Muon Collider Physics

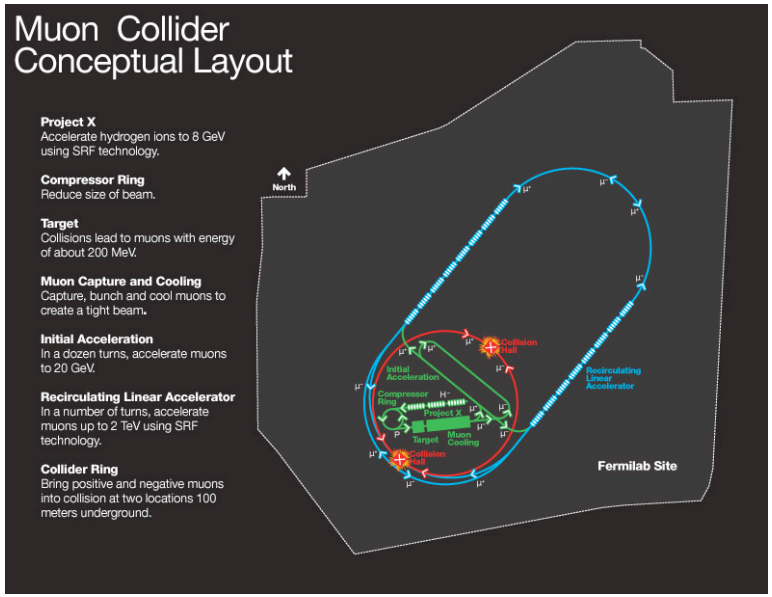
Estia Eichten
Fermilab

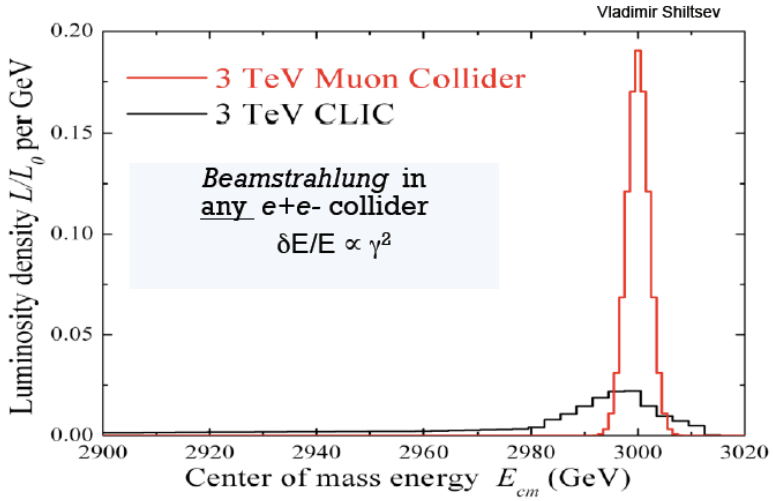
- Basics of a Muon Collider
- Implications of Early LHC Results
- The Scalar Sector
- Beyond the SM Opportunities
- Summary

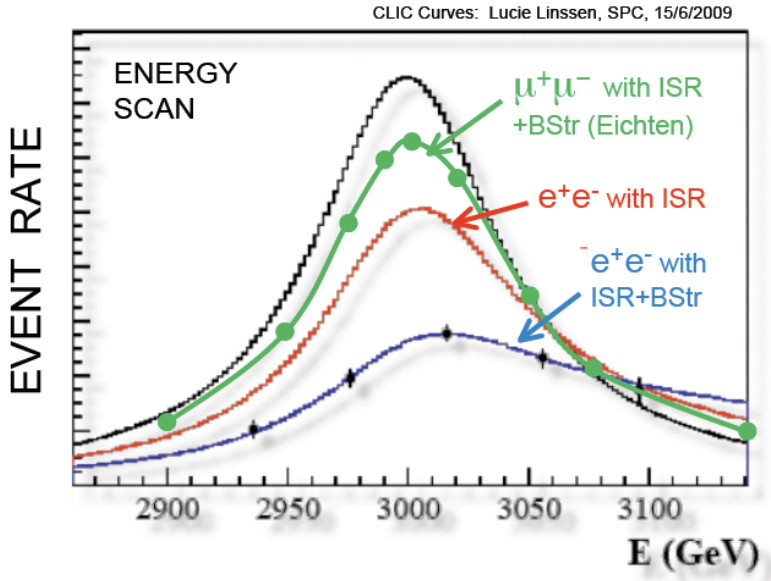
Muon Collider Higgs Factory Mini-Workshop
Fermilab
November 13, 2012

Basics of a Muon Collider

- $\mu^+\mu^-$ Collider:
  - Center of Mass energy: 1.5 - 6 TeV (3 Tev)
  - Luminosity > 10^{34} cm^{-2} sec^{-1} (350 fb^{-1}/yr)
  - Compact facility
    - 3 TeV - ring circumference 3.8 km
    - 2 Detectors
  - Superb Energy Resolution
    - MC: 95% luminosity in dE/E ~ 0.1%
    - CLIC: 35% luminosity in dE/E ~ 1%



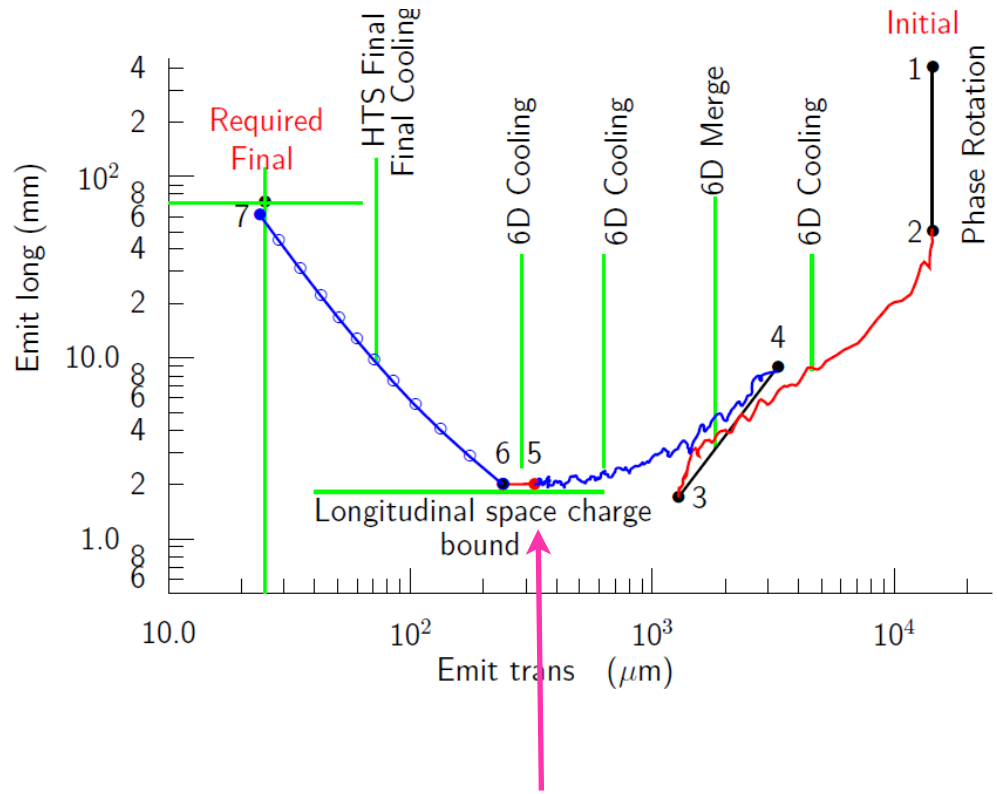




Basics of a Muon Collider

- Provides a flexible staging scenerio with physics at each stage.
  - Neutrino Factory
  - Higgs Factory

- But muons decay:
  - 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.
    - Detector background issues
    - Serious neutrino beam issue for Ecm ≥ 4 TeV

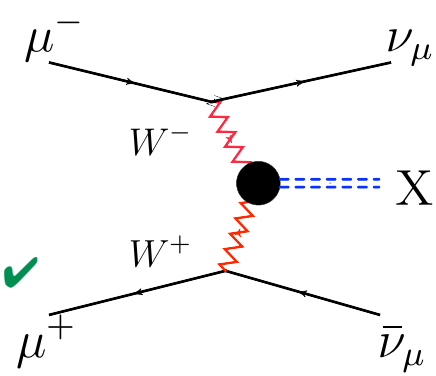


Higgs Factory

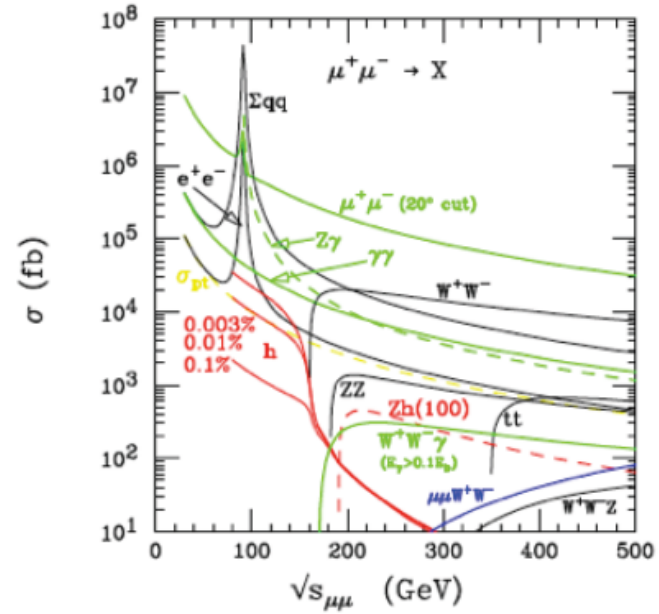
Basics of a Muon Collider

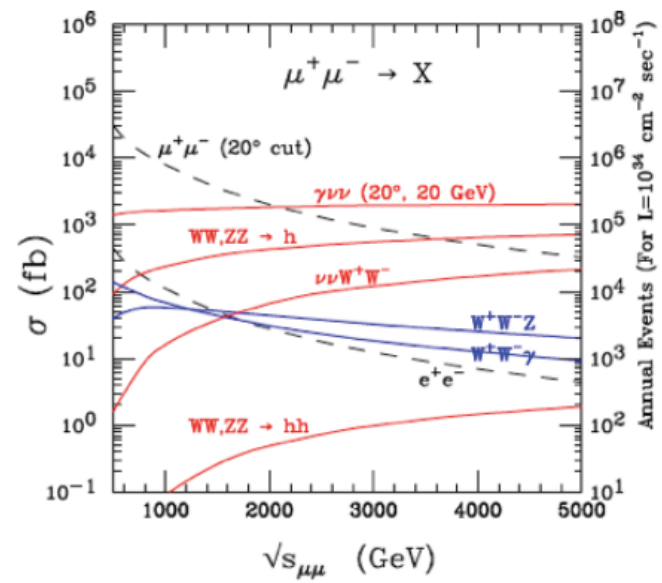
- For $\sqrt{s}$ < 500 GeV
  - SM thresholds: Z^0h, W^+W^-, top pairs
  - Higgs factory ($\sqrt{s} \approx$ 126 GeV) ✔
- For $\sqrt{s}$ > 500 GeV
  - Sensitive to possible Beyond SM physics.
  - High luminosity required. ✔
    - Cross sections for central ($|\theta|$ > 10°) pair production ~ R × 86.8 fb/s(in TeV^2) (R ≈ 1)
    - At $\sqrt{s}$ = 3 TeV for 100 fb^{-1} ~ 1000 events/(unit of R)
- For $\sqrt{s}$ > 1 TeV
  - Fusion processes important at multi-TeV MC

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



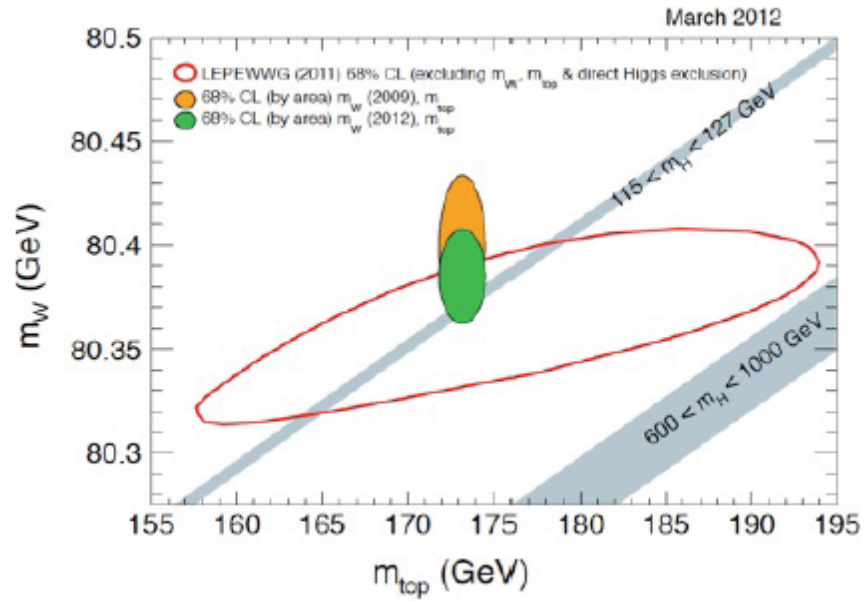
  - An Electroweak Boson Collider ✔



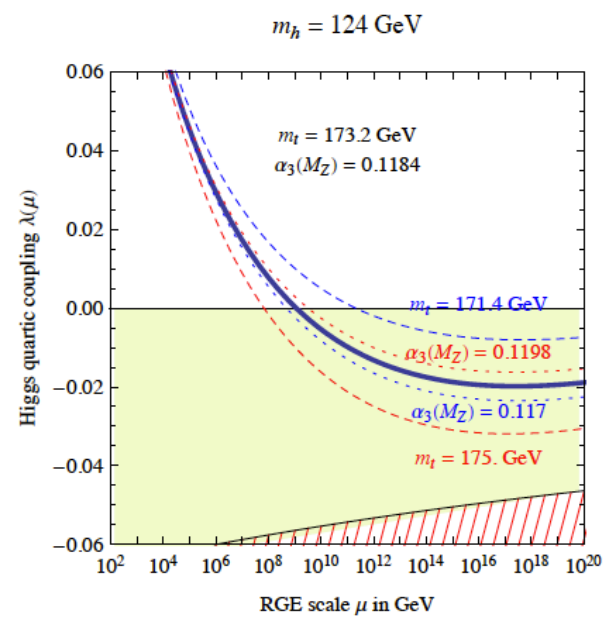


Implications of early LHC Results

- Indirect measurements are all consistent with a 126 GeV Higgs

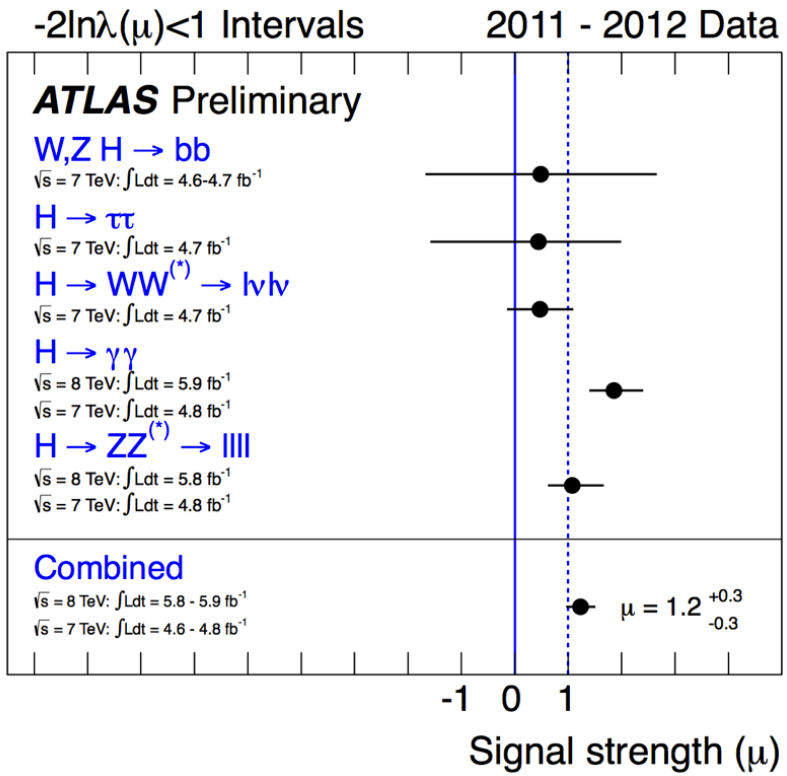


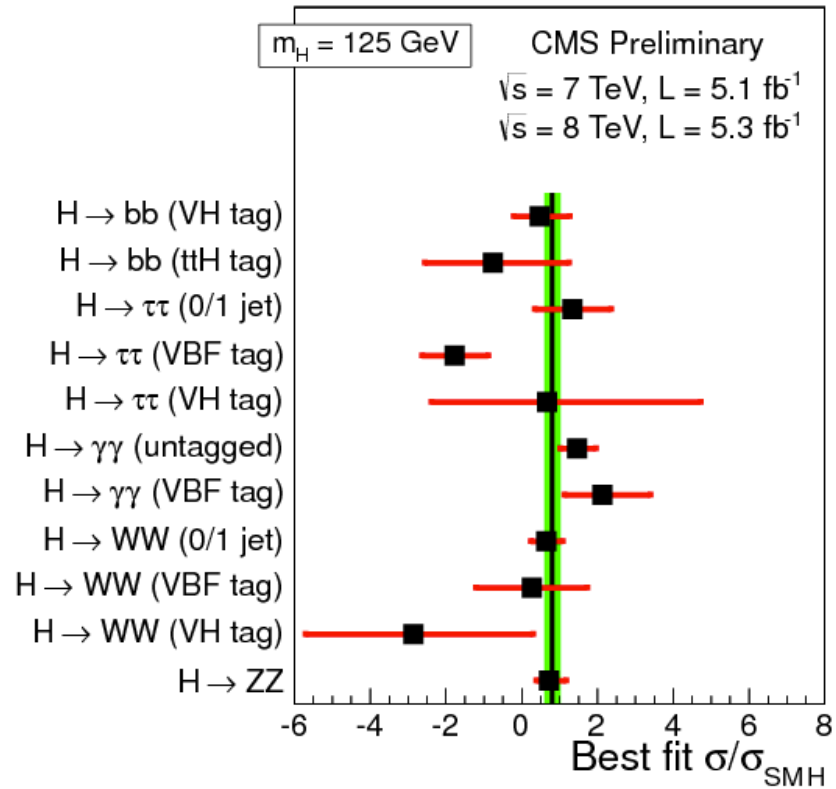
- For a 126 GeV Higgs the SM is consistent to the Planck scale; but the vacuum is only metastable above 10^{10} GeV.



Implications of early LHC Results

- Measure couplings to distinguish SM Higgs from BSM scalars

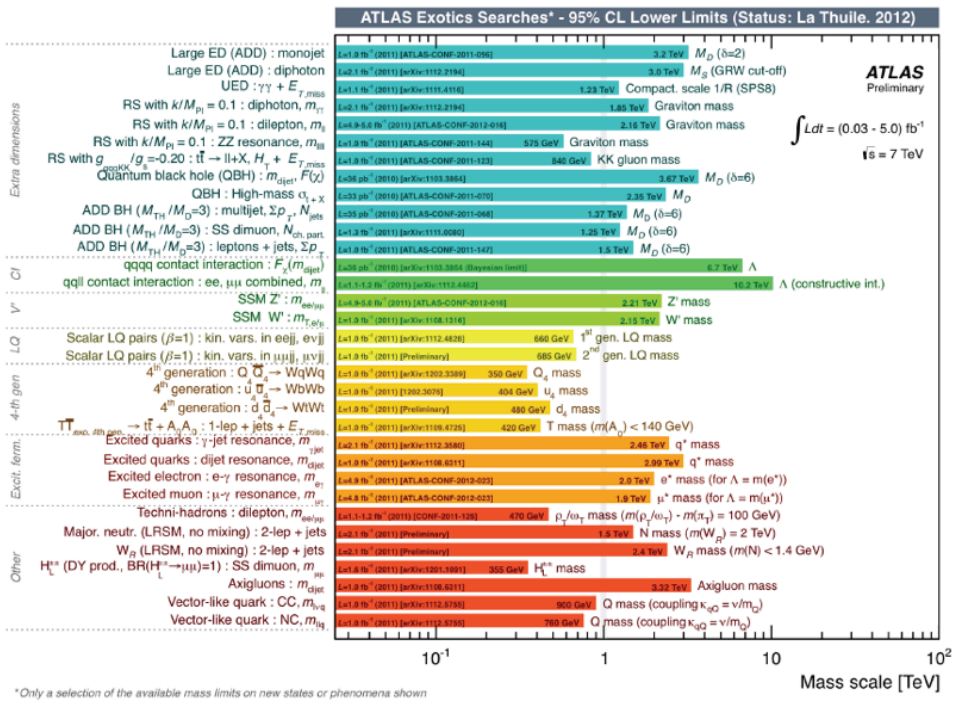




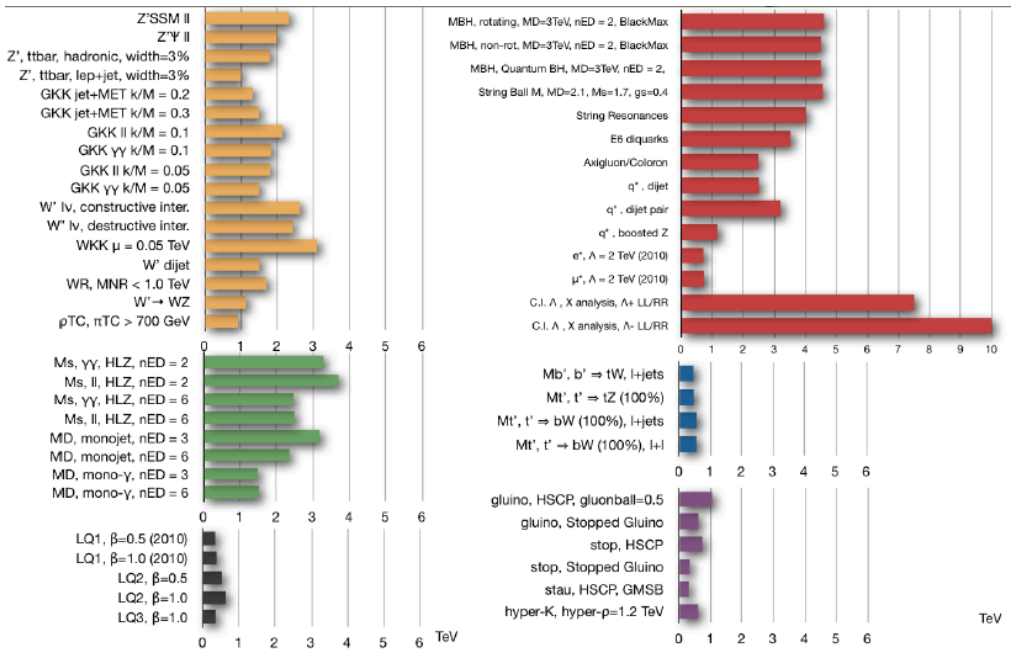
- Within large present errors, ATLAS and CMS results consistent with SM Higgs couplngs

Implications of early LHC Results

- No evidence for new physics beyond the Standard Model (BSM) to date:
  - ATLAS limits



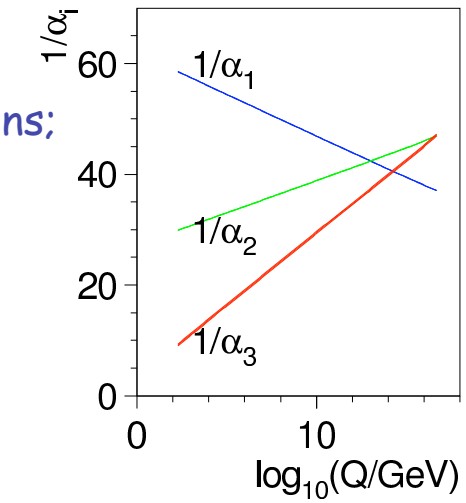
CMS limits



  - Scales already probed at the LHC suggest that the energy of a MC should be in the multi-TeV range to study BSM new physics.
  - However there must be new physics !!! WHY? Let me list the reasons

Implications of early LHC Results

1. 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



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

3. Theoretical problems with the SM:
   - Scalar sector problematic:
     $\mu^2 (\Phi^\dagger\Phi) + \lambda (\Phi^\dagger\Phi)^2 + \Gamma_{ij}\psi_{iL}^\dagger\psi_{jR}\Phi + \text{h.c.}$

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

     vacuum stability

     large range of fermion masses
   - The SM Higgs boson is unnatural. (m_H^2/μ^2)
   - Solutions: SUSY, New Strong Dynamics, ...

muon (g-2)

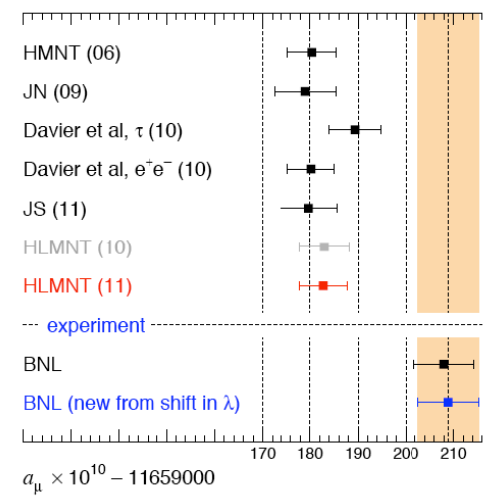
Davier, Hoecker, Malaescu, Zhang

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 Standard Model Higgs ?

- The SM Higgs:
  - All properties are determined for given mass.
  - Any deviations signal new physics.

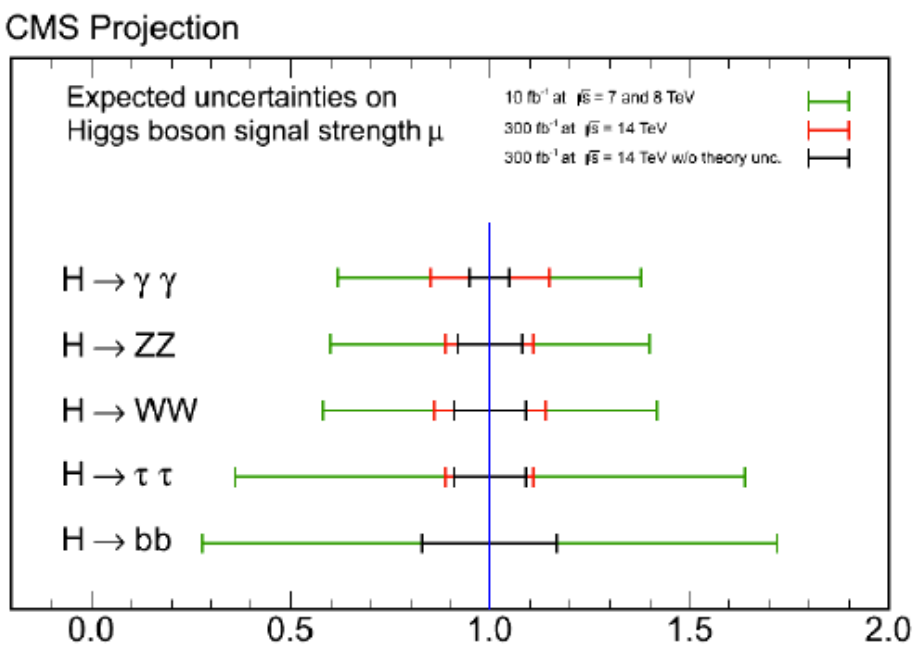
$$m(H) = 126 \text{ GeV} \qquad \Gamma(H) = 4.31 \text{ MeV}$$

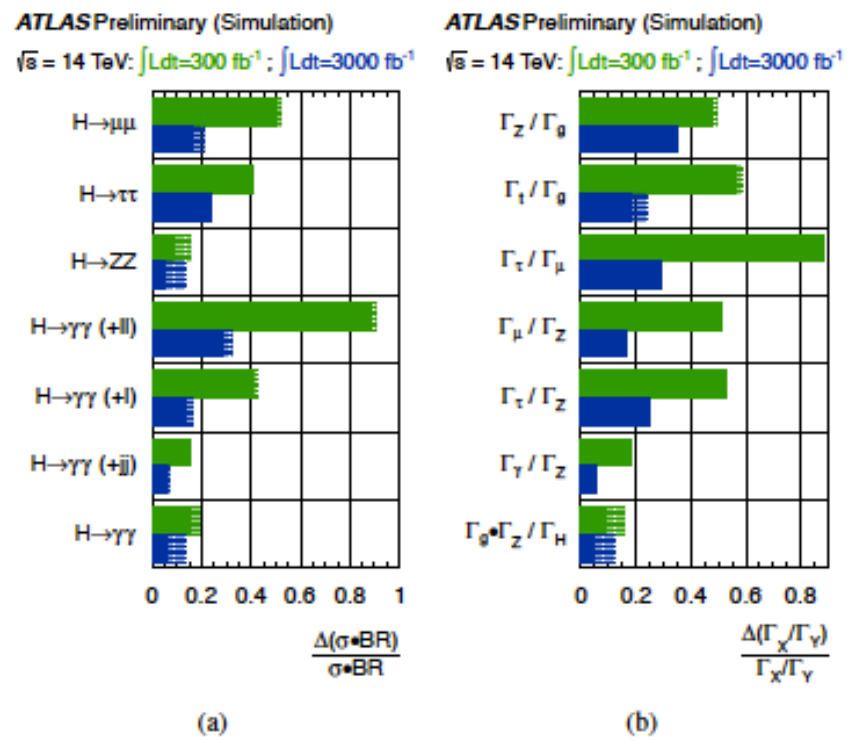
$$\begin{array}{llll} \text{branching fractions :} & b\bar{b} = 0.584 & W^+W^- = 0.229 \\ & \tau\bar{\tau} = 6.02 \times 10^{-2} & Z^0\ Z^0 = 2.82 \times 10^{-2} \\ & c\bar{c} = 2.57 \times 10^{-2} & gg = 6.81 \times 10^{-2} \\ & s\bar{s} = 4.40 \times 10^{-4} & \gamma\gamma = 2.26 \times 10^{-3} \\ & \mu^+\mu^- = 2.09 \times 10^{-4} & Z^0\gamma = 1.58 \times 10^{-3} \end{array}$$

- Theoretical questions:
  - Couplings and width SM?
  - Scalar self-coupling SM?
  - Any additional scalars? EW doublets, triplets or singlets? (e.g. SUSY requires two Higgs doublets)
  - Any invisible decay modes?

The Standard Model Higgs ?

- What can be done at the LHC?
  - New projections from ATLAS and CMS for European Strategy Study
  - With 3000 fb^{-1} at 14 TeV:
    - Further error reduction by factor of 3 (stat)
    - Observe H->$\mu^+\mu^-$ to 6 σ. (ATLAS)
    - Measure the Higgs self-coupling to 30% (ATLAS)





The Standard Model Higgs ?

- The Role for Lepton Colliders
  - Only lepton collider can measure the h -> cc and h -> gg decays directly.
  - Precise measurements of the h -> W^+W^-, Z^0Z^0 probe if the higgs is composite or if there is any other mechanism contributing to EWSB.
  - Electron colliders (linear or circular) do detailed studies of Higgs decays using the associated production process: $\sigma(e^+e^- \to Zh \to l^+l^- h) = 19.1$ fb

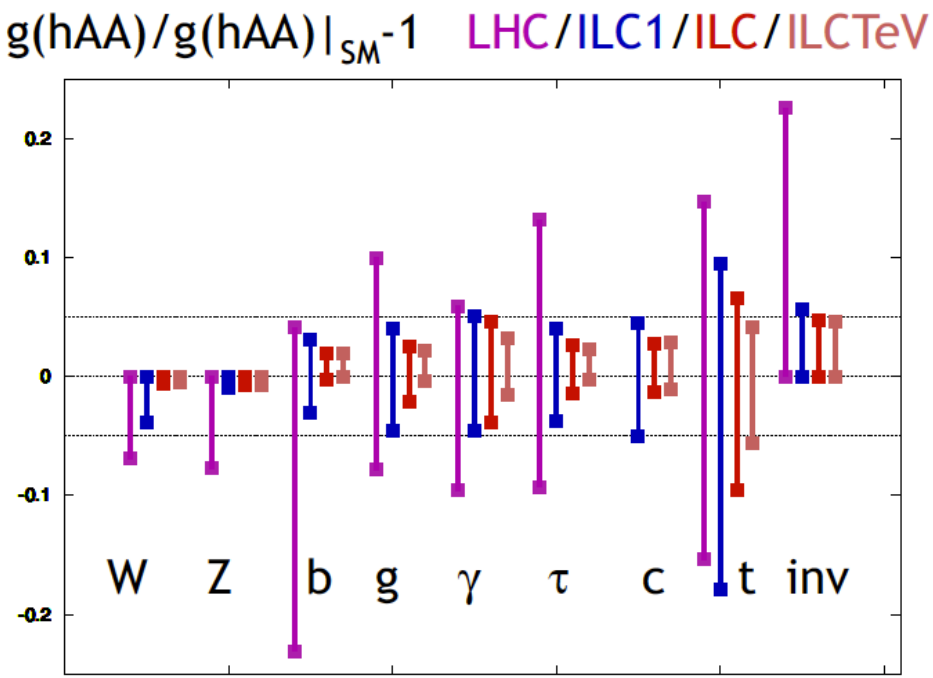
Table 5: Summary of results obtained in the Higgs studies for $m_H = 120$ GeV. All analyses at centre-of-mass energies of 350 GeV and 500 GeV assume an integrated luminosity of 500 fb^{-1}, while the analyses at 1.4 TeV (3 TeV) assume 1.5 ab^{-1}(2 ab^{-1}).

Higgs studies for $m_H = 120$ GeV

$\sqrt{s}$ (GeV)	Process	Decay mode	Measured quantity	Unit	Generator value	Stat. error	Comment
350	SM Higgs production	$ZH \to \mu^+\mu^- X$	σ	fb	4.9	4.9%	Model independent, using Z-recoil
			Mass	GeV	120	0.131	
500		$ZH \to q\bar{q}q\bar{q}$	$\sigma \times$ BR	fb	34.4	1.6%	$ZH \to q\bar{q}q\bar{q}$ mass reconstruction
			Mass	GeV	120	0.100	
500		$ZH, H\nu\bar{\nu} \to \nu\bar{\nu}q\bar{q}$	$\sigma \times$ BR	fb	80.7	1.0%	Inclusive sample
			Mass	GeV	120	0.100	
1400	WW fusion	$H \to \tau^+\tau^-$	$\sigma \times$ BR	fb	19.8	<3.7%	
3000		$H \to b\bar{b}$			285	0.22%	
		$H \to c\bar{c}$			13	3.2%	
		$H \to \mu^+\mu^-$			0.12	15.7%	
1400	WW fusion		Higgs tri-linear coupling g_{HHH}			~20%	
3000						~20%	

The Standard Model Higgs ?

- Lepton Colliders compared to LHC results



M. E. Peskin [arXiv:1207.2516]

- Awaiting undates on LHC based onthe 2012 run exprience
- HL-LHC (3000 fb^{-1}) has errors approximately 1/2 the LHC (300 fb^{-1}) shown here
- missing comparsions: $A=\mu$ [20%] $\Delta m(h)$ [100 MeV], $\Delta\Gamma(h)$ [5-10%] for both HL-LHC and ILCTeV

The Standard Model Higgs ?

- A muon collider can directly produce the Higgs as an s-channel resonance.
  - Higgs couples to mass so rate enhanced by $\left[\frac{m_\mu}{m_e}\right]^2 = 4.28 \times 10^{\ 4}$ so the cross section is $\sigma(\mu^+\mu^- \to h) = 49.2$ pb ($\Delta \ll \Gamma$)
  - The excellent energy resolution Δ of a muon collider makes the process observable.

Tao Han and Zhen Liu [arXiv:1210.7803]

$$\sigma(\mu^+\mu^- \to h \to X) = \frac{4\pi\Gamma_h^2 \mathrm{Br}(h \to \mu^+\mu^-)\mathrm{Br}(h \to X)}{(\hat{s} - m_h^2)^2 + \Gamma_h^2 m_h^2}.$$

$$\sigma_{\mathrm{eff}}(s) = \int d\sqrt{\hat{s}}\ \frac{dL(\sqrt{s})}{d\sqrt{\hat{s}}}\sigma(\mu^+\mu^- \to h \to X)$$

$$\propto \begin{cases} \Gamma_h^2 B/[(s - m_h^2)^2 + \Gamma_h^2 m_h^2] & (\Delta \ll \Gamma_h), \\ B\exp[\frac{-(m_h - \sqrt{s})^2}{2\Delta^2}](\frac{\Gamma_h}{\Delta})/m_h^2 & (\Delta \gg \Gamma_h). \end{cases}$$

$\Gamma_h = 4.21$ MeV	L_{step} (fb^{-1})	$\delta\Gamma_h$ (MeV)	δB	$\delta m_h (MeV)$
Case A	0.005	1.5	13%	0.51
$R = 0.01\%$	0.025	0.85	6.1%	0.32
	0.2	0.34	2.2%	0.13
Case B	0.01	0.61	8.3%	0.40
$R = 0.003\%$	0.05	0.30	3.8%	0.13
	0.2	0.17	2.0%	0.10

20 steps

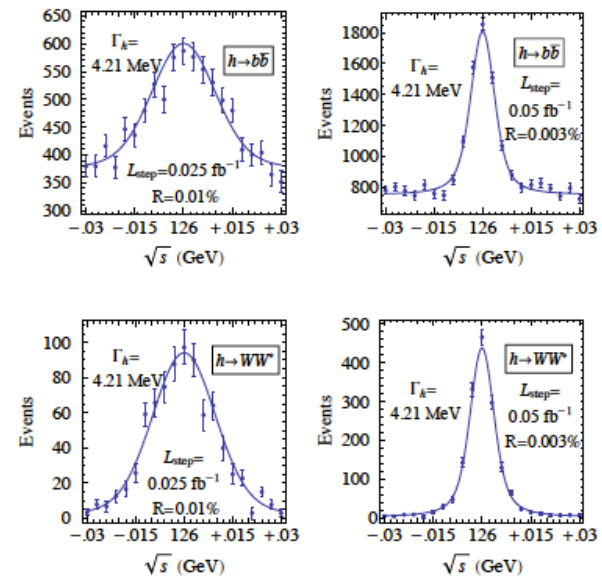


FIG. 2: Number of events of the Higgs signal plus backgrounds and statistical errors expected for Cases A and B as a function of the collider energy $\sqrt{s}$ in $b\bar{b}$ and WW^* final states with a SM Higgs $m_h = 126$ GeV and $\Gamma_h = 4.21$ MeV.

  - To obtain the same sensitivity to Higgs decay modes in a electron collider via Zh process as s-channel production at a MC requires more than 100 times the integrated luminosity.

The Standard Model Higgs ?

- List of issues for MC Higgs Factory
  - Requires precise energy resolution: $\Delta E/E \sim$ few x 10^{-5}
    - Can such a resolution be achieved?
    - What error on the Higgs width would be possible?
    - Integrated luminosity?
    - Beam energy stability - store-to-store?
  - What branching ratios could be measured?
    - W^+W^-, ZZ (very small backgrounds)
    - bb (S/B ~ 1), Δ(BR($\mu^-\mu^+$)xBR(WW)) [2%]
    - Detector backgrounds from muon decays in beams
    - S/B studies?
- Preliminary studies:
  - ΔE = 2 MeV and $\mathcal{L} > 10^{31}$ cm^{-2}sec^{-1}
  - Can use nearby Z pole to tune machine.
  - Use spin precession to measure beam energy.
- Given the LHC discovery, it is imperative that a feasibility study be done for the Higgs factory option within a staged MC scenerio.

$$\sqrt{s} = 126 \text{ GeV} \quad (10^0 \text{ cut})$$

Background Cross Sections (fb) :

$$\mu^- + \mu^+ \to e^- + e^+ = 9,705$$
$$\to j + \bar{j} = 73,020 \quad (j = u, d, s, c)$$
$$\to b + \bar{b} = 17,950$$
$$\to \gamma + \gamma = 36,680$$
$$\to \gamma + Z = 60,410$$
$$\to u + \bar{u} + g = 3,130$$
$$\to \tau^- + \bar{\nu}_\tau + W^+ = 2.56$$
$$\to \bar{u} + d + W^+ = 0.260$$

Collider parameter	Small δE 125 GeV Collider
Energy/beam	62.5 GeV
Luminosity	10^{31}
Proton Energy, Power	8GeV, 4MW
N_p/bunch, frequency	5×10^{13}, 60 Hz
N_μ/ bunch	1.5×10^{12}
ε_L, ε_T	0.002, 0.0005m
β^*	0.1m
σ_{IR}	0.3mm
Collider circumference C	350m
δE	2 MeV
σ_{bunch}	10cm
$\delta\nu_{beam\text{-}beam}$	0.0003

D. Neuffer, 15th Advanced Accelerator Concepts Workshop, Austin, TX (June 10-15, 2012)

The Standard Model Higgs ?

- 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: tth^0
    - R ~ 0.01
    - measure top coupling

MC or CLIC:

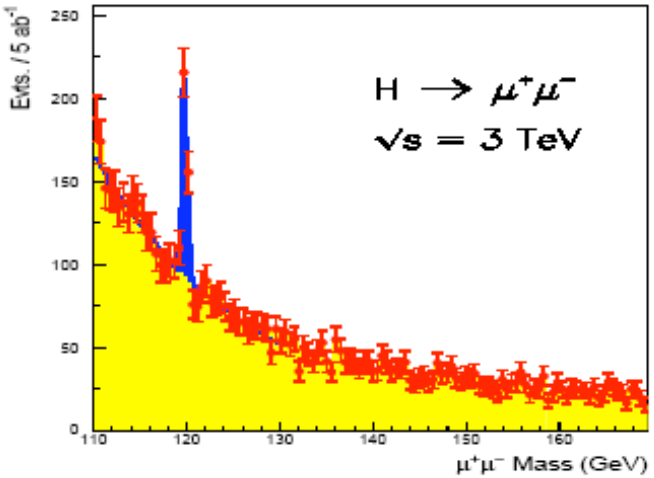
needs 10 ab^{-1}

  - W*W* fusion (m_h = 120 GeV)
    - $\nu_\mu\nu_\mu h^0$: R ~ 1.1 s ln(s) (s in TeV^2)
    - best measurements higgs decay rates (table)
    - $\nu_\mu\nu_\mu h^0h^0$: measure Higgs self couplings

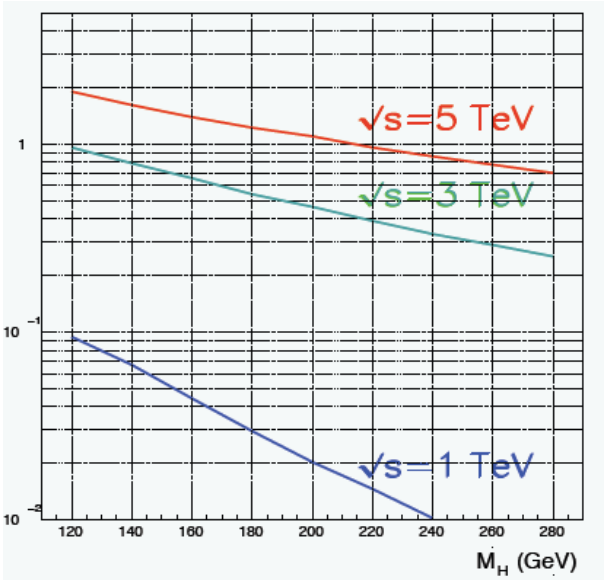
MC or CLIC:

good benchmark process

m(H) = 120 GeV



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



BSM Opportunities

- Many New Physics Options at a 3 TeV Muon Collider
  - 4th generation: Z,' W'; KK modes
  - Two Higgs Doublets
  - Supersymmetry
  - New Strong Dynamics
  - Contact Terms
  - ...
- The LHC is already putting constraints on the BSM physics options.
  - 4th generation: $t' \to b\, W^+$ $M(t') > 552$ GeV
  - Z', W', KK modes: $b' \to t\, W^-$ $M(b') > 600$ Gev
  - All beyond the reach of a ILC (1 TeV)

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

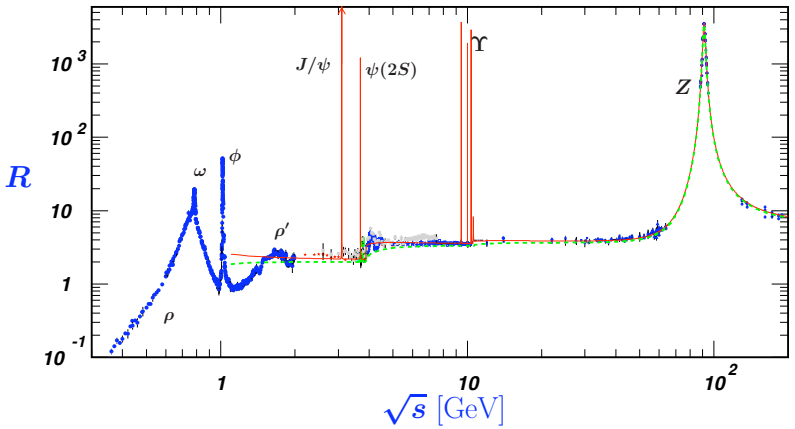
$m_{G^*} > 2.16$ TeV @ 95% for $k/M_{Pl} = 0.1$

- Benchmarks discussed at Muon Collider 2011 meeting. Will be undate as the 2012 run LHC data is analysed

http://conferences.fnal.gov/muon11/
talks by C. Hill, M. Battaglia, J. Gunion, T. Han, E.E.

More S-channel Resonances

- New Z', W'
  - S-channel resonances - factories for lepton colliders
  - Set minimum lumonisity for MC.



Minimum luminosity at Z' peak:
$\mathcal{L}$ = 1.0-5.0 x 10^{30} cm^{-2} sec^{-1}
for M(Z') -> 2.5-5.0 TeV

- 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 an s-channel resonace well in excess of 10 TeV could be studied in detail at such a muon collider.

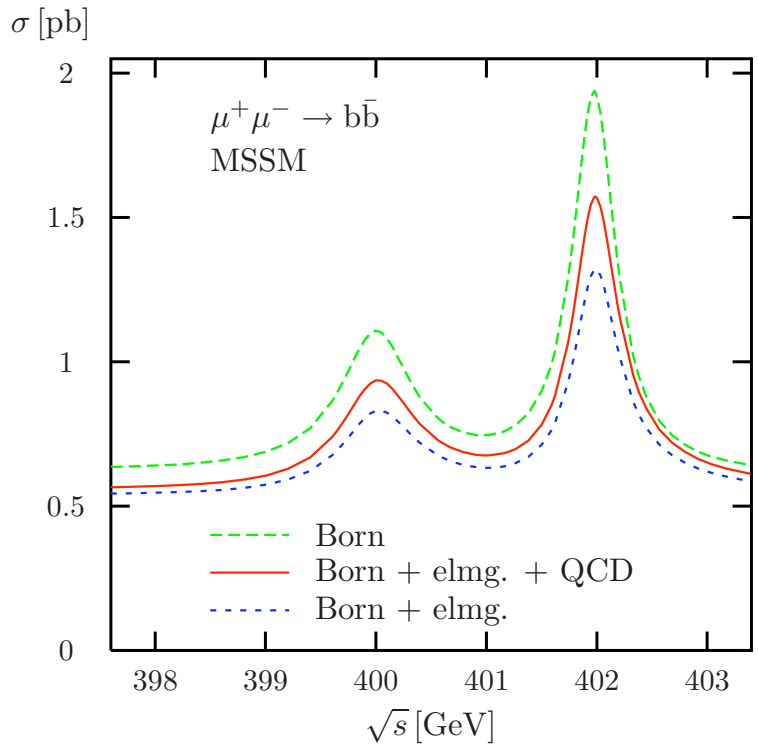
More Scalars (MSSM)

- Two Higgs doublets expected in MSSM
  - Five scalar particles: h^0, H^0, A^0, $H^\pm$
  - The LHC has difficulty observing the H, A especially for masses > 500 GeV. Even at $\sqrt{s}$ = 14 TeV and 300 fb^{-1}
  - Pair produced easily at a multi-TeV lepton collider.
- Decoupling limit $m_{A^0} >> m_{Z^0}$:
  - h^0 couplings close to SM values
  - H^0, $H^\pm$ and A^0 nearly degenerate in mass
  - H^0 small couplings to VV, large couplings to ZA^0
  - For large $\tan\beta$, 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

More Scalars (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 for MC

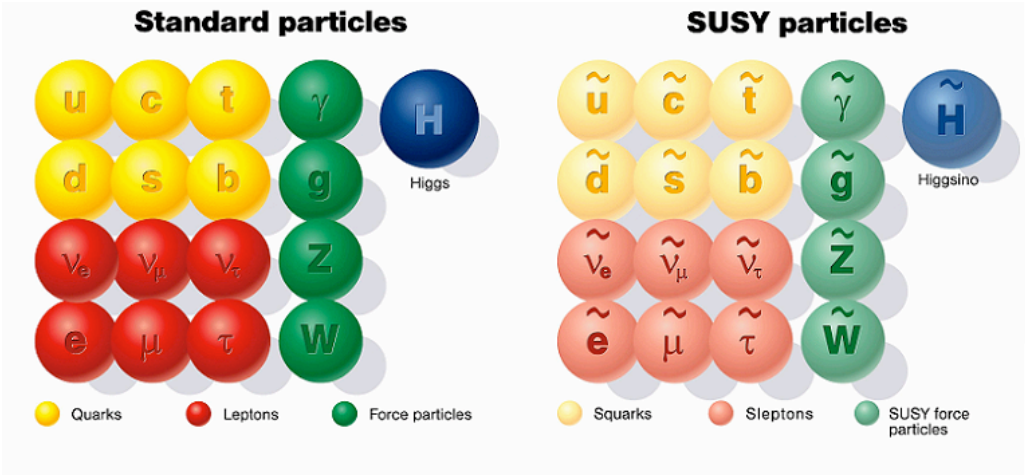


Dittmaier and Kaiser [hep-ph/0203120]

- Strong case for a Muon Collider

Supersymmetry

- Symmetry charges Q_{susy} have spin 1/2. Not a purely internal symmetry
  - $\{Q_{susy}, Q_{susy}\} = 2\ \gamma^{\mu} P_{\mu}$; $Q_{susy}\, H|state\rangle = H\, Q_{susy}|state\rangle$
- $Q_{susy}\,|boson\rangle = |fermion\rangle$: gluon -> gluino ,... ; W boson -> wino; higgs -> higgino, ... $Q_{susy}\,|fermion\rangle = |boson\rangle$:top quark (L,R) -> top squark (L,R), ...; electron(L,R) -> selectron(L,R), ...



- 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?

- Supersymmetry dictates the couplings between particles and sparticles
- Dark matter candidates, GUT unification
- No superpartner has yet been observed => Supersymmetry is broken Msparticle ≠

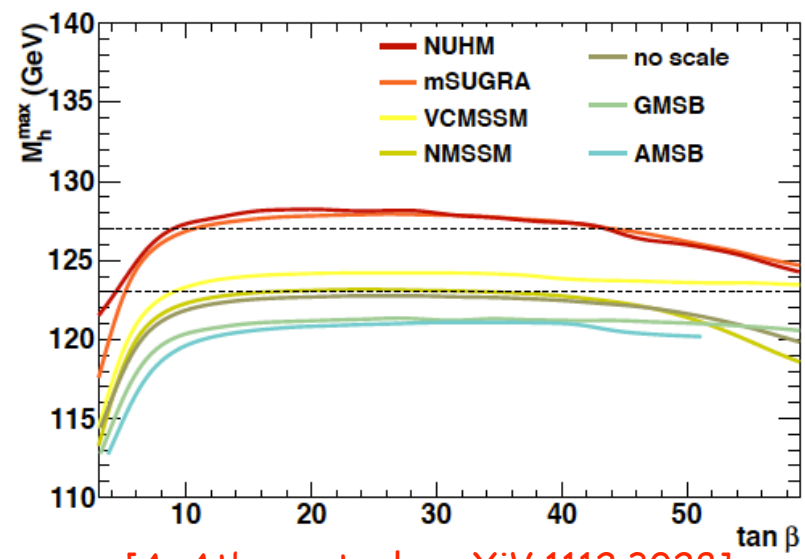
Supersymmetry

- cMSSM - simple model with only 5 parameters (m_0, $m_{1/2}$, $\tan\beta$, A/m_0, sign(μ))
- LHC limits on SUSY sparticles in various cMSSM scenerios:
  - Gluino and light squark masses limits ~ 1 TeV
  - The detailed study of SUSY will require a multiTev lepton collider
- As mass scales increase (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($m_{\tilde{t}}/m_t$)

- Are various constrained models consistent with a Higgs mass of 126 GeV?
  - Parameters varied in wide range. Upper bound - m_h in top 1%
  - 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: $m_0 \simeq A_0 \simeq 0$

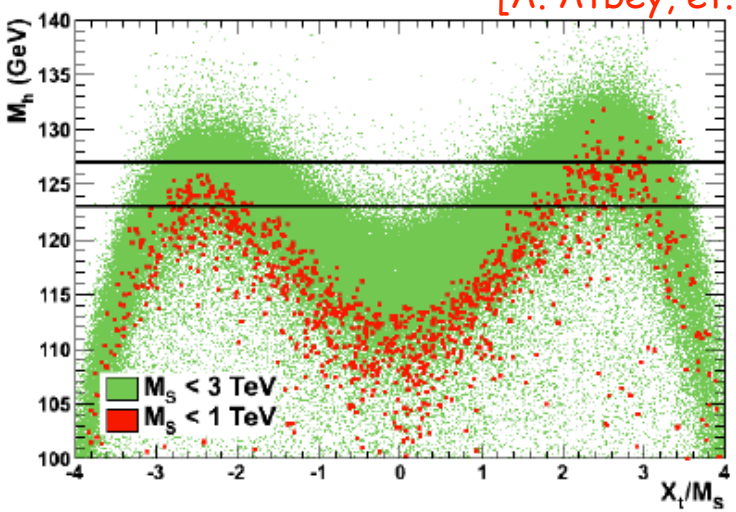


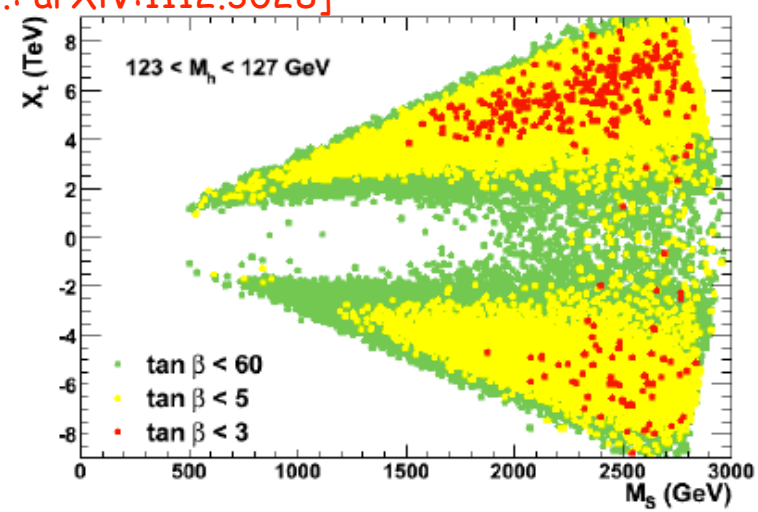
[A. Atbey, et. al.: arXiV:1112.3028]

Supersymmetry

- pMSSM – minimal assumptions on SUSY breaking parameters
  - 22 parameters varied $1 \leq \tan\beta \leq 60\,,\ 50\ \mathrm{GeV} \leq M_A \leq 3\ \mathrm{TeV}\,,\ -9\ \mathrm{TeV} \leq A_f \leq 9\ \mathrm{TeV}\,,$ $50\ \mathrm{GeV} \leq m_{\tilde{f}_L}, m_{\tilde{f}_R}, M_3 \leq 3\ \mathrm{TeV}\,,\ 50\ \mathrm{GeV} \leq M_1, M_2, |\mu| \leq 1.5\ \mathrm{TeV}.$
  - stop mixing parameter $X_t = A_t - \mu \cot\beta$; $M_S = \sqrt{m_{\tilde{t}_R} m_{\tilde{t}_L}}$

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





  - Consistence requires: $M_A \gg M_h$; ; tan β > 10; M_S large; maximal mixing ~ $\sqrt{6}\, M_S$

- Sleptons, charginos and neutralinos still remain easily assessible at a multi-TeV lepton collider.
- Supersymmetry provides a very strong case for a multi-TeV muon collider.

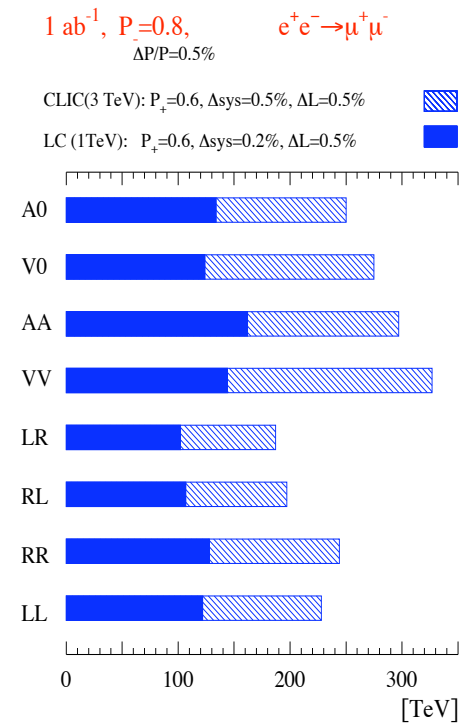
New Dynamics

- Electroweak Symmetry Breaking is generated dynamically at nearby scale
  - Technicolor, ETC, walking TC, topcolor, Two Scale TC, composite Higgs models, ...
  - New strong interaction around 1 TeV:
    - What is the spectrum of low-lying states? s-channel production π_T (technipion) (0^-), ρ_T, ω_T (technirho, techniomega) nearly degenerate - needs good energy resolution
    - 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?

- Contact interactions
  - e.g. Compositeness, broken flavor symmetries, ...
  - Present LHC bounds (~ 10 TeV)

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

  - Muon collider sensitive to scales > 200 TeV
    - Forward cone cut not important
    - Polarization useful in determining chiral character of the interaction.



In Summary

- 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.
- The observation of a new state at 126 GeV by both ATLAS and CMS revitalizes consideration of a Higgs factory as part of a staged multi-Tev muon collider. This is particularly attractive if there is an enlarged scalar sector (eg. THDM, SUSY)
- Issues to address for MC Higgs factory:
  - What energy resolution (when) can be obtained (goal 0.003%)
  - What integrated lumimosity can be expected (goal few fb^{-1})
  - Can the shot to shot energy of the beams be controlled to 10^{-5} accuracy
  - Detailed studies of S/B required for physics reach.
  - Studies shuold combine information available from LHC results to determine the added benefit of any future lepton collider.

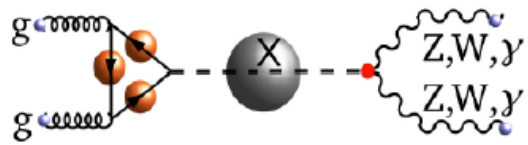
BACKUP SLIDES

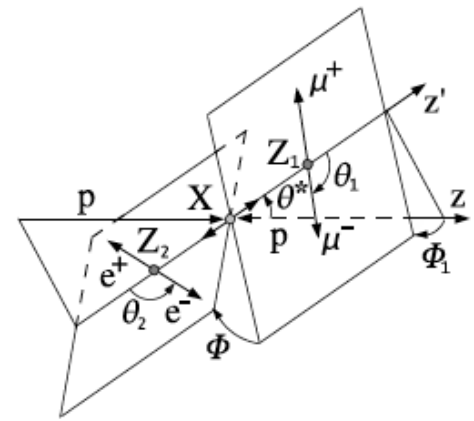
Implications of early LHC Results

- Excess in the 126 GeV region : Is it the SM higgs?
  - spin and parity : 0^+ or 0^- (or $2^\pm$)

▪ **Spin 0:** $A(X \to V_1 V_2) = v^{-1} \varepsilon_1^{*\mu} \varepsilon_2^{*\nu} \left(a_1 g_{\mu\nu} M_X^2 + a_2 q_{1\mu} q_{2\nu} + a_3 \varepsilon_{\mu\nu\alpha\beta} q_1^\alpha q_2^\beta \right)$

- ▶ SM Higgs→ZZ,WW: $a_1 \neq 0, a_2 \sim O(10^{-2}), a_3 \sim O(10^{-11})$
- ▶ SM Higgs→ $\gamma\gamma$: $a_1 = -a_2/2 \neq 0$
- ▶ BSM pseudo-scalar Higgs $a_3 \neq 0$



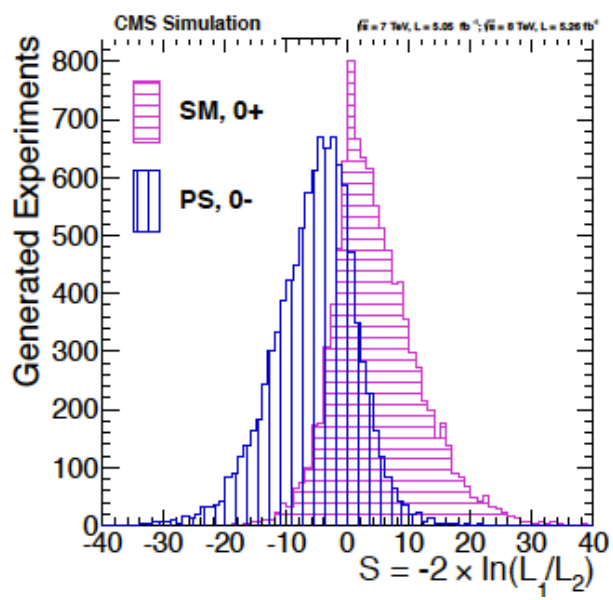


  - use ZZ* -> 4 leptons, WW* -> lepton + E_T (missing) + 2jets angular correlations

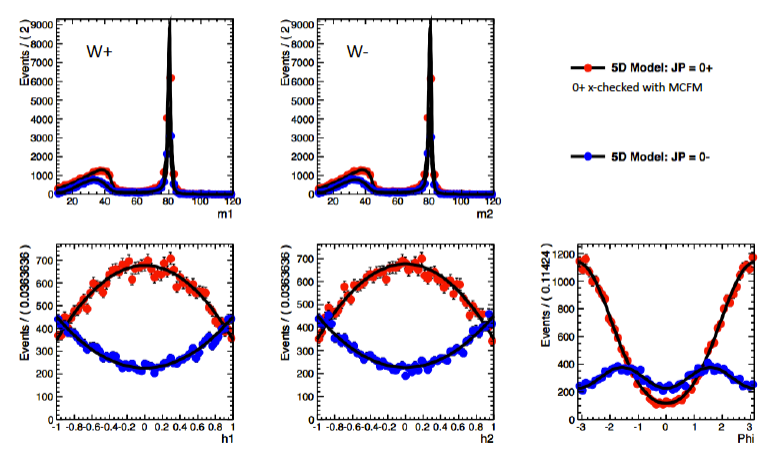
[Z^0Z^0] P.S. Bhupal Dev, et. al. [arXiv:0707.2878]; Yanyan Gao et. al. [arXiv:1001.3396]
[W^+W^-] J. Ellis and D.S. Hwang [arXiv:1202.6660]

S. Bolognesi [ICHEP 2012]

Integ. Lumi. 7 (8) TeV	Expected Separation
5/fb (5/fb)	1.6σ
5/fb (20/fb)	2.6σ
5/fb (30/fb)	3.1σ



0+ vs 0- in WW channel (125 GeV)



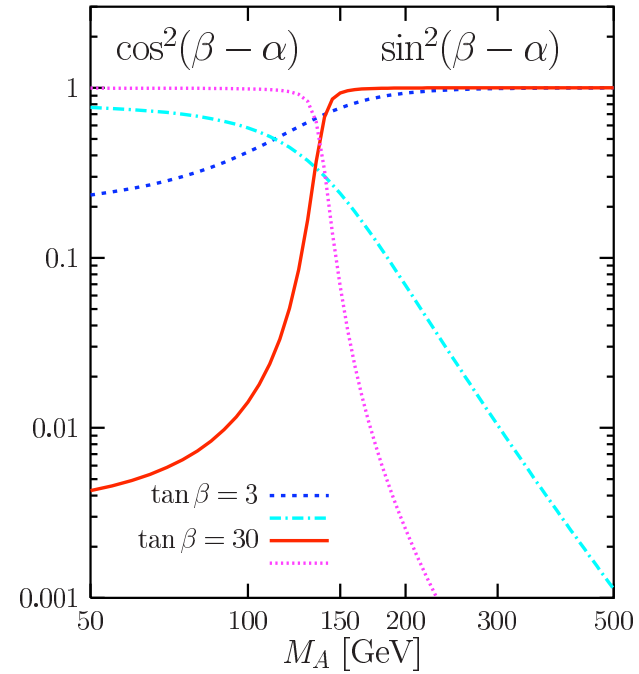
Sara Bolognesi (Johns Hopkins University) 15 ICHEP 2012, Melbourne

Two Higgs Doublet Model (MSSM)

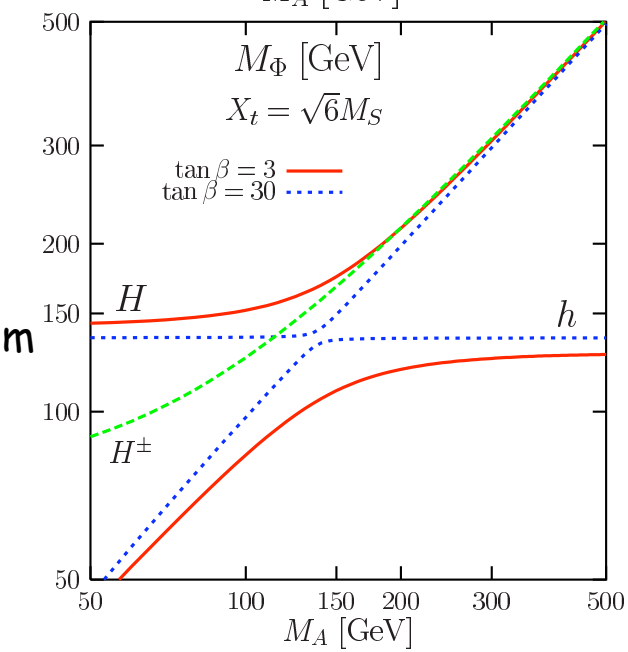
- Five scalar particles: h^0, H^0, A^0, $H^\pm$
- Decay amplitudes depend on two parameters: (α, β)

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

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

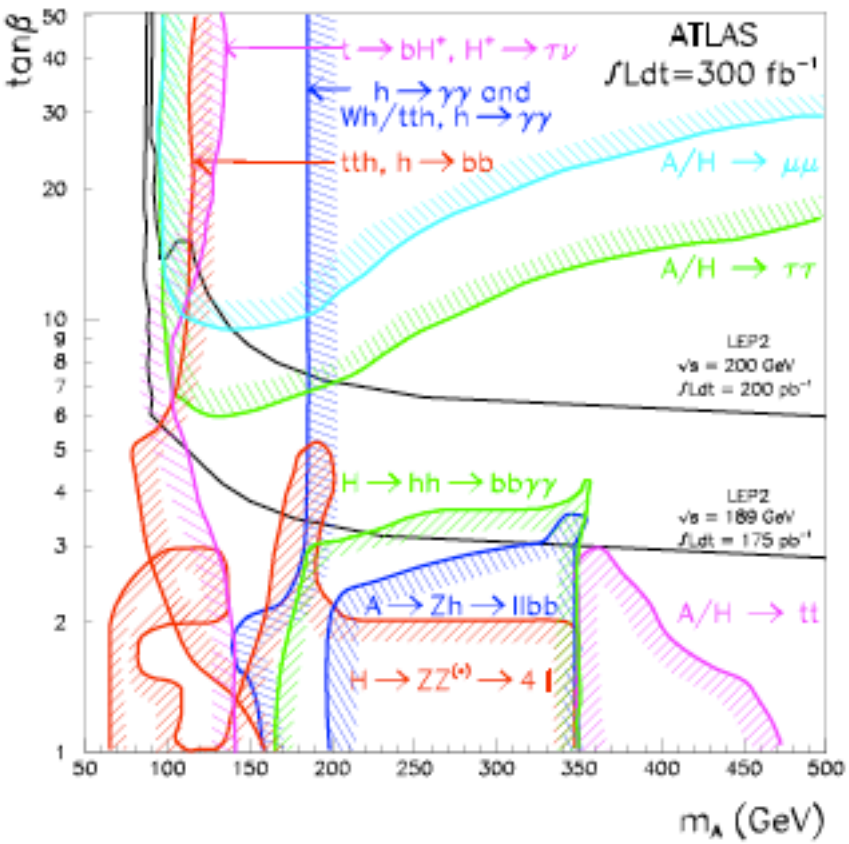


- decoupling limit $m_{A^0} >> m_{Z^0}$:
  - h^0 couplings close to SM values
  - H^0, $H^\pm$ and A^0 nearly degenerate in mass
  - H^0 small couplings to VV, large couplings to ZA^0
  - For large $\tan\beta$, H^0 and A^0 couplings to charged leptons and bottom quarks enhanced by $\tan\beta$. Couplings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

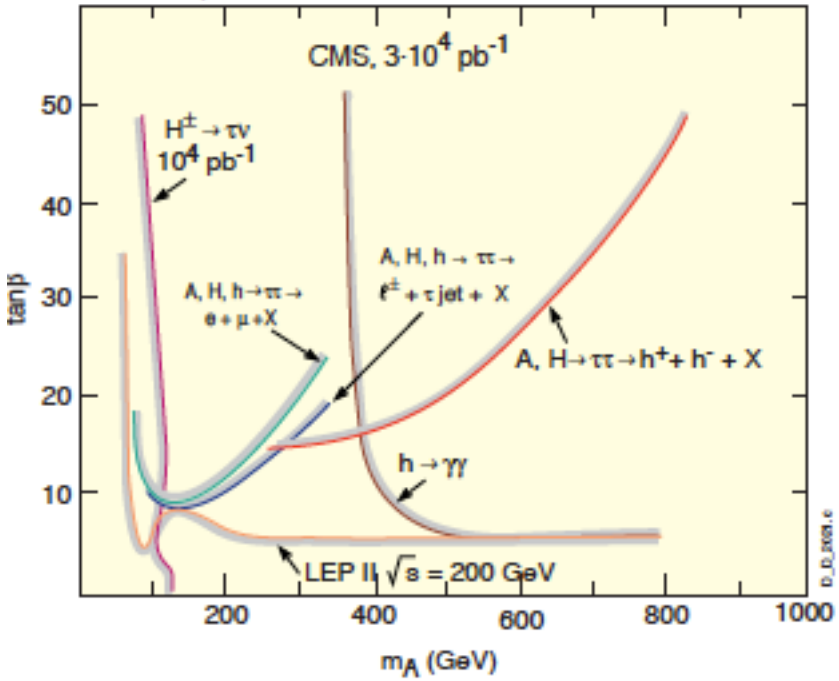


- Pair produced with easy at a multi-TeV lepton collider.

Significance contours for SUSY Higgses

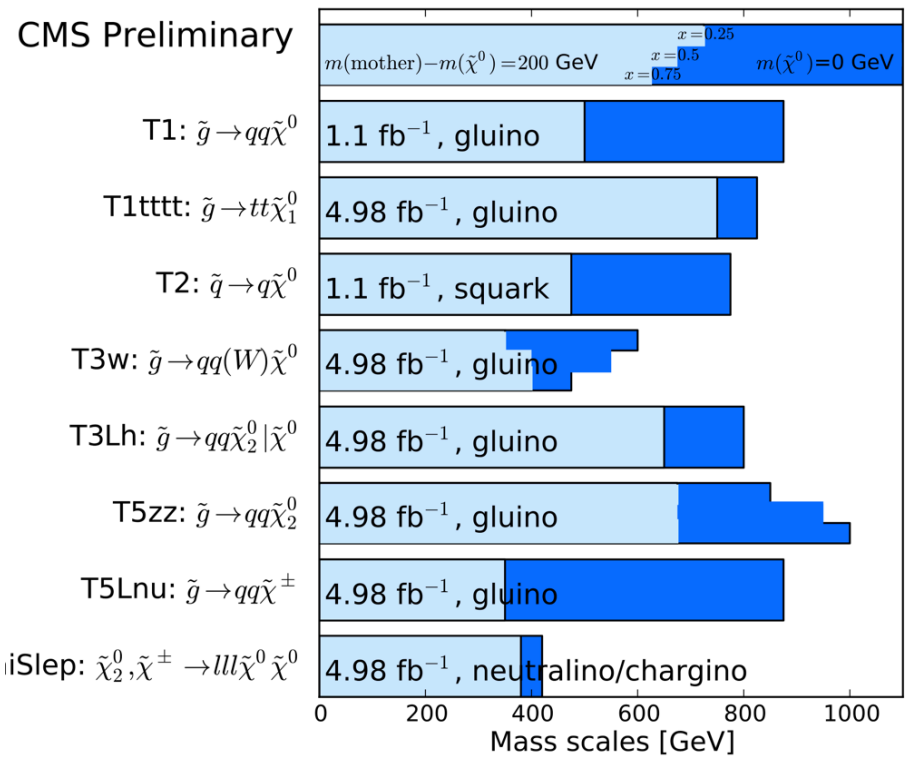
Regions of the MSSM parameter space (m_A, tgβ) explorable through various SUSY Higgs channels

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

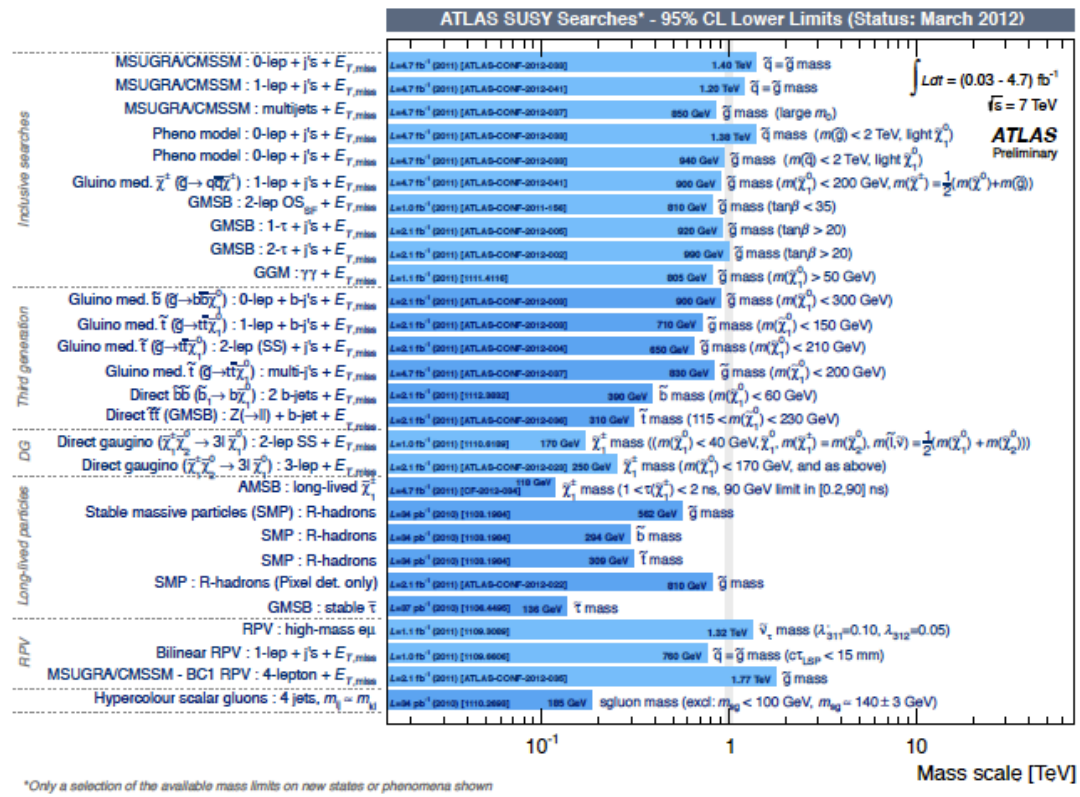


Supersymmetry

- LHC limits on SUSY sparticles in various cMSSM scenerios:
  - Gluino and light squark masses limits ~ 1 TeV
  - The detailed study of SUSY will require a multiTev lepton collider



ATLAS



SUSY

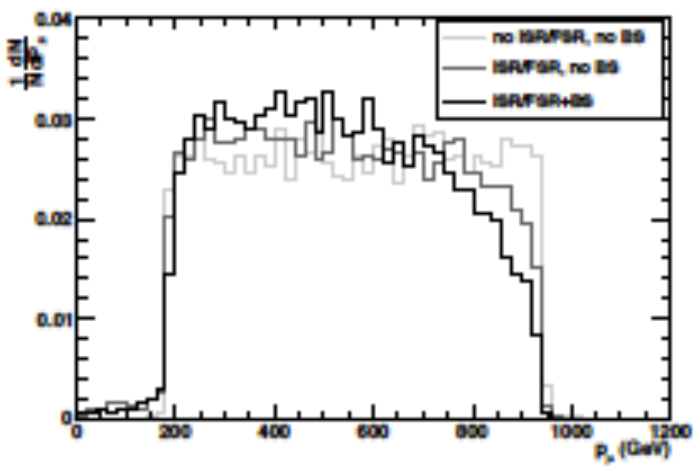
- Example study of slepton pair production:

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

  - 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.



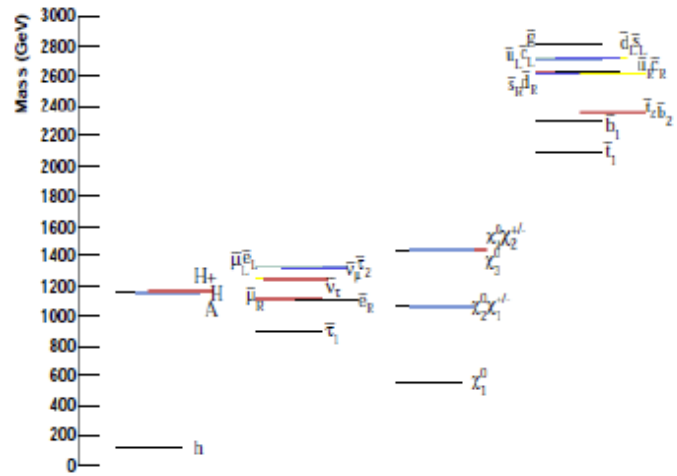


Table 2: Summary of the results of the fits to the smuon and neutralino mass for various assumptions on track momentum resolution, beamstrahlung, polarisation and number of bunch crossings integrated in one events. The results obtained on signal only (S) at generator level are also compared to those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

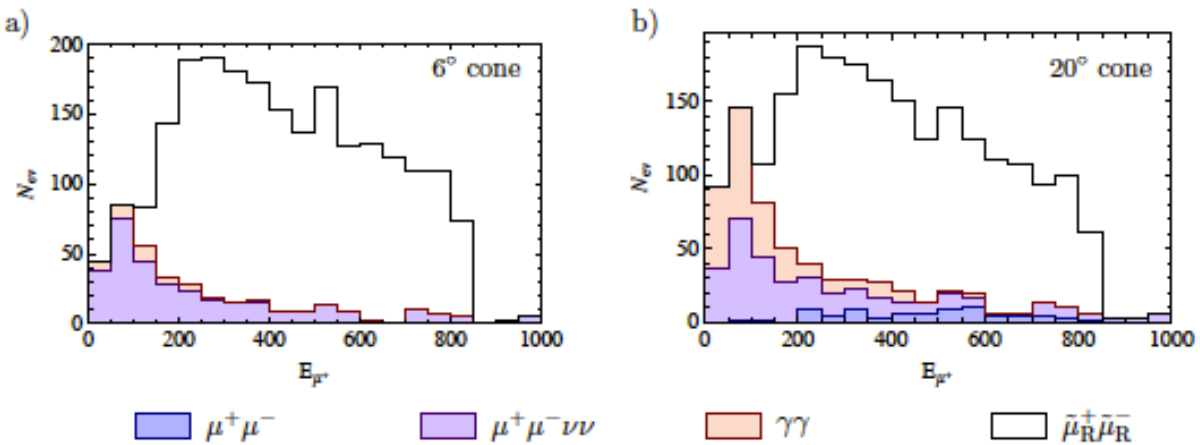
N. Alster and M. Battaglia [arXiv:1104.0523]

SUSY

- Detailed study for muon collider

[A. Freitas: arXiV:1107.3853]

  - large backgrounds



good benchmark process for MC

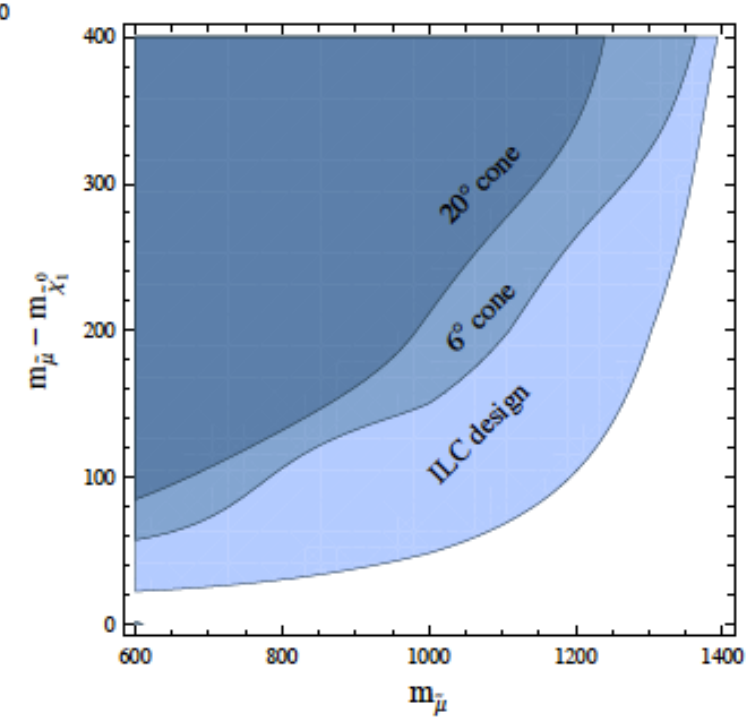
  - suitable cuts reduce backgrounds but limit sensitivity to small mass difference between smuon and its decay products.

$\sqrt{s} = 3$ 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.



New Dynamics

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

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?
- ...

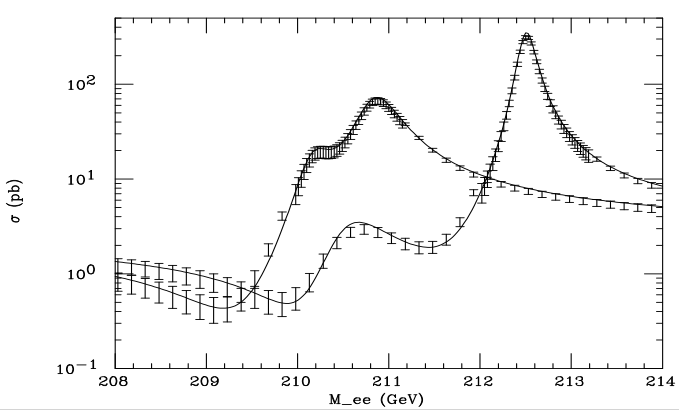
- State observed at 125 GeV would more naturally be a pseudoscalar (0^-)

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

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

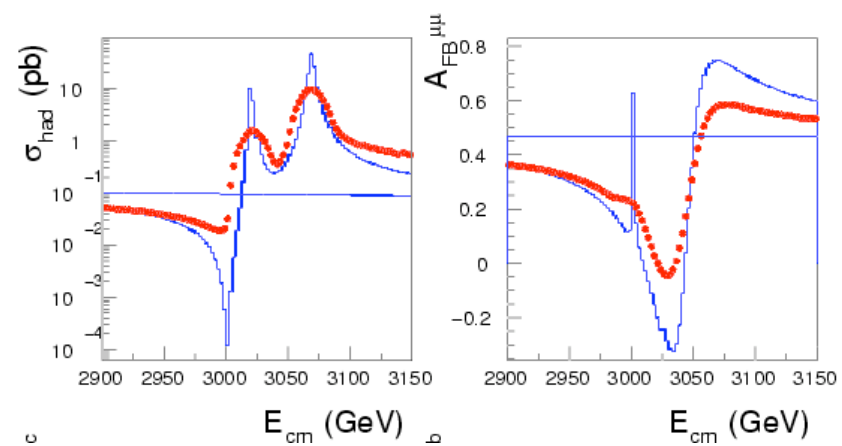
- Technipions - s channel production (Higgs like)
- Technirhos - Nearby resonances (ρ_T,ω_T)- need fine energy resolution of muon collider.

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

- The SM is only an effective theory valid below the compositeness scale.
  - New interactions (at scales not directly accessible) give rise to contact interactions.

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

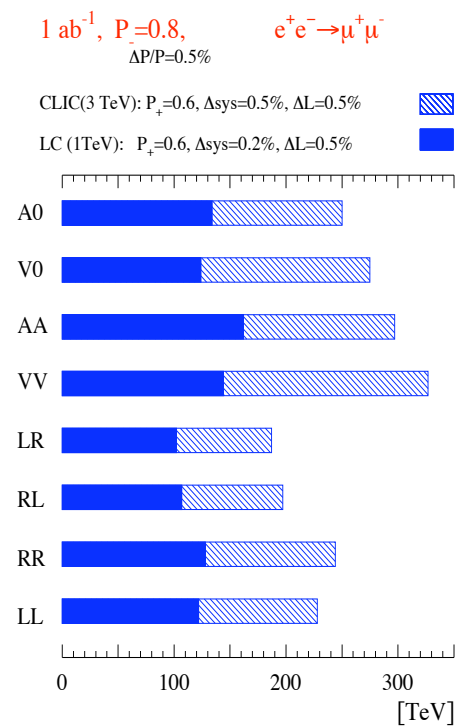
CI model	Observed limit (TeV)	Expected limit (TeV)
NLO $\Lambda^{+}_{LL/RR}$	7.5	$7.0^{+0.4}_{-0.6}$
NLO $\Lambda^{-}_{LL/RR}$	10.5	$9.7^{+1.0}_{-1.7}$
LO $\Lambda^{+}_{LL/RR}$	8.4	$7.9^{+0.5}_{-0.7}$
LO $\Lambda^{-}_{LL/RR}$	11.7	$10.9^{+1.7}_{-2.4}$
LO $\Lambda^{+}_{VV/AA}$	10.4	$9.5^{+0.5}_{-1.0}$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