Neutrino Factory and Muon Collider Physics

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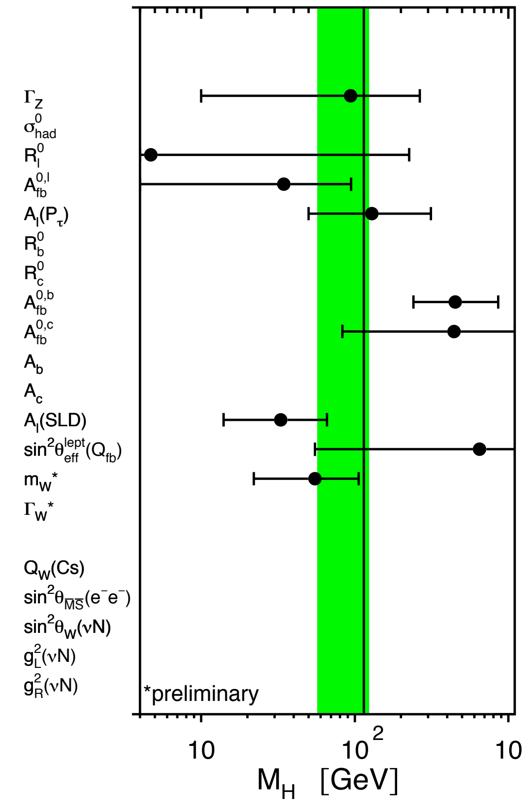
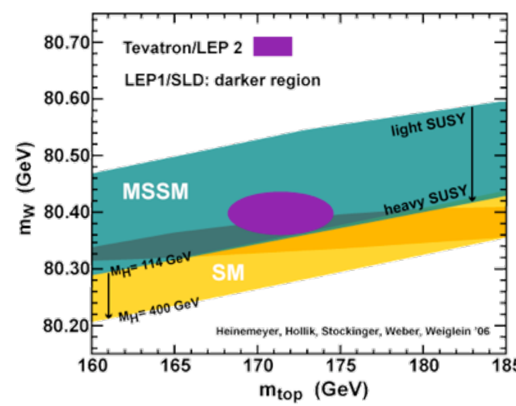
- Where We Stand
- Neutrino Physics
- Muon Collider
  - The Basics
  - Scalar Sector
  - Beyond the Standard Model
- Conclusions

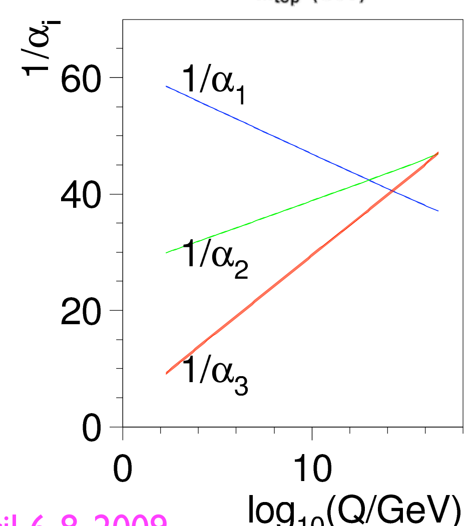
2009 MUTAC Review
April 6-8, 2009 Fermilab

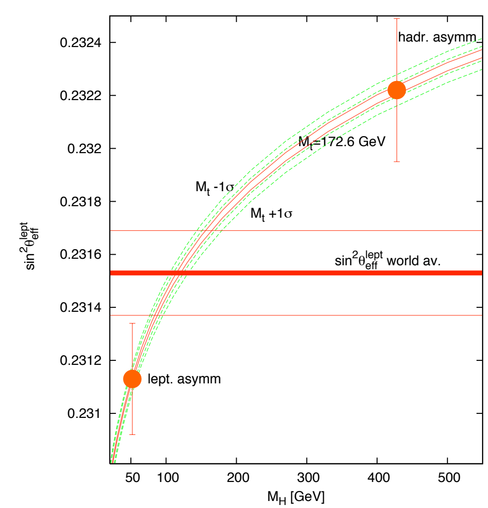
Present Status

- All data consistent with Standard Model - but:
- incomplete
  - dark matter and dark energy
  - neutrino masses and mixing
    - new fields ν_R or new interactions $\frac{1}{\Lambda}\nu^c H^\dagger H \nu$
  - baryon asymmetry
    - more CP violation
- experimental hints
  - higgs mass (see figs)
  - muon (g-2)
- theoretical questions
  - origin of mass:
    - naturalness and higgs
  - gauge unification: (see fig)
    - new interactions
  - gravity: strings and ED









Neutrino Physics

SM leptons: $L_e = \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L$ $L_\mu = \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L$ $L_\tau = \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L$ $R_{e,\mu,\tau} = e_R, \mu_R, \tau_R$

No ν_R needed. Singlet under $SU(3)_c \times SU(2)_L \times U(1)_Y$

Lepton number conserved.

Observation of neutrino flavor mixing drastically changes the picture

Flavor mixing ⇒ neutrino masses

$$\Delta m^2_{\rm solar} << \Delta m^2_{\rm atm}$$

Simple two flavor (α,β) case: with mass eigenstates (i,j)

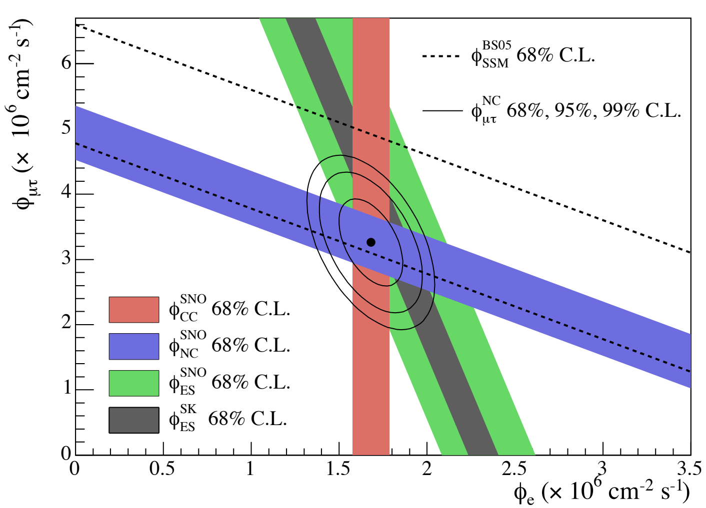
$$\nu_\alpha = \nu_i \cos\theta + \nu_j \sin\theta$$

$$\nu_\beta = -\nu_i \sin\theta + \nu_j \cos\theta$$

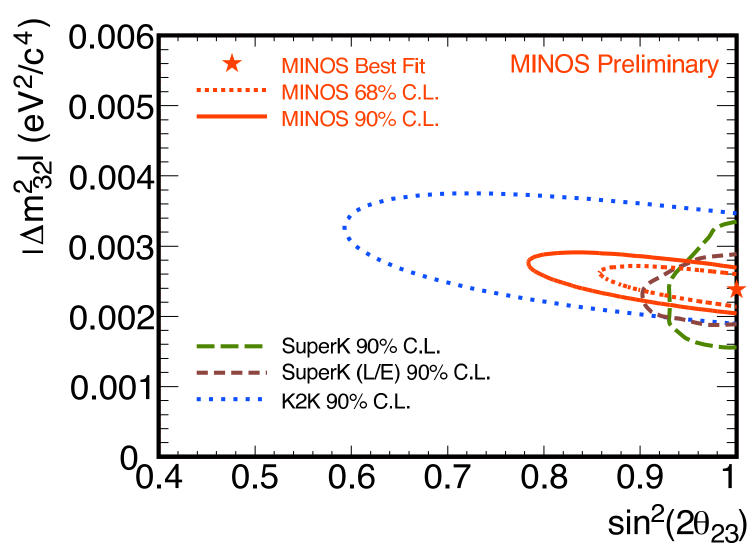
Oscillation probability (P) for energy (E) and distance (L)

$$P_{\alpha\to\beta} = \sin^2 2\theta \sin^2\left(\Delta m^2 L/4E\right)$$

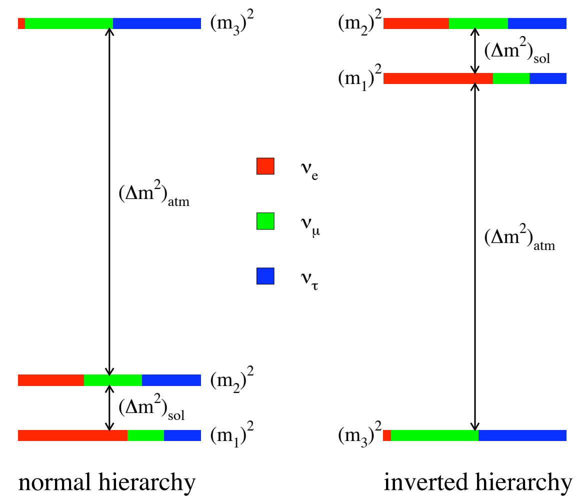
Solar



Atmospheric



Normal or inverted mass hierarchy?



Majorana or Dirac particles?

Usual Dirac fermion can be expressed as a left-handed particle χ and its charge conjugate (C) particle ϕ

$$\psi_D = \begin{pmatrix} \chi \\ \sigma_2 \phi^* \end{pmatrix} \quad C = \begin{pmatrix} -\sigma_2 & 0 \\ 0 & \sigma_2 \end{pmatrix} \quad \psi_D^c = C\bar{\psi}_D^T = \begin{pmatrix} \phi \\ \sigma_2 \chi^* \end{pmatrix}$$

A majorana fermion is its own charge conjugate.

Dirac mass term:

$$\bar{\psi}_D m \psi_D = m(\phi\sigma_2\chi + h.c) = \frac{m}{2}\sum_{\alpha=1,2} \rho_\alpha \sigma_2 \rho_\alpha + h.c.$$

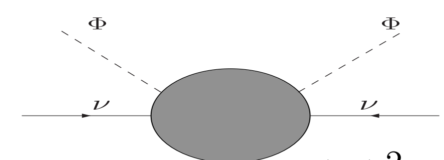
$$\phi \equiv \frac{1}{2}(\rho_2 + i\rho_1)$$
$$\chi \equiv \frac{1}{2}(\rho_2 - i\rho_1)$$

Dirac fermion is equivalent to two Majorana fermions with equal mass.

Majorana fermions: ρ_1 ρ_2

Majorana: no ν_R - mass term violates lepton number conservation

$$\mathcal{L}_{\rm mass} = \bar{\nu}_L^c M_L \nu_L + h.c.$$



$$m_\nu = \lambda_0 \frac{\langle\Phi\rangle^2}{M_X}$$

Dirac: ν_R

$$\mathcal{L}_{\rm mass} = \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix}^\dagger \mathcal{M} \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix} + h.c.$$

ν_R has no SM gauge interactions.
Does it have new gauge interactions?

Pure Dirac: $\mathcal{M} = \begin{pmatrix} 0 & M \\ M^\dagger & 0 \end{pmatrix}$

Seesaw I: $\mathcal{M} = \begin{pmatrix} 0 & M \\ M^\dagger & M_R \end{pmatrix}$

Seesaw II: $\mathcal{M} = \begin{pmatrix} M_L & M \\ M^\dagger & M_R \end{pmatrix}$

Standard three flavor neutrino mixing matrix

$$\begin{pmatrix} \nu_{eL} \\ \nu_{\mu L} \\ \nu_{\tau L} \end{pmatrix} = U_{\rm PMNS} \begin{pmatrix} \nu_{1L} \\ \nu_{2L} \\ \nu_{3L} \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_{1L} \\ \nu_{2L} \\ \nu_{3L} \end{pmatrix}$$

Pontecorvo-Maki-Nakagawa-Sakata Matrix

Three angles: $\theta_{12}, \theta_{23}, \theta_{13}$

CP phases: δ(Dirac) (α,β,δ)(Majorana)

$$\mathrm{U_{PMNS}} = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} diag(1, e^{i\alpha/2}, e^{i\beta/2})$$

$c_{ij}= \cos(\theta_{ij})$ $s_{ij}= \sin(\theta_{ij})$

Atmos. L/E $\mu \to \tau$ Atmos. L/E $\mu \leftrightarrow e$ Solar L/E $e \to \mu, \tau$

500km/GeV 15km/MeV

The additional Majorana CP phases appear in lepton number violating interactions: eg. neutrinoless double beta decay.

Matter effects:

Interactions in matter EW flavor dependent and differ for neutrino/antineutrino. (Compare K_L-K_S)
Induces new terms in mixing formulae.

Present Status

T. Schwetz, M. Tortola and J. Valle [arXiv:0808.2016v2]

parameter	best fit	2σ	3σ	
Δm^2_{21} $[10^{-5}\mathrm{eV}^2]$	$7.65^{+0.23}_{-0.20}$	7.25–8.11	7.05–8.34	KamLAND
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\mathrm{eV}^2]$	$2.40^{+0.12}_{-0.11}$	2.18–2.64	2.07–2.75	K2K, MINOS
$\sin^2\theta_{12}$	$0.304^{+0.022}_{-0.016}$	0.27–0.35	0.25–0.37	SNO
$\sin^2\theta_{23}$	$0.50^{+0.07}_{-0.06}$	0.39–0.63	0.36–0.67	SuperK
$\sin^2\theta_{13}$	$0.01^{+0.016}_{-0.011}$	≤ 0.040	≤ 0.056	CHOOZ

Reactor Neutrinos: Daya Bay

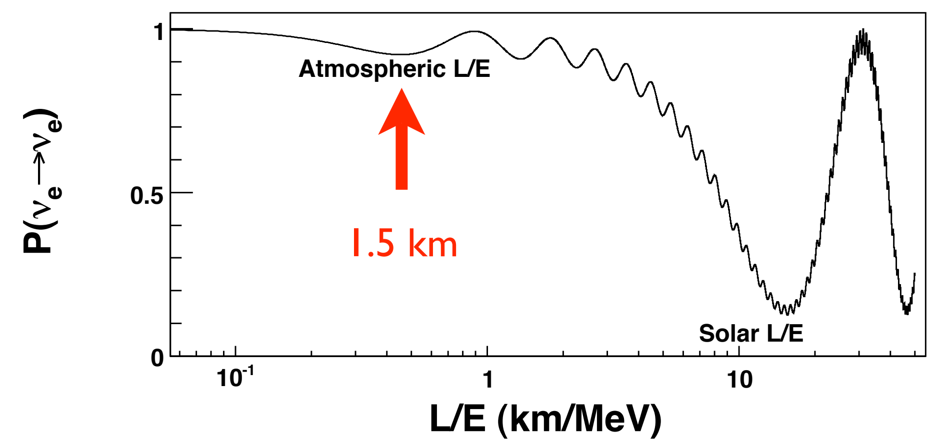
$$\Delta_{ij} \equiv \frac{\delta m^2_{ij} L}{4E}$$

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} - \sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32})$$

$$\approx 1 - \sin^2 2\theta_{13}\sin^2\left(\frac{\delta m^2_{ee} L}{4E}\right) - \mathcal{O}(\Delta_{21})^2$$

< 0.002

Daya Bay sensitivity ≈ 0.01



Nova and T2K:

$$P(\nu_\mu \to \nu_e) \approx |\sqrt{P_{atm}}e^{-i(\Delta_{32}\pm\delta)} + \sqrt{P_{solar}}|^2$$

where

$$\sqrt{P_{atm}} = \sin\theta_{23}\sin 2\theta_{13}\frac{\sin(\Delta_{13}\mp aL)}{(\Delta_{31}\mp aL)}\Delta_{31}$$

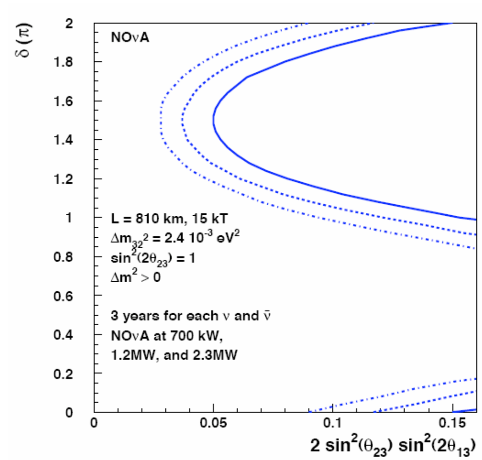
$$\sqrt{P_{solar}} = \cos\theta_{23}\sin 2\theta_{12}\frac{\sin(aL)}{(aL)}\Delta_{21}$$

and the matter effect parameter

$$a = G_F N_e/\sqrt{2} = (4000\ \text{km})^{-1}$$

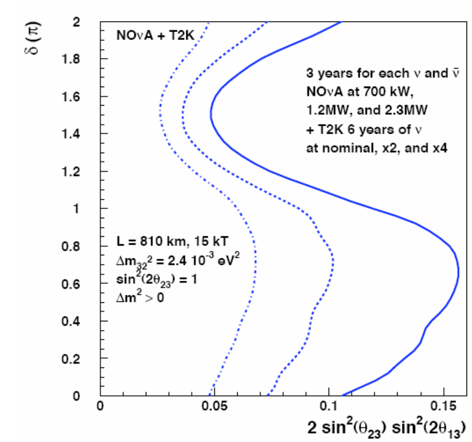
S. Parke [talk NFMCC 2009 (1/25/2009) LBNL]

95% CL Resolution of the Mass Ordering
NOνA Alone



Normal Ordering

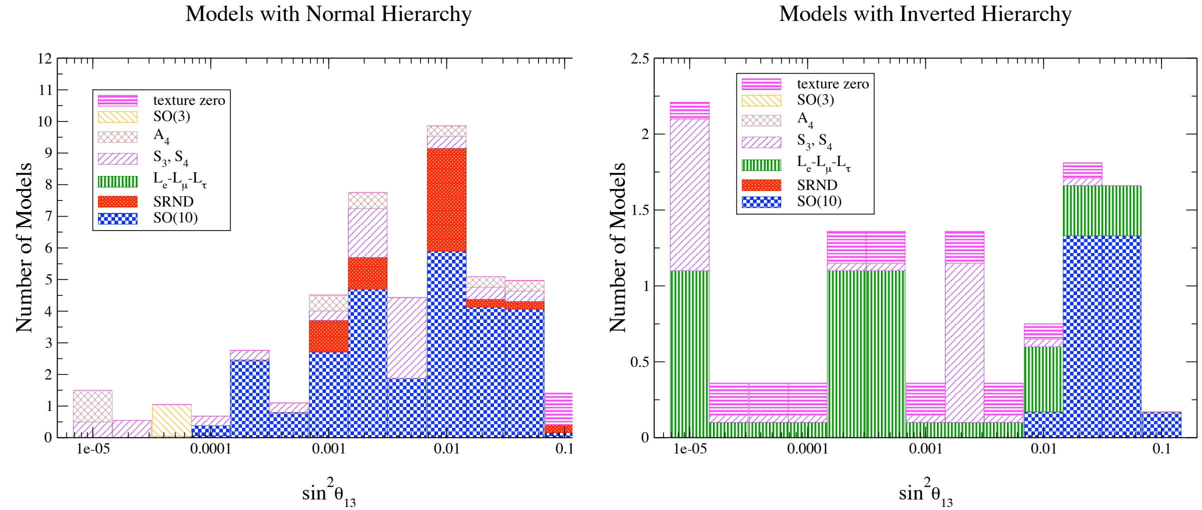
95% CL Resolution of the Mass Ordering
NOνA Plus T2K



Normal Ordering

for Inverted Hierarchy $\delta \to \pi - \delta$

Expected $\sin^2\theta_{13}$ for a variety of theoretical models



Neutrino Factory

Muon storage ring:

$\sqrt{s} \approx 50$ GeV

Long straight sections

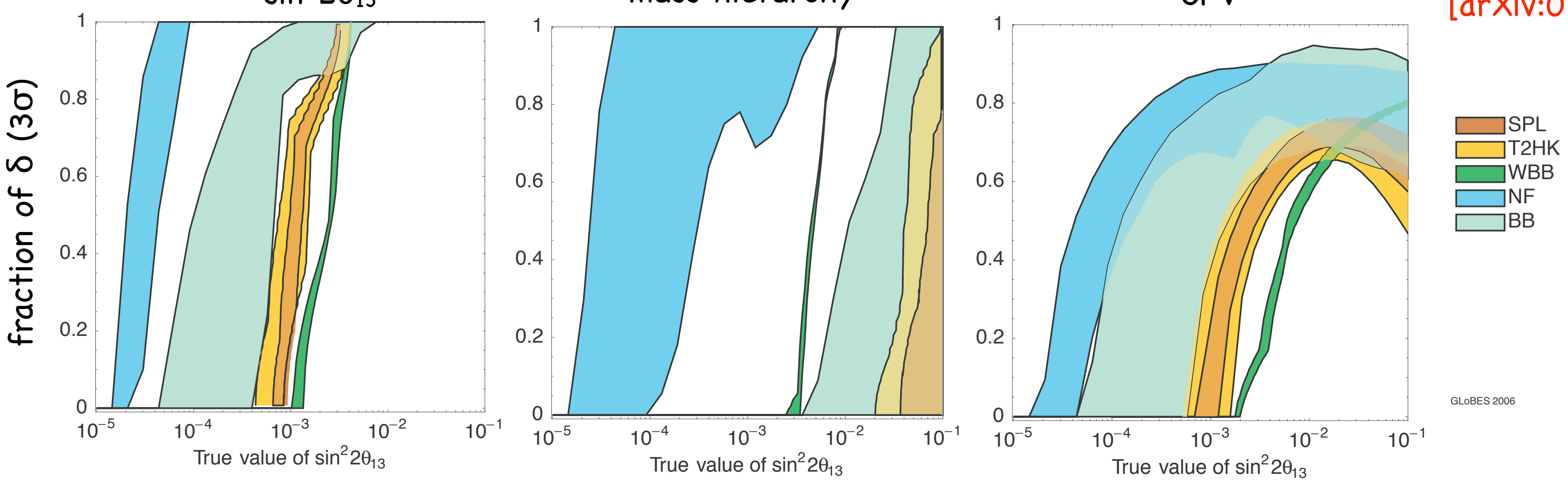
High intensity: 10^{21} muon decays/yr

Compare

Discovery reach for various proposed facilities

ISS Physics Working Group [arXiv:0710.4947]

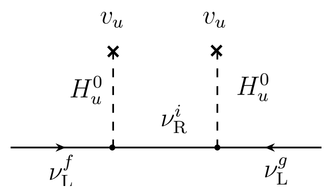
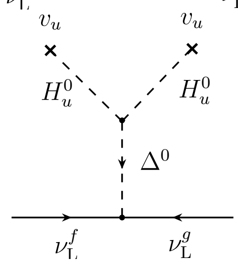
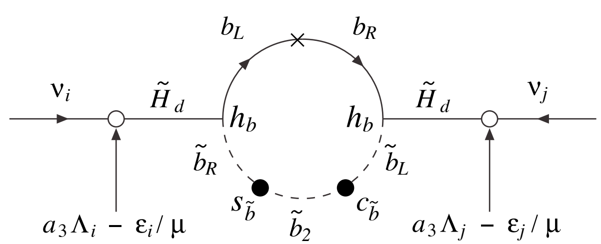
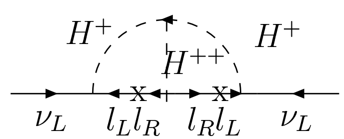
$\sin^2 2\theta_{13}$ mass hierarchy CPV



Very likely Neutrino Factory needed to disentangle θ_{13}, mass hierarchy, and measure CPV parameter.

Non-Standard Neutrino Interactions

A Plethora of Theoretical Models

Model	Interaction	New Particles	Comments
(1-2-3) Seesaw I		ν_R, Majoron	Very light majoron dark matter candidate
(1-2-3) Seesaw II		heavy higgs triplet	
L-R Seesaw SU(3)×SU(2)×SU(2)×U(1)	Both types above	new gauge bosons	No majoron B-L Terascale physics
SUSY models		SUSY partners	Calculable in terms of Smasses and Smixings. R parity violating
Babu model		charged $SU(2)_L$ singlet scalars	H^{++} scalar
Texture models			no comment
⋮			

Basic goals of Neutrino program:

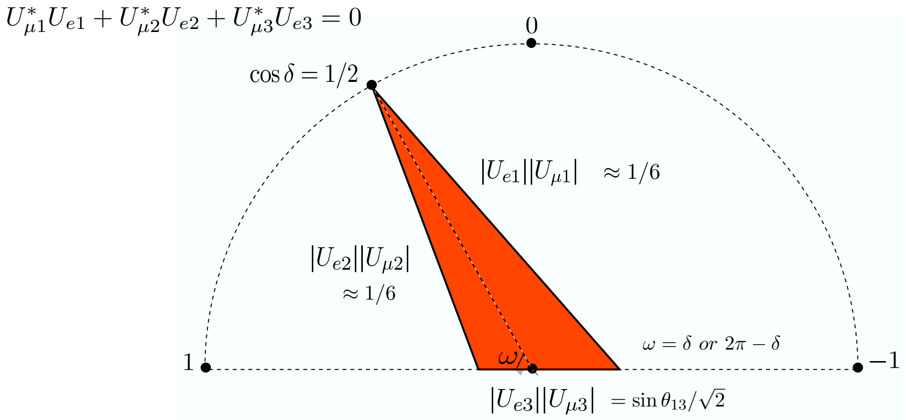
(a) Determine Dirac or Majorana nature of neutrinos.

(b) Determine the mass hierarchy.

(b) Measure θ_{13}, δ and improve θ_{12}, θ_{23} measurements

(c) Study unitarity of PMNS matrix.
Are there additional mixing or CPV from new particles or interactions?

Unitarity Triangle:



$$|J| = 2 \times Area$$

$$J = s_{12}c_{12}s_{23}c_{23}s_{13}c_{13}^2 \sin\delta$$

Why is this important?

(a) Neutrino masses are very small. Theoretical models for these masses predict new particles at the Terascale or a new scale beyond.

(b) Potential source of lepton number violation and CP violation. Leptogenesis might be responsible the observed baryon asymmetry in the universe.

(c) Contributions to dark matter and cosmological evolution.

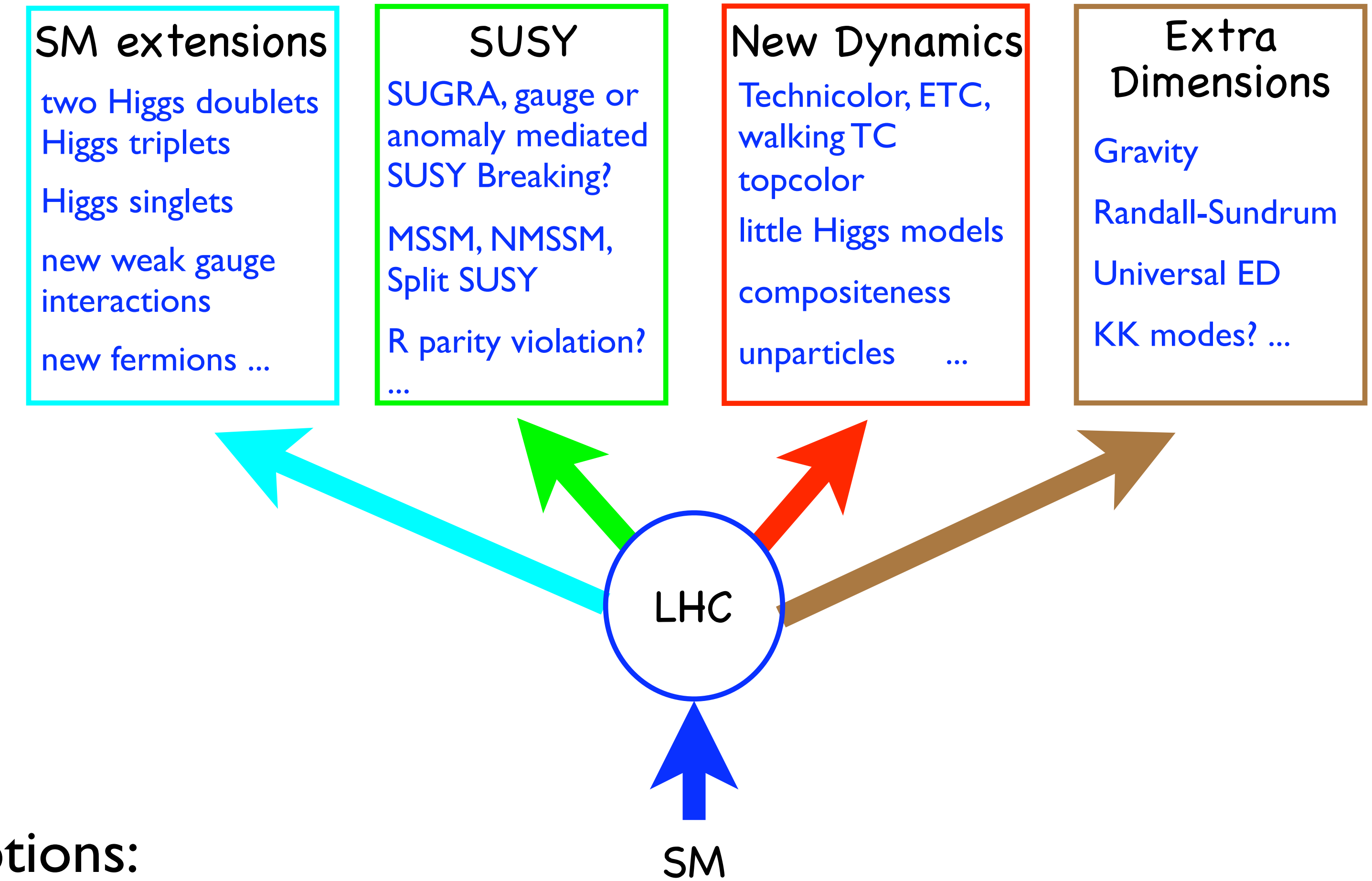
(d) Complimentary to energy frontier physics (LHC)

Why a Neutrino Factory?

(a) Large $\sin^2(2\theta_{13})$ (≥ 0.005) - can explore new physics as subleading effects.

(b) Small $\sin^2(2\theta_{13})$ - provides unmatched sensitivity.

Muon Collider Physics



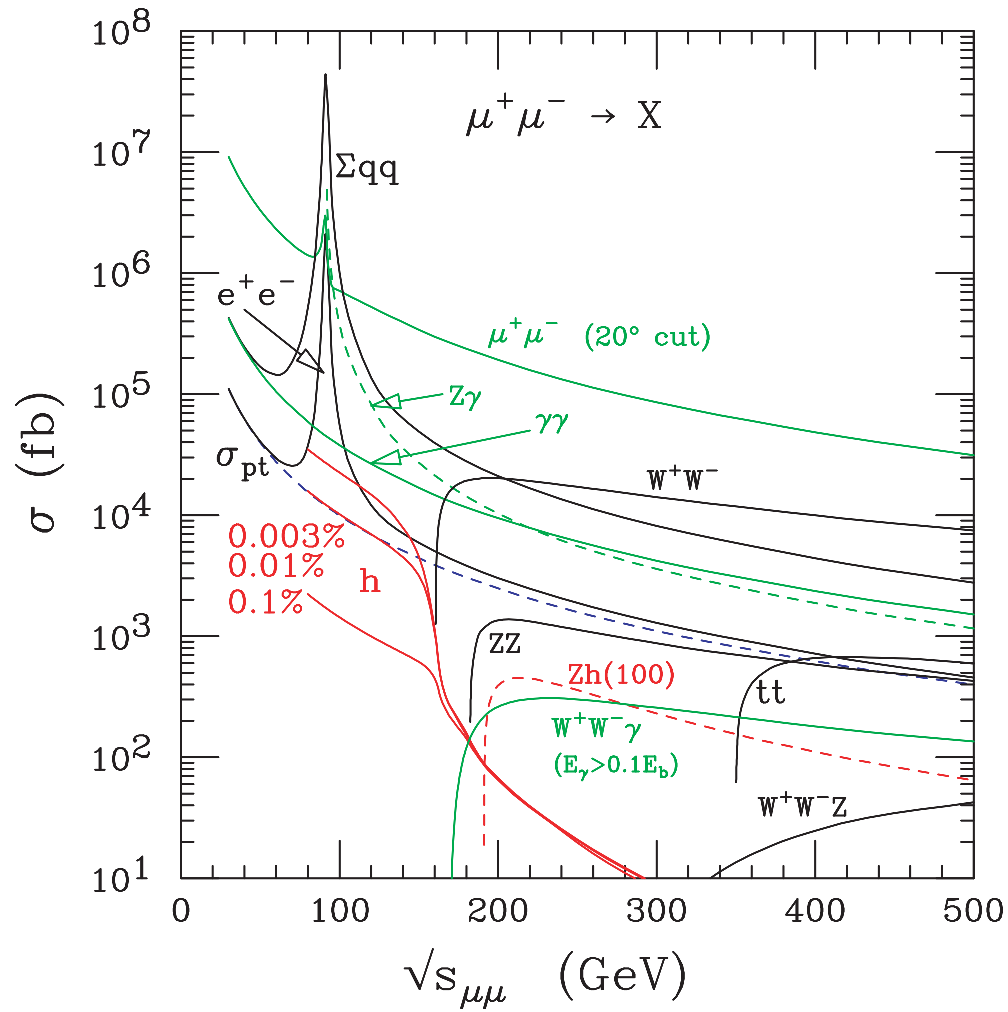
Options:

- low energy lepton collider (< 1 TeV) 500 GeV ILC (upgradable) or Higgs Factory
- lepton collider in multi Tev range. CLIC or muon collider
  - Energy, Luminosity, Polarization?
- hadron collider in hundred TeV range. VLHC

Muon Collider Basics

- For √s < 500 GeV lepton collider
  - threshold regions:
    - top pairs
    - electroweak boson pairs
    - Zh production
  - s-channel Higgs production:
    (requires muon collider)
    - coupling ∝ mass production
      $$\left[\frac{m_\mu}{m_e}\right]^2 = 4.28 \times 10^{4}$$
    - narrow state
      $$m(h) = 110 \text{ GeV}: \quad \Gamma = 2.8 \text{ MeV}$$
      $$m(h) = 120 \text{ GeV}: \quad \Gamma = 3.6 \text{ MeV}$$
      $$m(h) = 130 \text{ GeV}: \quad \Gamma = 5.0 \text{ MeV}$$
      $$m(h) = 140 \text{ GeV}: \quad \Gamma = 8.1 \text{ MeV}$$
      $$m(h) = 150 \text{ GeV}: \quad \Gamma = 17 \text{ MeV}$$
      $$m(h) = 160 \text{ GeV}: \quad \Gamma = 72 \text{ MeV}$$
    - direct width measurement
      $$\Delta E/E \approx 0.003\% \text{ and more than } 2\ pb^{-1}$$

Standard Model
Cross Sections



For $\sqrt{s}$ > 500 GeV

- Above SM thresholds:
- R essentially flat:

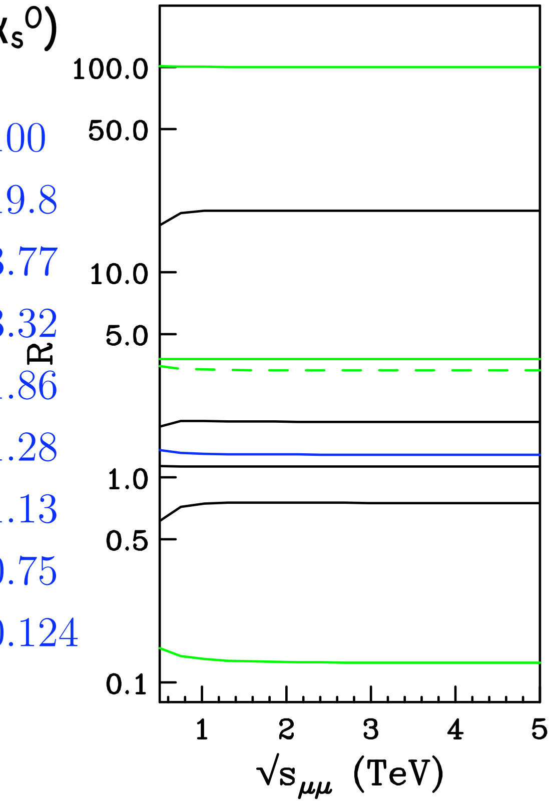
(one unit of R)

$$\sigma_{\rm QED}(\mu^+\mu^- \to e^+e^-) = \frac{4\pi\alpha^2}{3s} = \frac{86.8 \text{ fb}}{s(\text{TeV}^2)}$$

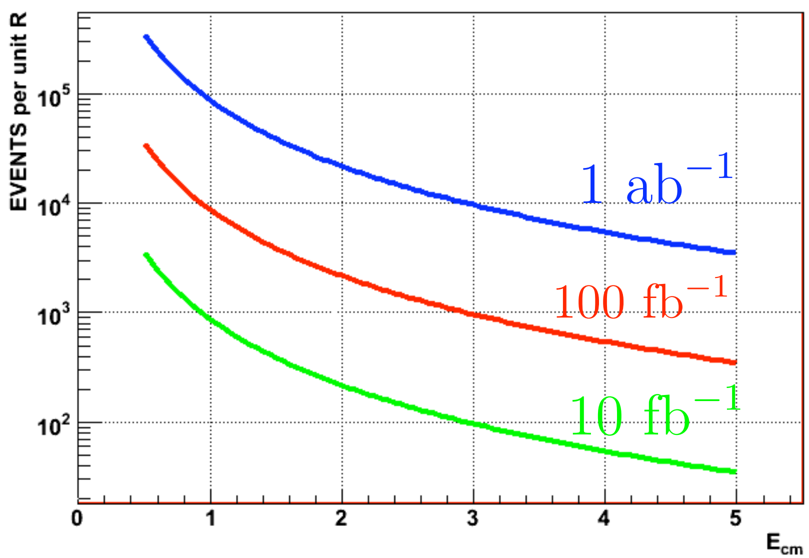
R at $\sqrt{s}$ = 3 TeV

$O(\alpha_{em}^2)$ $O(\alpha_s^0)$

$\mu^+\mu^-(20^o \text{ cut})$	=	100
W^+W^-	=	19.8
$\gamma\gamma$	=	3.77
$Z\gamma$	=	3.32
$t\bar{t}$	=	1.86
$b\bar{b}$	=	1.28
e^+e^-	=	1.13
ZZ	=	0.75
$Zh(120)$	=	0.124



Luminosity Requirements



For example: $\sqrt{s} = 1.5 \text{ TeV}$ $\Rightarrow$ 3860 events/unit of R

$$\mathcal{L} = 10^{34} \text{ cm}^{-2}\text{sec}^{-1}$$
$$\to 100 \text{ fb}^{-1}\text{year}^{-1}$$

Total - 510 K SM events per year

Processes with R ≥ 0.01 can be studied

Minimum Luminosity for Muon Collider

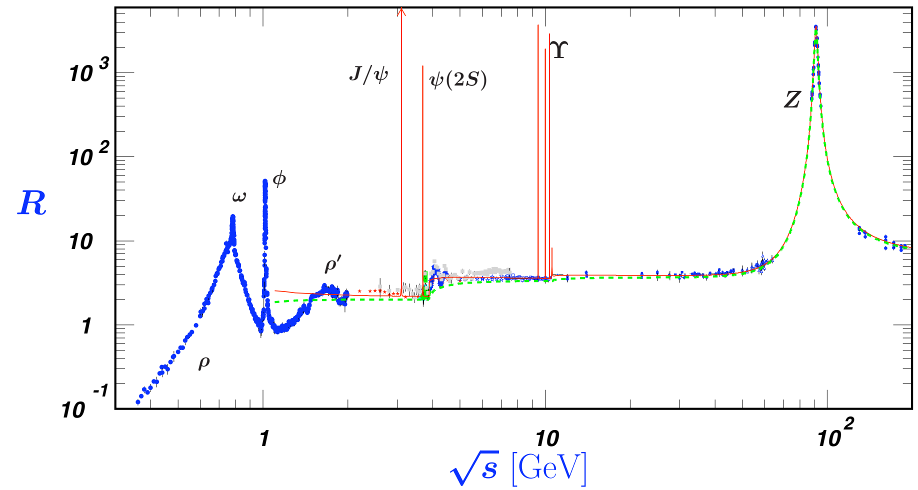
Universal behavior

$$\sigma(E) = \frac{2J+1}{(2S_1+1)(2S_2+1)}\frac{4\pi}{k^2}\left[\frac{\Gamma^2/4}{(E-E_0)^2+\Gamma^2/4}\right]B_{in}B_{out}$$

Convolute with beam resolution ΔE.

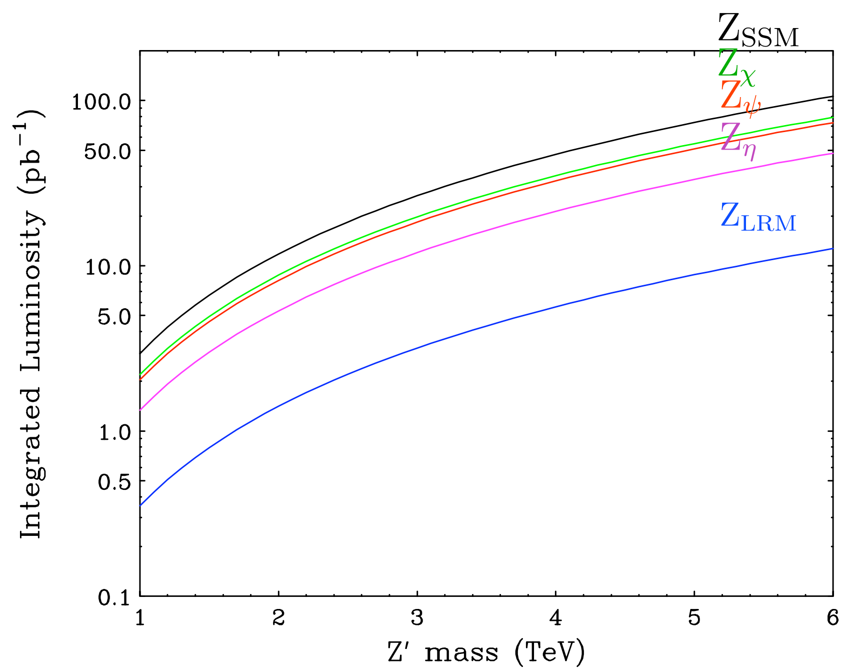
If $\Delta E \ll \Gamma$

$$R_{\rm peak} = (2J+1)3\frac{B(\mu^+\mu^-)B(visible)}{\alpha_{\rm EM}^2}$$



Can use to set minimum required luminosity

- Likely new physics candidates:
  - scalars: h, H^0, A^0,...
  - gauge bosons: Z′
  - new dynamics: bound states
  - ED: KK modes
- Best case example - new gauge boson: Z′
  - examples: SSM, E6, LRM
  - 5σ discovery limits: 4-5 TeV at LHC (@ 300 fb^{-1})



Minimum luminosity at Z′ peak:
$\mathcal{L}$ = 0.5-5.0 x 10^{30} cm^{-2} sec^{-1}
for M(Z′) -> 1.5-5.0 TeV

The integrated luminosity required to produce 1000 $\mu^+\mu^-$ -> Z′ events on the peak

Scalar Sector

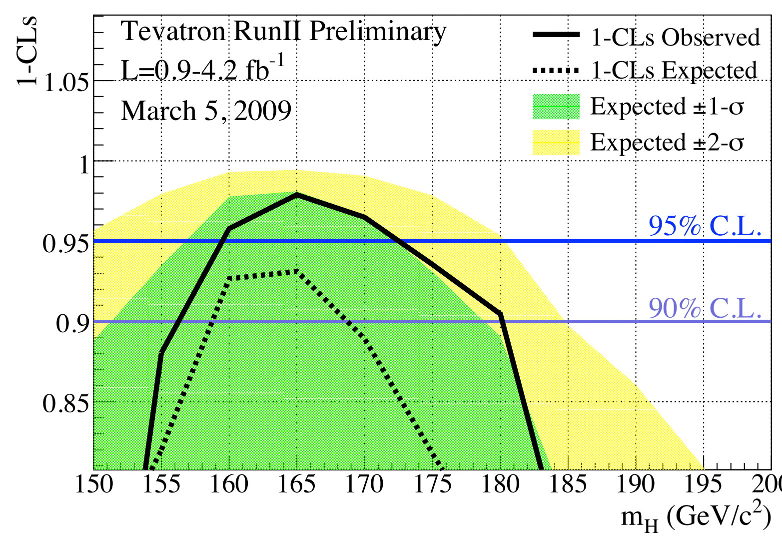
Theoretical issues for SM framework

- Higgs boson couplings SM?
- Scalar interaction self-coupling SM?
- Any additional scalars? EW doublets, triplets or singlets ?
- More fermions?
- Addition gauge interactions ?
- Where's the next scale? GUT?

Standard Model Higgs

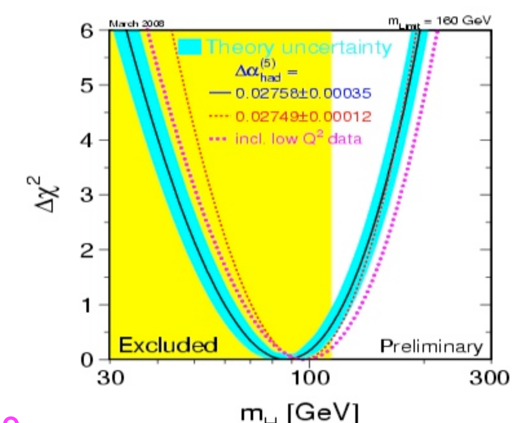
- LHC will discover the SM Higgs, if not found at the Tevatron.

New Limit CDF/D0: $160 \leq m_h \leq 170$ (GeV) excluded (95 % CL)

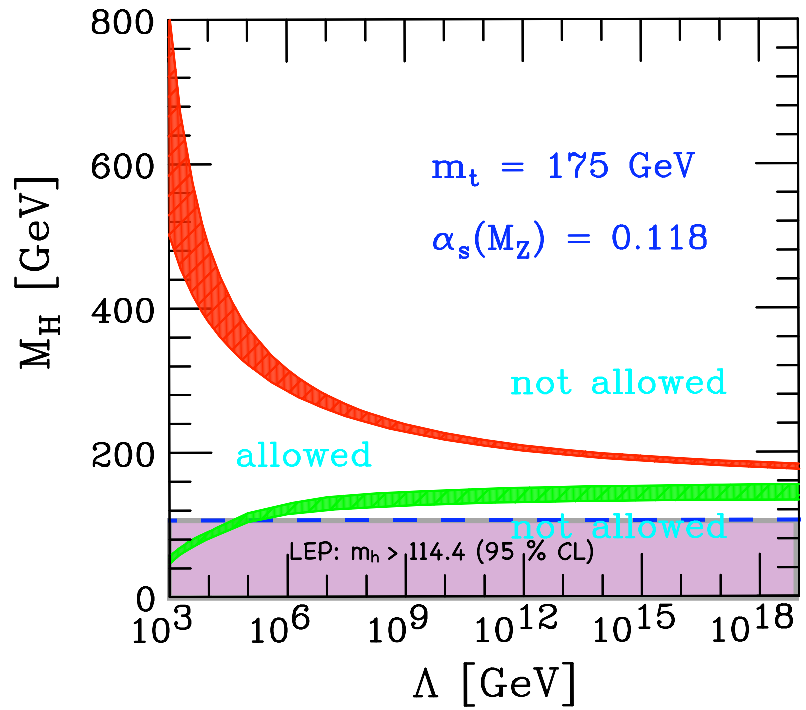


- Indirect bounds on the SM Higgs.

LEP/SLC $m_h \geq 190$ (GeV) excluded (95 % CL)



• The theoretically allowed range of validity (Λ) of the SM versus the Higgs mass. [Upper bound non-perturbative Higgs self-coupling. Lower bound vacuum instability.]



Planck chimney -- 132 ≤ m_h ≤ 190 (GeV)

Constrained by CDF/D0 results

Metastable vacuum stability

$$m_H(\mathrm{GeV}) > 132 + 2.1\,[\mathrm{m_t} - 172.6] - 4.5\,\frac{\alpha_s(\mathrm{m_Z}) - 0.118}{0.006}\,.$$

• If Higgs mass is not in the Planck chimney, new physics is "nearby".

• Large Higgs mass implies a strong Higgs self interaction and presumably a nearby strong interaction.

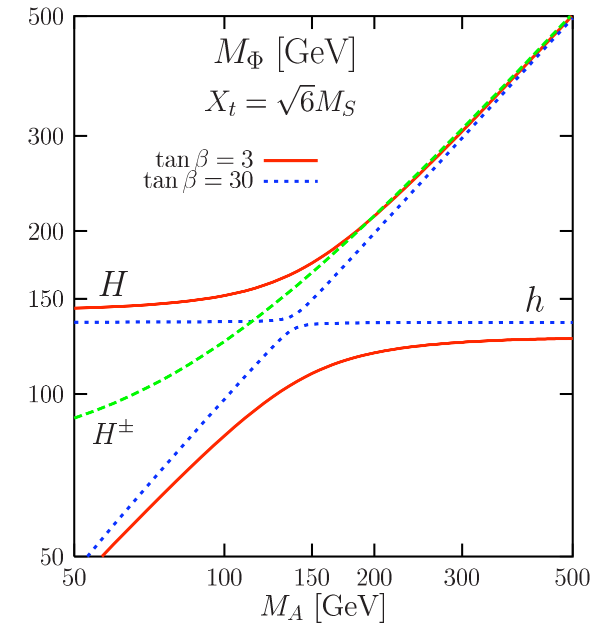
• For a low mass Higgs, the new physics can be perturbative. Many of the Higgs couplings could be measured at the LHC. The ILC(500) allows detailed study of the light Higgs properties.

- Various processes available for studying the Higgs at a muon collider:
  - s-channel direct production: h^0 ($\sqrt{s} = m_h$)
  - associated production: Zh^0
    - R ~ 0.12
    - search for invisible h^0 decays
  - W^*W^* fusion : $\bar{\nu}_\mu \nu_\mu h^0$
    - R ~ 1.1 s ln(s) (s in TeV^2) (m_h = 120 GeV)
    - study some rare decay modes
    - measure Higgs self coupling
  - Higgsstrahlung: $\bar{t}th^0$
    - R ~ 0.01
    - measure top coupling

Two Higgs doublets (MSSM)

- decay amplitudes depend on two parameters:

	$\mu^+\mu^-, b\bar{b}$	$t\bar{t}$	ZZ, W^+W^-	ZA^0
h^0	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$	$\sin(\beta-\alpha)$	$\cos(\beta-\alpha)$
H^0	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$	$\cos(\beta-\alpha)$	$-\sin(\beta-\alpha)$
A^0	$-i\gamma_5\tan\beta$	$-i\gamma_5/\tan\beta$	0	0



- decoupling limit $m_{A^0} \gg m_{Z^0}$:
  - h^0 couplings close to SM values
  - H^0, $H^\pm$ and A^0 nearly degenerate in mass
  - H^0 small couplings to VV, large couplings to ZA^0
  - For large tanβ, H^0 and A^0 couplings to charged leptons and bottom quarks enhanced by tanβ. Couplings to top quarks suppressed by 1/tanβ factor.

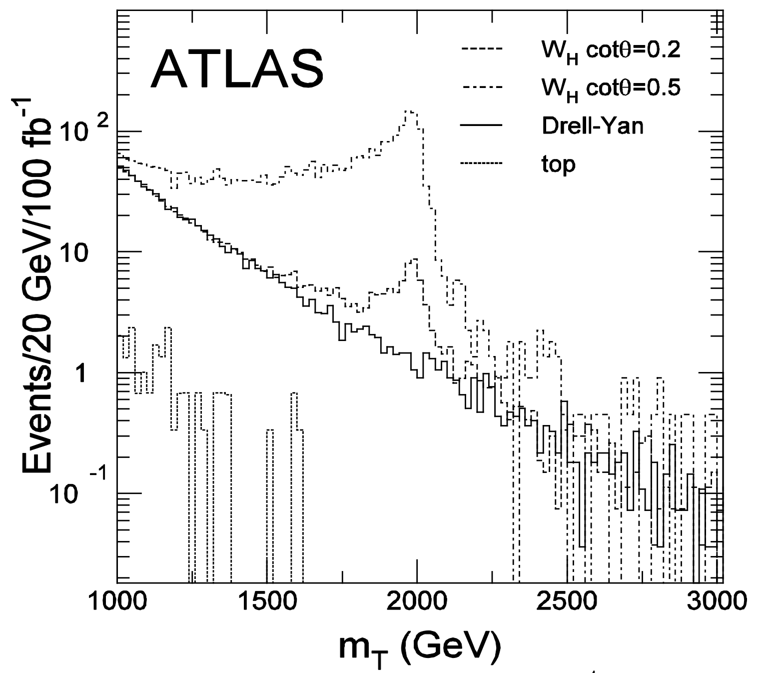
- good energy resolution is needed for H^0 and A^0 studies:
  - for s-channel production of H^0 : $\Gamma/M \approx 1\%$ at tanβ = 20.
  - nearby in mass need good energy resolution to separate H and A.
  - can use bremsstrahlung tail to see states using bb decay mode.

New fermions and gauge bosons

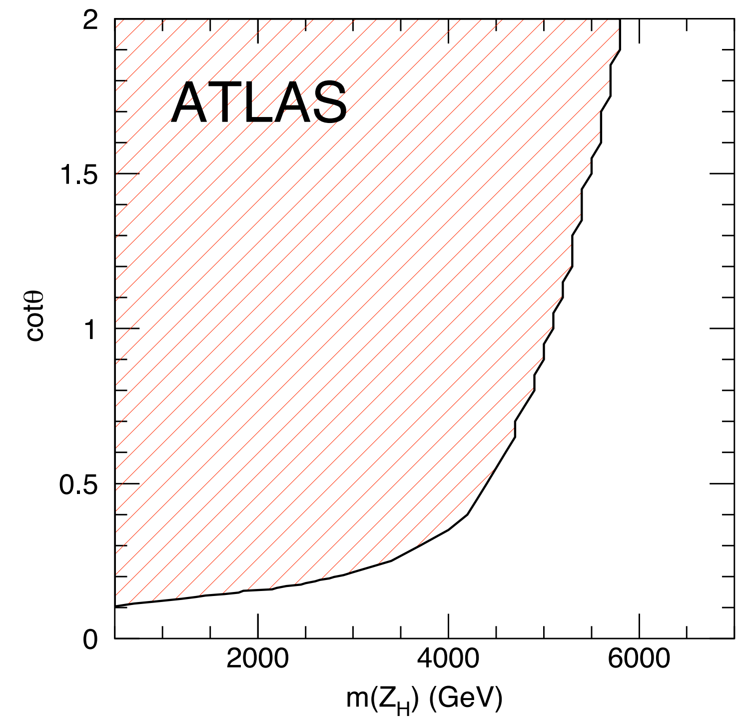
Present CDF/D0 bounds on W′, Z′, and new quarks effectively rule out production at ILC(500).

State	CDF/D0 Limit (GeV)
Quark: (W,Z,h) + jet	295
Z′ (SM)	923
W′ (SM)	860

ATLAS study LHC [hep-ph/0402037]



$Z_H \to ee$ 5 σ reach for 300 fb^{-1}



Littlest Higgs Model –
charge (2/3) quark T (EW singlet),
new W, Z, and A gauge bosons, Higgs triplet

At the LHC, T observable for m(T) < 2.5 TeV
For W, Z, and A dependent on mixing parameters

Muon collider will allow detailed study
Requires high luminosity 1 ab^{-1} for T

Supersymmetry

Theoretical issues

- What is the spectrum of superpartner masses? Dark matter candidates?
- Are all the couplings correct?
- What is the structure of flavor mixing interactions?
- Are there additional CP violating interactions?
- Is R parity violated?
- What is the mechanism of SUSY breaking?
- What is the mass scale at which SUSY is restored?
- ...

MSSM

- Supersymmetry dictates the couplings between particles and sparticles.
- The masses of the superpartners depend on the pattern of SUSY breaking.
- The most studied model is mSUGRA
- Setting soft breaking couplings equal at the GUT scale. Fewest parameters

Many studies of allowed MSSM models

- Parameters mSUGRA: m_0 (< 4TeV), $m_{1/2}$ (< 2TeV), (-10<) A/m_0 (<10), (1<) $\tan\beta$ (<60), sign(μ)

D. Feldman, Zuowei Lui and Pran Nath, PRL 99, 251802 (07); arXiv:0802.4085

- Randomly sample parameter space using with flat priors. Sample size 2×10^6.
  Calculate MSSM mass spectrum and check experimental constraints: (MICROMEGAS and SUSPECT2.3)

$$0.086 < \Omega_{\tilde{\chi}_1^0} h^2 < 0.118\,,\ 2.8\times10^{-4} < Br(b\to s\gamma) < 4.6\times10^{-4}\,,$$
$$\Delta\rho < 2\times10^{-3}\,,\ (g-2)_\mu < 5.1\times10^{-10}\,,\ B_s\to\mu^+\mu^- < 9\times10^{-6}$$
$$m_h > 100\ \text{GeV}\,,\ m_{\tilde{\chi}_1^\pm} > 104.5\ \text{GeV}\,,$$
$$m_{\tilde{t}_1} > 101.5\ \text{GeV}\,,\ m_{\tilde{\tau}_1} > 98.8\ \text{GeV}$$

- If within bounds accept, otherwise reject.

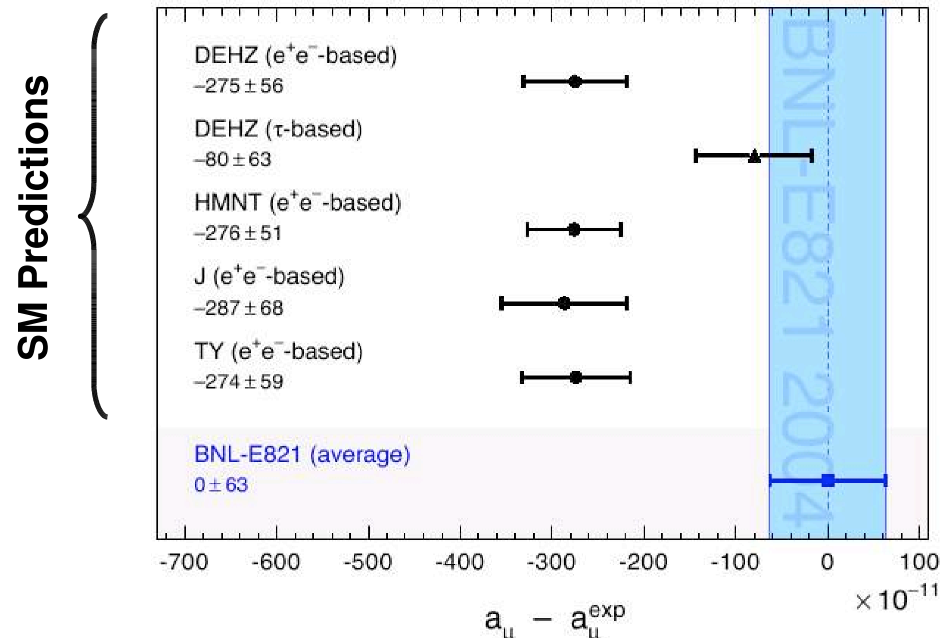
- Old style best fit studies of allowable cMSSM:

J. Ellis, S. Heinemeyer, K.A. Olive, A.m. Weber, G. Wieglein [arXiv:0706.0652]

$$a_\mu^{\rm exp} = 11\,659\,208.0(5.4)(3.3) \times 10^{-10}$$

$(g_\mu-2)/2 = a_\mu$

3.2 σ discrepancy between theory (e^+e^-) and experiment. Pulled the fit for slepton masses low.



New BaBar result

$e^+e^- \to \pi^+\pi^-(\gamma)$ ISR

presented at TAU08

$$a_\mu(SM) = (462.5 \pm 0.9 \pm 3.1) \times 10^{-10}$$
$$a_\mu(\exp) - a_\mu(SM) = (14.8 \pm 8.4) \times 10^{-10}$$

PRELIMINARY!

Reduces model "phase" space for a ILC(500) study of SUSY.

Allowed regions in parameter space are narrow filaments

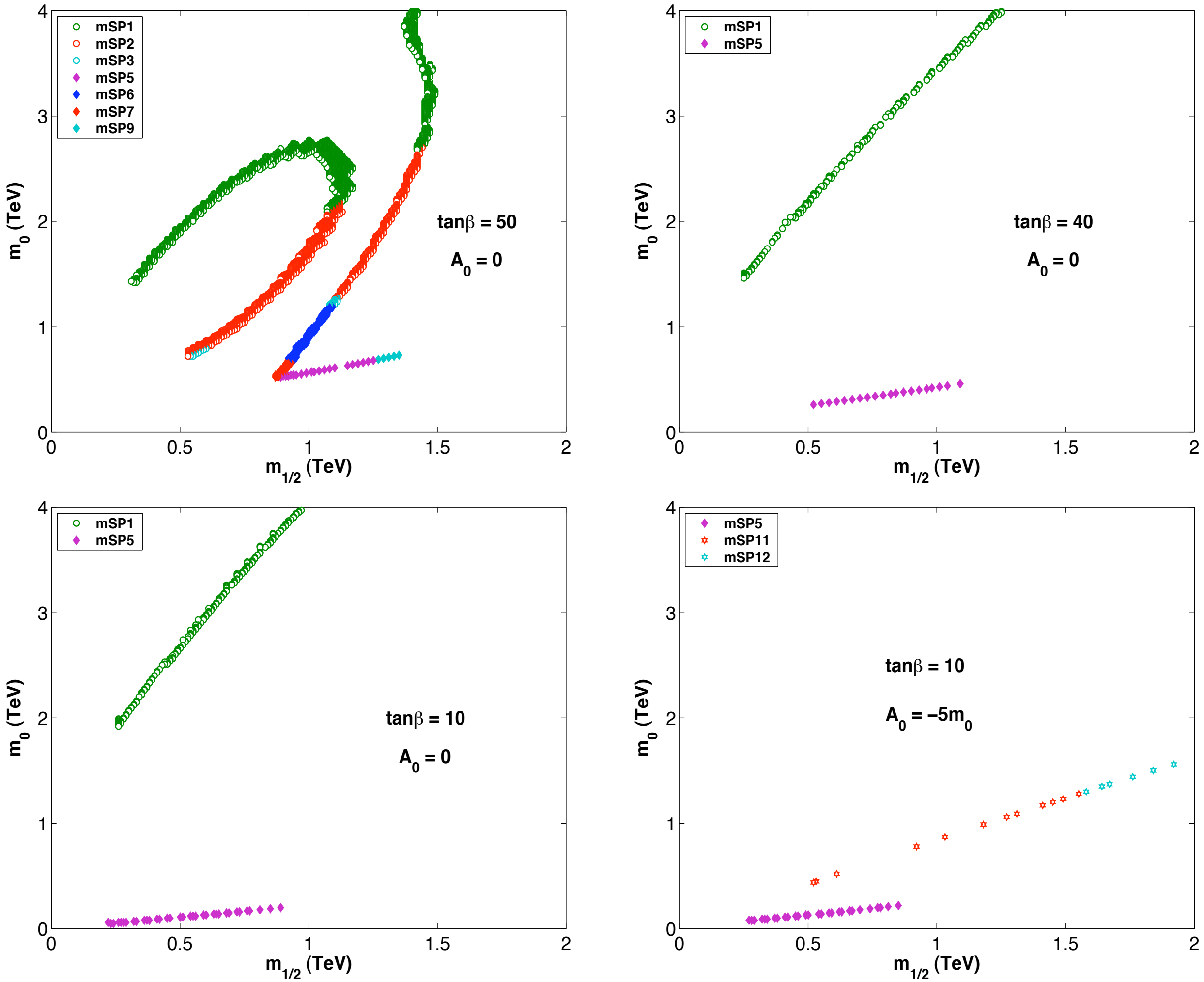


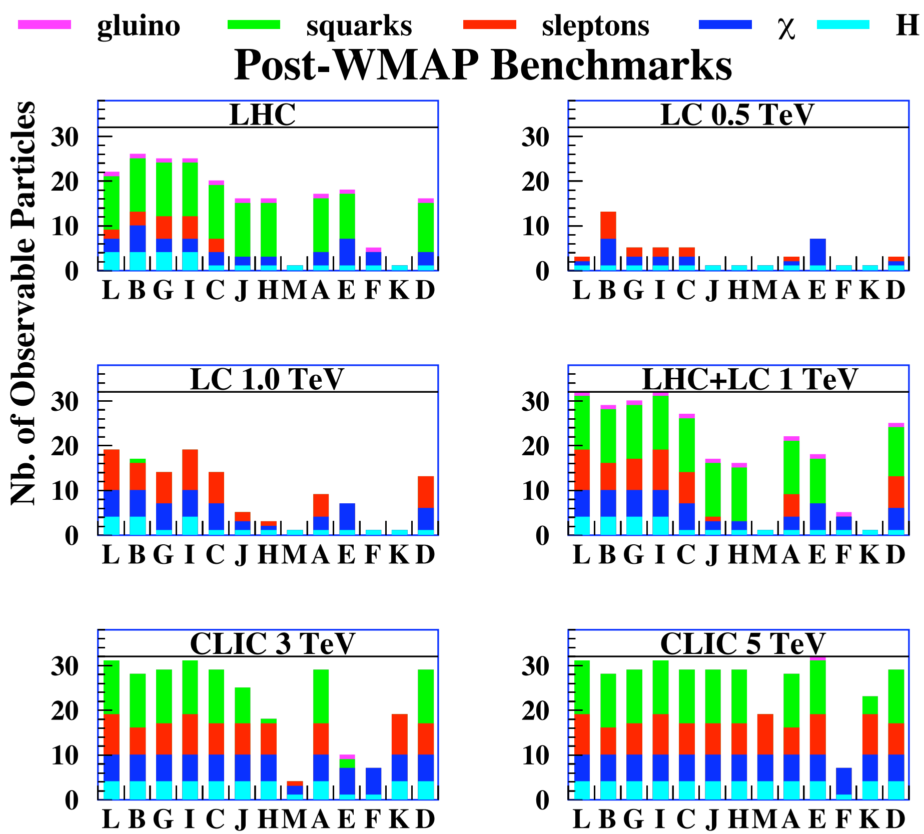
Figure 4: Dispersion of patterns in the m_0 vs $m_{1/2}$ plane for fixed values of $\tan\beta$ and A_0/m_0. The region scanned is in the range $m_0 < 4$ TeV and $m_{1/2} < 2$ TeV with a 10 GeV increment for each mass. Only a subset of the allowed parameter points relative to Fig.(3) remain, since the scans are on constrained surfaces in the mSUGRA parameter space.

Pattern of 4 lightest sparticles

- 22 patterns found (more than 2004 CLIC study).
- New regions because allowed large |A|
- Classified by next to lightest sparticle: chargino, stau, stop, CP even/odd Higgs, neutralino patterns found.

However the general conclusions of the 2004 CLIC study survive.

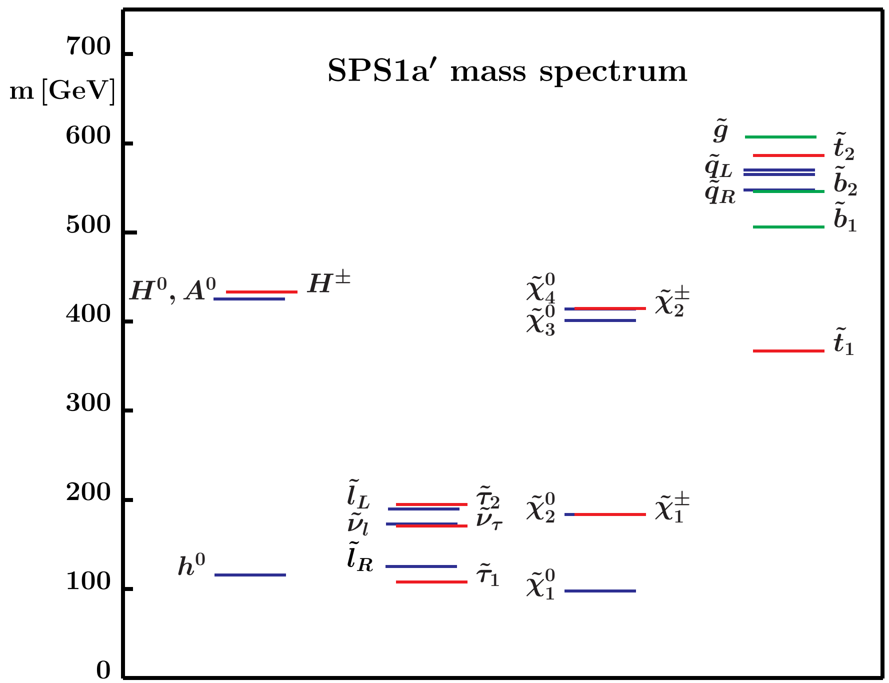
"Supersymmetry at a Muon Collider", Anupama Atre, Low Emittance Muon Collider Workshop Fermilab, April 2008



A multiTev lepton collider needed for full coverage.

- Fine tuning problems in the cMSSM - Allow nonuniversal $m_{1/2}$

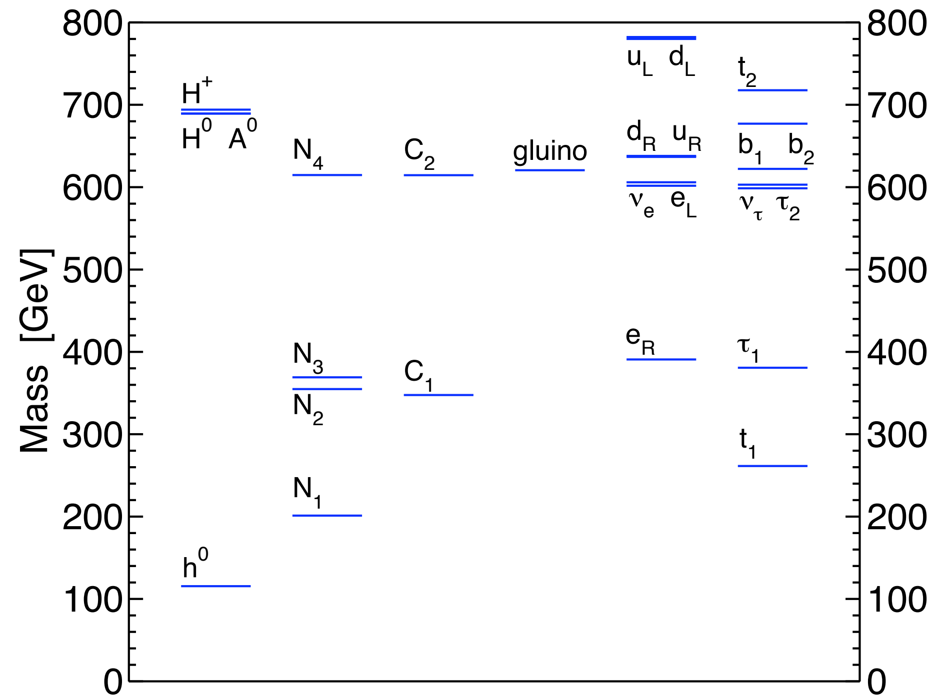
cMSSM ILC Benchmark



Many visible superpartners within reach of the ILC (500 GeV).
All pair production thresholds are below 1.2 TeV.

Compressed SUSY

S. Martin [PR D75:115005,2007]



No visible superpartners within reach of the ILC (500 GeV).
All pair production thresholds are below 1.6 TeV.

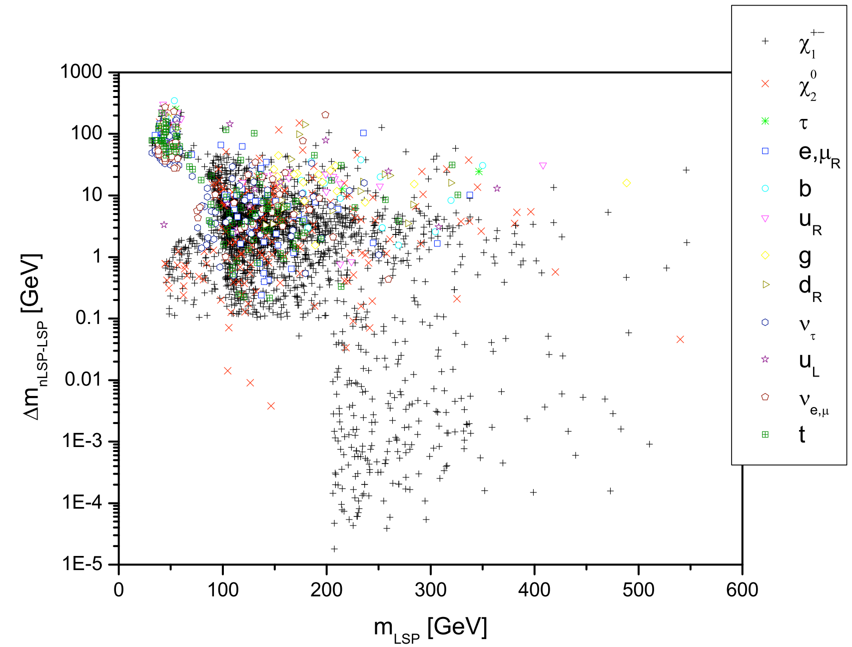
Supersymmetry provides strong case for a multi-TeV lepton collider

pMSSM - relax the unification of soft breaking parameters at the GUT scale.

19 parameters. 10^7 points studied (flat priors)

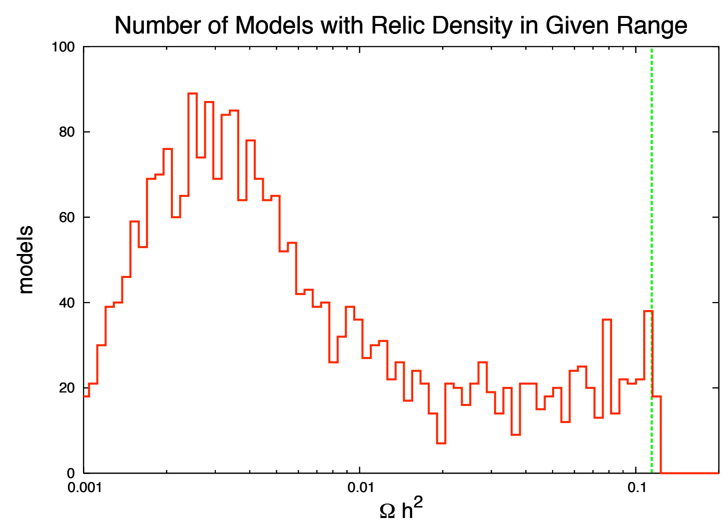
2×10^6 points studied (log priors)

C. Berger, J. Gainer, J. Hewett and T. Rizzo [arXiv:0812.0980]



Required agreement with direct and indirect experimental limits on SUSY, but used the WMAP dark matter density measurements as an upper bound on SUSY dark matter.

Constraints on models from Tevatron direct SUSY searches taken fully into account. D0 limit on charged stable particles was particularly powerful.



Models that satisfied all experimental constraints generally accounted for only a fraction of WMAP dark matter observations !

New Strong Dynamics

Theoretical issues

- What is the spectrum of low-lying states?
- What is the ultraviolet completion? Gauge group? Fermion representations?
- What is the energy scale of the new dynamics?
- Any new insight into quark and/or lepton flavor mixing and CP violation?
- ...

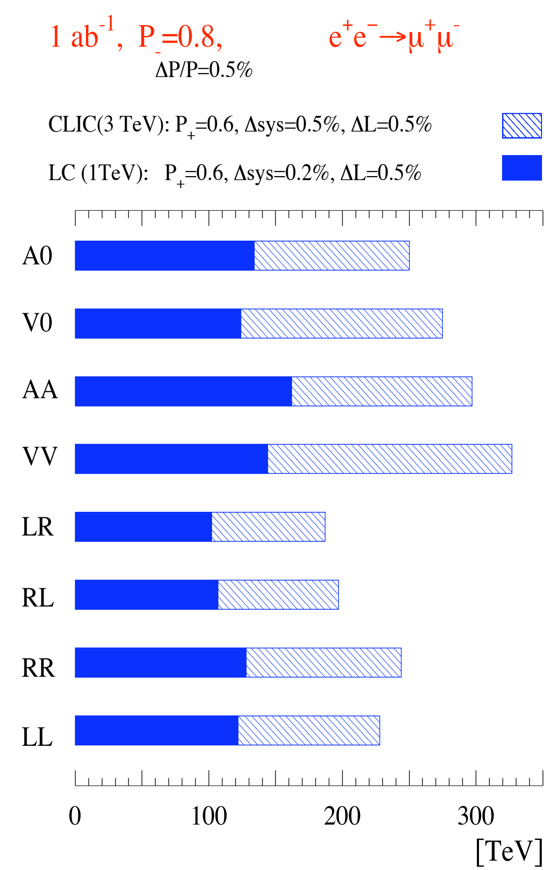
Technicolor, ETC, Walking TC, Topcolor , ...

- Technipions - s channel production (Higgs like)
- Technirhos - Nearby resonances - need fine energy resolution of muon collider.

Contact Interaction

$$\mathcal{L} = \frac{g^2}{\Lambda^2}(\bar{\Psi}\Gamma\Psi)(\bar{\Psi}\Gamma'\Psi)$$

- Muon collider is sensitive to contact interaction scales over 200 TeV.
- Cuts on forward angles for a muon collider not an issue
- Polarization useful to disentangle the chiral structure of the interaction.



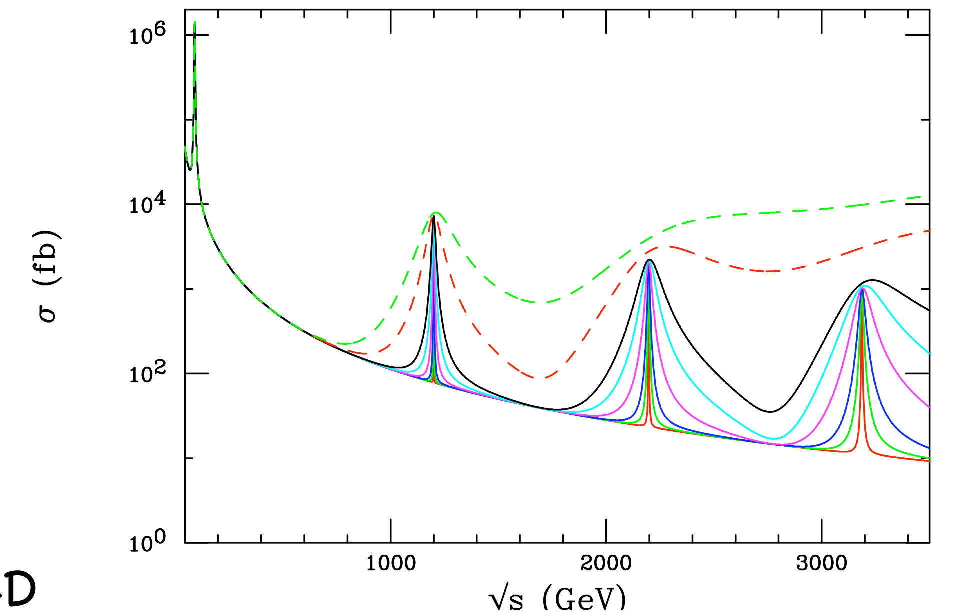
Extra Dimensions

Theoretical issues

LHC discovery - Detailed study at a muon collider

- How many dimensions?
- Which interactions (other than gravity) extend into the extra dimensions?
- At what scale does gravity become a strong interaction?
- What happens above that scale?
- ...

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



possible KK modes of the Z^0

Randall-Sundrum model:
warped extra dimensions

- two parameters:
  - mass scale ∝ first KK mode;
  - width ∝ 5D curvature / effective 4D Planck scale.

Conclusions

- Precise knowledge of the neutrino sector has wide impact from cosmology (dark matter, baryon asymmetry, ...) to the nature of gauge unification near the Planck scale. A Neutrino Factory will be needed to fully disentangle neutrino physics.
- A multiTeV lepton collider is required for full coverage of Tevascale physics. Recent experimental results continue to limit the SUSY potential of a 500 GeV ILC.
- The physics potential for a muon collider at $\sqrt{s} \sim 3$ TeV and integrated luminosity of 1 ab^{-1} is outstanding. Particularly strong case for SUSY and new strong dynamics.
- Narrow s-channel states played an important role in past lepton colliders. If such states exist in the multi-TeV region, they will play a similar role in precision studies for new physics. Sets the minimum luminosity scale.
- A detailed study of physics case for 1.5-4.0 TeV muon collider is needed:
  - Dependence on initial beam [electron/muon, polarization and beam energy spread] as well as luminosity should be considered.
  - Estimates of collision point environment and detector parameters needed.
  - Must be able to withstand the real physics environment after ten years of running at the LHC.

Backup Slides

Appearance probabilities in long baseline neutrino oscillation experiments

$$P(\nu_\mu \to \nu_e) = X_+ \sin\theta_{13}^2 + Y_+ \sin\theta_{13}\cos(\Delta_{13}+\delta) + P_{\rm sol}$$
$$P(\bar\nu_\mu \to \bar\nu_e) = X_- \sin\theta_{13}^2 - Y_- \sin\theta_{13}\cos(\Delta_{13}+\delta) + P_{\rm sol}$$

(normal hierarchy)

where

$$X_\pm = 4\sin^2\theta_{23}\left[\frac{\Delta_{31}\sin(aL\mp\Delta_{31})}{(aL\mp\Delta_{31})}\right]^2$$
$$Y_\pm = \pm 2\sqrt{X_\pm P_{\rm sol}}$$
$$P_{\rm sol} = \cos^2\theta_{23}\sin^2 2\theta_{12}\left[\frac{\Delta_{21}\sin(aL)}{aL}\right]^2$$
$$\Delta_{ij} \equiv |\Delta m_{ij}^2| L/4E$$

and the index of refraction in matter is:

$$a = G_F N_e/\sqrt{2}$$

J. Burguet-Castell et.al. NP B608 (2001) 301

Note that the interference term is the only term that depends on CP phase δ. Also the only term that differs for neutrino/antineutrino beside matter effects.

SM Higgs

- Mass
- Higgs boson couplings?
- Scalar interaction self-coupling?

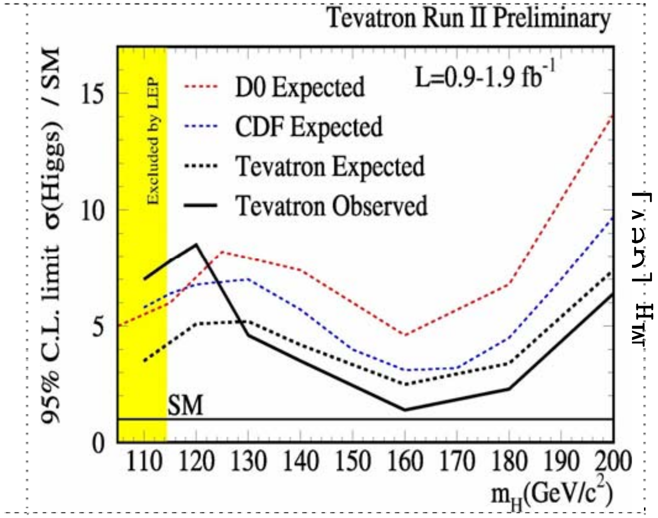
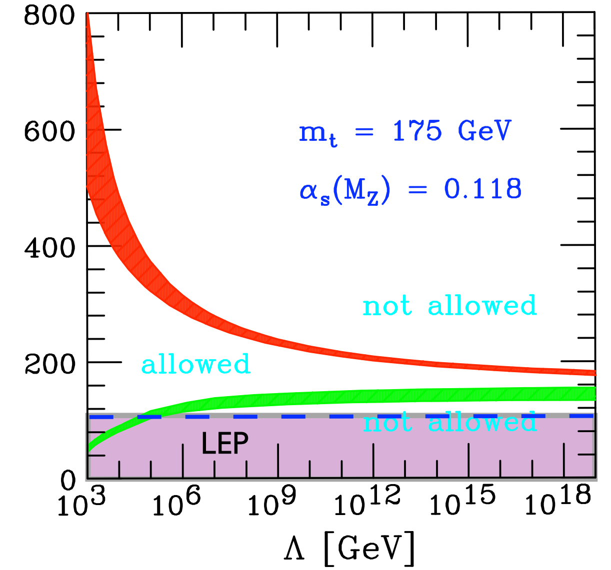
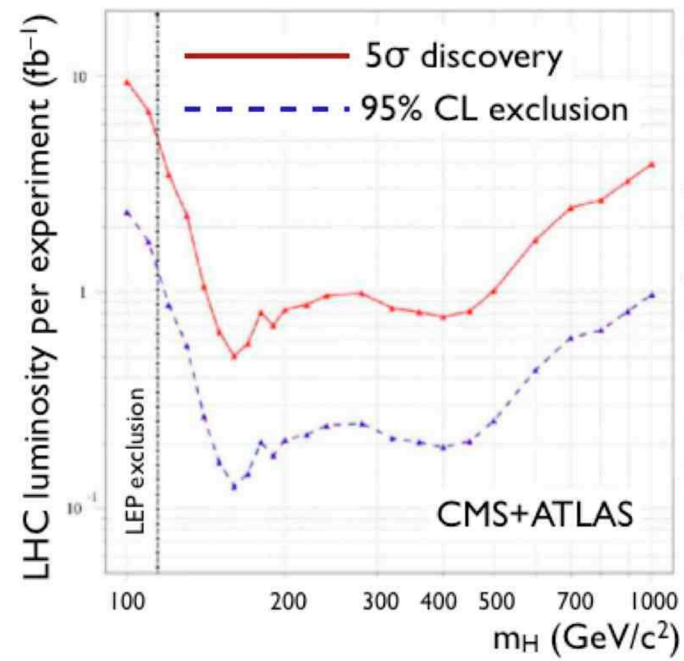


Figure 4. Tevatron combined upper limits normalized by SM expectation

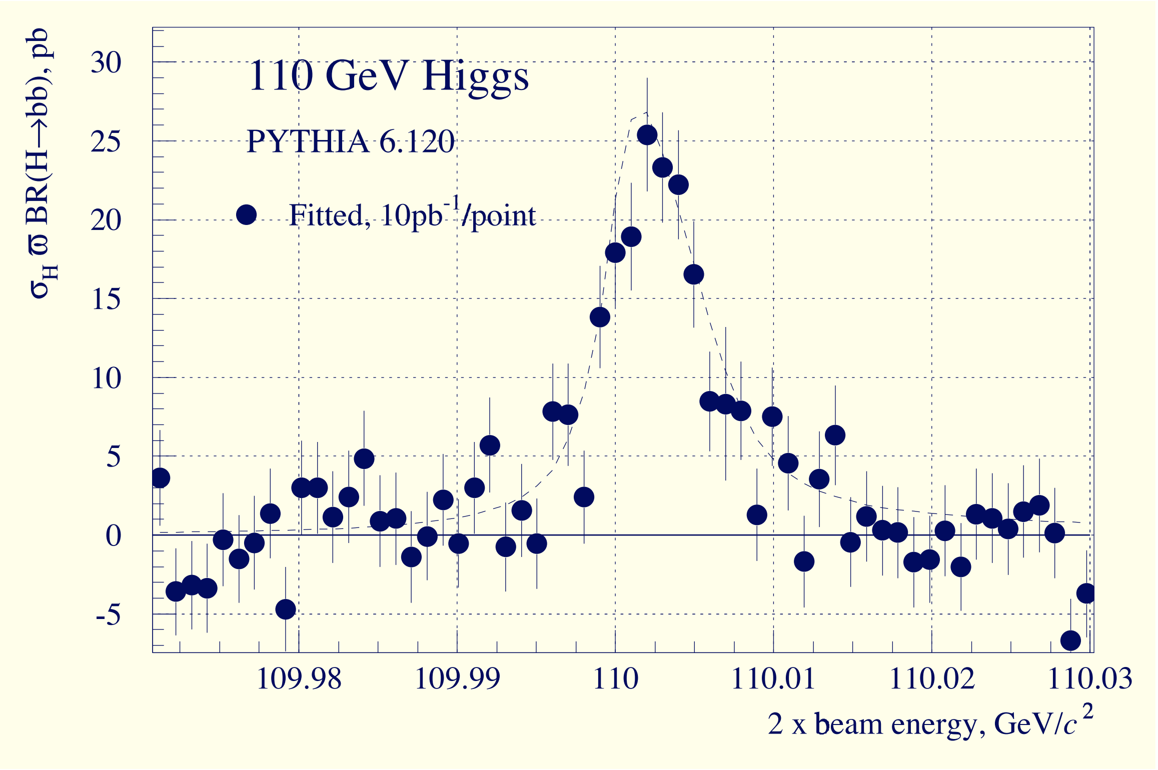


- Higgs bound (LEP): $m_h > 114.4$ (95 % CL)
- LHC will discover the SM Higgs. If Higgs mass is not in the Planck chimney (130-190), new physics “nearby”.
- Large Higgs mass implies a strong Higgs self interaction and presumably a nearby strong interaction.
- For a low mass Higgs, the new physics can be perturbative. This case is favored by the present indirect Higgs bounds. Many of the Higgs couplings could be measured at the LHC.
- The ILC(500) allows detailed study of the light Higgs properties.
- A dedicated Higgs factory would be a high priority if no new physics at the LHC.



$\Delta E/E = 0.03\%$

$10\ pb^{-1}$/point



J. Gunion

Fine energy resolution (ΔE/E) is possible for muon colliders

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

$$\sigma_{\sqrt{s}} = (7~{\rm MeV})\left(\frac{R}{0.01\%}\right)\left(\frac{\sqrt{s}}{100~{\rm GeV}}\right).$$

$$\overline{\sigma}_h = \frac{2\pi^2\Gamma(h\to\mu\mu)\,BF(h\to X)}{m_h^2} \times \frac{1}{\sigma_{\sqrt{s}}\sqrt{2\pi}} \qquad (\Gamma_h^{\rm tot} \ll \sigma_{\sqrt{s}}).$$

$$\overline{\sigma}_h = \frac{4\pi BF(h\to\mu\mu)BF(h\to X)}{m_h^2} \qquad (\Gamma_h^{\rm tot} \gg \sigma_{\sqrt{s}})$$

Measuring SM Higgs width directly requires: ΔE/E < 0.003% with an integrated luminosity > 2 pb^{-1}

Easier for large tanβ SUSY Higgs

h

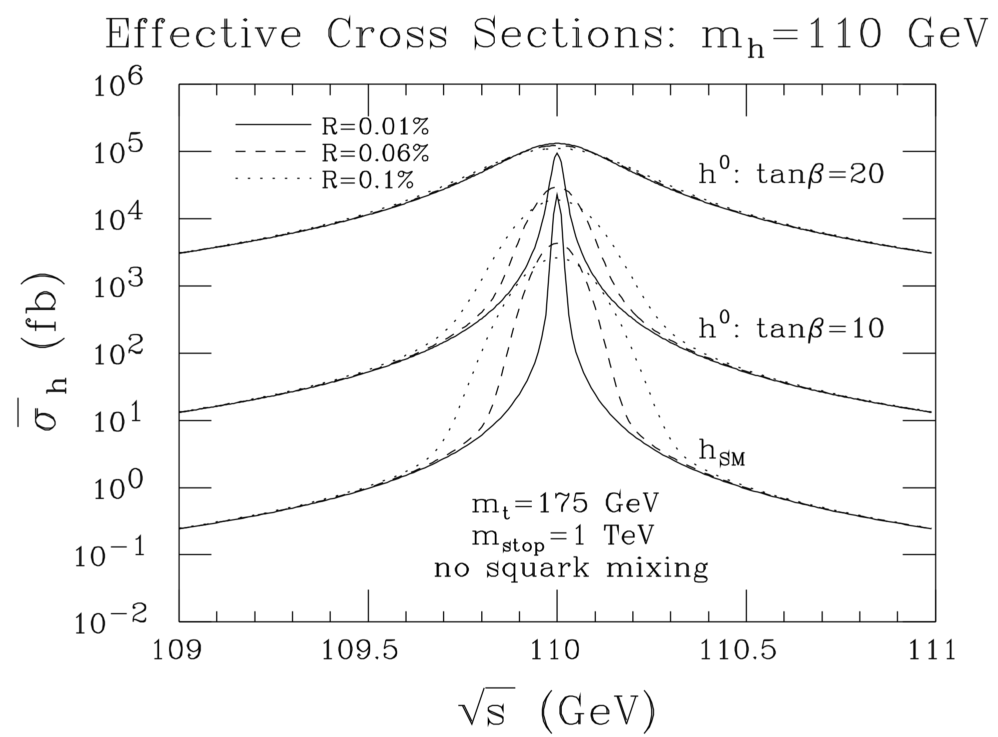
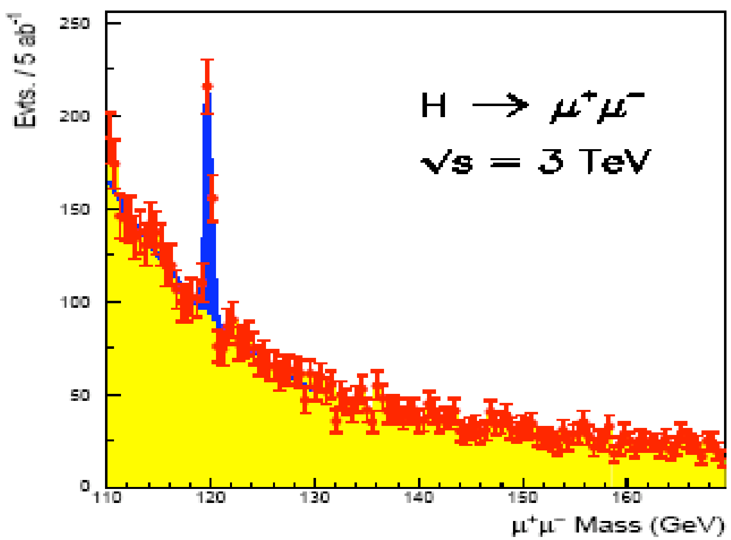


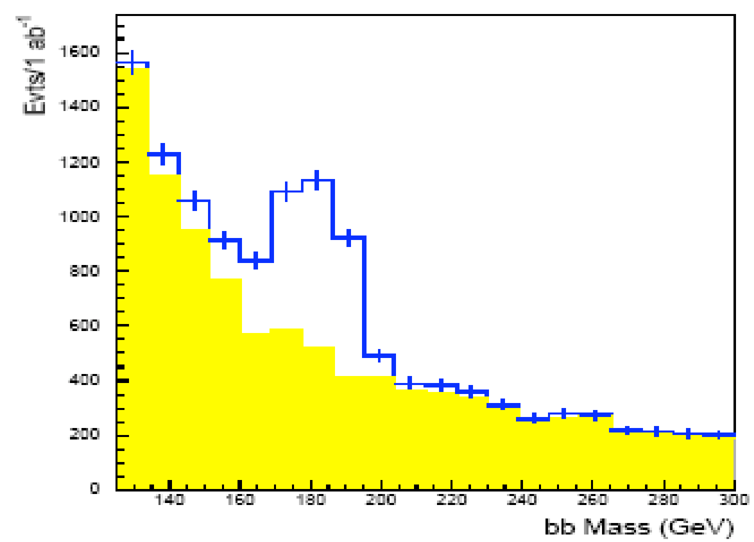
Figure 7: The effective cross section, $\overline{\sigma}_h$, obtained after convoluting σ_h with the Gaussian distributions for $R = 0.01\%$, $R = 0.06\%$, and $R = 0.1\%$, is plotted as a function of $\sqrt{s}$ taking $m_h = 110$ GeV. Results are displayed in the cases: h_{SM}, h^0 with $\tan\beta = 10$, and h^0 with $\tan\beta = 20$. In the MSSM h^0 cases, two-loop/RGE-improved radiative corrections have been included for Higgs masses, mixing angles, and self-couplings assuming $m_{\widetilde{t}} =$ 1 TeV and neglecting squark mixing. The effects of bremsstrahlung are not included in this figure.

ZH (CLIC)

m(H) = 120 GeV



m(H) = 200 GeV



W*W* fusion

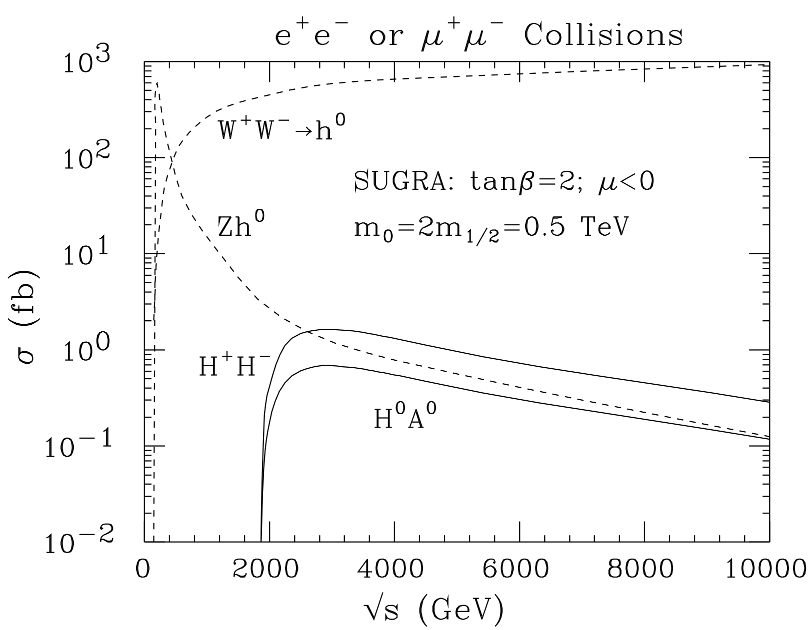
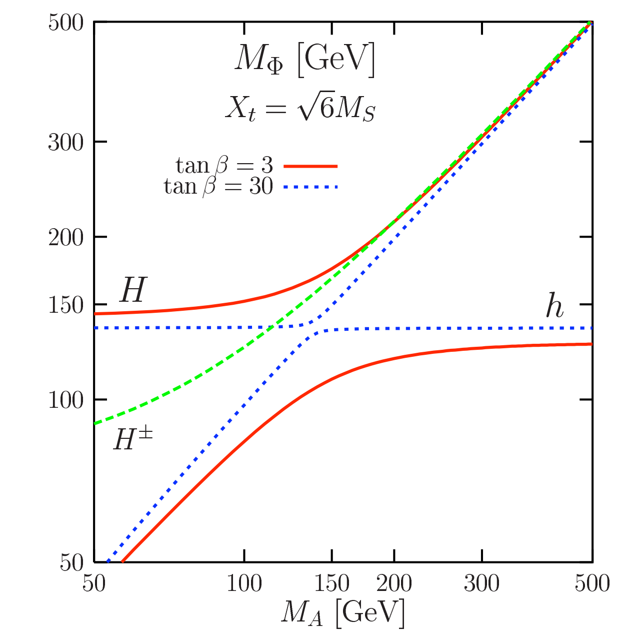


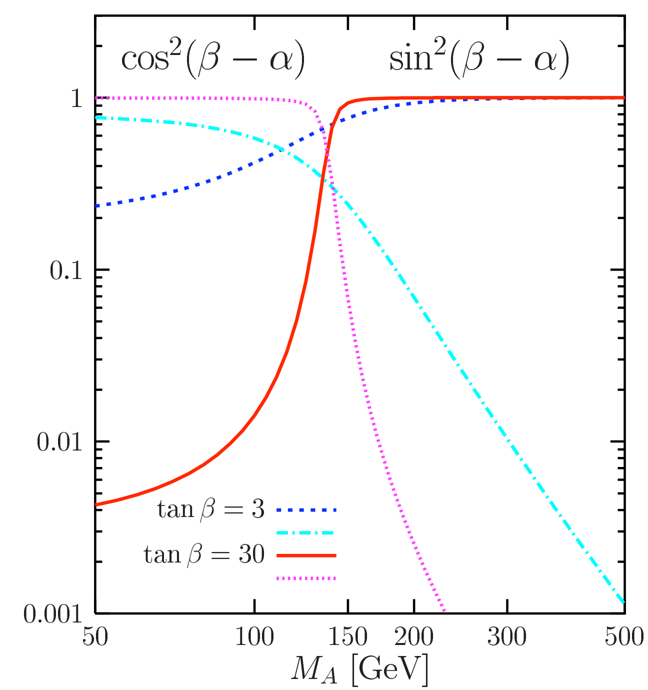
FIGURE 6. Pair production of heavy Higgs bosons at a high energy lepton collider. For comparison, cross sections for the lightest Higgs boson production via the Bjorken process $\mu^+\mu^- \to Z^* \to Zh^0$ and via the WW fusion process are also presented.

Two Higgs doublets (MSSM)

	$\mu^+\mu^-, b\bar{b}$	$t\bar{t}$	ZZ, W^+W^-	ZA^0
h^0	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$	$\sin(\beta-\alpha)$	$\cos(\beta-\alpha)$
H^0	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$	$\cos(\beta-\alpha)$	$-\sin(\beta-\alpha)$
A^0	$-i\gamma_5\tan\beta$	$-i\gamma_5/\tan\beta$	0	0



- **decoupling limit $m_{A^0} \gg m_{Z^0}$:**
  - h^0 couplings close to SM values
  - H^0, $H^\pm$ and A^0 nearly degenerate in mass
  - H^0 small couplings to VV, large couplings to ZA^0
  - For large tanβ, H^0 and A^0 couplings to charged leptons and bottom quarks enhanced by tanβ. Couplings to top quarks suppressed by 1/tanβ factor.



- good energy resolution is needed for H^0 and A^0 studies:
    - for s-channel production of H^0 : $\Gamma/M \approx 1\%$ at $\tan\beta = 20$.
    - nearby in mass need good energy resolution to separate H and A
    - can use bremsstrahlung tail to see states using bb decay mode

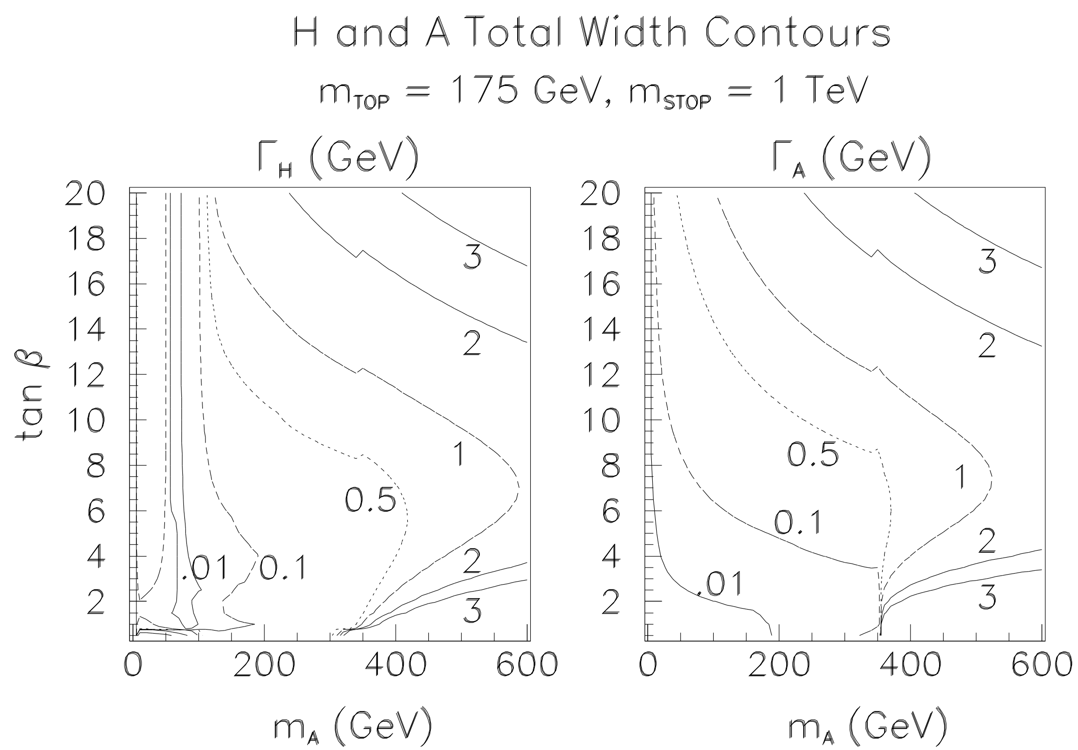


Figure 20: Contours of H^0 and A^0 total widths (in GeV) in the $(m_{A^0}, \tan\beta)$ parameter space. We have taken $m_t = 175$ GeV and included two-loop/RGE-improved radiative corrections using $m_{\tilde{t}} = 1$ TeV and neglecting squark mixing. SUSY decay channels are assumed to be absent.

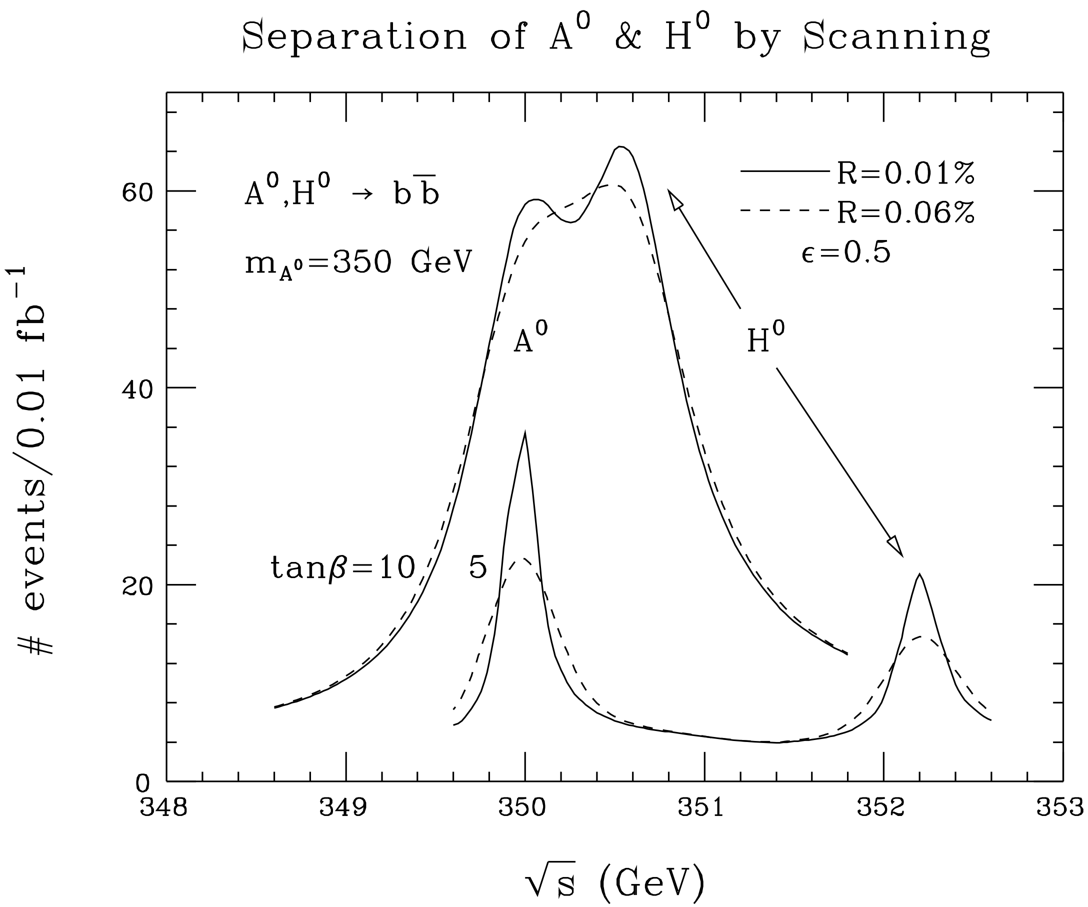


FIGURE 4. Plot of $b\bar{b}$ final state event rate as a function of $\sqrt{s}$ for $m_{A^0} = 350$ GeV, in the cases $\tan\beta = 5$ and 10, resulting from the H^0, A^0 resonances and the $b\bar{b}$ continuum background. We have taken $L = 0.01$ fb^{-1} (at any given $\sqrt{s}$), efficiency $\epsilon = 0.5$, $m_t = 175$ GeV, and included two-loop/RGE-improved radiative corrections to Higgs masses, mixing angles and self-couplings using $m_{\widetilde{t}} = 1$ TeV and neglecting squark mixing. SUSY decays are assumed to be absent. Curves are given for two resolution choices: $R = 0.01\%$ and $R = 0.06\%$

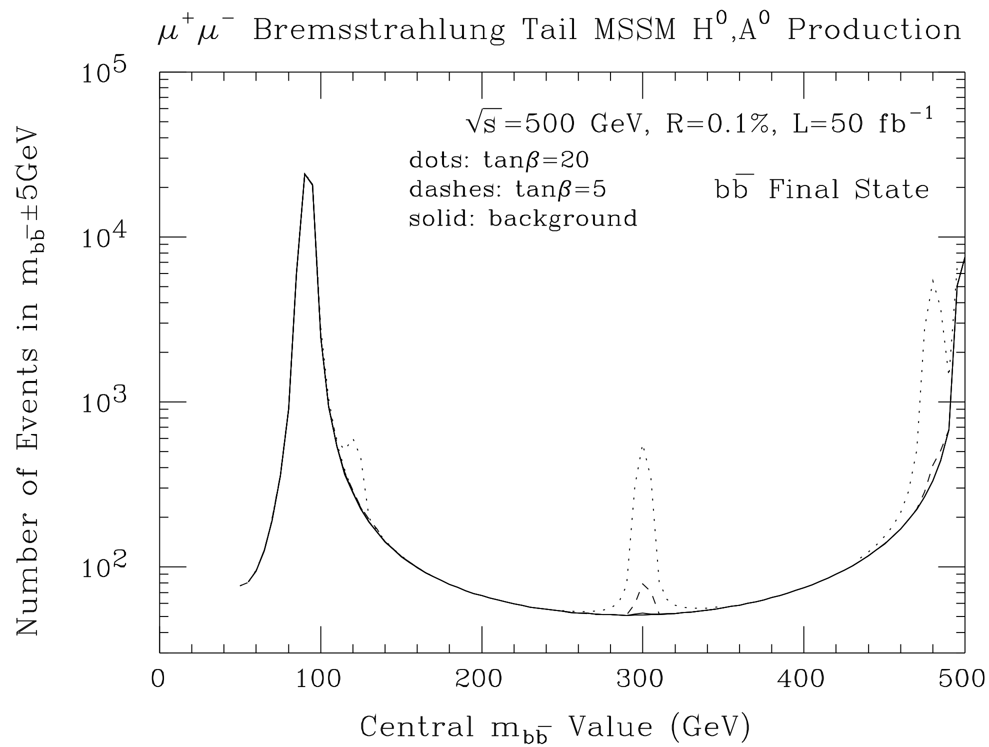


FIGURE 5. Taking $\sqrt{s} = 500$ GeV, integrated luminosity $L = 50$ fb^{-1}, and $R = 0.1\%$, we consider the $b\overline{b}$ final state and plot the number of events in the interval $[m_{b\bar{b}} - 5\text{ GeV}, m_{b\bar{b}} + 5\text{ GeV}]$, as a function of the location of the central $m_{b\bar{b}}$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

CMSSM – Soft breaking couplings set equal at GUT scale.
Fewest parameters (aka mSUGRA)

- Detailed study benchmark points for CLIC - CERN report 2004

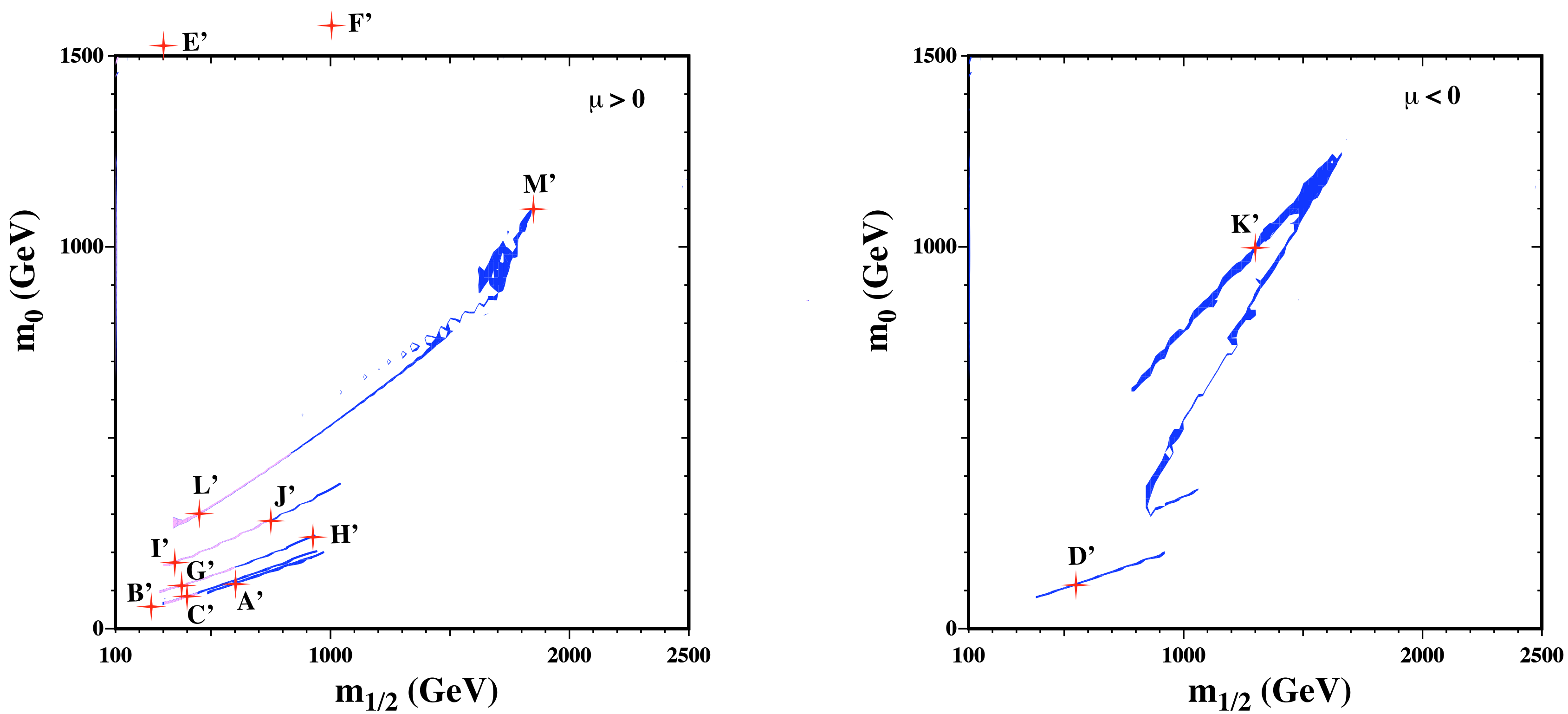


Fig. 5.2: Overview of the updated proposed CMSSM benchmark points in the $(m_0, m_{1/2})$ planes, superposed on the strips allowed by laboratory limits and the relic density constraint, for $\mu > 0$ and $\tan\beta$ = 5, 10, 20, 35, 50, and for $\mu < 0$ and $\tan\beta$ = 10, 35 [8]

Pattern of 4 lightest sparticles

- New regions because allow large |A|
- Classified by next to lightest sparticle: chargino, stau, stop, CP even/odd Higgs, neutralino patterns found.
- The general conclusions of the 2004 CLIC study survive.

Benchmark models

mSP	Mass Pattern	$\mu > 0$	$\mu < 0$
mSP1	$\widetilde{\chi}_1^0 < \widetilde{\chi}_1^\pm < \widetilde{\chi}_2^0 < \widetilde{\chi}_3^0$	Y	Y
mSP2	$\widetilde{\chi}_1^0 < \widetilde{\chi}_1^\pm < \widetilde{\chi}_2^0 < A/H$	Y	Y
mSP3	$\widetilde{\chi}_1^0 < \widetilde{\chi}_1^\pm < \widetilde{\chi}_2^0 < \widetilde{\tau}_1$	Y	Y
mSP4	$\widetilde{\chi}_1^0 < \widetilde{\chi}_1^\pm < \widetilde{\chi}_2^0 < \widetilde{g}$	Y	Y
mSP5	$\widetilde{\chi}_1^0 < \widetilde{\tau}_1 < \widetilde{l}_R < \widetilde{\nu}_\tau$	Y	Y
mSP6	$\widetilde{\chi}_1^0 < \widetilde{\tau}_1 < \widetilde{\chi}_1^\pm < \widetilde{\chi}_2^0$	Y	Y
mSP7	$\widetilde{\chi}_1^0 < \widetilde{\tau}_1 < \widetilde{l}_R < \widetilde{\chi}_1^\pm$	Y	Y
mSP8	$\widetilde{\chi}_1^0 < \widetilde{\tau}_1 < A \sim H$	Y	Y
mSP9	$\widetilde{\chi}_1^0 < \widetilde{\tau}_1 < \widetilde{l}_R < A/H$	Y	Y
mSP10	$\widetilde{\chi}_1^0 < \widetilde{\tau}_1 < \widetilde{t}_1 < \widetilde{l}_R$	Y	
mSP11	$\widetilde{\chi}_1^0 < \widetilde{t}_1 < \widetilde{\chi}_1^\pm < \widetilde{\chi}_2^0$	Y	Y
mSP12	$\widetilde{\chi}_1^0 < \widetilde{t}_1 < \widetilde{\tau}_1 < \widetilde{\chi}_1^\pm$	Y	Y
mSP13	$\widetilde{\chi}_1^0 < \widetilde{t}_1 < \widetilde{\tau}_1 < \widetilde{l}_R$	Y	Y
mSP14	$\widetilde{\chi}_1^0 < A \sim H < H^\pm$	Y	
mSP15	$\widetilde{\chi}_1^0 < A \sim H < \widetilde{\chi}_1^\pm$	Y	
mSP16	$\widetilde{\chi}_1^0 < A \sim H < \widetilde{\tau}_1$	Y	
mSP17	$\widetilde{\chi}_1^0 < \widetilde{\tau}_1 < \widetilde{\chi}_2^0 < \widetilde{\chi}_1^\pm$		Y
mSP18	$\widetilde{\chi}_1^0 < \widetilde{\tau}_1 < \widetilde{l}_R < \widetilde{t}_1$		Y
mSP19	$\widetilde{\chi}_1^0 < \widetilde{\tau}_1 < \widetilde{t}_1 < \widetilde{\chi}_1^\pm$		Y
mSP20	$\widetilde{\chi}_1^0 < \widetilde{t}_1 < \widetilde{\chi}_2^0 < \widetilde{\chi}_1^\pm$		Y
mSP21	$\widetilde{\chi}_1^0 < \widetilde{t}_1 < \widetilde{\tau}_1 < \widetilde{\chi}_2^0$		Y
mSP22	$\widetilde{\chi}_1^0 < \widetilde{\chi}_2^0 < \widetilde{\chi}_1^\pm < \widetilde{g}$		Y

Table 1: Hierarchical mass patterns for the four lightest sparticles in mSUGRA when $\mu < 0$ and $\mu > 0$. The patterns can be classified according to the next to the lightest sparticle. For the mSUGRA analysis the next to the lightest sparticle is found to be either a chargino, a stau, a stop, a CP even/odd Higgs, or the next lightest neutralino $\widetilde{\chi}_2^0$. The notation A/H stands for either A or H. In mSP14-mSP16 it is possible that the Higgses become lighter than the LSP. Y stands for appearance of the pattern for the sub case.

Options

- It's a small fine tuning

- Modify GUT boundary conditions:

  - Compressed SUSY - S. Martin [hep-ph/0703097]
    Non universal $m_{1/2}$ at GUT scale. Choose the gluino term smaller than the others. Then constrain the model using all the data.

  - NUHM - the scalar mass soft breaking terms not universal.-
    Ellis et.al. [hep-ph/0706.0652]

- Add additional degrees of freedom
  NMSSM, ...

- Avoid the LEP bound on the Higgs mass
  Have a light a_0 of the NMSSM so $Br(h \to aa) > 0.7$ and $m(a) < 2m(b)$.
  Avoids the LEP limits on Higgs -
  Dermisek,Gunion, McElrath [hep-ph/0612031]

Fine tuning problems in the cMSSM

M(h^0) > 114.4 GeV (95% cl) LEP combined bound]

tan β = v_u/v_d

top squark

masses: $m_{\tilde{t}_1}, m_{\tilde{t}_2}$

mixing: $c_{\tilde{t}}, s_{\tilde{t}}$

\+ ...

tree 1-loop

$$M^2_{h^0} = m^2_Z \cos^2(2\beta) + \frac{3}{4\pi^2}\sin^2\beta\, y^2_t \Big[m^2_t \ln\left(m_{\tilde{t}_1} m_{\tilde{t}_2}/m^2_t\right) + c^2_{\tilde{t}} s^2_{\tilde{t}} (m^2_{\tilde{t}_2} - m^2_{\tilde{t}_1}) \ln(m^2_{\tilde{t}_2}/m^2_{\tilde{t}_1}) + c^4_{\tilde{t}} s^4_{\tilde{t}} \Big\{ (m^2_{\tilde{t}_2} - m^2_{\tilde{t}_1})^2 - \frac{1}{2}(m^4_{\tilde{t}_2} - m^4_{\tilde{t}_1}) \ln(m^2_{\tilde{t}_2}/m^2_{\tilde{t}_1}) \Big\} / m^2_t \Big].$$

with measured top mass and tan β constraints,

need large top squark mass. BUT

$$m^2_Z = -2\left(|\mu|^2 + m^2_{H_u}\right) - \frac{1}{v_u}\frac{\partial}{\partial v_u}\Delta V + \mathcal{O}(1/\tan^2\beta).$$

soft SUSY breaking mass term in higgs field coupling to top

loop part of effective potential

the largeness the soft SUSY breaking mass term means a fine tuned cancellation between the μ^2 and m^2_H terms to more than a few percent.

Relax the soft breaking restrictions at the GUT scale ?

Technicolor, ETC, Walking TC, Topcolor, ...

Technipions:

S channel production - higgs like

$$\frac{d\sigma(\mu^+\mu^- \to \pi_T^0 \text{ or } \pi_T^{0\prime} \to \bar{f}f)}{dz} = \frac{N_f}{2\pi}\left(\frac{C_\mu C_f m_\mu m_f}{F_T^2}\right)^2 \frac{s}{(s-M_{\pi_T}^2)^2 + s\,\Gamma_{\pi_T}^2}\,,$$

$$\frac{d\sigma(\mu^+\mu^- \to \pi_T^{0\prime} \to gg)}{dz} = \frac{C_{\pi_T}}{32\pi^3}\left(\frac{C_\mu m_\mu \alpha_S N_{TC}}{F_T^2}\right)^2 \frac{s^2}{(s-M_{\pi_T}^2)^2 + s\,\Gamma_{\pi_T}^2}\,.$$

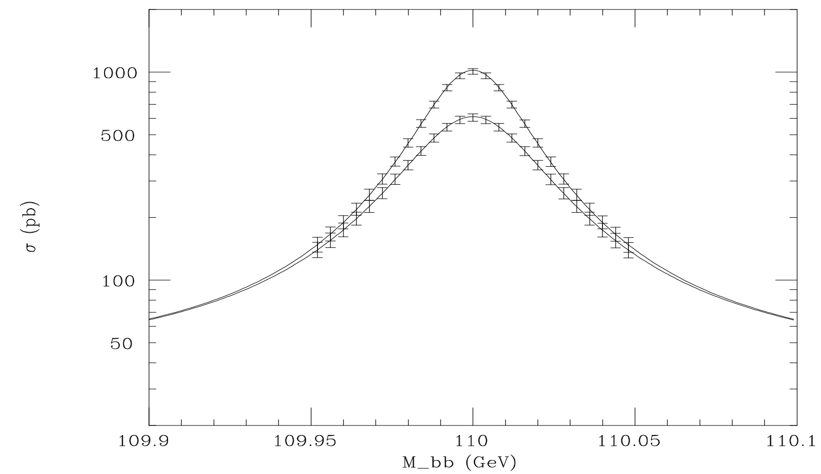


Figure 1: Cross sections for $\mu^+\mu^- \to \pi_T^0 \to \bar{b}b$ (upper curve) and $\pi_T^{0\prime} \to \bar{b}b$. Statistical errors only are shown for a luminosity of $1\,\mathrm{pb}^{-1}$ per point. Cuts and efficiencies are described in the text. The solid lines are the theoretical cross sections (perfect resolution).

Technirhos:

Can have nearby vector resonances that interfere:

Would need the fine resolution to disentangle states

Common case with new strong dynamics

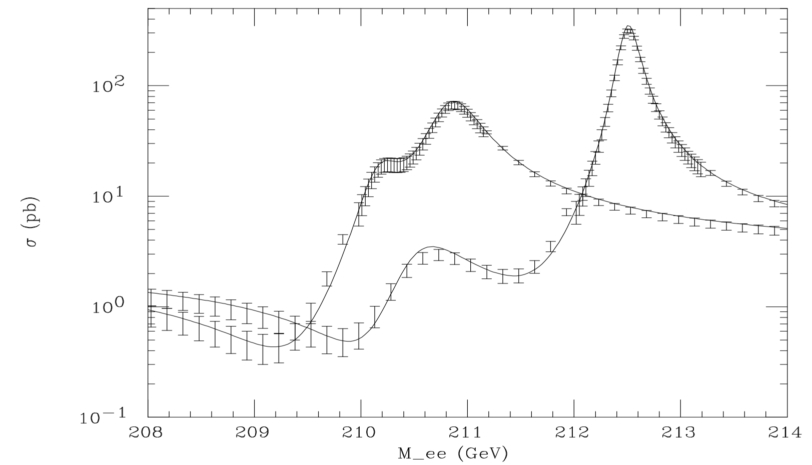


Figure 2: Cross sections for $\mu^+\mu^- \to \rho_T, \omega_T \to e^+e^-$ for $M_{\rho_T} = 210\,\mathrm{GeV}$ and $M_{\omega_T} = 211\,\mathrm{GeV}$ (higher-peaked curve) and $209\,\mathrm{GeV}$. Statistical errors only are shown for resolutions and luminosities described in the text. The solid lines are the theoretical cross sections (perfect resolution).

CMS - TDR

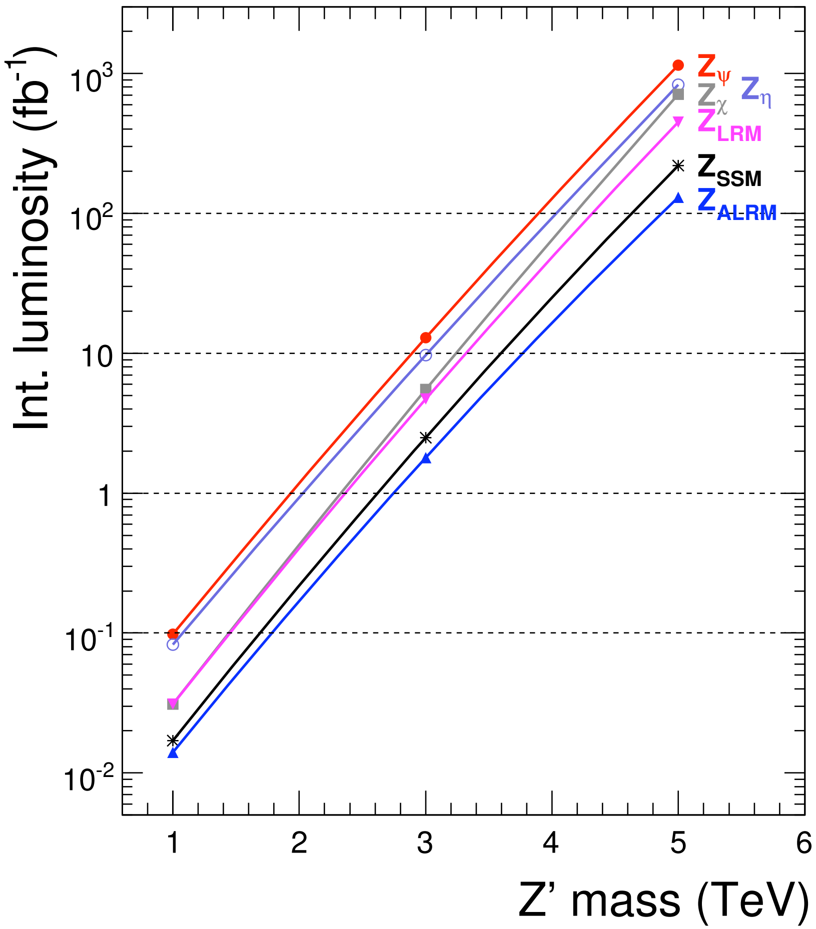


Figure 3.20: Integrated luminosity needed to reach 5σ significance ($S_{\mathcal{L}} = 5$) as a function of Z′ mass for (top to bottom) Z_ψ, Z_η, Z_χ, Z_{LRM}, Z_{SSM} and Z_{ALRM}. Symbols indicate fully-simulated mass-luminosity points, lines are the results of interpolations between the points.