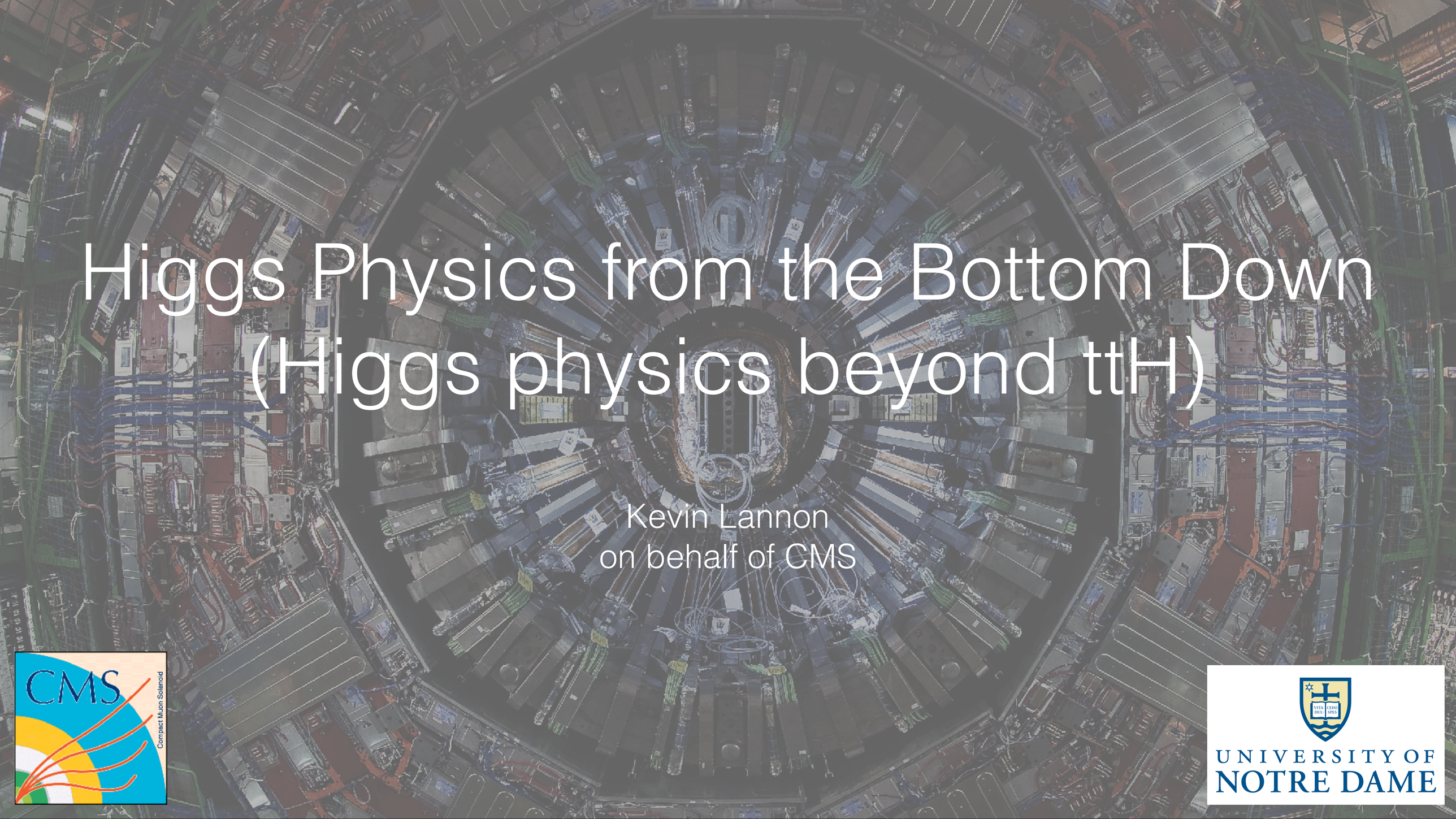


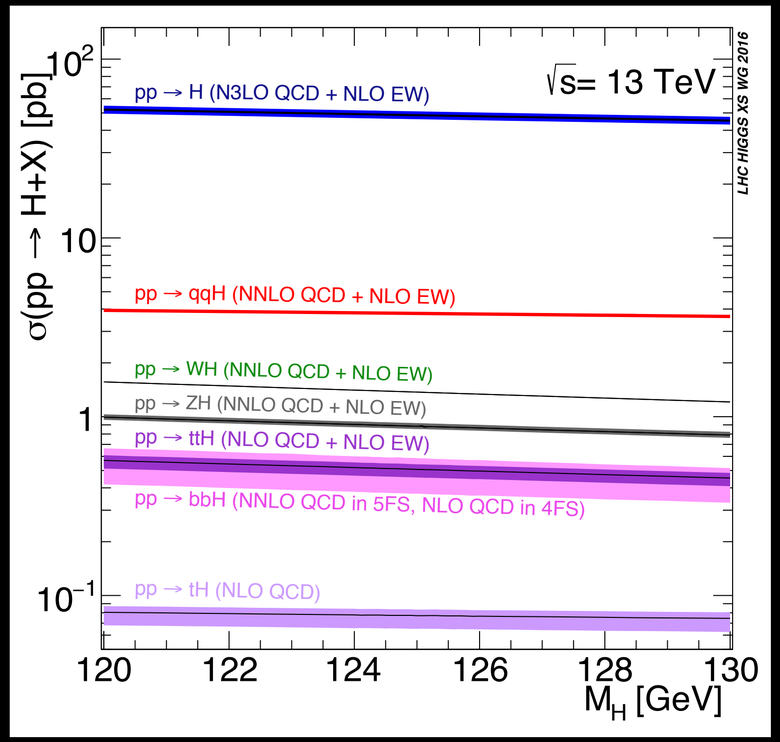
Higgs Physics from the Bottom Down (Higgs physics beyond ttH)

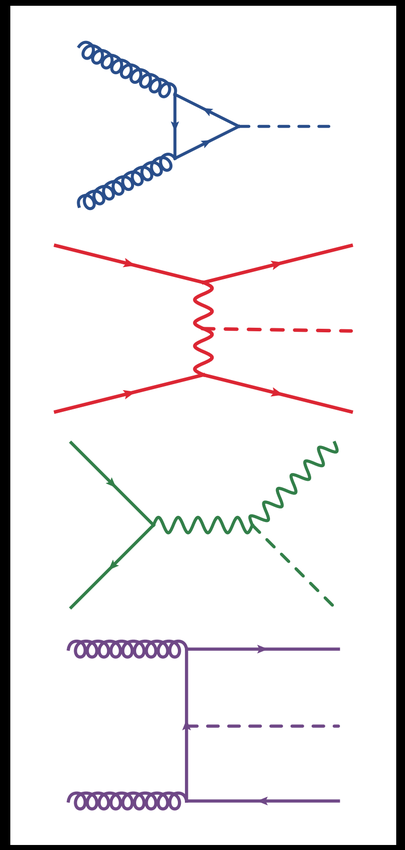
Kevin Lannon
on behalf of CMS

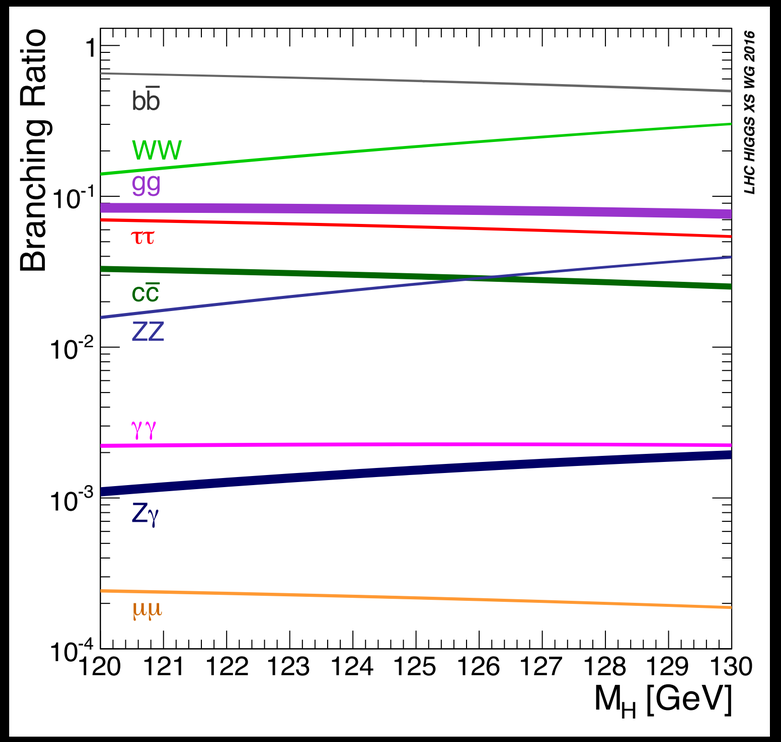
What's Special About Higgs?

- Higgs boson solves two problems in SM
  - Gives mass to the vector bosons to break EWSB
  - Gives mass to the fermions without spoiling gauge invariance
- Higgs is the only fundamental scalar boson observed in nature
  - Or is it…?
- Higgs has natural ($y_t \sim 1$) coupling to top quark

Higgs Production and Decay





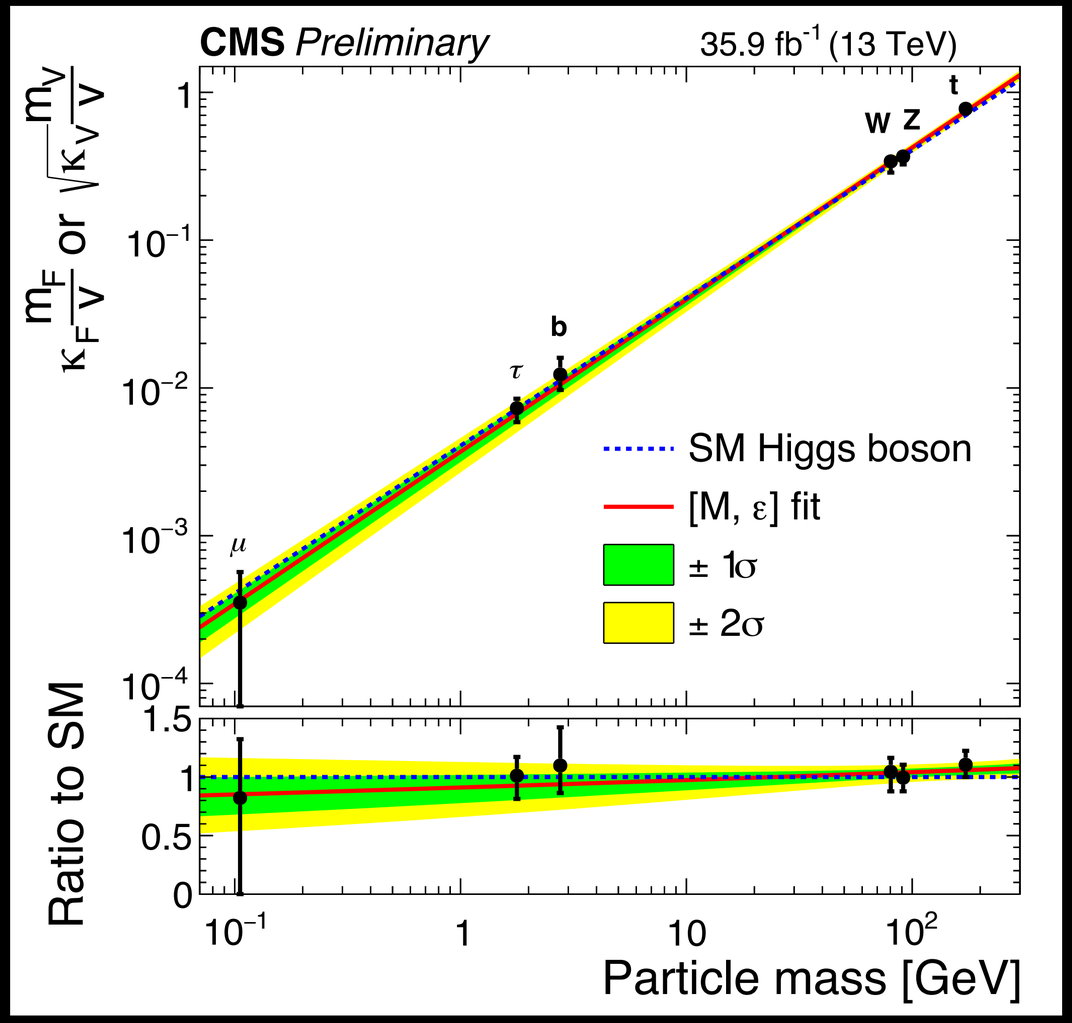


- Given observed mass, Higgs participates in variety of production and decay modes leading to rich set of accessible final states

Higgs Physics Program

- Establish consistency with SM expectations
  - Couplings vs particle masses
  - Spin and parity
- Precise measurement of mass
- Search for non-SM decays
- Search for additional Higgs bosons (e.g. 2HDM, SUSY, etc.)
- Higgs as a portal to new physics

Higgs Couplings Summary + Recent Progress

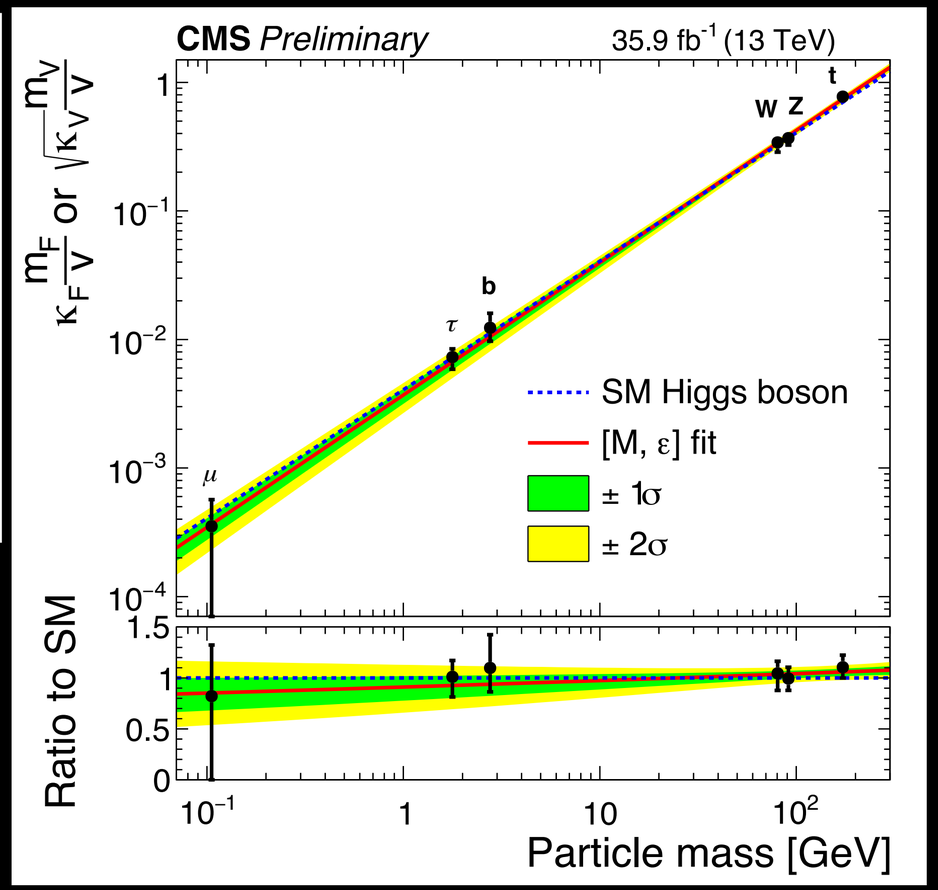


CMS-PAS-HIG-17-031

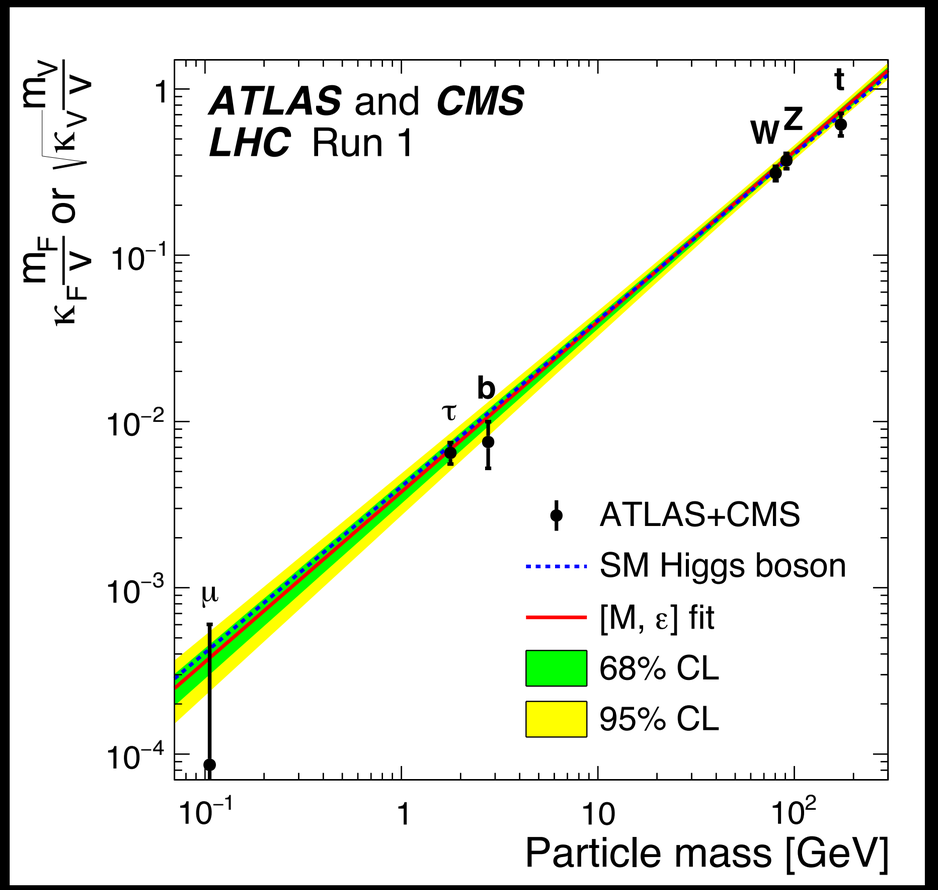
- Crucial test of SM Higgs: do measured couplings match measured mass values?
- So far, excellent within experimental uncertainties
- Couplings to W, Z, quarks, and leptons tested
- Since most recent combination in March, several measurements updated

Comparison to Run 1

CMS-PAS-HIG-17-031

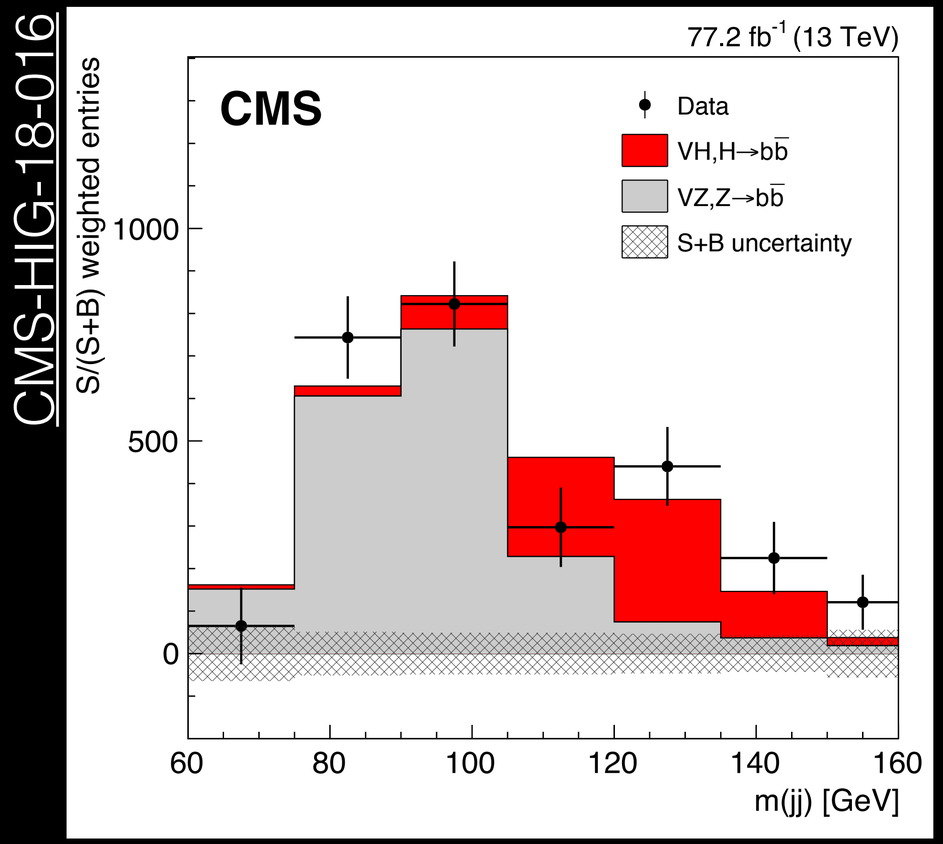


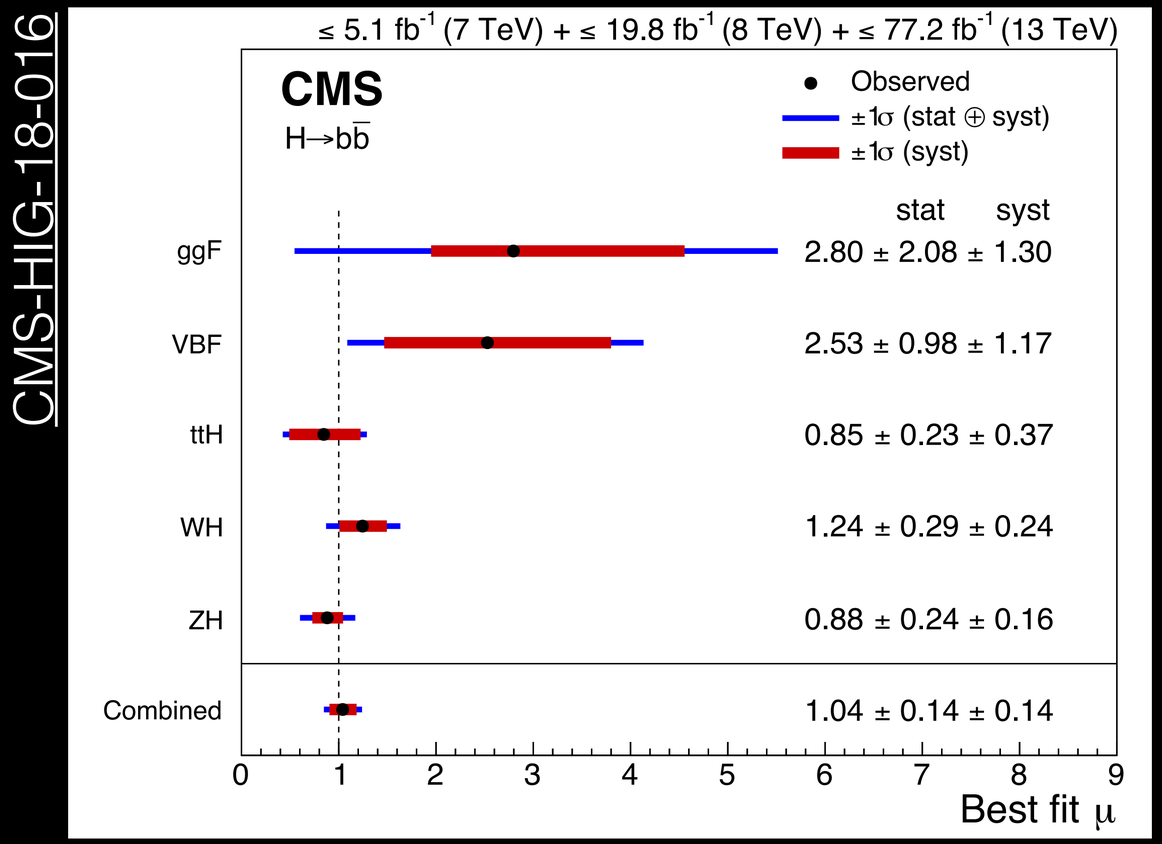
JHEP 08 (2016) 045



- CMS-only Run 2 results have comparable or better precision to CMS+ATLAS Run 1 combination!

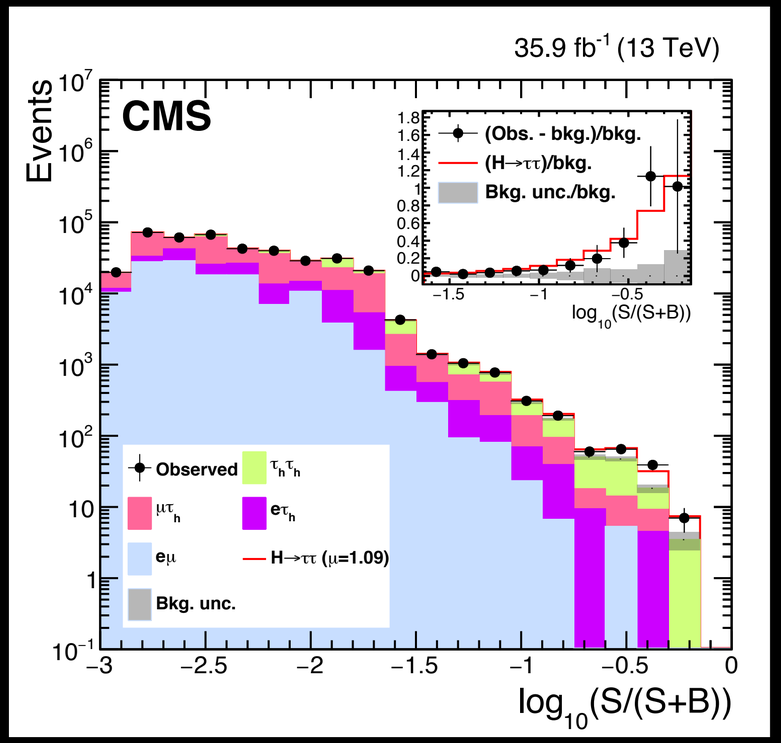
Higgs to Bottom Observation!



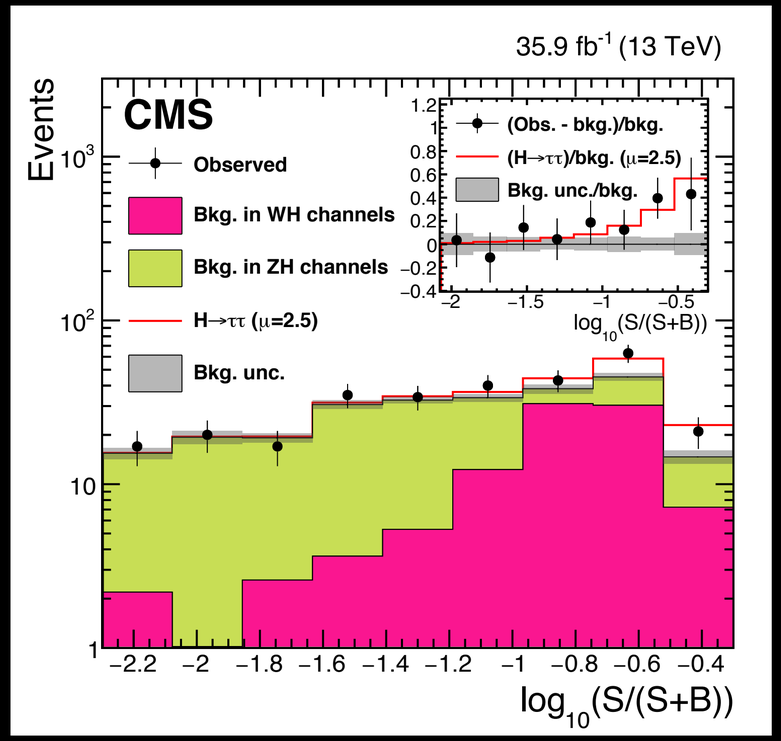


- Combines all available results from Run 1 and Run 2
- Combination has 5.6 std. dev. significance including all channels (4.9 std. dev. in VH alone).

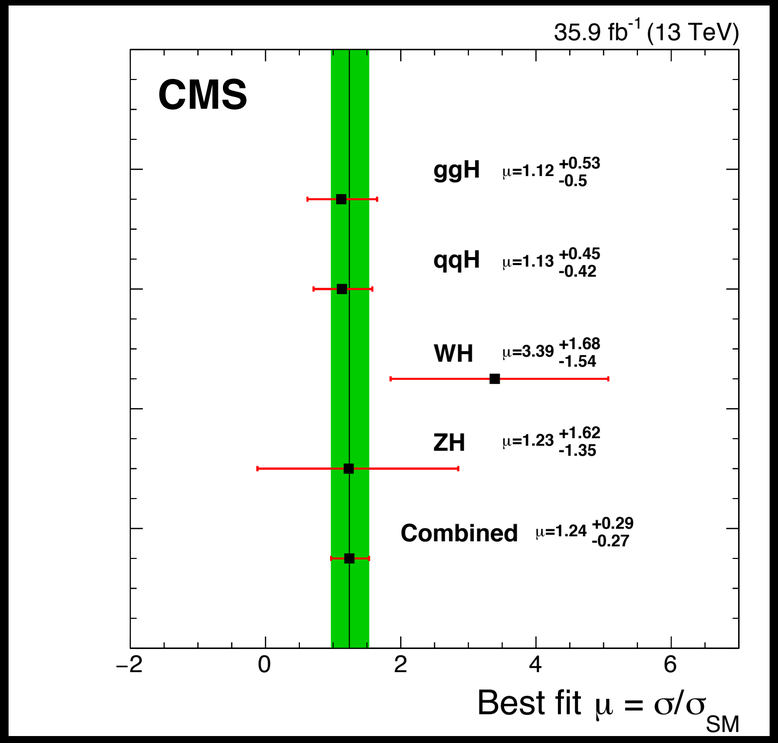
Higgs Coupling to Tau Leptons



CMS-HIG-16-043



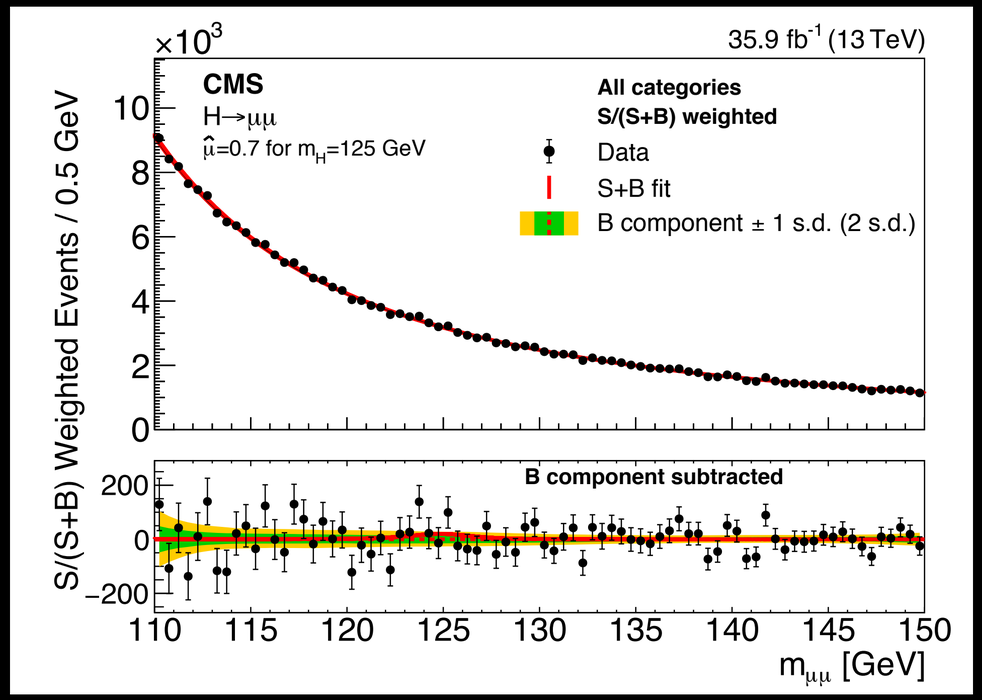
CMS-HIG-18-007



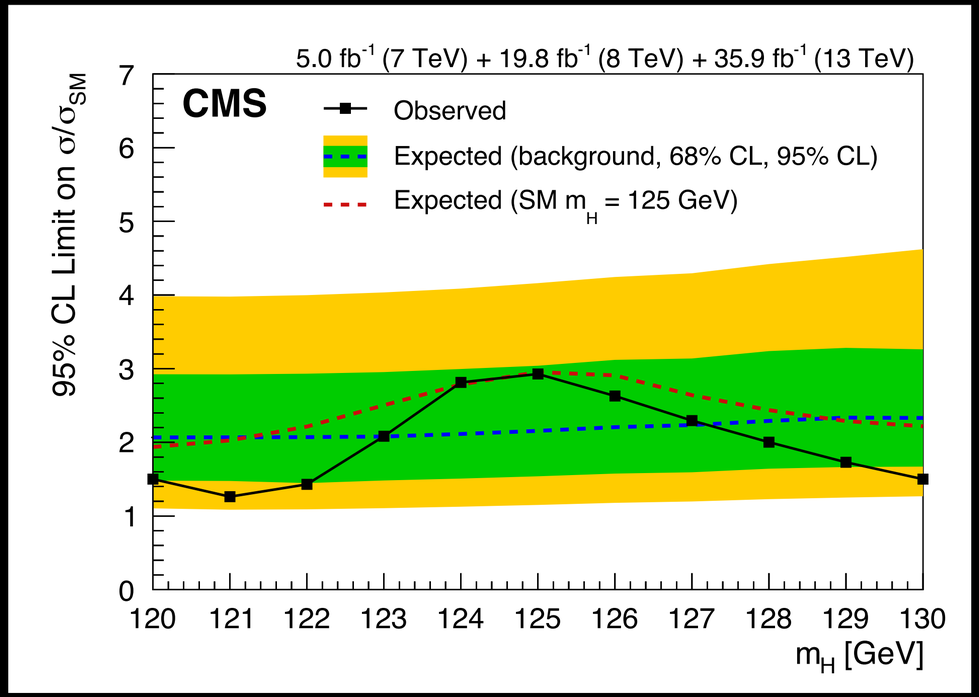
CMS-HIG-18-007

- Tau: Combined (Run 1+ Run 2): 5.9 std. dev. (4.7 std. dev. from Run 2 alone)
- Recent improvement (since last combination) is adding VH channels for Run 2.

Higgs Coupling to Muons



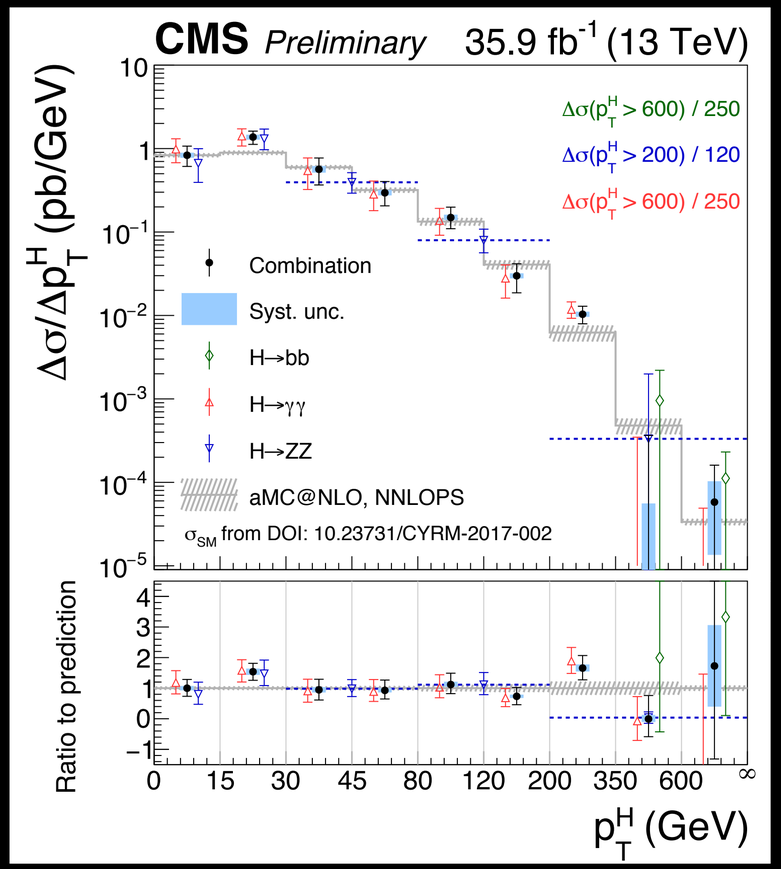
CMS-HIG-17-019

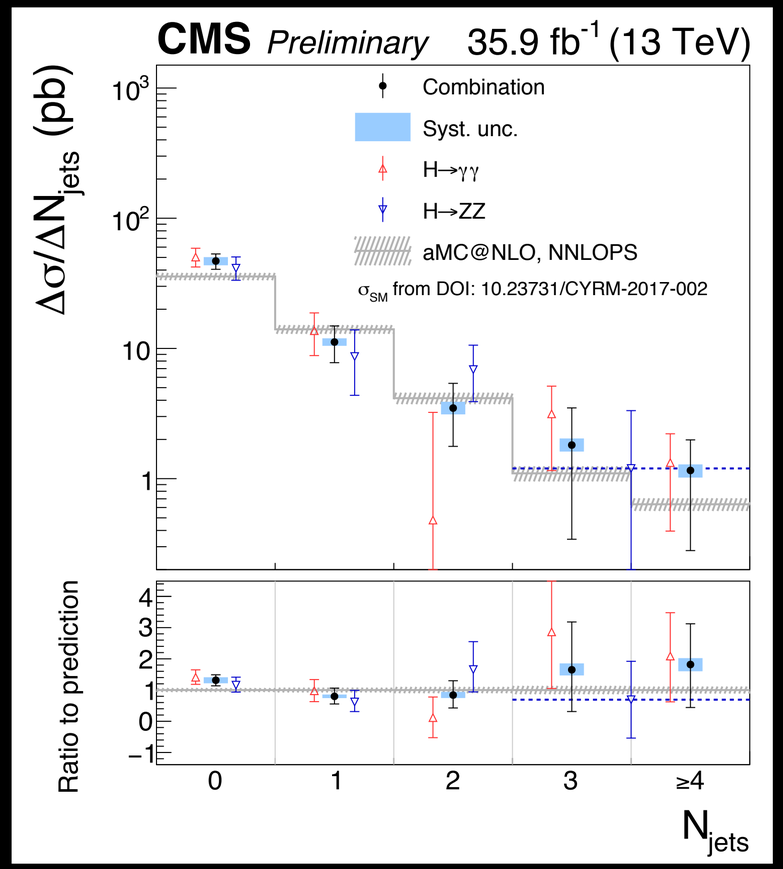


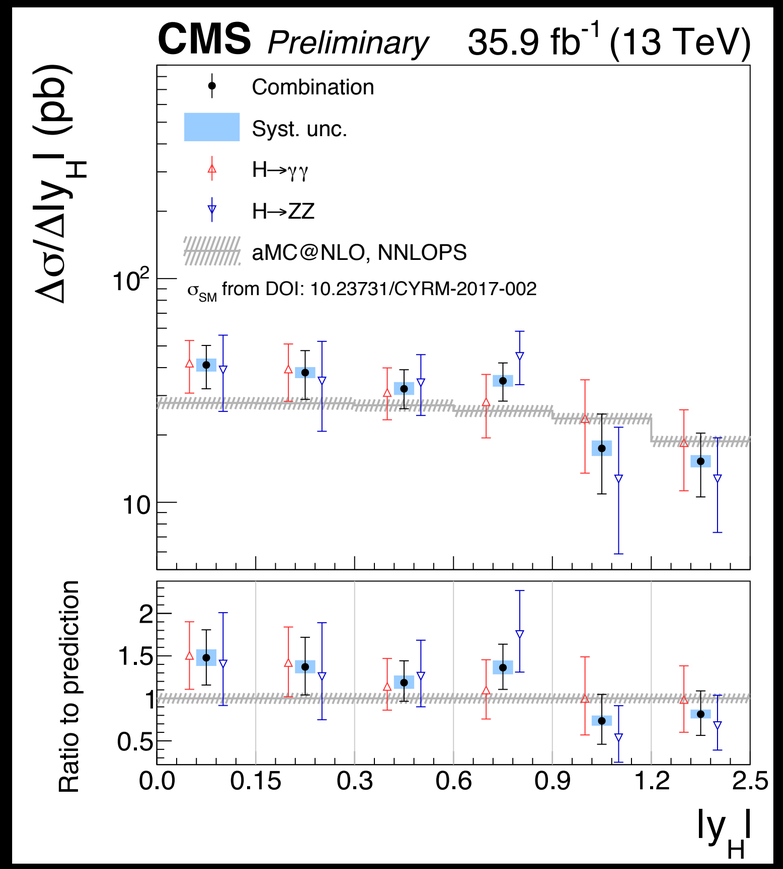
CMS-HIG-17-019

- Muons: Nothing significant yet, but some excess visible in combined Run 1 + Run 2 dataset

Differential Cross Sections



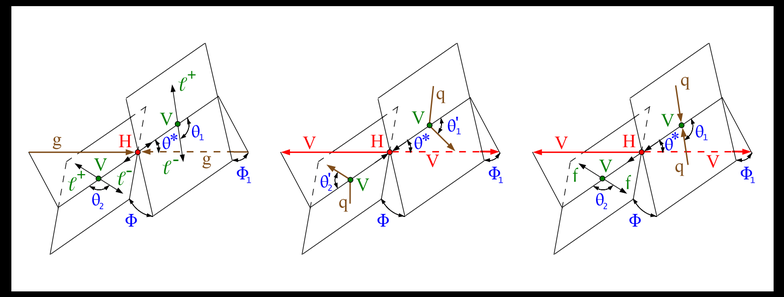




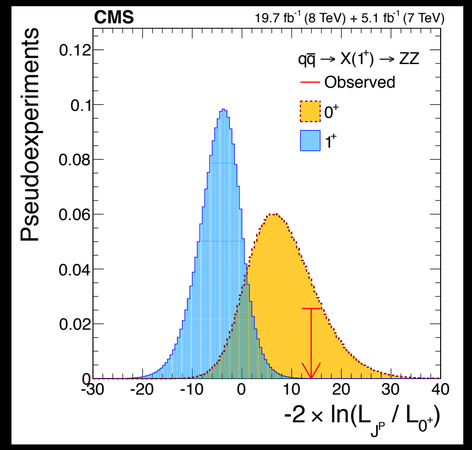
- Stats in “workhorse” channels (ZZ, γγ) sufficient for differential measurements. H→bb provides additional input for some parts of phase space.
- Gives some sensitivity to Higgs to charm coupling!

CMS-PAS-HIG-17-028

Higgs Spin/Parity

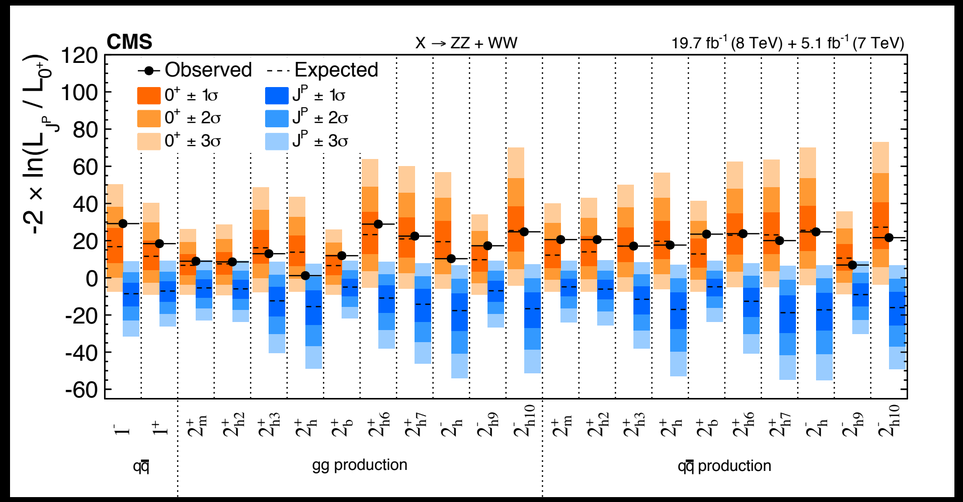


Use kinematics information from final state to calculate matrix element discriminants for different scenarios



CMS-HIG-14-018

Compare distribution in data to SM and alternative hypotheses



CMS-HIG-14-018

Repeat for a number of spin and parity hypotheses. All non-SM options ruled out at > 99% C.L.

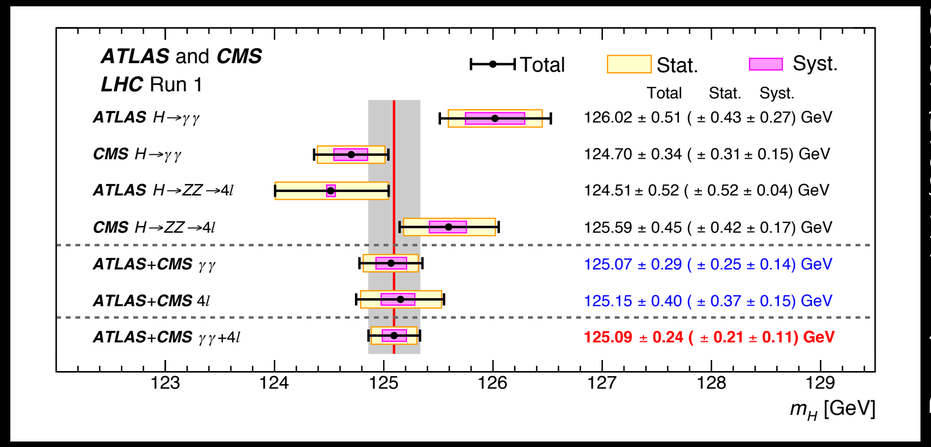
Continue to study possibility that observed Higgs is mixture of SM and non-SM spin-0.

E.g. Can limit pseudo-scalar fraction (f_{a3}) to fraction of a percent, depending on phase. Using off-shell contributions from 4-lepton channel lead to this very recent improvement!

Parameter	Observed	Expected
$f_{a3}\cos(\phi_{a3})$	$0.0000^{+0.0005}_{-0.0011}$ $[-0.0067, 0.0050]$	$0.0000^{+0.0014}_{-0.0014}$ $[-0.0098, 0.0098]$
$f_{a2}\cos(\phi_{a2})$	$0.0005^{+0.0025}_{-0.0008}$ $[-0.0029, 0.0129]$	$0.0000^{+0.0011}_{-0.0017}$ $[-0.0100, 0.0117]$
$f_{\Lambda 1}\cos(\phi_{\Lambda 1})$	$0.0001^{+0.0020}_{-0.0010}$ $[-0.0150, 0.0501]$	$0.0000^{+0.0010}_{-0.0010}$ $[-0.0152, 0.0158]$

CMS-HIG 18-002

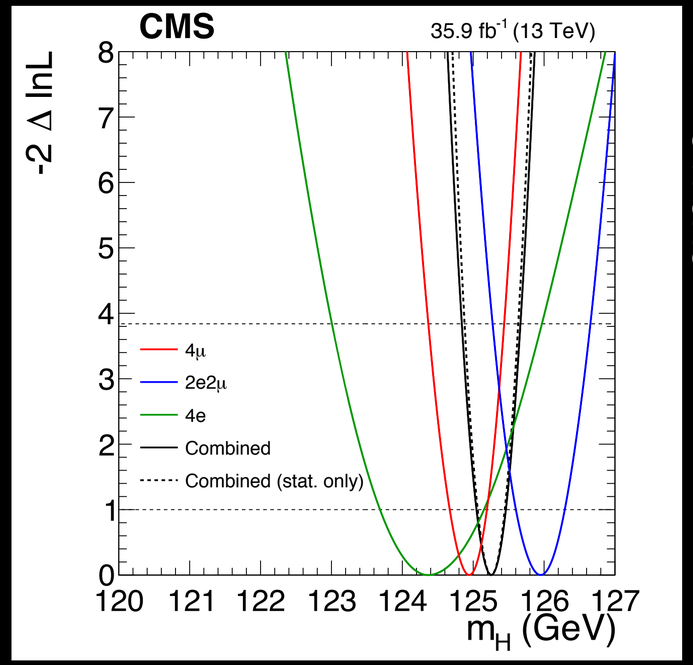
Higgs Mass and Width



Phys. Rev. Lett. 114 (2015) 191803

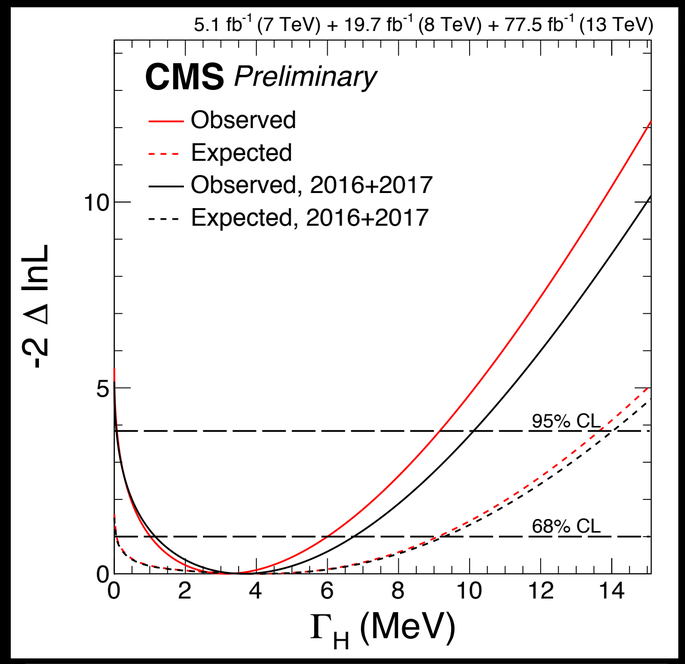
Run 2 mass from 4-lepton final states already comparable precision to Run 1 CMS + ATLAS combination.

Also able to measure Higgs width, using both on-shell and off-shell production.
Approaching sensitivity to SM. Can exclude zero at 95% C.L.!



CMS-HIG-16-041

$m_{\mathrm{H}} = 125.26 \pm 0.21\ \mathrm{GeV}$



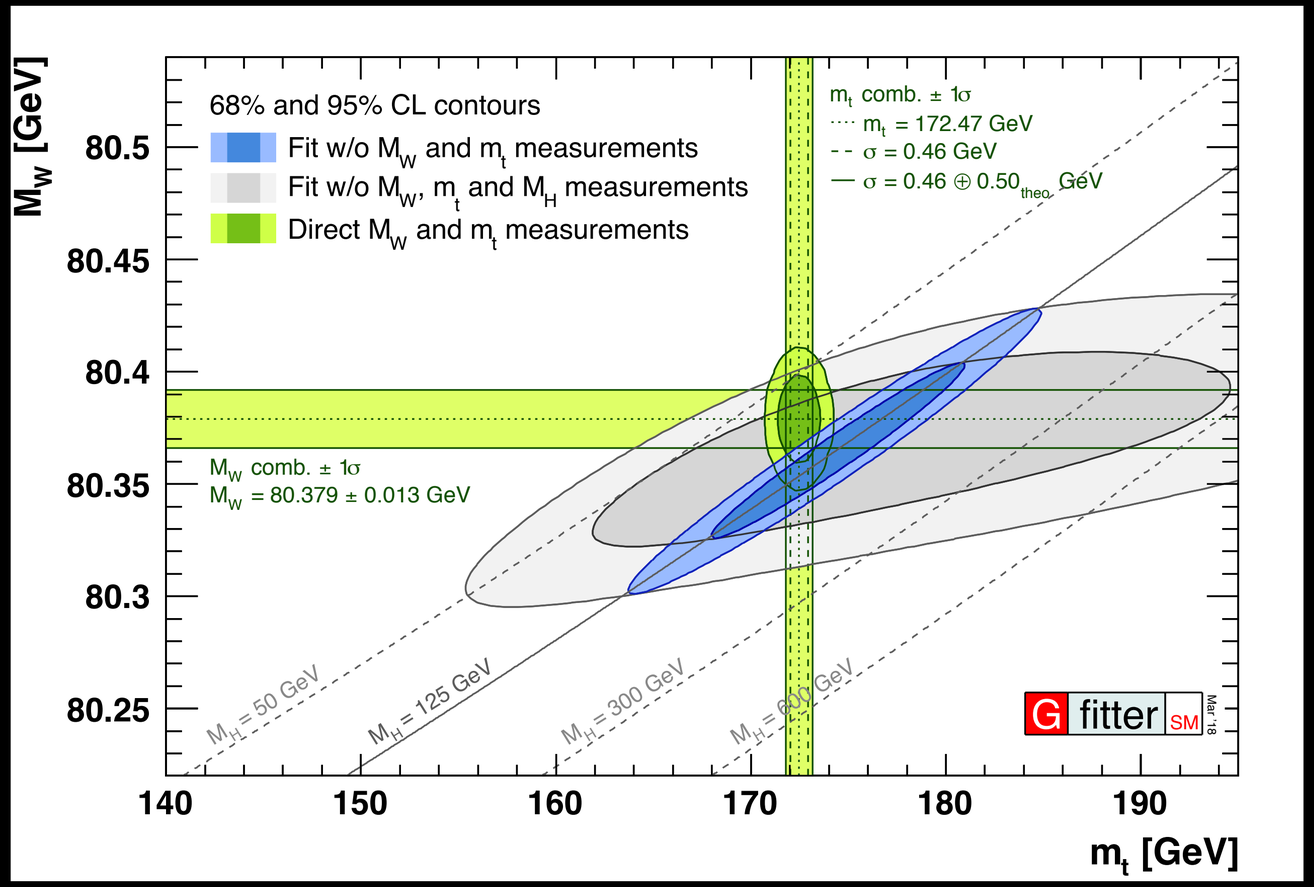
CMS-HIG 18-002

Parameter	Observed	Expected
Γ_{H} (MeV)	$3.2^{+2.8}_{-2.2}$ [0.08, 9.16]	$4.1^{+5.0}_{-4.0}$ [0.0, 13.7]

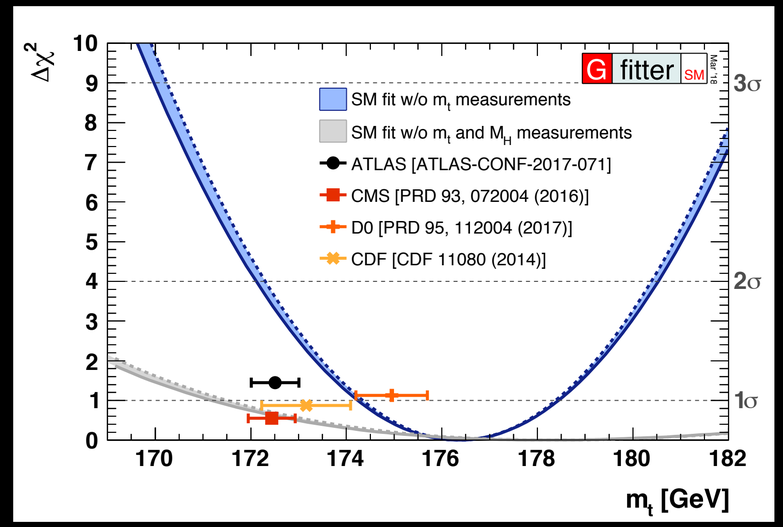
Predicted width in SM is 4 MeV

- Higgs is most recently discovered particle but has most precisely measured mass.

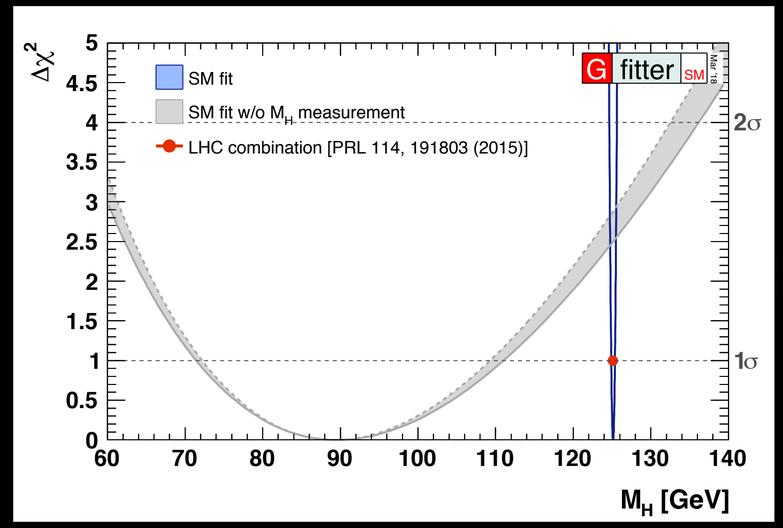
Higgs and Top Mass in EW Global Fits



arXiv:1803.01853



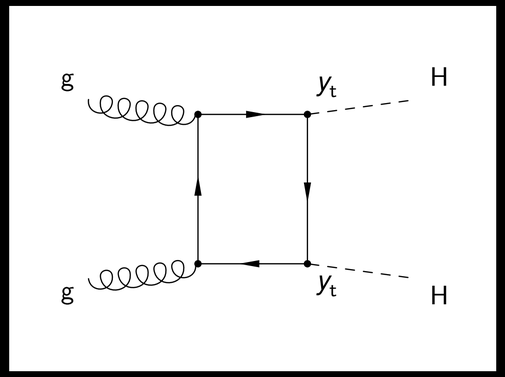
arXiv:1803.01853

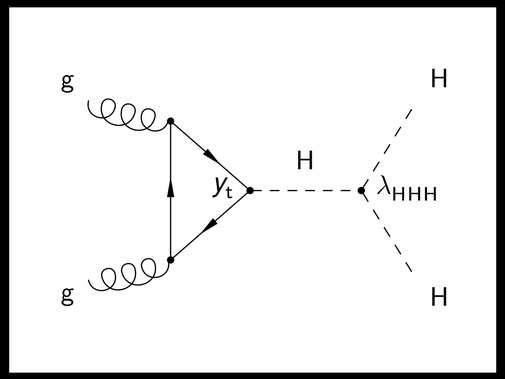


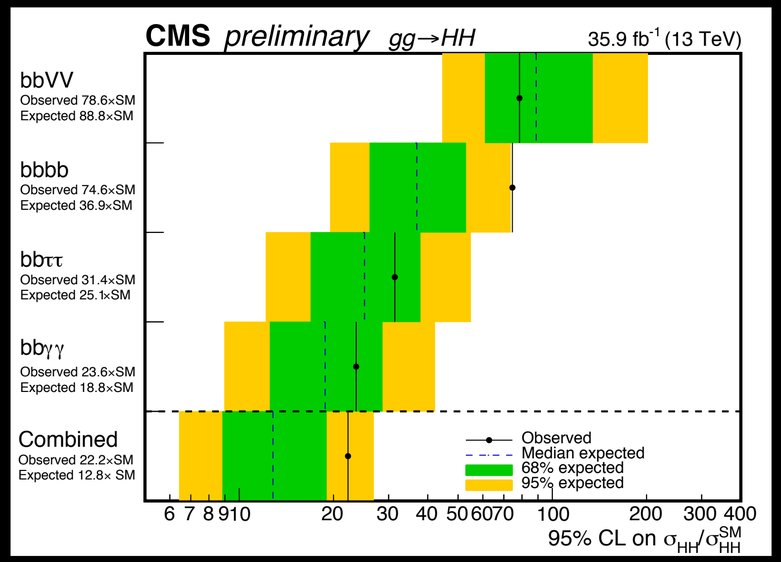
arXiv:1803.01853

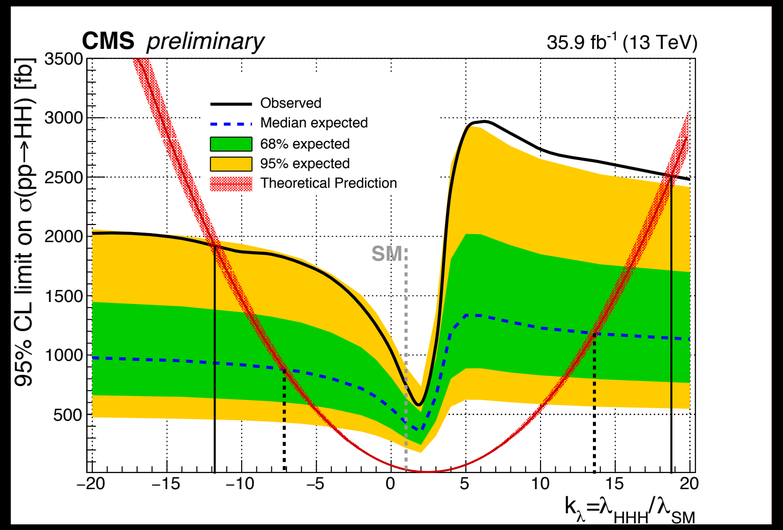
- Long standing (but not statistically significant) tension between direct and indirect mass determinations still lingers

HH Production: Probing Higgs Potential





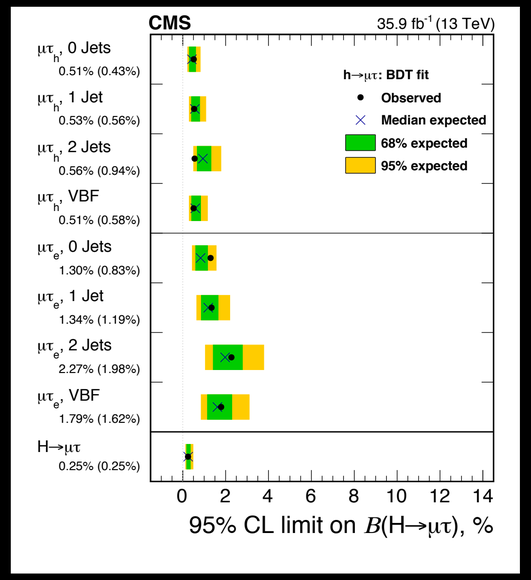




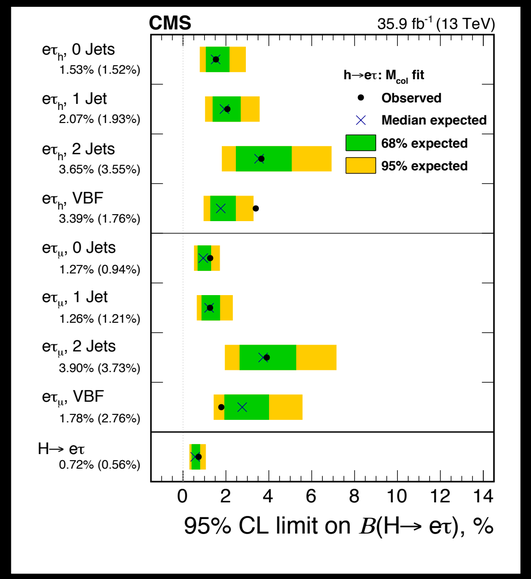
CMS-PAS-HIG-17-030

- Measuring HH production gives information about Higgs self coupling, connected to shape of Higgs potential
- Current sensitivity far from SM level. Likely require for HL-LHC to measure.

BSM Higgs Decays



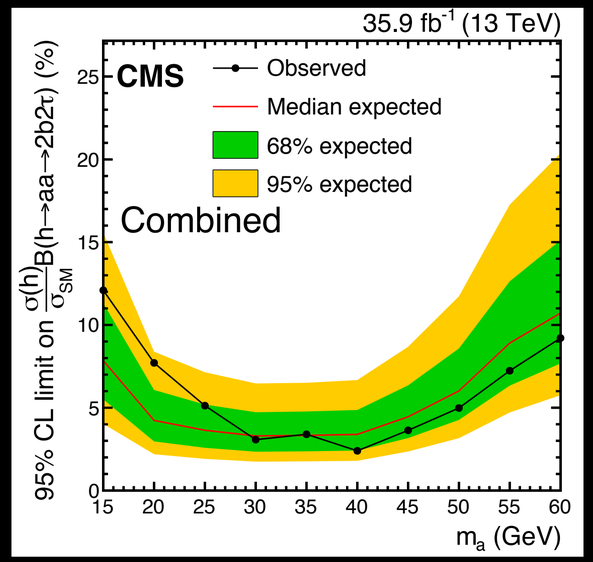
CMS-HIG-17-001



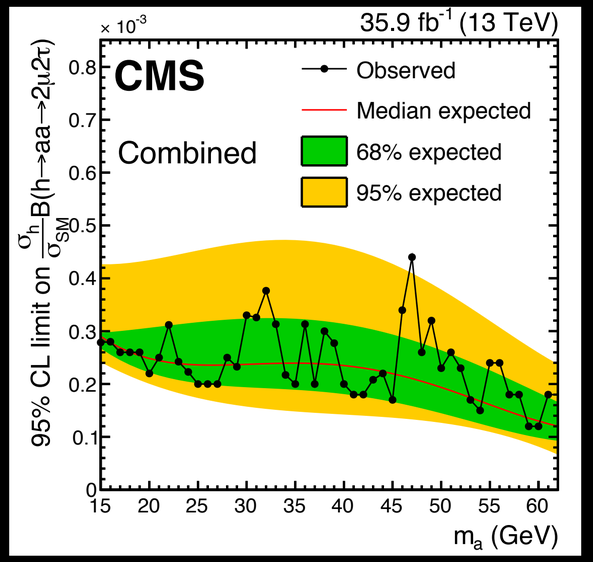
CMS-HIG-17-001

Lepton Flavor Violating Higgs Decays: Search for Higgs mass peak in invariant mass of lepton pairs with different flavor (eτ, μτ)

Set limits on such branching fractions sub-percent in all cases.



CMS-HIG-17-024

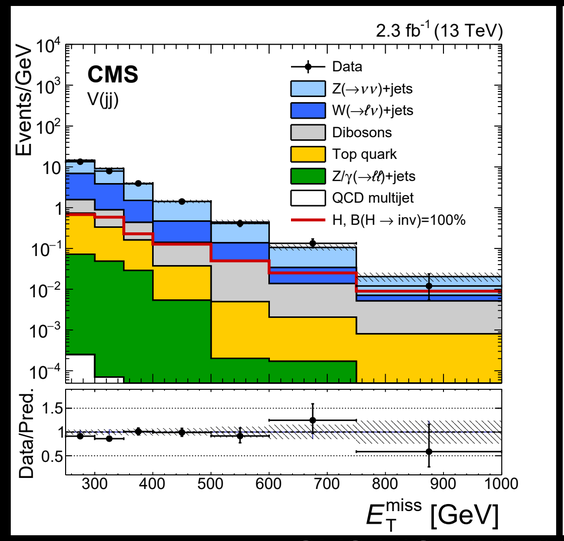


CMS-HIG-17-029

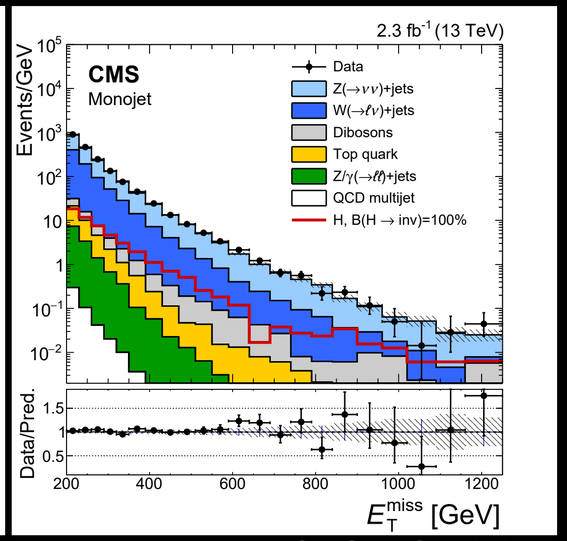
Higgs decaying to light pseudoscalar pair: pseudoscalar can decay various ways (e.g. bb, ττ, or μμ). Limits depend strongly on pseudoscalar decay mode.

- Look for evidence of decays ***not*** predicted by SM

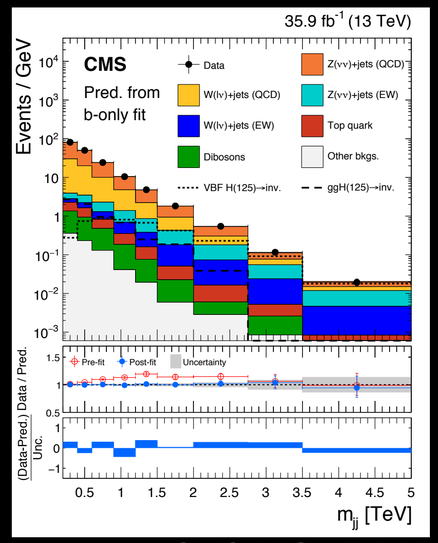
Invisible Higgs Decays



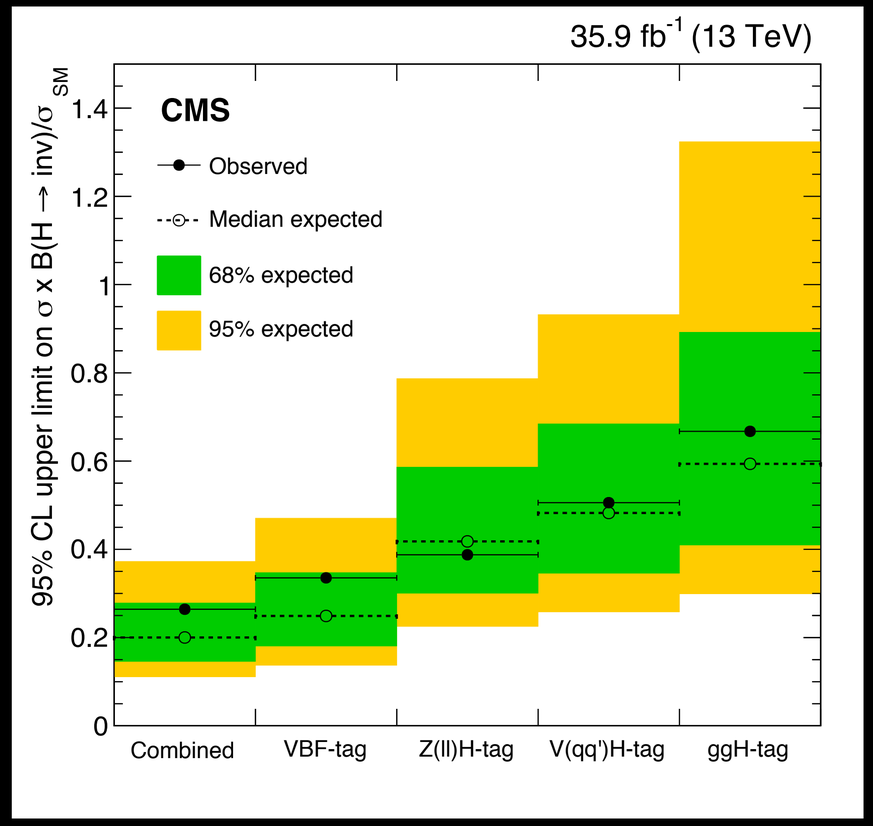
CMS-HIG-16-016



CMS-HIG-16-016



CMS-HIG-17-023



CMS-HIG-17-023

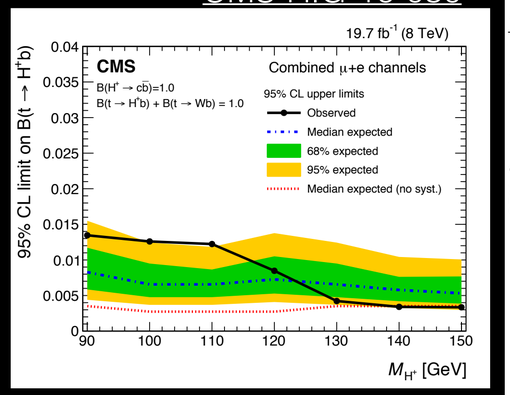
Events with leptonic or hadronic signatures of VBF, VH, gluon fusion as well as large missing transverse momentum selected.

$\mathcal{B}(\mathrm{H} \to \mathrm{inv}) < 0.26$ at 95% C.L.

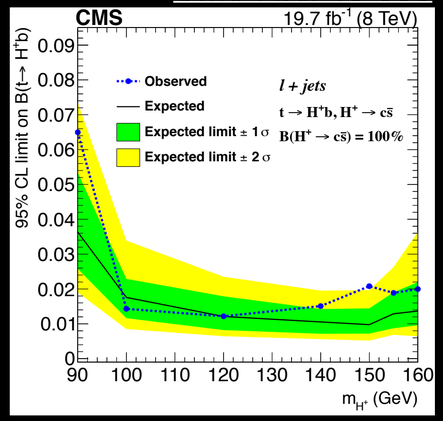
- Even without excess, data still leave possibility that 26% of Higgs decays are invisible.

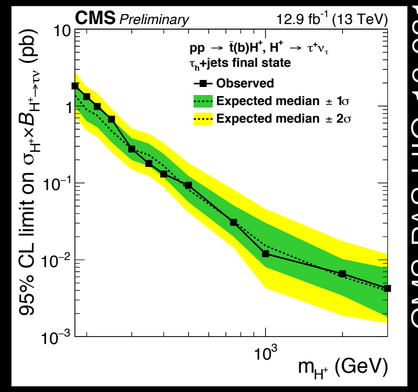
Are There Additional Higgs Bosons?

CMS-HIG-16-030

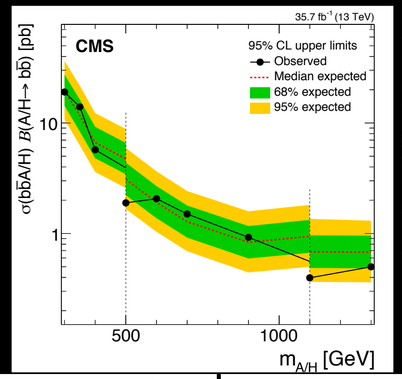


CMS-HIG-13-035

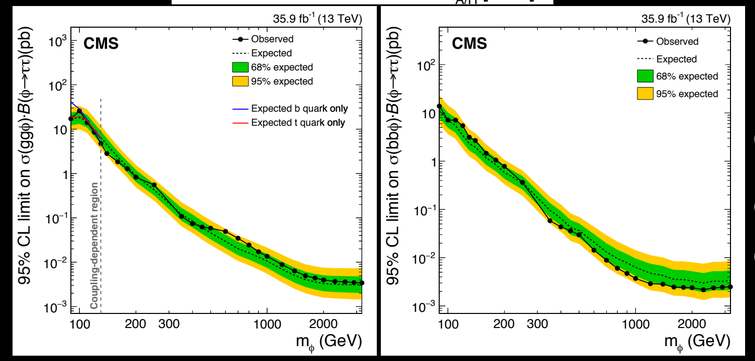




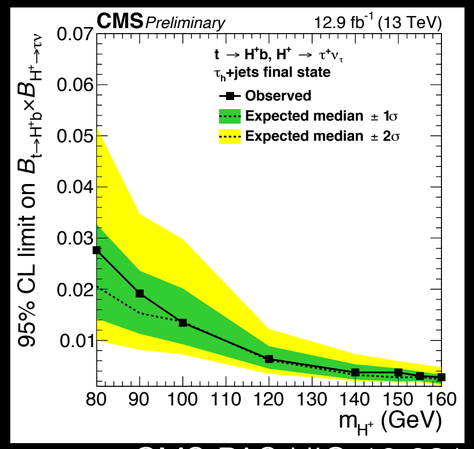
CMS-PAS-HIG-16-031



CMS-HIG-16-018

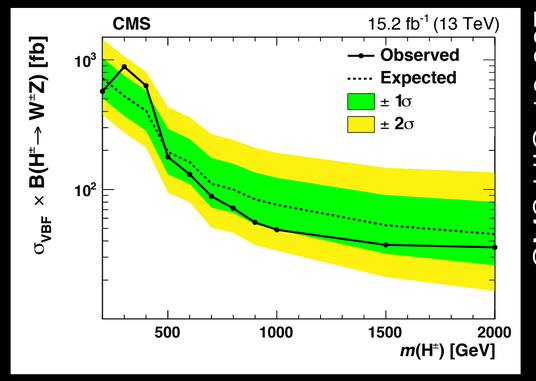


CMS-HIG-17-020



CMS-PAS-HIG-16-031

Low Mass Charged Higgs: Look for decays of t→H⁺b. Consider different H⁺ decays (cs, cb, τν). Limits on B(t→H⁺b) at percent level.



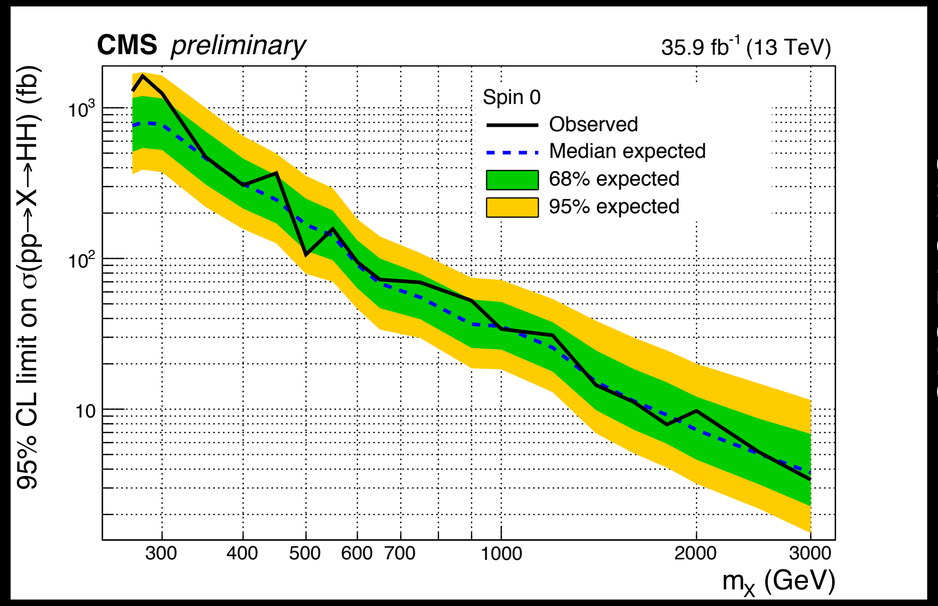
CMS-HIG-16-027

High Mass Charged Higgs: Look in associated tb production (H⁺→τν) or VBF (H⁺→WZ). Limits on σ×B(H⁺→XY) in range of ~1 pb and lower depending on mass.

BSM Neutral Higgs: Look for bb or ττ resonance for additional Higgs. Limits on σ×B(H→XX) ~ 1-10 pb depending on mass.

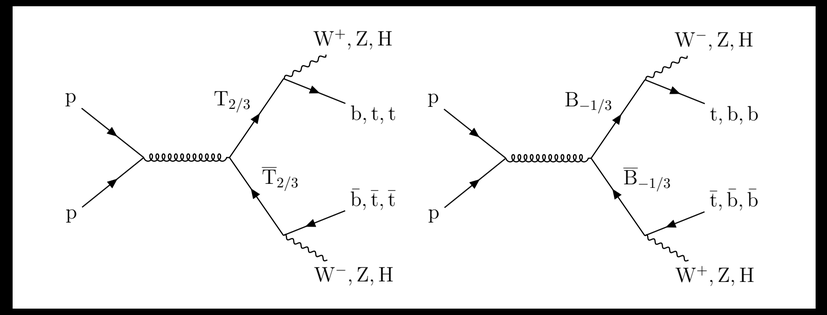
Results also obtained for specific theoretical framework (MSSM)

Higgs as Gateway to New Physics

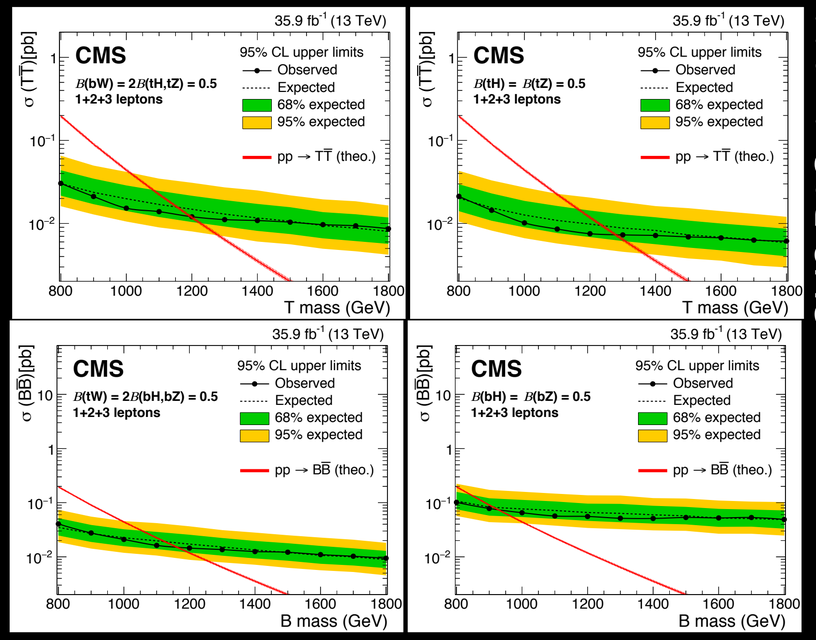


CMS-PAS-HIG-17-030

HH Resonance Search: Extend HH analysis to look specifically for resonant production as a function of mass.



Vector Top Partners: Decay signatures that include t and b quarks plus W, Z, or H. Limits depend on nature of top partners and assumptions of branching fractions.



CMS-B2G-17-011

- Use Higgs as a probe of new physics via possible Higgs coupling to new higher mass states.

Conclusions

- Much progress made on Higgs physics program
  - Couplings to vector bosons and heaviest quarks and leptons consistent with SM expectations
  - Major deviations from SM spin/parity expectations excluded
  - Mass precisely determined. Closing in on precise measurement of width.
  - HH production measurements still far from SM sensitivity (look to HL-LHC)
- Moving to use Higgs as a probe for new physics
  - Precision coupling measurements
  - BSM and rare decays
  - Higgs coupling to new particles
- Higgs and top physics connected via $y_t \sim 1$. Watch for more interesting things in future.