Imperial College London

Standard Model Higgs Boson Properties Measurements

Seth Zenz, on behalf of the ATLAS and CMS Collaborations

SUSY 2018
23 July 2018

- Introduction
- Couplings to ZZ and γγ: precision measurements
  - Higgs Mass and Width
  - Measurements in kinematic bins
- Couplings to fermions: discoveries and searches
  - Bottom Quarks
  - τ Leptons
  - Top Quarks
- Combined measurements

The SM Higgs Boson

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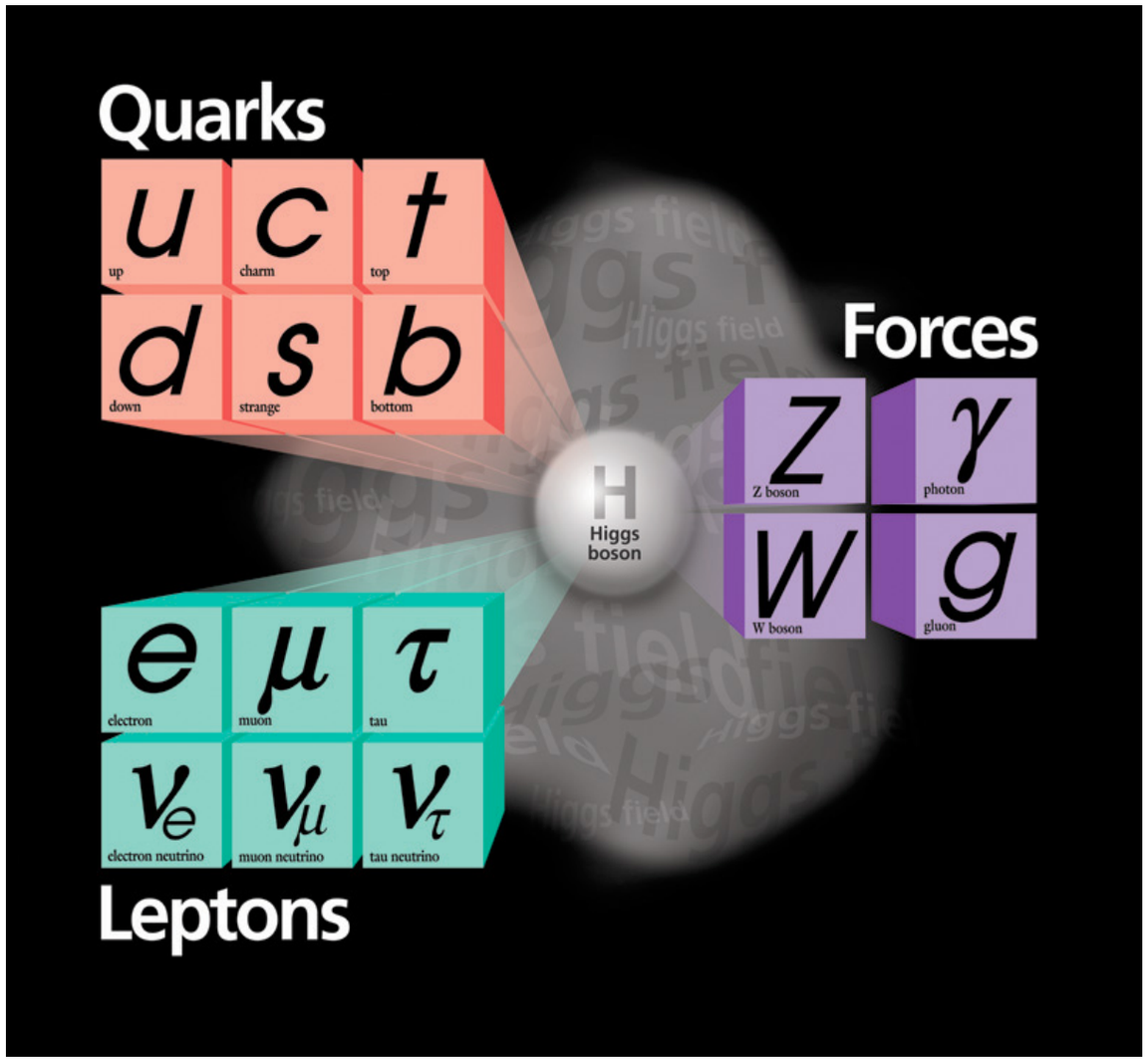

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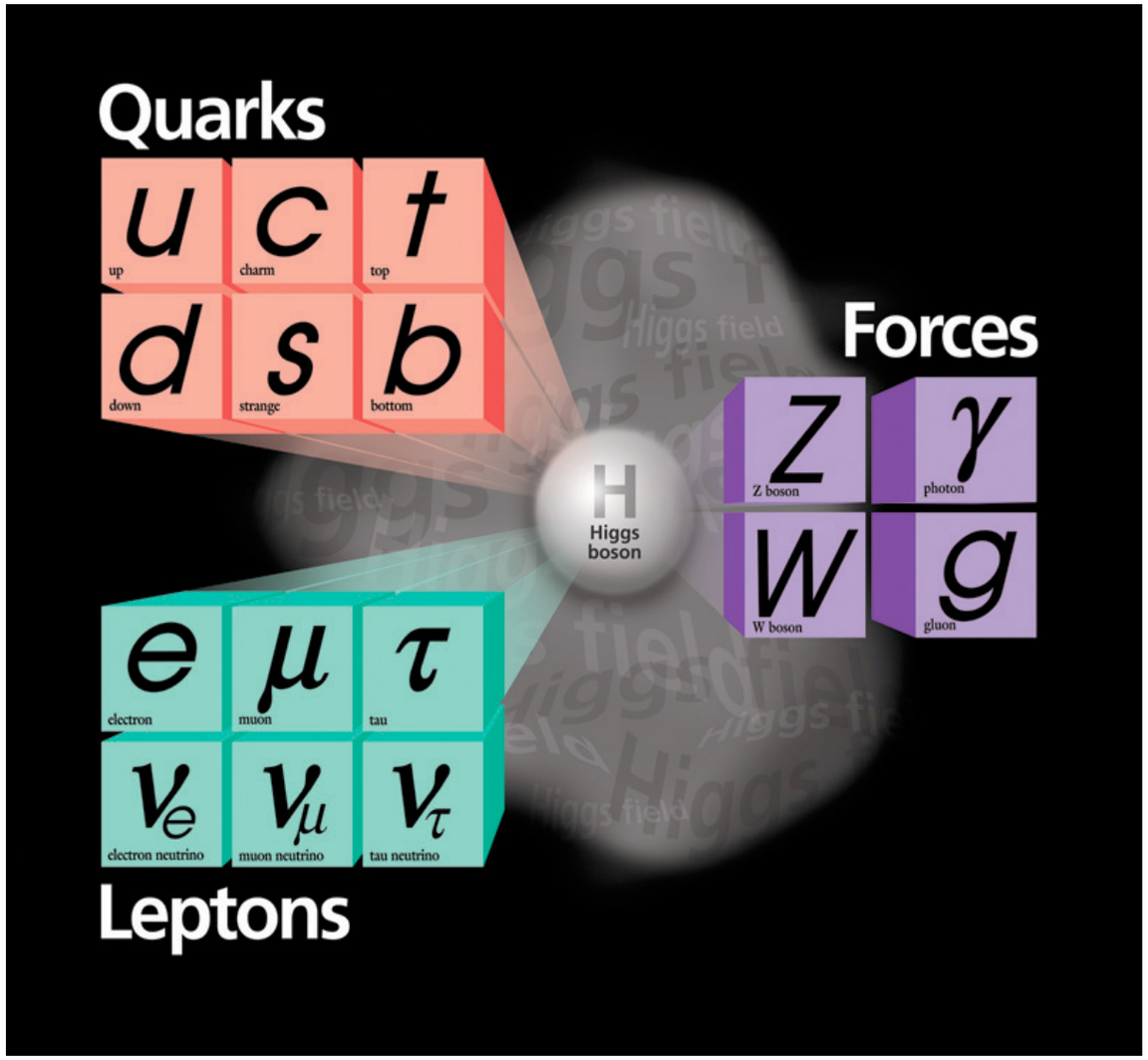

The Higgs field …

…Interacts with gauge bosons to leave
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…Interacts with 3 generations of
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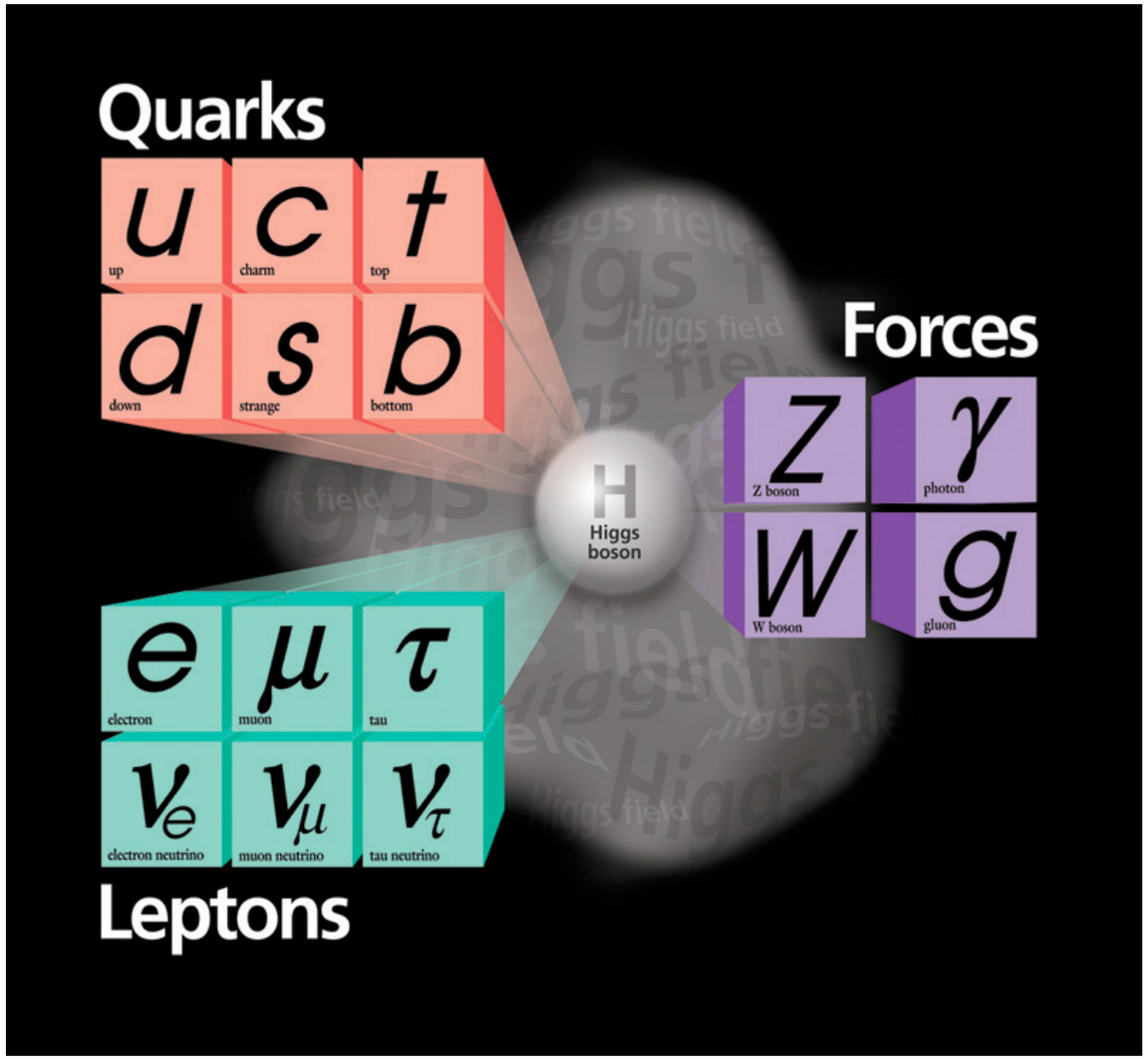

Now that we know the Higgs mass, the SM predicts all interaction rates, so we can test:

- Decay Rates
- Production Cross Sections

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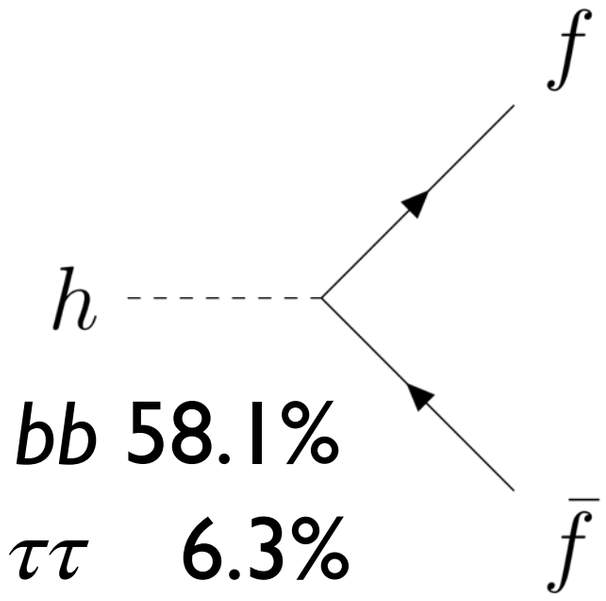

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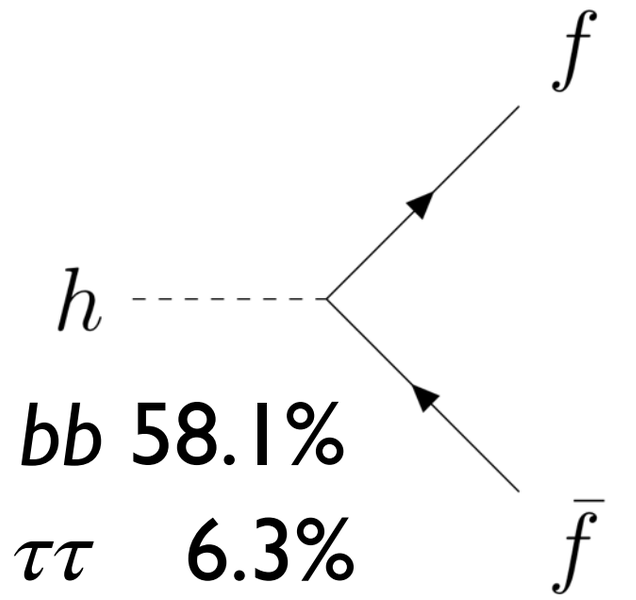

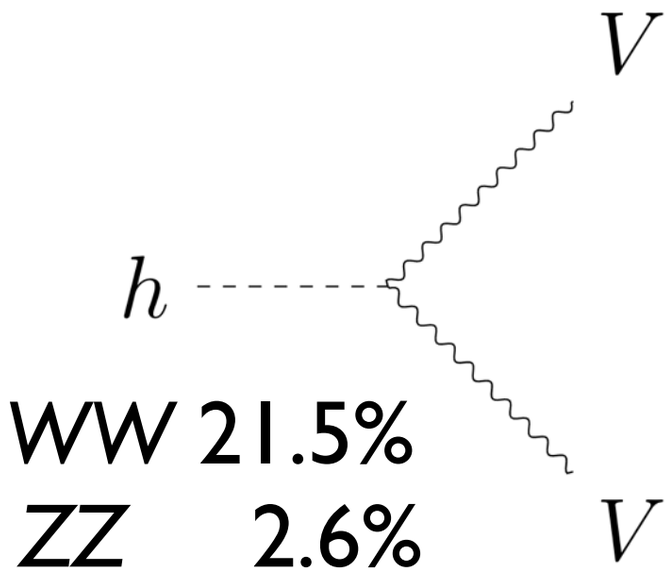

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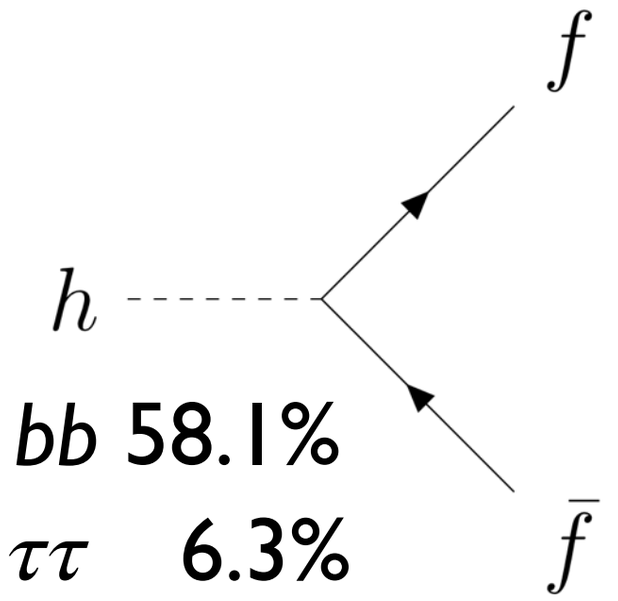
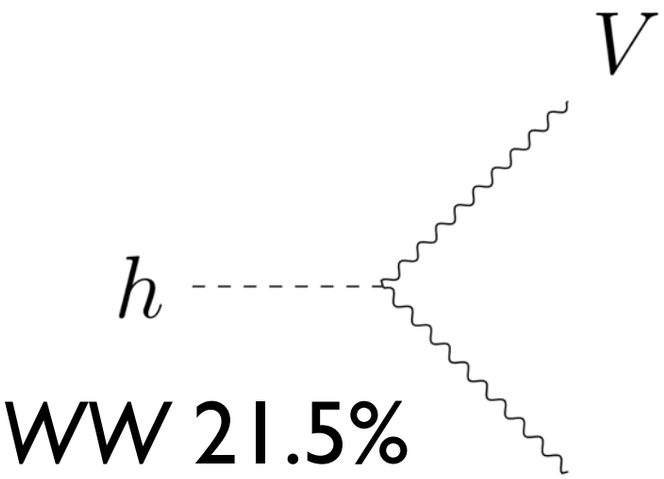


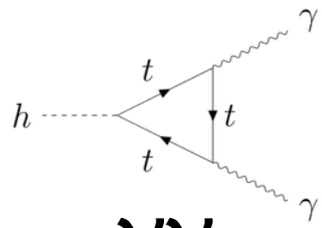
bb 58.1%

$\tau\tau$ 6.3%

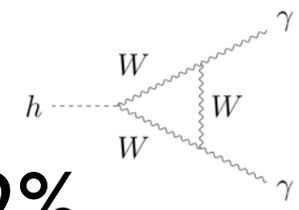


WW 21.5%

ZZ 2.6%



γγ 0.2%



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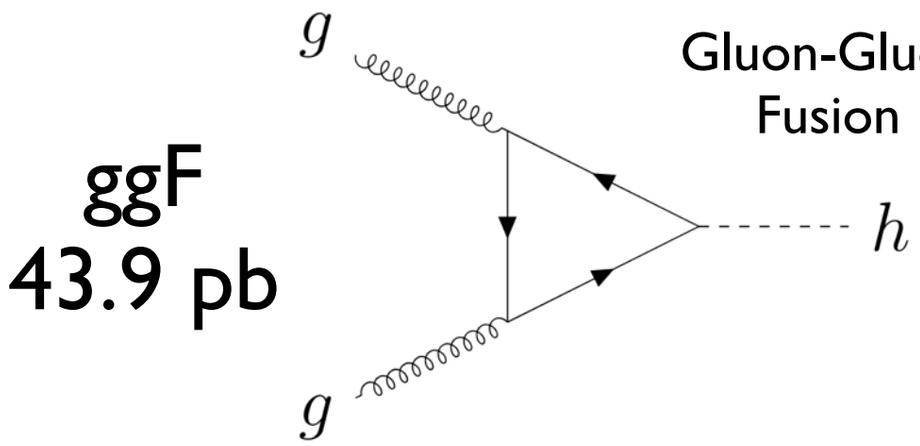
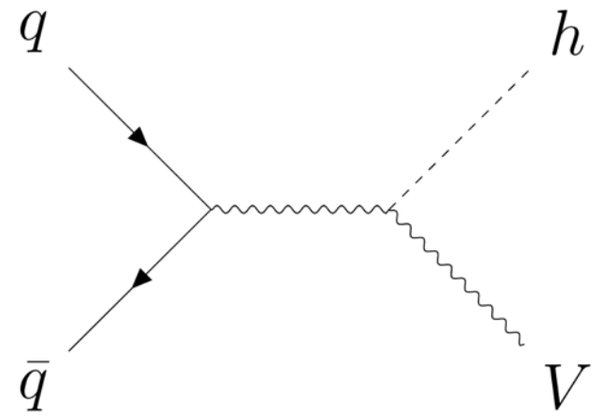
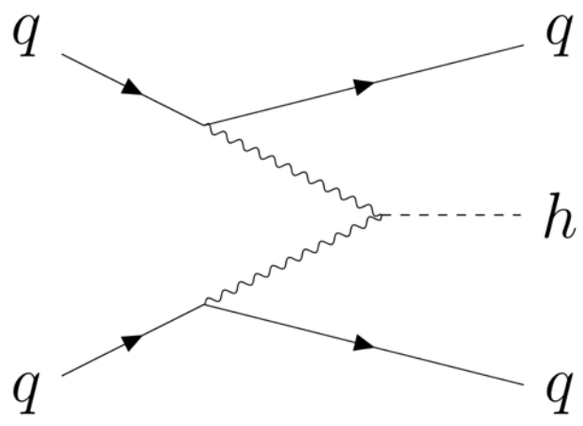


Gluon-Gluon Fusion

ggF
43.9 pb

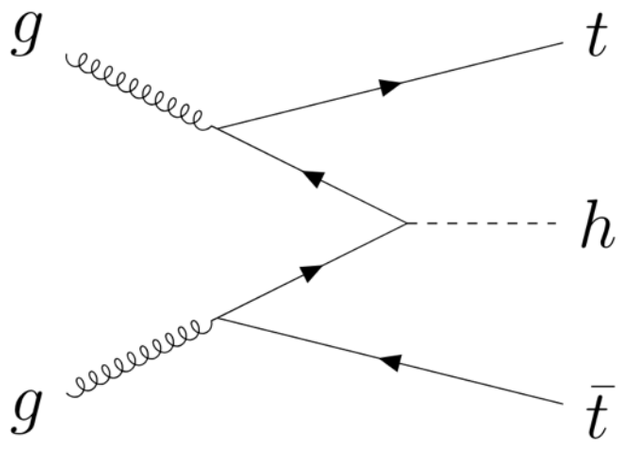


VH
2.2 pb



Vector Boson Fusion

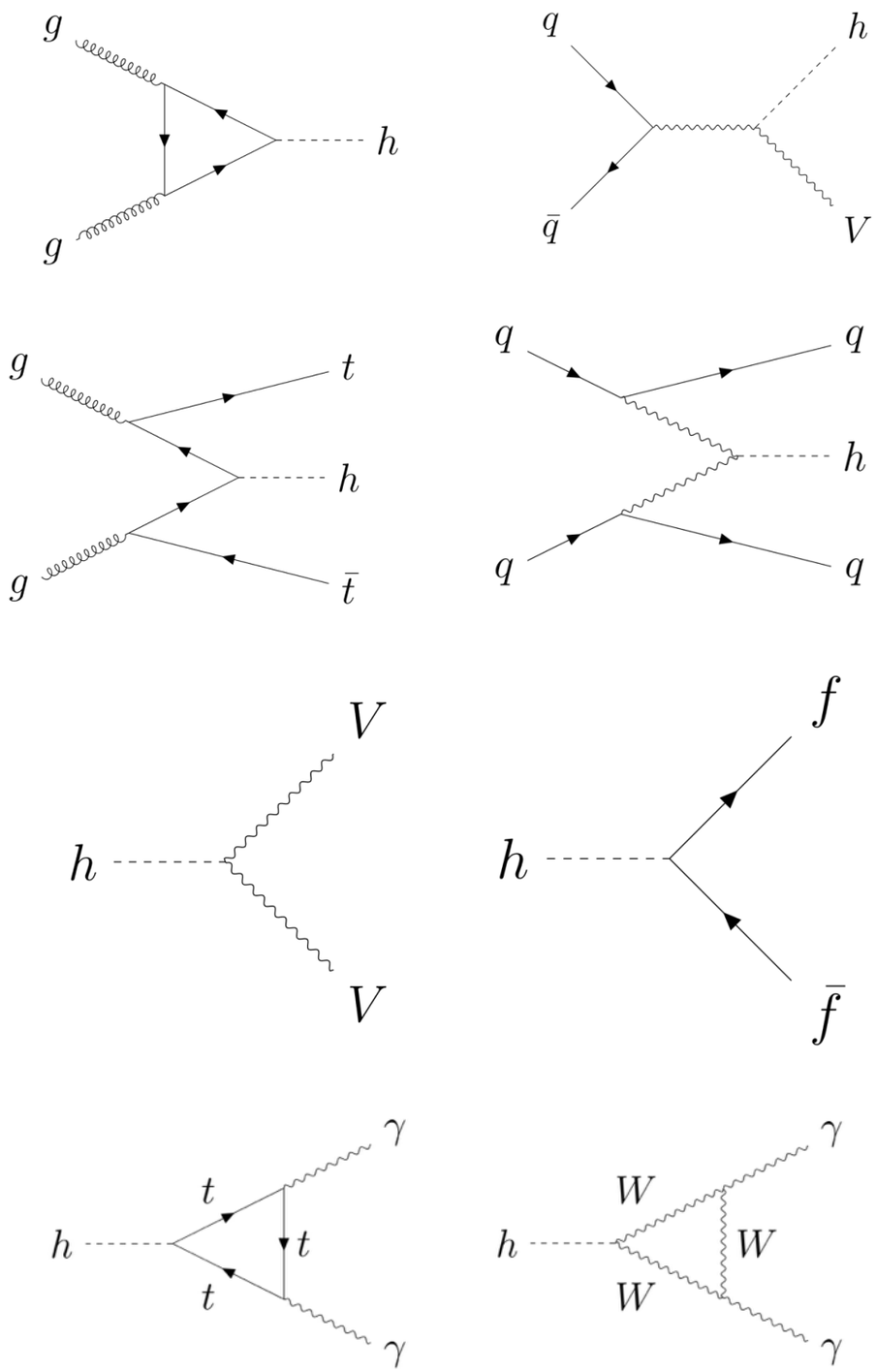
VBF
3.7 pb



ttH
0.5 pb

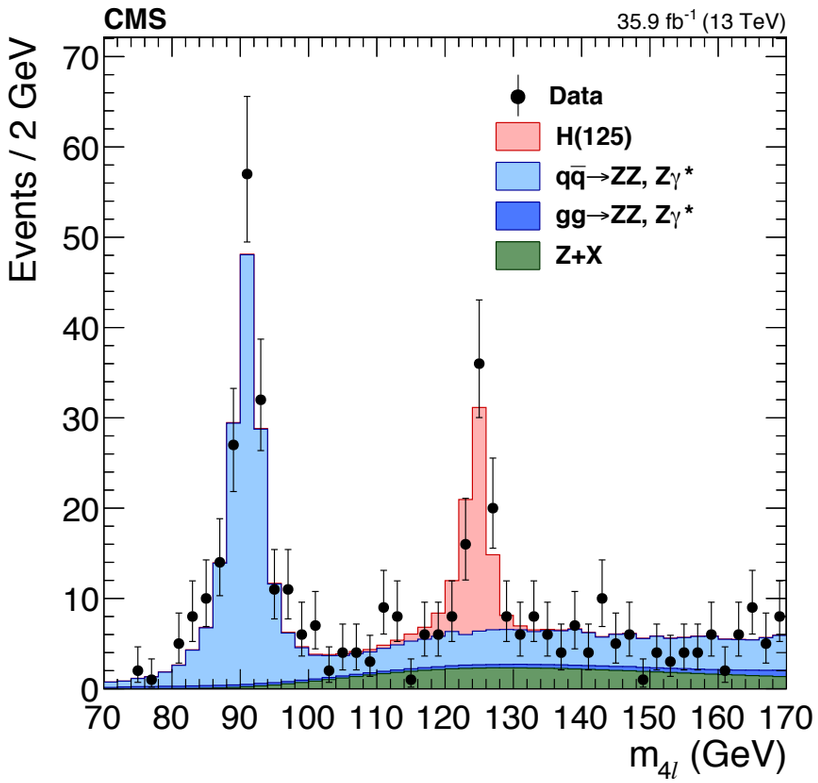
The SM Higgs Boson

- The Higgs boson is a window of discovery for new particles and interactions
- Why? The Standard Model (SM) precisely predicts Higgs interactions
  - Decay Rates
  - Production Cross Sections
- Do these rates agree with the SM? If not, there are new particles and interactions!

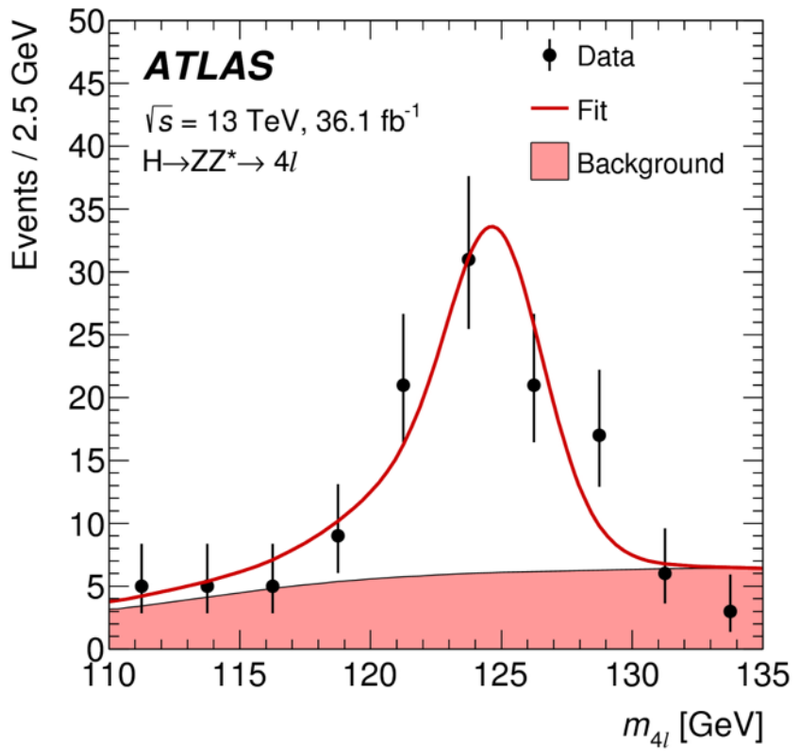


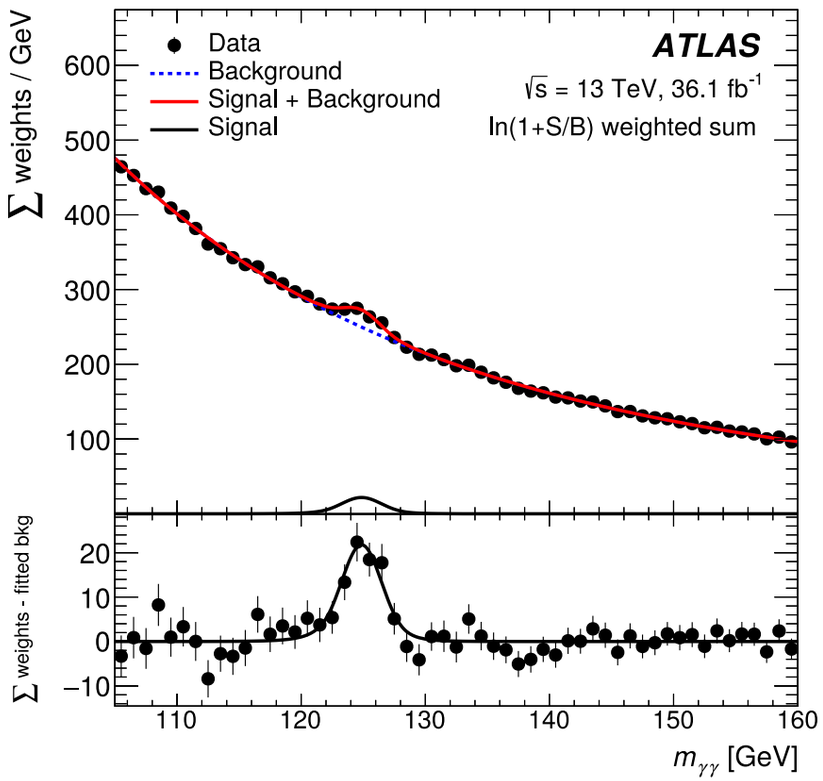
Higgs Mass

JHEP 11 (2017) 047



arXiv:1806.00242





124.79 ± 0.36 (stat) ±0.05 (syst) GeV

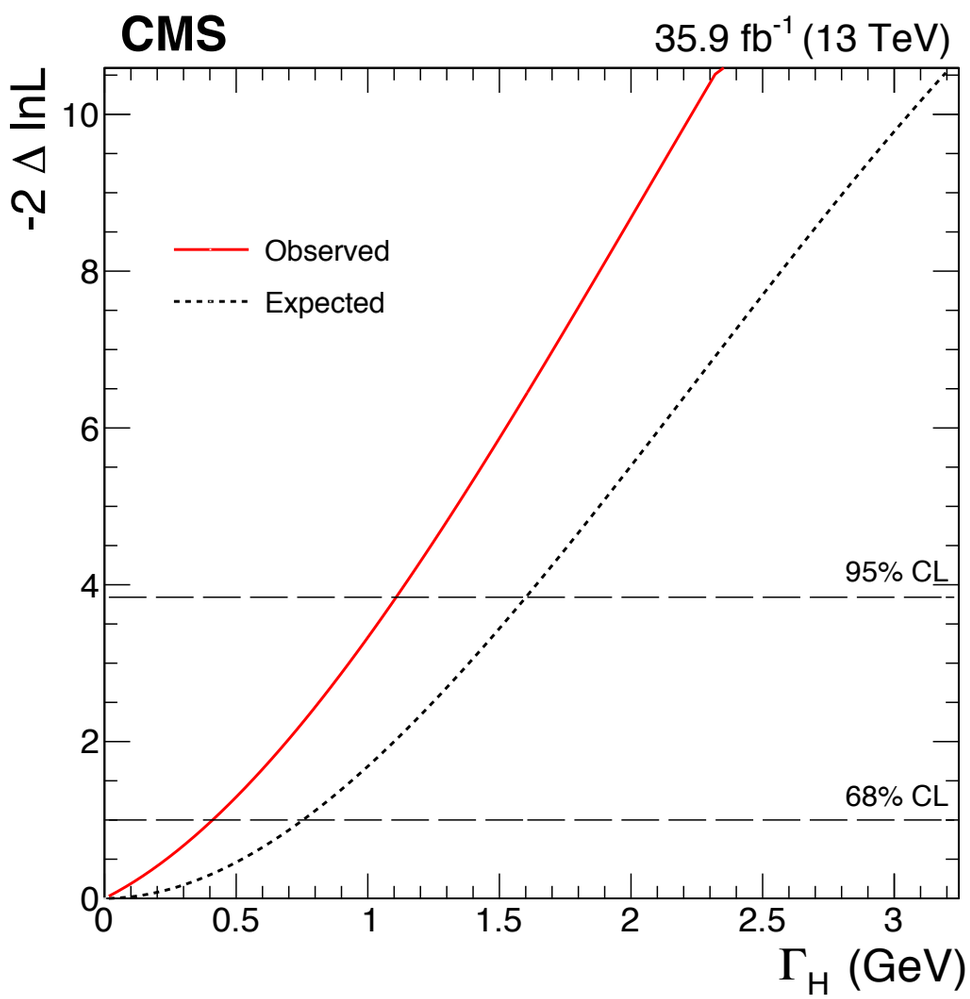
125.26 ± 0.20 (stat) ± 0.08 (syst) GeV

124.93 ± 0.21 (stat) ± 0.34 (syst) GeV

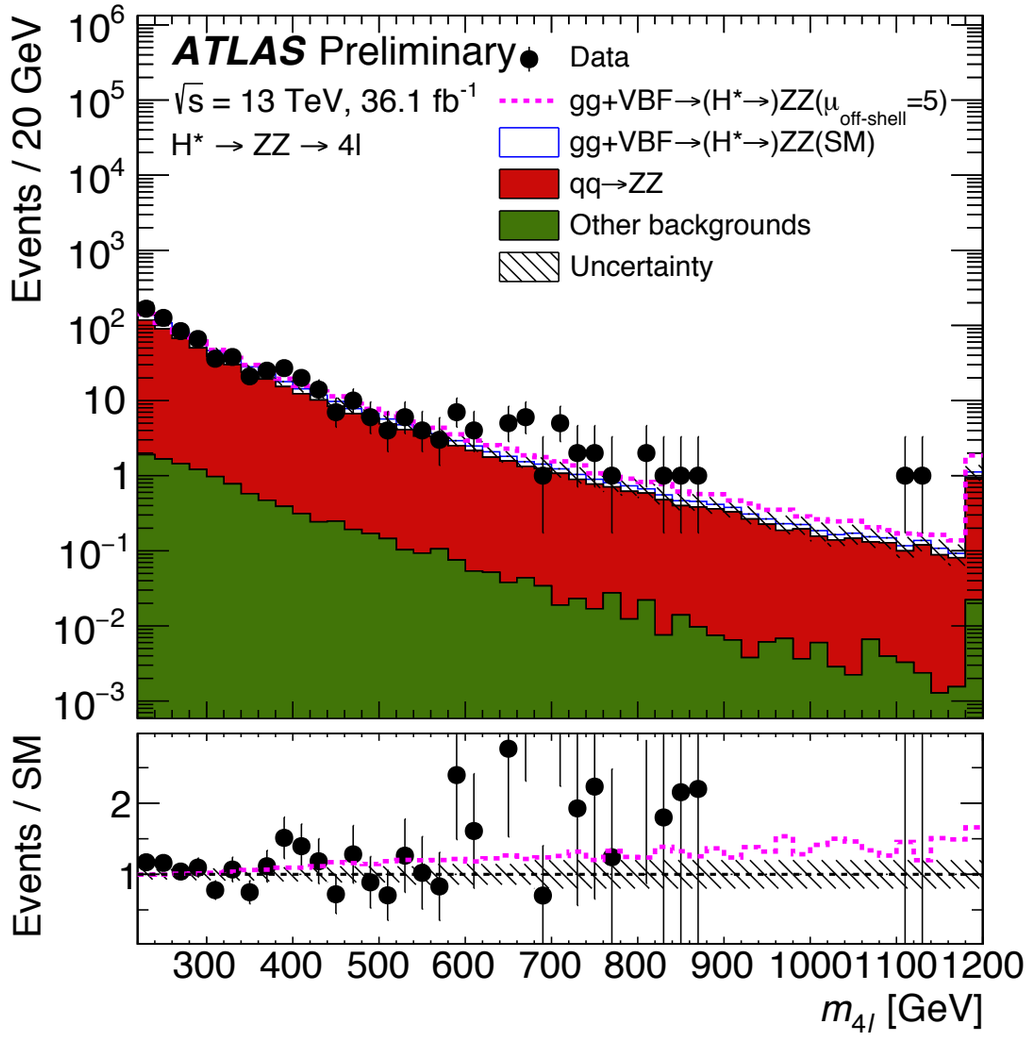
- CMS H to 4ℓ: 125.26 ± 0.21 GeV
- ATLAS Run 2 Combined: 124.86 ± 0.27 GeV
- ATLAS Run 1 + Run 2: 124.97 ± 0.24 GeV

Higgs Width

- SM Width: 4 MeV
- Direct limit: CMS $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$: $\Gamma_H < 1.1$ GeV (95% CL)
- From on-shell/off-shell cross section ratio (ATLAS): $\Gamma_H < 14.4$ MeV
  - Combines $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$ and $H \rightarrow ZZ^{(*)} \rightarrow 2\ell 2\nu$
  - Assumes effective couplings are the same in both on and off-shell



JHEP 11 (2017) 047



CERN-EP-2018-178

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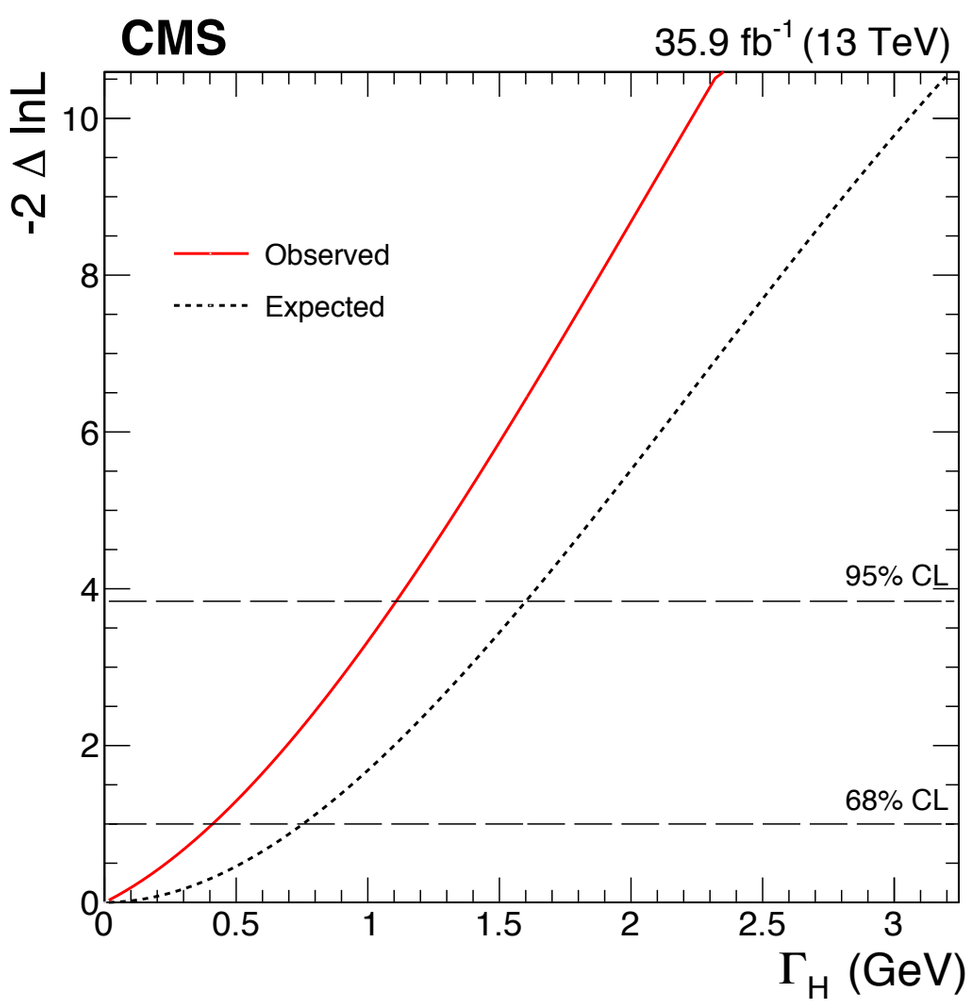

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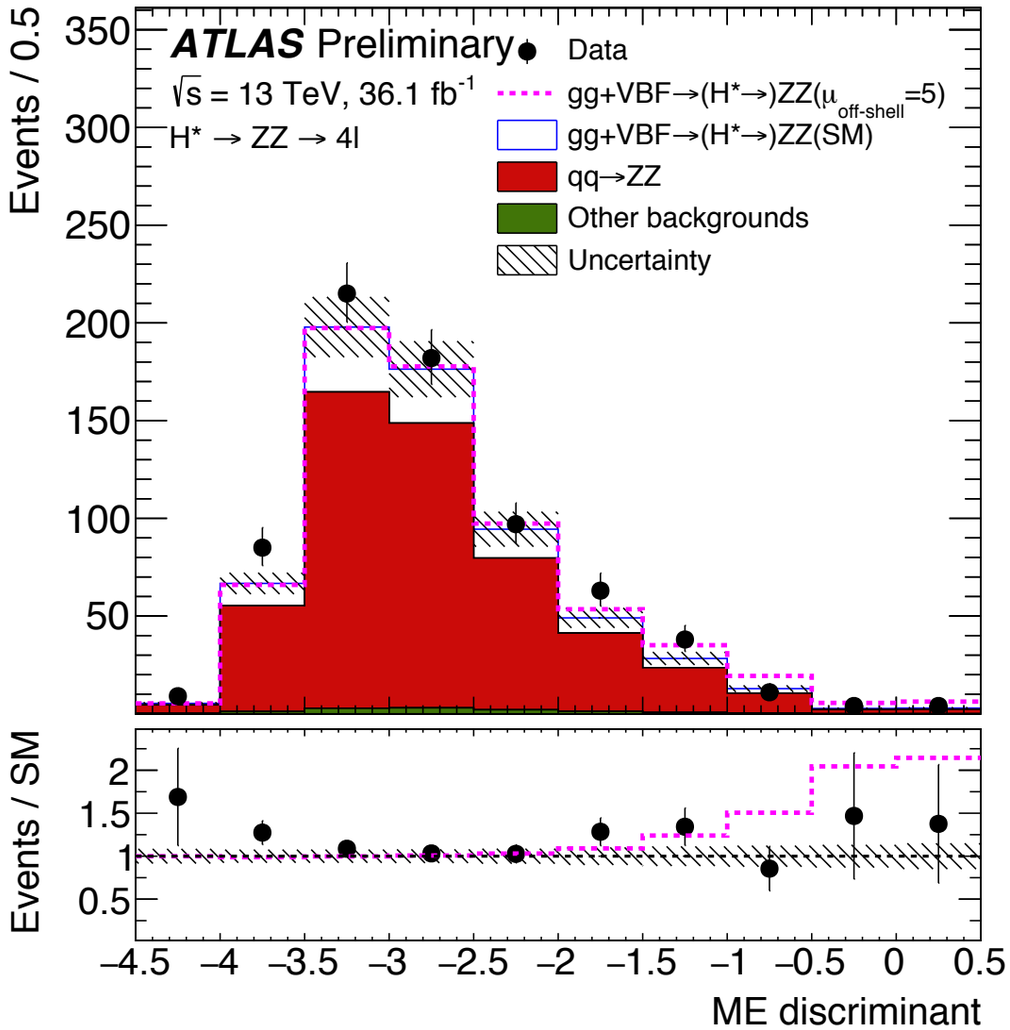

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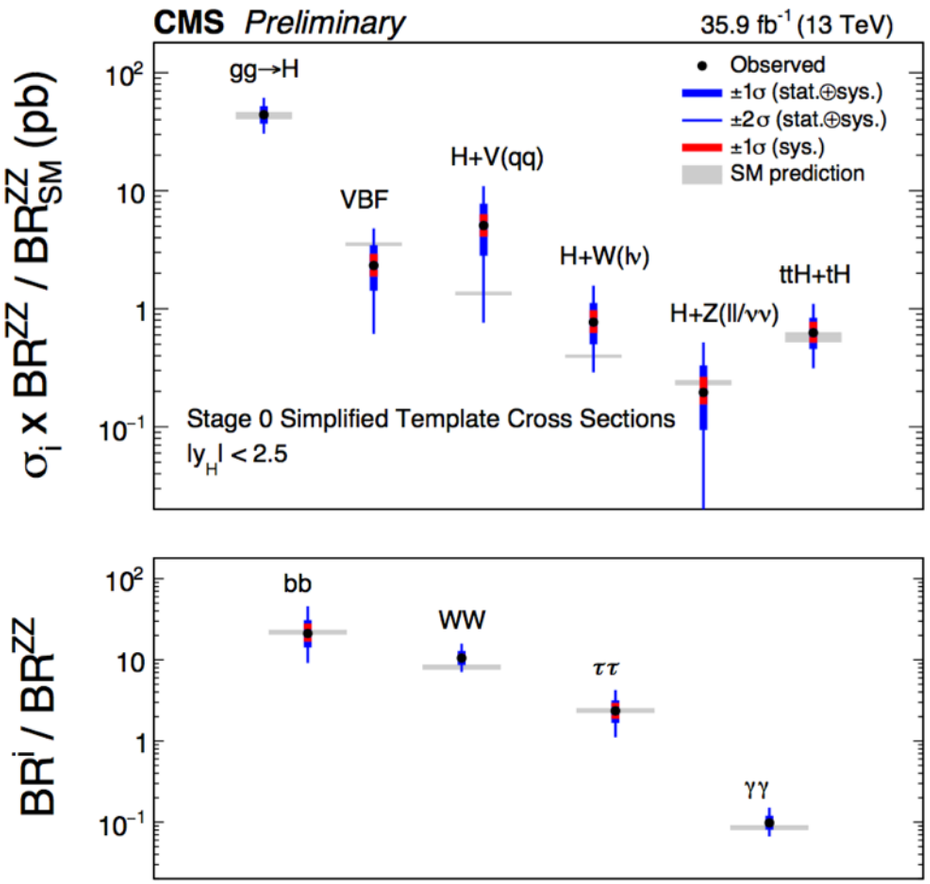
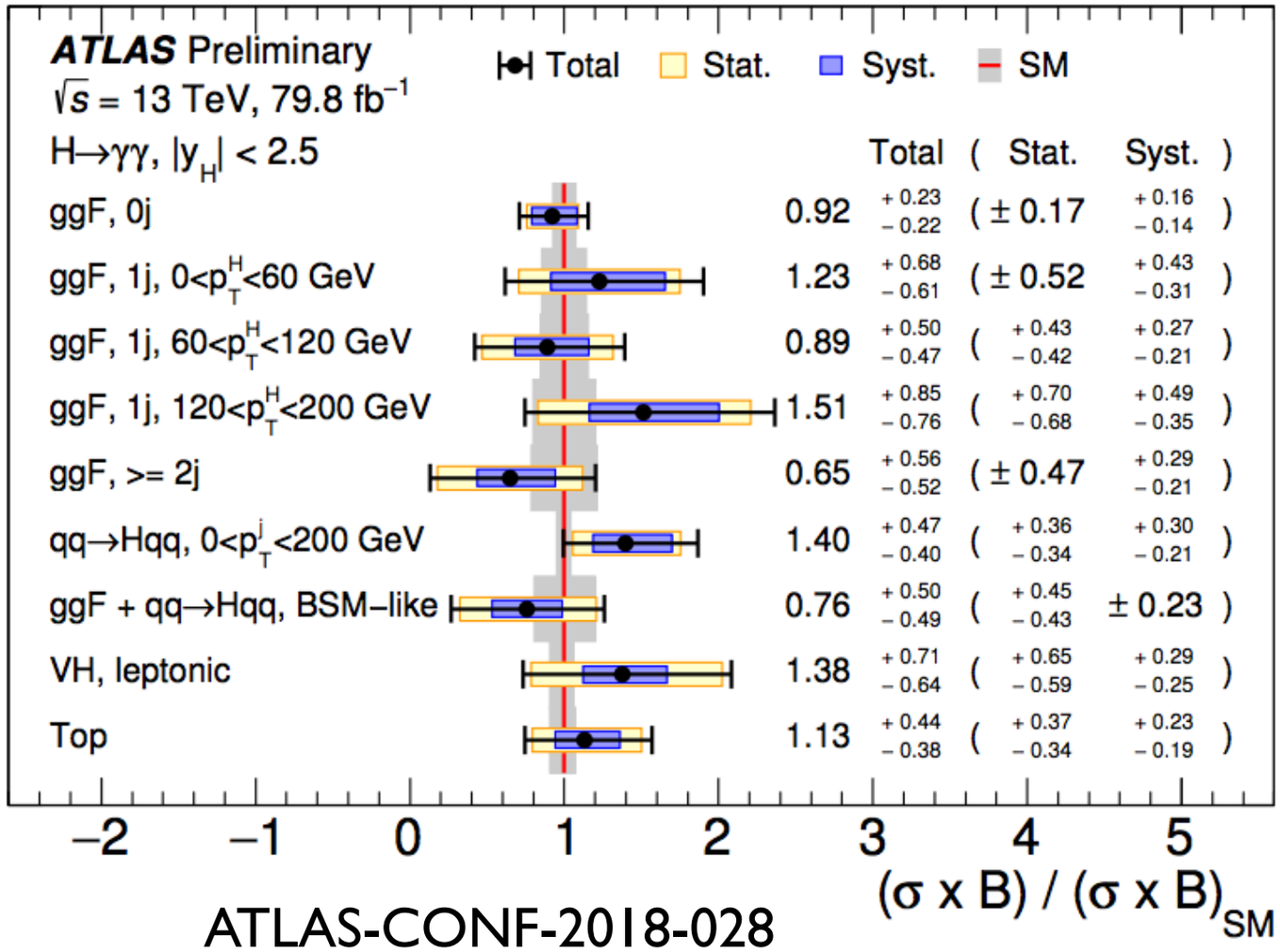
Simplified Template Cross Sections

- Measure Higgs cross sections by production mode and kinematic bins
- More straightforward to reinterpret results in specific BSM models



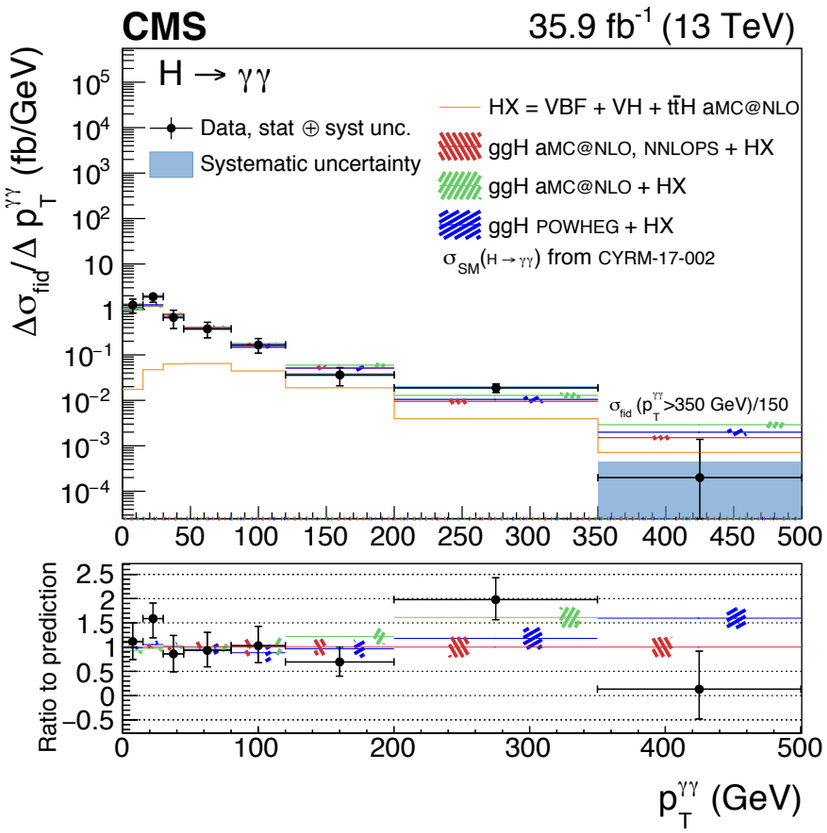
CMS-PAS-HIG-17-031



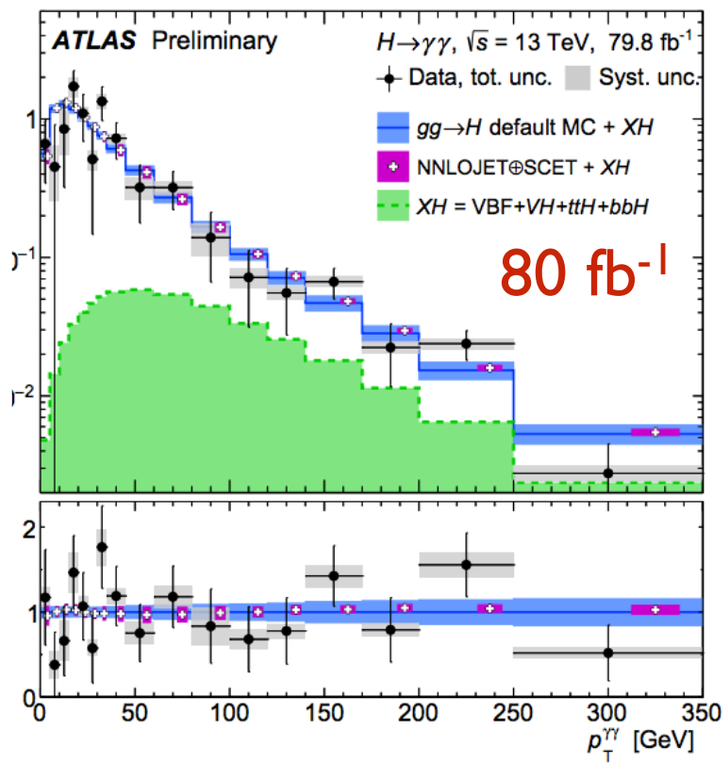
ATLAS-CONF-2018-028

Differential Distributions

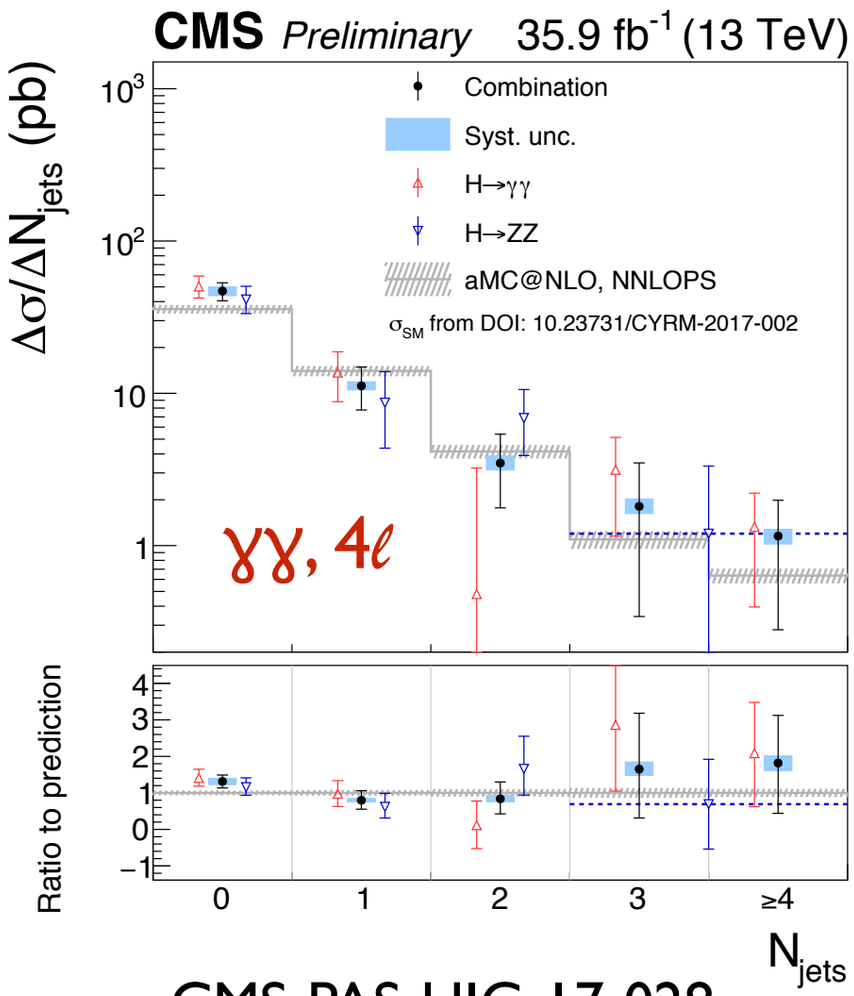
- Fully unfolded distributions binned in kinematic properties
- Higgs events, defined phase space



arXiv:1807.03825



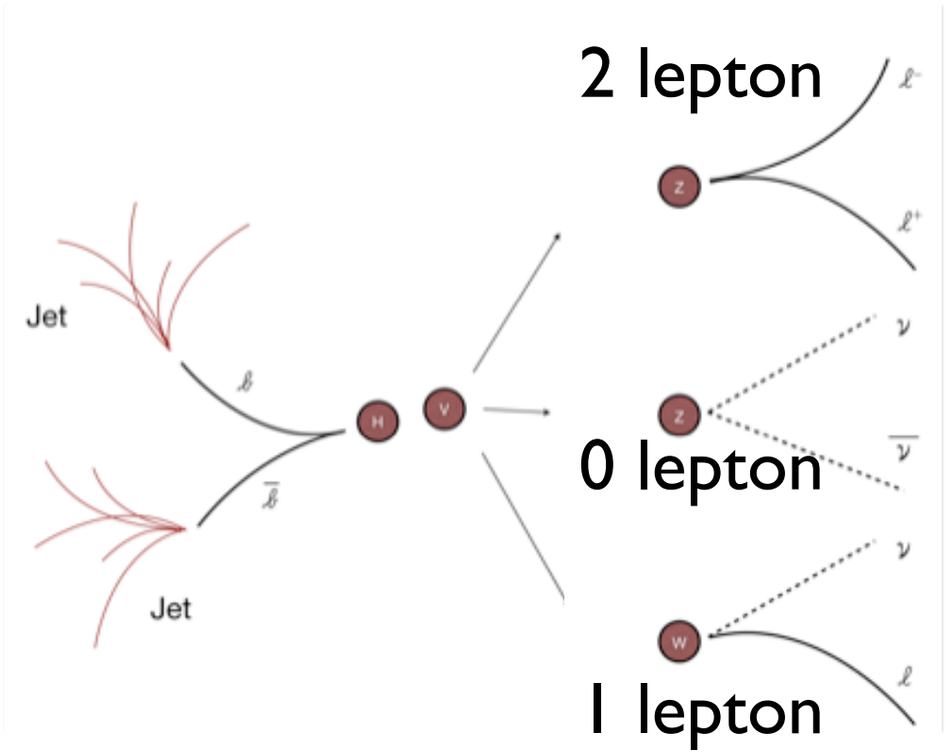
ATLAS-CONF-2018-028



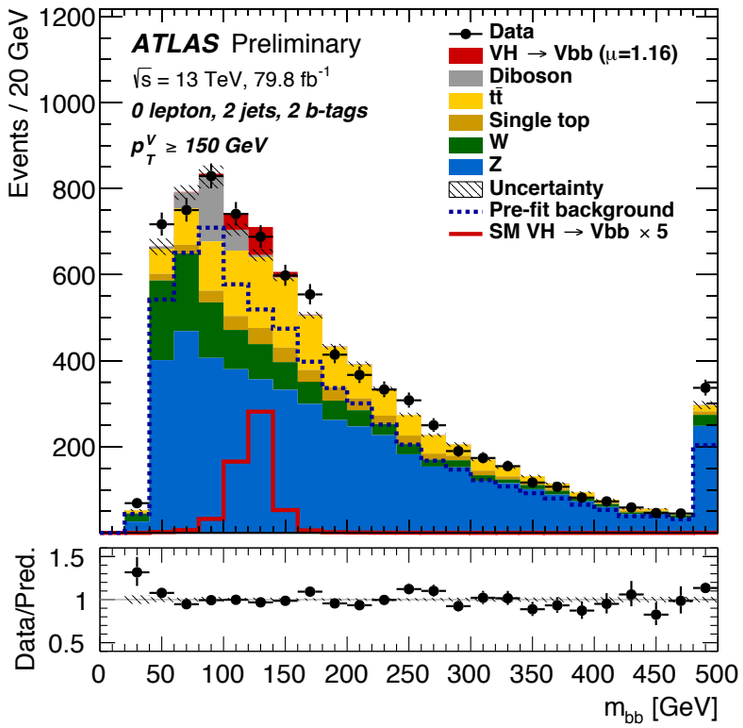
CMS-PAS-HIG-17-028

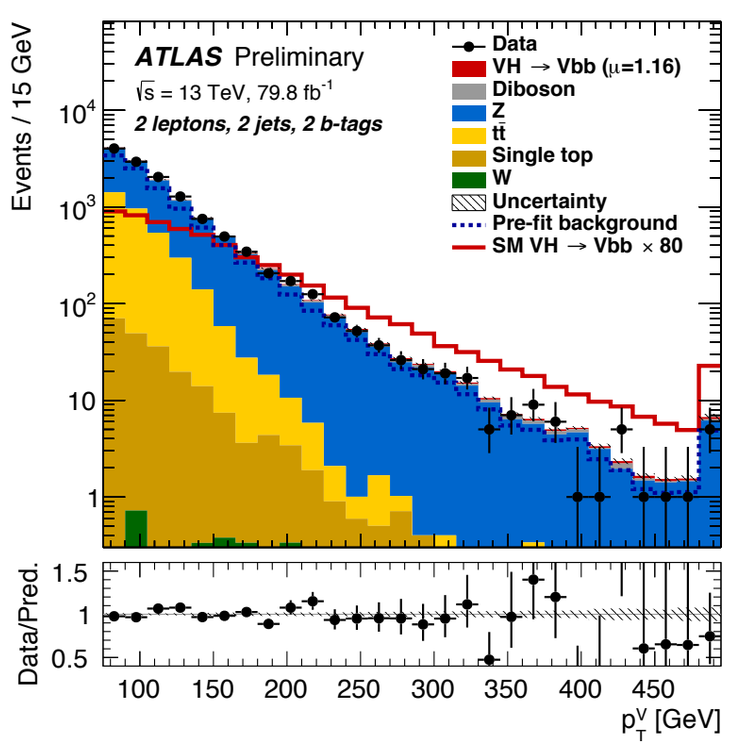
VH, H → bb

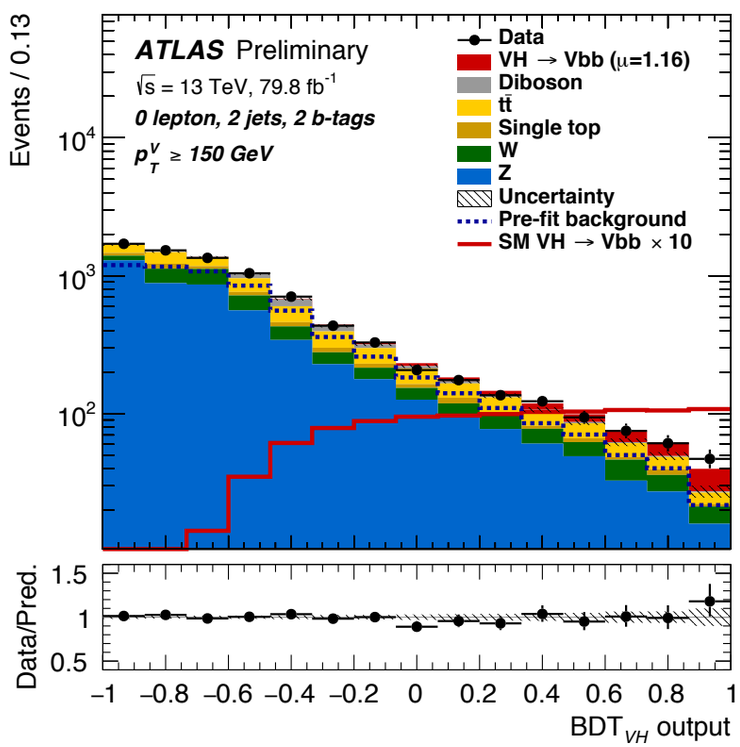
80 fb^{-1}



- Largest decay mode with challenging backgrounds reduced through:
  - Vector boson: 0, 1, or 2 leptons
  - High p_T selection
  - Main discriminants in BDT: m(bb), pT(V) and ΔR(bb)



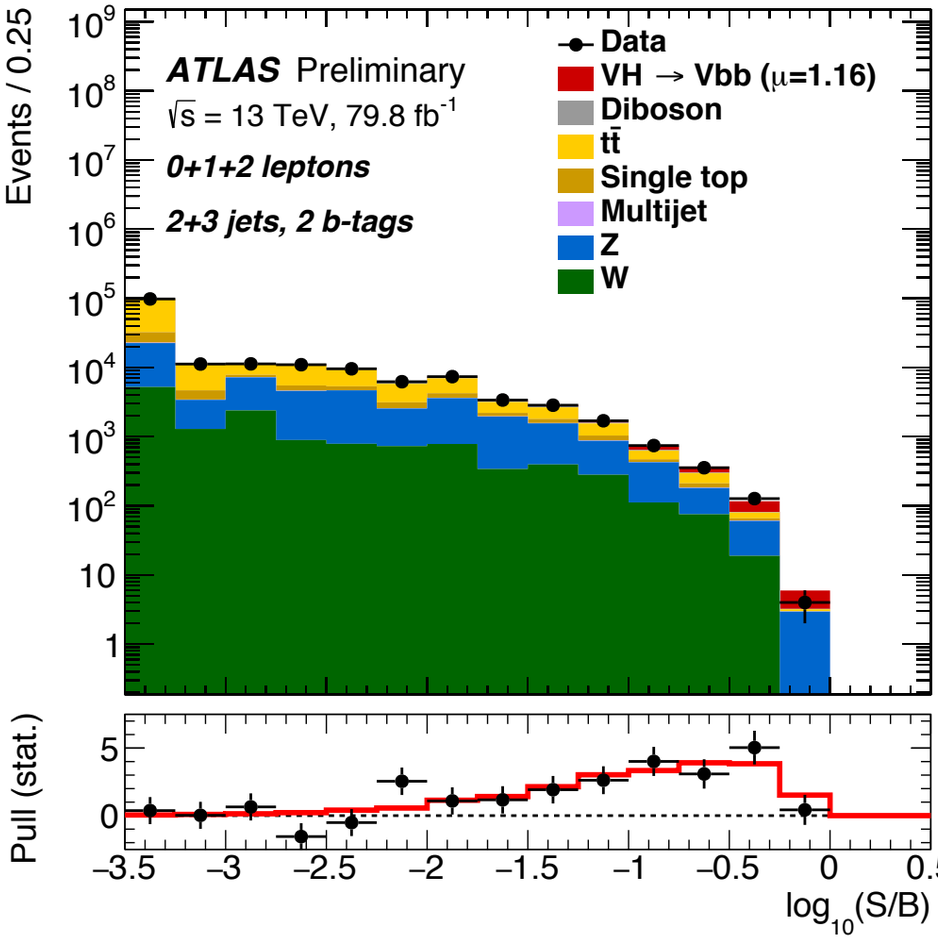


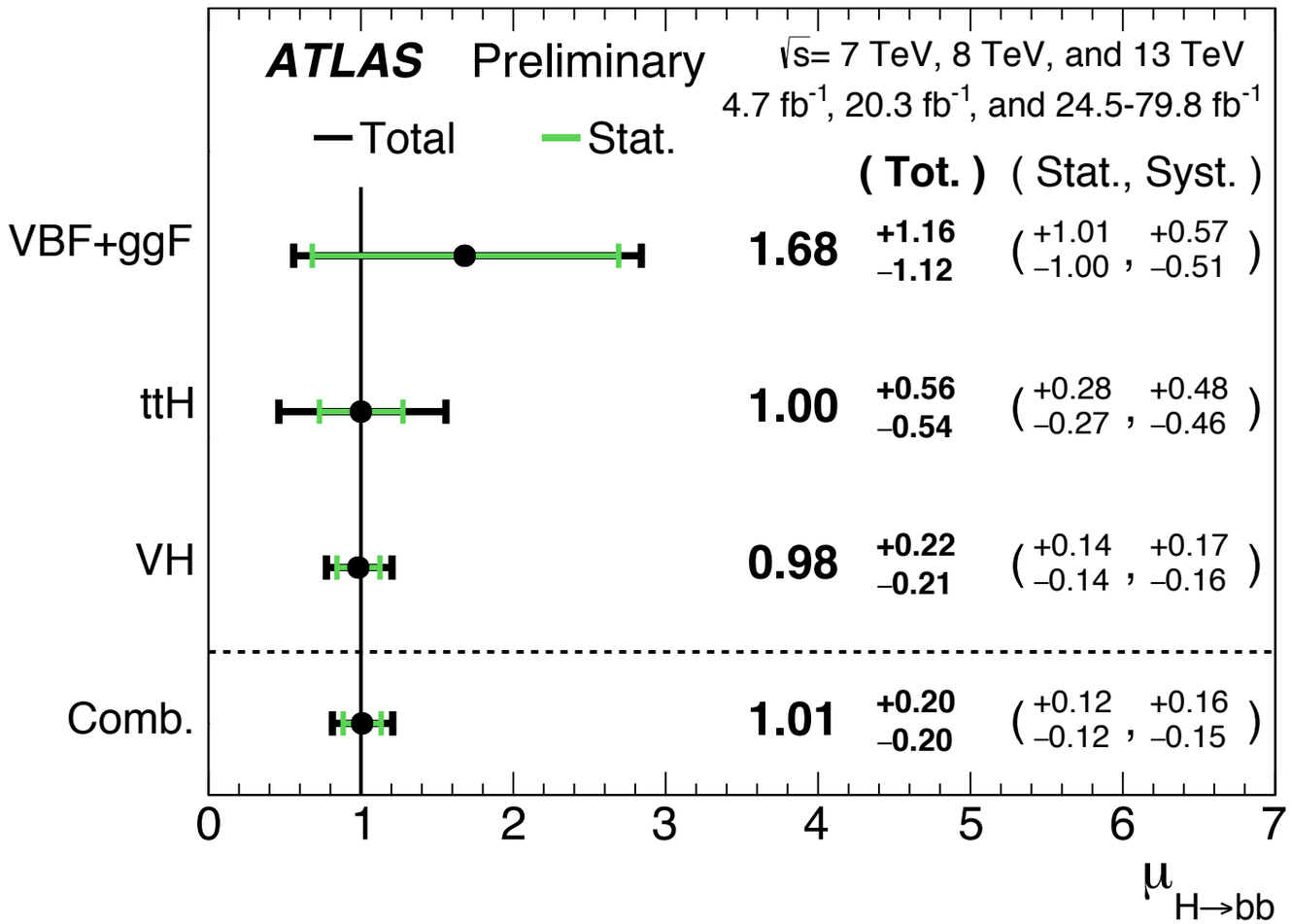


ATLAS-CONF-2018-036

VH and H→bb Observation

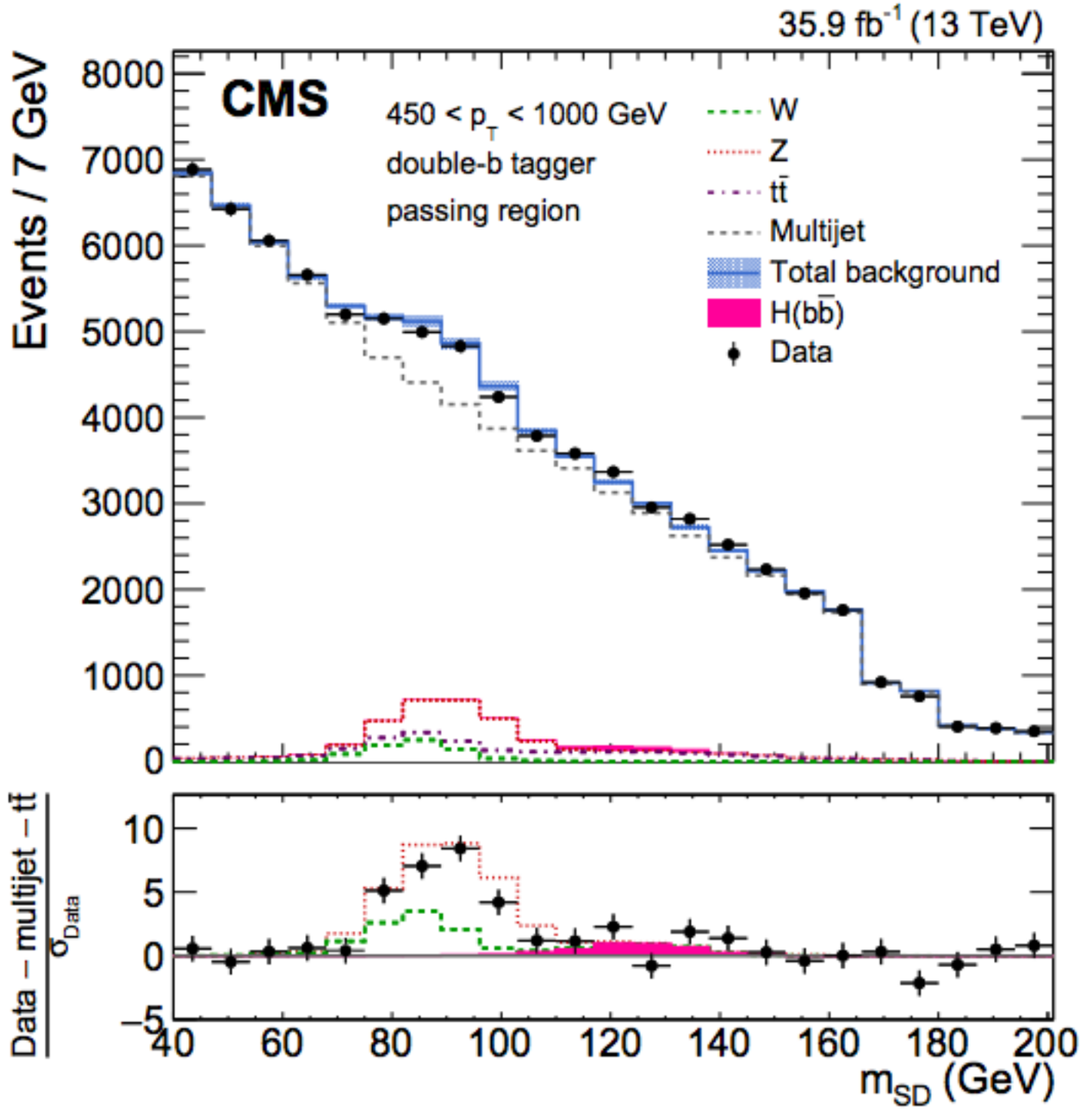
- Run 2 VH, H→bb significance: 4.9σ (4.3σ expected)
- Combined with Run 1: 4.9σ (5.1σ expected)
- Combined with VBF(+ggF) and ttH analyses: 5.4σ (5.5σ exp.)
- VH production combination with γγ, ZZ*: 5.3σ (4.8σ expected)





Boosted Higgs in Gluon Fusion

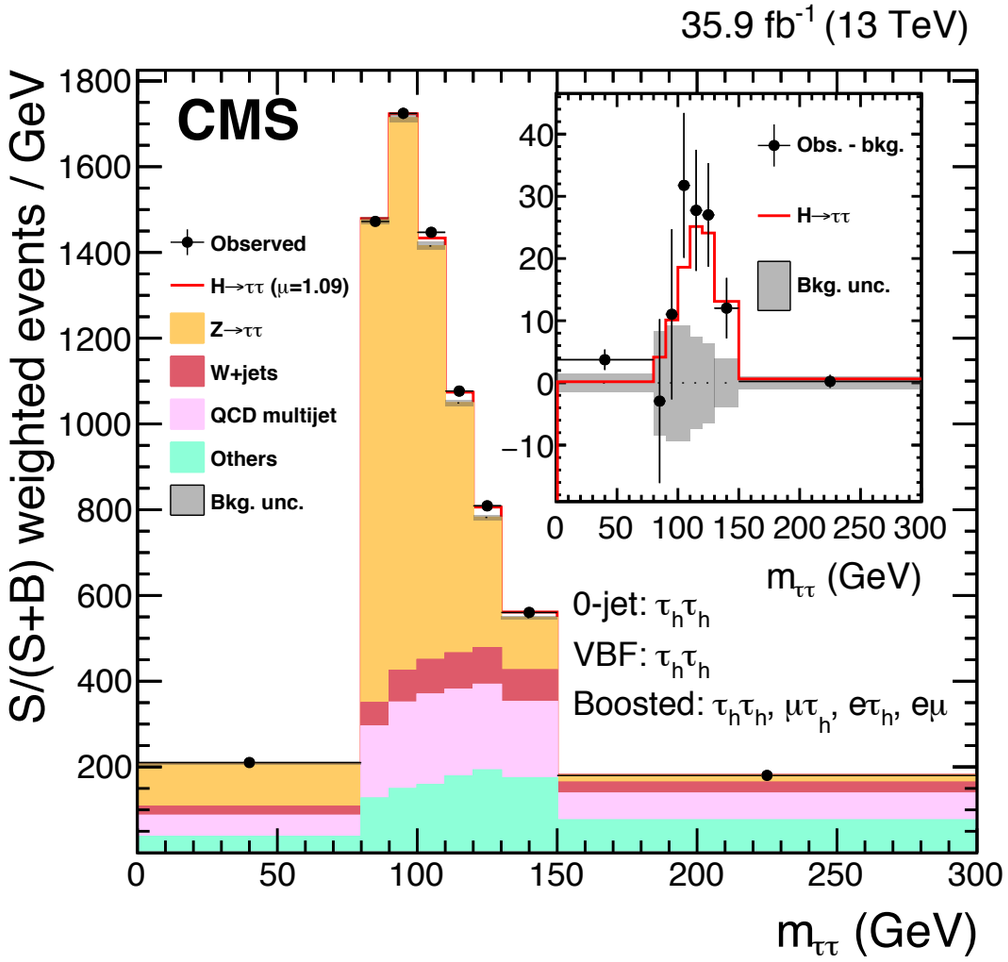
- Large radius jet with with two b-tagged subjets
- p_T > 450 GeV
- Higgs excess 1.5σ (0.7σ expected)
- Such "Higgs-tagging" techniques applicable to BSM events containing Higgs bosons



Phys. Rev. Lett. 120, 071802 (2018)

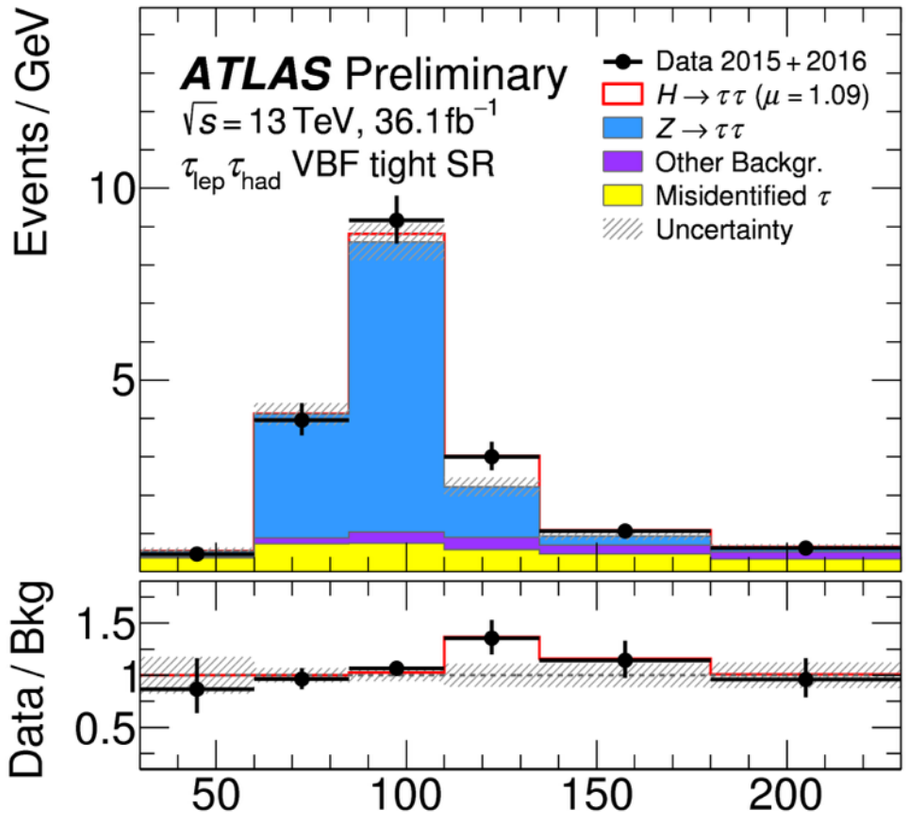
H→ ττ Observations

- Run 1: H→ ττ observation achieved by combining ATLAS+CMS
- 2016 data: independent observations from both experiments
- CMS (ATLAS) has 9 (13) categories to cover hadronic and leptonic τ decays and high p_T regions



Phys. Lett. B 779 (2018) 283

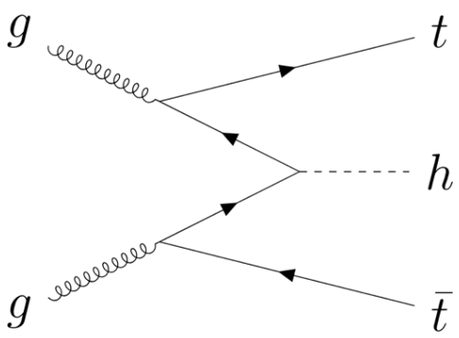
$$1.09^{+0.15}_{-0.15}(\text{stat})^{+0.16}_{-0.15}(\text{syst})^{+0.10}_{-0.08}(\text{th})^{+0.13}_{-0.12}(\text{MCstat})$$



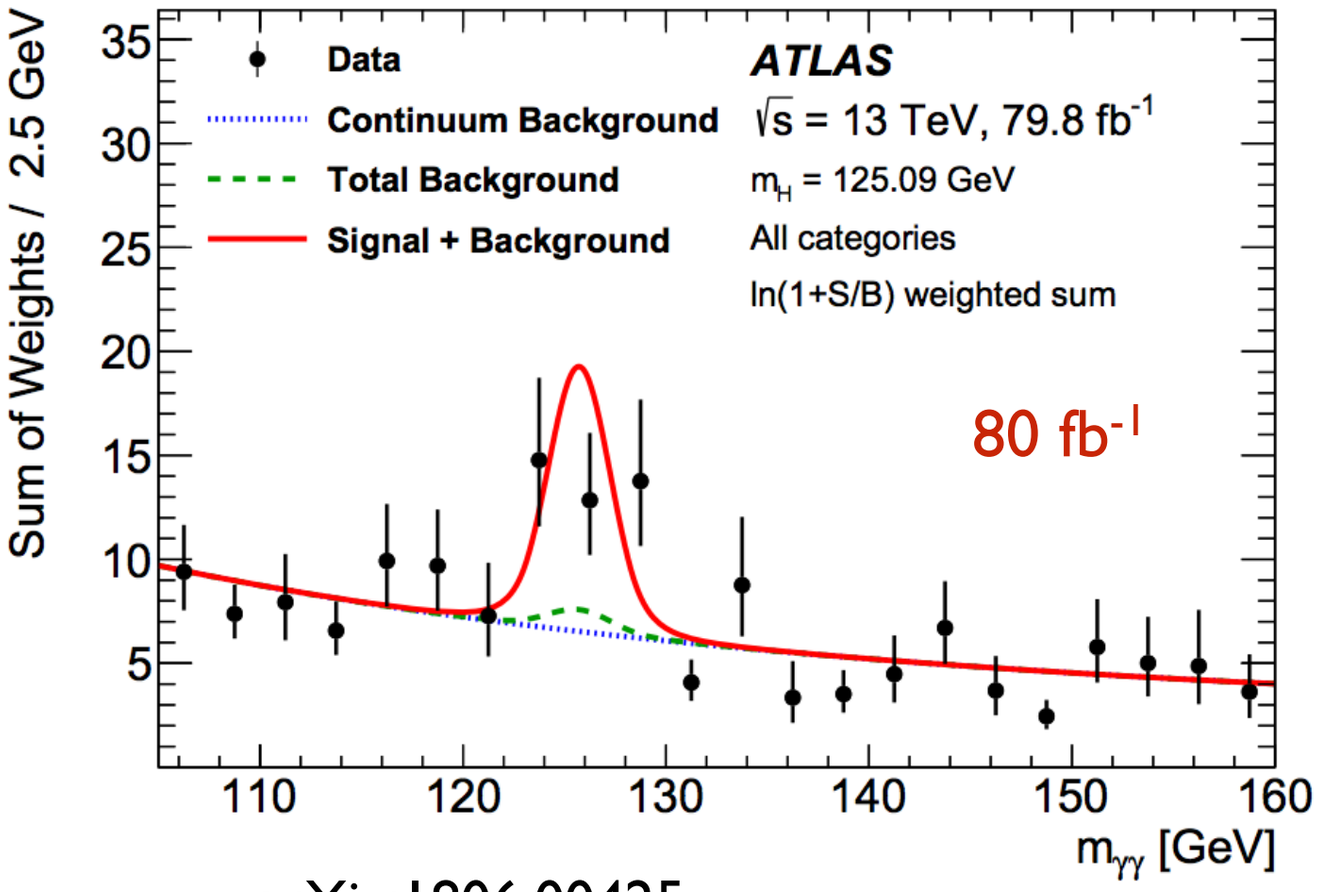
ATLAS-CONF-2018-021

$$1.09^{+0.18}_{-0.17}(\text{stat})^{+0.27}_{-0.22}(\text{syst})^{+0.16}_{-0.11}(\text{th})$$

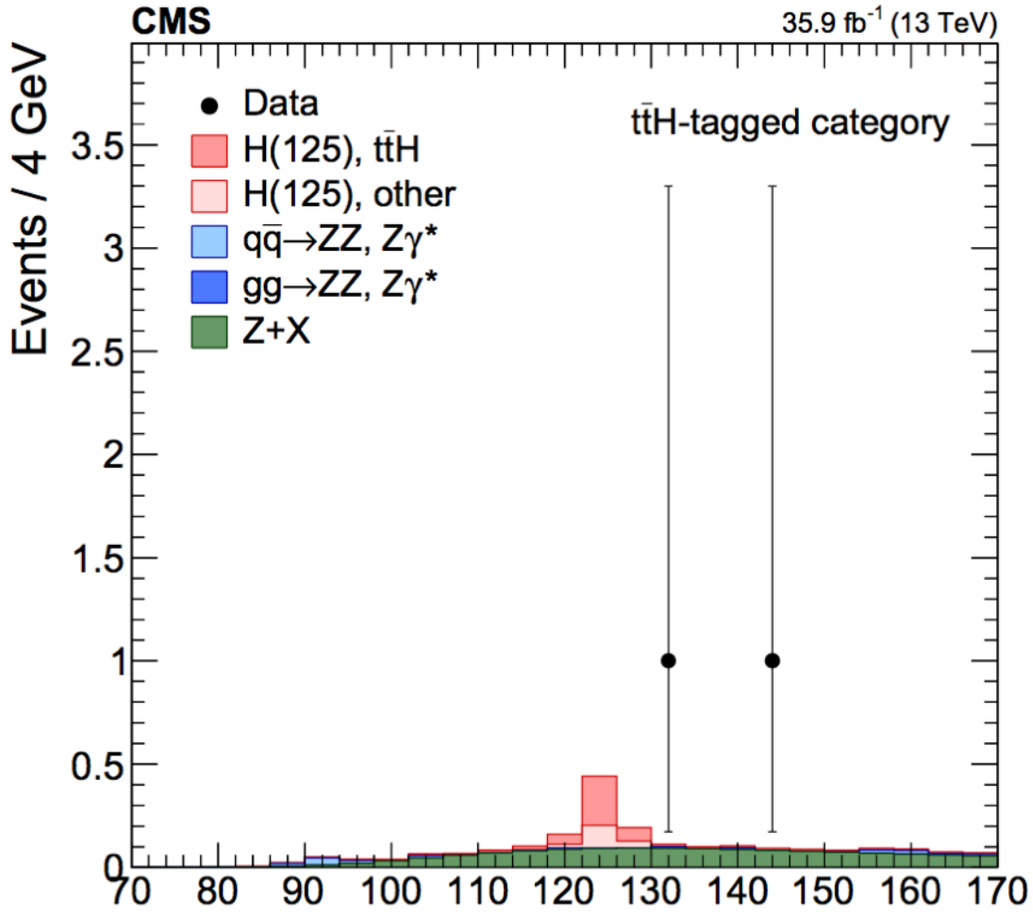
ttH Production



- Identification of ttH production combines many decays
  - ttH-tagged channels from $\gamma\gamma$ and 4ℓ: pure but low rate

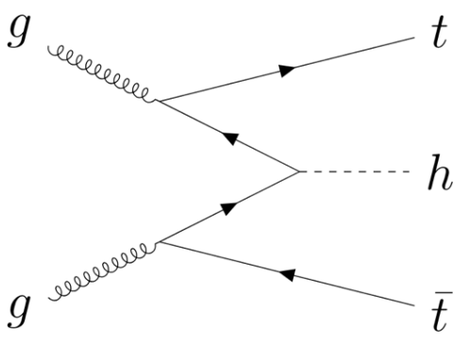


arXiv:1806.00425



JHEP 11 (2017) 047

ttH Production



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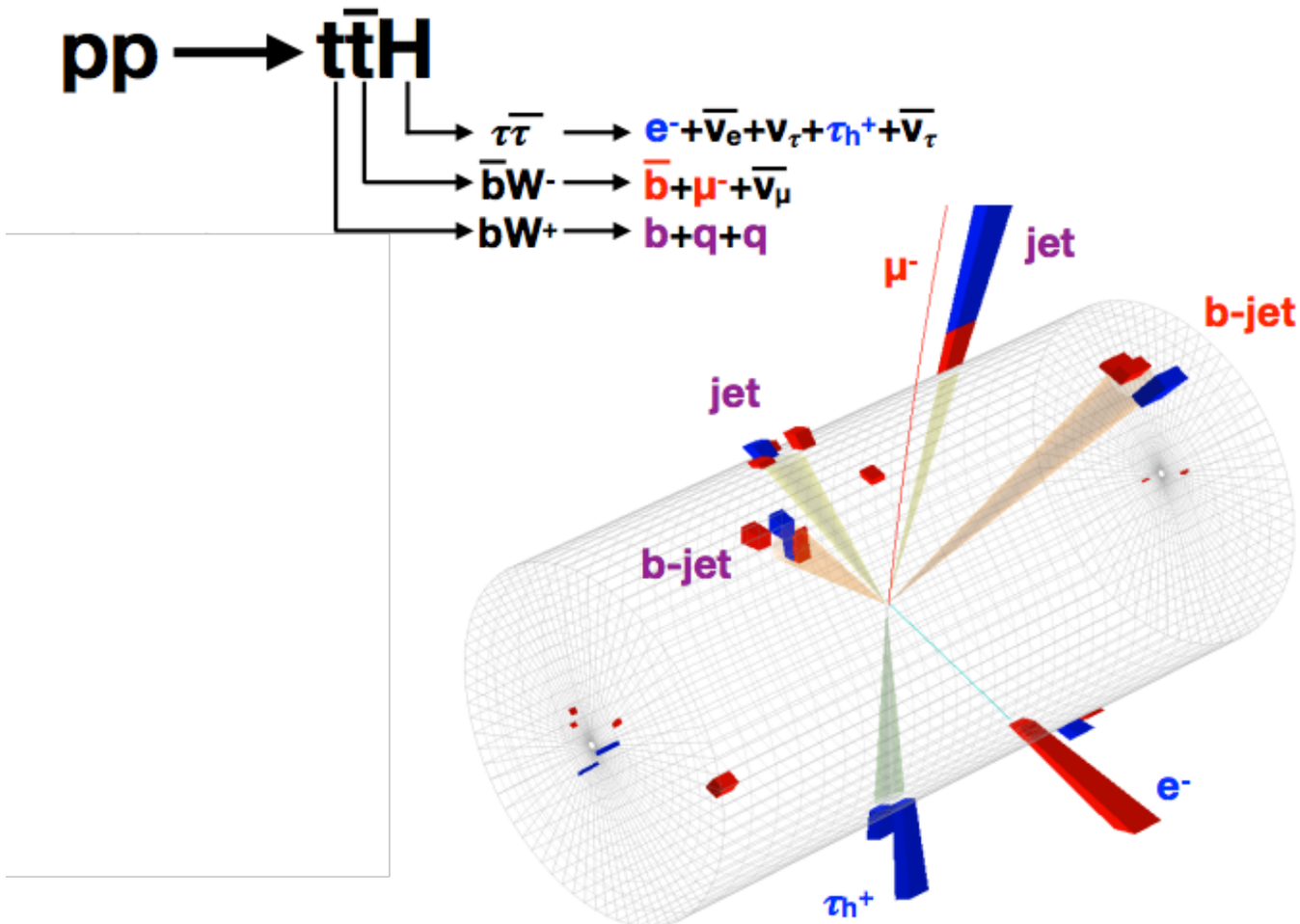
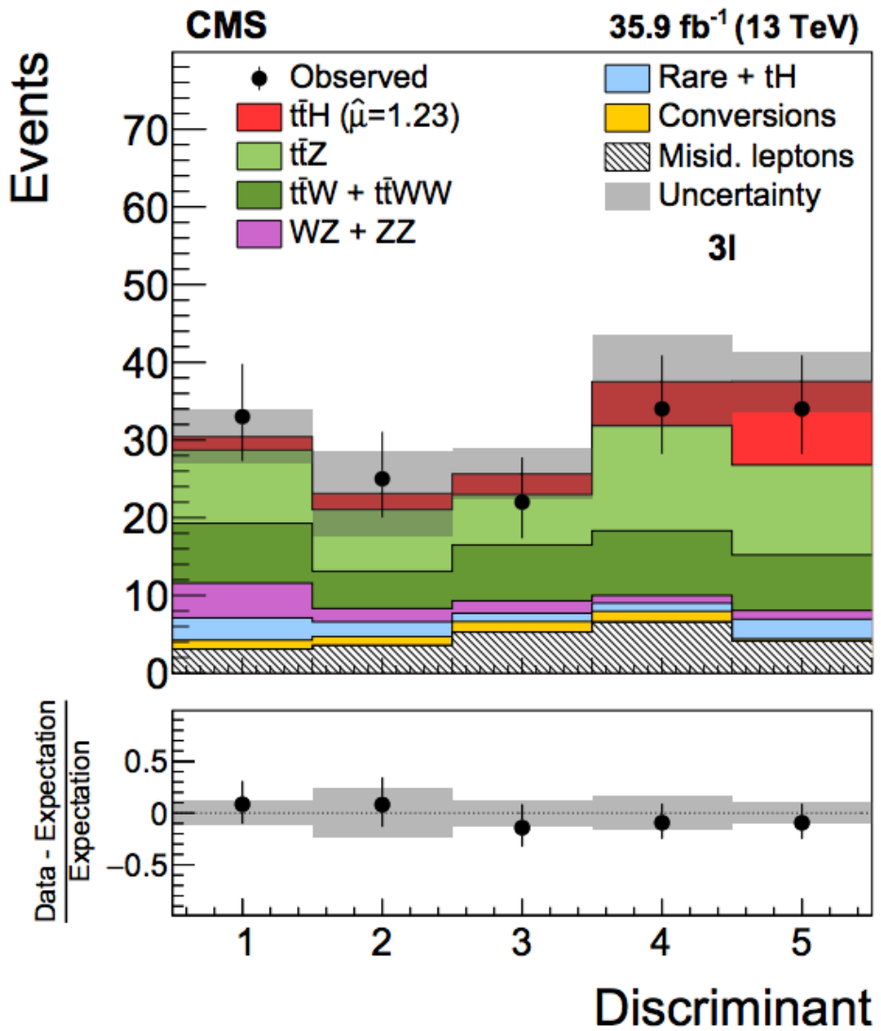
  - ttH multi-lepton: H→WW*→ℓνℓν, H→ττ, H→ZZ*

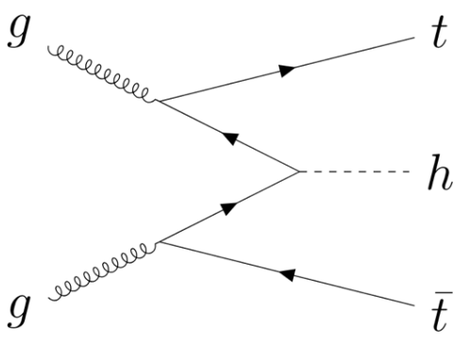




Three lepton: complex but highly sensitive topology

CMS arXiv:1803.05485
ATLAS Phys.Rev.D.97(2018)072003

ttH Production



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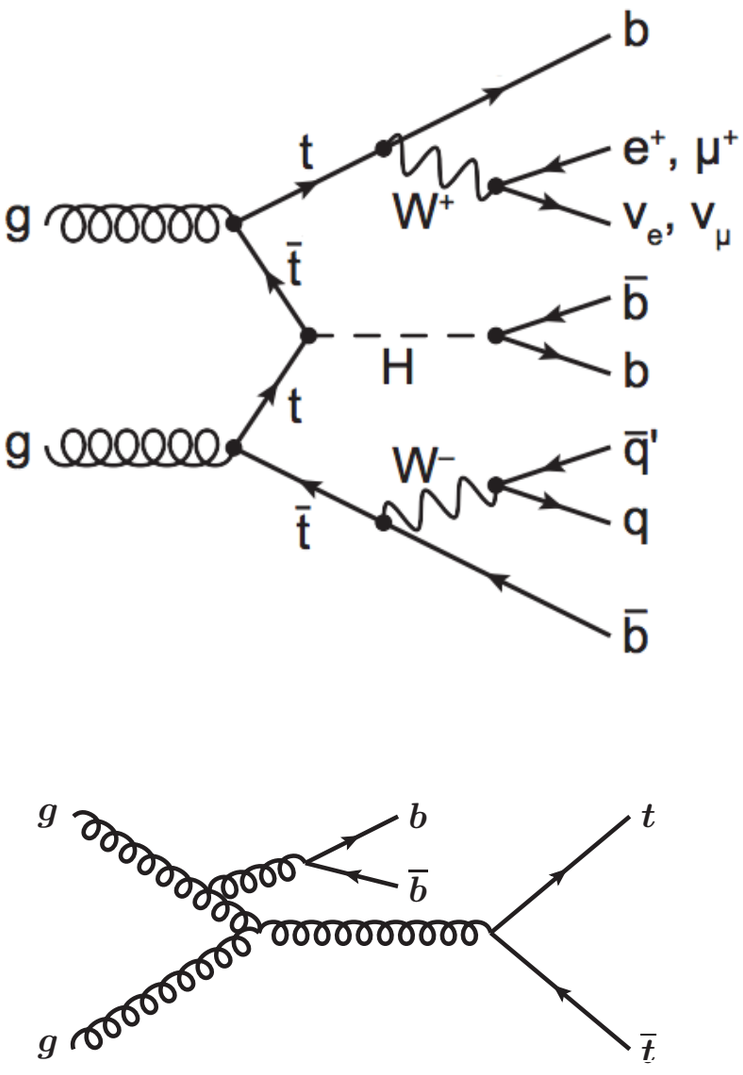
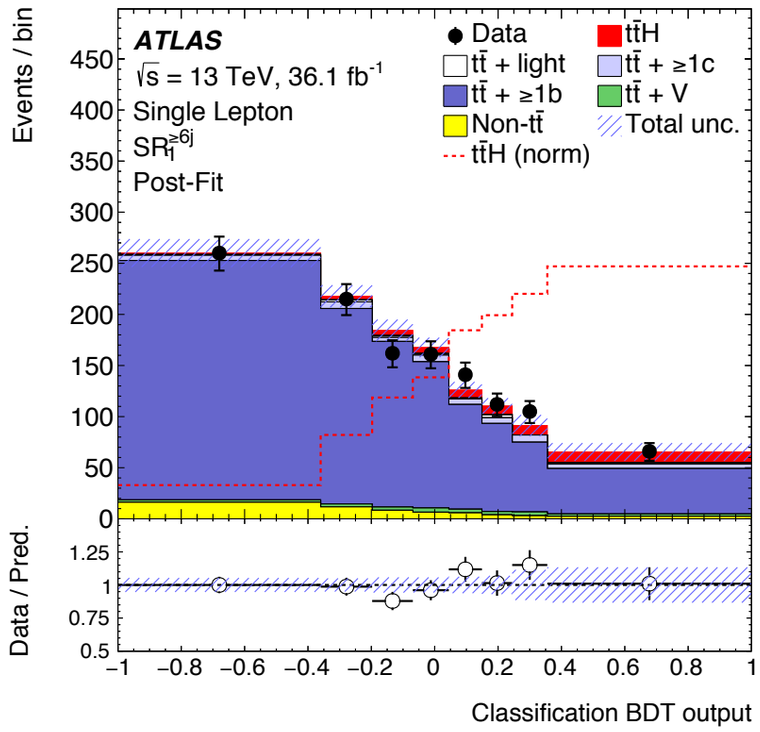
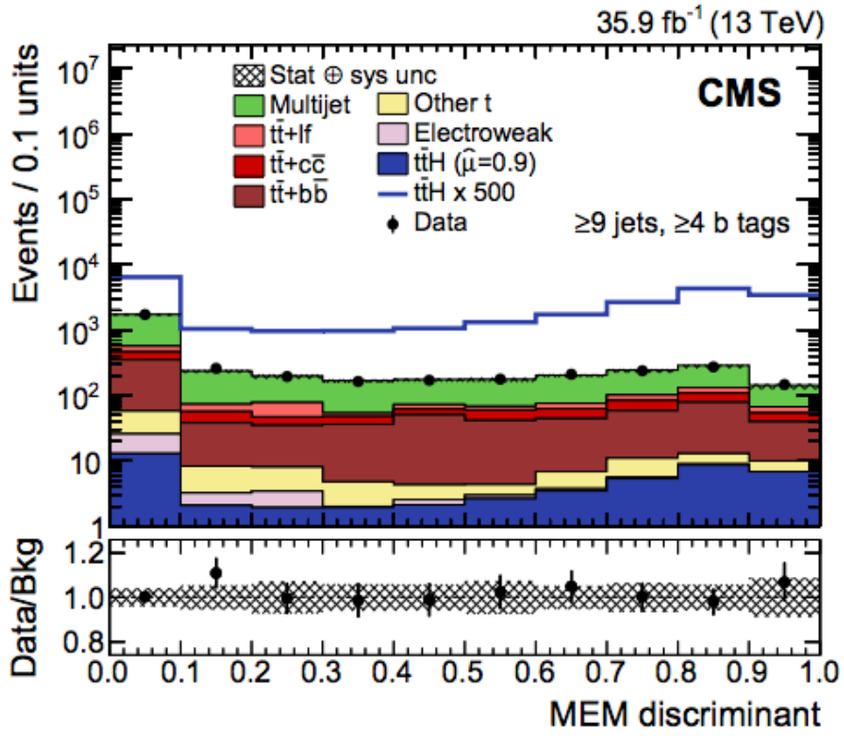
  - H→bb: single- and double-lepton, plus jet counting, then multivariate discriminants





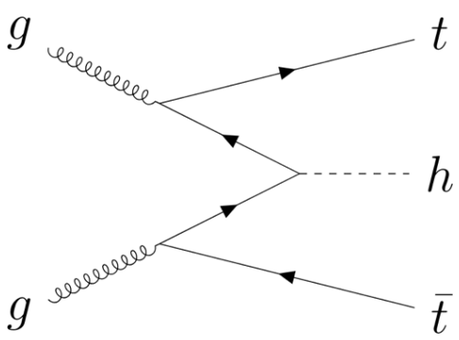
Phys. Rev. D 97 (2018) 072016

CMS: all-hadronic

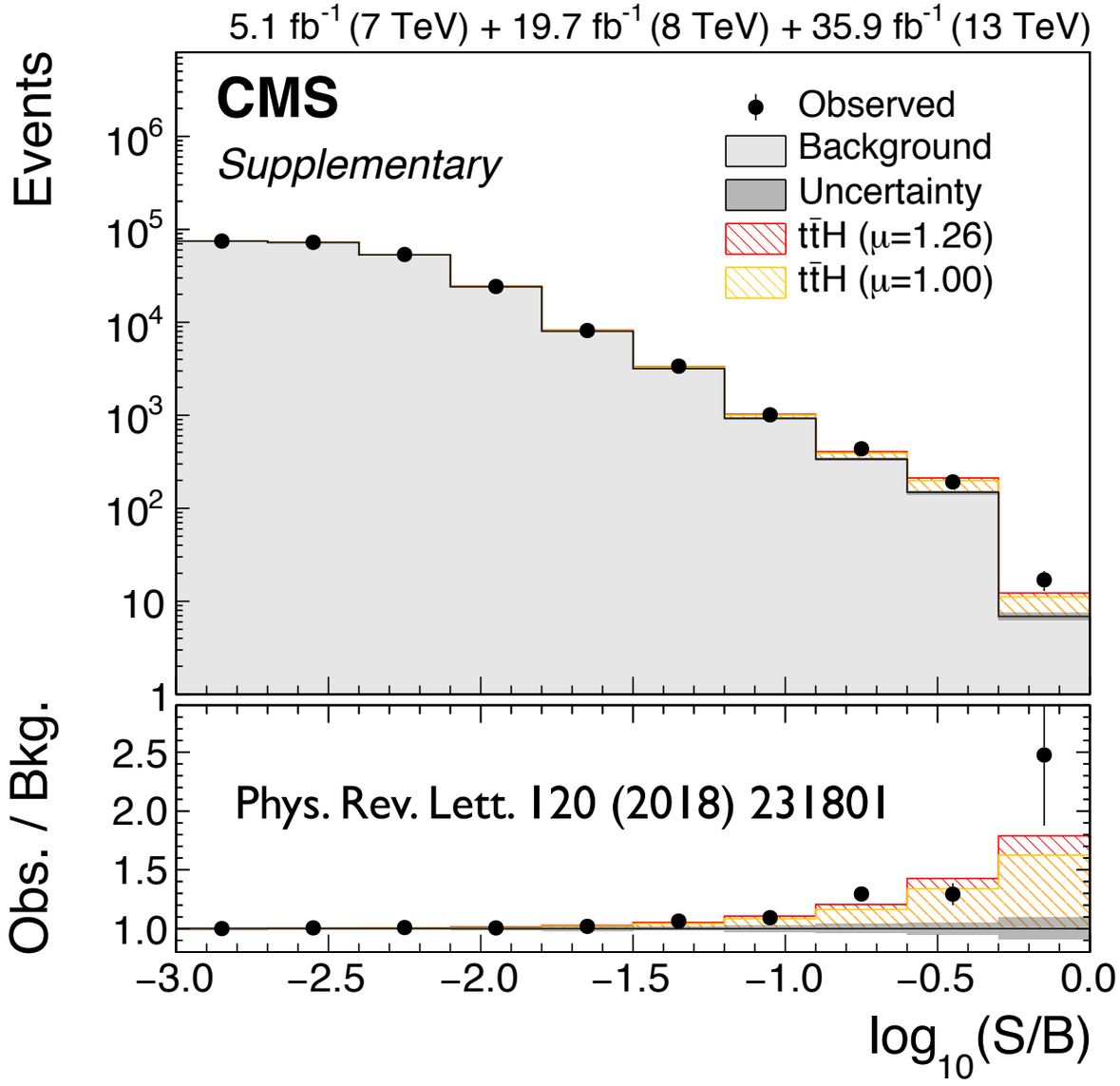


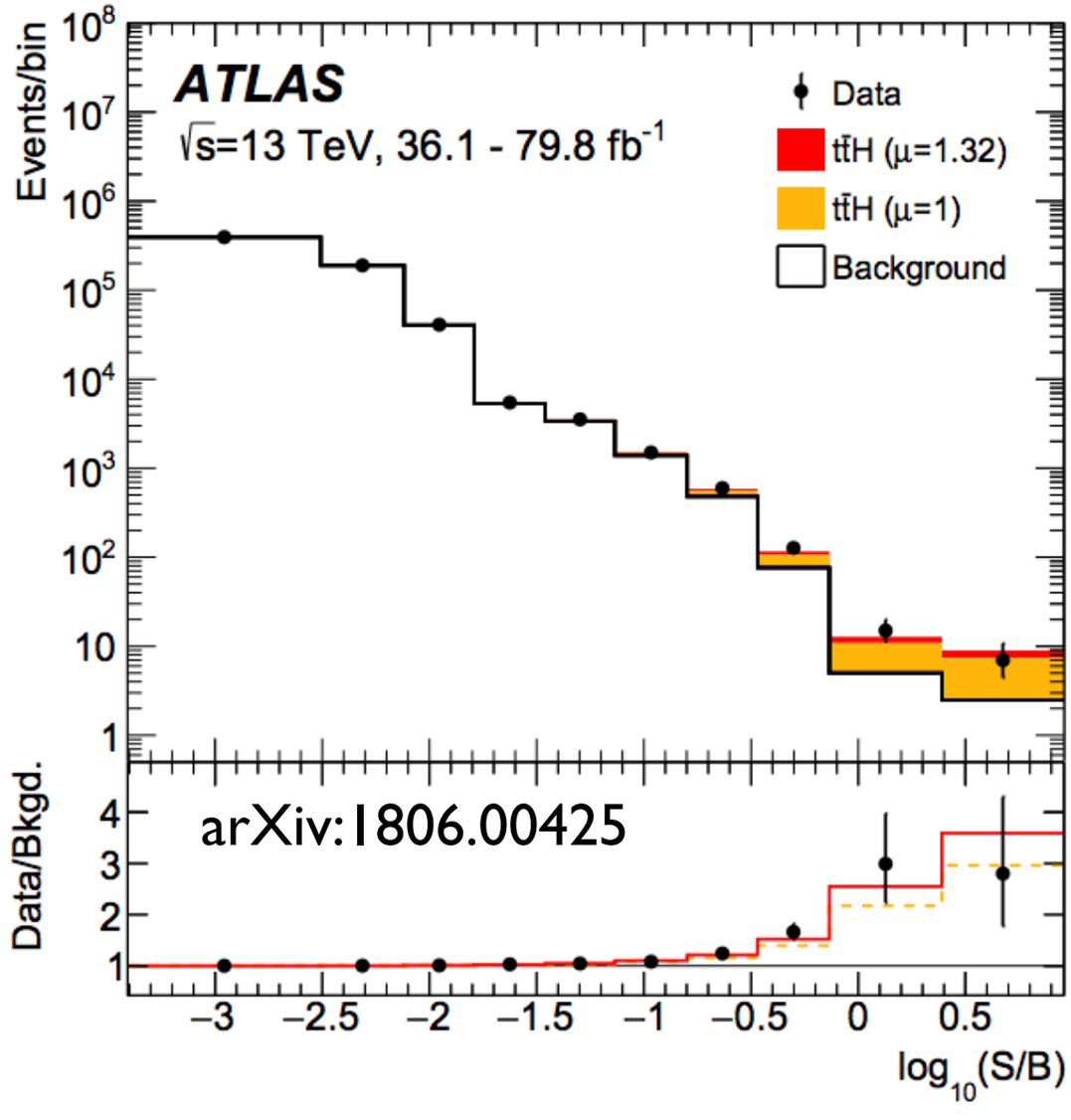
arXiv:1803.06986
arXiv:1804.03682

ttH Observation

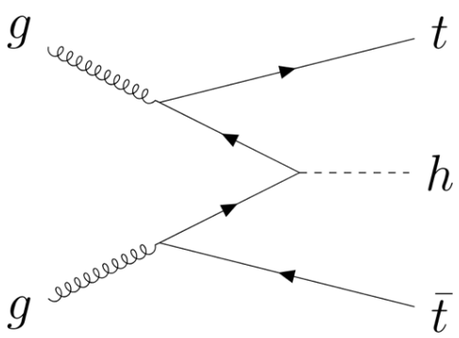


- CMS 5.2σ (4.2σ expected) Run 1 + 2016
- ATLAS 6.3σ (5.1σ expected) Run 1 + 2015-17





ttH Observation



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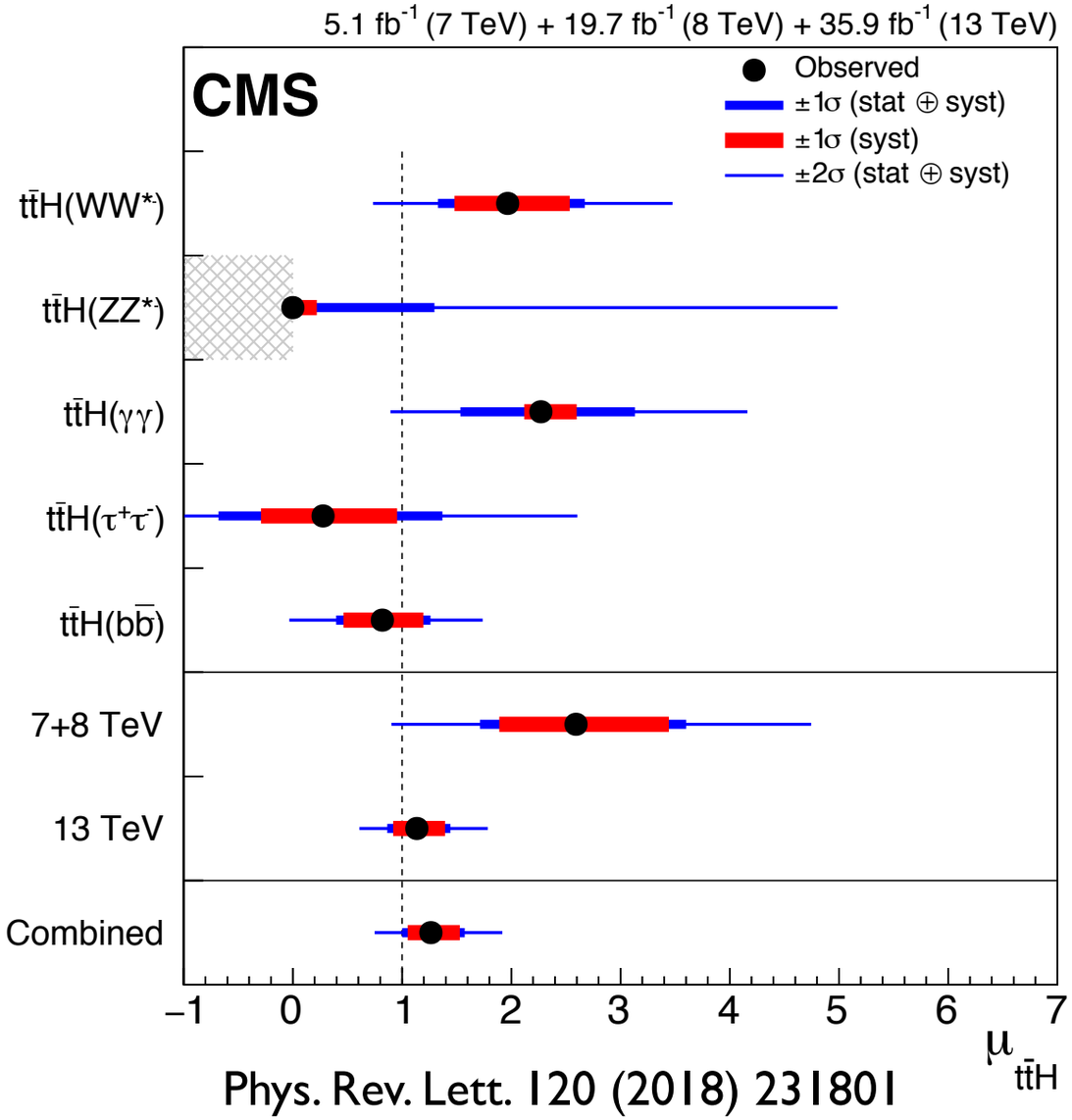
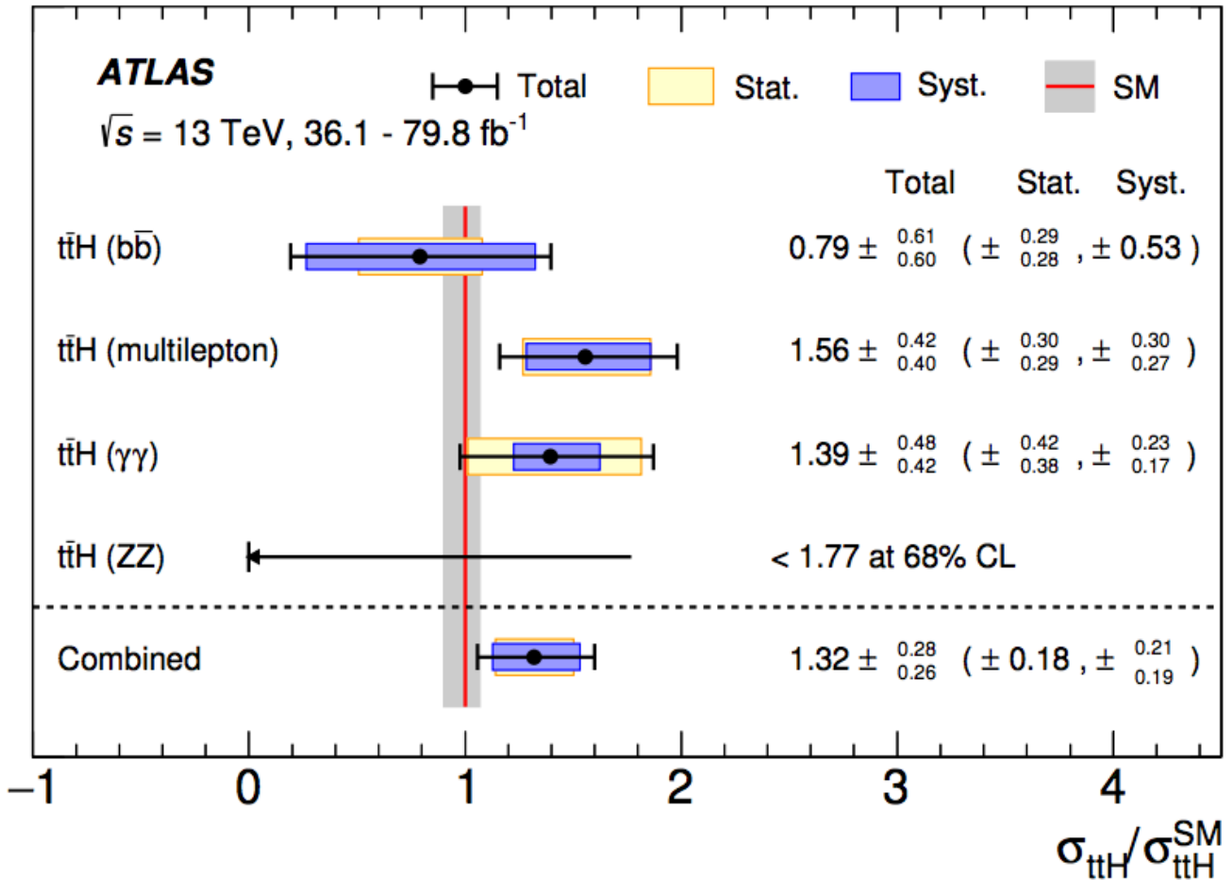
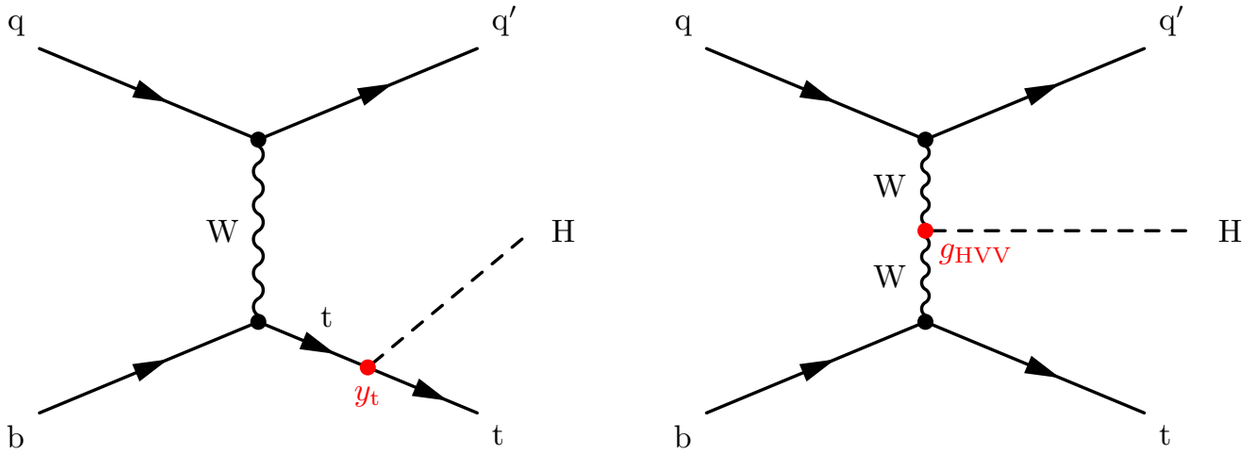


Phys. Rev. Lett. 120 (2018) 231801



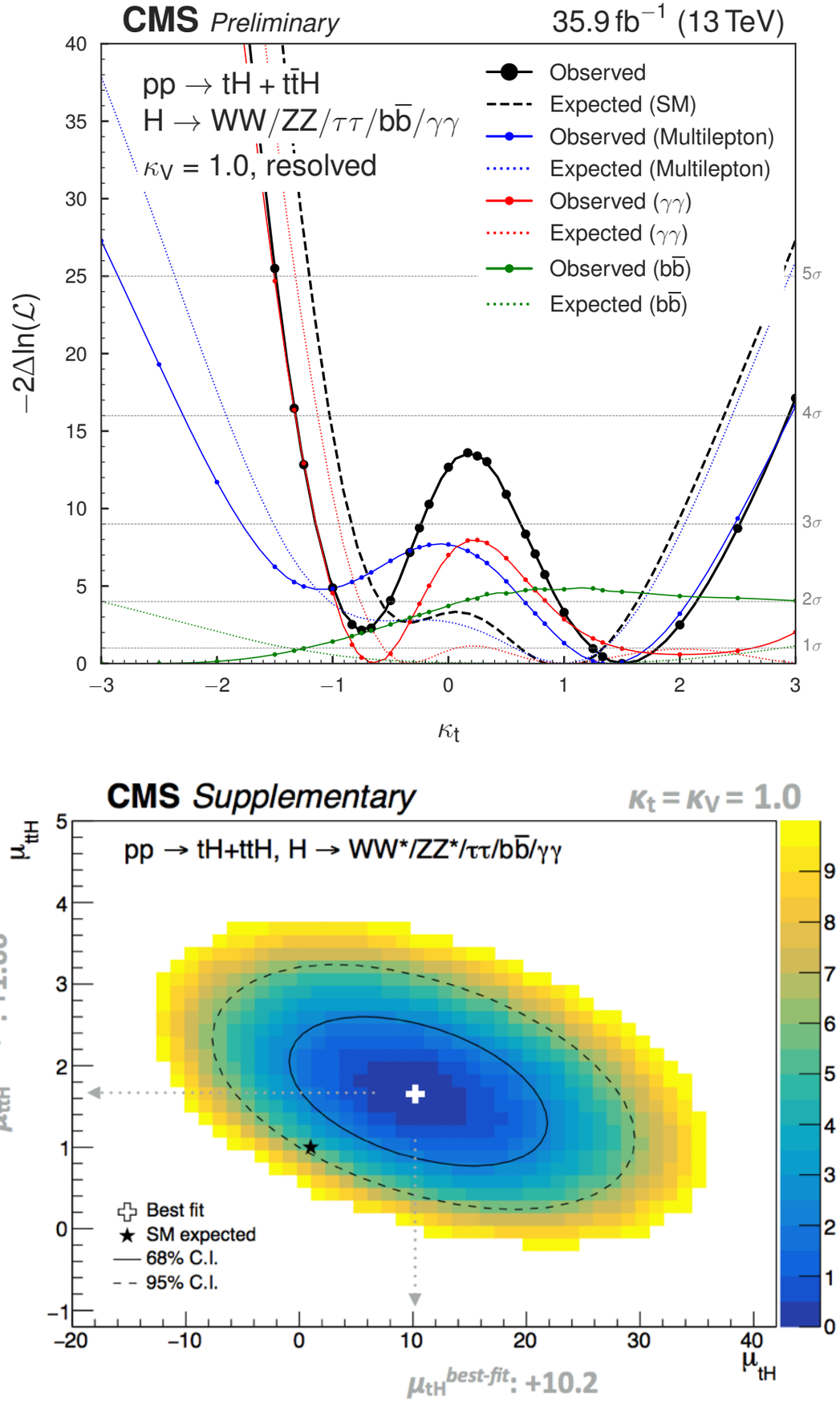
arXiv:1806.00425

Single Top Production

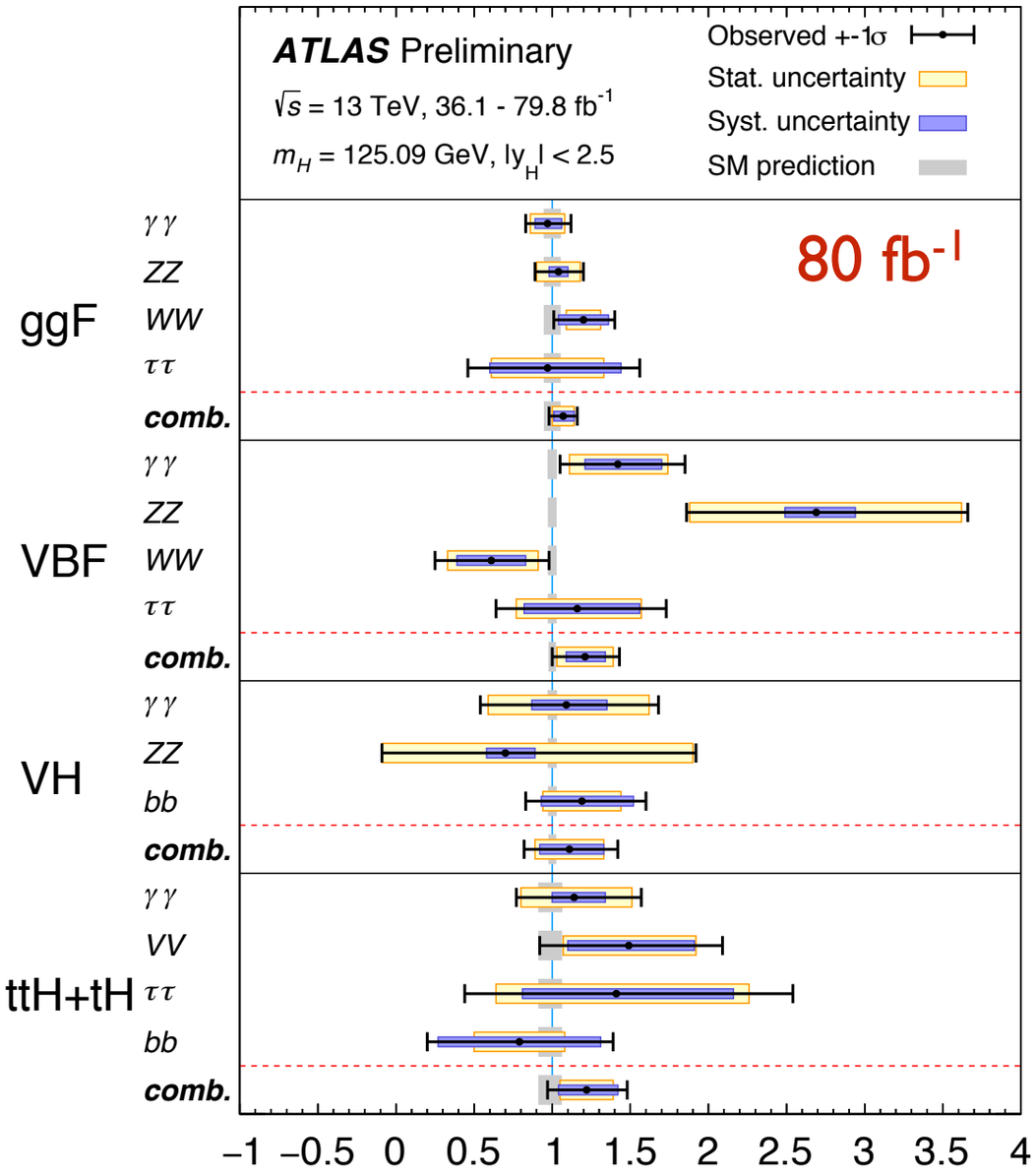


- Rare production in SM due to interference: roughly 70 fb
- CMS Result combines:
  - tH multilepton channel
  - tH, H → bb
  - Reinterpretation of ttH categories from H→γγ
- Given SM ttH yield and acceptance $\mu_{tH} < 26.5$ (13.6 exp.)

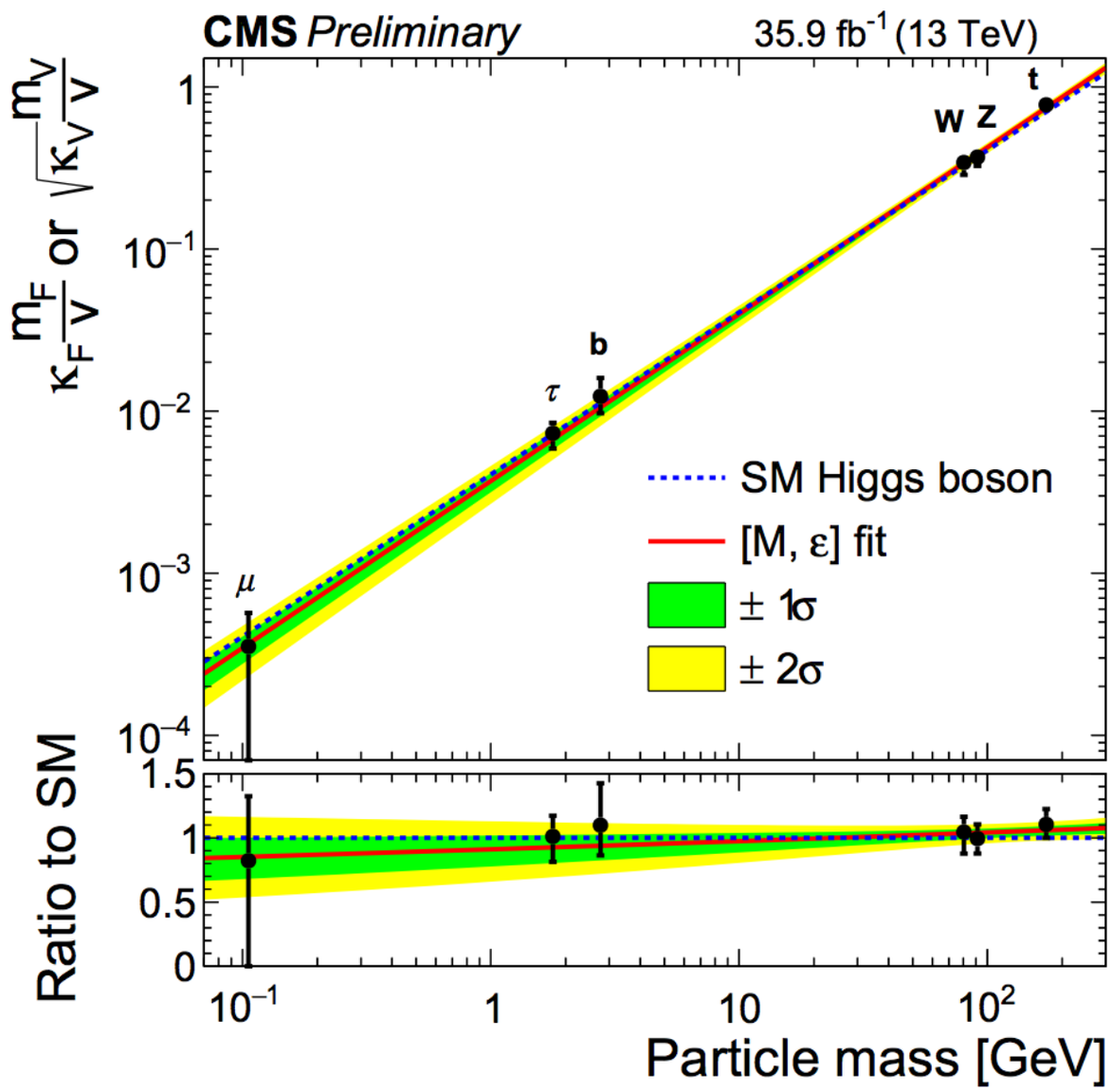
CMS-PAS-HIG-18-009



Combined Results



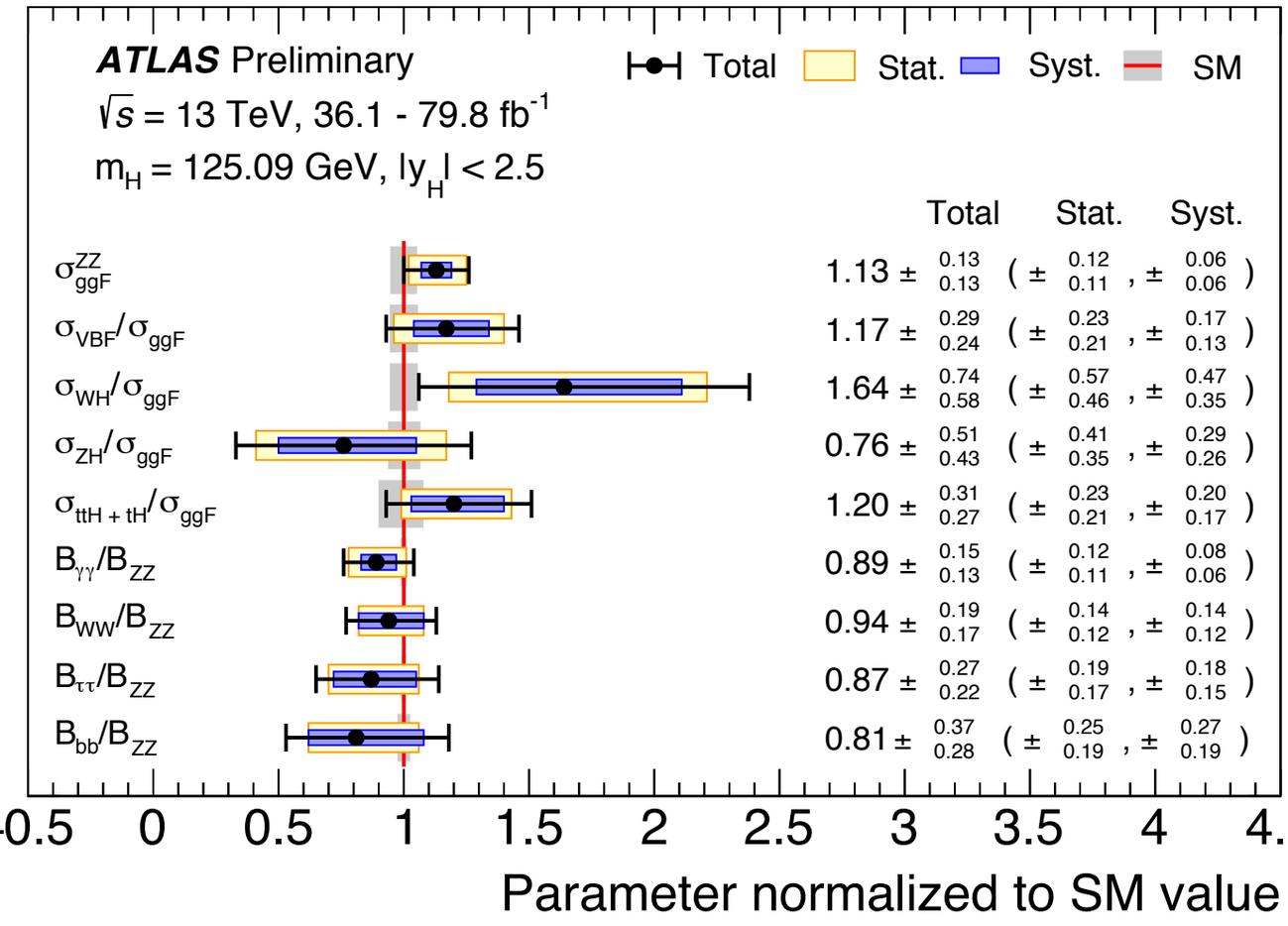
ATLAS-CONF-2018-031

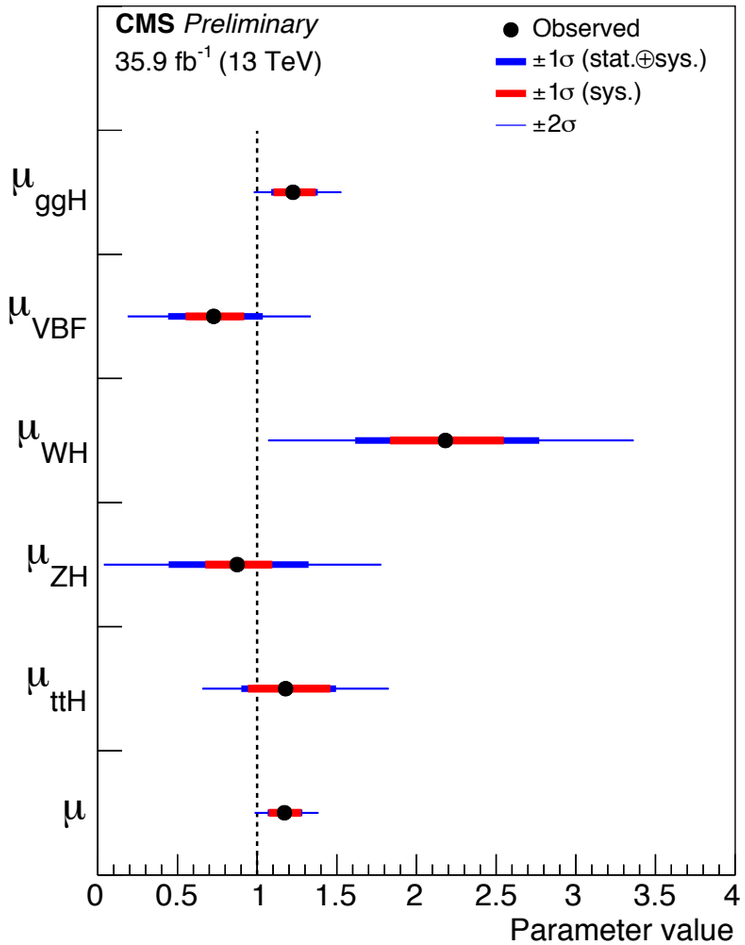


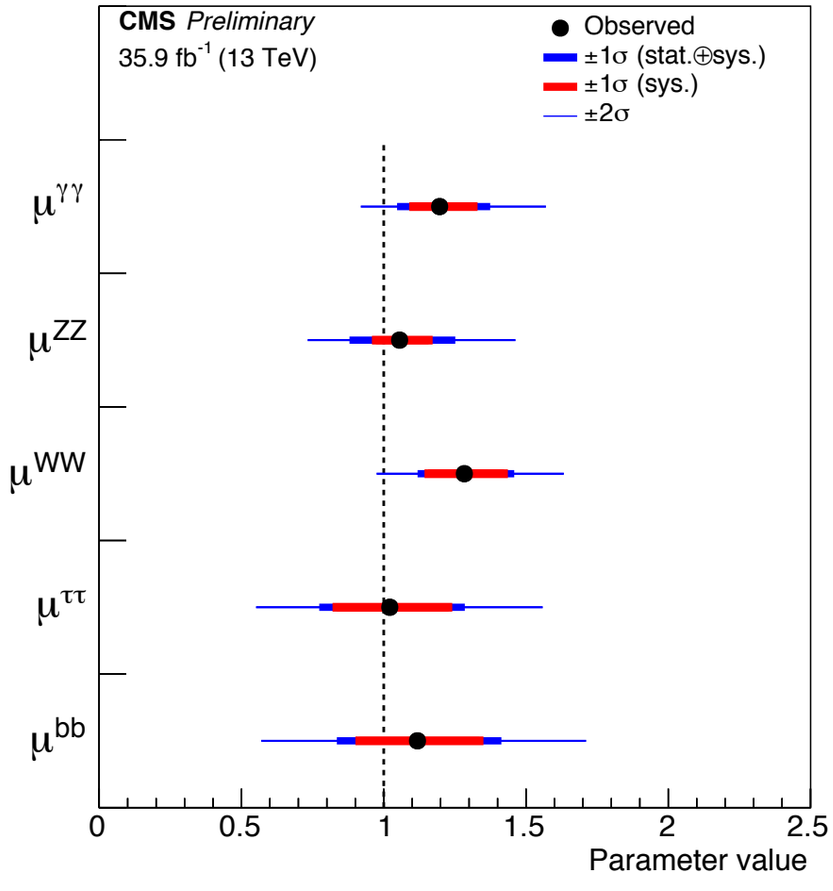
CMS-PAS-HIG-17-031

By Production and Decay

- Several possible choices for model parameters allowed to account for SM deviations in combinations
- Ratios of cross sections and branching ratios cancel out some uncertainties

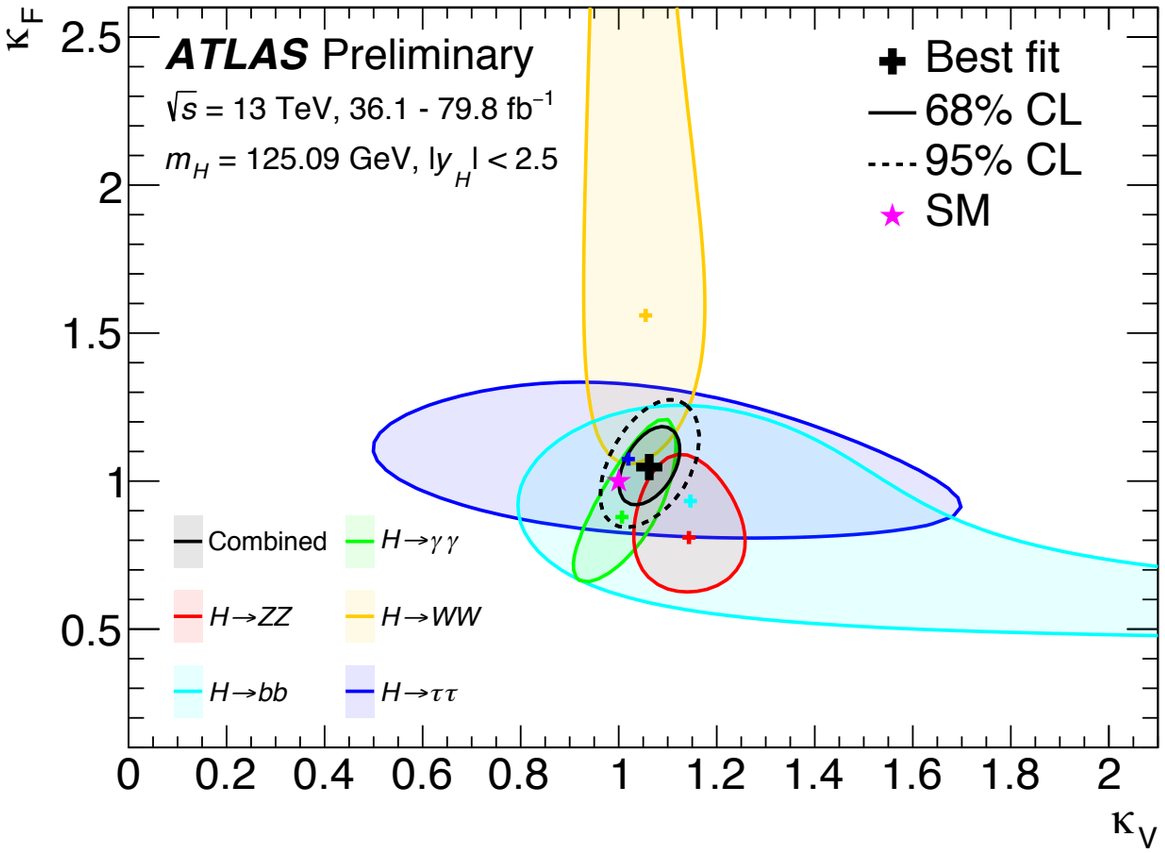


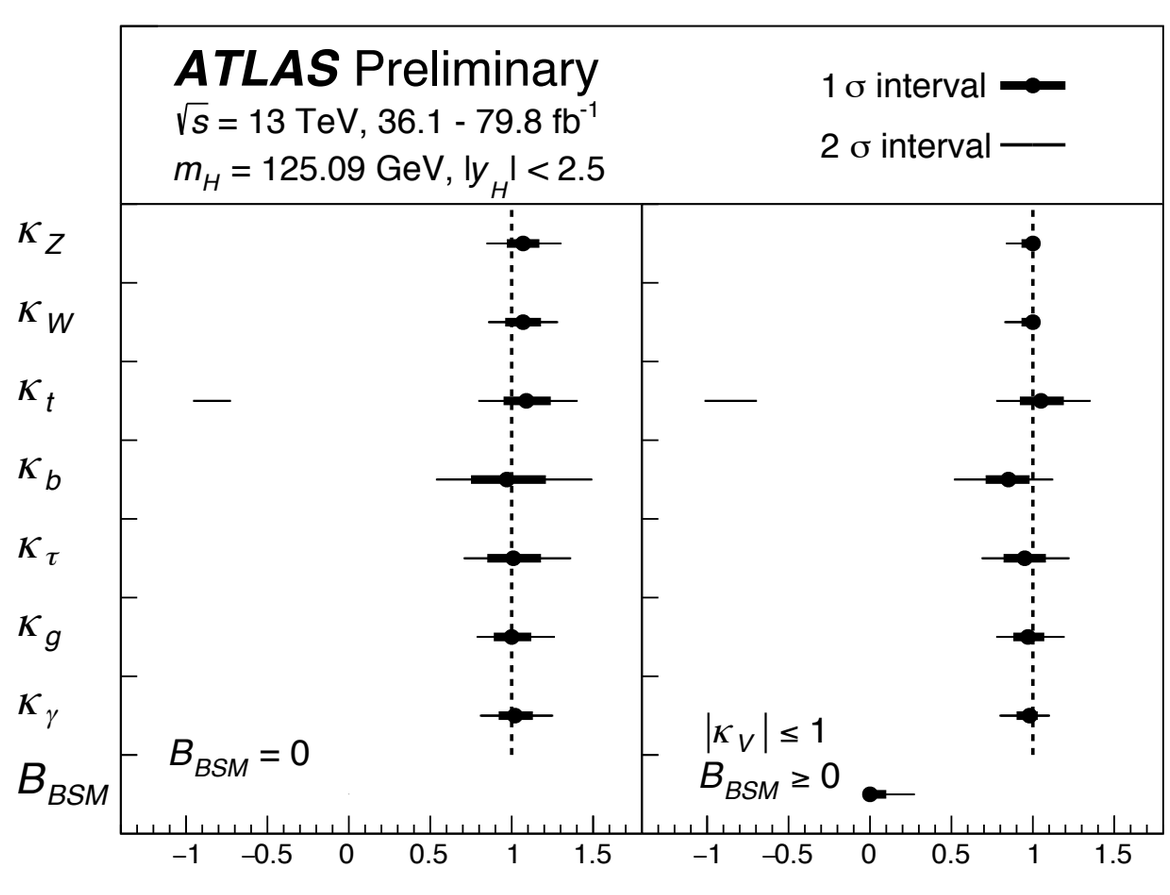


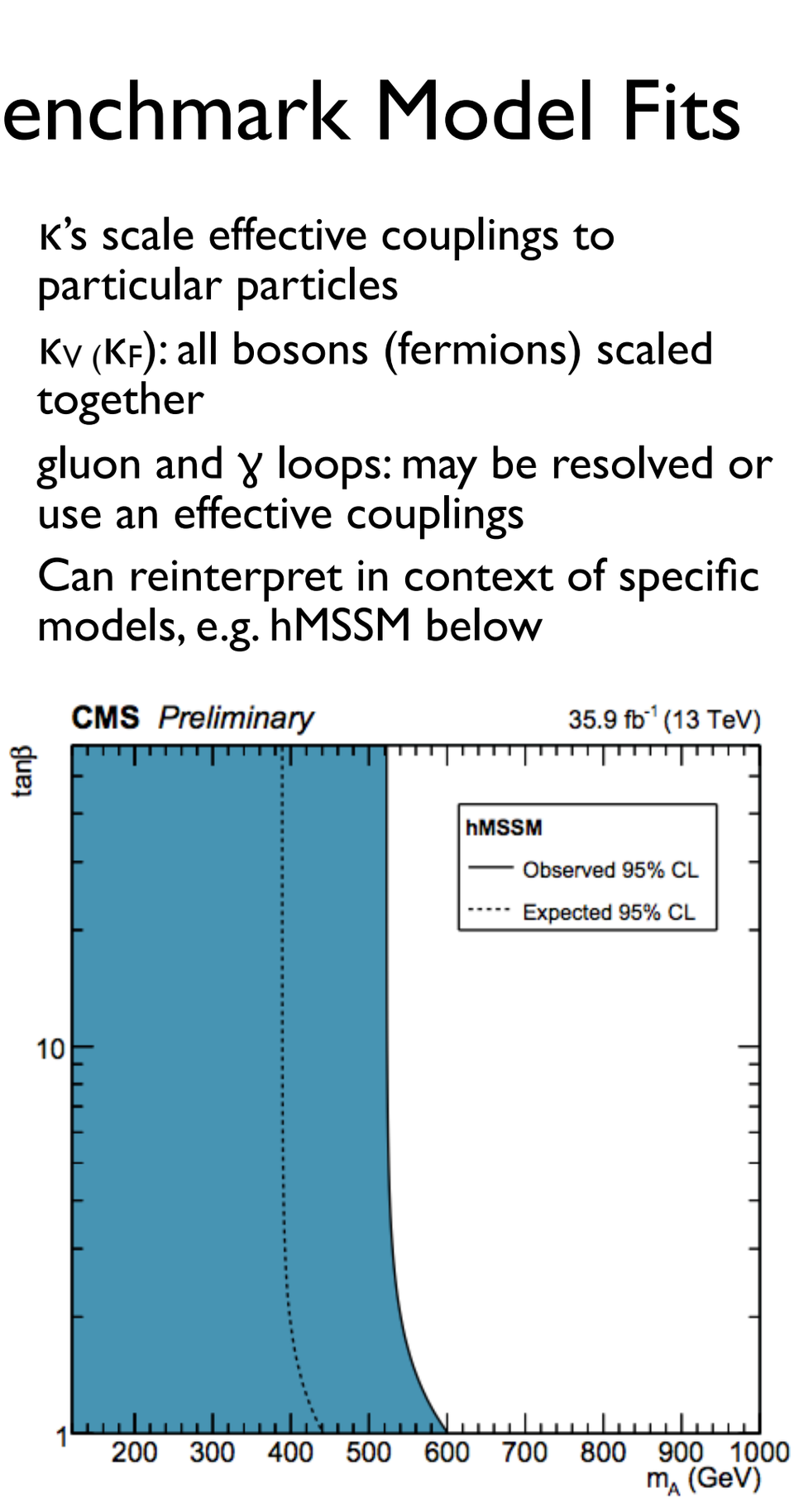


Benchmark Model Fits

- κ's scale effective couplings to particular particles
- κ_V (κ_F): all bosons (fermions) scaled together
- gluon and γ loops: may be resolved or use an effective couplings
- Can reinterpret in context of specific models, e.g. hMSSM below

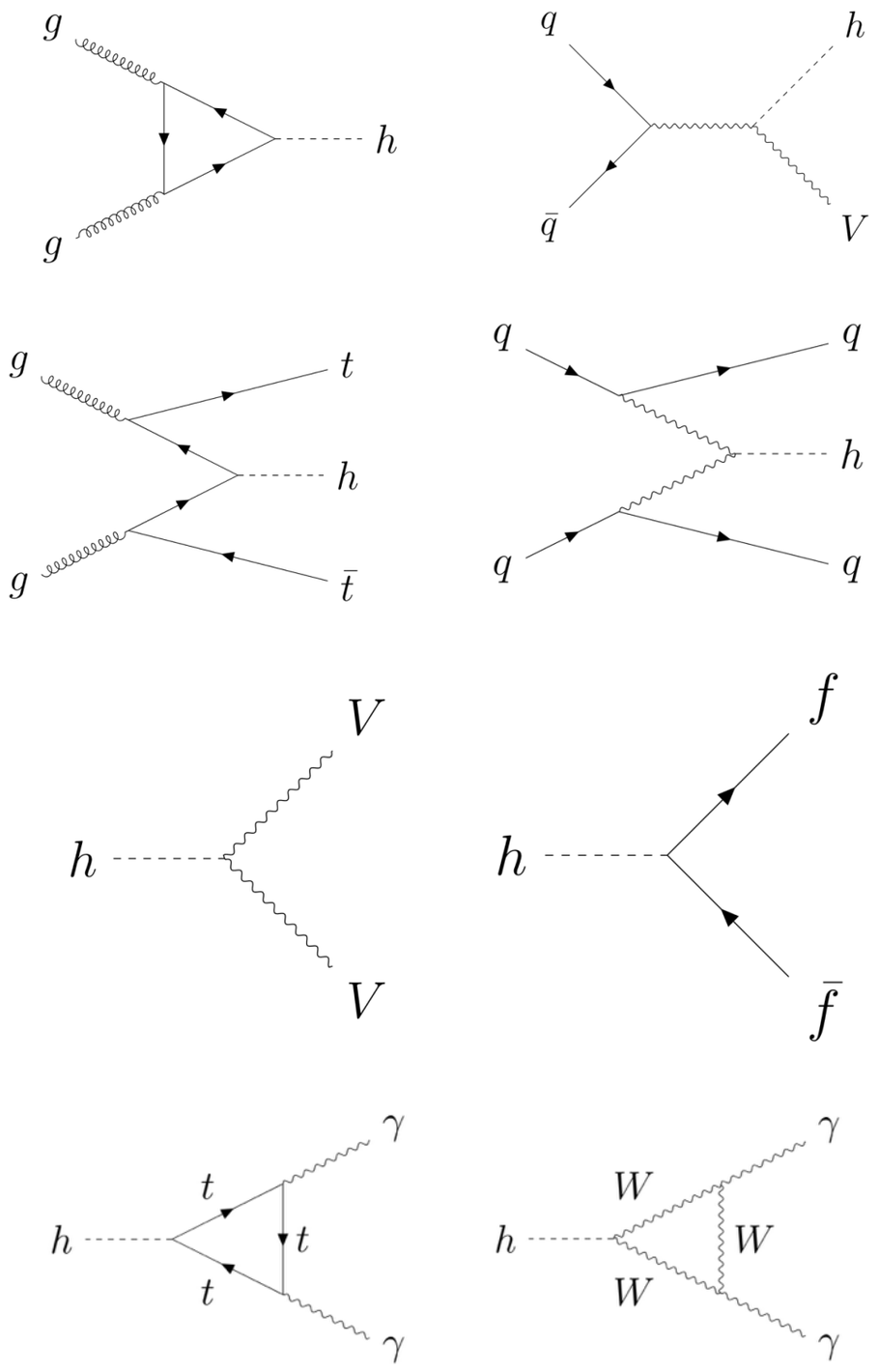






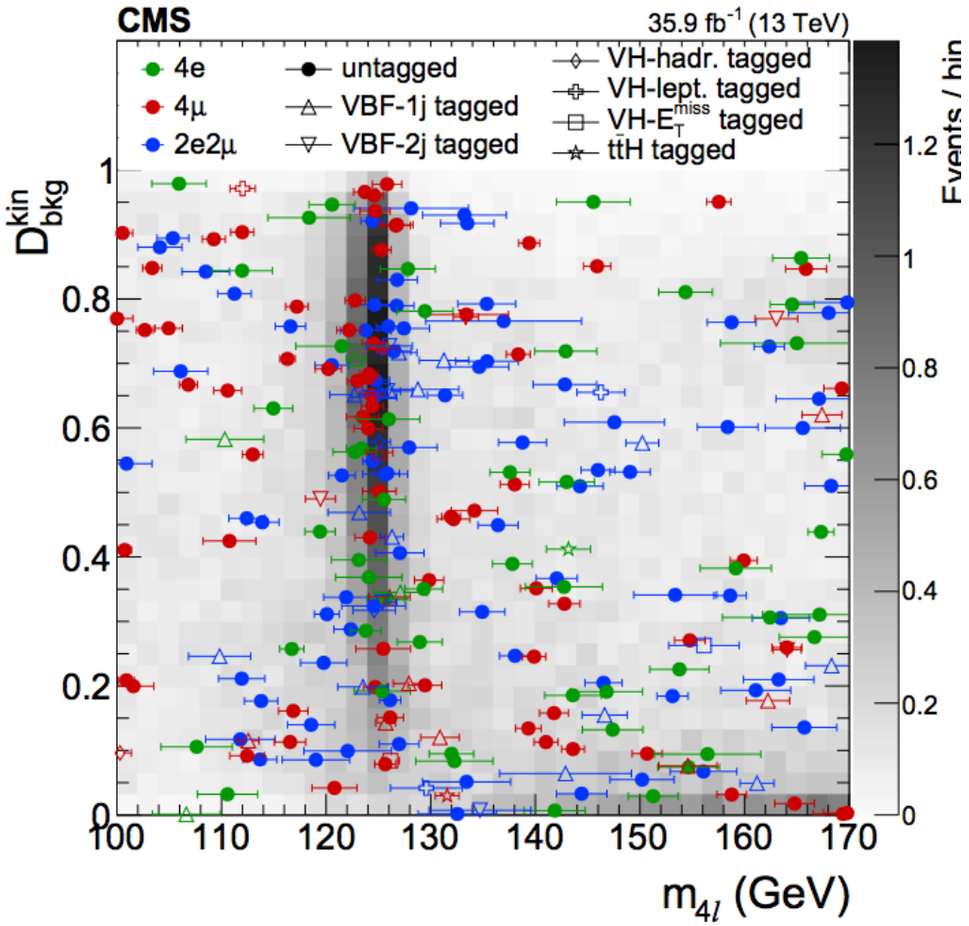
Conclusions

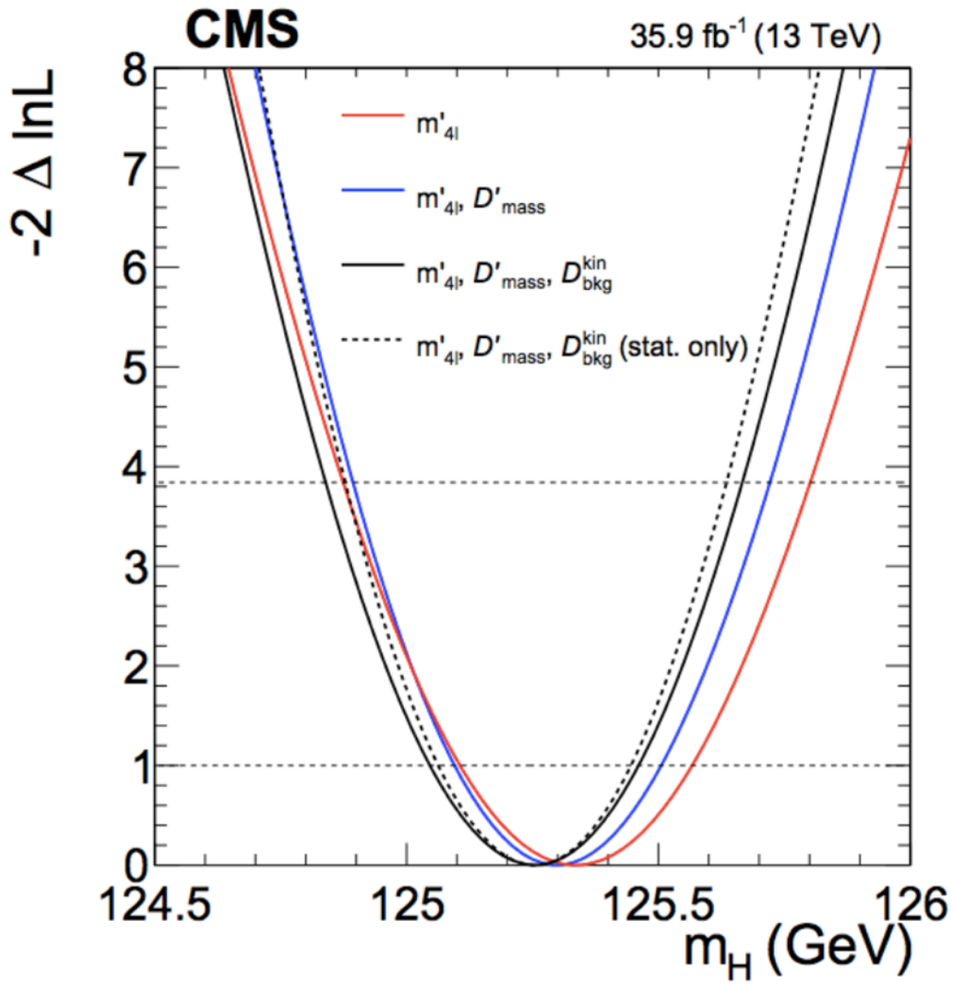
- Main production and decay modes from discovery era have now all been observed individually
  - gluon fusion, VH, VBF, and ttH production
  - vector boson, photon, and 3rd generation fermion decays
- Next discovery targets: rare production modes, 2nd generation
- Run 2 dataset allows an increasing range of precision measurements
- The Higgs looks a lot like the SM so far… but the LHC is only just getting started!



Extras

CMS ZZ to 4ℓ Mass





No $m(Z_1)$ constraint	3D: $\mathcal{L}(m_{4\ell}, \mathcal{D}_{\text{mass}}, \mathcal{D}^{\text{kin}}_{\text{bkg}})$	2D: $\mathcal{L}(m_{4\ell}, \mathcal{D}_{\text{mass}})$	1D: $\mathcal{L}(m_{4\ell})$
Expected m_{H} uncertainty change	+8.1%	+11%	+21%
Observed m_{H} (GeV)	125.28±0.22	125.36±0.24	125.39±0.25
With $m(Z_1)$ constraint	3D: $\mathcal{L}(m'_{4\ell}, \mathcal{D}'_{\text{mass}}, \mathcal{D}^{\text{kin}}_{\text{bkg}})$	2D: $\mathcal{L}(m'_{4\ell}, \mathcal{D}'_{\text{mass}})$	1D: $\mathcal{L}(m'_{4\ell})$
Expected m_{H} uncertainty change	—	+3.2%	+11%
Observed m_{H} (GeV)	125.26±0.21	125.30±0.21	125.34±0.23

H→μμ Searches

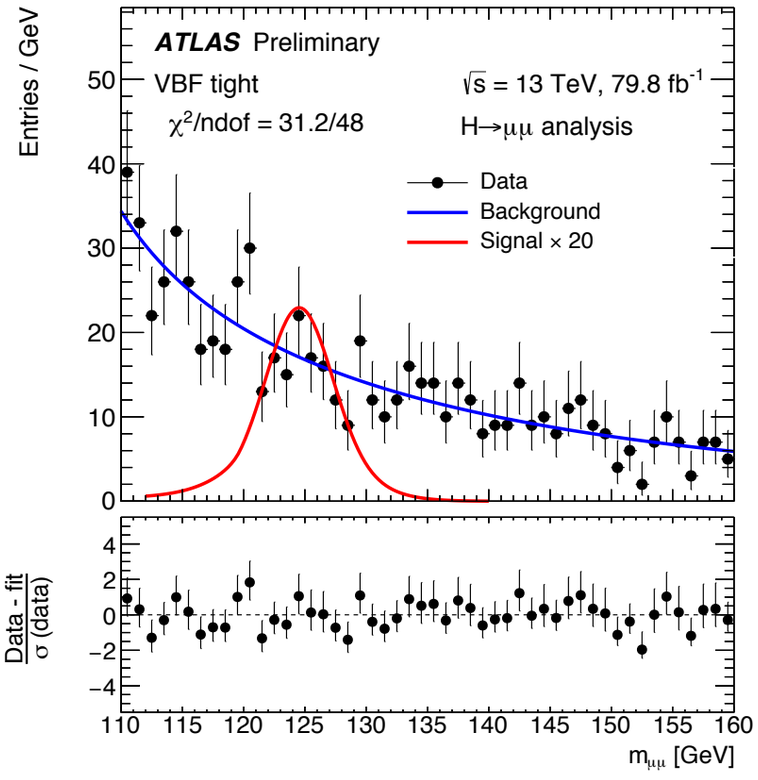
- Events categorized to enhance S/B: based on muon η(μ), p_T(μμ), BDT to enhance VBF
- Background from sidebands

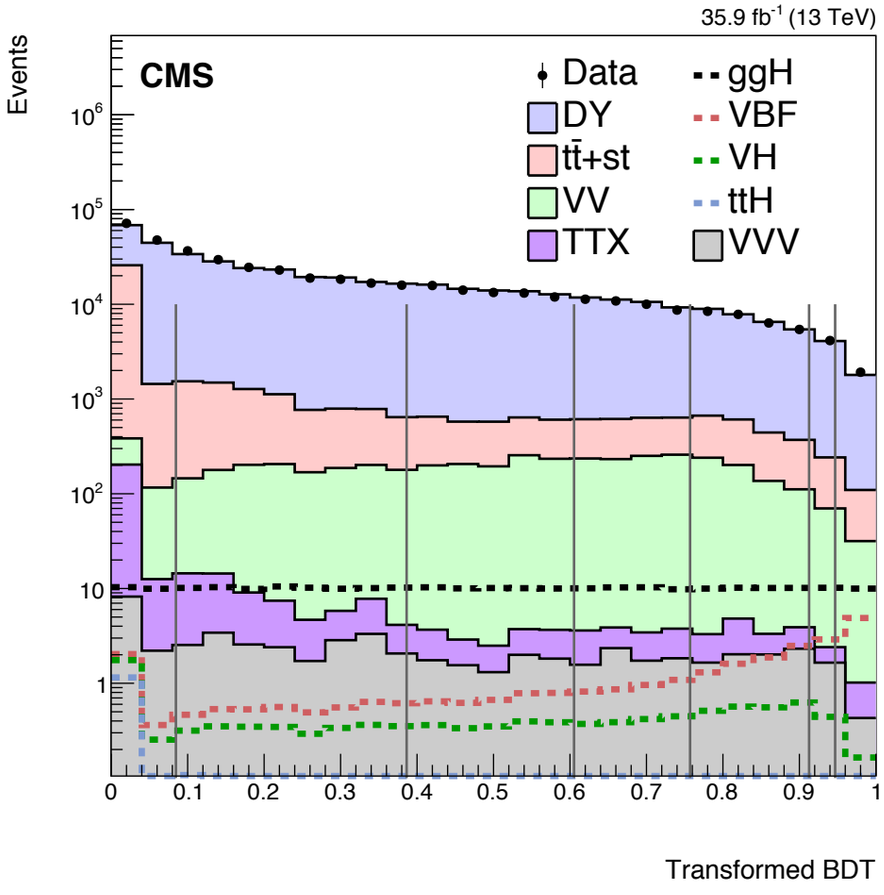
Limits on ratio of cross section to SM:

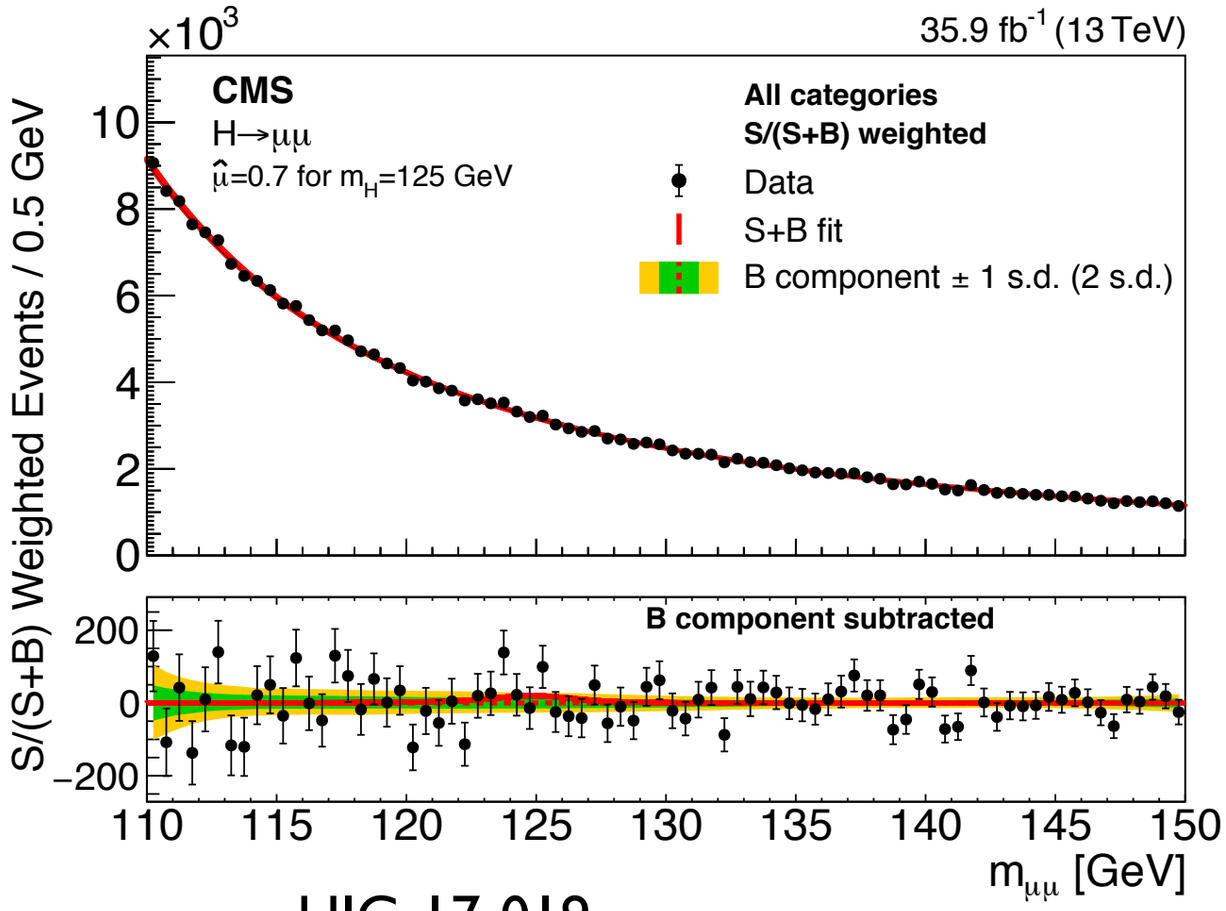
ATLAS: $\mu_{\mu\mu} < 2.1$ (2.0 exp.)

CMS: $\mu_{\mu\mu} < 2.95$ (2.45 exp.)

ATLAS-CONF-2018-026







HIG-17-019