Round Table

"Which Accelerator for Higgs Physics?"

- SM Higgs and BSM
- What to measure and how well ?
- A few words about a Muon Collider

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The Standard Model Higgs

- 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]

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

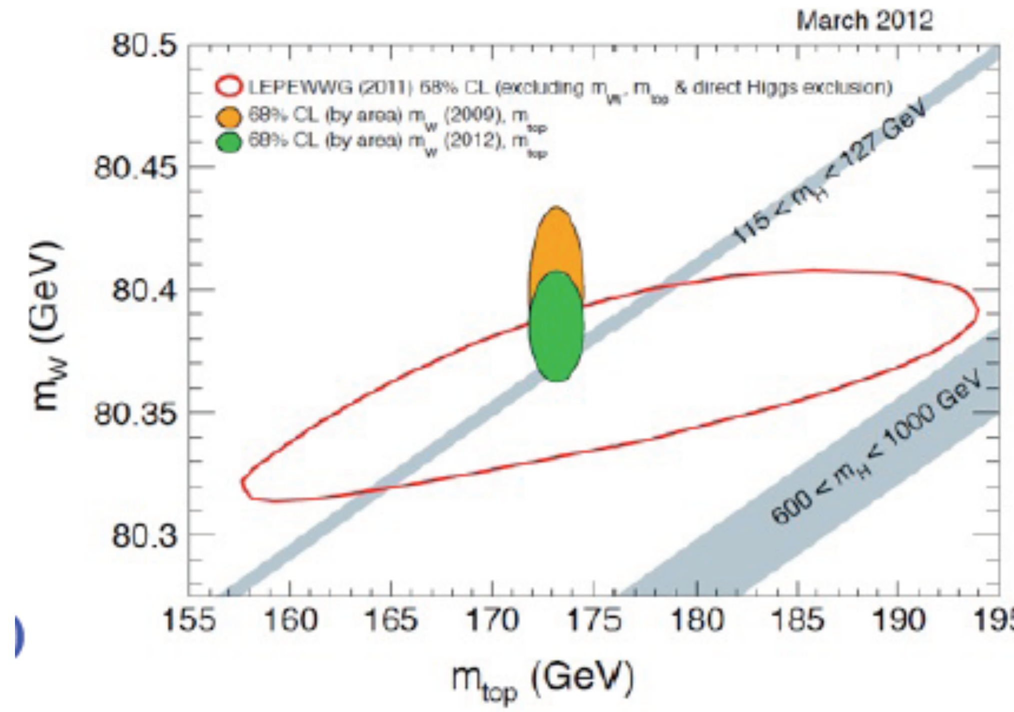
branching fractions : error(%)

$b\bar{b}$	$= 0.561$	(3.4%)	WW^*	$= 0.231$	(4.1%)
$\tau\bar{\tau}$	$= 6.15 \times 10^{-2}$	(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?

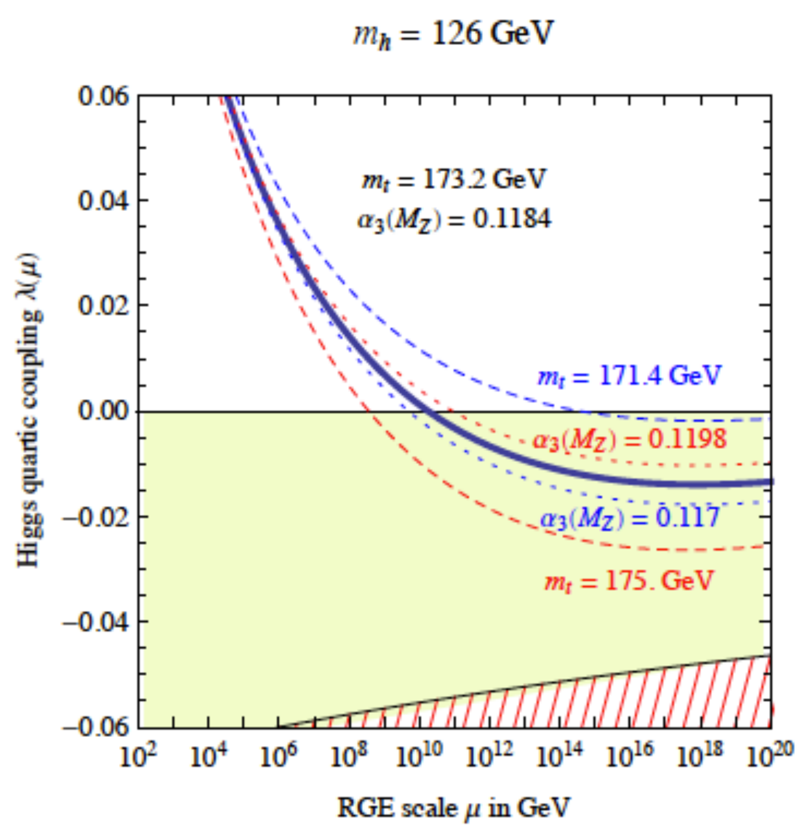
The Standard Model Higgs ?

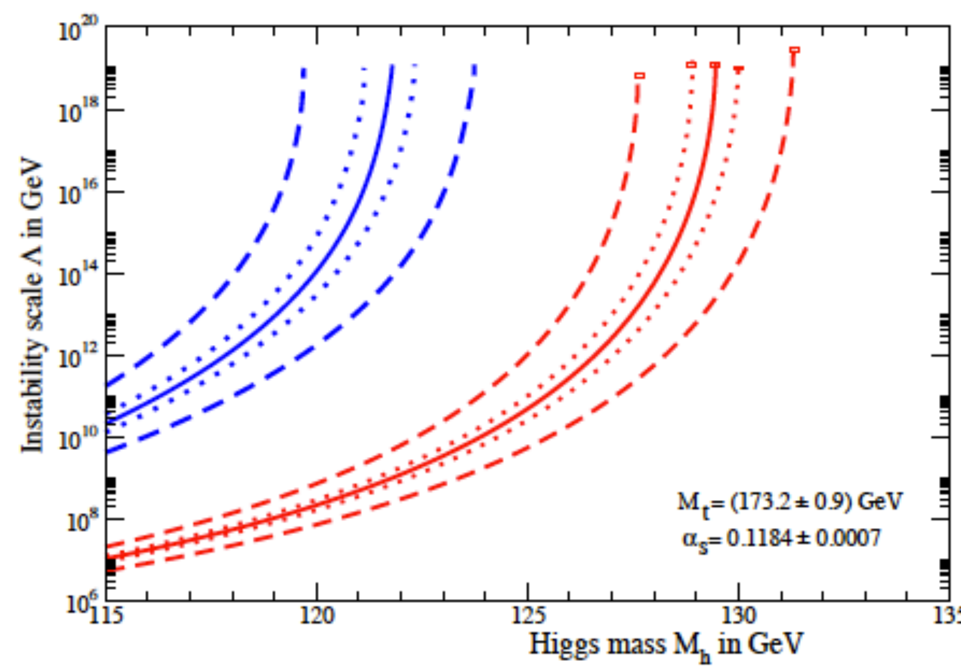
- Indirect measurements are all consistent with a 126 GeV Higgs



- 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]



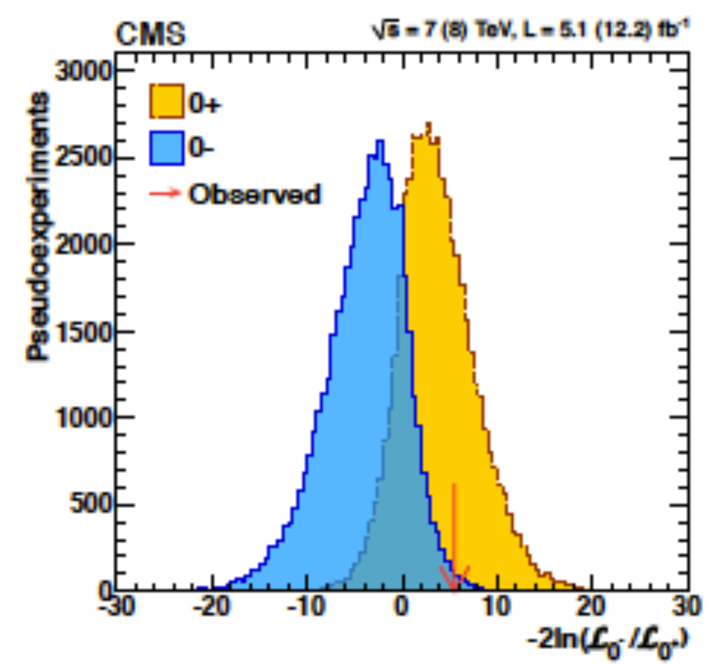


- To theorists :"When life gives you lemons, make lemonade"

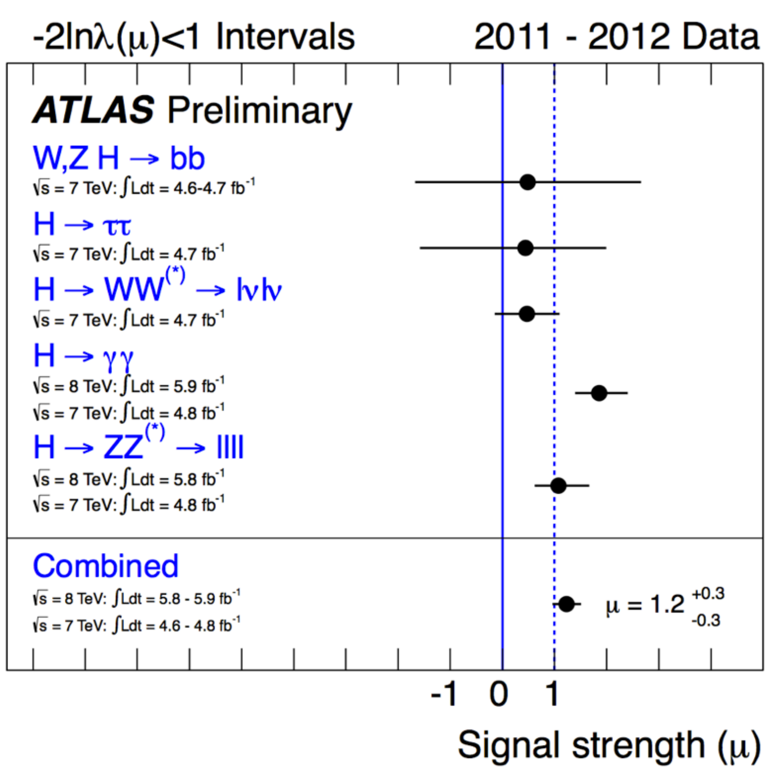
The Standard Model Higgs ?

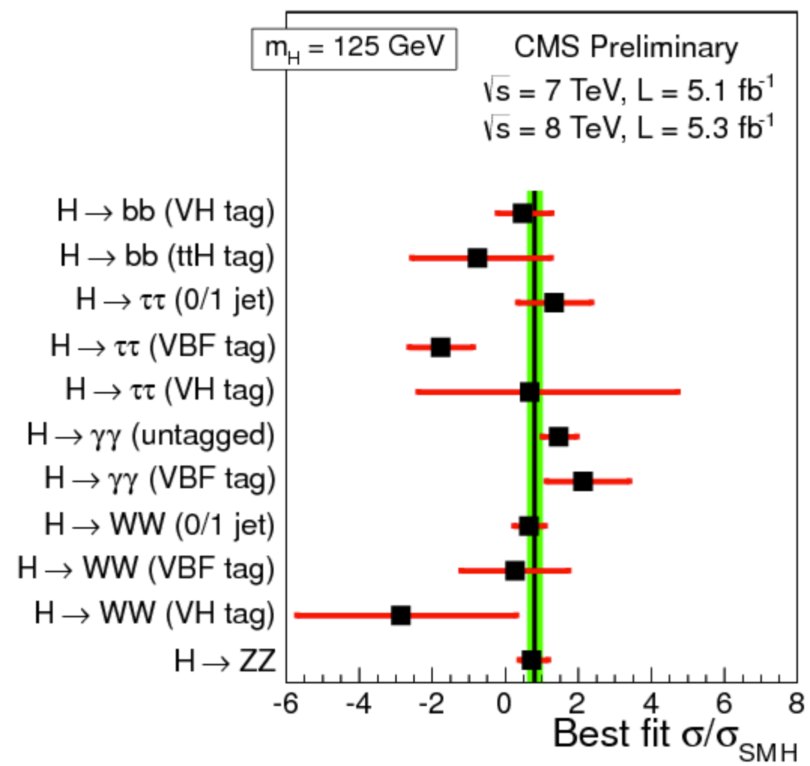
- Pseudoscalar versus Scalar
  - Light pseudoscalars often appear in dynamical EWSB models
  - However they don't couple to WW/ZZ in lowest order.
  - Assuming spin zero - a pure pseudoscalar is experimentally disfavored.

CMS [arXiv:1212.6639]



- Measure couplings to distinguish SM Higgs from BSM scalars

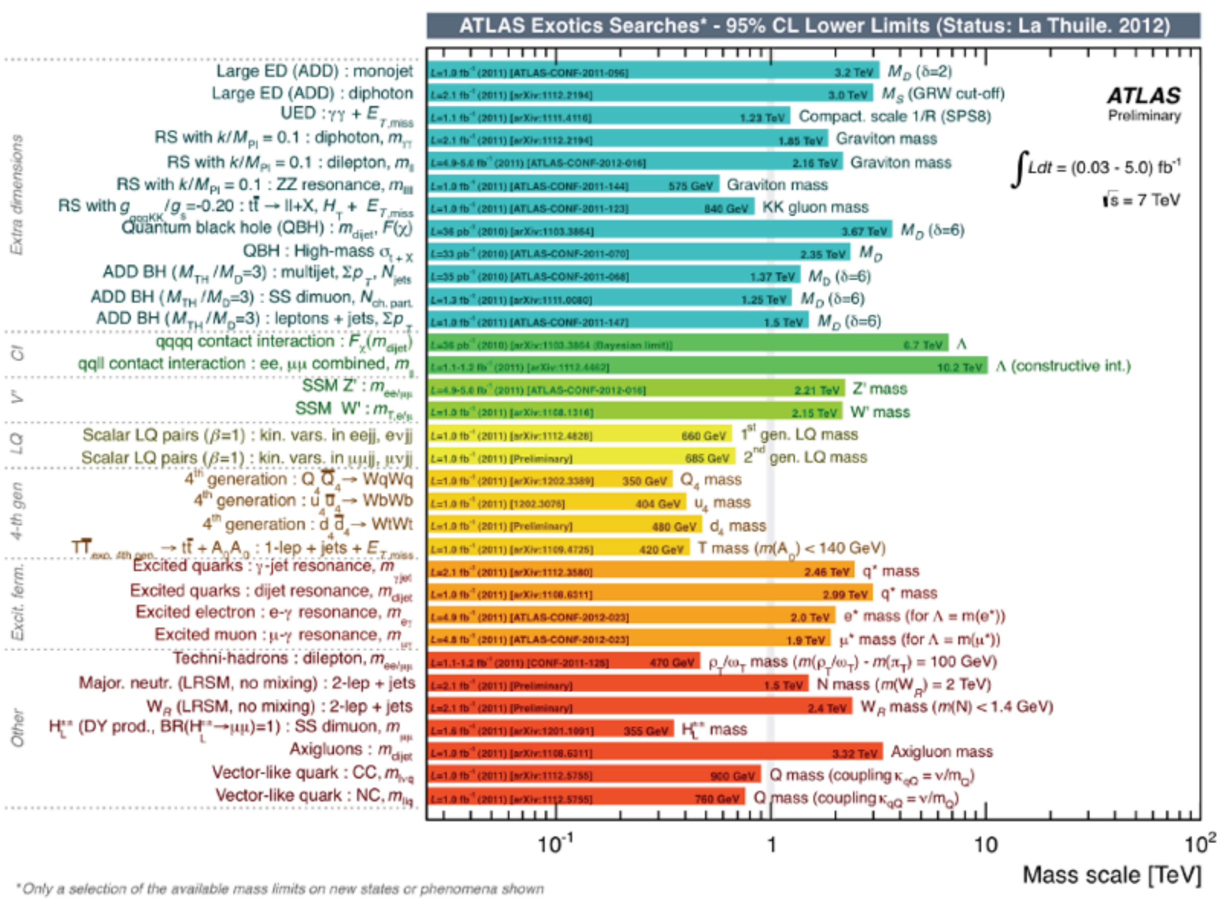


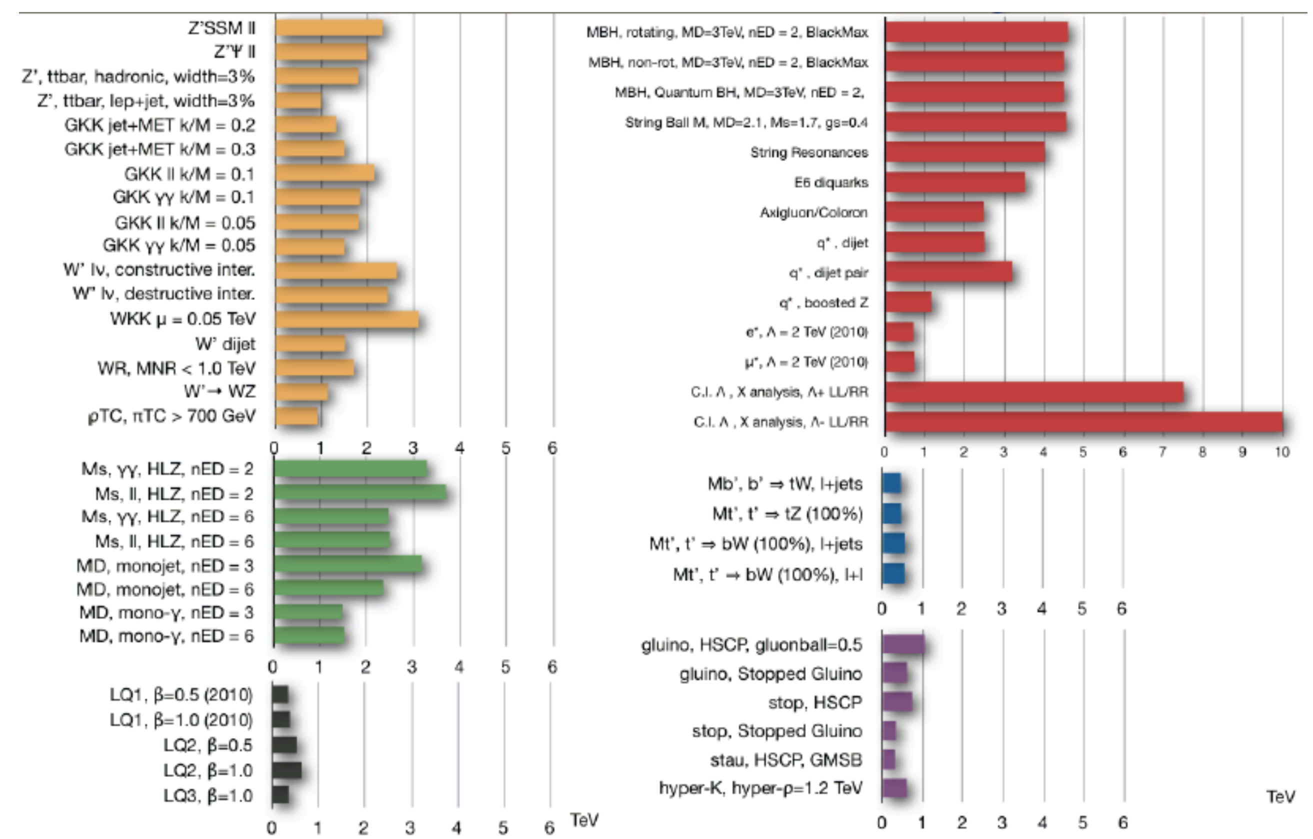


- Within large present errors, ATLAS and CMS results consistent with SM Higgs couplings.

BSM ?

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





  - TeV scales are already being probed at the LHC.

The SM Higgs and BSM

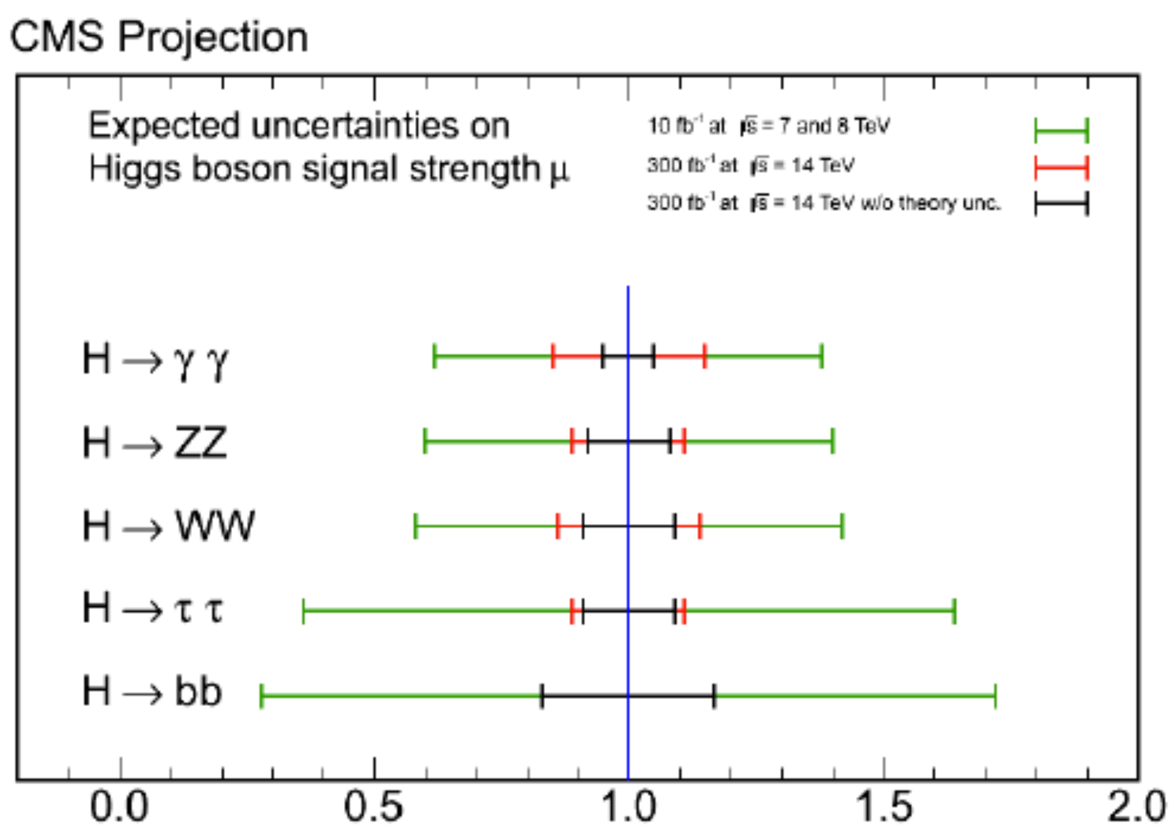
- The strong case for a Tev scale hadron collider rested on two arguments:
  1. Unitarity required that a mechanism for EWSB was manifest at or below the TeV scale.
  2. The SM is unnatural ('t Hooft conditions) and incomplete (dark matter, insufficient CP violation for the observed baryon excess, gauge 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 the probe the BSM physics in the multi-TeV range.

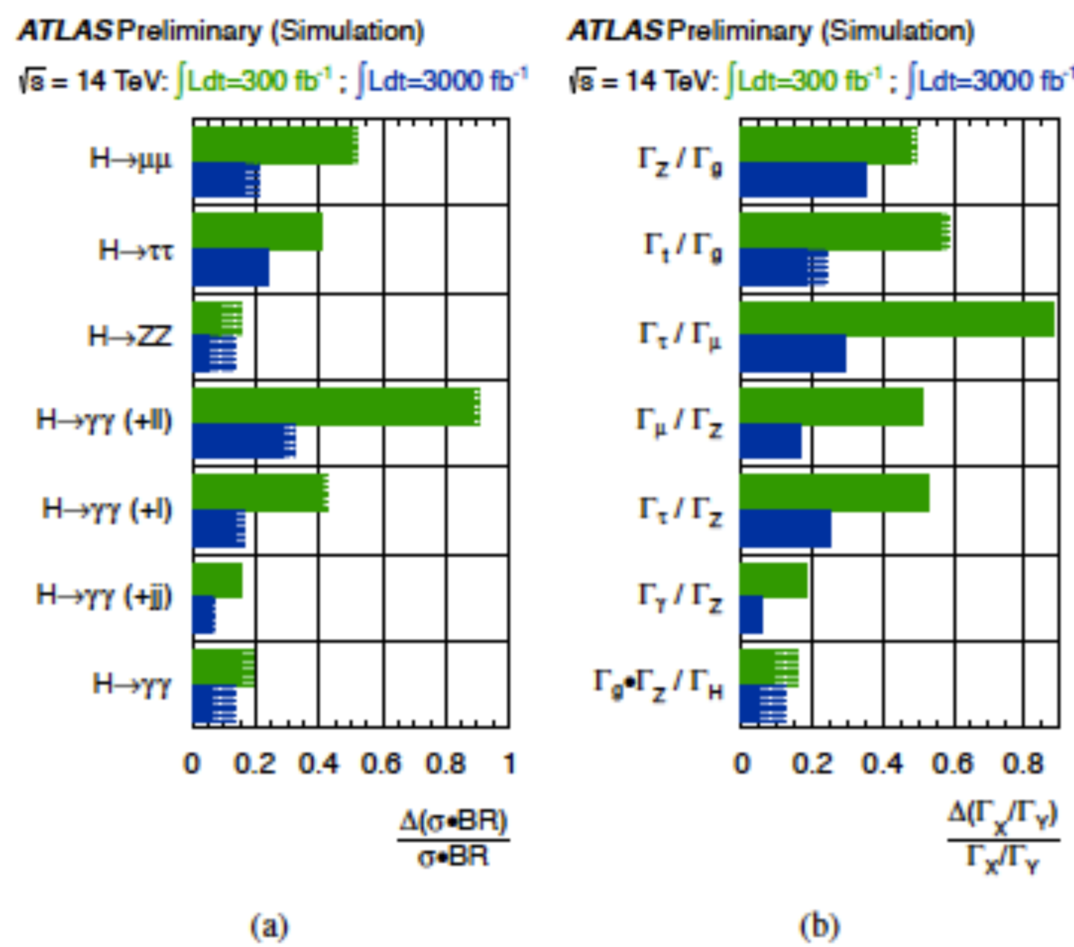
What to measure and how well ?

- 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:
    - $< \Phi^\dagger \Phi > = v^2/2 = m_h^2 / 2\lambda$ $[v = (G_F \sqrt{2})^{-1/2} \approx 247\ \mathrm{GeV}]$
    - 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 to measure and how well ?

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





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

What to measure and how well ?

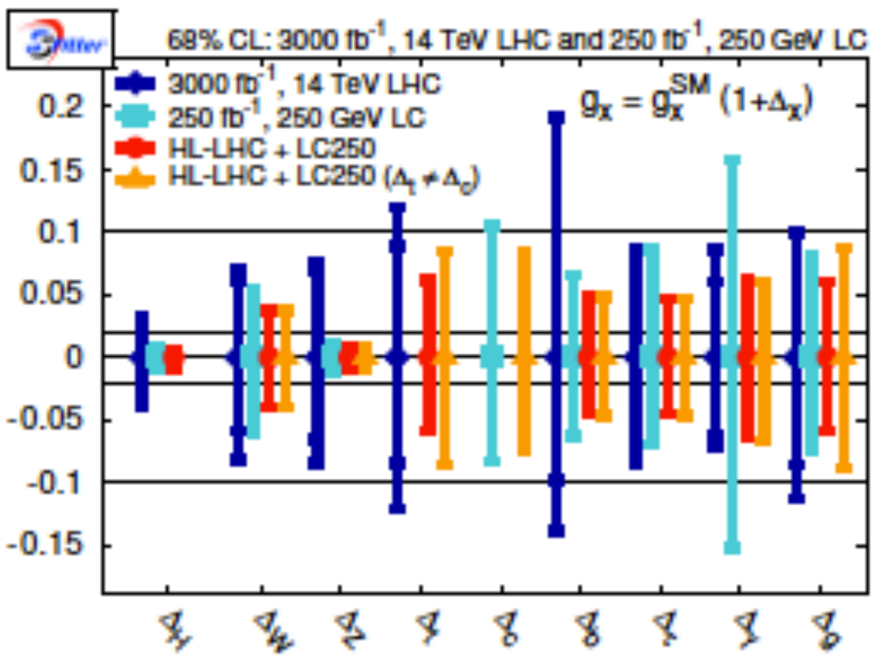
- The Role for Lepton Colliders
  - Only lepton collider can measure the h -> cc and h -> gg decays directly.
  - Precise measurements of the h -> W^+W^-, Z^0Z^0 probe if the higgs is composite or if there is any other mechanism contributing to EWSB.
  - Electron colliders (linear or circular) do detailed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

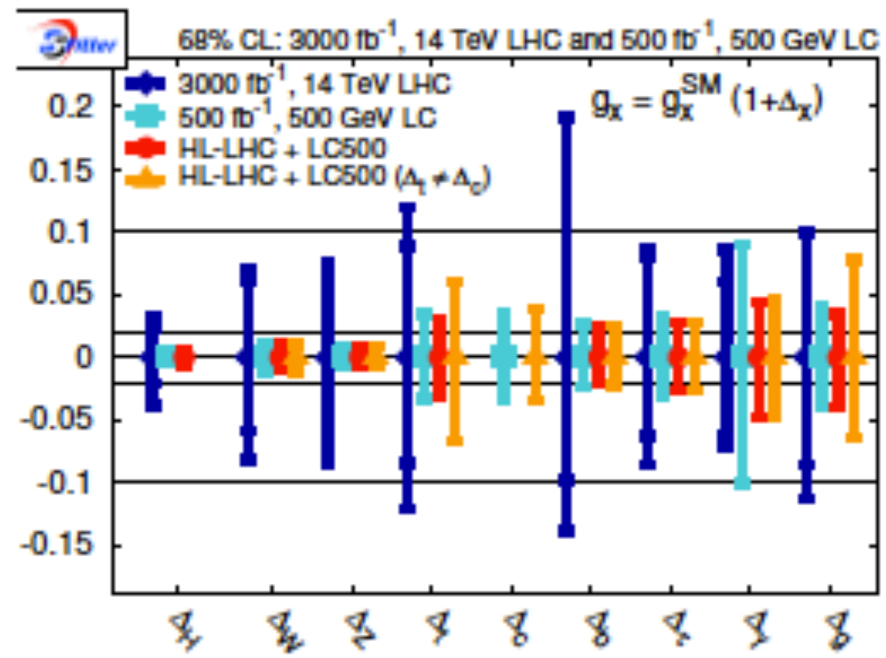
Table 5: Summary of results obtained in the Higgs studies for $m_H = 120$ GeV. All analyses at centre-of-mass energies of 350 GeV and 500 GeV assume an integrated luminosity of 500 fb^{-1}, while the analyses at 1.4 TeV (3 TeV) assume 1.5 ab^{-1}(2 ab^{-1}).

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%	

What to measure and how well ?

- Lepton Colliders compared to LHC results for various decay channels





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

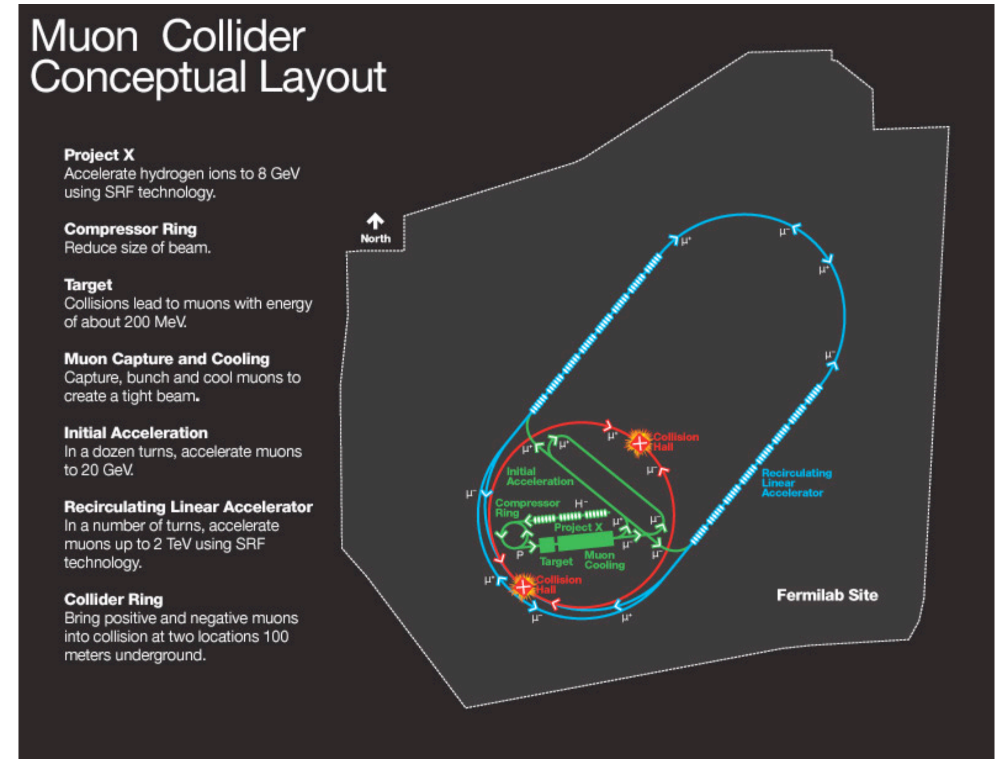
- Awaiting updates on LHC capabilities based on the 2012 run experience.
- Missing comparsions: A=μ [20%], Δm(h) [100 MeV], $\Delta\,\Gamma$(h) [5-10%] for both HL-LHC and ILC TeV
- The lepton collider results are limited by statistics.

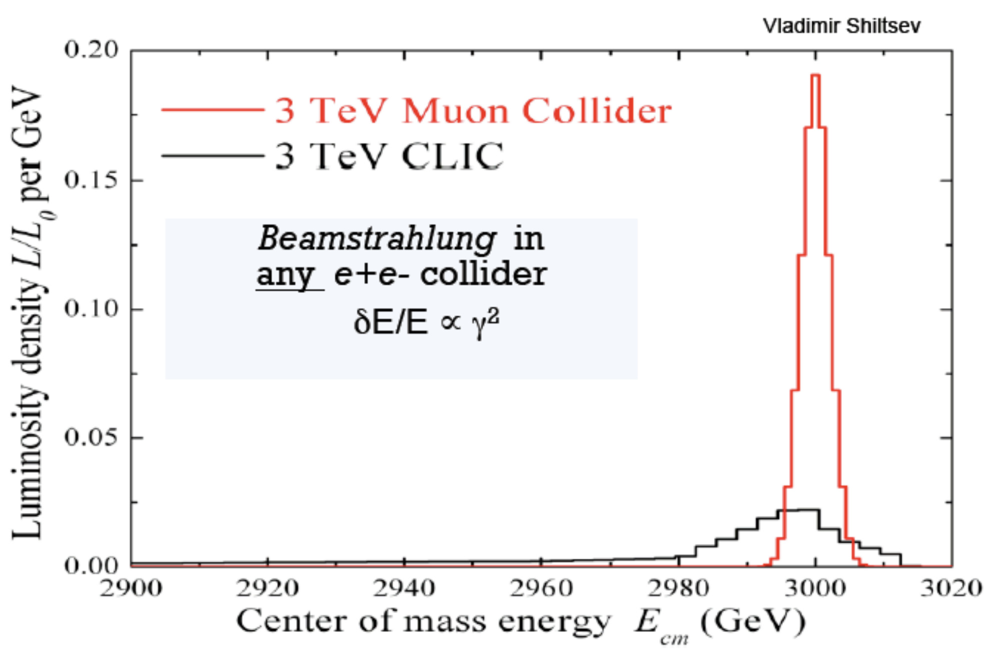
What to measure and how well ?

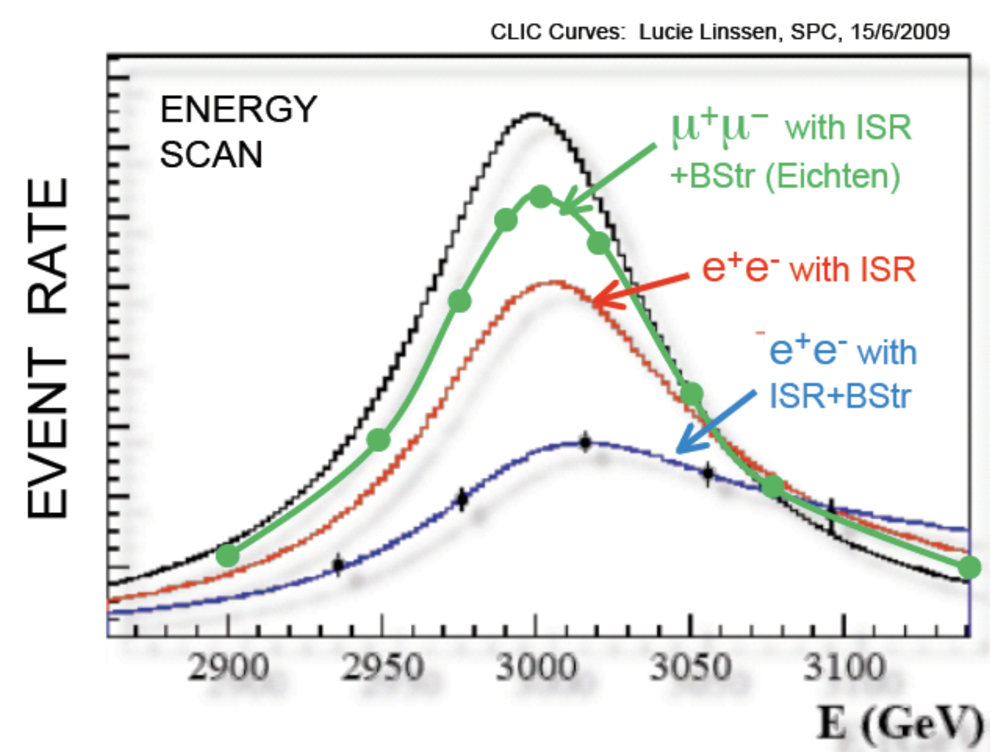
- How well do these quantities need to be measured after the LHC ?
  - Not a completely trivial question. For example, $\Delta\ m_h \simeq 0.1$ MeV is possible at a muon collider higgs factory.
  - Decay rates have SM theoretical uncertainities. So independent methods to reduce the theory errors are required, if you want to push sensitivity to smaller BSM effects.
  - What level of sensitivity is associated with the (non) observation of the actual BSM particles at the LHC?
  - What level of sensitivity is associated with scales beyond the range of a 200 TeV hadron collider or a 10 TeV lepton collider?
  - Topics for discussion today and detailed studies before any decision about a new expensive accelerator is made.

A few words about 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%

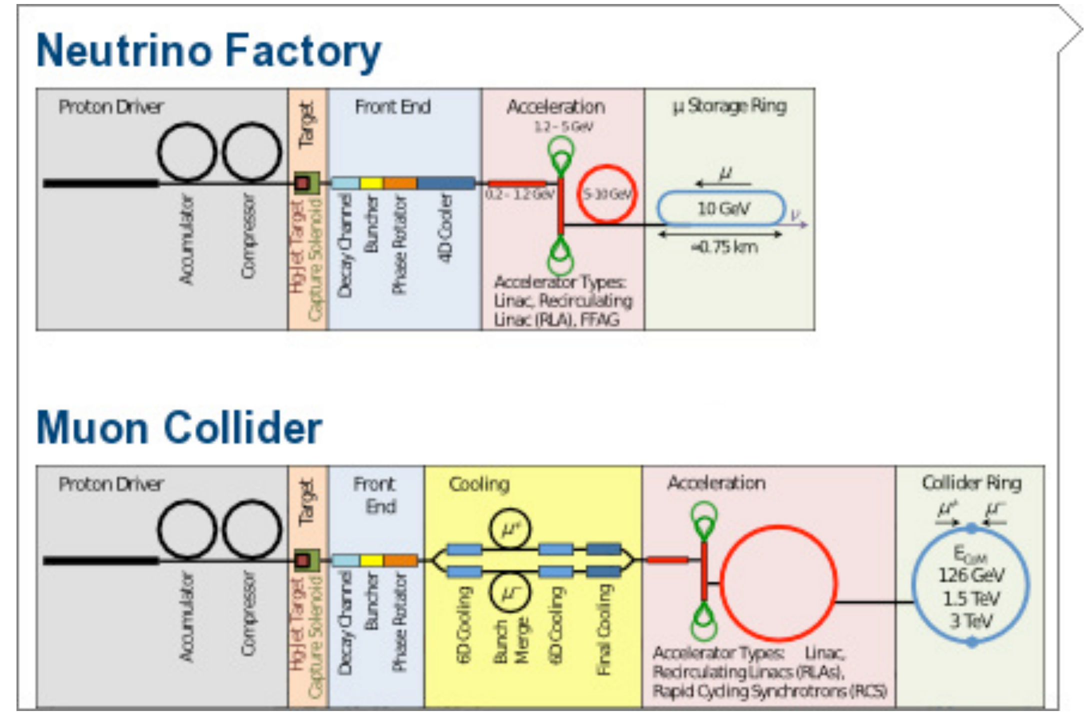




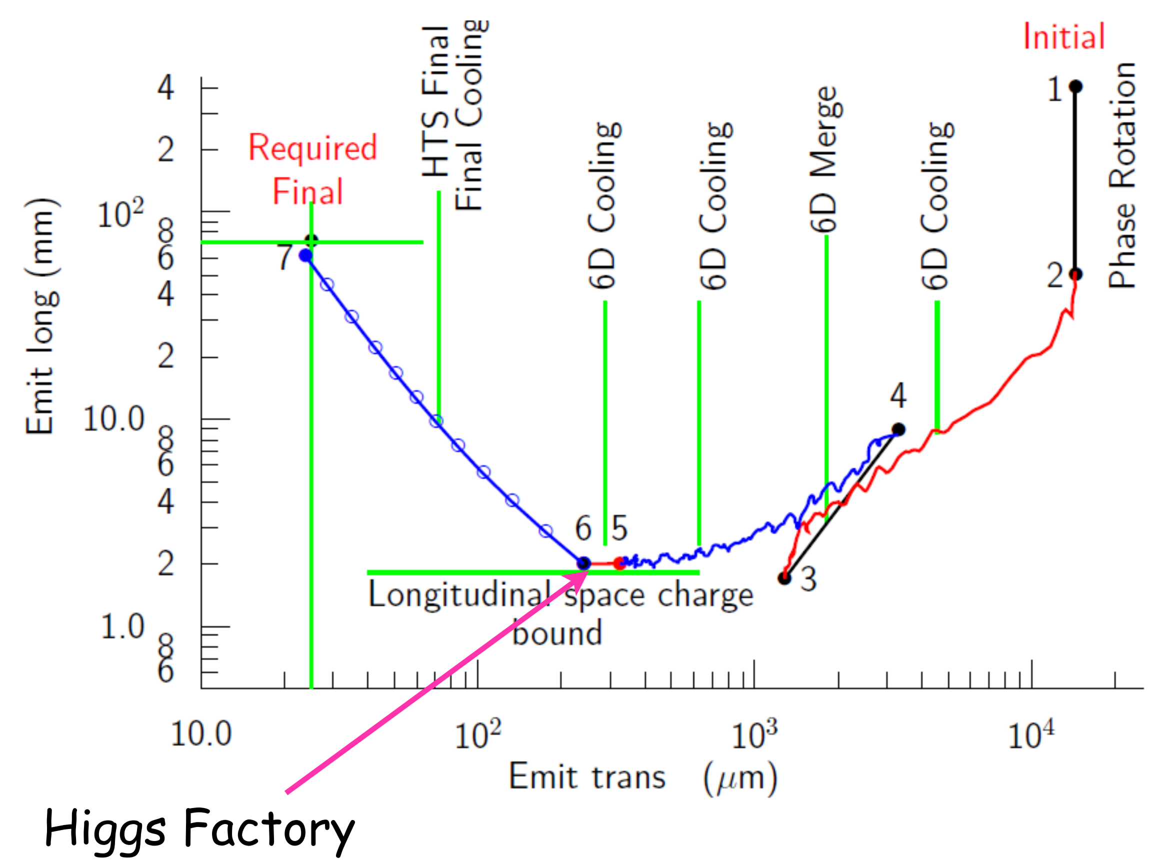


A few words about a Muon Collider

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



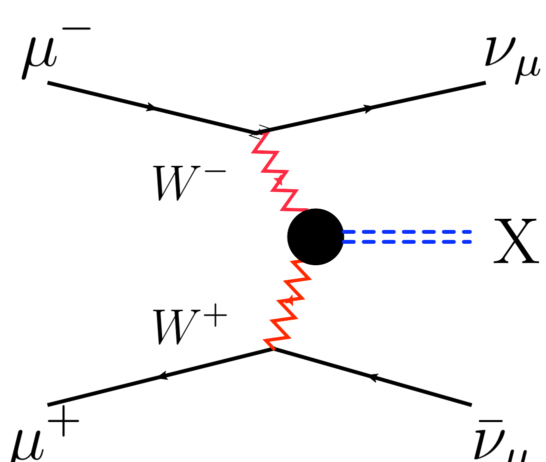
- But muons decay: ($\tau = 2.2 \times 10^{-6}$ sec)
  - The muon beams must be accelerated and cooled in phase space (factor $\approx 10^6$) rapidly -> ionization cooling
  - requires a complex cooling scheme
  - The decay products ($\mu^- \rightarrow \nu_\mu \nu_e e^-$) have high energies.
    - Detector background issues
    - Serious neutrino beam issue for Ecm ≥ 4 TeV



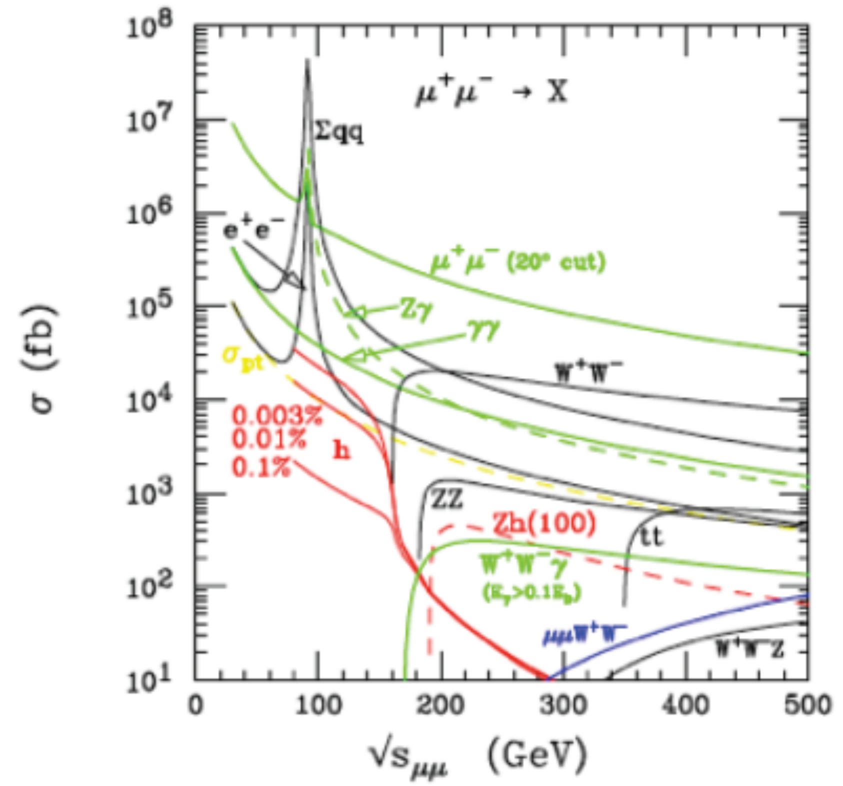
A few words about a Muon Collider

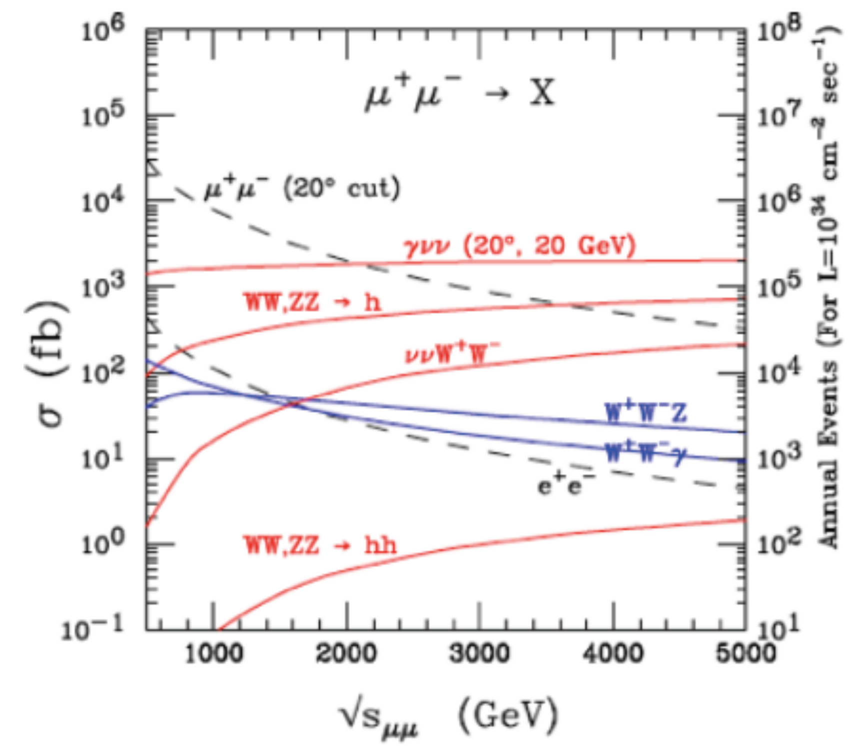
- For $\sqrt{s}$ < 500 GeV
  - SM thresholds: Z^0h ,W^+W^-, top pairs
  - Higgs factory ($\sqrt{s} \approx$ 126 GeV) ✔
- For $\sqrt{s}$ > 500 GeV
  - Sensitive to possible Beyond SM physics.
  - High luminosity required. ✔
    - Cross sections for central ($|\theta|$ > 10°) pair production ~ R × 86.8 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 ✔





A few words about a Muon Collider

- 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), $\Delta(BR(\mu^-\mu^+) \times BR(WW))$ [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) :

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

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)

A few words about a Muon Collider

- 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 ($\Delta = \Gamma$)
  - The excellent energy resolution Δ of a muon collider makes the process observable.

Tao Han and Zhen Liu [arXiv:1210.7803]

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

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

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

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

20 steps

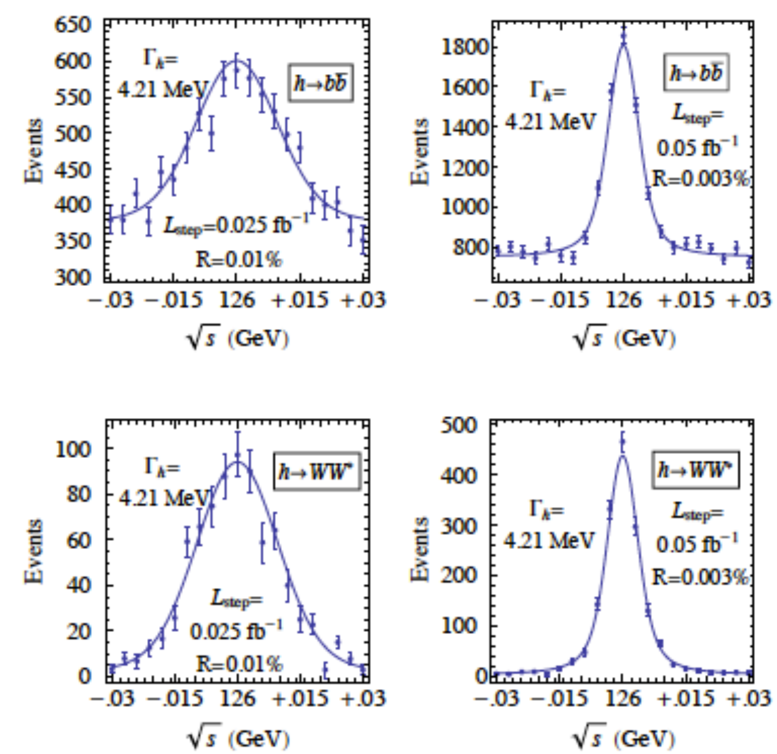
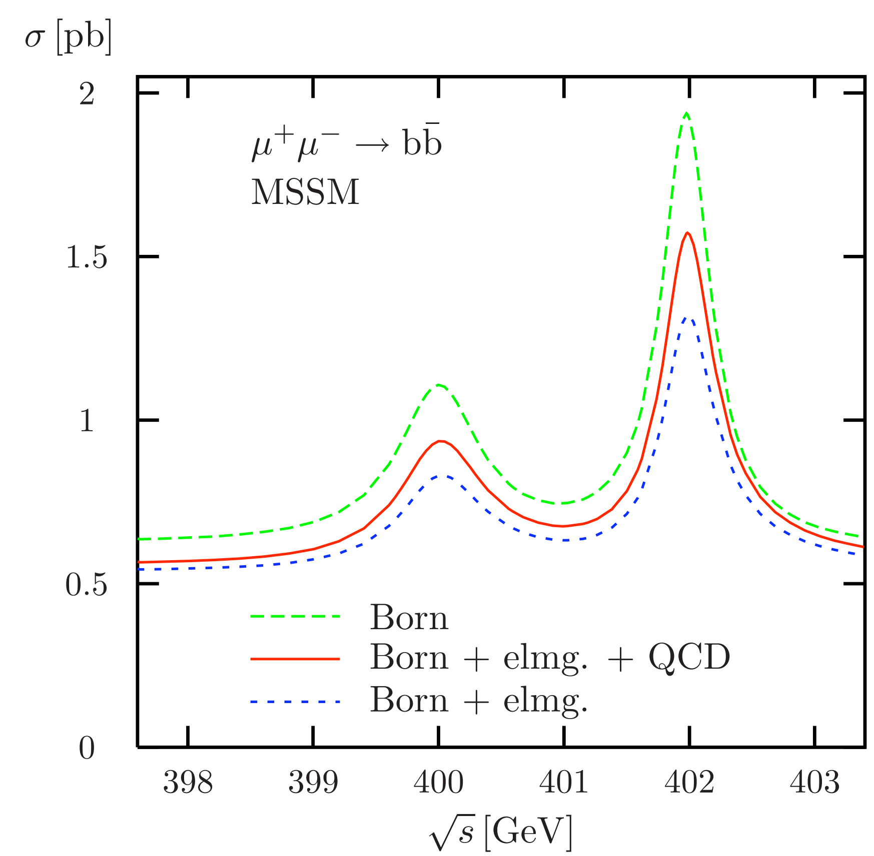


FIG. 2: Number of events of the Higgs signal plus backgrounds and statistical errors expected for Cases A and B as a function of the collider energy $\sqrt{s}$ in $b\bar{b}$ and WW^* final states with a SM Higgs $m_h = 126$ GeV and $\Gamma_h = 4.21$ MeV.

  - 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.

A few words about a Muon Collider

- Two Higgs doublets expected in MSSM
  - Five scalar particles: h^0, H^0, A^0, $H^\pm$
  - The LHC may have 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 $m_{A^0} \gg m_{Z^0}$:
  - h^0 couplings close to SM values
  - H^0, $H^\pm$ and A^0 nearly degenerate in mass
- 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]

Which Accelerator for Higgs Physics?

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 ~14 TeV running OR the discovery of BSM physics, chose the next accelerator for Higgs physics.