Study of the properties of the Higgs boson

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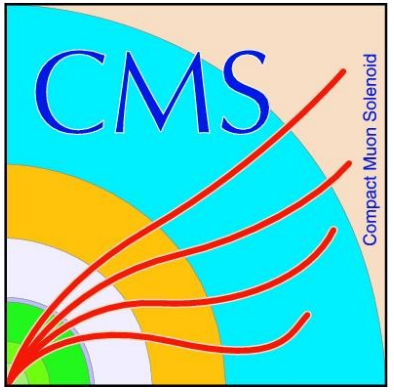
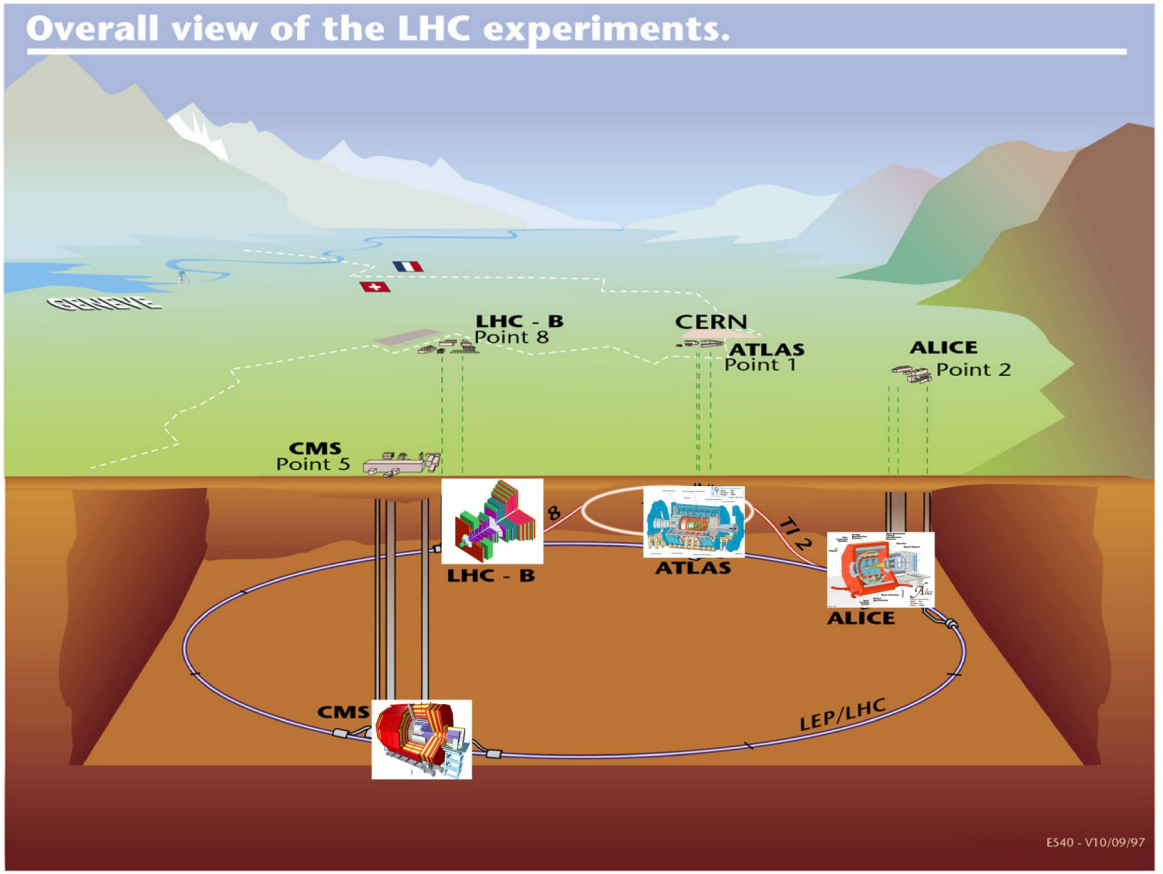
on behalf of the ATLAS and CMS collaborations



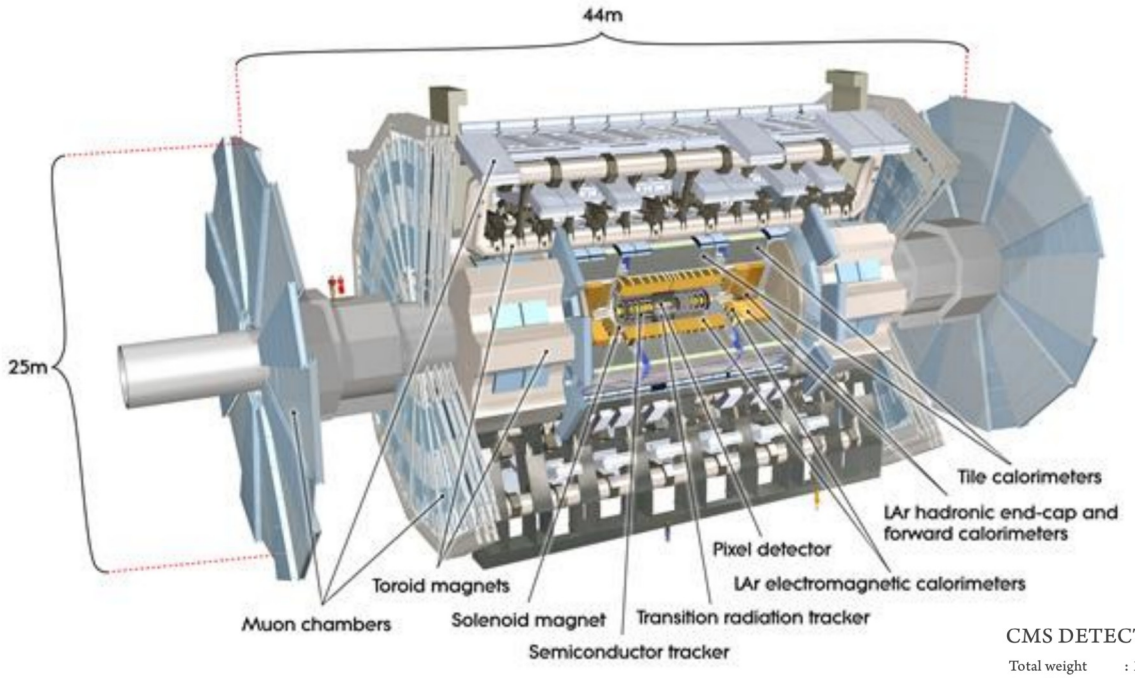
NTIHEP, 2018

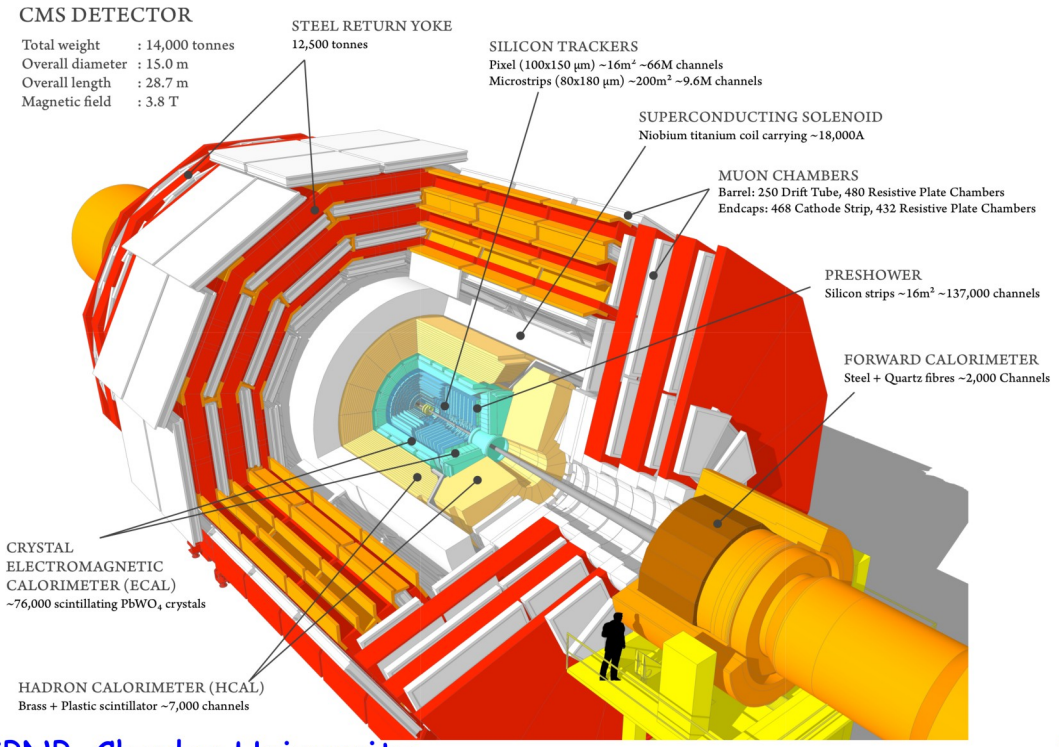
Large Hadron Collider

- Run-1 (2010-2012)
  - pp collisions at $\sqrt{s}$=7 and 8 TeV
  - collected ~25 fb^{-1}
- Run-2 (2015-2018)
  - $\sqrt{s}$= 13 TeV
  - so far collected more than 130 fb^{-1} of proton-proton data
- **Excellent accelerator performance !!!**



ATLAS and CMS experiments





Introduction to Higgs boson (1)

- Higgs boson discovery reported in July 2012, when ATLAS and CMS reported results from $H \to \gamma\gamma$, $H \to ZZ \to 4\ell$ and $H \to WW \to \ell\nu\ell\nu$ searches
- With full Run-1 data analyzed, several decay modes were experimentally discovered

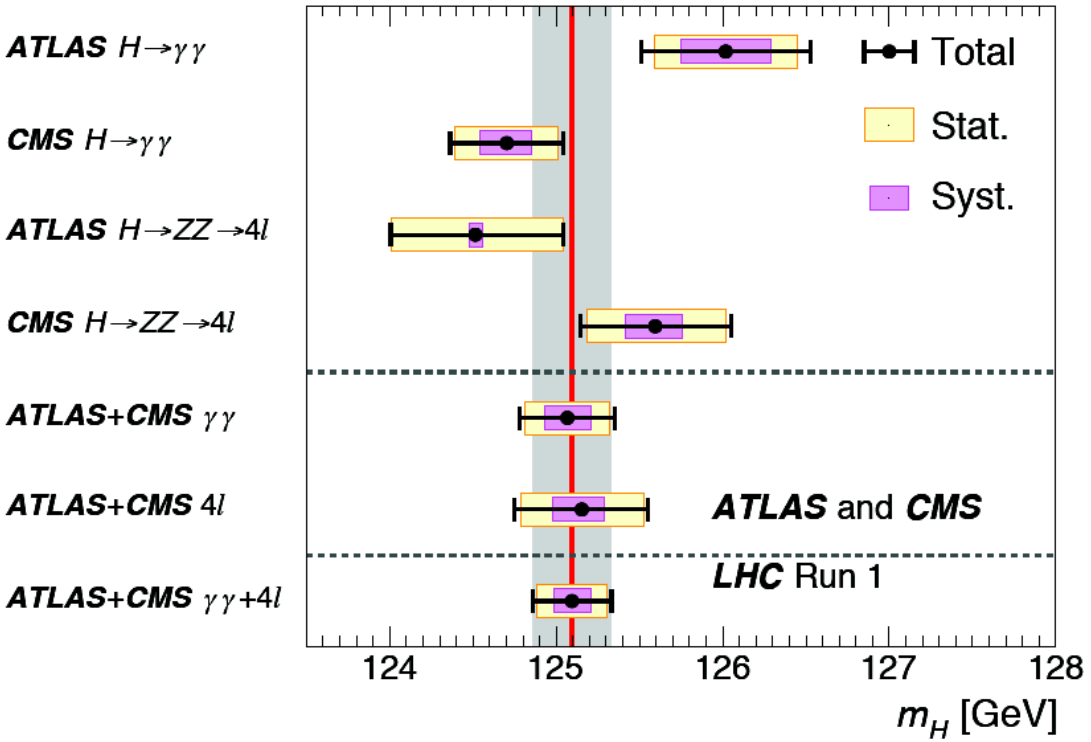
	$H \to \gamma\gamma$	$H \to 4\ell$	$H \to WW$	$H \to \tau\tau$	$H \to b\bar{b}$
ATLAS	5.0σ	7.6σ	6.8σ	4.4σ	1.7σ
CMS	5.6σ	7.0σ	4.8σ	3.4σ	2.0σ

JHEP 08 (2016) 045

- ATLAS+CMS combination in $H \to \tau\tau$ also exceeded 5σ
- ggF and VBF production modes observed
- All signal strengths compatible with Standard Model, although still suffering from rather large uncertainties

Introduction to Higgs boson (2)

- The Higgs boson mass was determined in H → γγ and H → ZZ → 4ℓ channels



Phys.Rev.Lett. 114 (2015) 191803

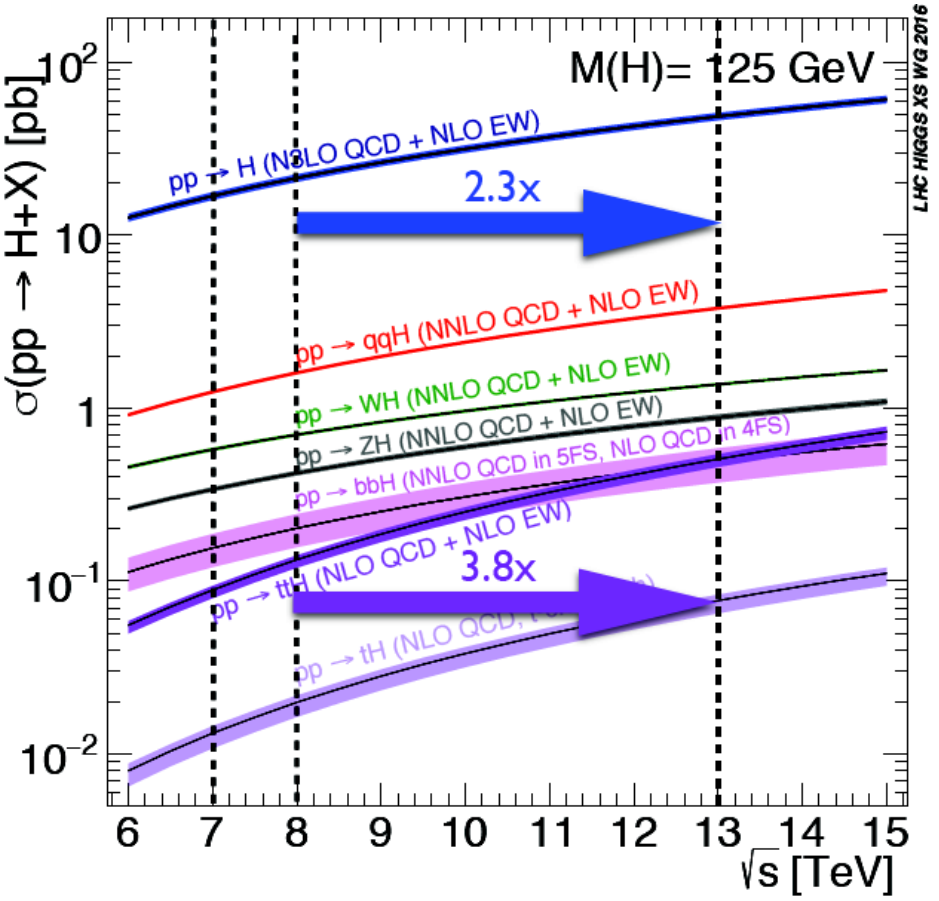
$$\mathbf{m_H = 125.09 \pm 0.24\ (\pm 0.21\ stat \pm 0.11\ syst)\ GeV}$$

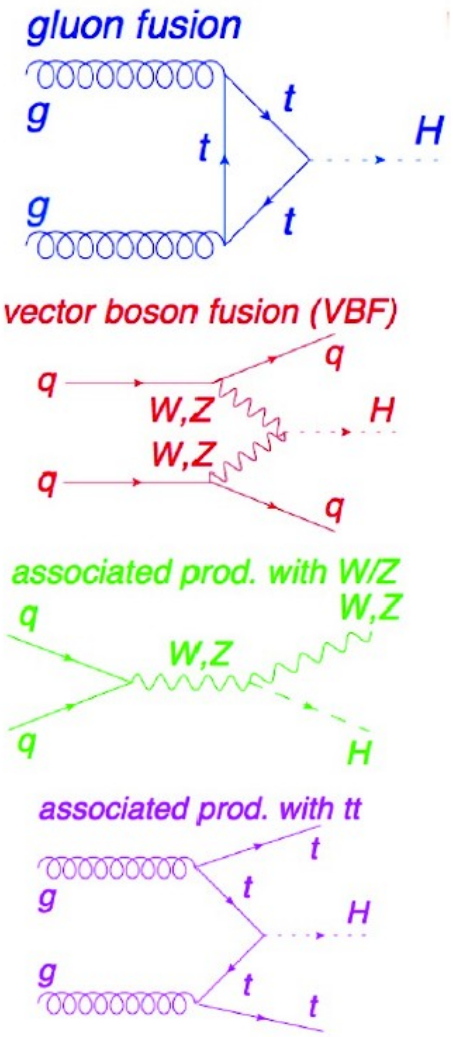
Goal in Run-2: move from discovery to precision measurements

Higgs boson production at the LHC

- Four main production modes

(LHC Higgs Xsec WG)

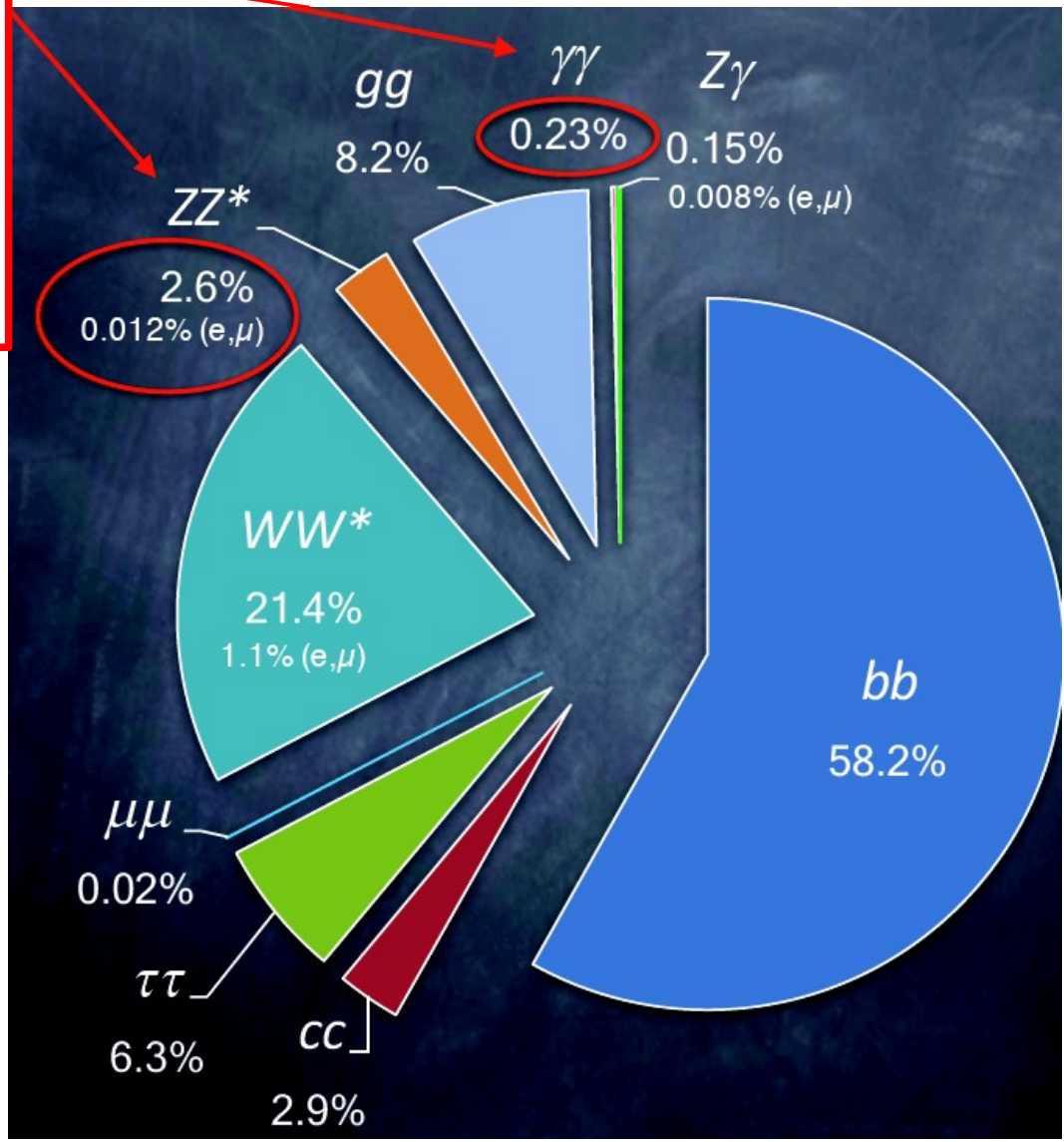




- Significant increase in the production rate due to higher energy in Run-2 (8 → 13 TeV)

Higgs decay modes for m(H) = 125 GeV

- ZZ, γγ: despite low BR, these channels provide high-precision results on Higgs boson properties (mass, width, couplings, cross-sections, ...)
- W^+W^-: high BR, but low mass resolution
- $b\bar{b}$, $\tau^+\tau^-$: high BR, but low S/B. Important for determining couplings to fermions
- $\mu^+\mu^-$: very low BR, but gives access to fermions of 2nd generation
- Zγ, $c\bar{c}$ also studied



Current Run-2 results

- Precision mass, width and cross-section (total, simplified template, differential) measurements performed mainly in two channels

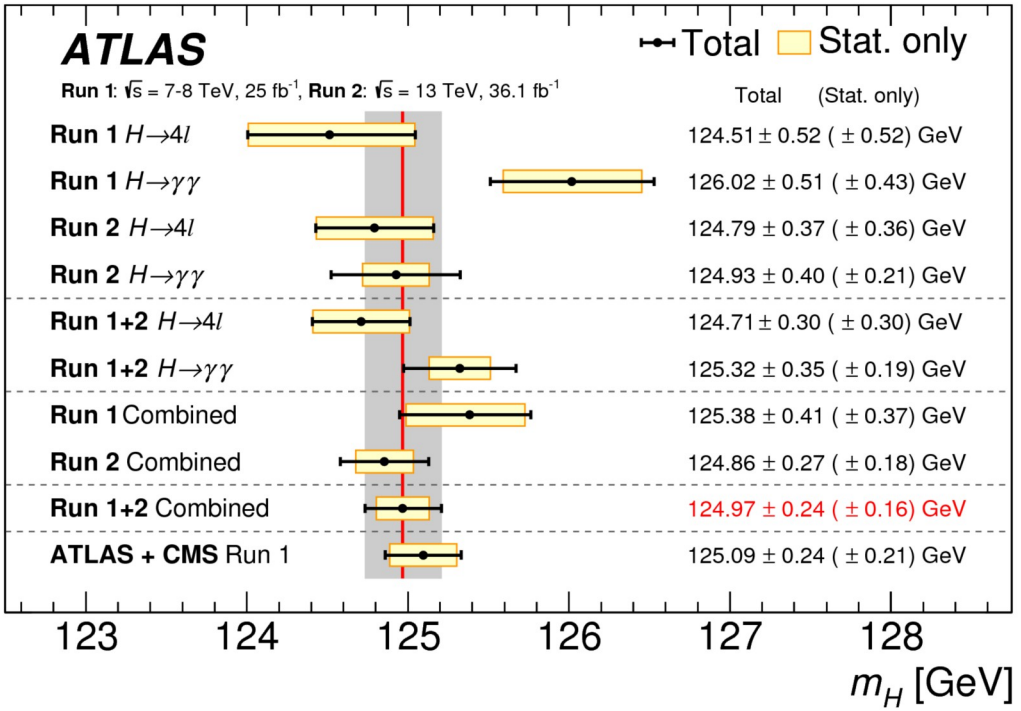
$$H \to \gamma\gamma \text{ and } H \to ZZ \to 4\ell$$

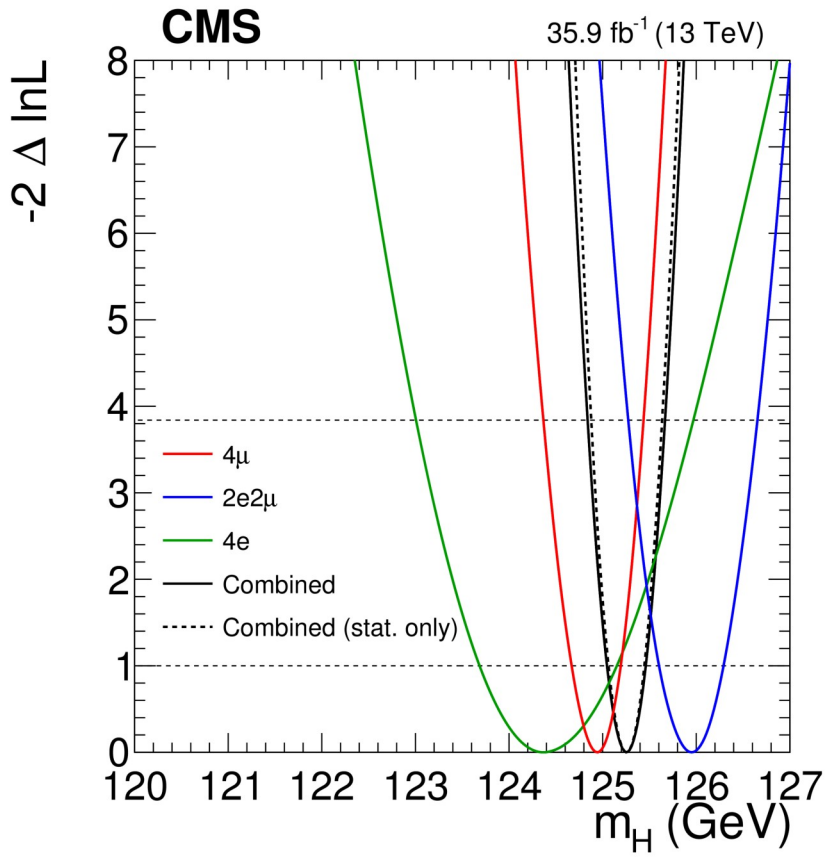
  - full kinematic reconstruction possible, Higgs mass determined as invariant mass of two photons or 4 leptons (e/μ). Analysis event selection and example of the mass spectra shown in backup.
  - results from these measurements summarized in next slides

- Coupling and total cross-section measurements performed in many other channels (WW, ττ, $b\bar{b}$, μμ, …), highlights from these analyses also reported

Higgs boson mass

- ATLAS combined measurement (PLB 784 (2018) 345)
  - H → γγ and H → ZZ → 4ℓ
  - combined Run-1 and Run-2
    m(H) = 124.97 ± 0.24 GeV





- Update from CMS based on H → ZZ → 4ℓ results (JHEP 11 (2017) 047)

  m(H) = 125.26 ± 0.21 GeV

- Both ATLAS and CMS standalone Run-2 results show better precision than combined ATLAS+CMS Run-1 results

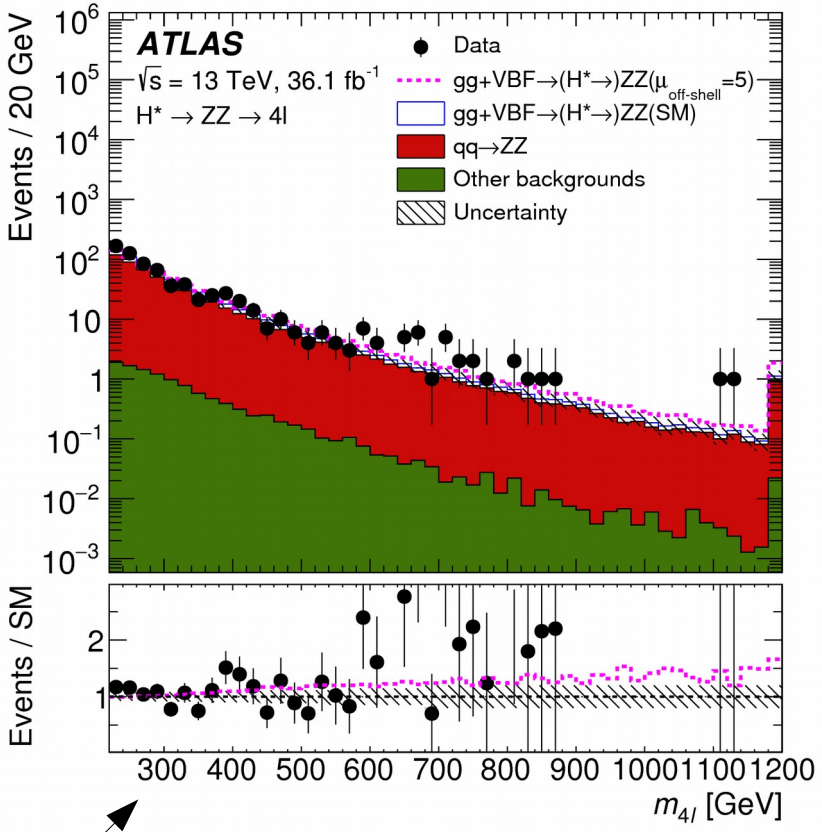
Higgs boson width

- SM predicts Γ(H) = 4 MeV, too small to be measured directly.
- **CMS** provides the best direct limit H → ZZ → 4ℓ: Γ(H) < 1.10 GeV @ 95% CL (JHEP 11 (2017) 047)
- Indirect measurements compare on-shell and off-shell cross-section in H → ZZ*/WW*

$$\sigma_{off-shell} \propto \kappa^2_{g,off-shell} \cdot \kappa^2_{Z,off-shell}$$

$$\sigma_{on-shell} \propto \frac{\kappa^2_{g,on-shell} \cdot \kappa^2_{Z,on-shell}}{\Gamma(H)/\Gamma^{SM}(H)}$$

  - assuming $\kappa_{on\text{-}shell} = \kappa_{off\text{-}shell}$ one can derive the width
  - **CMS** Run-1 results: Γ(H) < 13 MeV @ 95% CL (JHEP 09 (2016) 051)

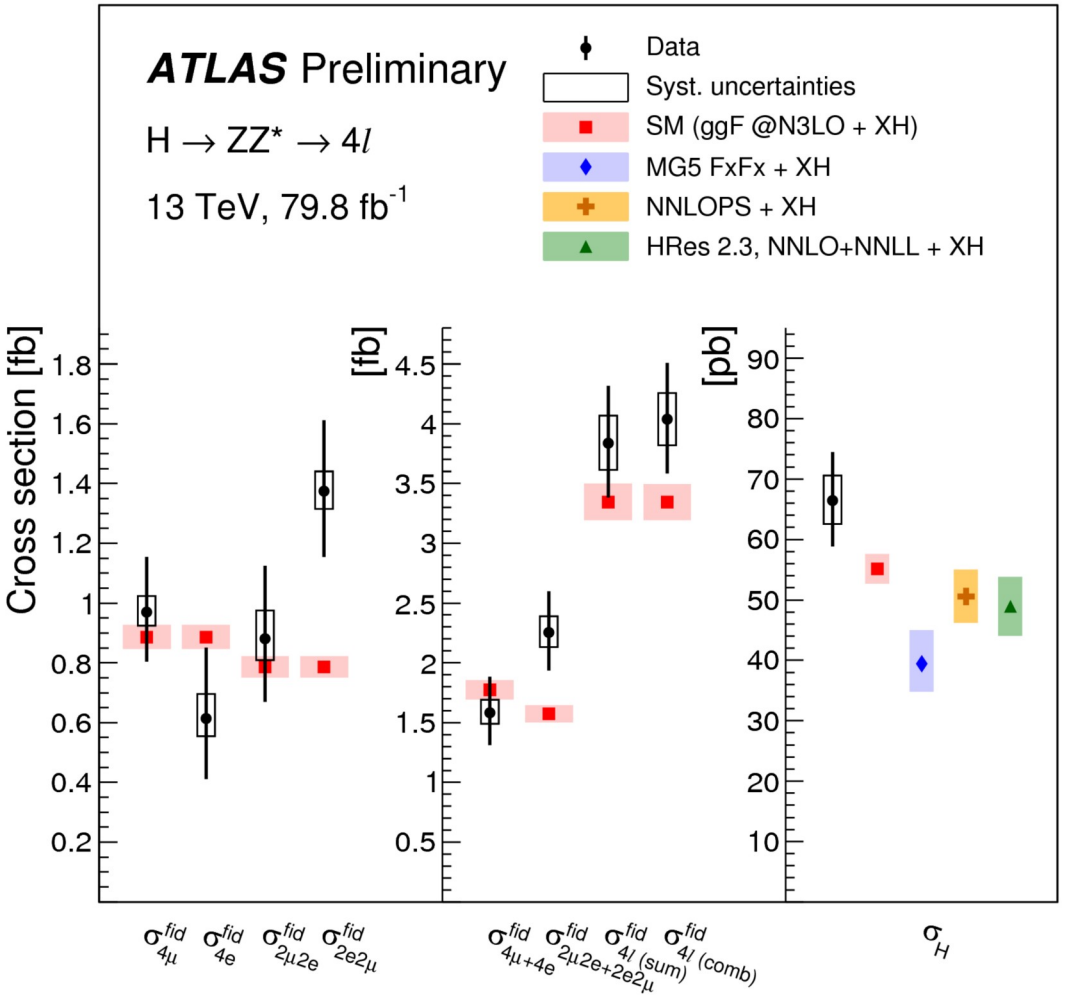


- recent **ATLAS** Run-2 measurement of H → ZZ → 4ℓ/2ℓ+2ν: Γ(H) < 14.4 MeV @ 95% CL (arXiv:1808.01191)

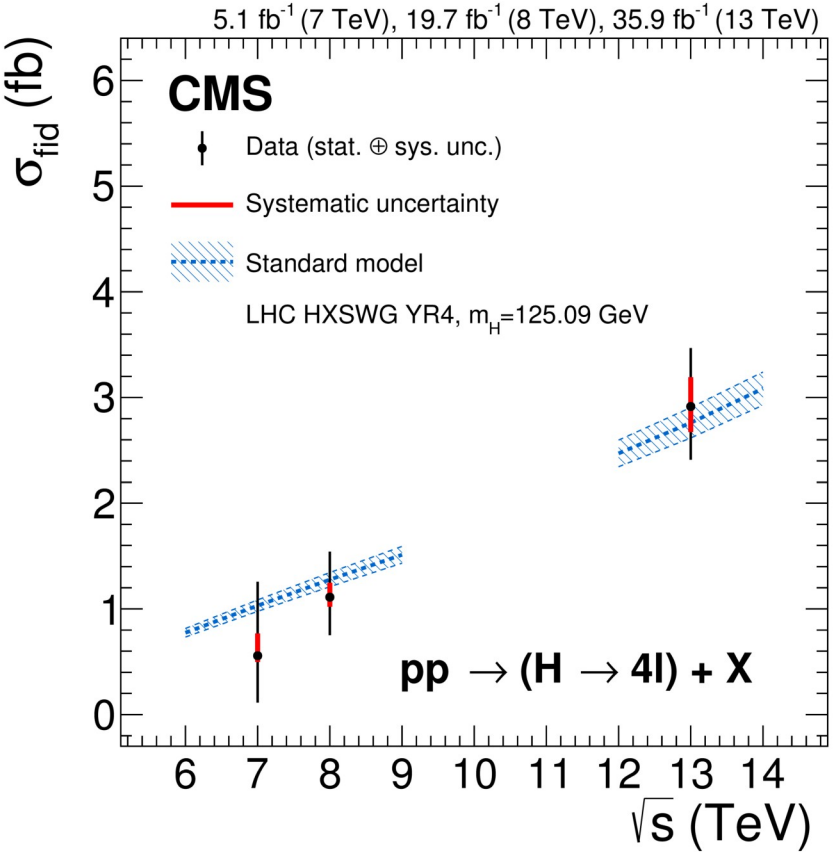
Cross-section measurements (1)

- Total cross-section measurements with $H \to ZZ \to 4\ell$

ATLAS-CONF-2018-018

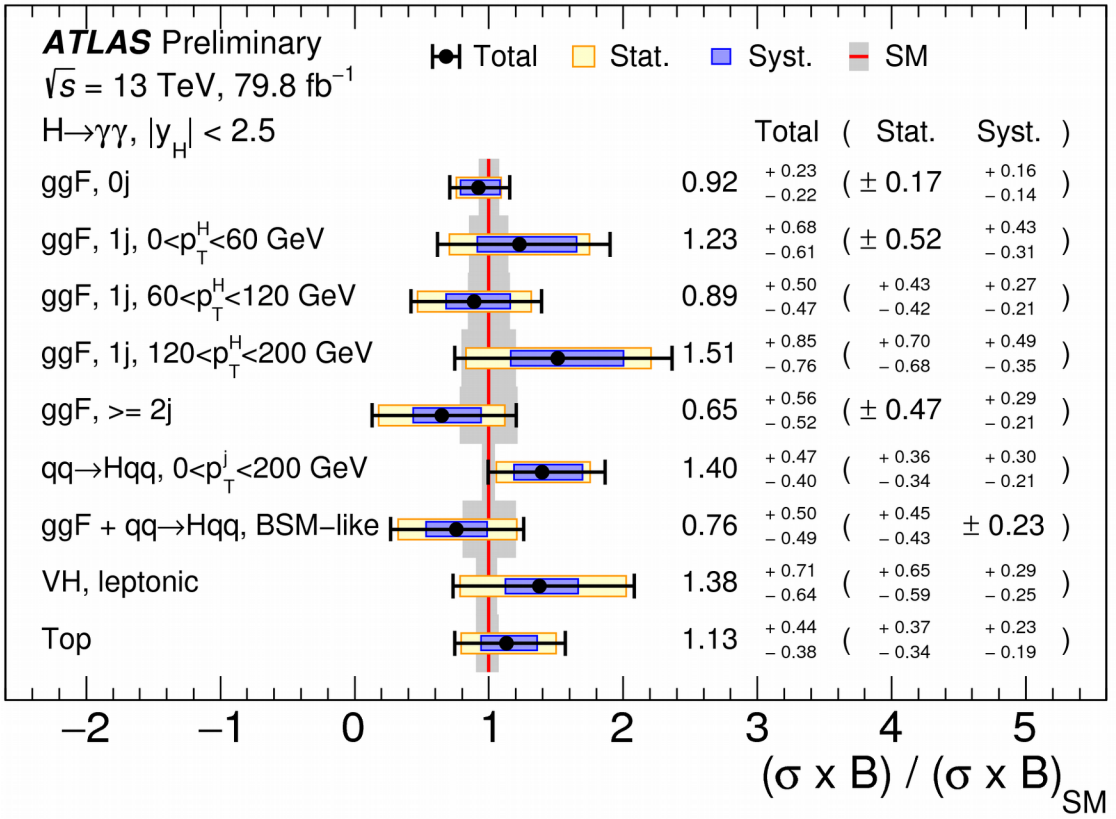


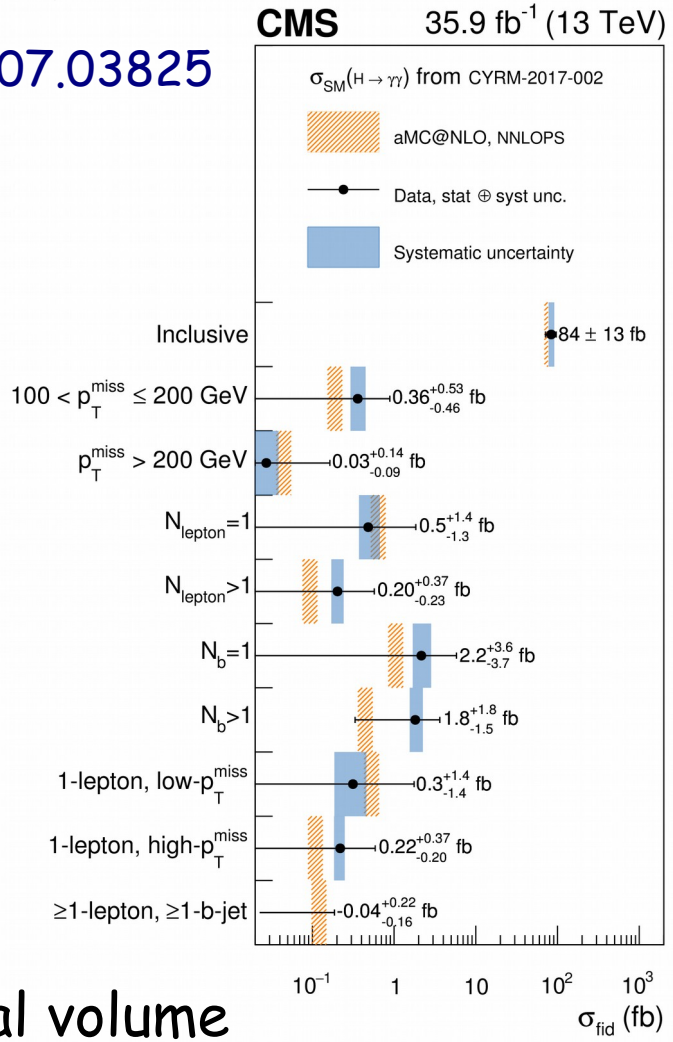
JHEP 11 (2017) 047



Cross-section measurements (2)

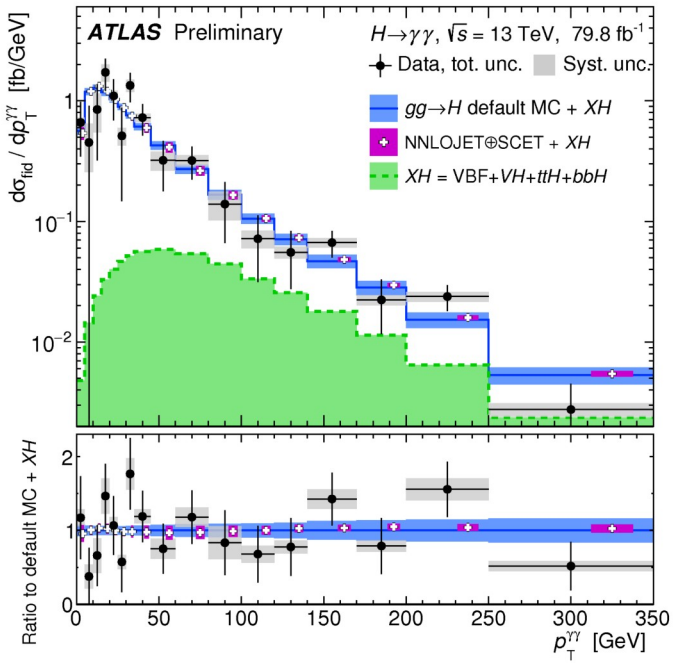
- Simplified template cross-section measurements in H → γγ ATLAS-CONF-2018-028 arXiv:1807.03825

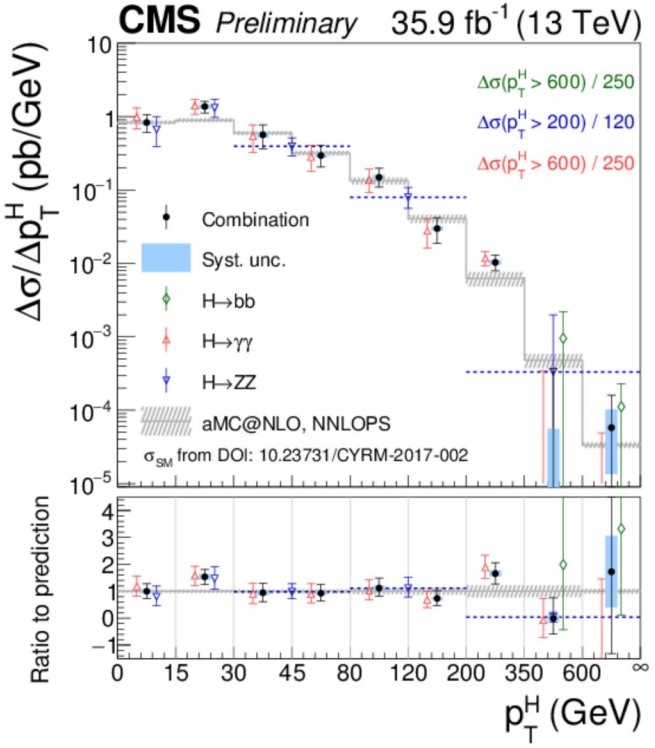


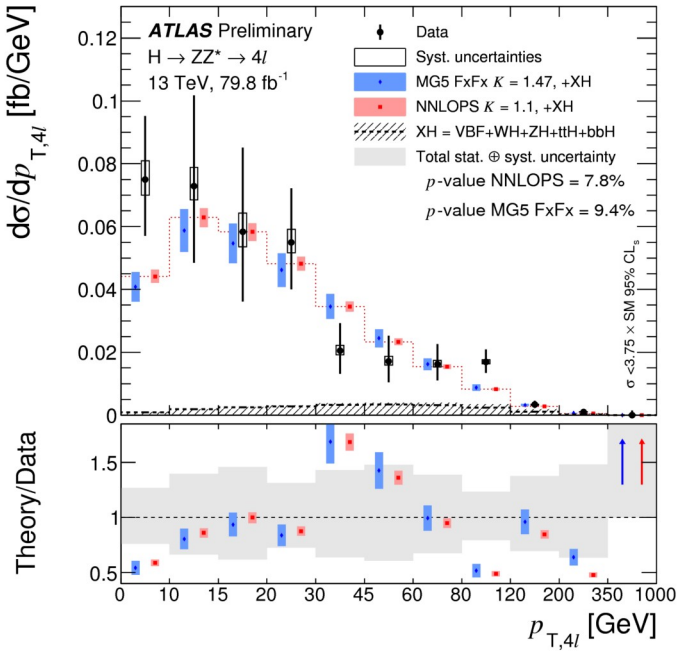


- … as well as total cross-section in the fiducial volume
  - ATLAS: 60.4 ± 8.6 fb^{-1}, predicted by SM 63.5 ± 3.3 fb^{-1}
  - CMS: 84 ± 13 fb^{-1}, predicted by SM 73 ± 4 fb^{-1}

Cross-section measurements (3)







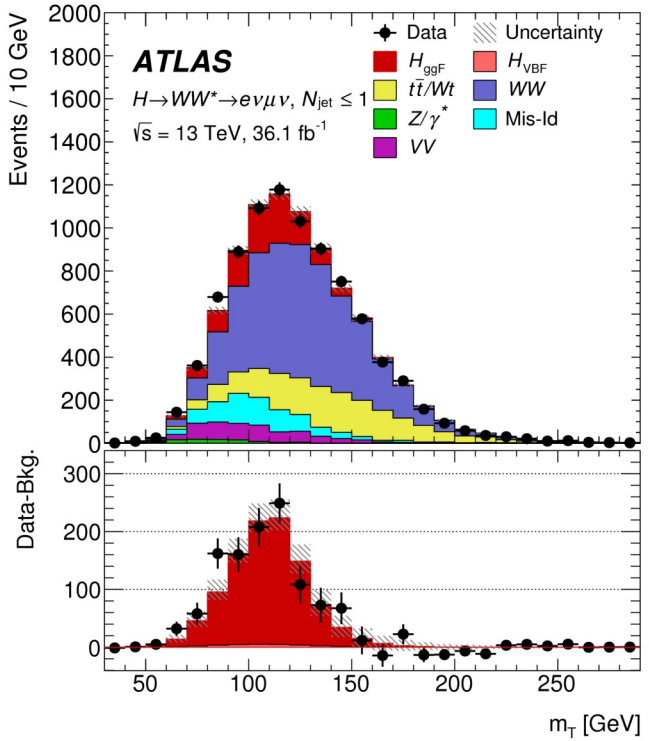
- Many differential Xsec measurements exist, few examples given here. For more details, see
  - ATLAS-CONF-2018-028, ATLAS-CONF-2018-018
  - CMS-PAS-HIG-17-028
  - older ATLAS combined results available in arXiv:1805.10197
- Good agreement with Standard Model, no sign of new physics yet

H → WW (1)

- Clean signature from W → ℓν, i.e. 2 neutrinos in the final state. Use of transverse mass $m_T = \sqrt{2\, p_T(\ell\ell)\, p_T^{miss} \left[1 - \cos\Delta\phi(\vec{p}_T(\ell\ell), \vec{p}_T^{miss})\right]}$

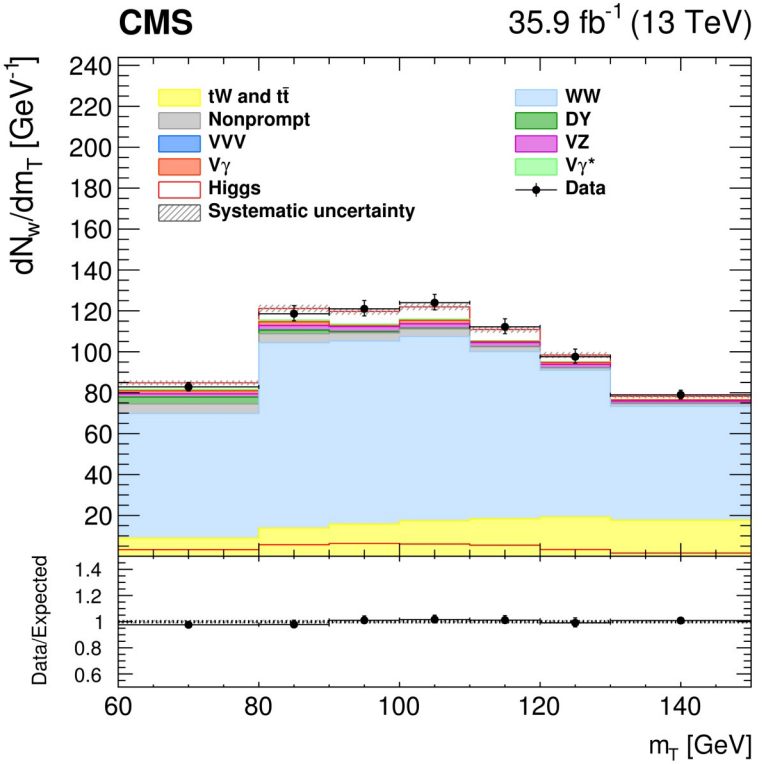
ATLAS (arXiv:1808.09054)

- only different flavour leptons in the final state H → WW → eνμν
- 3 main categories based on Njets, further splitting according to m(ℓℓ) and p_T(ℓ2)
- use of m_T (Njets=0, 1) or BDT (VBF)



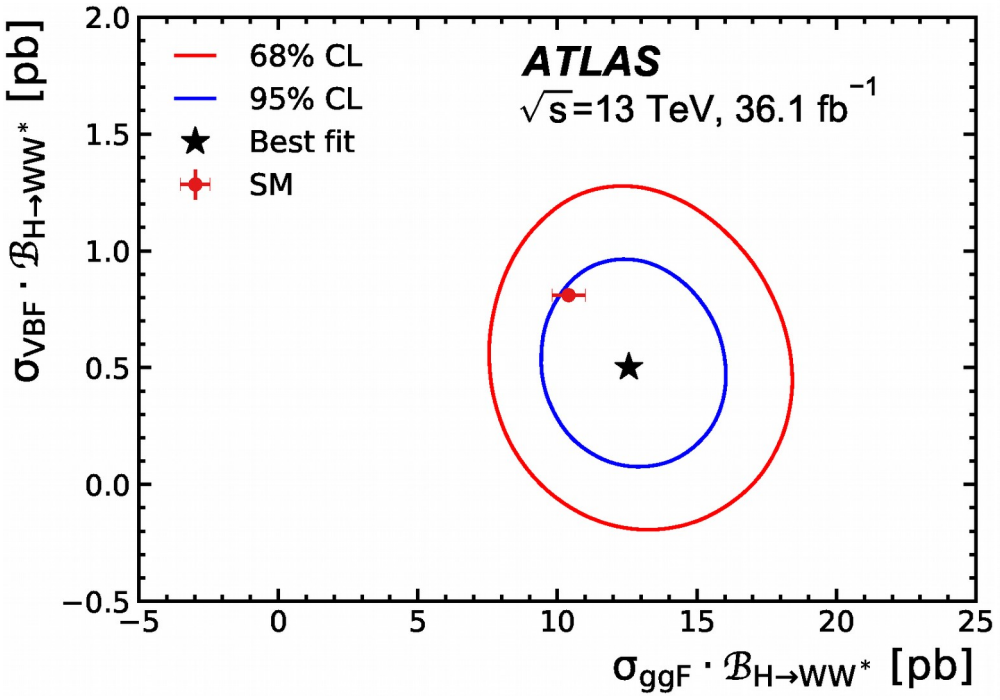
CMS (arXiv:1806.05246)

- uses same and different flavour leptons as well as multi-lepton channel (WH, ZH)
- 9 categories based on Njets and p_T(j2)
- 2-dim analysis with m_T and $m_{\ell\ell}$

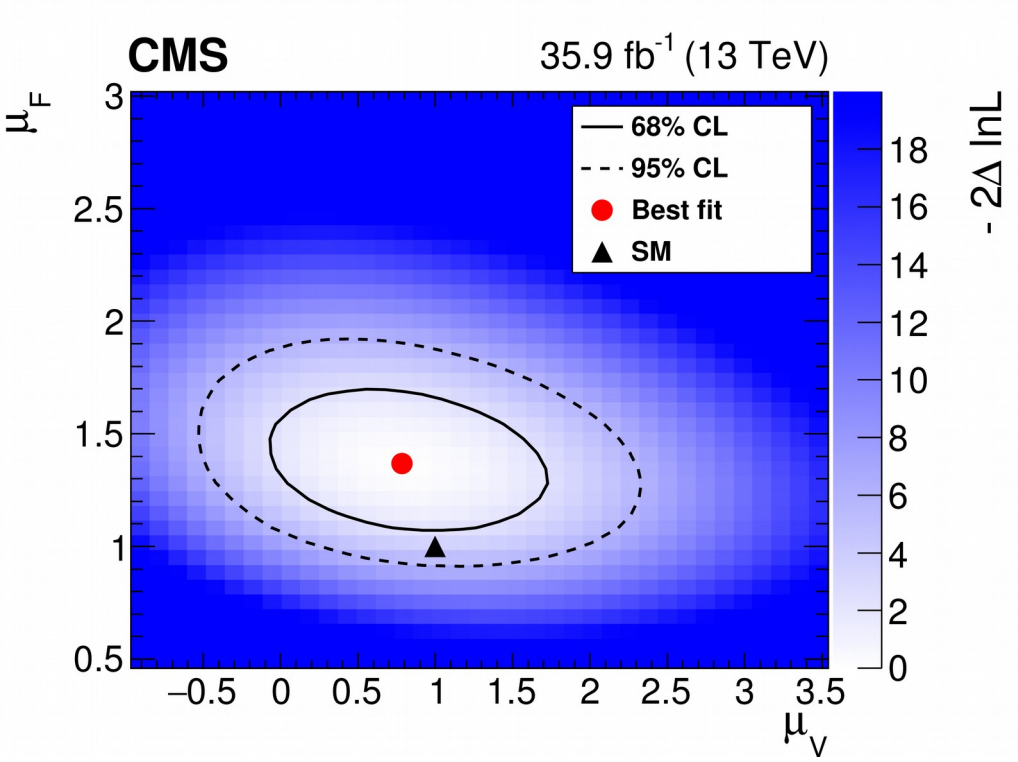


H → WW (2)

- Measured coupling constants are consistent with Standard Model predictions



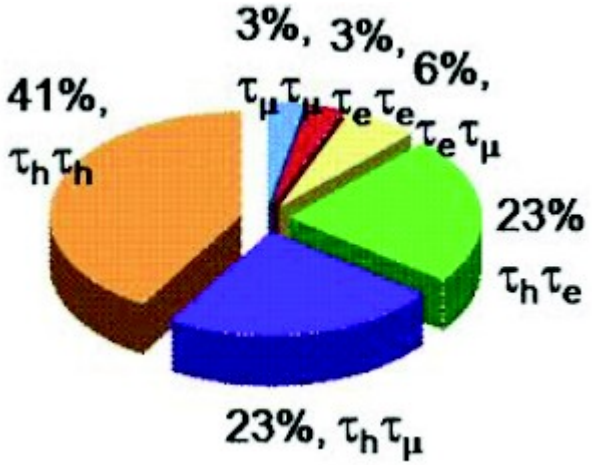
arXiv:1808.09054



arXiv:1806.05246

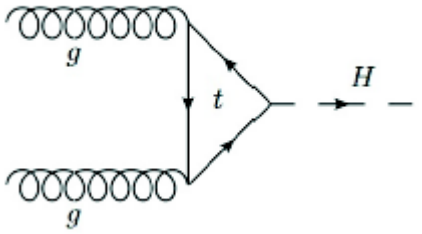
H → τ τ (1)

- The final state depends on the tau-lepton decay mode
  - di-lepton channel: $H \to \tau\,\tau \to 2\ell\ 4\nu$
  - semi-lepton channel: $H \to \tau\,\tau \to \ell\ n\pi\ 3\nu$ (n=1 - 3)
  - hadronic channel: $H \to \tau\,\tau \to n\pi\ 2\nu$

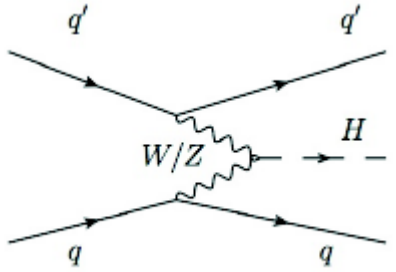


- Signatures in the detector
  - isolated electron(s) and/or muon(s)
  - missing transverse energy
  - reconstructed hadronic τ
  - accompanying jets (reflect the production mechanism)

gluon-gluon fusion (dominant production mode)



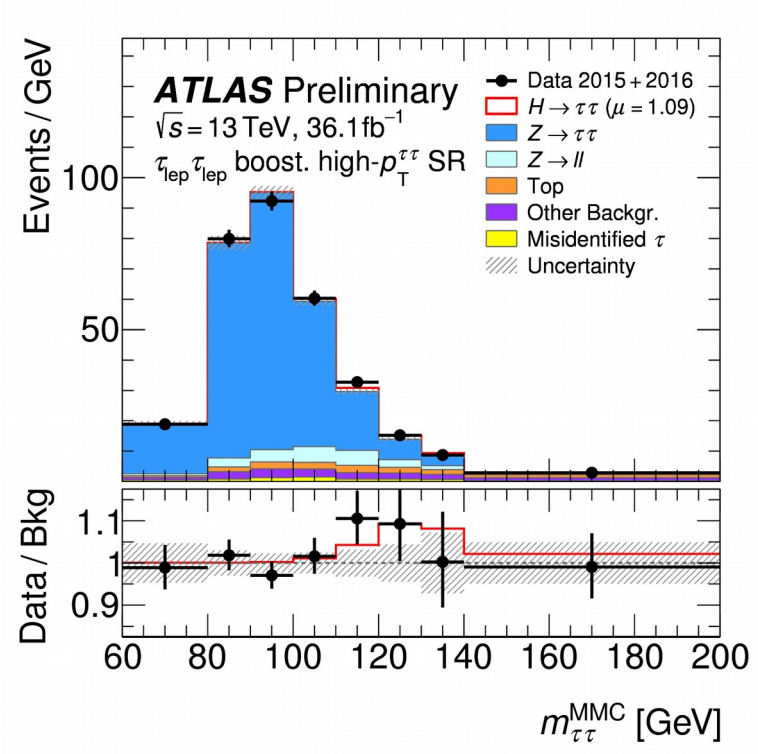
VBF (subdominant, ~10 weaker)

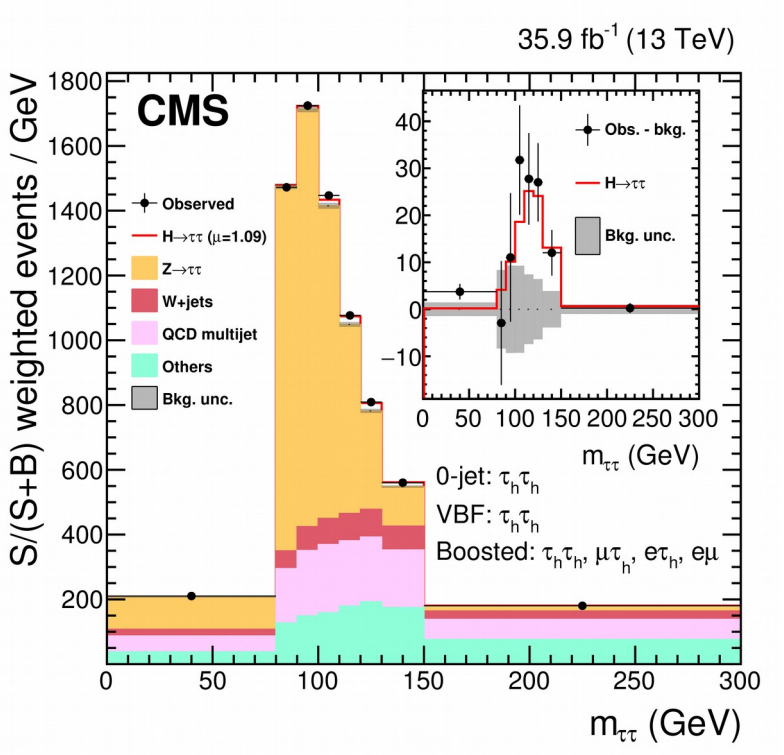


- Dominant background comes from $Z \to \tau\,\tau$, also top, $Z \to \ell\ell$ and fakes contribute

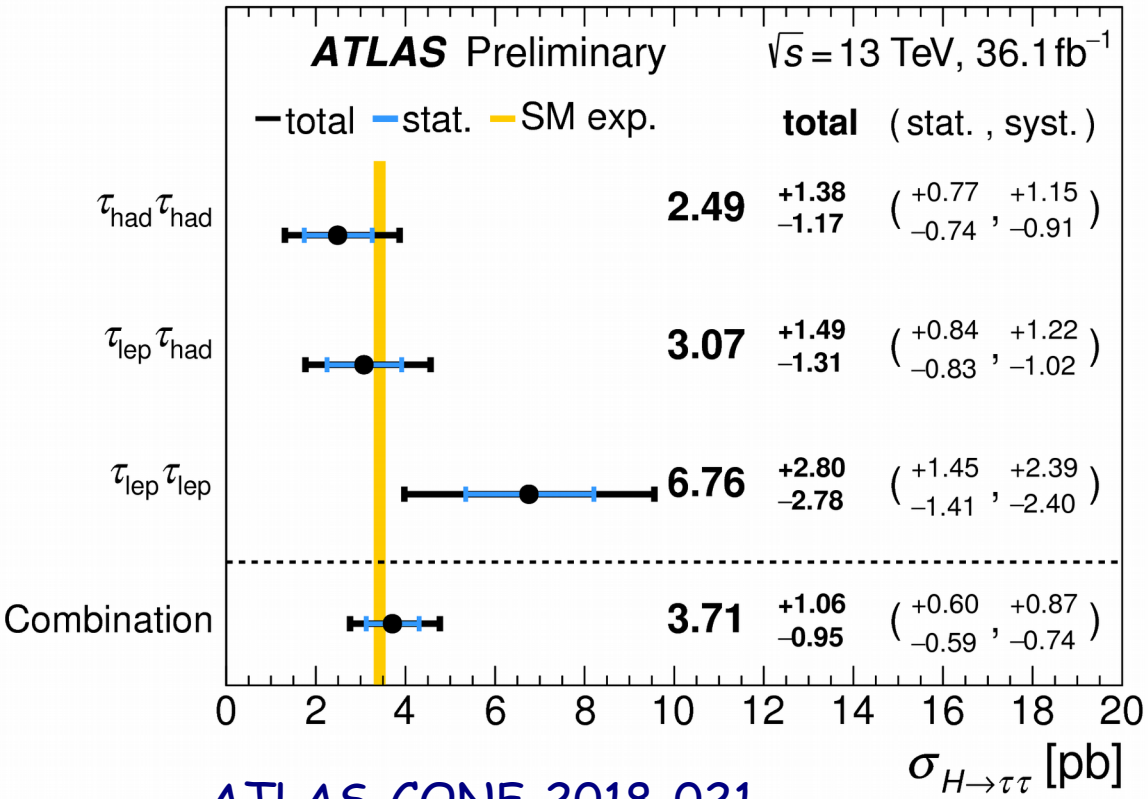
H → τ τ (2)

- ATLAS (CONF-2018-021)
  - VBF and Boosted category in each channel, further splitting to enhance sensitivity
  - reconstructed MMC mass as final discriminant
- CMS (arXiv:1803.06553)
  - 0-jet, VBF and Boosted categories
  - 2-dim fit on m(ττ), m(jj) or p_T(ττ)

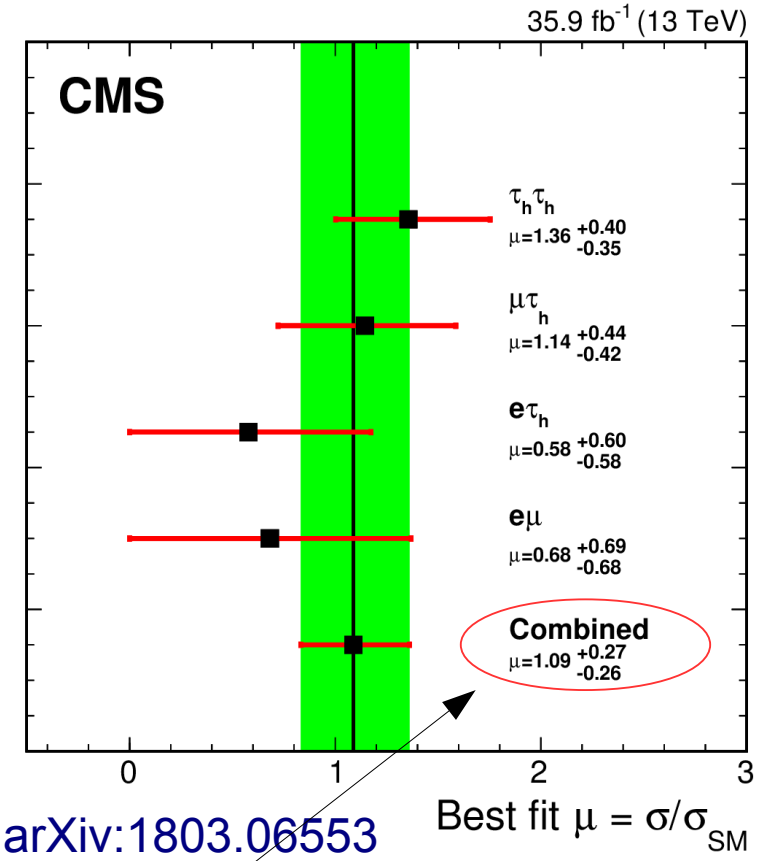




H → τ τ (3)



ATLAS-CONF-2018-021



arXiv:1803.06553

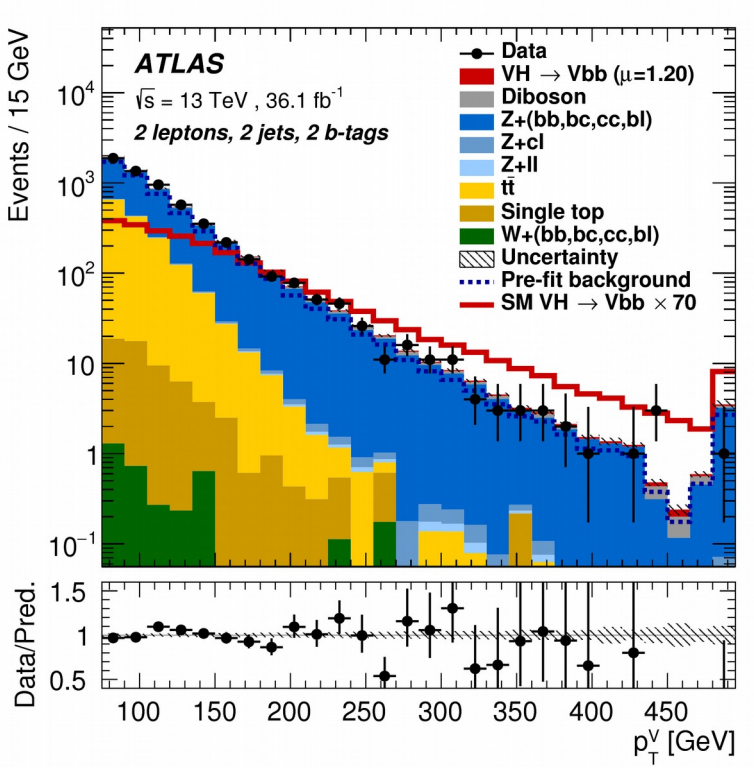
- Same signal strength measured by ATLAS and CMS
  - total cross-section measured by ATLAS corresponds to $\mu = 1.09^{+0.31}_{-0.28}$

In combination with Run-1 results, but experiments observe this decay mode (ATLAS 6.4σ, CMS 5.9σ) independently

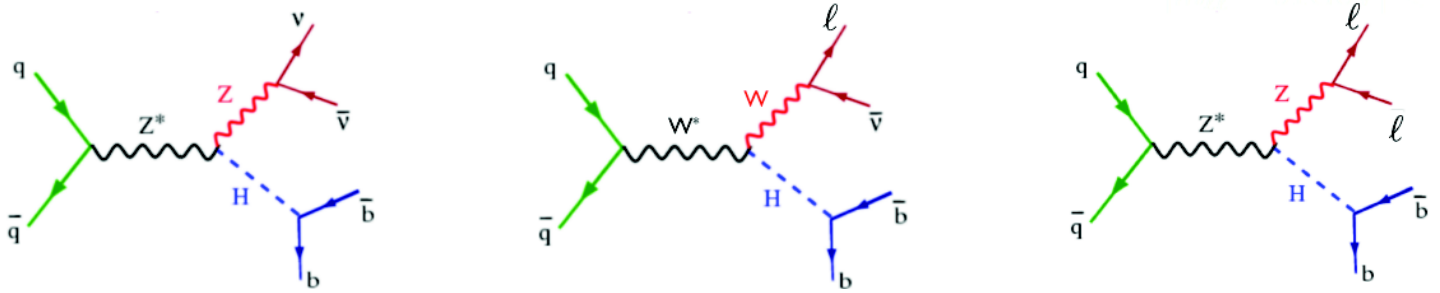
- CMS also published measurement in W/Z+H channel (CMS-PAS-HIG-18-007)

$H \to b\bar{b}$ (1)

- Searches started at LEP (imposed m(H) > 114.4 GeV), then continued at Tevatron (observed at 2.8σ)
- Most sensitive channel @ LHC: W/Z+H
  - key elements are b-tagging and dijet invariant mass reconstruction
  - background significantly reduced at high p_T(W/Z)
  - three main categories (0-,1- and 2-leptons), further split according to Njets (2, 3)
    - ATLAS uses BDT in further analysis
    - CMS exploits deep NN to discriminate S/B as well as backgrounds in CRs

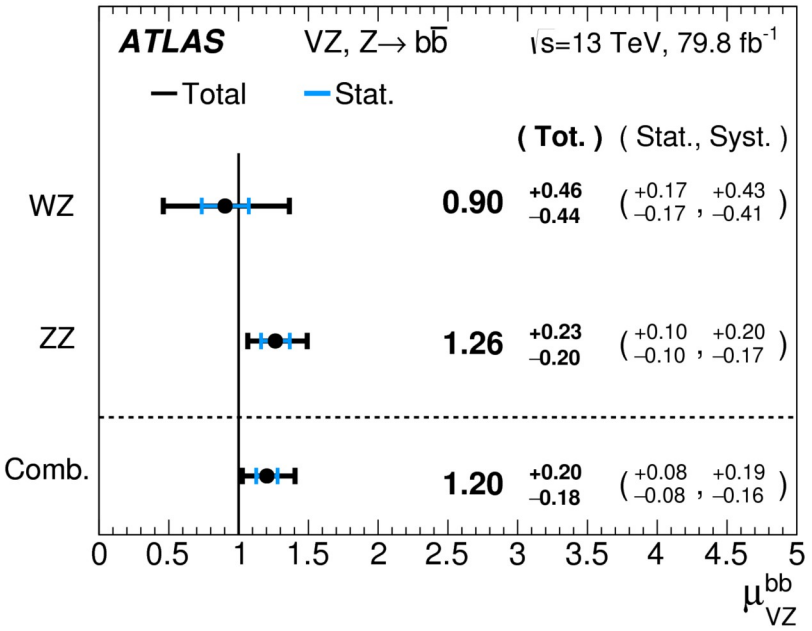


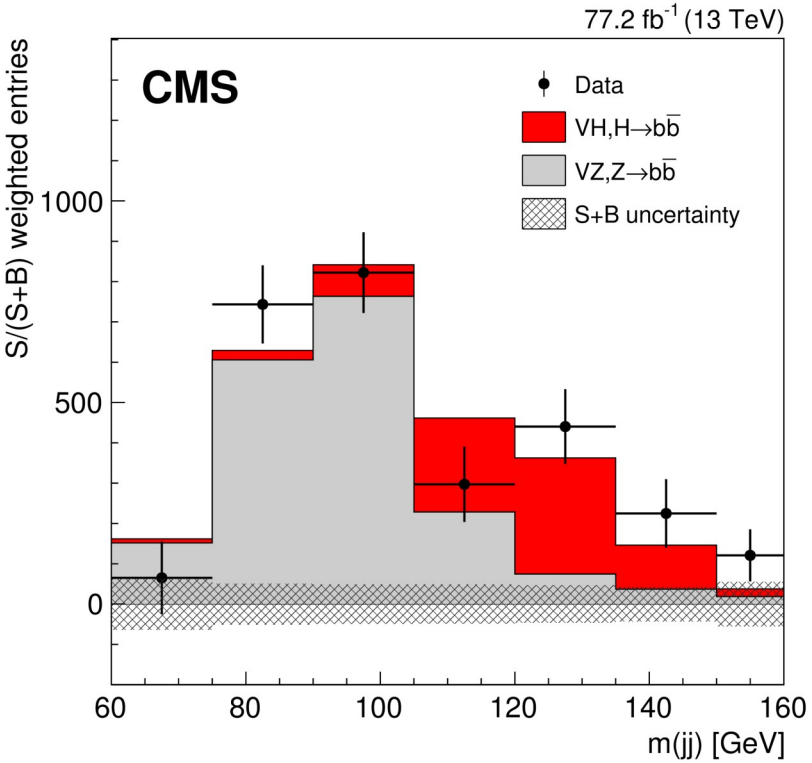
arXiv:1808.08238



H → bb̄ (2)

- W/Z+H (→ bb̄) analysis
  - cross-check with standard candle W/Z+Z(→ bb̄)
  - event excess clearly seen in dijet invariant mass spectrum
  - combined Run-1 + Run-2 results
    - **ATLAS**: $\mu = 1.16^{+0.27}_{-0.25}$ significance 4.9σ (arXiv:1808.08238)
    - **CMS**: $\mu = 1.01 \pm 0.23$ significance 4.8σ (arXiv:1808.08242)

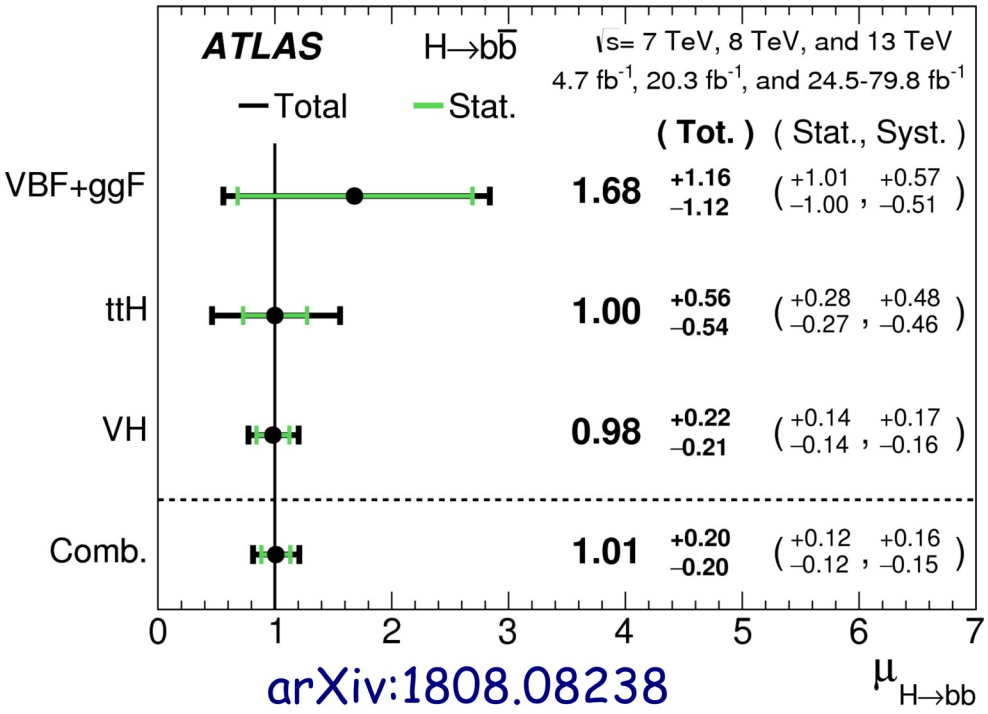




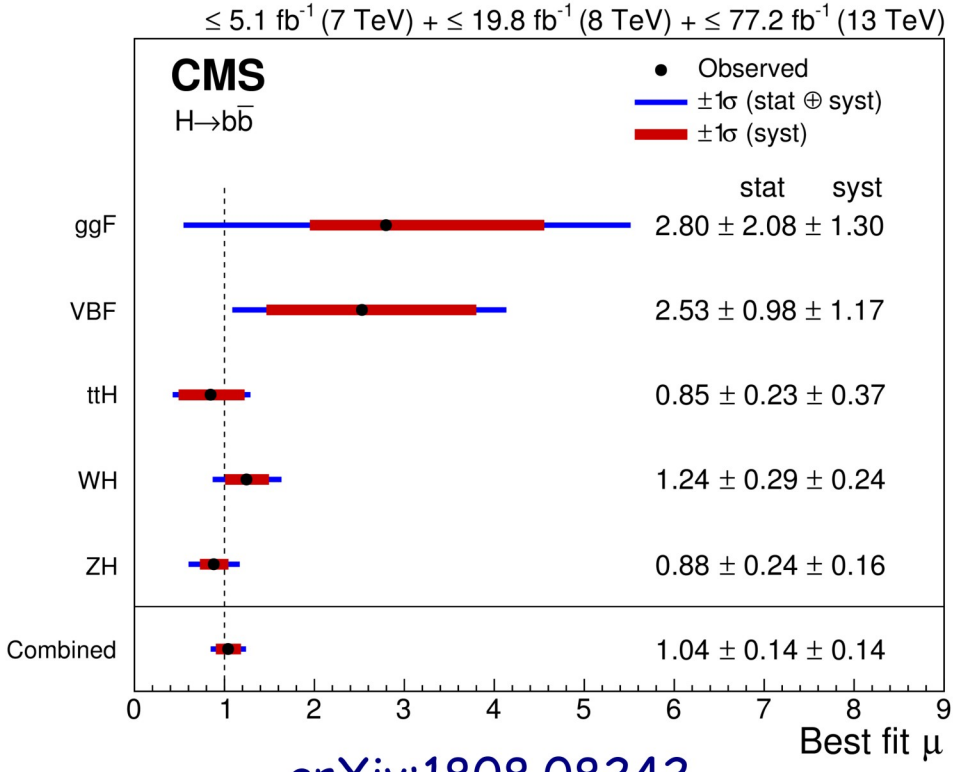
H → bb̄ (3)

New !!

- Searches also performed in ggF (boosted topology), VBF and tt̄H production modes (see backup slides)
- Combined H → bb̄ results



arXiv:1808.08238



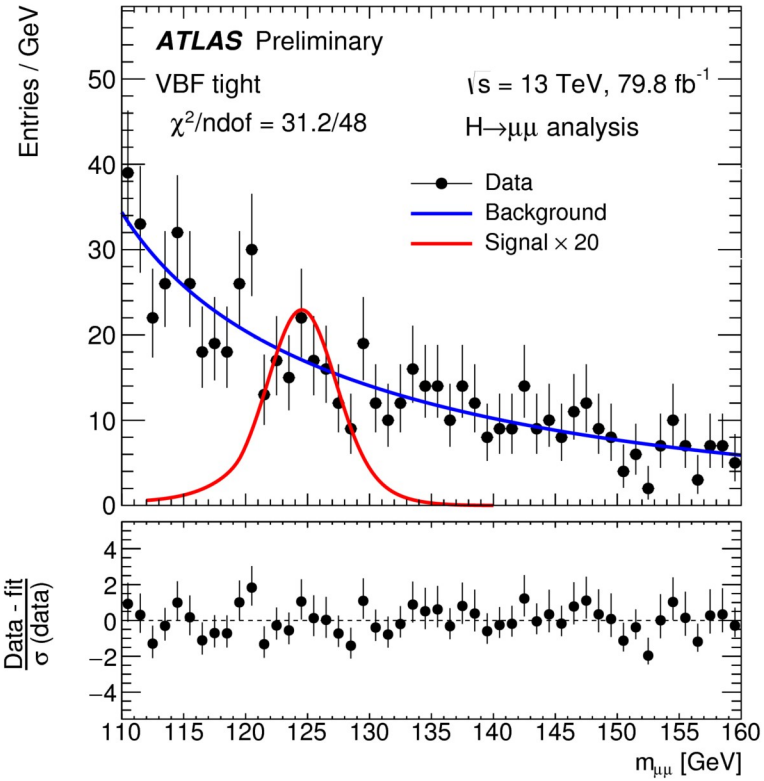
arXiv:1808.08242

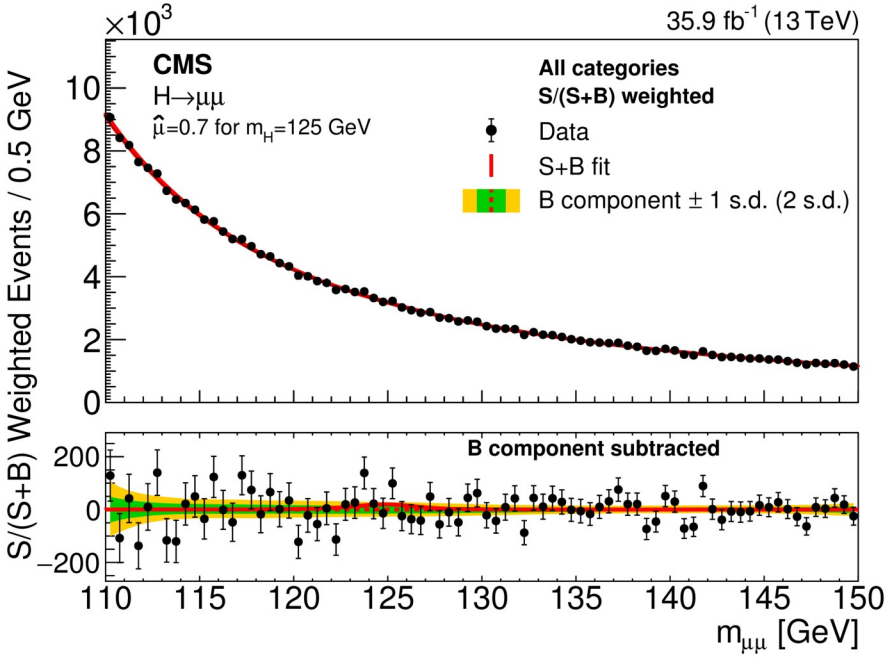
- significances: 5.4σ (ATLAS), 5.6σ (CMS)

H → bb̄ decay mode observed independently by both experiments

H → μμ (1)

- **ATLAS** (ATLAS-CONF-2018-026)
  - selects 2 isolated muons with p_T > 15 GeV, low MET, b-veto
  - then use BDT to select VBF-like events (2 cats.), remaining events split into 6 cats. (according to $p_T(\mu\mu)$, η_μ)
- **CMS** (arXiv:1807.06325)
  - BDT is built using input variables uncorrelated to di-muon invariant mass: $p_T(\mu\mu)$, $\eta(\mu\mu)$, $\Delta\eta(\mu\mu)$, $\Delta\eta(jj)$, two highest di-jet masses, ...
  - split then into 14 categories





H → μμ (2)

- No signal observed yet, setting the upper limits on the production cross-section x BR @ 95% CL:
  - ATLAS: 2.1 x SM (ATLAS-CONF-2018-026)
  - CMS: 2.64 x SM (arXiv:1807.06325)

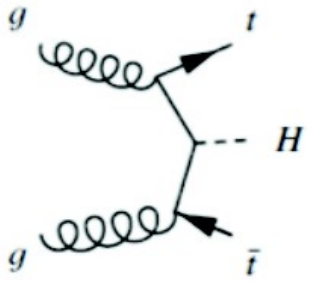
Both experiments are approaching the sensitivity of the SM prediction

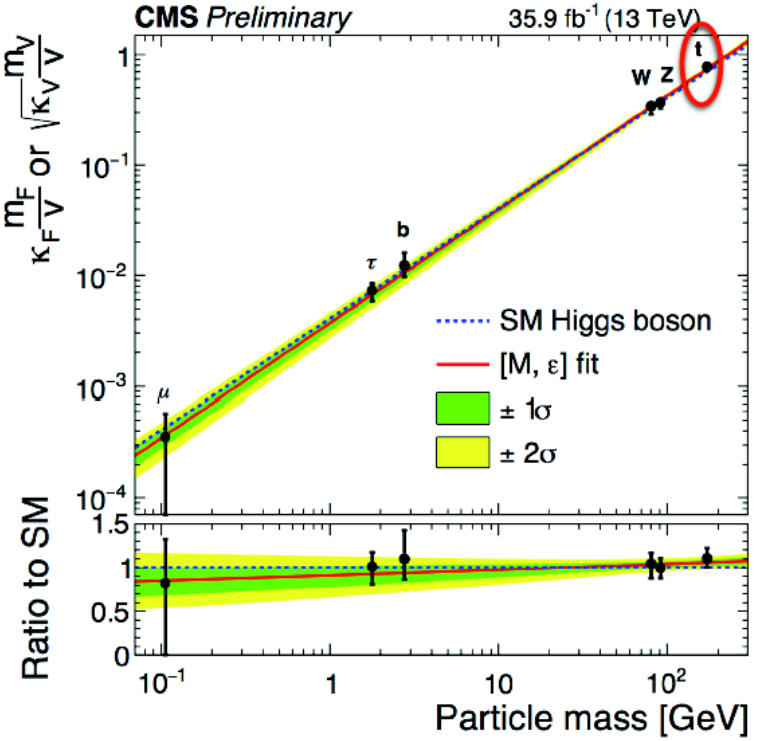
$t\bar{t}H$ production (1)

- Higgs coupling to top-quark is the largest Yukawa coupling to fermions
  - sensitive to new physics
- Complex final states, depend on the Higgs boson decay mode:
  - $H \to \gamma\gamma$, $H \to ZZ^* \to 4\ell$
  - multilepton
    - $H \to WW \to \ell\nu\ell\bar{\nu}$ or $\ell\nu q\bar{q}$
    - $H \to ZZ^* \to \ell\ell\nu\bar{\nu}$ or $\ell\ell q\bar{q}$
    - $H \to \tau_{lep}\tau_{lep}$
  - $H \to b\bar{b}$

higher S/B

higher σ x BR



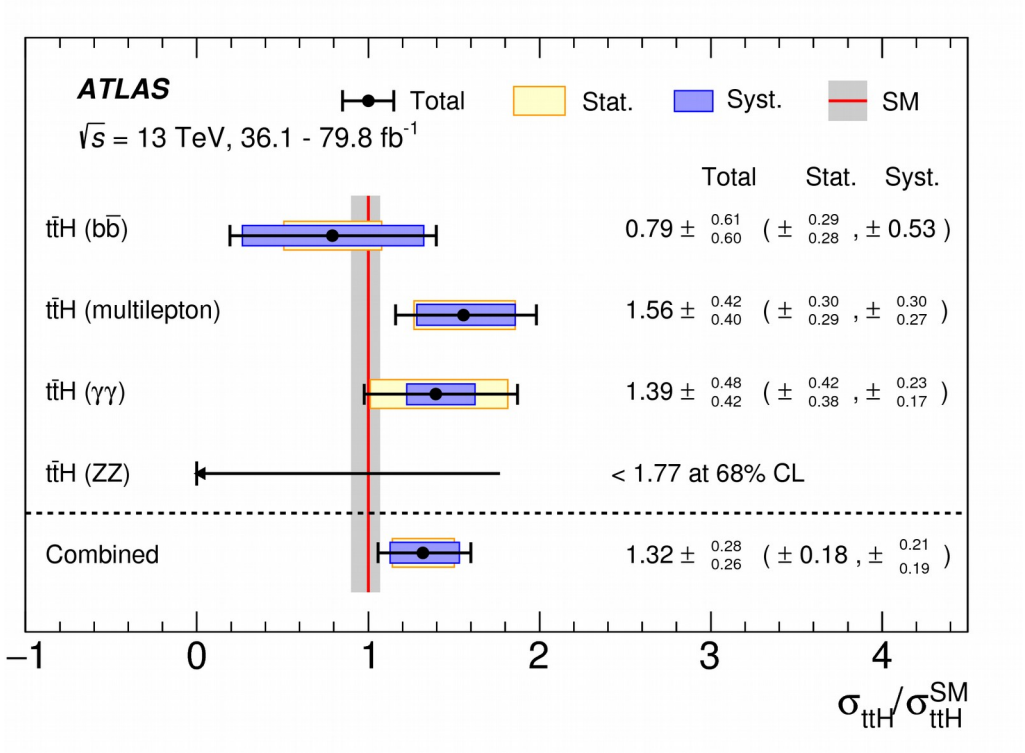


CMS-PAS-HIG-17-031

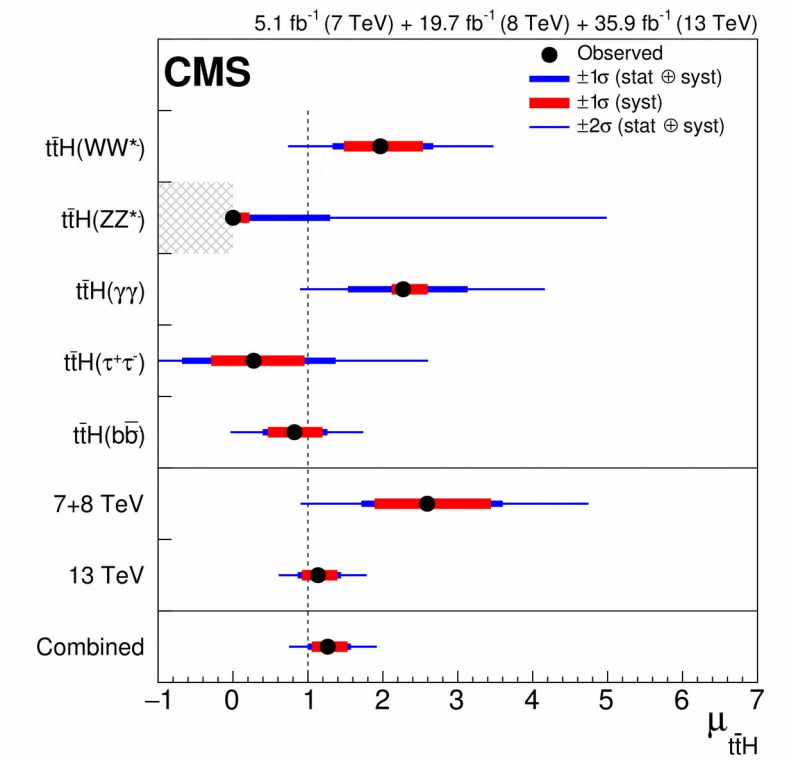
$t\bar{t}H$ production (2)

- Combination of $t\bar{t}H$ measurements

Phys.Lett.B 784 (2018) 173



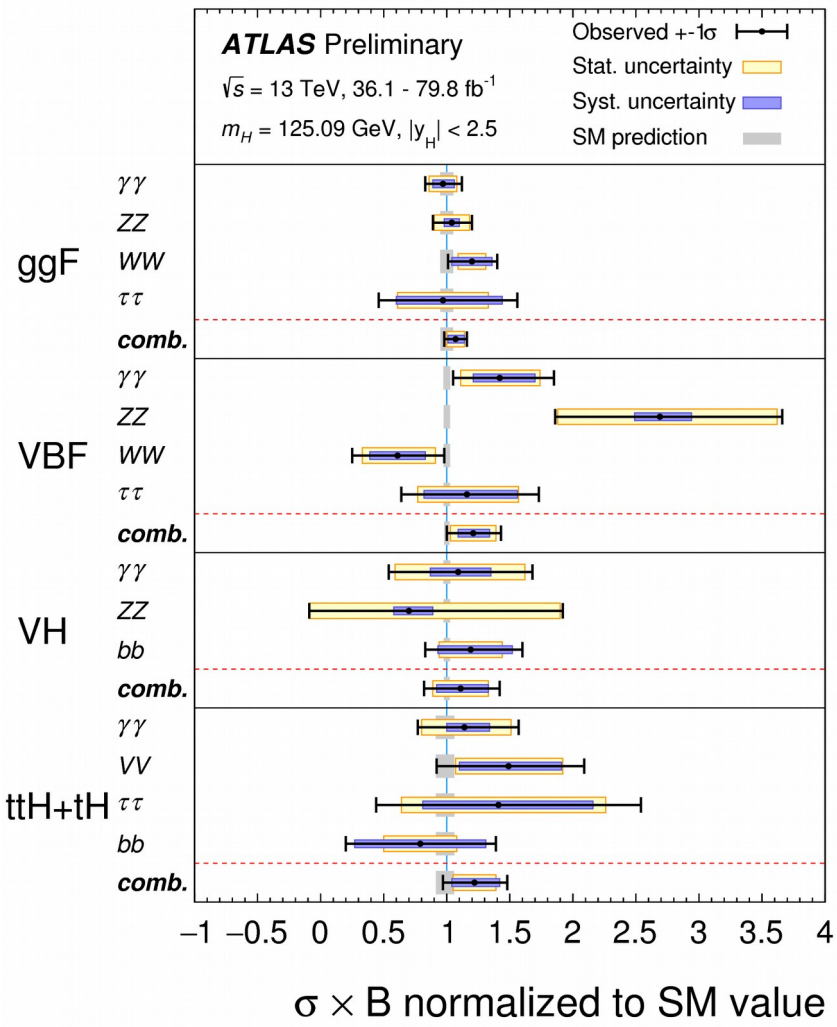
Phys.Rev.Lett. 120 (2018) 231801



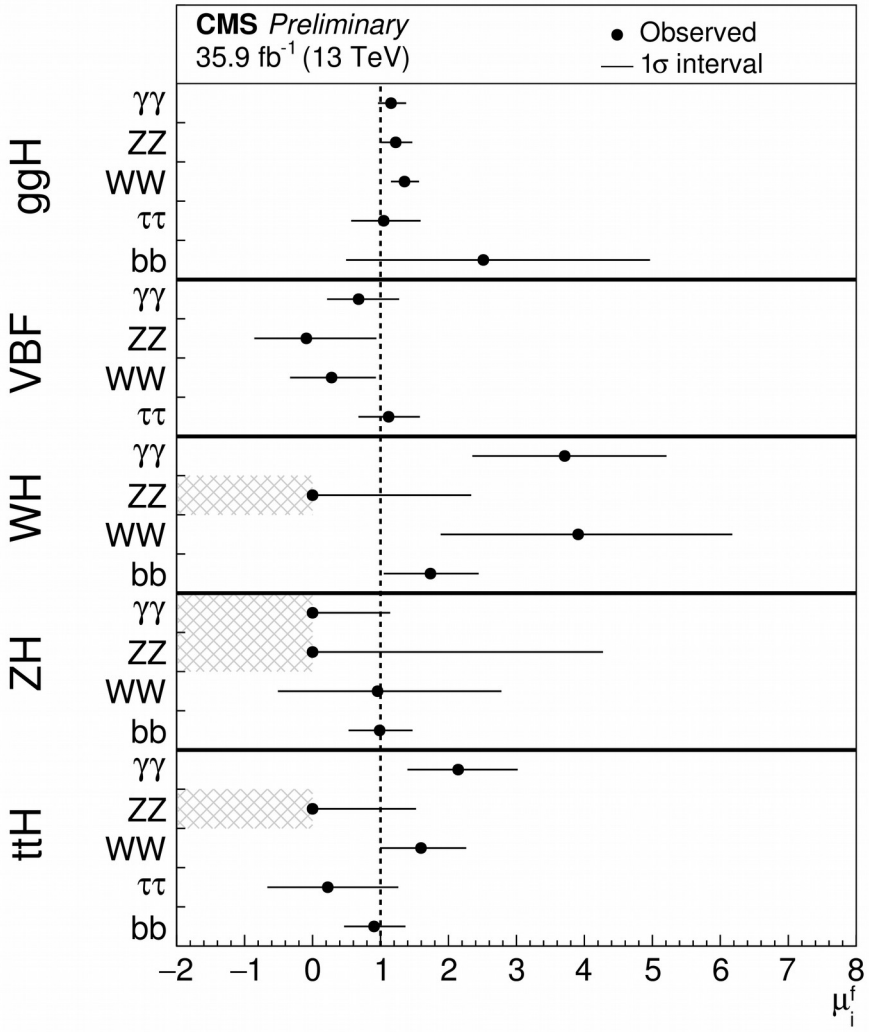
- **Observation of $t\bar{t}H$ production**
  - ATLAS Run-1+Run-2: **6.3σ** (5.1σ expected)
  - CMS Run-1+Run-2: **5.2σ** (4.2σ expected)

Combined measurements (1)

ATLAS-CONF-2018-031



CMS-PAS-HIG-17-031



Combined signal strength:

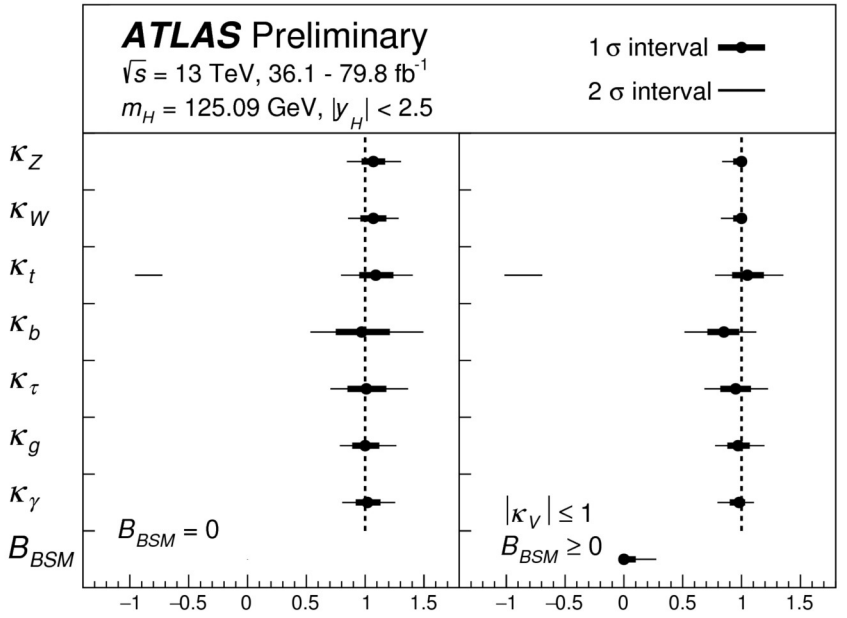
$\mu = 1.13^{+0.09}_{-0.08}$

$\mu = 1.17 \pm 0.10$

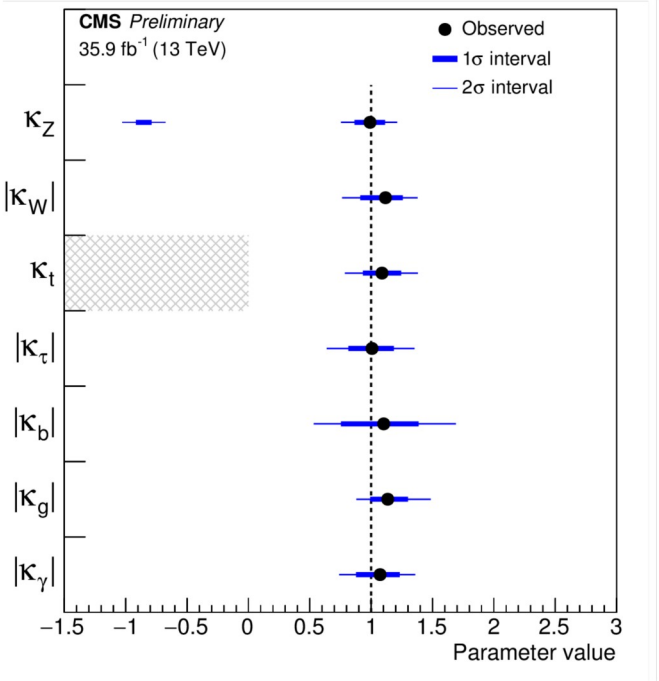
Combined measurements (2)

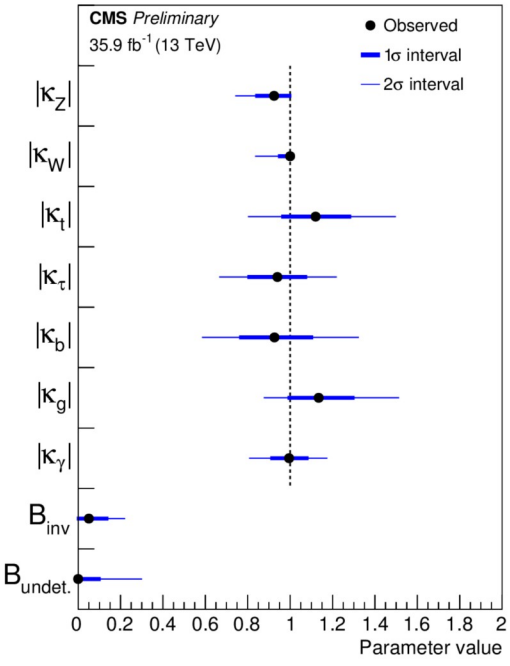
- Combined fit with coupling modifiers ($\kappa^2_i = \sigma_i/\sigma_{i,SM}$, $\kappa^2_f = \Gamma_f/\Gamma_{f,SM}$)
  - provide constraints on new physics phenomena (2HDM, simplified MSSM)

ATLAS-CONF-2018-031



CMS-PAS-HIG-17-031





Other Higgs-related searches

- Double Higgs ($HH \to b\bar{b}b\bar{b}$, $b\bar{b}\tau\tau$, $b\bar{b}\gamma\gamma$, …)
  - both experiments provided upper limits
    - ATLAS observes: $\sigma < 6.4 \cdot \sigma_{SM}$ (ATLAS-CONF-2018-043)
    - CMS observes: $\sigma < 21.8 \cdot \sigma_{SM}$ (CMS-PAS-HIG-17-030)

- … as well as many non- or beyond-SM searches, e.g.
  - $H \to$ invisible
  - lepton flavour violating decays ($H \to e\tau$, $H \to \mu\tau$)
  - searches for additional Higgs boson(s), both neutral and charged

Conclusions

- Higgs boson interaction with gauge bosons already established in Run-1, now entering the precision measurement era
- Yukawa couplings to fermions ($t\bar{t}$, $b\bar{b}$, $\tau\tau$) observed.
- All major Higgs production modes also observed

Everything consistent with Standard Model so far

- Next challenges include couplings to $\mu\mu$, $c\bar{c}$ as well detailed cross-section measurements

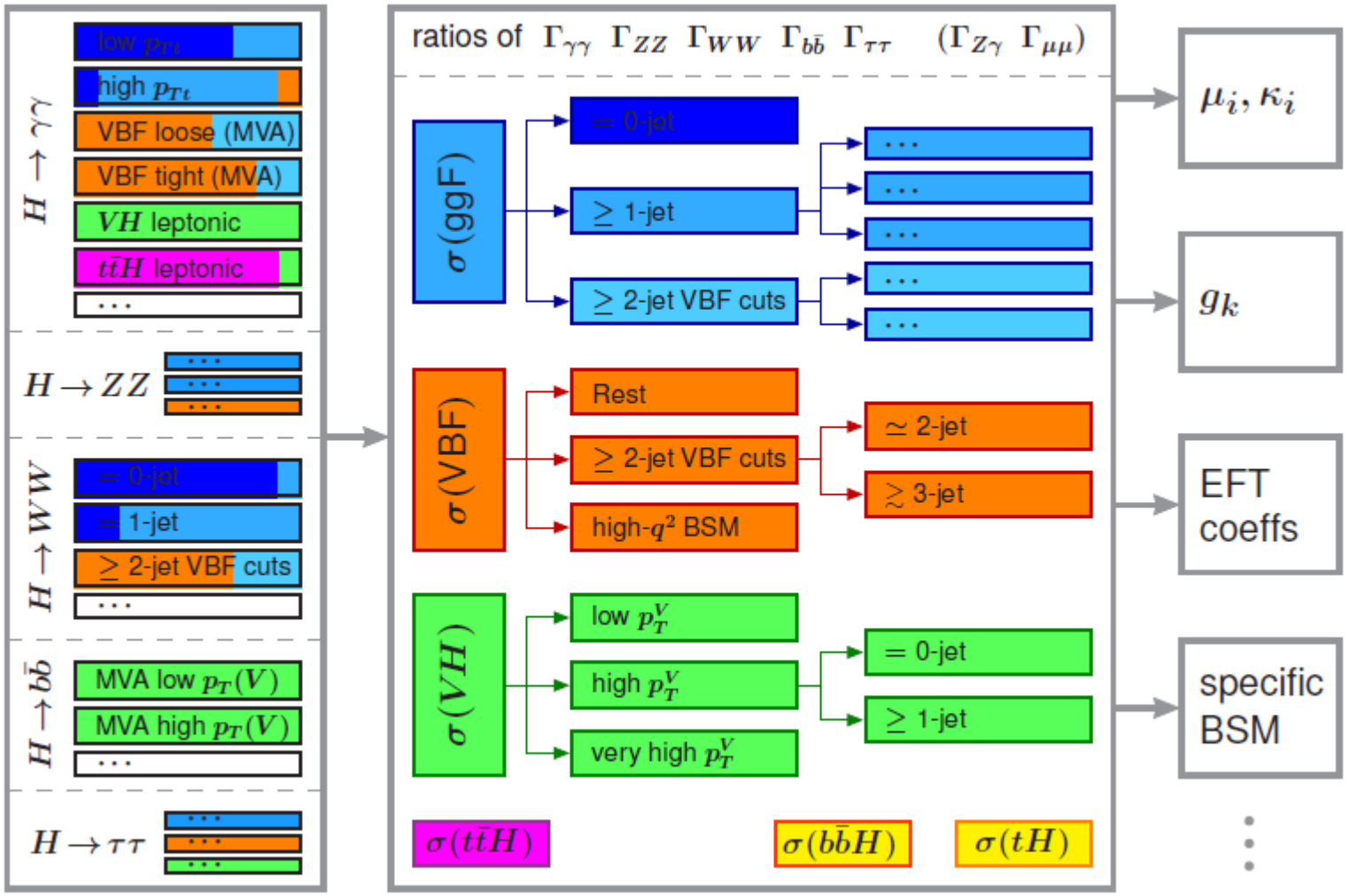
Eagerly awaiting complete 2018 data-set and full Run-2 results

BACKUP

Simplified template cross-section (1)

- Common ATLAS+CMS framework. It uses the fiducial cross-sections as measured for specific production modes on the input and enables to obtain global combinations across all decay channels.
- **Stage 0**: basically the splitting according to the production mechanism (ggF, VBF, VH, $t\bar{t}H$, $b\bar{b}H$, tH)
- **Stage 1** defines further binning in Higgs p_T and/or associated jet topology

Simplified template cross-section (2)



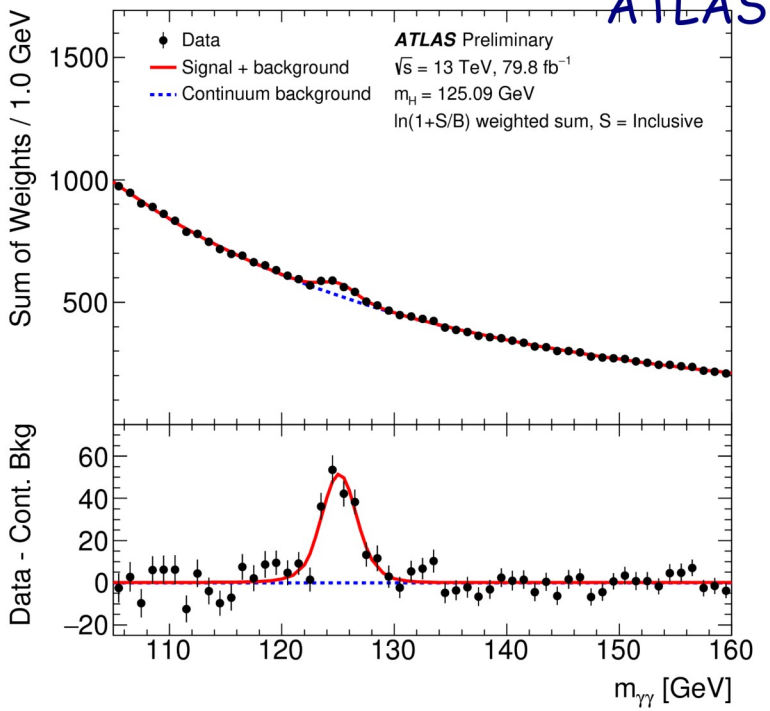
H → γγ

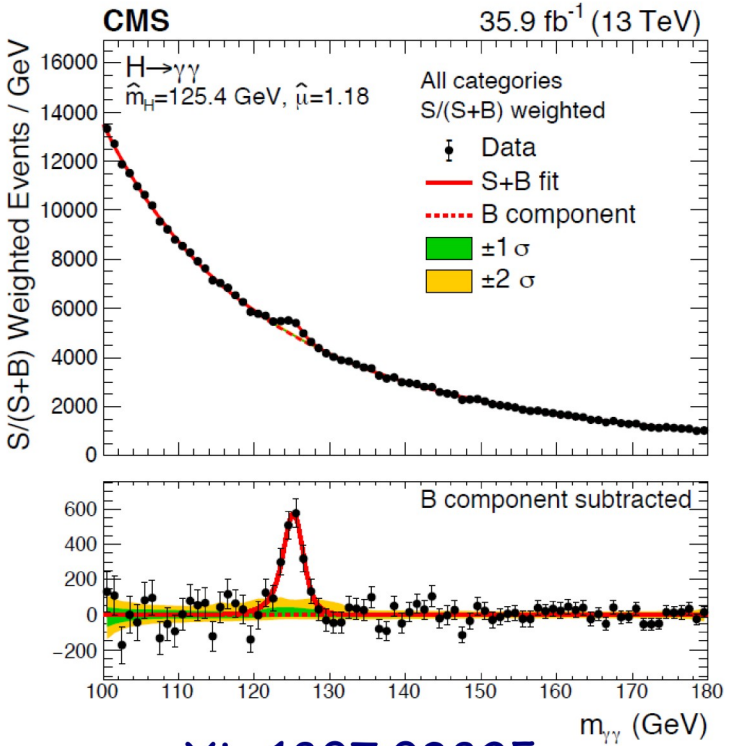
- Search for isolated high-p_T photons with invariant mass ~ 125 GeV

$$m_{\gamma\gamma} = \sqrt{2 E_1 E_2 (1 - \cos\theta_{12})}$$

- Measurements are performed in several categories, targetting
  - different Higgs production (ggF, VBF, W/Z+H, top) and decay modes of the associated particles (W, Z, top)
  - different kinematic regions

ATLAS-CONF-2018-028

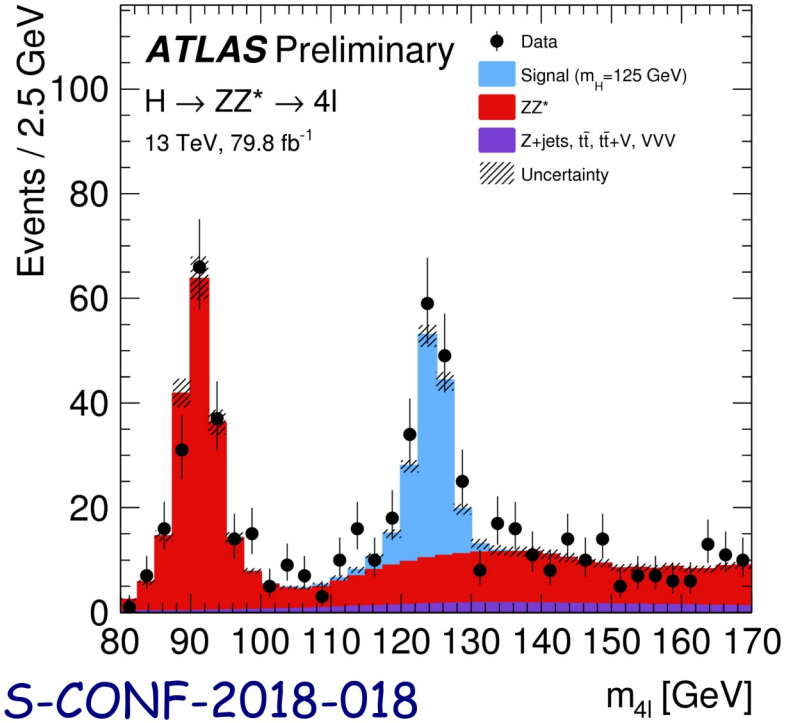




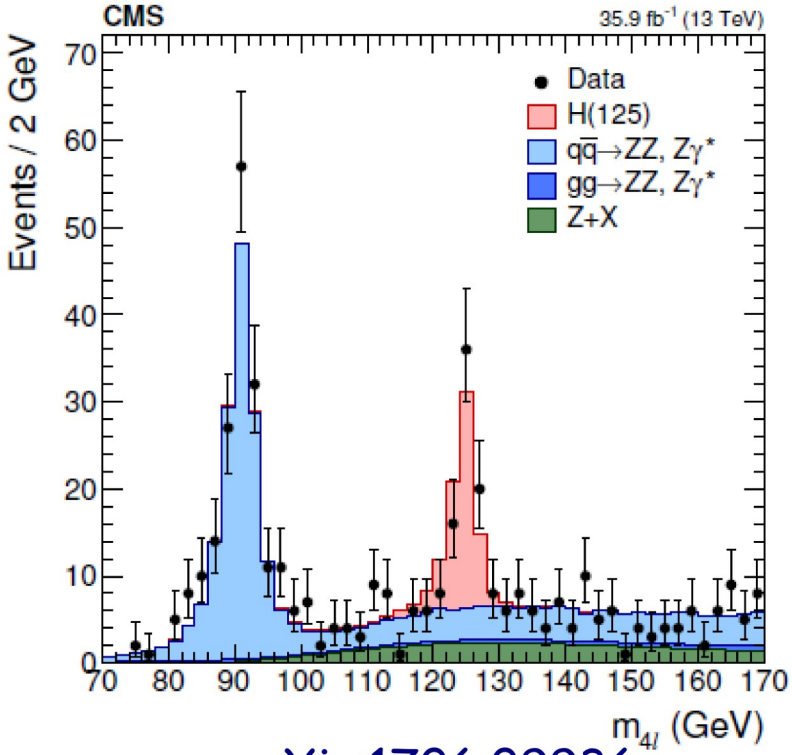
arXiv:1807.03825

$H \to ZZ \to 4\ell$

- Search for isolated high-p_T electrons/muons: 4e, 2e2μ, 2μ2e, 4μ
  - leading pair's invariant mass in m(Z) window, subleading pair m_{34} < 115 GeV
  - tracks coming from the primary vertex
  - in case of W/Z+H and $t\bar{t}H$ production modes more leptons might be present
- Reconstruct the invariant mass of the four leptons
- Measurements are performed again in several categories



ATLAS-CONF-2018-018



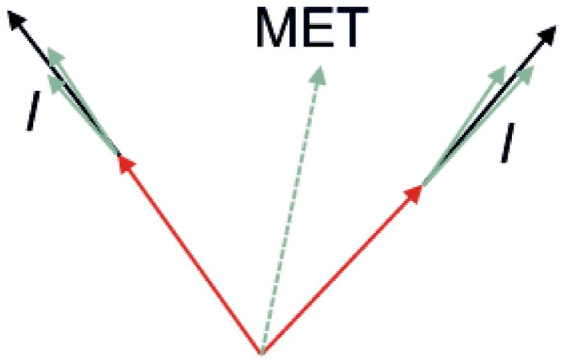
arXiv:1706.09936

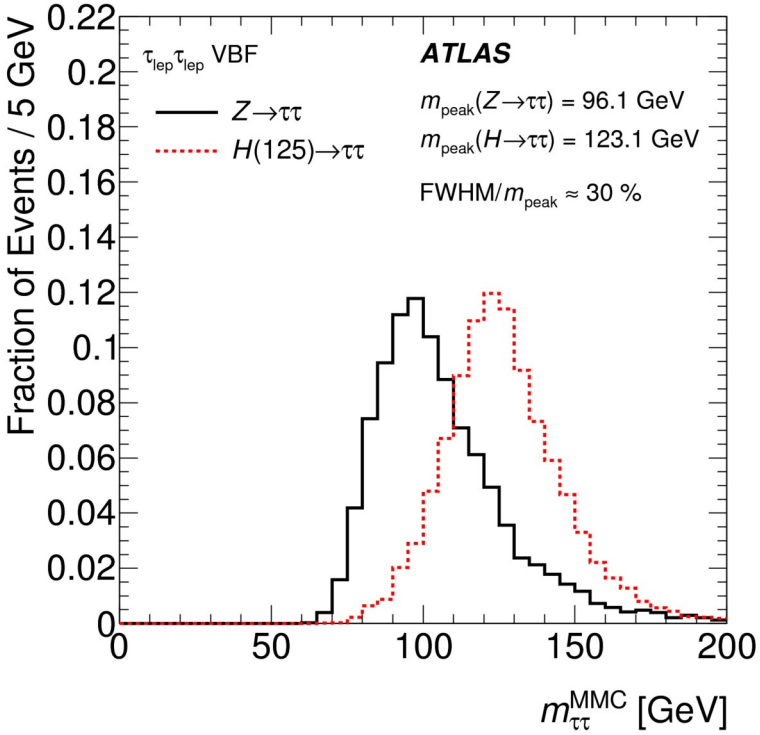
H → τ τ mass reconstruction

- Invariant mass cannot be properly reconstructed due to 2-4 neutrinos
- **Collinear mass approximation**
  - assumes all τ-decay products are collinear

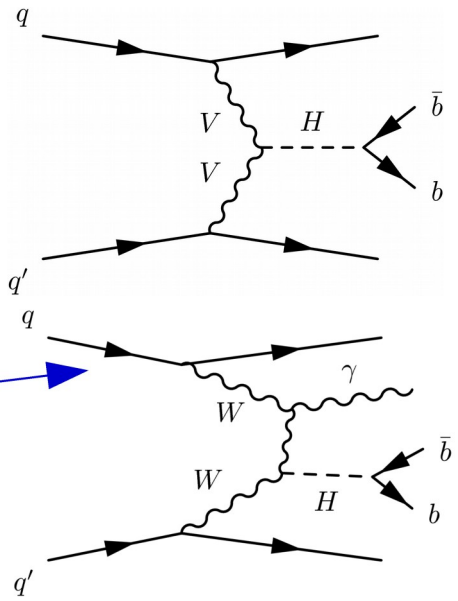
$$\vec{p}^{\,miss} = k_1 \vec{p}_{vis\,1} + k_2 \vec{p}_{vis\,2}$$

- **Missing Mass Calculator (ATLAS)**
  - takes into account the probability of the angular distribution between the τ-decay products (NIM *A* **654** (2011))
  - better resolution than collinear mass, critically depends on the MET resolution
- **SVFIT (CMS)**
  - similar combination of MET and visible τ-decay products (J.Phys.Conf.Ser. **513** (2014))



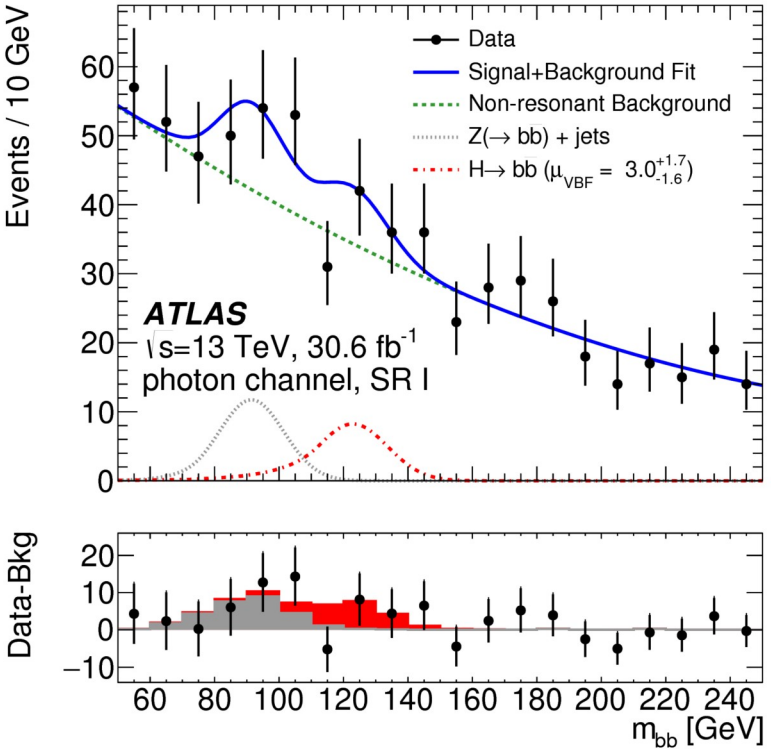


$H \to b\bar{b}$



- Search for VBF production mode in **ATLAS** in three categories (Phys.Rev.D 98 (2018) 052003):
  - all hadronic (2 central jets, 4 central jets), photon-associated channel (sensitive only to VBF)
  - selection based on BDT discriminator, 9 SR in total
  - simultaneous fit to m($b\bar{b}$) applied, results

$$\mu = 2.5^{+1.4}_{-1.3}\ \text{(inclusive)}, \mu = 3.0^{+1.7}_{-1.6}\ \text{(VBF)}$$



- Similar studies published by **CMS**:
  - VBF mode (CMS-PAS-HIG-16-003)

$$\mu = 1.3^{+1.2}_{-1.1}$$

  - inclusive production in high-boosted topology $p_T(H) > 450$ GeV (targets ggF mode) measured with 1.5σ significance (Phys.Rev.Lett. 120 (2018) 071802)