Measurements of Higgs boson production and decay rates and their interpretation with the ATLAS experiment

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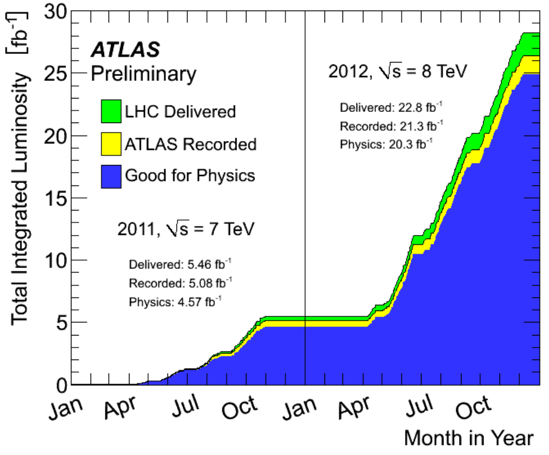
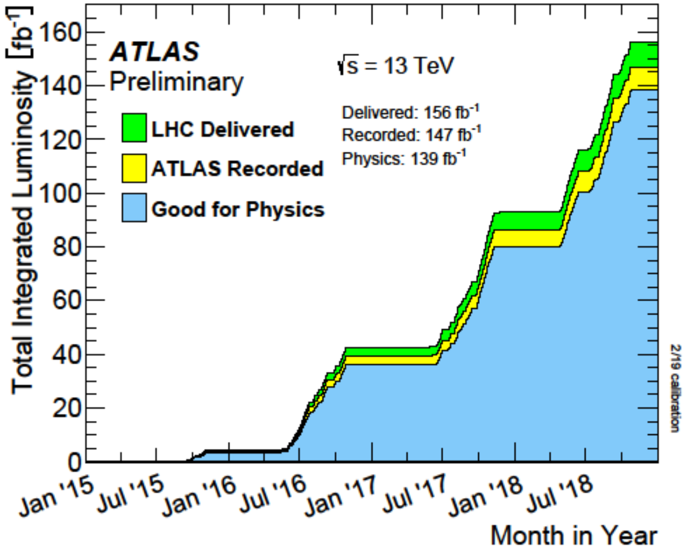
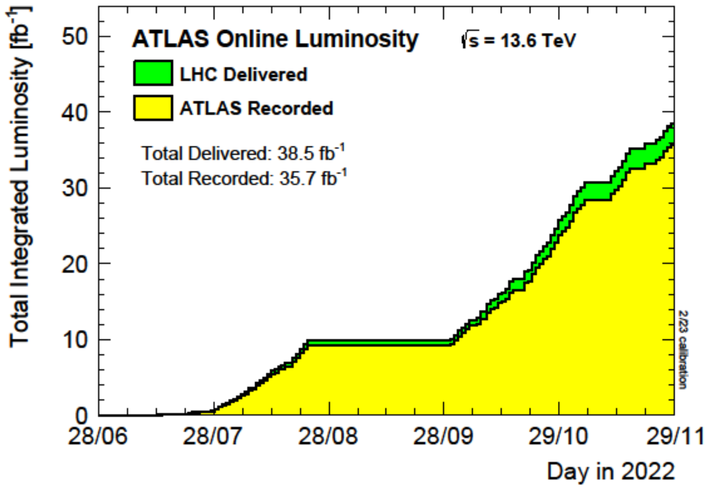
34th Rencontres de Blois

ATLAS Higgs timeline







In 2011-2012
7 TeV pp RUN 1 data analysis states the «new» discovered particle is compatible with SM Higgs boson.

In 2015-2018
With 8 to 13 TeV pp RUN 2, 30xHiggs events recorded, improving precision and accessing new analysis channels.

In 2022-
Ongoing RUN 3 with √s=13.6 TeV

The aim is to study all the possible Higgs boson production and decays

→ To measure the interactions between Higgs boson and elementary particles and their properties

→ To provide experimental test of SM and constraints of BSM, probe particle to understand the universe

Content of talk

Overview of recent analyses where statistic uncertainties were reduced w.r.t Run 1 / new accessible processes were investigated in LHC Run 2

Inclusive cross sections of Higgs boson production

- ggF+VBF with $H \rightarrow WW*$ arXiv:2207.00338v1
- VH with $H \rightarrow WW*$ ATLAS-CONF-2022-067

Fiducial and differential cross sections

- ggF with $H \rightarrow WW* \rightarrow \mu\nu e\nu$ arXiv:2301.06822v1
- VBF with $H \rightarrow WW* \rightarrow \mu\nu e\nu$ arXiv:2304.03053v1

Rare processes

- VH with $H \rightarrow b\bar{b}$ and $H \rightarrow c\bar{c}$ arXiv:2201.11428v4

Combined measurement and its interpretation

- Combined measurement arXiv.2207.00092
- Interpretation ATLAS-CONF-2021-053

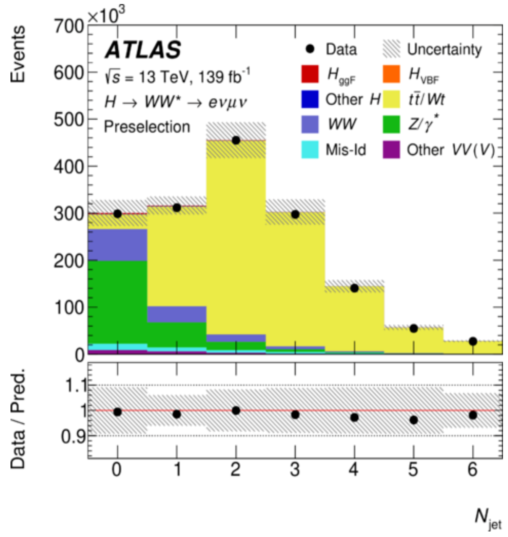
First look at Run-3 data new LHC center-of-mass energy.

- $H \rightarrow \gamma\gamma$ ATLAS-CONF-2023-003

Inclusive $\sigma_{prod} * BR$ of ggF+VBF with $H \to WW^* \to e\nu\mu\nu$

Analysis workflow:

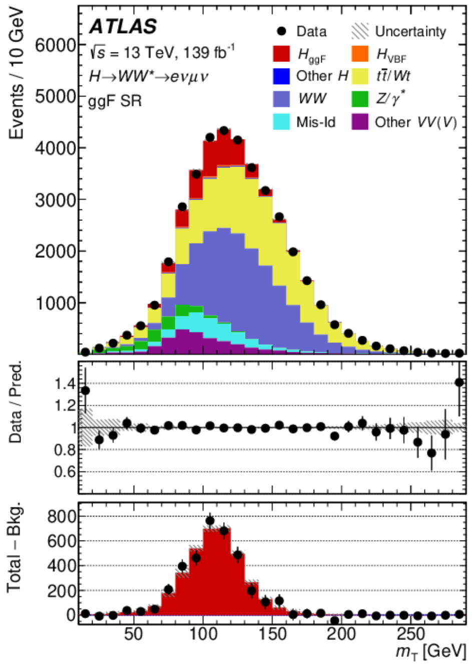
- Common preselection

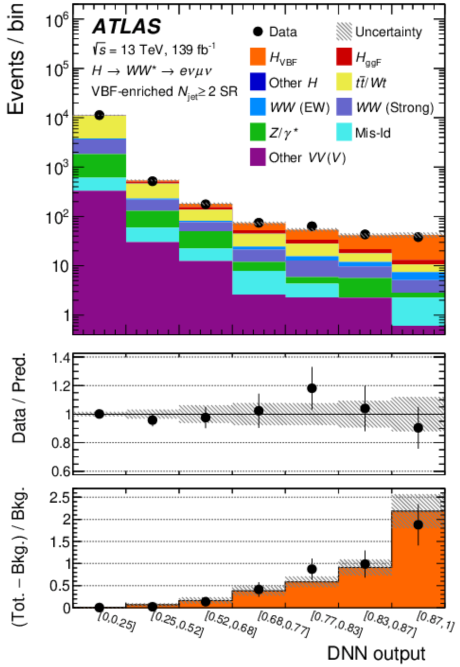


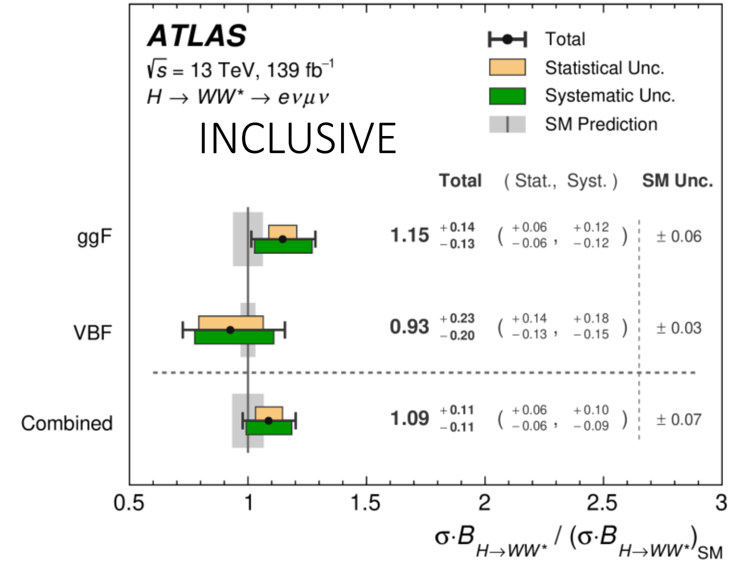
- Separate MVA analyses are performed in N_{jets}= 0, 1, >=2 categories (N_{jets} >=2 is split in ggF-enriched and VBF-enriched).
  - Dominant background processes: WW, top, Z/γ*
  - Discriminant variables: di-lepton + E^{T}_{miss} transverse mass m_T (ggF) and DNN (VBF N_{jet} >2 jet category)

$$m_T = \sqrt{(E_T^{\ell\ell} + E_T^{\text{miss}})^2 - |\vec{p}_T^{\ell\ell} + \vec{E}_T^{\text{miss}}|^2}$$

- Profile likelihood fit







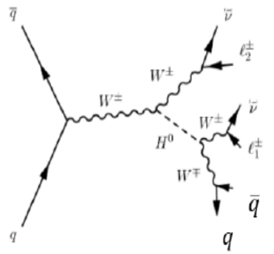
arXiv:2207.00338v1

Inclusive $\sigma_{prod} * BR$ of VH with $H \rightarrow WW^*$

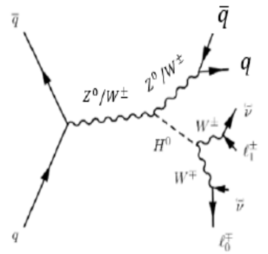
At √s of LHC Run 1 and 2, VH is the third most probable production process (~4% in Run 2 cases).
NEW improvements with respect to the previous analysis:

ATLAS-CONF-2022-067

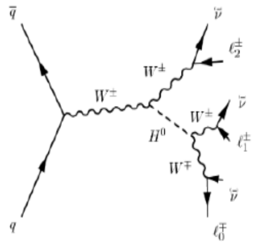
- Addition of two semileptonic channels with 2 charged leptons in the final state;



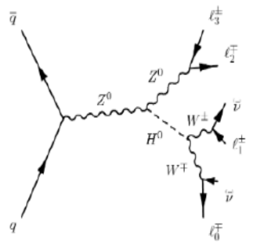
Same sign 2l-SS-WH



Different sign 2l-DS-VH

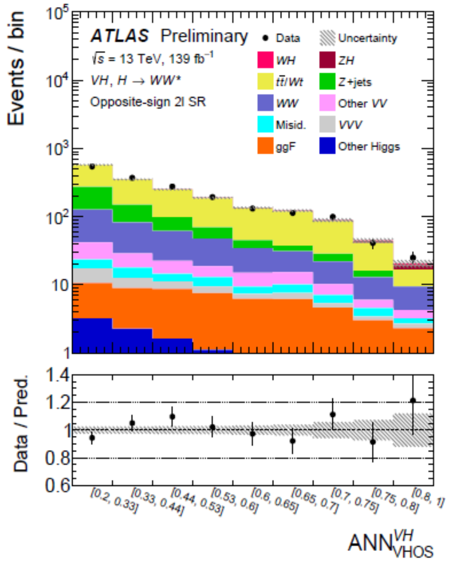


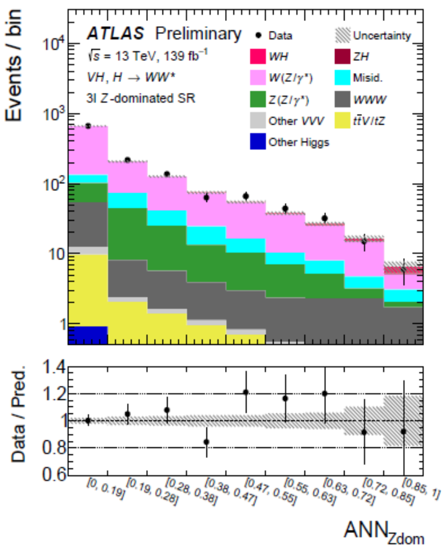
3l-WH

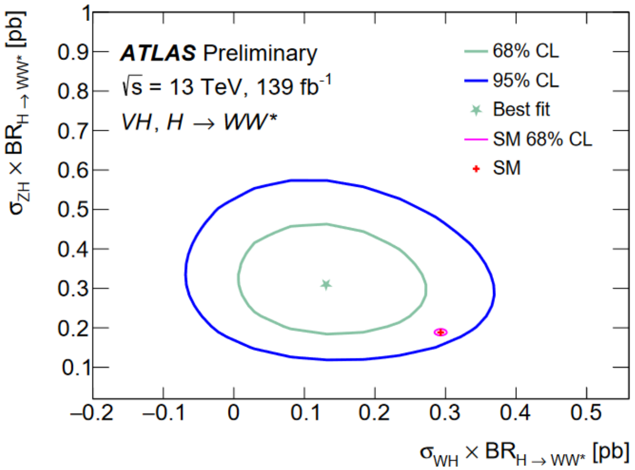


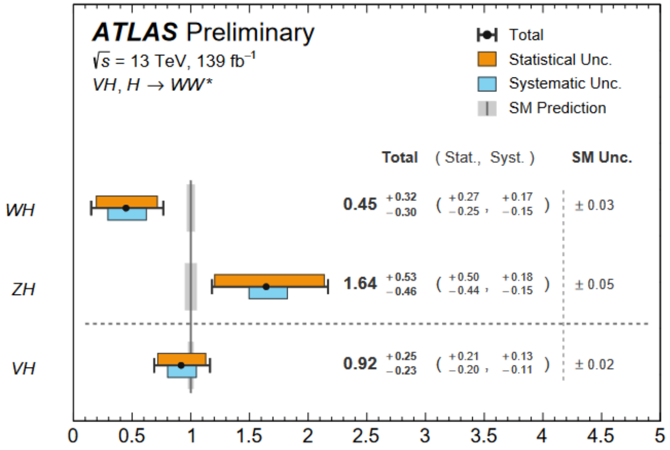
4l-ZH

- Different MVA analysis approaches optimised for the background composition of each SR: Migration to Neural Network (NN) discriminants (other 4);





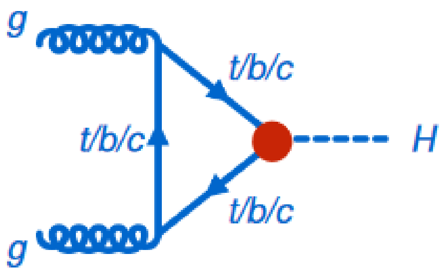




$$\mu = (\sigma \times B_{H\rightarrow WW^*}) / (\sigma \times B_{H\rightarrow WW^*})_{SM}$$

The measurements are compatible with the SM expectations.

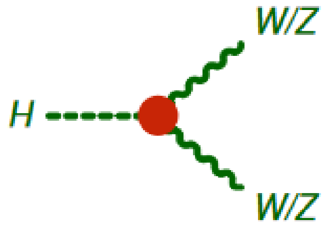
Differential σ of ggF with $H \to WW^* \to \mu\nu e\nu$



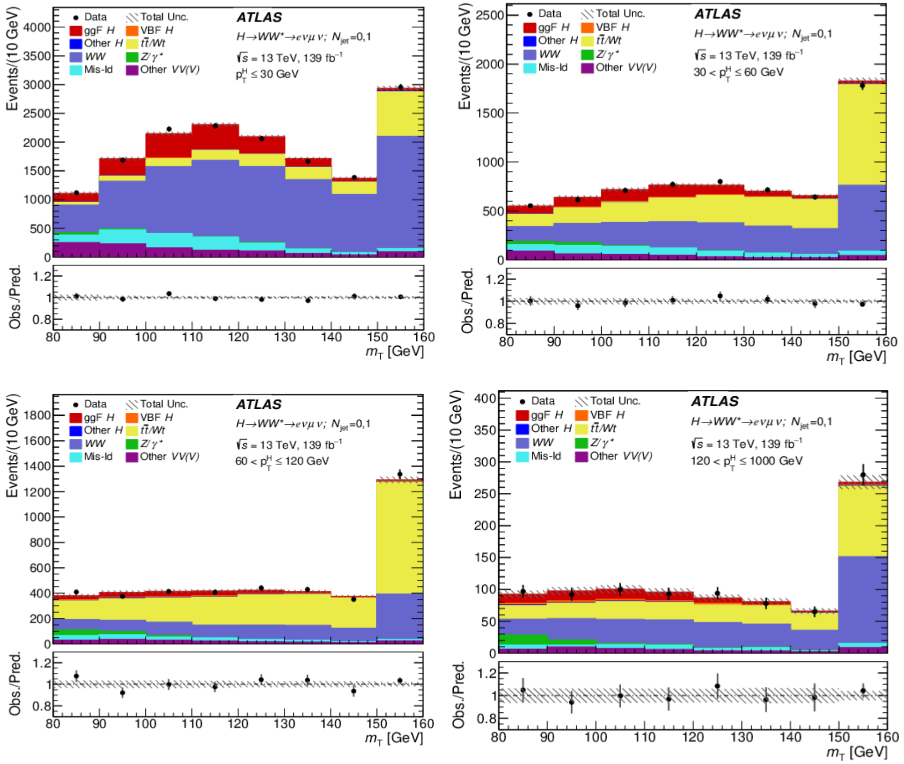
- Particle level (dilepton variables, E_T^{miss}, m_T)

$$m_T = \sqrt{(E_T^{\ell\ell} + E_T^{\text{miss}})^2 - |\vec{p}_T^{\ell\ell} + \vec{E}_T^{\text{miss}}|^2}$$

- Dominant backgrounds:
  $qq \to WW$, $t\bar{t}$ and Wt, $Z/\gamma* \to \tau\tau$

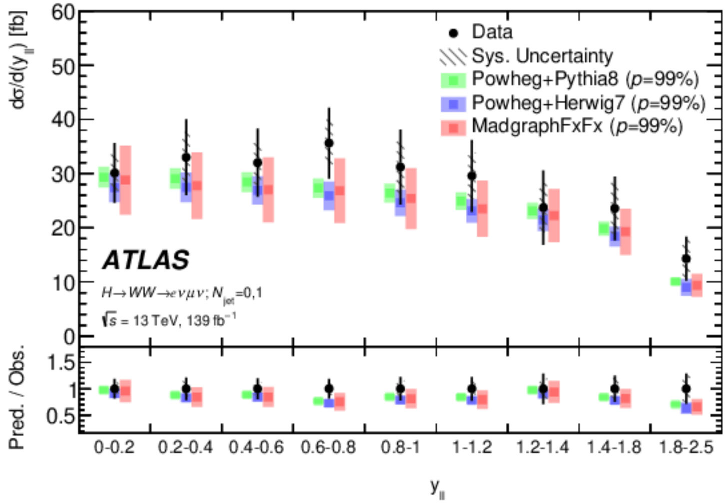


- Profile likelihood fit (new strategy w.r.t Run 1 bkg subtraction)
- Unfolding back to generator level.



- Differential cross-section in terms of $|y_{j0}|$, $p^H{}_T$, $p^{\ell 0}{}_T$, $p^{\ell\ell}{}_T$, $m^{\ell\ell}$, $y^{\ell\ell}$, $\Delta\phi^{\ell\ell}$, and $\cos\theta^*$
  the dilepton system's rapidity $y^{\ell\ell}$ is highly correlated with the rapidity of the reconstructed Higgs boson (y^H)

The results agree with SM expectations.

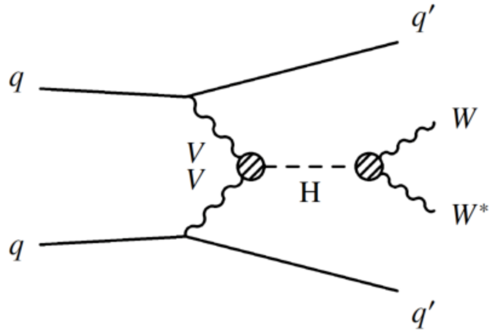


arXiv:2301.06822v1

Fiducial and differential cross-section of VBF with $H \to WW^* \to \mu\nu e\nu$

- A bi-dimensional discriminant is formed in the SR by utilizing two distinct BDTs to separate the signal from the dominant backgrounds: $t\bar{t}$ and Wt, not resonant WW and other diboson processes;

- Profile likelihood fit with an unfolding method

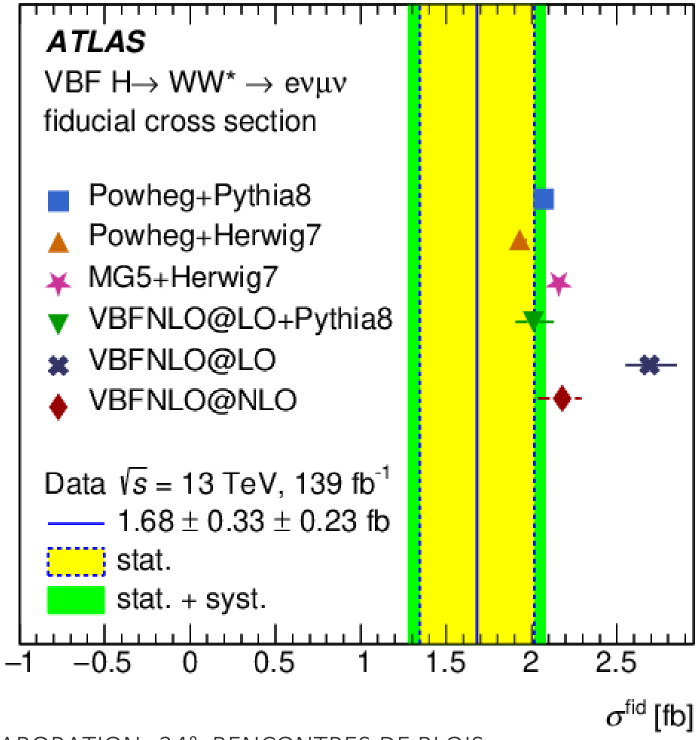


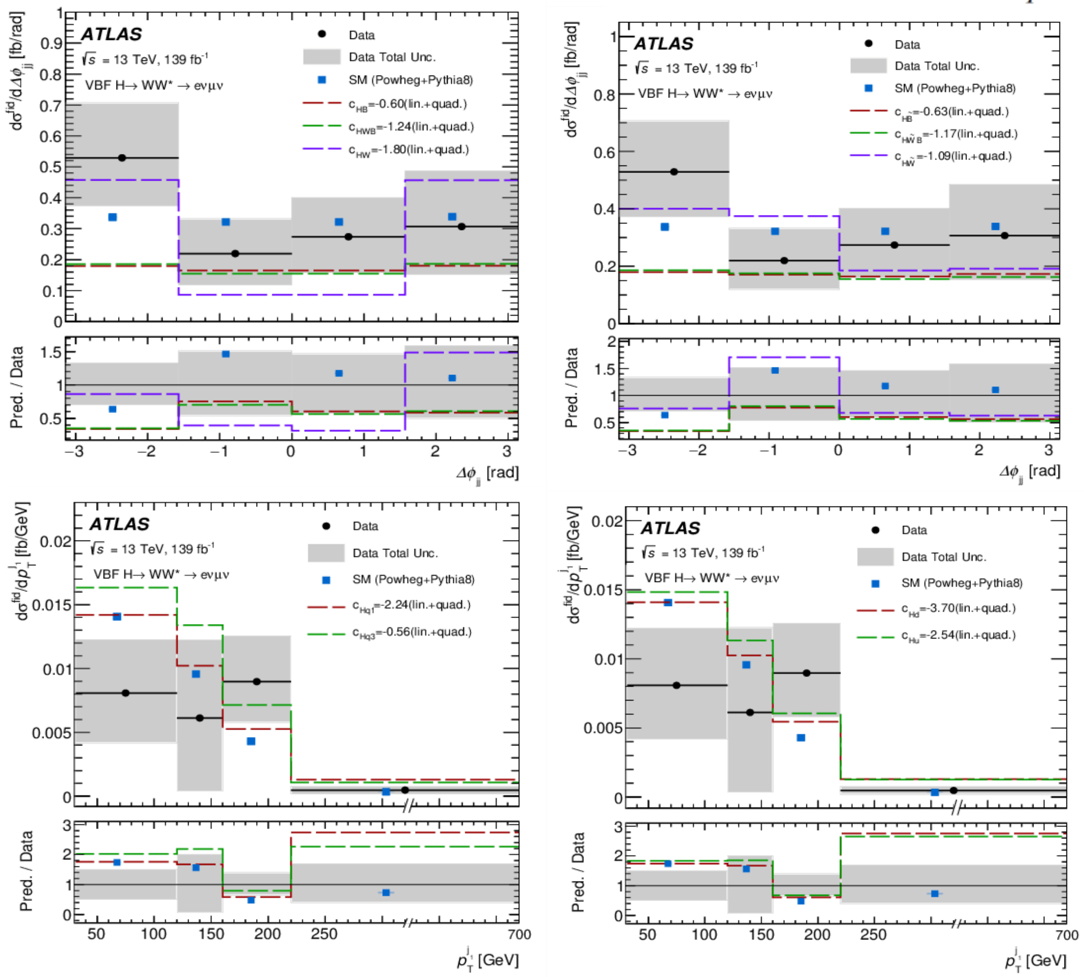
Fiducial cross section

$$\sigma^{\text{fid}} = \frac{N^{\text{SR}}_{\text{data}} - N^{\text{SR}}_{\text{bkg}}}{C \times \mathcal{L}}$$

where *C* factorises the detector inefficiencies

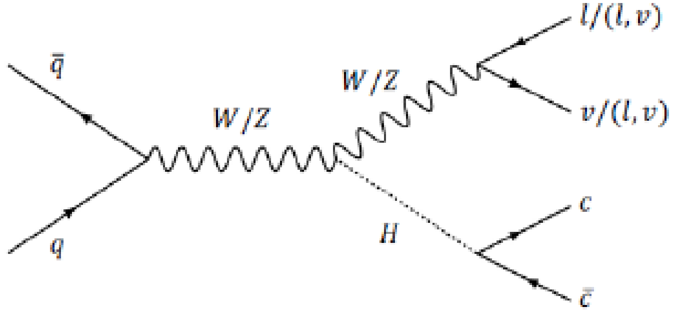
arXiv:2304.03053v1





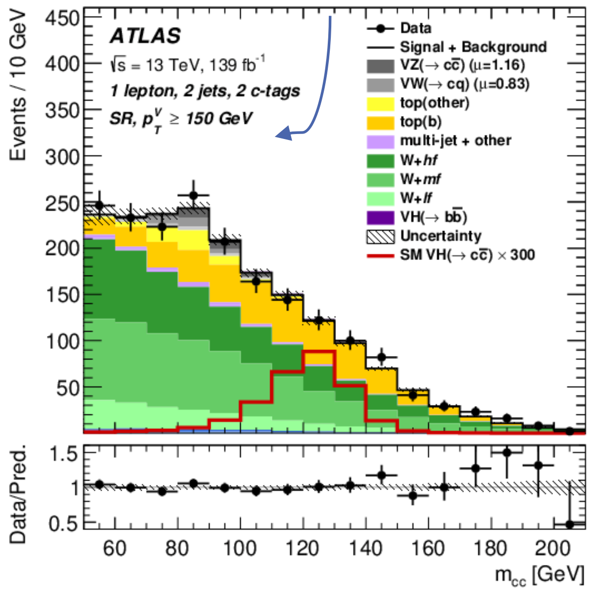
VH with $H \to c\bar{c}$

- Discriminant variable = invariant mass $m_{c\bar{c}}$ from the two jets with highest $p_{T,}$ tagged as containing c-or b-hadrons using multivariate flavour tagging algorithms;

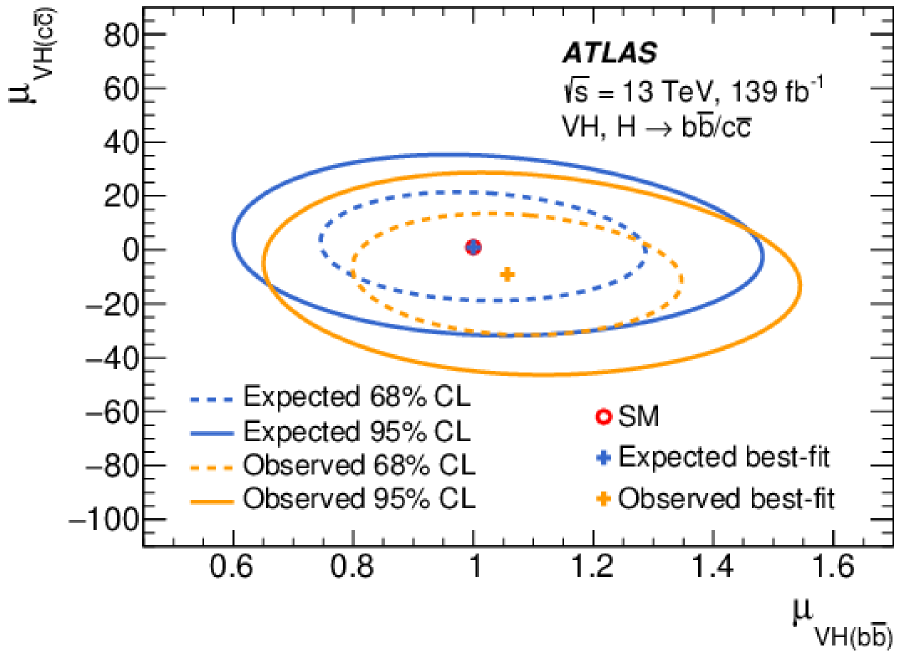


- Results are also interpreted in terms of the coupling strength κ_c and κ_b modifiers

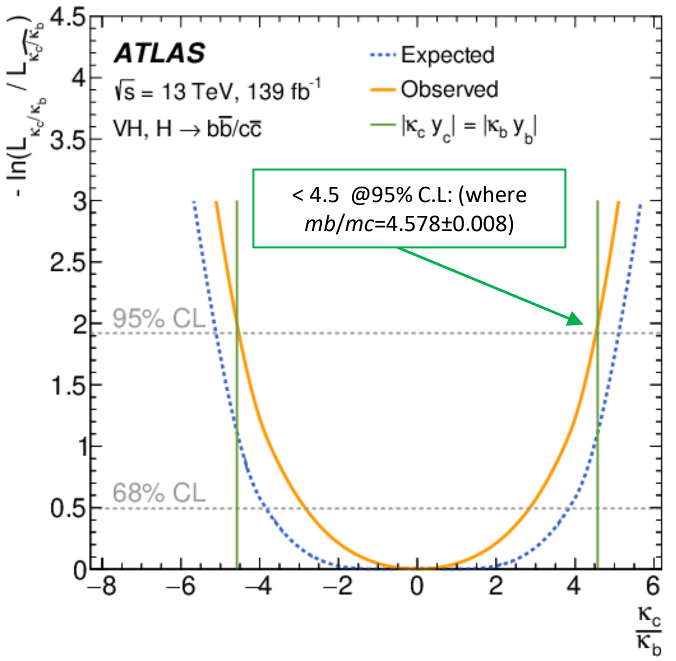
One of 44 analysis regions



Signal strength $\mu = \frac{N_{signal}}{N_{signal}^{SM}}$



κ_b is a free parameter



arXiv:2201.11428v4

Combination of ATLAS Higgs boson production and decay measurements

- Run2 results with partial inclusion of Run1 previous combination (back-up slide 20)

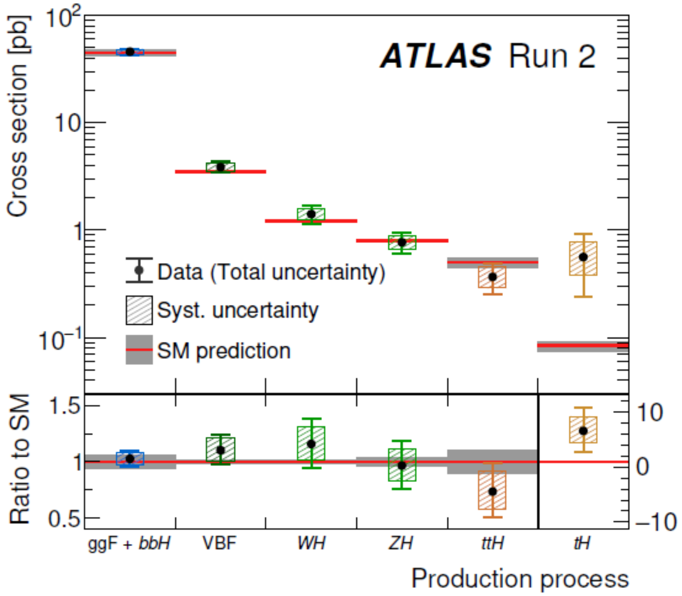
(firstly obs in Run 2)

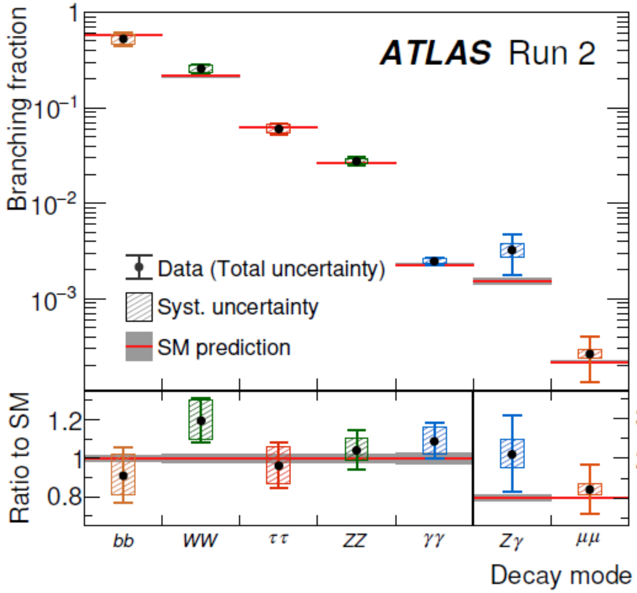
Production process	Obs. (Exp) Significance arXiv.2207.00092	Run 1 Obs. (Exp) Significance arXiv:1903.10052v2
WH	5.8 (5.1)σ	2.4 (2.7) σ
ZH	5.0 (5.5) σ	2.3 (2.9) σ
$t\bar{t}H + tH$	6.4 (6.6) σ	4.4 (2.0) σ only $t\bar{t}H$
Decay channel with improved significance		
$H \rightarrow \mu\mu$	2.0 (1.7) σ	-
$H \rightarrow Z\gamma$	2.3 (1.1) σ	-

Global signal strength for Higgs boson production

$$\mu = 1.05 \pm \begin{cases} 0.03\ (\text{stat}) \\ 0.03\ (\text{exp}) \\ 0.04\ (\text{sig modelling th}) \\ 0.02\ (\text{bkg modelling th}) \end{cases}$$

This result supersedes the previous ATLAS combination with a partial Run 2 dataset, decreasing the latest total measurement uncertainty by about 30%.





- In Run2, ggF and VBF reach 7% and 12% precision, respectively
- Both the experimental and the theoretical uncertainties are almost a factor of two lower than in the Run 1 results arXiv:1903.10052v2 (comparison in back-up).
- The estimates are compatible with SM expectations

Interpretation within κ-framework

Parametrisation in term of coupling strength modifiers κ_j:

$$\sigma \cdot \mathcal{B}\,(i \to H \to f) = \kappa_i^2 \cdot \kappa_f^2 \cdot \sigma_i^{SM} \cdot \frac{\Gamma_f^{SM}}{\Gamma_H(\kappa_i^2, \kappa_f^2)}$$

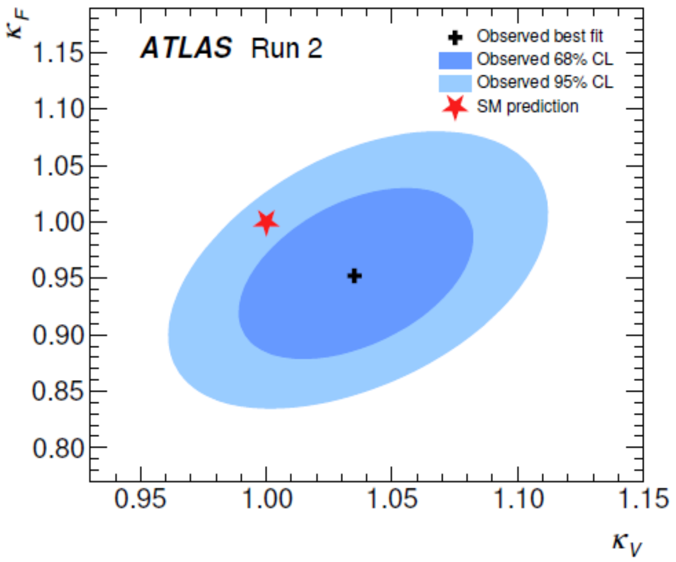
Where $\kappa_j^2 = \frac{\sigma_j}{\sigma_j^{SM}}, \kappa_j^2 = \frac{\Gamma_j}{\Gamma_j^{SM}}$, Γ_f^{SM} is the partial width of Higgs boson decay into final state f, Γ_H is total width of Higgs boson

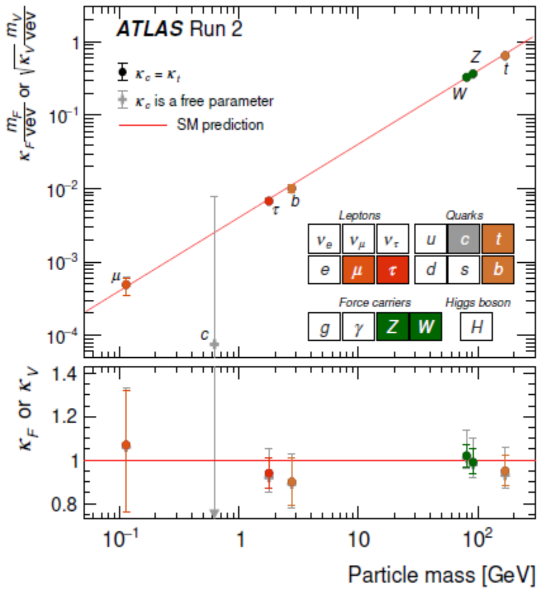
1. Modifiers κ_V and κ_F to probe Higgs boson couplings to bosons and fermions, respectively

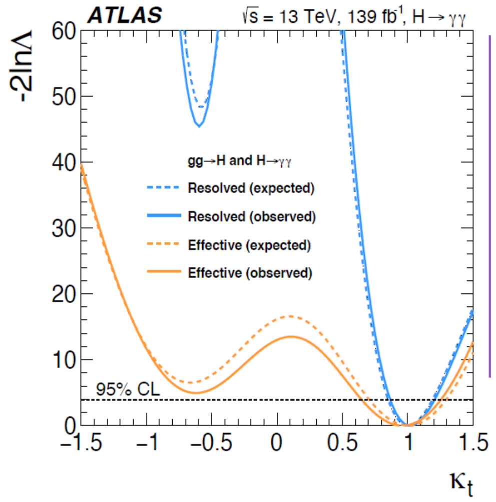
2. Independent modifiers κ for W,Z, b,t, μ to test the predicted scaling of the couplings of the Higgs boson to the SM particles (assuming two scenarios for c quark)

3. It includes non-SM particles in the loop-induced processes, parametrized by the effective coupling strength modifiers κ_g, κ_γ and $\kappa_{Z\gamma}$

arXiv.2207.00092

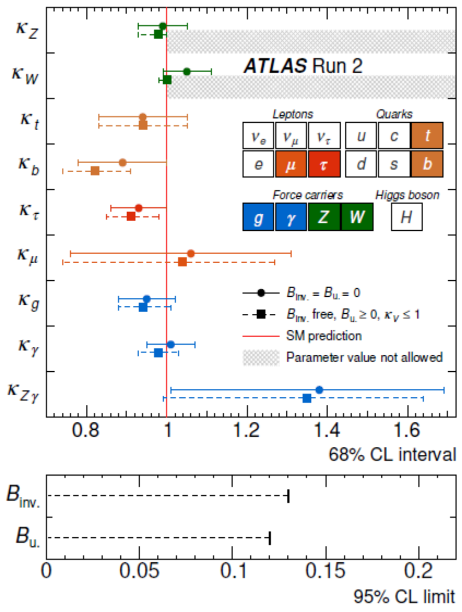






arXiv:2207.00348v1

tH with $H \to \gamma\gamma$ allows to distinguish sign of κ_t



It is assumed that there are no invisible (arXiv:2301.10731v1) or undetected Higgs boson decays beyond the SM in model 1,2

STXS measurements

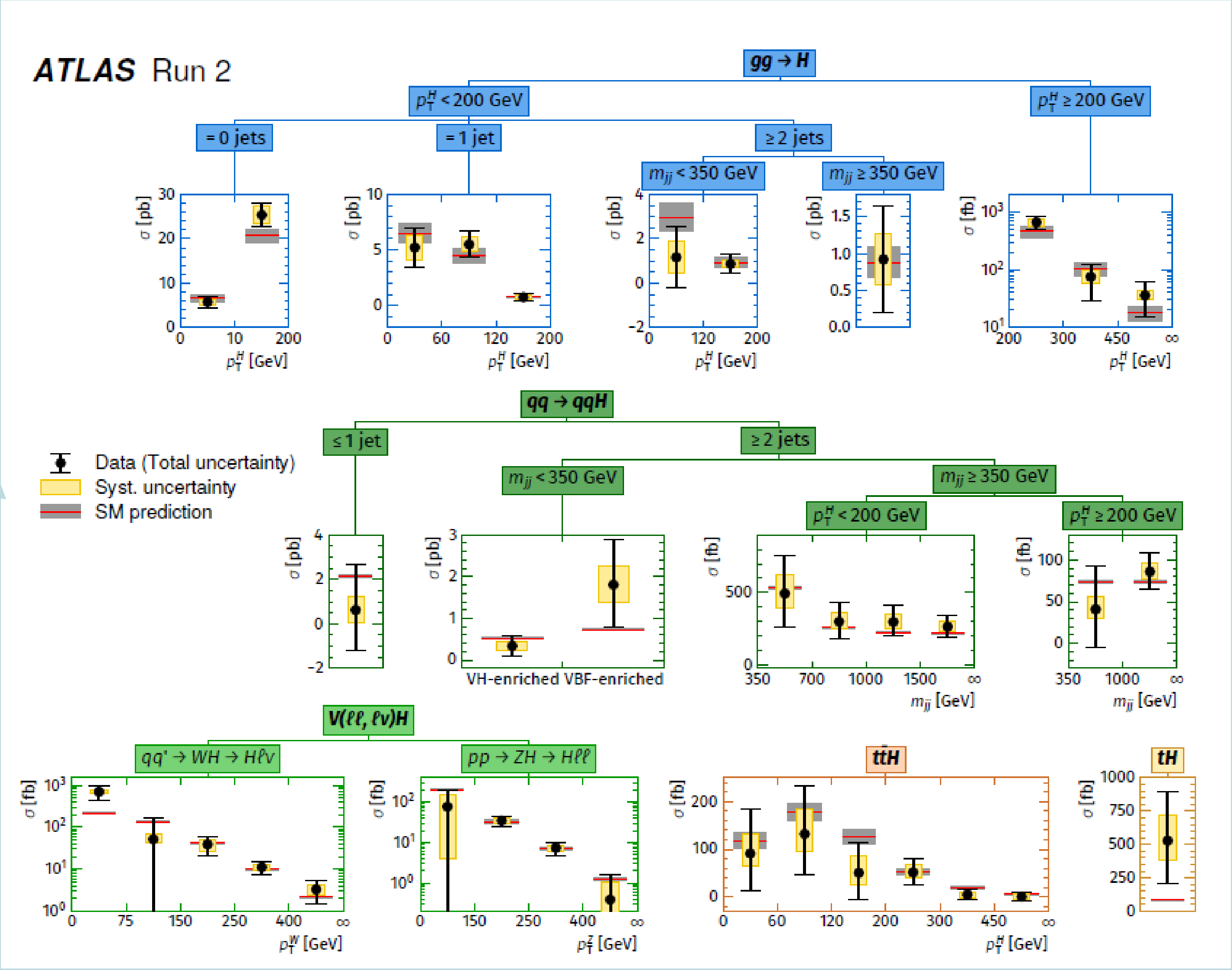
Simplified Template cross section (STXS)

Phase space divided into simplified fiducial volumes based on kinematic properties of Higgs and associated particles, aiming :

- to maximize sensitivity to BSM couplings (expected at high Higgs transverse momenta)
- to reduce theory uncertainties and model dependence from extrapolation to fiducial volume

Moreover STXS measurements can be combined across decay channels

The STXS scheme covers 36 kinematic regions



arXiv.2207.00092

All the measurements are consistent with the SM expectations

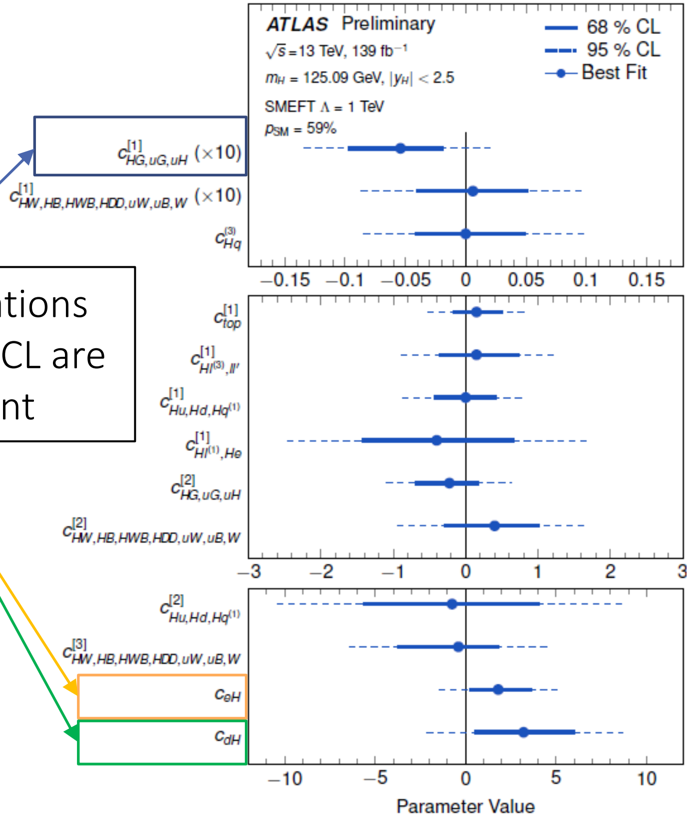
SM Effective Field Theory (EFT) interpretation

SMEFT assumes that new physics will only appear at higher scales

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{i}^{N_{d6}} \frac{c_i}{\Lambda^2} O_i^{(6)} + \sum_{j}^{N_{d8}} \frac{b_i}{\Lambda^4} O_i^{(8)} + \ldots,$$

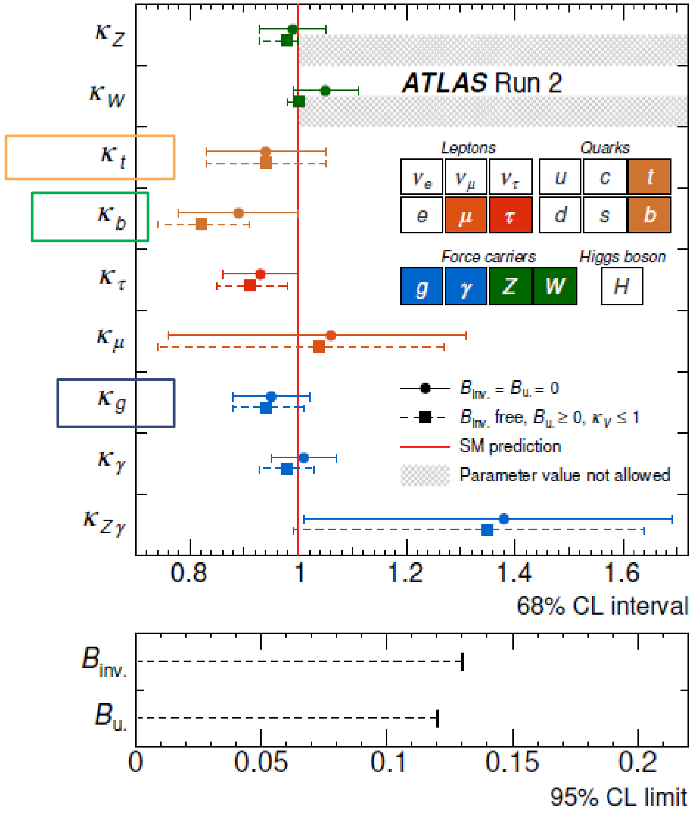
Combined STXS measurements used to constrain Wilson coefficients (corresponding to dimension-six operators) ATLAS-CONF-2021-053

Observed measurements of the fit parameters c_i' (linear combination of the chosen Wilson coefficient in Warsaw basis) within the SMEFT linearised model



The small deviations from SM @68% CL are not significant

Comparison with one of the previous parametrisation within the κ-framework



Positive correlated impact on ggF

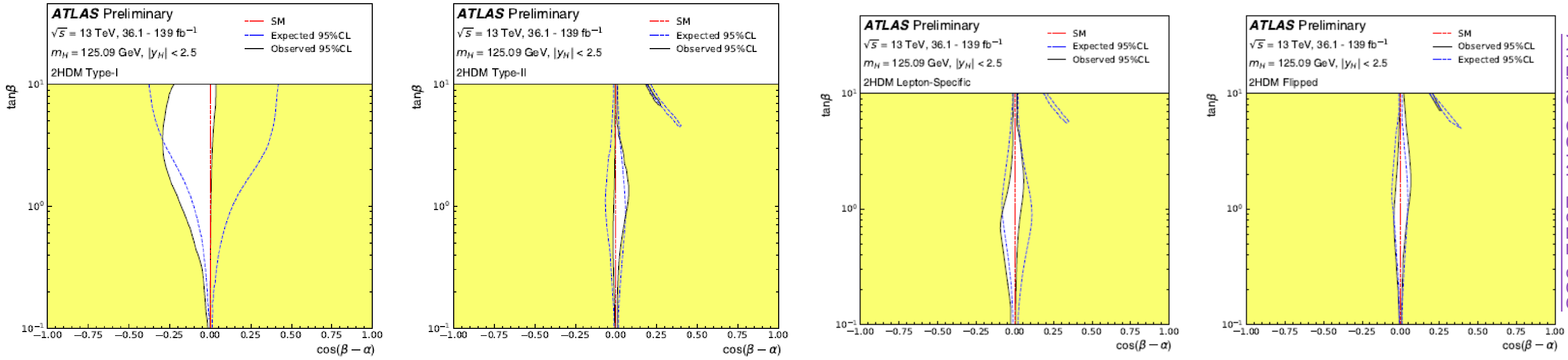
Negative correlated impact on $H \to \tau\tau$ rate

Related with on $H \to b\bar{b}$ vertex

Interpretation in the context of UV-complete BSM theories

Four types of 2HDMs satisfy the Paschos–Glashow–Weinberg condition:

- Type I: One Higgs doublet couples to vector bosons, while the other one couples to fermions. The first doublet is *fermiophobic* in the limit where the two Higgs doublets do not mix.
- Type II: One Higgs doublet couples to up-type quarks and the other one to down-type quarks and charged leptons.
- Lepton-specific: The Higgs bosons have the same couplings to quarks as in the Type I model and to charged leptons as in Type II.
- Flipped: The Higgs bosons have the same couplings to quarks as in the Type II model and to charged leptons as in Type I.



ATLAS-CONF-2021-053

α = the mixing angle between the light and the heavy CP-even neutral scalars
tanβ = ratio of the vacuum expectation values of the two Higgs doublets

The observed Higgs boson is identified with the light CP-even neutral scalar predicted by 2HDMs, and its accessible production and decay modes are assumed to be the same as those of the SM Higgs boson

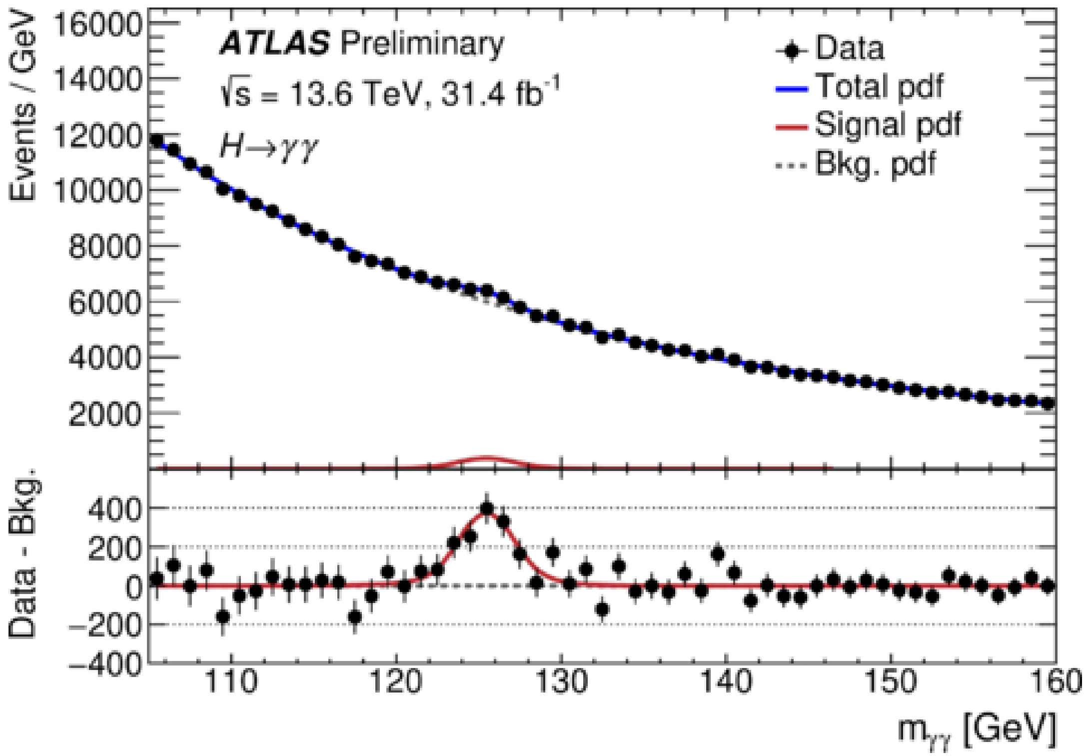
First look at Run-3 data

new LHC center-of-mass energy (√s=13.6 TeV)

Previous analysis arXiv:2301.10486v1

ATLAS-CONF-2023-003

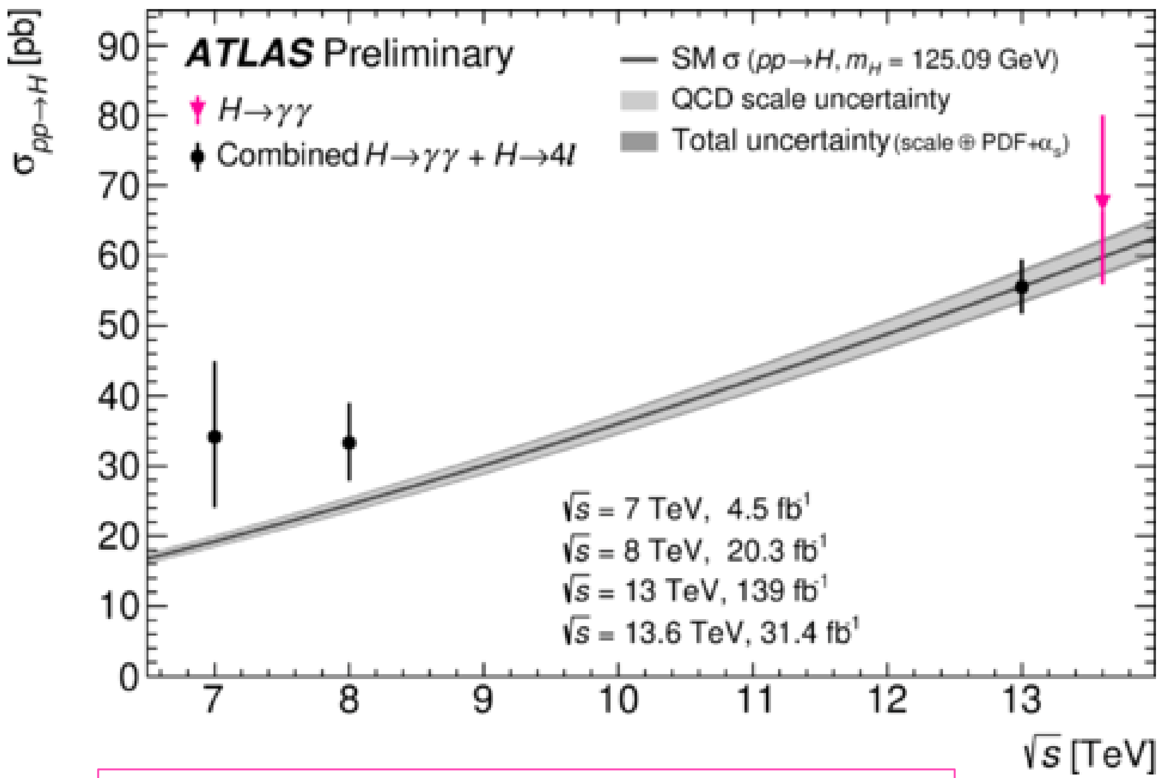
Fiducial cross section of $pp \to H \to \gamma\gamma$



$$\sigma_{fid}(pp \to H \to \gamma\gamma) = 76^{14}_{-13}\ \text{fb}$$

(good agreement with SM: 67.5±3.4 fb)

The total cross-section vs LHC center-of-mass energy



$$\sigma(pp \to H) = 67^{13}_{-12}\ \text{pb}$$

(good agreement with SM: 59.8 ± 2.6 pb)

Conclusions

- All the presented results are compatible with SM expectations:

  - Even if differential measurements and small branching ratio channels still have significant statistical uncertainties, Run 2 data statistics and new analysis channels improved measurement precision w.r.t Run 1;
  - discovery channels start to enter precision regime < 10% uncertainty.

- Interpretations within κ-framework, using SMEFT or model-dependent approach

  - constraints on different groups of linear combinations of SMEFT parameters are improved by up to 70%. For the first time, two additional SMEFT parameters, related to the τ-lepton and b-quark Yukawa couplings are probed separately from other parameters of interest in the fit.
  - the sensitivity on the $(\cos(\beta - \alpha), \tan\beta)$ parameter space for selected benchmark scenarios of the Two Higgs Doublet Model is also improved by about 20% compared to the previous results.

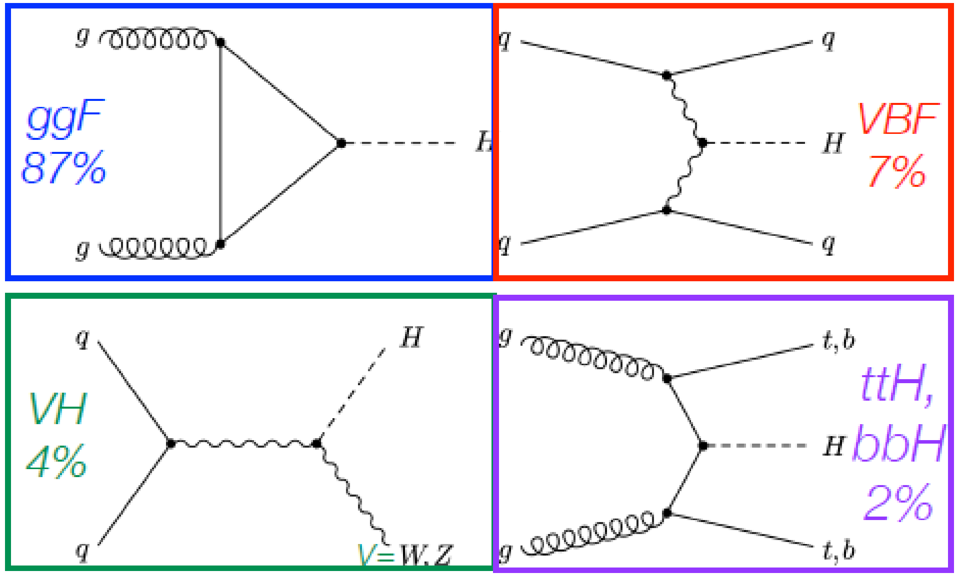
→ Moving towards precision measurement era, large expectations on Run 3 data

BACK-UP

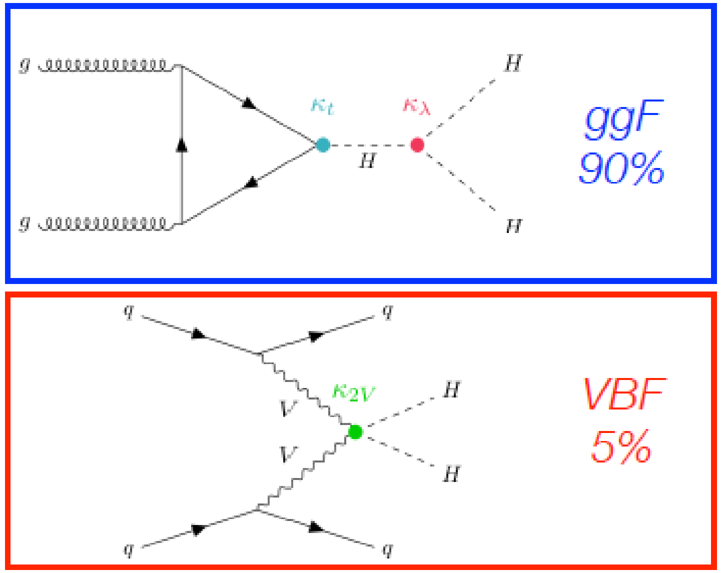
RUN 2 expectations and observations

ATL-PHYS-SLIDE-2023-092

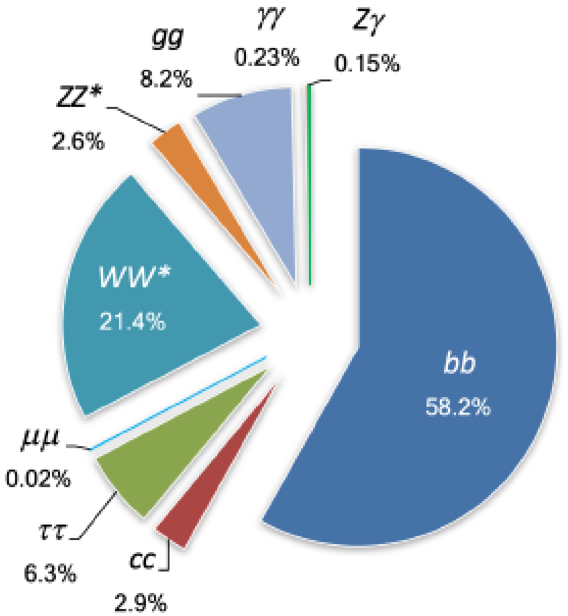
single-Higgs production



double-Higgs production



decay



σ(pp→H) @ 13 TeV = 56 pb

~8M produced in Run 2, ~600k in Run 1

σ(pp→HH) @ 13 TeV = 34 fb

~5k produced in Run 2

Total width: Γ_H ~4 MeV

BR(H→invisible)~0.1%

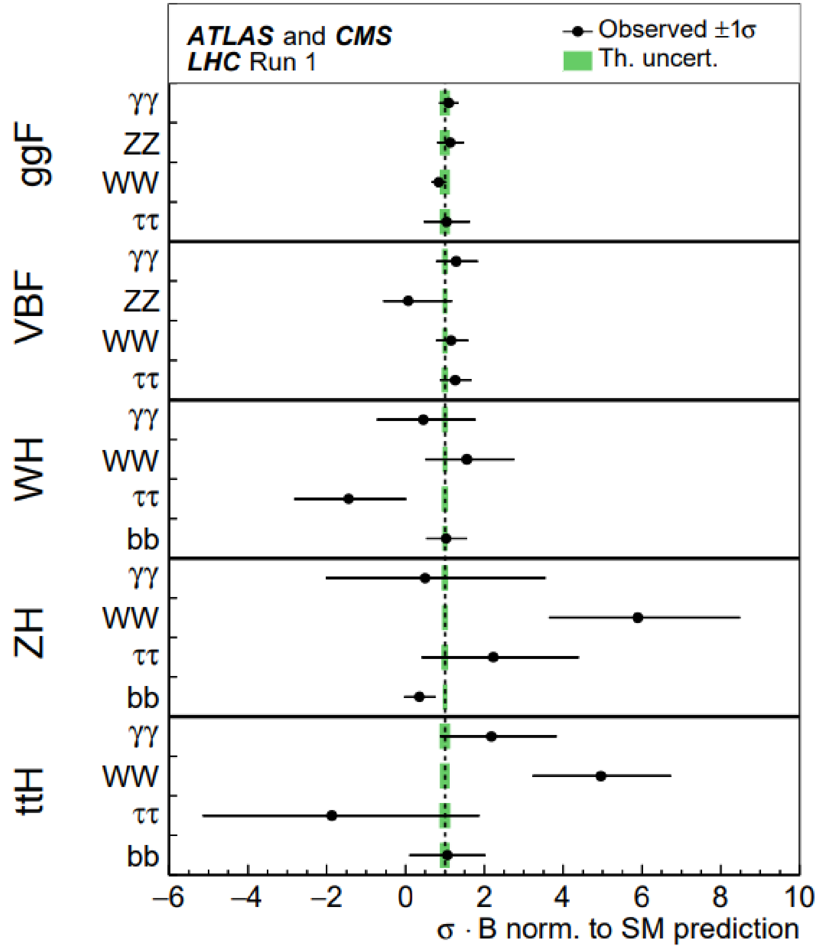
Input analysis in the combined measurement of ATLAS Higgs boson production and decay processes, STXS and SMEFT interpretation

Measurements in input to combination and the interpretations in ATLAS-CONF-2021-053:

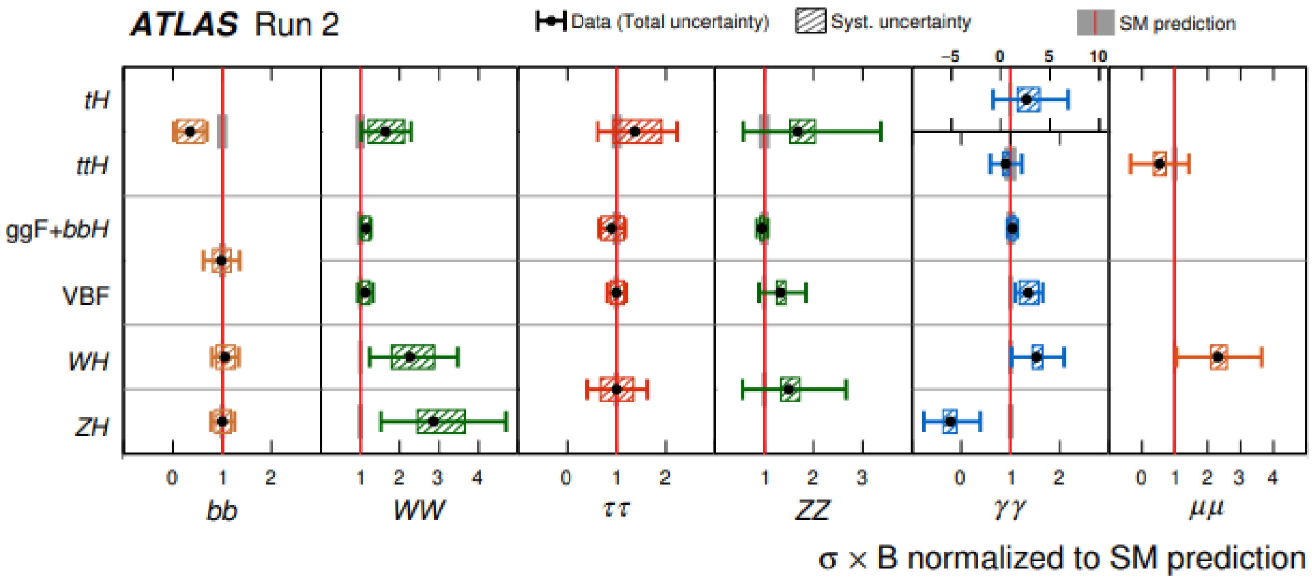
Decay channel	Target Production Modes	$\mathcal{L}$ [fb^{-1}]	Used in combined measurement
$H \to \gamma\gamma$	ggF, VBF, $WH, ZH, t\bar{t}H, tH$	139	Everywhere
$H \to ZZ^*$	ggF, VBF, $WH, ZH, t\bar{t}H(4\ell)$	139	Everywhere
	$t\bar{t}H$	36.1	Everywhere but STXS and SMEFT
$H \to WW^*$	ggF, VBF	139	Everywhere
	$t\bar{t}H$	36.1	Everywhere but STXS and SMEFT
$H \to \tau\tau$	ggF, VBF, $WH, ZH, t\bar{t}H(\tau_{\text{had}}\tau_{\text{had}})$	139	Everywhere
	$t\bar{t}H$	36.1	Everywhere but STXS and SMEFT
$H \to b\bar{b}$	WH, ZH	139	Everywhere
	VBF	126	Everywhere
	$t\bar{t}H$	139	Everywhere
$H \to \mu\mu$	ggF, VBF, $VH, t\bar{t}H$	139	Everywhere but STXS and SMEFT
$H \to Z\gamma$	ggF, VBF, $VH, t\bar{t}H$	139	Everywhere but STXS and SMEFT
$H \to inv$	VBF	139	In a subset of interpretations

Comparison of Run 1 and Run 2 Higgs boson

RUN 1 [ARXIV:1606.02266V2]

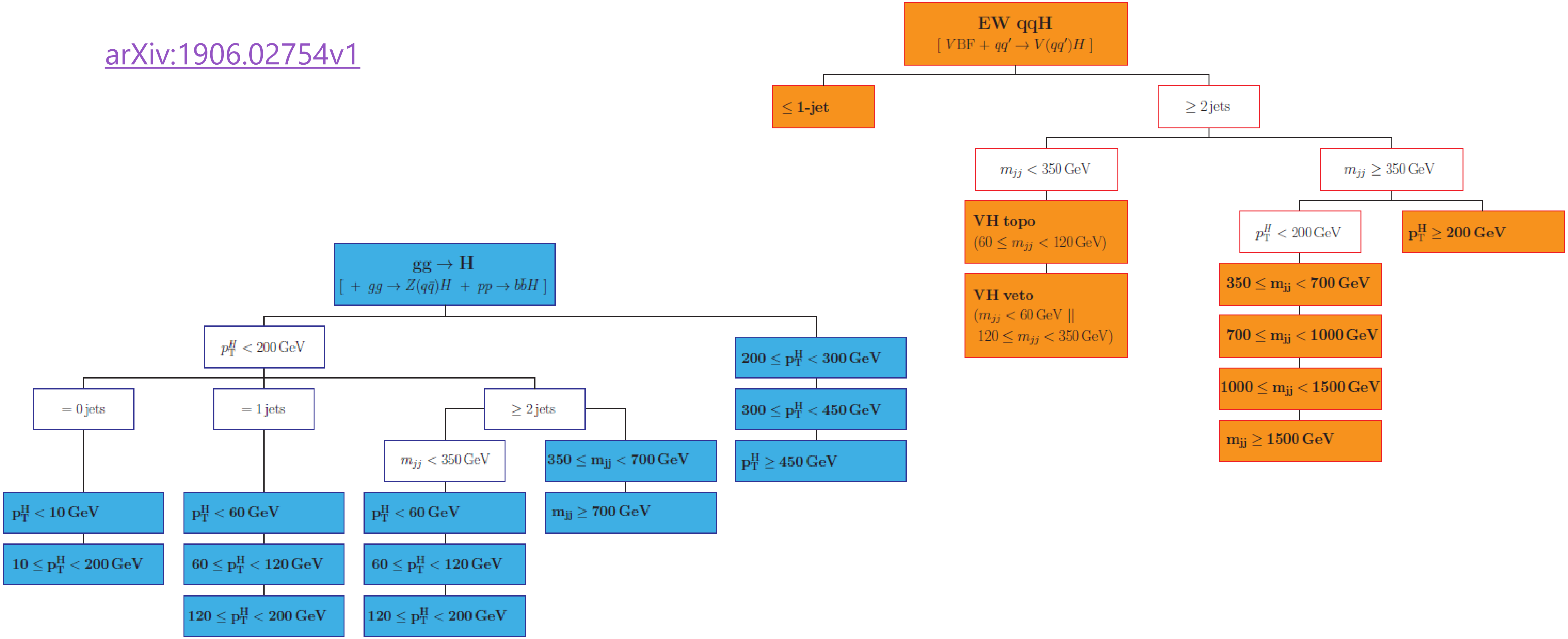


RUN 2 [ARXIV.2207.00092]



Definition of the STXS measurement regions for ggF and VBF

arXiv:1906.02754v1

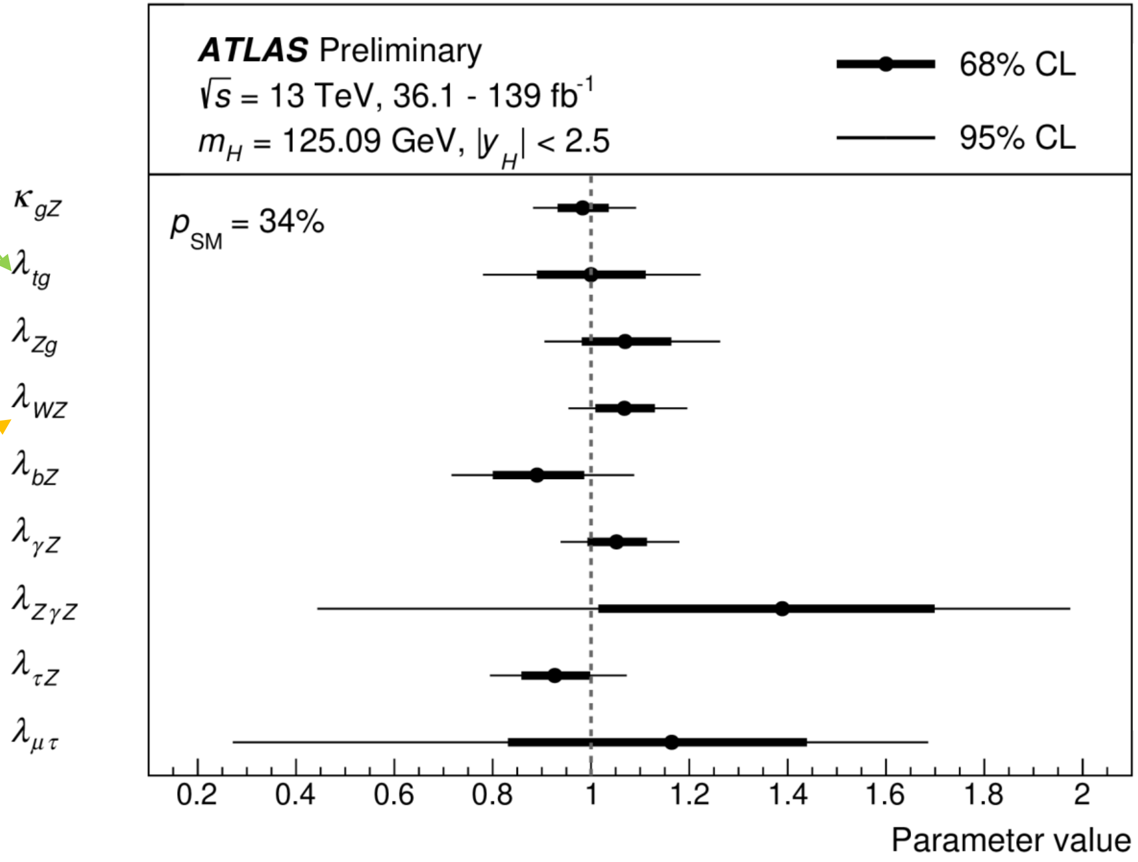


Model-independent coupling-strength scale factors λ in the κ-framework

This is sensitive to new colored particles contributing through the ggF loop

Identical coupling-strength scale factors for the W and Z bosons are required within tight bounds by the SU(2) custodial symmetry and the ρ parameter measurements at LEP and at the Tevatron.

These are sensitive to new charged particles contributing to the $H \to \gamma\gamma, H \to Z\gamma$ loops



ATLAS-CONF-2021-053

Parameter	Definition in terms of κ modifiers
κ_{gZ}	$\kappa_g \kappa_Z / \kappa_H$
λ_{tg}	κ_t / κ_g
λ_{Zg}	κ_Z / κ_g
λ_{WZ}	κ_W / κ_Z
$\lambda_{\gamma Z}$	κ_γ / κ_Z
$\lambda_{Z\gamma Z}$	$\kappa_{Z\gamma} / \kappa_Z$
$\lambda_{\tau Z}$	κ_τ / κ_Z
λ_{bZ}	κ_b / κ_Z
$\lambda_{\mu\tau}$	κ_μ / κ_τ

More material about SMEFT interpretation

Simulated impact of the most relevant SMEFT operators on the STXS regions and decay modes, relative to the SM cross-section, under the assumption of the linearised SMEFT model to evaluate dedicated acceptance corrections for the Wilson coefficients (in most of decay they are negligible)