Physics of a TeV Lepton Collider

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- Physics Landscape
- The LHC Era Begins
- Lepton Collider Physics Opportunities
- Summary and To Do List

Physics Landscape

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

$\psi \to \exp\{iQ\}\,\psi$

$L = \bar{\psi}(-i\,\gamma\cdot\partial + M)\,\psi$

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

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

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. Confirmed by Lattice QCD
  - 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 EW 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

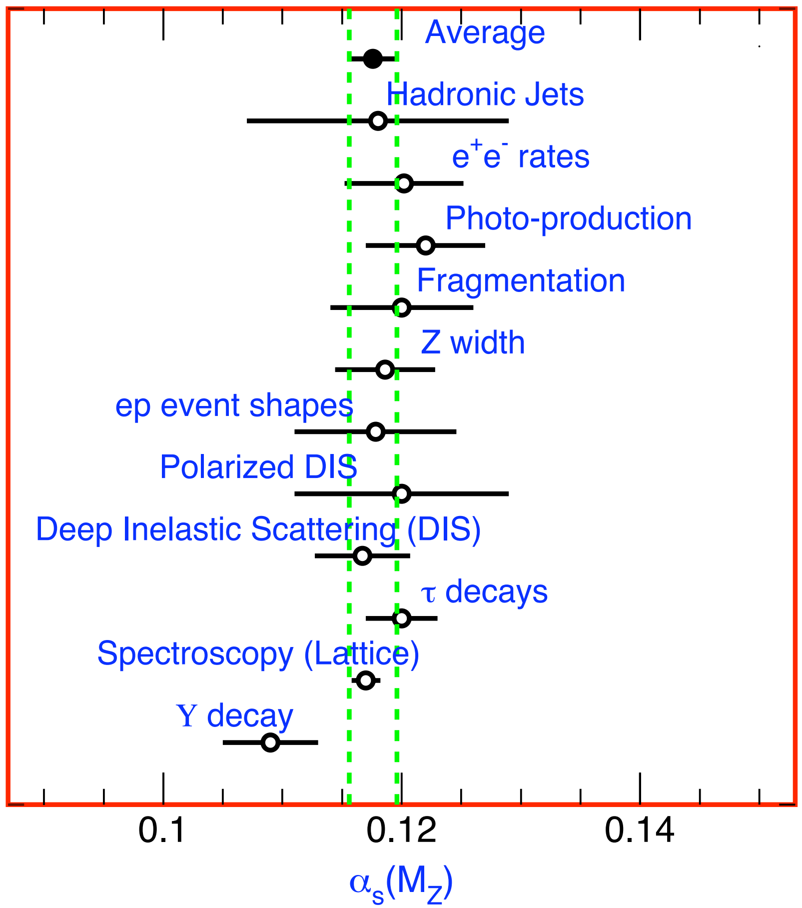
- Electroweak Symmetry Breaking (EWSB)
  - Introduce a $SU(2)_L$ complex doublet scalar field Φ, with self interactions
    - $\mu^2 (\Phi^\dagger\Phi) + \lambda (\Phi^\dagger\Phi)^2$ with EWSB -> $< \Phi^\dagger\Phi > = v^2 = -\mu^2 / \lambda$;
      one physical Higgs boson (mass $m_H^2 = 2\lambda v^2$) $\sqrt{2}\, v = (G_F\sqrt{2})^{-1/2} \approx 247$ GeV
  - 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



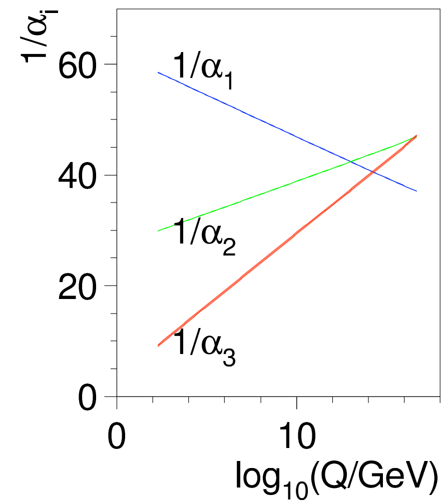
EW

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
$\Gamma(\text{had})$ [GeV]	1.7444 ± 0.0020	1.7434 ± 0.0010	—
$\Gamma(\text{inv})$ [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
$Q_W(\text{Cs})$	-72.62 ± 0.46	-73.17 ± 0.03	1.2
$Q_W(\text{Tl})$	-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

June 12, 2007 11:05

Physics Landscape

- The Standard Model is incomplete
  - dark matter; neutrino masses and mixing -> new fields or interactions;
  - baryon asymmetry in the universe -> more CP violation
  - gauge unification -> new interactions;
  - gravity: strings and extra dimensions



- Theoretical questions
  - Scalar sector problematic:
    - $\mu^2 (\Phi^\dagger\Phi) + \lambda (\Phi^\dagger\Phi)^2 + \Gamma_{ij}\psi_{iL}^\dagger\psi_{jR}\Phi$ + h.c.

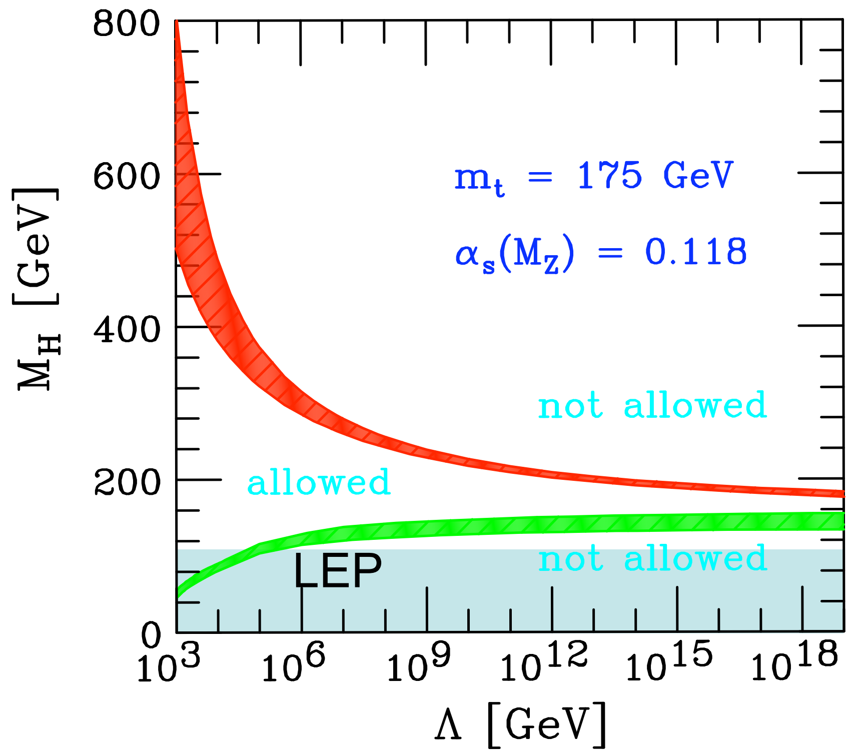
$m_H^2/M^2_{planck} \approx 10^{-34}$
Hierarchy problem

vacuum
stability

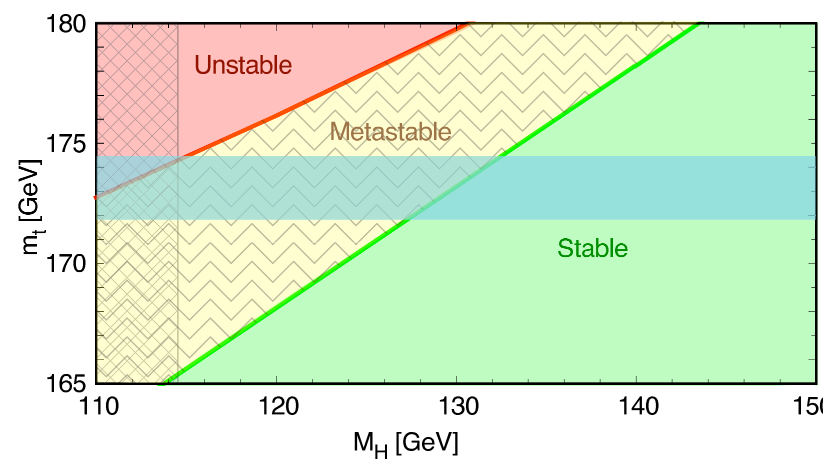
large range of
fermion masses

SM Scalar Sector

- 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.
  - Origin of 1 TeV Unitarity bound
    - Lee, Quigg and Thacker, PR D16, 1519 (1977)
    - Later Lattice studies
  - 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) ~ (130-190) GeV
- The SM Higgs boson or new physics must appear by the TeV scale (Terascale).



Lower bounds for Planck chimney



SM Scalar Sector

- Concept of naturalness.
  - K. Wilson, G. 't Hooft
  - A theory [L(μ)] is natural at scale μ $\Leftrightarrow$ for any small dimensionless parameter λ (e.q. m/μ) in L(μ) the limit λ -> 0 enhances the symmetries of L(μ)
- The SM Higgs boson is unnatural. (m_H^2/μ^2)
- Three potential solutions:
  - scalars not elementary
    - New strong dynamics (TC, walking TC, little Hggs, top color, ...)
  - fermion masses are natural
    - Symmetry coupling fermions and bosons (SUSY)
  - no large gap in scales (Extra Dimensions)
- Quest for the "natural" theory to replace the SM has preoccupied theorists since the early 80's

G. 't Hooft in Proceedings of Recent Developments in Gauge Theories, Cargese, France (1980)

NATURALNESS, CHIRAL SYMMETRY, AND SPONTANEOUS CHIRAL SYMMETRY BREAKING

G. 't Hooft

Institute for Theoretical Fysics

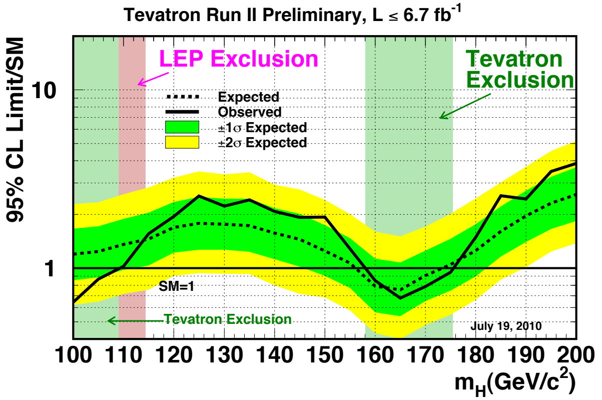
Utrecht, The Netherlands

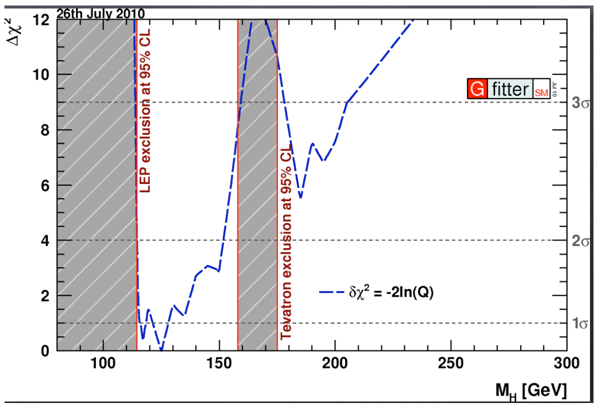
ABSTRACT

A properly called "naturalness" is imposed on gauge theories. It is an order-of-magnitude restriction that must hold at all energy scales μ. To construct models with complete naturalness for elementary particles one needs more types of confining gauge theories besides quantum chromodynamics. We propose a search

Present Status

- Standard model continued to fit the data in this period
  - Top discovery at CDF/D0 (1995): m(top) = 172.70±0.63± 0.89 GeV
  - Precision $W^{\pm}$, Z^0 mass and width measurements
  - CKM parameters determined
- Experimental constraints tighten allowed mass range for standard model Higgs boson
  - Direct: LEP $m_H > 114.7$ GeV (95% CL)
    CDF/D0 $m_H < 158$ or > 173 GeV (95% CL)
  - Indirect: LEP/SLC $m_H < 190$ GeV (95% CL)
  - Combined all information: Gfitter
    $114.6 < m_H < 151.8$ GeV ($2\,\sigma$)
- New elements
  - Discovery of neutrino masses and mixing
  - Dark matter/dark energy observations

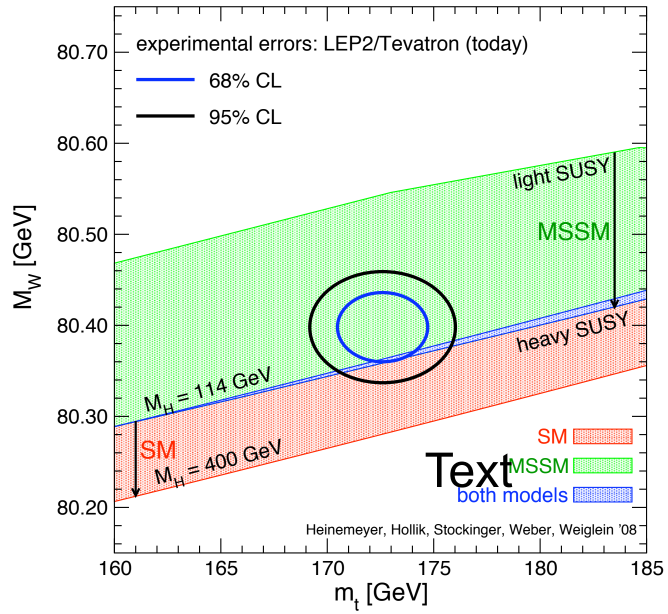




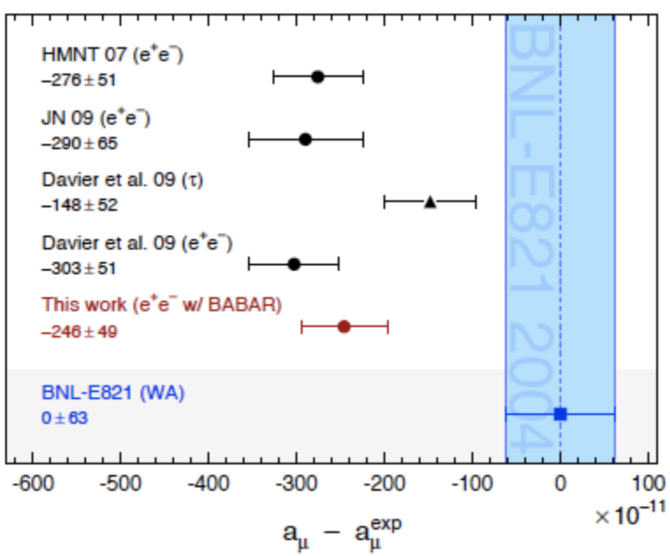
Present Status

- A few experimental hints for new physics

Higgs



muon (g-2)

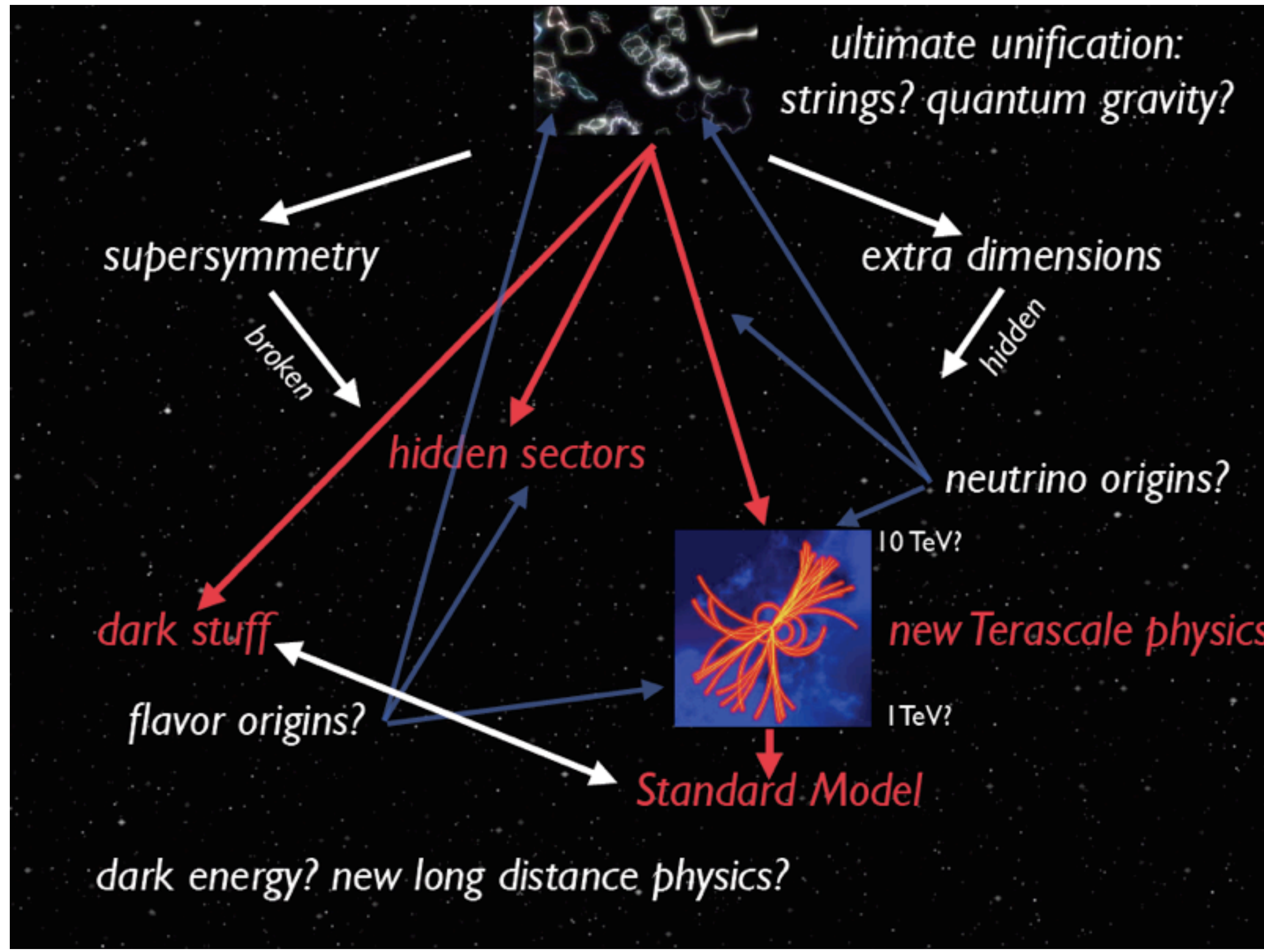


Present Status

- theorists' have generated grand visions

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

What is the origin and scale of fermion masses?



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

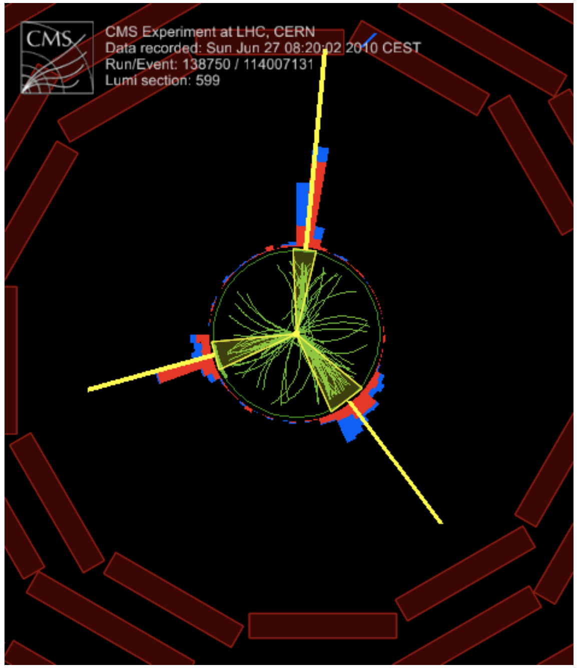
The LHC Era Begins

- LHC -- Online

$\sqrt{s}$ = 7.0 TeV p p (2011-2012)
$\int L\,dt > 1\ fb^{-1}$ now

$\sqrt{s}$ = 14 TeV p p (2014)
Luminosity - $10^{34}\ cm^{-2}\ sec^{-1}$

ATLAS, CMS, LHCb, ALICE



- Standard Model Higgs

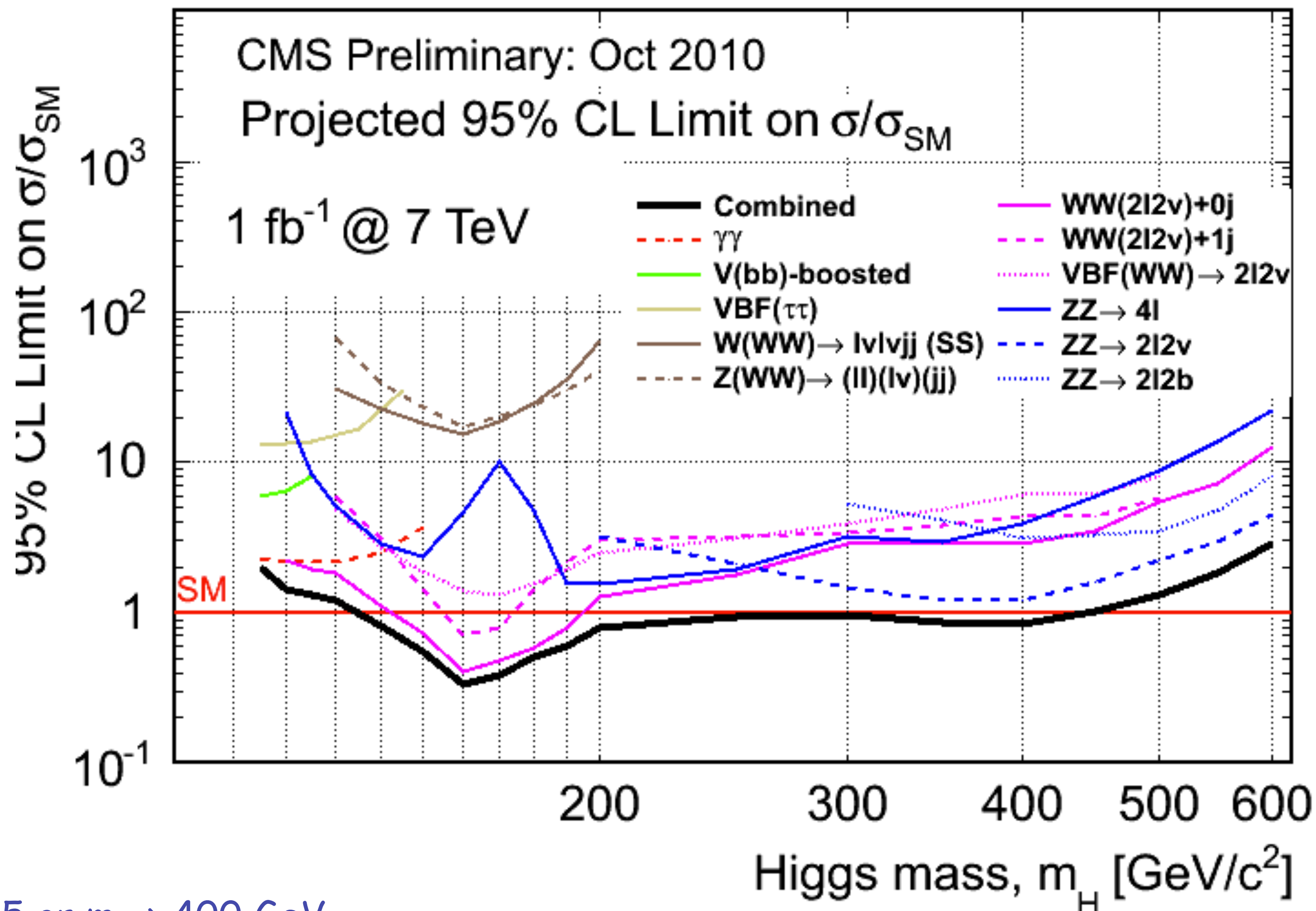
  - LHC will discover the SM Higgs. If Higgs mass is not in the Planck chimney (130-190), new physics "nearby".

  - 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 LHC Era Begins

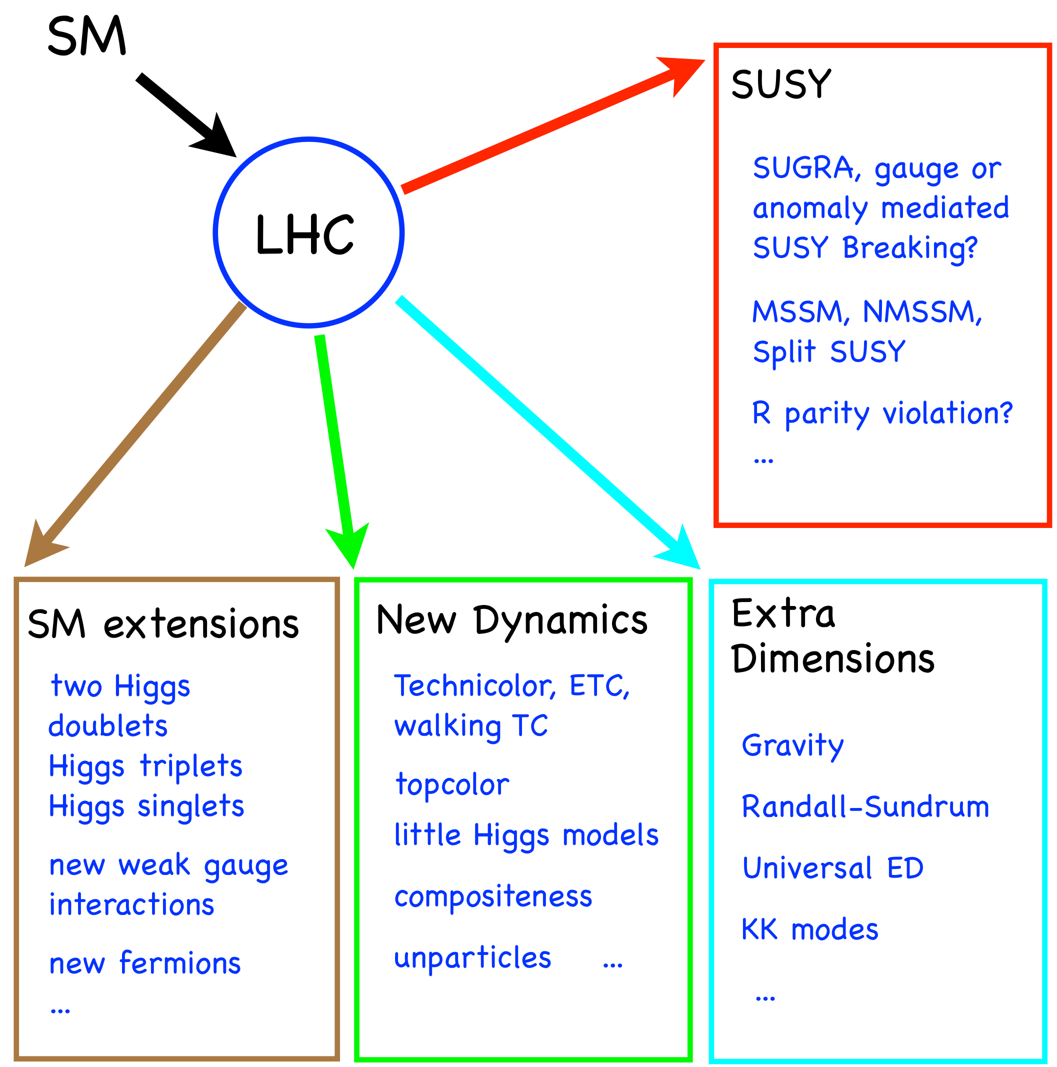
- CMS SM Higgs expected limits (1 fb^{-1})



  - $m_H < 135$ or $m_H > 400$ GeV

The LHC Era Begins

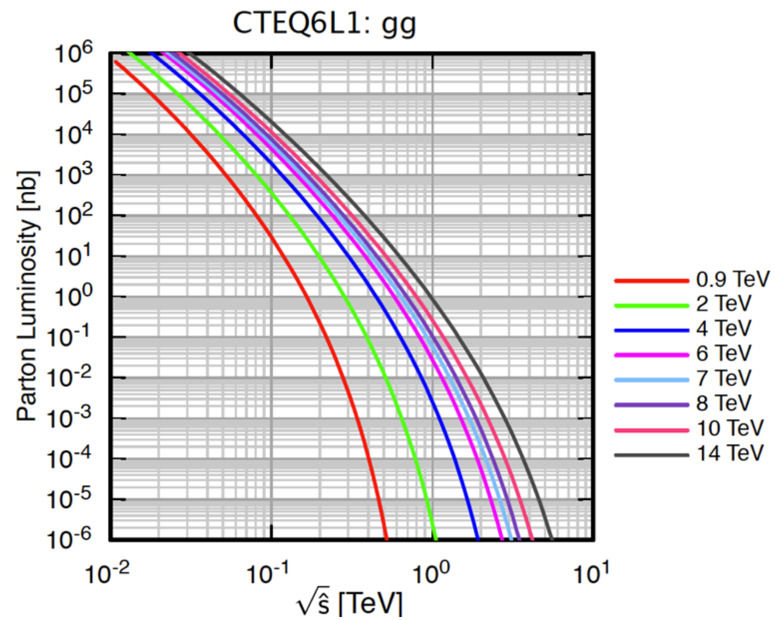
- New Physics
  - Each path (SM-like, SUSY, New Dynamics and Extra Dimensions) represents a different mechanism for Electroweak Symmetry Breaking
  - There is great excitement in the field, that after more than 25 years of theoretical speculation we will have an answer.
  - We expect the results from the LHC will determine the mechanism of EWSB.
  - Will collapse the options laid out in the intervening 25 years.



The LHC Era Begins

- ATLAS Limits on New Physics
  - https://twiki.cern.ch/twiki/pub/AtlasPublic/CombinedSummaryPlots/AtlasSearches_6Jun11.pdf
  - based on integrated luminosities 31-236 pb^{-1}
  - already beginning to constrain new physics possibilities

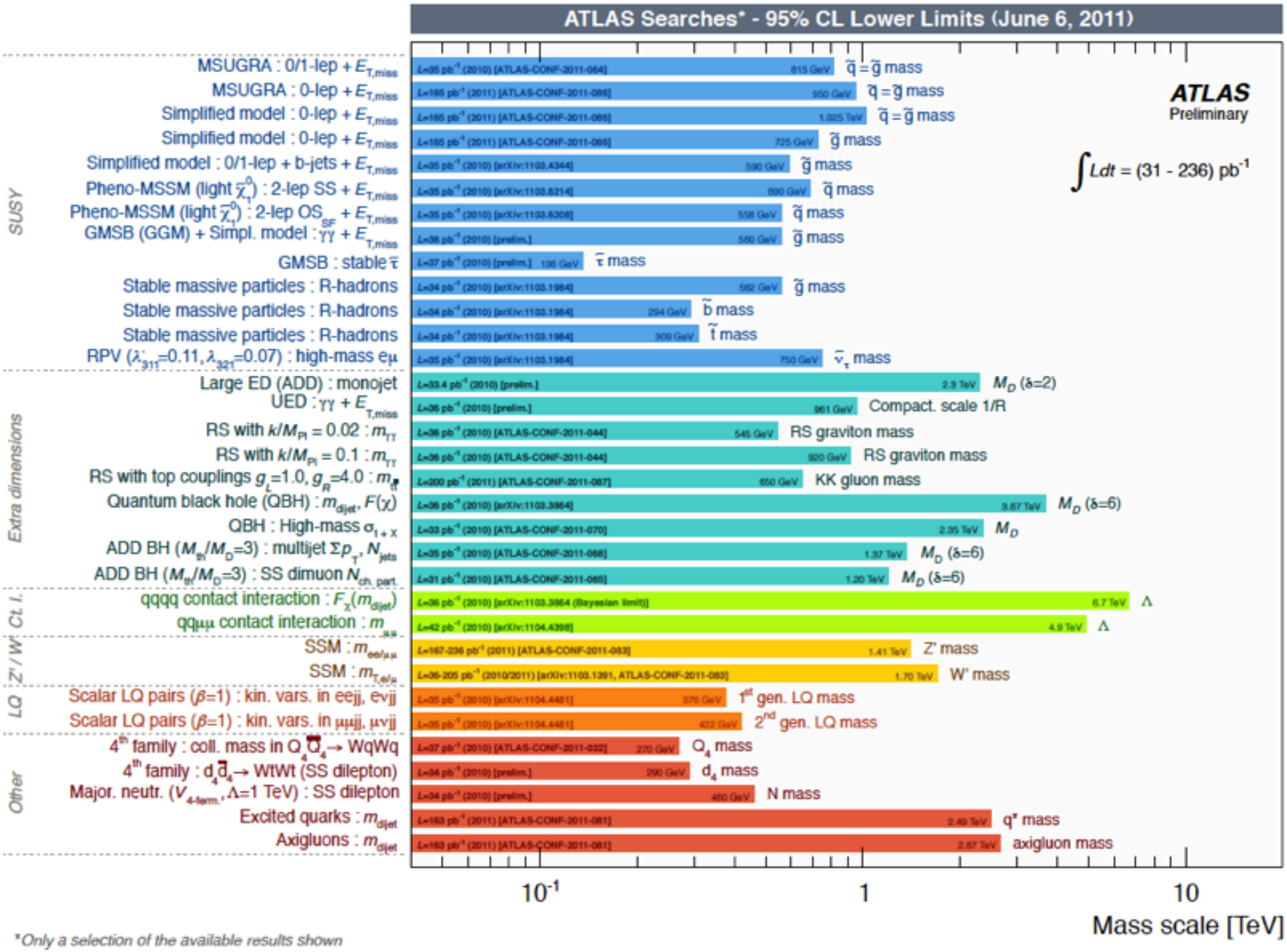
- ~ 1 fb^{-1} results should be available for the summer conferences from CMS/ATLAS
- 5-10 fb^{-1} results by the end of 2012
- Eventually 100 fb^{-1} at ~14 TeV
- Can just use parton luminosity curves to project limits on new physics if no discoveries
  Quigg arXiv:1101.3201]



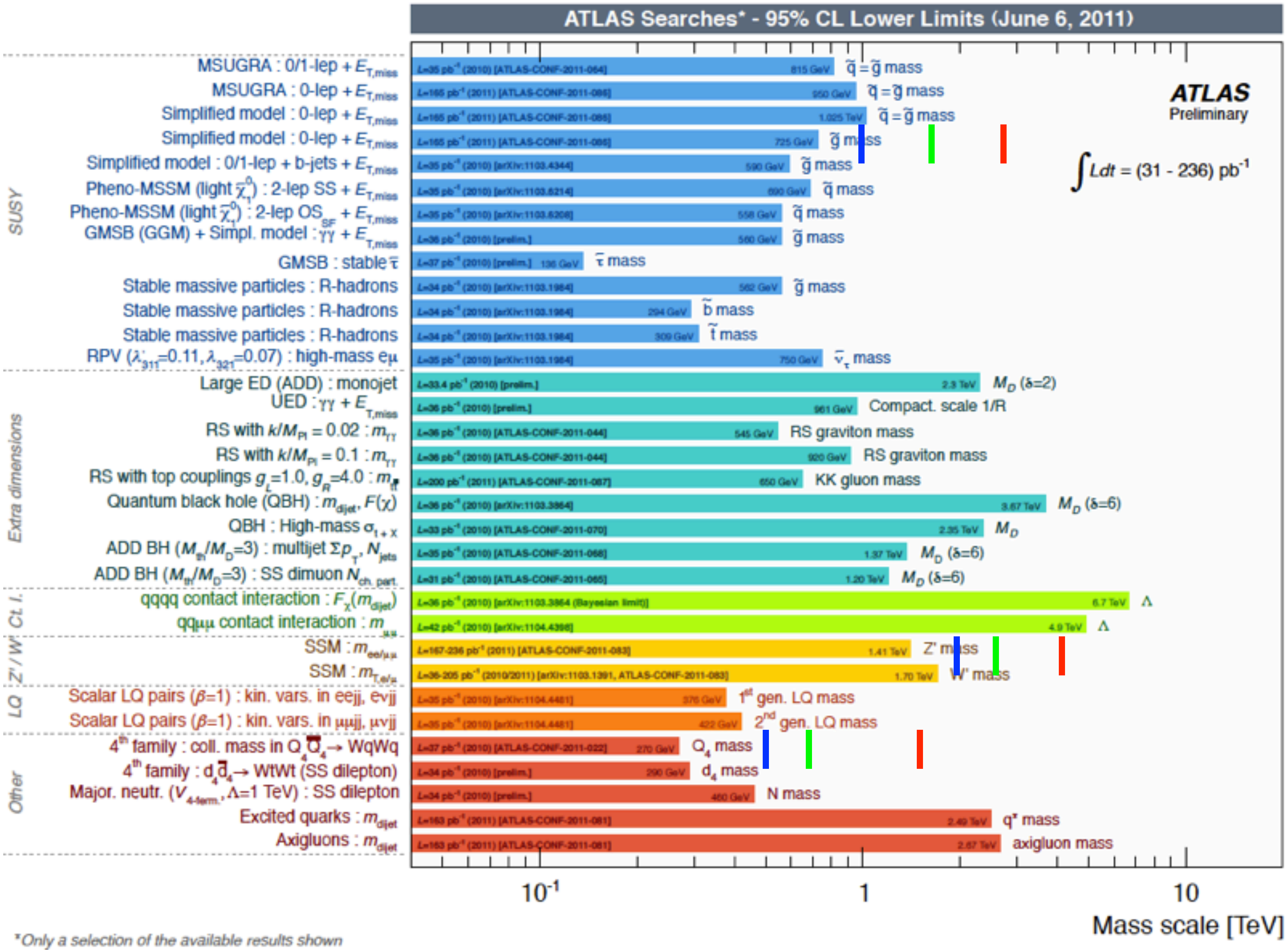
1 fb^{-1}@7TeV | 10 fb^{-1}@7TeV | 100 fb^{-1}@14TeV |

- Examples: Gluino mass, Z', 4th family Q->qW

The LHC Era Begins



The LHC Era Begins



Why think about the next collider now?

- Timescales for energy frontier complexes:
  - Using the LHC experience. Operating now - full energy operation 2014.
  - Initial research on the LHC begin in 1980's, before the Large Electron-Positron collider even started operation (1989).
  - Decision to go to construction: Dec. 1994
  - 20-30 years
- Costs:
  - CERN costs for LHC: x ~ 3 billion Euros
  - Total worldwide cost with detectors ~ 2x
  - Can't continue on this trajectory forever.

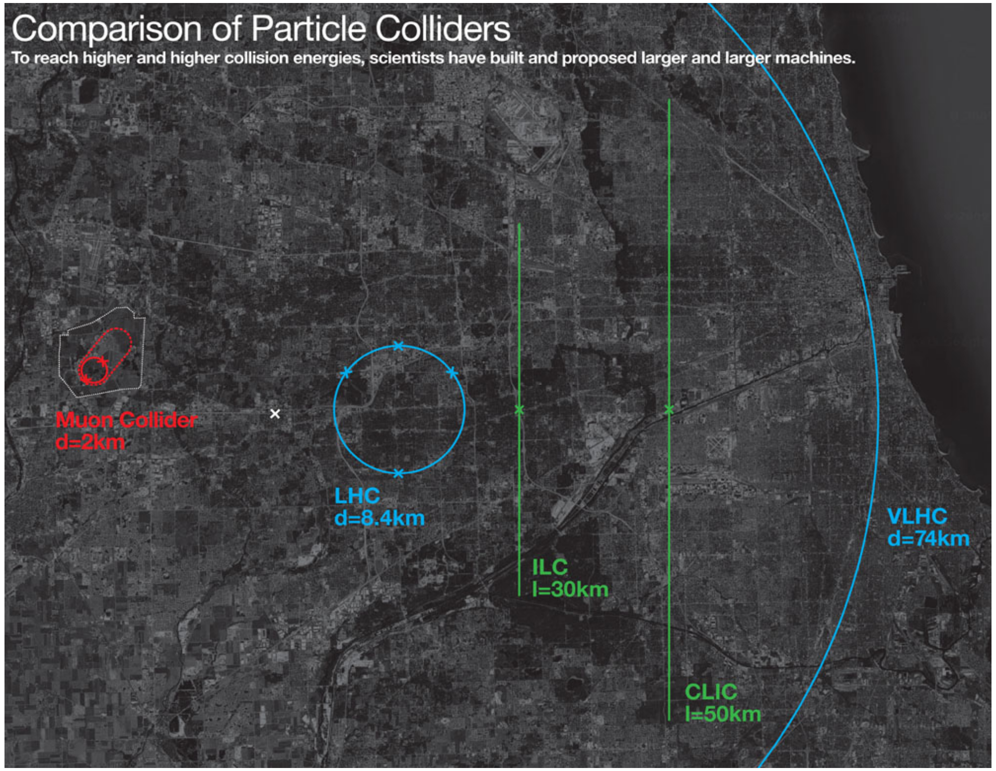
Construction costs (BCHF)	Personnel	Materials	Total
LHC Machine and areas	0.92	3.68	**4.60** *)
CERN share to Detectors	0.78	0.31	**1.09**
LHC injector upgrade	0.09	0.07	**0.16**
LHC computing (CERN share)	0.09	0.09	**0.18**
Total	**1.88**	**4.15**	**6.03**

*) *(including 0.43 BCHF of in-kind contributions)*

- Need staged projects with physics at each stage

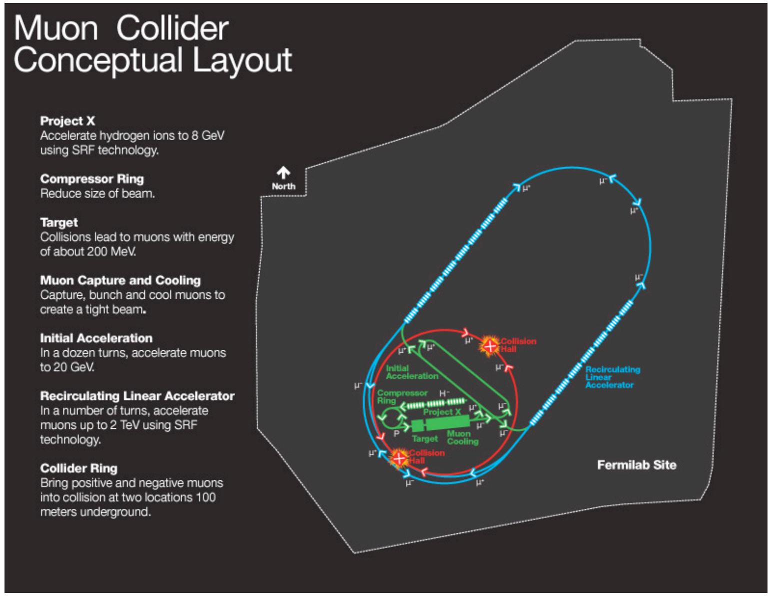
Options for the Next Collider

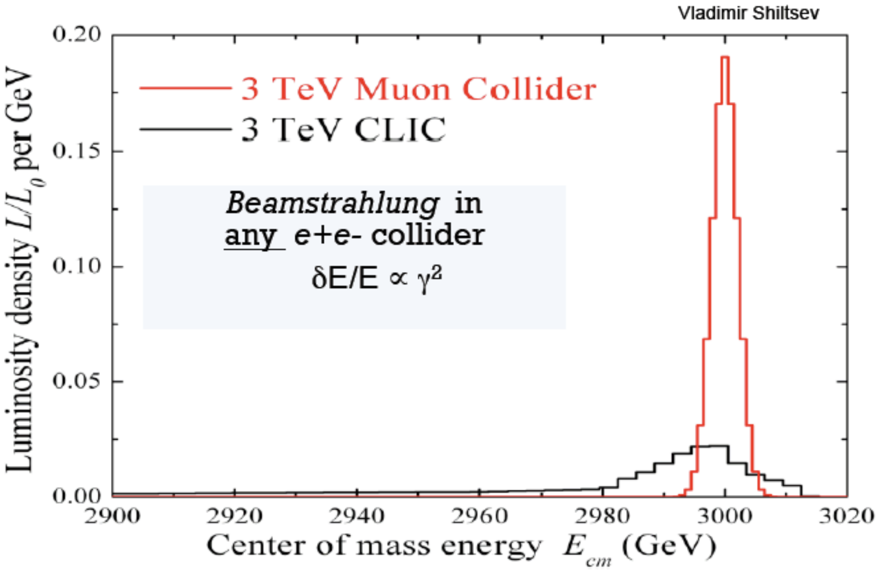
- Existing facilities in 2025:
  - LHC with luminosity or energy upgrade
- Options for next facility:
  - low energy lepton collider:
    ILC (500 GeV) (upgradable) or
    muon collider - Higgs Factory
  - lepton collider in the multi-TeV range:
    CLIC or muon collider
  - hadron collider in hundred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

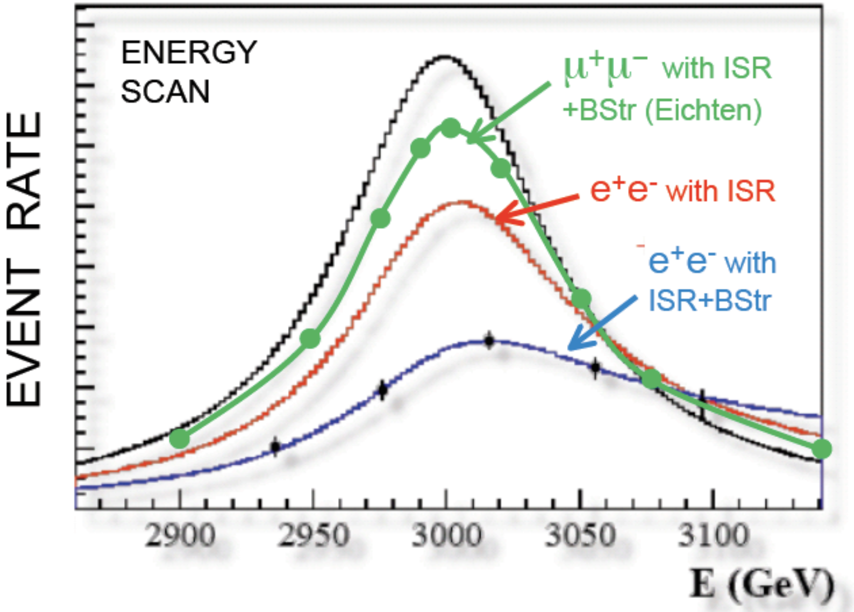


A Future Muon Collider

- $\mu^+\mu^-$ Collider:
  - Center of Mass energy: 1.5 - 5 TeV
  - Luminosity > 10^{34} cm^{-2} sec^{-1}
- Compact facility
  - 3 TeV - ring circumference 3.8 km
- Superb Energy Resolution
  - MC: 95% luminosity in dE/E ~ 0.1%

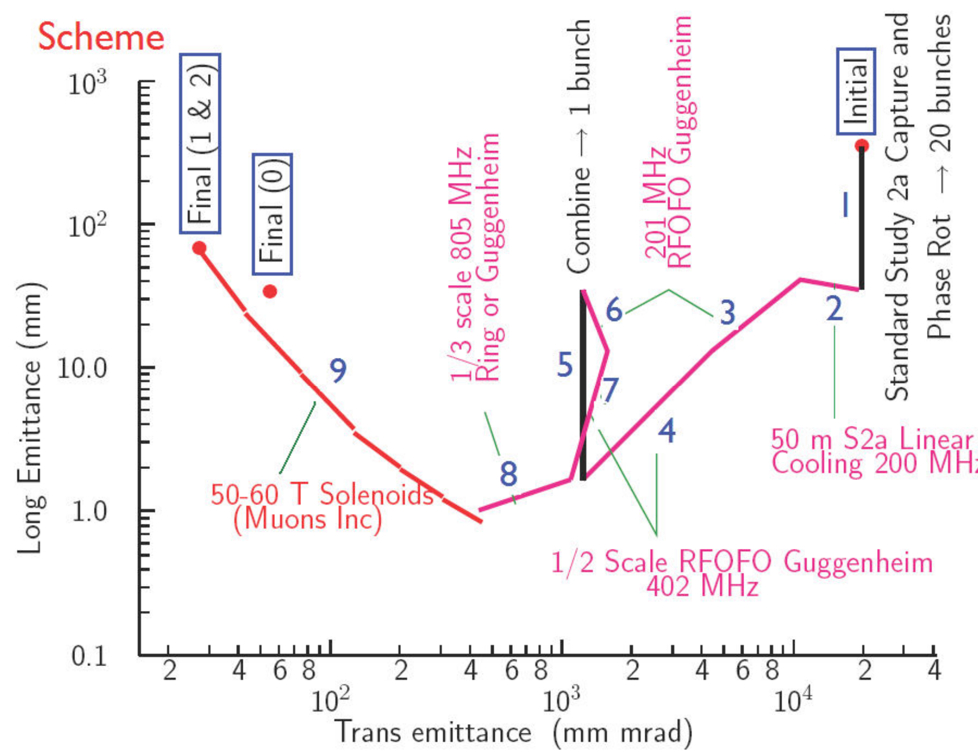






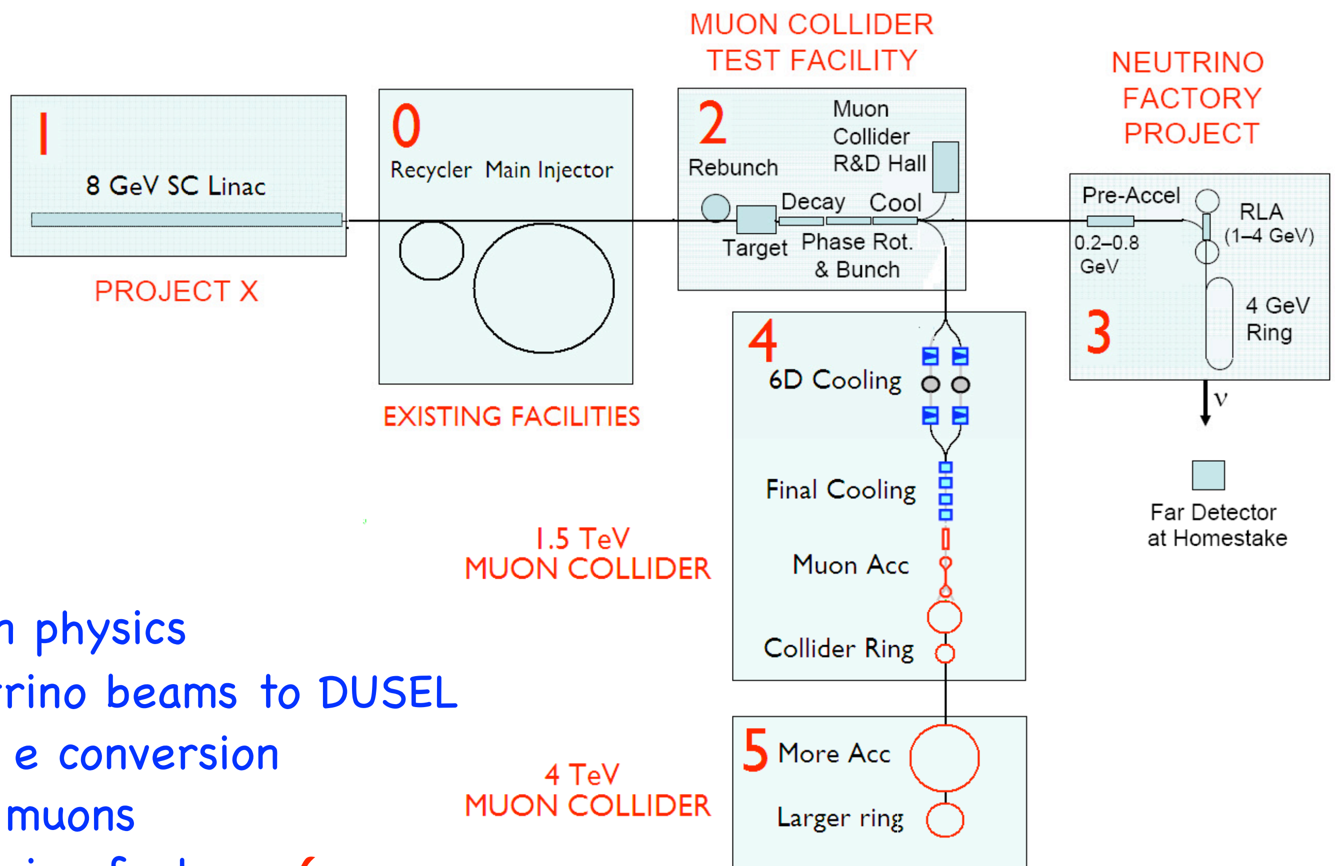
A Future Muon Collider

- Muons decay:
  - muon lifetime: (2.197034 ± 0.000021) × 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 ($\mu^- \rightarrow \nu_\mu \bar{\nu}_e e^-$) have high energies. Serious issue for Ecm ≥ 4 TeV



A Future Muon Collider

- 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 ✓

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)

Abridged Parameter List

Machine	1.5-TeV $\mu^+\mu^-$	3.0-TeV $\mu^+\mu^-$	CLIC 3 TeV
$\mathcal{L}_{\rm peak}$ [cm^{-2} s^{-1}]	7×10^{34}	8.2×10^{34}	8×10^{34} tot
$\mathcal{L}_{\rm avg}$ [cm^{-2} 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

MultiTeV Lepton Collider Basics

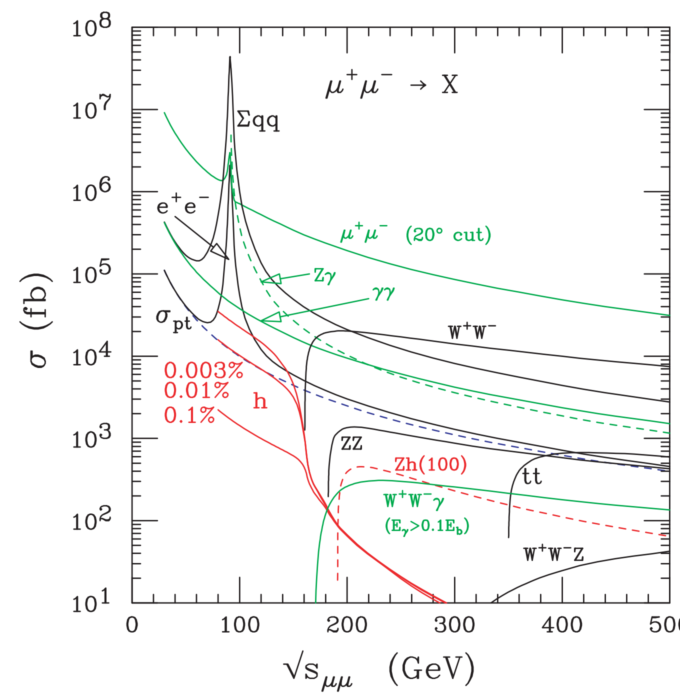
- For $\sqrt{s}$ < 500 GeV
  - SM threshold region: top pairs; W^+W^-; Z^0Z^0; Z^0h; ...
- For $\sqrt{s}$ > 500 GeV
  - For SM pair production (| θ | > 10°)

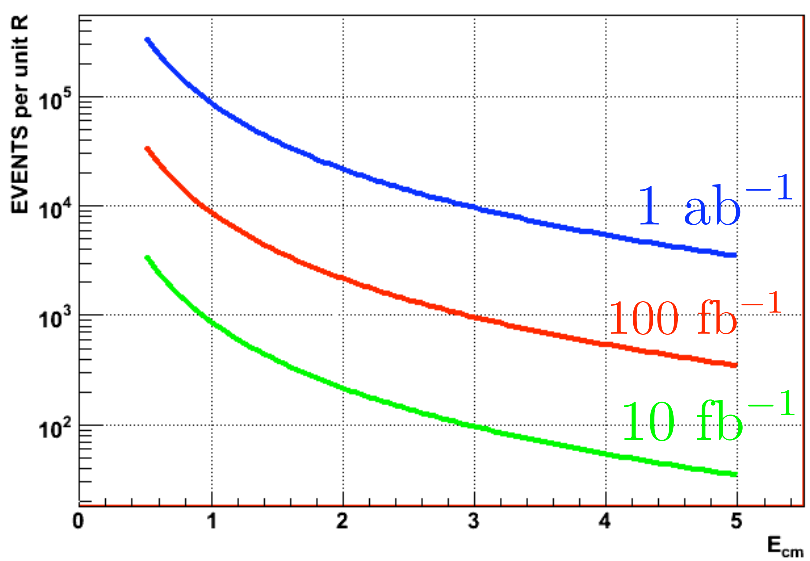
    R = $\sigma / \sigma_{QED}(\mu^+\mu^- \to e^+e^-)$ ~ flat

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

  - High luminosity required

Standard Model Cross Sections





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

⇒ 965 events/unit of R

Processes with R ≥ 0.1 can be studied

Total - 540 K SM events per year

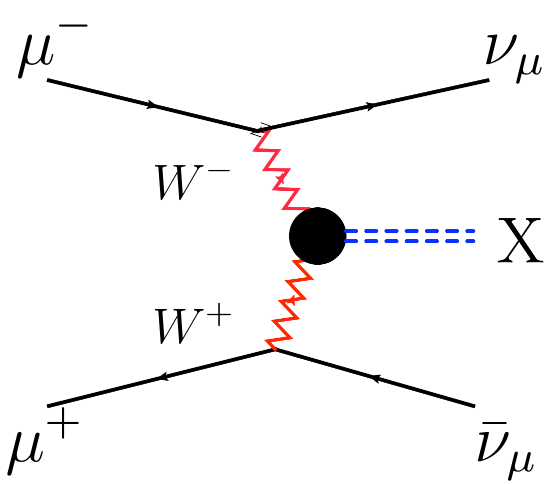
Fusion Process

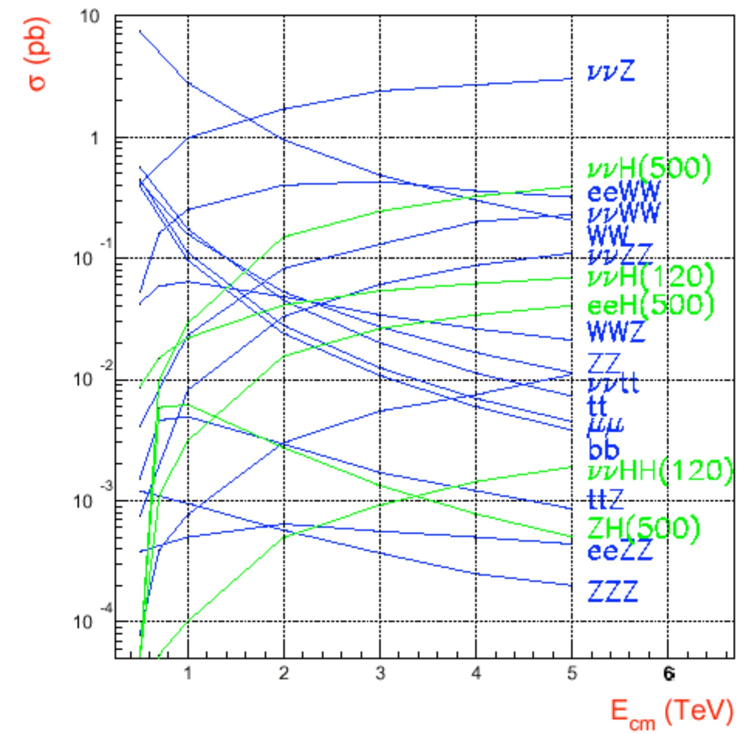
CLIC (or MC e<->μ)

- For $\sqrt{s}$ > 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

S Channel Resonances

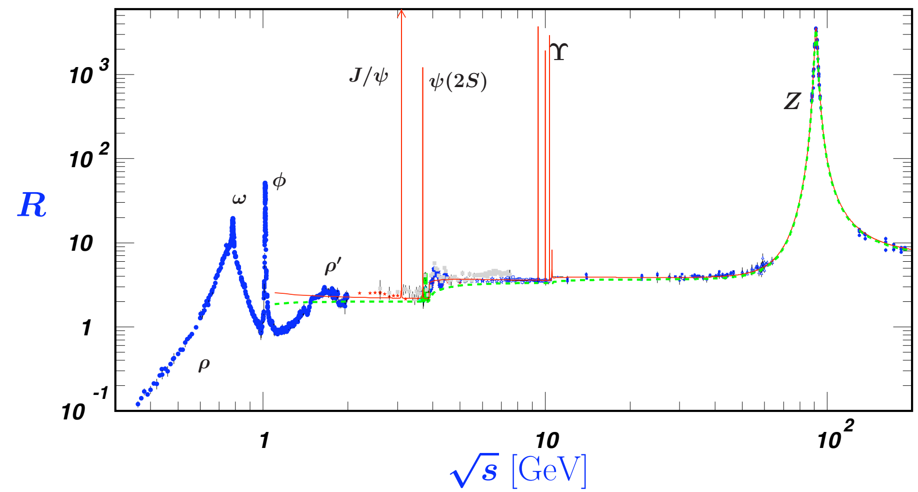
- Universal behavior for s-channel resonance

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

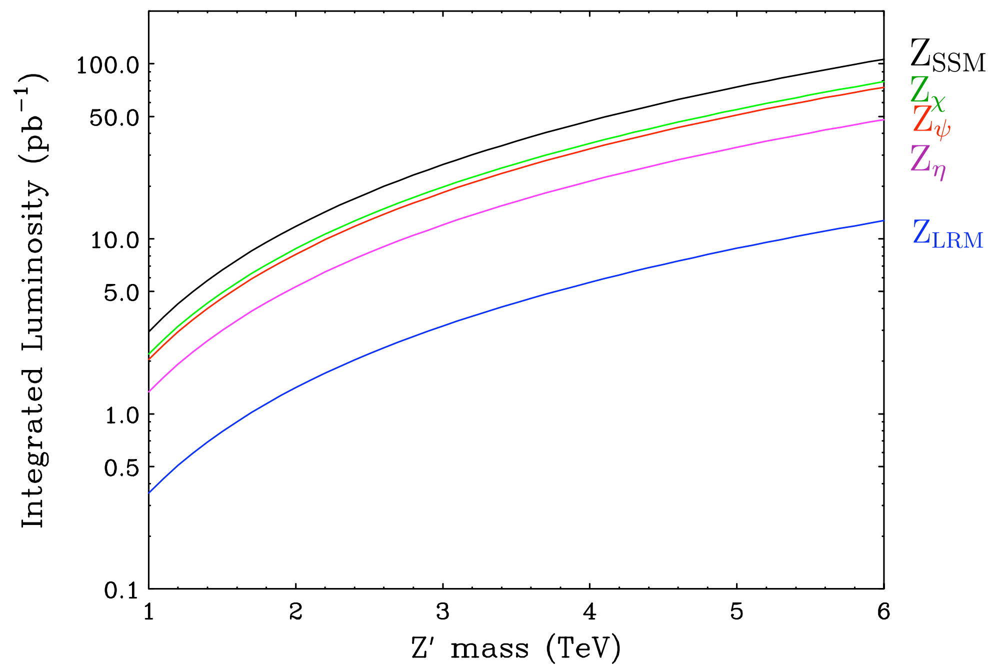
Convolute with beam resolution ΔE.

If ΔE« Γ

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



- Can use to set minimum required luminosity for a muon colider:
  - 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})



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

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

Studying the Higgs Boson

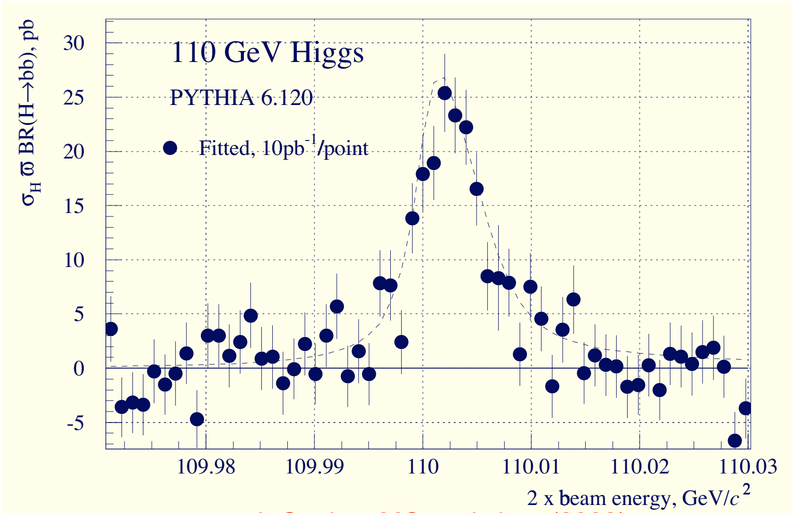
- Theoretical Issues:
  - Higgs boson couplings SM?
  - Scalar interaction self-coupling SM?
  - Any additional scalars? EW doublets, triplets or singlets?
  - Where's the next scale? GUT

- Low energy lepton collider

  - Many of the Higgs couplings could be measured at the LHC.
  - The ILC(500) allows detailed study of the light Higgs properties.
  - S-channel Higgs production
    - couples to mass $[\frac{m_\mu}{m_e}]^2 = 4.28 \times 10^{4}$
    - narrow state

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

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



J. Gunion, MC workshop (2008)

Studying the Higgs Boson

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

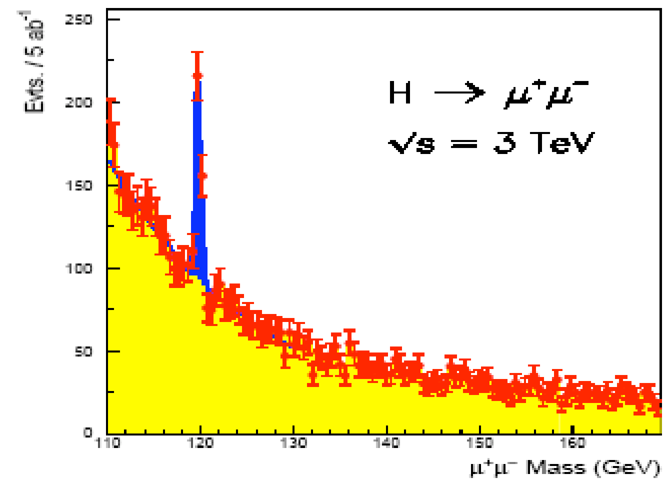
MC or CLIC:

needs 10 ab^{-1}

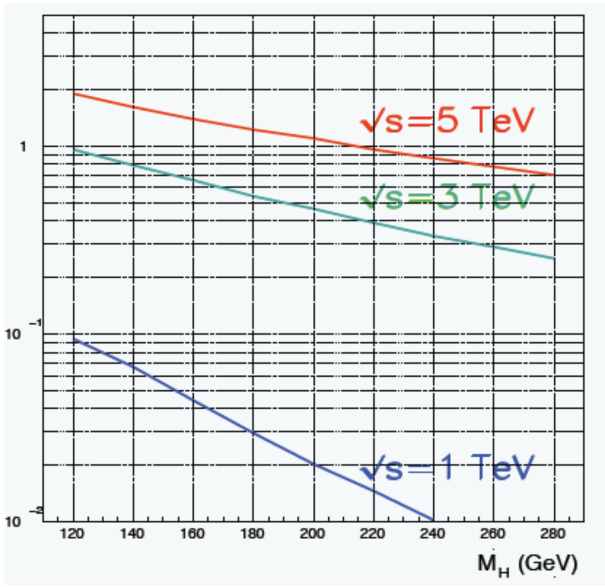
MC or CLIC:

good benchmark process

m(H) = 120 GeV



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

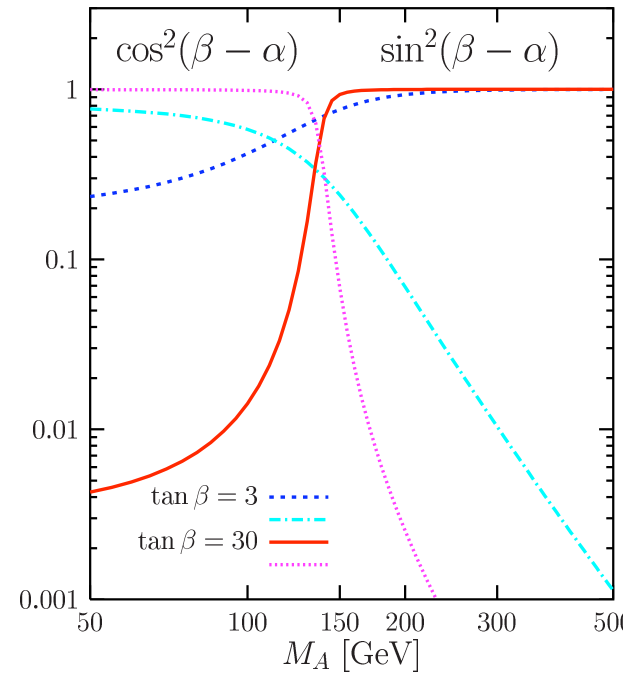


Two Higgs Doublets (MSSM)

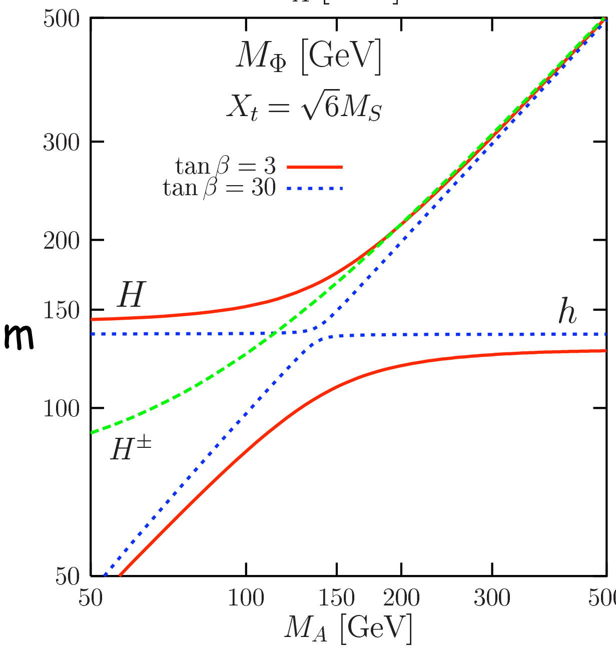
- Five scalar particles: h^0, H^0, A^0, $H^\pm$
- Decay amplitudes depend on two parameters: (α, β)

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

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



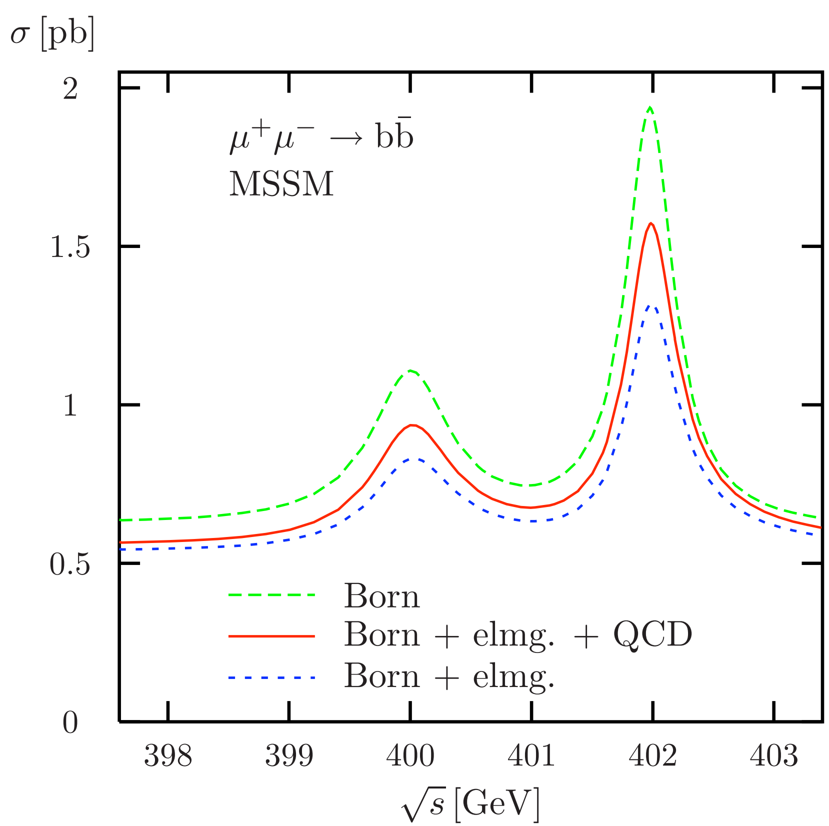
- decoupling limit $m_{A^0} \gg m_{Z^0}$:
  - h^0 couplings close to SM values
  - H^0, $H^\pm$ and A^0 nearly degenerate in mass
  - H^0 small couplings to VV, large couplings to ZA^0
  - For large $\tan\beta$, H^0 and A^0 couplings to charged leptons and bottom quarks enhanced by $\tan\beta$. Couplings 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 bounds on W′, Z′, and new quarks effectively rule out production at ILC.

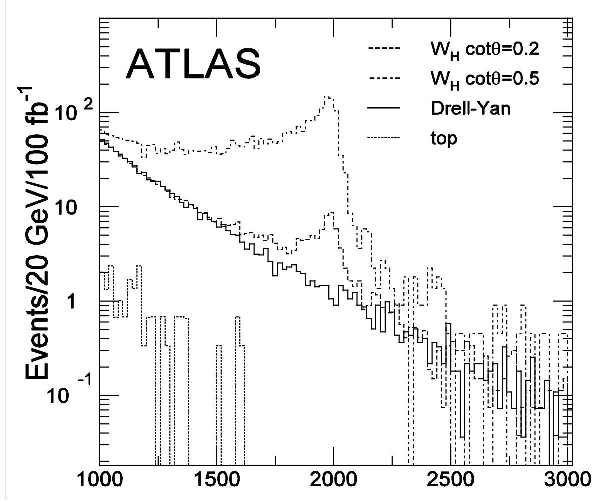
State	Limit (GeV)
Quark: (W,Z,h) + jet	335 (CDF/DZERO)
Z′ (SM)	1410 (ATLAS)
W′ (SM)	1700 (ATLAS)

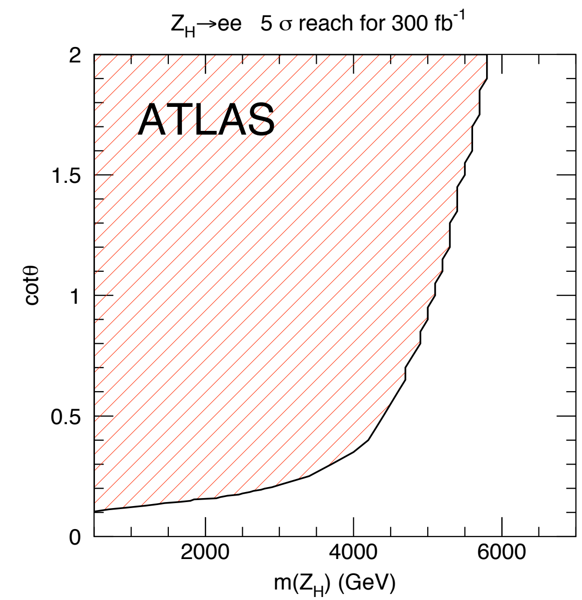
- Littlest Higgs Model: good benchmark processes
  charge (2/3) quark T (EW singlet),
  new W, Z, and A gauge bosons, Higgs triplet

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

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

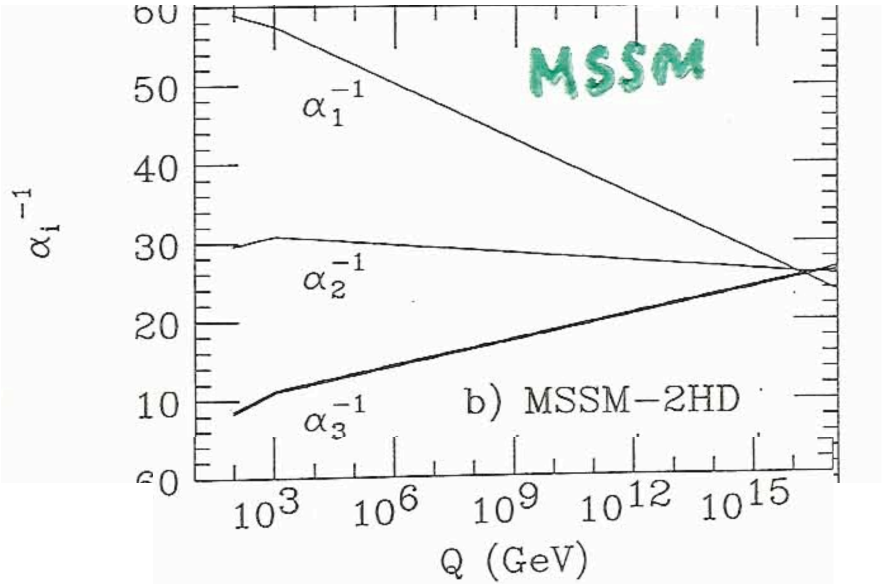
ATLAS study LHC [hep-ph/0402037]





SUSY

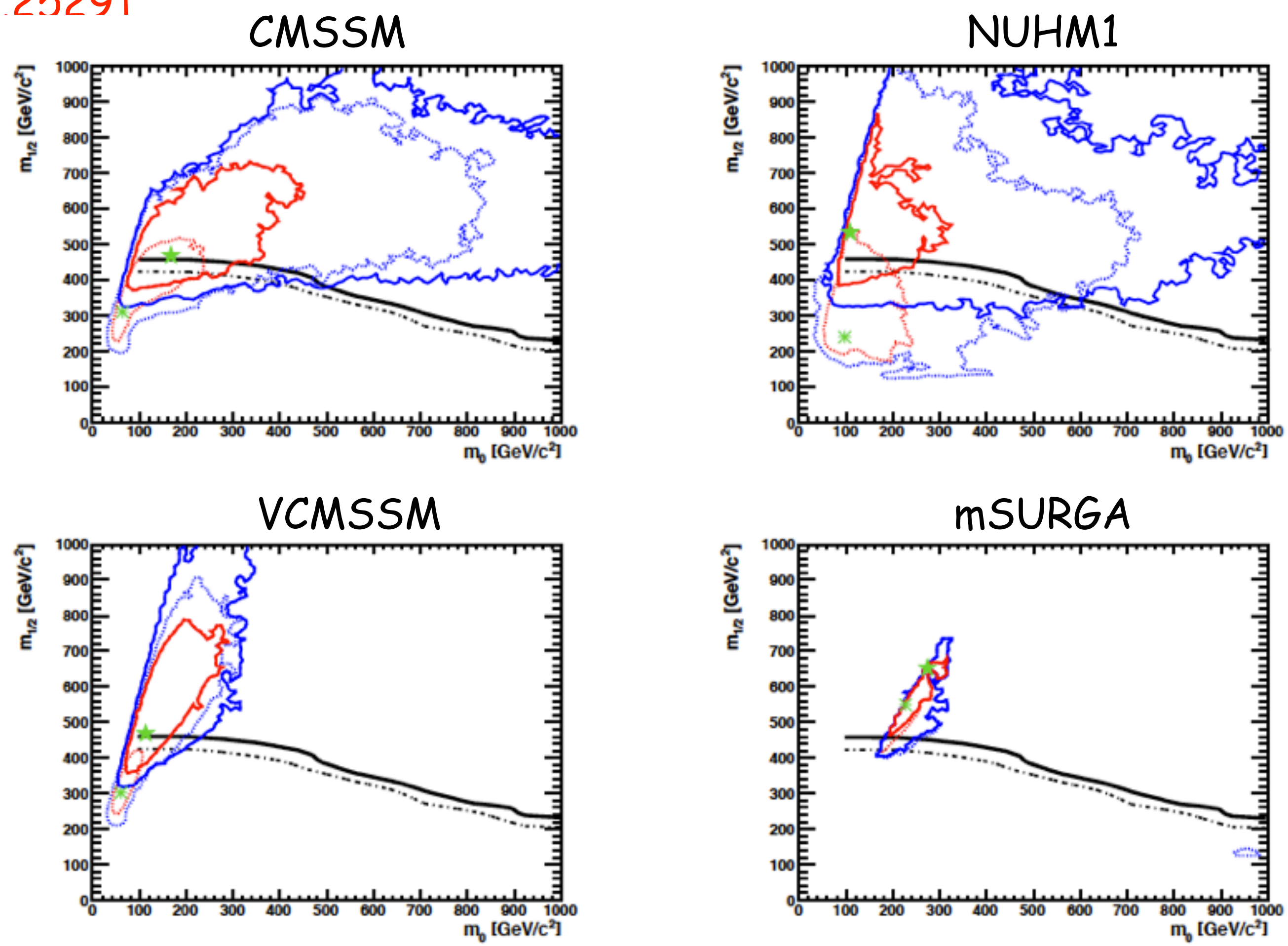
- Solves the Naturalness Problem: Scalars associated with fermions. Higgs mass associated with SUSY breaking scale.
- Couplings of sparticles determined by symmetry. Masses depend on SUSY breaking mechanism.
- If discovered at LHC ->
  - What is the spectrum of superpartner masses?
  - Dark matter candidates?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

SUSY

- Effects of new LHC limits on SUSY models
  O. Buchmueller, et. al. [arXiv:1106.2529]
  - Update
    - LHC 20101 SUSY limits.
    - Xenon 100
  - Four models studied
    - CMSSM
    - NUHM1
    - VCMSSM
    - mSUGRA
  - New ATLAS limits (solid line)
  - Soon new results (~1 fb^{-1})



- Hard SUSY

Figure 1. The $(m_0, m_{1/2})$ planes in the CMSSM (upper left), the NUHM1 (upper right), the VCMSSM (lower left) and mSUGRA (lower right). In each plane, the best-fit point after incorporation of the 2010 LHC and Xenon100 constraints is indicated by a filled green star, and the pre-LHC fit by an open star. The 68 and 95% CL regions are indicated by red and blue contours, respectively, the solid lines including the 2010 LHC and Xenon100 data, and the dotted lines showing the pre-LHC fits.

SUSY

- Present best fits:

Model	Minimum χ^2/dof	Probability	$m_{1/2}$ (GeV)	m_0 (GeV)	A_0 (GeV)	$\tan\beta$	M_h (GeV) (no LEP)
CMSSM pre-LHC	22.5/19	26%	310^{+120}_{-50}	60^{+90}_{-10}	-60^{+410}_{-840}	10^{+10}_{-4}	108.6
post-2010-LHC	26.1/19	13%	470^{+140}_{-70}	170^{+330}_{-80}	-780^{+1410}_{-820}	22^{+27}_{-13}	115.7
post-Xenon (50 ± 14)	26.2/20	16%	470^{+140}_{-70}	170^{+330}_{-80}	-780^{+1410}_{-820}	22^{+27}_{-13}	115.7
NUHM1 pre-LHC	20.5/17	25%	240^{+150}_{-50}	100^{+70}_{-40}	920^{+360}_{-1260}	7^{+11}_{-2}	119.4
post-2010-LHC	24.1/18	15%	530^{+220}_{-90}	110^{+80}_{-20}	-370^{+1070}_{-1000}	27^{+24}_{-10}	117.9
post-Xenon (50 ± 14)	24.2/19	19%	530^{+220}_{-90}	110^{+80}_{-20}	-370^{+1070}_{-1000}	27^{+24}_{-10}	117.9
VCMSSM pre-LHC	22.6/20	31%	300^{+60}_{-40}	60^{+20}_{-10}	30^{+50}_{-30}	8^{+3}_{-1}	110.0
post-2010-LHC	27.9/20	11%	470^{+150}_{-80}	110^{+110}_{-30}	120^{+300}_{-190}	13^{+14}_{-8}	115.0
post-Xenon (50 ± 14)	28.1/21	14%	470^{+150}_{-80}	110^{+110}_{-30}	120^{+300}_{-190}	13^{+14}_{-8}	115.0
mSUGRA pre-LHC	29.4/19	6.0%	550^{+170}_{-90}	230^{+80}_{-40}	430^{+190}_{-90}	28^{+5}_{-2}	107.8
post-2010-LHC	30.2/20	6.7%	650^{+70}_{-130}	270^{+50}_{-50}	530^{+130}_{-130}	30^{+4}_{-3}	122.2
post-Xenon (50 ± 14)	30.3/21	8.6%	650^{+70}_{-130}	270^{+50}_{-50}	530^{+130}_{-130}	30^{+4}_{-3}	122.2

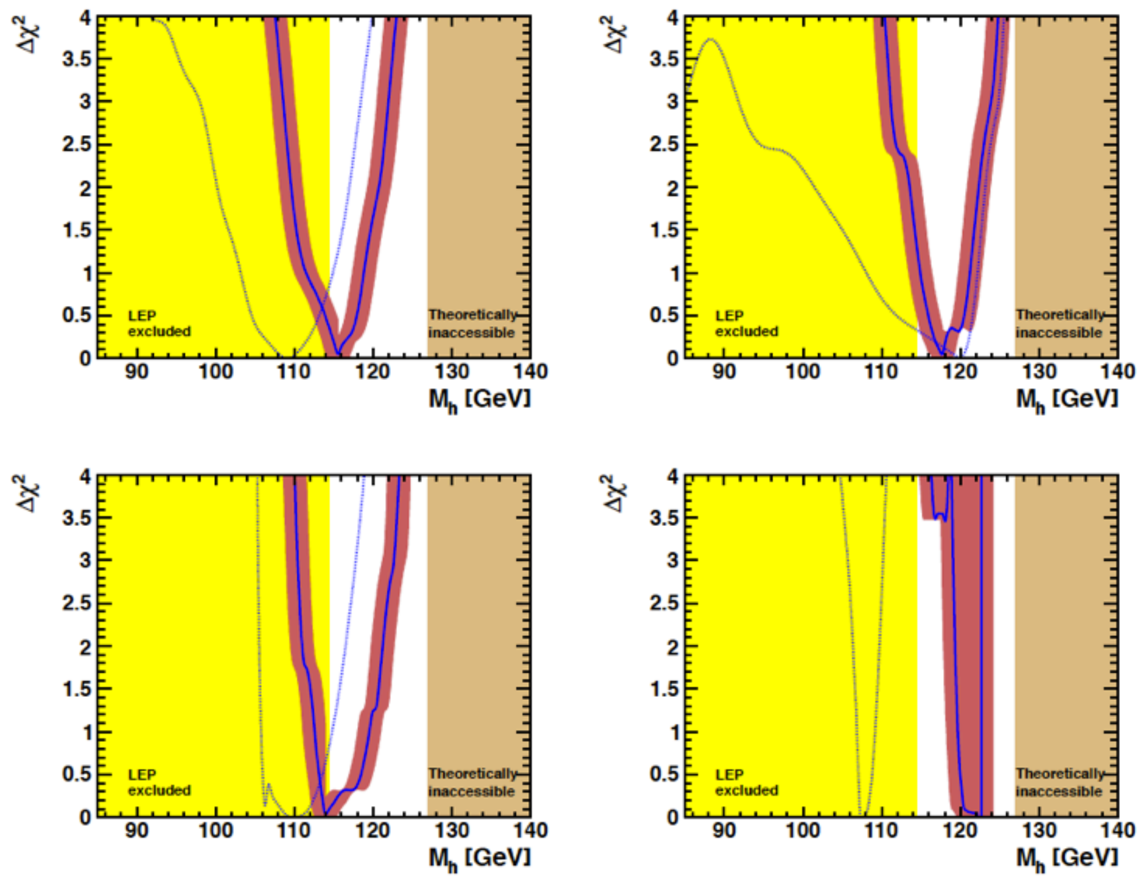
Table 1

Comparison of the best-fit points found in the pre-LHC analysis in the CMSSM, the NUHM1, the VCMSSM and the coannihilation region of mSUGRA [2, 6–8], and our latest results incorporating the CMS, ATLAS, LHCb, CDF, DØ and Xenon100 constraints. We also include the minimum value of χ^2 and the fit probability in each scenario, as well as the predictions for M_h without imposing the LEP constraint.

- Tension between LHC bounds and $(g\text{-}2)_\mu$ visible in generally worse χ^2 fits.

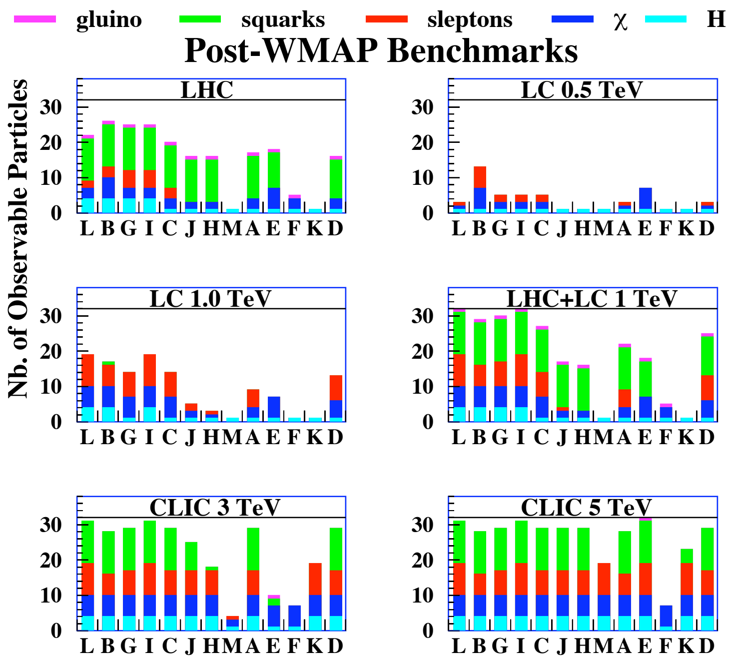
Constraints on SUSY Models

- Effect on Higgs mass expectation (without imposing LEP constraint)

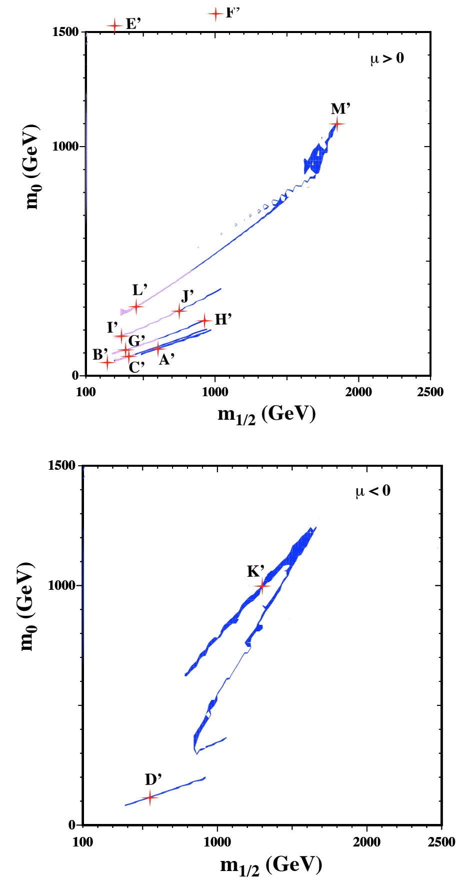


SUSY

- 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

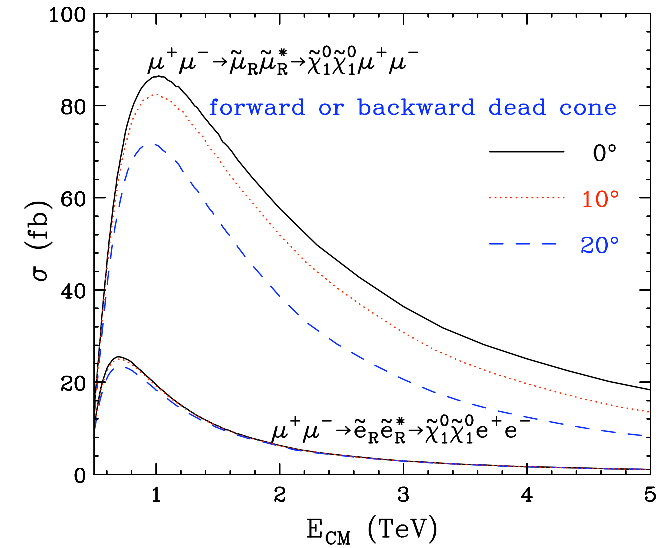
  - Alternate supersymmetry breaking schemes (mGMSB, mAMSB) also require multiTeV lepton collider. S. Heinemeyer, X. Miao, S. Su, G. Wieglein [arXiv:0805.2359]

- Supersymmetry provides a strong case for a multiTeV muon collider

Example SUSY Process at Muon Collider

- $\mu^+\mu^- \rightarrow \tilde{e}_1^+\tilde{e}_1^- \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0 e^+e^-$
  - 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:

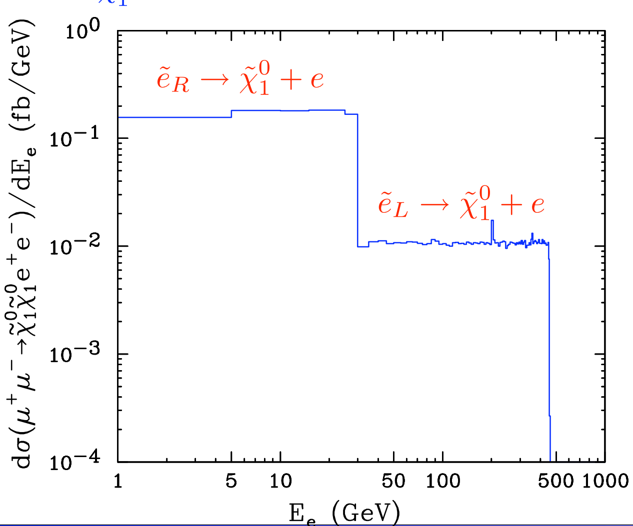
$$E_{\max/\min} = \frac{1}{2}M_{\tilde{e}}\left[1 - \frac{M^2_{\tilde{\chi}^0_1}}{M^2_{\tilde{e}}}\right]\gamma(1 \pm \beta)$$



Effect of beamstrahlung

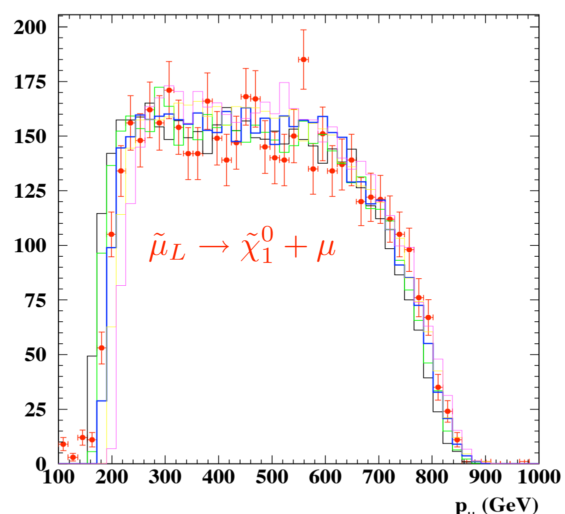
Kong, Winter (MC)

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

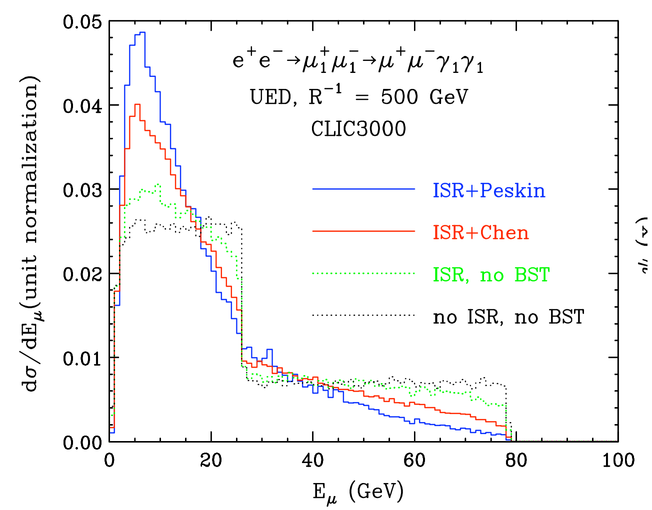


CLIC report (2004)

$m_{\tilde{\chi}_1^0} = 660$ 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

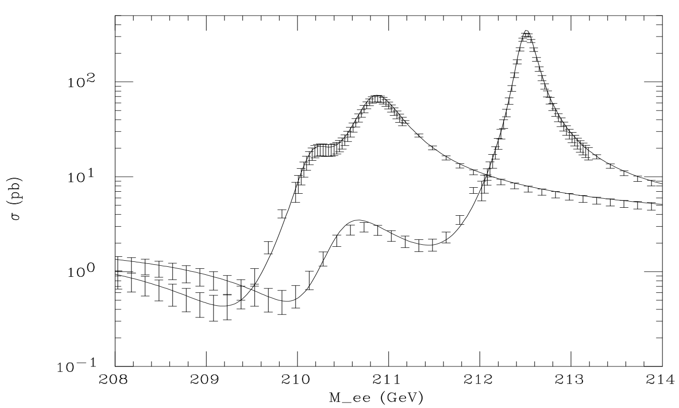
- What is the spectrum of low-lying states?
- What is the ultraviolet completion? Gauge group? Fermion representations?
- What is the energy scale of the new dynamics?
- Any new insight into quark and/or lepton flavor mixing and CP violation?
- ...

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

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

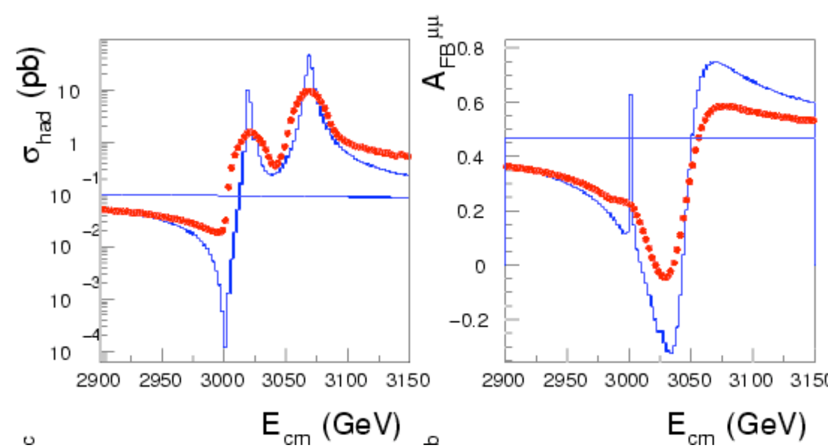
- Technipions – s channel production (Higgs like)
- Technirhos – Nearby resonances (ρ_T,ω_T)- need fine energy resolution of muon collider.

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.

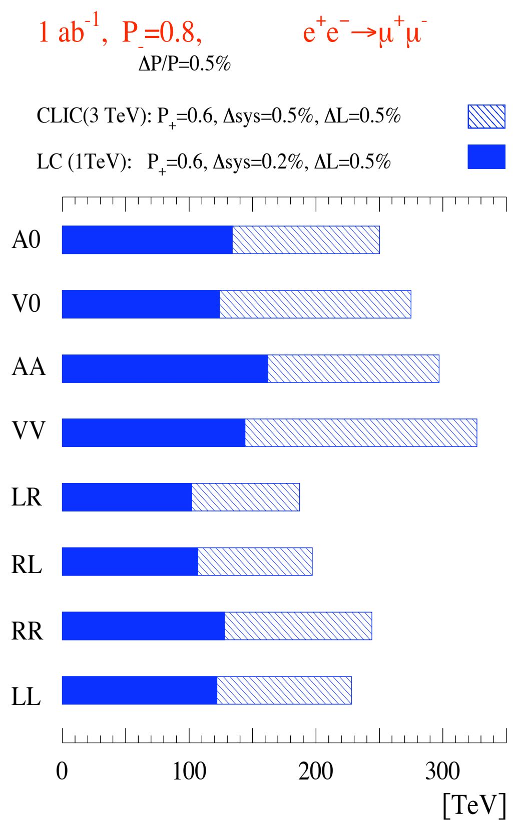
$$\mathcal{L} = \frac{g^2}{\Lambda^2}(\bar{\Psi}\Gamma\Psi)(\bar{\Psi}\Gamma'\Psi)$$

  - 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.

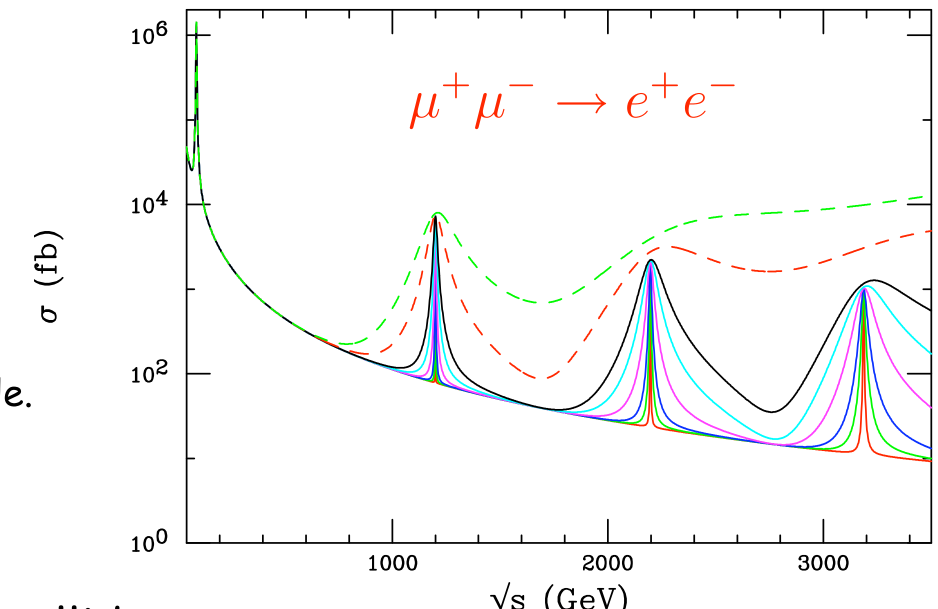
Theoretical issues

- 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

In Summary

- The nature of electroweak symmetry breaking has remained unresolved for the last 30 years.
- The era of the LHC has begun.
  - We fully expect to uncover which physical mechanism is responsible for EW symmetry breaking in the near future.
  - Many details will remain to be understood even after the LHC. In particular the origin of fermion masses and mixing will likely still be a mystery. Even the scale of that physics is unknown at present.
- A multiTeV lepton collider will be 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.

Physics: To Do List

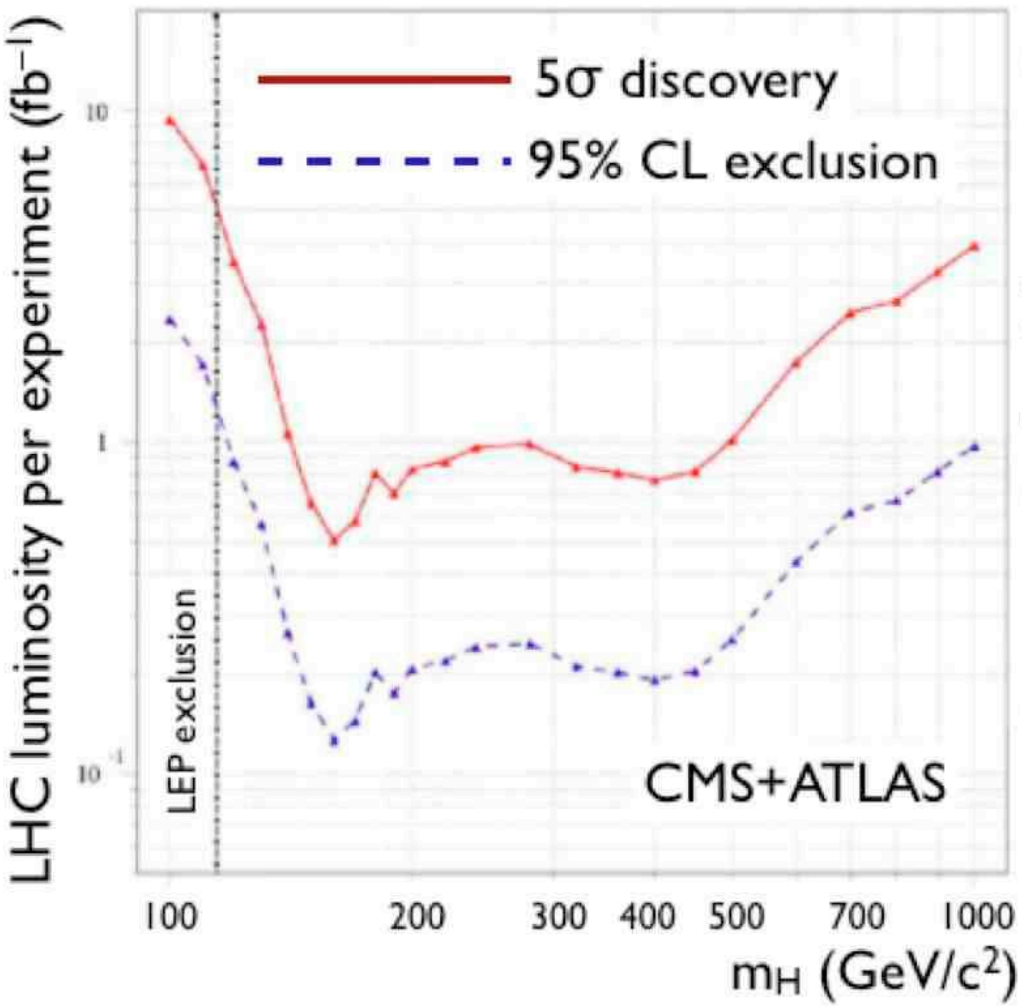
- Identify benchmark processes: pair production (slepton; new fermion), Z′ pole studies, contact interaction studies, distinguish W/Z in jets, h^0 plus missing energy, resolving nearby states (H^0-A^0; ρ_T-ω^0_T), ...
- Dependence on initial beam [electron/muon, polarization and beam energy spread] as well as luminosity to be considered.
- Detemine the effect of forward cone cut of 10° on physics.
- Estimates of collision point environment and detector parameters needed.
- Must present a compelling physics case even after more than ten years of running at the LHC.

- The extraordinary opportunity justifies the serious research efforts presently underway into the feasibility of such a muon collider.

Backup Slides

LHC - Discovery of the SM Higgs

14 TeV

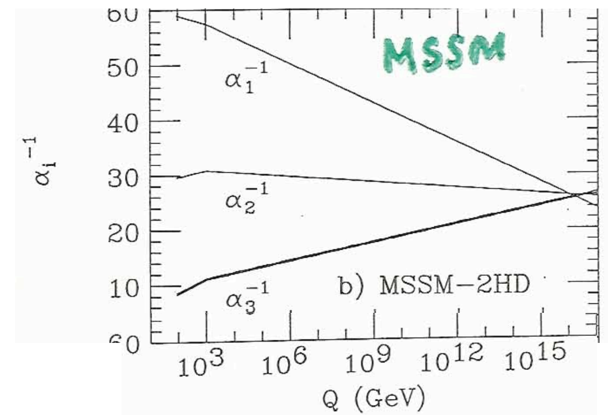


Challenges Ahead

- 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 two 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.

Supersymmetry

- Supersymmetry
  - Q_{susy} |boson> = |fermion>: gluon -> gluino ,... ; W boson -> wino; higgs -> higgino, ...
    Q_{susy} |fermion>=|boson>: top quark -> top squark (L,R), ...; electron -> selectron(L,R), ...
    - spin 1/2 symmetry charges $\{\bar{Q}_{susy}, Q_{susy}\} = 2\gamma^{\mu}P_{\mu}$; Q_{susy} H|state> = H Q_{susy}|state>
  - supersymmetry dictates the couplings between particles and sparticles
  - supersymmetry is broken $M_{sparticle} \neq M_{particle}$



- Solves the hierarchy and GUT unification problems

- Theoretical issues after discovery at the 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?

Names		spin 0	spin 1/2	$SU(3)_c$, $SU(2)_L$, $U(1)_y$
squarks, quarks	Q	$(\tilde{u}_L, \tilde{d}_L)$	(u_L, d_L)	**3**, **2**, 1/3
(× 3 families)	$\bar{u}$	$\tilde{\bar{u}}_L(\tilde{u}_R)$	$\bar{u}_L \sim (u_R)^c$	$\bar{\mathbf{3}}$, **1**, -4/3
	$\bar{d}$	$\tilde{\bar{d}}_L(\tilde{d}_R)$	$\bar{d}_L \sim (d_R)^c$	$\bar{\mathbf{3}}$, **1**, 2/3
sleptons, leptons	L	$(\tilde{\nu}_{eL}, \tilde{e}_L)$	(ν_{eL}, e_L)	**1**, **2**, -1
(× 3 families)	$\bar{e}$	$\tilde{\bar{e}}_L(\tilde{e}_R)$	$\bar{e}_L \sim (e_R)^c$	**1**, **1**, 2
higgs, higgsinos	H_u	(H_u^+, H_u^0)	$(\tilde{H}_u^+, \tilde{H}_u^0)$	**1**, **2**, 1
	H_d	(H_d^0, H_d^-)	$(\tilde{H}_d^0, \tilde{H}_d^-)$	**1**, **2**, -1

Table 1: Chiral supermultiplet fields in the MSSM.

Names	spin 1/2	spin 1	$SU(3)_c$, $SU(2)_L$, $U(1)_y$
gluinos, gluons	$\tilde{g}$	g	**8**, **1**, 0
winos, W bosons	$\widetilde{W}^\pm$, $\widetilde{W}^0$	$W^\pm$, W^0	**1**, **3**, 0
bino, B boson	$\widetilde{B}$	B	**1**, **1**, 0

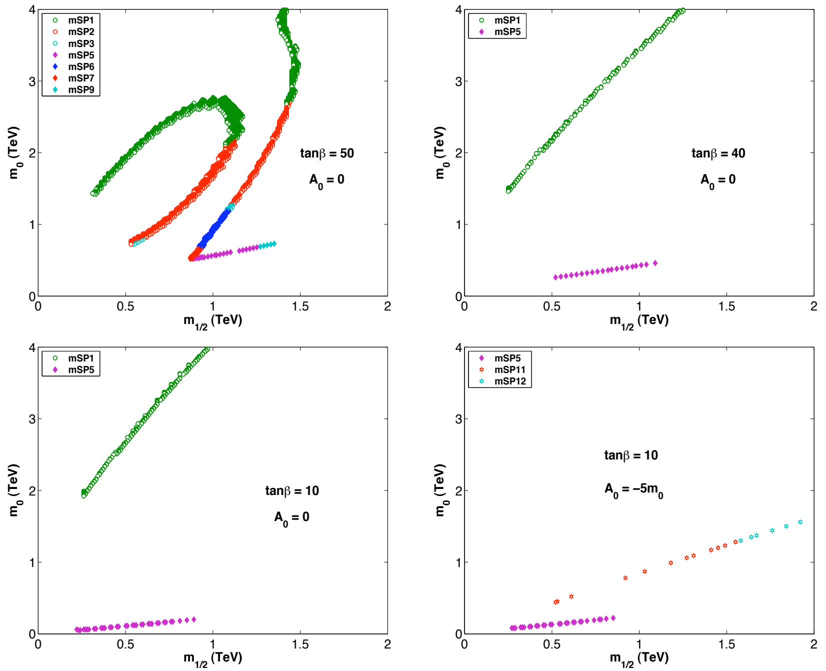
Table 2: Gauge supermultiplet fields in the MSSM.

cMSSM

- Many studies of constraints on cMSSM
  - Present 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
  - Theoretical fine tuning

Monte Carlo searches of parameter space

J. Ellis, S. Heinemeyer, K.A. Olive, A.M. Weber, G. Wieglein [arXiv:0706.0652] ;
D. Feldman, Zuowei Lui and Pran Nath, PRL 99, 251802 (07); [arXiv:0802.4085] ; ...



$M_{h0} > 113.8 \Rightarrow$ large m_{stop}

requires large cancellations in the Higgs potential
$\Rightarrow$ fine tuning (to a few %)

tree 1-loop

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

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: $\chi_2^0 \rightarrow \chi_1^0 + X$

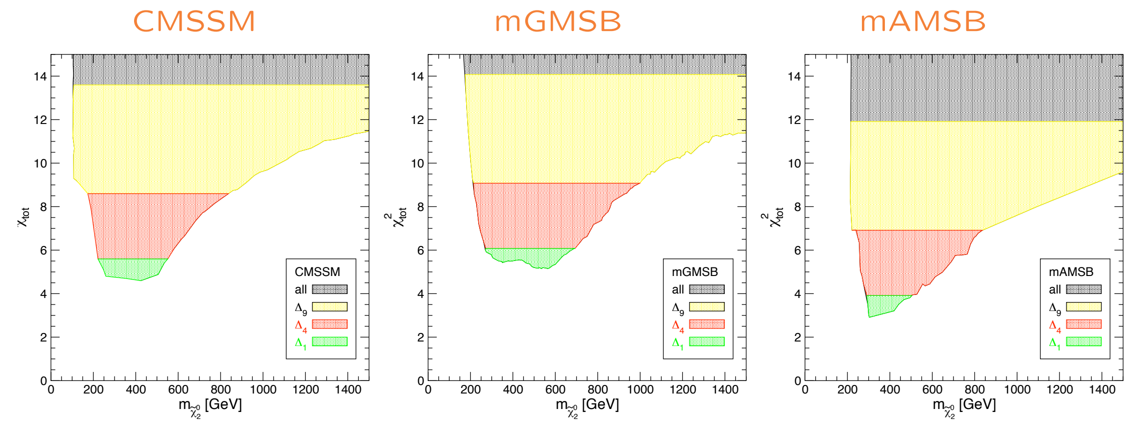
Lightest chargino:

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

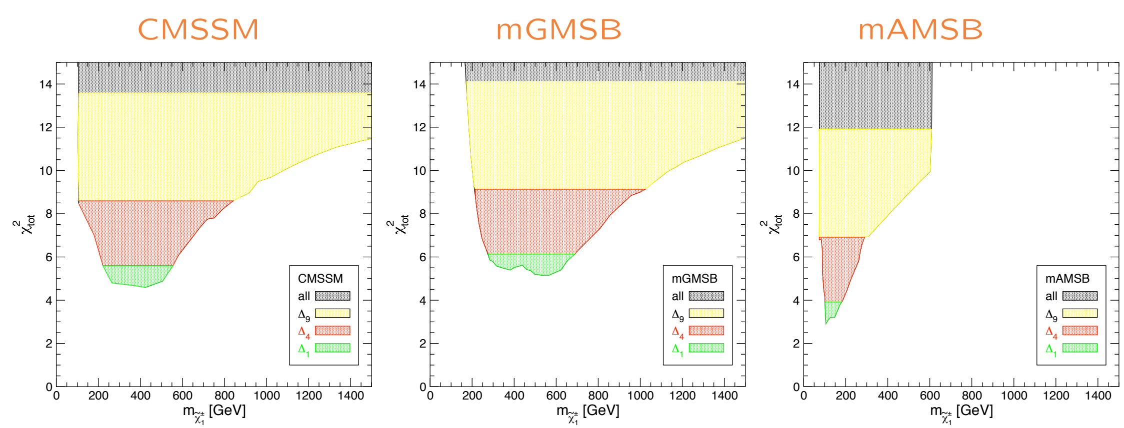
Lightest stop, sbottom and gluino:

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

Second lightest neutralino

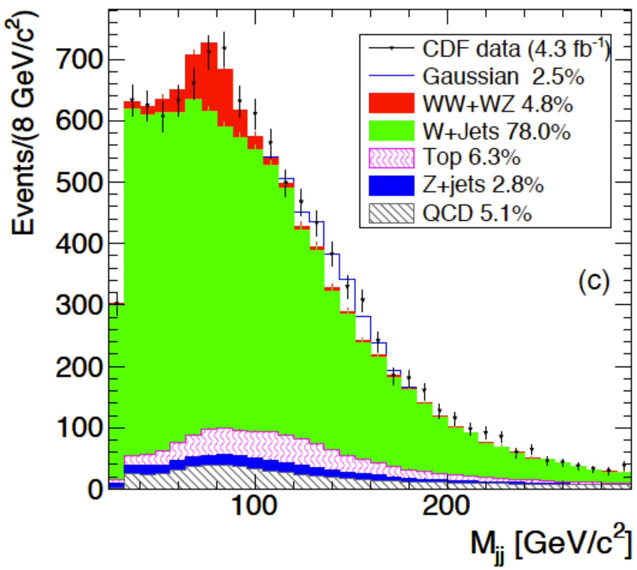


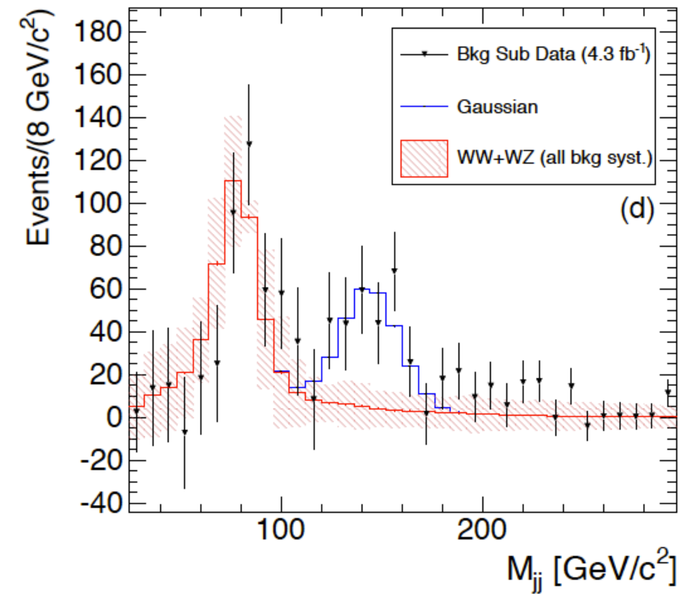
Lightest chargino



Hint of new strong dynamics?

- CDF W+2jets [PRL 106:171801 (2011)]





- DZero [arXiv:1106.1921]