Higgs Physics at Future Facilities

Snowmass Higgs working group report

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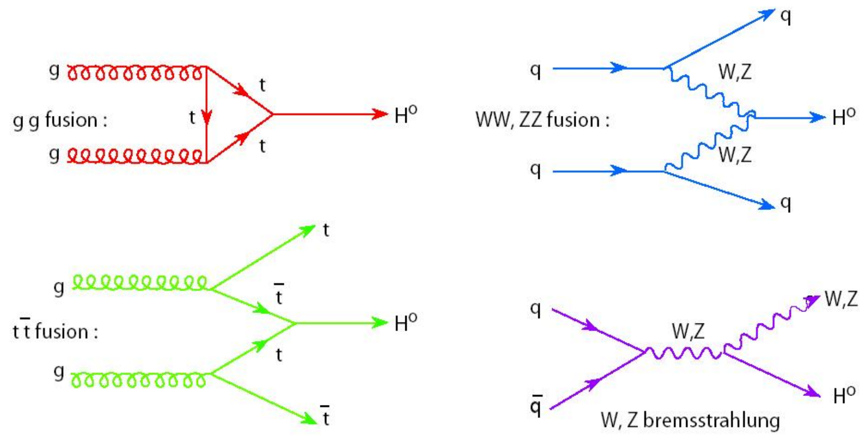
for Sally Dawson, Andrei Gritsan,
Heather Logan, Chris Tully, Rick van Kooten
and the Higgs working group

Snowmass Energy Frontier Workshop
University of Washington, June 30 – July 3, 2013

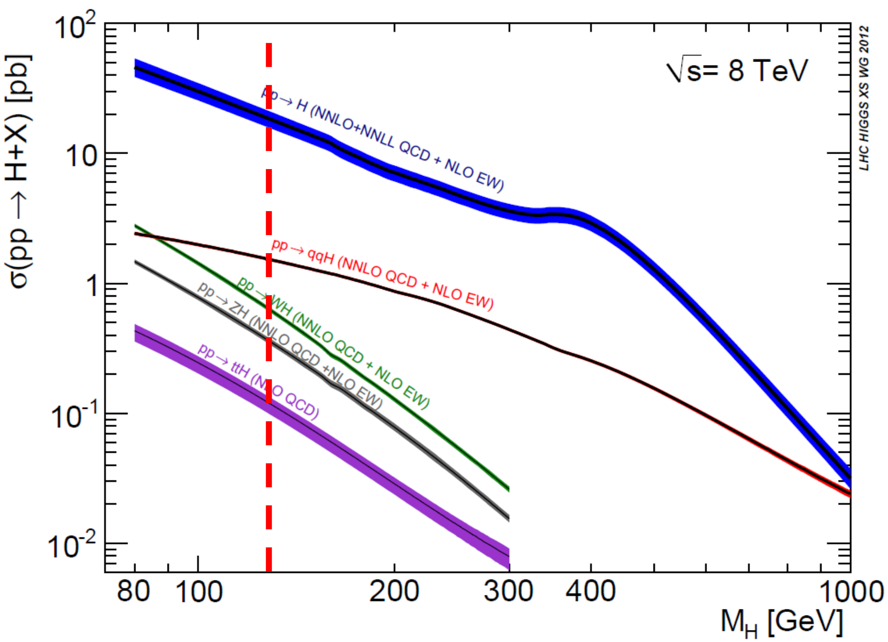
Charge: Current Status

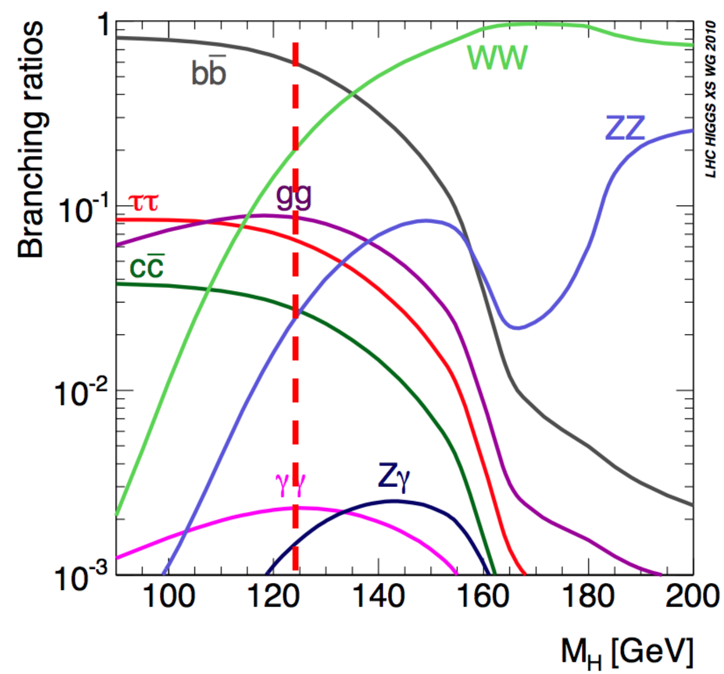
Please provide a compact summary of the measurements on and searches for the SM Higgs Boson, including information from LEP, the Tevatron, and the LHC. Include in this summary a survey of searches for non-minimal Higgs sectors.

LHC – Production and Decay



$m_H = 125$ GeV	$\sigma_H = 22.3$ pb
Branching ratio	
$H \to b\bar{b}$	57.7%
$H \to WW^*$	21.5%
$H \to \tau\tau$	6.32%
$H \to ZZ^*$	2.64%
$H \to \gamma\gamma$	0.23%
$H \to \mu\mu$	0.02%

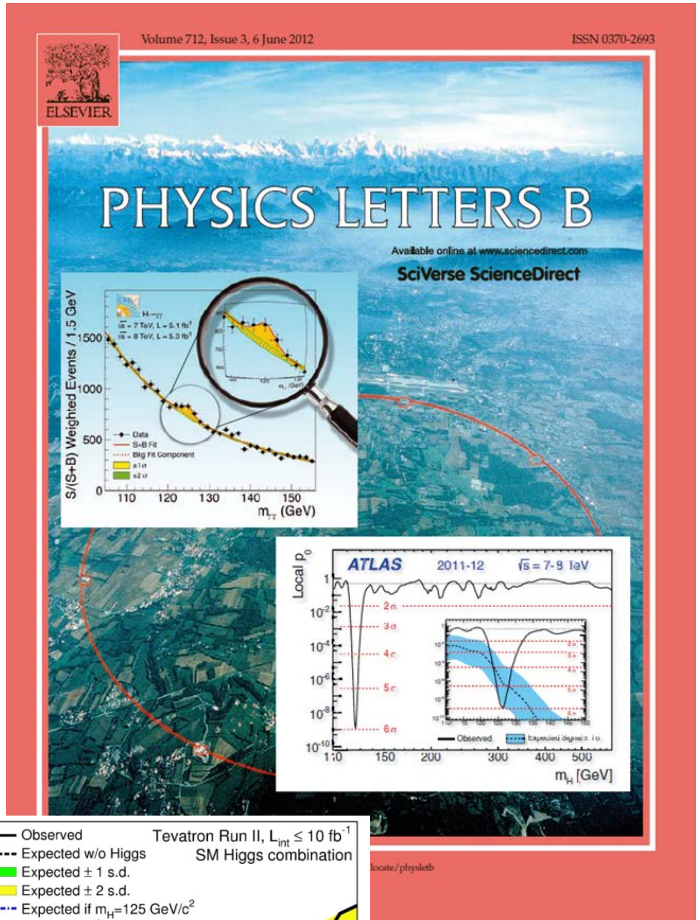


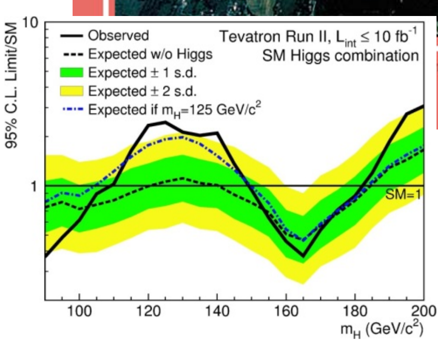


Over 1,000,000 Higgs bosons produced at LHC so far ⇒ Higgs factory !

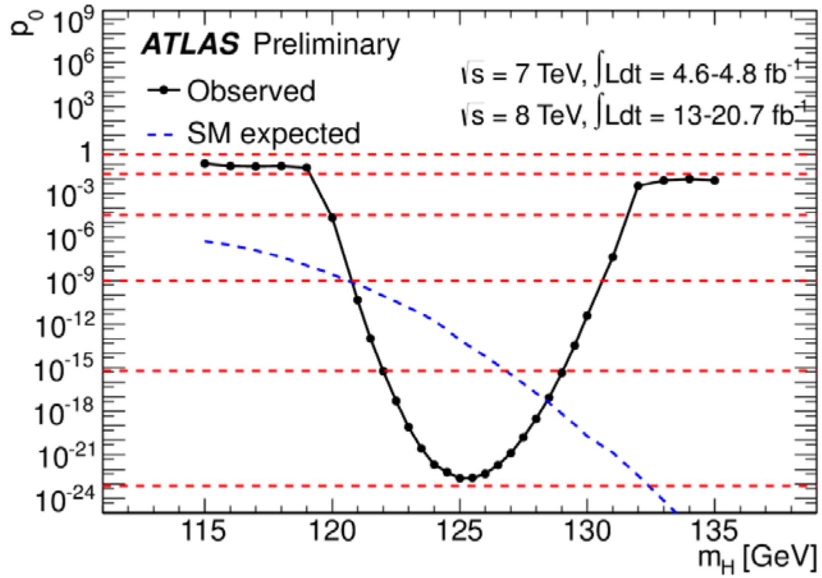
LHC – the Discovery

Then





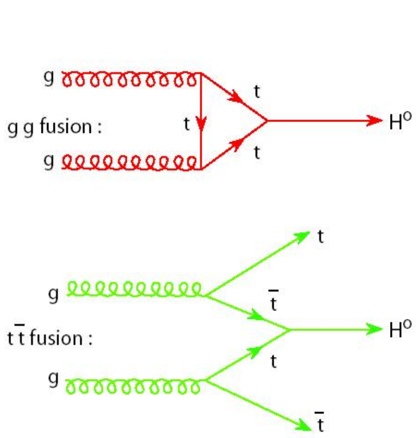
And now…



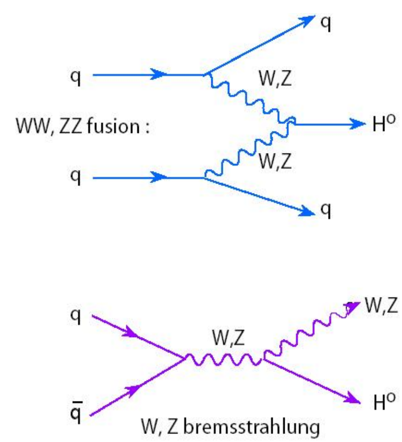
CMS	Significance (m_H = 125.7 GeV)		
Combination	Expected (pre-fit)	Expected (post-fit)	Observed
H→ZZ	7.1 σ	7.1 σ	6.7 σ
H→γγ	4.2 σ	3.9 σ	3.2 σ
H→WW	5.6 σ	5.3 σ	3.9 σ
H→bb	2.1 σ	2.2 σ	2.0 σ
H→ττ	2.7 σ	2.6 σ	2.8 σ
H→ττ and H→bb	3.5 σ	3.4 σ	3.4 σ

Both ATLAS and CMS have close to 10σ significance!

LHC – Production Processes



Htt coupling

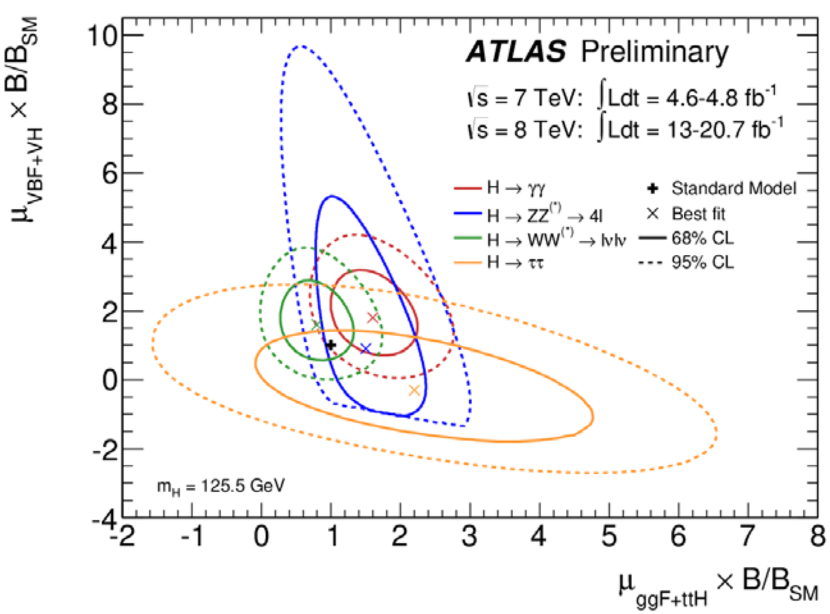


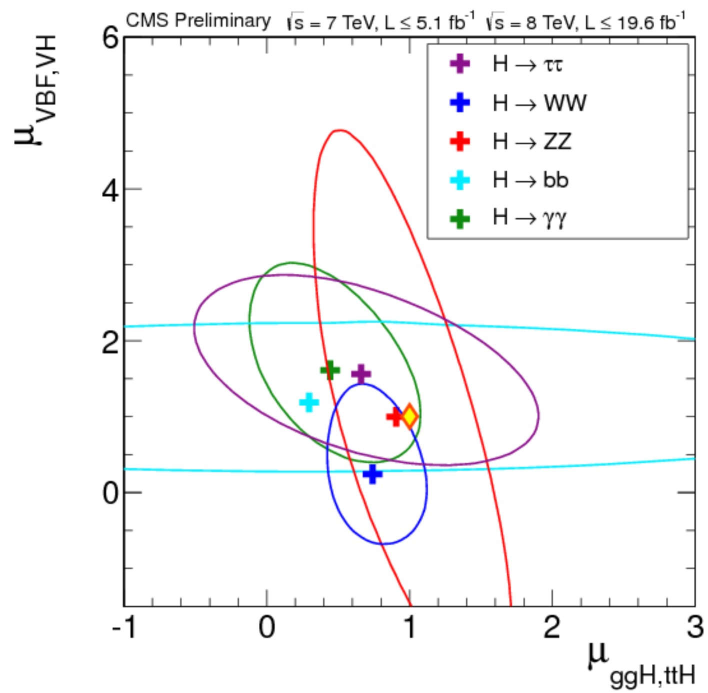
HVV coupling

What else are there in an event?

Jets? Leptons? or $\not{E}_T$?

These information provide handles to differentiate different production processes.





LHC – Coupling Measurements

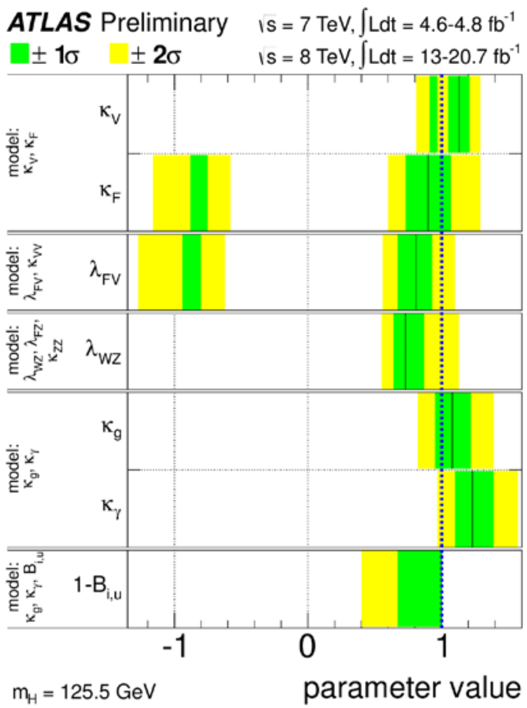
Always measure the rates ($\sigma\times$BR) $\Rightarrow$ only ratios can be determined in a model-independent way.

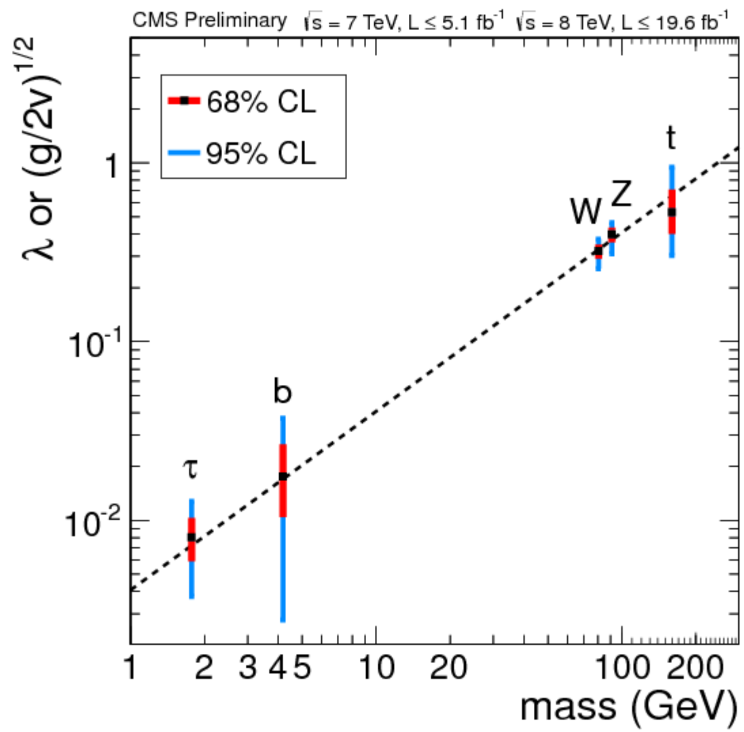
$$(\sigma \cdot \mathrm{BR})\,(gg \to H \to ZZ^* \to 4\ell) =$$

$$[\sigma(gg \to H) \cdot \mathrm{BR}(H \to ZZ^* \to 4\ell)]_{\mathrm{SM}} \times \boxed{\frac{\kappa_g^2 \cdot \kappa_Z^2}{\kappa_H^2}}$$

SM: $\lambda \propto m$ (fermions)

$g \propto m^2$ (bosons)

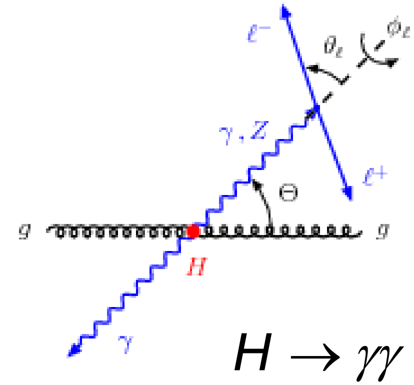


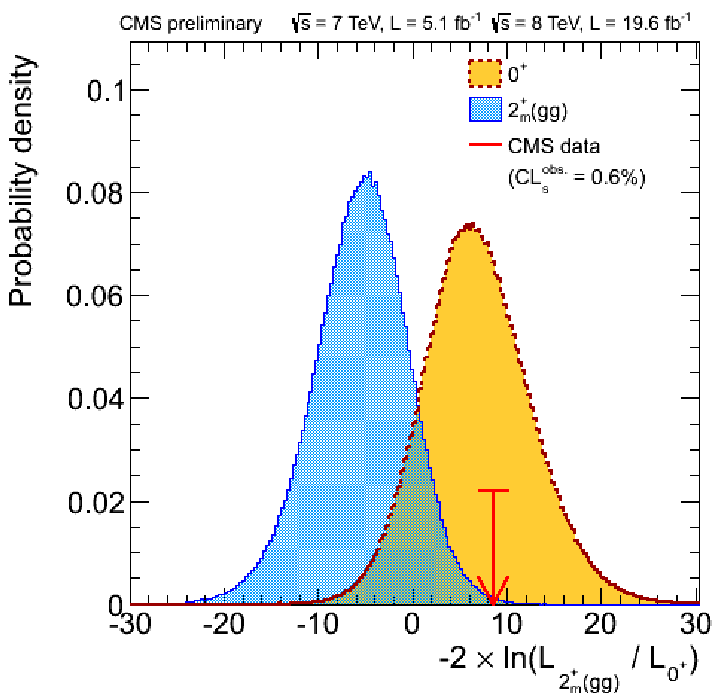


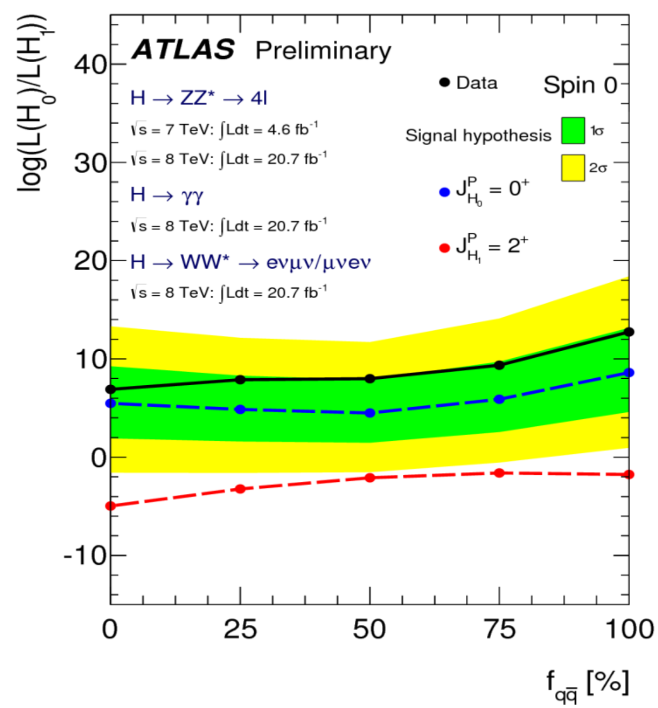
Couplings are SM like !

LHC – Spin Determination

Higgs decay kinematics depends on its properties of spin and parity. $H \to \gamma\gamma$, $H \to ZZ^* \to 4\ell$ and $H \to WW^* \to \ell\nu\ell\nu$ final states have been analyzed to determine these properties.







SM prediction of $J^p=0^+$ is strongly favored, most alternatives studied are excluded @ 95% CL or higher

Charge – Theory

Please provide a compact summary of the theoretical motivations to explore the properties of the Higgs boson to high precision.

1. What is the full phenomenological profile of the Higgs boson? What are the predicted production modes, the final states, and the experimental observables?
2. What are the ranges of predictions for deviations from Standard Model properties that enter from new physics? Which production and decay channels and boson properties are most sensitive to these deviations?
3. What can be learned from the discovery of bosons from non-minimal Higgs sectors? What is the phenomenology of non-minimal Higgs models?
4. To what extent are properties of the Higgs boson and the Higgs sector in general important for understanding fundamental physics and the universe?

Theory – SM Calculations

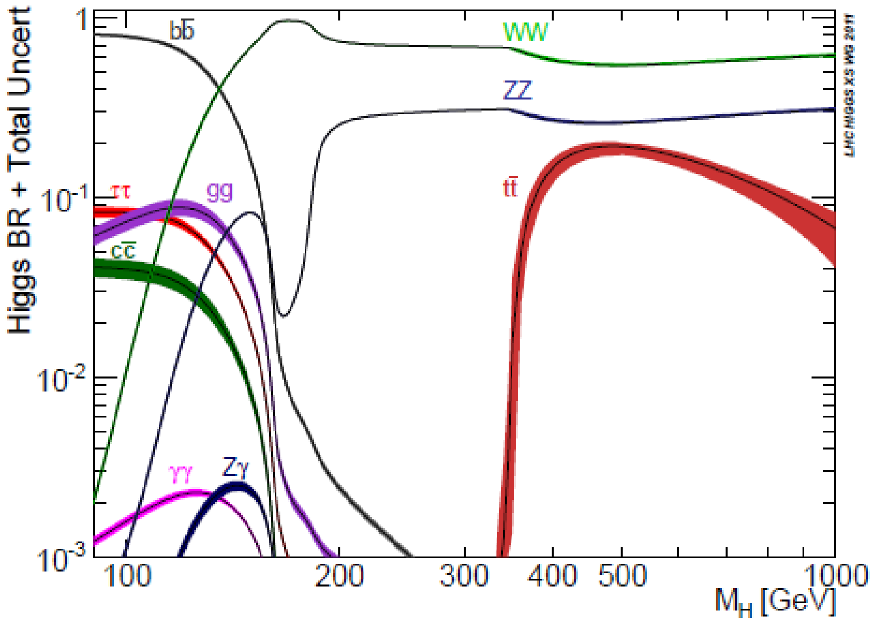
$\Delta\sigma/\sigma$ for pp at8 TeV

Process	QCD scale	PDF+α_s	Total (linear sum)
ggF	±8%	±8%	±15%
$t\bar{t}$H	±7%	±8%	±15%
VBF	±1%	±4%	±5%
VH	±1%	±4%	±5%

Starting to be dominant for some analyses, much worse for analysis split in jet bins

issues mostly for hadron colliders

Precision in BRs affect both pp and lepton colliders



$\Gamma_{b\bar{b}} \approx 0.57\Gamma_H \Rightarrow \Delta m_b$ has a large impact

ΔBR/BR at $M_H = 125$ GeV

decay	theory	parameters	total (linear sum)
$H \to bb$	±1.3%	±1.5%	±2.8%
$H \to \tau\tau$	±3.6%	±2.5%	±6.1%
$H \to \mu\mu$	±3.9%	±2.5%	±6.4%
$H \to WW^*$	±2.2%	±2.5%	±4.8%
$H \to ZZ^*$	±2.2%	±2.5%	±4.8%
$H \to \gamma\gamma$	±2.9%	±2.5%	±5.4%

A. Denner et al., arXiv:1107.5909

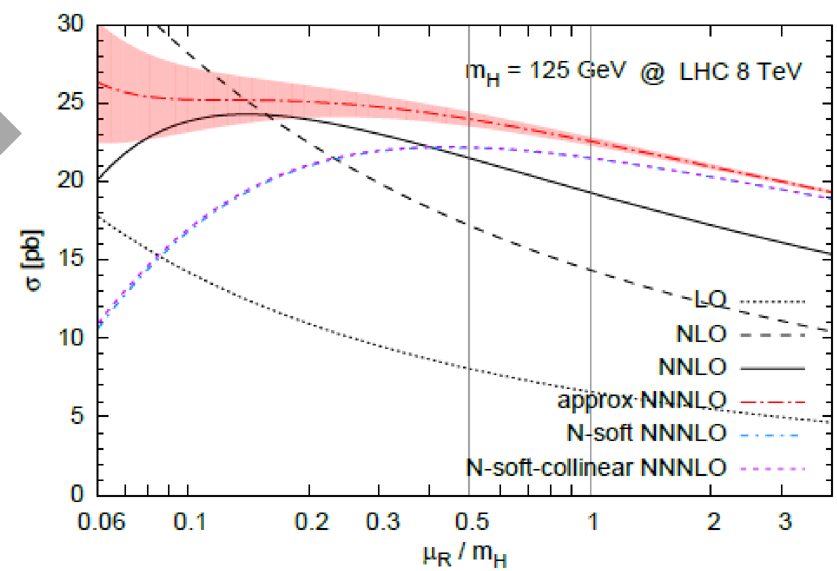
Need to improve SM calculations and their inputs!

Theory – Progress in σ Calculations

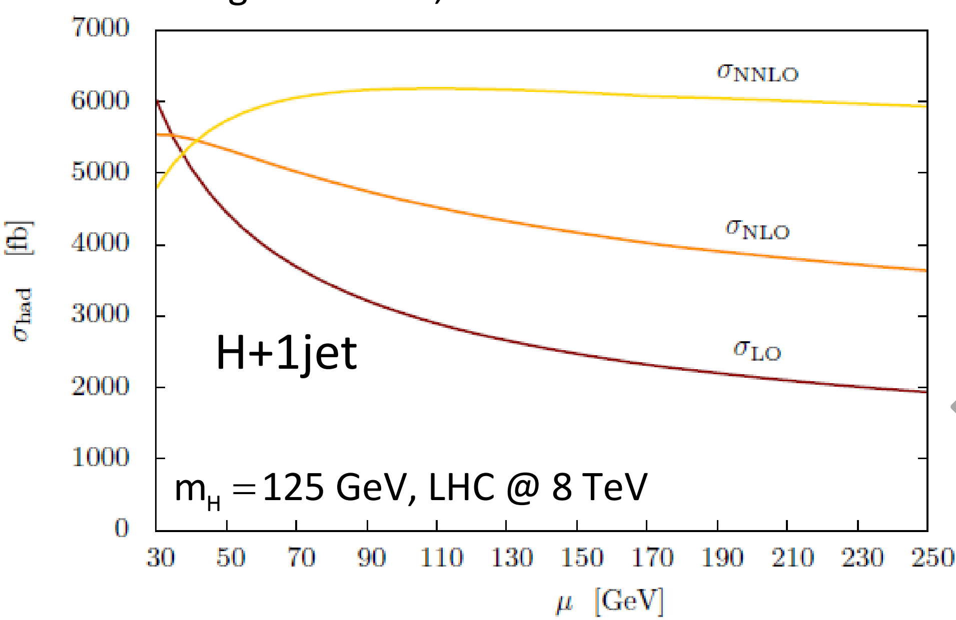
The gg→H cross section at LHC is calculated from NNLO+NNLL, but it still suffers from large QCD scale variations at ~8%.

Approximate NNNLO calculations are becoming available which can reduce the uncertainty to a few percent

Ball et al., arXiv:1303.3590



Boughezal et al., arXiv:1302.6216



Not just the inclusive cross sections, analyses are often done in jet bins:

- better signal-background ratio;
- separate production processes

Theory – Coupling Deviations

How large are potential deviations from BSM physics? How well do we need to measure them to be sensitive?

To be sensitive to a deviation Δ, the measurement precision needs to be much better than Δ, at least Δ/3 and preferably Δ/5!

Since the couplings of the 125 GeV Higgs boson are found to be very close to SM ⇒ deviations from BSM physics must be small.

Typical effect on coupling from heavy state M or new physics at scale M:

$$\Delta \sim \left(\frac{\upsilon}{M}\right)^2 \sim 6\% \ @ \ \mathrm{M} \sim 1 \ \mathrm{TeV}$$

(Han et al., hep-ph/0302188, Gupta et al. arXiv:1206.3560, …)

MSSM decoupling limit

Δ at sub-percent to a few percent, will be challenging to distinguish the MSSM decoupling limit from the SM in the case of no direct discovery.

$$\frac{g_{hVV}}{g_{h_{\rm SM}VV}} \simeq 1 - 0.3\% \left(\frac{200\ \mathrm{GeV}}{m_A}\right)^4$$

$$\frac{g_{htt}}{g_{h_{\rm SM}tt}} = \frac{g_{hcc}}{g_{h_{\rm SM}cc}} \simeq 1 - 1.7\% \left(\frac{200\ \mathrm{GeV}}{m_A}\right)^2$$

$$\frac{g_{hbb}}{g_{h_{\rm SM}bb}} = \frac{g_{h\tau\tau}}{g_{h_{\rm SM}\tau\tau}} \simeq 1 + 40\% \left(\frac{200\ \mathrm{GeV}}{m_A}\right)^2 .$$

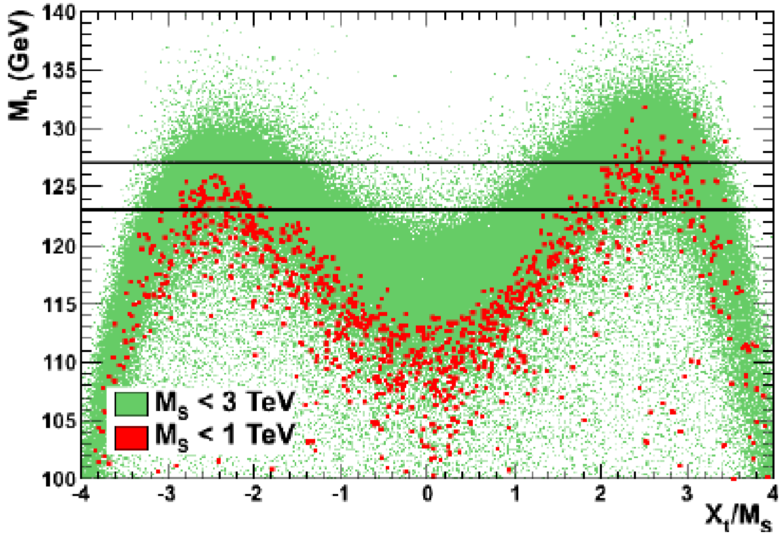
(ILC DBDPhysics)

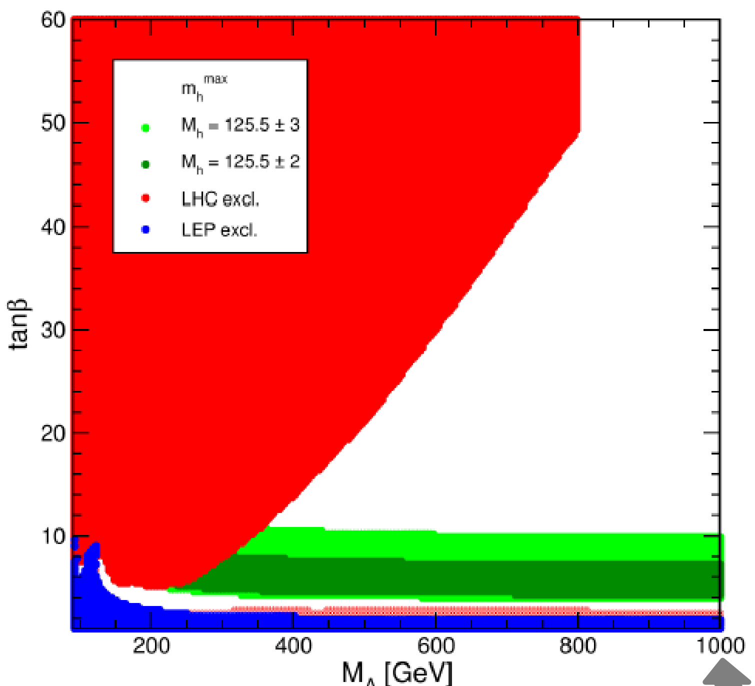
Theory – Beyond Standard Model

Understand the implication of a 125 GeV Higgs boson, whatever it is, it's SM-like…

For pMSSM, favoring large Ms
$\Rightarrow$ opens up small tanβ regions

Arbey et al., arXiv: 1112.3028





Carena et al., arXiv:1302.7033

Develop new benchmark models
- Electroweak singlet
- Composite model
- 2 Higgs doublet model
- MSSM
- …

Theory – 2 Higgs Doublet Model

5 Higgs bosons, the neutral scalars h and H share the role of electroweak symmetry breaking. Four types of general models:

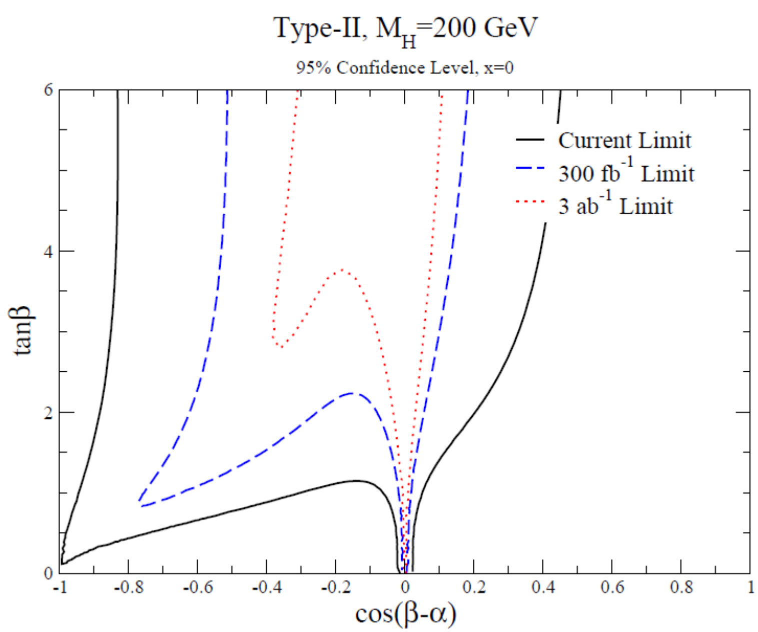
Type I: one doublet couples to bosons, the other to fermions;

Type II: one to up-quarks, the other to down-quarks or leptons

Two other types: Lepton-specific and flipped

Couplings relative to SM

Coupling	Type I	Type II
hVV	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
hQu	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
hQd	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
hLe	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
HVV	$\cos(\beta-\alpha)$	$\cos(\beta-\alpha)$
HQu	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$
HQd	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$
HLe	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$



Chen et al., arXiv:1305.1624

Heavy Higgs will primarily decay to WW and ZZ bosons

HL-LHC will significantly increase the discovery potential or tighten the limit.

See the talk by Chien-Yi Chen this afternoon for details

Charge – Prospects

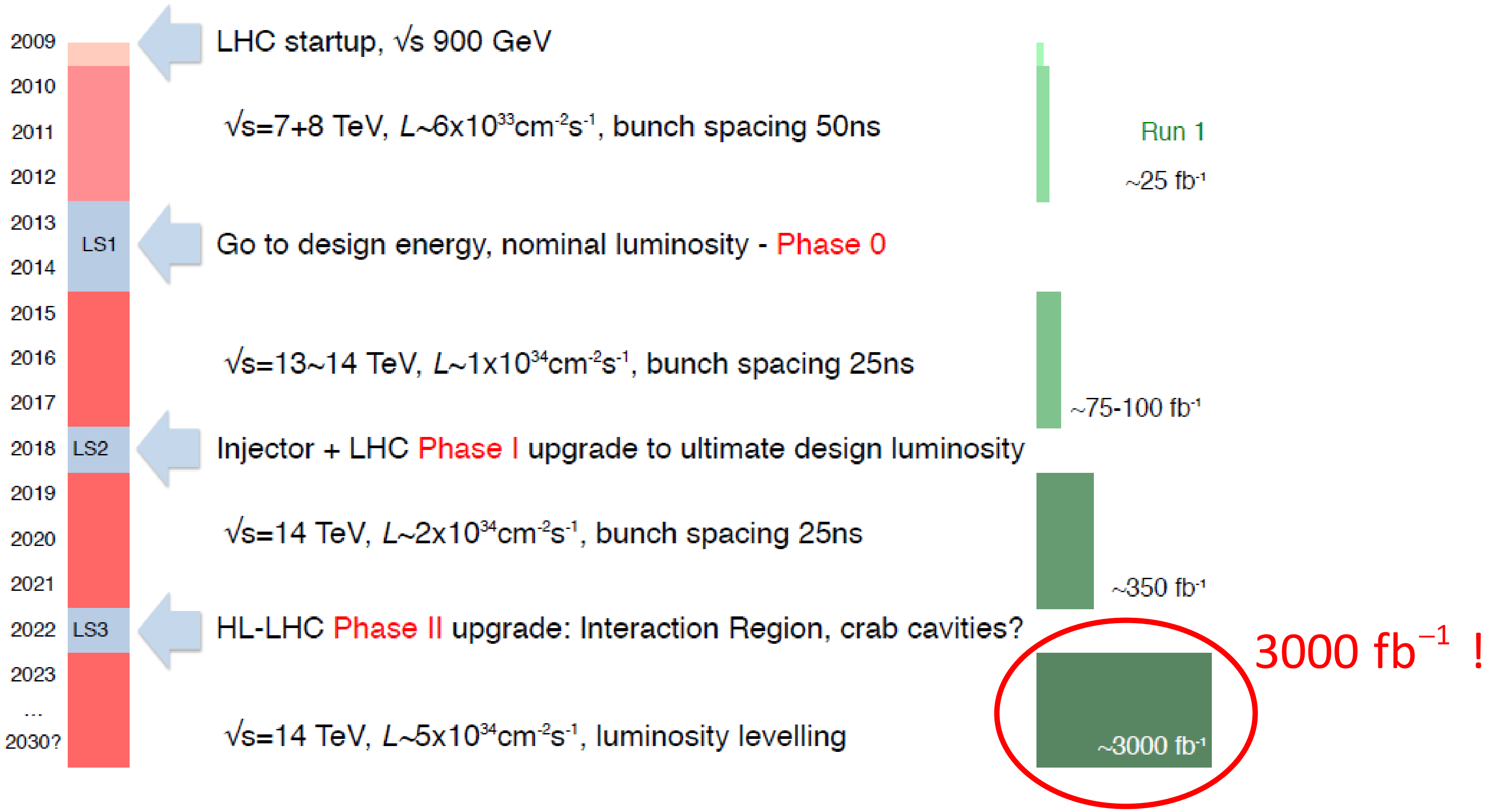
Please organize a set of simulation studies to evaluate the level of precision that can be achieved on Higgs physics measurements for the range of choices of accelerator facilities and detector capabilities under consideration by the Facilities/Instrumentation groups. Include studies of search sensitivities for non-minimal Higgs sectors.

1.To what degree can a particular experimental program ascertain whether the resonance at 125-126 GeV is the Standard Model Higgs boson? To what precision can each of the measured properties of the Higgs boson be determined and tested against SM predictions?
2. What are the search sensitivities for bosons in non-minimal Higgs sectors?
3. The studies should summarize their results in terms of these areas:
    1. Mass and width measurements;
    2. "Couplings" in terms of production cross section by process and branching fractions by decay mode, including searches for non-SM couplings;
    3. "Tensor structure" in terms of quantum numbers (JCP) and effective couplings in the Lagrangian;
    4. Couplings and properties governing the Higgs potential.
4. What are intrinsic advantages of particular experimental programs? Are there unique capabilities to reconstructing particular decays or unique sensitivities to particular rare decay rates? Are there properties that can be determined in some experimental programs and not in others? To what extent can complementary programs enhance the overall Higgs physics program?
5. Provide cross-calibration for the simulation tools to provide a record of what intrinsic performances and assumptions went into these results.

LHC – High Luminosity Upgrade

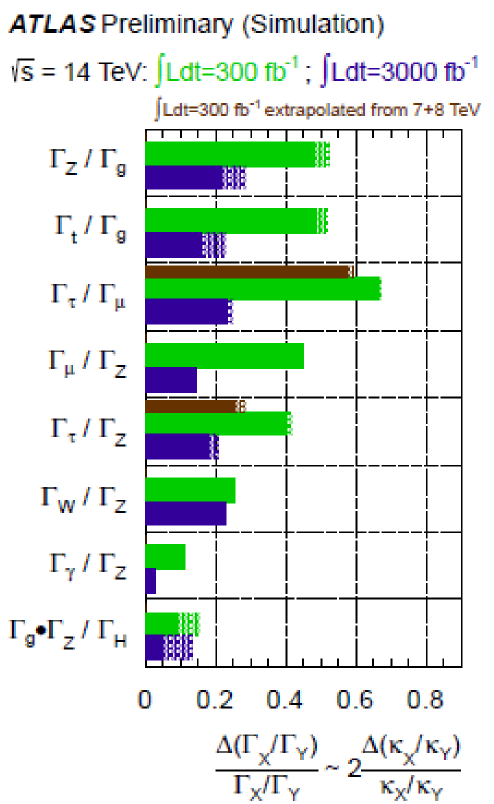
Update of European Strategy for Particle Physics:

"Europe's top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030."

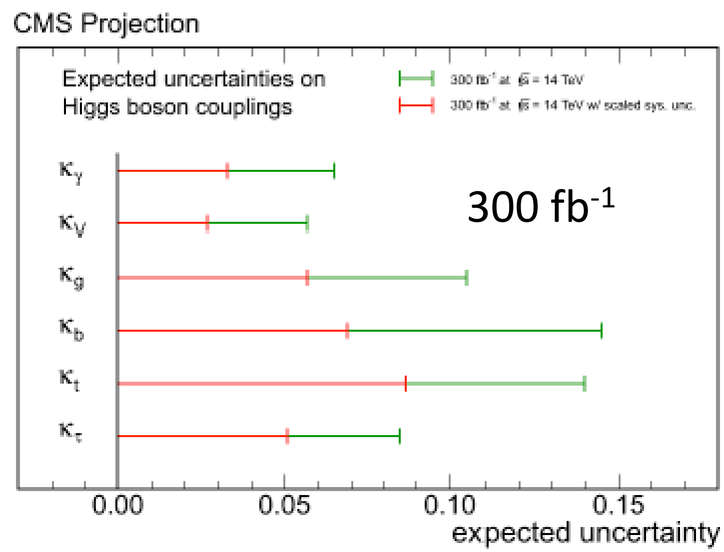


LHC – Coupling Projections

Many studies done for European Strategy planning summarized in the Physics Briefing Book. Studies are being revisited and expanded.



(Based on parametric simulation)



(Extrapolated from 2011/2012 results)

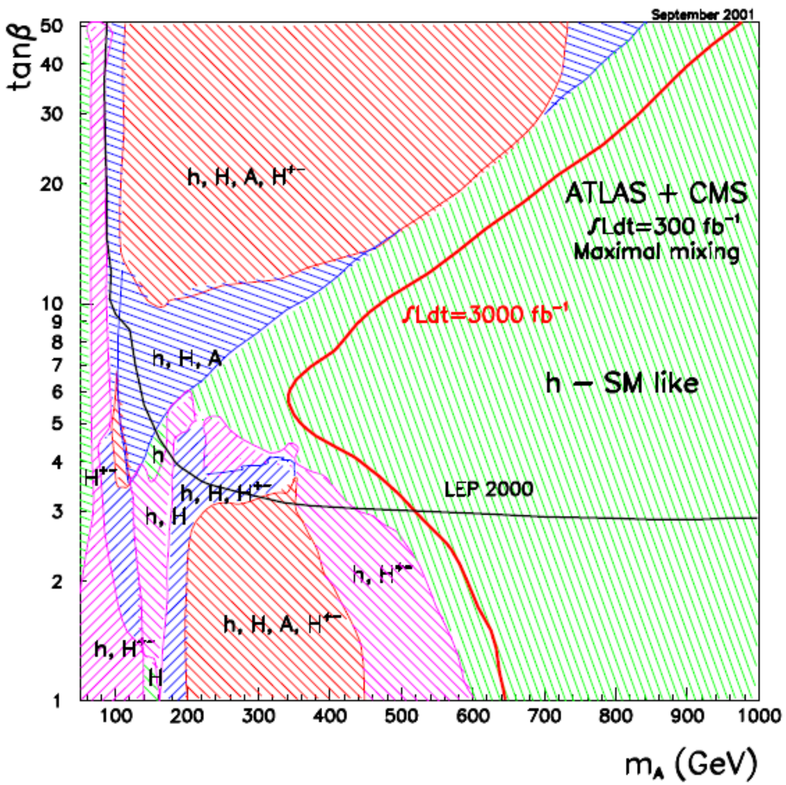
Two assumptions on systematics:

1. no change
2. $\Delta(\text{theory})/2$, rest $\propto 1/\sqrt{Lumi}$

Ratios can be measured with better precisions, some can be measured at percent level.

LHC – Beyond Standard Model

Gianotti et al., hep-ph/0204087



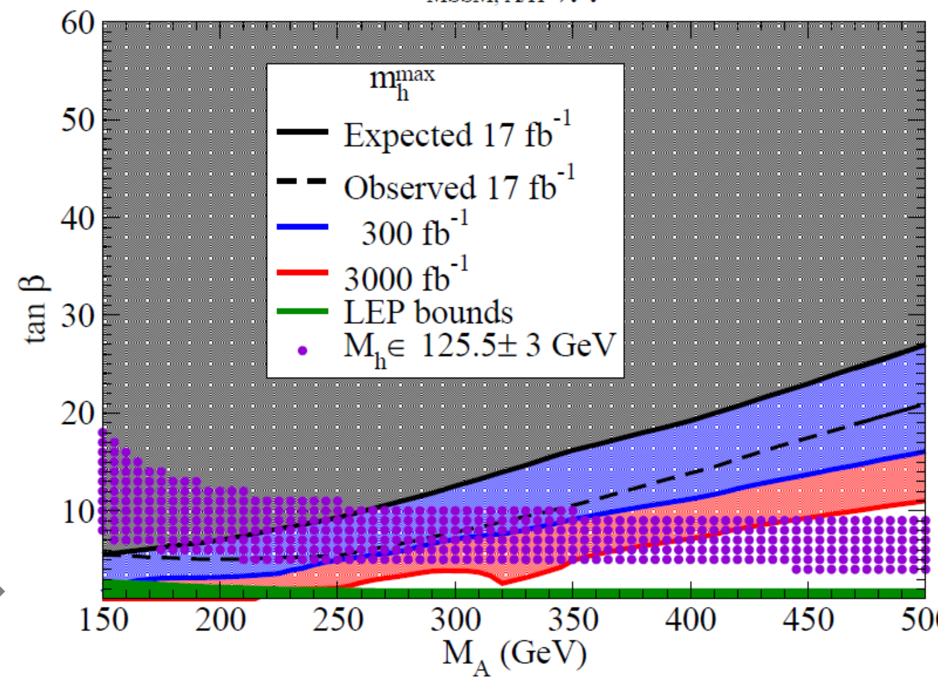
Most projections haven't been updated for 10 years ⇐ having too much fun with data

Nevertheless, the sensitivities are not expected to change much.

We know more than we did before

Extrapolation of Expected CMS bounds

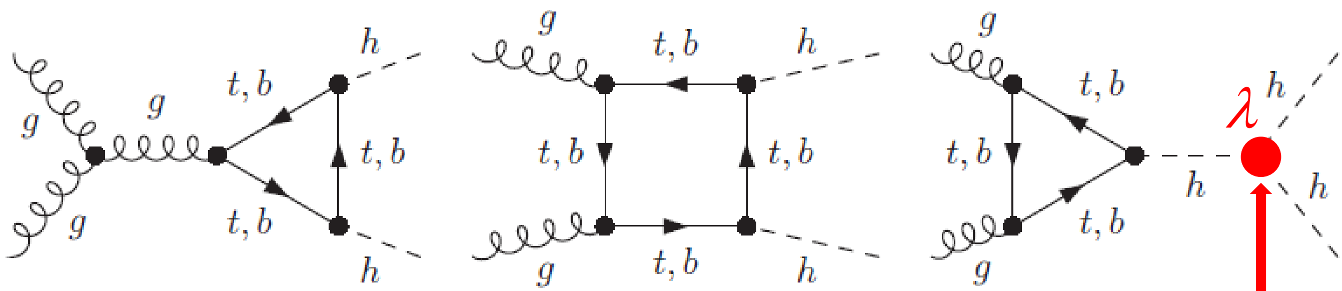
MSSM, $A/H \to \tau^+\tau^-$



Experimentalists are busy playing with data, theorists are helping us !

See for example the talk by Ian Lewis this afternoon…

LHC – Selfcoupling Study



$$V(\phi) = \mu^2 \left(\phi^\dagger \phi\right) + \lambda \left(\phi^\dagger \phi\right)^2$$

$\sigma(pp \to HH)$@14 TeV	34 fb

Events in 3000 fb^{-1}	
$HH \to bb\gamma\gamma$	270
$HH \to bb\tau\tau$	7,400
$HH \to bbWW$	25,000

Small cross section and the destructive interference between self- and non-self-coupling diagrams.

bb$\gamma\gamma$ appears to have the best sensitivity, bb$\tau\tau$ should help too, bbWW has a higher rate, but is buried by $t\bar{t} \to bbWW$ production.

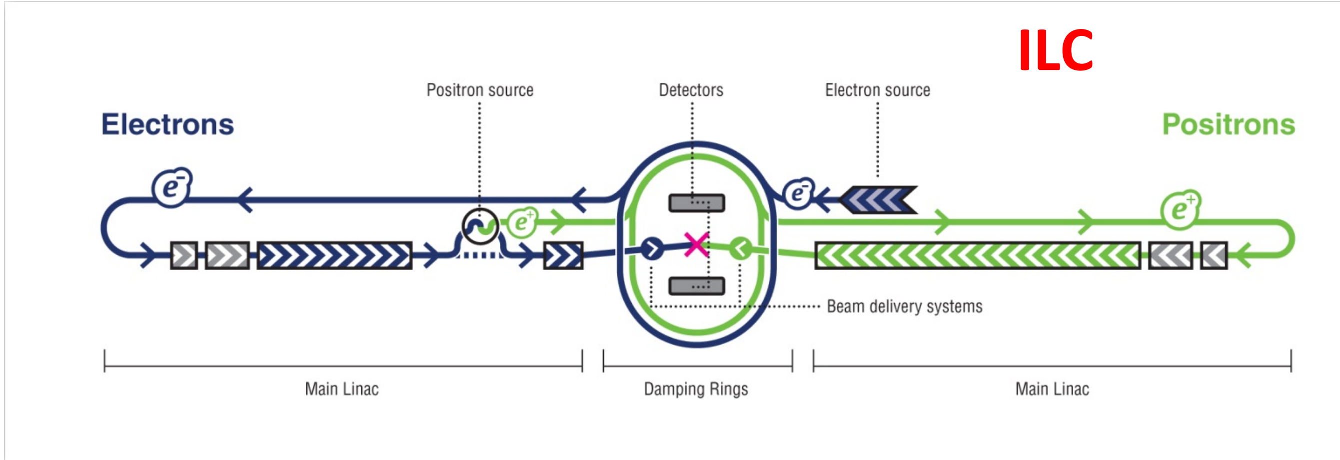
Will likely need to combine many final states to maximize the sensitivity

Expect to achieve $\frac{\Delta\lambda}{\lambda} \sim 30\%$

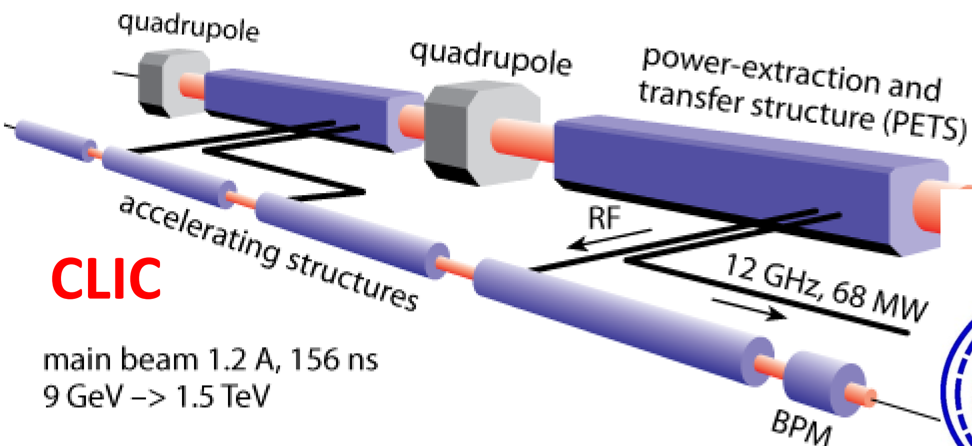
(two experiments)

At 33 TeV, cross section increases by ~x7 for both the signal and main backgrounds

e^+e^- Colliders

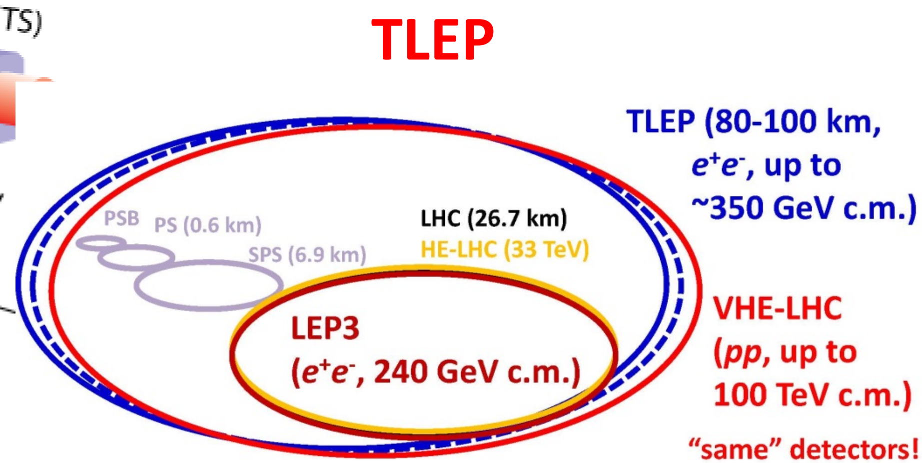


2.38 GeV –> 240 MeV



CLIC

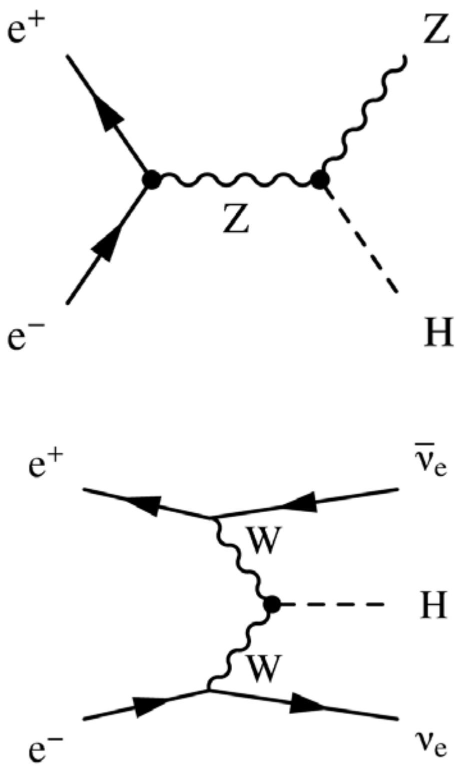
main beam 1.2 A, 156 ns
9 GeV –> 1.5 TeV

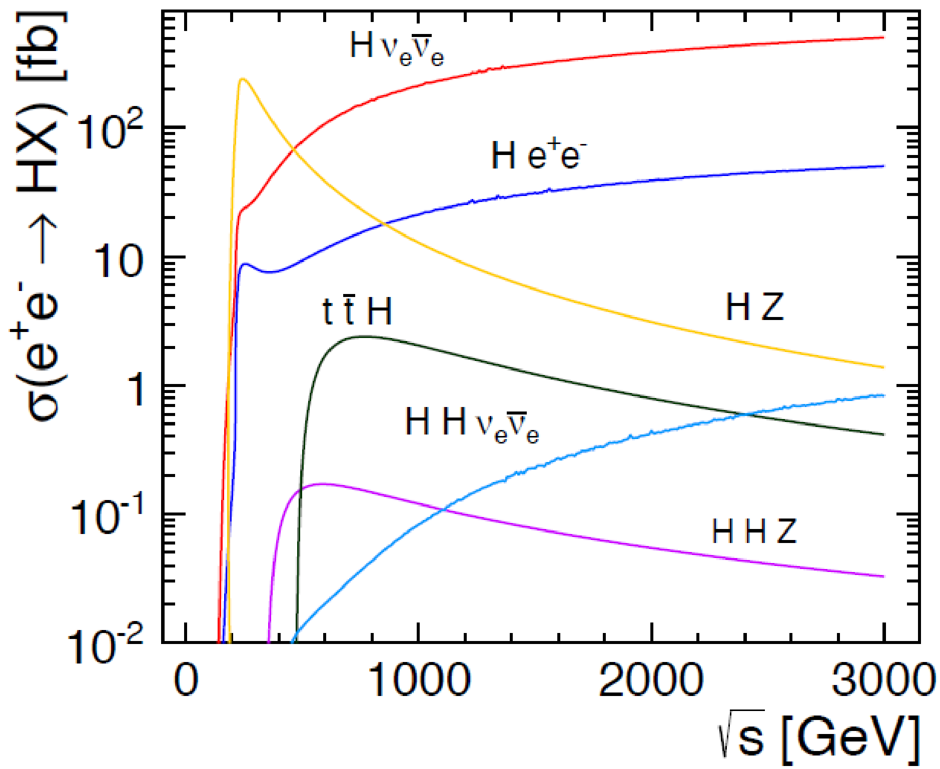


& $e^{\pm}$ (120 GeV) – p (7, 16 & 50 TeV) collisions ([(V)HE-]TLHeC)

Give the same energy and luminosity, physics should have little differences

e^+e^- Colliders – Production Rates

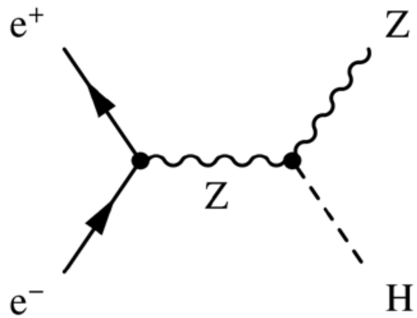




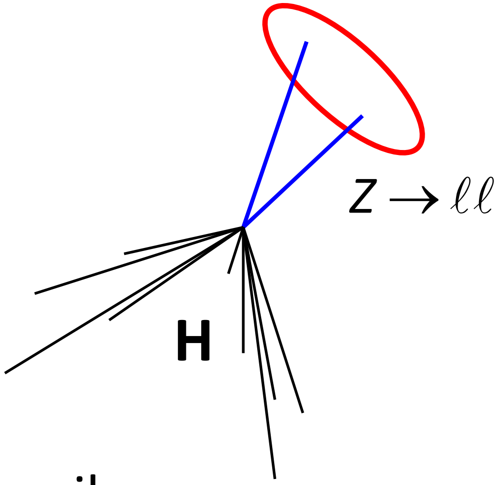
Facility	ILC		CLIC	LEP3 (4 IP)	TLEP (4 IP)	
Energy (GeV)	250	500+1000	350+500+1500	240	240	350
Luminosity (fb^{-1})	250	500+1000	500+500+1500	2000	10,000	1400
# ZH events	75,000	42,000	102,000	600,000	3,000,000	180,000
# $\nu\nu$H events	4,500	248,000	516,000	–	15,000	42,000

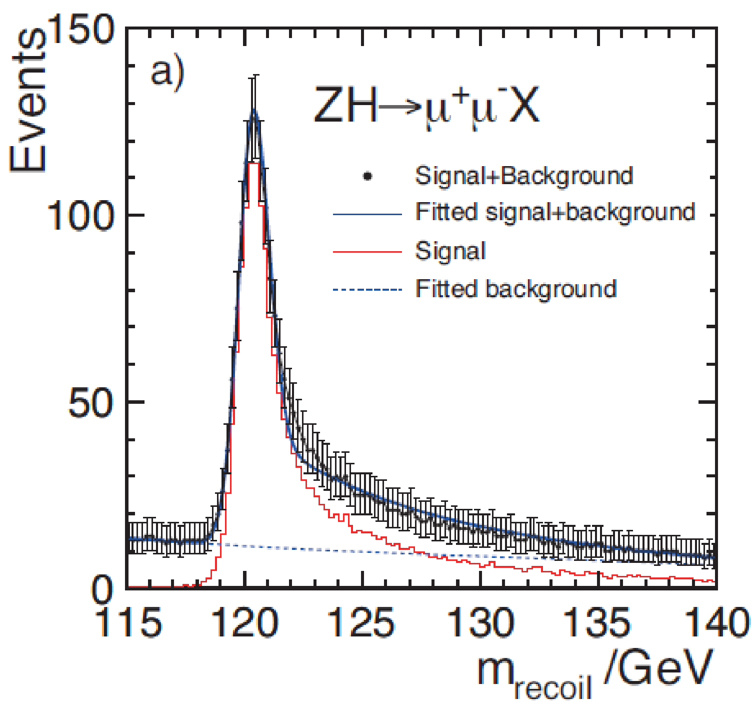
Note: Luminosity upgrade planned for ILC: 250/500/1000 GeV at 1150/1600/2500 fb^{-1}.

e^+e^- Colliders – Coupling Measurements



$$\sigma_{ZH}\left(\sqrt{s}=250\text{ GeV}\right)\approx 300\text{ fb}$$





Reconstruct recoil mass

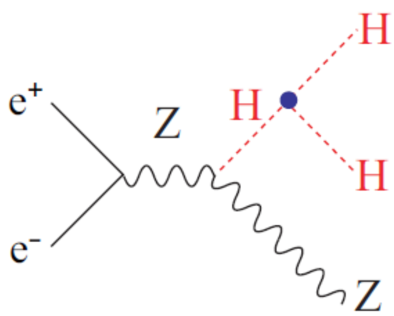
$$m^2_{\text{recoil}}=\left(\sqrt{s}-E_{\ell\ell}\right)^2-\left|\vec{p}_{\ell\ell}\right|^2$$

$\Rightarrow$ identify Higgs independent of its decay

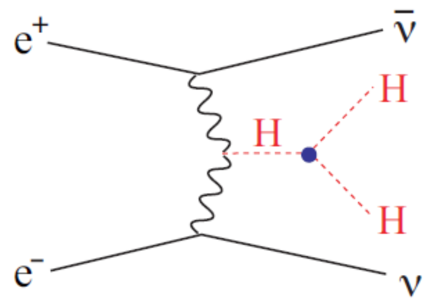
- ZH cross section measurement $\Delta\sigma_{ZH}/\sigma_{ZH}\sim 2.6\%$
- Classify the rest of events to measure $\text{BR}(H\to XX)$

Independent and separate measurements of σ and BR

e⁺e⁻ Colliders – Self-coupling



$$\frac{\Delta\lambda}{\lambda} \approx 1.8 \frac{\Delta\sigma}{\sigma}$$

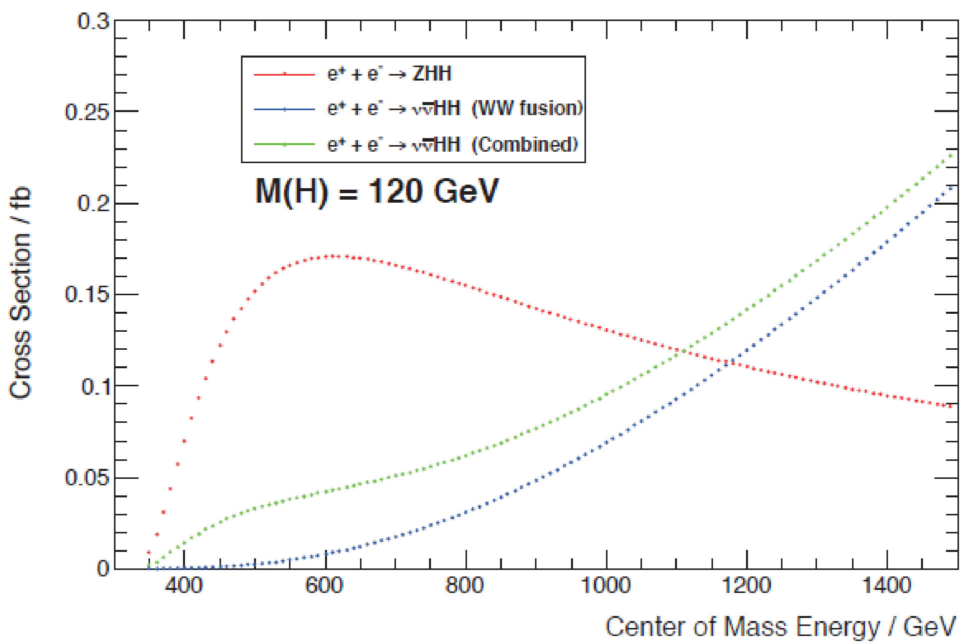


$$\frac{\Delta\lambda}{\lambda} \approx 0.85 \frac{\Delta\sigma}{\sigma}$$

$$\sqrt{s} \geq\sim 500\ \text{GeV}$$

$$(\text{ILC} + \text{CLIC})$$

$$V(\phi) = \mu^2(\phi^\dagger\phi) + \lambda(\phi^\dagger\phi)^2$$



Low rates:

~400 events total at ILC

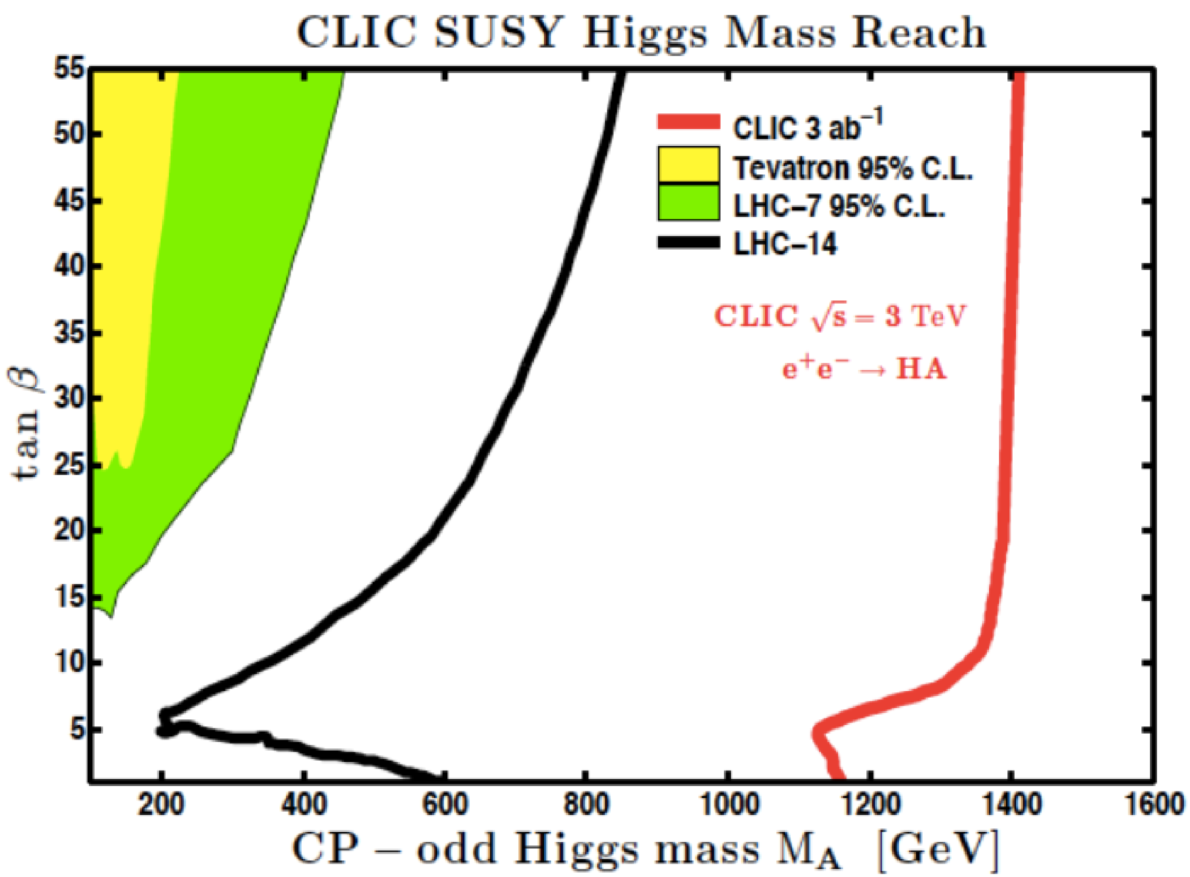
~1000 events at CLIC

and there is a significant contamination from continuum HH production

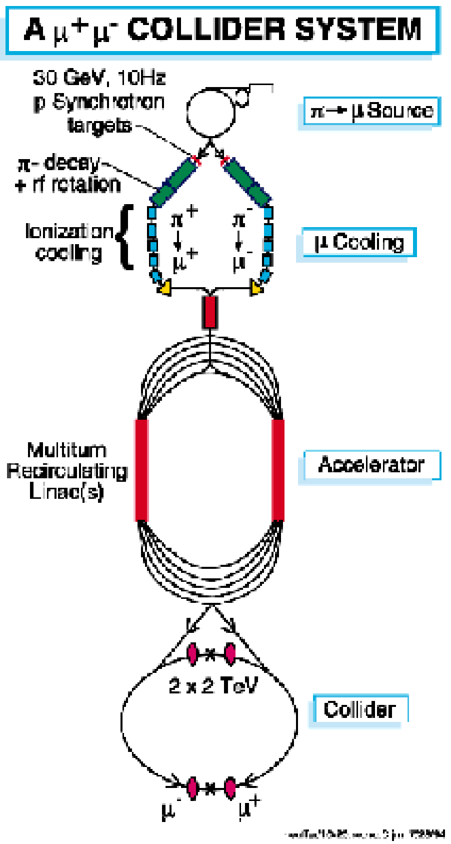
$$\Rightarrow \frac{\Delta\lambda}{\lambda} \sim 26\%\ (\text{ILC}),\ 16\%\ (\text{CLIC})$$

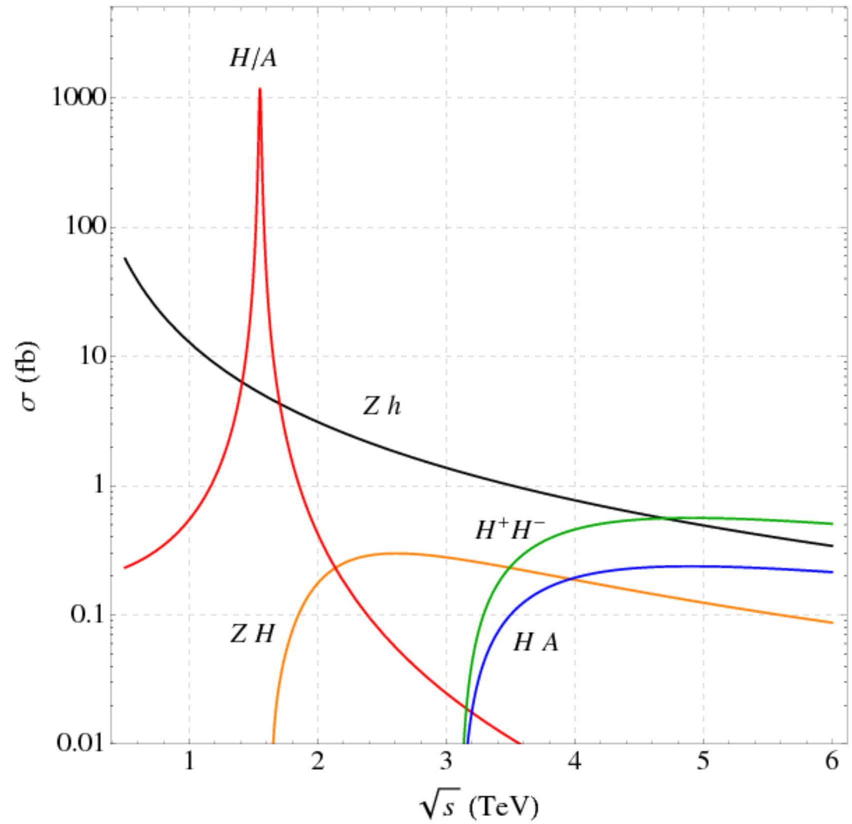
e^+e^- Colliders – BSM Higgs

The mass reach of direct searches is about half of the total beam energy if particles can be pair produced…



$\mu^+\mu^-$ Collider





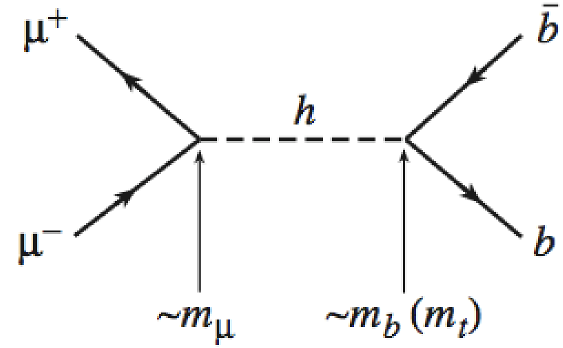
direct s-channel production of Higgs bosons

high energy ⇒ high potential for heavy Higgs boson discoveries

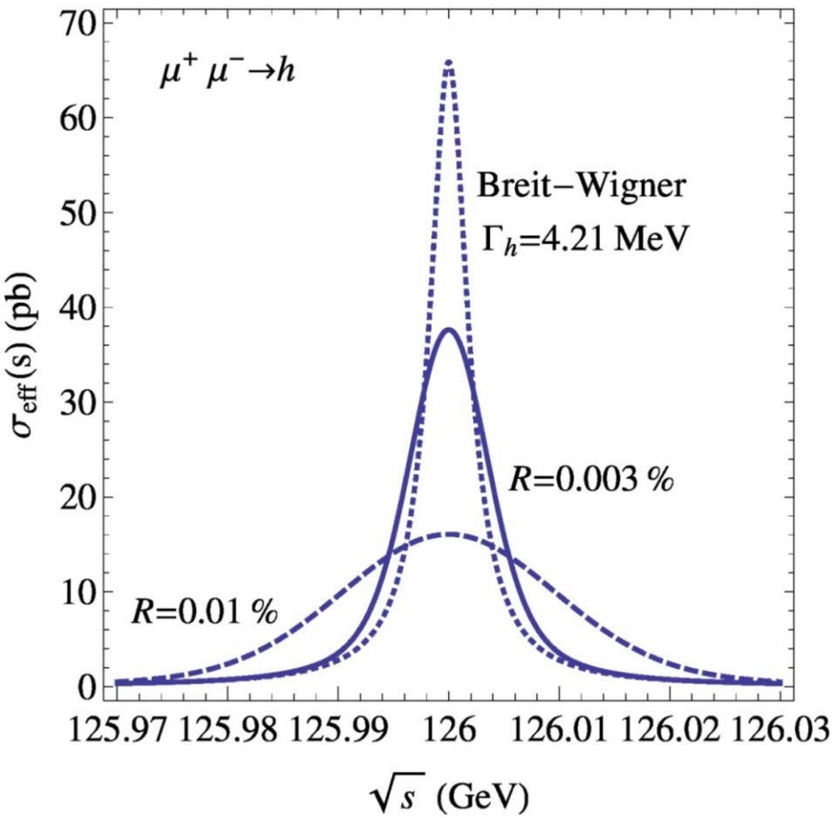
Given energy and luminosity, most other physics potential should be similar to those of e^+e^- colliders (need to be demonstrated).

$\mu^+\mu^-$ Collider – Lineshape Scan

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



Han & Liu: arXiv:1210.7803



Similar to Z scan at LEP !

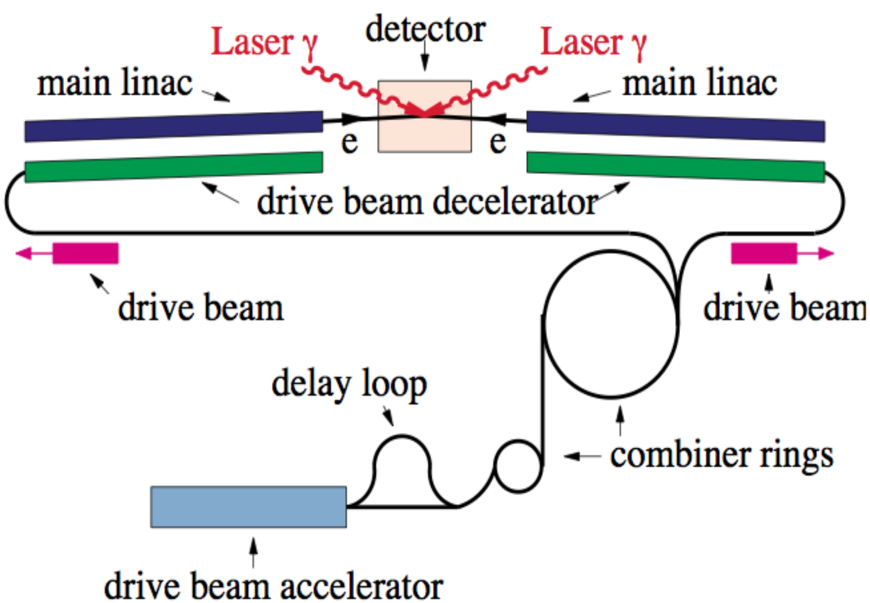
Studied two cases:

$R = 0.01\%(\Delta = 8.9\text{ MeV}),\ L = 0.5\ fb^{-1}$

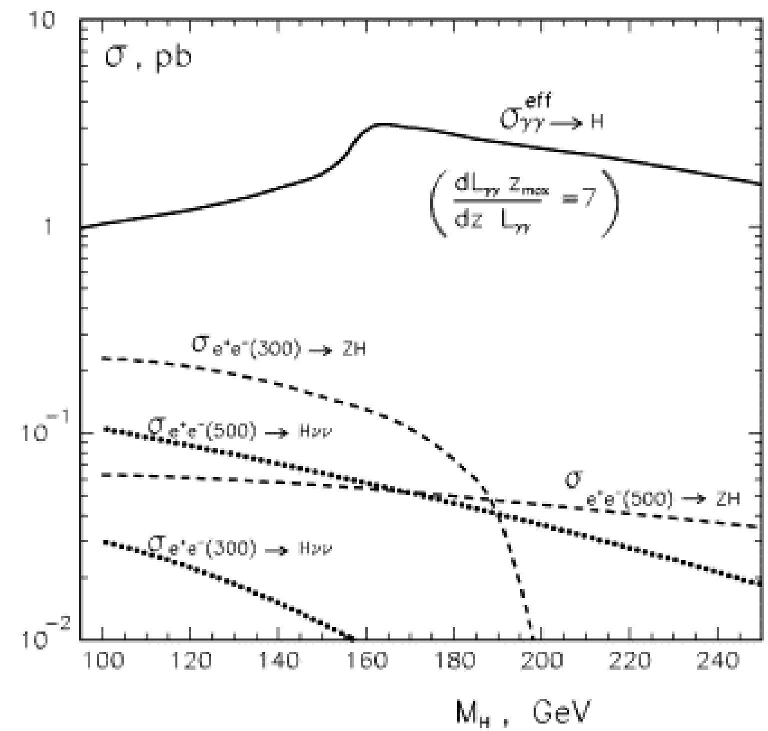
$R = 0.003\%(\Delta = 2.7\text{ MeV}),\ L = 1\ fb^{-1}$

Expect to measure both mass and total width with sub-MeV precision

γγ Collider



Boos et al., NIM A472, 100 (2001)



Large $\sigma(\gamma\gamma \to \mathrm{H})$~1 pb

Selective production of Spin and CP states through photon polarization

circular polarization $\Rightarrow$ J=0,2

linearly polarization $\Rightarrow$ CP states

$\gamma_{\parallel} \parallel \gamma_{\parallel} \Rightarrow$ CP even

$\gamma_{\parallel} \perp \gamma_{\parallel} \Rightarrow$ CP odd

Expect ~2% precision on $\Gamma_{\gamma\gamma}$

Ideal for studying Spin/CP properties of the Higgs boson

Coupling Comparison

ILC projections are from Tim Barklow. The rest is mostly taken from the presentation by Patrick Janot at the BNL workshop. The LHC numbers are *per experiment* (unless noted) of CMS projections of two scenarios of systematics assumptions.

Facility	LHC	HL-LHC	ILC	Full ILC	CLIC	LEP3 (4 IP)	TLEP (4 IP)
Energy (GeV)	14,000	14,000	250	250+500+1000	350+500+1500	240	240+350
$\int \mathcal{L}dt$ (fb^{-1})	300/expt	3000/expt	250	250+500+1000	500+500+1500	2000	10000+1400
N_H produced	1.7×10^7	1.7×10^8	80,000	370,000	618,000	600,000	3,200,000

Measurement precision

m_H (MeV)	100	50	35	35	70	26	7
$\Delta\Gamma_H$	–	–	11%	6%	6%	4%	1.3%
BR_{inv}	NA	NA	<0.8%	<0.8%	NA	<0.7%	<0.3%
$\Delta g_{H\gamma\gamma}$	5.1 – 6.5%	1.5 – 5.4%	18%	4.1%	NA	3.4%	1.4%
Δg_{Hgg}	5.7 – 11%	2.7 – 7.5%	6.4%	1.8%	NA	2.2%	0.7%
Δg_{HWW}	2.7 – 5.7%†	1.0 – 4.5%†	4.8%	1.4%	1%	1.5%	0.25%
Δg_{HZZ}	2.7 – 5.7%†	1.0 – 4.5%†	1.3%	1.3%	1%	0.25%	0.2%
$\Delta g_{H\mu\mu}$	< 30%	< 10%	–	16%	15%	14%	7%
$\Delta g_{H\tau\tau}$	5.1 – 8.5%	2.0 – 5.4%	5.7%	2.0%	3%	1.5%	0.4%
Δg_{Hcc}	–	–	6.8%	2.0%	4%	2.0%	0.25%
Δg_{Hbb}	6.9 – 15%	2.7 – 11%	5.3%	1.5%	2%	0.7%	0.22%
Δg_{Htt}	8.7 – 14%	3.9 – 8.0%	–	4.0%	3%	–	30%
Δg_{HHH}	–	30%‡	–	26%	16%	–	–

Note: with the luminosity upgrade, the ILC coupling precision improves by a factor of ~ 2.
$\dagger$ assuming the same deviation for the HWW and HZZ couplings. $\ddagger$ two experiments.

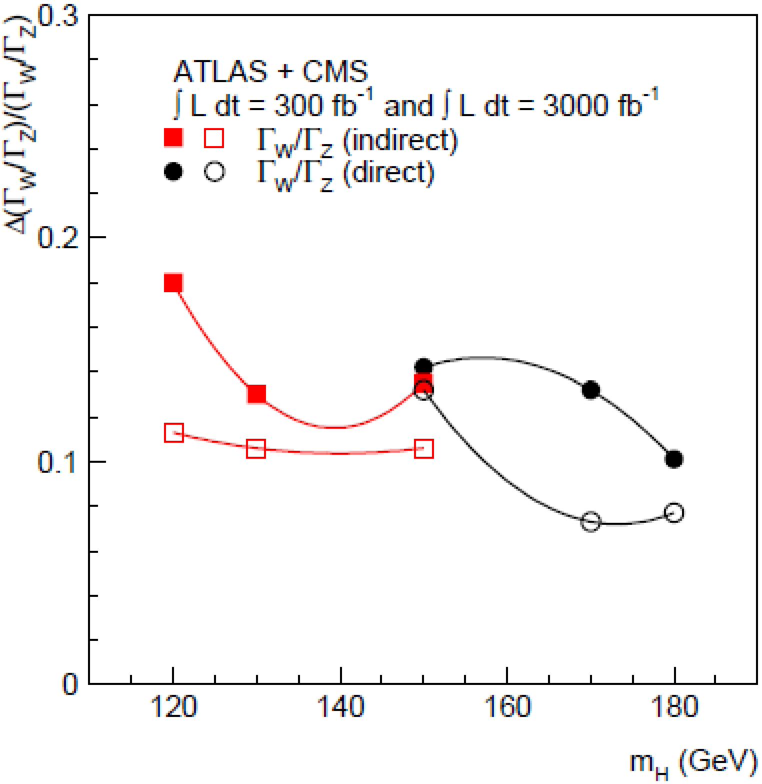
A word of optimism...

Projections/predictions are often subject to pleasant surprises as we learn and do better than expected.

A case in point:

$H \to WW^* \to \ell\nu\ell\nu$ was thought not possible 10 years ago at low mass...

Gianotti et al., hep-ph/0204087



"At smaller masses the process $H \to WW^* \to \ell\nu\ell\nu$ has too low a rate but one can use the measured rate of $H \to \gamma\gamma$ to extract Γ_W"

Not only the $H \to WW^* \to \ell\nu\ell\nu$ has been directly observed, the projected precision on Γ_W/Γ_Z is far better.

We have done far better than predicted...

Conclusion

- **The discovery of a ~125 GeV Higgs boson has opened a new era in the exploitation of electroweak symmetry breaking. There are many rich physics to be studied.**
- **LHC is the place to be to study the Higgs boson and search for additional Higgs bosons in the foreseeable future. It is a Higgs factory and can do precision measurements!**
- **Precision tests of Higgs boson properties to the level of one-percent will require complementary precision programs. Proposed Higgs factories will be able to achieve these precisions.**
- **Full exploitation of the Higgs measurements will require advances in theoretical calculations of production cross sections and decay branching ratios as well as precision in inputs to these calculations.**

See the next few pages for the draft summary points of the Snowmass Higgs report. Your inputs/comments are appreciated.

Disclaimer:

The following draft summary points for the Snowmass Higgs report are based on our current understanding. As white papers with details are still coming in, more information may be added and the numbers may change. These updates may impact the details of the conclusions. Furthermore, we will continue to deliberate the exact wording of the summary.

The Higgs working group is only concerned with physics capability of each facility. The feasibility of these facilities is not within the purview of our working group.

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Higgs Physics Summary

1. Many extensions to the Standard Model predict deviations of Higgs couplings from SM values. The sizes of deviations vary. However for new physics at TeV scale, percent level deviations are expected from many models.

2. Full exploitation of LHC and HL-LHC Higgs measurements will require improvements in theoretical calculations of the gluon fusion Higgs production cross section, both inclusive and with jet vetoes. To match sub-percent experimental uncertainties on Higgs partial widths from Higgs factories will require consistent inclusion of higher order electroweak corrections to Higgs decays, as well as an improvement of the bottom quark mass determination to below ±0.01 GeV.

3. LHC is the place to study Higgs boson in the foreseeable future. The expected precision of Higgs couplings to fermions and vector bosons are estimated to be 5-15% for 300 fb^{-1} and 2-10% for 3000 fb^{-1} at 14 TeV. Better precisions can be achieved for some coupling ratios.

4. Precision tests of Higgs boson couplings to one-percent will require complementary precision programs. Proposed Higgs factories such as linear or circular e^+e^- colliders and potentially a muon collider will be able to achieve these precisions for many of the couplings, and in a more model-independent way than the LHC.

Higgs Physics Summary

5. LHC can measure the Higgs boson mass with a precision of ~100 MeV, however has limited sensitivity to Higgs decay width. Higgs factories such as ILC, LEP3 or TLEP will improve the mass precision to about 35 MeV and measure Higgs decay width up to ~1.3% in precision. Through a line-shape scan, a muon collider can measure the width directly and the mass to sub-MeV precisions.

6. Direct ttH coupling measurements can be done at LHC, ILC, CLIC and muon colliders. The expected precisions are ~8% at HL-LHC, ~4% at ILC and ~3% at CLIC. A high energy muon collider is expected to have the comparable precision as CLIC.

7. Higgs self-coupling is difficult to measure at any of these facilities. A ~30% ultimate measurement is expected from HL-LHC and lepton colliders at 1 TeV. Improvement would need higher energy hadron or lepton colliders such as a CLIC or muon collider, HE-LHC, or VLHC.

8. The spin of the 125 GeV boson will be constrained by the LHC. A limited parameter space of spin-two couplings may be left to be constrained by the data from the future facilities. Potential CP admixture in spin-zero $H\rightarrow ZZ^*$ decay will be measured by LHC to a few percent precision. Lepton colliders operating at ZH maximum can measure this to a greater precision.

Higgs Physics Summary

9. **There are strong theoretical arguments for physics beyond the Standard Model. LHC has the highest discovery potential for heavy Higgs bosons as predicted by many Standard Model extensions. Mass reach can be 1 TeV or higher with 3000 fb^{-1} at 14 TeV, but is strongly model dependent. The mass reach is generally limited to less than half the collision energy for e^+e^- colliders and potentially up to the collision energy for a muon collider through s-channel processes.**

Facility Comparison

1. LHC or other higher-energy pp colliders will be able to study most aspects of the Higgs physics. The precision achievable at HL-LHC for many couplings is comparable to those of a circular or first-phase linear collider at 250 GeV with 250 fb^{-1}. The hadron colliders generally have the highest discovery potential for heavy Higgs bosons.

2. TeV-scale e^+e^- linear colliders (ILC and CLIC) will offer the full menu of measurements of the 125 Higgs boson, their mass reach for heavy Higgs bosons are generally weaker than high-energy pp colliders. The two linear colliders have different capabilities – the ILC can drop down to the Z peak while CLIC has a higher energy reach and better precision in Higgs self-coupling measurement.

3. TLEP has the best precisions for most of the Higgs coupling measurements. By itself it has no sensitivity to ttH and HHH couplings. However a higher energy pp collider that could potentially be operated in the same tunnel, would have the best sensitivity to the Higgs self-coupling as well as the highest discovery potential for heavy Higgs bosons.

4. A TeV-scale muon collider should have the same physics capability as the ILC and CLIC combined, but this needs to be demonstrated with more complete simulations. The potential polarization is important for testing CP in Higgs-fermion couplings.

Facility Comparison

5. LEP3 has comparable sensitivities with lepton colliders in most of the Higgs coupling measurements, but has no possibility for studying ttH and HHH couplings and no potential for discovering heavy Higgs bosons.

6. A $\gamma\gamma$ collider is ideal to study CP mixture and violation in the Higgs sector. It can significantly improve the precision of the effective $\gamma\gamma$H coupling measurement, therefore more sensitive to potential new physics in the loop.

Conclusion

The discovery of the 125 GeV Higgs boson creates a new dimension for further discoveries in elementary particle physics. An assessment of the Higgs physics reach conducted on a wide range of potential new colliders and collider options shows that deviations in the coupling of the Higgs field to matter can be tested at an order of magnitude higher sensitivity than with the current LHC program. To challenge the precision of the Higgs theory with experiment at these levels will determine the future evolution of the physical vacuum and therefore the fate of the universe and answer the question within our current theoretical understanding as to whether the universe came about under natural conditions.