Higgs boson couplings at ATLAS

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on behalf of the ATLAS Collaboration

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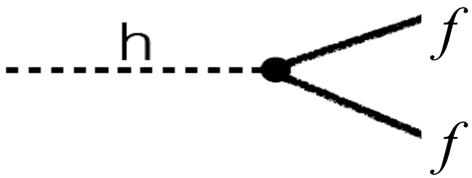
ATLAS EXPERIMENT

Higgs sector in the SM

- Importance of Higgs sector in the SM Lagrangian.
  - Only fundamental scalar particle: $J^{PC} = 0^{++}$ (vacuum quantum numbers).



$$\mathcal{L}_{\rm Yuk} = -\sum_f \left(m_f + \frac{m_f}{v}H\right) \psi_f \psi_f + \cdots$$

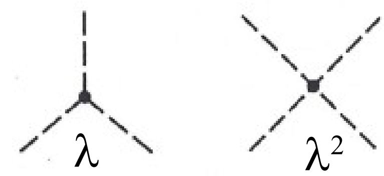
New kind of interaction

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\psi} \not{D} \psi + \psi_i y_{ij} \psi_j \phi + |D_\mu \phi|^2 - V(\phi)$$

Citation: R.L. Workman *et al.* (Particle Data Group), Prog.Theor.Exp.Phys. **2022**, 083C01 (2022)

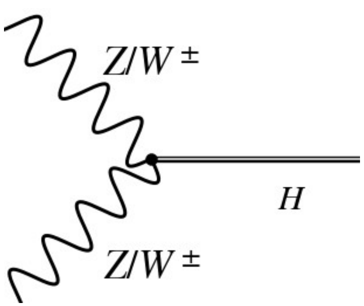
H^0 $J = 0$

Mass $m = 125.25 \pm 0.17$ GeV (S = 1.5)
Full width $\Gamma = 3.2^{+2.8}_{-2.2}$ MeV (assumes equal on-shell and off-shell effective couplings)



$$V(\phi) = \tfrac{1}{2}\mu^2 \phi^\dagger \phi + \tfrac{1}{4}\lambda(\phi^\dagger\phi)^2$$

Potential making the Higgs field "special"



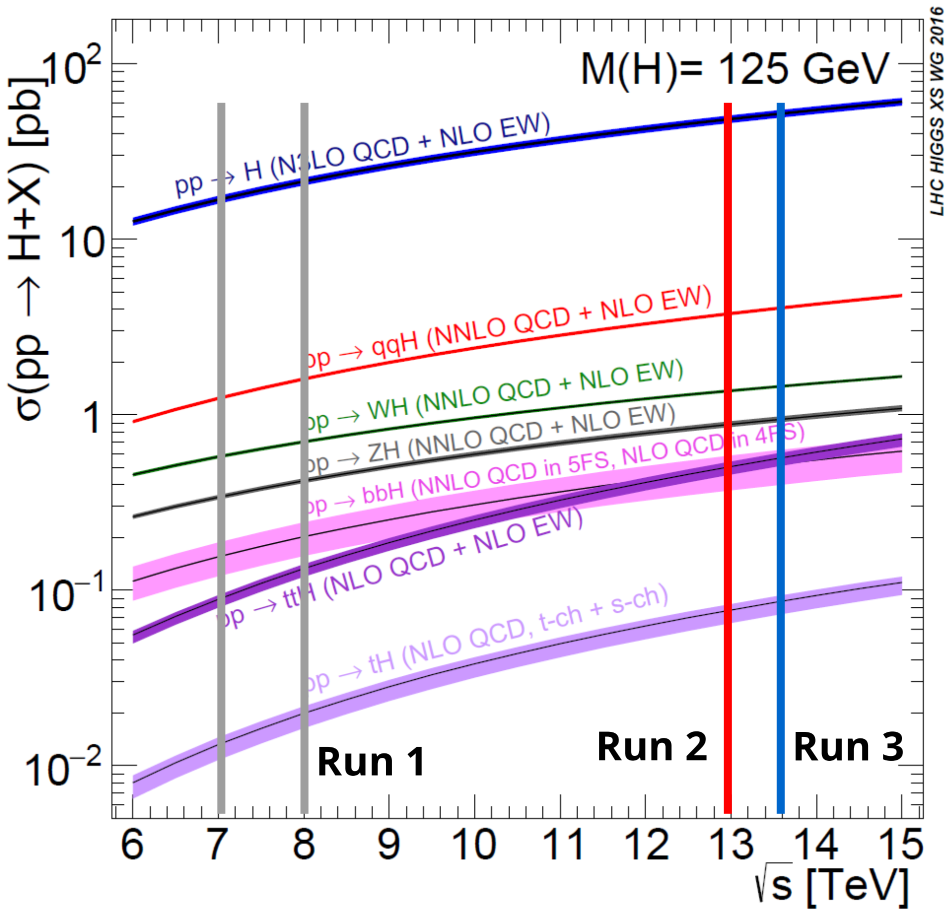
$$+\left|\left(i\partial_\mu - g\frac{1}{2}\tau.W_\mu - g'\frac{Y}{2}B_\mu\right)\varphi\right|^2$$

"Standard" interaction with gauge bosons

Self-coupling results in R. Hyneman talk tomorrow

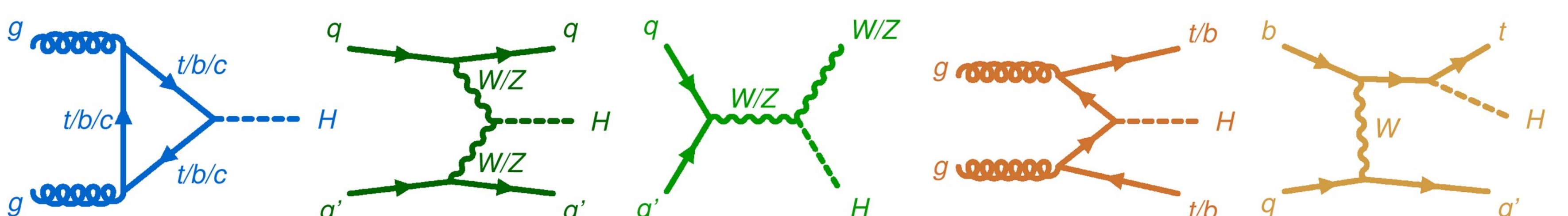
- The BEH field is responsible for the EW symmetry breaking.
- Its coupling to fermions is through a Yukawa interaction, proportional to the mass of the fermions.

Higgs Production Modes



- In ATLAS, about 56000 Higgs bosons produced/fb^{-1}, about 200 reconstructed/fb^{-1} during Run 2.
- gluon-fusion (ggF) is the main production mode at LHC, providing indirect measurement of top-quark coupling (via virtual loops).
- ttH provides direct measurement of Yukawa coupling, but much lower rate.
- ggF and VBF observed during Run 1 of LHC.
- ttH, VH (and ZH individually) observed during Run 2 of LHC.

@13 TeV

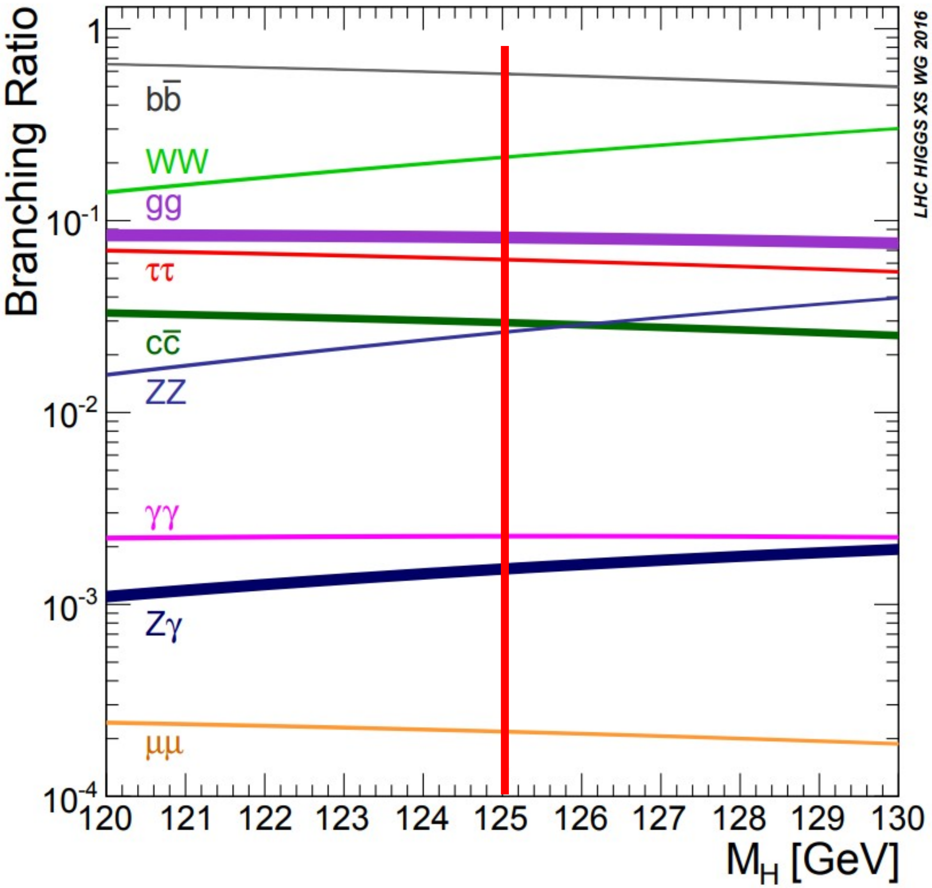


87% | 7% | 5% | <1% | <1%

Higgs Decay Modes

- Higgs boson first discovered mainly from the analysis of its decay into the bosonic channels:
 $H \to WW^*$, $H \to ZZ^*(\to 4\ell)$ and $H \to \gamma\gamma$, the latter provides indirect measurement of couplings to quarks (via virtual loops).

- The Higgs boson decays into third generation fermions, $H \to \tau\tau$ and $H \to bb$, allow precise test the Yuwaka coupling.
- Evidence of interactions with second generation fermions (mainly muons) are emerging.



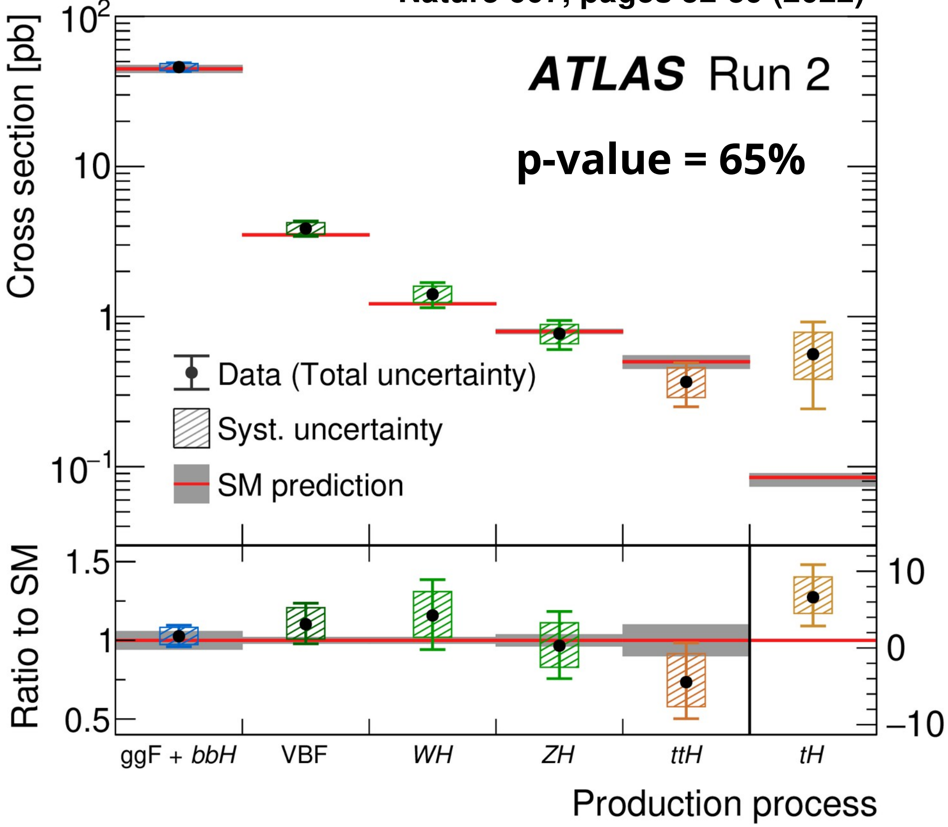
Channel	Branching ratio	Mass resolution
$H \to bb$	High	Low
$H \to \tau\tau$	High	Low
$H \to WW$	High	Very Low
$H \to ZZ^*$ ($\to 4l$)	Low	High
$H \to \gamma\gamma$	Low	High

13 TeV Higgs cross-section

- Comprehensive picture of the Higgs physics in Run 2 produced for the 10 year of the Higgs boson discovery.
- **Precision era**: combination of all available decay modes (including $H \rightarrow \mu\mu$//invisible) allows much finer splitting and improved sensitivity.
- Combined measurement of the common signal strength (μ):

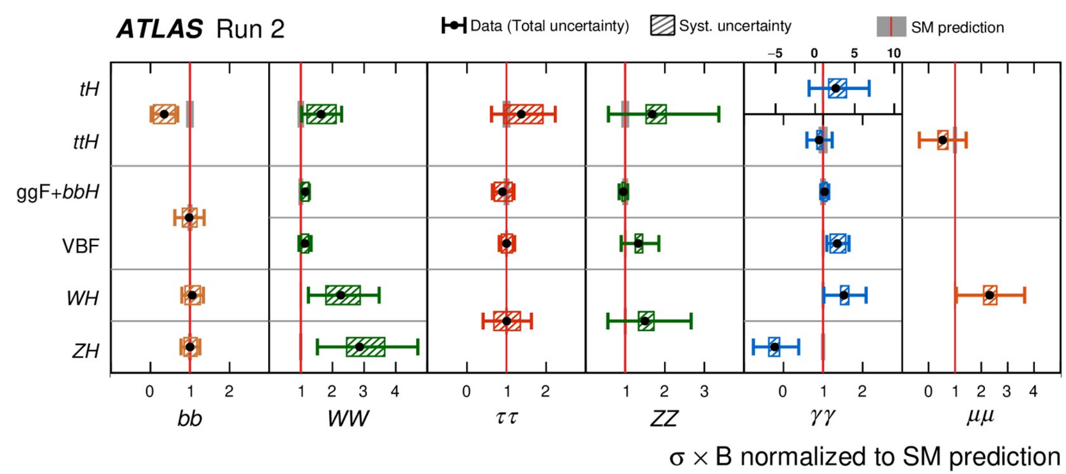
$$\mu = \sigma/\sigma_{SM} = 1.05 \pm 0.06 = 1.05 \pm 0.03\ (\text{stat.}) \pm 0.03\ (\text{exp.}) \pm 0.04\ (\text{sig. th.}) \pm 0.02\ (\text{bkg. th.})$$

Nature 607, pages 52-59 (2022)



Measurement of the signal strength by production mode: up to **6 production modes** and **8 decay channels** (incl. Zγ, cc).

p-value = 72%



Higgs Coupling with 13 TeV data

- ***Kappa*-framework**: modification of the Higgs boson couplings vertex at LO:

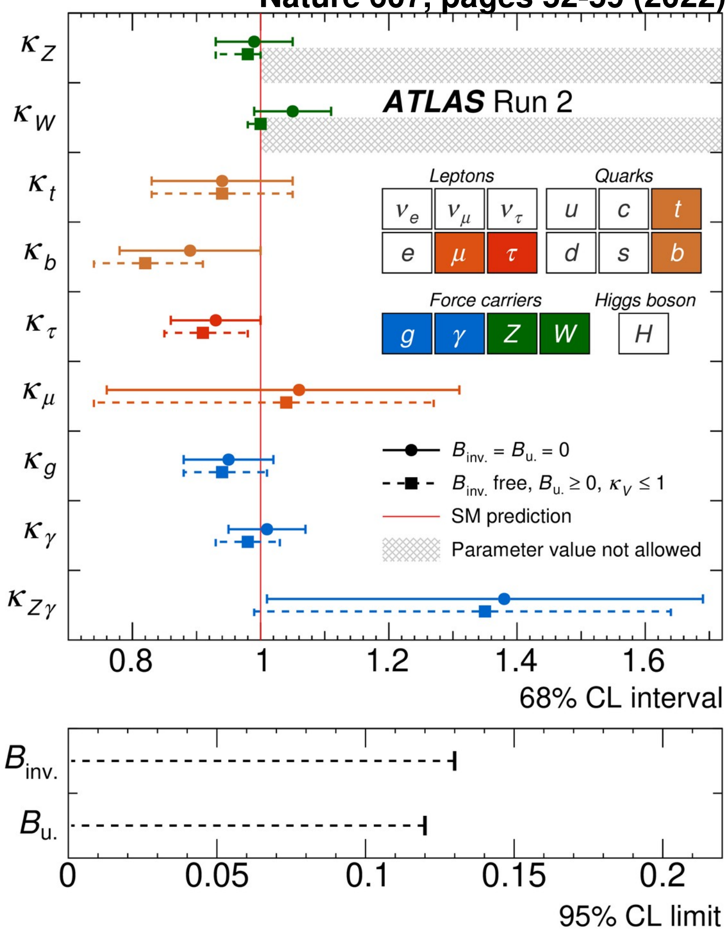
$$\sigma_i \times \mathrm{B}(H \to f) = \frac{\sigma_i \times \Gamma_f}{\Gamma_H} = \frac{\kappa_i^2 \kappa_f^2}{\kappa_H^2} \sigma_i^{\mathrm{SM}} \times \mathrm{B}^{\mathrm{SM}}(H \to f)$$

Constraints on the total width to infer kappas

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

- Theoretical methods developed to interpret and combine the cross-section measurements.

Nature 607, pages 52-59 (2022)



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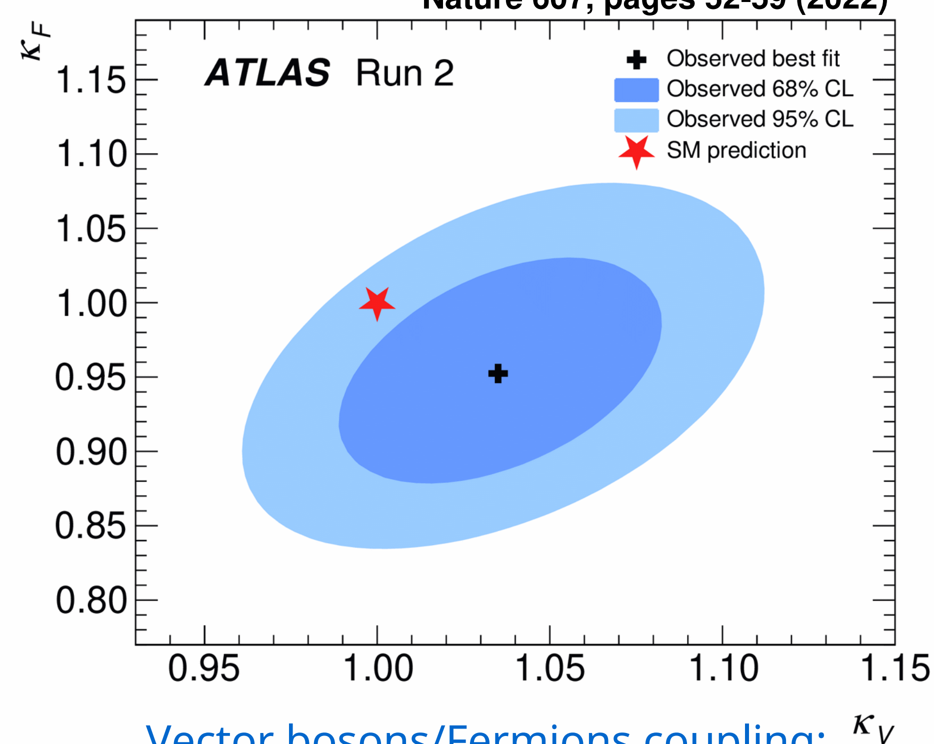


Vector bosons/Fermions coupling:

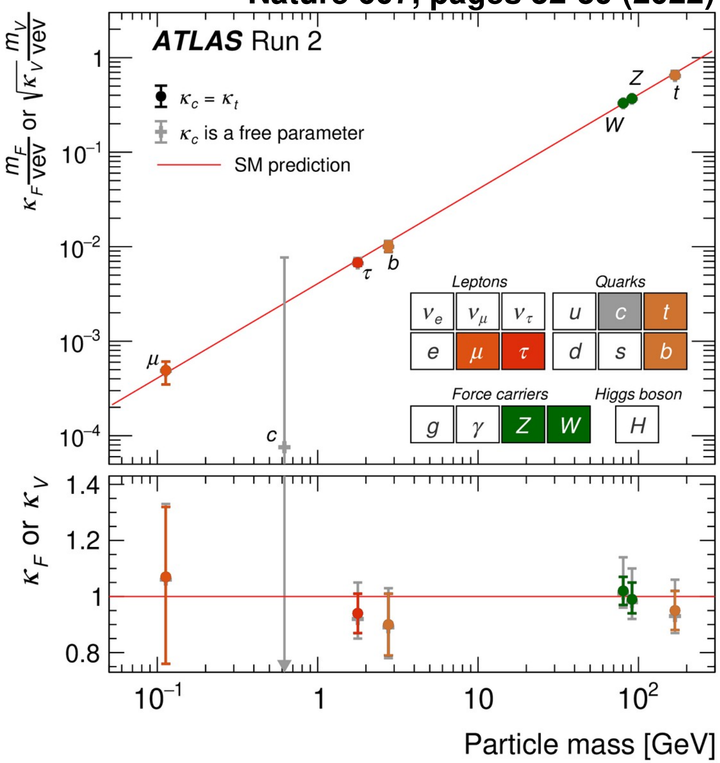
κ_V=1.035 ± 0.031, κ_F = 0.95 ± 0.05

- Most of the *kappa*-modifiers known with an accuracy of 6%-12%.
- Results obtained under different Br assumptions for Undetected/Invisible Higgs decays.

Higgs Coupling Summary

- Results are in good agreement with SM.
- Additionally, combined measurement where κ_c is left unconstrained provides constrain for $\kappa_c < 5.7$ (7.6) at 95% CL, which improves the $\kappa_c < 8.5$ limit from the H→cc analysis, with constraining power from the Higgs total width.

Nature 607, pages 52-59 (2022)



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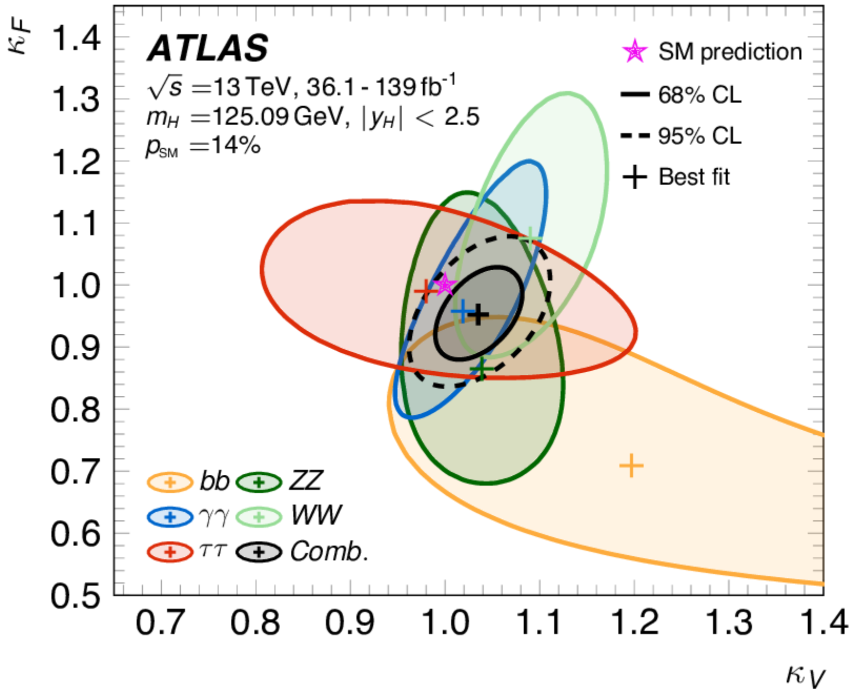
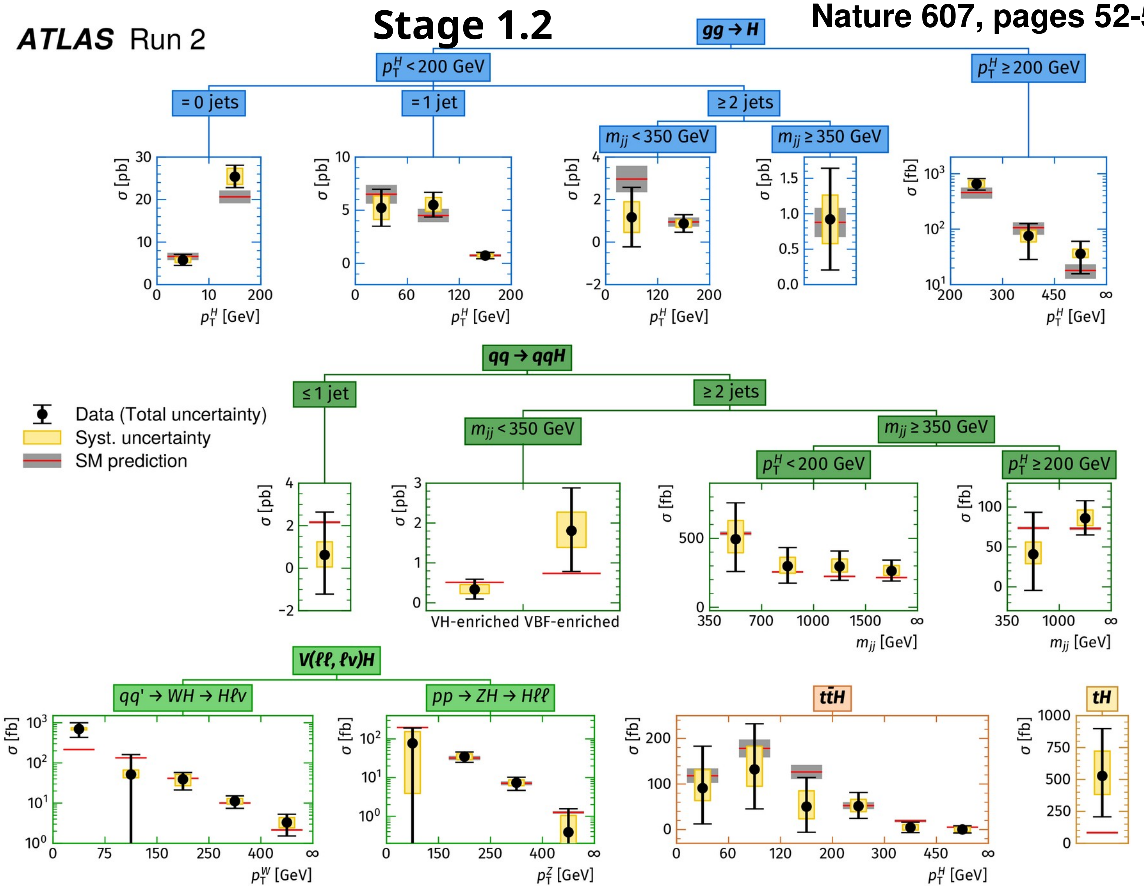


Vector bosons/Fermions coupling measured in each decay channel.

13 TeV Higgs cross-section

- **Simplified template cross sections (STXS)** [LHCXSWG YR4]:
- Aimed to efficiently exploit data balancing exp. precision and theory uncert.
- Isolate possible BSM contribution in high p_T and high mass bins.
- Increasing level of precision (Stage 0, Stage 1, Stage 2)

Stage 1.2 **Nature 607, pages 52-59 (2022)**

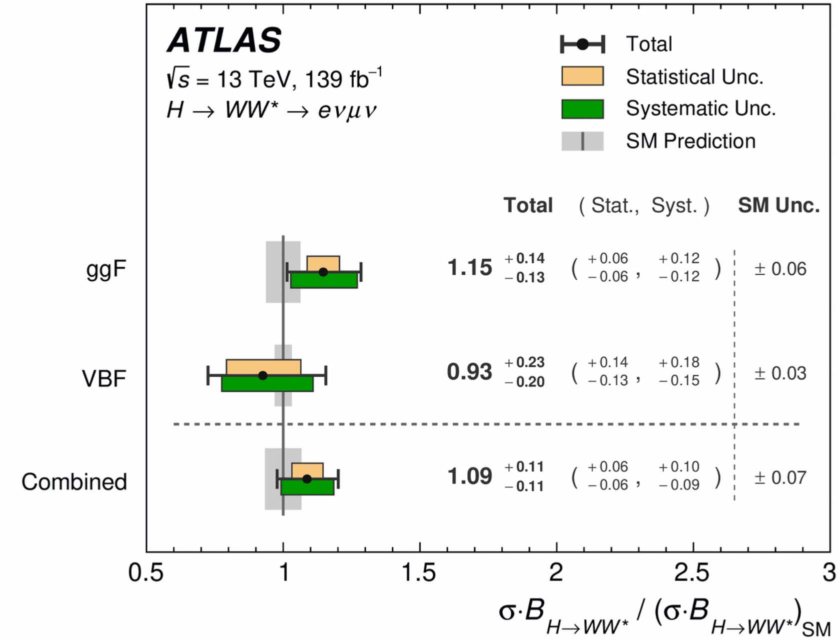


- Measurement in 36 mutually exclusive regions of phase space ("bins") specific to the different production modes.
- Results are in good agreement with the SM (p-value 94%)

H → WW* Recent Results

- **H → WW decay mode:** High branching ratio allows to target ggF,
- VBF and VH decay mode.
- Final states with ≥ 2 light leptons.
- Results from ggH and qqH are also interpreted in terms of STXS measurements

arXiv:2207.00338



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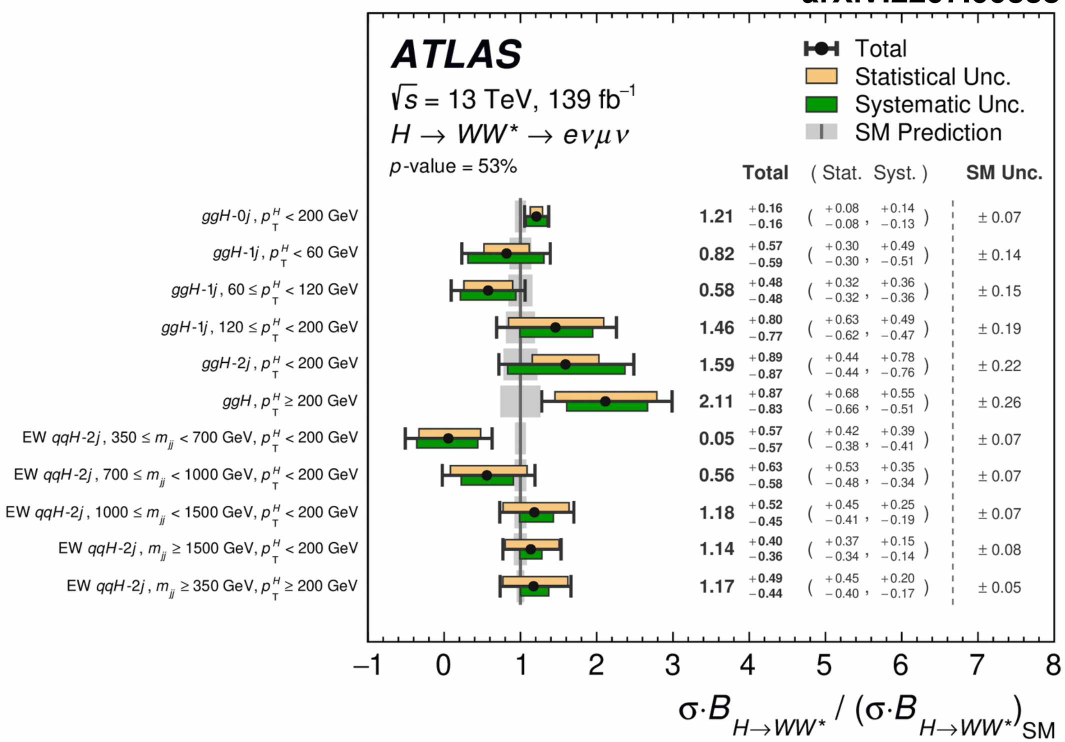

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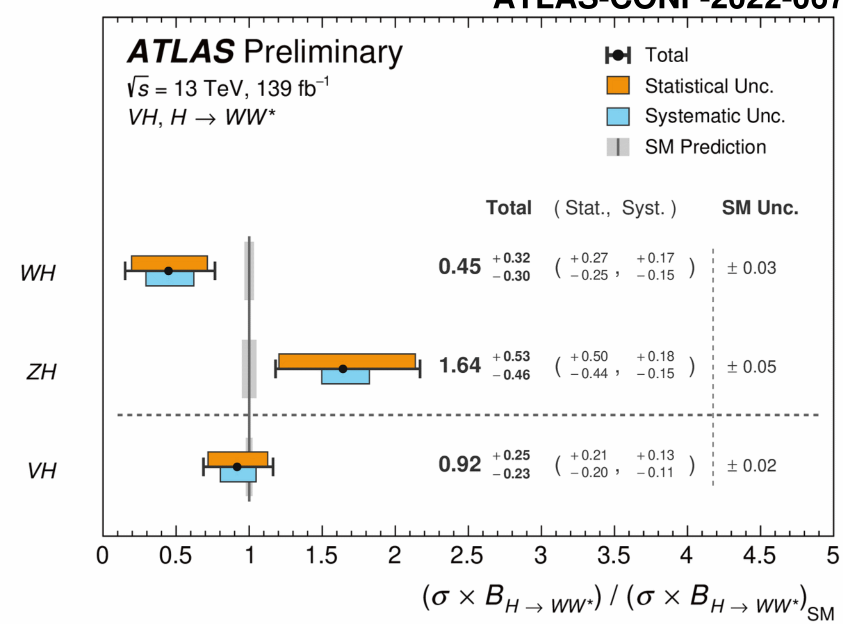
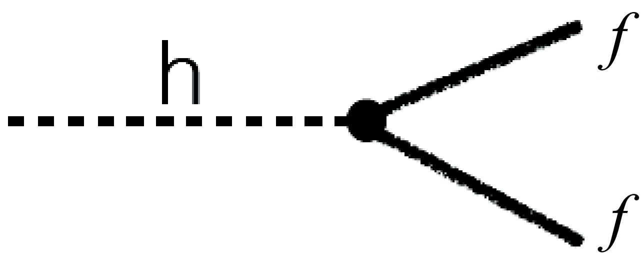
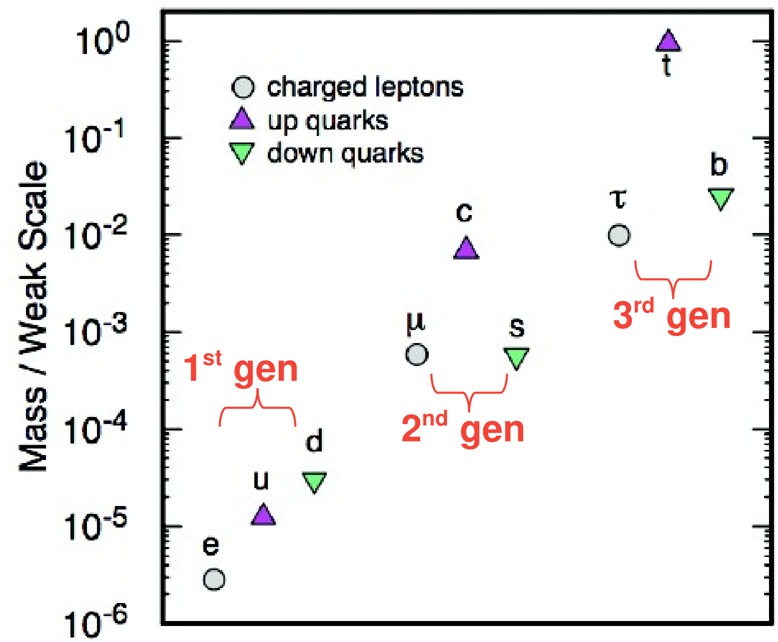


Yukawa couplings



$$\mathcal{L}_Y = -m_i \bar{f}^i_L f^i_R - Y_{ij}(\bar{f}^i_L f^j_R)h + h.c. + \cdots ,$$

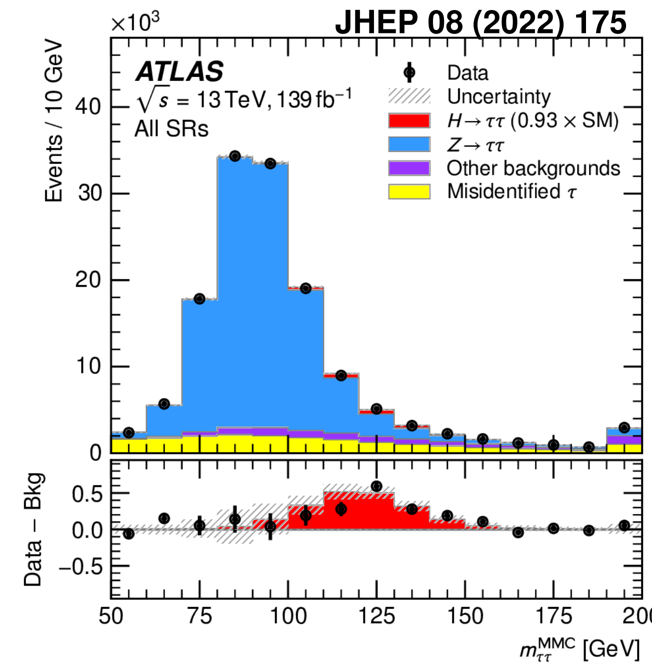
In the SM: $Y_{ij} = (m_i/v)\delta_{ij}$

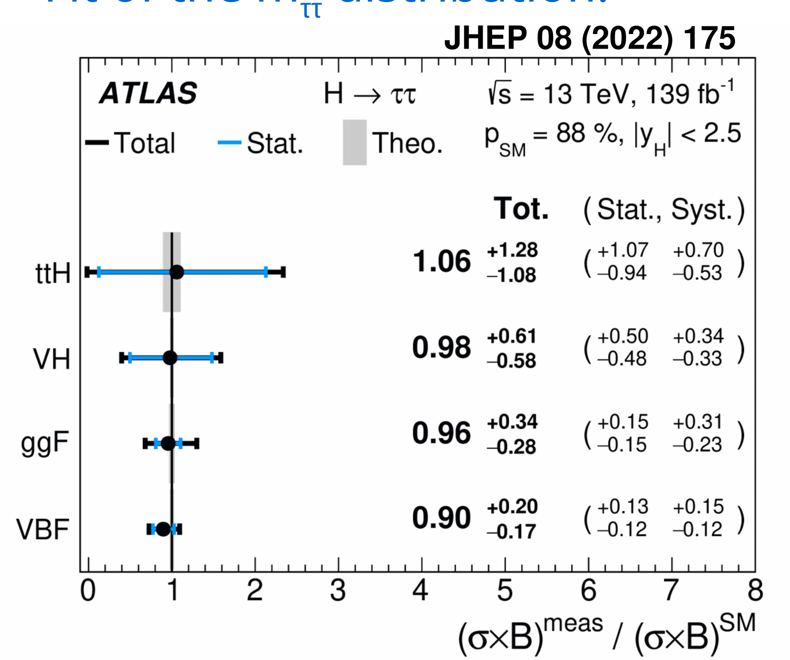


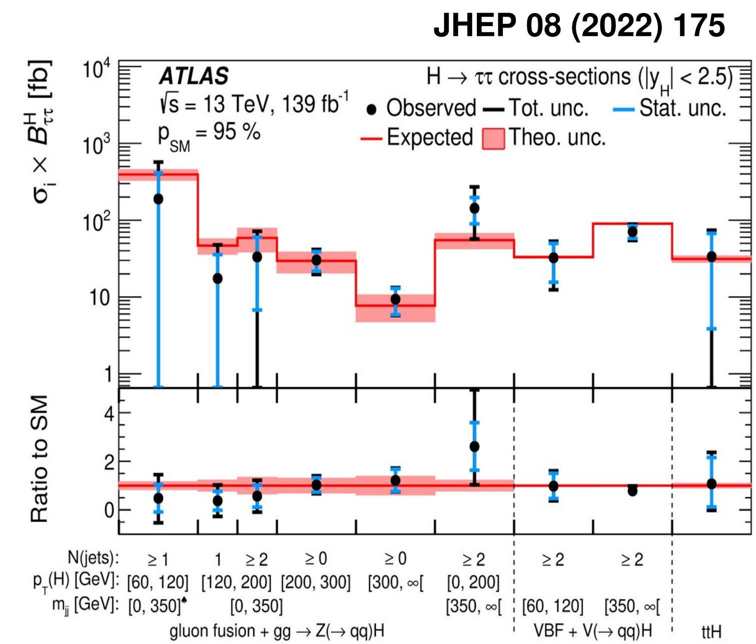
- The Higgs boson is the only fundamental boson of the SM to exhibit Yukawa couplings.
- The study of this new kind of interaction can reveal novel features not seen in gauge boson interactions, like flavour violation or anomalous CP-odd coupling.
- Higgs interactions at the origin of the flavour structure in the SM (Yukawa proportional to mass):
  - Interaction strength proportional to fermion mass, spanning about 6 orders of magnitude (neglecting neutrinos).

Run 2 $H \to \tau\tau$ Analysis

- Precise test of Yukawa coupling.
- Main background is $Z \to \tau\tau$ modelled by MC simulation and τ-embedding for normalization.
- Analysis channels: $\tau_e\tau_{had}$, $\tau_\mu\tau_{had}$, $\tau_e\tau_\mu$, $\tau_{had}\tau_{had}$
- Fit of the $m_{\tau\tau}$ distribution.





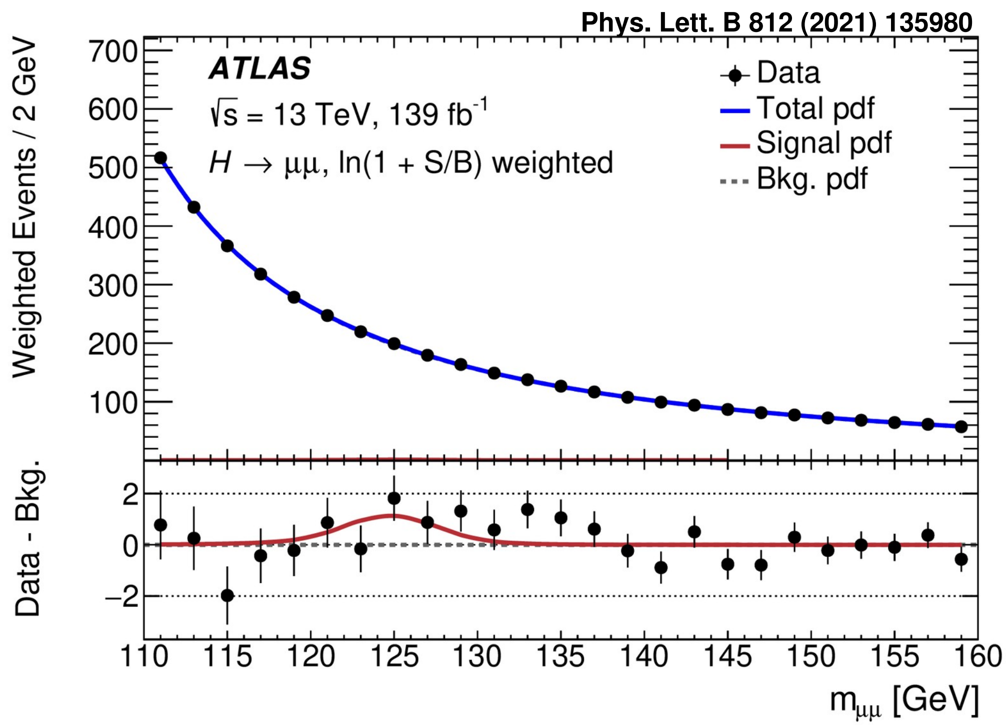


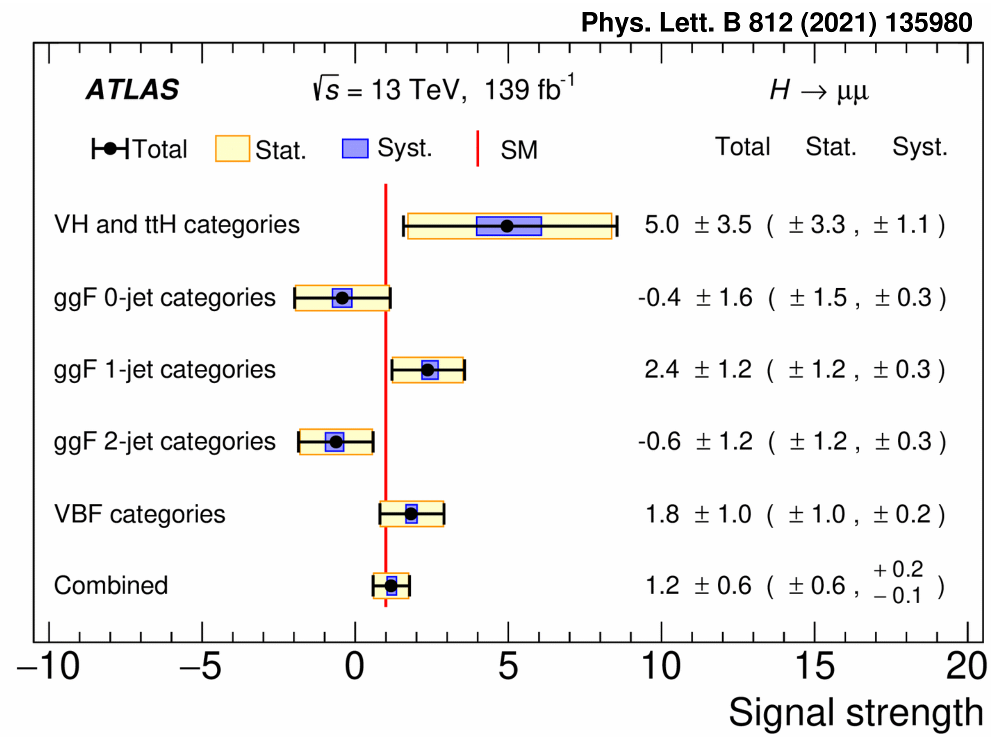
- Measured cross section $\sigma(pp \to H \to \tau\tau)$:
- 2.94 ± 0.21 (stat) $^{+0.37}_{-0.32}$(syst) pb

  in agreement with the SM prediction: 3.17 ± 0.09 pb.
- $H \to \tau\tau$ channel has high sensitivity to VBF process.

Run 2 $H \to \mu\mu$ Analysis

- Unbinned fit of the $m_{\mu\mu}$ mass spectrum.
- Events are separated in 20 categories (VBF, VH, ttH; Number of jets and BDT score).
- Background modeled by the product of a core function common to all categories and an empirical component (power law or exponential).
- Signal modeled by a double sided Crystal Ball.

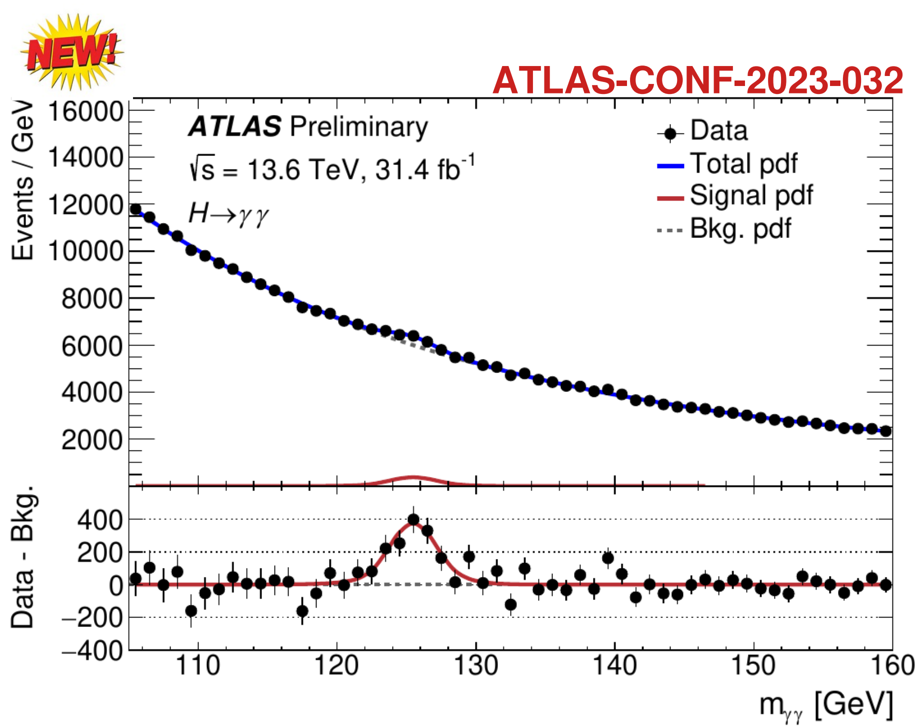


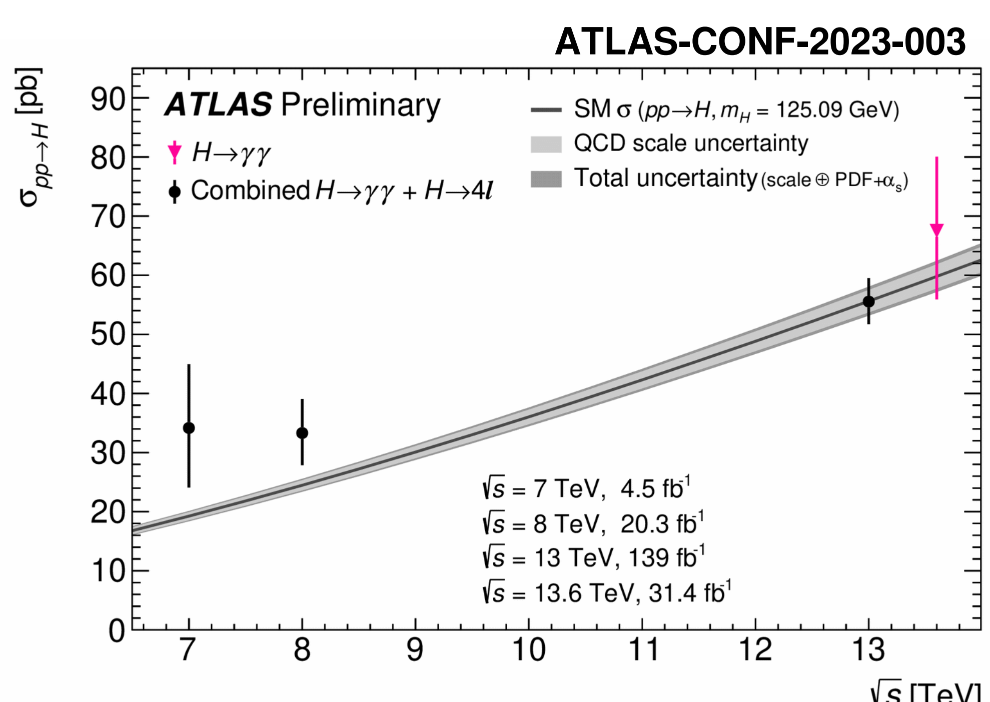


- The observed (expected) significance over the background-only hypothesis for a Higgs boson with a mass of 125.09 GeV is 2.0σ (1.7σ).

Cross section measurement @13.6 TeV

- **First preliminary Higgs cross-section measurement @13.6 TeV with Run 3** data (lumi = 31.4 fb^{-1}) obtained in Winter 2023 (ATLAS-CONF-2023-003).
- Now being finalized for publication.
- Analysis performed in the $\gamma\gamma$ final state at a center of mass energy of 13.6 TeV.
- The result of the total cross-section @ 13.6 TeV is $\sigma = 67^{+12}_{-11}$ pb, compatible with the SM prediction of 59.9 ± 2.6 pb.
- Uncertainties conservatively extrapolated from Run 2. Precise photon calibration studies with Run 3 data are ongoing.

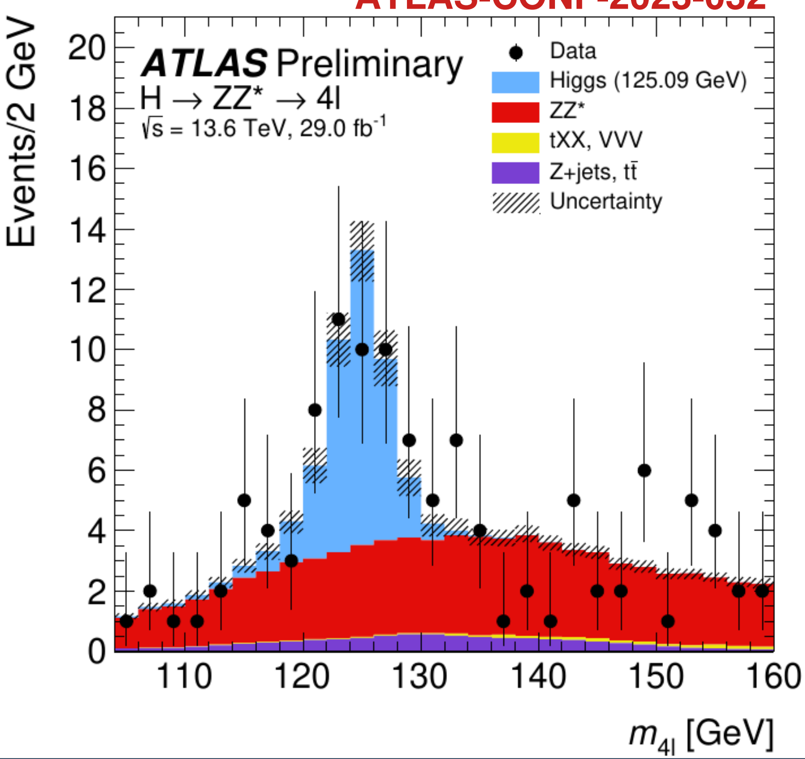




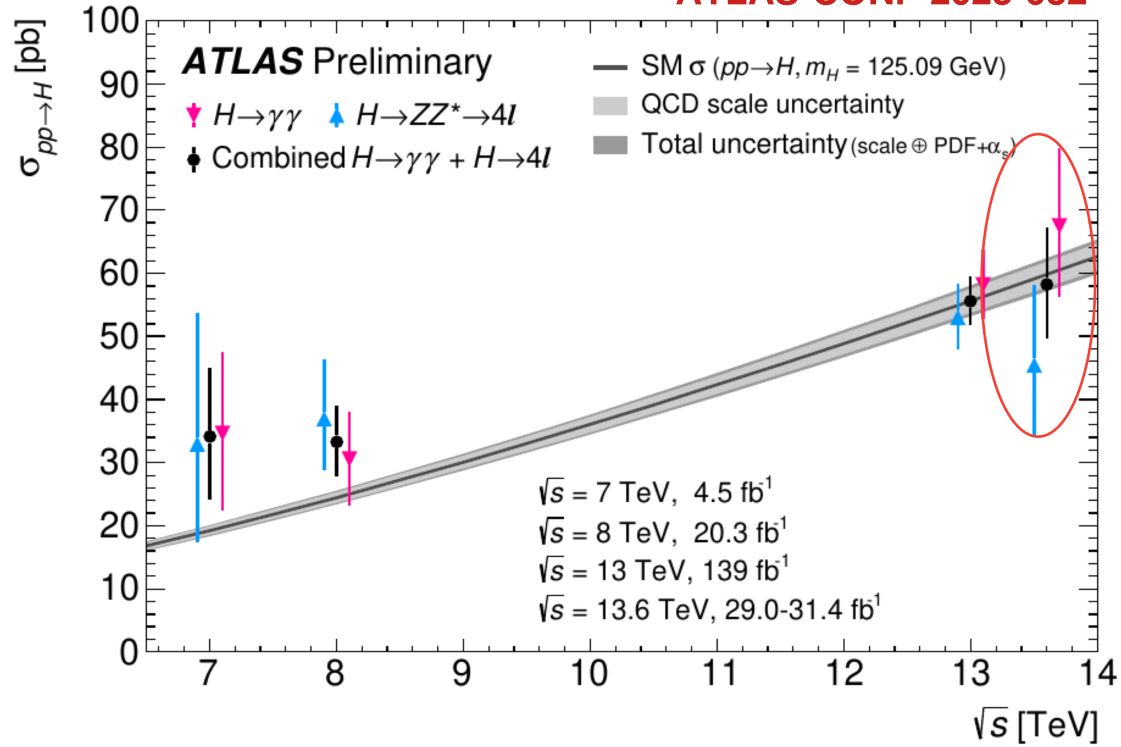
Run 3 cross-sec. meas in $H \rightarrow 4\ell$

- **Cross-section measurement with Run 3** data (lumi = 29 fb^{-1}), performed in the $H \rightarrow ZZ^* \rightarrow 4\ell$ final state at a center of mass energy of 13.6 TeV.
- A binned fit of the reconstructed invariant mass mass $m_{4\ell}$ distribution for 4 different channels (4μ, 2e2μ, 2μ2e and 4e).
- The result of the total cross-section @ 13.6 TeV is σ = 46±12 pb, is combined with $H \rightarrow \gamma\gamma$: **$\sigma(pp \rightarrow H)_{H4l+H\gamma\gamma}$ = 58.2 ± 7.5(stat.) ± 4.2(syst.) pb**, compatible with the SM prediction of 59.9 ± 2.6 pb.

ATLAS-CONF-2023-032



ATLAS-CONF-2023-032



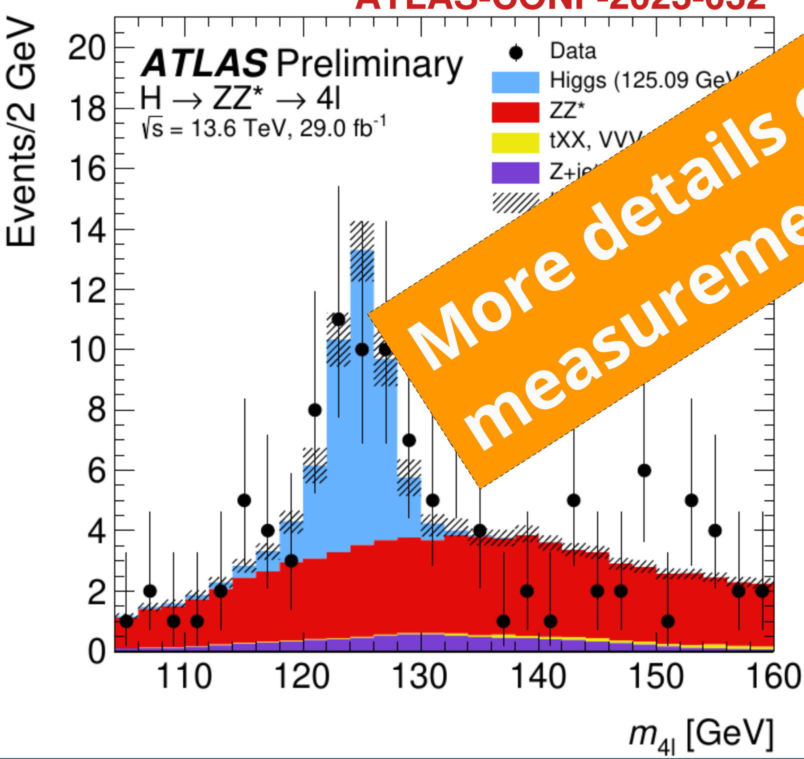
Run 3 cross-sec. meas in $H \rightarrow 4\ell$

NEW!

- **Cross-section measurement with Run 3** data (lumi = 29 fb^{-1}), performed in the $H \rightarrow ZZ^* \rightarrow 4\ell$ final state at a center of mass energy of 13.6 TeV.
- A binned fit of the reconstructed invariant mass mass m… …tribution for 4 different channels (4μ, 2e2μ, 2μ2e and 4e).
- The result of the total cross-section @ 13.6 TeV … …pb, is combined with $H \rightarrow \gamma\gamma$: **$\sigma(pp \rightarrow H)_{H4l+H\gamma\gamma}$ = 58.2 ± 7.5(stat…** … **pb**, compatible with the SM prediction of 59.9 ± 2.6 pb.

More details on the fiducial measurement in R. Di Nardo talk

ATLAS-CONF-2023-032



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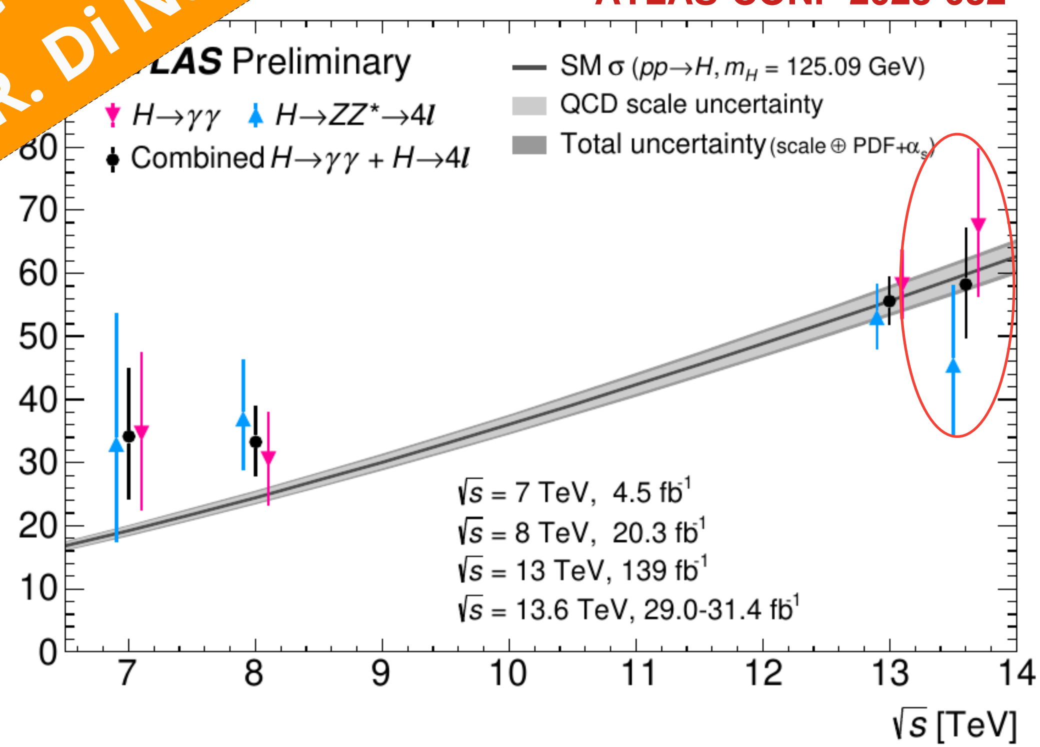


Summary

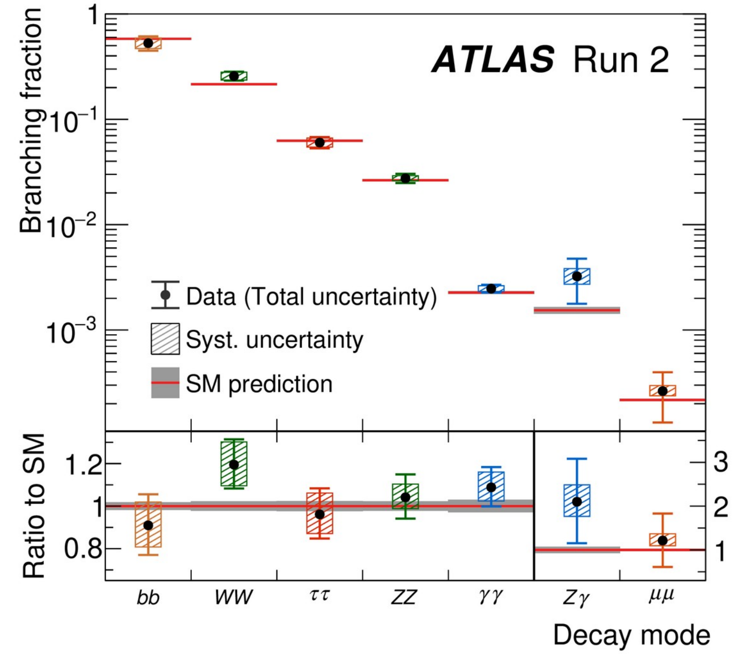
- Thanks to the impressive performance of the LHC, detectors and theory community, we are now in the **precision era** of the Higgs boson measurements with several coupling uncertainties at the level of <~10%.

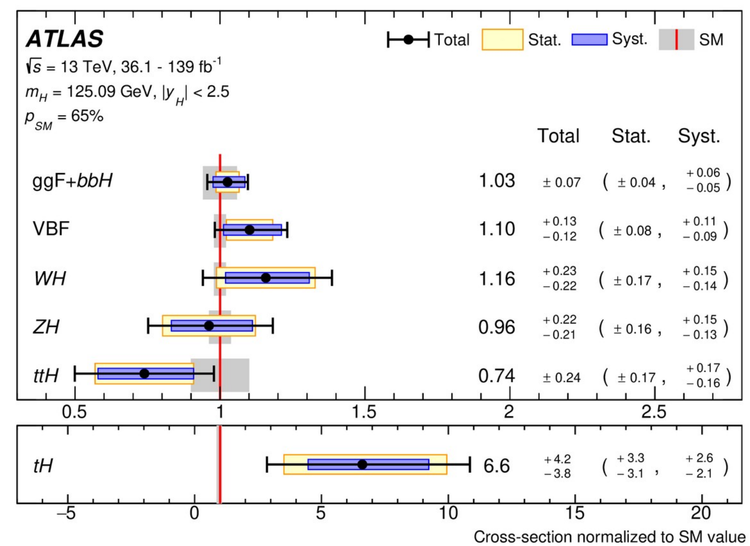
- Measurement of the Higgs boson production and decay rates are among the top priorities of the LHC.

- Many ATLAS results with full Run 2 data have been published.

- First Higgs results with Run 3 data are available.

- Higgs measurements are in a good agreement with the predictions of the Standard Model.



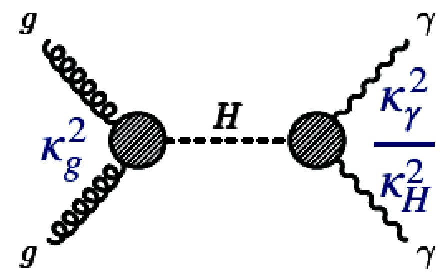


Bonus Slides

kappa Fit

	(a) $B_{inv.} = B_{u.} = 0$	(b) $B_{inv.}$ free, $B_{u.} \geq 0$, $\kappa_{W,Z} \leq 1$
κ_Z	$0.99^{+0.06}_{-0.06}$	$0.98^{+0.02}_{-0.05}$
κ_W	$1.05^{+0.06}_{-0.06}$	$1.00_{-0.02}$
κ_t	$0.94^{+0.11}_{-0.11}$	$0.94^{+0.11}_{-0.11}$
κ_b	$0.89^{+0.11}_{-0.11}$	$0.82^{+0.09}_{-0.08}$
κ_τ	$0.93^{+0.07}_{-0.07}$	$0.91^{+0.07}_{-0.06}$
κ_μ	$1.06^{+0.25}_{-0.30}$	$1.04^{+0.23}_{-0.30}$
κ_g	$0.95^{+0.07}_{-0.07}$	$0.94^{+0.07}_{-0.06}$
κ_γ	$1.01^{+0.06}_{-0.06}$	$0.98^{+0.05}_{-0.05}$
$\kappa_{Z\gamma}$	$1.38^{+0.31}_{-0.37}$	$1.35^{+0.29}_{-0.36}$
$B_{inv.}$	-	< 0.13
$B_{u.}$	-	< 0.12

$$\sigma_i \times \mathrm{B}(H \to f) = \frac{\sigma_i \times \Gamma_f}{\Gamma_H} = \frac{\kappa_i^2 \kappa_f^2}{\kappa_H^2} \sigma_i^{\mathrm{SM}} \times \mathrm{B}^{\mathrm{SM}}(H \to f)$$



$$\sigma \times BR(gg \to H \to \gamma\gamma) \propto \kappa_g^2 \frac{\kappa_\gamma^2}{\kappa_H^2}$$

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

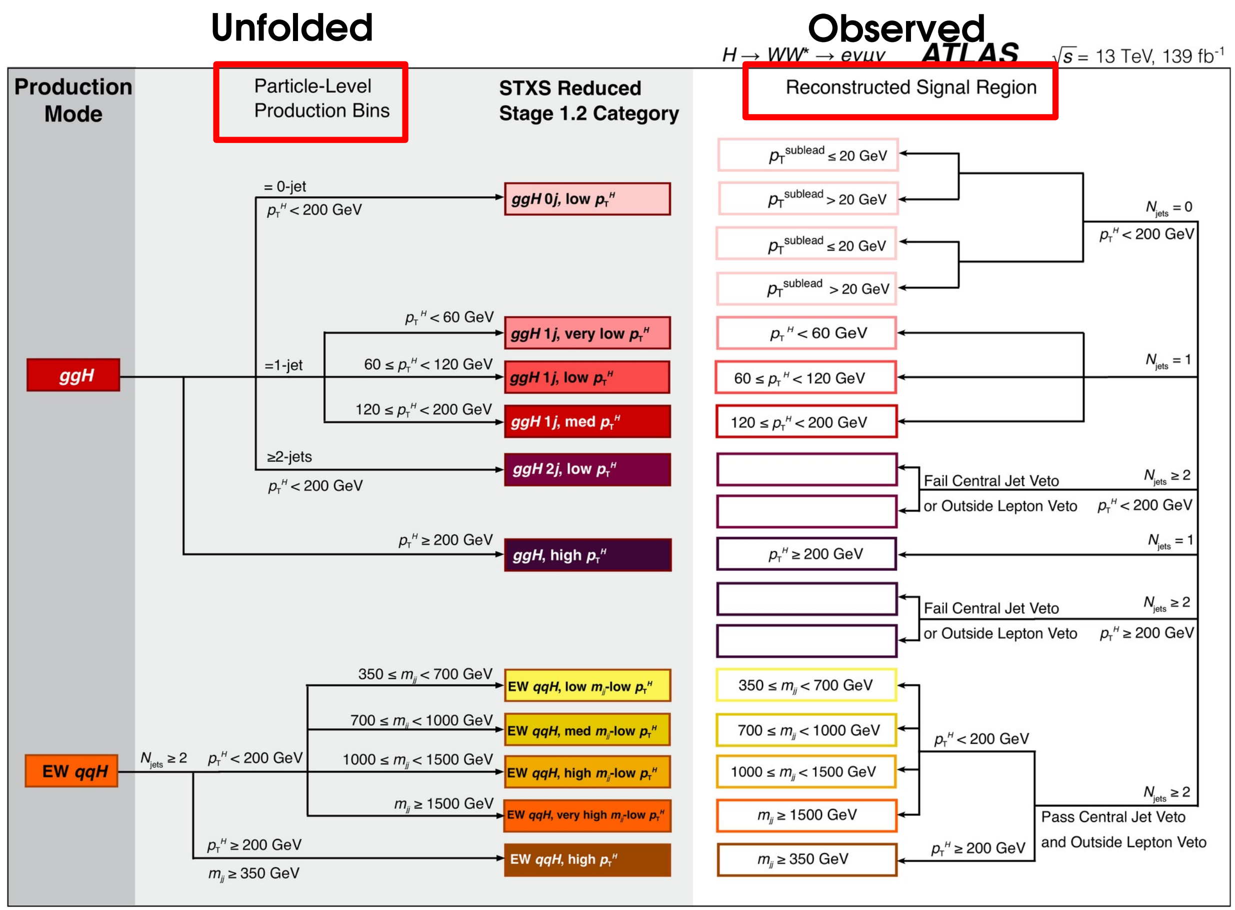
with $$\kappa_H^2(\kappa, B_{\mathrm{inv.}}, B_{\mathrm{u.}}) = \frac{\sum_p B_p^{\mathrm{SM}} \kappa_p^2}{(1 - B_{\mathrm{inv.}} - B_{\mathrm{u.}})}$$

13 TeV Higgs cross-section

- **Simplified template cross sections (STXS)** [LHCXSWG YR4]:
  - Aimed to efficiently exploit data balancing exp. precision and theory uncert.
  - Measurement in exclusive fiducial regions of phase space ("bins") specific to the different production modes.
  - Isolate possible BSM contribution in high p_T and high mass bins.
  - Increasing level of precision (Stage 0, Stage 1, Stage 2)

- Independent simple fiducial region definitions for each Higgs production mode based on Higgs kinematics and associated particles.

- STXS definitions are common for ATLAS, CMS and theory to ease combination, minimize theoretical uncertainties and maximize experimental sensitivity



Run 3 cross section uncertainties

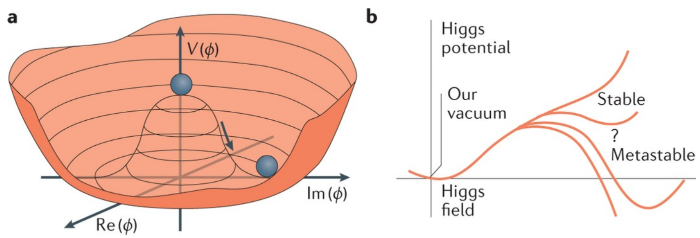
Source	Uncertainty [%]
Statistical uncertainty	14.0
Systematic uncertainty	10.3
Background modelling (spurious signal)	6.0
Photon trigger and selection efficiency	5.8
Photon energy scale & resolution	5.5
Luminosity	2.2
Pile-up modelling	1.2
Higgs boson mass	0.1
Theoretical (signal) modelling	< 0.1
Total	17.4

$H \rightarrow \gamma\gamma$

Source	Uncertainty [%]
Statistical uncertainty	25.1
Systematic uncertainty	7.9
Electron uncertainties	6.3
Muon uncertainties	3.8
Luminosity	2.2
ZZ^* theoretical uncertainties	0.7
Reducible background estimation	0.6
Other uncertainties	< 1
Total	26.4

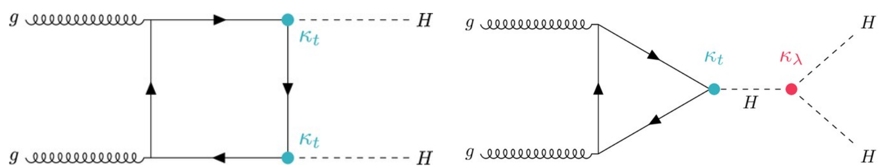
$H \rightarrow ZZ^* \rightarrow 4\ell$

Higgs self-coupling

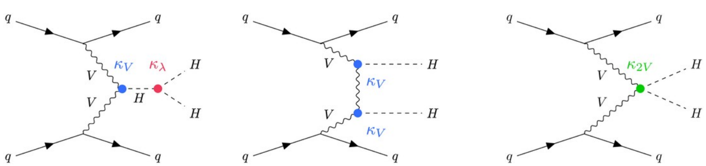


- The Higgs self-coupling λ is a fundamental SM parameter (EW symmetry breaking).
- It can be measured at LHC measuring di-Higgs production.

ggF ~ 90% of HH production

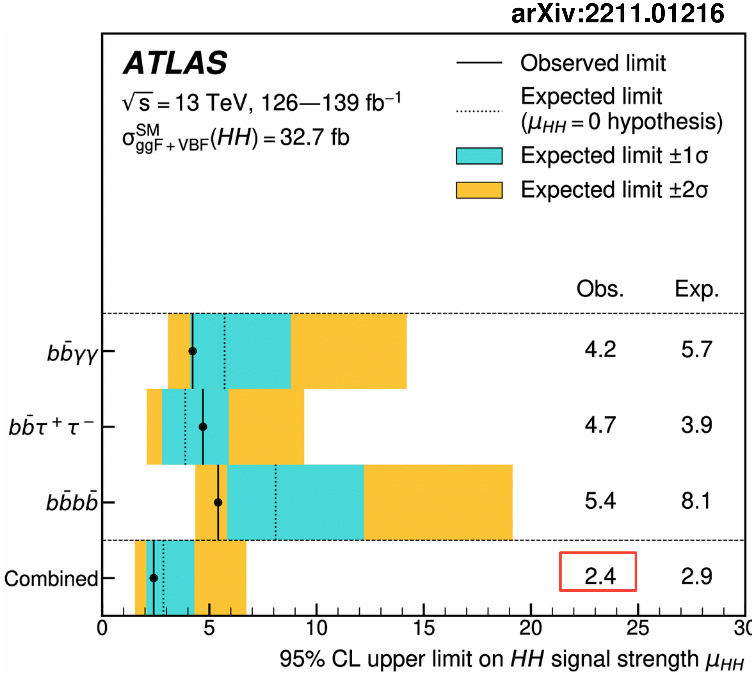


VBF ~ 5% of HH production



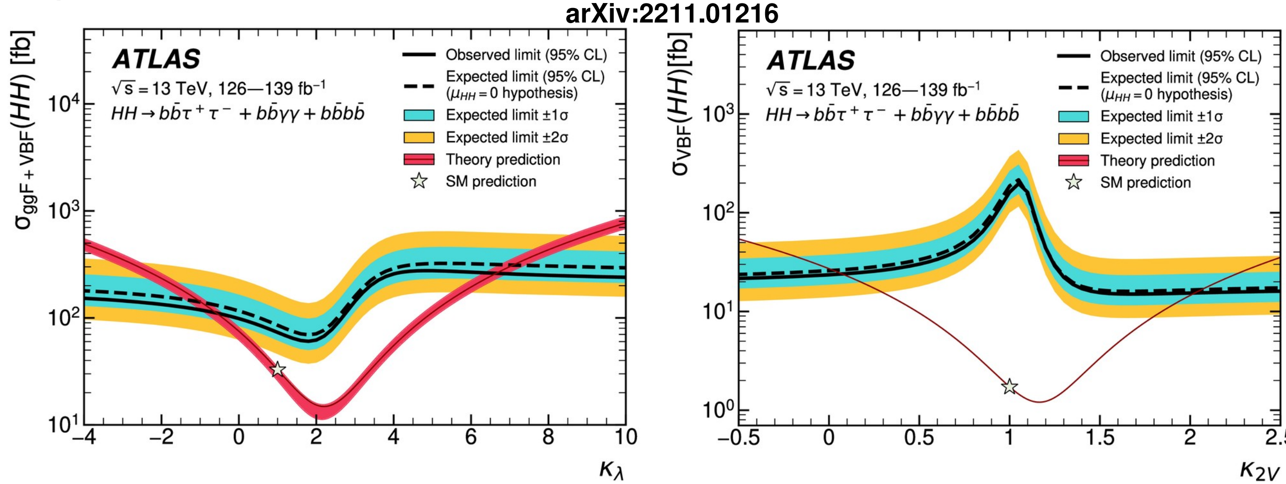
- No evidence of di-Higgs production yet, but stringent constraints on σ_{HH} and κ_λ from combination of HH searches in 3 most sensitive channels.

arXiv:2211.01216



Most stringent limit to date

arXiv:2211.01216



Higgs self-coupling

- Constraints on κ_λ are further improved by removing of the degeneracy of κ_λ with κ_t and κ_V performing a combination of the HH searches in 3 most sensitive channels with the single Higgs cross-section measurements.
- NLO EW corrections parametrized vs 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, κ_t, κ_V, κ_b, κ_τ floating	$-1.4 < \kappa_\lambda < 6.1$	$-2.2 < \kappa_\lambda < 7.7$	$\kappa_\lambda = 2.3^{+2.1}_{-2.0}$