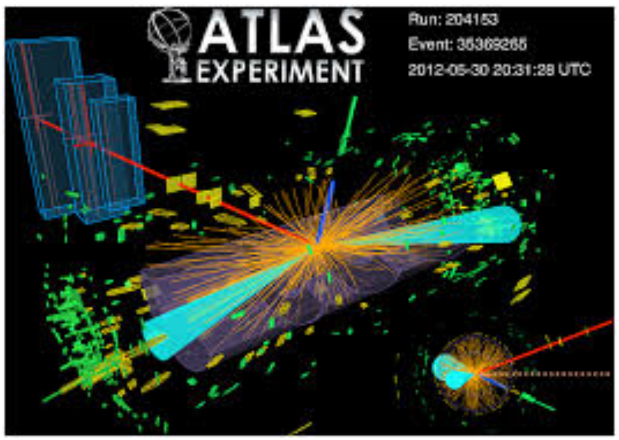
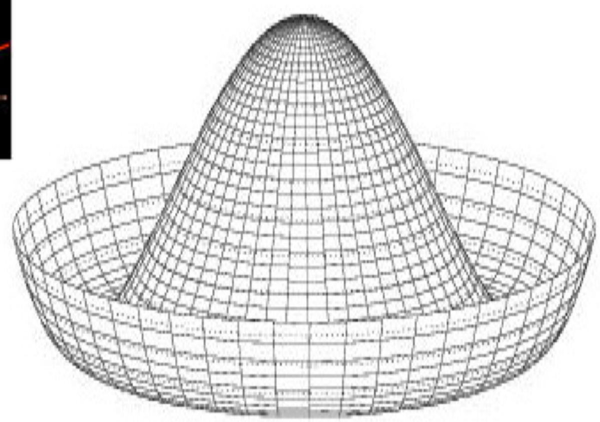
Science Status of the Higgs

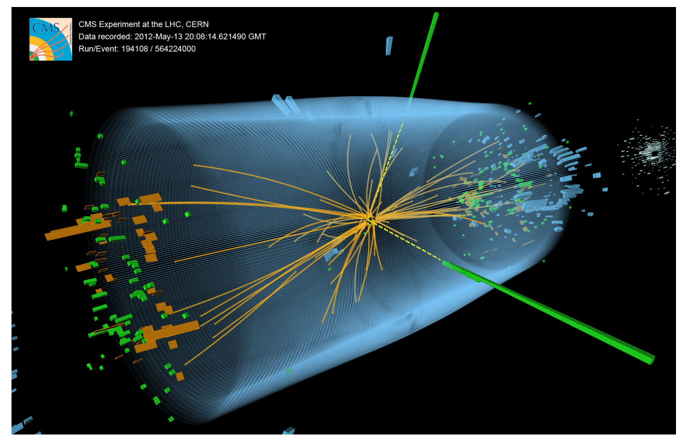
S. Dawson, BNL

November 22, 2019

Report to HEPAP







P5 Driver

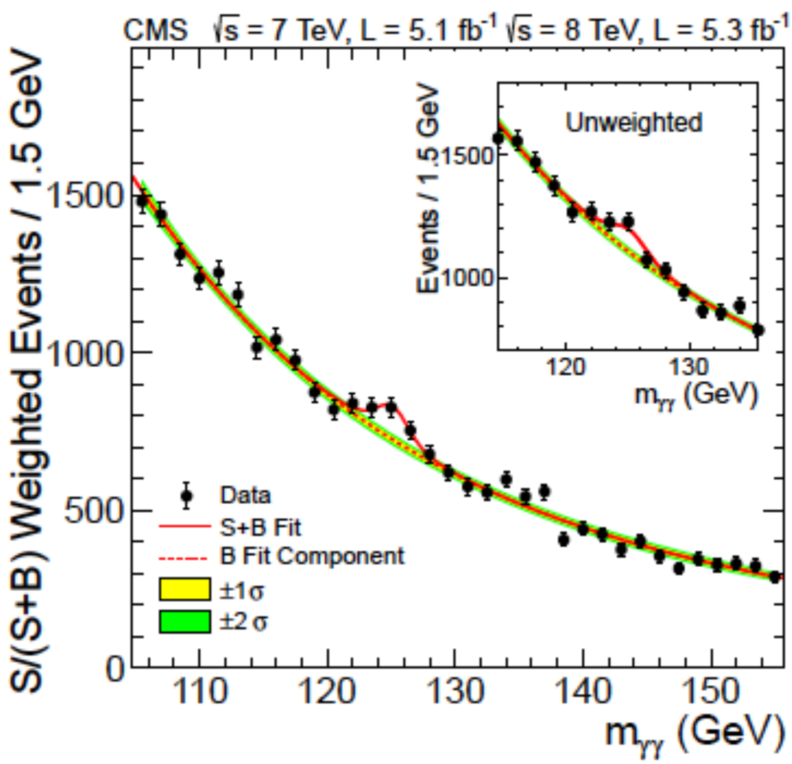
- Use the Higgs Boson as a new tool for discovery
  - "What principles determine its effects on other particles?"
  - "How does it interact with neutrinos or with dark matter?"
  - "Is there one Higgs particle or many?"
  - "Is the new particle really fundamental, or is it composed of others?"

Still driving questions for our field

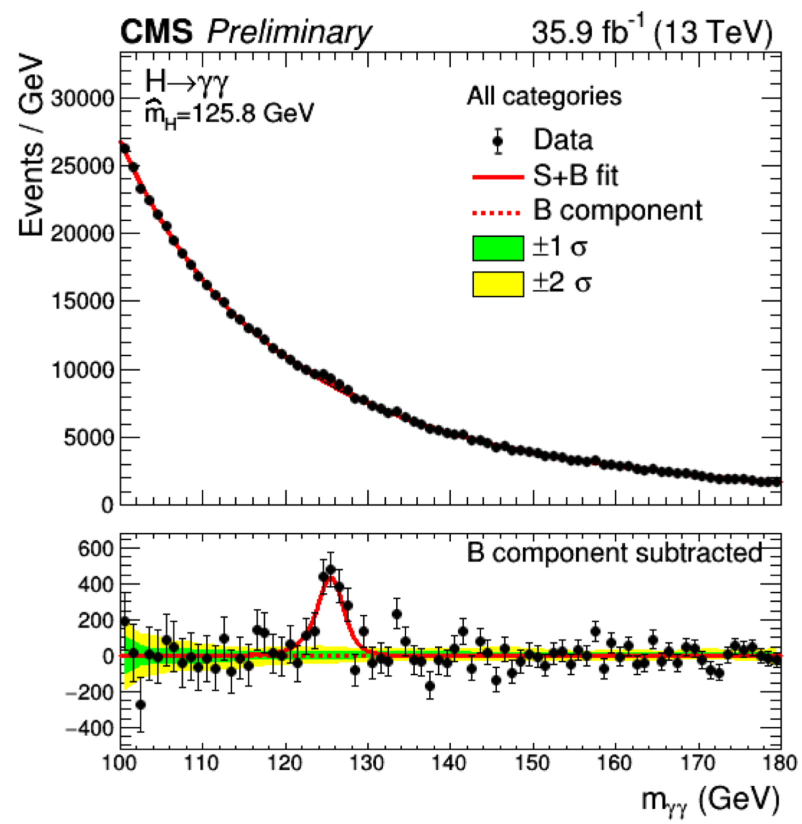
Discovery to precision

H→γγ

2012

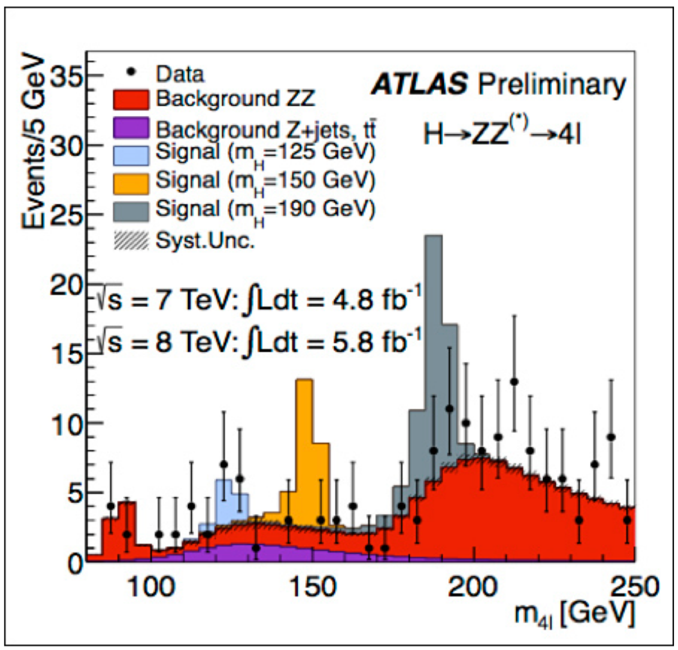


2019

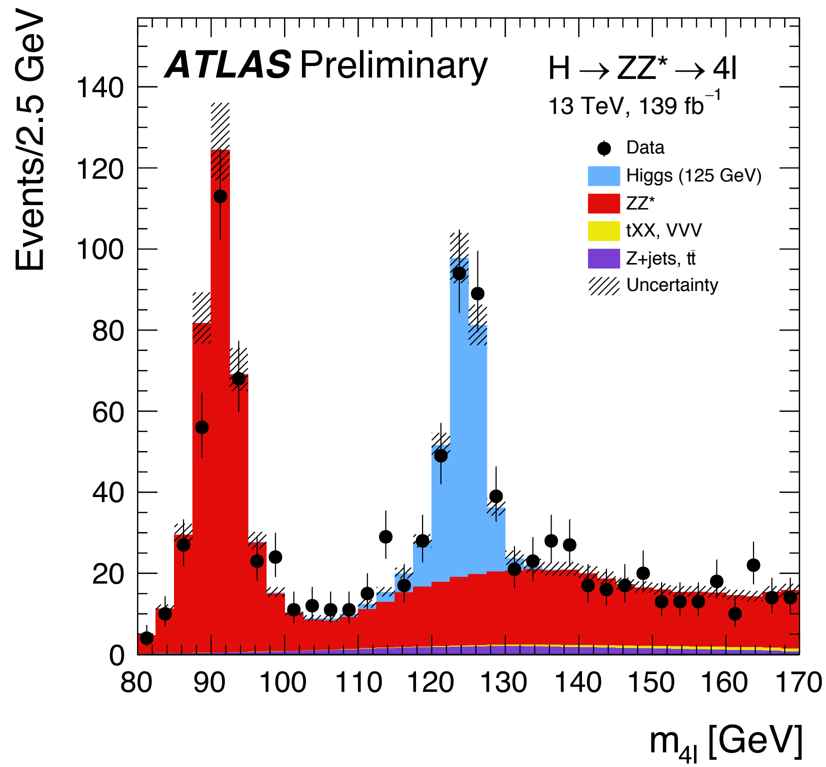


Discovery to precision

2012



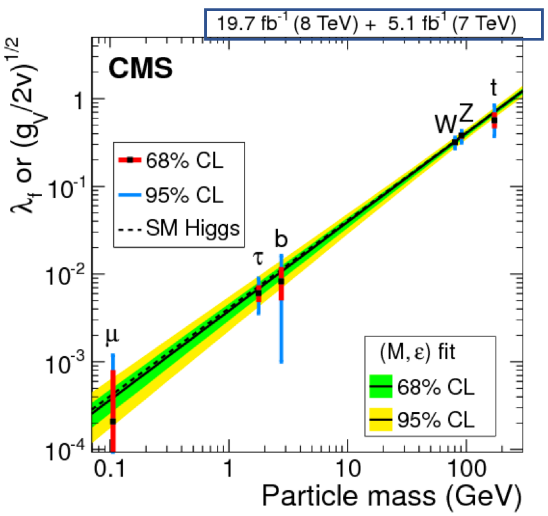
2019

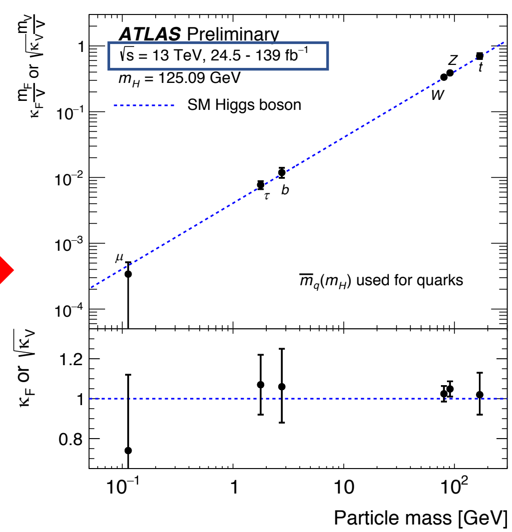


H→ZZ→4l

Discovery to precision measurements

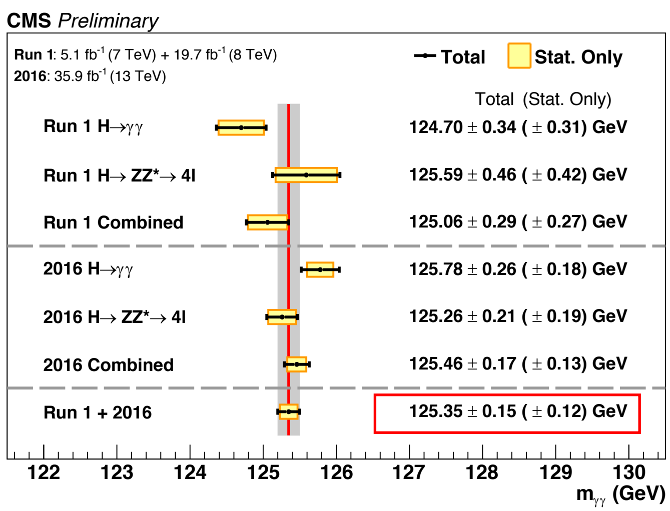
- SM has very precise predictions
  - Couplings to fermions proportional to mass
  - Couplings to gauge bosons proportional to gM_V
  - Higgs self-couplings proportional to M_H^2

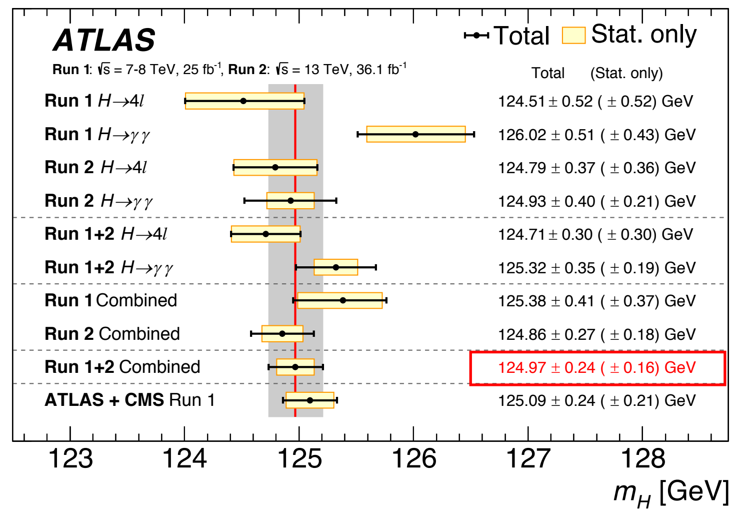




If couplings didn't have this pattern, it would indicate that not all mass comes from a single Higgs boson

Discovery to precision measurements





.1% measurement of Higgs mass!

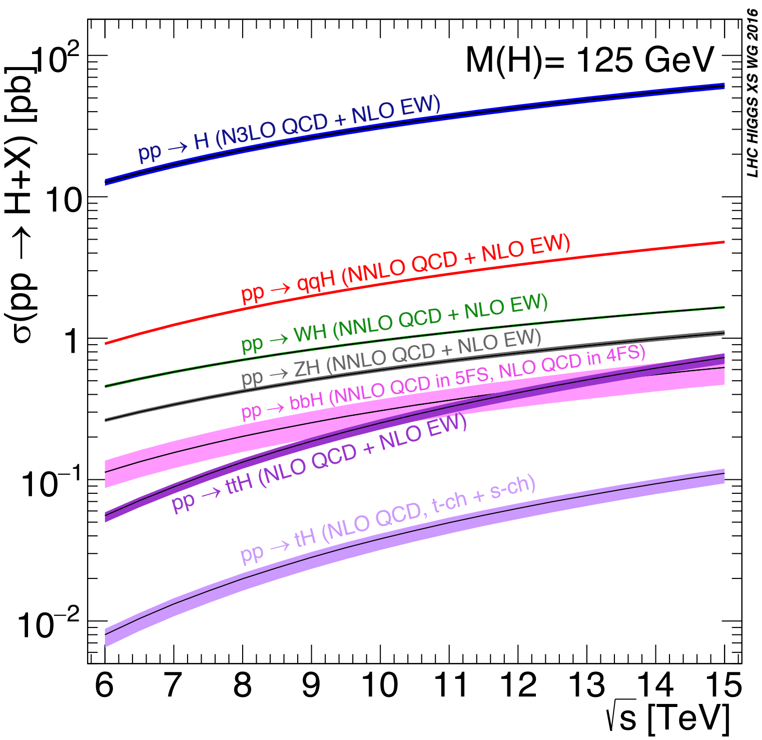
Preliminary limits on Higgs width, Γ/Γ_{SM} < 14.4 (ATLAS), 9.6 (CMS)

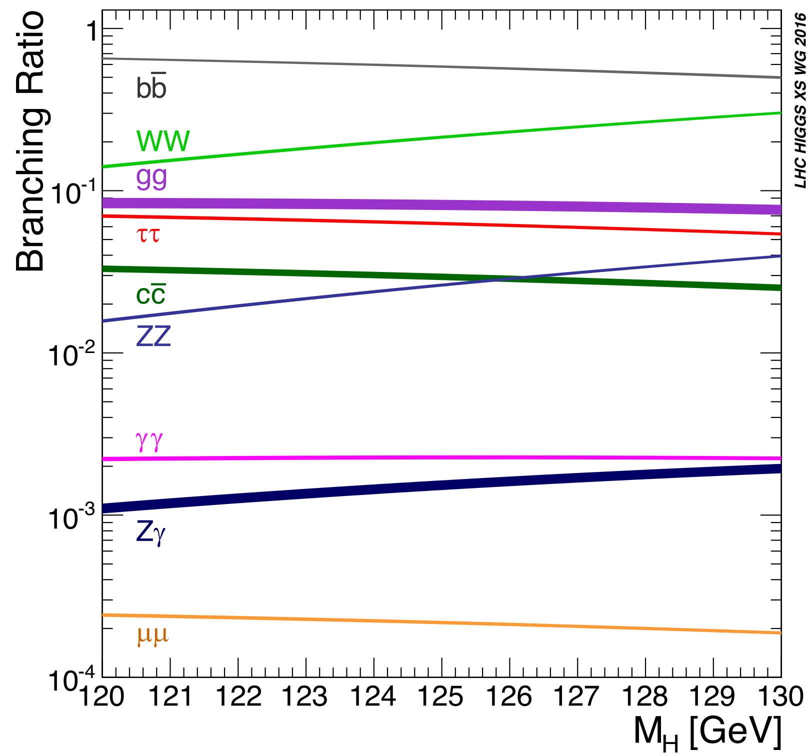
Higgs is a scalar to very high probability (from angular distributions of decays to Z's)

Explicit to do list:

- Precision measurements of production and decay channels exploiting kinematics
  - This will be a major effort in the next decade
- Determine the shape of the Higgs potential
- Explore rare decays and flavor violating decays
- Does the Higgs have CP odd couplings?
- Look for Beyond the Standard Model effects both through searches for heavy Higgs bosons and exotic Higgs decays
- Measure the Higgs width
- …..many other interesting topics

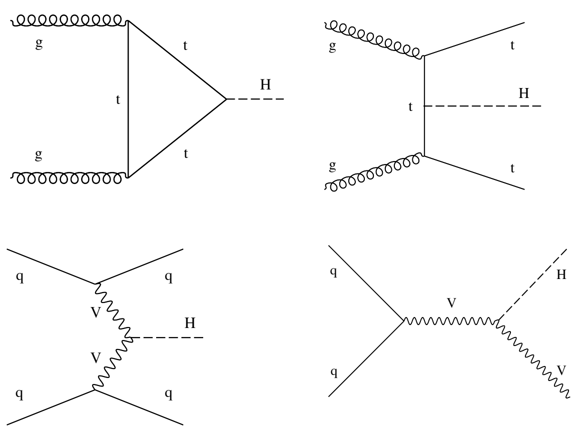
Production and decay rates accurately known

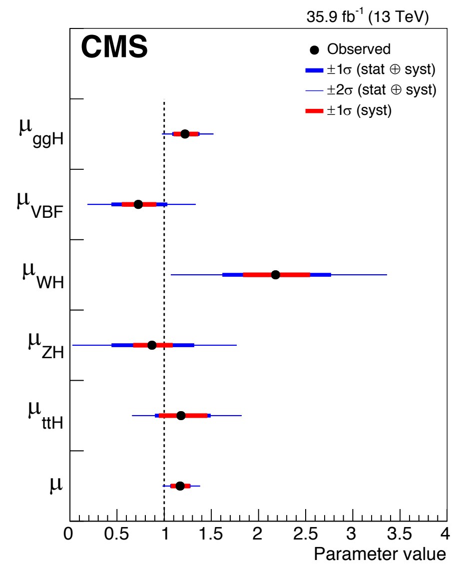


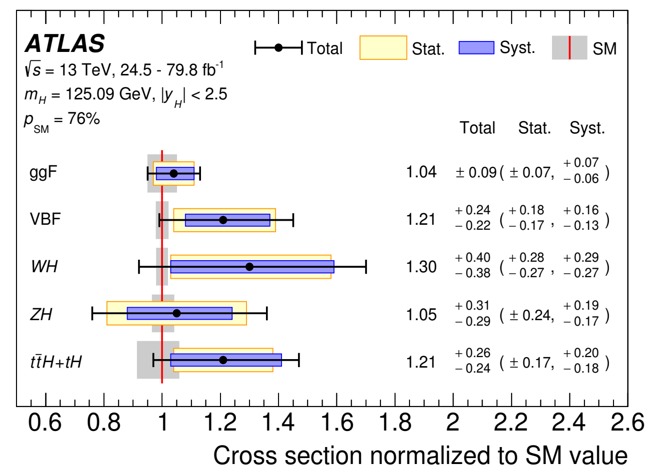


Higgs Production: 2019

- Higgs has been observed in predicted channels at about the SM rates



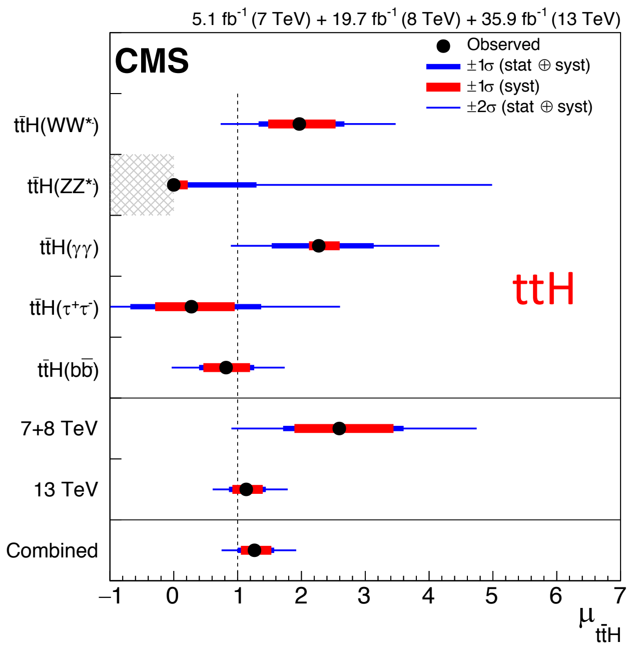


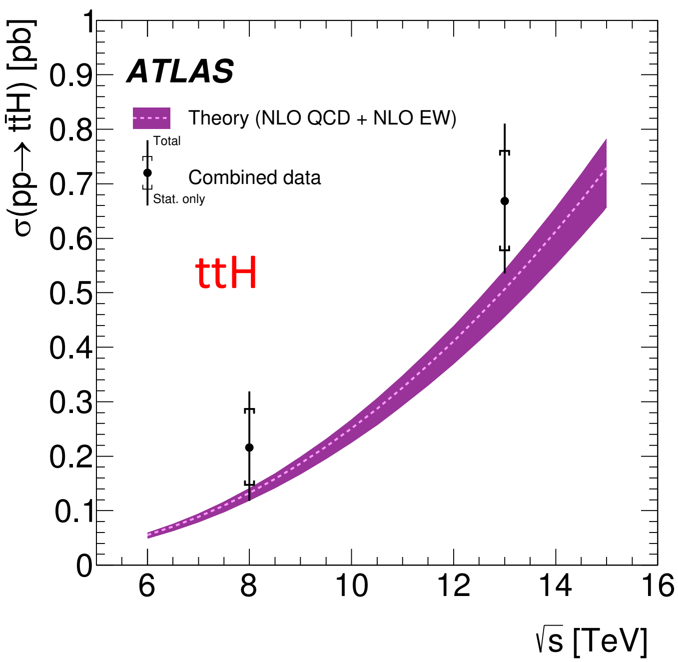


- Early measurements were ggH and VBF
- ttH gives direct measurement of top Yukawa
- VH, H→bb, yields b Yukawa

Higgs Production: Recent Triumphs

- CMS and ATLAS each observed all 3rd generation couplings at about the expected rates
  - Clear experimental evidence, entering the precision era for both theory and experiment





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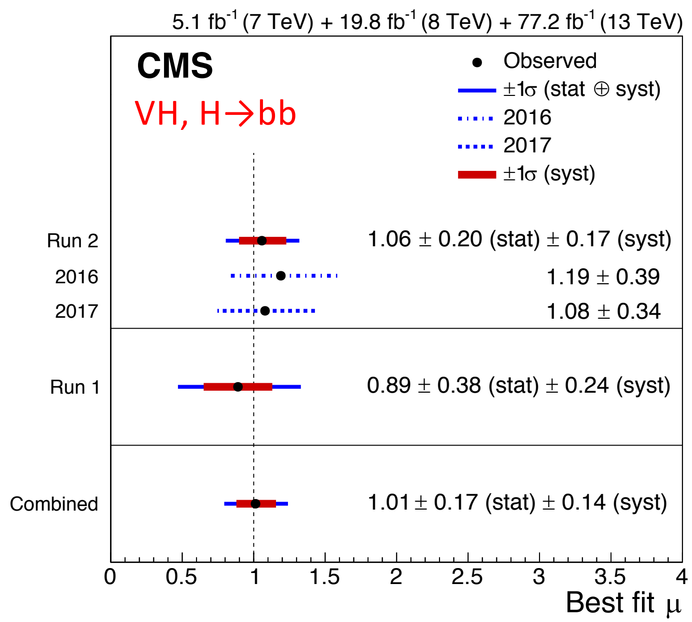
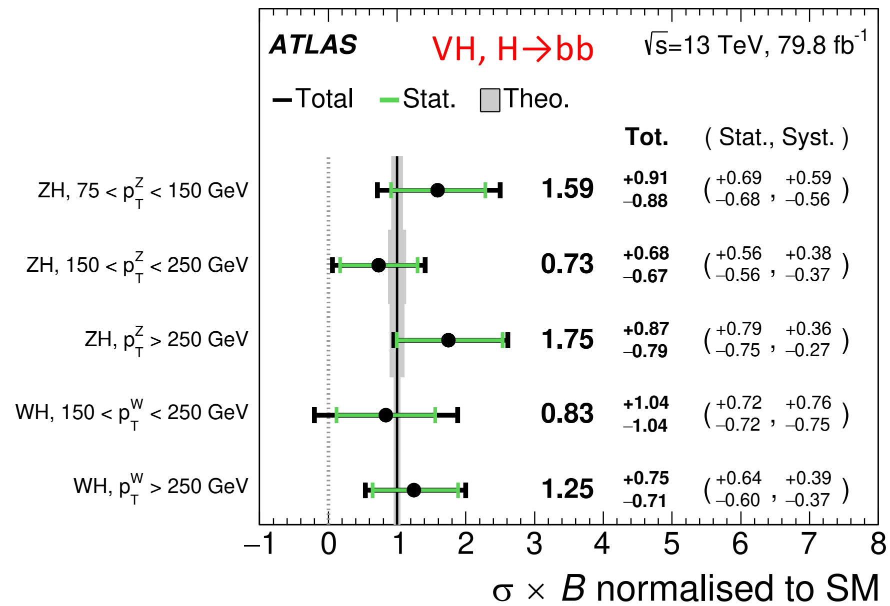
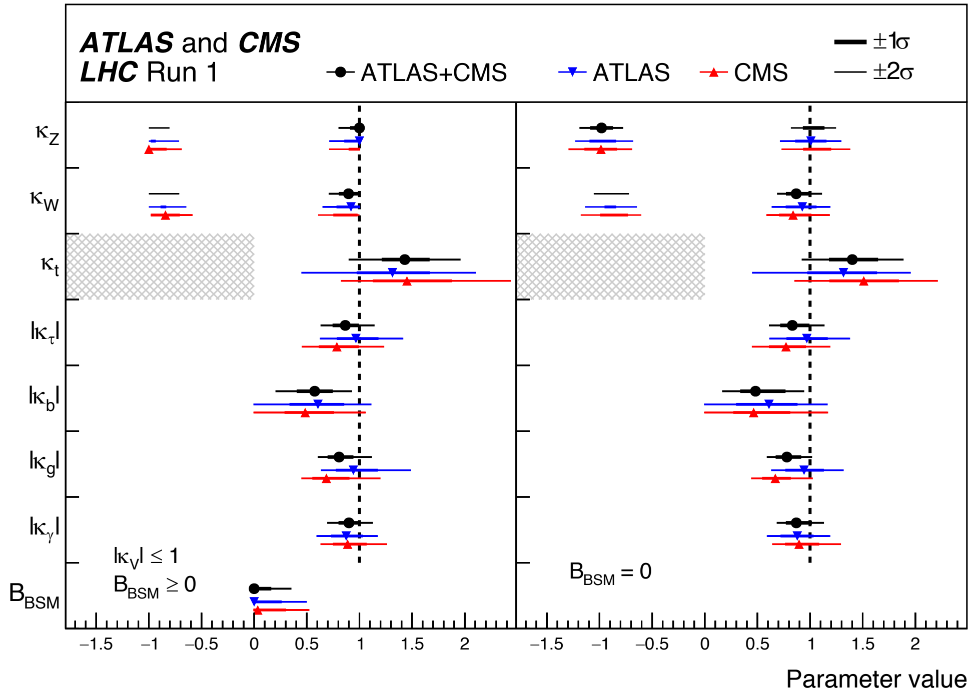




Couplings from Run 1



Note significant uncertainties on b and t couplings

First step to Higgs couplings: κ approach

- κ_i=(Higgs coupling to particle i)/(SM Higgs coupling to particle i)
  - Simple rescaling; no momentum dependence
- Assuming loops resolved and no BSM:

Current Limits

	CMS	ATLAS
k_Z	$.99^{+.11}_{-.12}$	$1.10^{+.08}_{-.08}$
k_W	$1.10^{+.12}_{-.17}$	$1.05^{+.08}_{-.08}$
k_t	$1.11^{+.12}_{-.10}$	$1.02^{+.11}_{-.10}$
k_b	$-1.10^{+.33}_{-.23}$	$1.06^{+.19}_{--.18}$
k_τ	$1.01^{+.16}_{-.20}$	$1.07^{+.15}_{-.15}$
k_μ	$.79^{+.58}_{-.79}$	<1.51 at 95% cl

- Couplings to gauge bosons at 8-12%
- Couplings to 3rd generation fermions at 15-20%

We are just getting to the interesting regime: ***Generically*** expect deviations

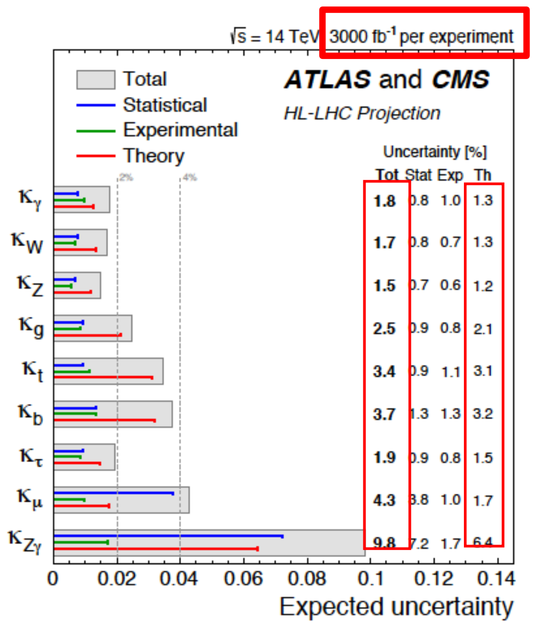
$$\kappa \sim \frac{v^2}{\Lambda^2}\left(\frac{1\ TeV}{\Lambda}\right)^2$$

CMS, arXiv:1809.10733

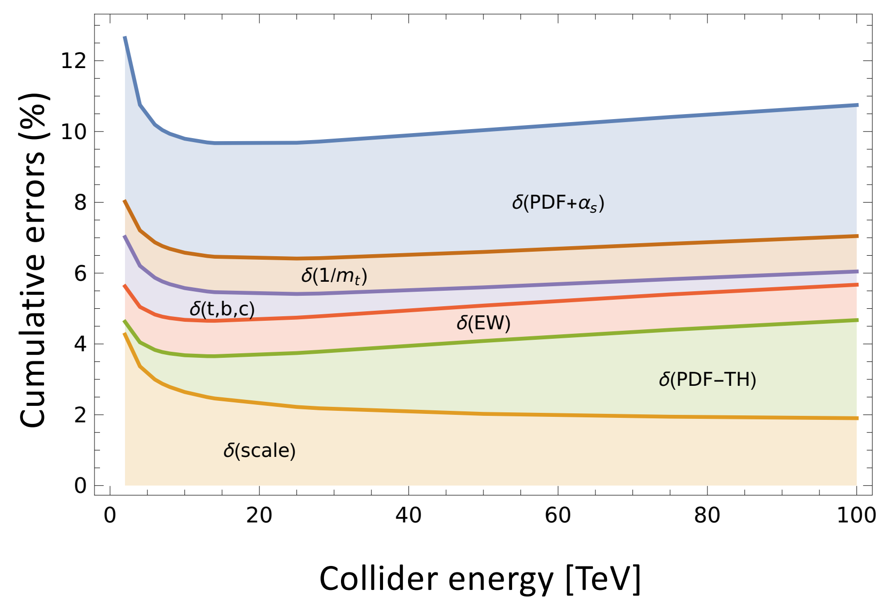
ATLAS, arxiv:1909.02845

The future (3 fb^{-1} at the LHC)

- Theory uncertainties will ***dominate*** extraction of Higgs couplings even assuming major progress: Know gluon fusion to N^3LO QCD



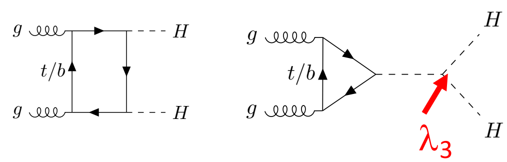
Uncertainties on gluon fusion prediction



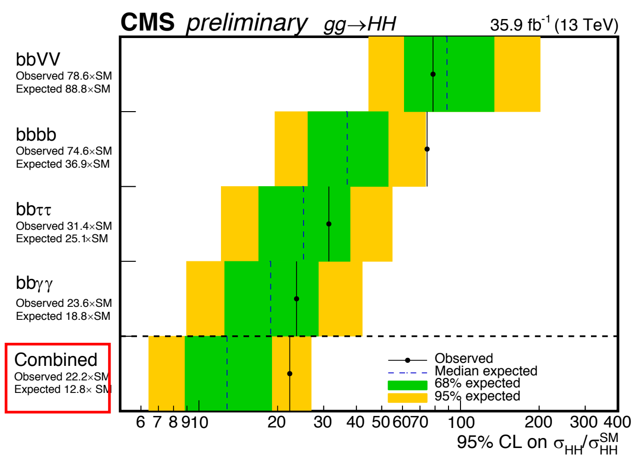
[Dulat, Lazopoulos, Mistlberger, 1802.00827]

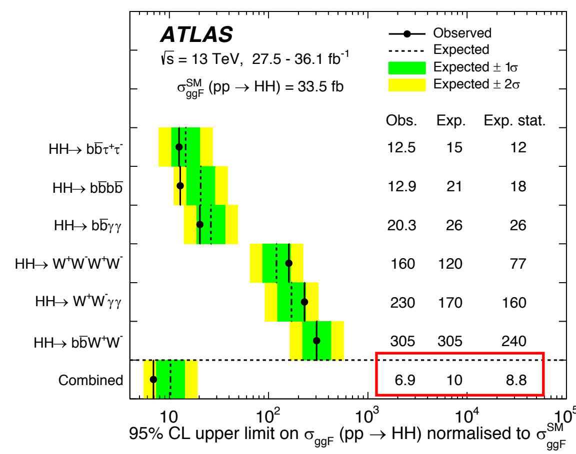
Determining the Higgs potential

- Measure λ_3 from HH production: $V \to -\frac{M_H^2}{2} H^2 + \lambda_3 H^3 + \lambda_4 H^4$ $\quad \lambda_3 = \frac{M_H^2}{2v} = .13v$
- SM rate is very small (~37 fb)



Steady progress in both theory and experiment….

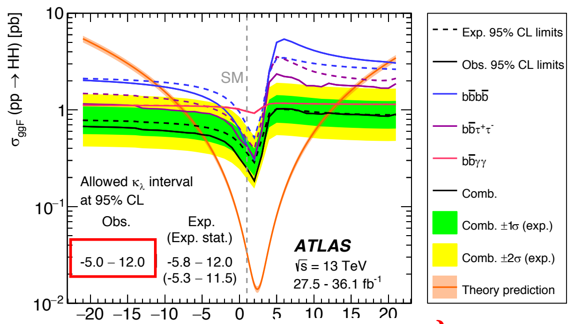




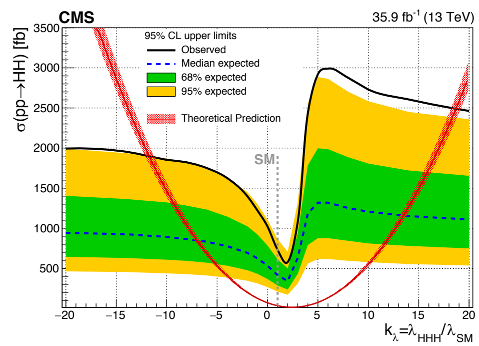
Determining the Higgs potential

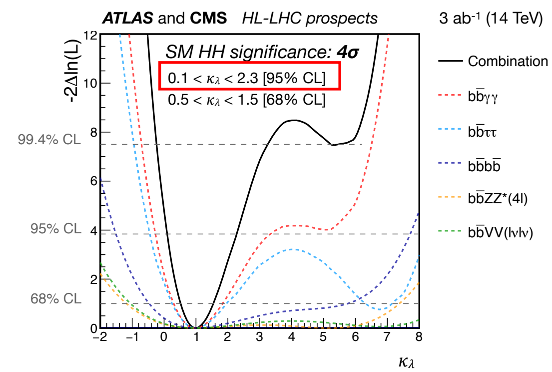
- Measure λ_3 from HH production (assuming everything else SM)
- Theory differential cross section known at NLO QCD

Steady progress….



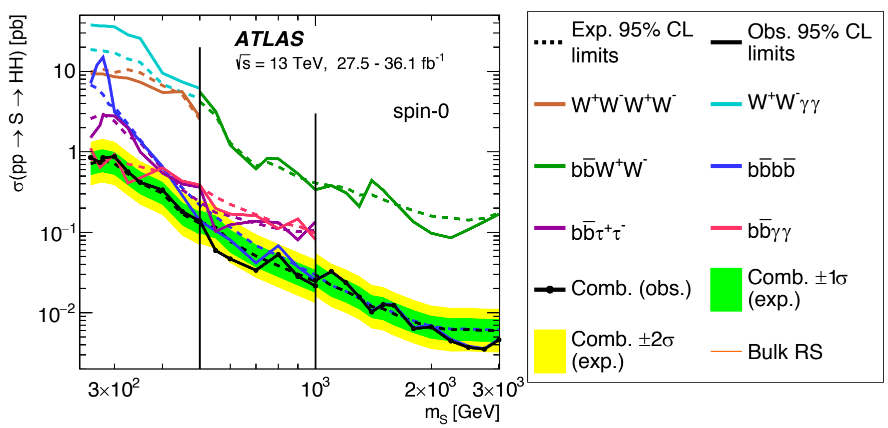
$$\kappa_\lambda = \frac{\lambda_3}{\lambda_3^{SM}}$$

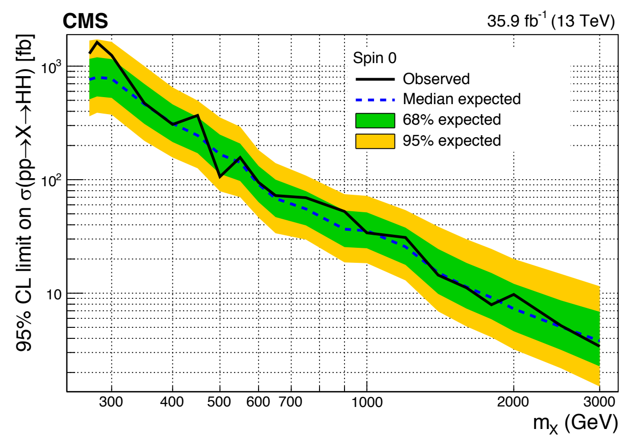




Determining the Higgs potential

- HH production is ***smoking gun*** for new physics since it is sensitive to resonance effects from new scalars (and hence can be enhanced)
- Resonance parameters can be arranged such that the theory has first order electroweak phase transition





Observing rare Higgs decays

- SM channels limited by statistics:
  - H→μμ

$$\frac{\sigma \cdot BR}{[\sigma \cdot BR]_{SM}} < 2.9 \text{ @ } 95\%\ CL,\ CMS$$

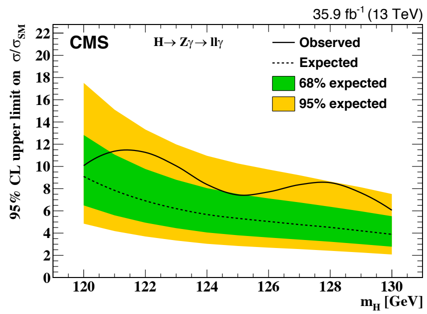
$$< 1.7 \text{ @ } 95\%\ CL,\ ATLAS$$

Closing in on the SM

- Are second generation Higgs couplings those predicted by SM?
- Know 3rd generation couplings to 15-20%

  - H→Zγ (sensitive to new physics in loop)

$$\frac{\sigma \cdot BR}{[\sigma \cdot BR]_{SM}} < 6.6 \text{ @ } 95\ \%CL, ATLAS$$

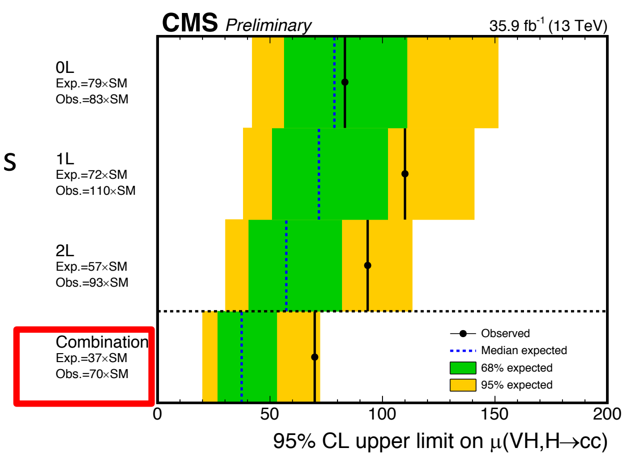


Rare decays

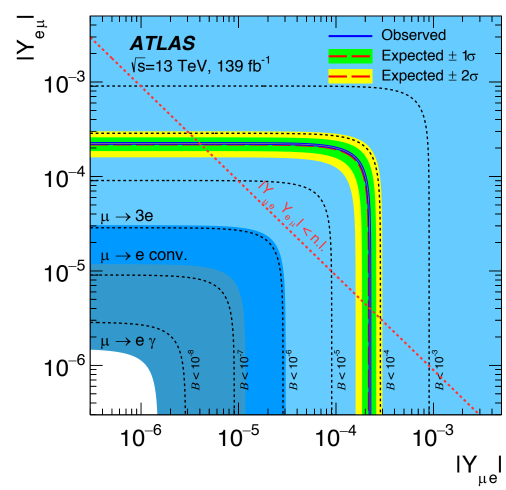
- Higgs decays to charm difficult, but necessary for SM understanding
  - Boosted VH, H→cc
  - Ideas for measurement in J/ψ γ production (BR~10^{-6})
- Look for exotic decays of Higgs in BSM models

Higgs to charm

Progress in analysis techniques: Machine learning, charm tagging….



Flavor violation in Higgs decays



Flavor violation occurs in many well motivated models

The New Paradigm

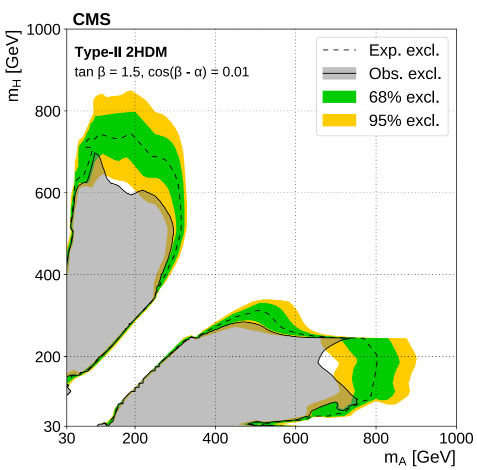
- Past: Guaranteed discoveries ensured by no-lose theorems
  - Beyond the Fermi theory (the W)
  - Beyond the bottom quark (the top)
  - Beyond the electroweak theory (the Higgs)
    - Scattering amplitudes grow with energy without W, top, Higgs….
    - Knew the scale of new physics

Future : No guarantees, need to examine many possibilities

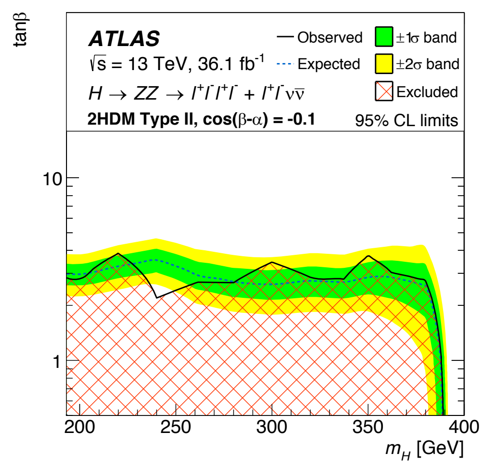
Beyond the SM

- Heavy Higgs particles
  - 2 Higgs doublet model (why should there be just one doublet?
  - Complementarity between Higgs coupling measurements and direct searches for heavy Higgs bosons and with flavor physics limits

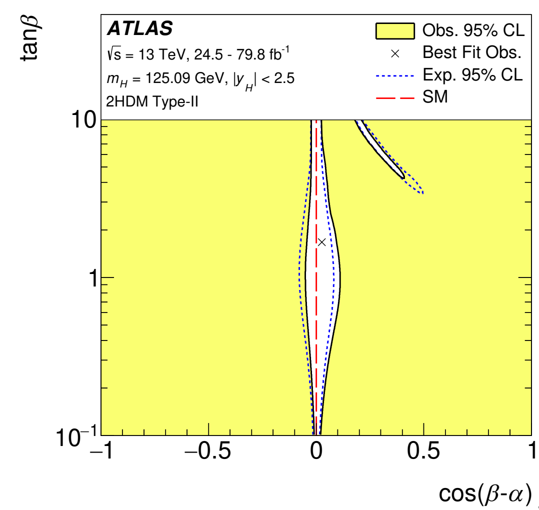
$H \to ZA$



$H \to ZZ$



Limits from Higgs couplings



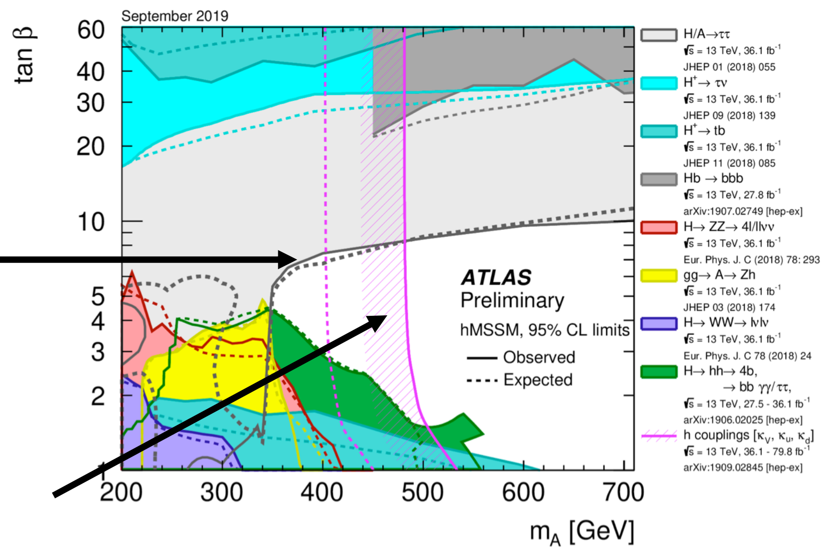
*H is heavy Higgs, A is pseudoscalar

Beyond the SM

- Still lots of unexplored parameter space for supersymmetric models
- Theoretical motivation remains strong
- Higgs coupling measurements and direct searches for Higgs bosons complementary

Heavy Higgs searches

Higgs couplings

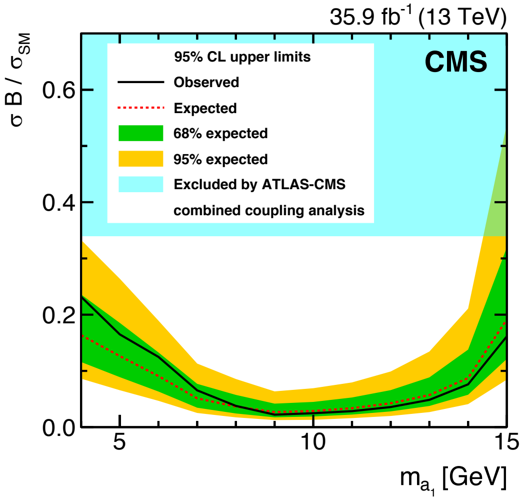


Current limits significantly stronger than Snowmass 2013

Beyond the SM

- Look for exotic decays, e.g. H→AA
- Look for decays to long-lived particles, H→XX
- Many well motivated models and large unexplored parameter spaces

$H \rightarrow AA, A \rightarrow \tau^+\tau^-$

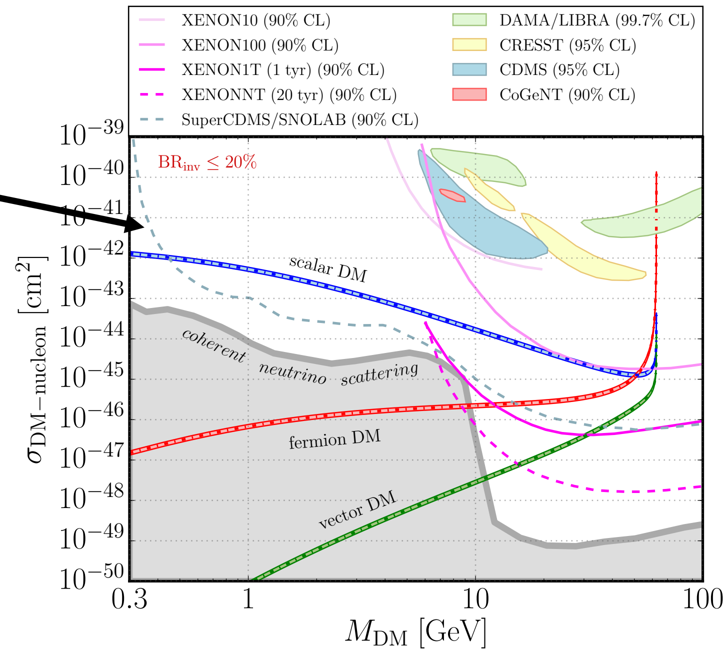


*Not a SUSY plot

Beyond the SM

- Can Higgs physics explain dark matter?
  - Look for Higgs to invisible (invisible=dark matter?)
  - Current limit is BR(H→invisible) < 25% (<60% in 2013),

  primarily from vector boson scattering
- Invisible can be scalar, fermion, or vector in dark matter models
- Higgs limits complementary to dark matter direct detection



arxiv:1902.00134

Interconnectedness

- Higgs physics doesn't stand alone
- In the absence of new light particles, Higgs physics can be understood in an effective field theory (EFT) framework
  - Takes advantage of kinematic distributions
- EFTs connect Higgs physics, top quark physics, gauge boson interactions into a single framework
- Requires a unified theoretical and experimental effort

We are in the precision era

P5: Higgs as a science driver

- SM measurements of gauge boson and 3rd generation fermion Higgs couplings at 10-15% level; need higher experimental precision, requires improved theory input
  - Observed ttH
  - Observed VH→Vbb
  - Higgs mass at 0.1%

Great triumphs!

- 1st and second generation Yukawa couplings need to be measured
- Characterization of Higgs potential in its infancy
- Heavy Higgs searches and exotic Higgs decays offer many yet unexplored windows to beyond the SM physics

Higgs physics remains an important science driver for the future
Immense progress since 2012 in understanding the Higgs, but a lot to be done!