Measurement of the Higgs boson properties using the ATLAS detector

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on behalf of the ATLAS Collaboration

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Outline

- The Higgs Boson at LHC

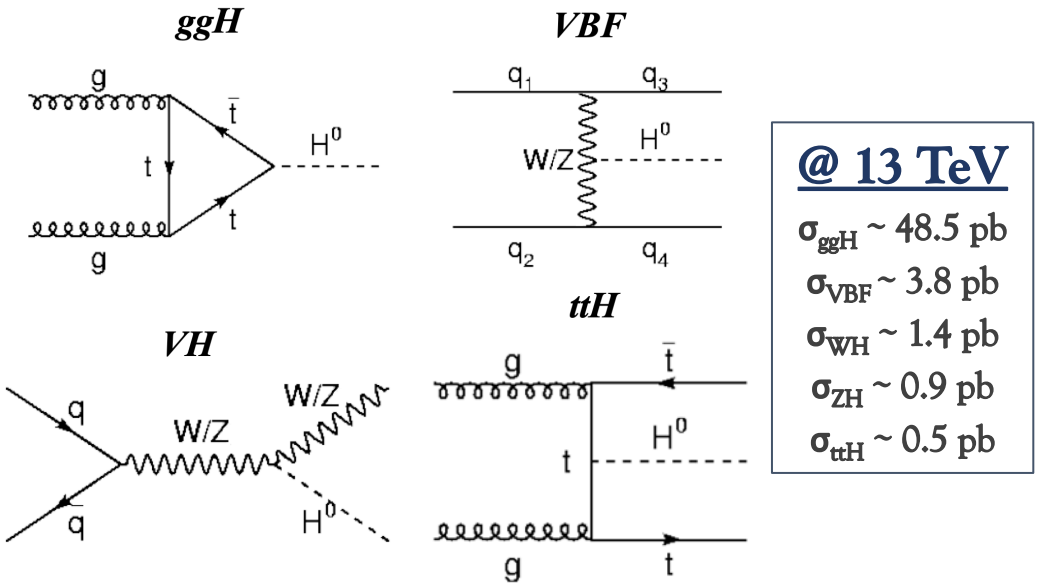
- Run2: Higgs boson properties
  - Mass, Spin – CP and Width
  - Differential Cross Section
  - Production Cross Section in the most sensitive decay channels

    → Combined measurements
    - Interpretation of the results in different framework

The Higgs Boson @ LHC

Production mechanisms

- Gluon – Gluon Fusion (ggF)
- Vector Boson Fusion (VBF)
- Associated production with a vector boson (VH)
- Associated production with a top quark pair (ttH)



@ 13 TeV

σ_{ggH} ~ 48.5 pb
σ_{VBF} ~ 3.8 pb
σ_{WH} ~ 1.4 pb
σ_{ZH} ~ 0.9 pb
σ_{ttH} ~ 0.5 pb

Decay Channels

- H→ZZ: low BR, very good signal – background ratio, high mass resolution
- H→WW: high BR, low mass resolution
- H→ $\gamma\gamma$: low BR, large background, high mass resolution
- H→bb and H→$\tau\tau$: high BR, large background, low mass resolution
- H→Zγ and H→$\mu\mu$: very low BR

Decay mode	Branching fraction [%]
$H \to bb$	57.5 ± 1.9
$H \to WW$	21.6 ± 0.9
$H \to gg$	8.56 ± 0.86
$H \to \tau\tau$	6.30 ± 0.36
$H \to cc$	2.90 ± 0.35
$H \to ZZ$	2.67 ± 0.11
$H \to \gamma\gamma$	0.228 ± 0.011
$H \to Z\gamma$	0.155 ± 0.014
$H \to \mu\mu$	0.022 ± 0.001

The Higgs Boson: from Run 1 to Run 2

During **Run1** ($\sqrt{s}$ =7–8 TeV, 25 fb^{-1}) measurements of Higgs properties has been interpreted in terms of

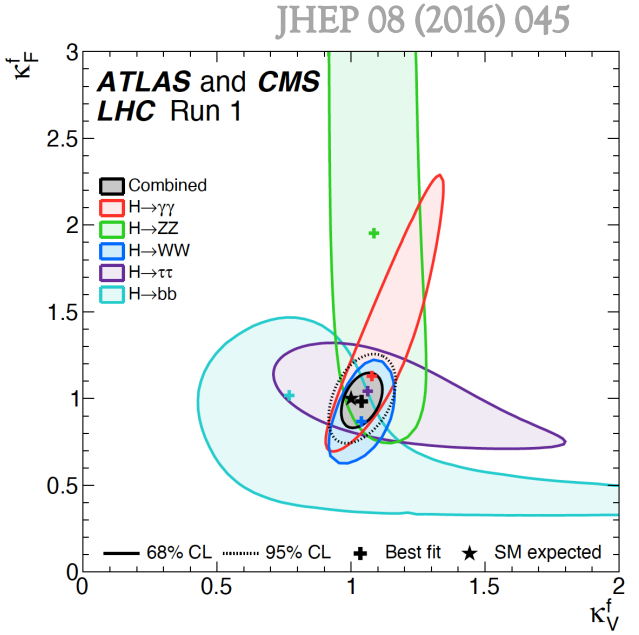
- **Signal Strength**, defined as the ratio of XS×BR observed with respect to the SM: $\mu = \frac{(\sigma \cdot BR)_{\text{obs}}}{(\sigma \cdot BR)_{\text{SM}}}$
- **Couplings modifiers κ** introduced as scale factors to the cross sections or partial decay widths

$$\sigma_i \times \text{BR}^f = \frac{\sigma_i(\vec{\kappa})\Gamma^f(\vec{\kappa})}{\Gamma_H}$$

$$\kappa_j^2 = \frac{\sigma_j}{(\sigma_j)_{SM}}$$

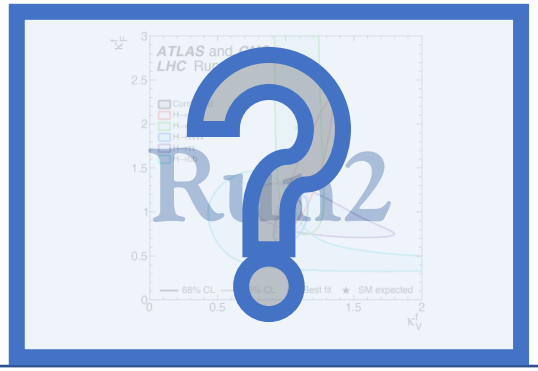
$$\kappa_j^2 = \frac{\Gamma^j}{(\Gamma^j)_{SM}}$$

JHEP 08 (2016) 045



Moving to the *Precision Era* with full **Run2** statistics ($\sqrt{s}$ =13 TeV, 139 fb^{-1})

- **Mass, Spin–CP , Width**
- **Cross Section measurements**
  - Fiducial differential cross sections
  - Cross sections per production mode
    - **Simplified Template Cross Sections (STXS)** framework to define exclusive regions for each production mode
- **Interpretation of the results** via theoretical frameworks on top of the **κ**–framework to put constraints on anomalous couplings of the Higgs boson with the other SM particles and to probe New Physics phenomena:
  - Effective Field Theory, Pseudo–Observables, …



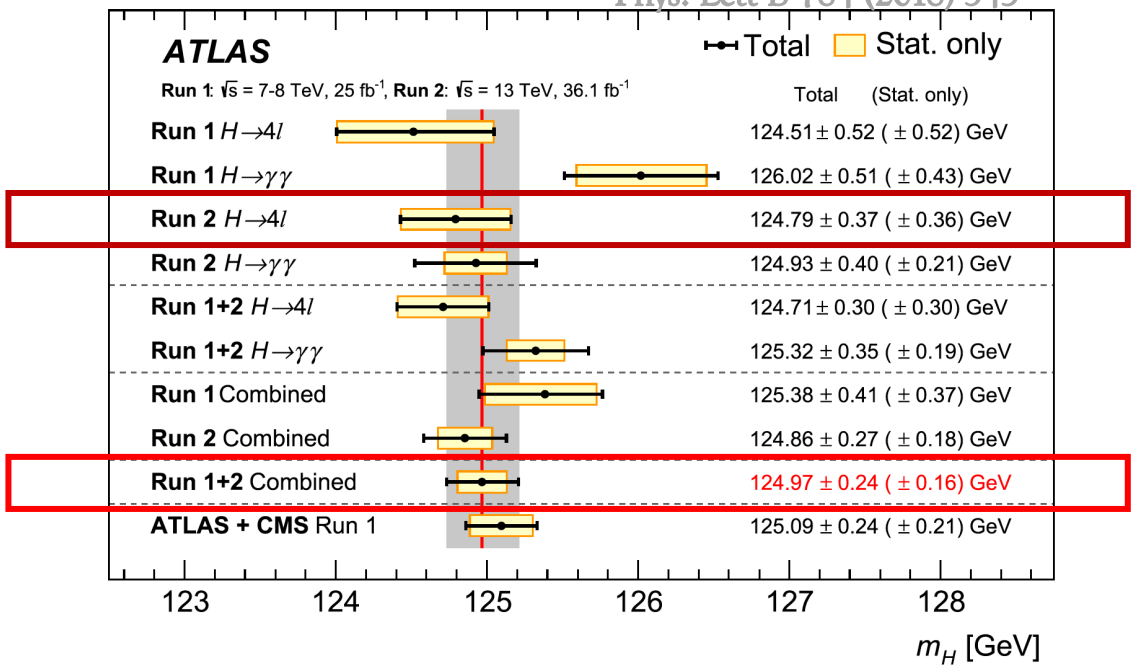
Higgs Precision Measurements

Mass

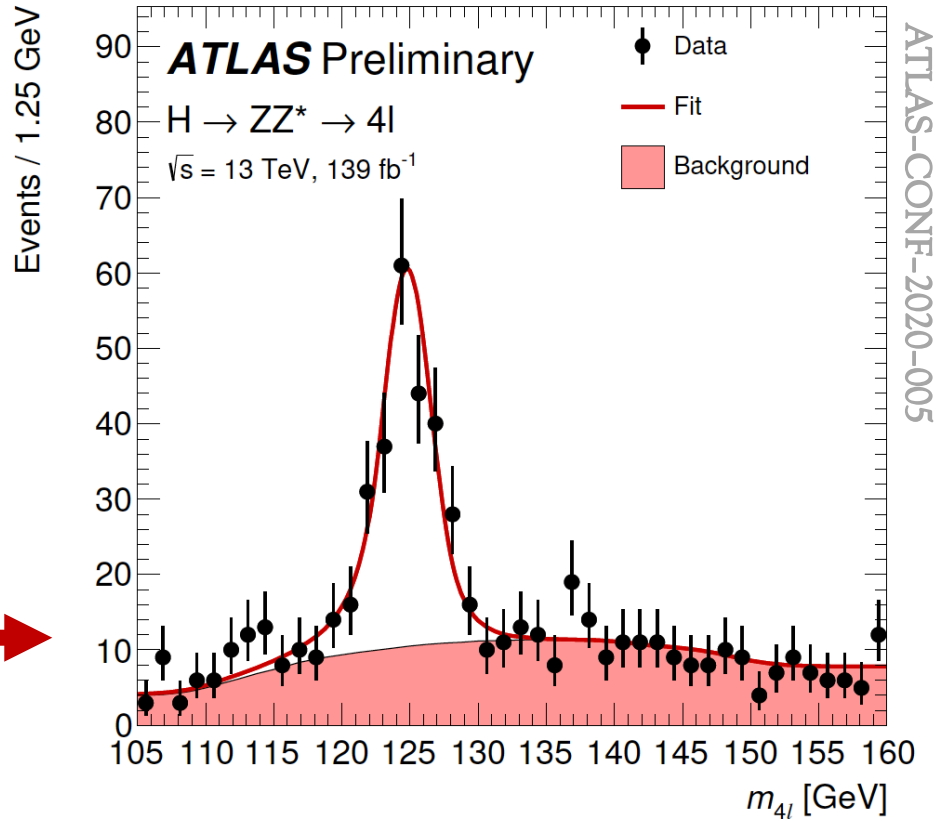
- H→ZZ* and H→γγ are the most sensitive channels → clear signature
- Resolution on mass 1–2%
- Main uncertainties: muon momentum scale (H→ZZ*→4l) and photon energy scale (H→γγ)
- H→ZZ*→4l + H→γγ: Results with 36 fb^{-1} combined with Run1
- H→ZZ*→4l: Preliminary results with 139^{-1}

Phys. Lett B 784 (2018) 345

36 fb^{-1}



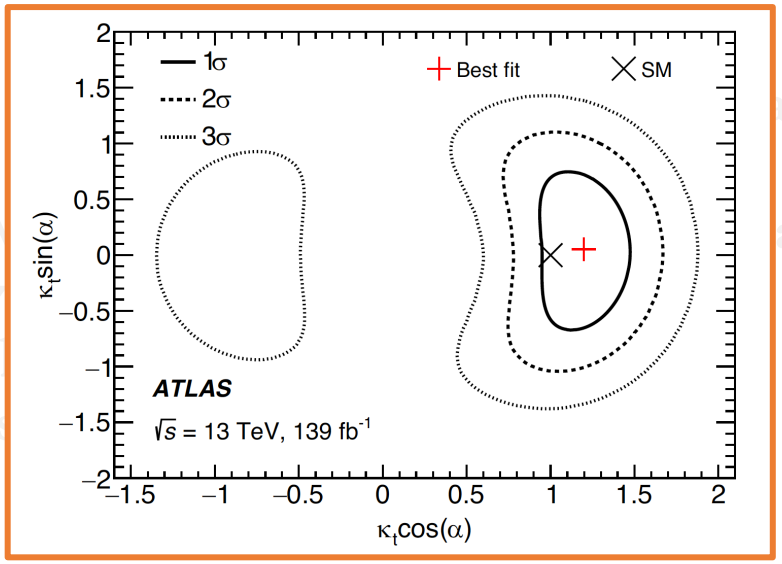
139 fb^{-1}



$$m_H = 124.92^{+0.21}_{-0.20}\ \text{GeV}$$

Higgs Precision Measurements

Spin-CP

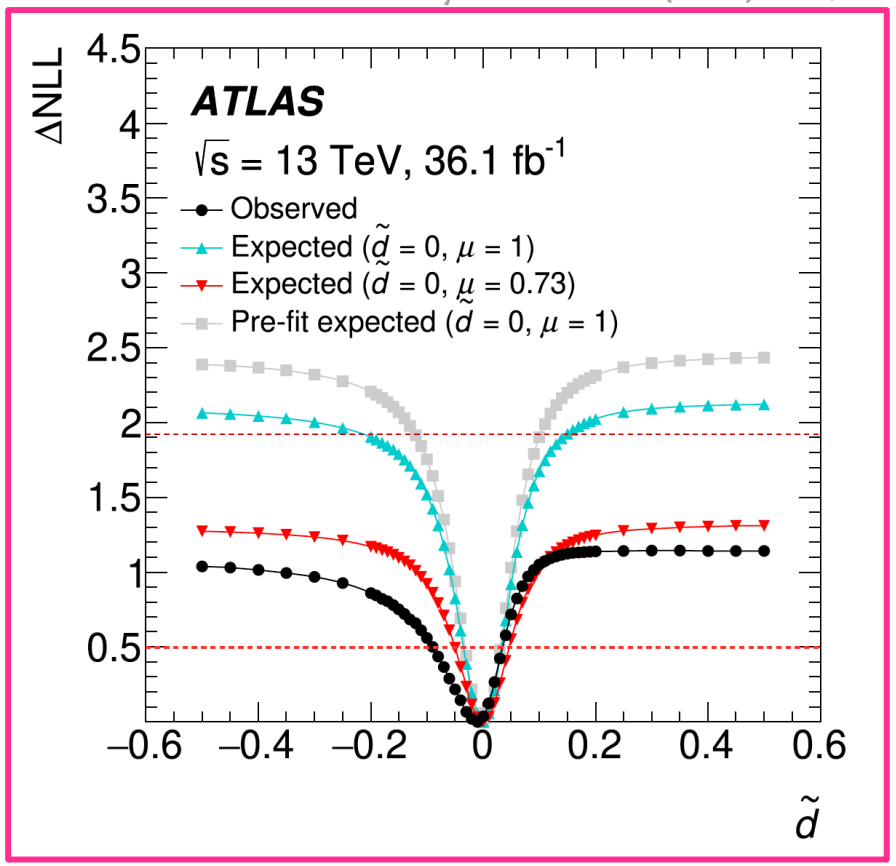


Phys. Rev. Lett. 125 (2020) 061802

SM compatibility : p-value = 35%
A pure CP-odd coupling is excluded at 3.9σ, and
|CP-mixing angle| > 43° is excluded at 95% CL

- H→$\gamma\gamma$ (139 fb^{-1}): Search of CP-violation signs in the **Yukawa couplings of Higgs boson and top quark** in the ttH production
- H→$\tau\tau$ (36 fb^{-1}): Test of CP invariance from Optimal Observable distribution in the VBF production, limits on **Higgs couplings with electroweak gauge bosons**

Phys. Lett. B 805 (2020) 135426



EFT parameter in the Hawk basis

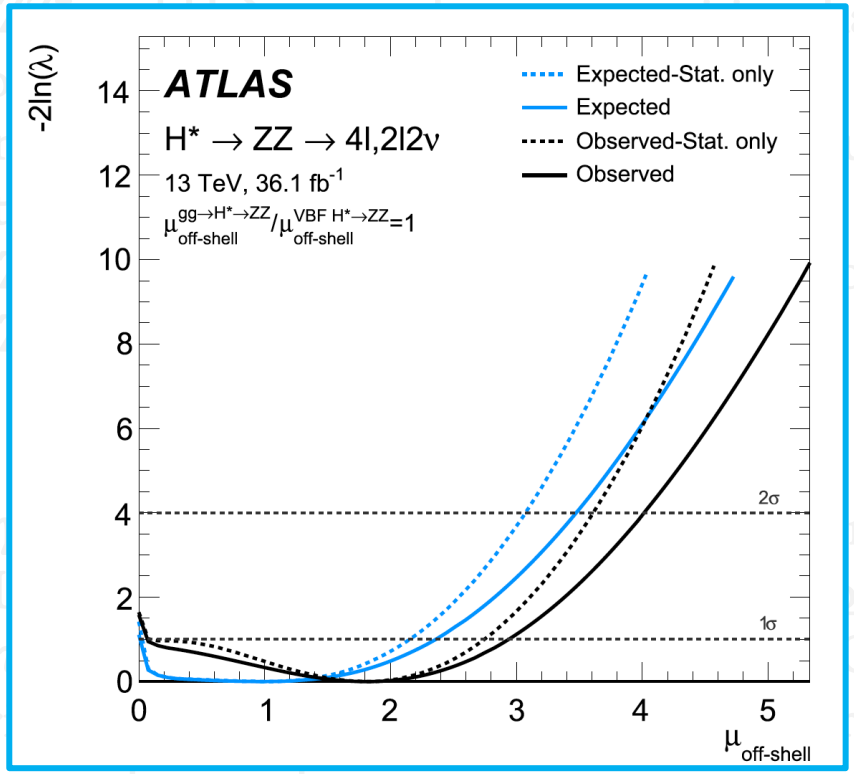
$$\tilde{d} = [-0.090, 0.035] \ @ \ 68\% \ \text{CL (obs.)}$$

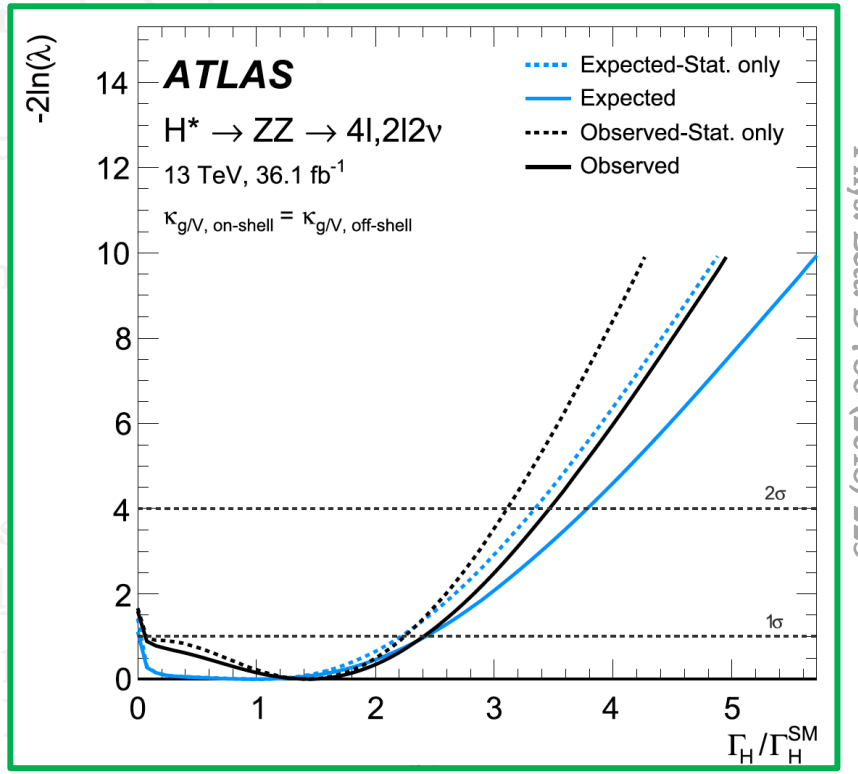
Higgs Precision Measurements

Width

$$\mu_{\text{off-shell}} = \kappa^2_{\text{g,off-shell}} \cdot \kappa^2_{\text{Z,off-shell}}$$

$$\mu_{\text{on-shell}} = \frac{\kappa^2_{\text{g,on-shell}} \cdot \kappa^2_{\text{Z,on-shell}}}{\Gamma_{\text{H}}/\Gamma^{\text{SM}}_{\text{H}}}$$





Phys. Lett. B 786 (2018) 223

Discriminating observable

H→4l: Matrix-Element based discriminant D_{ME}

H→2l2ν: transverse mass of ZZ system m_T^{ZZ}

- H→ZZ*→4l (36 fb^{-1})
  - Constraint the off-shell signal strength
  - Upper limit on Higgs width

$$\mu_{\text{off-shell}} < 3.8\ (3.4)\ @\ 95\%\ \text{CL}$$

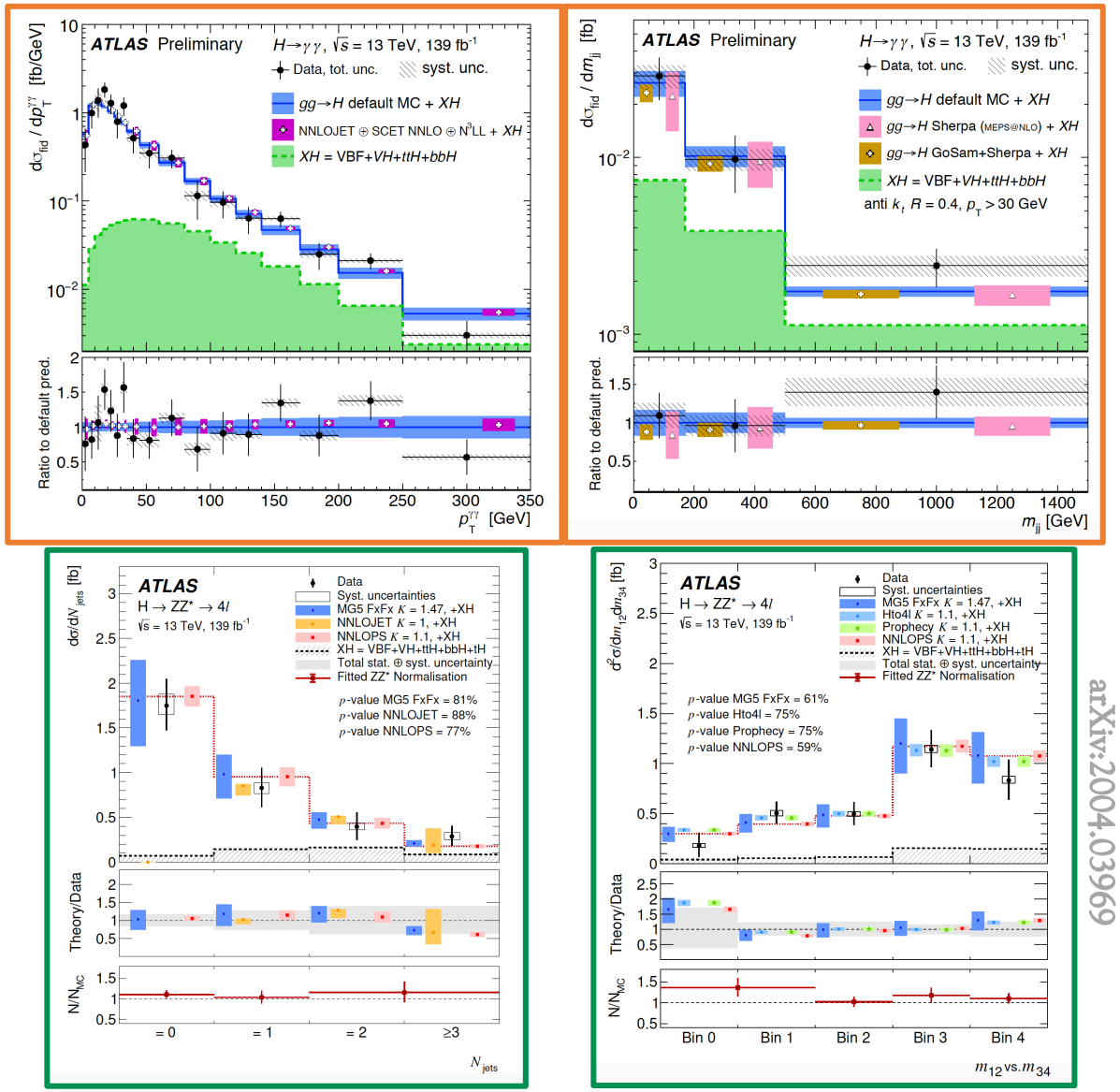
$$\Gamma_{\text{H}}/\Gamma^{\text{SM}}_{\text{H}} < 3.5\ (3.7)\ @\ 95\%\ \text{CL}$$

Differential Cross Section Measurements

- **Fiducial phase space** based on detector acceptance to minimize the model dependency
- **Unfolding** to correct for detector level effects, efficiency and resolutions
- **Variables sensitive to the Higgs boson properties** related to the Higgs kinematics or to the jets produced in association with the Higgs: p_T , $m_{12}m_{34}$, N_{jets}, m_{jj}, …
  - Several observables related to the Higgs decay into 4 leptons has been unfolded as the leptons decays angles
- **Run2 measurements with 139 fb^{-1}**
  - H→ZZ* and H→$\gamma\gamma$: statistically limited

Good agreement with SM!

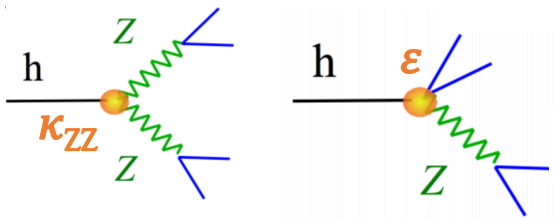
- **Interpretation of the results**



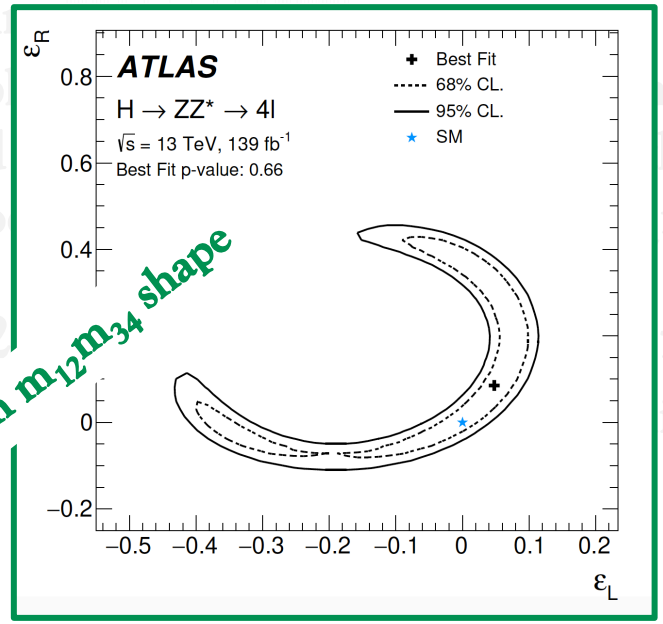
ATLAS-CONF-2019-029

arXiv:2004.03969

Differential Cross Section Measurements



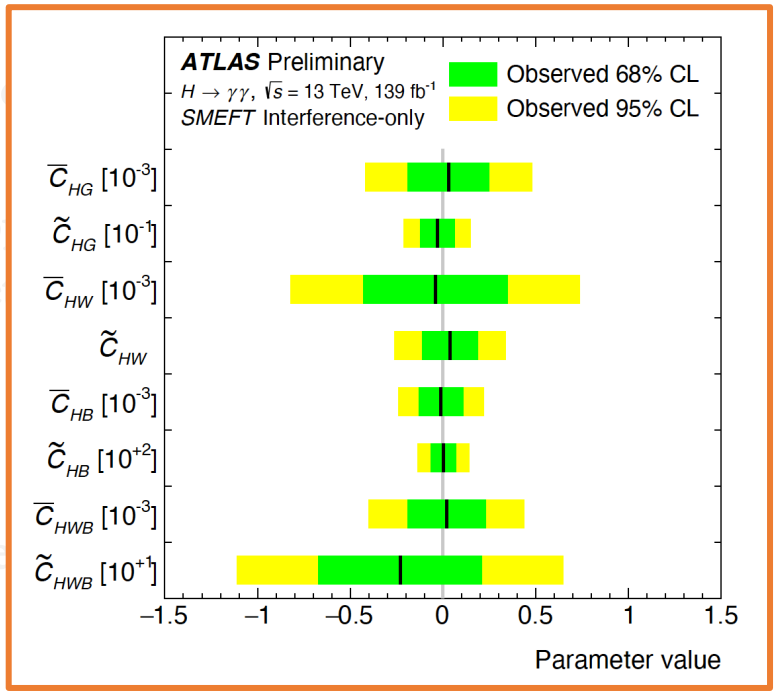
Pseudo-Observable



Effects on $m_{12}m_{34}$ shape

arXiv:2004.03969

SILH EFT



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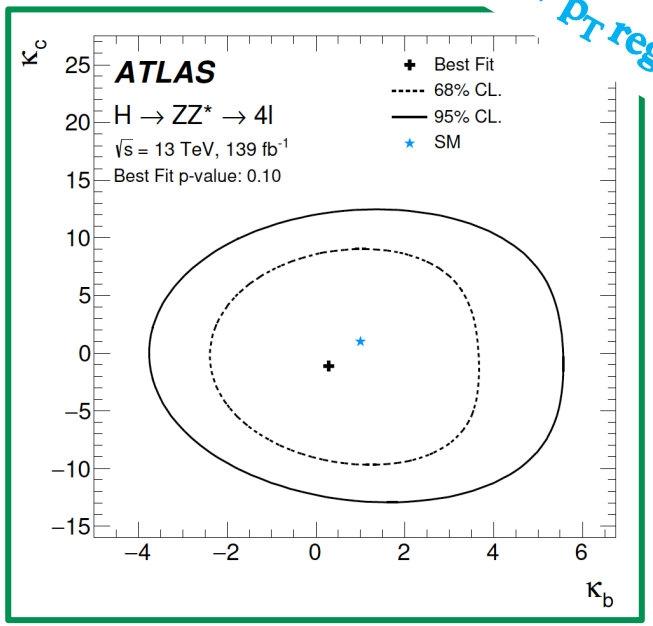
Effects on p_T, N_{jets}, m_{jj}, $\Delta\phi_{jj}$, $p_T^{lead.jet}$

Light Yukawa

Effects on low p_T region



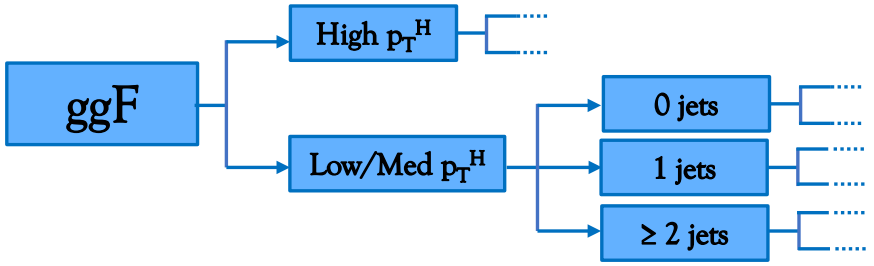
H→ZZ* $\kappa_c = [-12, 11]$ @ 95% CL

H→γγ $\kappa_c = [-19, 24]$ @ 95% CL

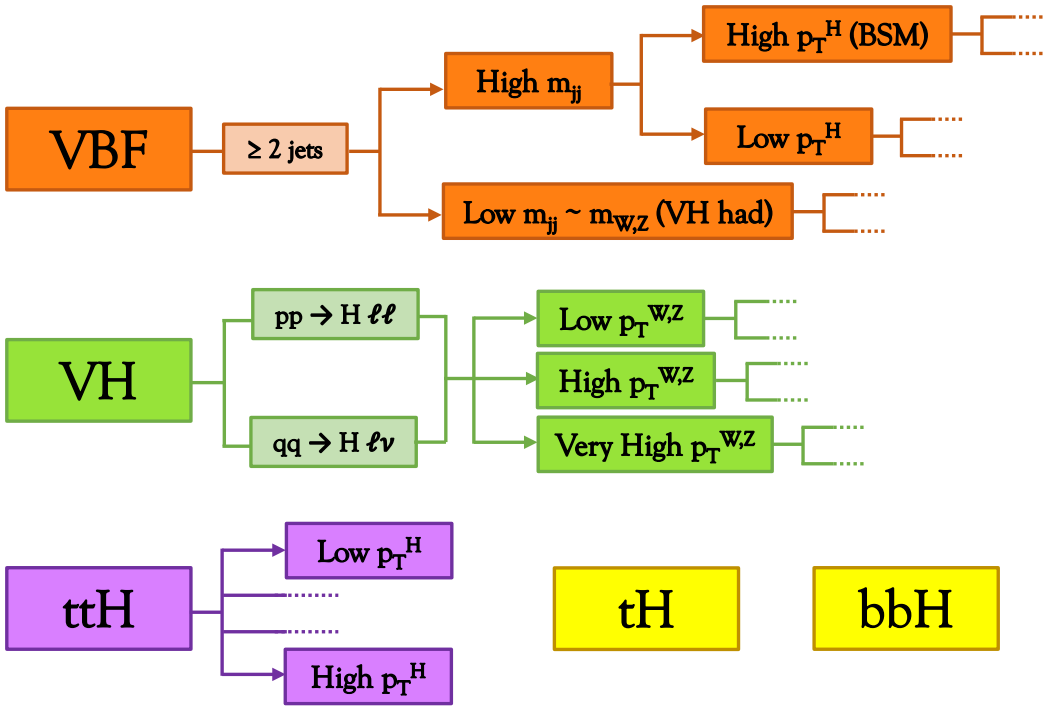
- **Interpretation of the results**
  - H→ZZ*: Limits on modified Higgs boson interaction within the Pseudo-Observable framework
  - H→γγ: Constraints on Wilson coefficients in the Warsaw basis for SILH EFT.
  - H→ZZ* and H→γγ: Constraint on the Yukawa coupling to the charm quark

Production Cross Section Measurements

- **Production cross sections** are a way to probe the strength of the Higgs boson coupling with SM particles and possible BSM effects



- **STXS** framework define exclusive regions in the Higgs phase space of the Higgs production processes, based on the kinematics of the Higgs and of the particles/jets produced in association: p_T^{Higgs} , N_{jets} , m_{jj} , $p_T^{W,Z}$
  - Criteria:
    - Minimizing the dependence on theoretical uncertainties
    - Maximizing experimental sensitivity also to possible BSM effects
  - Different STXS Stages definition, corresponding to increasingly fine granularity
  - Not all the analyses are sensitive to all the STXS bins



- Reco-level categorization in each analysis, in which the measurement is performed, as close as possible to the Particle-level categorization → minimize model-dependent extrapolation

Production Cross Section Measurements

ATLAS-CONF-2020-026

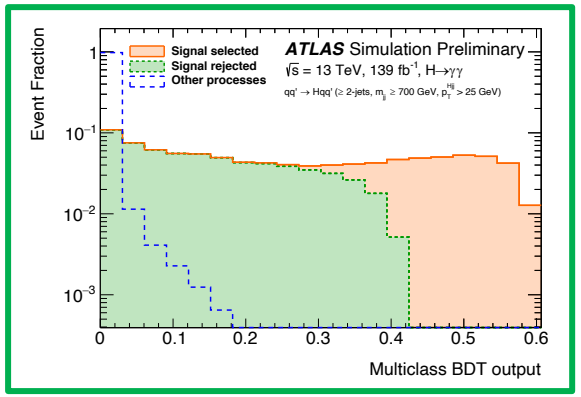
H→γγ @ 139 fb^{-1}

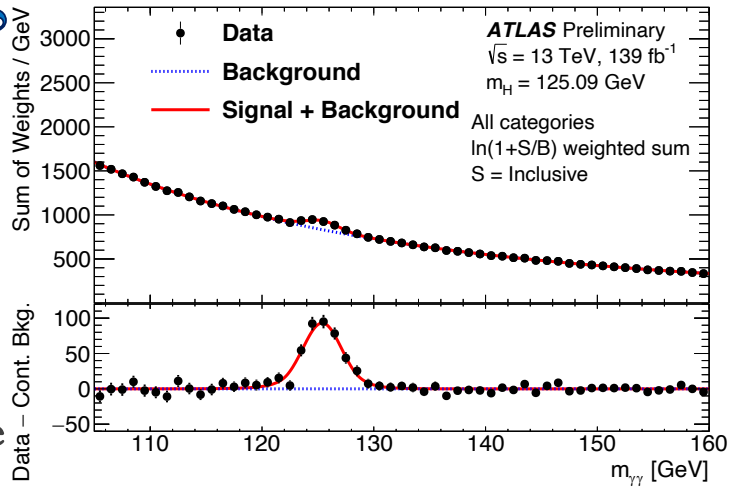
Results

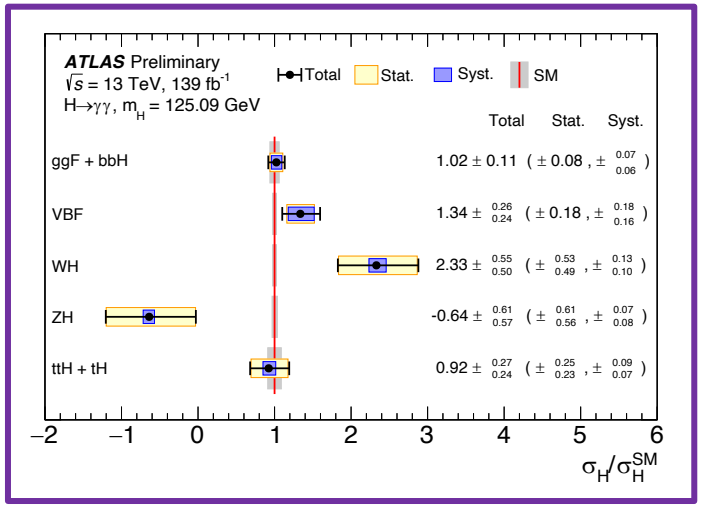
- 27 STXS categories (based on Stage 1.2)
- Two-step Categorization
  - 1st step: 44 reco event categories: Multiclass BDT to discriminate different production mode
  - 2nd step: split each category in 2-3 subcategories to separate signal from continuum background using a BDT

→ 88 Reco categories

- Fit on $m_{\gamma\gamma}$ to extract signal in each category







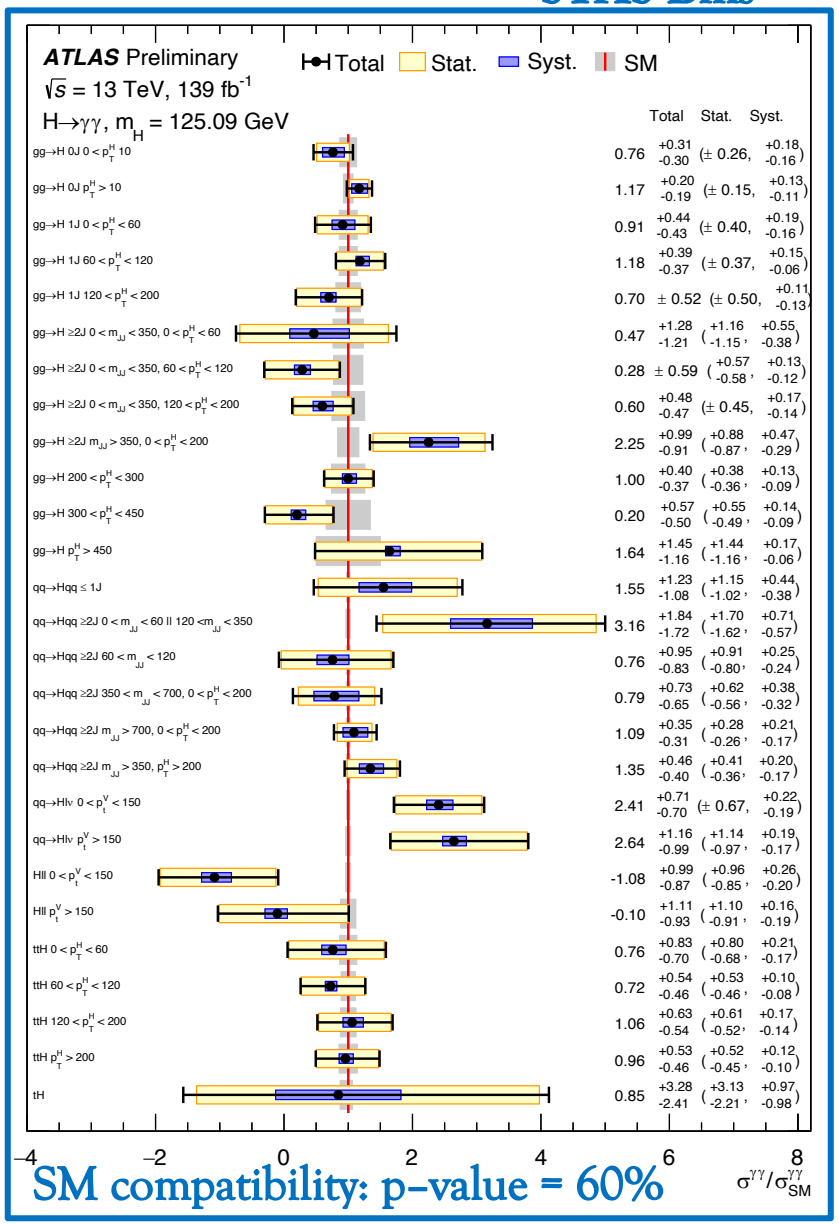
Production XS

- SM compatibility of 5-POI fit: p-value = 3% (1.9 σ deviation)
- Large anti-correlation (42%) between WH and ZH

→ Total VH measurement: $\sigma_{VH} = 5.9 \pm 1.4$ fb

($\sigma_{VH,exp} = 4.53 \pm 0.12$ fb)

STXS Bins



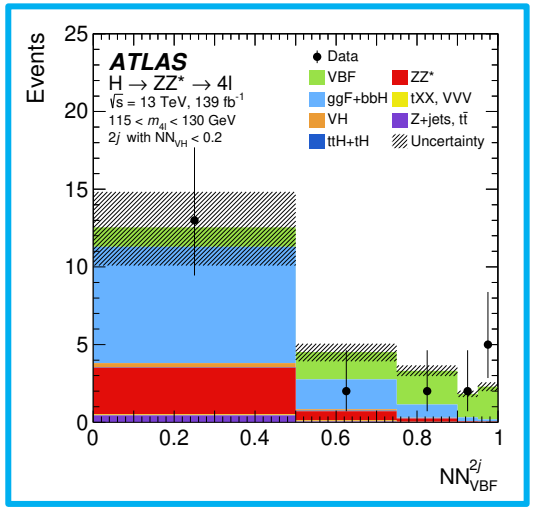
SM compatibility: p-value = 60%

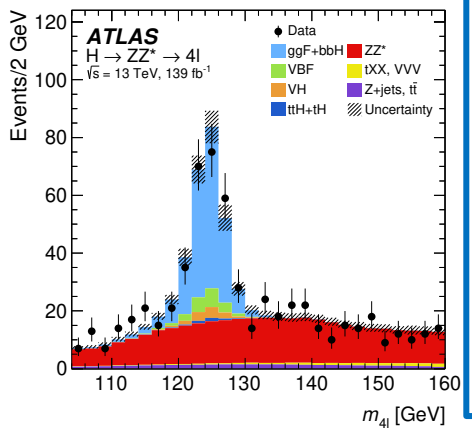
Production Cross Section Measurements

arXiv:2004.03447

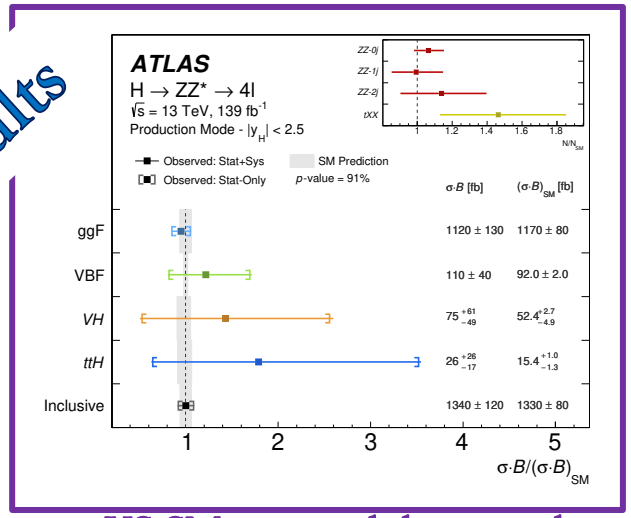
H→ZZ*→4l @ 139 fb^{-1}

- 12 STXS categories (based on Stage 1.1)
- 12 Signal Reco categories: based on number of additional jets and leptons in the final state
- + 5 ZZ Sideband categories: m4l∈[105,115]∪[130,160] GeV to constraint the non-resonant ZZ* background
- Neural Network as multivariate discriminant in each category, used as observable in the fit

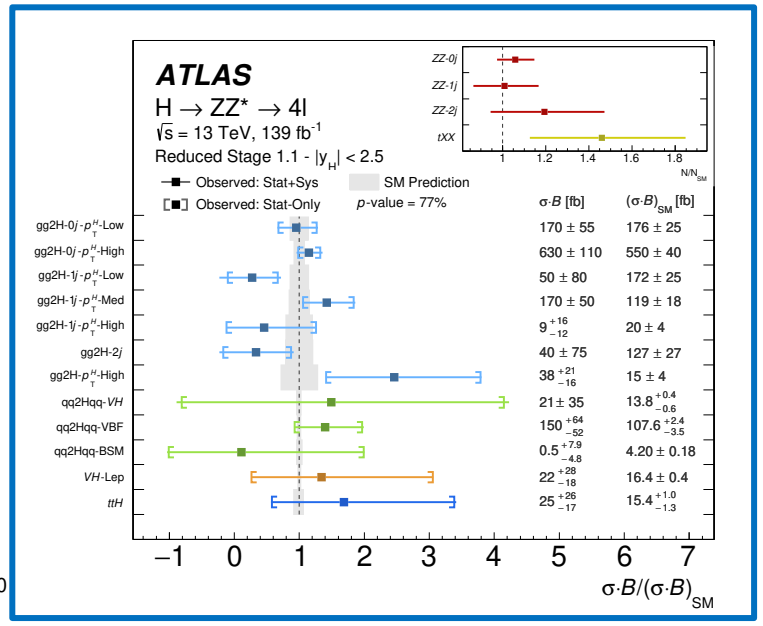




Results

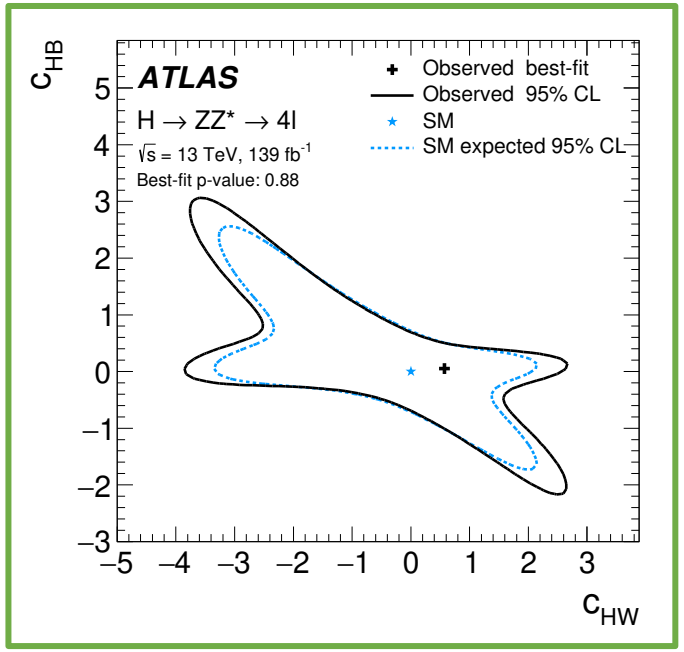


Production XS SM compatibility: p-value = 91%



STXS SM compatibility: p-value = 77%

EFT Interpretation



EFT CP-even and CP-odd couplings

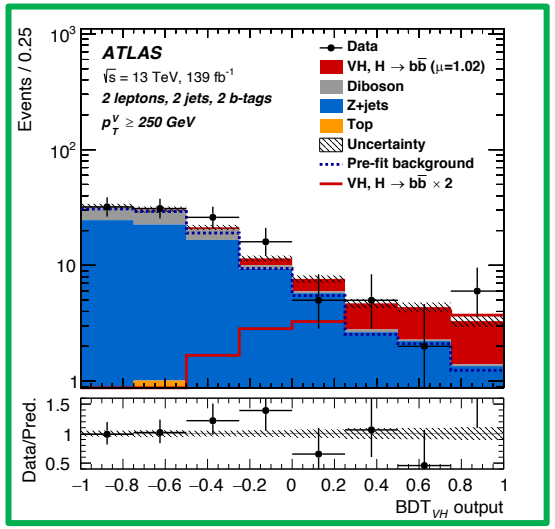
EFT coupling parameter	Expected 68% CL	Expected 95% CL	Observed 68% CL	Observed 95% CL	Best-fit value	Best-fit p-value
c_{HG}	[−0.004, 0.004]	[−0.007, 0.008]	[−0.005, 0.003]	[−0.008, 0.007]	−0.001	0.79
c_{uH}	[−8, 20]	[−14, 26]	[−12, 6]	[−18, 30]	−6, 18	0.50
c_{HW}	[−1.6, 0.9]	[−2.9, 1.6]	[−1.5, 1.3]	[−3.4, 2.1]	0.5	0.66
c_{HB}	[−0.43, 0.38]	[−0.62, 0.60]	[−0.42, 0.37]	[−0.62, 0.59]	−0.03	0.98
c_{HWB}	[−0.75, 0.63]	[−1.09, 0.99]	[−0.71, 0.63]	[−1.06, 0.99]	0.1	0.93
$c_{H\tilde{G}}$	[−0.022, 0.022]	[−0.031, 0.031]	[−0.019, 0.019]	[−0.029, 0.029]	0.000	1.00
$c_{\tilde{u}H}$	[−26, 26]	[−40, 40]	[−37, 37]	[−50, 50]	±21	0.48
$c_{H\tilde{W}}$	[−1.3, 1.3]	[−2.1, 2.1]	[−1.5, 1.5]	[−2.4, 2.4]	±0.6	0.84
$c_{H\tilde{B}}$	[−0.39, 0.39]	[−0.57, 0.57]	[−0.37, 0.37]	[−0.56, 0.56]	0.00	1.00
$c_{H\tilde{W}B}$	[−0.71, 0.71]	[−1.05, 1.05]	[−0.69, 0.69]	[−1.03, 1.03]	0.0	1.00

Production Cross Section Measurements

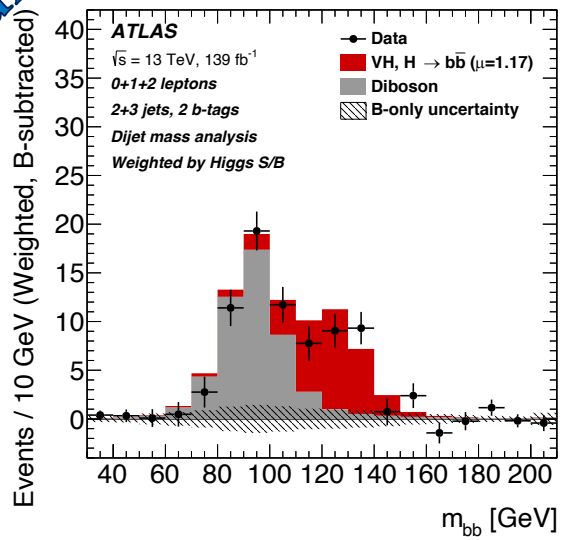
arXiv:2007.02873

VH, H→bb̄ @ 139 fb^{-1}

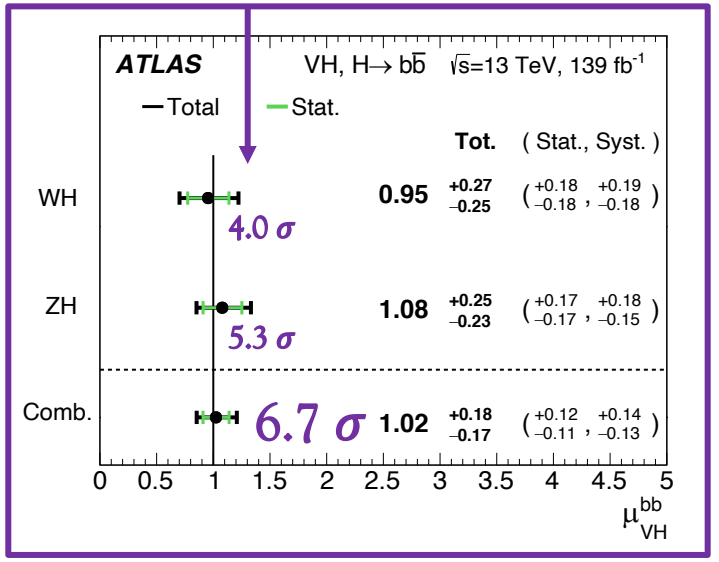
- 5 STXS categories (based on Stage 1.2)
- Categorization: based on charged lepton multiplicity, p_T^V and jet multiplicity
  - 14 analysis regions split in three categories: 1 Signal Region and 2 Control Regions enriched in V+jets and tt̄
  - → 42 Reco categories
- BDT_{VH} designed to discriminate the VH signal from the background processes and used as fit observable



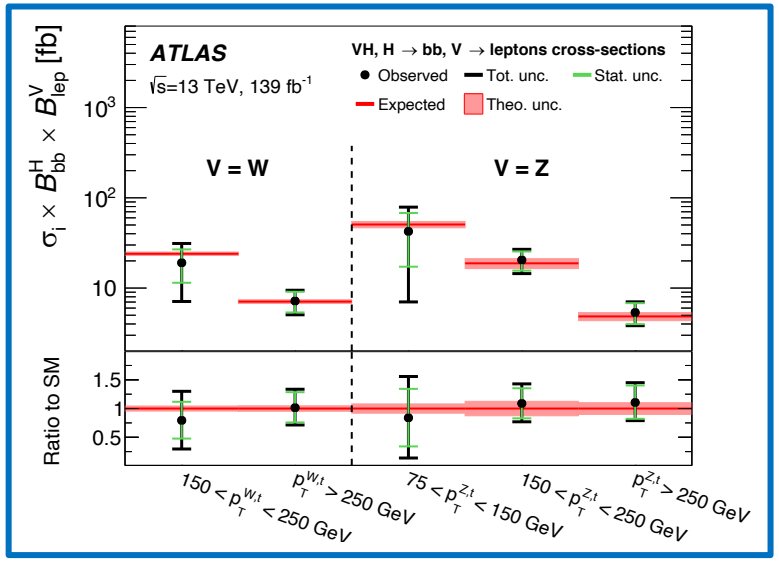
Results



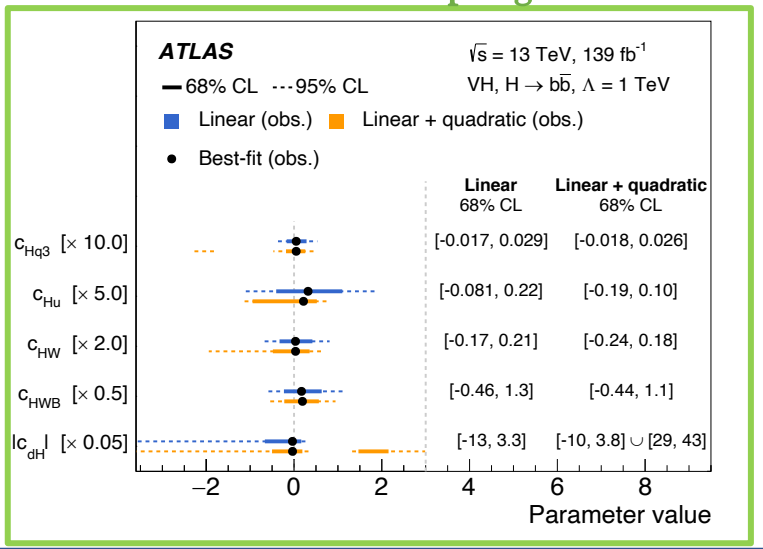
Observed signal significance



STXS in good agreement with SM



Constraints on EFT couplings



Production Cross Section Measurements

H→WW*→eν μν and H→ττ

H→WW*

- 36.1 fb^{-1} Analysis targets ggF and VBF production
  Categorization based on N_{jets} = 0,1 (ggF); ≥2 (VBF). CRs used to estimate backgrounds. Use of BDT in the VBF category.

$$\sigma_{\mathrm{ggF}} \cdot \mathcal{B}_{H\to WW*} = 11.4^{+2.2}_{-2.1}\ \mathrm{pb}$$

$$\sigma_{\mathrm{VBF}} \cdot \mathcal{B}_{H\to WW*} = 0.50^{+0.29}_{-0.28}\ \mathrm{pb}$$

Expected: 10.4 ± 0.6 pb (ggF); 0.81 ± 0.02 pb (VBF)

Observed ggF and VBF signals have significances of 6.0 σ and 1.8 σ → low significance for VBF

- 139 fb^{-1} Preliminary analysis targets VBF
  Improve the VBF signal sensitivity with DNN.

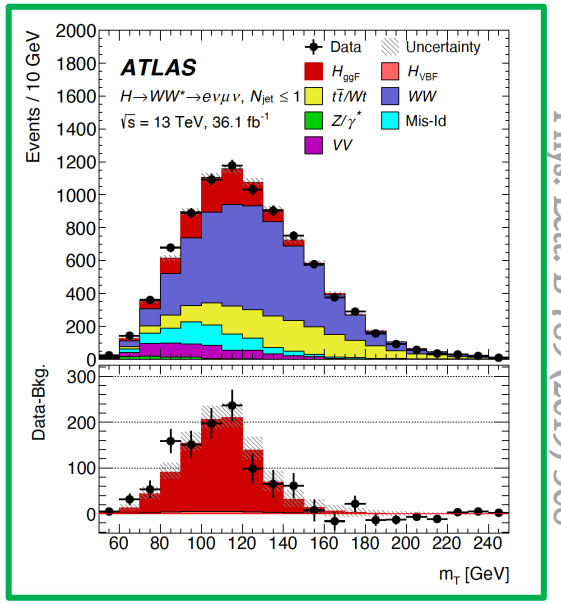
$$\sigma_{\mathrm{VBF}} \cdot \mathcal{B}_{H\to WW*} = 0.85^{+0.20}_{-0.17}\ \mathrm{pb}$$

Observed VBF signals

significance of 7.0 σ

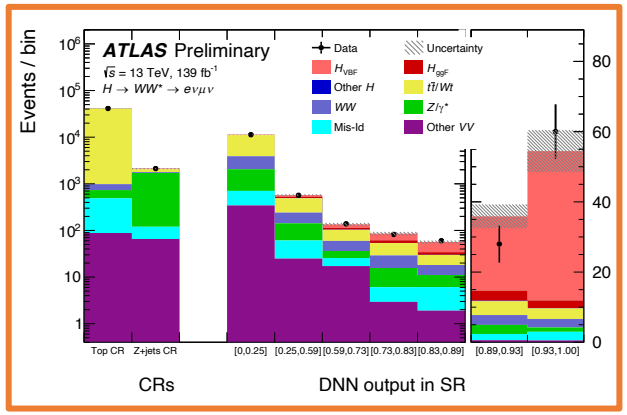
First Observation of VBF in H→WW*

36.1 fb^{-1} ggF categories



Phys. Lett. B 789 (2019) 508

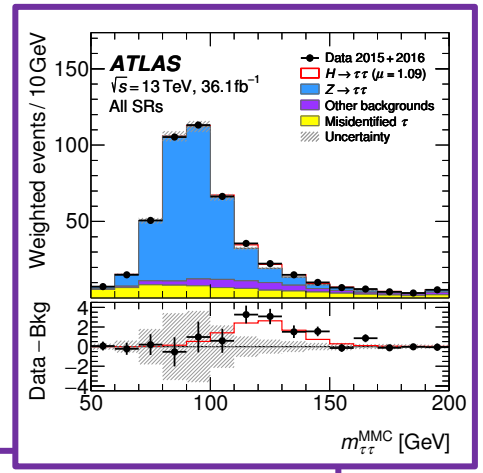
139 fb^{-1} VBF SR + CR



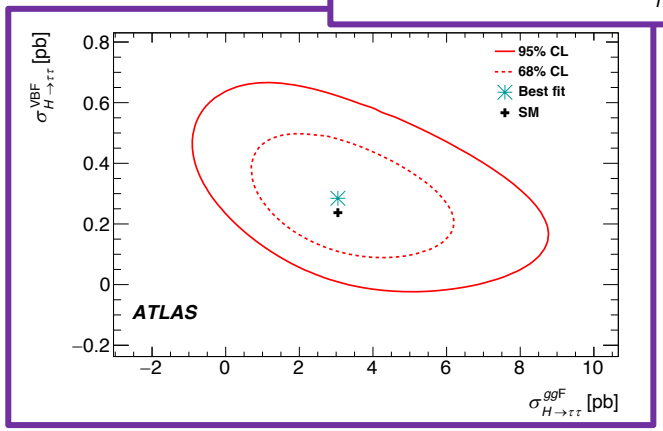
ATLAS-CONF-2020-045

H→ττ Phys. Lett. D 99 (2019) 072001

- 36.1 fb^{-1} Analysis targets ggF and VBF production Categorization with N_{jets}≥2 for VBF and $p_T^{\tau\tau}$>100 GeV for high-p_T^H (mainly ggF). CRs to constraint normalization for main backgrounds.
- Fit performed on $m_{\tau\tau}$.



Measurements consistent with SM



Production Cross Section Measurements

Searches H→*inv*, H→*Zγ* and H→μμ

VBF, H→*inv* @ 139 fb^{-1} ATLAS-CONF-2020-008

- Probe possible Higgs decay in WIMPs (Dark Matter candidates)
- Categorization based on N_{jets}, m_{jj} and $\Delta\phi_{jj}$; adding CRs to constraint V+jets and multi-jet background processes.
- Results
  - Assuming a SM cross section with m_H = 125 GeV

$$\mathcal{B}_{inv} < 0.13 \text{ @ } 95\% \text{ CL}$$

H→*Zγ* @ 139 fb^{-1} arXiv:2005.05382

- Search Higgs decay in $Z\gamma$
- Categorization based on jets and $Z\gamma$ system kinematics. Use of BDT for VBF category.

Observed significance of 2.2σ

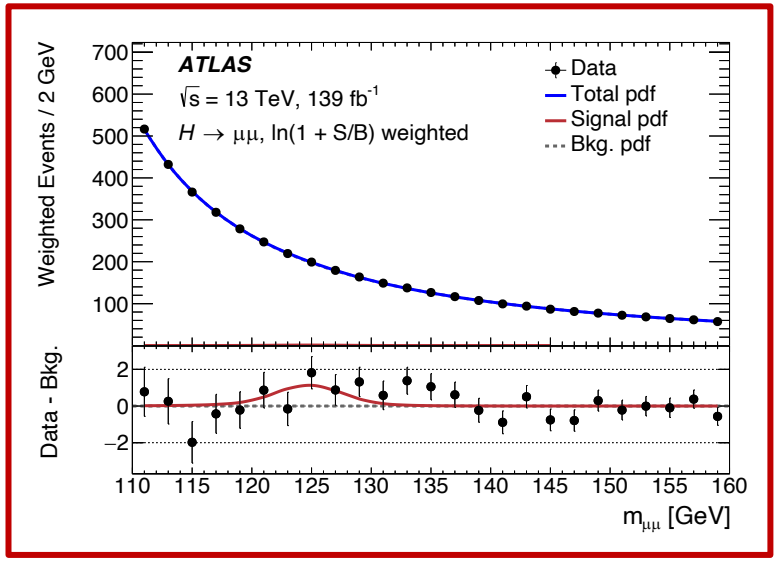
$$\mu_{H\to Z\gamma} = 3.6 \times \mu^{SM}_{H\to Z\gamma}$$

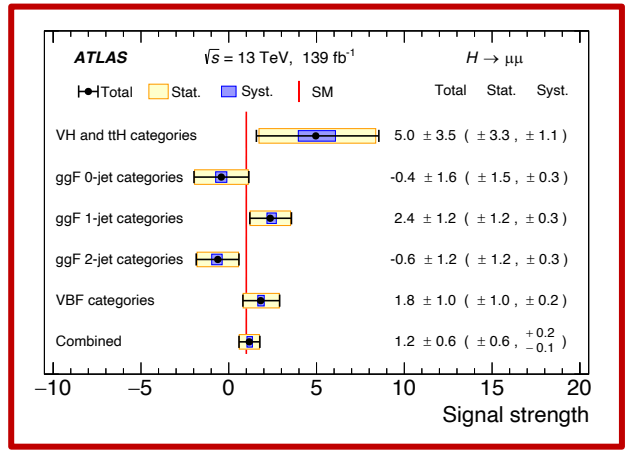
H→*μμ* @ 139 fb^{-1} arXiv:2007.07830

- Search a resonance at 125 GeV in the invariant mass spectrum $m_{\mu\mu}$ for pairs of opposite-charge muons, dominated by Drell-Yan contribution.
- Categorization based on number of additional jets and leptons in the final state. Further split for ggF and VBF using BDTs: 20 categories.

Observed significance of 2σ

$$\mu_{H\to\mu\mu} < 2.2 \text{ @ } 95\% \text{ CL}$$





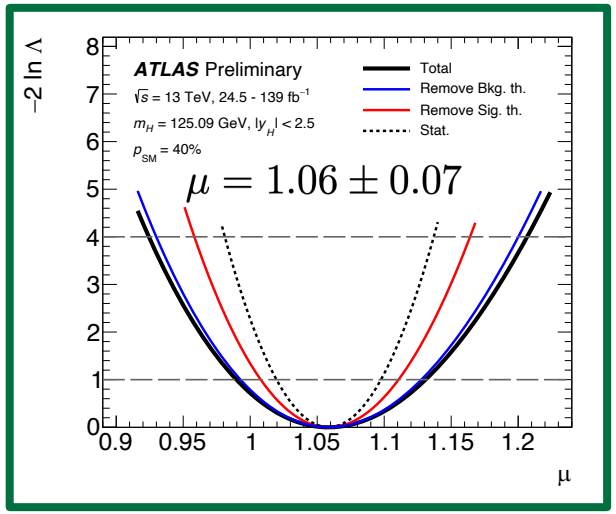
Production Cross Section Measurements

ATLAS-CONF-2020-027

Combined Results @ 139 fb^{-1}

STXS

Global Signal Strength

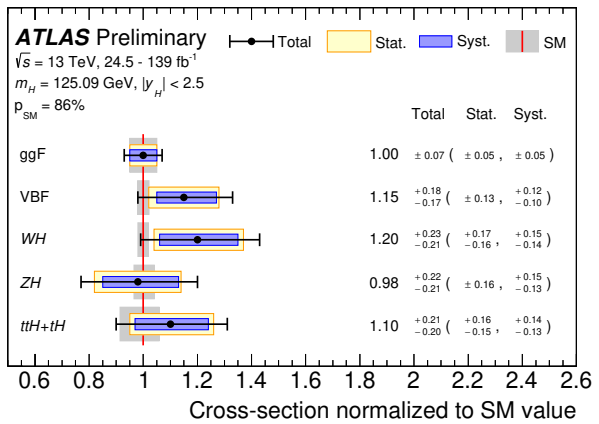


Good agreement with SM expectation

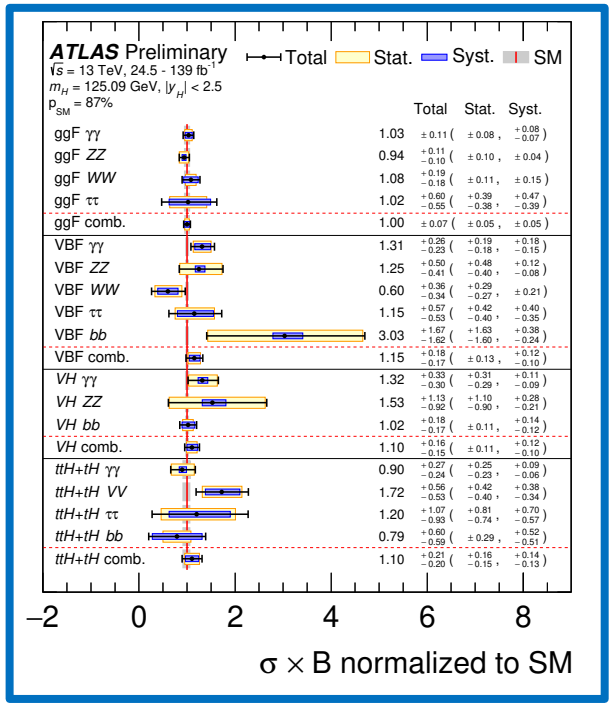
- **Prod XS** significance > 5 σ for all production mode. SM compatibility: p-value 86%
- **σ×BR** assumes SM values for (ggF)H→bb; (VH) H→WW and (VH)H→$\tau\tau$. SM compatibility: p-value 87%
- **STXS** results normalized wrt: $(\sigma \times B)_{if} = (\sigma \times B)_{i,ZZ} \cdot \left(\frac{B_f}{B_{ZZ}}\right)$

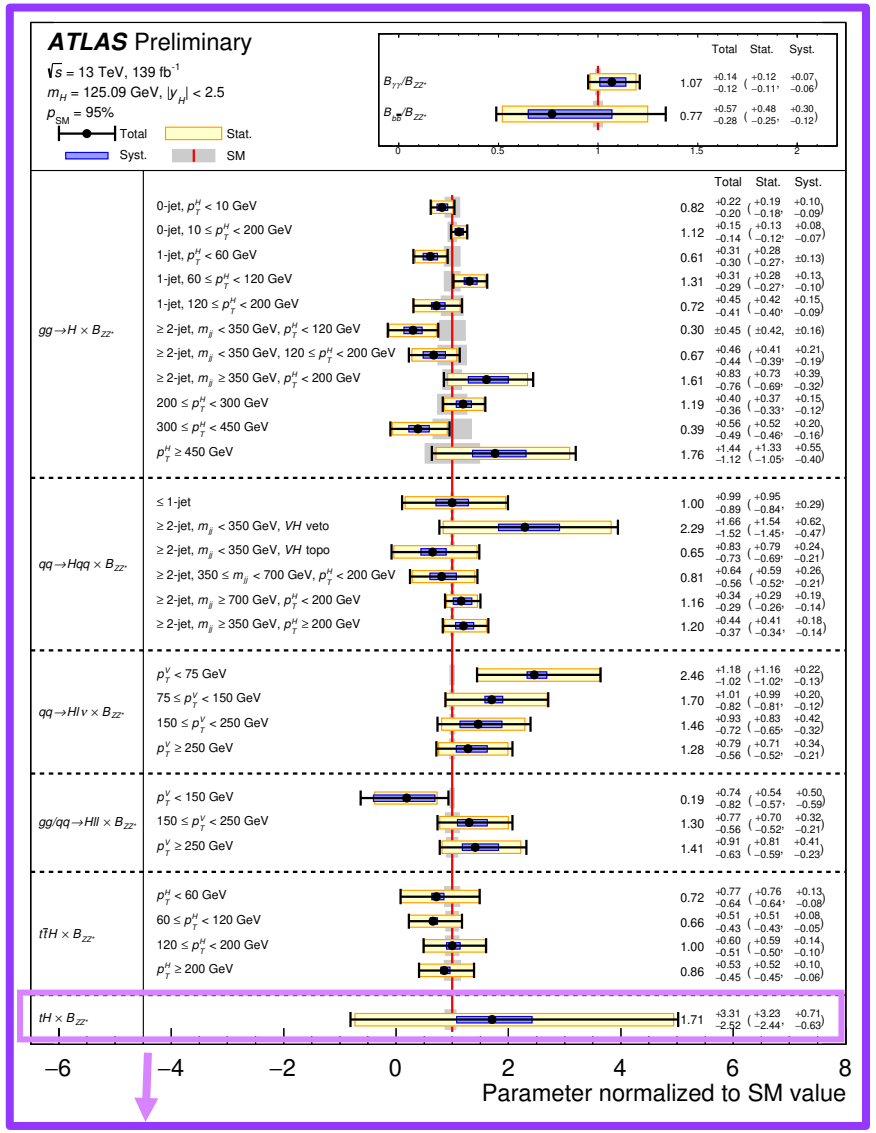
SM compatibility: p-value 95%

Production Cross Sections



Production and Decay





$\sigma_{tH,obs} < 8.4 \times \sigma_{tH,SM}$ @ 95% CL

Production Cross Section Measurements

ATLAS-CONF-2020-027

Combined Results @ 139 fb^{-1}

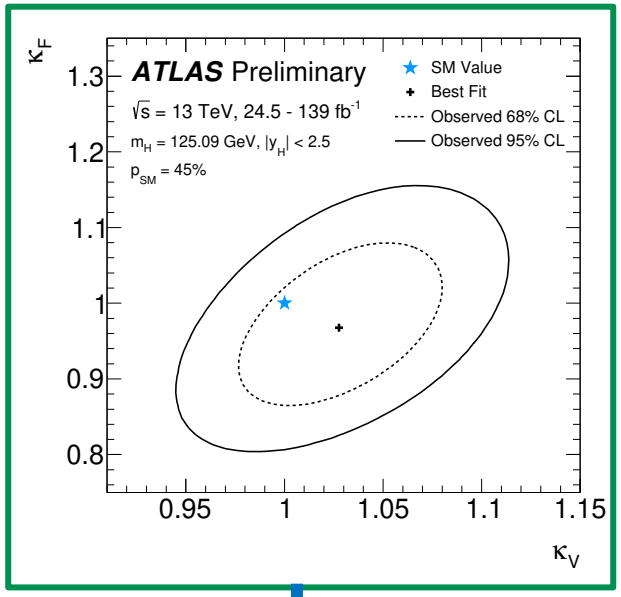
Interpretation of Results in the κ framework

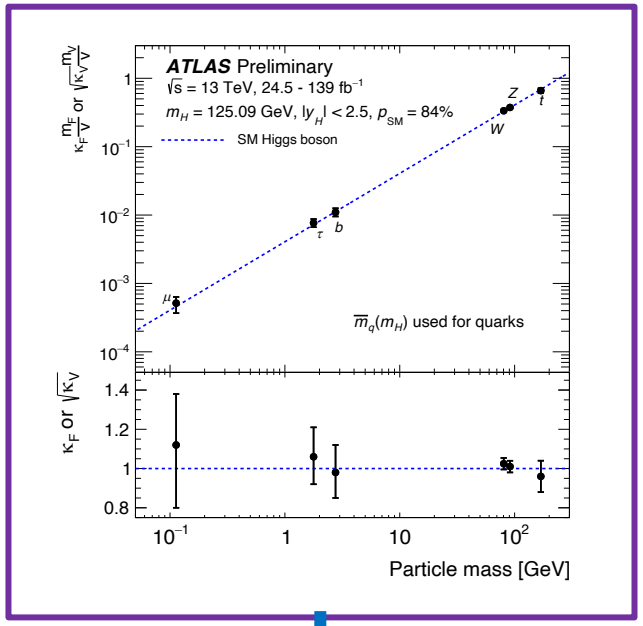
Coupling modifiers to the SM particles: scale factor to XS and BR

Different level of assumptions:

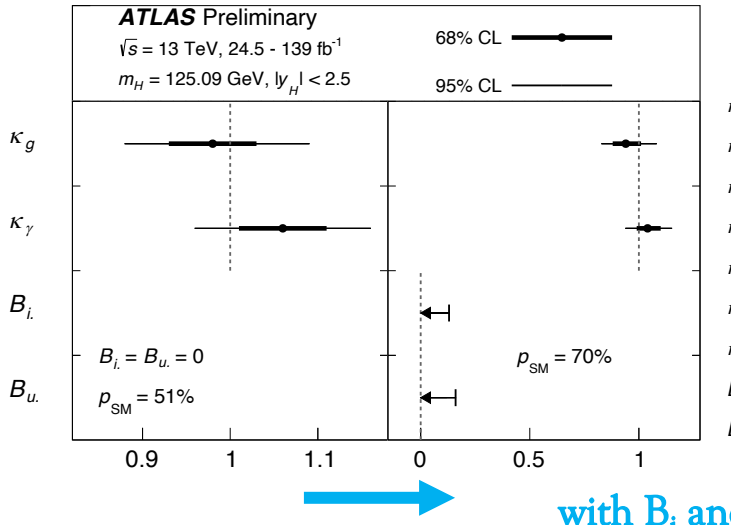
- Universal coupling-strength scale factors κ_V (vector bosons) and κ_F (fermions) → SM particle in loops
- Generic parametrization with coupling-strength to W, Z, t, b, τ and μ independent → SM particle in loops
- Including BSM contributions in loops: effective couplings κ_g and κ_γ.
  - May contribute to the total Higgs width, sensitive to possible invisible decay (B_i) and undetected decay (B_u)

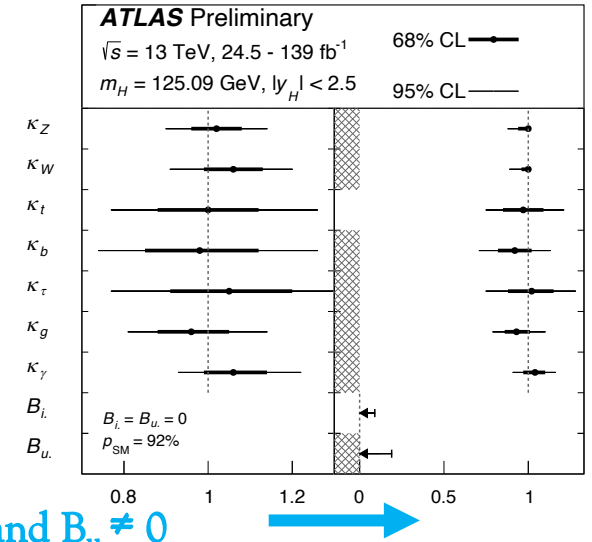
$$\kappa_H^2(\kappa, B_{\mathrm{i.}}, B_{\mathrm{u.}}) = \frac{\sum_j B_j^{\mathrm{SM}} \kappa_j^2}{(1 - B_{\mathrm{i.}} - B_{\mathrm{u.}})}$$





Including BSM in loops





with B_i and $B_u \neq 0$

Production Cross Section Measurements

ATLAS-CONF-2020-027

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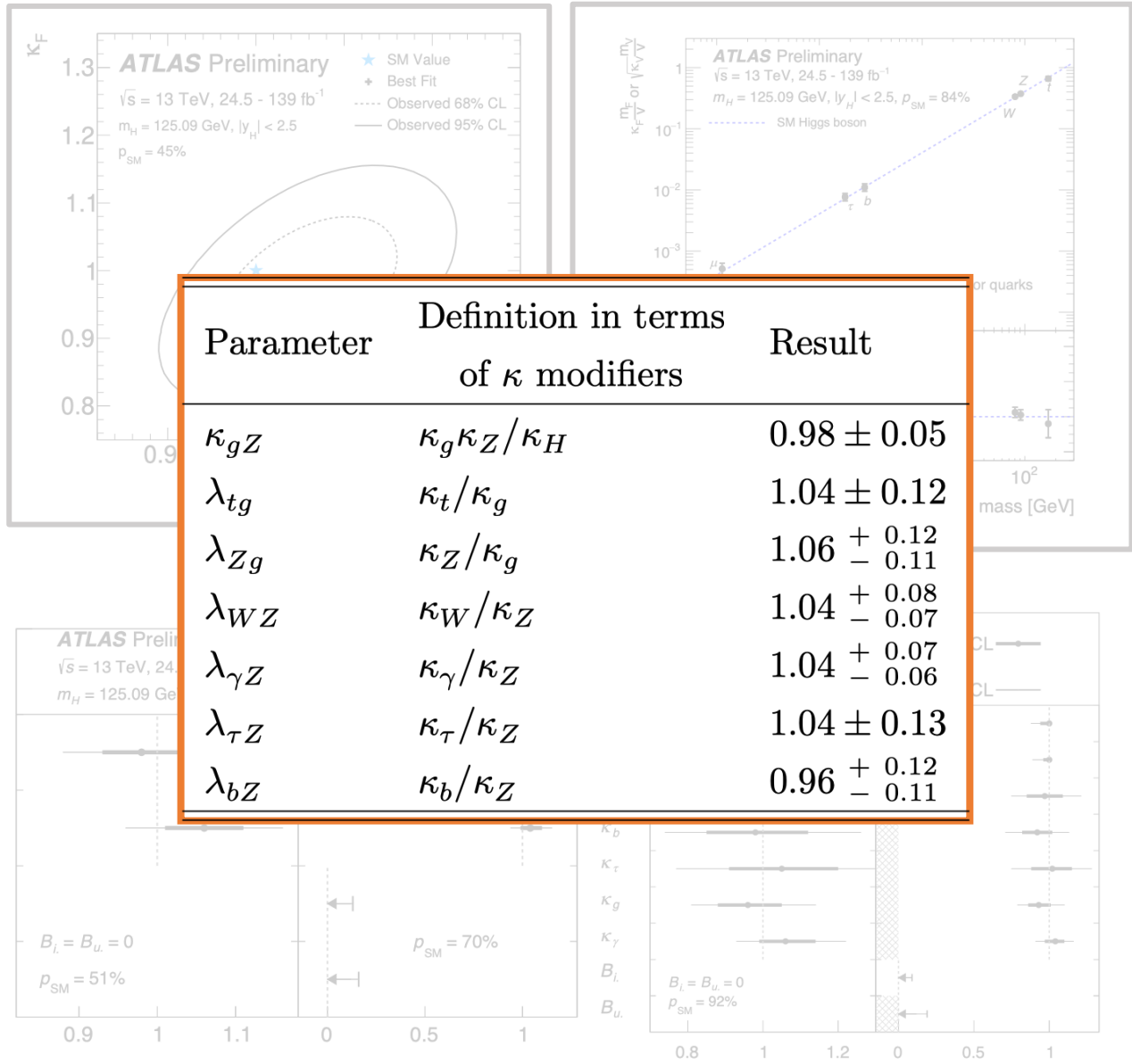
- Generic parametrization using ratio of coupling modifiers: most model-independent coupling strength determination



Parameter	Definition in terms of κ modifiers	Result
κ_{gZ}	$\kappa_g\kappa_Z/\kappa_H$	0.98 ± 0.05
λ_{tg}	κ_t/κ_g	1.04 ± 0.12
λ_{Zg}	κ_Z/κ_g	$1.06 \,^{+\,0.12}_{-\,0.11}$
λ_{WZ}	κ_W/κ_Z	$1.04 \,^{+\,0.08}_{-\,0.07}$
$\lambda_{\gamma Z}$	κ_γ/κ_Z	$1.04 \,^{+\,0.07}_{-\,0.06}$
$\lambda_{\tau Z}$	κ_τ/κ_Z	1.04 ± 0.13
λ_{bZ}	κ_b/κ_Z	$0.96 \,^{+\,0.12}_{-\,0.11}$

Production Cross Section Measurements
Combined Results @ 139 fb^{-1}

ATLAS-CONF-2020-027

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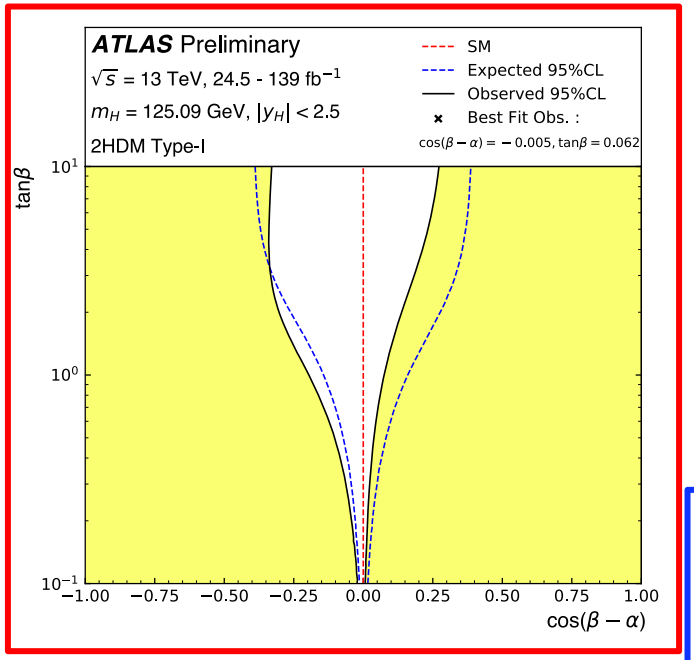

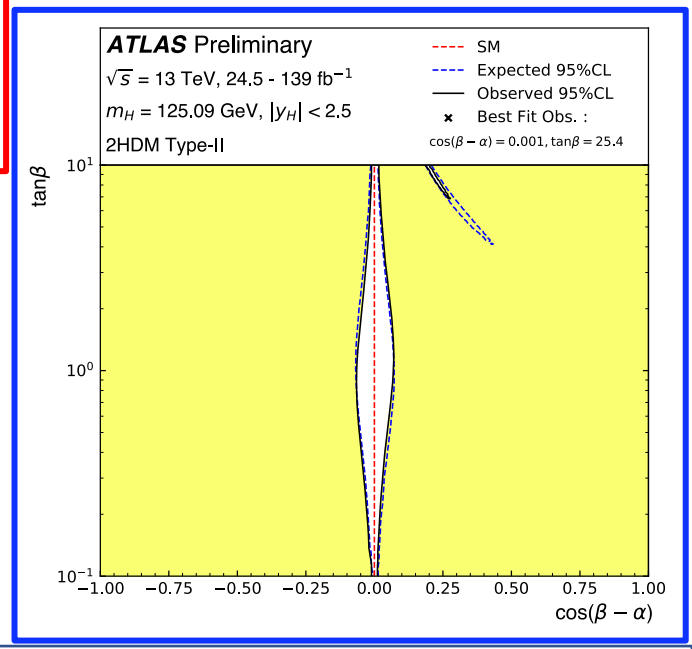

Interpretation in Two-Higgs-doublet models (2HDMs)

Additional complex isodoublet scalar field. Different models based on coupling type:

- Type I: One Higgs doublet couples to vector bosons and the other to fermions
- Type II: One Higgs doublet couples to up-type quarks and the other to down-type quarks and charged leptons

Conclusions

- In LHC Run2 the enhancement of statistics allow to investigate Higgs boson properties, performing precision measurements and probing its couplings with SM particles and possible BSM effects
  - All measurements in good agreement with SM expectations!

- Mass, Spin – CP and Width: preliminary results with partial (36.1 fb^{-1}) or full Run 2 statistics (139 fb^{-1}) in some decay channels
- Differential Cross Section measurements @ 139 fb^{-1} performed by $H \to ZZ^* \to 4l$ and $H \to \gamma\gamma$, including new interpretations to put constraint on anomalous Higgs couplings
- Production Cross Section in almost all the decay channels:
  - Improvement of the sensitivity in the STXS framework
  - First observation of VBF, $H \to WW^*$ (→Ekaterina Ramakoti's Poster)
  - Combined Results: main Higgs production modes observed with significance > 5σ
- Search in $H \to \mu\mu$: observed significance of 2σ
- Search in $H \to Z\gamma$: observed significance of 2.2σ

(→Yuya Kano's Talk)

Waiting for new results with full Run 2 dataset!


Thanks for the attention!