Precision Higgs Measurements at the LHC

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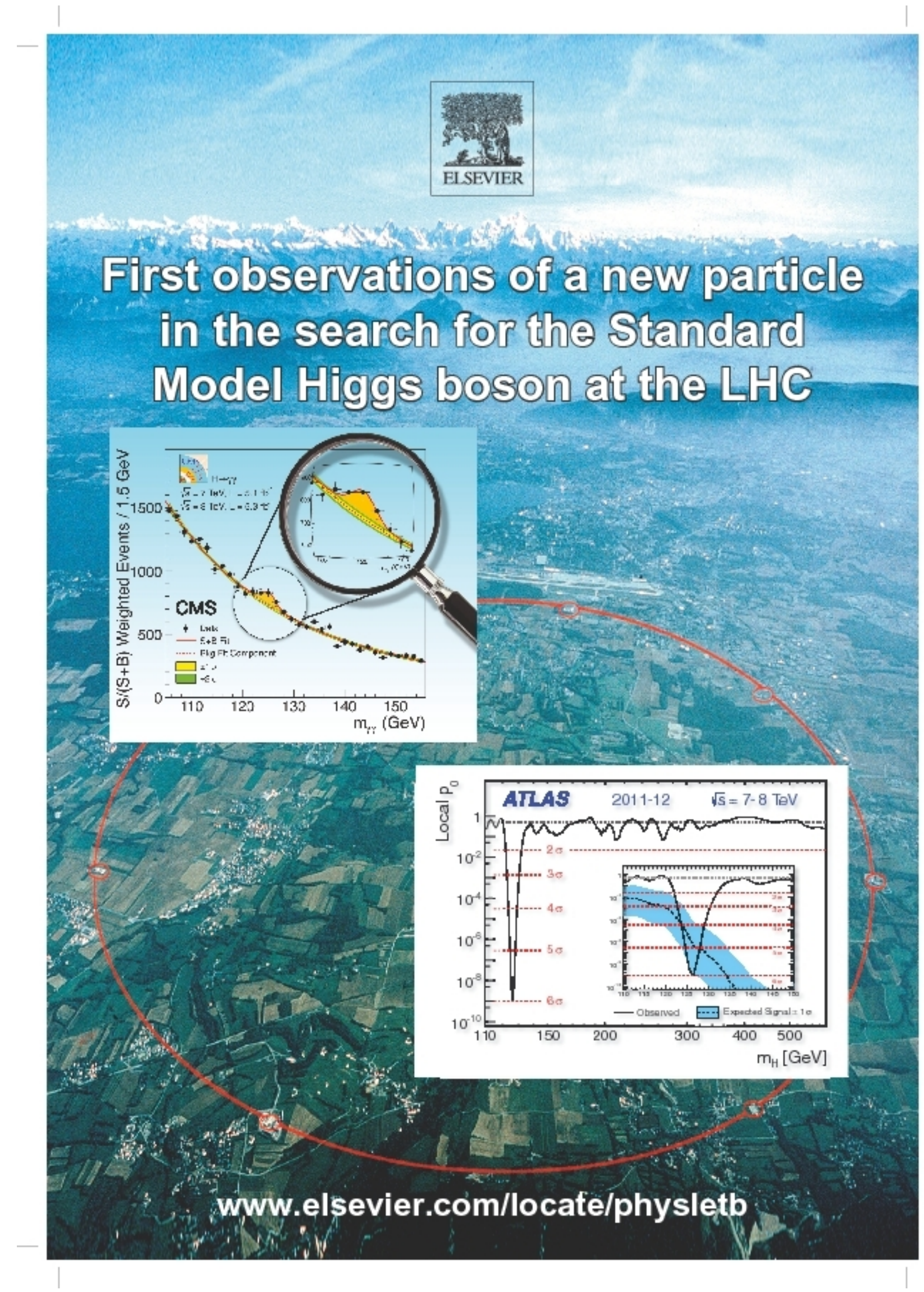
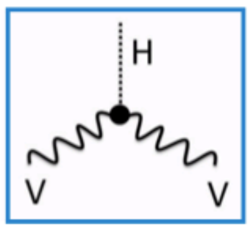
The Higgs boson

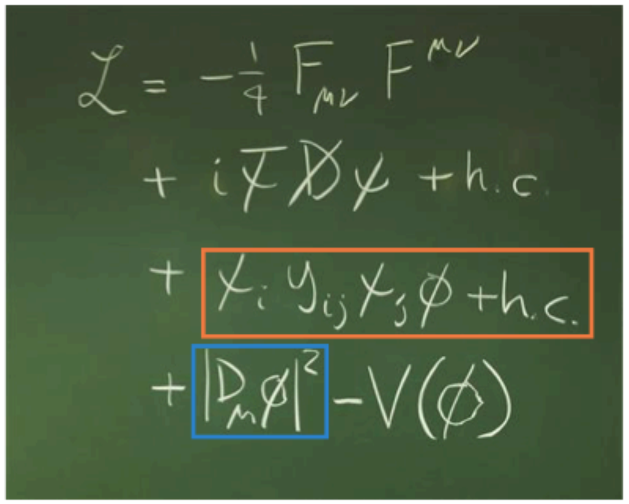
- **The Higgs boson** was discovered by the ATLAS and CMS experiments at the Large Hadron Collider (LHC) in 2012
  - a major milestone for particle physics
- It opened a new way to refine our understanding of the electroweak symmetry breaking
  - many studies of **Higgs boson properties** have been performed
  - deviation from the Standard Model (SM) predictions on Higgs boson properties would provide clue for new physics



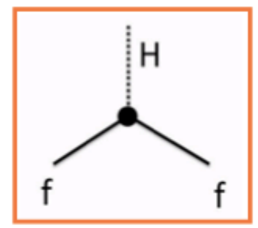
Higgs boson production and decay modes

Vector bosons



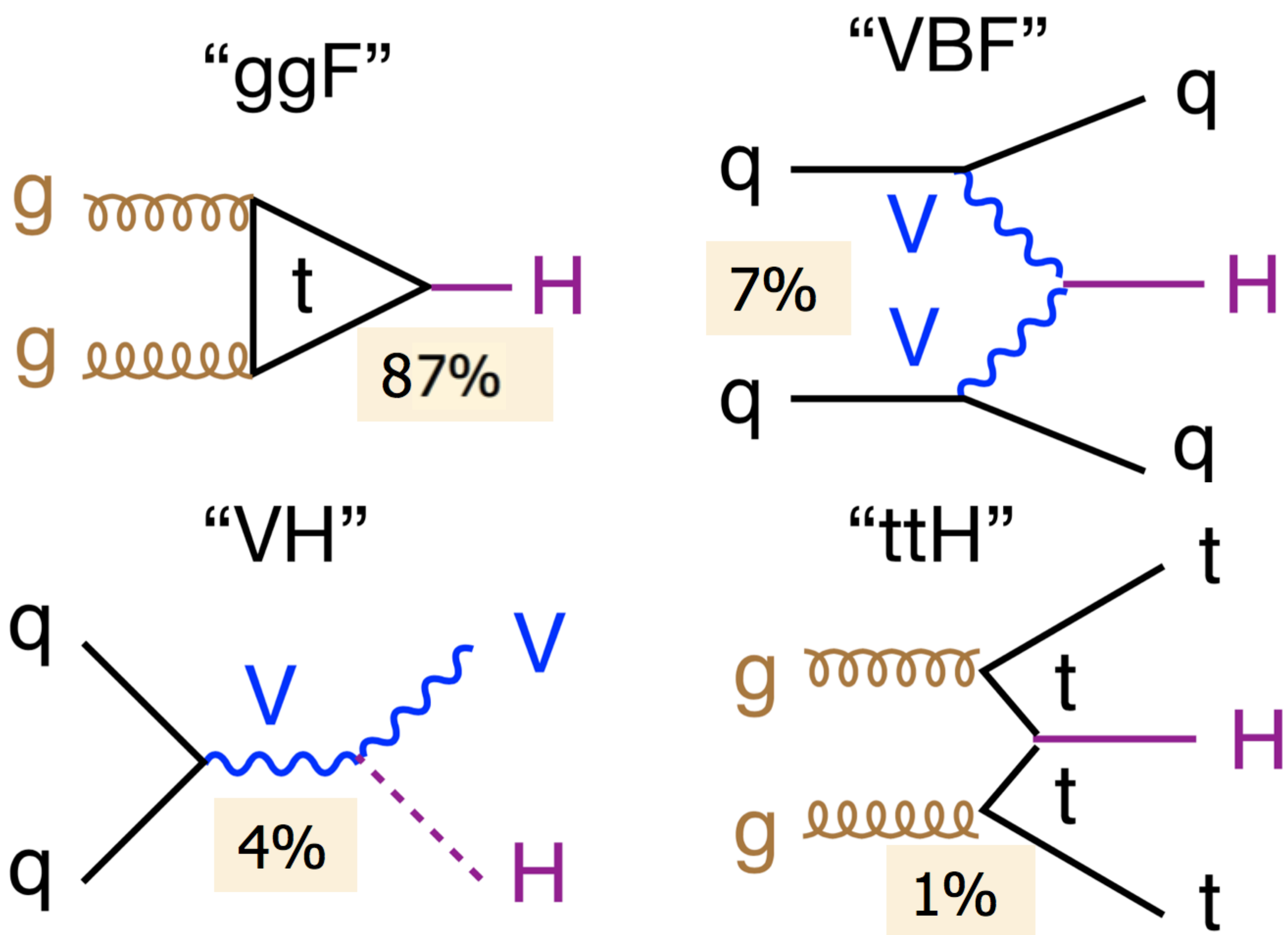


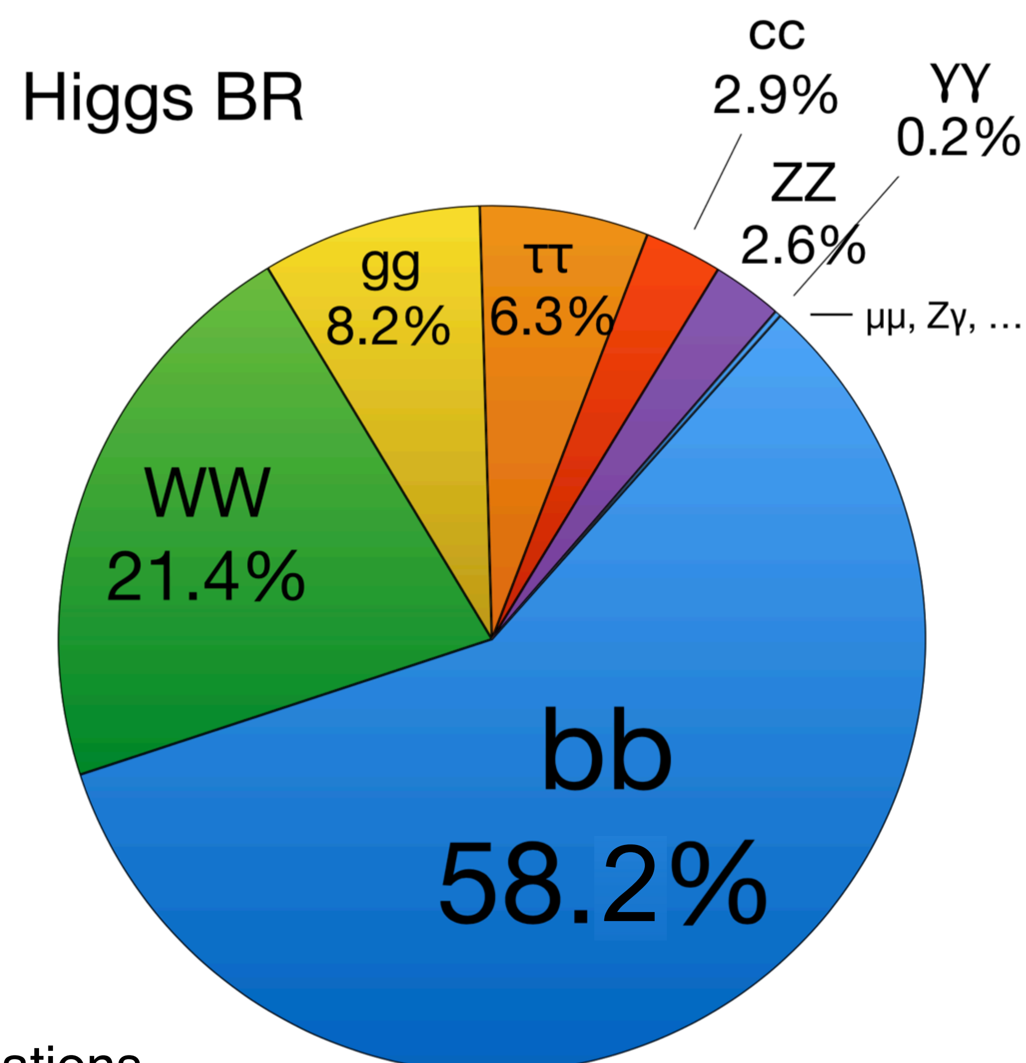
Fermions
(Yukawa coupling)



In the Standard Model, the Higgs boson couples to massive bosons and fermions

These couplings determine the Higgs boson production and decay modes:





Figures from https://msneubauer.github.io with modifications

Contents of this talk

- Measurements of Higgs cross sections and couplings
  - using the $H\to\gamma\gamma$, $H\to ZZ$, $H\to WW$, $H\to bb$, $H\to\tau\tau$ decay channels and the combination of these channels

- Measurements of Higgs mass, width, CP

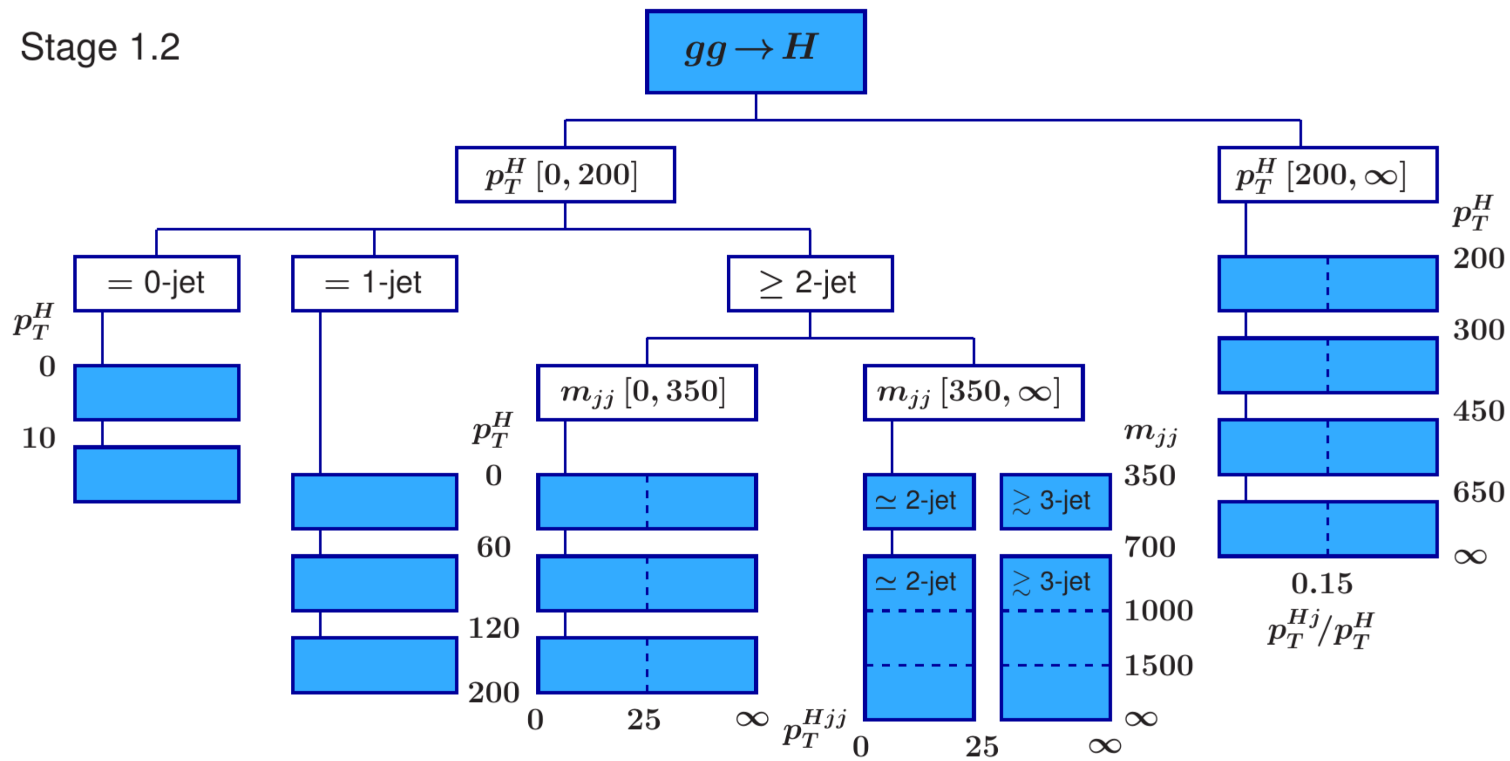
- Focus more on full Run-2 results released this year

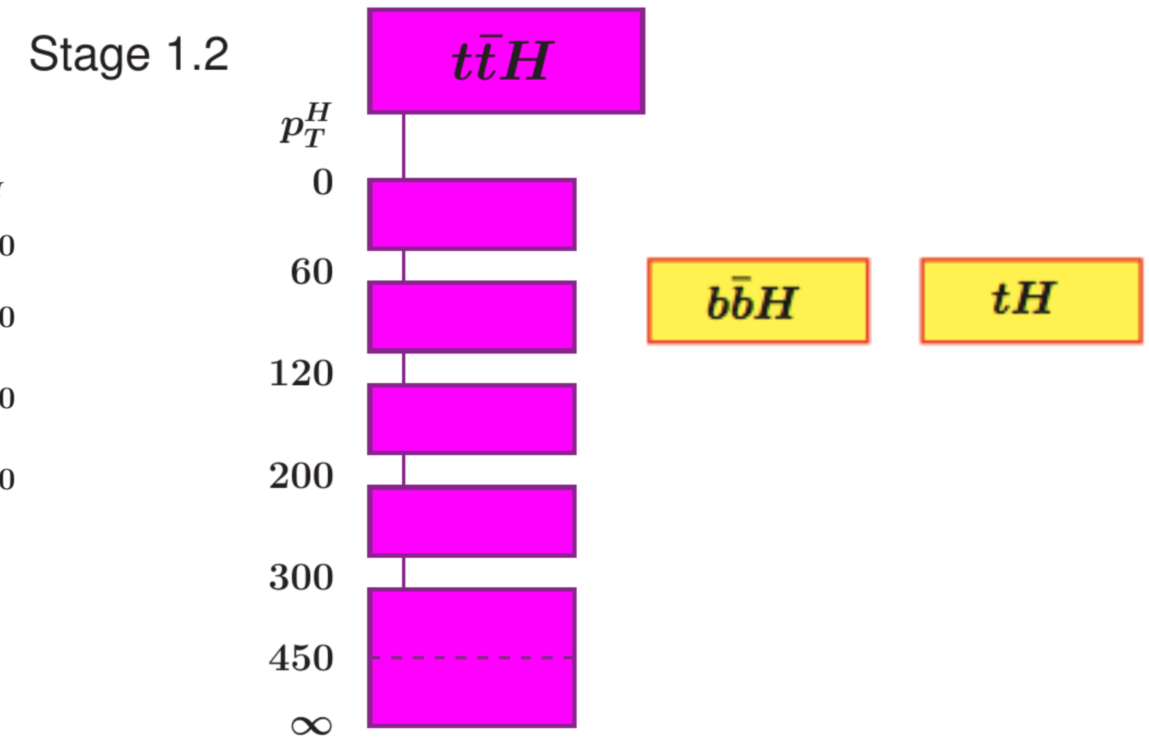
Measurements of Higgs cross sections and couplings

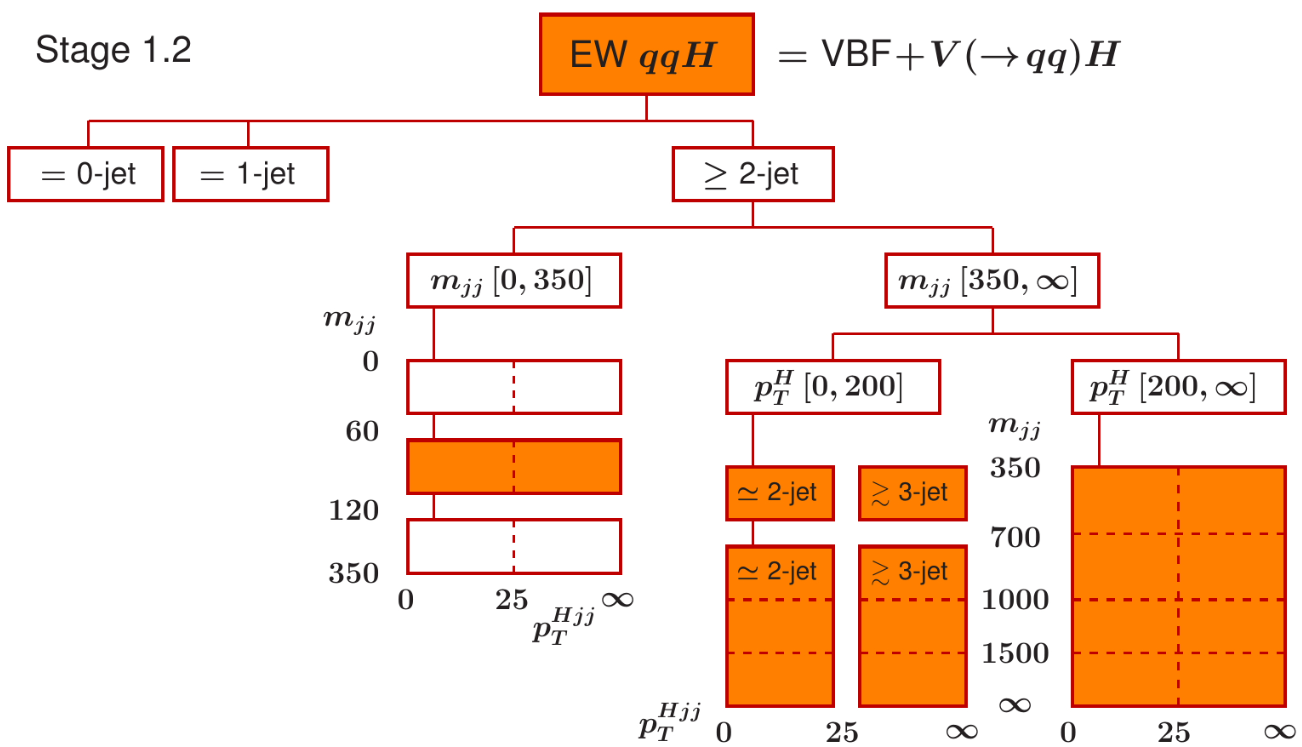
Two kinds of cross section measurements

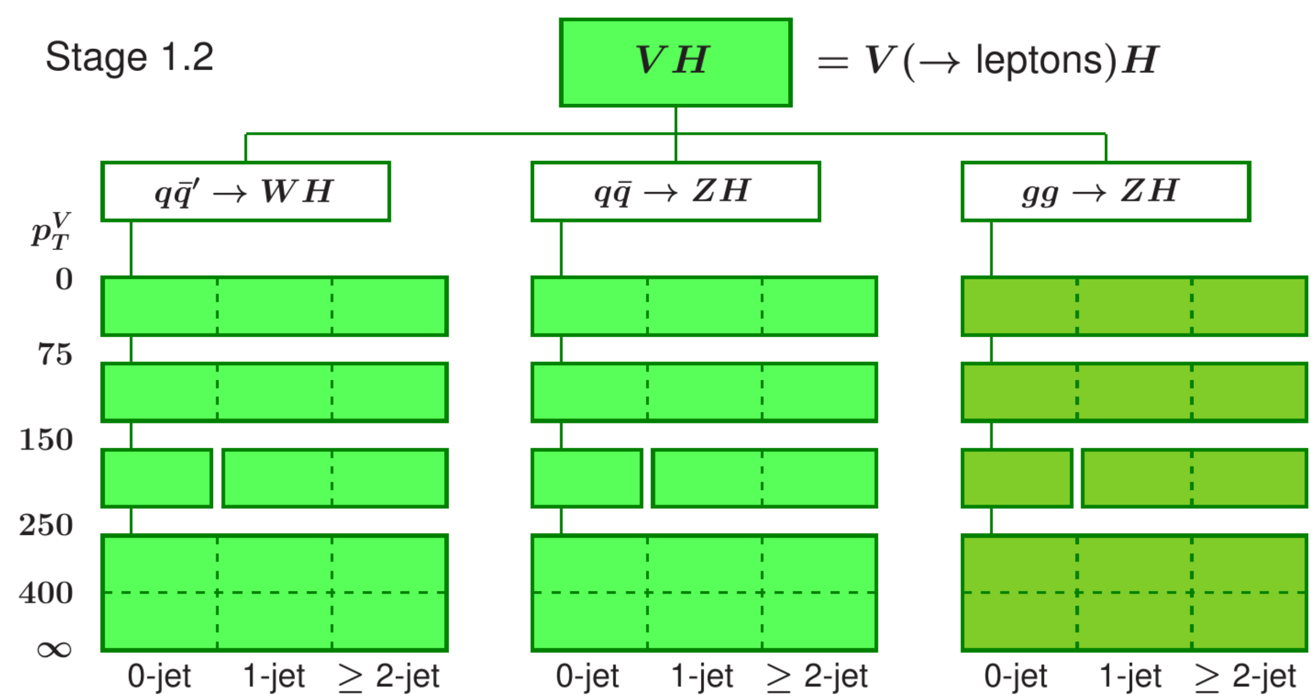
- **Simplified template cross section (STXS)**
  - Split production mode cross-sections into various phase-space regions, which are chosen according to sensitivity to beyond Standard Model effects, avoidance of large theory uncertainties, matching to experimental selections
  - For each STXS region, use the SM predicted signal templates to fit data
- **Fiducial cross section**
  - Define fiducial phase space based on Higgs decay products, measure cross section inclusively or differentially with physics quantities to minimize dependence on theoretical uncertainties and provide sensitivity to BSM effects
  - Some differences from STXS: inclusive in Higgs production modes; avoid using machine learning for event-level analysis

Stage 1.2 STXS



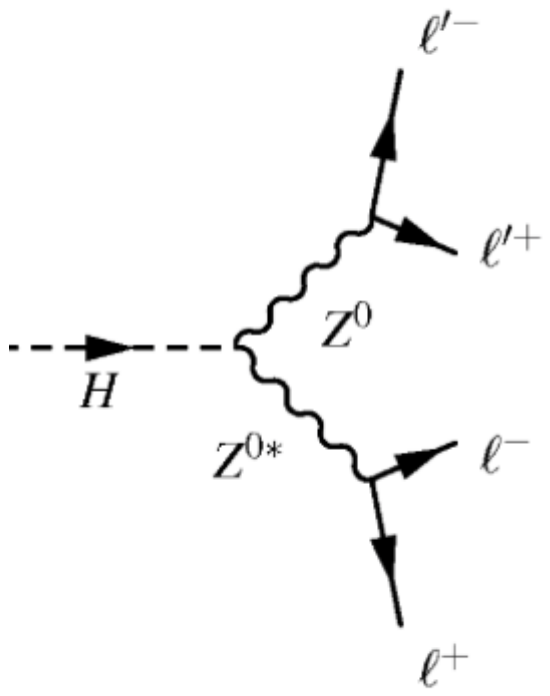


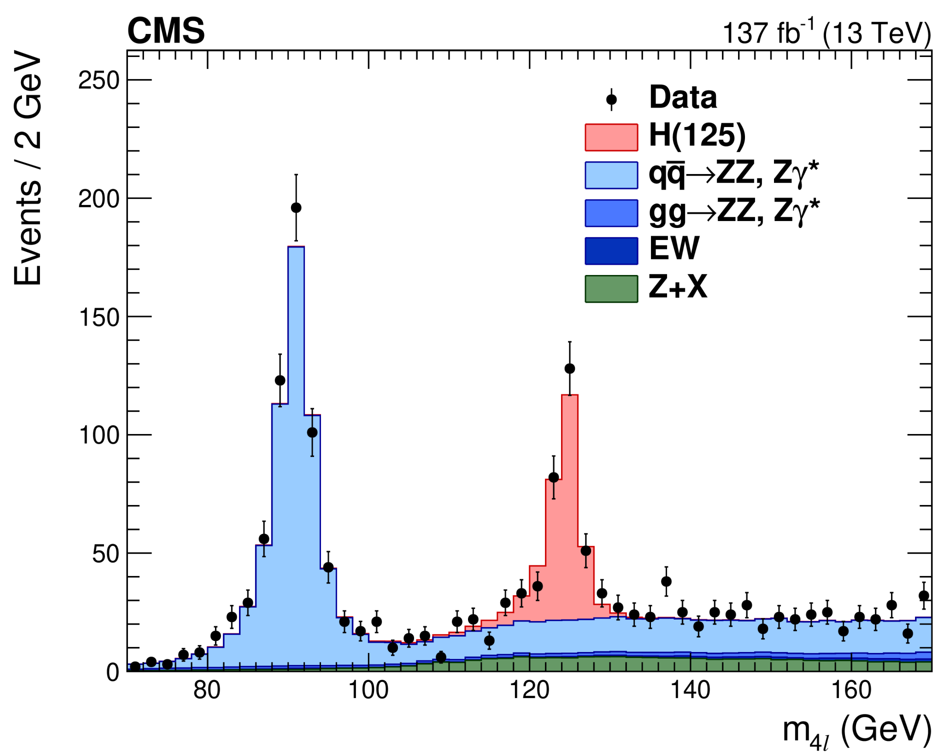




H→ZZ*→4l analysis

- "Golden" Higgs decay channel with **excellent S/B ratio and complete reconstruction**
  - **but tiny branching ratio**
- Select events with **four leptons** forming two same-flavor opposite-charge lepton pairs
  - **m_{4l}** is used to extract signal yields
- Major background: irreducible ZZ production





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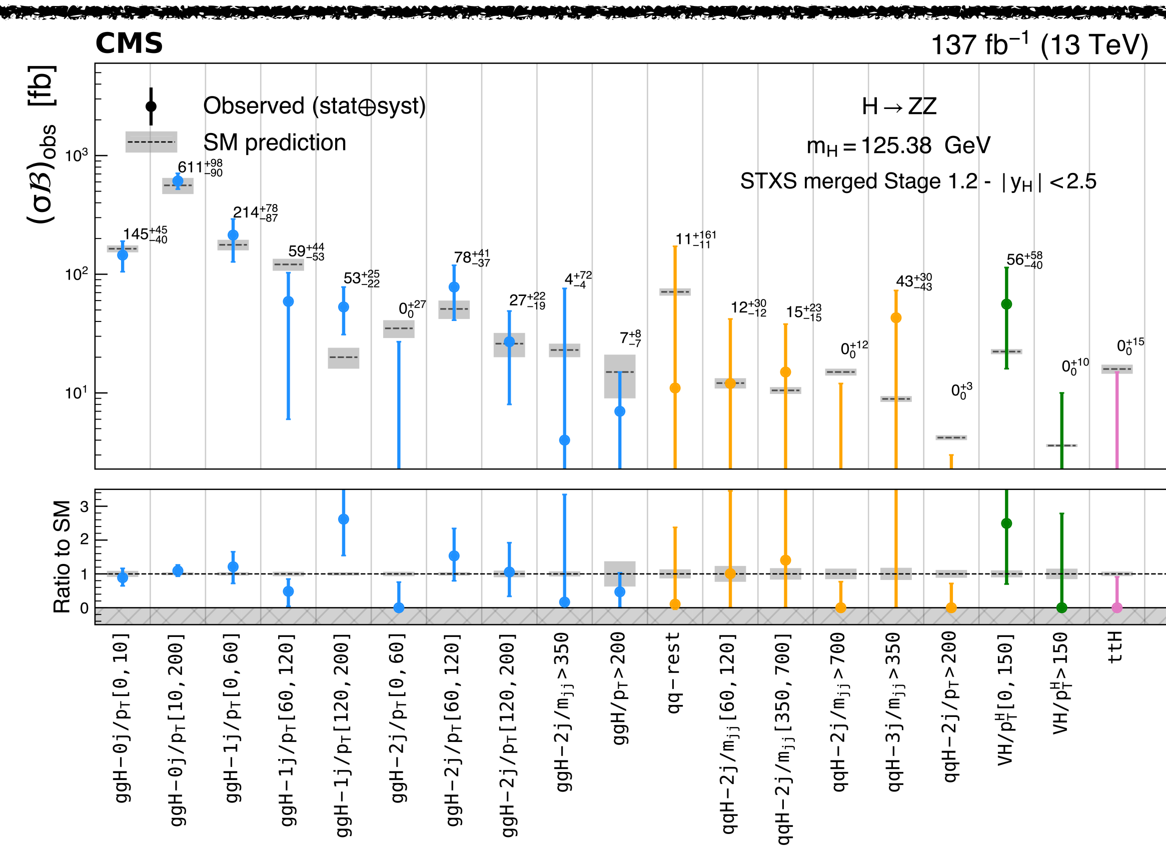
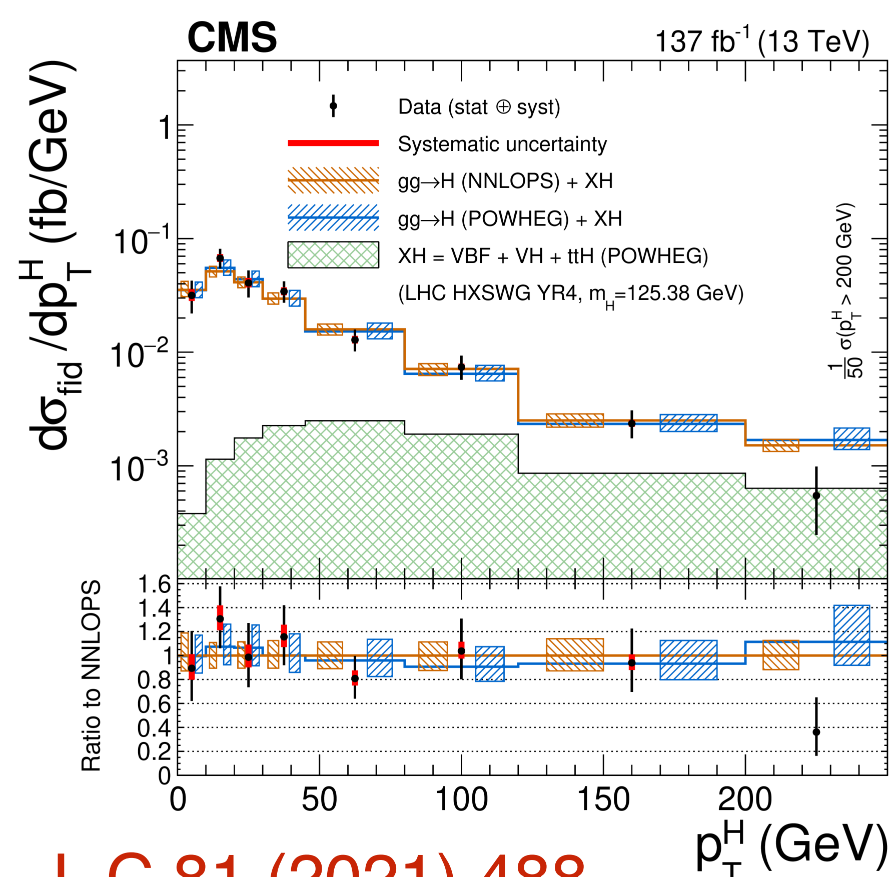
STXS and fiducial x-sec results

- STXS analysis: **machine learning** or **matrix element discriminants** are also used
  - sensitive to ggF, but not yet sensitive to other modes
- Fiducial x-sec analysis: **unfold signal yields to cross sections** using response matrix from simulation
  - detailed information for fiducial regions defined by lepton and jet kinematics
- Both measurements dominated by statistical uncertainties





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H→γγ analysis

Small BR, but good S/B and resolution

Select events with **two photons**

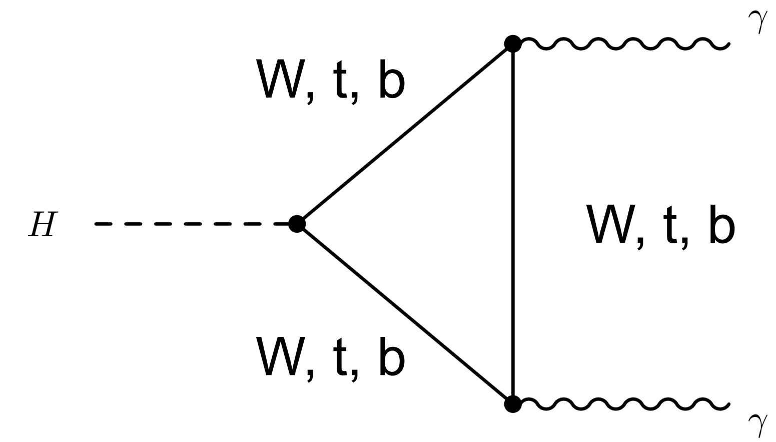
➔Separate events to **categories**

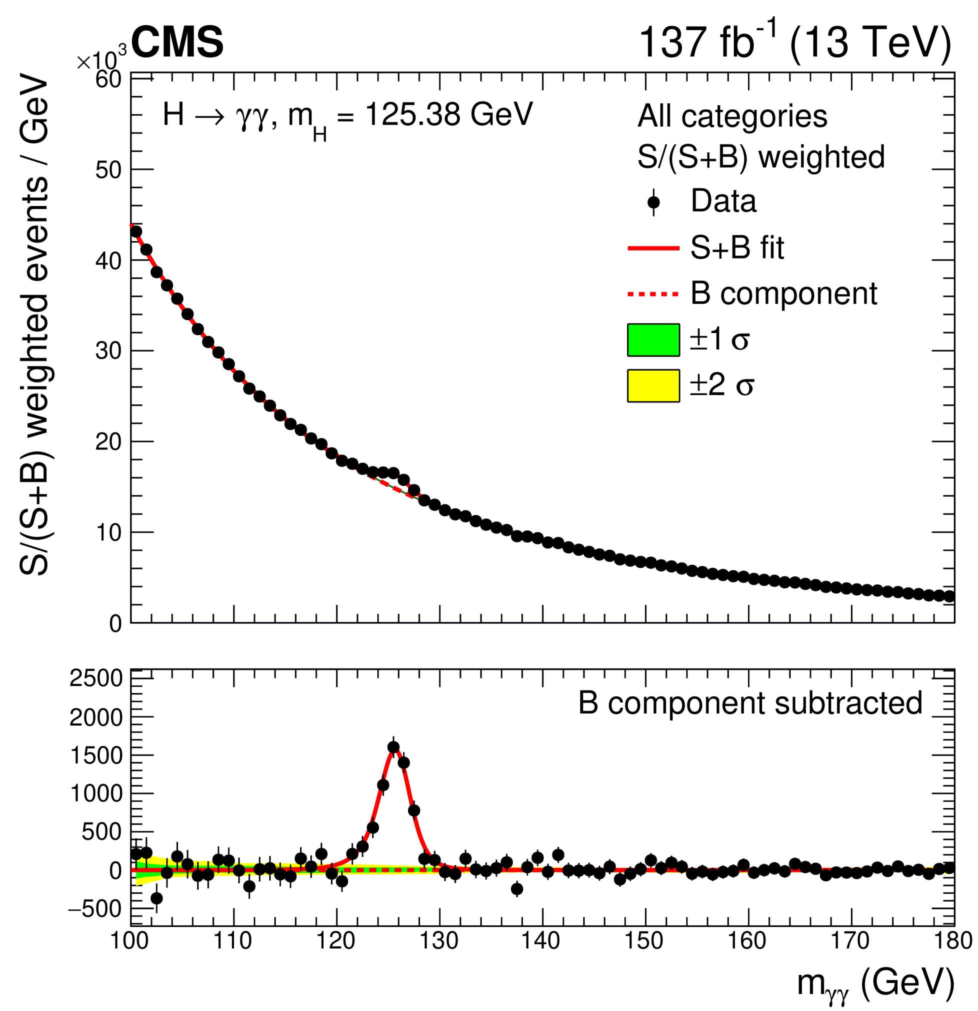
- For STXS analysis: O(100) categories using machine learning

➔Fit **diphoton mass** over all categories

- Signature: a narrow resonance above a smooth background (QCD γγ production, etc.)

➔Measure simplified template cross sections, etc.



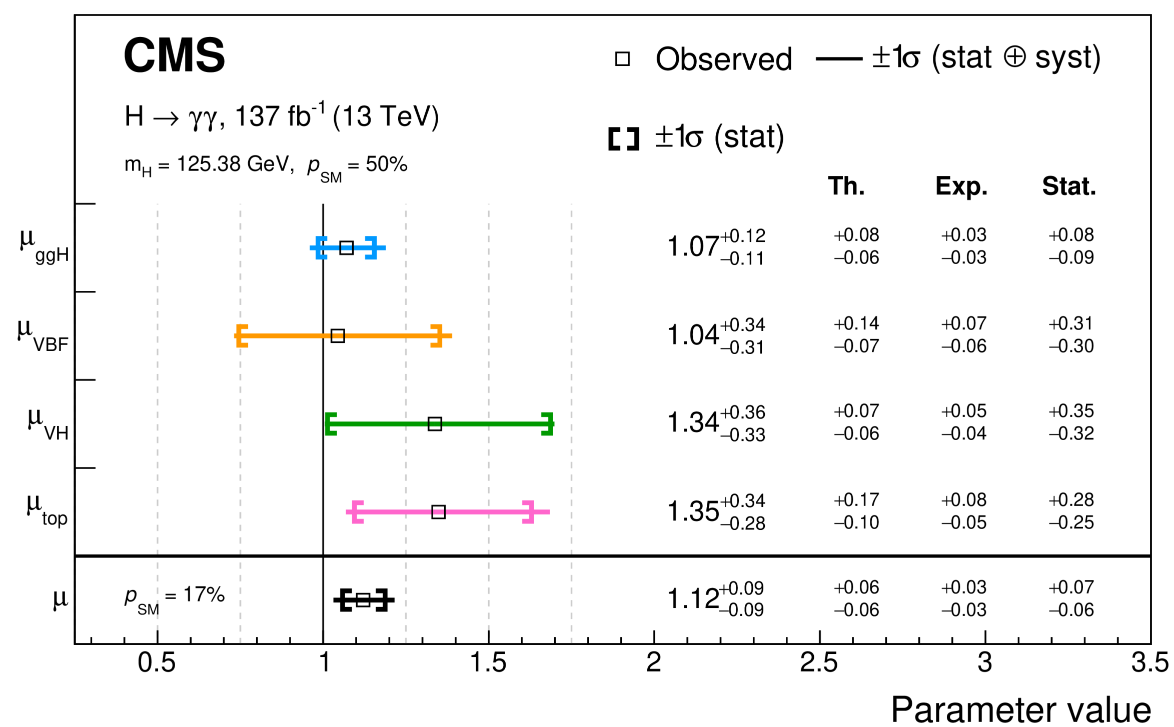


JHEP 07 (2021) 027

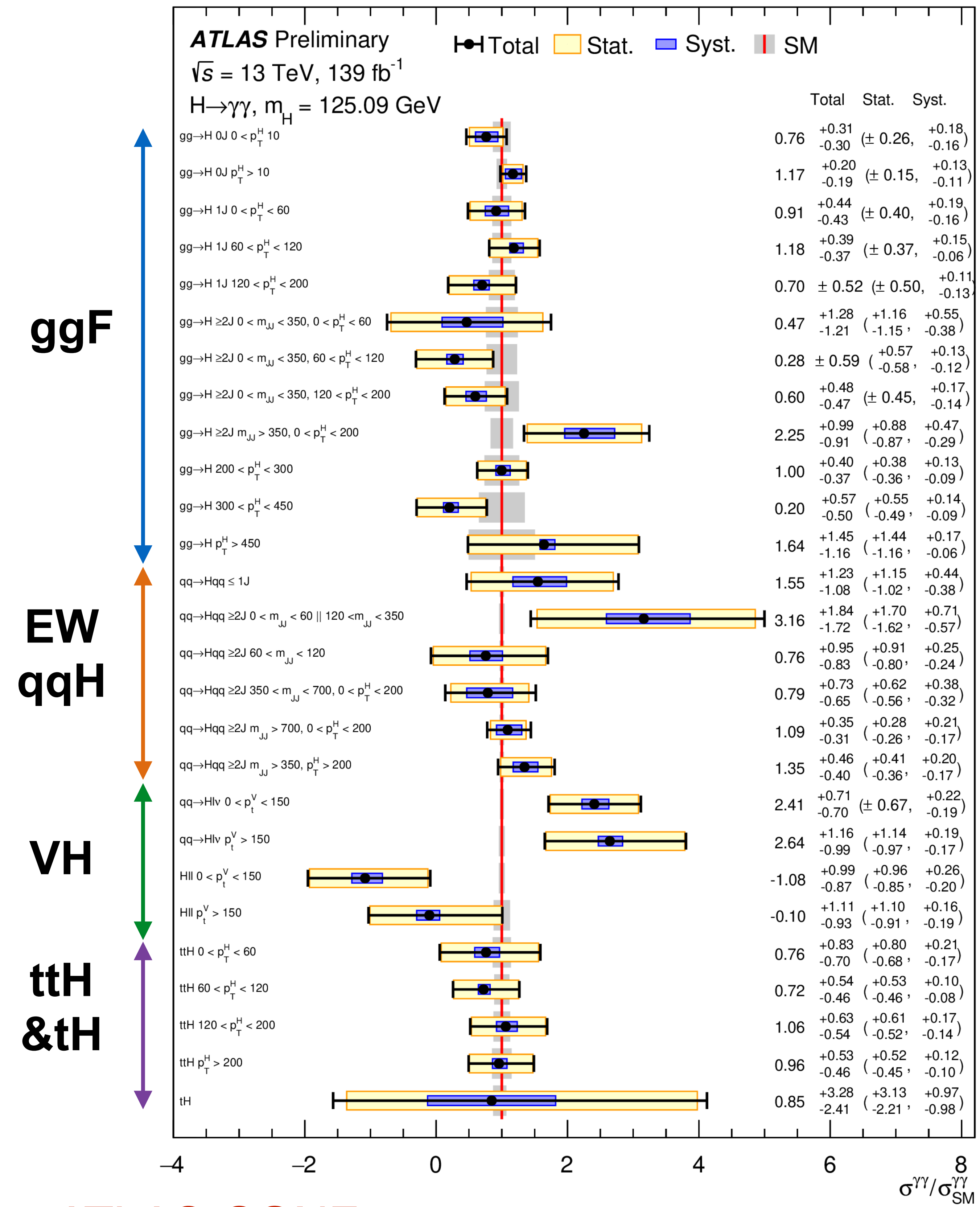
STXS analysis results

H→γγ

- H→γγ is one of the most sensitive channels for ggF, VBF, $t\bar{t}H$ and tH
- Measure Higgs production granularly for ggF, VBF, VH and ttH
  - e.g. 4-5 bins in Higgs pT for ttH
  - Uncertainties range from 20% to more than 100%, mostly statistically dominated
- Limit on tH: 14xSM (CMS); 8xSM (ATLAS)

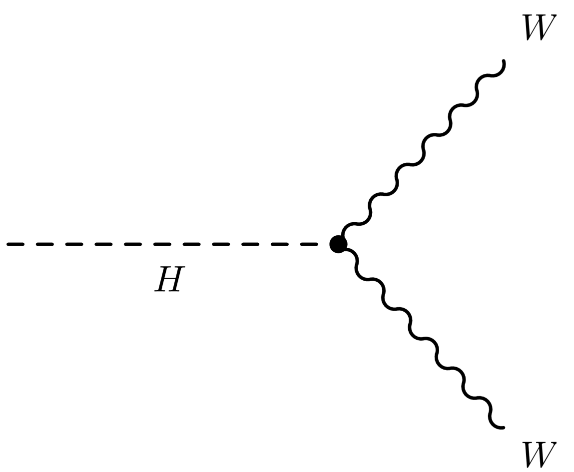


[JHEP 07 (2021) 027]

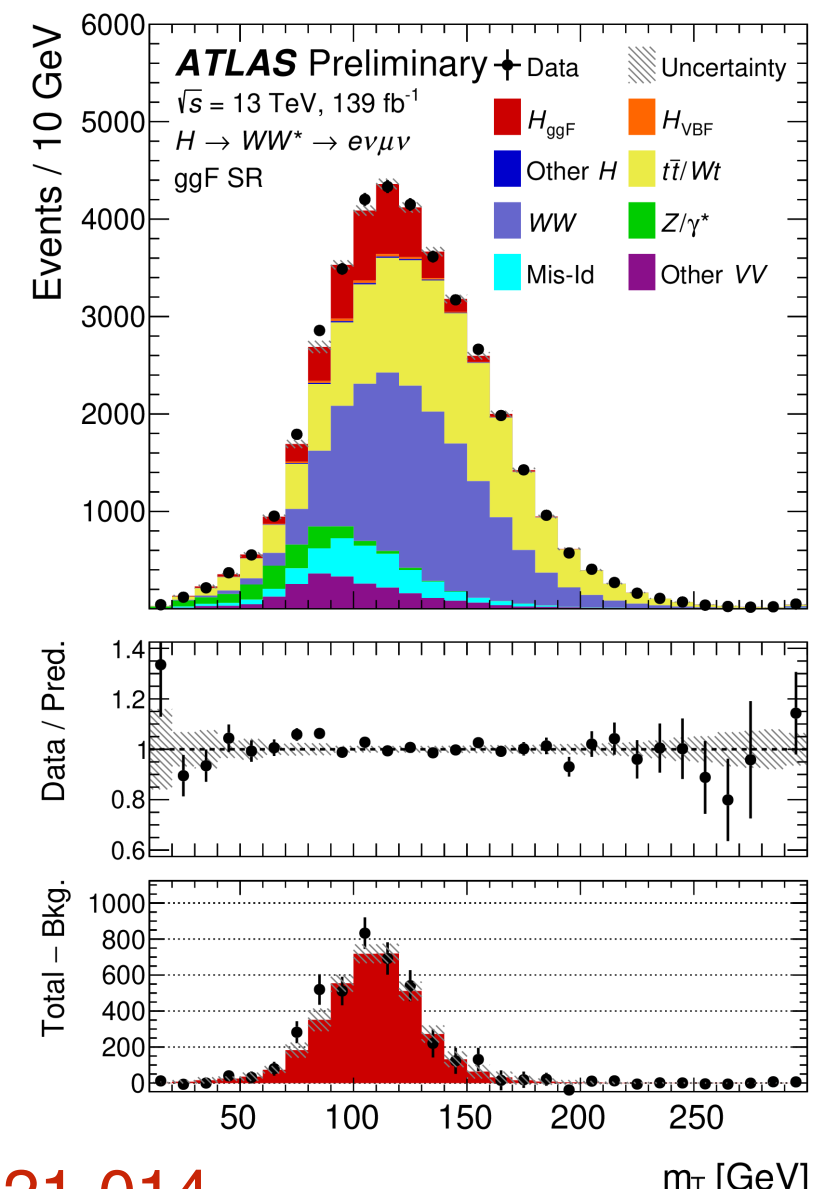


[ATLAS-CONF-2020-026]

H→WW* analysis



- Larger BR but worse resolution due to neutrinos
- Signature: e + μ + missing transverse momentum
- Main backgrounds are WW, $t\bar{t}$ and Z+jets
- Lepton kinematic variables (e.g. transverse mass) helpful for suppressing backgrounds



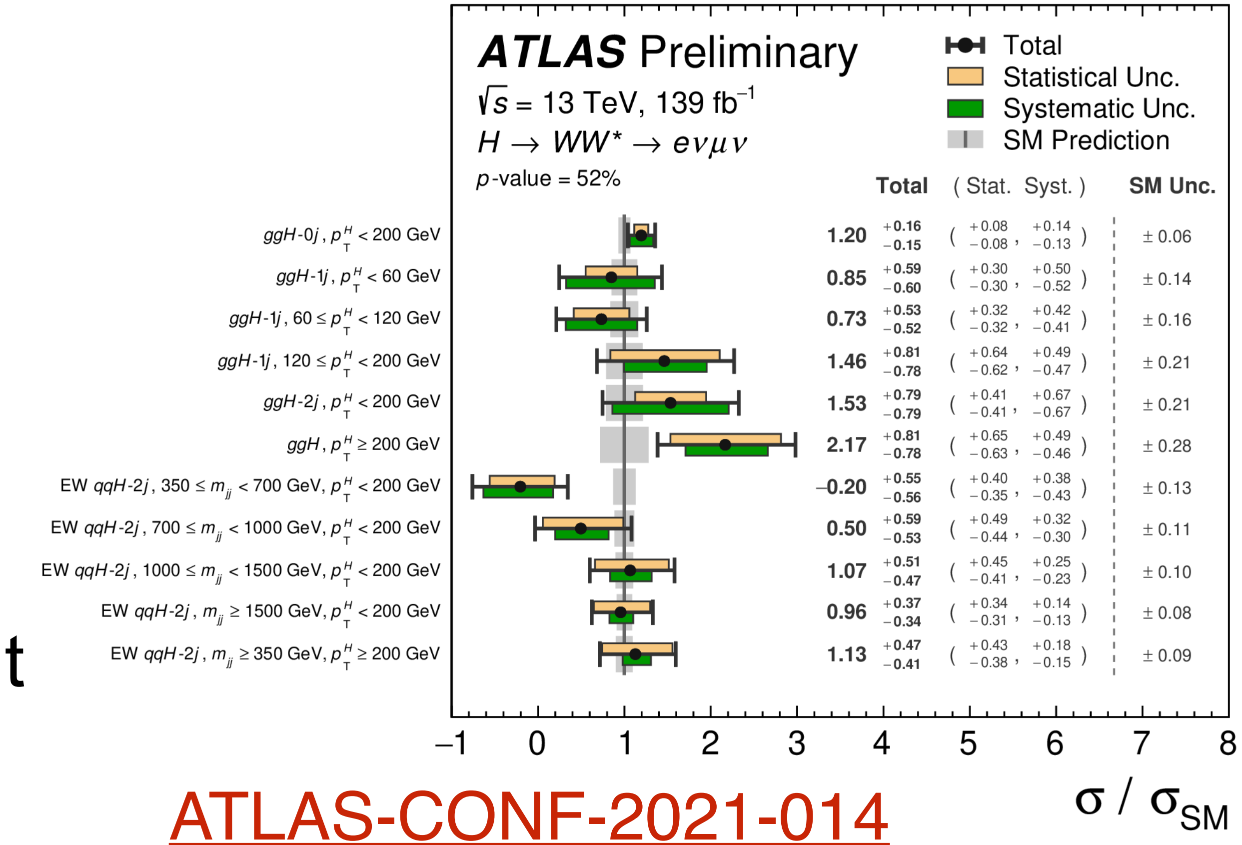
ATLAS-CONF-2021-014

STXS analysis results

$H \rightarrow WW^*$

ggF & VBF

- ATLAS probes 11 STXS bins using 0-jet, 1-jet and 2-jet event categories
- Sensitivity comparable with $H \rightarrow \gamma\gamma$ channel
- VBF significance **6.6σ**
- Theoretical uncertainties are important



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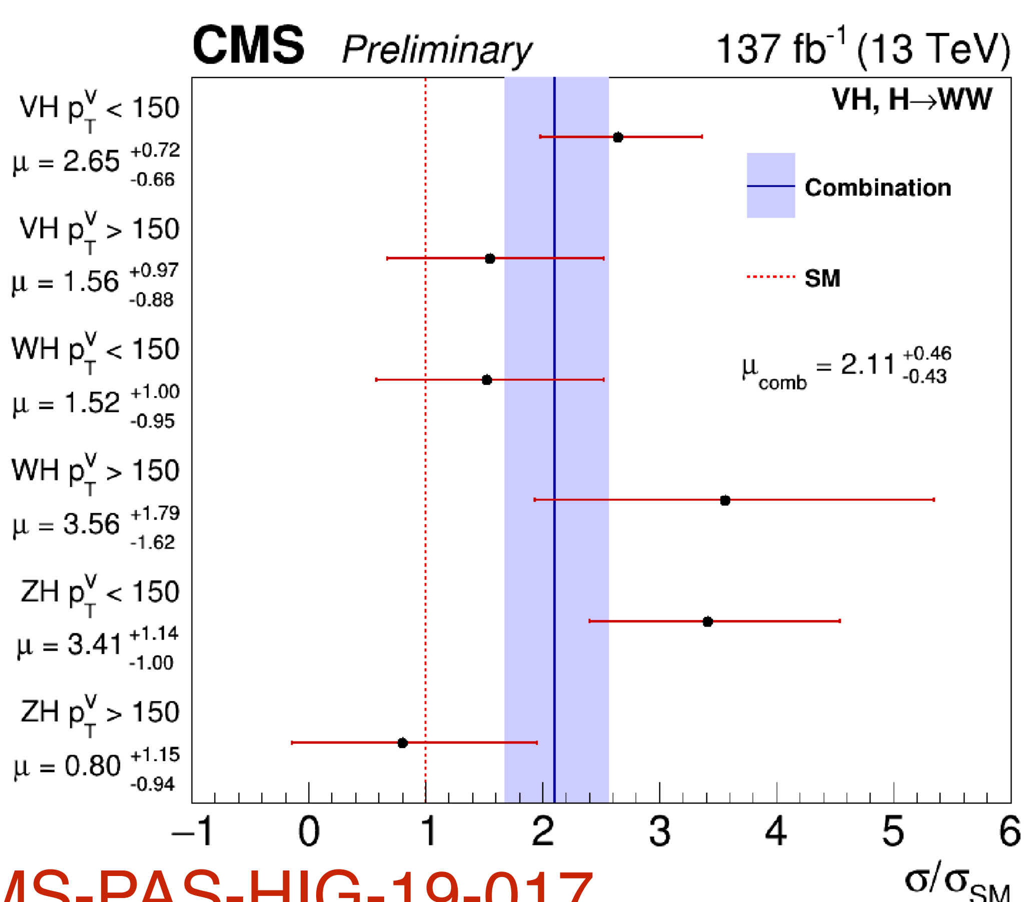


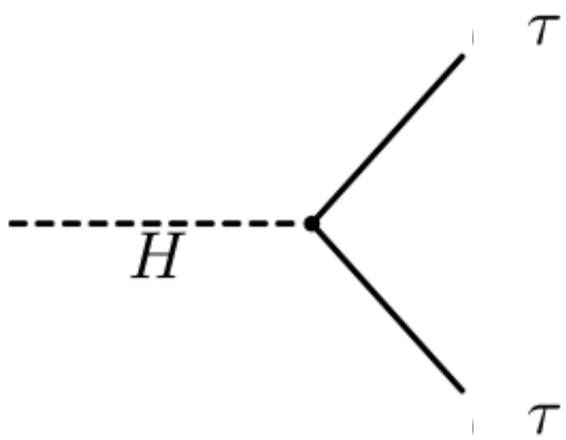
CMS-PAS-HIG-19-017

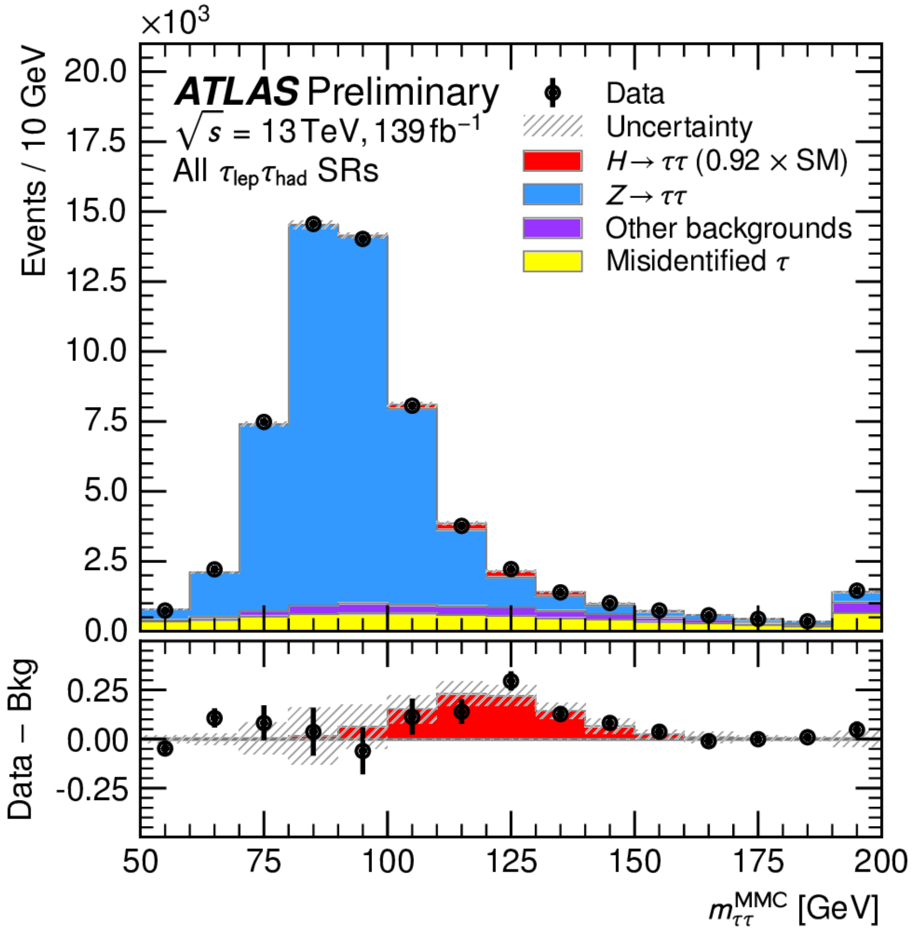
VH

- CMS probes up to 4 STXS bins using events with 2, 3 and 4 leptons
- VH significance **4.7σ**
- Statistical and systematic uncertainties comparable

H→$\tau\tau$ Analysis

- H→$\tau\tau$ is currently the only **established leptonic decay mode** of the Higgs boson
- **3 analysis channels** to consider all combinations of the leptonic and hadronic tau decays:
  - $\tau_{\mathbf{lep}}\tau_{\mathbf{lep}}$ (~12%), $\tau_{\mathbf{lep}}\tau_{\mathbf{had}}$ (~46%), $\tau_{\mathbf{had}}\tau_{\mathbf{had}}$ (~42%)
- Perform **simultaneous fits** using reconstructed di-tau masses
- Major background: **Z→$\tau\tau$ production,** misidentified hadronic tau





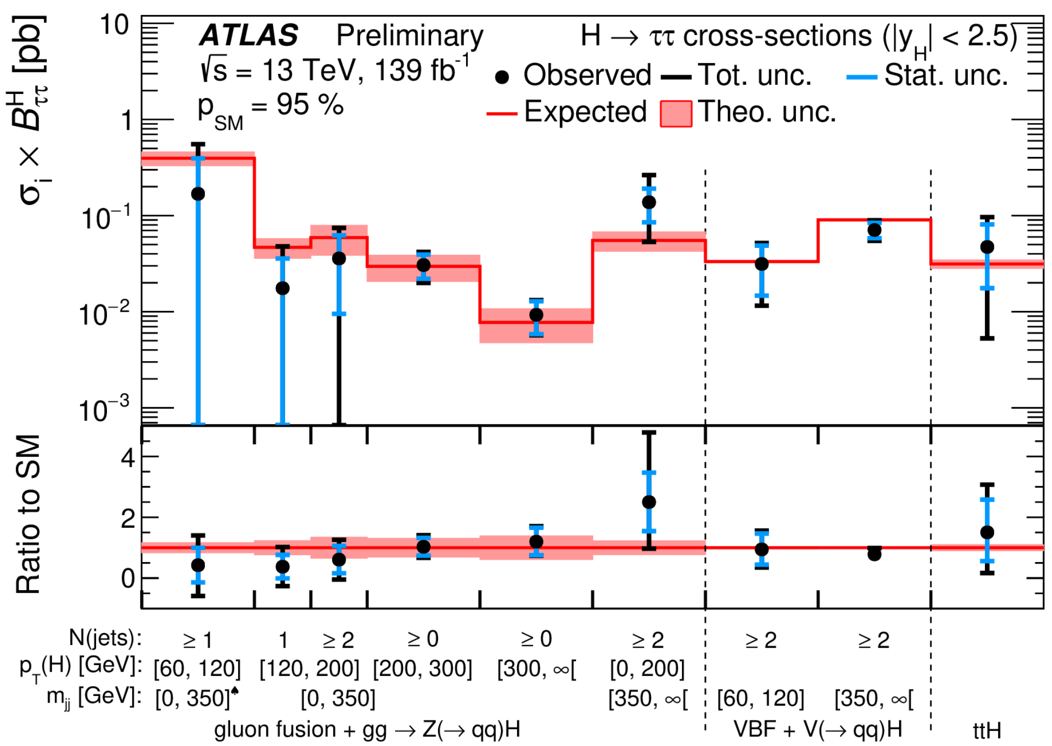
ATLAS-CONF-2021-044

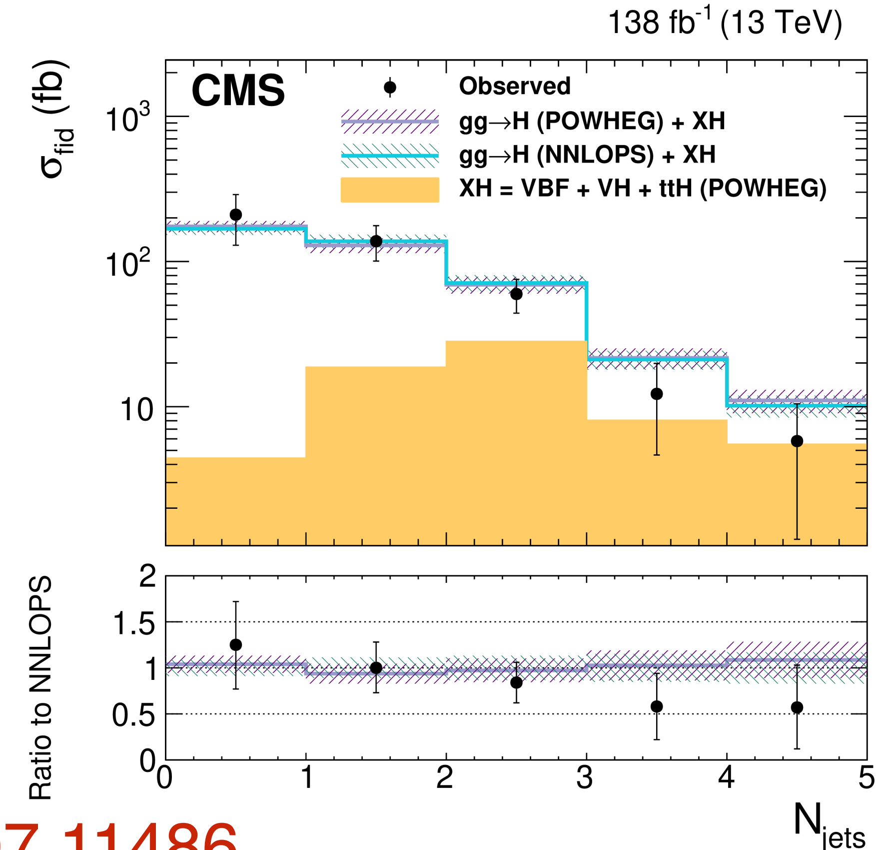
STXS and fiducial x-sec results

STXS

ATLAS-CONF-2021-044

- ATLAS measures kinematic regions of ggH, VBF, VH and ttH using STXS framework
- Sensitive to VBF topology and boosted ggH regions
- ggH significance **3.9σ**
- VBF significance **5.3σ**





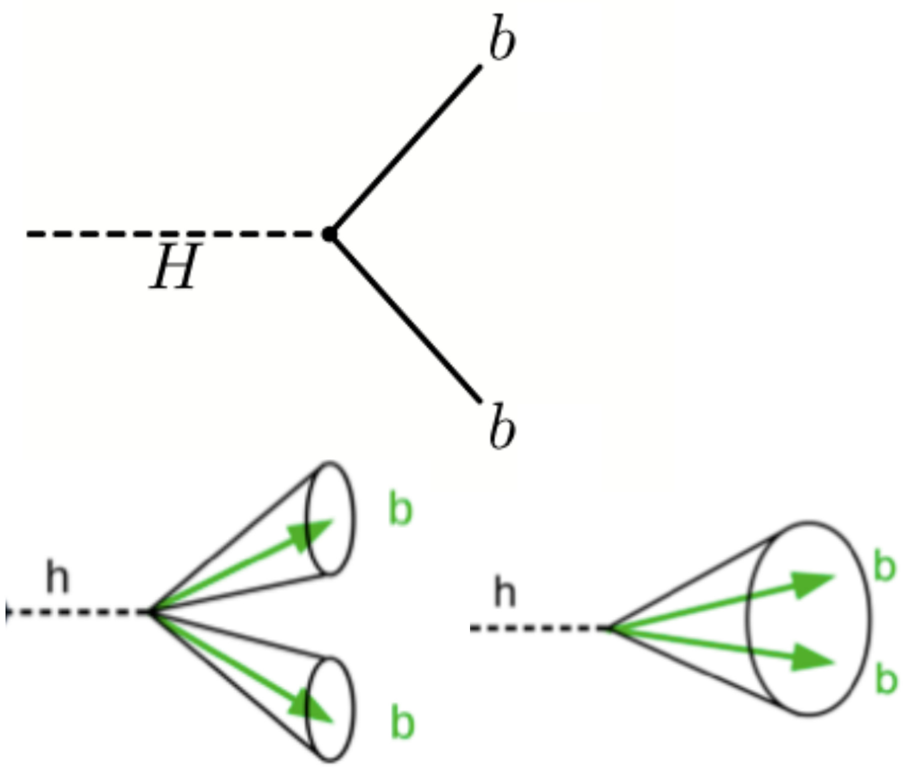
arxiv:2107.11486

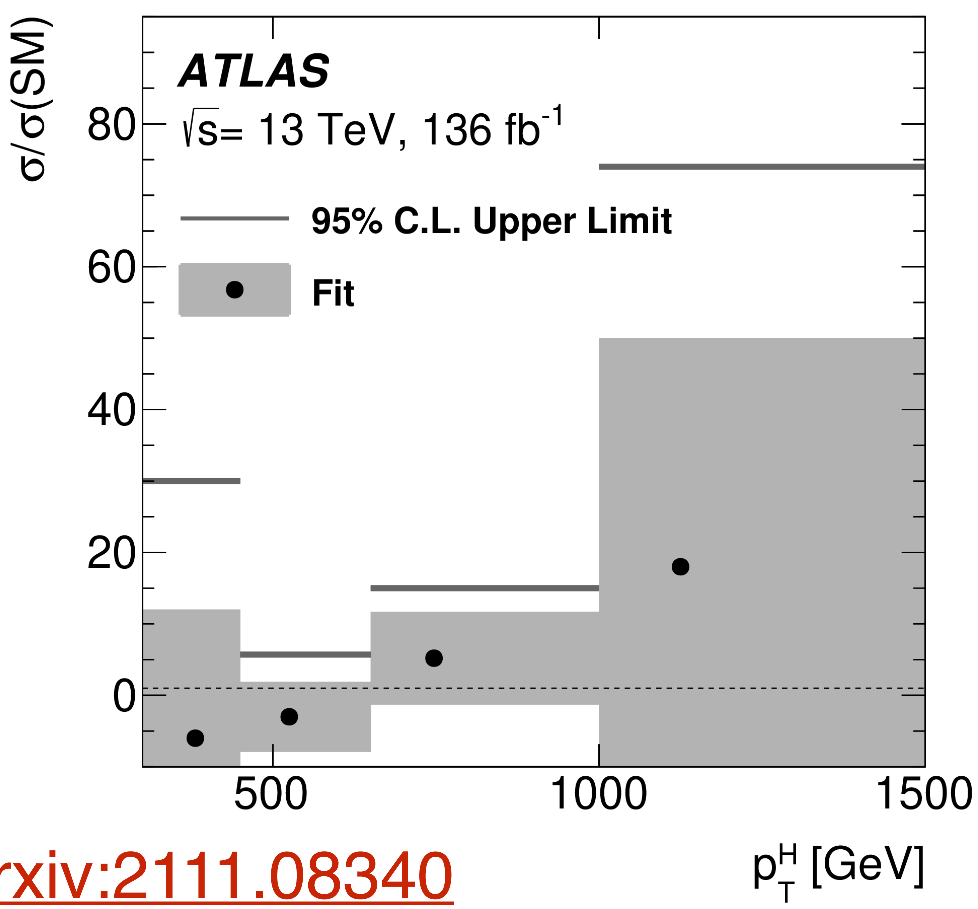
Fiducial x-sec

- CMS measures differential Higgs cross sections in the $\tau\tau$ channel for the first time
- Competitive precision in phase spaces with a large jet multiplicity or with a Higgs transverse momentum above 120 GeV

$H \to b\bar{b}$ analysis

- **$H \to b\bar{b}$ decay mode observed in 2018**
- **Large branch ratio (~58%)**
- Reconstruct Higgs as two separate small-radius jets (resolved channel) or one large-radius jet (boosted channel)
- Typically large background, tackled by requiring large Higgs pT or associated particles





arxiv:2111.08340

Study Higgs Boson production with large pT (where some BSM effects are enhanced)

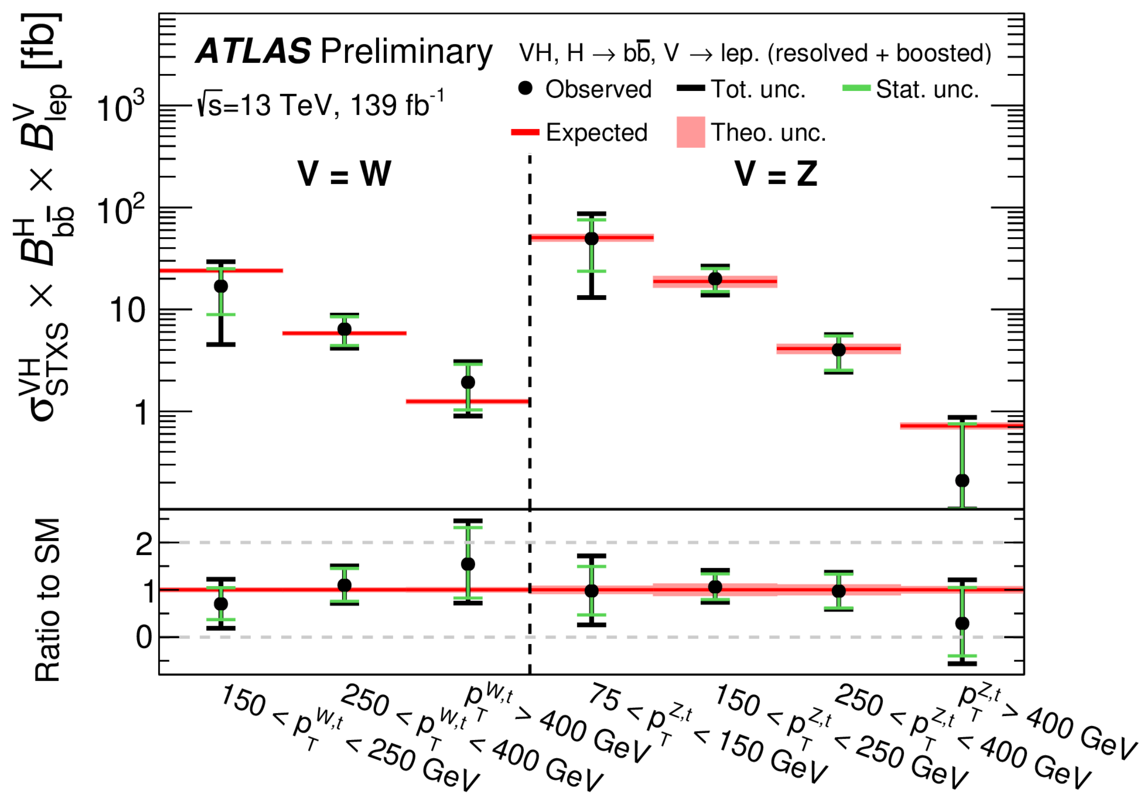
- Higgs reconstructed as single large-radius jet recoiling against a hadronic system
- Main bkg: multi-jet, V+jet and $t\bar{t}$
- Inclusive in production modes
- Differential measurement in four pT(H) bins: agree with SM prediction given the data statistics

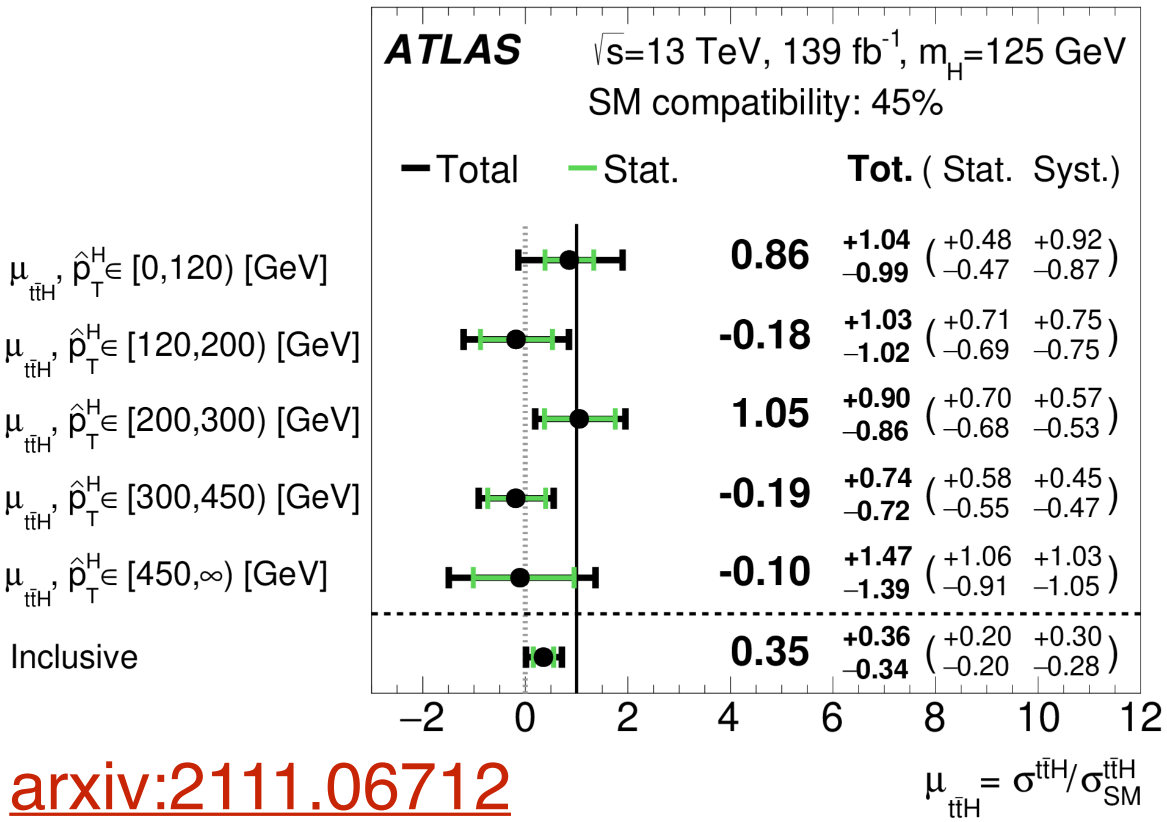
STXS analysis results

[ATLAS-CONF-2021-051]

VH

- Tag leptonically decaying W/Z boson
- **Combine both resolved and boosted analyses**
- Main bkg: W/Z+heavy flavor, $t\bar{t}$
- VH significance: **6.4σ**
- STXS measurement in different pT(V) bins: uncertainties range between 30% and 300%





[arxiv:2111.06712]

ttH

- **Two separate channels** targeting different top pair decays: 1-lepton, 2-lepton
- Main background: $t\bar{t}$+heavy flavor
- The observed ttH significance is **1.0σ**
- STXS measurement in 5 bins of pT(H)

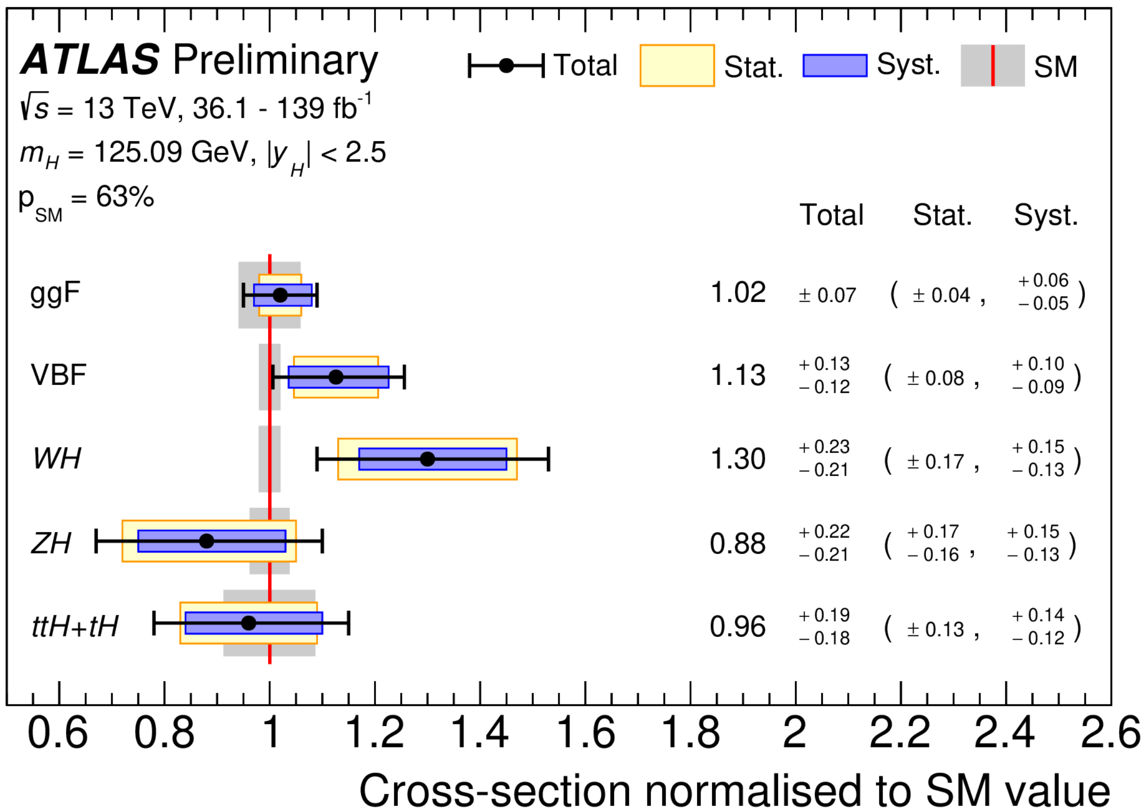
Combined measurements of Higgs coupling properties

	ggF	VBF	VH	ttH+tH
H→γγ	✔ (139 fb^{-1}) ✔ (77 fb^{-1})	✔ (139 fb^{-1}) ✔ (77 fb^{-1})	✔ (139 fb^{-1})	✔ (139 fb^{-1}) ✔ (77 fb^{-1})
H→ZZ	✔ (139 fb^{-1}) ✔ (137 fb^{-1})	✔ (139 fb^{-1}) ✔ (137 fb^{-1})	✔ (139 fb^{-1}) ✔ (137 fb^{-1})	✔ (36-139 fb^{-1}) ✔ (77-139 fb^{-1})
H→WW	✔ (139 fb^{-1}) ✔ (36 fb^{-1})	✔ (139 fb^{-1}) ✔ (36 fb^{-1})	✔ (36 fb^{-1})	
H→ττ	✔ (139 fb^{-1}) ✔ (77 fb^{-1})	✔ (139 fb^{-1}) ✔ (77 fb^{-1})	✔ (139 fb^{-1}) ✔ (77 fb^{-1})	
H→bb	✔ (36 fb^{-1})	✔ (126 fb^{-1}) ✔ (77 fb^{-1})	✔ (139 fb^{-1}) ✔ (77 fb^{-1})	✔ (139 fb^{-1}) ✔ (77 fb^{-1})
H→μμ	✔ (139 fb^{-1}) ✔ (36 fb^{-1})	✔ (139 fb^{-1}) ✔ (36 fb^{-1})	✔ (139 fb^{-1})	✔ (139 fb^{-1})
H→Zγ	✔ (139 fb^{-1})	✔ (139 fb^{-1})	✔ (139 fb^{-1})	✔ (139 fb^{-1})
H→invisible		✔ (139 fb^{-1})		

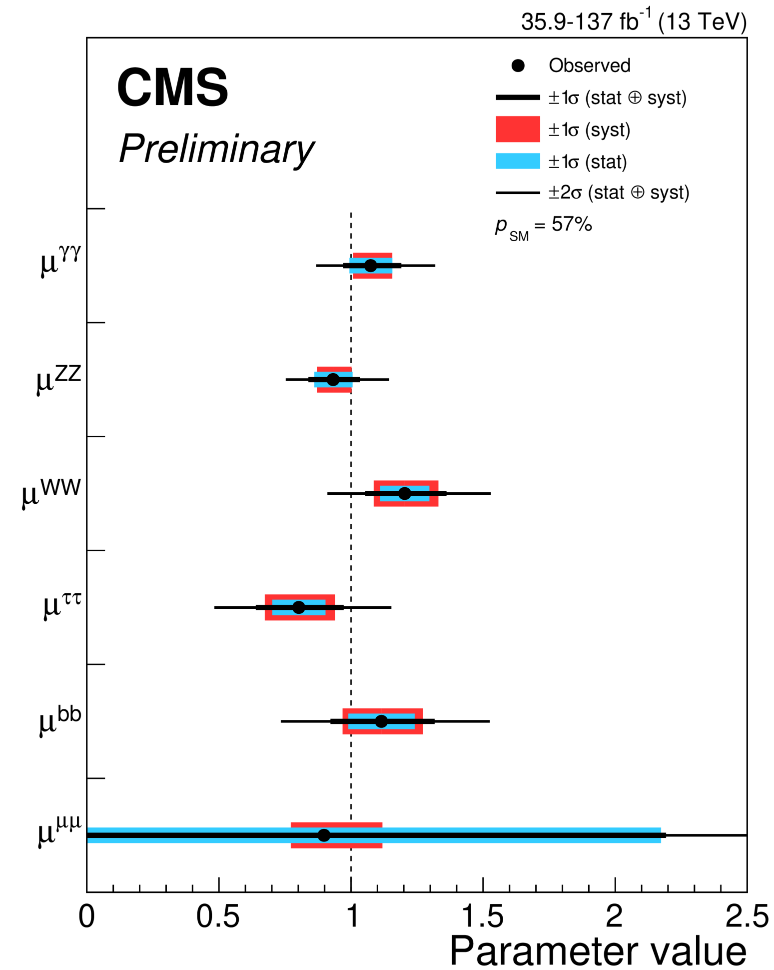
✔: channel included in the ATLAS combination
✔: channel included in the CMS combination

Production and decay rates

ATLAS-CONF-2021-053

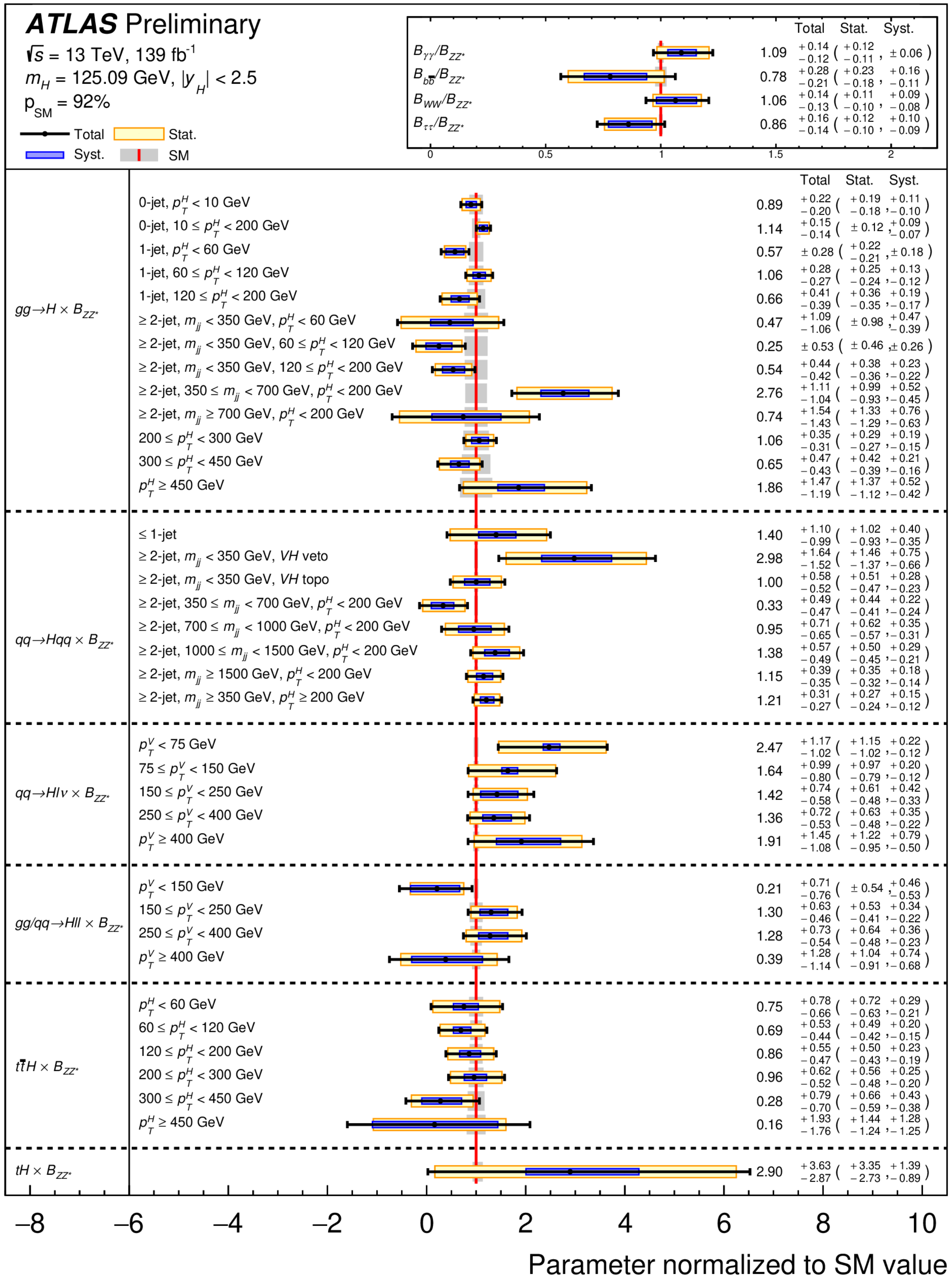


CMS-PAS-HIG-19-005



- ggF cross section is now measured with 7% precision
    - Precision of N3LO cross section prediction: 5%
- All major production modes (ggF, VBF, WH, ZH, ttH) and decay modes (H→γγ, H→ZZ, H→WW, H→ττ, H→bb) are observed

STXS results (w/o assuming the SM decays)



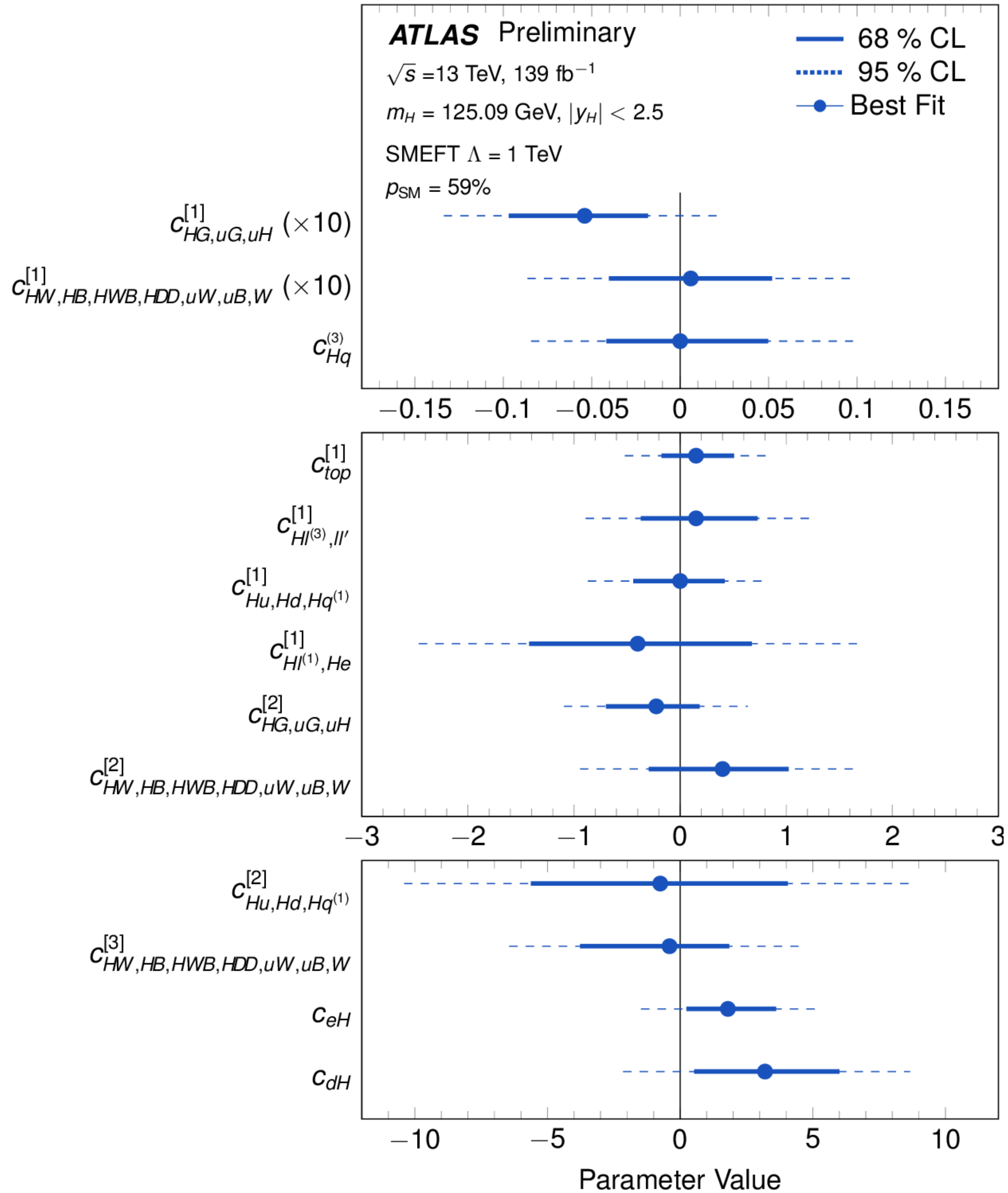
ATLAS-CONF-2021-053

- STXS are measured granularly in this combination: 41 regions are probed
  - VBF, ggF+2jets: more granular in mass(jj)
  - VH: reach high pT(V)
  - ttH: reach high pT(H)
- All regions are statistically limited; in some regions (e.g. ggF 0-jet) systematics are not negligible

Interpretation of STXS with EFT

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_{i}^{N_{d6}} \frac{c_i}{\Lambda^2} O_i^{(6)} + \sum_{j}^{N_{d8}} \frac{b_j}{\Lambda^4} O_j^{(8)} + \ldots$$

- Parameterize the signal strengths directly with Wilson coefficients of d=6 SMEFT operators
- Rotate the SMEFT basis cj to eigenvector cj' and fit 13 sensitive eigenvectors simultaneously
- All measured parameters are consistent with the SM expectation within their uncertainties

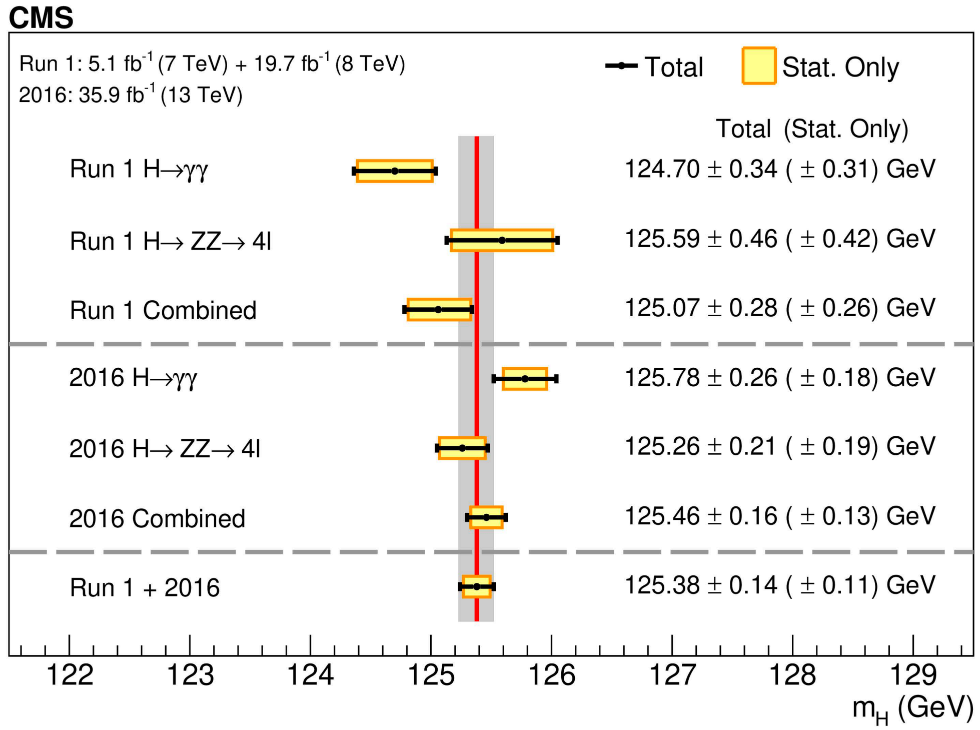


ATLAS-CONF-2021-053

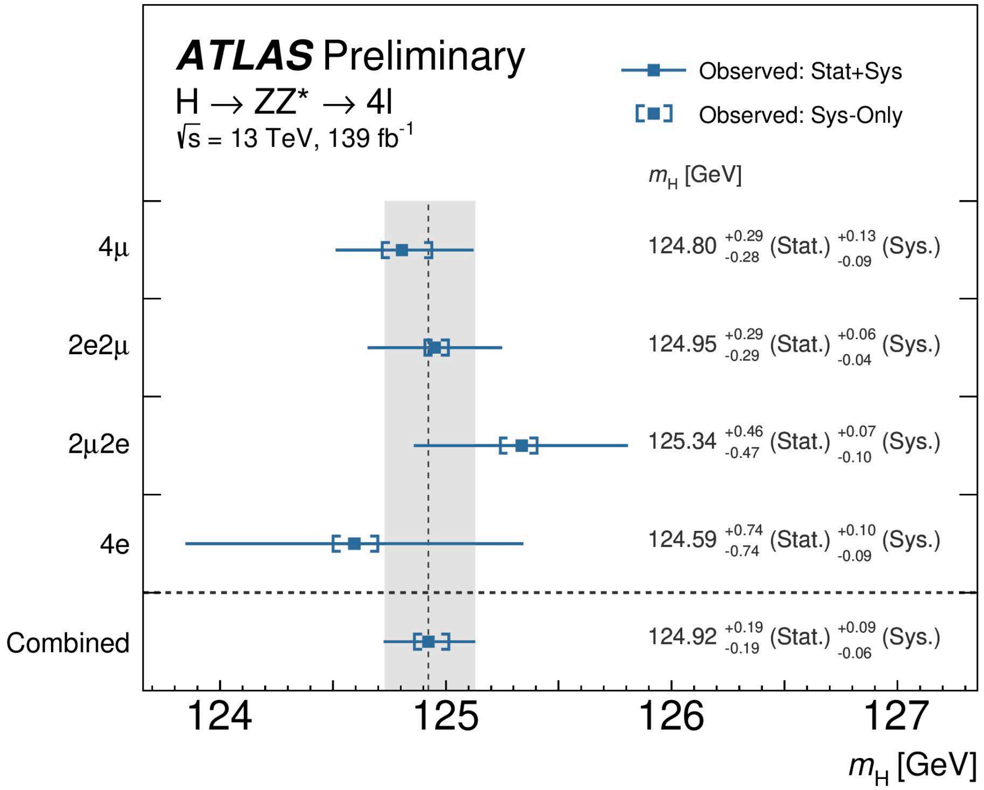
Measurements of Higgs mass, width, CP

Higgs mass

- Higgs mass is the only free parameter in the SM Higgs sector
- Measured in channels with best resolution: $H\to ZZ^*\to 4l$ and $H\to\gamma\gamma$
  - Rely on energy/momentum calibration
- ATLAS+CMS Run 1 combination: $H\to ZZ^*\to 4l$ and $H\to\gamma\gamma$, 125.09 ± 0.24 GeV
  - 0.19% uncertainty
- CMS Run 1+2016 data: $H\to ZZ^*\to 4l$ and $H\to\gamma\gamma$, 125.38 ± 0.14 GeV
  - 0.11% uncertainty
- ATLAS full Run 2: $H\to ZZ^*\to 4l$, $124.92^{+0.21}_{-0.20}$ GeV
  - 0.16% uncertainty
- Precision not a limiting factor for other Higgs measurements



Phys. Lett. B 805 (2020) 135425



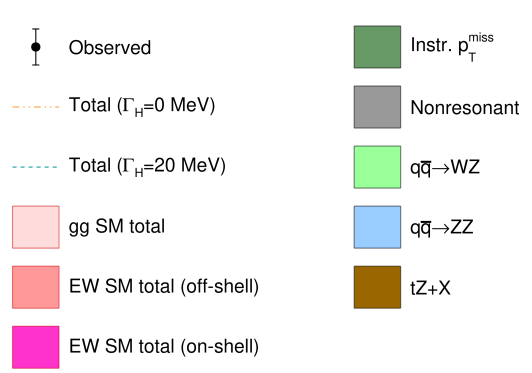
ATLAS-CONF-2020-005

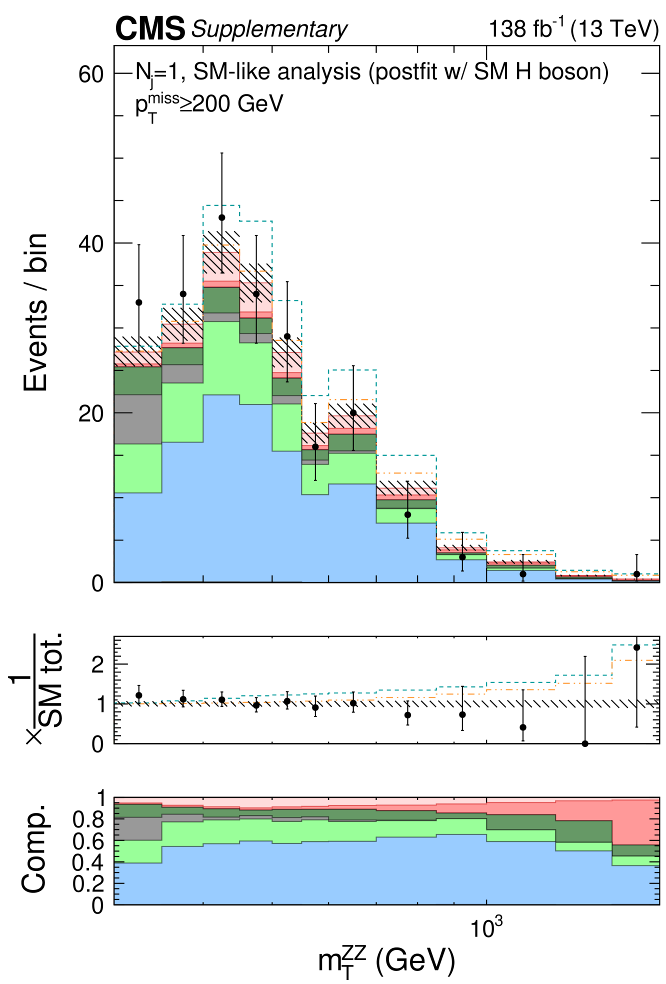
Higgs width and off-shell production

- SM prediction Higgs width 4.1 MeV
  - direct measurement limited by detector resolution: width < 1.1 GeV at 95% CL
- Constrain Higgs width by comparing on-shell and off-shell Higgs rates using $H \to ZZ^* \to 4l$ and $H \to ZZ^* \to 2l2\nu$

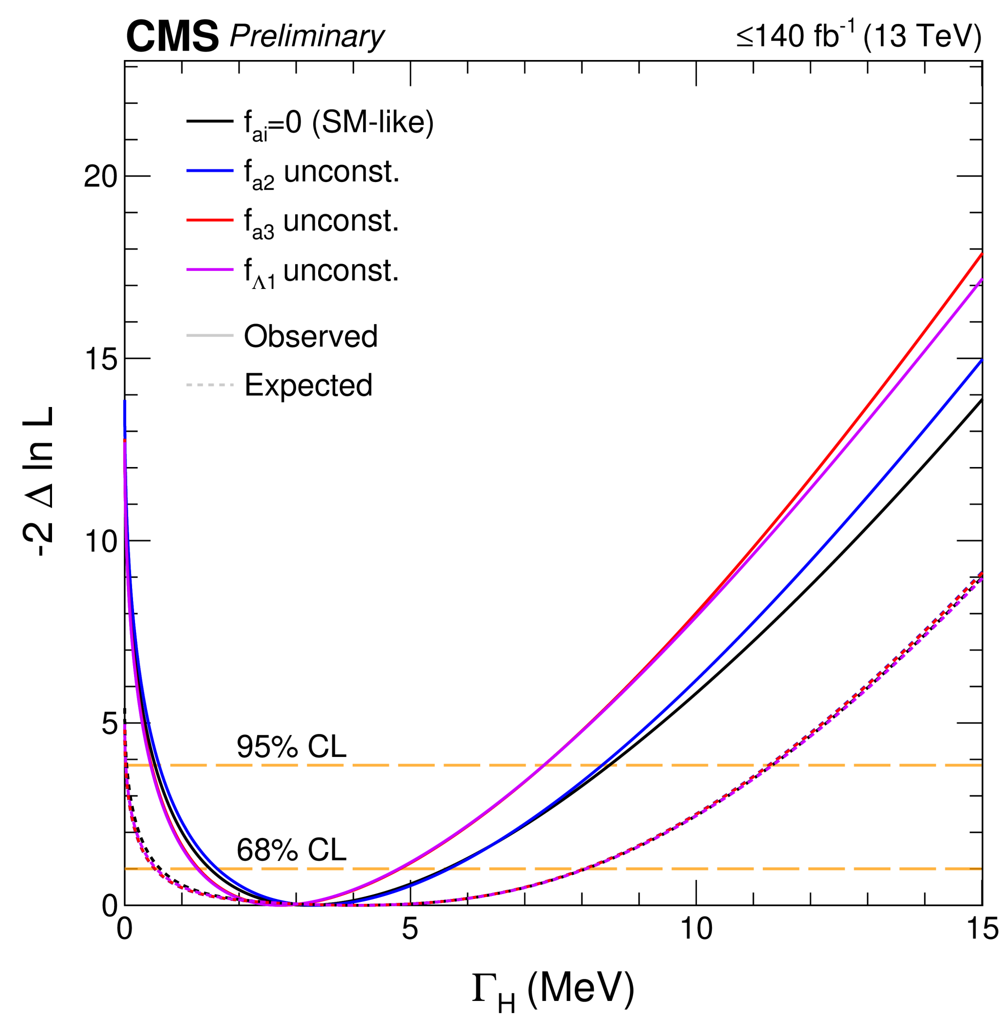
$$\Gamma_H = \frac{\mu_{off\ shell}}{\mu_{on\ shell}} \times \Gamma_H^{SM} \qquad (\kappa_t^2 \kappa_V^2)_{on\ shell} = (\kappa_t^2 \kappa_V^2)_{off\ shell}$$

- **Scenario with no off-shell production is excluded at 3.6σ**
  - Higgs width is determined to be $3.2^{+2.4}_{-1.7}$ MeV





$$m_T^{ZZ\,2} = \left[\sqrt{p_T^{\ell\ell\,2} + m_{\ell\ell}^2} + \sqrt{p_T^{miss\,2} + m_Z^2}\right]^2 - \left|\vec{p}_T^{\,\ell\ell} + \vec{p}_T^{\,miss}\right|^2$$



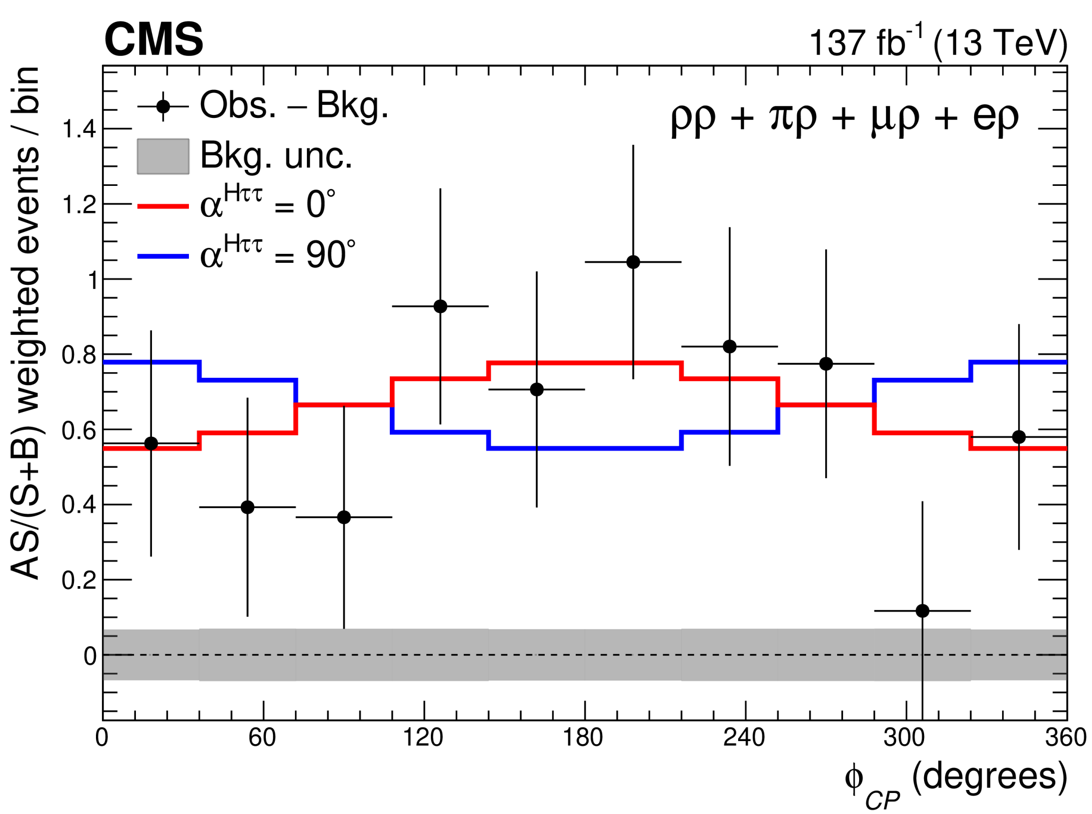
CMS-PAS-HIG-21-013

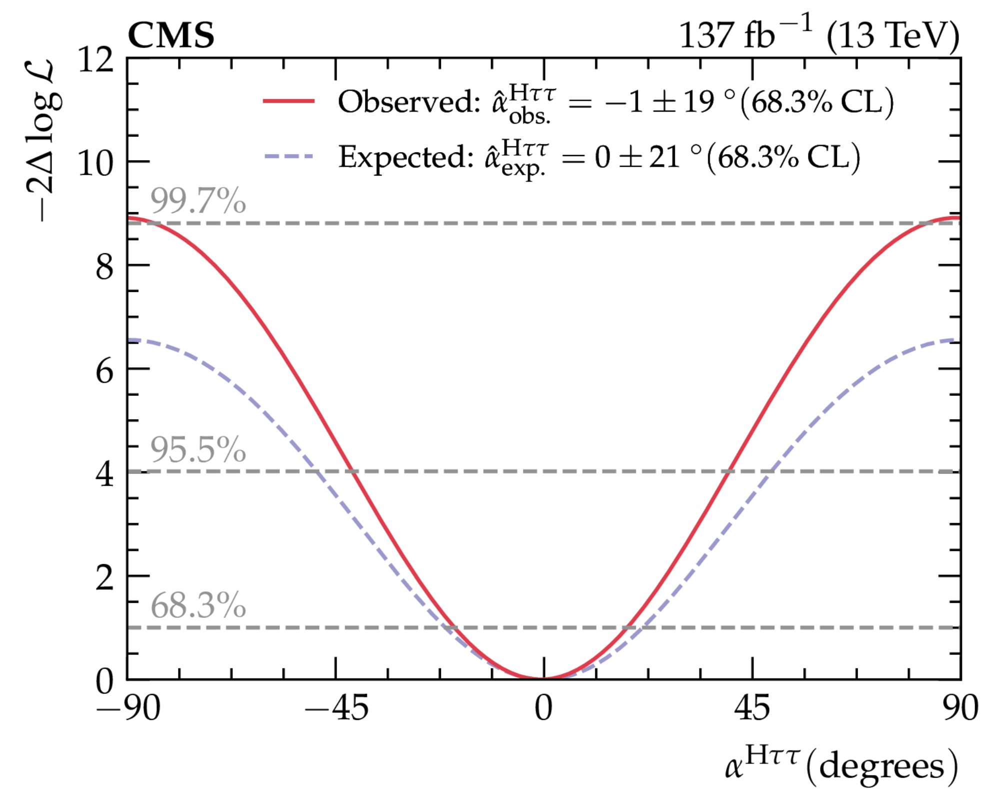
CP and anomalous coupling

$H \to \tau\tau$

$$\mathcal{L}_Y = -\frac{m_\tau H}{v}(\kappa_\tau \bar{\tau}\tau + \tilde{\kappa}_\tau \bar{\tau} i\gamma_5 \tau) \qquad \tan(\phi_{\tau\tau}) = \frac{\tilde{\kappa}_\tau}{\kappa_\tau}$$

- CMS performed first measurement of CP structure of Yukawa coupling between Higgs Boson and τ leptons
- Angular correlation between the decay products of the two τ leptons were employed (left plot)
- **Data disfavor the pure CP-odd scenario at 3.0 standard deviations**
- Effective mixing angle found to be -1 +/- 19° (right plot)
  - Leading uncertainty is statistical





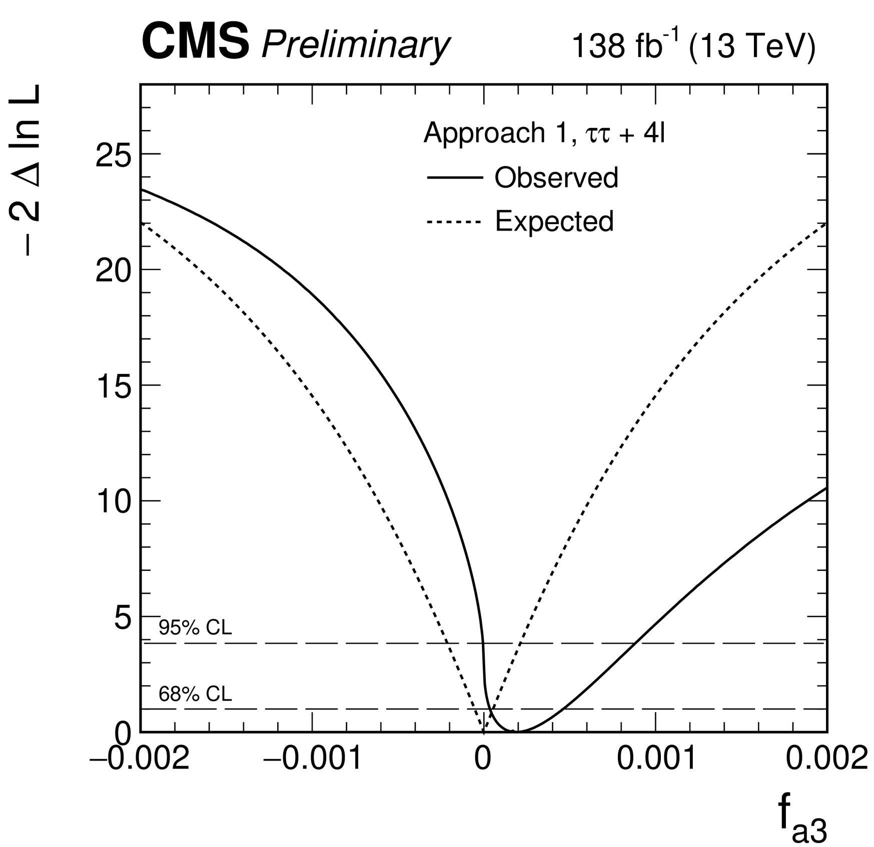
CMS-PAS-HIG-20-006

CP and anomalous coupling

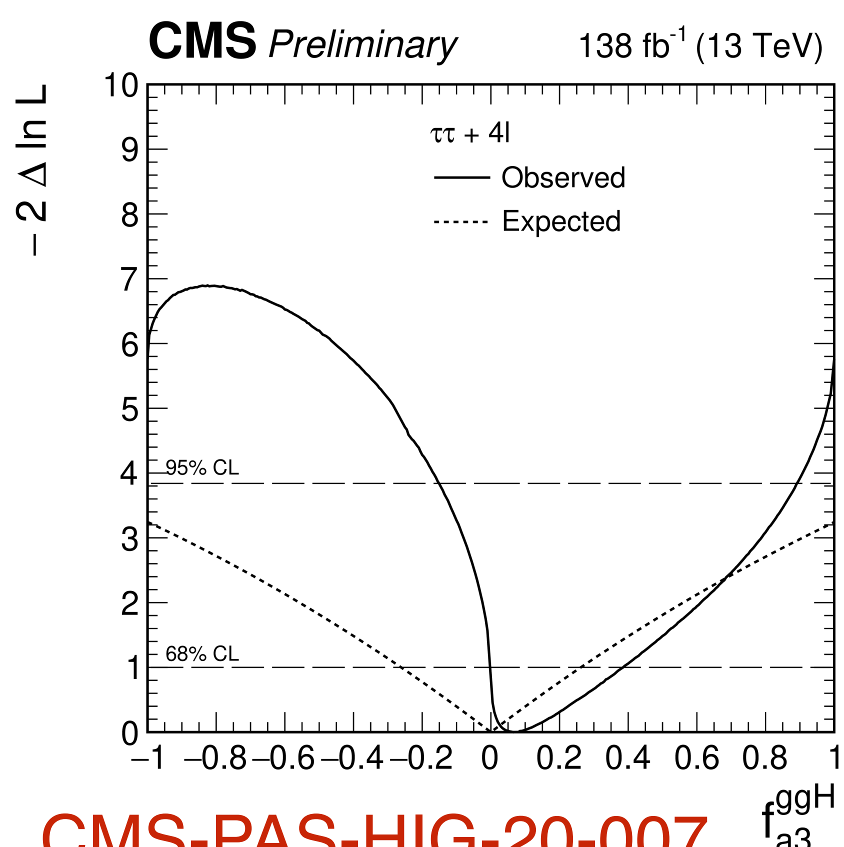
$$\mathcal{A}(\mathrm{HVV}) \sim \left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_1^2 + \kappa_2^{\mathrm{VV}} q_2^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2}\right] m_{\mathrm{V1}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2)\mu\nu} + a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2)\mu\nu},$$

- CMS searches for anomalous couplings using ggH+2j, VBF, VH and ttH in H→4l and H→$\tau\tau$ decays
- Matrix element and multi-variate techniques were employed
- Two independent categorizations:
  - One for HVV vertices: study four anomalous couplings
  - One for Hgg and Htt vertices: exclude pure CP odd Hgg couplings for the first time
    - Combine with ttH (H→γγ) CP analysis for probing Htt coupling
- **No indication of CP violation and non-SM couplings, most stringent constraints are given**

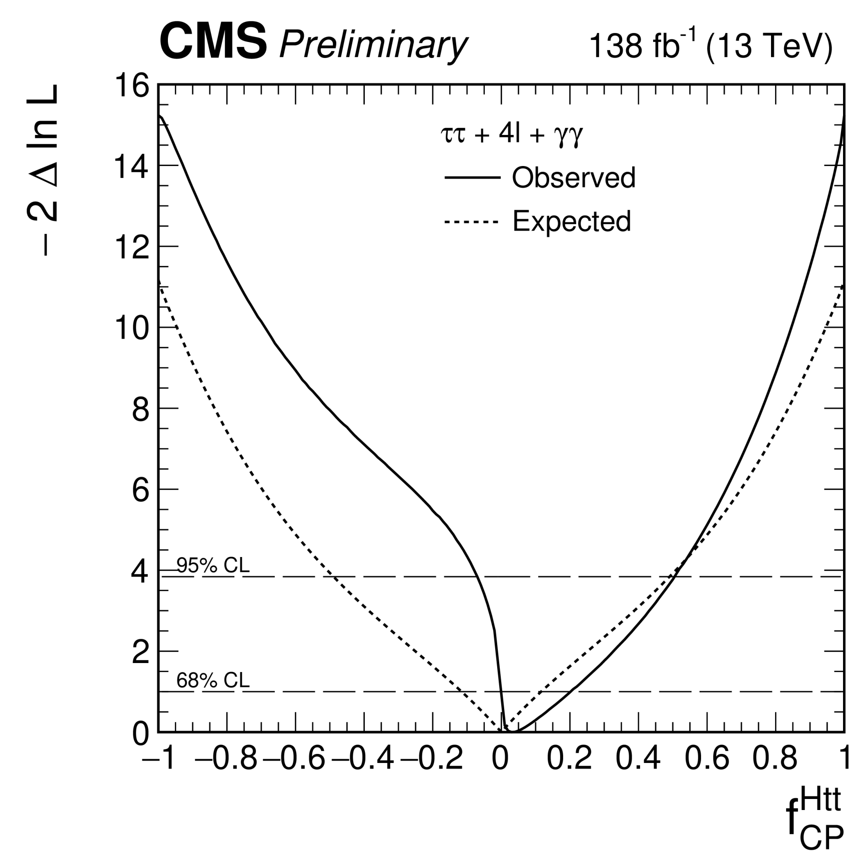
HVV vertices



Hgg vertices



Htt vertices



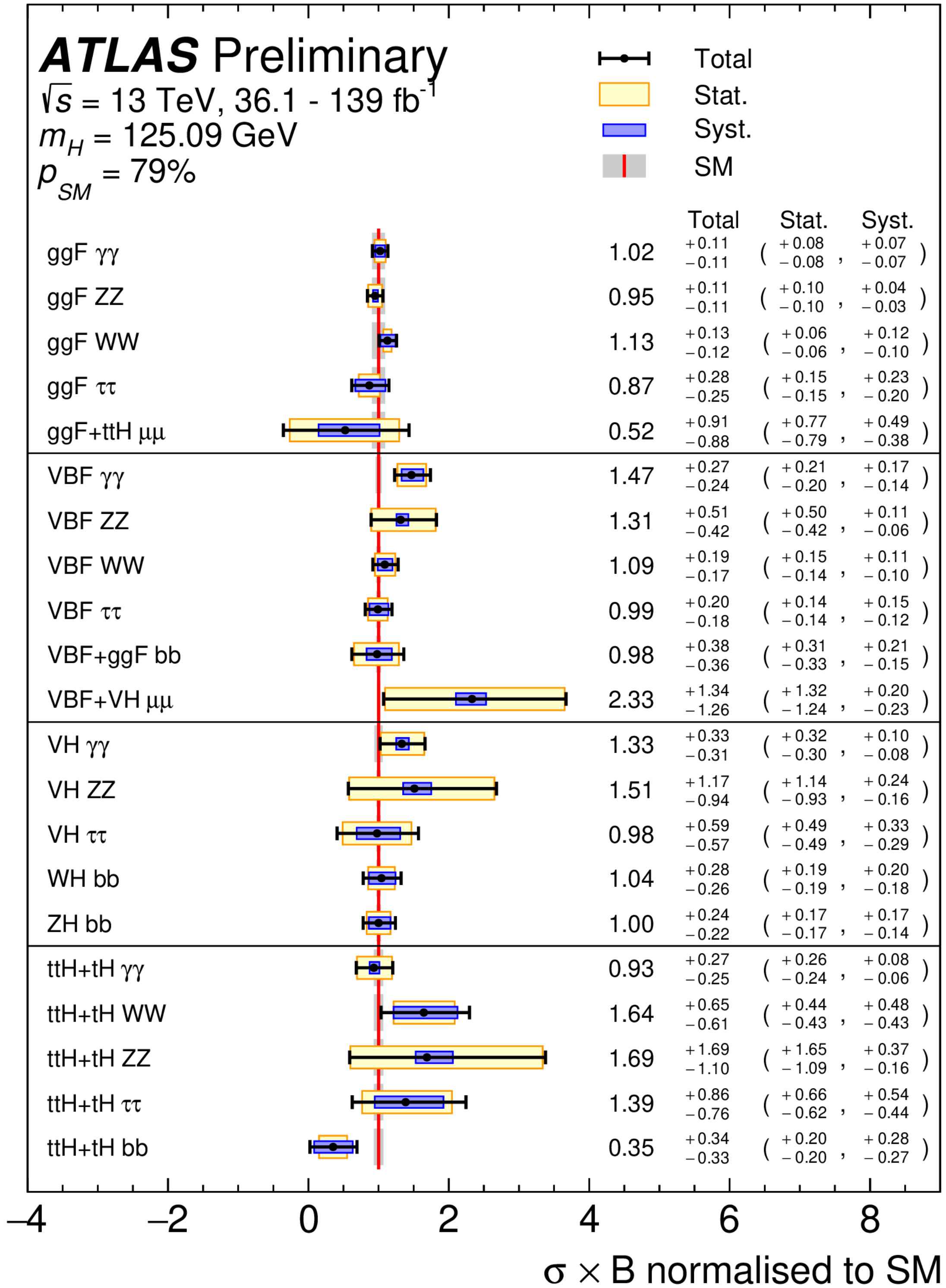
CMS-PAS-HIG-20-007

Summary

- ATLAS and CMS experiments keep **improving precision for Higgs property measurements**
  - All major production modes (ggF, VBF, WH, ZH, ttH) and decay modes (H→γγ, H→ZZ, H→WW, H→$\tau\tau$, H→bb) are observed
  - Simplified template cross sections and fiducial cross sections are measured granularly
  - Scenario with no off-shell production is excluded
  - Pure CP-odd Higgs-tau coupling is excluded
  - Results are **currently in agreement with the SM predictions** and can be interpreted using EFT and BSM models
- Run 3 is now approaching. **Stay tune for the new results!**
- Other plenary talks on experimental Higgs results
  - Rare and BSM Higgs (Bing Li)
  - HH production (Yanping Huang)

Backup slides

Production mode cross sections times decay branching ratios



- Most sensitive to ggF: H→γγ, H→ZZ, H→WW
- Most sensitive to VBF: H→WW, H→ττ, H→γγ
- Most sensitive to VH: H→bb, H→γγ
- Most sensitive to ttH and tH: H→γγ, H→bb
- Measurements consistent with SM predictions

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Coupling modifier ("kappa")

- Leading order motivated framework: assign coupling modifier to each (effective) interaction vertex (e.g. κ_W, κ_t…)
- In this framework, production cross section times decay branch fraction of i→H→f can be parameterized as

$$\sigma_i \times B_f = \frac{\sigma_i(\boldsymbol{\kappa}) \times \Gamma_f(\boldsymbol{\kappa})}{\Gamma_H},$$

  - (this allows for a consistent treatment of production and decay)
- Total width of Higgs boson can be expressed as

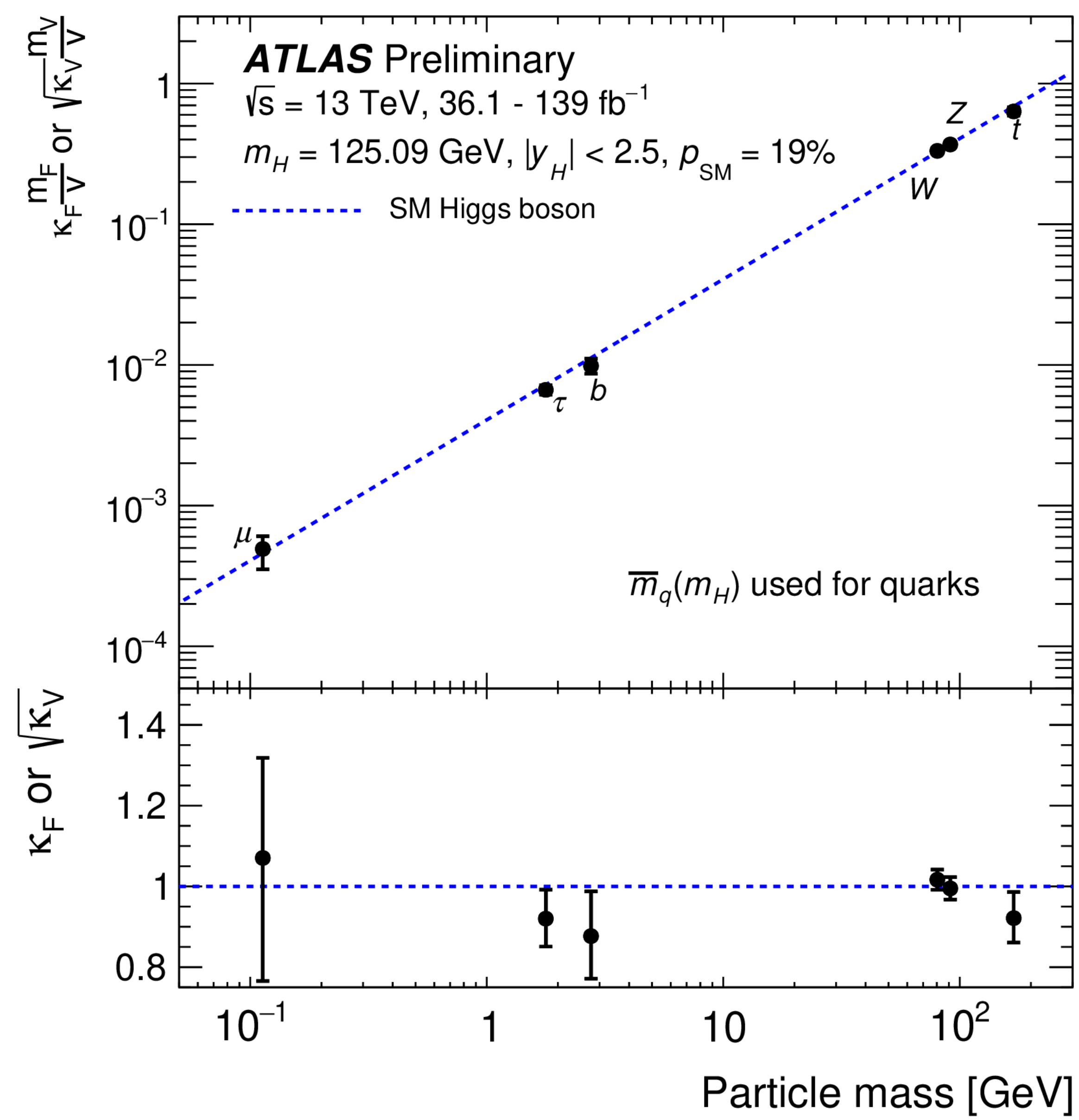
$$\Gamma_H(\boldsymbol{\kappa}, B_{\mathrm{i.}}, B_{\mathrm{u.}}) = \kappa_H^2(\boldsymbol{\kappa}, B_{\mathrm{i.}}, B_{\mathrm{u.}})\,\Gamma_H^{\mathrm{SM}}$$

$B_{i.}$= BSM contribution to BR of invisible decays

$B_{u.}$= BSM contribution to BR of undetected decays

Coupling modifier

- "Kappa" framework: assign coupling modifier to each interaction vertex (e.g. κ_W, κ_t…)
- Here assume no BSM contribution in loop-induced processes (ggF, H→γγ etc.) or total width
- Good agreement with the SM across 3 orders of magnitude of particle mass!



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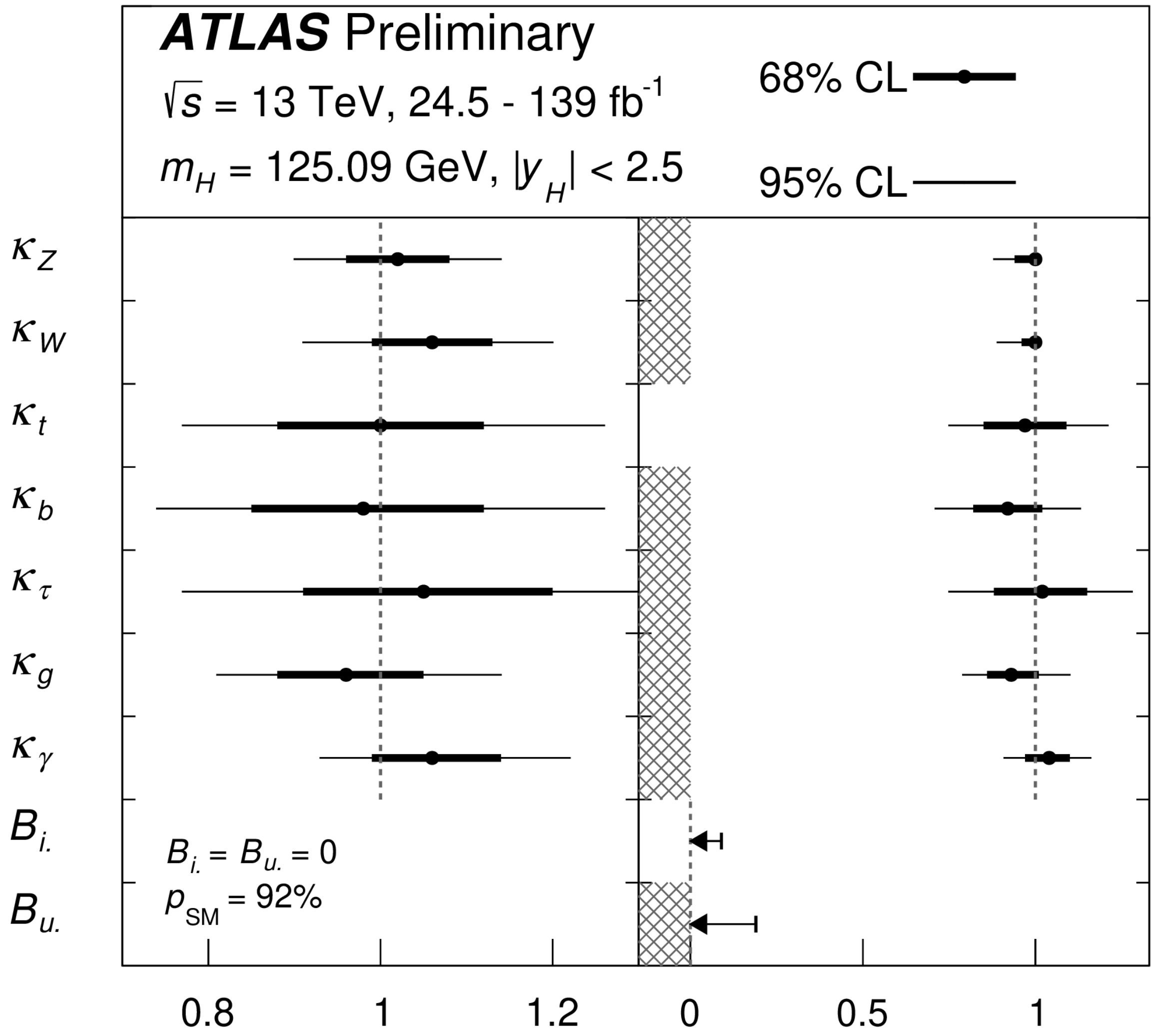
Coupling modifier

- Not resolving ggF and Hγγ effective vertices (and introducing corresponding coupling modifiers κ_g, κ_γ), explore two different scenarios for:
  - **Left**: assume $B_{i.}=B_{u.}=0$ ($B_{i.}$: BSM decay with MET, $B_{u.}$: BSM decay without MET)
  - **Right**: constrain $B_{i.}$ and $B_{u.}$ using H→invisible analysis and $\kappa_V < 1$
- All coupling modifiers are measured to be compatible with the SM
  - Negative κ_t excluded at 4.3σ
  - κZγ probed for the first time



$B_{i.}<0.09$ at 95% CL
$B_{u.}<0.16$ at 95% CL

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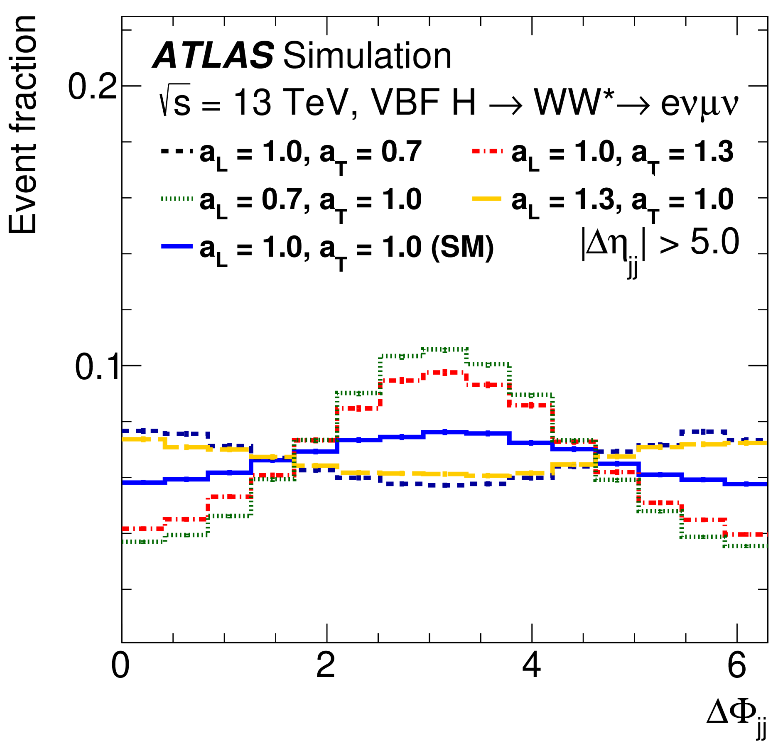
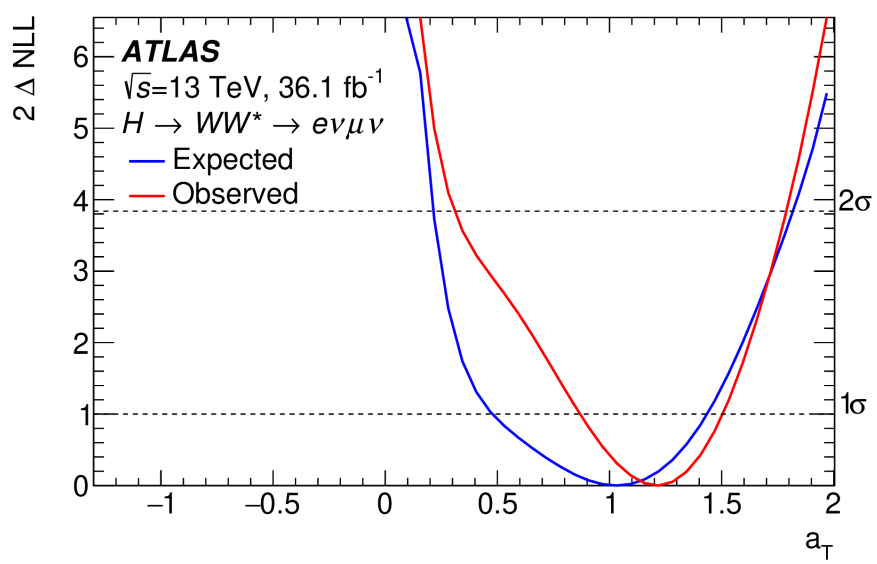
Polarisation-dependent coupling strengths

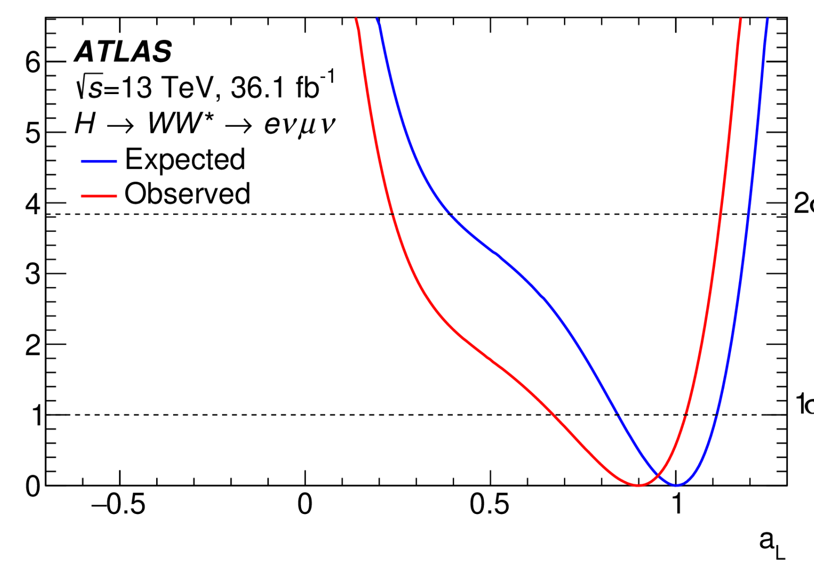
H→WW

$$a_{\mathrm{L}} = \frac{g_{HV_{\mathrm{L}}V_{\mathrm{L}}}}{g_{HVV}}, \quad a_{\mathrm{T}} = \frac{g_{HV_{\mathrm{T}}V_{\mathrm{T}}}}{g_{HVV}},$$

- ATLAS performed first measurement of Higgs coupling strengths to longitudinally and transversely polarized W and Z bosons, using VBF (H→WW) process
- Azimuthal angle difference between the two leading jets were employed (left plot)
- Results consistent with SM (a_T=a_L=1)
  - $a_T=0.91^{+0.10}_{-0.18}(\mathrm{stat.})^{+0.09}_{-0.17}(\mathrm{syst.})$
  - $a_L=1.2\pm0.2(\mathrm{stat.})^{+0.2}_{-0.3}(\mathrm{syst.})$







arxiv:2109/13808