



**University of  
Zurich<sup>UZH</sup>**



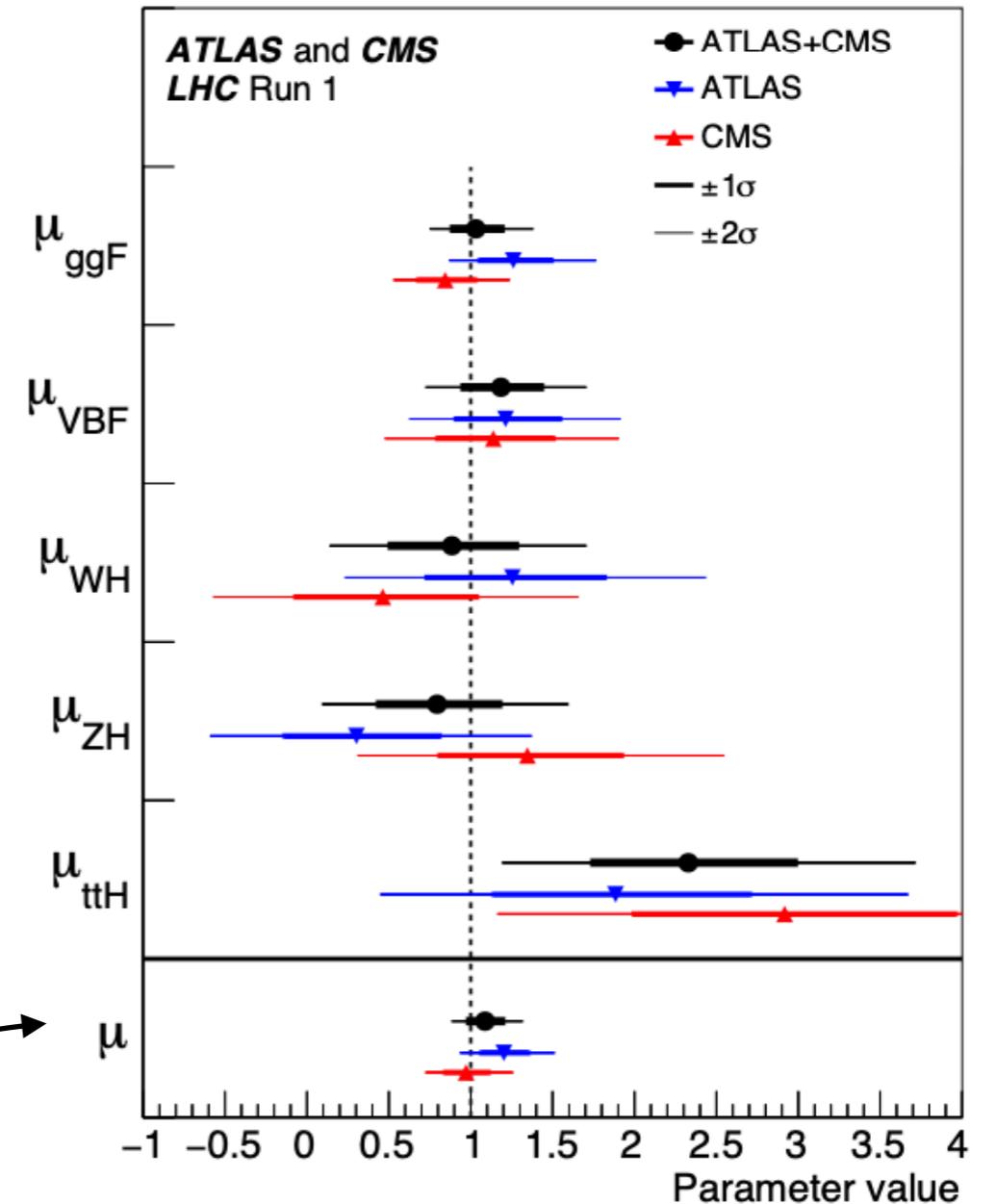
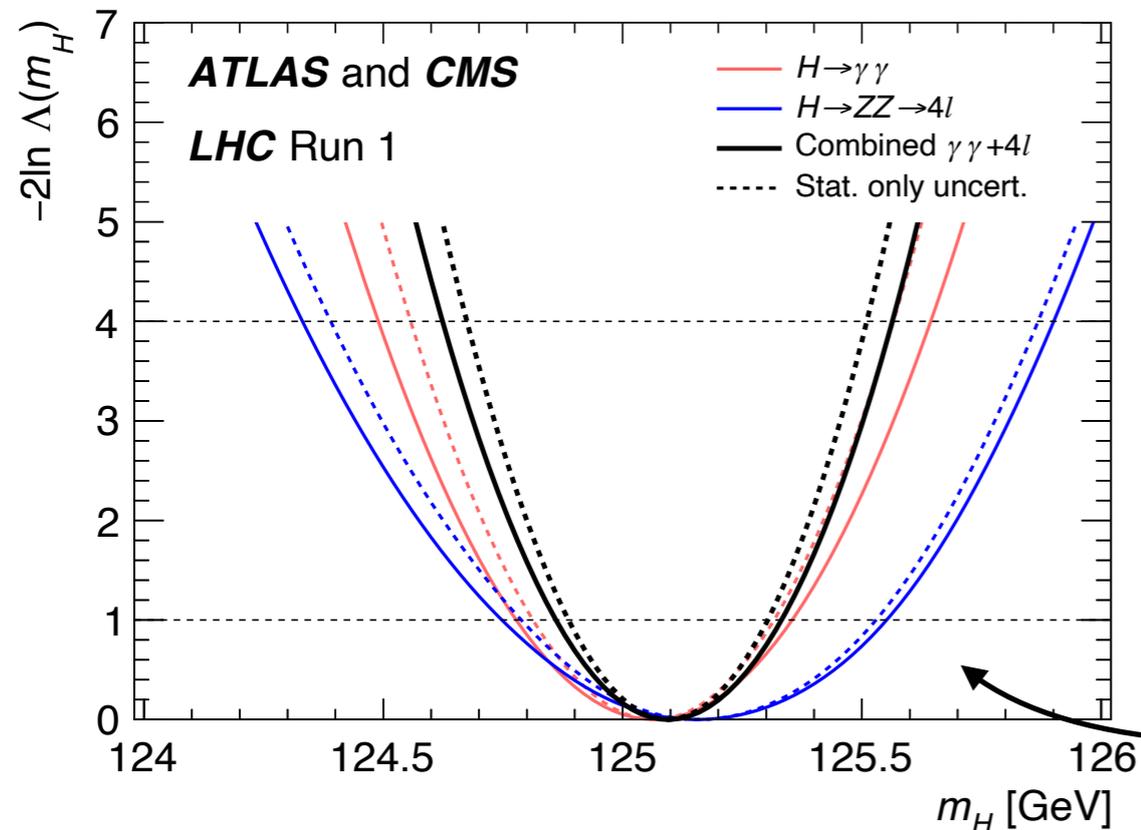
# Higgs boson production cross sections and couplings

**Higgs@10**

**A. de Wit on behalf of the ATLAS and CMS collaborations**

# Introduction & overview

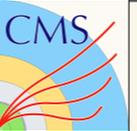
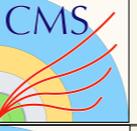
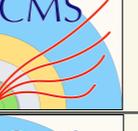
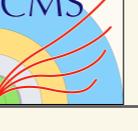
- What have we learned from 10 years of studying the Higgs boson?
- Focus on **production cross sections & couplings** from **combined measurements** with Run 2 data
- Results from both ATLAS and CMS



ATLAS + CMS Run 1 combined measurements - signal strengths, mass

# Combined measurements: ingredients

- Individual analyses study **specific** Higgs boson characteristics  
 → need to **combine** them to get a **full view** of the Higgs boson
- Targeted signatures **included in combined measurements:**

	ggH		qqH		VH		ttH/tH	
$H \rightarrow \gamma\gamma$								
$H \rightarrow ZZ$								
$H \rightarrow WW$								
$H \rightarrow \tau\tau$								
$H \rightarrow bb$								
$H \rightarrow \mu\mu$								
$H \rightarrow cc$								
$H \rightarrow Z\gamma$								
$H \rightarrow \text{inv}$								

Most of the main production x decay channels included

Note: some additional channels not yet included in combined measurements

← Rare decay modes starting to feature in combined measurements

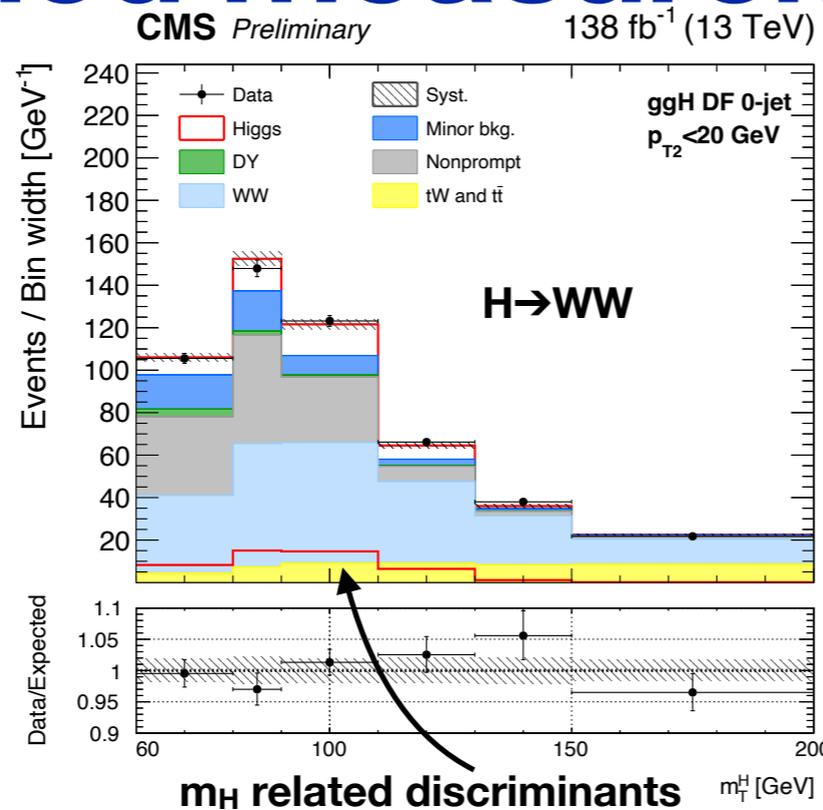
← Searches for invisible H decays (for coupling strengths)

# Combined measurements: ingredients

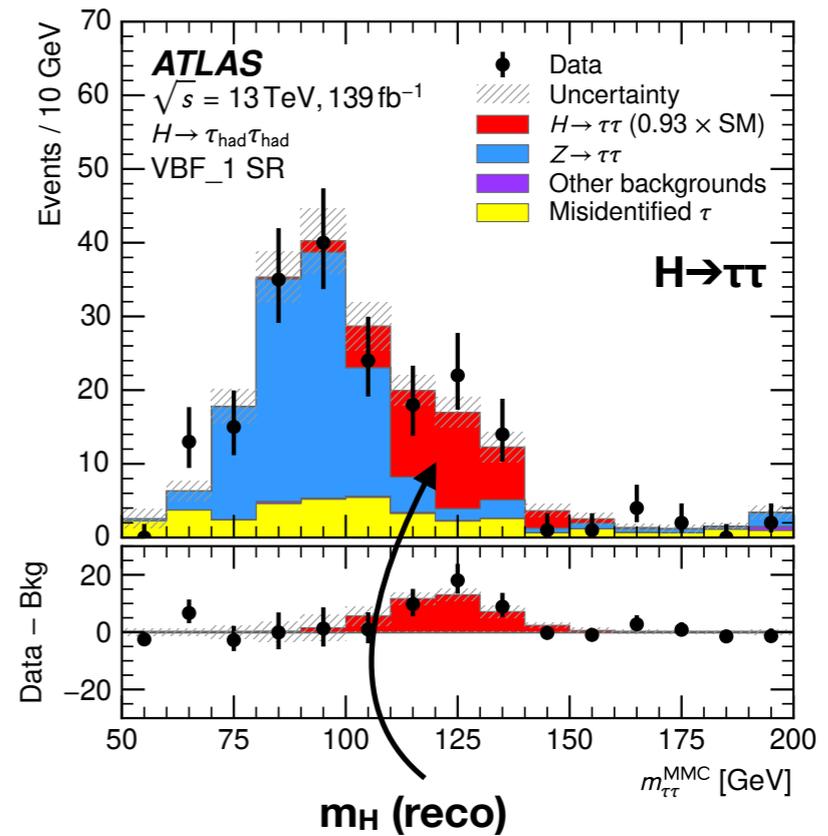
Measurements in many decay channels included  $\rightarrow$  range of analysis techniques

- S/B discrimination, classification
  - S/B separating variables
  - BDT, DNN
  - Matrix element

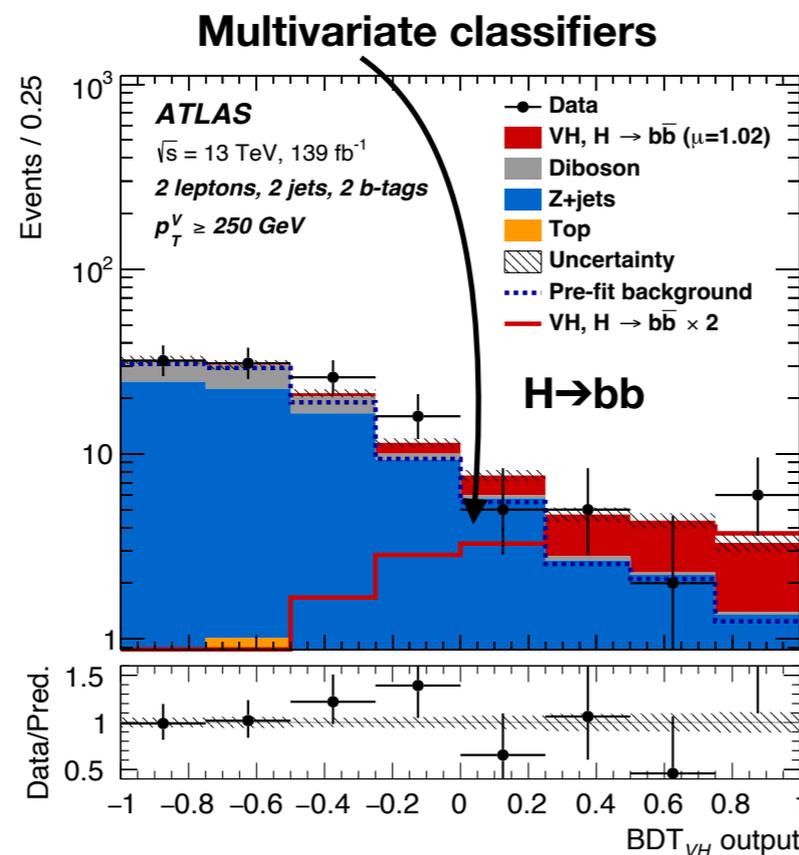
- Background estimation
  - Data sidebands
  - Data/simulation mixture



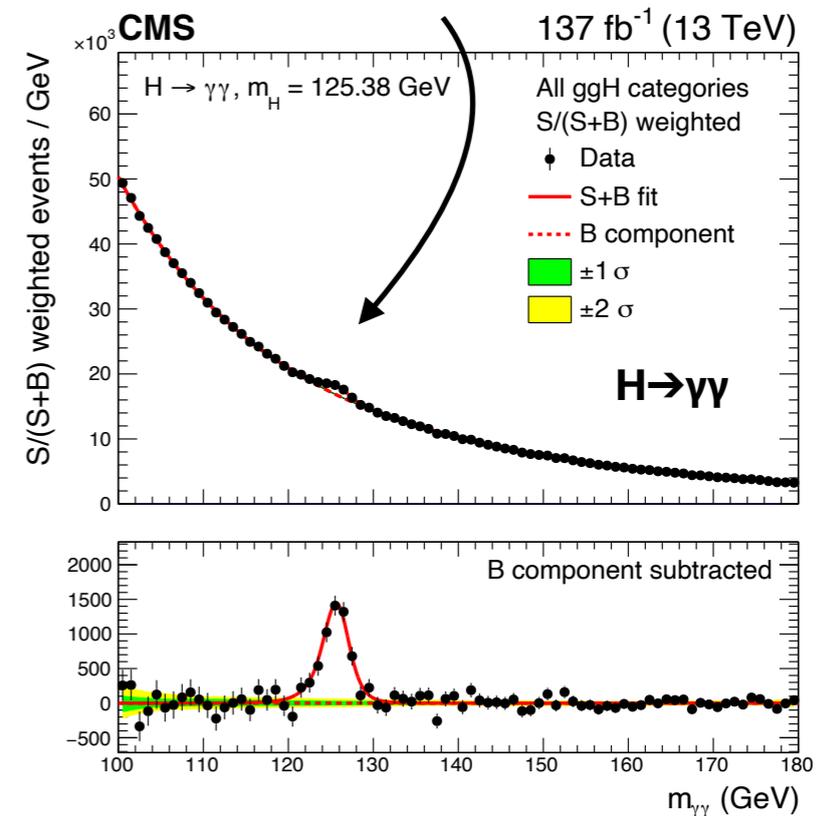
arXiv: (sub. to EPJ C)



arXiv:2201.08269 (sub. to JHEP)



Eur. Phys. J C 81 (2021) 178



JHEP 07 (2021) 027

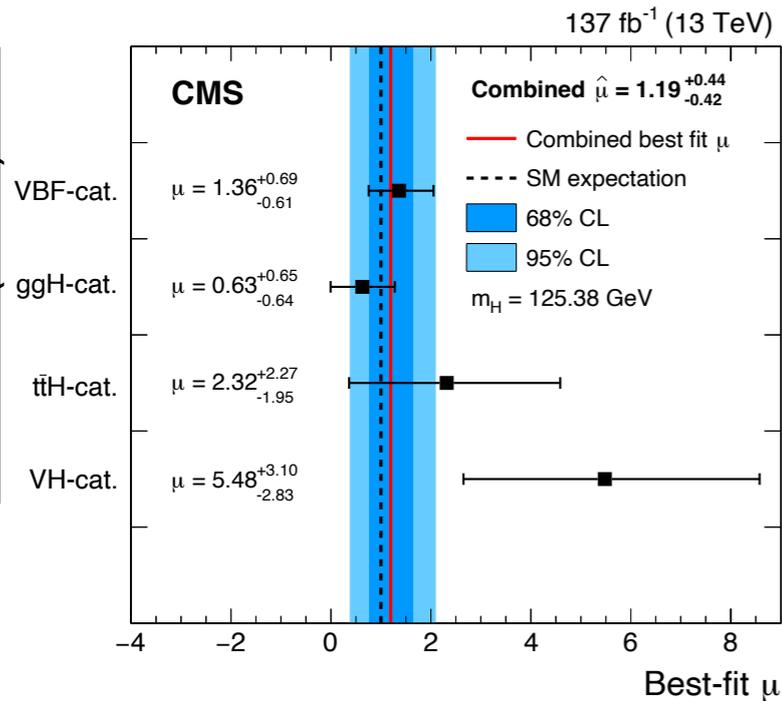
# Cross section measurements

(Inclusive) signal strength or cross section

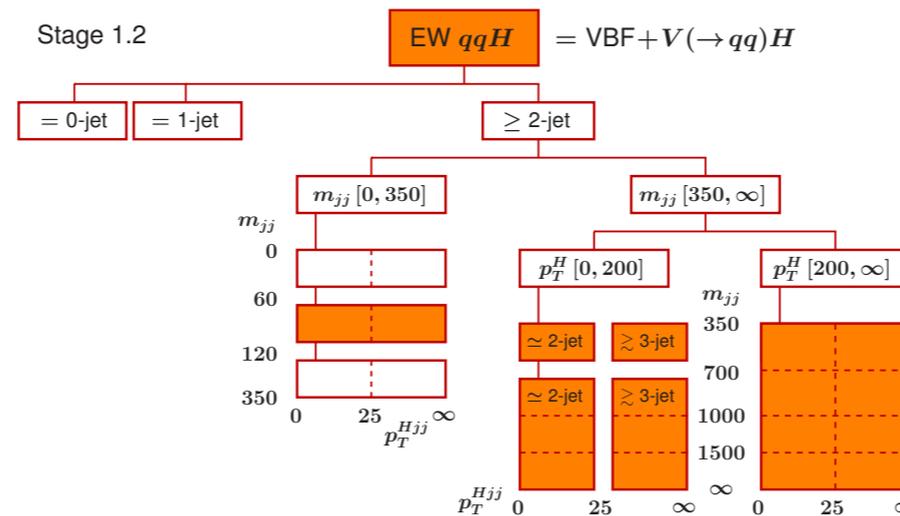
Simplified template cross sections

Differential, fiducial measurements

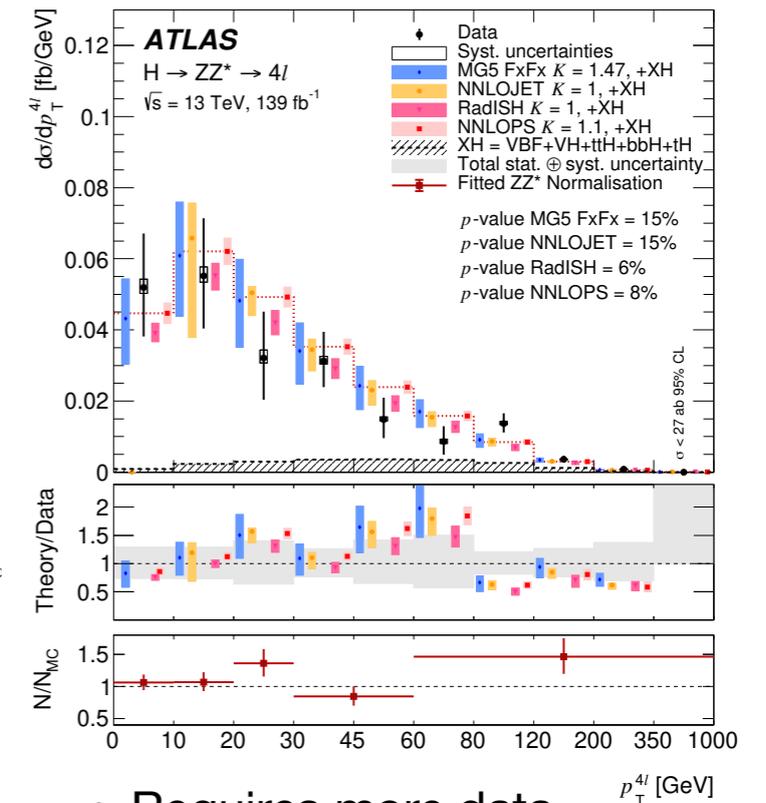
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- First quantity to measure when establishing a channel
- Still powerful with more data: **global** effects



- Requires more data
- Maximise BSM sensitivity / minimising theory dependence → Theory + experiment common ground
- Exploit many variables simultaneously
- Considers inclusive decays - easier combination of channels



- Requires more data
- Generally with fiducial selection for the decay

EPJC 80 (2020) 942

# NEW Signal strengths, cross sections

- Signal strength modifiers  $\mu$  scale cross sections and branching fractions relative to the SM:

$$\mu_i = \frac{\sigma_i}{\sigma_i^{\text{SM}}} \quad \mu^f = \frac{\mathcal{B}^f}{\mathcal{B}_{\text{SM}}^f} \quad \mu_i^f = \frac{\sigma_i \cdot \mathcal{B}^f}{(\sigma_i \cdot \mathcal{B}^f)_{\text{SM}}} = \mu_i \times \mu^f$$

- Or define a global signal strength scaling all channels:

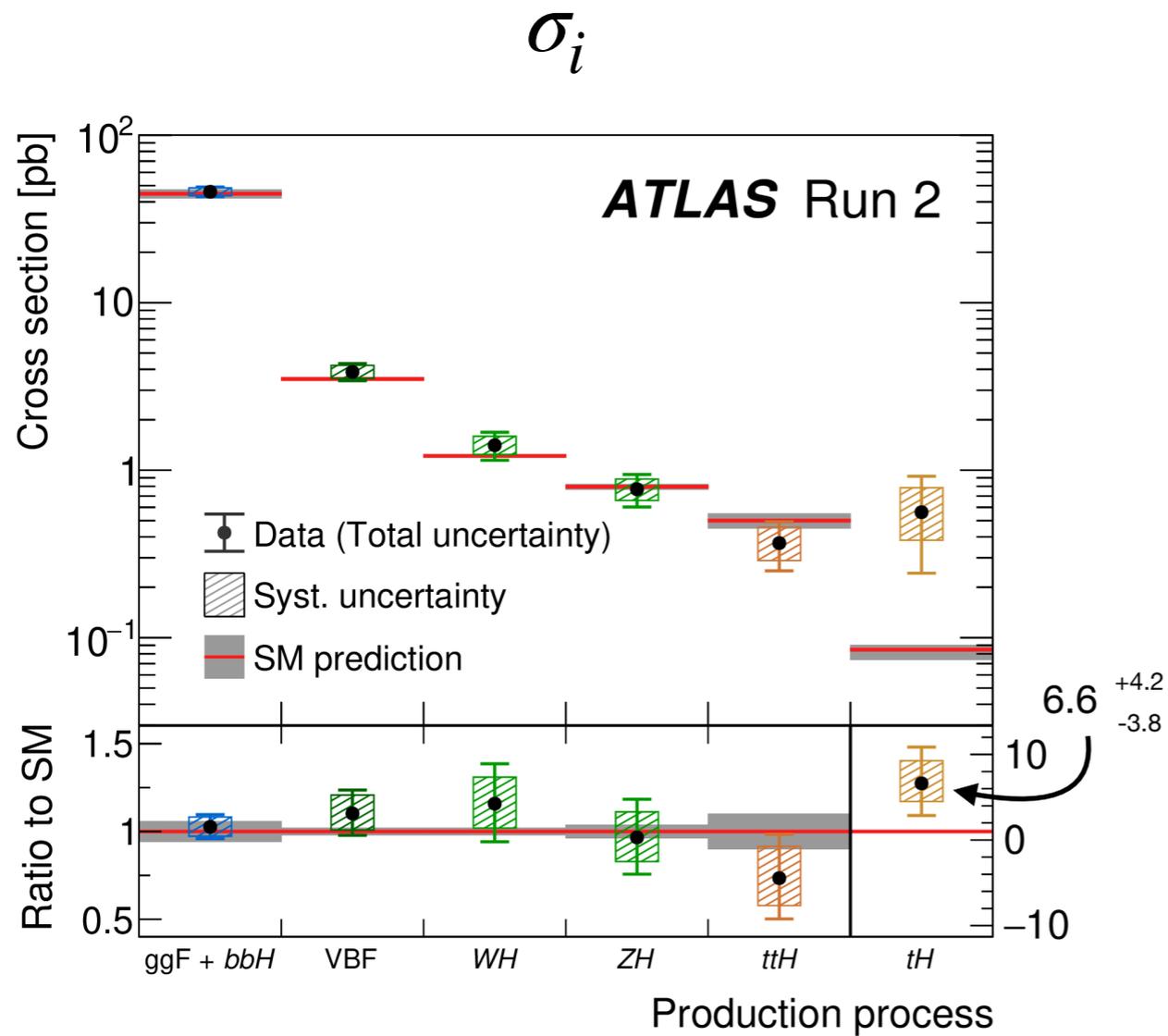
$$\mu = 1.002 \pm 0.057 = 1.002 \pm 0.036 \text{ (theo)} \pm 0.033 \text{ (syst)} \pm 0.029 \text{ (stat)} \quad \text{CMS}$$

$$\mu = 1.05 \pm 0.06 = 1.05 \pm 0.04 \text{ (theo)} \pm 0.03 \text{ (syst)} \pm 0.03 \text{ (stat)} \quad \text{ATLAS}$$

- Improvement in relative precision: 14% (Run 1)  $\rightarrow$  6% (Run 2)
  - Theory uncertainty: 7% (Run 1)  $\rightarrow$  4% (Run 2)

# NEW Production modes

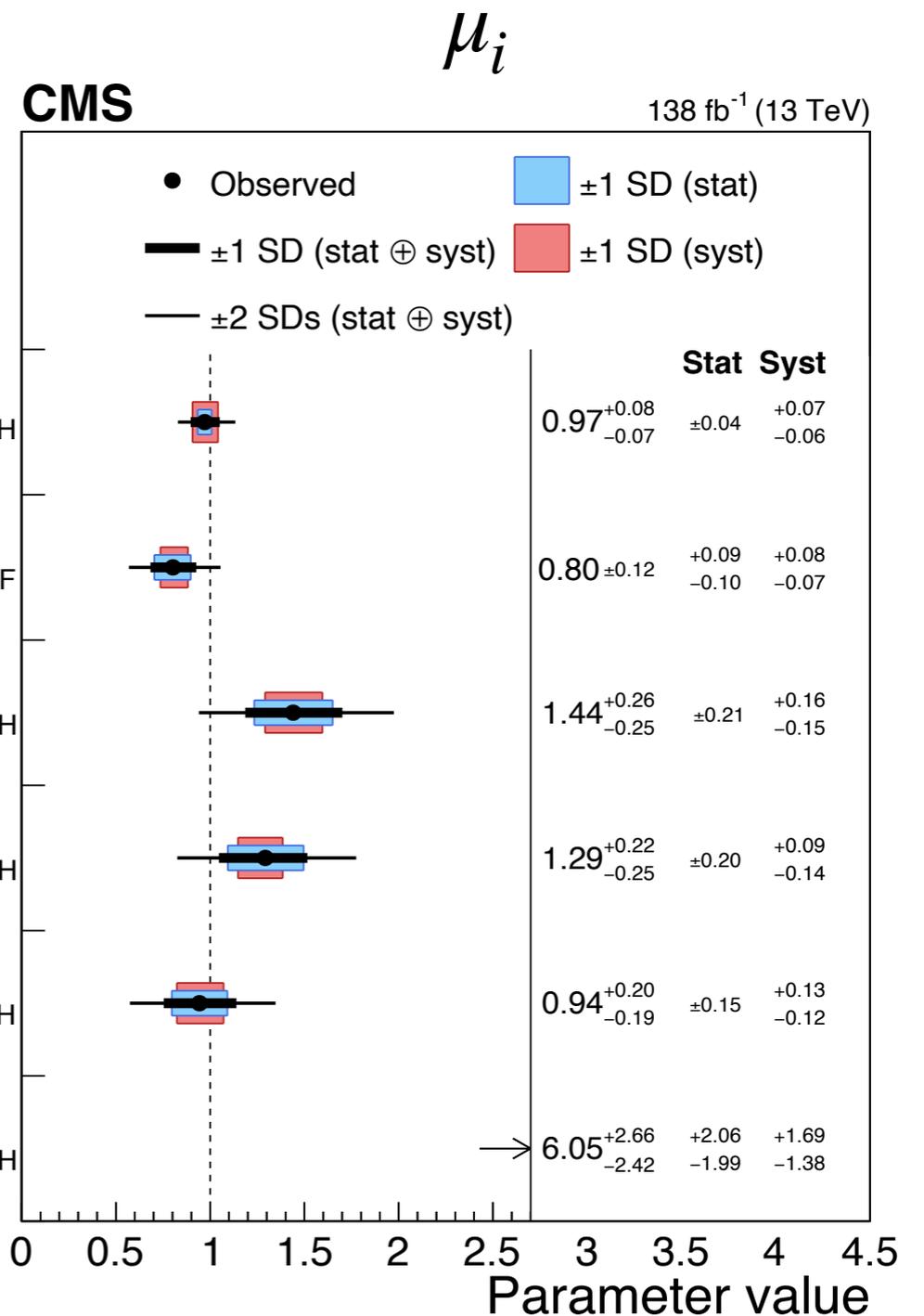
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**gluon-gluon fusion precision better than 10%!**

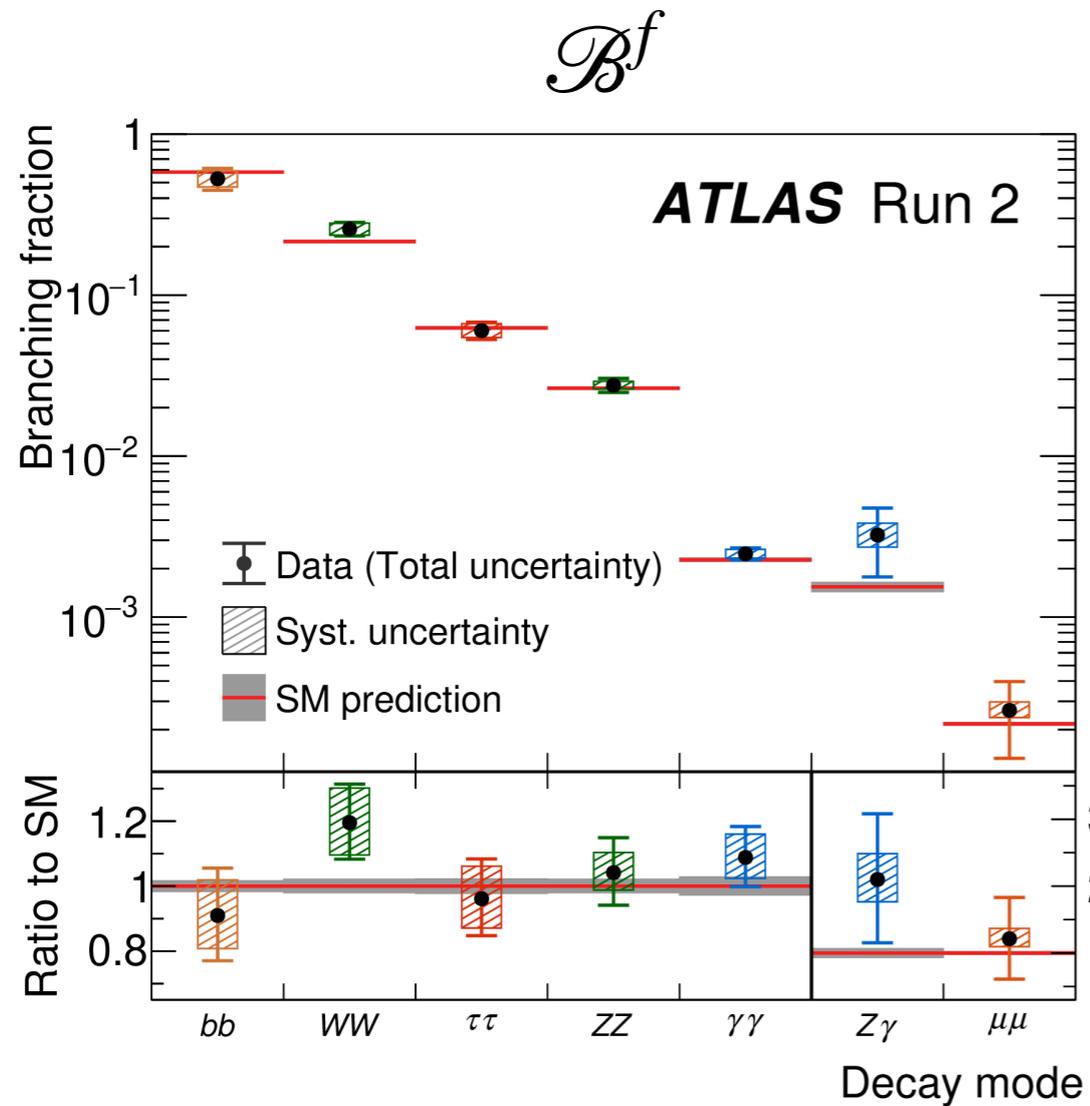
**10-20%** precision on other major production modes

Measurement of  $\sigma_{tH}$   $\rightarrow$  gaining access to rare production modes



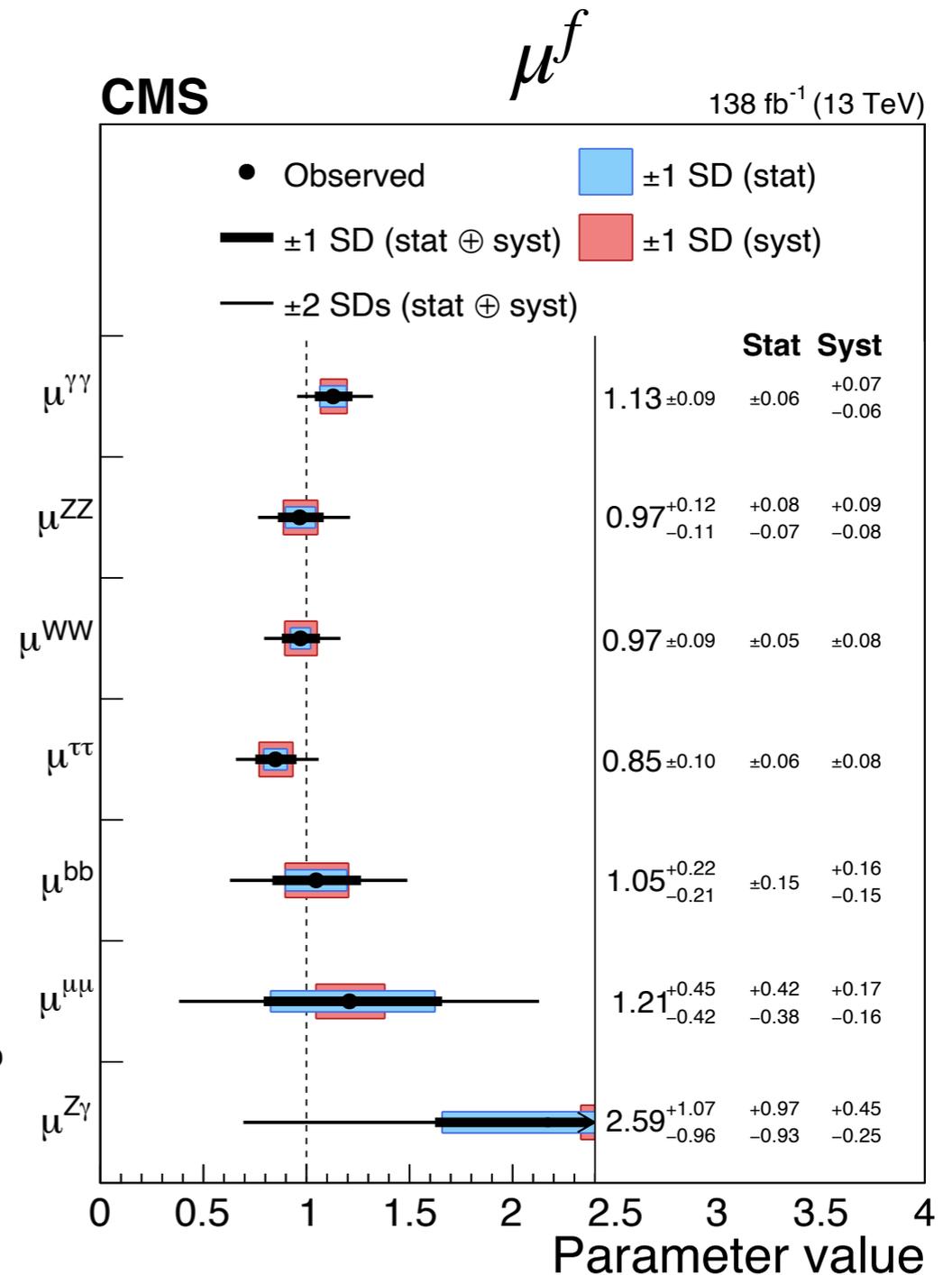
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# NEW Decay channels



Precision on bosonic decays, decays to tau leptons: **~10%**

Uncertainties on rare decay branching fractions ( $\mu\mu$ ,  $Z\gamma$ ) still sizeable



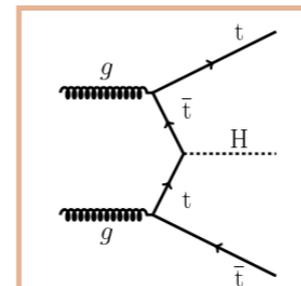
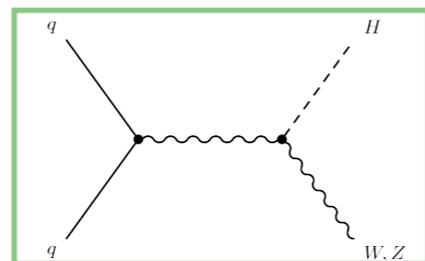
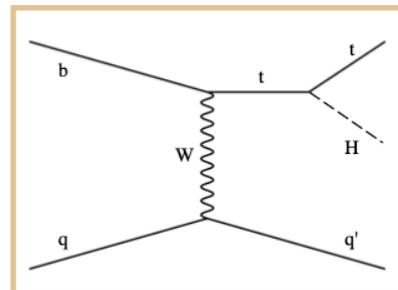
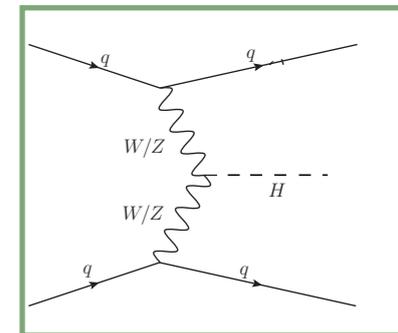
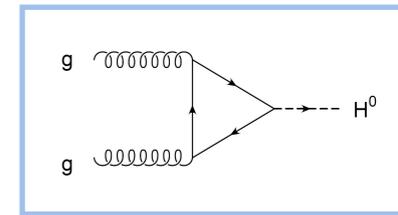
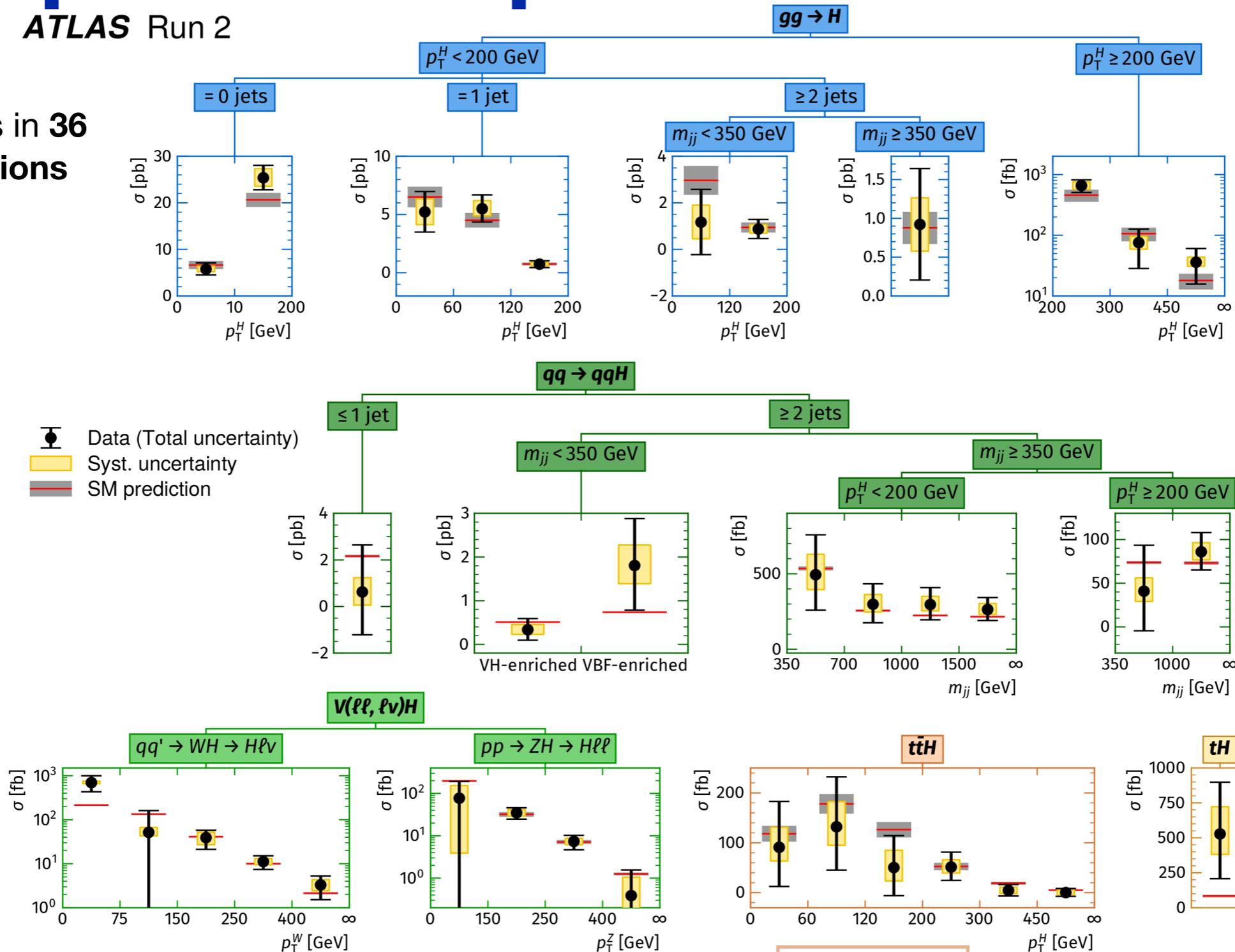
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# NEW Simplified template cross sections

ATLAS Run 2

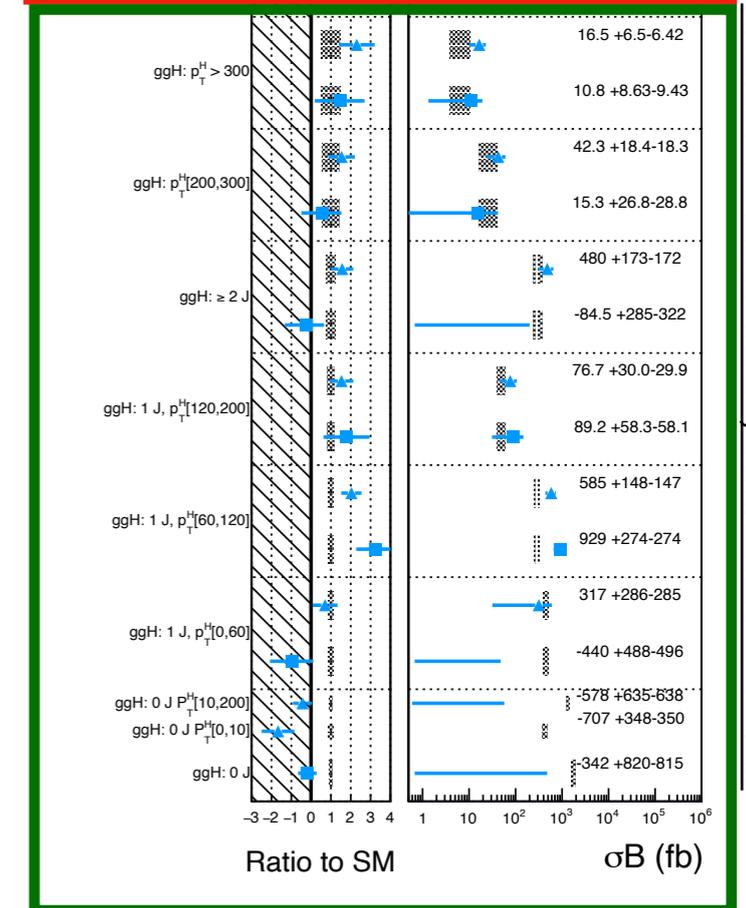
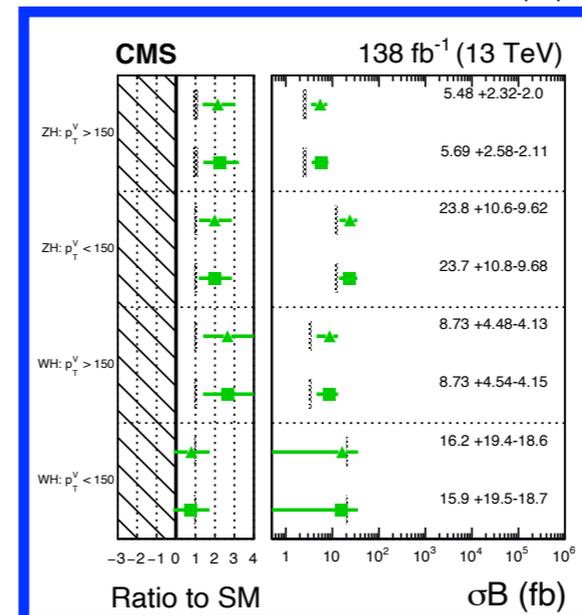
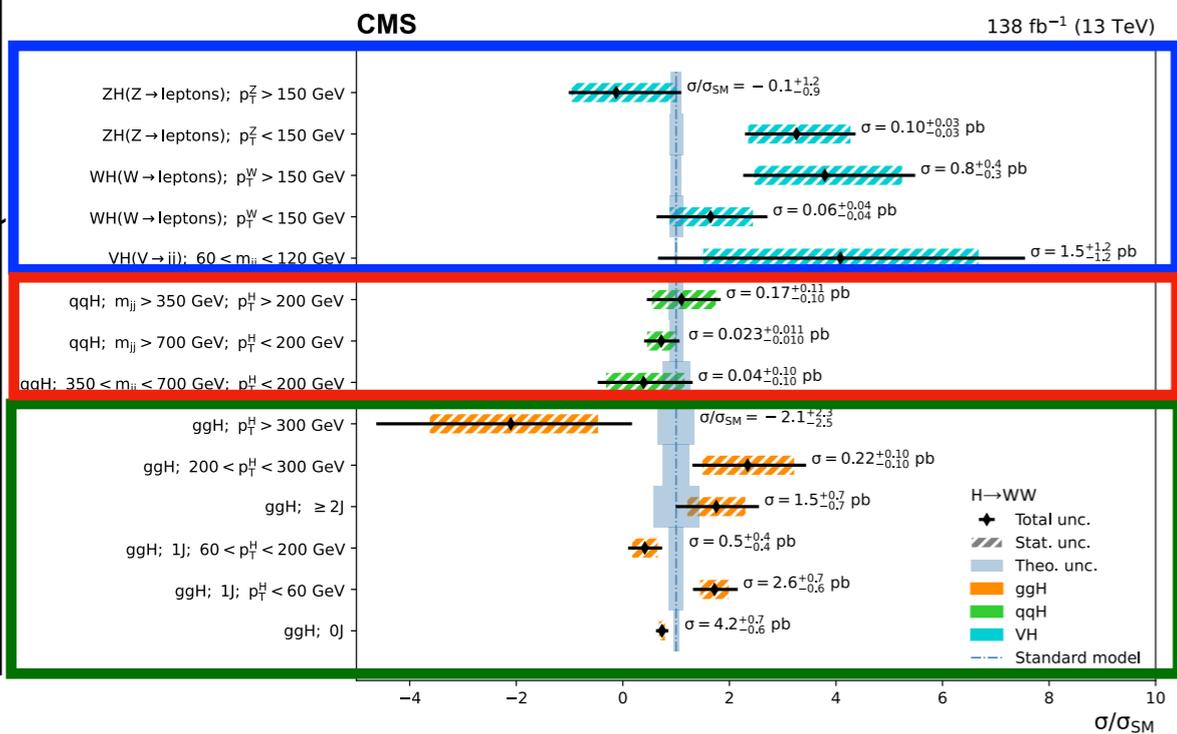
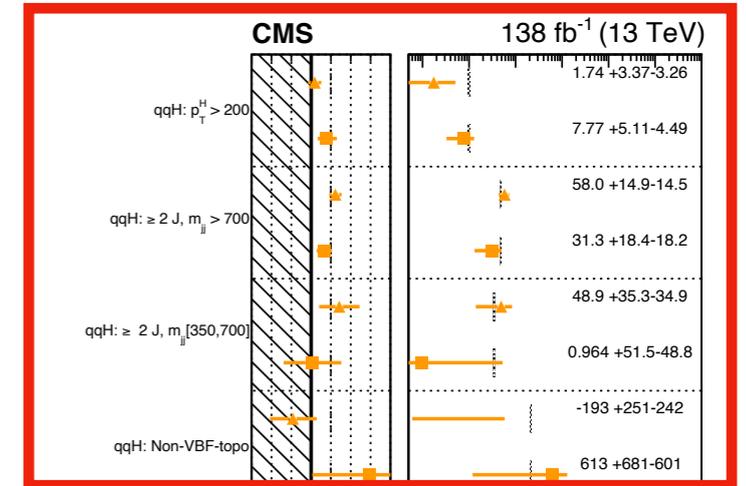
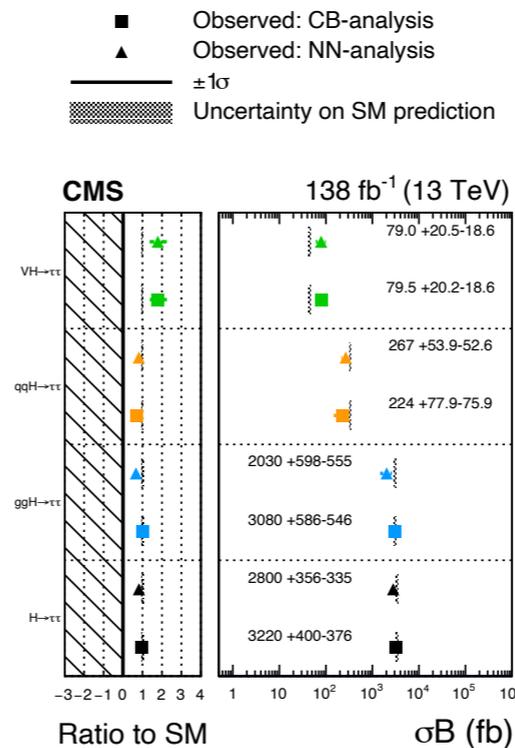
Measurements in **36** kinematic regions



VH, ttH: very precise measurements at high  $p_T^{H/V} \rightarrow$  **BSM sensitivity**

# Simplified template cross sections

- Recent results from CMS in individual decay channels
- Examples:  $H \rightarrow \tau\tau$ ,  $H \rightarrow WW$  (sensitive for **VBF**, **ggH**, low  $p_T$  **VH**)



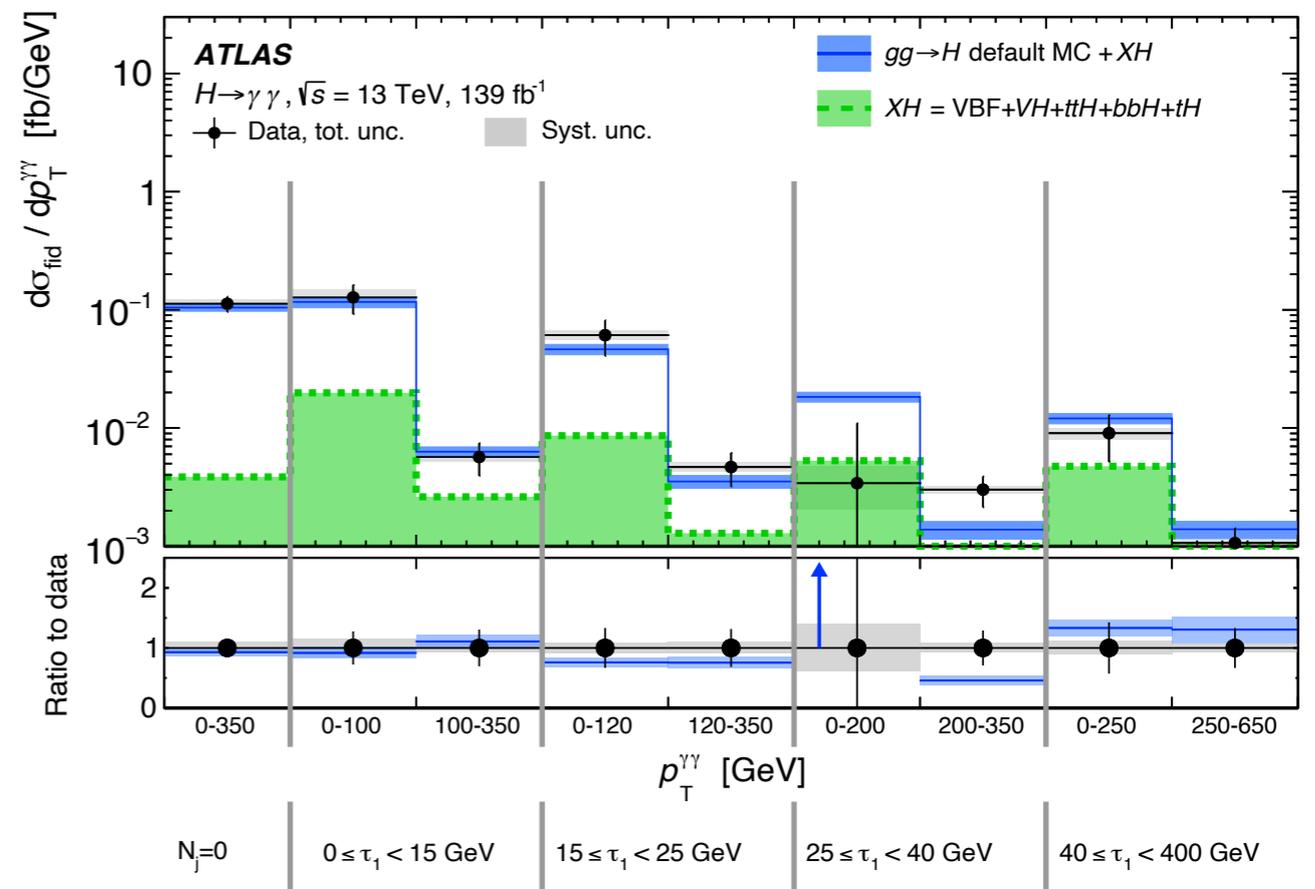
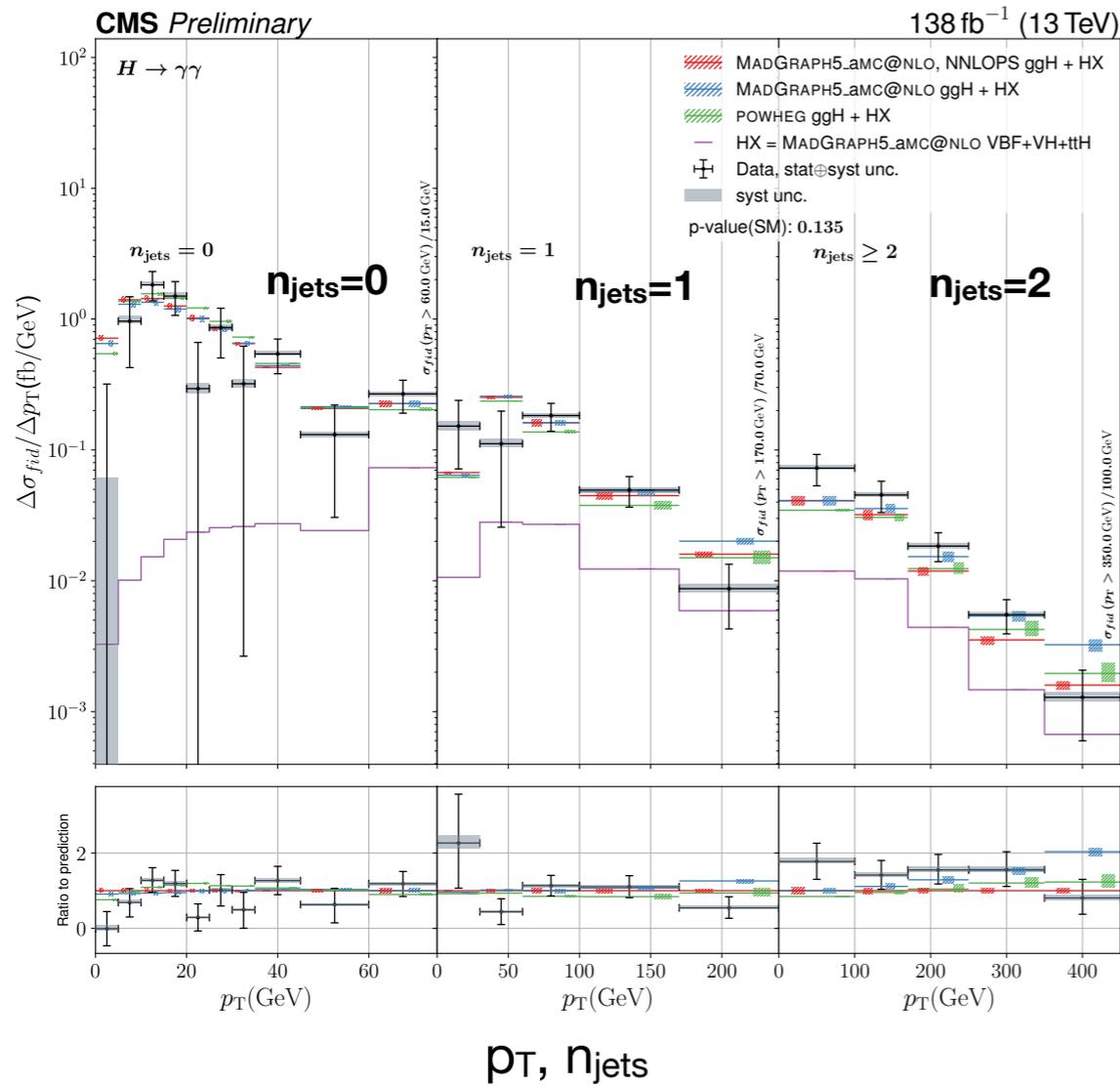
$H \rightarrow WW$

$H \rightarrow \tau\tau$

# Differential measurements

- Differential cross section measurements in several channels ( $H \rightarrow \gamma\gamma$ ,  $H \rightarrow ZZ$ ,  $H \rightarrow \tau\tau$ ,  $H \rightarrow WW$ )
- Example: large range of variables measured in the  $H \rightarrow \gamma\gamma$  channel

CMS-PAS-HIG-19-016



arXiv:2202.00487 (sub'd to JHEP)

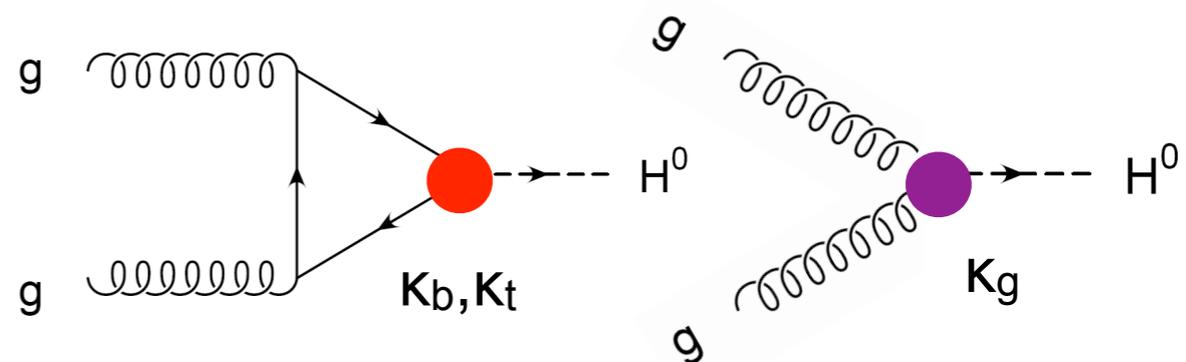
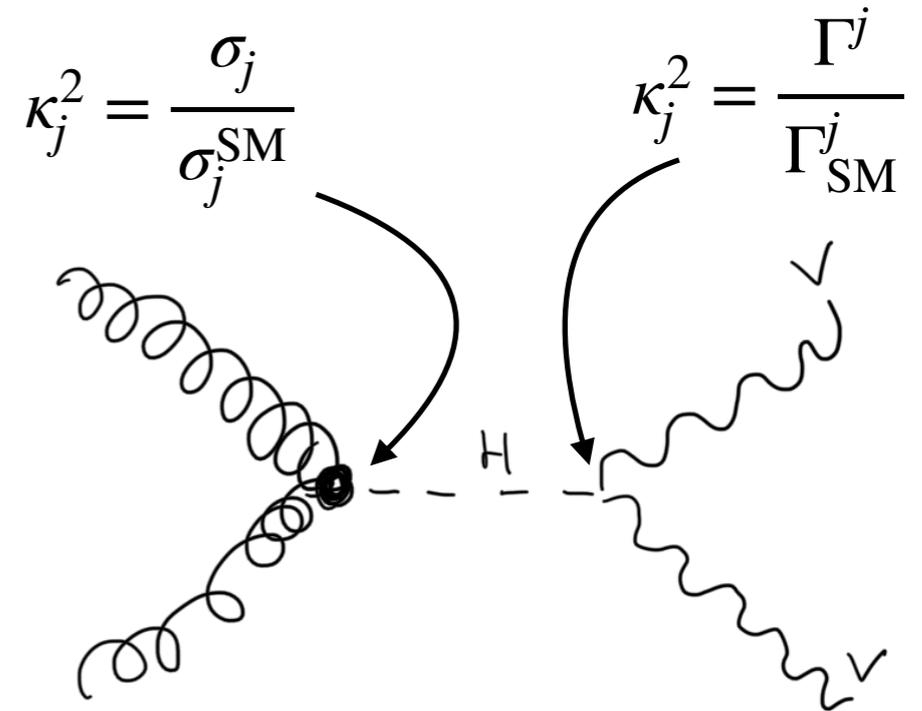
Generally good agreement between measurements and predictions  
 Interpretations: see later

$$\tau_{C,j} = \frac{\sqrt{p_T^2 + m^2}}{2 \cosh y_j - y_{\gamma\gamma}}$$

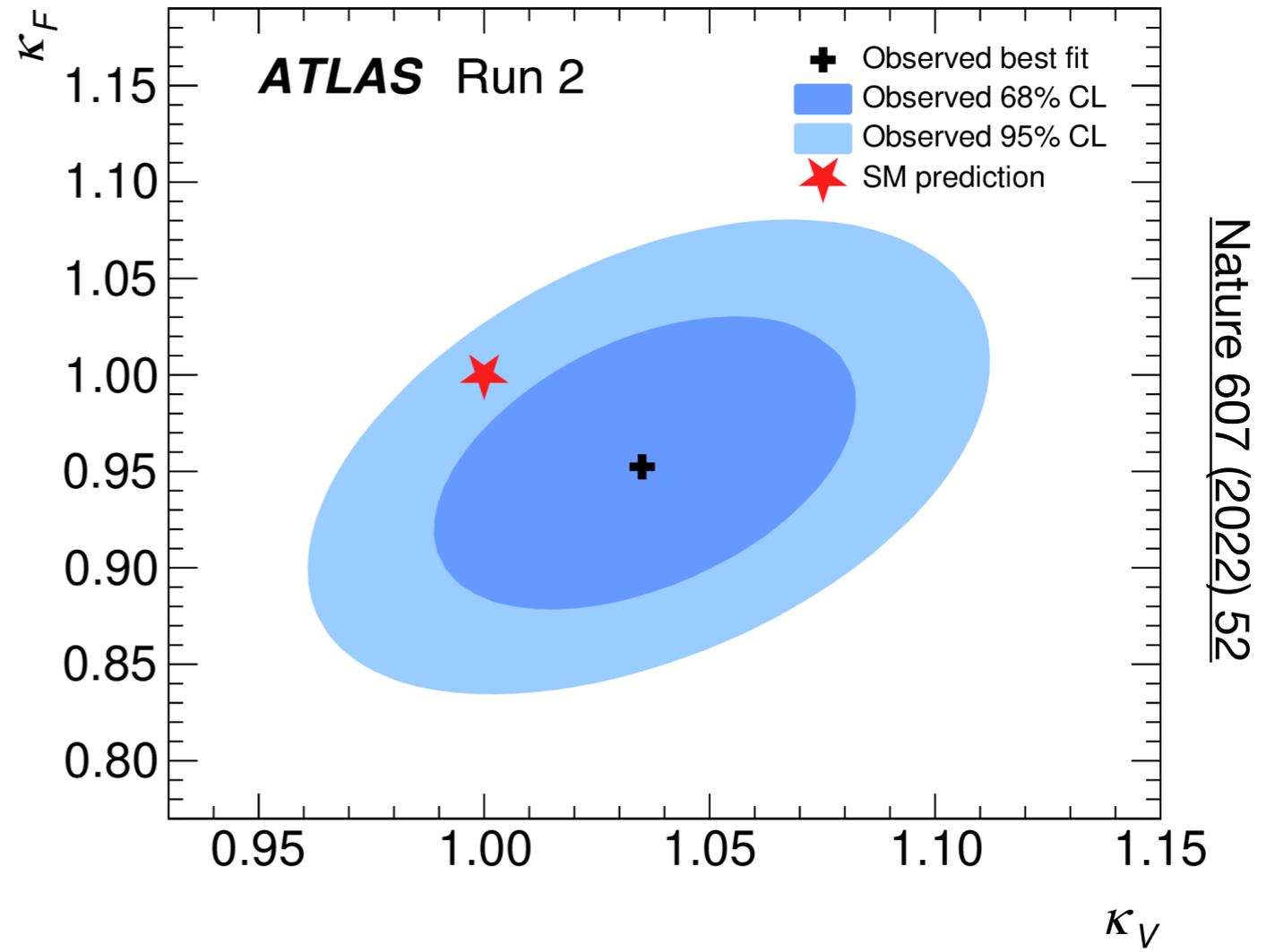
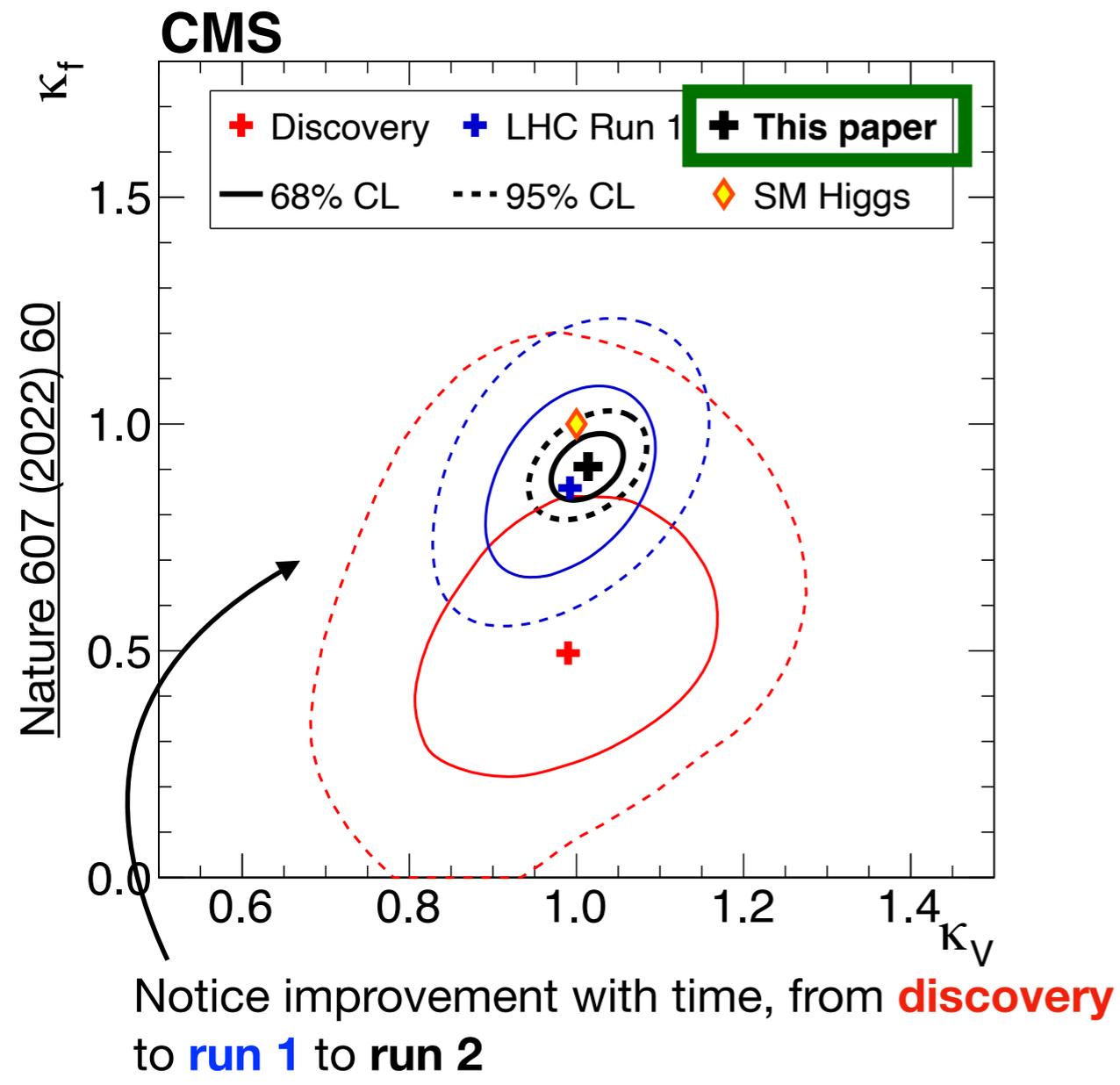
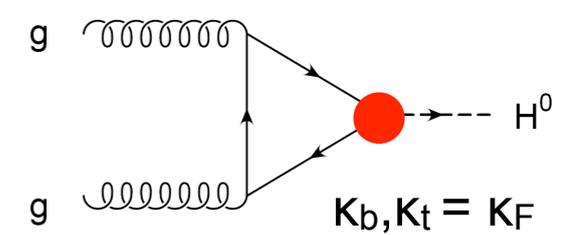
# Coupling measurements

- **Coupling modifier** framework → parameterisation of inclusive production and decay rates
- Processes with loops:
  - Can **resolve** loops or consider **effective** coupling modifiers
- Constrain possible BSM contributions to Higgs width in effective case:

$$\frac{\Gamma_H}{\Gamma_H^{\text{SM}}} = \frac{\kappa_H^2}{(1 - \mathcal{B}_{\text{inv}} - \mathcal{B}_{\text{undet}})}$$

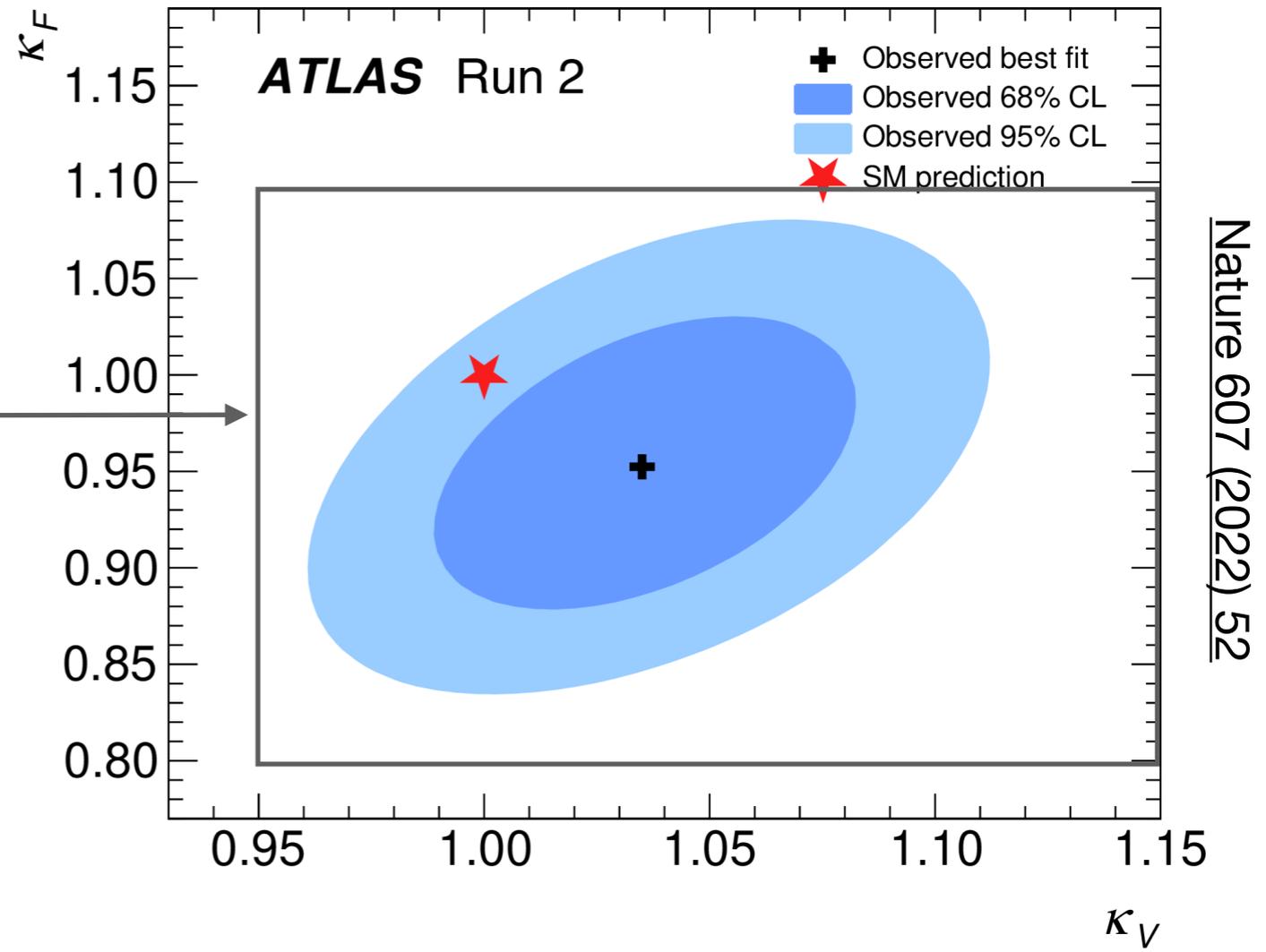
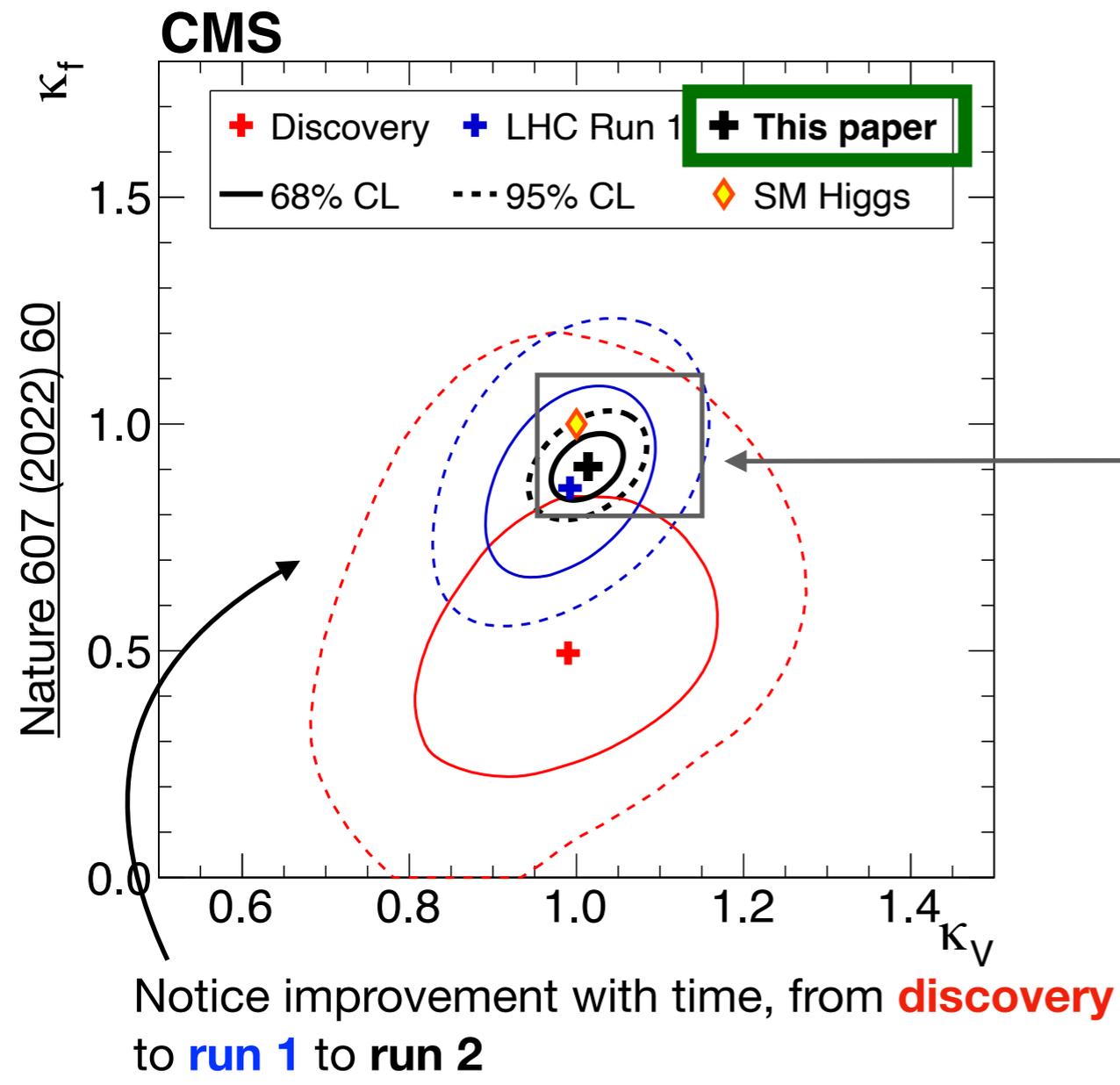
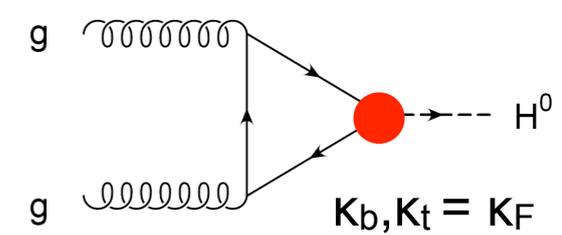


# NEW Vector bosons/fermions



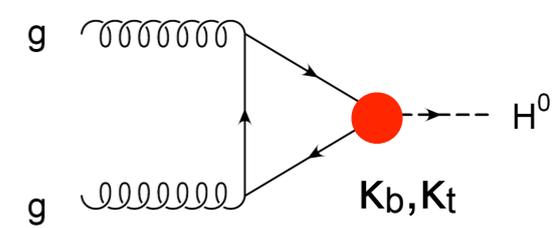
Scale all vector boson couplings with  $\kappa_V$ , all fermion couplings with  $\kappa_F$

# NEW Vector bosons/fermions

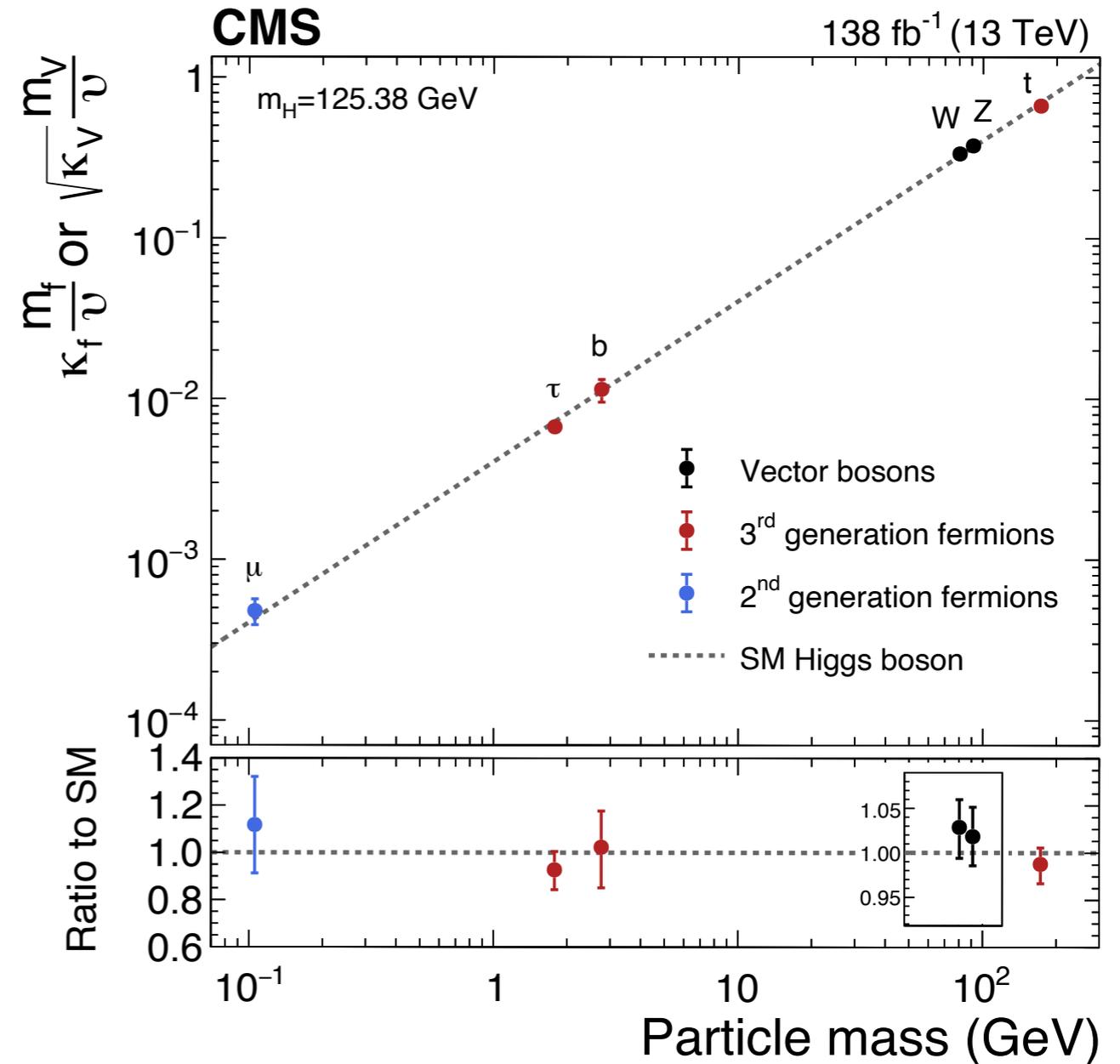
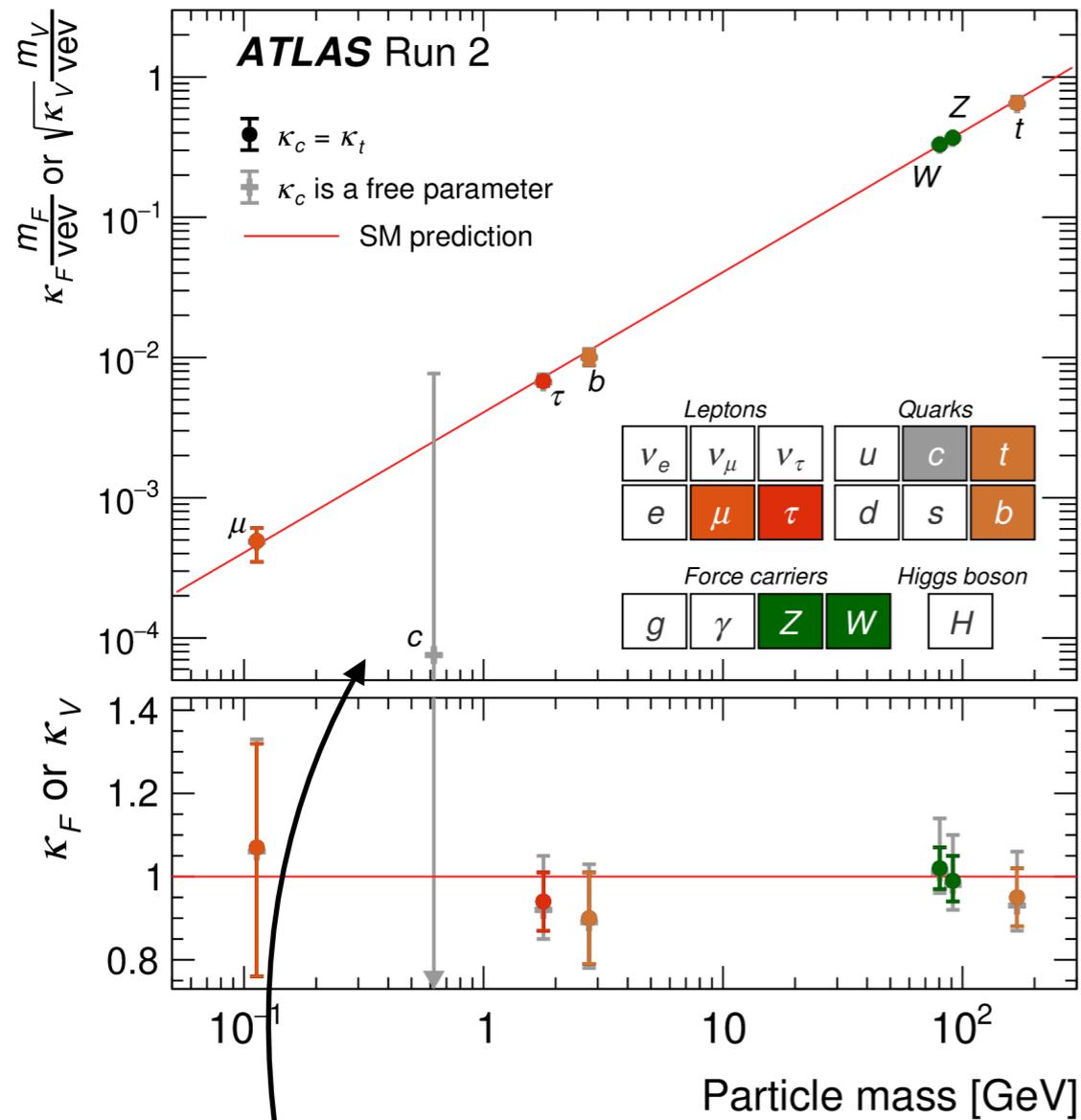


Scale all vector boson couplings with  $\kappa_V$ , all fermion couplings with  $\kappa_F$

# NEW Coupling vs mass



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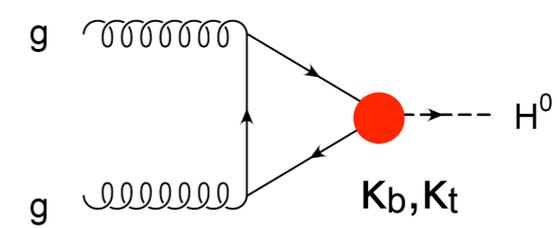


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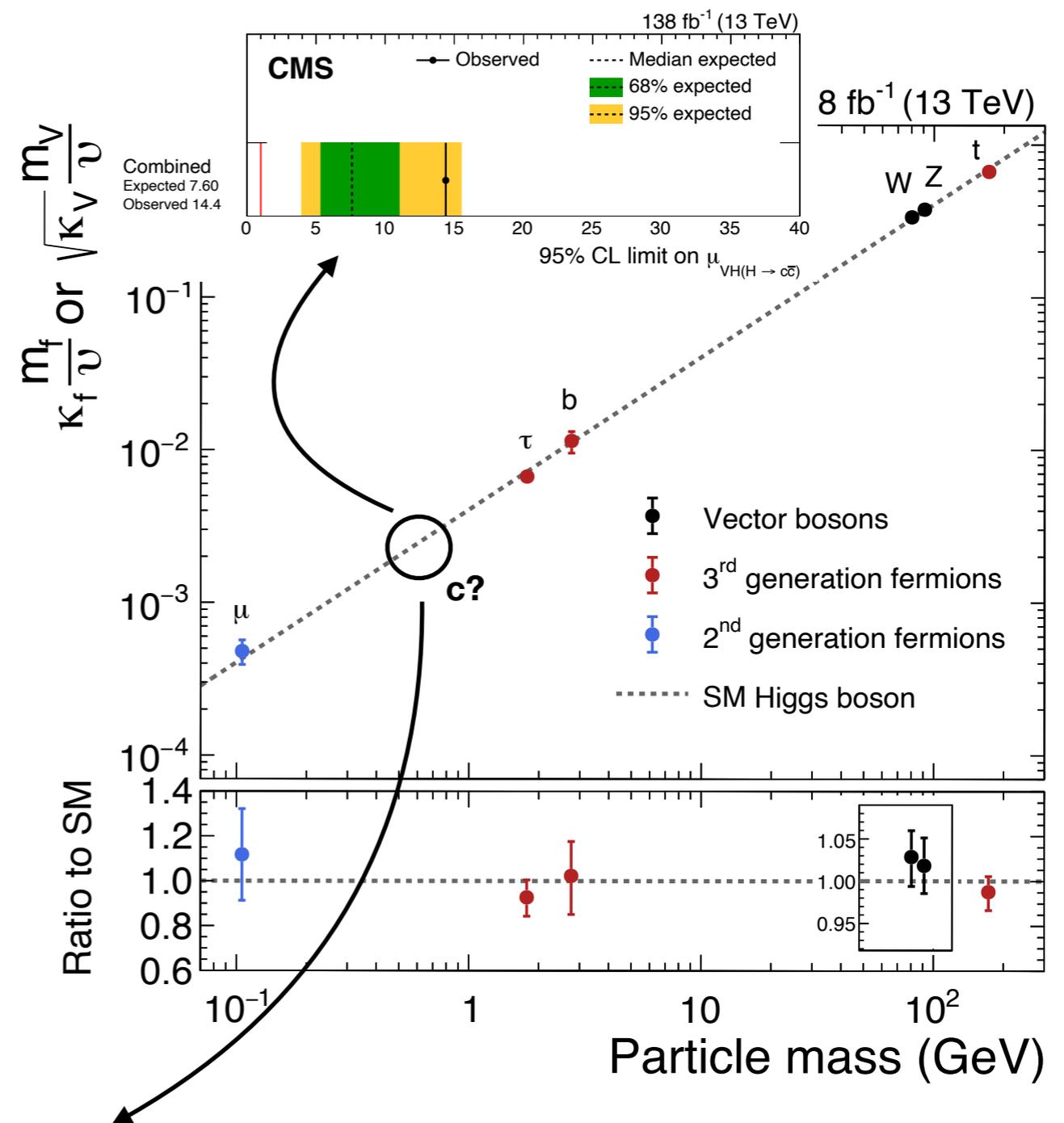
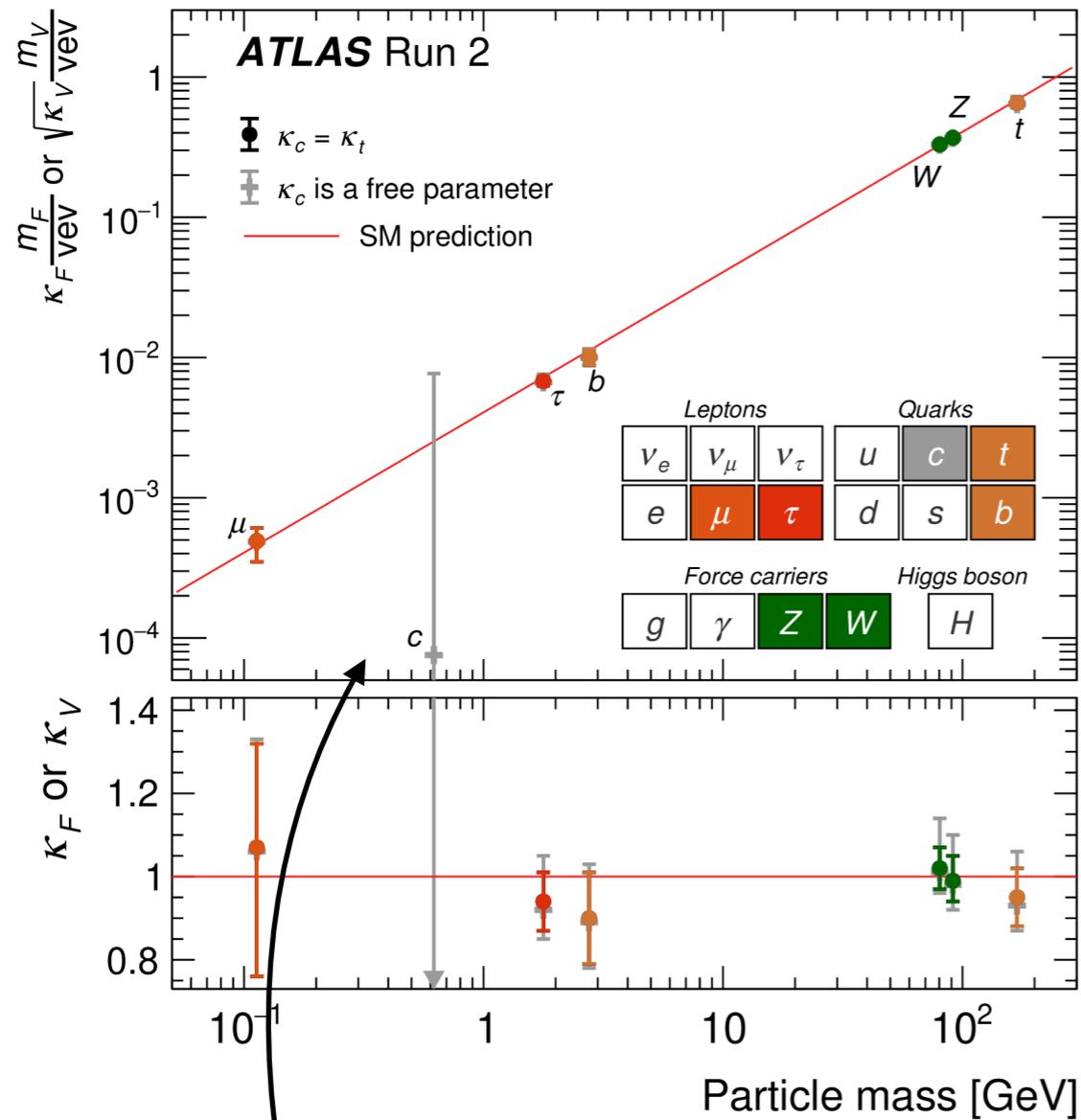
Higgs-charm coupling: see A. Marini's talk after the coffee break

**Reduced coupling modifiers vs particle mass**  
Follows pattern expected in SM

# NEW Coupling vs mass



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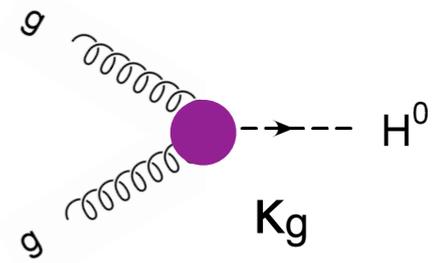
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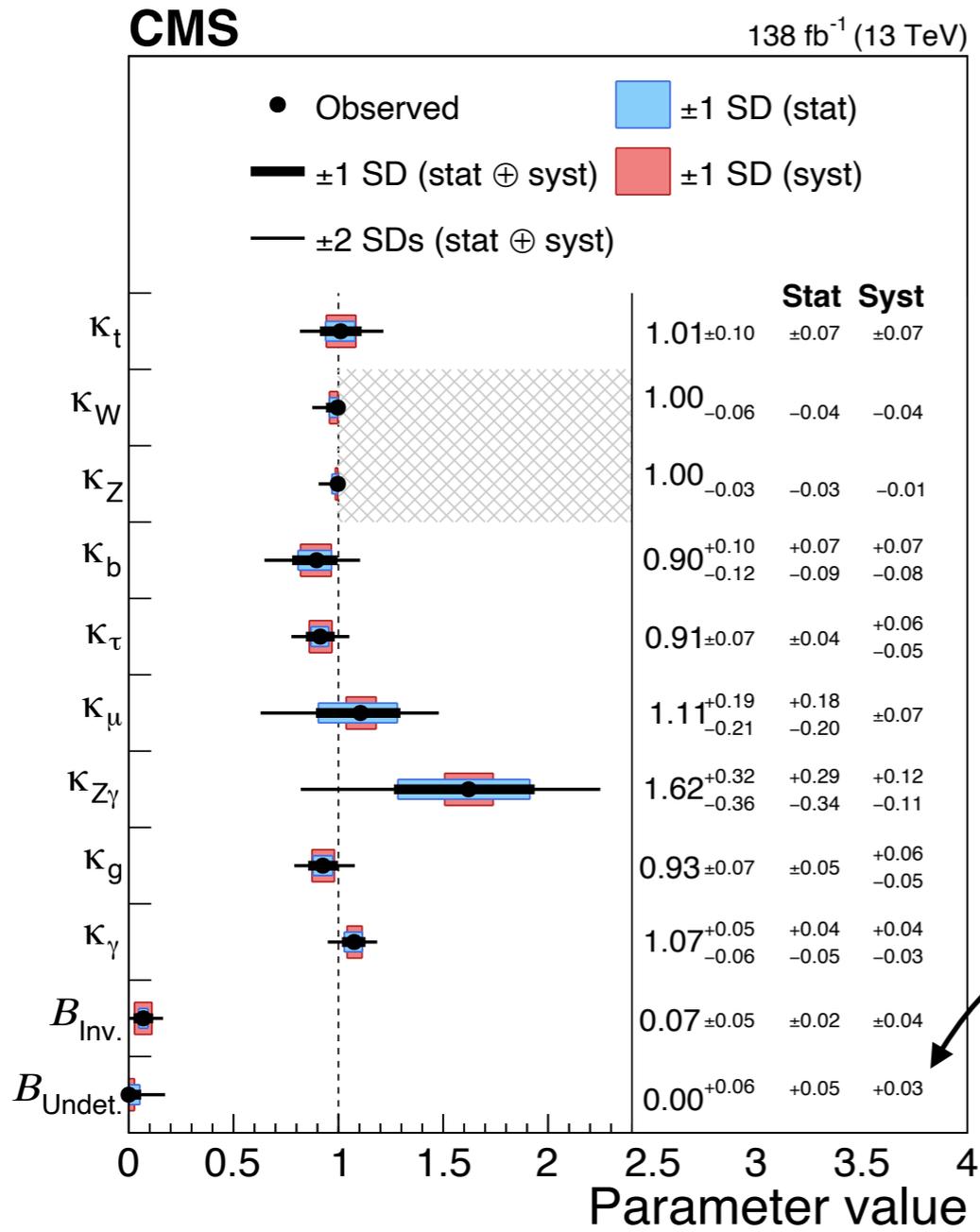
**NEW**

# Couplings, undetected BR

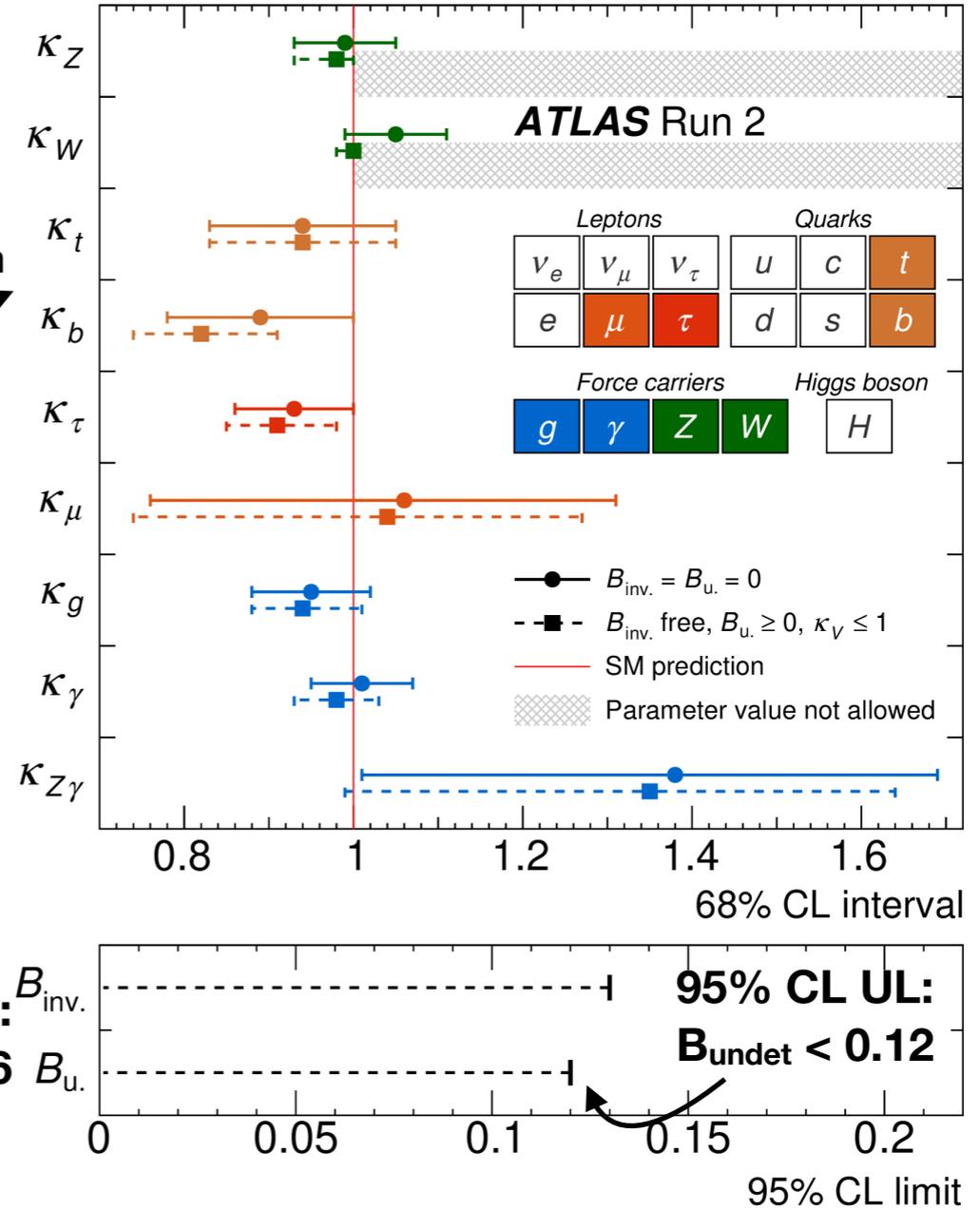


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Compare with squares



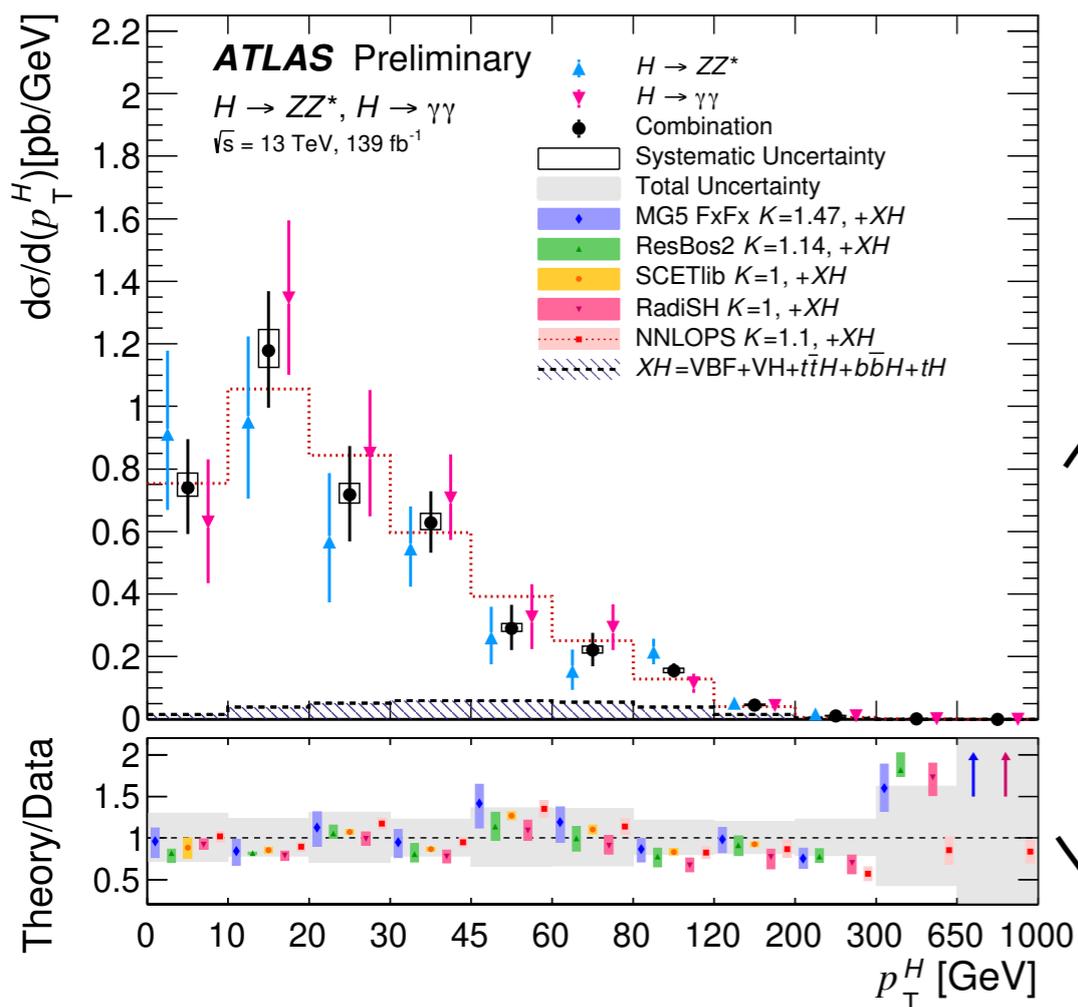
To constrain  $B_{Undet}$ : assume  $\kappa_W, \kappa_Z \leq 1$

Strongest constraints on effective coupling modifiers: **O(5%)**

NEW

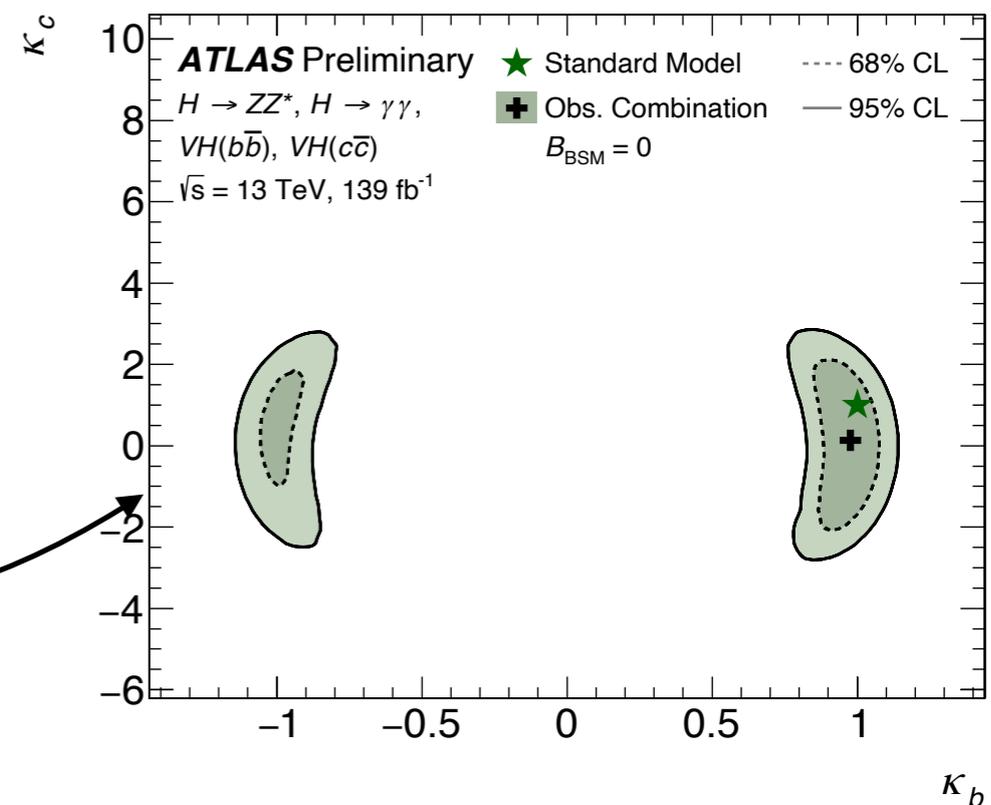
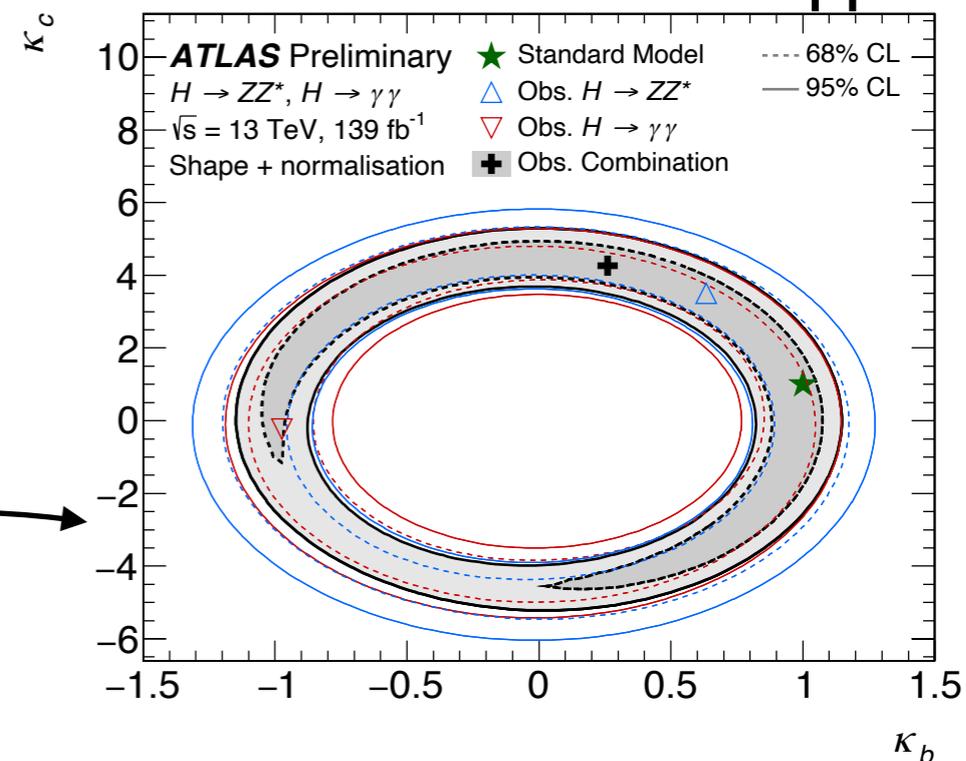
# Couplings from cross sections

- Combined measurements of differential cross sections in  $H \rightarrow \gamma\gamma$  and  $H \rightarrow ZZ$  channels



Constraints on  $\kappa_b$  and  $\kappa_c$  from shape + normalisation of  $p_T^H$

Constraints from shape + normalisation of  $p_T^H$  and direct  $VH \rightarrow bb/cc$  measurement



# Summary & outlook

- We have learned much about the 125 GeV Higgs boson since its discovery
- Increasingly precise measurements of Higgs boson production cross sections and couplings to other particles
- Measurements of cross sections in different kinematic regions advancing
- More properties under study: see A. Ferrari's talk on HH production next
- **Run 3 starts tomorrow:** ready for the next decade of Higgs boson exploration!

