Neutrino Factory and Muon Collider Physics

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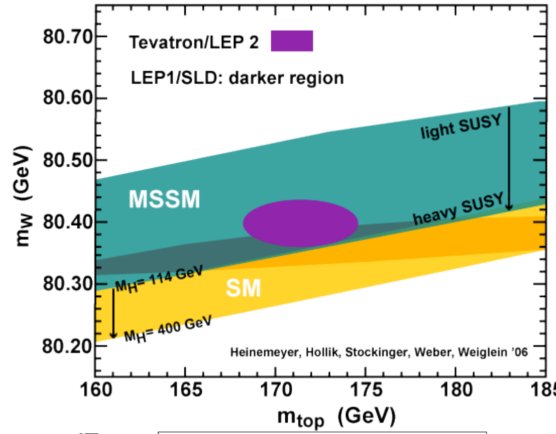
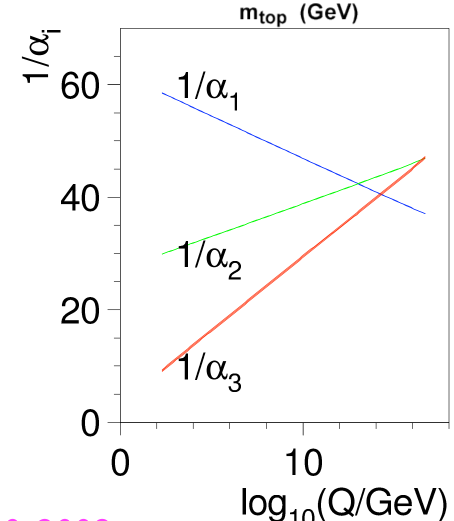
OUTLINE

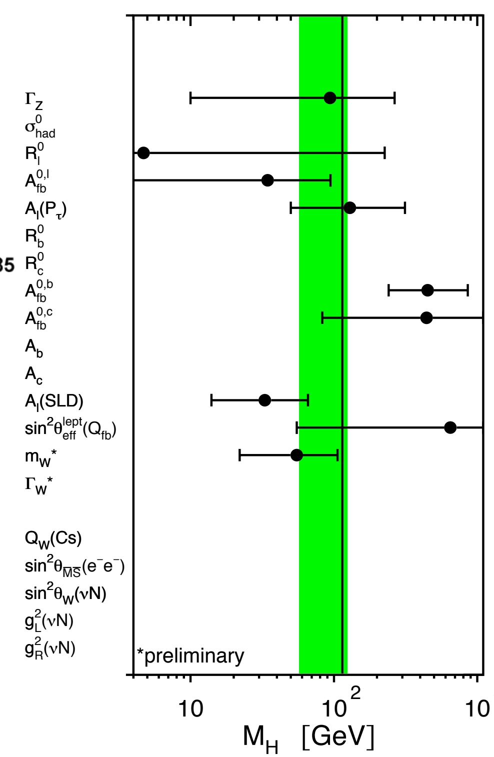
- Where We Stand
- Neutrino Physics
- Muon Collider
  - Higgs Sector
  - Beyond the Standard Model
  - Minimum Luminosity
- Conclusions

Theory Status

- All data consistent with Standard Model - but:
- incomplete
  - dark matter
  - 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
  - muon (g-2)
- theoretical questions
  - origin of mass:
    - naturalness and higgs
  - gauge unification:
    - new interactions
  - gravity: strings and ED







Neutrino Physics

SM leptons: $\mathsf{L}_e = \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_{\rm L}$ $\mathsf{L}_\mu = \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_{\rm L}$ $\mathsf{L}_\tau = \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_{\rm L}$ $\mathsf{R}_{e,\mu,\tau} = e_{\rm R}, \mu_{\rm R}, \tau_{\rm R}$

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 changes the picture drastically

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)

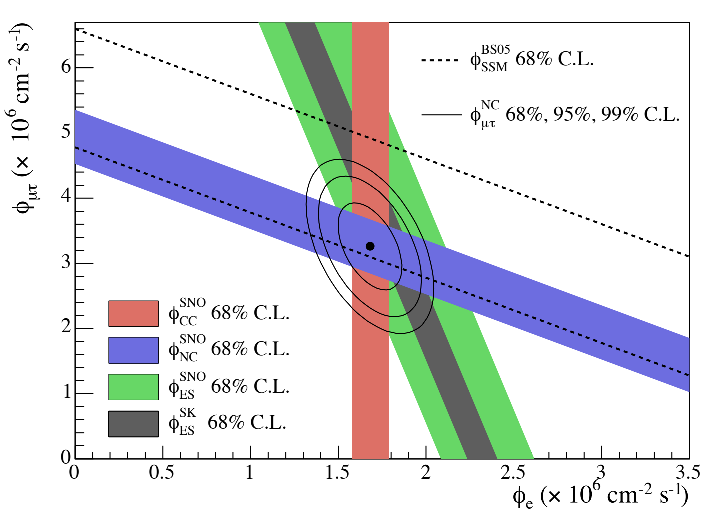
$$\nu_\alpha = \nu_i \cos\theta + \nu_j \sin\theta$$

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

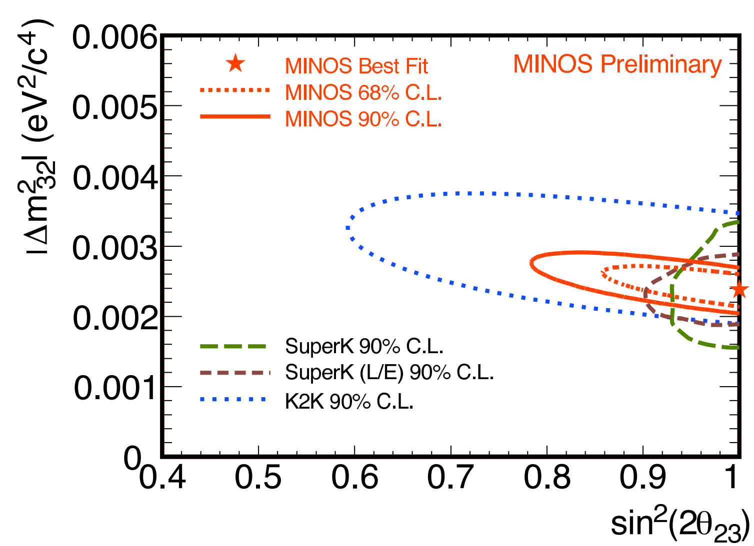
Oscillation probability (P) for energy (E) and distance (L)

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

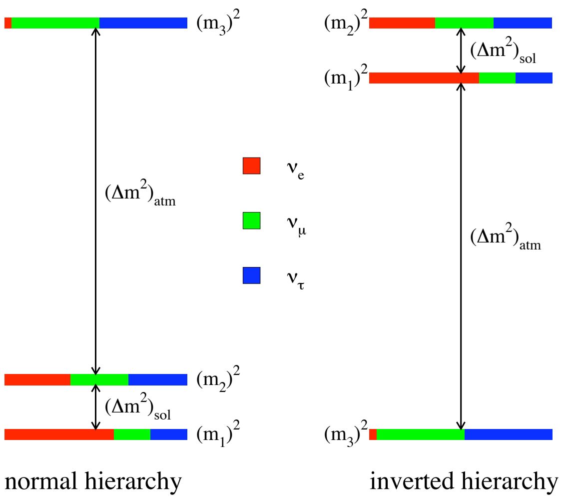
Solar



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:

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

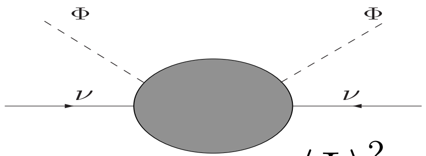
$$\phi \equiv \frac{1}{2}(\rho_2 + i\rho_1)$$
$$\chi \equiv \frac{1}{2}(\rho_2 - i\rho_1)$$

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

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

Pontecorvo-Maki-Nakagawa-Sakata Matrix

Three angles: $\theta_{12}, \theta_{23}, \theta_{13}$
CP phases: δ(Dirac) (α,β,δ)(Majorana)

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

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

Matter effects:

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

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

Present Status

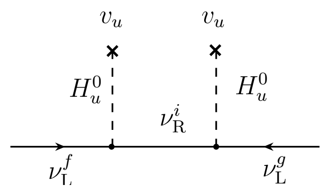
parameter	best fit	2σ	3σ	4σ
Δm^2_{21} [10^{-5} eV^2]	7.9	7.3–8.5	7.1–8.9	6.8–9.3
Δm^2_{31} [10^{-3} eV^2]	2.6	2.2–3.0	2.0–3.2	1.8–3.5
$\sin^2\theta_{12}$	0.30	0.26–0.36	0.24–0.40	0.22–0.44
$\sin^2\theta_{23}$	0.50	0.38–0.63	0.34–0.68	0.31–0.71
$\sin^2\theta_{13}$	0.000	≤ 0.025	≤ 0.040	≤ 0.058

Maltoni, et. al. [hep-ph/0405172.v5]

A Plethora of Theoretical Models

Model | **Interaction** | **New Particles** | **Comments**

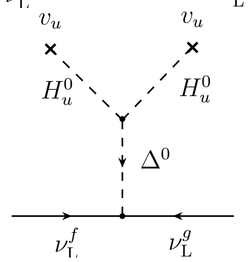
(1-2-3) Seesaw I



ν_R, Majoron

Very light majoron
dark matter candidate

(1-2-3) Seesaw II



heavy higgs
triplet

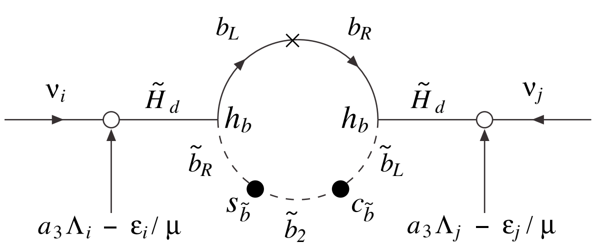
L-R Seesaw
SU(3)×SU(2)×SU(2)×U(1)

Both types above

new gauge bosons

No majoron
B-L
Terascale physics

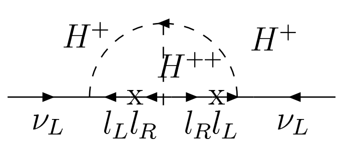
SUSY models



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

⋮

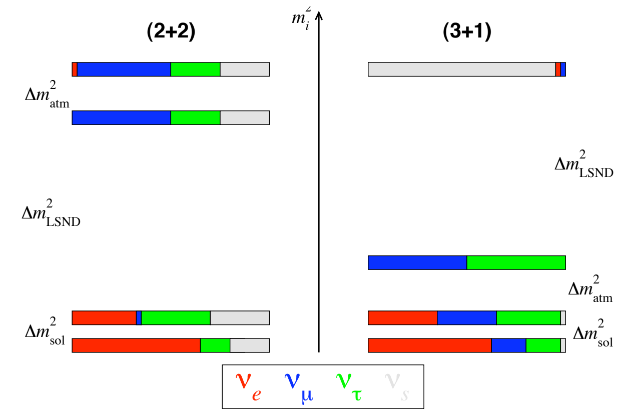
Basic goals of Neutrino program:

(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?



Why is this important?

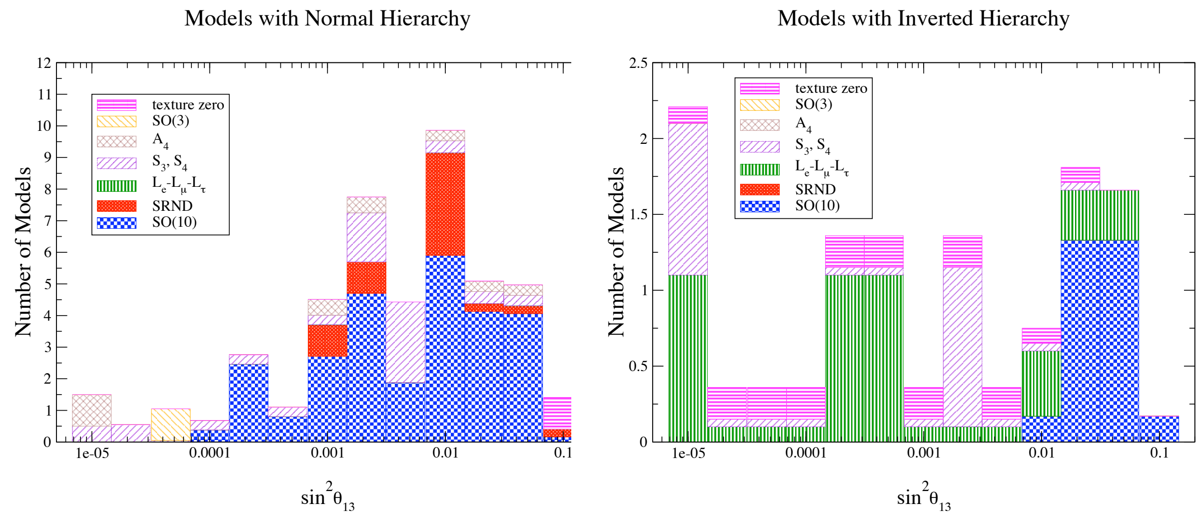
(a) Neutrino masses are very small. Theoretical models for these masses predict new particles at the Terascale or a new scale beyond.

(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)

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

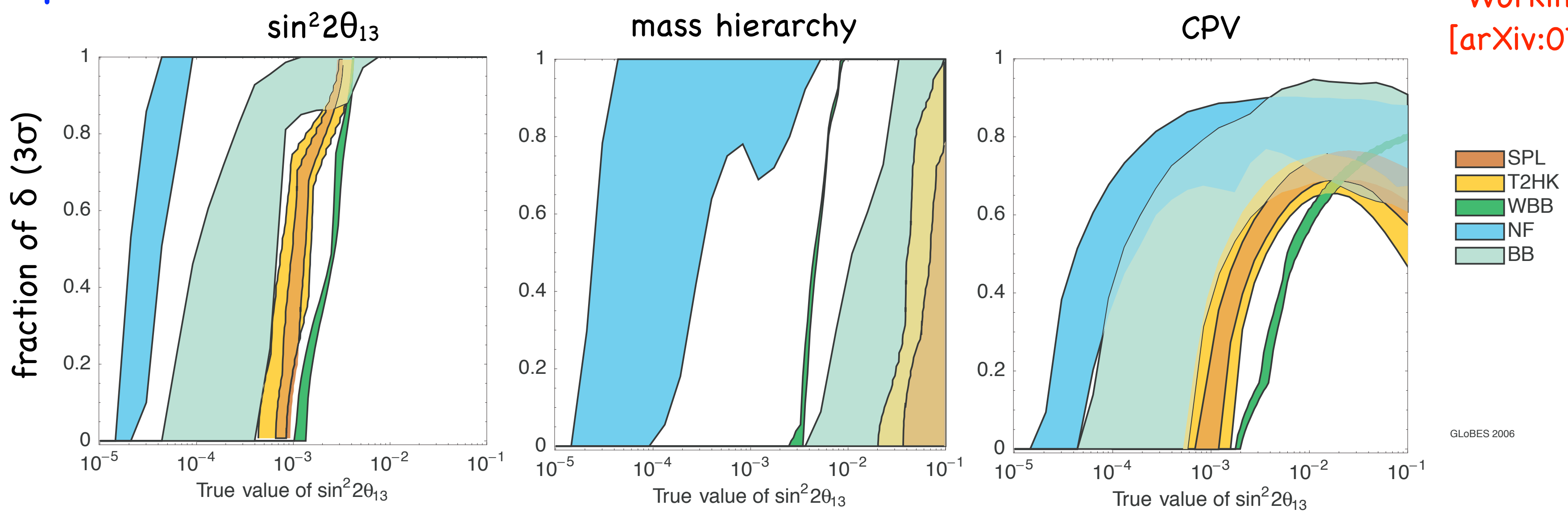


Neutrino Factory

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]

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

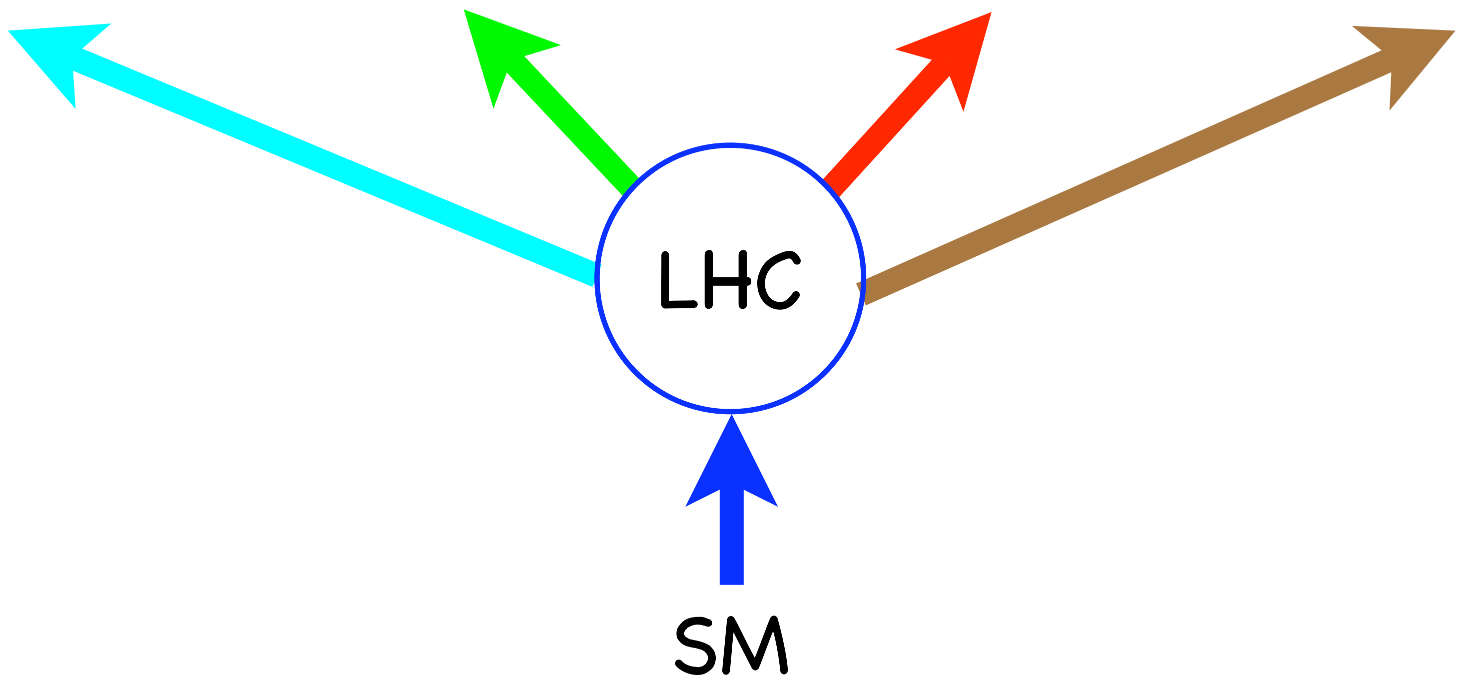
Theoretical Physics - 2020

SM extensions
- two Higgs doublets
- Higgs triplets
- Higgs singlets
- new weak gauge interactions
- new fermions
- ...

SUSY
- SUGRA, gauge or anomaly mediated SUSY Breaking?
- MSSM, NMSSM, Split SUSY
- R parity violation?
- ...

New Dynamics
- Technicolor, ETC, walking TC
- topcolor
- little Higgs models
- compositeness
- unparticles ...

Extra Dimensions
- Gravity
- Randall-Sundrum
- Universal ED
- KK modes?
- ...



Muon Collider Physics

- Existing facilities in 2020:
  - LHC with luminosity or energy upgrade
- Options:
  - low energy lepton collider (< 1 TeV)
    ILC (500 GeV) (upgradable) (decision 2012 ?)
    or muon collider - Higgs Factory
  - lepton collider in multi Tev range.
    CLIC or muon collider
    - Energy, Luminosity, Polarization?
  - hadron collider in hundred TeV range
    VLHC

Muon Colider Cross Sections

- 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

      $$[\frac{m_\mu}{m_e}]^2 = 4.28 \times 10^{\ 4}$$

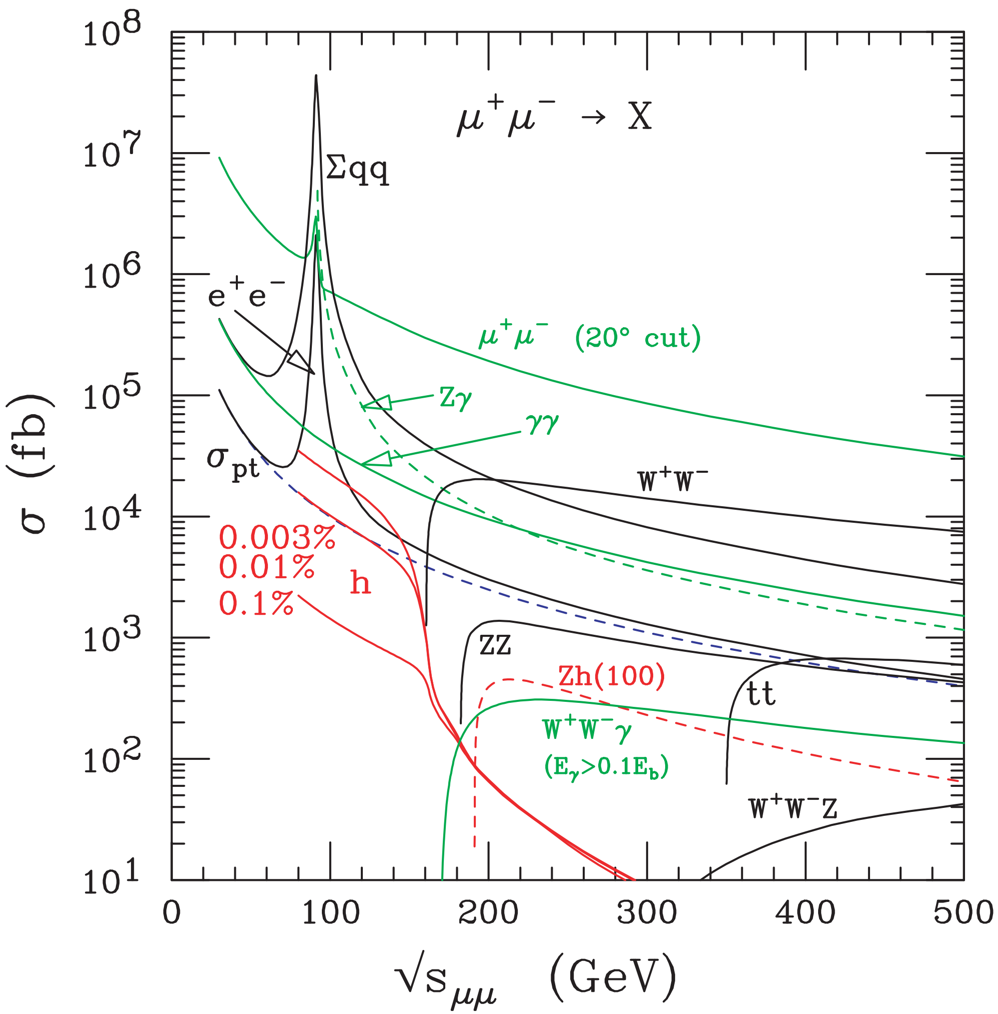
    - narrow state

      $m(h) = 110$ GeV : $\Gamma = 2.8$ MeV
      $m(h) = 120$ GeV : $\Gamma = 3.6$ MeV
      $m(h) = 130$ GeV : $\Gamma = 5.0$ MeV
      $m(h) = 140$ GeV : $\Gamma = 8.1$ MeV
      $m(h) = 150$ GeV : $\Gamma = 17$ MeV
      $m(h) = 160$ GeV : $\Gamma = 72$ MeV

    - direct width measurement

      $\Delta E/E \approx 0.003\%$ and more than 2 pb^{-1}

Standard Model
Cross Sections



- For $\sqrt{s}$ > 500 GeV
  - Above SM thresholds:
  - R essentially flat:

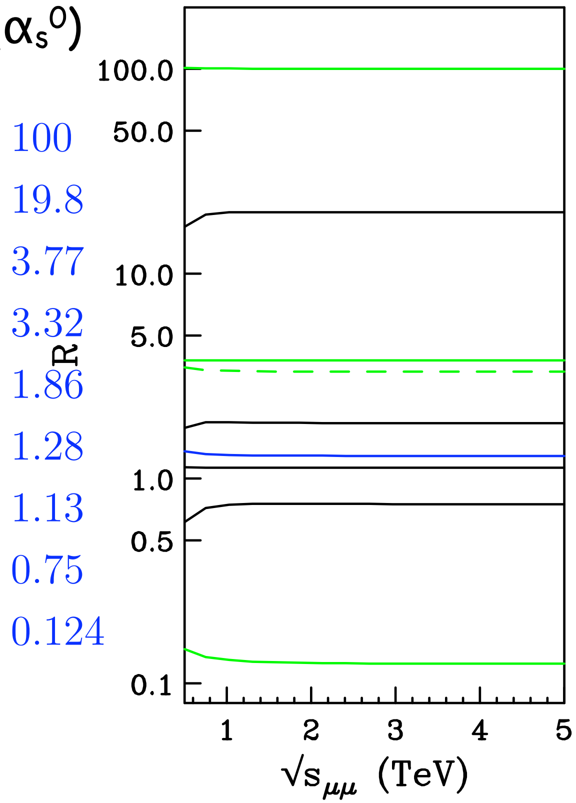
    (one unit of R)

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

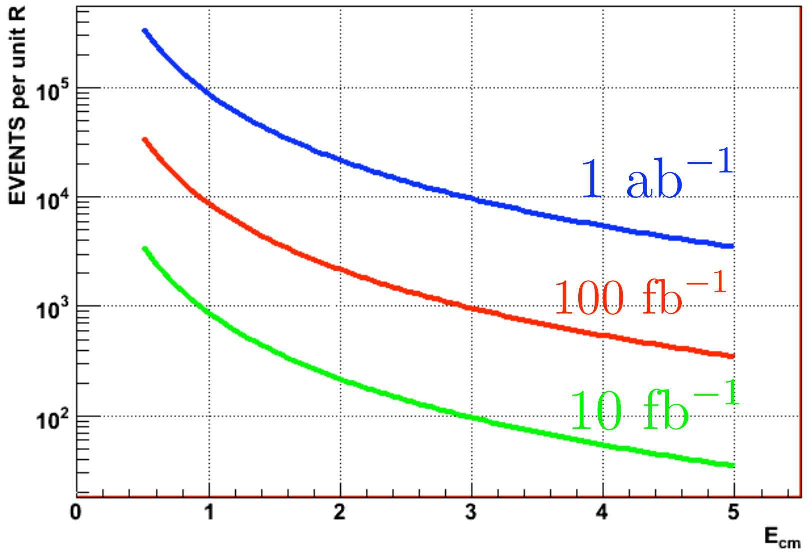
R at $\sqrt{s}$ = 3 TeV

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

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



- Luminosity Requirements



For example: $\sqrt{s} = 1.5$ TeV ⇒ 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

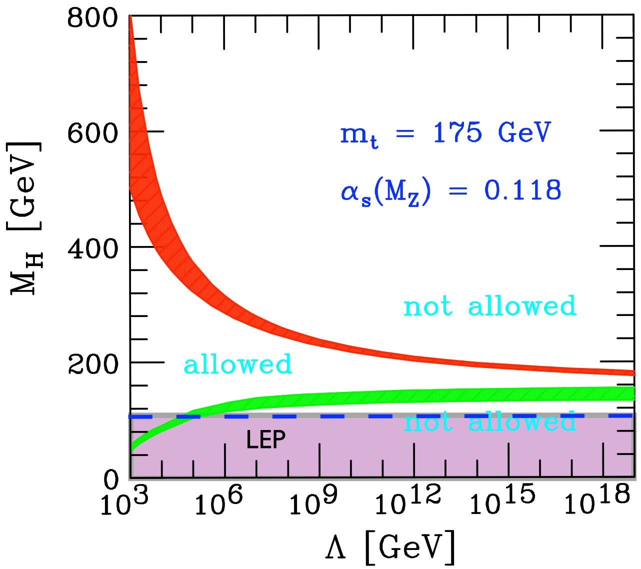
Standard Model and Extensions

Theoretical issues

- 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 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.



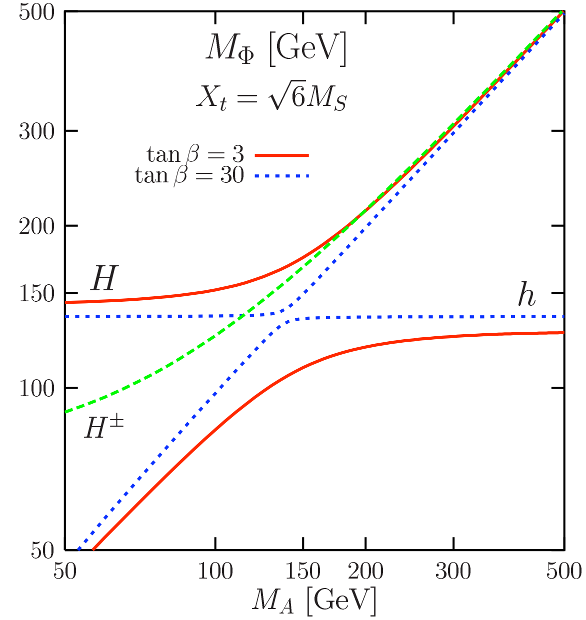
LEP: $m_h > 114.4$ (95 % CL)

- 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
    - $R \sim 0.12$
    - search for invisible h^0 decays
  - W^*W^* fusion : $\bar{\nu}_\mu \nu_\mu\, h^0$
    - $R \sim 1.1\ s\ \ln(s)$ (s in TeV^2) (m_h = 120 GeV)
    - study some rare decay modes
    - measure Higgs self coupling
  - Higgsstrahlung: $\bar{t}th^0$
    - $R \sim 0.01$
    - 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 $m_{A^0} >> m_{Z^0}$:
  - 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.

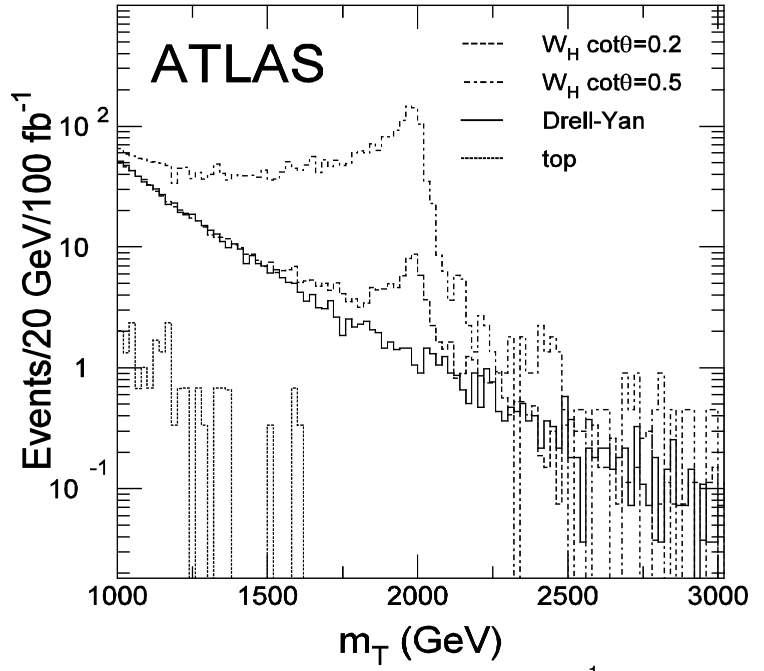
- good energy resolution is needed for H^0 and A^0 studies:
  - for s-channel production of H^0 : $\Gamma/M \approx 1\%$ at tanβ = 20.
  - nearby in mass need good energy resolution to separate H and A.
  - can use bremsstrahlung tail to see states using bb decay mode.

New fermions and gauge bosons

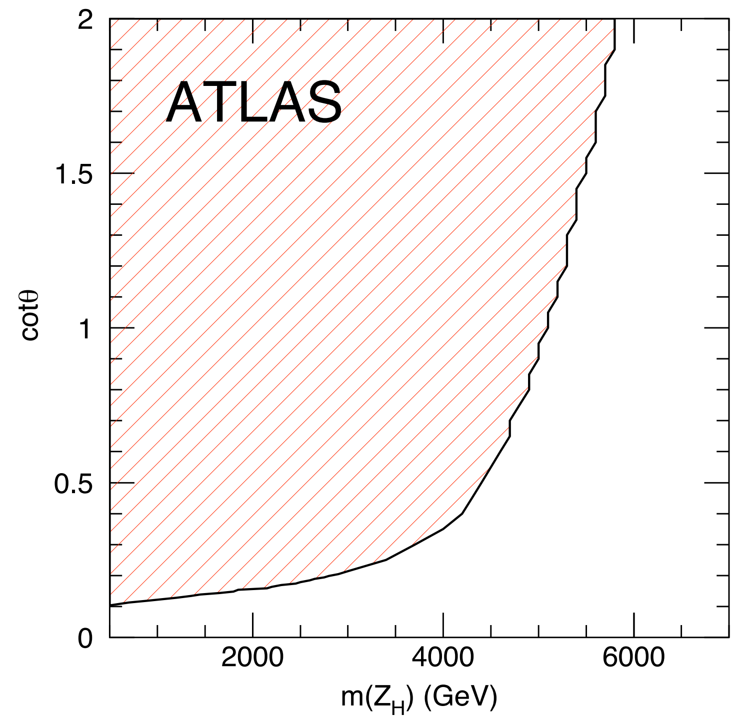
Present CDF/D0 bounds on W′, Z′, and new quarks effectively rule out production at ILC(500).

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

New study of allowed MSSM models

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

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

- 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.

Allowed regions in parameter space are narrow filaments

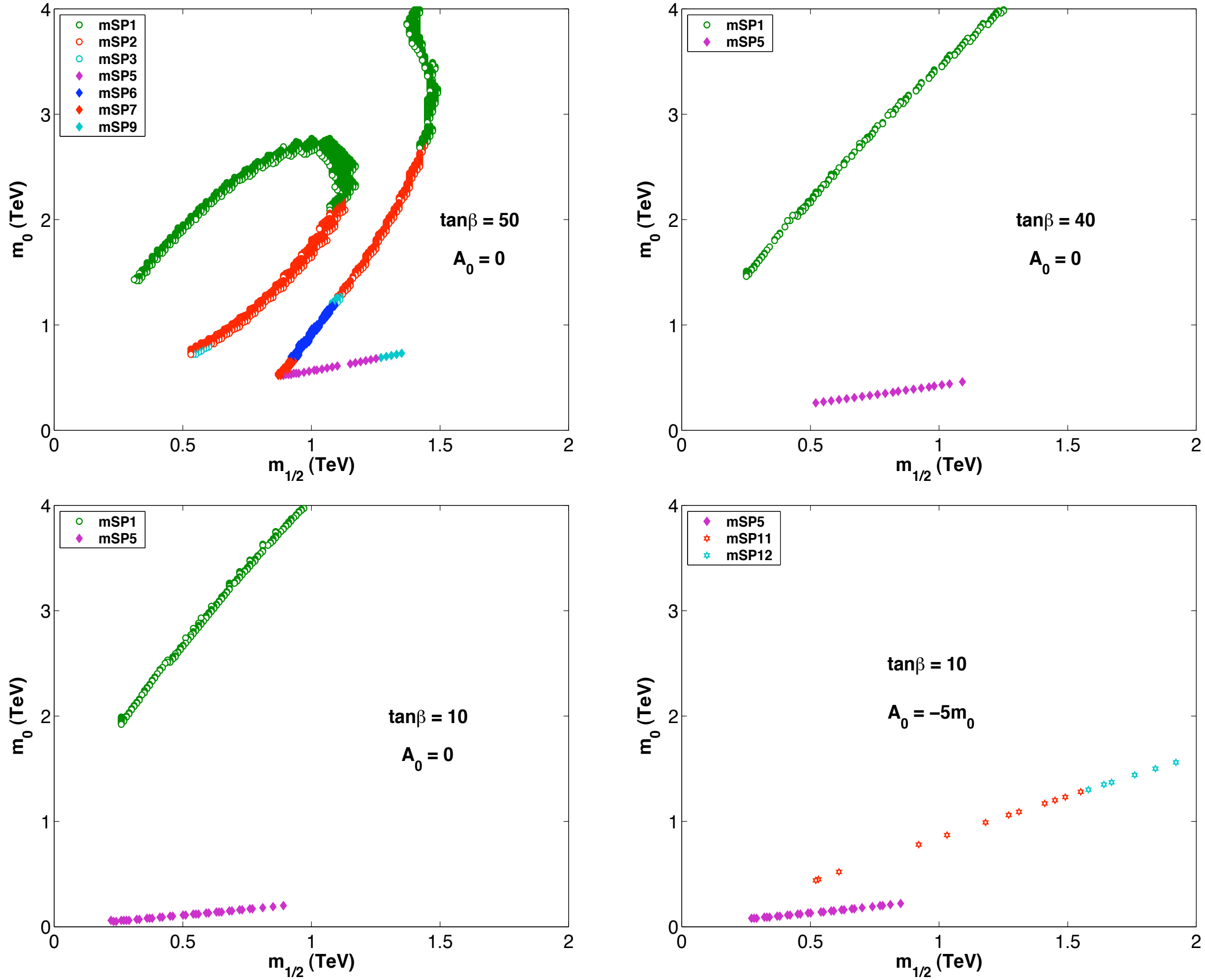


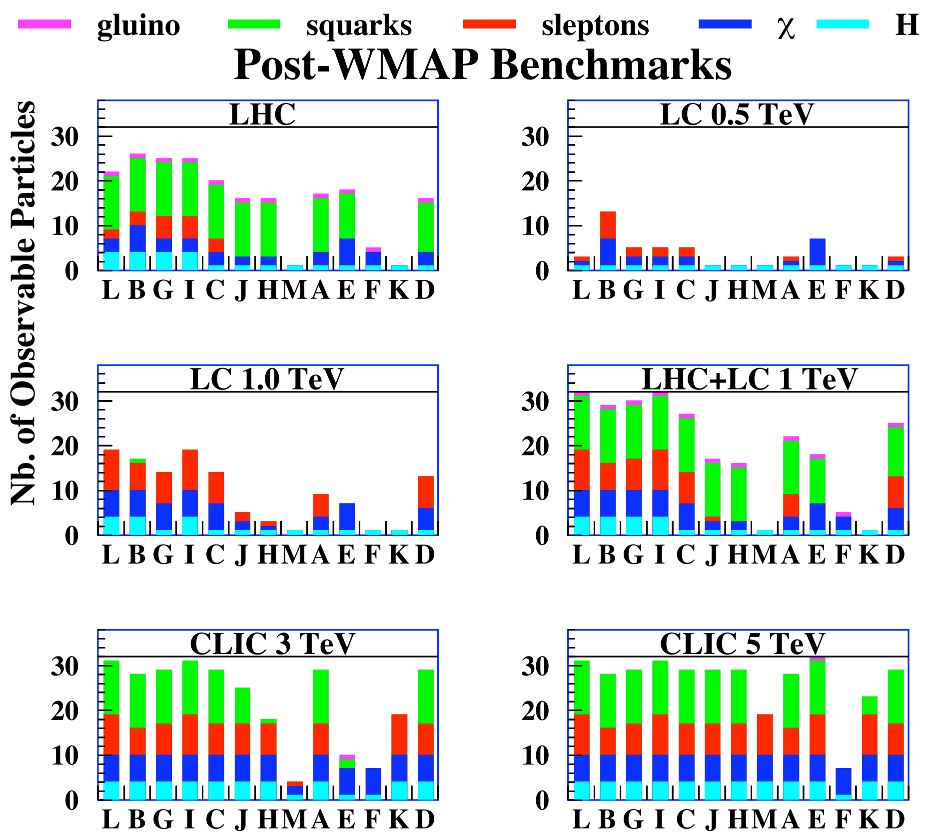
Figure 4: Dispersion of patterns in the m_0 vs $m_{1/2}$ plane for fixed values of $\tan\beta$ and A_0/m_0. The region scanned is in the range $m_0 < 4$ TeV and $m_{1/2} < 2$ TeV with a 10 GeV increment for each mass. Only a subset of the allowed parameter points relative to Fig.(3) remain, since the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

A multiTev lepton collider needed for full coverage.



Fine tuning problems in the cMSSM

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

$\tan\beta = v_u/v_d$

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

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

tree — 1-loop

$$M_{h^0}^2 = m_Z^2 \cos^2(2\beta) + \frac{3}{4\pi^2}\sin^2\beta\, y_t^2 \Big[m_t^2 \ln\left(m_{\tilde{t}_1} m_{\tilde{t}_2}/m_t^2\right) + c_{\tilde{t}}^2 s_{\tilde{t}}^2 (m_{\tilde{t}_2}^2 - m_{\tilde{t}_1}^2)\ln(m_{\tilde{t}_2}^2/m_{\tilde{t}_1}^2) + c_{\tilde{t}}^4 s_{\tilde{t}}^4 \Big\{ (m_{\tilde{t}_2}^2 - m_{\tilde{t}_1}^2)^2 - \frac{1}{2}(m_{\tilde{t}_2}^4 - m_{\tilde{t}_1}^4)\ln(m_{\tilde{t}_2}^2/m_{\tilde{t}_1}^2) \Big\} / m_t^2 \Big].$$

+ ...

with measured top mass and $\tan\beta$ constraints,

need large top squark mass. BUT

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

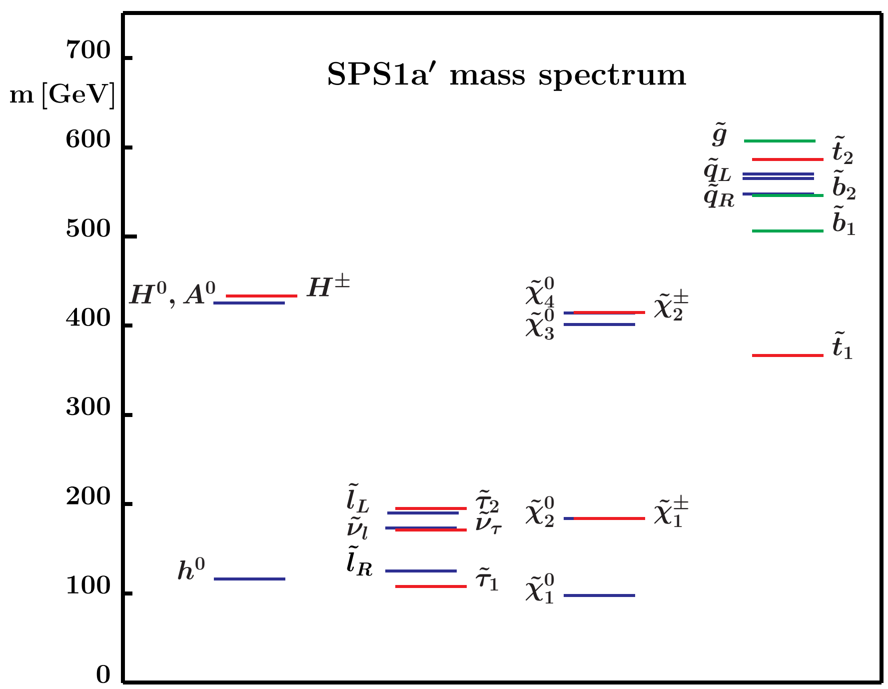
soft SUSY breaking mass term in higgs field coupling to top

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 ?

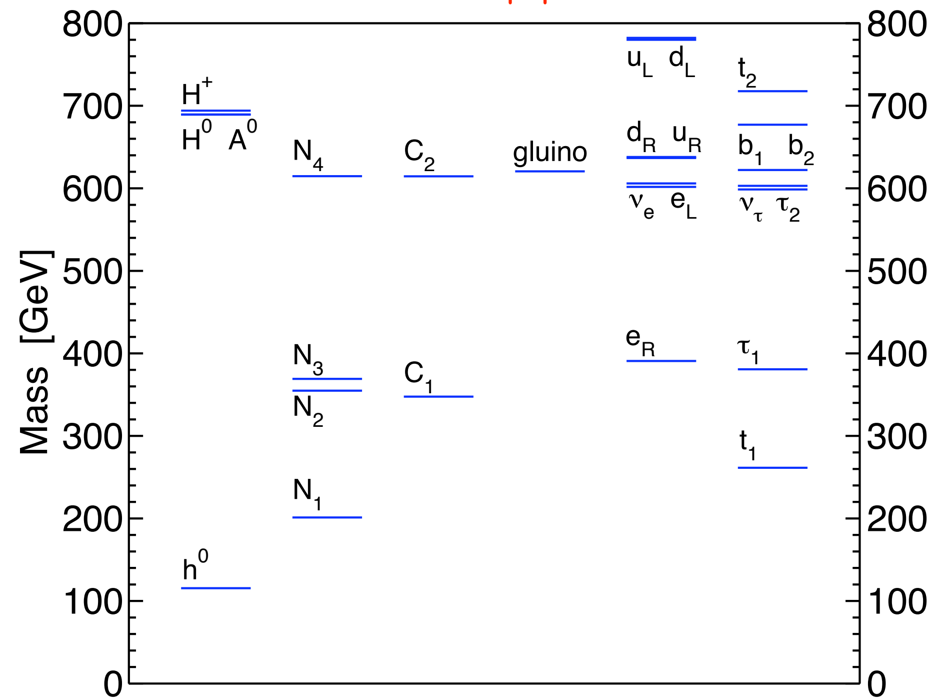
cMSSM ILC Benchmark



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

Compressed SUSY

S. Martin [hep-ph/0703097]



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

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?
- ...

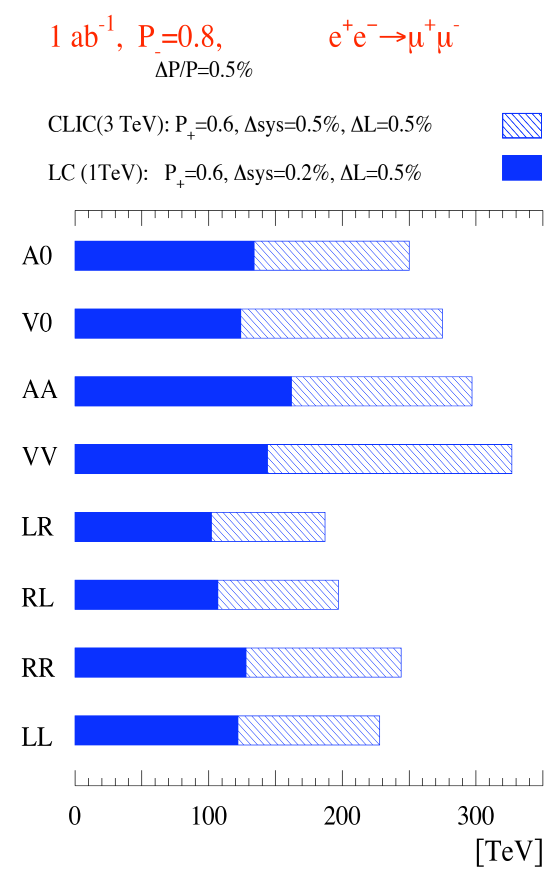
Technicolor, ETC, Walking TC, Topcolor , ...

- 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

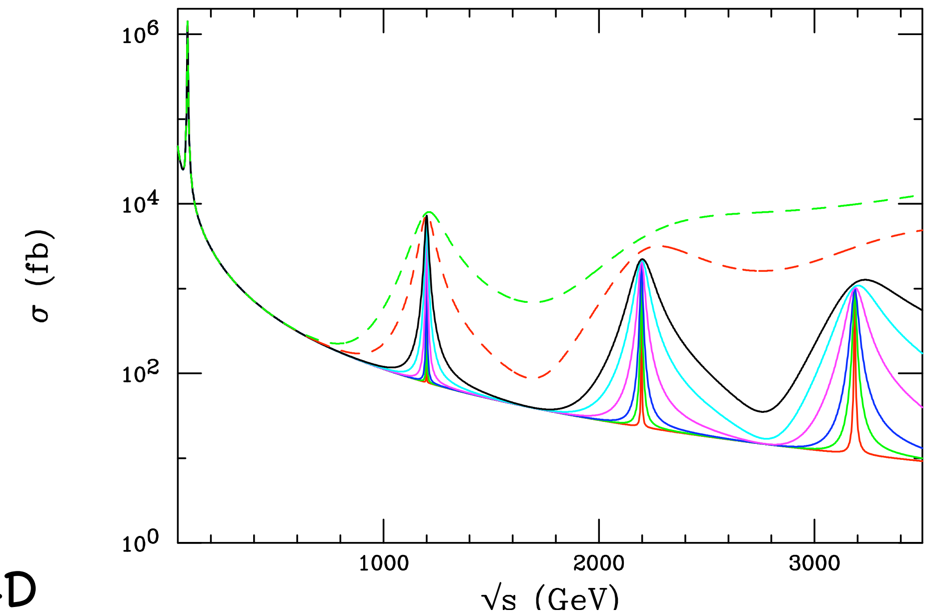
- How many dimensions?
- Which interactions (other than gravity) extend into the extra dimensions?
- At what scale does gravity become a strong interaction?
- What happens above that scale?
- ...

Randall-Sundrum model:
warped extra dimensions

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

LHC discovery - Detailed study at a muon collider

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



possible KK modes of the Z^0

Minimum Luminosity for Muon Collider

Narrow resonances in lepton colliders play a vital role in precision studies

	State	$\mathrm{BR}(\mu^+\mu^-)$	Γ/M	
■	$\phi(1.019)$	2.9×10^{-4}	3.98×10^{-3}	Kaons CPV
■	$J/\psi(3.097)$	5.9×10^{-2}	3.02×10^{-5}	1D - $D^{\pm,0}$ 3S - D, D*; 2D - D_s
■	$\Upsilon(9.460)$	2.5×10^{-2}	5.71×10^{-6}	4S - B factory, tau, charm
■	$Z^0(91.19)$	3.4×10^{-2}	2.74×10^{-2}	precision tests - SM
■ if	$h^0(115)$	2.5×10^{-4}	2.78×10^{-5}	Higgs couplings - EW

Universal behavior

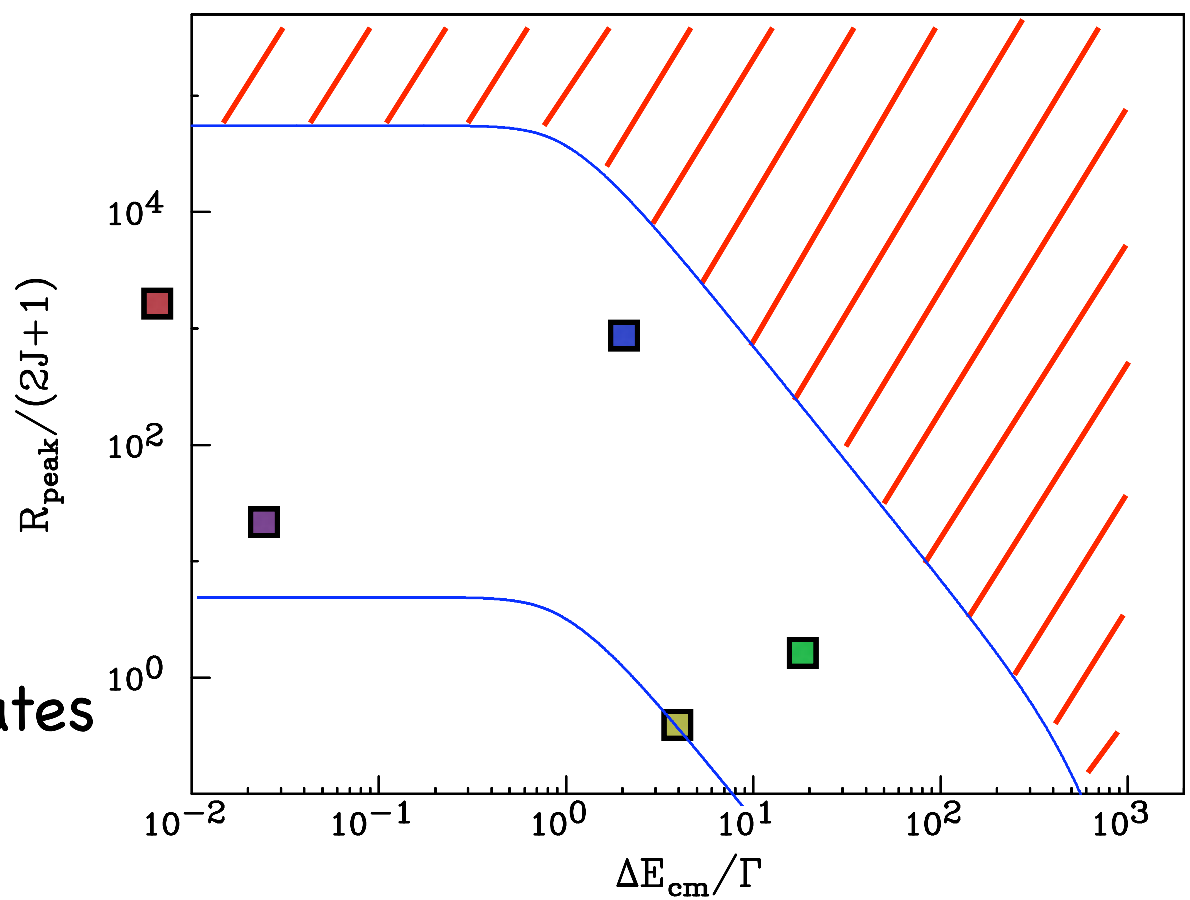
$$\sigma(E) = \frac{2J+1}{(2S_1+1)(2S_2+1)} \frac{4\pi}{k^2} \left[\frac{\Gamma^2/4}{(E-E_0)^2 + \Gamma^2/4} \right] B_{in} B_{out}$$

beam spread

$$\rightarrow R_{\mathrm{peak}} = (2J+1) 3 \frac{B(\mu^+\mu^-)B(visible)}{\alpha^2_{\mathrm{EM}}}$$

$$\frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{(E-E_0)^2}{2\sigma^2}\right) \qquad \rightarrow \Delta E_{\mathrm{cm}}/E_{\mathrm{cm}} = 2\ln(2)\sigma$$

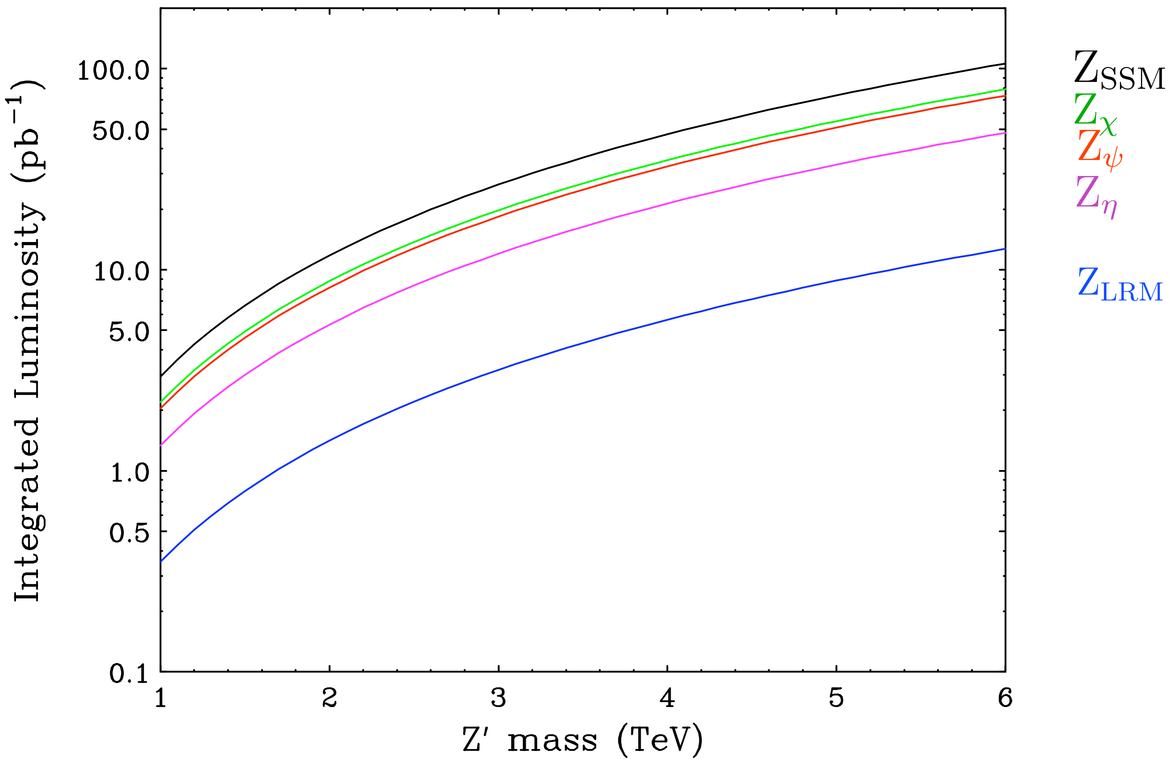
Assuming $\Delta E_{cm}/E_{cm}$= 0.01%



Can use to set minimum required luminosity

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

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



(Beam spread 0.1% assumed)

Hence minimum luminosity -> 0.5–5.0 x 10^{30} cm^{-2} sec^{-1}

for M(Z′) -> 1.5–5.0 TeV

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 likely be needed to fully disentangle neutrino physics.
- A multiTeV lepton collider is likely required for full coverage of Tevascale physics.
- The physics potential for a muon collider at $\sqrt{s}$ ~ 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.
  -

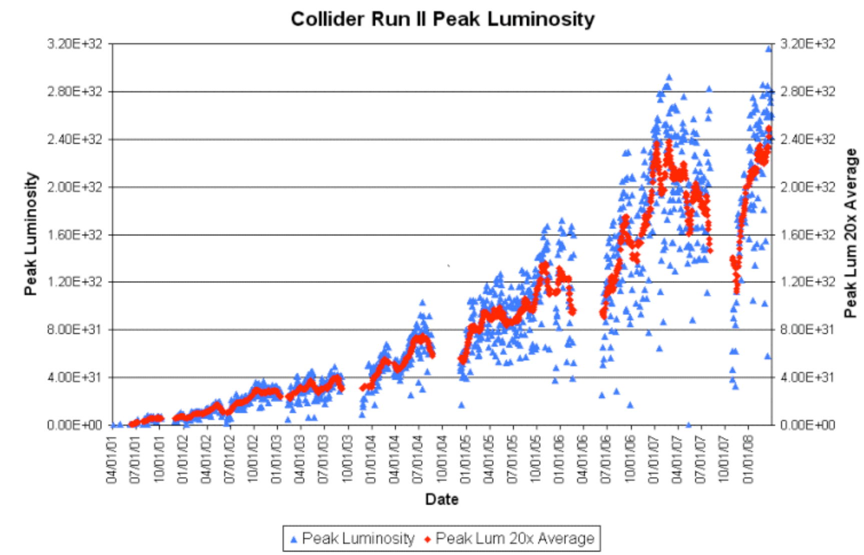
Backup Slides

Experimental Status

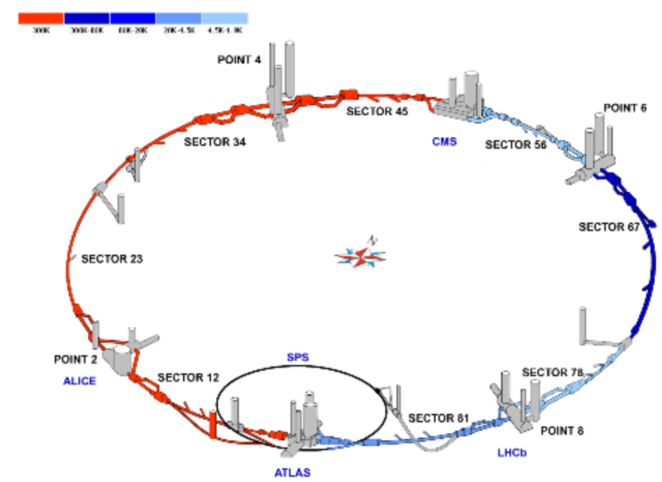
Energy Frontier Accelerators

Tevatron – Operating well

$\sqrt{s}$ = 1.96 TeV pbar p
Luminosity – 3.16×10^{32} cm^{-2} sec^{-1} (peak)
3.8 pb^{-1} (to date Run II)
CDF, D0



LHC – Cooldown Status April 6, 2008



LHC – About to come online

$\sqrt{s}$ = 14 TeV p p
Luminosity – 10^{34} cm^{-2} sec^{-1}

ATLAS, CMS, LHCb, ALICE

Neutrino Experiments

Accelerators: MiniBooNE, SciBooNE, MINOS, OPERA, NOvA, T2K, ...
Reactors: Double CHOOZ, Daya Bay, ...
Double Beta Decay, Super Beams, Beta Beams, Astrophysical Sources

Appearance probabilities in long baseline neutrino oscillation experiments

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

(normal hierarchy)

where

$$X_\pm = 4\sin^2\theta_{23}\Big[\frac{\Delta_{31}\sin(aL\mp\Delta_{31})}{(aL\mp\Delta_{31})}\Big]^2$$
$$Y_\pm = \pm 2\sqrt{X_\pm P_{\text{sol}}}$$
$$P_{\text{sol}} = \cos^2\theta_{23}\sin^2 2\theta_{12}\Big[\frac{\Delta_{21}\sin(aL)}{aL}\Big]^2$$

$$\Delta_{ij} \equiv |\Delta m^2_{ij}|L/4E$$

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?

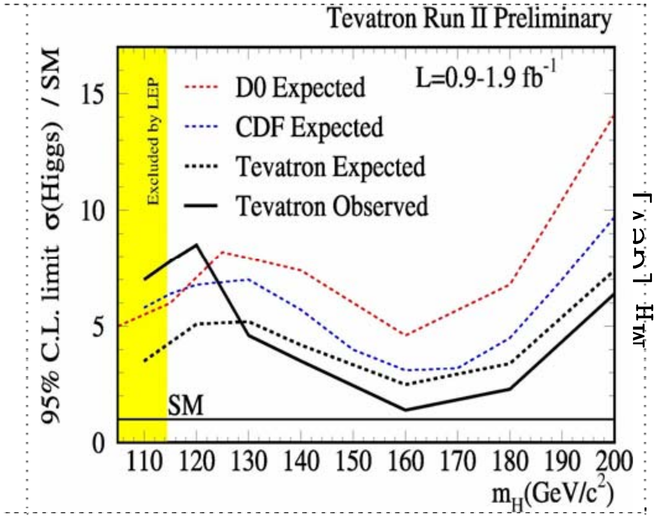
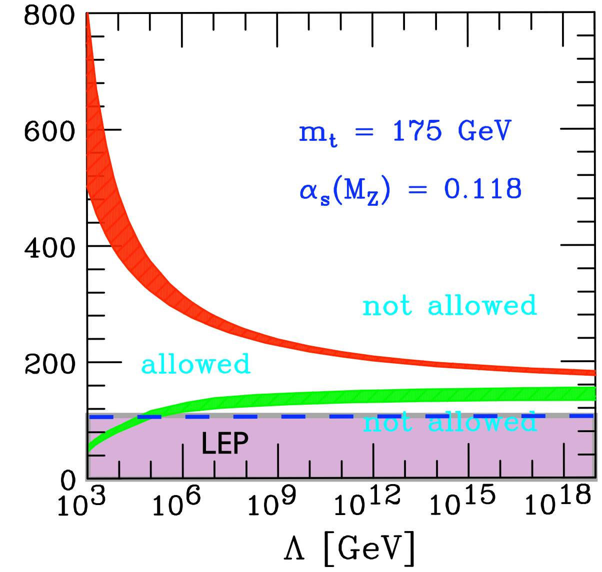
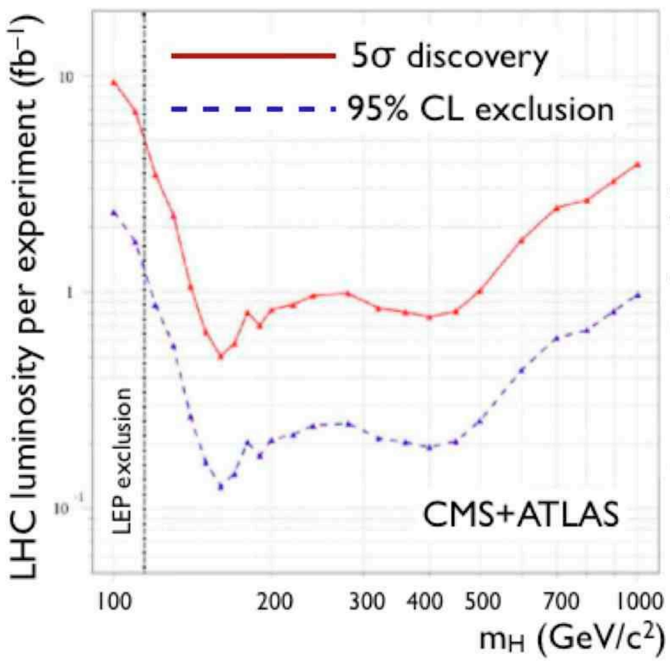


Figure 4. Tevatron combined upper limits normalized by SM expectation

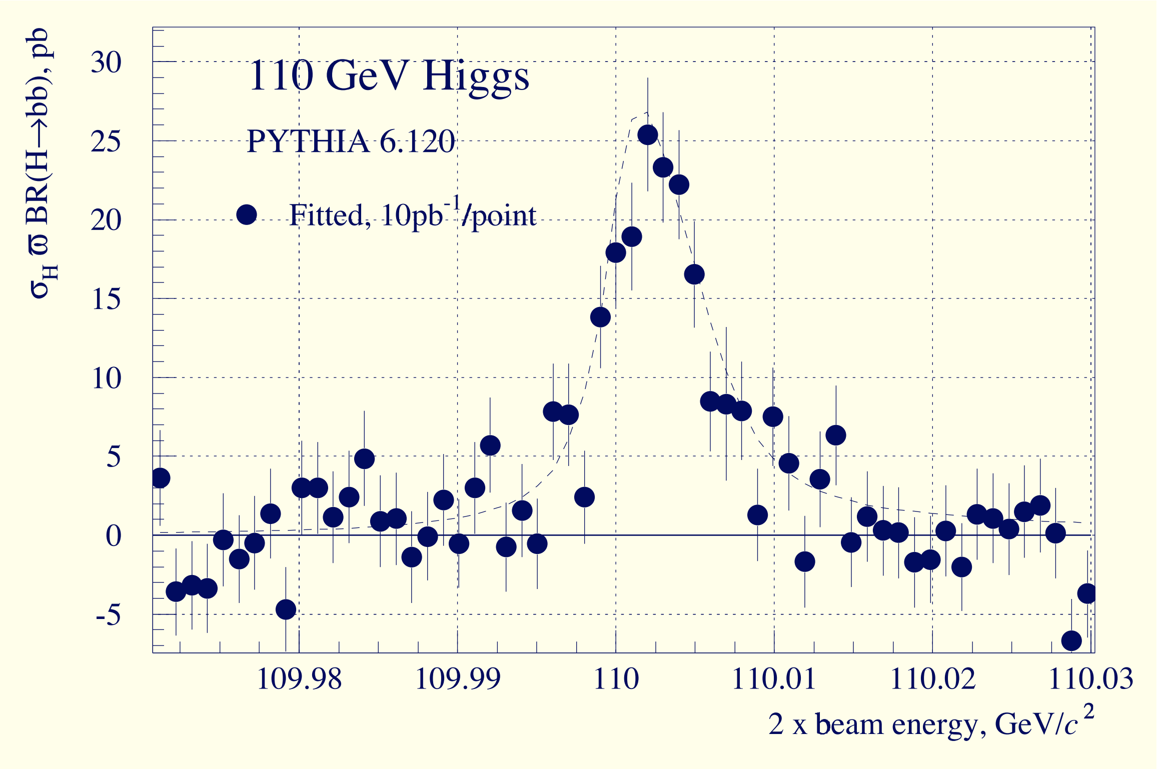


- Higgs bound (LEP): m_h > 114.4 (95 % CL)
- LHC will discover the SM Higgs. If Higgs mass is not in the Planck chimney (130-190), new physics "nearby".
- Large Higgs mass implies a strong Higgs self interaction and presumably a nearby strong interaction.
- For a low mass Higgs, the new physics can be 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 ($\Delta E/E$) 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: $\Delta E/E < 0.003\%$ with an integrated lumonisity > 2 pb^{-1}

Easier for large tanβ SUSY Higgs

h

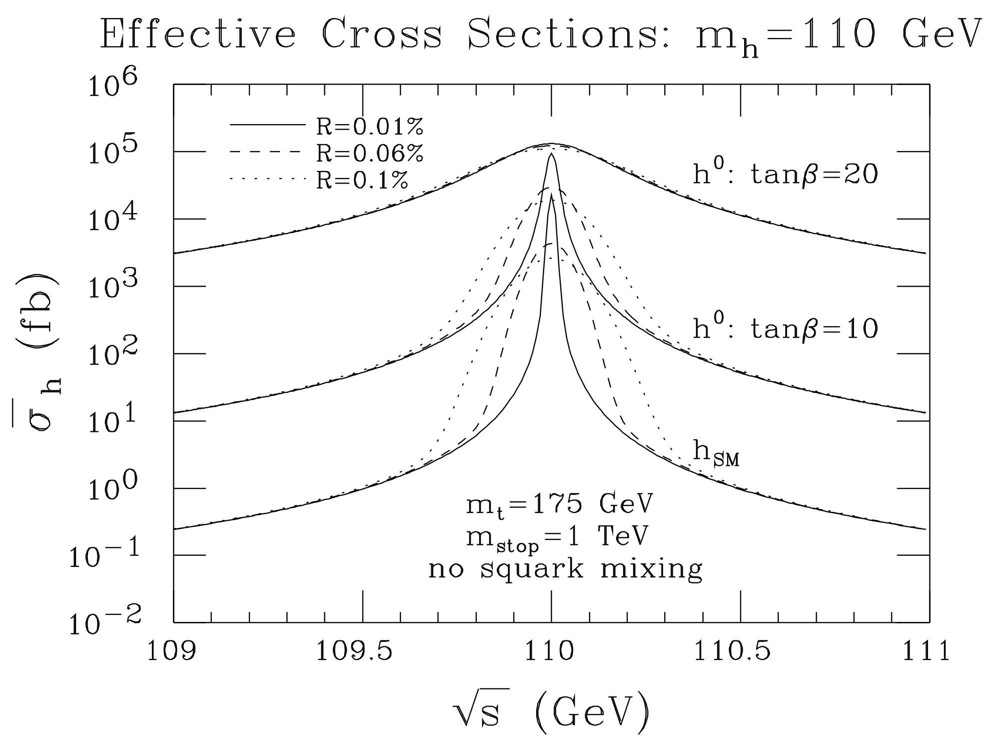
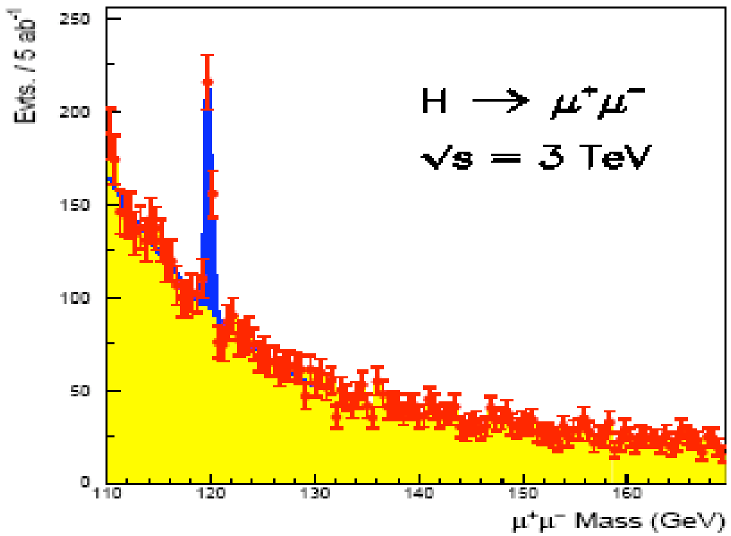


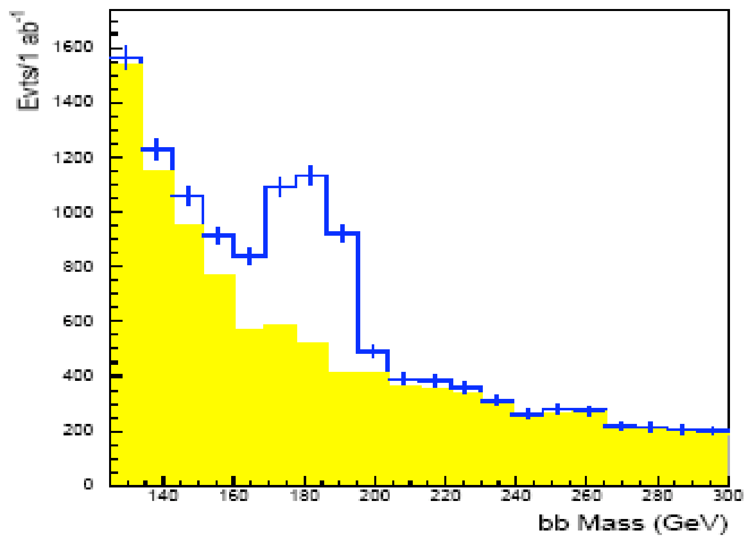
Figure 7: The effective cross section, $\overline{\sigma}_h$, obtained after convoluting σ_h with the Gaussian distributions for $R = 0.01\%$, $R = 0.06\%$, and $R = 0.1\%$, is plotted as a function of $\sqrt{s}$ taking $m_h = 110$ GeV. Results are displayed in the cases: h_{SM}, h^0 with $\tan\beta = 10$, 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

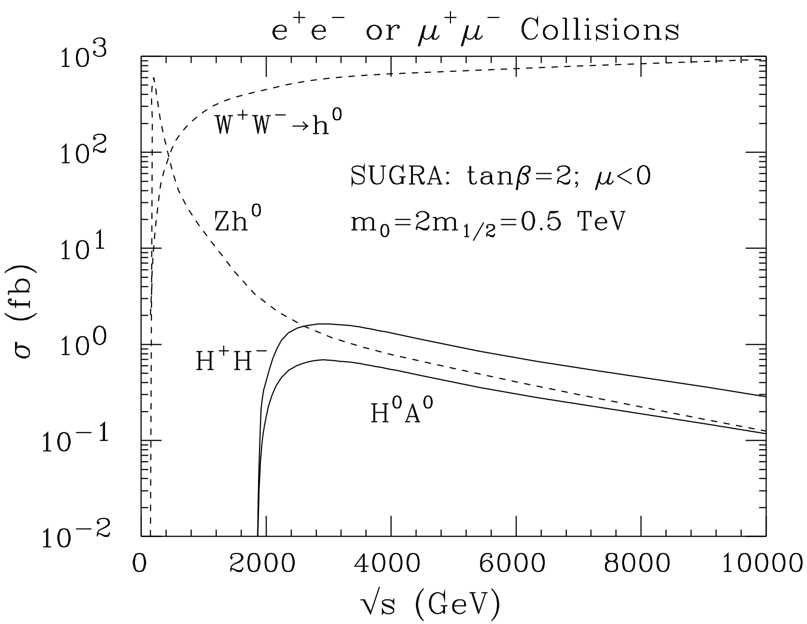
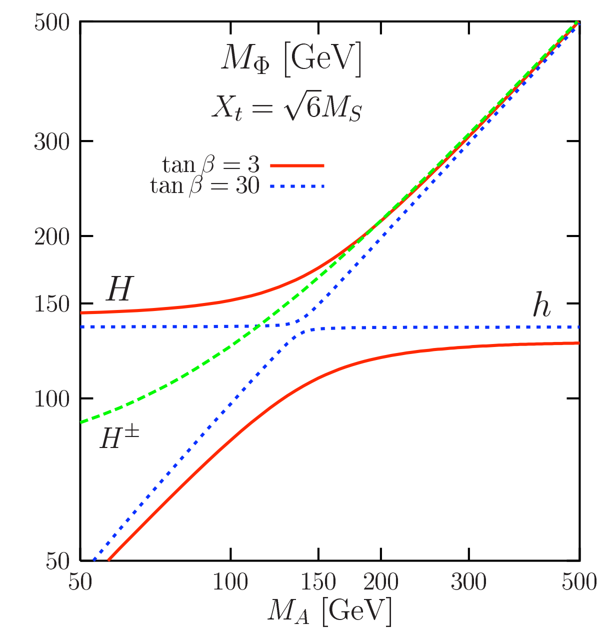


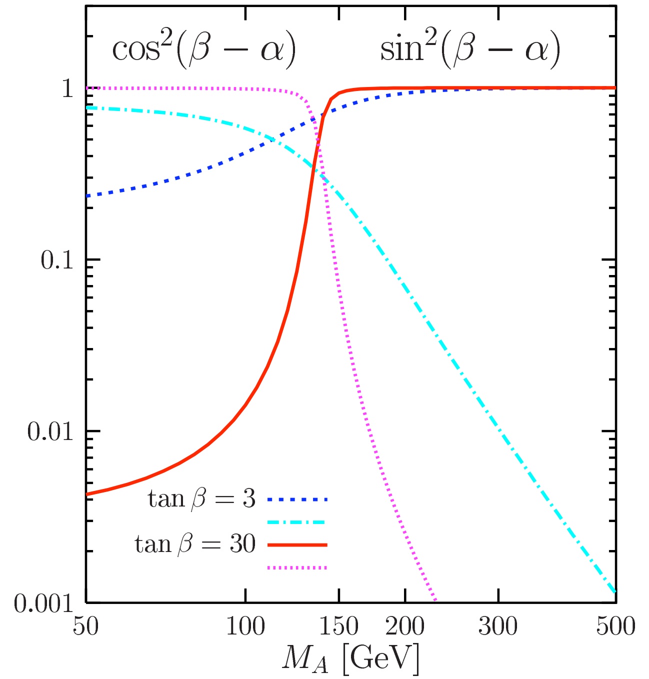
FIGURE 6. Pair production of heavy Higgs bosons at a high energy lepton collider. For comparison, cross sections for the lightest Higgs boson production via the Bjorken process $\mu^+\mu^- \to Z^* \to Zh^0$ and via the WW fusion process are also presented.

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

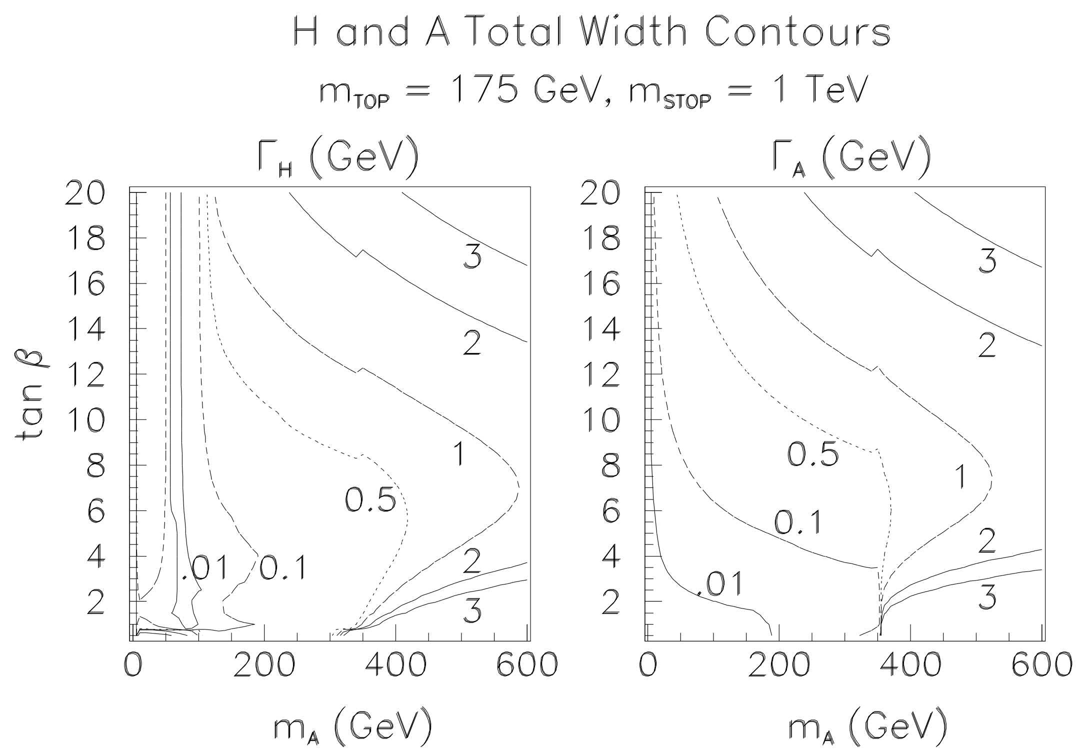


Figure 20: Contours of H^0 and A^0 total widths (in GeV) in the $(m_{A^0}, \tan\beta)$ parameter space. We have taken $m_t = 175$ GeV and included two-loop/RGE-improved radiative corrections using $m_{\widetilde{t}} = 1$ TeV and neglecting squark mixing. SUSY decay channels are assumed to be absent.

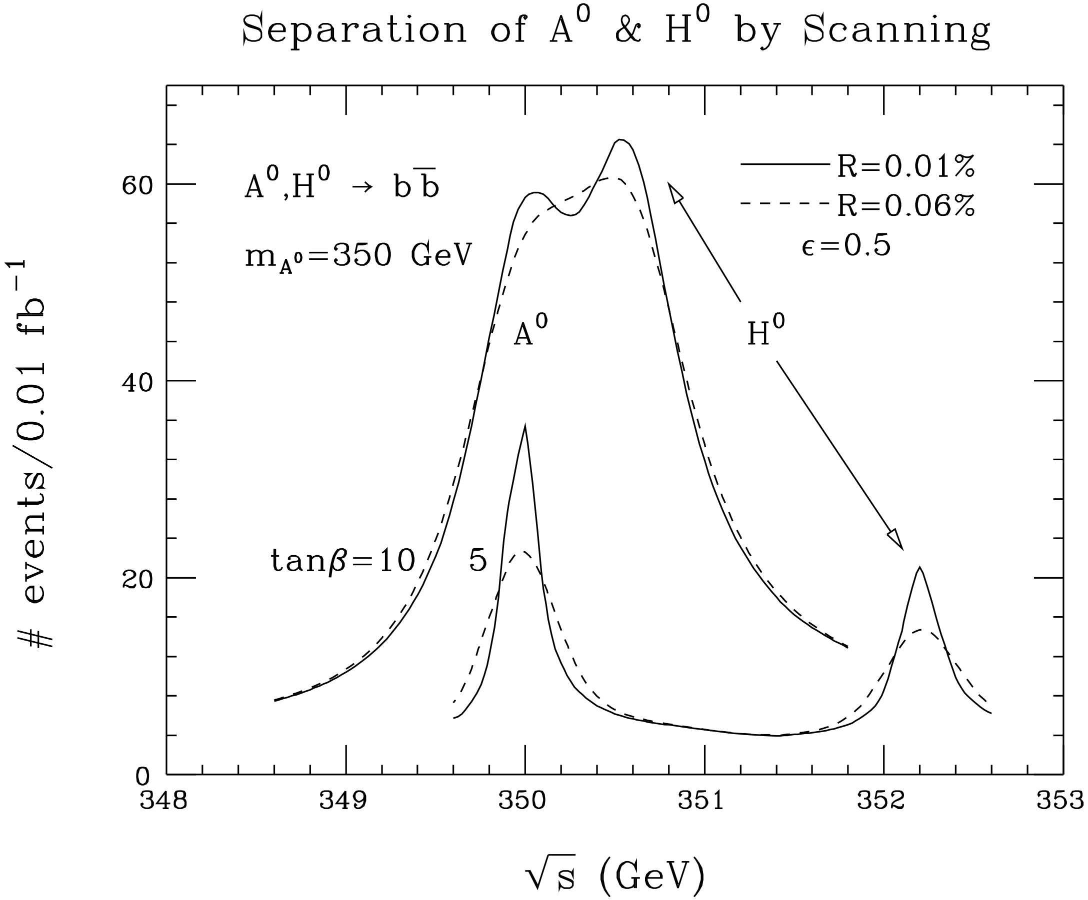


FIGURE 4. Plot of $b\bar{b}$ final state event rate as a function of $\sqrt{s}$ for $m_{A^0} = 350$ GeV, in the cases $\tan\beta = 5$ and 10, resulting from the H^0, A^0 resonances and the $b\bar{b}$ continuum background. We have taken $L = 0.01\ \mathrm{fb}^{-1}$ (at any given $\sqrt{s}$), efficiency $\epsilon = 0.5$, $m_t = 175$ 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 $R = 0.06\%$

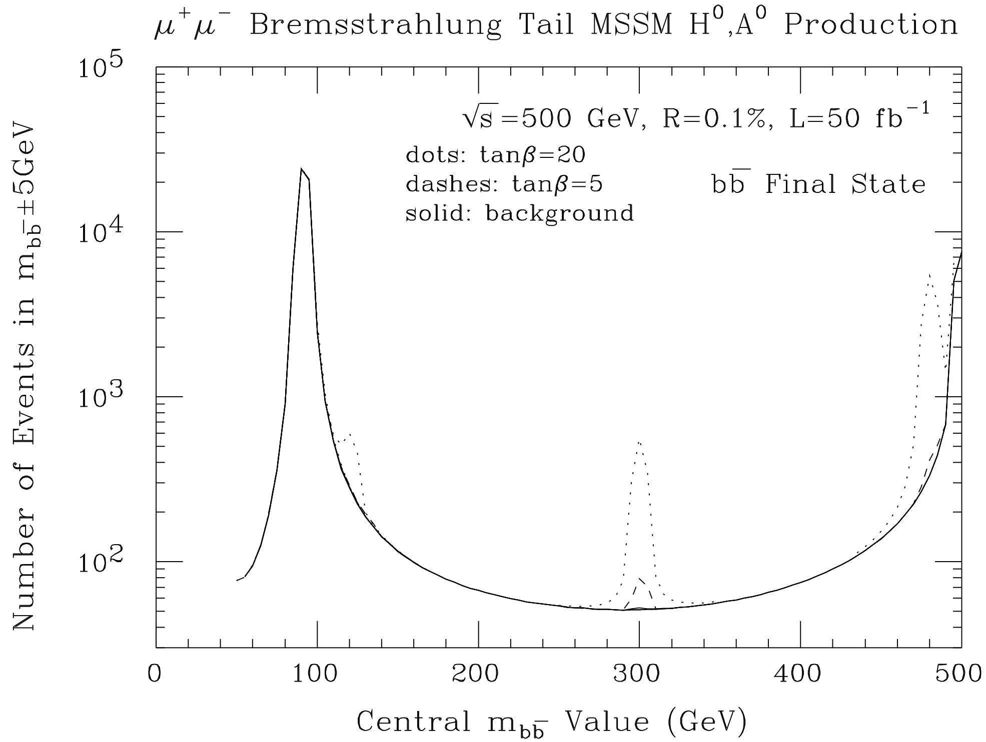


FIGURE 5. Taking $\sqrt{s} = 500$ GeV, integrated luminosity $L = 50\ \mathrm{fb}^{-1}$, and $R = 0.1\%$, we consider the $b\bar{b}$ final state and plot the number of events in the interval $[m_{b\bar{b}} - 5\ \mathrm{GeV}, m_{b\bar{b}} + 5\ \mathrm{GeV}]$, as a function of the location of the central $m_{b\bar{b}}$ 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

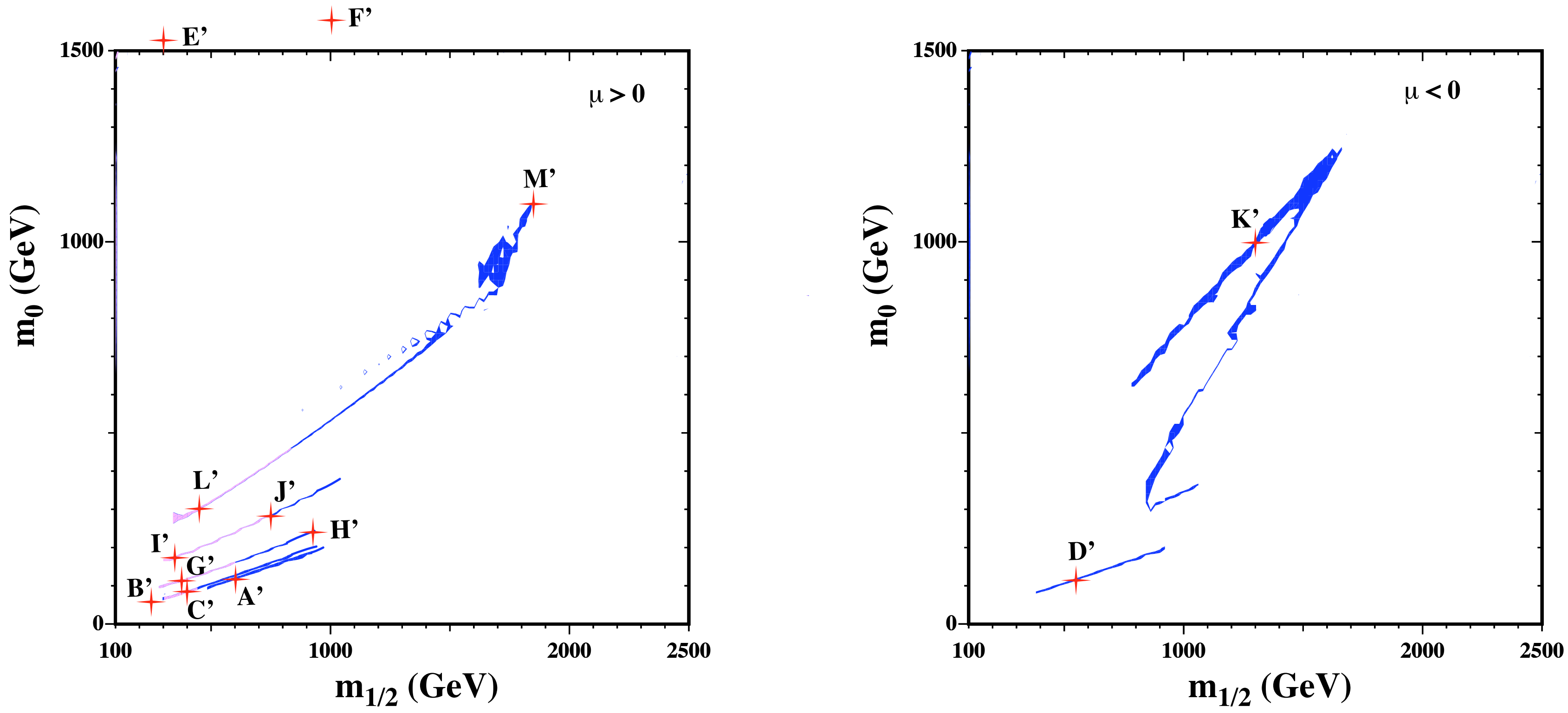


Fig. 5.2: Overview of the updated proposed CMSSM benchmark points in the $(m_0, m_{1/2})$ planes, superposed on the strips allowed by laboratory limits and the relic density constraint, for $\mu > 0$ and $\tan\beta$ = 5, 10, 20, 35, 50, and for $\mu < 0$ and $\tan\beta$ = 10, 35 [8]

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

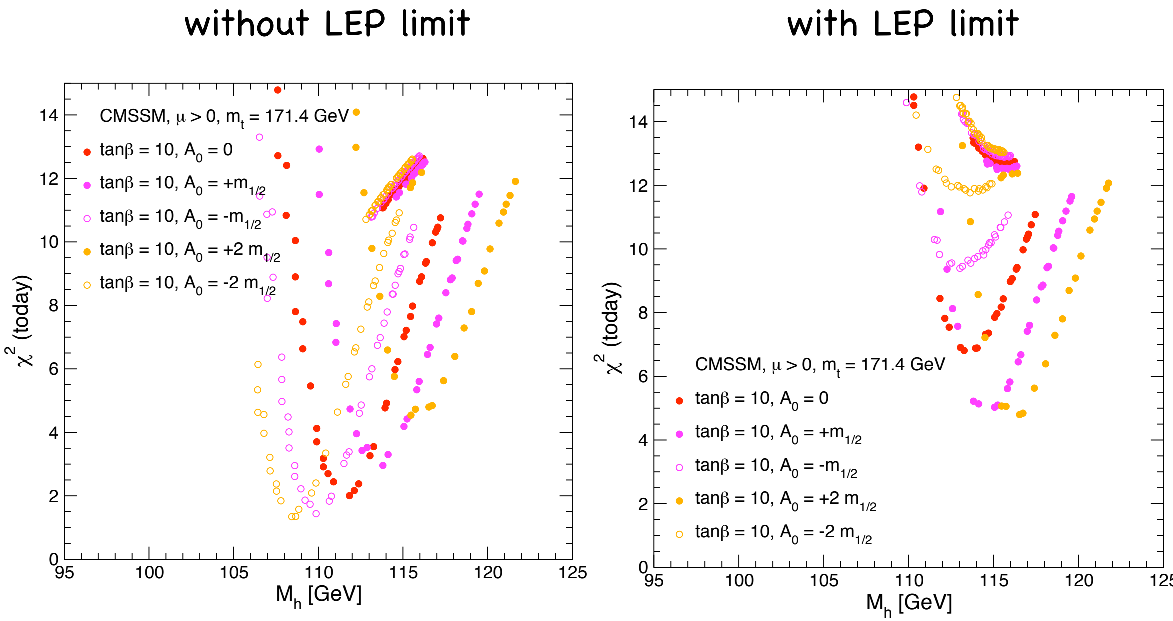
Table 1: Hierarchical mass patterns for the four lightest sparticles in mSUGRA when $\mu < 0$ and $\mu > 0$. The patterns can be classified according to the next to the lightest sparticle. For the mSUGRA analysis the next to the lightest sparticle is found to be either a chargino, a stau, a stop, a CP 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.

Tensions in Fits

Tension between fits using
EW data and B physics data.

Fitting to WMAP results greatly
constrains allowed parameter ranges

The LEP limit on Higgs mass has
large effect on fits.



Ellis et.al. [hep-ph/0706.0652]

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->aa) > 0.7 and m(a)<2m(b).
  Avoids the LEP limits on Higgs -
  Dermisek,Gunion, McElrath [hep-ph/0612031]

Comparison of Muon Collider and CLIC (same $\sqrt{s}$ and $\mathcal{L}$)

- Present theoretical studies of physics potential of multi-TeV muon colliders are inadequate.
- For many processes the cross sections are essentially the same as for CLIC.
- For scalars (eg h, A, H) with fermion mass dependent couplings, the muon collider has advantage of s-channel single production.
- Especially for SUSY options, lepton beam polarization is useful.
- For muon collider, the effects of muon decay backgrounds and required angular cuts needs detailed study.

- Point C has very low masses, and is representative also of points A, B, D, G, I, L. In these cases, the LHC would have discovered the $H^{\pm}$, as well as seen the h^0, and also the gauginos $\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^{\pm}$, the charged sleptons, the squarks and the gluino. A 1-TeV linear collider would enable the detailed study of the h^0 and of the same gauginos and sleptons, and it might discover the missing gauginos in some of the scenarios. However, one would require CLIC, perhaps running around 2 TeV, to complete the particle spectrum by discovering and studying the heavy Higgses and the missing gauginos. CLIC could also measure more precisely the squarks and in particular disentangle the left- and right-handed states and, to some extent, the different light squark flavours.
- Point J features intermediate masses, much like point K. Here, the LHC would have discovered all the Higgs bosons, the squarks and the gluino, but no gauginos or sleptons. The 1-TeV e^+e^- linear collider would study in detail the h^0 and could discover the $\tilde{e}_R$, $\tilde{\mu}_R$ and $\tilde{\tau}_1$, but other sparticles would remain beyond its kinematic reach. CLIC3000 could then study in detail the heavy Higgses, as discussed in the previous chapter. It would also discover and study the gauginos and the missing sleptons, and even observe in more detail a few of the lighter squarks that had already been discovered at the LHC. However, to see the remaining squarks at a linear collider would require CLIC to reach slightly more than 3 TeV.
- Point E has quite distinctive decay characteristics, due to the existence of heavy sleptons and squarks. In this situation, the LHC would have discovered the h^0, all squarks and the gluino. The gauginos are in principle accessible, but their discovery may be made more difficult by their predominant decays into jets, contrary to the previous benchmark points, and sleptons would remain unobserved. At a 1-TeV e^+e^- linear collider, the detailed study of the h^0 and of the gauginos could be undertaken. The discovery of the first slepton, actually a $\tilde{\nu}_e$, could be made at CLIC3000, which could also study the three lightest squarks. The discovery and analysis of the heavy Higgses would then require the CLIC energy to reach about 3.5 TeV, which would also allow the discovery of all sleptons and the observation of all squarks. A detailed analysis of the accuracy in the determination of the smuon mass at $\sqrt{s}$ = 3.8–4.2 TeV is presented later in this chapter.

- Point H has quite heavy states, as does scenario M. The LHC would only discover the h^0, all other states being beyond its reach, so the LHC might leave the existence of supersymmetry as an open question! At point H, a 1-TeV linear collider would discover the lighter $\tilde{\tau}$ and the LSP χ, but no other sparticles. A 1-TeV linear collider would discover no sparticles at point M. However, CLIC at 3 TeV would be able to discover most of the gauginos and sleptons. The CLIC sensitivity to the smuon mass, using both a muon energy technique and a threshold scan, is discussed later. On the other hand, to discover all the squarks, $\ell^+\ell^-$ collisions in excess of 5 TeV would be needed. There is currently no e^+e^- project aiming at such energies, and we recall that neutrino radiation would become a hazard for a $\mu^+\mu^-$ collider at such a high energy.
- Along the lines defined by the WMAP constraints, the reach in supersymmetric particles for a given collider and the phenomenology of their decays change significantly. As we discuss later, the CLIC reach for the dilepton decay signature of a heavier neutralino, $\chi_2 \rightarrow \ell^+\ell^-\chi$ is significantly greater than that of the LHC or a 1-TeV linear collider. Additionally, we have chosen a point at $m_{1/2}$ = 750 GeV and $\tan\beta$ = 10 to study the potential accuracy in the determination of the mass of the sleptons and of the $\tilde{\chi}^0_2$. This point is located at the limit of the sensitivity of the LHC and of a 1-TeV linear collider for probing the heavy neutralinos and the slepton sectors, and represents the limit of the coverage of the full supersymmetric spectrum at CLIC at 3 TeV.
- As in the case of a 1-TeV e^+e^- linear collider, a photon collider option for CLIC would extend the discovery range for heavy Higgs bosons. Additionally, it would allow one to discover all four Higgs bosons in scenarios E, H and M, for a 3-TeV collider, and also in F, for a 5-TeV collider. The detection of heavier MSSM Higgs bosons at a CLIC-based $\gamma\gamma$ collider is discussed in more detail in the previous section.

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

Technipions:

S channel production - higgs like

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

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

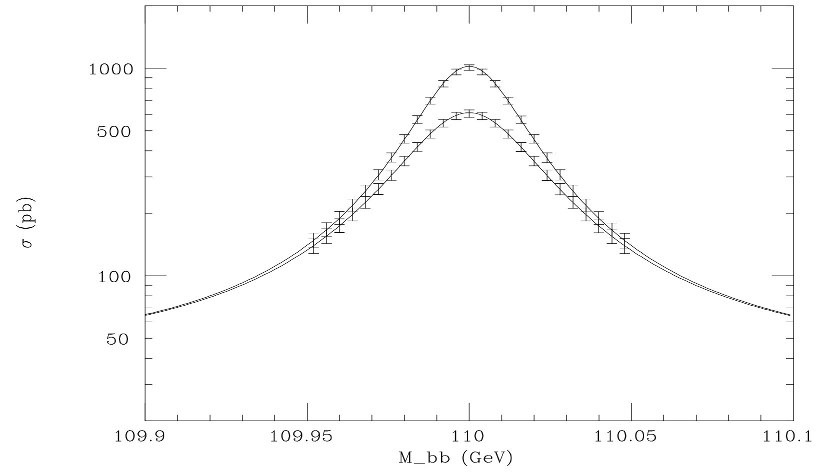


Figure 1: Cross sections for $\mu^+\mu^- \to \pi_T^0 \to \bar{b}b$ (upper curve) and $\pi_T^{0\prime} \to \bar{b}b$. Statistical errors only are shown for a luminosity of $1\,\mathrm{pb}^{-1}$ per point. Cuts and efficiencies are described in the text. The solid lines are the theoretical cross sections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

Technirhos:

Can have nearby vector resonances that interfere:

Would need the fine resolution to disentangle states

Common case with new strong dynamics

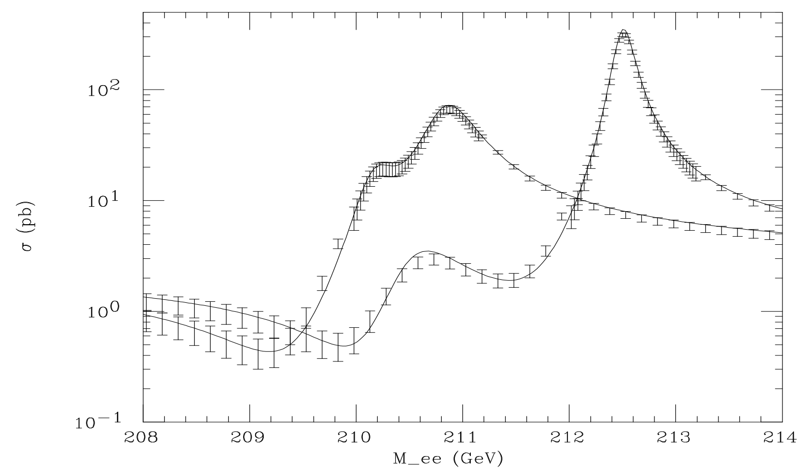
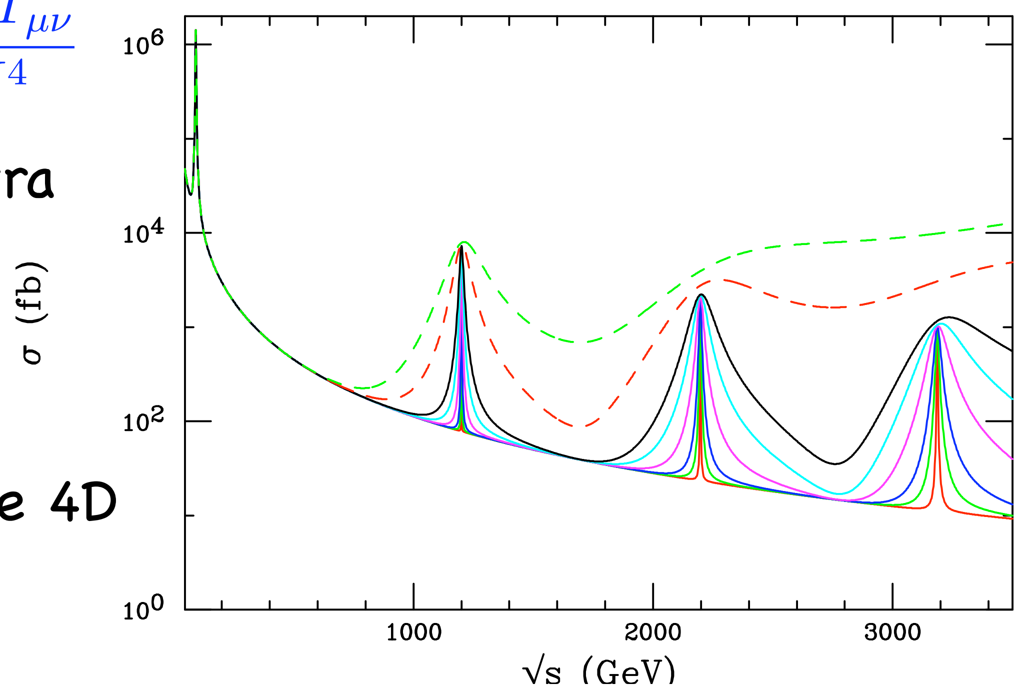


Figure 2: Cross sections for $\mu^+\mu^- \to \rho_T, \omega_T \to e^+e^-$ for $M_{\rho_T} = 210\,\mathrm{GeV}$ and $M_{\omega_T} = 211\,\mathrm{GeV}$ (higher-peaked curve) and 209 GeV. Statistical errors only are shown for resolutions and luminosities described in the text. The solid lines are the theoretical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

LHC discovery - Detailed study at muon collider

- A variety of models -nonrenormalizable effective theories at low energies.
- Arkani-Hamed, Dimopoulos, Dvali model:
  - effective contact interaction $\propto \lambda \frac{T^{\mu\nu}T_{\mu\nu}}{M^4}$
- Randall-Sundrum model: warped extra dimensions
  - two parameters:
    - mass scale ∝ first KK mode;
    - width ∝ 5D curvature / effective 4D Planck scale.

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



CMS - TDR

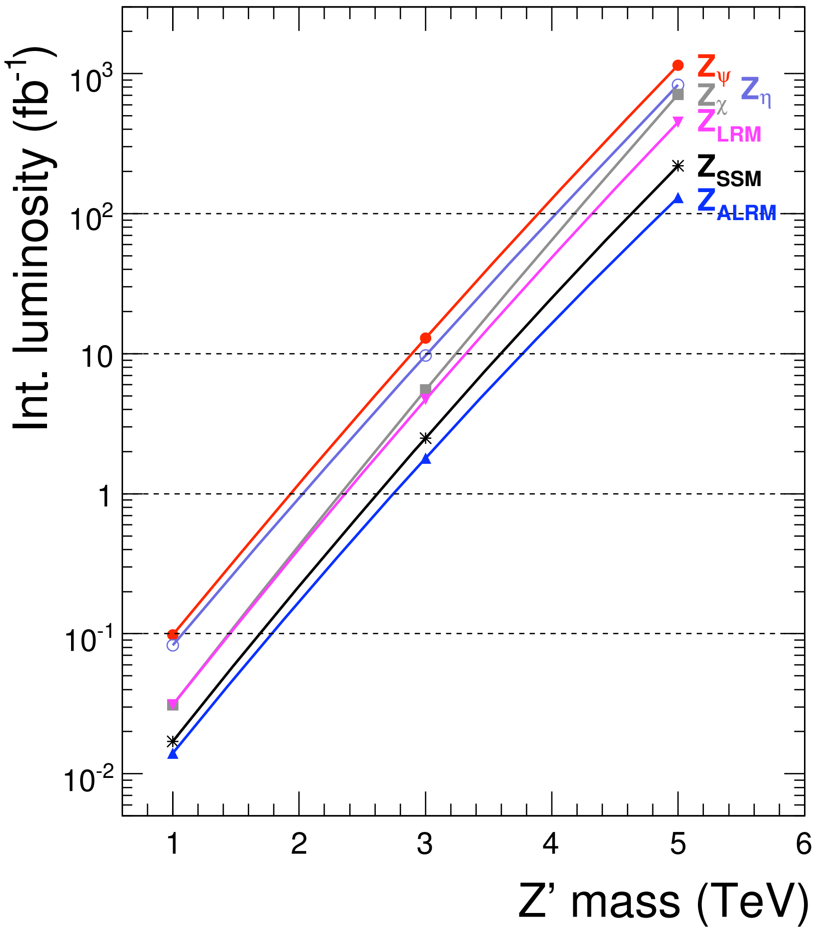


Figure 3.20: Integrated luminosity needed to reach 5σ significance ($S_{\mathcal{L}} = 5$) as a function of Z′ mass for (top to bottom) Z_ψ, Z_η, Z_χ, Z_{LRM}, Z_{SSM} and Z_{ALRM}. Symbols indicate fully-simulated mass-luminosity points, lines are the results of interpolations between the points.