Opportunities & Challenges at the HL-LHC

Matthew Klimek
Cornell University
Korea University

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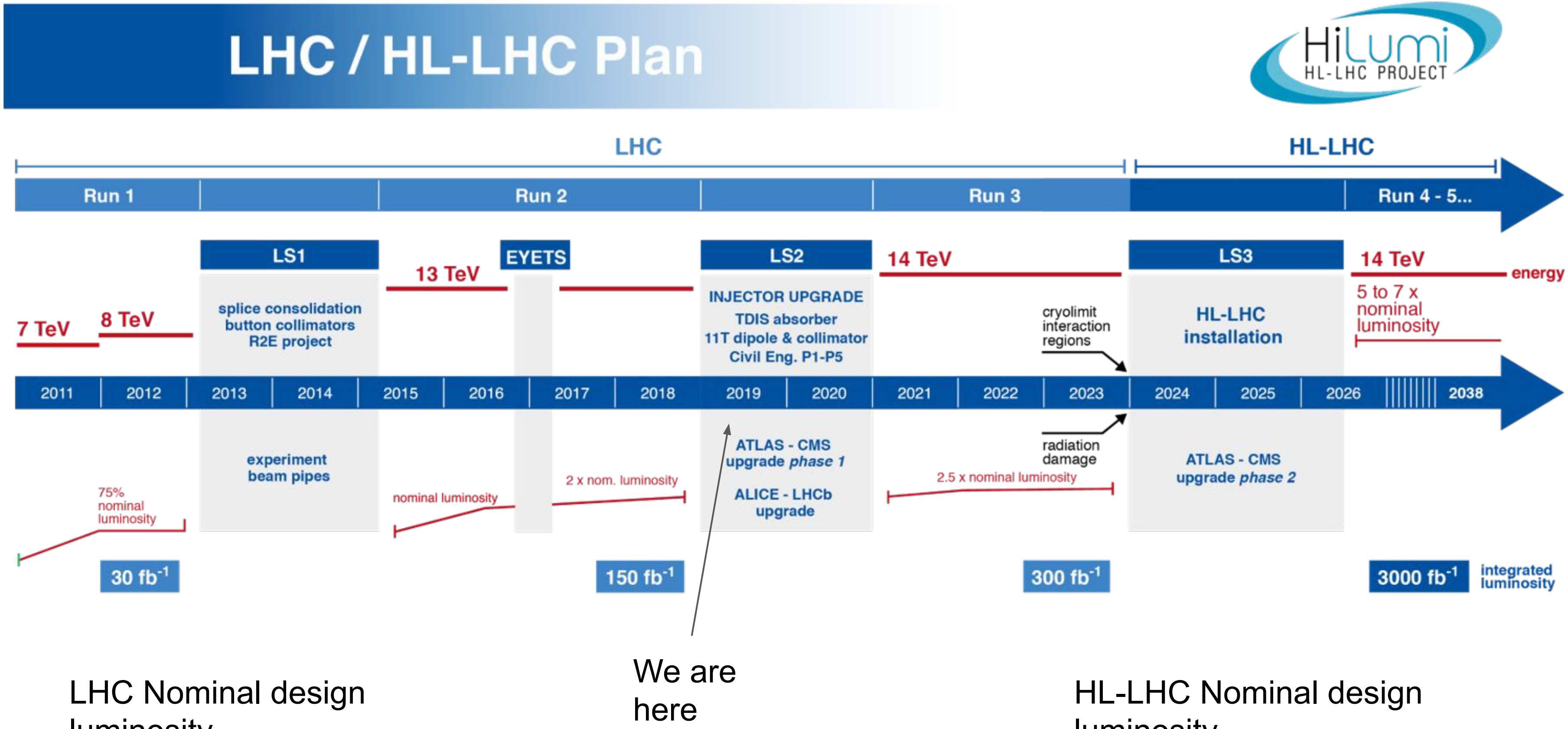
Outline

- **Major changes for High Luminosity phase**
  - Collider parameters
  - Detector upgrades
- **Impact Higgs & EW physics**
  - SM Higgs parameters
  - Searches for BSM Higgs
- **Impact of theory uncertainties**

LHC / HL-LHC Plan



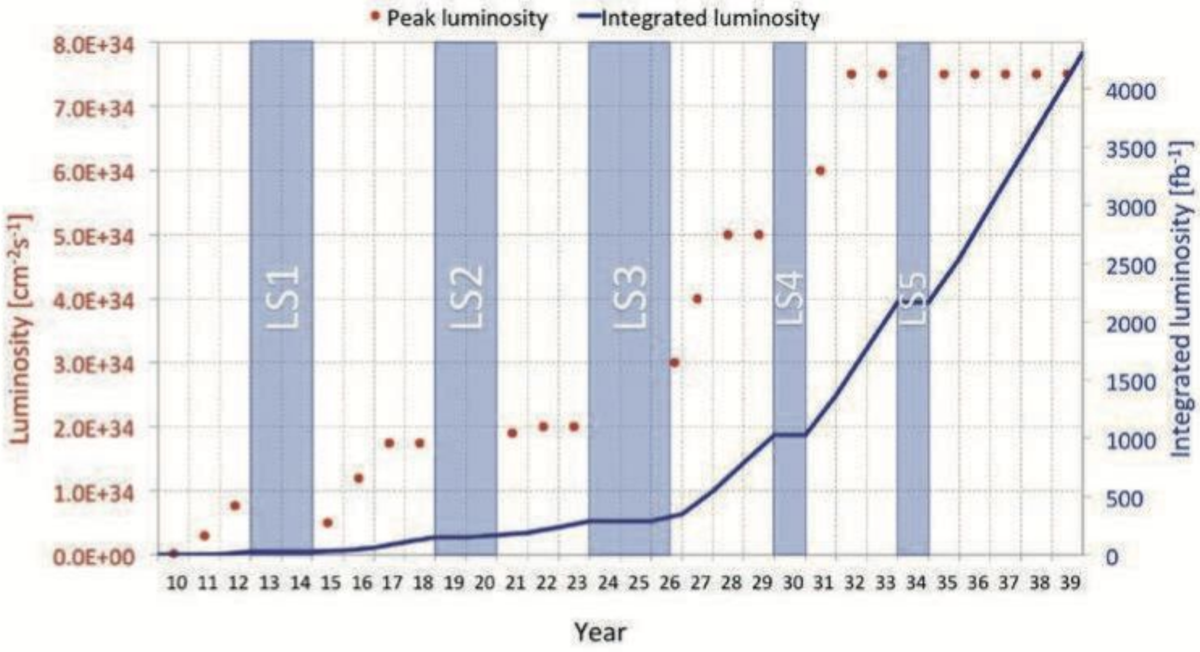
LHC Nominal design luminosity

$1 \times 10^{34} / cm^2 / s$

HL-LHC Nominal design luminosity

$5 \times 10^{34} / cm^2 / s$

Changes in HL-LHC



HL-LHC target peak luminosity *5x* original LHC design luminosity.

Current total LHC data set projected to be 300 /fb.

HL-LHC:

10 year operation → 3000 /fb.

<u>10x greater dataset than LHC.</u>

Detector Changes in HL-LHC

With the increase in luminosity, the many detector components must be replaced to withstand the high levels of radiation damage.

The main data taking challenge comes from increased pile-up, i.e. number of collisions that occur in each bunch crossing.

LHC bunch spacing of 25 ns remains the same in HL phase.

Luminosity increase comes from putting more protons in each bunch.

<u>Each crossing contains a factor of a few more events.</u>

Detector Changes in HL-LHC

- **Increase resolution of tracker to detangle all the collisions and coverage.**
  - Average vertex spacing < 1mm
- **Add timing information.**
  - Resolve the bunch crossing in time: turn one crossing into several to reduce pileup
- **Improve readout electronics.**
- **Incorporate tracking in L1 trigger.**
  - More efficient triggering for large data sets

What does this mean for theory?

10x more data → good!

What's in this data?

Energy is the same, so there's nothing we couldn't have produced before.

More data = higher precision + rare events

- ❑ Higher precision:

  SM parameters, are there deviations from predictions?

- ❑ Rare events:

  Heavy particles with low cross section at these energies (BSM)

  Weakly coupled particles (BSM, or SM e.g. Higgs couplings to light generations)

What does this mean for theory?

Theory challenges:

Do we really understand what the SM predicts, both as signal and background?

Do we understand what our models predict?

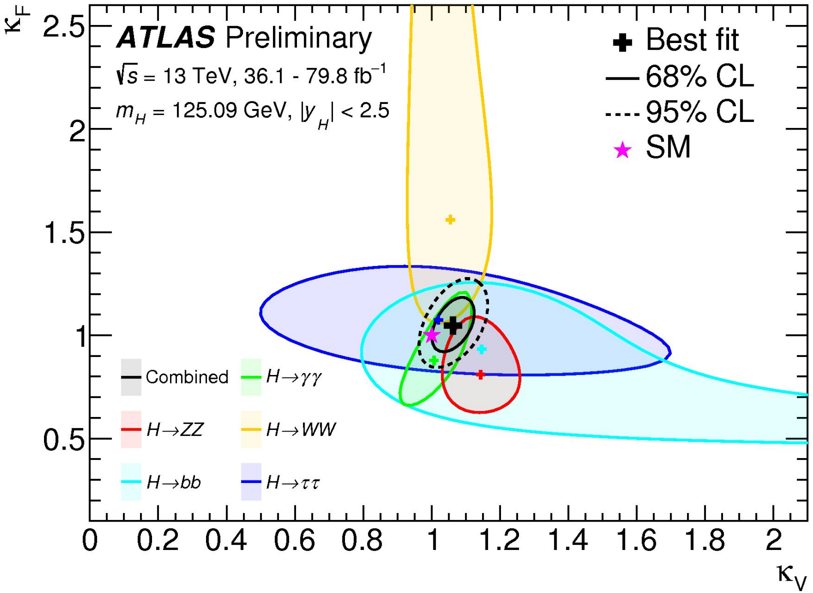
Can we interpret our data also in a model-independent way?

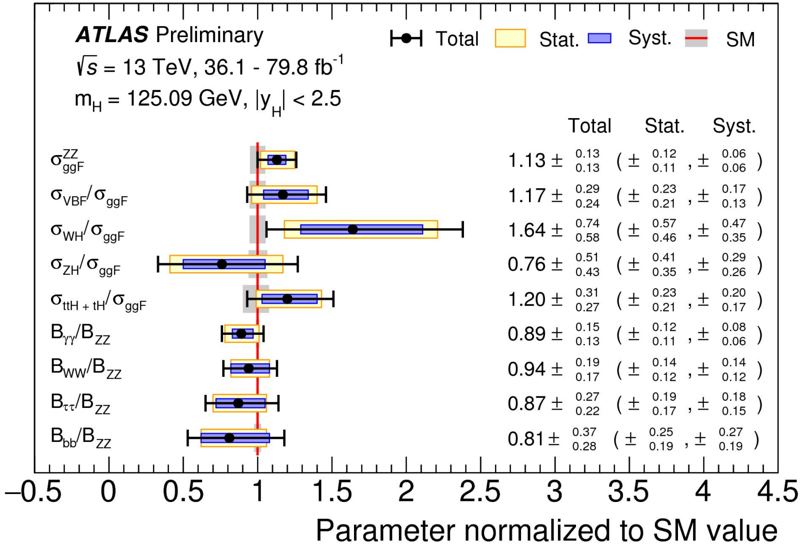
Hadron collider: Do we understand QCD?

Higgs physics @ LHC

The LHC has so far given us one definite positive discovery: “the” Higgs boson

All measured properties so far agree with SM predictions!





Higgs physics @ HL-LHC?

- **The observed Higgs boson:**
  - Is a scalar boson
  - Plays a role in EWSB of the general form described by the SM

*But not most of the mass in the universe ;)

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  - One scalar
  - One term in the potential
  - Same coupling mechanism to all SM fermions
  - All SM masses arise from this Higgs*
  - The End.

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Is that really it?
What can we learn at the HL-LHC?
What should we be looking for?

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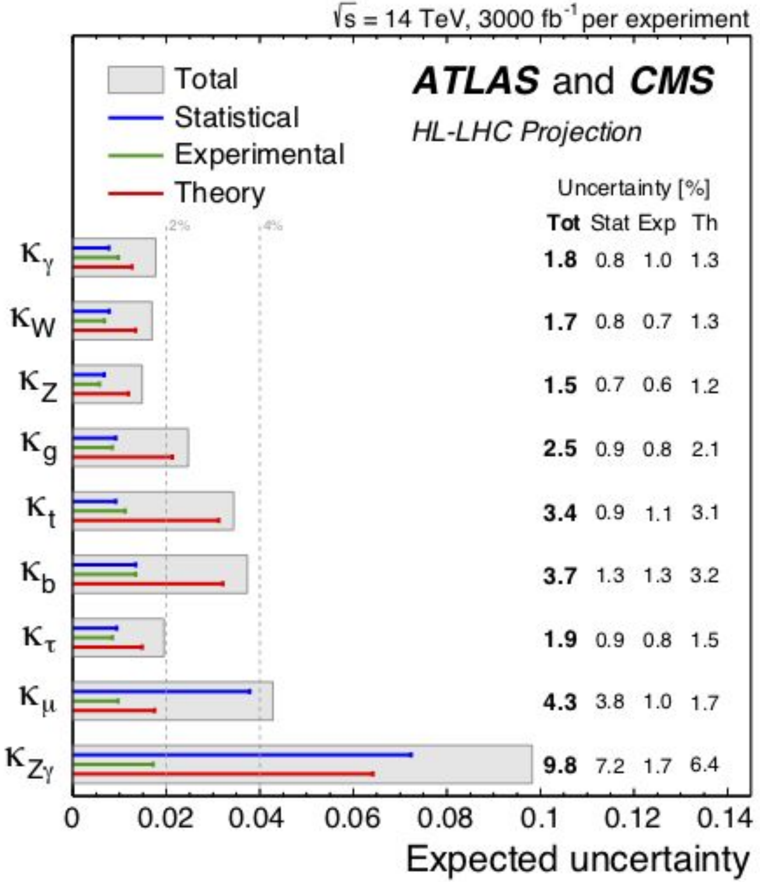
Higgs/SM fermion couplings

The HL-LHC will detect Higgs in all production channels (ggF, VBF, VH/WH, ttH) and decay modes ($\gamma\gamma$, WW, ZZ, $\tau\tau$, bb, μμ, Zγ) including two that have not been observed yet.

These test new aspects of the theory. (2nd generation, EWSB)

Will be measured at % level.

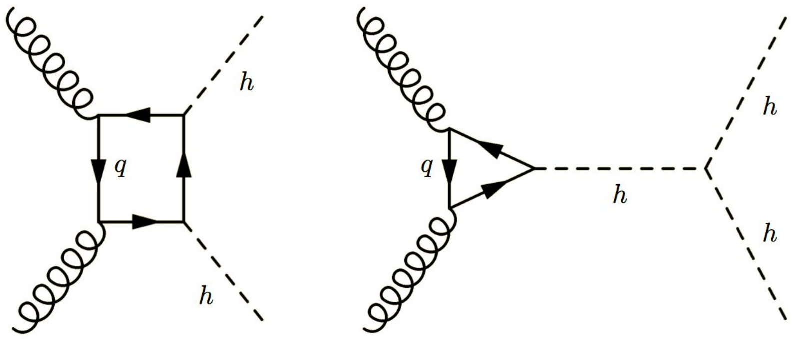
The data set will be so large that the largest uncertainties come from theory!



Higgs potential = self coupling

The SM describes that Higgs potential with a single parameter λ.

This one parameter connects the Higgs mass, SM fermion masses, and the Higgs self-coupling.



Higgs potential = self coupling

$$L_H \sim \lambda h^4 \rightarrow m_h^2 \sim \mu^2/\lambda, m_f \sim y_f \mu^2/\lambda, \kappa_3 \sim \mu\sqrt{\lambda}$$

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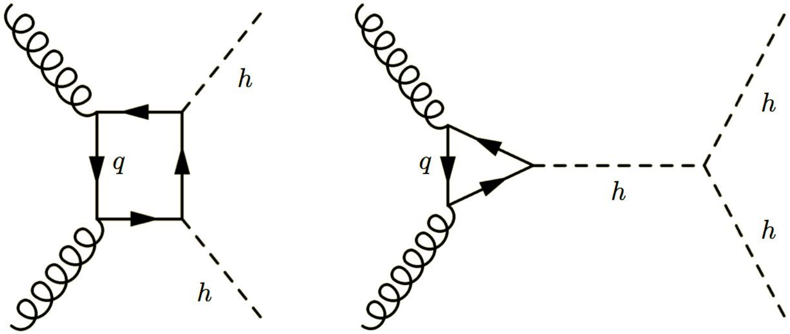
The di-Higgs production process (dominantly through ggF) involves all of these things in a highly non-trivial way.

Also could be shifted by new physics in the top loop



Higgs potential = self coupling

Theory uncertainties:

PDFs?

Top mass?

SM calculation: NNLO in heavy top limit, NLO with top mass

	Statistical-only		Statistical + Systematic	
	ATLAS	CMS	ATLAS	CMS
$HH \to b\bar{b}b\bar{b}$	1.4	1.2	0.61	0.95
$HH \to b\bar{b}\tau\tau$	2.5	1.6	2.1	1.4
$HH \to b\bar{b}\gamma\gamma$	2.1	1.8	2.0	1.8
$HH \to b\bar{b}VV(ll\nu\nu)$	-	0.59	-	0.56
$HH \to b\bar{b}ZZ(4l)$	-	0.37	-	0.37
combined	3.5	2.8	3.0	2.6
	Combined		Combined	
	4.5		4.0	

Higgs width: coupling to other sectors?

The Higgs (seems to) couple to most SM particles.
If there are other sectors, might it couple to them too?
What if those sectors are invisible?

They still affect the width! (Optical theorem)

But, the width is very narrow: 4 MeV in the SM

Compare to detector resolution of order 1 GeV!

Higgs width: coupling to other sectors?

Off shell technique:

On shell cross sections depend on a combination of couplings and width, in the narrow width approximation.

Far off-shell, the width is negligible, only couplings matter.

Measure both on- and off-shell cross sections to separate couplings from width.

$$\sigma \sim \frac{g_{\text{prod}}^2 \times g_{\text{dec}}^2}{(s - {m_H}^2)^2 + {m_H}^2 {\Gamma_H}^2}$$

On-shell, narrow width

$$\sigma \sim \frac{g_{\text{prod}}^2 \times g_{\text{dec}}^2}{\Gamma_H}$$

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But those couplings are being measured at different energy scales!

- Do we understand how to run them?
- Do we understand QCD at the different scales?
- What if there is new physics that affects the running?

ATLAS 14.4 M CMS 9.2 MeV

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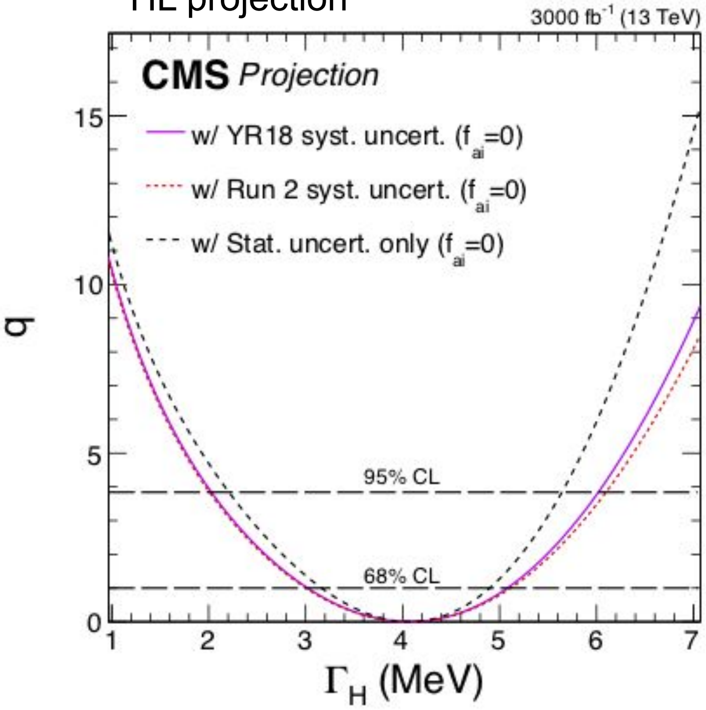
Run-II results:

ATLAS: Width < 14.4 MeV
CMS: Width < 9.2 MeV

HL projection

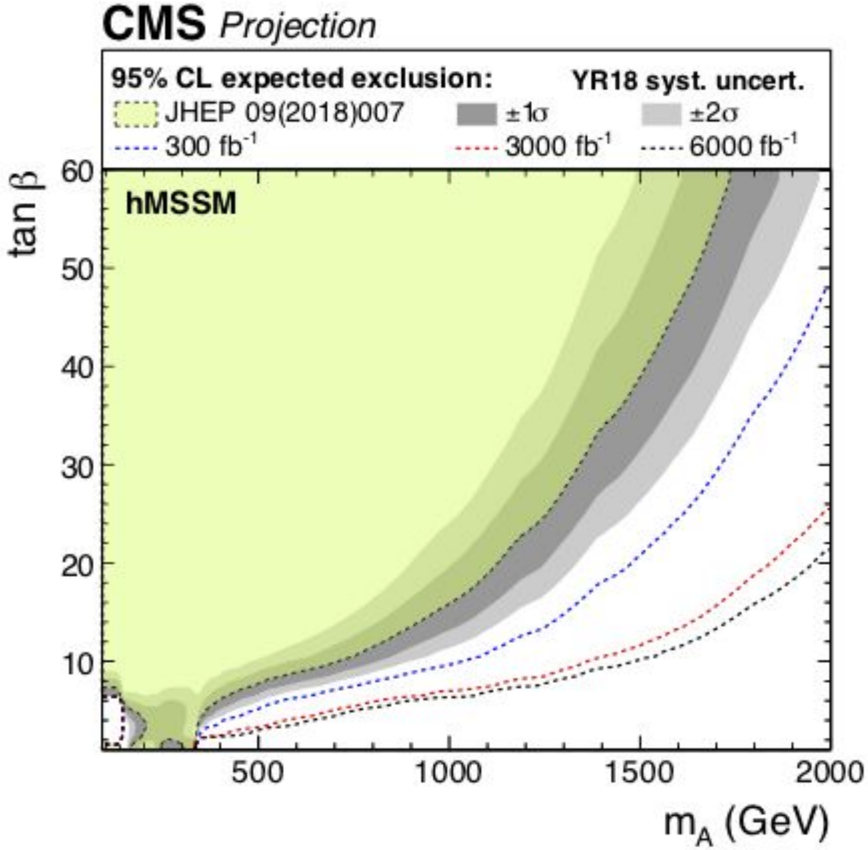


Extended EWSB (“Other Higgses”)

Canonical example:
MSSM contains two Higgs doublets. 5 components →

- Light higgs
- Heavy neutral Higgs
- Charged Higgs
- Pseudoscalar Higgs

In many scenarios, the heavy Higgs couples preferentially to leptons and decays to tau are a favorable search channel.



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Caveat: Tau is not always a good channel!

In 2 Higgs Doublet Models, the two doublets “share” the couplings to the SM.

If the light Higgs is very SM-like, the heavy higgs has very suppressed couplings to SM fermions. Tau decay mode not sensitive.

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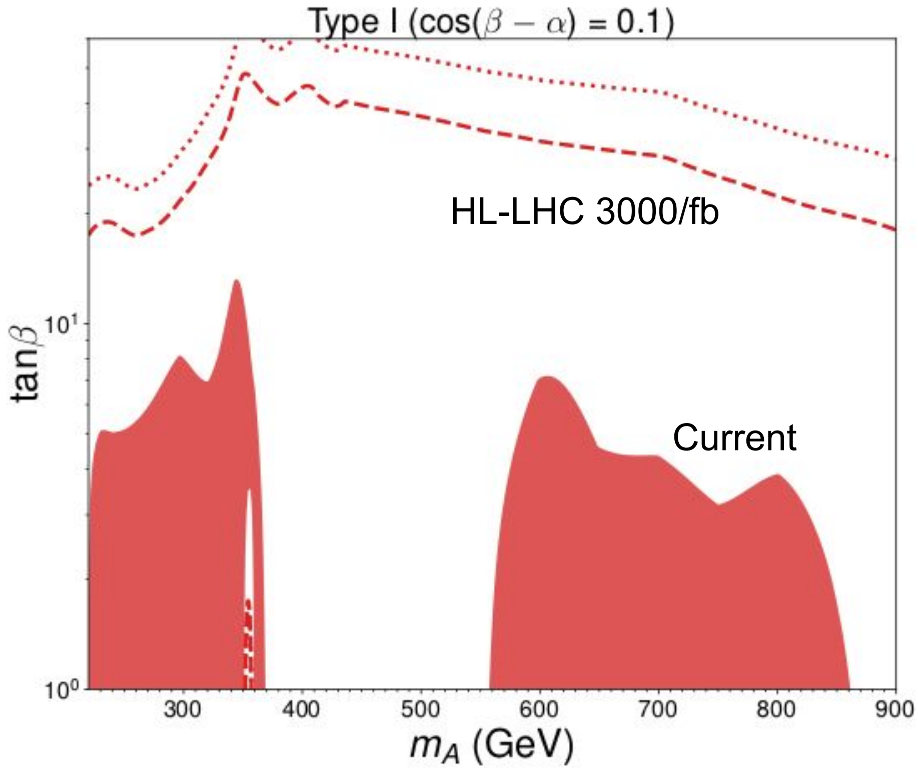
In this case, the Heavy higgs can decay to the light SM-like Higgs.

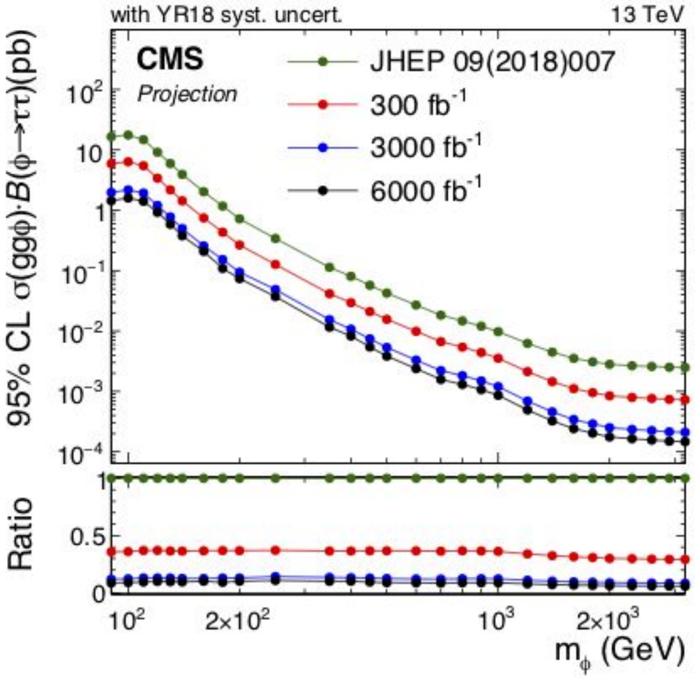
pp → A → Zh → (*ll*)(*bb*)

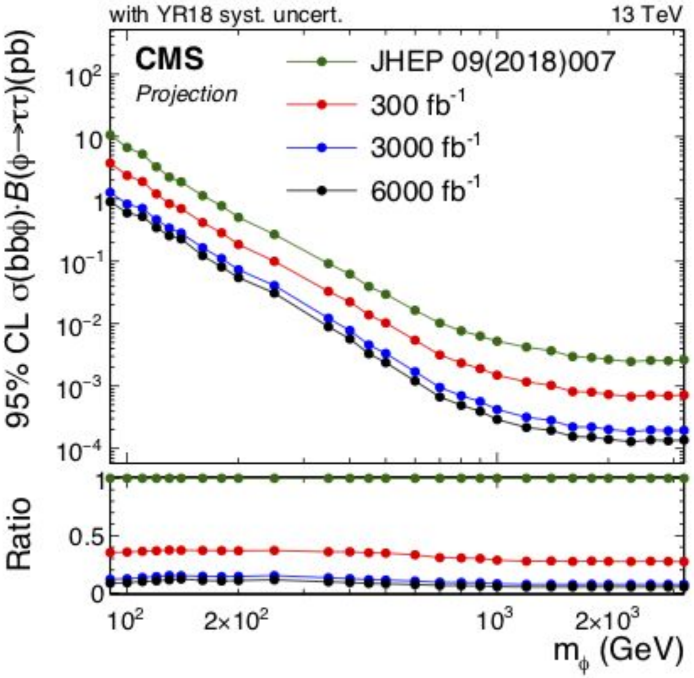


Extended EWSB ("Other Higgses")

The SM Higgs has a gauge neutral component (the higgs we observe), so it can mix with any other gauge neutral new particle.

Important to have model independent bounds.





SM theory considerations

Many measurements are theory uncertainty limited. What is responsible for this?

> PDF uncertainty. Will be measured at HL-LHC!

Ratio of uncertainties at HL-LHC vs LHC

PDF uncertainties HLLHC / Current	10 GeV < M_X < 40 GeV	40 GeV < M_X < 1 TeV	1 TeV < M_X < 6 TeV
g-g luminosity	0.58 (0.49)	0.41 (0.29)	0.38 (0.24)
q-g luminosity	0.71 (0.65)	0.49 (0.42)	0.39 (0.29)
quark-quark luminosity	0.78 (0.73)	0.46 (0.37)	0.60 (0.45)
quark-antiquark luminosity	0.73 (0.70)	0.40 (0.30)	0.61 (0.50)
up-strange luminosity	0.73 (0.67)	0.38 (0.27)	0.42 (0.38)

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Model-dependent results:

Are we missing something because of the models we consider, e.g., SUSY/Heavy higgs searches?

Conclusions

- The HL-LHC will provide an order of magnitude increase in 14 TeV pp data in 10 years of operation.
- A major goal will be the indirect search for new physics through increased precision.
- This presents many exciting opportunities for us to look forward to.
- Exploiting the full capabilities of this exciting experiment will require careful work by theorists

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