III. PHYSICS GOALS OF FUTURE COLLIDERS

V. Barger/G. Kane/D. Neuffer, Chairs

III. PHYSICS GOALS OF FUTURE COLLIDERS, *V. Barger* (UW–Madison)/ *G. Kane* (U Mich)/*D. Neuffer* (FNAL), Chairs

Strongly-Interacting ElectroWeak Physics

— A Comparative Study for future Colliders

T. Han @ UC-Davis
UW-Madison

- General Remarks on SEWS
- $W_L W_L$ Scattering at

  LHC ($\sqrt{s_{pp}} = 14$ TeV, $\mathcal{L} \sim 100\ fb^{-1}$)

  NLC ($\sqrt{s_{e^+e^-}} = 1.5$ TeV, $\mathcal{L} \sim 200\ fb^{-1}$)

  $\mu^+\mu^-$ ($\sqrt{s_{\mu^+\mu^-}} \sim 4$ TeV, $\mathcal{L} \sim 200-1000\ fb^{-1}$)
- Concluding Remarks

Strongly-interacting ElectroWeak Sector remains a logical possibility

- In dynamical E.W.S.B. Models, besides $W_L^\pm, Z_L^0$
  [Technicolor and such]

  $\pi_T^a,\ \eta_T^a,\ \rho_T^a,\ \omega_T^a \cdots$

  with $M \sim \mathcal{O}(100 - 1000\ \text{GeV})$

  $\Rightarrow$ rich physics at

  Tevatron, LHC, NLC, μ-Colliders ...

- No pheno. viable models

  give $W^\pm, Z$ masses AND fermion masses;

  avoid large FCNC;

  accommodate small m_q/m_ℓ AND large m_t;

  Consistent w/ precision e.w. data.

Necessity: $\omega^\pm, \omega^0$ + Least Extension:

Model-independent Parameterization

(1). Non-resonance: $\omega^{\pm,0}$ only $\Sigma = \exp\{i\omega^a\tau^a/v\}$

$$\mathcal{L}_{eff} \sim \frac{v^2}{4}\mathrm{Tr}\,\partial_\mu\Sigma^\dagger\partial^\mu\Sigma + L_1\frac{v^2}{\Lambda^2}(\mathrm{Tr}\,\partial_\mu\Sigma^\dagger\partial^\mu\Sigma)^2 + L_2\frac{v^2}{\Lambda^2}(\mathrm{Tr}\,\partial_\mu\Sigma^\dagger\partial_\nu\Sigma)^2+\cdots$$

$\mathcal{M}_{LET}\sim s/v^2$ $[SU(2)_L \times SU(2)_R]$

$f(L_1,L_2)\frac{s^2}{\Lambda^2 v^2}$

anomal. Couplings: W^i_μ, B_μ: $k_{1,2}$, λ ...

(2). Scalar resonance: $J^I = 0^0$

$$\mathcal{L}_{eff}\sim +\frac{1}{2}\partial_\mu s\,\partial^\mu s - \frac{1}{2} m_s^2 s^2 + \frac{1}{2} g_s v\, s\, \mathrm{Tr}\,\partial_\mu\Sigma^\dagger\partial^\mu\Sigma+\cdots$$

H-like model, SM-like when $g_s=1$,

or 2 parameters: m_s, Γ_s

(3). Vector resonance: $J^I = 1^1$

$$\mathcal{L}_{eff}\sim + a g_s^2 v^2\, \mathrm{Tr}\, V^\mu V_\mu - \frac{1}{4} V_{\mu\nu}V^{\mu\nu}+\cdots$$

"ρ"-like model, 2 paramtrs: m_V, Γ_V

or other states $A_1(1^1)$ $\omega_T(1^0)$ ...

$W_LW_L\to W_LW_L$

the most direct probe to E.W.S.B.

$W_L^{\pm,0}\to\omega^{\pm,0}+\mathcal{O}(\frac{M_W}{E_W})$

$M(W_LW_L\to W_LW_L)\sim m_H^2/v^2$

or $\sim s/v^2$ for $m_H^2\gg s$

reach Unitarity bound at

m_H or $\sqrt{s}\sim$ 1-2 TeV

ee, Quigg, Thacker; Chanowitz Gaillard.

T(I)

In terms of the "isospin" amplitudes, the physical scattering amplitudes can be written as

$$\mathcal{M}(W_L^+ W_L^- \to Z_L Z_L) = \tfrac{1}{3}[T(0) - T(2)] ,$$

$$\mathcal{M}(W_L^+ W_L^- \to W_L^+ W_L^-) = \tfrac{1}{6}[2T(0) + 3T(1) + T(2)] ,$$

A $$\mathcal{M}(W_L^\pm W_L^\pm \to W_L^\pm W_L^\pm) = T(2) ,$$

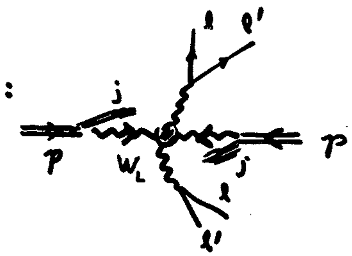
$$\mathcal{M}(W_L^\pm Z_L \to W_L^\pm Z_L) = \tfrac{1}{2}[T(1) + T(2)] ,$$

Consequently:

underlying physics:

final state:	$J^I = 0^0$ Scalar: H	1^1 Vector: ρ	Non-res LET
$Z_L Z_L$	LARGE	Small	large
$W_L^+ W_L^-$	LARGE	LARGE	mid.
$W_L^\pm W_L^\pm$	Small	mid.	large
$W_L^\pm Z_L$	Small	LARGE	Mid.

I. $W_L W_L$ Scattering at LHC:



$\sigma(pp \to jj W_L W_L) \simeq \mathcal{O}(10 fb)$

But, to avoid large bckgrnd:

BR(WW → 4ℓ's) ≃ a few%.

Table 1: Event rates per LHC-year for $W_L W_L$ fusion signals from the different models, together with backgrounds, assuming $\sqrt{s} = 14$ TeV, an annual luminosity of 100 fb^{-1}, and $m_t = 175$ GeV. Cuts are listed in Table I of Ref. 12. The $W^\pm Z(DY)$ row refers to the DY process $q\bar{q} \to V \to W^\pm Z$, with $0.85 < M_T(WZ) < 1.05$ TeV optimized for a 1 TeV vector state.

	Bkgd.	Scalar	Vec 1.0	Vec 2.5	LET-K
$ZZ(4\ell)$	0.7	4.6	1.4	1.3	1.4
$ZZ(2\ell 2\nu)$	1.8	17	4.7	4.4	4.5
W^+W^-	12	18	6.2	5.5	4.6
$W^\pm Z$	4.9	1.5	4.5	3.3	3.0
$W^\pm Z(DY)$	22		69		
$W^\pm W^\pm$	3.7	7.0	12	11	13

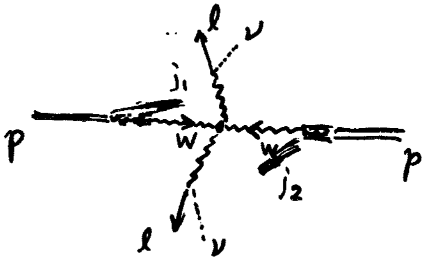
Bagger et al.

Table 2: Number of years (if < 10) at LHC required for a 99% confidence level signal.

Channel	Model			
	Scalar	Vec 1.0	Vec 2.5	LET K
$ZZ(4\ell)$	2.5			
$ZZ(2\ell 2\nu)$	0.75	3.7	4.2	4.0
W^+W^-	1.5	8.5		
$W^\pm Z$		0.07		
$W^\pm W^\pm$	3.0	1.5	1.5	1.2

* ATLAS simulations reached similar results;

Signal kinematical feature & acceptance cuts:



- high $M_{ww} \sim 1$ TeV
- high $P_T(\ell) \sim M_{ww}/4$
- Central $|y(\ell)| \lesssim 2.5$
- ℓ-ℓ back-to-back in transv. plane;

- one or two forward-jet
- Central quite (rapidity gap)

example for cuts: $pp \to j_1 j_2 W^+ W^-$, $W^- \to \ell^- \nu$, $W^+ \to \ell^+ \nu$

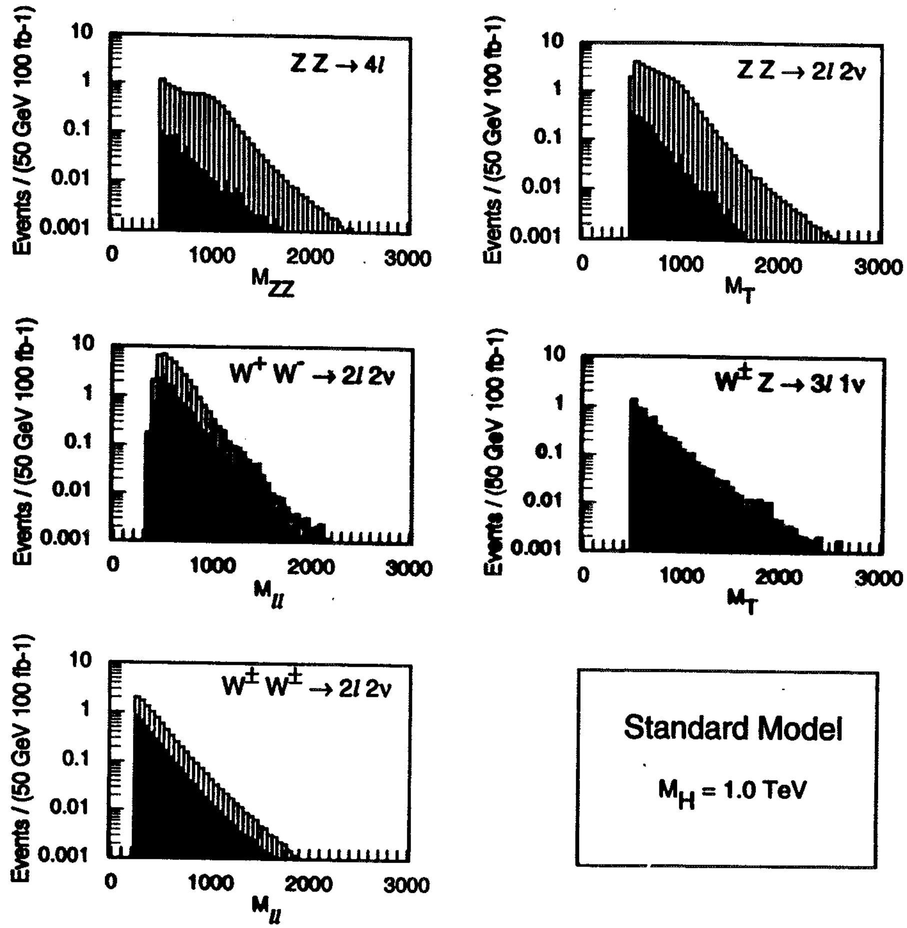
leptons: $|y(\ell)| < 2$

$P_T(\ell) > 100$ GeV, $\Delta P_T(\ell\ell) > 440$ GeV

$\cos\phi_{\ell\ell} < -0.8$, $M(\ell\ell) > 250$ GeV

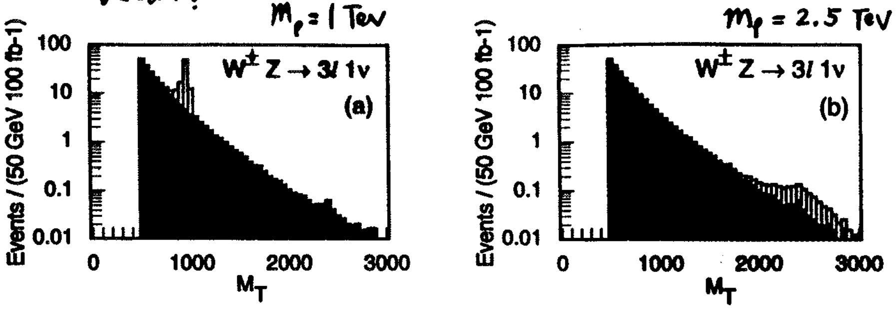
jets: 1-jet tagging: $\begin{cases} E(j_{tag}) > 0.8 \text{ TeV}, & P_T(j_{tag}) > 40 \text{ GeV} \\ 3 < |y_{jtag}| < 5 \end{cases}$

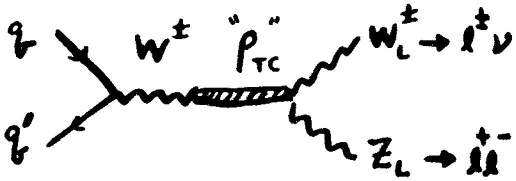
Central jet Vetoing: $P_T(j_{veto}) > 30$ GeV



Bagger et al.

Vector:





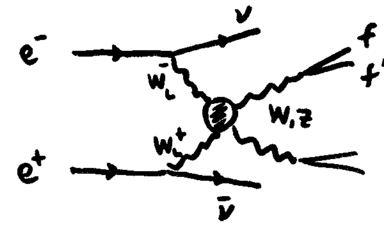
$$p_T^W \simeq \frac{1}{2} m_\rho$$

P.R. D52, 3878 (1995)

Bagger et al.

(also, Chanowitz & Kilgore)

II. e^+e^- Linear Colliders

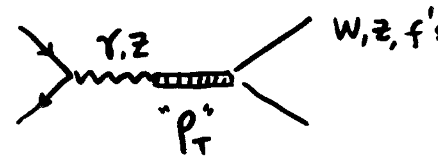


at $\sqrt{s_{e^+e^-}} = 1.5$ TeV for $m_H = 1$ TeV

$$\sigma(e^+e^- \to \nu\bar\nu W_L^+ W_L^-) \simeq 8 \text{ fb}$$
$$\nu\bar\nu Z_L Z_L \qquad 5 \text{ fb}$$

And
$$\frac{\sigma(W_L^+W_L^- \to W_L^+W_L^-)}{\sigma(W_L^+W_L^- \to Z_L Z_L)} \simeq \begin{cases} 2 & \text{for } H^0 \\ \gg 1 & \text{for } \rho_T \\ 2/3 & \text{for LET} \end{cases}$$

Especially for a Vector state:



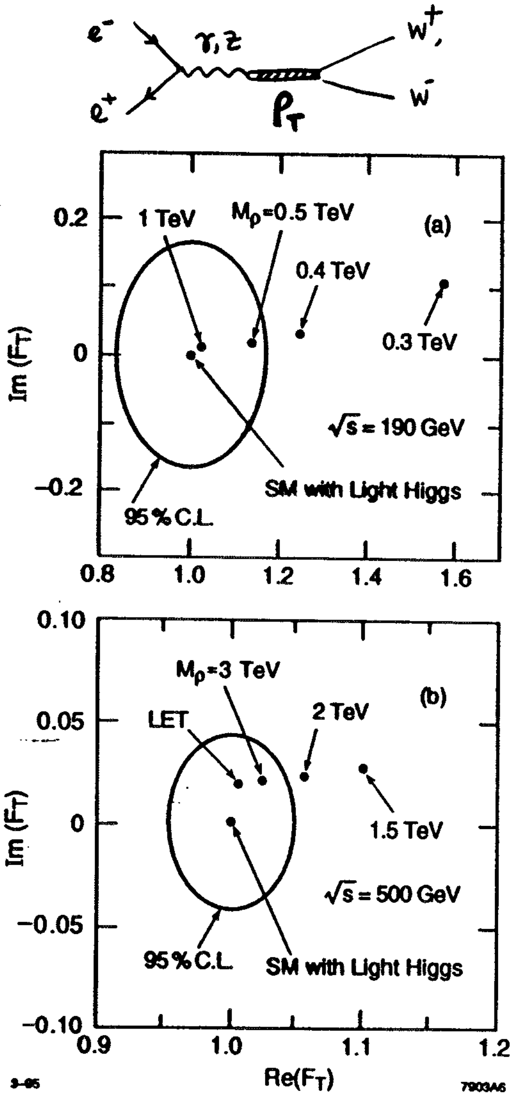


Figure 7: 95% confidence level contours for the real and imaginary parts of F_T at (a) $\sqrt{s} = 190$ GeV with 0.5 fb^{-1} and at (b) $\sqrt{s} = 500$ GeV with 80 fb^{-1}. The values of F_T for various technirho masses are indicated.

b'

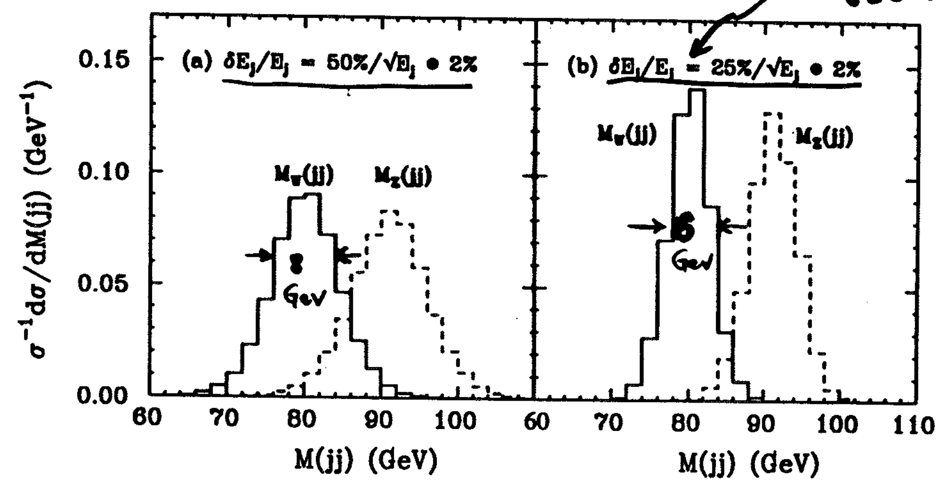
T. Barklow.

Similar results were also obtained by: Hikasa; Tanabashi; Miyamoto.

W/Z discrimination by $m(W \to jj) < m(Z \to jj)$

* use only hadronic decays;
* Smear the jet-energy at paton level

Miyamoto; JLC book.



$\Delta M_W \sim 18$ GeV

Fig. 1

Define W's: 68 ~ 86 GeV Z's:

$m(jj) = \left(0.85 M_W, \frac{M_W + M_Z}{2}\right)$; $\left(\frac{M_W + M_Z}{2}, 1.15 M_Z\right)$

then

Production:		identified by jj modes:			
		WW	WZ	ZZ	reject
WW	⇒	73%	17%	1%	9%
WZ	⇒	19%	66%	7%	8%

At $\sqrt{s_{e^+e^-}} = 1.5$ TeV, $\sigma(e^+e^- \to \nu\nu W_L^+W_L^-) \approx \mathcal{O}(1\sim 2$ fb$)$ ⇒ a few 100 evts / 200 fb^{-1}
(LET)

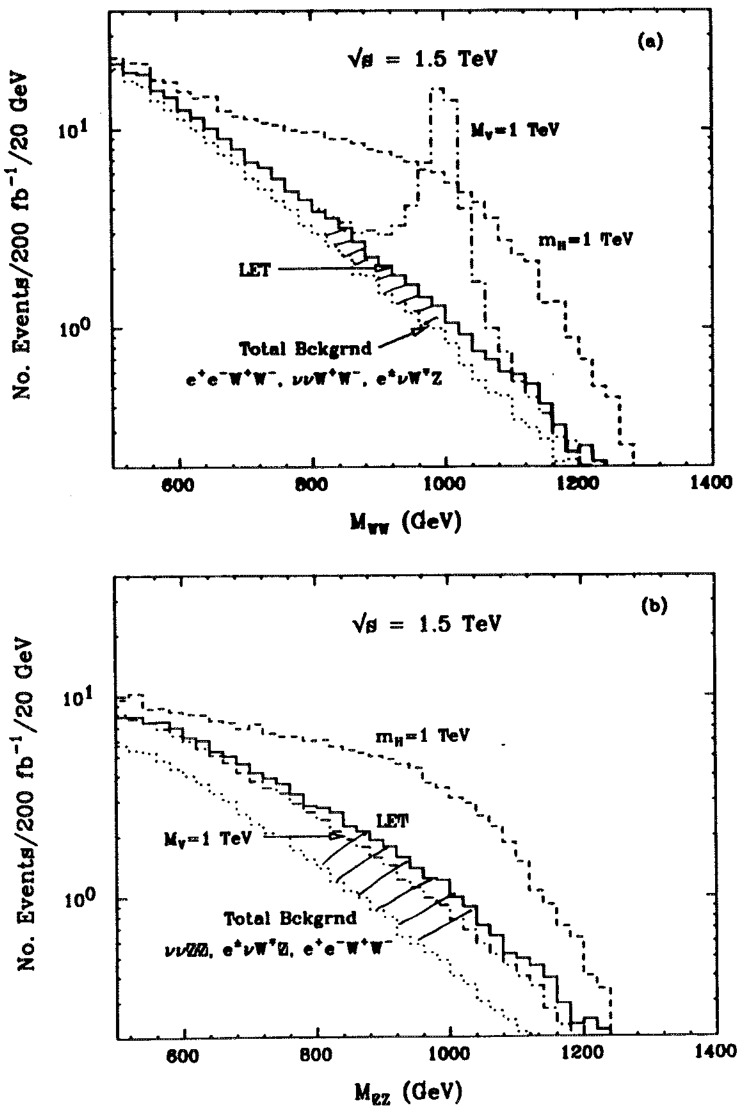


Fig. 7

Barger, Cheung, Han, phillips

Table 3: Total numbers of $W^+W^-, ZZ \to$ 4-jet signal S and background B events calculated for a 1.5 TeV NLC with integrated luminosity 200 fb^{-1}. Events are summed over the mass range $0.5 < M_{WW} < 1.5$ TeV except for the W^+W^- channel with a narrow vector resonance in which $0.9 < M_{WW} < 1.1$ TeV. The statistical significance $S/\sqrt{B}$ is also given. For comparison, results for $e^-e^- \to \nu\nu W^-W^-$ are also presented, for the same energy and luminosity and the W^+W^- cuts. The hadronic branching fractions of WW decays and the $W^\pm/Z$ identification/misidentification are included (see Ref. 17 for more details).

channels	Scalar $M_S = 1$ TeV	Vector $M_V = 1$ TeV	LET
$S(e^+e^- \to \bar{\nu}\nu W^+W^-)$	160	46	31
B(backgrounds)	170	4.5	170
$S/\sqrt{B}$	[illegible]	[illegible]	2.4
$S(e^+e^- \to \bar{\nu}\nu ZZ)$	130	36	45
B(backgrounds)	63	63	63
$S/\sqrt{B}$	[illegible]	4.5	[illegible]
$S(e^-e^- \to \nu\nu W^-W^-)$	35	36	42
B(backgrounds)	230	230	230
$S/\sqrt{B}$	2.3	2.4	[illegible]

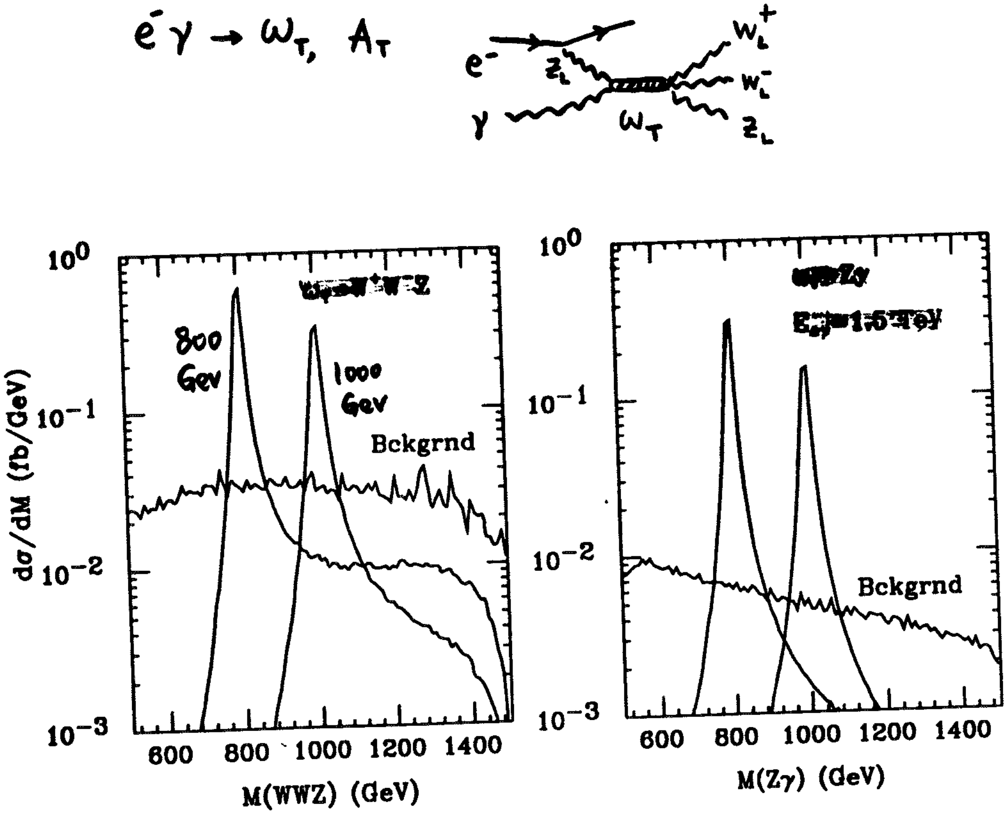
Table 3. Signals for different models of strongly-interacting W sector at an e^-e^- collider for $\sqrt{s}$ = 1.5 TeV, with cuts discussed in the text. Polarization effects for P_e=0, 85% and 100% (both electron beams) are compared. Backgrounds are summed over W^-W^- with a light Higgs exchange, W^+W^- and W^-Z. Entries correspond to the number of events with hadronic W,Z decays for an integrated luminosity of 200 fb^{-1}. W/Z identification via dijet mass has been implemented, as discussed in the text to improve the signal/background ratio. As a rough indication of the signal observability, values of $S/\sqrt{B}$ are also given.

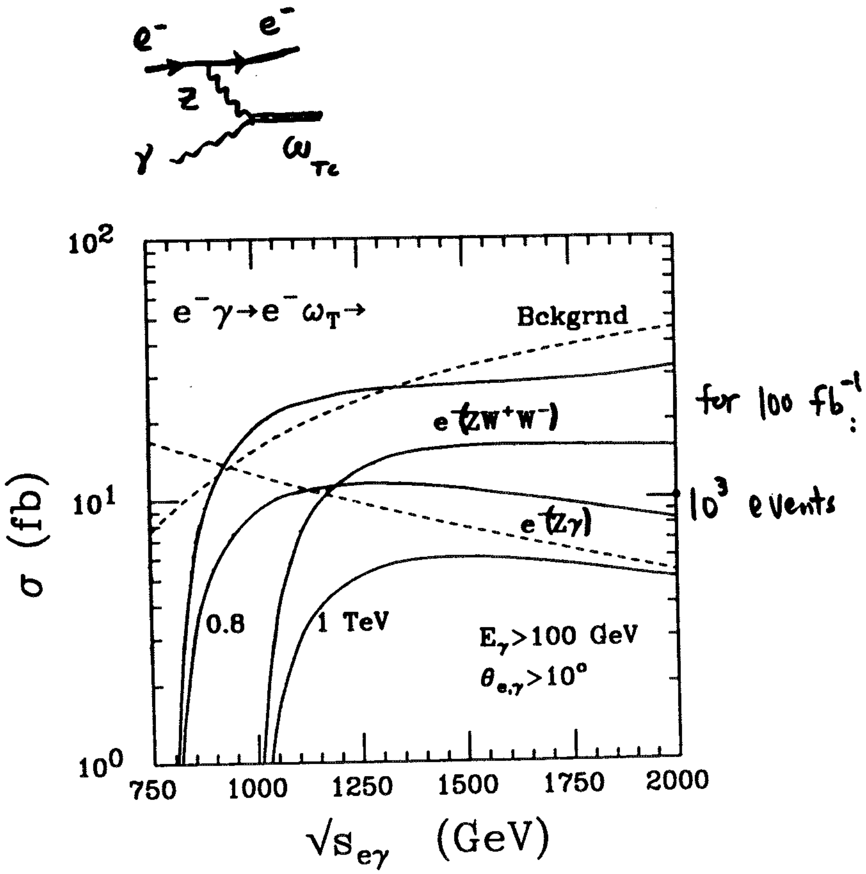
$\sqrt{s}$ = 1.5 TeV M_{WW}^{min}=0.5 TeV	SM m_H = 1 TeV	Scalar m_S = 1 TeV	Vector m_V = 1 TeV	LET	Bckgnds
Signal $P_e = 0$	27	35	36	42	230
$S/\sqrt{B}$	1.8	2.3	2.4	2.8	
Signal $P_e = 85\%$	93	121	123	144	620
$S/\sqrt{B}$	3.8	4.8	5.0	5.8	
Signal $P_e = 100\%$	109	141	144	168	713
$S/\sqrt{B}$	4.1	5.3	5.4	6.3	

Table 4. Signals for different models of strongly-interacting W sector at an e^-e^- collider for $\sqrt{s}$ = 1.5 TeV, with cuts discussed in the text. Polarization effects for P_e=0, 85% and 100% (both electron beams) are compared. Backgrounds are summed over W^-W^- with a light Higgs exchange, W^+W^- and W^-Z. Entries correspond to the number of events with hadronic W,Z decays for an integrated luminosity of 300 fb^{-1}. W/Z identification via dijet mass has been implemented, as discussed in the text to improve the signal/background ratio. As a rough indication of the signal observability, values of $S/\sqrt{B}$ are also given.

$\sqrt{s}$ = 1.5 TeV M_{WW}^{min}=0.5 TeV	SM m_H = 1 TeV	Scalar m_S = 1 TeV	Vector m_V = 1 TeV	LET	Bckgnds
Signal $P_e = 0$	41	53	54	63	345
$S/\sqrt{B}$	2.2	[redacted]	[redacted]	[redacted]	
Signal $P_e = 85\%$	140	181	185	216	930
$S/\sqrt{B}$	4.6	[redacted]	[redacted]	[redacted]	
Signal $P_e = 100\%$	164	212	216	252	1070

$e^- \gamma \to \omega_T,\ A_T$





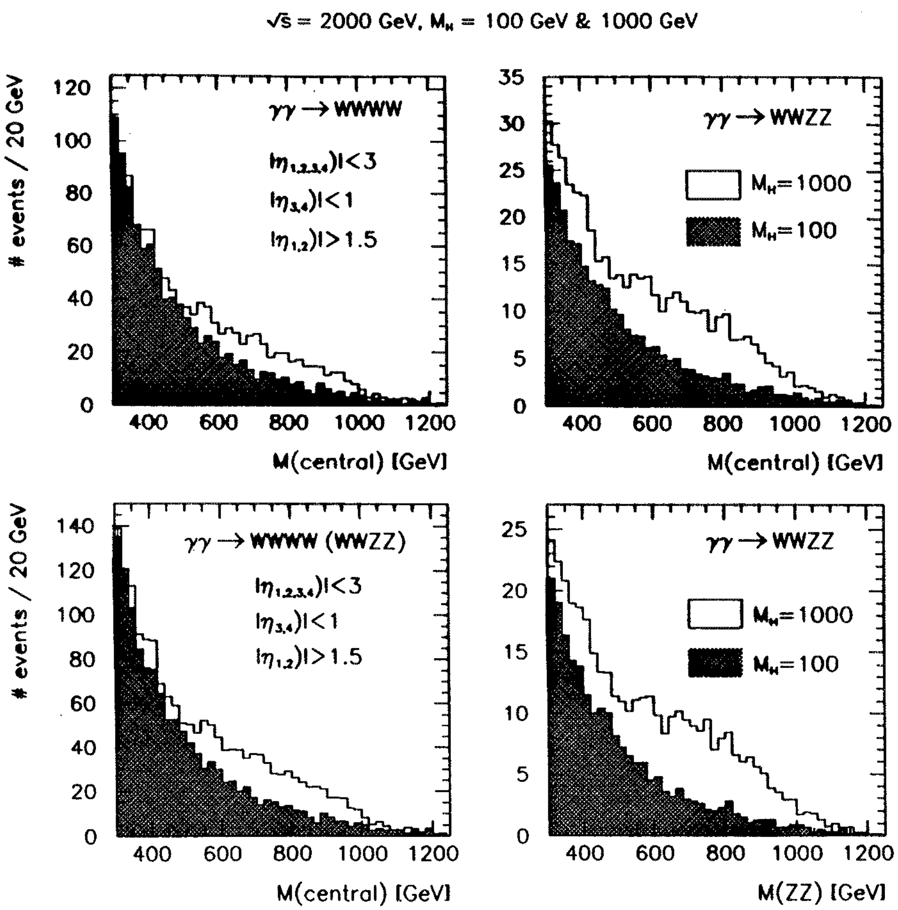
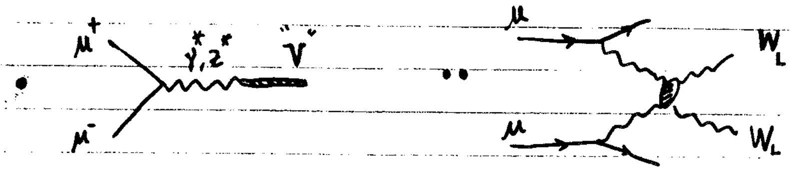


Figure 14.

III. 4 TeV $\mu^+\mu^-$ Collider (200–1000 fb^{-1})



spectacular !

primarily due to higher { energy reach; luminosity

* if $\sqrt{s} \sim m_V$, truely factory:

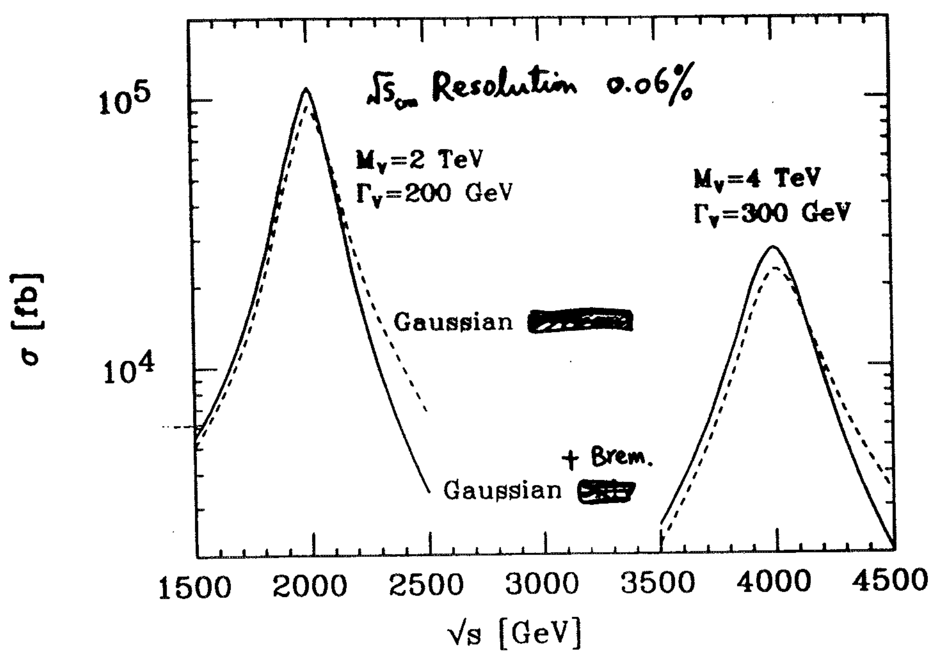
million evnts / 100 fb^{-1}

* for $\sigma(\mu^+\mu^- \to \nu\nu W_L^+ W_L^-) \approx \mathcal{O}(40\, fb)$

$\Rightarrow 8 \cdot 10^3$ evnts / yr

σ in $\sqrt{s} = \sqrt{s}/\sqrt{2}$ * Res.

$\mu^+\mu^- \to$ Vector (ρ_{TC})

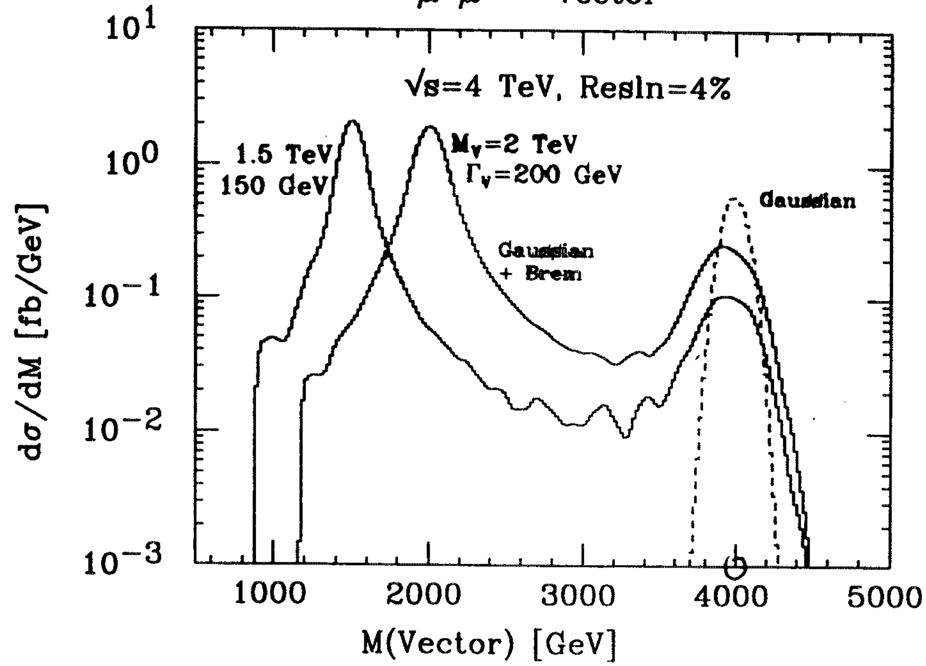


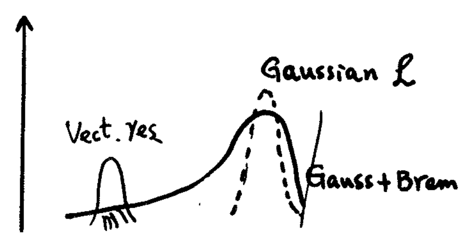
with good resolution, near the resonance
$\sqrt{s} \sim m_V$ $\Rightarrow$ "ρ_{TC}" factory!

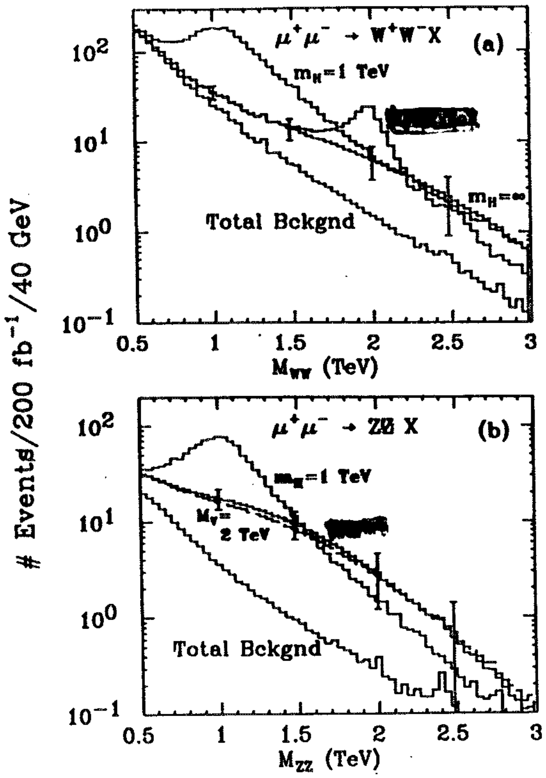
Barger
Berger

What if $\sqrt{s}$ far from M_V ?
(without knowing M_V a priori)

$\mu^+\mu^- \to$ Vector







← observe a 2-TeV bump

* observe the deviat. $M \to \infty \leftrightarrow$ SM (LH)

* observe the deviat. $M_V \sim 2$ TeV $\leftrightarrow M \to \infty$

Figure 5: Number of events at [redacted] versus M_{VV} for SEWS models (including the combined backgrounds) and for the combined backgrounds alone in the (a) W^+W^- and (b) ZZ final states after imposing all cuts, I–III. Sample signals shown are: (i) the SM Higgs with $m_H = 1$ TeV; (ii) the SM with $m_H = \infty$ unitarized via K-matrix techniques (LET-K model); and (iii) the Vector model with $M_V = 2$ TeV and $\Gamma_V = 0.2$ TeV. In the ZZ final state the histogram for (iii) falls just slightly lower than that for model (ii) at lower M_{VV}. Sample statistical uncertainties for the illustrated 40 GeV bins are shown in the case of the $m_H = \infty$ model.

Barger, Berger, Gunion, Han.

For a 1-TeV Scalar, Γ_S ?

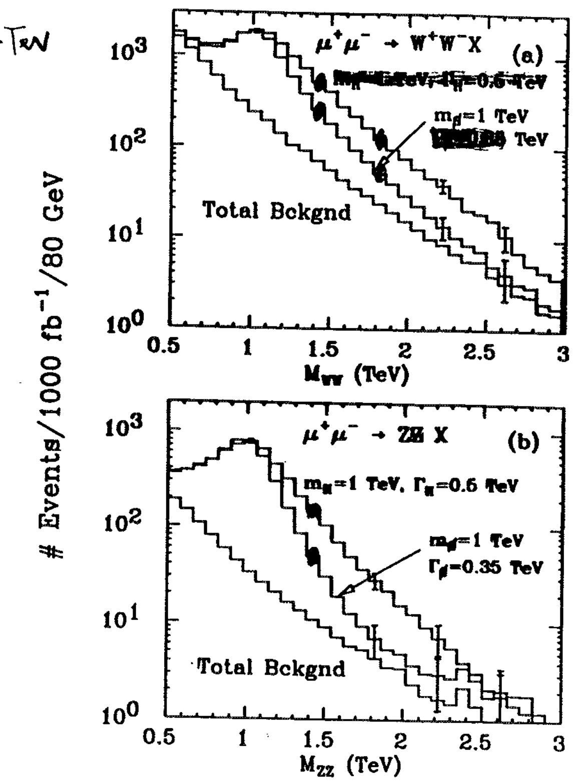


Figure 6: Events versus M_{VV} for two SEWS models (including the combined backgrounds) and for the combined backgrounds alone in the (a) W^+W^- and (b) ZZ final states after imposing all cuts, I–III. Signals shown are: (i) the SM Higgs with $m_H = 1$ TeV, $\Gamma_H = 0.5$ TeV; (ii) the Scalar model with $M_S = 1$ TeV, $\Gamma_S = 0.35$ TeV. Results are for $L = 1000$ fb^{-1} and $\sqrt{s} = 4$ TeV. Sample error bars are shown at $M_{VV} = 1.02, 1.42, 1.82, 2.22$ and 2.62 TeV for the illustrated 80 GeV bins.

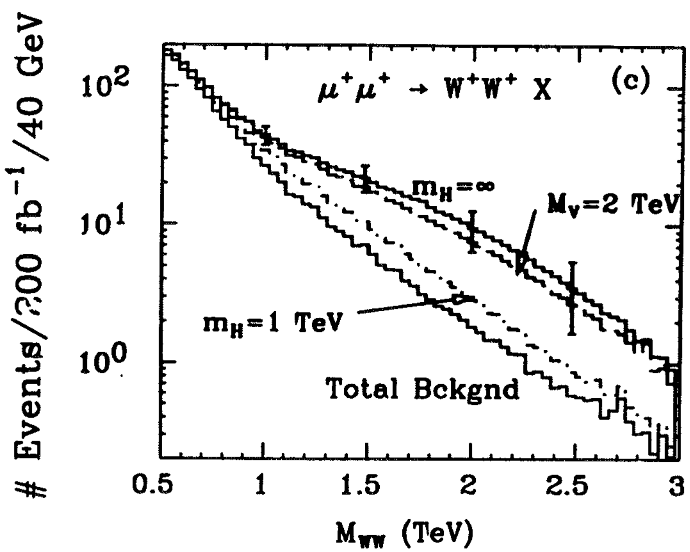
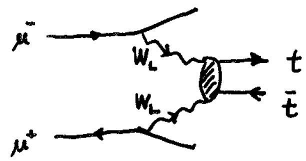
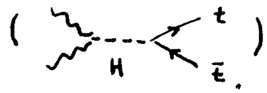
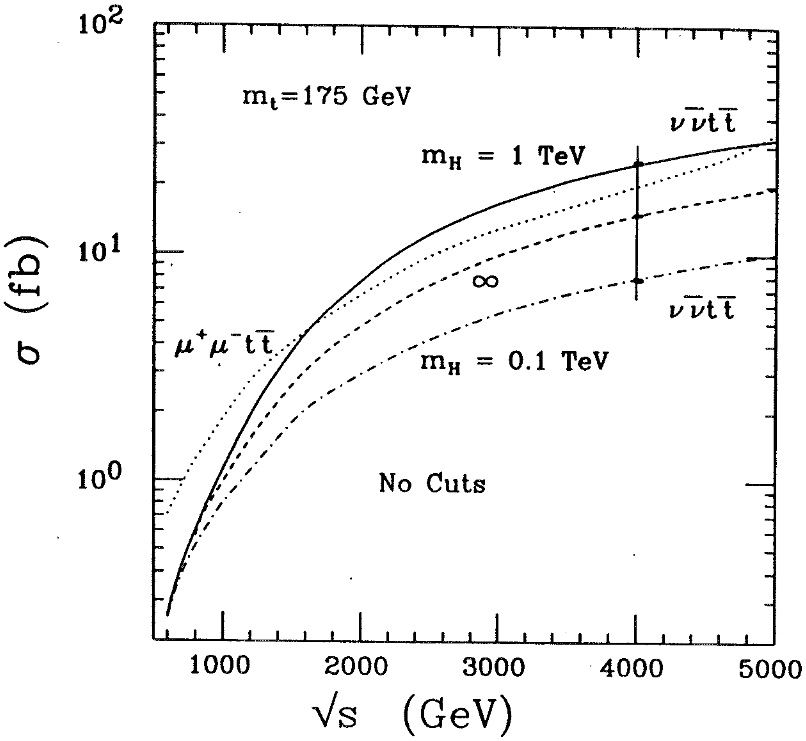


Table 5: Total numbers of W^+W^-, ZZ and $W^+W^+ \to$ 4-jet signal (S) and background (B) events calculated for a 4 TeV $\mu^+\mu^-$ collider with integrated luminosity 200 fb^{-1} (1000 fb^{-1} in the parentheses), for cuts of $M_{VV} \geq 500$ GeV, $p_T(V) \geq 150$ GeV, $|\cos\theta_V| \leq 0.8$ and $p_T(WW) \geq 30$ GeV, $p_T(ZZ) \geq 20$ GeV. (For the case of a 2 TeV vector state, events for the W^+W^- channel are summed around the mass peak over the range $1.7 < M_{VV} < 2.3$ TeV.) Events containing a μ^+ or μ^- with $\theta_\mu \geq 12°$ and $E_\mu \geq 50$ GeV are vetoed. The signal rate S is that obtained by computing the total rate (including all backgrounds) for a given SEWS model and then subtracting the background rate; see Eq. (4.1). The statistical significance $S/\sqrt{B}$ is given for the signal from each model. The hadronic branching fractions of VV decays and the $W^\pm/Z$ identification/misidentification are included.

channels	Scalar $m_H = 1$ TeV $\Gamma_H = 0.5$ TeV	Vector $M_V = 2$ TeV $\Gamma_V = 0.2$ TeV	LET-K $m_H = \infty$ Unitarized
$\mu^+\mu^- \to \bar{\nu}\nu W^+W^-$			
S(signal)	2400 (12000)	180 (890)	370 (1800)
B(backgrounds)	1200 (6100)	25 (120)	1200 (6100)
$S/\sqrt{B}$	68 (152)	36 (81)	11 (24)
$\mu^+\mu^- \to \bar{\nu}\nu ZZ$			
S(signal)	1030 (5100)	360 (1800)	[illegible]00 (2000)
B(backgrounds)	160 (800)	160 (800)	[illegible]60 (800)
$S/\sqrt{B}$	81 (180)	28 (64)	[illegible]2 ([illegible])
$\mu^+\mu^+ \to \bar{\nu}\bar{\nu} W^+W^+$			
S(signal)	240 (1200)	530 (2500)	640 (3200)
B(backgrounds)	1300 (6400)	1300 (6400)	1300 (6400)
$S/\sqrt{B}$	7 (15)	15 (33)	18 (40)

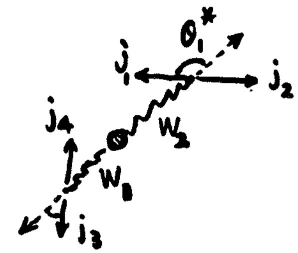






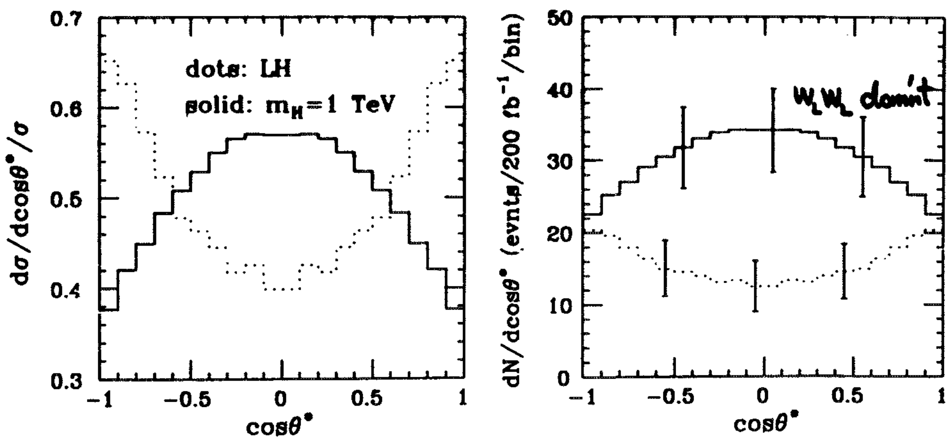
$$\sigma(\text{signal}) = \begin{cases} 17 \text{ fb} & \text{for } m_H \sim 1 \text{ TeV} \\ 7 \text{ fb} & \text{for } m_H \to \infty \end{cases}$$

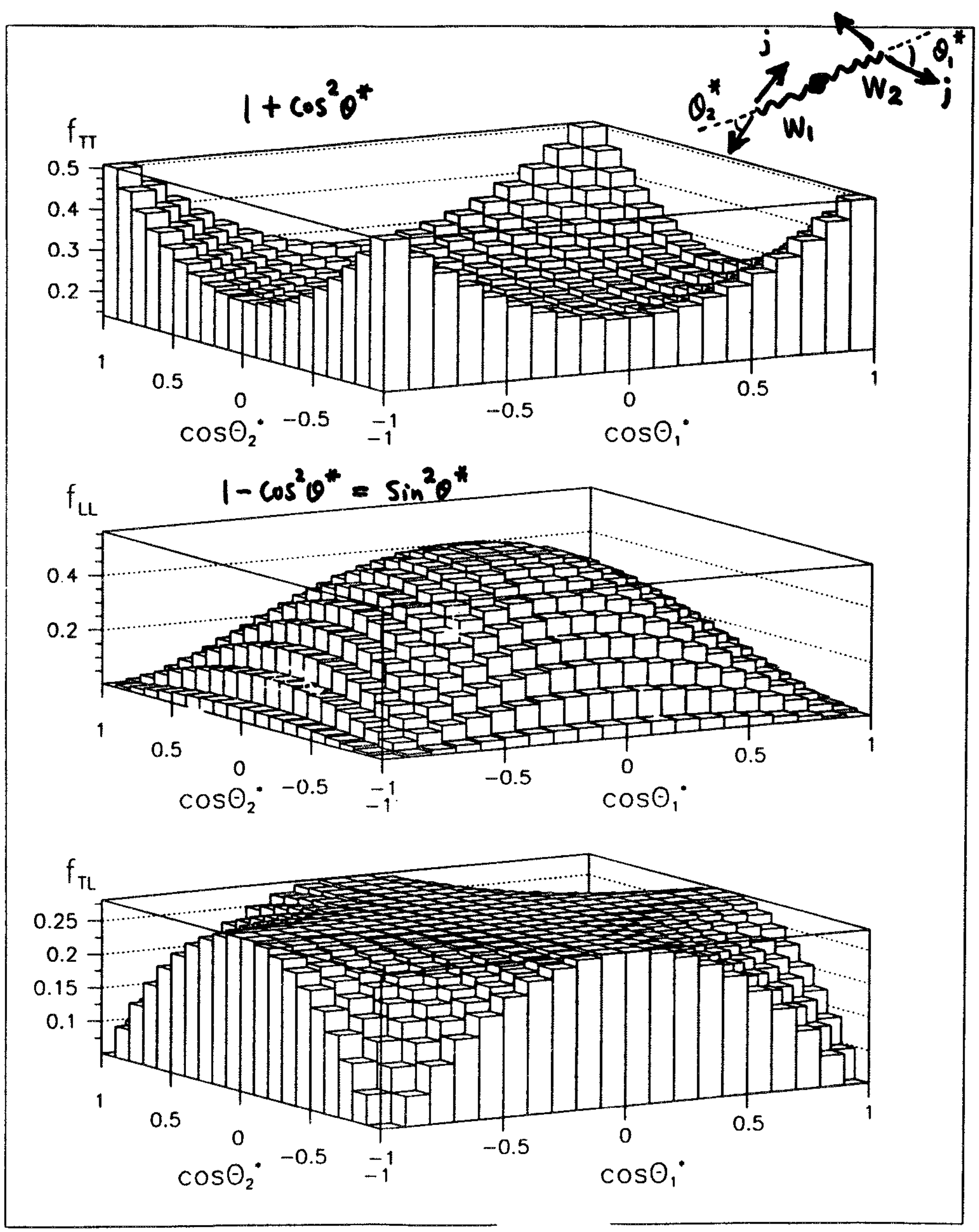
$\mathcal{L}/\text{yr} \sim 200\text{-}1000 \text{ fb}^{-1}$



$\mu^+\mu^+ \to \overline{\nu}\overline{\nu}\ W^+W^+ \to \overline{\nu}\overline{\nu}$ 4 jets

$\sqrt{s}$ = 4 TeV, with cuts





- Going to higher energies ?
  - * Stronger Signal :

    e.g. $M_{LET} \sim s/v^2 \quad (s = M^2_{ww})$

    and: $\sigma(W_L^+W_L^- \to W_L^+W_L^-) \simeq \begin{cases} 8 \text{ fb} & \text{at } 1.5 \text{ TeV} \\ 80 \text{ fb} & 4 \text{ TeV} \end{cases}$

    $(m_H \simeq 1 \text{ TeV})$

    $2 \times E_{cm} \Leftrightarrow 10 \times \mathcal{L}$

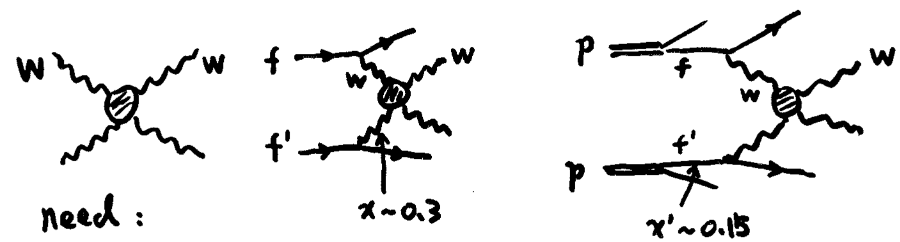
  - * Lower bckgrnds :

    irreducible bckgrnds: $\frac{d\mathcal{L}(W_T W_T)}{d\tau} \sim \ln^2 s/M_W^2$

    reducible : $\sigma(W^+W^-, t\bar{t}) \sim 1/s$

- "desirable" energy ?

  $\Lambda \lesssim 4\pi v \sim 3$ TeV



need :

$\sqrt{s_{ww}} \sim 1-2$ TeV $\quad \sqrt{s_{ff'}} \sim \sqrt{s_{ww}}/x \quad \sqrt{s_{pp}} \sim \sqrt{s_{ff'}}/x'$

Threshold Cross Section Measurements

M. Berger

MuMu97 December 11, 1997

Threshold corrections can be used to measure:

- masses
- widths
- couplings

Threshold shape is controlled by:

- angular momentum (s-wave, p-wave, etc.)
- final state interactions ($t\bar{t}$, QCD)
- particle widths

Collaborators: Barger, Gunion, Han

Muon-muon Collider

- Sharp beam energy profile - monochromaticity of the beams will prove critically important for some of the physics that can be done at a $\mu^+\mu^-$ collider.

  - Gaussian in shape.

  - RMS spread R in range ¡ 0.1%

  Then the rms deviation in the center-of-mass energy is

$$\sigma = (0.25\ \text{GeV}) \left(\frac{R}{0.1\%}\right) \left(\frac{\sqrt{s}}{360\ \text{GeV}}\right)$$

  – Beamstrahlung (Bremsstrahlung from beam particles in the EM field of the opposing beam) is reduced.

- Initial State Radiation (ISR)

$\Rightarrow$ possibly more precise measurements of thresholds

Threshold Processes

$\mu^+\mu^- \to W^+W^-$

- W mass
- indirect measurement of Higgs mass

$\mu^+\mu^- \to t\bar{t}$

- t mass
- α_s
- top width

$\mu^+\mu^- \to ZH$

- Higgs mass
- Higgs coupling g_{ZZH}
- Higgs width

$\mu^+\mu^- \to \tilde{\chi}^+\tilde{\chi}^-$

- chargino mass
- sneutrino mass

$\mu^+\mu^- \to W^+W^-$

Motivation:
- provides measurement of the W mass
- prediction for the Higgs boson mass
- test Standard Model at one-loop level

The W and Z masses are related by the equation

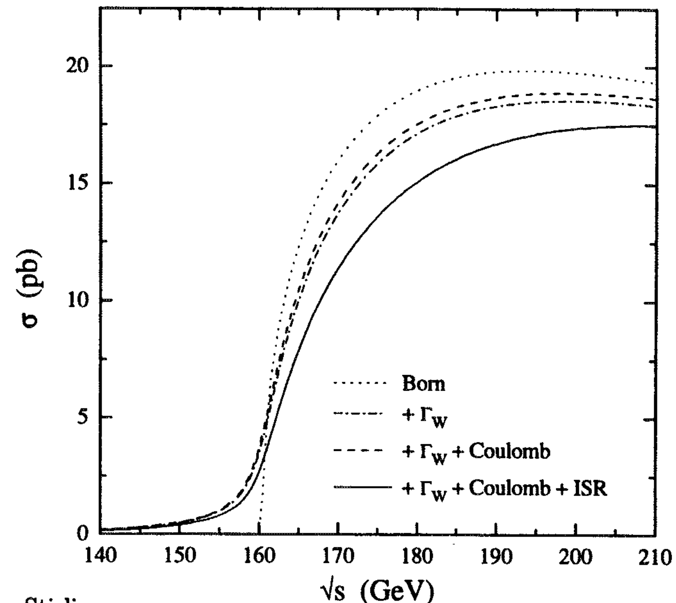
$$M_W = M_Z \left[1 - \frac{\pi\alpha}{\sqrt{2}G_\mu M_W^2(1-\delta r)}\right]^{1/2}$$

Δr is the one-loop correction: $\sim m_t^2$, $\sim \ln M_H^2$
Threshold cross section

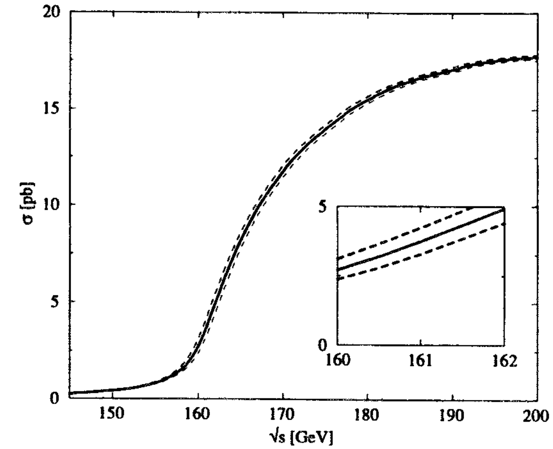
$$\sigma(s) = \int_0^s ds_1 \int_0^{(\sqrt{s}-\sqrt{s_1})^2} ds_2 \rho(s_1)\rho(s_2)\sigma_0(s,s_1,s_2)\left[1+\delta_C(s,s_1,s_2)\right]$$

σ_0: Born cross section
$\delta_C(s,s_1,s_2)$: Coulomb correction

$$\rho(s) = \frac{1}{\pi}\frac{\Gamma_W}{M_W}\frac{s}{(s-M_W^2)^2+s^2\Gamma_W^2/M_W^2}$$



Stirling



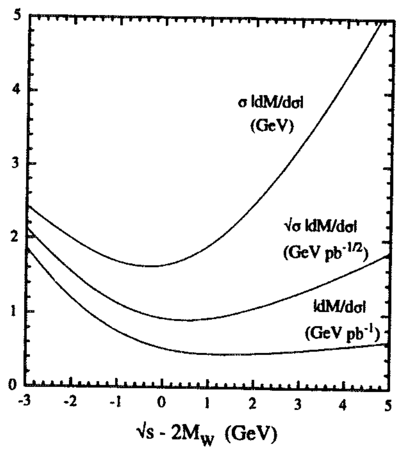
- Near threshold, σ is dominated by neutrino exchange
- At LEP II, error is dominated by statistical error
- Best determination of M_W comes from a single measurement at $\sqrt{s} = 161$ GeV

Statistical uncertainty (assuming 100% signal efficiency and no background):

$$\Delta M_W \sim 10\ \text{MeV}\sqrt{\frac{10\ \text{fb}^{-1}}{\mathcal{L}}}$$

Error on M_W

$$\Delta\sigma_{WW} = \frac{\sigma_{WW}}{\sqrt{N}} = \frac{\sqrt{\sigma_{WW}}}{\sqrt{\epsilon\mathcal{L}}}$$
$$\Delta M_W = \sqrt{\sigma_{WW}}\frac{dM_W}{d\sigma_{WW}}\frac{1}{\sqrt{\epsilon\mathcal{L}}}$$



- Maximize $\sqrt{\sigma_{WW}}\frac{dM_W}{d\sigma_{WW}}$ at $\sqrt{s} - 2M_W \approx 0.5$.

- To determine m_H, need to measure m_t, M_W (also $\alpha^{-1}(M_Z)$ and $\alpha_s(M_Z)$)

- With 100 fb^{-1} luminosity:

$$\Delta M_W \sim 10 \text{ MeV}\sqrt{\frac{10 \text{ fb}}{100 \text{ fb}}} \sim 3 \text{ MeV}$$

statistical error

- Can measure the signal to $< 1\%$ accuracy, so background level, signal efficiencies, theoretical cross section must be determined

- Devote some luminosity to measure background and efficiencies to eliminate systematic errors

$$\sqrt{s} = 150 \text{ GeV}$$

- $\alpha^{-1}(M_Z)$ measurement must be improved from $e^+e^- \to$ hadrons from 1 GeV to 5 GeV.
Known to 10% accuracy: $\Rightarrow \alpha^{-1}(M_Z) = 128.99 \pm 0.06$
If measured to 1%: $\Rightarrow \pm 0.03$

Uncertainty in the beam energy $E_{\rm beam}$:

$$\Delta M_{\rm W} = \left|\frac{d\sigma}{dM_{\rm W}}\right|^{-1} \left|\frac{d\sigma}{dE_{\rm beam}}\right| \Delta E_{\rm beam}$$

$\Delta M_{\rm W} \simeq 1.0\ \Delta E_{\rm beam}$.

Muon collider: $\Delta E_{\rm beam} < 10^{-5} E_{\rm beam}$

Uncertainty in the W width $\Gamma_{\rm W}$

$$\Delta M_{\rm W} = \left|\frac{d\sigma}{dM_{\rm W}}\right|^{-1} \left|\frac{d\sigma}{d\Gamma_{\rm W}}\right| \Delta\Gamma_{\rm W} \simeq 0.16\ \Delta\Gamma_{\rm W}$$

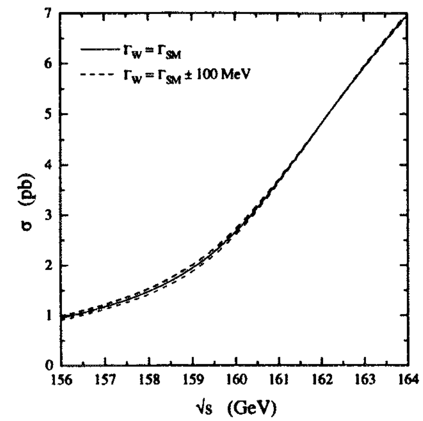
at $\sqrt{s} = 161$ GeV.

$$\Gamma_{\rm W} = 2.087 \left(\frac{M_{\rm W}}{80.356\ {\rm GeV}}\right)^3$$

$M_{\rm W} = 80.356 \pm 0.125 \Rightarrow \Delta\Gamma_{\rm W} = 10$ MeV

If one assumes the Standard Model, the W width is known to a few MeV theoretically $\Rightarrow$ impact on threshold curve is negligible (1.6 MeV).

If the W width is a free parameter, measure cross section at $\sqrt{s} =$ 162 GeV where it is independent of Γ_W



Initial State Radiation (ISR)

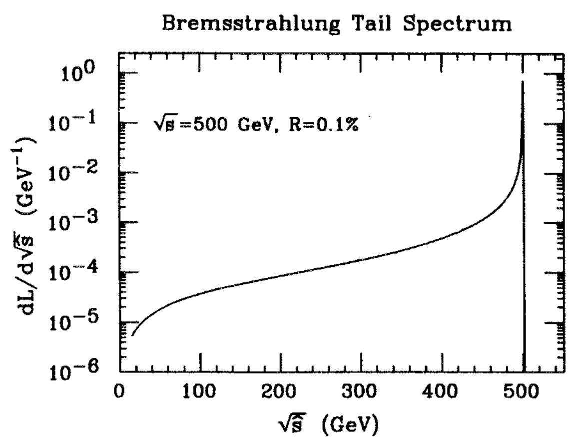
Convolute Radiator Function

$$\mathcal{D}(x) \;=\; 1+\frac{2\alpha}{\pi}(\pi^2/6-1/4)\left[\beta x^{\beta-1}\left(1+\frac{3}{4}\beta\right)-\beta\left(1-\frac{x}{2}\right)\right]$$

where

$$\beta \;=\; \frac{2\alpha}{\pi}\ln\left(\frac{s}{m_\ell^2}-1\right)$$

- ISR reduces the size of the cross section at the threshold.
- ISR is reduced for muons.



Channels:*

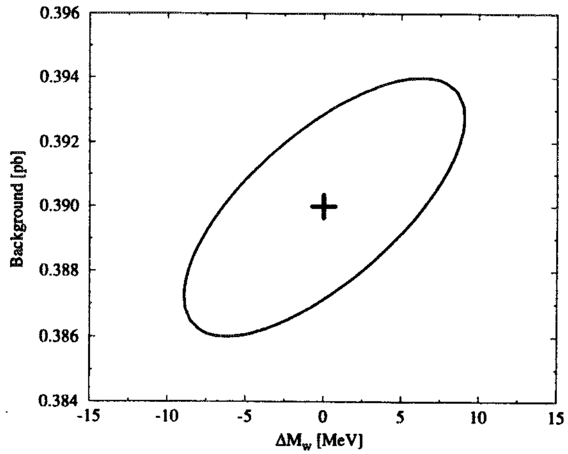
Fully hadronic channel: $WW \to q\bar{q}q\bar{q}$
Branching ratio:46%
Signal Efficiency:55%
Signal at $\sqrt{s} = 161$ GeV:0.97 pb
Background:0.39pb

Semileptonic channel: $WW \to q\bar{q}\ell\nu$
Branching ratio:43%
Signal Efficiency:47%
Signal at $\sqrt{s} = 161$ GeV:0.77 pb
Background:0.03pb

Fully leptonic channel: $WW \to \ell\nu\ell\nu$
Branching ratio:11%
Signal Efficiency:60%
Signal at $\sqrt{s} = 161$ GeV:0.25 pb
Background:0.01pb

* Signal efficiencies and backgrounds from detailed study in CERN yellow report.

An example mode: $WW \to q\bar{q}q\bar{q}$



Background $\sim 0.39pb$
$\ell^+\ell^- \to Z(\gamma)Z(\gamma)$

Divide luminosity into

- 1/3 below threshold: $\sqrt{s} = 150$ GeV
- 2/3 on the threshold: $\sqrt{s} = 161$ GeV

Signal and background cross sections for $\mu^+\mu^- \to W^+W^-$ and the achievable precision in M_W with 100 fb^{-1} luminosity. A central mass value $M_W = 80.356$ GeV is assumed.

	$q\bar{q}q\bar{q}$	$q\bar{q}\ell\nu$	$\ell\nu\ell\nu$
Signal [pb] at $\sqrt{s} = 161$ GeV	0.97	0.77	0.25
Signal [pb] at $\sqrt{s} = 150$ GeV	0.11	0.086	0.028
Background [pb]	0.39	0.03	0.01
ΔM_W [MeV]	9	8	14

Combined precision: $\Delta M_W = 6$ MeV

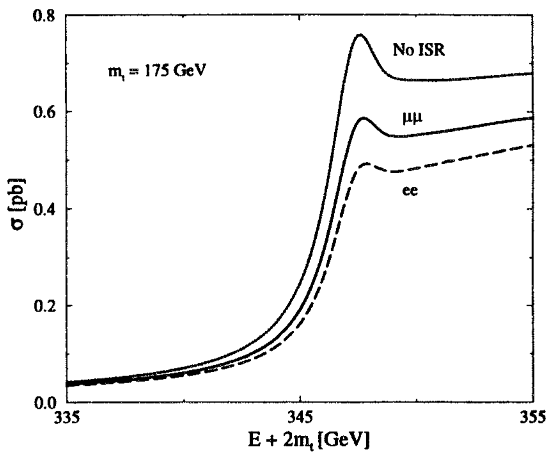
Unconstrained W width

TeV-2000 Group Report:
$\Delta\Gamma_W \simeq 20$ MeV$\Rightarrow$ $\Delta M_W = 3$ MeV.

Take data at $\sqrt{s} = 162$ GeV.

Take data at additional $\sqrt{s} \Rightarrow$ measure Γ_W

$\ell^+\ell^- \to t\bar{t}$



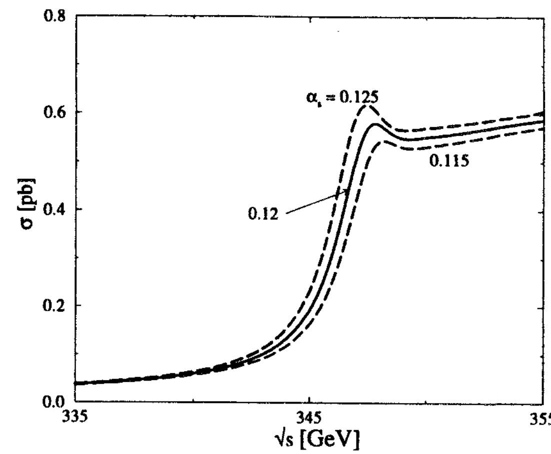
$$\left[-\frac{\Delta}{m_t} + V(r) - \left(E + i\frac{\Gamma_\Theta}{2}\right)\right] G(\mathbf{x}; E) = \delta^3(\mathbf{x})$$

where Γ_Θ is the (running) toponium width, and $E = \sqrt{s} - 2m_t$.

$$\sigma_{t\bar{t}} = \frac{96\pi^2\alpha^2}{s^2}\left\{1 - \frac{16\alpha_s}{3\pi}\right\}[(Q_eQ_t + v_ev_t\chi)^2 + (a_e^2v_t^2\chi^2)]$$
$$\times \mathrm{Im}\ G(\mathbf{x}=0; E=\sqrt{s}-2m_t)$$

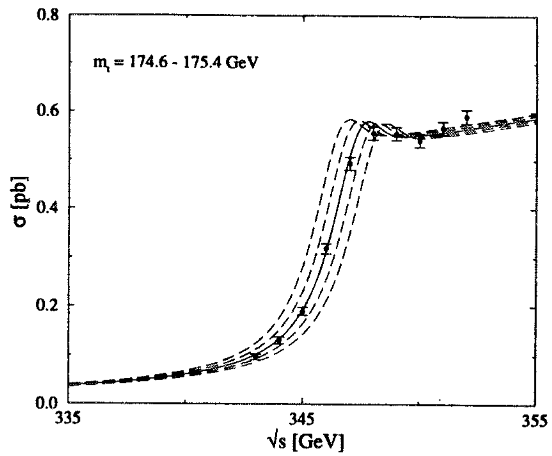
where $\chi = s/(s - M_Z^2)$.

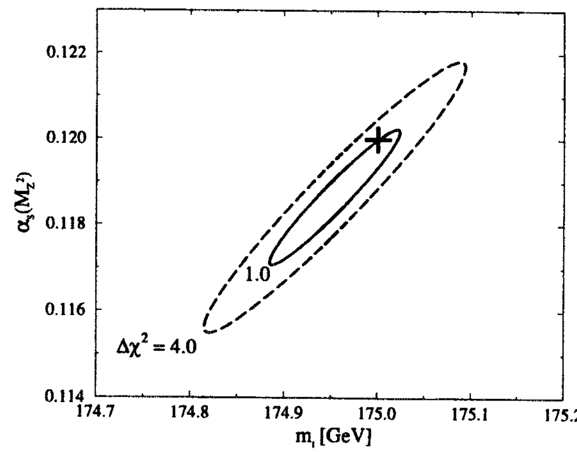
Dependence on the strong coupling $\alpha_s(M_Z)$



- Larger $\alpha_s \Rightarrow$ tighter binding
- Larger $\alpha_s \Rightarrow$ larger cross section

10 point scan

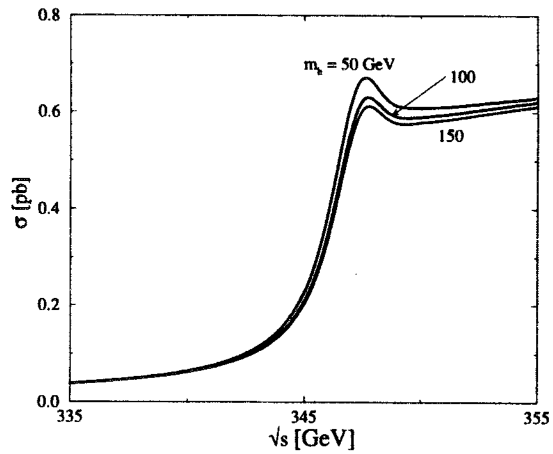




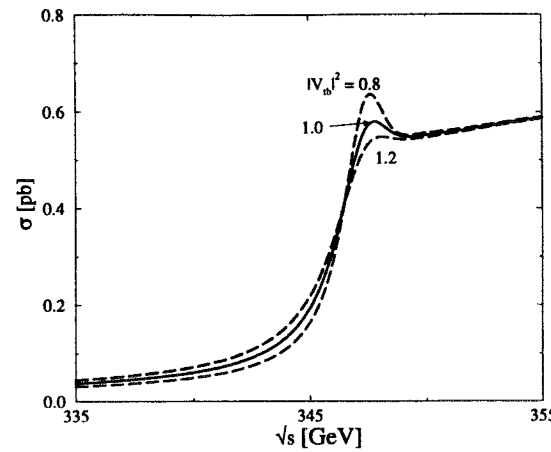
- Can't measure all undetermined variables at a single energy
- Scan can be optimized
- 10 fb^{-1} at 10 pts.
- Nominal values: $m_t = 175$ GeV, $\alpha_s(M_Z) = 0.120$

- $\Delta m_t \sim 70$ MeV, $\Delta\alpha_s \sim 0.0015$
- Theoretical ambiguity in the pole mass $\sim \Lambda_{QCD}$

Dependence on m_h

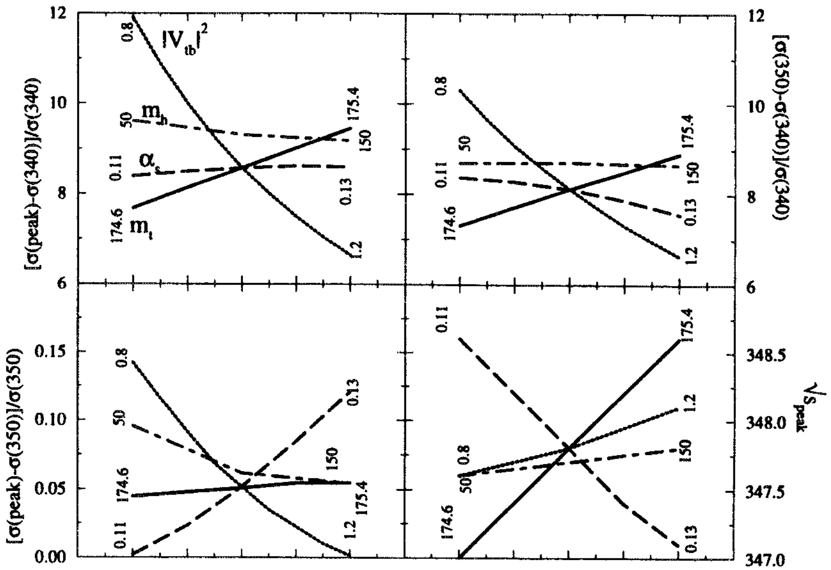


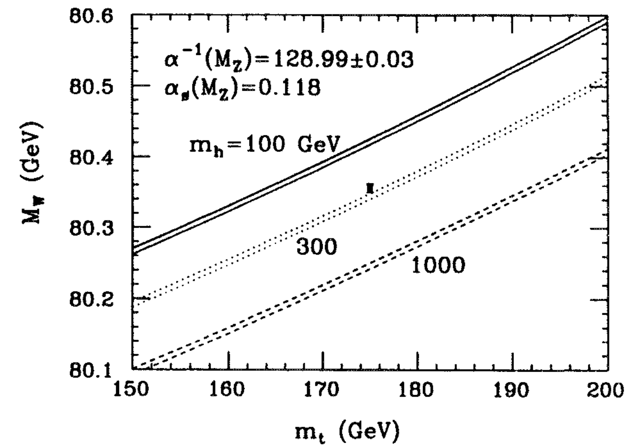
Top quark width



- Higgs mass
- Yukawa coupling

$M_W = 80.356 \pm 0.006$ GeV, $m_t = 175 \pm 0.2$ GeV,
+ improvement in $\alpha^{-1}(M_Z)$



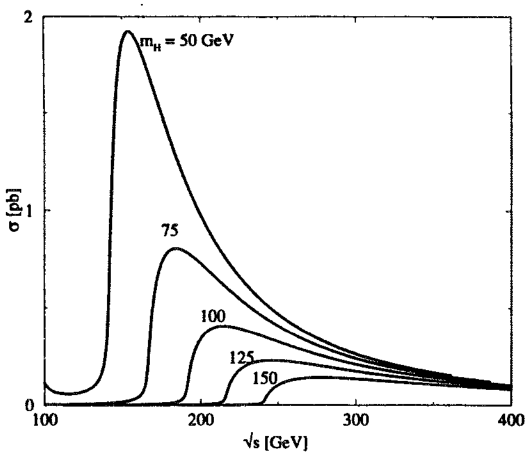


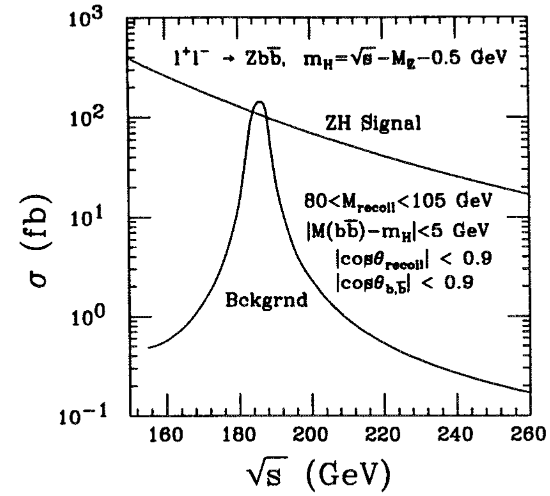
Comparison for the achievable precision in M_W and m_t measurement at different future colliders.

	LEP2		Tevatron		LHC	NLC	$\mu^+\mu^-$	
$\mathcal{L}$ (fb^{-1})	0.1	2	2	10	10	50	10	100
ΔM_W (MeV)	144	34	35	20	15	20	20	6
Δm_t (GeV)	–	–	4	2	2	0.2	0.2	0.07

a) $[\sigma(\text{peak}) - \sigma(340)]/\sigma(340)$
b) $[\sigma(350) - \sigma(340)]/\sigma(340)$
c) $[\sigma(\text{peak}) - \sigma(350)]/\sigma(350)$
d) $\sqrt{s}_{\text{peak}}$

$\ell^+\ell^- \to ZH$ (Bjorken process)





- $\sqrt{s} = m_H + M_Z + 0.5$ GeV: single measurment to maximize statistical significance
- ISR + beam effects
- Error in Z width (7 MeV) is negligible;Higgs width potentially measurable.

Cuts:

1) tagging of both b's in the event (for which an overall 50% efficiency will be assumed)

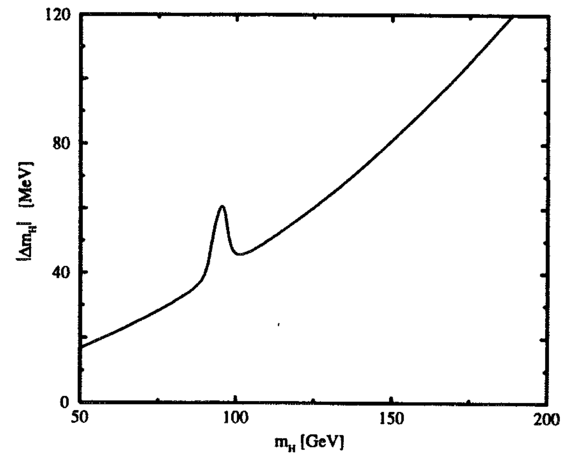
2) $|M_{b\bar{b}} - M_{\rm H}| < 5$ GeV

3) $80 < M_{\rm recoil} < 105$ GeV

4) $|\cos\theta_{b,\bar{b},{\rm recoil}}| < 0.9$ (detector coverage)

Remaining background: $\ell^+\ell^- \to Zb\bar{b}$ only a problem for $m_H \approx M_Z$

Mass determination in the Standard Model



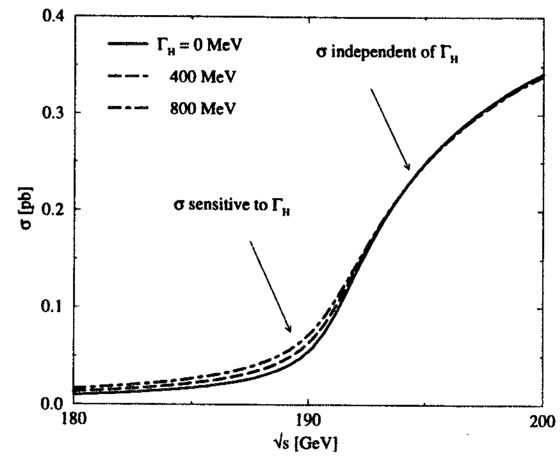
Include ISR & and beam smearing:

$$R_\mu \; = \; 0.1\%$$

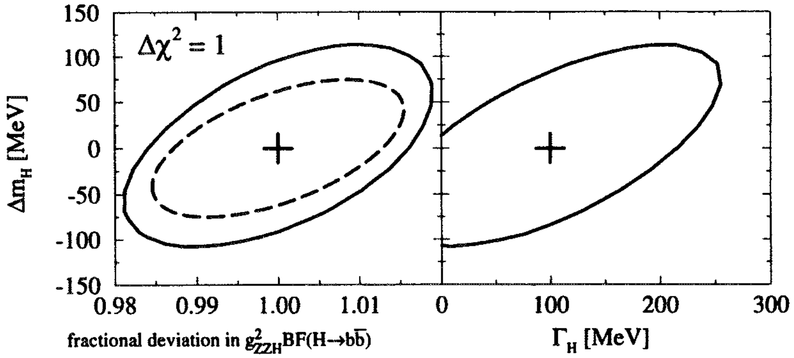
- Z-pole
- Precision degrades with larger m_H

Beyond SM:

Unknown $g^2_{ZZH} BF(H \to b\bar{b}) \Rightarrow \sqrt{s} = m_H + M_Z + 20$ GeV
Unknown Higgs width $\Gamma_H \Rightarrow \sqrt{s} = m_H + M_Z - 2$ GeV



Negligible Γ_H: $\sqrt{s} = m_H + M_Z + 0.5, +20$ GeV
Γ_H as free parameter: $\sqrt{s} = m_H + M_Z - 2.0, +0.5, +20$ GeV

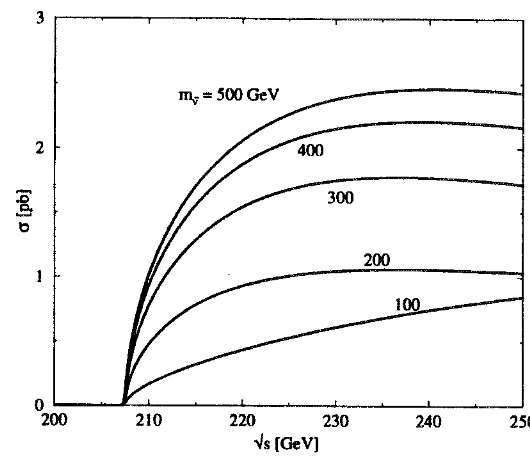


- Higgs width small $\Rightarrow$ 50 fb^{-1} at each
  $\sqrt{s} = m_H + M_Z + 0.5, +20$ GeV
  $\Delta M_H = 75$ MeV, $g^2_{ZZH} BF(H \to b\bar{b})$ to 1.5%
- Higgs width undetermined $\Rightarrow \frac{100}{3}$ fb^{-1} at each
  $\sqrt{s} = m_H + M_Z - 2.0, +0.5, +20$ GeV
  $\Delta M_H = 110$ MeV, $g^2_{ZZH} BF(H \to b\bar{b})$ to 2.0%, $\Gamma_H < 250$ MeV

$\mu^+\mu^- \to \tilde{\chi}_1^+ \tilde{\chi}_1^-$

Motivation:
- provides measurement of the $\tilde{\chi}_1^\pm$ mass

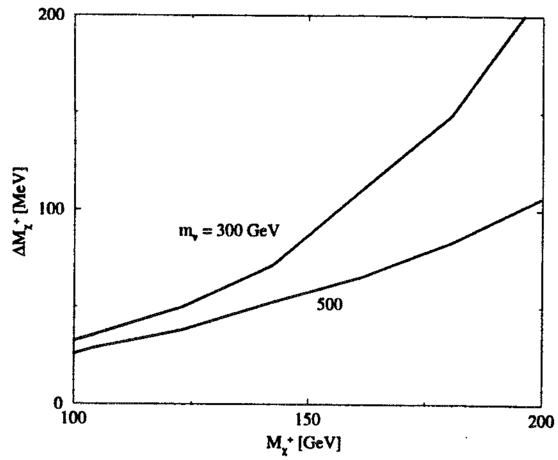
- test radiative correction to chargino pair production



More stringent cuts (than required at a $\sqrt{s}$ = 500 GeV) are needed because
- signal cross section is smaller near threshold

- WW pair production is less forward-backward peaked

- The sneutrino mass can be determined to a few GeV with 100 fb^{-1} integrated luminosity.



- Cross section depends on $m_{\tilde{\chi}_1^\pm}$ and $m_{\tilde{\nu}_\mu}$.
- Sneutrino graphs destructively interfere with the s-channel graphs.
- The sneutrino mass can be determined to a few GeV with 100 fb^{-1} integrated luminosity.

Conclusions:

1) Precise measurements of particle masses is possible:

$\Delta M_W \sim 6$ MeV

$\Delta m_t \sim 70$ MeV

$\Delta m_H \sim 20 - 100$ MeV for $m_H < 150$ GeV

$\Delta m_{\tilde{\chi}} < 350$ MeV

2) Measure particle widths:

$\Delta\Gamma_W \sim 36$ MeV

$\Delta\Gamma_t \sim 1\%\Gamma_t$

$\Delta\Gamma_H \sim 100$ MeV

3) Measure couplings

α_s

$g^2_{ZZH} BF(H \to b\bar{b})$

4) Constraints on SM Higgs ($\Delta m_H = 10$ MeV for $m_H = 100$ GeV) or virtual effects.

Top Physics at a Polarized Muon Collider

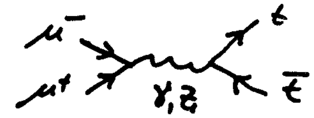
(above threshold)

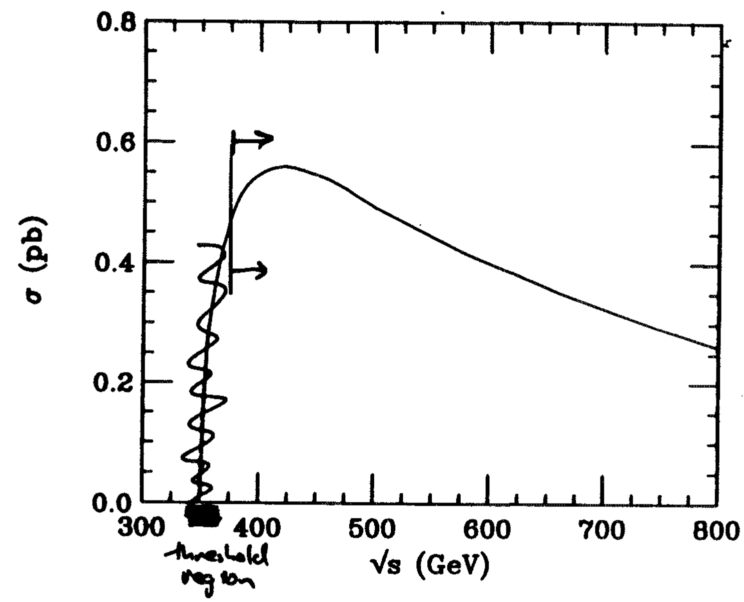
Stephen Parke
— FNAL
μμ97

- Introduction
- $\frac{d\sigma}{d\cos\theta^*}$, spin correlations
- Polarized Beams
- Angular Correlations of Decay Products (with spin direction)
- Discussion + Conclusions

S.P. + Y. Shadmi
Phys Lett B380, 199 (1996)

$\mu^+\mu^- \to t\bar{t}$





$$\sigma = (\text{const}) \frac{\beta}{S} \underset{\text{approx. const}}{f(\beta)}$$

maximum of $\beta(1-\beta^2)$ is at $\beta = \frac{1}{\sqrt{3}} \sim 0.58$

$$\sqrt{s} \sim 430 \text{ GeV}$$

$\mathcal{L} = 3\times10^{32}\ cm^{-2}\,s^{-1}$ $\sigma_{pk} = 0.5\ pb$

$N_{ev} = 1500$ / snowmass yr ($3\ fb^{-1}$)

Check Standard Model Couplings
+ search for anomalous couplings

Why? — no hadronization
Spin preserved from production to decay

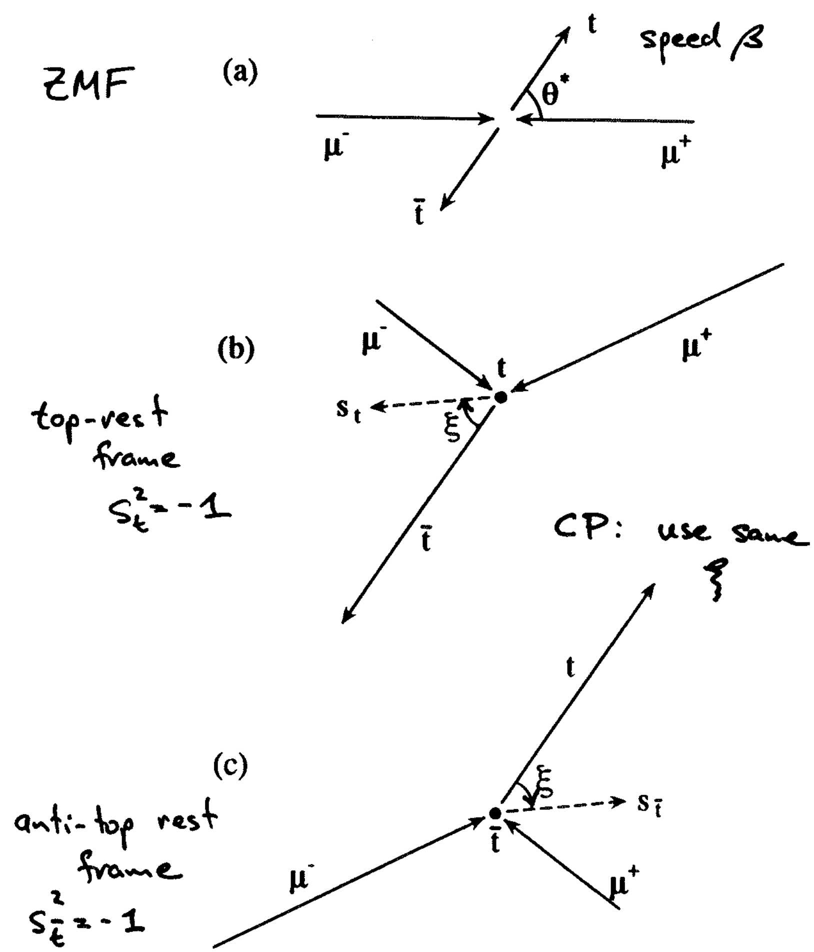
$$\frac{\Lambda^2_{QCD}}{m_t} \ll \Gamma_t \sim 1.5\ \text{GeV}$$

- In Production: Couplings to γ, Z
  σ, $\frac{d\sigma}{d\cos\theta^*}$, spin correlations between $t, \bar{t}$

- In Decay: couplings to W-boson
  angular correlations of decay products with spin direction of t and $\bar{t}$

- Search for new particles in production + decay
  ($\mu^+\mu^- \to X \to t\bar{t}$) ($t \to H^+ b$)

NOTATION + FRAMES:



CROSS SECTION for $\mu^-\mu^+ \to t\bar{t}$

$$\frac{d\sigma}{d\cos\theta^*}\left(\mu_L^-\mu_R^+ \to t_\uparrow \bar{t}_\uparrow \text{ or } t_\downarrow \bar{t}_\downarrow\right) = \frac{3\pi\alpha^2}{2s}\beta\left|A_{LR}\cos\xi - B_{LR}\sin\xi\right|^2$$

$$\frac{d\sigma}{d\cos\theta^*}\left(\mu_L^-\mu_R^+ \to t_\uparrow \bar{t}_\downarrow \text{ or } t_\downarrow \bar{t}_\uparrow\right) = \frac{3\pi\alpha^2}{2s}\beta\left|A_{LR}\sin\xi + B_{LR}\cos\xi \pm D_{LR}\right|^2$$

$$A_{LR} = (f_{LL}+f_{LR})\sqrt{1-\beta^2}\,\sin\theta^*/2$$

$$B_{LR} = \left[f_{LL}(\cos\theta^*+\beta) + f_{LR}(\cos\theta^*-\beta)\right]/2$$

$$D_{LR} = \left[f_{LL}(1+\beta\cos\theta^*) + f_{LR}(1-\beta\cos\theta^*)\right]/2$$

$$f_{IJ} = Q_\gamma(e)\,Q_\gamma(t) + \frac{Q_Z^I(e)\,Q_Z^J(t)}{\sin^2\theta_W}\cdot\frac{s}{(s-M_Z^2)^2+iM_Z\Gamma_Z}$$

$I,J \in (L,R)$

$s \gg M_Z^2$

for top

$f_{LL} = -1.19$, $f_{LR} = -0.434$, $f_{RR} = -0.868$

$f_{RL} = -0.217$

Couplings:

$Q_\gamma = Q$

$$Q_Z^L(f) = \frac{T_3 - Q\sin^2\theta_W}{\cos\theta_W}$$

$$Q_Z^R(f) = -\frac{Q\sin^2\theta_W}{\cos\theta_W}$$

Q is electric charge; $Q_\gamma(e) = -1$, $Q_\gamma(t) = 2/3$

$T_3 = +\frac{1}{2}$ ν's, up quarks (t)

$T_3 = -\frac{1}{2}$ charged leptons, down quarks (e)

$\mu_R^-\mu_L^+ \to t\bar{t}$

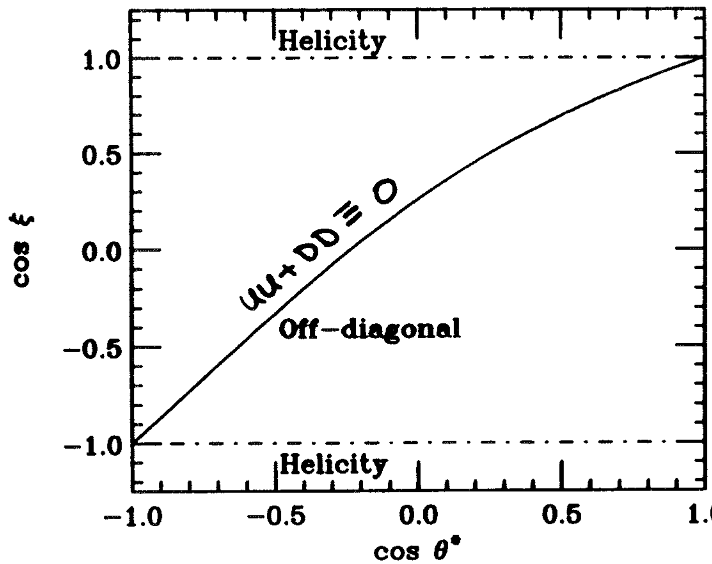
($L \leftrightarrow R$ and $\uparrow \leftrightarrow \downarrow$)

<u>useful identity</u>

$$\frac{1+\gamma_5 \not{s}}{2}\,u(P) = \frac{1+\gamma_5}{2}\,u\!\left(\frac{P+Ms}{2}\right) + e^{i\phi}\,\frac{1-\gamma_5}{2}\,u\!\left(\frac{P-Ms}{2}\right)$$

massless; known phase; L chirality; massless spinor

$\sqrt{s} = 400$ GeV



helicity $\cos\xi = \pm 1$

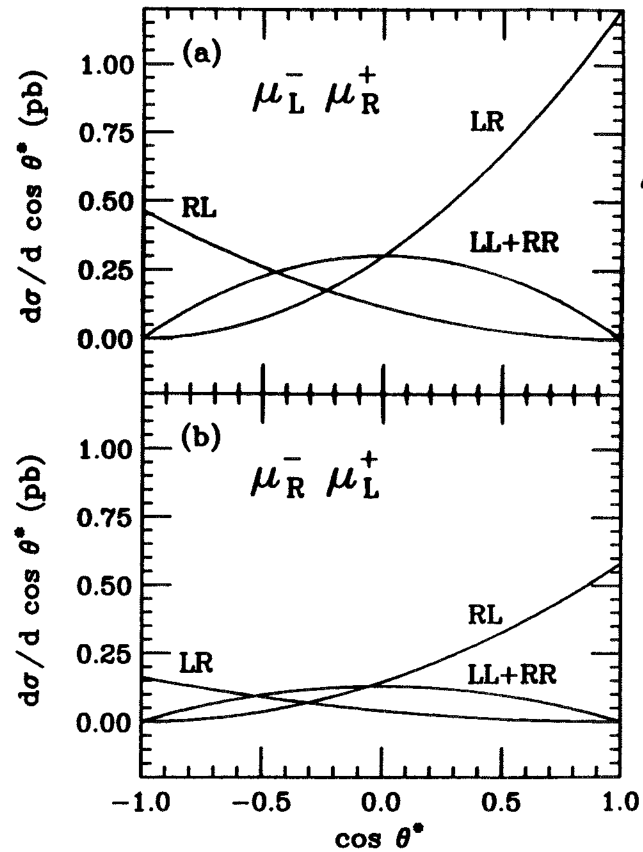
Off-Diagonal

$$\tan\xi = \frac{(f_{LL} + f_{LR})\sqrt{1-\beta^2}\,\sin\theta^*}{f_{LL}(\cos\theta^* + \beta) + f_{LR}(\cos\theta^* - \beta)}$$

$$\begin{pmatrix} uu & uD \\ Du & DD \end{pmatrix} = \begin{pmatrix} 0 & \Delta \\ \delta & 0 \end{pmatrix} \quad \text{for all } \beta$$

$\beta = 0$ $\tan\xi = \tan\theta^*$ along beamline

$\sqrt{s} = 400$ GeV



1.5 pb

LR : 52%

LL+RR : 27%

RL : 21%

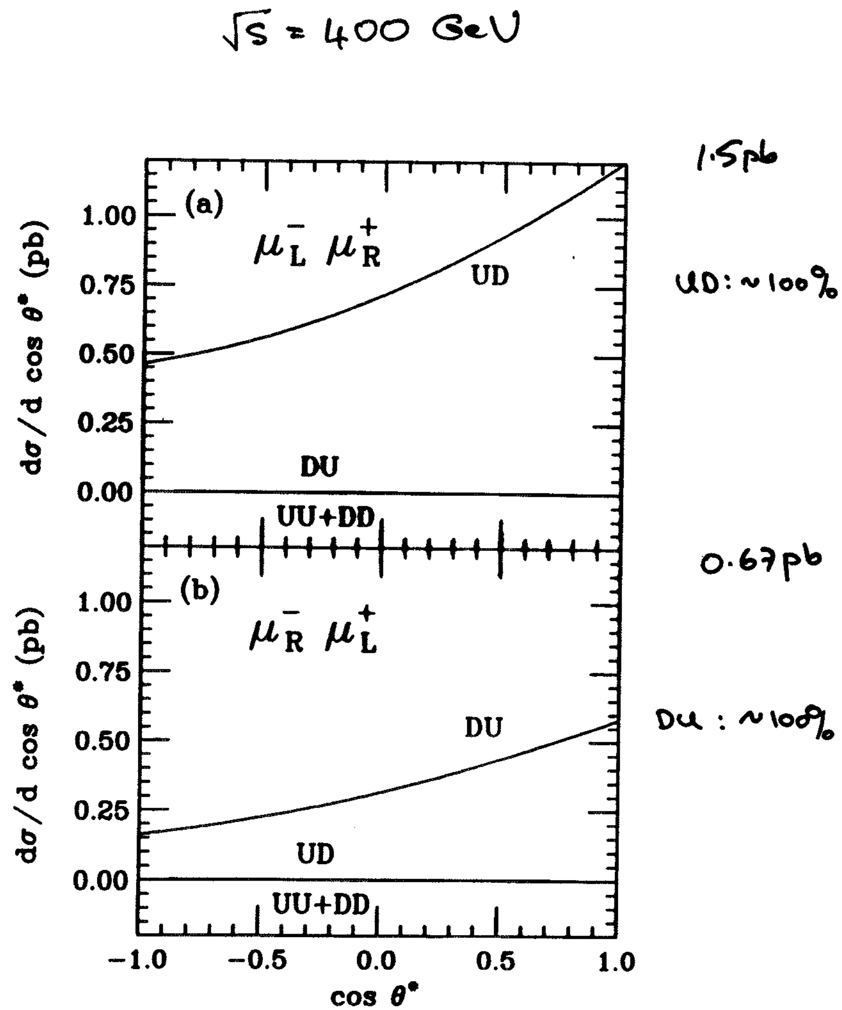
0.67 pb

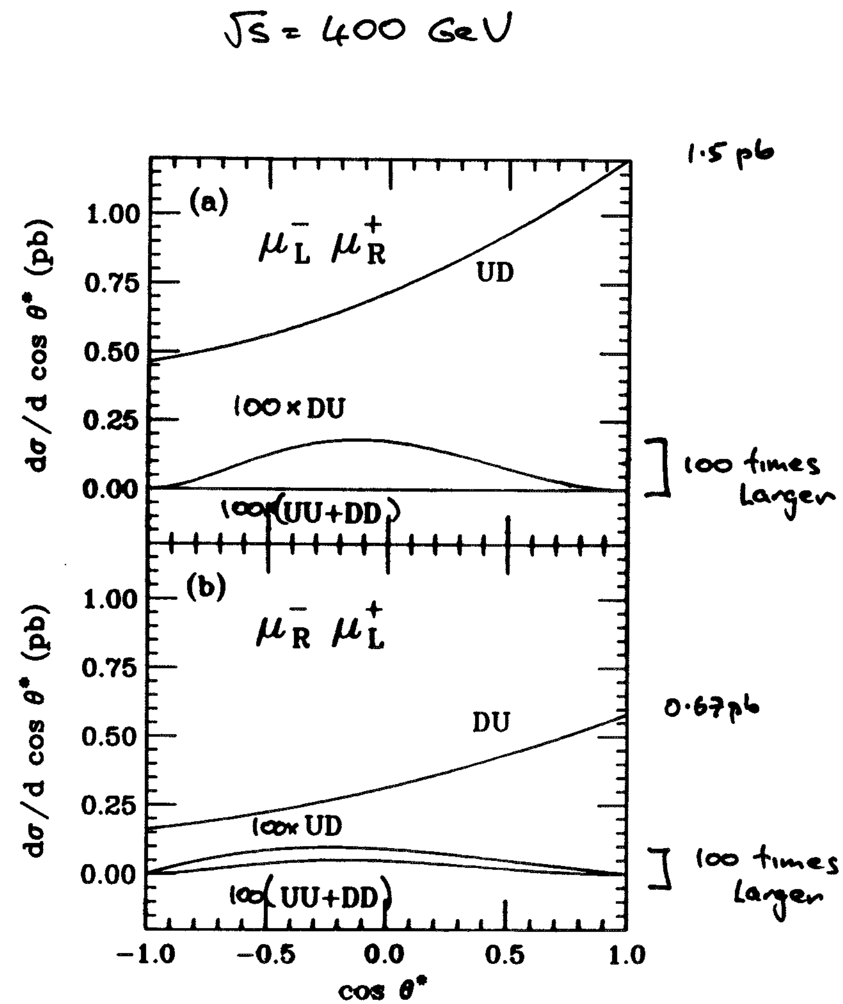
RL : 57%

LL+RR : 26%

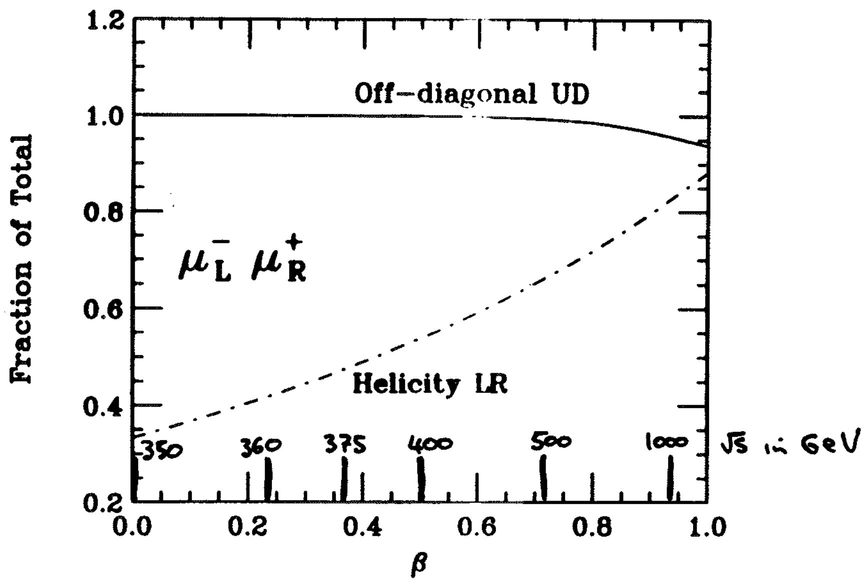
LR : 16%

Peskin + Schmidt


√s = 400 GeV
1.5pb
(a)
$\mu^-_L \ \mu^+_R$
UD
UD: ~100%
DU
UU+DD
0.67pb
(b)
$\mu^-_R \ \mu^+_L$
DU
DU : ~100%
UD
UU+DD
dσ/d cos θ* (pb)
cos θ*
1.00
0.75
0.50
0.25
0.00
−1.0
−0.5
0.0
0.5
1.0


√s = 400 GeV
1.5 pb
(a)
$\mu^-_L \ \mu^+_R$
UD
100×DU
100 times Larger
100×(UU+DD)
(b)
$\mu^-_R \ \mu^+_L$
DU
0.67pb
100×UD
100 times Larger
100(UU+DD)
dσ/d cos θ* (pb)
cos θ*
1.00
0.75
0.50
0.25
0.00
−1.0
−0.5
0.0
0.5
1.0

$M_t = 175$ GeV

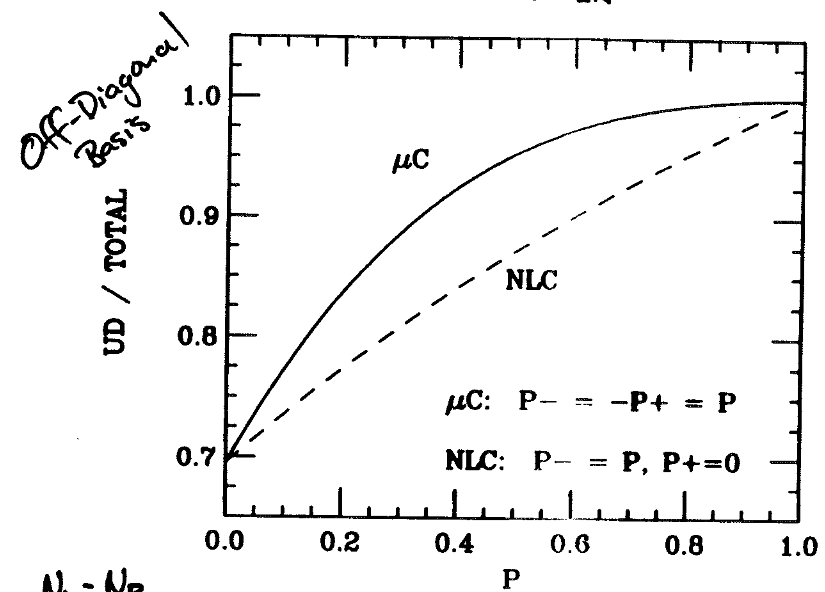


$$\frac{UD}{TOTAL} = \frac{(1+P^-)(1-P^+)\,\sigma_{LR}}{(1+P^-)(1-P^+)\,\sigma_{LR} + (1-P^-)(1+P^+)\,\sigma_{RL}}$$

POLARIZED BEAMS

$\sqrt{s} = 400$ GeV $\quad \sigma_{RL}/\sigma_{LR} = 0.44$

Off-Diagonal Basis



$$P = \frac{N_L - N_R}{N_L + N_R}$$

μC	NLC	UD/TOTAL
0	0	0.69
0.20	0.40	0.84
— 0.30	0.55	0.89 —
0.50	0.80	0.95

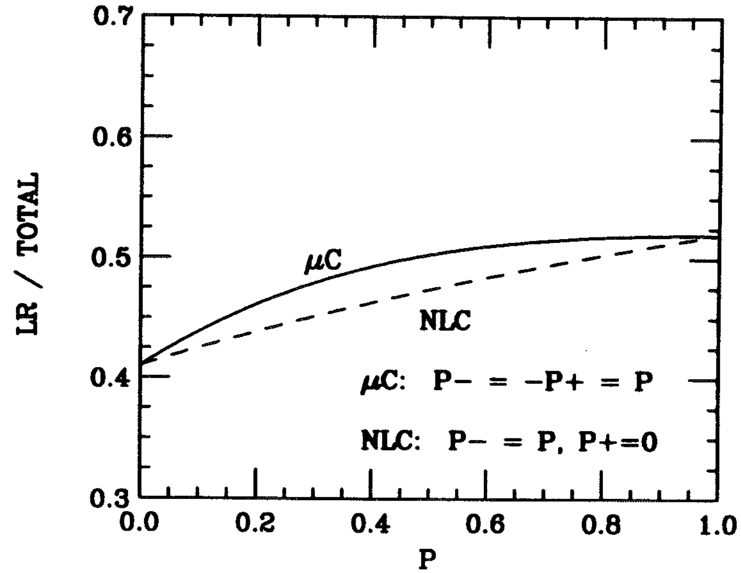
in helicity basis

$$\frac{LR}{TOTAL} = 0.52 \quad \text{at } P^- = 1$$

otherwise smaller.

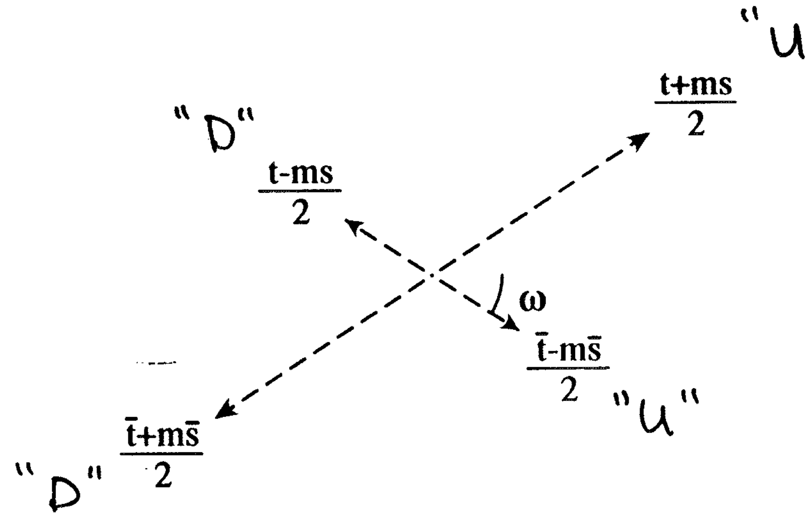
RL ... ...

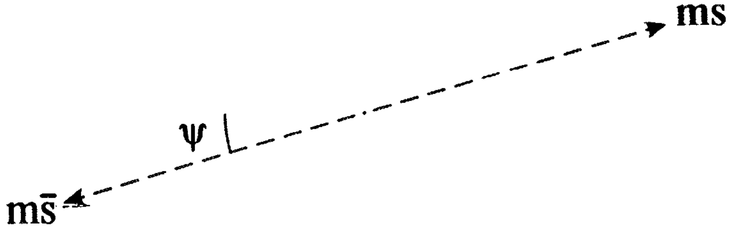
Helicity Basis

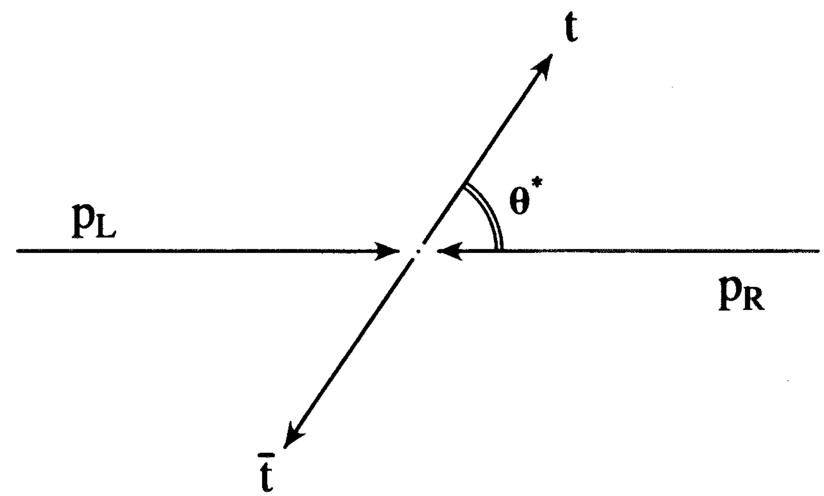


$t \to b\, e^+ \nu$
$\quad\;\; b\, \bar{d}\, u$

↑ highly correlated with t-spin

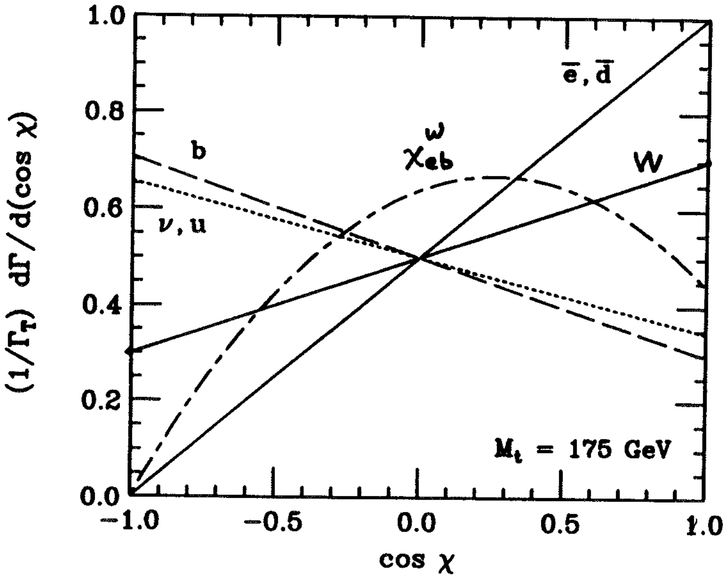


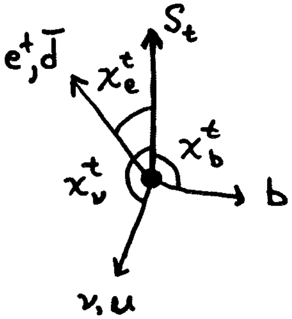


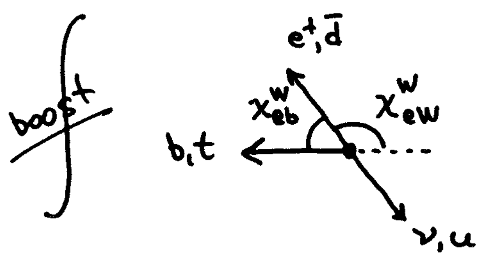


zero momentum frame
($\beta_t = 0.6$)

One Particle Correlations:





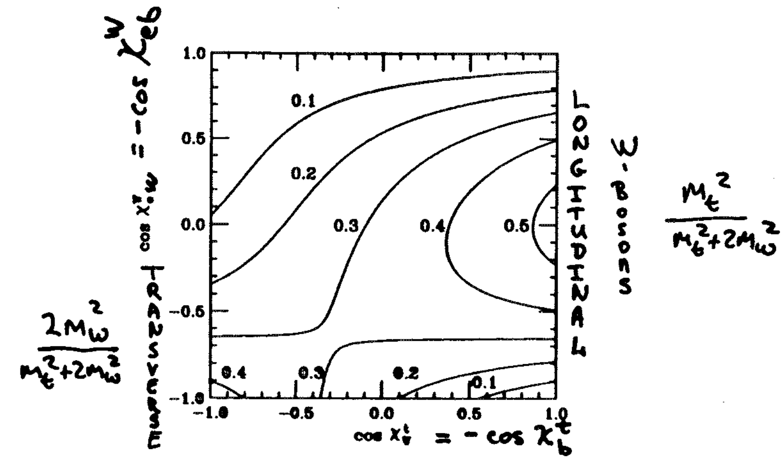


top rest frame

W-boson rest frame

TWO PARTICLE CORRELATIONS:

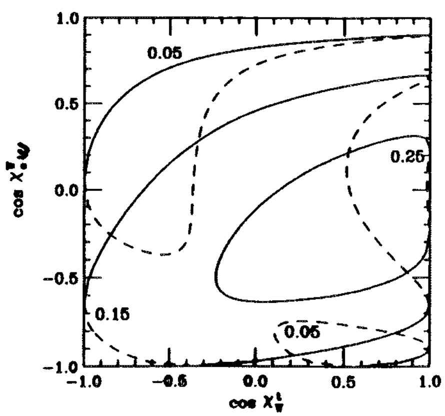
contours of $\frac{1}{\Gamma_T} \frac{d^2\Gamma}{d\cos\chi^t_W \; d\cos\chi^W_{eW}}$



Longitudinal-Transverse Interference

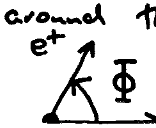
—— $\cos\Phi > 0$

- - - - $\cos\Phi < 0$

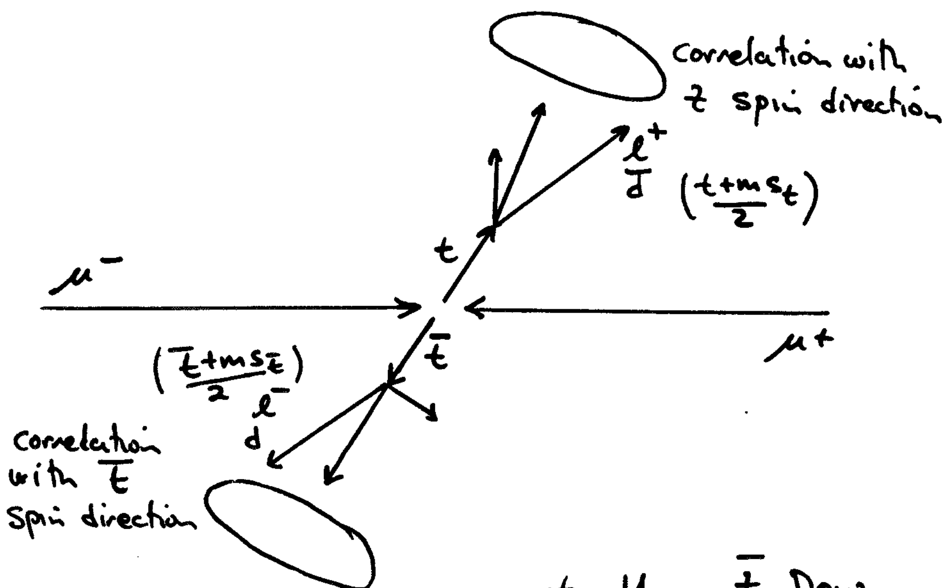


Φ azimuthal angle between e^+($\bar{d}$) direction of motion and top-quark spin around the direction of motion of W-boson.

If W-boson is



Theorist's Cartoon:



t Up $\bar{t}$ Down

t Down $\bar{t}$ Up

Discussion:

* QCD corrections – spin dependent

$$|M(\mu^+\mu^- \to t_\uparrow \bar{t}_\downarrow g)|^2 \xrightarrow[E_g \to 0]{}$$

$$\left(\begin{matrix}\text{eikonal} \\ \text{factor}\end{matrix}\right) |M(\mu^+\mu^- \to t_\uparrow \bar{t}_\downarrow)|^2$$

$$\text{eikonal factor} = \frac{t \cdot \bar{t}}{t \cdot g \; \bar{t} \cdot g} - \frac{m_t^2}{(2t \cdot g)^2} - \frac{m_t^2}{(2\bar{t} \cdot g)^2}$$

Soft gluons do not flip top spin.

QCD corrections on $\frac{UD}{TOTAL}$ small. Kodaira, Nasuno + S.P.

* Anomalous Couplings

helicity basis – done
Off-Diagonal basis – needed

} ref: ✯

Conclusions:

Top quark pairs above the threshold region at muon colliders are a great place to search for anomalous couplings of the top quark.

For $\sqrt{s} < 1\,\text{TeV}$ the Off-Diagonal basis is far superior to helicity basis in describing the events in their simpliest possible terms. Polarization of the incoming beams enhances this effect.

Detailed studies of the QCD corrections as well as the effects of anomalous couplings are needed in the Off-Diagonal basis.

HEAVY SUPERSYMMETRY AT A HIGH-ENERGY MUON COLLIDER

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

Collaborators: Barger, Berger, Carena, Han, Kelly

OUTLINE OF TOPICS

- Cross Sections for SUSY pairs
- Cross Sections for given final state, and contributing pairs
- Techniques for determining SUSY-GUT parameters: errors

First question: **Is SUSY heavy?**

- There is no guarantee that SUSY will be light.
- Naturalness allows SUSY masses of order a TeV.
- Fine tuning constraints that point to a lower mass scale are somewhat adhoc, and certainly allow heavy $\tilde{u}, \tilde{d}$.
- Increasing restrictions from low energy data and rare decays (e.g. $b \to s\gamma$) are pushing up the mass scale.
- Gauge coupling unification is best (i.e. 'low' $\alpha_s(m_Z)$) for $m_{SUSY} \gtrsim$ 1 TeV.

Why the muon collider?

While the LHC will discover SUSY even if masses are $\gtrsim$ 1 TeV, backgrounds and low event rates may make *detailed study* difficult.

A lepton collider with $\sqrt{s} \gtrsim 2$ TeV may be necessary to study heavy SUSY. In fact, for $m_{SUSY} \sim 1$ TeV, the β^3 p-wave threshold suppression factor for scalar pair states suggests a need for much higher energies. The muon collider may be the only lepton collider capable of reaching the required energies.

Sample scenarios:

A representative choice of parameters illustrating the power of a $\mu^+\mu^-$ collider is:

$$m_0 = 2m_{1/2} = 500 \text{ GeV}, \quad \tan\beta = 2, \quad A_0 = 0, \quad \mu < 0\,. \tag{0.1}$$

Large $m_0/m_{1/2} = 2 \Rightarrow$ heavy scalars compared to gauginos. The particle and sparticle masses obtained from renormalization group evolution are:

$$m_{h^0} = 88 \text{ GeV}, \quad m_{A^0} = 921 \text{ GeV}\,, \tag{0.2}$$

$$m_{H^\pm} = m_{H^0} = 924 \text{ GeV}\,, \tag{0.3}$$

$$m_{\tilde{q}_L} \simeq 752 \text{ GeV}, \quad m_{\tilde{q}_R} \simeq 735 \text{ GeV}\,, \tag{0.4}$$

$$m_{\tilde{b}_1} = 643 \text{ GeV}, \quad m_{\tilde{b}_2} = 735 \text{ GeV}\,, \tag{0.5}$$

$$m_{\tilde{t}_1} = 510 \text{ GeV}, \quad m_{\tilde{t}_2} = 666 \text{ GeV}\,, \tag{0.6}$$

$$m_{\tilde{\nu}} \sim m_{\tilde{l}} \sim 510 - 530 \text{ GeV}\,, \tag{0.7}$$

$$m_{\tilde{\chi}^0_{1,2,3,4}} = 107, 217, 605, 613 \text{ GeV}\,, \tag{0.8}$$

$$m_{\tilde{\chi}^+_{1,2}} = 217, 612 \text{ GeV}\,. \tag{0.9}$$

Pair production of heavy scalars is only accessible at a high energy machine.

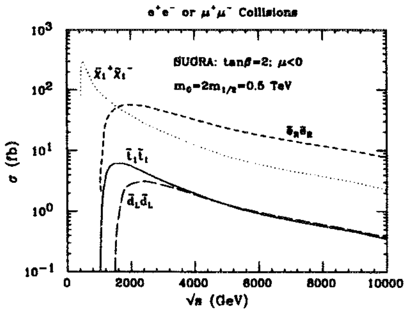


Figure 1: The production cross sections for SUSY particles in a typical supergravity model with heavy scalars.

Another scenario: $m_0 = 500$ GeV, $m_{1/2} = 350$ GeV, $\tan\beta = 2$ and $\mathrm{sign}(\mu) = -$. We show the $\tilde{\nu}_L\tilde{\nu}_L$, $\tilde{\mu}_L\tilde{\mu}_L$, $\tilde{\mu}_L\tilde{\mu}_R$ and $\tilde{\mu}_R\tilde{\mu}_R$ cross sections. For $\tilde{\mu}_L\tilde{\mu}_L$ and $\tilde{\mu}_R\tilde{\mu}_R$ note big cancellation between s-channel γ, Z diagram and t-channel $\widetilde{\chi}_1^0$ diagram.

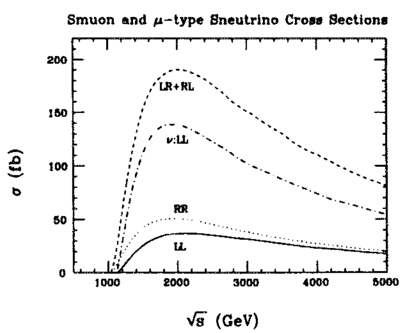


Figure 2: The production cross sections for $\tilde{\mu}$ and $\tilde{\nu}_\mu$ pairs in an mSUGRA model with $m_0 = 500$ GeV, $m_{1/2} = 350$ GeV, $\tan\beta = 2$ and $\mathrm{sign}(\mu) = -$.

Scaling law: $\sigma_{\rm max}$ occurs at $4m_0$ for scalars.

The question is: **how well will a high energy muon collider be able to study a heavy SUSY scenario?**

In particular,

- How well can we determine soft-SUSY-breaking parameters at a very high $\sqrt{s}$ muon collider? Especially, **simply running at maximum machine energy.**
  - **45 different sparticle pairs have significant σ.**

$$\tilde{e}_L^+\tilde{e}_L^-,\quad \tilde{e}_R^+\tilde{e}_R^-,\quad \tilde{\nu}_{eL}\overline{\tilde{\nu}}_{eL},\quad \widetilde{\mu}_L^+\widetilde{\mu}_L^-,\quad \widetilde{\mu}_R^\pm\widetilde{\mu}_L^\mp,\quad \widetilde{\mu}_R^+\widetilde{\mu}_R^-,\quad \tilde{\nu}_{\mu L}\overline{\tilde{\nu}}_{\mu L}$$

$$\tilde{\tau}_1^+\tilde{\tau}_1^-,\quad \tilde{\tau}_1^\pm\tilde{\tau}_2^\mp,\quad \tilde{\tau}_2^+\tilde{\tau}_2^-,\quad \widetilde{\chi}_i^0\widetilde{\chi}_j^0\ (\text{all } i,j),\quad \widetilde{\chi}_i^+\widetilde{\chi}_j^-\ (\text{all } i,j)$$

$$\tilde{q}_L\overline{\tilde{q}}_L, \tilde{q}_R\overline{\tilde{q}}_R\ (q = u,d,c,s),\quad \tilde{b}_{1,2}\overline{\tilde{b}}_{1,2},\quad \tilde{t}_{1,2}\overline{\tilde{t}}_{1,2}$$

$$h^0A^0, H^0A^0, H^+H^-$$

  - **$\Rightarrow$ contributions to many overlapping channels.**
  - **How to organize? = List of observables.**

(A) Look at the number of events in channels with large missing energy specified by the numbers of:

$$(t, b, j, e^-, e^+, \mu^-, \mu^+, \tau^-, \tau^+, h^0, Z, W^+, W^-)$$

where the t, Z, W is called a t, Z, W only if it is hadronically reconstructable. (Note W^+ and W^- not actually distinguishable in jet modes, but we separate for now.)

(B) End points of lepton spectra, and other kinematic distributions.

– **Parameters to be probed:**

* M_1, M_2, $\tan\beta$, m_{A^0}, $\mu \Rightarrow 5$.
* $A_t, A_b, A_\tau \Rightarrow 3$.
* $m_{\tilde{\ell}_L}$, $m_{\tilde{\ell}_R}$, $m_{\tilde{q}_L}$, $m_{\tilde{u}_R}$, $m_{\tilde{d}_R}$ $\times$ 3 families $\Rightarrow$ 15.

$\Rightarrow$ 23 parameters, 21 if we assume $e-\mu$ universality, 19 if we assume $e-\mu-\tau$ universality, . . .

Note, we will want to avoid mSUGRA assumptions.

– **Sample very heavy scenario:**

$m_0 = M_{1/2} = 0.7$ TeV, $A_0 = 0$, $\tan\beta = 2$, sign$(\mu) = +$.

Evolve to m_W, $\Rightarrow$

$$m_{\tilde{\chi}_1^0} = 304 \text{ GeV}, \; m_{\tilde{\chi}_2^0} \sim m_{\tilde{\chi}_1^\pm} \sim 588 \text{ GeV},$$
$$m_{\tilde{\chi}_3^0}, m_{\tilde{\chi}_4^0}, m_{\tilde{\chi}_2^\pm} \sim 1.3 \text{ TeV},$$
$$m_{\tilde{\ell}_L} \sim 852 \text{ GeV}, \; m_{\tilde{\ell}_R}, m_{\tilde{\nu}} \sim 750 \text{ GeV},$$
$$m_{\tilde{q}} \sim 1.6 \text{ TeV}, \; m_{\tilde{t}_1} \sim 1.1 \text{ TeV}, \; m_{\tilde{t}_2} \sim 1.5 \text{ TeV},$$
$$m_{A^0}, m_{H^\pm}, m_{H^0} \sim 1.7 \text{ TeV}.$$

$\Rightarrow$ Nothing observable for $\sqrt{s} \lesssim 0.5$ TeV.

We have begun by focusing on simple event class numbers, but will eventually examine kinematic end points and other kinematical distributions that might give more 'physical' handle on sparticle masses etc.

Sample scenario at $\sqrt{s} = 3.6$ TeV, $L = 1000$ fb^{-1} $\Rightarrow$:

* Event numbers for (0000000000011):

$\tilde{e}_L^+\tilde{e}_L^-$=196, $\tilde{\mu}_L^+\tilde{\mu}_L^-$=1511, $\tilde{\tau}_L^+\tilde{\tau}_L^-$=196, $\tilde{\chi}_1^0\tilde{\chi}_4^0$=13, $\tilde{\chi}_3^0\tilde{\chi}_4^0$=18,
$\tilde{\chi}_1^+\tilde{\chi}_1^-$=4904, $\tilde{\chi}_1^+\tilde{\chi}_2^-$ = $\tilde{\chi}_1^-\tilde{\chi}_2^+$=9.4, $\tilde{\chi}_2^+\tilde{\chi}_2^-$=57.

* Event numbers for (0000000010001):

$\tilde{e}_L^+\tilde{e}_L^-$=32, $\tilde{\mu}_L^+\tilde{\mu}_L^-$=243, $\tilde{\tau}_L^+\tilde{\tau}_L^-$=150, $\tilde{\nu}_\tau\overline{\tilde{\nu}_\tau}$=52,
$\tilde{\chi}_1^+\tilde{\chi}_1^-$=790, $\tilde{\chi}_2^+\tilde{\chi}_2^-$=10.

* etc.; $\Rightarrow$ **$\sim$ 307 channels in all with at least 5 events.**
* Channels dominated by particular sparticle pairs are those which could benefit from kinematics, end point etc. study.
* Background sources must be included. But, for these very high SUSY masses, all the final state particles will be very energetic, $\Rightarrow$ reasonably efficient cuts should remove backgrounds.
* Errors on parameters? Compute

$$V_{jk} = \sum_i \frac{\frac{\partial N_i}{\partial p_j}\frac{\partial N_i}{\partial p_k}}{N_i}\,.$$

then the 1σ errors on parameter p_k are given by $\Delta p_k = \left[V_{kk}^{-1}\right]^{1/2}$.
Preliminary results assuming that backgrounds are suppressed with cuts 40% efficient for signals, and neglecting cross-talk and detection inefficiencies, are sufficiently wonderful that good results may emerge even after including the experimental effects.

```
Ecm=3600 GeV,  L= 1000 fb-1
*****************************************
  m0      mhalf     tanb    A0     sign(mu)
  700     700       2       2      +1
*****************************************
 3ASUGRA spectrum:
 (GL)   =  1671.29
M(UL)   =  1601.95   M(UR)   =  1550.06   M(DL)   =  1603.14   M(DR)  =  1542.73
M(B1)   =  1431.60   M(B2)   =  1542.41   M(T1)   =  1124.83   M(T2)  =  1468.12
M(SN)   =   850.15   M(EL)   =   852.40   M(ER)   =   750.38
M(NTAU)=    849.99   M(TAU1)=    749.92   M(TAU2)=   852.35
M(Z1)   =  -303.72   M(Z2)   =  -587.71   M(Z3)   =  1264.71   M(Z4)  = -1274.51
M(W1)   =  -587.64   M(W2)   = -1273.08
M(HL)   =   101.26   M(HH)   =  1706.22   M(HA)   =  1703.22   M(H+)  =  1706.19
*******************************************
MUL-     MUL+       rate=    12172.73
MUL-     MUR+       rate=    33378.03
MUR-     MUL+       rate=    33833.79
MUR-     MUR+       rate=    17885.11
EL-      EL+        rate=    1554.167
ER-      ER+        rate=    1533.069
TAU1-    TAU1+      rate=    1539.191
TAU1-    TAU2+      rate=   0.7034547
TAU2-    TAU1+      rate=   0.6959620
TAU2-    TAU2+      rate=    1573.151
NUMUL    ANUMUL     rate=    45228.20
NUEL     ANUEL      rate=    651.5657
NUTL     ANUTL      rate=    653.4714
UPL      UBL        rate=    398.0474
UPR      UBR        rate=    354.4904
DNL      DBL        rate=    274.3336
DNR      DBR        rate=    94.29294
 IL      CBL        rate=    397.1439
CHR      CBR        rate=    357.3556
STL      SBL        rate=    269.9235
STR      SBR        rate=    93.09464
BT1      BB1        rate=    633.5463
BT1      BB2        rate=   0.8070134
BT2      BB1        rate=   0.7995916
BT2      BB2        rate=    92.45900
TP1      TB1        rate=    1231.120
TP1      TB2        rate=    82.04109
TP2      TB1        rate=    81.56010
TP2      TB2        rate=    732.1298
Z1SS     Z2SS       rate=    2690.753
Z1SS     Z3SS       rate=    9.618688
Z1SS     Z4SS       rate=    47.57231
Z2SS     Z2SS       rate=    4367.847
Z2SS     Z3SS       rate=    49.19982
Z2SS     Z4SS       rate=    64.59089
Z3SS     Z3SS       rate=   9.9108985E-04
Z3SS     Z4SS       rate=    3316.737
Z4SS     Z4SS       rate=   0.1961340
W1SS+    W1SS-      rate=    10724.61
W1SS+    W2SS-      rate=    163.7627
W2SS+    W1SS-      rate=    164.6032
W2SS+    W2SS-      rate=    7952.125
HL0      HA0        rate=   2.4226173E-03
HH0      HA0        rate=    31.41072
         H-         rate=    73.50754
```

```
 tbjm+e+t+hzw-     MUL-       MUL+
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
(0001100002000)     S=  849.22,     SUM:B=   33.47,     S/B=     25.37
     Backgrounds:
        Z3SS      Z4SS        6.951
        W2SS+     W2SS-      26.520
****************************************************************
 tbjm+e+t+hzw-     MUR-       MUR+
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
(0001100000000)     S=17883.23,     SUM:B=20293.59,     S/B=      0.88
     Backgrounds:
        MUL-      MUL+      884.293
        MUL-      MUR+     8995.840
        MUR-      MUL+     9118.672
        TAU2-     TAU2+       5.003
        NUMUL     ANUMUL   1164.108
        W1SS+     W1SS-     125.670
****************************************************************
 tbjm+e+t+hzw-     EL-        EL+
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
(0000011001000)     S=  219.57,     SUM:B=   29.75,     S/B=      7.38
     Backgrounds:
        NUEL      ANUEL      17.750
        W2SS+     W2SS-      12.002
****************************************************************
 tbjm+e+t+hzw-     ER-        ER+
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
(0000011000000)     S= 1532.91,     SUM:B=  279.86,     S/B=      5.48
     Backgrounds:
        MUL-      MUL+       35.985
        EL-       EL+       111.164
        NUEL      ANUEL      16.152
        W1SS+     W1SS-     116.564
****************************************************************
 tbjm+e+t+hzw-     TAU1-      TAU1+
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
(0000000110000)     S= 1537.06,     SUM:B=  304.80,     S/B=      5.04
     Backgrounds:
        MUL-      MUL+       39.515
        EL-       EL+         5.045
        TAU2-     TAU2+     115.261
        NUTL      ANUTL      16.979
        W1SS+     W1SS-     127.998
****************************************************************
 tbjm+e+t+hzw-     TAU2-      TAU2+
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
(0000000111000)     S=  224.78,     SUM:B=   31.97,     S/B=      7.03
     Backgrounds:
        NUTL      ANUTL      18.648
        W2SS+     W2SS-      13.320
****************************************************************
```

```
 tbjm+e+t+hzw-      NUMUL      ANUMUL
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
(0000000000000)     S= 2374.46,     SUM:B=    74.49,      S/B=     31.87
     Backgrounds:
        NUEL     ANUEL     34.207
        NUTL     ANUTL     34.321
        Z1SS     Z2SS       5.965
(0001100000011)     S= 5579.38,     SUM:B=    27.89,      S/B=    200.05
     Backgrounds:
        Z3SS     Z4SS      27.890
(0001100010001)     S=  898.72,     SUM:B=     0.00,      S/B=     -1.00
(0001100100010)     S=  898.72,     SUM:B=     0.00,      S/B=     -1.00
(0001100110000)     S=  145.31,     SUM:B=     0.00,      S/B=     -1.00
(0001101000001)     S=  857.64,     SUM:B=     0.00,      S/B=     -1.00
(0001101100000)     S=  138.15,     SUM:B=     0.00,      S/B=     -1.00
(0001110000010)     S=  857.64,     SUM:B=     0.00,      S/B=     -1.00
(0001110010000)     S=  138.15,     SUM:B=     0.00,      S/B=     -1.00
(0001111000000)     S=  132.38,     SUM:B=     0.00,      S/B=     -1.00
(0001200000001)     S=  892.22,     SUM:B=     0.00,      S/B=     -1.00
(0001200100000)     S=  143.72,     SUM:B=     0.00,      S/B=     -1.00
(0001210000000)     S=  137.15,     SUM:B=     0.00,      S/B=     -1.00
(0002100000010)     S=  892.22,     SUM:B=     0.00,      S/B=     -1.00
(0002100010000)     S=  143.72,     SUM:B=     0.00,      S/B=     -1.00
(0002101000000)     S=  137.15,     SUM:B=     0.00,      S/B=     -1.00
(0002200000000)     S=  142.68,     SUM:B=     0.00,      S/B=     -1.00
****************************************************************
 tbjm+e+t+hzw-      NUEL      ANUEL
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
(0000011010001)     S=   12.95,     SUM:B=     0.00,      S/B=     -1.00
(0000011100010)     S=   12.95,     SUM:B=     0.00,      S/B=     -1.00
(0000012000001)     S=   12.38,     SUM:B=     0.00,      S/B=     -1.00
(0000021000010)     S=   12.38,     SUM:B=     0.00,      S/B=     -1.00
(0000111000001)     S=   12.83,     SUM:B=     0.00,      S/B=     -1.00
(0001011000010)     S=   12.83,     SUM:B=     0.00,      S/B=     -1.00
****************************************************************
 tbjm+e+t+hzw-      NUTL      ANUTL
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
(0000000120001)     S=   13.01,     SUM:B=     0.00,      S/B=     -1.00
(0000000210010)     S=   13.01,     SUM:B=     0.00,      S/B=     -1.00
(0000001110001)     S=   12.39,     SUM:B=     0.00,      S/B=     -1.00
(0000010110010)     S=   12.39,     SUM:B=     0.00,      S/B=     -1.00
(0000100110001)     S=   12.87,     SUM:B=     0.00,      S/B=     -1.00
(0001000110010)     S=   12.87,     SUM:B=     0.00,      S/B=     -1.00
****************************************************************
 tbjm+e+t+hzw-      BT1       BB1
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
(0200000002000)     S=   22.82,     SUM:B=     0.00,      S/B=     -1.00
(1100000000012)     S=   10.50,     SUM:B=     0.00,      S/B=     -1.00
(1100000000021)     S=   10.50,     SUM:B=     0.00,      S/B=     -1.00
(2000000000011)     S=   48.60,     SUM:B=     0.00,      S/B=     -1.00
****************************************************************
 tbjm+e+t+hzw-      BT2       BB2
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
(0200000000000)     S=   77.70,     SUM:B=     0.00,      S/B=     -1.00
****************************************************************

 tbjm+e+t+hzw-      TP1       TB1
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
(1000000010000)     S=   29.98,     SUM:B=     0.00,      S/B=     -1.00
(1000000011000)     S=   13.54,     SUM:B=     0.00,      S/B=     -1.00
(1000000100000)     S=   29.98,     SUM:B=     0.00,      S/B=     -1.00
(1000000101000)     S=   13.54,     SUM:B=     0.00,      S/B=     -1.00
(1000001000000)     S=   29.98,     SUM:B=     0.00,      S/B=     -1.00
(1000001001000)     S=   13.54,     SUM:B=     0.00,      S/B=     -1.00
(1000010000000)     S=   29.98,     SUM:B=     0.00,      S/B=     -1.00
(1000010001000)     S=   13.54,     SUM:B=     0.00,      S/B=     -1.00
(1000100000000)     S=   29.98,     SUM:B=     0.00,      S/B=     -1.00
(1000100001000)     S=   13.54,     SUM:B=     0.00,      S/B=     -1.00
(1001000000000)     S=   29.98,     SUM:B=     0.00,      S/B=     -1.00
(1001000001000)     S=   13.54,     SUM:B=     0.00,      S/B=     -1.00
(2000000000000)     S=  179.88,     SUM:B=     0.00,      S/B=     -1.00
****************************************************************
 tbjm+e+t+hzw-      TP2       TB2
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
(2000000001100)     S=   22.65,     SUM:B=     0.00,      S/B=     -1.00
****************************************************************
 tbjm+e+t+hzw-      Z3SS      Z4SS
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
(0000000000022)     S=  265.38,     SUM:B=     0.00,      S/B=     -1.00
(0000000003100)     S=  220.24,     SUM:B=     0.00,      S/B=     -1.00
(0000000010012)     S=   85.95,     SUM:B=     0.00,      S/B=     -1.00
(0000000100021)     S=   85.95,     SUM:B=     0.00,      S/B=     -1.00
(0000001000012)     S=   81.98,     SUM:B=     0.00,      S/B=     -1.00
(0000001010002)     S=   13.28,     SUM:B=     0.00,      S/B=     -1.00
(0000001100011)     S=   26.55,     SUM:B=     0.00,      S/B=     -1.00
(0000010000021)     S=   81.98,     SUM:B=     0.00,      S/B=     -1.00
(0000010010011)     S=   26.55,     SUM:B=     0.00,      S/B=     -1.00
(0000010100020)     S=   13.28,     SUM:B=     0.00,      S/B=     -1.00
(0000100000012)     S=   85.11,     SUM:B=     0.00,      S/B=     -1.00
(0000100010002)     S=   13.78,     SUM:B=     0.00,      S/B=     -1.00
(0000100100011)     S=   27.56,     SUM:B=     0.00,      S/B=     -1.00
(0000101000002)     S=   13.15,     SUM:B=     0.00,      S/B=     -1.00
(0000110000011)     S=   26.29,     SUM:B=     0.00,      S/B=     -1.00
(0001000000021)     S=   85.11,     SUM:B=     0.00,      S/B=     -1.00
(0001000010011)     S=   27.56,     SUM:B=     0.00,      S/B=     -1.00
(0001000100020)     S=   13.78,     SUM:B=     0.00,      S/B=     -1.00
(0001001000011)     S=   26.29,     SUM:B=     0.00,      S/B=     -1.00
(0001010000020)     S=   13.15,     SUM:B=     0.00,      S/B=     -1.00
****************************************************************
 tbjm+e+t+hzw-      W2SS+     W2SS-
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
(0000000000211)     S=  169.11,     SUM:B=     0.00,      S/B=     -1.00
(0000000010201)     S=   27.24,     SUM:B=     0.00,      S/B=     -1.00
(0000000100210)     S=   27.24,     SUM:B=     0.00,      S/B=     -1.00
(0000001000201)     S=   26.00,     SUM:B=     0.00,      S/B=     -1.00
(0000010000210)     S=   26.00,     SUM:B=     0.00,      S/B=     -1.00
(0000100000201)     S=   26.99,     SUM:B=     0.00,      S/B=     -1.00
(0001000000210)     S=   26.99,     SUM:B=     0.00,      S/B=     -1.00
(0200000011001)     S=   23.51,     SUM:B=     0.00,      S/B=     -1.00
(0200000101010)     S=   23.51,     SUM:B=     0.00,      S/B=     -1.00
(0200001001001)     S=   22.43,     SUM:B=     0.00,      S/B=     -1.00
(0200010001010)     S=   22.43,     SUM:B=     0.00,      S/B=     -1.00
(0200100001001)     S=   23.29,     SUM:B=     0.00,      S/B=     -1.00
(0201000001010)     S=   23.29,     SUM:B=     0.00,      S/B=     -1.00
```

Our example case, with $E_{cm} = 3600$ GeV, $\mathcal{L}_{int} = 1000$ fb^{-1}

$m_0 = 700$, $m_{1/2} = 700$, $A_0 = 0$, $\tan\beta = 2$, sign(μ) = +1

(masses in GeV)

	μ	m_A	$\tan\beta$
P	1264	1703	2
$\Delta P_{1\sigma}$	4.8	7.5	0.018
$\Delta P/P$	0.004	0.004	0.009

	A_t	A_b	A_τ	M_1	M_2
P	−1107	−1808	−450	305	596
$\Delta P_{1\sigma}$	11	18	2000??	2.1	0.18
$\Delta P/P$	0.01	0.01	4??	0.007	0.0003

	$\tilde{m}_{\tilde{Q}1_L}$	$m_{\tilde{d}_R}$	$m_{\tilde{u}_R}$	$m_{\tilde{l}1_L}$	$m_{\tilde{e}_R}$
P	1602	1542	1550	852	750
$\Delta P_{1\sigma}$	6.2	1100??	92000??	7.6	9.9
$\Delta P/P$	0.004	0.7??	60??	0.009	0.01

	$\tilde{m}_{\tilde{Q}2_L}$	$m_{\tilde{s}_R}$	$m_{\tilde{c}_R}$	$m_{\tilde{l}2_L}$	$m_{\tilde{\mu}_R}$
P	1602	1542	1550	852	750
$\Delta P_{1\sigma}$	12	1100??	87000??	21	14
$\Delta P/P$	0.007	0.7??	60??	0.02	0.02

	$\tilde{m}_{\tilde{Q}3_L}$	$m_{\tilde{b}_R}$	$m_{\tilde{t}_R}$	$m_{\tilde{l}3_L}$	$m_{\tilde{\tau}_R}$
P	1431	1542	1152	851	749
$\Delta P_{1\sigma}$	7.6	8.2	6.2	3.1	17
$\Delta P/P$	0.005	0.005	0.005	0.004	0.02

??'s $\Rightarrow$ increased accuracy needed in computing derivatives; ignore for now.

$E_{cm} = 500$ GeV, $\mathcal{L}_{int} = 20$ fb^{-1}

$m_0 = 200$, $m_{1/2} = 150$, $A_0 = 0$, $\tan\beta = 2$, sign(μ) = +1

(masses in GeV)

	μ	m_A	$\tan\beta$
P	326	441	2
$\Delta P_{1\sigma}$	2.7	5.0	0.078
$\Delta P/P$	0.008	0.01	0.04

	A_t	A_b	A_τ	M_1	M_2
P	−290	−481	−104	61	126
$\Delta P_{1\sigma}$	6.0	27	1300	3.2	1.5
$\Delta P/P$	0.02	0.05	10	0.05	0.01

	$\tilde{m}_{\tilde{Q}1_L}$	$m_{\tilde{d}_R}$	$m_{\tilde{u}_R}$	$m_{\tilde{l}1_L}$	$m_{\tilde{e}_R}$
P	417	404	406	227	208
$\Delta P_{1\sigma}$	15	62	264??	1.3	1.2
$\Delta P/P$	0.04	0.2	0.7??	0.006	0.006

	$\tilde{m}_{\tilde{Q}2_L}$	$m_{\tilde{s}_R}$	$m_{\tilde{c}_R}$	$m_{\tilde{l}2_L}$	$m_{\tilde{\mu}_R}$
P	417	404	406	227	208
$\Delta P_{1\sigma}$	16??	61	200	2.8	3.0
$\Delta P/P$	0.04??	0.2	0.5	0.01	0.01

	$\tilde{m}_{\tilde{Q}3_L}$	$m_{\tilde{b}_R}$	$m_{\tilde{t}_R}$	$m_{\tilde{l}3_L}$	$m_{\tilde{\tau}_R}$
P	368	404	297	227	208
$\Delta P_{1\sigma}$	3.7	6.1	6.3	2.0	4.1
$\Delta P/P$	0.01	0.02	0.02	0.008	0.02

??'s $\Rightarrow$ increased accuracy needed in computing derivatives; ignore for now.

This second case displays **a remarkable feature:**

Good determinations of squark and slepton masses are possible even when these particle pairs are not directly produced.

This sensitivity arises from the dependence of the braniching ratios for decays mediated by off-shell (below threshold) virtual exchanges of the squarks and sleptons on the masses.

$$E_{cm} = 500 \text{ GeV}, \ \mathcal{L}_{int} = 20 \text{ fb}^{-1}$$

$$m_0 = 200, \ m_{1/2} = 150, \ \mathrm{A}_0 = 0, \ \tan\beta = 2, \ \mathrm{sign}(\mu) = +1$$

(masses in GeV)

	μ	m_A	$\tan\beta$
P	326	441	2
$\Delta P/P_{n=3000}$	0.008	0.01	0.04
$\Delta P/P_{n=10000}$	0.008	0.01	0.06

	A_t	A_b	A_τ	M_1	M_2
P	−290	−481	−104	61	126
$\Delta P/P_{n=3000}$	0.02	0.05	10	0.05	0.01
$\Delta P/P_{n=10000}$	0.02	0.07	8	0.06	0.01

	$\tilde{m}_{\tilde{Q}1_L}$	$m_{\tilde{d}_R}$	$m_{\tilde{u}_R}$	$m_{\tilde{\ell}1_L}$	$m_{\tilde{e}_R}$
P	417	404	406	227	208
$\Delta P/P_{n=3000}$	0.04	0.2	0.7	0.006	0.006
$\Delta P/P_{n=10000}$	0.04	0.2	0.02	0.003	0.004

	$\tilde{m}_{\tilde{Q}2_L}$	$m_{\tilde{s}_R}$	$m_{\tilde{c}_R}$	$m_{\tilde{\ell}2_L}$	$m_{\tilde{\mu}_R}$
P	417	404	406	227	208
$\Delta P/P_{n=3000}$	0.04	0.2	0.5	0.01	0.01
$\Delta P/P_{n=10000}$	0.003	0.2	0.4	0.01	0.02

	$\tilde{m}_{\tilde{Q}3_L}$	$m_{\tilde{b}_R}$	$m_{\tilde{t}_R}$	$m_{\tilde{\ell}3_L}$	$m_{\tilde{\tau}_R}$
P	368	404	297	227	208
$\Delta P/P_{n=3000}$	0.01	0.02	0.02	0.008	0.02
$\Delta P/P_{n=10000}$	0.01	0.04	0.02	0.009	0.02

CONCLUSIONS

- **High energy is definitely needed for decent sparticle pair rates in the typical heavy SUSY scenario: scalar pair cross sections peak at $\sqrt{s} \sim 4m_0$.**
- Heavy SUSY at high energy $\Rightarrow$ many different final state channels

$$(t, b, j, e^-, e^+, \mu^-, \mu^+, \tau^-, \tau^+, h^0, Z, W^+, W^-),$$

  with many different contributors.

- Rates in each channel depend significantly on the (**23**) model parameters, $\Rightarrow$ expect to demonstrate ability to extract parameters with good accuracy, even after including mis-identification, detection losses, beam hole loses, and so forth. (Of course, these experimental ingredients must be fairly accurately known.)
- **Provided the large luminosities we have assumed are achieved, we have high hopes that one can simply turn on the high-$\sqrt{s}$ muon collider and determine the soft-SUSY-breaking parameters after a few years running.**
- Parameter determinations can be checked/confirmed via detailed final state kinematics, such as spectrum end points, and by seeing how channel rates and kinematical structures change as a function of machine energy.

Sparticle masses from kinematic end-points at a muon collider

Joe Lykken
Fermilab
December 11, 1997

Topic: $\mu^+\mu^- \to$ sparticle pairs

with two-body decays:

sparticle(1)
  ↳ sparticle(2) + particle
                          ↗ fully reconstructible
                          e.g. $e, \mu, W, Z, h, \ldots$

Two precision methods;

1. Kinematic endpoints $\Rightarrow M_1$ and M_2

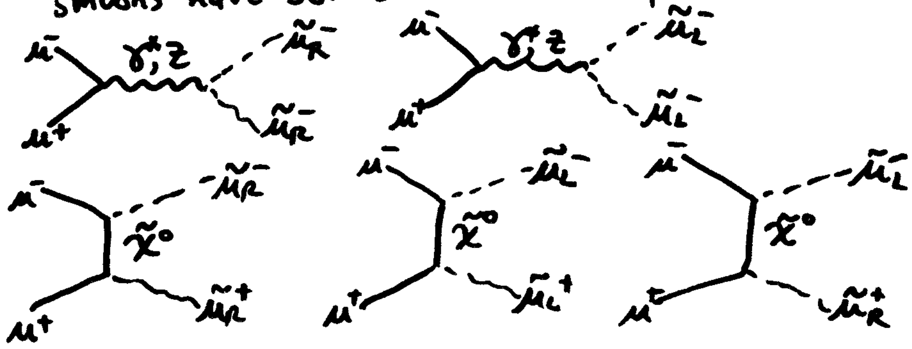
2. Feng-Finnell $\Rightarrow M_1$ given M_2

Some References:

F. Paige, in proc. of "Workshop on physics at the first muon collider"; Fermilab Nov 97
T. Tsukamoto et al, PRD 51 (1995) 3153
H. Baer et al, PRD 54 (1996) 6735
J. Feng and M. Strassler, PRD 55 (1997) 1326
M. Nojiri, PRD 51 (1995) 6281

Smuon and selectron pair production

smuons have both s and t channel production:



Selectrons have only s channel

Decays:

$\tilde{\mu}_R^\pm \to \tilde{\chi}_1^0 \mu^\pm$ almost 100%

$\tilde{\mu}_L^\pm \to \tilde{\chi}_1^0 \mu^\pm$

$\tilde{\chi}_2^0 \mu^\pm$ branching ratios are model dependent

$\tilde{\chi}_1^\pm \nu_\mu$

LHC Point 5

$m_0 = 100$ GeV, $m_{1/2} = 300$ GeV,
$A_0 = 300$ GeV, $\tan\beta = 2.1$, sgn$\mu = 1$

$M(\tilde{\chi}_1^0) = 119$ GeV $M(\tilde{\chi}_2^0) = 228$ GeV
$M(\tilde{\chi}_1^\pm) = 228$ GeV $M(\tilde{\chi}_2^\pm) = 565$ GeV
$M(\tilde{e}_R) = 157$ GeV $M(\tilde{e}_L) = 241$ GeV
$M(\tilde{\mu}_R) = 157$ GeV $M(\tilde{\mu}_L) = 241$ GeV
$M(\tilde{\nu}_L) = 232$ GeV
$M(\tilde{g}) = 769$ GeV $M(\tilde{t}_1) = 494$ GeV
$M(h_0) = 95$ GeV $M(H_A) = 613$ GeV

Note: differences between Pythia and ISAJET spectra are important here.

LHC Point 5

Cross-sections in fb for $\mu^+\mu^- \to X$:

$\sqrt{s} =$	500	600	800	1400 GeV
$\chi_1^+\chi_1^-$:	32	92	131	80
$\tilde{\mu}_R\tilde{\mu}_R$:	208	239	220	147
$\tilde{\mu}_R\tilde{\mu}_L$:	143	121	83	31
$\tilde{e}_R\tilde{e}_R$:	50	47	32	13
$\tilde{\mu}_L\tilde{\mu}_L$:	3	38	85	92
$\tilde{e}_L\tilde{e}_L$:	2	17	23	14
$\chi_2^+\chi_2^-$:	0	0	0	33
$\tilde{\chi}_3\tilde{\chi}_4$:	0	0	0	11
$\tilde{t}_1\bar{\tilde{t}}_1$:	0	0	0.1	8
W^+W^- :	7700	6300	4400	2300
Z, γ^* :	6100	4400	2700	1000
$W\mu\nu_\mu$:	5100	6400	8900	14000
$Z\mu^+\mu^-$:	2800	3100	3300	3700
$\mu^+\mu^- f\bar{f}$:	1900	2300	3300	5400
ZZ :	560	480	290	150

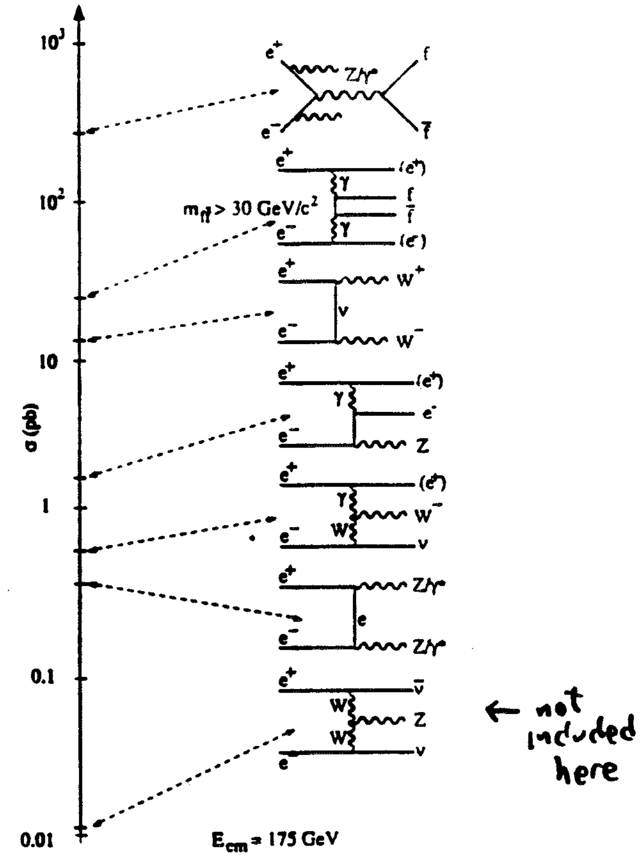


Fig. 1: Standard model reaction cross-sections at LEP–200. (From J-F Grivaz LAL 92-64)

Two-body decays

$\tilde{\mu}_R \to \tilde{\chi}_1^0 \mu$ 100%

$\tilde{\mu}_L \to \tilde{\chi}_1^0 \mu$ 94%

$\tilde{e}_R \to \tilde{\chi}_1^0 e$ 100%

$\tilde{e}_L \to \tilde{\chi}_1^0 e$ 94%

In rest frame of slepton (neglecting lepton mass)

$$E^0_{lepton} = \frac{M^2_{slepton} - M^2_{LSP}}{2M_{slepton}}$$

Use max and min boosts to lab frame to find

$$E^{max,min}_{lepton} = \frac{E^0_{lepton}}{2M_{slepton}\sqrt{s}}\left\{ s + M^2_{slepton} - M'^2_{slepton} \pm \sqrt{(s - M^2_{slepton} - M'^2_{slepton})^2 - 4M^2_{slepton}M'^2_{slepton}} \right\}$$

In simplest cases e.g. $\mu^+\mu^- \to \tilde{\mu}_R^+ \tilde{\mu}_R^-$

$M_{slepton} = M'_{slepton} = M(\tilde{\mu}_R)$

$\Rightarrow$ Measure E^{max}_{lepton}, E^{min}_{lepton} to find $M_{slepton}$, M_{LSP}

Cuts for smuon, selectron production:

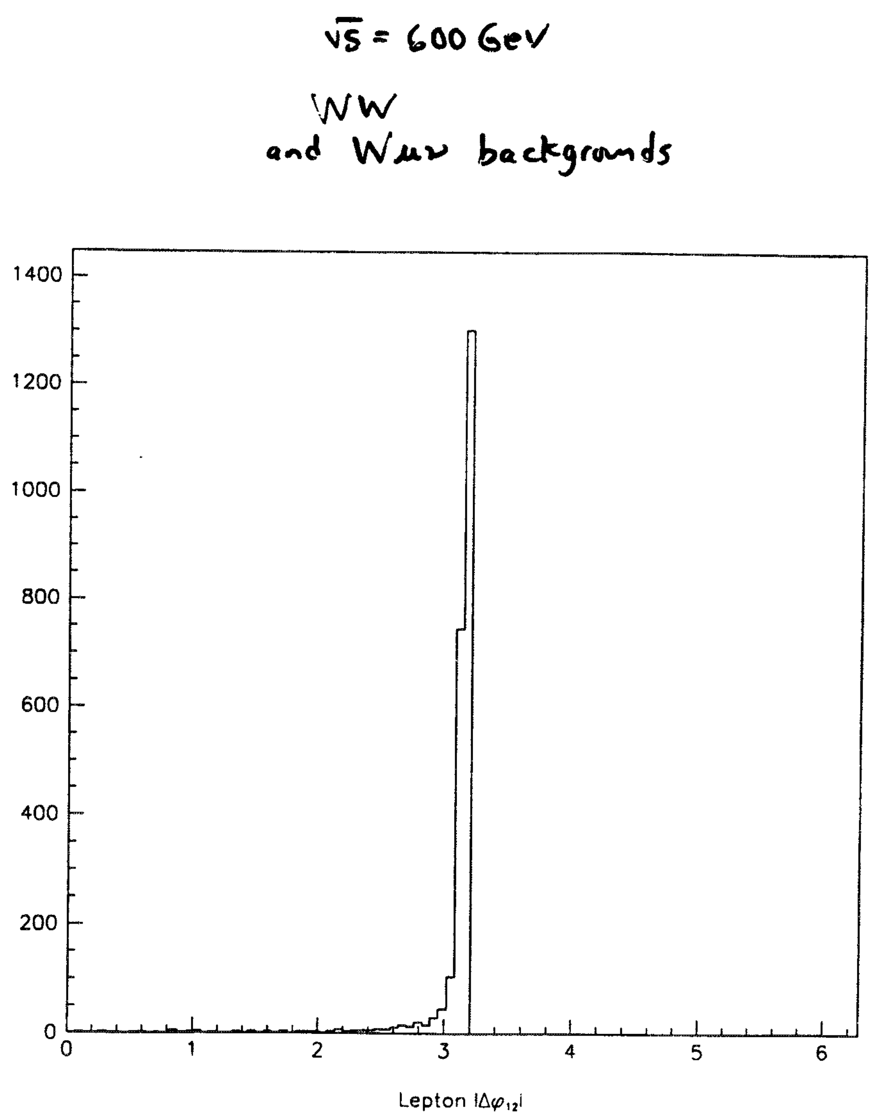
- Exactly 2 isolated muons, electrons and no jets
- $E_{lepton} > 10$ GeV
- $|\eta_{lepton}| < 1.3$
- $|\Delta\phi_{12}| < 0.9\pi$
- $\not{E}_T > 20$ GeV

$\Rightarrow$ signal acceptance $\sim 50\%$

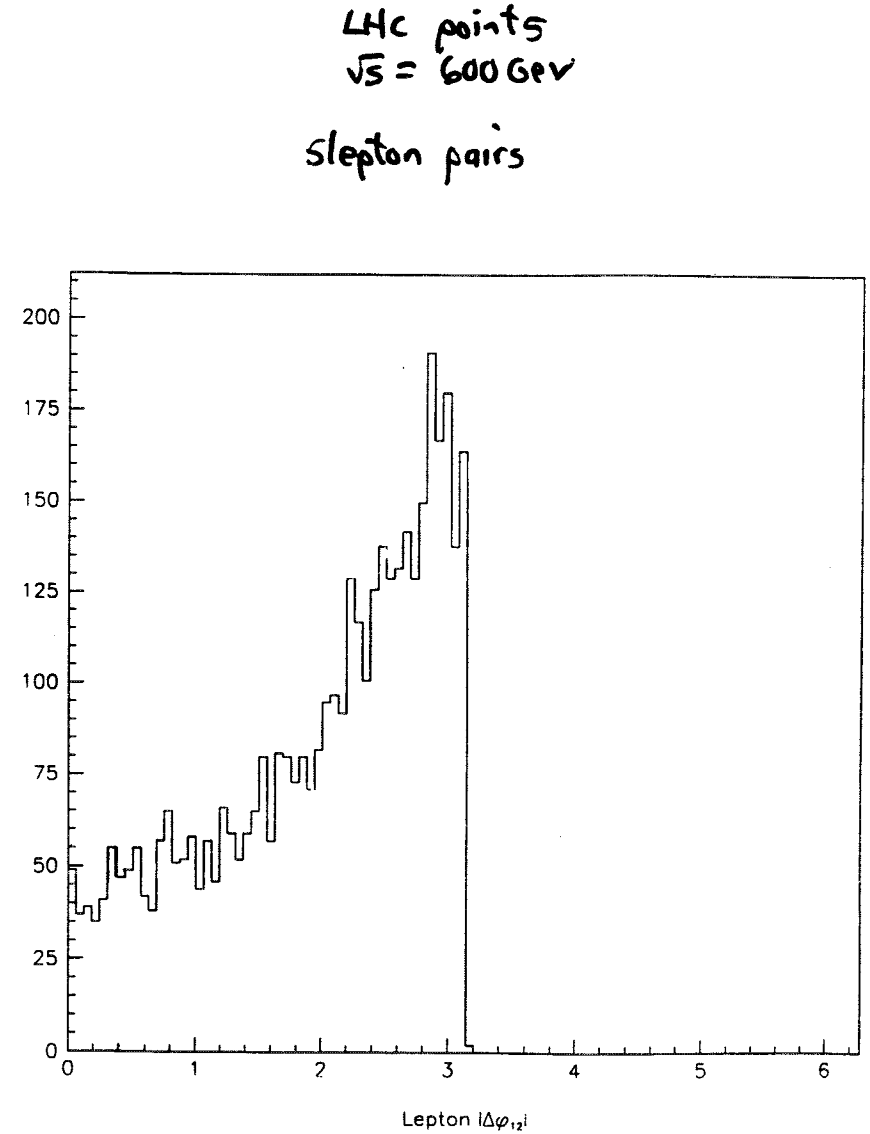
Pythia 6.1
ATLFAST 1.25

Ignore: detector backgrounds
smearing
...

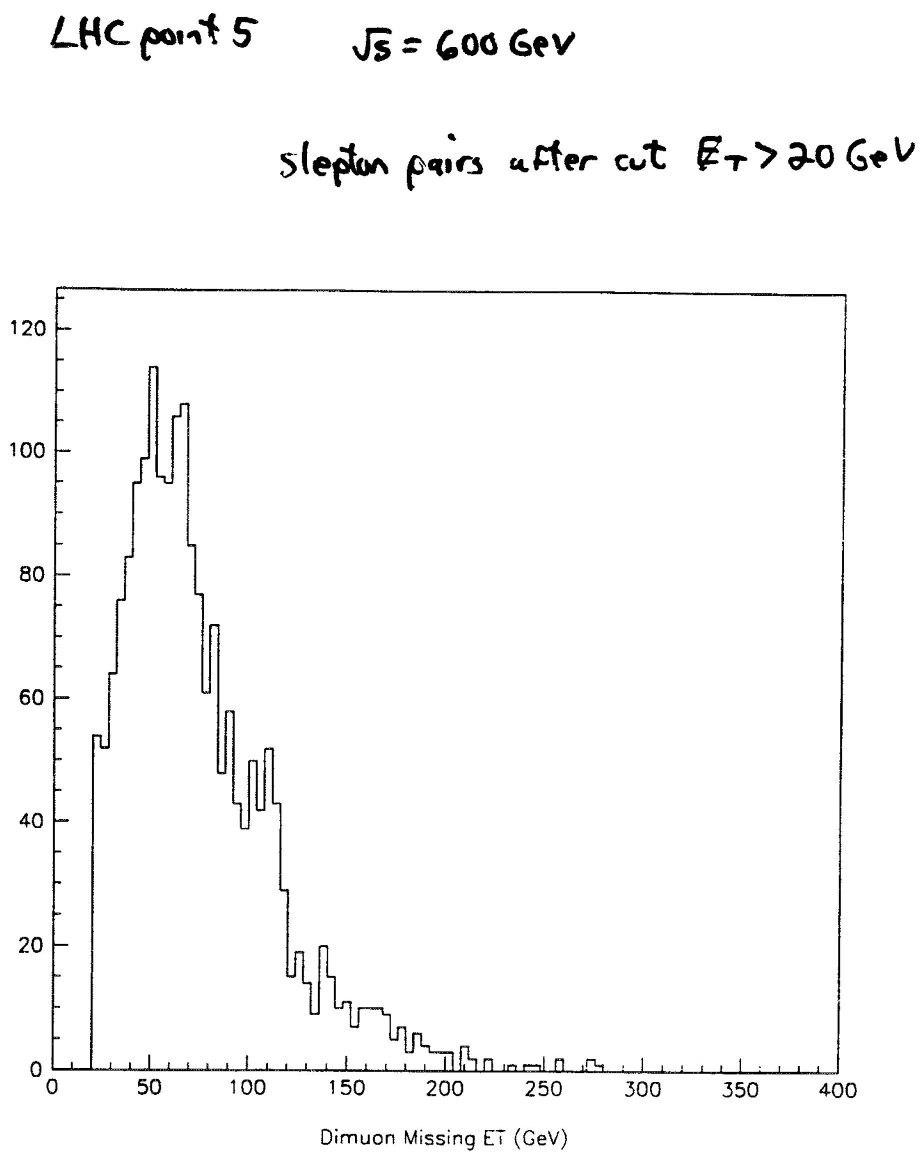
Ignore: polarization

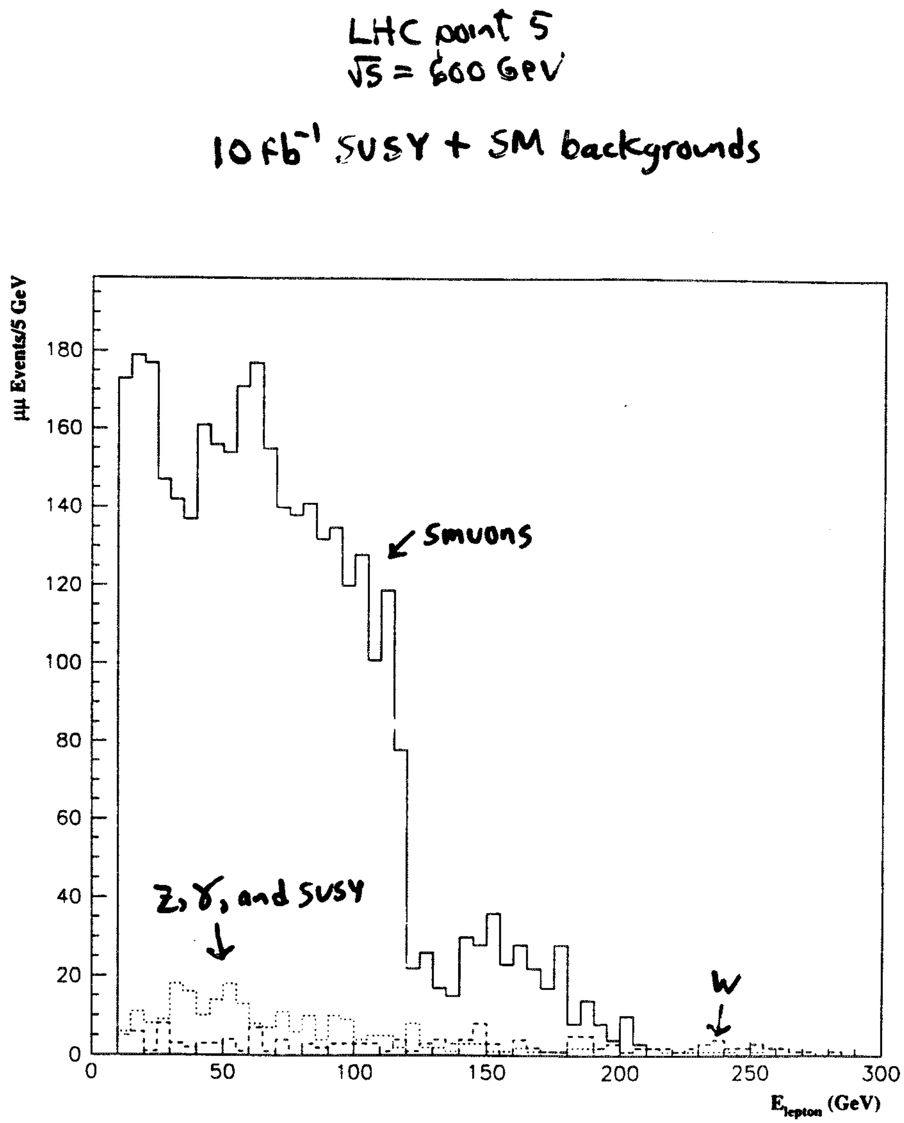


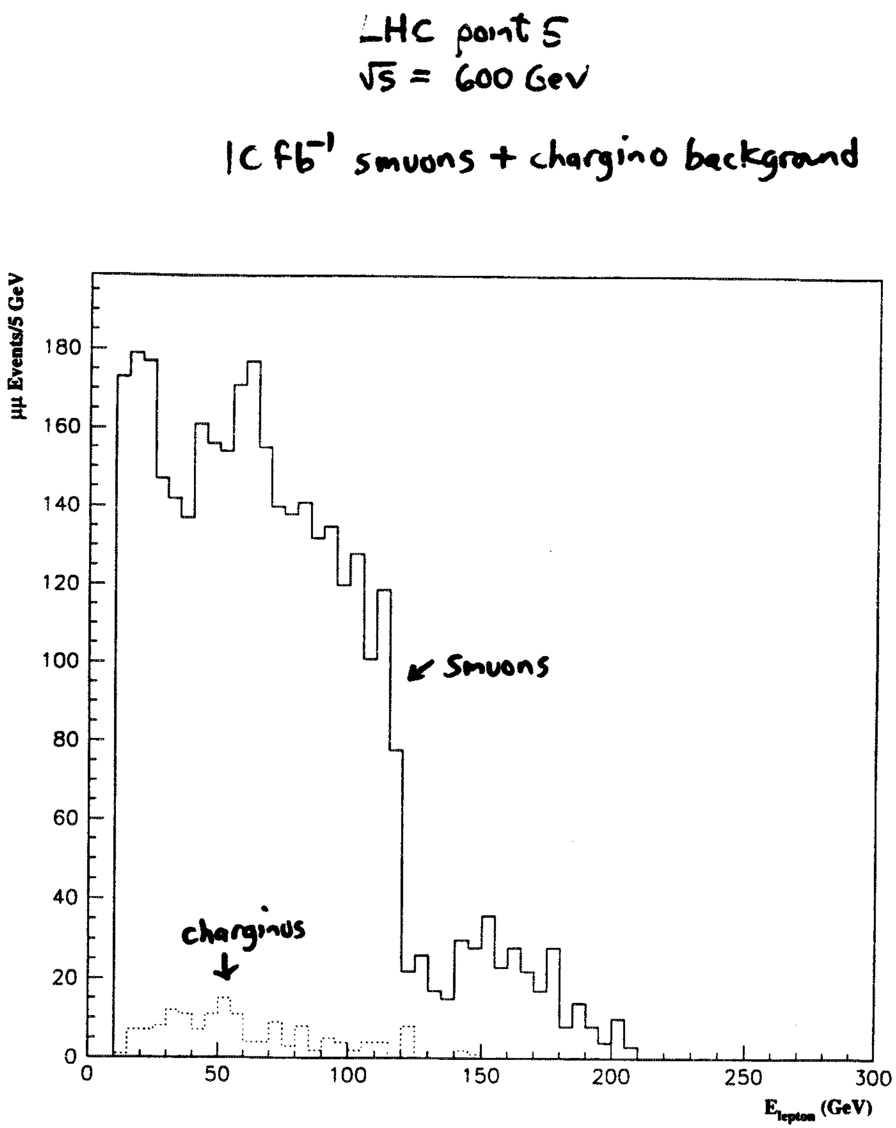
√s = 600 GeV
WW
and Wμν backgrounds
1400
1200
1000
800
600
400
200
0
0
1
2
3
4
5
6
Lepton |Δφ12|

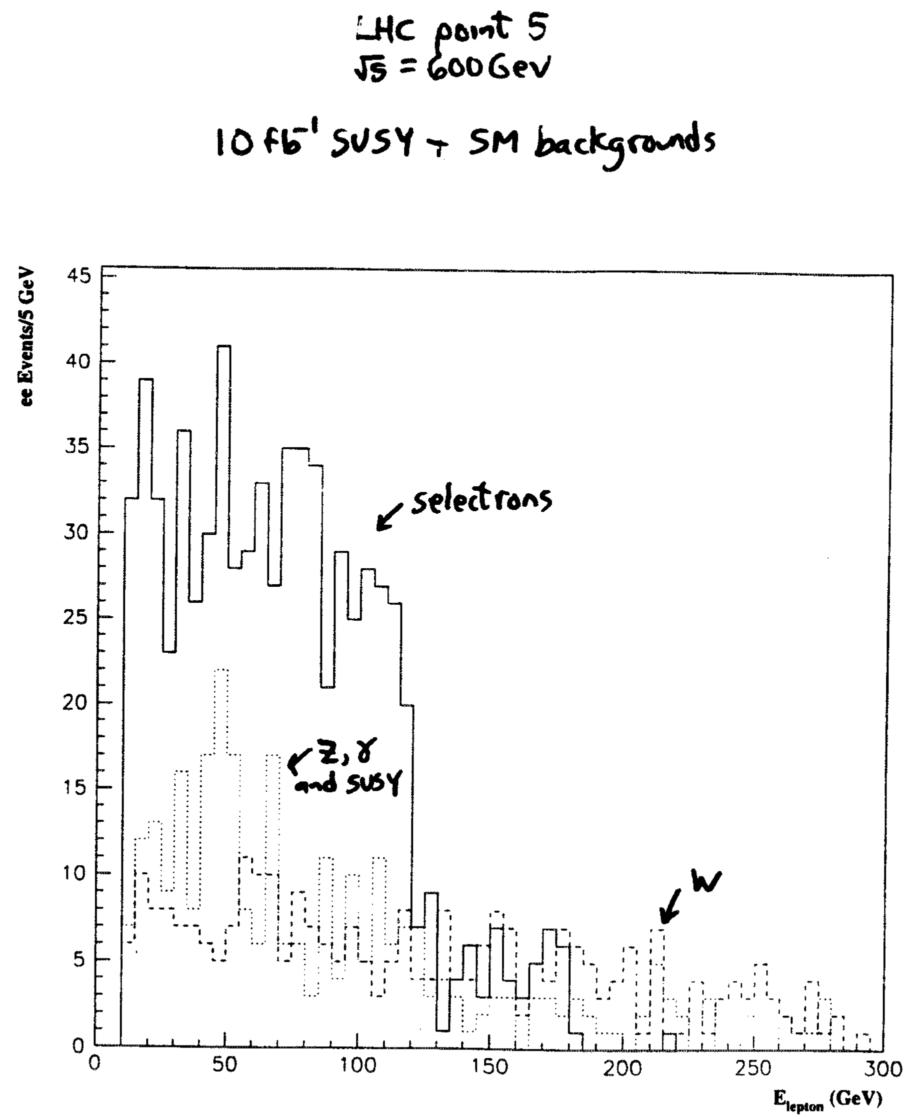


LHC points
√s = 600 GeV
Slepton pairs
200
175
150
125
100
75
50
25
0
0
1
2
3
4
5
6
Lepton |Δφ12|


LHC point 5
$\sqrt{s}$ = 600 GeV
slepton pairs after cut $\not{E}_T$ > 20 GeV
Dimuon Missing ET (GeV)

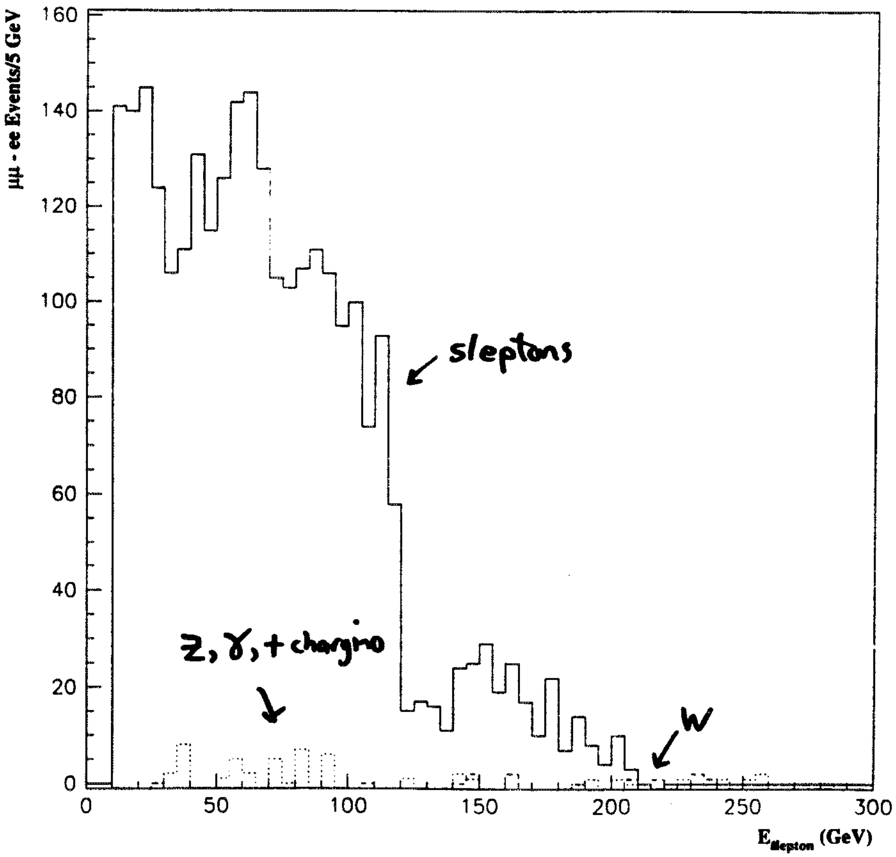

LHC point 5
$\sqrt{s}$ = 600 GeV
10 fb^{-1} SUSY + SM backgrounds
μμ Events/5 GeV
Smuons
Z, γ, and SUSY
W
E_{lepton} (GeV)


LHC point 5
√s = 600 GeV
10 fb⁻¹ smuons + chargino background
μμ Events/5 GeV
Smuons
charginos
E_lepton (GeV)


LHC point 5
√s = 600 GeV
10 fb⁻¹ SUSY + SM backgrounds
ee Events/5 GeV
selectrons
Z, γ and SUSY
W
E_lepton (GeV)

LHC point 5
$\sqrt{s} = 600$ GeV

$10\,fb^{-1}$ SUSY + SM backgrounds



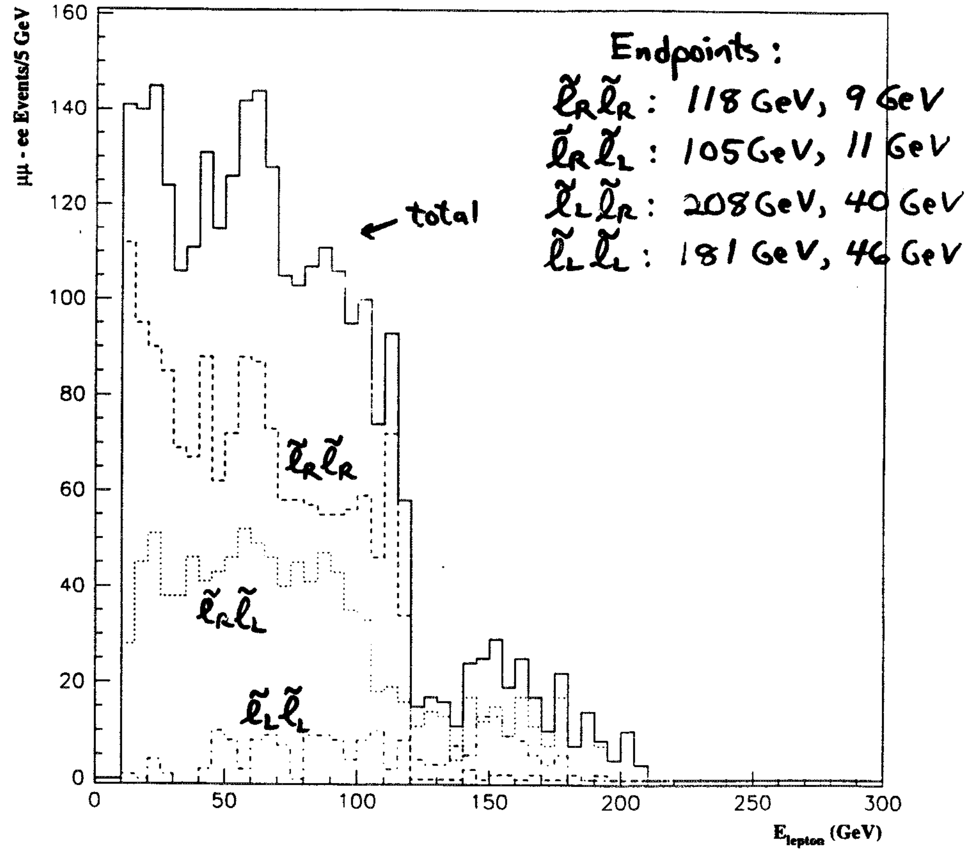
Two flavor subtractions are possible:

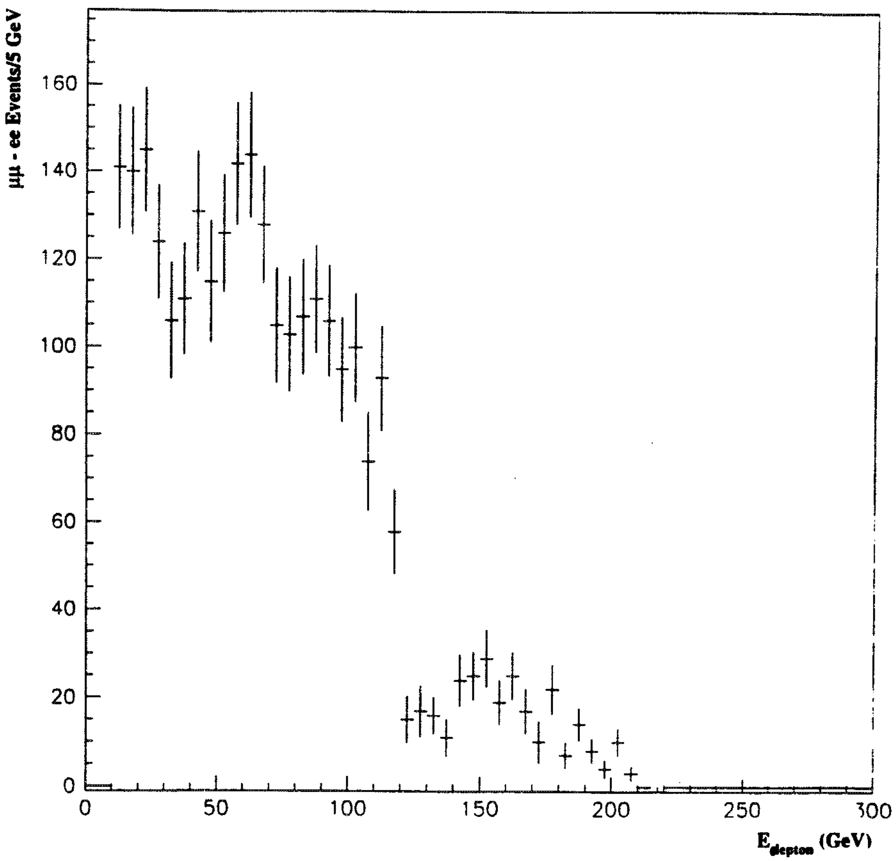
$\mu^+\mu^- - e^+e^-$

or $\mu^+\mu^- + e^+e^- - \mu^+e^- - \mu^-e^+$

LHC point 5
$\sqrt{s} = 600$ GeV

$10\,fb^{-1}$ SUSY signal, flavor subtracted

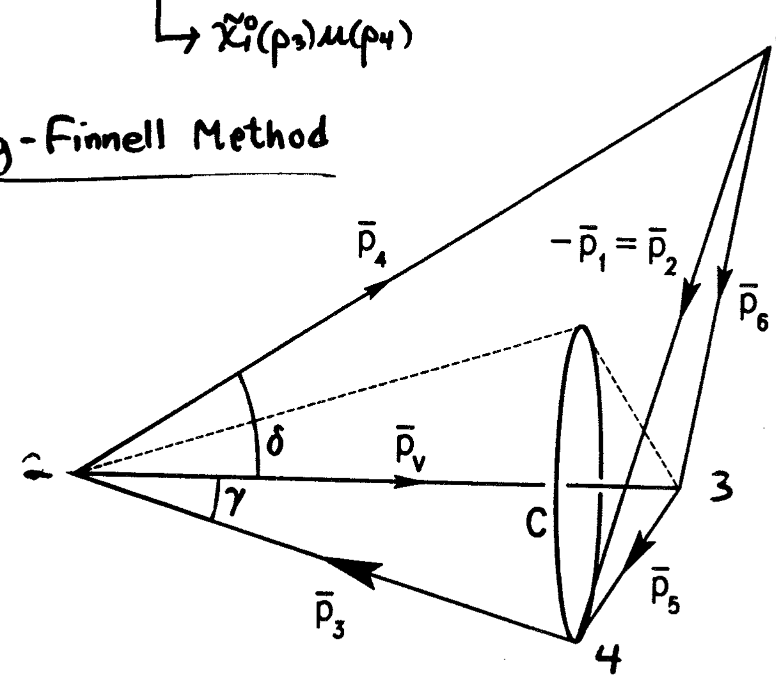




E.g.

$$\mu^+\mu^- \to \tilde{\mu}_R(p_1)\tilde{\mu}_R(p_2)$$
$$\hookrightarrow \tilde{\chi}_1^0(p_5)\mu(p_6)$$
$$\hookrightarrow \tilde{\chi}_1^0(p_3)\mu(p_4)$$

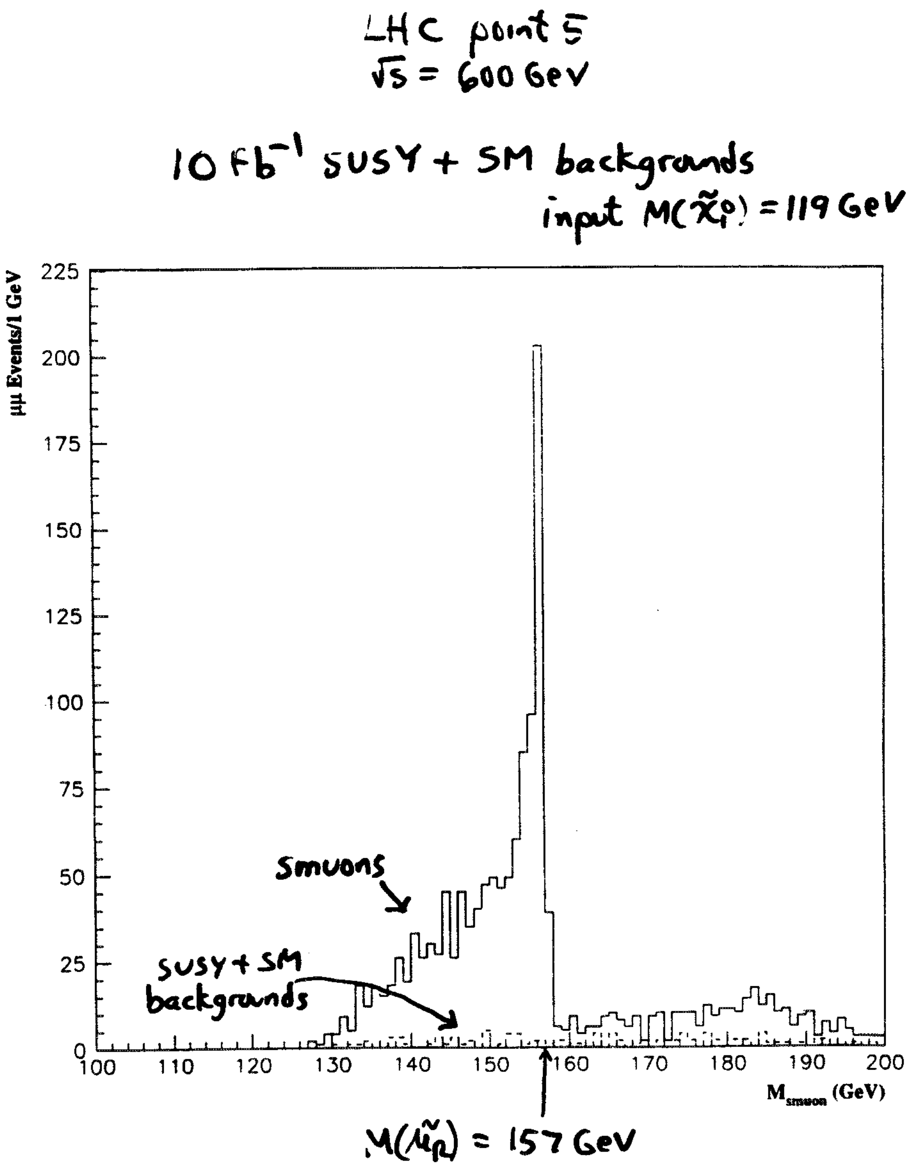
Feng-Finnell Method



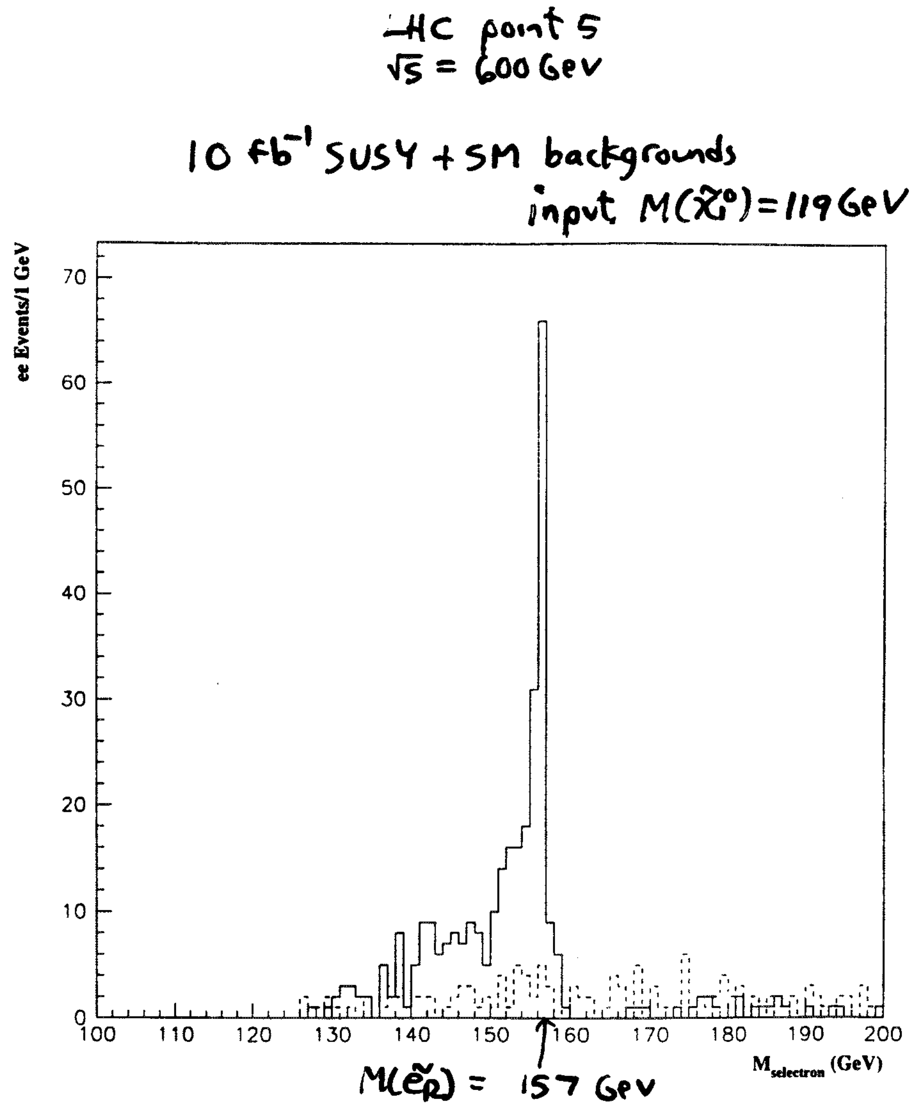
$$M^2_{\tilde{\mu}_R} = E_2^2 - |\vec{p}_3|^2 - |\vec{p}_4|^2 + 2|\vec{p}_3||\vec{p}_4|\cos\theta_{34}$$

Use $\gamma+\delta$ as estimator of θ_{34}

From J. Feng and D. Finnell
PRD49 (1994) 2369



LHC point 5
√s = 600 GeV
10 fb⁻¹ SUSY + SM backgrounds
input M(χ̃₁⁰) = 119 GeV
μμ Events/1 GeV
smuons
SUSY + SM backgrounds
M_smuon (GeV)
M(μ̃_R) = 157 GeV



LHC point 5
√s = 600 GeV
10 fb⁻¹ SUSY + SM backgrounds
input M(χ̃₁⁰) = 119 GeV
ee Events/1 GeV
M_selectron (GeV)
M(ẽ_R) = 157 GeV

Another SUGRA point

Good for sneutrino pairs

$m_0 = 225$ GeV, $m_{1/2} = 200$ GeV,
$A_0 = 0$ GeV, $\tan\beta = 2$, $\text{sgn}\mu = 1$

$M(\tilde{\chi}_1^0) = 77$ GeV	$M(\tilde{\chi}_2^0) = 146$ GeV
$M(\tilde{\chi}_1^\pm) = 144$ GeV	$M(\tilde{\chi}_2^\pm) = 436$ GeV
$M(\tilde{e}_R) = 240$ GeV	$M(\tilde{e}_L) = 269$ GeV
$M(\tilde{\mu}_R) = 240$ GeV	$M(\tilde{\mu}_L) = 269$ GeV
$M(\tilde{\nu}_L) = 262$ GeV	
$M(\tilde{g}) = 546$ GeV	$M(\tilde{t}_1) = 325$ GeV
$M(h_0) = 92$ GeV	$M(H_A) = 547$ GeV

$\sqrt{s} = 800$ GeV
Cross-section for $\mu^+\mu^- \to \tilde{\nu}_{\mu L}\tilde{\nu}_{\mu L} = 560$ fb

Decays:

$$\tilde{\nu}_{\mu L} \longrightarrow \tilde{\chi}_1^\pm \mu^\mp \quad 55\%$$
$$\tilde{\chi}_1^0 \nu_\mu \quad 23\%$$
$$\tilde{\chi}_2^0 \nu_\mu \quad 22\%$$

Use $\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 + \text{jets}$ 64%

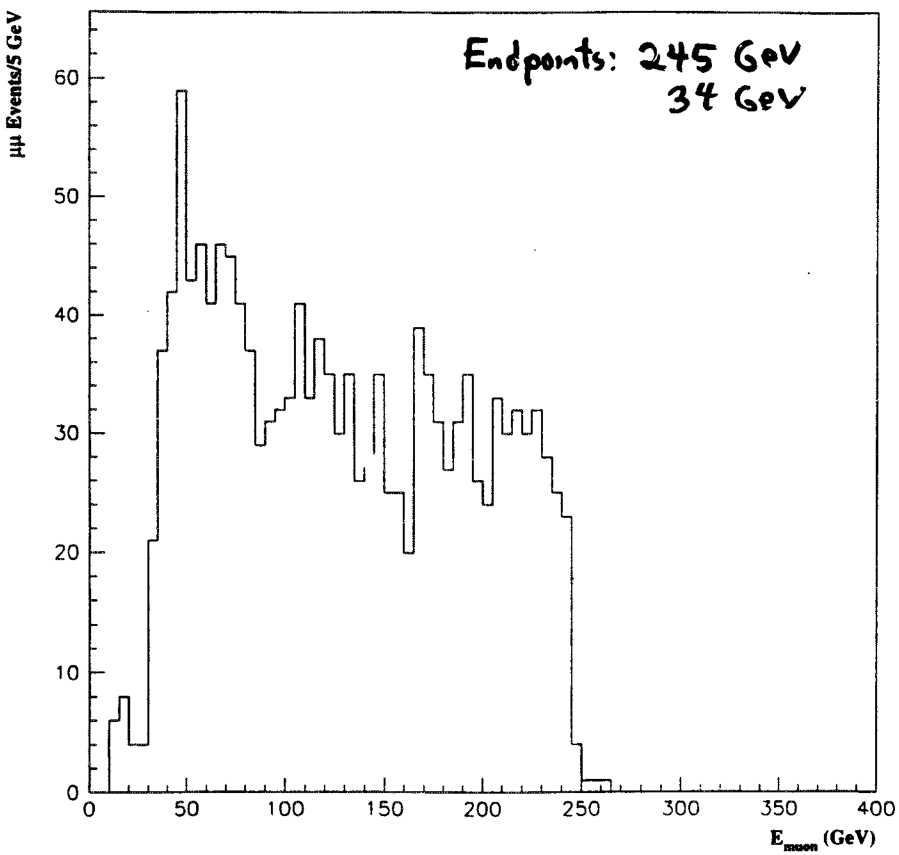
Signal for sneutrino pairs:

$$\mu^+\mu^- + \text{jets} + \not{E}_T$$

Use <u>same</u> cuts as previous except require $N_{jet} \geq 2$

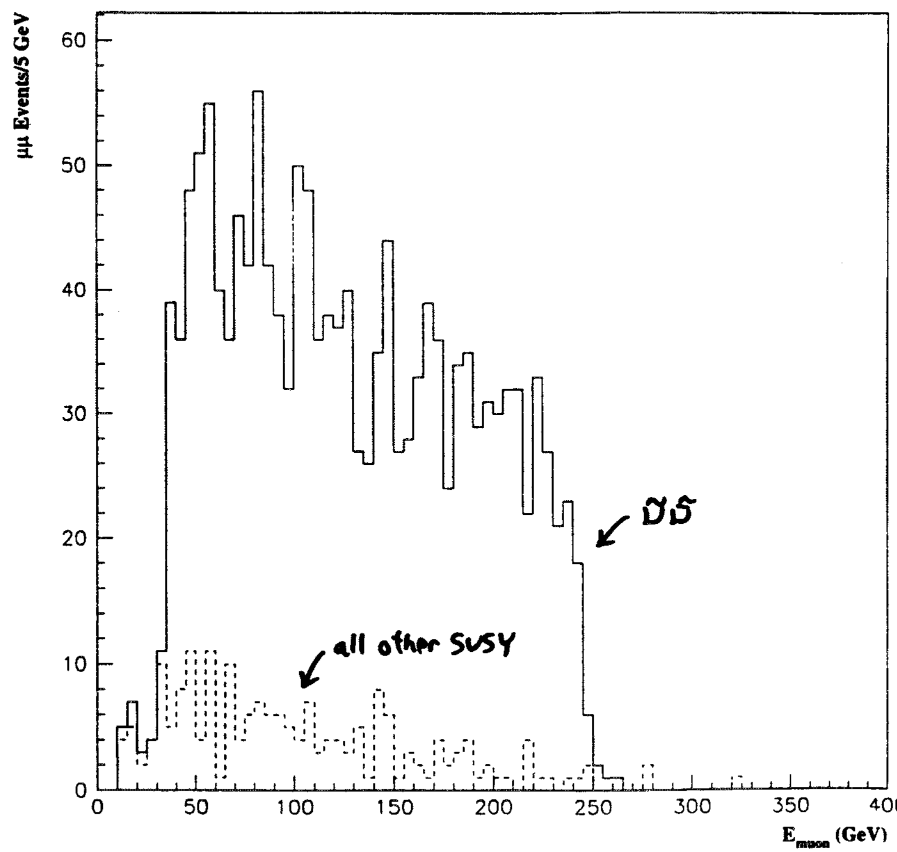
Another SUGRA point
$\sqrt{s} = 800$ GeV

$20\ fb^{-1}\ \tilde{\nu}_{\mu L}\bar{\tilde{\nu}}_{\mu L}$



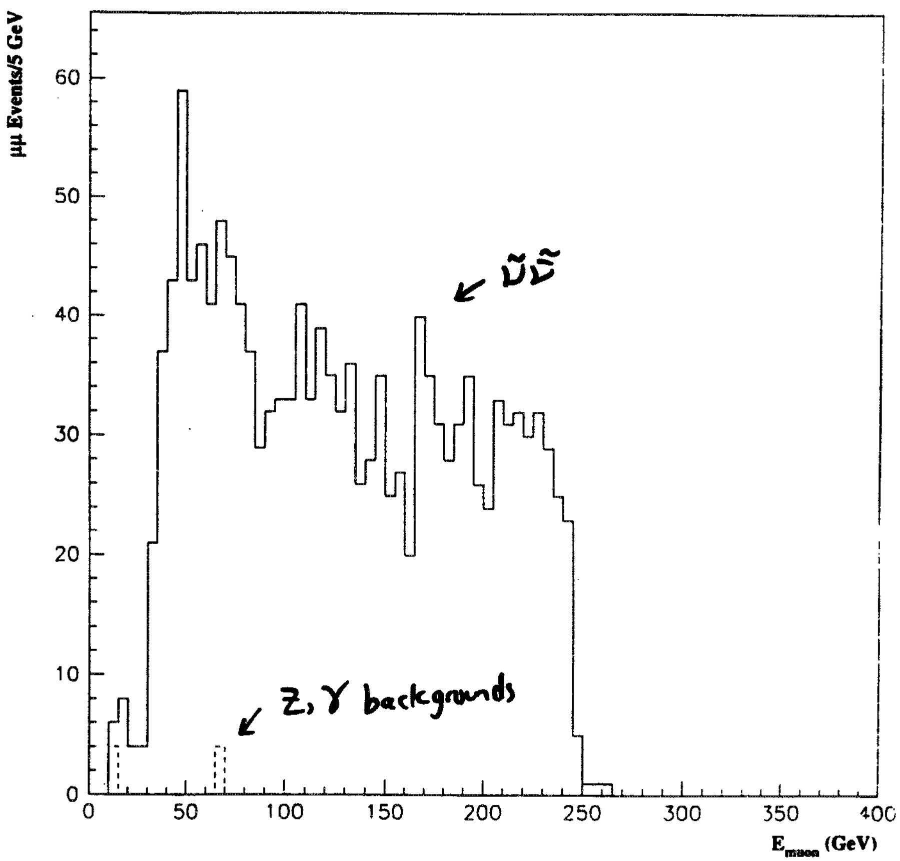
Another SUGRA point
$\sqrt{s} = 800$ GeV

$20\ fb^{-1}\ \tilde{\nu}_{\mu L}\bar{\tilde{\nu}}_{\mu L}$ + other SUSY



Another SUGRA point
$\sqrt{s} = 800$ GeV

20 fb^{-1} $\tilde{\nu}_{\mu L} \tilde{\bar{\nu}}_{\mu L}$ + SM backgrounds
(but no $t\bar{t}$)

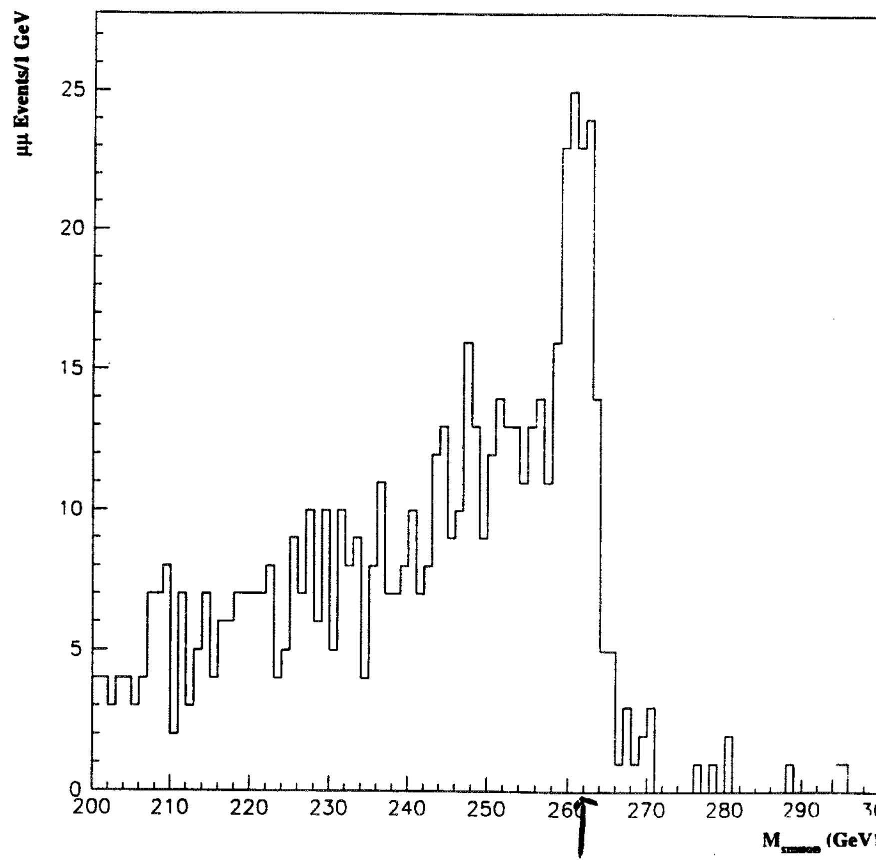


⇒ don't need to use the trilepton + jets + $\not{E}_T$ signal of Baer et al to kill backgrounds?

Another SUGRA point
$\sqrt{s} = 800$ GeV

20 fb^{-1} $\tilde{\nu}_{\mu L} \tilde{\bar{\nu}}_{\mu L}$

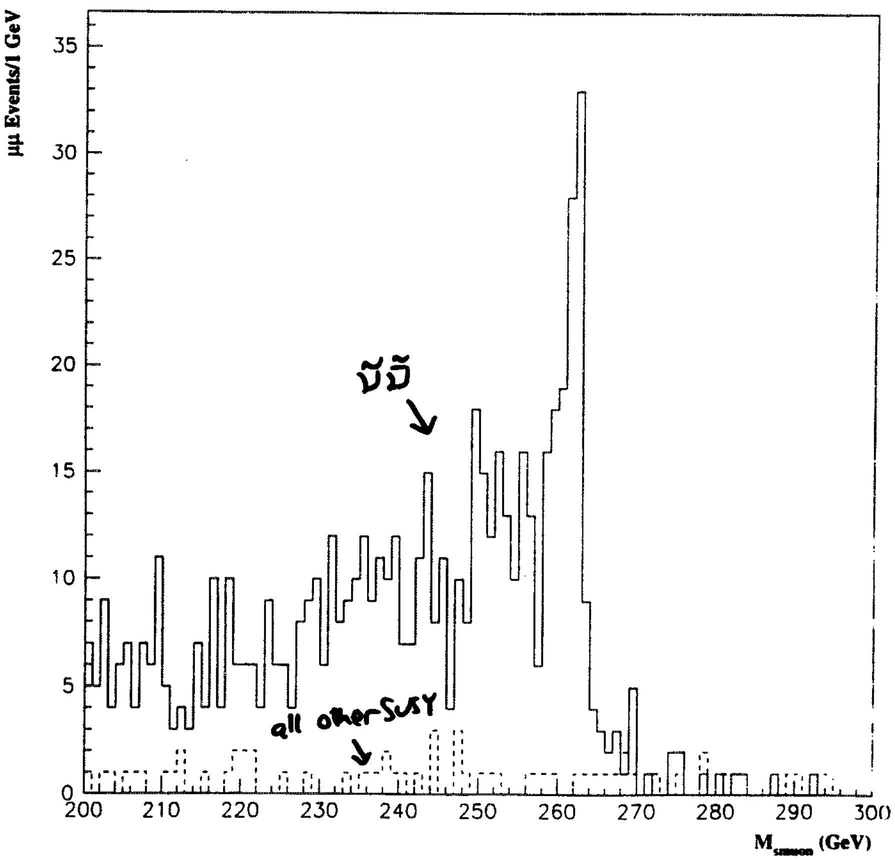
input $M(\tilde{\chi}_1^{\pm}) = 144$ GeV



262 GeV

Another SUGRA point
$\sqrt{s} = 800$ GeV

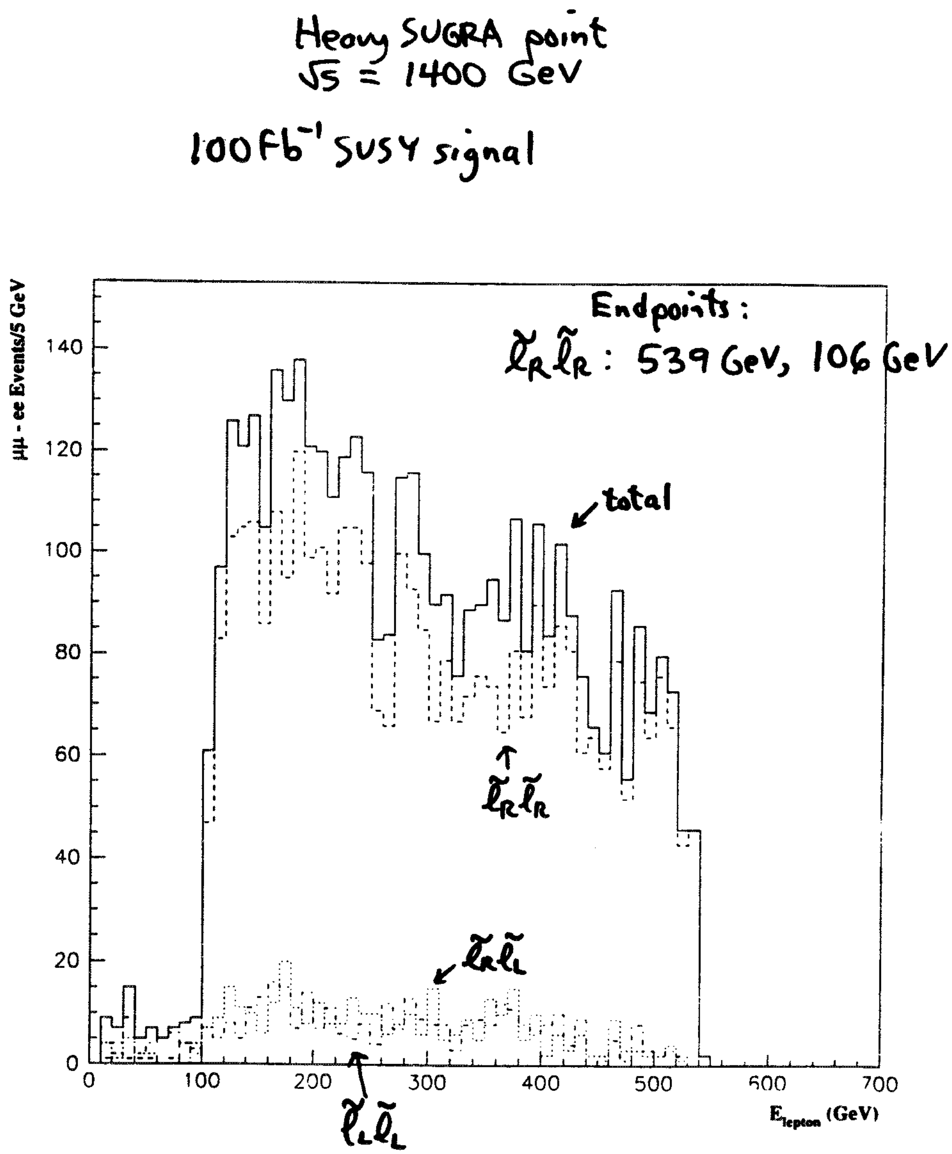
20 fb^{-1} $\tilde{\nu}_{\mu L} \tilde{\nu}_{\mu L}$ + other SUSY

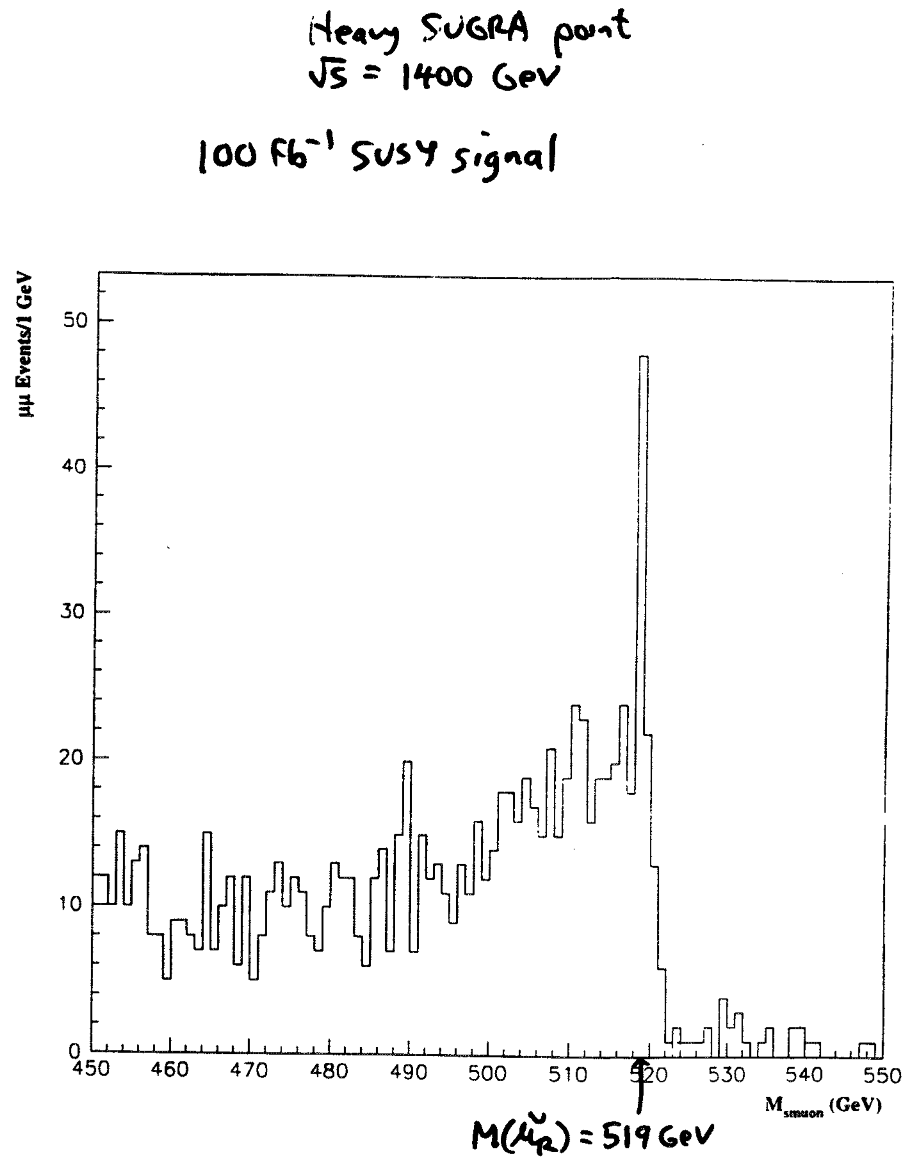


A heavy SUGRA point

$m_0 = 500$ GeV, $m_{1/2} = 350$ GeV,
$A_0 = 0$ GeV, $\tan\beta = 2$, $\text{sgn}\mu = -1$

$M(\tilde{\chi}_1^0) = 145$ GeV	$M(\tilde{\chi}_2^0) = 300$ GeV
$M(\tilde{\chi}_1^\pm) = 300$ GeV	$M(\tilde{\chi}_2^\pm) = 741$ GeV
$M(\tilde{e}_R) = 519$ GeV	$M(\tilde{e}_L) = 558$ GeV
$M(\tilde{\mu}_R) = 519$ GeV	$M(\tilde{\mu}_L) = 558$ GeV
$M(\tilde{\nu}_L) = 555$ GeV	
$M(\tilde{g}) = 906$ GeV	$M(\tilde{t}_1) = 650$ GeV
$M(h_0) = 87$ GeV	$M(H_A) = 1029$ GeV


Heavy SUGRA point
√s = 1400 GeV
100 fb⁻¹ SUSY signal
Endpoints:
l̃R l̃R : 539 GeV, 106 GeV
total
l̃R l̃R
l̃R l̃L
l̃L l̃L
μμ - ee Events/5 GeV
E_lepton (GeV)
0
20
40
60
80
100
120
140
0
100
200
300
400
500
600
700


Heavy SUGRA point
√s = 1400 GeV
100 fb⁻¹ SUSY signal
μμ Events/1 GeV
M_smuon (GeV)
M(μ̃R) = 519 GeV
0
10
20
30
40
50
450
460
470
480
490
500
510
520
530
540
550

CONCLUSIONS

1. Precision measurements w/o polarization are possible, but disentangling sleptons is a challenge.

2. Need a **minimum** of 10-20 fb^{-1} integrated luminosity for this type of analysis at $\sqrt{s}$ =500-800 GeV.

3. Detector resolutions, not backgrounds, will dominate the final error bars.

4. Variety of possible measurements complements LHC, NLC. May be prerequisite in some cases for finding s-channel resonances. $(\tilde{\nu})$ May be only game in town for heavy sleptons.

R–Parity Violation and Sneutrino Resonances at Muon Colliders

Jonathan Feng 12/11/97
UC Berkeley, LBNL

w/ J. Gunion
T. Han

hep-ph/9711414

MOTIVATION

What is new for SUSY at μ Colliders?

- Searches: Straightforward,
  $\approx$ up to kinematic limit.
- Studies: Many e^+e^- analyses apply.
- Important new features:

  Beam energy resolution – improved mass measurements

  High $\sqrt{s} = 4$ TeV – Backgrounds?

SUSY Studies at LEP:

$L = 1\ fb^{-1}$

no beam pol.

$\sqrt{s} \leq 190$ GeV

⟹ First Muon Collider

For example: Chargino Pair Production

$$e^+e^- \to \tilde{\chi}^+\tilde{\chi}^-$$

JF, Strassler

Model independent analysis of

$m_{\tilde{\chi}^+}$, $m_{\tilde{\chi}^0}$, $\frac{d\sigma}{d\Omega}$, $\tilde{\chi}^+$ branching ratios, ... :

$\frac{M_1}{M_2}$, gaugino mass unification ⟹ SU(5) GUT

χ_1^0 gauginoness ⟹ dark matter

$m_{\tilde{\nu}}$ indirect measurement ⟹ future searches

Is anything qualitatively new at a muon collider?

(Cf. h resonance.)

R_p Violation ⟹ Sneutrino Resonances.

OUTLINE

I. $R\!\!\!/_p$ Review

II. $\tilde{\nu}$ Production and Decay

III. Low energy bounds

IV. Discovery Reach and $R\!\!\!/_p$ Coupling Measurement

V. $\tilde{\nu}$ Resonance Splitting.

VI. Conclusions

$R\!\!\!/_p$ REVIEW

$$W_{R_p} = H_1 L E + H_1 Q D + H_2 Q U$$

gives the SM Yukawa couplings, respects

$$R_p = \begin{cases} +1, & \text{SM} \\ -1, & \text{superpartner.} \end{cases}$$

But if R_p is violated,

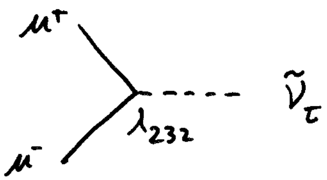
$$H_1 = \begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix} \longleftrightarrow L = \begin{pmatrix} \tilde{\nu} \\ \tilde{\ell} \end{pmatrix}$$

$$W_{R\!\!\!/_p} = \lambda_{ijk} L_i L_j E_k + \lambda'_{ijk} L_i Q_j D_k$$

Renormalizable, gauge-invariant terms.

$\tilde{\nu}$ Production

R_p Violation $\Rightarrow$ $h \leftrightarrow \tilde{\nu}$



Dimopoulos, Hall
Barger, Giudice, Han
Dreiner, Lola
Erler, JF, Polonsky

Unique probe of $\tilde{m}$ up to $\sqrt{s}$;

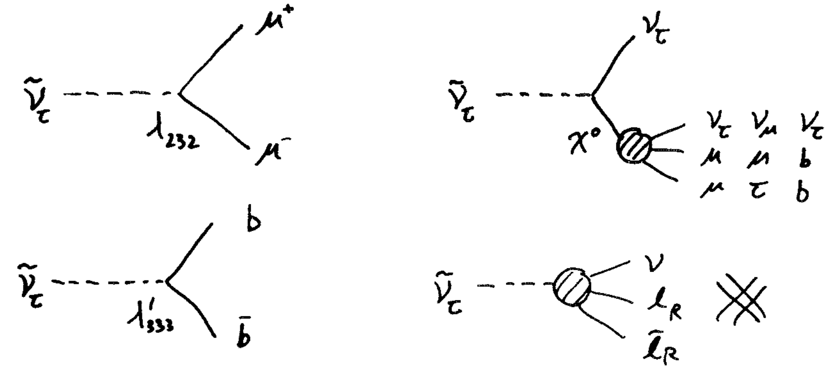
FMC, 80 GeV $< \sqrt{s} <$ 250 GeV, covers much of "typical" $m_{\tilde{\nu}}$ range

$$\bar{\sigma}(m_{\tilde{\nu}}) \propto \begin{cases} \frac{\Gamma_{\tilde{\nu}}}{\sigma_{\sqrt{s}}} B(\mu^+\mu^-) B(X), & \Gamma_{\tilde{\nu}} < \sigma_{\sqrt{s}} \\ B(\mu^+\mu^-) B(X), & \Gamma_{\tilde{\nu}} >> \sigma_{\sqrt{s}} \end{cases}$$

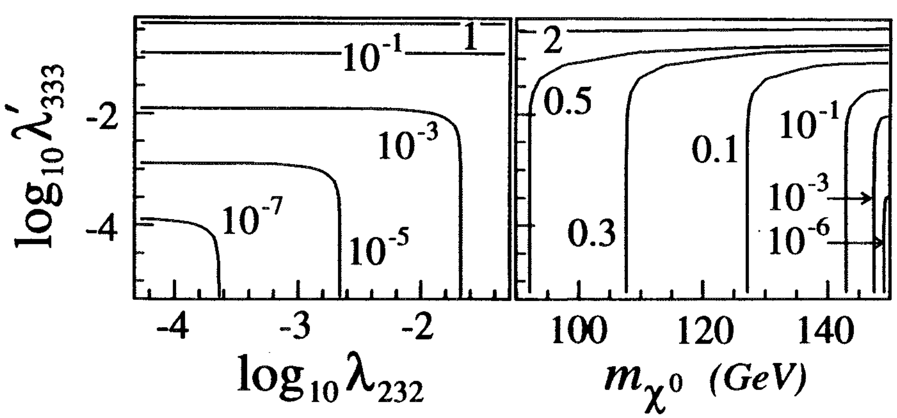
Advantages over e^+e^-:

- Expect $\lambda_{232} > \lambda_{131}$
- For small R_p couplings, small $\sigma_{\sqrt{s}}$ enhances $\bar{\sigma}(m_{\tilde{\nu}})$ – large statistics!

$\tilde{\nu}$ Decay

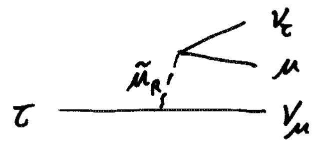


$m_{\tilde{\nu}_\tau} < m_{\chi^0}$ $\qquad$ $m_{\tilde{\nu}_\tau} > m_{\chi^0}$



$\Gamma_{\tilde{\nu}_\tau}$ (GeV)

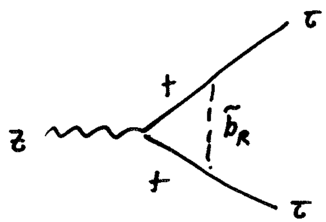
Current Bounds



$\Gamma(\tau \to \mu\nu\bar{\nu})/\Gamma(\tau \to e\nu\bar{\nu})$

$\lambda_{232} < 0.06 \left(\frac{m_{\tilde{\mu}_R}}{100\ \mathrm{GeV}} \right) \quad (2\sigma)$

Dreiner
Barger, Giudice, Han

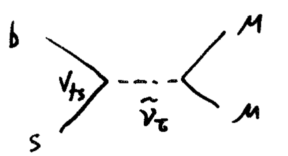


$\Gamma(Z \to \tau\bar{\tau})$

$\lambda'_{333} < 0.6 - 1.3 \quad (2\sigma)$

$m_{\tilde{q}} = 300 - 1000$ GeV

Bhattacharya, Ellis, Sridhar



$B_s \to \mu^+\mu^-$

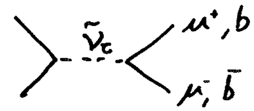
$\lambda_{232}\lambda'_{333} < 0.001 \left(\frac{m_{\tilde{\nu}_\tau}}{100\ \mathrm{GeV}} \right)^2$

Erler, JF, Polonsky

Scenario I

$m_{\tilde{\nu}} = 100$ GeV $< m_{\chi^0}$

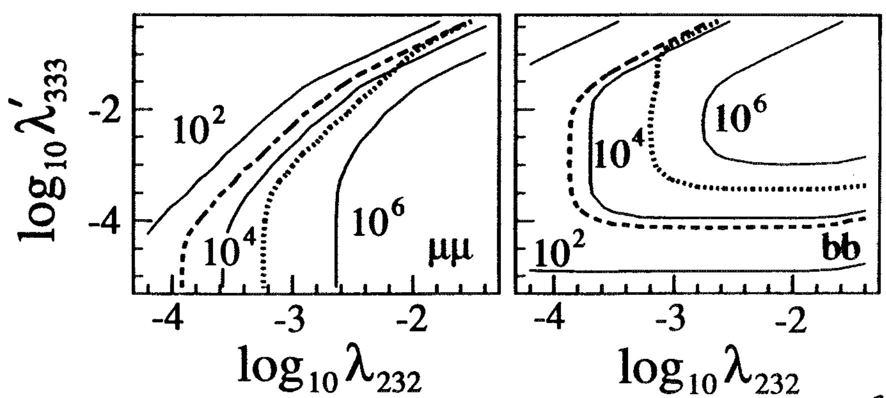
Signal is



, no $\not{E}_T$

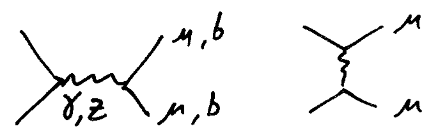
Cross Section (fb)

R = 0.063%
incl. brem.



3σ

Background is



Cuts: $\mu^+\mu^-$: $|\cos\theta| < 0.5$

$b\bar{b}$: b tagging

$|m_{f\bar{f}} - m_{\tilde{\nu}_\tau}| < 7.5$ GeV

Discovery Reach

Optimistic: Sit at peak with $L \sim .1\ fb^{-1}$

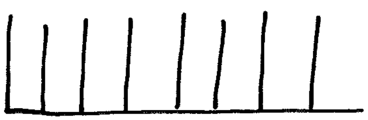
Pessimistic: Only know $m_{\tilde{\nu}_\tau}$ approx.

from fully reconstructible decays

$(\Delta m_{\tilde{\nu}} \sim 100\ MeV)$.

Split this interval into $2\sigma_{\sqrt{s}}$ intervals,

require 3σ in last 2 scan pts.

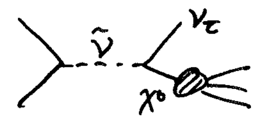


Optimize: 6 11 7 2 8 4 1 9

Can probe $\lambda, \lambda' \sim 1$

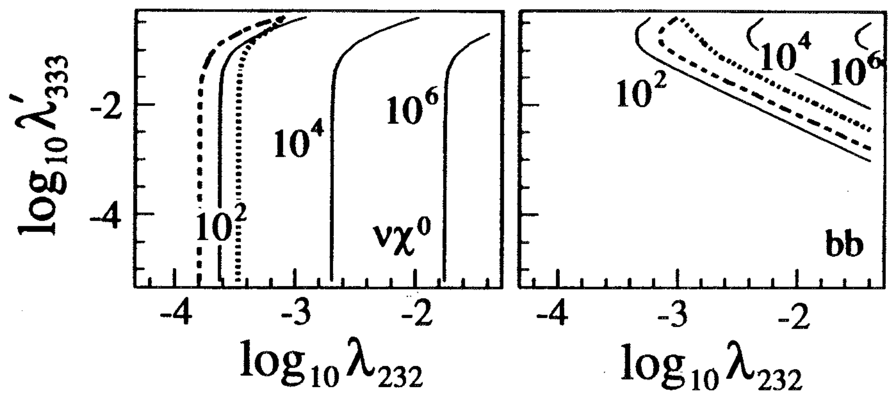
Scenario II

$m_{\tilde{\nu}_\tau} = 150\ GeV > m_{\chi^0} = 100\ GeV$

Signal is 

$\begin{Bmatrix} \mu\mu \\ \mu\tau \\ b\bar{b} \end{Bmatrix} + \not{E}_T$

Cross Section (fb) $\quad b\bar{b} \quad$ R = 0.1% incl. brem.



3σ

Background is $WW^* \to (\mu\mu, \mu\tau) + \not{E}_T$

$ZZ^* \to (\mu\mu, b\bar{b}) + \not{E}_T$

Cuts: $\not{E}_T > 25$ GeV

$p_T > 25$ GeV for each μ, τ, b

$m_{..} \sim 50$ GeV

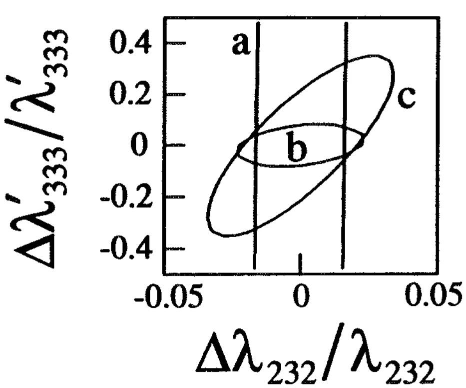
Measurements of λ, λ'

Scenario I

$L = 0.1\ fb^{-1}$, $R = 0.003\%$

$\sqrt{s} = m_{\tilde\nu_\tau}, m_{\tilde\nu_\tau} \pm \frac{\Delta}{2}$

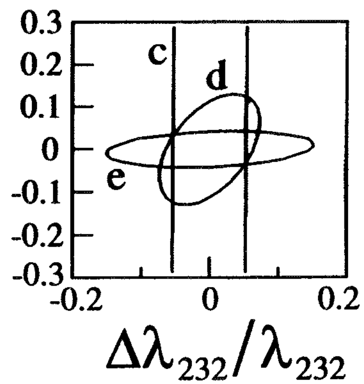
$\Delta = \max[2\sigma_{\sqrt{s}}, \Gamma_{\tilde\nu_\tau}]$



Scenario II

$\Gamma(\tilde\nu \to \nu\chi^0)$ large, calculable

$L = 3\ fb^{-1}$ at peak, $R = 0.1\%$



$\chi^2 = 1$

$\lambda_{232} = 5 \times 10^{-4}$

	Scenario I	Scenario II
$\lambda'_{333} =$	10^{-5} (a)	10^{-2} (c)
	5×10^{-4} (b)	10^{-1} (d)
	10^{-2} (c)	0.3 (e)

Eg., Scenario Ib: $\lambda'_{333} = 5\times10^{-4}(1 \pm 7\%)$

$\lambda_{232} = 5\times10^{-4}(1 \pm 3\%)$

$\tilde\nu$, $\tilde\nu^*$ Splitting

$\tilde\nu$ complex scalar

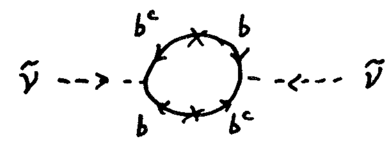
$\downarrow$ $R\!\!\!/_p$

$\tilde\nu_1$ CP-even, real scalar

$\tilde\nu_2$ CP-odd, real scalar

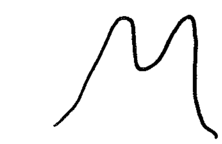
from tree level mixing with Higgses,

also loop-level:



$\Delta m_{\tilde\nu_\tau} \sim m_{\nu_\tau}$

$m_{\nu_\tau} \le 18$ MeV, so μ collider with $\sigma_{\sqrt{s}} \approx 2$ MeV could see double peak.



CONCLUSIONS

- In $\not R_p$ SUSY, $\tilde{\nu}$ resonances offer
  - Large Reach ($\tilde{m} \sim \sqrt{s}$)
  - Large Resonance Statistics
- Discovery for $\lambda \gtrsim 10^{-4}$
- Measurements at 1-10% level possible.
  (Note: χ^0 decay gives only ratios.)
- Can see $\Delta m_{\tilde{\nu}}$ splitting.
  - $\not R_p$ source of neutrino masses.

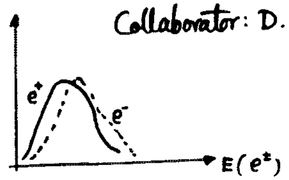
244 Blank

CP violation at the Muon Collider

Wai-Yee KEUNG
U. of Illinois at Chicago (UIC)
Collaborator: D. Chang.

Energy spectrum $E(e^-) \leftrightarrow E(e^+)$

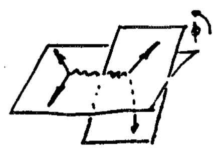
in $H \to t\bar{t}$, W^+W^-



Angular distribution

$$\phi(e^+e^-; e'^+e'^-)$$

in $H \to ZZ$, $Z \to e^+e^-$, $Z \to e'^+e'^-$



Also in $H \to t\bar{t}$, $t \to e^+ b \nu$, $\bar{t} \to e^- \bar{b} \bar{\nu}$

$$\langle \vec{p}_{e^+} \times \vec{p}_{e^-} \cdot \vec{p}_t \rangle \neq 0$$

Related Work : Gunion and Grzadkowski
Atwood and Soni
...

References.

- C. Schmidt, M. Peskin PRL 69, 410 ('92)
- G. Kane, G. Ladinsky and C.P. Yuan PR D 45, 124 ('92)
- Grzadkowski and Gunion PL B289, 440 ('92)
- Bernreuther et al (Heidelberg Group) NP B388, 53 ('92)

} t

- Hagiwara et al, NP B282, 253 ('87)

Gavela et al PRD39, 1870 ('89)

Bilal, Massó, DeRújula NP B355, 549 (1991)

} WW

Related Works:

Grzadkowski ...

Soni and Xu, etc.

He, Ma and McKellar (Melbourne)

Christova and Fabbrichesi CERN

Donoghue and Valencia

Cuypers and Rindani

Higgs : CP carrier

SM : NEEDS three generation interference (K , B physics)

MSSM: probably in $\tilde{e}, \tilde{\mu}, \tilde{\tau}$ oscillation — Arkani-Hamed, Cheng, Feng and Hall.

No CP-even and CP-odd Higgs mixing — KEUNG and Bowser-Chao PRD 56, 3924 (97)

$m_{12}\, \phi_1^\dagger \phi_2 + \lambda_5 (\phi_1^\dagger \phi_2)^2$: both terms competing

↳ absent in SUSY

2HDM and Beyond ✓

$$\mathcal{L} = -(\sqrt{2} G_F)^{\frac{1}{2}}\, \bar{t}\left(A \frac{1-\gamma_5}{2} + A^* \frac{1+\gamma_5}{2}\right) t\, H^0$$

phase cannot be rotated away because of the mass term $m \bar{t} t$.

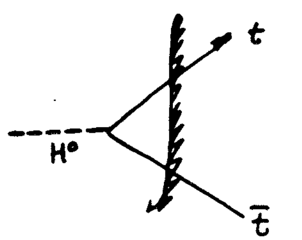
$$\mathcal{L} = -\sqrt{\sqrt{2} G_F}\, \bar{t}\,(A_R \mathbb{1} - i A_I \gamma_5)\, t\, H^0$$

p-wave   s-wave

$\text{Amp}(H^0 \to t_L \bar{t}_L) \sim A_R \beta + i A_I$

$\text{Amp}(H^0 \to t_R \bar{t}_R) \sim A_R \beta - i A_I$

$\sigma(t_L \bar{t}_L) \overset{?}{=} \sigma(t_R \bar{t}_R)$

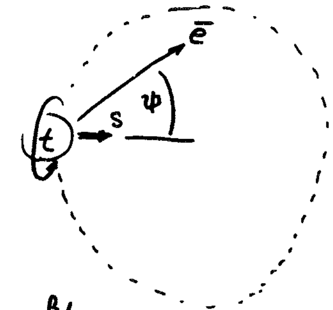


→ $\text{Amp}(t_L \bar{t}_L) \sim A_R \beta + i a + i A_I$

$\text{Amp}(t_R \bar{t}_R) \sim A_R \beta + i a - i A_I$

$P(t_L \bar{t}_L) - P(t_R \bar{t}_R) \sim 4 a A_I$

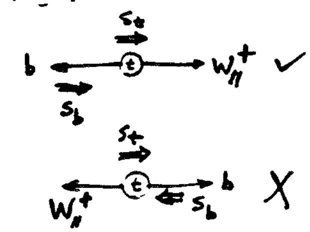
$t \to b\, \bar{e}\, \nu$



$$\frac{dN}{d\cos\psi} = 1 + \cos\psi$$ ✓

when t is moving

$\bar{e}$ has higher energy profile from t_R than t_L.

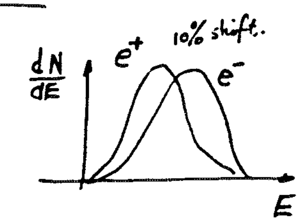


In parallel,

e has higher energy profile from $\bar{t}_L$ than $\bar{t}_R$.

So, in $t_L \bar{t}_L$ production

$$E_e > E_{\bar{e}}$$



but in $t_R \bar{t}_R$ production

$$E_e < E_{\bar{e}}$$

If $t_L \bar{t}_L$ and $t_R \bar{t}_R$ are produced equally, difference is even out. But $N(t_L \bar{t}_L) \neq N(t_R \bar{t}_R)$;

⇒ Asymmetry in the energy of the secondary leptons.

Gluon Exchange

Chang, K.

$$i\mathcal{M} = \left(-\frac{m_t}{v}\right) g^2 \frac{1}{f^2}\, \bar{u}\, \frac{\gamma^\mu (\not k + m)(AP_L + A^* P_R)(\not k' + m)\gamma_\mu}{(k^2 - m^2)\,(k'^2 - m^2)}\, v\, \frac{d^4k}{(2\pi)^4} \cdot C_F$$

C_F = 4/3 QCD

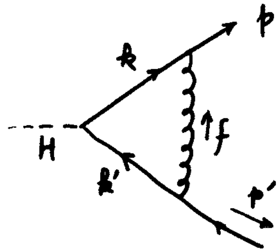
$$\mathrm{Im}\,\mathcal{M} = \left(-\frac{m_t}{v}\right)\frac{g^2}{f^2}\, \bar{u} \left(\gamma^\mu (\not k + m)(AP_L + A^* P_R)(\not k' + m) \dots\right) v \left(\frac{d\Omega}{4\pi}\right)\frac{\beta}{16\pi} \cdot C_F$$

$$(\dots) = 4\, k\cdot k' (AP_L + A^* P_R) + 4m^2 (AP_R + A^* P_L)$$

$$-2m\, \not k' (AP_L + A^* P_R) - 2m\, \not k\, (A^* P_L + AP_R)$$

$\not k' = \not p - \not f \doteq m - \not f$, $\quad \not k = -\not p' - \not f \doteq m - \not f$

$$\to 2m\, \not f\, (2\,\mathrm{Re}\,A)$$



Since $\int \frac{f^\mu}{f^2} \frac{d\Omega}{4\pi} = -\frac{p^\mu - p'^\mu}{m_H^2 \beta^2}$

$$\mathrm{Im}\,\mathcal{M} = \left(-\frac{m_t}{v}\right)\left(-\frac{g^2}{2\pi}\right)\left(\frac{m^2}{m_H^2 \beta}\right)(\mathrm{Re}\,A)\, \bar{u}\, v \cdot C_F$$

$$i\mathcal{M} = i\left(-\frac{m_t}{v}\right) \bar{u} \left[AP_L + A^* P_R - i \frac{\alpha_s}{2\beta} \frac{4m^2}{m_H^2} \mathrm{Re}\,A \right] v$$

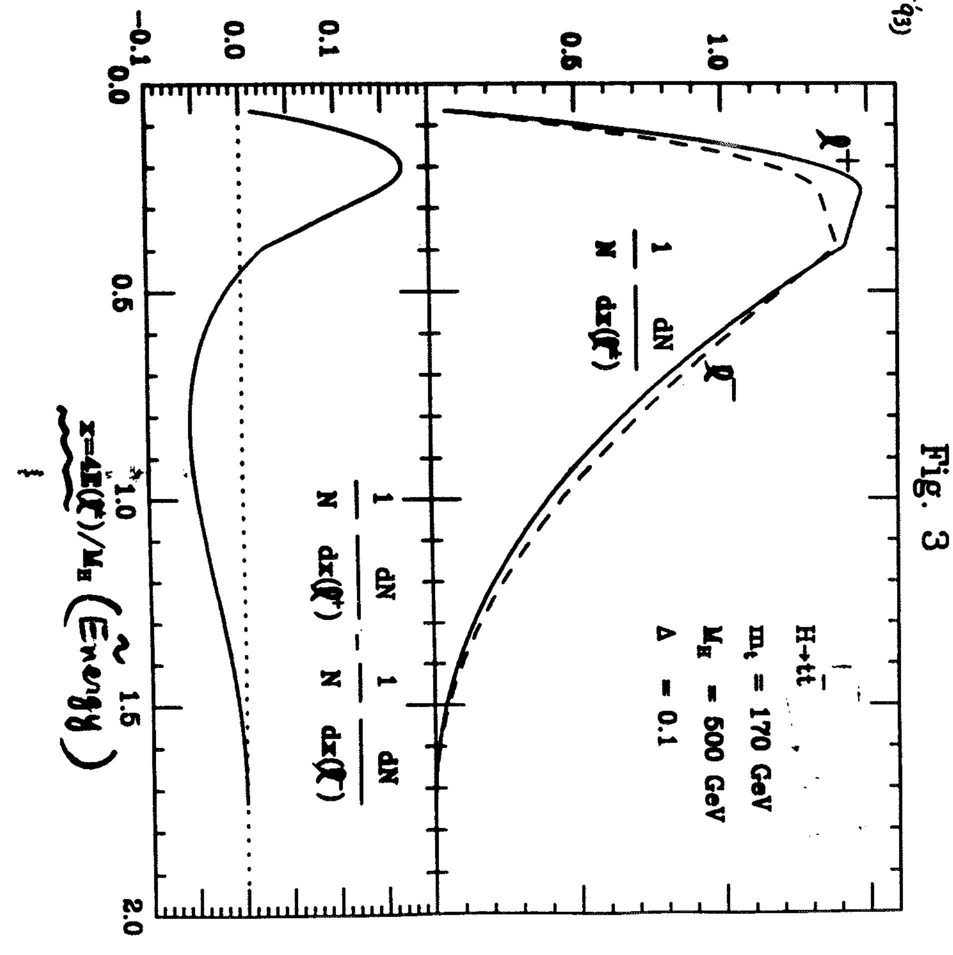
$$\frac{N(t_L \bar{t}_L) - N(t_R \bar{t}_R)}{N(H \to t\bar{t}\ \text{all})} = \frac{C_F \alpha_s\, A_R A_I\, (4m_t^2/M_H^2)}{\beta^2 A_R^2 + A_I^2}$$

β: velocity $\sqrt{1 - \frac{4m^2}{s}}$

$\parallel$

Δ

PL, B305, 261('93)



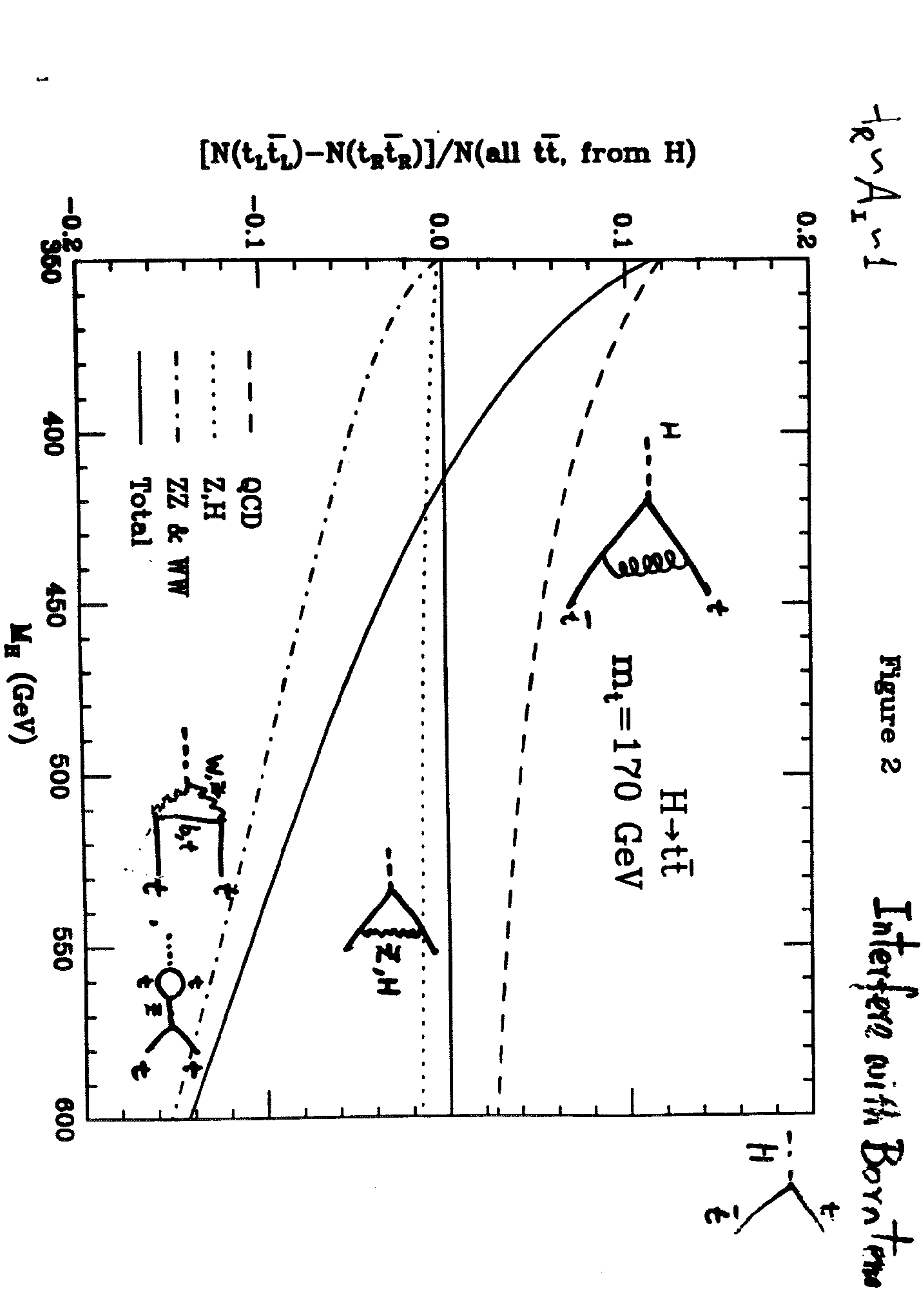
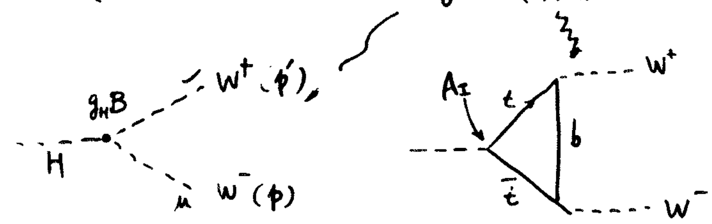


Figure 2

Interfere with Born term

$$\mathcal{M}(H\to W^-W^+) = i g_H B g^{\mu\nu} + (D/M_H^2)\,\epsilon^{\mu\nu\alpha\beta} p_\alpha p'_\beta$$



$\mathcal{M}_{RR} = g_H(B - \frac{i}{2}D\beta)$; $\mathcal{M}_{LL} = g_H(B + \frac{i}{2}D\beta)$; $\mathcal{M}_{h,\bar{h}} = -g_H B\frac{1+\beta^2}{1-\beta^2}$

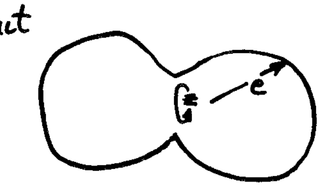
enhancing factor

when D is complex (absorptive)

$$|\mathcal{M}_{RR}|^2 \neq |\mathcal{M}_{LL}|^2$$

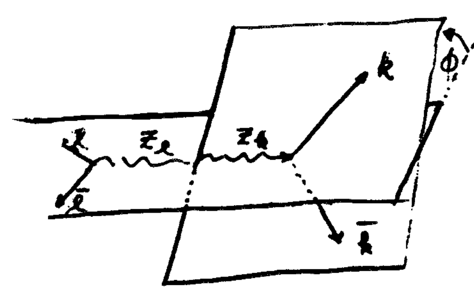
⟶ refected in ℓ^+,ℓ^- spectrum.

Same for ZZ production, but since $g_V \ll g_A$, not much energy asymmetry.



So we change our attention to <u>DISPERSIVE PART</u> in D

Need azimuthal phase $e^{i\lambda\phi}$ to produce CPX



odd distribution in ϕ is <u>CPX</u>

Chang, Keung, Phillips, Soni & Xu.

Fig. 6

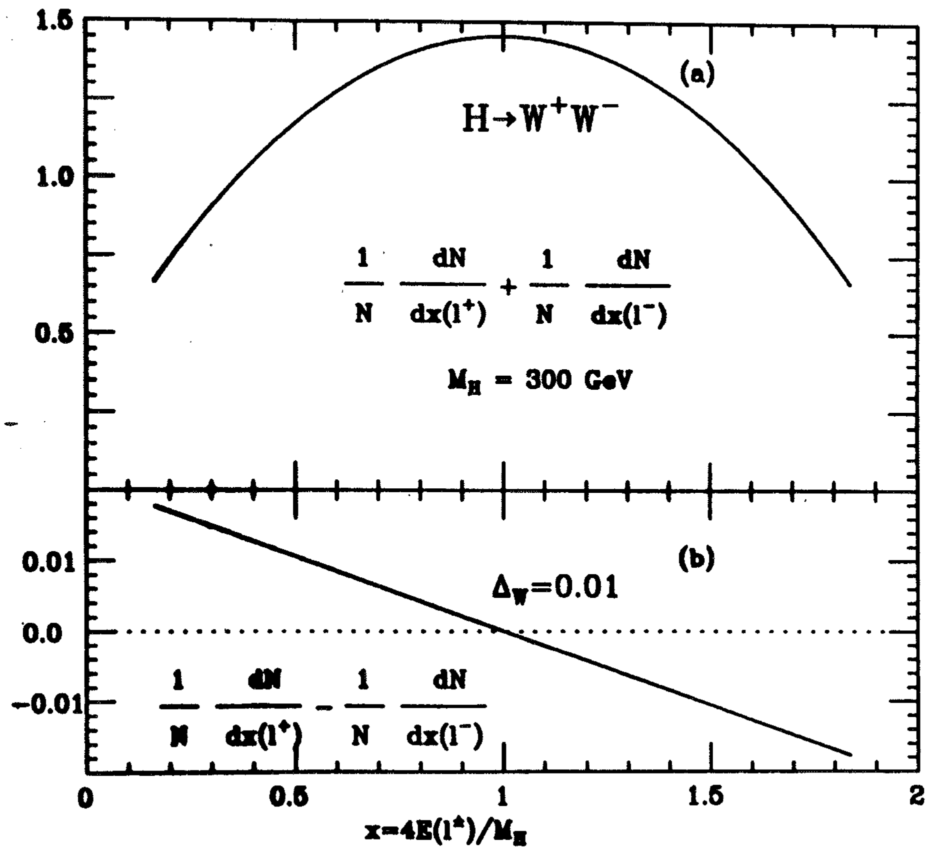
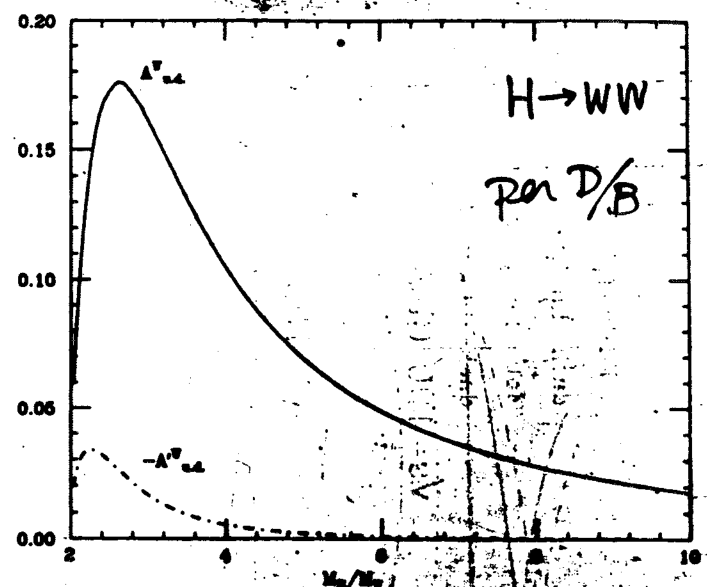


Figure 3



purely leptonic mode ✗

mixed mode $l\bar{\nu}q\bar{q}'$ or $\bar{l}\nu\bar{q}q'$

plane of $q\bar{q}'$ is un oriented

II, IV quadrant unresolved

Good to measured sin 2φ CP violating term

Measure A'^{W}_{ud}

PRD, 48, 3225 (93)

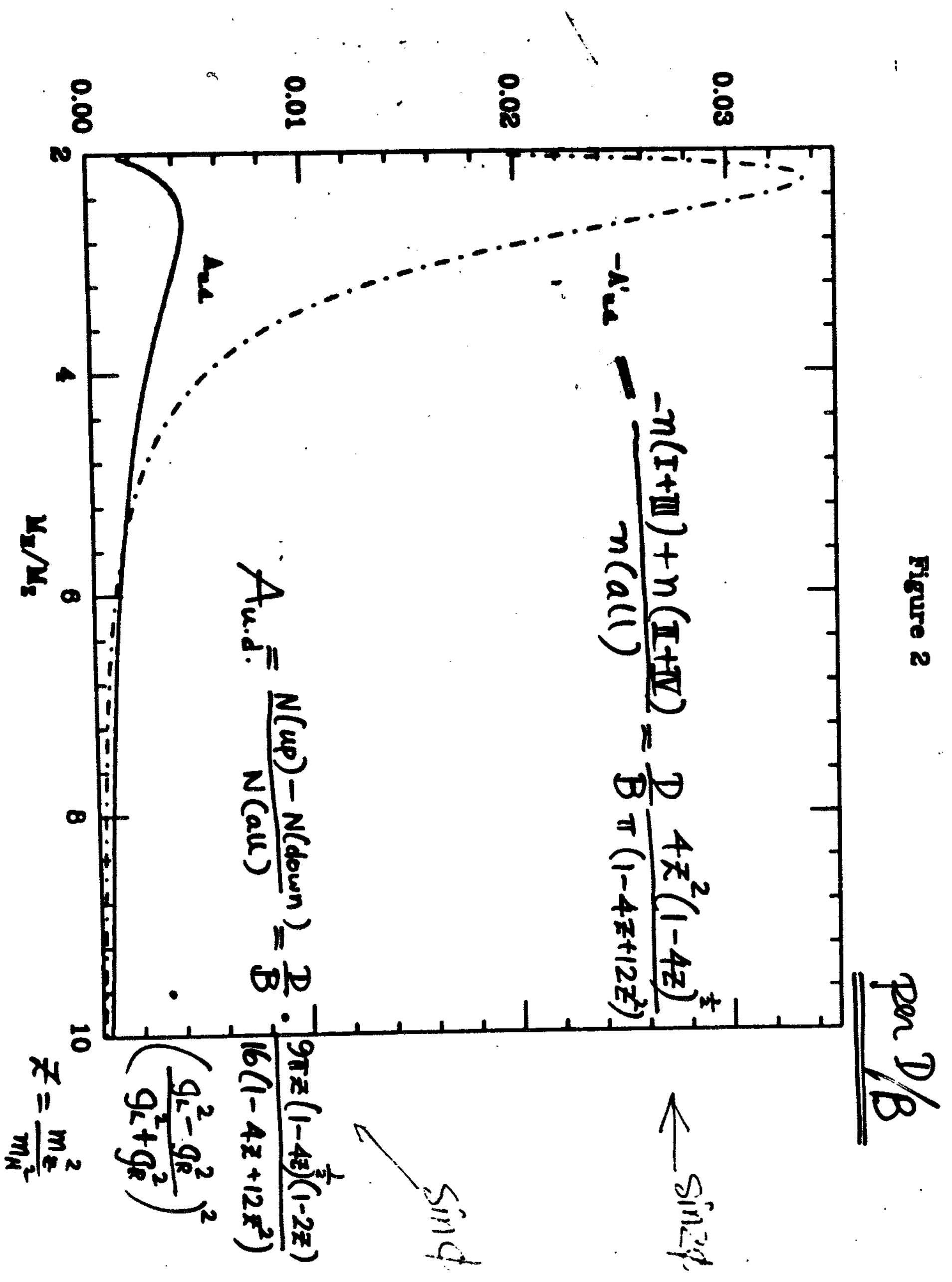


Figure 2

$$H \longrightarrow t\,\bar{t}$$

$$t \to b e^+ \nu, \qquad \bar{t} \to \bar{b} e \bar{\nu}$$

$$|M|^2 \sim \Big[(e\cdot H\,\bar{e}\cdot H - e\cdot\bar{e}\,H^2)\,A_I^2 + (e\cdot(t-\bar{t})\,\bar{e}\cdot(t-\bar{t}) - e\cdot\bar{e}\,(t-\bar{t})^2)\,A_R^2 + 4\,\varepsilon(e,\bar{e},t,\bar{t})\,A_I A_R \Big]_{b\cdot\nu,\ \bar{b}\cdot\bar{\nu}}$$

↑ Epsilon tensor, CP violation.

- Simple formula
- adaptable to Expt. Set up for simulation.

Integrated result. Cottingham and Whittingham, Grzadkowski and Gunion.

Scalar Lepton Mixing

$$\mathcal{L}_{c.c.} = \frac{-g}{\sqrt{2}} (\bar{u}_L, \bar{c}_L, \bar{t}_L)\, U_{KM} \begin{pmatrix} d_L \\ s_L \\ b_L \end{pmatrix}$$

$$U_{KM} = \begin{pmatrix} \text{real} & \text{real} & \text{real} \\ \text{real} & & \\ \text{real} & & \end{pmatrix}$$

↑ one complex phase is allowed in three generation.

$$U_{KM} = \begin{pmatrix} c_1 & s_1 c_3 & s_1 s_3 \\ -s_1 c_2 & c_1 c_2 c_3 + s_2 s_3 e^{i\delta} & c_1 c_2 s_3 - s_2 c_3 e^{i\delta} \\ -s_1 s_2 & c_1 s_2 c_3 - c_2 s_3 e^{i\delta} & c_1 s_2 s_3 + c_2 c_3 e^{i\delta} \end{pmatrix}$$

Need three generations to achieve CPX.

cheng, Feng, Hall ...
PRL 77, 1937 '96 —

SUSY leptons

$$|\tilde{\ell}_\alpha\rangle = \sum_i U_{\alpha i} |s_i\rangle \quad \text{or} \quad |s_i\rangle = \sum_i U^*_{\alpha i} |\tilde{\ell}_\alpha\rangle$$

↑ flavor states $\tilde{e}, \tilde{\mu}, \tilde{\tau}$ ↑ mass eigen states of masses, m_1, m_2 and m_3.

$\tilde{e} \to e\tilde{\gamma}$; $\tilde{\mu} \to \mu\tilde{\gamma}$ ...
(can be tagged)

$$A(\tilde{e} \to \tilde{\mu}, t) = \sum U_{..} U^*_{..}\, e^{-im_i t - \frac{1}{2}\Gamma t}$$

Barger et al
[illegible]

$$A(\tilde{\alpha} \to \tilde{\beta}; t) = \sum_i U_{\alpha i} U^*_{\beta i} \exp(-im_i t - \tfrac{1}{2}\Gamma t)$$

$$p(\tilde{\alpha} \to \tilde{\beta}; t) = |A(\tilde{\alpha} \to \tilde{\beta}; t)|^2$$

$$P(\tilde{\alpha} \to \beta) = \frac{\int_0^\infty p(\tilde{\alpha} \to \tilde{\beta}; t)\, dt}{\int_0^\infty \sum_\beta p(\tilde{\alpha} \to \tilde{\beta}; t)\, dt} = U_{\alpha i} U^*_{\beta i} U^*_{\alpha j} U_{\beta j} \cdot \frac{\Gamma}{\Gamma + (m_i - m_j) i}$$

$$= P(\tilde{\bar{\beta}} \to \bar{\alpha}) \quad \text{CPT relation.}$$

more specifically,

$$P(\tilde{\mu} \to e) = P(\tilde{\bar{e}} \to \mu)$$

but $P(\tilde{\mu} \to e) \neq P(\tilde{\bar{\mu}} \to \bar{e})$

$$A = P(\tilde{e} \to \mu) \quad - \quad P(\bar{\tilde{e}} \to \bar{\mu})$$

$$= -4\, \mathrm{Im}\left(U_{e1} U^*_{\mu 1} U^*_{e2} U_{\mu 2}\right) \mathrm{Im}\left(\phi_{12} + \phi_{23} + \phi_{31}\right)$$

$$\phi_{ij} = \frac{\Gamma}{\Gamma + (m_i - m_j) i} \; ; \quad \mathrm{Im}\, \phi_{ij} = \frac{(m_j - m_i)\,\Gamma}{\Gamma^2 + (m_i - m_j)^2}$$

A universal CPX parameter in 3-family

$$X_{cp} = \mathrm{Im}\left(U_{e1} U^*_{\mu 1} U^*_{e2} U_{\mu 2}\right) = -s_1^2 c_1 c_2 s_2 c_3 s_3 s_\delta$$

$|X_{cp}|$ maximum at $\sqrt{3}/18 \simeq 0.01$.

$Br\,(\mu \to e\gamma)$ constraints $\left(\frac{\Delta m}{m}\right) \sin 2\theta \lesssim 0.01$.

$$P(\tilde{\alpha} \to \beta) - P(\bar{\tilde{\alpha}} - \bar{\beta}) = \varepsilon_{\alpha\beta} A \; ; \quad \epsilon_{e\mu} = \varepsilon_{\mu\tau} = \varepsilon_{\tau e} = 1.$$

muon collider (e rate − $\bar{e}$ rate) ⇝ S_e

$$S_e = \frac{\sigma(\tilde{\mu}\bar{\tilde{\mu}})[P(\tilde{\mu} \to e) - P(\bar{\tilde{\mu}} \to \bar{e})] + \sigma(\tilde{\tau}\bar{\tilde{\tau}})[P(\tilde{\tau} \to e) - P(\bar{\tilde{\tau}} \to \bar{e})]}{\sigma(\tilde{\mu}\bar{\tilde{\mu}}) + \sigma(\tilde{e}\bar{\tilde{e}}) + \sigma(\tilde{\tau}\bar{\tilde{\tau}})}$$

$$= \underbrace{\left(P(\tilde{\mu} \to e) - P(\bar{\tilde{\mu}} \to \bar{e})\right)}_{-A} \; \underbrace{\frac{\sigma(\tilde{\mu}\bar{\tilde{\mu}}) - \sigma(\tilde{\tau}\bar{\tilde{\tau}})}{\sigma\,(\text{sleptons})}}_{f \,\simeq\, 0.75}$$

Since $S_\tau = -S_e$; lump the asymmetry : $S_e - S_\tau$

with 10^4 slepton events, one can probe $S_e \sim 0.02$ (5 σ effect) ; see Bowser-Chao & K, PRD.Oct, 1997.

Cheng, Feng, Hall ...
hep-ph /9704205

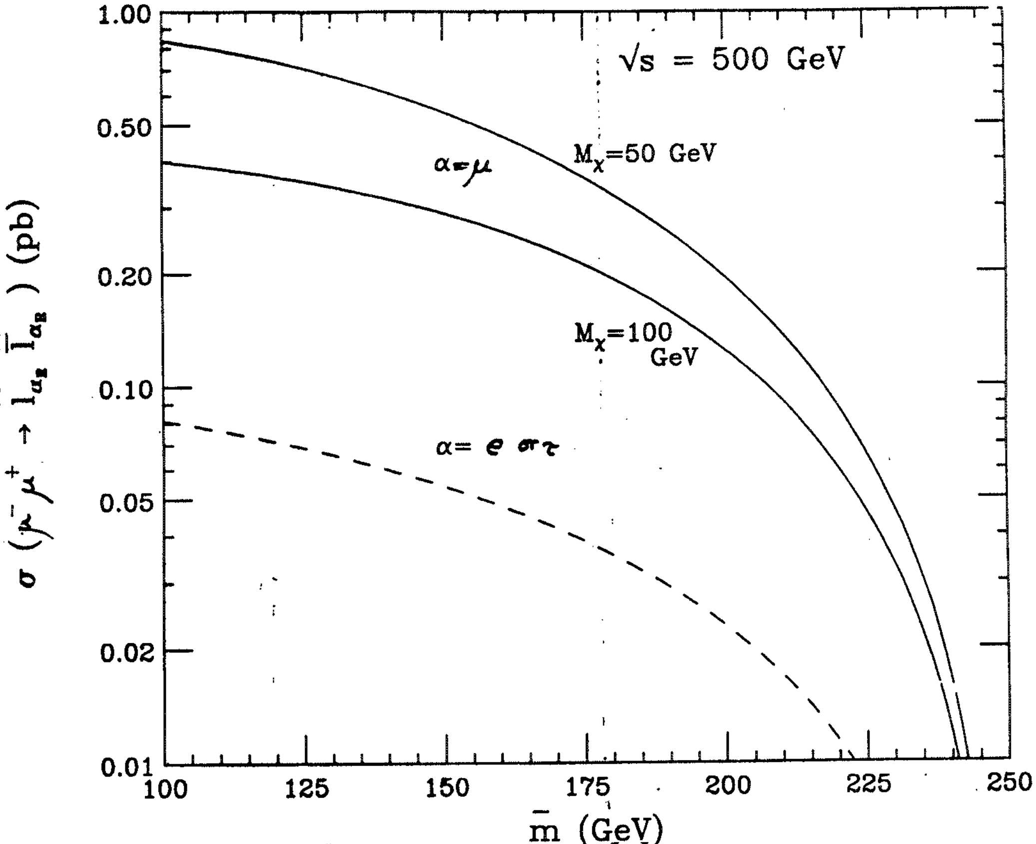
$S_e \to 0$ if $\sigma(\tilde{\mu}\bar{\tilde{\mu}}) = \sigma(\tilde{\tau}\bar{\tilde{\tau}})$ (in $\gamma\gamma$ collider)

use $N(\mu^- e^+) - N(\mu^+ e^-)$ correlated asymmetry which is not zero in general.

slepton production in muon collider

PRD, Oct (1997)

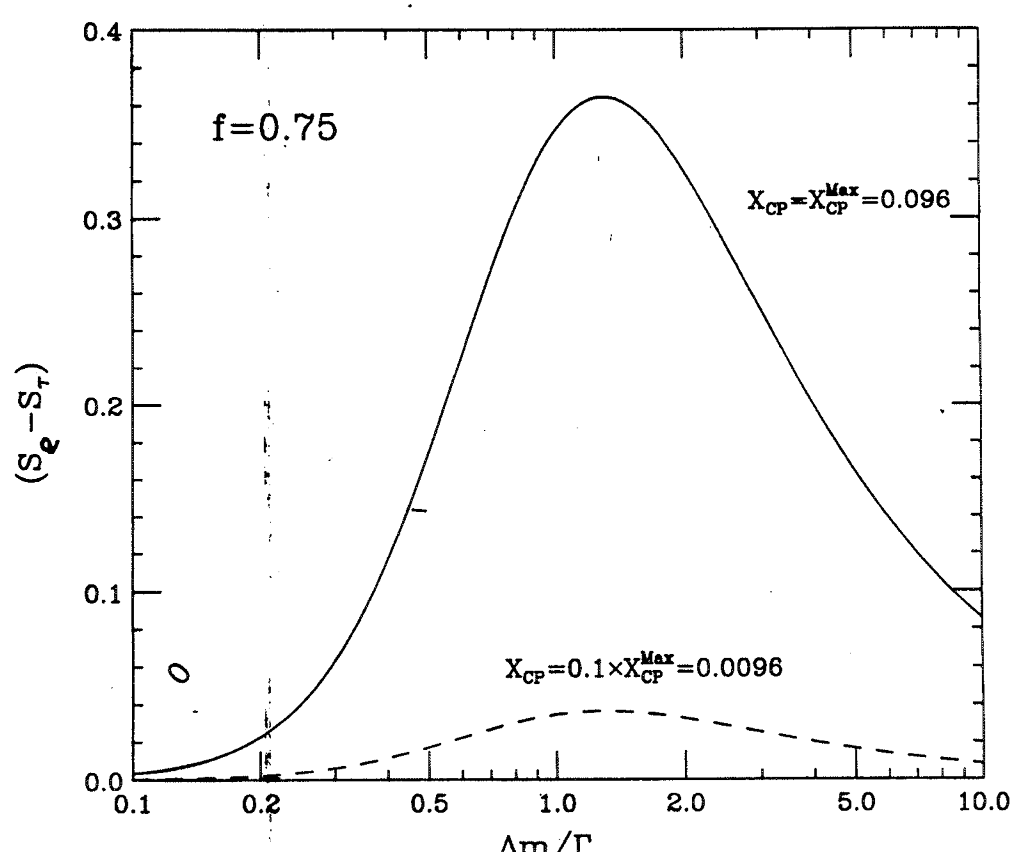
Fig. 1



muon collider at $\sqrt{s}$ = 500 GeV

PRD, Oct (1997)

Fig. 2



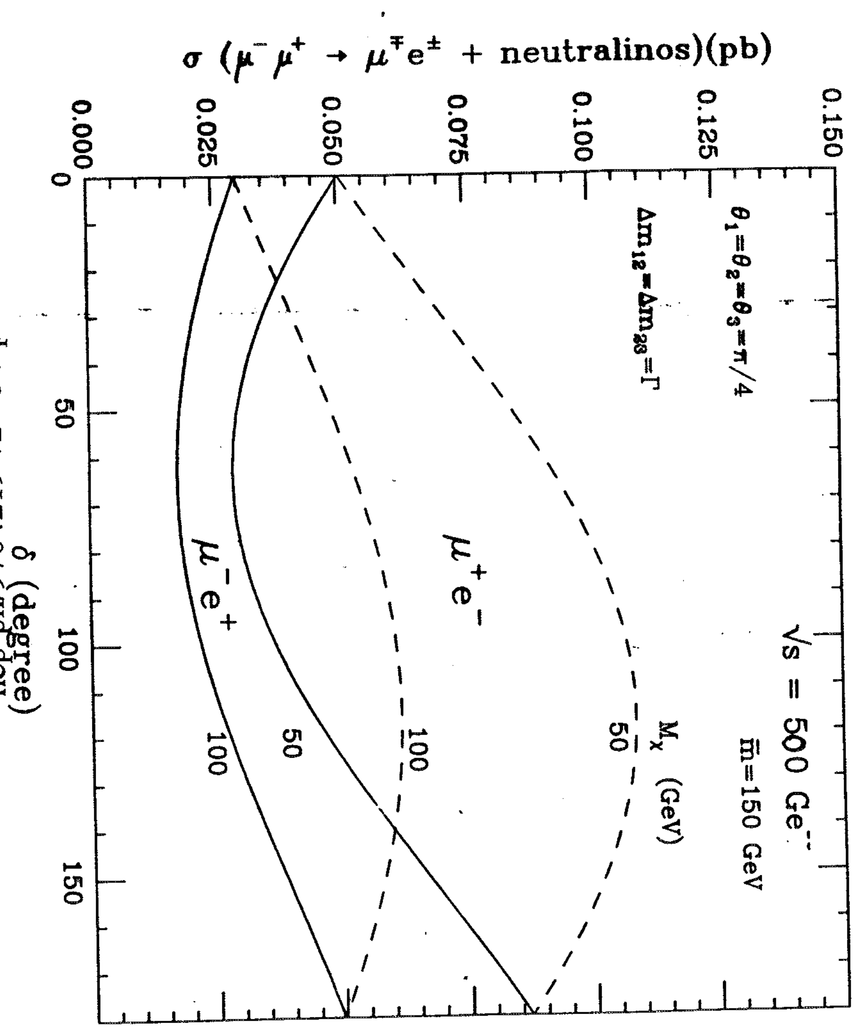

σ (μ⁻μ⁺ → μ∓e± + neutralinos)(pb)
0.000
0.025
0.050
0.075
0.100
0.125
0.150
δ (degree)
0
50
100
150
θ1=θ2=θ3=π/4
Δm12=Δm23=Γ
√s = 500 GeV
m̄=150 GeV
Mχ (GeV)
50
100
50
100
μ⁺e⁻
μ⁻e⁺

Fig. 3

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$\mu^+\mu^-$'97
San Francisco
December 11, 1997

New Particles and Interactions at High Energy Muon Colliders

1. Models and Types of New Particles
2. New Fermions
3. Leptoquarks
4. New Gauge Bosons
5. Contact Interactions
6. Final Comments

Snowmass'96: New Directions for High-Energy Physics
The 1996 DPF/DPB Summer Study on High-Energy Physics

1 Models and Types of New Particles

- Many models approximate SM at present energies but have much richer particle spectrum above 100 GeV
  - Extensions of Standard Model Gauge Group
    - (SUSY) GUT
      - Extra U(1) Factors : $E_6 \to SU(5) \times U(1)_\chi \times U(1)_\psi$
      - Left-Right Symmetric Model
        $E_6/SO(10) \to SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)$
    - non-GUT
      - Un-unified model (Georgi et al)
      - Horizontal model (Bagneid et al, Li & Ma)
      - Axigluon (Frampton et al)
      - Topcolour (Hill and Parke)
      - and on and on and on ...
  - Composite Models
  - Technicolour Models
- Many Many Models

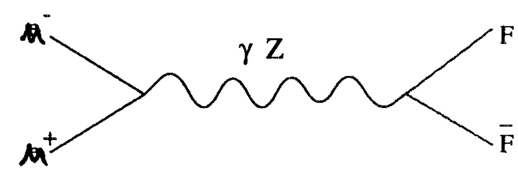
- To extrapolate to Planck scale need complete low energy particle content
- Need to elucidate and complete the TeV particle spectrum
- Many types of new particles:
  - Extra Gauge Bosons
  - Leptoquarks (B=±1/3, L=±1)
  - New Fermions
    - 4th generations: $\begin{pmatrix} t' \\ b' \end{pmatrix}_L$, t'_R, b'_R
    - Mirror Fermions: t'_L, b'_L, $\begin{pmatrix} t' \\ b' \end{pmatrix}_R$
    - Vector fermions: $\begin{pmatrix} t' \\ b' \end{pmatrix}_L$, $\begin{pmatrix} t' \\ b' \end{pmatrix}_R$
    - Singlets (like massive neutrinos)
  - Excited Fermions; Substructure so $f \to f^{(1)}(\gamma, W, Z, g)$
  - Extended Higgs Sector
  - Dileptons: $B = 0$ and $L = \pm 2$
  - Diquarks: $B = \pm 2/3$ and $L = 0$
  - Pseudo Goldstone Bosons
  - Vector Resonances
  - TRULY WEIRD

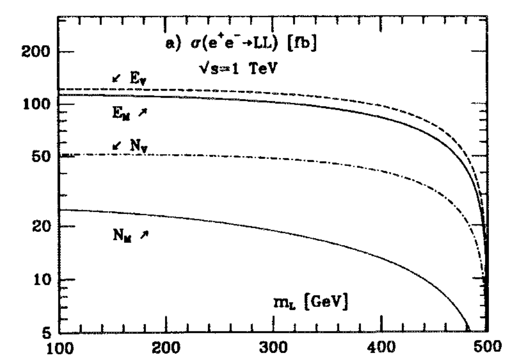
New Particles and Interactions at High Energy Muon Colliders

2 New Fermions

- 4th generation fermions
- vector-like fermions
- mirror fermions

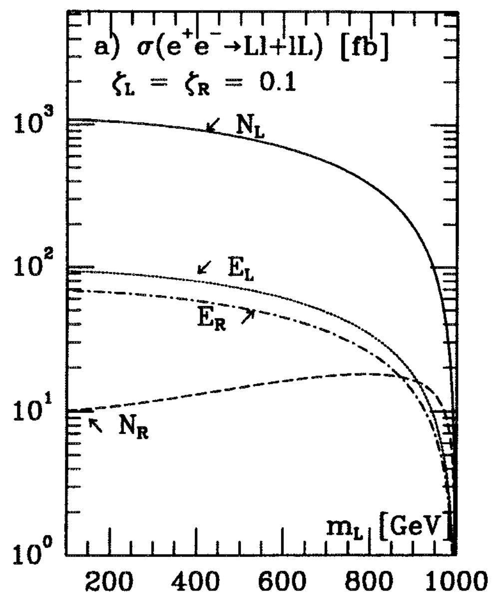
Except for singlet neutrinos new fermions couple to the photon and/or weak bosons with full strength allowing for pair production with unambiguous cross section





- Produced via $\mu^+\mu^- \to F\bar{F}$ through s-channel so $\sigma \sim \sigma_0$
- Masses close to kinematic limit can be probed

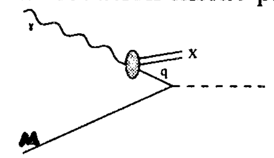
- For conventional QN's new fermions can mix with their SM partners
- Mixing constrained by non-observation of FCNC
- If mixing not too small can produce singly in association with light partners
- If possible the mass search is much higher for a given collider
- Dominant decay via charged current



New Particles and Interactions at High Energy Muon Colliders

3 Leptoquark Production

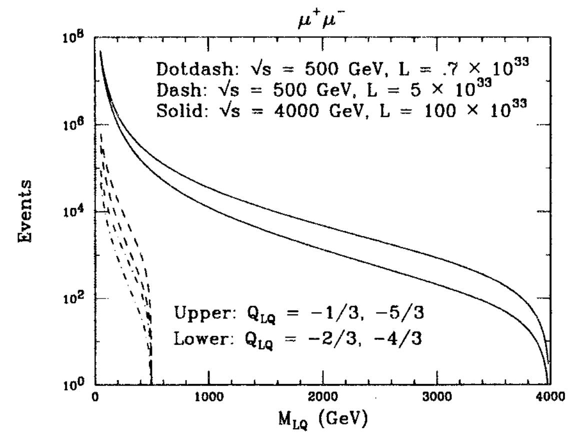
- Colour (anti-) triplets
- Spin 0 or 1
- Carry baryon and lepton quantum numbers
- Appear in Guts, technicolour, composite models
- Signal is high p_T lepton balanced by a jet
- Convolute with quark distribution inside photon



$$\sigma(s) = \int f_{q/\gamma}(z, M_s^2)\hat{\sigma}(\hat{s})dz = f_{q/\gamma}(M_s^2/s, M_s^2)\frac{2\pi^2\kappa\alpha_{em}}{s}$$

- And convolute with the photon distribution:

$$\sigma(\mu^+\mu^- \to XS) = \frac{2\pi^2\alpha_{em}\kappa}{s}\int_{M_s^2/s}^{1}\frac{dx}{x}f_{\gamma/\mu}(x, \sqrt{s}/2)f_{q/\gamma}(M_s^2/(xs), M_s^2)$$



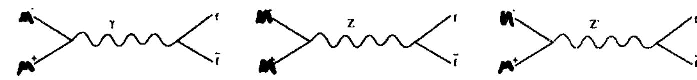
Note that produce 2nd generation LQ

Leptoquark discovery reach in GeV based on 100 events

$\mu^+\mu^-$ Colliders					
$\sqrt{s}$ (TeV)	L fb^{-1}	Scalar		Vector	
		-1/3, -5/3	-4/3, -2/3	-1/3, -5/3	-4/3, -2/3
0.5	7	250	170	310	220
0.5	50	400	310	440	360
4.0	1000	3600	3000	3700	3400

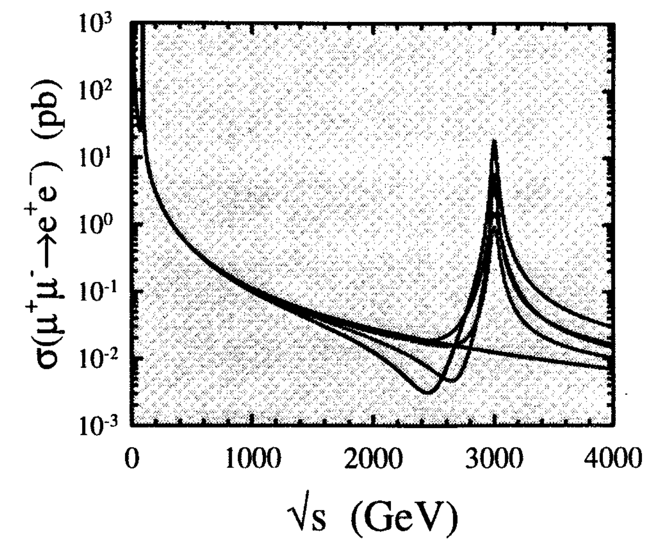
New Particles and Interactions at High Energy Muon Colliders

4 New Gauge Bosons



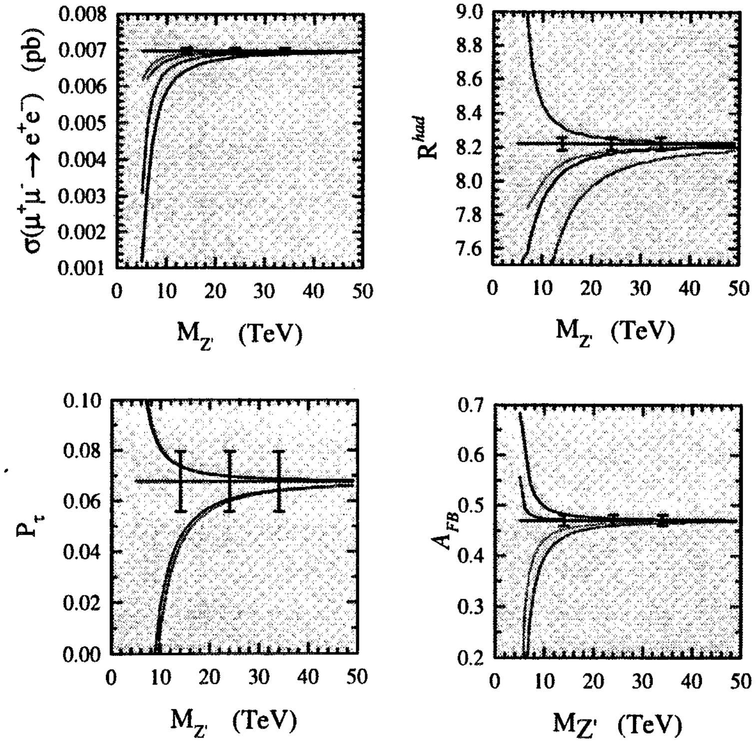
$$\frac{d\sigma_L}{d\cos\theta} = \frac{\pi\alpha^2}{4s}\left\{|C_{LL}|^2(1+\cos\theta)^2 + |C_{LR}|^2(1-\cos\theta)^2\right\}$$

$$C_{ij} = -Q_f + \frac{C_i^e C_j^f}{c_w^2 s_w^2}\frac{s}{(s-M_Z)^2 + i\Gamma_Z M_Z} + \frac{(g_{Z'}/g_{Z^0})^2 C_i^{e\prime} C_j^{f\prime}}{c_w^2 s_w^2}\frac{s}{(s-M_{Z'})^2 + i\Gamma_{Z'} M_{Z'}}$$



SM, $M_{Z'} = 3$ TeV: Z_χ, Z_{LR}, Z_{ALR}, Z_{SSM}

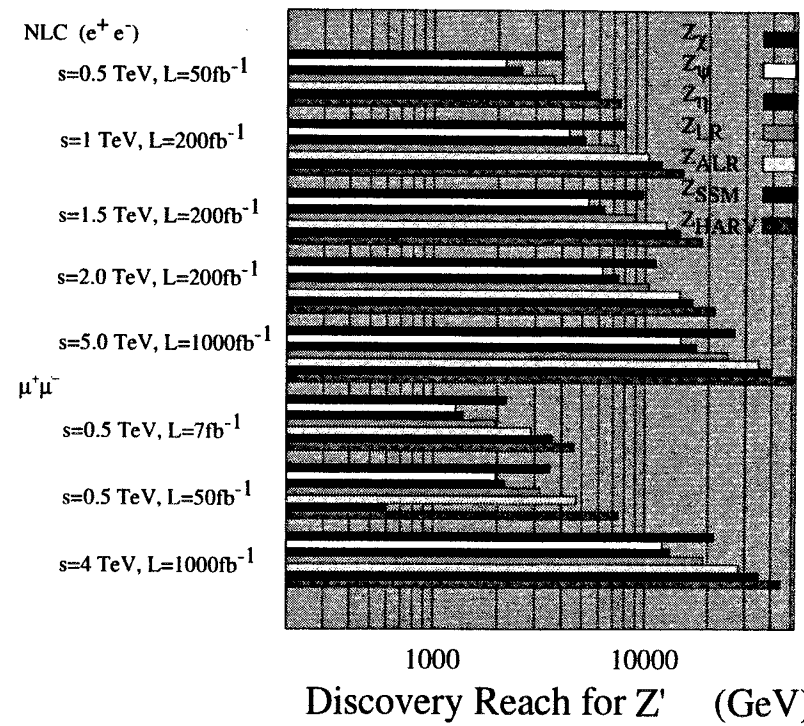
σ_f $\quad R^{had} = \sigma^{had}/\sigma_0$ $\quad A_{FB}^f$ $\quad P_\tau$ $\quad A_{LR}^f$ $\quad A_{FB}^f(pol)$



$\sqrt{s} = 4$ TeV

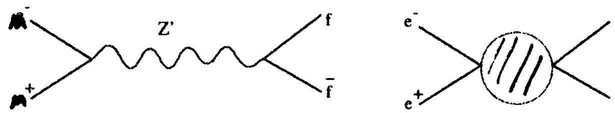
SM, Z_χ, Z_{LR}, Z_{ALR}, Z_{SSM}

New Particles and Interactions at High Energy Muon Colliders

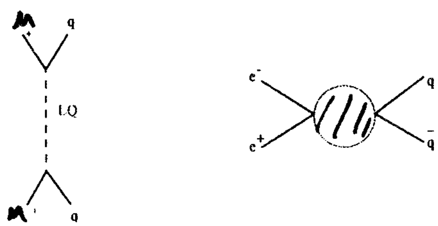


5 Contact Interactions

- Z': $\frac{g^2_{Z'}}{s-M^2_{Z'}} \overset{M_{Z'}>>\sqrt{s}}{\longrightarrow} \frac{g^2_{Z'}}{M^2_{Z'}}$



- LQ: $\frac{\lambda\alpha_{em}}{t+M^2_{LQ}} \overset{M_{LQ}>>\sqrt{s}}{\longrightarrow} \frac{\lambda\alpha_{em}}{t+M^2_{LQ}}$

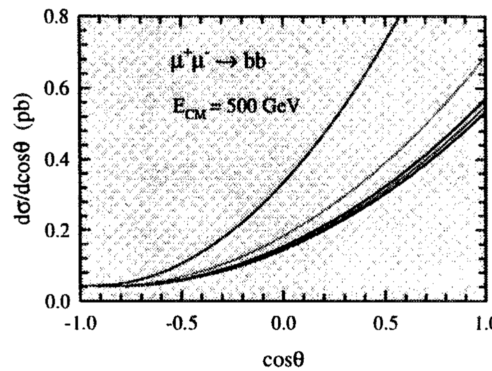


- Substructure
- Generalize to:

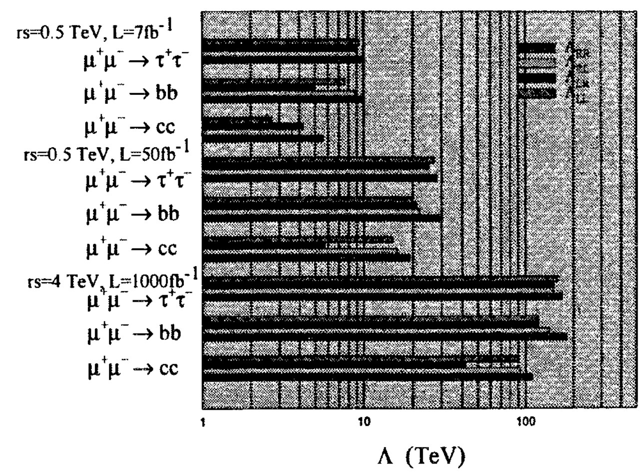
$$\begin{aligned}\mathcal{L} &= \frac{4\pi}{2\Lambda^2}[\eta_{LL}(\bar{e}_L\gamma_\mu e_L)(\bar{f}_L\gamma^\mu f_L) \\ &+ \eta_{LR}(\bar{e}_L\gamma_\mu e_L)(\bar{f}_R\gamma^\mu f_R) + \eta_{RL}(\bar{e}_R\gamma_\mu e_R)(\bar{f}_L\gamma^\mu f_L) \\ &+ \eta_{RR}(\bar{e}_R\gamma_\mu e_R)(\bar{f}_R\gamma^\mu f_R)]\,.\end{aligned}$$

We obtain

$$C_{LL} = -Q_f + \frac{C^e_L C^f_L}{c^2_w s^2_w}\frac{s}{s-M^2_Z+i\Gamma_Z M_Z} + \frac{s\eta_{LL}}{2\alpha\Lambda^2}$$



SM, $\lambda = 5$, 10, 20, 30 TeV for $\eta_{LL} = +1$.



6 Final Comments

- High energy reach
- Relatively clean environment
- Need to consider polarization
- Need Z' identification studies
- Need detailed simulation studies with backgrounds
- Look for Genuine Surprises!

μμ SAN FRANCISCO
Dec. 1997
C. A. HEUSCH

LIKE - SIGN MUON COLLIDERS

Physics Motivation
Technical features
Need for Development

FACTS OF LIFE (as expected in 1997):

- TeV-33 will operate in 2002
- LHC has been approved, will run in 2006
- (some version of) NLC will likely come online ~ 2008/10

WHY IS THE MUON COLLIDER NEEDED?

- Energy reach (w.r.t. NLC)
- SUB- Energy reach (w.r.t. LHC)
- clean (point-like) initial state (w.r.t. hadron colliders)
- precise energy definition (~ no radiative tail)
- μ^+, μ^- equally hard (or easy) to produce, define
- High luminosity
- 2 like-sign beam possibilities: $\mu^+\mu^+$, $\mu^-\mu^-$

POTENTIALLY IMPORTANT FEATURES:

I
- AS WE ATTEMPT TO UNDERSTAND THE MECHANISM(-S) OF E.W. SYMMETRY BREAKING, THE ADDED ENERGY REACH, BEYOND THE ~1.5 TeV PRESENTLY FOR THE NEXT ELECTRON COLLIDER, CAN MAKE A **DECISIVE** DIFFERENCE.

  i.e., STRONG E.W.S.B

II
- GENERATION - SPECIFIC COUPLINGS ADD A POTENTIALLY VITAL NEW FEATURE:

  ⇒ SUSY, EXTENDED GAUGE SECTOR : $L_e = 0$; $L_\mu = \pm 2$

- MASS-DEPENDENT COUPLINGS FAVOR $m_\mu \gg m_e$

  ⇒ EXTENDED HIGGS SECTOR

- FINAL-STATE RECONSTRUCTION ADVANTAGES:

  ⇒ $\sqrt{s}$ RECONSTRUCTION EASIER THAN e^+e^- DUE TO GREATLY REDUCED RADIATIVE LOSSES

  ⇒ HIGH-$p_\perp$ MUONS WILL STICK OUT; ARE MOMENTUM-ANALYZABLE

IN CATEGORY (I), $\mu\mu$ IS VITAL FOR A FULL EXPLORATION OF

STANDARD } HIGGS SECTORS
MSSM }

SUPERSYMMETRY

STRONG WW SCATTERING

ANOMALOUS COUPLINGS

COMPOSITENESS STUDIES

IN CATEGORY (II), IT OPENS THE DOOR TO THE STUDY OF

EXTENDED HIGGS SECTORS

MASSIVE MAJORANA NEUTRINOS

DILEPTON GAUGE BOSONS

IF CLEAN EXPERIMENTATION AT GOOD LUMINOSITY CAN BE ASSURED.

MANY OF THE PHYSICS FEATURES OF LIKE-SIGN CHARGED-LEPTON COLLISIONS

MØLLER SCATTERING & BEYOND

HAVE BEEN EXTENSIVELY INVESTIGATED IN THE e^-e^- CASE

→ UP TO $\sqrt{s} = 2$ TeV

→ FIRST GENERATION

→ EASILY POLARIZED FOR e^- ONLY

MUTATIS MUTANDIS,

WE CAN APPLY MOST OF THESE STUDIES TO THE SECOND-GENERATION $\mu^+\mu^+$ OR $\mu^-\mu^-$ CONFIGURATION

⇒ HIGHER $\mathcal{L}$

" $\sqrt{s}$

⇒ UNCERTAIN POLARIZATION – BUT FOR μ^+, μ^- EQUALLY

• A UNIQUE SET OF $|in\rangle$ QUANTUM NUMBERS

$\lvert in\rangle$	Q_{el}	S_z	L	L_e	L_μ	I_3^w	Y^w
$\mu_R^+\mu_R^+$	+2	1	−2	0	−2	1	2
$\mu_R^+\mu_L^+$	+2	0	−2	0	−2	½	3
$\mu_L^+\mu_L^+$	+2	−1	−2	0	−2	0	4
$\mu^+\mu^+$	+2	1,0,−1	−2	0	−2	1,½,0	2,3,4
$\mu_L^-\mu_L^-$	−2	−1	2	0	2	−1	−2
$\mu_R^-\mu_L^-$	−2	0	2	0	2	−½	−3
$\mu_R^-\mu_R^-$	−2	1	2	0	2	0	−4
$\mu^-\mu^-$	−2	1,0,−1	2	0	2	0,−½,−1	−2,−3,−4

THE FULL DEFINITION OF THESE INITIAL STATES PROVIDES A POWERFUL SET OF

SELECTION RULES

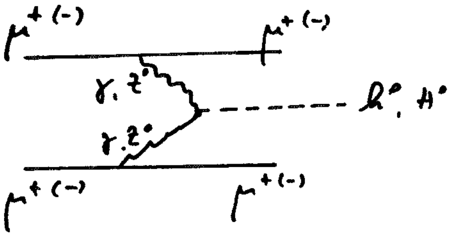
EXPERIMENTAL CHALLENGE:

HOW WELL CAN WE DO TO PROVIDE HIGHLY POLARIZED μ^+, μ^- BEAMS ?

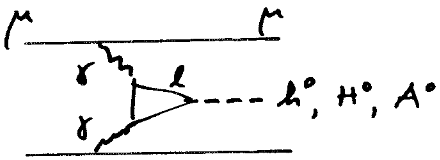
- **HIGGS SCALARS:**

SINGLE H^0, h^0 PRODUCTION

via $\gamma\gamma$, Z^0Z^0 FUSION



ADD CP-odd A^0



AT ENERGIES $\sqrt{s} > 2.5\, m_H$,

"CENTRAL PRODUCTION"

WITH MASS DETERMINATION FROM THE DETECTION OF HIGH-$p_\perp$ $\mu^{+\pm}_{(-\mp)}$ IS

THE PREFERRED DETECTION MECHANISM:

→ LARGE (SATURATED) X-SECTION

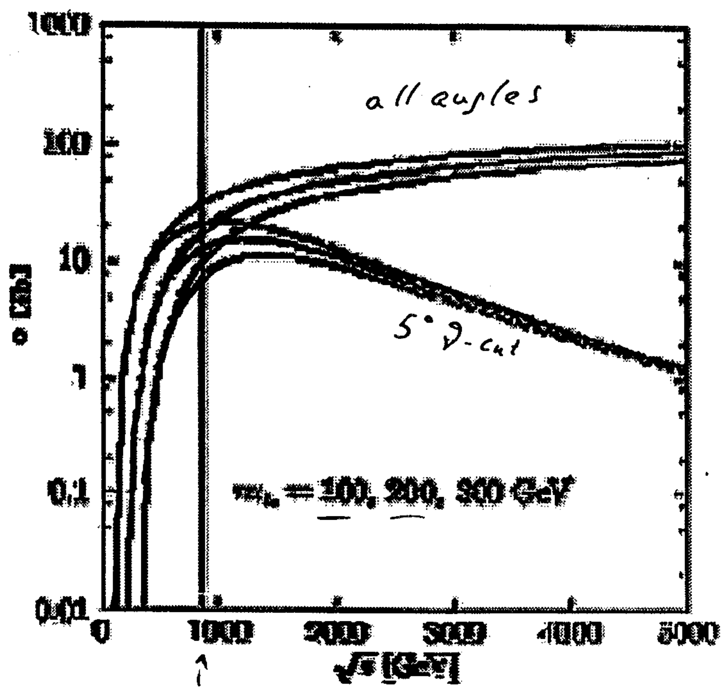
→ GOOD $m(H)$ RESOLUTION

→ APPLIES TO "INVISIBLE DECAYS"

CROSS SECTION (σ_{LL}) SATURATES

all angles $\sigma_{LL} \to$ const? $\frac{1}{m_Z^2}$ $\sqrt{s} \to \infty$

OR, WITH CUT $\vartheta_{ij} > 5^\circ$ $\sigma_{LL} \to$ const $\frac{1}{s}$ $\sqrt{s} \to \infty$



$\sqrt{s} = 850$ GeV

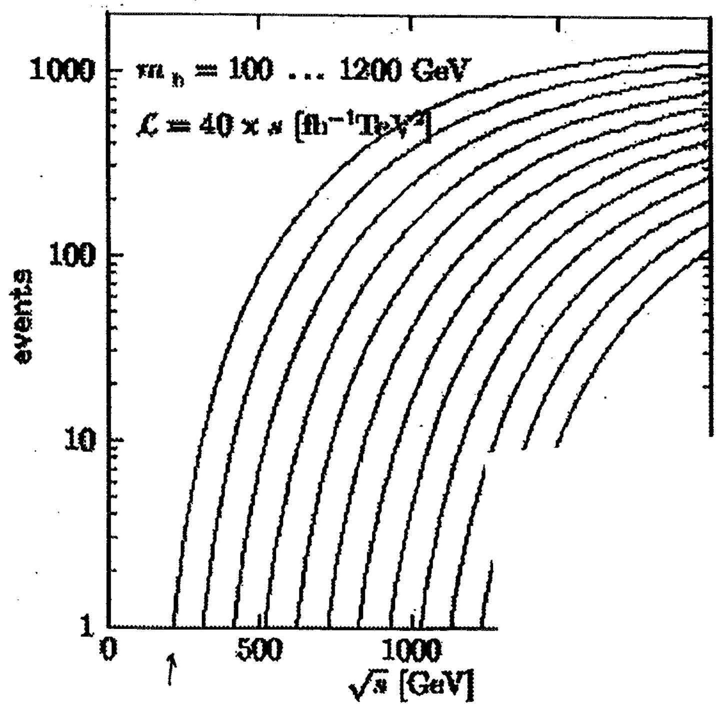
→ $\sqrt{s} = 500$ GeV is sufficient to cover a narrower m_H band: $m_H \leq 150$ GeV

$\sigma_{LL} \cdot \mathcal{L} = N_{LL}$ event rates for $m_H = [100, (100), 1200]$ GeV.

$\mathcal{L} = 40 \cdot \frac{s}{1 (\text{TeV})^2} \frac{1}{fb}$ assumed.

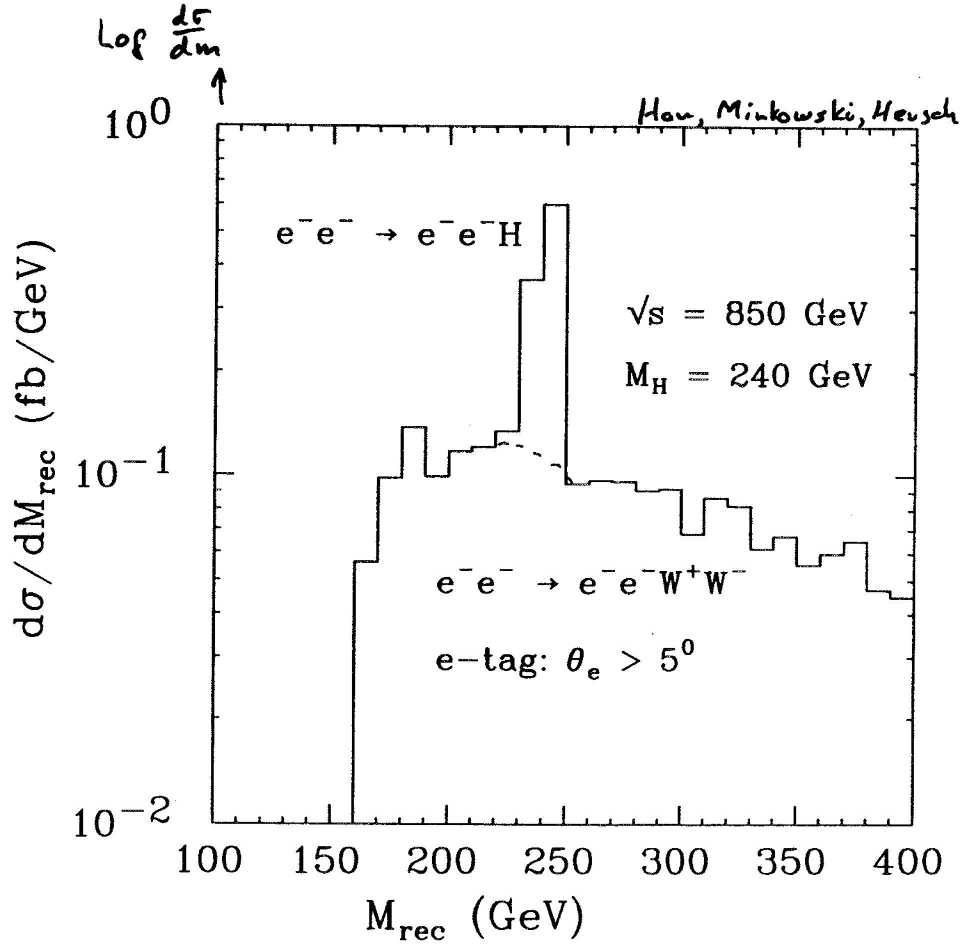
events

no angular cuts.



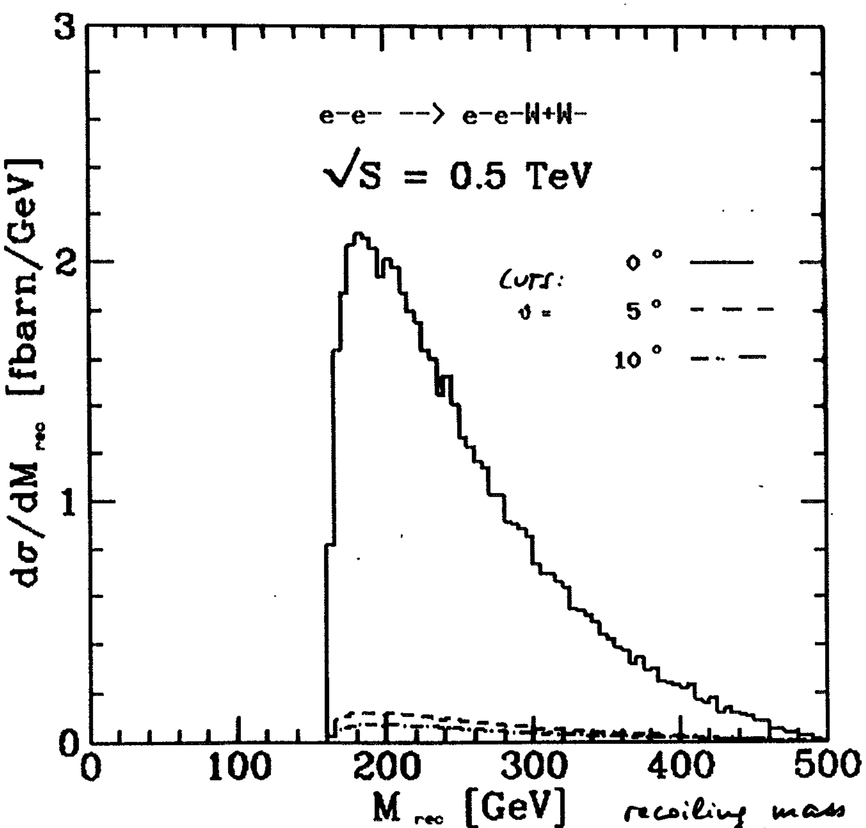
↑ $m_H = 100$ GeV

$m_{\cdot}$



PRINCIPAL BACKGROUND:

$\mu^\pm\mu^\pm$ or e^-e^- : unpolarized

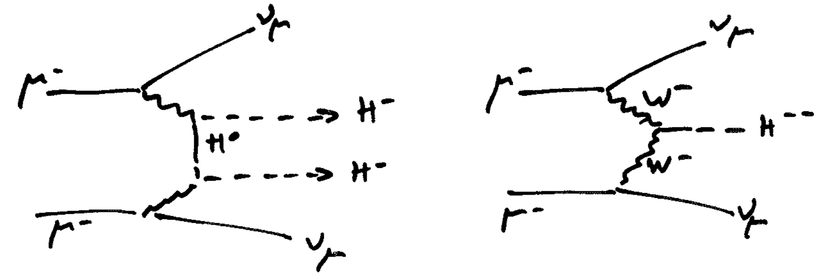


⇒ EASILY SUPPRESSED BY ANGULAR (DETECTOR) CUTS

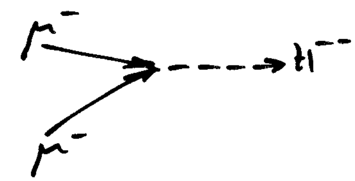
- EXTENDED HIGGS SECTOR

(STRONGLY MODEL-DEPENDENT)

W^-W^- FUSION TO $\begin{cases} H^-H^- \\ H^{--} \end{cases}$



OR, VIA DIRECT DILEPTON COUPLING



(pair production at LHC ? $H^{--}H^{++}$ ...

IN THE STANDARD $SU_{2,L}$ CASE WITH $Q_{em} = I_3^w + \frac{Y^w}{2}$

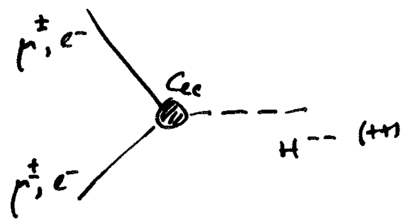
$\mu_R^-\mu_R^- \to H^{--}$ ($I^w=0$, $I_3^w=0$, $Y=-4$)

CHOOSE POL'NS: $\mu_L^-\mu_R^- \to H^{--}$ ($\frac{1}{2}$ $-\frac{1}{2}$ -3)

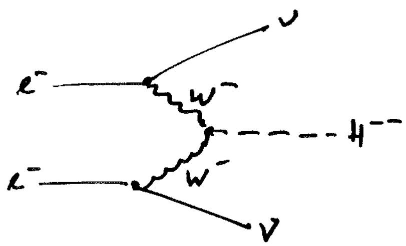
$\mu_L^-\mu_L^- \to H^{--}$ (1 -1 -2)

TO UNEARTH CORRECT REP'N

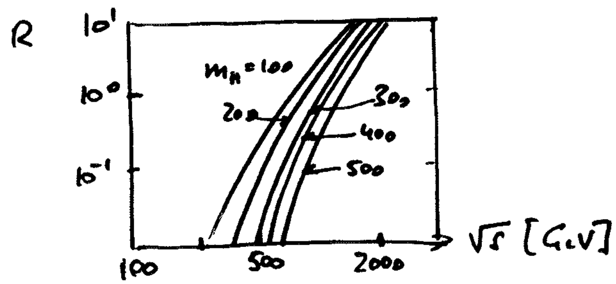
WE DO NOT KNOW THE COUPLING STRENGTH OF DIRECT $H^{--}e^-e^-$ COUPLING, c_{ee}



BUT CAN CALCULATE $W^-W^-H^{--}$ "FUSION"



TO AMOUNT TO A FULL UNIT OF R



CLEARLY, THE MUON COLLIDER IN ITS TWO LIKE-SIGN VERSIONS COULD PLAY A PIVOTAL ROLE IN ASCERTAINING THE NATURE OF A LARGER HIGGS SECTOR

μ Polarization plays a distinctive role in this!

I^w, I_3^w, Y^w CHOICES TELL THE DIFFERENCE BETWEEN MORE EXOTIC REP'S

HIGHER ENERGY
MUON vs ELECTRON MASS
} CAN VITALLY ADD TO EVIDENCE FROM e^-e^- COLLISIONS !

SUSY

IF SUPERSYMMETRY IS DISCOVERED,

MEASURING SPARTICLE

MASSES, COUPLINGS, MIXINGS

WILL BE A MAJOR CONCERN.

PRECISION SUSY MEASUREMENTS

CAN DRAW ON e^-e^-

$\mu^+\mu^+/\mu^-\mu^-$ COLLISIONS

FOR VITAL INFORMATION!

MASS DETERMINATION FOR SLEPTONS:

$e^-e^- \to \tilde{e}^-\tilde{e}^-$

$\mu^-\mu^- \to \tilde{\mu}^-\tilde{\mu}^-$

} LOW BACKGROUNDS

POLARIZATION CAN MAKE A PIVOTAL DIFFERENCE!

TAKE A HINT FROM SELECTRON CASE:

searches for $\tilde{e}^-$ production were considered by

Cuypers, van Oldenborgh, + Rückl

hep-ph/9305287

$$e^-e^- \to \tilde{e}^-\tilde{e}^- \to e^-e^-\tilde{\chi}_1^0\tilde{\chi}_1^0$$

also include $e^-\tilde{\chi}_2^0$, $\nu\chi_1^-$ where relevant

SM backgrounds:

$$e^-e^- \to e^-e^-Z^0$$
$$\hookrightarrow \nu\bar{\nu}$$

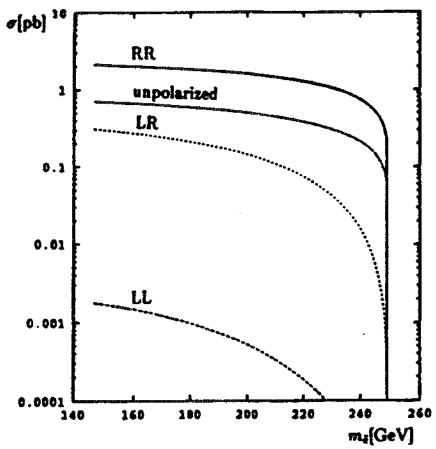
$$e^-e^- \to e^-\nu W^-$$
$$\hookrightarrow e^-\bar{\nu}$$

(e_L^- only)

in both cases, one e^- must be close to the beam energy

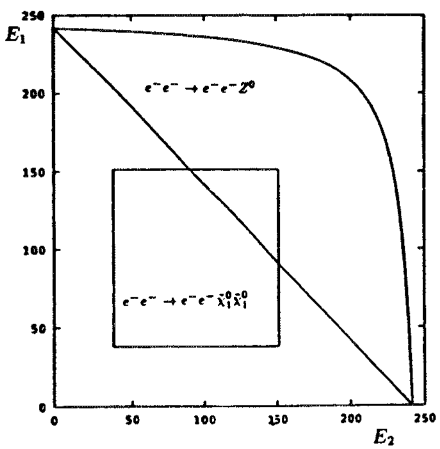
can easily be eliminated:

cut in $E_1 E_2$ plane



IMPORTANCE OF POLARIZATION!

Figure 12: Cross-section of selectron pair production for a given SUSY parameter set, as a function of selectron mass, for different helicity combinations of the incoming e^- (μ^-) beams, at a 500 GeV NLC / μ Collider



for e^-e^- case, analogous in $\mu\mu$.

Figure 13: The allowed electron ranges for a pair of 200 GeV selectrons decaying into e^-e^- plus a pair of 100 GeV neutralinos (box) and for the principal background, Z "bremsstrahlung" ($e^-e^- \to e^-e^-Z$). This example illustrates the relative ease with which backgrounds can be removed by cuts on the final-state electrons (from ref. 26).

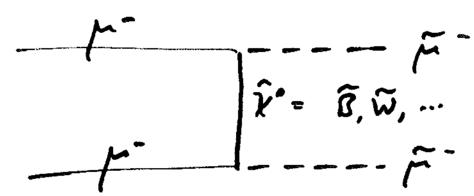
Cuypers et al.

$\left.\begin{matrix}\mu^+\mu^+\\ \mu^-\mu^-\end{matrix}\right\}$ CAN LEAD TO A PRECISE $\tilde{\mu}$ MASS MEASUREMENT:

S WAVE TURN-ON AT KINEMATICAL THRESHOLD GIVES $m(\tilde{\mu})$ TO FEW 100 MeV;

ALL **SUSY** MODELS CONTAIN MAJORANA FERMIONS THAT COUPLE TO $\mu^\pm$:

$B^\mu, W^\mu \longrightarrow \tilde{B}, \tilde{W}$, gauginos



Kenny, Littenberg

→ NEUTALINO MASS MEASUREMENT

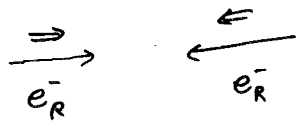
PHASE IN NEUTRALINO MASS MATRIX ?

H. C. CHENG

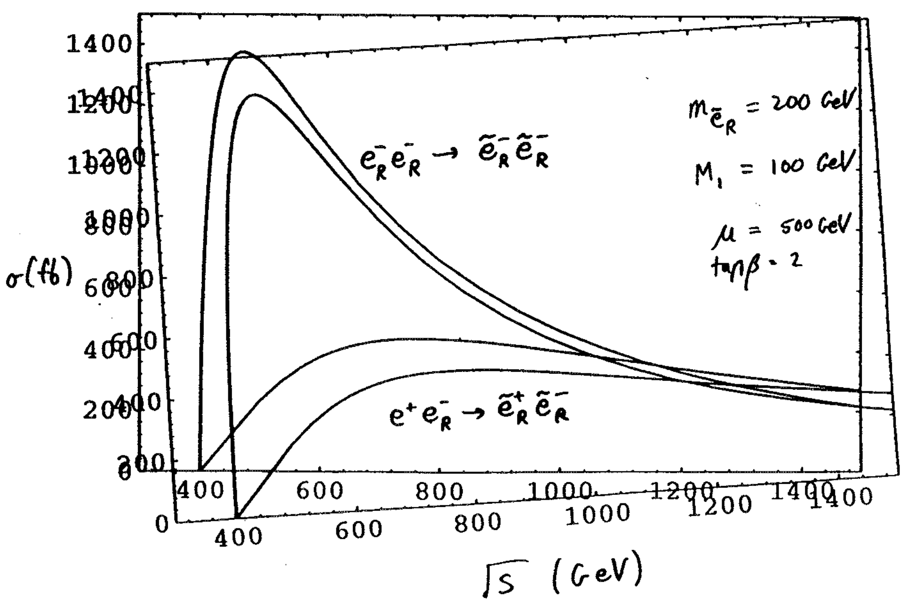
IN ANALOGOUS SELECTRON CASE,

Mass Measurement

Threshold:



S wave, β behavior!

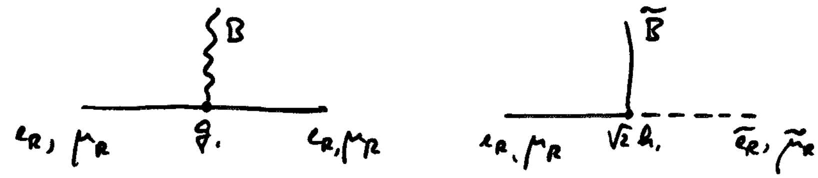


NOTE: IMPORTANCE OF POLARIZATION.

J. FENG
H. C. CHENG

MEASUREMENT OF SPARTICLE COUPLINGS

RELATED TO ORDINARY GAUGE COUPLINGS BY SUSY



$g_1 = h_1$ in EXACT SUSY ?

A PRECISE MEASUREMENT OF THESE RELATIONS CAN

- TEST SUPERSYMMETRY
- PROBE FOR HEAVIER S-PARTICLES BEYOND KINEMATICAL REACH

⇒ TEST OF SUSY FLAVOR STRUCTURE

(HEAVY QCD MODELS
2-1 MODELS, ...)

A COMPARISON OF $\mu^- \mu^- \to \tilde{\mu}^- \tilde{\mu}^-$
$e^- e^- \to \tilde{e}^- \tilde{e}^-$ MAY BE
VERY INSTRUCTIVE!

LOOK FOR FLAVOR VIOLATION

$\mu_R^- \mu_R^- \to e^- \mu^- \tilde{B} \tilde{B}$

STRONG $W_L W_L$ SCATTERING

SUPPOSE WE DO NOT FIND AN ELEMENTARY HIGGS SCALAR UP TO 1 TeV

$\Rightarrow$ partial-wave unitarity will be violated (below $4\pi v$)

... THERE **MUST** BE A PROCESS FOR E.W.S.B.

if no $\left\{ \begin{array}{l} \text{light } h^0, H^0, A^0, H^\pm \\ \text{sparticles} \end{array} \right\}$ are observed,

$\Rightarrow$ THERE REMAINS THE POSSIBILITY OF A STRONGLY INTERACTING E.W. SECTOR:

W_L take the place of Goldstone bosons

$W_L W_L$ acquires a $\left.\begin{array}{l}\text{NEW}\\ \text{STRONG}\end{array}\right\}$ interaction

THIS NEW INTERACTION (Technicolor, ...?) MUST BE INVESTIGATED AS FULLY AS π-π INTERACTIONS WERE IN THE '60's

$\rightarrow$ all J, I channels.

SEWS phenomenology at $\left.\begin{array}{l}\mu^-\mu^-\\ e^-e^-\end{array}\right\}$ Colliders

1. $W_L^- W_L^- \rightarrow W_L^- W_L^-$ $(I=2)$

$\left\{\begin{array}{l} e^-e^- \\ \mu^-\mu^- \end{array}\right\} \rightarrow \nu\nu W_L^- W_L^-)$

2. $\gamma Z_L \rightarrow \omega_H^0 \rightarrow \left\{\begin{array}{l} W_L^+ W_L^- Z_L \\ \gamma Z_L \end{array}\right.$

$(e^-\gamma \rightarrow e^- \omega_H^0)$

for $e\gamma$ collider

THIS IS A PHENOMENON THAT NEEDS STUDYING IN **ALL** J, I CHANNELS:

$e^+e^-, \mu^+\mu^- \rightarrow$ only $J=1$, $I=0,1$

$\left.\begin{array}{l} e^-e^- \\ \mu^\pm\mu^\pm \end{array}\right\}$ single out $I=2$ channel

MAY DISCOVER A NEW DYNAMICS

Can't miss a $I = 2$ resonance! 10.

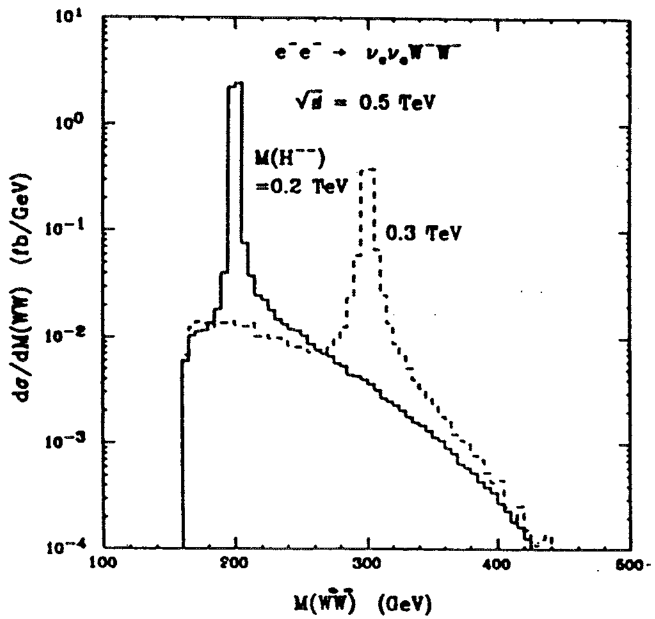


FIG. 11. The distribution in the W^-W^- invariant mass for $e^-e^- \to \nu_e\nu_e W^-W^-$ including the contribution of a doubly charged Higgs boson of mass $M(H^{--}) = 0.2$ or 0.3 TeV.

COMPOSITENESS

WHEN EVER WE ENTER A NEW KINEMATIC REGIME, WE CHECK FOR THE (STILL MYSTERIOUS) "POINT-LIKE" QUALITY OF PARTICLES

e
μ
τ

THAT DO HAVE "INTERNAL" QUANTUM NUMBERS.

($\to$ SPIN...)

Møller Scattering

IS A PARTICULARLY SUCCESSFUL TOOL TO INVESTIGATE "SUBSTRUCTURE" LEVELS.

A CANONICAL STUDY OF THE SENSITIVITY OF MØLLER SCATTERING TO CONTACT INTERACTION TERMS AT ENERGY Λ SHOWS THE IMPORTANCE OF

$\to$ HIGH ENERGY

$\to$ HIGH DEGREES OF POLARIZATION FOR BOTH BEAMS

COMPOSITENESS STUDIES

T. Barklow
e^+e^- 97

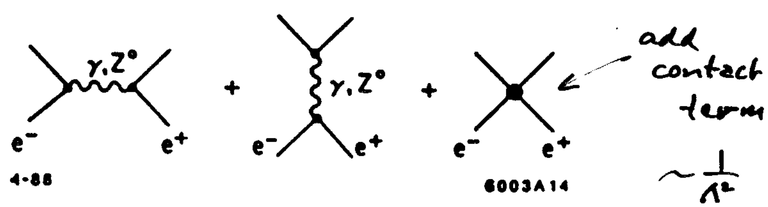


Figure 14. Contributions to the cross section for Bhabha scattering in a model with lepton substructure.

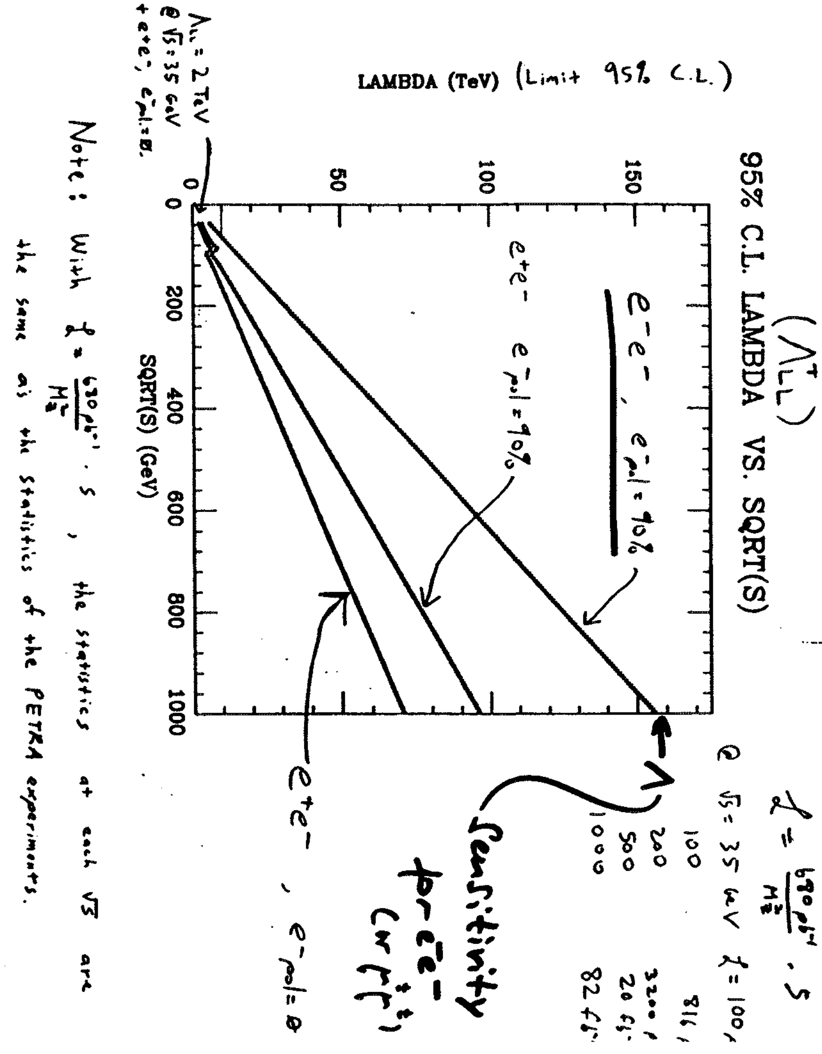
effective Lagrangian:

$$\mathcal{L}_{\psi\psi} = \underbrace{(g^2/2\Lambda^2)}[\eta_{LL}\bar{\psi}_L\gamma_\mu\psi_L\bar{\psi}_L\gamma^\mu\psi_L + \eta_{RR}\bar{\psi}_R\gamma_\mu\psi_R\bar{\psi}_R\gamma^\mu\psi_R + 2\eta_{RL}\bar{\psi}_R\gamma_\mu\psi_R\bar{\psi}_L\gamma^\mu\psi_L].$$

$$\frac{g^2}{4\pi} = 1 \quad \text{(convention)}$$

Λ = energy scale of compositeness

$\Lambda^{\pm}_{LL}$ denotes limit when $(\eta_{LL}, \eta_{RR}, \eta_{RL}) = (\pm 1, 0, 0)$



WHY THIS SENSITIVITY?

Crossing:

$$Y_{e^+e^-} = \sqrt{2a}\,(s^4+u^4+t^4)^{1/2}\left(\frac{1}{3w_0}\right)\left(\frac{1}{\mathcal{L}}\right)^{1/2}\cdot\frac{1}{u^2}$$

$\Lambda = Y^{-1/2}$ so

$$\Lambda_{e^-e^-} = (2a)^{-\frac{1}{4}}\,(s^4+u^4+t^4)^{-1/4}\,(3w_0)^{1/2}\cdot\left(\tfrac{1}{2}\mathcal{L}\right)^{1/4}\, s^{3/4}$$

$$\Lambda_{e^+e^-} = (2a)^{-\frac{1}{4}}\,(s^4+u^4+t^4)^{-1/4}\,(3w_0)^{1/2}\,(\mathcal{L})^{1/4}\,u^{3/4}$$

$$\frac{\Lambda_{e^-e^-}}{\Lambda_{e^+e^-}} = 2^{-1/4}\left(\frac{s}{u}\right)^{3/2}$$

similar for $\mu^\pm\mu^\pm$

$$= 2^{-1/4}\left(\frac{2}{1+z}\right)^{3/2}$$

$$= \frac{2^{5/4}}{(1+z)^{3/2}} = 2.38 \text{ @ } 90^\circ$$

(neglecting Z exchange)

WILL REACH ~ $\Lambda \approx 600$ TeV for 4 TeV COLLIDER

II PROCESSES INACCESSIBLE TO e^+e^-

(except, potentially, at much higher energy)

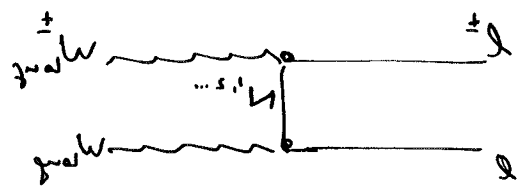
- EXTENDED HIGGS SECTORS
- MASSIVE MAJORANA NEUTRINOS
- DILEPTON GAUGE BOSONS
- CERTAIN LEPTOQUARK PAIRS

• HEAVY MAJORANA NEUTRINOS

SENSITIVITY OF THE PROCESSES

$$e^-_L e^-_L \to W^- W^-$$
$$\mu^\pm \mu^\pm \to W^\pm W^\pm$$

TO MASSES, COUPLINGS OF EXCHANGED



HEAVY NEUTRINO(S)

$\Delta L = 2 \rightarrow N = N_{Majorana}$

SPECIAL INTEREST OF MUON COLLIDER:

• POSSIBLE GENERATION-DEP' COUPLINGS

• ENERGY REACH

TWO CONUNDRUMS OF THE S.M.:

• THE KNOWN NEUTRINOS ARE VERY LIGHT ($m_{\nu_i} \overset{?}{=} 0$) $i = e, \mu, \tau$

• WE IGNORE THE PROPER FIELD-THEORETICAL MASS TERM FOR NEUTRINOS:

$$\mathcal{L}_\nu^{mass} = -\overline{\nu_L}\, m_D\, \nu_R - \frac{1}{2}\, \overline{\nu_R^c}\, m_M\, \nu_R + h.c.$$

m_D: 3×3 Dirac mass matrix; m_M: 3×3 Majorana mass matrix

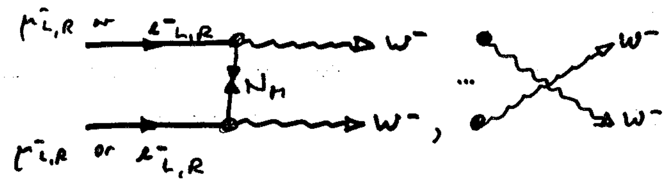
BOTH PROBLEMS MAY BECOME ACCESSIBLE BY THE STUDY OF THE PROCESS

• $e^-_L e^-_L \to W^- W^-$, $\mu^-_L \mu^-_L \to W^- W^-$ AT ELECTRON LINEAR COLLIDERS, $\sqrt{s} \geq 0.5$ TeV

mediated by **heavy ν_M** exchange

A UNIQUE OPPORTUNITY AT LIKE-SIGN MUON & e^-e^- COLLIDERS:

SIMPLE CONFIGURATION IS ACCESSIBLE



IF CROSS-SECTIONS ARE PROMISING,

THERE ARE SOME UNIQUE ADVANTAGES:

- PLENTIFUL SOURCES AVAILABLE
- EASY BACK-TO-BACK FINAL-STATE KINEMATICS
- POLARIZABILITY OF e^- BEAMS MAKES CHIRAL COUPLINGS ADJUSTABLE
- ? MUON POLARIZATION?

earlier work: Ushio (1982)
Rizzo (1982)
London et al (1987)
Maalampi et al (1992)

work done with
PETER MINKOWSKI

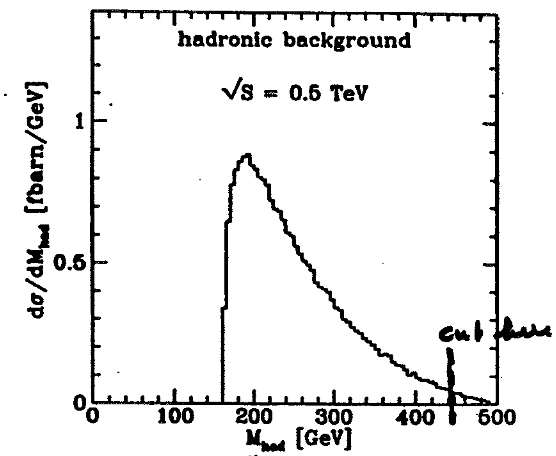
Nucl. Phys. B416, 3(1994)
Phys. Lett. 199..

BUT:

— LARGEST CROSS-SECTION B.G.

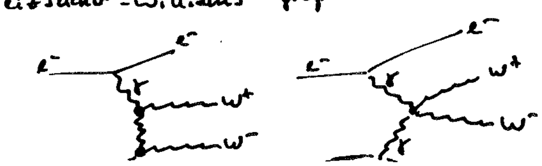
— if charges of W's cannot all be determined —

$e^-e^- \to \underbrace{W^+W^-}_{\text{jets}} \; \underbrace{e^-e^-}_{\text{down beampipe}}$



$M_{had} = M_{W^+W^-}$

Weizsäcker-Williams graphs



Dilepton Searches

Frampton et al.

Definition:
- couple to 2 leptons ⇒ $SU(2)_L$ (1,2,3)
- non-derivative couplings ⇒ lowest dim. op.

Quantum numbers:
- $J = 0, 1$
- $L = 0, 2$
- $Q = 0, \pm 1, \pm 2$

⇒ 14 different fields

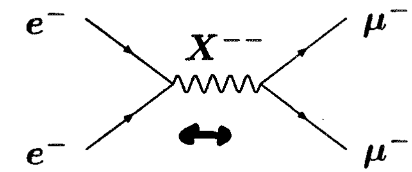
Nature:
- composite fields ⇒ minimal coupling to photon via $D_\mu = \partial_\mu - ieQA_\mu$
- Yang-Mills fields ⇒ gauge coupling to photon

$L = 0$: familiar Z', W', H, H^-

$L = 2$: 7 unfamiliar bosons

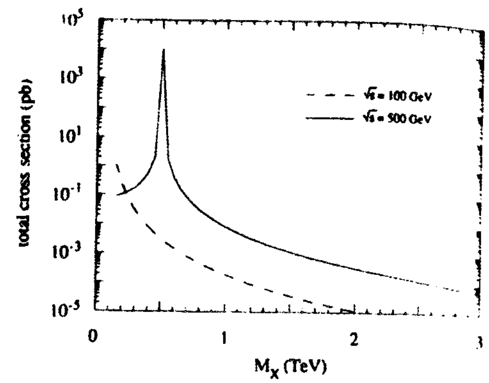
$e^- e^- \leftrightarrow \mu^- \mu^-$

With dileptons we have



- dileptons X^{--} are gauge bosons
- they couple universaly to leptons
- ∃ if $SU(2)_L \otimes U(1) \subset SU(3)_\ell$

} [Frampton, Lee]



$m_{X^{--}} = 1.8$ TeV

⇒ $N = 5$

Leptoquark Searches

Definition:
- couple to ℓ & $q \Rightarrow SU(2)_L$ (1,2,3)
- non-derivative couplings $\Rightarrow$ lowest dim. op.
- conserve B & $L \Rightarrow$ proton stable

Quantum numbers:
- $J = 0, 1$
- $F = L + 3B = 0, 2$
- $Q = \pm\frac{1}{3}, \pm\frac{2}{3}, \pm\frac{4}{3}, \pm\frac{5}{3}$

$\Rightarrow$ 18 ~~different fields~~

Nature:
- composite fields $\Rightarrow$ minimal coupling to photon via $D_\mu = \partial_\mu - ieQA_\mu$
- Yang-Mills fields $\Rightarrow$ gauge coupling to photon

Decays: $L \rightarrow q\,\ell$

$\ell =$	ν	bummer
	e	good
	μ	super!

Fermion number: can be unambigously determined only at LEP-LHC or in $\left\{ \begin{matrix} e^-e^- \\ \mu^\pm\mu^\pm \end{matrix} \right\}$

	L	J	T	T_3	Q	couples to
L_1	2	0	0	0	-1	$e_L\nu_L$
$\tilde{L}_1$	2	0	0	0	-2	e_Re_R
L_2^μ	2	1	1/2	$-1/2$ $1/2$	-2 -1	e_Re_l $e_R\nu_L$
L_3	2	0	1	-1 0 1	-2 -1 0	e_Le_L $e_L\nu_L$ $\nu_L\nu_L$

and similarly for
2nd- family leptoquarks!

→ polarization is important !

AGAIN, WATCH POLARIZATION!

$(\mu\mu)^{\pm\pm}$ ADDS A SPECIAL, WELL-DEFINED WINDOW ON LQ's.

CONCLUSIONS

- $\mu^+\mu^+$, $\mu^-\mu^-$ AT HIGH ENERGY AND LUMINOSITY

ENRICH THE PHYSICS PROMISE OF THE

MUON COLLIDER

IN ALMOST ALL OF ITS PURSUITS

HIGH $\mathcal{L}$
HIGH $\sqrt{s} \cdot 2E_B$
"without" radiative tail
EASY DETECTABILITY OF
HIGH-$p_\perp$ μ's.

COMBINED WITH THE

$m(\mu) \gg m(e)$
GENERATION STRUCTURE
OF INTERACTIONS
"EXOTIC" QUANTUM NUMBERS
OF INITIAL STATE,

THERE ARE A NUMBER OF TASKS THAT CAN **NOT** BE TACKLED BY $\mu^+\mu^-$ VERSION.

MACHINE PLANNERS: NOTE! INCLUDE LIKE-SIGN VERSION

$\mu\mu$ '97
San Francisco.

DOUBLY CHARGED PARTICLES AT A $\mu\mu$ COLLIDER

Subhash Rajpoot
California State Univ
Long Beach.

The merits of $\mu\mu$ collider is 'NOT' an issue any more.

(a) $\mathcal{L} \sim 10^{34}\ cm^{-2} s^{-1}$

(b) Beam energy ¼ TeV to 2 TeV

(c) Narrow beams give greater sensitivity for pinpointing masses etc, etc.

In a $\mu^+\mu^-$ collider,

$$\sum_i Q_{f_i} = 0 \qquad f_i = i^{th} \text{ final state particle}$$

In a $\mu^\pm\mu^\pm$ collider,

$$\sum_i Q_{f_i} = \pm 2$$

In many respects, a $\mu^-\mu^-$ collider complements physics at a $\mu^+\mu^-$ collider.

1

A class of interesting particles that can be studied at a $\mu^-\mu^-$ collider are particles carrying two units of electric charge. These could be

1. Spin - 0 scalars
2. Spin - ½ leptons
3. Spin - 1 gauge bosons

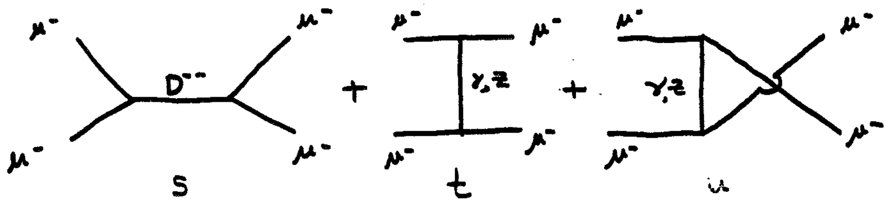
The standard $SU(3) \times SU(2) \times U(1)$ model, in its zeroth order, does not require such particles.

BUT

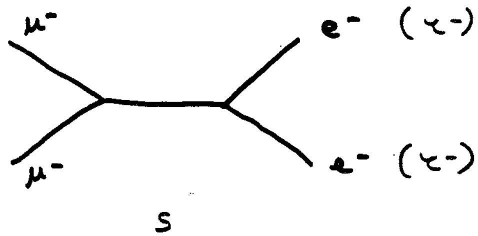
An inevitable consequence of going beyond the standard model is the occurence of doubly charged particles

1. Neutrino masses
2. Unification — Partial / complete
3. 'Dream - up' models

$\mu^-\mu^- \to \mu^-\mu^-$ MØLLER SCATTERING



$\mu^-\mu^- \to e^-e^-$ or $\tau^-\tau^-$



WILL ONLY CONSIDER $\mu^-\mu^- \to e^-e^-$

DOUBLY CHARGED SCALARS (DCS)

Neutrinos are massive Majorana particles
Can achieve this in the standard model in a variety of ways

1. Scalar Triplet carrying two units of Hypercharge

$$\begin{pmatrix} T^0 & T^+ \\ T^+ & T^{++} \end{pmatrix}$$

$$m_\nu^{ij} = y^{ij}\langle T^0\rangle \qquad \langle T^0\rangle \gtrsim \text{few GeV}$$

$i = 1, 2, 3$

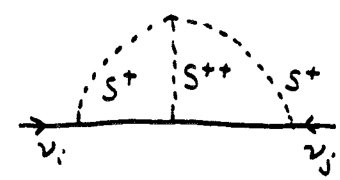
coupling of T^{++} to charged leptons

$$y \gtrsim g\frac{m_\nu}{\eta M_W} \qquad \eta < 0.1$$

$$\lesssim 10^{-7}$$

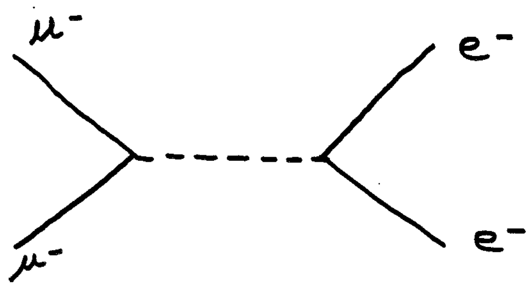
2. Singlet DCS S^{++}

(explains smallness of neutrino masses)



In this model, S^{++} couplings to leptons not suppressed,

$$y \sim g$$



$\mu^-\mu^- \to e^-e^-$

$$\sigma(\mu^-\mu^- \to e^-e^-) = \frac{Y^{\mu\mu\,2}\, Y^{ee\,2}}{4\pi} \frac{s}{(s - M^{--2})^2}$$

$\sqrt{s} = 0.5$ TeV $-$ 1 TeV

$M^{--} = 0.25$ TeV

duration 1 yr

$\mathcal{L} = 10^{33}\ cm^{-2}\, s^{-2}$

\# (model I) abysmally small

\# (model II) 100 ~ 1000

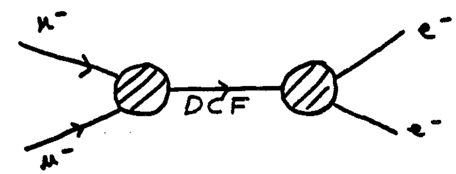
So in model II expectation are good

DOUBLY CHARGED FERMIONS (DCF)

Here the sky is the limit

	Singlets	doublets	Triplets	......
	σ^{++}	$\begin{pmatrix} \delta^{+} \\ \delta^{++} \end{pmatrix}$	$\begin{pmatrix} \rho^{0} & \rho^{+} \\ \rho^{+} & \rho^{++} \end{pmatrix}$	
Hyper-charge	4 units	3 units	2 units	....

Take these to be vectorlike to avoid ABJ anomalies.



The reaction $\mu^-\mu^- \to e^-e^-$ proceeds via 'dressed' vertices

$\sigma(\mu^-\mu^- \to e^-e^-) \sim 10^{-40}\ cm^2$

\# events handful

DOUBLY CHARGED VECTOR BOSONS (DCVB)

DCVB's exist in two types of standard model extensions

1. GUT models
2. Non-GUT models

GUT models

In these models quarks and leptons belong to one common multiplet of the grand Unifying symmetry G.
The scheme 'does not' work in practise since no Proton decay observed.
DCVB belong to the coset space

$$G / SU(3) \times SU(2) \times U(1)$$

When $G \longrightarrow SU(3) \times SU(2) \times U(1)$
DCVB acquire GUT masses $\gtrsim 10^{15}$ GeV

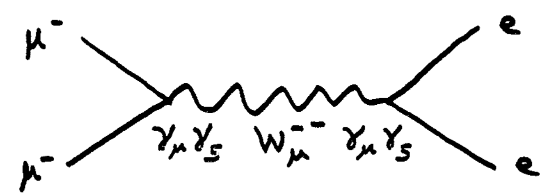
NON-GUT SCHEMES

standard model extension with leptonic matter and anti-matter in one multiplet (S. Rajpoot, PLB 1981)

$$\begin{pmatrix} \nu_e \\ e^- \\ \overline{e^-} \\ \overline{N} \end{pmatrix}_L$$

N need to generate 'see-saw' masses for light neutrinos

$$\mathcal{L} = g \; \mu_L^T C \gamma^\mu \mu_L W_\mu^{--} + \dots$$



$M_{W^{--}} \sim 0.25$ TeV
$\sqrt{s} \sim 1$ TeV
$\mathcal{L} \sim 10^{34}$ cm^{-2} s^{-1}
1000 per year.

CONCLUSIONS

1. $\mu^-\mu^-$ collider will complement physics of a $\mu^+\mu^-$ collider
2. DC particles is an interesting hypothesis which can be tested readily at a $\mu^-\mu^-$ collider
3. Study indicates (theoretically) spin-0 and spin-1 doubly charged particles look more promising in SM extension
4. Require detailed study of CM distribution and/or polarisations to establish the nature of DCP

$\mu^-\mu^-$ COLLIDER IS A MUST.