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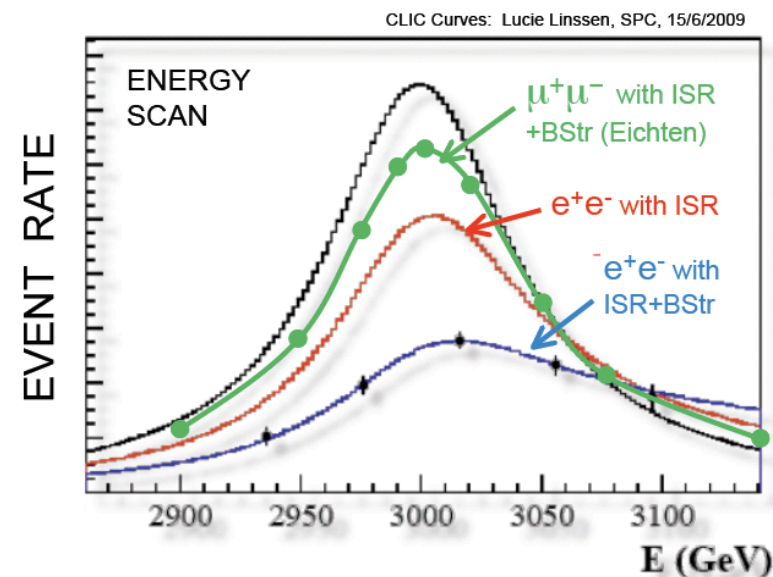
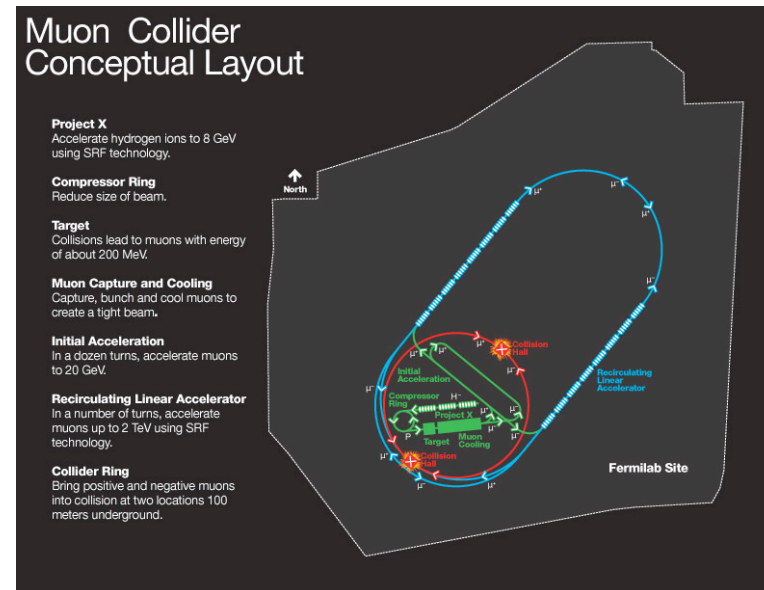
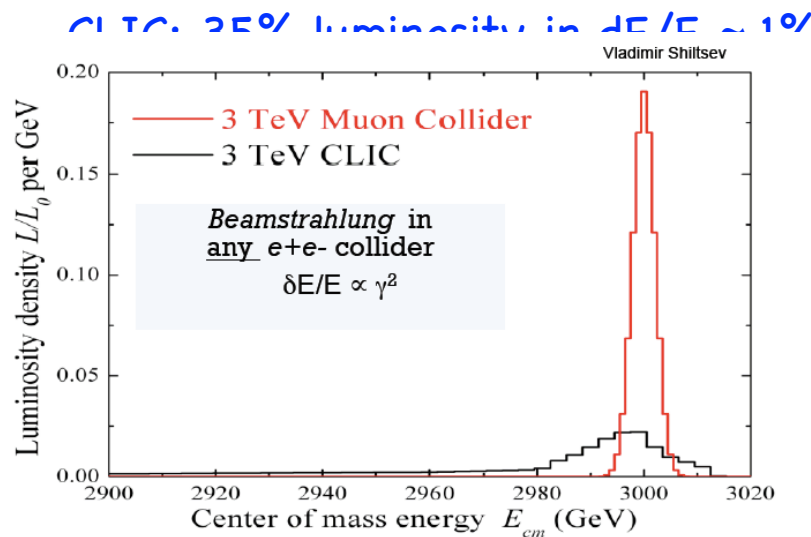
- General Remarks
- The SM Higgs
 - Finding the Higgs
 - Higgs mass and width
 - Higgs couplings
- Beyond the Standard Model
 - THDM and SUSY
 - New Dynamics
- Summary

2013 MAP Collaboration Meeting
Fermilab
June 19-21, 2013



- $\mu^+ \mu^-$ Collider:
 - Center of Mass energy: 1.5 - 6 TeV (3 TeV)
 - Luminosity $> 10^{34} \text{ cm}^{-2} \text{ sec}^{-1}$ (440 fb $^{-1}$ /yr)
 - Compact facility
 - 3 TeV - ring circumference 3.8 km
 - 2 Detectors
 - Superb Energy Resolution

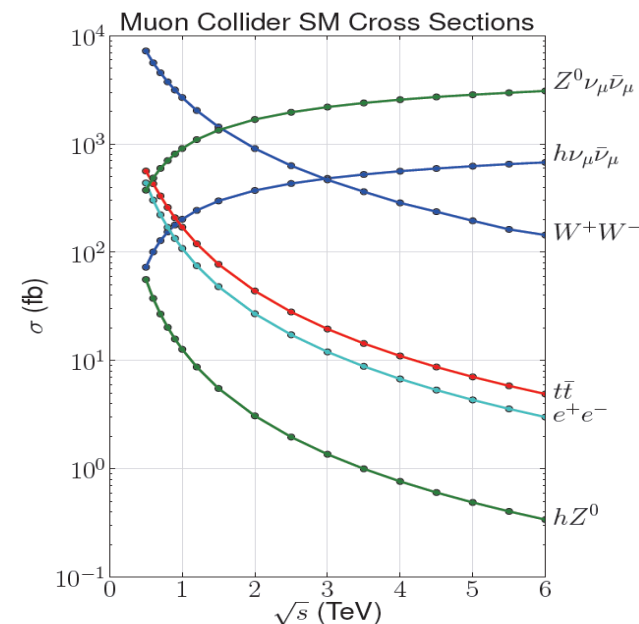
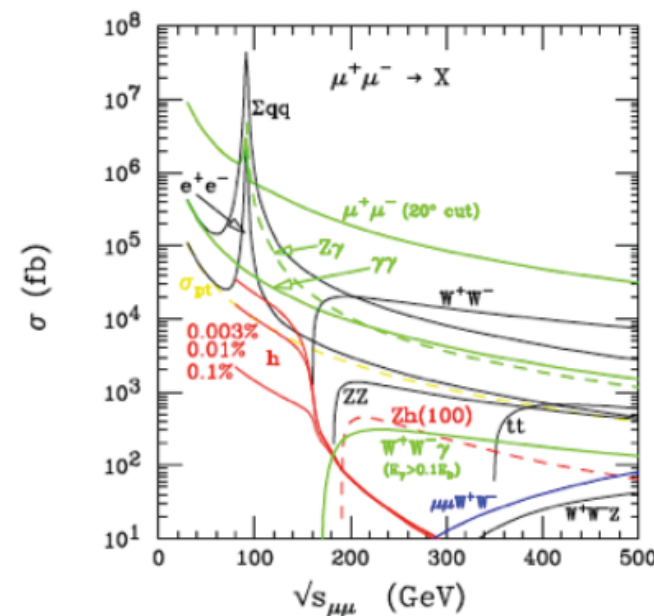
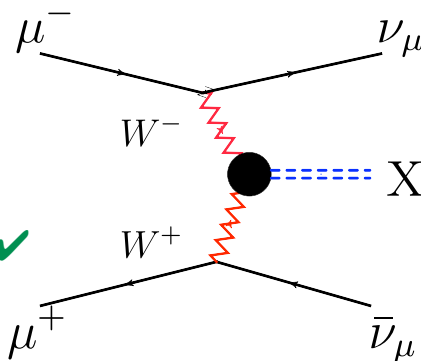
- MC: 95% luminosity in $dE/E \sim 0.1\%$



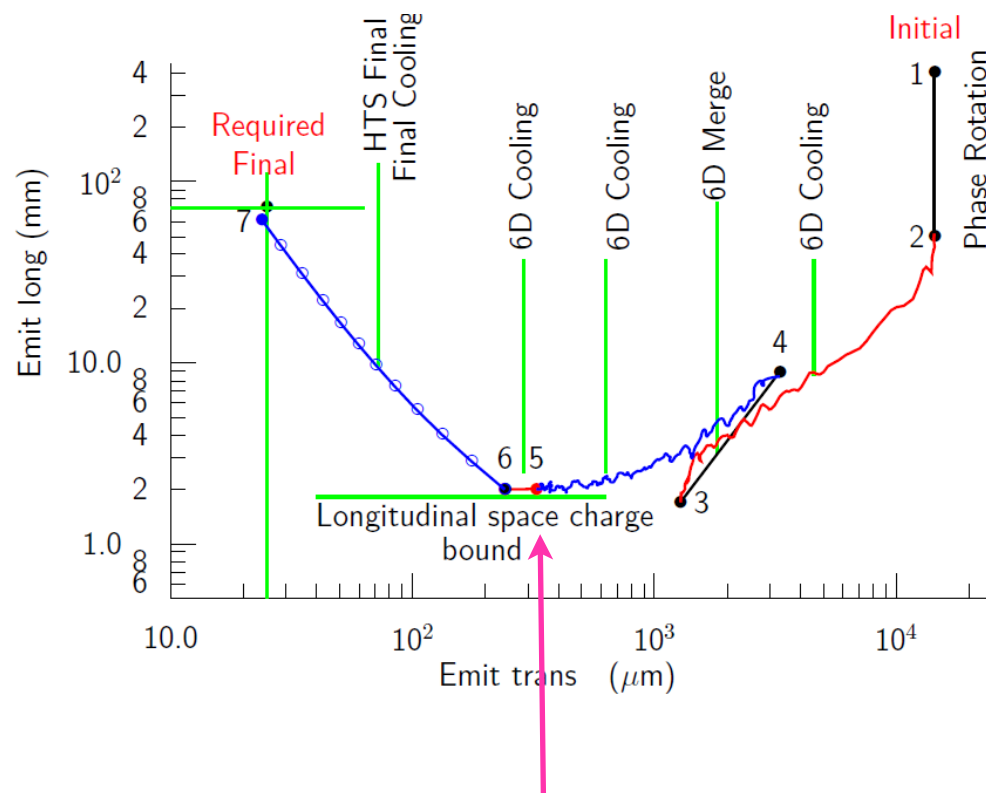
- For $\sqrt{s} < 500 \text{ GeV}$
 - SM thresholds: $Z^0 h$, $W^+ W^-$, top pairs
 - Higgs factory ($\sqrt{s} \approx 126 \text{ GeV}$) ✓
- For $\sqrt{s} > 500 \text{ GeV}$
 - Sensitive to possible Beyond SM physics.
 - High luminosity required. ✓
 - Cross sections for central ($|\theta| > 10^\circ$)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

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

- An Electroweak Boson 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 $\approx 10^6$) rapidly \rightarrow ionization cooling
 - requires a complex cooling scheme
 - The decay products ($\mu^- \rightarrow \bar{\nu}_\mu \nu_e e^-$) have high energies.
 - Detector background issues
 - Serious neutrino beam issue for $E_{cm} \geq 4$ TeV



Higgs Factory

- Staging Steps:

- Higgs factory $\sqrt{s} = m_H \approx 126 \text{ GeV}$

- Some initial running on Z peak for calibration.
 - Nominal Luminosity $1.7 \times 10^{31} \sim 170 \text{ pb}^{-1} / \text{yr}$; beam energy spread 0.003%
 - Upgraded Luminosity: $8 \times 10^{31} \sim 800 \text{ pb}^{-1} / \text{yr}$; beam energy spread 0.004%

- High Energy Muon Collider:

- The choice of the high energy muon collider design energy will depend on the scale of BSM physics discovered at the LHC with $\sqrt{s} \approx 14 \text{ TeV}$ after 300 fb^{-1}
 - $\sqrt{s} = 1.5 \text{ TeV}$; luminosity $1.25 \times 10^{34} \sim 125 \text{ fb}^{-1} / \text{yr}$; beam energy spread 0.1% (present detector and machine detector interface studies)
 - $\sqrt{s} = 3.0 \text{ TeV}$; luminosity $4.4 \times 10^{34} \sim 440 \text{ fb}^{-1} / \text{yr}$; (beginning studies)
 - $\sqrt{s} = 6.0 \text{ TeV}$; luminosity $1.6 \times 10^{35} \sim 1.6 \text{ ab}^{-1} / \text{yr}$ (Palmer's scaling)

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

Theory errors (LHC Higgs Cross Section WG)
[arXiv:1107.5909v2]

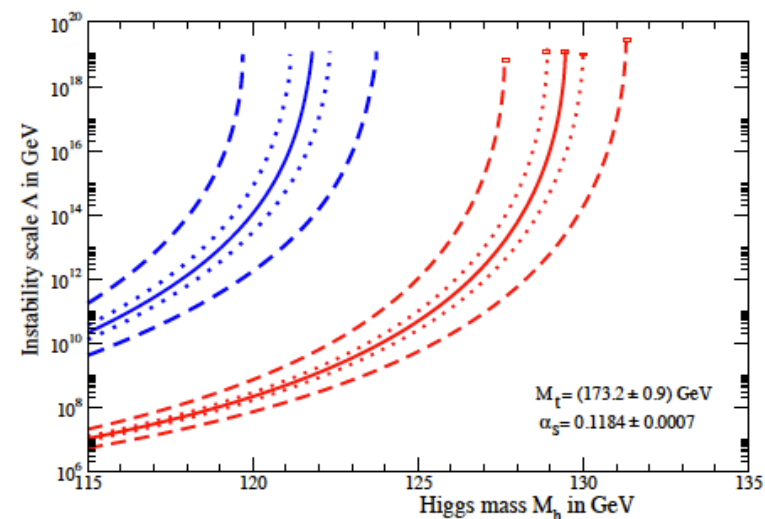
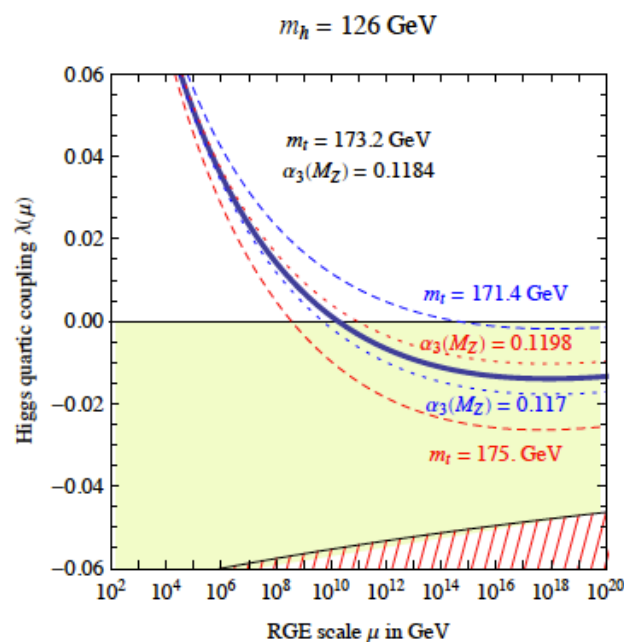
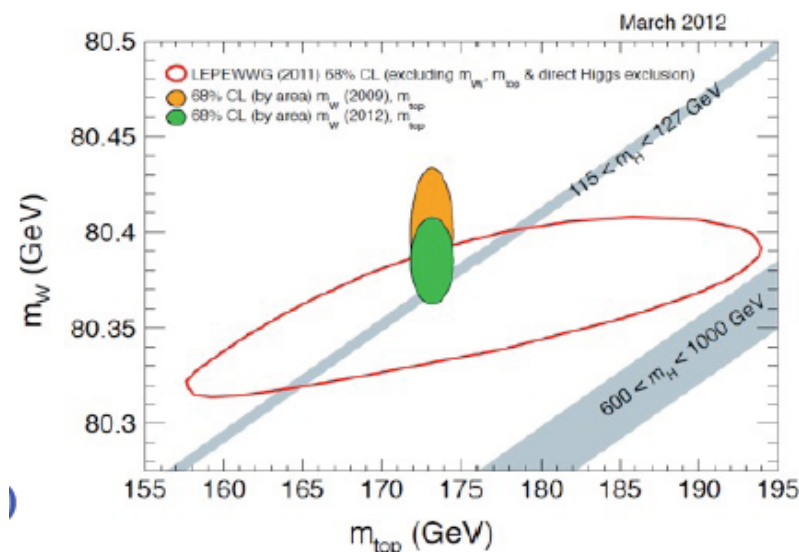
$$m(H) = 126 \text{ GeV} \quad \Gamma(H) = 4.21 \pm 0.16 \text{ MeV}$$

branching fractions :	$b\bar{b} = 0.561$	(3.4%)	$WW^* = 0.231$	(4.1%)
error(%)	$\tau\bar{\tau} = 6.15 \times 10^{-2}$	(5.8%)	$ZZ^* = 2.89 \times 10^{-2}$	(4.1%)
	$c\bar{c} = 2.83 \times 10^{-2}$	(12.2%)	$gg = 8.48 \times 10^{-2}$	(10.0%)
	$\mu^+\mu^- = 2.14 \times 10^{-4}$	(5.8%)	$\gamma\gamma = 2.28 \times 10^{-3}$	(4.9%)
			$Z^0\gamma = 1.62 \times 10^{-3}$	(8.8%)

- 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?

- 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.

Jean Elias-Miro et. al.
[arXiv:1112.3022]



- Theorists are intrigued by this edge of stability.

- Moriond 2013 results:

- ATLAS (Tim Adye)

- $m_H = 125.5 \pm 0.2 \text{ (stat)} {}^{+0.5}_{-0.6} \text{ (sys)} \text{ GeV}$
- $\mu = 1.30 \pm 0.13 \text{ (stat)} \pm 0.14 \text{ (sys)}$
- $\mu_{\text{VBF+VH}} / \mu_{\text{ggF+ttH}} = 1.2^{+0.7}_{-0.5}$
- 3.1σ evidence for VBF production

- CMS (Andrew Whitbeck)

$$m_H = 125.8 \pm 0.4 \text{ (stat)} \pm 0.4 \text{ (syst)} \text{ GeV}$$

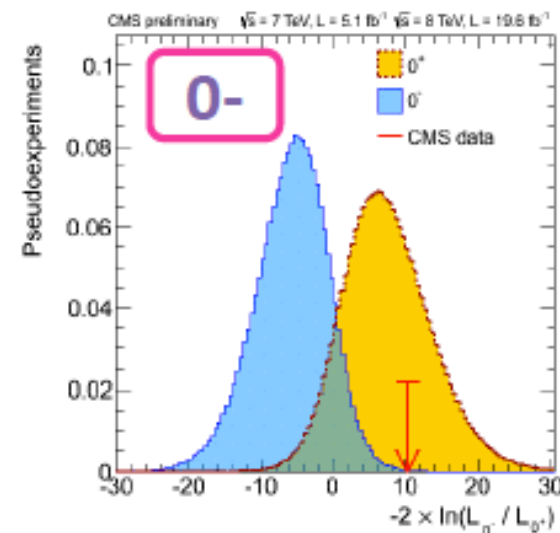
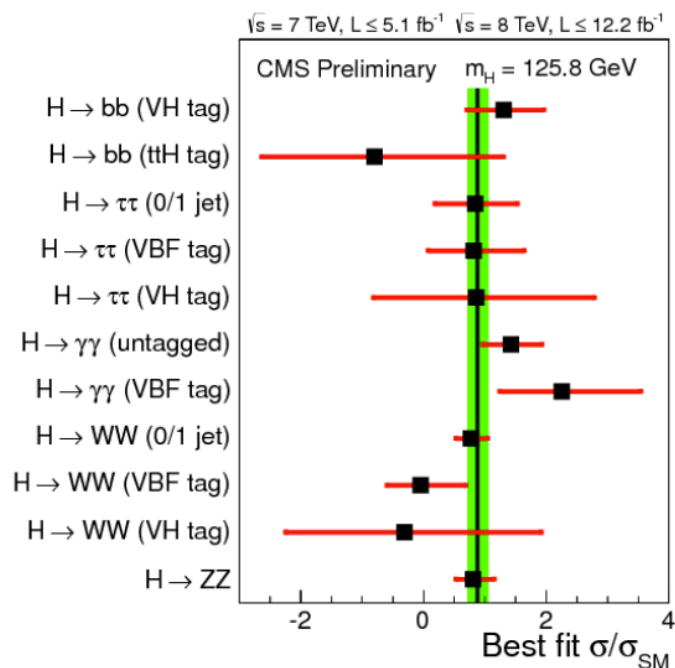
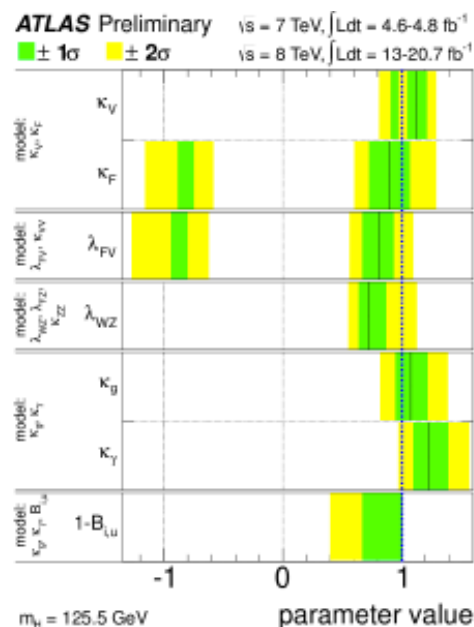
$$\sigma / \sigma_{\text{SM}} = .88 \pm 0.21$$

- Data consistent with
 - Custodial symmetry
 - Fermion universality tests
 - Fermionic and bosonic couplings expected from SM Higgs

- Pseudoscalar versus Scalar

- Light pseudoscalars often appear in dynamical EWSB models
- However they don't couple to WW/ZZ in lowest order.
- Assuming spin zero - a pure pseudoscalar is experimentally disfavored.

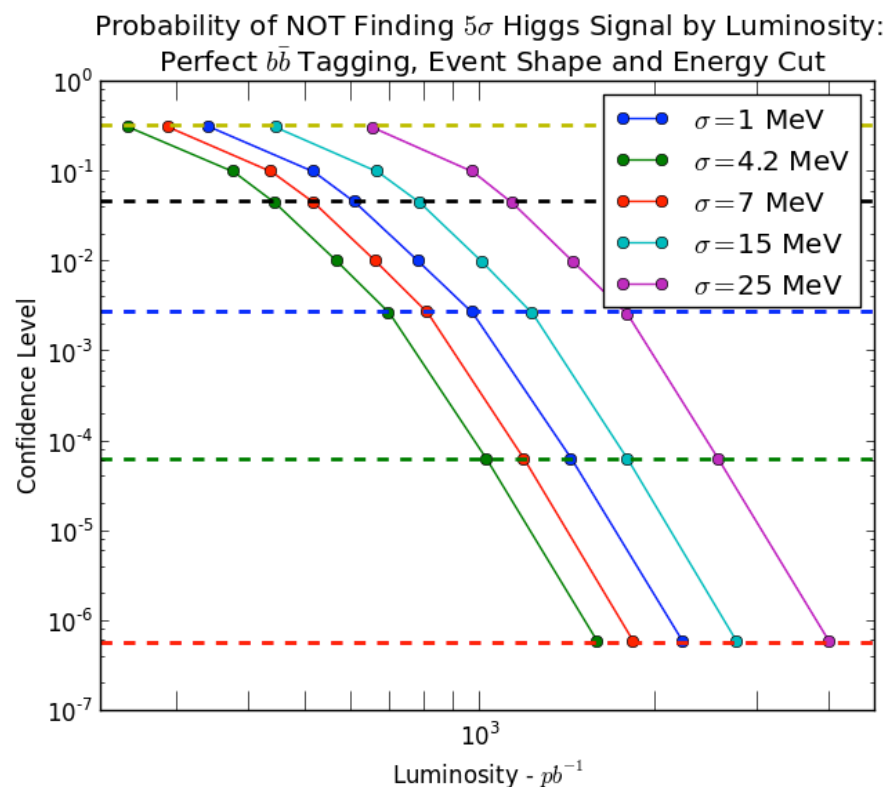
- Measure couplings to distinguish SM Higgs from BSM scalars



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

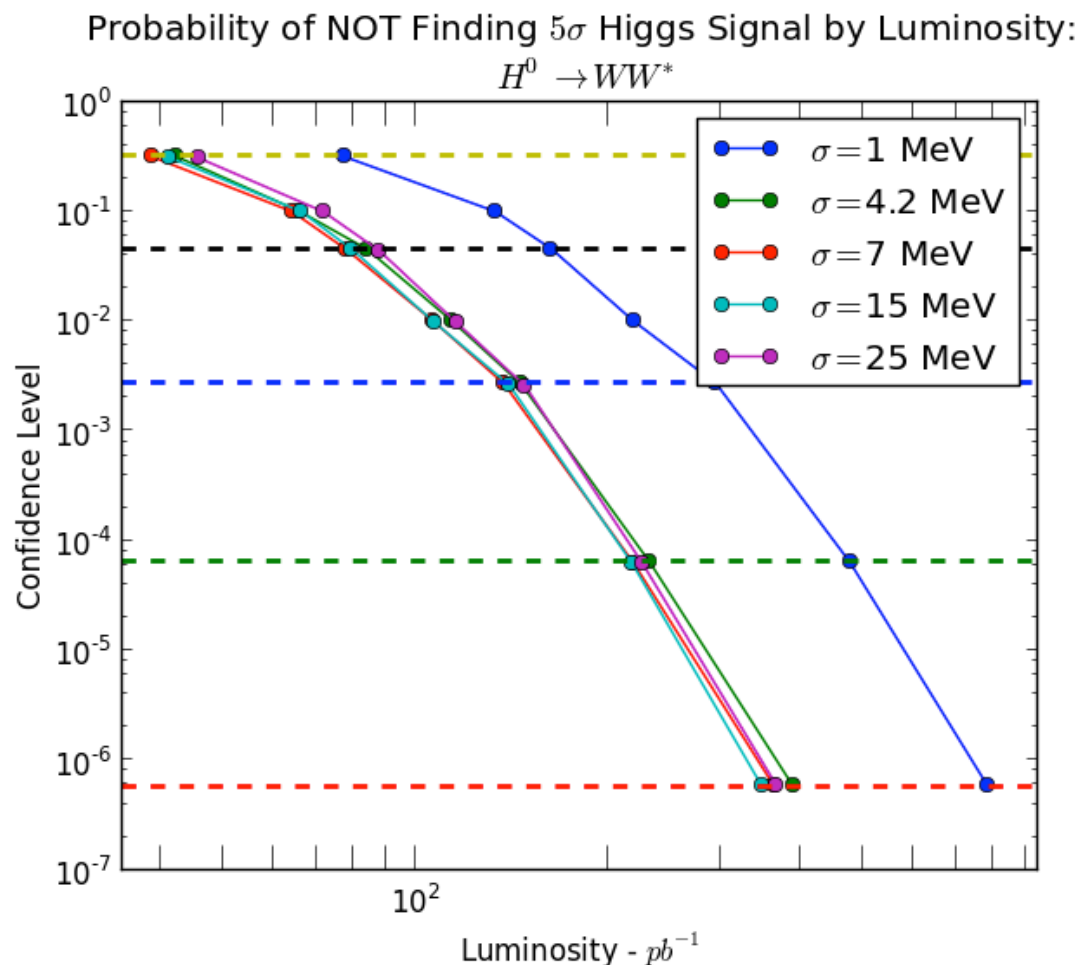
- List of issues for MC Higgs Factory
 - Requires precise energy resolution: $\Delta E/E \sim \text{few} \times 10^{-5}$
 - Can such a resolution be achieved?
 - What error on the Higgs width would be possible?
 - Integrated luminosity?
 - Beam energy stability - store-to-store?
 - What branching ratios could be measured?
 - W^+W^- , ZZ (very small backgrounds)
 - bb ($S/B \sim 1$)
 - $\Delta(\text{BR}(\mu^-\mu^+)\times\text{BR}(WW))$ [2%]. Will provide the most accurate measure a Yukawa coupling. (Grinstein)
 - Detector backgrounds from muon decays in beams
 - S/B studies?
- Preliminary studies:
 - $\Delta E = 4 \text{ MeV}$ and $\mathcal{L} > 10^{31} \text{ cm}^{-2}\text{sec}^{-1}$
 - Can use nearby Z pole to tune machine.
 - Use spin precession to measure beam energy.
 - Initial studies of decay modes with backgrounds

- The Higgs mass will be known to 100 MeV from the LHC (or ILC). But we need to find m_H to ~ 4 MeV then sit on the resonance at a muon collider.
- Alex Conway and H. Wenzel [1304.5270] and E.E.(unpublished) have studied the question of what integrated luminosity is required to discover the Higgs to 3σ (5σ) as a function of beam energy spread
- b-bbar channel.
 - $\sigma = \Gamma_H$ best
 - p-value $< 0.0027 \Rightarrow$
 - 700 pb^{-1} (3σ)
 - 1,600 pb^{-1} (5σ)



A. Conway & H. Wenzel
[ArXiv:1304.5270]

- $W W^*$ channel.
 - Very small backgrounds WW^*
 - Use the $lv + 2\text{jets}$ final state
 - Expect backgrounds to this channel with appropriate cuts approximately 0.1 pb^{-1}
 - $p\text{-value} < 0.0027 \Rightarrow 150 \text{ pb}^{-1}$
- Can improve results by using both channels



A. Conway & H. Wenzel
 [ArXiv:1304.5270]

- Combining the two channels:

- needed luminosity for a (5σ) Higgs signal

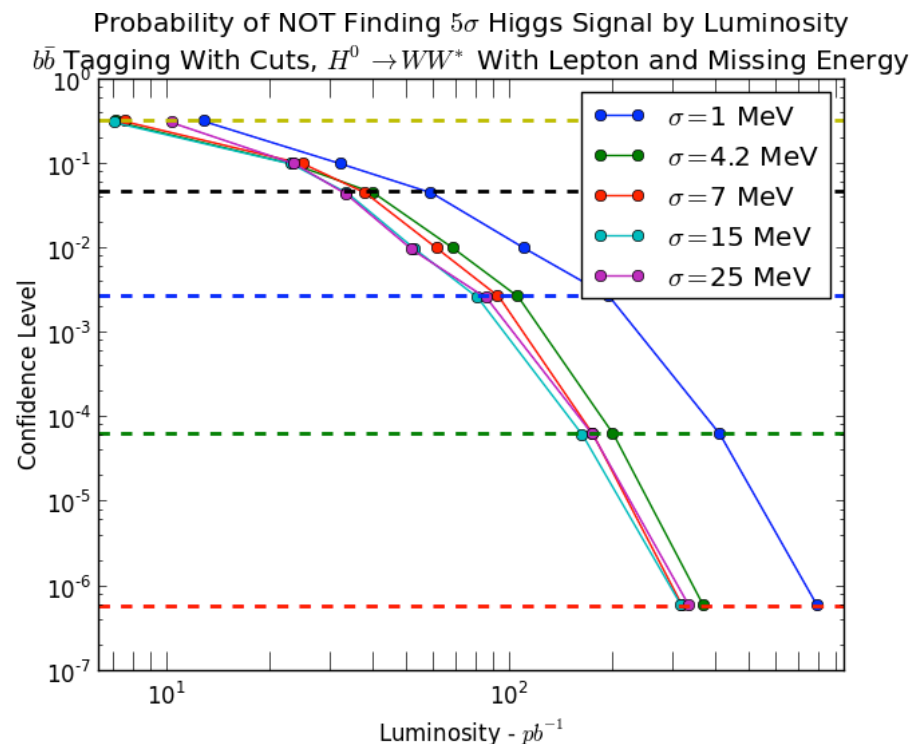
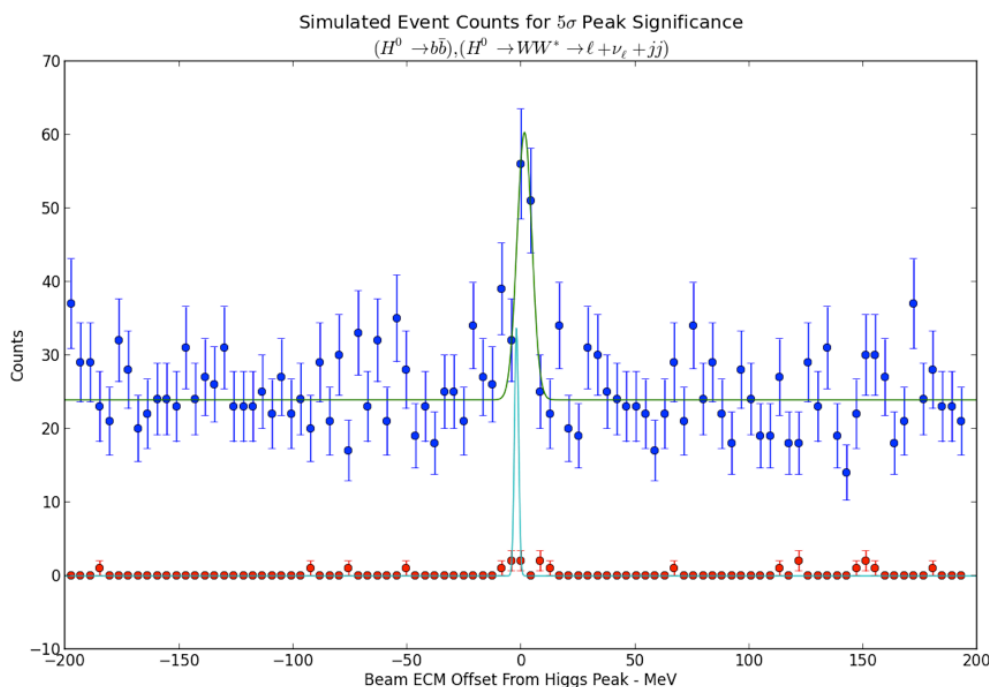
p-value = 2.7×10^{-3} (3σ):

bin = 4.2 MeV

int $L = 370 \text{ pb}^{-1}$

- needed luminosity for a (3σ) Higgs signal

int $L \approx 105 \text{ pb}^{-1}$



A. Conway & H. Wenzel
[ArXiv:1304.5270]

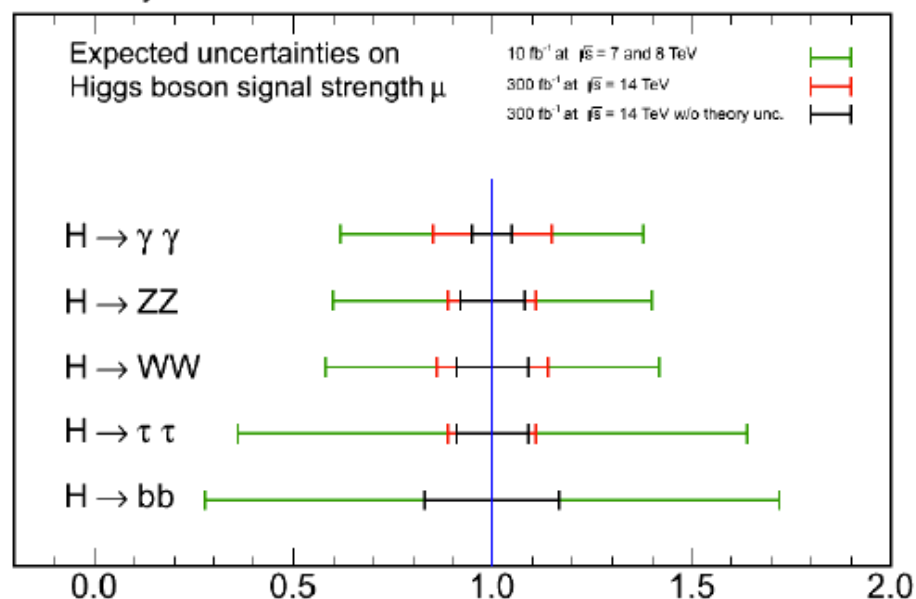
Finding the Higgs requires a
six months running at
 1.7×10^{31} luminosity



- Measurements for a Higgs factory
 - partial decay widths into WW^* and ZZ^* :
 - Establishes whether the Higgs is the sole agent of EWSB.
 - If additional contributors to EWSB are all $SU_L(2)$ doublets then $\Gamma/\Gamma_{SM} < 1$
 - The relative couplings of the Higgs to WW and ZZ is fixed by EW symmetry.
 - mass, total width and self coupling λ :
 - $\langle \Phi^\dagger \Phi \rangle = v^2/2 = m_h^2 / 2 \lambda$ [$v = (G_F/\sqrt{2})^{-1/2} \approx 247$ GeV]
 - look for invisible decays associated with BSM particles
 - Branching fractions into fermions:
 - Establishes whether the Higgs is the sole agent of fermion masses.
 - N.B. The original technicolor model provided for EWSB but not fermion masses.
 - Measure coupling to (top, bottom, tau) 3rd gen. and (charm, muon) 2nd gen. (2HDM)
 - Branching fractions into gauge bosons ($Z\gamma$, gg , $\gamma\gamma$)
 - Sensitive to BSM particles contributing in loops.

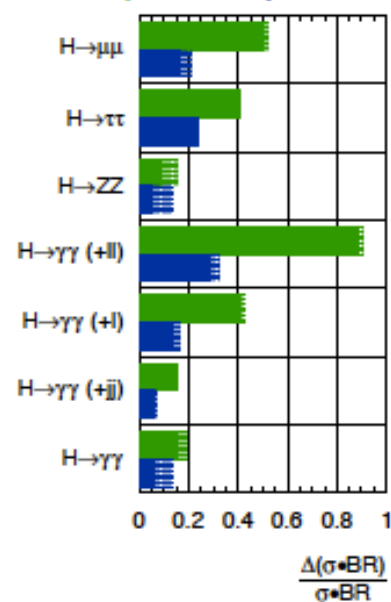
- What can be done at the LHC?
 - New projections from ATLAS and CMS for European Strategy Studies

CMS Projection



ATLAS Preliminary (Simulation)

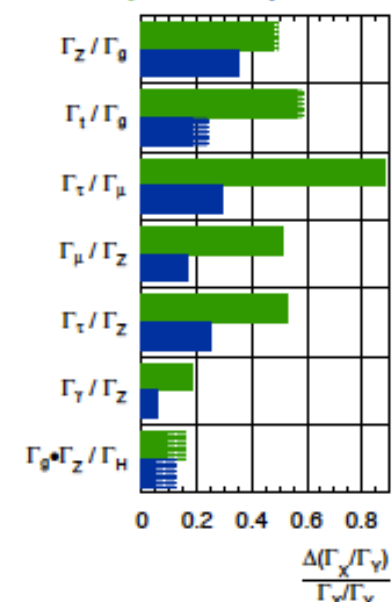
$\sqrt{s} = 14$ TeV: $\int L dt = 300 \text{ fb}^{-1}$; $\int L dt = 3000 \text{ fb}^{-1}$



(a)

ATLAS Preliminary (Simulation)

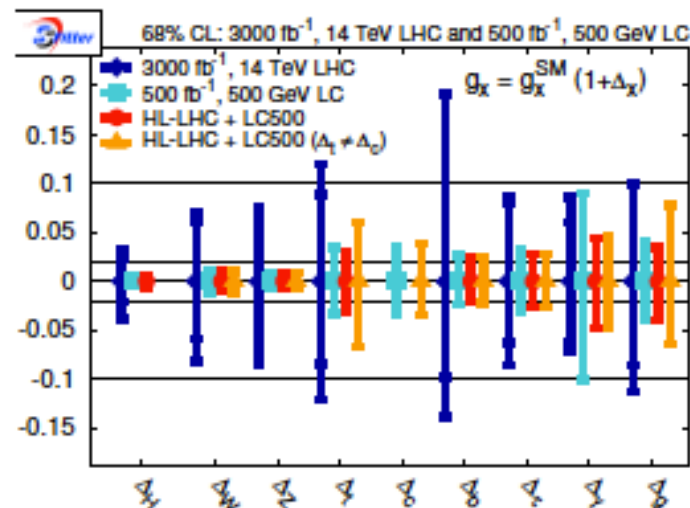
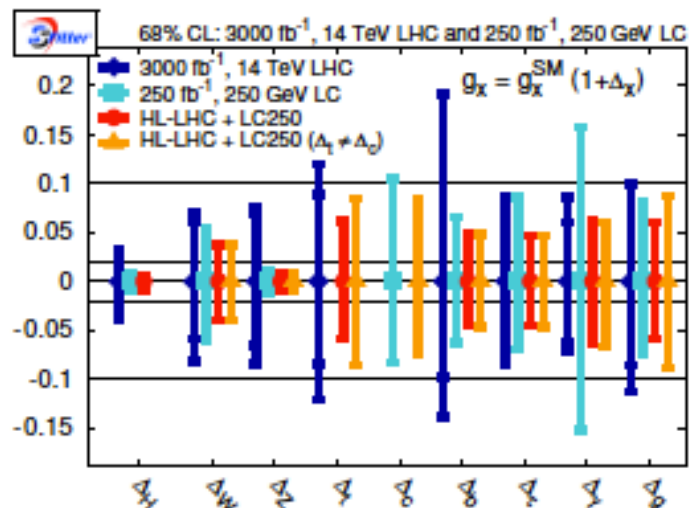
$\sqrt{s} = 14$ TeV: $\int L dt = 300 \text{ fb}^{-1}$; $\int L dt = 3000 \text{ fb}^{-1}$



(b)

- With 3 ab⁻¹ HL-LHC may well:
 - Observe $H \rightarrow \mu^+ \mu^-$ to 6 σ . (ATLAS)
 - Measure the Higgs self-coupling to 30% (ATLAS)

- Linear Colliders compared to LHC results for various decay channels



M. Klute et.al. [arXiv:1301.1322]

- Awaiting updates on LHC capabilities based on the 2012 run experience.
- Missing comparisons: $A=\mu$ [20%], $\Delta m(h)$ [100 MeV], $\Delta \Gamma(h)$ [5-10%] for both HL-LHC and ILC TeV
- The lepton collider results are limited by statistics.

- Distinguish background processes: $\mu^+\mu^- \rightarrow \gamma + Z$ (ISR) (71%) from $\mu^+\mu^- \rightarrow Z^*$ (29%) [A. Conway, H. Wenzel]
- Jet momenta, opening angles, event shape.
- WW^*/ZZ^* decay modes has very small background
- b-bbar decay mode has $S/B = 1.47$

	Background (pb)	Higgs signal at peak (pb)	s/b
Basic counting:	376	42.5	0.11
Z/gamma* tag:	113	42.5	0.38
b-tagging:	56.4	24.8	0.44
Combined:	16.9	24.8	1.47

- c-cbar decay mode more difficult. (M. Purohit - UCLA 2013 workshop)

(in pb)	Background (Z^*/γ^*)	Signal (H)	s/b
c cbar	19.4	1.2	0.062
$\tau^+\tau^-$	9.5	2.9	0.31
light quarks/gluons	46	3.6	0.078

- 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 $\sigma(\mu^+\mu^- \rightarrow h) = 49.2 \text{ pb}$ ($\Delta = \Gamma$)
 - The excellent energy resolution Δ of a muon collider makes the process observable.

Tao Han and Zhen Liu [arXiv:1210.7803]

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

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

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

$\Gamma_h = 4.21 \text{ MeV}$	$L_{\text{step}} (\text{fb}^{-1})$	$\delta\Gamma_h (\text{MeV})$	δB	$\delta m_h (\text{MeV})$
$R = 0.01\%$	0.005	0.73	6.5%	0.25
	0.025	0.35	3.0%	0.12
	0.2	0.17	1.1%	0.06
$R = 0.003\%$	0.01	0.30	4.4%	0.12
	0.05	0.15	2.0%	0.06
	0.2	0.08	1.0%	0.03

20 steps

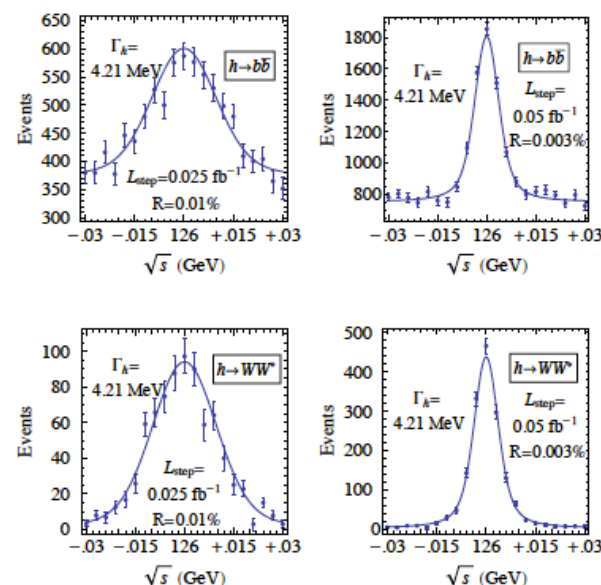
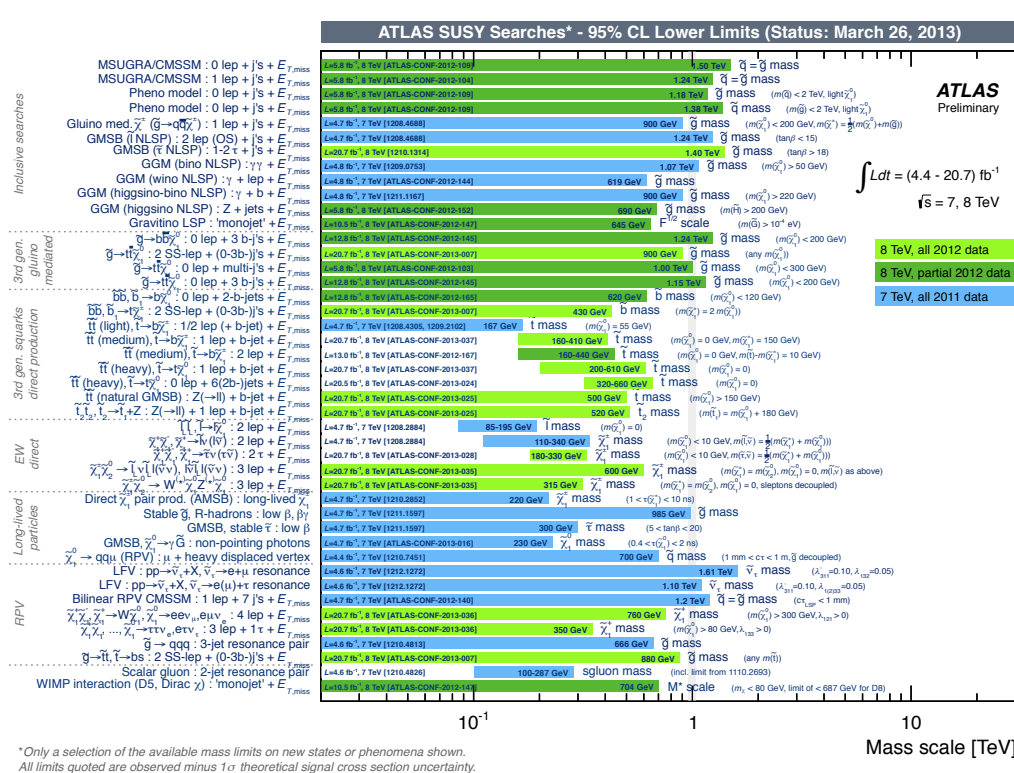


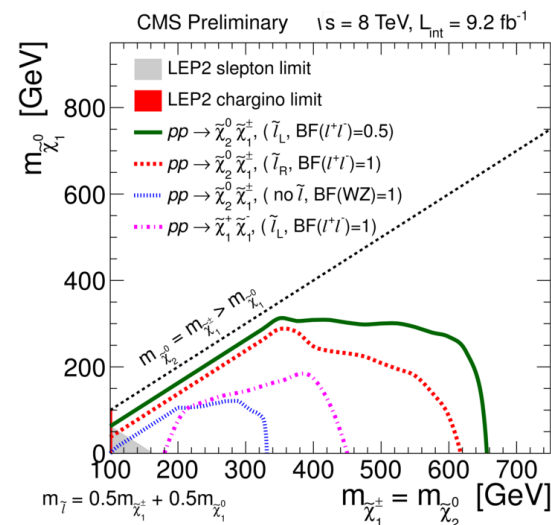
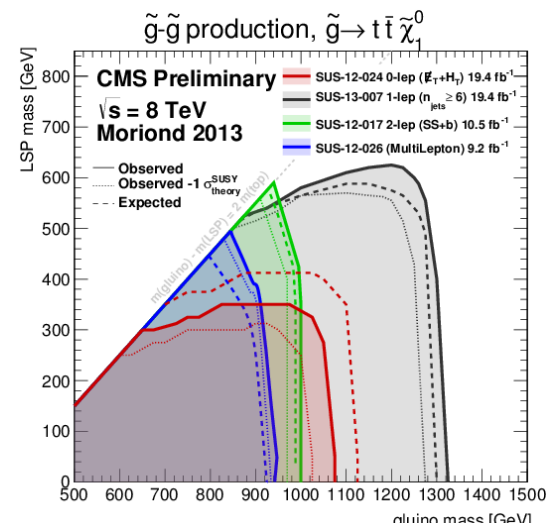
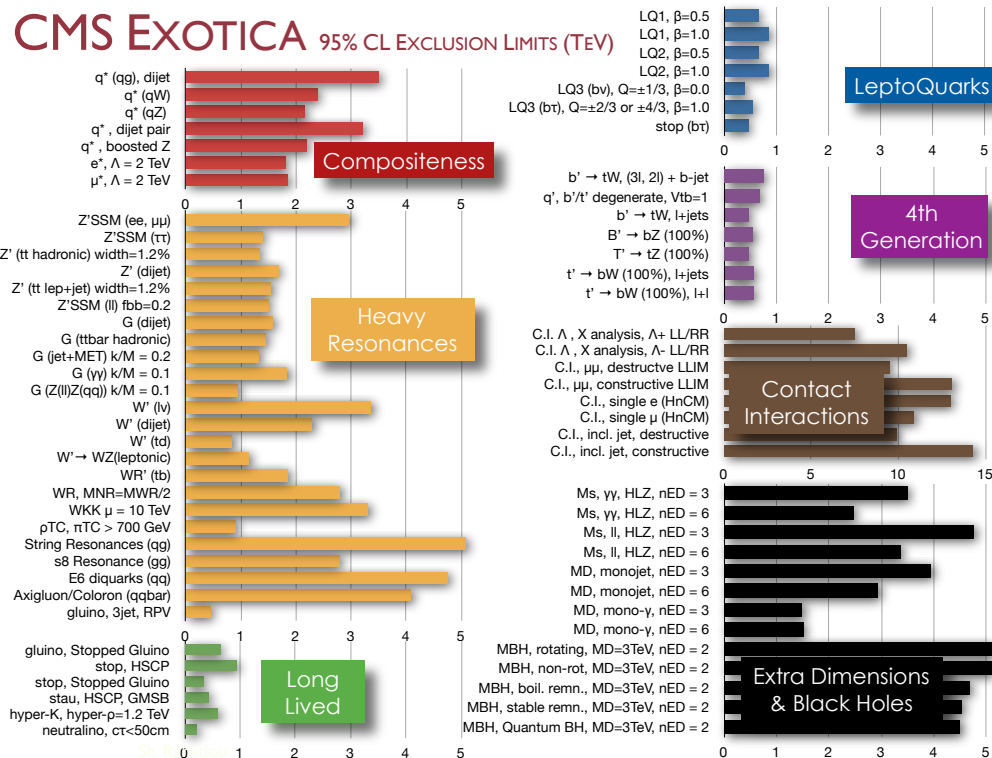
FIG. 2: Number of events of the Higgs signal plus backgrounds and statistical errors expected for Cases A and B as a function of the collider energy \sqrt{s} in $b\bar{b}$ and WW^* final states with a SM Higgs $m_h = 126 \text{ GeV}$ and $\Gamma_h = 4.21 \text{ MeV}$.

- 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 strong case for a TeV scale hadron collider rested on two arguments:
 1. Unitarity required that a mechanism for EWSB was manifest at or below the TeV scale.
 2. The SM is unnatural ('t Hooft conditions) and incomplete (dark matter, insufficient CP violation for the observed baryon excess, gauge unification, gravity and strings)
- If after the analysis of the 2012 CMS/ATLAS data, the 126 GeV state is found to be a 0^+ state with couplings consistent with the SM Higgs, the first argument is satisfied.
 - The second argument remains strong, but is less strongly tied to the TeV scale.
 - Scales already probed at the LHC suggest that any new collider (of LHC level costs) should be able to probe the BSM physics in the multi-TeV range.



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

1. The Standard Model is incomplete:

- dark matter; neutrino masses and mixing \rightarrow new fields or interactions;
- baryon asymmetry in the universe \rightarrow more CP violation
- gauge unification \rightarrow new interactions;
- gravity: strings and extra dimensions

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

3. Theoretical problems with the SM:

- Scalar sector problematic:

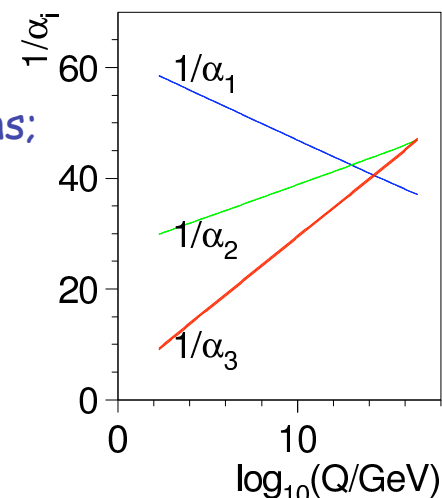
$$\mu^2 (\Phi^\dagger \Phi) + \lambda (\Phi^\dagger \Phi)^2 + \Gamma_{ij} \psi_{iL}^\dagger \psi_{jR} \Phi + \text{h.c.}$$

$m_H^2/M_{\text{planck}}^2 \approx 10^{-34}$
Hierarchy problem

vacuum
stability

large range of
fermion masses

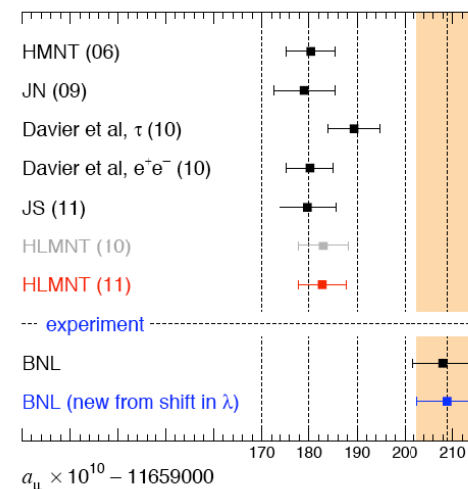
- The SM Higgs boson is unnatural. (m_H^2/μ^2)
- Solutions: SUSY, New Strong Dynamics, ...



muon $(g-2)$

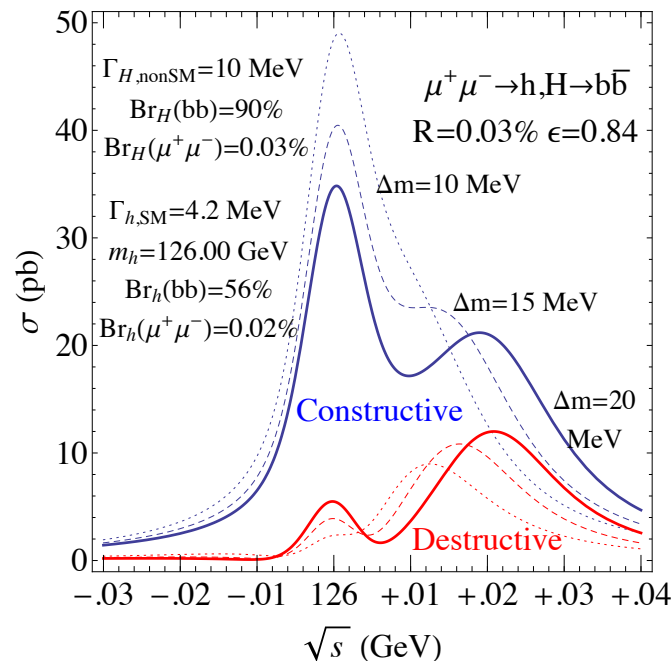
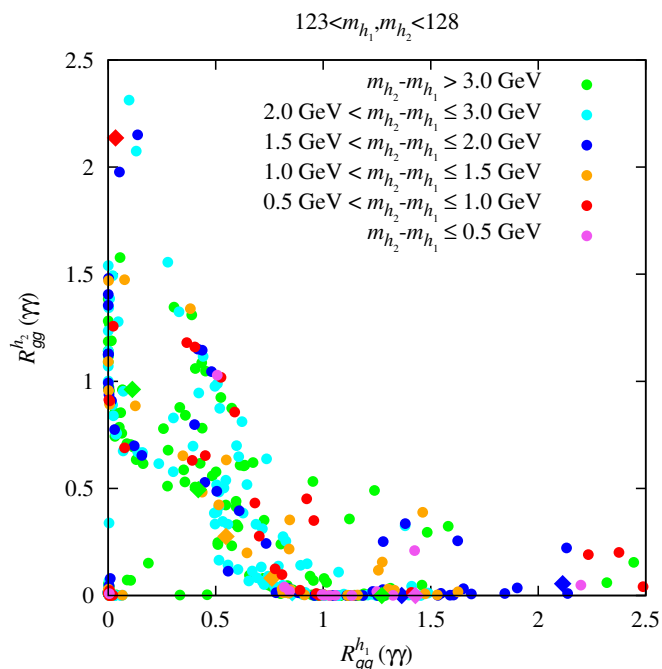
Davier, Hoecker, Malaescu, Zhang
Jegerlehner, Szafron
Hagiwara, Liao, Martin, Nomura, Teubner

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



There remains a persistent discrepancy of 3.3-3.6 σ

- Dilaton - (B. Grinstein's talk)
 - couplings proportional to mass
 - loops can vary from SM because of new particles in the loops.
- NMSSM - possibility of nearly degenerate (h, S) scalars:
 - J. Gunion, Y. Jiang, S. Kram [arXiv:1207.1545]
 - Models exist with very nearly degenerate pair of scalars
 - The various decay rates could be disentangled at a muon collider.



- Two Higgs doublets (MSSM):

- Five scalar particles: h^0, H^0, A^0, H^\pm

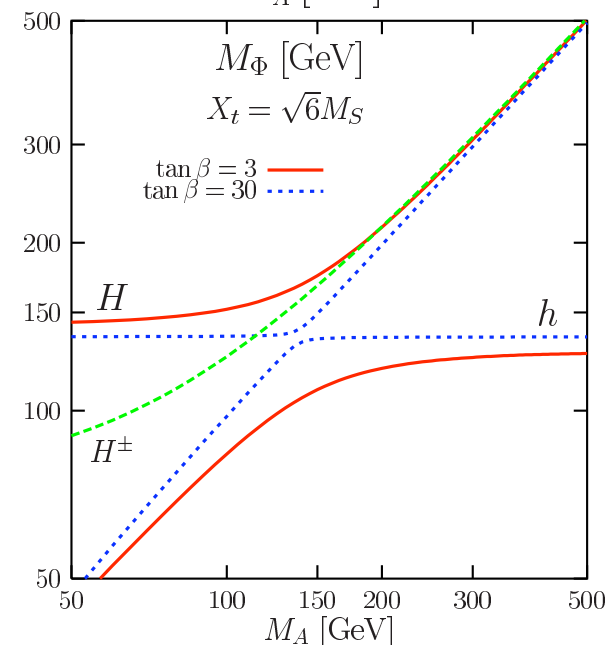
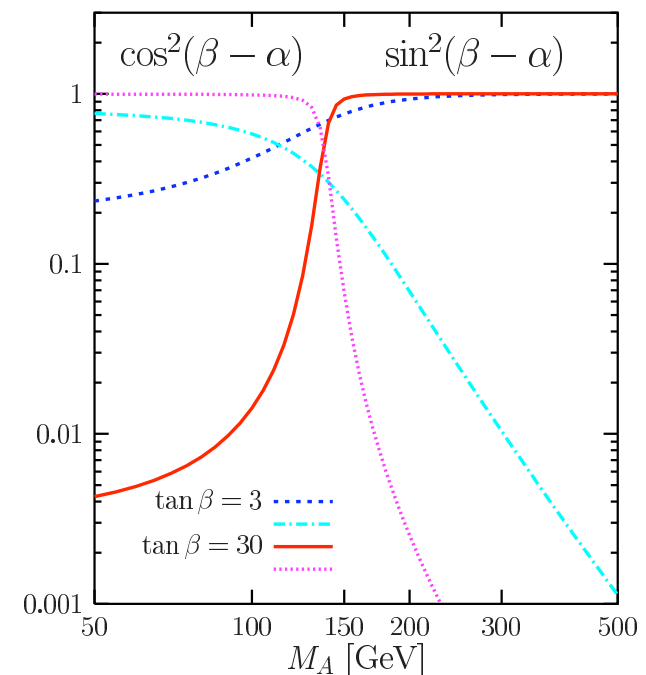
- Decay amplitudes depend on two parameters: (α, β)

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

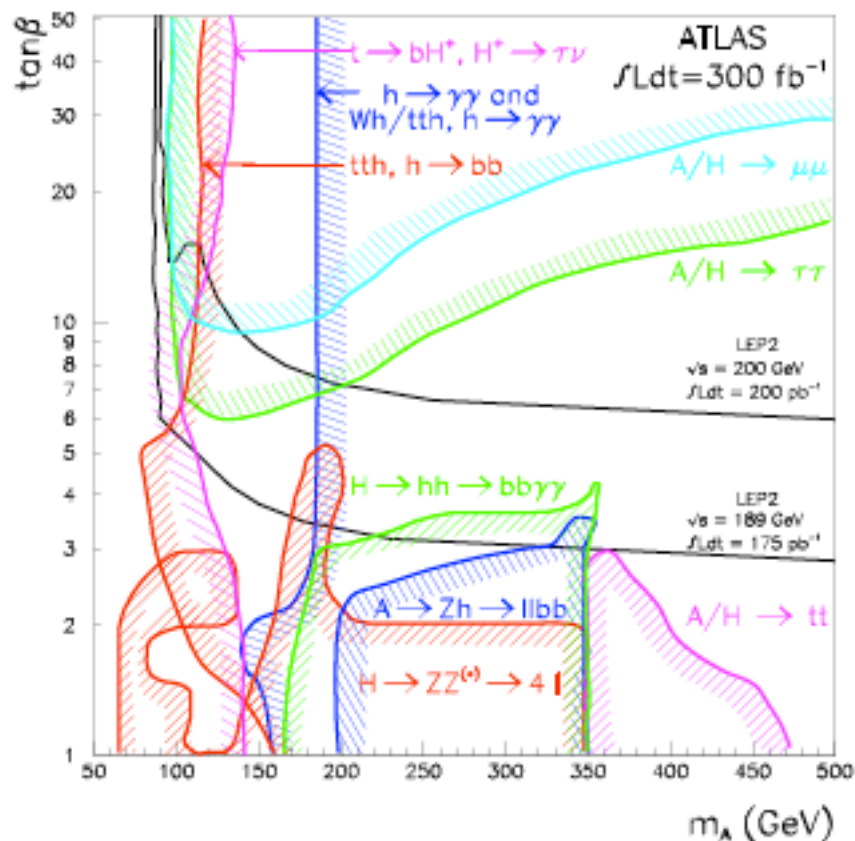
$$\tan 2\alpha = \frac{M_A^2 + M_Z^2}{M_A^2 - M_Z^2} \tan 2\beta.$$

- 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.



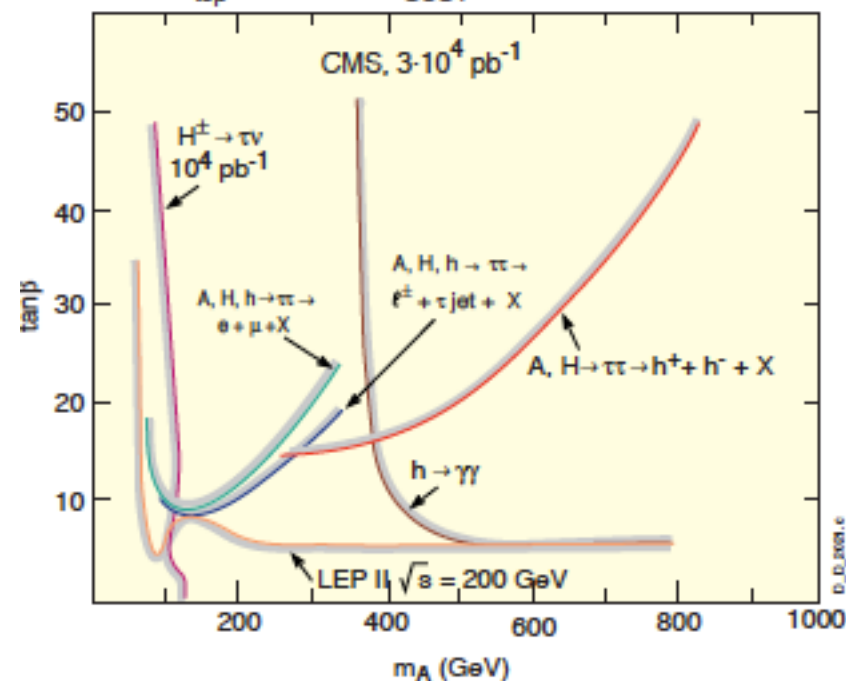
- The LHC has difficulty observing the H, A especially for masses > 500 GeV. Even at $\sqrt{s} = 14$ TeV and 300 fb^{-1} .



Significance contours for SUSY Higgses

Regions of the MSSM parameter space (m_A , $\tan\beta$) explorable through various SUSY Higgs channels

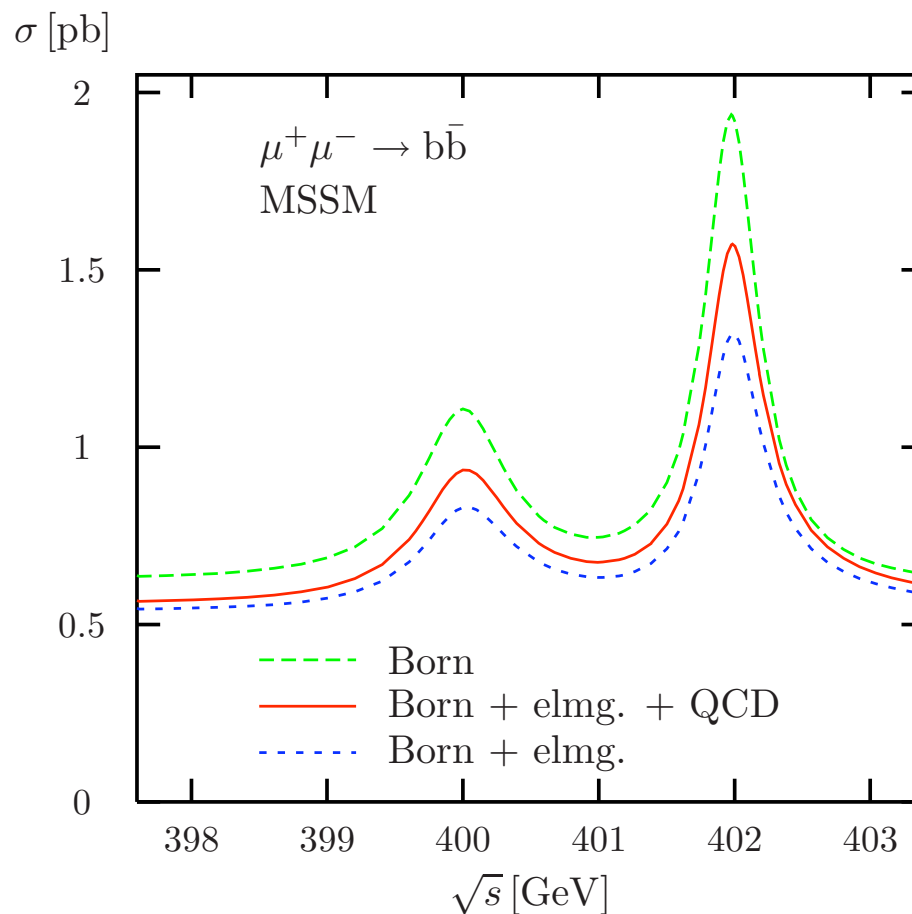
- 5σ significance contours
- two-loop / RGE-improved radiative corrections
- $m_{\text{top}} = 175 \text{ GeV}$, $m_{\text{SUSY}} = 1 \text{ TeV}$, no stop mixing :



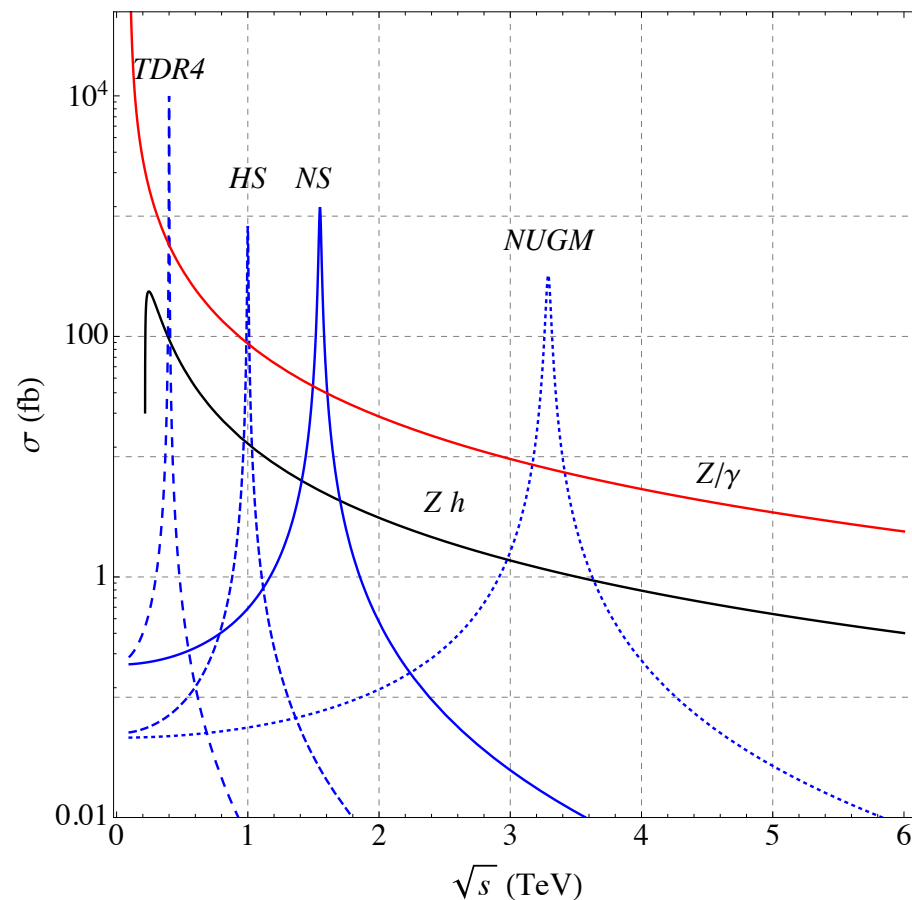
- Pair produced with easy at a multi-TeV lepton collider.

- Good energy resolution is needed for H^0 and A^0 studies:
- At a μC the states can be separated for $m_A < 900$ GeV

Dittmaier and Kaiser
[hep-ph/0203120]



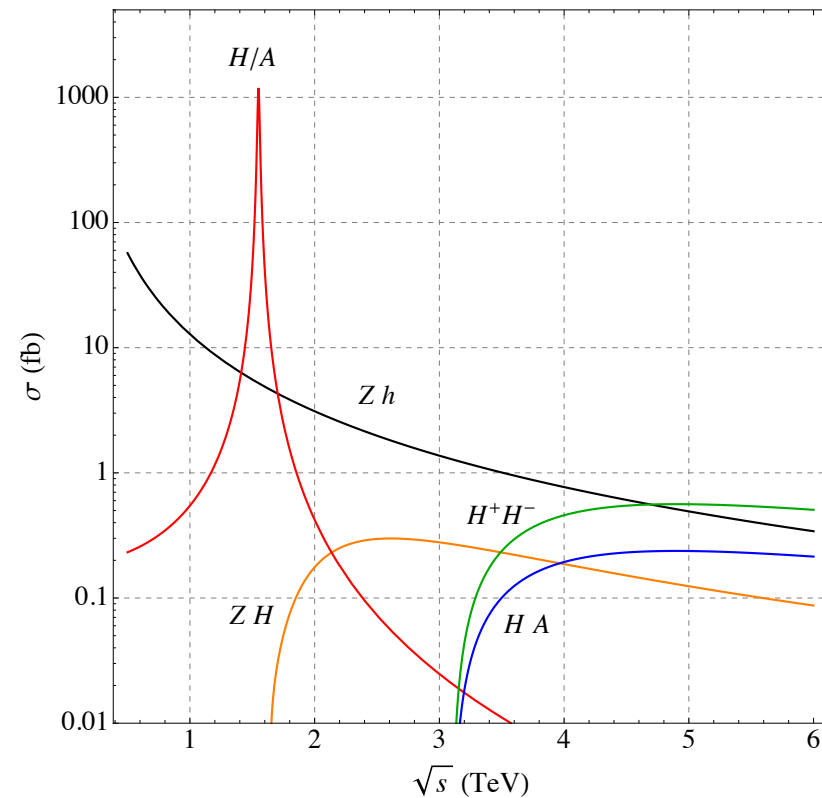
- LHC bounds on the H/A (H^\pm)
 - Present bounds: 300 GeV ($\tan \beta = 10$); 600 GeV ($\tan \beta = 40$)
 - LHC 14 TeV with 150 fb^{-1} : 900 GeV ($\tan \beta = 10$); 1.5 TeV ($\tan \beta = 40$)
- Viable SUSY models with present LHC limits favor:
 - heavy $H/A \rightarrow$
 - nearly degenerate masses
 - alignment limit \rightarrow small couplings to WW and ZZ
 - few sparticles below 500 GeV
 - \rightarrow narrow widths (10's of GeV's)
 - Some ILC Benchmark examples:
 - light-slepton NLSP model (TDR4)
 - hidden supersymmetry (HS)
 - natural supersymmetry (NS)
 - non-universal Higgs mass (NUHM)



- Muon Collider as a H/A factory (E. Eichten and A. Martin [ArXiv:1306.2609])
 - Generic features but look in detail at NS example:

TABLE I. Properties of the H and A states in the Natural Supersymmetry benchmark model [35]. In addition to masses and total widths, the branching ratios for various decay modes are shown.

	H		A	
Mass	1.560 TeV		1.550 TeV	
Width	19.5 GeV		19.2 GeV	
(Decay)	Br	(Decay)	Br	
$(b\bar{b})$	0.64	$(b\bar{b})$	0.65	
$(\tau^+\tau^-)$	8.3×10^{-2}	$(\tau^+\tau^-)$	8.3×10^{-3}	
$(s\bar{s})$	3.9×10^{-4}	$(s\bar{s})$	4.0×10^{-3}	
$(\mu^+\mu^-)$	2.9×10^{-4}	$(\mu^+\mu^-)$	2.9×10^{-4}	
$(t\bar{t})$	6.6×10^{-3}	$(t\bar{t})$	7.2×10^{-3}	
(gg)	1.4×10^{-5}	(gg)	6.1×10^{-5}	
$(\gamma\gamma)$	1.1×10^{-7}	$(\gamma\gamma)$	3.8×10^{-9}	
$(Z^0 Z^0)$	2.6×10^{-5}	$(Z^0 \gamma)$	4.3×10^{-8}	
$(h^0 h^0)$	4.4×10^{-5}			
$(W^+ W^-)$	5.3×10^{-5}			
$(\tilde{\tau}_1^\pm \tilde{\tau}_2^\mp)$	9.2×10^{-3}	$(\tilde{\tau}_1^\pm \tilde{\tau}_2^\mp)$	9.5×10^{-3}	
$(\tilde{t}_1 \tilde{t}_1^*)$	3.1×10^{-3}	$(\tilde{t}_1 \tilde{t}_2^*)$	1.1×10^{-3}	
$(\chi_1^0 \chi_1^0)$	2.6×10^{-3}	$(\chi_1^0 \chi_1^0)$	3.2×10^{-3}	
$(\chi_2^0 \chi_2^0)$	1.3×10^{-3}	$(\chi_2^0 \chi_2^0)$	1.1×10^{-3}	
$(\chi_1^0 \chi_3^0)$	2.8×10^{-2}	$(\chi_1^0 \chi_3^0)$	3.9×10^{-2}	
$(\chi_1^0 \chi_4^0)$	1.7×10^{-2}	$(\chi_1^0 \chi_4^0)$	4.0×10^{-2}	
$(\chi_2^0 \chi_3^0)$	3.8×10^{-2}	$(\chi_2^0 \chi_3^0)$	2.7×10^{-2}	
$(\chi_2^0 \chi_4^0)$	4.0×10^{-2}	$(\chi_2^0 \chi_4^0)$	1.5×10^{-2}	
$(\chi_1^\pm \chi_2^\mp)$	5.7×10^{-2}	$(\chi_1^\pm \chi_2^\mp)$	6.0×10^{-2}	



- Muon Collider as a H/A factory

- Large production rate: $\text{Events/year} = 154,000 \times \left(\frac{\mathcal{L}}{10^{34} \text{ cm}^{-2} \text{ s}^{-1}} \right) \left(\frac{1 \text{ TeV}}{m_{H/A}} \right)^2 \frac{BR(H/A \rightarrow \mu^+ \mu^-)}{10^{-4}}$
- Use b b decays to extract H and A properties:

TABLE II. Fit of the H/A region to background plus Breit-Wigner resonances. Both a single and two resonance fits are shown. General form of the background fit is $\sigma_B(\sqrt{s}) = c_1(1.555)^2/s$ (in TeV^2). The values of the best fit for one or two Breit-Wigner resonances are given.

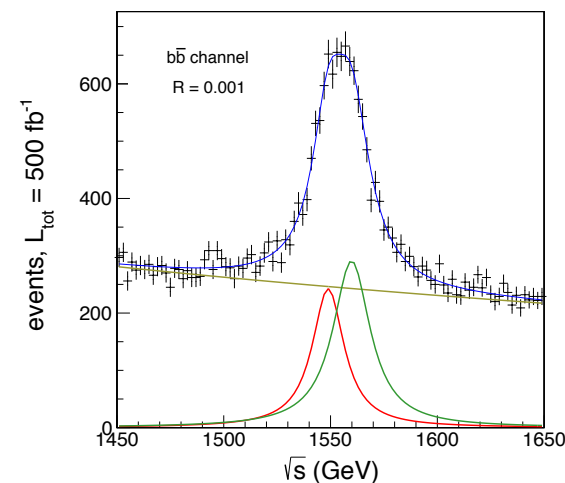
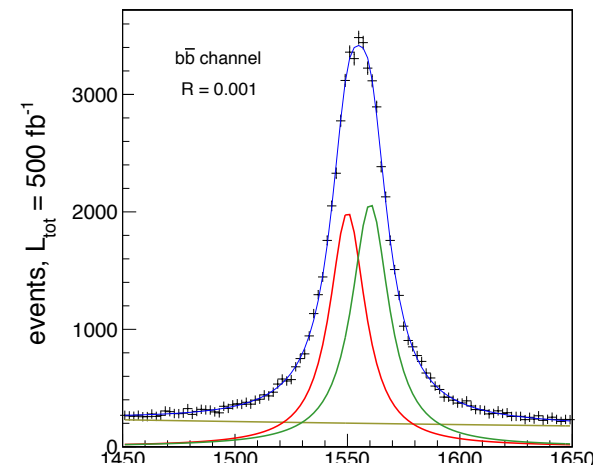
One Resonance			
Mass(GeV)	$\Gamma(\text{GeV})$	σ_{peak} (pb)	
$1555 \pm 0.1 \text{ GeV}$	24.2 ± 0.2	1.107 ± 0.0076	
$\chi^2/\text{ndf} = 363/96$		$c_1 = 0.0354 \pm 0.0006$	
Two Resonances			
Mass(GeV)	$\Gamma(\text{GeV})$	σ_{peak} (pb)	
$1550 \pm 0.5 \text{ GeV}$	19.3 ± 0.7	0.6274 ± 0.0574	
$1560 \pm 0.5 \text{ GeV}$	20.0 ± 0.7	0.6498 ± 0.0568	
$\chi^2/\text{ndf} = 90.1/93$		$c_1 = 0.040 \pm 0.0006$	

- $\tau^+\tau^-$

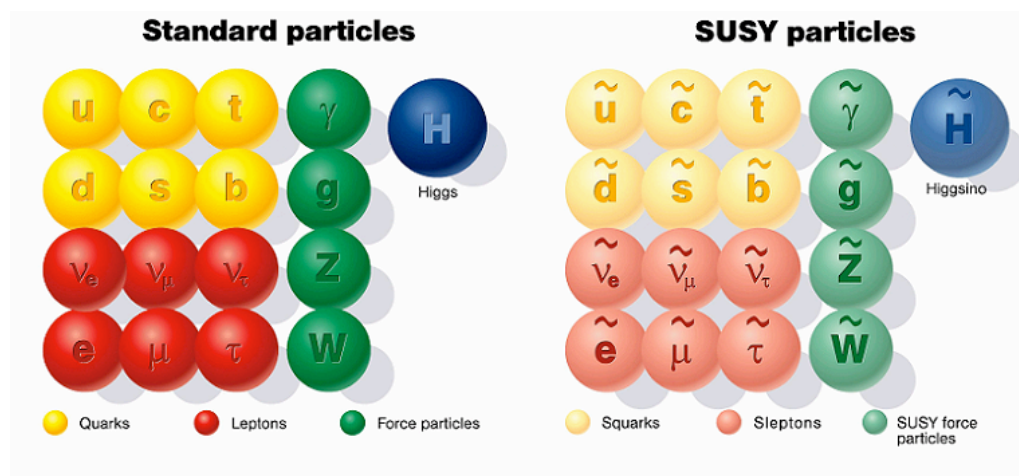
- Extract branching ratios
- Use tau decays to measure CP

- electroweakino's

- 20% of decays
- self analysing - unlike the ILC, initial beam polarization not essential.



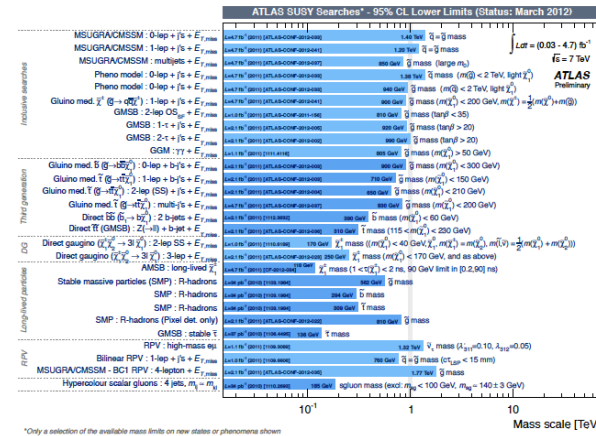
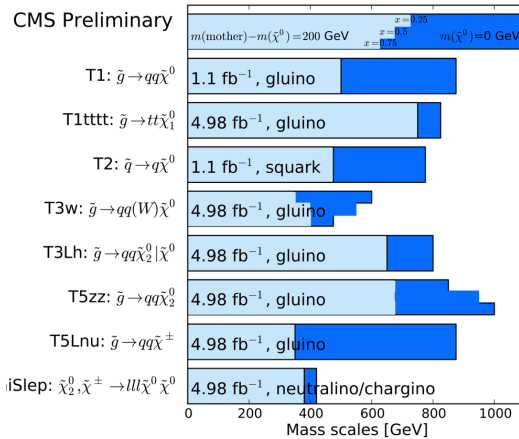
- Symmetry charges Q_{susy} have spin 1/2. Not a purely internal symmetry
 - $\{Q_{\text{susy}}, Q_{\text{susy}}\} = 2 \gamma^\mu P_\mu$; $Q_{\text{susy}} H|\text{state}\rangle = H Q_{\text{susy}}|\text{state}\rangle$
- $Q_{\text{susy}} |\text{boson}\rangle = |\text{fermion}\rangle$: gluon \rightarrow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



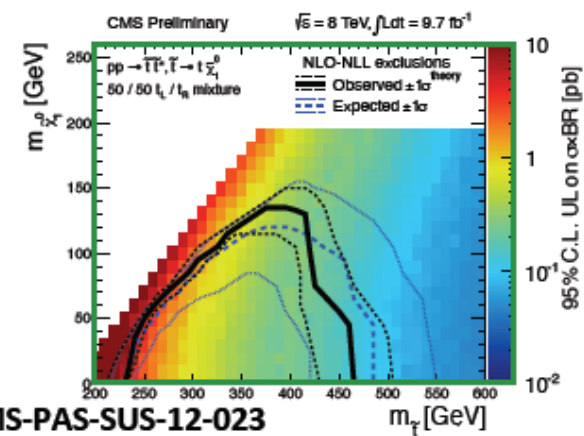
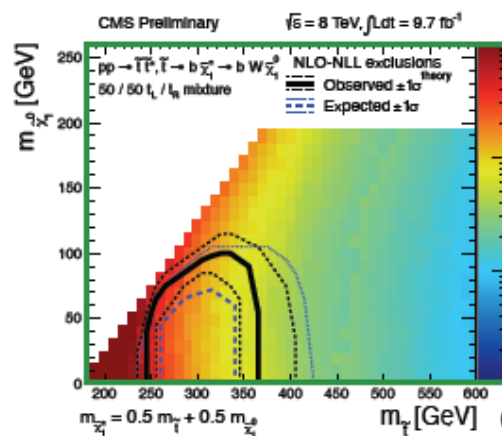
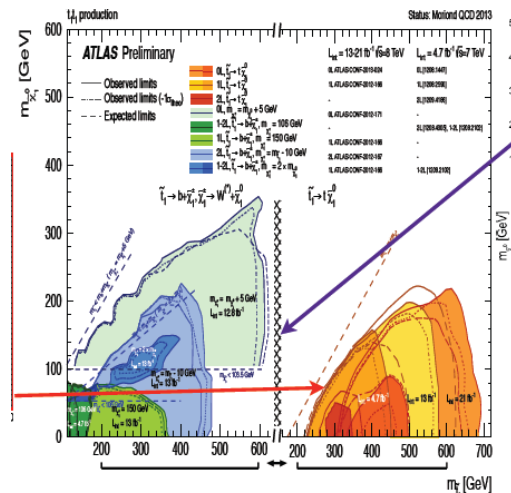
- What is the spectrum of superpartner masses?
- Dark matter candidates?
- Are all the couplings correct?
- What is the structure of flavor mixing interactions?
- Are there additional CP violating interactions?
- Is R parity violated?
- What is the mass scale at which SUSY is restored?
- What is the mechanism of SUSY breaking?

- Supersymmetry dictates the couplings between particles and sparticles
- Dark matter candidates, GUT unification
- No superpartner has yet been observed \Rightarrow Supersymmetry is broken $M_{\text{sparticle}} \neq M_{\text{particle}}$

- LHC limits on SUSY sparticles in various cMSSM scenerios:
 - Gluino and light squark masses limits ~ 1 TeV



- Stop (3rd generation) ~ 600 GeV (except very near top mass)



- The detailed study of SUSY will require a multiTeV lepton collider

- cMSSM - simple model with only 5 parameters (m_0 , $m_{1/2}$, $\tan\beta$, A/m_0 , $\text{sign}(\mu)$)
- 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

$$m_Z^2 = 2 \frac{M_{Hd}^2 - \tan^2 \beta M_{Hu}^2}{\tan^2 \beta - 1} - 2\mu^2 \quad + \text{loop corrections: } \log(m_{\tilde{t}}/m_t)$$

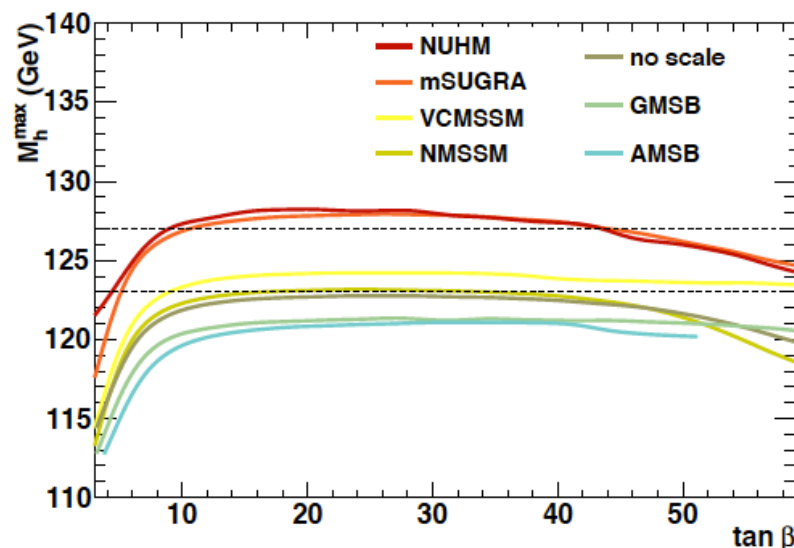
- Are various constrained models consistent with a Higgs mass of 126 GeV?

- Parameters varied in wide range.
Upper bound - m_h in top 1%

- GMSB, AMSB ✗

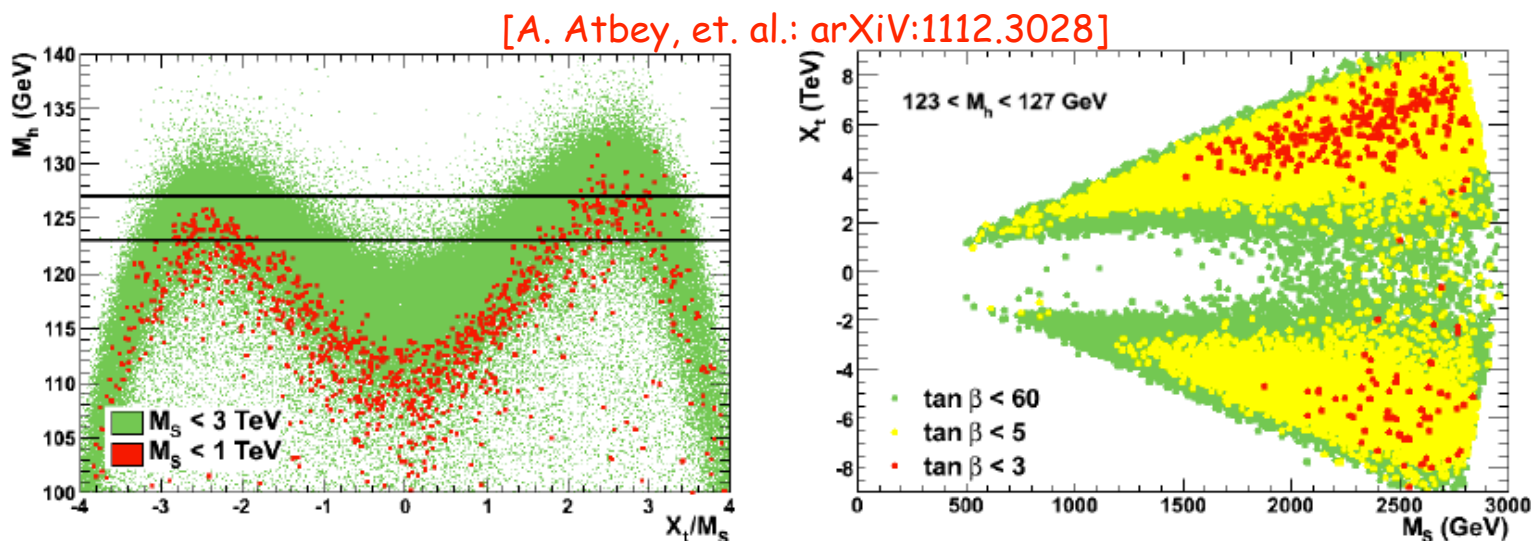
- mSUGRA ✓

- NUHM: non universal m_0
- VCMSSM: $m_0 \approx -A_0$
- NMSSM: $m_0 \approx 0$ $A_0 \approx -1/4 m_{1/2}$
- no scale: $m_0 \approx A_0 \approx 0$



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

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



- Consistence requires: $M_A \gg M_h$; $\tan \beta > 10$; M_S large; maximal mixing $\sim \sqrt{6} M_S$
- 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.

- 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?

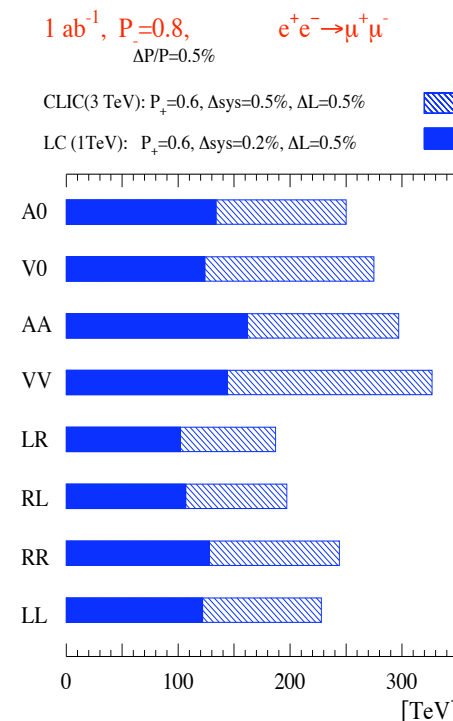
- Contact interactions

- 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.




- The unique measurements of the Muon Higgs factory (1 fb^{-1})
 - Most precise measurement of Higgs mass: $\Delta m_H = 0.1 \text{ MeV}$
 - Direct Higgs width measurement: $\Delta \Gamma_H = 0.17 \text{ MeV}$.
 - Measurement of $\text{BR}(\mu^+\mu^-)$ $\text{BR}(WW^*)$ to 2%. Other channels: bb , ZZ , $\tau^+\tau^-$, cc under investigation.
 - Disentangle nearly degenerate scalar resonances.
- Issues to address for MC Higgs factory:
 - Can the shot to shot energy of the beams be controlled to a few $\times 10^{-5}$ accuracy
 - Detailed studies of S/B required for physics reach.
 - High backgrounds in the detectors from muon decays upstream.
 - Studies should combine information available from LHC results to determine the added benefit of any future lepton collider.
- The high energy Muon Collider is the only lepton machine capable of reaching $\approx 3 \text{ TeV}$ energy scales in an affordable way.
 - For SUSY and THDM - the muon collider is a unique H/A factory.
 - New dynamics not at sub-TeV scale.

BACKUP SLIDES

- Parameters of various stages (MAP review J-P Delahaye's talk)

Difference Between Higgs Factory and Muon Collider



Muon Collider Baseline Parameters					
Parameter	Units	Higgs Factory		Multi-TeV Baselines	
		Initial Cooling	Upgraded Cooling / Combiner		
CoM Energy	TeV	0.126	0.126	1.5	3.0
Avg. Luminosity	$10^{34} \text{cm}^{-2} \text{s}^{-1}$	0.0017	0.008	1.25	4.4
Beam Energy Spread	%	0.003	0.004	0.1	0.1
Circumference	km	0.3	0.3	2.5	4.5
No. of IPs		1	1	2	2
Repetition Rate	Hz	30	15	15	12
β^*	cm	3.3	1.7	1 (0.5-2)	0.5 (0.3-3)
No. muons/bunch	10^{12}	2	4	2	2
No. bunches/beam		1	1	1	1
Norm. Trans. Emittance, ϵ_{TN}	mm-rad	0.4	0.2	0.025	0.025
Norm. Long. Emittance, ϵ_{LN}	mm-rad	1	1.5	70	70
Bunch Length, σ_s	cm	5.6	6.3	1	0.5
Beam Size @ IP	μm	150	75	6	3
Beam-beam Parameter / IP		0.005	0.02	0.09	0.09
Proton Driver Power	MW	4 [#]	4	4	4

[#]Could begin operation at lower beam power (eg, with Project X Phase 2 beam)

See Plot and
comments at
bottom of slide 4



- Excess in the 126 GeV region : Is it the SM higgs?

- spin and parity : 0^+ or 0^- (or 2^\pm)

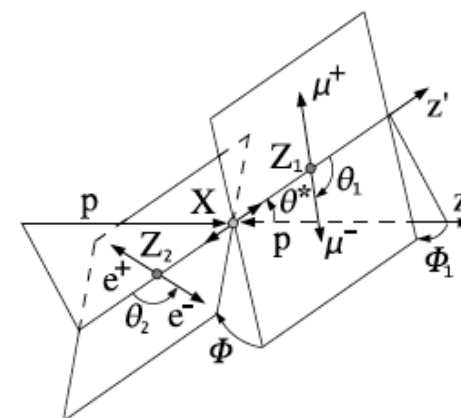
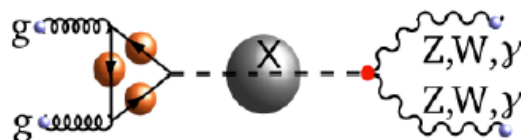
▪ Spin 0: $A(X \rightarrow V_1 V_2) = v^{-1} \epsilon_1^{*\mu} \epsilon_2^{*\nu} \left(a_1 g_{\mu\nu} M_X^2 + a_2 q_{1\mu} q_{2\nu} + a_3 \epsilon_{\mu\nu\alpha\beta} q_1^\alpha q_2^\beta \right)$

- SM Higgs $\rightarrow ZZ, WW$:

$a_1 \neq 0, a_2 \sim O(10^{-2}), a_3 \sim O(10^{-11})$

- SM Higgs $\rightarrow \gamma\gamma$: $a_1 = -a_2/2 \neq 0$

- BSM pseudo-scalar Higgs $a_3 \neq 0$



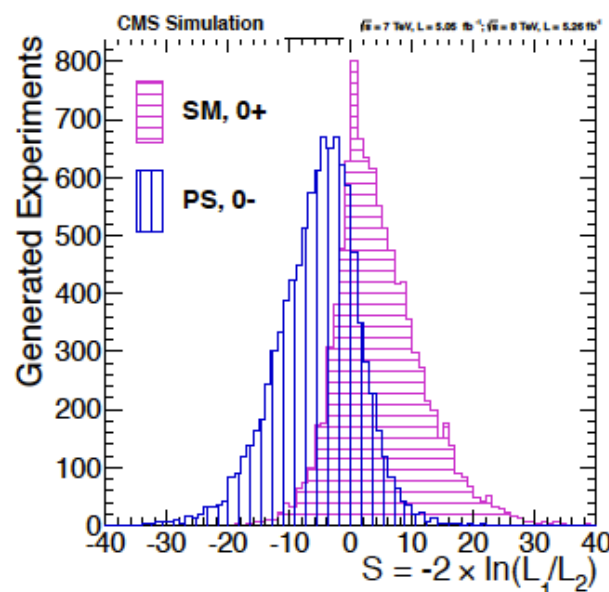
- use $ZZ^* \rightarrow 4$ leptons, $WW^* \rightarrow$ lepton + E_T (missing) + 2jets angular correlations

$[Z^0 Z^0]$ P.S. Bhupal Dev, et. al. [arXiv:0707.2878]; Yanyan Gao et. al. [arXiv:1001.3396]

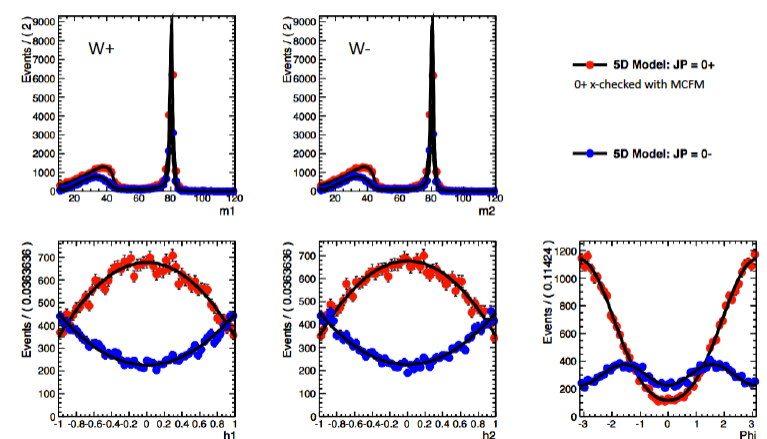
$[W^+ W^-]$ J. Ellis and D.S. Hwang [arXiv:1202.6660]

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

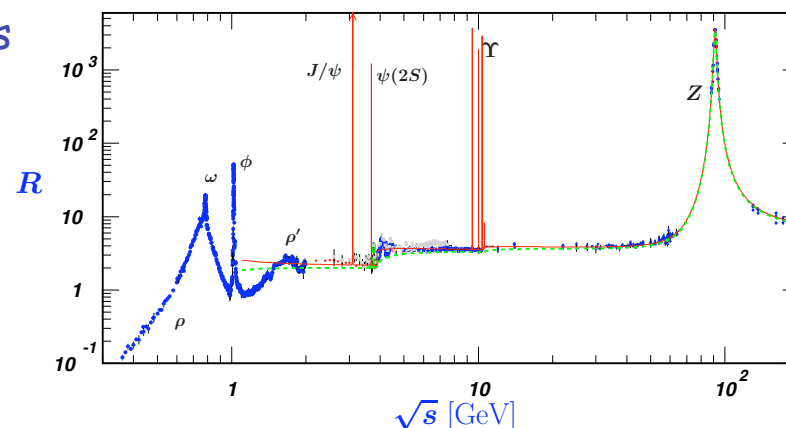
ICHEP 2012, Melbourne

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

Minimum luminosity at Z' peak:

$$\mathcal{L} = 1.0\text{--}5.0 \times 10^{30} \text{ cm}^{-2} \text{ sec}^{-1}$$

for $M(Z') \rightarrow 2.5\text{--}5.0 \text{ TeV}$



- A muon collider can be built to operate well above 4 TeV :

- Keeping the same limits on neutrino radiation.

The luminosity will scale as:

$$L(E_{cm})/L(4 \text{ TeV}) = [E_{cm}/(4 \text{ TeV})]^{-2}$$

- 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 resonance well in excess of 10 TeV could be studied in detail at such a muon collider.

- Example study of slepton pair production:

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

- Mass measurements of neutrino using edge method:

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

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

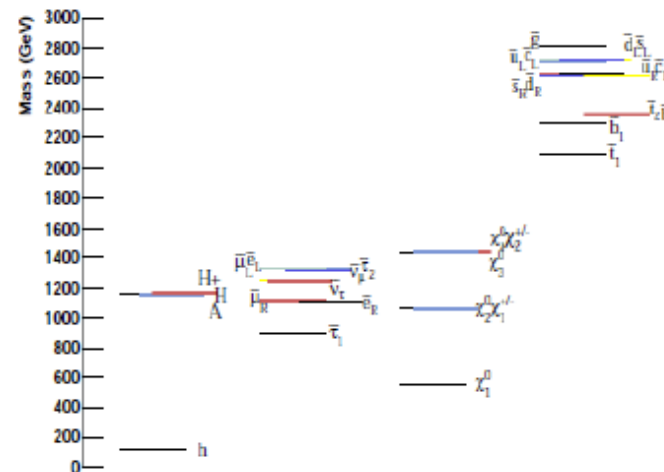
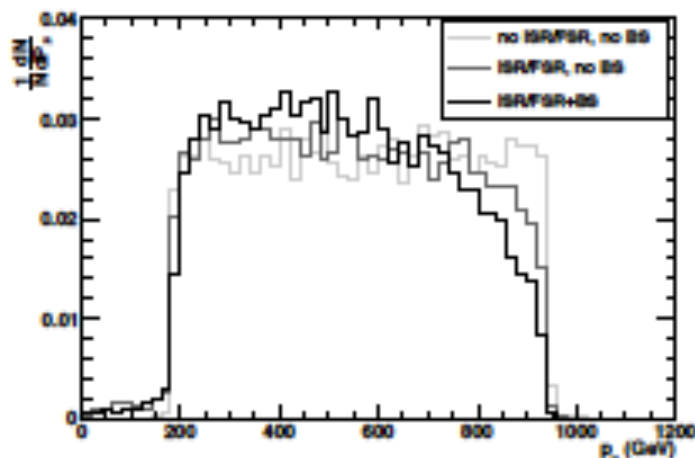


Table 2: Summary of the results of the fits to the smuon and neutralino mass for various assumptions on track momentum resolution, beamstrahlung, polarisation and number of bunch crossings integrated in one events. The results obtained on signal only (S) at generator level are also compared to those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

$\delta p_t/p_t^2$ ($\times 10^{-5} \text{ GeV}^{-1}$)	$\sqrt{s} >$ (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

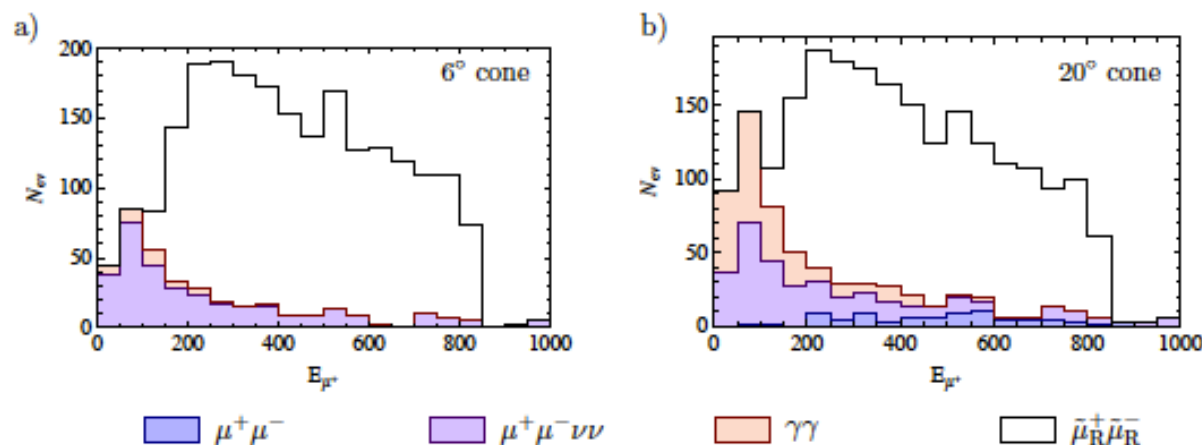
N. Alster and M. Battaglia [arXiv:1104.0523]

- Detailed study for muon collider

[A. Freitas: arXiv:1107.3853]

- large backgrounds

good benchmark
process for MC



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

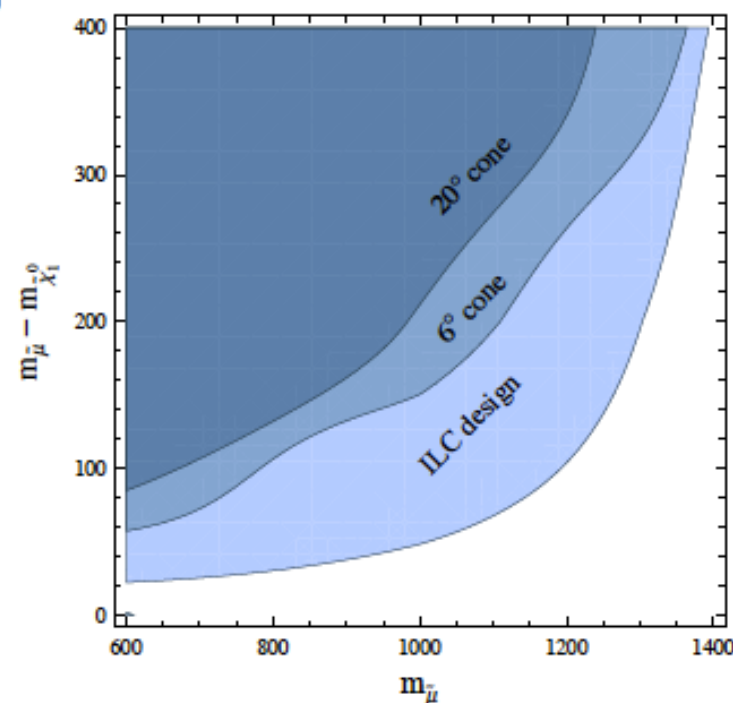
$$\sqrt{s} = 3 \text{ TeV}, m_{\tilde{L}_R} = 1 \text{ TeV}, m_{\tilde{\chi}_1^0} = 0.6 \text{ TeV}$$

1 ab⁻¹

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

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

- Shows the advantage of instrumenting the shielding cone.



- 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, ...

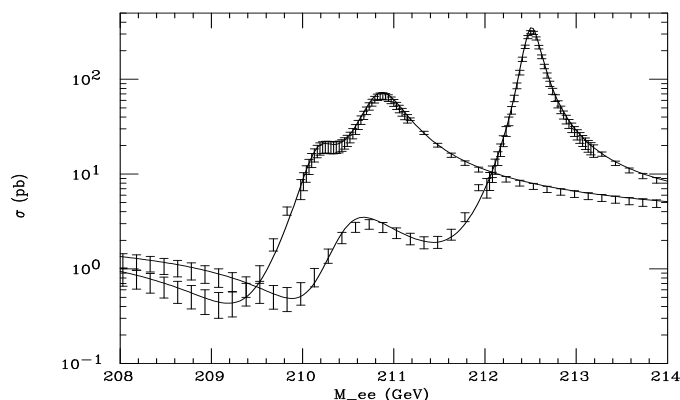
For example with a new strong interaction at TeV scale expect:

- 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)

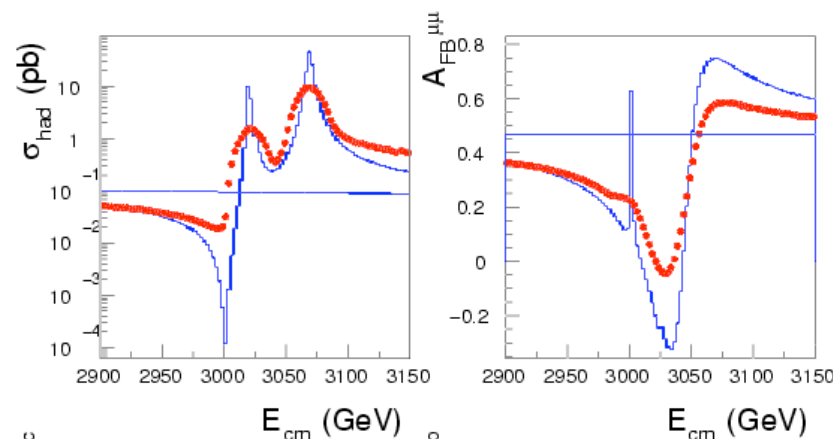
$M(\rho_T) = 210$ GeV $M(\omega_T) = 211, 209$ GeV

MC 40 steps (total 1 fb $^{-1}$)



good benchmark
processes

CLIC - D-BESS model (resolution 13 GeV)



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

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

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

- 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

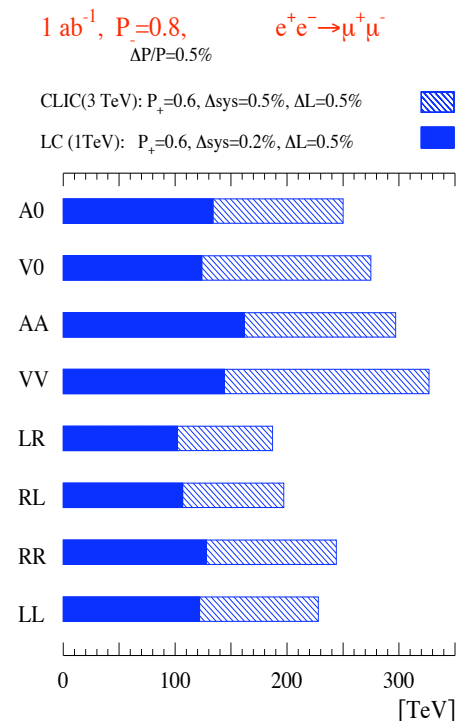
E.Eichten, S.~Keller, [arXiv:hep-ph/9801258]

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

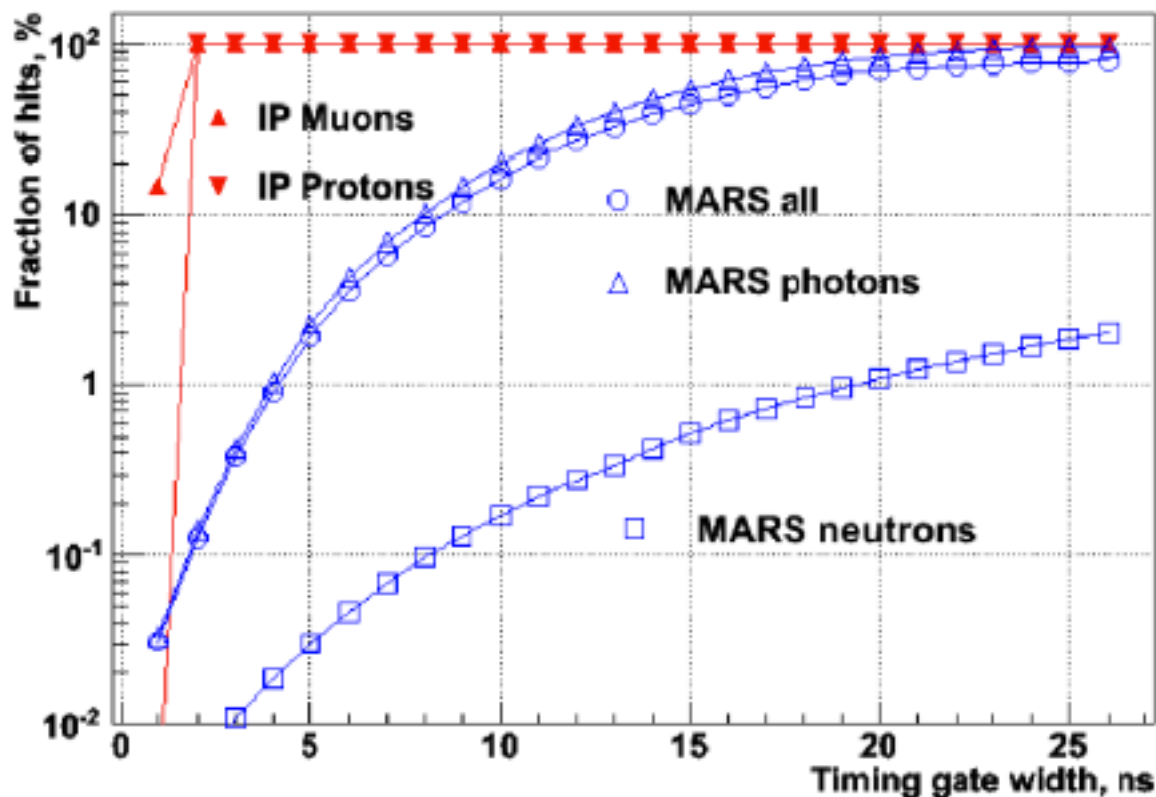
good benchmark process

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 $\Lambda_{(V-A)}^\pm$	8.0	$7.8^{+1.0}_{-1.1}$

CLIC Study



- ILC-like detector requirements for efficient heavy quark tags, muon and electron id, and jet energy scale calibration.
- The high backgrounds events entering the detector from muon decays in the beam upstream requires a detector employing a traveling time gate to reduce out of time hits.



1. The LHC is the Higgs Accelerator - Continue -> HL-LHC
2. Continue research and development of lepton colliders. In particular the muon collider needs a convincing proof of 6D cooling.
3. Push neutrino physics - Lepton sector
4. After 300 fb^{-1} of $\sim 14 \text{ TeV}$ running OR the discovery of BSM physics, chose the next accelerator for Higgs physics.

