

Higgs Working Report: Next Steps

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for

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Plans between now and Minnesota meeting

- Collect all the input from this meeting
- Collect all the White papers: need your references
- Write the report (target ~ 30 pages)
- Iterate
 - 1st draft \sim July 15 (goes to the working group)
 - 2nd draft \sim July 29 (goes public)
 - more during August
- Conclusion points being discussed (more later in these slides)
 - many thanks to comments already received
 - more comments welcome today and in the coming days
 - we are collecting comments carefully, without making quick changes

Draft report

0th draft \sim exists

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Couplings: Table from Sunday

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_{HHHH}	—	30% [‡]	—	26%	16%	—	—

Note: with the luminosity upgrade, the ILC coupling precision improves by a factor of ~ 2 .

[†] assuming the same deviation for the HWW and HZZ couplings. [‡] two experiments.

CP Mixture / Spin: Table from Parallel Session

Facility	LHC	HL-LHC	e^+e^-	e^+e^-	e^+e^-	$\mu^+\mu^-$	$\gamma\gamma$	target
Energy (GeV)	14,000	14,000	250	500	other	?	?	(theory)
$\int \mathcal{L} dt$ (fb $^{-1}$)	300/expt	3000/expt	250	500	other	?	?	
Measurement precision								
spin-2 $_m^+$	$\sim 10\sigma$	$\gg 10\sigma$	$>10\sigma$	$>10\sigma$?	?	$>5\sigma$
...	
ZZH	± 0.08 (?)	± 0.03 (?)	0.0008 (?)	0.00005 (?)		?	?	$< 10^{-5}$ (?)
WWH	?	?	?	?		?	–	$< 10^{-5}$ (?)
ggH	?	?	–	–		–	–	$< 10^{-2}$ (?)
$\gamma\gamma H$	–	(?)	–	–		–	?	$< 10^{-2}$ (?)
$Z\gamma H$	–	(?)	–	–		–	–	$< 10^{-2}$ (?)
$\tau\tau H$?	?	~ 0.01 (?)	~ 0.01 (?)		?	?	$< 10^{-2}$ (?)
ttH	?	?	–	?		–	–	$< 10^{-2}$ (?)
$\mu\mu H$	–	–	–	–		?	–	$< 10^{-2}$ (?)
bbH	–	–	–	–	–	–	–	$< 10^{-2}$ (?)

Note: precision quoted is on CP -odd cross-section fraction, such as f_{a3} defined for $H \rightarrow ZZ^*$

Plan for couplings

- We rely on input and projections from proposed facilities
 - all comparison tables rely on this
 - assumptions are sometimes different or questioned
- We would like to have several options:
 - precision on all measurables (e.g. $\sigma \times \mathcal{B}$ + correlations)
(both σ and \mathcal{B} contain couplings)
 - general coupling fit (e.g. N parameters)
 - fit assuming only SM decays for consistent comparisons
(i.e. constraints on invisible, undetectable decays)
 - test individual BSM models in a coherent way
- We may also try such a fit using input from facilities
 - to complement projections from facilities if needed

Missing or Incomplete Input

- Couplings:
 - comments from previous slides
 - white papers from ATLAS and CMS, some input
 - need input from $\gamma\gamma$ and $\mu^+\mu^-$ colliders
- BSM Higgs
 - projections on direct discovery of heavy Higgs
 - $H/A \rightarrow \mu\mu$
- CP -mixture
 - CP -mixture precision in ttH coupling and jet correlation on LHC
 - quantify CP -mixture precision on $\gamma\gamma$ and $\mu^+\mu^-$ colliders
- . . .

Conclusion Points

- Conclusion points being discussed

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Conclusion Points

- (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.

Conclusion Points

(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) *Additional item regarding accessibility of Higgs invisible (and "undetectable") decay modes – wording being worked on.*

Conclusion Points

(9) 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 -odd fraction in $H \rightarrow ZZ^*$ cross-section (f_{a3}) will be measured by LHC to a few percent precision. The e^+e^- machines can measure this to a greater precision in the $ee \rightarrow ZH$ mode. CP admixture in fermion couplings is not expected to suffer from loop suppression and can be studied in $H \rightarrow \tau\tau$ decay and ttH production, leading to interesting measurements on lepton colliders, and potentially hadron colliders. The photon and muon colliders are unique in their capability to probe CP violation directly with polarized beams.

(10) 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.

Conclusion Points: 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.

Conclusion Points: 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.