Combined measurements of the Higgs Boson coupling and cross sections with the ATLAS detector

Fábio Lucio Alves on behalf of the ATLAS Collaboration

Higgs 2023, IHEP, Beijing November 27 - December 02

ATLAS EXPERIMENT

NANJING UNIVERSITY 1902

中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

Motivation

More than 10 years of the Higgs Boson discovery at LHC:

- Measurements of the Higgs Boson properties (mass, spin, width, cross sections, couplings) with increased precision
  - Consistency with SM predictions intensively tested

... that is the moment to perform the combination!

- **Combination of the single Higgs analysis** allows to test the Higgs sector and constraint the strength of the interaction between the Higgs and the SM particles
  - $\kappa-$framework, Simplified template cross sections (STXS) and differential cross sections
  - Measurements can be interpreted under BSM/EFT scenarios
- $H + HH, H \rightarrow$ **invisible and** $H \rightarrow Z\gamma$ **combinations are also explored**
- **Combination using golden channels with early Run3 data is also performed**

Credit: CERN webpage

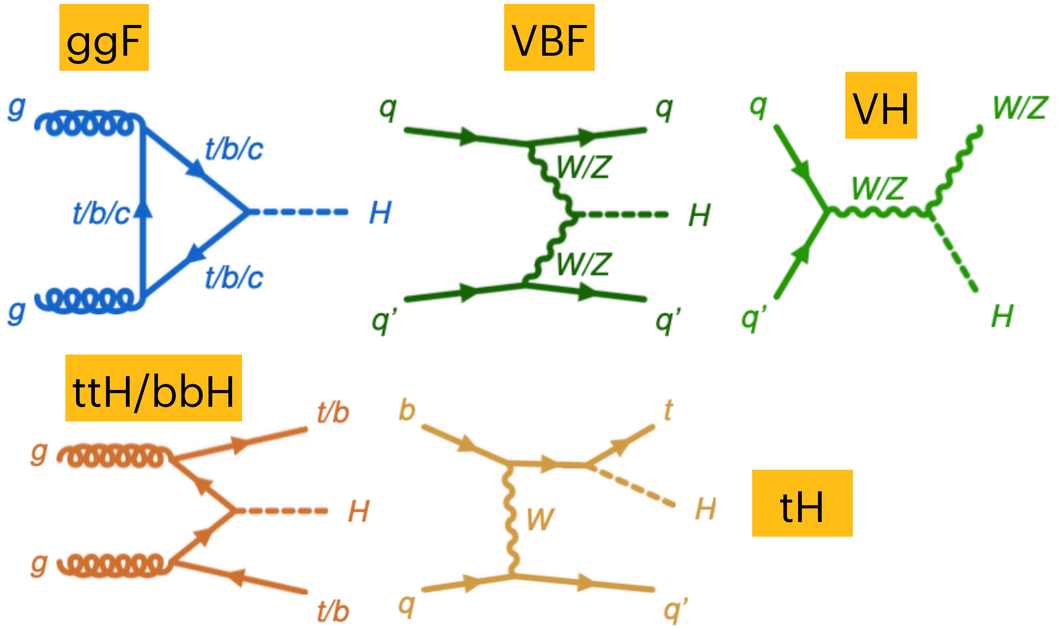
Higgs Symposium at CERN for 10 years discovery

Higgs Boson production and decay at LHC

Nature, vol. 607, 52-59 (2022)

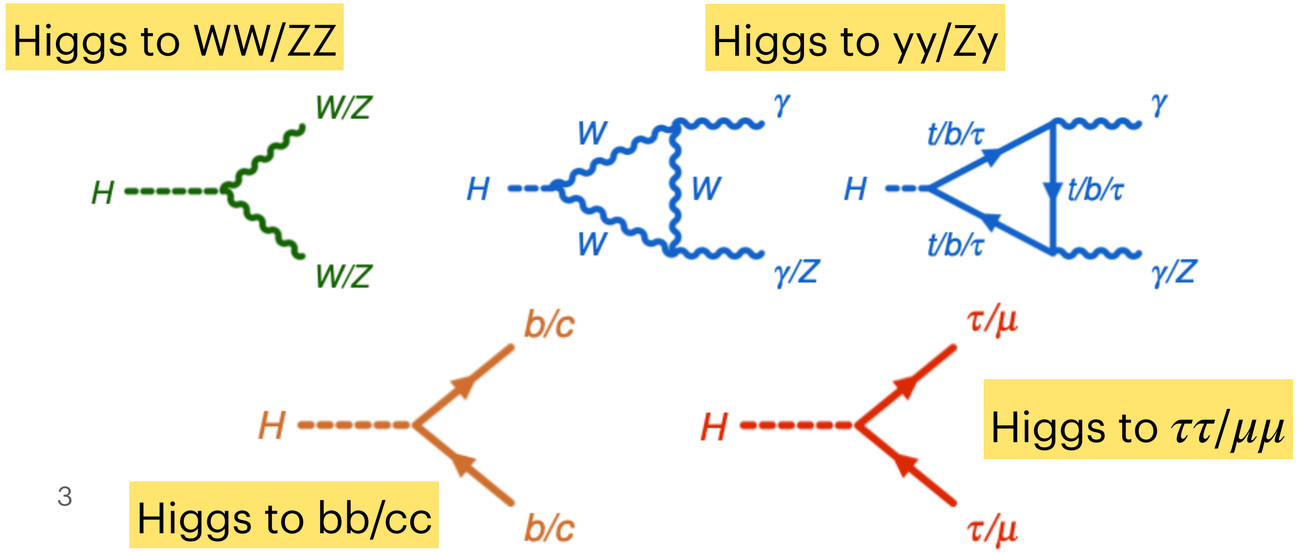
Higgs Production processes:

- Gluon-gluon fusion (ggF) (*dominant production mode*)
- Vector-boson fusion (VBF)
- Association with a vector boson (VH)
- Association with top and bottom quark pair (ttH/bbH)



Higgs Decay channels:

- $H \to ZZ^* \to 4l$ and $H \to \gamma\gamma$
  - Low BR and high mass resolution
- $H \to b\bar{b}, H \to W^{\pm}W^{\mp}, H \to \tau^{+}\tau^{-}$ and $H \to c\bar{c}$
  - High BR and low mass resolutions
- Rare decays: $H \to \mu^{+}\mu^{-}$ and $H \to Z\gamma$



Cross sections and Branching ratio measurements

Production cross sections (free parameter in the fit, BR fixed to SM values):

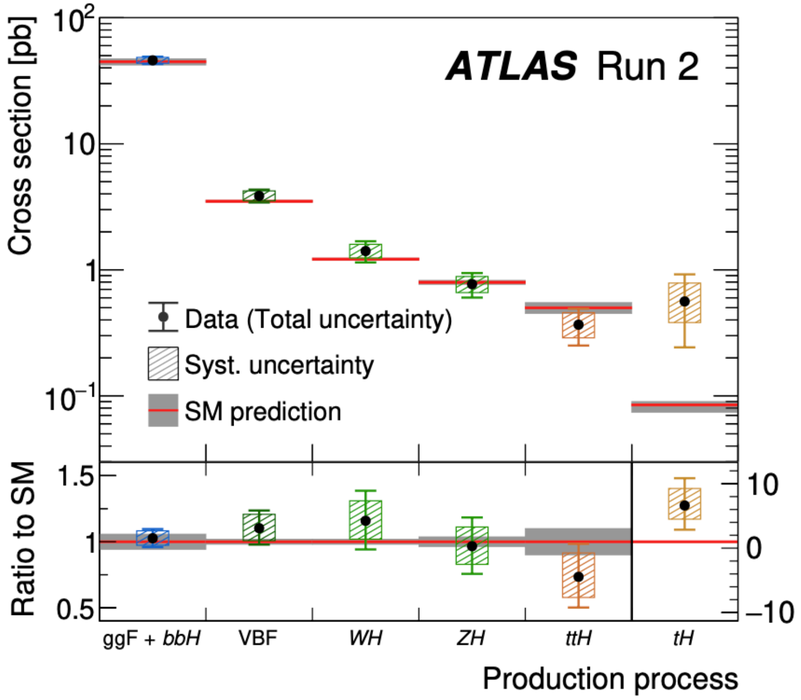
- ggF and VBF observed in Run1, precision in Run2 7% and 12% respectively
- Observed in Run2: WH (5.8σ), ZH (5.0σ) and $ttH + tH$ (6.4σ)

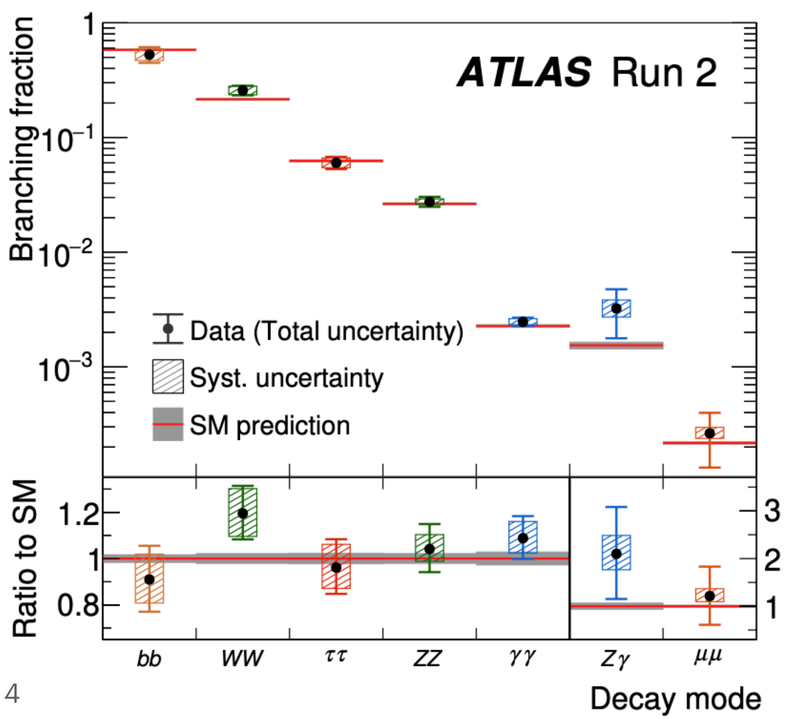
Nature, vol. 607, 52-59 (2022)

Branching ratio (free parameter in the fit, XS fixed to SM values):

- $\gamma\gamma$, ZZ, $W^{\pm}W^{\mp}$ and $\tau^{+}\tau^{-}$ already observed during Run 1, precision in Run2 ranges from 10% to 12%
- $H \to b\bar{b}$ decay mode observed with 7.0σ, $H \to \mu^{+}\mu^{-}$ and $H \to Z\gamma$ signal significances measured to be 2.0σ and 2.3σ, respectively

P-value compatibility with SM: 65%





P-value compatibility with SM: 56%

Higgs Boson production rates measurements

- Measurements for different combinations of production and decay processes
  - Relaxed assumptions by measuring the $\sigma \times B$
- *Good agreement between the measurements and SM predictions*

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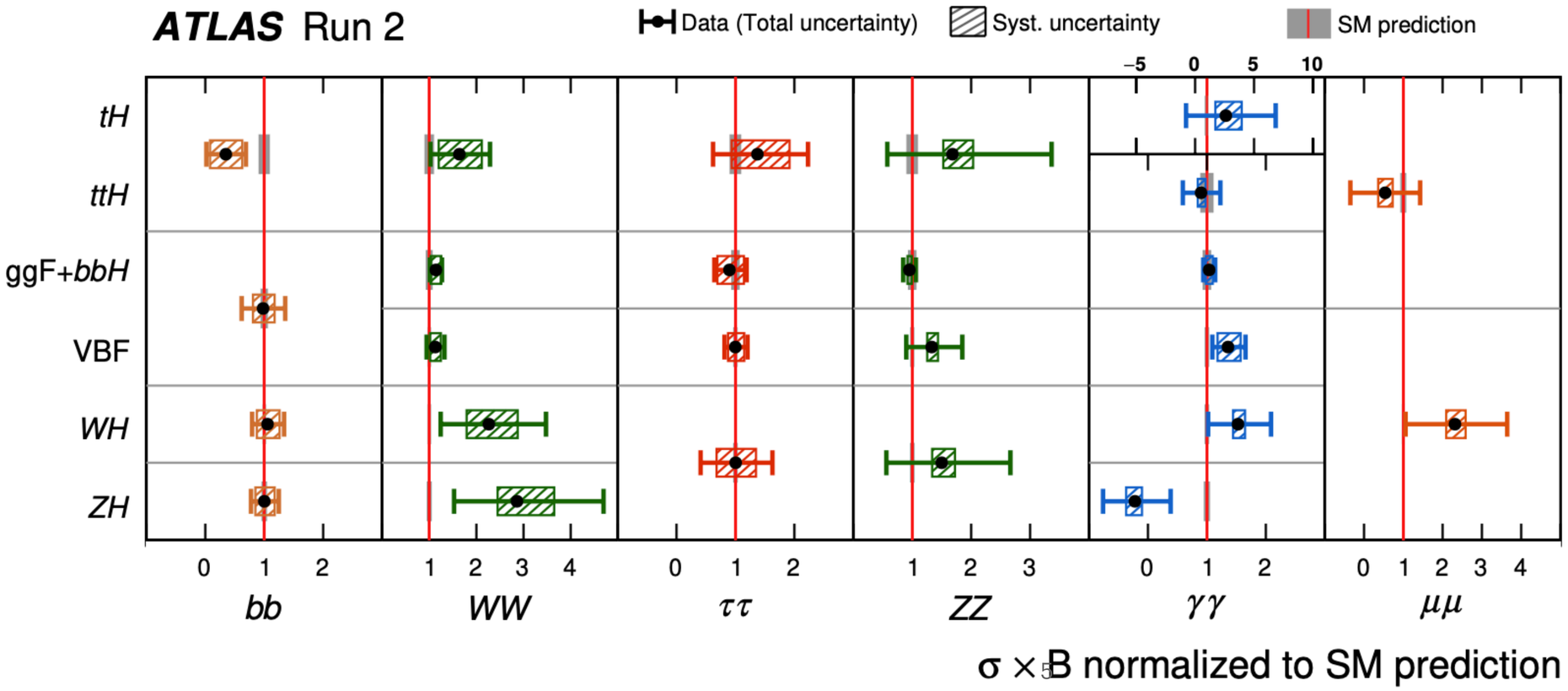


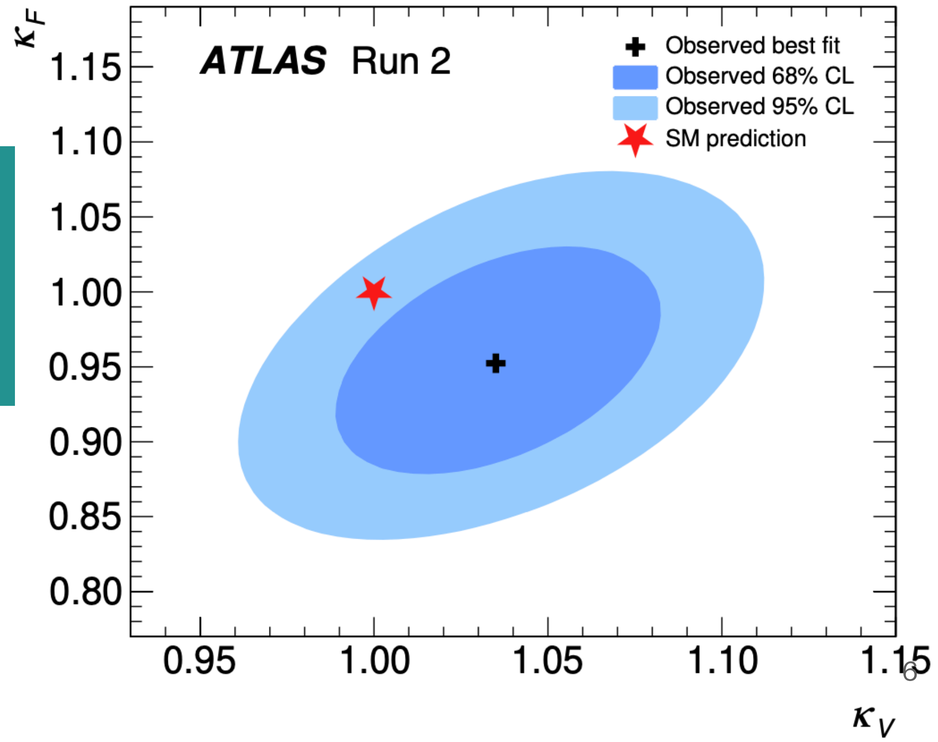
P-value compatibility with SM: 72%

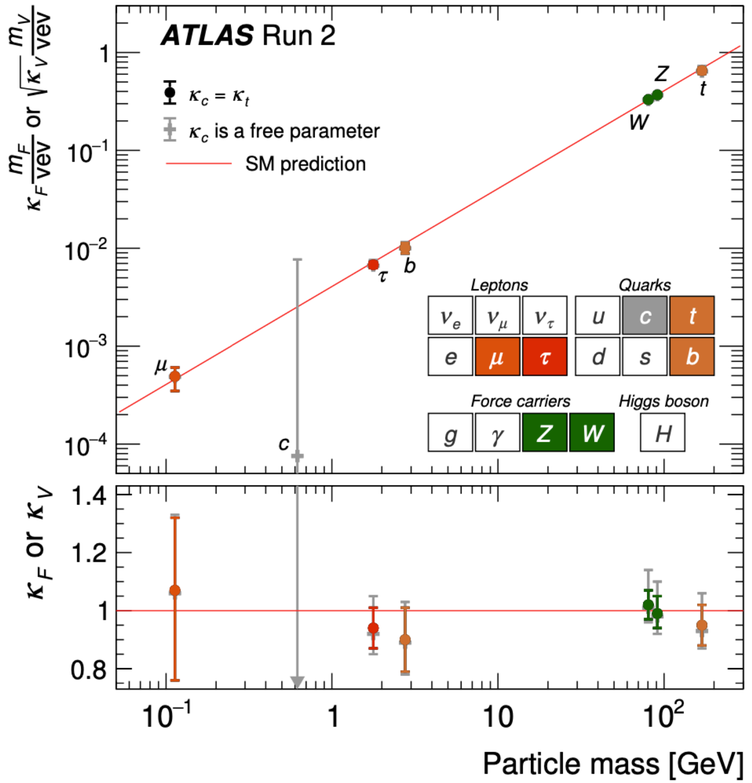
Higgs Boson coupling measurements

Nature, vol. 607, 52-59 (2022)

- $\sigma \times B$ **is parametrized in terms of multiplicative coupling strength modifiers (κ) (κ-framework)**
  - Total decay width accounts for all decay modes, direct/indirect decays and hypothetical decays to non-SM particles
- $\kappa_V = \kappa_Z = \kappa_W$ (for the weak bosons), κ_F (all fermions)
  - Assuming no invisible or undetected Higgs Boson decays beyond SM ($B_{inv.} = 0$ and $B_{u.} = 0$)
- Test predicted scaling of the Higgs Boson coupling to SM particles as a function of their masses: $\kappa_W, \kappa_Z, \kappa_t, \kappa_b, \kappa_c, \kappa_\tau, \kappa_\mu$, are treated independently

$\kappa_V = 1.035 \pm 0.031$
$\kappa_F = 0.95 \pm 0.05$
Compatible with SM predictions
(p-value 14%)





Compatible with SM predictions
(p-value 56% for $\kappa_c = \kappa_t$)
(p-value 65% for κ_c floating)

The simplified template cross section measurements

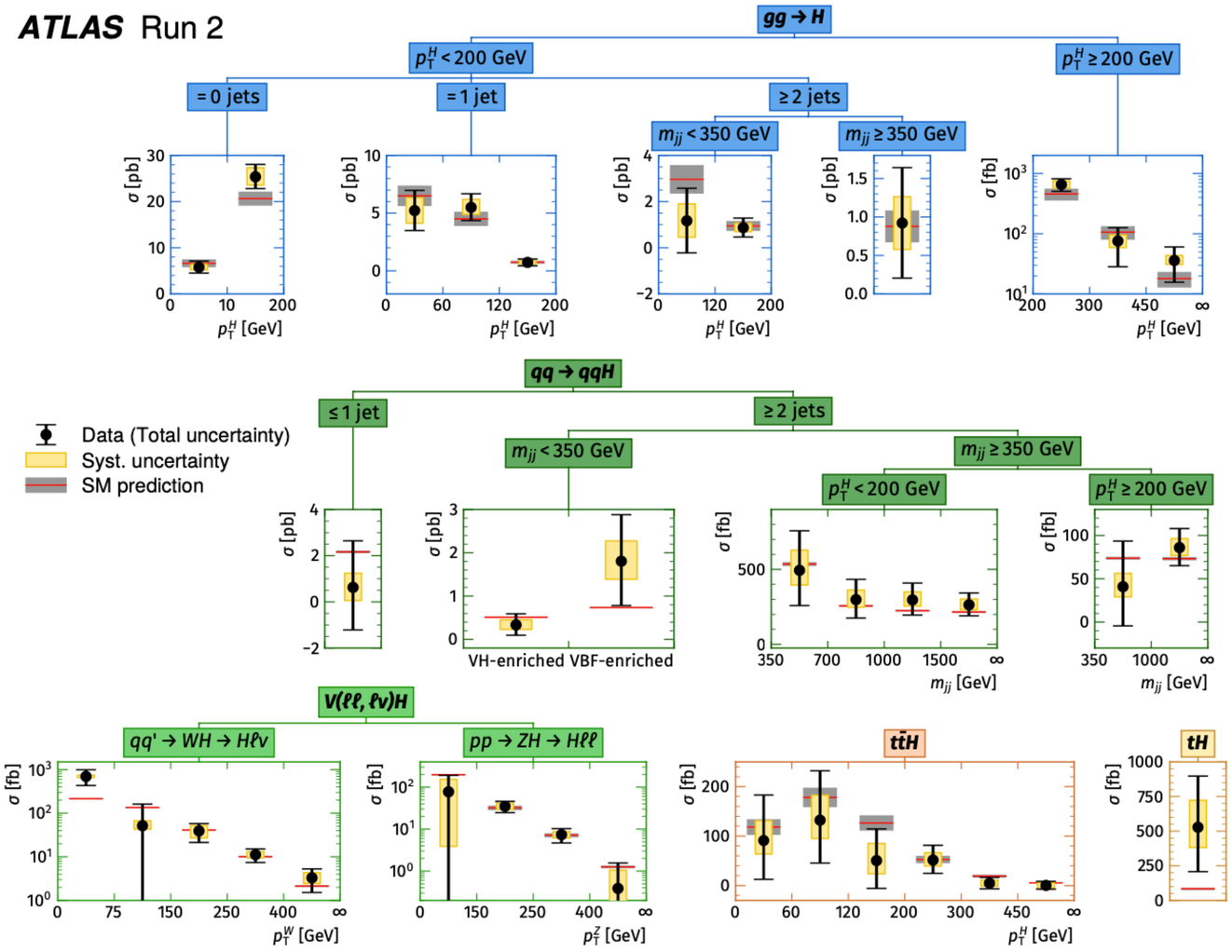
Nature, vol. 607, 52-59 (2022)

Simplified template cross section framework:

- Mutually exclusive regions (36) of the phase space split based on Higgs kinematics (+ W or Z bosons and associated jets)
- Sensitive to SM deviations; reduce large theory uncertainties and minimize model-dependence when extrapolating to accessible signal regions
- More regions are probed compared to previous result [1], specially for High Pt Higgs Boson

Good compatibility between the measurements and the SM predictions!

P-value compatibility of combined measurement and SM: 94%

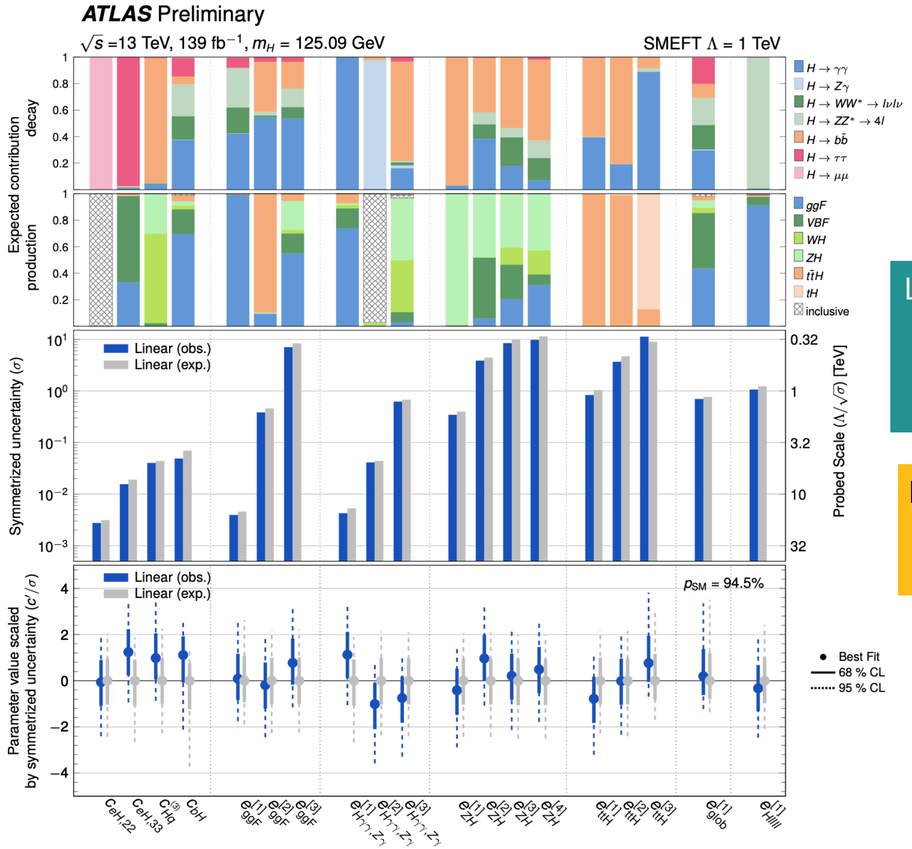


[1]: PhysRevD.101.012002

ATLAS-CONF-2023-052

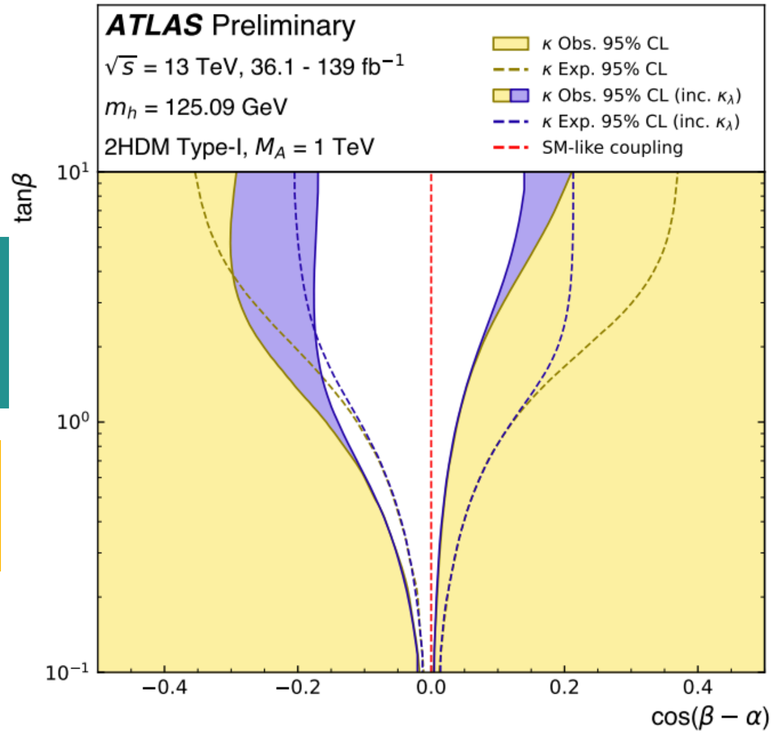
BSM/EFT interpretations

- **The STXS measurements and differential cross sections are interpreted in the context of:**
  - Effective Field Theory (EFT)
- **The production cross section and decay branching ratio measurements are interpreted in the context of:**
  - BSM scenarios: Two-Higgs-Doublet Model (2HDM) or Minimal Supersymmetric Extension of the SM (MSSM)



Linear SMEFT model result: Constraining power from the Higgs decay and production modes

No deviations from the SM predictions
P-value (94.5%)



2HDM interpretation:
Plane of $\tan\beta - cos(\beta - \alpha)$
Excluded regions at 95%CL for Type-I model (all fermions couple to same Higgs doublet)

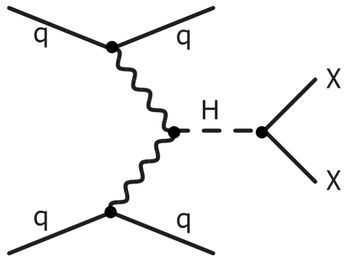
More details on Yuhao Wang and Chen Zhou's talk

$H \rightarrow$ invisible combination

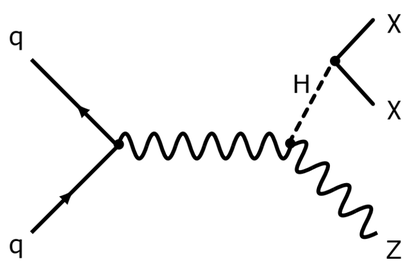
Phys. Lett. B 842 (2023) 137963

- In the SM, branching ratio to invisible final state is about 0.1% from $H \rightarrow ZZ^* \rightarrow 4\nu$
- **ATLAS direct searches for invisible decays of the Higgs Boson using Full Run 2 dataset:**
  - ggF, VBF, VH and ttH production mechanisms

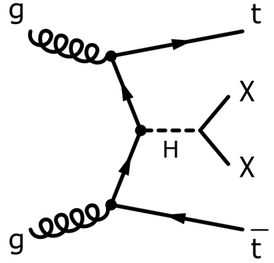
H-> invisible: no interaction with ATLAS detector



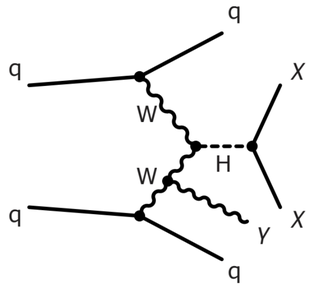
(a) VBF topology



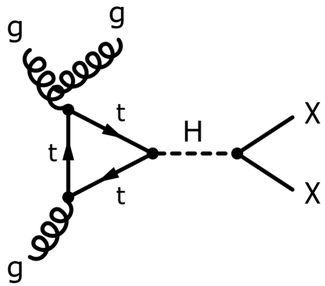
(b) $Z + H$ topology



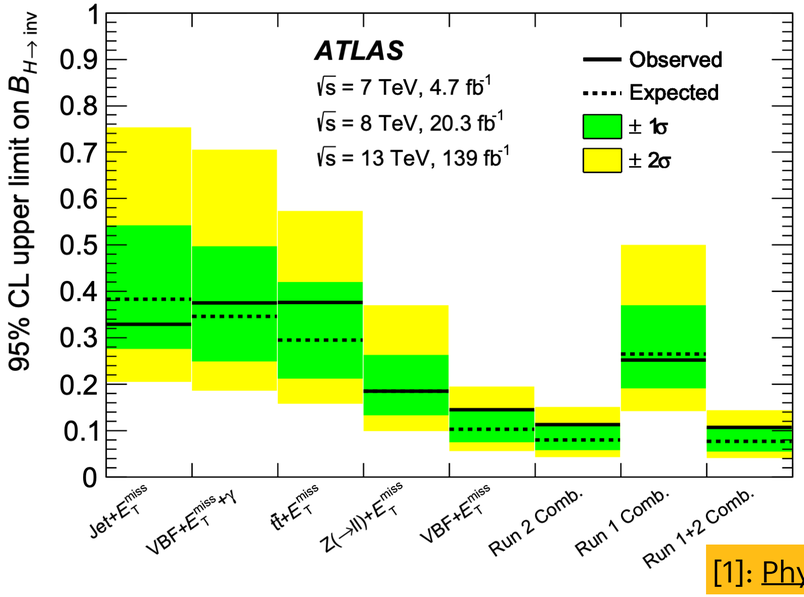
(c) $t\bar{t}H$ topology



(d) VBF + photon topology



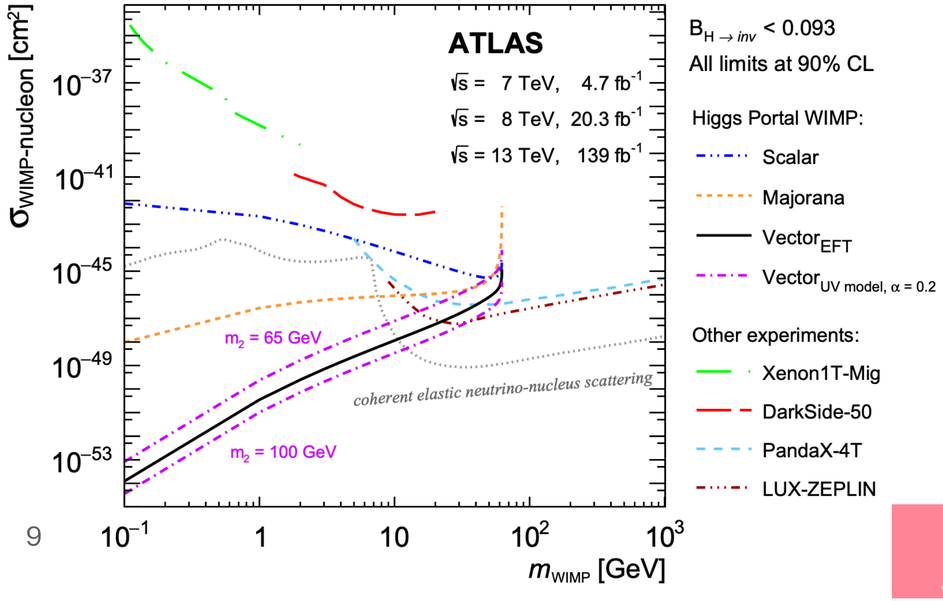
(e) H+jet topology



$B_{H\rightarrow inv.} < 0.107$ **(obs.)**

Improved by more than a factor of 2 wrt Run1 and partial Run2 combination result [1]

[1]: Phys. Rev. Lett. 122, 231801 (2019)



Comparison of the constraint on $B_{H\rightarrow inv}$ with direct dark matter (DM) experiments

More details on Shih-Chieh Hsu's talk

H + HH combination

Phys. Lett. B 843 (2024) 137745

The single Higgs input analysis have been combined with the three most sensitive double Higgs channels:
$HH \to b\bar{b}\gamma\gamma$, $HH \to b\bar{b}\tau^+\tau^-$ **and** $HH \to b\bar{b}b\bar{b}$

- Correlation between nuisance parameters of different analysis coherently taking into account

H+HH combination provides the most stringent constraints to date

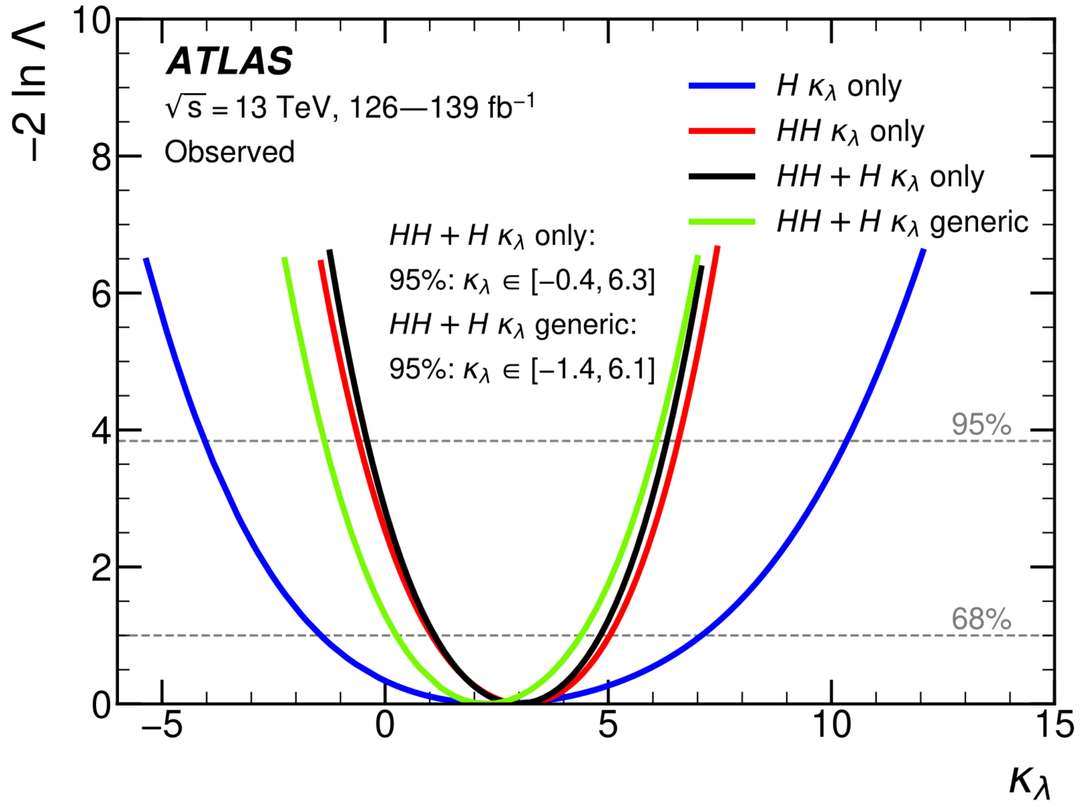
$-0.4 < \kappa_\lambda < 6.3$ @ 95%CL

The addition of the single-Higgs analyses to the combination allow relaxing assumptions on κ_t

$-0.4 < \kappa_\lambda < 6.3$ @ 95%CL (sensitivity on κ_λ is kept)

Generic model where $\kappa_\lambda, \kappa_V, \kappa_t, \kappa_b, \kappa_\tau$ are floated simultaneously in the fit

$-1.4 < \kappa_\lambda < 6.1$ @ 95%CL (there is still strong constraint on κ_λ)



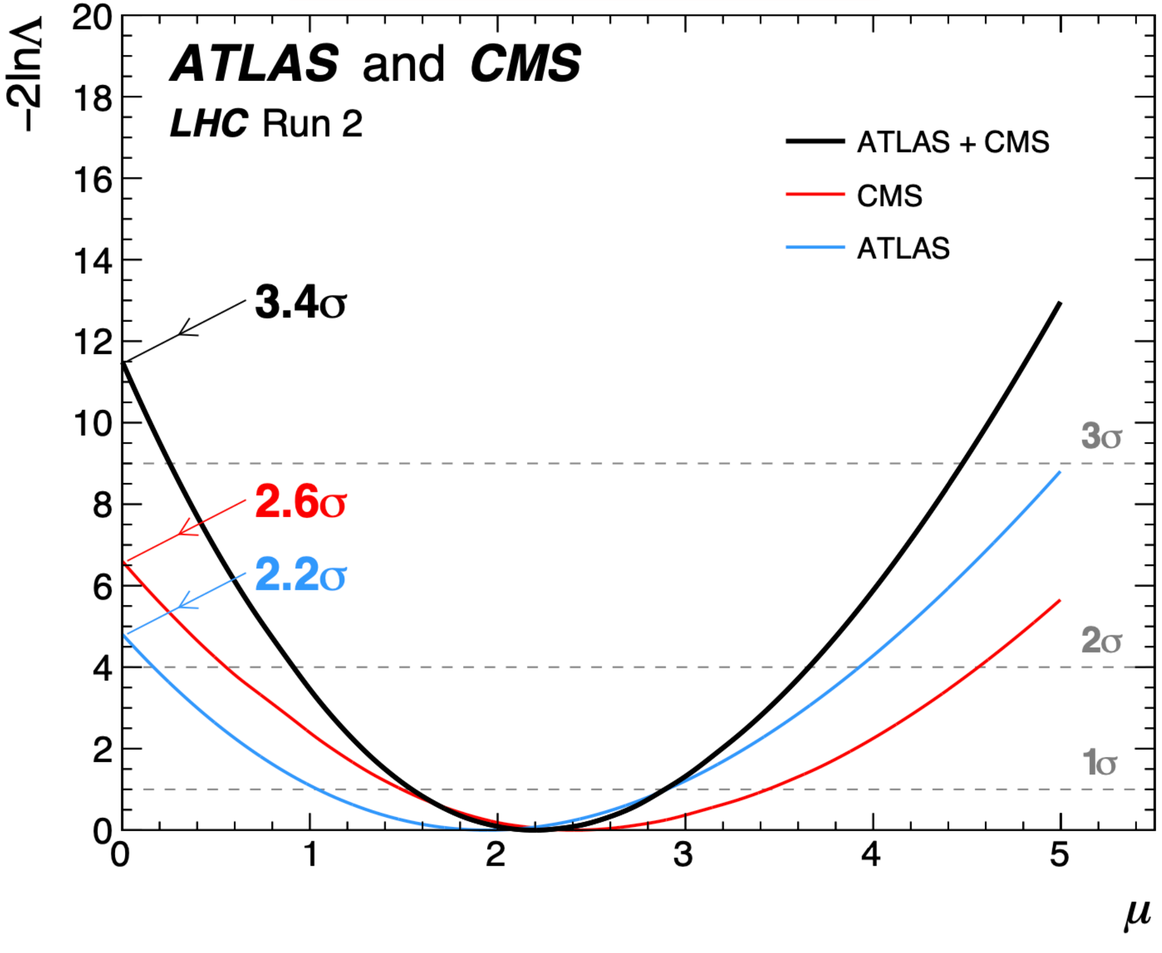
Combination assumption	Obs. 95% CL	Exp. 95% CL	Obs. value $^{+1\sigma}_{-1\sigma}$
HH combination	$-0.6 < \kappa_\lambda < 6.6$	$-2.1 < \kappa_\lambda < 7.8$	$\kappa_\lambda = 3.1^{+1.9}_{-2.0}$
Single-H combination	$-4.0 < \kappa_\lambda < 10.3$	$-5.2 < \kappa_\lambda < 11.5$	$\kappa_\lambda = 2.5^{+4.6}_{-3.9}$
HH+H combination	$-0.4 < \kappa_\lambda < 6.3$	$-1.9 < \kappa_\lambda < 7.6$	$\kappa_\lambda = 3.0^{+1.8}_{-1.9}$
HH+H combination, κ_t floating	$-0.4 < \kappa_\lambda < 6.3$	$-1.9 < \kappa_\lambda < 7.6$	$\kappa_\lambda = 3.0^{+1.8}_{-1.9}$
HH+H combination, $\kappa_t, \kappa_V, \kappa_b, \kappa_\tau$ floating	$-1.4 < \kappa_\lambda < 6.1$	$-2.2 < \kappa_\lambda < 7.7$	$\kappa_\lambda = 2.3^{+2.1}_{-2.0}$

$H \to Z\gamma$ Run2 combination

First evidence for the Higgs Boson decay to $Z\gamma$

- **Statistical combination of the ATLAS and CMS searches for $H \to Z\gamma$:**
  - **Signal strength (μ):**
    - $\mu = 2.2 \pm 0.7$ $(1.0 \pm 0.6,$ exp.)
  - **Significance** (no $H \to Z\gamma$ signal hypothesis)
    - 3.4σ (1.6σ, **exp.**)
  - **Measured branching fraction as** $(3.4 \pm 1.1) \times 10^{-3}$
- Important systematic uncertainties related to $H \to Z\gamma$ branching fraction and background modelling
- Uncertainties in the measurement dominated by statistical component

arXiv:2309.03501 (Submitted to PRL)



$H \to \gamma\gamma$ and $H \to ZZ^* \to 4l$ combination at 13.6 TeV

Submitted to EPJC, arXiv:2306.11379

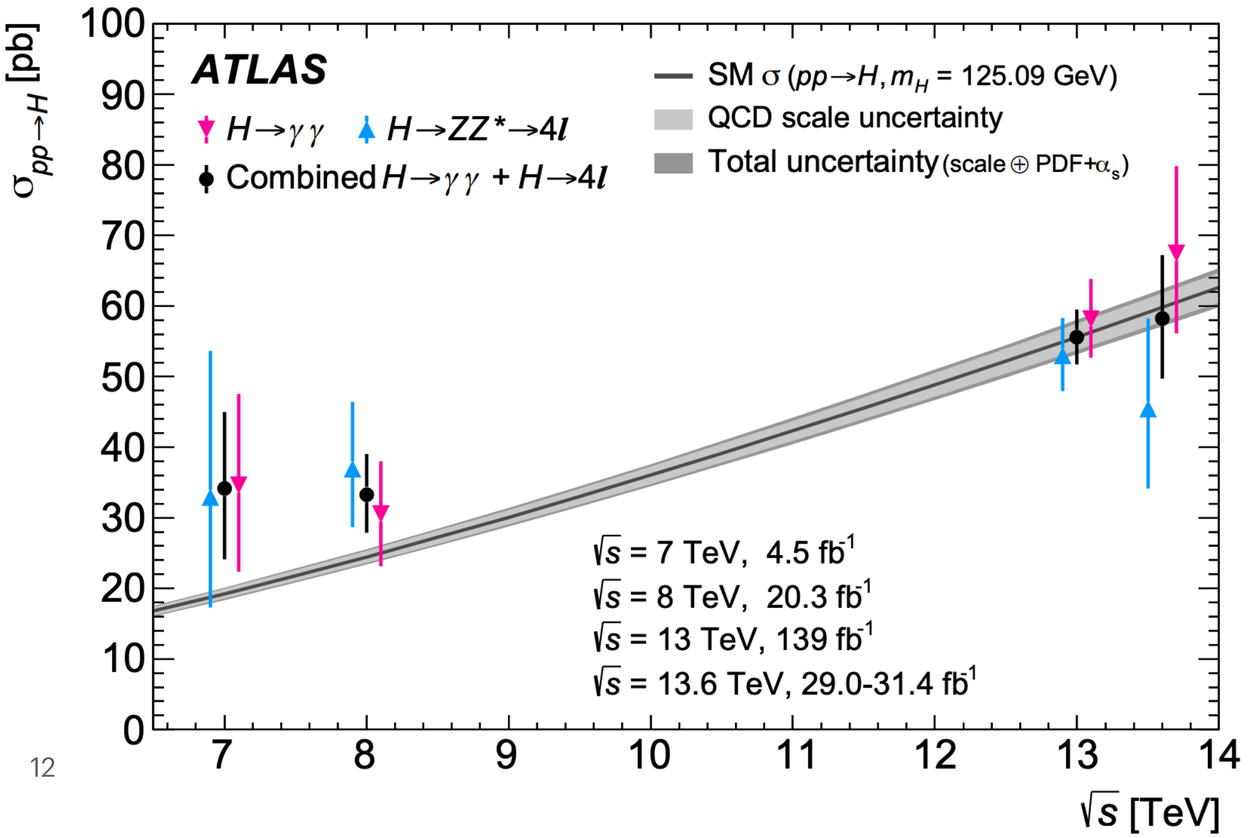
- **$H \to \gamma\gamma$ and $H \to ZZ^* \to 4l$: golden channels** in Higgs discovery
  - Fully reconstructible final state with excellent mass resolution
- Statistical combination for measuring the total cross section using early Run3 data
  - **Total cross section:** Extrapolation to the full phase space by assuming the SM acceptance and branching fractions
- **Total combined cross section comparison:**
  - $55.5^{+4.0}_{-3.8}$ pb (at 13 TeV) versus 58.2 ± 8.7 pb (at 13.6 TeV)
    - Relative increase of the total combined cross section is ~ 5%

Total cross section ($H \to \gamma\gamma$) @ Run 3: $\sigma = 67^{+12}_{-11}$ pb

Total cross section ($H \to 4l$) @ Run 3: $\sigma = 47 \pm 12$ pb

Combined cross section = 58.2 ± 8.7 pb

Consistent with SM (59.9 ± 2.6) pb



Summary

The combination of the single Higgs measurements has been performed with the LHC Run 2 dataset:

- It has allowed to test the Higgs sector by measuring the Higgs production and decay rates and the its couplings to the SM particles
  - ***All measurement show excellent agreement with the SM predictions***
- These combined measurements have been used for interpretations in the context of the EFT, 2HDM and MSSM models
  - **No significant deviation with respect to the SM is observed**
- Combinations of the direct invisible decays searches are complementary to the direct dark matter searches
  - **Improved limits using Full Run 2 dataset with respect to Run 1 and partial Run 2**
- Combination with double Higgs most sensitive channels
  - **Most stringent constraint on the Higgs Boson trilinear self-coupling to date**
- $H \to Z\gamma$ ATLAS+CMS combination: first evidence for this Higgs Boson decay
  - **Sensitivity is enhanced by the combination**

Run 3 data-taking just started! There are much more to come!
Stay tuned!

Additionally, since the Run 3 is already here, the combination of the total cross sections in the golden channels is obtained using the Run 3 dataset collected at 13.6 TeV

Back-up slides

Single Higgs combination: input analysis

Decay mode	Targeted production processes	$\mathcal{L}$ [fb^{-1}]	Ref.	Fits deployed in
$H \to \gamma\gamma$	ggF, VBF, WH, ZH, $t\bar{t}H$, tH	139	31	All
$H \to ZZ$	ggF, VBF, $WH + ZH$, $t\bar{t}H + tH$	139	28	All
	$t\bar{t}H + tH$ (multilepton)	36.1	39	All but fit of kinematics
$H \to WW$	ggF, VBF	139	29	All
	WH, ZH	36.1	30	All but fit of kinematics
	$t\bar{t}H + tH$ (multilepton)	36.1	39	All but fit of kinematics
$H \to Z\gamma$	inclusive	139	32	All but fit of kinematics
$H \to b\bar{b}$	WH, ZH	139	33,34	All
	VBF	126	35	All
	$t\bar{t}H + tH$	139	36	All
	inclusive	139	37	Only for fit of kinematics
$H \to \tau\tau$	ggF, VBF, $WH + ZH$, $t\bar{t}H + tH$	139	38	All
	$t\bar{t}H + tH$ (multilepton)	36.1	39	All but fit of kinematics
$H \to \mu\mu$	ggF + $t\bar{t}H + tH$, VBF + $WH + ZH$	139	40	All but fit of kinematics
$H \to c\bar{c}$	$WH + ZH$	139	41	Only for free-floating κ_c
$H \to$ invisible	VBF	139	42	κ models with $B_{\text{u.}}$ & $B_{\text{inv.}}$
	ZH	139	43	κ models with $B_{\text{u.}}$ & $B_{\text{inv.}}$

Not used in STXS measurement due to limited sensitivity

Only used in STXS measurement

Global signal strength

Observed signal yield for a given process can be expressed as:

- $\mu_{if} = \frac{\sigma_i}{\sigma_i^{SM}} \times \frac{B_f}{B_f^{SM}}$ (signal strength for a production mode i and decay mode f)
- Assuming all the production and decay processes scale with same global signal strength:

$\mu = \mu_{if}$

$$\mu = 1.05 \pm 0.05 = 1.05 \pm 0.03(\text{stat.}) \pm 0.03(\text{exp.}) \pm 0.04(\text{sig. theo.}) \pm 0.02(\text{bkg. theo})$$

Measured inclusive Higgs Boson production rate with respect to SM prediction

Total uncertainty is reduced by about 30% wrt previous combination with partial Run2 (80 fb-1)

Higgs Boson coupling measurements

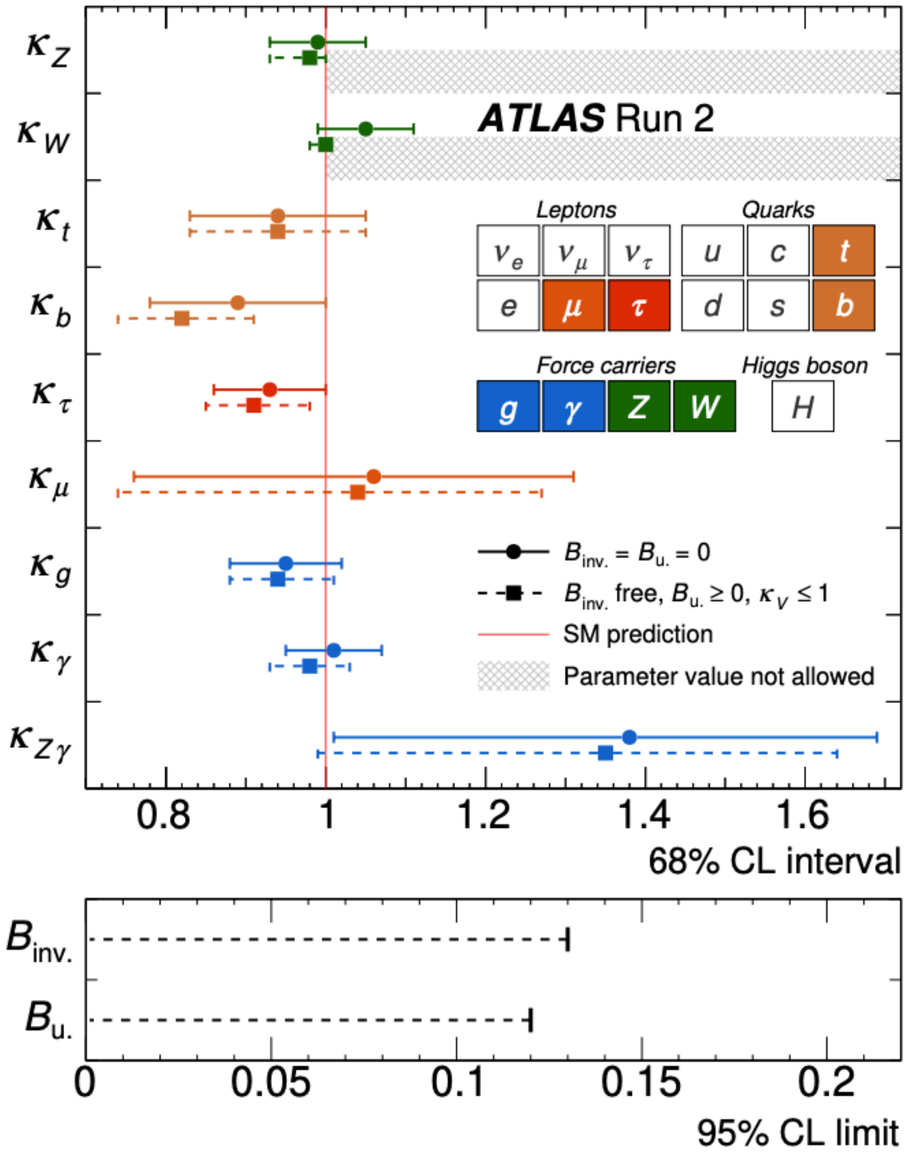
$\sigma \times B$ is parametrized in terms of multiplicative coupling strength modifiers (κ) (κ-framework)

- Allow for the presence of non-SM particles in the loops-induced processes
  - Parametrized by the effective coupling strength modifiers $\kappa_g, \kappa_\gamma, \kappa_{Z\gamma}$
- **Scenarios studies:**
  - $B_{inv.} = B_{u.} = 0$ (no contribution to the total Higgs decay width)
  - $B_{inv.}, B_{u.}$ are allowed to contribute to the total Higgs decay width ($\kappa_V \leq 1, B_{u.} \geq 0$)

Observed Upper limits: $B_{inv.} < 0.13$ and $B_{inv.} < 0.12$ @ 95%CL

Measured coupling strength modifiers are compatible with the SM predictions

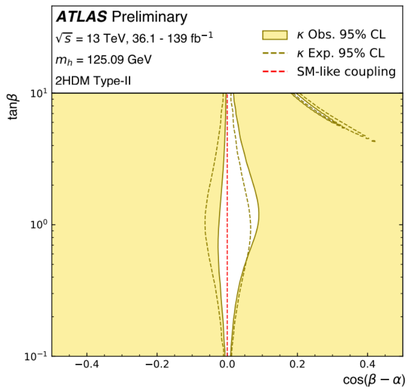
P-value compatibility with SM: 61% for $B_{inv.} = B_{u.} = 0$

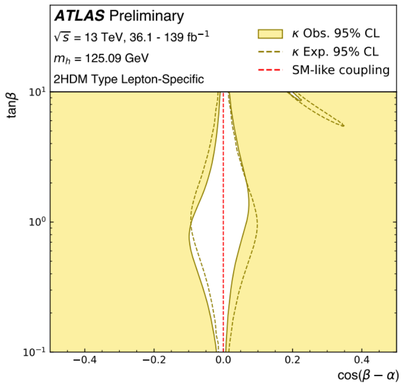


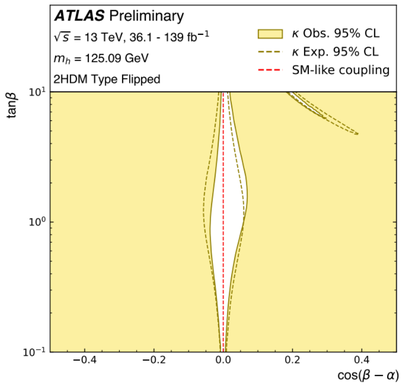
BSM/EFT interpretations

2HDM interpretation

Coupling	Type I	Type II	Lepton-specific	Flipped
u, c, t	$s_{\beta-\alpha} + c_{\beta-\alpha}/\tan\beta$			
d, s, b	$s_{\beta-\alpha} + c_{\beta-\alpha}/\tan\beta$	$s_{\beta-\alpha} - c_{\beta-\alpha} \times \tan\beta$	$s_{\beta-\alpha} + c_{\beta-\alpha}/\tan\beta$	$s_{\beta-\alpha} - c_{\beta-\alpha} \times \tan\beta$
e, μ, τ	$s_{\beta-\alpha} + c_{\beta-\alpha}/\tan\beta$	$s_{\beta-\alpha} - c_{\beta-\alpha} \times \tan\beta$	$s_{\beta-\alpha} - c_{\beta-\alpha} \times \tan\beta$	$s_{\beta-\alpha} + c_{\beta-\alpha}/\tan\beta$
W, Z	$s_{\beta-\alpha}$			
H	$s^3_{\beta-\alpha} + \left(3 - 2\frac{\bar{m}^2}{m_h^2}\right) c^2_{\beta-\alpha} s_{\beta-\alpha} + 2\cot(2\beta)\left(1 - \frac{\bar{m}^2}{m_h^2}\right) c^3_{\beta-\alpha}$			

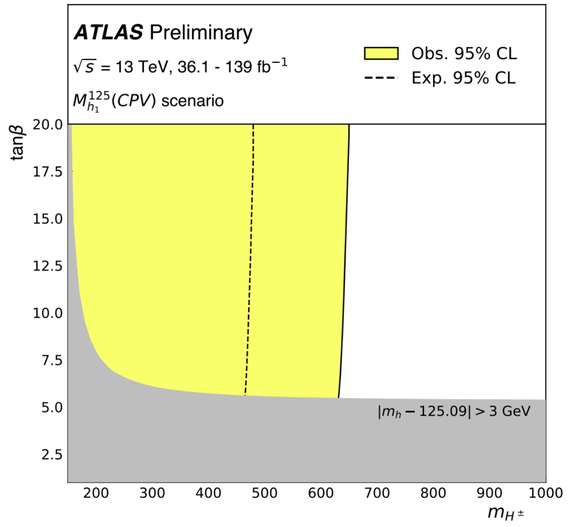


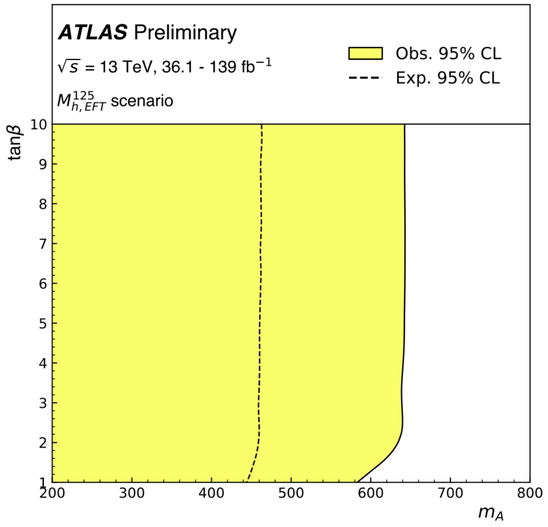


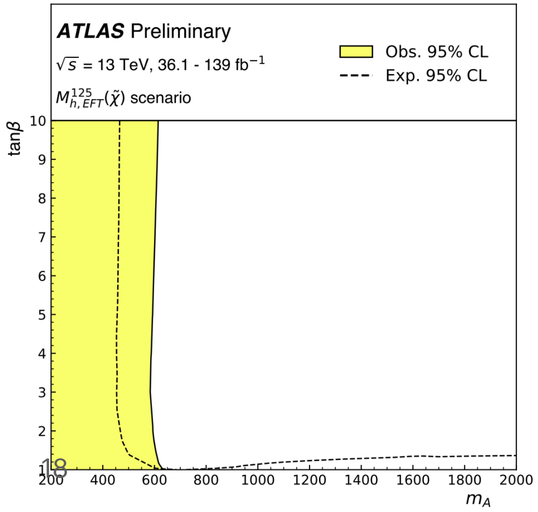


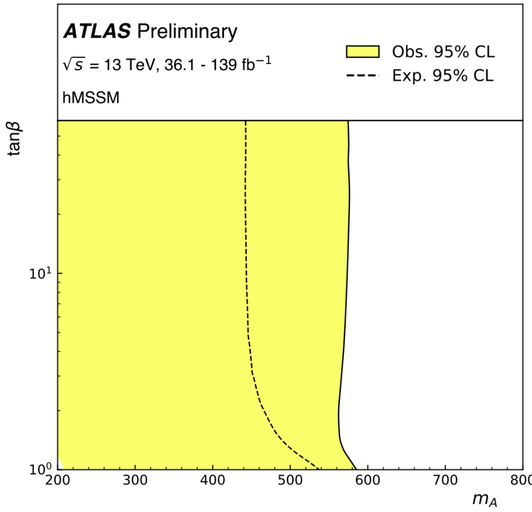
Minimal Supersymmetric Standard Model (MSSM) interpretation

- Minimal extension of the SM that addresses open questions in the SM as the hierarchy problem and Dark Matter particle candidate

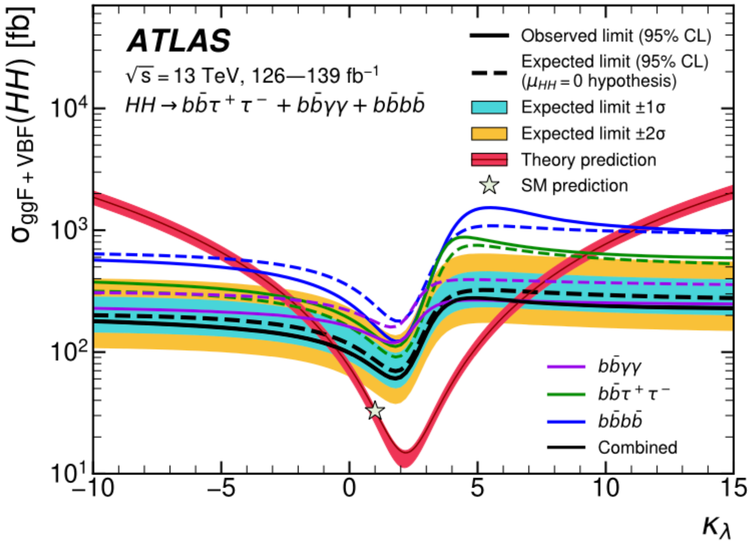


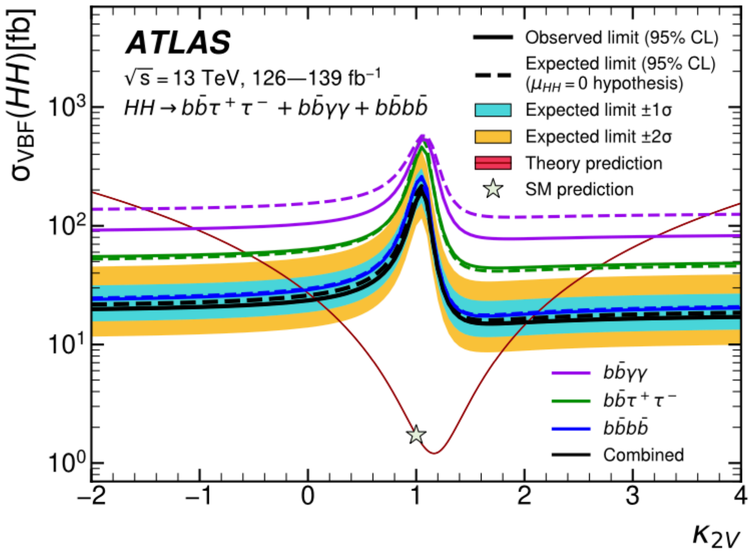






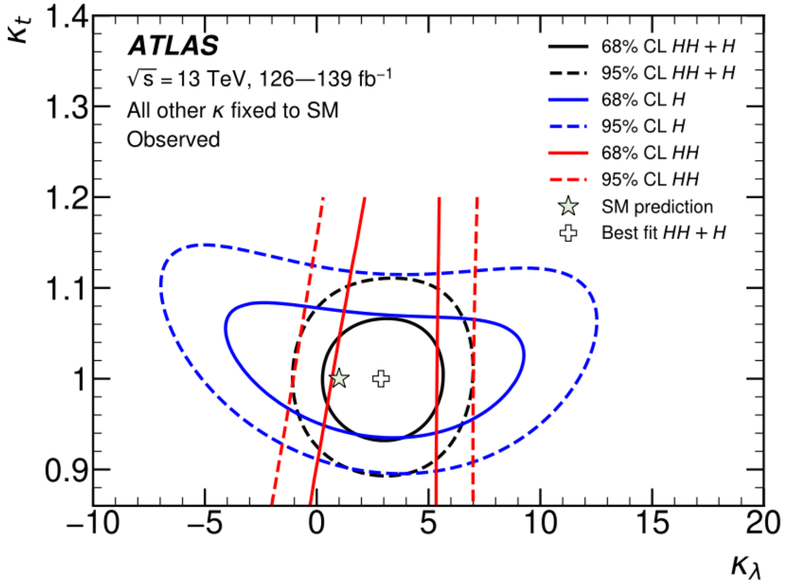
H + HH combination





95%CL Observed and expected exclusion limits on the HH production cross section for ggF+VBF as a function of κ_λ and VBF production mode versus κ_{2V}

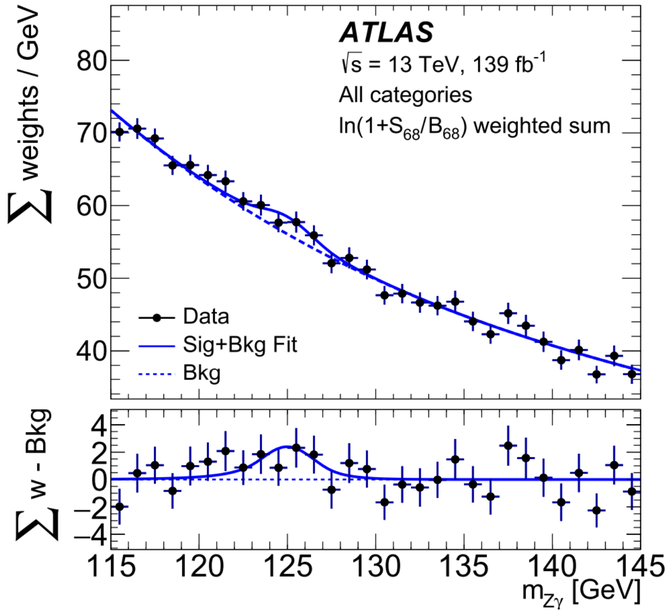
- Combination of the three most HH sensitive channels



2D contour curves in the κ_t-κ_λ plane

- All other coupling modifiers are fixed to the unity

$H \to Z\gamma$ Run2 combination



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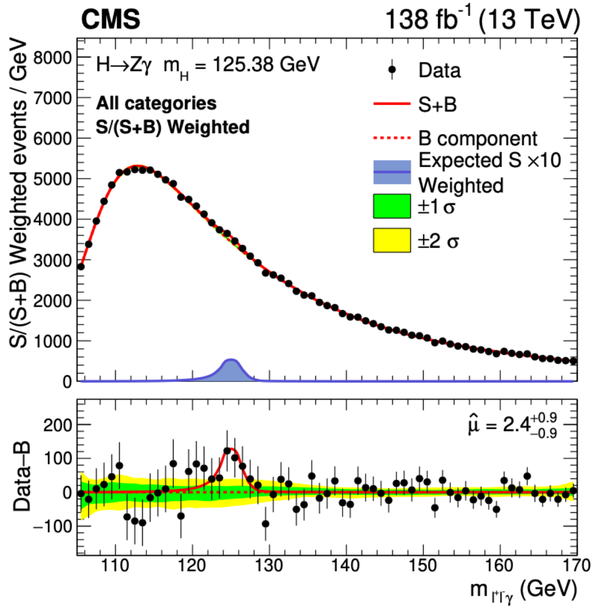
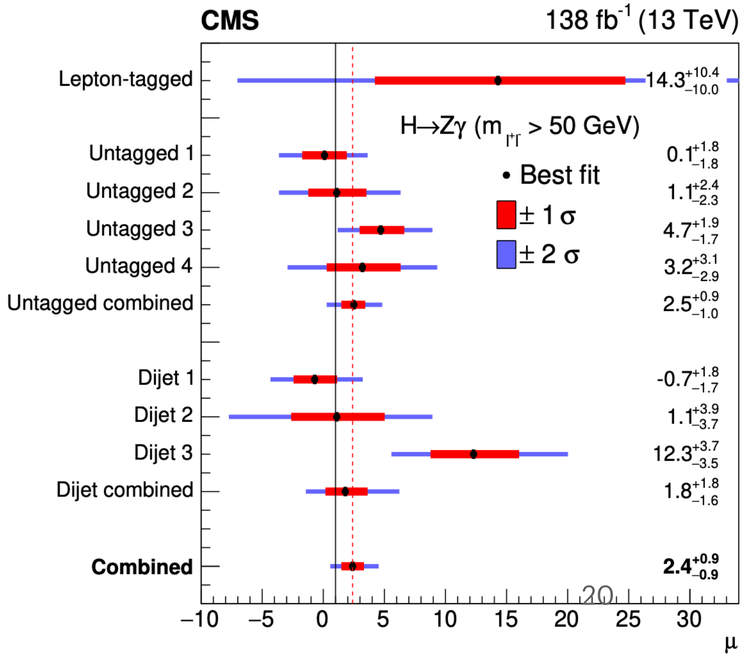
Signal strength = $2.0^{+1.0}_{-0.9}$
(Assuming the presence of the SM Higgs Boson)

Significance is measured as 2.2σ (observed) and 1.2σ (expected)

Observed 95%CL limit on μ is 3.6 (2.6, expected) with the assumption of the SM Higgs





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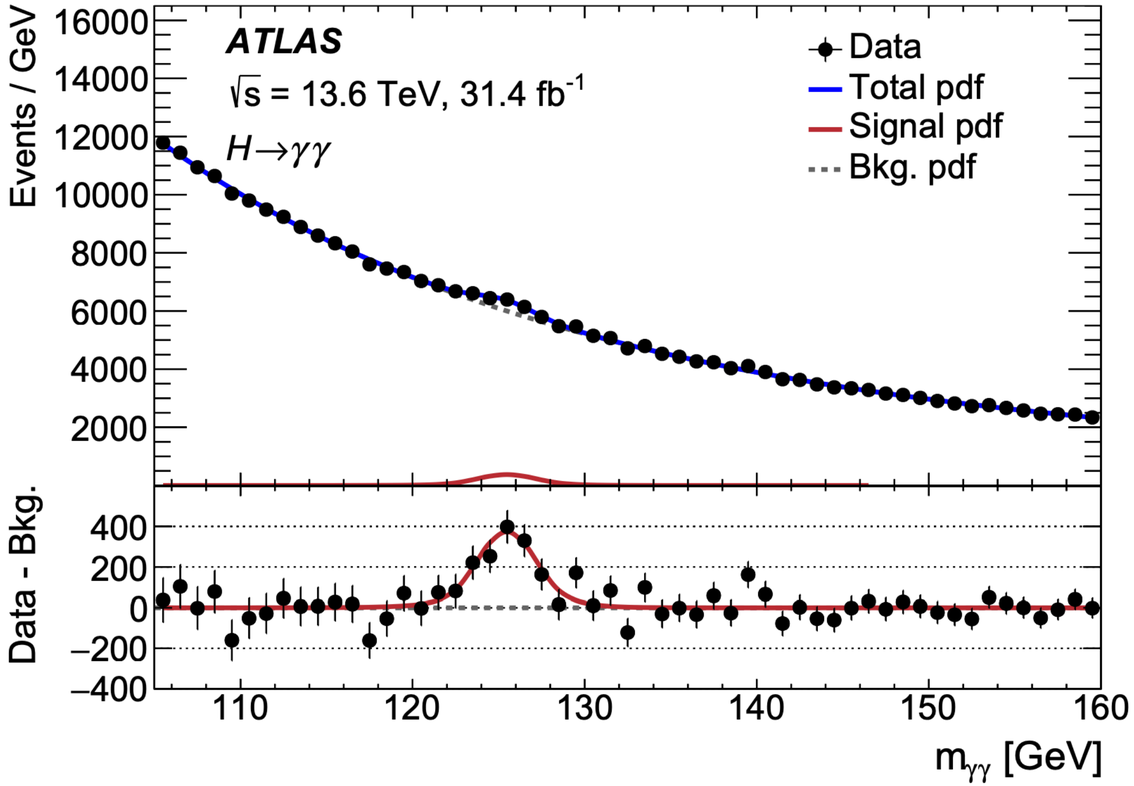
Signal strength = 2.4 ± 0.9
Compatible with SM prediction: p-value of 0.02

$\sigma(pp \to H) \times B(H \to Z\gamma) = 0.21 \pm 0.08$ pb

$B(H \to Z\gamma)/B(H \to \gamma\gamma) = 1.5^{+0.7}_{-0.6}$
Consistent with SM prediction!

$H \to \gamma\gamma$ and $H \to ZZ^* \to 4l$ combination at 13.6 TeV

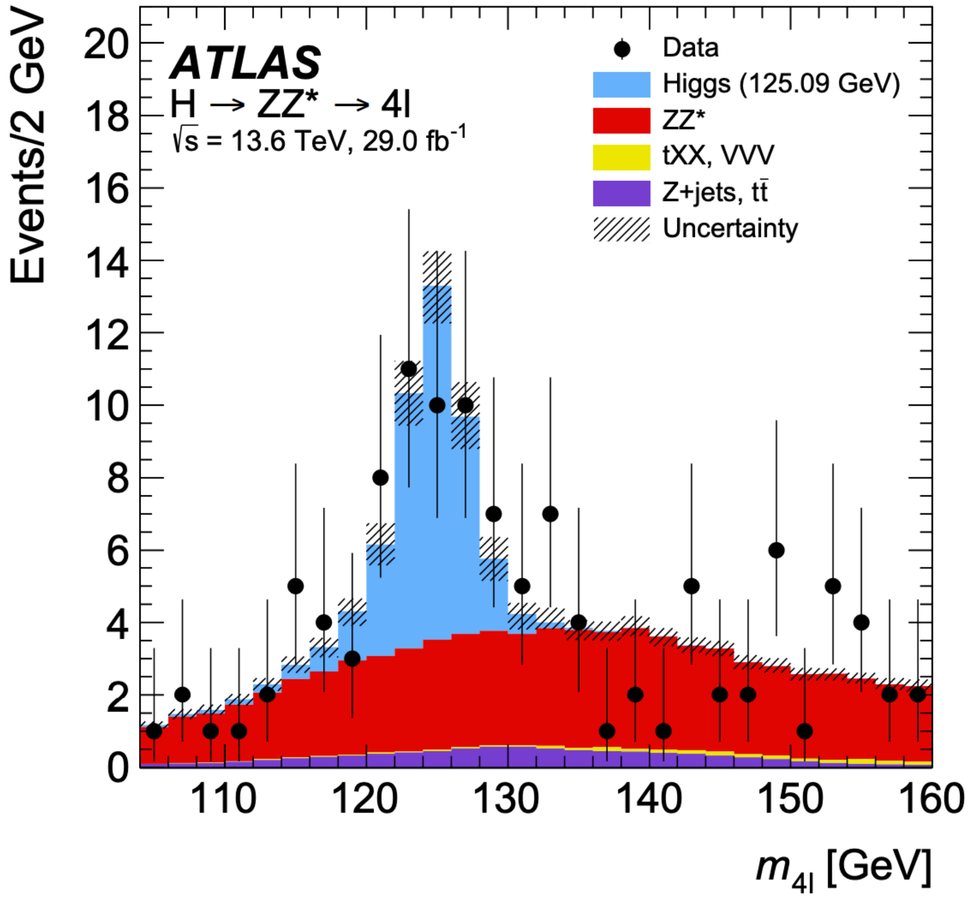
Higgs to yy channel



Fiducial cross section measurement:

$\sigma_{fid.} = 76 \pm 11(\text{stat.})^{+9}_{-7}(\text{syst.})$

Higgs to ZZ (4leptons) channel



Fiducial cross section measurement:

$\sigma_{fid.} = 2.80 \pm 0.70(\text{stat.}) \pm 0.21(\text{syst.})$