Combined Higgs boson measurements and their interpretations with the ATLAS experiment

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Introduction

Over a decade has passed since the discovery of the Higgs Boson at the LHC:

- Measurements of the Higgs Boson's properties including mass, spin, width, cross sections, and couplings have achieved increased precision
- The consistency of these measurements with Standard Model (SM) predictions has been thoroughly tested

LHC Run I + Run II provides unprecedented amount of data to perform comprehensive combinations and interpretations!

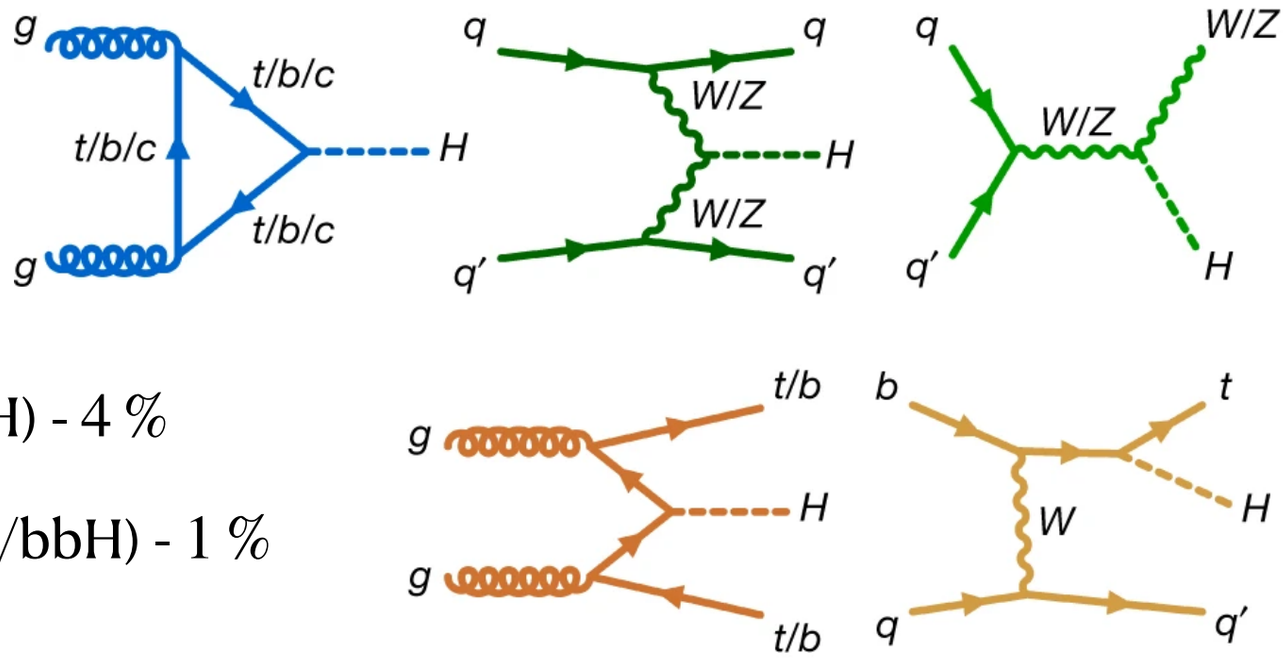
- Combining individual Higgs analyses allows for a rigorous test of the Higgs boson sector and constrains the strength of interactions between the Higgs boson and SM particles
- This utilizes frameworks such as Simplified Template Cross Sections (STXS) & κ-framework
- Measurements can be interpreted within Beyond the Standard Model (BSM) scenarios or SM Effective Field Theory (SMEFT)
- **NEW Run III data:** Combination of golden channels at center-of-mass energy of 13.6 TeV

Higgs Production and Decay

Paper: Nature 607, 52–59 (2022)

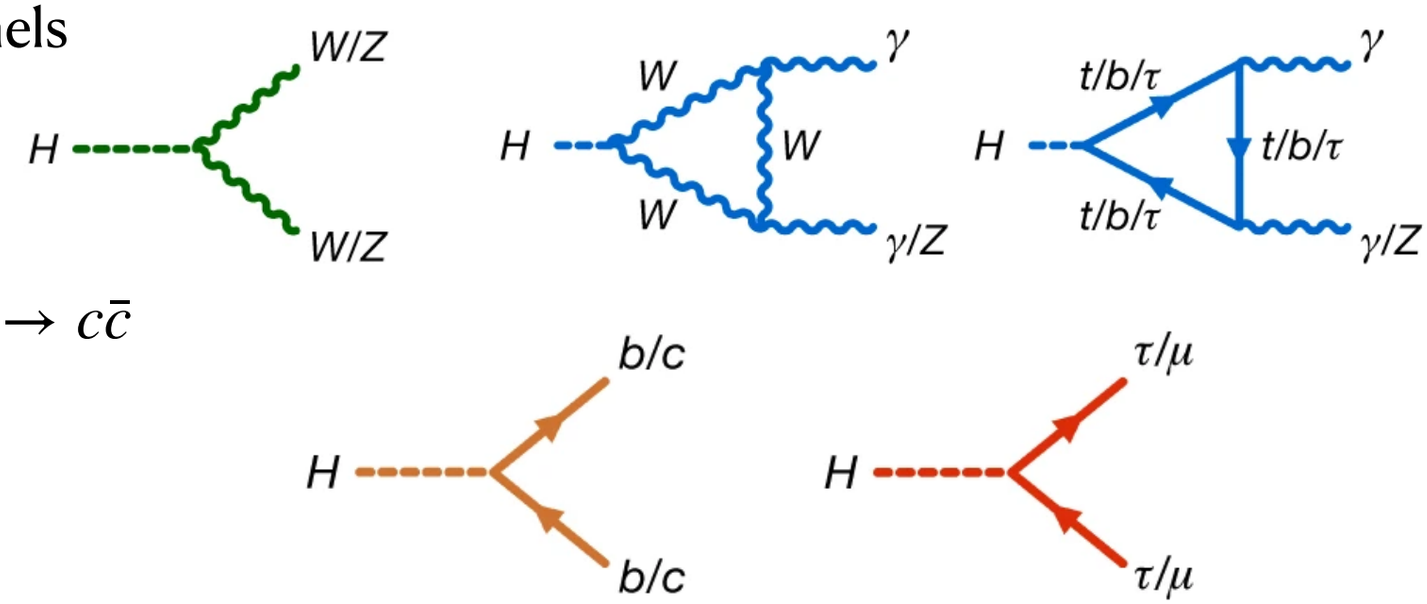
Higgs boson production channels:

- Gluon-gluon fusion (ggF) - 87 %
- Vector boson fusion (VBF) - 7 %
- Associated prod. with gauge boson (WH/ZH) - 4 %
- Associated prod. with heavy quark pair (ttH/bbH) - 1 %



Higgs decay channels:

- Low rate & precise mass resolution channels
  $H \to ZZ^* \to 4l$ and $H \to \gamma\gamma$
- Large rate & low resolution channels
  $H \to b\bar{b}, H \to W^{\pm}W^{\mp}, H \to \tau^{+}\tau^{-}$ and $H \to c\bar{c}$
- Rare decay channels
  $H \to \mu^{+}\mu^{-}, H \to Z\gamma$



Cross Sections and Branching Fractions

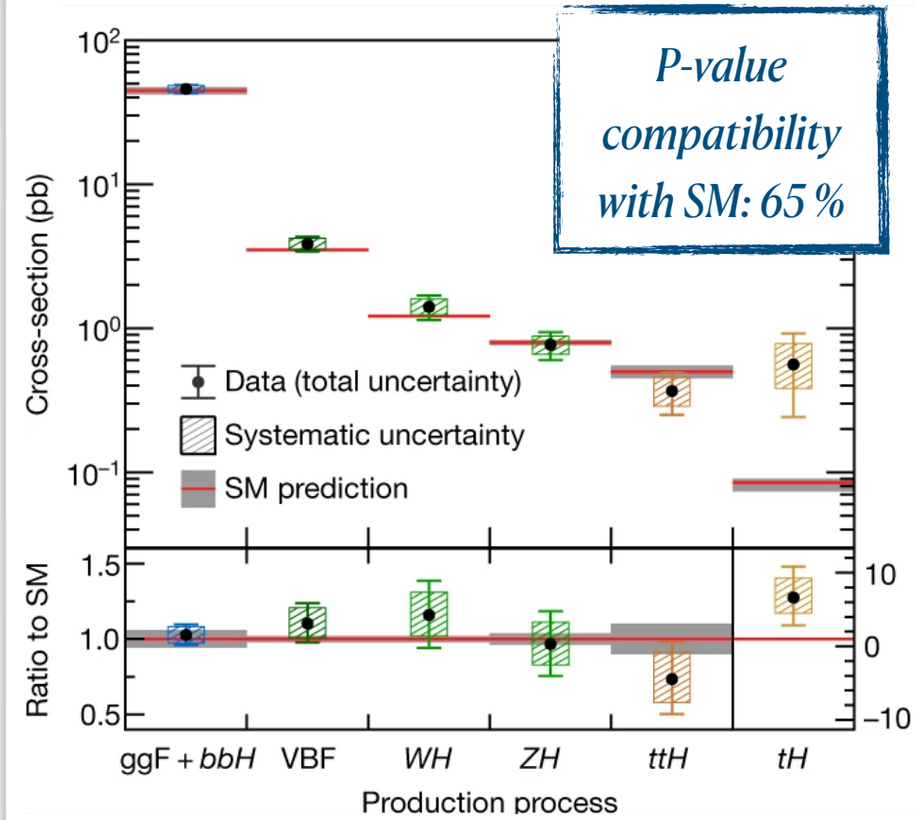
Paper: Nature 607, 52–59 (2022)

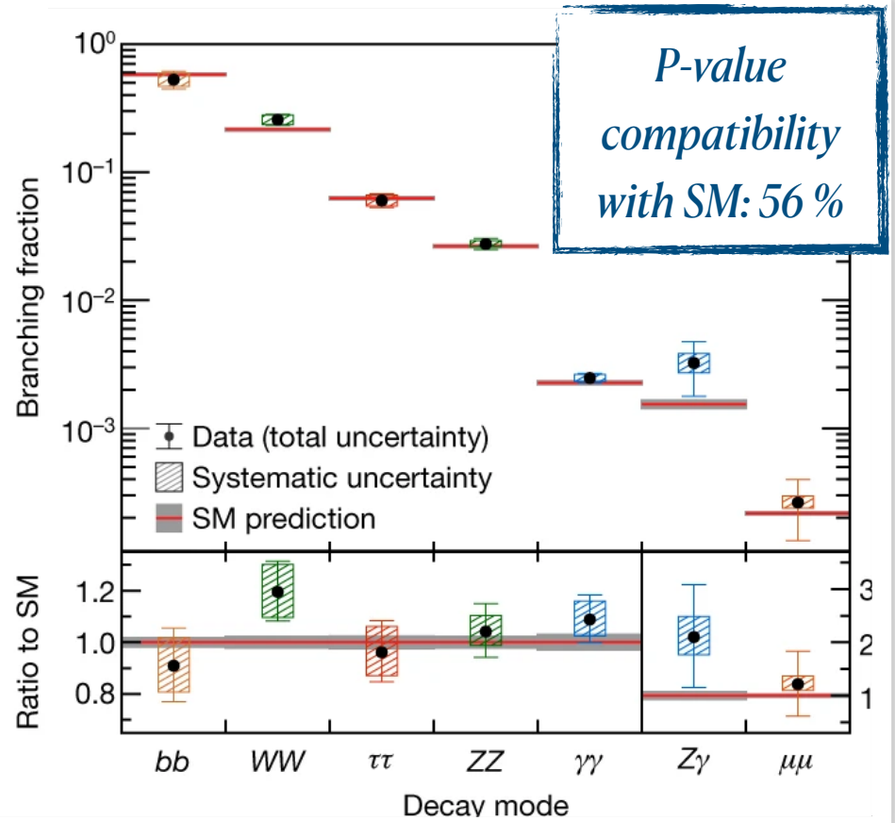
Production cross sections (free parameter in the fit, BR fixed to SM values):

- Observed in Run I: ggF and VBF, precision in Run II 7% and 12%, respectively
- Observed in Run II: WH (5.8σ), ZH (5.0σ) and ttH (6.4σ)

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

- Coupling to gauge bosons and 3rd gen. fermions $H \to \gamma\gamma, ZZ, W^{\pm}W^{\mp}, \tau\tau$ observed, precision $10 - 12$ %
- $H \to b\bar{b}$ decay mode observed (7.0σ) - Rare Higgs decays $H \to \mu\mu$ (2.0σ), $H \to Z\gamma$ (2.3σ)

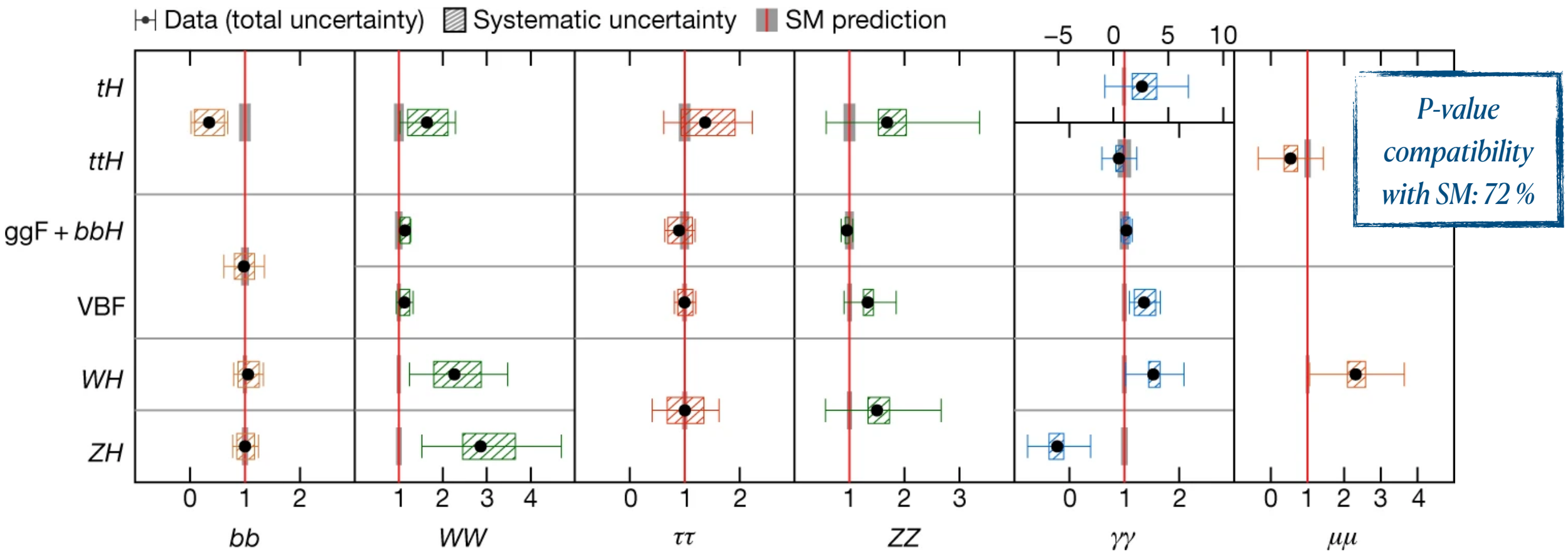




Higgs Boson Signal Strength

Paper: Nature 607, 52–59 (2022)

- Directly measuring the **product of production cross-section and branching fraction** for different combinations of production and decay processes
- Allows for relaxed assumptions about the relative contributions of different decay or production processes in the previous measurements



- Good agreement between measurements and SM predictions -

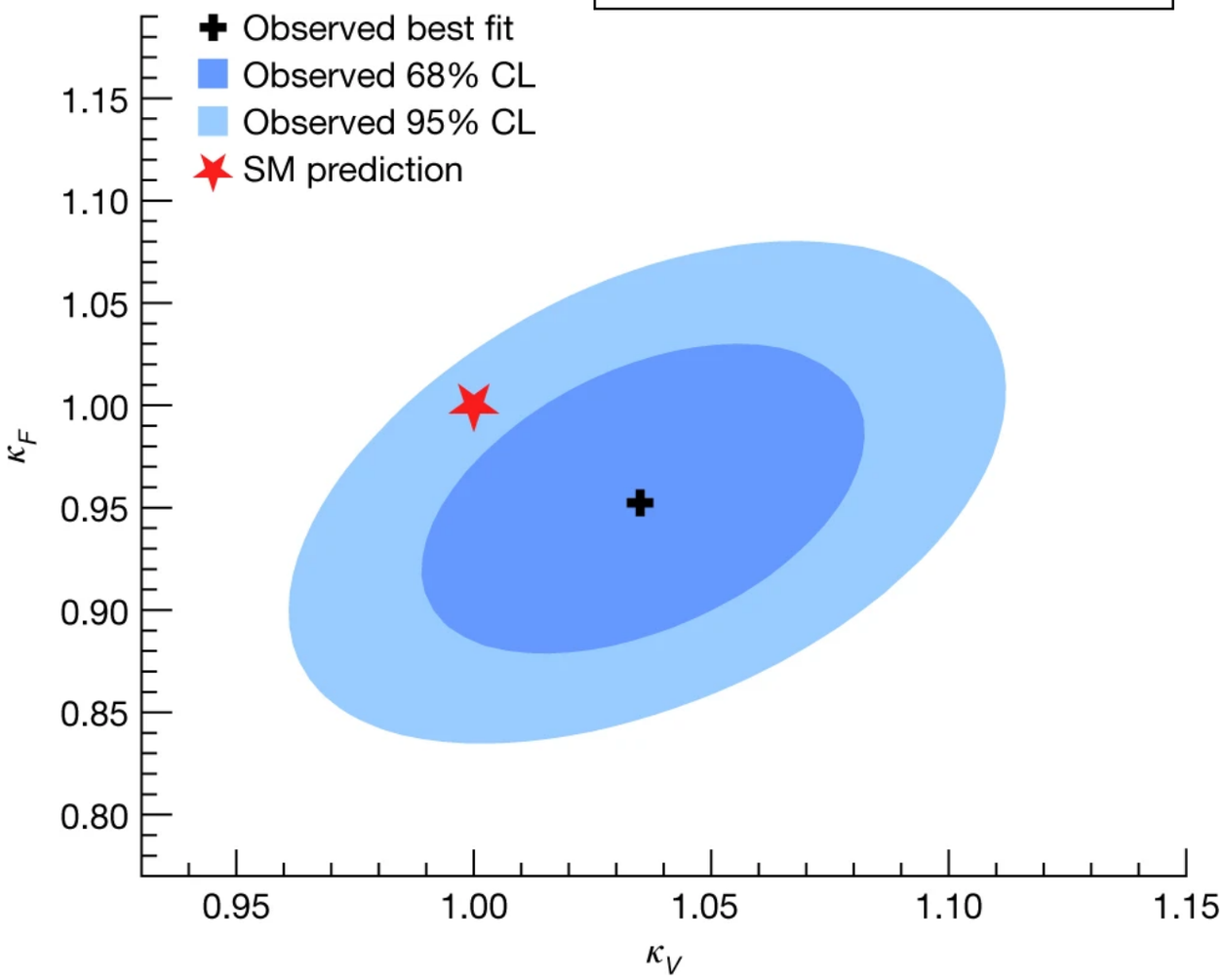
Higgs boson coupling interpretation

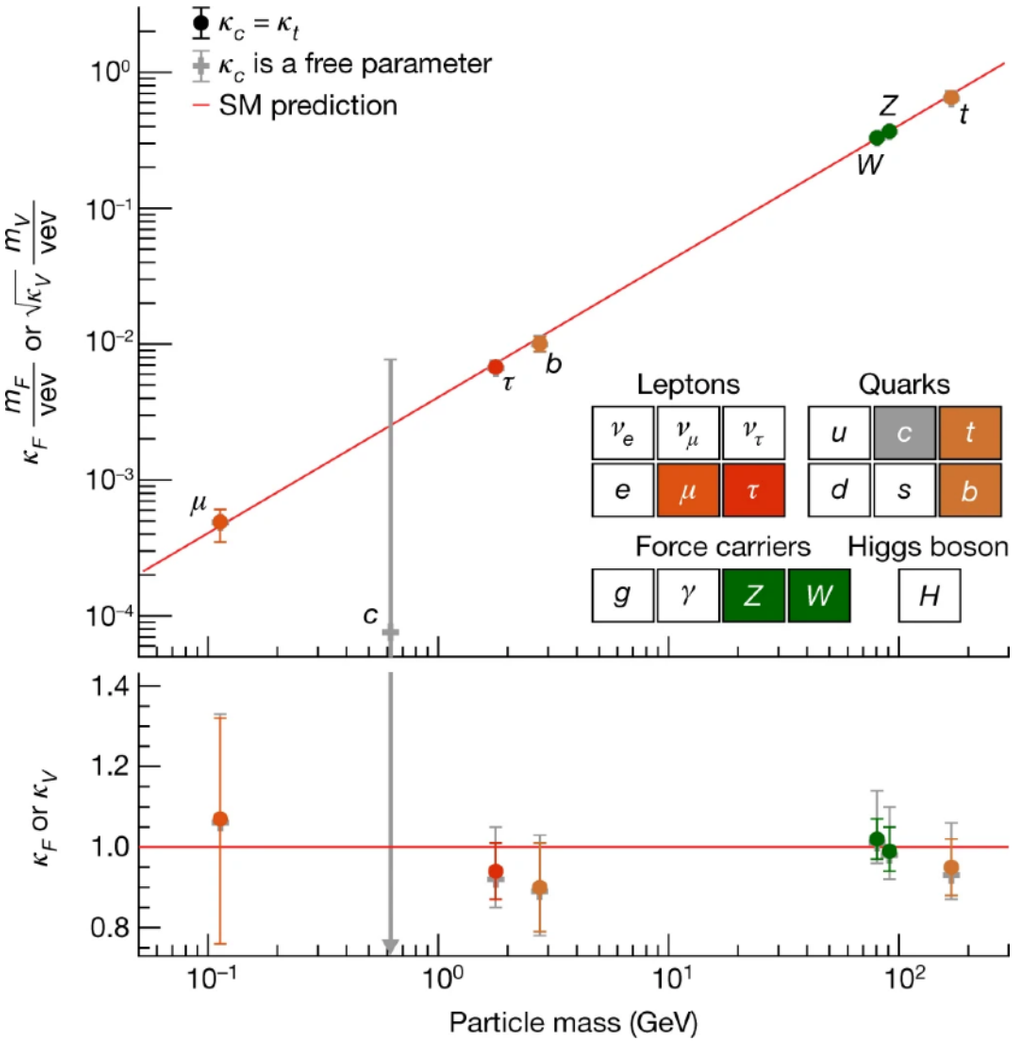
Paper: Nature 607, 52–59 (2022)

Determine the value of Higgs boson couplings

- Simultaneous fit of individual production times branching fraction measurements is performed with a set of **parameters κ** that affect the Higgs boson coupling strengths without altering kinematic features

$$\sigma_i \times B_f = \frac{\sigma_i(\kappa) \times B(\kappa)}{\Gamma_H(\kappa, B_i, B_u)}$$



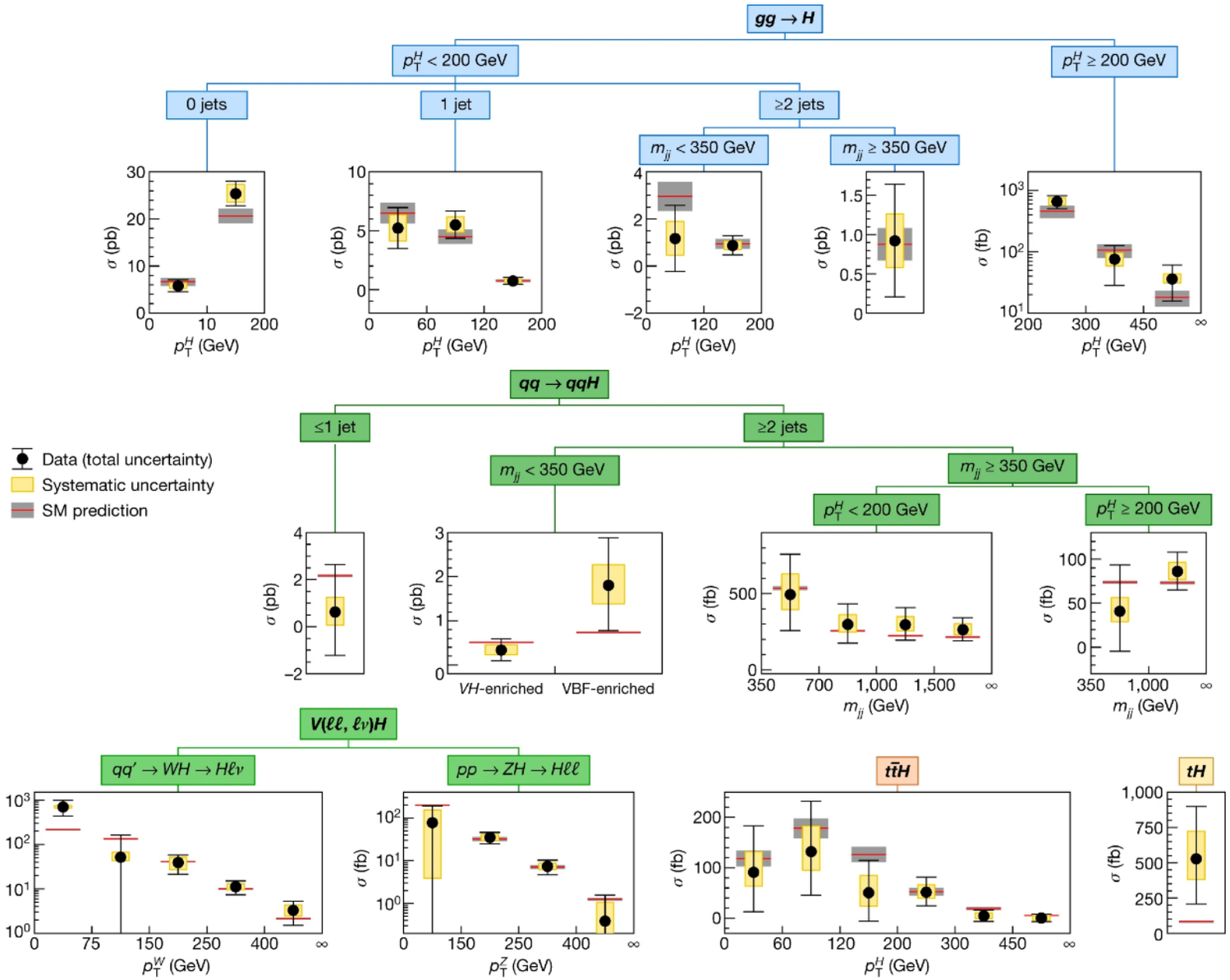


Simplified Template Cross Sections

Paper: Nature 607, 52–59 (2022)

The STXS framework

- Measurements of cross sections σ in 36 mutually exclusive regions split based on Higgs kinematics (+ W or Z bosons and associated jets)
- Reduce large theory uncertainties and minimize model-dependence when extrapolating to signal regions
- Maximize sensitivity to possible BSM



Higgs production modes

- Gluon-gluon fusion: $p_T(H)$, N_{jets}, m_{jj}
- Vector-boson fusion: $p_T(H)$, N_{jets}, m_{jj}, VH
- Associated prod. (WH/ZH): $p_T(W)$, $p_T(Z)$
- Associated prod. (ttH, tH): $p_T(H)$

SMEFT interpretation

- **SMEFT extends the SM Lagrangian** with higher-dimensional operators constructed from the SM fields and their symmetries
- Technically - Taylor expansion of the SM in E/Λ (with Λ=1TeV)

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i^{N_{d6}} \frac{c_i}{\Lambda^2} O_i^{(6)} + \sum_j^{N_{d8}} \frac{b_j}{\Lambda^4} O_j^{(8)} + \dots$$

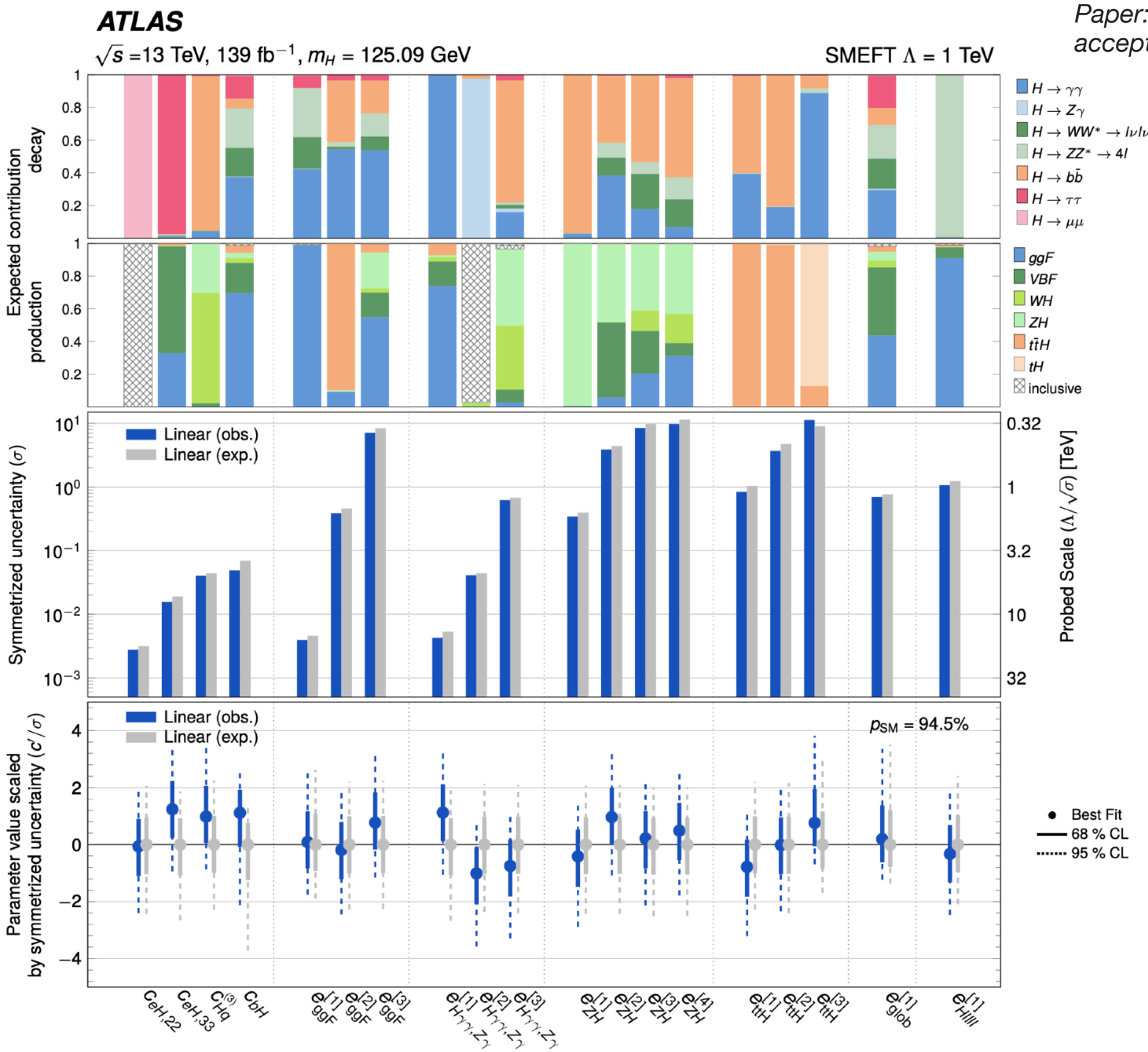
Wilson coefficients (free parameters)

Higher order operators from SM fields (dim 6)

- **Wilson coefficients** have to be **determined from experiment**
- **Warsaw basis** forms a complete set of dim 6 operators
- 2499 parameters for dim 6 can be reduced using additional flavour symmetry
- Using the "top" flavour scheme - $U(2)_q \times U(2)_u \times U(2)_d \times U(1)_e \times U(1)_\mu \times U(1)_\tau$
  - First two generation quarks treated similarly
  - All lepton generations separately
  - 204 CP-even operators, 45 related to Higgs boson sector, 19 parameters fitted simultaneously

SMEFT interpretation

Paper: arXiv:2402.05742v1
accepted by JHEP



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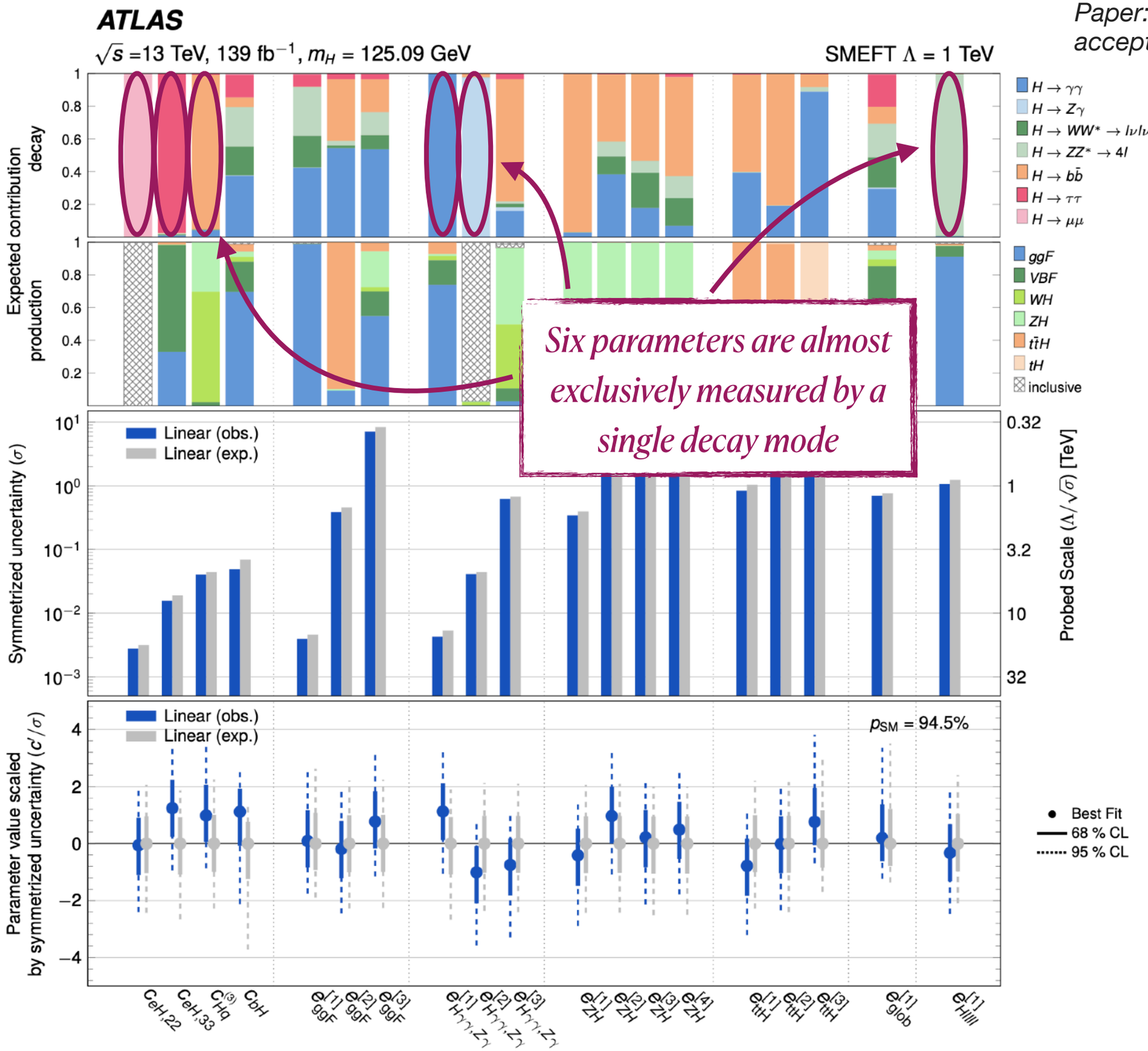

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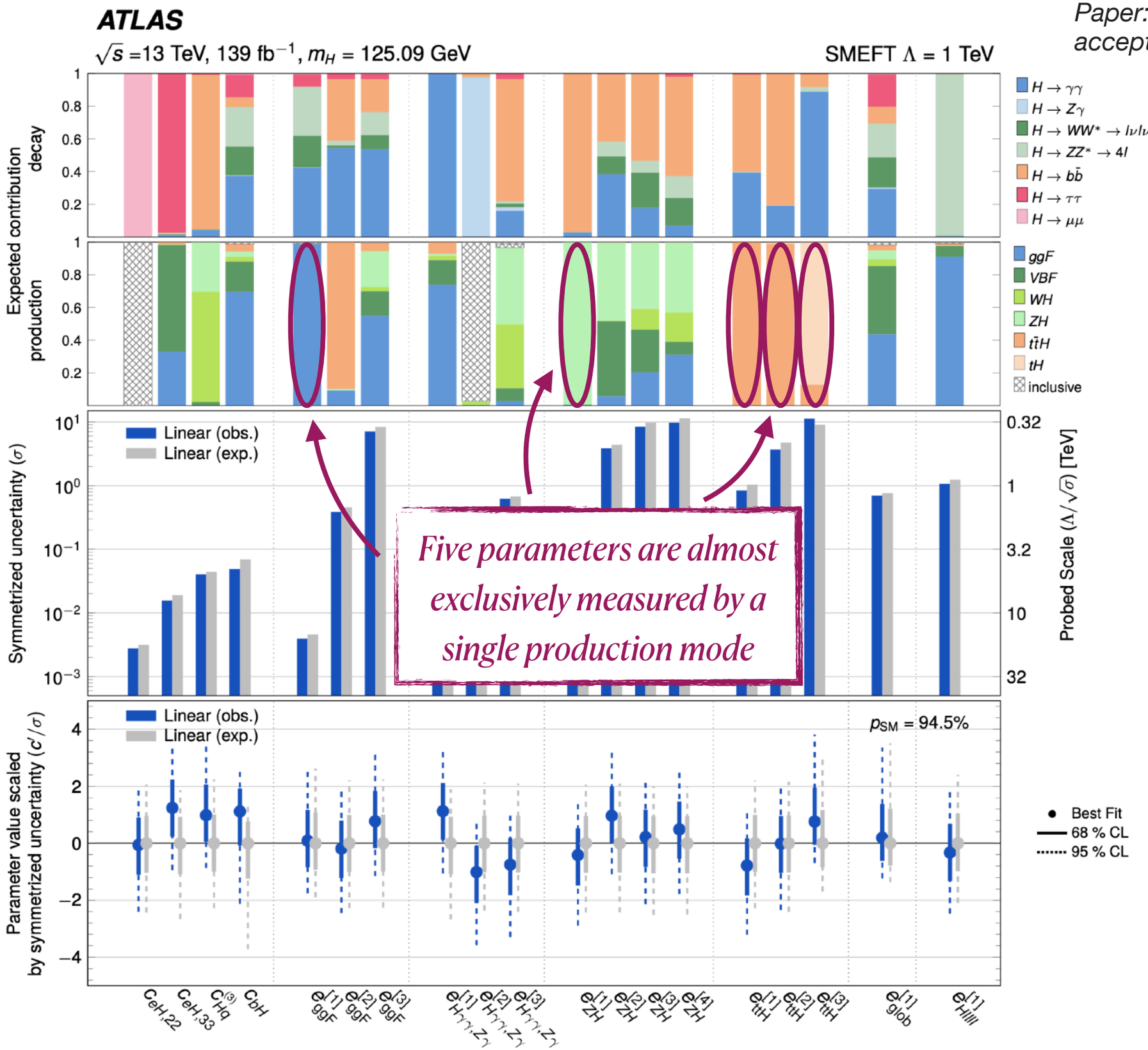

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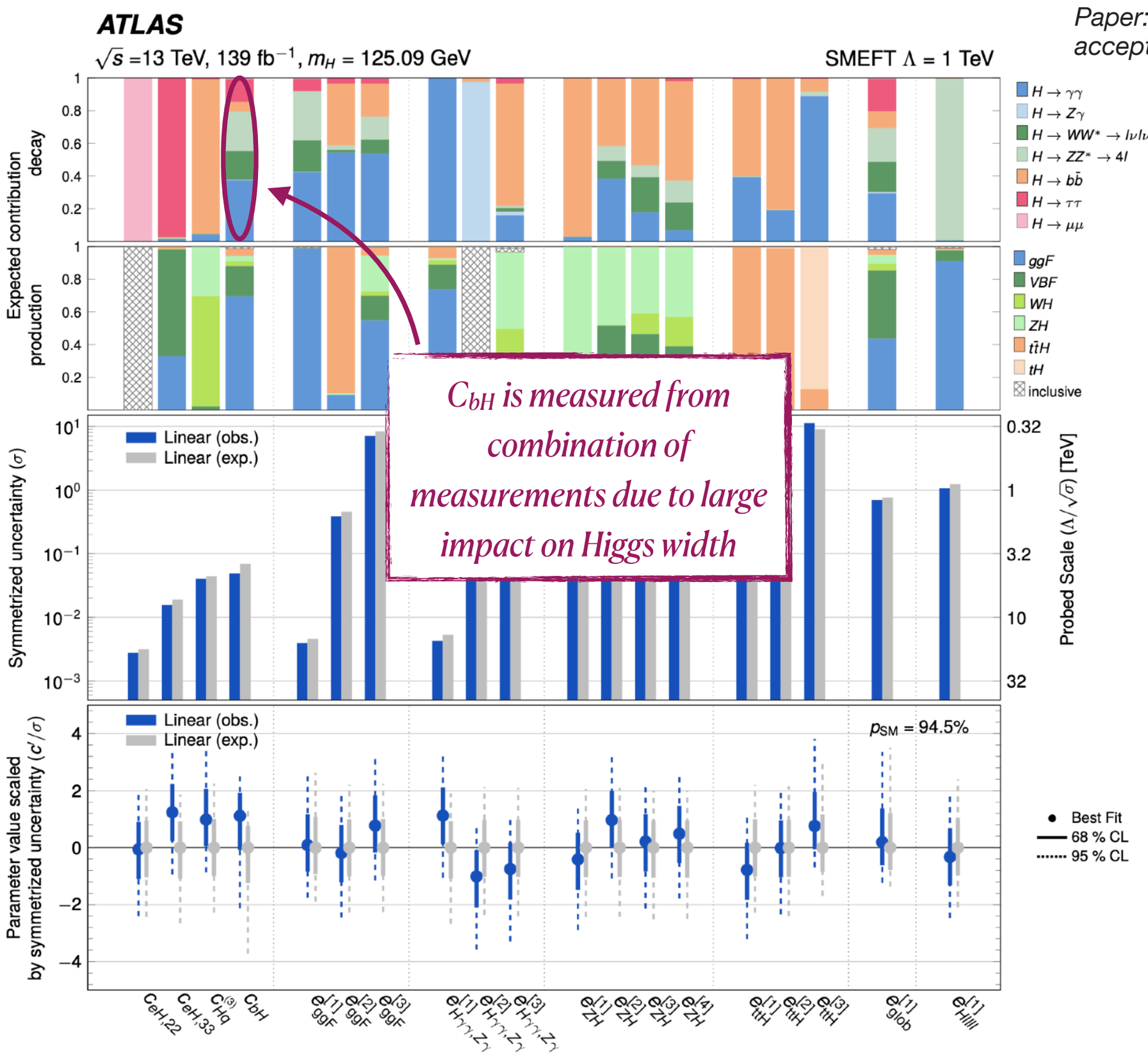


BSM interpretation

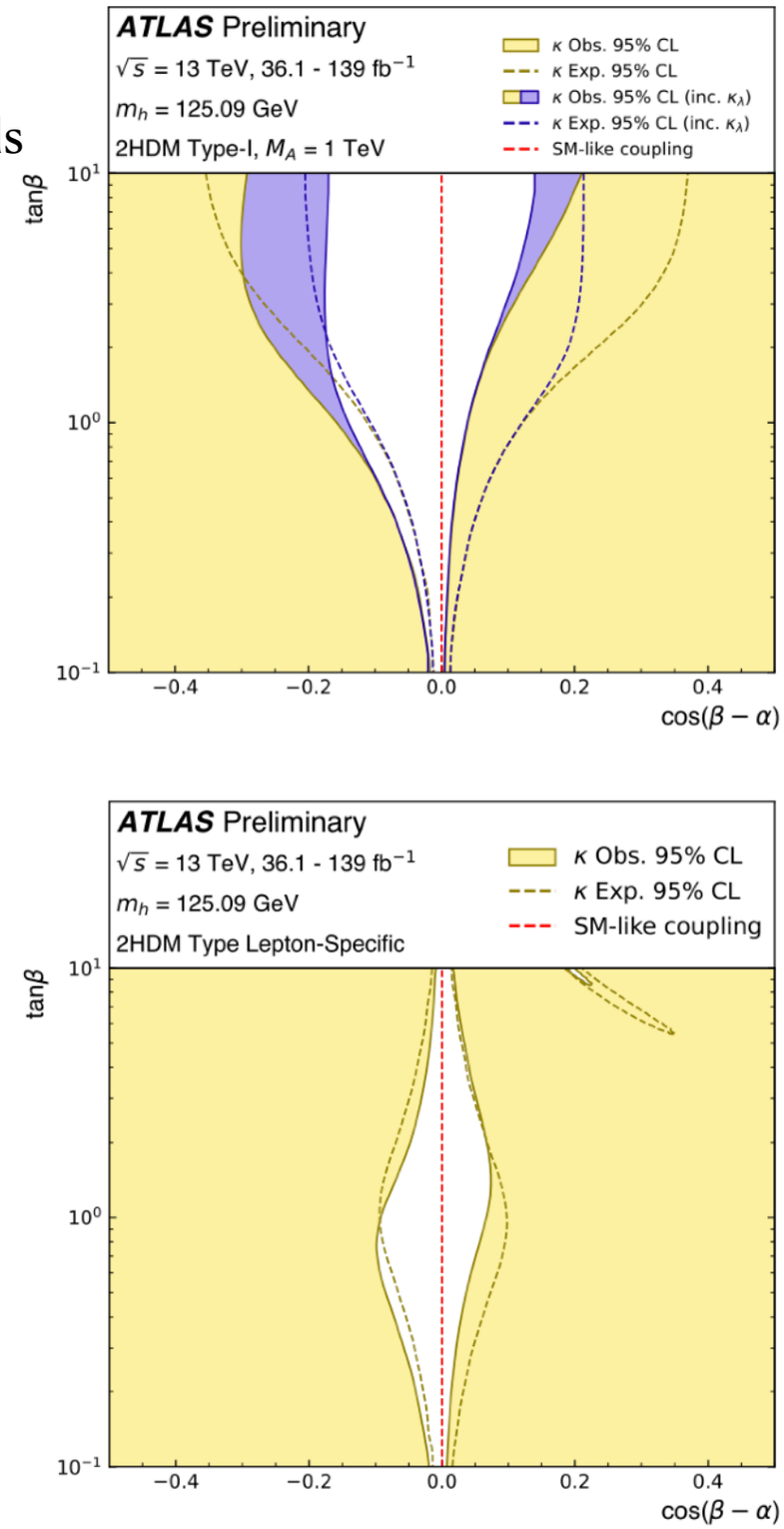
Paper: arXiv:2402.05742v1
accepted by JHEP

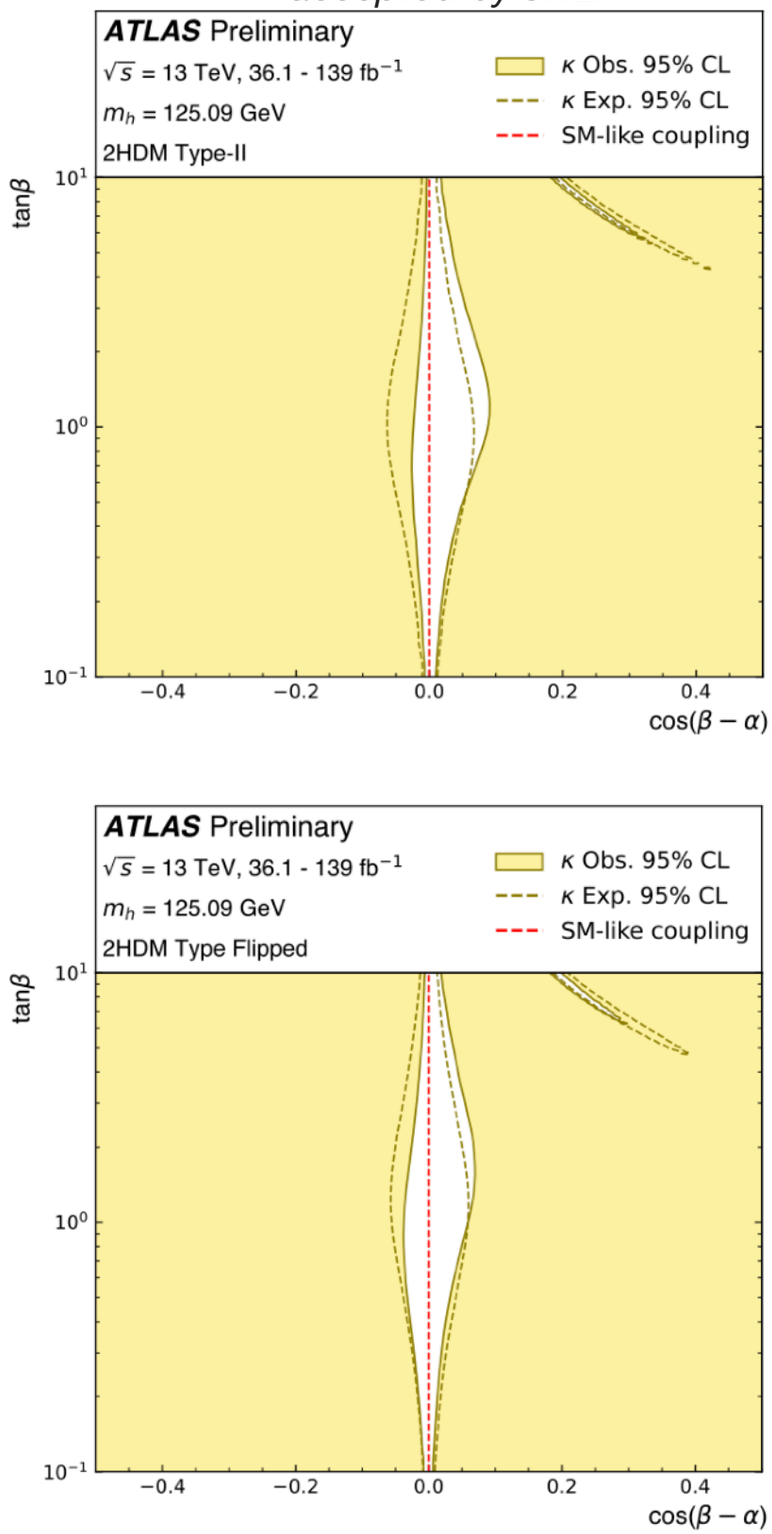
Interpretation in terms of UV-models

- 4 benchmarks: Two Higgs Doublet Models

Two Higgs Doublet Models

- Type I: All fermions couple to the same Higgs doublet.
- Type II: One Higgs doublet couples to up-type quarks while the other one couples to down-type quarks and charged leptons.
- Lepton-specific: One Higgs doublet couples to leptons while the other one couples to up- and down-type quarks.
- Flipped: One Higgs doublet couples to down-type quarks while the other one couples to up-type quarks and leptons.



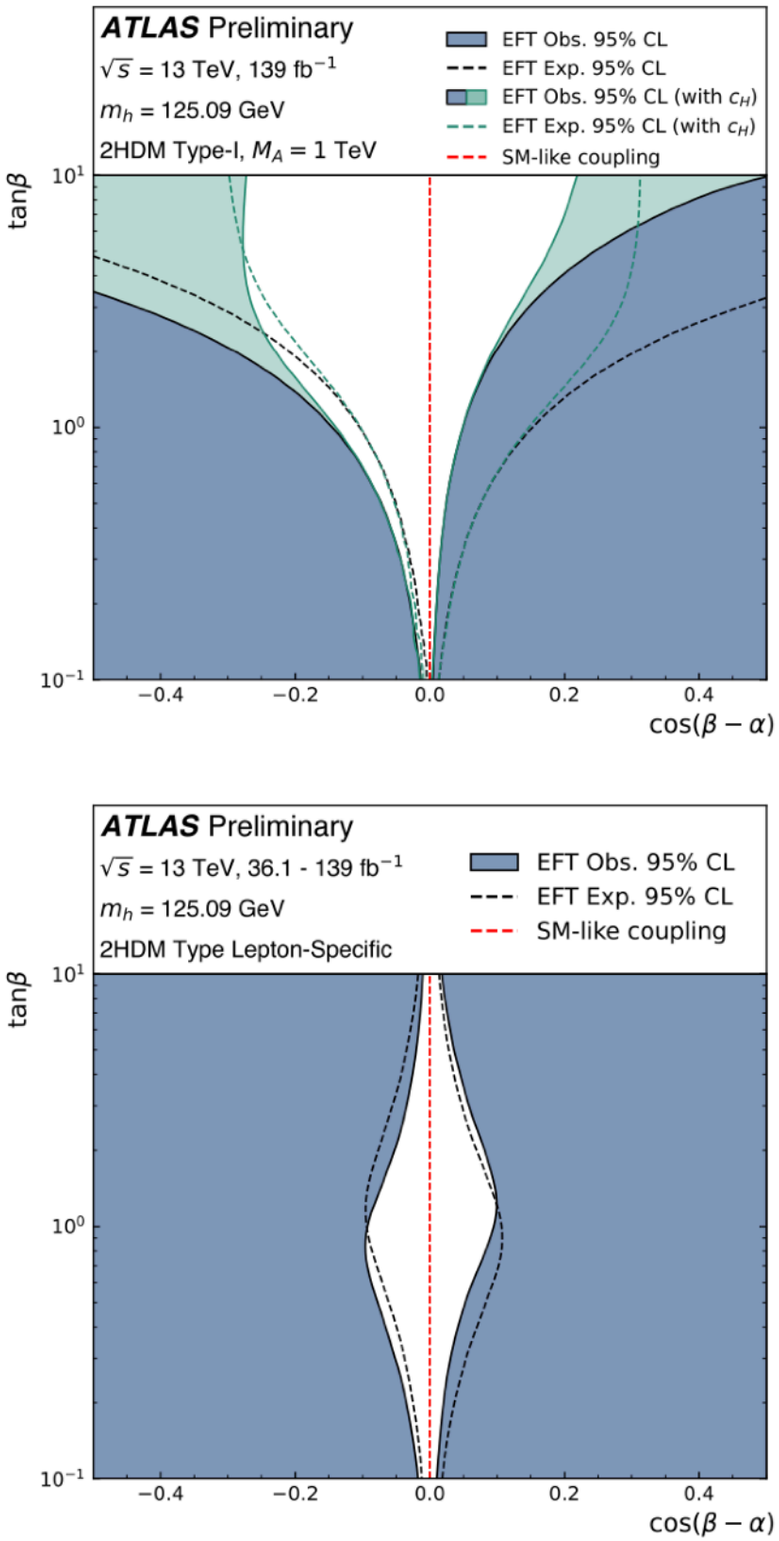


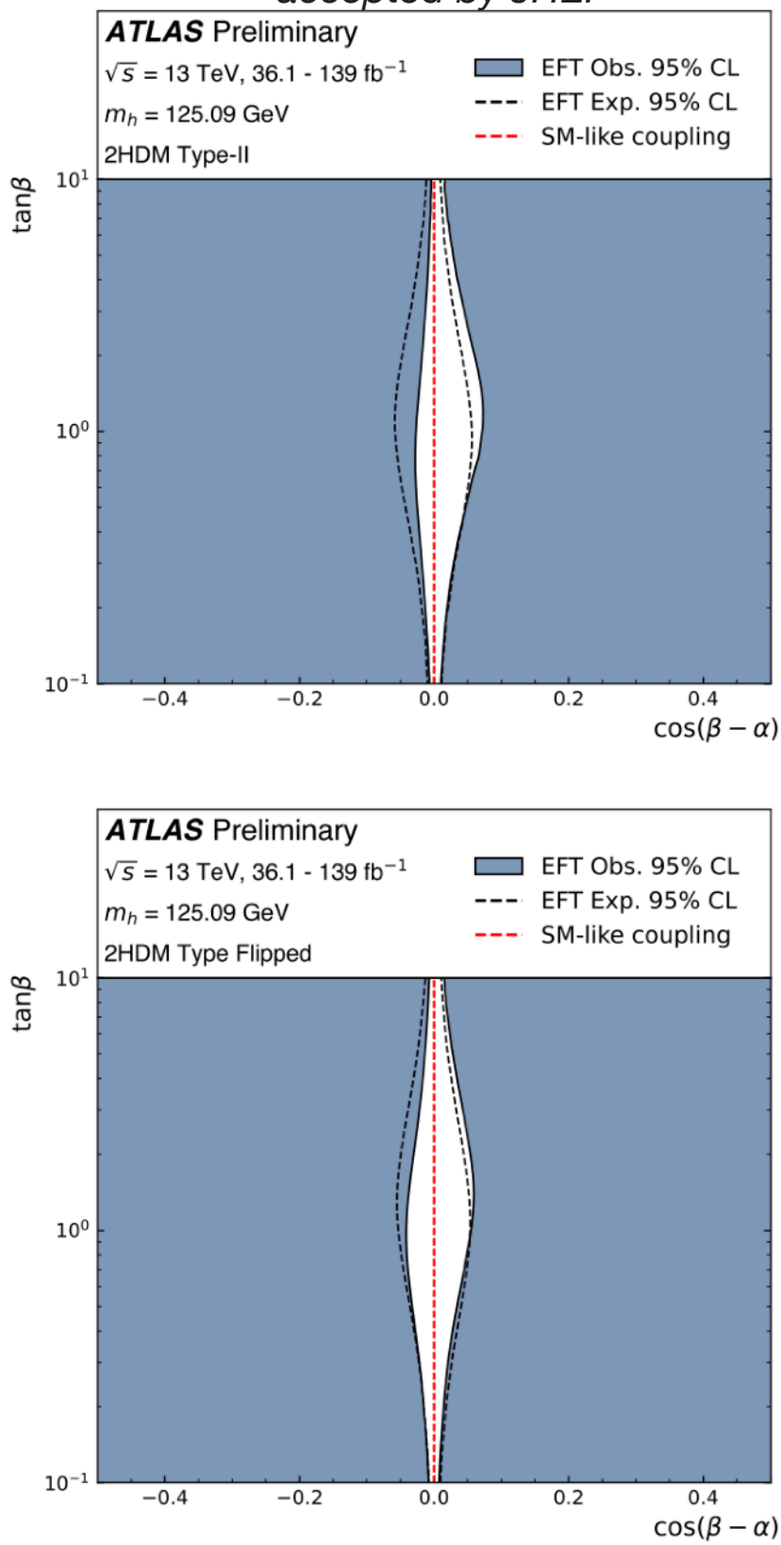
EFT to UV model

Paper: arXiv:2402.05742v1
accepted by JHEP

Translation from Wilson coefficient to several model's parameters

$$\frac{v^2 c_{bH}}{\Lambda^2} = -Y_b \eta_b \frac{\cos(\beta-\alpha)}{\tan\beta},$$
$$\frac{v^2 c_{tH}}{\Lambda^2} = -Y_t \frac{\cos(\beta-\alpha)}{\tan\beta},$$
$$\frac{v^2 c_{\tau H}}{\Lambda^2} = -Y_\tau \eta_\tau \frac{\cos(\beta-\alpha)}{\tan\beta}.$$





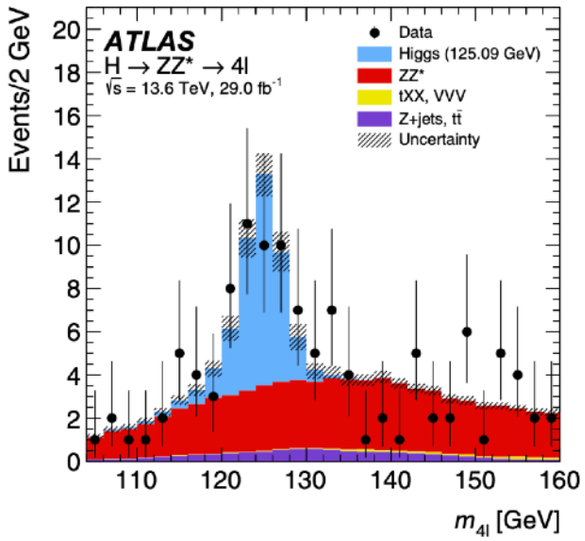
- In general, the EFT approach has similar constraint than direct BSM interpretation!
- Type-I: The EFT approach misses the constraint from HVV couplings, which will only be present with dim-8 operators
- For the other types, the petal region shows weaker constraints due to the linear expansion of EFT approach

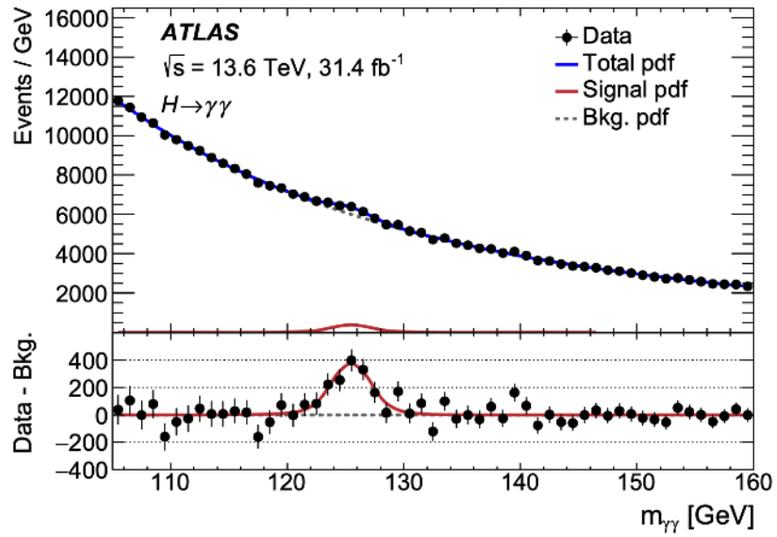
Run III - Golden Channels at 13.6 TeV

Paper: Eur. Phys. J. C 84, 78 (2024)

Golden channels of the Higgs discovery

- Fully reconstructable final state with excellent mass resolution
- Statistical combination for measuring the total cross section using 2022 Run III data
- Extrapolation to the full phase space based on SM acceptance and branching fractions to extract total cross section

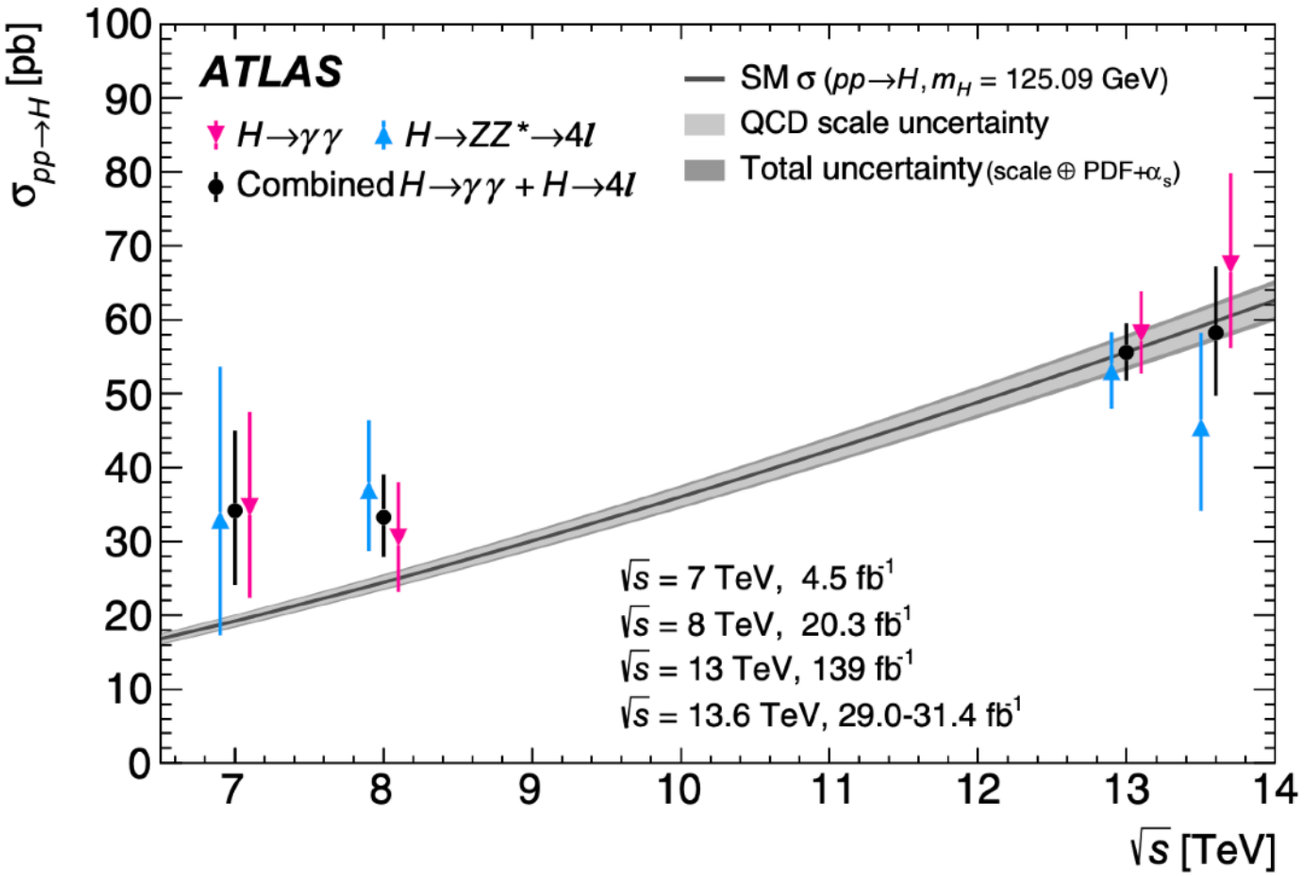




Total combined cross section comparison

- $55.5^{+4.0}_{-3.8}$ pb (Run II, 13 TeV)

  58.2 ± 8.7 pb (Run III (2022), 13.6 TeV)
- Relative increase of total combined cross section is ~ 5% between Run II and Run III



Summary

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

- Probing the Higgs boson sector by measuring the Higgs production and decay rates and its couplings to SM particles
  - All measurement show excellent agreement with the SM predictions -
- Combined measurements have been used for interpretations in the context of SMEFT, and four 2HDM scenarios
  - No significant deviation with respect to the SM is observed -

First cross-section measurement with 2022 RunIII data:

- Relative increase of the total combined cross section ~ 5% between Run II and Run III due to larger center-of-mass energy of 13.6 TeV
  - Measured cross section in agreement with the SM prediction -

Remarkable success of the SM continues (unfortunately) . . .

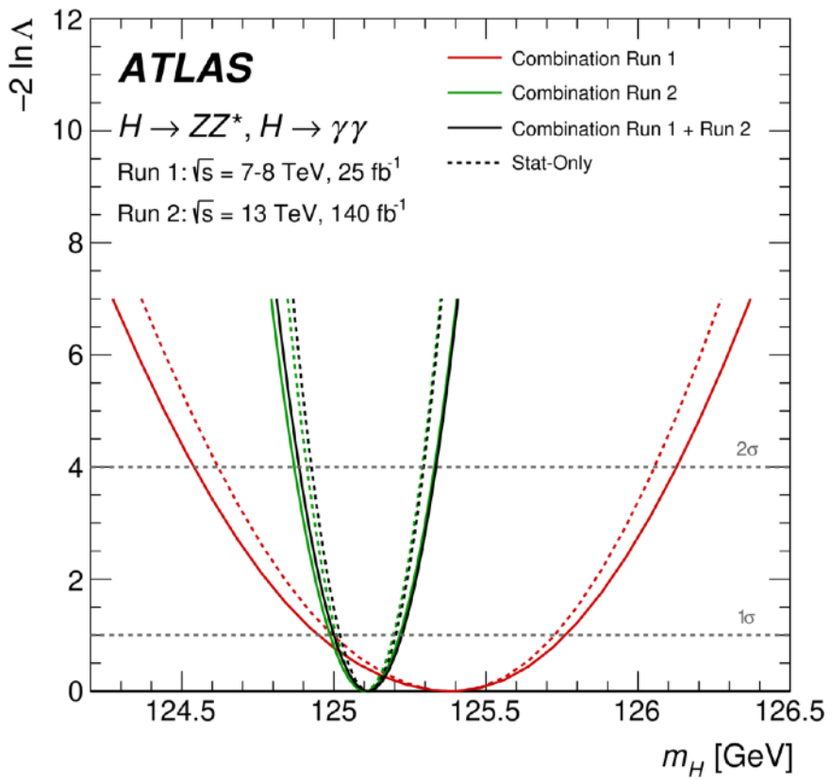
More insights to be gained with RunIII data, stay tuned!

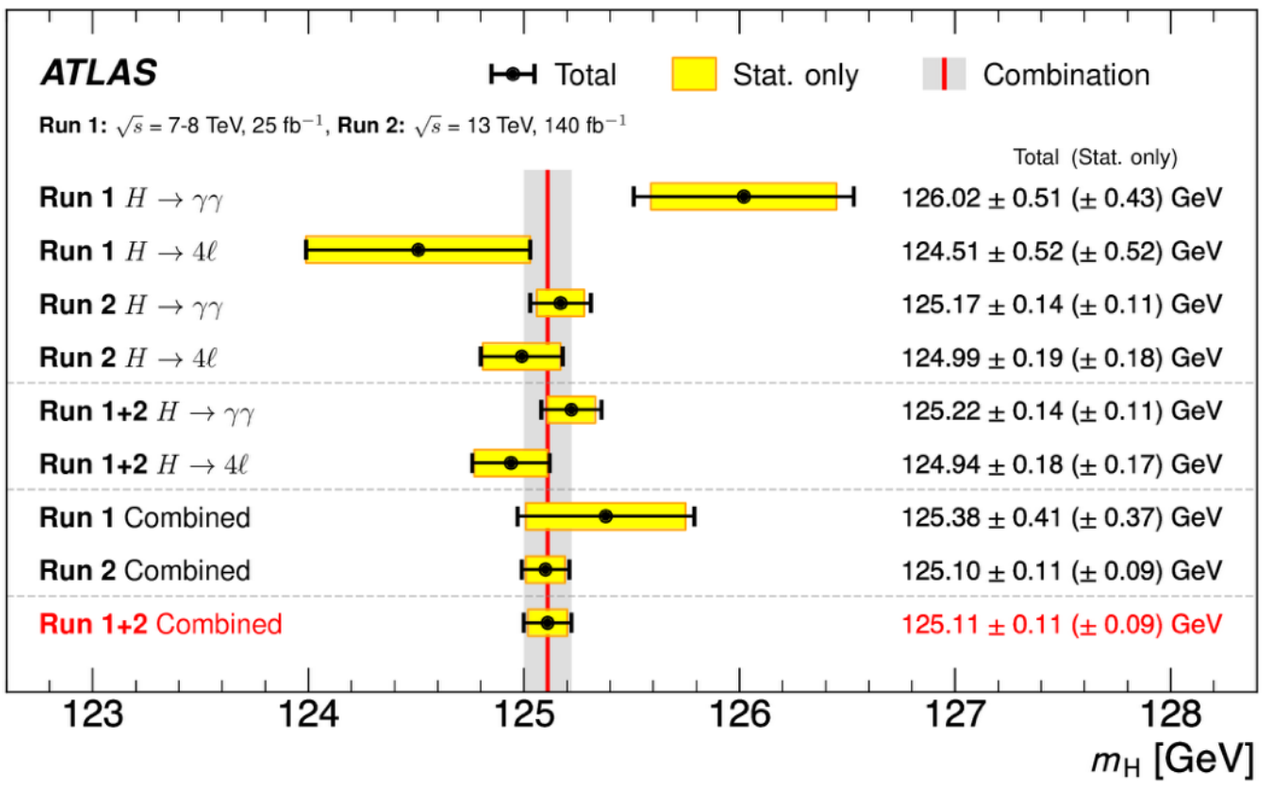
Backup

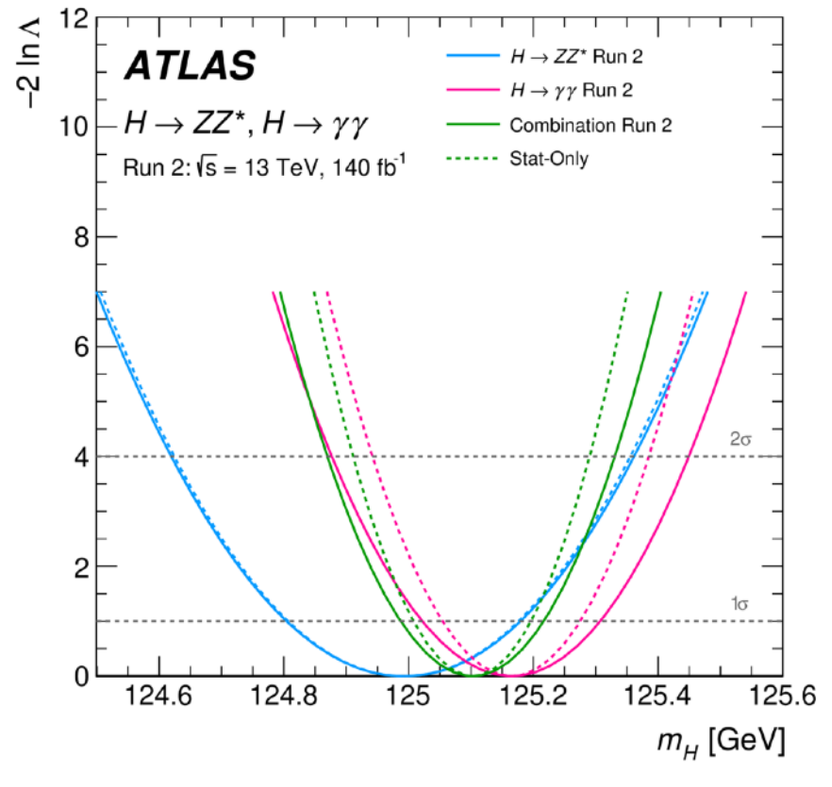
Mass measurement

Combined mass measurement of the Higgs boson

- Fully reconstructable final state with excellent mass resolution $H \to ZZ^* \to 4l$ and $H \to \gamma\gamma$
- Combination Run II + Run I ATLAS mass measurements
- Resulting Higgs boson mass of
  $125.11 \pm 0.09\ (\text{stat.}) \ \pm 0.06\ (\text{syst.})$ GeV
- This corresponds to a relative precision of 0.09 %



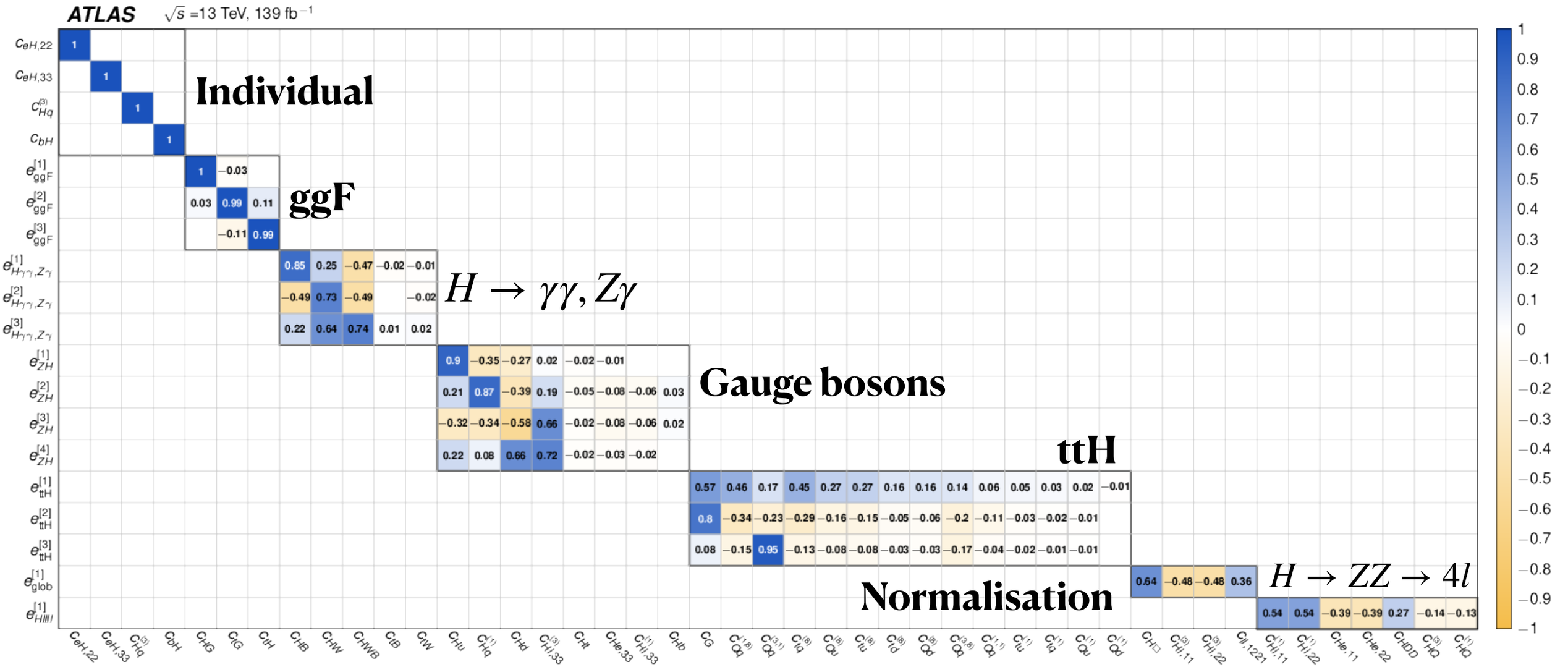




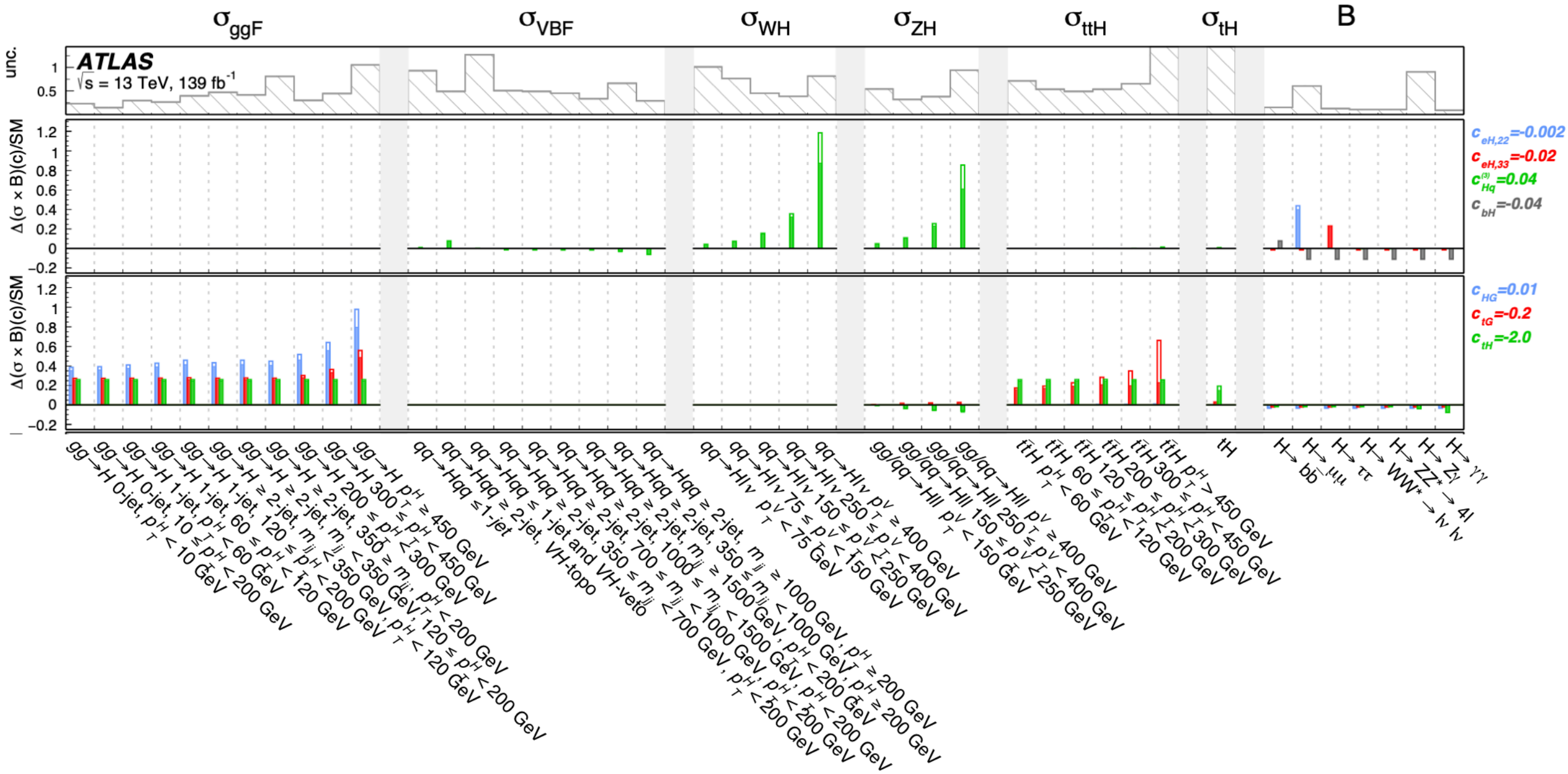
SMEFT: Sensitive directions

A total of 19 directions are chosen with a Principle Component Analysis

- Operators are grouped according to the physics impact
- Remaining flat directions are profiled to zero



SMEFT parameterisation



Uncertainty breakdown