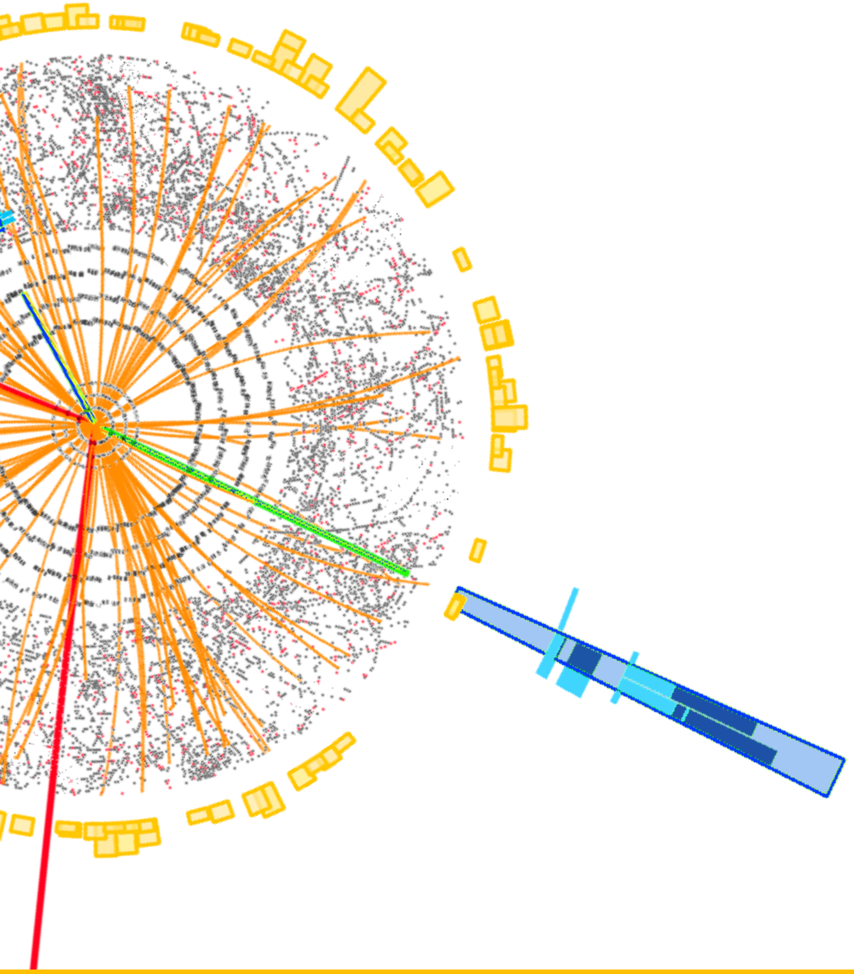


Higgs couplings and properties: current status

Alessia Murrone on behalf of the ATLAS and CMS collaborations

INFN Milano

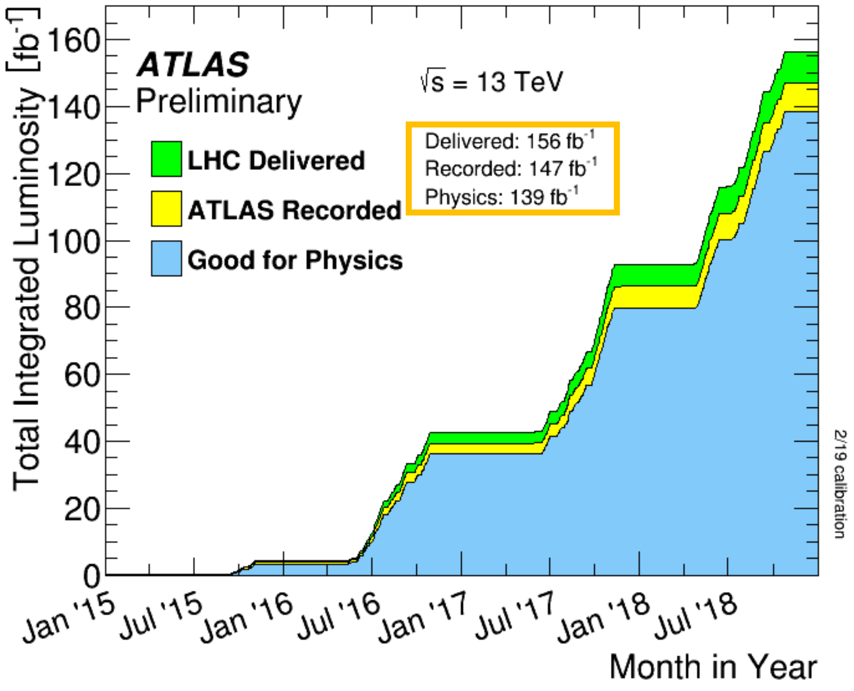
SM@LHC 2021, 26/04/2021

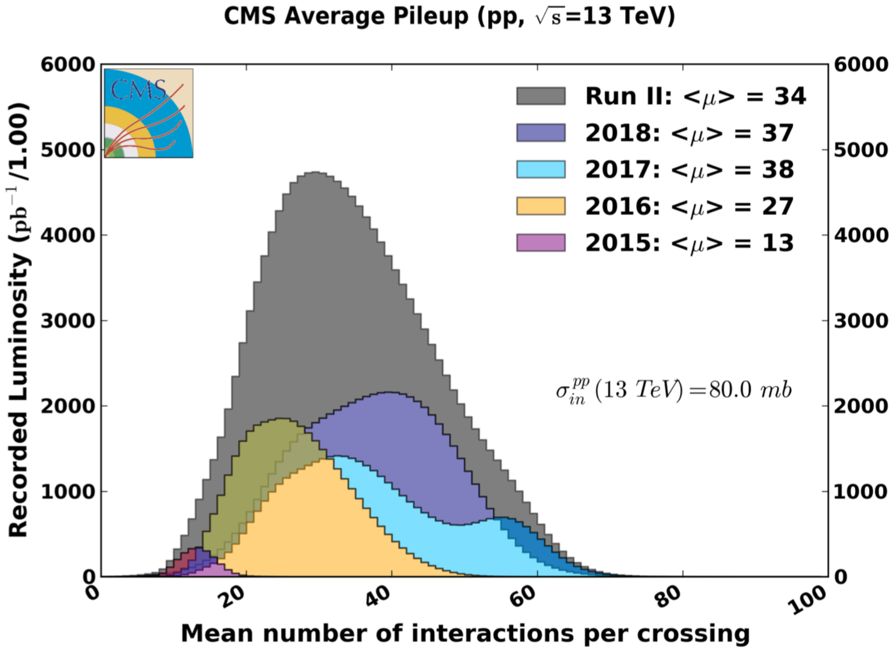
Outline

- **Couplings and cross sections measurements**
  - Combined measurements (CMS, ATLAS)
  - $H \to \gamma\gamma$ (CMS, ATLAS)
  - $V(H \to WW^*)$ (CMS)
  - $H \to WW^*$ (ATLAS)
  - $V(H \to b\bar{b})$ (ATLAS)
  - $H \to \tau\tau$ (CMS, ATLAS)
- **Mass measurements**
  - $H \to ZZ^*, H \to \gamma\gamma$ (CMS, ATLAS)
- **CP measurements**
  - ggH (CMS, ATLAS)
  - HVV in VBF production (CMS, ATLAS)
  - $H \to \tau\tau$ (CMS)
- Not covered by this talk:
  - $H \to ZZ^* \to 4l$ (backup)
  - $H \to b\bar{b}$ (backup)
  - CP structure of $t\bar{t}H$ → see talk by T. Strebler (backup)
  - $t\bar{t}H$ → see talk by T. Strebler
  - EFT interpretations → see talk by T. Calvet (backup)
  - Double Higgs production → see talk by F. Monti
  - Rare decays ($H \to \mu\mu, H \to Z\gamma, H \to c\bar{c}$) → see talk by S. Donato
  - STXS vs fully fiducial measurements → see talk by N. Berger
  - Differential cross sections measurements → see talk by F. Alves

Introduction

- Since the Higgs discovery in 2012 we have performed more and more precise measurements
- Focus on measuring the Higgs properties looking for confirmation of the SM or any possible sign of new physics
- LHC Run 2 finished in 2018 collecting 140 fb^{-1} per experiment at $\sqrt{s} = 13$ TeV → excellent performance of LHC!

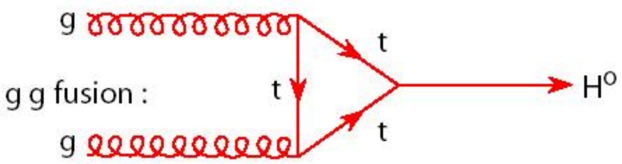




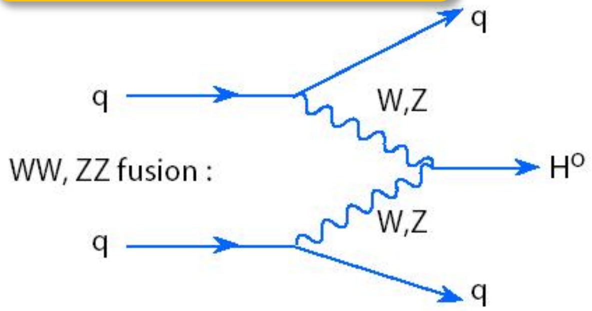
Higgs production and decays

Main production processes at the LHC (cross sections at $\sqrt{s} = 13$ TeV for $m_H = 125$ GeV)

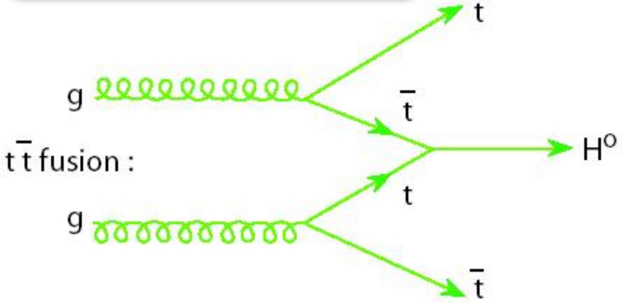
$\sigma_{ggF} = 48.6 \pm 2.4$ pb



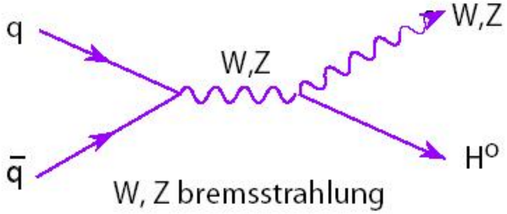
$\sigma_{VBF} = 3.78 \pm 0.08$ pb



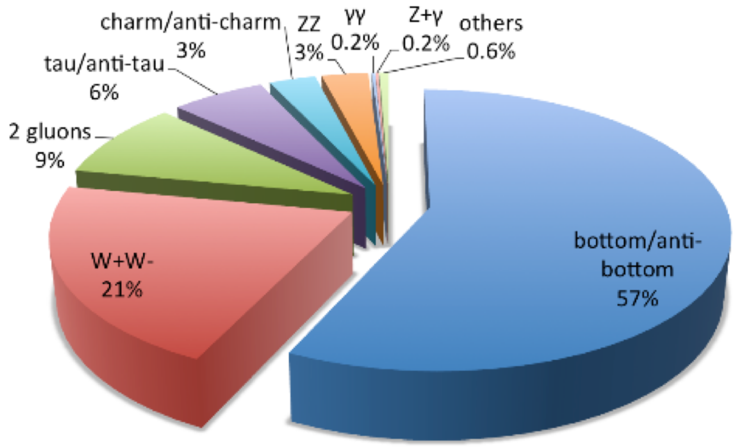
$\sigma_{t\bar{t}H} = 0.51^{+0.03}_{-0.05}$ pb



$\sigma_{WH} = 1.37 \pm 0.03$ pb
$\sigma_{ZH} = 0.88^{+0.04}_{-0.03}$ pb



LHCHXSWG



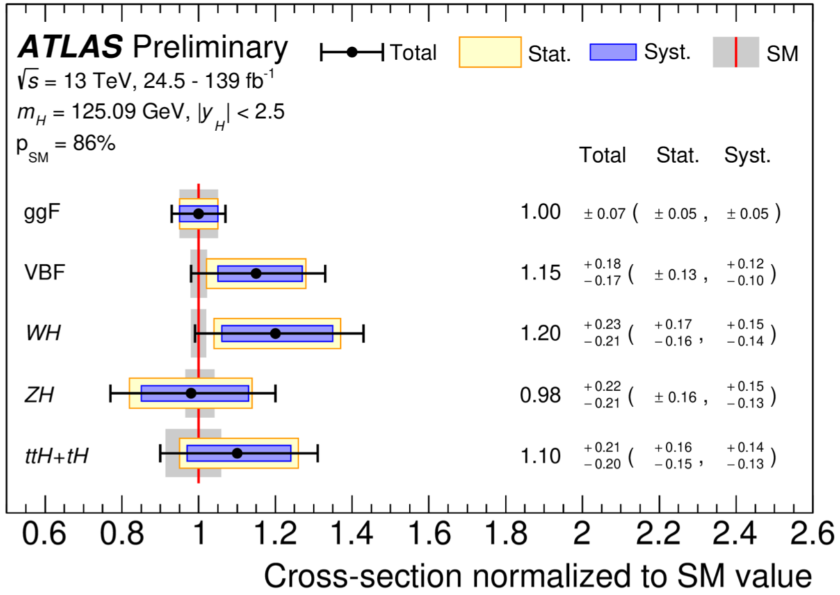
- Large BR for $\boldsymbol{H \to b\bar{b}, H \to WW^*}$ and $\boldsymbol{H \to \tau\tau}$, however more challenging channels: poor mass resolution, background contamination and jets tagging for $H \to b\bar{b}$
- Small BR for $\boldsymbol{H \to ZZ^*}$ and $\boldsymbol{H \to \gamma\gamma}$, however cleaner channels with high mass resolution

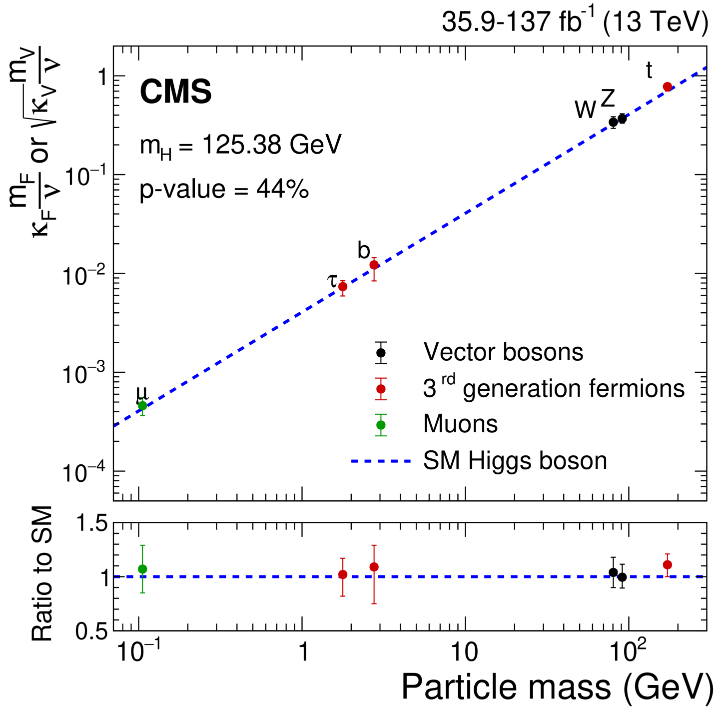
Higgs couplings and cross section measurements

Status

Observation during Run 2
Evidence during Run 2

- **Observation** of all main **production processes** (ggF, VBF, $\boldsymbol{WH}, \boldsymbol{ZH}$ and $\boldsymbol{t\bar{t}H}$)
- **Observation** of most of the **bosonic** and all main **fermionic decay modes** ($H \rightarrow ZZ^*$, $H \rightarrow \gamma\gamma$, $H \rightarrow WW^*$, $\boldsymbol{H \rightarrow b\bar{b}}$, $\boldsymbol{H \rightarrow \tau\tau}$)
- **Evidence for $\boldsymbol{H \rightarrow \mu\mu}$** by CMS experiment
- All measurements in **agreement with the SM predictions**





JHEP 01 (2021) 148

- Results from ATLAS and CMS combined measurement using $H \rightarrow ZZ^*$, $H \rightarrow \gamma\gamma$, $H \rightarrow WW^*$, $H \rightarrow b\bar{b}$, $H \rightarrow \tau\tau$ (ATLAS-CONF-2020-027, Eur. Phys. J. C 79 (2019) 421)

$$\mu_{if} = \frac{\sigma_i \times B_f}{\sigma_i^{SM} \times B_f^{SM}}$$

$$\mu = 1.06 \pm 0.04\,(\text{stat.}) \pm 0.03(\text{exp. syst.})^{+0.05}_{-0.04}(\text{sig. th.}) \pm 0.02(\text{bkg th.})$$

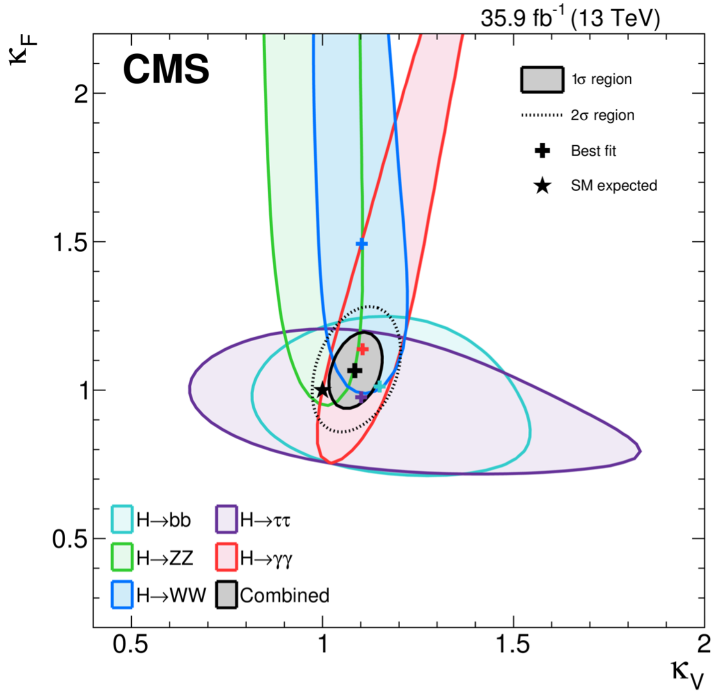
- **Global signal strength** from ATLAS combined measurement
- Experimental systematic and theory uncertainties comparable to statistical ones

k-framework

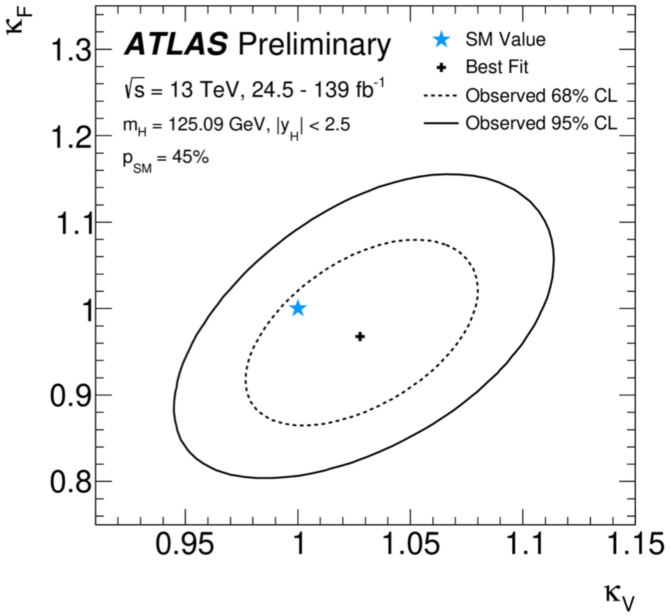
- **Coupling strength modifiers** introduced to study possible deviations of Higgs couplings from SM
- Use common coupling modifiers for bosons and fermions → k_V, k_F

$$(\sigma_i \times B_f) = k_i^2 \sigma_i^{SM} \frac{k_f^2 \Gamma_f^{SM}}{k_H^2 \Gamma_H^{SM}}$$

i, f → production mode, Higgs decay final state
SM → SM expectation
Γ_H → total Higgs width



Eur. Phys. J. C 79 (2019) 421



ATLAS-CONF-2020-027

CMS

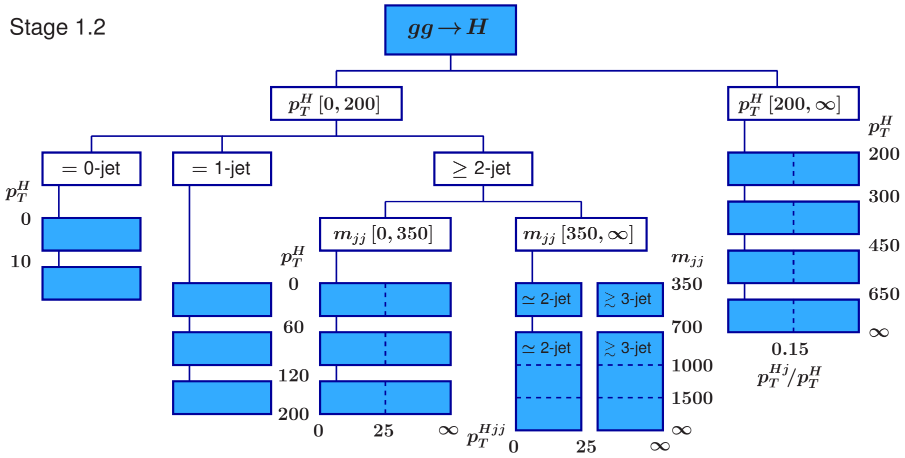
- Analysis with 36 fb^{-1}
- Results compatible with the SM prediction within the 2σ region

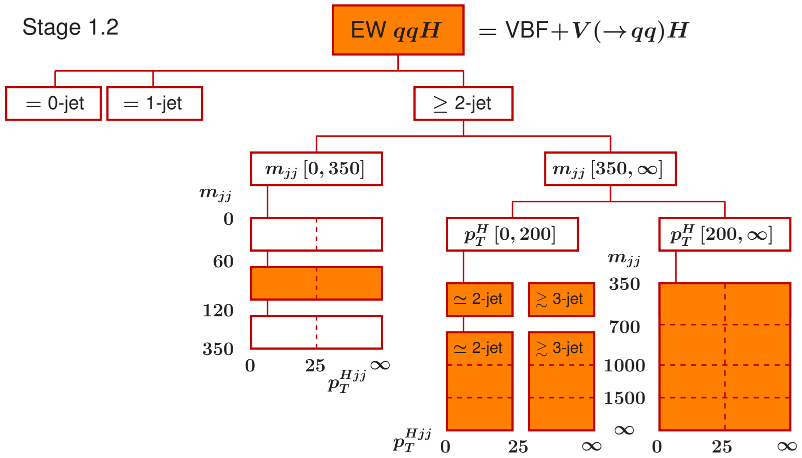
ATLAS

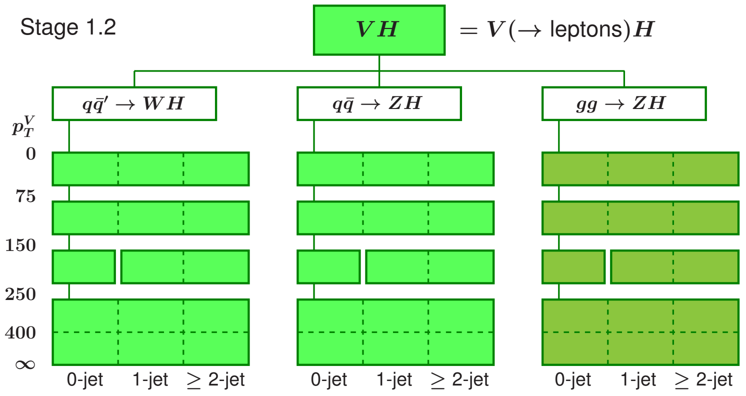
- Partial or full Run 2 statistics according to the decay channel
- Results compatible with the SM prediction within the 68% C.L.
- Level of compatibility with the SM hypothesis corresponds to p-value $p_{SM} = 45\%$

Simplified Template Cross Sections (STXS)

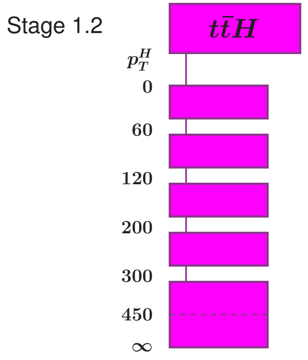
Stage 1.2







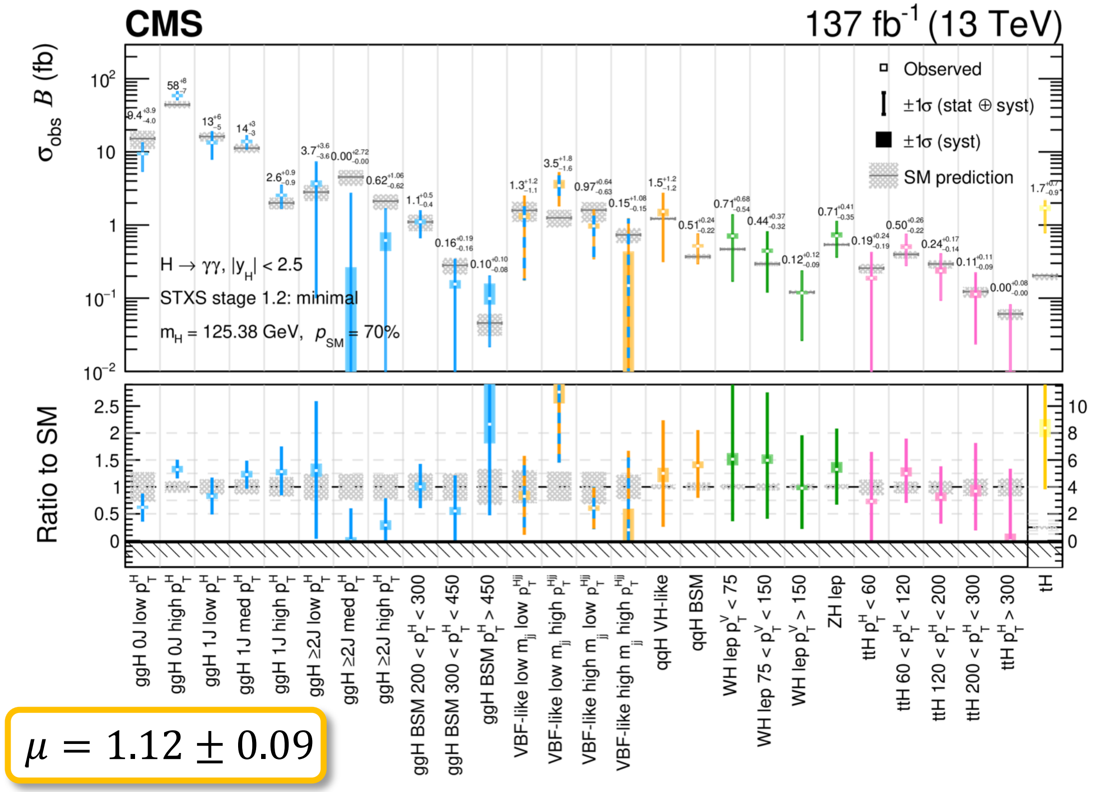
- From signal strength/total cross sections to **simplified template cross sections** measurements
- Cross sections measured separately for different production modes in **mutually exclusive kinematic regions** → identified using variables like $p_T^H, N_{jets}, m_{jj}, p_T^V$
- **Less model-dependent** measurements and minimization of theory uncertainties impact
- **No dependency on the Higgs decay channel** → makes the combination easier
- Maximization of experimental sensitivity
- Isolate possible BSM effects
- Used different granularity depending on channel sensitivity



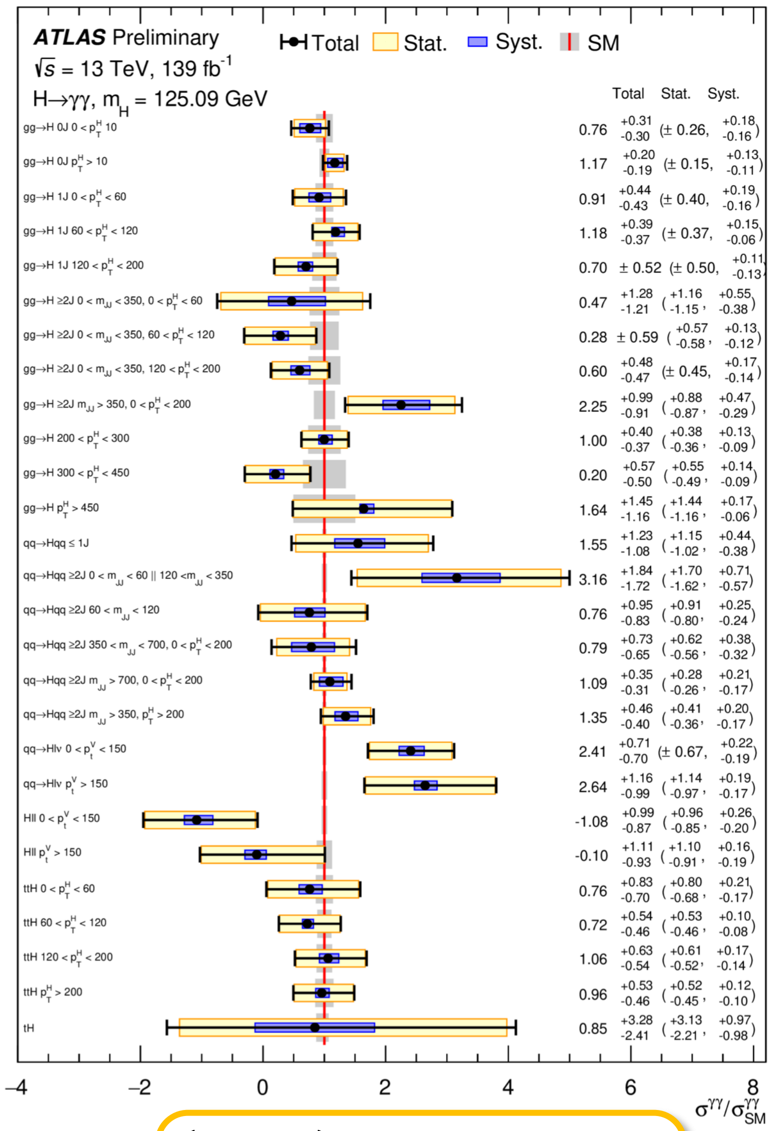
ATLAS-CONF-2020-026

$H \to \gamma\gamma$

CMS-HIG-19-015



$\mu = 1.12 \pm 0.09$



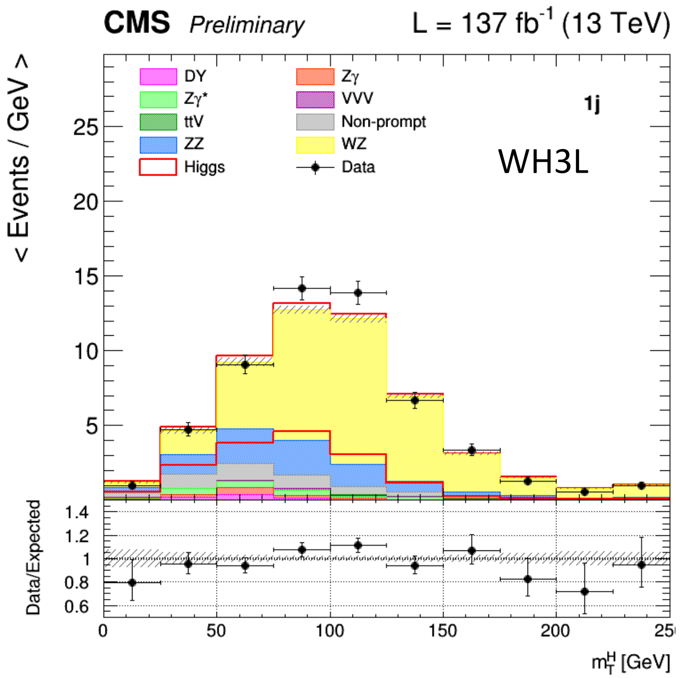
- Cross section measured in 27 kinematic regions
- Extensive use of Machine Learning techniques in both analyses
  - **Multiclass BDT** is used for separating events in different STXS bins, then a binary BDT is trained to improve separation of signal from background events (CMS also uses Deep Neural Networks)
- Dominated by statistical uncertainties but **results in agreement with the SM** expectations

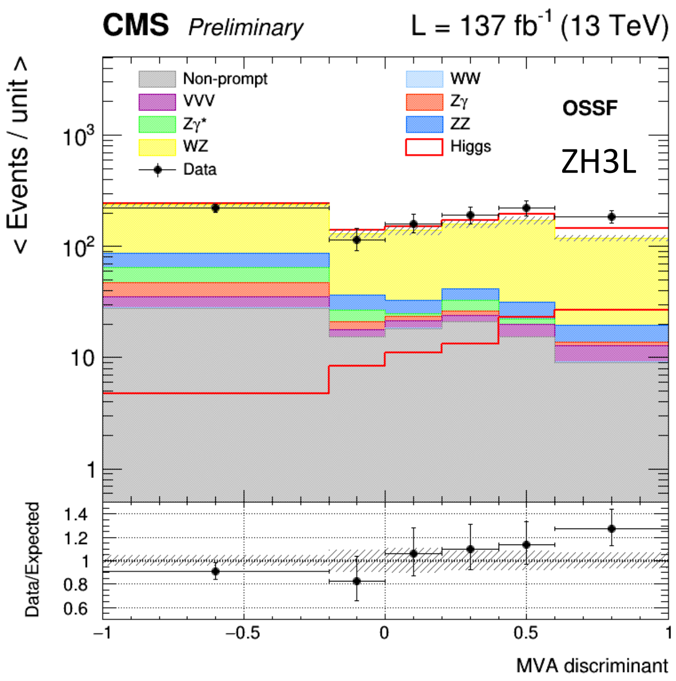
$$(\sigma \times B_{\gamma\gamma})_{\text{obs}} = 127 \pm 10 \text{ fb}$$

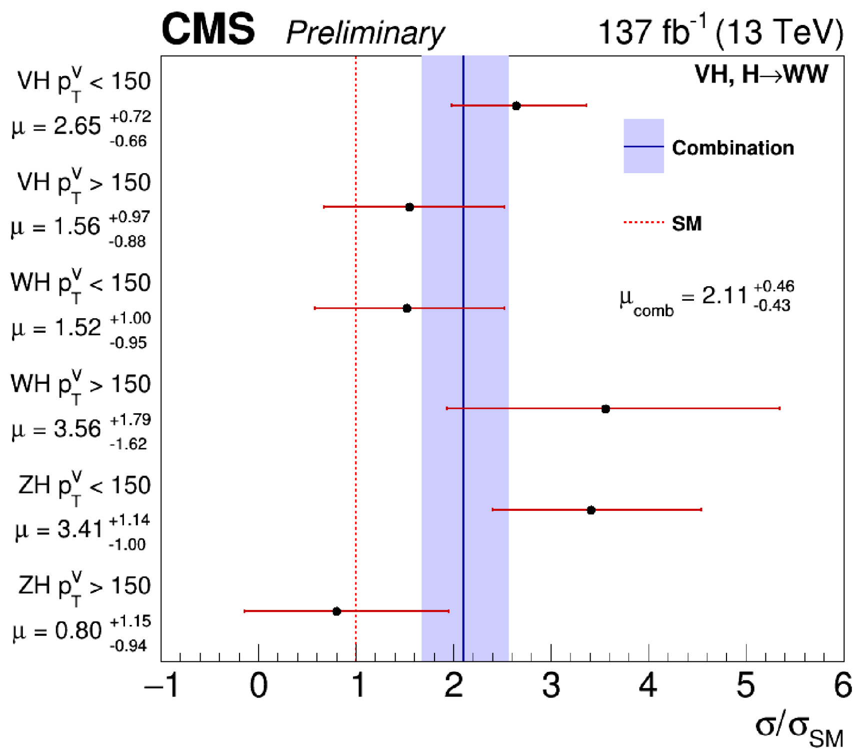
$$(\sigma \times B_{\gamma\gamma})_{\text{SM}} = 115 \pm 5 \text{ fb}$$

$V(H \to WW^*)$(CMS)

CMS-PAS-HIG-19-017







$$\mu = 1.85^{+0.33}_{-0.32}(\text{stat.})^{+0.27}_{-0.25}(\text{exp.})^{+0.10}_{-0.07}(\text{th.})$$

From inclusive measurement

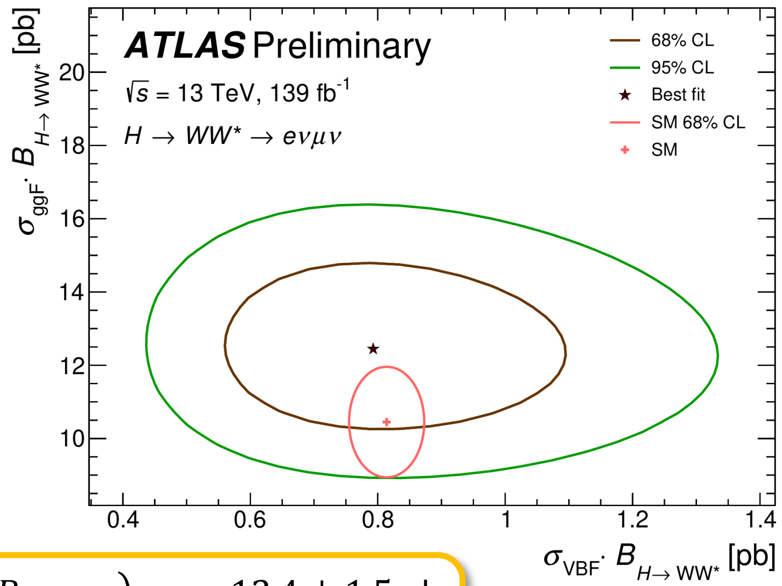
- Targeting **VH production**
- Different categories according to the final state (from 2 to 4 leptons and 0 or ≥ 1 jets)
- **Maximum likelihood fit** to the reconstructed mass of the Higgs or to the BDT ouptut according to the category
- Measurement in **4 STXS bins**
- **Results compatible with SM** predictions

$H \rightarrow WW^*$(ATLAS)

$(\sigma_{\mathrm{VBF}} \times B_{H\rightarrow WW})_{\mathrm{obs}} = 0.79^{+0.19}_{-0.16}$ pb

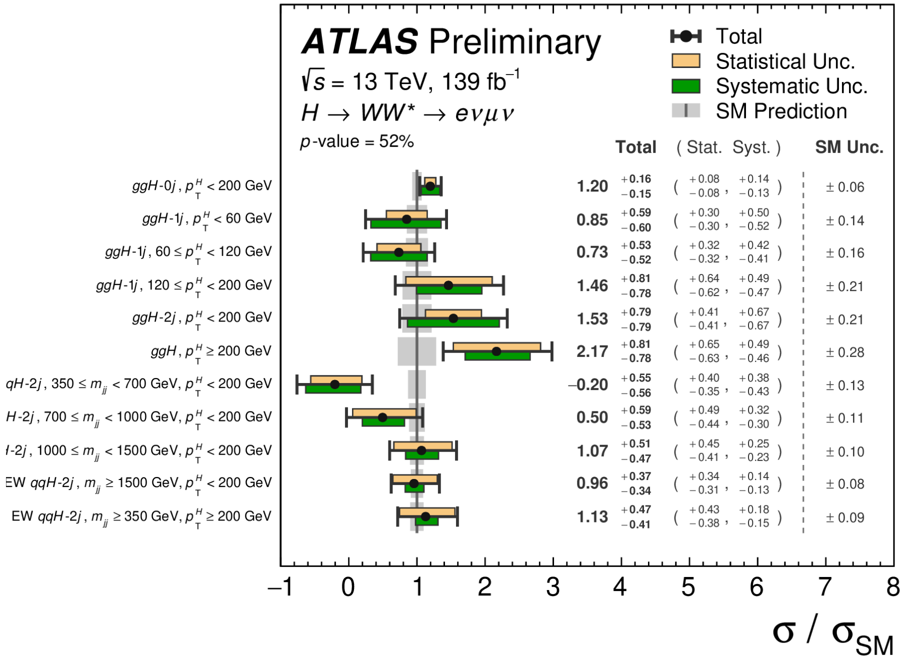
$(\sigma_{\mathrm{VBF}} \times B_{H\rightarrow WW})_{\mathrm{SM}} = 0.81 \pm 0.02$ pb

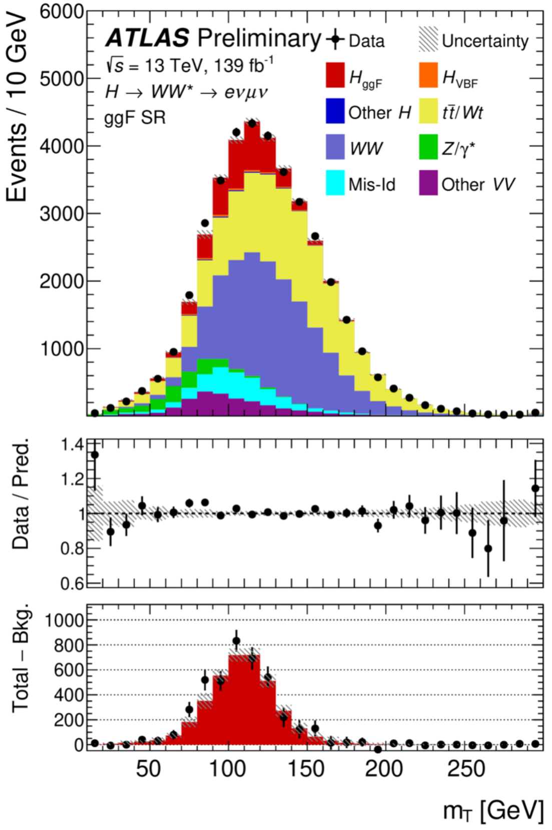
ATLAS-CONF-2021-014



$(\sigma_{\mathrm{ggF}} \times B_{H\rightarrow WW})_{\mathrm{obs}} = 12.4 \pm 1.5$ pb

$(\sigma_{\mathrm{ggF}} \times B_{H\rightarrow WW})_{\mathrm{SM}} = 10.4 \pm 0.6$ pb





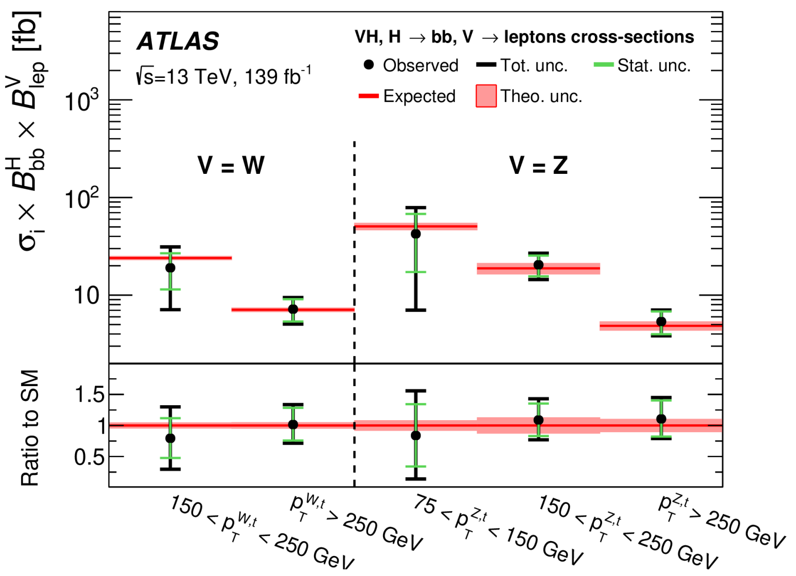
- **ggF** and **VBF** production cross sections measured
- Required two different flavour and opposite charge leptons in the final state
- Discriminant variable→ **transverse mass of the dilepton system** m_T in ggF categories and **Deep Neural Network output** in VBF category
- **STXS** measurements in 11 kinematic bins
- Systematic uncertainties larger than statistical ones in inclusive measurements and in some STXS bins, signal theory uncertainties among the most relevant ones
- **Results in agreement with the SM** expectations

$V(H \to b\bar{b})$ (ATLAS)

[Eur. Phys. J. C 81 (2021) 178]

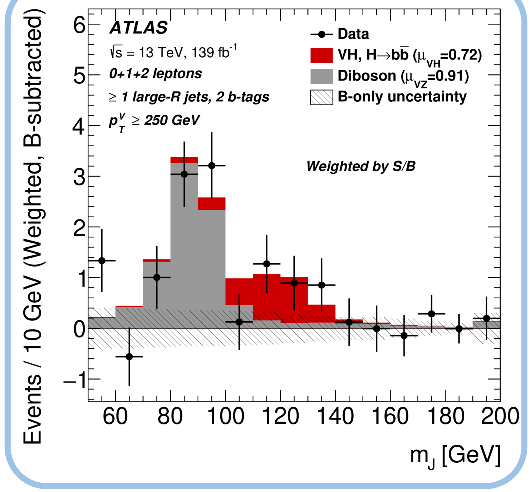
- $H \to b\bar{b}$ most sensitive channel to **VH production**
- WH and ZH measured separately

$$\mu_{VH}^{bb} = 0.93^{+0.07}_{-0.06}(\text{stat.})^{+0.14}_{-0.12}(\text{exp.})$$



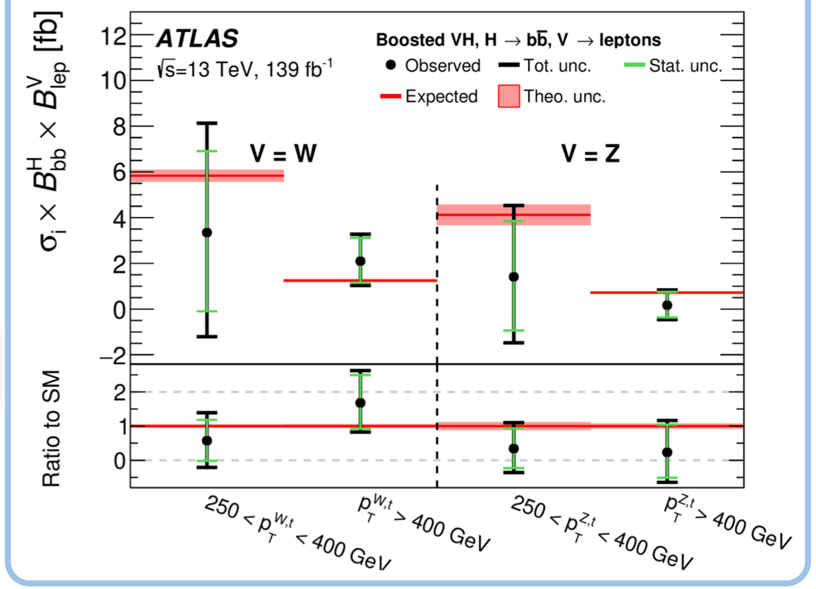
- ***VH → bb̄* resolved**
  - Higgs candidate reconstructed as two separate jets
  - BDT output used as observable for the fit
  - Single bin for STXS measurement with $p_T^V > 250$ GeV

- ***VH → bb̄* boosted** ($p_T^V > 250$ GeV)
  - Higgs candidate reconstructed as a single large radius jet
  - Signal strength and STXS measurements performed using a binned maximum likelihood fit to the mass of the jet m_j using all SRs and CRs



$$\mu_{VH}^{bb} = 0.72^{+0.29}_{-0.28}(\text{stat.})^{+0.26}_{-0.22}(\text{exp.})$$

[Phys. Lett. B 816 (2021) 136204]

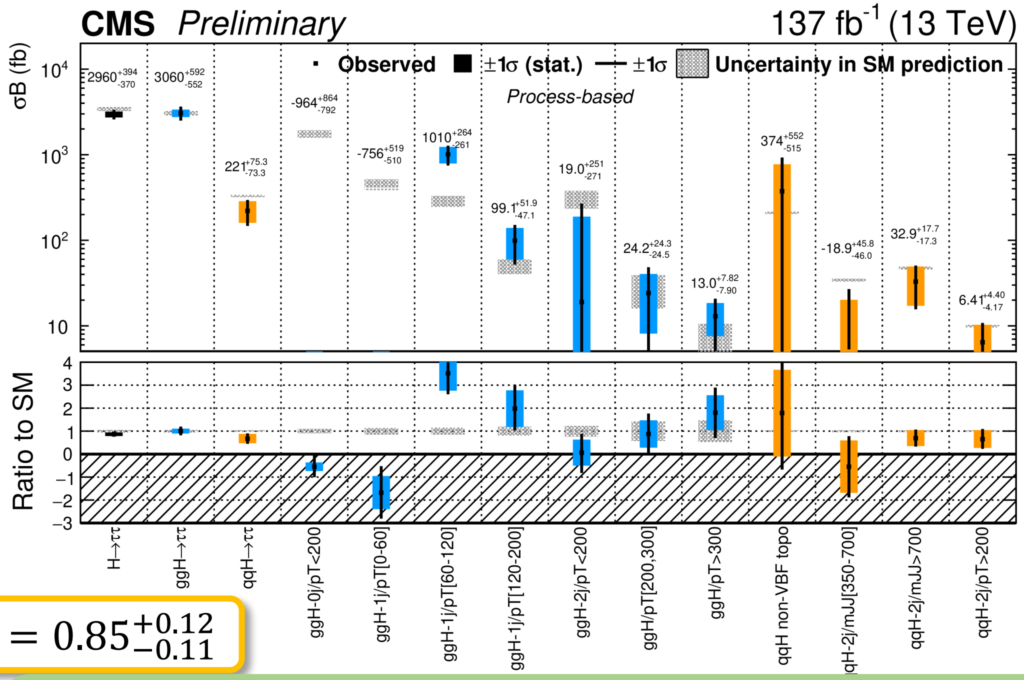


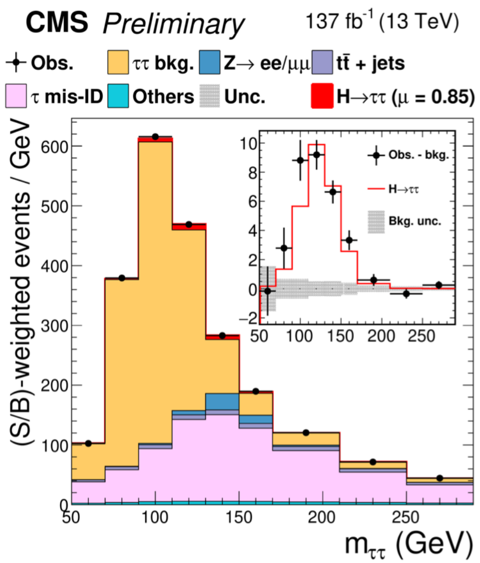
CMS analysis with 36 fb^{-1}

[Phys. Lett. B 780 (2018) 501]

$H \to \tau\tau$

[CMS-PAS-HIG-19-010](CMS-PAS-HIG-19-010)



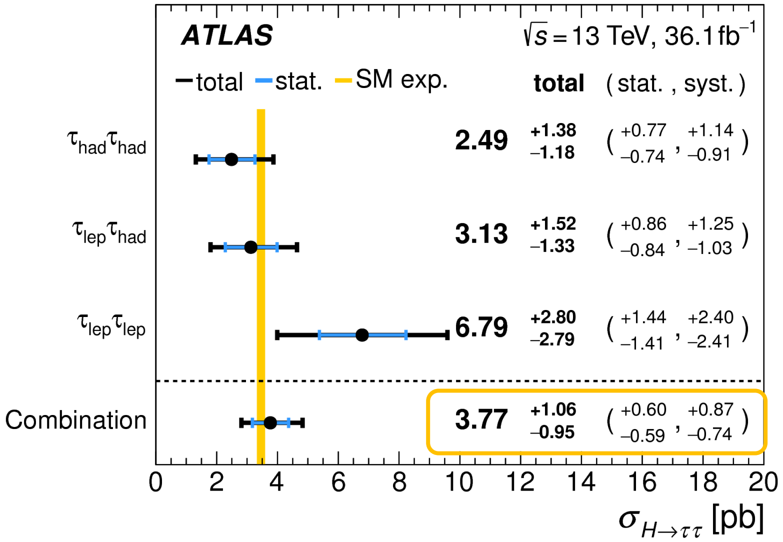


$\mu = 0.85^{+0.12}_{-0.11}$

- First **STXS measurements** in $\boldsymbol{H \to \tau\tau}$ using full hadronic ($\tau_{\text{had}}\tau_{\text{had}}$) and semileptonic ($\tau_{\text{lep}}\tau_{\text{had}}$) final states
- Cross section measured only **in ggH and qqH bins** → $H \to \tau\tau$ most sensitive to ggF with high p_T^H and VBF
- $\boldsymbol{Z \to \tau\tau}$ main irreducible background evaluated with data-driven method, embedding technique
- 2D maximum likelihood fit to reconstructed $m_{\tau\tau}$ and other variable like p_T^H for ggH and m_{jj} for qqH
- **Agreement with SM** predictions

CMS

Phys. Rev. D 99 (2019) 072001



STXS

Process	Particle-level selection	σ [pb]	σ^{SM} [pb]
ggF	$N_{\text{jets}} \geq 1,\ 60 < p_T^H < 120\,\text{GeV},\ \lvert y_H \rvert < 2.5$	$1.79 \pm 0.53\,(\text{stat.}) \pm 0.74\,(\text{syst.})$	0.40 ± 0.05
ggF	$N_{\text{jets}} \geq 1,\ p_T^H > 120\,\text{GeV},\ \lvert y_H \rvert < 2.5$	$0.12 \pm 0.05\,(\text{stat.}) \pm 0.05\,(\text{syst.})$	0.14 ± 0.03
VBF	$\lvert y_H \rvert < 2.5$	$0.25 \pm 0.08\,(\text{stat.}) \pm 0.08\,(\text{syst.})$	0.22 ± 0.01

- Results with 36 fb^{-1} which leads to first ATLAS $H \to \tau\tau$ observation
- **First attempt of STXS measurements** with 3 bins
- **Agreement with SM** predictions

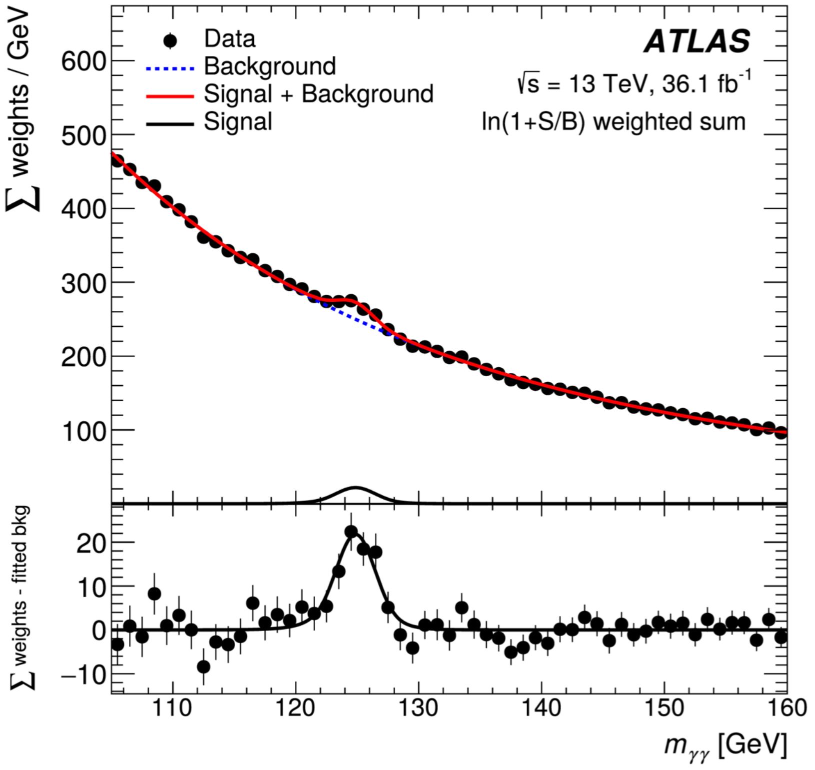
ATLAS

Higgs mass

Mass measurements

ATLAS+CMS Run 1 combination:
$m_H = 125.09 \pm 0.24$ GeV

Phys. Lett. B 784 (2018) 345

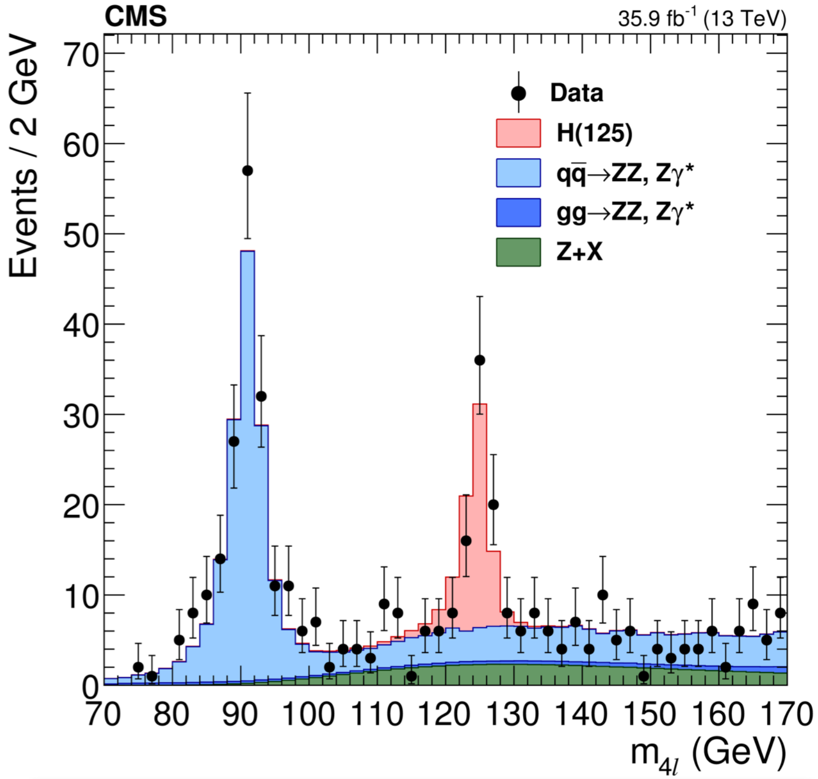


$m_H = 124.97 \pm 0.16\,(\text{stat.}) \pm 0.18\,(\text{syst.})$ GeV

ATLAS $H \to ZZ^*$ and $H \to \gamma\gamma$ combination, Run 2 36 fb^{-1} combined with Run 1 measurements at $\sqrt{s}$ =7 and 8 TeV

Phys. Lett. B 805 (2020) 135425

JHEP 11 (2017) 047

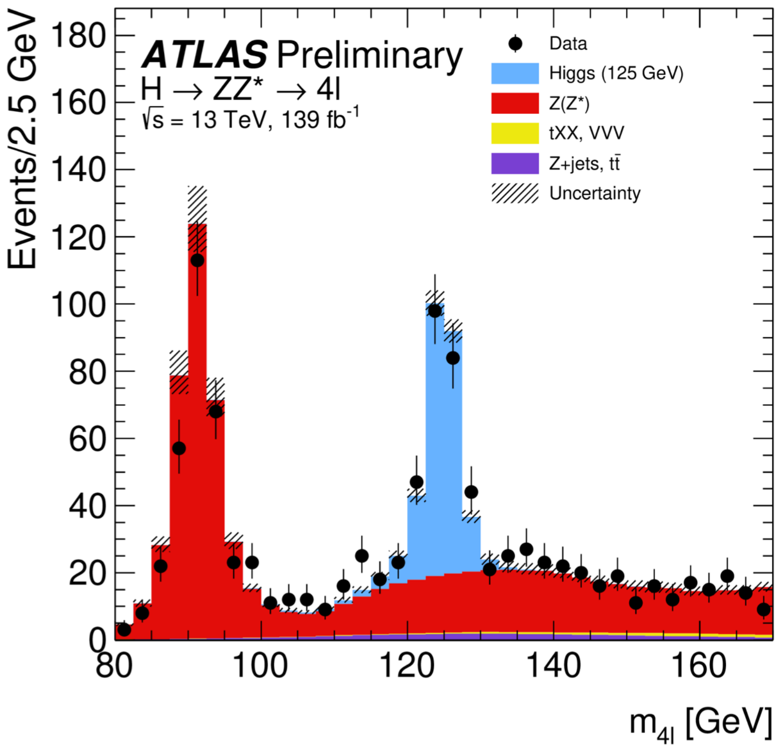


$m_H = 125.38 \pm 0.11\,(\text{stat.}) \pm 0.08\,(\text{syst.})$ GeV

CMS $H \to ZZ^*$ and $H \to \gamma\gamma$ combination, Run 2 36 fb^{-1} combined with Run 1 measurements at $\sqrt{s}$ =7 and 8 TeV

Most accurate result so far!

ATLAS-CONF-2020-005

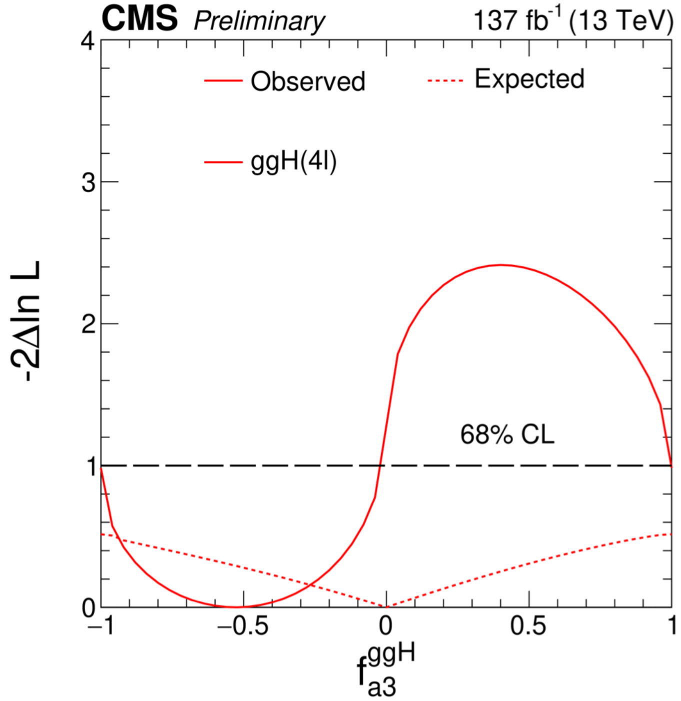


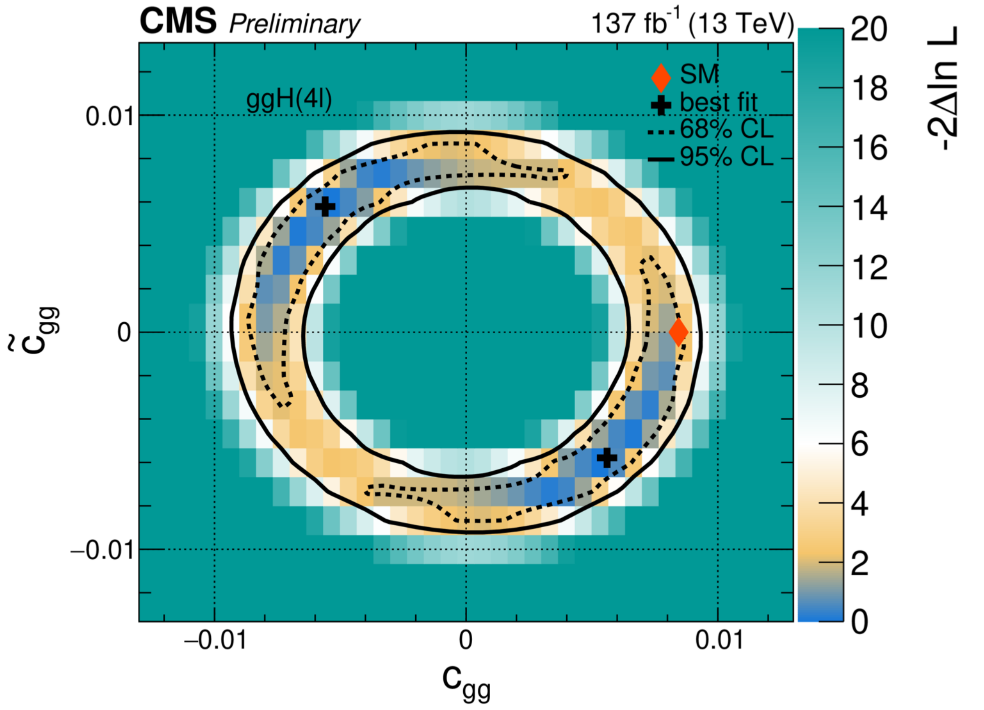
$m_H = 124.92 \pm 0.19\,(\text{stat.})\,^{+0.09}_{-0.06}\,(\text{syst.})$ GeV

Result with 139 fb^{-1}: ATLAS $H \to ZZ^*$

Higgs CP

ggH





- Test **CP** structure of **Higgs coupling to gluons** using $\boldsymbol{H \rightarrow ZZ^* \rightarrow 4l}$ events
- Use discriminant variable based on **matrix elements** both for separating signal from background events, and CP-even from CP-odd events
- $\boldsymbol{f_{a3}^{ggH}}$ parameter extract from likelihood fit (a_3→ CP-odd coupling, a_2→ CP-even coupling)

$$f_{a3}^{ggH} = \frac{|a_3^{gg}|^2}{|a_2^{gg}|^2 + |a_3^{gg}|^2} \operatorname{sign}\left(\frac{a_3^{gg}}{a_2^{gg}}\right).$$

$$c_{gg} = -\frac{1}{2\pi\alpha_s} a_2^{gg}, \quad \tilde{c}_{gg} = -\frac{1}{2\pi\alpha_s} a_3^{gg}.$$

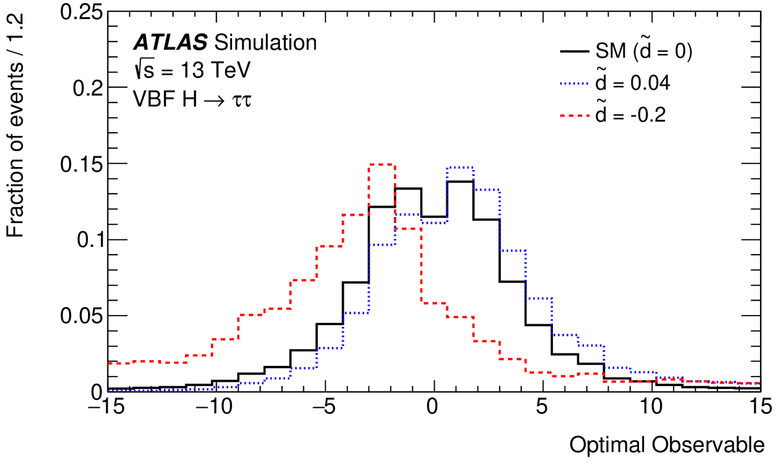
- Limited by statistics
- $f_{a3}^{ggH} = -0.53^{+0.51}_{-0.47}$ at 68% C.L., **compatible with CP-even SM prediction**

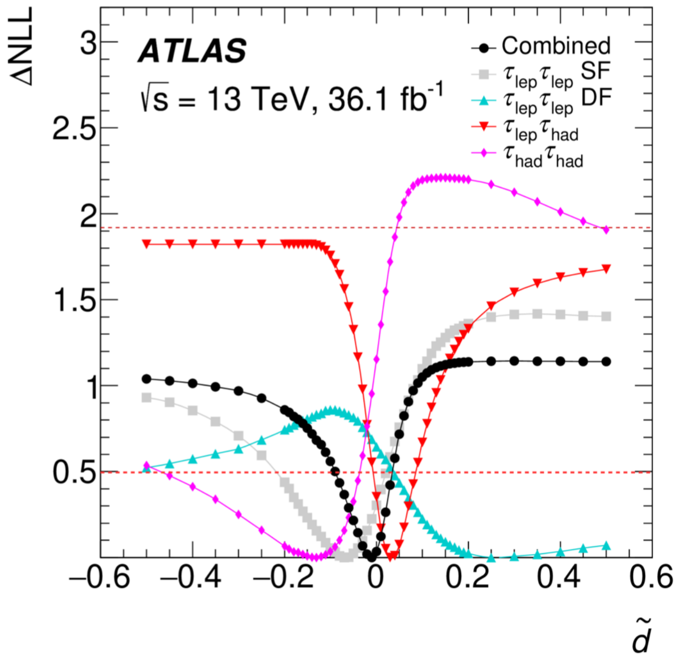
- CP structure of **ggH vertex** also measured in ATLAS
- $H \rightarrow WW^*$ events
- Exploit both rate and shape informations (signed $\Delta\Phi_{jj}$ between the two leading jets)
- $\boldsymbol{k_{Agg}/ k_{Hgg} = 0.0 \pm 0.4(\text{stat.}) \pm 0.3(\text{syst.})}$ at 68% C.L.

ATLAS-CONF-2020-055

HVV vertex in VBF production

Phys. Lett. B 805 (2020) 135426





- **Test CP violation** in **VBF** production (HVV vertex) using $\boldsymbol{H \to \tau\tau}$ events
- Parametrisation:

$$|M^2| = \left|M_{SM}^2\right| + \tilde{d} \cdot 2\,Re(M_{SM}^* M_{CP-odd}) + \tilde{d}^2\left|M_{CP-odd}^2\right|$$

- Use discriminant variable sensitive to CP-odd contribution → **Optimal Observable**

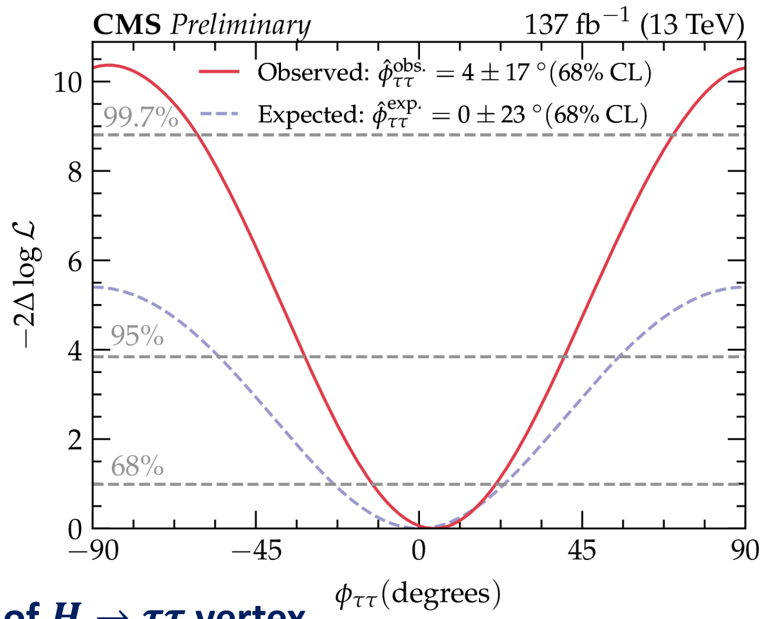
$$O_1 := \frac{2\,Re(M_{SM}^* M_{CP-odd})}{|M_{SM}^2|}$$

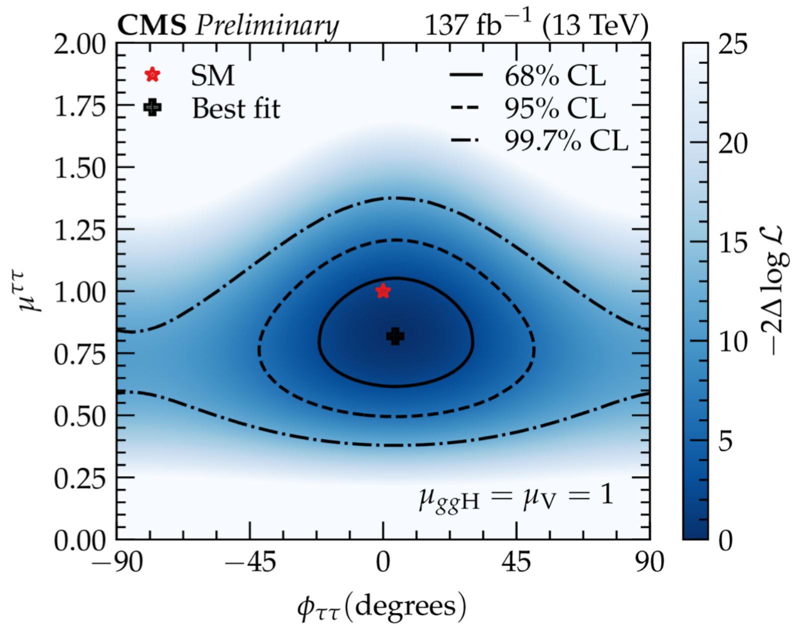
- BDT for separating VBF Higgs events from background and then maximum likelihood fit to Optimal Observable
- **No sign of CP violation** → $\boldsymbol{\tilde{d} < -0.090}$ **and** $\boldsymbol{\tilde{d} > 0.035}$ **excluded at 68% C.L.**

- Similar analysis in CMS targeting VBF production
- Different parametrisation
- Discriminant variables based on matrix element calculations
- **Results consistent with SM**
  - $\boldsymbol{f_{a3}\cos(\phi_{a3}) < -0.27}$ **and** $\boldsymbol{f_{a3}\cos(\phi_{a3}) > 0.27}$ **at 68% C.L.** in combination with $H \to 4l$ decay
  - f_{a3} ratios of cross sections sensitive to CP-odd anomalous coupling

Phys. Rev. D 100 (2019) 112002

$H \to \tau\tau$ (CMS)





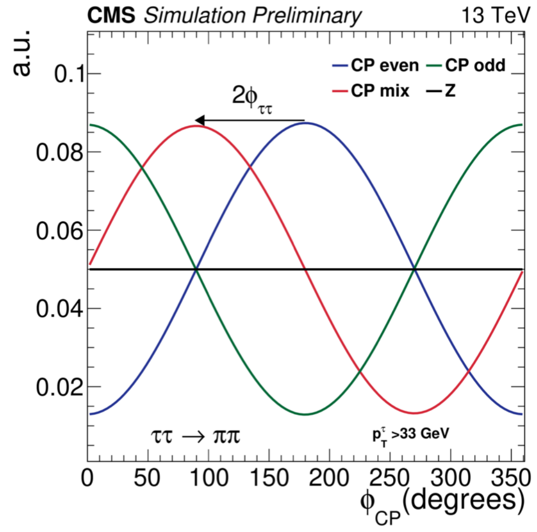
$\phi_{\tau\tau} = (4 \pm 17)°$ at 68% C.L.

- First direct study of **CP structure of $H \to \tau\tau$ vertex**
- Analysis exploiting $\tau_l\tau_h$ and $\tau_h\tau_h$ decay modes
- Parametrisations of the CP-odd and CP-even couplings using the $\phi_{\tau\tau}$ mixing angle

$$\tan(\phi_{\tau\tau}) = \frac{\tilde{k}_\tau}{k_\tau}$$

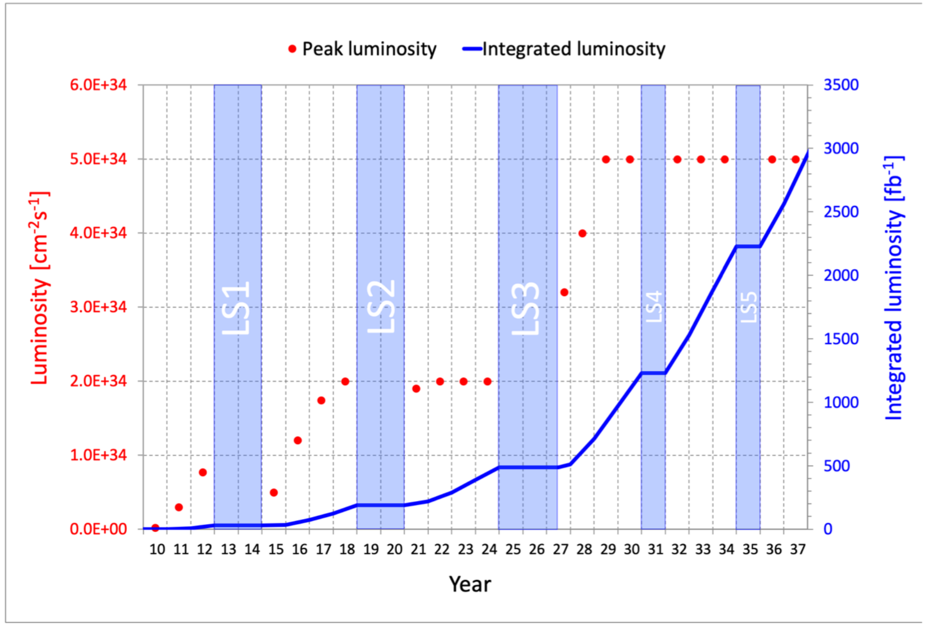
$k_t \to$ CP-even coupling
$\tilde{k}_t \to$ CP-odd coupling

- Discriminating variable → **angle between the τ decay planes, ϕ_{CP}**
  - Impact parameter method for τ decaying into $\mu^\pm$ or single π
  - Neutral pion method for the other production modes ($\rho^\pm \to \pi^\pm\pi^0, a_1^\pm \to \pi^\pm\pi^0\pi^0, a_1^\pm \to \pi^\pm\pi^\mp\pi^\pm$)
- BDT use to enhance sensitivity
- CP even distinguished from CP odd hypothesis at 3.2 σ
- **Mixing angle compatible with 0**



Conclusions and outlook

- Most of the ATLAS and CMS Higgs analyses with Run 2 full dataset are public or being finalized
- Many measurements results, a lot of progress regarding analyses techniques
- Higgs physics is entering the precision era
  - Precise measurements of Higgs couplings and other properties
  - Search for deviations from the SM predictions as a sign of BSM physics
- **All the results so far are consistent with the Standard Model**



- **Looking forward to Run 3 and High-Luminosity LHC with expected integrated luminosity of 300 fb^{-1} and 3000 fb^{-1}**
  - Access to 2nd generation fermion couplings
  - Higgs self couplings → explore Higgs potential and look for any sign of new physics

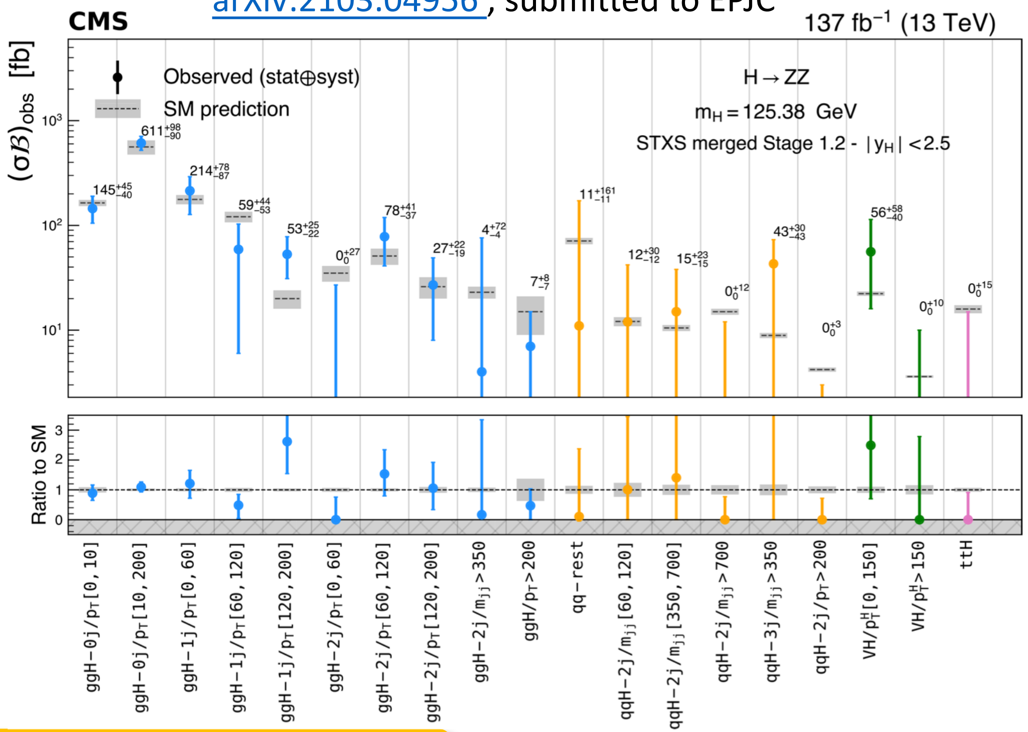
Stay tuned for more results!

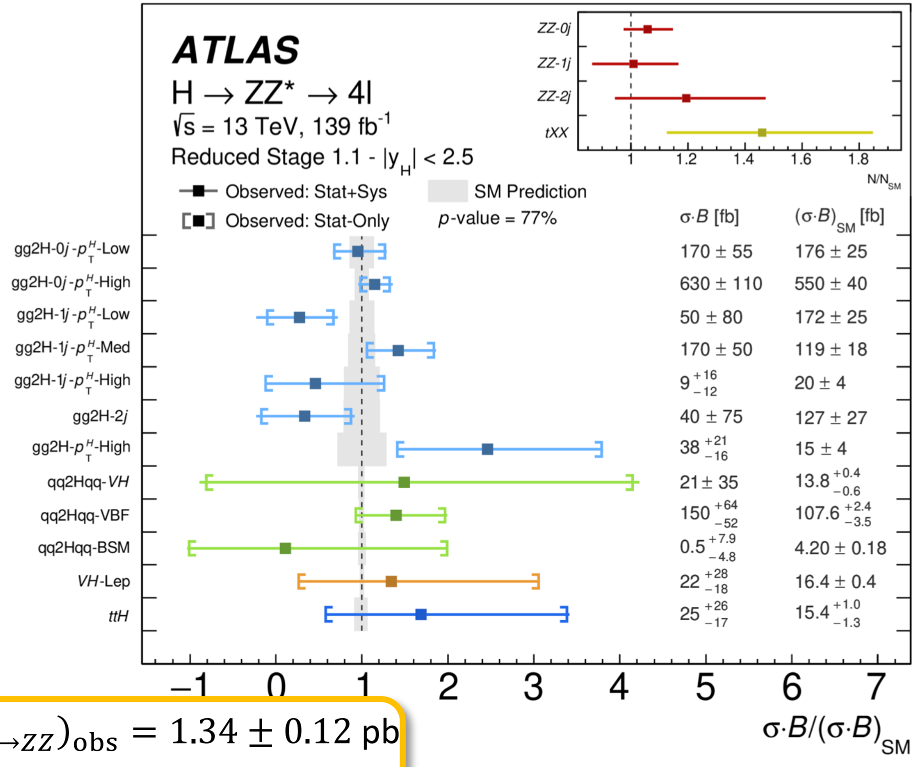
BACKUP

$H \rightarrow ZZ^* \rightarrow 4l$

Eur. Phys. J. C 81, 29 (2021)

arXiv:2103.04956 , submitted to EPJC





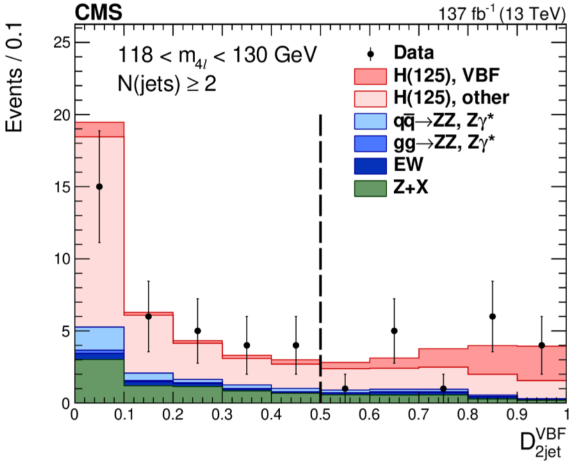
$$(\sigma \times B_{H\rightarrow ZZ})_{\mathrm{obs}} = 1.34 \pm 0.12 \text{ pb}$$

$$(\sigma \times B_{H\rightarrow ZZ})_{\mathrm{SM}} = 1.33 \pm 0.08 \text{ pb}$$

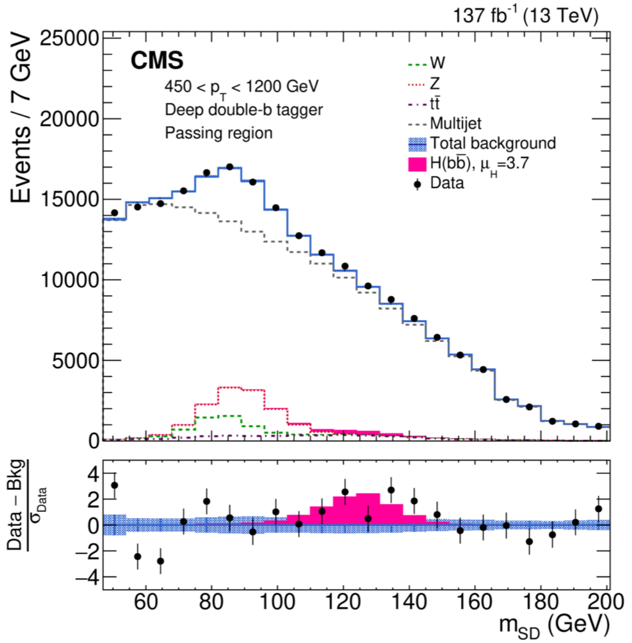
$$\mu = 0.94 \pm 0.07(\mathrm{stat.})^{+0.09}_{-0.08}(\mathrm{syst.})$$

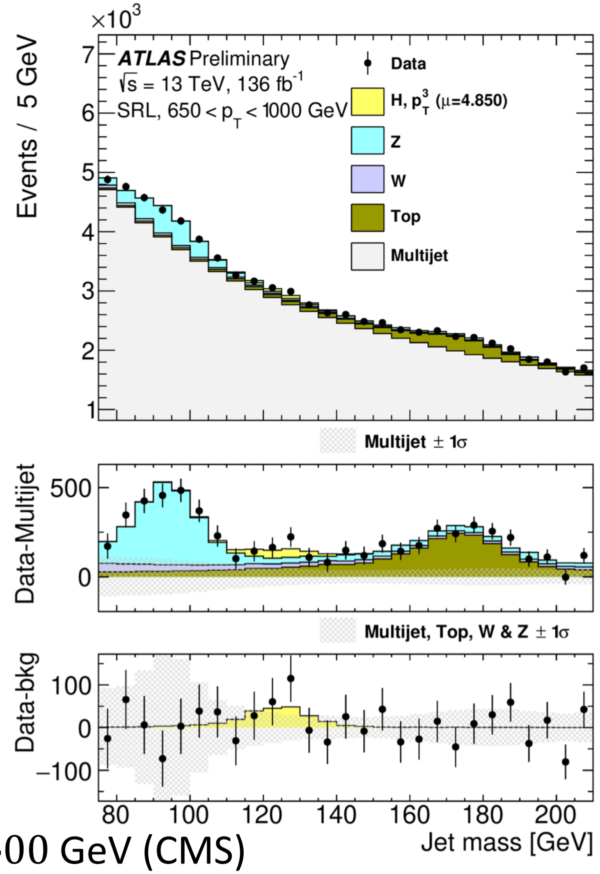
- Events classified using mutually exclusive categories
- To further increase the sensitivity **Neural Network output** are used as observables for the fit (ATLAS)
- Production-dependent discriminants related to the probability of having a certain production, calculated using **matrix elements** (CMS)
- Dominated by statistical uncertainty
- **Good agreement with SM expectations**

$$\mathcal{D}_{\mathrm{2jet}}^{\mathrm{VBF}} = \left[1 + \frac{\mathcal{P}_{\mathrm{Hjj}}(\vec{\Omega}^{\mathrm{H+jj}}|m_{4\ell})}{\mathcal{P}_{\mathrm{VBF}}(\vec{\Omega}^{\mathrm{H+jj}}|m_{4\ell})}\right]^{-1}$$

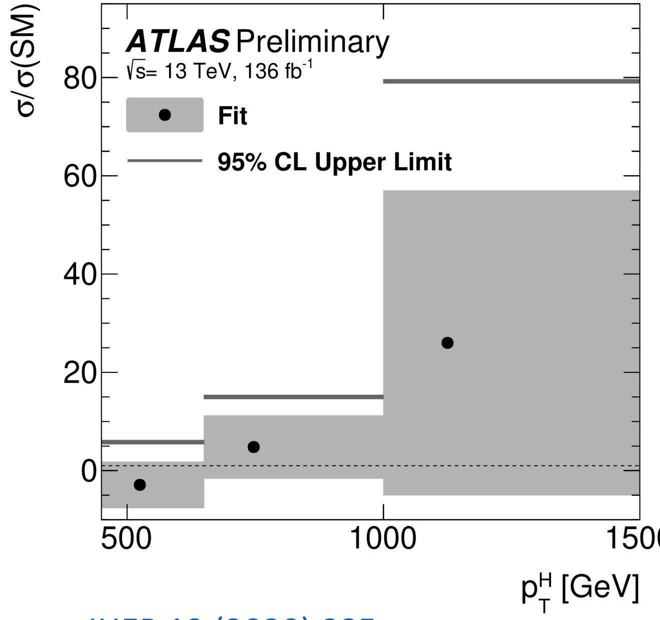


$H \to b\bar{b}$

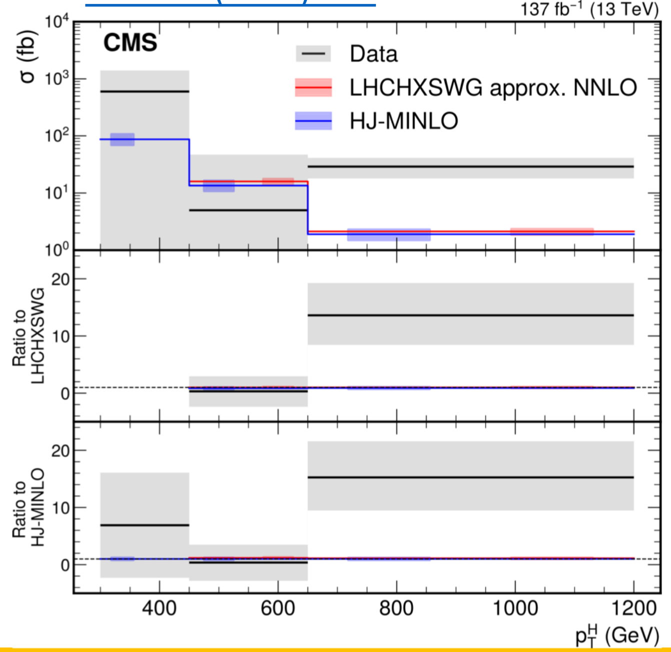




ATLAS-CONF-2021-010

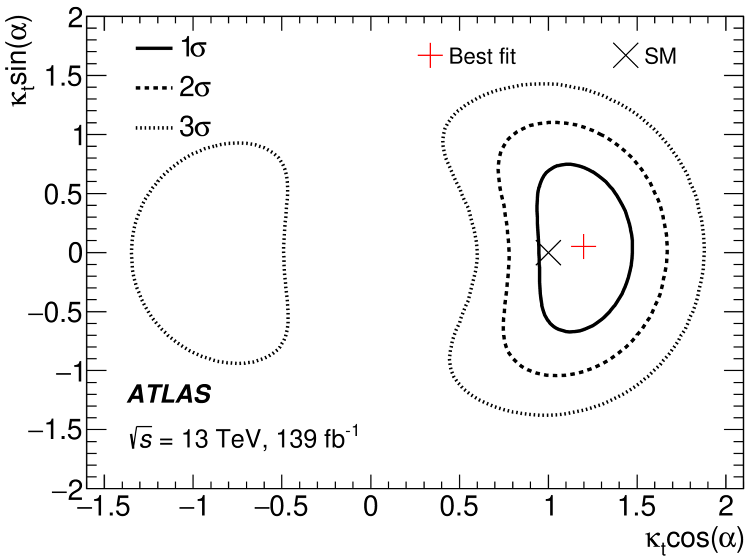


JHEP 12 (2020) 085

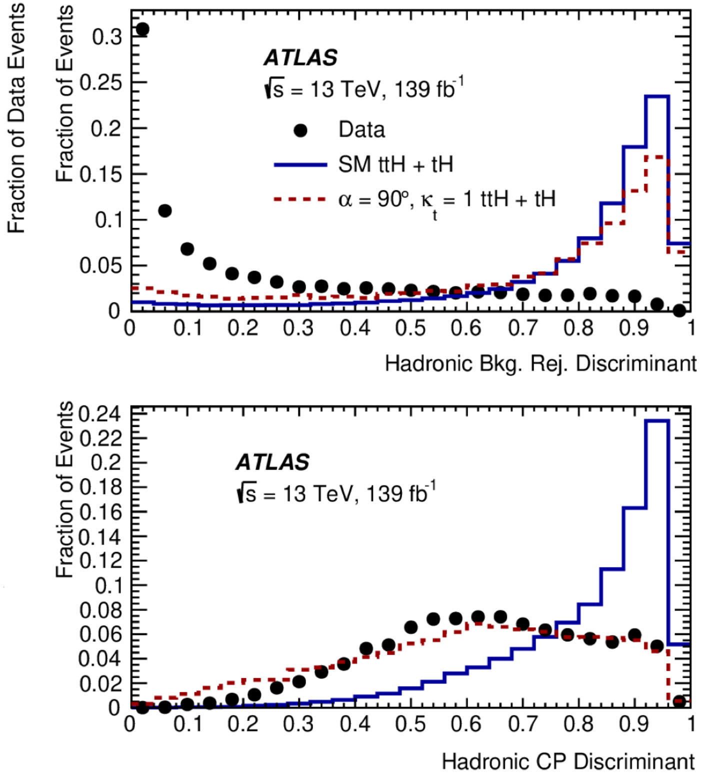


- **Boosted regime**: $p_T^H > 250$ GeV (ATLAS), $p_T^H > 400$ GeV (CMS)
- Inclusive in production modes
- **Higgs candidate** reconstructed as a **single large radius jet** containing at least two b-tagged track-jets (MVA likeihood-based algorithm in the case of ATLAS and Deep Neural Network algorithm in the case of CMS)
- Inclusive, fiducial and differential measurements
- Signal strengths and cross sections retrieved from **a binned maximum likelihood fit** to the mass of the jet using all SRs and CRs
- **Excess in region with $p_T^H > 650$ GeV** with a local significance of 2.6 σ seen by CMS
- **Results in agreement with SM** expectations

CP structure of $t\bar{t}H$ vertex



[Phys. Rev. Lett. 125 (2020) 061802](#)



- **Probe CP structure of ttH vertex using $H \rightarrow \gamma\gamma$** decay channel
- Parametrization of the coupling

$$\mathcal{L} = -\frac{m_t}{v}\left\{\bar{\psi}_t \kappa_t \left[\cos(\alpha) + \mathrm{i}\sin(\alpha)\gamma_5\right]\psi_t\right\} H$$

  - α is the CP-mixing angle, k_t is the top Yukawa coupling
    $\rightarrow \alpha = 0, k_t = 1$ (SM), $\alpha = 90°$ (pure CP-odd)
- A first BDT is trained for separate $t\bar{t}H$ events from background and a second BDT to separate CP-odd from CP-even couplings
- Maximum likelihood fit to $m_{\gamma\gamma}$
- **No sign of CP violation** $\rightarrow$ pure CP-odd excluded at 3.9 σ and **$|\alpha| \geq 43°$ excluded at 95% C.L.**

[Phys. Rev. Lett. 125 (2020) 061801](#)

- Similar analysis in CMS
- **No sign of CP violation** $\rightarrow$ pure CP-odd excluded at 3.2 σ and **$f_{CP}^{Htt} = 0.00 \pm 0.33$ at 68% C.L.**

$$f_{CP}^{Htt} = \frac{|\tilde{\kappa}_t|^2}{|\kappa_t|^2 + |\tilde{\kappa}_t|^2}\,\mathrm{sign}(\tilde{\kappa}_t/\kappa_t).$$

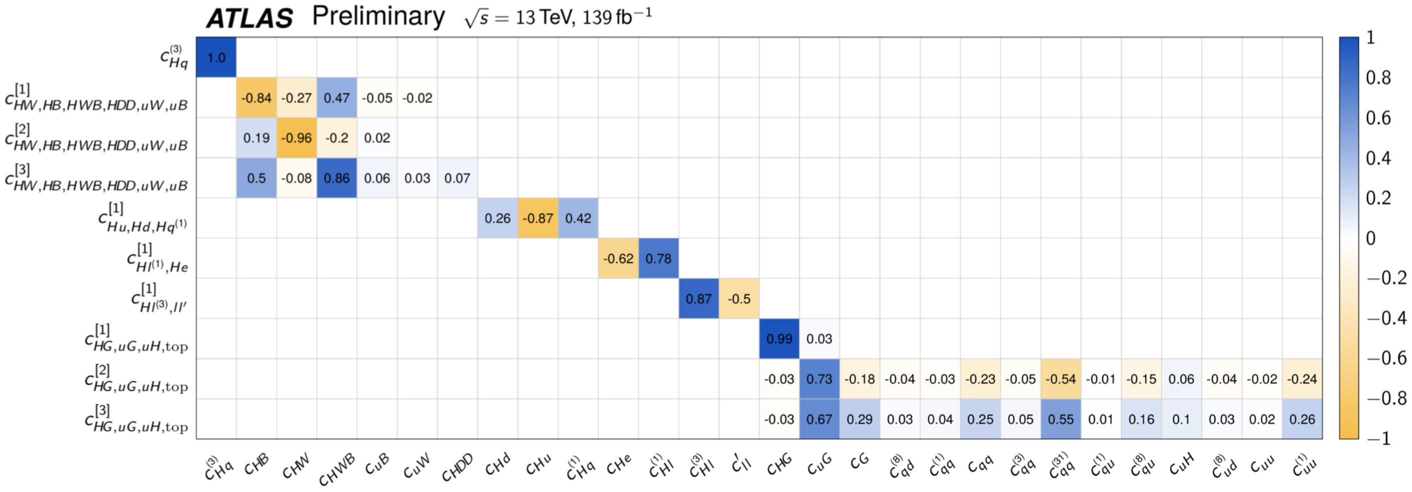
$k_t \rightarrow$ CP-even coupling
$\tilde{k}_t \rightarrow$ CP-odd coupling

EFT interpretations

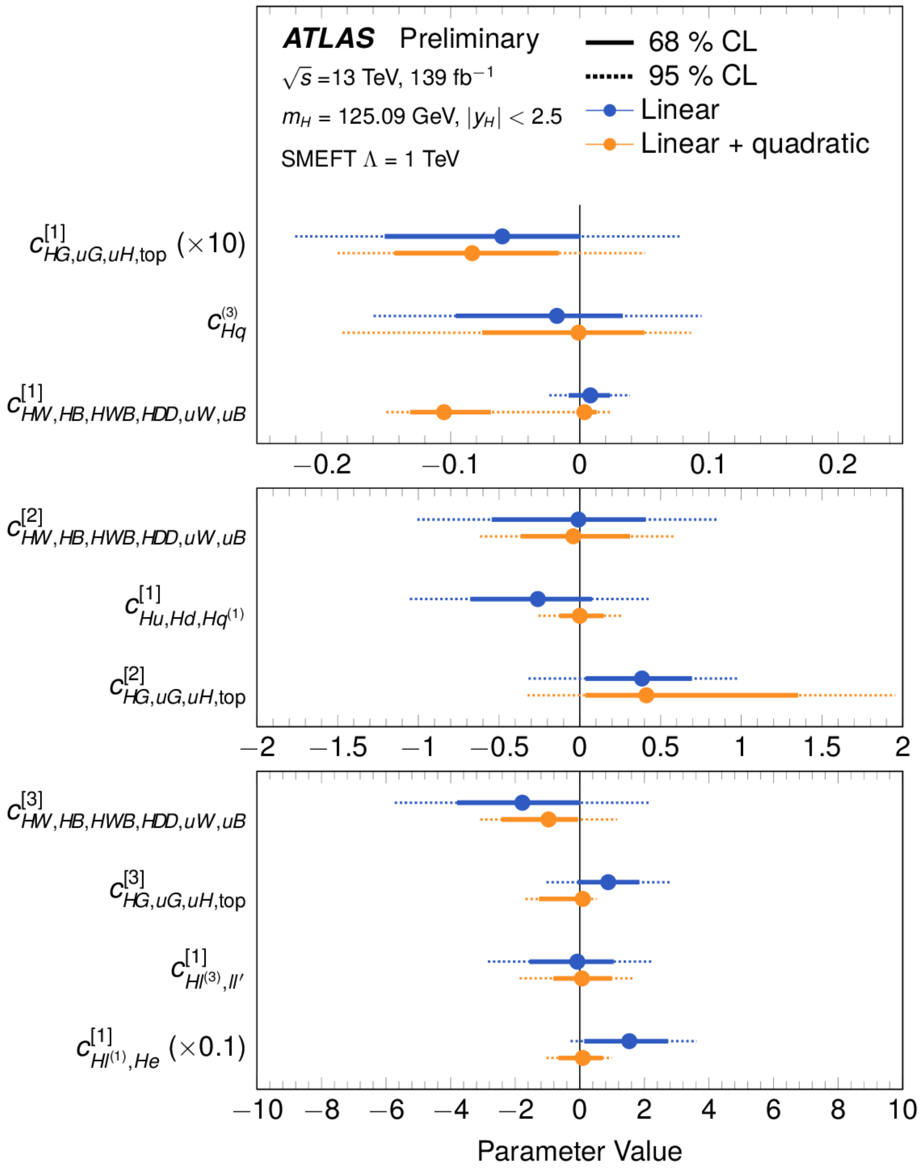
- STXS measurements in exclusive kinematic regions interpreted with **EFT approach**
- Allow to look for possibile non-SM contributions to the tensor structure of the Higgs boson couplings

$$\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{C_i^{(d)}}{\Lambda^{(d-4)}} O_i^{(d)} \quad \text{for } d > 4.$$

- **Wilson coefficients** expressed in the Warsaw basis and experimentally constrained
- **ATLAS EFT combination using** $H \to ZZ$, $H \to \gamma\gamma$, $H \to b\bar{b}$

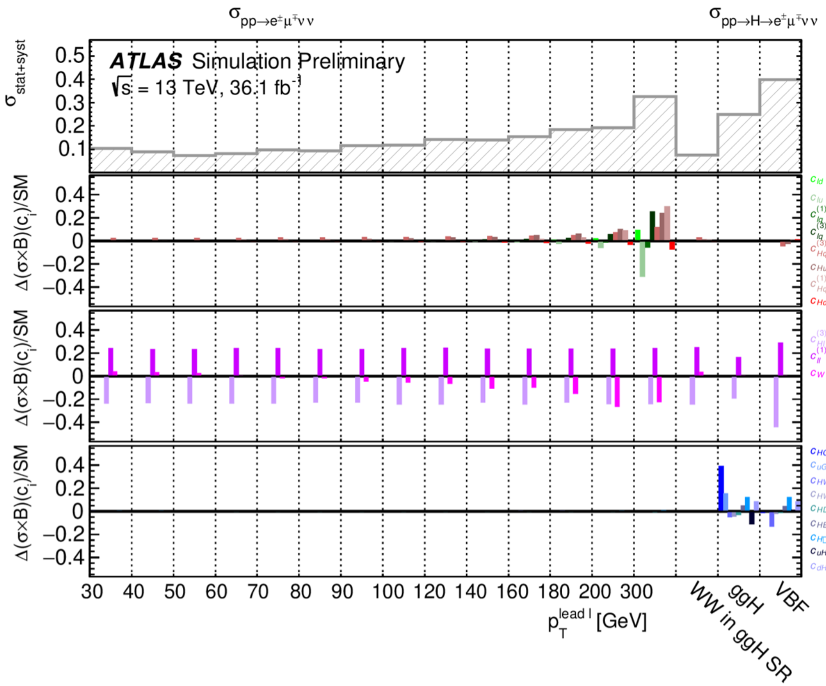


From dimension-6 parameters in Warsaw basis to dimension-6 parameters in fit basis

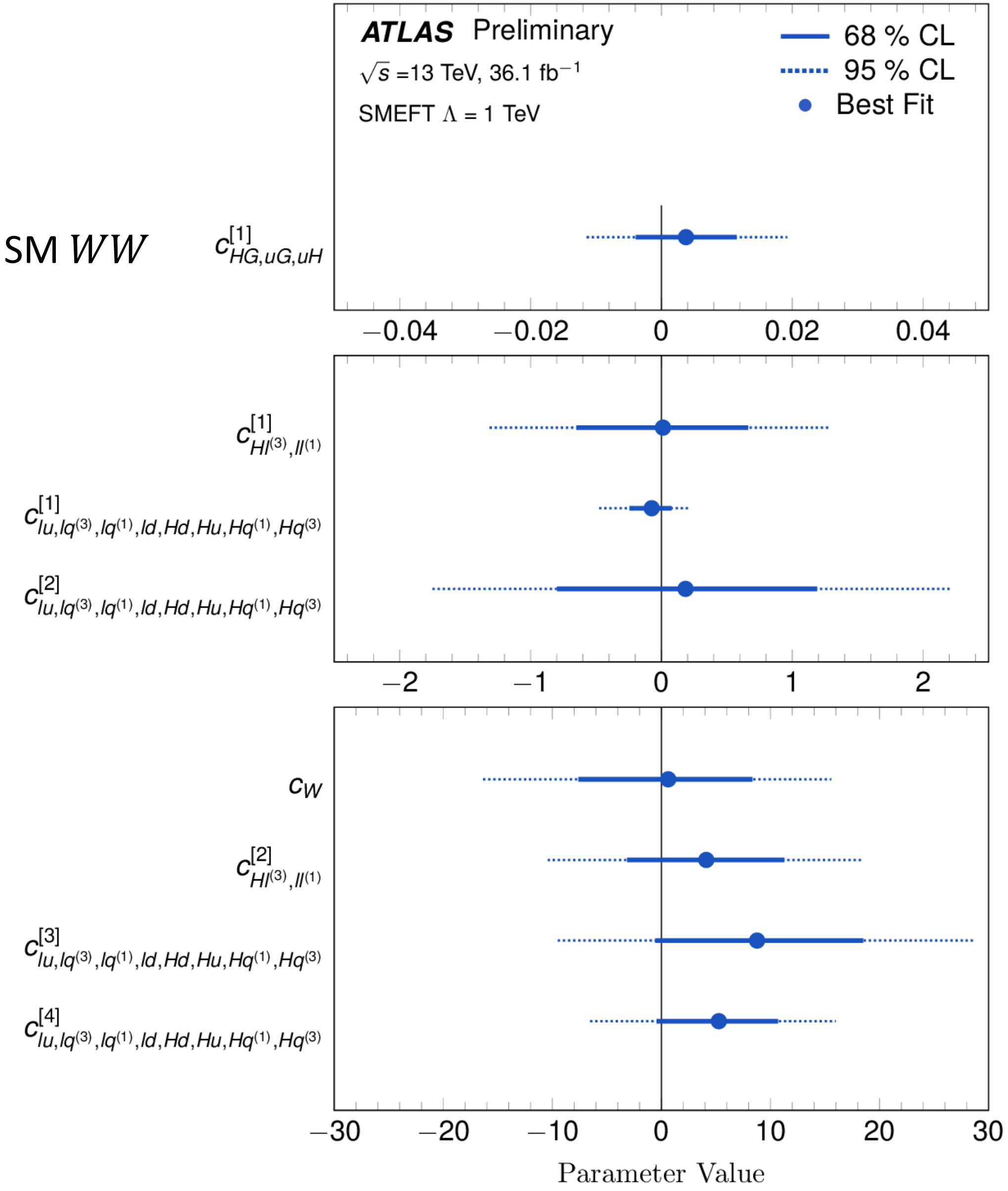


EFT interpretations

- **ATLAS $H \to WW^* \to 4l$ and diboson production analyses**
- Combination of different inputs, $H \to WW^*$ production cross section and SM WW differential cross section, use to constrain EFT parameters
- Stepping stone for global EFT measurements

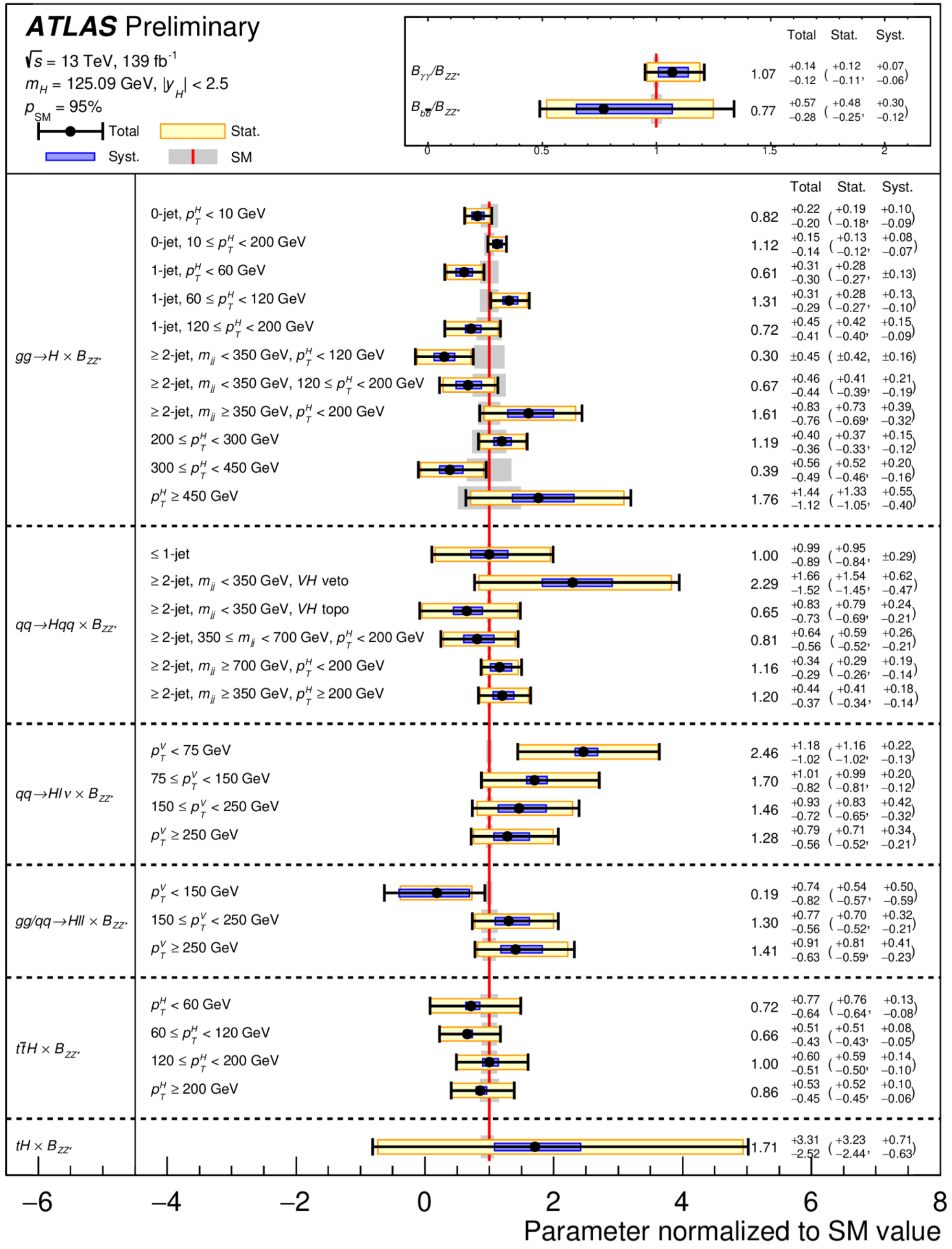


Impact of EFT parameters on $H \to WW^*$ signal strength modifier, normalisation of WW background in ggH and WW differential cross sections



STXS Combination

- $(\sigma_i \times B_{ZZ}) B_f / B_{ZZ}$ extracted from the fit
- Level of compatibility with SM → $p_{SM} = 95\%$



CP parametrisations

CMS parametrisation

- Scattering amplitude:

$$A(\mathrm{HVV}) = \frac{1}{v}\left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_{\mathrm{V1}}^2 + \kappa_2^{\mathrm{VV}} q_{\mathrm{V2}}^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2} + \frac{\kappa_3^{\mathrm{VV}} (q_{\mathrm{V1}} + q_{\mathrm{V2}})^2}{\left(\Lambda_Q^{\mathrm{VV}}\right)^2}\right] m_{\mathrm{V1}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + \frac{1}{v} a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + \frac{1}{v} a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu},$$

- f_{a3} parameter extracted from the fit (ratio of cross sections)

$$f_{a3}^{\mathrm{ggH}} = \frac{|a_3^{\mathrm{gg}}|^2}{|a_2^{\mathrm{gg}}|^2 + |a_3^{\mathrm{gg}}|^2}\,\mathrm{sign}\left(\frac{a_3^{\mathrm{gg}}}{a_2^{\mathrm{gg}}}\right).$$

ATLAS parametrisation

- Lagrangian in Higgs characterisation framework

$$\mathcal{L}_{eff} = H\left\{c_\alpha \kappa_{\mathrm{SM}}\left[\frac{1}{2}\frac{2m_V^2}{v} Z_\mu Z^\mu + g_{HWW} W_\mu W^\mu\right] - \frac{1}{4}\frac{1}{\Lambda} s_\alpha \kappa_{AZZ} Z_{\mu\nu}\tilde{Z}^{\mu\nu} - \frac{1}{2}\frac{1}{\Lambda} s_\alpha \kappa_{AWW} W_{\mu\nu}^{+}\tilde{W}^{-\mu\nu}\right\}$$

$$\mathcal{L}_0^{\mathrm{loop}} = -\frac{1}{4}\left(\kappa_{Hgg} g_{Hgg} G_{\mu\nu}^a G^{a,\mu\nu} + \kappa_{Agg} g_{Hgg} G_{\mu\nu}^a \tilde{G}^{a,\mu\nu}\right) H,$$

- $\boldsymbol{k_{AVV}/k_{HVV}}$ or similar extracted from the fit
- Other parametrisation in VBF $H \to \tau\tau$ which has CP-odd contribution parametrised by $\tilde{d}$

$$\tilde{d} = \frac{1}{4}\frac{v}{\Lambda}\frac{k_{AVV}}{k_{SM}}\tan\alpha$$