A MultiTeV Muon Collider:
The Physics Case

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Fermilab

Physics Landscape

- Matter fields interact with massless spin one gauge bosons. (The Gauge Principle)
  - Global Symmetry ⇒ Gauged Local Symmetry

    $\psi \to \exp\{iQ\}\,\psi$ $\psi(x) \to \exp\{i\,e\Lambda(x)\}\,\psi(x) \equiv G\,\psi(x)$; $A^\mu(x) \to G A^\mu(x) G^{-1} - (1/ie)[\partial^\mu, G]G^{-1}$

    $L = \bar{\psi}(-i\,\gamma\cdot\partial + M)\,\psi$ $L = \bar{\psi}(-i\,\gamma\cdot D + M)\,\psi - (1/4e^2)\,(F^{\mu\nu})\,(F_{\mu\nu})$

    with $D^\mu = [\partial^\mu + ie\,A^\mu(x)]$ and $(F^{\mu\nu}) = i[D^\mu, D^\nu]$
  - QED: Charged particles ψ (matter fields) interact with the photon A^μ (gauge particle)
- The Standard Model (SM) is based on this principle.
  - QCD - SU(3) gauge interactions:
    - color octet gluons (g) and color triplet quarks $(u,d,s,c,b,t)_{(L,R)}$
    - Confinement -> physical states color singlets.
  - Electroweak - $SU(2)_L X U(1)$ gauge interactions:
    - $SU(2)_L$ triplet gauge bosons: ($W^\pm$, W^0) and a $U(1)_Y$ gauge boson B
    - quarks: $SU(2)_L$ doublets: (u_L,d_L), (c_L,s_L), (t_L, b_L); and singlets: q_R
    - leptons $SU(2)_L$ doublets: (ν_e, e^-_L), (ν_μ, μ^-_L), (ν_τ, τ^-_L); and singlets l_R
    - No fermion or W, Z masses unless gauge symmetry spontaneously broken.
- Gravity is also a gauge theory. Hope to eventually unify of all four forces: Strong, Electromagnetic, Weak and Gravity. [String Theory]

Physics Landscape

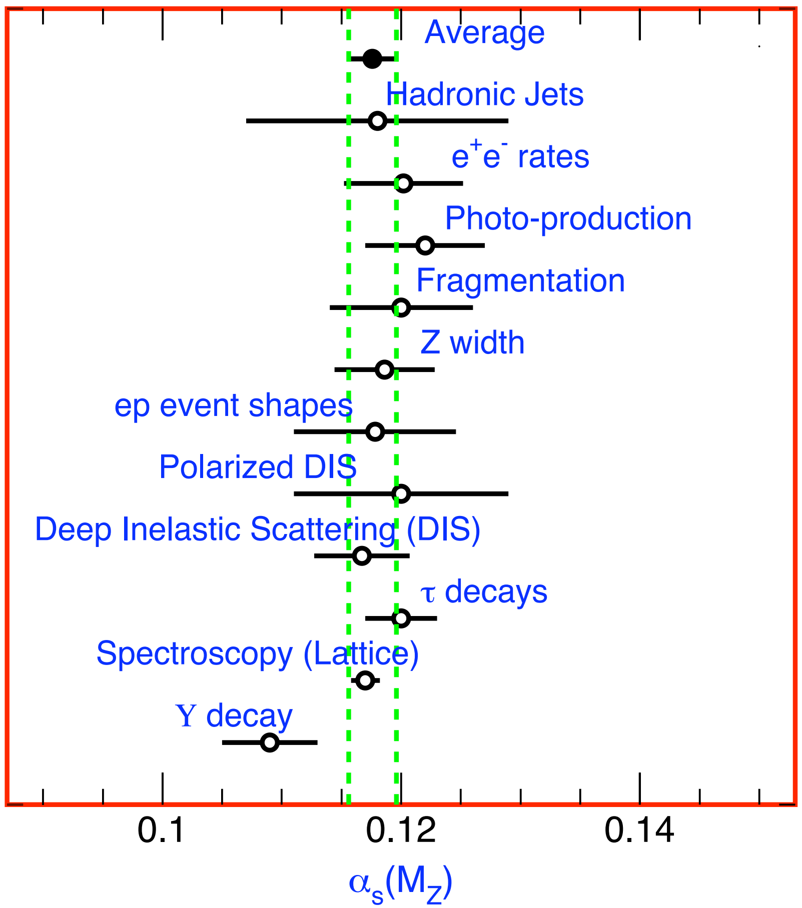
- Electroweak Symmetry Breaking (EWSB)
  - Introduce a $SU(2)_L$ complex doublet scalar field Φ, with self interactions
    - $\mu^2 (\Phi^\dagger\Phi) + \lambda (\Phi^\dagger\Phi)^2$ with EWSB -> $< \Phi^\dagger\Phi > = v^2 = -\mu^2 /\lambda$;
      one physical Higgs boson (mass $m_H^2=2\lambda v^2$)
  - Gauge interactions
    - $D^\mu\Phi^\dagger D_\mu\Phi$ with EWSB -> massive $W^\pm$,Z^0 and massless photon γ
  - Yukawa couplings to fermions
    - $\Gamma_{ij}\psi_{iL}{}^\dagger\psi_{jR}\Phi$ + h.c. with EWSB -> fermion masses and mixing of flavor eigenstates into mass eigenstates. CKM matrix for quarks.

- The Standard Model (SM) has been a spectacular success. For more than 30 years all new observations have fit naturally into this framework.
  - See figure and table

- Basic questions remain
  - There is as of yet no direct evidence for the Higgs boson or its interactions. Is this the correct mechanism for electroweak symmetry breaking?
  - How do the fermion masses and flavor mixings arise?

Physics Landscape

QCD



EW

Quantity	Value	Standard Model	Pull
m_t [GeV]	$172.7 \pm 2.9 \pm 0.6$	172.7 ± 2.8	0.0
M_W [GeV]	80.450 ± 0.058	80.376 ± 0.017	1.3
	80.392 ± 0.039		0.4
M_Z [GeV]	91.1876 ± 0.0021	91.1874 ± 0.0021	0.1
Γ_Z [GeV]	2.4952 ± 0.0023	2.4968 ± 0.0011	-0.7
$\Gamma(\mathrm{had})$ [GeV]	1.7444 ± 0.0020	1.7434 ± 0.0010	—
$\Gamma(\mathrm{inv})$ [MeV]	499.0 ± 1.5	501.65 ± 0.11	—
$\Gamma(\ell^+\ell^-)$ [MeV]	83.984 ± 0.086	83.996 ± 0.021	—
σ_{had} [nb]	41.541 ± 0.037	41.467 ± 0.009	2.0
R_e	20.804 ± 0.050	20.756 ± 0.011	1.0
R_μ	20.785 ± 0.033	20.756 ± 0.011	0.9
R_τ	20.764 ± 0.045	20.801 ± 0.011	-0.8
R_b	0.21629 ± 0.00066	0.21578 ± 0.00010	0.8
R_c	0.1721 ± 0.0030	0.17230 ± 0.00004	-0.1
$A_{FB}^{(0,e)}$	0.0145 ± 0.0025	0.01622 ± 0.00025	-0.7
$A_{FB}^{(0,\mu)}$	0.0169 ± 0.0013		0.5
$A_{FB}^{(0,\tau)}$	0.0188 ± 0.0017		1.5
$A_{FB}^{(0,b)}$	0.0992 ± 0.0016	0.1031 ± 0.0008	-2.4
$A_{FB}^{(0,c)}$	0.0707 ± 0.0035	0.0737 ± 0.0006	-0.8
$A_{FB}^{(0,s)}$	0.0976 ± 0.0114	0.1032 ± 0.0008	-0.5
$\bar{s}_\ell^2(A_{FB}^{(0,q)})$	0.2324 ± 0.0012	0.23152 ± 0.00014	0.7
	0.2238 ± 0.0050		-1.5
A_e	0.15138 ± 0.00216	0.1471 ± 0.0011	2.0
	0.1544 ± 0.0060		1.2
	0.1498 ± 0.0049		0.6
A_μ	0.142 ± 0.015		-0.3
A_τ	0.136 ± 0.015		-0.7
	0.1439 ± 0.0043		-0.7
A_b	0.923 ± 0.020	0.9347 ± 0.0001	-0.6
A_c	0.670 ± 0.027	0.6678 ± 0.0005	0.1
A_s	0.895 ± 0.091	0.9356 ± 0.0001	-0.4
g_L^2	0.30005 ± 0.00137	0.30378 ± 0.00021	-2.7
g_R^2	0.03076 ± 0.00110	0.03006 ± 0.00003	0.6
$g_V^{\nu e}$	-0.040 ± 0.015	-0.0396 ± 0.0003	0.0
$g_A^{\nu e}$	-0.507 ± 0.014	-0.5064 ± 0.0001	0.0
A_{PV}	-1.31 ± 0.17	-1.53 ± 0.02	1.3
$Q_W(\mathrm{Cs})$	-72.62 ± 0.46	-73.17 ± 0.03	1.2
$Q_W(\mathrm{Tl})$	-116.6 ± 3.7	-116.78 ± 0.05	0.1
$\frac{\Gamma(b\to s\gamma)}{\Gamma(b\to Xe\nu)}$	$3.35^{+0.50}_{-0.44} \times 10^{-3}$	$(3.22 \pm 0.09) \times 10^{-3}$	0.3
$\frac{1}{2}(g_\mu - 2 - \frac{\alpha}{\pi})$	4511.07 ± 0.82	4509.82 ± 0.10	1.5
τ_τ [fs]	290.89 ± 0.58	291.87 ± 1.76	-0.4

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Physics Landscape

- All data consistent with Standard Model - but it's incomplete
  - dark matter; neutrino masses and mixing -> new fields or interactions;
  - baryon asymmetry in the universe -> more CP violation

- Theoretical questions
  - The issue of naturalness and the origin of mass;
    - $\mu^2 (\Phi^\dagger\Phi) + \lambda (\Phi^\dagger\Phi)^2 + \Gamma_{ij}\psi_{iL}{}^\dagger\psi_{jR}\Phi$ + h.c.

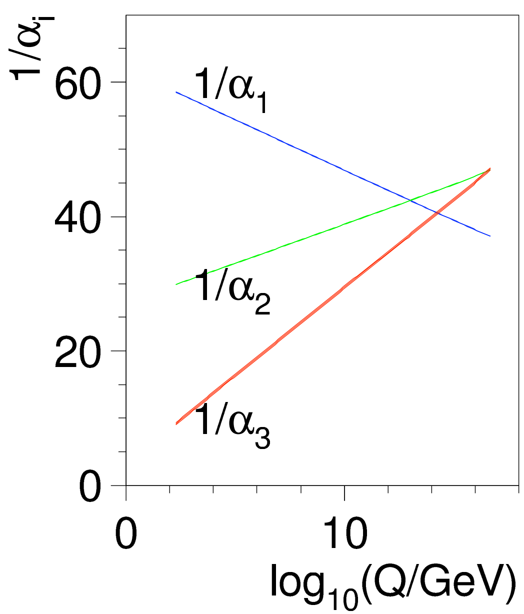
$m_H{}^2/M^2{}_{planck} \approx 10^{-34}$
Hierarchy problem

vacuum
stability

large range of
fermion masses

  - Many theoretical speculations on how to solve the naturalness problems:
    SUSY, New Dynamics, Extra Dimensions, ...

  - gauge unification -> new interactions;
  - gravity: strings and extra dimensions

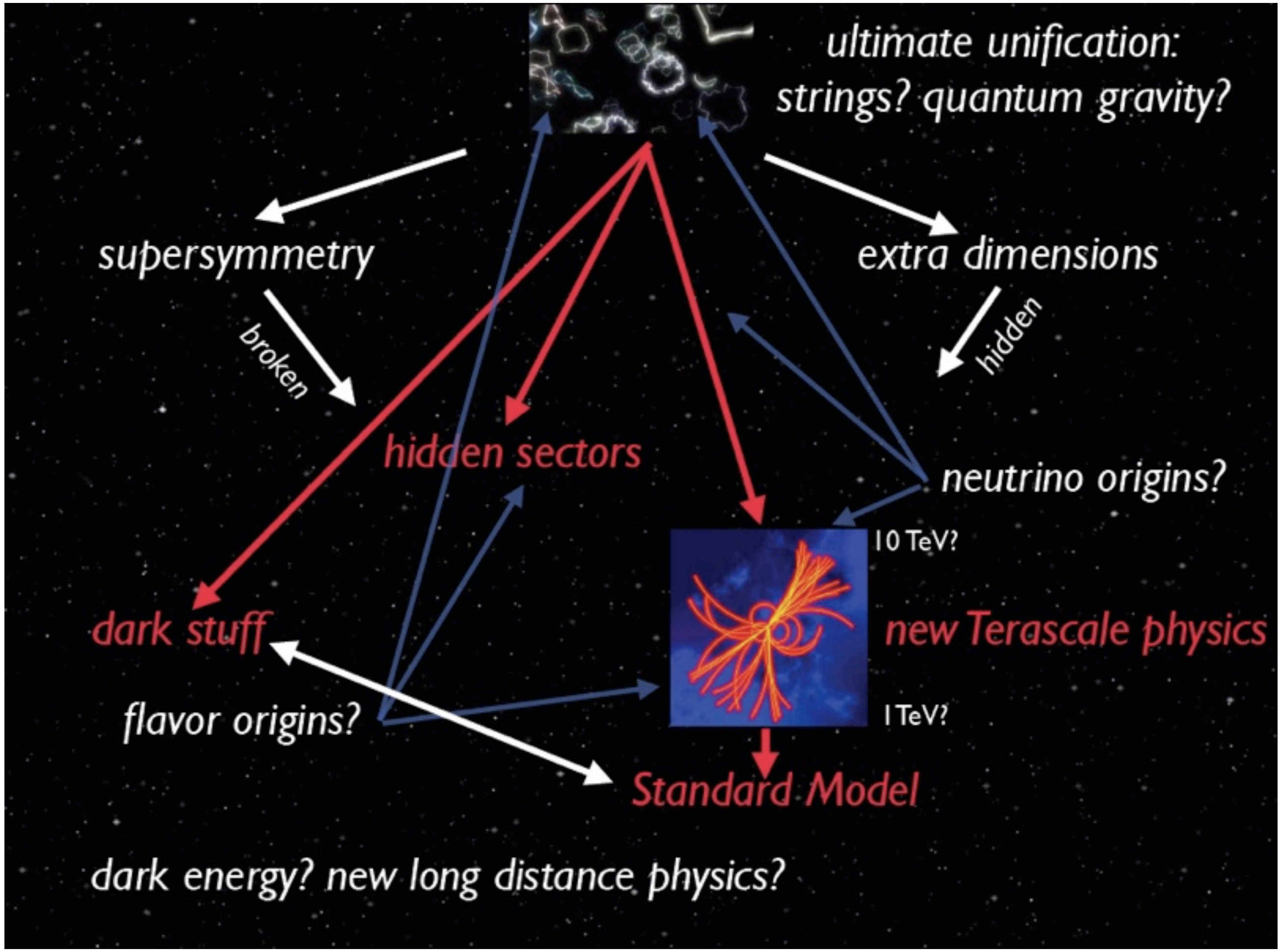


Theorists' Grand View

- New Scales and Symmetry Breaking

What is the origin and scale of fermion masses?

Physics	Symmetry	Scale
QCD	confinement	$m_{glueball}$
	χ SB	m_{proton}
EW	$SU(2)_L \times U_Y(1)$ --> $U_{EM}(1)$	M_W/g

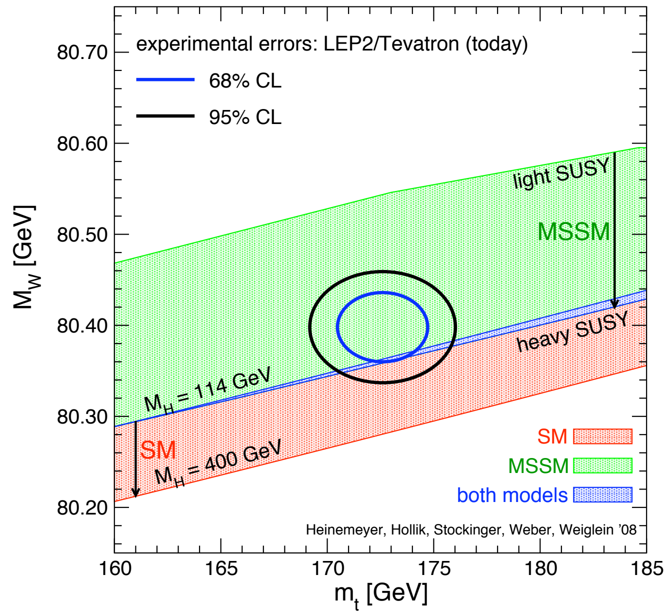


Lykken's talk at the "Muon Collider Physics, Detectors and Backgrounds Workshop"

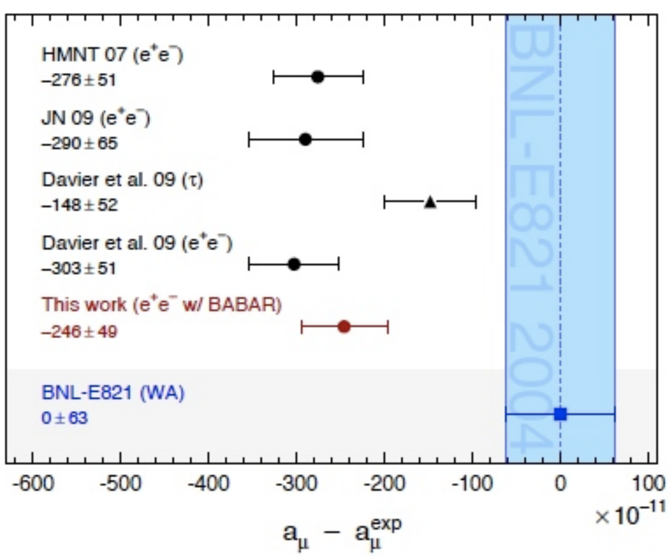
Physics Landscape

- Experimental hints for new physics

Higgs



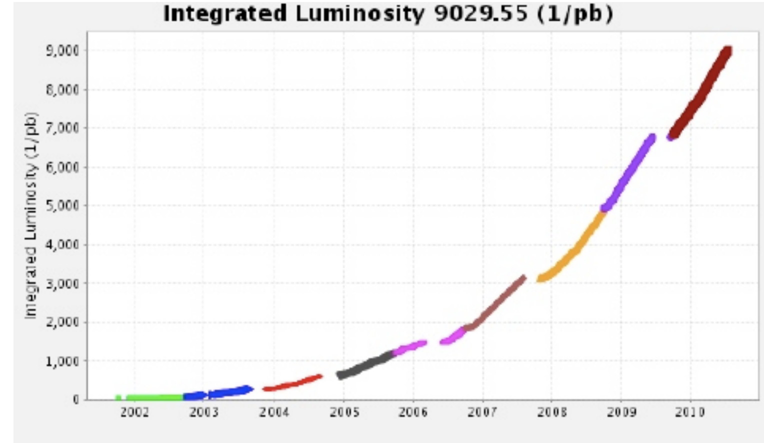
muon (g-2)



Crossroad In Theoretical Physics

- Energy Frontier Experiments
  - Tevatron - Operating well

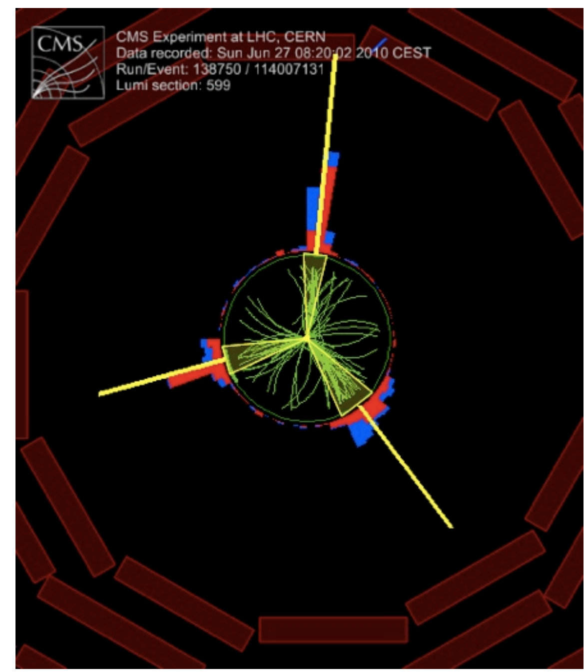
    $\sqrt{s}$ = 1.96 TeV pbar p
    Luminosity - 3.52×10^{32} cm^{-2} sec^{-1} (peak)
    $9.1 fb^{-1}$ (to date Run II)
    CDF, D0



  - LHC - Online
    $\sqrt{s}$ = 7.0 TeV p p
    Luminosity - 1 fb^{-1} in 2011

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

    ATLAS, CMS, LHCb, ALICE

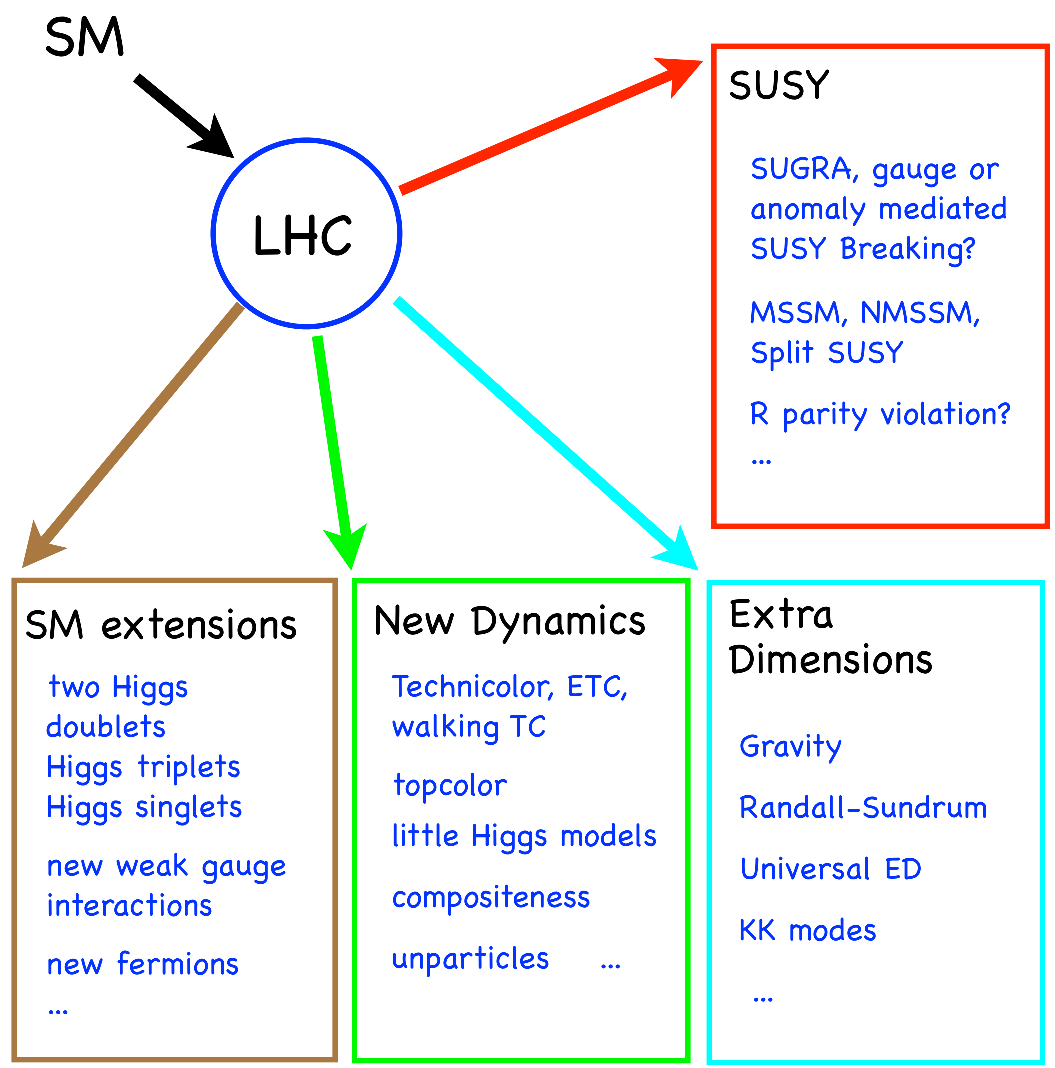


- Neutrino Experiments

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

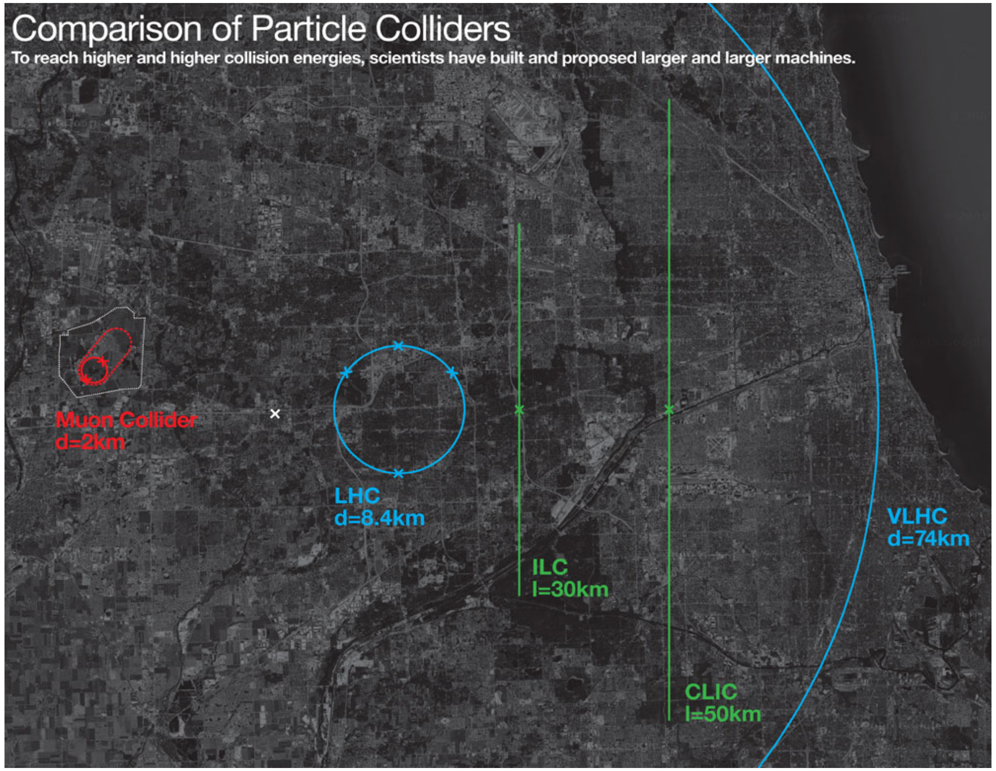
Crossroad In Theoretical Physics

- Each path (SM-like, SUSY, New Dynamics and Extra Dimensions) represents a different mechanism for Electroweak Symmetry Breaking
- There is great excitement in the field, that after more than 25 years of theoretical speculation we will have an answer.
- We expect the results from the LHC will determine the mechanism of EWSB.
- However it will likely be necessary to build a further collider to fully explore physics at the Terascale.



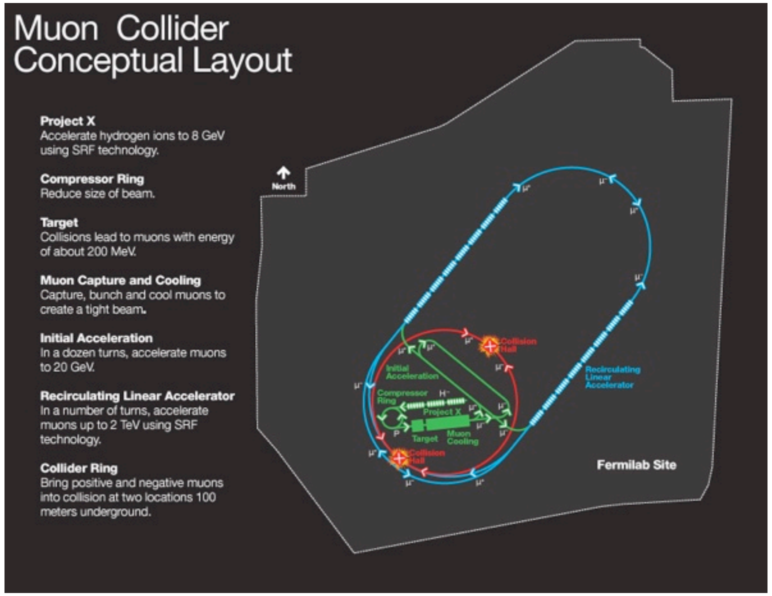
Options for the Next Collider

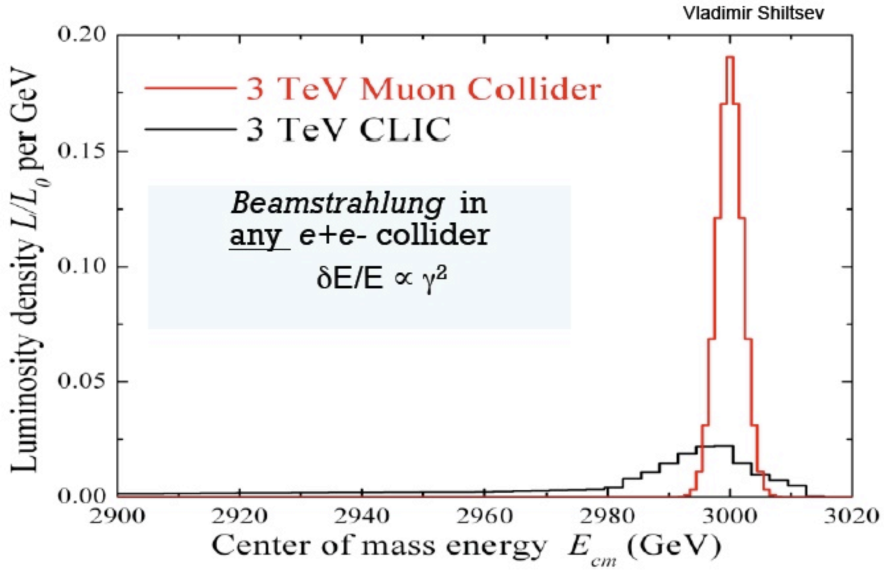
- Existing facilities in 2025:
  - LHC with luminosity or energy upgrade
- Options for next facility:
  - low energy lepton collider:
    ILC (500 GeV) (upgradable) or
    muon collider - Higgs Factory
  - lepton collider in the multi-TeV range:
    CLIC or muon collider
  - hadron collider in hundred TeV range:
    VLHC
- I will argue that a high energy lepton collider will likely be required for full study of Tevascale physics.
- Will explore the Muon Collider option.

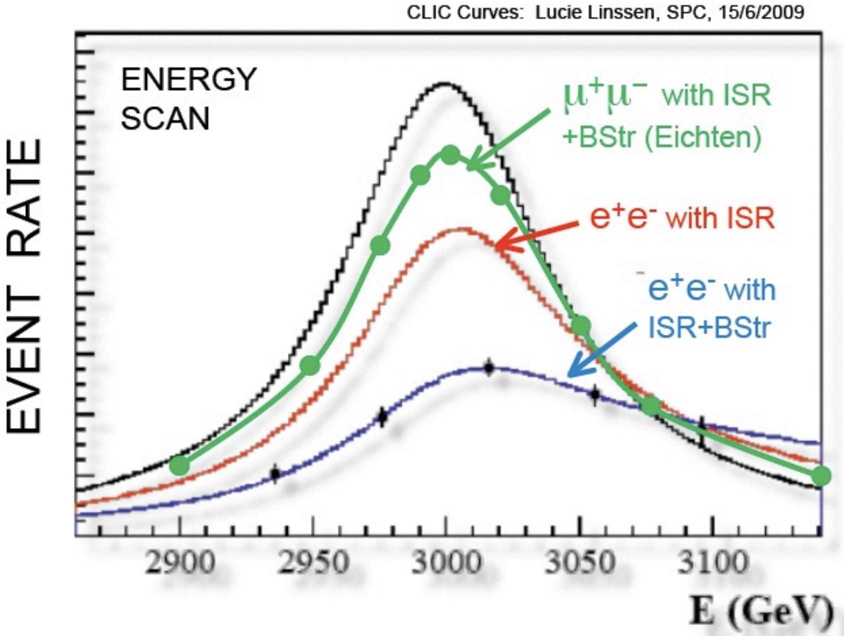


A Muon Collider

- $\mu^+\mu^-$ Collider:
  - Center of Mass energy: 1.5 - 5 TeV (focus 3 TeV)
  - Luminosity > 10^{34} cm^{-2} sec^{-1} (focus 400 fb^{-1} per year)
- Compact facility
- Superb Energy Resolution
  - MC: 95% luminosity in dE/E ~ 0.1%
  - CLIC: 35% luminosity in dE/E ~ 1%

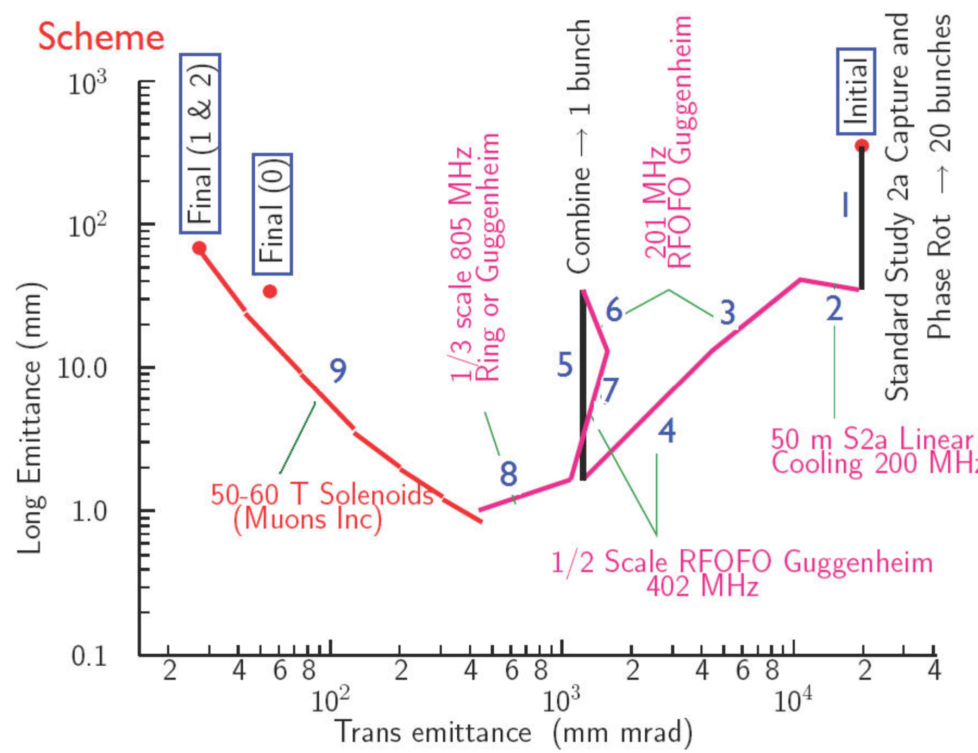






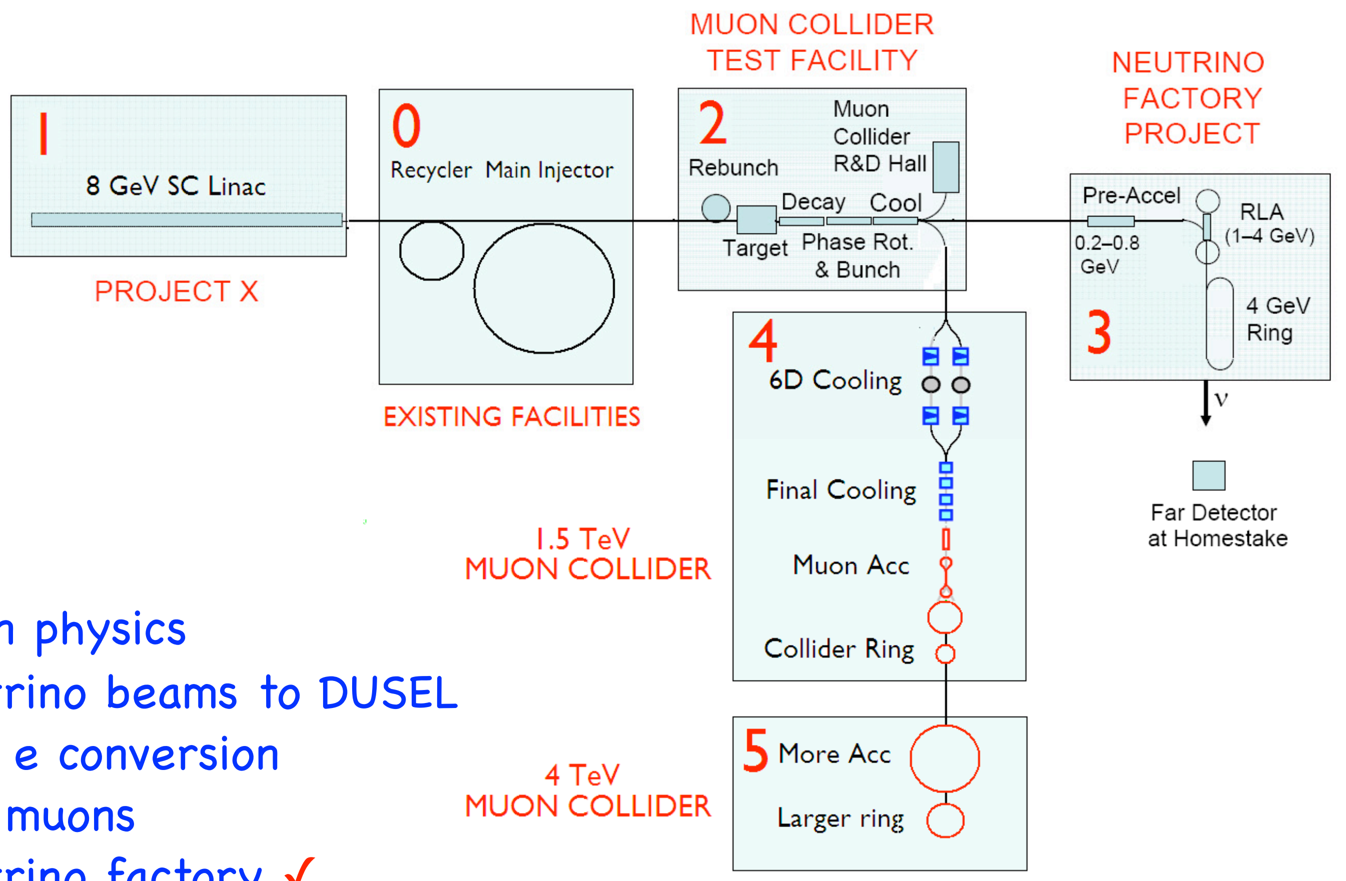
A Muon Collider

- Muons decay:
  - muon lifetime: $(2.197034 \pm 0.000021) \times 10^{-6}$ sec
  - A 3 GeV muon travels 18.7 km in one lifetime
  - A 1.5 TeV muon travels 9,300 km in this time -> More than 2000 turns in final collider ring.
  - The muon beams must be accelerated and cooled in phase space (factor ≈ 10^6) rapidly -> ionization cooling
  - requires a complex cooling scheme
  - The decay products ($\mu^- \to \nu_\mu \bar{\nu}_e e^-$) have high energies. Serious issue for Ecm ≥ 4 TeV



Path to Muon Collider Facility

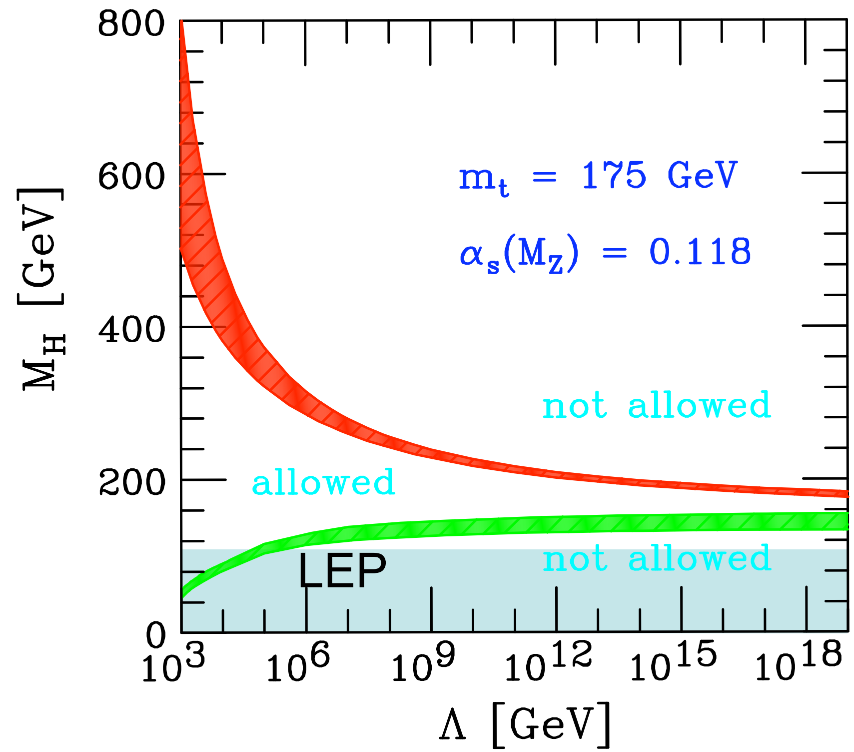
- A flexible scenario with physics at each stage:

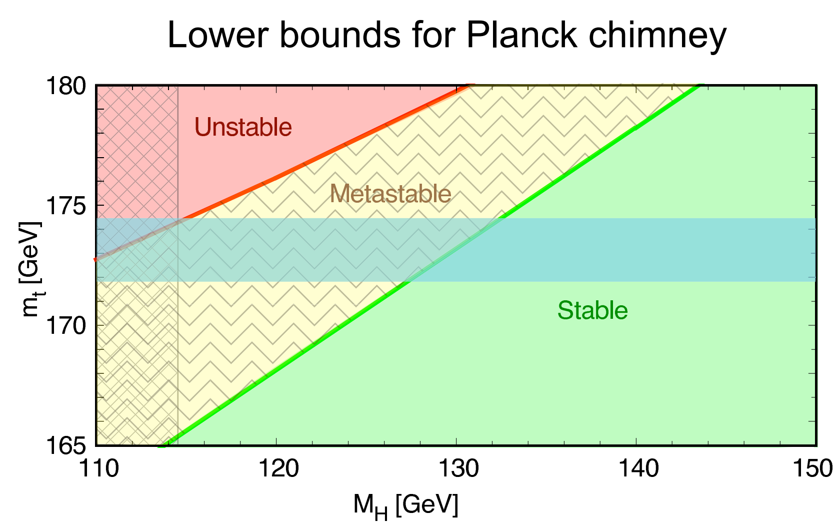


- Kaon physics
- Neutrino beams to DUSEL
- μ -> e conversion
- cold muons
- Neutrino factory ✓
- Muon collider - Higgs factory ✓
- Multi-TeV Muon Collider ✓

The Standard Model Higgs Boson

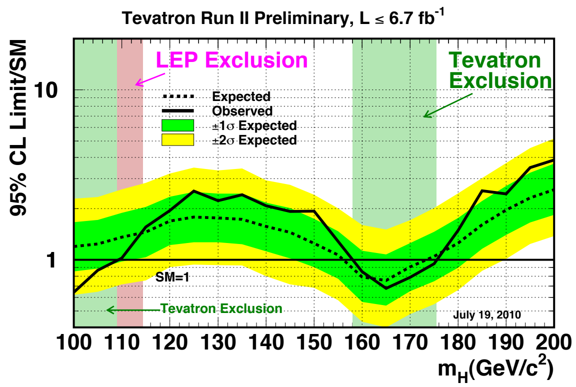
- Theoretical Constraints:
  - The standard model with an elementary Higgs scalar is only self-consistent up to some maximum energy scale (Λ).
  - Upper bound - A large Higgs mass requires a large higgs self-coupling term. This coupling increases with the scale Λ until perturbative theory breaks down.
  - Lower bound - For small Higgs mass, the quantum corrections can lead to vacuum instability.
  - Planck Chimney: SM self-consistent to Planck scale ($\approx 10^{19}$ GeV)

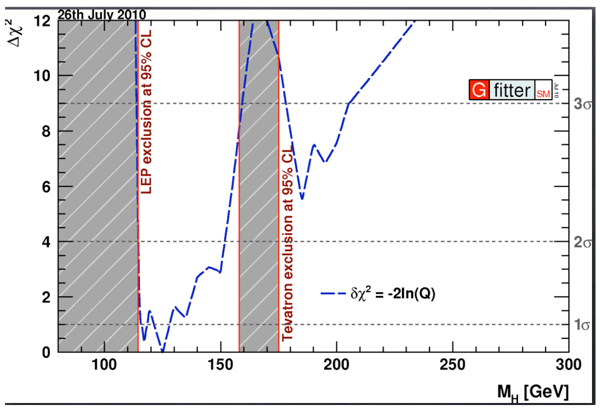




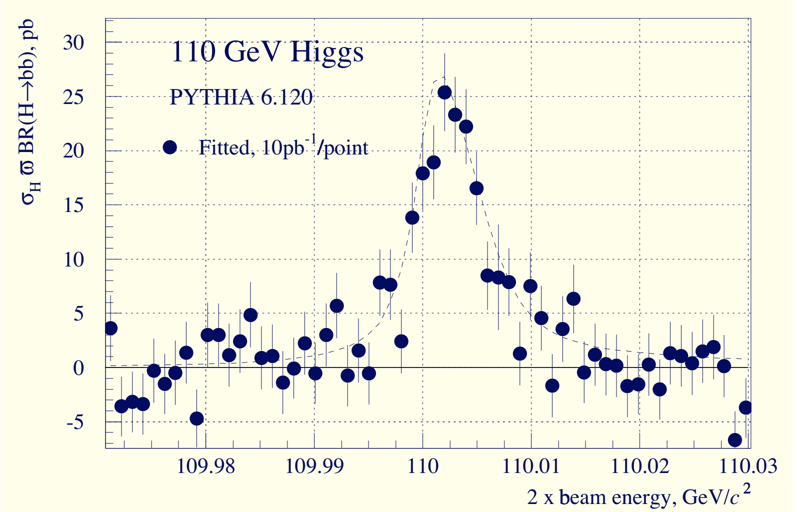
The Standard Model Higgs Boson

- Experimental Constraints:
  - Direct: LEP $m_H > 114.7$ GeV (95% CL)
    CDF/D0 $m_H < 158$ or > 175 GeV (95% CL)
  - Indirect: LEP/SLC $m_H < 190$ GeV (95% CL)
  - Combined all information: Gfitter
    $114.6 < m_H < 151.8$ GeV ($2\,\sigma$)





- 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.
- Only a low energy Muon Collider can directly measure Higgs width.



J. Gunion, MC workshop (2008)

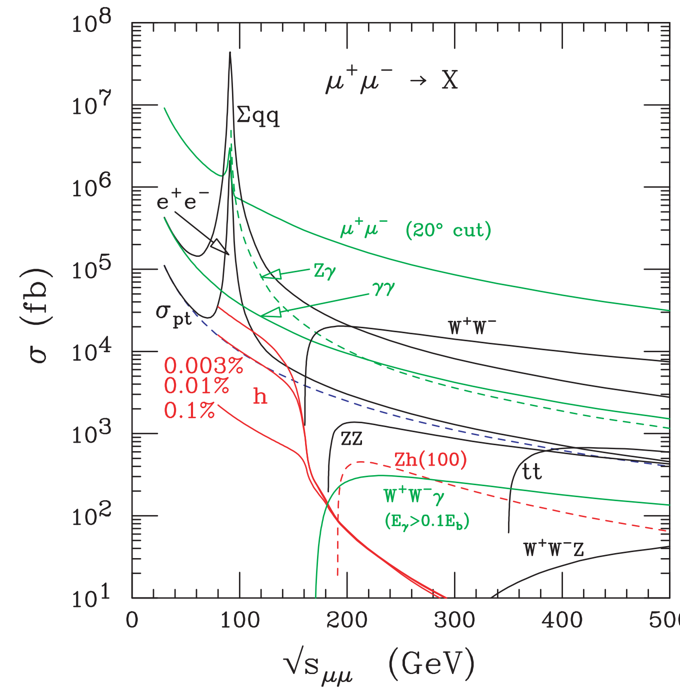
MultiTeV Muon Collider Basics

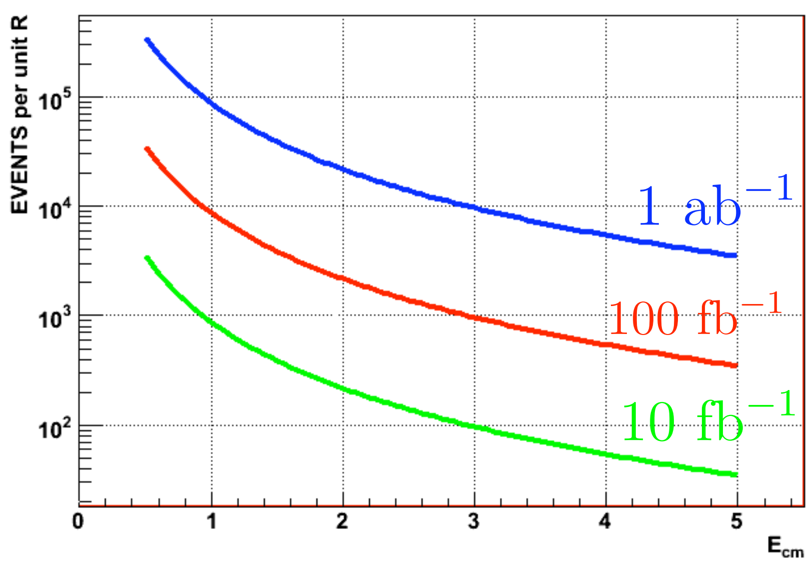
- For $\sqrt{s}$ < 500 GeV
  - SM threshold region: top pairs; W^+W^-; Z^0Z^0; Z^0h; ...
- For $\sqrt{s}$ > 500 GeV
  - For SM pair production (| θ | > 10°)

    R = $\sigma / \sigma_{QED}(\mu^+\mu^- \to e^+e^-)$ ~ flat

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

Standard Model Cross Sections





$$\sqrt{s} = 3.0 \text{ TeV} \quad \mathcal{L} = 10^{34} \text{ cm}^{-2}\text{sec}^{-1} \to 100 \text{ fb}^{-1}\text{year}^{-1}$$

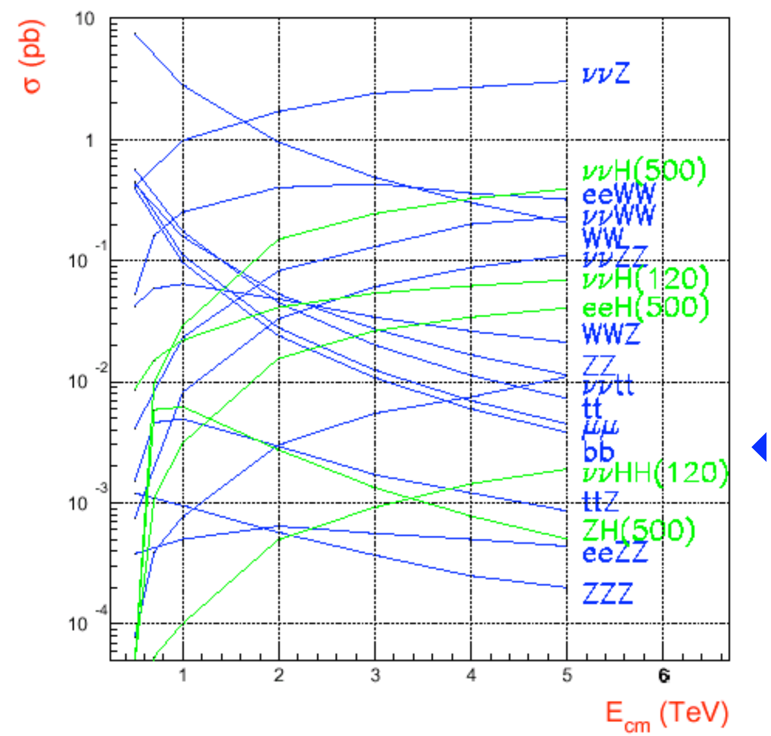
$\Rightarrow$ 965 events/unit of R

Processes with R ≥ 0.1 can be studied

Total - 540 K SM events per year

Fusion Process

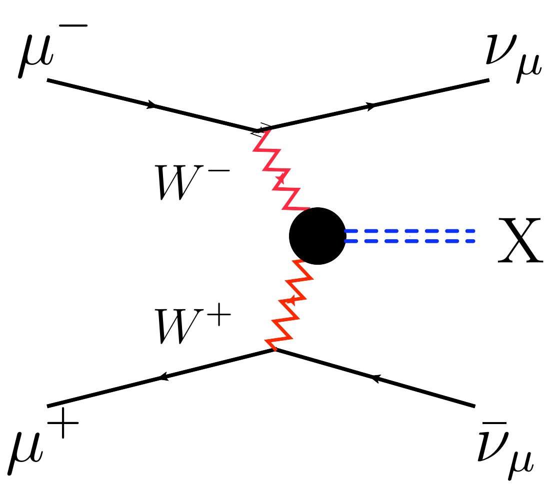
CLIC (or MC e<->μ)



- For √s > 1 TeV - Fusion Processes

  - Large cross sections
  - Increase with s.
  - Important at multi-Tev energies
  - $M_X^2 < s$

  - Backgrounds for SUSY processes
  - t-channel processes sensitive to angular cuts



$$\sigma(s) = C \ln(\frac{s}{M_X^2}) + \ldots$$

- An Electroweak Boson Collider

Minimum Luminosity for Muon Collider

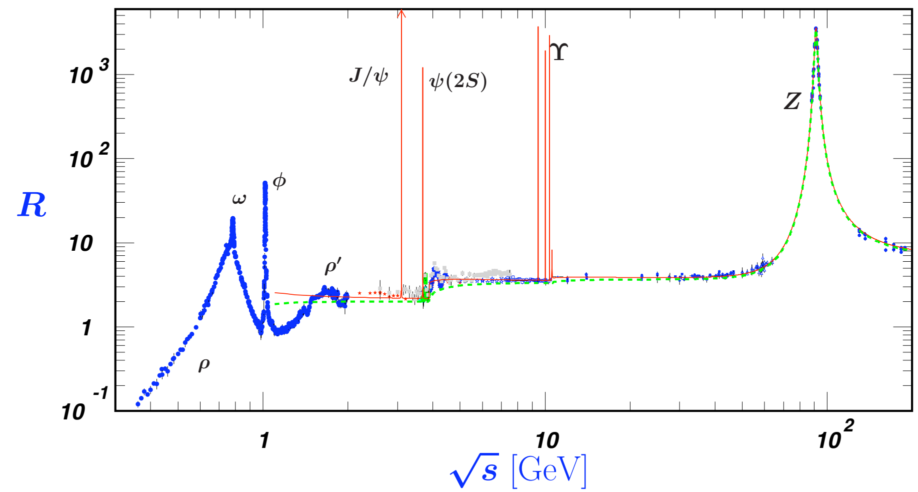
- Universal behavior for s-channel resonance

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

Convolute with beam resolution ΔE.

If $\Delta E \ll \Gamma$

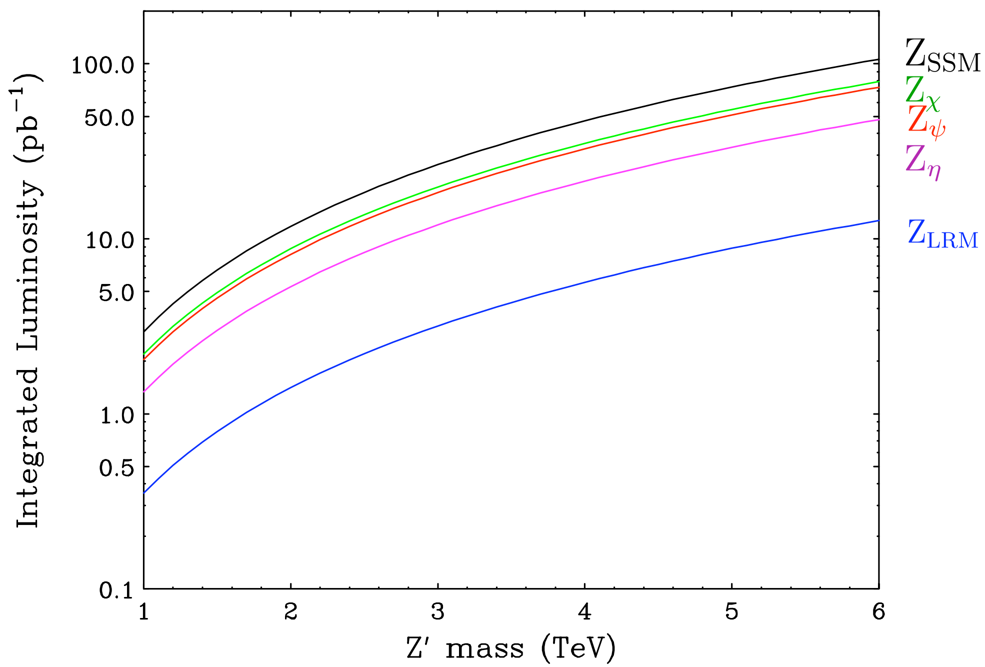
$$R_{\text{peak}} = (2J+1)3\frac{B(\mu^+\mu^-)B(visible)}{\alpha^2_{\text{EM}}}$$



- 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
  - Example - new gauge boson: Z′
    - SSM, E6, LRM
    - 5σ discovery limits: 4-5 TeV at LHC (@ 300 fb^{-1})

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



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

Studying the Higgs Boson

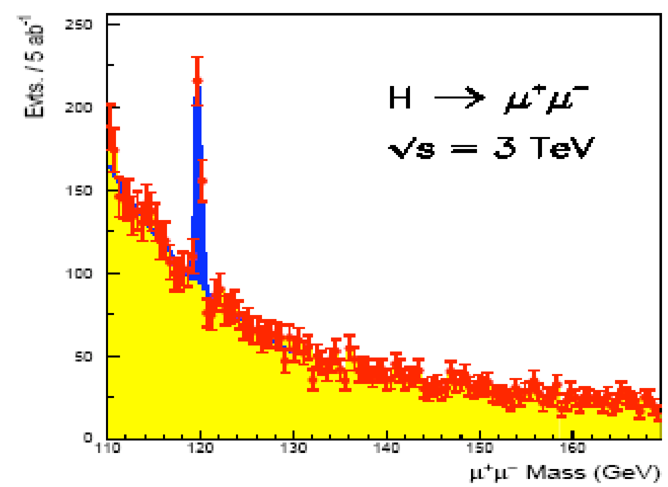
- Theoretical Issues:
  - Higgs boson couplings SM?
  - Scalar interaction self-coupling SM?
  - Any additional scalars? EW doublets, triplets or singlets?
  - Where's the next scale? GUT?

- Various processes available for studying the Higgs at a multi-TeV muon collider
  - Associated production: Zh^0 MC or CLIC:
    - $R \sim 0.12$
    - search for invisible h^0 decays
  - Higgsstrahlung: $t\bar{t}h^0$ needs 10 ab^{-1}
    - $R \sim 0.01$
    - measure top coupling
  - W*W* fusion (m_h = 120 GeV)
    - $\nu_\mu \bar{\nu}_\mu h^0$: $R \sim 1.1\, s \ln(s)$ (s in TeV^2)
    - $\nu_\mu \bar{\nu}_\mu h^0 h^0$: measure Higgs self couplings

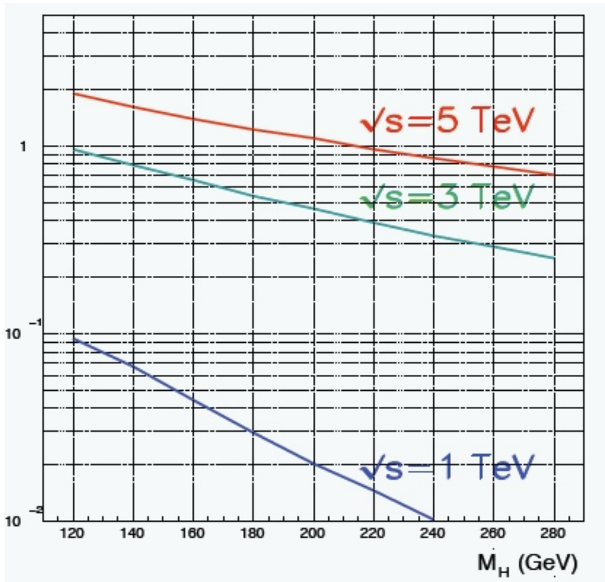
MC or CLIC:

good benchmark process

m(H) = 120 GeV



$\sigma(\mu^+\mu^- \to \nu\bar{\nu} h^0 h^0)$ (fb^{-1})

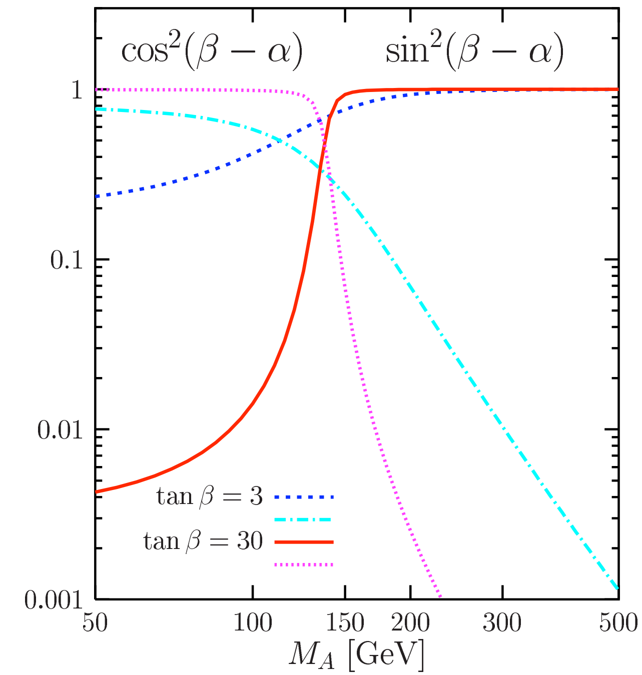


Two Higgs Doublets (MSSM)

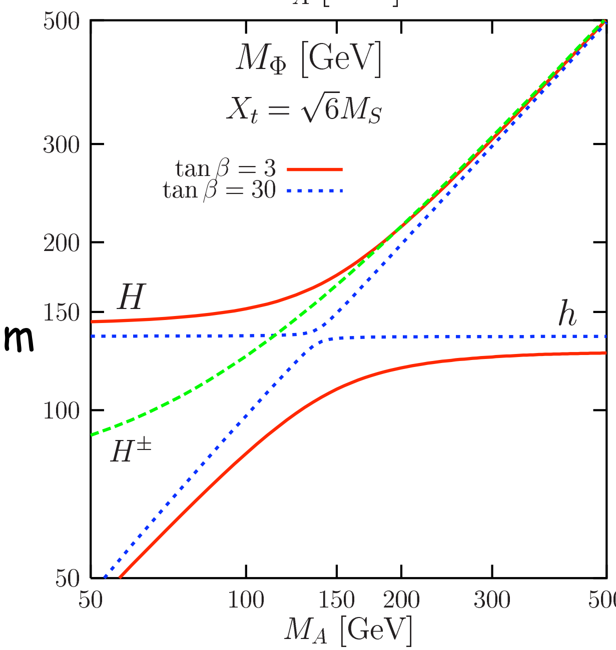
- Five scalar particles: h^0, H^0, A^0, $H^\pm$
- Decay amplitudes depend on two parameters: (α, β)

	$\mu^+\mu^-, b\bar{b}$	$t\bar{t}$	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

$$\tan 2\alpha = \frac{M_A^2 + M_Z^2}{M_A^2 - M_Z^2} \tan 2\beta.$$



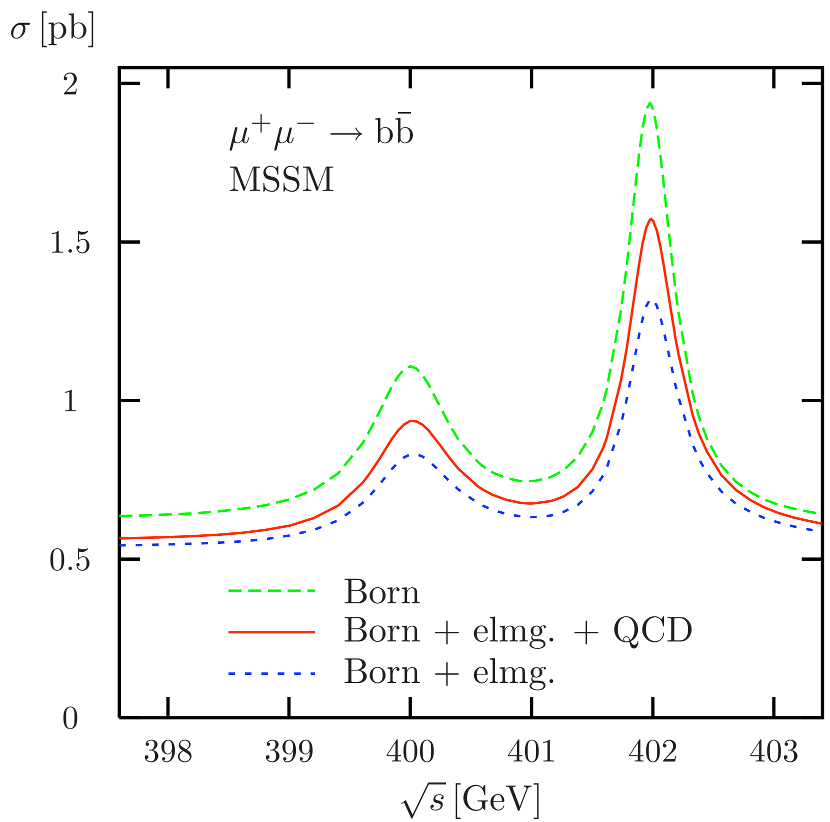
- decoupling limit $m_{A^0} \gg m_{Z^0}$:
  - h^0 couplings close to SM values
  - H^0, $H^\pm$ and A^0 nearly degenerate in mass
  - H^0 small couplings to VV, large couplings to ZA^0
  - For large $\tan\beta$, H^0 and A^0 couplings to charged leptons and bottom quarks enhanced by $\tan\beta$. Couplings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



Two Higgs Doublets (MSSM)

- 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.

good benchmark process



Dittmaier and Kaiser [hep-ph/0203120]

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	325
Z′ (SM)	923
W′ (SM)	860

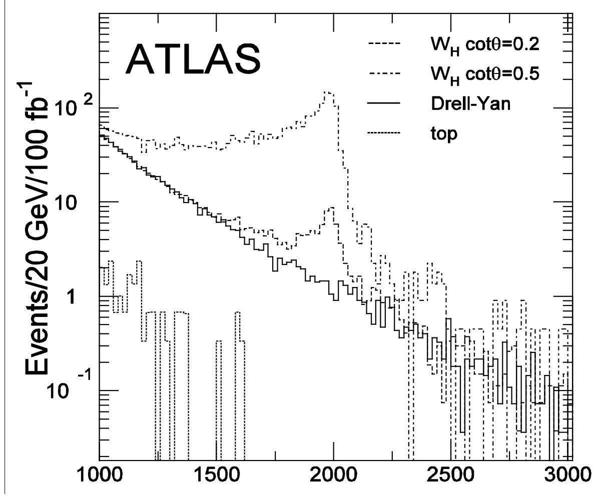
- Littlest Higgs Model: good benchmark processes

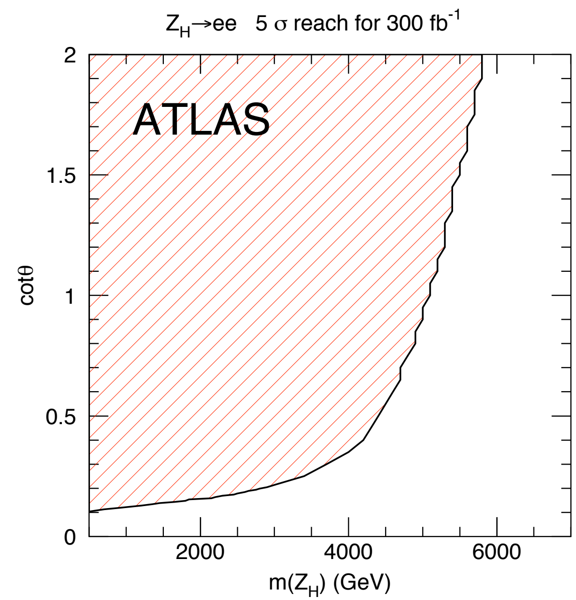
  charge (2/3) quark T (EW singlet),
  new W, Z, and A gauge bosons, Higgs triplet

  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

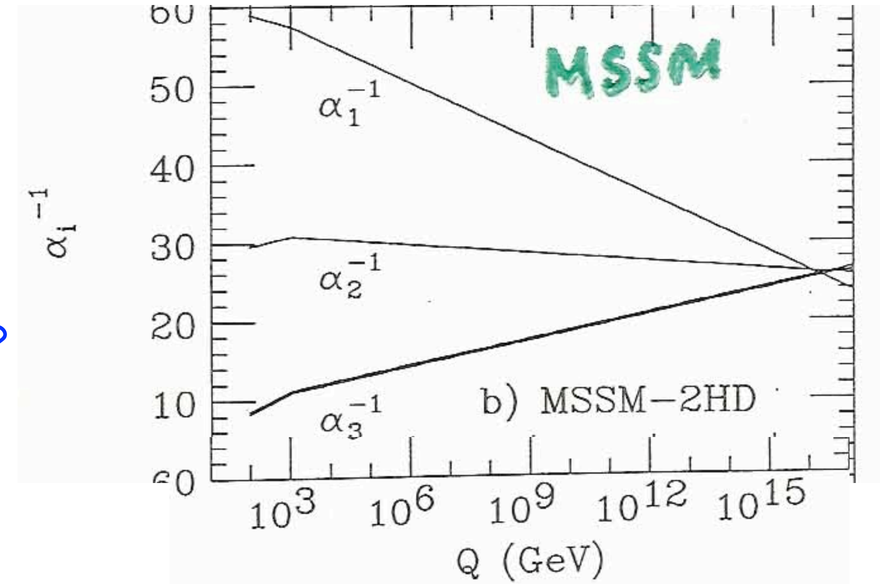
ATLAS study LHC [hep-ph/0402037]





Supersymmetry

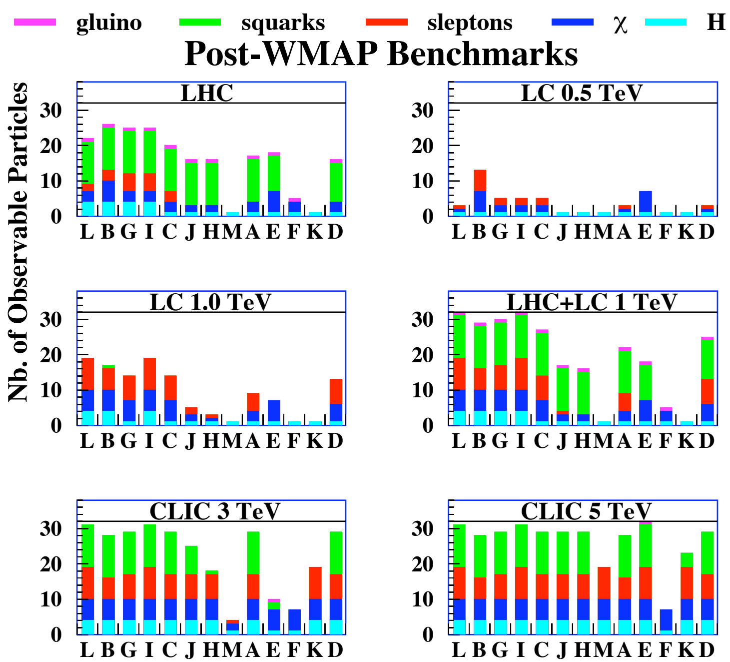
- Solves the Naturalness Problem: Scalars associated with fermions. Higgs mass associated with SUSY breaking scale.
- Couplings of sparticles determined by symmetry. Masses depend on SUSY breaking mechanism.
- If discovered at LHC ->
  - What is the spectrum of superpartner masses?
  - Dark matter candidates?
  - 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 mass scale at which SUSY is restored?
  - What is the mechanism of SUSY breaking?



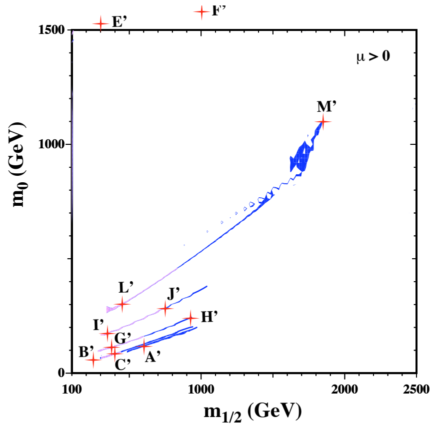
- cMSSM [Constrained Minimal Supersymmetric Standard Model]
  - Five parameters: m_0, $m_{1/2}$, $\tan\beta$, A/m_0, sign(μ)
  - Experimental constraints
    - Direct limit (LEP, CDF, Dzero): $m_{h^0}, m_{\chi^+}, m_{\tilde{t}}, \ldots$
    - Electroweak precision observables (EWPO): $M_W^2, \sin^2\theta_{sw}, (g-2)_\mu, \ldots$
    - B physics observables (BPO): $b \to s + \gamma,\ \mathrm{BR}(B_s \to \mu^+\mu^-), \ldots$
    - Cold dark matter (CDM): $\Omega_{DM} = .23 \pm .04$
  - Allowed regions are narrow filaments in parameter space

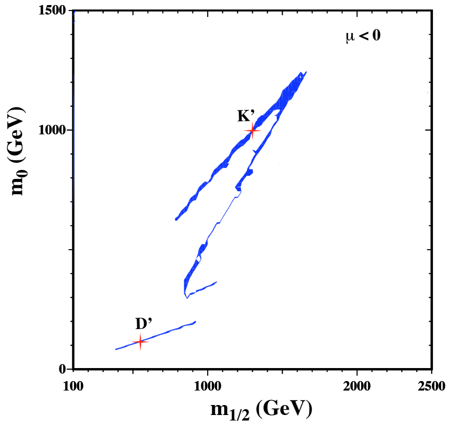
Supersymmetry

- The combination of the LHC and a multiTeV lepton collider is required to fully study the SUSY spectrum.
  - cMSSM 2004 CLIC study SUSY reach



Allowed regions and sample points





Similar Conclusion for MC

Anupama Atre, Low Emittance Muon Collider Workshop, Fermilab, April 2008

  - Alternate supersymmetry breaking schemes (mGMSB, mAMSB) also require multiTeV lepton collider.

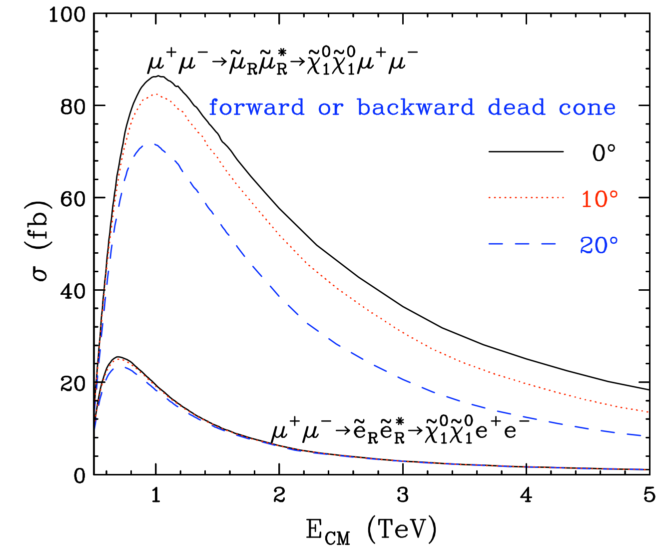
S. Heinemeyer, X. Miao, S. Su, G. Wieglein [arXiv:0805.2359]

- Supersymmetry provides a strong case for a multiTeV muon collider

Example Process at Muon Collider

- $\mu^+\mu^- \to \tilde{e}_1^+\tilde{e}_1^- \to \tilde{\chi}_1^0\tilde{\chi}_1^0 e^+e^-$
  - Angular cut at 20° from beam direction:
    - 50% reduction for smuon pairs
    - 20% reduction for selectron pairs
  - Mass measurements using edge method better for MC than CLIC:

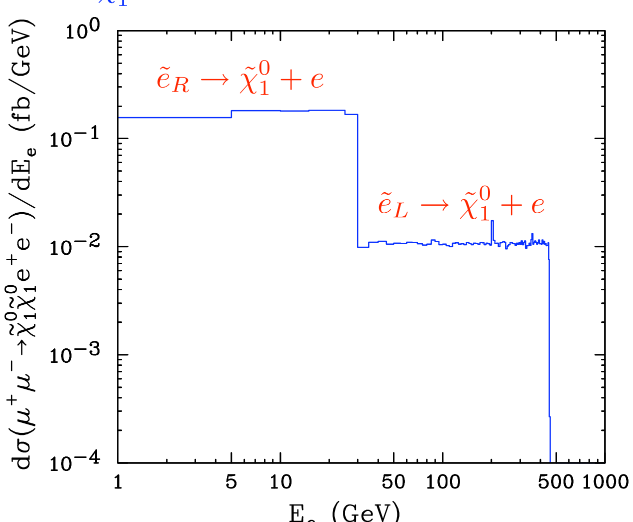
$$E_{\max/\min} = \frac{1}{2} M_{\tilde{e}} \left[1 - \frac{M^2_{\tilde{\chi}_1^0}}{M^2_{\tilde{e}}} \right] \gamma(1 \pm \beta)$$



Effect of beamstrahlung

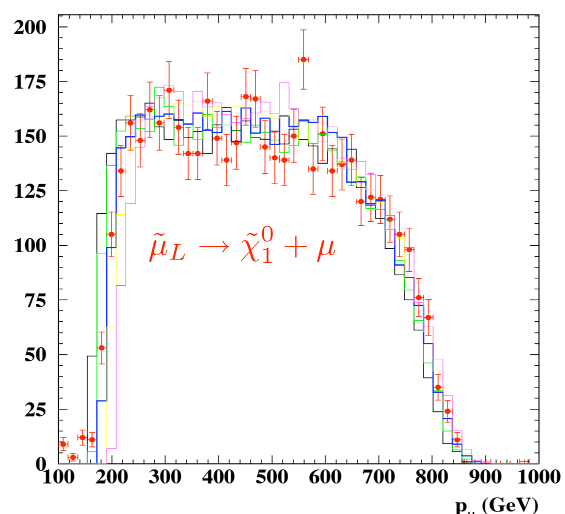
Kong, Winter (MC)

$m_{\tilde{\chi}_1^0} = 212;\ m_{\tilde{e}_R} = 222;\ m_{\tilde{e}_L} = 374$ GeV

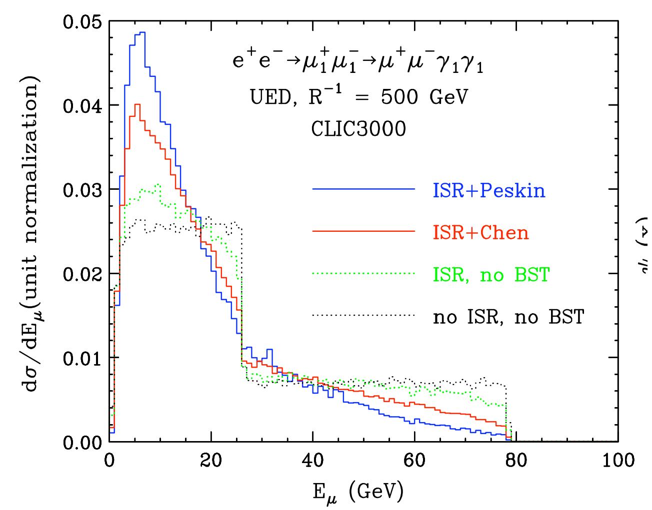


CLIC report (2004)

$m_{\tilde{\chi}_1^0} = 660$ GeV; $m_{\tilde{\mu}_L} = 1150$ GeV



Datta, Kong and Matchev [arXiv:hep-ph/0508161]



New Strong Dynamics

- Solves the Naturalness Problem: Electroweak Symmetry Breaking is generated dynamically at a nearby scale. May or may not be a light Higgs boson.

Theoretical issues

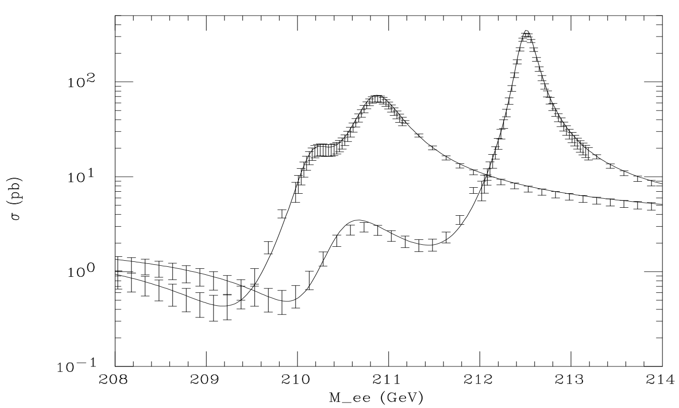
- What is the spectrum of low-lying states?
- What is the ultraviolet completion? Gauge group? Fermion representations?
- What is the energy scale of the new dynamics?
- Any new insight into quark and/or lepton flavor mixing and CP violation?
- ...

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

For example with a new strong interaction at TeV scale expect:

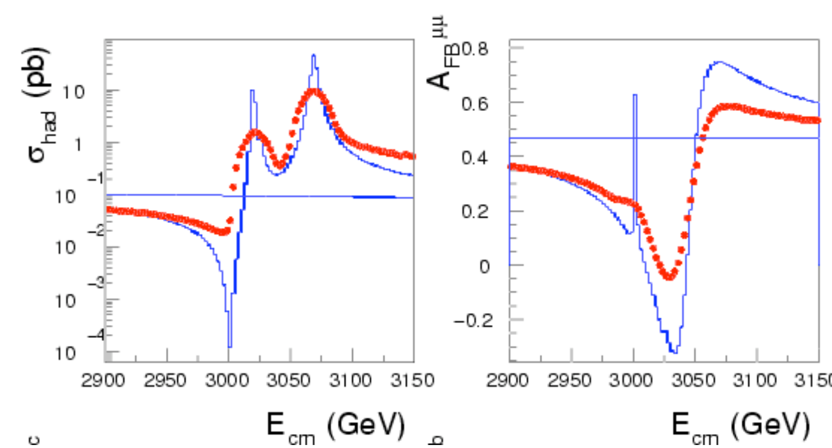
- Technipions - s channel production (Higgs like)
- Technirhos - Nearby resonances (ρ_T,ω_T)- need fine energy resolution of muon collider.

Eichten, Lane, Womersley PRL 80, 5489 (1998)
$M(\rho_T)$ = 210 GeV $M(\omega_T)$ = 211, 209 GeV
MC 40 steps (total 1 fb^{-1})



good benchmark processes

CLIC - D-BESS model (resolution 13 GeV)



Contact Interactions

- Solves the Naturalness Problem: The SM is only an effective theory valid below the compositeness scale.

  - New interactions (at scales not directly accessible) give rise to contact interactions.

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

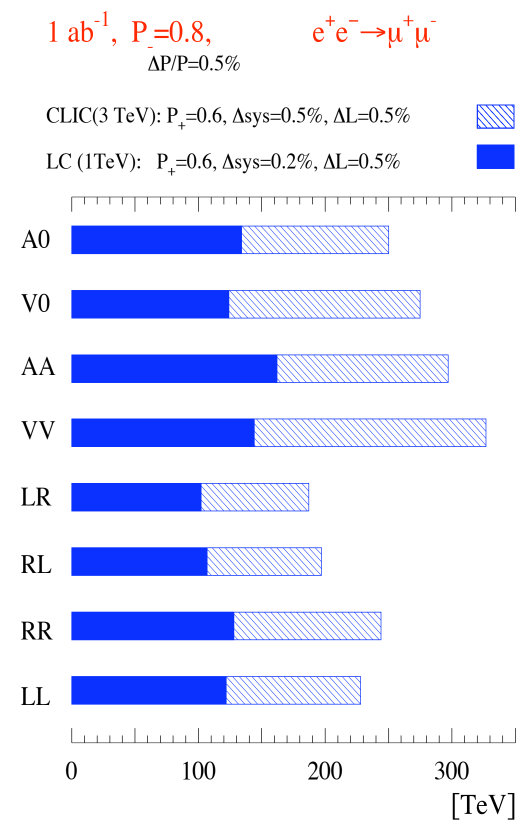
  - Muon collider is sensitive to contact interaction scales over 200 TeV as is CLIC.
  - Cuts on forward angles for a muon collider not an issue.
  - Polarization useful to disentangle the chiral structure of the interaction. (CLIC)

good benchmark process

Muon Collider Study

E.Eichten, S.~Keller, [arXiv:hep-ph/9801258]

CLIC Study



Extra Dimensions

- Solves the Naturalness Problem: The effective GUT scale is moved closer.

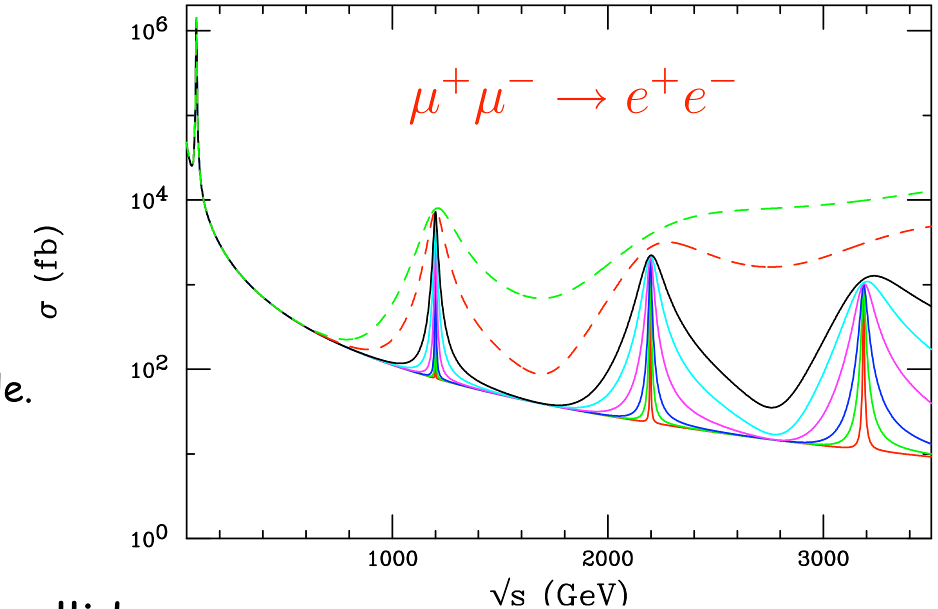
Theoretical issues

- 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.

possible KK modes



LHC discovery - Detailed study at a muon collider

Summary of Physics Potential

- A multiTeV lepton collider is required for full coverage of Terascale physics.
- 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 staged Muon Collider can provide a Neutrino Factory to fully disentangle neutrino physics.
- A detailed study of physics case for 1.5-4.0 TeV muon collider has begun. Goals:
  - Identify benchmark processes: pair production (slepton; new fermion), Z′ pole studies, h^0 plus missing energy, resolving nearby states (H^0-A^0; ρ_T-ω^0_T), ...
  - Dependence on initial beam [electron/muon, polarization and beam energy spread] as well as luminosity to be considered.
  - Estimates of collision point environment and detector parameters needed.
  - Must present a compelling case even after ten years of running at the LHC.

Backup Slides

Fine tuning problems in the cMSSM

M(h^0) > 113.8 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

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

with measured top mass and tan β 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, mGMSB, mAMSB Studies

- More generally, full coverage likely requires a multi TeV lepton collider

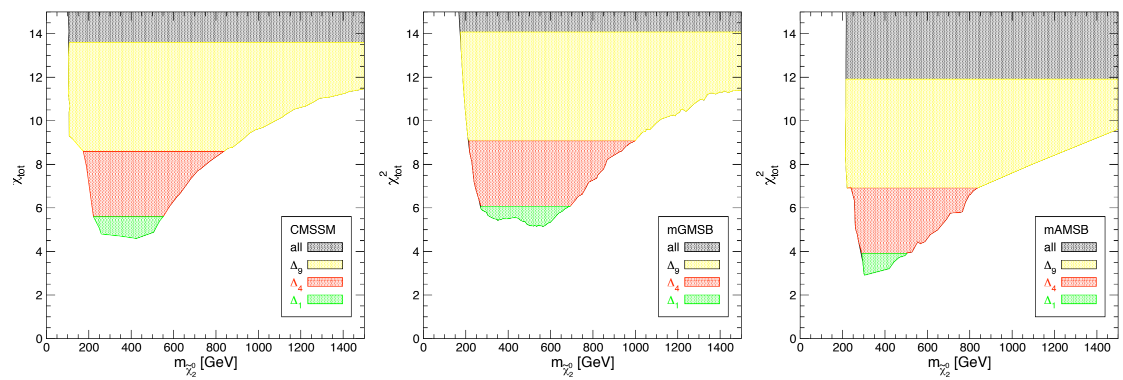
S. Heinemeyer, X. Miao, S. Su, G. Wieglein [arXiv:0805.2359]
(using only EWPO, BPO and LEP)

Second lightest neutralino:

m($\tilde{\chi}_2$) < 900 GeV for $\Delta\chi^2 < 4$
Heavy for LHC - possibly in decay chain ?
Lepton collider: $\chi_2^0 \to \chi_1^0 + X$

Second lightest neutralino

CMSSM mGMSB mAMSB

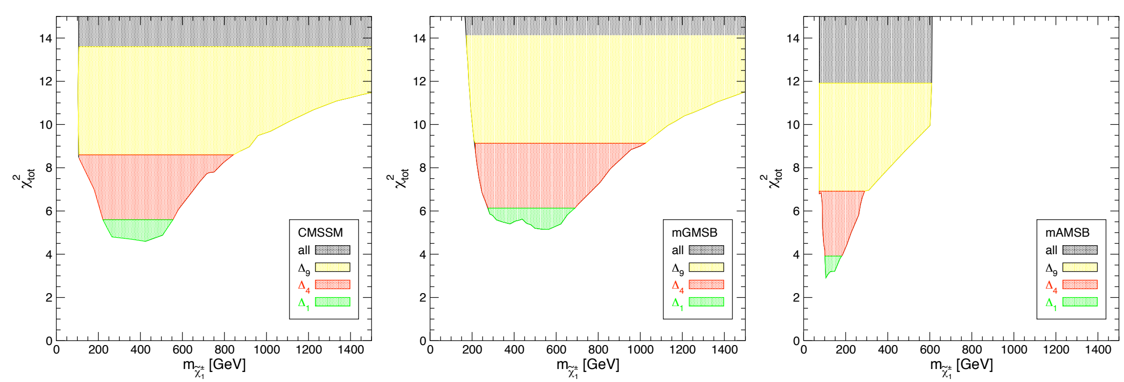


Lightest chargino:

m($\tilde{\chi}_1^+$) < 800, 900, 300 GeV for $\Delta\chi^2 < 4$
Heavy for LHC - possibly in decay chain ?
Lepton collider: Observable at ILC for mAMSB

Lightest chargino

CMSSM mGMSB mAMSB



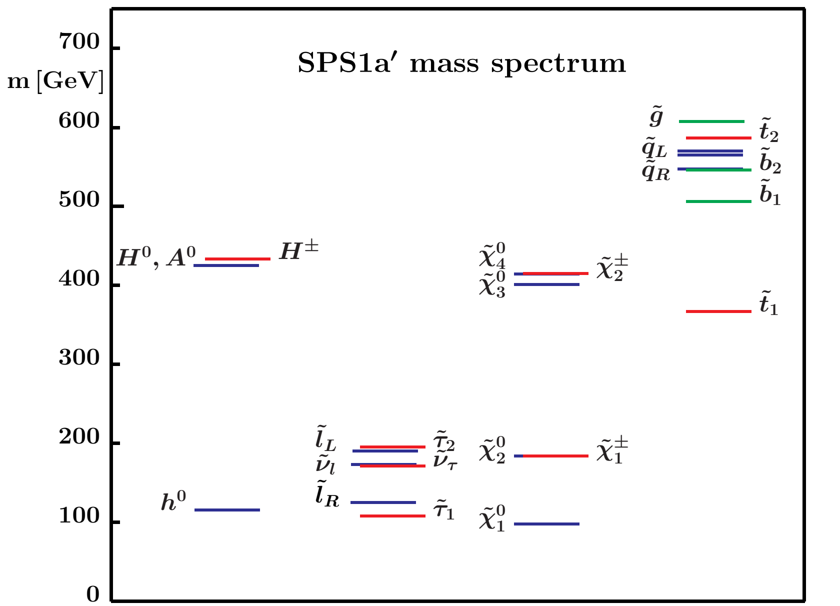
Lightest stop, sbottom and gluino:

m($\tilde{t}_1$) > 500 for $\Delta\chi^2 < 4$
Easy for LHC up to 2 TeV
Lepton collider: Detailed study?

Modifying cMSSM

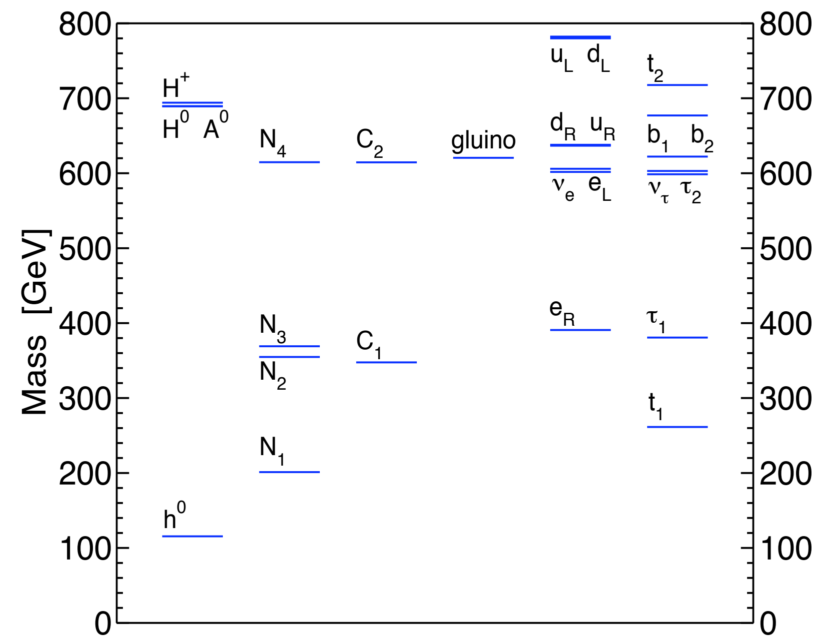
- Fine tuning problems in the cMSSM - Allow non universal $m_{1/2}$

cMSSM ILC Benchmark



Compressed SUSY

S. Martin [PR D75:115005,2007]



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

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

Challenges Ahead

- Many technical challenges exist. Two of the most difficult are:
  - 6D cooling - needed to obtain sufficient luminosity for physics.
  - The interaction region and detectors have to be designed to do physics with the background environment generated by nearby muon decays.
- Many practical issues also need consideration.
  - Cost of building a multi-TeV muon collider? - Staging likely necessary and desirable
  - How to deal with the high energy neutrinos from muon decay? - Limiting factor for energy reach of the Muon Collider?
- However a multiTeV Muon Collider would address the most fundamental issues in our field. It would allow a detailed look at the mechanism of EW symmetry breaking and likely provide clues to the origin of fermion masses.
- This extraordinary opportunity justifies the serious research efforts presently underway into the feasibility of such a collider.