# Higgs couplings and properties

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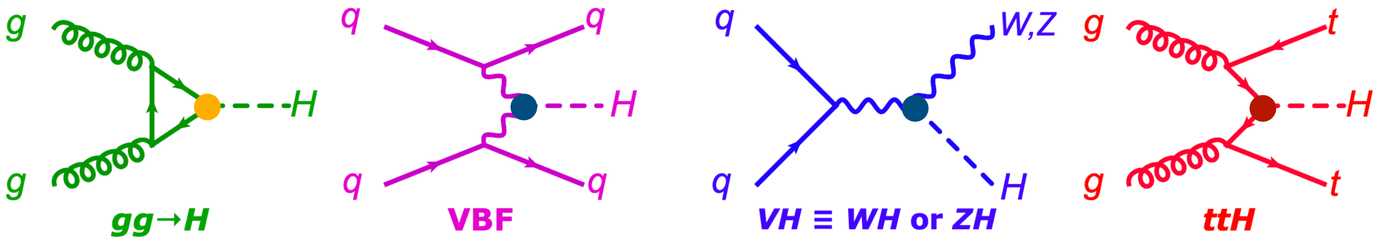
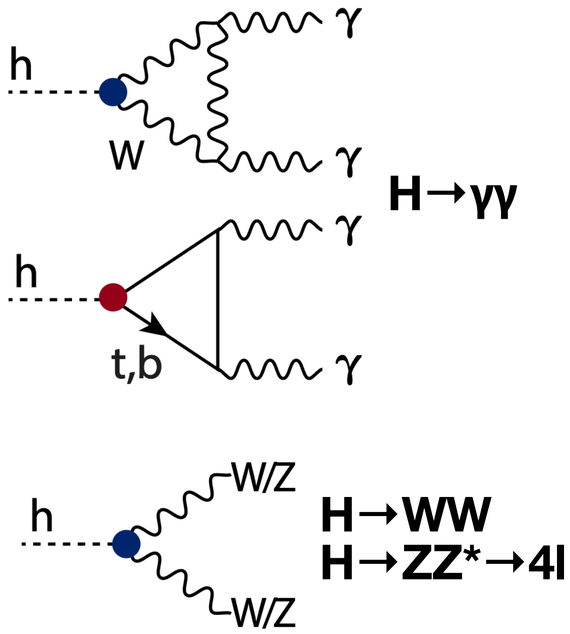
# Introduction

- Higgs couplings to other SM particles from **cross section measurements** in certain **final states**
  - Often targeted at several/all **production modes**




- More information on couplings using **fiducial**, **STXS** or **differential** cross sections
  - STXS bin: **split Higgs production modes** in gen-level bins in pT(H,V,Hjj,j), N(jets), m(jj)

# Introduction

- Disentangle couplings in cross section results in terms of **coupling modifiers (κ-framework)**
  - Different schemes possible: **generic**, **effective** $\kappa_\gamma$, $\kappa_g$, $\kappa_{Z\gamma}$ (BSM in loops), **fundamental** $\kappa_V$ and $\kappa_f$, etc.
  - Deviation of SM coupling **κ!=1**

$$\mathcal{L} = \kappa_3 \frac{m_H^2}{2v} H^3 + \kappa_Z \frac{m_Z^2}{v} Z_\mu Z^\mu H + \kappa_W \frac{2m_W^2}{v} W_\mu^+ W^{-\mu} H + \kappa_g \frac{\alpha_s}{12\pi v} G^a_{\mu\nu} G^{a\mu\nu} H + \kappa_\gamma \frac{\alpha}{2\pi v} A_{\mu\nu} A^{\mu\nu} H + \kappa_{Z\gamma} \frac{\alpha}{\pi v} A_{\mu\nu} Z^{\mu\nu} H + \kappa_{VV} \frac{\alpha}{2\pi v} \left(\cos^2\theta_W Z_{\mu\nu} Z^{\mu\nu} + 2\, W^+_{\mu\nu} W^{-\mu\nu}\right) H - \left( \kappa_t \sum_{f=u,c,t} \frac{m_f}{v} f\bar{f} + \kappa_b \sum_{f=d,s,b} \frac{m_f}{v} f\bar{f} + \kappa_\tau \sum_{f=e,\mu,\tau} \frac{m_f}{v} f\bar{f} \right) H.$$

- Interpretation with **effective field theory (SMEFT, HEL)**, higher-dimensional operators with their corresponding **Wilson coefficient $c_i$, $b_i$** or **$f_i$**
  - Hint for BSM **$c_i$, $b_i$** or **$f_i$ !=0**

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i^{N_{d6}} \frac{c_i}{\Lambda^2} O_i^{(6)} + \sum_j^{N_{d8}} \frac{b_i}{\Lambda^4} O_i^{(8)} + \ldots, \qquad \mathcal{L}_{\text{HEL}} = \mathcal{L}_{\text{SM}} + \sum_j \mathcal{O} f_j / \Lambda^2$$

- **Anomalous couplings** can be introduced by further **CP-odd** coupling modifiers **~κ** or operators and their corresponding Wilson coefficient **~$c_i$**

# Latest, notable cross section results

**Other results:**
- **H→WW:** ATLAS-CONF-2021-014 and CMS-PAS-HIG-19-017
- **H→bb:** ATLAS-CONF-2021-051 and JHEP 12 (2020) 085

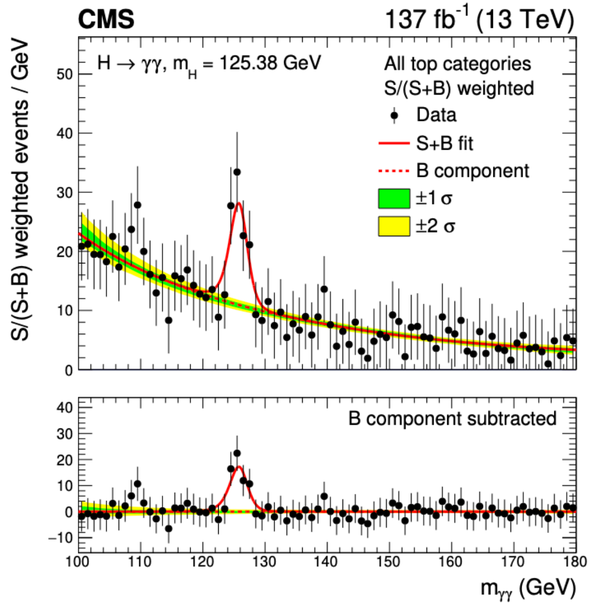
**Higgs to top coupling:**
- *Constraining the Top Quark Yukawa Coupling in tH Production with ATLAS,* Thomas Carter
- *ttH and tH production in multilepton channels with CMS,* Clara Ramon Alvarez

**Higgs to charm coupling:**
- *Direct Search for the Higgs Boson to Charm Quarks Coupling at ATLAS,* Antonio Jacques Costa

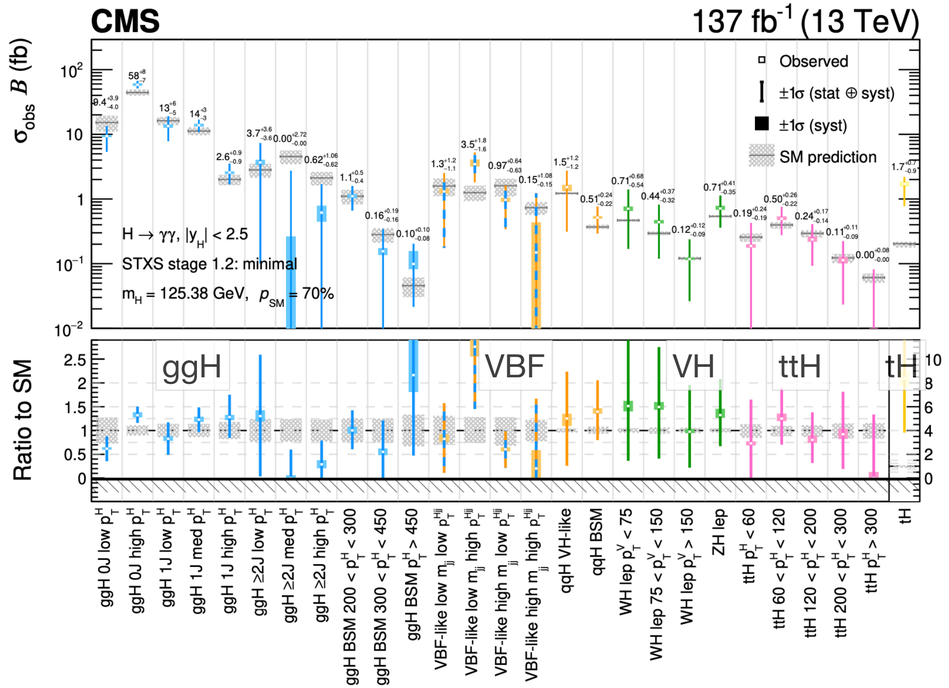
**Rare decays:**
- *Rare Higgs decays, Higgs BSM and HH,* Simone Gennai

# H→γγ STXS

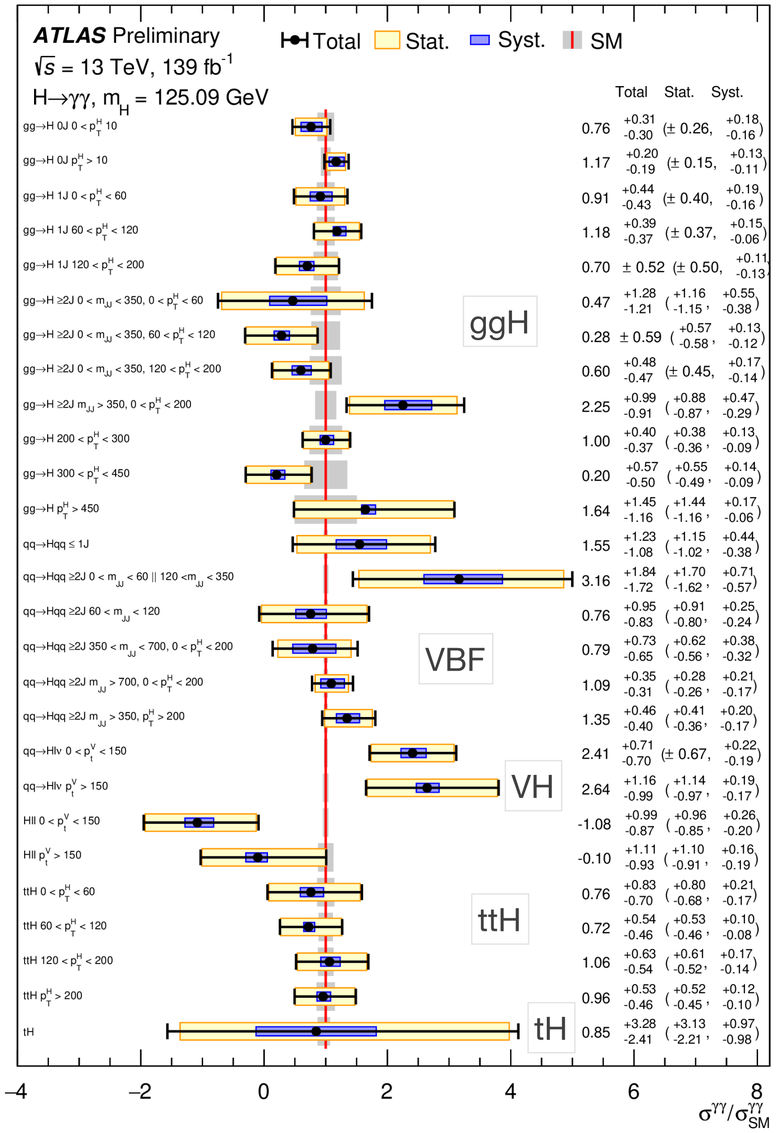
- **High statistics and good m(γγ) resolution** allows for fine binning
- Smoothly falling background in **m(γγ) spectrum**
- Allows for binning in 27 STXS categories (even **ttH+tH**)




JHEP 07 (2021) 027



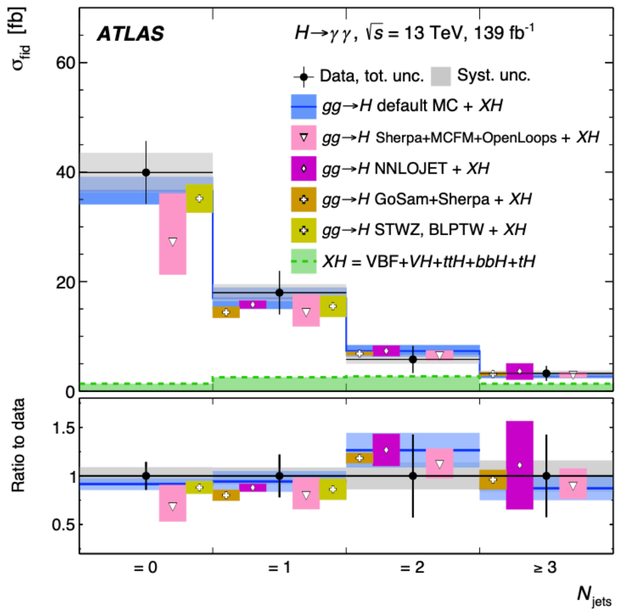

ATLAS-CONF-2020-026

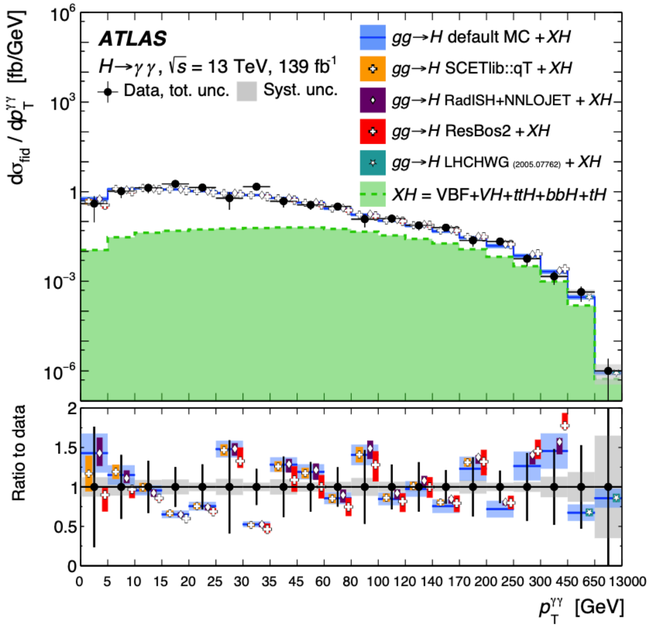


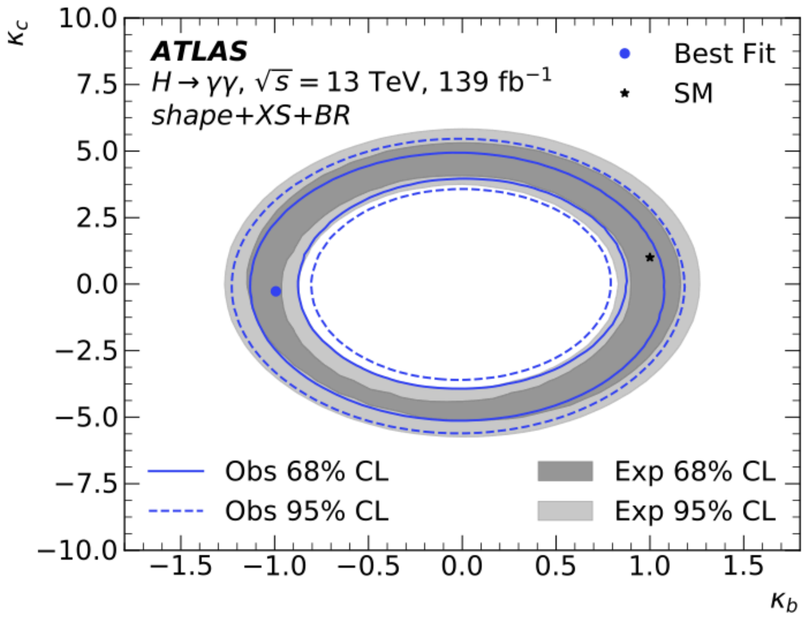
# H→γγ differential and fiducial

- **Fiducial cross section** 67±6 fb (64±4 fb) in agreement with SM
- **Differential distributions** also in agreement with SM
  - **probe $\kappa_c$ and $\kappa_b$** and **SMEFT** Wilson coefficients

arxiv:2202.00487



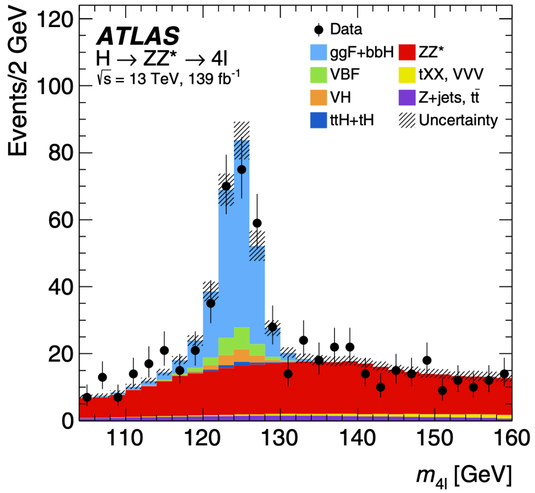



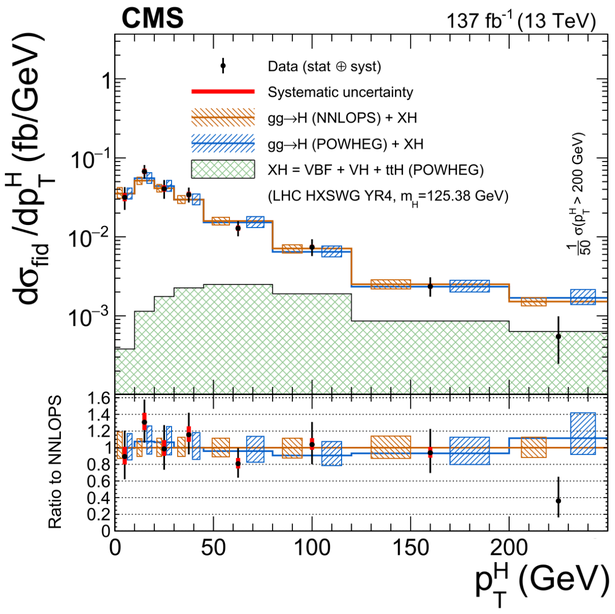



# H→ZZ*→4l STXS

- **Clean final** state with **low event yield**
  - DNN (ATLAS) or matrix element (CMS) to define STXS categories

Eur. Phys. J. C 80 (2020) 957

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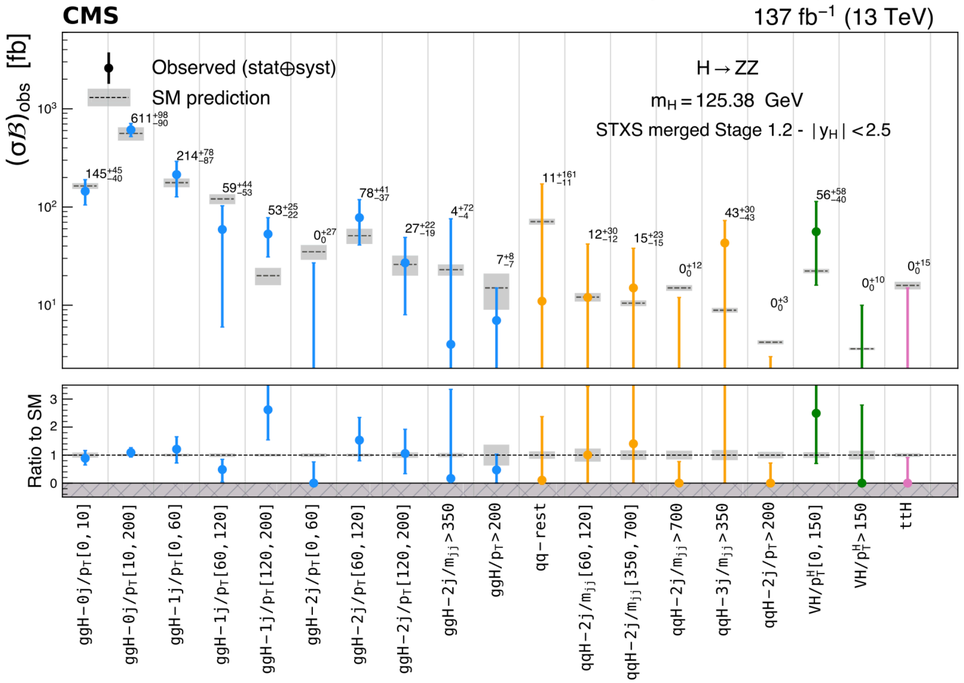
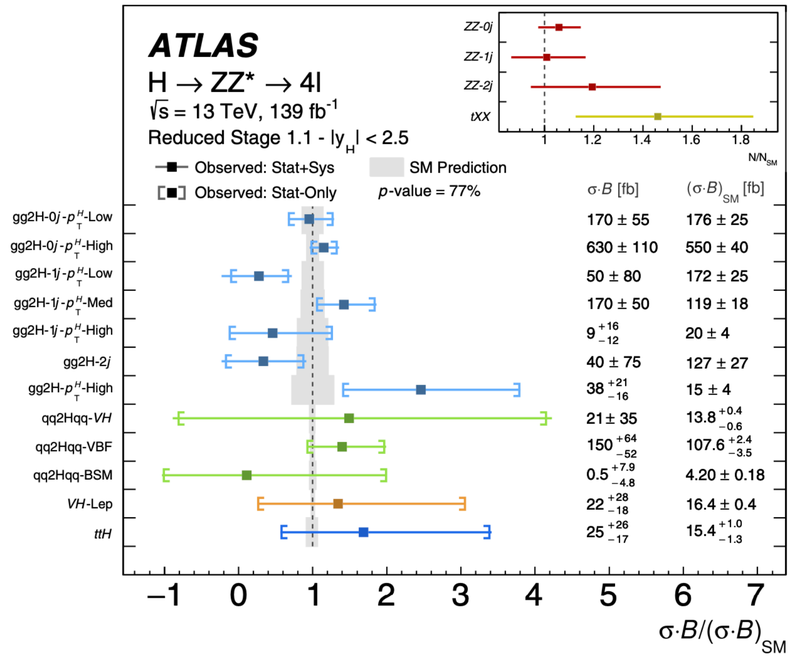
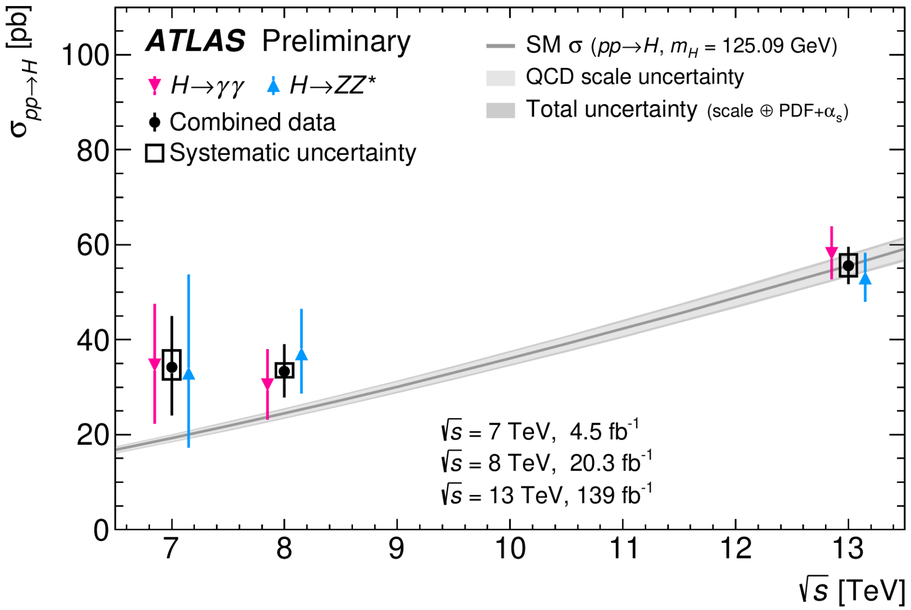


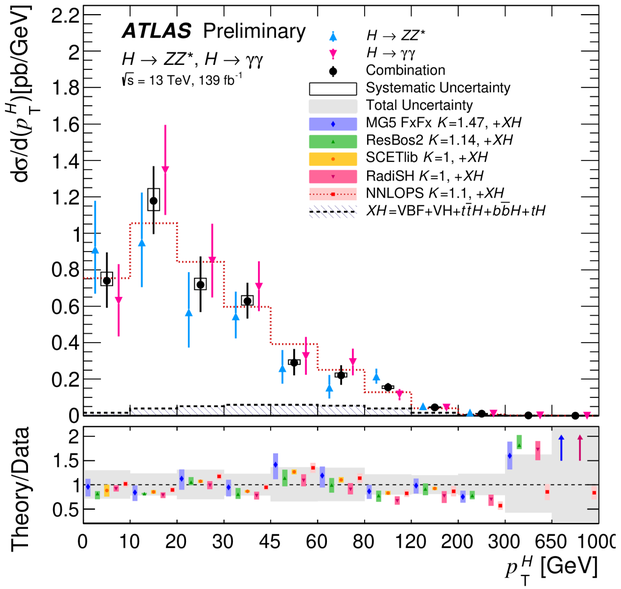



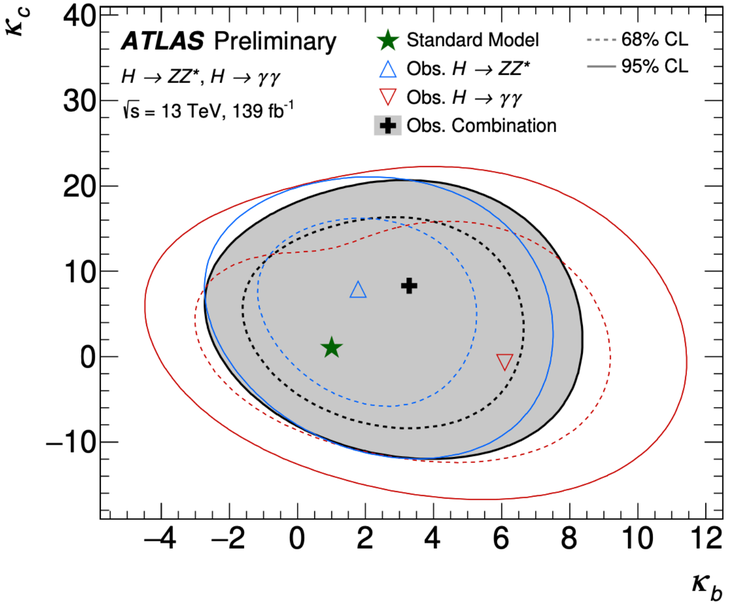
# H→γγ and H→ZZ*→4l differential and fiducial

- Combination of **inclusive cross sections** with full Run 2
- Combined **differential cross section** pT(H), y(H), N(jets), pT(jet1)
- Combined interpretation to **probe $\kappa_c$ and $\kappa_b$** using pT(H)

ATLAS-CONF-2022-002



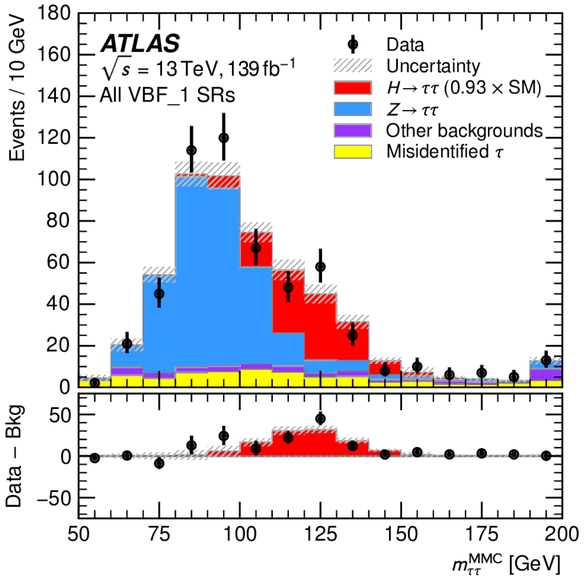



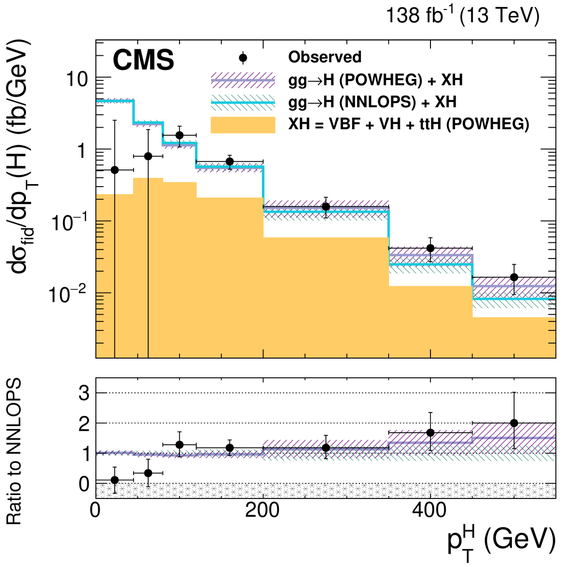
# H→ττ STXS

- Sensitivity for ggF with **high pT(H) >300 GeV** and VBF with **high m(jj) >700 GeV**
- Also **differential** measurement available

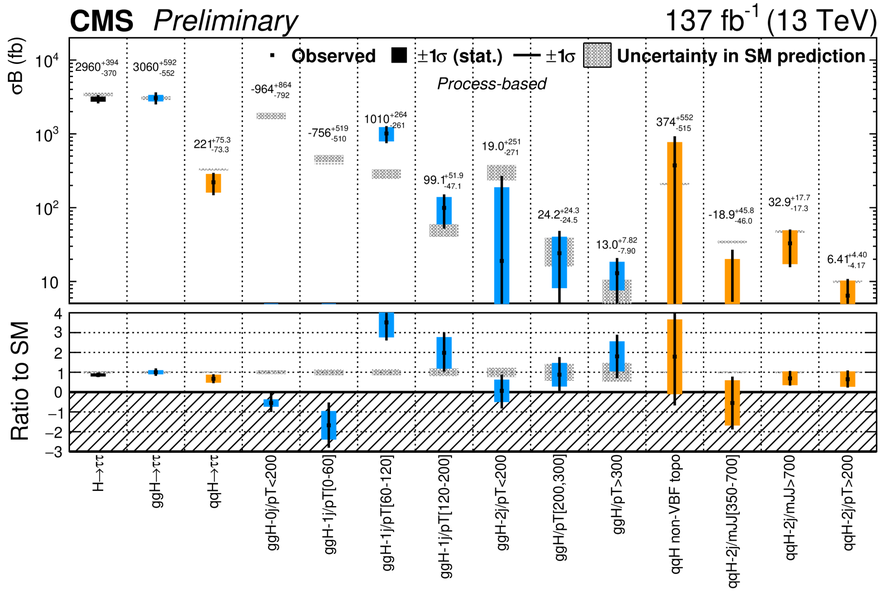
arxiv:2201.08269

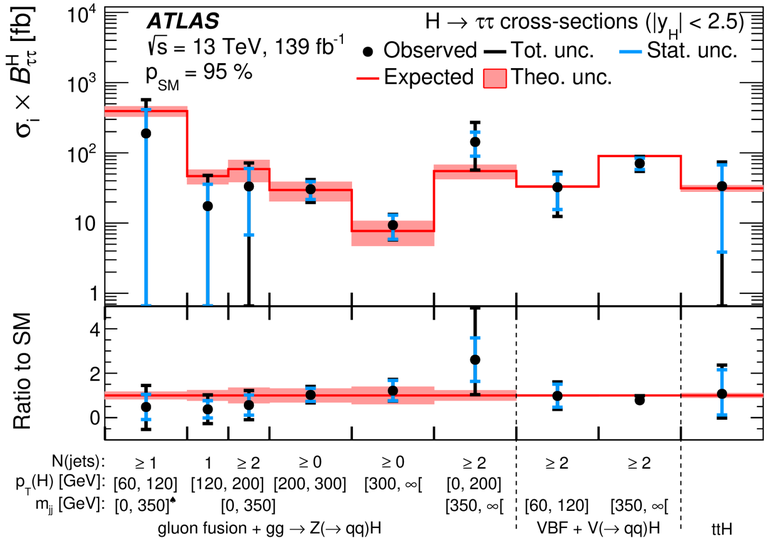



arXiv:2107.11486




CMS-PAS-HIG-19-010



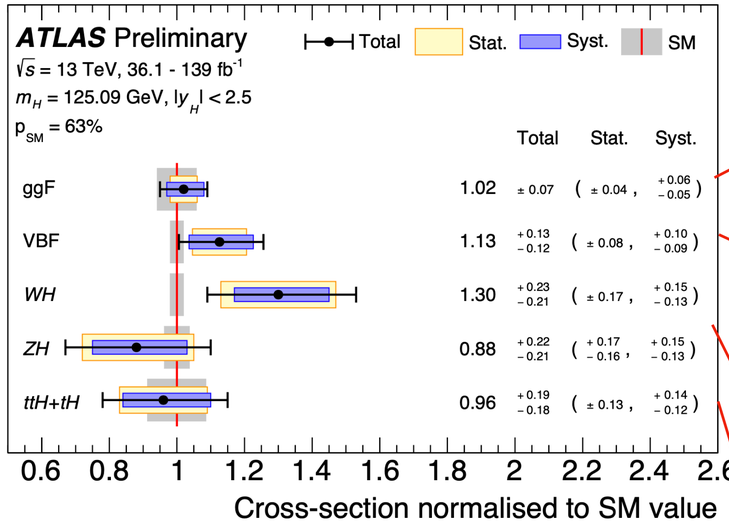



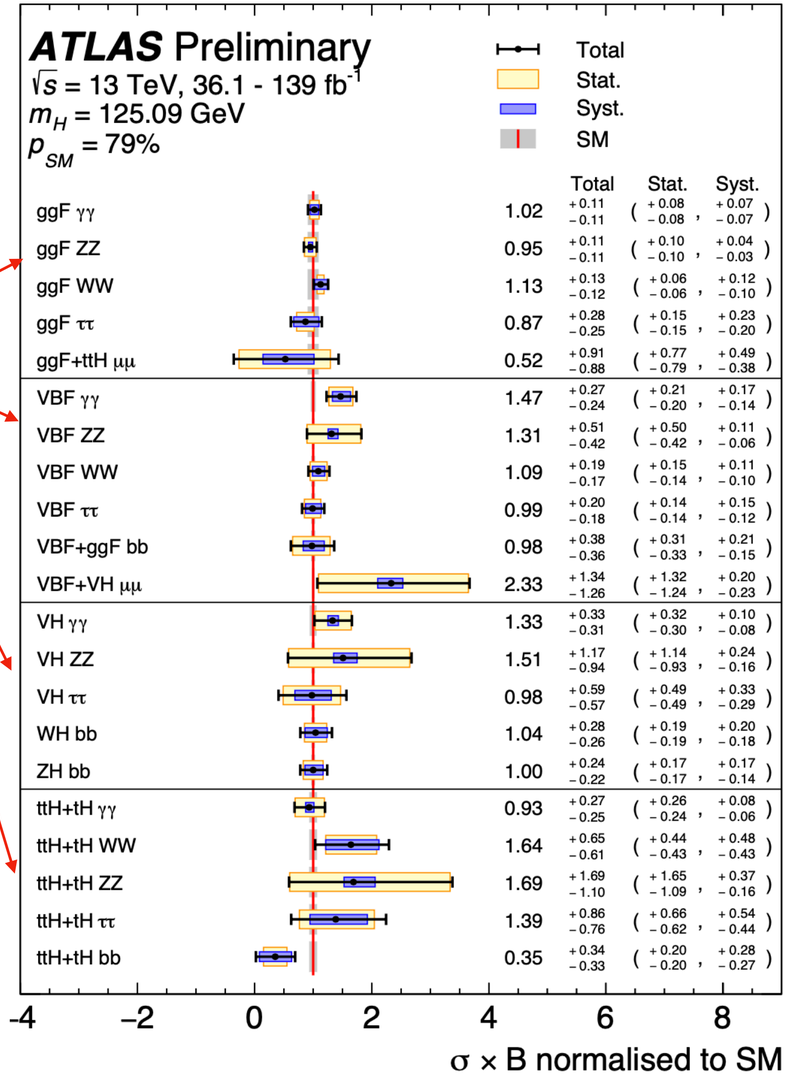
# Higgs couplings combination

ATLAS-CONF-2021-053

- Combination of **cross section measurements** in various production (ggF, VBF, VH, ttH+tH) and decay modes (γγ, bb, ZZ, WW, **ττ**, μμ)

ATLAS here only shown as example



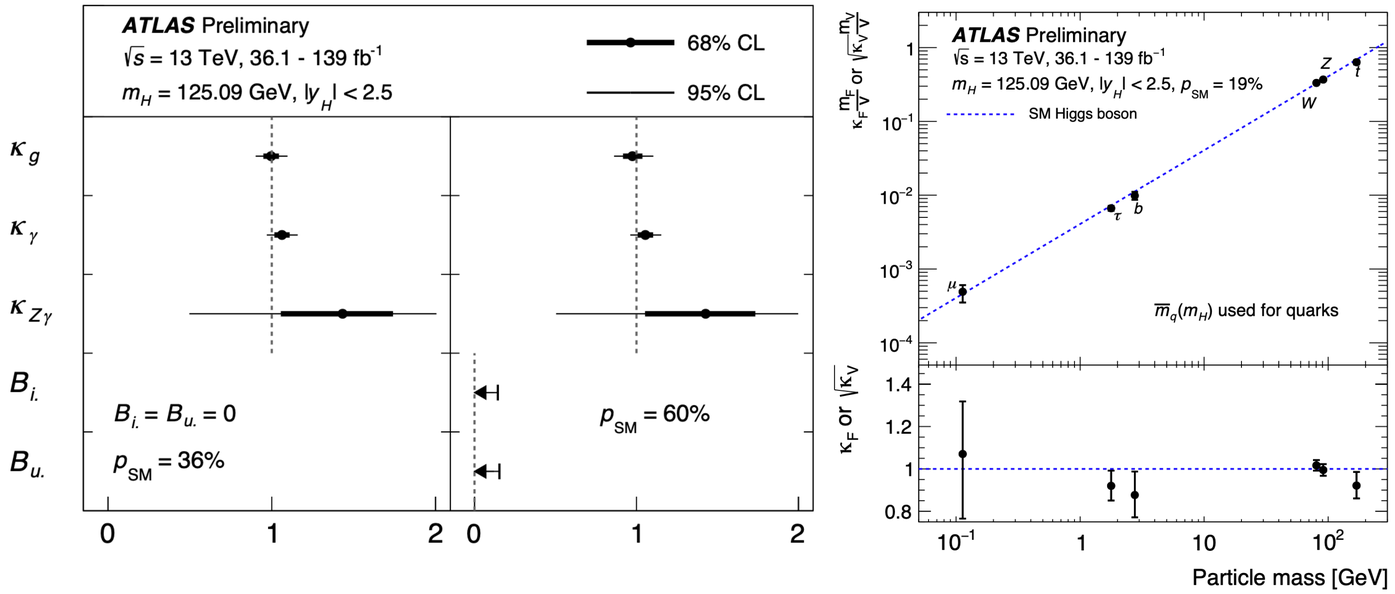




- **Total signal strength**
  **ATLAS** μ=1.06±0.06 (0.03 stat. 0.03 exp. 0.04 th.)
  **CMS** $\mu=1.02^{+0.07}_{-0.06}$ (0.04 stat. 0.04 exp. 0.04 th.)

# Higgs couplings interpretation

- Determination of **coupling modifier**
  - Generic, **effective, fundamental vector boson and fermion,…**
- SMEFT Wilson coefficients

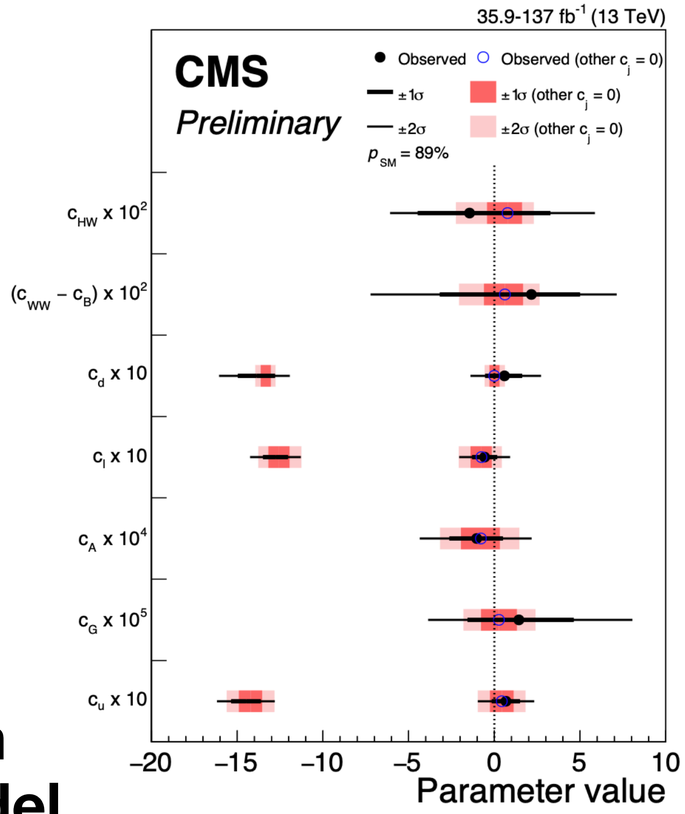
ATLAS-CONF-2021-053







CMS-PAS-HIG-19-005




- Constrain **HEL model parameters $c_i$**

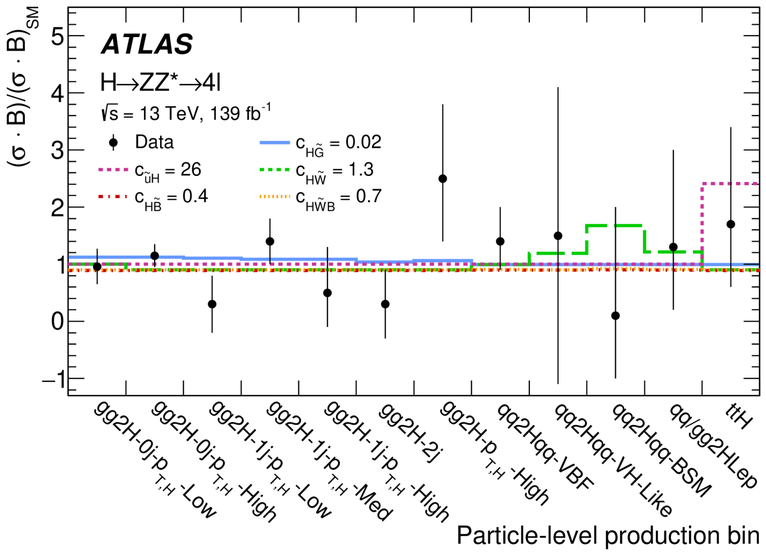
$$\mathcal{L}_{\mathrm{HEL}} = \mathcal{L}_{\mathrm{SM}} + \sum_j \mathcal{O}_j f_j / \Lambda^2$$

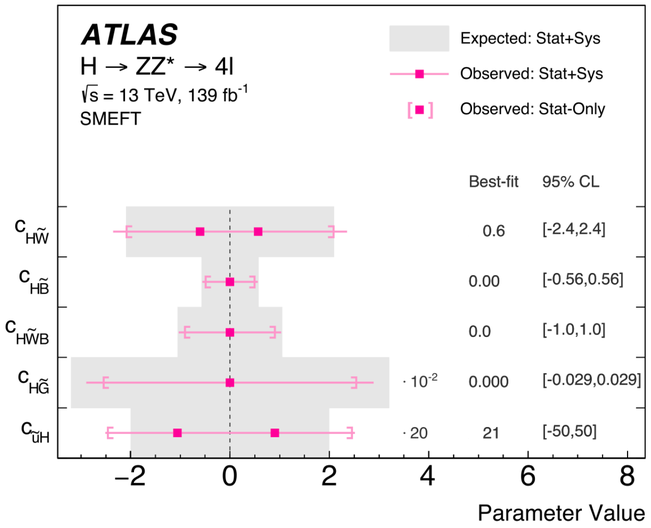
  - related to **Wilson coefficient $f_i$,** where **new physics manifest** in non-zero value

# Anomalous couplings and coupling structure

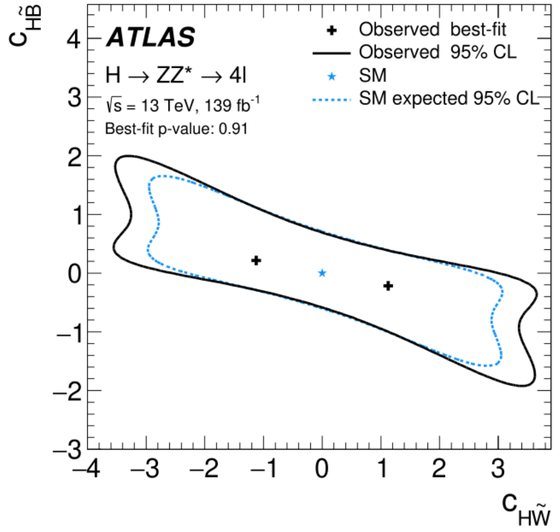
# H→4l anomalous couplings

- Clean selection ideal for probing **anomalous couplings**
- **SMEFT** with **CP odd** Wilson coefficients
  - **fit coupling in certain STXS bins,** parameterise as function of $c_i$
  - **2D limits on coefficients**




Eur. Phys. J. C 80 (2020) 957

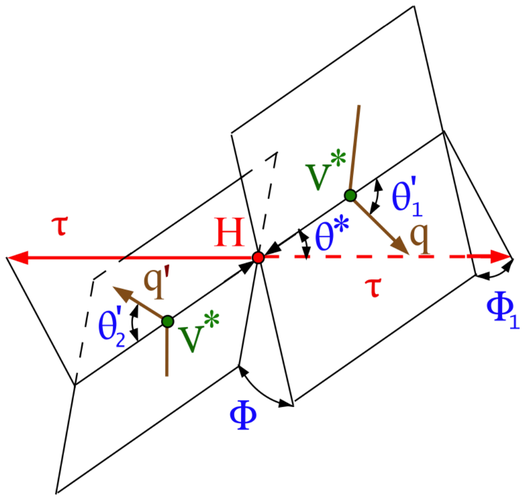


# Anomalous coupling using H→ττ final state

- Sensitivity to **anomalous HVV** (mainly gg,WW, ZZ, Zγ) and **Hff couplings**

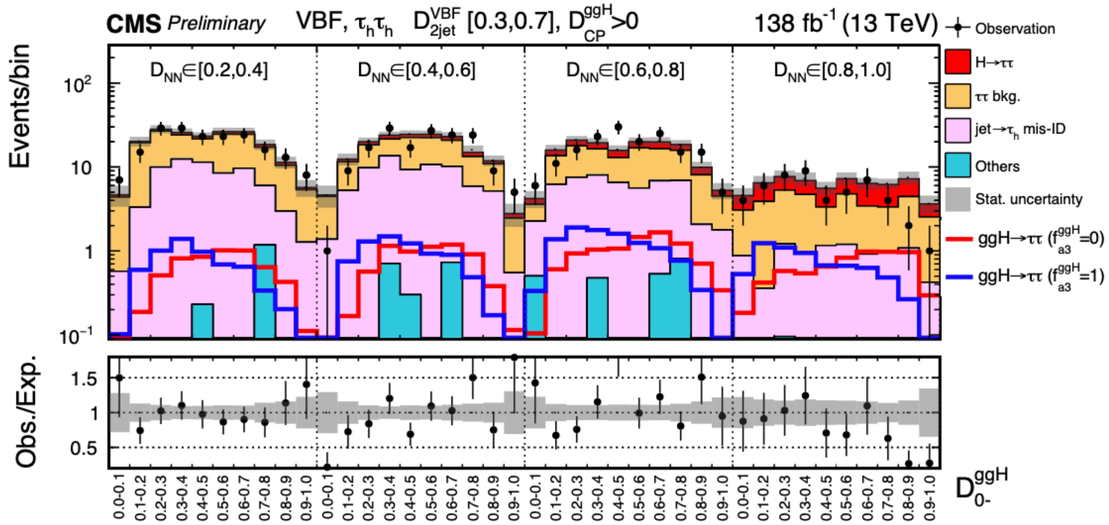
$$\mathcal{A}(\mathrm{HVV}) \sim \left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_1^2 + \kappa_2^{\mathrm{VV}} q_2^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2}\right] m_{\mathrm{V1}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2)\mu\nu} + a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2)\mu\nu} \qquad \mathcal{A}(\mathrm{Hff}) = -\frac{m_f}{v} \bar{\psi}_f \left(\kappa_f + i\tilde{\kappa}_f \gamma_5\right) \psi_f$$

- Using correlation of quark jets and leptons (VBF, VH)
- Correlation of two jets in QCD production (ggF)
- Correlation of quark jets in ttH or tH
- Correlation of the decay products of τs




qq'→qq'H (VBF)

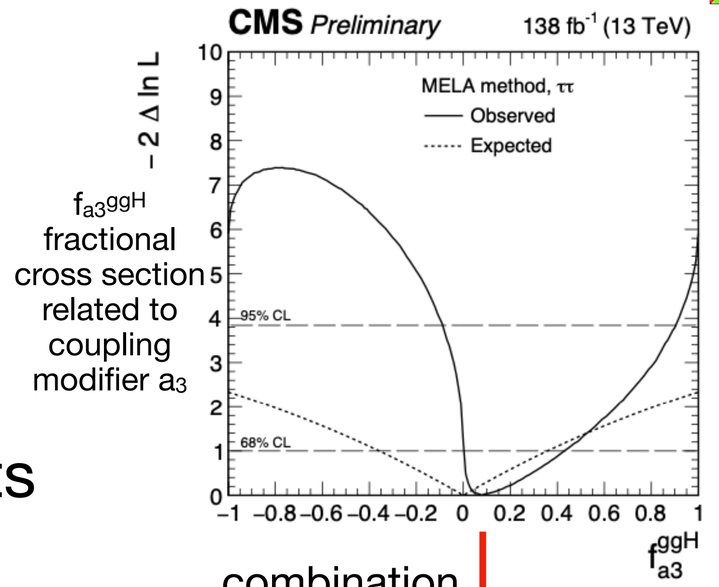
CMS-PAS-HIG-20-007



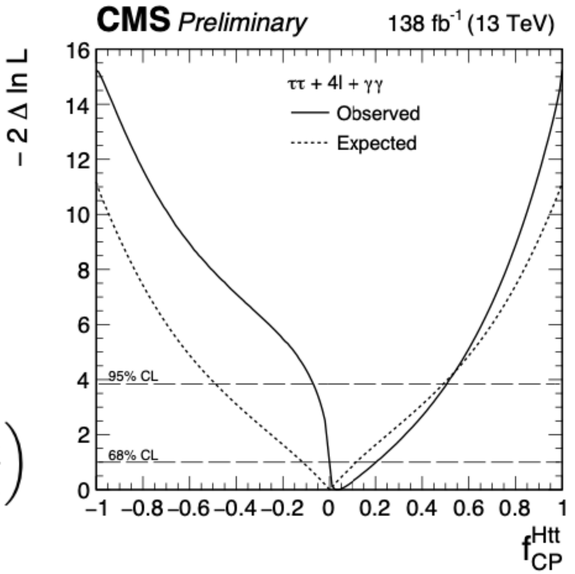
# Anomalous coupling using H→ττ

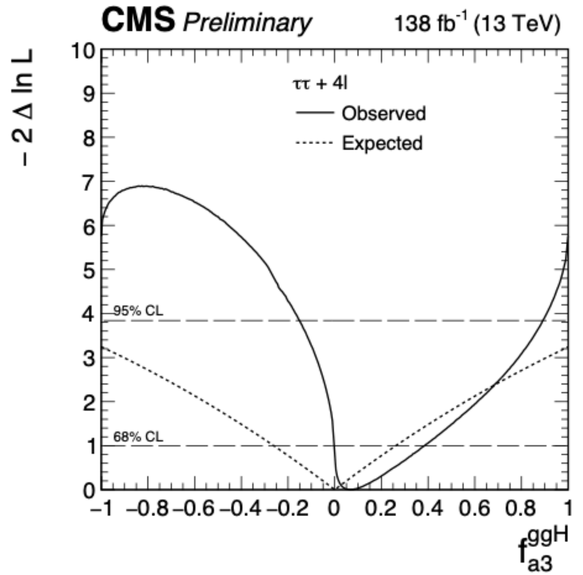
- **Improved** by adding (VBF, VH, ggF→) H→4l and ttH, tH→γγ, 4l channels
  - H→ττ provides larger sample of ggF and VBF events
  - ggH improved by ttH events assuming top quark dominated
- Limits also on **corresponding EFT couplings ggF** in the Higgs basis

$$f_{CP}^{Hff} = \frac{|\tilde{\kappa}_f|^2}{|\kappa_f|^2 + |\tilde{\kappa}_f|^2} \operatorname{sgn}\left(\frac{\tilde{\kappa}_f}{\kappa_f}\right)$$



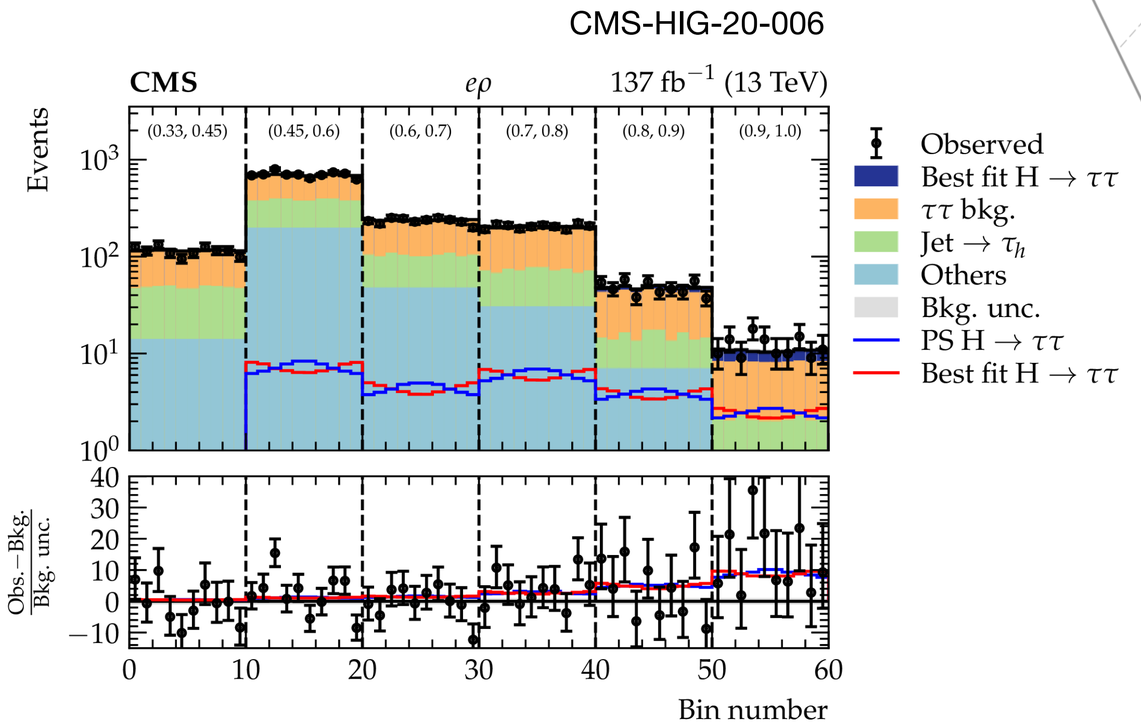

combination

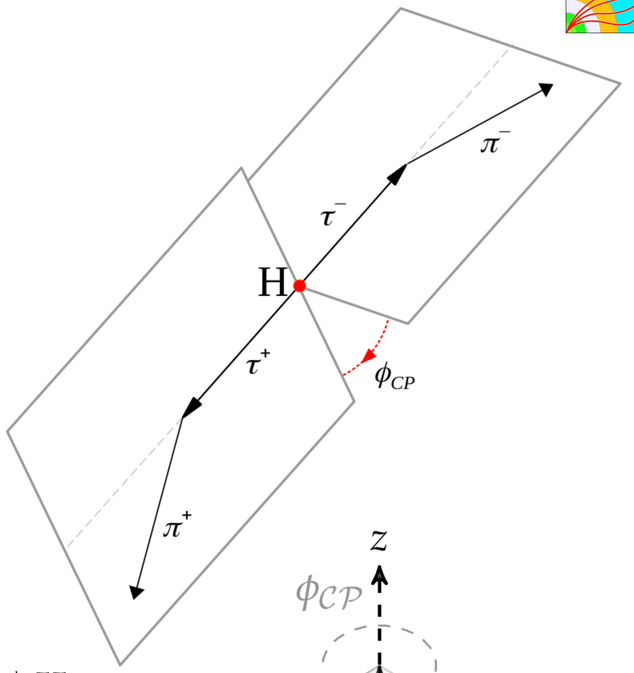


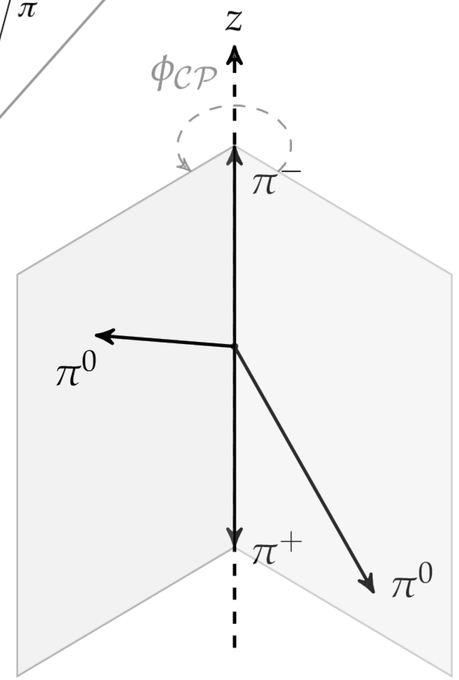



# Hτ CP coupling in H→ττ

- **Measure CP odd/even mixing** in H→ττ **decay**
- use decay modes with at least one had. **τ**
  - decays to $\pi^{\pm}$ or $\pi^0$ (via **ρ**$^{\pm}$ or a$^{\pm}$)
  - construct **decay planes of τ-decay products** and calculate CP sensitive angle $\phi_{CP}$



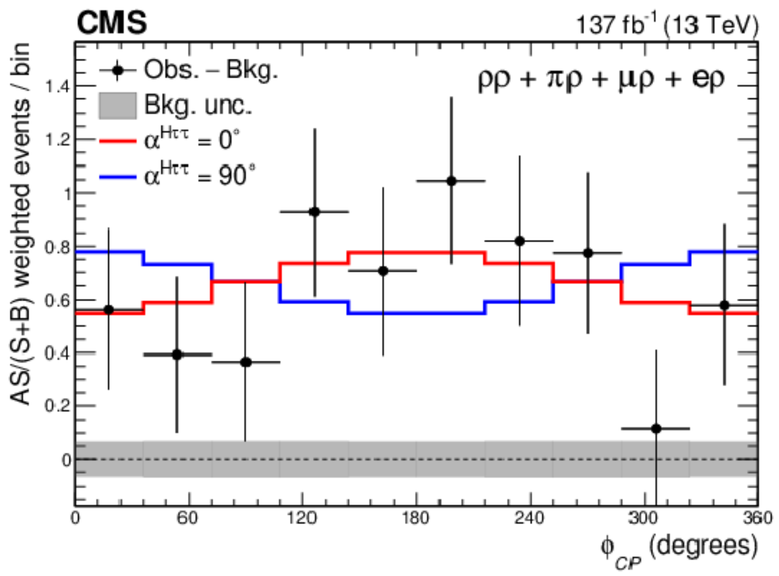



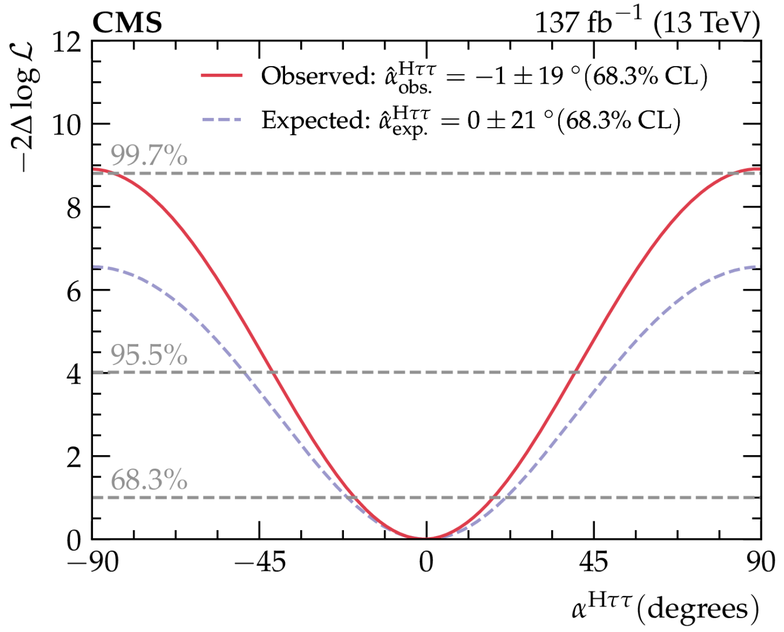



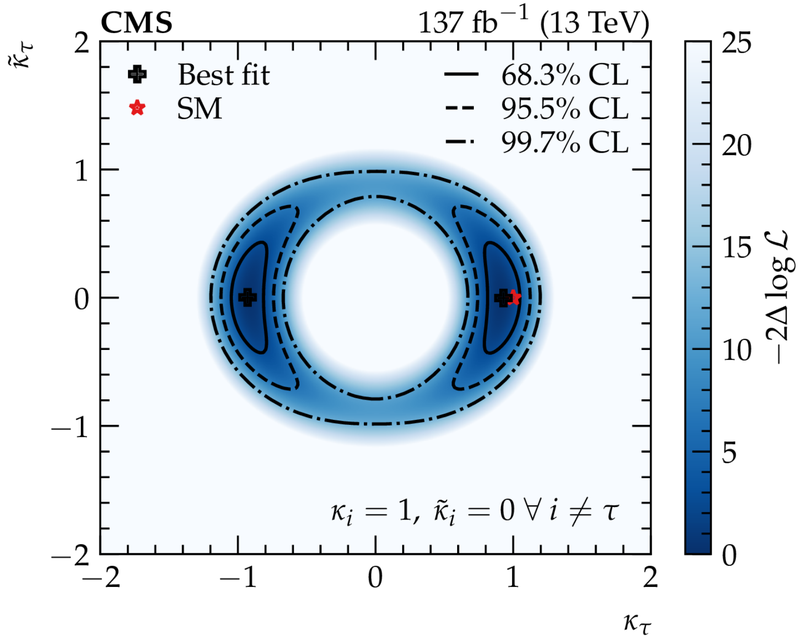
# Hτ CP coupling in H→ττ

- Most **sensitive final state** (μ/e)ρ, ρρ, $\pi\rho$ for $\phi_{CP}$
- Excluded **pseudo scalar hypothesis** $|\alpha^{H\tau\tau}|$=90° at 3.0σ with l**imit** $|\alpha^{H\tau\tau}|$**<41°**
- **2D limit** on CP-even $\kappa_\tau$ - CP-odd ~$\kappa_\tau$ τ-Yukawa coupling

CMS-HIG-20-006



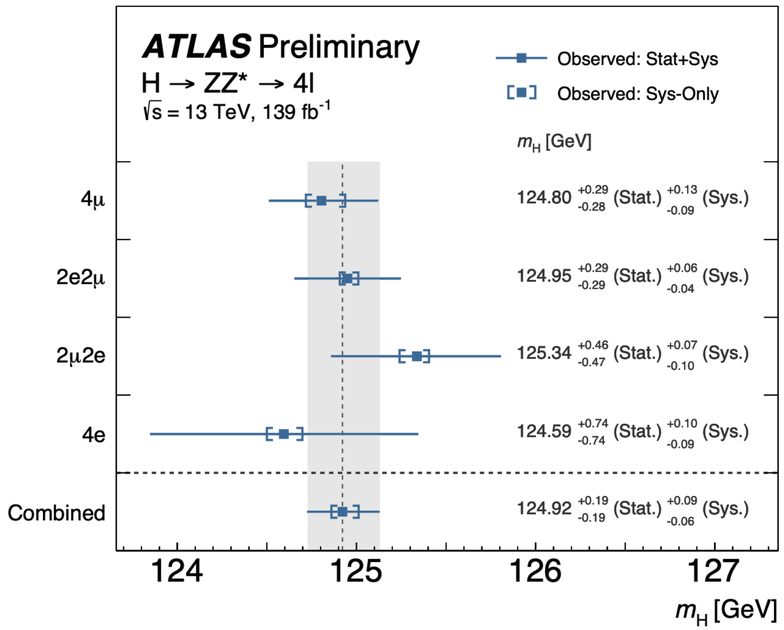



# Properties
# Higgs mass and width

# Higgs mass

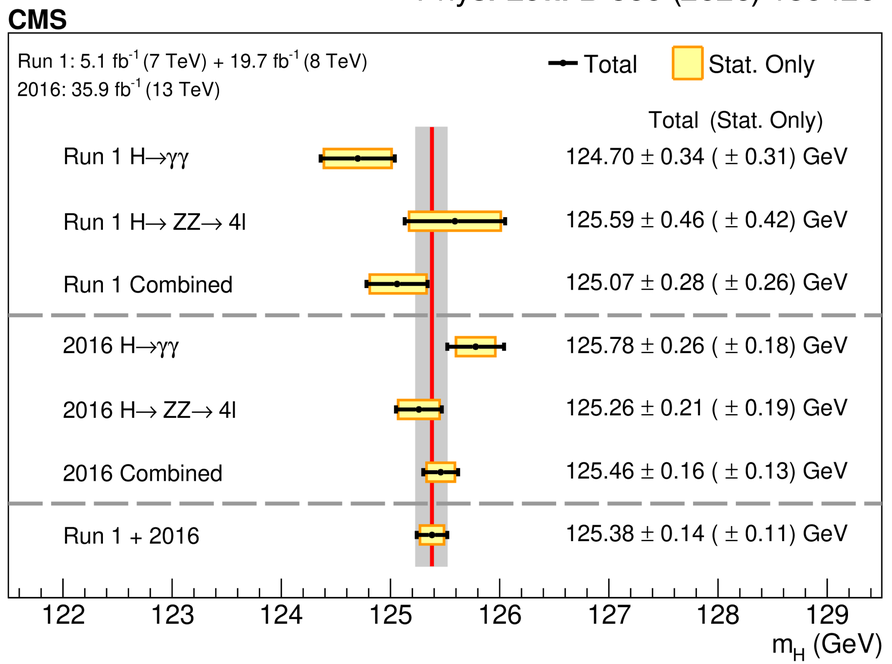
- Mass measurement only in **H→γγ and H→4l** with excellent exp. precision
  - dominated by **stat.** (Run 1+ part. Run 2) and **exp. systematics**: **140 MeV~0.1%**

ATLAS-CONF-2020-005




m(H)=124.92±0.19$^{+0.09}_{-0.06}$ GeV

Phys. Lett. B 805 (2020) 135425

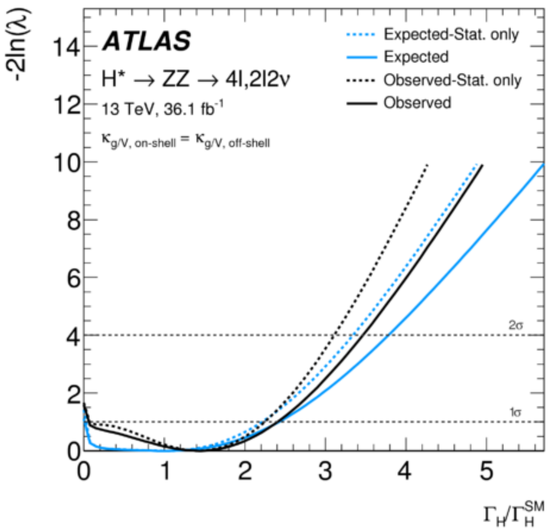



m(H)=125.38±0.14 (0.11) GeV

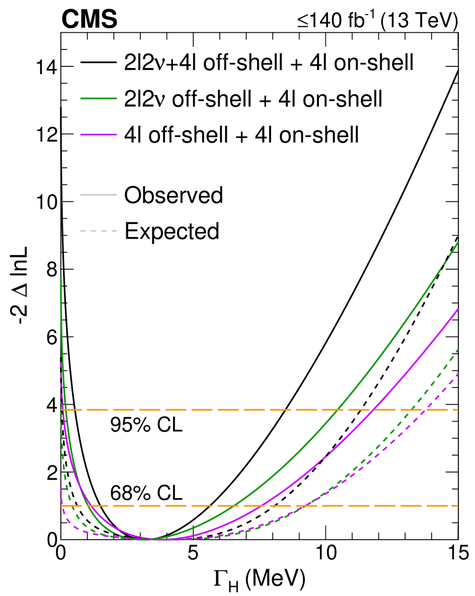
# Higgs width

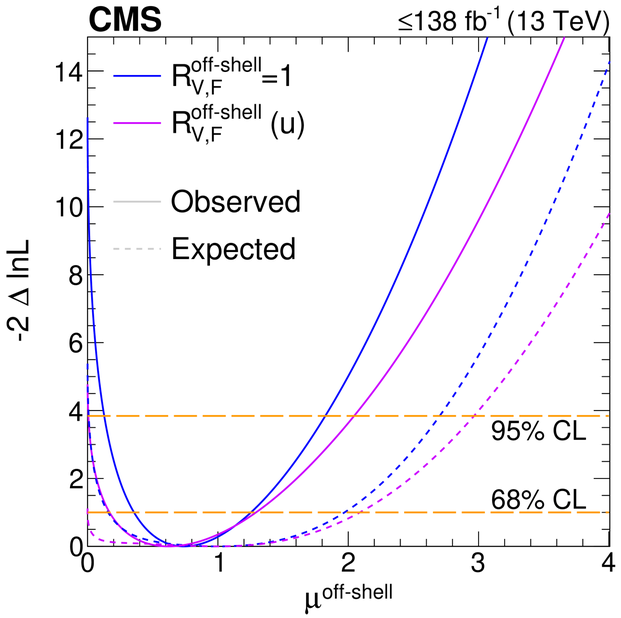
- **Direct** SM width measurement **($\Gamma$=4.1MeV)** experimentally challenging
- Higgs width from **ratio between on-shell and off-shell cross section** in VV (4l, 2l2$\nu$) invariant mass spectrum (assume same signal strength)
- Limit on width
  **$\Gamma$<14.4 MeV (ATLAS 36fb$^{-1}$)**
  **$\Gamma<3.2^{+2.4}_{-1.7}$MeV (CMS)**
- First **evidence for off-shell** H production @ 3.6 $\sigma$
- Also interpretation of anomalous coupling

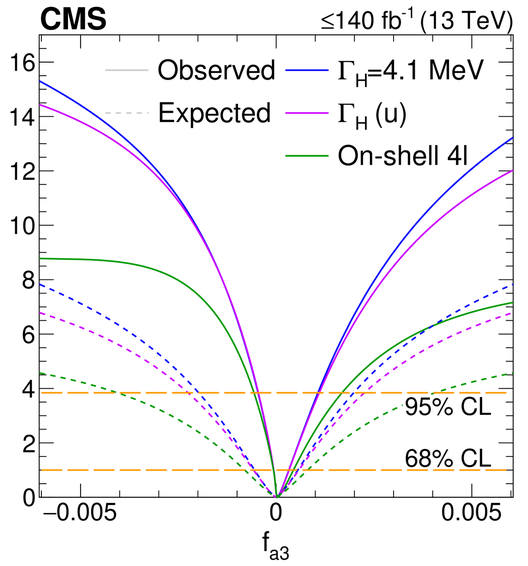
Phys. Lett. B 786 (2018) 223




CMS-HIG-21-013



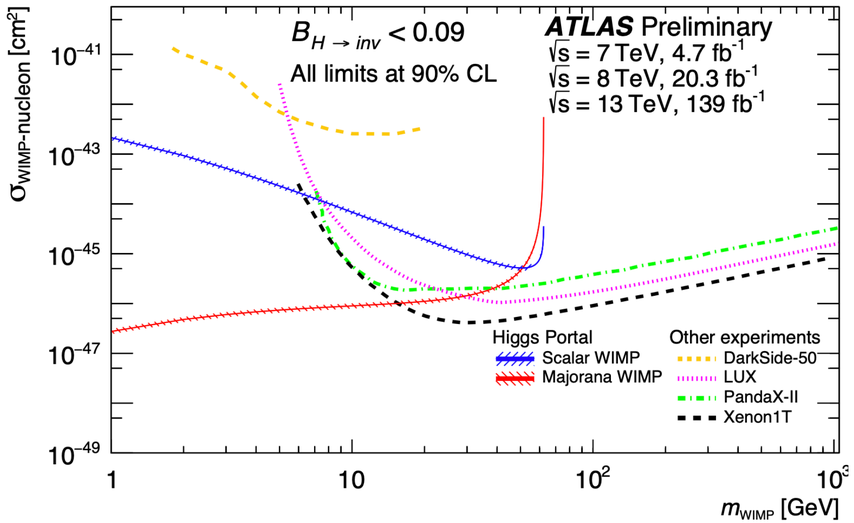



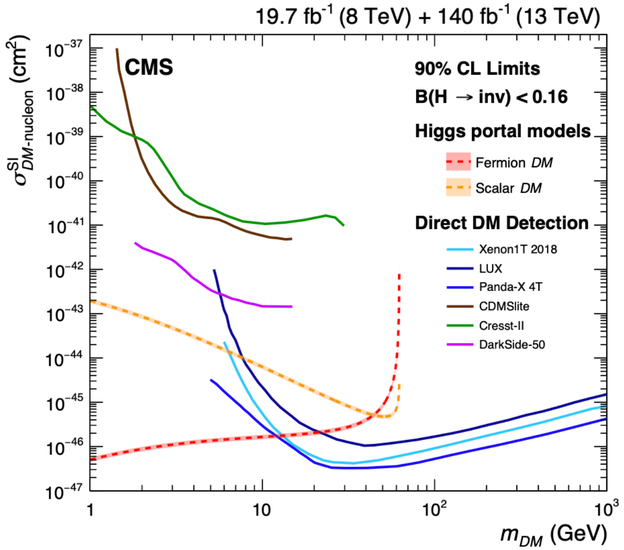
# H→invisible

- **Direct searches** for invisible decay modes instead of summing decay widths and compare with width
  - ATLAS: VBF+MET and ttH+MET **BR(H→inv)<0.11 (0.11)**
  - CMS: VBF-like (high m(jj)) + MET **BR(H→inv)<0.17 (0.11)**

ATLAS-CONF-2020-052




CMS-HIG-20-003



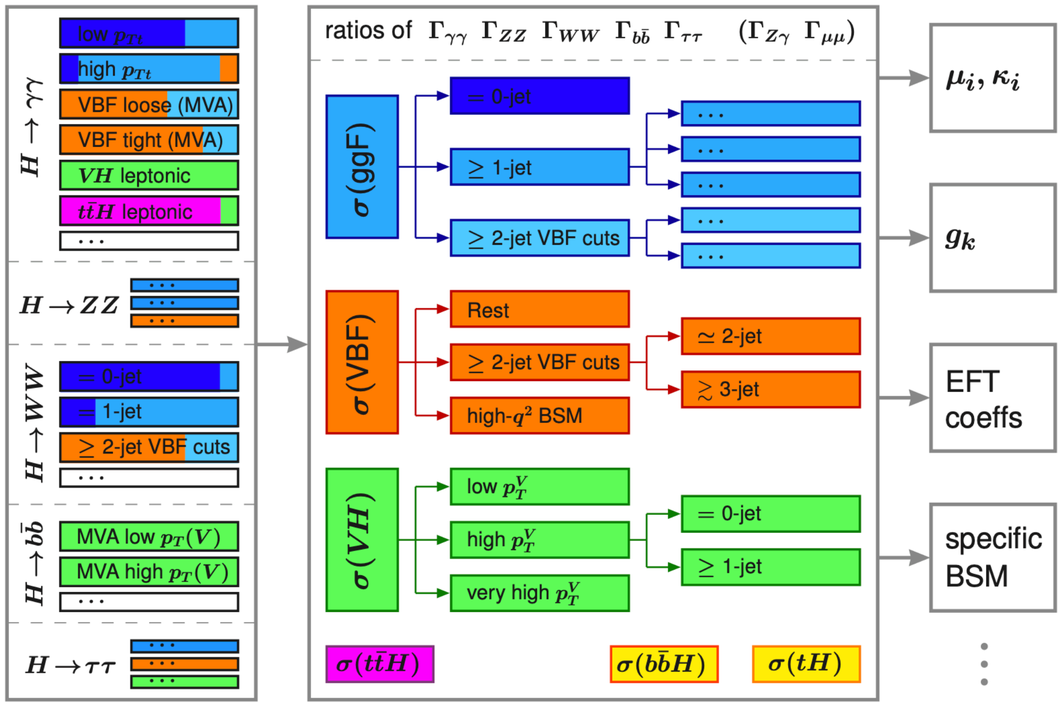
# Summary

- With full **LHC Run 2 dataset ATLAS and CMS** measured cross section in various final states
  - access to **major production** channels, also ttH+tH
  - access to **rarer decay modes** cc→μμ→Zγ→quarkonia (see earlier talk)
- Probing **coupling strength and structure in production and decay**
  - **STXS framework** allows combination and re-interpretation of results in different models
  - working towards more **differential measurements**
  - **Updated combination** expected
- While mass precisely measured already, going for (indirect) **SM width measurement**
- Still **more full Run2 results** to come while **LHC is restarting spring 2022** with CME=13.6GeV and total (Run 1-3) L=350-450fb$^{-1}$

# Backup

# Cross section STXS measurement

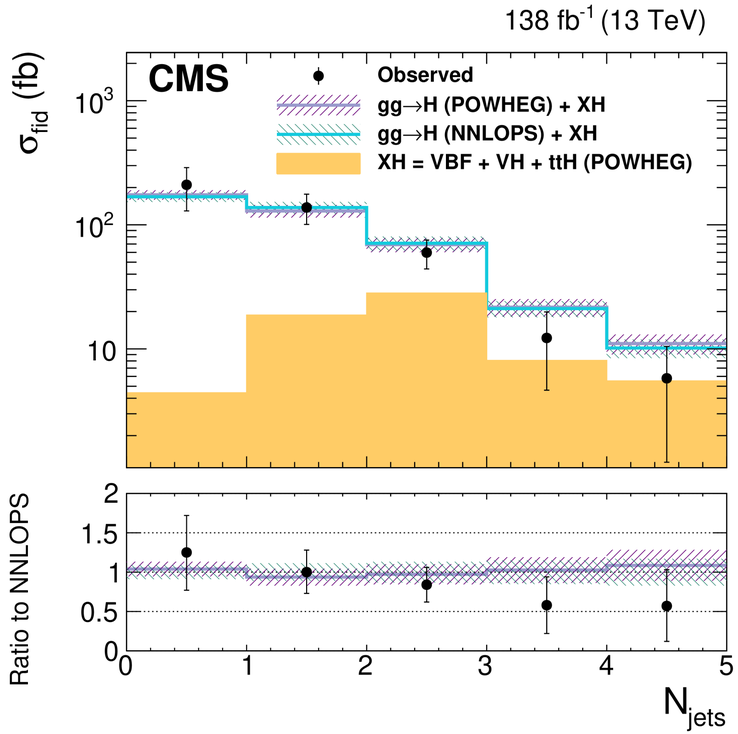
- Approach between inclusive and differential measurement
  - **split Higgs production modes** in gen-level bins in pT(H,V,Hjj,j), N(jets), m(jj) = **STXS bin**
  - acceptance in each bin only weakly depending on SM kinematics, proxy for true properties
- **Advantages**
  - minimize simultaneously experimental and theoretical uncertainties
  - allow re-interpretation of results in different models
  - isolation of possible BSM effects
- **Staging granularity** as statistics progresses
  - merging bins for less sensitive regions

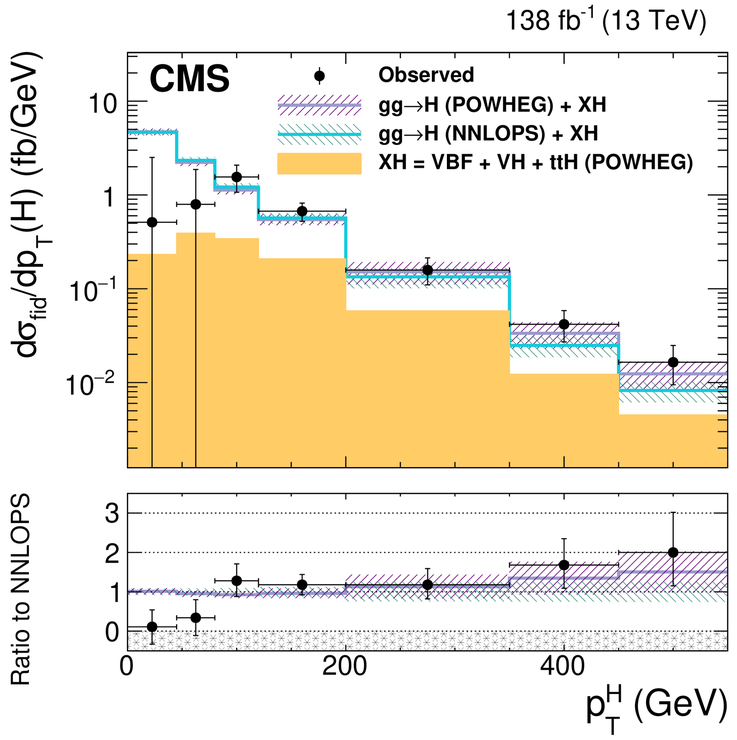


# H→ττ differential and fiducial

- Differential distributions N(jet), pT(H) and pT(j1), in agreement with SM (pT(H) >120 GeV)
- Fiducial cross section also in agreement with SM

HIG-20-015

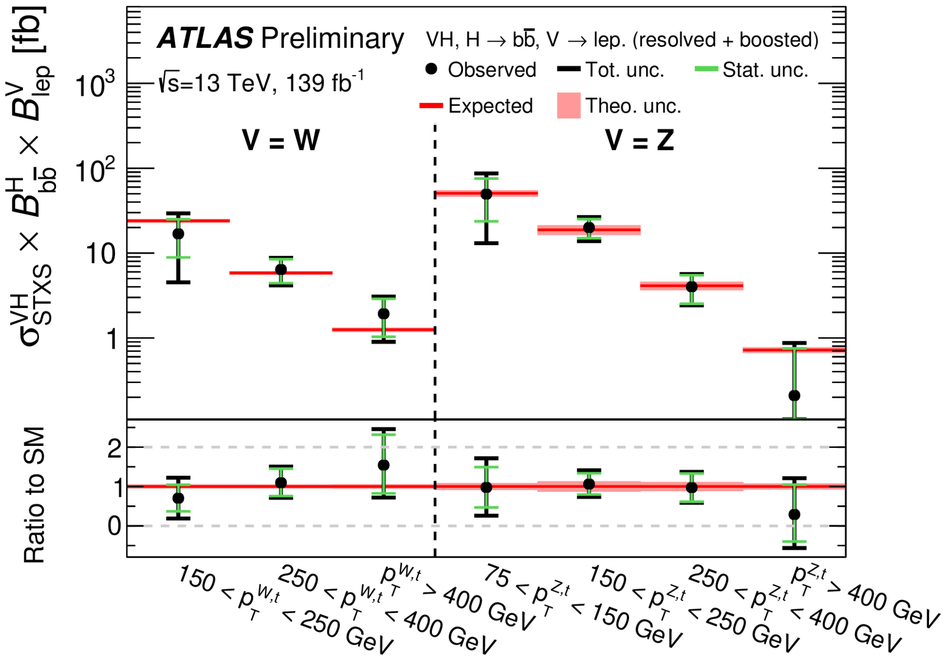


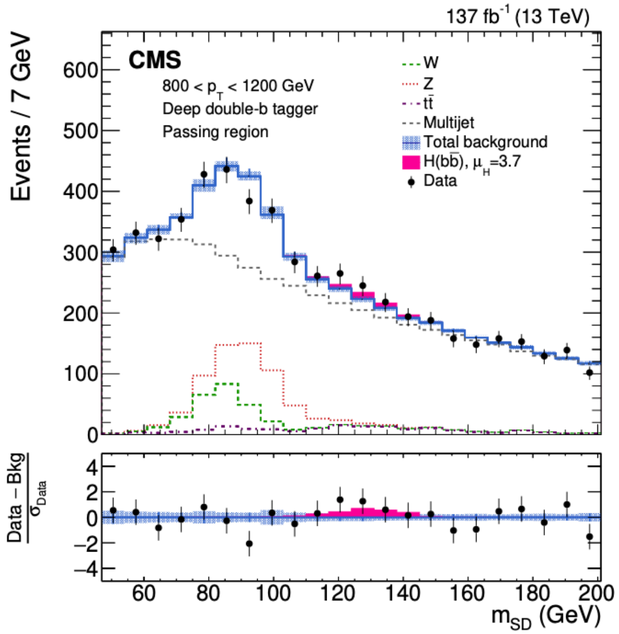



# H→bb

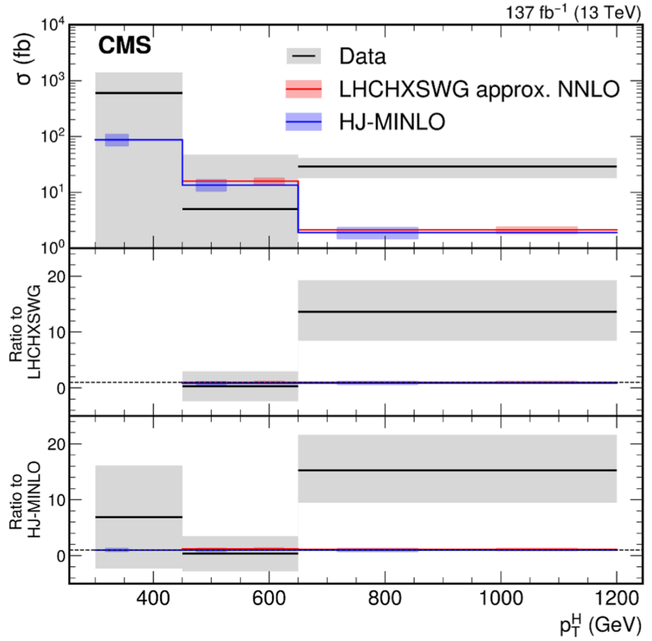
- Has been **challenging channel**, search in various production modes VBF bb, VBF bbγ, ttH bb, VH bb merged + boosted (pT(V) > 250GeV)
- Measurements in VH channel start to separate W and Z and become **systematically** limited

ATLAS-CONF-2021-051



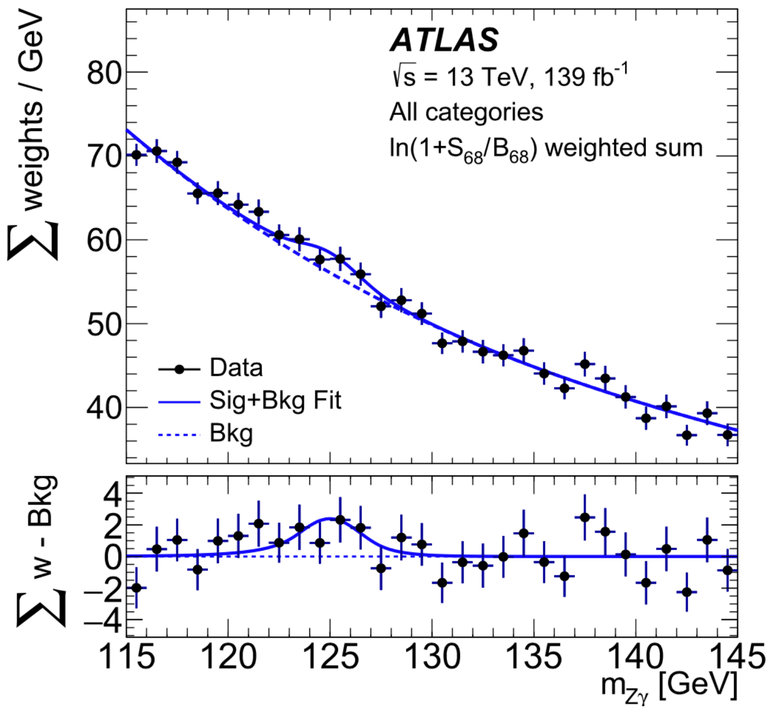

JHEP 12 (2020) 085



# H→Zγ

- Interactions HWW, HZZ, Hγγ and HZγ are related in $SU(2)_L$
- Mass reconstructed in di-lepton final state with additional photon
- Measured **signal strength μ** and **branching ratio** to H→γγ in agreement with SM
- Similar expected significance (1.2$\sigma$)
- **μ=2.0±0.9 @ 2.2$\sigma$ ATLAS**
  **μ=2.4±0.9 @ 2.7$\sigma$ CMS**

Phys. Lett. B 809 (2020) 135754

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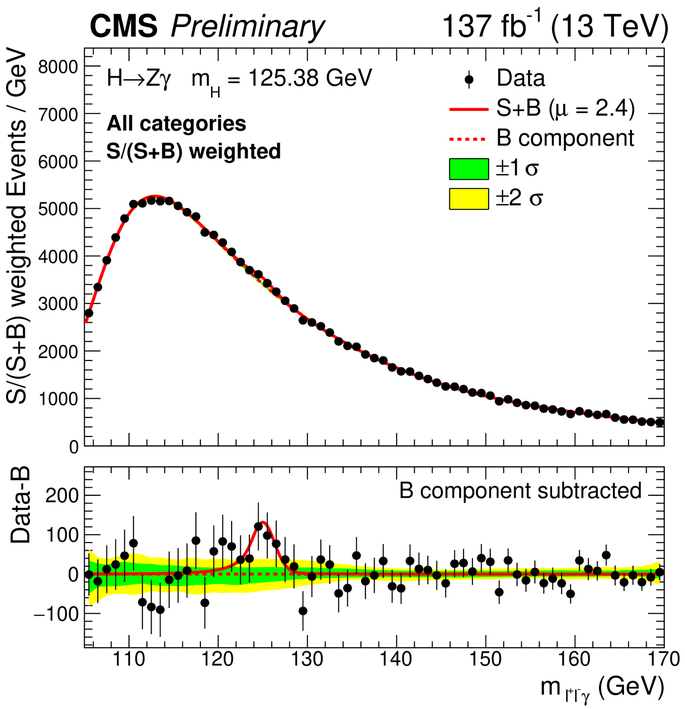
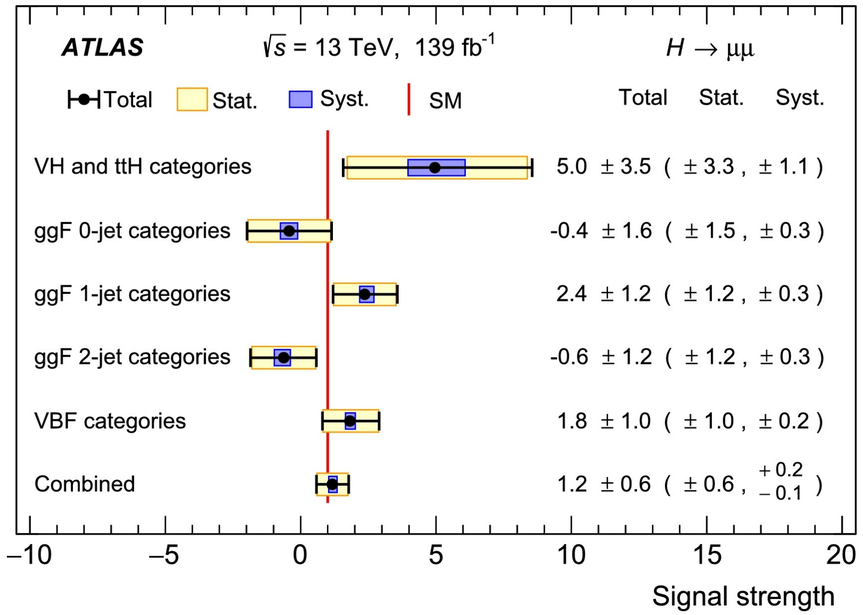


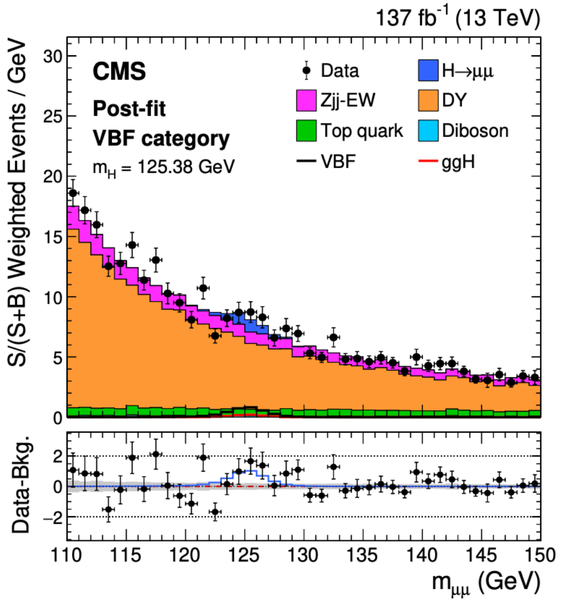
# H→μμ

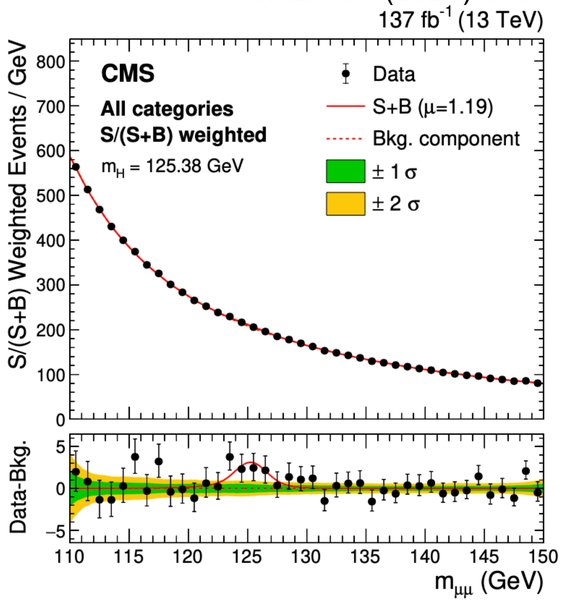
- Starting to probe **“rare” decays** with BR~2x10$^{-4}$ and large DY background (S/B ~0.1%)
- Evidence in CMS, STXS categories with large uncertainties
  - **μ=1.2±0.4 @ 3.0$\sigma$ (2.5$\sigma$) CMS and μ=1.2±0.6 @ 2.0$\sigma$ (1.7$\sigma$) ATLAS**
- Improvements in m(μμ), DY modelling and selection needed

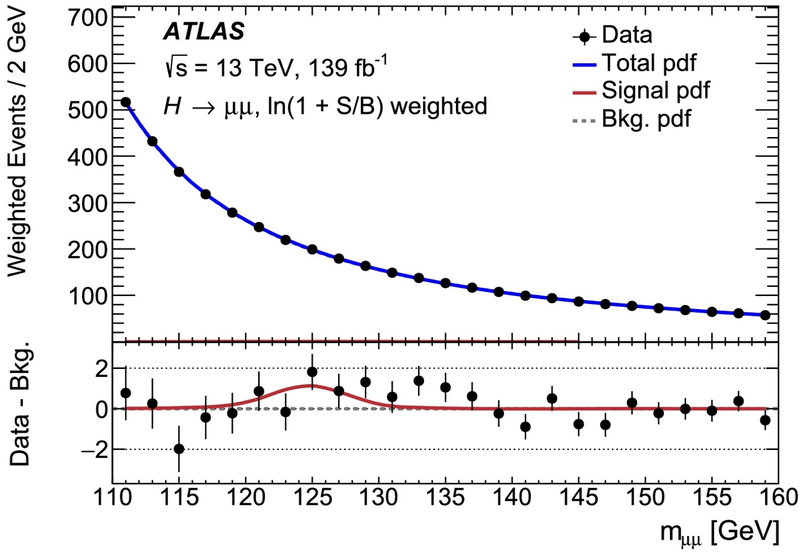
PLB 812 (2021) 135980




JHEP 01 (2021) 148

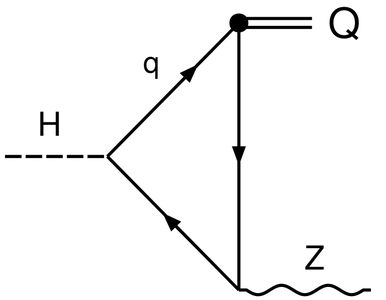


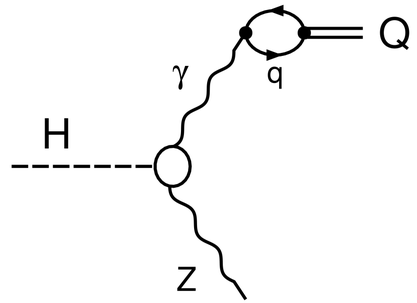



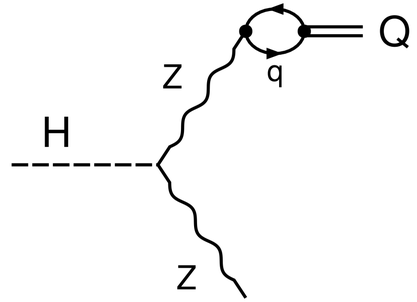
# H→quarkonia

CMS-HIG-20-008

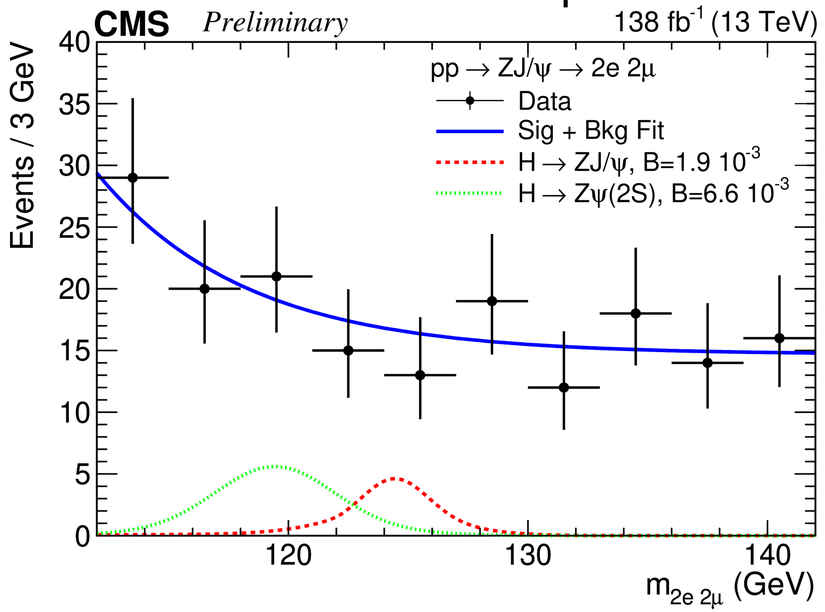



- Rare SM decays to **light-quark resonances**: Z J/ψ, J/ψ J/ψ, ϒϒ
- BR~$10^{-6}$, possibly larger with new physics (in loops)
- Leptonic final states: **BR<826 SM and BR<5.8 SM**

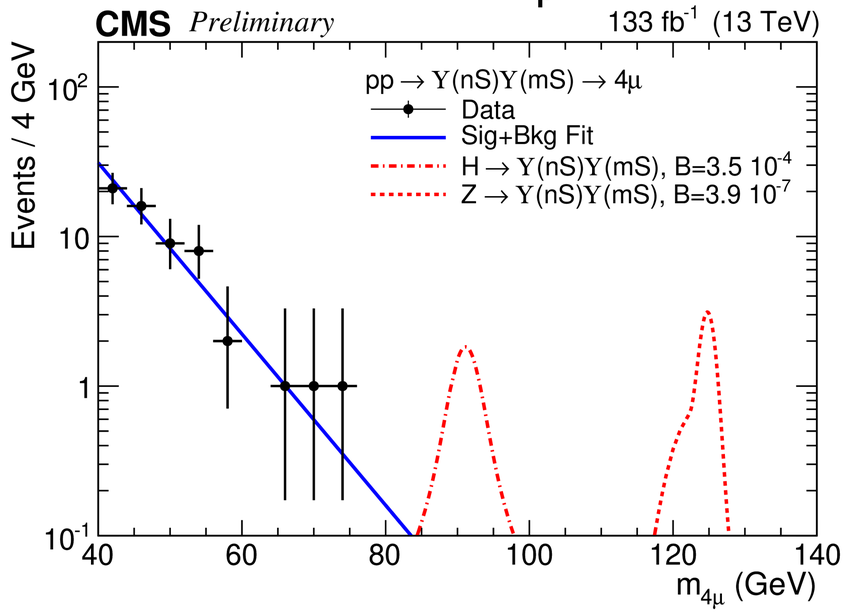



Z J/ψ→2e2μ




ϒϒ →4μ



# ATLAS combination input

| Decay channel | Target Production Modes | $\mathcal{L}$ [fb$^{-1}$] | Ref. | Used in combined measurement |
|---|---|---|---|---|
| $H \to \gamma\gamma$ | ggF, VBF, $WH, ZH, t\bar{t}H, tH$ | 139 | [10] | Everywhere |
| $H \to ZZ^*$ | ggF, VBF, $WH, ZH, t\bar{t}H(4\ell)$ | 139 | [11] | Everywhere |
| | $t\bar{t}H$ | 36.1 | [19] | Everywhere but STXS and SMEFT |
| $H \to WW^*$ | ggF, VBF | 139 | [12] | Everywhere |
| | $t\bar{t}H$ | 36.1 | [19] | Everywhere but STXS and SMEFT |
| $H \to \tau\tau$ | ggF, VBF, $WH, ZH, t\bar{t}H(\tau_{\text{had}}\tau_{\text{had}})$ | 139 | [13] | Everywhere |
| | $t\bar{t}H$ | 36.1 | [19] | Everywhere but STXS and SMEFT |
| $H \to b\bar{b}$ | $WH, ZH$ | 139 | [14–16] | Everywhere |
| | VBF | 126 | [17] | Everywhere |
| | $t\bar{t}H$ | 139 | [18] | Everywhere |
| $H \to \mu\mu$ | ggF, VBF, $VH, t\bar{t}H$ | 139 | [20] | Everywhere but STXS and SMEFT |
| $H \to Z\gamma$ | ggF, VBF, $VH, t\bar{t}H$ | 139 | [21] | Everywhere but STXS and SMEFT |
| $H \to inv$ | VBF | 139 | [22] | Sec. 6.3 & 6.5 |