I. OPENING SESSION

D. Cline, Chair

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Overview of Physics at a Muon Collider – *V. Barger* (UW-Madison)

Workshop on Physics at the FMC and Front End of a Muon Collider: A Brief Summary – S. Geer (FNAL)

Quantitative Higgs and Pseudo-Nambu-Goldstone Physics at the Muon Collider: Prospects at and Complementarity of LHC, NLC, MC – *J. Gunion* (UC Davis)

Recent Results at LEP II – *Y. Pan* (UW-Madison)

Physics Potential of CMS/LHC – *S. Dasu* (UW-Madison)

The Top Quark & Higgs Boson at Hadron Colliders – *C. Quigg* (Princeton/FNAL)

Comparison of Lepton and Hadron Colliders for the Discovery of SUSY – *H. Baer* (Florida St. U)

Higgs Searches at LEP-200: Present Status – *P. Bambade* (Orsay, France)

Overview of Physics at a Muon Collider

V. Barger

San Francisco Conference
December 10, 1997

Collaborators: M. Berger, J. Gunion, T. Han

The agenda:

Front End physics

- high intensity muon source for rare muon processes
- high energy μp collider for high Q^2 phenomena
- high intensity neutrino source for ν-oscillations

First Muon collider (FMC) physics

- Unique for s-channel Higgs or techni-resonances
- Precision threshold measurements $W^+W^-, t\bar{t}, Zh, \chi_1^+\chi_1^-, \ldots$
- SUSY chargino / neutralino / slepton pair production
- Precision tests of SUSY gauge couplings
- Z^0 factory for B-mixing and CP violation

Next Muon Collider (NMC) physics

- SUSY high mass particles
- Z' resonances
- Strong WW scattering if no Higgs

Plus . . . numerous other new physics possibilites

Front End Physics

current	$\sim 10^{8}$ muons/sec
muon collider	$\sim 10^{14}$ muons/sec

Probe rare muon processes Marciano (1997)

$\mu \to e\gamma$ now BF $< 0.49 \times 10^{-12}$

$\mu N \to e N$

muon EDM

Generic prediction of SUSY GUTs:
lepton flavor and CP violating processes
with significant rates (loop processes)
e.g. BF($\mu \to e\gamma$) $\sim 10^{-13}$

Barbieri, Hall, Strumia (1995);
Hisano, Moroi, Tobe, Yamaguchi (1997)

LPV also occurs via Z′, leptoquarks, . . .

μp collider H. Schellman (1997)
$\mu(200\text{ GeV}) \times p(1000\text{ GeV})$
max $Q^2 \sim 8 \times 10^5\ \text{GeV}^2$ ~ 90 × HERA
luminosity $\sim 10^{33}\ \text{cm}^{-2}\ \text{s}^{-1}$ ~ 300 × HERA

For $Q^2 > 5000\ \text{GeV}^2$
~ 326 NC events ZEUS now
~ 10^6 NC events μp collider

Search for leptoquarks up to $M_{LQ} \sim 800$ GeV

Search for contact interactions to $\Lambda \sim$ 6-9 [redacted] TeV
Kingman Cheung

Neutrino beam

μ-decay is the way to make neutrinos

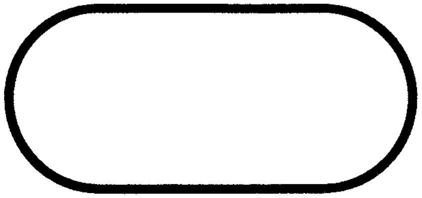
1000 × present neutrino flux
obtain 10^6 $\nu N, \bar{\nu} N$ events/year
measure charm production (6% of σ_{tot})
measure $\sin^2\theta_W$ [redacted]
infer $\Delta M_W = 30$–50 MeV in one year

NEUTRINO FLUX

P. Fisher (1997)

Muon storage ring

S. Geer (1997)



~ 10^{21} μ^+ or μ^- /year

~ 10^{20} neutrinos/year
with straight section
pointed towards detector

$$\mu^- \to \nu_\mu \bar{\nu}_e e^- , \quad \mu^+ \to \bar{\nu}_\mu \nu_e e^+$$

Known ν-fluxes for long baseline ν-oscillation experiments to any detector on Earth

$$P(\nu_a \to \nu_b) = \sin^2 2\theta \, \sin^2(1.27 \delta m^2 L/E)$$

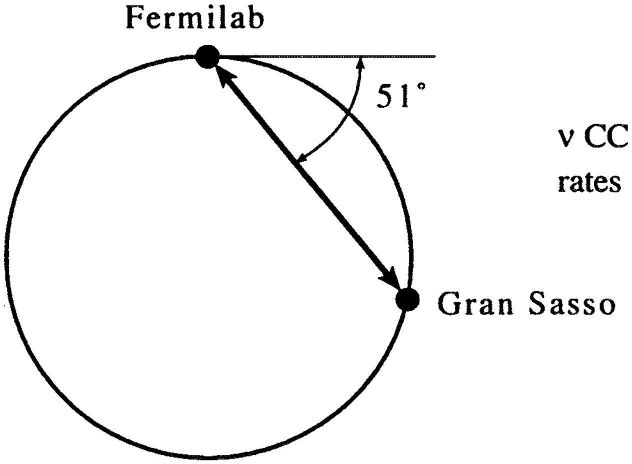
μ^- flux

oscillations	detect
$\nu_\mu \to \nu_e$	e^-
$\nu_\mu \to \nu_\tau$	τ^-
$\bar{\nu}_e \to \bar{\nu}_\mu$	μ^+
$\bar{\nu}_e \to \bar{\nu}_\tau$	τ^+

Very long baseline: Fermilab → Gran Sasso

$E_\nu = 10\text{–}50$ GeV

$L/E = 1000\text{–}200$ km/GeV



ν CC interaction
rates ~10^3/year

Sesitivity down to
$\delta m^2 \sim 10^{-5}$ eV^2 for $\sin^2 2\theta = 1$

First Muon Collider

R. Palmer (1997)

Parameters

	Low Energy		Medium Energy	Top Factory	Higher Energy
	Narrow σ_p	Broad σ_p			
$\sqrt{s}$ (GeV)	100	100	200	350	500
σ_p/p	3×10^{-5}	1×10^{-3}	1×10^{-3}	1×10^{-3}	1×10^{-3}
muons per bunch	3×10^{12}	3×10^{12}	2×10^{12}	2×10^{12}	2×10^{12}
number of bunches	1	1	2	2	2
repetition rate	15	15	15	15	15
turns/lifetime	820	820	890	1260	1560
L_{av} (cm^{-2} s^{-1})	5×10^{30}	6×10^{31}	1×10^{32}	3×10^{32}	7×10^{32}
L_{av} (fb^{-1}/year)	0.05	0.6	1	3	7

FMC Higgs Physics

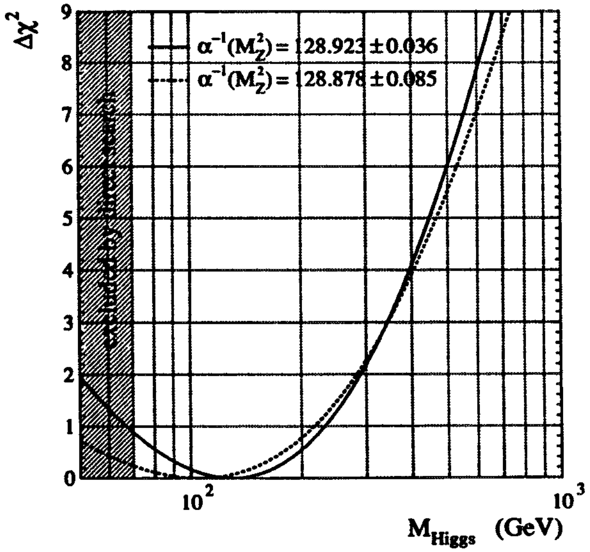
MSSM: 5 Higgs bosons h^0, H^0, A^0, $H^\pm$

lightest MSSM Higgs boson

$m_h \leq 125$ GeV

"The jewel in the SUSY crown"

Global EW analyses



Davier & Höcker (1997)

$m_h = 129^{+103}_{-92}$ GeV

Erler & Langacker (1997)

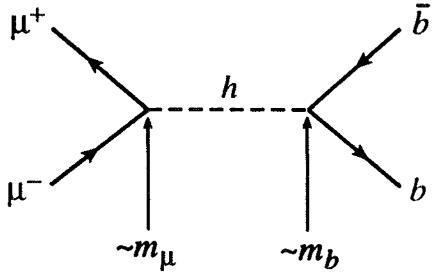
$m_h = 122^{+134}_{-77}$ GeV

Smoking gun for SUSY Higgs

Goals:

- precisely determine Higgs mass, width, and BFs
- differentiate $h_{\rm MSSM}$ from $h_{\rm SM}$
- find and study H^0, A^0

s-channel production unique to a muon collider



$$\sigma_h(\sqrt{\hat{s}}) = \frac{4\pi\,\Gamma(h \to \mu\bar{\mu})\,\Gamma(h \to X)}{(\hat{s} - m_h^2)^2 + m_h^2\,[\Gamma_h^{\rm tot}]^2}$$

Gaussian μ-beams with rms error $R(\%)$

rms error $\sigma_{\sqrt{s}}$ on $\sqrt{s}$:

$$\boxed{\sigma_{\sqrt{s}} = (2\ \mathrm{MeV})\left(\frac{R}{0.003\%}\right)\left(\frac{\sqrt{s}}{100\ \mathrm{GeV}}\right)}$$

Sensitive to the Higgs width with resolution $\sigma_{\sqrt{s}} \sim \Gamma_h$

$\Gamma_h \approx 2$ to 3 MeV   if $\tan\beta \sim 1.8$

Scan for s-channel Higgs

Important factors:

- beam resolution: $\sigma_{\sqrt{s}} \sim$ few MeV
- little bremsstrahlung and no beamstrahlung
- precise tuning of beam energy
  $\Delta E \sim 10^{-6} E$
  through continuous spin-rotation measurements

Raja

Case study: $m_h \approx$ **110 GeV**

Assume prior h-discovery at LHC

$$gg \to h \qquad h \to \gamma\gamma, 4\ell$$

$$\Delta m_h \sim 100\ \mathrm{MeV}$$

$$(L = 300\ \mathrm{fb}^{-1})$$

Design muon collider ring with $\sqrt{s} = m_h$

At $\sqrt{s} = m_h \approx 110$ GeV

$b\bar{b}$ signal $\approx 10^4$ events/fb
$b\bar{b}$ background $\approx 10^4$ events/fb

strong $\sqrt{s}$ dependence of background (Z^0-pole)

Luminosity / scan point
to observe or eliminate *h*-resonance

$L_{\rm s.p.} \sim 1.5 \times 10^{-3}\ {\rm fb}^{-1}, \quad S/\sqrt{B}=3$ ($L_{\rm s.p.} \uparrow \times 50$ for $m_h \sim M_Z$)

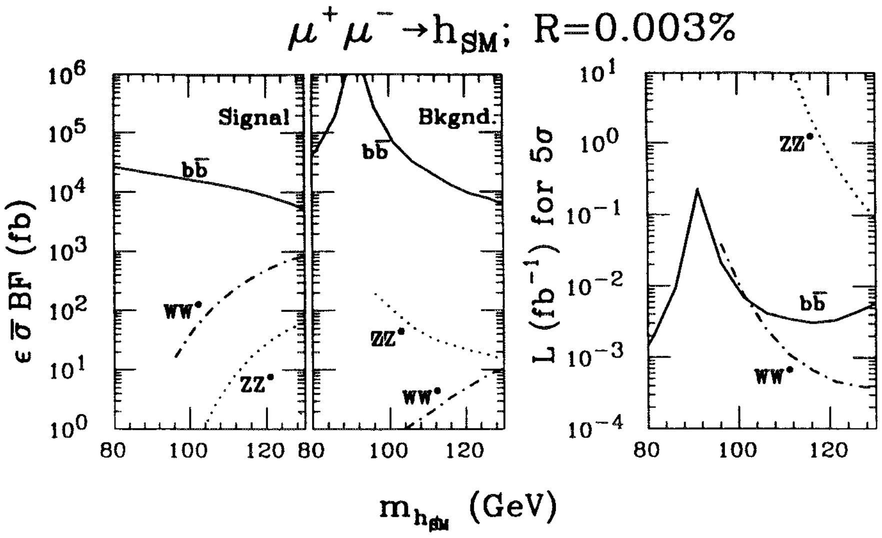
Number of scan points:
$n = 2\Delta m/\sigma_{\sqrt{s}} \approx 100$ for $\Delta m \sim 100$ MeV

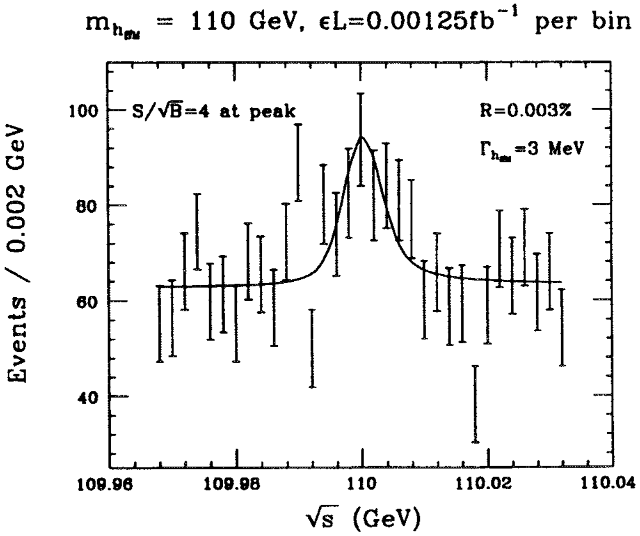
Total luminosity needed to locate *h*

$L_{\rm tot} \sim 0.15\ {\rm fb}^{-1}$

If machine delivers
$5 \times 10^{30}\ {\rm cm}^{-2}\ {\rm s}^{-1}$ 0.05 fb^{-1}/year
3 years running needed

Scan determines $\Delta m \sim 1$ MeV





Fine scan over resonance peak

With $L = 0.4\ \mathrm{fb}^{-1}$ obtain accuracies

Γ_h^{tot}	16%
$\sigma\mathrm{BF}(b\bar{b})$	1%
$\sigma\mathrm{BF}(WW^*)$	5%

Infer m_A from $r_{h_{\mathrm{MSSM}}}/r_{h_{\mathrm{SM}}}$

$$\boxed{r = \mathrm{BF}(WW^*)\ /\ \mathrm{BF}(b\bar{b})}$$

insensitive
to tanβ

	sensitivity up to
s-channel data alone	$m_A \approx 450$ GeV
s-channel + Zh data	$m_A \approx 600$ GeV

Higgs width contains information on "missing" SUSY decays $h_{\mathrm{MSSM}} \to \chi_1^0\chi_1^0$

Observing MSSM H^0 and A^0

Not so easy at other colliders

LHC:	not possible at $m_A > 200$ GeV for $3 \leq \tan\beta \leq 5$–10
NLC:	$e^+e^- \to H^0A^0$ may be kinematically inaccessible
γγ:	high luminosity (~200 fb^{-1}) needed for $\gamma\gamma \to H^0, A^0$

Muon collider s-channel

H^0, A^0 widths broader than h

$\Gamma \sim 30$ MeV	$m_A < 2m_t$
~ 3 GeV	$m_A > 2m_t$

So $R \sim 0.1\%$ ($\sigma_{\sqrt{s}} \sim 70$ MeV) adequate for scan

$L_{\mathrm{s.p.}} \sim 0.1\ \mathrm{fb}^{-1}$ probes $\tan\beta > 2$

Required range of scan depends on other information available on m_0, $m_{1/2}$ and tanβ to indicate A^0 and H^0 mass ranges

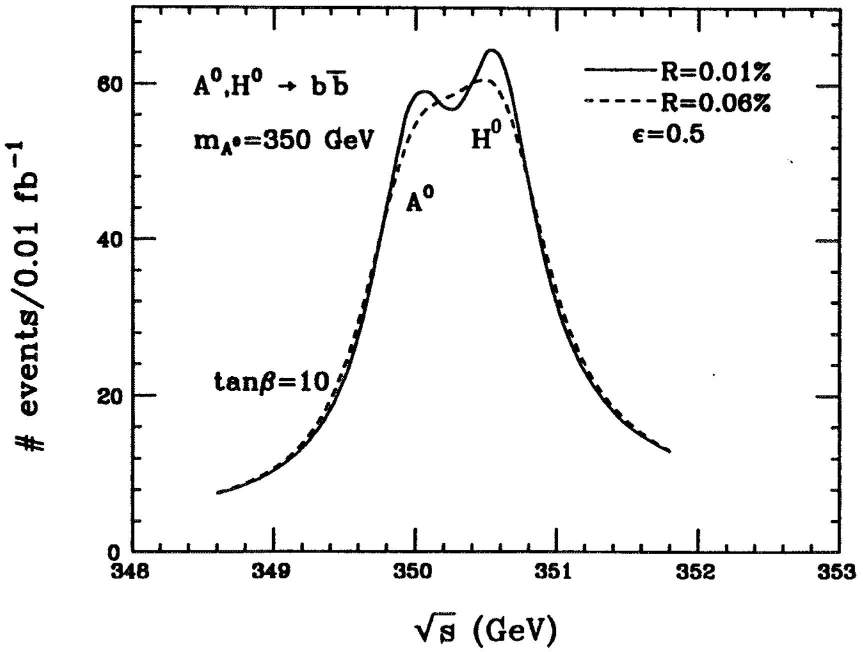
Nearly degenerate A^0 and H^0

In mSUGRA with large m_A,

$$m_{A^0} \approx m_{H^0} \approx m_{H^\pm}$$

with very close degeneracy at large tanβ

Only an s-channel scan may allow separation of A^0 and H^0



Walking Technicolor

Bhat, Eichten (1997)

in Eichten-Lane model (1995–97)

Technipion resonances in the s-channel

$$\mu^+\mu^- \to \pi_T^0,\ \rho_T^0,\ \omega_T^0$$
$$\pi_T^0 \to b\bar{b}.\ \tau\bar{\tau},\ t\bar{t}$$
$$\rho_T^0 \to \pi_T\pi_T,\ W\pi_T,\ WW$$
$$\omega_T^0 \to b\bar{b},\ \tau\bar{\tau},\ t\bar{t},\ \gamma\pi_T^0,\ Z\pi_T^0$$

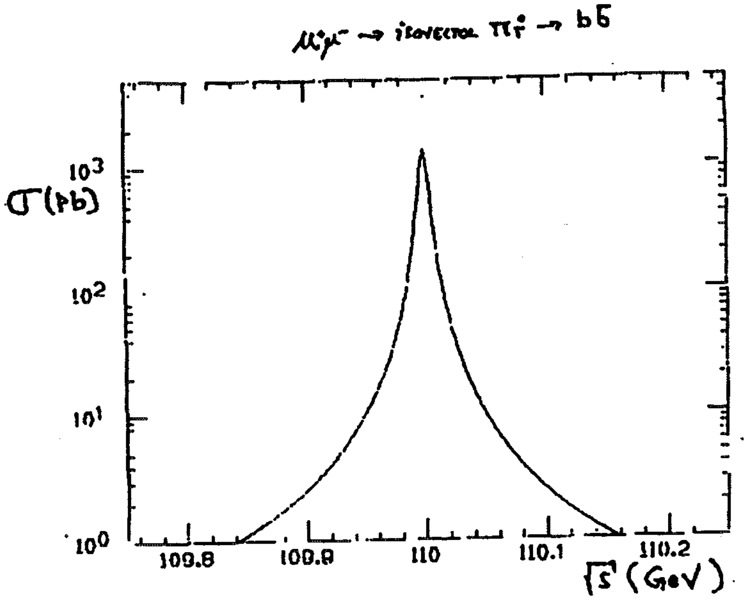
Resonance masses ≈ 100–500 GeV
widths ≈ 0.1–50 GeV

Peak cross sections ≈ 10^7–10^4 fb

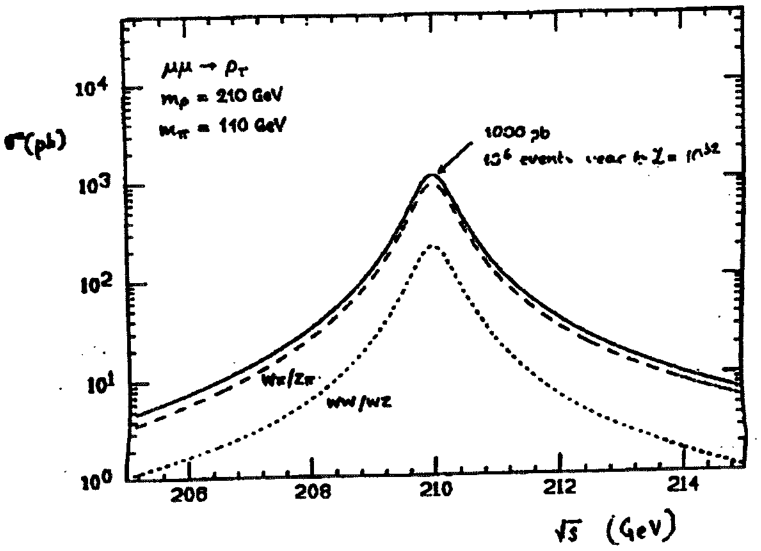
Easy to find and study at a muon collider

Threshold mass measurements (R = 0.1%)

cf. M. Berger talk



Bhat,
Eichten
(1997)

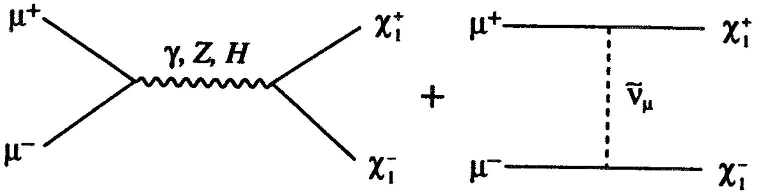


	$10\ \mathrm{fb}^{-1}$	
$\mu^+\mu^- \to W^+W^-$	ΔM_W = 20 MeV	
$\mu^+\mu^- \to t\bar{t}$	Δm_t = 0.2 GeV	
$\mu^+\mu^- \to Zh$	Δm_h = 140 MeV	(for m_h = 100 GeV)
$\mu^+\mu^- \to \chi_1^+ \chi_1^-$	$\Delta m_{\chi_1^+}$ = 700 MeV	(for $m_{\chi_1^+}$ = 200 GeV)

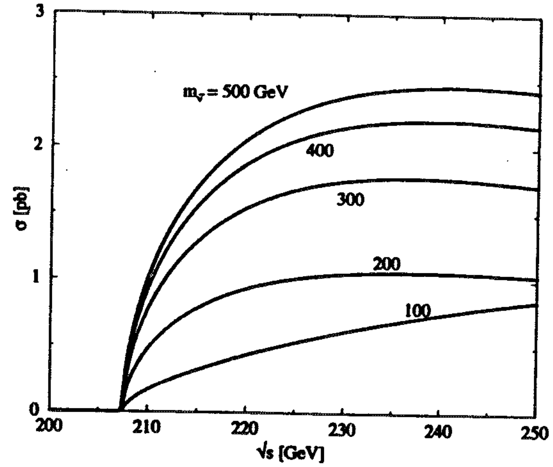
Improved test of EW radiative corrections once m_h known

SUSY particles

Lightest chargino



$$\chi_1^+ \to f\bar{f}'\chi_1^0$$



σ depends on

$m_{\chi_1^+}$ and $m_{\tilde{\nu}_\mu}$

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destructive interference

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infer $m_{\tilde{\nu}_\mu}$

Cuts suppress *WW* background leaving ~5% signal efficiency for 4 jets + $\not{E}$

2 point threshold measurement (with $L = 10\ \mathrm{fb}^{-1}$, $R = 0.1\%$)

$\Delta m_{\chi_1^+}$ (MeV)	$m_{\chi_1^+}$ (GeV)	$m_{\tilde{\nu}_\mu}$ (GeV)
100	100	500
100	100	300
300	200	500
700	200	300

Window to high mass squarks via radiative corrections

g_i: SM gauge couplings to $f\bar{f}$

h_i: SUSY gaugino couplings to $\tilde{f}f$

Unbroken SUSY $h_i = g_i$

Broken SUSY:

$$\frac{h_1 - g_1}{g_1} \simeq 1.8\% \log_{10}\left(\frac{M_{\tilde{Q}}}{m_{\tilde{\ell}}}\right)$$

$$\frac{h_2 - g_2}{g_2} \simeq 0.7\% \log_{10}\left(\frac{M_{\tilde{Q}}}{m_{\tilde{\ell}}}\right)$$

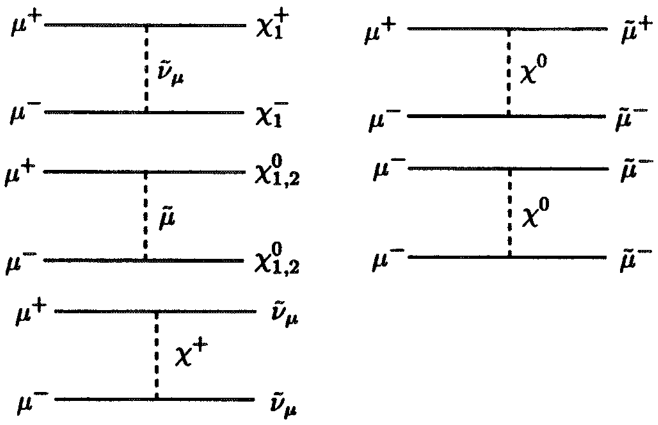
Chankowski (1990)
Nojiri, Fujii, Tsukamoto (1996)
Cheng, Feng, Polonsky (1997)
Diaz, King, Ross (1997)

One-loop amplitudes obtained from tree-level amplitudes by substitution of modified coupling *t*-channel exchange processes have cross-sections enhanced up to

$$9\% \log_{10}\left(\frac{M_{\tilde{Q}}}{m_{\tilde{\ell}}}\right)$$

$\Longrightarrow$ precision measurements sensitive to squarks with $M_{\tilde{Q}} \gtrsim 1$ TeV

Some interesting *t*-channel processes



Muon collider advantage: accurate mass measurements near thresholds

Technique relies on knowledge of exchanged particle mass

Z-factory

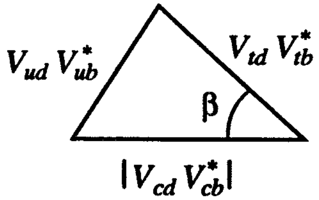
Han
Demarteau

Advantages:

μ-polarization, b & $\bar{b}$ separation, long b-decay length

- Study B-mixing and CP violation in $Z \rightarrow b\bar{b}$

  Measure angle β from $B^0 \rightarrow K_s\, J/\Psi$ decays



- Polarization allows measurement of LR and FB asymmetries

	A^0_{LR},	$A^{0,b}_{\mathrm{FB}}$,	$A^{0,\tau}_{\mathrm{FB}}$	
deviate by	2.4σ,	1.9σ,	1.7σ	from SM

A^0_{LR} gives best measurement of $\sin^2\theta_w$; statistics dominated

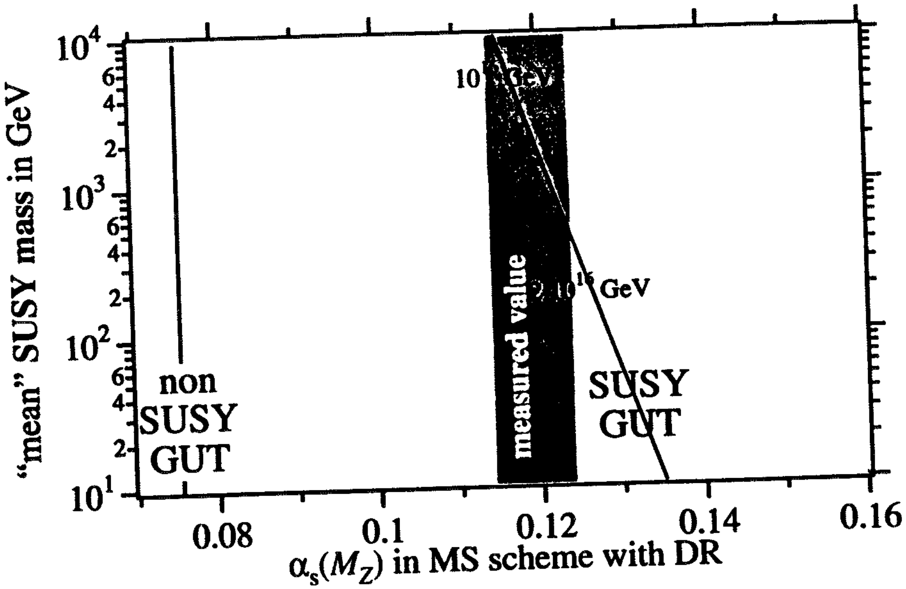
Need $> 10^7$ Z's

$L > 0.15\ \mathrm{fb}^{-1}$

Heavy supersymmetry

Use gauge coupling unification to predict mean SUSY mass scale

Langacker, Polonsky (1993);
Carena, Pokorski, Wagner (1993)



Barbieri (1997)

New global fit: $\alpha_s(M_Z) = 0.1214 \pm 0.0031$

Langacker, Erler (1997)

$\Longrightarrow (M_{\mathrm{SUSY}})_{\mathrm{mean}} \simeq 1$ TeV

Some SUSY particles will likely have masses at the TeV scale

e.g. first 2 generation sfermions can be heavy without conflict with naturalness

LHC: mainly gluinos and squarks produced — these decay to lighter SUSY particle

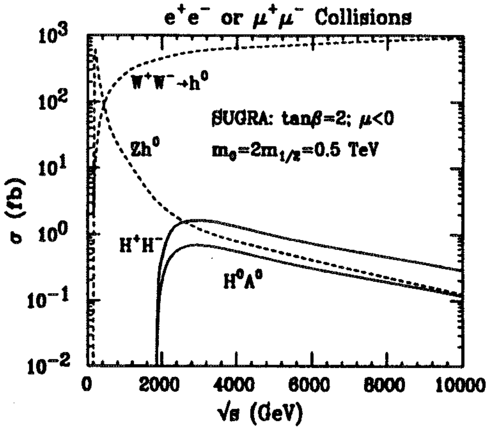
Baer, Tata

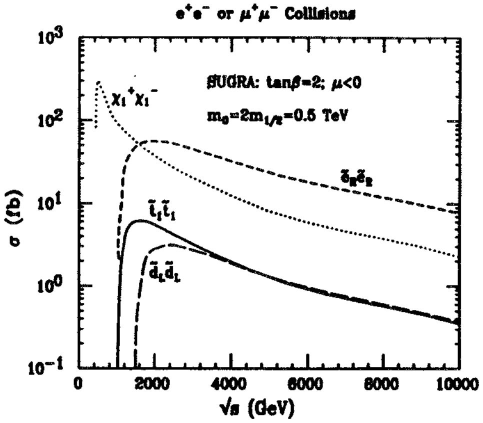
Great SUSY machine, but some measurements very difficult or impossible at LHC

Hinchliffe
Paige

- Mass of LSP
  measurements give SUSY mass differences
- Sleptons with mass ≳ 200 GeV
  Drell-Yan production too small at high mass
- Heavy Gauginos $\chi_2^\pm$, $\chi_{3,4}^0$
  mainly Higgsino
  direct production rate small
  useful BFs small
- Heavy Higgs bosons, $H^\pm, H, A$
  small cross sections
  $t\bar{t}$ decays likely dominate
  impossible if SUSY decays dominate

At a lepton collider, pair production of scalars is P-wave suppressed. Energies well above threshold are necessary for sufficient production rates





A 3–4 TeV muon collider with high luminosity (L ~10^2–10^3 fb^{-1}/year) would allow sufficient event rates to reconstruct heavy sparticles from their complex cascade decay chains

Z′ resonance

Z′s are a natural consequence of string models

Cvetic, Langacker

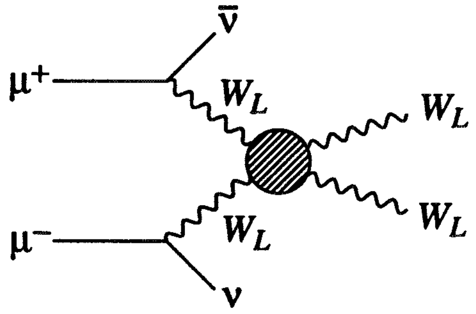
enormous event rates on resonance

Contact terms

test for virtual high mass Z′ effects

Strongly Interacting W_L-Sector (SEWS)

cf. T. Han talk



$$A_{W_L W_L}: \quad \begin{array}{ll} \sim m_H^2/v^2 & \text{if light Higgs} \\ \sim s_{WW}/v^2 & \text{if no light Higgs} \end{array}$$

If no Higgs with m_H<600 GeV, partial wave unitarity of $W_L W_L$ requires strong scattering at 1–2 TeV energy scale

Energy reach critical: $\sqrt{s_{WW}} \gtrsim 1.5\ \mathrm{TeV}$

Since $E_\mu \sim (3\text{–}5) E_W$

$\Rightarrow \sqrt{s_{\mu\mu}} \sim (3\text{–}5)\sqrt{s_{WW}} \gtrsim 4\ \mathrm{TeV}$

SEWS dynamics

- heavy scalar: resonances
- heavy vector: resonances
- non-resonant: $A_{W_L W_L} \sim s/v^2$ (LET)

Impressive signals in all models

$\sigma \sim 50$ fb

CONCLUSIONS

Front End offers dramatic improvements in sensitivity for

- flavor-violating transitions
- high Q^2 phenomena in DIS muon-proton interactions
- neutrino oscillations

First Muon Collider offers

- unique probes of supersymmetry, particularly s-channel resonances
- high precision threshold measurements of masses
- tests of SUSY radiative corrections and indirect probe of high mass squarks
- possible Z^0 factory for B-physics

Next Muon Collider guarantees access to

- heavy SUSY scalar particles
- strong WW scattering if no Higgs and no SUSY

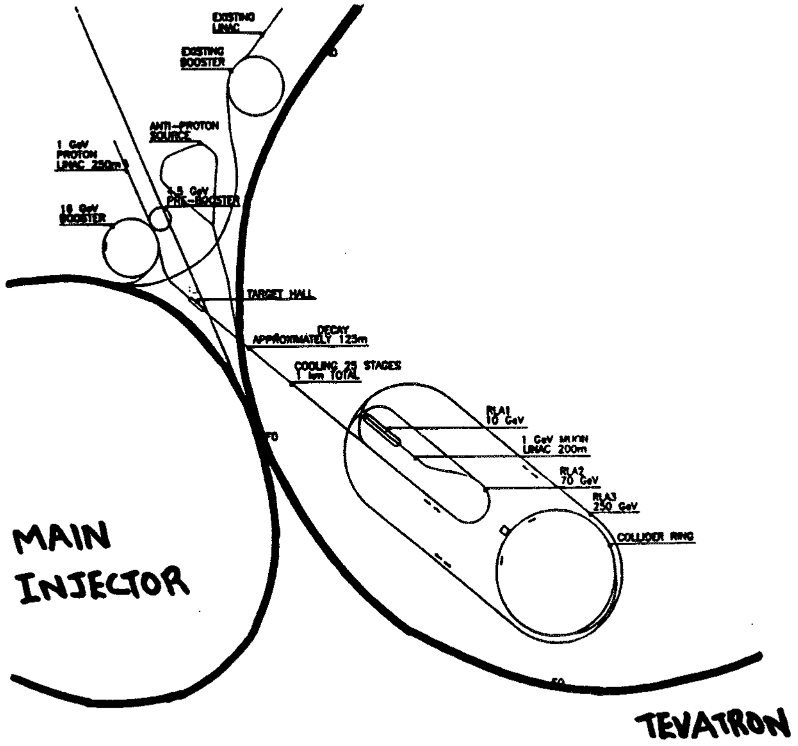
bottom line

Muon colliders are robust options for probing new physics. A lot has already been learned, but much remains to be explored!

Workshop on Physics at the First Muon Collider & Front–End of a Muon Collider: A Brief Summary

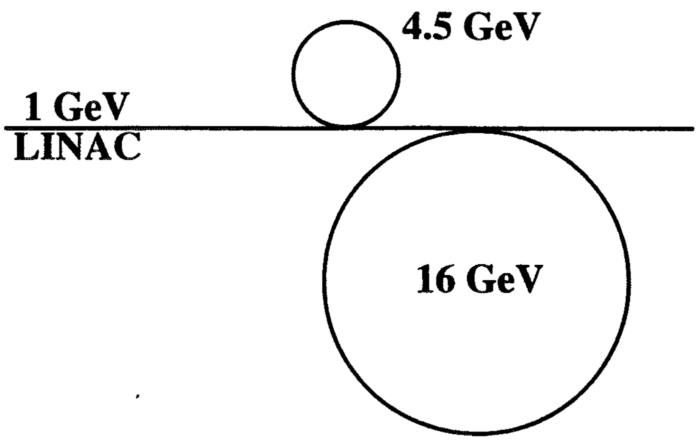
- Workshop at Fermilab, Nov. 6–9
  More than 200 people participated
- 9 Working Groups:
  - Accelerator
  - Low Energy Hadron Physics
  - Neutrino Physics
  - Deep Inelastic Scattering
  - Low Energy Muon Physics
  - Higgs & Z Factories at the FMC
  - SUSY at the FMC
  - Stong Dynamics at the FMC
  - Top Factory at the FMC

Enormous amount of material



Accelerator Working Group

- Concentrated on a few critical issues in proton driver design for a Fermilab source with 10^{14} protons per pulse at 15 Hz:



- RF system design

  Longitudinal space charge effects

  Short few ns bunches

  Instability issues

Bob Noble
Encouraging progress

Proton Sorce Parameters for the Workshop

Based on Summer Study -> *S.D. Holmes et al, Fermilab TM*-2021

	Step 1		Step 2	Step 3
	Scenario 1	Scenario 2		
Linac				
Kinetic Energy (MeV)	400	1000	1000	1000
Momentum Spread (95% FW)	1	1	1	1
Current (mA)	45	67.1	112	328.5
Pulse Length (μs)	0.75	0.75	0.75	0.75
H^- per pulse	1×10^{13}	1.5×10^{13}	2.5×10^{13}	1×10^{14}
Repetition Rate (Hz)	15	15	15	15
Pre–Booster				
Extraction Kinetic Energy (GeV)				4.5
Momentum Spread (95% HW)				0.5%
Circumference (m)				180.6
Protons per bunch				5×10^{13}
Number of Bunches				2
Repetition Rate (Hz)				15
Extracted bunch length (ns)				21
Transverse Emittance (mm–mr)				200π
Longitudinal Emittance (eV–sec)				1.8
Booster				
Extraction Kinetic Energy (GeV)	16	8	16	16
Momentum Spread (95% HW)	< 0.1%	< 0.1%	< 0.1%	1.2%
Crcumference (m)	474.2	474.2	474.2	474.2
Protons per Bunch	1.2×10^{11}	1.8×10^{11}	3.0×10^{11}	5×10^{13}
Number of Bunches	84	84	84	2
Repetition Rate (Hz)	15	15	15	15
Extracted bunch length (ns)	4.9	4.9	4.9	2.3
Transverse Emittance (mm–mr)	50π	30π	50π	240π
Longitudinal Emittance (eV–sec)	2.2	1.8	1.8	4.0

-> 1.5×10^{15} protons/sec at 16 GeV/c

Compared with effectively a few x 10^{12} protons/sec at 8 GeV/c from BOOSTER now.

Physics with Low Energy Hadrons

- Can inject a factor of 3–4 more into Main Injector -> direct benefit to MI physics program ... Kaons, neutrinos (see later), antiproton production, ...
- The most extensive low energy hadron physics that would benefit seems to be the Kaon physics program. For example searches for rare decays:

$K^+ \to \pi^+ \nu\bar{\nu}$	$K^0 \to \pi^0 \nu\bar{\nu}$	Windows on physics beyond the Standard Model
$K_S \to \pi^0 e^+ e^-$	$K \to \pi\mu e$	
$K_L \to \mu e$	etc ...	

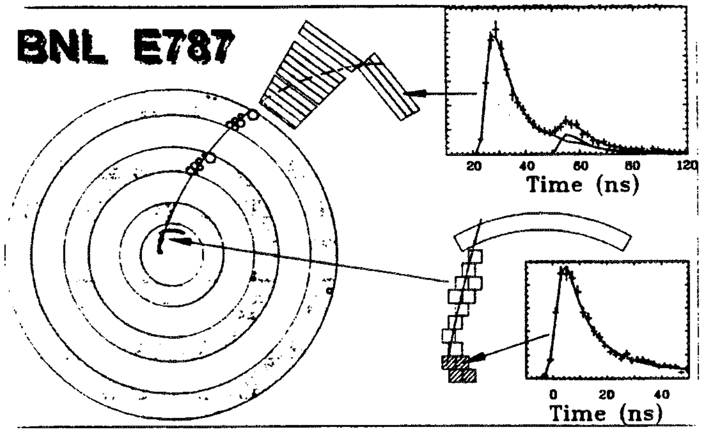
- Depending on what previous experiments had been run (MI, AGS′, JHF) the FEMC would enable improvements in sensitivity from a few -> x10.

	AGS	AGS′	MI	JHF	FEMC
p (GeV/c)	25	25	120	50	16
Duty factor	0.33	0.27	0.33	0.16	0.90
Tera–p / sec	20	30	10	60	400
K_L sensitivity	26	40	100	150	325
Stopped K^+	12	18	8	47	210

- Needs a stretcher ring -> duty factor 90%.

$K^+ \to \pi^+ \nu\bar{\nu}$

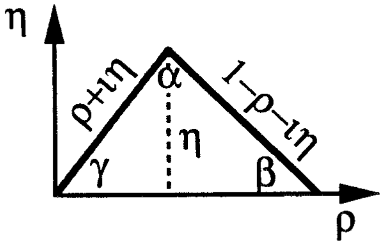
- Standard Model: BR = $(9.1 \pm 3.8) \times 10^{-11}$



1 event seen

-> BR = $(42^{+97}_{-35}) \times 10^{-11}$

New physics or statistical fluctuation ?

- Current goals (AGS2000 & KAMI) -> ± 15%
- 

W. Marciano

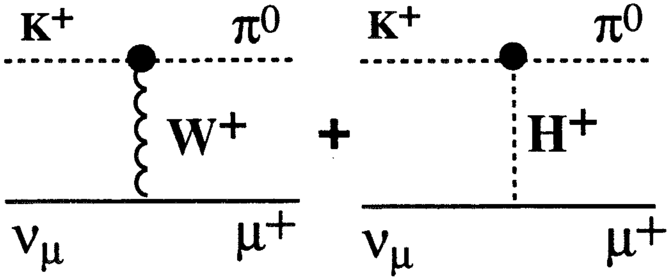
FMC Front–End

BR -> ± 4%

-> $\Delta\eta/\eta \sim \pm 0.02$!

- Also additional x 3 in MI would help KAMI ... note Experiments hard ... probably need both stopped K^+ and decay in flight techniques

$K^+ \rightarrow \pi^0 \mu^+ \nu$ T–Violating μ Polarization



W. Marciano

New Physics
~~CP~~ Interference
(Multi–Higgs)

- KEK E246 –> 9 x 10^{-4}
- Proposal for AGS2000 experiment –> 1.3 x 10^{-4}.
- At Front–End MC –> 10^{-5} ?

$$P_\mu^T = \hat{s}_\mu \cdot (\hat{p}_\mu \times \hat{p}_\pi)$$

T violating

K_S , $K_L \rightarrow \pi^+\pi^-$ Interference

- Produce almost pure K^0 beam using rf separated K^+ beam and charge exchange. Measure amplitude versus proper time t :

  Interference ~ $2D\,|\eta| \cos(\Delta m t - \phi_{+-}) \exp(-t/2\tau_S)$
- CPT experiment at MI –> $\Delta m/m < 4 \times 10^{-20}$ Plank scale CPT test ... would benefit from x(3–4) more protons in MI.
- Lower energy experiment at FEMC also possible. The K_S yield/proton for 25 GeV K_S/120 GeV p similar to 6 GeV K_S / 16 GeV p !

Physics with Low Energy Hadrons: Summary

- There is an extensive Kaon–physics program that could be pursued at the Front–End of a muon collider, which could provide experiments with a factor of a few – 10 more Kaons than will be available in the next few years.
- The physics motivation for rare–Kaon decay physics is likely to remain strong in the future –> window on physics beyond the LHC scale.
- In addition to an extensive K–physics program, there are also many hadronic physics topics looking for a home. The ones considered at the workshop were:

  Proton exclusive scattering and polarization
  Proton & antiproton forward scattering
  Proton form–factors
  Hypernuclear physics
  Baryon spectroscopy
  Rare η decays and symmetry tests
  Light quark spectroscopy
  Charmonium spectroscopy
  Exotic meson and glueball searches

Neutrino Physics

- **Exploit intense muon source to produce very intense neutrino/antineutrino beams.**
- **The resulting beams are qualitatively better than conventional beams from meson decays.**

Precisely known flavor content:

$\mu^- \to \nu_\mu + \bar{\nu}_e + e^-$ **and** $\mu^+ \to \bar{\nu}_\mu + \nu_e + e^+$

Great for $\nu_e - \nu_x$ oscillations (including $\nu_e - \nu_\tau$) !

Great for $\nu_x - \nu_\tau$ oscillations (No $D_S \to \nu_\tau$ in beam !)

Great for $\nu_\mu - \nu_e$ oscillations (No ν_e in ν_μ beam !)

Precisely known fluxes and differential distributions:

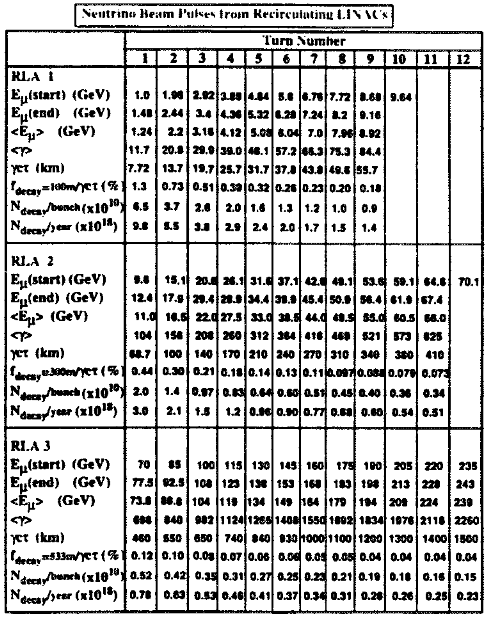
$$\nu_\mu : \frac{dn}{dx\,d\Omega} = \frac{1}{4\pi}\left[2x^2(3-2x) \mp 2x^2(1-2x)\mathcal{P}\cos\theta\right]$$

$$\nu_e : \frac{dn}{dx\,d\Omega} = \frac{1}{4\pi}\left[12x^2(1-x) \mp 12x^2(1-x)\mathcal{P}\cos\theta\right]$$

where $x = 2E_\nu/m_\mu$, θ is the angle between the neutrino and the muon spin, and $\mathcal{P}$ is the muon polarization.

Neutrino Beam Options

- **Use collider straight sections (*Bruce King*)**
- **Use Recirculating Linear Acceltrs (*Chuck Ankenbrandt*).**



Neutrino Beam Pulses from Recirculating LINACs

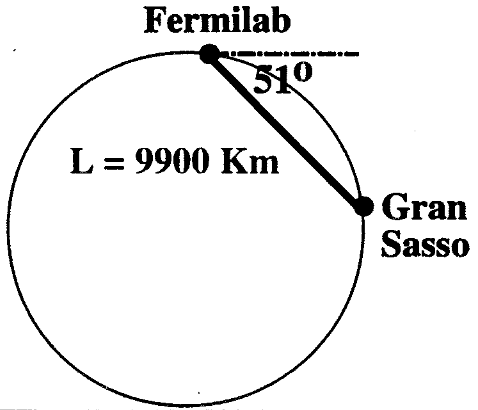
	Turn Number											
	1	2	3	4	5	6	7	8	9	10	11	12
RLA 1												
E_μ(start) (GeV)	1.0	1.96	2.92	3.88	4.84	5.8	6.76	7.72	8.68	9.64		
E_μ(end) (GeV)	1.48	2.44	3.4	4.36	5.32	6.28	7.24	8.2	9.16			
$<E_\mu>$ (GeV)	1.24	2.2	3.16	4.12	5.08	6.04	7.0	7.96	8.92			
$<\gamma>$	11.7	20.8	29.9	39.0	48.1	57.2	66.3	75.3	84.4			
$\gamma c\tau$ (km)	7.72	13.7	19.7	25.7	31.7	37.8	43.8	49.8	55.7			
f_{decay}=100m/$\gamma c\tau$ (%)	1.3	0.73	0.51	0.39	0.32	0.26	0.23	0.20	0.18			
N_{decay}/bunch (x10^{10})	6.5	3.7	2.6	2.0	1.6	1.3	1.2	1.0	0.9			
N_{decay}/year (x10^{18})	9.8	5.5	3.8	2.9	2.4	2.0	1.7	1.5	1.4			
RLA 2												
E_μ(start) (GeV)	9.6	15.1	20.6	26.1	31.6	37.1	42.6	48.1	53.6	59.1	64.6	70.1
E_μ(end) (GeV)	12.4	17.9	23.4	28.9	34.4	39.9	45.4	50.9	56.4	61.9	67.4	
$<E_\mu>$ (GeV)	11.0	16.5	22.0	27.5	33.0	38.5	44.0	49.5	55.0	60.5	66.0	
$<\gamma>$	104	156	208	260	312	364	416	468	521	573	625	
$\gamma c\tau$ (km)	68.7	100	140	170	210	240	270	310	340	380	410	
f_{decay}=300m/$\gamma c\tau$ (%)	0.44	0.30	0.21	0.18	0.14	0.13	0.11	0.097	0.088	0.079	0.073	
N_{decay}/bunch (x10^{10})	2.0	1.4	0.97	0.83	0.64	0.60	0.51	0.45	0.40	0.36	0.34	
N_{decay}/year (x10^{18})	3.0	2.1	1.5	1.2	0.96	0.90	0.77	0.68	0.60	0.54	0.51	
RLA 3												
E_μ(start) (GeV)	70	85	100	115	130	145	160	175	190	205	220	235
E_μ(end) (GeV)	77.5	92.5	108	123	138	153	168	183	198	213	228	243
$<E_\mu>$ (GeV)	73.8	88.8	104	119	134	149	164	179	194	209	224	239
$<\gamma>$	698	840	982	1124	1266	1408	1550	1692	1834	1976	2118	2260
$\gamma c\tau$ (km)	460	550	650	740	840	930	1000	1100	1200	1300	1400	1500
f_{decay}=533m/$\gamma c\tau$ (%)	0.12	0.10	0.08	0.07	0.06	0.06	0.05	0.05	0.04	0.04	0.04	0.04
N_{decay}/bunch (x10^{10})	0.52	0.42	0.35	0.31	0.27	0.25	0.23	0.21	0.19	0.18	0.16	0.15
N_{decay}/year (x10^{18})	0.78	0.63	0.53	0.46	0.41	0.37	0.34	0.31	0.28	0.26	0.25	0.23

RLA neutrino pulses ... workshop parameters (*Steve Geer*)

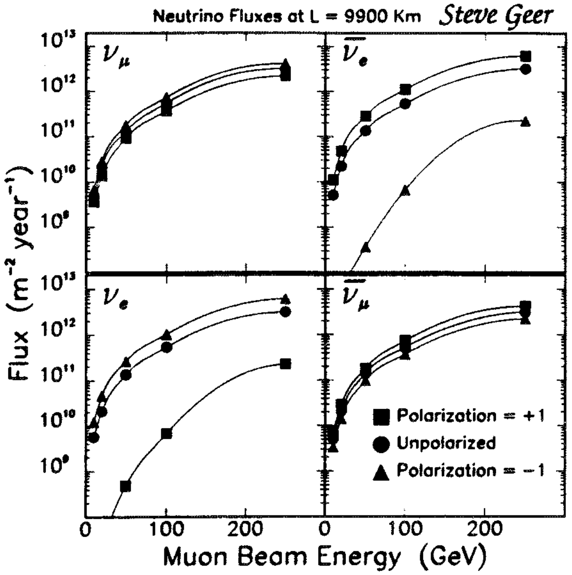
- **Build special storage ring with long straight section e.g. Straight section = arc length -> 25% of muons decay in right direction (*Steve Geer*)**

With 7.5 x 10^{20} μ^+ (or μ^-) per year, can get O(10^{20}) neutrinos/yr produced in the straight section.

Neutrino Fluxes: Fermilab -> Gran Sasso



E_ν (GeV)	L/E Km/GeV
10	990
20	495
30	330
40	71
50	20

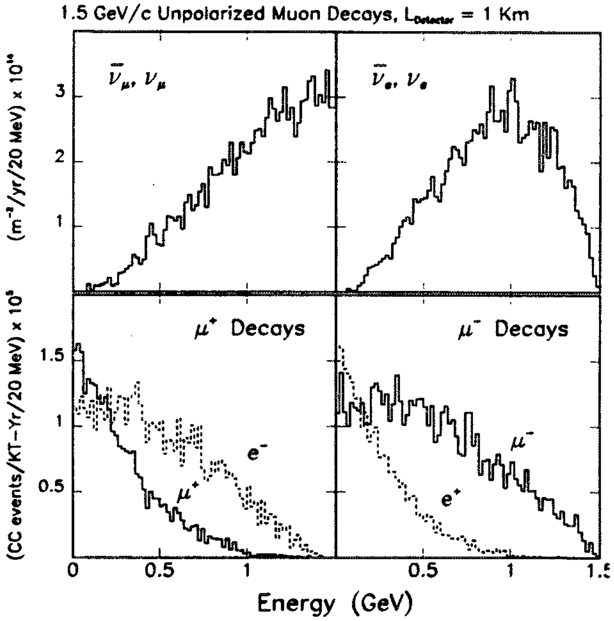


Example: for a 20 GeV initial muon beam the fluxes in Europe are a few x 10^{10} neutrinos per m^2 per year.

For fluxes at Soudan, multiply by 183 -> about 10 x currently forseen MINOS fluxes !

Low Energy Short Baseline Scenario

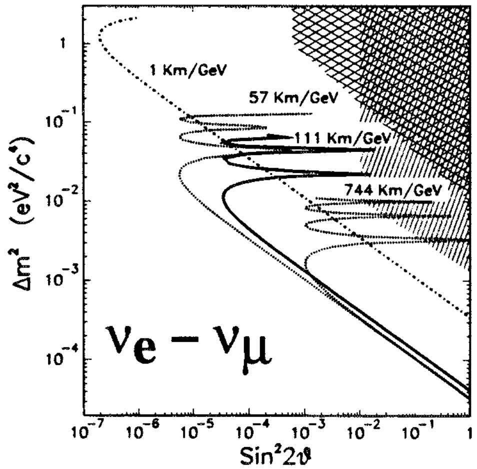
- **Consider a 1.5 GeV/c muon beam stored in a ring with a straight section pointing at an experiment 1 Km away:**

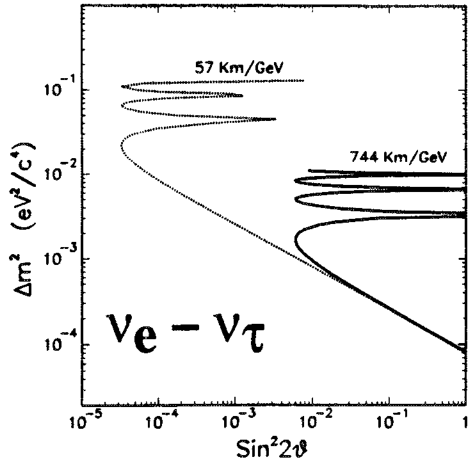


- **1.4 x 10^{16} ν_e m^{-2} yr^{-1}**
- **1.4 x 10^{16} ν_μ m^{-2} yr^{-1}**
- **6 x 10^6 ν CC interactions KT^{-1} yr^{-1}**
- **3 x 10^6 $\bar{\nu}$ CC interactions KT^{-1} yr^{-1}**

$P = \sin^2 2\theta \, \sin^2(1.27 \, \Delta m^2 \, L/E)$

Steve Geer: Fermilab–PUB/97–389



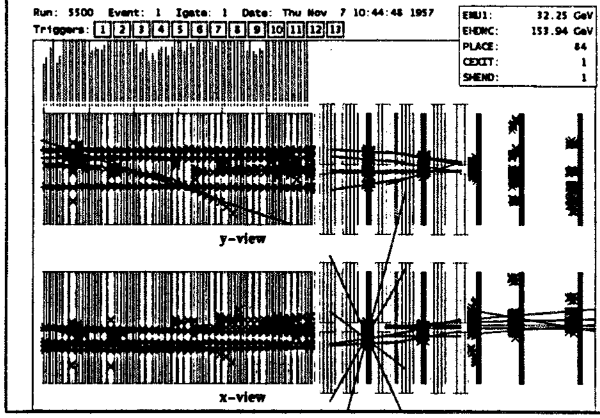


Single Event Sensitivity Contours in ($\sin^2 2\theta$, Δm^2)–plane

Search for wrong–sign μ

- **Hatched = MINOS**
- **Cross–hatched = MiniBooNE**
- **L/<E> = 1 km/GeV**
  1 km baseline
  E_μ = 1.5 GeV
- **L/<E> = 57 km/GeV**
  Fermilab–Soudan
  E_μ = 20 GeV
- **L/<E> = 111 km/GeV**
  Fermilab–Soudan
  E_μ = 10 GeV
- **L/<E> = 744 km/GeV**
  Fermilab–Gran Sasso, E_μ = 20 GeV

Deep Inelastic Scattering



Kevin McFarland

Simulation of NuTeV (CCFR) exposed to 1 turn 600m downstream of RLA3 (250 GeV muon decays)

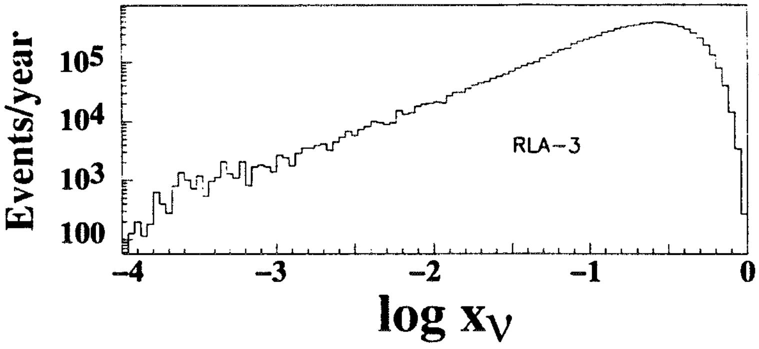
Multiple neutrino interactions (+ a bunch of muons)

- **Factor of 1000 more than present $\nu_\mu N$ rates !**
- **Beam spot small (90% ν within 40cm)**
- **Can use small precision detectors:**

Emulsion: (*Reay*)
H_2 Target + $\check{C}$ + CAL + μ (*B. King*)
Scint. target + CAL + μ range (*K. McFarland*)
Bubble Chamber at 15 Hz (*H. Schellman*)

- **With special purpose 250 GeV ring –> 800 000 ν interactions / year in a 10 kg detector (*S. Geer*) so why not use Si Pixel target ?**

νN DIS Physics



D. Harris & *K. McFarland*

900 kg
3m x 3m
target

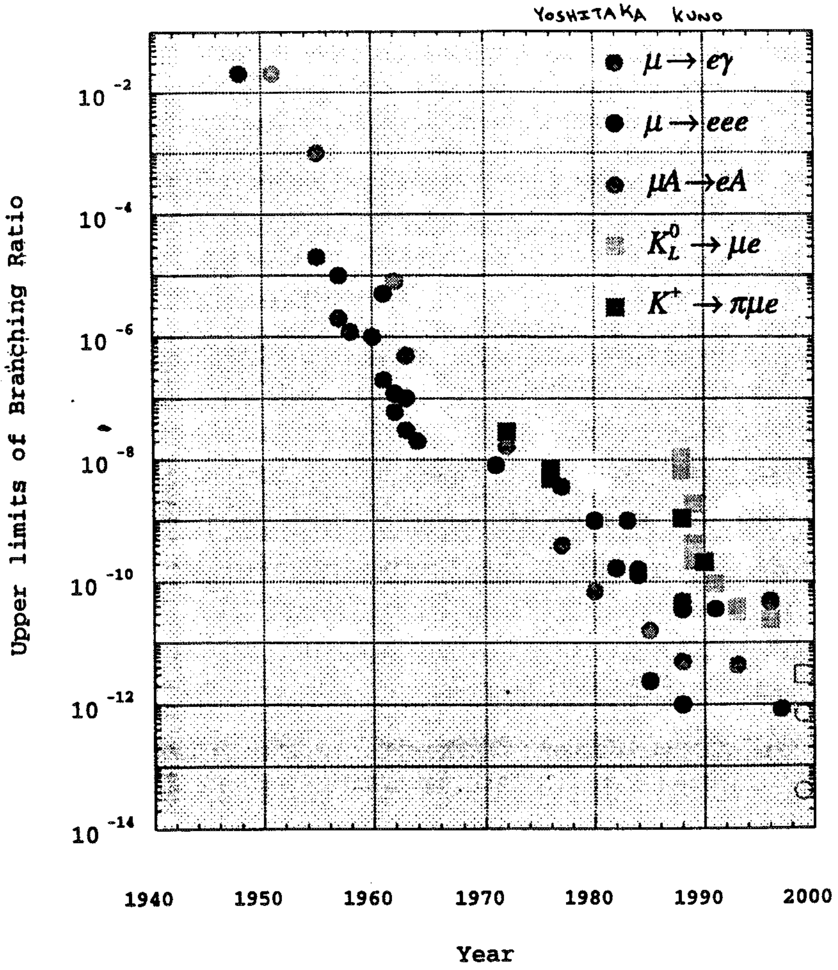
- RLA−3 (250 GeV muons) −> 1 m long LH_2 target −> ~10 million events/year ... dont need a heavy target so can measure proton structure directly !
- $\sin^2\theta_W$: NC/CC ratio −> statistical error = 0.2%. Main systematic from charm production ... measure it !! Estimate can get to $\Delta\sin^2\theta_W < 0.5\%$ −> ΔM_W ~ 20−50 MeV.
- Charm production: 1 m long LH_2 target −> 100 000 reconstruced events / year −> $|V_{dc}|^2$, s, $\bar{s}$.
- Spin physics (where does the proton spin come from ?). Look for polarization of, for example, strange sea quarks.
- B−Physics: $\nu_\mu u \rightarrow \mu^+ b$: 20 events/year/ 3 m H_2 −> $|Vub|^2$ ... for more statistics −> dedicated ring ?

Low Energy Muon Physics

Potentially an extensive experimental physics program but for many experiments the challenge comes from the instantaneous rate .... so the bunch structure is critical.

Exp.	Process	Topic
Rare Decays	μ+Z −> e+Z μ −> eγ μ −> eee	Lepton flavor viol SM test GUT, SUSY, ...
μ decay	lifetime spectrum	G_F, SM test SM test
g−2 Muon EDM	g−2 EDM	SM test P−, T−violation
Muonic atoms	μ^+e μp $\mu\mu$?	QED test EW Interference P−, T−violation
μ capture	μHe_3 μp μd μZ	low energy QCD SM test medium effects
T violation	μZ	SM test

Upper Limits for Lepton Flavor Violation



- **Want to get to, for example:**
  BR(μ –> e γ) < 10^{-14}, or BR(μN –> eN) < 10^{-16}

  –> Probes for leptoquarks, Higgs boson effects, contact interactions etc ... e.g. $\Lambda_C > 3000$ TeV !

- **Typically experiments want to maximize useful muon flux, whilst minimizing instantaneous rate:**

Wrong time structure for cooling channel

- **So either find a way of delivering muons DC or CW or ....**
  - ◆ **Find experiments that can use short intense muon pulses with low duty factor ...**
    Muon EDM may be an example but it requires polarization (50% ?).
  - ◆ **Find experiments that can use the muons before the cooling (large phase–space) .... in which case we can consider a DC or CW source .... example: MECO μ –> e conversion experiment.**

- **Is there a strong low energy muon physics program at the Front–End of a muon collider ? Needs work !**

First Muon Collider: Workshop Parameters

	Low Energy		Medium Energy	Top Factory	Higher Energy
	Narrow σ_p	Broad σ_p			
$\sqrt{s}$ (GeV)	100	100	200	350	500
beam energy (GeV)	50	50	100	175	250
σ_p/p	3×10^{-5}	1×10^{-3}	1×10^{-3}	1×10^{-3}	1×10^{-3}
muons per bunch	3×10^{12}	3×10^{12}	2×10^{12}	2×10^{12}	2×10^{12}
number of bunches	1	1	2	2	2
repetition rate (Hz)	15	15	15	15	15
norm. $\varepsilon_\perp$ (mm–mr)	297π	85π	67π	56π	50π
Collider Circum (m)	380	380	700	864	1000
f_{rev} (Hz)	7.9×10^5	7.9×10^5	4.3×10^5	3.5×10^5	3.0×10^5
turns/lifetime	820	820	890	1260	1560
β^* (cm)	13	4	3	2.6	2.3
σ_z (cm)	13	4	3	2.6	2.3
σ_r (μm)	286	85	47	30	22
$\mathcal{L}_{peak}$ (cm^{-2} s^{-1})	6×10^{32}	7×10^{33}	6×10^{33}	1×10^{34}	2×10^{34}
$\mathcal{L}_{av}$ (cm^{-2} s^{-1})	5×10^{30}	6×10^{31}	1×10^{32}	3×10^{32}	7×10^{32}

Z^0 Factory

- **LEP Z–pole era is over. To be worthwhile, a 2nd generation Z–factory (muon collider) would need to make 10^8 Z / year –> $\mathcal{L} = 2 \times 10^{32}$ cm^{-2} s^{-1}**
- **This luminosity seems out of reach of present design study parameters. Never–the–less, consider physics program if $\mathcal{L} = 2 \times 10^{32}$ cm^{-2} s^{-1} could be achieved.**

$\sin^2\theta_W$: Discrepancy (LEP vs SLD) likely to remain. If muon polarization = 45%, then with 10 million Zs A_{LR} –> $\delta(\sin^2\theta_W) < 10^{-4}$ ... this would be great. Note: $\Delta(\sin^2\theta_W) = 15 \times 10^{-4}$ as $m_H = 60$ GeV –> 1000 GeV.

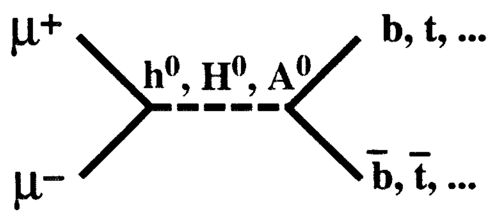
Γ_Z: Presently $\Gamma_Z = 2.4948 \pm 0.0020 \pm 0.0015$(energy). With continuos energy calibration (spin precession) & more statistics –> $\delta < 0.0003$.

$R_l = \Gamma_{had}/\Gamma_l$: Presently $R_l = 20.775 \pm 0.0025$ –> $\alpha_s = 0.124 \pm 0.004 \pm 0.002$ (theory, m_H). Improve statistics by 10 –> $\delta(\alpha_s) < 0.001$.

R_b, Michel parameters in τ decays, B_S oscillation, rare B decays, ...

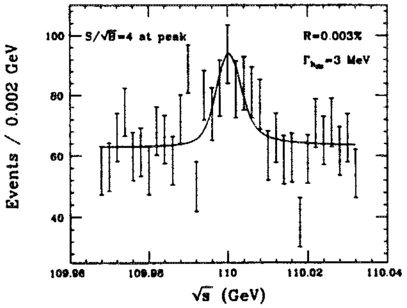
- **ISSUES: Luminosity measurement (needs work), polarization (45% ?), LUMINOSITY !**

Higgs Factory



The Jewel in the Crown !

Jack Gunion & V. Barger



Assume:

Center−of−mass energy spread R = 0.003%

A priori know from LHC:

m_h = 110 ± 100 MeV
GeV

−> 3 years at 0.05 fb^{-1}/yr

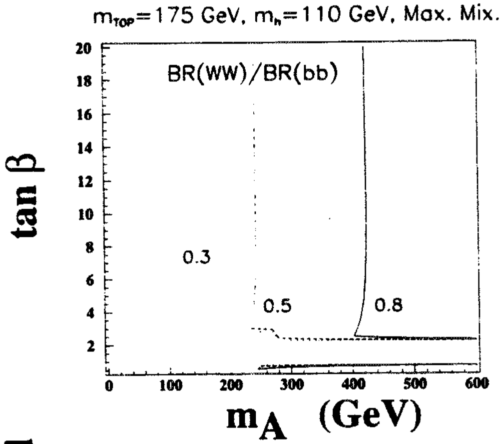
Once m_h known to 1 MeV, make a 3 point scan:

Γ_h^{tot} : 16%	**Δm_h ~ 0.1 MeV**
$\sigma \cdot BR(b\bar{b})$: 3%	**$\Delta\Gamma_h$ ~ 0.5 MeV**
$\sigma \cdot BR(WW^*)$: 15%	

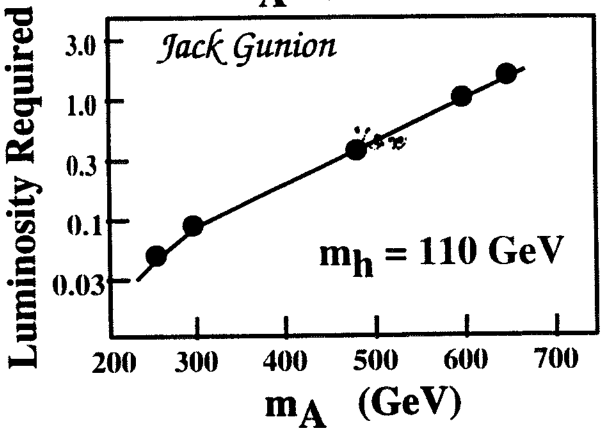
−> 8 years of running at 5 x 10^{30} cm^{-2} s^{-1}

- **A factor of 3 more luminosity than workshop parameters would make a big difference !**

m_h = 110 GeV



- **Note: For SM $BR(WW)/BR(b\bar{b}) = 1$**
- **Can distinguish between SM and MSSM over large region of parameter space.**
- **S−channel + Zh data −> sensitivity up to M_A ~ 600 GeV**

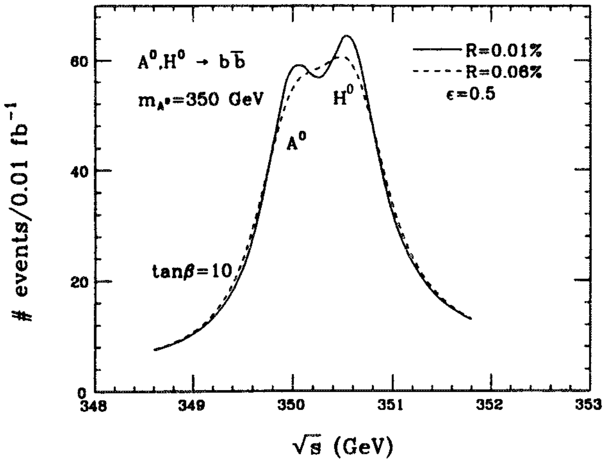


Luminosity needed for a 3σ discovery using BR(WW)/BR(bb) etc.

In the same way that the Sp$\bar{p}$S collider discovered the Z^0 & LEP/SLC milked the precision Z^0 physics, it could be that the LHC (or TEV33) discover the Higgs and the FMC milks the precision Higgs physics.

SUSY Physics

- **There are > 100 SUSY–breaking parameters (Milles [1984], Haber & Kane [1985]) and MANY models.**
- **To uniquely determine which model describes reality (if any) will require the observation of all (?) of the sparticles, and many precision measurements ... & will take more than one machine.**
- **The Higgs sector is a vital piece of the picture (h^0, H^0, A^0, $H^{\pm}$) –> compelling case for an FMC.**
- **H^0 and A^0 widths broader than h^0. Beam energy spread of 0.1% may be adequate for scan.**

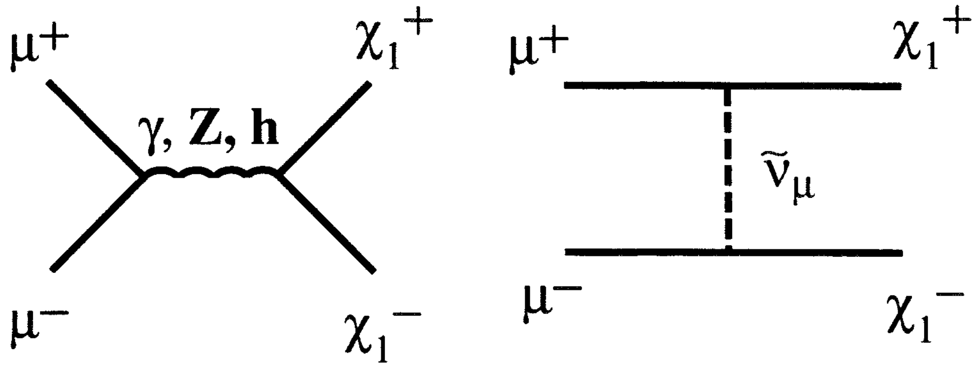


In mSUGRA with large m_A:

$m_A \sim m_{H^0} \sim m_{H^{\pm}}$

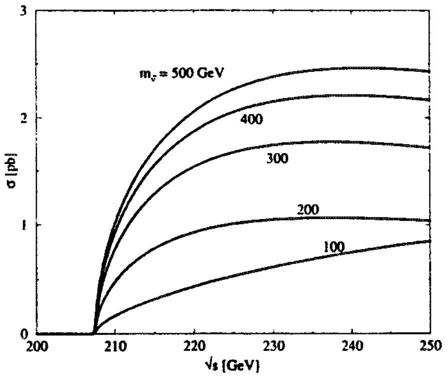
at large tan β ... only an S–channel scan may allow separation of A & H^0

Charginos



- **$\chi_1^+ \to f\bar{f}'\chi_1^0$ ... look for 4 jets + $\not{E}_T$**

V. Barger



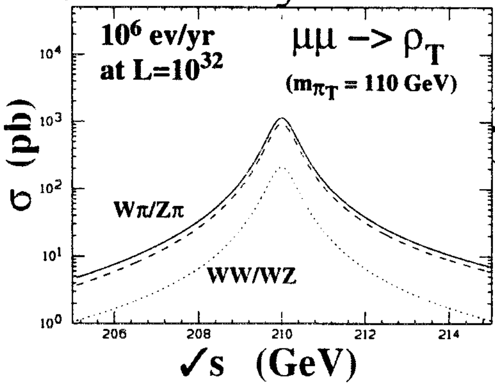
- **σ depends on $m_{\chi_1^+}$ and $m_{\tilde{\nu}_\mu}$ –> infer $m_{\tilde{\nu}_\mu}$**
- **Polarization can be used to turn off ν_μ contribution**

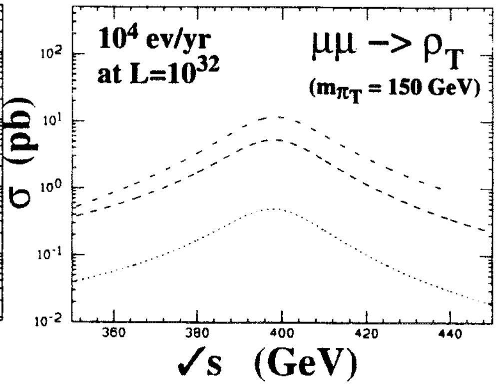
- *Final Remark:* **If we live in a SUSY world some sparticles may well be at the TeV scale .... sooner or later we will want a multi–TeV collider !**

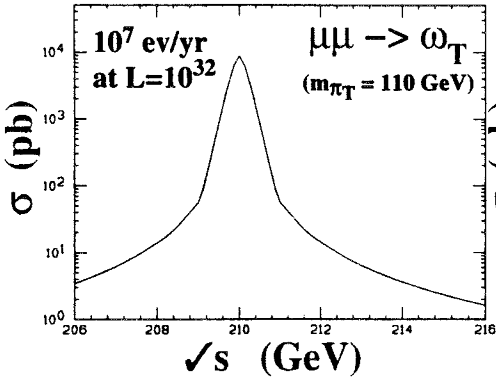
Strong Electroweak Sector

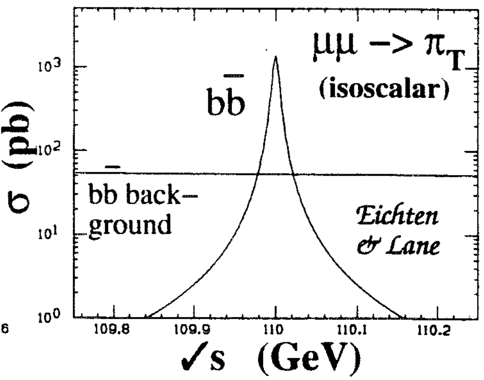
- **Technihadrons low enough in mass to be produced at the FMC will probably be first seen at TEV33 ... or if not, at the LHC. Need precision measurements of masses, widths, BRs, study ρ,ω interference, etc.**

John Wolmesely







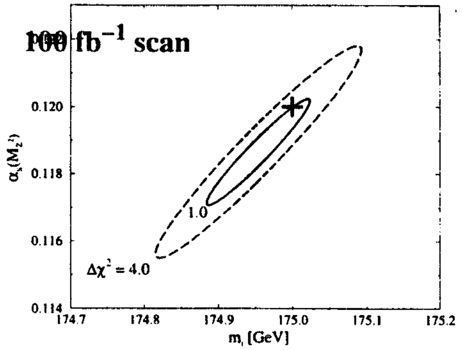


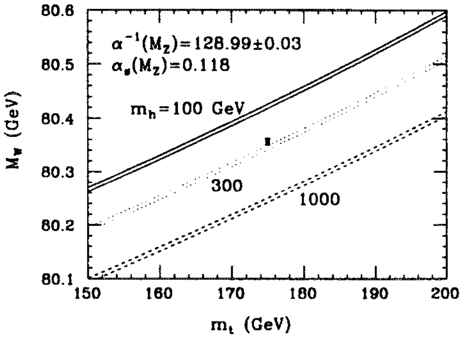
- **If no light Higgs boson exists then EW gauge bosons develop strong interactions at the 1–2 TeV scale -> 3–4 TeV muon collider needed.**

Top Factory

- **Precise m_W & m_t measurements test radiative structure of SM -> look for new physics. Important if nothing new found at TeV33/LHC**

Barger, Berger, Gunion, Han





- **Threshold $t\bar{t}$ production -> m_t, m_H, $|V_{tb}|^2$, α_s**

- **Example: 10 fb^{-1} scan**
  (3 yrs at 3 x 10^{32} cm^{-2} s^{-1})

  Δm_t ~ 200 MeV

- **Can check consistency of SM with Higgs Boson**

- **Theoretical uncertainties:**

  Deftn pole mass (*M. Smith*)
  NNLO correctns (*A. Hoang*)
  Final state interactions
  Final state gluons (*L. Orr*)

- **Can also search for anomalous top couplings (polarization would enhance capability) & new particles in production ($\mu\mu$ -> X -> $t\bar{t}$, $\mu\mu$ -> H -> $\bar{t}c + \bar{c}t$) and decay (e.g. t -> H^+b).**

Summary: Workshop Conclusions

- There is an enormous amount of Front–End physics to think about ! The neutrino physics possibilities look great ! Can we invent low energy muon experiments that match the Front–End bunch structure .... or a way to make the bunch structure match the experiments ?
- There is a strong cutting–edge physics program at the FMC in almost any scenario. If a Higgs–like object is discovered at TeV33/LHC an FMC Higgs factory would be GREAT ! If nothing is found at TeV33/LHC, precision m_W and m_t studies very desirable (–> top factory) and eventually a multi–TeV muon collider would be needed !
- Some things that were identified as important and/or need of more work:

◆ We cant afford to give up any luminosity ... in fact a factor of 3 more luminosity than given in workshop parameters seems plausible and is VERY desirable !

◆ How well can we measure the luminosity ?

◆ What B–tagging efficiency can we expect ? ...
i.e. more work on detector/backgrounds needed !

◆ What polarization can we really achieve ?
(vs luminosity).

Score Card

Rating	Topic	Comments
✱	Low Energy Hadrons	Adiabatic continuation of Kaon program
?	Low Energy Muons	Bunch structure ? More work needed.
✱✱✱	Neutrinos–Oscillations	Exciting qualitative & quantitative improvement
✱✱✱	Neutrinos – DIS	
☆☆☆☆	Higgs Factory	Jewel in the crown !
☆☆	SUSY	Higgs sector compelling & precision spectroscopy
☆☆	SEWS	Precision spectroscopy
☆	Top Factory	Important if TeV33/LHC find nothing
✝	Z Factory	Need higher luminosity than presently forseen

QUANTITATIVE HIGGS AND PSEUDO-NAMBU-GOLDSTONE PHYSICS AT THE MUON COLLIDER

Prospects at and Complementarity of LHC, NLC, MC

J. F Gunion, 4th International Conference on Muon Colliders, San Francisco, (December, 1997)

Collaborators: Barger, Berger, Han, Kelly, Grzadkowski, Martin, Poggioli, VanKooten, D. Dominici

OUTLINE OF TOPICS

- Prospects for and means for distinguishing the MSSM h^0 or other SM-like light Higgs bosons from the SM h_{SM} via branching ratios and couplings, and implications.
- Strategies for finding the MSSM H^0 and A^0 and the role of the MC.
- Higgs pair production at the MC.
  - Discovery
  - What we learn from the branching ratios of the H^0, A^0 in the supersymmetric GUT context.
- Verifying Higgs CP properties.
- Exotic Higgs sectors: complementarity of LHC and s-channel processes at electron and muon colliders.
- Discovering the pseudo-Nambu-Goldstone bosons of a technicolor model for a strongly interacting electroweak sector. (BESS example).

Some +'s and −'s and Critical Requirements for the Muon Collider

Key advantages as compared to an electron collider:

- There is less bremsstrahlung and no beamstrahlung.
- Beam energy resolution can be substantially better — in particular. $R = 0.003\%$ can be achieved at the low-energy Higgs factory so that the Gaussian spread in $\sqrt{s}$, given by
$$\sigma_{\sqrt{s}} \sim 2\text{ MeV}\left(\frac{R}{0.003\%}\right)\left(\frac{\sqrt{s}}{100\text{ GeV}}\right), \quad (0.1)$$
can be as small as the natural width of a light SM-like Higgs boson.
- The beam energy can be very precisely tuned: $\Delta E_{\text{beam}} \sim 10^{-5} E_{\text{beam}}$ is 'easy'; 10^{-6} is achievable and very important for scanning a narrow Higgs boson or other resonance.

Additional positive aspect:

Since the cost of a final storage ring is modest, several would be built as the energy of the machine is increased, each designed to optimize luminosity at specific energies designed for specific physics goals. The Higgs/PNGB list would include:

- s-channel Higgs factory production at $\sqrt{s} \sim m_h$ of any narrow width Higgs discovered at another facility.

  Compute $\overline{\sigma}_h$ by convoluting a Gaussian $\sqrt{s}$ distribution of width $\sigma_{\sqrt{s}}$ with the standard s-channel Breit Wigner Higgs resonance cross section. For $\sqrt{s} = m_h$, one obtains
$$\overline{\sigma}_h \simeq \frac{\pi\sqrt{2\pi}\,\Gamma(h\to\mu\mu)\,BF(h\to X)}{m_h^2\sigma_{\sqrt{s}}} \times \left(1+\frac{\pi}{8}\left[\frac{\Gamma_h^{\text{tot}}}{\sigma_{\sqrt{s}}}\right]^2\right)^{-1/2}. \quad (0.2)$$

Eq. (0.2) ⇒ small $\Gamma_h^{\rm tot}$ and $\sigma_{\sqrt{s}} \sim \Gamma_h^{\rm tot} \to$ big $\overline{\sigma}_h$.

- s-channel scan for P^0 technicolor resonance peak at $\sqrt{s} \sim m_{P^0}$, followed by detailed study. Lack of limits on the typical P^0 imply decent luminosity needed starting at $\sqrt{s} \sim 10$ GeV and going on up to $100 - 200$ GeV.
- Rings designed to scan for heavier Higgs bosons (e.g. MSSM H^0, A^0) that are expected theoretically, and predicted to have substantial $\mu^+\mu^-$ coupling, but that are not observed elsewhere because of e.g. weak ZZ, WW couplings
- Operation at high $\mathcal{L}$ near the Zh threshold for any Higgs with substantial ZZh coupling (e.g. SM Higgs). (This would actually be the first goal if a SM-like Higgs has been observed and has $m_h > 2m_W$.)

  Note: Even if $m_h < 2m_W$, there are important Higgs properties that are most easily measured at Zh maximal cross section rather than in s-channel production. If these measurements have not been covered at a e^+e^- collider, then the muon collider would have to perform them.
- Eventual operation at very high energy for Higgs pair production.

Discriminating among SM-like light Higgs bosons, *e.g.* h^0 vs. h_{SM}. (J.G., L. Poggioli, R. Van Kooten + . .)

With no NLC or MC:

- It is hard. Snowmass96 study ⇒ precision inadequate in 'decoupling' sort of limit of particular interest. In particular, very hard to probe the fermionic (*e.g.* $b\overline{b}$) couplings that → largest deviations in the decoupling limit. $m_h \sim m_Z$ = best case: LEP2, TeV33 and LHC data all available.

- LEP2 + TeV33 + LHC

Table 1: Summary of approximate errors for branching ratios and couplings-squared at $m_{h_{SM}} \sim m_Z$ in the M1 mass region. Where appropriate, estimated systematic errors are included. Quantities not listed cannot be determined in a model-independent manner. As discussed in the text, directly measured products of couplings-squared times branching ratios can often be determined with better accuracy.

Quantity	Error ($m_{h_{SM}} \sim m_Z$)
$BF(b\overline{b})$	±26%
$(WWh_{SM})^2/(ZZh_{SM})^2$	±14%
$(WWh_{SM})^2$	±20%
$(ZZh_{SM})^2$	±22%
$(\gamma\gamma h_{SM})^2/(b\overline{b}h_{SM})^2$	±17%
$BF(\gamma\gamma)$	±31%
$(ggh_{SM})^2$	±31%
$(t\overline{t}h_{SM})^2/(WWh_{SM})^2$	±21%
$(t\overline{t}h_{SM})^2$	±30%

Above are statistical errors only, for $L = 300\ {\rm fb}^{-1}$ each for ATLAS and CMS, $L = 30\ {\rm fb}^{-1}$ at Tevatron, and $L = 250\ {\rm pb}^{-1}$ per experiment at LEP192.

- No direct access to $(b\overline{b}h)^2$ or $(\tau^+\tau^-h)^2$ or $(\gamma\gamma h)^2$ couplings: **need total width to convert branching ratios to couplings.**
- Much less will be known if $m_{h_{SM}}$ is beyond LEP2 reach.
- Overall, without NLC and/or MC data, we will know that the Higgs is SM-like, but we will not be able to discriminate between different SM-like possibilities without going to NLC and MC.

NLC data alone:

- The best 'bet' for discriminating between SM-like Higgs bosons for $m_h \leq 130$ GeV is $\sigma BF(h \to c\bar{c})/\sigma BF(h \to b\bar{b})$; for $m_h \geq 130$ GeV (as in NMSSM), $\sigma BF(h \to WW^\star)/\sigma BF(h \to b\bar{b})$ valuable.
  - New results from Snowmass96 use 'topological tagging' (*e.g.* primary, secondary, tertiary for b jet but only primary and secondary for c jet). With state of the art vertex detector can separate with remarkable efficiency.
  - For $L = 200$ fb^{-1} at $\sqrt{s} = 500$ GeV and $m_h \leq 130$ GeV (and combining Zh, ZZ-fusion and WW-fusion production processes). $\Rightarrow$ statistical error in $BF(c\bar{c})/BF(b\bar{b})$ of $\sim \pm 7\%$.
  - Theoretical uncertainty in $m_c(m_c)$ and $m_b(m_b)$ (sum rules, lattice) and QCD running from $m_c, m_b \to m_h$ should reach $< 10\%$ level in a few years $\to$ net error of $\lesssim 10\%$.

$\Rightarrow$ distinguish h^0 from h_{SM} at $\geq 2\sigma$ level for $m_{A^0} \leq$ 450 GeV for $m_{h^0} = m_{h_{SM}} = 110$ GeV.

- Many other h properties can be determined, but:
  - the most accurately measured are not very useful for distinguishing h_{SM} from h^0 for large m_{A^0} due to rapid approach to decoupling limit;
  - others that could be very useful, e.g. $\Gamma_h^{\rm tot}$, must be measured very indirectly, and thus not very accurately.

Table 2: Summary of approximate errors for branching ratios, coupling-squared ratios, couplings-squared and $\Gamma^{\rm tot}_{h_{SM}}$ as determined using only data accumulated in $\sqrt{s} = 500$ GeV running at the NLC, assuming $L = 200$ fb^{-1} is accumulated. For $BF(h_{SM} \to \gamma\gamma)$ we have combined the NLC $\sqrt{s} = 500$ GeV results with results obtained using LHC data; the net accuracy so obtained for $BF(h_{SM} \to \gamma\gamma)$ is also reflected in the determination of $\Gamma^{\rm tot}_{h_{SM}}$ following the indirect procedure. The errors for $\Gamma(h_{SM} \to \gamma\gamma)$ quoted are for $L = 50$ fb^{-1} accumulated in $\gamma\gamma$ collider running at $\sqrt{s} \sim m_{h_{SM}}/0.8$, and are those employed in the indirect $\Gamma^{\rm tot}_{h_{SM}}$ determination.

Quantity	Errors			
$m_{h_{SM}}$ (GeV)	**80**	**100**	**110**	**120**
$(c\bar{c}h_{SM})^2/(b\bar{b}h_{SM})^2$	$\sim \pm 7\%$			
$(WWh_{SM})^2/(b\bar{b}h_{SM})^2$	–	–	–	±23%
$(\gamma\gamma h_{SM})^2/(b\bar{b}h_{SM})^2$	±52%	±33%	±29%	±26%
$(ZZh_{SM})^2$	±3% – ±4%			
$BF(h_{SM} \to b\bar{b})$	±5%			
$BF(h_{SM} \to c\bar{c})$	$\sim \pm 9\%$			
$BF(h_{SM} \to WW^\star)$	–			
$(WWh_{SM})^2$	±5%			
$(ZZh_{SM})^2/(WWh_{SM})^2$	±6% – ±7%			
$BF(h_{SM} \to \gamma\gamma)$	±15%	±14%	±14%	±14%
$(\gamma\gamma h_{SM})^2$	$\sim \pm 12\%$			
$\Gamma^{\rm tot}_{h_{SM}}$ (indirect)	±19%	±19%	±19%	±18%
$(b\bar{b}h_{SM})^2$	±20%	±19%	±19%	±19%
$m_{h_{SM}}$ (GeV)	**130**	**140**	**150**	**170**
$(c\bar{c}h_{SM})^2/(b\bar{b}h_{SM})^2$	±7%	?		
$(WWh_{SM})^2/(b\bar{b}h_{SM})^2$	±16%	±8%	±7%	±16%
$(\gamma\gamma h_{SM})^2/(b\bar{b}h_{SM})^2$	±27%	±30%	±41%	–
$(ZZh_{SM})^2$	±4%			
$BF(h_{SM} \to b\bar{b})$	±6%		±9%	$\sim$ 20%?
$BF(h_{SM} \to c\bar{c})$	$\sim \pm 9\%$	?		
$BF(h_{SM} \to WW^\star)$	±16%	±8%	±6%	±5%
$(WWh_{SM})^2$	±5%	±5%	±8%	±10%
$(ZZh_{SM})^2/(WWh_{SM})^2$	±7%	±7%	±9%	±11%
$BF(h_{SM} \to \gamma\gamma)$	±14%	±20%?	±41%	–
$(\gamma\gamma h_{SM})^2$	±15%	±17%	±31%	–
$\Gamma^{\rm tot}_{h_{SM}}$ (indirect)	±13%	±9%	±10%	±11%
$(b\bar{b}h_{SM})^2$	±14%	±11%	±13%	±23%
$m_{h_{SM}}$ (GeV)	**180**	**190**	**200**	**300**
$(ZZh_{SM})^2$	±4% – ±5%		±6%	±9%
$(WWh_{SM})^2$	±11%	±12%	±13%	±24%
$(ZZh_{SM})^2/(WWh_{SM})^2$	±12%	±13%	±14%	±25%
$BF(h_{SM} \to WW)$	±6%	±7%	±8%	±14%?
$(\gamma\gamma h_{SM})^2$	±13%	±12%	±12%	±22%
$\Gamma^{\rm tot}_{h_{SM}}$ (indirect)	±13%	±14%	±15%	±28%

Bring in the muon collider:

- MC $\Rightarrow$ big further gain (if $m_h \neq m_Z$) by focusing on $\mu^+\mu^- \to h$ production at $\sqrt{s} \simeq m_h$. (J.G., Barger, Berger, Han)

  For a Standard Model-Like Higgs $m_h \lesssim 2m_W$ is required for good s-channel cross section. Above that Γ_h becomes big and $\overline{\sigma}_h \propto BF(h \to \mu^+\mu^-)$ is too small.

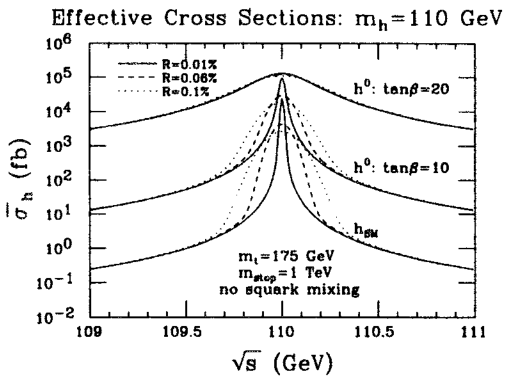


Figure 1: The effective cross section, $\overline{\sigma}_h$, obtained after convoluting σ_h with the Gaussian distributions for $R = 0.01\%$, $R = 0.06\%$, and $R = 0.1\%$, is plotted as a function of $\sqrt{s}$ taking $m_h = 110$ GeV.

  Strategy: First center on $\sqrt{s} \sim m_h$ and then measure Higgs properties.

- For a SM-like Higgs with $m_h \lesssim 2m_W$: $\Delta m_h \sim 100$ MeV from LHC ($L = 300$ fb^{-1}); $\Delta m_h \sim 50$ MeV from $\sqrt{s} = 500$ GeV NLC ($L = 200$ fb^{-1}).

  $\Rightarrow$ can design a final ring for $\sqrt{s} \sim m_h$.

  Once operating, scan over the Δm_h interval so as to center on $\sqrt{s} \simeq m_h$ within a fraction of $\sigma_{\sqrt{s}}$.

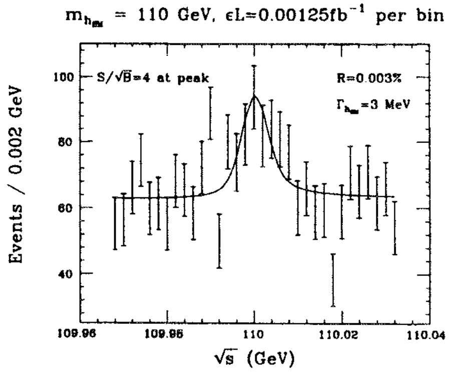


Figure 2: Initial scan for centering on $m_{h_{SM}} = 110$ GeV Higgs boson.

- "Typical case" — $m_h \sim 110$ GeV, $\sigma_{\sqrt{s}} \sim 2$ MeV, $\Delta m_h \sim 100$ MeV $\Rightarrow \sim 50$ points needed to center within $\lesssim \sigma_{\sqrt{s}}$. Each point requires $L \sim 0.0015$ fb^{-1} to observe or eliminate the h at the 3σ level. $\Rightarrow$ **$L = 0.075$ fb^{-1} needed to center $\Rightarrow$ for $L = 0.1$ fb^{-1}/yr, centering might take 1 yr.**
- Worst case — $m_h = m_Z$; a factor of 50 more $L_{\rm tot}$ needed $\Rightarrow$ 4 years even at $L = 1$ fb^{-1}/yr.
- The above is based on $b\overline{b}$ mode only, neglecting use of FB asymmetry of background, and assuming polarization beyond natural $P_+ \sim P_- \sim 0.2 \Rightarrow$ substantial L loss. Kamal, Marciano and Parsa have estimated that FB asymmetry and $\tau^+\tau^-$ mode $\to$ useful scan time reduction.

Once centered at $\sqrt{s} \sim m_h$, the crucial measurements are:

- The very tiny Higgs width: $\Gamma_h^{\rm tot} = 1 - 10$ MeV for a SM-like Higgs with $m_h \lesssim 140$ GeV (i.e. mass as predicted for h^0 of SUSY).

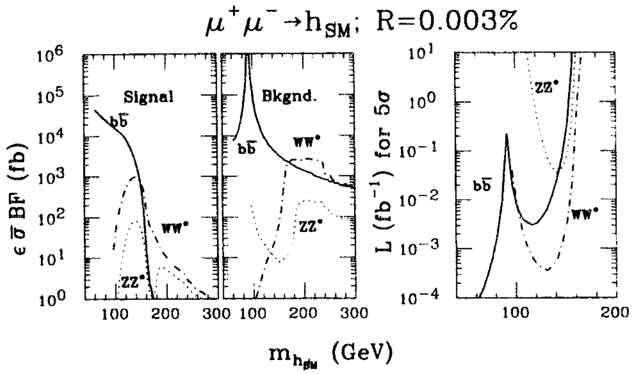


Figure 3: SM rates and L required for 5σ observation as a function of $m_{h_{SM}}$.

- $\sigma(\mu^+\mu^- \to h \to X)$ for $X = b\bar{b}, WW^\star, ZZ^\star, c\bar{c}, \tau^+\tau^-$.*

Accuracy achievable? Employ optimized 3-point scan.

At $L = 0.4\,\text{fb}^{-1}$ ($\geq$ 4 years at $R = 0.003\%$) the errors for $\sigma BF(h_{SM} \to b\bar{b})$ are small, but those for $\Gamma^{\text{tot}}_{h_{SM}}$ are not wonderful.

- **If no Zh NLC or MC data, use σBF ratios to distinguish h_{SM} from h^0.** At $m_{h_{SM}} = 110$ GeV, $L_{\text{tot}} = 0.4\,\text{fb}^{-1}$ (see Table 3):

$$\frac{(WW^\star h_{SM})^2}{(b\bar{b}h_{SM})^2} \to\sim \pm 15\%, \quad \frac{(c\bar{c}h_{SM})^2}{(b\bar{b}h_{SM})^2} \to\sim \pm 20\%$$

$$\frac{(WW^\star h_{SM})^2}{(\tau^+\tau^- h_{SM})^2} \to\sim \pm 18\%, \quad \frac{(c\bar{c}h_{SM})^2}{(\tau^+\tau^- h_{SM})^2} \to\sim \pm 22\%$$

Systematic errors $\sim \pm 5\% - \pm 10\%$ from uncertainty in m_b.

Combining above $\Rightarrow$ **$>$ 2σ deviation for m_{A^0} up to $\sim$ 400 GeV.**

$\Rightarrow$ similar to NLC for $L = 200\,\text{fb}^{-1}$.

Table 3: Percentage errors (1σ) for $\sigma BF(h_{SM} \to b\bar{b}, WW^\star, ZZ^\star)$ (extracted from channel rates) and $\Gamma^{\text{tot}}_{h_{SM}}$ for s-channel Higgs production at the MC assuming beam energy resolution of $R = 0.003\%$. Results are presented for two integrated four-year luminosities: $L = 0.4\,\text{fb}^{-1}$ ($L = 4\,\text{fb}^{-1}$). An optimized three-point scan is employed [which, for the cross section measurements, is equivalent to $L \sim 0.2\,\text{fb}^{-1}$ ($L = 2\,\text{fb}^{-1}$) at the $\sqrt{s} = m_{h_{SM}}$ peak].

Quantity	Errors			
Mass (GeV)	**80**	m_Z	**100**	**110**
$\sigma BF(b\bar{b})$	2.4%(0.8%)	21%(7%)	4%(1.3%)	3%(1%)
$\sigma BF(c\bar{c})$	?	?	?	19%(7%)
$\sigma BF(\tau^+\tau^-)$	?	?	?	8%(3%)
$\sigma BF(WW^\star)$	–	–	32%(10%)	15%(5%)
$\sigma BF(ZZ^\star)$	–	–	–	190%(62%)
$\Gamma^{\text{tot}}_{h_{SM}}$	10%(3%)	78%(25%)	30%(10%)	16%(5%)
Mass (GeV)	**120**	**130**	**140**	**150**
$\sigma BF(b\bar{b})$	3%(1%)	5%(1.5%)	9%(3%)	28%(9%)
$\sigma BF(WW^\star)$	10%(3%)	8%(2.5%)	7%(2.3%)	9%(3%)
$\sigma BF(ZZ^\star)$	50%(16%)	30%(10%)	16%(8%)	34%(1%)
$\Gamma^{\text{tot}}_{h_{SM}}$	16%(5%)	18%(6%)	29%(9%)	105%(34%)

Note: Γ^{tot}_h errors big + Γ^{tot}_h model-dependent $\Rightarrow$ no clearly useful. Still, deviations from SM substantial if $m_{A^0} \lesssim 500$ GeV.

- **If NLC and $\gamma\gamma$-collider facility at NLC data available $\Rightarrow$ determination of fundamental Higgs couplings.**

Best Example: 4 ways to determine $\Gamma(h \to \mu^+\mu^-)$:

1) $\Gamma(h_{SM} \to \mu^+\mu^-) = \frac{[\Gamma(h_{SM}\to\mu^+\mu^-)BF(h_{SM}\to b\bar{b})]_{\text{MC}}}{BF(h_{SM}\to b\bar{b})_{\text{NLC}}}$;

2) $\Gamma(h_{SM} \to \mu^+\mu^-) = \frac{[\Gamma(h_{SM}\to\mu^+\mu^-)BF(h_{SM}\to WW^\star)]_{\text{MC}}}{BF(h_{SM}\to WW^\star)_{\text{NLC}}}$;

3) $\Gamma(h_{SM} \to \mu^+\mu^-) = \frac{[\Gamma(h_{SM}\to\mu^+\mu^-)BF(h_{SM}\to ZZ^\star)]_{\text{MC}}\Gamma^{\text{tot}}_{h_{SM}}}{\Gamma(h_{SM}\to ZZ^\star)_{\text{NLC}}}$;

4) $\Gamma(h_{SM} \to \mu^+\mu^-) = \frac{[\Gamma(h_{SM}\to\mu^+\mu^-)BF(h_{SM}\to WW^\star)\Gamma^{\text{tot}}_{h_{SM}}]_{\text{MC}}}{\Gamma(h_{SM}\to WW^\star)_{\text{NLC}}}$.

Resulting errors are labelled $(\mu^+\mu^- h_{SM})^2|_{\text{NLC+MC}}$ in Table 4.

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*Note from Eq. (0.2) that $\sigma(\mu^+\mu^- \to h \to X)$ provides a determination of $\Gamma(h \to \mu^+\mu^-)BF(h \to X)$ unless $\sigma_{\sqrt{s}} \ll \Gamma^{\text{tot}}_h$.

Table 4: Percentage errors (1σ) for combining $L = 600$ fb^{-1} LHC, $L = 200$ fb^{-1}-$\sqrt{s} = 500$ GeV NLC, $L = 50$ fb^{-1} $\gamma\gamma$-collider and MC $R = 0.003\%$ s-channel data, with errors for the latter as quoted in Table 3. Results are presented for two total four-year integrated MC luminosities: $L = 0.4$ fb^{-1} ($L = 4$ fb^{-1}).

Quantity	Errors			
Mass (GeV)	**80**	**100**	**110**	**120**
$(b\bar{b}h_{SM})^2\vert_{\rm NLC+MC}$	10%(6%)	16%(10%)	13%(7%)	13%(7%)
$(c\bar{c}h_{SM})^2\vert_{\rm NLC+MC}$	13%(9%)	18%(12%)	15%(10%)	15%(10%)
$(\mu^+\mu^-h_{SM})^2\vert_{\rm NLC+MC}$	5%(5%)	5%(5%)	5%(4%)	4%(4%)
$(\gamma\gamma h_{SM})^2\vert_{\rm MC}$	18%(15%)	33%(17%)	21%(14%)	20%(14%)
$(\gamma\gamma h_{SM})^2\vert_{\rm NLC+MC}$	10%(9%)	11%(10%)	10%(9%)	10%(9%)
$\Gamma^{\rm tot}_{h_{SM}}\vert_{\rm NLC+MC}$	9%(3%)	16%(8%)	12%(5%)	12%(5%)
Mass (GeV)	**130**	**140**	**150**	**170**
$(b\bar{b}h_{SM})^2\vert_{\rm NLC+MC}$	12%(8%)	10%(9%)	13%(13%)	23%(23%)
$(c\bar{c}h_{SM})^2\vert_{\rm NLC+MC}$	14%(10%)	?		
$(\mu^+\mu^-h_{SM})^2\vert_{\rm NLC+MC}$	5%(4%)	4%(4%)	5%(4%)	14%(13%)
$(WW^\star h_{SM})^2\vert_{\rm MC}$	24%(17%)	30%(12%)	104%(33%)	–
$(WW^\star h_{SM})^2\vert_{\rm NLC+MC}$	5%(5%)	5%(5%)	8%(6%)	10%(10%)
$(\gamma\gamma h_{SM})^2\vert_{\rm MC}$	22%(14%)	34%(20%)	110%(48%)	–
$(\gamma\gamma h_{SM})^2\vert_{\rm NLC+MC}$	12%(10%)	15%(13%)	29%(25%)	–
$\Gamma^{\rm tot}_{h_{SM}}\vert_{\rm NLC+MC}$	10%(5%)	8%(6%)	10%(9%)	11%(11%)

Use combined measurements to distinguish between h_{SM} and h^0 of the MSSM $\Rightarrow$ constraints on H^0 and A^0.

In particular, $\Gamma(h \rightarrow \mu^+\mu^-)$ (error $\lesssim 5\%$ for MC $L_{\rm tot} = 0.4$ fb^{-1}).

$\Rightarrow$ probes at 3σ level out to $m_{A^0} \gtrsim 600$ GeV for all $m_h \lesssim 2m_W$. No systematics.

$L = 0.4$ fb^{-1} scan $\Rightarrow \frac{WW^\star}{\tau^+\tau^-} \rightarrow \pm 18\%$, $\frac{c\bar{c}}{\tau^+\tau^-} \rightarrow \pm 22\%$, $\frac{WW^\star}{b\bar{b}} \rightarrow \pm 15\%$, $\frac{c\bar{c}}{b\bar{b}} \rightarrow \pm 20\%$

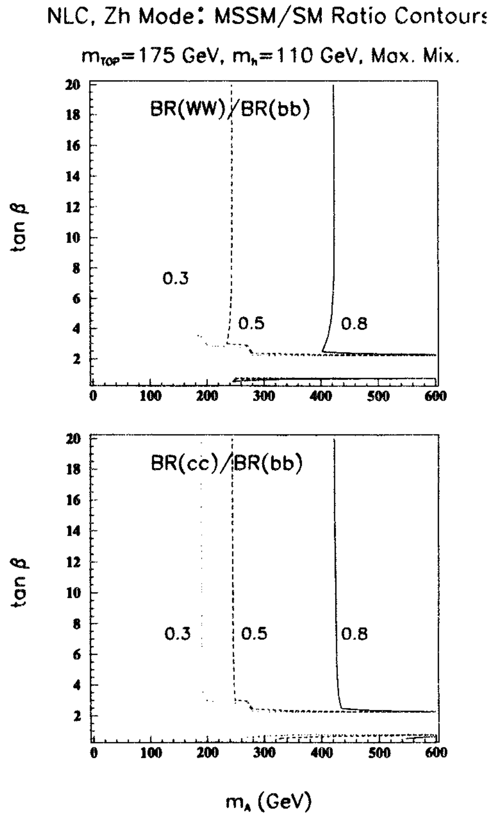


Figure 4: Constant value contours in $(m_{A^0}, \tan\beta)$ parameter space for the rate ratios $[WW^\star/b\bar{b}]_{h^0}/[WW^\star/b\bar{b}]_{h_{SM}}$ and $[c\bar{c}/b\bar{b}]_{h^0}/[c\bar{c}/b\bar{b}]_{h_{SM}}$, for "maximal-mixing" with fixed m_{h^0} = 110 GeV. Same contours apply for $b \rightarrow \tau$.

Combining $\Rightarrow$ 2σ sensitivity up to $m_{A^0} \sim 400$ GeV.

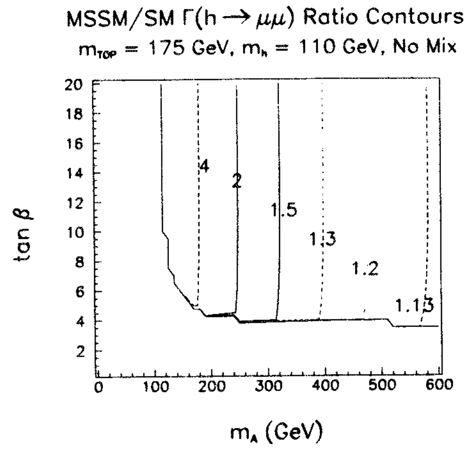


Figure 5: Constant value contours in $(m_{A^0}, \tan\beta)$ parameter space for the ratio $\Gamma(h^0 \to \mu^+\mu^-)/\Gamma(h_{SM} \to \mu^+\mu^-)$. We assume "no mixing" in the squark sector and present results for the case of fixed $m_{h^0} = m_{h_{SM}} = 110$ GeV. For "maximal mixing", the vertical contours are essentially identical — only the size of the allowed parameter range is altered. Contours for $\Gamma(h^0 \to b\bar{b})/\Gamma(h_{SM} \to b\bar{b})$ are identical.

Determine to $\pm 4\%$ with $L = 0.4$ fb^{-1} scan and NLC (200 fb^{-1}) and LHC (600 fb^{-1}, ATLAS+CMS) data $\Rightarrow$ 3σ sensitivity for m_{A^0} up to 600 GeV.

Heavy Higgs of the MSSM and the MC

- Possibilities for H^0, A^0 are limited at other machines.
  - The LHC has "h^0-only" regions at moderate $\tan\beta \gtrsim 3$, $m_{A^0} \geq 200$ GeV (see figure). **For given $m_{\tilde{t}} = 1$ TeV, $b \to s\gamma$ too big unless $m_{H^\pm} \sim m_{A^0} \gtrsim 350$ GeV.**

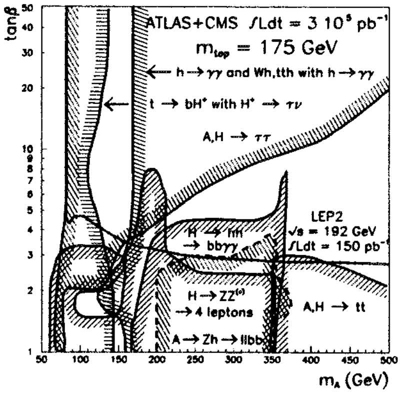


Figure 6: Discovery contours (5σ) in the parameter space of the minimal supersymmetric model for ATLAS+CMS at the LHC: $L = 300$ fb^{-1}. Two-loop/RGE-improved radiative corrections to the MSSM Higgs sector are included assuming $m_{\tilde{t}} = 1$ TeV and no squark mixing.

  - At the NLC $e^+e^- \to Z^\star \to H^0A^0$ is limited to $m_{H^0} \sim m_{A^0} \lesssim \sqrt{s}/2$ — *i.e.* 230 – 240 GeV at $\sqrt{s} = 500$ GeV.
  - A $\gamma\gamma$ collider could probe up to $m_{H^0} \sim m_{A^0} \sim 0.8\sqrt{s}_{e^+e^-}$, but this would require $L \sim 150 - 200$ fb^{-1}, especially if m_{A^0} near 400 GeV and $\tan\beta$ is large.

- In contrast, $\mu^+\mu^- \to H^0, A^0$ potentially allows production and study of H^0, A^0 up to $m_{A^0} \sim m_{H^0} \lesssim \sqrt{s}$. For $L = 50~\mathrm{fb}^{-1}$ (5 yrs running at $<\mathcal{L}>= 1 \times 10^{33}$, as possibly achievable for $R \gtrsim 0.1\%$ for $\sqrt{s} = 300 - 500$ GeV):
  - **With preknowledge/restrictions** on m_{A^0} (from h^0 data, LHC or NLC discovery, *etc.*) $\mu^+\mu^- \to H^0$ and $\mu^+\mu^- \to A^0$ can be studied with precision for all $\tan\beta \gtrsim 1$. In particular, a scan to determine their widths would be no problem. Fine resolution ($R \lesssim 0.01\%$) might be required to separate A^0 from H^0 if $\tan\beta$ is large. (Lower expected L for such a small R would be ok once the overall peak location had been determined.)

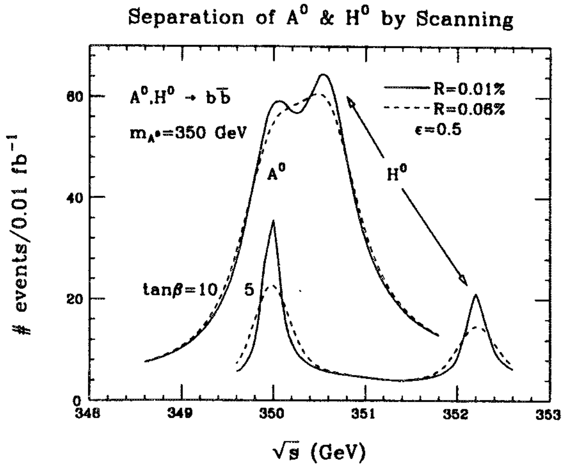


Figure 7: Plot of $b\bar{b}$ final state event rate as a function of $\sqrt{s}$ for $m_{A^0} = 350$ GeV, in the cases $\tan\beta = 5$ and 10, resulting from the H^0, A^0 resonances and the $b\bar{b}$ continuum background. We have taken $L = 0.01~\mathrm{fb}^{-1}$ (at any given $\sqrt{s}$), $\epsilon = 0.5$, $m_t = 175$ GeV, and included two-loop/RGE-improved radiative corrections to Higgs masses, mixing angles and self-couplings using $m_{\tilde{t}} = 1$ TeV and neglecting squark mixing. SUSY decays are assumed to be absent. Curves are given for two resolution choices: $R = 0.01\%$ and $R = 0.06\%$

  - **Without preknowledge?** From LHC and possibly also NLC, we will know that $m_{A^0}, m_{H^0} \gtrsim 250$ GeV if they are not seen (assumes $m_{\tilde{t}} \sim 1$ TeV) — $m_{A^0}, m_{H^0} > 350$ GeV if trust $b \to s\gamma$ and $m_{\tilde{t}}$ has been measured to be large.

    $\Rightarrow$ 2 strategies:
    - **Hope that $m_{A^0}, m_{H^0} \lesssim 500$ GeV and scan from 250 – 500 GeV.** $\Rightarrow$ discovery if $m_{A^0} \gtrsim 250$ GeV and $\tan\beta \gtrsim 4 - 5 \to$ **small no-LHC, no-MC gap for $3 \lesssim \tan\beta \lesssim 4 - 5$.**
    - **First run MC at $\sqrt{s} = 500$ GeV (or whatever) and use bremsstrahlung tail.** For $m_{b\bar{b}}$ resolution $\sim \pm 5$ GeV (either via direct reconstruction or hard photon recoil) and $L = 50~\mathrm{fb}^{-1}$ ($200~\mathrm{fb}^{-1}$) at $\sqrt{s} = 500$ GeV, the A^0, H^0 peak(s) are observable for $\tan\beta \geq 5 - 6$ ($3.5 - 4.5$) if $250~\mathrm{GeV} \leq m_{A^0} \leq 500$ GeV — *i.e.* the LHC/MC gap for $\tan\beta \gtrsim 3$ is essentially closed at the higher luminosity.

      Meanwhile, other physics results would be obtained.
  - **Net result: Together, the LHC and MC $\approx$ guarantee A^0, H^0 discovery if $\lesssim 500$ GeV;** $\tan\beta$ gap depends on $\mathcal{L}$ for $\sqrt{s} \lesssim 500$ GeV.
  - **For higher m_{H^0}, m_{A^0}, higher MC energies are required.** Without some restrictions or . . . from other data, scan interval large and discovery might be missed if $\tan\beta$ is not large.

    Thus, use of $\Gamma(h^0 \to \mu^+\mu^-)$ to decide if $m_{A^0} \gtrsim 600$ GeV very valuable.

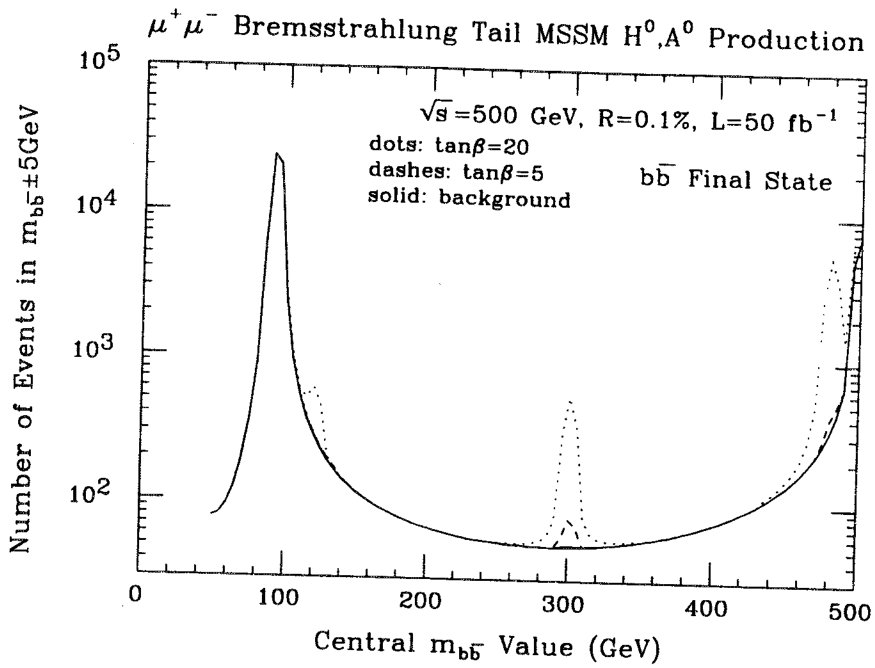


Figure 8: Taking $\sqrt{s}$ = 500 GeV, integrated luminosity L = 50 fb^{-1}, and R = 0.1%, we consider the $b\bar{b}$ final state and plot the number of events in the interval $[m_{b\bar{b}} - 5\ \text{GeV}, m_{b\bar{b}} + 5\ \text{GeV}]$, as a function of the location of the central $m_{b\bar{b}}$ value, resulting from the low $\sqrt{\hat{s}}$ bremsstrahlung tail of the luminosity distribution. MSSM Higgs boson H^0 and A^0 resonances are present for the parameter choices of m_{A^0} = 120, 300 and 480 GeV, with $\tan\beta = 5$ and 20 in each case. Enhancements for m_{A^0} = 120, 300 and 480 GeV are visible for $\tan\beta = 20$; $\tan\beta = 5$ yields visible enhancements only for m_{A^0} = 300 and 480 GeV. Two-loop/RGE-improved radiative corrections are included, taking m_t = 175 GeV, $m_{\tilde{t}}$ = 1 TeV and neglecting squark mixing. SUSY decay channels are assumed to be absent.

H^0A^0 and H^+H^- Pair Production

Value of H^0A^0 and H^+H^- pair production is great. (JFG, Kelly)
$m_{A^0} \gtrsim 1$ TeV cannot be ruled out simply on basis of hierarchy and naturalness (but → fine tuning stretched).
⇒ if A^0, H^0 not observed at LHC, MC scan, *etc.*, then must build $\sqrt{s} >$ 2 TeV muon collider if NLC can't be built with needed energy.
For high masses, the decays could be very messy. We have explored a number of GUT scenarios.

- Discovery of H^0A^0 in their $b\bar{b}$ or $t\bar{t}$ decay modes and H^+H^- in their $t\bar{b}$ and $b\bar{t}$ decays will be easy for expected luminosities, **even if SUSY decays are present.**
- Measurement of mass with reasonable accuracy will be possible.
- Measurement of branching ratios in combination with measurement of $m_{A^0} \sim m_{H^0} \sim m_{H^\pm}$ and, say, $m_{\tilde{\chi}_1^\pm}$ (chargino) discriminates with incredible statistical significance between different closely similar GUT scenarios.

Bottom line: Higgs pair production **and measurement of their decays** will be a powerful tool in determining the correct GUT-scale boundary conditions.

Verifying Higgs CP Properties

Direct verification that the SM Higgs is CP-even would be highly desirable. Direct determination of CP property of arbitrary neutral Higgs will be important.

If CP violation is detected in Higgs sector, then we must go beyond the SM and MSSM.

- $\gamma\gamma$ collisions and $\mu^+\mu^-$ s-channel provide the most elegant and reliable techniques.

  In $\gamma\gamma$ collisions at NLC:

  - In terms of the polarization vectors $\vec{e}_{1,2}$ of the two γ's photons in the photon-photon center of mass,

    $$\mathcal{L}_{\gamma\gamma h} = \vec{e}_1 \cdot \vec{e}_2 \mathcal{E} + (\vec{e}_1 \times \vec{e}_2)_z \mathcal{O},$$

    with $\mathcal{E}$ and $\mathcal{O}$ of similar size if the CP-even and CP-odd (respectively) components of the h are comparable.

  - The difference in rates for photons colliding with $++$ vs. $--$ helicities is non-zero only if CP violation is present.

    Experimentally this difference can be measured by simultaneously flipping the helicities of both of the initiating back-scattered laser beams. ⇒ Easily measurable for a large range of two-doublet parameter space if CP violation is present in the Higgs potential.

  - In the case of a CP-conserving Higgs sector, there is strong dependence of the $\gamma\gamma \to h$ cross section on the relative orientation of $\vec{e}_1$ and $\vec{e}_2$.

    Use parallel vs. perpendicular cross section asymmetry for colliding photons with substantial transverse polarization (obtained by transversely polarizing the incoming back-scattered laser beams).

    ⇒ $\gamma\gamma$ collisions may well allow a determination of whether a given h is CP-even or CP-odd.

  In $\mu^+\mu^-$ collisions:

  - A $\mu^+\mu^-$ collider might well prove to be the best machine for directly probing the CP properties of a Higgs boson that can be produced and detected in the s-channel mode.

  - The most elegant possibility arises if it is possible to transversely polarize the muon beams.

    For 100% transverse polarization assume that the μ^+ transverse polarization is rotated with respect to the μ^- transverse polarization by an angle ϕ.

    $$\sigma(\phi) \propto 1 - \frac{a^2 - b^2}{a^2 + b^2} \cos\phi + \frac{2ab}{a^2 + b^2} \sin\phi \,. \qquad (0.3)$$

    To prove that the h is a CP admixture, use the asymmetry

    $$A_1 \equiv \frac{\sigma(\pi/2) - \sigma(-\pi/2)}{\sigma(\pi/2) + \sigma(-\pi/2)} = \frac{2ab}{a^2 + b^2} \,. \qquad (0.4)$$

    For a pure CP eigenstate the asymmetry

    $$A_2 \equiv \frac{\sigma(\pi) - \sigma(0)}{\sigma(\pi) + \sigma(0)} = \frac{a^2 - b^2}{a^2 + b^2} \qquad (0.5)$$

    is $+1$ or -1 for a CP-even or CP-odd h, respectively.

    Background processes and only partial transverse polarization will dilute the statistics; further study needed.

Exotic Higgs Sectors: Complementarity of LHC, NLC and MC

- Doubly-Charged Higgs Bosons (Δ^{--}):

  Theoretical issues:

  - Consider models where $\rho = 1$ is natural (not infinitely renormalized).

    $\Rightarrow$ vev of any neutral member of the same multiplet $= 0$. $\Rightarrow$ no $W^- W^- \to \Delta^{--}$ coupling. $\Rightarrow$ narrow width in general, especially if $\Delta^{--} \to W^- \Delta^-$ is kinematically forbidden (as is likely).

  - Especially interesting = lepton-number-violating $\ell^- \ell^- \to \Delta^{--}$ coupling. For $Q = T_3 + \frac{Y}{2} = -2$ the allowed cases are:

$$\begin{aligned} \ell_R^- \ell_R^- &\to \Delta^{--}(T = 0, T_3 = 0, Y = -4)\,, \\ \ell_L^- \ell_R^- &\to \Delta^{--}(T = \tfrac{1}{2}, T_3 = -\tfrac{1}{2}, Y = -3)\,, \\ \ell_L^- \ell_L^- &\to \Delta^{--}(T = 1, T_3 = -1, Y = -2)\,. \end{aligned} \tag{0.6}$$

    Note the above cases include the $T = 1/2, Y = -3$ doublet representation with no neutral member, and the popular $T = 1, Y = -2$ triplet representation.

  - In the case of a $|Y| = 2$ triplet representation (to which we now specialize)

$$\mathcal{L}_Y = i h_{ij} \psi_{iL}^T C \tau_2 \Delta \psi_{jL} + \text{h.c.}\,, \tag{0.7}$$

    where $i, j = e, \mu, \tau$ are generation indices, the ψ's are the two-component left-handed lepton fields ($\psi_{\ell L} = (\nu_\ell, \ell^-)_L$), and Δ is the Higgs field matrix:

$$\Delta = \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{pmatrix}. \tag{0.8}$$

  - Limits on the h_{ij} by virtue of the $\Delta^{--} \to \ell^- \ell^-$ couplings include: Bhabbha scattering, $(g-2)_\mu$, muonium-antimuonium conversion, and $\mu^- \to e^- e^- e^+$.

$$\begin{aligned} |h_{ee}^{\Delta^{--}}|^2 &\lesssim 10^{-5} m_{\Delta^{--}}^2(\text{ GeV}) \\ |h_{\mu\mu}^{\Delta^{--}}|^2 &\lesssim 4 \times 10^{-5} m_{\Delta^{--}}^2(\text{ GeV}) \\ |h_{ee}^{\Delta^{--}} h_{\mu\mu}^{\Delta^{--}}| &\lesssim 6 \times 10^{-5} m_{\Delta^{--}}^2(\text{ GeV}) \\ |h_{e\mu}^{\Delta^{--}} h_{ee}^{\Delta^{--}}| &\lesssim 5 \times 10^{-11} m_{\Delta^{--}}^2(\text{ GeV}) \end{aligned} \tag{0.9}$$

    from the above respective sources. Last suggests small off-diagonal couplings as we shall assume. Adopt convention

$$|h_{\ell\ell}^{\Delta^{--}}|^2 \equiv c_{\ell\ell} m_{\Delta^{--}}^2(\text{ GeV})\,, \tag{0.10}$$

    where $c_{ee} \lesssim 10^{-5}$ is the strongest of the limits.

  - For a $T = 1, Y = -2$ triplet,

$$\begin{aligned} \Gamma(\Delta^{--} \to \Delta^- W^-) &= (1.3 \text{ GeV}) \left(\tfrac{m_{\Delta^{--}}}{100 \text{ GeV}}\right)^3 \beta_{\Delta^- W^-}^3\,, \\ \Gamma(\Delta^{--} \to \ell\ell) &= (0.4 \text{ GeV}) \left(\tfrac{c_{\ell\ell}}{10^{-5}}\right) \left(\tfrac{m_{\Delta^{--}}}{100 \text{ GeV}}\right)^3 . \end{aligned} \tag{0.11}$$

    Result:

    $\Gamma_{\Delta^{--}}^{\text{tot}}$ big if $\Delta^{--} \to \Delta^- W^-$ allowed or some $c_{\ell\ell}$ near upper limit.

    $\Gamma_{\Delta^{--}}^{\text{tot}}$ small if all $c_{\ell\ell} \ll$ limit and $\Delta^{--} \to \Delta^- W^-$ not allowed. (For extremely tiny c's, virtual versions of $\Delta^- W^-$ can enter.)

Strategy:

- Discover Δ^{--} in $p\overline{p} \to \Delta^{--}\Delta^{++}$ with $\Delta^{--} \to \ell^-\ell^-, \Delta^{++} \to \ell^+\ell^+$ ($\ell = e, \mu, \tau$) at TeV33 or LHC (J.G., Loomis, Pitts).

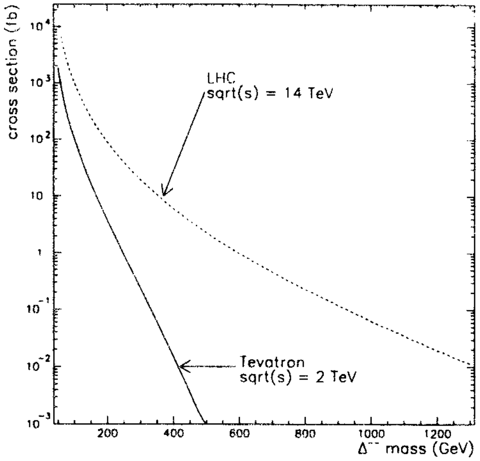


Figure 9: $\Delta^{++}\Delta^{--}$ pair production cross section as a function of Δ^{--} mass for both the Tevatron and the LHC.

- $*$ Δ^{--} detection at the Tevatron ($\sqrt{s} = 2$ TeV, $L = 30$ fb^{-1}) ok for $m_{\Delta^{--}}$ up to 300 GeV for $\ell = e$ or μ and 180 GeV for $\ell = \tau$. (Criteria: $\sim$ 10 evts. for $\ell = e, \mu$ and $\sim$ 300 evts. for $\ell = \tau$).
- $*$ At LHC $m_{\Delta^{--}}$ discovery ok up to roughly 925 GeV (1.1 TeV) for $\ell = e, \mu$ and 475 GeV (600 GeV) for $\ell = \tau$, for $L = 100$ fb^{-1} ($L = 300$ fb^{-1}).

$\Rightarrow$ TeV33 + LHC will tell us if such a Δ^{--} exists in the mass range accessible to NLC and MC.

- **Study Δ^{--} in e^-e^- and $\mu^-\mu^-$ s-channel collisions via the allowed Majorana-like bi-lepton coupling.**
  - At e^-e^- machine, spectrum $\sim$ Gaussian near $\sqrt{s}$, with a 1σ rms resolution of $\sigma_{\sqrt{s}} \sim 0.2\%\sqrt{s}$, + tail (beamstrahlung and bremsstrahlung). $\sim$ 38% of total L resides in Gaussian peak at $\sim \sqrt{s}$. Assume 2 1/2 years, $\Rightarrow L = 50$ fb^{-1} in the central 0.2% Gaussian peak.
  - A useful mnemonic, for $\sqrt{s} = m_{\Delta^{--}}$, is

$$\sigma_{\sqrt{s}} \sim 0.2 \text{ GeV} \left(\frac{m_{\Delta^{--}}}{100 \text{ GeV}}\right)\left(\frac{R_{\sqrt{s}}}{0.2\%}\right), \qquad (0.12)$$

    The crucial issue: $\sigma_{\sqrt{s}}$ vs. $\Gamma^{\rm tot}_{\Delta^{--}}$.

    For $c_{\ell\ell} = 10^{-5}$ and $R_{\sqrt{s}} = 0.2\%$, Eq. (0.11) $\Rightarrow \Gamma(\Delta^{--} \to \ell^-\ell^-) = \sigma_{\sqrt{s}}$ for $m_{\Delta^{--}} \sim 70$ GeV. If all c's $\ll 10^{-5}$ and the $\Delta^{--} \to \Delta^- W^-$ decay is disallowed, $\Rightarrow \Gamma^{\rm tot}_{\Delta^{--}} \ll \sigma_{\sqrt{s}}$.
  - The cross section (after convolution) is denoted by $\overline{\sigma}_{\Delta^{--}}$. Recall, for $\sqrt{s} = m_{\Delta^{--}}$,

$$\overline{\sigma}_{\Delta^{--}} = \begin{cases} \frac{4\pi BR(\Delta^{--}\to e^-e^-)}{m^2_{\Delta^{--}}}, & \Gamma^{\rm tot}_{\Delta^{--}} \gg \sigma_{\sqrt{s}}; \\ \frac{\sqrt{\pi}}{2\sqrt{2}} \frac{4\pi \frac{\Gamma(\Delta^{--}\to e^-e^-)}{\sigma_{\sqrt{s}}}}{m^2_{\Delta^{--}}}, & \Gamma^{\rm tot}_{\Delta^{--}} \ll \sigma_{\sqrt{s}}. \end{cases} \qquad (0.13)$$

    Here, we consider $\Gamma^{\rm tot}_{\Delta^{--}} \ll \sigma_{\sqrt{s}}$ case.
  - Taking $L = 50$ fb^{-1}, and using Eq. (0.12) for $\sigma_{\sqrt{s}}$ and the result in Eq. (0.11) for $\Gamma(\Delta^{--} \to e^-e^-)$, Eq. (0.13) (for $\Gamma^{\rm tot}_{\Delta^{--}} \ll \sigma_{\sqrt{s}}$) $\Rightarrow$

$$N(\Delta^{--}) \sim 3 \times 10^{10} \left(\frac{c_{ee}}{10^{-5}}\right)\left(\frac{0.2\%}{R_{\sqrt{s}}}\right); \qquad (0.14)$$

    $\Rightarrow$ enormous if c_{ee} not too far below its upper bound.

    Note: if the Δ^{--} is observed at the LHC or NLC, we will know ahead of time what final state to look in.

    Note: if $\Gamma^{\rm tot}_{\Delta^{--}} \ll \sigma_{\sqrt{s}}$, Eq. (0.14) $\Rightarrow$ **event rate alone is sufficient to determine c_{ee}.** (This is unlike the $\Gamma^{\rm tot}_{\Delta^{--}} \gg \sigma_{\sqrt{s}}$ case for which scan measurement of $\Gamma^{\rm tot}_{\Delta^{--}}$ and/or observation of $\Delta^{--} \to e^-e^-$ decays needed.)
  - Ultimate sensitivity to c_{ee} when $\Gamma^{\rm tot}_{\Delta^{--}} \ll \sigma_{\sqrt{s}}$: suppose 100 events are required. Eq. (0.14) $\to$ 100 Δ^{--} events for

$$c_{ee}|_{100 \text{ events}} \sim 3.3 \times 10^{-14}(R_{\sqrt{s}}/0.2\%), \quad \Gamma^{\rm tot}_{\Delta^{--}} \ll \sigma_{\sqrt{s}}. \qquad (0.15)$$

    independent of $m_{\Delta^{--}}$. $\Rightarrow$ **dramatic sensitivity.** Even if 1000 events needed (e.g. when the semi-virtual modes dominate the final state), we achieve a nearly **8 orders of magnitude improvement over the current limits on c_{ee}.** If the $\mu^-\mu^-$ final state were dominant, as few as 10 events would probably constitute a viable signal.

* **At $\mu^-\mu^-$ collider,** $\mathcal{L}$ at $\sqrt{s} \sim 100$ GeV (say) would be smaller and depend upon the choice of $R_{\sqrt{s}}$. Absence of beamstrahlung and smaller bremsstrahlung ⇒ 2× more of total L in central Gaussian peak vs. e^-e^-. For the muon collider I consider **two options:**

1. $R = 0.14\%$ beam energy resolution option, implying $R_{\sqrt{s}} \sim 0.1\%$.

   For this option the 2 1/2 year luminosity in central Gaussian peak would be about $L = 2.5\,\mathrm{yr} \times 1\,\mathrm{fb}^{-1}\,\mathrm{yr}^{-1} \times 0.8 \sim 2\,\mathrm{fb}^{-1}$, if $\sqrt{s} \sim 100$ GeV (higher at higher $\sqrt{s} \sim m_{\Delta^{--}}$).

   The e^-e^-, $\Gamma^{\mathrm{tot}}_{\Delta^{--}} \ll \sigma_{\sqrt{s}}$ results change by factor of

$$\frac{0.2\%}{0.1\%} \times \frac{2\ \mathrm{fb}^{-1}}{50\ \mathrm{fb}^{-1}} \sim 0.1 \qquad (0.16)$$

2. $R = 0.003\%$, implying $R_{\sqrt{s}} \sim 0.002\%$.

   In this case, $L_{2\ 1/2} \sim 0.2\ \mathrm{fb}^{-1}$ and the $\Gamma^{\mathrm{tot}}_{\Delta^{--}} \ll \sigma_{\sqrt{s}}$ scaling factor is

$$\frac{0.2\%}{0.002\%} \times \frac{0.2\ \mathrm{fb}^{-1}}{50\ \mathrm{fb}^{-1}} \sim 0.4 \qquad (0.17)$$

The excellent R possible at the MC compensates for the smaller L expected, provided $\Gamma^{\mathrm{tot}}_{\Delta^{--}}$ is very small.

If $\Gamma^{\mathrm{tot}}_{\Delta^{--}}$ large (e.g. $\Delta^{--} \to \Delta^- W^-$) $\overline{\sigma}_{\Delta^{--}} \sim$ independent of R, ⇒ run with R that gives largest L.

The PNGB's of an Extended Technicolor Model

- Most non-minimal technicolor models of a strongly interacting electroweak sector will contain PNGB's, although the number and their exact properties are model dependent.

- In the extended BESS model, the PNGB mass derives from gauge contributions and a contribution from the effective low-energy Yukawa interactions between the PNGB and ordinary fermions.

- The lightest neutral PNGB's are combinations of the isosinglet and isotriplet components:

$$P^0 = \frac{\tilde{\pi}_3 - \pi_D}{\sqrt{2}}, \qquad P^{0\prime} = \frac{\tilde{\pi}_3 + \pi_D}{\sqrt{2}} \qquad (0.18)$$

  The P^0 boson couples to the $T_3 = -1/2$ component of the fermion doublet while $P^{0\prime}$ couples to the $T_3 = 1/2$ component. It is the P^0 that could be looked for at a muon collider.

-

$$m^2_{P^0} = \frac{2\Lambda^2}{\pi^2 v^2} m_b^2, \qquad m^2_{P^{0\prime}} = \frac{2\Lambda^2}{\pi^2 v^2} m_t^2 \qquad (0.19)$$

  where $\Lambda \sim$ few TeV is an UV cut-off. ⇒

$$m_{P^0} \sim 8\ \mathrm{GeV} \times \Lambda(\mathrm{TeV})\,.$$

  $\to m_{P^0} \lesssim 80$ GeV for $\Lambda \lesssim 10$ TeV (as expected in the present model).

- The P^0 Yukawa couplings to fermions are

$$\mathcal{L}_Y = -i\lambda_b \bar{b}\gamma_5 b P^0 - i\lambda_\tau \bar{\tau}\gamma_5 \tau P^0 - i\lambda_\mu \bar{\mu}\gamma_5 \mu P^0 \qquad (0.20)$$

  with

$$\lambda_b = \sqrt{\frac{2}{3}\frac{m_b}{v}}, \quad \lambda_\tau = -\sqrt{6}\frac{m_\tau}{v}, \quad \lambda_\mu = -\sqrt{6}\frac{m_\mu}{v} \qquad (0.21)$$

For the P^0, the $\gamma\gamma$ and gluon-gluon channels (from ABJ anomaly couplings) are also important.

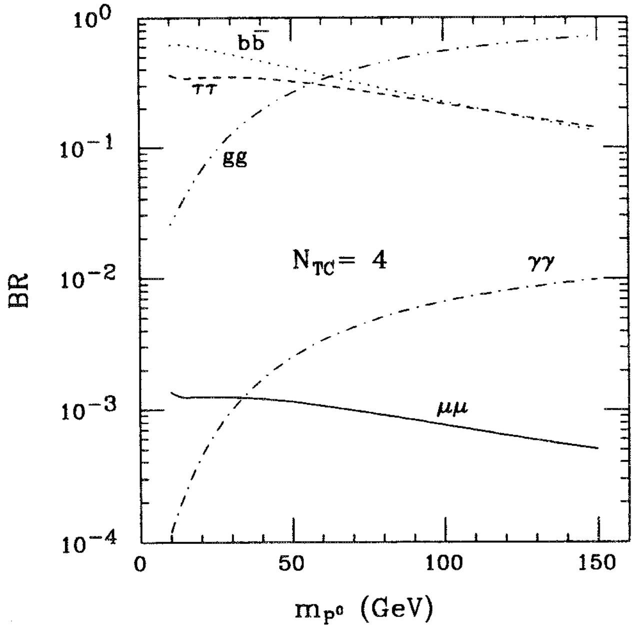


Figure 10: Branching ratios for P^0 decay into $\mu^+\mu^-$, $\tau^+\tau^-$, $b\bar{b}$, $\gamma\gamma$, and gg.

- The important widths:

$$\Gamma(P^0 \to \bar{f}f) = C\frac{m_{P^0}}{8\pi}\lambda_f^2(1-\frac{4m_f^2}{m_{P^0}^2})^{1/2}$$

$$\Gamma(P^0 \to gg) = \frac{\alpha_s^2}{48\pi^3 v^2}N_{TC}^2 m_{P^0}^3$$

$$\Gamma(P^0 \to \gamma\gamma) = \frac{2\alpha^2}{27\pi^3 v^2}N_{TC}^2 m_{P^0}^3 \qquad (0.22)$$

where $C = 1(3)$ for leptons (down-type quarks) and N_{TC} is the number of technicolors.

Corresponding branching ratios are shown in Fig. 10.

- Limits from elsewhere? Nothing definitive!

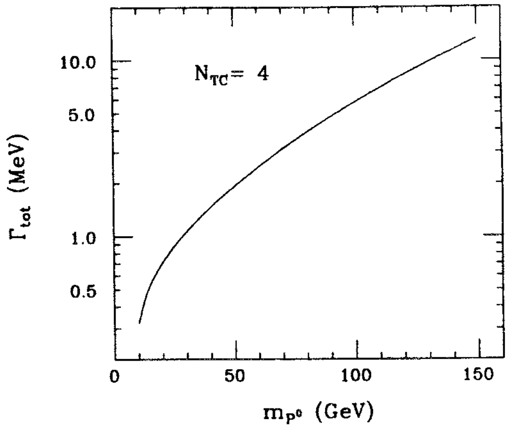


Figure 11: Γ_{tot} for the P^0 as a function of m_{P^0}.

- $\Rightarrow$ Muon Collider search for P^0.
  - Recall:

$$\sigma_{\sqrt{s}} \sim 1 \text{ MeV}\left(\frac{R}{0.003\%}\right)\left(\frac{\sqrt{s}}{50 \text{ GeV}}\right) ; \qquad (0.23)$$

    is actually smaller than $\Gamma_{\rm tot}^{P^0}$ of Fig. 11.
  - Final states considered:

    Separate $\tau^+\tau^-$, $b\bar{b}$, $c\bar{c}$ and $q\bar{q}$, gg final states by using topological and τ tagging with efficiencies and mistagging probabilities as estimated by B. King.

    A jet final state is deemed to be:
    - $b\bar{b}$ if one or more jets is tagged as a b;

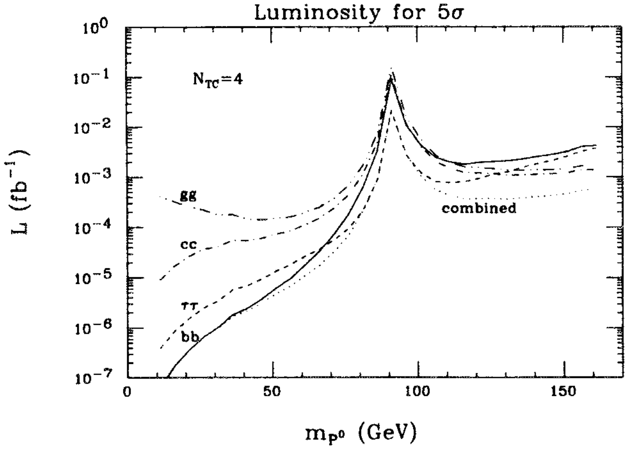


Figure 12: Luminosity for a 5σ signal of P^0 for the channels: $b\bar{b}$, $\tau^+\tau^-$, $c\bar{c}$, gg, and for the optimal combination of these four channels.

- $c\bar{c}$ if no jet is tagged as a b, but one or more jets is tagged as a c;
- $q\bar{q}, gg$ if neither jet is tagged as a b or a c.

Note that even though the P^0 does not decay to $c\bar{c}$, some of its $b\bar{b}$ and gg decays will be identified as $c\bar{c}$.

Require jets or τ's to have $|\cos\theta| < 0.94$ (corresponding to a nose cone of 20°).

- In Fig. 12, we plot L for $S_i/\sqrt{B_i} = 5$ in a given channel, i (as defined after tagging), with $\sqrt{s} = m_{P^0}$.

  Also shown is L for optimal $\Sigma_i S_k/\sqrt{\Sigma_i B_k} = 5$.

  Very modest L is needed unless $m_{P^0} \sim m_Z$.
- If m_{P^0} unknown $\Rightarrow$ **SCAN**. Choose $\sqrt{s}$ values separated by $2\sigma_{\sqrt{s}}$ and assume resonance sits midway between the two $\sqrt{s}$ values.

Table 5: Luminosity (in units of 0.01 fb^{-1}) required to scan from $M_{\rm min}+(m_Z-90)$ to $M_{\rm min}+(m_Z-90)+5$ (GeV units) and either discover or eliminate the P^0 at the 3σ level. For scan details, see text.

$M_{\rm min}$	11	16	21	26	31	36
L	0.028	0.051	0.079	0.10	0.13	0.18
$M_{\rm min}$	41	46	51	56	61	66
L	0.23	0.29	0.40	0.55	0.77	1.2
$M_{\rm min}$	71	76	81	86	91	96
L	2.2	5.3	17	166	274	52
$M_{\rm min}$	101	106	111	116	121	126
L	23	15	11	9.4	8.5	8.1
$M_{\rm min}$	131	136	141	146	151	156
L	8.2	8.2	8.3	8.7	8.9	9.0

Require $N_{SD} = 3$.

Table 5 gives L for a 3σ P^0 discovery after scanning the indicated 5 GeV intervals.

Prospects for discovery by scanning would be excellent. For example:

- To cover [11 GeV, 76 GeV] at 3σ level requires just 0.11 fb^{-1}, distributed in proportion to the (combined) luminosity plotted in Fig. 12.
- For [106 GeV, 161 GeV], require ~ 1 fb^{-1}.
- $m_{P^0} \sim m_Z$, $\Rightarrow$ need to know ahead of time.

CONCLUSIONS

1. Higgs boson physics remains as exciting as ever. Measurements of Higgs production rates, decays, couplings and widths provide a very powerful probe of a wide range of new physics. Once we have accelerators capable of detecting Higgs bosons, we will be very busy.
2. A muon collider is needed for precision studies of the SM Higgs or the MSSM h^0, and, possibly, to discover and, certainly, to study the heavier MSSM H^0, A^0.
3. A muon collider is at least as useful should the Higgs sector be more complicated, e.g. a 2 doublet + 1 singlet NMSSM model, or a general 2HDM.
4. A triplet Higgs sector with bi-lepton couplings can only be fully explored with a muon collider. We will want to determine the absolute magnitude of each type of bi-lepton coupling.
5. The pseudo-Nambu-Goldstone bosons of an extended technicolor model could have a very rich structure, some of it very difficult to explore at any accelerator other than a muon collider.
6. **We will be very hard pressed to find sufficient L for all the complementary studies that are needed to fully explore and quantify a Higgs or PNGB sector.**

   Increased muon collider luminosity at low $\sqrt{s}$ could be crucial.
7. ⇒ **Will one NLC and one MC be enough?**

Recent Results at LEP II

Yibin Pan
University of Wisconsin
December 10, 1997
MM97, San Francisco

- **Introduction**
- **Results on W Physics:**
  - Mass and cross section
- **Results on Searches:**
  - SUSY particles (MSSM)
  - Higgs Bosons (SM, MSSM)
  - 4-jet events
  - Photonic events
- **Conclusions**

Introduction

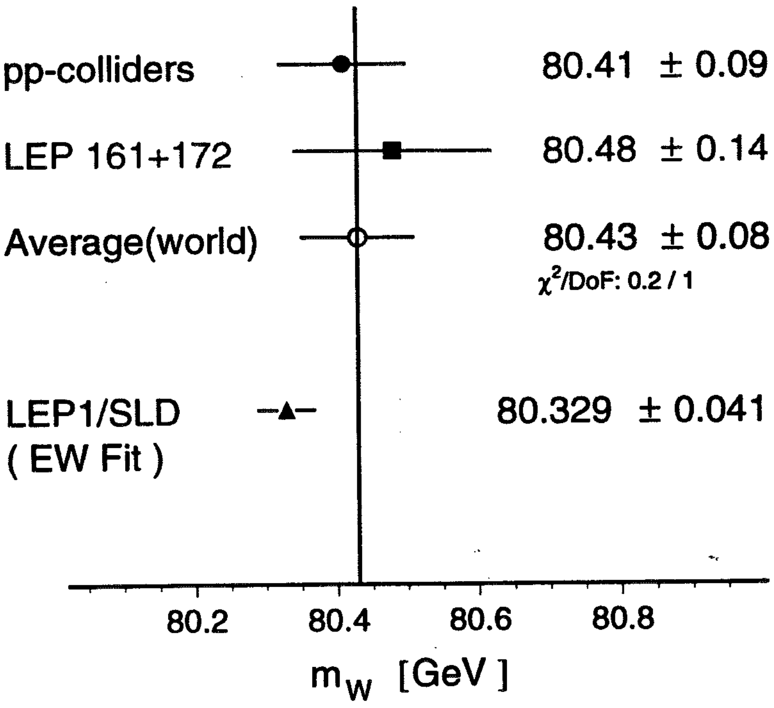
- **LEP Experiments:**

  ALEPH , DELPHI , L3 , OPAL

- **LEP runs**

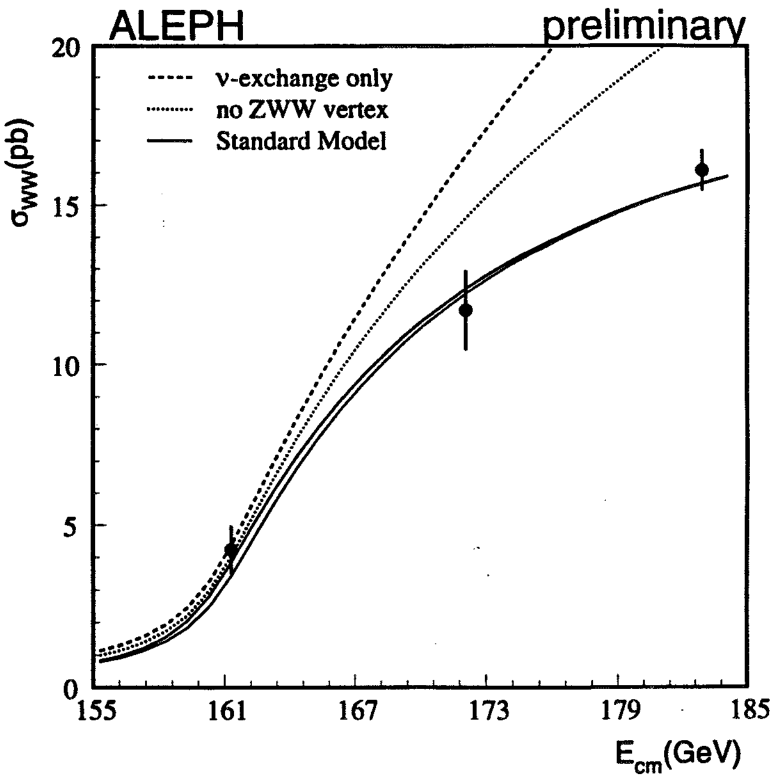
		per experiment
LEP I (1989--1995)	Z peak	~ 160 pb^{-1}
LEP 1.5 (Fall 95)	130, 136 GeV	~ 6 pb^{-1}
LEP II		
Summer 96	161 GeV	~ 10 pb^{-1}
Fall 96	172 GeV	~ 10 pb^{-1}
1997	130,136 GeV	~ 6 pb^{-1}
1997	~183 GeV	~ 60 pb^{-1}
1998	~190 GeV	100~150 pb^{-1}

W-Boson Mass



- **With 1997 LEP data (60 pb^{-1}/exp. at 183 GeV)**
  $\sigma(Mw)_{LEP}$ ~ 0.07 GeV
- **End of LEPII: $\sigma(Mw)_{LEP}$ ~ 0.03-0.04 GeV**

WW Cross Section



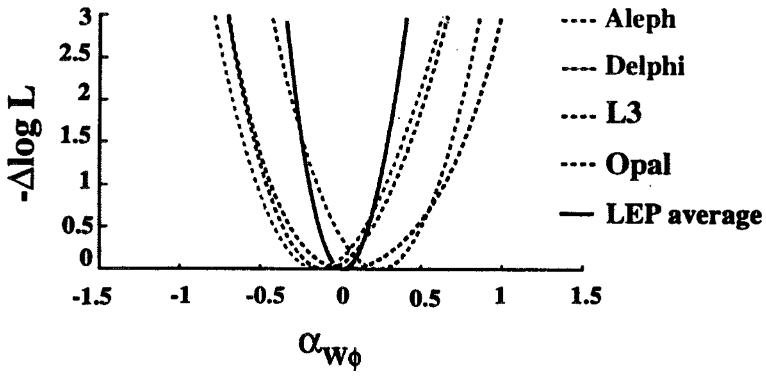
- **σ_{WW} in good agreement with SM**

Triple gauge couplings (LEP)

Parameters: $\alpha_{W\phi}$, α_W, $\alpha_{B\phi}$

SM $\Rightarrow$ $\alpha_{W\phi} = \alpha_W = \alpha_{B\phi} \equiv 0$

Preliminary LEPII Results		Ward/EPS 97
	α	95% c.l. limits
$\alpha_{W\phi}$	$0.02\pm^{0.16}_{0.15}$	$-0.28 < \alpha < 0.33$
α_W	$0.15\pm^{0.27}_{0.27}$	$-0.37 < \alpha < 0.68$
$\alpha_{B\phi}$	$0.45\pm^{0.57}_{0.67}$	$-0.81 < \alpha < 1.50$



Search for Supersymmetric Particles

- **Candidates for SUSY particles:**

Charginos	$\tilde{\chi}_i^\pm$	(i=1,2)
Neutralinos	$\tilde{\chi}_i^0$	(i=1,2,3,4)
Sleptons	$\tilde{e}, \tilde{\mu}, \tilde{\tau}, \tilde{\nu}$	(L and R)
Squarks	$\tilde{q}$	(L and R)

- **General Assumptions*:**
  - R parity conservation
  - $\tilde{\chi}_1^0$ = Lightest SUSY Particle (LSP)
- **Common event signature:**

  $e^+e^- \longrightarrow$ (S particle) pair

  S particle $\longrightarrow$ $\tilde{\chi}_1^0$ X... ($\tilde{\chi}^0$= missing energy)
- **Backgrounds:**

  $e^+e^- \longrightarrow \gamma Z^0$, WW , ZZ

  $\gamma\gamma \longrightarrow f\bar{f}$

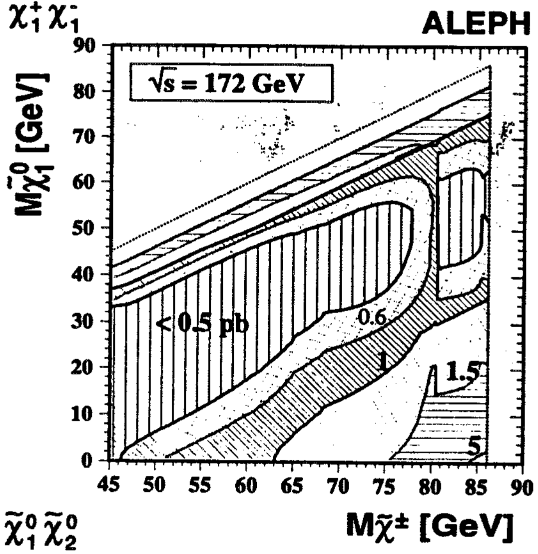
---

* searches based on other assumptions have also been performed: e.g. R parity violation

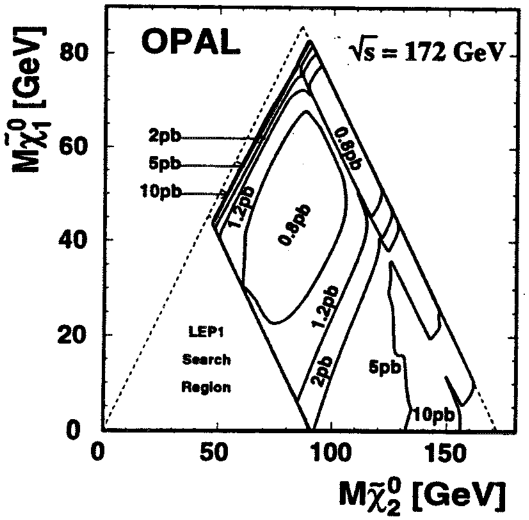
cross-section limits for charginos and neutralinos

(95%CL)

$e^+e^- \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^-$

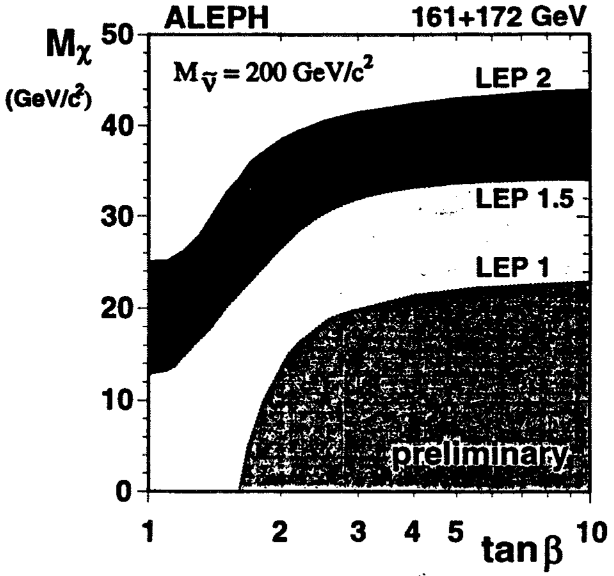


$e^+e^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_2^0$



Neutralino Mass Limit :

(Assuming GUT unification for M_1,M_2)



95 % CL lower mass limits in GeV: (tanβ >1)

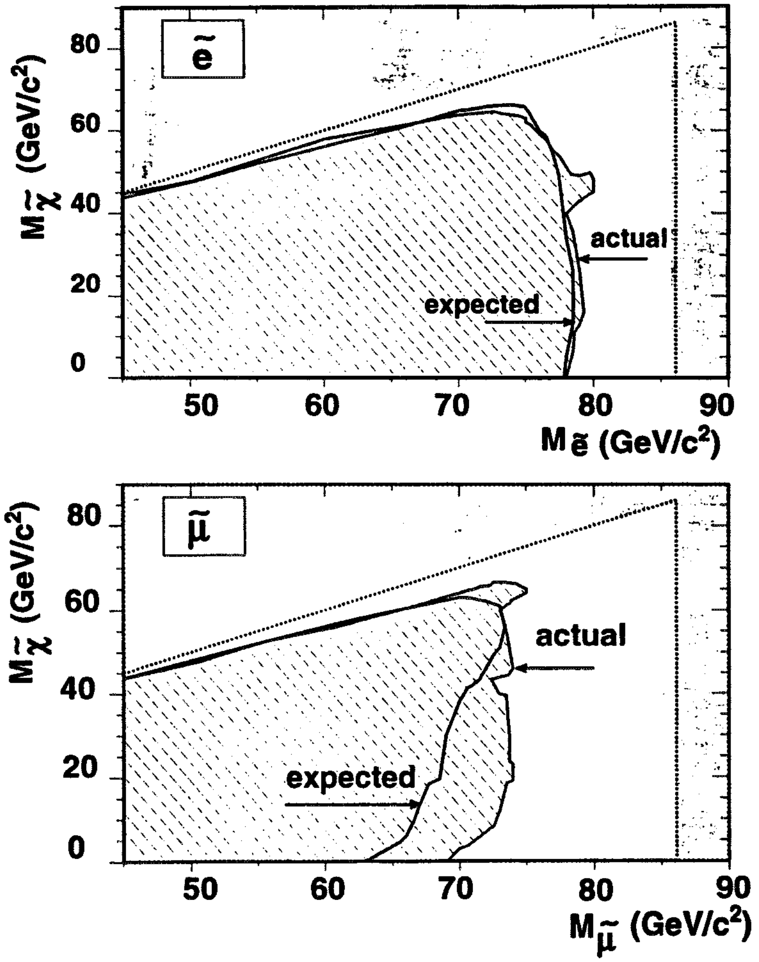
ALEPH	DELPHI	L3	OPAL	
25	24.9	24.6	24.7	($M_{\tilde{\nu}}$ >~200 GeV)
14			13.3	($M_{\tilde{\nu}}$ > excluded)

- The lightest neutralino (~LSP), if stable, could be a significant part of the dark matter of the universe.

* Preliminary 183 GeV result: m_χ > 30 GeV

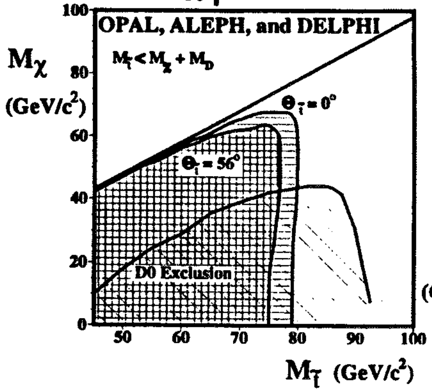
Slepton $e^+e^- \rightarrow \tilde{\ell}^+\tilde{\ell}^-$

ALEPH DELPHI L3 OPAL preliminary 95% CL

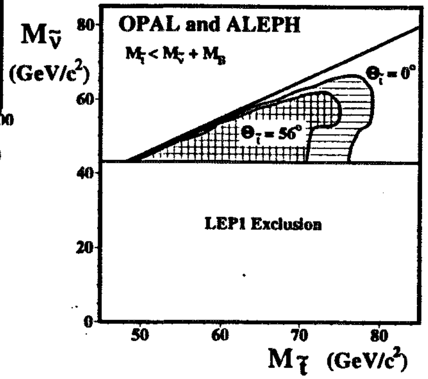


Squark $e^+e^- \rightarrow \tilde{q}\bar{\tilde{q}}$

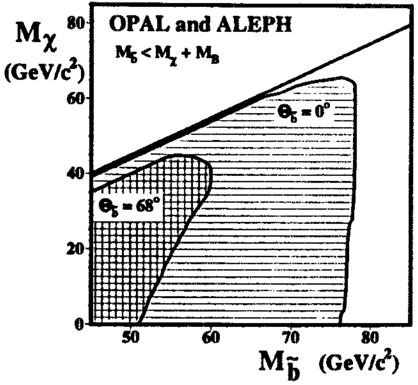
$\tilde{t} \rightarrow c\tilde{\chi}^0_1$



$\tilde{t} \rightarrow b\ell\tilde{\nu}\ (\ell = e, \mu, \tau)$



$\tilde{b} \rightarrow b\tilde{\chi}^0_1$



$\tilde{q} = \tilde{q}_L\cos\theta_q + \tilde{q}_R\sin\theta_q$

95% C.L. Exclusion
Preliminary

More SUSY: MSSM with RpV

- **additional RpV term:**

$$W_{RpV} = \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$$
$$(LL\bar{E}) \qquad (LQ\bar{D}) \qquad (\bar{U}\bar{D}\bar{D})$$

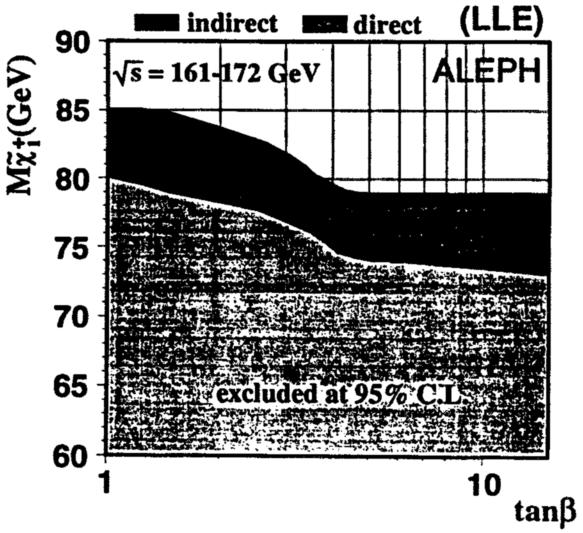
=> Sparticles can decay into SM particles
(including LSP)

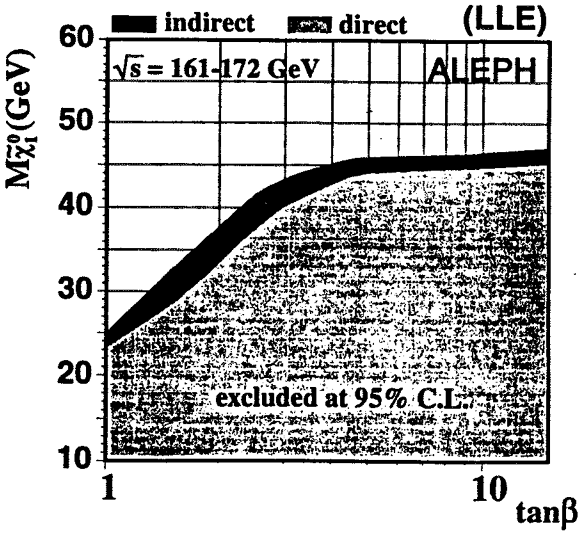
- **New Topologies:** $\left\{ \begin{array}{l} \text{LESS } \not{E} \\ \text{more leptons, or jets ...} \end{array} \right.$

e.g.: $e^+e^- \rightarrow \tilde{\nu}\,\tilde{\nu}$

$$=> \left\{ \begin{array}{lll} 4\,\ell & (\tilde{\nu} \xrightarrow[LL\bar{E}]{} \ell_j\,\ell_k) \\ 4 \text{ jets} & (\tilde{\nu} \xrightarrow[LQ\bar{D}]{} d_j\,\bar{d}_k) \\ 4\,\ell + \not{E} & (\tilde{\nu} \longrightarrow \nu_i\,\tilde{\chi}^0 \\ & \qquad\qquad \hookrightarrow_{LL\bar{E}}\ \nu \ell_j\,\ell_k\ ) \end{array} \right.$$

RpV: Charginos and Neutralinos

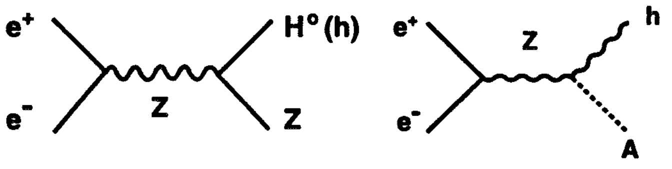




Search for Neutral Higgs Bosons

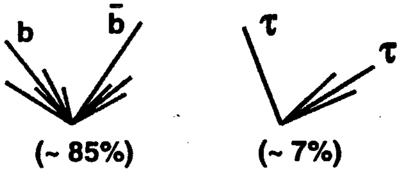
- **Neutral Higgs Candidates :** H^0 (SM) h, H, A. (MSSM) — too heavy ↙ (over H)

- **Production :**

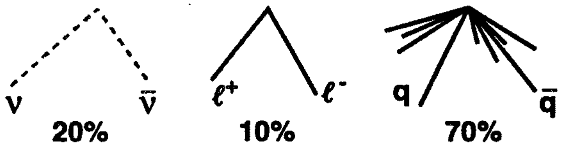


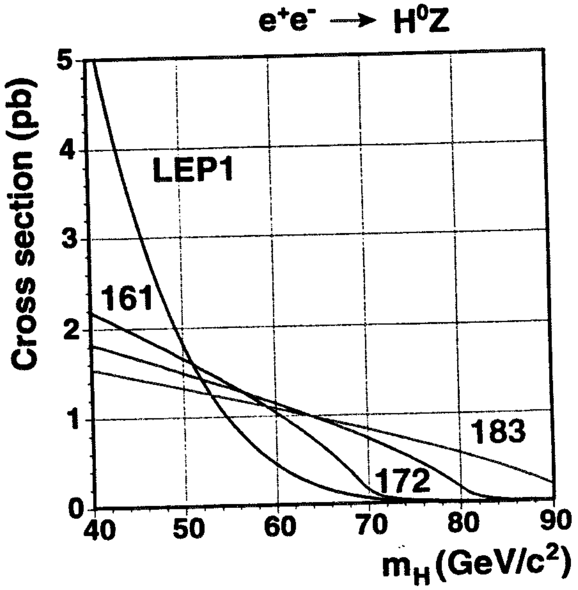
- **Decays:**

Higgs →



Z →
(on shell at LEP II)





Important:

* b tagging is essential.

HZ ⟶ bbll Candidate Event

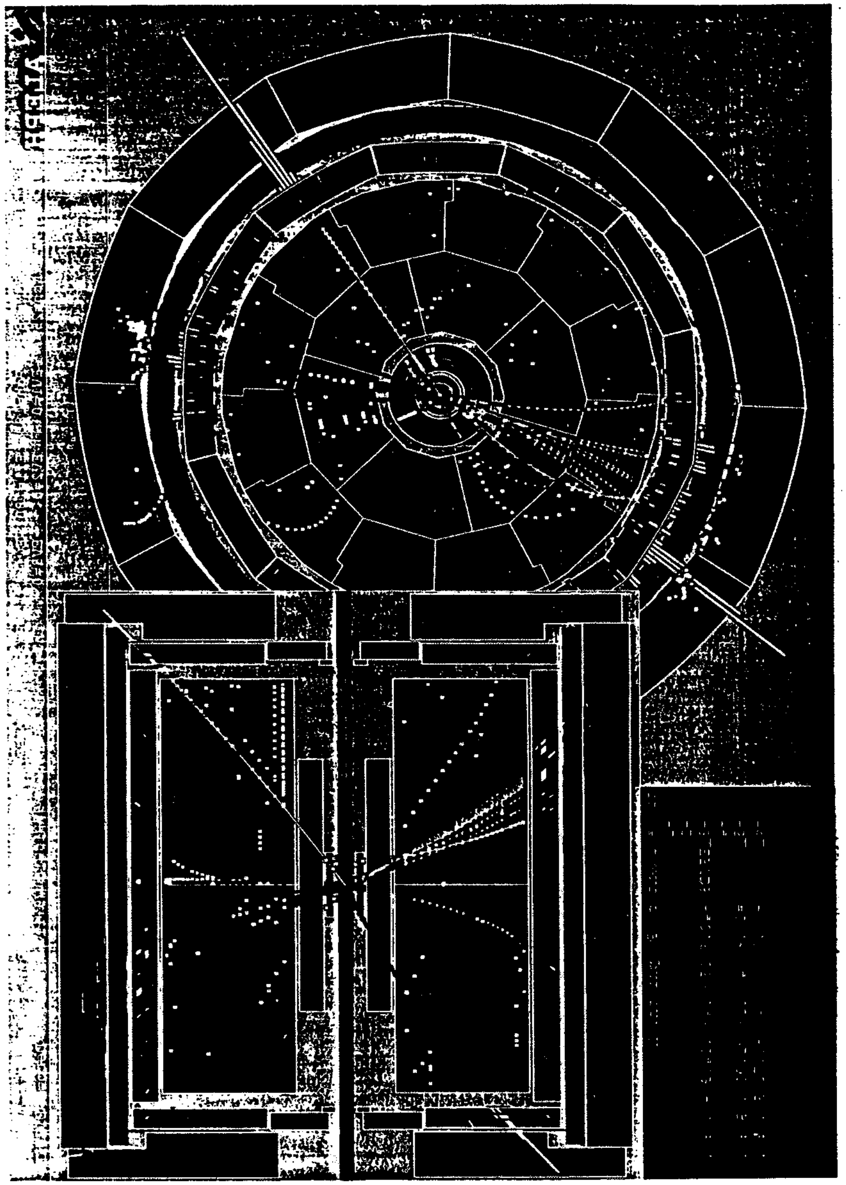
Run: 44577 Event: 9277

e^+ p = 40.64 GeV/c ECAL E = 40.75 GeV
e^- p = 42.98 GeV/c ECAL E = 44.78 GeV

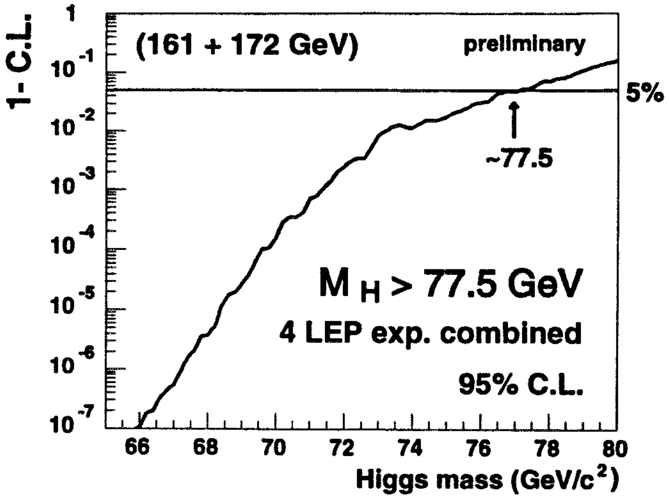
$M(e^+e^-) = 84.78$ GeV/c^2
M(recoil) = 97.47 GeV/c^2
M(b jets) = 96.06 GeV/c^2

NN btag output (Jet 1) = 0.946
NN btag output (Jet 2) = 0.993

Total Background Expected (no btag):
2.2 Events
2 events seen
(with b-tag 0.3 ZZ events expected)



H^0 Mass Limits



	ALEPH	DELPHI	L3	OPAL	
$M_H >$	70.7	66.2	69.5	69.4	(LEP I + II)
(GeV)	63.9	55.7	60.2	59.6	(LEP I)

---

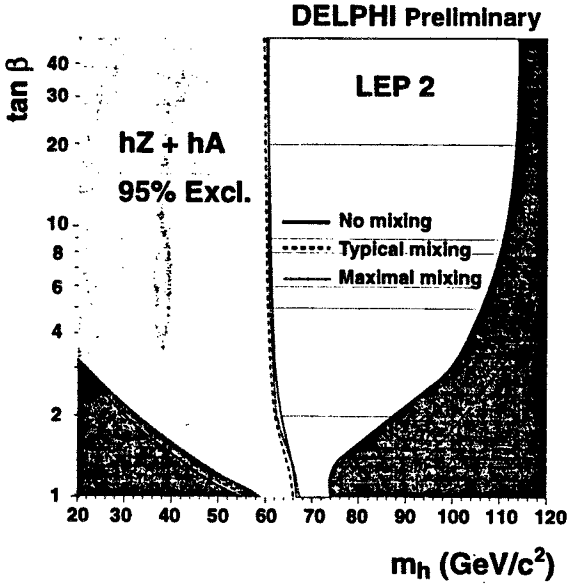
* very preliminary NON OFFICIAL 183 GeV results

	A	D	L (60%)	O (70%)
$M_H >$	88	83.6	82.2	82

EW fit: $m_H = 115^{+116}_{-66}$ GeV (< 420 GeV @ 95% C.L.)

Limits on the MSSM Neutral Higgs Bosons

$\sqrt{s} \leq 172$ GeV



no mixing:
$A = 0$
$|\mu| << M_S$

maximal mixing:
$A = \sqrt{6}\, M_S$
$|\mu| << M_S$

"typical" mixing:
$A = M_S = -\mu$

($M_S \sim 1000$GeV)

lower mass limits at 95% C.L.

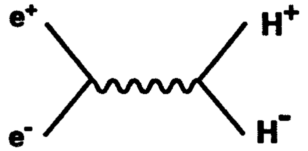
	ALEPH	DELPHI	L3	OPAL	
$M_h >$	62.5	59.5	58.4	56	GeV
$M_A >$	62.5	51.0	-	56	GeV

(tanβ > 1)

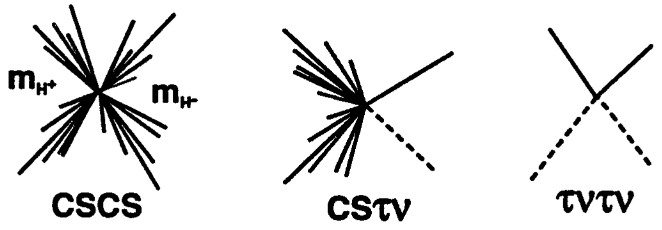
---

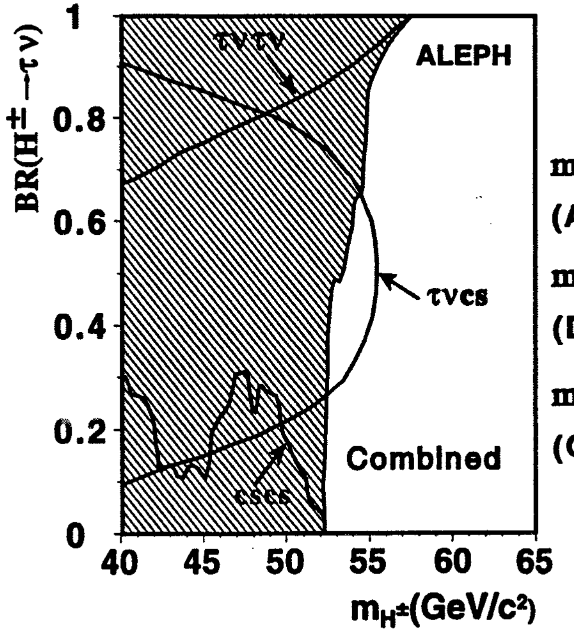
* very preliminary result with 183 GeV data:
M_h, $M_A > 73$ GeV (ALEPH, DELPHI)

Searches for Charged Higgs Bosons



$H^{\pm} \longrightarrow CS, \tau\nu$





$m_{H^{\pm}} > 52.0$ GeV/c²
(ALEPH)

$m_{H^{\pm}} > 54.5$ GeV/c²
(DELPHI)

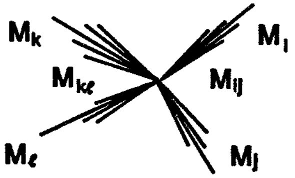
$m_{H^{\pm}} > 52.0$ GeV/c²
(OPAL)

More Searches: 4-Jet Final states

–Why 4-Jet?

-To study hA -> 4 (b) jets without b-tagging.

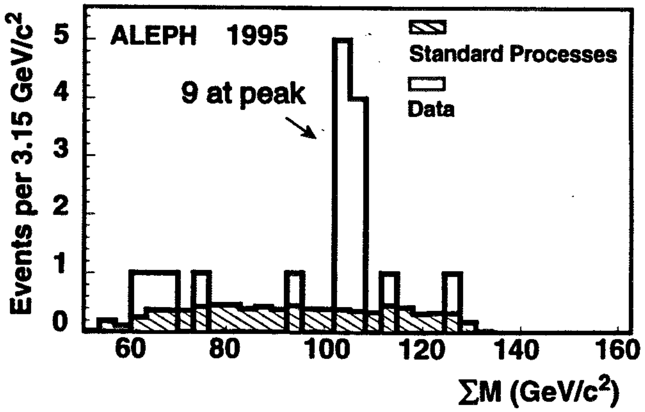
–What to look for?



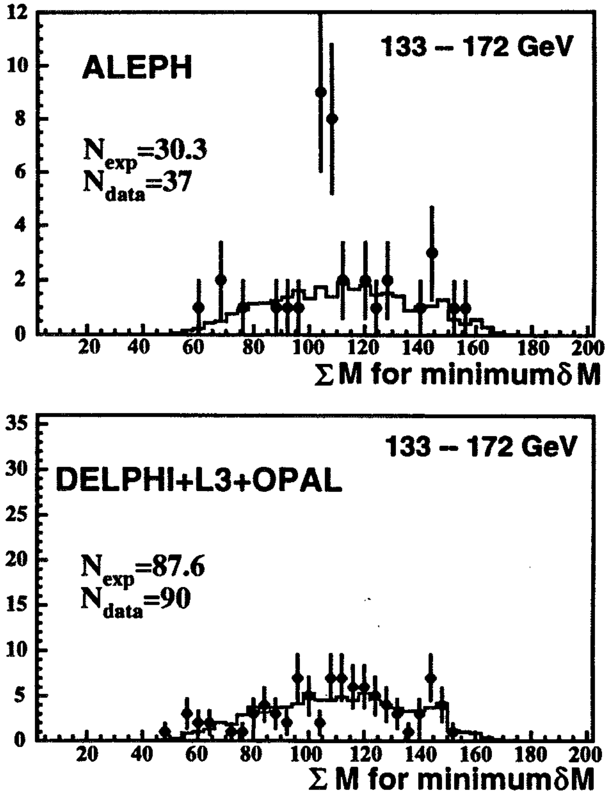
- **well balanced 4 jet events:**
- **$M_{lj} \sim M_{kl}$**
- Plot $\Sigma M = M_{lj} + M_{kl}$, better resolution

– Why Interesting?

130 + 136 GeV (6 pb^{-1})



total : 8.6 expected , 16 observed

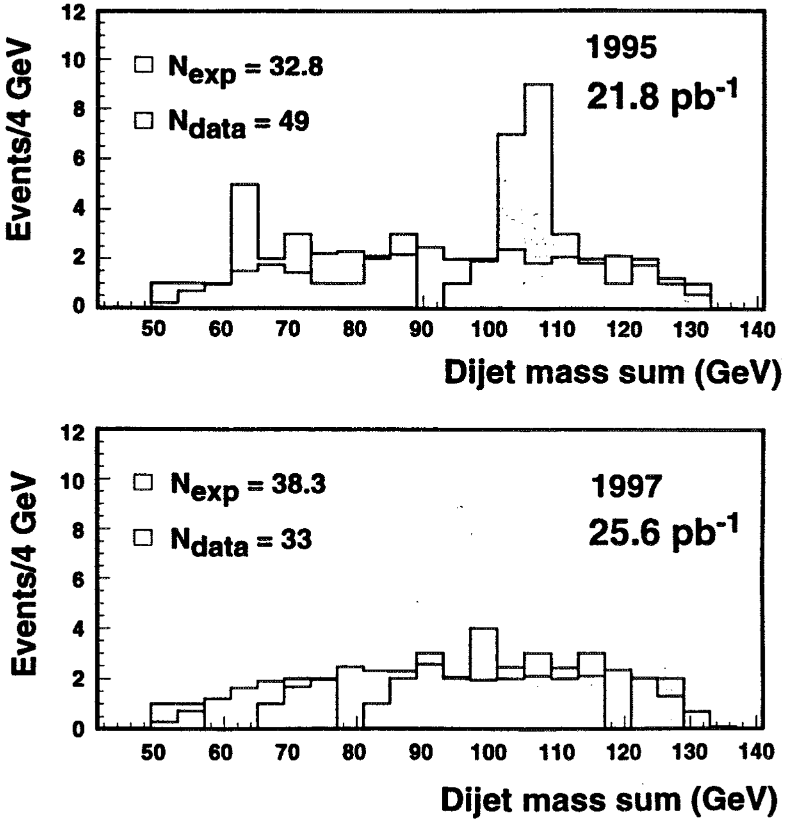


- -- Probability of fluctuation ~ 10^{-4}

  (DLO down or ALEPH up?)

- -- 130 GeV specific?

LEP at 130/136 GeV
(ALEPH+DELPHI+L3+OPAL)



More Searches: Photonic Events

– Event topology:

- $\gamma + \not{E}$, $\gamma\gamma + \not{E}$, $\gamma\gamma\gamma + \not{E}$ .....

– Possible source:

SM: $e^+e^- \to \nu\nu\gamma(\gamma)$

New physics: $e^+e^- \to XY, XX$ $X \to \gamma Y$

e.g.   Y: invisible

(a) A light gravitino could be the LSP:

$e^+e^- \to \tilde{\chi}^0_1 \tilde{G}$
$\quad \hookrightarrow \gamma\tilde{G}$

$e^+e^- \to \tilde{\chi}^0_1 \tilde{\chi}^0_1$
$\quad \hookrightarrow \gamma\tilde{G}$
$\quad \hookrightarrow \gamma\tilde{G}$

(b) Excited neutrino:

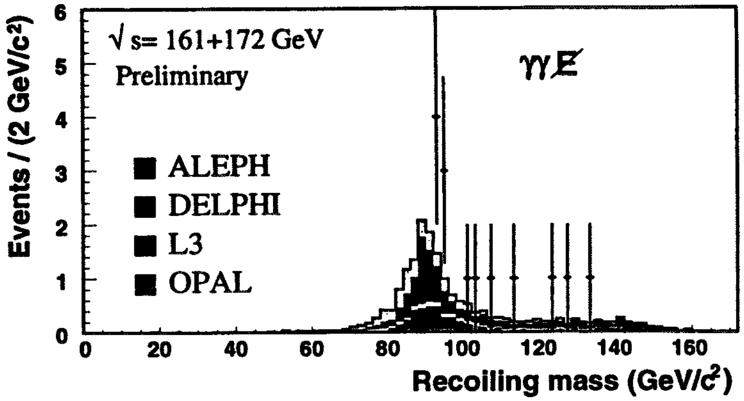
$e^+e^- \to \nu^*\nu$
$\quad \hookrightarrow \nu\gamma$

(c) In certain region of SUSY parameter space:

$e^+e^- \to \tilde{\chi}^0_2 \tilde{\chi}^0_1$
$\quad \hookrightarrow \gamma\tilde{\chi}^0_1$

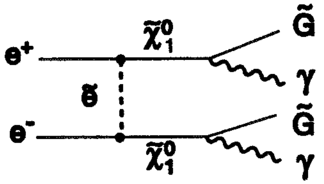
ALEPH, DELPHI, L3, OPAL:

No excess beyond $\nu\nu\gamma(\gamma)$ predictions



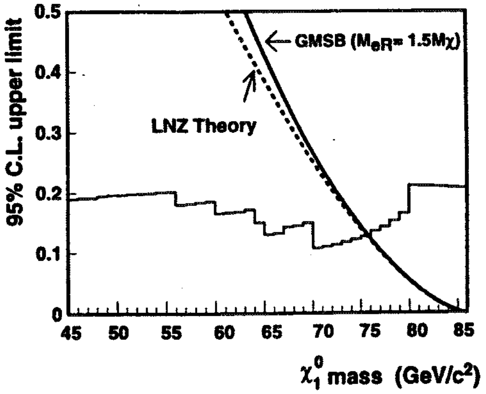
Limits can be set on the light gravitino (and other) theories predicting $\gamma(\gamma)\not{E}$ topology

For example $\gamma\gamma\tilde{G}\tilde{G}$ channel:



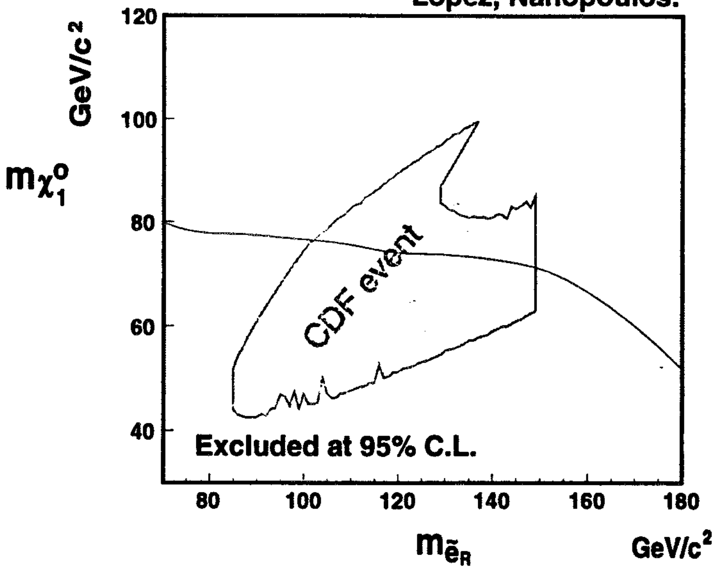
95% C.L

$M_{\tilde{\chi}^0} > 76$ GeV



CDF $ee\gamma\gamma$ in the context of:

$$p\,p \rightarrow \tilde{e}\,\tilde{e}\,x$$
$$\tilde{e} \rightarrow \tilde{\chi}_1^0 e$$
$$\quad\quad\quad\;\; \hookrightarrow \gamma\tilde{G}$$


Lopez, Nanopoulos.

CONCLUSIONS

- $M_W = 80.48 \pm 0.14$ GeV
- Higher energy at LEP II improves the limits on the SUSY particle searches, BUT no SUSY discovery yet.
  $M_{\tilde{\chi}_1^0} > 25$ GeV large m_0
  14.0 GeV any m_0 (E_{cm} up to 172 GeV)
- Limits on the masses of the Higgs Bosons have also been extended.
  SM : $M_{H^0} > 77.5$ GeV
  MSSM : $M_h > 62.5$ GeV (E_{cm} up to 172 GeV)
  $M_A > 62.5$ GeV ($\tan\beta > 1$)
  $M_{H^\pm} > 54.5$ GeV
- End of the 4-jet story
- New leptons, leptoquarks, and many other topologies have been searched for, no discovery yet.
- The future
  1998 , 1999 : @ 189 - 192 GeV
  2000 : @ 200 GeV ($M_H \sim 105$ GeV)

Physics potential of CMS/LHC

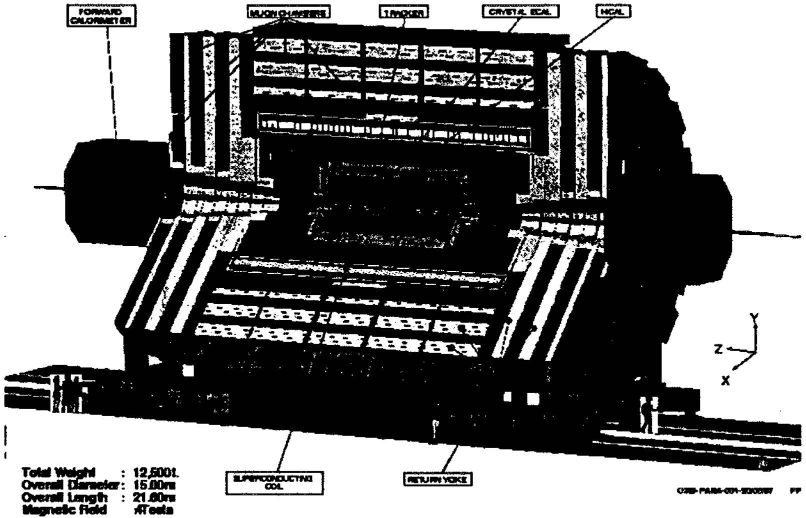
Sridhara Dasu

University of Wisconsin
Department of Physics
Madison

for CMS collaboration

- Standard model Higgs
- Minimal SUSY model Higgs
- SUSY sparticle search

CMS Detector



Basic design criteria

- A general purpose detector optimized for runs at the highest LHC luminosity (10^{34} cm^{-2} s^{-1})
- But also well adapted for studies at the initial lower luminositie

Technologies

- Muon - Central Drift tubes, Forward Cathode Strip Chambers, Additional Resistive Plate Chambers for trigger
- 4 Tesla superconducting coil
- Calorimeter - $PbWO_4$ Crystal ECAL, Cu-Scintillator HCAL, Quartz VFCAL, Pb-Scintillator preshower
- Tracker - Inner Si Pixels, Central Si Strips, Outer Micro-strip gas chambers

CMS Detector Summary

Magnet
- 4 Tesla strength, 5.9 m diameter, 13m length solenoid
- Muon measurement with single magnet upto $\eta=2.4$
- Large enough to accommodate trackers and calorimeters inside

Tracking
- Needed for isolated lepton measurement
- $\Delta P_t/P_t \sim 0.1 P_t$ (P_t in TeV) resolution (central)
- Charge measurement of leptons upto ~2 TeV
- Provide b-tagging with impact parameter resolution of 20μm in transverse and 100μm in z, for both low and high luminosity physics
- Highly segmented (10^7 channels) for pattern recognition at high luminosity

Electromagnetic calorimeter
- Strictest performance requirement from Higgs decays to $\gamma\gamma$
- 0.5% constant term and $2\%/\sqrt{E}$ resolution
- $50\text{mrad}/\sqrt{E}$ angular resolution in barrel
- Additional preshower detector with better angular resolution needed at high luminosity

Hadron Calorimeter
- Hermetic coverage upto η of 5 needed to reconstruct missing E_t
- 0.087 ϕ x 0.087 η granularity to match EM and muon chambers to provide good dijet separation and aid in trigger.

Muon system
- Coverage upto η of 2.4
- At least 16λ material to ensure good muon id
- Together with tracker, muon P_t resolution of 0.5% at 10 GeV, to few% at 100GeV, to <20% at few TeV.
- Correct charge assignment (99% confidence) up to 7 TeV
- Correct beam crossing tag with 99% efficiency
- Triggers from few GeV up to 100 GeV

CMS Trigger Summary

- Triggers at hadron collider and in particular at CMS/LHC is a challenge
- QCD interactions with 30 GeV E_t particles occur at MHz rate.
- The data acquisition bandwidth to tape and analysis computing is limited to 100 Hz, requiring hardware triggers that enable lepton/photon id and essentially full event reconstruction in software triggers.
- CMS reduces the interaction rate from 40 MHz to 100 kHz using hardware triggers, and reduces it to 100 Hz level with higher level triggers running on scalable and programmable CPUs.
- Efficiencies and rate capability of hardware triggers is particularly problematic and has been simulated extensively.

For a selection of trigger cutoffs at low and high luminosity high efficiency for physics is realized while limiting QCD background rate to 15 kHz. (Only calorimeter triggers simulated)

High Luminosity:

Process	Efficiency (%)
H (80 GeV) $\to \gamma\gamma$	94
H (120 GeV) $\to ZZ \to ee\mu\mu$	74*
H (200 GeV) $\to ZZ \to eejj$	95
$pp \to tt \to eX$	82
$pp \to tt \to H_+ X \to$ [illegible]X e	76
SUSY CMS TP Scenario A ($M_{LSP} = 45$, $M_{spart} \sim 300$ GeV)	83#

*Inclusion of muon trigger provides full efficiency

Low Luminosity:

Process	Efficiency (%)
$pp \to tt \to eX$	97
$pp \to tt \to H+ X \to$ [illegible]X e	94
$pp \to bb$ (hadronize), $B \to eX$	0.2 (But 400Hz)
SUSY CMS TP Scenario A ($M_{LSP} = 45$, $M_{spart} \sim 300$ GeV)	98#
SUSY Neutral Higgs (Range of tan b and M_H values)	40 - 98

Physics at the LHC

pp Collisions :

i) Hard collisions
- Standard Model Higgs search, up to ~ 1 TeV
- SUSY Higgs searches (h^0, H^0 , A^0 , $H^{\pm}$)
- Squark , gluino searches, up to ~ 2.5 TeV
- New gauge bozons: W', Z', up to ~ 4.5 TeV
- Alternative symmetry breaking mechanims (ρ_{TC} , $V^{\pm}_{bess}$,V_{DHT}
- Detailed studies of top
- Tests of QCD ; compositness
- Tests of ew gauge couplings - triple gauge boson vertices

ii) CP violation in the B sector

iii) Soft physics: σ_{tot}, σ_{el} , $d\sigma/dt$ etc..

Heavy Ion Collisions : from O-O to Pb-Pb

- Search for quark - gluon plasma

e – p Collisions :

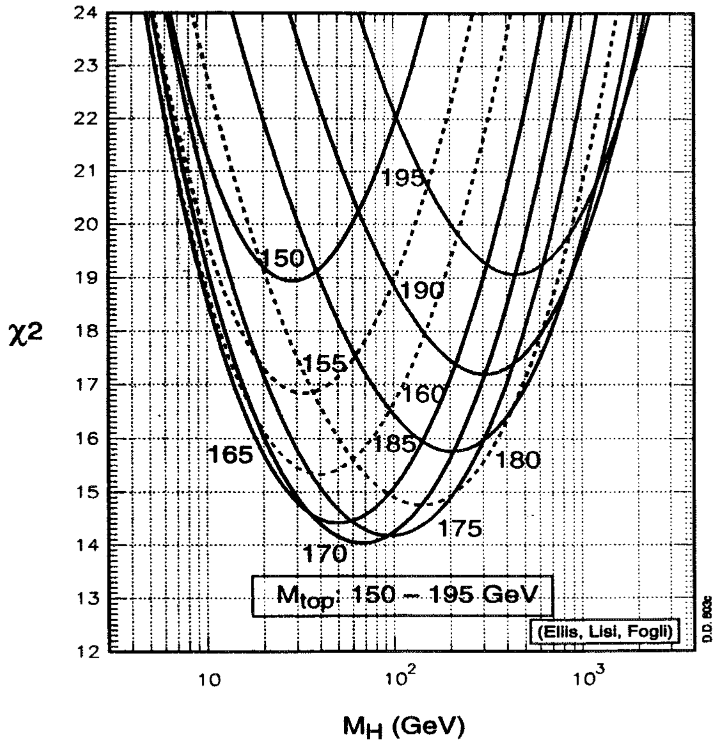
- Low-x physics
- Structure functions
- Search for leptoquarks

D_D_579c

Higgs mass estimate

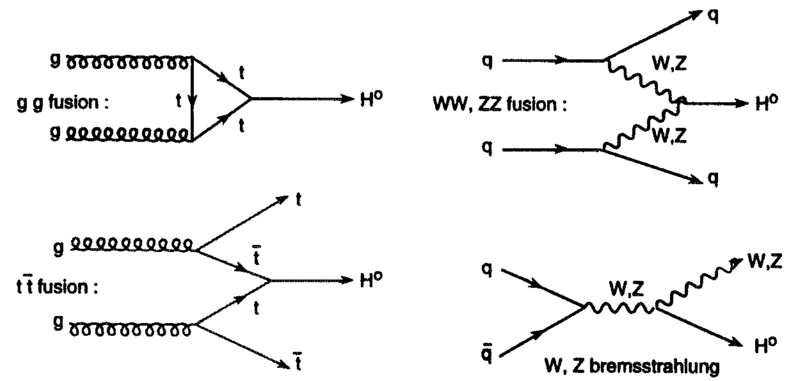
M_H versus M_{top}

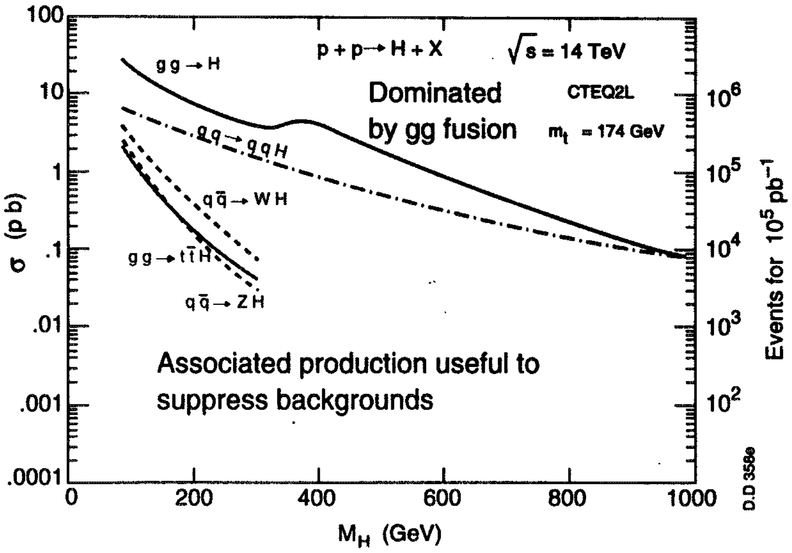
from all data available up to June 1995
including M_{top} (CDF + DØ) and A_{LR} from SLD



80 < M_H < 1000 GeV is still interesting at LHC.

H^o production at hadron colliders:





Dominated by gg fusion

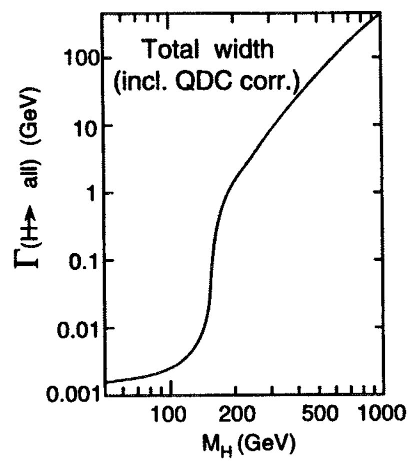
Associated production useful to suppress backgrounds

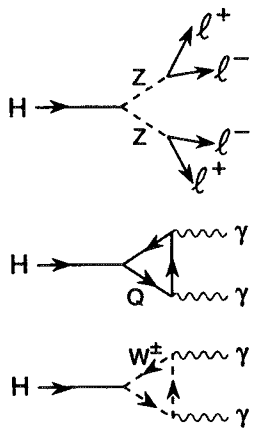
But : $BR(H \to Z^o Z^o \to 4l^{\pm}) = 1.4 \cdot 10^{-3}$

$BR(H \to Z^o Z^o \to 4\mu^{\pm}) = 3 \cdot 10^{-4}$

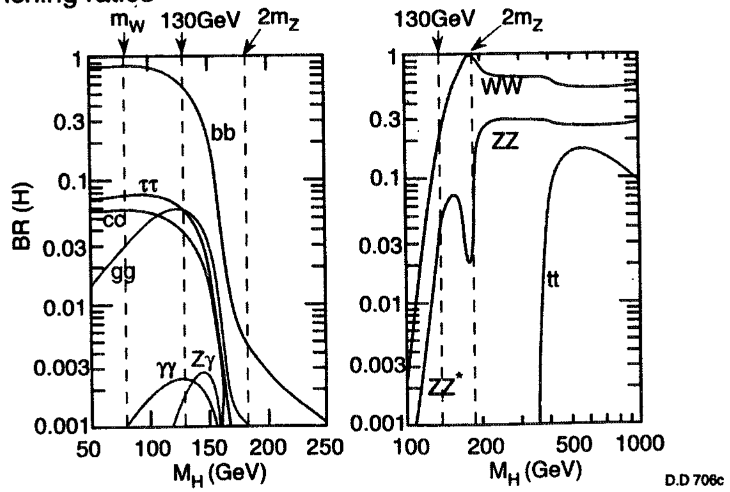
Higgs Decays

Total width





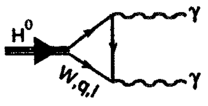
Branching ratios

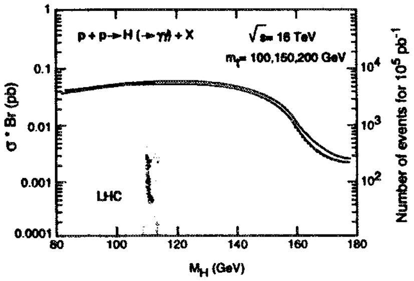


$H \rightarrow \gamma\gamma$

- Signal:

Signature : 2 isolated photons with $E_T^{\gamma} \sim 50$ GeV

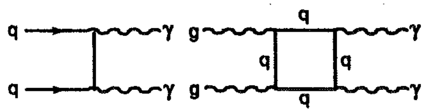




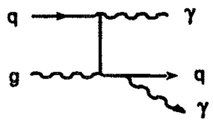
Observed width is dominated by instrumental mass resolution

- Backgrounds:

i) Irreducible background from:



\+ Bremsstrahlung diagrams :



\+ ...

⟹ Calorimeter resolution in $M_{\gamma\gamma}$ is essential: $\delta M_{\gamma\gamma} \lesssim 1$ GeV is required

γ-γ mass resolution: $\sigma_M/M = 1/2\,[\,\sigma_{E_1}/E_1 \oplus \sigma_{E_2}/E_2 \oplus \sigma_\theta/\mathrm{tg}(\theta/2)\,]$

At high luminosity 3rd term can dominate unless angle of emission of photons is determined

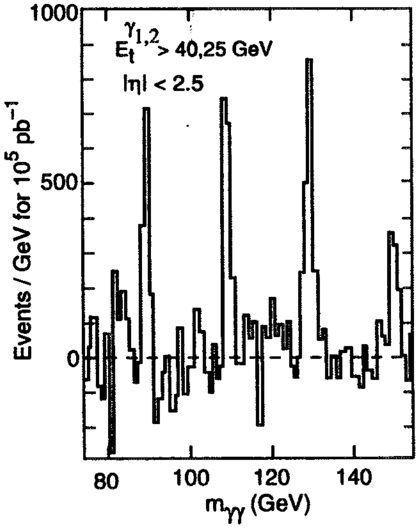
ii) QCD jet-jet and γ-jet bkgd faking "$\gamma\gamma$":
Rate larger by ~ 10^7 than signal but can be reduced

⟹ photon isolation and calorimeter granularity are essential to supress $\pi^0 \rightarrow \gamma\gamma$ background

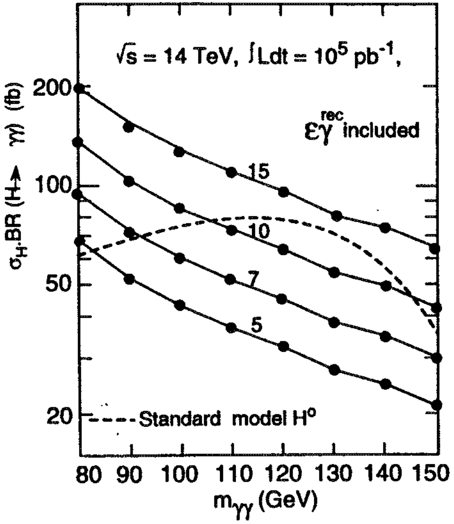
D_D_474dc

Higgs → $\gamma\gamma$

- $PbWO_4$ calorimeter
- 10^5 pb^{-1} taken at high luminosity **(1 year)**
- $\varepsilon\gamma^{\text{reconstr.}} = 64\%$



σ.BR required to give specified significance



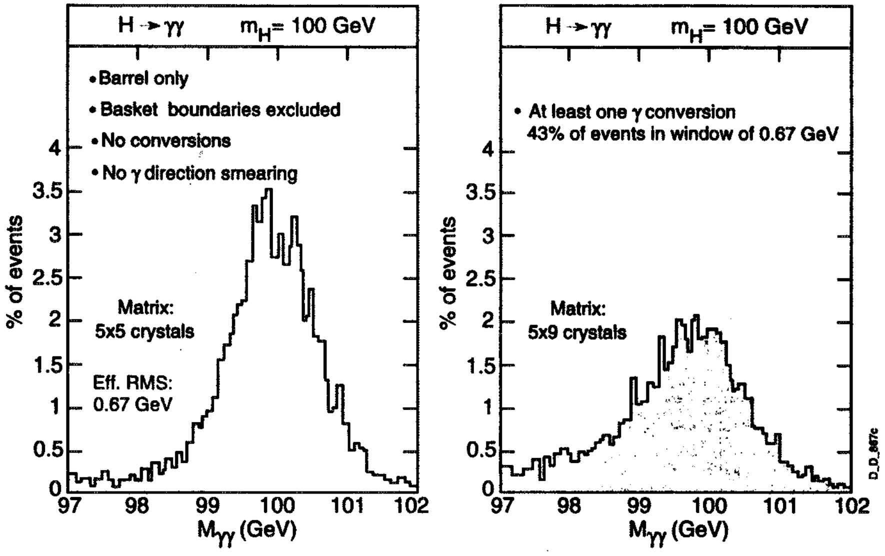
- $\sigma/E = \begin{cases} 2\%/\sqrt{E} \oplus 0.5\% \oplus 200\ \text{MeV}/E & \text{barrel} \\ 5\%/\sqrt{E} \oplus 0.5\% \oplus 200\ \text{MeV}/E & \text{end-cap} \end{cases}$
  and barrel $|\eta| < 1.1$
- $\Delta\alpha = 40$ mrad $/\sqrt{E}$ with preshower

Better than 5σ significance discovery in the Higgs mass range 80-150 GeV

Conversions

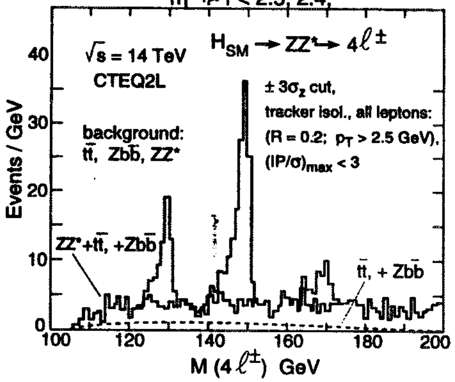
$H \rightarrow \gamma\gamma$ studies in CMS

Mass resolution; recovery of conversions



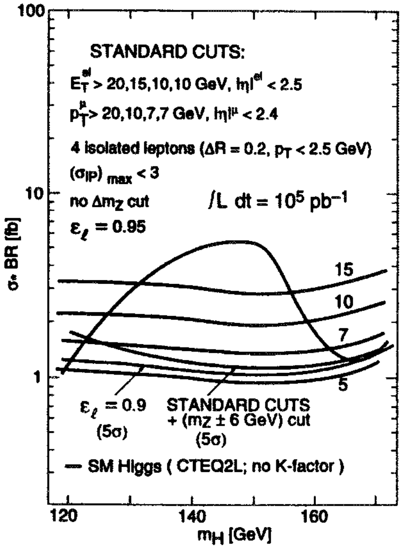
Higgs → ZZ

$E_t^e > 20,15,10,10$ GeV; $p_t^\mu > 20,10,5,5$ GeV; $|\eta^{e,\mu}| < 2.5, 2.4;$



$\sqrt{s}$ = 14 TeV, m_{top} = 174 GeV, CTEQ2L str. func.

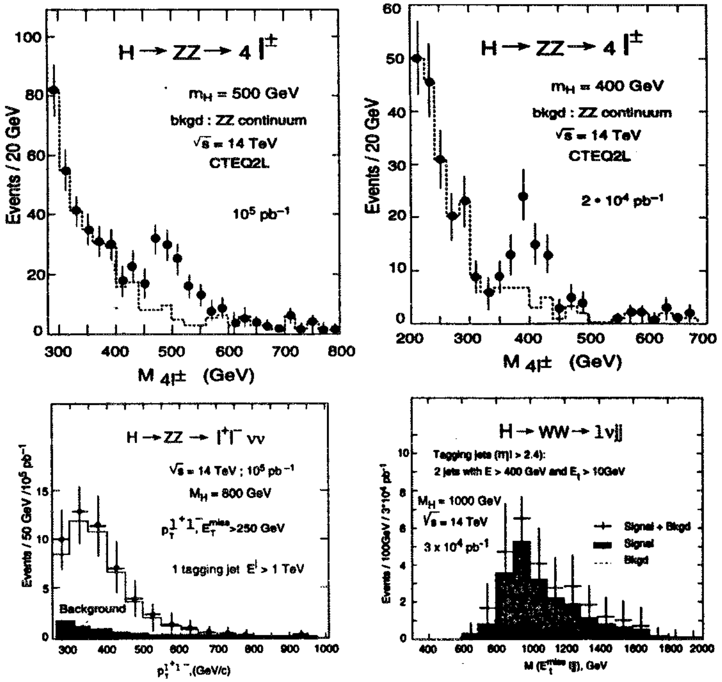
σ × BR required to give specified significance



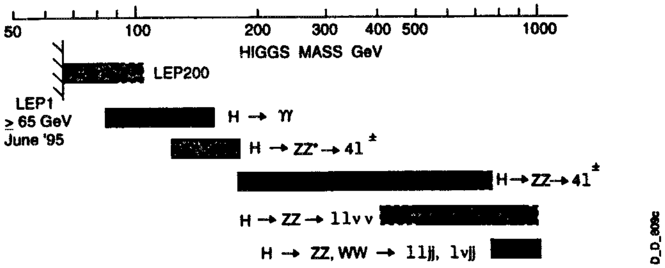
Golden events

Better than 5σ significance discovery in the Higgs mass range 125-165 GeV in one year of high luminosity running.

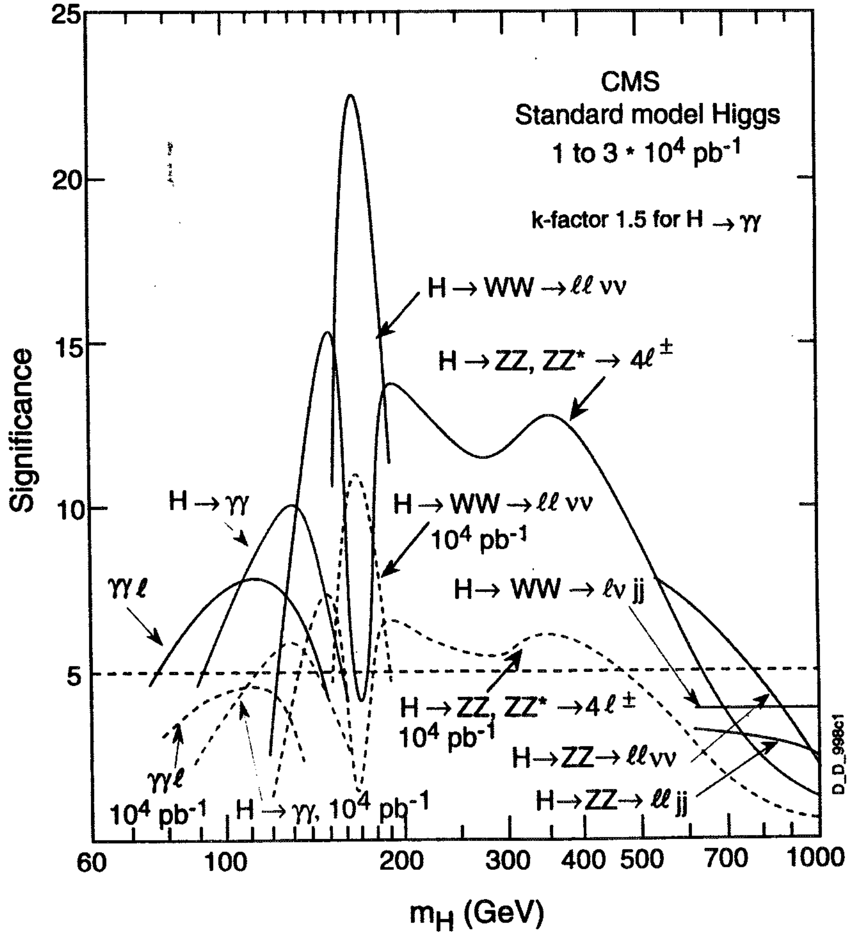
Heavy Standard Model Higgs



Explorable mass range at $\sqrt{s}$ =14 TeV with 10^5 pb^{-1} taken at 10^{34} cm^{-2} s^{-1}:



Expected observability of Standard Model Higgs in CMS with 3 ·10^4 pb^{-1}



Supersymmetry

Additional particles expected:

fermions → boson super-partners
bosons → fermion super- partners

SUSY is a broken symmetry, but:

$|m^2_{part} - m^2_{spart}| \lesssim 1\ \mathrm{TeV}^2$

if of relevance at e-w scale

The Minimal Supersymmetric Model particle spectrum:

Squarks ($\tilde{q}$), gluinos ($\tilde{g}$), sleptons ($\tilde{\ell}$)
neutralinos $\tilde{\chi}^0_i$ (i= 1,4), charginos $\tilde{\chi}^\pm_i$ (i= 1,2)
Higgs sector: h^0, H^0, A^0, $H^\pm$

Production and decay:

Sparticles are pair produced (if R-parity conserved)
Lightest sparticle (LSP) is stable and weakly interacting

This LSP, if it is the lightest neutralino $\tilde{\chi}^0_1$, it is an excellent cold (or mixed) dark matter candidate

D_D_956c

MSSM Higgs Sector

$$m^2_{H^\pm} = m^2_{A^0} + m^2_W \qquad (1)$$

$$m^2_{H^0,h^0} = \frac{1}{2}\left[m^2_{A^0} + m^2_Z \pm \sqrt{(m^2_{A^0} + m^2_Z)^2 - 4m^2_Z m^2_{A^0}\cos^2 2\beta}\right] \qquad (2)$$

- Three neutral h, H, A and two charged $H^\pm$ Higgs needed to generate masses for up and down type quarks
- Two independent parameters, e.g., M_A and the ratio of vacuum expectation values, $\tan\beta$
- The lightest Higgs, h, increases with the mass of A and reaches a plateau for A heavier than 200 GeV
- Although there is a good chance of seeing h at LEPII, the upper bound on h mass is outside of its range.
- If A is heavy, h behaves like Standard Model Higgs - LEPII cannot tell if it is MSSM, even if it discovers h.
- LHC needed to sort out MSSM
- Couplings of A and H to charge 1/3 quarks and leptons is enhanced when compared to SM higgs at large $\tan\beta$
- A does not couple to gauge boson pairs
- H, A $\rightarrow \gamma\gamma$, $\tau\tau$ and $\mu\mu$, and H $\rightarrow$ hh, A $\rightarrow$ Zh and A $\rightarrow$ tt are useful modes

MSSM Higgs Searches

Channels

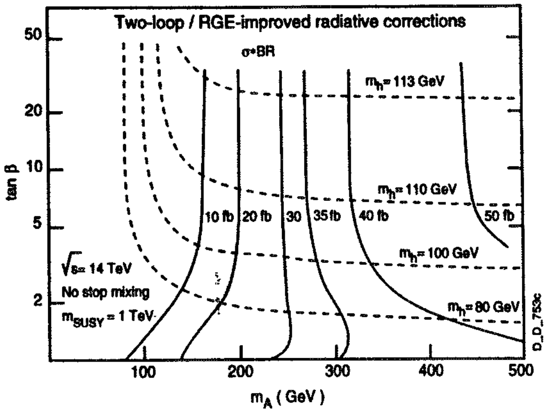
- h, H → $\gamma\gamma$
- h → $\gamma\gamma$ in associated production with W and top
- h, H → Z Z*, ZZ → 4 leptons
- h, H, A → $\tau\,\tau$
  - $\tau\tau$ → lepton+hadron+missing E_t
  - $\tau\tau$ → electron+muon
- h, H, A → $\mu^+\mu^-$
- $H^\pm \to \tau\,\nu$ when produced in top decay

Regions of sensitivity in (m_A, tanβ)

Simulation with

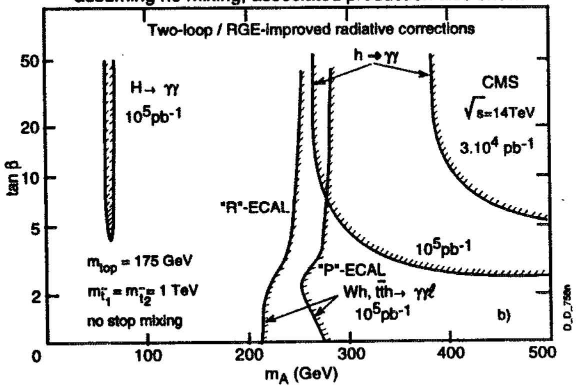
- M_{top} = 174 GeV
- Masses and couplings at two loops level
- CTEQ2L structure functions

SUSY Higgs to two photons



Expected production cross section σ BR (h → $\gamma\gamma$) for the MSSM light scalar h^0 in (tgβ, m_A) space at the LHC

5 σ significance contours h, H → $\gamma\gamma$ assuming no mixing; associated production also shown

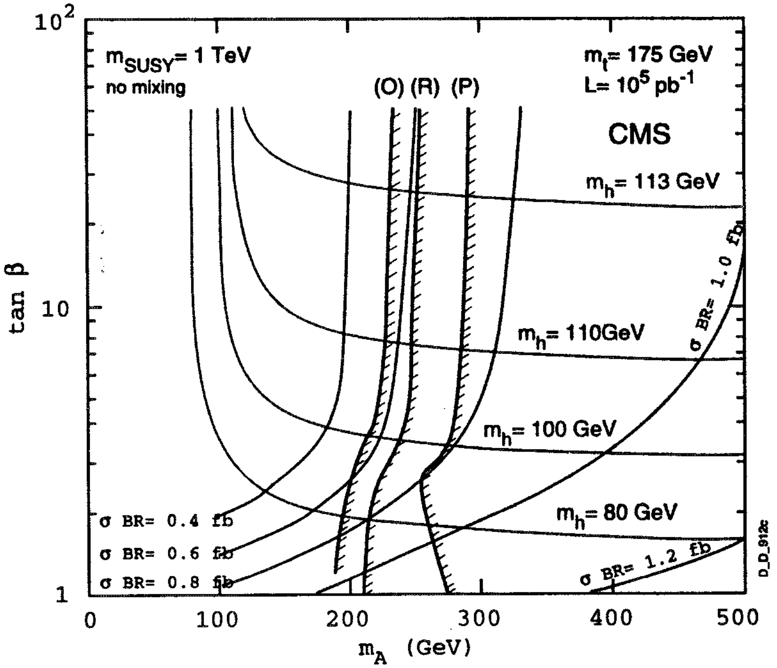


Regions of the MSSM parameter space (m_A, tgβ) explorable through the $\gamma\gamma$ channel

5σ significance contours obtained using σ.BR plot shown in Standard Model Higgs discussion

See next plot for W/top associated production

5 σ significance contours for Wh, $t\bar{t}h \rightarrow \ell\gamma\gamma$



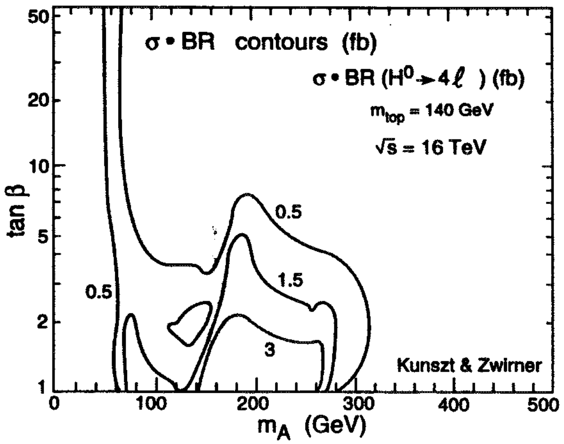
"O" "optimistic" ECAL $\frac{\Delta E}{E} = \frac{2.5\%}{\sqrt{E}} \oplus \frac{0.2}{E} \oplus 0.5\%$

"R" "realistic" ECAL $\frac{\Delta E}{E} = \frac{3.5\%}{\sqrt{E}} \oplus \frac{0.2}{E} \oplus 0.7\%$

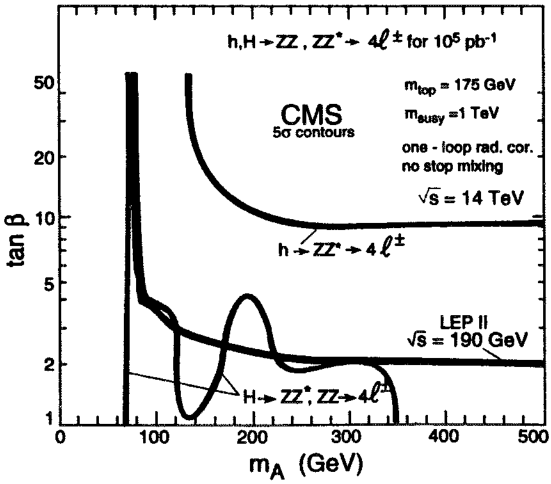
"P" "pessimistic" ECAL $\frac{\Delta E}{E} = \frac{5.0\%}{\sqrt{E}} \oplus \frac{0.2}{E} \oplus 1.0\%$

SUSY Higgs to 4 leptons

Production of $H^0 \rightarrow ZZ \rightarrow 4\ell^{\pm}$ at LHC



Regions of the MSSM parameter space (m_A, tgβ) explorable through various SUSY Higgs channels



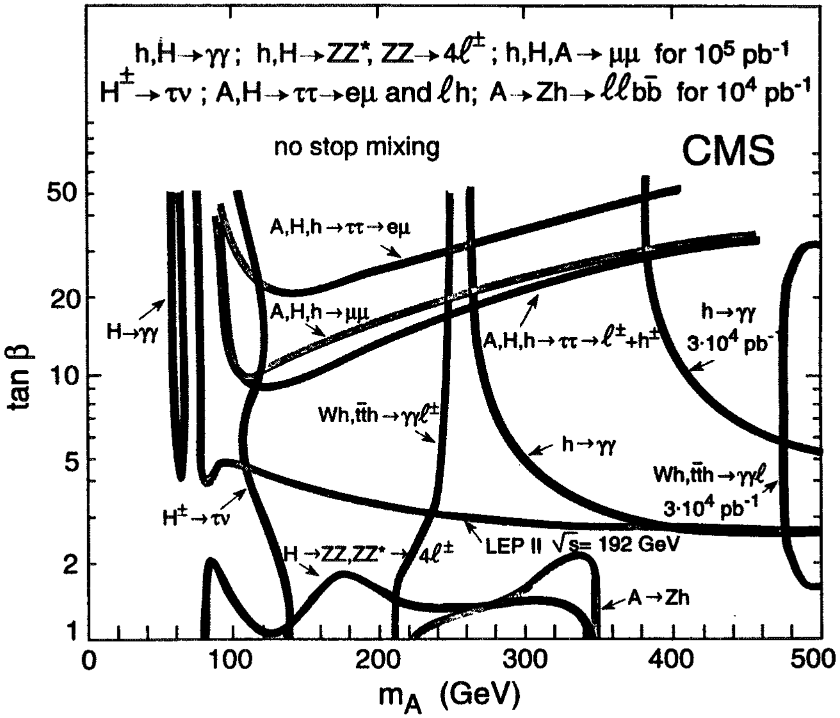
5σ significance contours obtained using σ.BR plot shown in Standard Model Higgs discussion

Two photon and four lepton modes do not span the allowed (m_A,tanβ) plane.

Significance contours for SUSY Higgses

Regions of the MSSM parameter space (m_A, tgβ) explorable through various SUSY Higgs channels

- 5σ significance contours
- two-loop / RGE-improved radiative corrections
- $m_{top} = 175$ GeV, $m_{SUSY} = 1$TeV



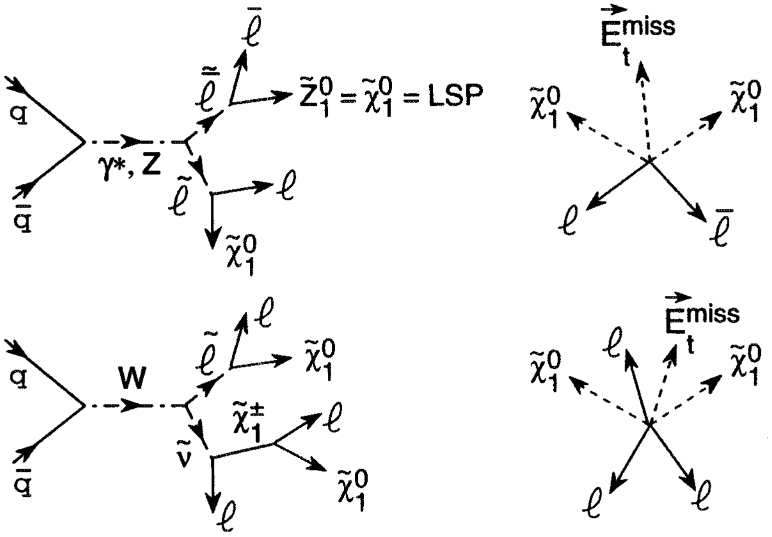
Can exclude the entire M_A-tanβ plane at 95% c.l. with 10^5 p

Ensuring 5σ discovery over the entire M_A-tanβ plane require

more luminosity

How to look for Sleptons at LHC

- production



➤ Search in: $\ell\bar{\ell}$ ($\ell\ell\bar{\ell}$) + E_T^{miss} events

Require for example:

- 2 same flavour leptons, $p_t^{\ell} > 20$ GeV to > 50 GeV
- $E_T^{miss} > 100$ GeV
- relative azymuthal cut E_T^{miss} vs leptons
- Central jet veto, ex. no jet with $E_T > 25$ GeV in $|\eta| < 3.0$

Backgrounds : $\tau\tau$, WW, $t\bar{t}$, $\bar{b}b$ production, other SUSY channels

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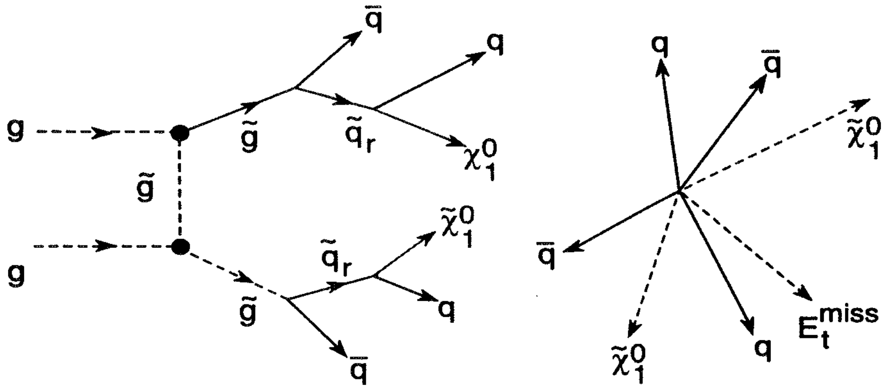
Squark and gluino searches in E_T^{miss} + jets

ex: $\tilde{g}\tilde{g}$ production with direct decay to LSP ($\tilde{\chi}_1^0$)



➤ Final states with jets + E_T^{miss}
(number of decay jets from 2 to 8)

Large background expected from:

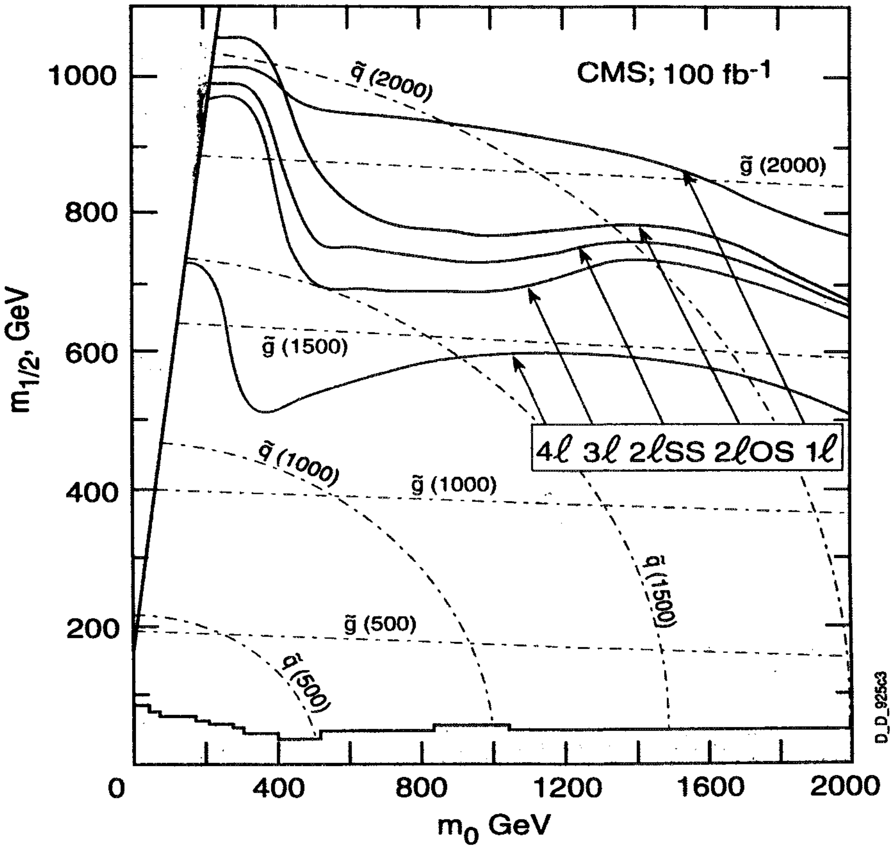
- QCD multi jet production, with mismeasurement of jets

- $t\bar{t} \rightarrow Wb\ Wb \rightarrow \ell\nu bjjb$
- $W(\rightarrow \ell\nu)$ + jets
- $Z(\rightarrow \nu\nu)$ + jets

D_D_836c

Explorable domain of $m_0, m_{1/2}$ parameter space with 100 fb^{-1} in $\tilde{q}, \tilde{g}$ searches in n leptons + E_t^{miss} + $\geq$ 2 jets final states

m SUGRA; tg $\beta = 2$, $A_0 = 0$, $\mu < 0$
5 σ contours ($\sigma = N_{sig} / \sqrt{N_{sig} + N_{bkgd}}$) for 10^5pb^{-1}



Summary

Standard model Higgs can be searched over most of the expected mass range (80 GeV < M_H < 1000 GeV) with good significance

- Calorimeter performance is a challange for H → $\gamma\gamma$ for 80 < M_H < 130 GeV
- There is a weak spot at 160 GeV < M_H < 170 GeV

CMS/LHC will allow tests of SUSY at Electro-weak scale in a decisive way

- Most of the MSSM Higgs sector parameter space (M_A, tanβ) can be explored
- sparticle searches can reach
  - squark, gluino masses of 2 TeV
  - slepton masses of 400 GeV
  - neutralino masses of 350 GeV

There are plenty of other physics channels to explore at both low and high luminosities.

CMS @ LHC with 14 TeV c.m. energy and 10^{34} cm^{-2}s^{-1} luminosity will be ready to explore TeV physics whether or not it is described by SM or MSSM.

The Top Quark & Higgs Boson at Hadron Colliders

Chris Quigg
Fermilab
quigg@fnal.gov

- Preamble
- The Top Quark
  What is known?
  What will be known?
  What do we want to know?
- The Higgs Boson
  What is known?
  LEP Prospects
  Higgs search and study at the Tevatron Collider
  Higgs physics at the LHC
- Envoi

C. Quigg, "Hadron Colliders, the Top Quark, and the Higgs Sector," hep-ph/9707508, FERMILAB–CONF–97/157–T.

The Big Questions for $\mu^+\mu^-$ Colliders

- What machines are possible?
  When?
  At what cost?
- What are the physics opportunities?
- Can we do physics in the environment?
  (What does it take?)
- How will these experiments add to existing knowledge *when they are done?*

The Hadron Colliders

Fermilab Tevatron + Main Injector
$\bar{p}p$ collisions at 2 TeV
CDF and D0 detectors

- Run I: 100 fb^{-1} recorded in 1994–1996
- Run II: 2 fb^{-1} in 2000–2002
- Run III: 30 fb^{-1} by 2006

CERN Large Hadron Collider
pp collisions at 14 TeV
ATLAS and CMS detectors

- $\int \mathcal{L}dt = 100\ \text{fb}^{-1}$ in 2005–2009

Key considerations

- High sensitivity from high integrated luminosity
- The success of b-tagging in the hadron-collider environment:
  + CDF: Silicon Microvertex Detector (SVX), with resolution . . .
  + CDF and D0: Soft-lepton tag from $b \to c\ell\nu$
- The great mass of the top quark

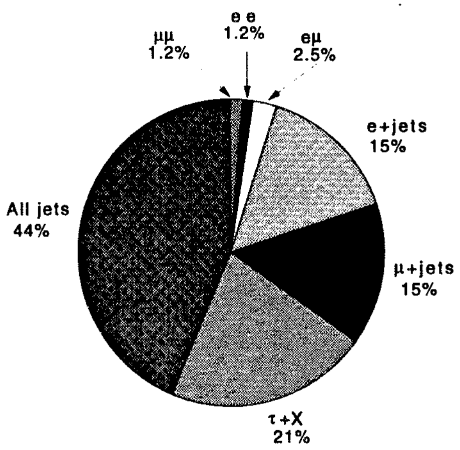
The Top Quark

Observed at the Tevatron in

$$\begin{array}{lll} \bar{p}p & \to & t\bar{t}+\cdots \\ & & \quad \hookrightarrow W^-\bar{b} \\ & & \hookrightarrow W^+b \end{array}$$

b-quarks identified as

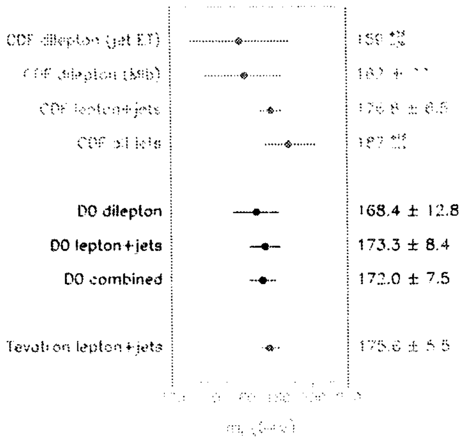
- displaced vertices
- "soft" lepton tags $b \to c\ell\nu$



Channels studied to date: dileptons (including $\tau + (e, \mu)$), lepton + jets, all jets.

Slide 5

Top Mass



"Unofficial" average including latest data:

$$\boxed{m_t = 174.3 \pm 5.3\ \mathrm{GeV}/c^2}$$

Top's Yukawa coupling:

$$m_f = \frac{\zeta_f v}{\sqrt{2}} \approx (176\ \mathrm{GeV}/c^2) \cdot \zeta_f$$

$$\Longrightarrow \zeta_t \approx 1$$

- Is top special?
- Is it the only normal fermion?

Slide 6

Top Lifetime

Governed by semiweak decay $t \to bW^+$

$$\Gamma(t \to bW^+) = \frac{G_F m_t^3}{8\pi\sqrt{2}} |V_{tb}|^2 \left(1 - \frac{M_W^2}{m_t^2}\right)^2 \left(1 + \frac{2M_W^2}{m_t^2}\right)$$

Three generations:

$$|V_{tb}| = 0.9991 \pm 0.0002 \approx 1$$

$$\Longrightarrow \Gamma(t \to bW^+) \approx 1.55 \text{ GeV}$$

Corresponds to a top lifetime

$$\boxed{\tau_t \approx 0.4 \times 10^{-24} \text{ s}}$$

Compare time scale for confinement

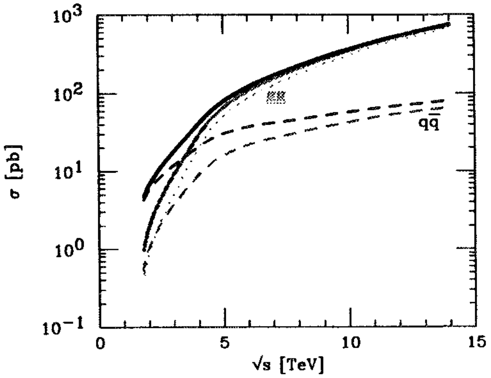
$$1/\Lambda_{\text{QCD}} \approx \text{few} \times 10^{-24} \text{ s}$$

- t decays before it can be hadronized
- No discrete lines in $t\bar{t}$ spectrum; no dressed hadronic states containing top

Characteristics of top production and the hadronic environment near top in phase space should be calculable in pQCD

Slide 7

Top Production

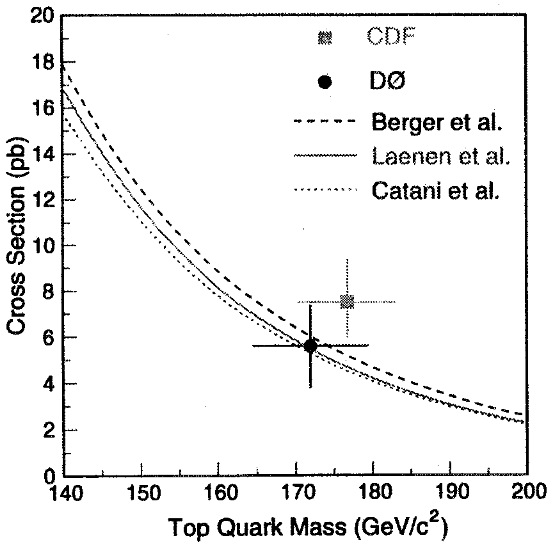


Important characteristics:

- At Tevatron, $\sigma \approx 6$ pb
  90% $q\bar{q} \to t\bar{t}$ 10% $gg \to t\bar{t}$
- At LHC, $\sigma \approx 800$ pb
  10% $q\bar{q} \to t\bar{t}$ 90% $gg \to t\bar{t}$

Slide 8

Top Cross Section

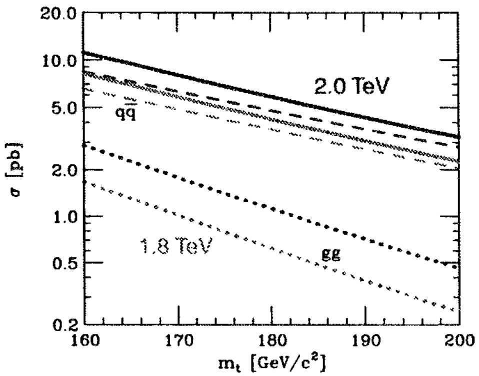


CDF: $7.6^{+1.8}_{-1.5}$ pb DØ: 5.5 ± 1.8 pb

Slide 9

Future Top Yields

Tevatron energy increases to 2 TeV $\Longrightarrow \sigma(t\bar{t}) \times 1.4$



225K $t\bar{t}$ pairs produced in 30 fb^{-1}

Mode	2 fb^{-1}	30 fb^{-1}	S/B
Dilepton	80	1200	5:1
$\ell +$ 3jets/1b	1300	20000	3:1
$\ell +$ 4jets/2b	600	9000	12:1
Single top (all)	170	2500	1:2.2
Single top ($W^\star$)	20	300	1:1.3

LHC produces 8×10^6 $t\bar{t}$ pairs in 10 fb^{-1}

Expect $\boxed{\delta m_t = \text{(1-2) GeV}/c^2}$ at Tevatron, LHC

R. Frey, *et al.*, "Top Quark Physics: Future Measurements," in *Snowmass '96*.

Slide 10

Measuring $|V_{tb}|$

CDF measures

$$B_b \equiv \frac{\Gamma(t \to bW)}{\Gamma(t \to qW)} = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2} = 0.99 \pm 0.29$$

With three generations,

$$|V_{tb}| > 0.76 \ \ (95\% \text{ CL})$$

Without the unitarity constraint, learn only that

$$|V_{tb}| \gg |V_{td}|, |V_{ts}|$$

Expected improvements in δB_b:

Run II: ±10%   Run III: ± few %   LHC: ±1%

Direct measurement of $|V_{tb}|$ in single-top production

$$\bar{q}q \to W^\star \to t\bar{b} \qquad gW \to t\bar{b}$$

$$\sigma(t) \propto |V_{tb}|^2$$

Expect $\delta|V_{tb}| = \pm(10\%, 5\%)$ in Run II and III, using both $W^\star$ and gW fusion.

LHC: gW fusion cross section is 100× larger

S. Willenbrock, "Top Quark Physics for Beautiful and Charming Physicists," hep-ph/9709355.

Searches for new physics

Top decay is an excellent source of longitudinally polarized gauge bosons

|helicity| = 1, weight = 1   helicity = 0, weight $= m_t^2/M_W^2$

Expect longitudinal fraction $f_0 \approx 70\%$

$$\frac{d\Gamma(W^+ \to \ell^+\nu_\ell)}{d(\cos\theta)} = \tfrac{3}{8}(1 - f_0)(1 - \cos\theta)^2 + \tfrac{3}{4} f_0 \sin^2\theta$$

Prospects: $\delta f_0 = \pm 3\%$, Run II, ±1%, LHC.

FCNC decays $t \to \begin{pmatrix} g \\ Z \\ \gamma \end{pmatrix} + \begin{pmatrix} c \\ u \end{pmatrix}$

unobservably small ($\ll 10^{-10}$) in standard model.

Present constraints allow few % branching fractions

Prospects: Tevatron $\sim 10^{-2}$, LHC $\sim 10^{-4}$

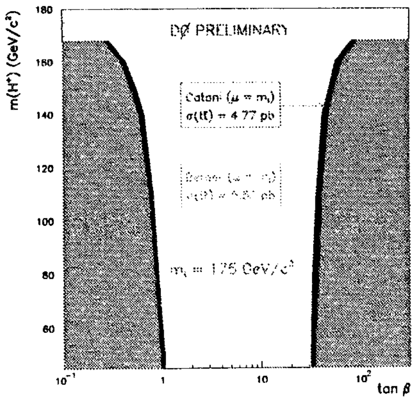
Rare decay $t \to bWZ$ (BR $\sim 10^{-6}$ in SM) might be detectable at LHC

Charged Higgs Search

Because top is so massive, top decays may surprise.

Semiweak decay $t \to bP^+$ may occur in multi-Higgs models, supersymmetry, technicolor, ...

Search begun in CDF and DØ:



Resonances in $t\bar{t}$ Production?

Top-condensate models, multiscale technicolor both imply

color-octet resonances $\to t\bar{t}$

with masses of several hundred GeV.

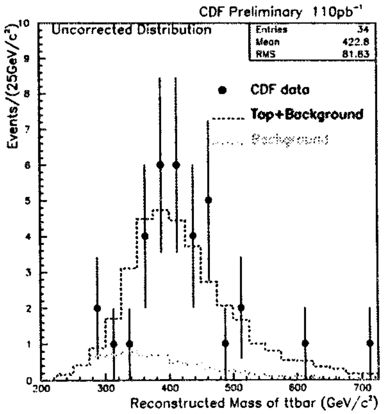
Technicolor:

$$gg \to \eta_T \to (t\bar{t}, gg)$$

Topcolor:

$$q\bar{q} \to V_8 \to (t\bar{t}, b\bar{b})$$

Look for structure in $t\bar{t}$ invariant mass.



CDF excludes $M \lesssim 500$ GeV/c^2

Top Quark Measurements

Only possible at the Tevatron until LHC operates.

LHC is a veritable fountain of tops.

- $\delta m_t \approx$ 1-2 GeV/c^2 at Tevatron and LHC
- $\delta\sigma(t\bar{t}) \approx \pm5\%$ at Tevatron,
  ± few % at LHC
- $\delta\dfrac{\Gamma(t \to bW)}{\Gamma(t \to qW)}$ will improve to ±10% in Run II,
  ± few % in Run III,
  ±1% at LHC
- $\delta|V_{tb}| \approx \pm10\%$ in Run II,
  ±5% in Run III
- Searches are under way for $t\bar{t}$ resonances, rare decays, and other signs of new physics.

Slide 15

The Higgs Boson

Central challenge in particle physics:
explore the 1-TeV scale, elucidate the nature of electroweak symmetry breaking

A key element: search for the Higgs boson

(Why the Higgs boson must exist)

$\boxed{\text{unique opportunity: } \mu^+\mu^- \to H}$

Calls attention to a not-too-heavy Higgs boson, as favored in supersymmetric models

$$M_h^2 = M_Z^2 \cos^2 2\beta + \frac{3g^2 m_t^4}{8\pi^2 M_W^2}\left[\log\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right) + \cdots\right] \lesssim 130 \text{ GeV}/c^2$$

Heavy Higgs remains a logical possibility

(Abbreviate to standard-model Higgs)

Slide 16

Constraints on M_H …

Perturbative unitarity:

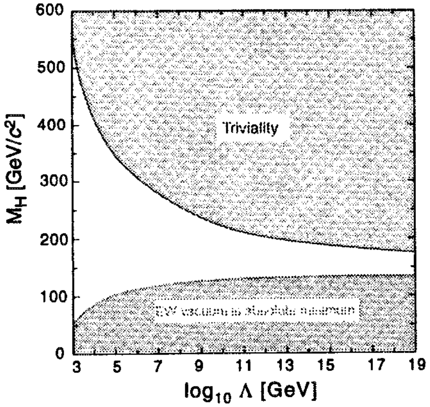
$$M_H \lesssim \left(\frac{8\pi\sqrt{2}}{3G_F}\right)^{1/2} = 1\ \text{TeV}/c^2$$

Triviality:

$$\Lambda < M_H \exp\left(\frac{4\pi^2 v^2}{3M_H^2}\right)$$

Vacuum stability:

$$M_H^2 > \frac{3G_F\sqrt{2}}{16\pi^2}(2M_W^4 + M_Z^4 - 4m_t^4)\cdots$$



Higgs Physics Working Group (convened by M. Carena and P. Zerwas), in Vol. 1 of *Physics at LEP2*, G. Altarelli, T. Sjøstrand and F. Zwirner, eds., Report CERN 96-01, Geneva (1996).

Slide 17

Higgs searches at LEP2

Current status:

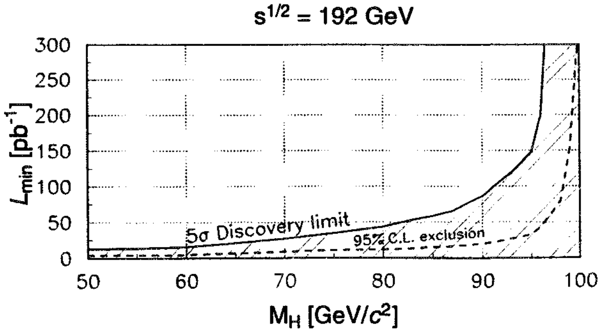
$$e^+e^- \to HZ \text{ at } 161 + 172 + 183 \text{ GeV}$$

Examine $qqbb, \nu\nu qq, \tau\tau qq, (ee + \mu\mu)qq$ channels
Representative preliminary results from OPAL, including 39 pb^{-1} at $\sqrt{s} = 183$ GeV:

$$M_H \gtrsim 82\ \text{GeV}/c^2$$

Projected sensitivity after running at 192 GeV,

$$M_H \gtrsim 96\ \text{GeV}/c^2$$



Running at 200 GeV in 2000?

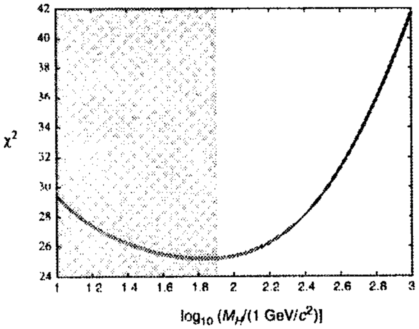
Slide 18

Clues about M_H

Higgs constraints from precision EW measurements are sensitive to light-quark contribution to the vacuum polarization for $\alpha(M_Z)$.

Using $e^+e^- \to$ light hadrons:

$$M_H = 69^{+85}_{-43}\ \mathrm{GeV}/c^2$$



$$M_H < \left\{\begin{array}{c} 236 \\ 287 \\ 413 \end{array}\right\} \mathrm{GeV}/c^2 \text{ at } \left\{\begin{array}{c} 90\% \\ 95\% \\ 99\% \end{array}\right\} \text{CL}$$

J. Erler and P. Langacker, October 1997 update of "Electroweak model and constraints on new physics," for the *Review of Particle Physics*

Clues . . .

Using pQCD for $\delta\alpha^{(5)}_{\mathrm{had}}$:

$$M_H = 97^{+79}_{-48}\ \mathrm{GeV}/c^2$$

$$M_H < \left\{\begin{array}{c} 229 \\ 273 \\ 377 \end{array}\right\} \mathrm{GeV}/c^2 \text{ at } \left\{\begin{array}{c} 90\% \\ 95\% \\ 99\% \end{array}\right\} \text{CL}$$

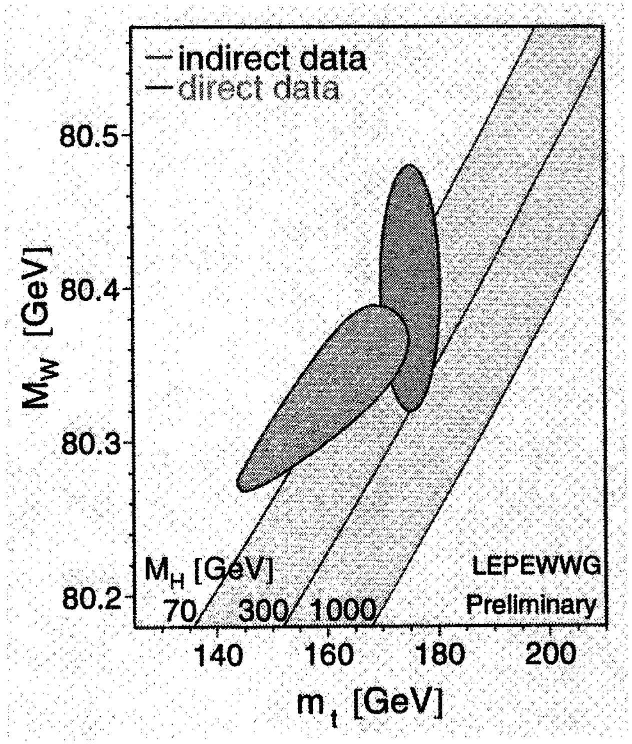
SLD's measurement of A_{LR} favors very low values of M_H. Using $e^+e^- \to$ light hadrons and PDG scale factors:

$$M_H = 122^{+134}_{-77}\ \mathrm{GeV}/c^2$$

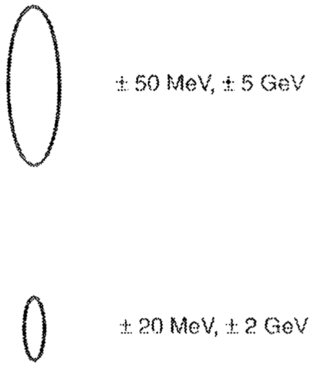
$$M_H < \left\{\begin{array}{c} 329 \\ 408 \\ 613 \end{array}\right\} \mathrm{GeV}/c^2 \text{ at } \left\{\begin{array}{c} 90\% \\ 95\% \\ 99\% \end{array}\right\} \text{CL}$$

Jens Erler, private communication.

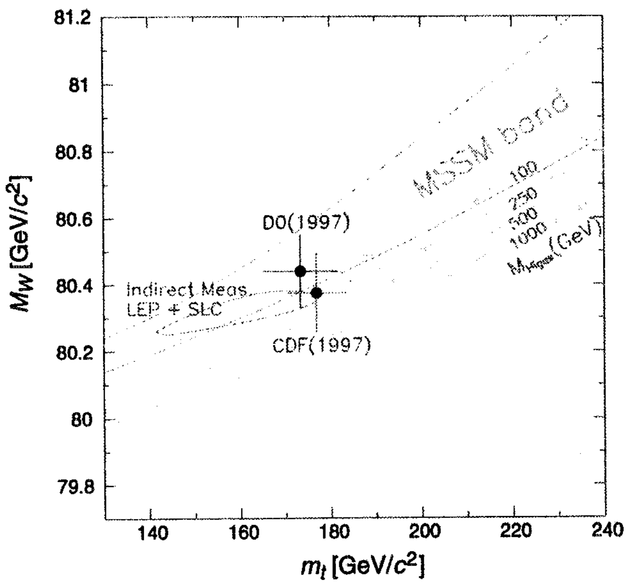
Clues . . .



Slide 21



Slide 22



P. Chankowski, *et al.*, *Nucl. Phys.* **B417**, 101 (1994); A. Dabelstein, W. Hollik, W. Mosle, hep-ph/9506251. The variation shown is for 90 GeV/$c^2 \lesssim M_H \lesssim$ 1 TeV/c^2, assuming that no supersymmetric particles are detected at LEP2.

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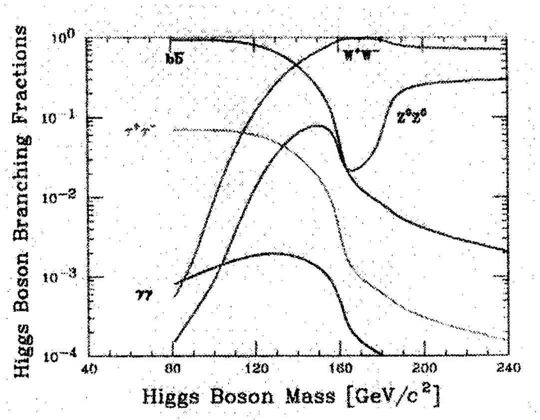
Search for a not-too-heavy Higgs boson



- Tevatron:

$$\begin{array}{lll} q\bar q & \to & H(W,Z) \\ & & \hookrightarrow b\bar b \end{array}$$

- LHC:

$$gg \to H \to \gamma\gamma,$$

$$\begin{array}{lll} q\bar q & \to & HW \\ & & \hookrightarrow b\bar b \end{array}$$

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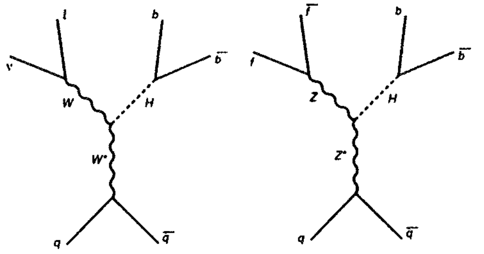
Tevatron Search Strategies

- $gg \to H \to b\bar{b}$ is swamped by QCD production of $b\bar{b}$.
  Even with 30 fb^{-1}, only $<$ 1-σ excess.
  By-product: $Z^0 \to b\bar{b}$ observable in Run II.
- Special topologies improve signal/background and significance:

$$\begin{array}{lll} \bar{p}p & \to & HW + \text{anything} \\ & & \quad \hookrightarrow \ell\nu \\ & & \hookrightarrow b\bar{b} \end{array}$$

$$\begin{array}{lll} \bar{p}p & \to & HZ + \text{anything} \\ & & \quad \hookrightarrow \ell^+\ell^- + \nu\bar{\nu} \\ & & \hookrightarrow b\bar{b} \end{array}$$



A. Stange, W. Marciano and S. Willenbrook, *Phys. Rev.* D**49**, 1354 (1994); *Phys. Rev.* D**50**, 4491 (1994).

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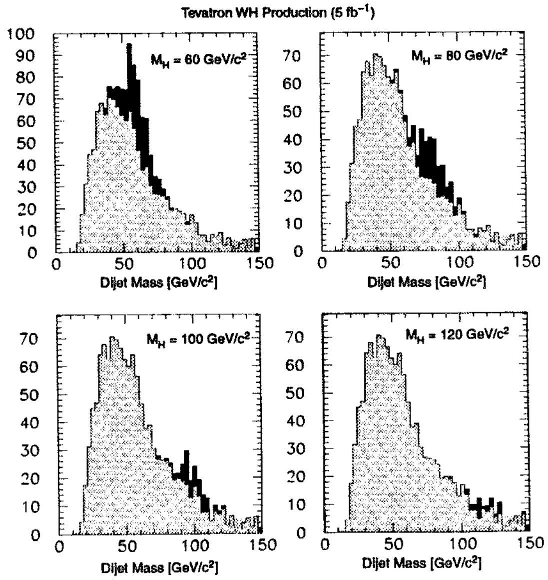
Simulated Higgs signals at the Tevatron

$$\begin{array}{lll} q\bar{q} & \to & HW \\ & & \quad \hookrightarrow \ell\nu \\ & & \hookrightarrow b\bar{b} \end{array}$$

Backgrounds: $Wb\bar{b} + Wc\bar{c} + t\bar{t} + (W^\star \to t\bar{b}) + (Wg \to t\bar{b}q)$



S. Kim, S. Kuhlmann, and W.-M. Yao, "Improvement of signal significance in $WH \to \ell + \nu + b + \bar{b}$ search at TeV33," in *Snowmass '96*.

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Tevatron Collider Rates

Number of signal and background events in Run III (30 fb^{-1}) for WH and ZH processes, and signal significance.

M_H[GeV/c^2]	60	80	90	100	110	120
WH signal S	681	420		228		117
Background B	2085	1260		789		456
S/B	0.33	0.33		0.29		0.26
$S/\sqrt{B}$	14.9	11.8		8.1		5.5
ZH signal S			108	92	82	51
Background B			533	495	462	378
S/B			0.20	0.19	0.18	0.13
$S/\sqrt{B}$			4.7	4.1	3.8	2.6

Number of signal and background events in Run II (2 fb^{-1}) for WH and ZH processes, and signal significance.

M_H[GeV/c^2]	60	80	90	100	110	120
WH signal S	45	28		15		8
Background B	139	84		53		30
$S/\sqrt{B}$	3.8	3.1		2.1		1.4
ZH signal S			7	6	5	3
Background B			36	33	31	25
$S/\sqrt{B}$			1.2	1.1	1.0	0.7

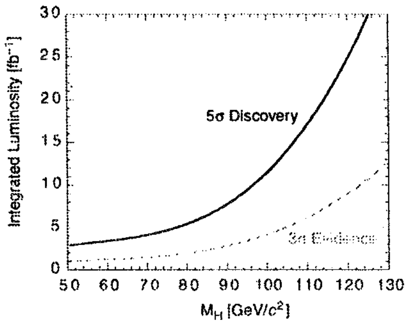
Based on J. Wormersley,"Discovering the Higgs at TeV33: a Status Report," DØ Note 3227, April 1997 (unpublished).

Luminosity required for Higgs observation

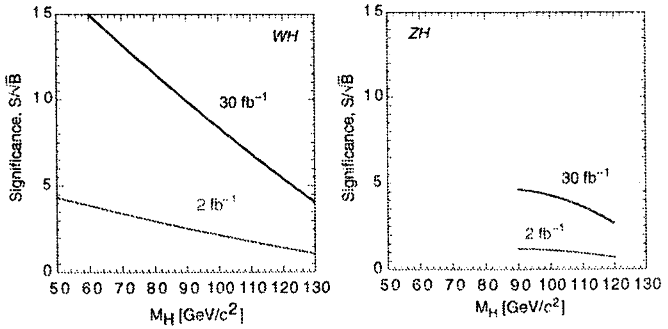
$$\bar{p}p \;\rightarrow\; HW + \text{anything}$$

$$\hookrightarrow \ell\nu$$

$$\hookrightarrow b\bar{b}$$



Significance of Higgs observation in Tevatron Run II & Run III



Based on J. Wormersley,"Discovering the Higgs at TeV33: a Status Report," DØ Note 3227, April 1997 (unpublished).

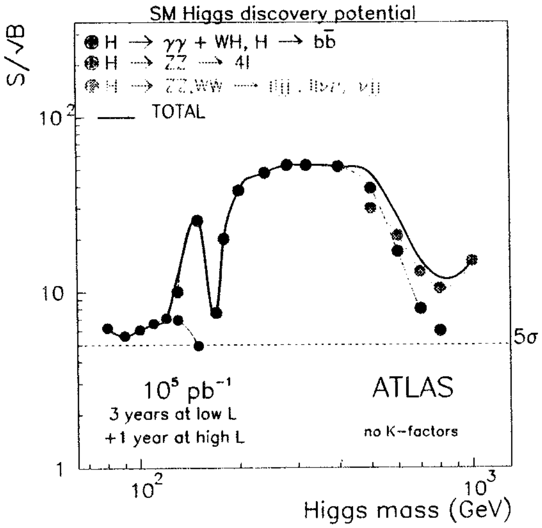
Higgs at the Tevatron: Summary

- If Higgs boson is discovered at LEP2:
  $\Longrightarrow$ observed in WH with $\int \mathcal{L}dt \lesssim 10$ fb^{-1}
- If $M_H \gtrsim$(95-100) GeV/c^2:
  $\Longrightarrow$ 5-σ discovery possible in WH in Run III (30 fb^{-1}) up to $M_H \approx 125$ GeV/c^2
- 3-σ observation possible in ZH in Run III (30 fb^{-1}) up to $M_H \approx 110$ GeV/c^2
  $\Longrightarrow$ ±15% measurement of g^2_{WWH}/g^2_{ZZH}

  If g_{ZZH} and $B(H \to b\bar{b})$ are known from LEP, determine g_{WWH} to ±10%.

$\boxed{M_H \text{ determined to } \pm(1\text{-}3)\ \text{GeV}/c^2}$

Higgs Search at the LHC



Higgs at the LHC: Summary

- 5-σ discovery is possible up to $M_H \approx 800$ GeV/c^2 in

$H \to Z\,Z$
  ↳ $\ell^+\ell^-$
  ↳ $\ell^+\ell^-$

$H\,W$
  ↳ $\ell\nu$
  ↳ $b\bar{b}$

$H \to \gamma\gamma$

- Reach extended in

$H \to Z\,Z$
  ↳ $\ell^+\ell^-$ or $\nu\bar{\nu}$
  ↳ jet jet

$H \to W\,W$
  ↳ $\ell\nu$
  ↳ jet jet

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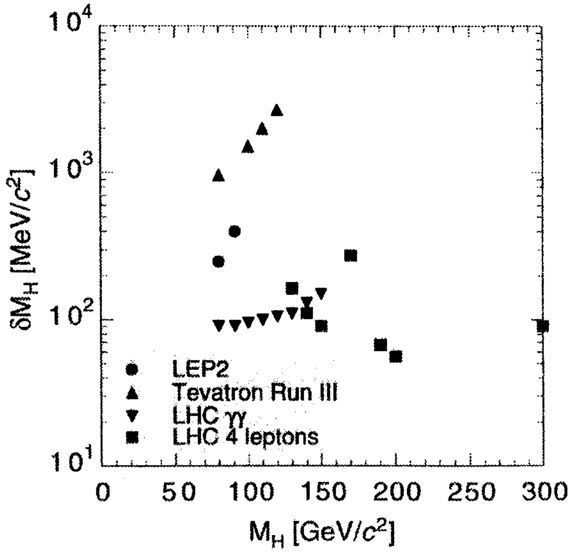
Higgs Mass: Summary



J. F. Gunion, L. Poggioli, R. Van Kooten, C. Kao, P. Rowson, *et al.*, "Higgs Boson Discovery and Properties," *Snowmass '96*.

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Summary

Tevatron exists!

- Expect considerable improvements in m_t, M_W, searches for nonstandard production and decay in Run II (2 fb^{-1}).
- Run III (30 fb^{-1}) holds great promise for top properties, including measurement of $|V_{tb}|$ in single-top production.
- Run III extends the search for a light Higgs boson throughout the low-mass region favored by supersymmetry.
- Low-scale supersymmetry should be found at the Tevatron.

Summary . . .

The LHC will exist!

- A fountain of tops: $\sim$ 8 million pairs produced per year at $\mathcal{L} = 10^{33}\ \text{cm}^{-2}\ \text{s}^{-1}$; hundreds to thousands of interesting events detected per day.
- Extends the search for the agent of electroweak symmetry breaking toward 1 TeV. Good sensitivity to the standard-model Higgs boson throughout the interesting range.
- Will explore the spectrum of superpartners up to $\sim$ 1 TeV and make possible detailed measurements of supersymmetric parameters.
- Many other possibilities for exploration.

Comparison of Lepton and Hadron Colliders for Discovery of SUSY:

H.B.: μ-collider mtg.

Topics:

Overview of models

LEP2 prospects

Tevatron - MI
TeV33
large $\tan\beta$ case

LHC

Next Lepton Collider

H. BAER (FLORIDA STATE U)

Supersymmetry: a spacetime symmetry relating fermions to bosons Wess-Zumino

- a generalization of relativity:
  - Poincaré group: maximal set of spacetime symmetries for QFT described by Lie algebras Coleman Mandula
  - Super Poincaré group: <u>graded</u> Lie algebra
- needed in string theory to include fermions
- local SUSY ⇒ graviton field and general relativity
- Hard to believe SUSY is <u>not</u> realized in nature at some level
- Certainly, SUSY is broken: but at M_{pl}? at M_{weak}? in between?

Specific motivations for <u>weak-scale</u> SUSY:

- SUSY allows cancellation of quadratic divergences of scalar masses "fine-tuning problem"
- gauge coupling unification:
  occurs if $M_{susy} \approx M_{weak}$
- EW rad. corrections wildly prefer light Higgs scalar:
  hard to realize without weak scale SUSY
- Radiative breaking of EW symmetry (heavy top)

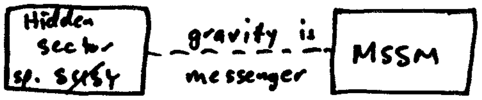
MSSM:

- Rules well known for constructing $\mathcal{L}_{SUSY\text{-}sym}$
- But spontaneous $\cancel{\text{SUSY}}$ not phenom. viable
- Add soft $\cancel{\text{SUSY}}$ terms by hand

$\Rightarrow$ 124 parameter model: MSSM

How do soft $\cancel{\text{SUSY}}$ terms arise? 2 approaches

- SUGRA: postulate "hidden sector" of theory; an arena for sp. SUSY breaking

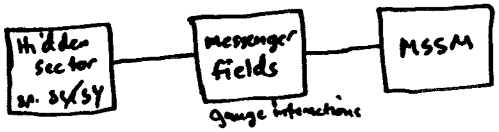


Arnowitt, Chamseddine, Nath
Barbieri, Ferrara, Savoy
Hall, Lykken, Weinberg

minimal SUGRA model

- universal soft $\cancel{\text{SUSY}}$ terms at $M_{GUT} - M_{Pl}$?
  $m_0,\ m_{1/2},\ A_0,\ B$
- desert between $M_{GUT} \rightarrow M_{weak}$;
  calc. weak scale parameters via RGE
- EW symmetry broken radiatively
  $m_0,\ m_{1/2},\ A_0,\ \tan\beta\ ;\ sgn(\mu)$

- Gauge-mediated SUSY breaking



Dine-Nelson
Nir
Shirman

- parameter set
  $\Lambda,\ M_{mes},\ \tan\beta,\ sgn(\mu)$; (# mes. fields?)
- light gravitino, so $\widetilde{Z}_1 \rightarrow \gamma \widetilde{G}$?
  $\widetilde{\tau}_1 \rightarrow \tau \widetilde{G}$?

Mass evolution in mSUGRA

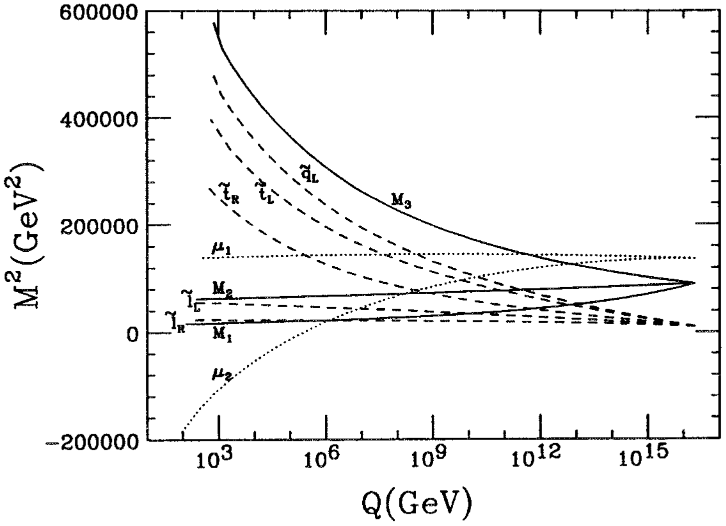
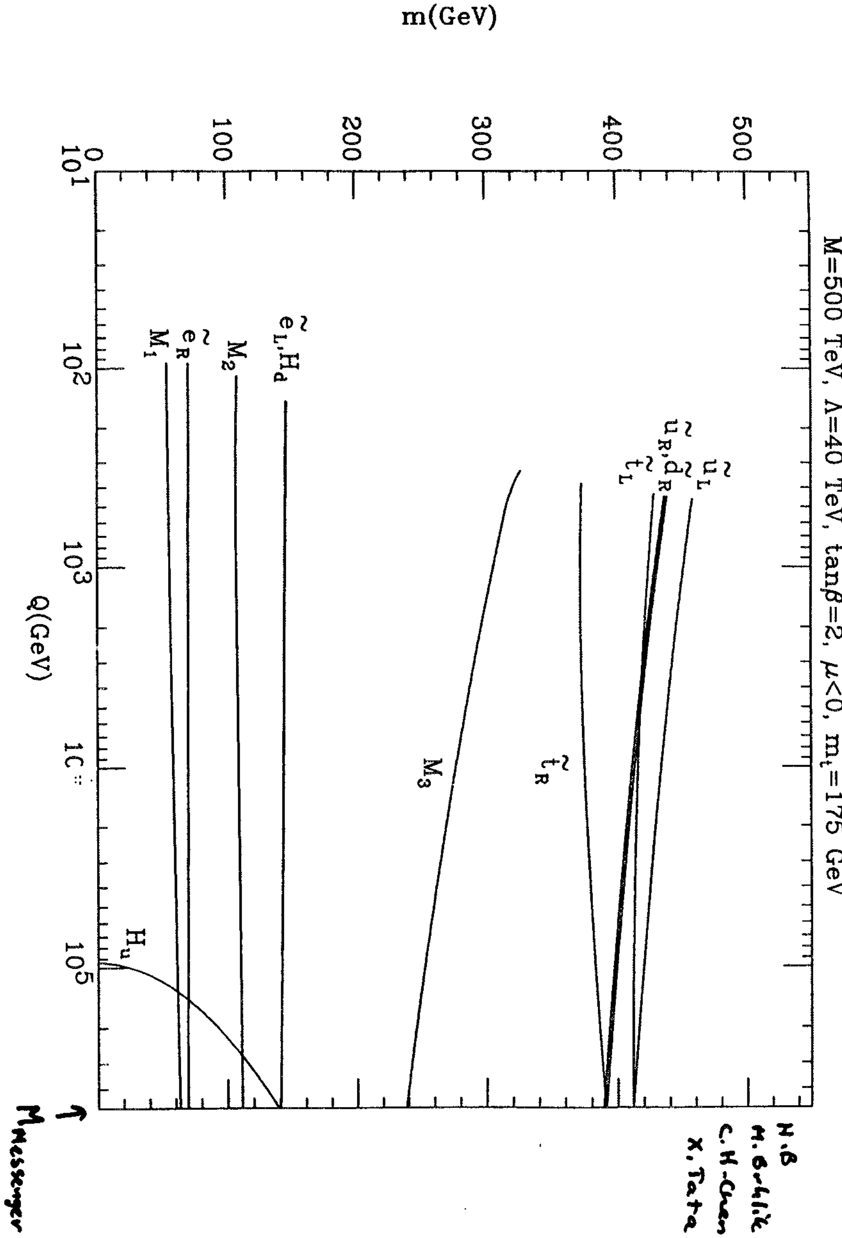


Figure 1.1: A SUGRA mass evolution for gaugino (solid), sfermion (dashed), and higgs (dotted) interaction eigenstates. The SUGRA parameters used here are $m_0 = 100$ GeV, $m_{\frac{1}{2}} = 300$ GeV, $A_0 = 0$, $\tan\beta = 2$, and $\mu < 0$ (See Sec. 4.2.2). Here M_1, M_2 and M_3 are the "bino", "wino" and "gluino" interaction masses, respectively, prior to radiative electroweak symmetry breaking (see Table 1.5) which is induced by μ_2^2 becoming negative. Except for $m_{\tilde{t}_R}$, the squark interaction masses range from $m_{\tilde{t}_L}$ to $m_{\tilde{q}_L}$ and some are omitted for clarity. See Appendix A for more details.

Soft - SUSY breaking terms evolve with scale in minimal gauge-mediated model



H.B
M. Brhlik
C.H. Chen
X. Tata

Promising Signatures at LEP2 :

- $e^+e^- \to \widetilde{W}_1 \overline{\widetilde{W}}_1$

  $\bar{u} d \widetilde{Z}_1 \swarrow \quad \hookrightarrow \bar{e} \nu_e \widetilde{Z}_1$

- $e^+e^- \to \tilde{e}_R \bar{\tilde{e}}_R$

  $e \widetilde{Z}_1 \swarrow \quad \hookrightarrow \bar{e} \widetilde{Z}_1$

- $e^+e^- \to \widetilde{Z}_1 \widetilde{Z}_2$

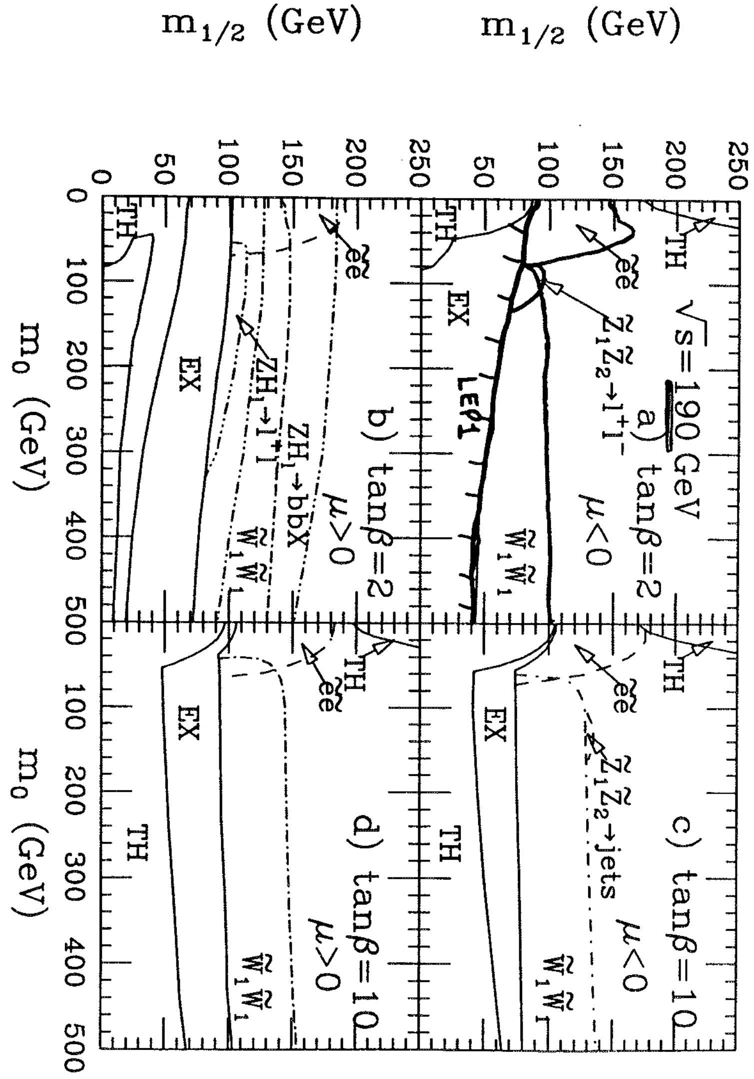
  $\hookrightarrow \ell \bar{\ell} \widetilde{Z}_1$ or $q \bar{q} \widetilde{Z}_1$

- $e^+e^- \to Z H_\ell$

  $\ell \bar{\ell} \swarrow \quad \hookrightarrow b \bar{b}$ or $\widetilde{Z}_1 \widetilde{Z}_1$

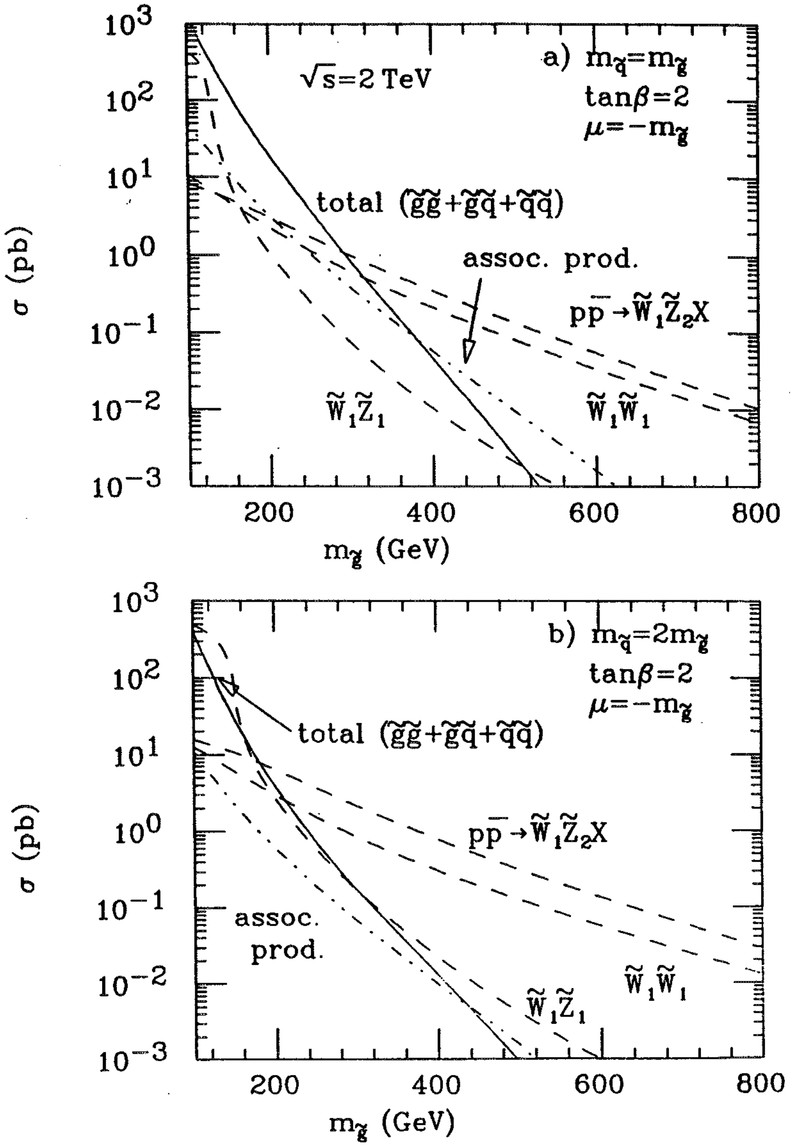
BG: WW, ZZ, $b\bar{b}$, (ZH_ℓ)

Where is Signal $> 5\sqrt{BG}$ after cuts ?



HB
M. Brhlik
R. Munroe
X. Tata

Tevatron:



HB
C.H.Chen
C.Kao
X.Tata

Tevatron:

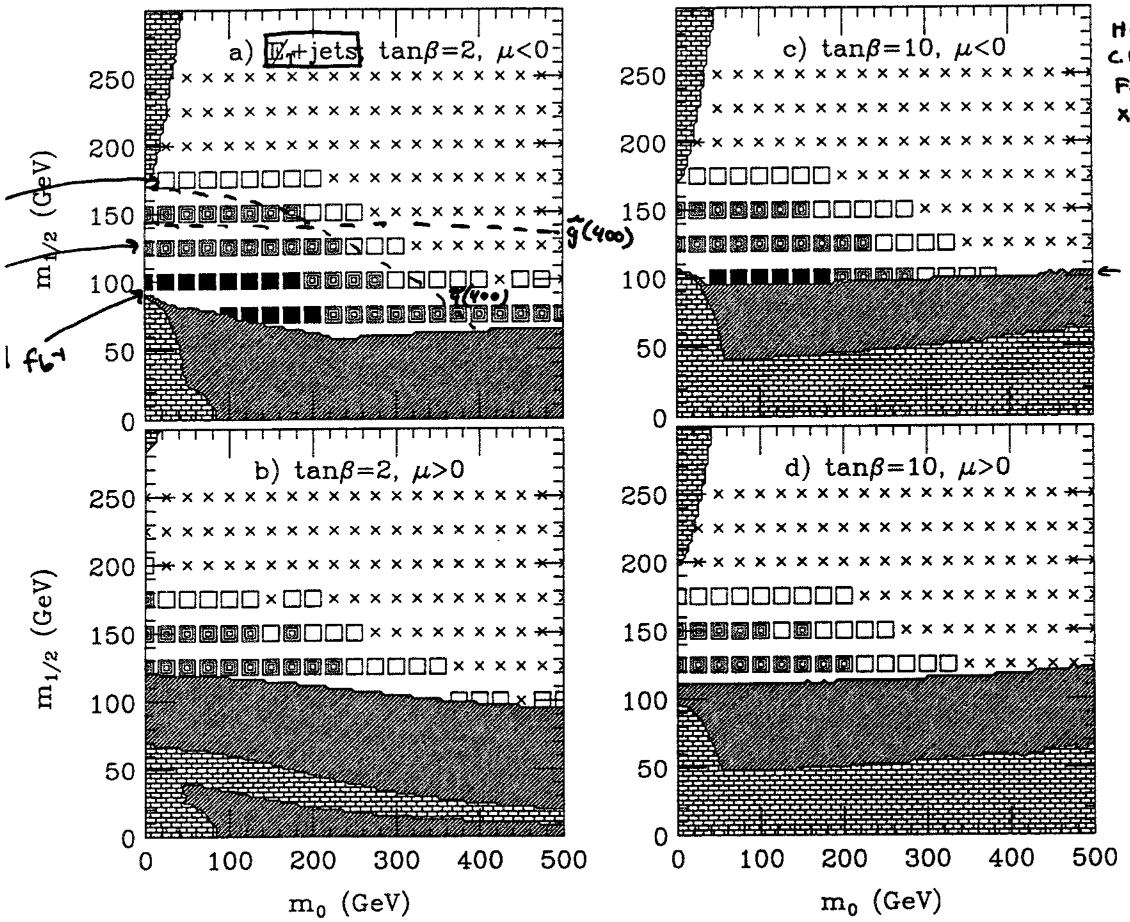
Parameter space analyses of various signals from minimal SUGRA

(HB, Chen, Paige, Tata; ~~to appear~~)

also
Barnett, Gunion, Haber
Kamon, Lopez, McIntyre + White
Mrenna, Kane, Kribs + Wells
TeV33 report

Procedure:

- Pick pt. in $[m_0, m_{1/2}, A_0, \tan\beta; \mathrm{sgn}(\mu)]$
- Generate lots of events (all subprocesses)
- Pass thru toy detector program ISAPLT
- Generate backgrounds: $t\bar t$, W+jets, Z+jets, QCD, WW, WZ, ZZ
- Select various event topologies (cuts)
  - $\not{E}_T$ + jets
  - 1ℓ + jets + $\not{E}_T$
  - OS + " "
  - SS + " "
  - 3ℓ + " "
  - 2B + " "
  - clean $3\ell+\not{E}_T$
  - " $2\ell+\not{E}_T$
  - $\widetilde W_1\widetilde Z_2\to 2\ell$ + jets + $\not{E}_T$
- When is Signal $> 5\sqrt{BG}$ for $\int L\,dt = .1, 2, 25$ fb^{-1} ?



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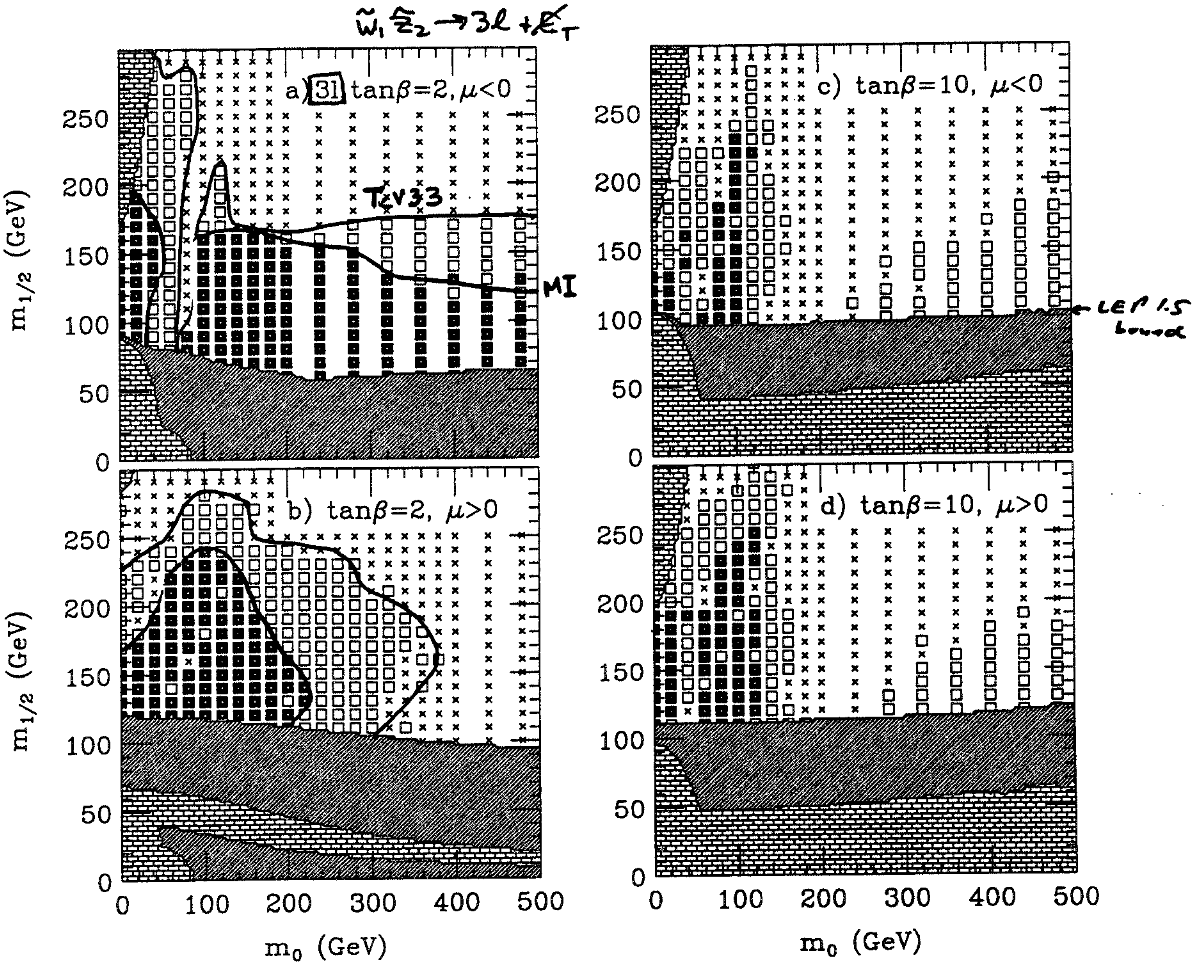
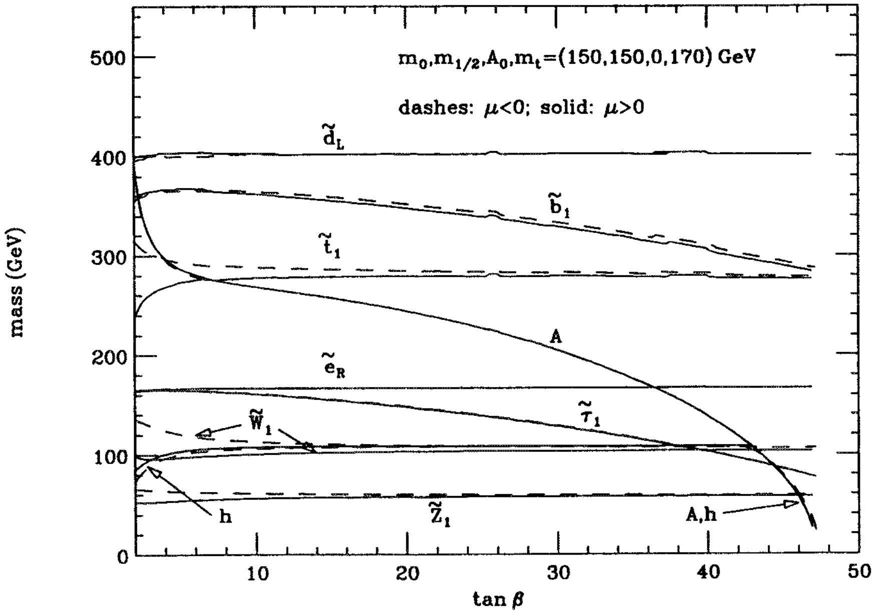
C.H. Chen
F. Paige
X. Tata



H B
C. H. Chen
M. Drees
F. Paige
X. Tata

Variation of sparticle masses vs. ~~tan~~ β



H B
C.H. Chen
M. Drees
F. Paige
X. Tata

ISAJET large tanβ solution:

- For large tanβ, b, τ Yukawa's are large
- Calculate $\tilde{b}_{1,2}$, $\tilde{\tau}_{1,2}$ masses mixings
- Minimization of 1-loop eff. pot'l: unstable against scale variations at large tanβ
  optimized scale choice $Q \sim \sqrt{m_{\tilde{t}_L} m_{\tilde{t}_R}}$
- Re-calculate sparticle decays including b, τ Yukawas and mixings
  $\tilde{g}$, $\tilde{b}_i$, $\tilde{t}_i$, $\tilde{\tau}_i$, $\tilde{\nu}_\tau$, $\widetilde{W}_i$, $\widetilde{Z}_i$, h, A, H, $H^\pm$

$$\left.\begin{array}{l} \tilde{g} \to t\bar{t}\widetilde{Z}_i,\ b\bar{b}\widetilde{Z}_i \\ \quad \to tb\widetilde{W}_i \end{array}\right\} \text{agrees with Bartl et.al.}$$

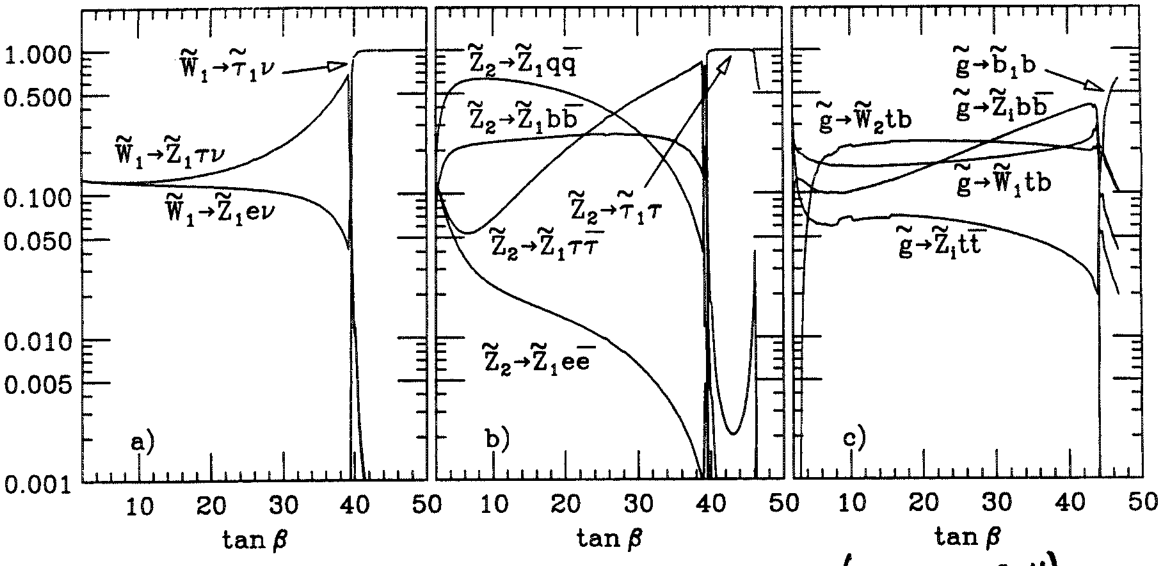
$$\left.\begin{array}{l} \widetilde{Z}_i \to bb\widetilde{Z}_j \\ \quad \to \tau\bar{\tau}\widetilde{Z}_j \end{array}\right\} \text{8 diagrams} \qquad \text{(new!)}$$

$$\widetilde{W}_i \to \tau\nu\widetilde{Z}_j \ \Big\} \text{5 diagrams}$$

- Re-calculate sparticle production including mixing effects

$$q\bar{q} \to \tilde{\tau}_i \bar{\tilde{\tau}}_j$$
$$q\bar{Q} \to \tilde{\tau}\tilde{\nu}$$
$$e^+e^- \to \tilde{\tau}_i \bar{\tilde{\tau}}_j$$

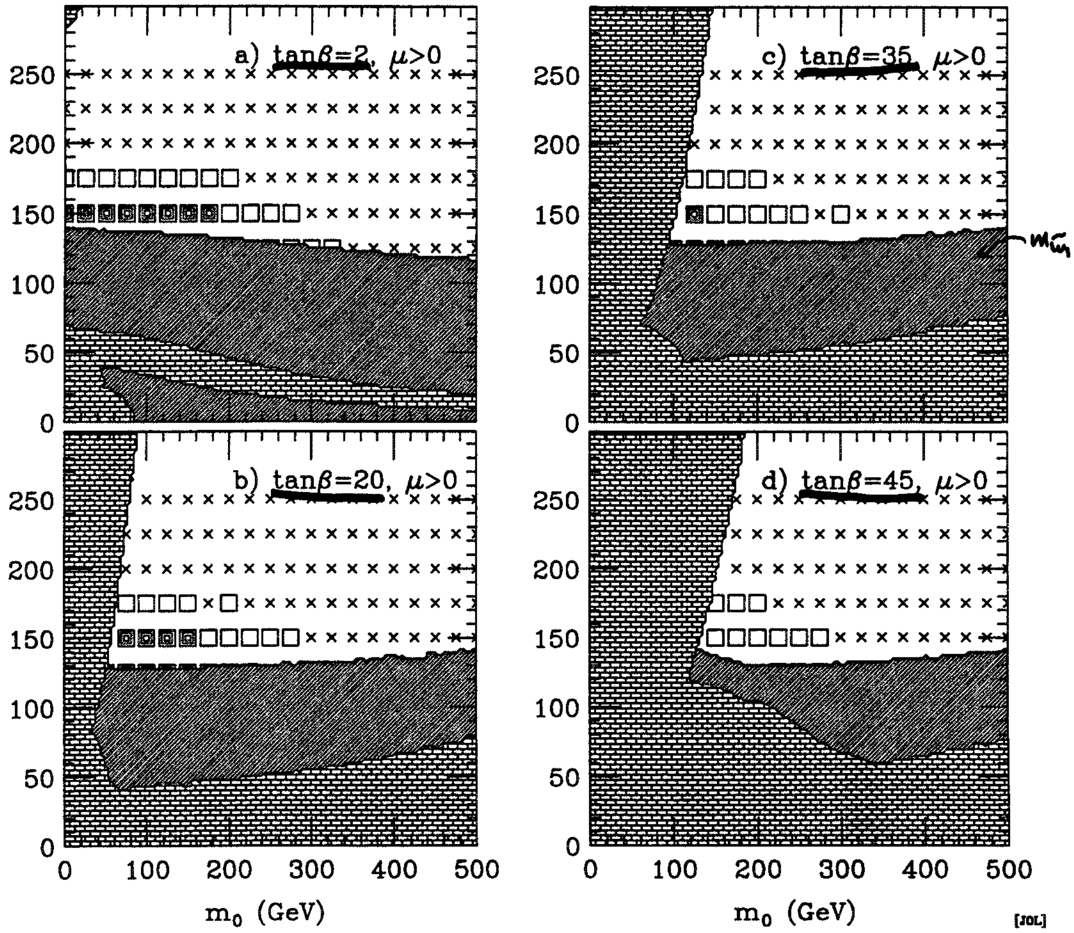
$m_0, m_{1/2}, A_0$ = 150, 150, 0 GeV ; $\mu > 0$



(700, 250, 0, +1)

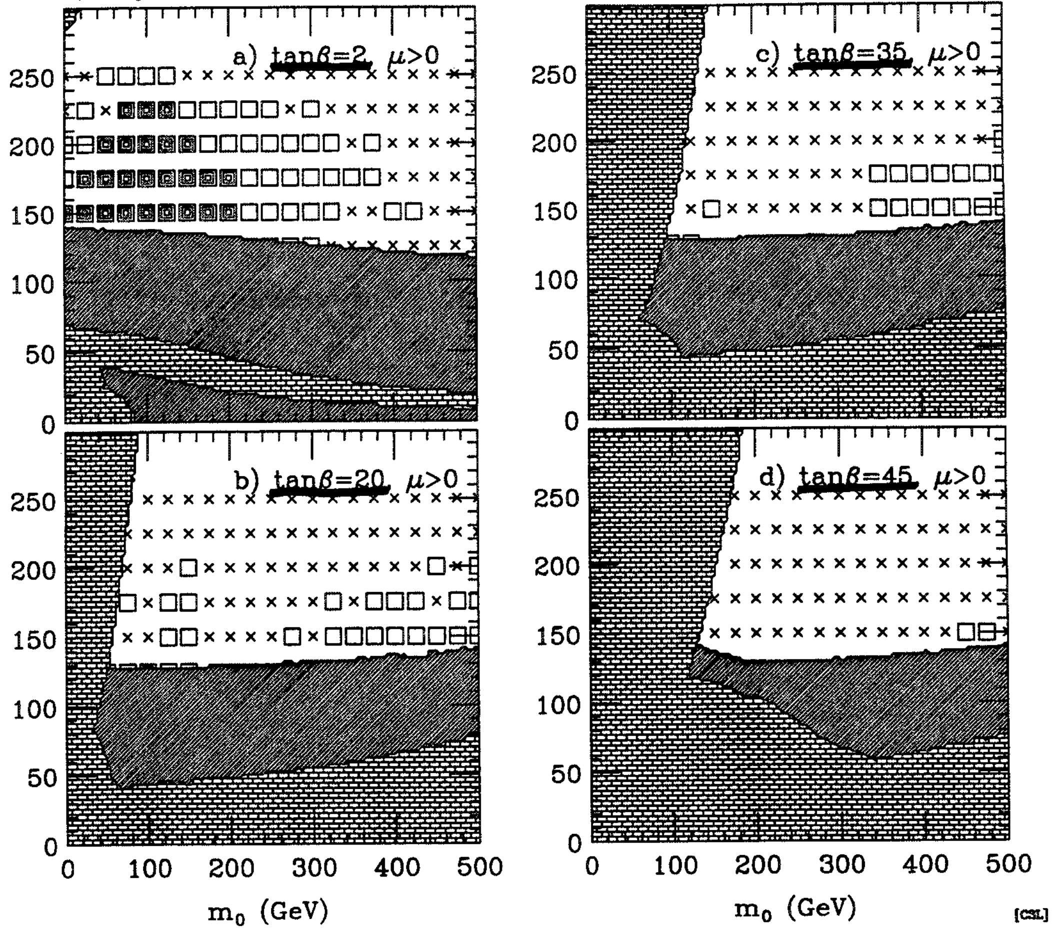
TeVatron reach for mSUGRA via multijets + $E\!\!\!/_T$

NB
Chen
Drees
Paige
Tata

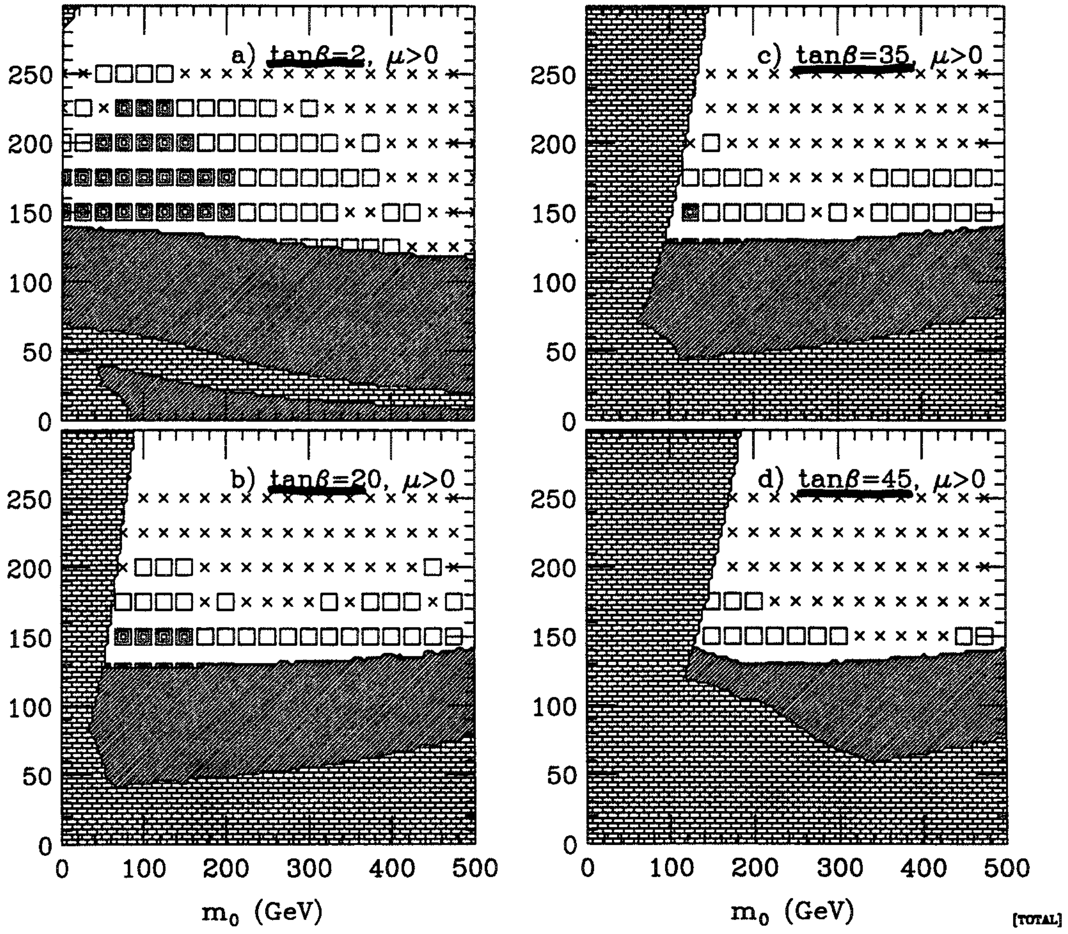


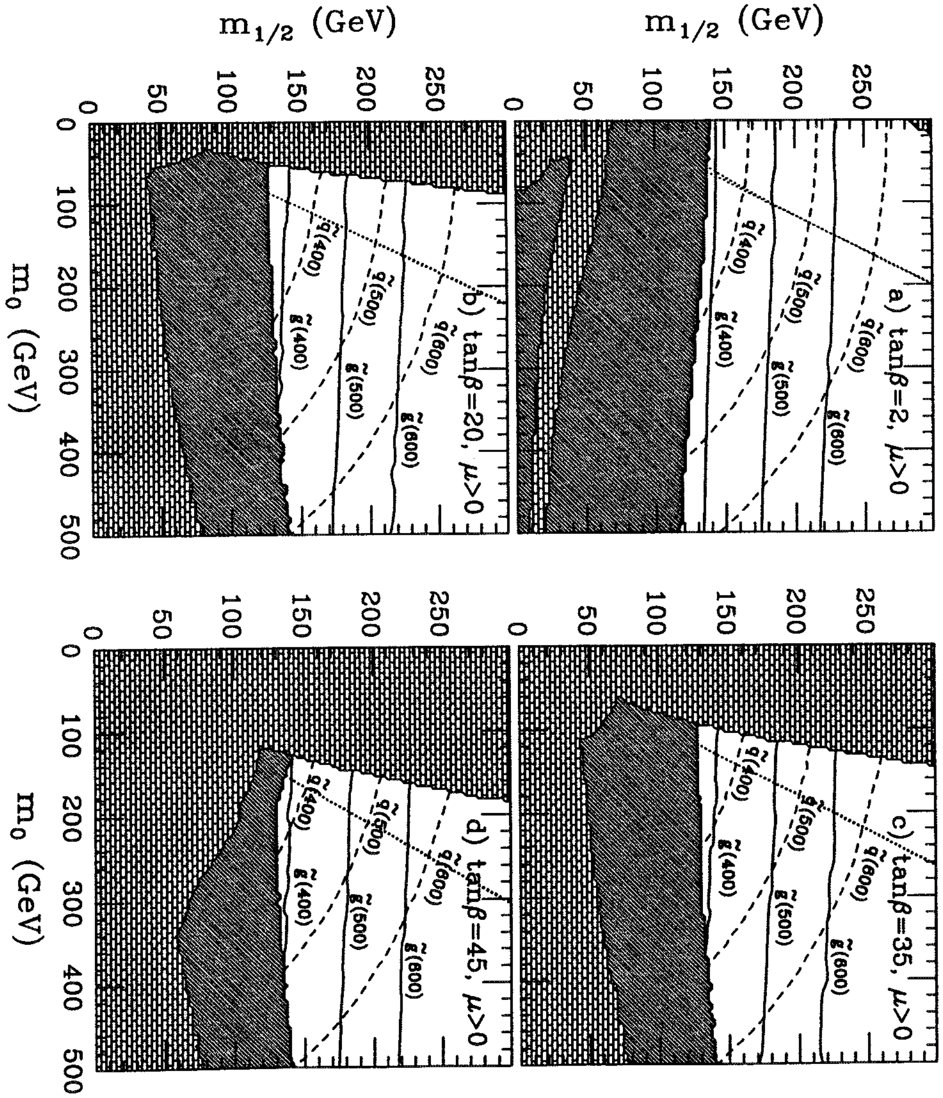
$m_{\tilde{W}_1} < 80$ GeV

Tevatron reach for mSUGRA via $3\ell + \not\!\!E_T$



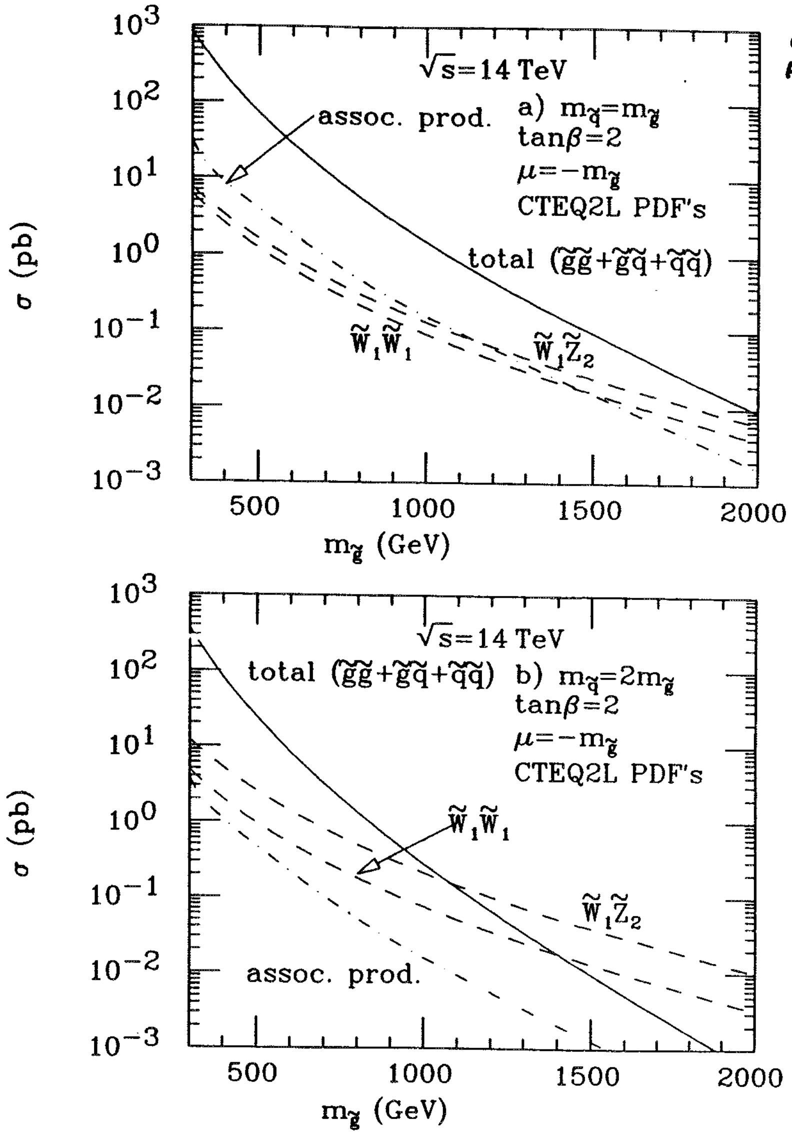
Tevatron reach for mSUGRA via all channels





LHC total cross-sections

HB
C.H Chen
F. Paige
X. Tata



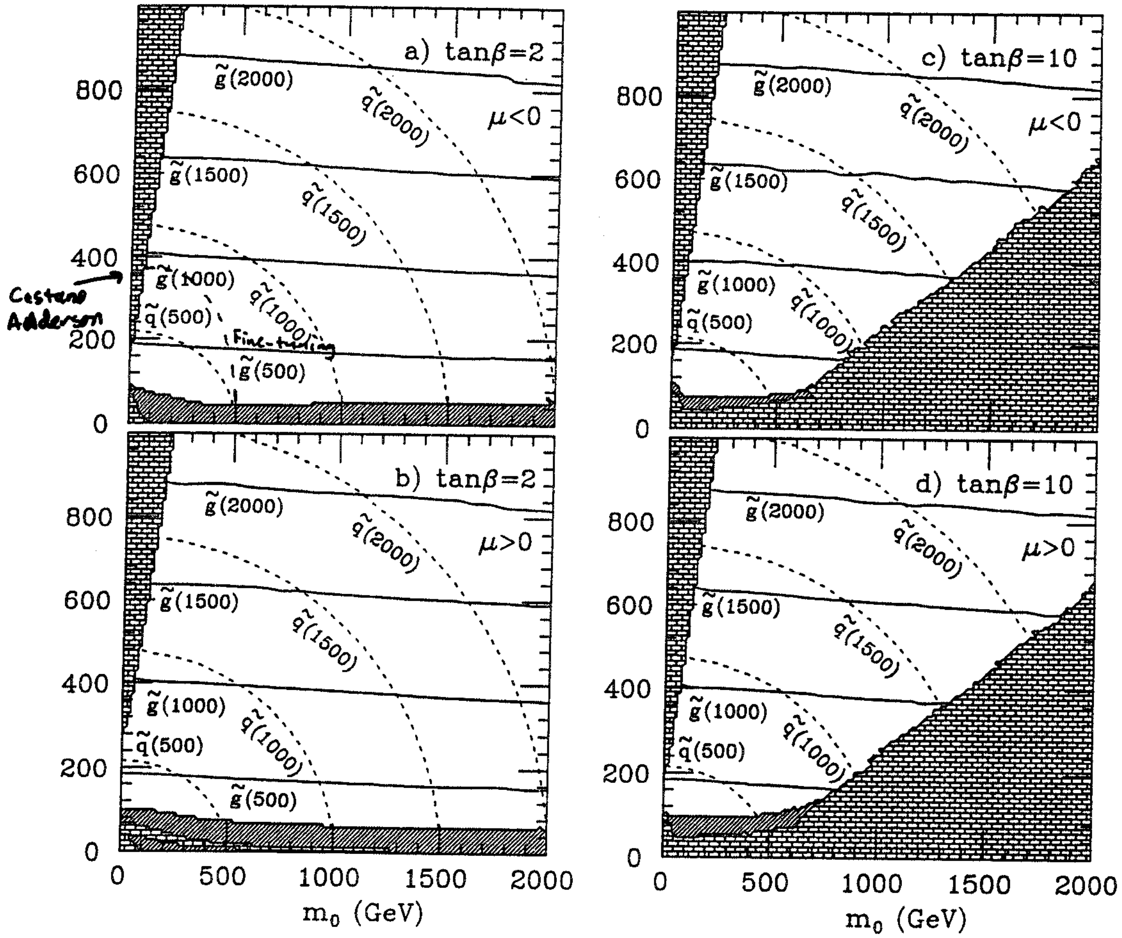
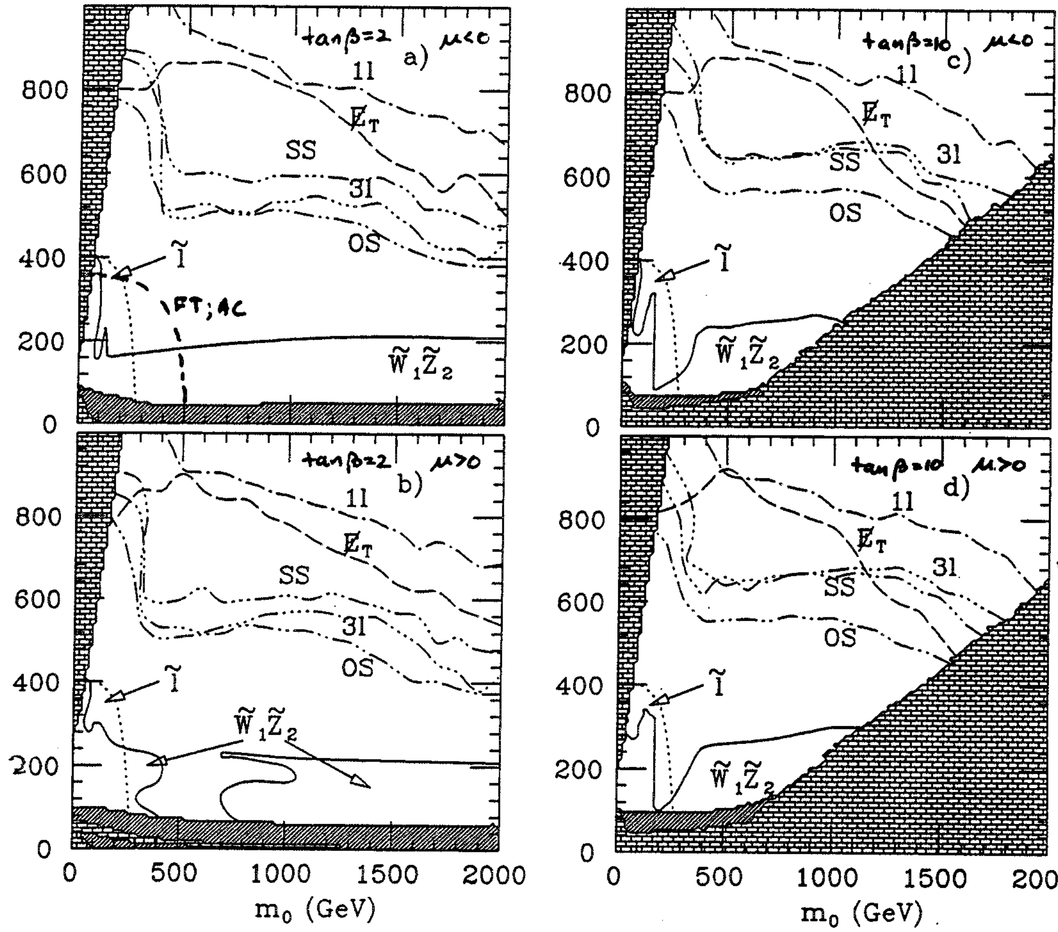


Figure 1

Comparison of reach via different channels: $A_0=0$



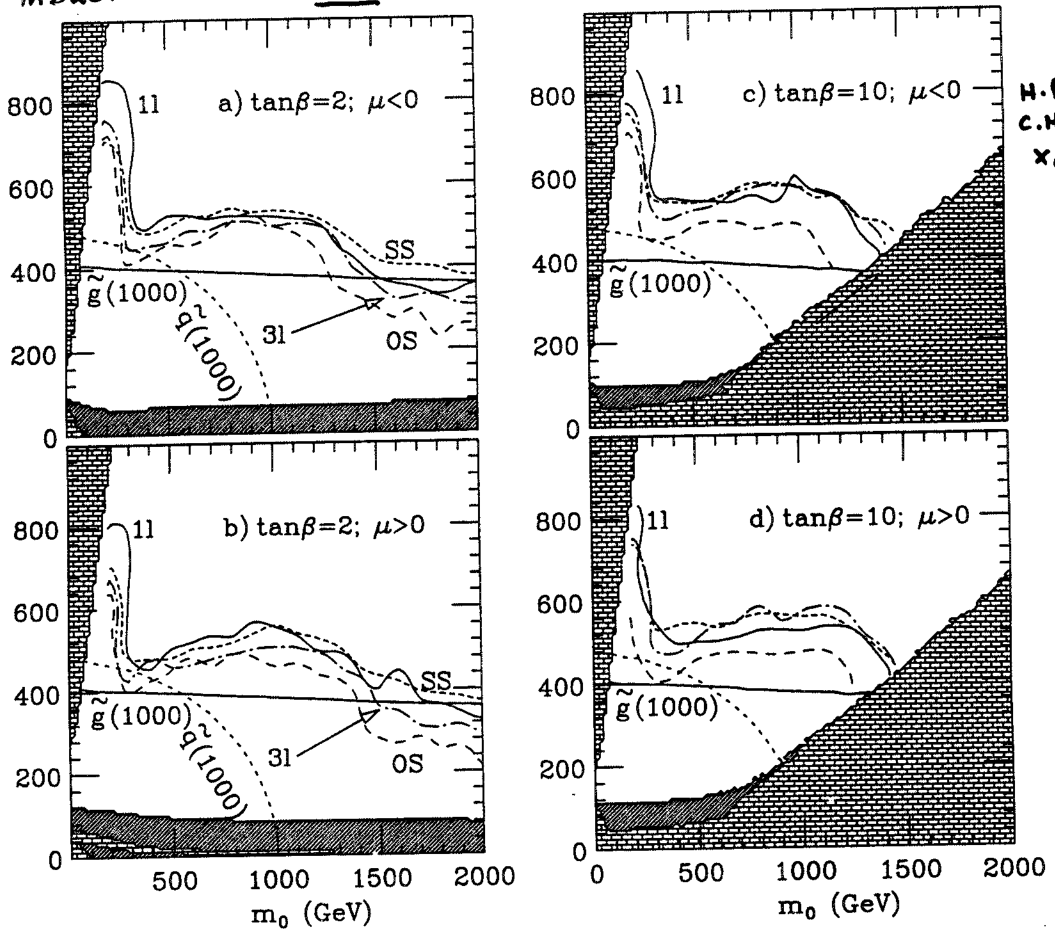
H.B.
C.H.Chen
F. Paige
X. Tata

10 fb^{-1}
LHC

for update,
see
D. Denegri
et.al.,
CMS group

Figure 18

mSUGRA reach of <u>LHC</u> if $\tilde{Z}_1 \to cds, \bar{c}\bar{d}\bar{s}$ 10 fb^{-1}



H.B.
C.H. Chen
X. Tata

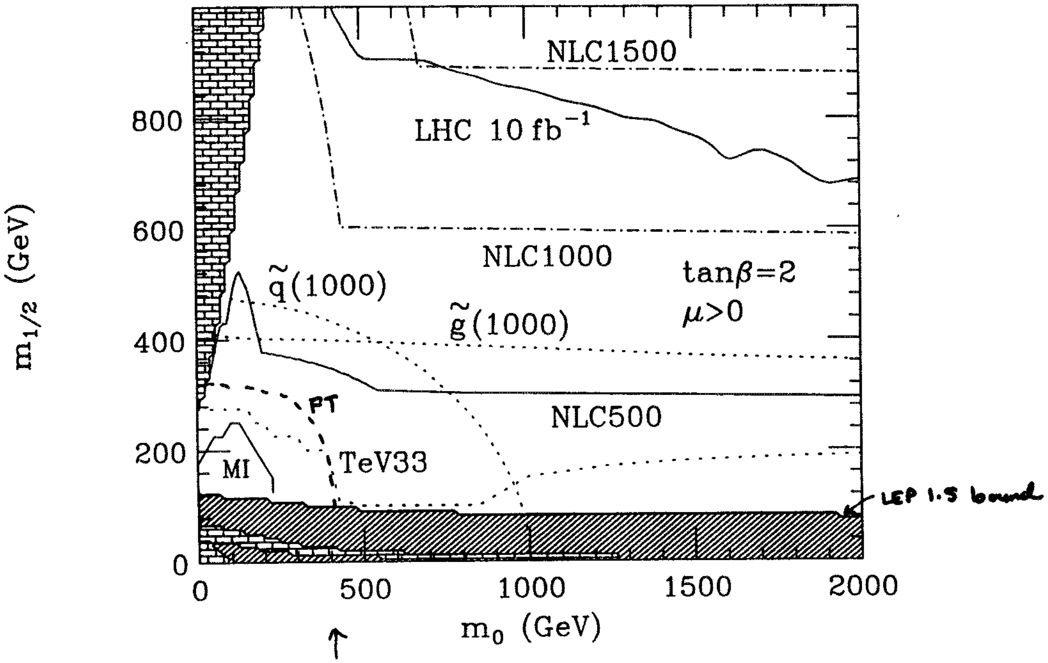
Next Linear Collider (NLC):

For SUSY:

$e^+e^- \to Zh$ ✓

$\to \tilde{W}_1 \tilde{W}_1$
$\to \tilde{e}_R \bar{\tilde{e}}_R$ } define reach for sparticles
$\to \tilde{Z}_1 \tilde{Z}_2$

Reach of various colliders in mSUGRA parameter space:



↑ Anderson/Castaño Fine-tuning region

At NLC/JLC,

precision measurements possible!

Tsukamoto
Fujii
Murayama
Yamaguchi
Okada

$\tilde{W}_1$:

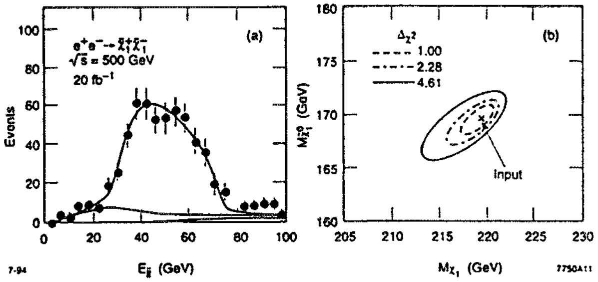


Fig. 8. Determination of the lightest chargino mass in the decay $\tilde{\chi}_1^+ \to q\bar{q}\tilde{\chi}_1^0$, according to the simulation results of Ref. 25. The right-hand figure shows the χ^2 distribution as a function of the masses of $\tilde{\chi}_1^+$ and $\tilde{\chi}_1^0$.

$\tilde{\ell}_R$:

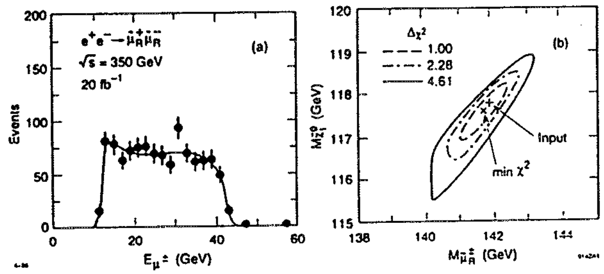


Fig. 15. Determination of the $\tilde{\mu}_R$ mass in the decay $\tilde{\mu}_R^- \to \mu^-\tilde{\chi}_1^0$, according to the simulation results of Ref. 25. The analysis assumes right-handed electron polarization $P = 0.95$. The right-hand figure shows the χ^2 distribution as a function of the masses of $\tilde{\mu}_R^-$ and $\tilde{\chi}_1^0$.

Also:

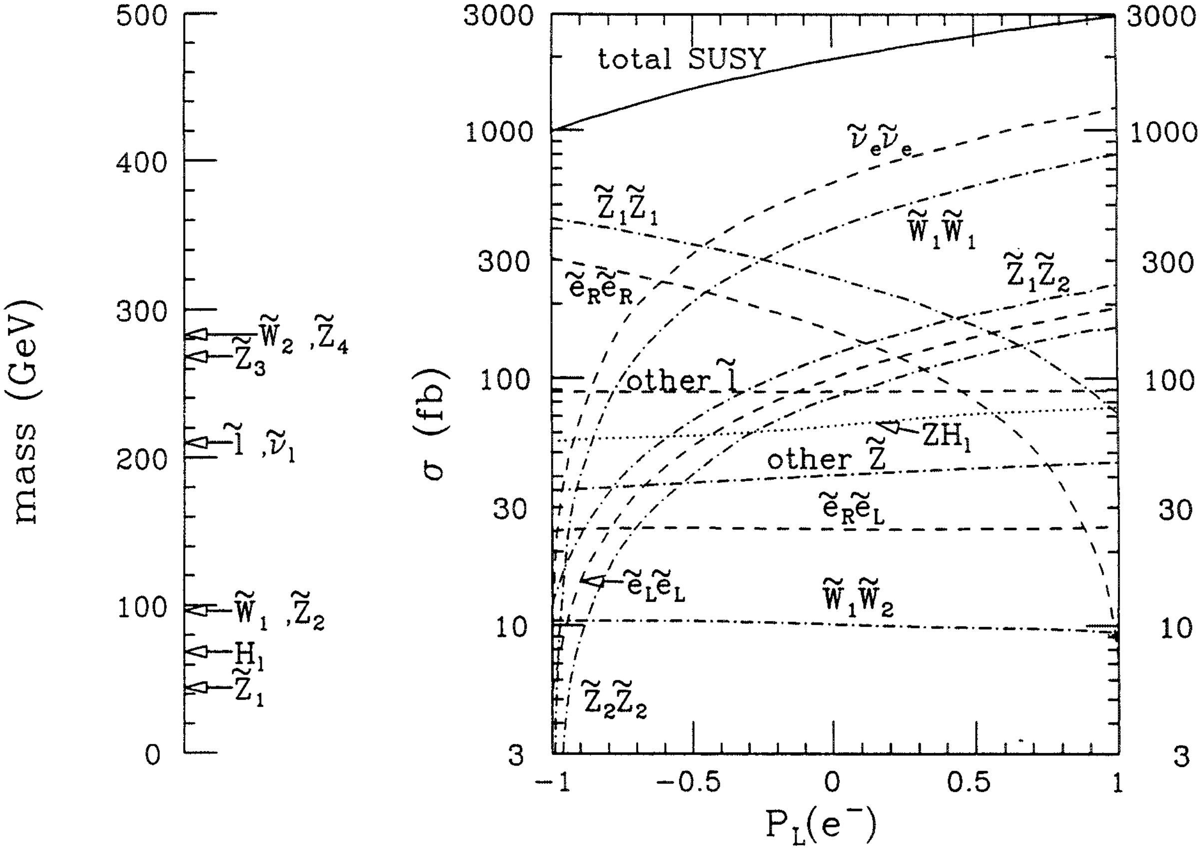
- spin measurements
- extract ino mass matrix parameters
- test ino mass unification
- test susy

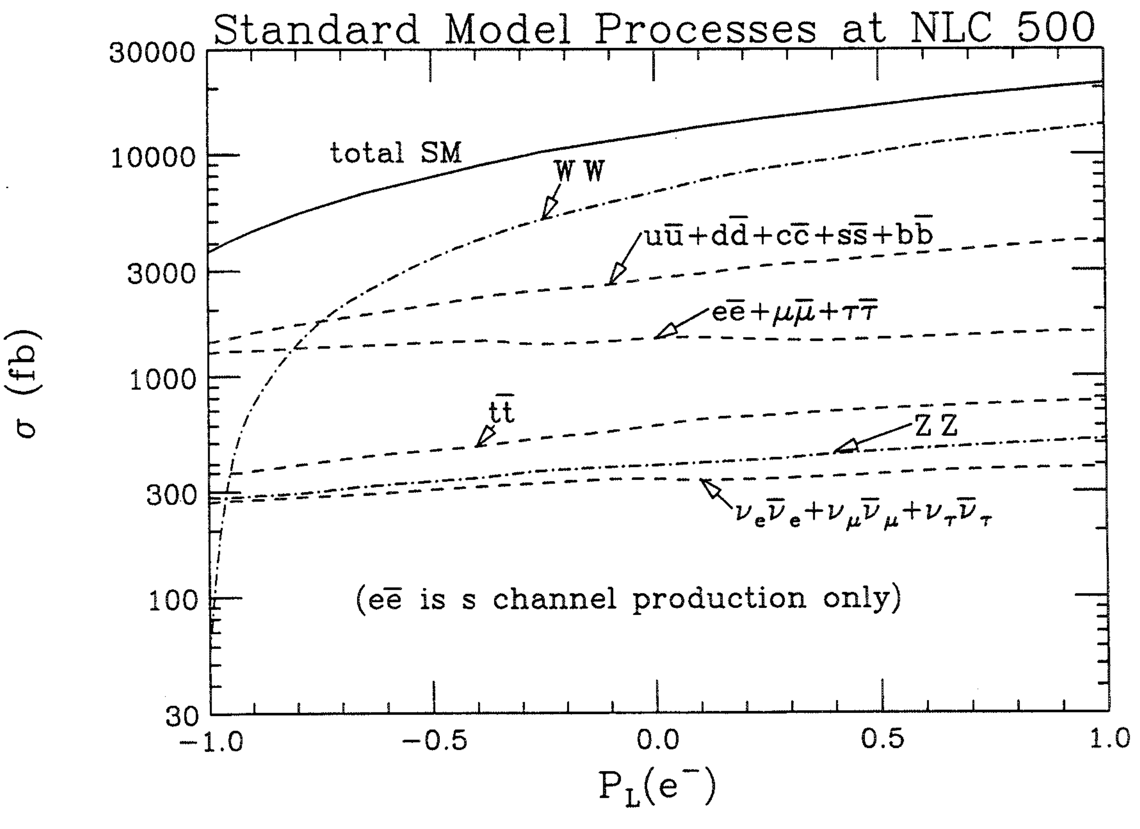
⋮

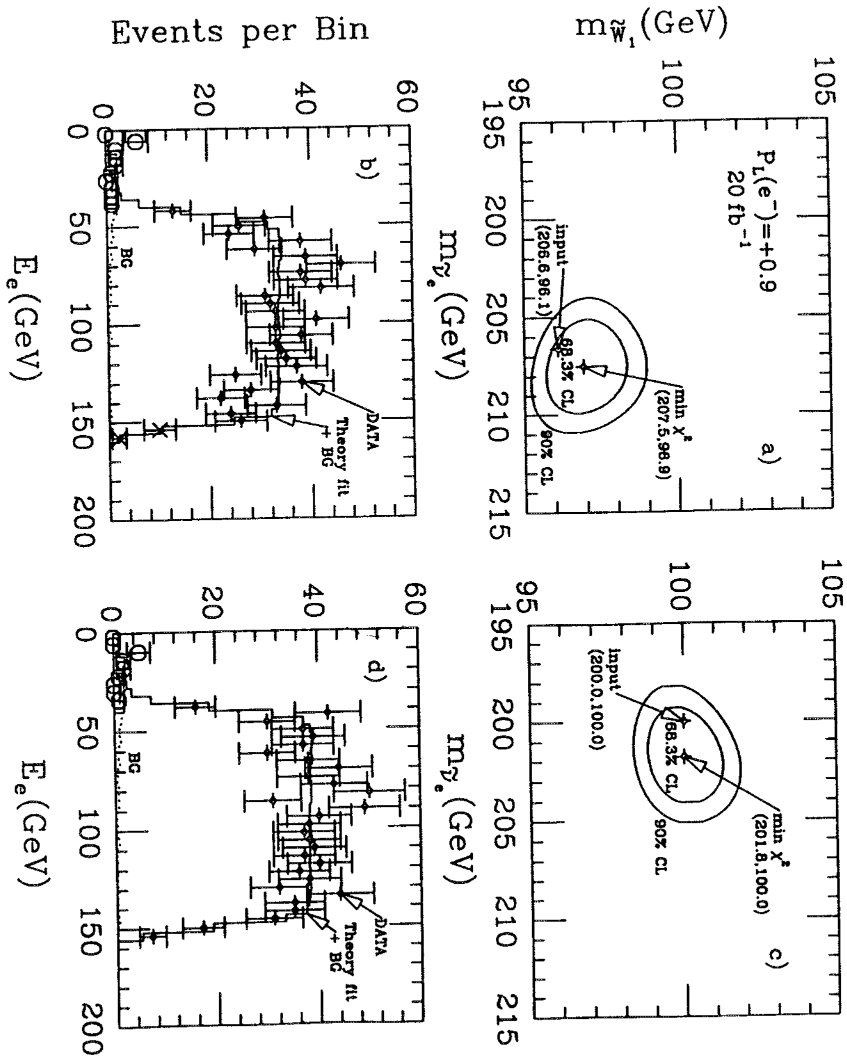
NLC working group

HB
& Munroe
X.Tata

Point 3: m_0=200 GeV, $m_{1/2}$=100 GeV, A_0=0, $\tan\beta$=2, μ<0



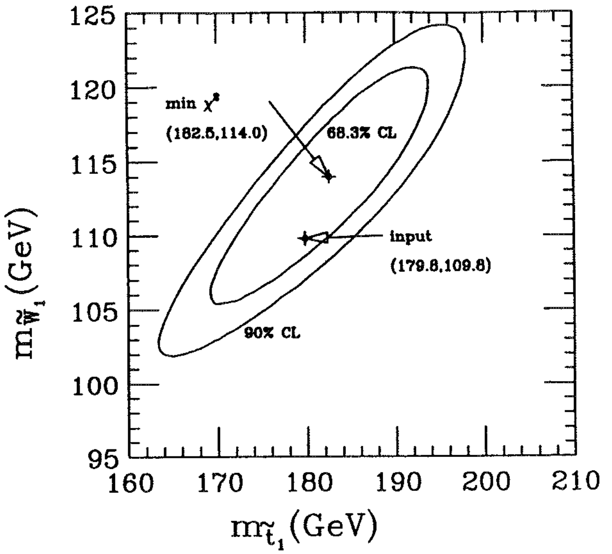

Standard Model Processes at NLC 500



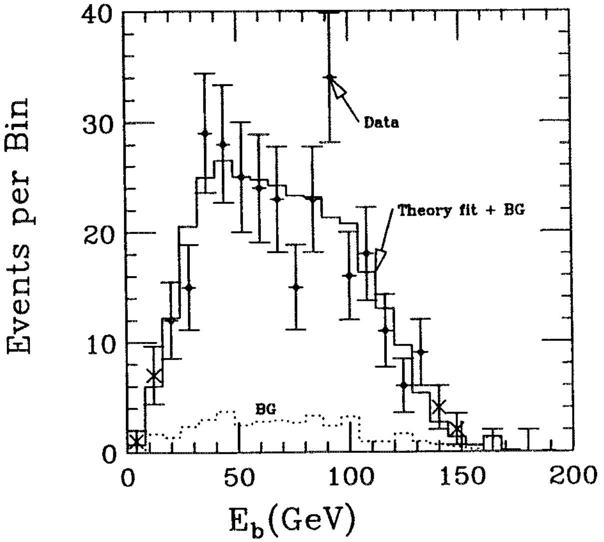
$\tilde{\nu}_e \rightarrow e \widetilde{W}_1$ at NLC

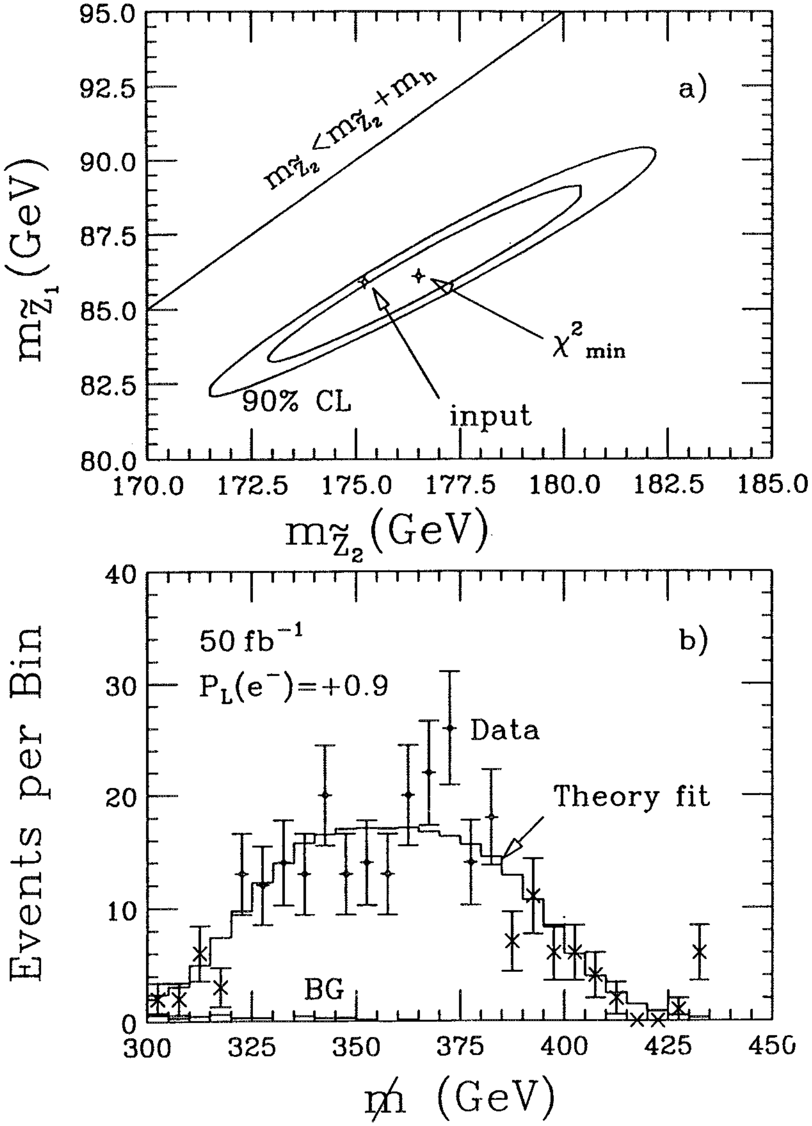
NLC fit to $m_{\tilde{t}_1}$, $m_{\widetilde{W}_1}$:

HB
R. Munroe
X. Tata



$\tilde{t}_1 \rightarrow b \widetilde{W}_1$





Conclusions: Colliders for SUSY (mSUGRA)

- LEP2: $m_{\widetilde{W}_1} > 85.5$ GeV ⇝ 95 GeV
  $m_{\tilde{e}_R} > 75$ GeV ⇝ 90 GeV
  $m_H > 77.5$ GeV ⇝ 95 GeV !!

- Tevatron MI: low tan β – $3\ell + \not{E}_T$
  high tan β – jets + $\not{E}_T$

  TeV33: some increase in reach
  some precision measurements possible
  $m_H \rightarrow$ 100-120 GeV !?

- LHC: data in 2005 ?

  ★ Prove or disprove weak-scale SUSY ★

  If SUSY discovered, large data set
  ⇒ lots to learn; model dependent
  (Snowmass '96)

- Next Lepton Collider: e^+e^- or $\mu^+\mu^-$ or both ?
  light Higgs $m_H \sim \sqrt{s} - 100$ GeV
  sparticle spectroscopy
  polarization

  <u>Special to a $\mu\mu$ collider</u>:
  ★ • Higgs resonance
  ★ • upgrade to 2-4 TeV

Higgs Searches at LEP-200: Present Status

Philip BAMBADE, I
MUMUS
San Francisco, 10 F

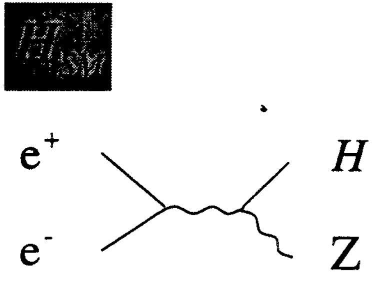
OUTLINE

- Theoretical framework and mass limits
- Higgs detection at LEP-200
- Tools: b-tagging and mass reconstruction
- Final results from 1996, using combination techniques
- Preliminary results from 1997
- Expected limits and discovery potential at 189 GeV (1998)

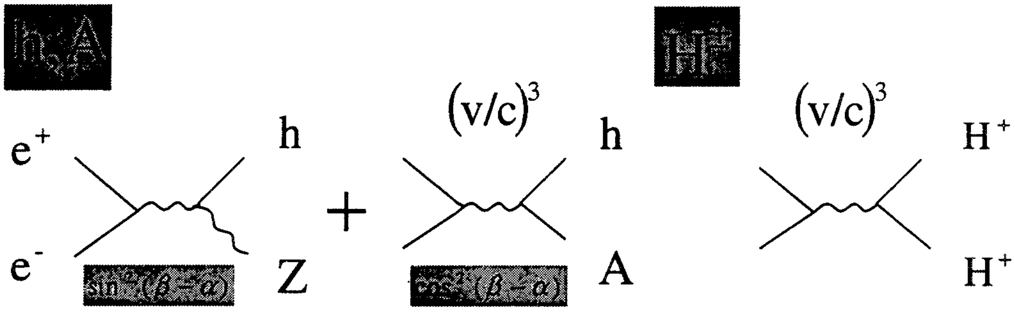
Theoretical Framework and Mass Limits

- Standard Model: *H* => not for LEP
  mass $(H) > 100$ GeV ($\Lambda \sim 100$ TeV mass (t) = 175 GeV)
- MSSM: h, A, H, H±
  mass (h) < 130 GeV (< 150 in NMSSM)
- CMSSM (b,τ Yukawa couplings unify @ GUT scale)
  ➔ $\tan\beta \sim$ mass (t) / mass (b)
  ruled out unless very heavy H, χ (97, W.de Boer, Jerusalem)
  ➔ "low tanβ scenario" $1 < \tan\beta < 3$
  => mass (h) < 105 GeV (mass (t) = 175 GeV)
- LEP-200 rule of thumb : mass $(H) <$ Ecms – 95

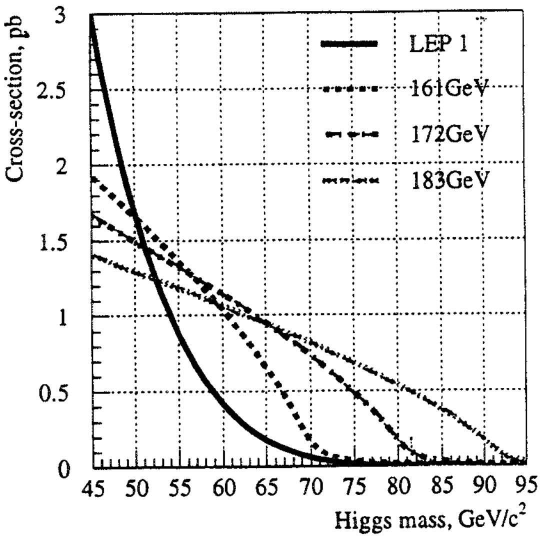
Higgs Boson Production at LEP-200



+ WW fusion (10%) + ZZ fusion (1%)



SM Higgs Production Cross-Section at LEP-200



(W. MURRAY, Jerusale.

SM Higgs Decays, Final State Topologies at LEP-200

HZ

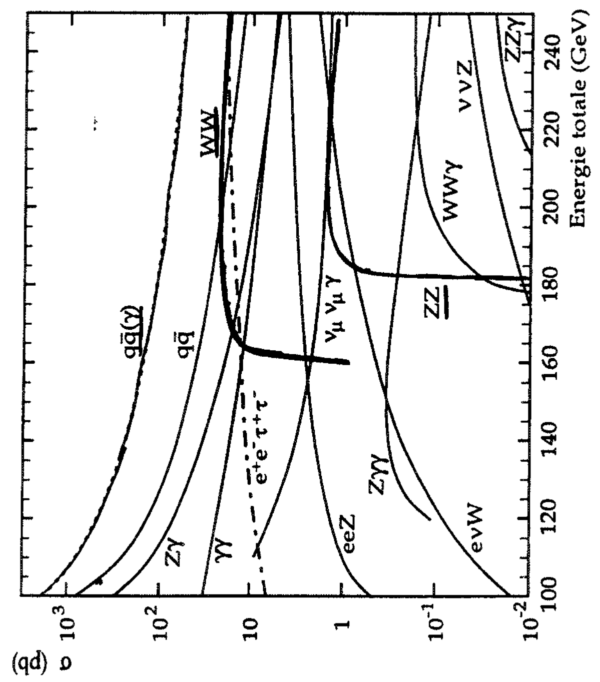
⊙ bbqq	86 % ⊗ 0.7	= 60 %	4 jets
⊙ bbνν	86 % ⊗ 0.2	= 17 %	~ 2 jets + missing E
⊙ bbμμ	86 % ⊗ 0.034	= 3 %	2 jets + 2 muons
⊙ bbee	86 % ⊗ 0.034	= 3 %	2 jets + 2 electrons
⊙ bbττ	86 % ⊗ 0.034	= 3 %	2 jets + 2 taus
⊙ ττqq	8 % ⊗ 0.7	= 5.6 %	2 jets + 2 taus

hZ	**hA**	**H^+H^-**
	bbbb	cscs
~ SAME AS SM	bbττ	csτν
	(bbbbbb (for h →AA))	τντν

Search Methods

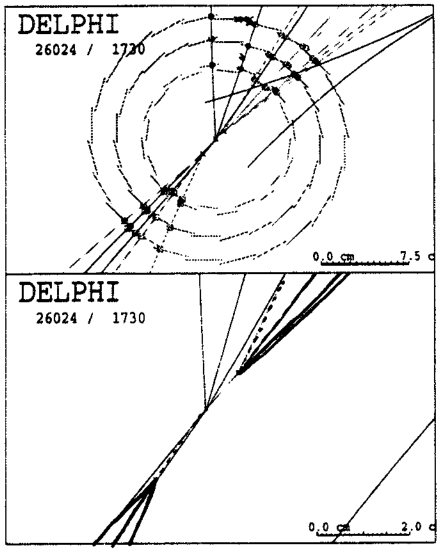
	Search Channel	Dominant Background	Reconstruction Focus	Typical Efficiency
60%	4 jets	WW, ZZ	b-tagging	30-50 %
	bbqq, bbbb	qqgg	Mass rec.	
17%	2 jets+Emis.	Z+N gamma	Energy flow	30-40 %
	bb + nunu	Z+N gamma	Hermeticity	
		WW, ZZ	b-tagging	
6%	qq + 2 muons	WW	Muon ID	70-80 %
		ZZ	(b-tagging)	
	qq + 2 electrons	WW	Electron ID	50-60 %
		ZZ	(b-tagging)	
8.6%	qq+tautau	Z+N gamma	Tau rec.	15-25 %
	tautau+qq	WW, ZZ	(b-tagging)	

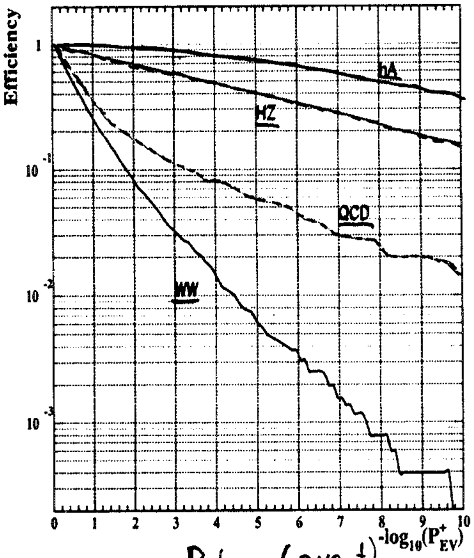
Backgrounds @ LEP-200



$\sigma_{HZ} \lesssim 1$ pb

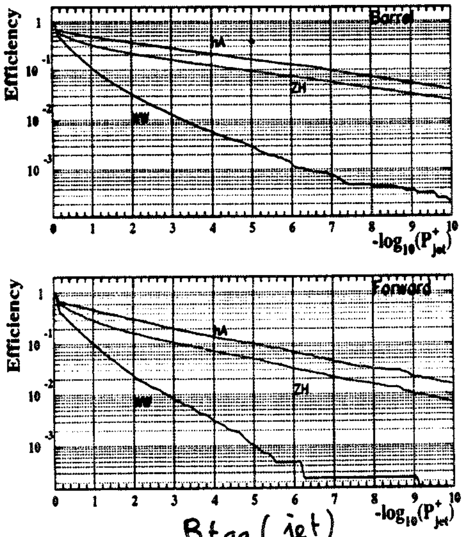
B tagging at LEP-200





Btag (event)

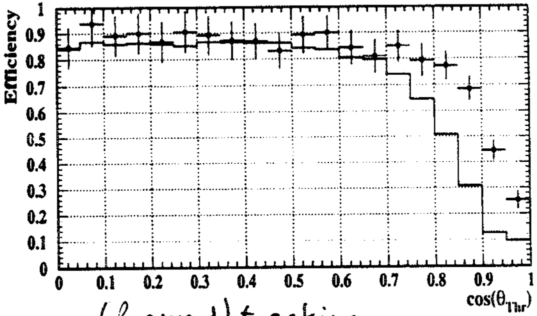
B Tagging Angular Coverage and Charm Separation Important



Btag (jet)

Likelihood combines:

1. Impact parameters
2. Secondary vertex mass, rapidity, and charged energy (→ charm) (+ leptons !)

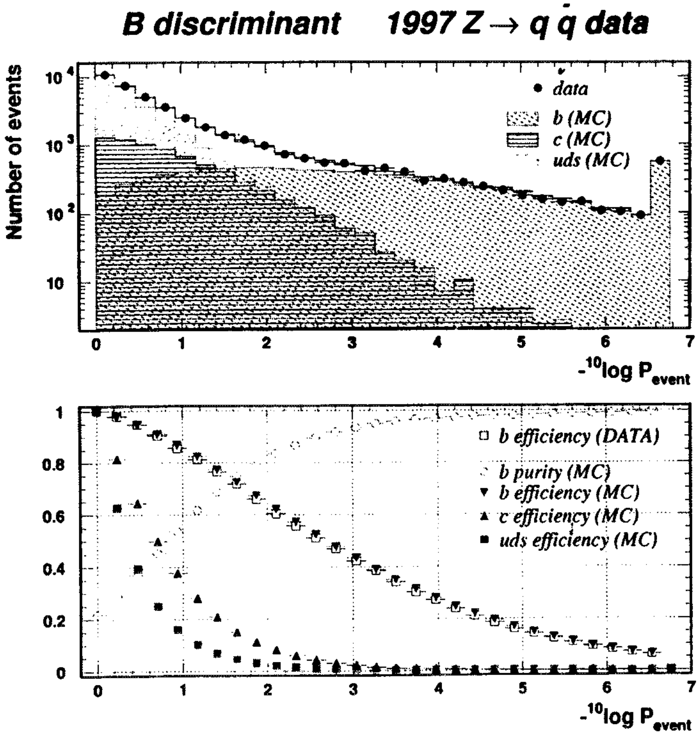


(forward) tracking alignment

L3 @ LEP-2 (11.97)

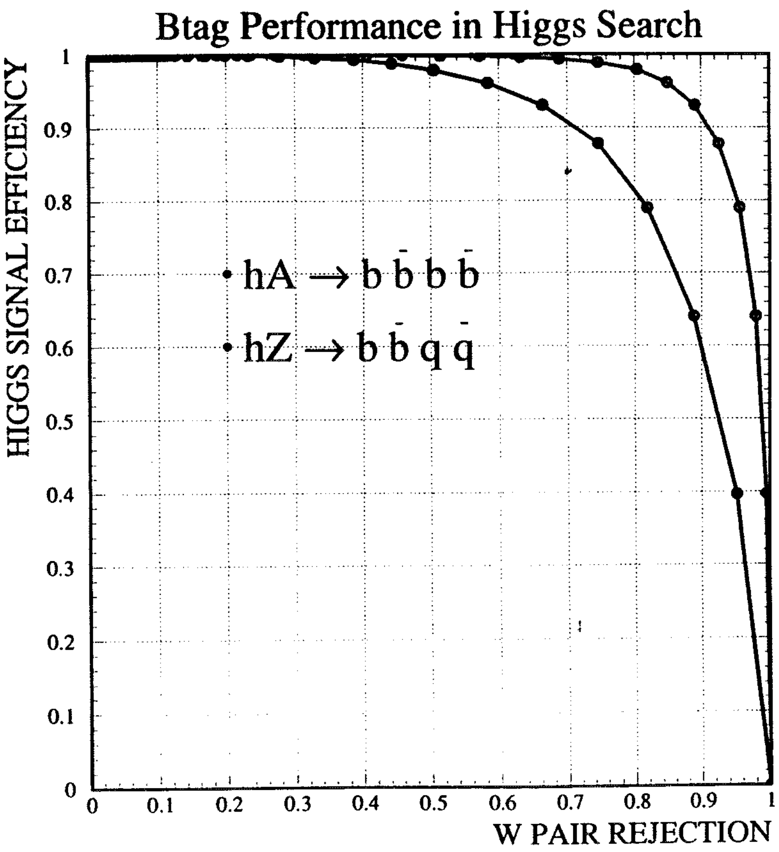
B-tag Progress

Since then: 3-D b-tag progress



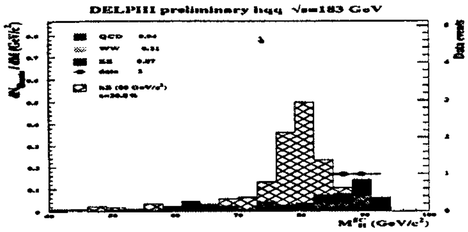
B discriminant 1997 $Z \rightarrow q\bar{q}$ data

Increased Sensitivity at 183 GeV

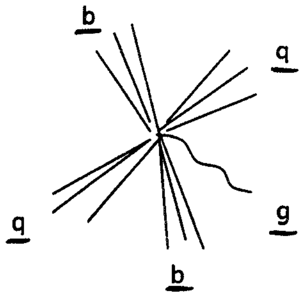


Btag Performance in Higgs Search

Mass Reconstruction in 4 jet Topology ⇒ critical in *HZ*, hZ Search



$\sigma \sim 3$ GeV
+ 25% tail

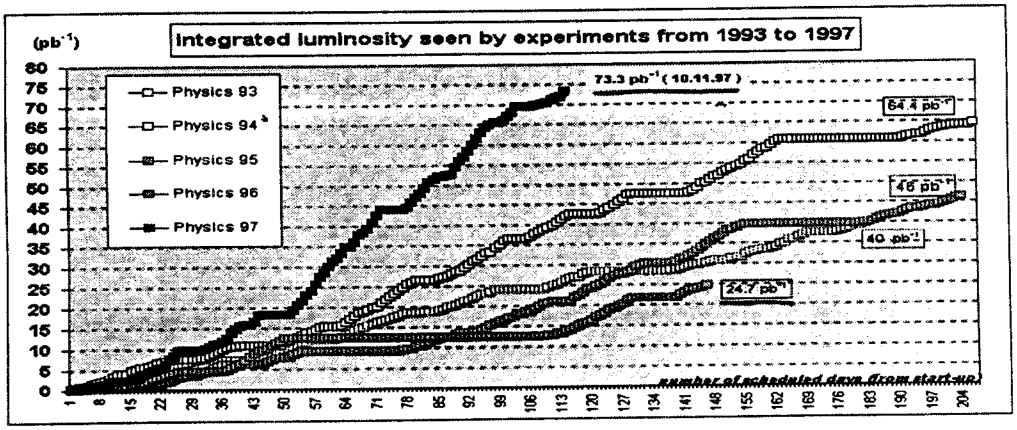


- Require clustering into 4 jets
- Perform 5C kinematical fits requiring M(qq)=M(Z) for 6 pairing hypothesis
- Help pairing choice with jet b-tag

- allow 4 and 5 jet clustering in prog.
- likelihood to combine fit, b-tag probabilities (for jets in VD and Z→udsc) and jet angular shapes

LEP-200 Performance

End of 97':
~ 2 pb⁻¹/day

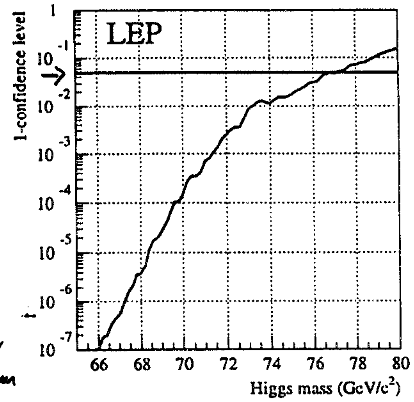


- 95 130-136 GeV 6 pb-1
- ⊙ 96 161-172 GeV 20 pb-1 final results + combined LEP (*HZ*)
- ⊙ 97 183 GeV 55 pb-1 prelim. results as of Nov.11 (LEP-C)

Summary of SM Higgs Search at 161-172 GeV

- ALEPH: 0 candidates, 29 % eff. 0.5 backgr.
- DELPHI: 2 candidates, Hqq: mass ~ 59 GeV, Hνν: mass > 65 GeV, 30 % eff. 2.3 backgr.
- OPAL: 1 candidate, Hqq: mass ~ 75 GeV, 33 % eff. 2.4 backgr.
- L3: 33 candidates selected ⇒ weight technique to measure Higgs-likeness of signal

Combined LEP Higgs Mass Limit from 161-172 GeV



W.MURRAY
Jerusalem

→ **Mass > 77 GeV @ 95 % CL**

Method: combined (Poisson) probability for observing N events with specific masses and other values of discriminating variables, given the expected number from signal (and background), and the respective shapes of the masses and other variables considered

CERN/LEPC 97-11

PRELIMINARY RESULTS @ 183 GeV

(HZ) (LEPC 11-97)

L3 Candidates under study (3D B-tag!)

Limit based on 60% of 97' data

$m_H > 82.2$ GeV @ 95% CL

OPAL 80% of 97' data

11 events expected, 7 found

$m_H > 82$ GeV @ 95% CL (N99)

one nice Z Z event (→ HZ ?!)

$\downarrow \quad \searrow$

$e^+e^- \quad \tau^+\tau^- \longrightarrow \pi^- X$

$\hookrightarrow \mu^+ \nu_\mu \bar{\nu}_\tau$

DELPHI 100% of 97' data

6 events expected, 7 found

$m_H > 83.6$ GeV @ 95% CL

ALEPH 100% of 97' data

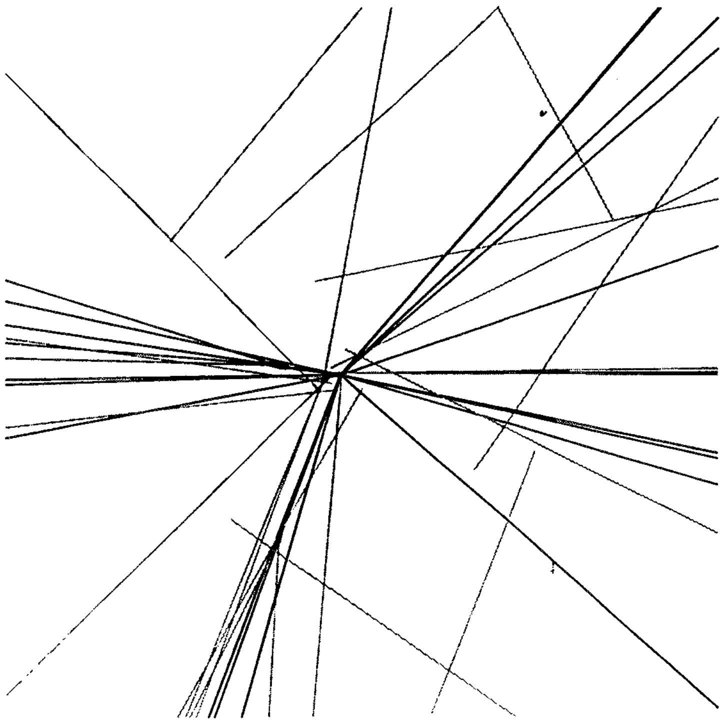
5 events expected, 3 found

$m_H > 88.6$ GeV @ 95% CL

(exp. limit ~ 83 GeV)

Higgs Candidate Example

Run# 685703 Event# 3598



Vertex at 1.5 mm

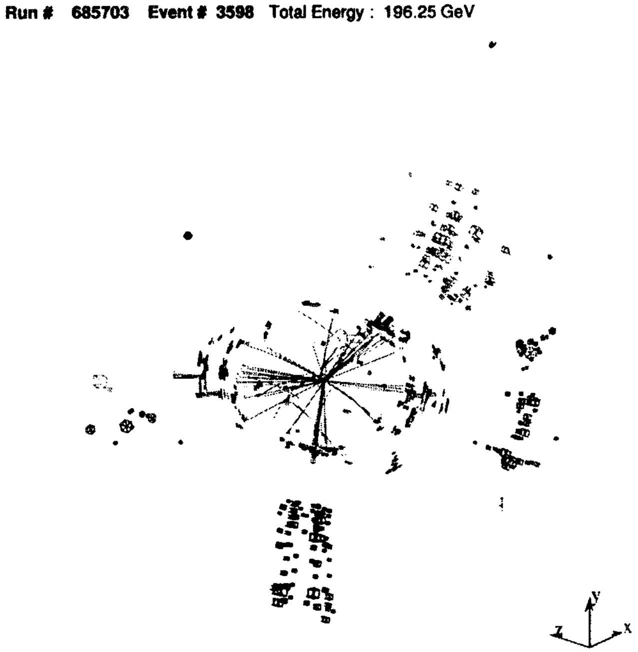
Vertex at 4.1 mm

Higgs Candidate Example

$M_Z^{rec} = 93.2$GeV

$M_H^{rec} = 78.2$GeV

$B_{tag} = 3.3$

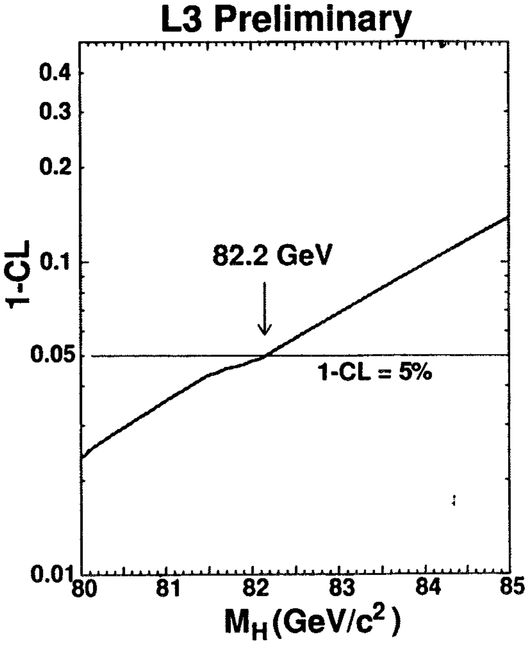


Candidates under study, no new limits

Limit on Standard Model Higgs

Intermediate result from 36 pb^{-1}:

(Data collected untill 29.09.97)



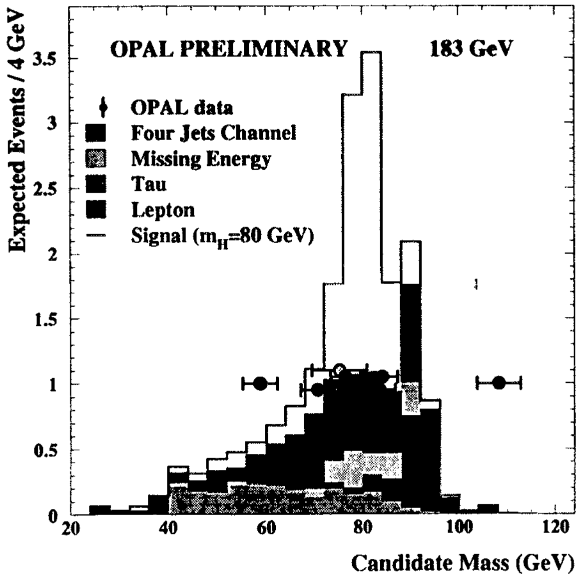
$M_H > 82.2$GeV at 95% CL

OPAL New Physics Search: SM Higgs

- $e^+e^- \to ZH$, uses $\int \mathcal{L} \approx 39\text{pb}^{-1}$
- Search in 4 channels: qqbb, $\nu\nu$qq, $\tau\tau$qq, and eeqq+$\mu\mu$qq
- Likelihood for 4-jet, $\nu\nu$qq

$\sqrt{s}$ (GeV)	161	172	183	Total
N_{exp}	1.9 ±0.1 ±0.3	2.2 ±0.1 ±0.3	10.8 ±0.5 ±2.0	14.9 ±0.5 ±2.5
N_{obs}	1	1	7	9

Higgs candidate mass for selected events:



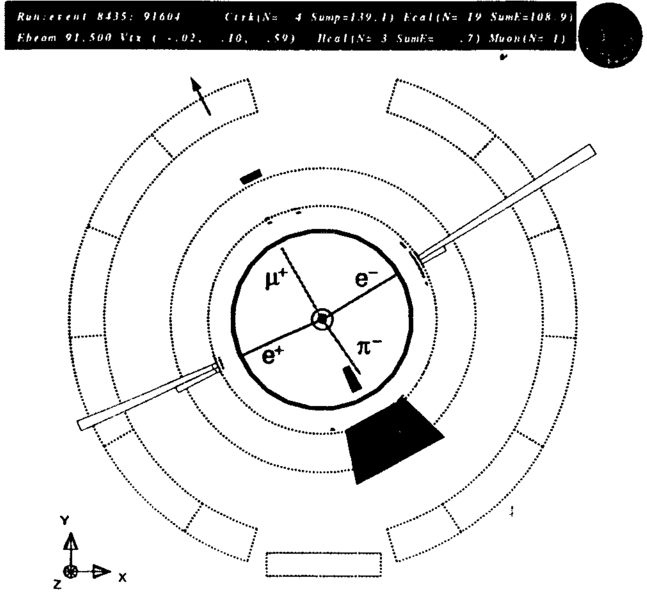
OPAL SM physics: ZZ, 4f

$< E_{beam} >$ = 91.3 GeV ⇒ just above ZZ threshold.

$e^+e^- \to Z^0Z^0 \to e^+e^- \tau^+\tau^-$

$\to \pi^- X$

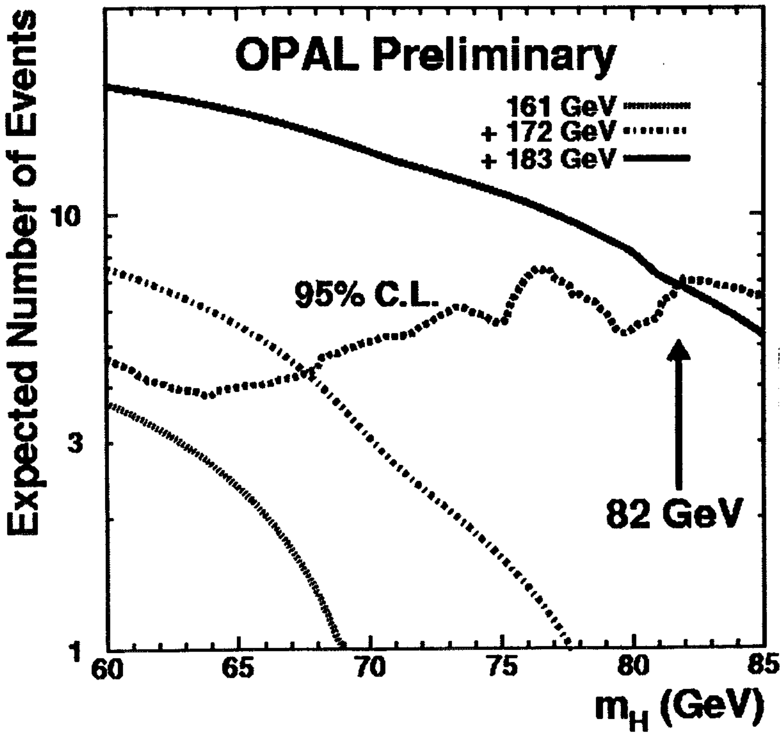
$\to \mu^+ \nu_\mu \bar{\nu}_\tau$



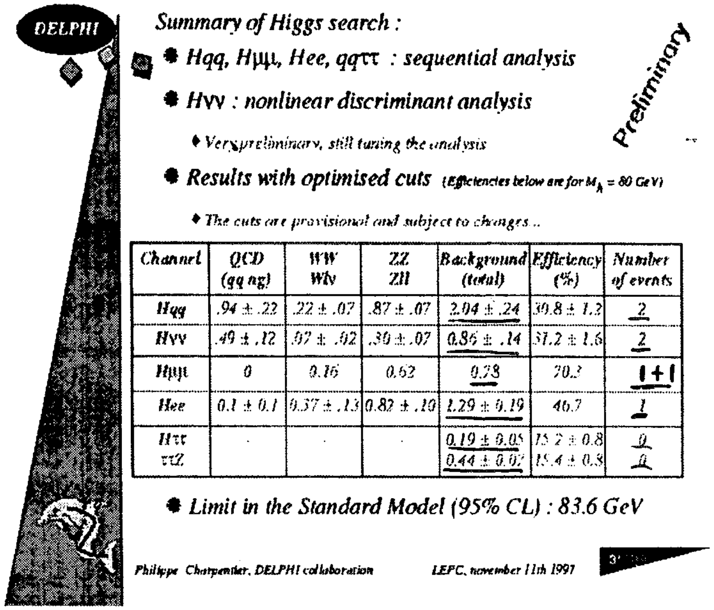
Mass (e⁺e⁻) = 89.5 +/- 3.4 GeV
Mass (recoil) = 90.7 +/- 3.1 GeV

Expectation from ZZ:

channel	N_{exp}	N_{obs}
eeqq, $\mu\mu$qq	0.7	0
$llll$	0.1	1



lepc_31.gif à wwwinfo.cern.ch



Summary of Higgs search :

- *Hqq, Hμμ, Hee, qqττ : sequential analysis*
- *Hνν : nonlinear discriminant analysis*
  - *Very preliminary, still tuning the analysis*
- ***Results with optimised cuts*** *(Efficiencies below are for M_h = 80 GeV)*
  - *The cuts are provisional and subject to changes ..*

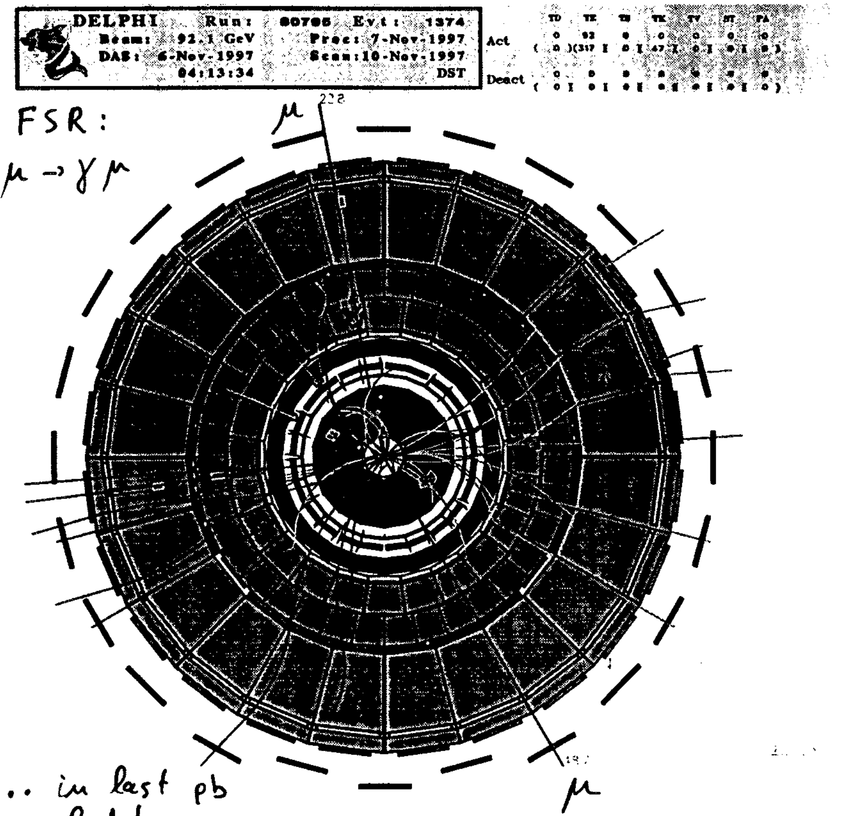
Channel	QCD (qq ng)	WW Wlν	ZZ Zll	Background (total)	Efficiency (%)	Number of events
Hqq	.94 ± .22	.22 ± .07	.87 ± .07	2.04 ± .24	30.8 ± 1.2	2
Hνν	.49 ± .12	.07 ± .02	.30 ± .07	0.86 ± .14	31.2 ± 1.6	2
Hμμ	0	0.16	0.62	0.78	70.3	1+1
Hee	0.1 ± 0.1	0.37 ± .13	0.82 ± .10	1.29 ± 0.19	46.7	1
Hττ ττZ	.	.	.	0.19 ± 0.05 0.44 ± 0.07	15.2 ± 0.8 15.4 ± 0.3	0 0

- *Limit in the Standard Model (95% CL) : 83.6 GeV*

Philippe Charpentier, DELPHI collaboration *LEPC, november 11th 1997* 3

γ μμ bb event

FSR:
μ → γμ



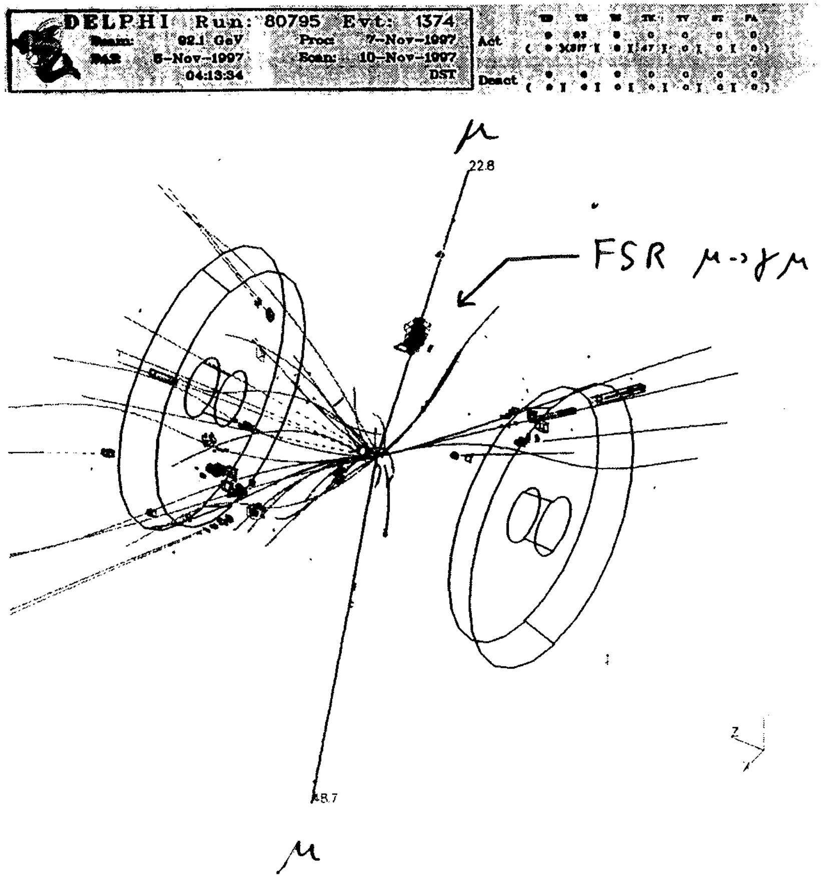
... in last pb
of data

$m_{\mu\mu} \sim 68$ GeV
$m_{qq} \sim 107$ GeV

btag lifetime > 13
btag combined ≳ 2

(mass fit bad because of FSR γ

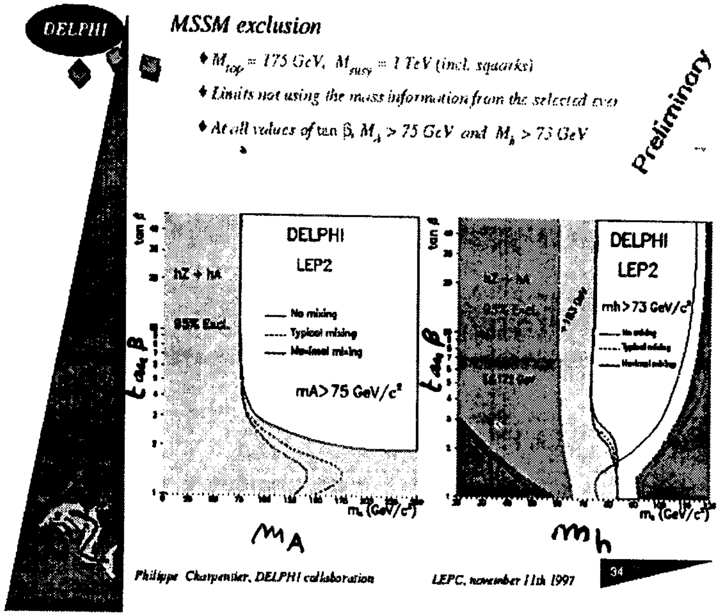
γ μμ bb event



$m_{\mu\mu} \sim 68$ GeV
$m_{qq} \sim 107$ GeV

btag lifetime > 13
btag combined ≳ 2

pc_34.gif à wwwinfo.cern.ch



DELPHI

MSSM exclusion

- $M_{top} = 175$ GeV, $M_{susy} = 1$ TeV (incl. squarks)
- Limits not using the mass information from the selected evts
- At all values of tan β, $M_A > 75$ GeV and $M_h > 73$ GeV

Preliminary

Philippe Charpentier, DELPHI collaboration

LEPC, november 11th 1997

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$m_{H_{SM}} > 83.6$

$m_A > 75$ }
$m_h > 73$ } ∀ ta

Aleph Status Report -- P.J. Dornan

HZ Analyses

Final State	Expected Background	No. of Candidates
Hqq	1.5	0
Hll	2.2	2
Hνν	0.9	1

hA Analyses

Final State	Expected Background	No. of Candidates
bbbb	1.1	1
bbττ	0.2	0

HZ ⟶ bbll Candidate Event

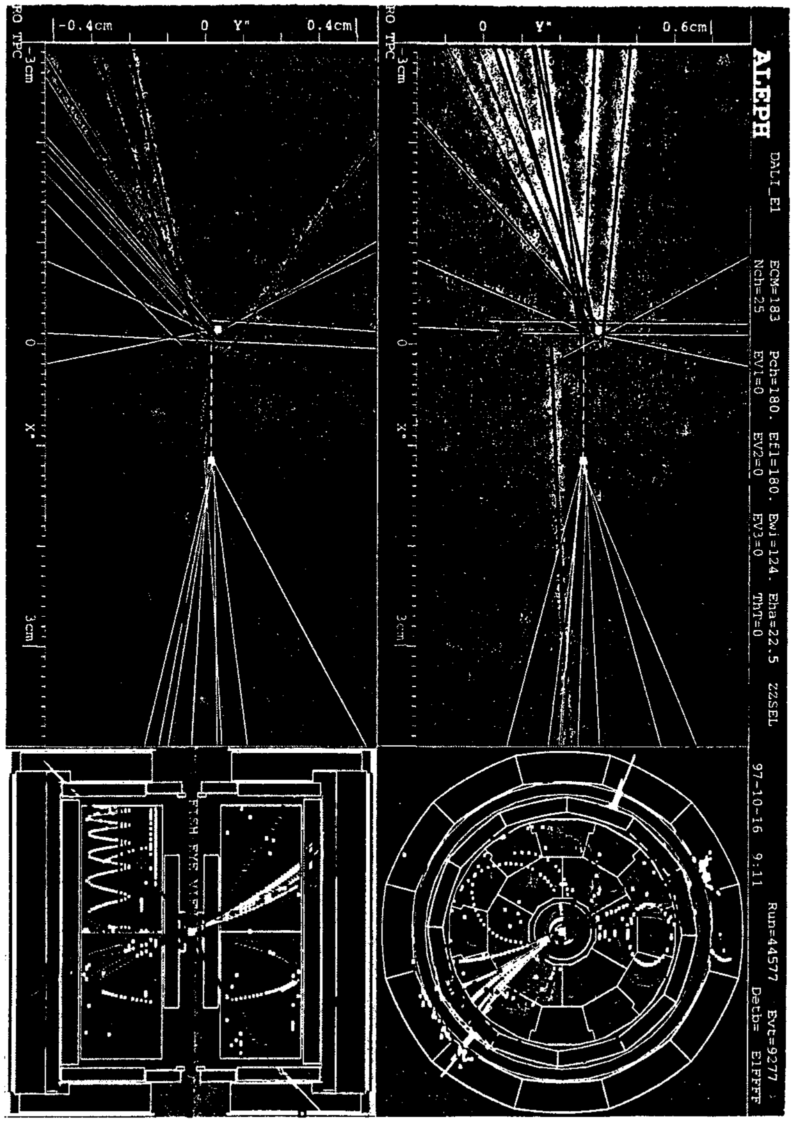
Run: 44577 Event: 9277

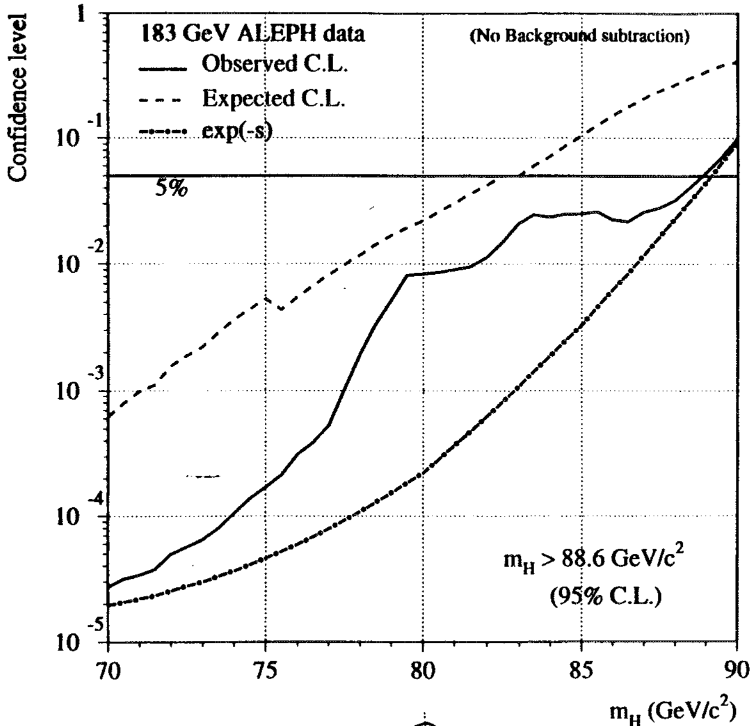
e^+ p = 40.64 GeV/c ECAL E = 40.75 GeV
e^- p = 42.98 GeV/c ECAL E = 44.78 GeV

$M(e^+e^-) = 84.78$ GeV/c^2
M(recoil) = 97.47 GeV/c^2
M(b jets) = 96.06 GeV/c^2

NN btag output (Jet 1) = 0.946
NN btag output (Jet 2) = 0.993

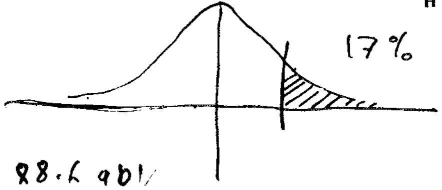
Total Background Expected (no btag): 2.2 Events
2 events seen
(with b-tag 0.3 ZZ events expected)





Expected
mass limit
~83 GeV

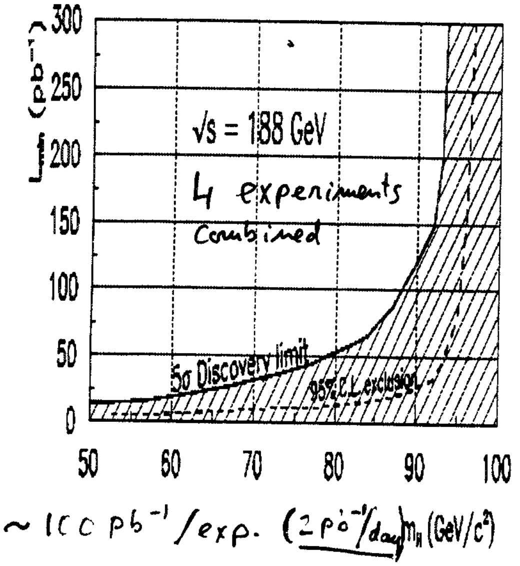
OBSERVED ~ 88.6 GeV



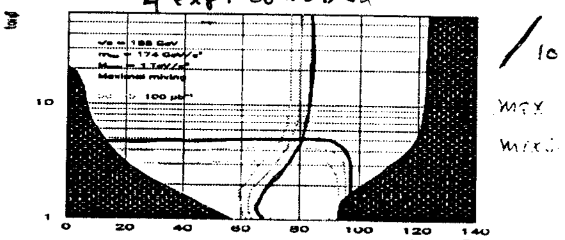
17% probability
to realize
high observed
CL

Expected Limit and Discovery Potential at 189 GeV

J. Fauch



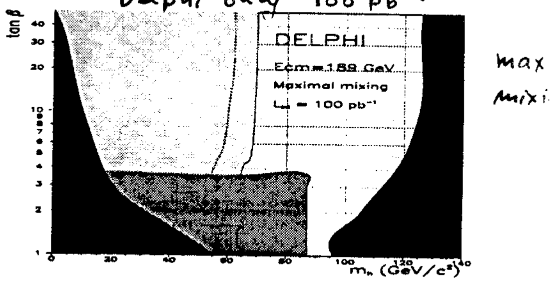
4 exp. combined



/10

max mixi

Delphi only 100 pb^{-1}



max mixi

need ~ 100 pb^{-1}/exp. ($\underline{2 pb^{-1}/day}$)

San Francisco 10/12/97 Philip Bambade, LAL, Orsay

1998: find evidence for Higgs or exclude "low tan β scenario"

Conclusion and Outlook

$m_{H_{SM}}$ > 77 GeV @ 95% CL ~~publish~~ official combined LE 96' result

$m_{H_{SM}}$ > 88 GeV @ 95% CL Best Preliminary 97' result (Alep

90 geV HSM exclusion possibly within reach with 97' data by combining A.D.O.L.

BUT : - monitor ZZ X-section
- deal with very higgs-like background candidat

full coverage of "low tan β scenario" within reach :

1998' @ 189 GeV { upgraded cryogenics OK
1999' @ $\underline{200}$ GeV { 98% SC cavities 6→7 MV/m
(2000' @ 200 GeV) formal decision pending.