Strengthening the Physics Case for a Muon Collider

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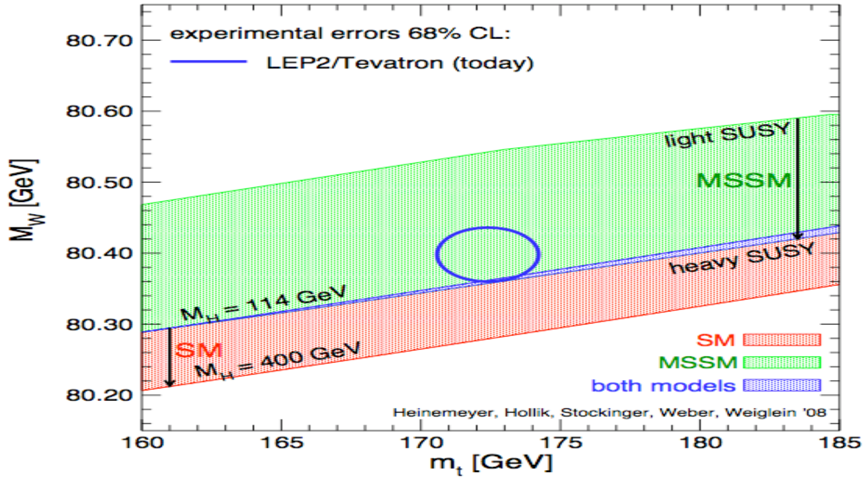
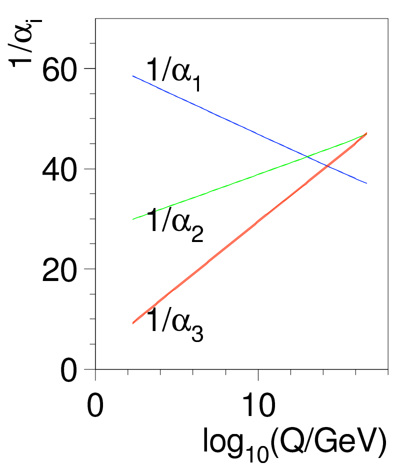
- Where We Stand
- Muon Collider Physics
  - Higgs Sector
  - Beyond the Standard Model
  - Minimum Luminosity
- The Next Step

2009 Neutrino Factory and Muon Collider Collaboration Meeting
January 25-28, 2009 LBNL, Berkeley, CA

Where We Stand

- All data consistent with Standard Model - but:
- incomplete
  - dark matter
  - neutrino masses and mixing (Stephen Parke)
    - new fields or new interactions
  - 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





Crossroad in Theoretical Physics

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

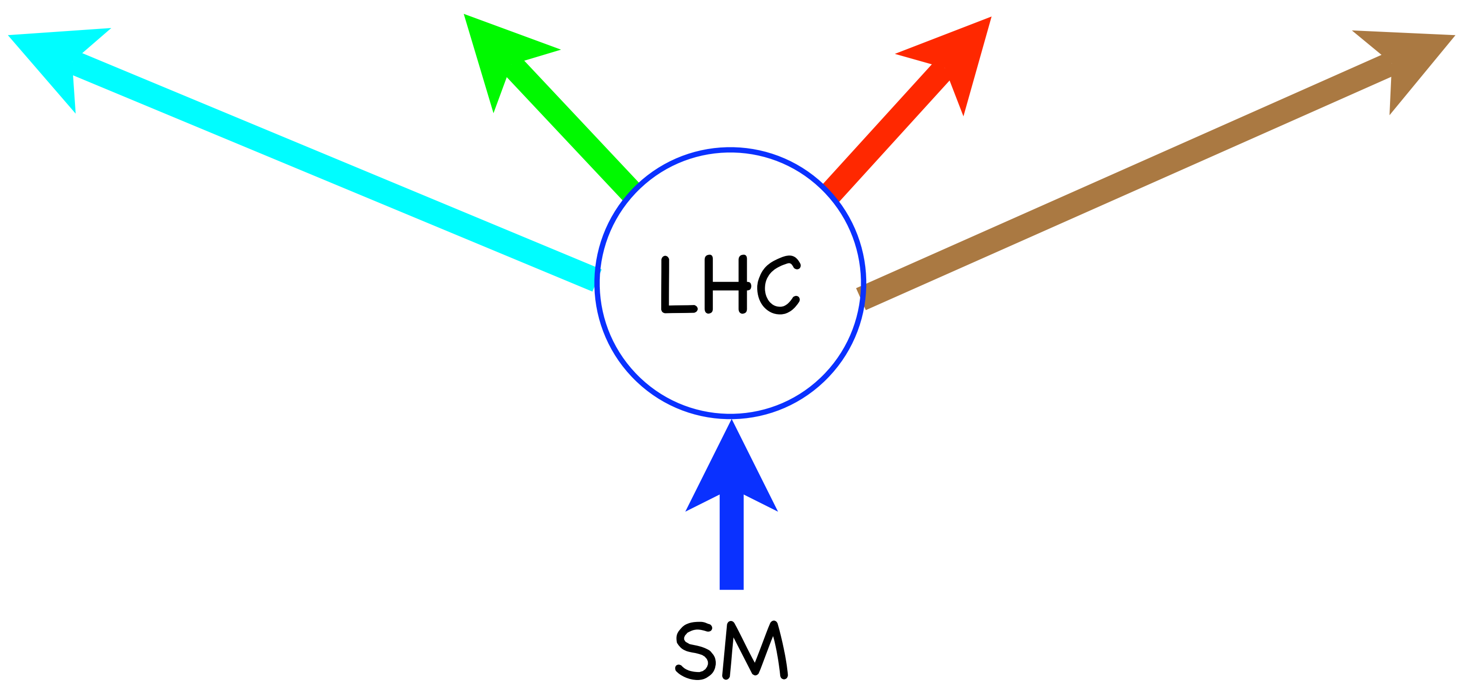
Gravity

Randall-Sundrum

Universal ED

KK modes?

...



Muon Collider Physics

Existing facilities in 2020:

- LHC with luminosity or energy upgrade

Options:

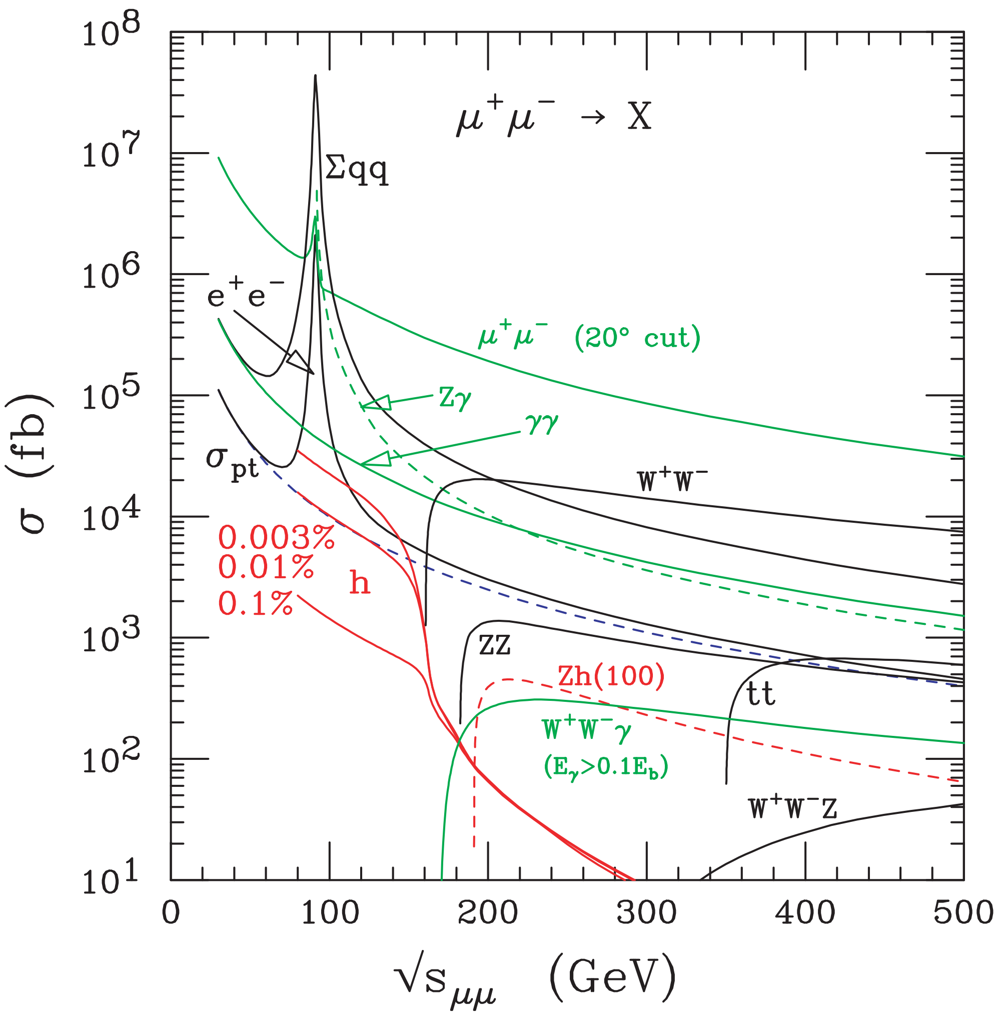
- low energy lepton collider (< 1 TeV)
  ILC (500 GeV) (upgradable)
  or muon collider - Higgs Factory
- lepton collider in multi Tev range.
  CLIC or muon collider
  - Energy, Luminosity, Polarization?
- hadron collider in hundred TeV range
  VLHC

Muon Collider 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
      $$\left[\frac{m_\mu}{m_e}\right]^2 = 4.28 \times 10^{4}$$
    - 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

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

Standard Model
Cross Sections



For $\sqrt{s}$ > 500 GeV

- Above SM thresholds:
- R essentially flat:

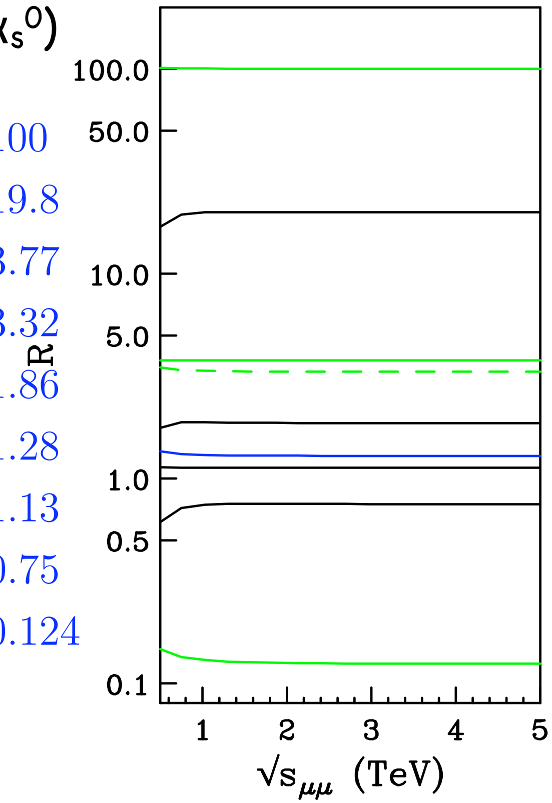
(one unit of R)

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

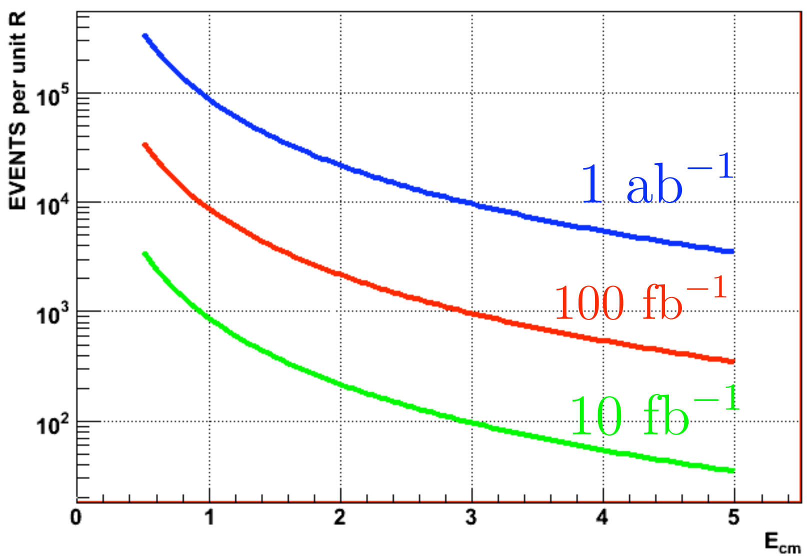
R at $\sqrt{s}$ = 3 TeV

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

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



Luminosity Requirements



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

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

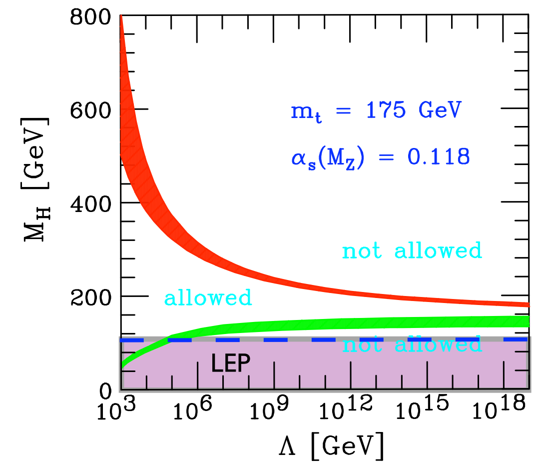
Total - 510 K SM events per year

Processes with R ≥ 0.01 can be studied

Standard Model and Extensions

Theoretical issues

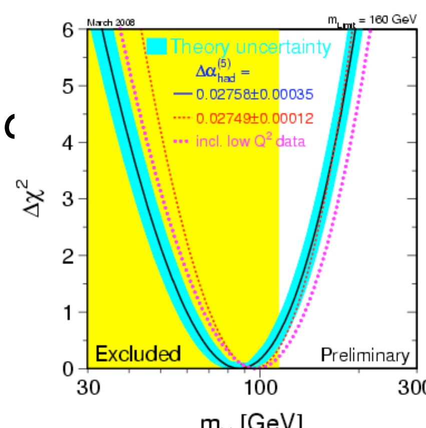
- Higgs boson couplings SM?
- Scalar interaction self-coupling SM?
- Any additional scalars? EW doublets, triplets or singlets ?
- More fermions?
- Addition gauge interactions ?
- Where's the next scale? GUT?



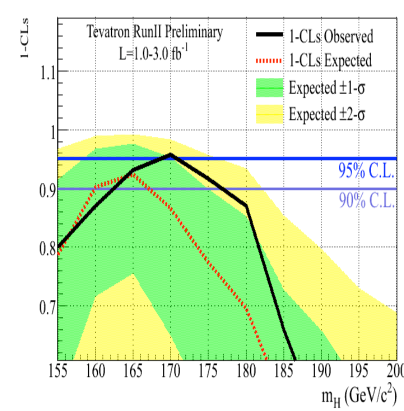
Standard Model Higgs

- 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 c be measured at the LHC.
- The ILC(500) allows detailed study of the Higgs properties.

LEP: m_h > 114.4 (95 % CL)



CDF/D0: m_h = 170 excluded (95 % CL)

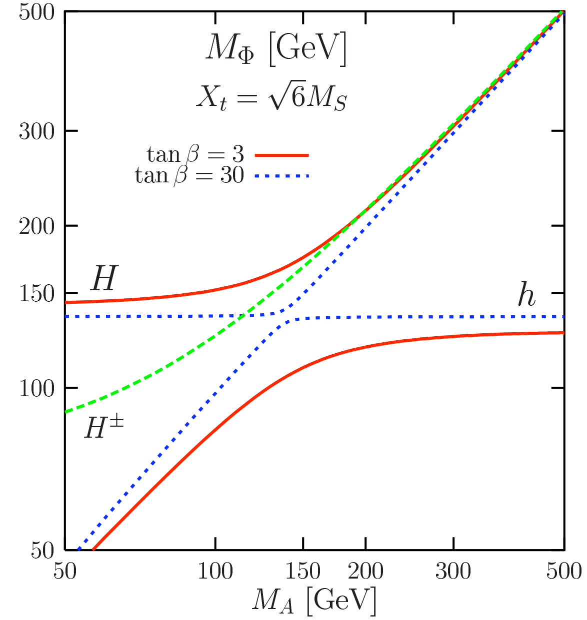


- Various processes available for studying the Higgs at a muon collider:
  - s-channel direct production: h^0 ($\sqrt{s} = m_h$)
  - associated production: Zh^0
    - $R \sim 0.12$
    - search for invisible h^0 decays
  - W^*W^* fusion : $\bar{\nu}_\mu \nu_\mu\ h^0$
    - $R \sim 1.1\ s \ln(s)$ (s in 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 $m_{A^0} \gg m_{Z^0}$:
  - 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.

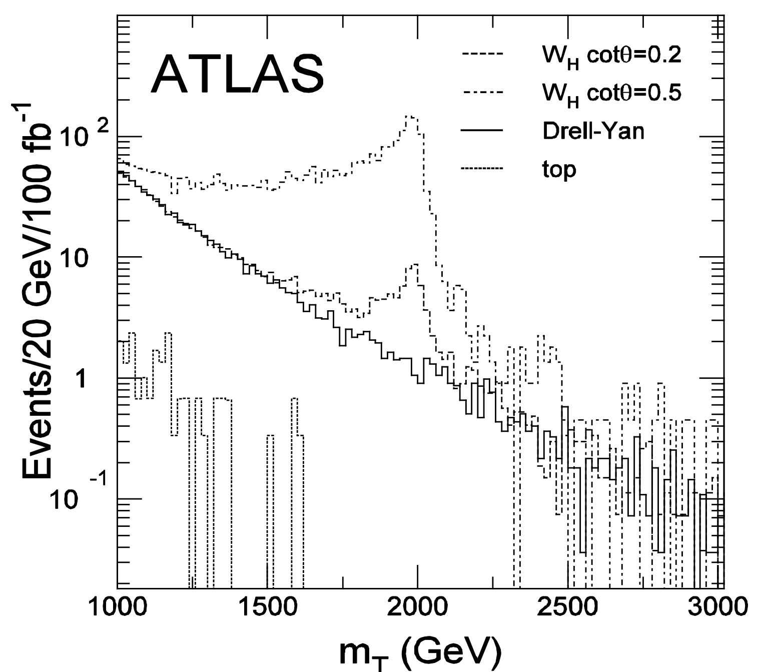
- good energy resolution is needed for H^0 and A^0 studies:
  - for s-channel production of H^0: $\Gamma/M \approx 1\%$ at tanβ = 20.
  - nearby in mass need good energy resolution to separate H and A.
  - can use bremsstrahlung tail to see states using bb decay mode.

New fermions and gauge bosons

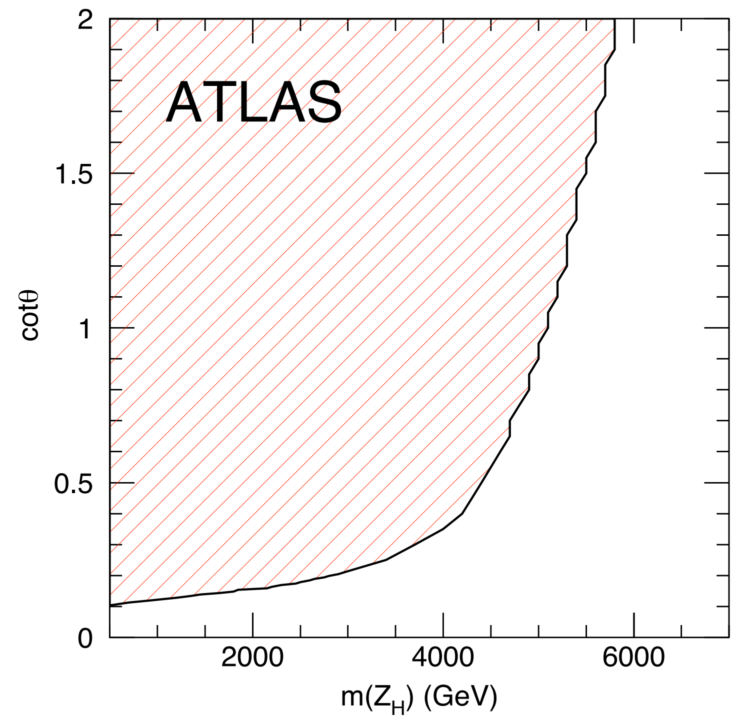
Present CDF/D0 bounds on W′, Z′, and new quarks effectively rule out production at ILC(500).

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 $2\text{x}10^6$.
  Calculate MSSM mass spectrum and check experimental constraints: (MICROMEGAS and SUSPECT2.3)

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

- If within bounds accept, otherwise reject.

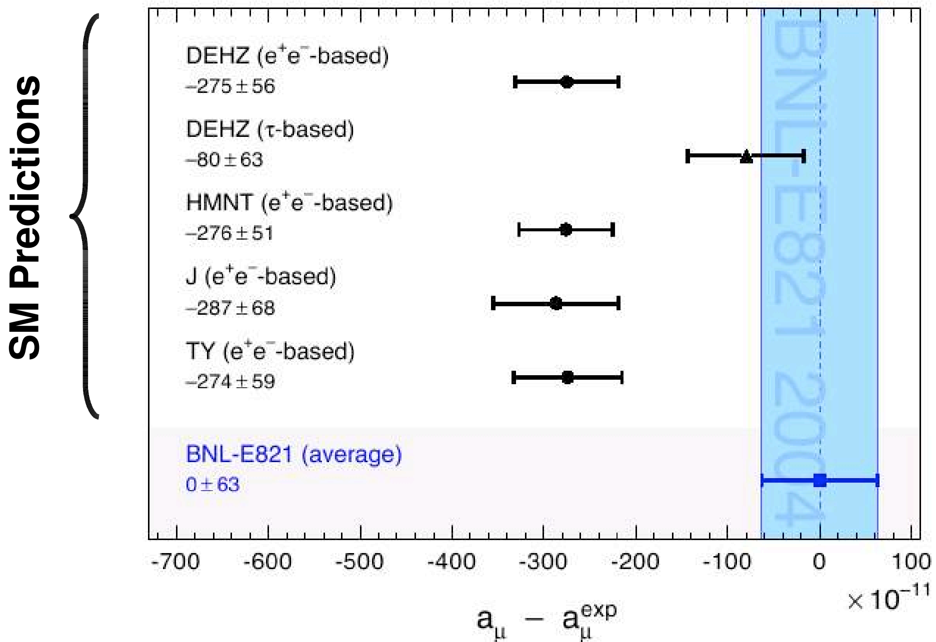
- Old style best fit studies of allowable cMSSM:

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

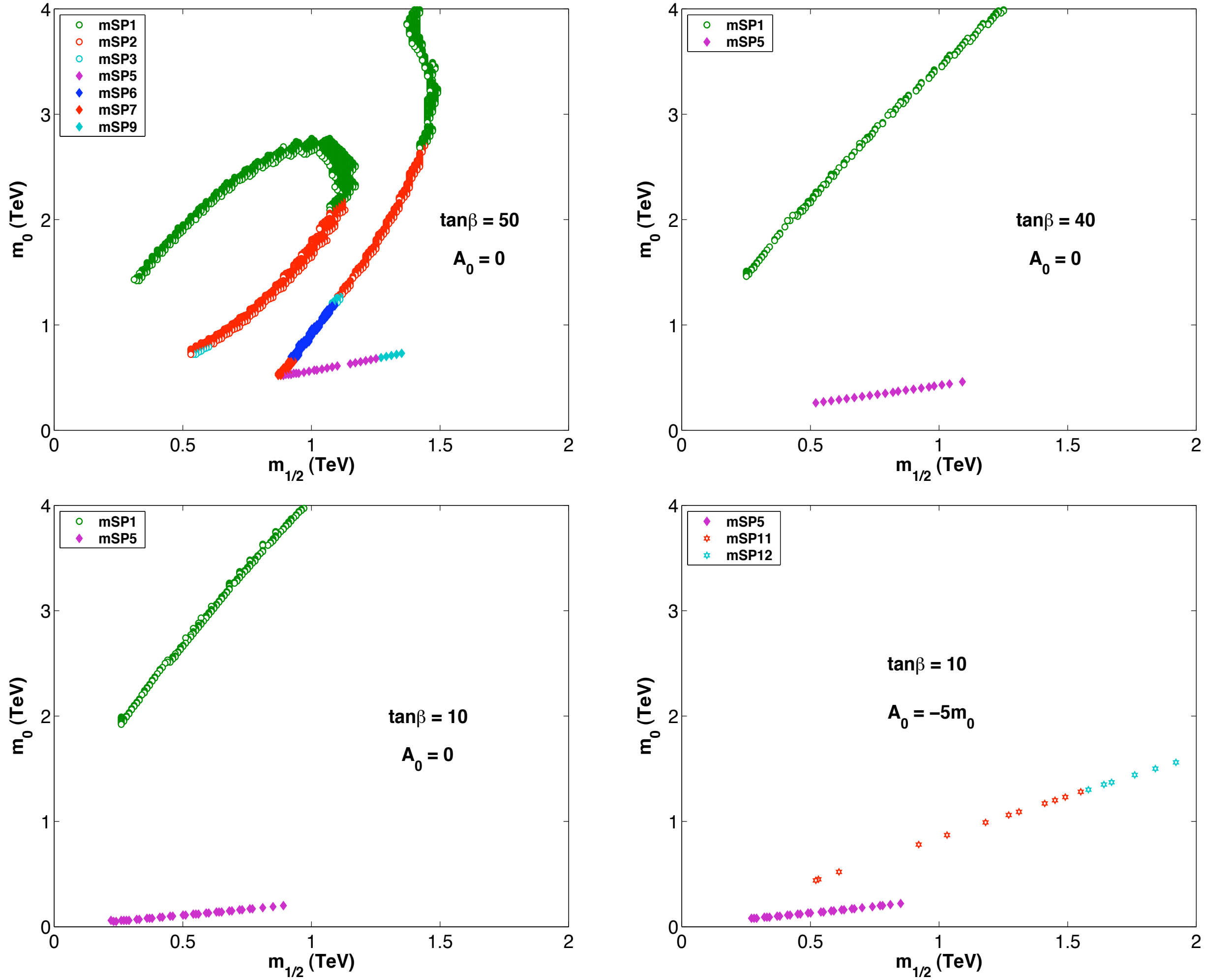


Figure 4: Dispersion of patterns in the m_0 vs $m_{1/2}$ plane for fixed values of $\tan\beta$ and A_0/m_0. The region scanned is in the range $m_0 < 4$ TeV and $m_{1/2} < 2$ TeV with a 10 GeV increment for each mass. Only a subset of the allowed parameter points relative to Fig.(3) remain, since the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

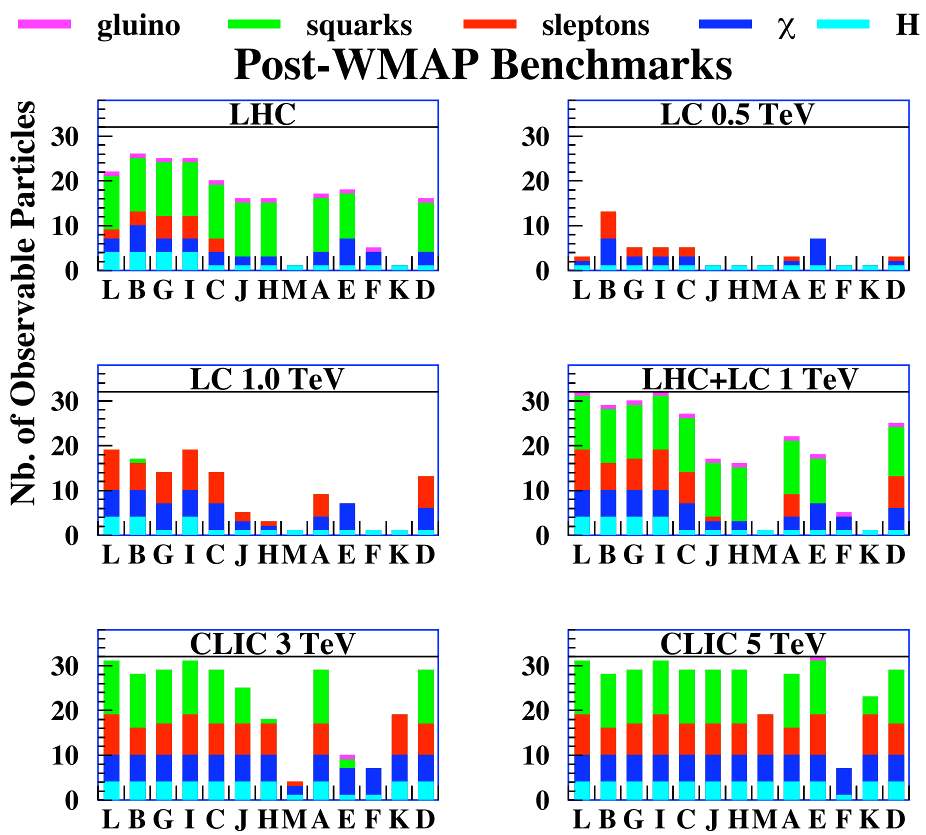
Pattern of 4 lightest sparticles

- 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.

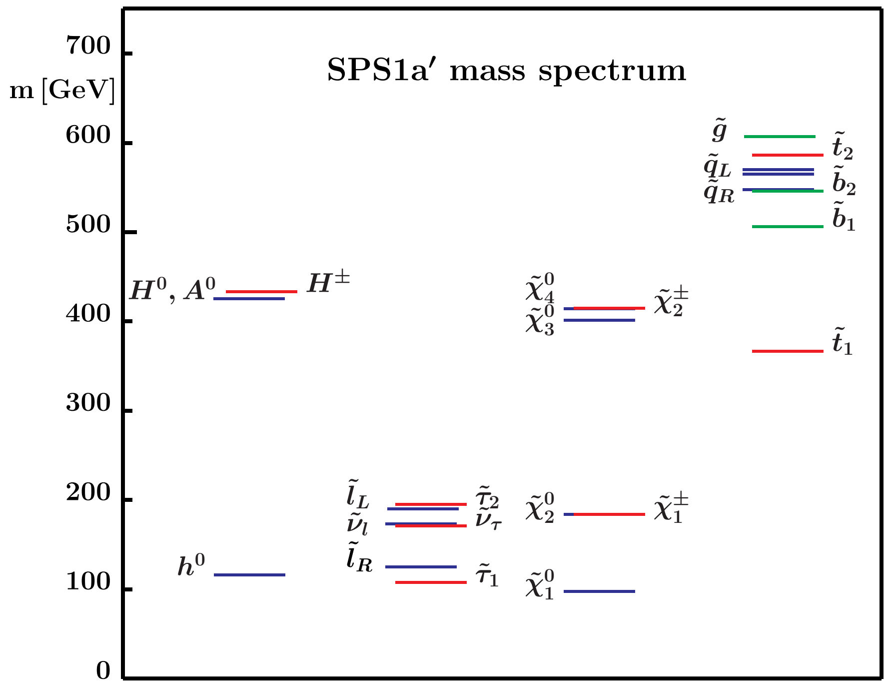
"Supersymmetry at a Muon Collider", Anupama Atre,
Low Emittance Muon Collider Workshop
Fermilab, April 2008

A multiTev lepton collider needed for full coverage.



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

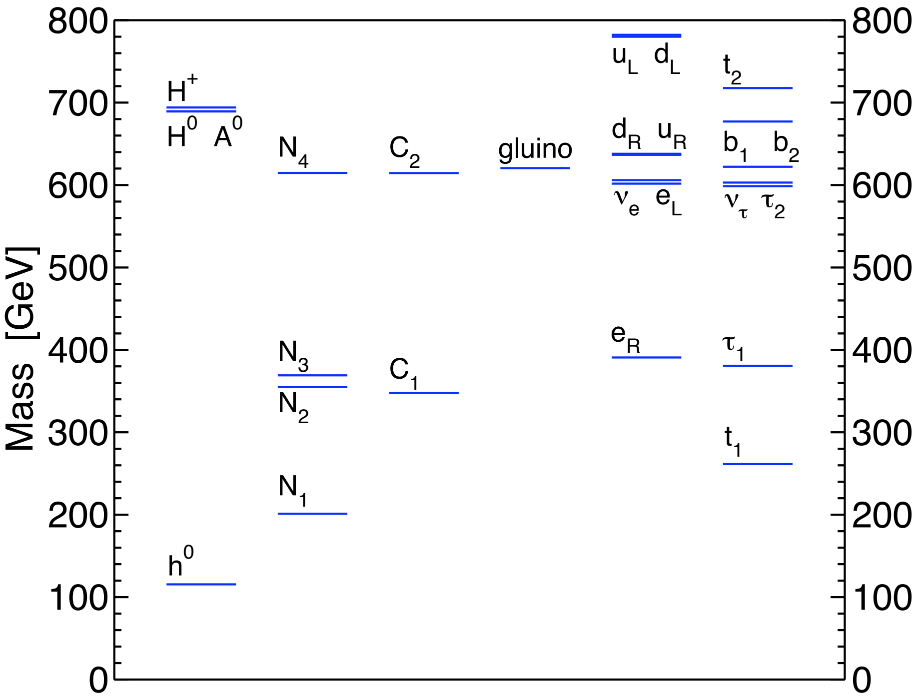
cMSSM ILC Benchmark



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

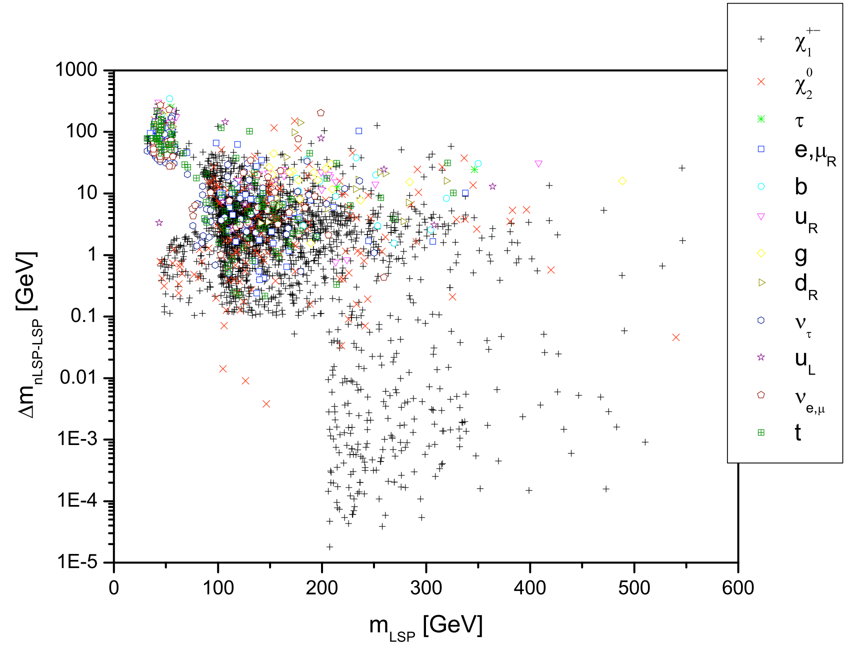
pMSSM - relax the unification of soft breaking parameters at the GUT scale.

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

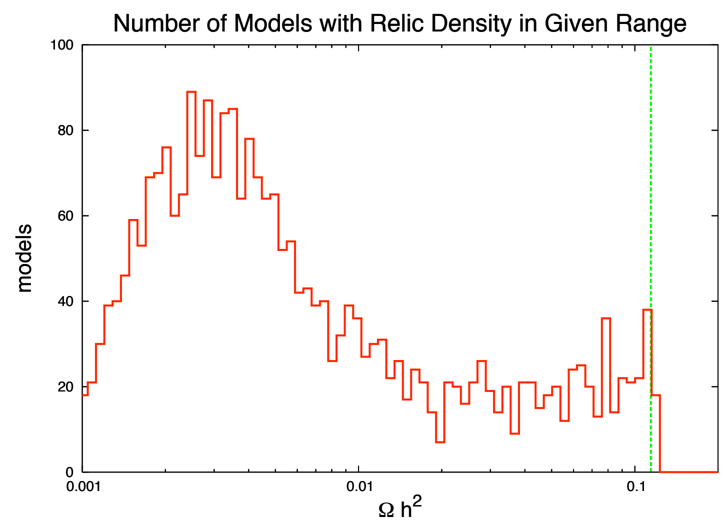
2×10^6 points studied (log priors)

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?
- ...

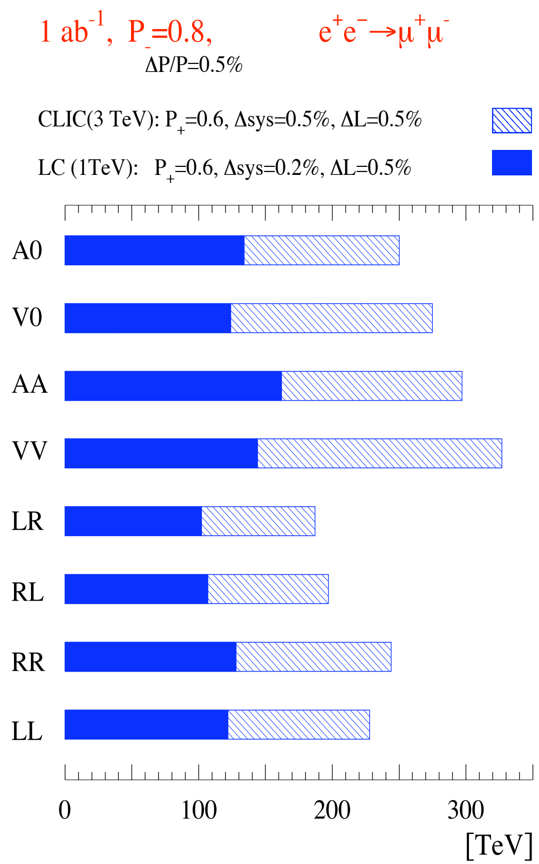
Technicolor, ETC, Walking TC, Topcolor , ...

- 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

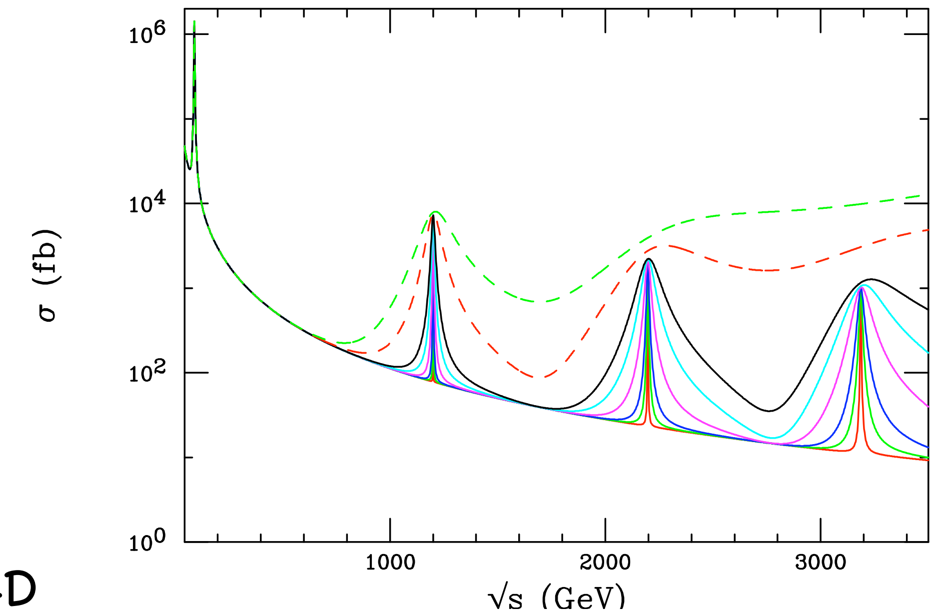
LHC discovery - Detailed study at a muon collider

- 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?
- ...

Randall-Sundrum model:
warped extra dimensions

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

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



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	$BR(\mu^+\mu^-)$	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

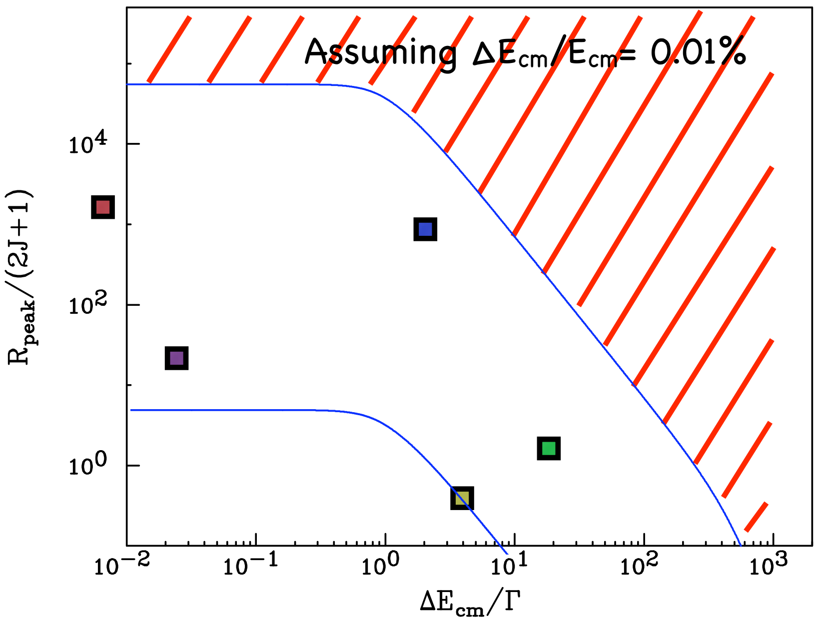
$$\sigma(E) = \frac{2J+1}{(2S_1+1)(2S_2+1)}\frac{4\pi}{k^2}\left[\frac{\Gamma^2/4}{(E-E_0)^2+\Gamma^2/4}\right]B_{in}B_{out}$$

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

Convolute with beam spread

$$\frac{1}{\sqrt{2\pi}\sigma}\exp\left(-\frac{(E-E_0)^2}{2\sigma^2}\right)$$

$$\rightarrow \Delta E_{\text{cm}}/E_{\text{cm}} = 2\ln(2)\sigma$$

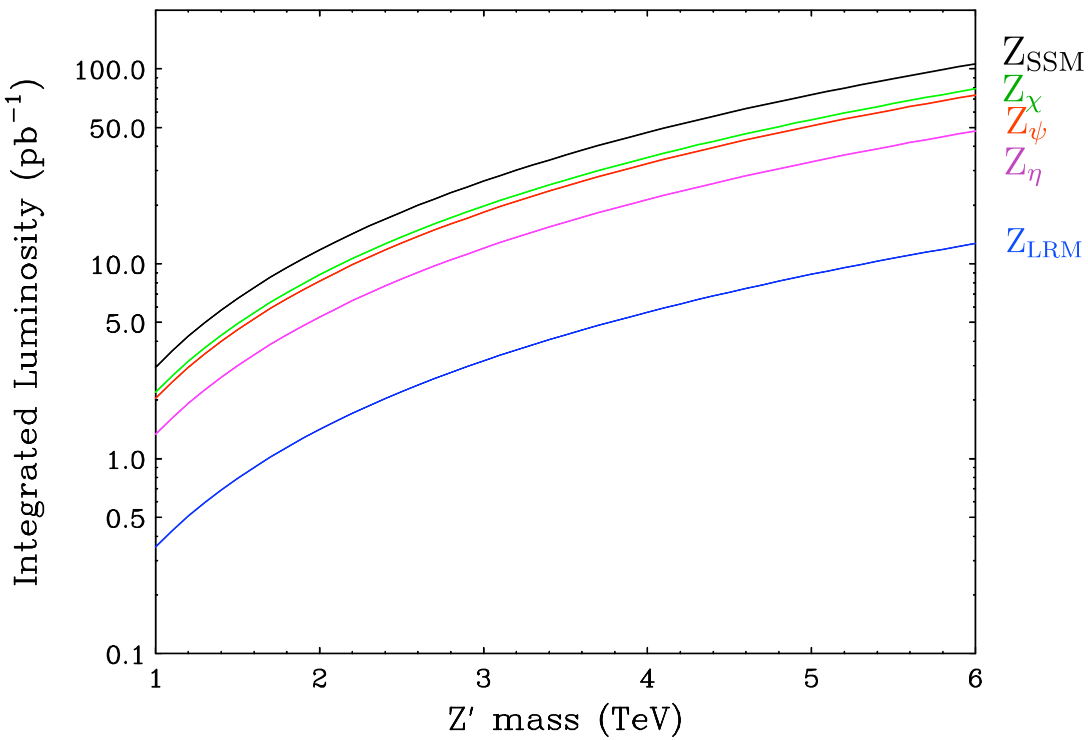


Can use to set minimum required luminosity

- 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



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

for M(Z') -> 1.5-5.0 TeV

Preliminary Conclusions

- A multiTeV lepton collider is likely required for full coverage of Tevascale physics.
- Recent experimental results further limit the SUSY potential of a 500 GeV ILC.
- 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.

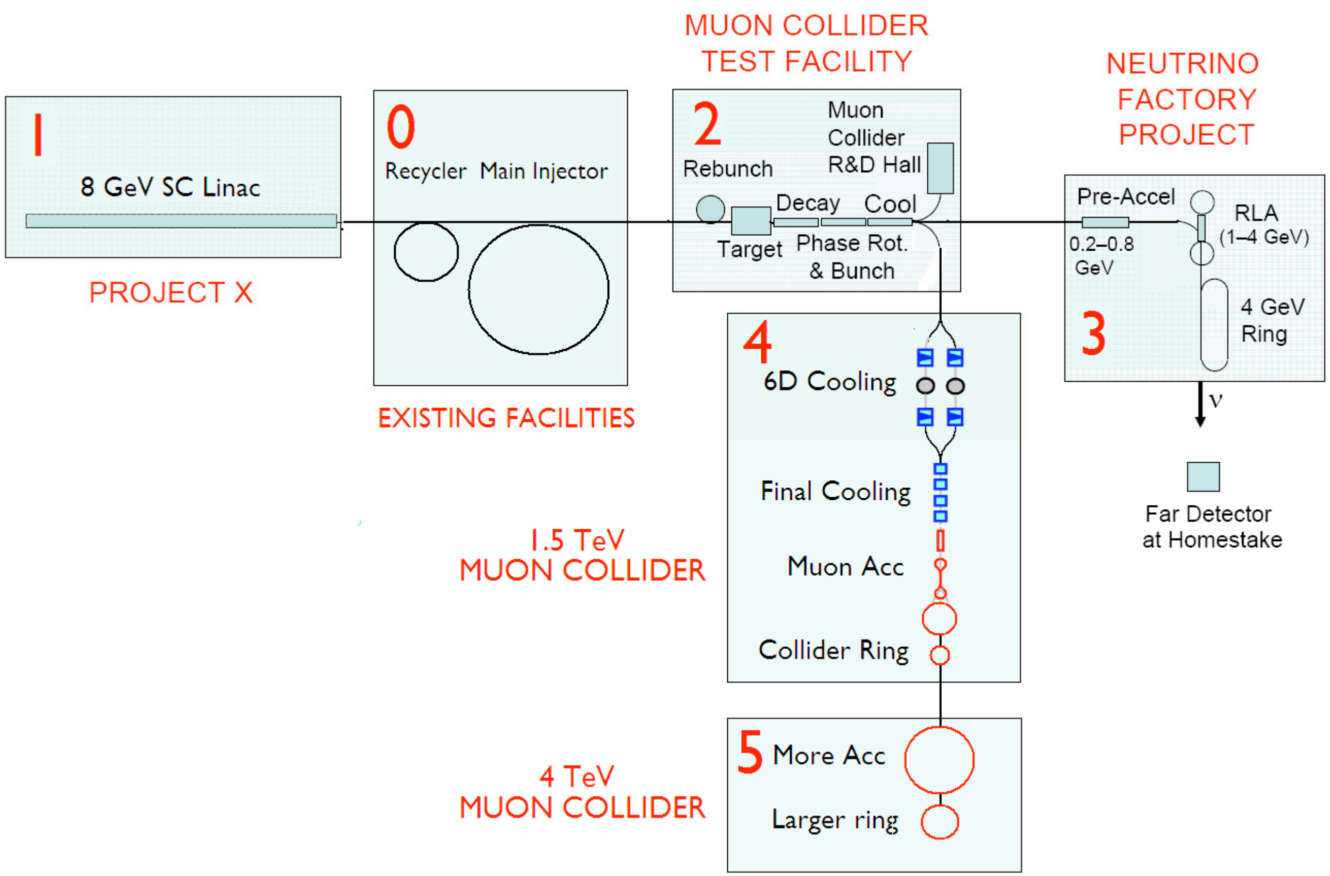
The Next Step

- Proceed to a detailed study of physics case for 1.5-4.0 TeV muon collider:
  - 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

Path to Muon Collider Facility

A Scenerio:



Options:

- Neutrino Factory
- Lower Energy Muon Collider - Higgs Factory

Abridged Parameter List

Machine	1.5-TeV $\mu^+\mu^-$	3.0-TeV $\mu^+\mu^-$	CLIC 3 TeV
$\mathcal{L}_{\text{peak}}$ [$\text{cm}^{-2}\ \text{s}^{-1}$]	7×10^{34}	8.2×10^{34}	8×10^{34} tot
$\mathcal{L}_{\text{avg}}$ [$\text{cm}^{-2}\ \text{s}^{-1}$]	3.0×10^{34}	3.5×10^{34}	3.1×10^{34} 99%
$\Delta p/p$ [%]	1	1	0.35
$\beta^\star$	0.5 cm	0.5 cm	35 μm
Turns / lifetime	2000	2400	
Rep. rate [Hz]	65	32	
Mean dipole field	10 T	10 T	
Circumference [m]	2272	3842	33.2 km site
Bunch spacing	0.75 μs	1.28 μs	0.67 ns

cMSSM – Soft breaking couplings set equal at GUT scale.

Fewest parameters

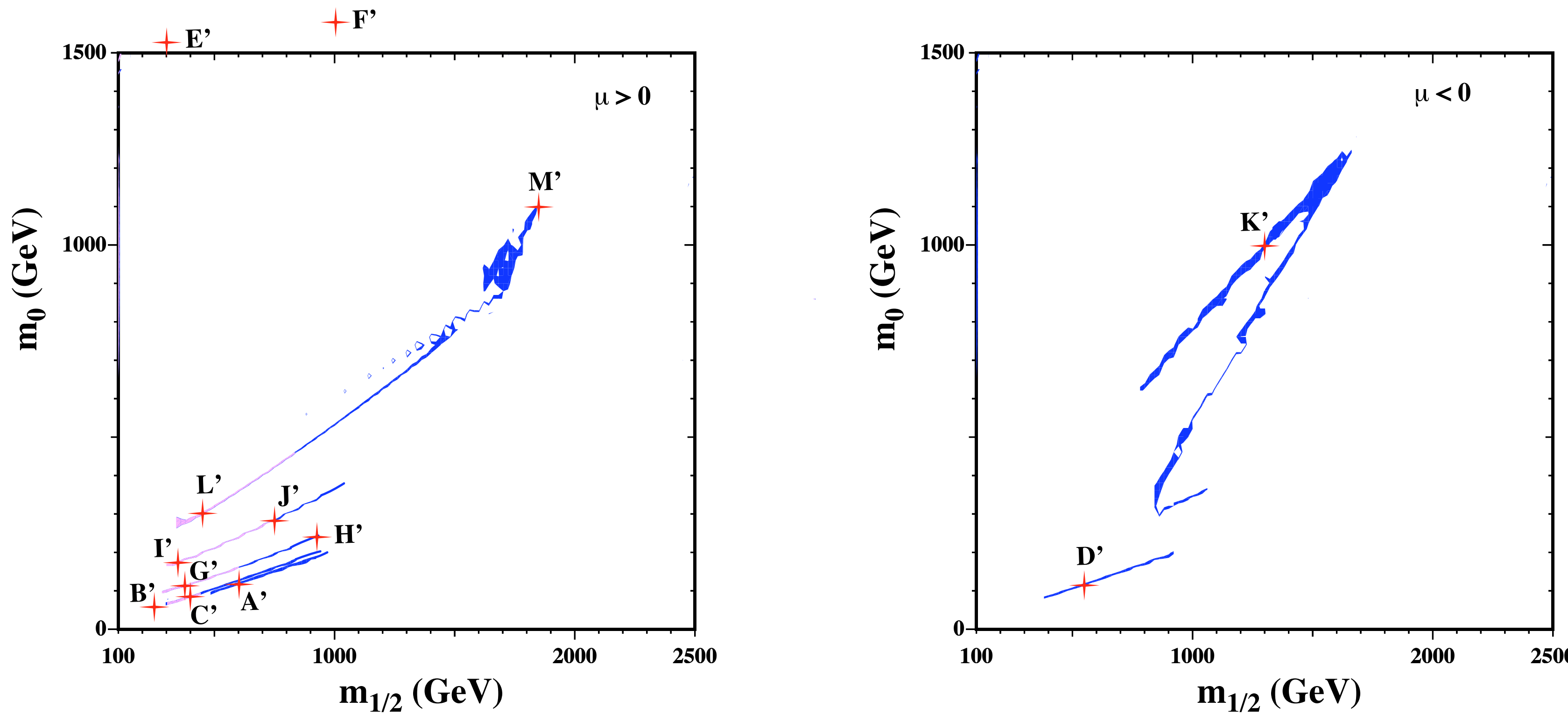


Fig. 5.2: Overview of the updated proposed CMSSM benchmark points in the $(m_0, m_{1/2})$ planes, superposed on the strips allowed by laboratory limits and the relic density constraint, for $\mu > 0$ and $\tan\beta$ = 5, 10, 20, 35, 50, and for $\mu < 0$ and $\tan\beta$ = 10, 35 [8]

CLIC detailed study - CERN report 2004

○ 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 ?