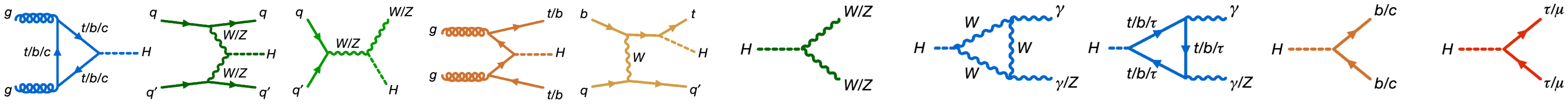



# Measurements of the Higgs boson with the ATLAS experiment

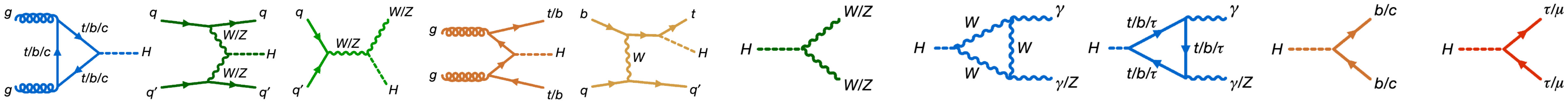
Gregory Penn,

Yale University

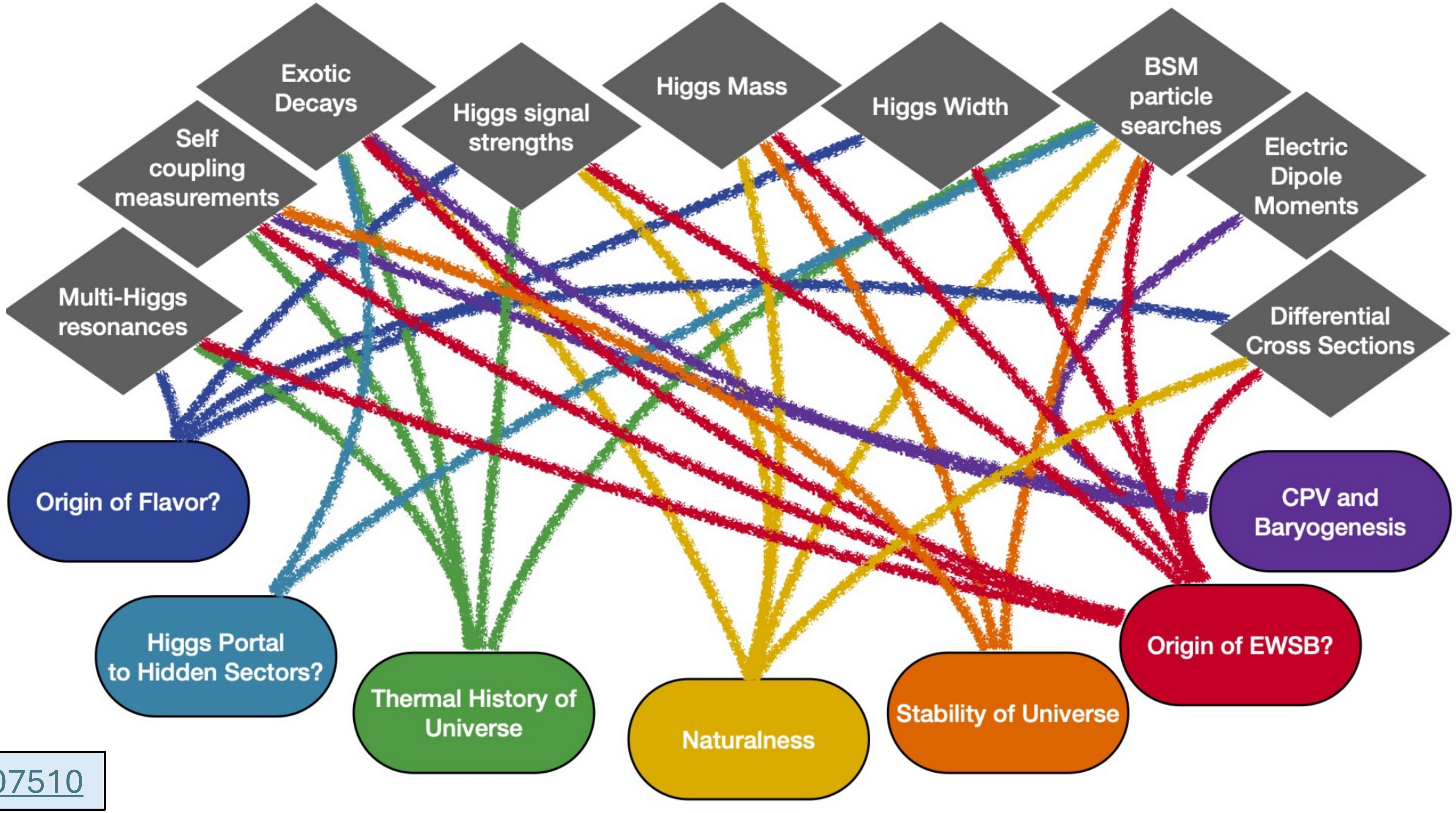
On behalf of the ATLAS Collaboration

ATLAS EXPERIMENT

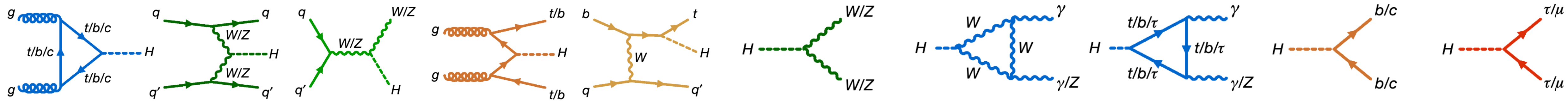
Yale




# So much to talk about!

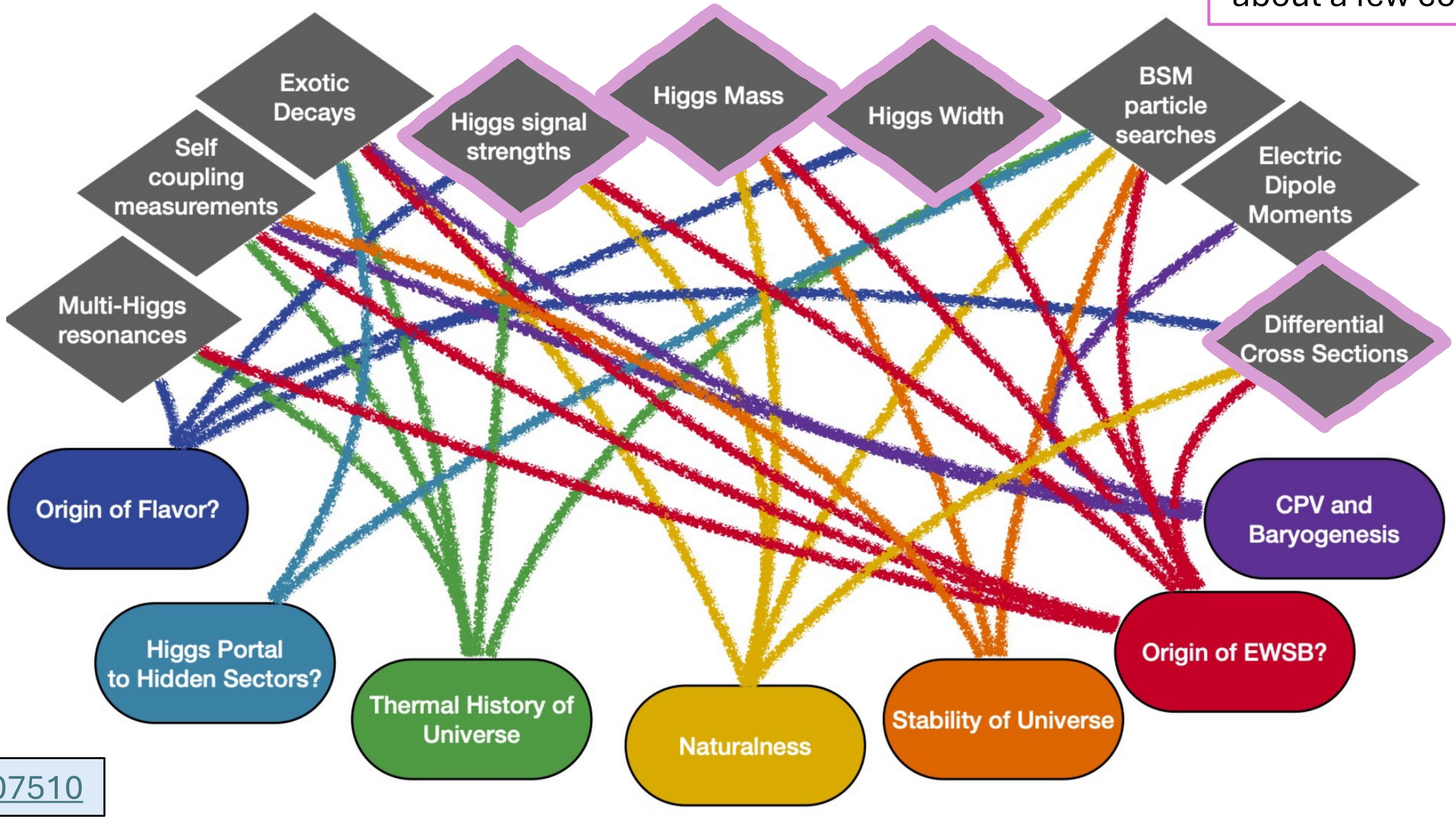



arXiv:2209.07510




# So much to talk about!

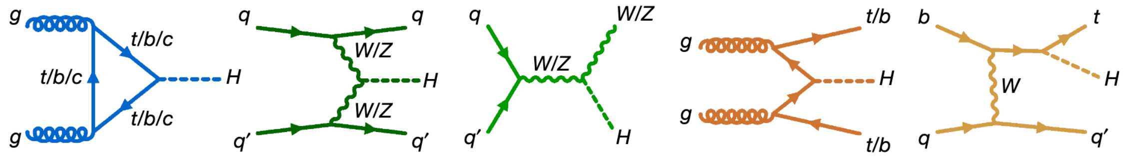
I only have time to talk about a few components!

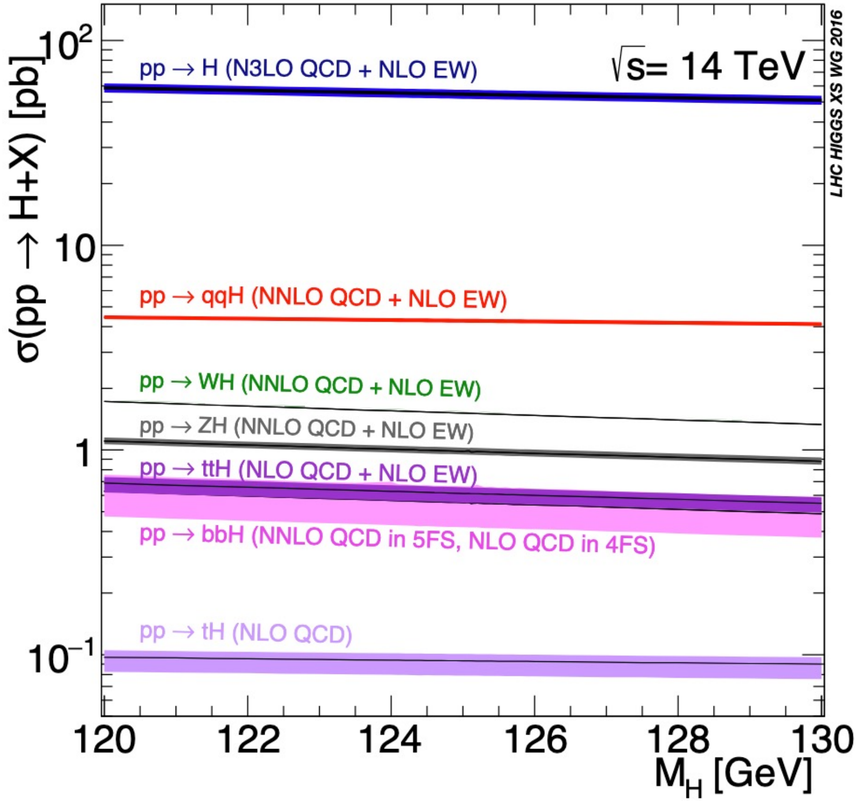



arXiv:2209.07510

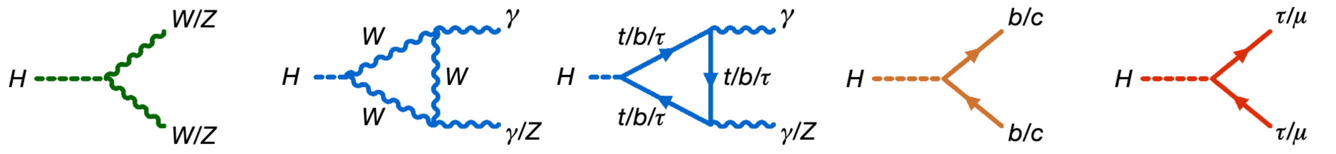
# How to find a Higgs at the Large Hadron Collider

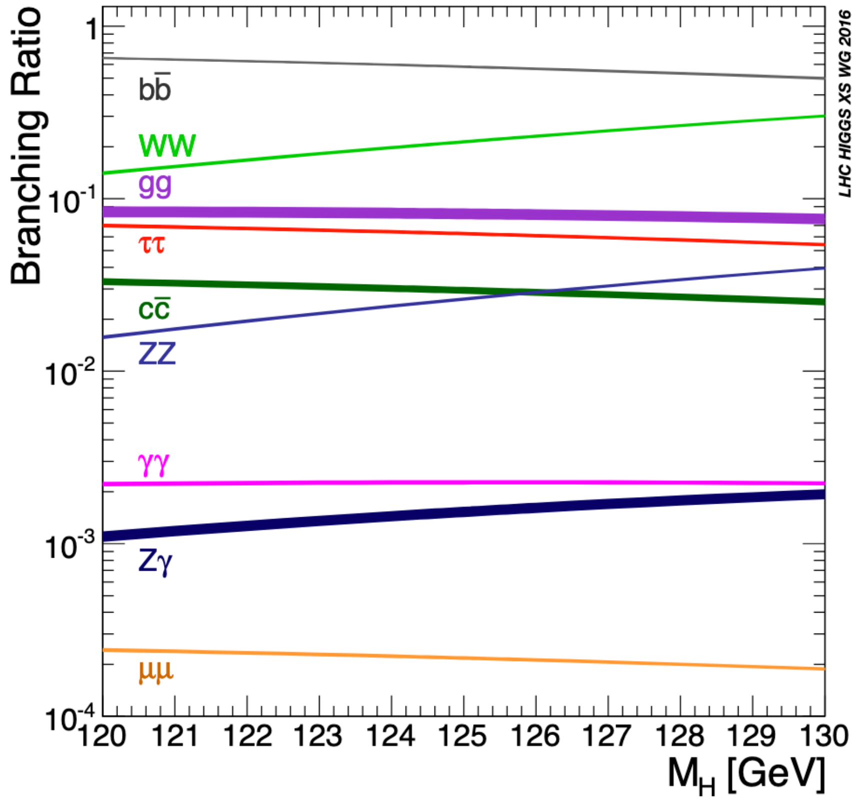
## Higgs Production at the LHC

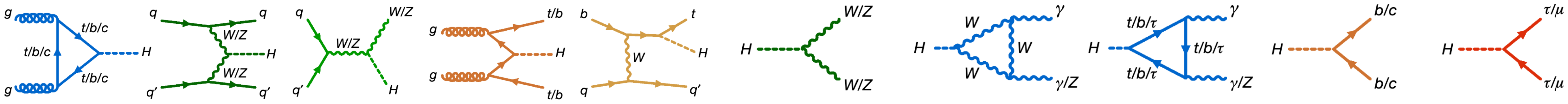


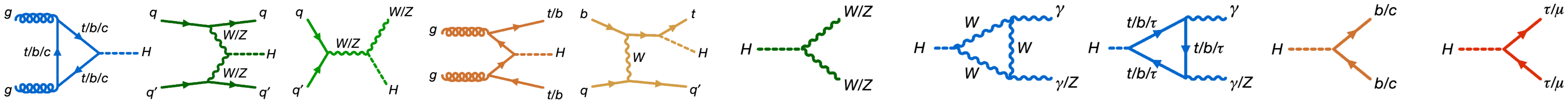

## Higgs Decay






# Higgs Property Measurements



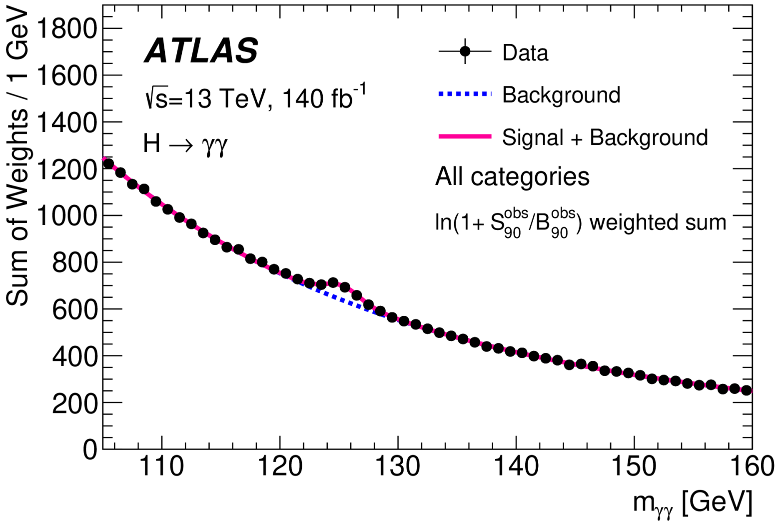

# Higgs Mass

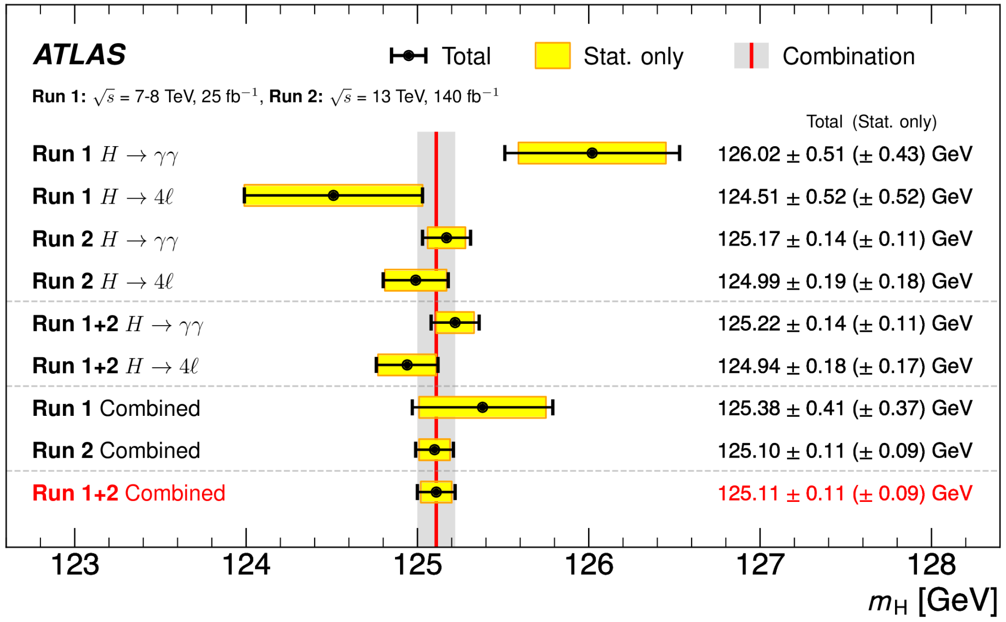
- Input to EW fits: requires precision!
- Measured in Run 2 H→ $\gamma\gamma$ and H→ $ZZ^* \rightarrow 4l$
- Requires deep understanding of detector response to $\gamma$, e, $\mu$
- Combined: $m_H$ = 125.11 $\pm$ 0.09 (stat) $\pm$ 0.06 (syst) GeV

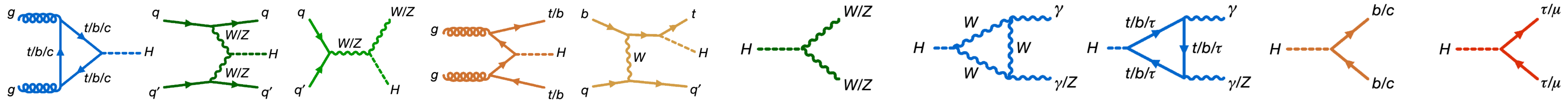
$H \rightarrow \gamma\gamma$
Phys.Lett.B 847 (2023) 138315

$H \rightarrow ZZ^* \rightarrow 4l$
Phys. Lett. B 843 (2023) 137880

Combination
Phys. Rev. Lett. 131 (2023) 251802



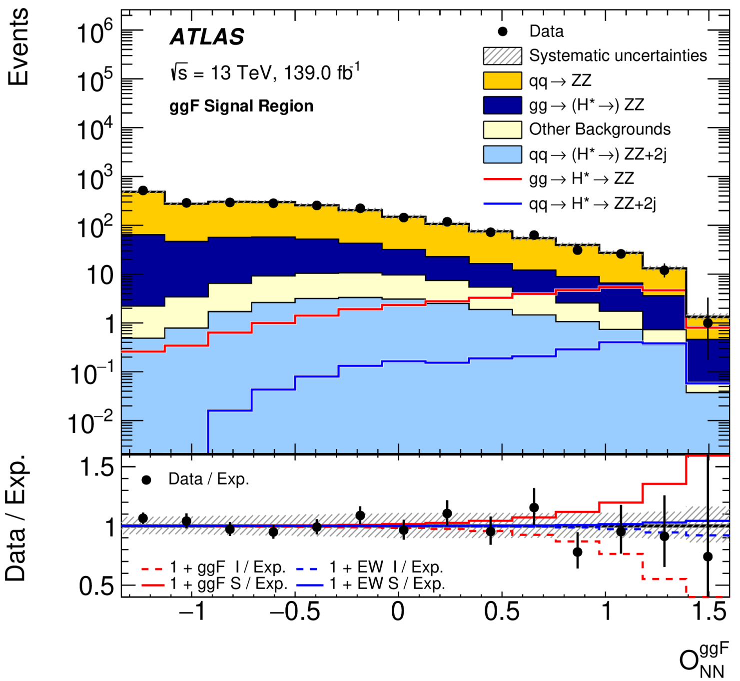



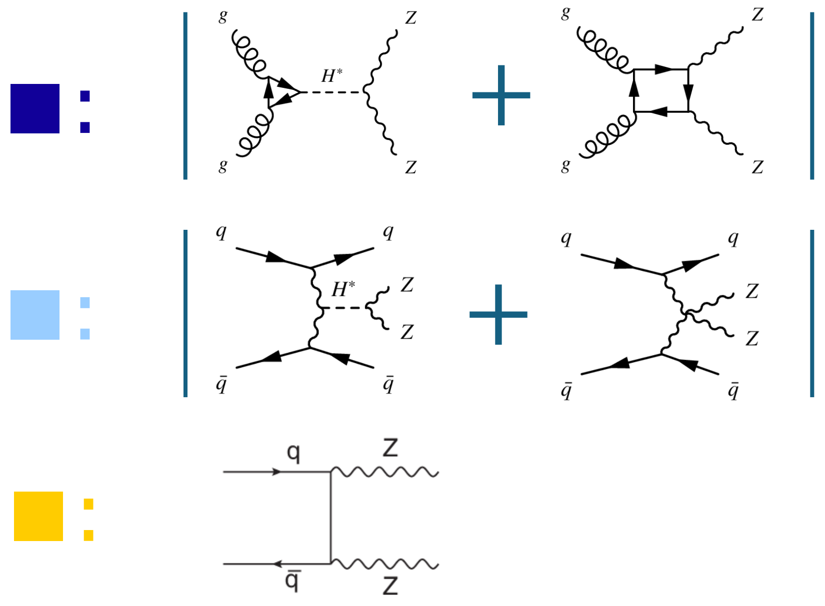


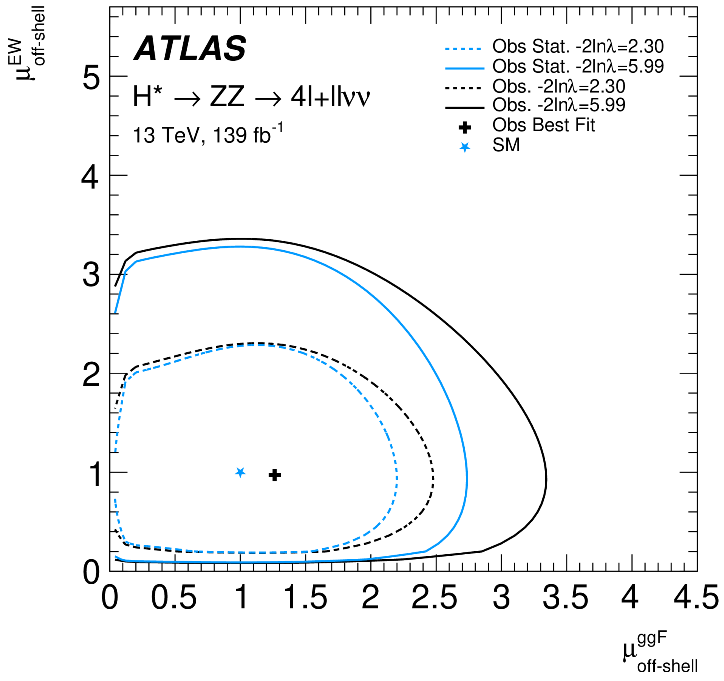
# Higgs Width

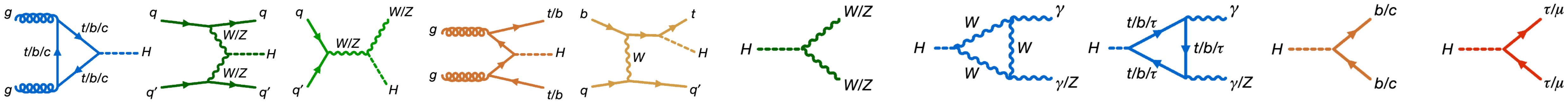
Phys. Lett. B 846 (2023) 138223

- SM Prediction $\Gamma_H^{SM}$ = 4.1 MeV too small to measure directly with good precision
  - Indirect measurement requires cross section of $H^* \rightarrow ZZ \rightarrow 4l, 2l2\nu$
- Signal is a dip in continuous $ZZ$ distribution
- NN observable in $ZZ \rightarrow 4l$ improves sensitivity to off-shell Higgs signal








# Higgs Width

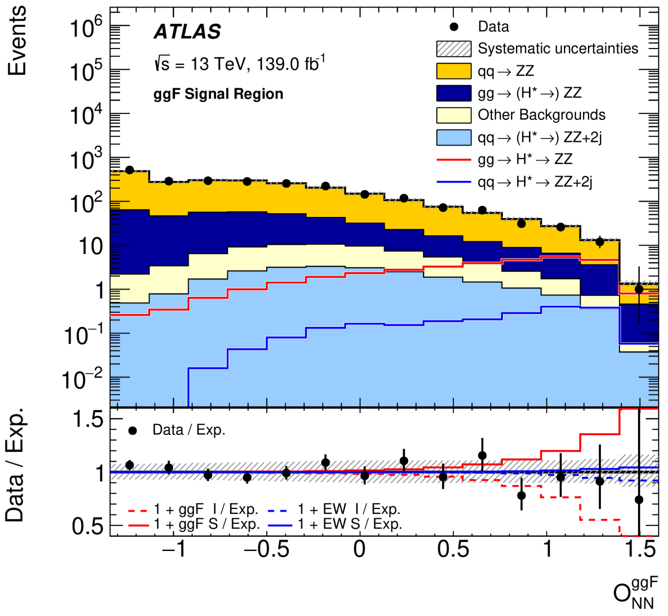
Off-shell $H^* \to ZZ$
Phys. Lett. B 846 (2023) 138223

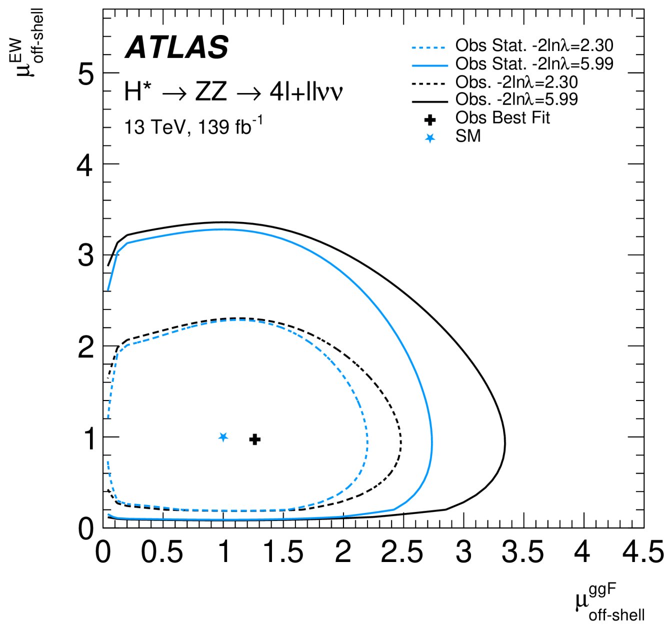
On-shell $H \to ZZ^*$
Eur. Phys. J. C 80 (2020) 957

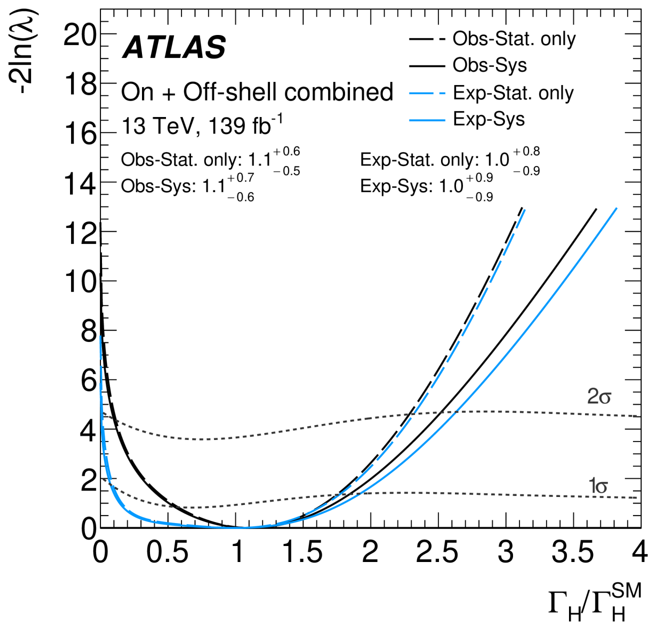
Theory:
N. Kauer & G. Passarino (2012)
F. Caola & K. Melnikov (2013)
J.Campbell, R. Keith Ellis, C. Williams (2013)

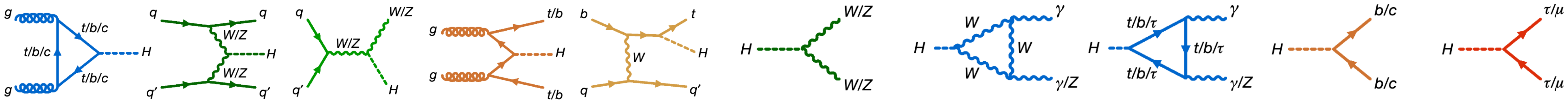
- Compare off- and on-shell cross sections to extract width
- $\Gamma_H = 4.5^{+3.3}_{-2.5}$ MeV, compared to $\Gamma_\mathrm{H}^\mathrm{SM} = 4.1$ MeV

$$\sigma^{\text{off-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{\text{ggF}} g^2_{\text{HZZ}}}{m^2_{ZZ}} \qquad \sigma^{\text{on-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{\text{ggF}} g^2_{\text{HZZ}}}{m_H \Gamma_H}$$






# Higgs Spin and CP Structure

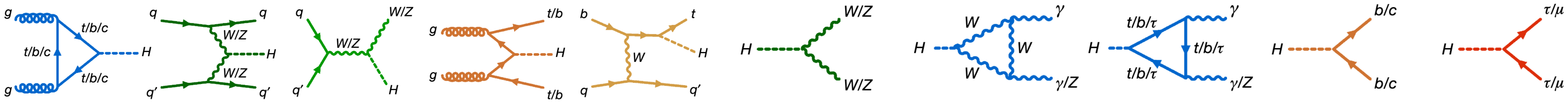
- Higgs spin and Charge-Parity (CP) structure is known to be $J^{CP} = 0^{++}$
- The CP property of its couplings can still vary
- CP violation is a necessary ingredient to explain baryon asymmetry
    - Motivates thorough investigation into CP nature of Higgs sector!

**CP-odd couplings can enter at operator dimension = 4 for fermions (Parameterized by $\alpha$)**

**CP-odd couplings can enter at operator dimension = 6 for bosons (Parameterized by Wilson coefficients)**

$$\mathcal{L}_{HFF} = -\frac{m_F}{v}\kappa_F(\cos\alpha\,\bar{\psi}\psi + \sin\alpha\,\bar{\psi}i\gamma_5\psi)H$$

| | CP-odd | | |
|---|---|---|---|
| Operator $O_i^{(d=6)}$ | $H^\dagger H\tilde{W}^n_{\mu\nu}W^{n\mu\nu}$ | $H^\dagger H\tilde{B}_{\mu\nu}B^{\mu\nu}$ | $H^\dagger\tau^n H\tilde{W}^n_{\mu\nu}B^{\mu\nu}$ |
| Wilson coefficient | $c_{H\tilde{W}}$ | $c_{H\tilde{B}}$ | $c_{H\tilde{W}B}$ |



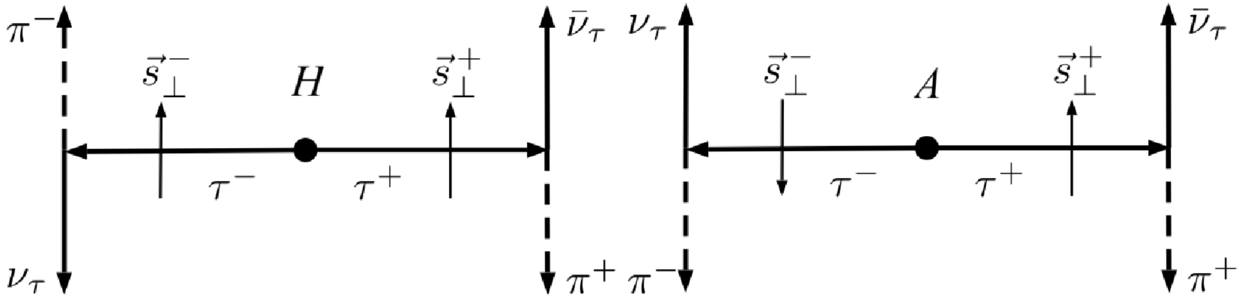

# Higgs CP Structure (Fermions)

Eur. Phys. J. C 83, no.7, 563 (2023)

- $H \rightarrow \tau\tau$: CP-sensitive acoplanarity angle ($\varphi^*_{CP}$)

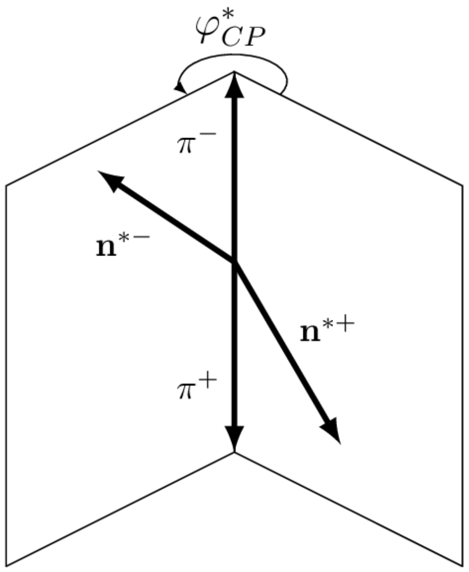
$$d\Gamma_{H\rightarrow\tau^+\tau^-} \approx 1 - b(E_+)b(E_-)\frac{\pi^2}{16}\cos(\varphi^*_{CP} - 2\phi_\tau)$$

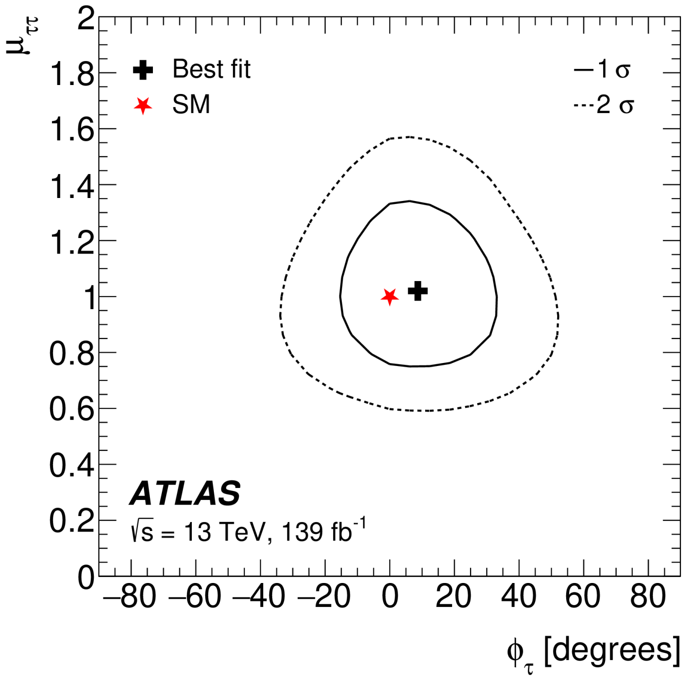
- Requires accurate tagging of tau decay mode (Boosted Decision Tree)
- $\phi_\tau = 9^\circ \pm 16^\circ$ [15.6° $stat$] $\phi_\tau == \alpha$
  - CP-odd exclusion at $3.4\sigma$

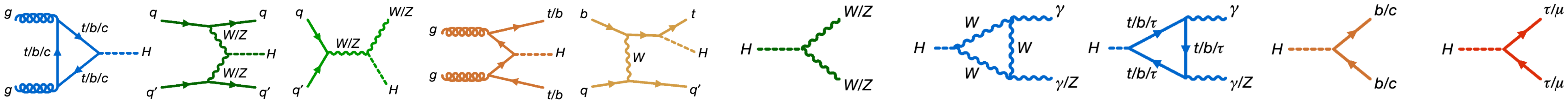



(a) Scalar

(b) Pseudo-scalar



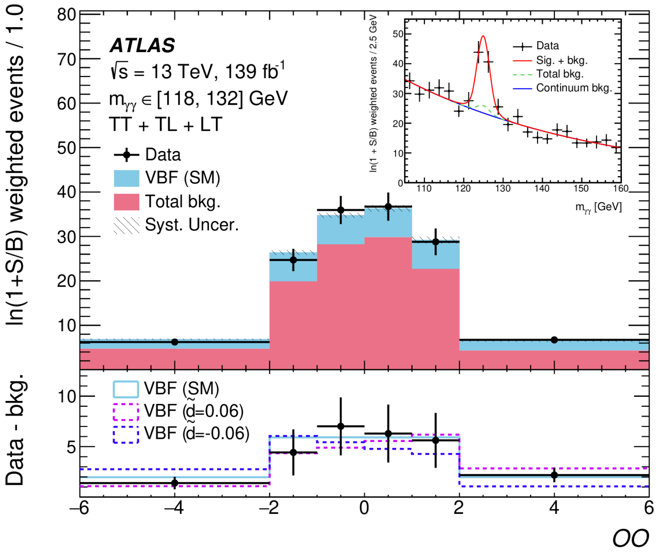



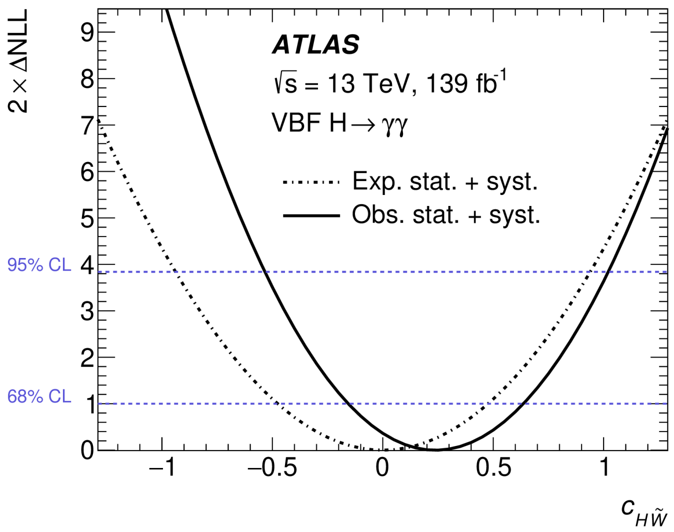


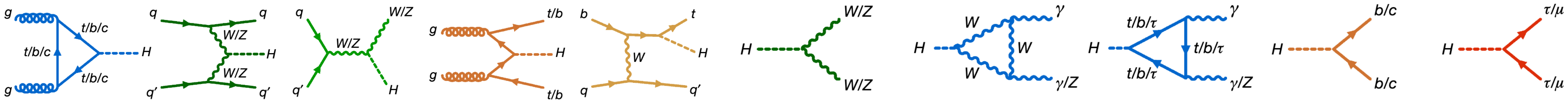

# Higgs CP Structure (Bosons)

Phys.Rev.Lett. 131 (2023) 6, 061802

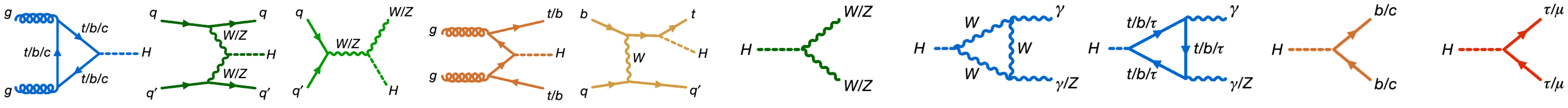
- $H \to \gamma\gamma$: Measurement targeting Higgs production w/ vector bosons
- "Optimal Observable": $OO = 2Re(\mathcal{M}^*_{SM}\mathcal{M}_{CP-odd})/|\mathcal{M}_{SM}|^2$
  - Calculated from 4-vectors of Higgs candidate and di-jet system
- Limits on couplings of dimension-6 operators in an effective field theory formalism
  - HISZ basis: $\tilde{d}$: 95% CI = $[-0.034\ \ +0.071]$
  - Warsaw basis: $c_{H\tilde{W}}$: 95% CI = $[-0.55, +1.07]$






# Higgs Signal Strengths / Cross Sections

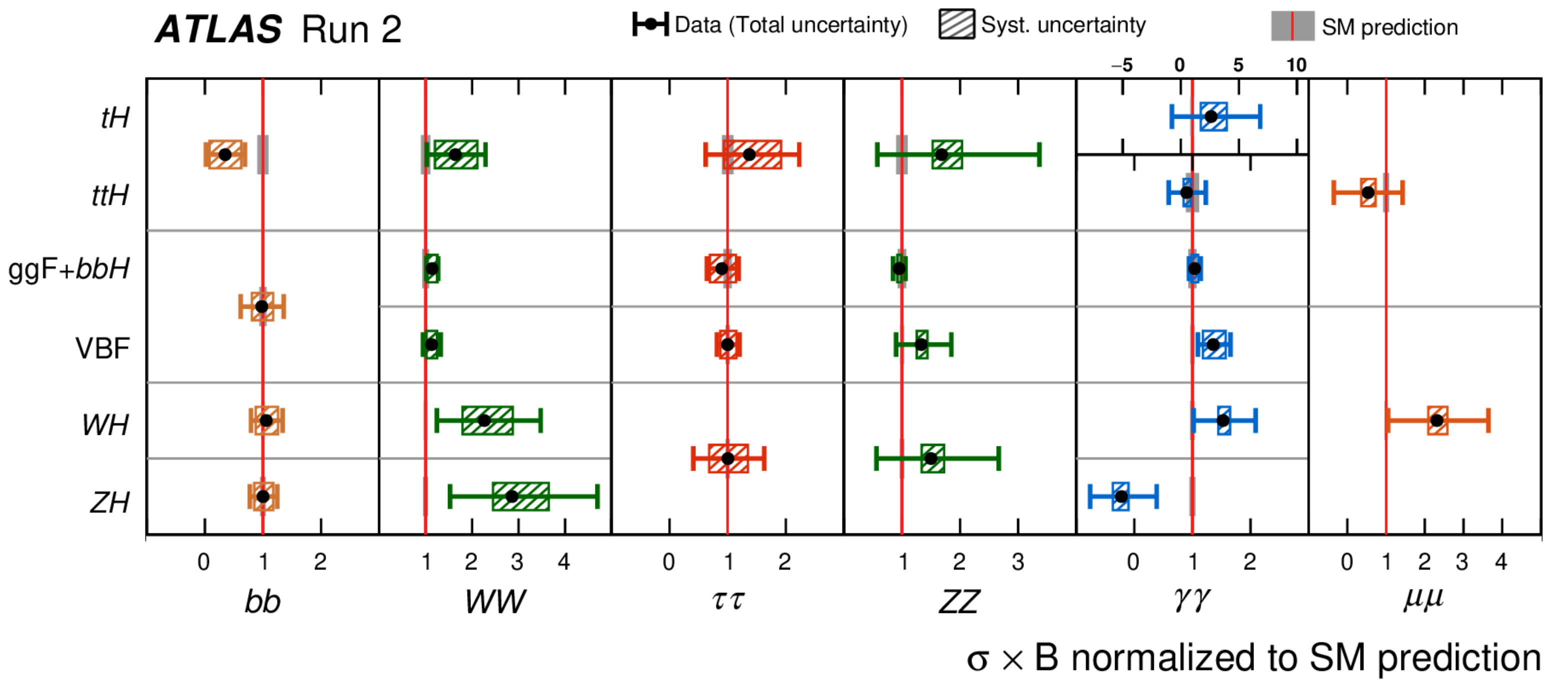


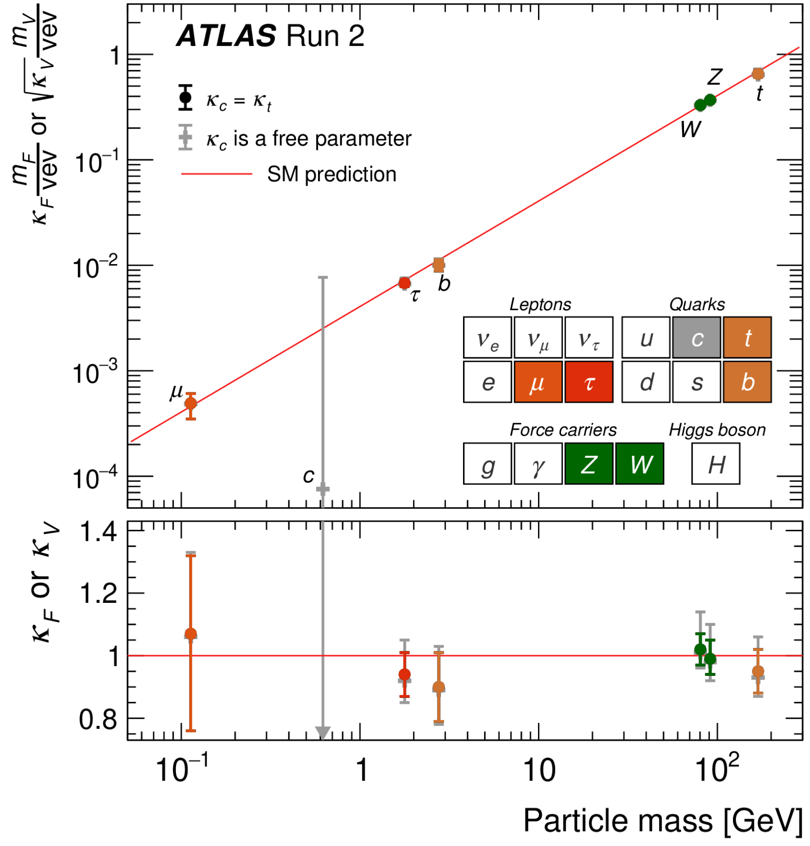

# Higgs Cross Sections / Signal Strengths

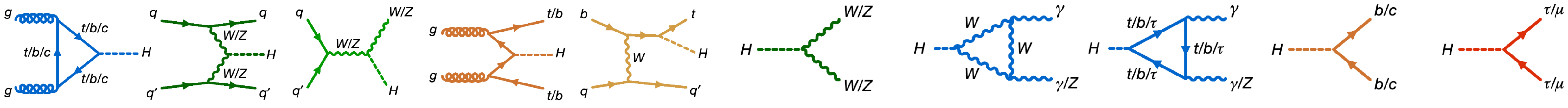
ATLAS Run 2 Higgs Report: arXiv:2404.05498

- Combine results for comprehensive picture of Higgs cross sections and branching ratios
- "$\kappa$ framework": effective coupling strength modifiers

$$\sigma_i \times B_i = \frac{\sigma_i(\kappa) \times \Gamma_f(\kappa)}{\Gamma_H} \qquad \kappa_i^2 = \frac{\sigma_i}{\sigma_i^{SM}} \qquad \kappa_i^2 = \frac{\Gamma_i}{\Gamma_i^{SM}}$$



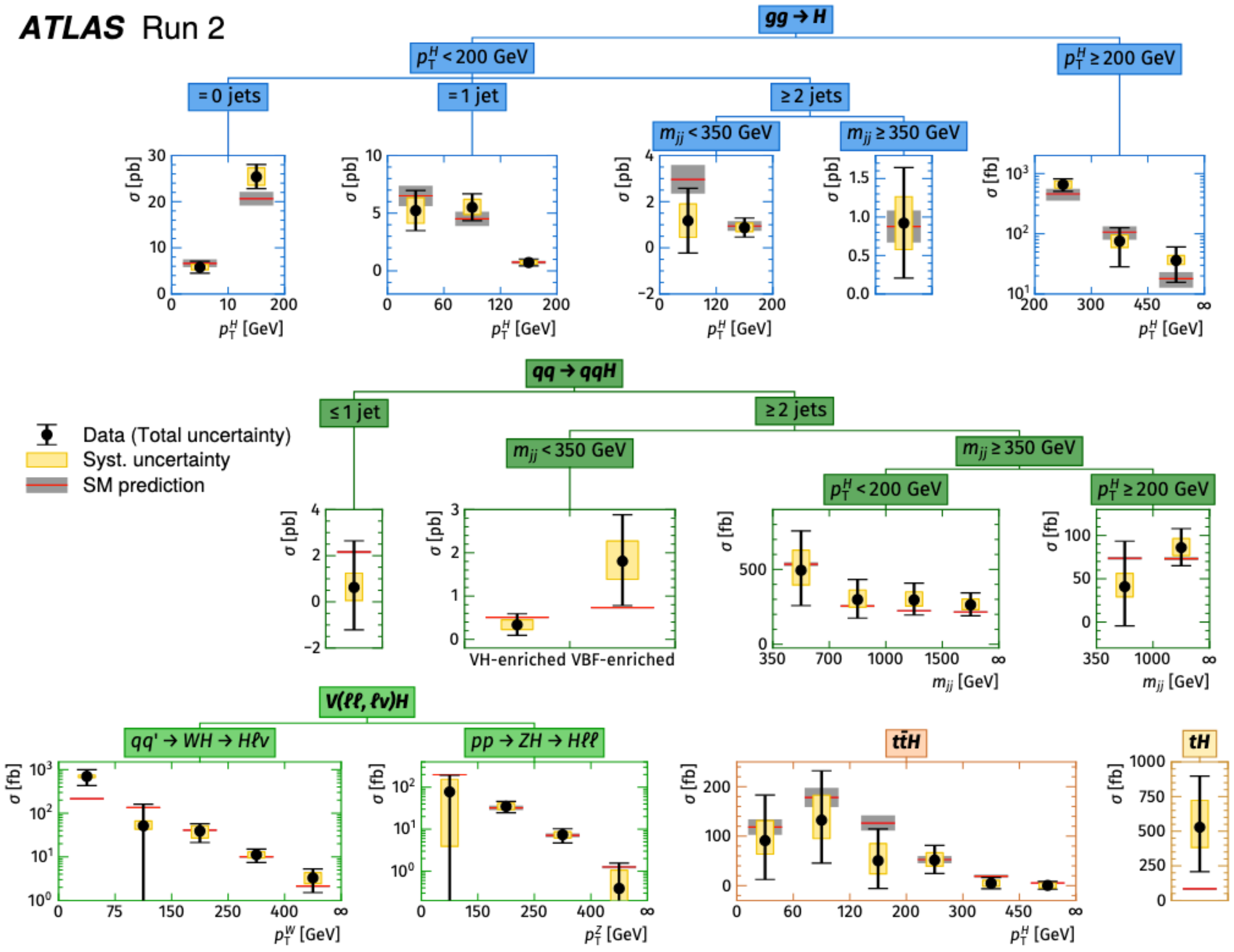



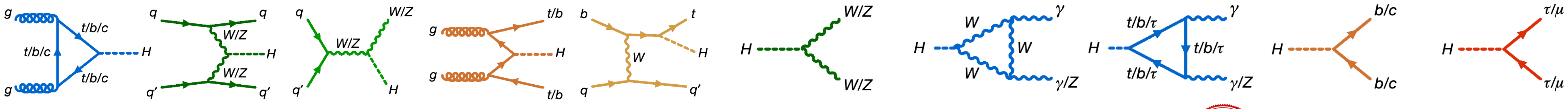



# Combinations: Simplified Template Cross Sections

ATLAS Run 2 Higgs Report:
arXiv:2404.05498

- Look deeper at Higgs interactions in phase space!
- *Simplified Template Cross Section* (STXS) optimizes:
  - Sensitivity to BSM contributions
  - Experimental sensitivity
  - Interest from theory community

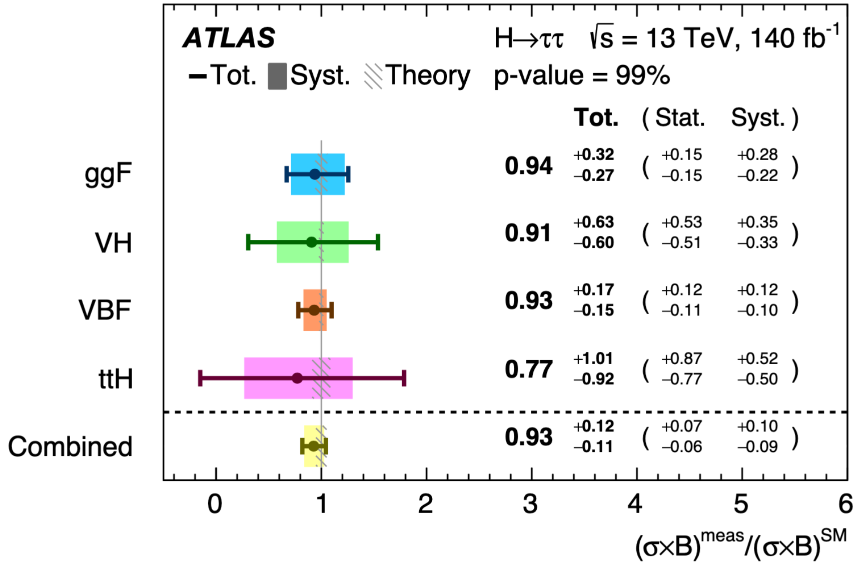


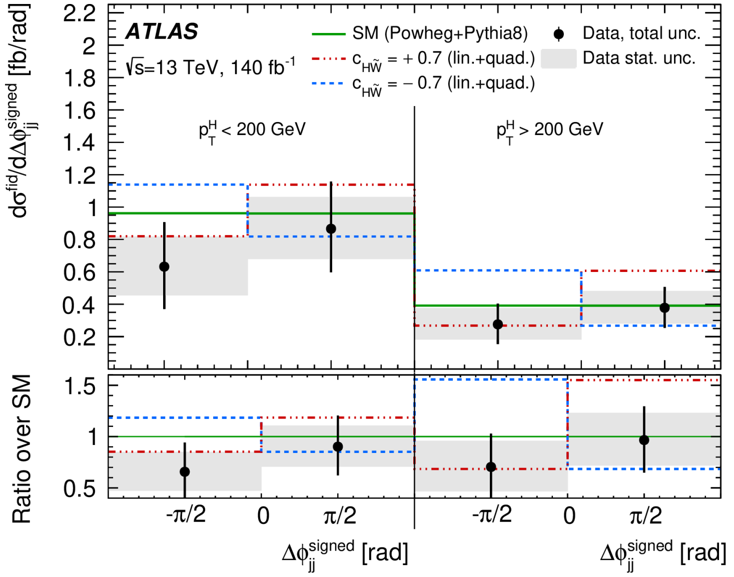


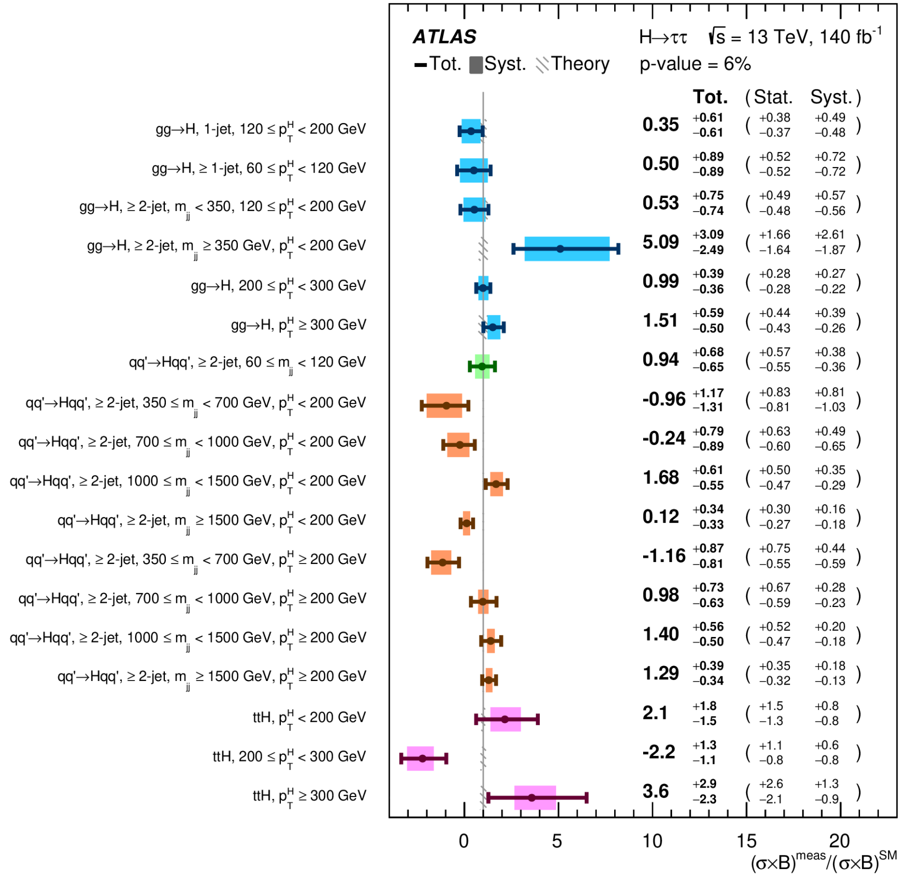

# STXS & Differential Measurements: H→ $\tau\tau$

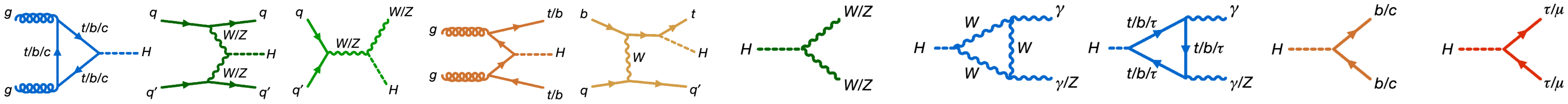
NEW [arXiv:2407.16320]

- Comphrehensive measurement in STXS bins
  - Most precise single-channel VBF signal strength: $0.93^{+0.17}_{-0.15}$
- Differential measurement targeting Higgs production
  - Most stringent constraint of CP-odd SMEFT coefficient:
  - $c_{H\tilde{W}}$: 95% CI = $[-0.31, +0.88]$



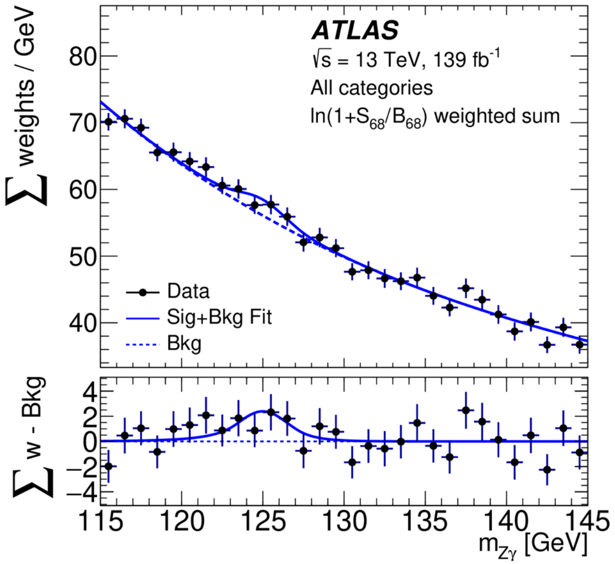



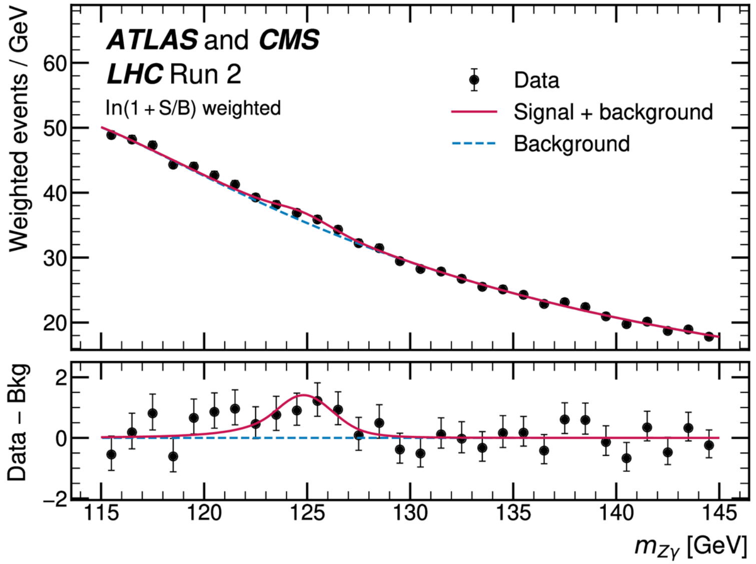


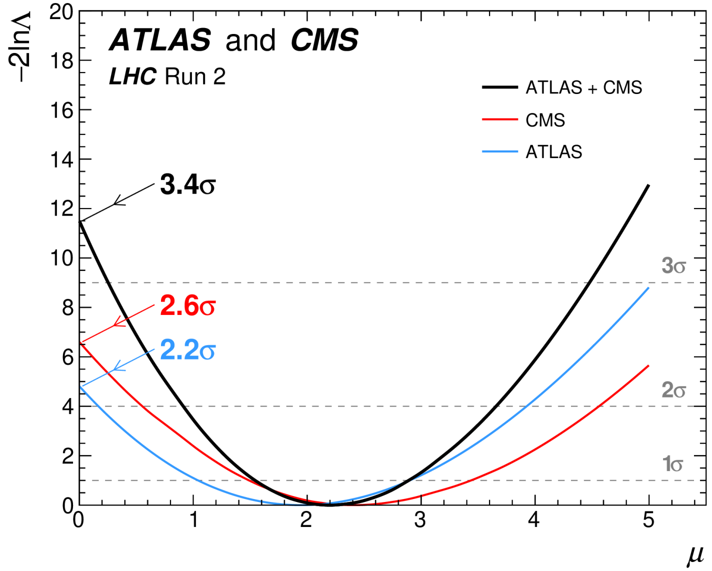
# Rare Decays: $H \rightarrow Z\gamma$

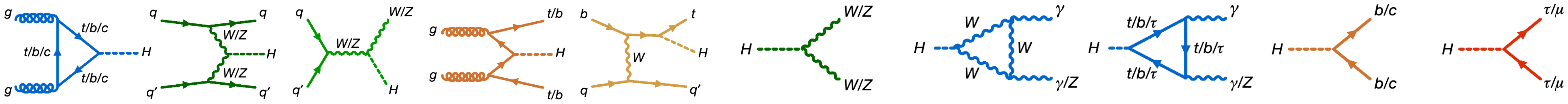
- Branching ratio: $\sim 1.5 \times 10^{-3}$
- ATLAS Run 2 signal yield: $2.0^{+1.0}_{-0.9}$
- Combine with CMS Run 2 signal yield ($2.2^{+0.7}_{-0.7}$) for ***3.4σ significance!***

| ATLAS | CMS | Combination |
|---|---|---|
| Phys. Lett. B 809 (2020) 135754 | JHEP 05 (2023) 233 | Phys. Rev. Lett. 132 (2024) 021803 |



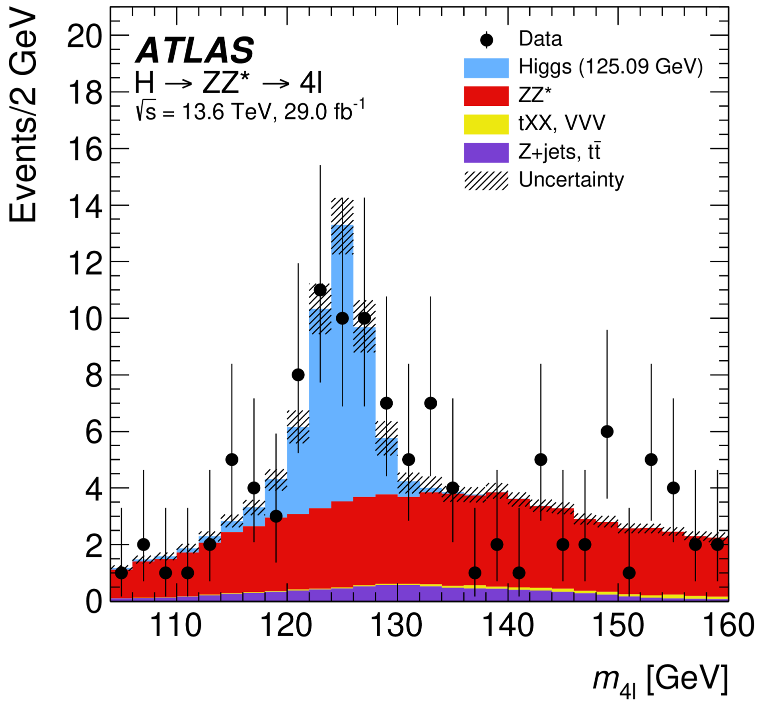



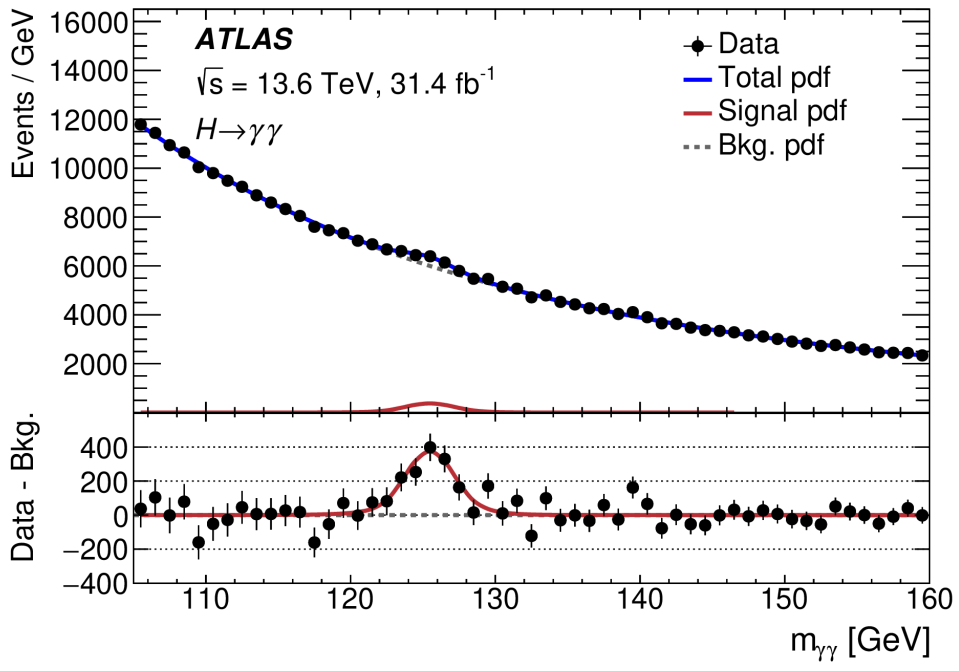


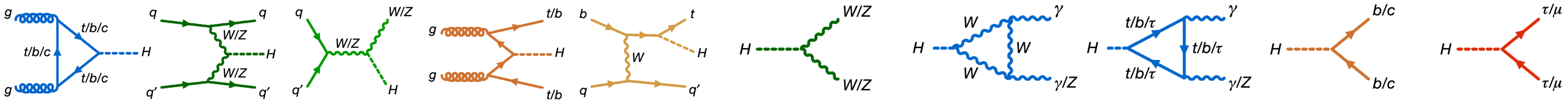
# Run 3 Measurements: H→ $\gamma\gamma$, H→ $ZZ^* \rightarrow 4l$

Eur. Phys. J. C 84 (2024) 78

- New dataset incoming - make sure the Higgs is still there!
- Early measurements already innovating on methods
  - Machine learning method for generation of large-statistic background template






# Summary

- Plenty of work done by ATLAS to inspect the nature of the Higgs
  - Mass, Spin / CP, Width
  - Comprehensive study of production and decay cross sections
- Interpretations are becoming increasingly sophisticated:
  - Simplified Template Cross Section, Effective Field Theories
- Run 3 doubles the dataset – increased ability to measure rare Higgs production and decay modes, measurements becoming more and more differential
- Early Run 3 measurements promise an invigorating Run 3 program!
- Keep an eye out for new discoveries: $\mathrm{H} \rightarrow Z\gamma$!