Hard Questions

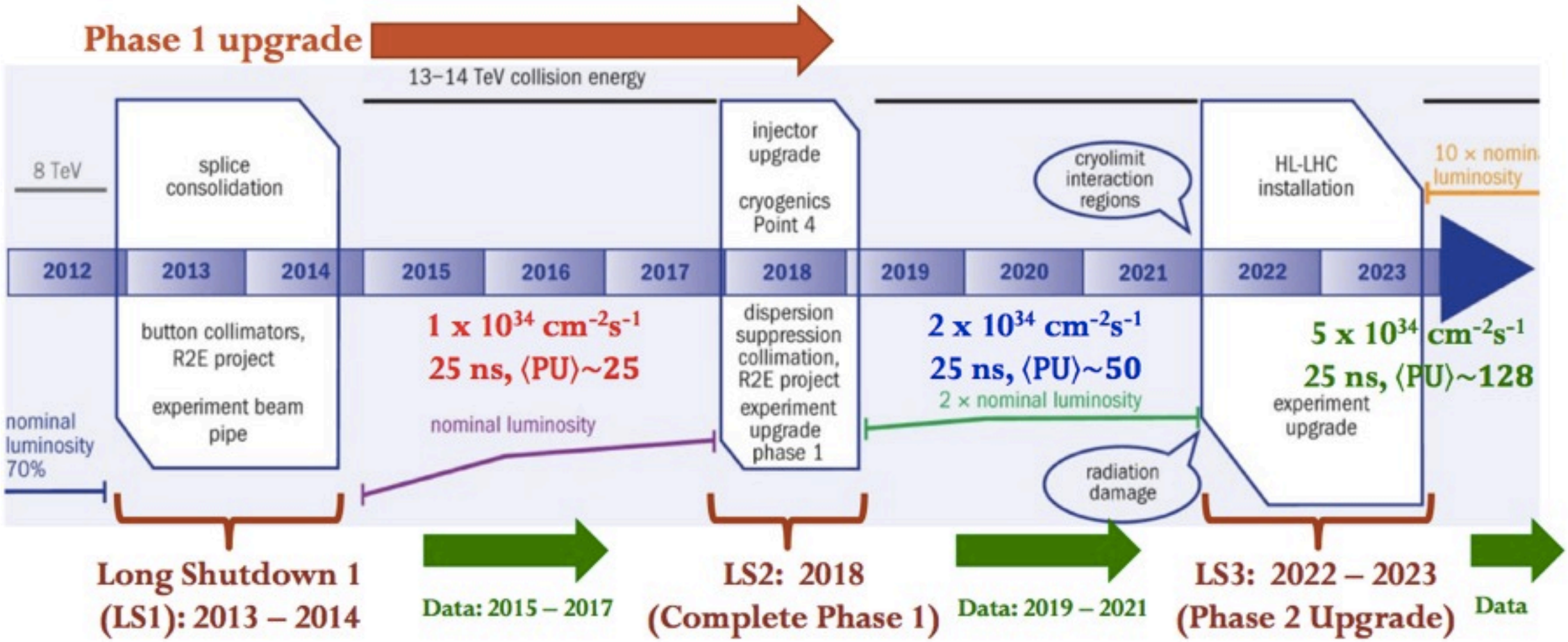
EF1: What is the physics case for a dedicated Higgs factory? How does this change if the properties of the Higgs boson discovered at the LHC remain consistent with SM expectations? What is the ultimate reach for the LHC at each of its anticipated stages in terms of precision Higgs~~,~~ ~~top, and other electroweak~~ measurements?

EF4: The message from the LHC seems to be that with data in hand, we consistently outperform expectations for extraction of Higgs properties. In that case, what would an ILC contribute? What key assumptions are we making now that we could relax with ILC inputs?

EF5: What are the key questions involving the Higgs boson that the ILC can answer whereas hadron colliders cannot? What do we learn about new physics scenarios from percent-level Higgs couplings measurements?

EF10: What is the physics motivation for the high-luminosity LHC run? ~~Do we need to be involved in both ATLAS and CMS experiments?~~ What should we do next if LHC13 does not find new physics?

LHC Upgrade Stages



LHC

Reach $10^{34}cm^{-2}s^{-1}$ by LS2, double by LS3 and integrate $300fb^{-1}$ by 2022
<PU> = 50

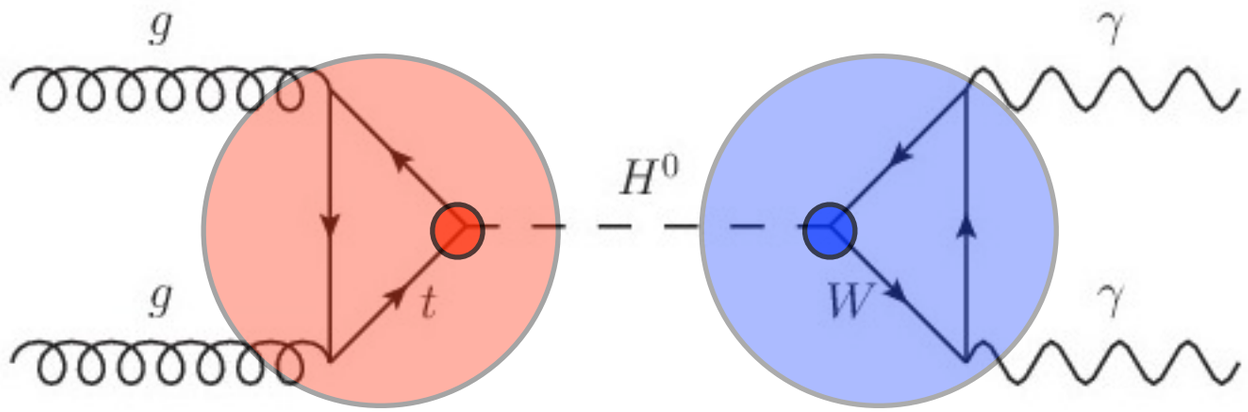
HL-LHC

Lumi-level 5x $10^{34}cm^{-2}s^{-1}$ and integrate $3000fb^{-1}$after L3
<PU> = 140

Higgs Boson Coupling

$$(\sigma \cdot \mathrm{BR})(ii \to \mathrm{H} \to ff) = \frac{\sigma_{ii} \cdot \Gamma_{ff}}{\Gamma_H}$$

Effective theory approach.
Fit deviation from the SM expectation.



$$(\sigma \cdot \mathrm{BR})(gg \to \mathrm{H} \to \gamma\gamma) = \kappa_g^2 \sigma_{\mathrm{SM}}(gg \to \mathrm{H}) \cdot \frac{\kappa_\gamma^2}{\kappa_\mathrm{H}^2} \mathrm{BR}_{\mathrm{SM}}(\mathrm{H} \to \gamma\gamma)$$

Higgs Boson Coupling

Δm of 100(50) MeV achievable for 300(3000) fb^{-1}

κ_g, κ_γ, $\kappa_{Z\gamma}$: loop diagrams ➜ allow potential new physics

κ_W, κ_Z: vector bosons

κ_t, κ_b: up- and down-type quarks

κ_τ, κ_μ: charged leptons

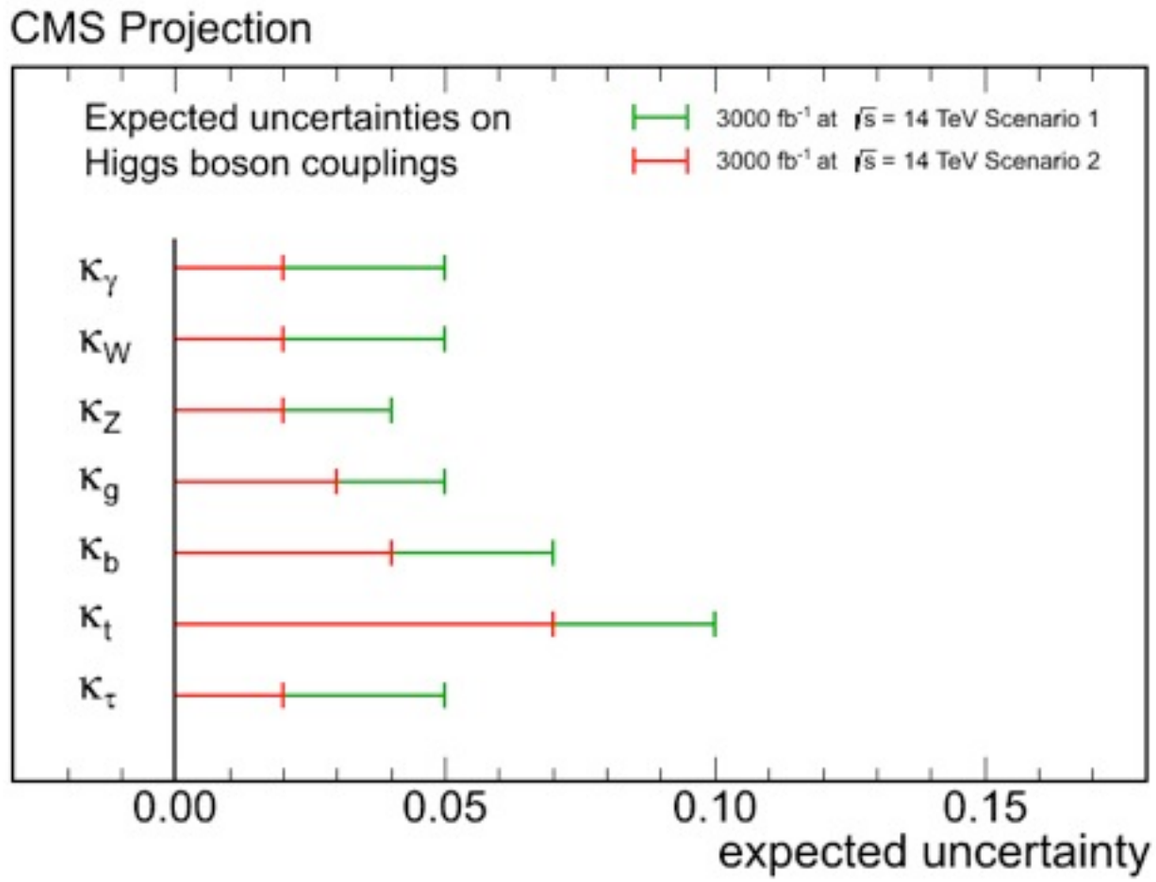
total width from sum of partial widths

alternatively:

$$\Gamma_{\text{tot}} = \sum \Gamma_{ii} + \Gamma_{\text{BSM}}$$

$$\text{BR}_{\text{BSM}} = \Gamma_{\text{BSM}} / \Gamma_{\text{tot}}$$

assumption here κ_W, $\kappa_Z < 1$



L (fb^{-1})	κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	BR_{inv}
300	[5, 7]	[4, 6]	[4, 6]	[6, 8]	[10, 13]	[14, 15]	[6, 8]	[41, 41]	[14, 18]
3000	[2, 5]	[2, 5]	[2, 4]	[3, 5]	[4, 7]	[7, 10]	[2, 5]	[10, 12]	[7, 11]

coupling precision 2-10 %
factor ~2 improvement from HL-LHC

* additional channels under study, e.g. ttH, H to VV
* $\Delta\kappa_\mu$ ~ 10%

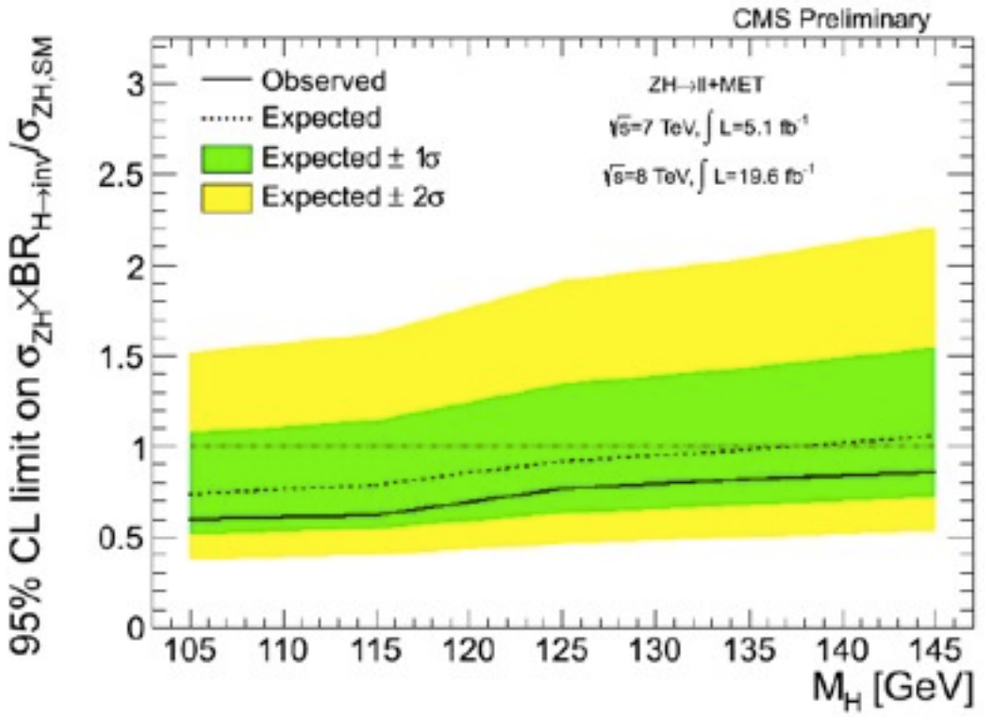
Invisible Higgs Decays

Accessible via VBF and ZH production.

Results available from ATLAS and CMS using ZH production. Assuming SM production cross section, observed (expected) 95% CL limits are

ATLAS: BR_{inv} < 65% (81%)

CMS: BR_{inv} < 75% (95%)



Estimate from CMS for future performance based in ZH analysis

L (fb^{-1})	H → inv.
300	[17, 28]
3000	[6, 17]

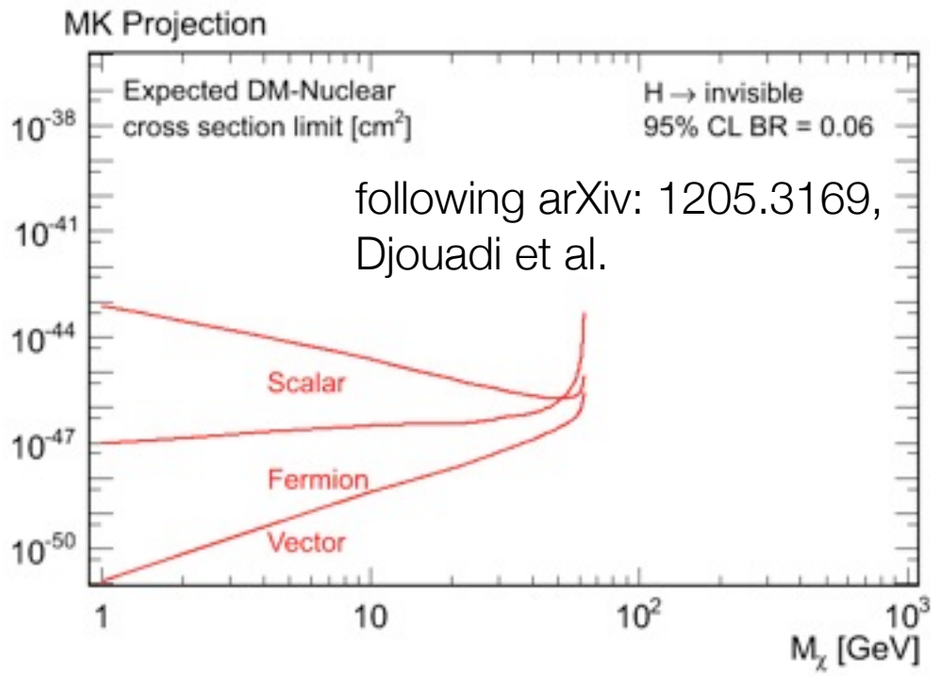
Extended Higgs coupling fit has sensitivity to BR_{BSM}

L (fb^{-1})	BR_{inv}
300	[14, 18]
3000	[7, 11]

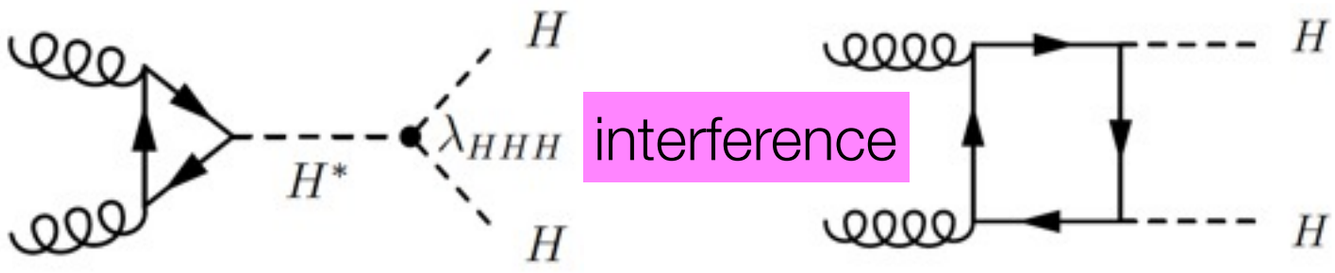
$$\Gamma_{tot} = \sum \Gamma_{ii} + \Gamma_{BSM}$$

$$BR_{BSM} = \Gamma_{BSM} / \Gamma_{tot}$$

Connection to Dark Matter searches



Higgs Self-Coupling



interference

Literature

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- S. Dawson, S. Dittmaier and M. Spira, Phys. Rev. **D58** (1998) 115012.
- A. Djouadi, W. Kilian, M. Mühlleitner and P.M. Zerwas, Eur. Phys. J. **C10** (1999) 45–49 .
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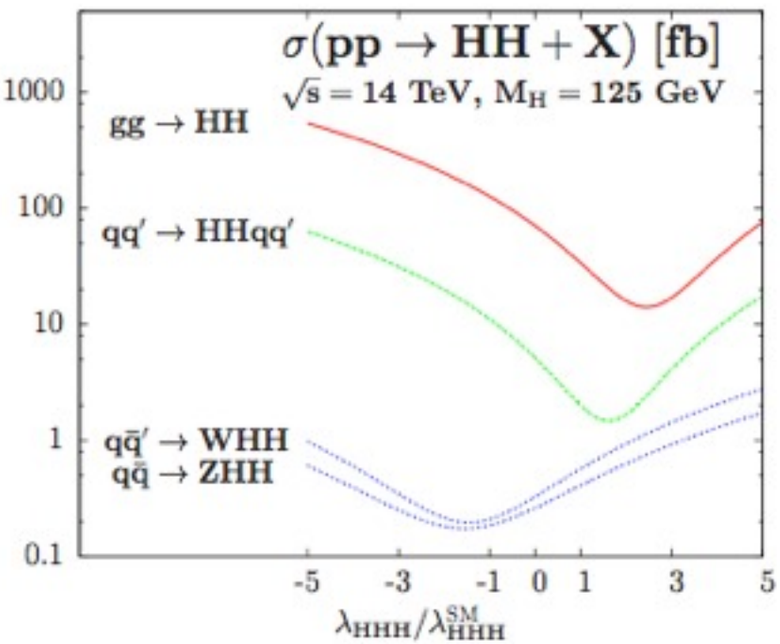
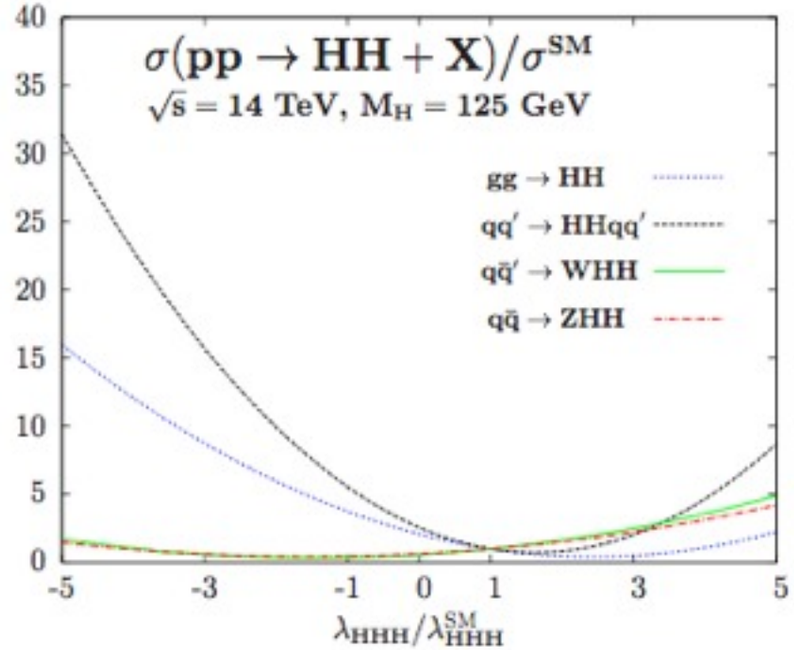
$\sqrt{s}$ [TeV]	$\sigma^{\mathrm{NLO}}_{gg\to HH}$ [fb]
8	8.16
14	33.89





Interesting channels:

HH ➜ bbγγ

HH ➜ bbττ

HH ➜ bbWW

Needs further investigation by ATLAS and CMS; expected precision is ~30%

Extra Material

Hard Question - EF1

What is the physics case for a dedicated Higgs factory?

- Investigation of the Higgs boson with ultimate precision.
- Complement program with EWK and top precision measurements as closure test to SM (indirect search for new physics).
- Study of particles discovered at LHC.
- Potential discovery of new particles.

How does this change if the properties of the Higgs boson discovered at the LHC remain consistent with SM expectations?

Higgs factory physics case does not change of Higgs boson is consistent with the SM expectation within the LHC precision. However, the expected HF precision has to significantly supersedes the LHC performance.

What is the ultimate reach for the **LHC** at each of its **anticipated stages** in terms of **precision Higgs**~~, top, and other electroweak~~ **measurements?**

See previous slides or EF plenary talk on ATLAS and CMS WP for more details.

Hard Question - EF10

What is the physics motivation for the high-luminosity LHC run?
Precision measurements of the Higgs boson including rare decays and Higgs self-couplings. Searches for new physics (increase mass range through luminosity), study of vector boson scattering, etc. (see Beate Heinemann's talk in EF Plenary tomorrow)

Do we need to be involved in both ATLAS and CMS experiments?
Yes! Jianming will give more detail.

What should we do next if LHC13 does not find new physics?
Continue with HL-LHC program and carefully consider our options. Jianming will give more detail.

Precision Higgs Measurement

Imagine we do not find new (Higgs) particles in LHC data.

How large are deviations to couplings from BSM?

Deviations studied in numerous articles, e.g Gupta & Wells, arXiv:1206.3560.

They studied three types of models,

SUSY,

mixed-in hidden sector,

and composite Higgs bosons.

	ΔhVV	$\Delta h\bar{t}t$	$\Delta h\bar{b}b$
Mixed-in Singlet	6%	6%	6%
Composite Higgs	8%	tens of %	tens of %
Minimal Supersymmetry	$< 1\%$	3%	$10\%^a$, $100\%^b$

Conclusion, they find 1-10% deviations for vector bosons and few percent to tens of percent for fermion couplings.

Most popular, MSSM Higgs sector in decoupling limit (large mA)

Theoretical Uncertainties

To test the importance of theoretical uncertainties we show the effect of removing them.

Theoretical uncertainties dominated by QCD scale and PDF uncertainties. Uncertainty on BR become relevant at few % precision.