Physics prospects at a Muon Collider

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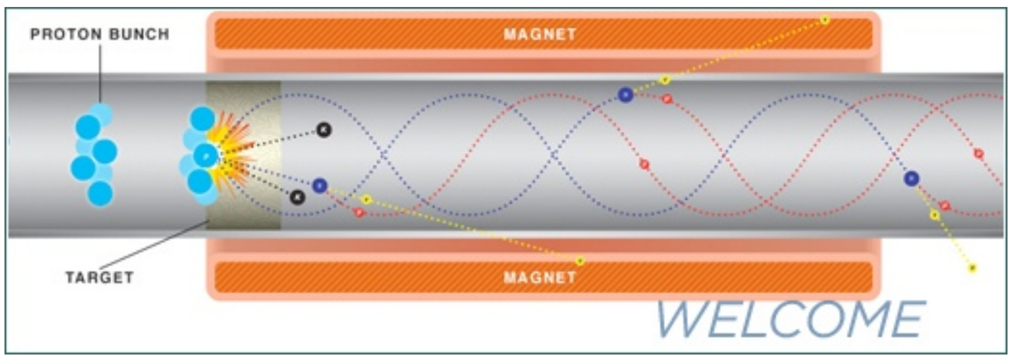
- Basics of a Muon Collider
- Implications of Early LHC Results
- The Scalar Sector
- Beyond the SM - Opportunities and Benchmarks
- Summary

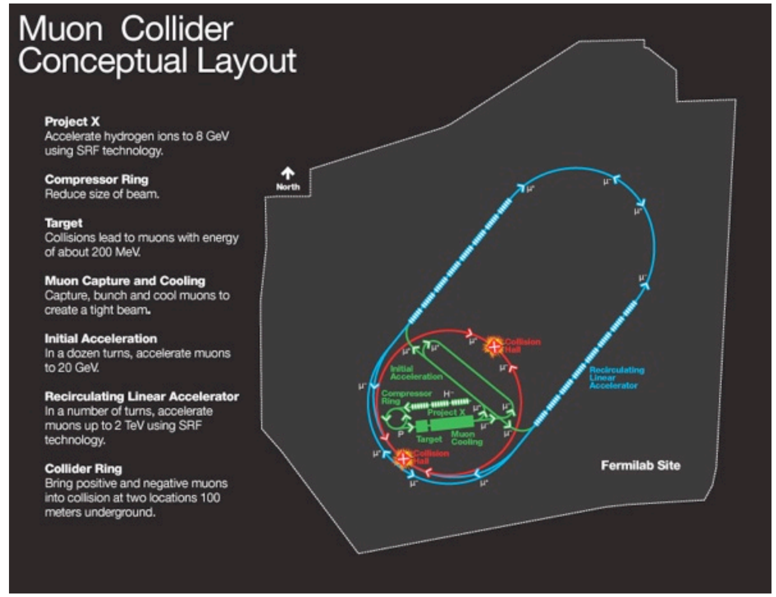


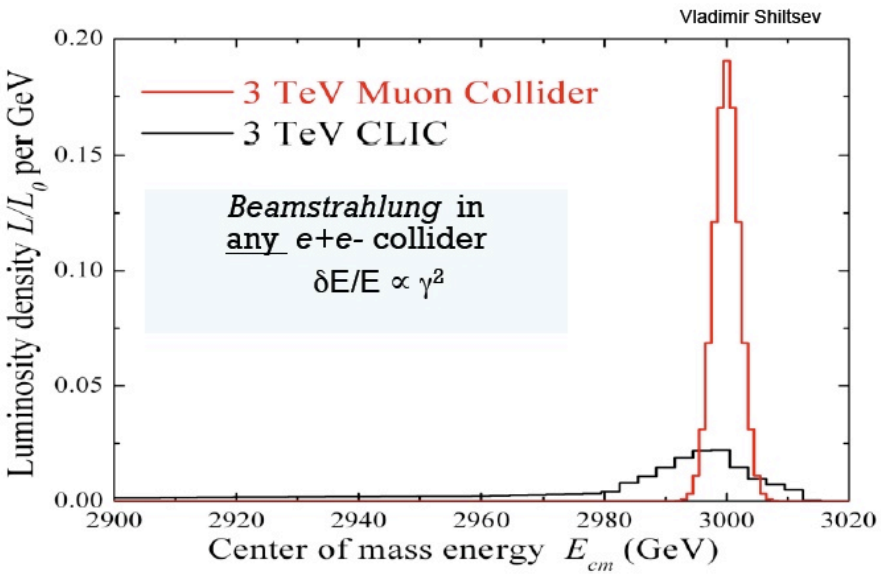
MUON ACCELERATOR PROGRAM
collaboration meeting

March 4-8, 2012, SLAC National Accelerator Laboratory Menlo Park CA

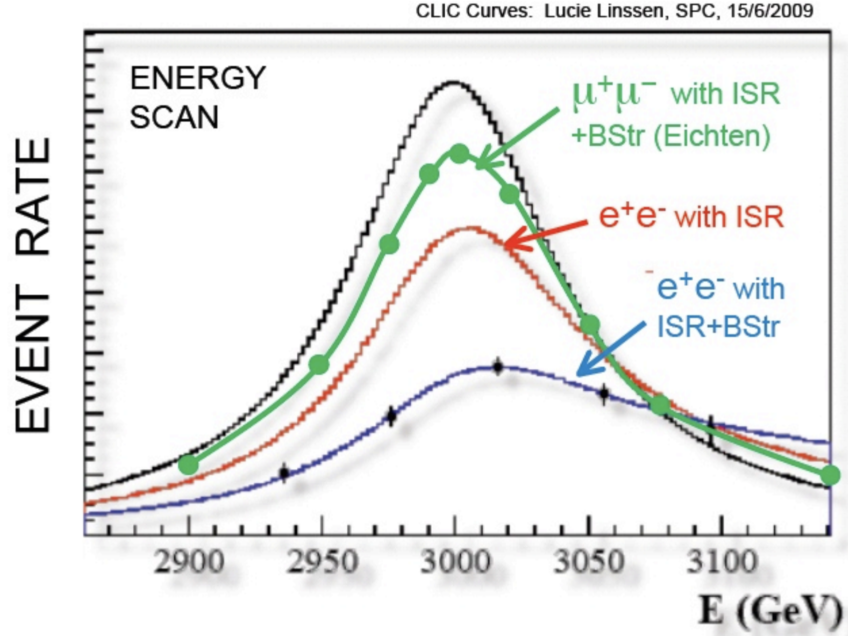
Basics of a Muon Collider

- $\mu^+\mu^-$ 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
  - 2 Detectors
- Superb Energy Resolution



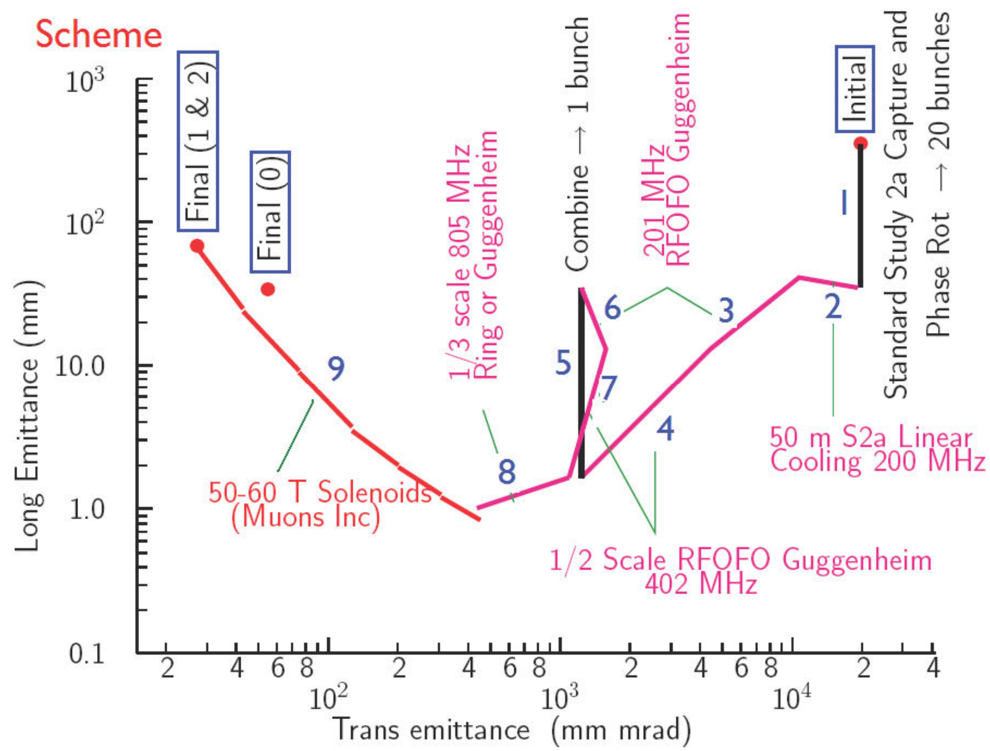


CLIC Curves: Lucie Linssen, SPC, 15/6/2009



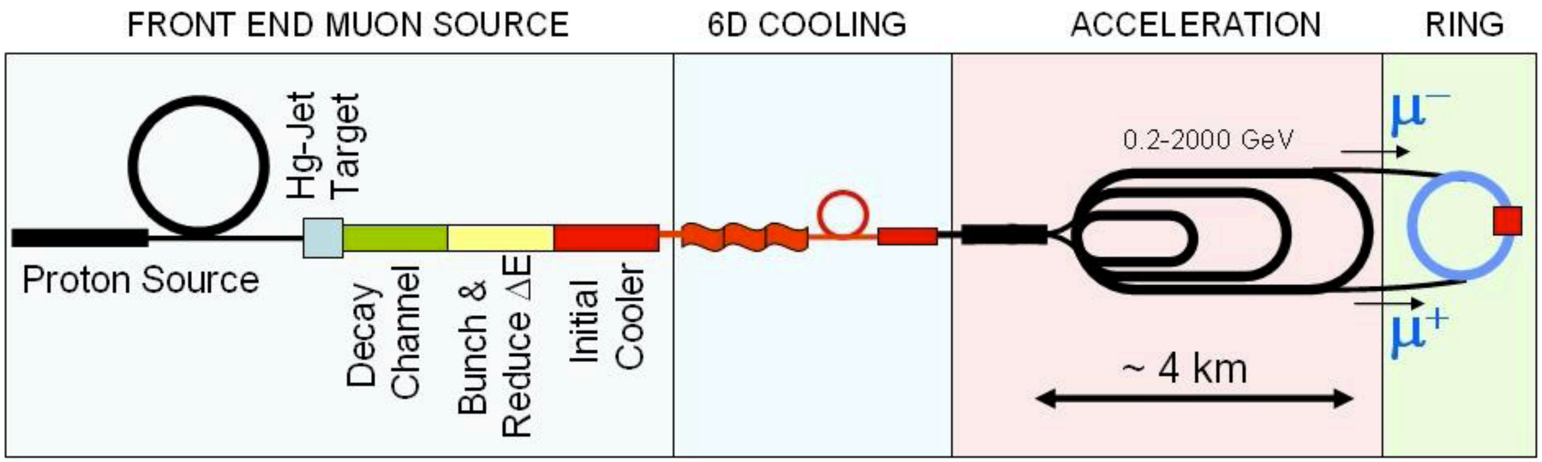
Basics of a Muon Collider

- 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 ($\mu^- \to \nu_\mu \nu_e e^-$) have high energies.
    - Detector background issues
    - Serious neutrino beam issue for Ecm ≥ 4 TeV



Basics of a Muon Collider

- A flexible scenario with physics at each stage:



Proton Source:
Upgraded PROJECT X
(4MW, 2±1 ns long bunches)

- μ -> e conversion
- Kaon physics
- EMD electron
- cold muons

10^{21} muons per year which fit within acceptance:

$\varepsilon_\perp \approx 6000\,\mu$m

$\varepsilon_{||} \approx 25$ mm

- neutrino beams to DUSEL

Muon final acceleration

- Neutrino factory
- MC Higgs Factory

Multi-TeV MC

- $\sqrt{s}$ = 3 TeV
- L = 3.5 x 10^{34} cm^{-2} sec^{-1}
- μ/bunch = 2×10^{12}
- circumference = 4.5 km
- $\sigma(p)/p$ = -0.1%

Basics of 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)
  - ΔT (bunch) ≈ 10 μsec (lots of time for readout; backgrounds don't pile up)

MC Ring Parameters (Y Alexahin) + RL modifications

				CLIC
C of m Energy	1.5	3	TeV	3
Luminosity	1	2 (4)	10^{34} cm^{2}sec^{-1}	2
Beam-beam Tune Shift	0.087	0.087		
Muons/bunch	2	2	10^{12}	
Total muon Power	7.2	11.5	MW	14
Ring <bending field>	6.04	8.4	T	
Ring circumference	2.6	4.5	km	
β^* at IP $= \sigma_z$	10	10 (5)	mm	4/.07 mm
rms momentum spread	0.1	0.1	%	29
Wall Power	147	159	MW	~415
Beam Size at IP	4	4	µm	0.001
Repetition Rate	15	12 (15)	Hz	
Proton Driver power	4	3.2 (4)	MW	
Muon Trans Emittance	25	25	pi mm mrad	660/20 nm
Muon Long Emittance	72,000	72,000	pi mm mrad	

Ronald Lipton 3/1/2012

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Basics of a Muon Collider

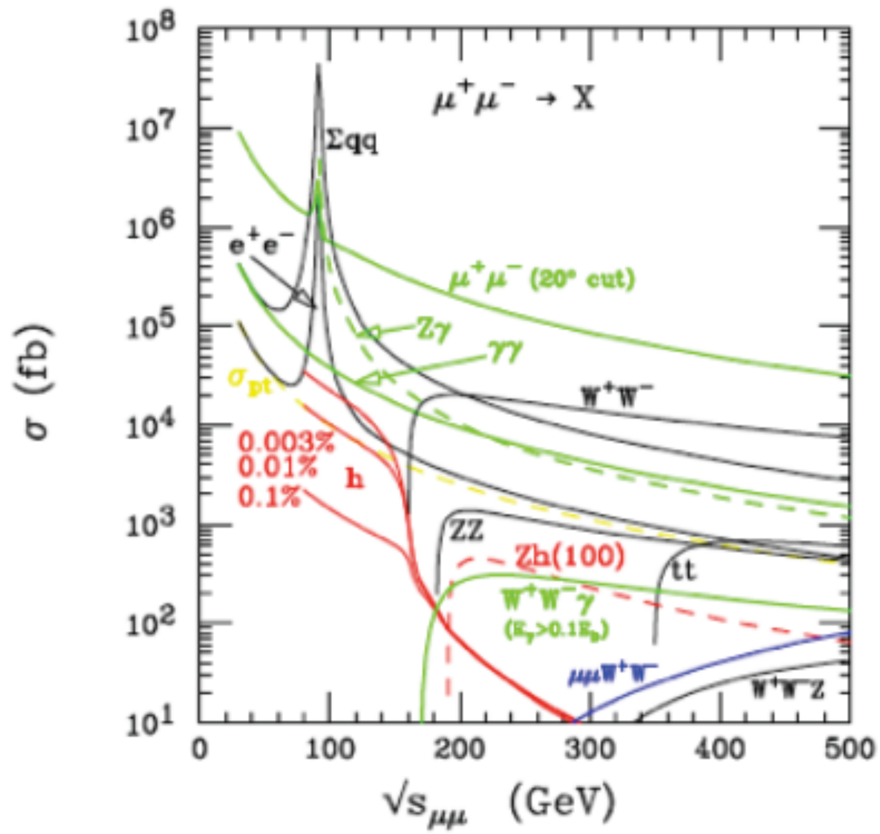
- For $\sqrt{s}$ < 500 GeV
- SM threshold region: top pairs; W^+W^-; Z^0Z^0; Z^0h; ...
- For $\sqrt{s}$ > 500 GeV
- For SM pair production ($|\theta| > 10°$)

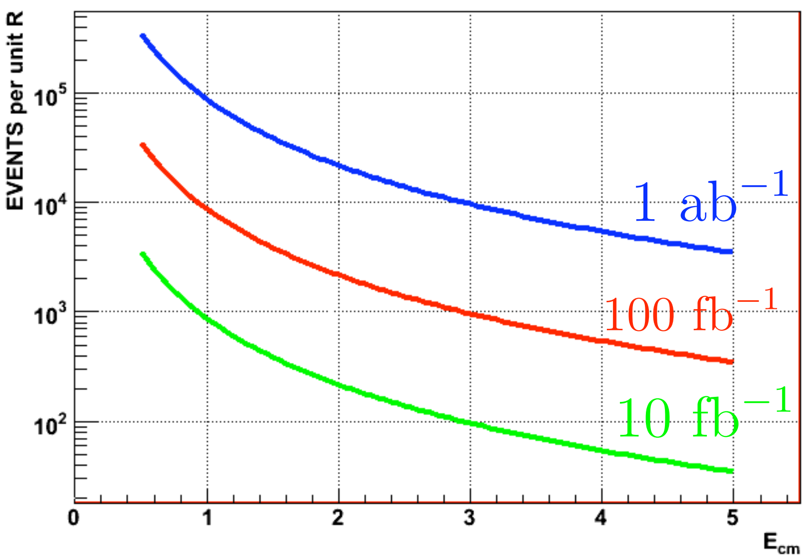
  R = $\sigma / \sigma_{QED}(\mu^+\mu^- \to e^+e^-)$ ~ flat

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

- High luminosity required

Standard Model Cross Sections





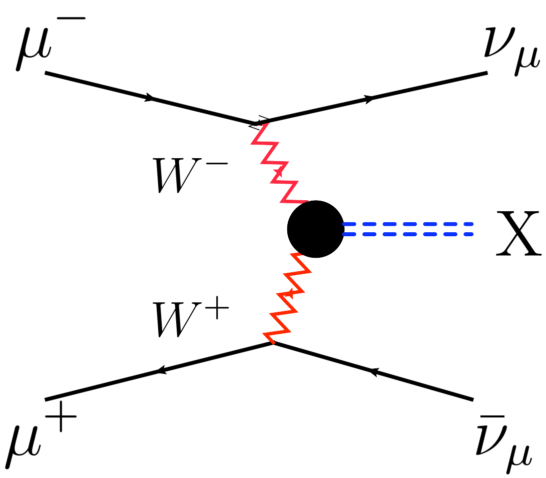
$$\sqrt{s} = 3.0 \text{ TeV} \qquad \mathcal{L} = 10^{34} \text{ cm}^{-2}\text{sec}^{-1}$$
$$\to 100 \text{ fb}^{-1}\text{year}^{-1}$$

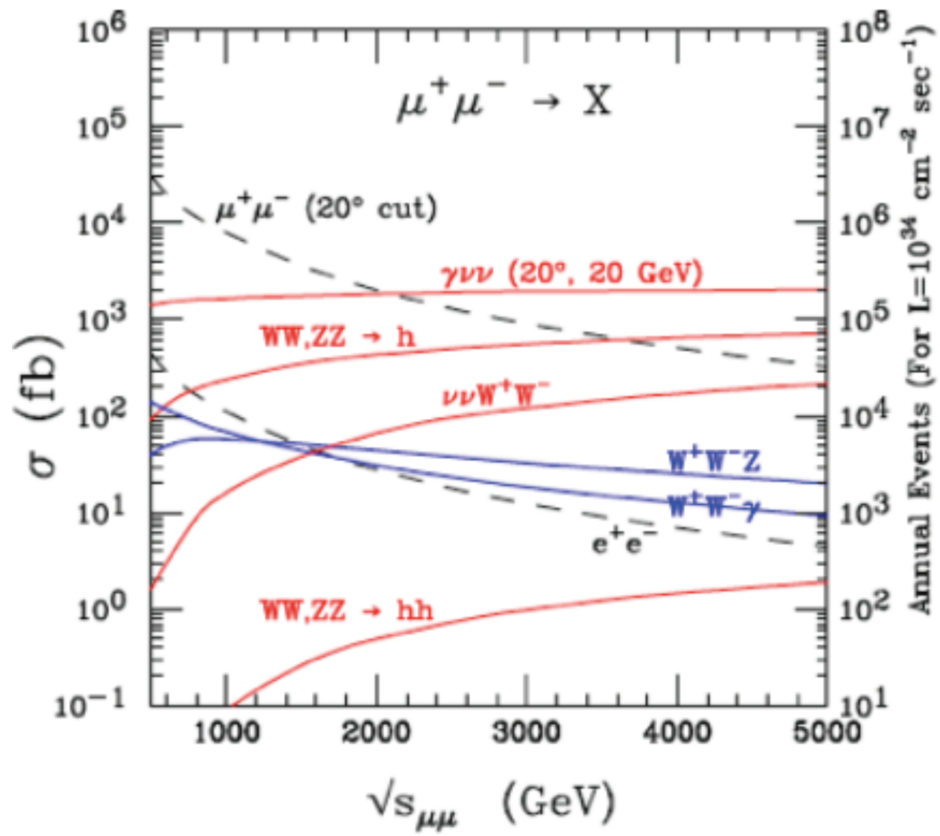
$\Rightarrow$ 965 events/unit of R

Processes with R ≥ 0.1 can be studied

Basics of a Muon Collider

- Fusion Processes
  - $\sqrt{s} > 1$ TeV large cross sections
  - Increase with $\sqrt{s}$
  - Important at multi-TeV energies
  - $M_X^2 < s$
  - t- channel processes (angular cuts)
  - Backgrounds for SUSY processes





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

- An Electroweak Boson Collider

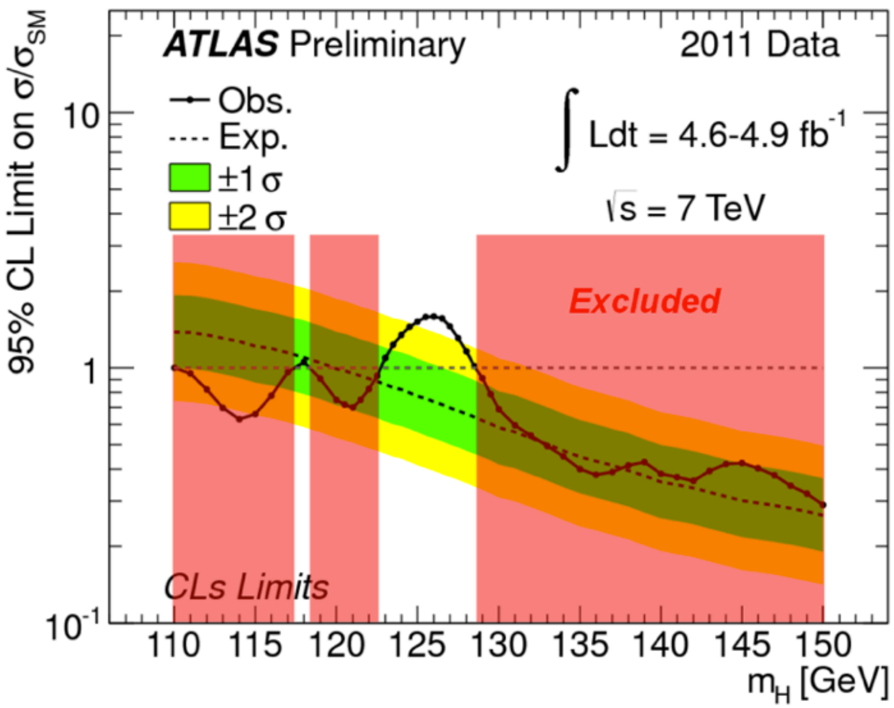
Implications of early LHC Results

- SM Higgs
  - SM Higgs boson mass excluded at 95% C.L.:

ATLAS
$$110 < m_h < 117.5 \text{ GeV}$$
$$118.5 < m_h < 122.5 \text{ GeV}$$
$$129 < m_h < 539 \text{ GeV}$$

CMS
$$127.5 < m_h < 600 \text{ GeV}$$

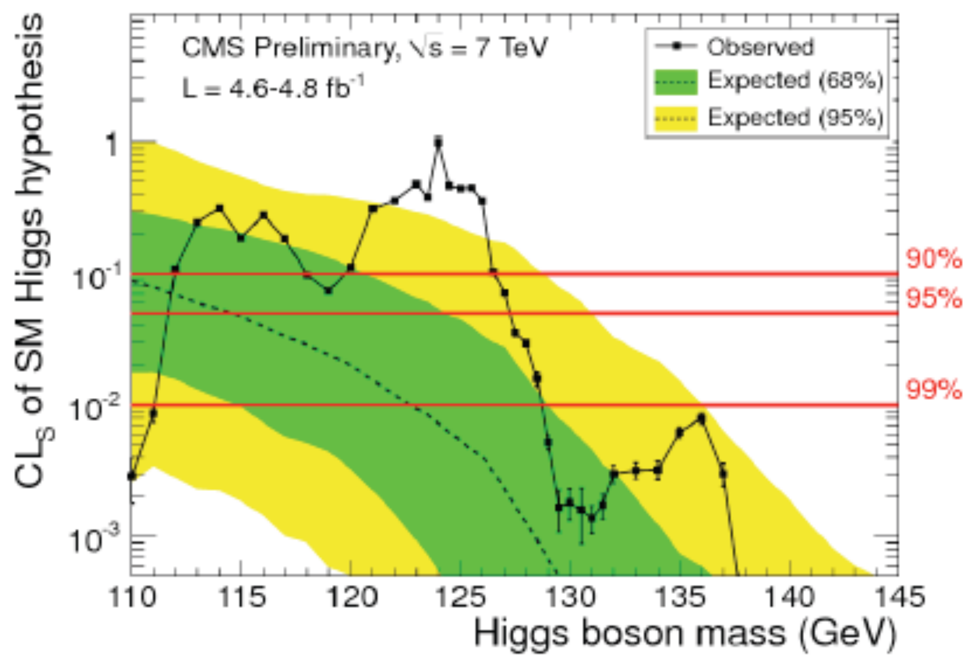
[S. Kortner Moriond(2012)]



[M. Pieri - Moriond(2012)]

CMS document HIG-12-008

Low mass region

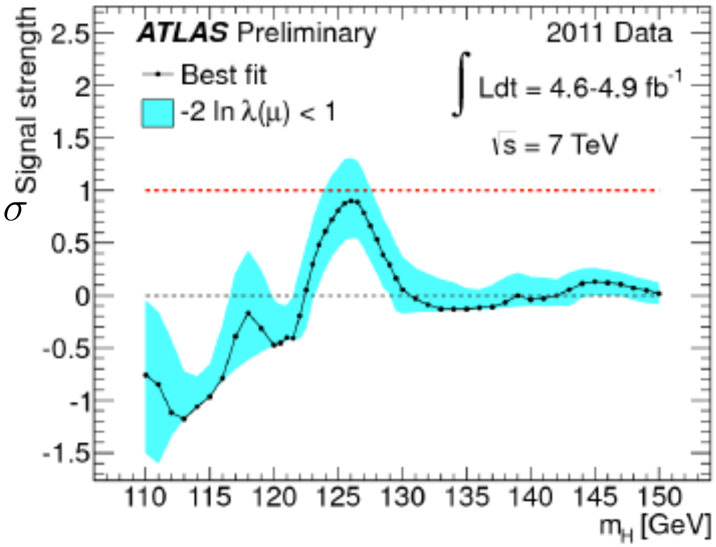


  - Excess at 125 GeV region

Implications of early LHC Results

- Compare to SM Higgs cross sections

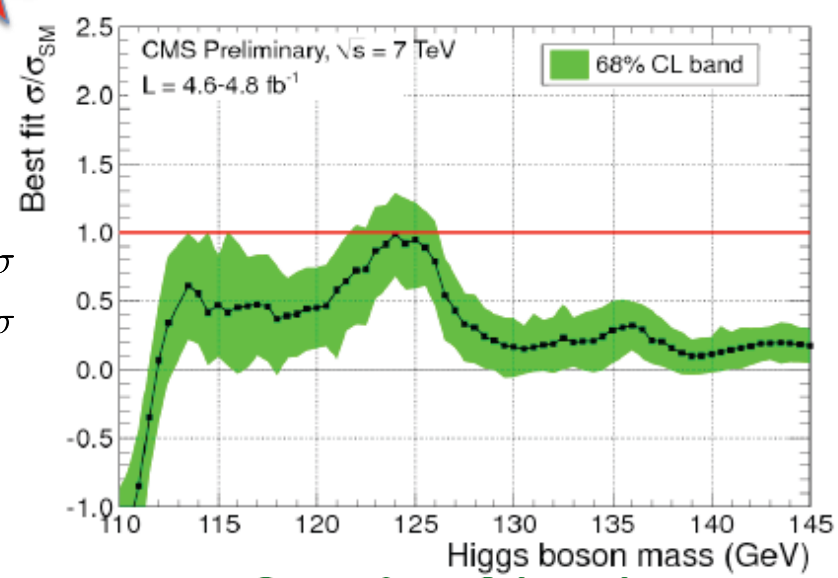
[local] $2.5\ \sigma$



NEW

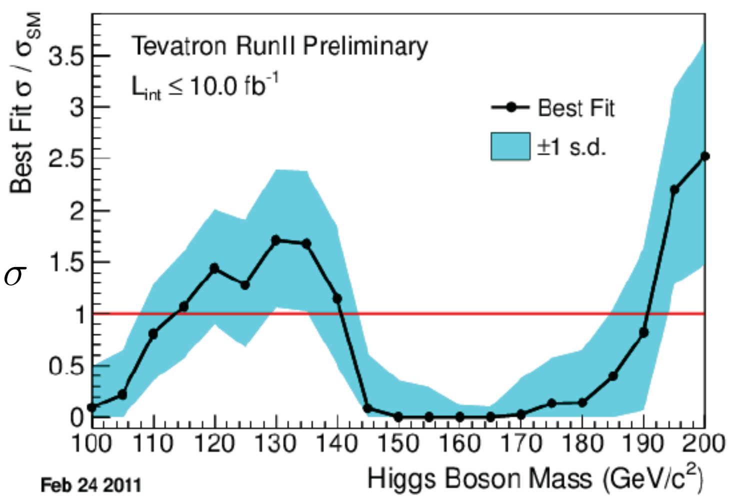
[local] $2.8\ \sigma$

$[110-145]\ 2.1\ \sigma$

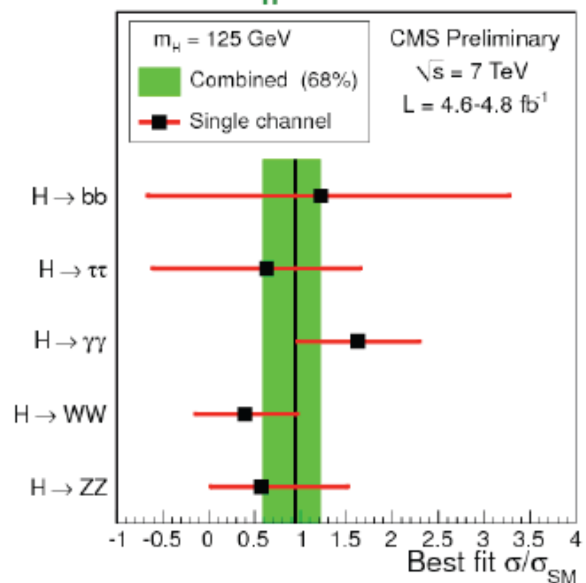


- Tevatron - 3/7/12 result dominately H->bb

[local] $2.7\ \sigma$



Comparison of channels for M_H=125 GeV



Implications of early LHC Results

- Excess in the 125 GeV region : If confirmed - Is it the SM higgs?
- spin and parity :

  $[Z^0Z^0]$ P.S. Bhupal Dev, et. al. [arXiv:0707.2878]

  $[W^+W^-]$ J. Ellis and D.S. Hwang [arXiv:1202.6660]

- measure couplings

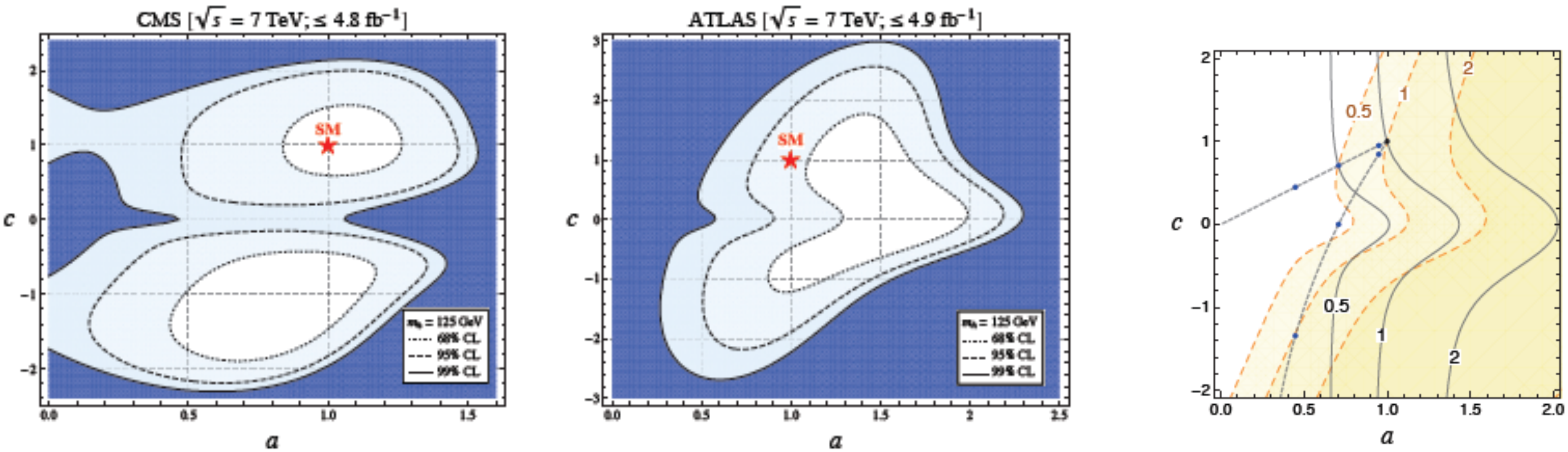
$$\Sigma(x) = \exp\left(i\sigma^a \chi^a(x)/v\right)$$

$$\mathcal{L} = -V(h) + \mathcal{L}^{(2)} + \mathcal{L}^{(4)} + \dots$$

$$\begin{aligned}\mathcal{L}^{(2)} = & \frac{1}{2}(\partial_\mu h)^2 + \frac{v^2}{4}\mathrm{Tr}\left(D_\mu \Sigma^\dagger D^\mu \Sigma\right)\left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + \cdots\right) \\ & - \frac{v}{\sqrt{2}}\lambda^u_{ij}\left(\bar{u}^{(i)}_L, \bar{d}^{(i)}_L\right)\Sigma\left(u^{(i)}_R, 0\right)^T\left(1 + c_u\frac{h}{v} + c_{2u}\frac{h^2}{v^2} + \cdots\right) + h.c. \\ & - \frac{v}{\sqrt{2}}\lambda^d_{ij}\left(\bar{u}^{(i)}_L, \bar{d}^{(i)}_L\right)\Sigma\left(0, d^{(i)}_R\right)^T\left(1 + c_d\frac{h}{v} + c_{2d}\frac{h^2}{v^2} + \cdots\right) + h.c. \\ & - \frac{v}{\sqrt{2}}\lambda^l_{ij}\left(\bar{\nu}^{(i)}_L, \bar{l}^{(i)}_L\right)\Sigma\left(0, l^{(i)}_R\right)^T\left(1 + c_l\frac{h}{v} + c_{2l}\frac{h^2}{v^2} + \cdots\right) + h.c.\end{aligned}$$

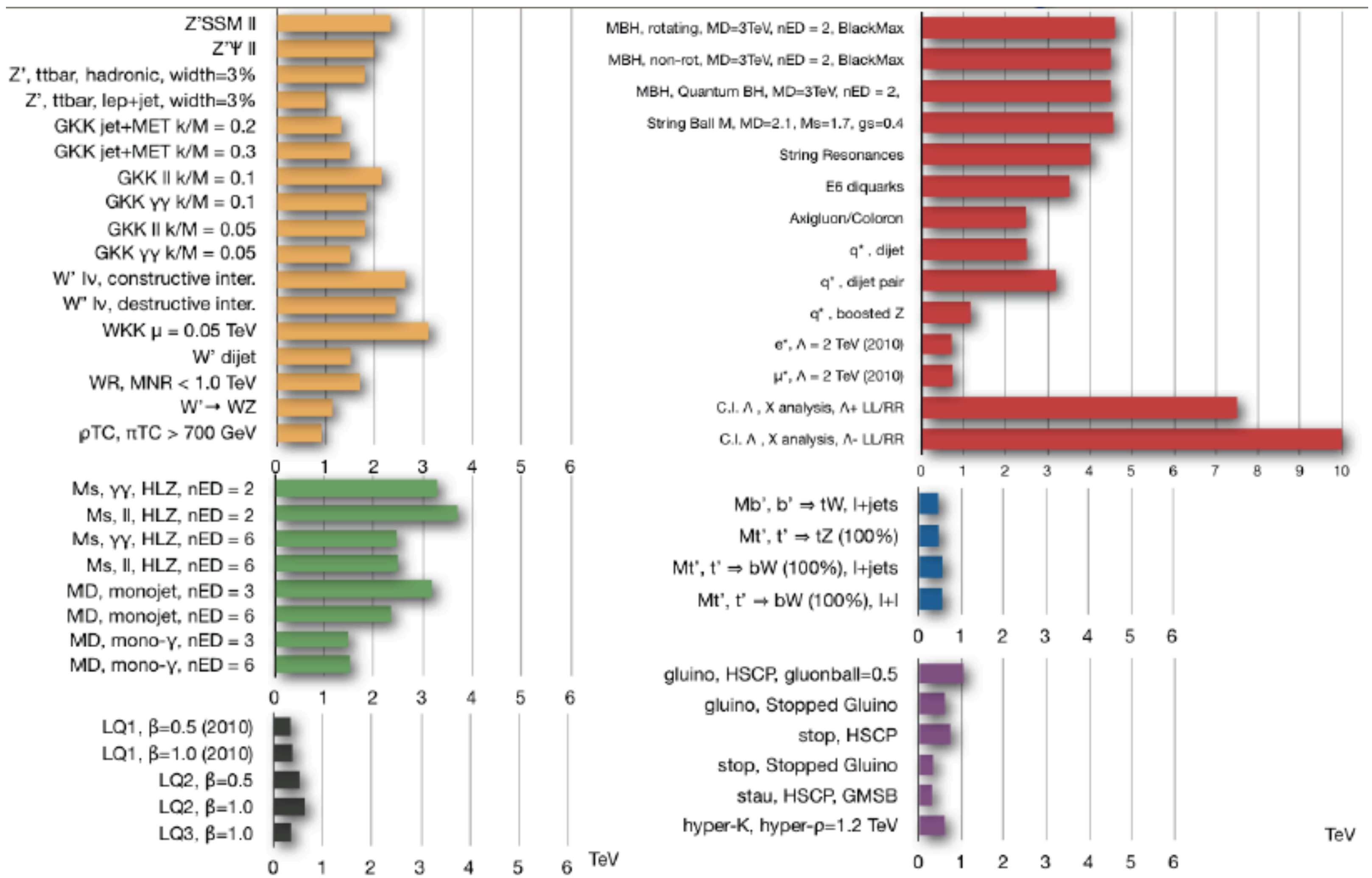
A. Azatov, R. Contino, J. Gallowa
[arXiv:1202.3415]

assume $c_u = c_d = c_l$



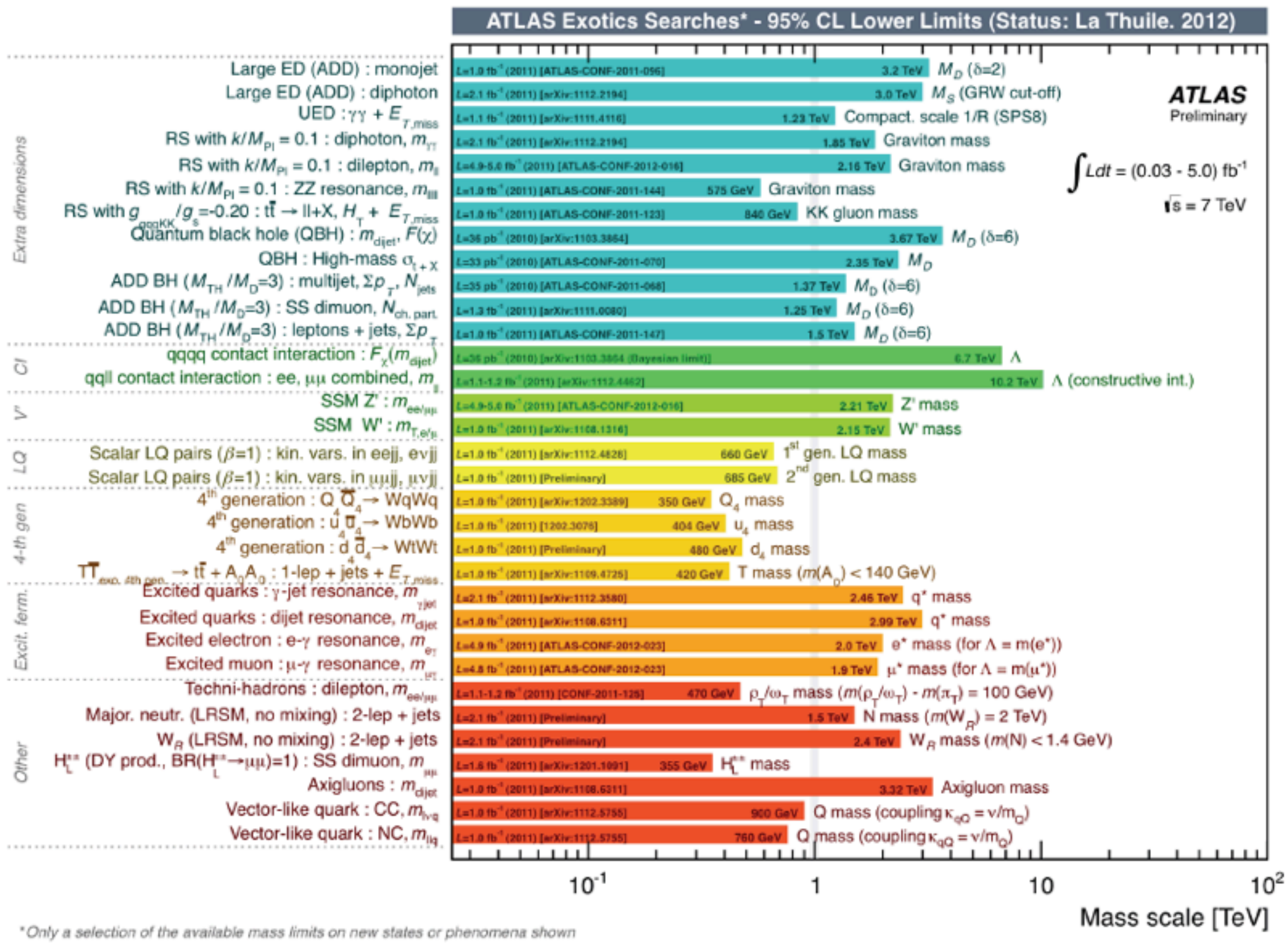
Implications of early LHC Results

- BSM Limits
  - CMS



Implications of early LHC Results

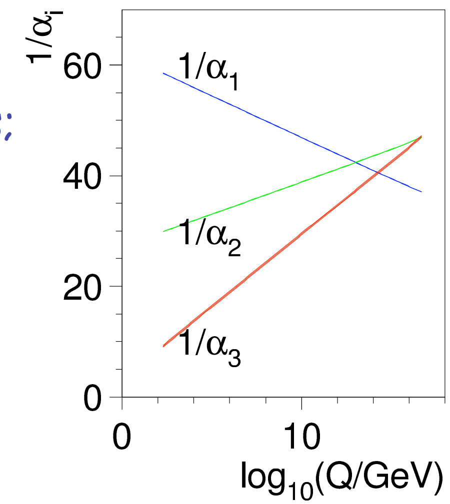
- BSM Limits
  - ATLAS



- No evidence from CMS/ATLAS for anything beyond the standard model yet.

Implications of early LHC Results

- But we know that 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



- Experimental hints: $(g\text{-}2)_\mu$, top A_{fb}, ...

- 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

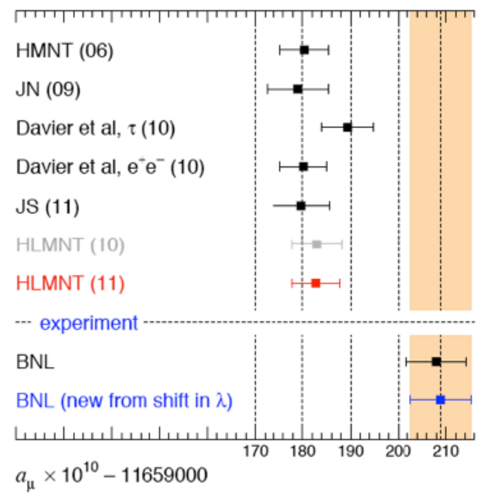
muon (g-2)

Davier, Hoecker, Malaescu, Zhang

Jegerlehner, Szafron

Hagiwara, Liao, Martin, Nomura, Teubner

hadronic VP contributions
$(685 \pm 4) \times 10^{-10}$



There remains a persistent discrepancy of 3.3-3.6 σ

The Scalar Sector

- Concept of naturalness.
  - K. Wilson, G. 't Hooft
  - A theory [L(μ)] is natural at scale μ ⇔ for any small dimensionless parameter λ (e.g. 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 Higgs, 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

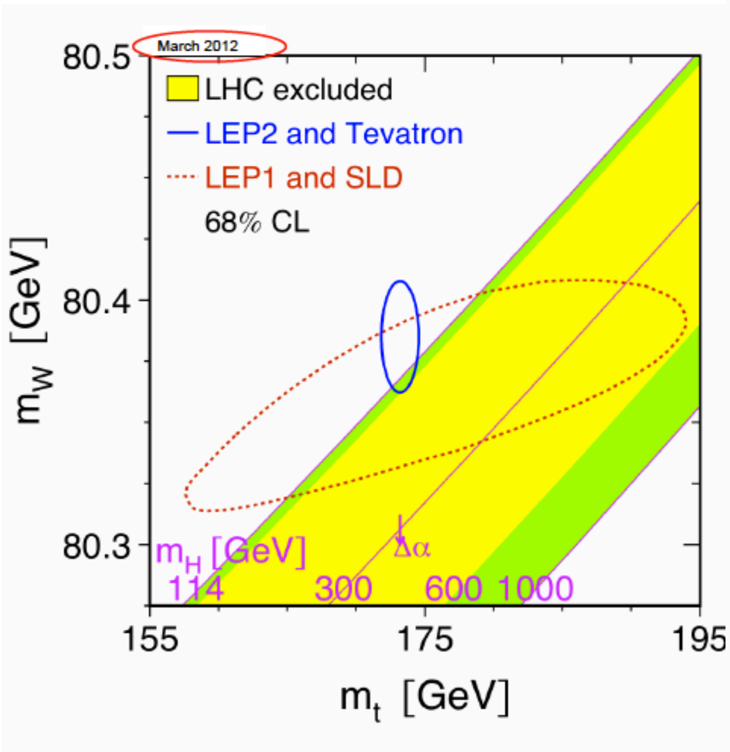
Utrecht, The Netherlands

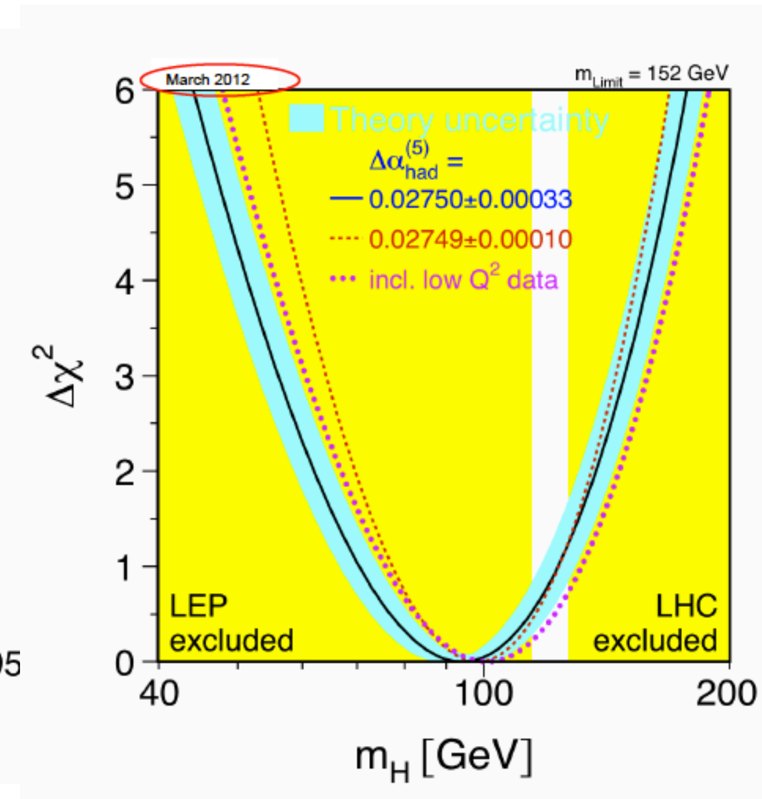
ABSTRACT

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

The Scalar Sector

- SM Higgs
  - New m(W) measurements from CDF/Dzero





Zfitter, LEPEWWG

<u>Previous SM Higgs fit:</u>

$m_H = 92^{+34}_{-26}$ GeV

$m_H < 161$ @ 95% C.L.

<u>New preliminary SM Higgs fit:</u>

$m_H = 94^{+29}_{-24}$ GeV

$m_H < 152$ @ 95% C.L.

  - Consistent with 125 GeV SM Higgs

The Scalar Sector

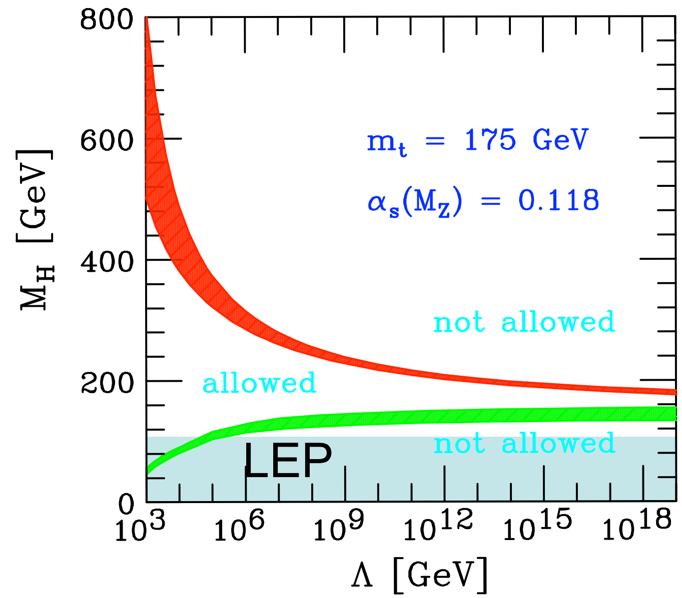
- Consistency of SM :
  - Upper bound - A large Higgs mass requires a large higgs self-coupling term. This coupling increases with the scale Λ.

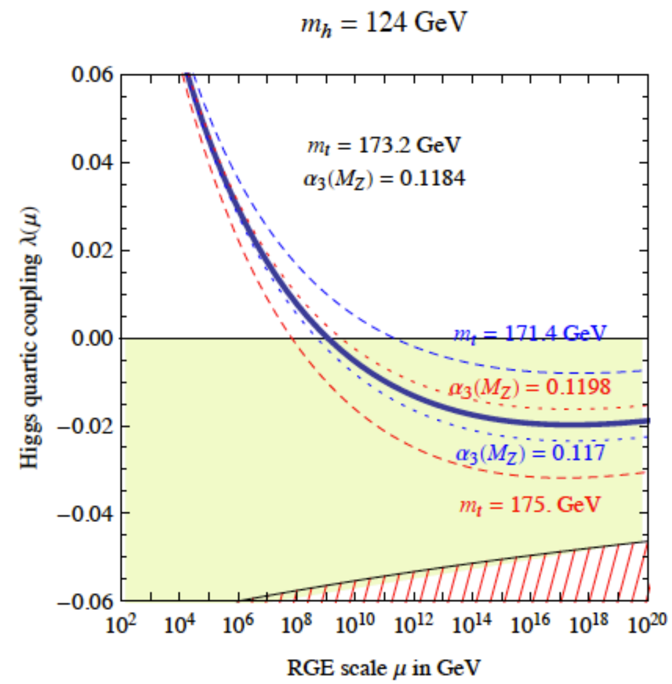
    No higgs below 600 GeV -> New strong dynamics nearby.
  - Lower bound - For small Higgs mass, the quantum corrections can lead to vacuum instability.
  - m_h ~ 125 GeV:

    SM consistent all the way to Planck scale.

    Vacuum metastable.

    Favors SM or SUSY





J. Elias-Miro, et. al. [arXiv:1112.3022]

The Scalar Sector

- Theoretical issues
  - Couplings and width SM?
  - Scalar self-coupling SM?
  - Any additional scalars? EW doublets, triplets or singlets?

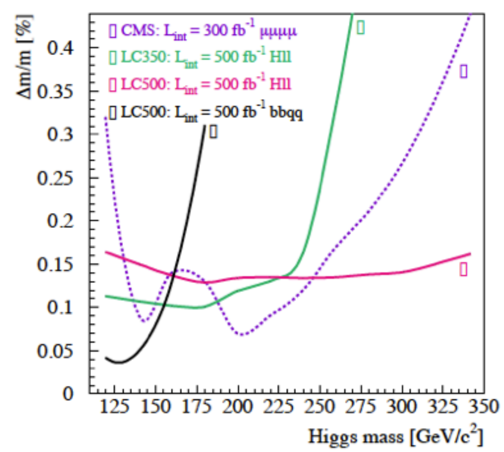
$h(125)$	$\longrightarrow$	$b\bar{b}$	5.78×10^{-1}	W^+W^-	2.16×10^{-1}
		$\tau\bar{\tau}$	6.37×10^{-2}	Z^0Z^0	2.67×10^{-2}
		$c\bar{c}$	2.68×10^{-2}	gg	8.56×10^{-2}
		$s\bar{s}$	4.40×10^{-4}	$\gamma\gamma$	2.30×10^{-3}
		$\mu^+\mu^-$	2.21×10^{-4}	$Z^0\gamma$	1.55×10^{-3}

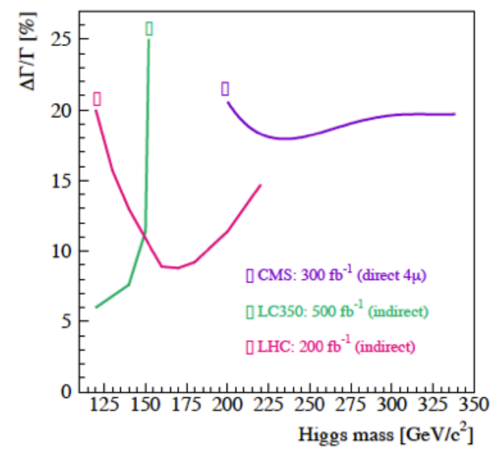
- Role of Lepton Colliders
  - Many couplings can be determined at the LHC
  - A Linear Collider allows detailed study of the Higgs properties.
  - S channel Higgs production
    - Higgs couples to mass

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

    - Narrow width

$$\Gamma(h(125)) = 4.03 \text{ MeV}$$





The Scalar Sector

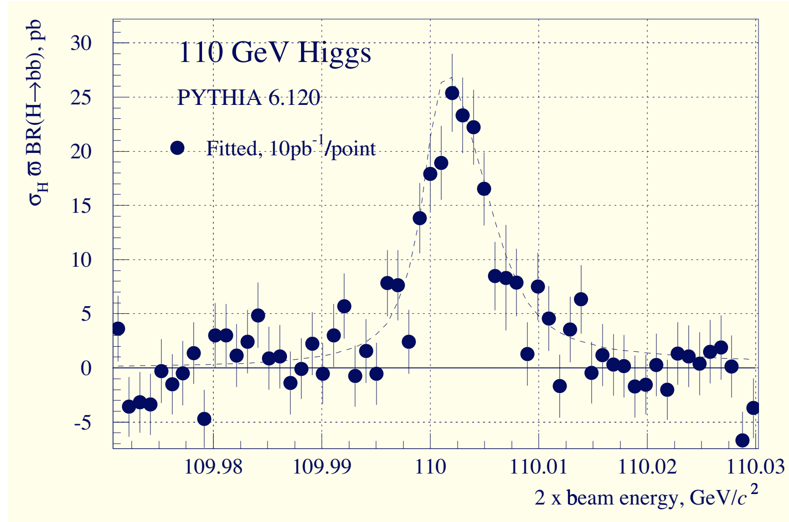
- Only a low energy Muon Collider could directly measure width of h(125).
  - Requires precise energy resolution

    $\Delta E/E = 10^{-5}$

  - Can such a resolution be achieved?
  - S/B studies?
  - Integrated luminosity?

    scan 109-111 -> 20 fb^{-1}

  - What error on the Higgs width would be possible?



J. Gunion, MC workshop (2008)

- Detailed study needed here !!!

The Scalar Sector

- Various processes available for studying the Higgs at a multi-TeV muon collider
  - Associated production: Zh^0
    - $R \sim 0.12$
    - search for invisible h^0 decays
  - Higgsstrahlung: $t\bar{t}h^0$
    - $R \sim 0.01$
    - 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)
    - $\nu_\mu\bar{\nu}_\mu h^0h^0$: measure Higgs self couplings

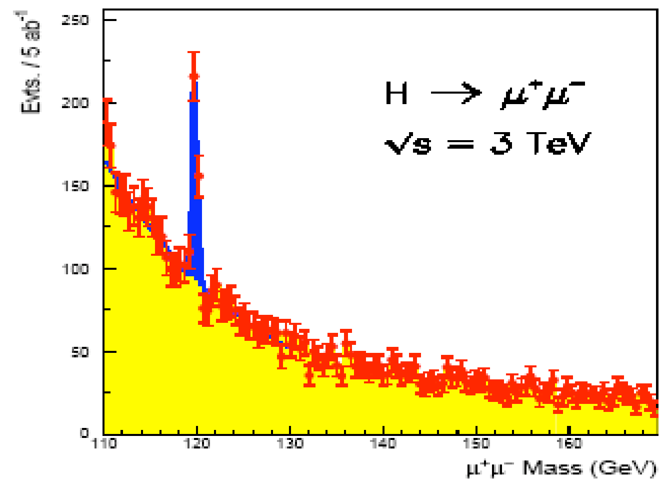
MC or CLIC:

needs 10 ab^{-1}

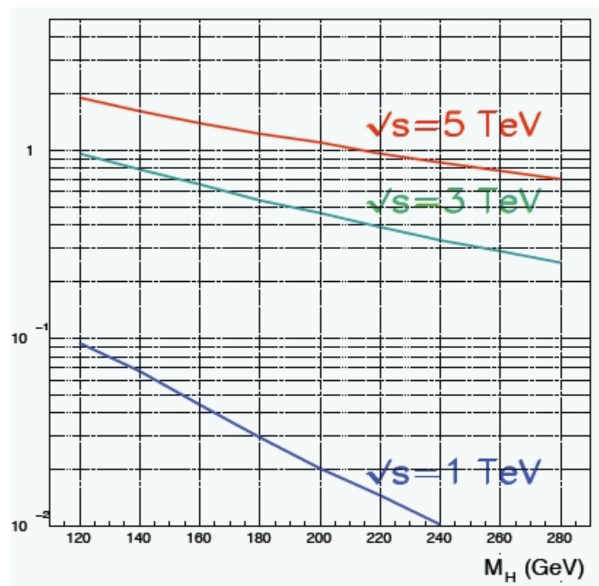
MC or CLIC:

good benchmark process

m(H) = 120 GeV



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



BSM Opportunities and Benchmarks

- Many Options
  - Two Higgs Doublets
  - 4th generation: Z,' W'; KK modes
  - SUSY
  - New Strong Dynamics
  - Contact Terms
  - ...
- The early data from the LHC is already putting constraints on the BSM physics options.
- Benchmarks discussed at Muon Collider 2011 meeting.

  http://conferences.fnal.gov/muon11/
  - Physics talks by Chris Hill, Marco Battaglia, Jack Gunion, Tao Han, E.E.
- Will need adjustment as the 2012 run LHC data is analysed.

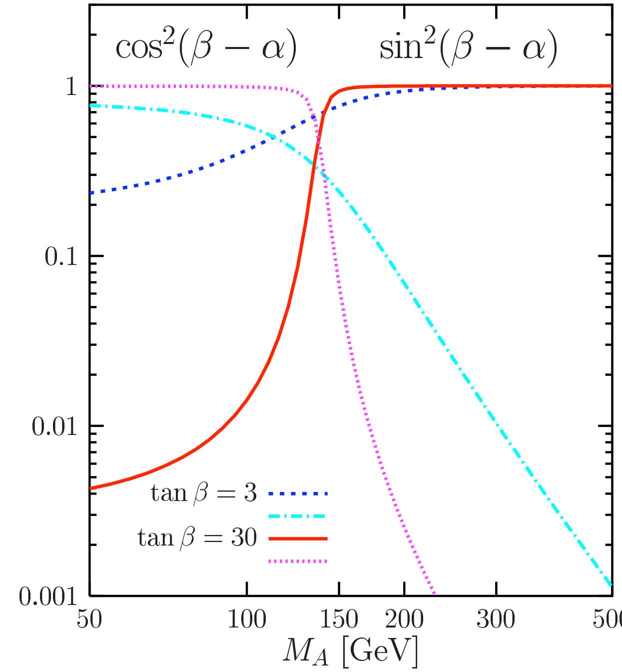
Two Higgs Doublets (MSSM)

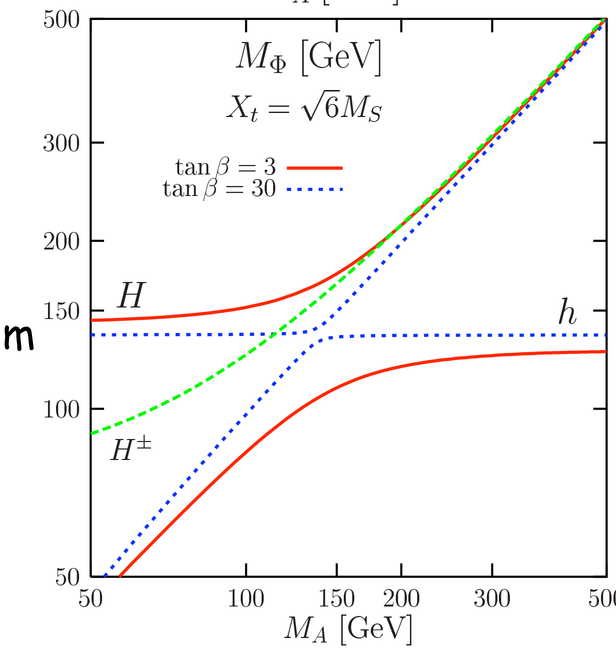
- Five scalar particles: h^0, H^0, A^0, $H^\pm$
- Decay amplitudes depend on two parameters: (α, β)

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

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

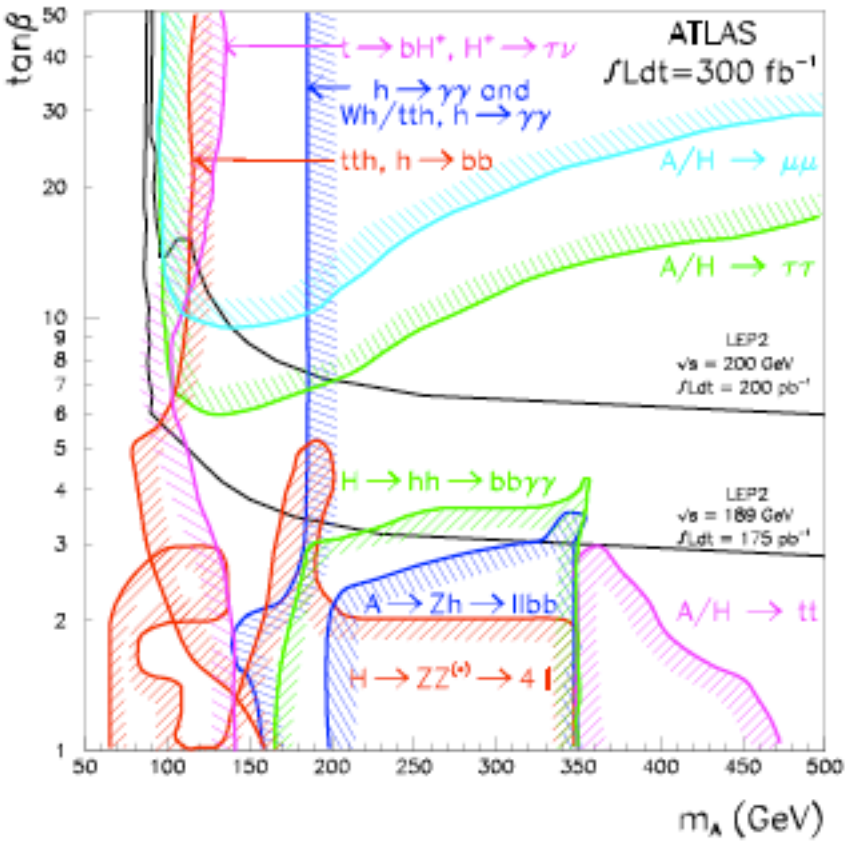
- decoupling limit $m_{A^0} \gg m_{Z^0}$:
  - h^0 couplings close to SM values
  - H^0, $H^\pm$ and A^0 nearly degenerate in mass
  - H^0 small couplings to VV, large couplings to ZA^0
  - For large $\tan\beta$, H^0 and A^0 couplings to charged leptons and bottom quarks enhanced by $\tan\beta$. Couplings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





Two Higgs Doublets (MSSM)

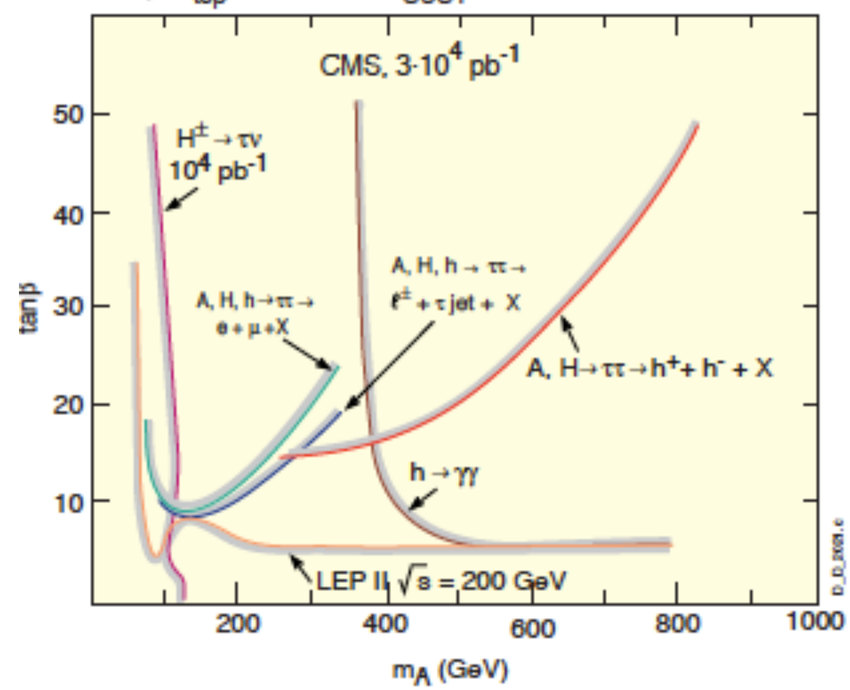
- The LHC has difficulty observing the H, A especially for masses > 500 GeV. Even at $\sqrt{s}$ = 14 TeV and 300 fb^{-1}.



Significance contours for SUSY Higgses

Regions of the MSSM parameter space (m_A, tgβ) explorable through various SUSY Higgs channels

- 5 σ significance contours
- two-loop / RGE-improved radiative corrections
- m_{top} = 175 GeV, m_{SUSY} = 1 TeV, no stop mixing ;

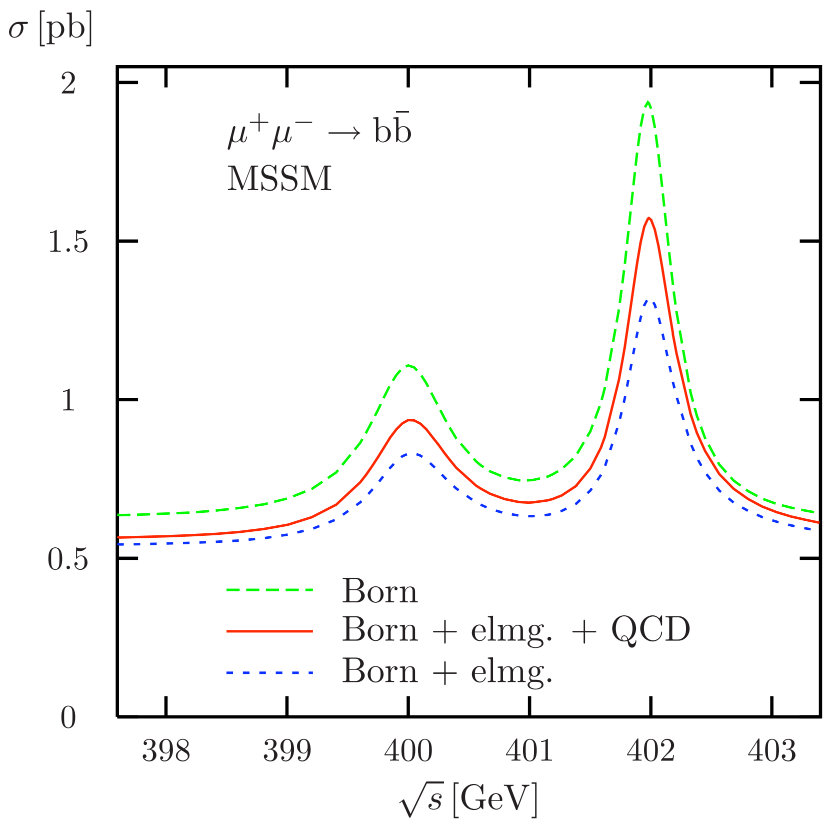


- Pair produced with easy at a multi-TeV lepton collider.

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



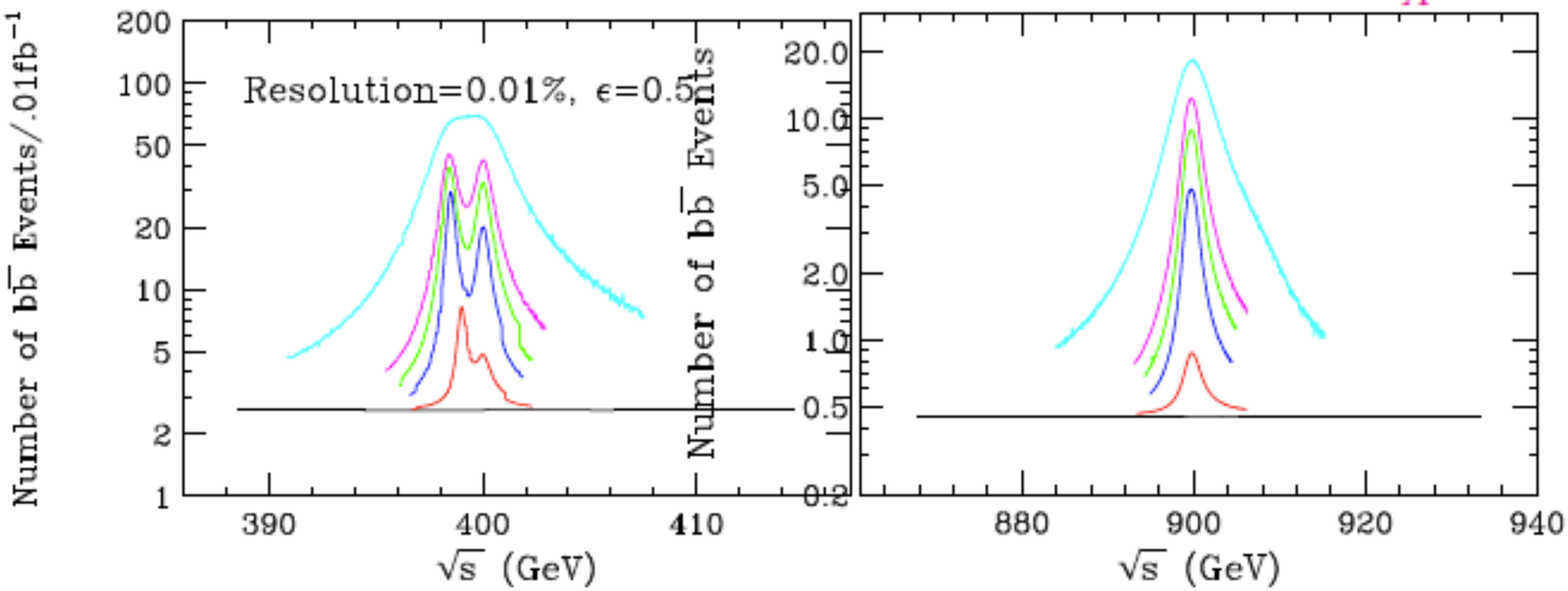
Dittmaier and Kaiser [hep-ph/0203120]

Two Higgs Doublets (MSSM)

- Enlarged scalar sector
  - Two Higgs Doublet Models: (h, H^0, $H^\pm$, A^0)

[J. Gunion and T. Han, Muon ColliderWorkshop 2011)

Heavy Higgs degenerate as M_A large: $\delta M \approx \frac{M_Z^2}{2M_A}\sin^2 2\beta$.



400 GeV Higgses resolved! 900 GeV Higgses not resolvable.‡

4th generation; Z', W'; and KK modes

- Fourth generation quarks:
  - Standard
  - Vectorlike
  - Small pair production cross sections in a lepton collider requires high luminosity (1 ab^{-1})
- New Z', W'
  - S-channel resonances - factories for lepton colliders
  - Set minimum lumonisity for MC.
- KK Modes
  - Expected in models with Extra Dimensions
  - Discover at LHC - detailed study at MC

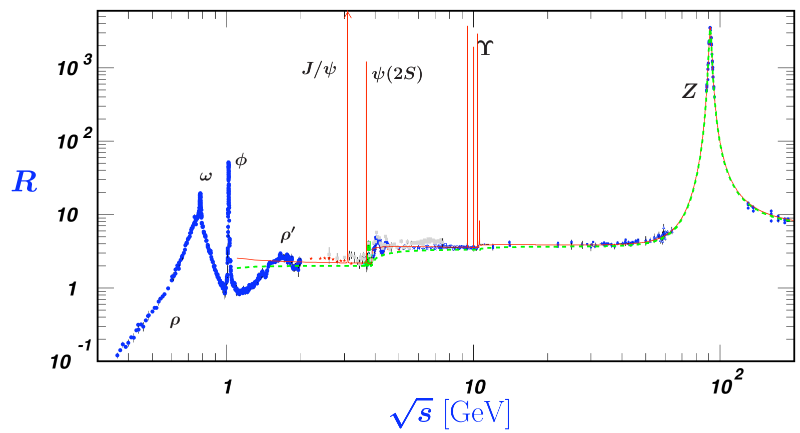
$t' \to b\, W^+$ M(t') > 552 GeV [CMS]

$b' \to t\, W^-$ M(b') > 600 Gev [CMS]

VLQ -> V + q (V = Z, W) [ATLAS]

CC: m_{VLQ} > 0.90 TeV @ 95%

NC: m_{VLQ} > 0.76 TeV @ 95%



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

4th generation; Z', W'; and KK modes

- New limits from the ATLAS and CMS

[CMS] $M'_W > 2.53(+)$ TeV; $M_W > 2.43(-)$ TeV

ATLAS-CONF-2012-007

	E_6 Z' models						RS graviton			
Model/Coupling	Z'_ψ	Z'_N	Z'_η	Z'_I	Z'_S	Z'_χ	0.01	0.03	0.05	0.1
Mass limit [TeV]	1.76	1.78	1.84	1.84	1.90	1.96	0.91	1.45	1.71	2.16

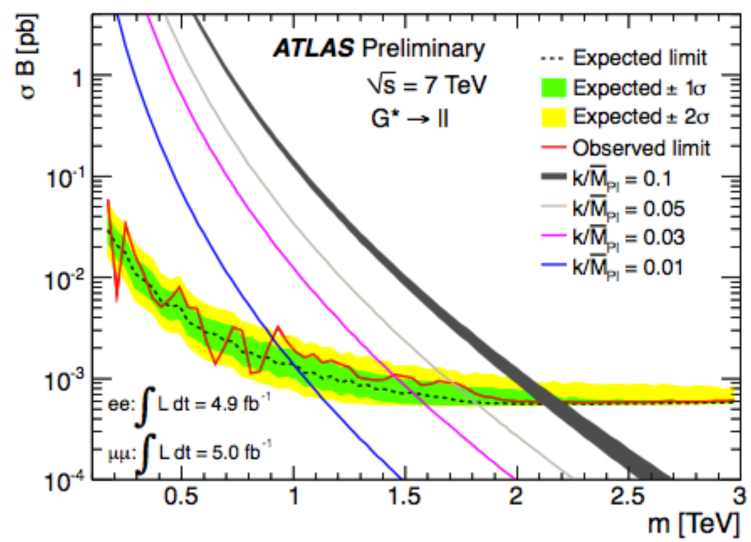
- Beyond reach of an ILC.
- A muon collider can be built to operate well above 4 TeV :
  - Keeping the same limits on neutrino radiation. The luminosity will scale as:

$$L(\mathrm{E}_{cm})/L(4\ \mathrm{TeV}) = [\mathrm{E}_{cm}/(4\ \mathrm{TeV})]^{-2}$$

  - If the emittance can be reduced as the energy is increased, up to one power of energy ratio can be recovered.
  - Hence s-channel resonaces well in excess of 10 TeV can be studied in detail at a muon collider. [If theory or experiment predicts such a resonance at a known mass.]

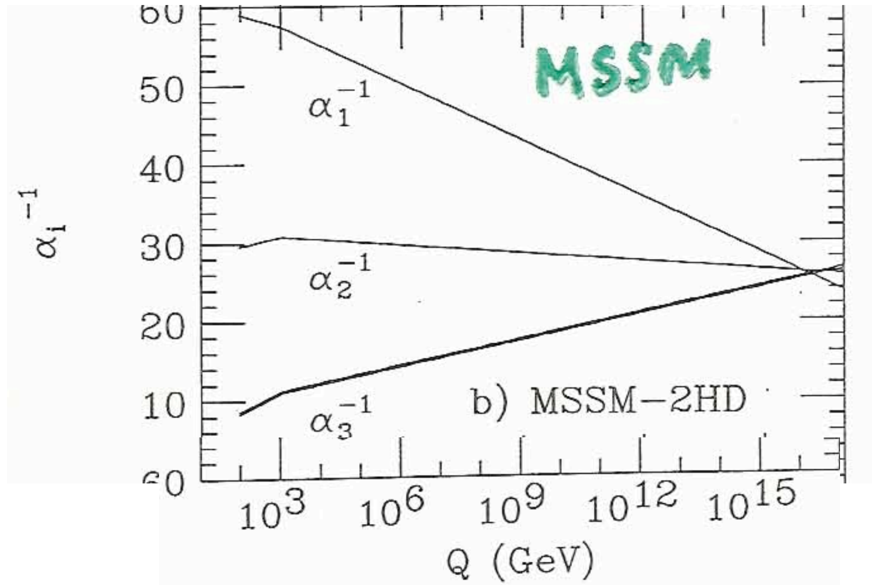
$m_{Z'} > 2.21$ TeV @ 95%

$m_{G^*} > 2.16$ TeV @ 95% for $k/M_{Pl} = 0.1$



SUSY

- 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?

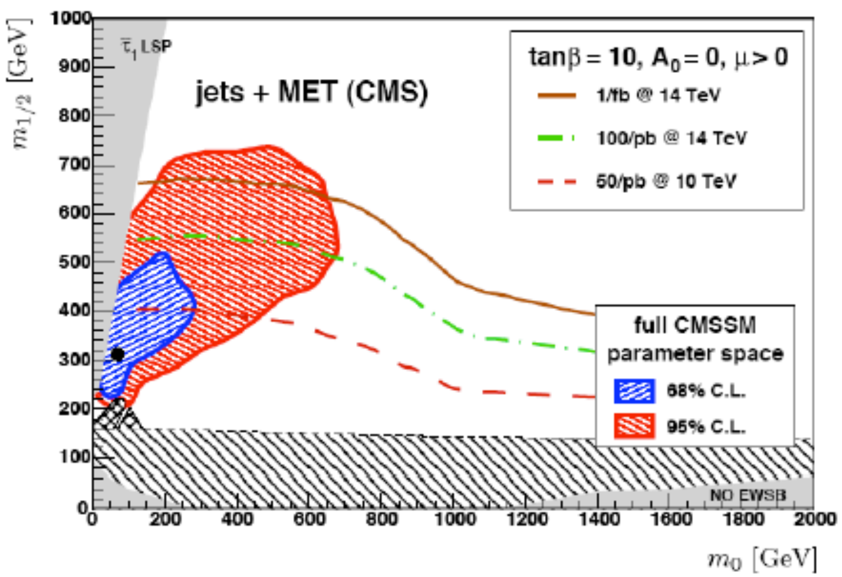


- cMSSM [Constrained Minimal Supersymmetric Standard Model]
  - Five parameters: m_0, $m_{1/2}$, $\tan\beta$, A/m_0, sign(μ)
  - Experimental constraints
    - Direct limit (LEP, CDF, Dzero, CMS, ATLAS): $m_{h^0}, m_{\chi^+}, m_{\tilde{t}}, \ldots$
    - Electroweak precision observables (EWPO): $M_W^2,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

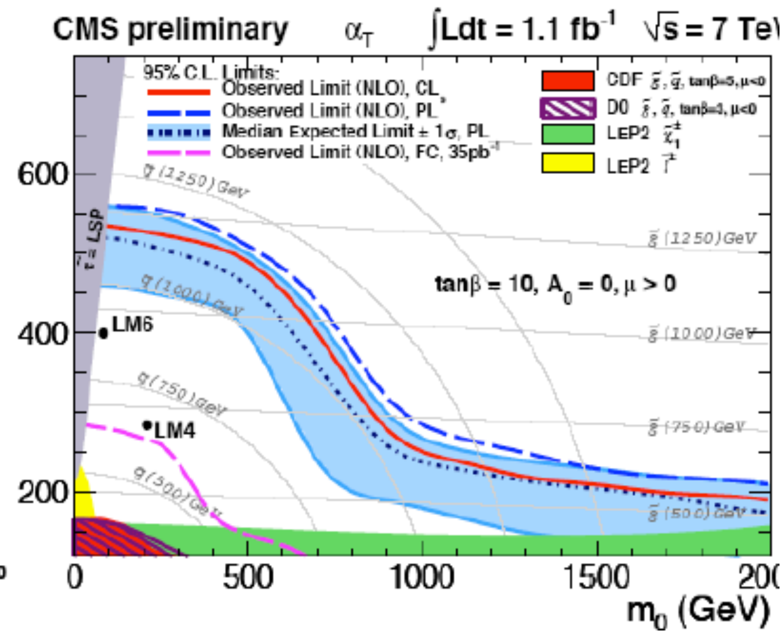
SUSY

- "It is time to give up on the cMSSM" M. Peskin, Lepton-Photon 2011 Summary

Buchmuller, … , DeRoeck, Ellis …
2008



CMS LP11 α_T analysis



As μ^2 increases,

more fine tuning

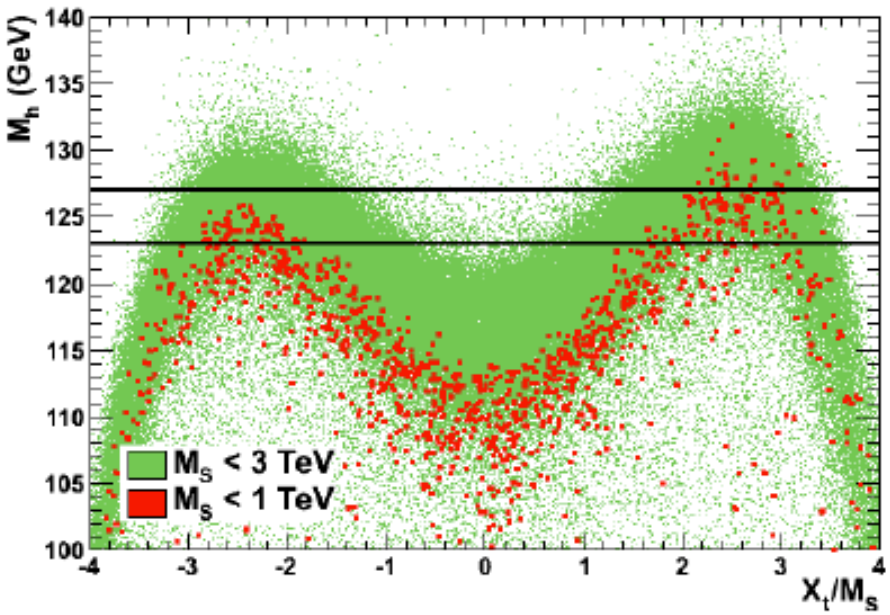
$$m_Z^2 = 2\,\frac{M_{Hd}^2 - \tan^2\beta M_{Hu}^2}{\tan^2\beta - 1} - 2\mu^2$$

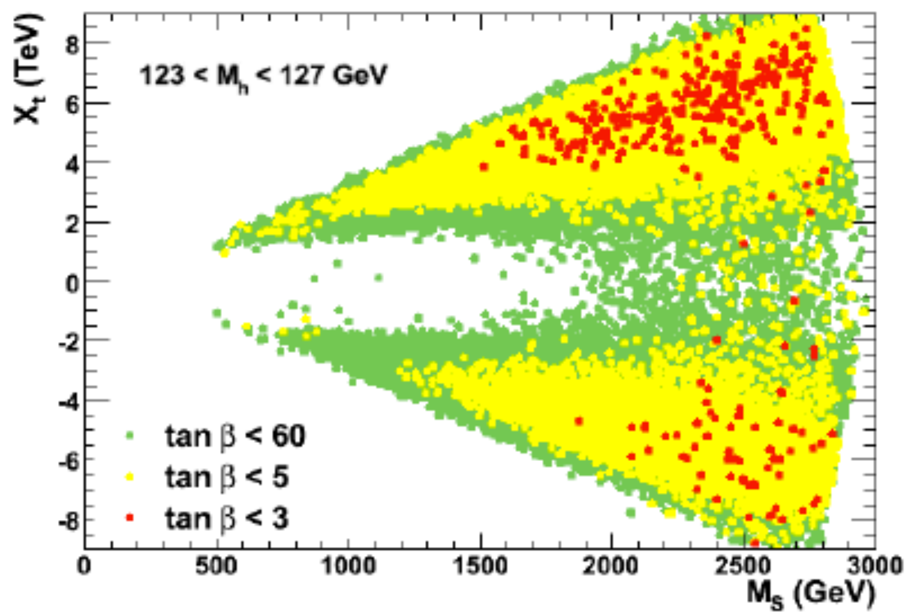
+ loop corrections: logs($m_{\tilde{t}}/m_t$)

SUSY

- pMSSM - minimal assumptions on SUSY breaking parameters
  - 22 parameters varied $$1 \le \tan\beta \le 60\,,\ 50\ \mathrm{GeV} \le M_A \le 3\ \mathrm{TeV}\,,\ -9\ \mathrm{TeV} \le A_f \le 9\ \mathrm{TeV}\,,$$ $$50\ \mathrm{GeV} \le m_{\tilde f_L}, m_{\tilde f_R}, M_3 \le 3\ \mathrm{TeV}\,,\ 50\ \mathrm{GeV} \le M_1, M_2, |\mu| \le 1.5\ \mathrm{TeV}.$$
  - stop mixing parameter $X_t = A_t - \mu \cot\beta$; $M_S = \sqrt{m_{tr\sim}\, m_{tl\sim}}$

[A. Atbey, et. al.: arXiV:1112.3028]





  - Consistence requires: $M_A \gg M_h$; ; tan β > 10; M_S large;

    maximal mixing ~ $\sqrt{6}\, M_S$

SUSY

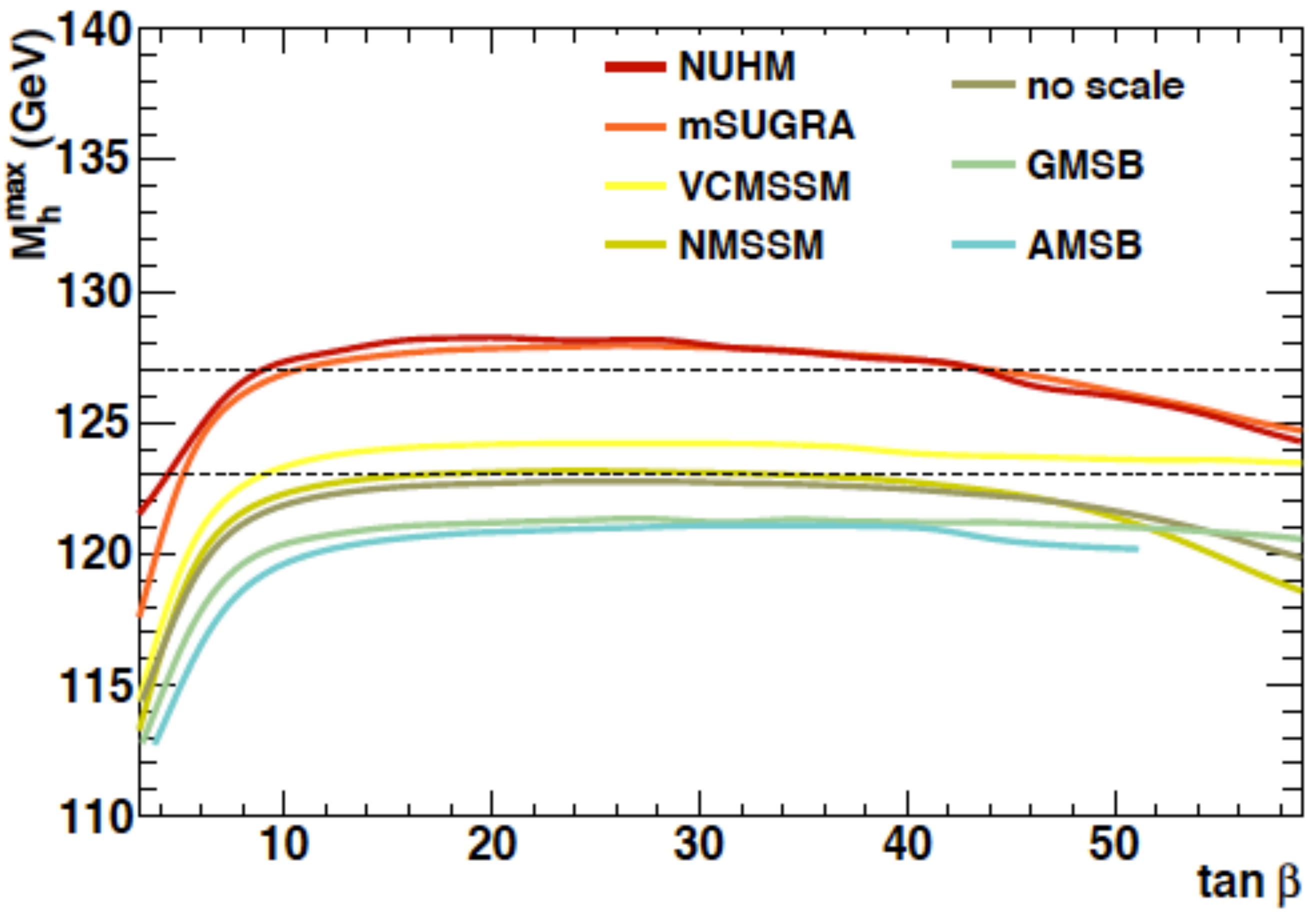
- various constrained models
  - parameters varied:

$$\begin{array}{rlll} \text{mSUGRA:} & 50\text{ GeV} \leq m_0 \leq 3\text{ TeV}, & 50\text{ GeV} \leq m_{1/2} \leq 3\text{ TeV}, & |A_0| \leq 9\text{ TeV}; \\ \text{GMSB:} & 10\text{ TeV} \leq \Lambda \leq 1000\text{ TeV}, & 1 \leq M_{\text{mess}}/\Lambda \leq 10^{11}, & N_{\text{mess}} = 1; \\ \text{AMSB:} & 1\text{ TeV} \leq m_{3/2} \leq 100\text{ TeV}, & 50\text{ GeV} \leq m_0 \leq 3\text{ TeV}. & \end{array}$$

  - Upper bound - m_h in top 1%

[A. Atbey, et. al.: arXiV:1112.3028]

  - GMSB, AMSB ✖
  - mSUGRA ✔
    - NUHM: non universal m_0
    - VCMSSM: $m_0 \simeq -A_0$
    - NMSSM: $m_0 \simeq 0$, $A_0 \simeq -1/4 m_{\frac{1}{2}}$
    - no scale: $m_0 \simeq A_0 \simeq 0$



SUSY

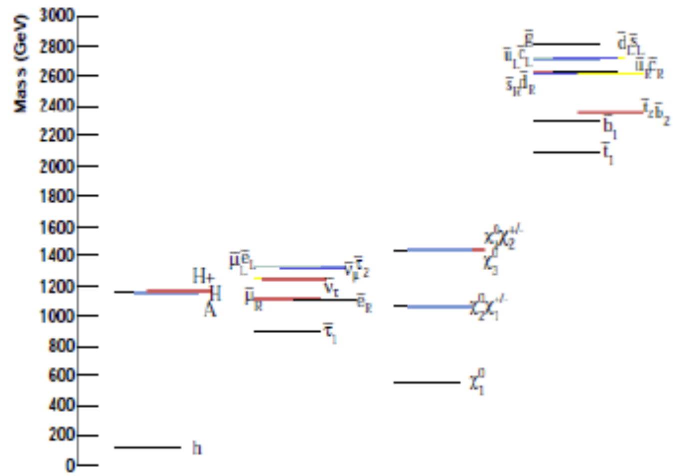
- Example study of slepton pair production:

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

  - Mass measurements of neutrino using edge method:

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

  - Inherently better at MC. No beamstrahlung. CLIC does well for slepton pair production near threshold.



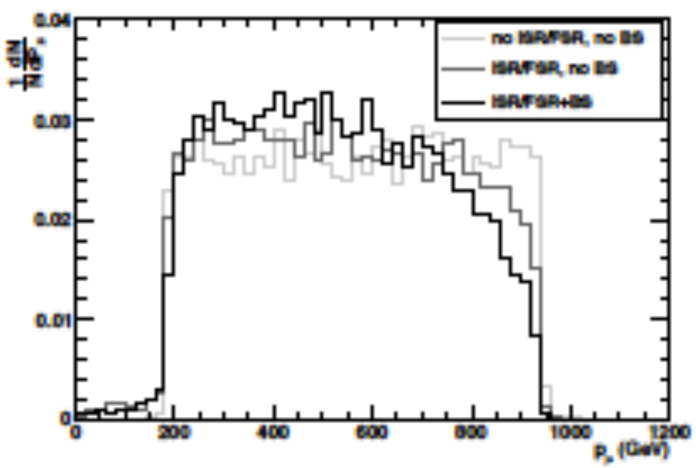


Table 2: Summary of the results of the fits to the smuon and neutralino mass for various assumptions on track momentum resolution, beamstrahlung, polarisation and number of bunch crossings integrated in one events. The results obtained on signal only (S) at generator level are also compared to those from full simulation and reconstruction and signal+background (S+B) fits.

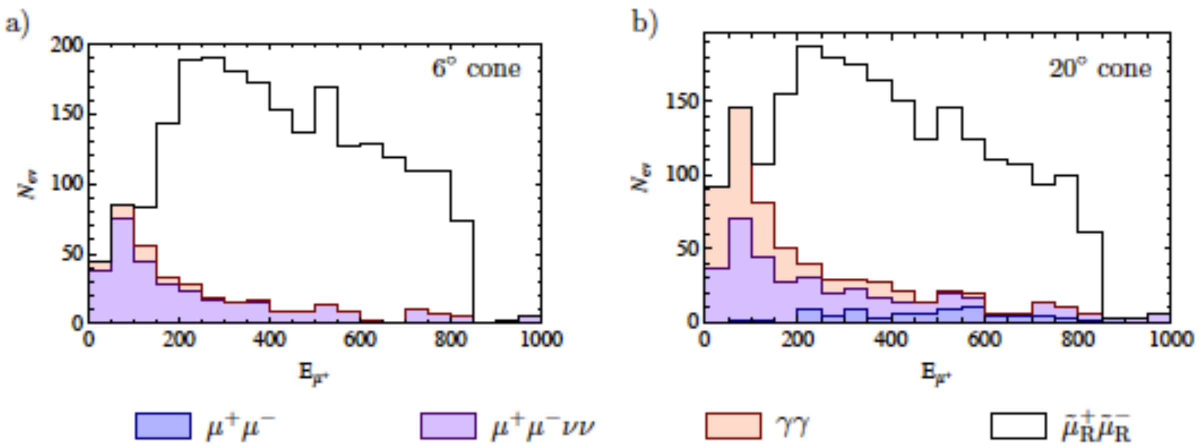
$\delta p_t/p_t^2$ ($\times 10^{-5}$ GeV^{-1})	$\sqrt{s}$ > (GeV)	Data Set	Pol (e^-/e^+)	BX	$(M\pm\sigma_M)$ (GeV) $\tilde{\mu}_R^\pm$	$\tilde{\chi}_1^0$
0.	2950	S	0/ 0	0	1106.3± 2.9	558.8 ± 1.3
0.	2500	S	0/ 0	0	1098.8± 2.6	555.4 ± 1.2
0.	2500 (ISR only)	S	0/ 0	0	1109.2± 3.2	555.4 ± 1.2
0.	2500	S (No FSR Cor)	0/ 0	0	1095.3± 3.2	557.7 ± 1.3
2.	2500	S	0/ 0	0	1104.6± 2.9	560.0 ± 1.7
2.	2500	S (G4+Reco)	0/ 0	0	1107.1± 2.8	560.1 ± 1.5
4.	2500	S	0/ 0	0	1102.8± 2.9	557.2 ± 2.8
6.	2500	S	0/ 0	0	1098.8± 3.1	559.1 ± 3.6
8.	2500	S	0/ 0	0	1101.0± 3.4	564.2 ± 4.0
20.	2500	S	0/ 0	0	1107.5± 4.2	575.7 ± 5.3
2.	2500	S+B (0.8)	0/ 0	0	1107.5±15.5	542.5 ± 11.3
2.	2500	S+B (0.9)	0/ 0	0	1107.5±14.4	551.2 ± 12.0
2.	2500	S+B (0.8)	80/ 0	0	1107.7± 8.7	542.6 ± 4.6
2.	2500	S+B (0.8)	80/60	0	1118.5± 6.1	551.3 ± 3.0
2.	2500	S+B (0.8)	80/60	5	1105.7± 6.3	549.4 ± 3.9
2.	2500	S+B (0.8)	80/60	20	1113.2± 6.8	550.3 ± 3.4

N. Alster and M. Battaglia [arXiv:1104.0523]

- Detailed study for muon collider

[A. Freitas: arXiV:1107.3853]

  - large backgrounds from processes



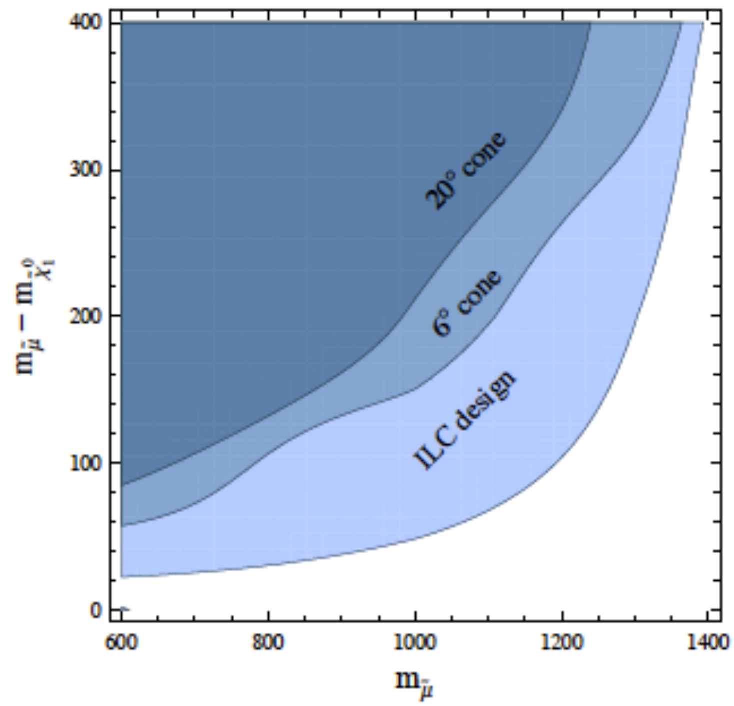
  - suitable cuts reduce backgrounds but limit sensitivity to small mass difference between smuon and its decay products.

$\sqrt{s} = 3$ TeV, $m_{\tilde{\ell}_R} = 1$ TeV, $m_{\tilde{\chi}_1^0} = 0.6$ TeV   1 ab^{-1}

for 6° shielding cone: $\delta m_{\tilde{\mu}_R,\mathrm{fit}} = ^{+32}_{-40}$ GeV, $\delta m_{\tilde{\chi}_1^0,\mathrm{fit}} = ^{+18}_{-14}$ GeV,

for 20° shielding cone: $\delta m_{\tilde{\mu}_R,\mathrm{fit}} = ^{+40}_{-46}$ GeV, $\delta m_{\tilde{\chi}_1^0,\mathrm{fit}} = ^{+20}_{-18}$ GeV,

  - Shows the advantage of instrumenting the shielding cone.



SUSY

- Tension between LHC bounds and $(g\text{-}2)_\mu$ has increased.
- Too early to dismiss cMSSM or MSUGRA; but theorists are pursuing less tightly constrained models of SUSY
- In many cases the we are in the decoupling region: $H^{0,\pm}$, A^0 heavy and nearly degenerate.
- For the LHC, if direct pair production of squark pairs is inaccessible:
  - Associated production of squarks and gauginos would likely still be open.
  - For pair production of sleptons and charginos, the reach of the LHC (even at full energy and luminosity) is limited (~ 300 GeV) due to electroweak couplings.
- Sleptons, charginos and neutralinos still remain easily assessible at a multi-TeV lepton collider.
- Supersymmetry provides a very strong case for a multi-TeV collider.

New Strong Dynamics

- Electroweak Symmetry Breaking is generated dynamically at a nearby scale.

May or may not be a light Higgs boson.

Theoretical issues

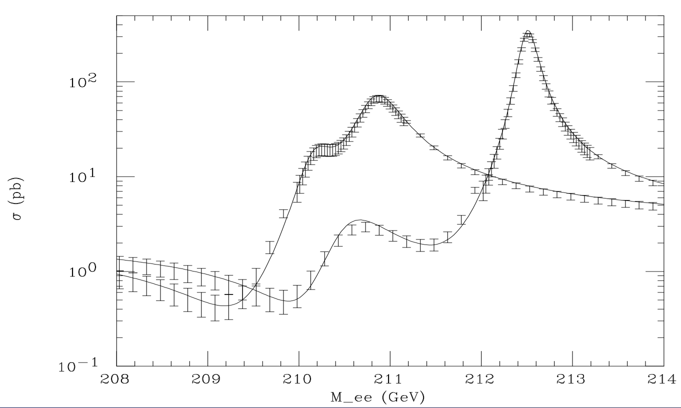
- What is the spectrum of low-lying states?
- What is the ultraviolet completion? Gauge group? Fermion representations?
- What is the energy scale of the new dynamics?
- Any new insight into quark and/or lepton flavor mixing and CP violation?
- ...

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

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

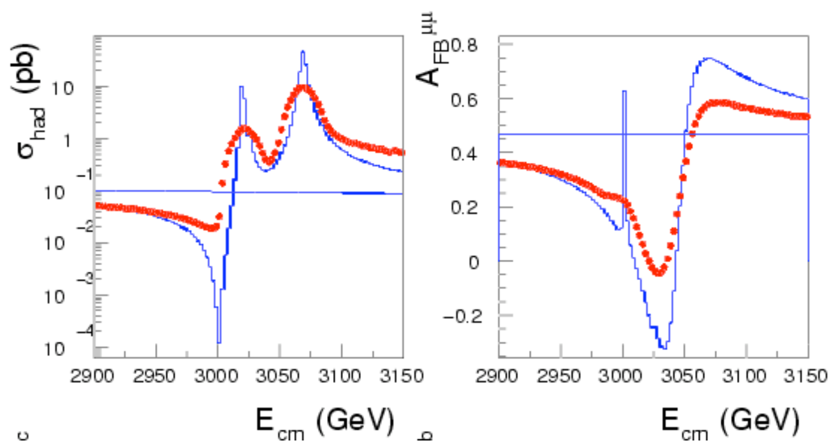
- Technipions - s channel production (Higgs like)
- Technirhos - Nearby resonances (ρ_T,ω_T)- need fine energy resolution of muon collider.

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})



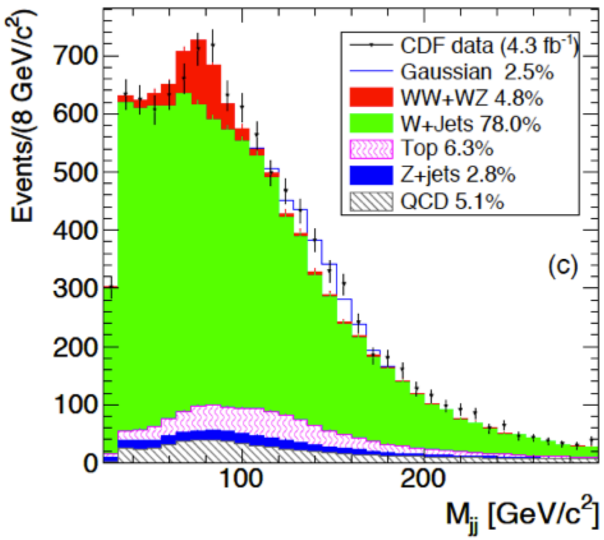
good benchmark processes

CLIC - D-BESS model (resolution 13 GeV)

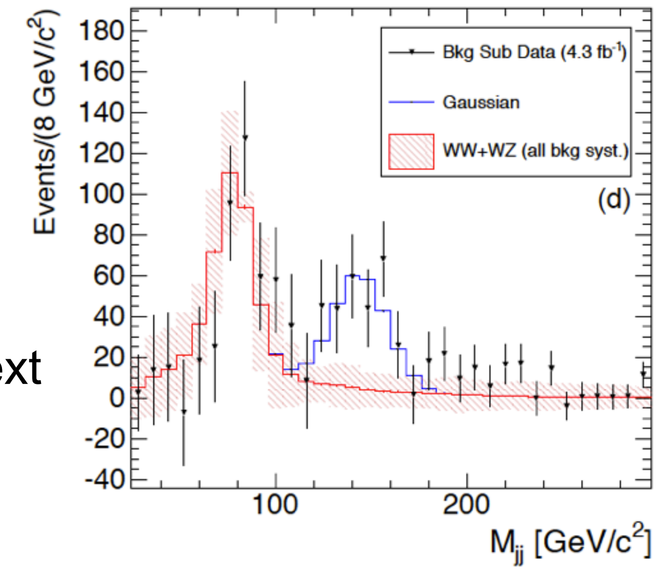


New Strong Dynamics

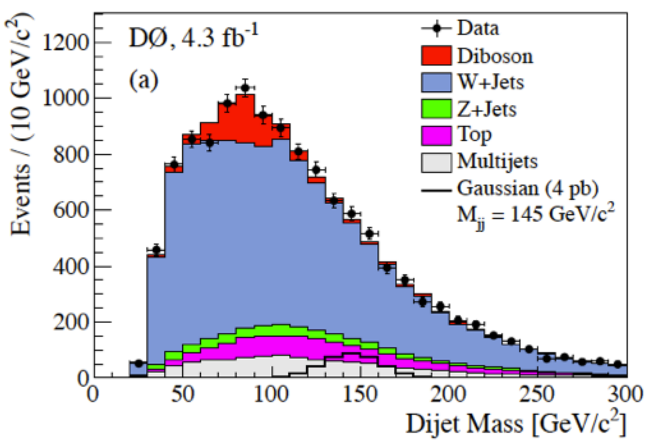
- Hint of new strong dynamics?
  - CDF W+2jets [PRL 106:171801 (2011)] (maybe)

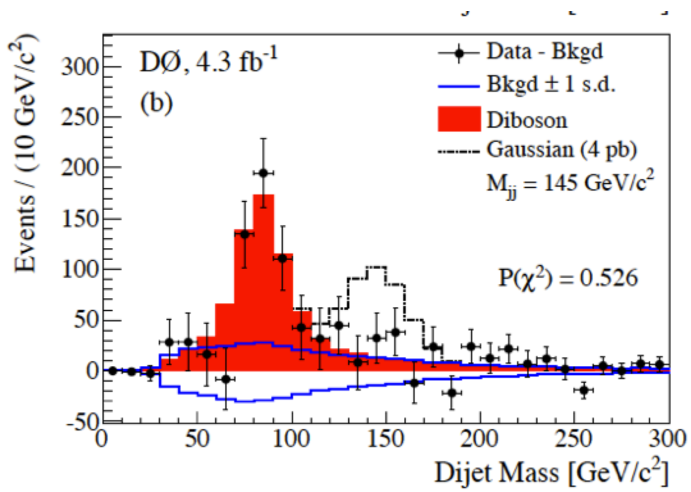


Text



  - DZero [arXiv:1106.1921] (no)





New Strong Dynamics

- $W_L W_L$ scattering at high energy

If no $h_i/SUSY$ found at the LHC, $W_L W_L$ Scattering must reveal new dynamics

- Unitarity scale: $\Lambda_{EW}(W_L W_L \to W_L W_L) \sim \sqrt{8\pi}\ v \sim 1.2$ TeV.

$$\sqrt{s_W} \sim 2 \text{ TeV} \Rightarrow \sqrt{s_f} \sim 4 \text{ TeV}$$

$$\frac{\sigma(W_L^+ W_L^- \to W_L^+ W_L^-)}{\sigma(W_L^+ W_L^- \to Z_L Z_L)} \begin{cases} \sim 2 & \text{scalar } H^0, \\ \gg 1 & \text{vector } \rho^0_{TC}, \\ \sim 2/3 & \text{LET } \sqrt{s} \ll M. \end{cases}$$

-

$$\Lambda_f(WW \to f\bar{f}) = \frac{8\pi v^2}{3m_f} \sim \begin{cases} 3 \ \text{ TeV} & m_t = 175 \text{ GeV} \\ 97 \ \text{ TeV} & m_b = 5 \text{ GeV}. \end{cases}$$

So, consider $\mu^+\mu^- \to \nu\nu W^+W^-$, $\nu\nu ZZ$, $\nu\nu t\bar{t}$ via H, ρ_{TC} or non-resonance.

[J. Gunion and T. Han, Muon ColliderWorkshop 2011)

Contact Interactions

- The SM is only an effective theory valid below the compositeness scale.

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

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

CI model	Observed limit (TeV)	Expected limit (TeV)
NLO $\Lambda^+_{LL/RR}$	7.5	$7.0^{+0.4}_{-0.6}$
NLO $\Lambda^-_{LL/RR}$	10.5	$9.7^{+1.0}_{-1.7}$
LO $\Lambda^+_{LL/RR}$	8.4	$7.9^{+0.5}_{-0.7}$
LO $\Lambda^-_{LL/RR}$	11.7	$10.9^{+1.7}_{-2.4}$
LO $\Lambda^+_{VV/AA}$	10.4	$9.5^{+0.5}_{-1.0}$
LO $\Lambda^-_{VV/AA}$	14.5	$13.7^{+2.9}_{-2.6}$
LO $\Lambda^\pm_{(V-A)}$	8.0	$7.8^{+1.0}_{-1.1}$

- Present LHC Limits (CMS table)

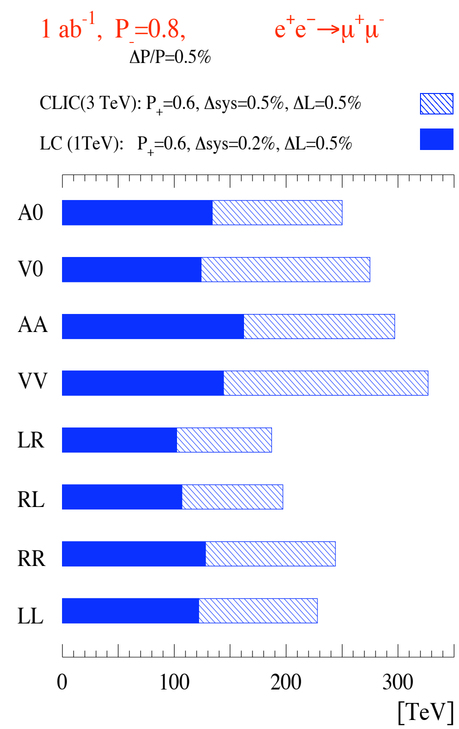
- Muon collider is sensitive to contact interaction scales over 200 TeV as is CLIC.

- Cuts on forward angles for a muon collider not an issue.

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

- Polarization useful to disentangle the chiral structure of the interaction. (CLIC)

CLIC Study



good benchmark process

Physics Benchmarks

[Marco Battaglia, Muon ColliderWorkshop 2011)

Physics Signatures	Higgs Sector	SUSY	SSB	New Gauge Bosons	Extra Dimensions
Resonance Scan		SUSY Thresholds	D-BESS	Z'	KK
EW Fits				A_{LR}, A_{FB}	$A^{b\bar{b}}_{FB}$
Multi-Jets	H^+H^- $t\bar{t}H$ $HH\nu\bar{\nu}$ HHZ $HHH\nu\bar{\nu}$ $HHHZ$		Techni-ρ		
E_{miss}, Fwd	He^+e^-	$\tilde{\ell}^+\tilde{\ell}^-$ $\tilde{\chi}^+\tilde{\chi}^-$	WW scattering		

In Summary

- 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.