# Higgs Physics

## End Game

Saturday May 20, 2023 — Patrick Bryant — Mel Fest

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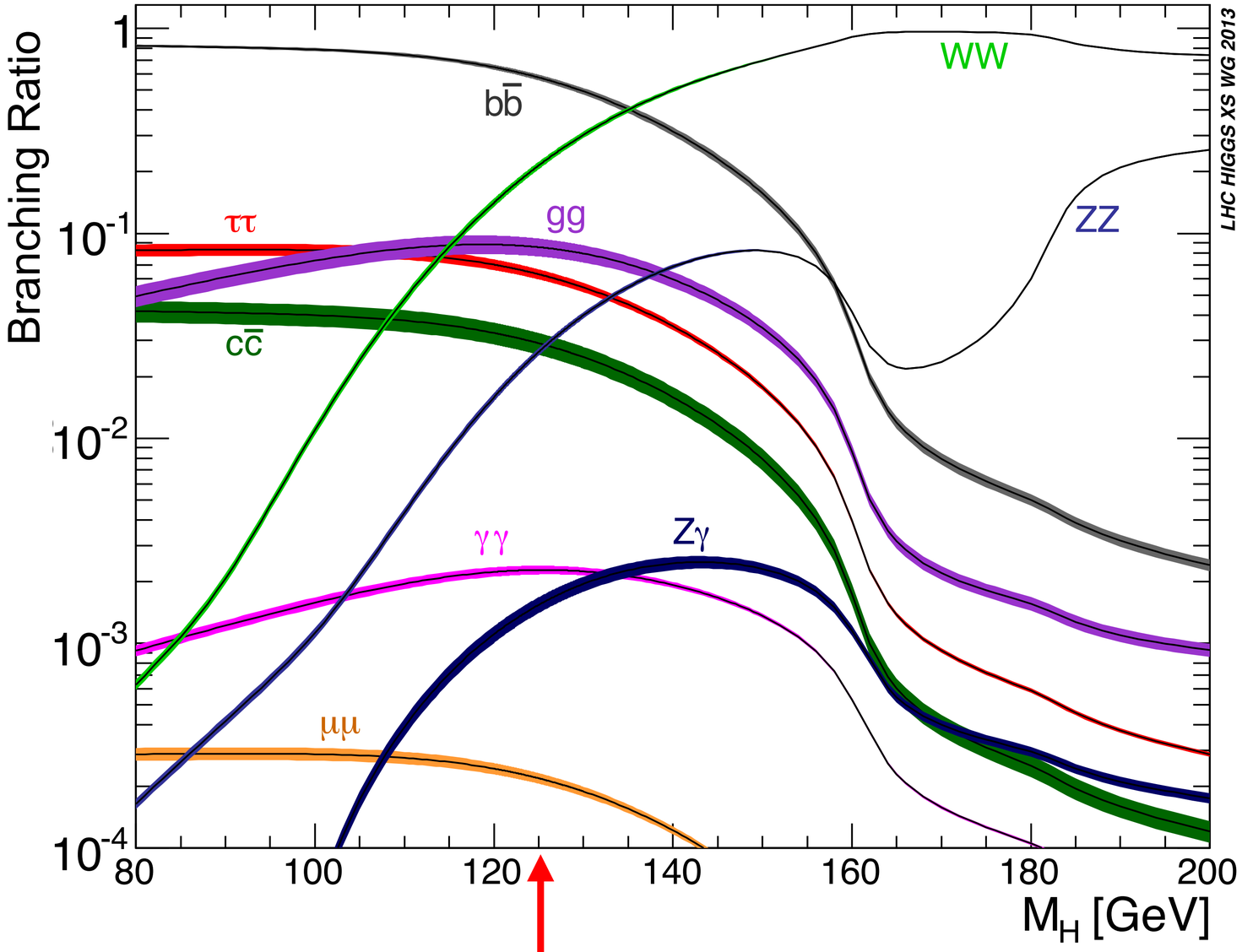
Starting in September

Saturday May 20, 2023 — Patrick Bryant — Mel Fest

# Higgs Physics

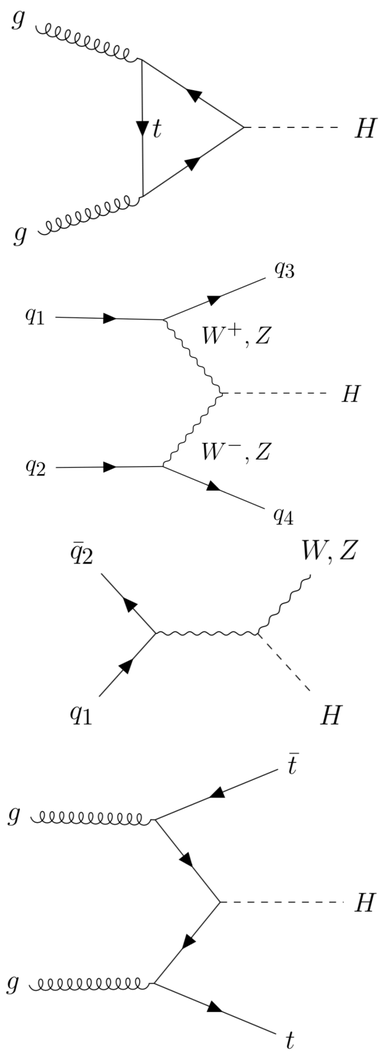


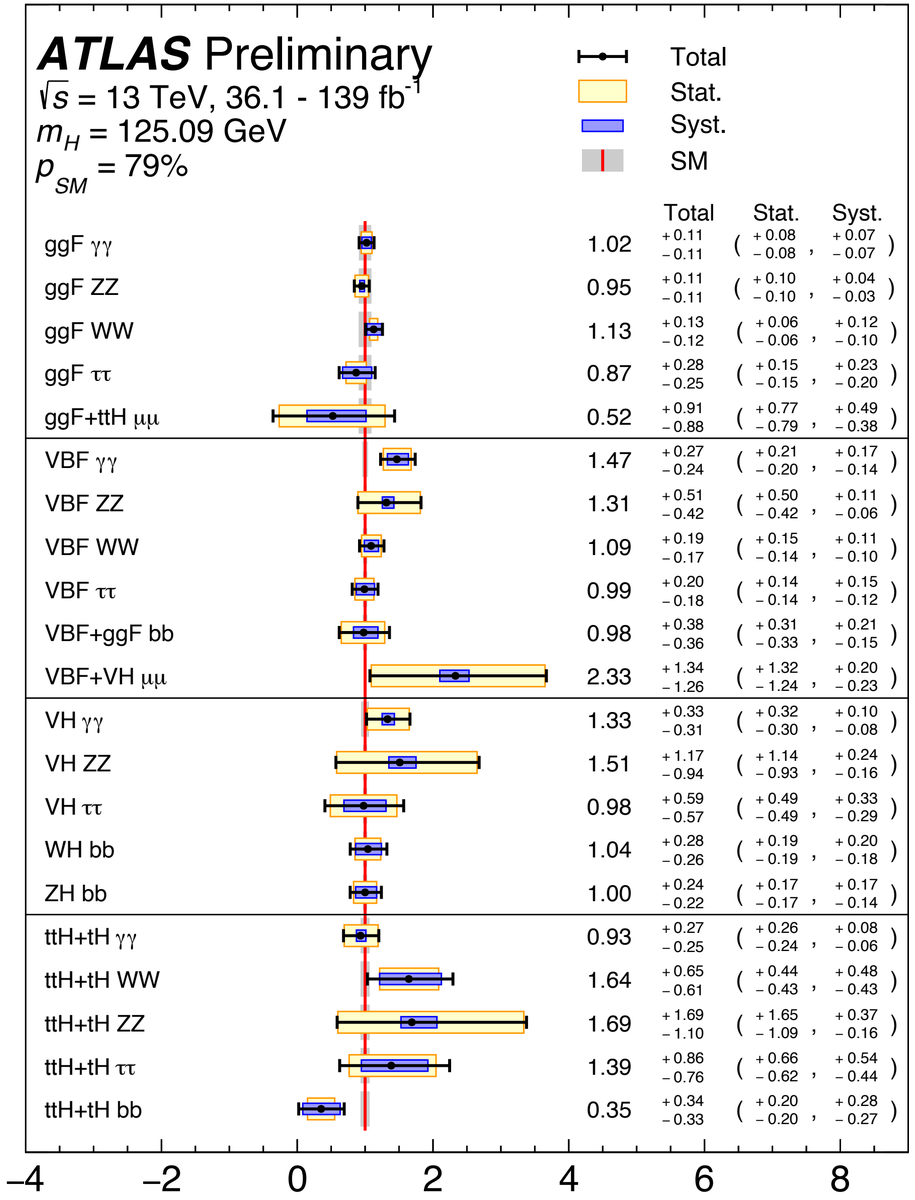

observed $m_H$=125 GeV

- Observed 'Higgs like' boson in phenomenological sweet spot
  - A little lighter → bosonic decays suppressed
  - A little heavier → fermionic decays suppressed

# Higgs Physics

- So many fun things to measure!
  - Observed four primary production modes and five decay modes

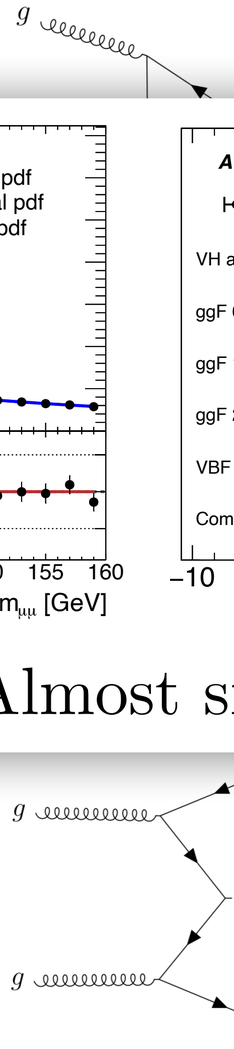


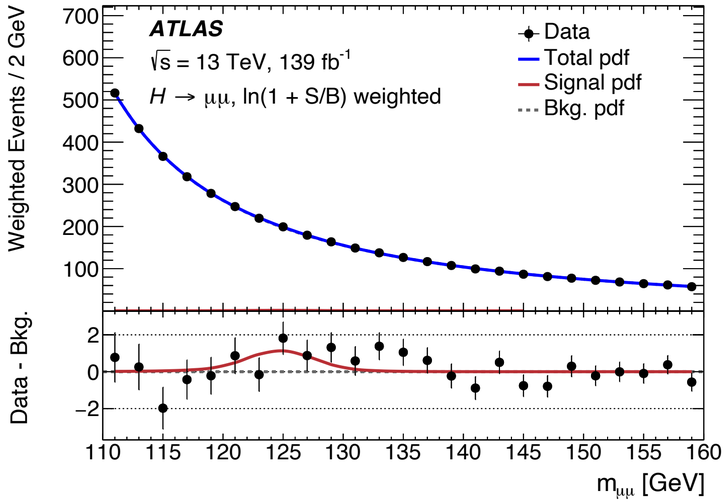



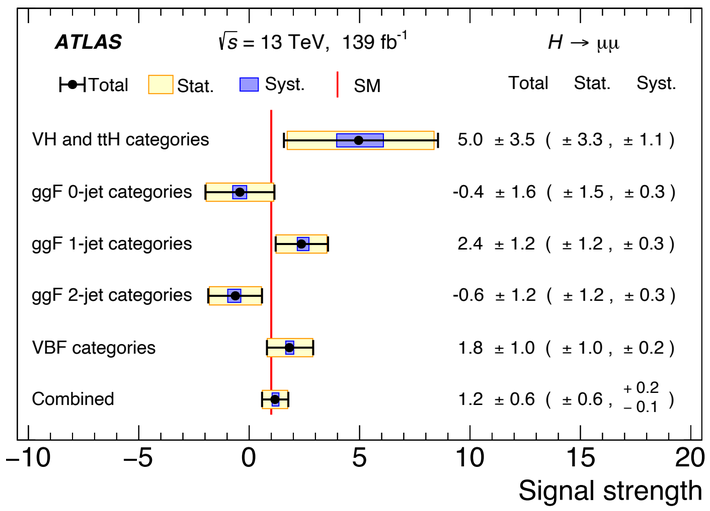

ATLAS-CONF-2021-053

# Higgs Physics

- So many fun things to measure!
  - Observed four primary production m
    decay modes

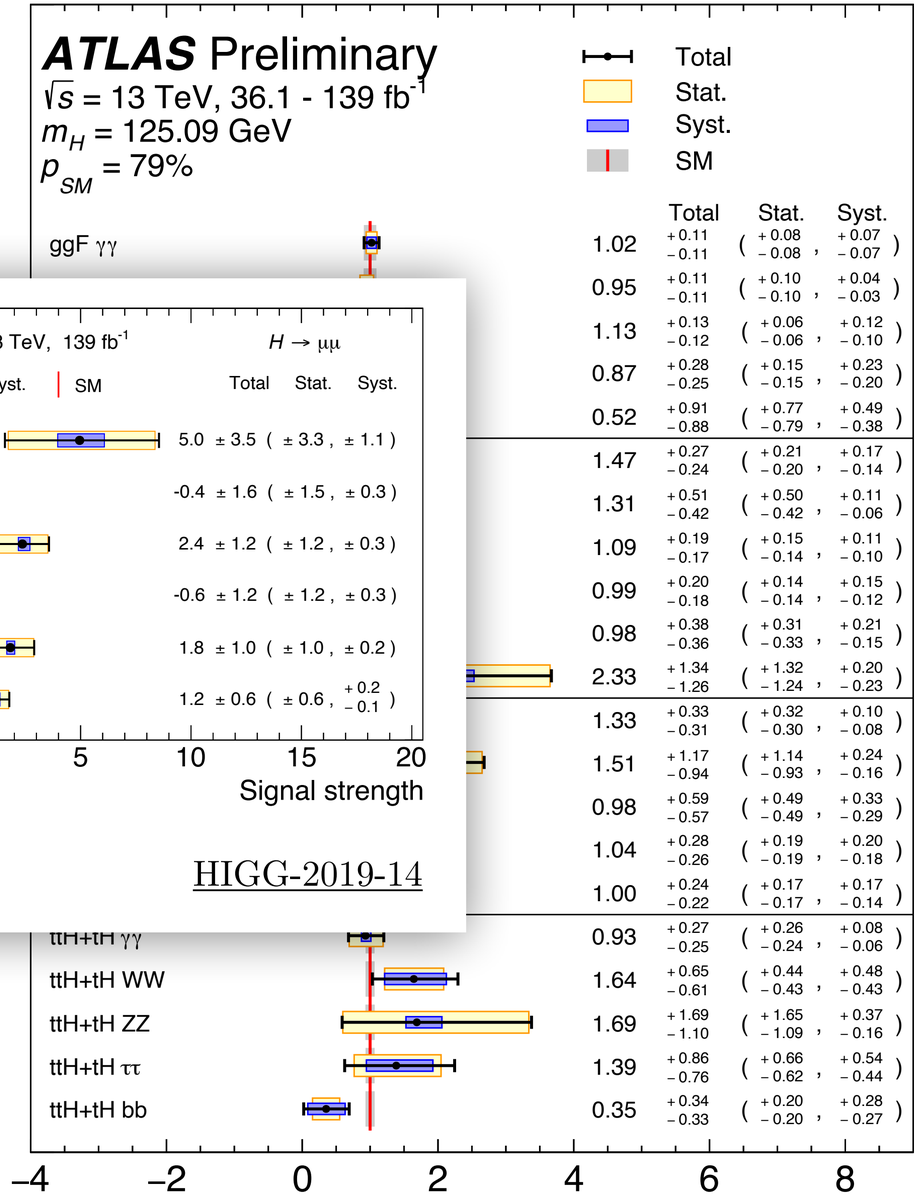



*Almost six!

HIGG-2019-14

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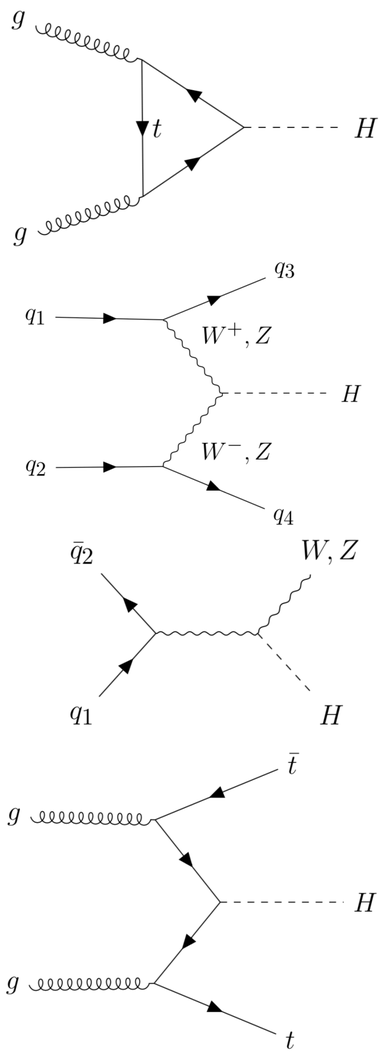
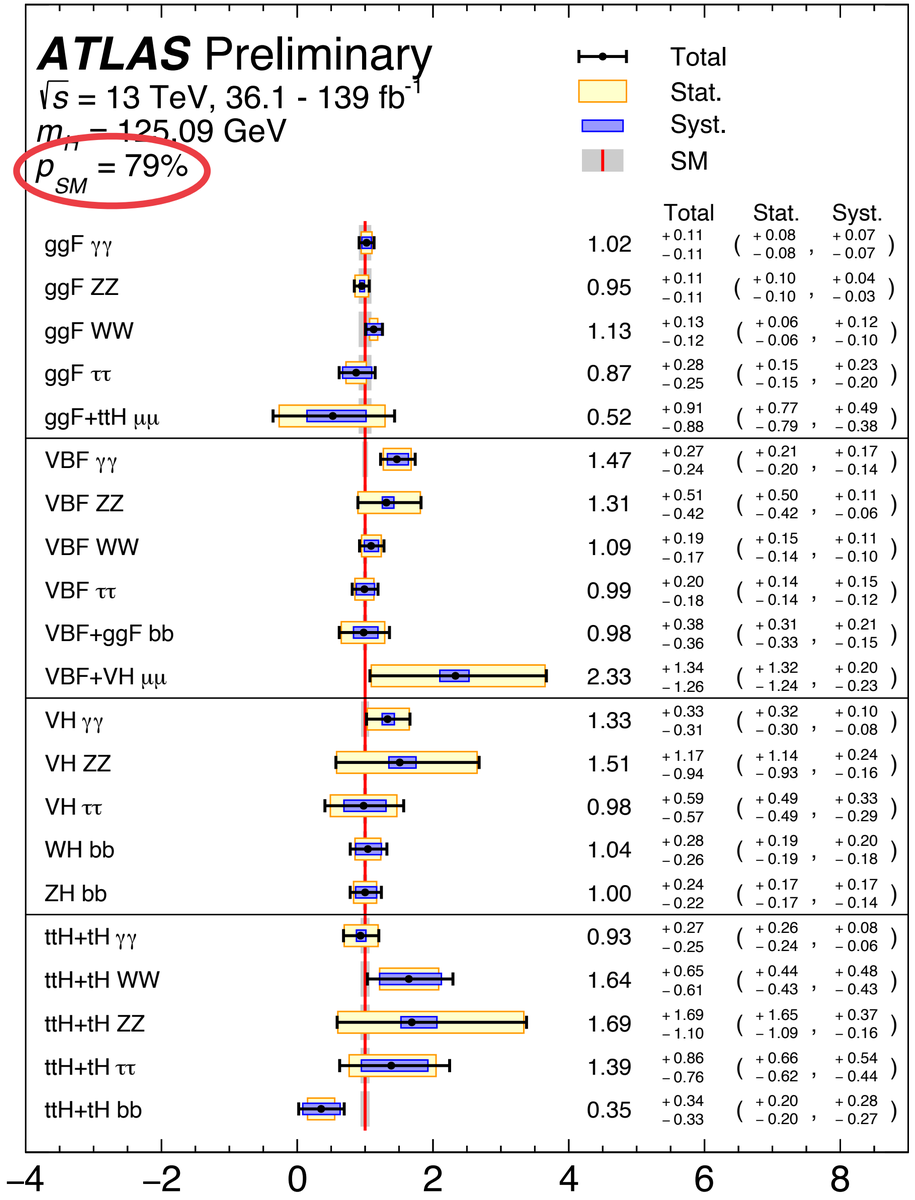
# Higgs Physics

- So many fun things to measure!
  - Observed four primary production modes and five* decay modes
  - Very ‘Higgs like’



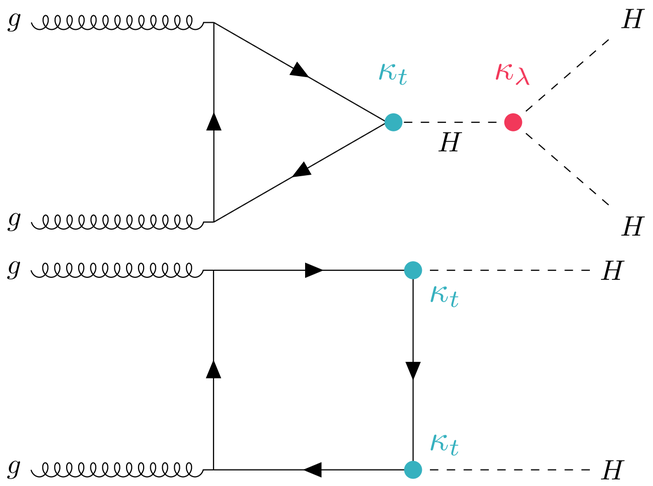

ATLAS-CONF-2021-053

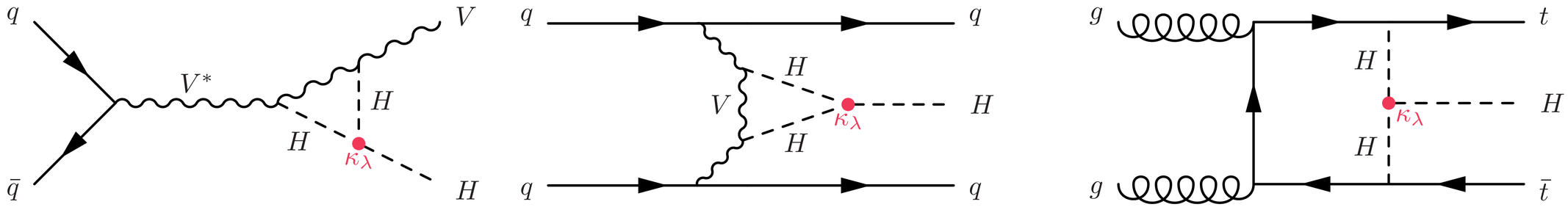
# Higgs Physics

- Four parts of the Higgs mechanism to check:
  - Higgs self-coupling
  - Higgs total width
  - Higgs to invisible
  - Yukawa CP violation

# Higgs Self-Coupling

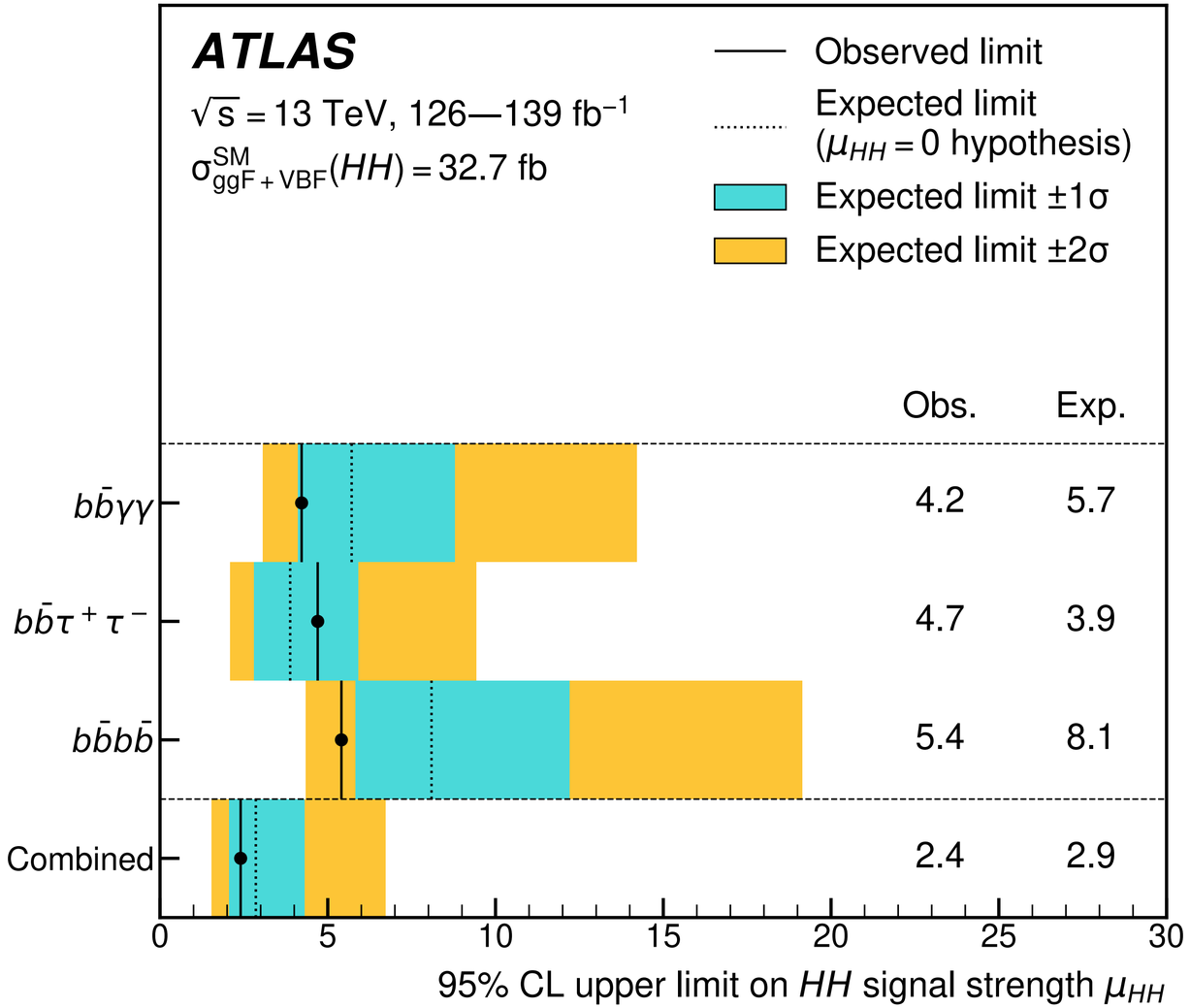
- Standard HH measurements combined with all single H measurements



# Higgs Self-Coupling

- $b\bar{b}\gamma\gamma$, $b\bar{b}\tau\tau$, $b\bar{b}b\bar{b}$ remarkably competitive!



# Higgs Self-Coupling

- $b\bar{b}\gamma\gamma$, $b\bar{b}\tau\tau$, $b\bar{b}b\bar{b}$ remarkably competitive!
  - Standard candles for $b\bar{b}\tau\tau$, $b\bar{b}b\bar{b}$, critical for anyone to believe results

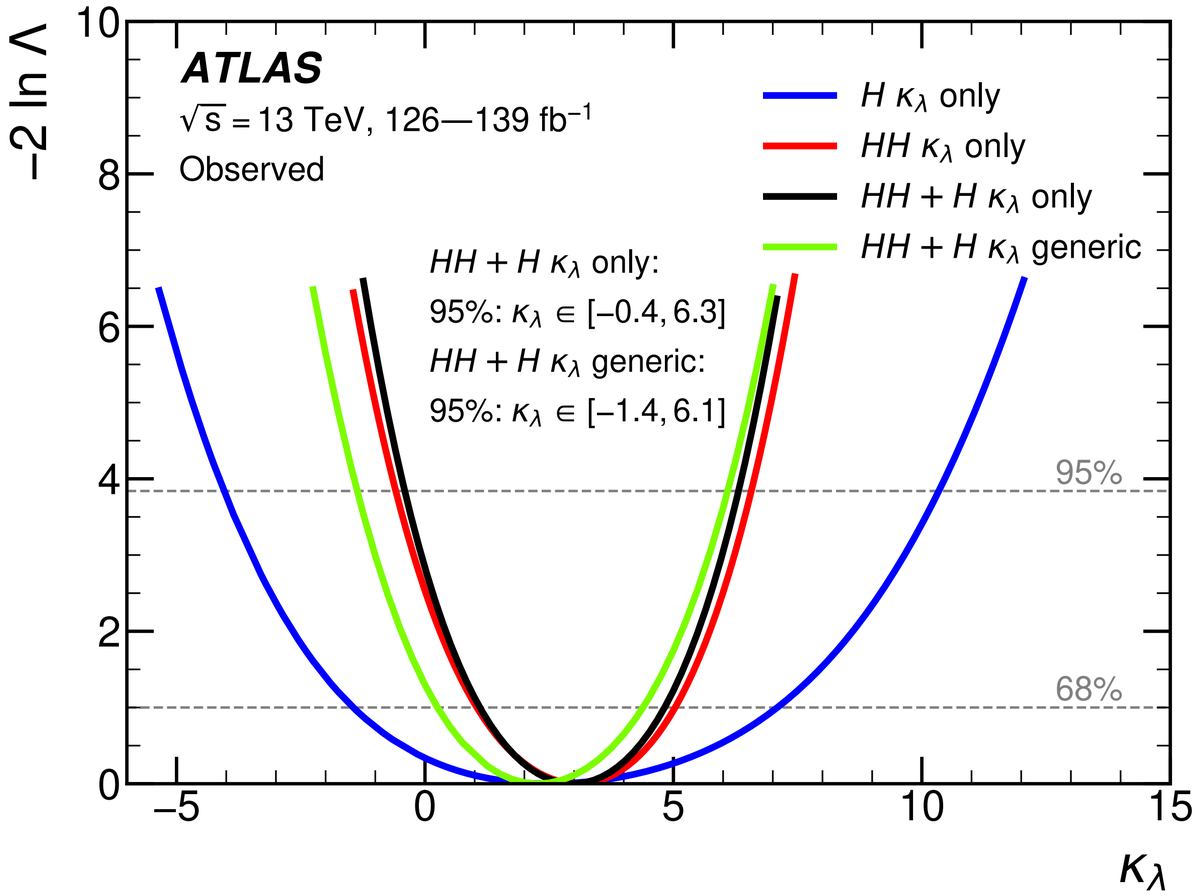
$$\frac{\sigma(pp \to ZZ \to b\bar{b}b\bar{b})}{\sigma(pp \to HH \to b\bar{b}b\bar{b})} \approx 31 \qquad \frac{\sigma(pp \to ZZ \to b\bar{b}\tau\tau)}{\sigma(pp \to HH \to b\bar{b}b\bar{b})} \approx 63$$

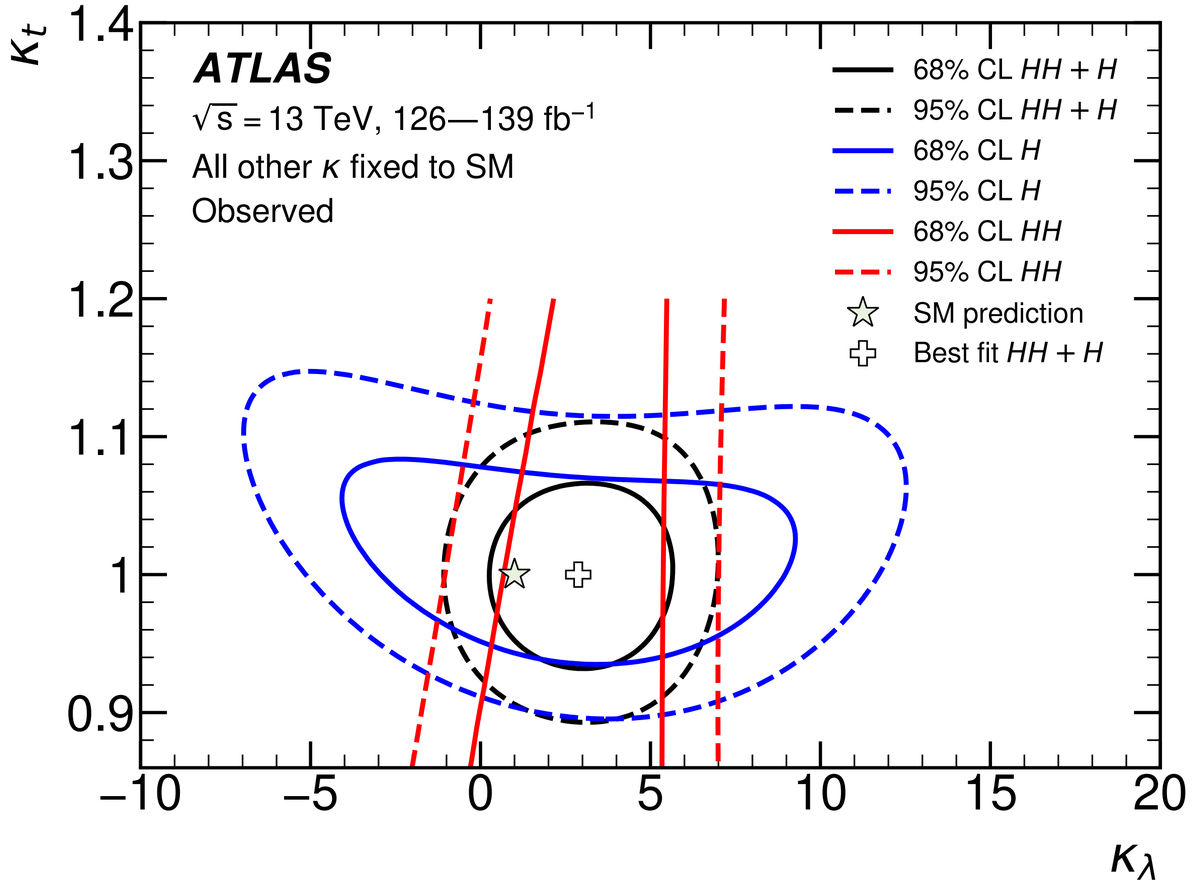
$$\frac{\sigma(pp \to ZH \to b\bar{b}b\bar{b})}{\sigma(pp \to HH \to b\bar{b}b\bar{b})} \approx 7 \qquad \frac{\sigma(pp \to ZH \to b\bar{b}\tau\tau)}{\sigma(pp \to HH \to b\bar{b}b\bar{b})} \approx 13^*$$

$^*\left(3.5[b\bar{b}\tau\tau] + 9.7[\tau\tau b\bar{b}]\right)$

# Higgs Self-Coupling

- Combination with single H measurements mostly serves to constrain $\kappa_t$



# Higgs Width

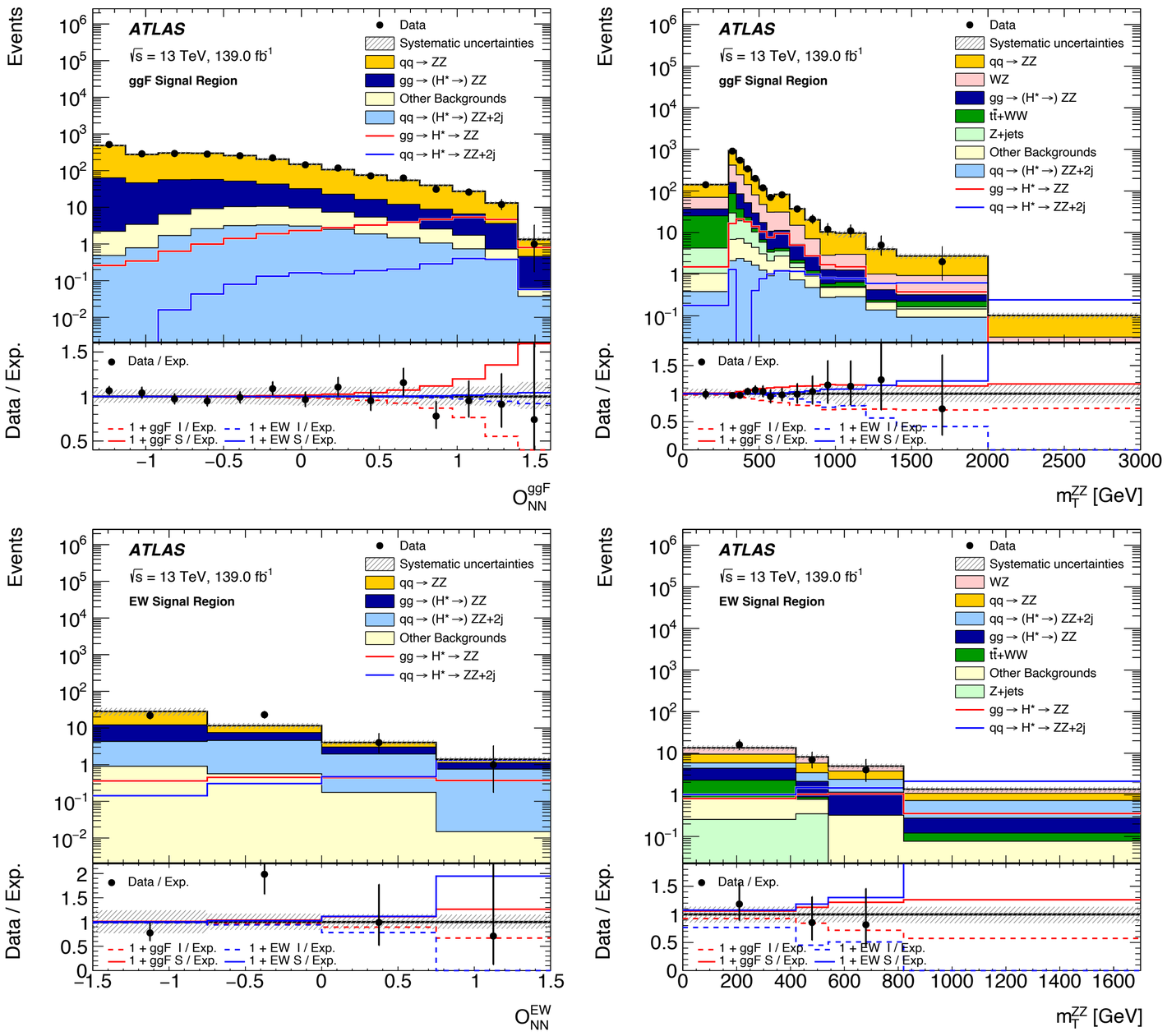
- Any new couplings can change width, particularly BSM decay modes which may be hard to observe directly
  - Direct measurement is hopeless
  - Rely on ratio of off/on-shell cross section, some model dependence

$$\frac{\sigma^{\text{off-shell}}_{gg\to H\to ZZ}}{\sigma^{\text{on-shell}}_{gg\to H\to ZZ}} \propto \frac{\Gamma_H m_H}{m_{ZZ}^2} \times f\left(\text{scale dependence of HZZ and ggH couplings}\right)$$

# Higgs Width

HIGG-2018-32

- Precision calculations of non-resonant ZZ cross section
  - NLO QCD k-factors as function of $m_{ZZ}$ 1.5-2
  - N3LO QCD norm k-factor 1.32
  - Impressive to find 3$\sigma$ evidence of an effect which is smaller than these k-factors



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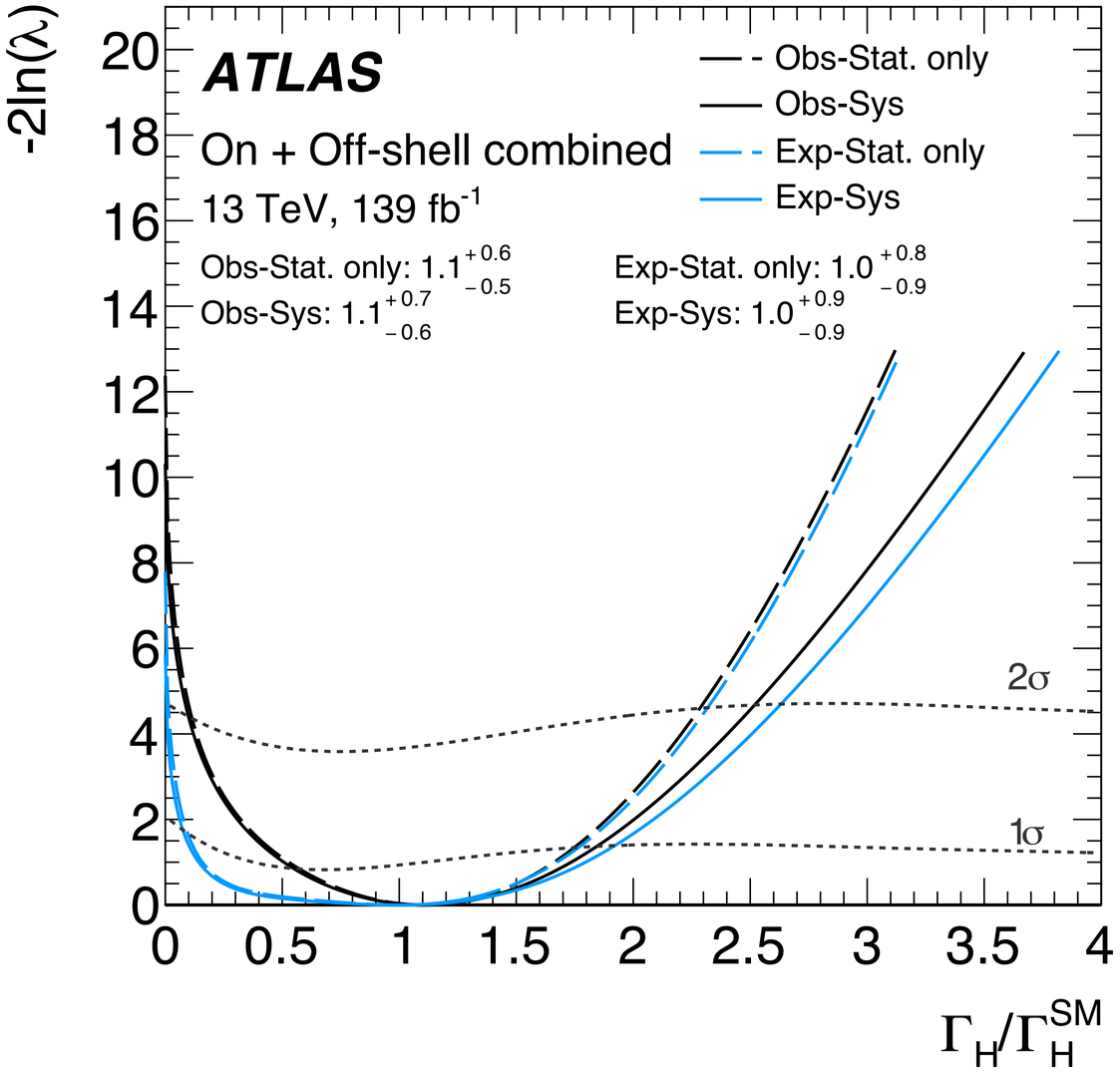
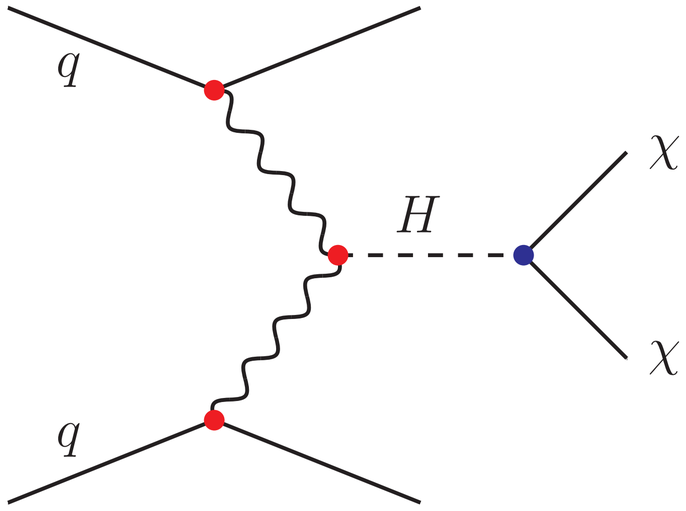
HIGG-2018-32



# Higgs → Invisible

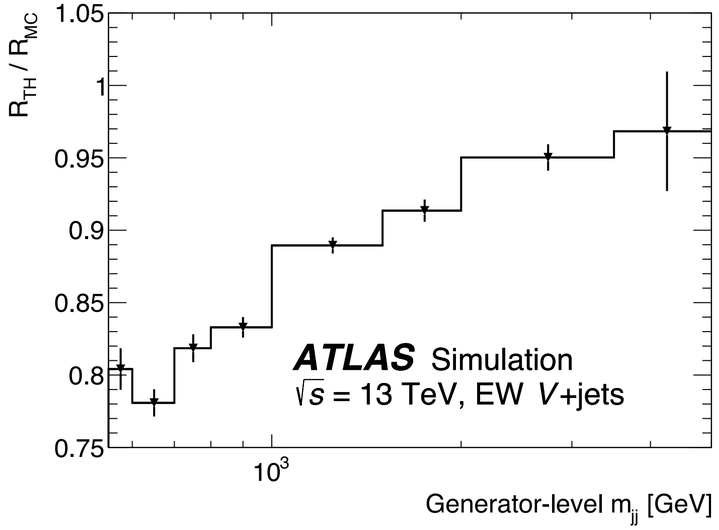
- Combination of visible Higgs decays gives indirect and model dependent constraint on BSM Higgs to invisible BR.
  - Direct search in VBF production gives strongest constraint

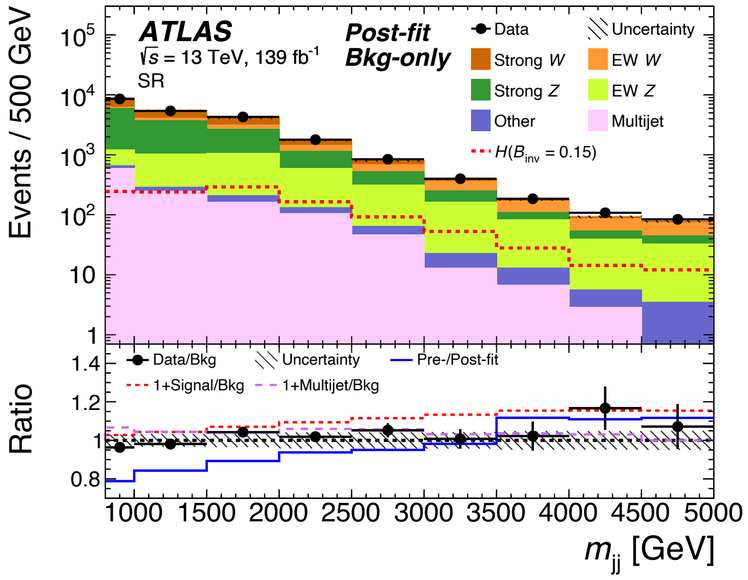


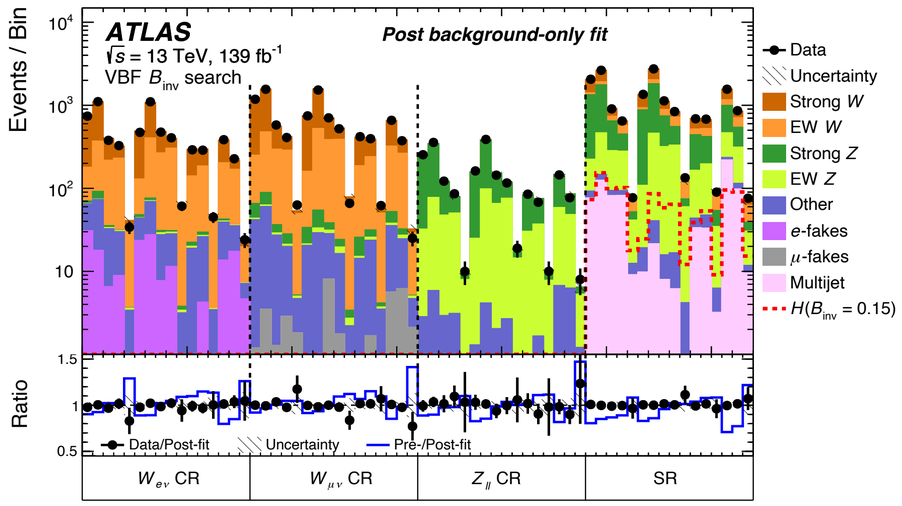
# Higgs → Invisible

EXOT-2020-11

- Another impressive measurement relying on large theory k-factors
  - In this case double ratio of EW Z/W+jets vs $m_{jj}$



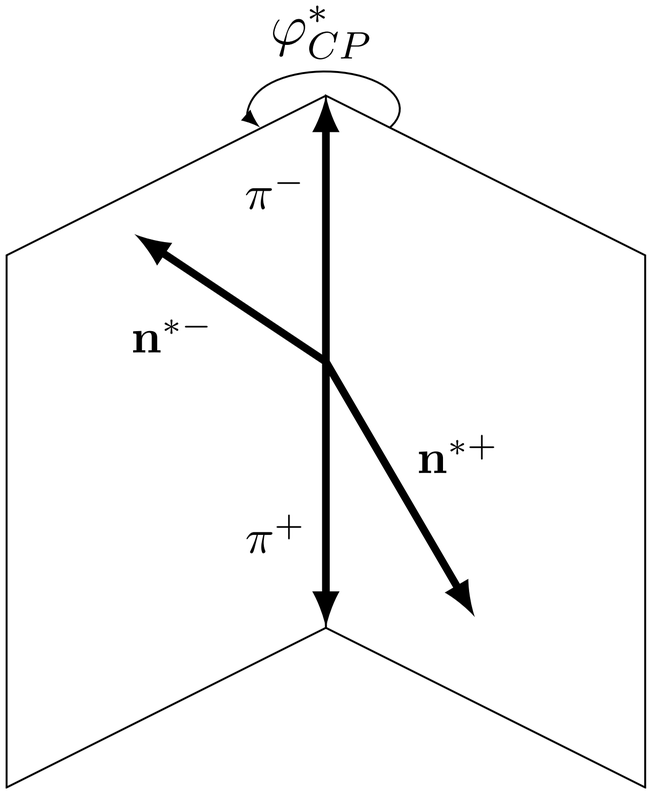



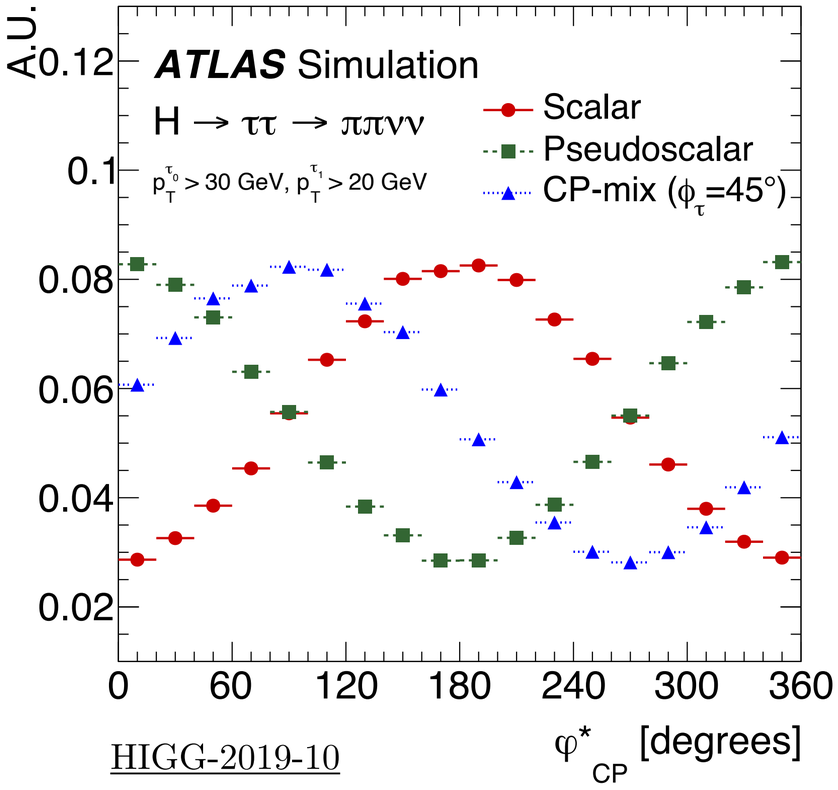




| Observed | Expected | $+1\sigma$ | $-1\sigma$ | $+2\sigma$ | $-2\sigma$ |
|---|---|---|---|---|---|
| 0.145 | 0.103 | 0.144 | 0.075 | 0.196 | 0.055 |

# Yukawa CPV

- Tree level CP Violation is possible in Yukawa couplings
  - CPV in gauge couplings is suppressed by $\Lambda^{-2}$
  - $H \to \tau\tau$ is the only option at the LHC



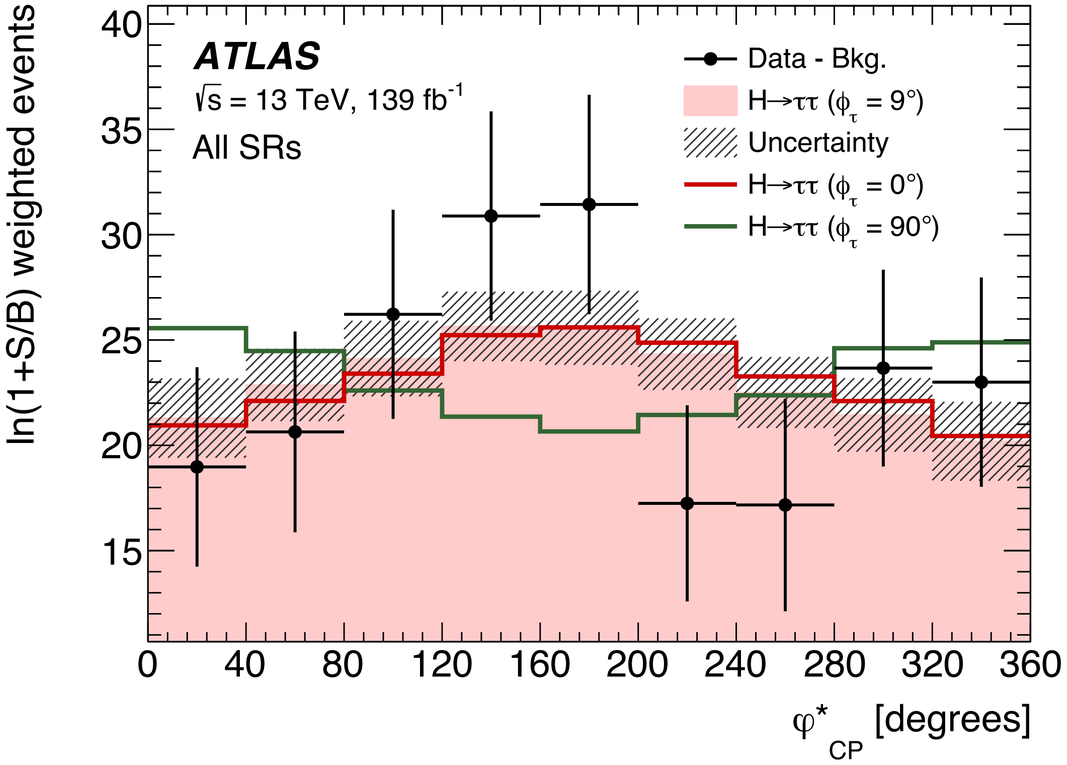



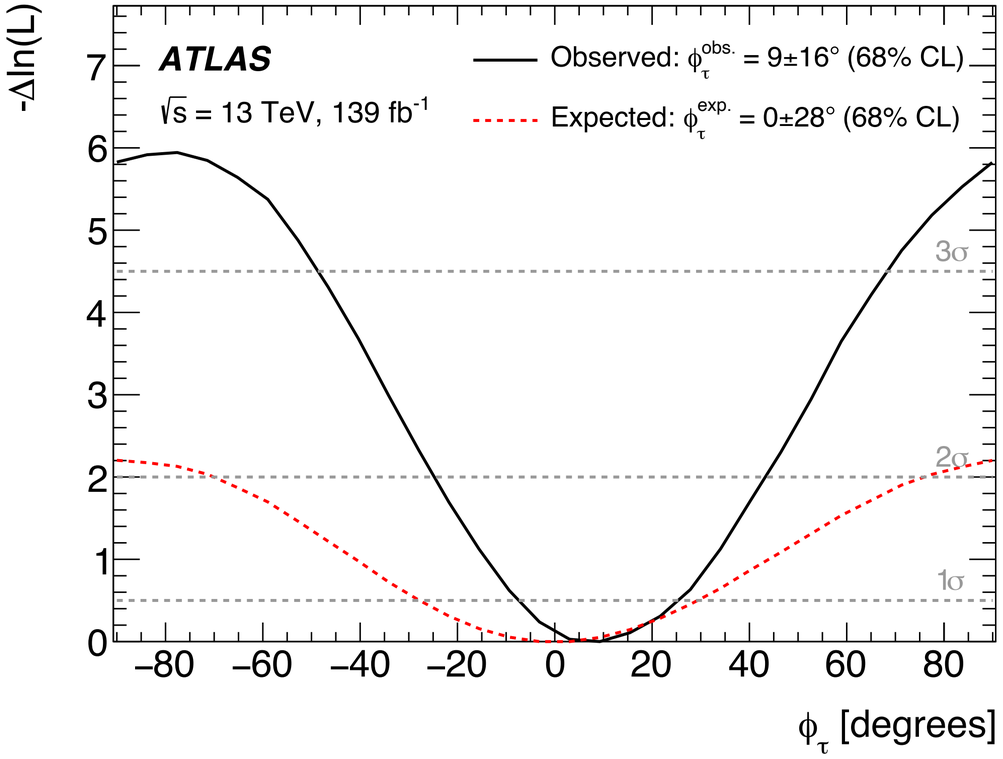

HIGG-2019-10

# Yukawa CPV

- Pure CP-odd hypothesis disfavored at $3.4\sigma$
  - 10 different combinations of $\tau$ decay modes, 16 signal regions

HIGG-2019-10




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

# Conclusions

- Incredibly rich Higgs phenomenology made possible by $m_{\mathrm{H}} = 125\,\mathrm{GeV}$
- Huge combination of measurements consistent with SM Higgs
  - LHC beginning to constrain:
    - Self-coupling
    - Width
    - BR(H→Inv.)
    - Yukawa CP violation
- My money is on SM Higgs
  - If you have to retire and do something else, now is the time


ATLAS