HIGGS POTENTIAL 2024
HIGGS POTENTIAL AND BSM OPPORTUNITIES

Higgs precision measurements at LHC

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Higgs Potential 2024
Hefei, Anhui
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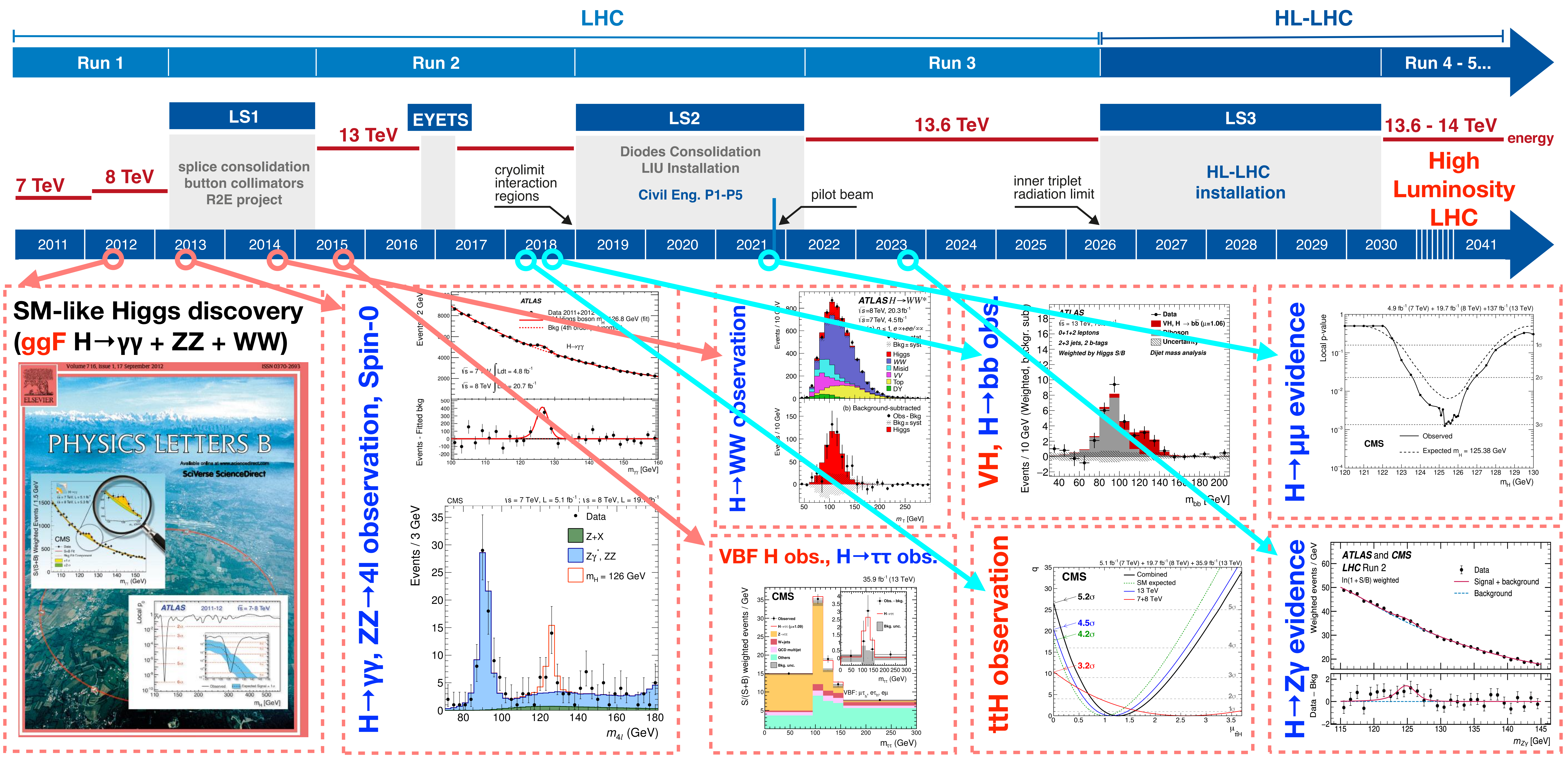
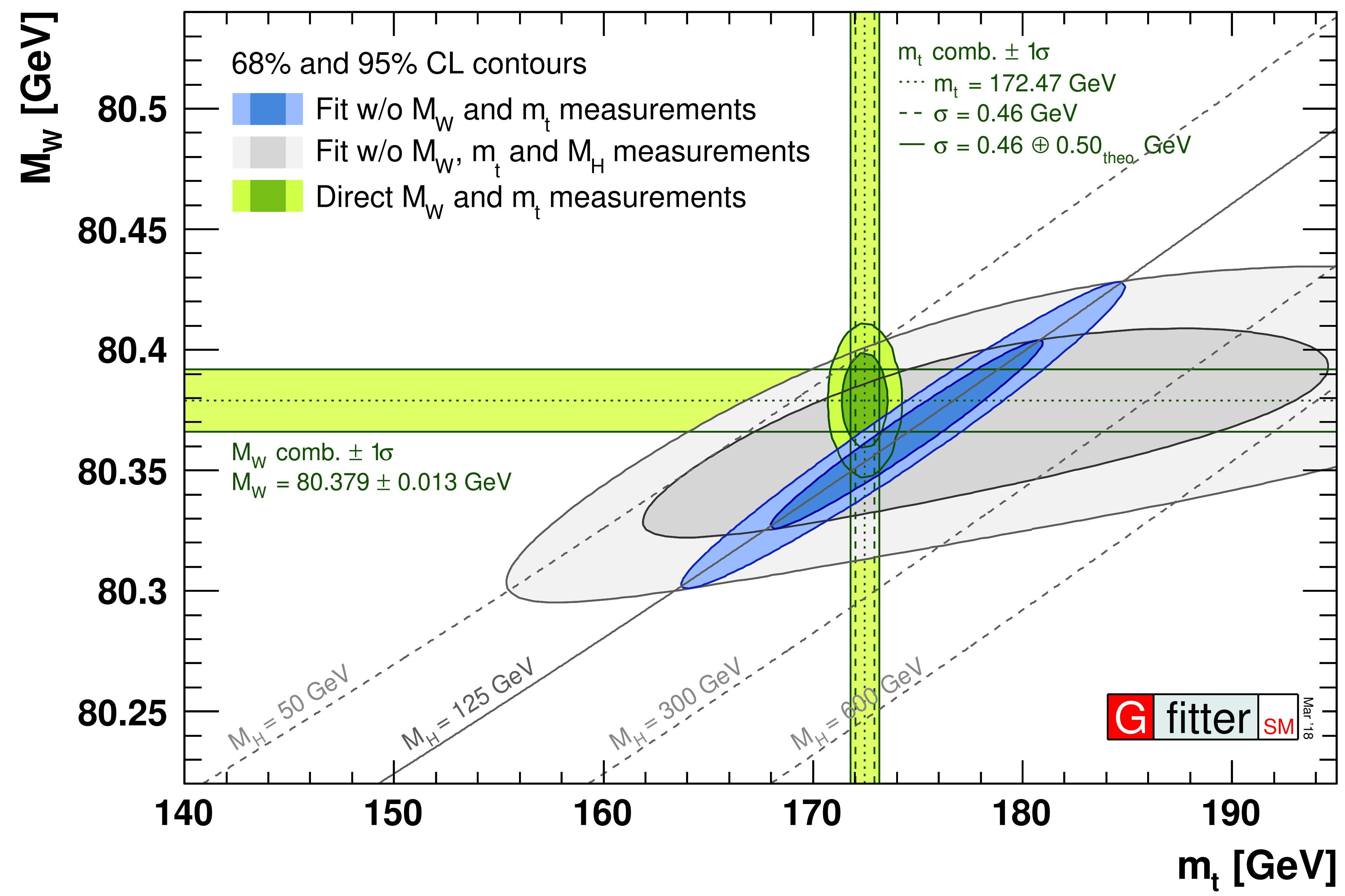
Roadmap of Higgs boson measurements

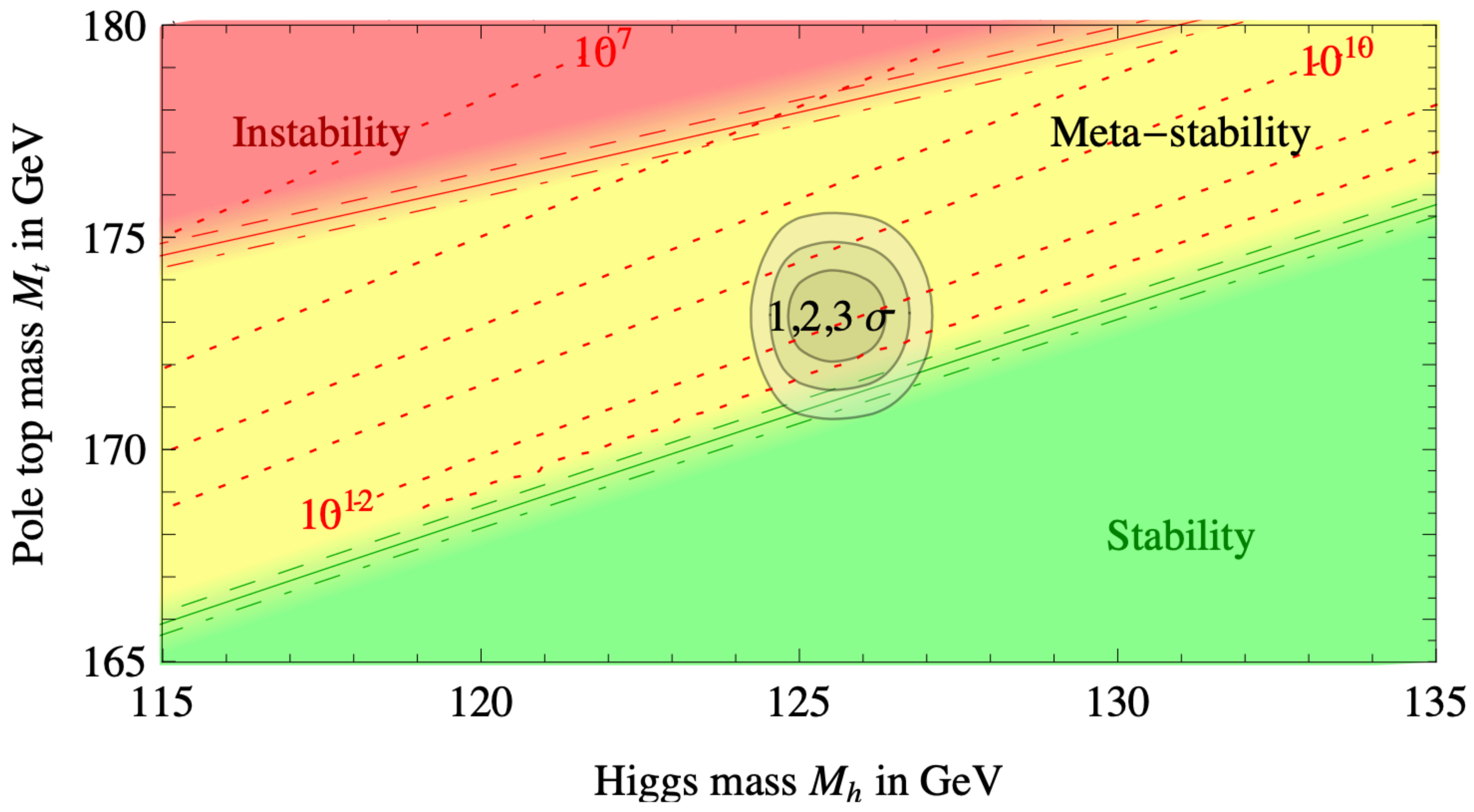
Courtesy of Kun Liu



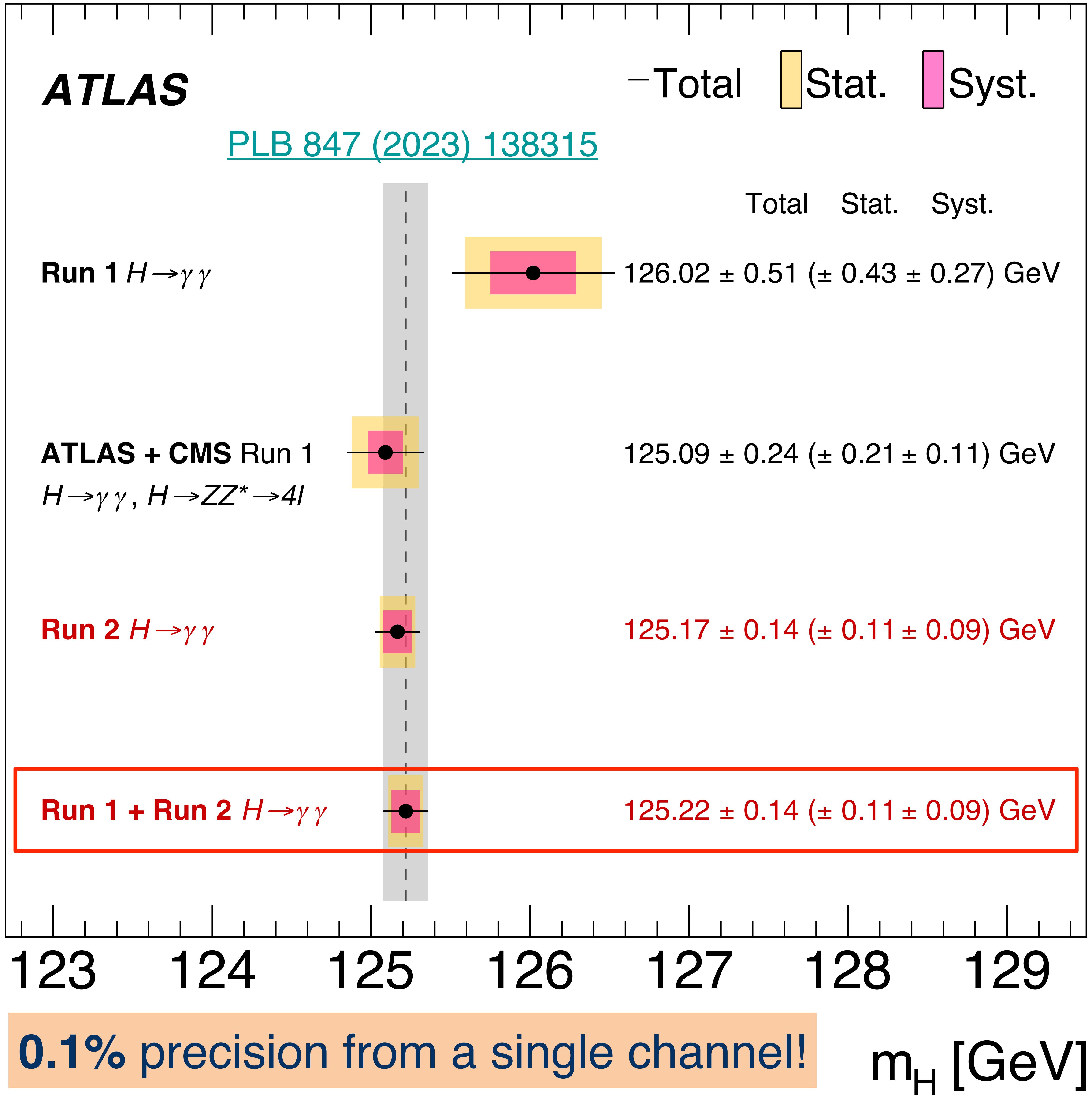
Mass measurement

- Fundamental free parameter of SM, important for validation of SM consistency, understanding vacuum stability etc.
- **Mainly an experimental effort**: "final exam" of detector performance (e/γ/μ)
  - Theory inputs (e.g. interference between Higgs boson and continuum) also important!





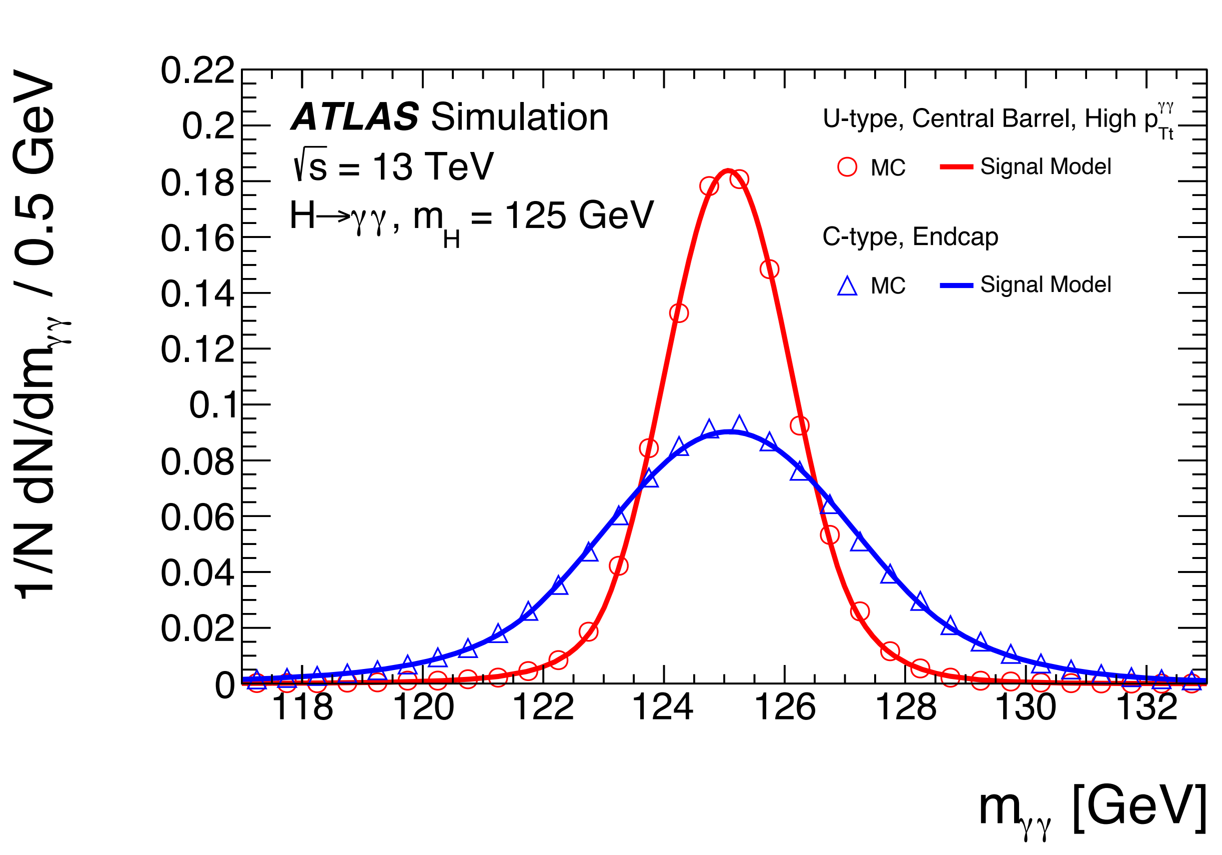
Mass measurement: H→γγ

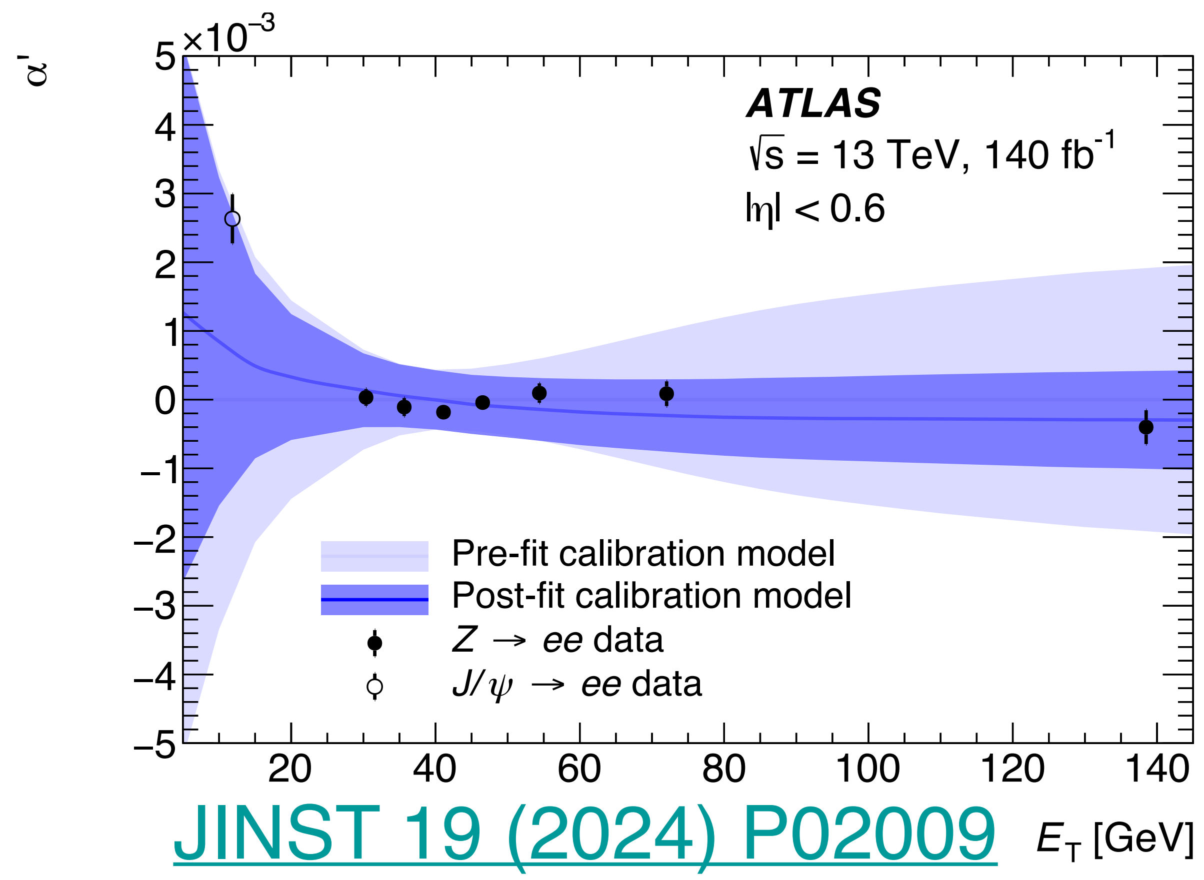


0.1% precision from a single channel!

Syst. source	Impact [MeV]
Photon energy scale	83
Signal-bkg interference	26
Energy resolution	15
Bkg modeling	14
Vertex	4
Signal modeling	1

Photon energy scale	Impact [MeV]
Z→ee calibration	59
E_T-dep. e energy scale	44
e→γ extrapolation	30
Conversion modeling	24



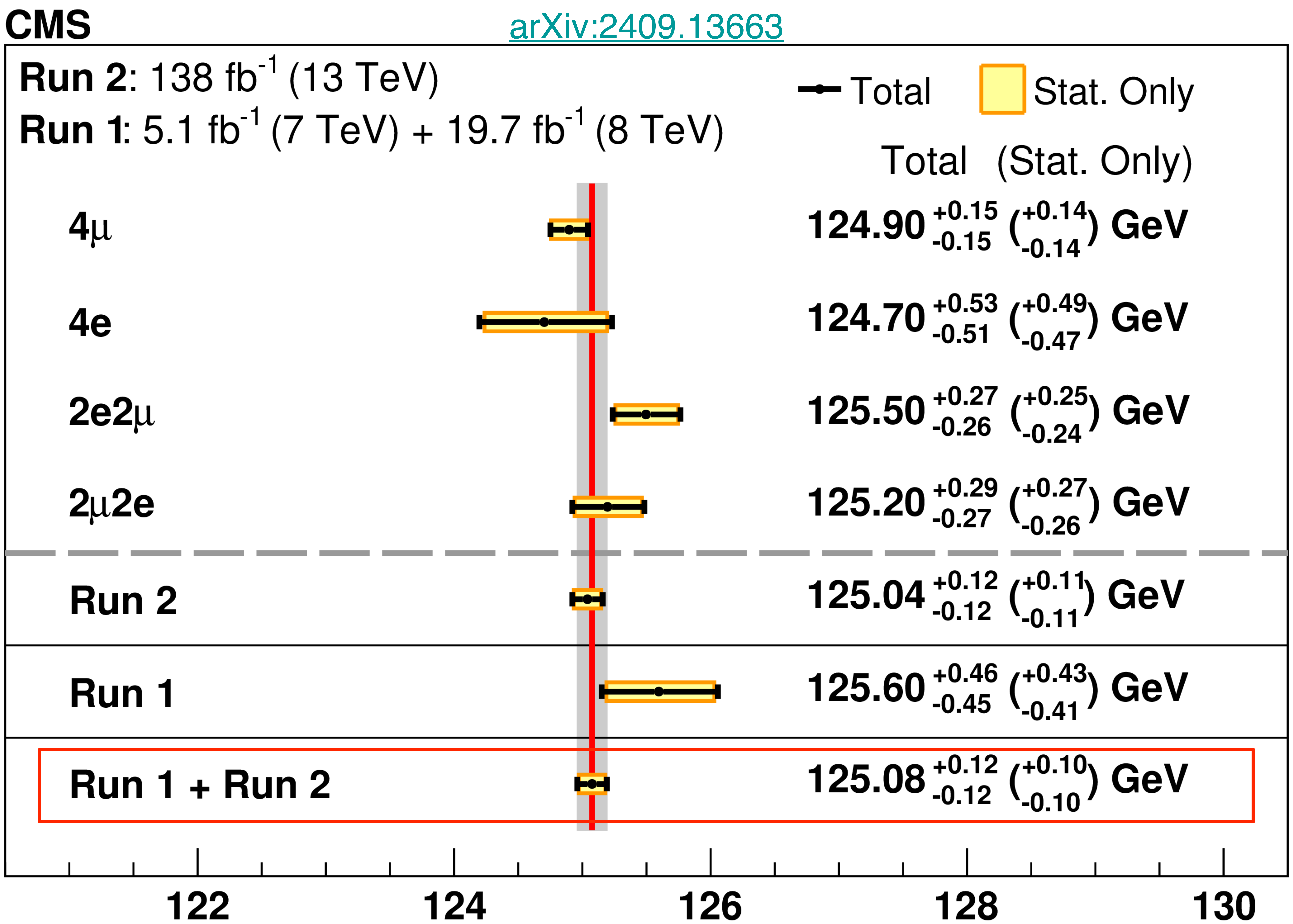


JINST 19 (2024) P02009

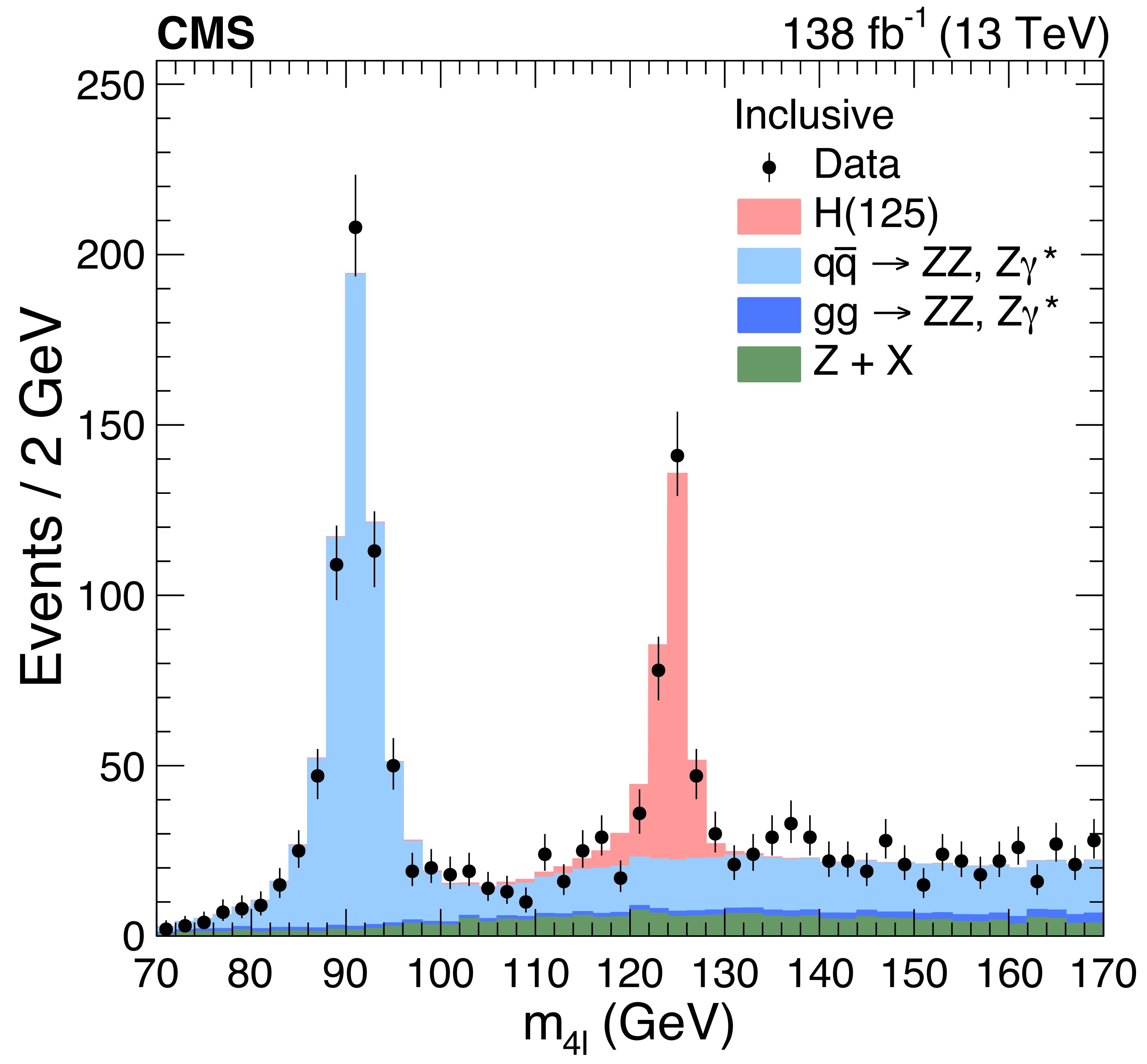
- Signal mass resolution 1~2 GeV
- x4 reduction of uncertainty compared with previous iteration (36 fb^{-1})

Mass measurement: H→ZZ*→4l

arXiv:2409.13663

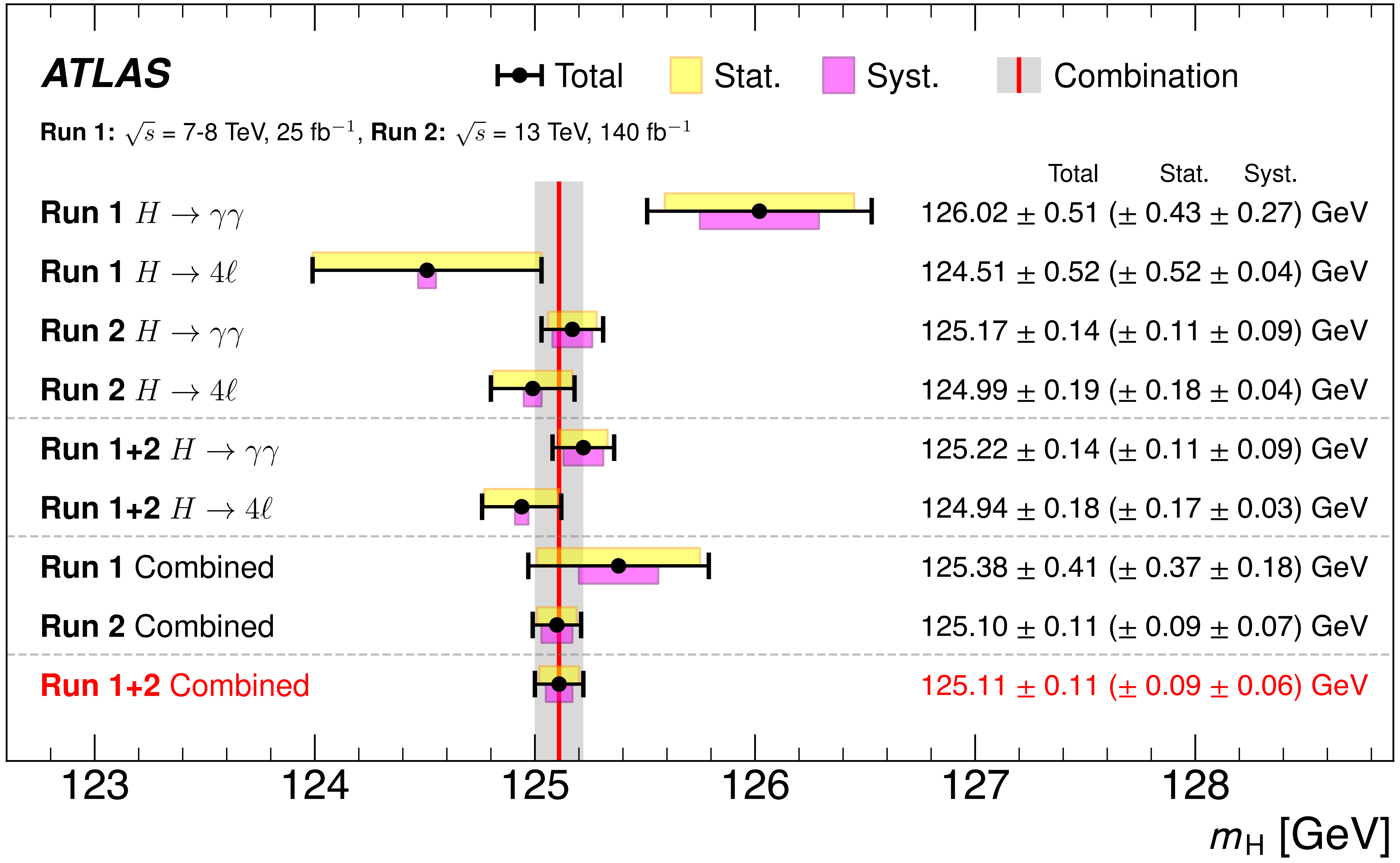


Most precise single-channel measurement!



- Signal mass resolution can be as good as 0.7 GeV (4μ)
  - Beam-spot constraint + kinematic fit to Z-pole (**+15%**), per-event resolution (**+8%**), MELA (**+4%**)

Mass measurement: combination



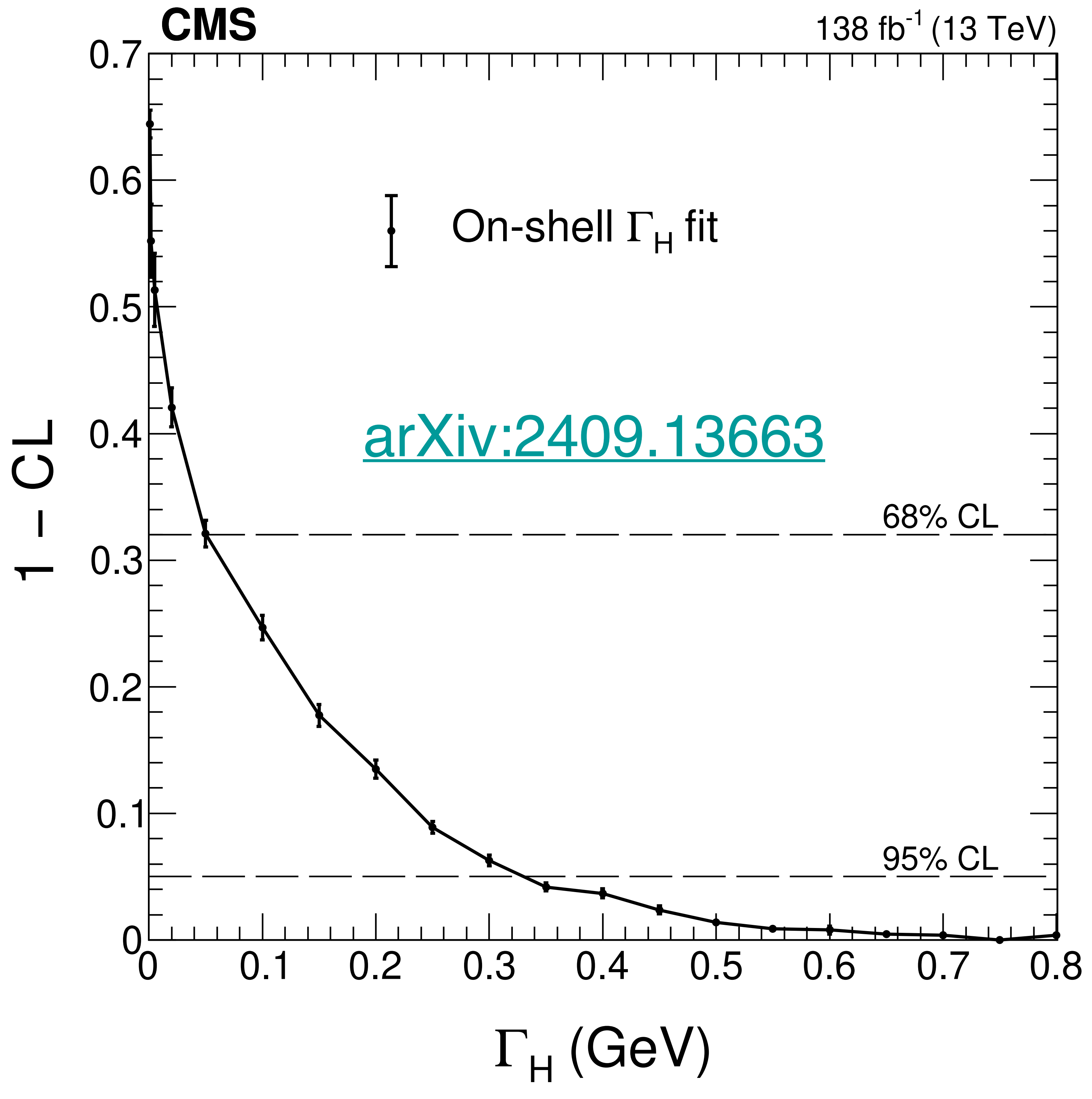
Syst. source	Impact [MeV]
Z→ee calibration	44
E_T-dep. e energy scale	28
H→γγ signal-bkg interference	17
γ lateral shower shape	16
γ conversion modeling	15
e/γ energy resolution	11
H→γγ background modeling	10
Muon momentum scale	8
Others	7

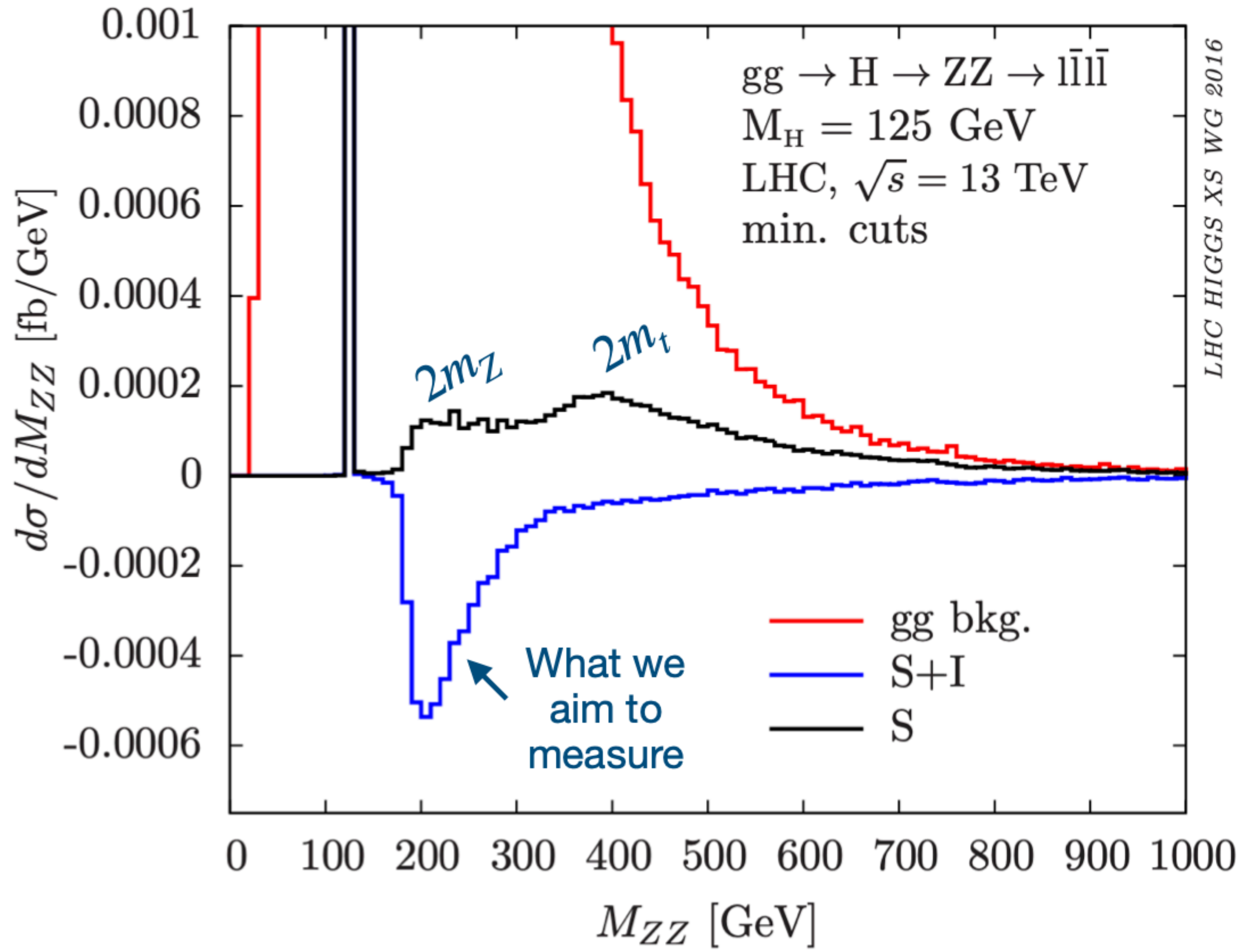
PRL 131 (2023) 251802

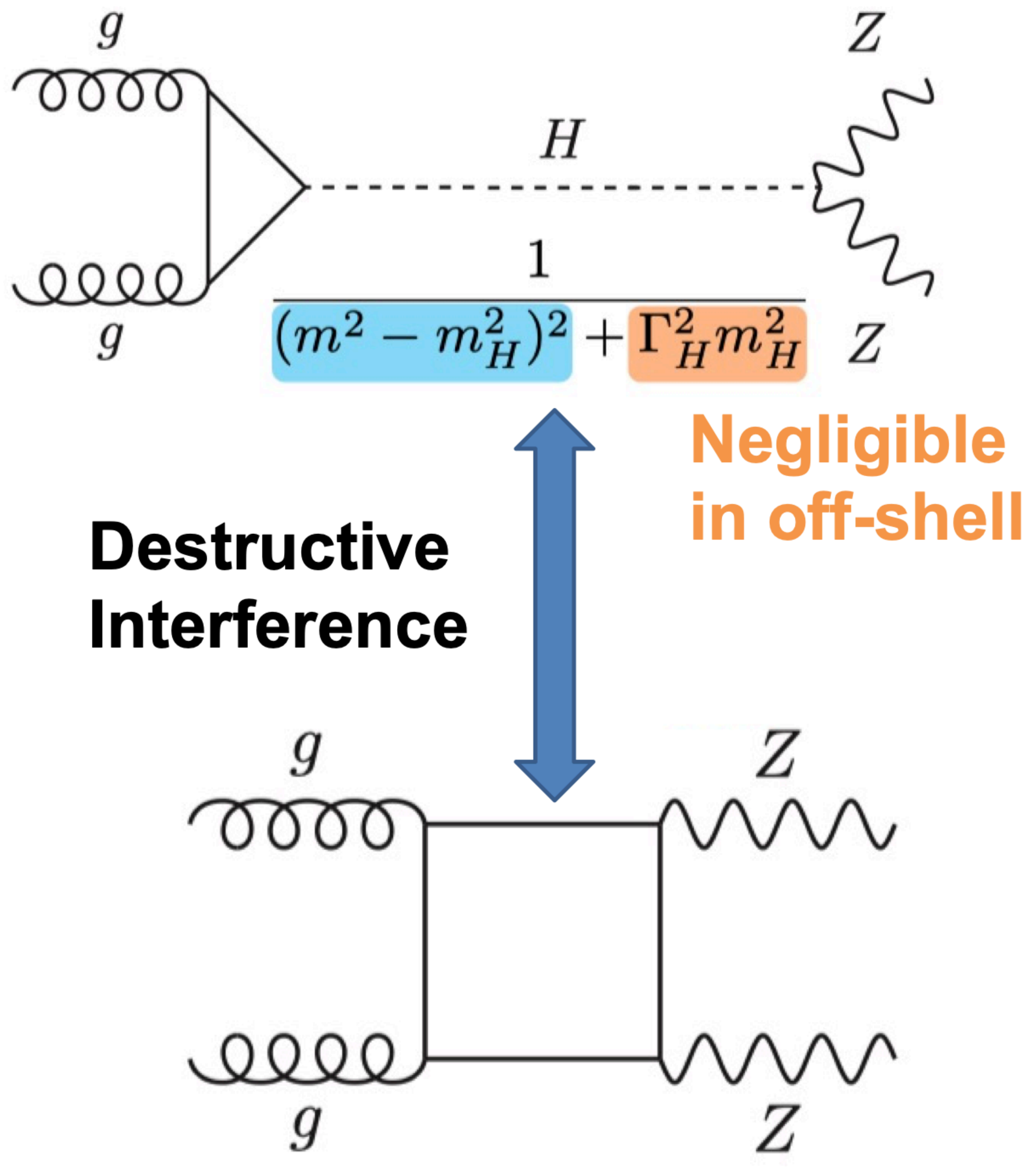
- ATLAS reach **0.09% precision** with Run 2. Waiting for CMS H→γγ to start LHC combination of Run 2 + Run 1 data
  - Will provide input m_H value for Run 3 & HL-LHC

Current most precise measurement

Width measurement







- SM Higgs width Γ~4 MeV ($\tau \sim 10^{-22}$ s). Cannot be constrained by line-shape (~1 GeV) or flight distance (~10 μm) measurements at LHC experiments
- Exploit **off-shell production** in H→ZZ/WW/tt to indirectly constrain the width

Width measurement: H→ZZ→llll/llνν

Overview: Neural Simulation-Based Inference

Full test statistic function with nuisance parameters α:

$$t(\mu) = -2 \cdot \log \frac{\text{Pois}(N_{obs}|\mu,\hat{\hat{\alpha}})}{\text{Pois}(N_{obs}|\hat{\mu},\hat{\alpha})} - 2 \cdot \sum_{i=1}^{N_{obs}} \log \frac{p(x_i|\mu,\hat{\hat{\alpha}})/\cancel{p_{ref}(x_i)}}{p(x_i|\hat{\mu},\hat{\alpha})/\cancel{p_{ref}(x_i)}} - 2 \cdot \sum_{k}^{N_{syst}} \log \frac{L_{subs}(\hat{\hat{\alpha}})}{L_{subs}(\hat{\alpha})}$$

[J. Sandesara's talk at Higgs 2024]

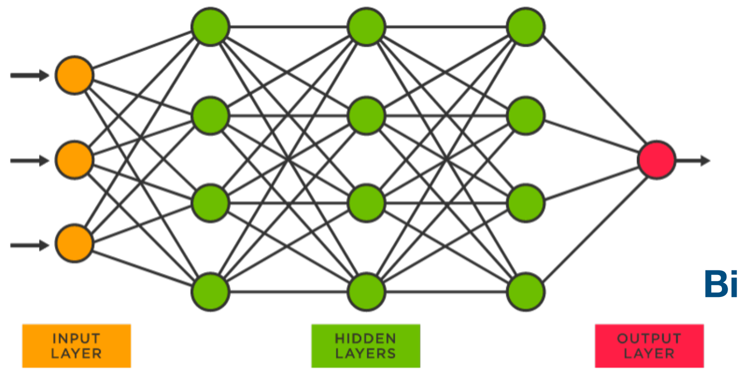
sum over processes $c = S, B,$ etc.

$$\frac{p(x_i|\mu,\alpha)}{p_{ref}(x_i)} = \frac{1}{\sum_c G_c(\alpha) \cdot f_c(\mu) \cdot \nu_c} \sum_c \left[f_c(\mu) \cdot g_c(x_i|\alpha) \cdot \nu_c \cdot \frac{p_c(x_i)}{p_{ref}(x_i)} \right]$$

$x \sim p_c$, $S = 1$

$x \sim p_{ref}$, $S = 0$

Two hypothesis: p_c and p_{ref}



Classification NN

$$\underset{\omega}{\text{argmin}}\ L \longrightarrow \hat{s}(x) = \frac{p_c}{p_{ref} + p_c}(x) \longrightarrow \frac{p_c}{p_{ref}}(x) = \frac{\hat{s}(x)}{1.0 - \hat{s}(x)}$$

Binary Cross-Entropy loss

"Likelihood ratio trick"

Many examples in ATLAS - HH4b background estimation, Omnifold, etc.

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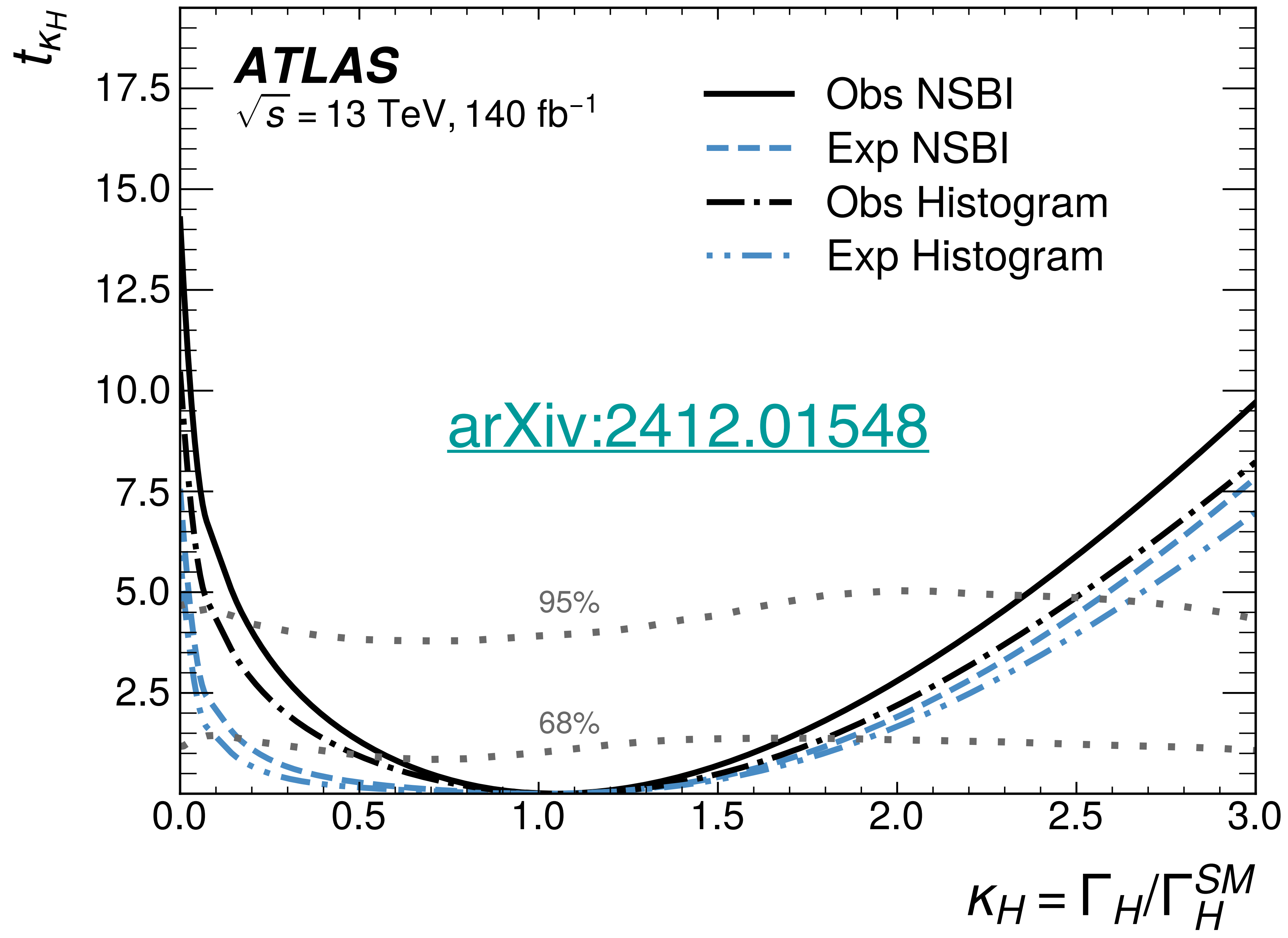
llll + llνν	Width [MeV]	Off-shell significance
ATLAS	$4.3^{+2.7}_{-1.9}$	3.7σ
CMS	$3.0^{+2.0}_{-1.5}$	3.8σ

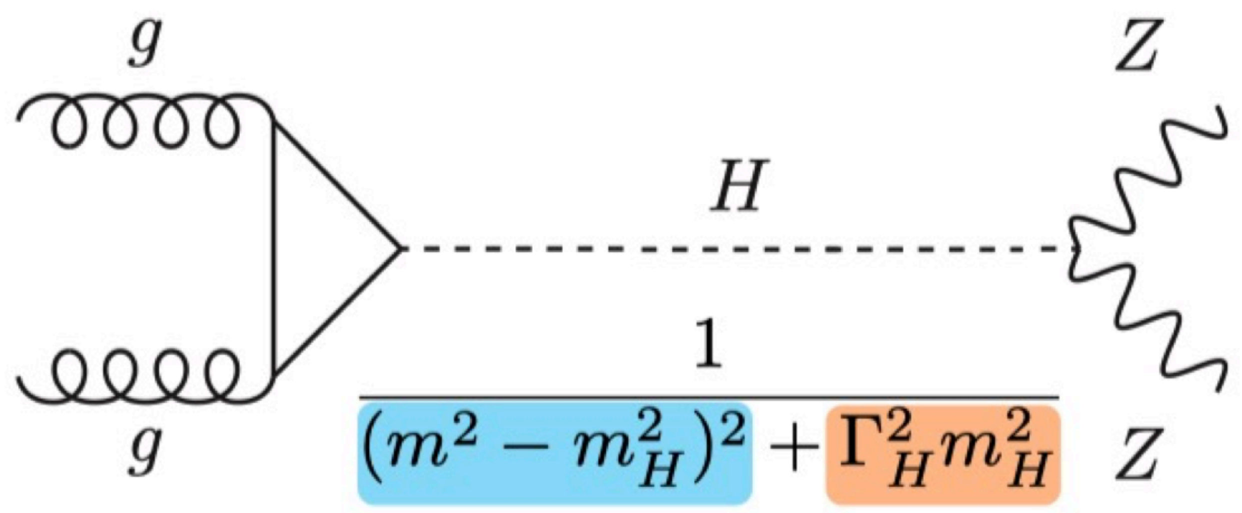
- Significant improvement in interference-rich region

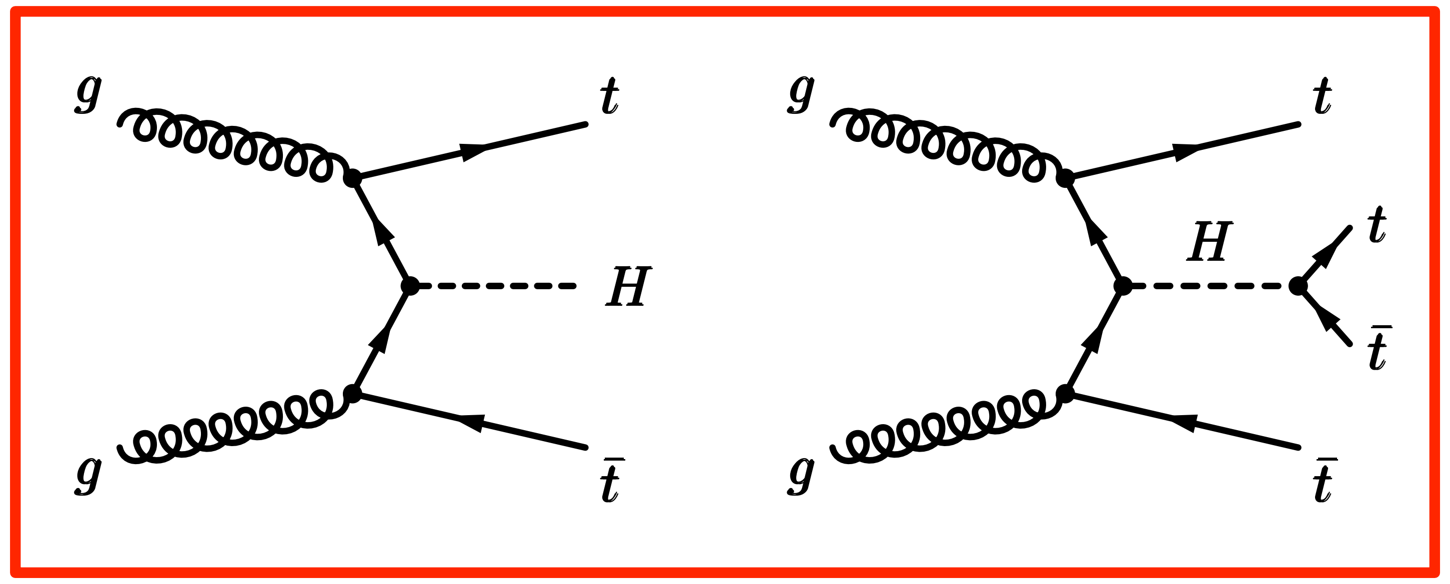


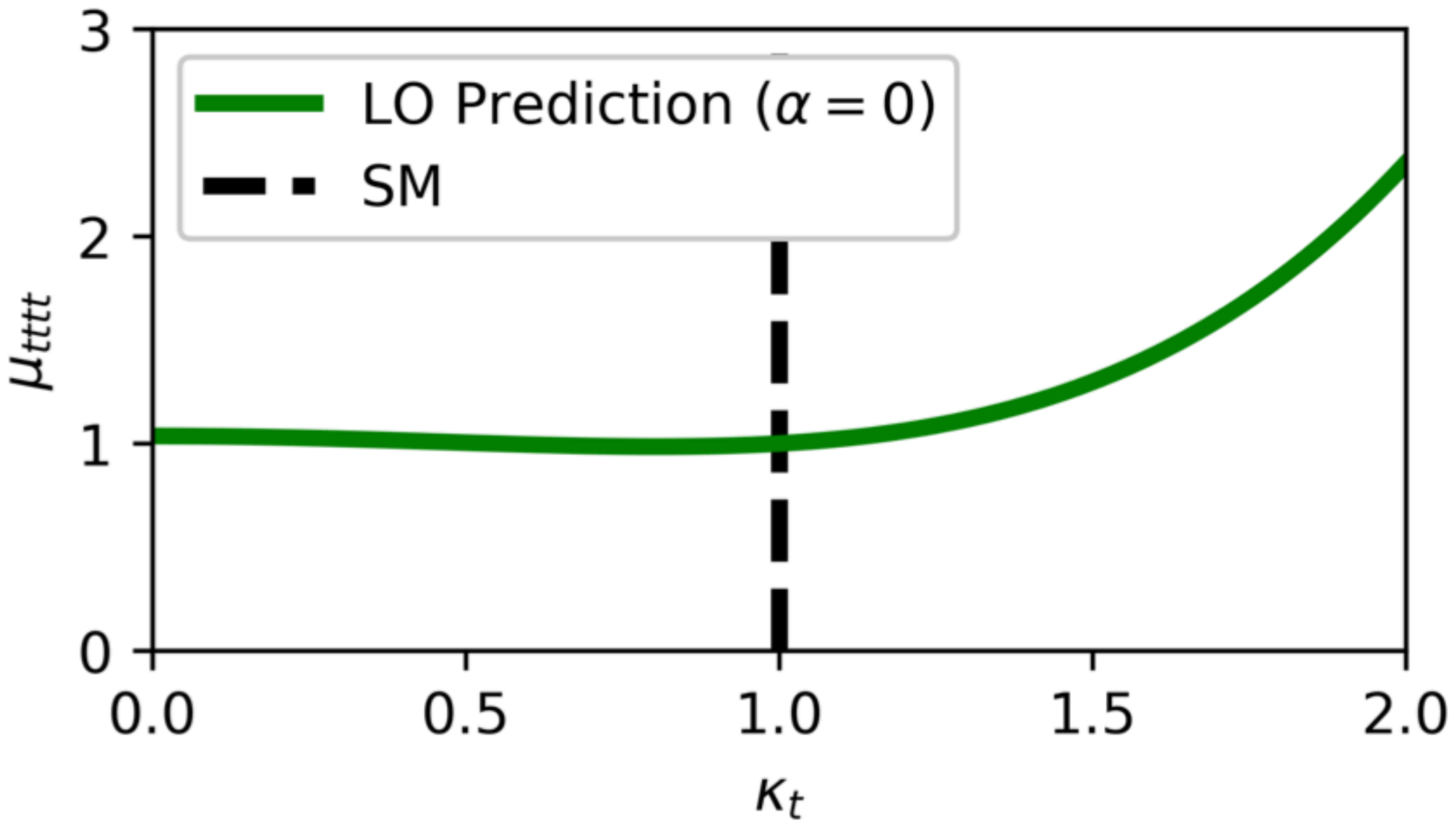
[arXiv:2412.01548]

Width measurement: ttH + tttt

- H→ZZ channel sensitivity mainly from ggF
  - If the H-g coupling running is different than SM, the result is invalid
- ttH + tttt channel relies on **tree-level H-t Yukawa coupling κ_t**
  - $\Gamma_H < 450$ **MeV obs. (75 MeV exp.) using only on-shell ttH to constrain κ_t,**
  - $\Gamma_H < 160$ MeV obs. (55 MeV exp.) with indirect constraint from ggF/H→γγ

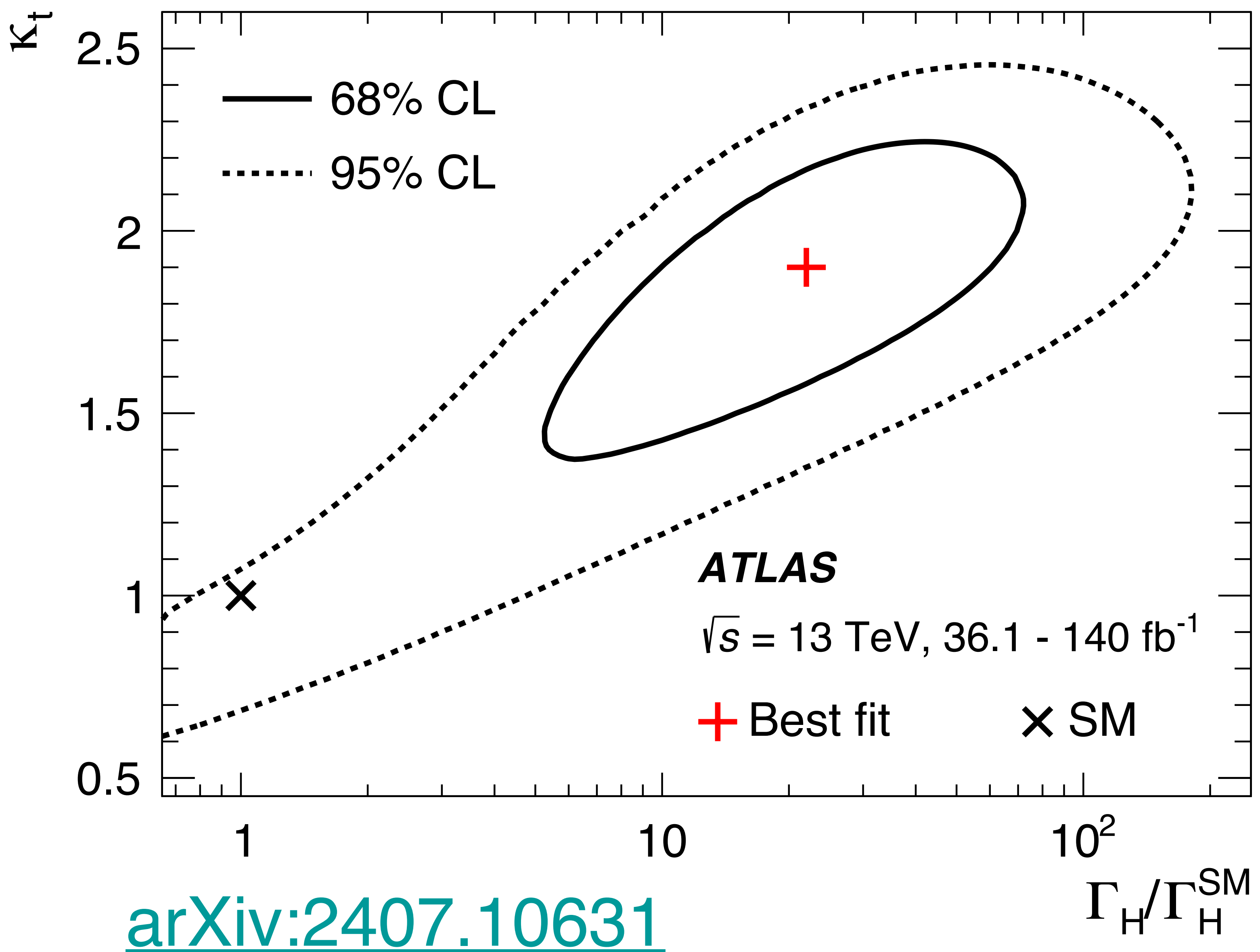




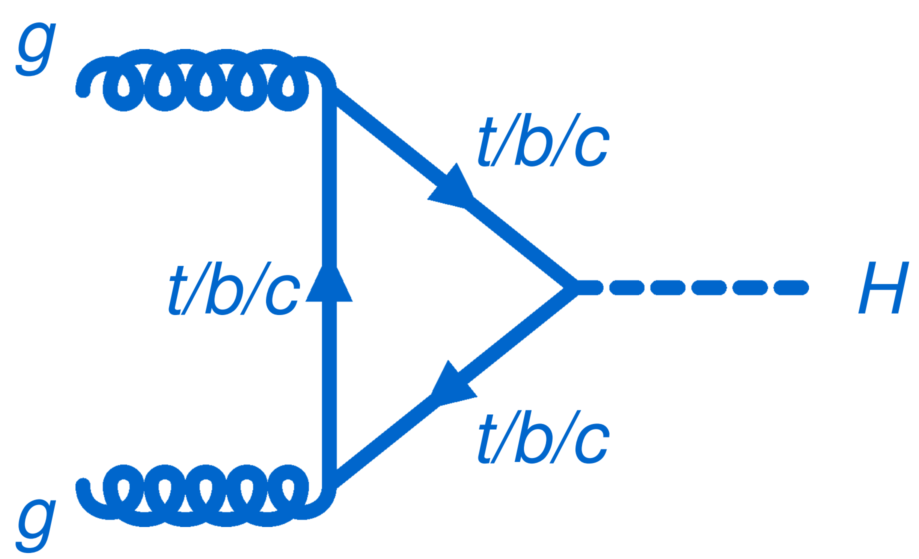


4-top rate dependence on κ_t

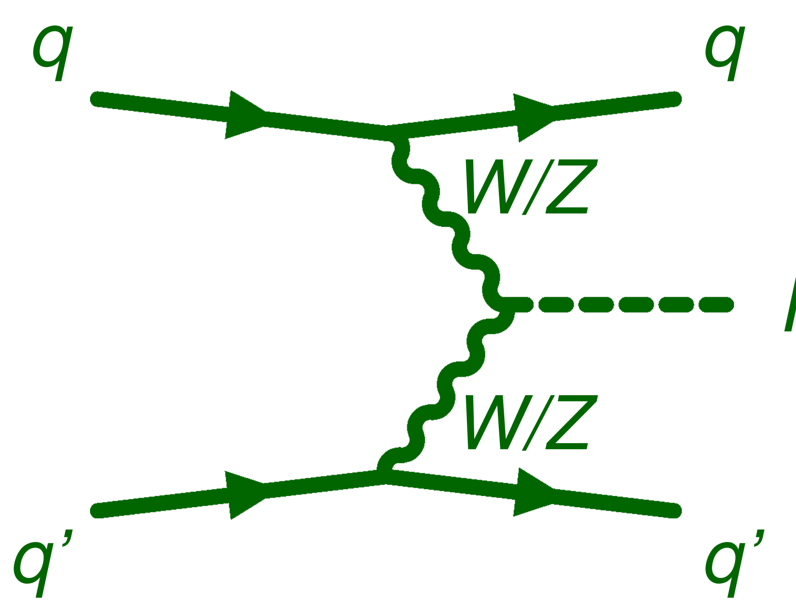
Q-H Cao et al, PRD 99 113003



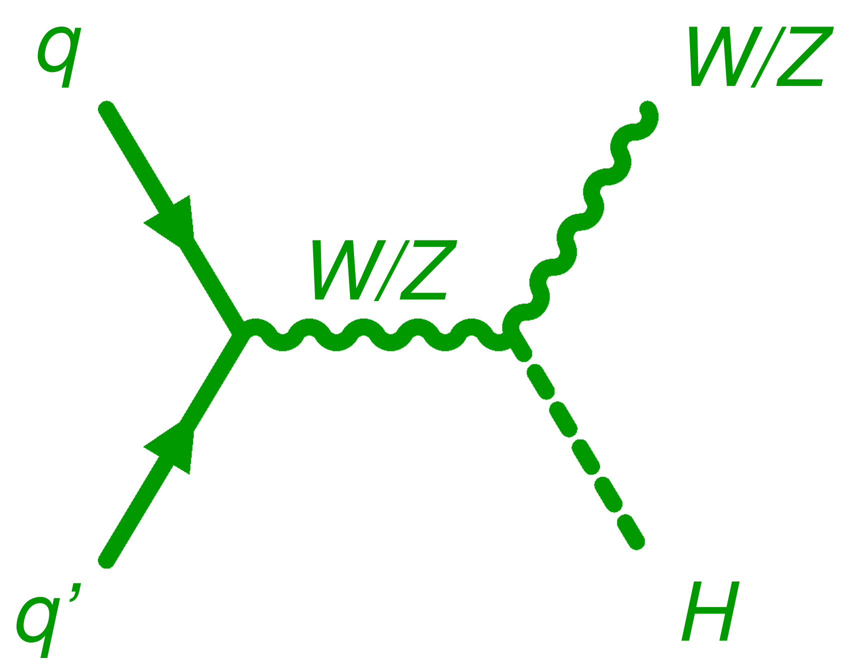
arXiv:2407.10631



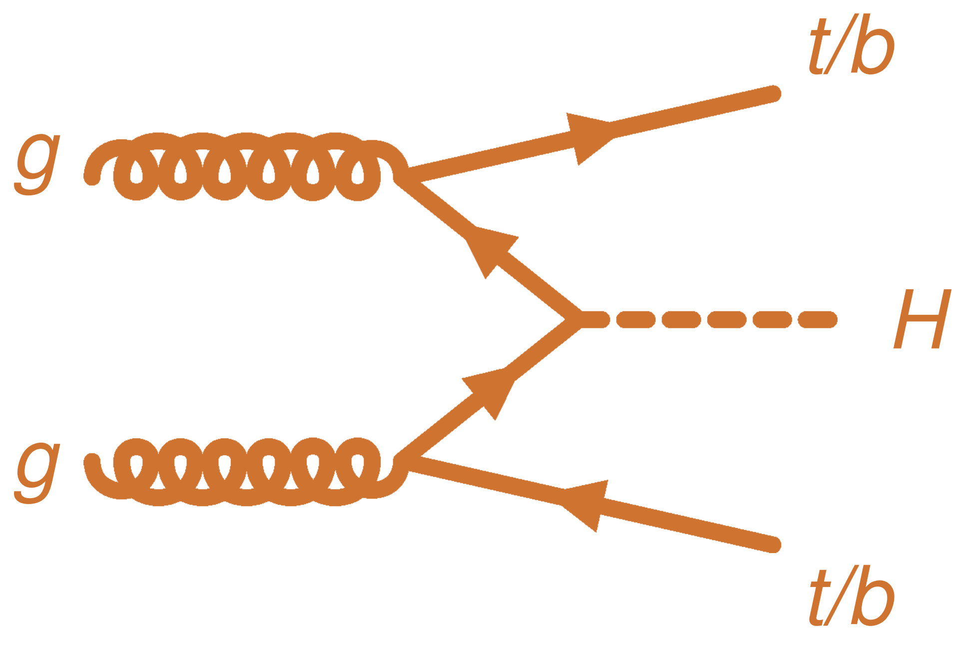
ggF (87%)



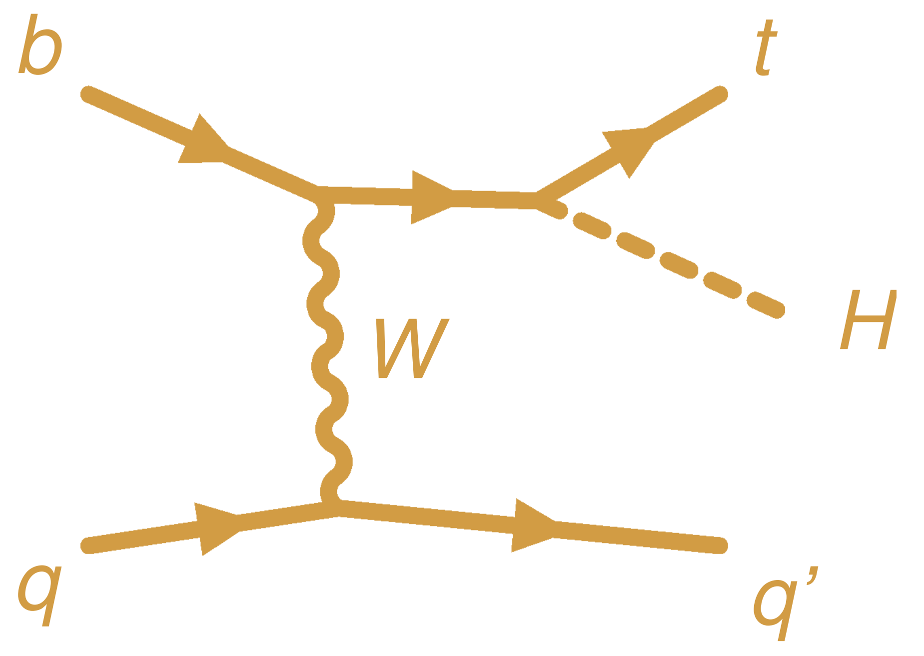
VBF (7%)



VH (4%)

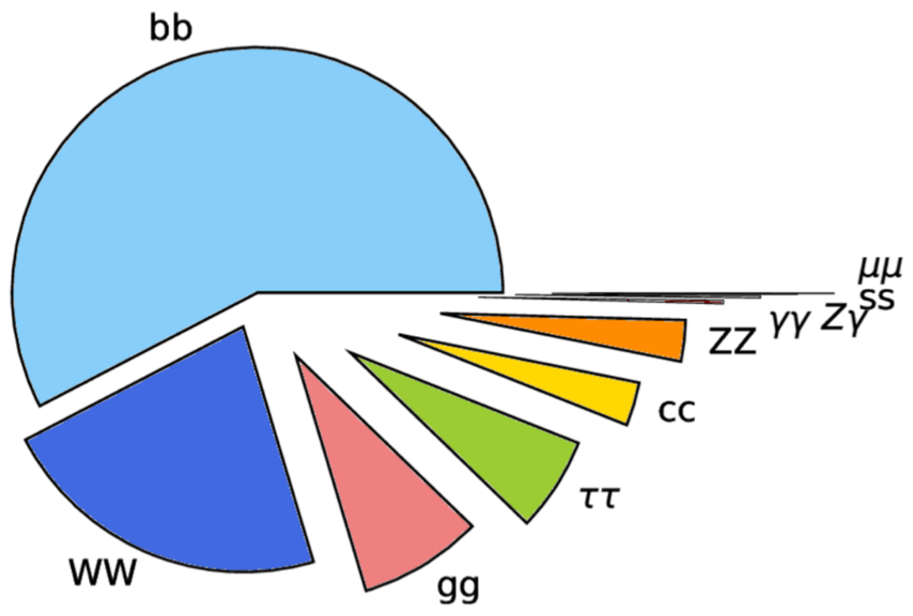


ttH/bbH (2%)

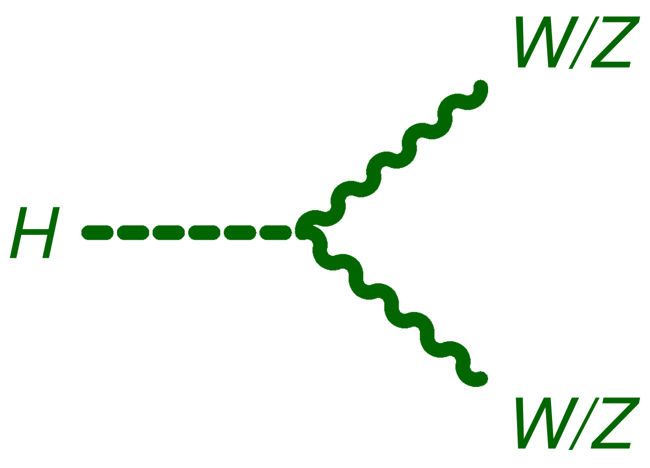


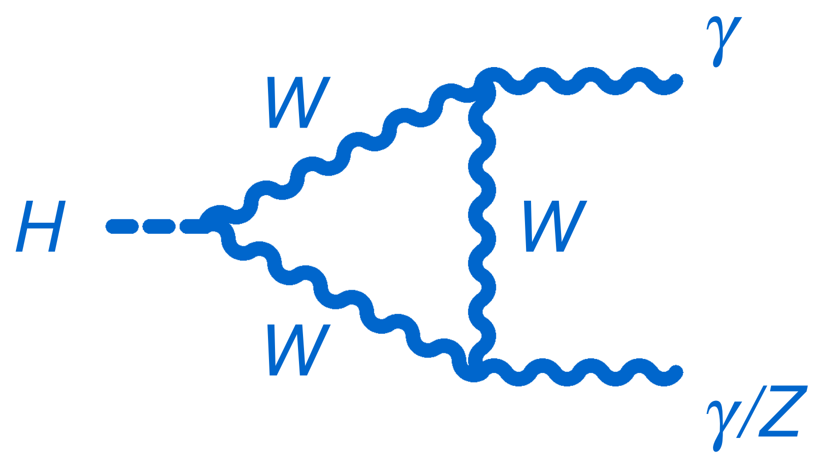
tH (0.1%)

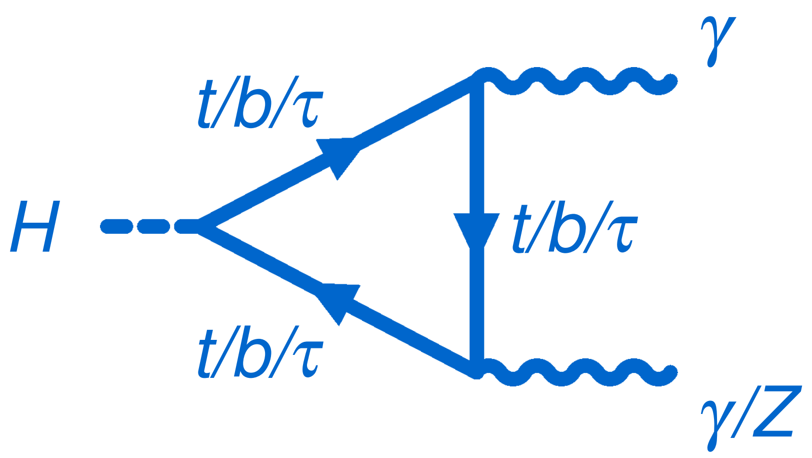
Cross-section measurements

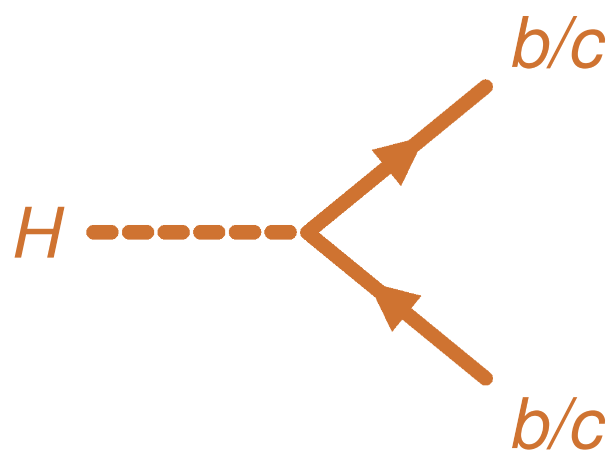


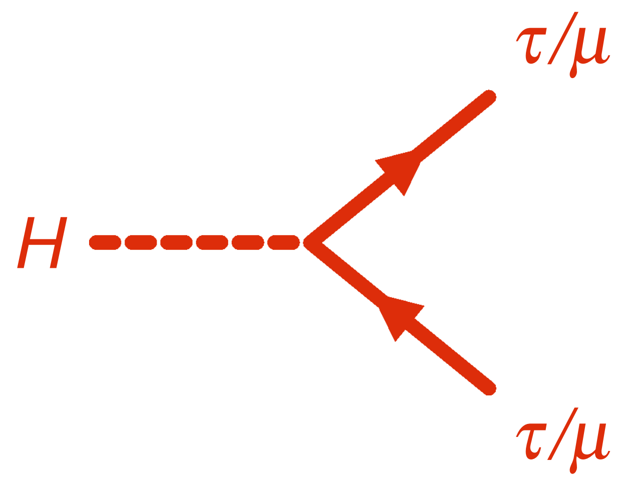
Higgs boson decay BR



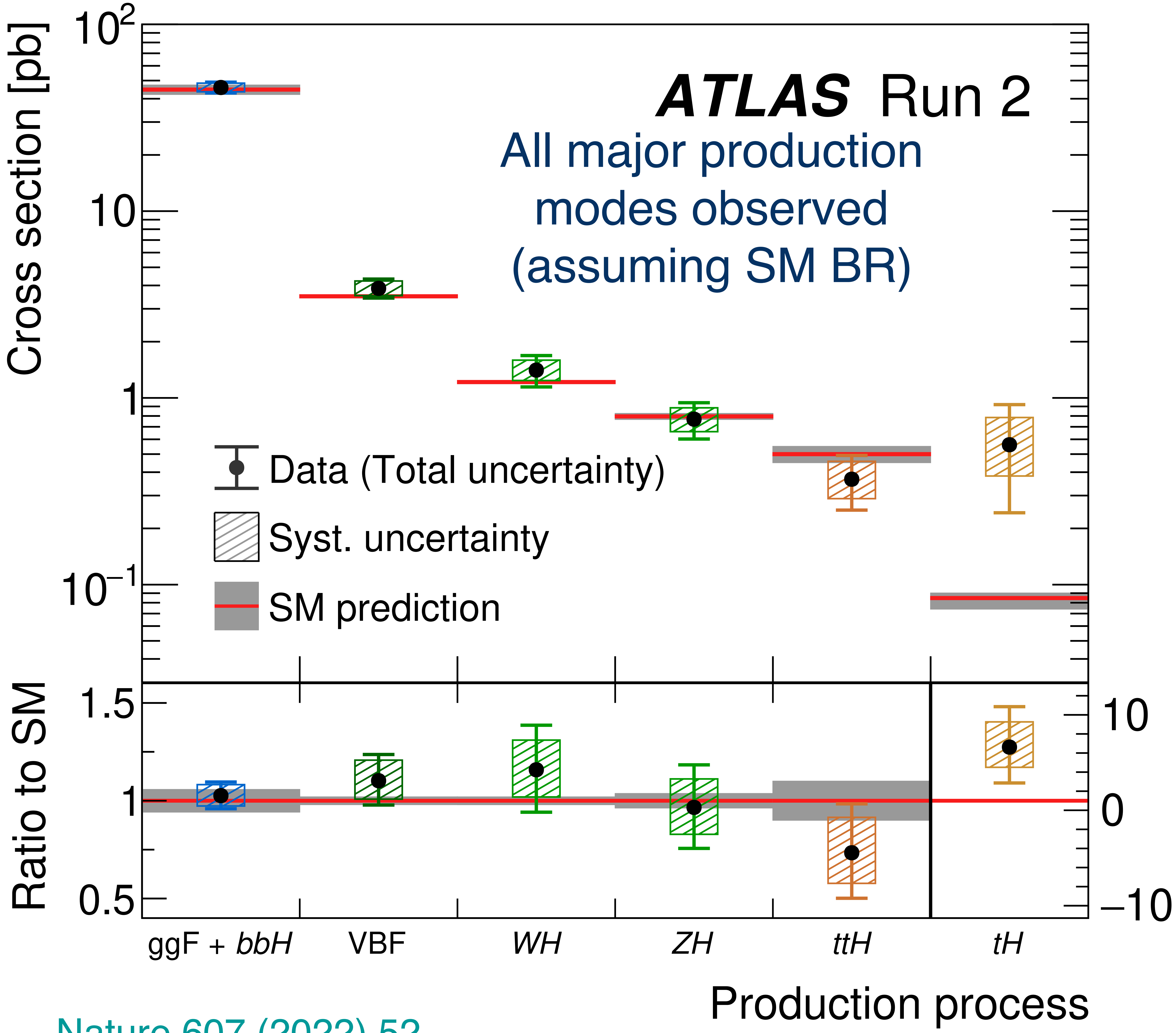








Inclusive production cross-sections



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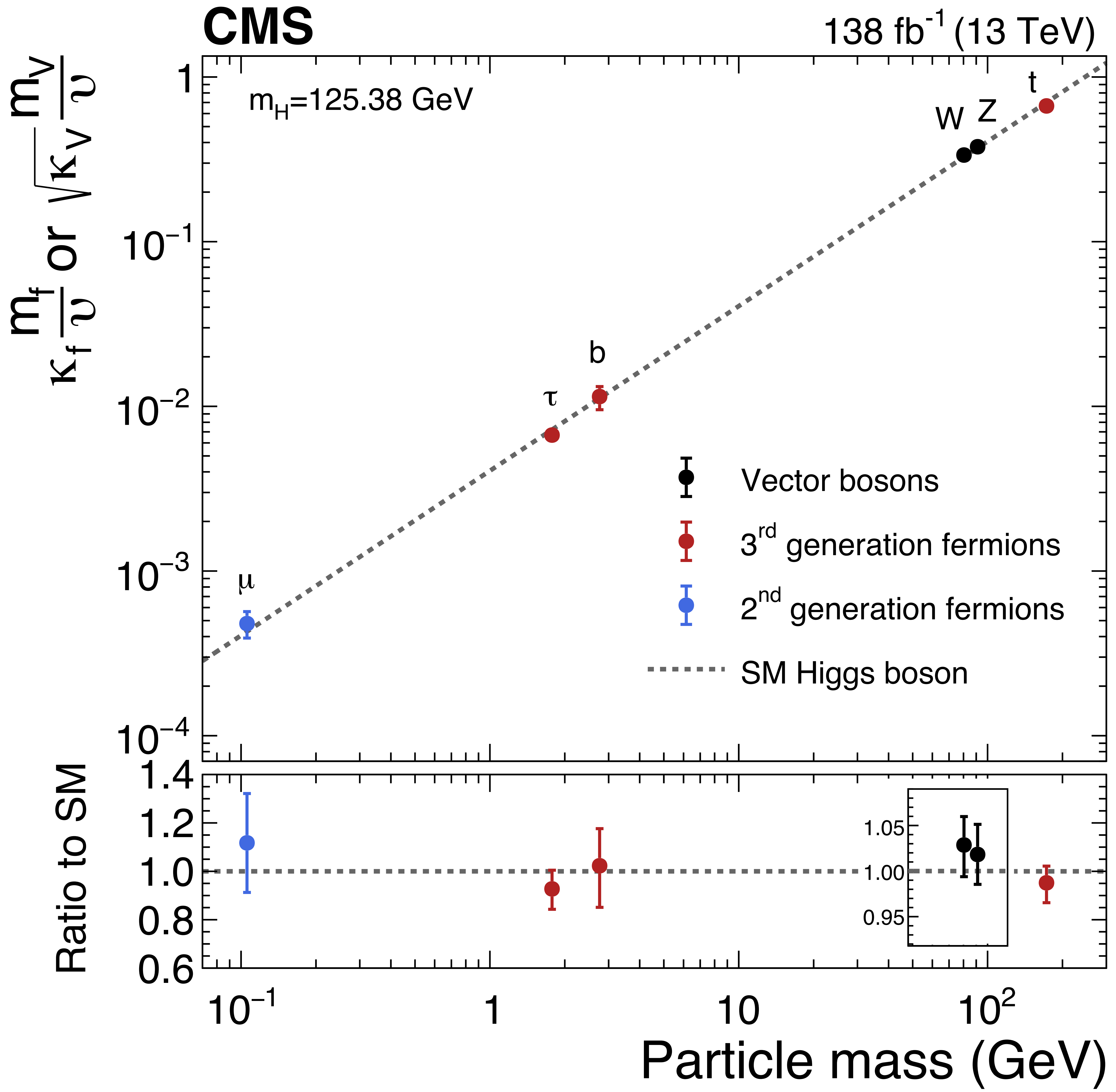

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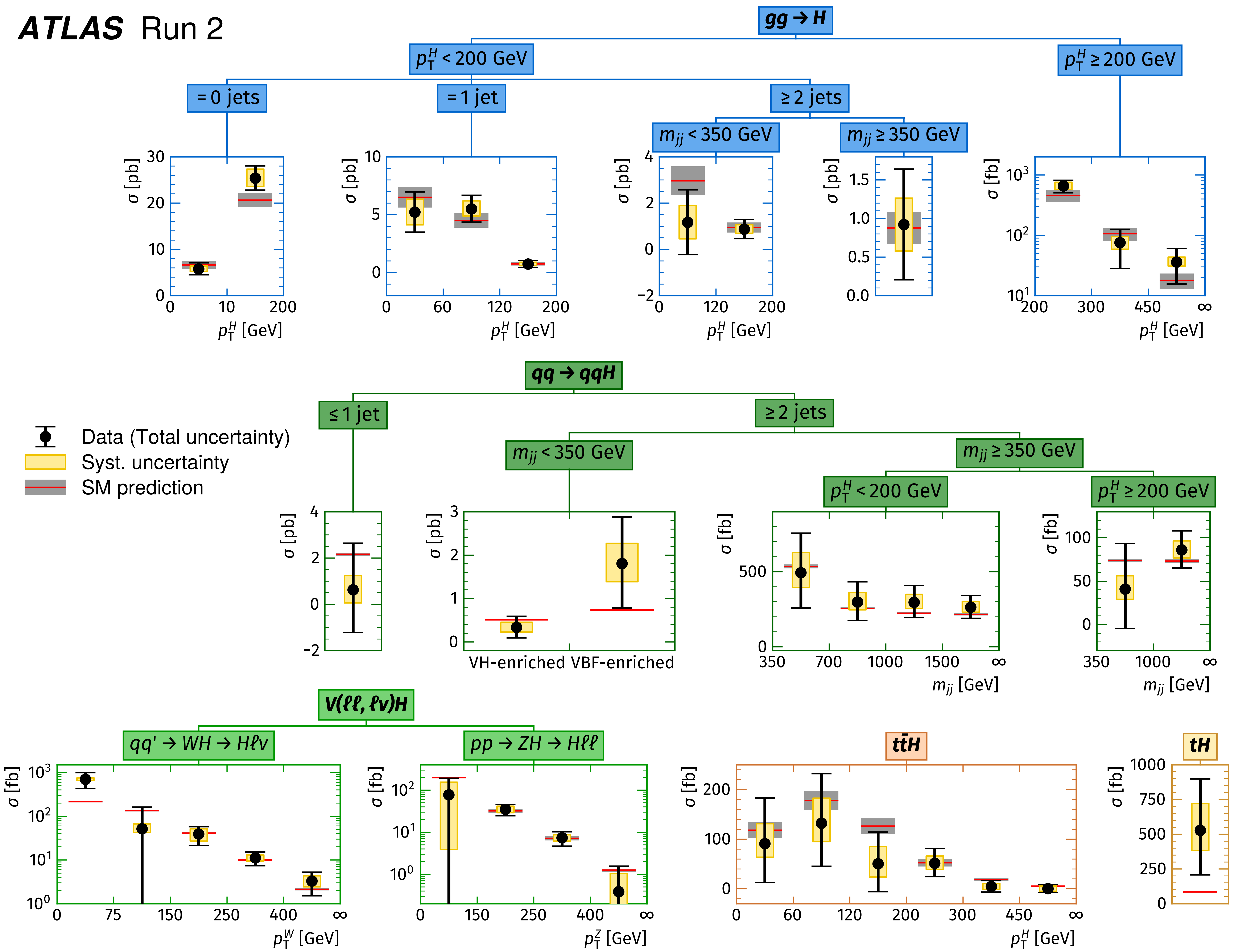
Simplified Template Cross-Section (STXS)

- Need to **go differential** to better validate SM & probe potential new physics
  - **A common binning scheme** is needed among decay channels & between experiments
- **STXS framework** has been widely implemented in ATLAS/CMS Higgs measurements
  - **Feedback from people with first-hand experience is crucial for its future development!**



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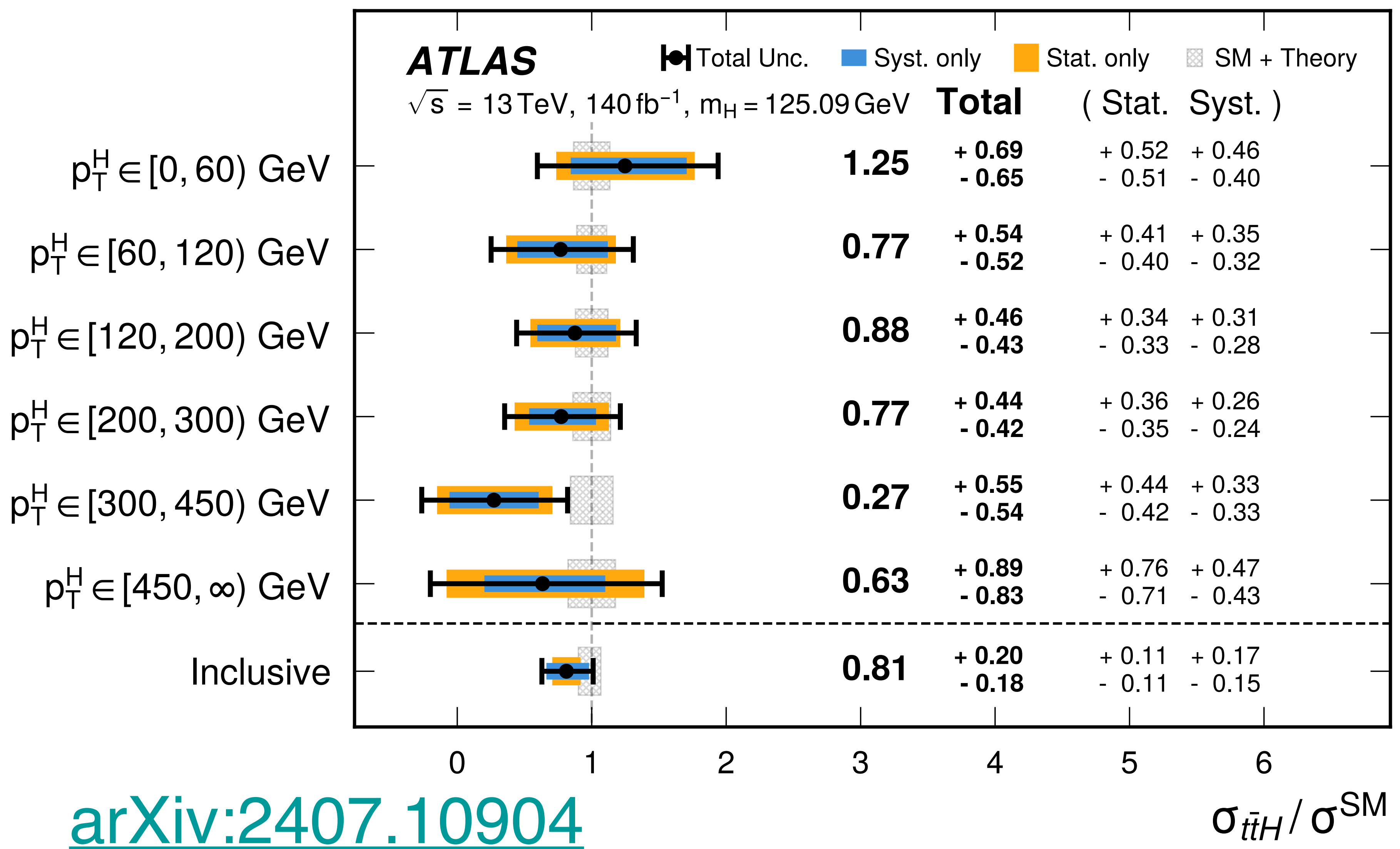
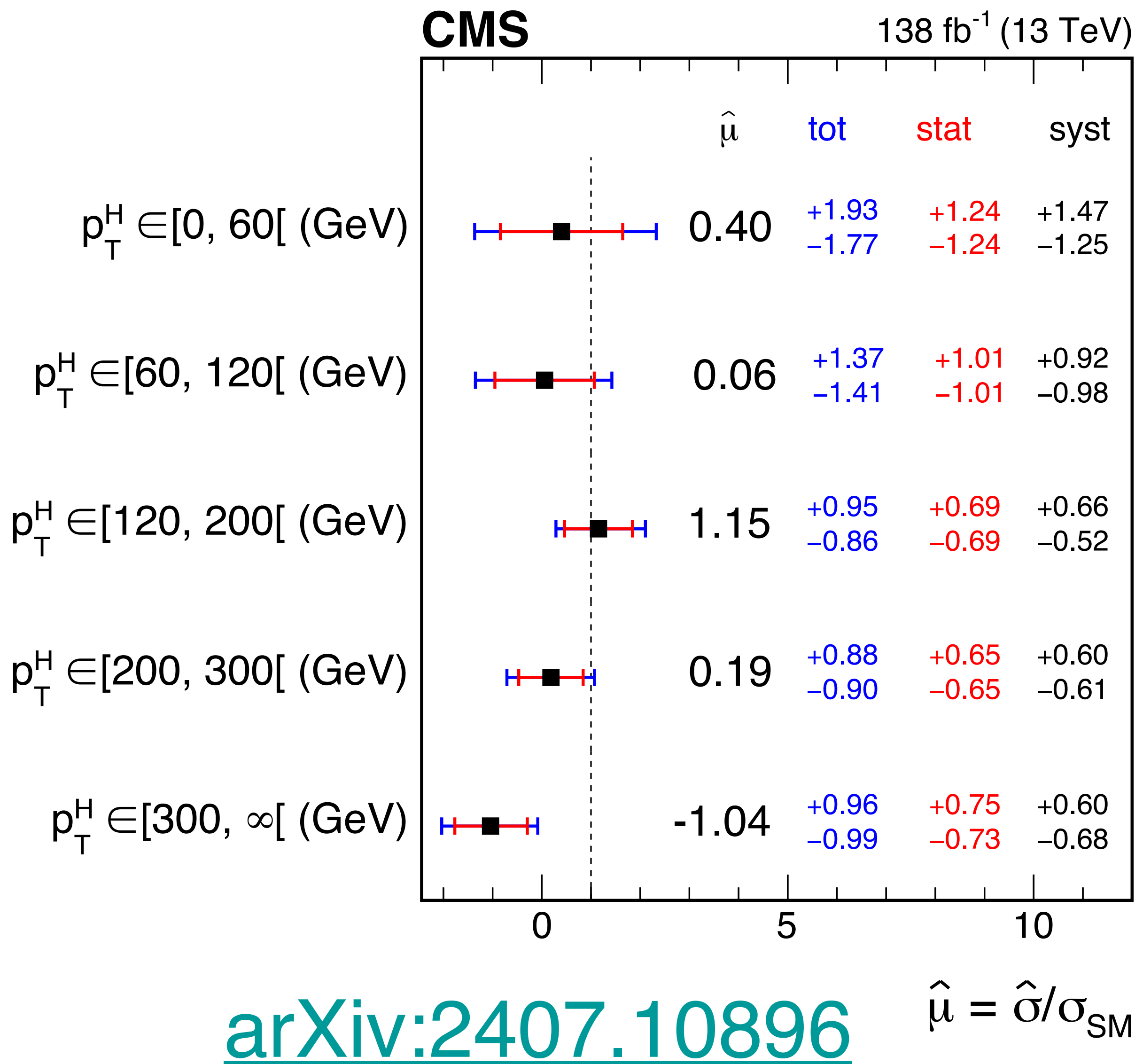
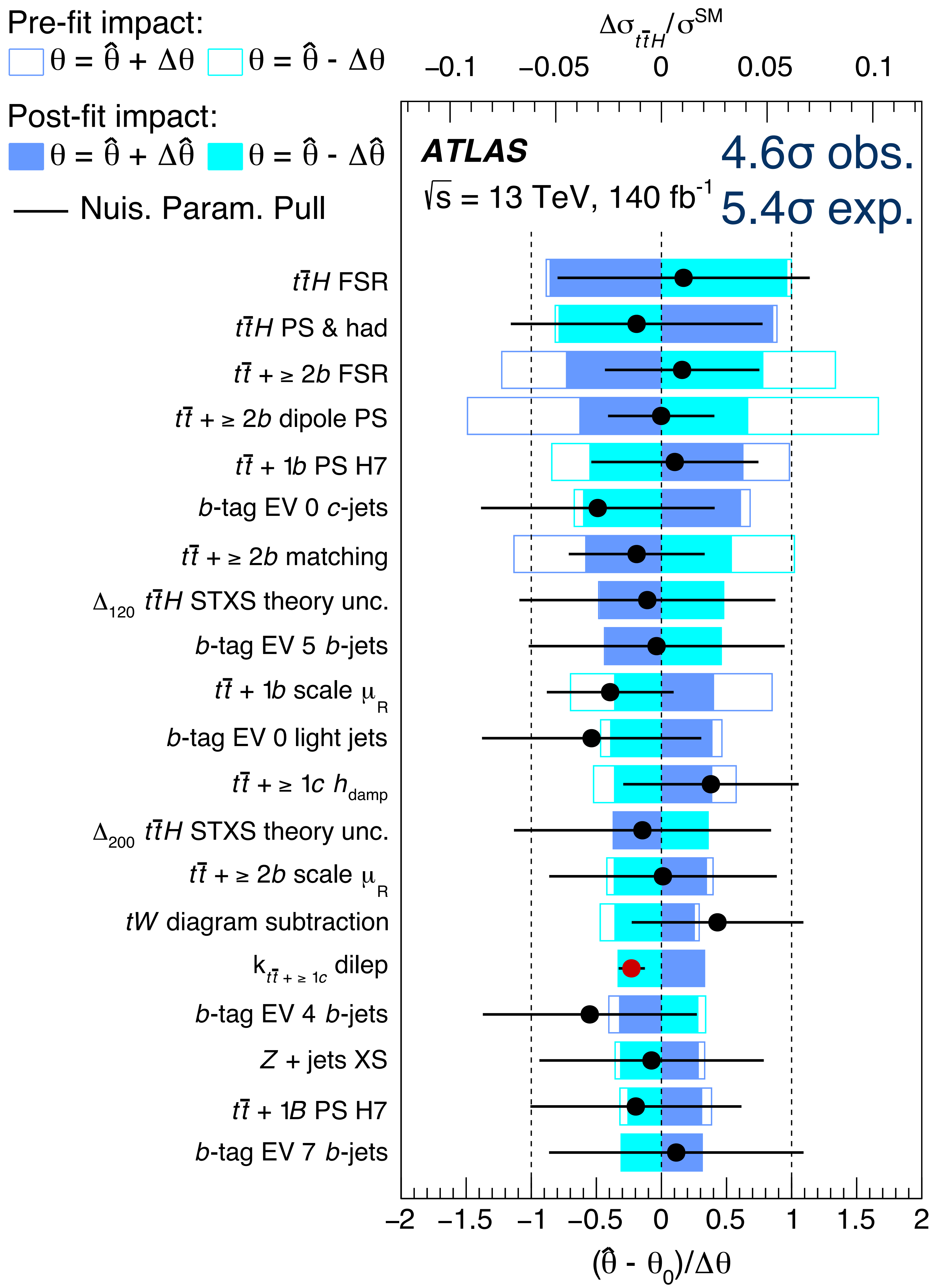
STXS measurement: ttH, H→bb



[arXiv:2407.10904](https://arxiv.org/abs/2407.10904)



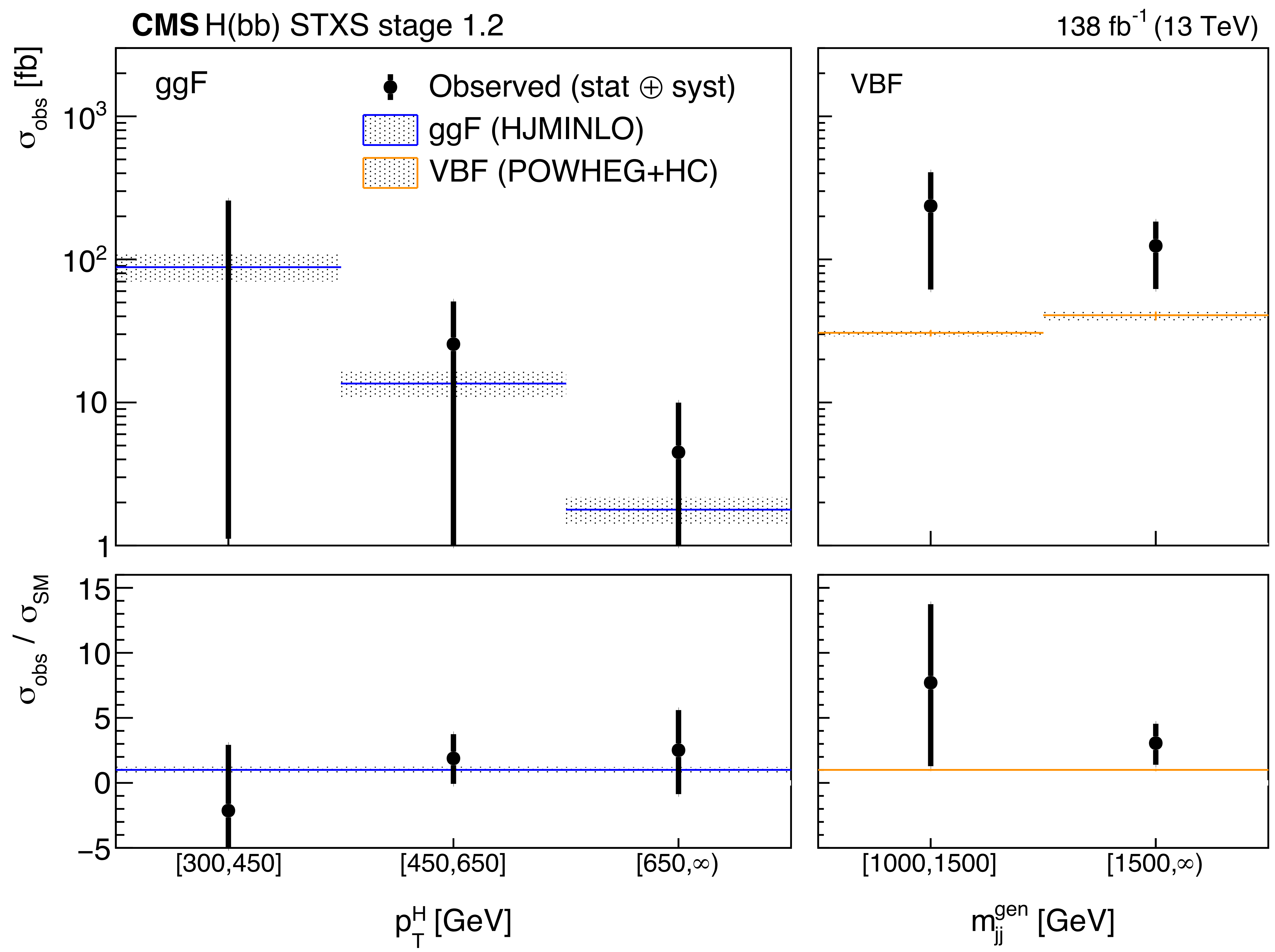
[arXiv:2407.10896](https://arxiv.org/abs/2407.10896)

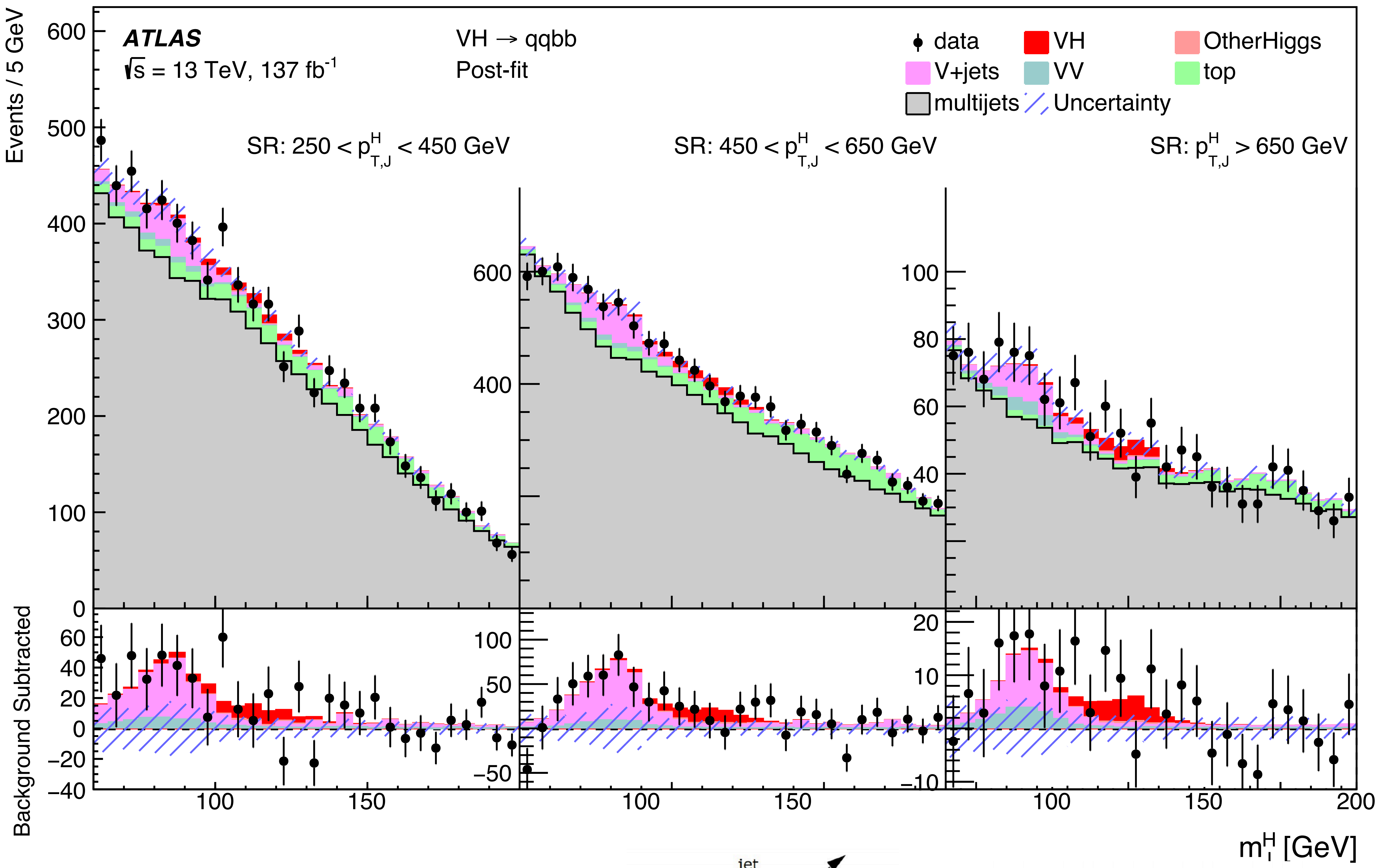


- ATLAS achieves **x2 better sensitivity** compared with previous analysis based on the same dataset
  - Better b-tagging algorithm, better tt+HF modeling (no longer leading syst.) , NN for Higgs boson reconstruction

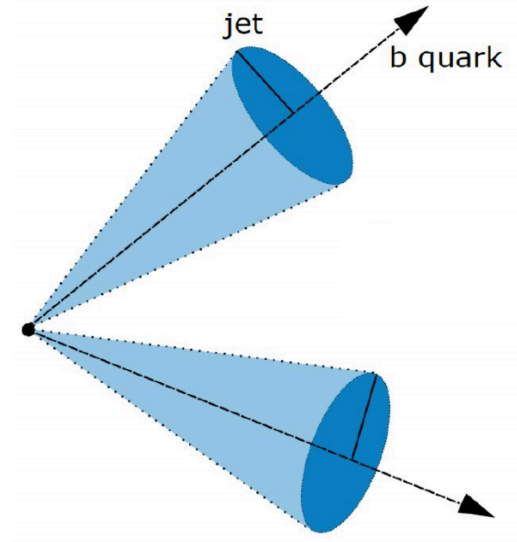
	Rate	Obs. Z0 [σ]	Exp. Z0 [σ]
ATLAS	$\sigma/\sigma_{SM} = 0.81 \pm 0.11(\text{stat.})^{+0.17}_{-0.15}(\text{syst.})$	4.6	5.4
CMS	$\mu = 0.33 \pm 0.17(\text{stat.}) \pm 0.21(\text{syst.})$	1.3	4.1

STXS measurement: boosted H→bb

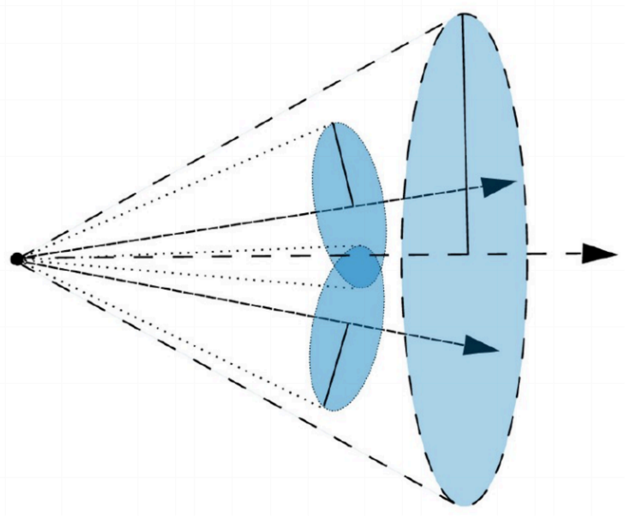




- Use **boosted H→bb** to probe **very high p_T regime** that is sensitive to BSM physics

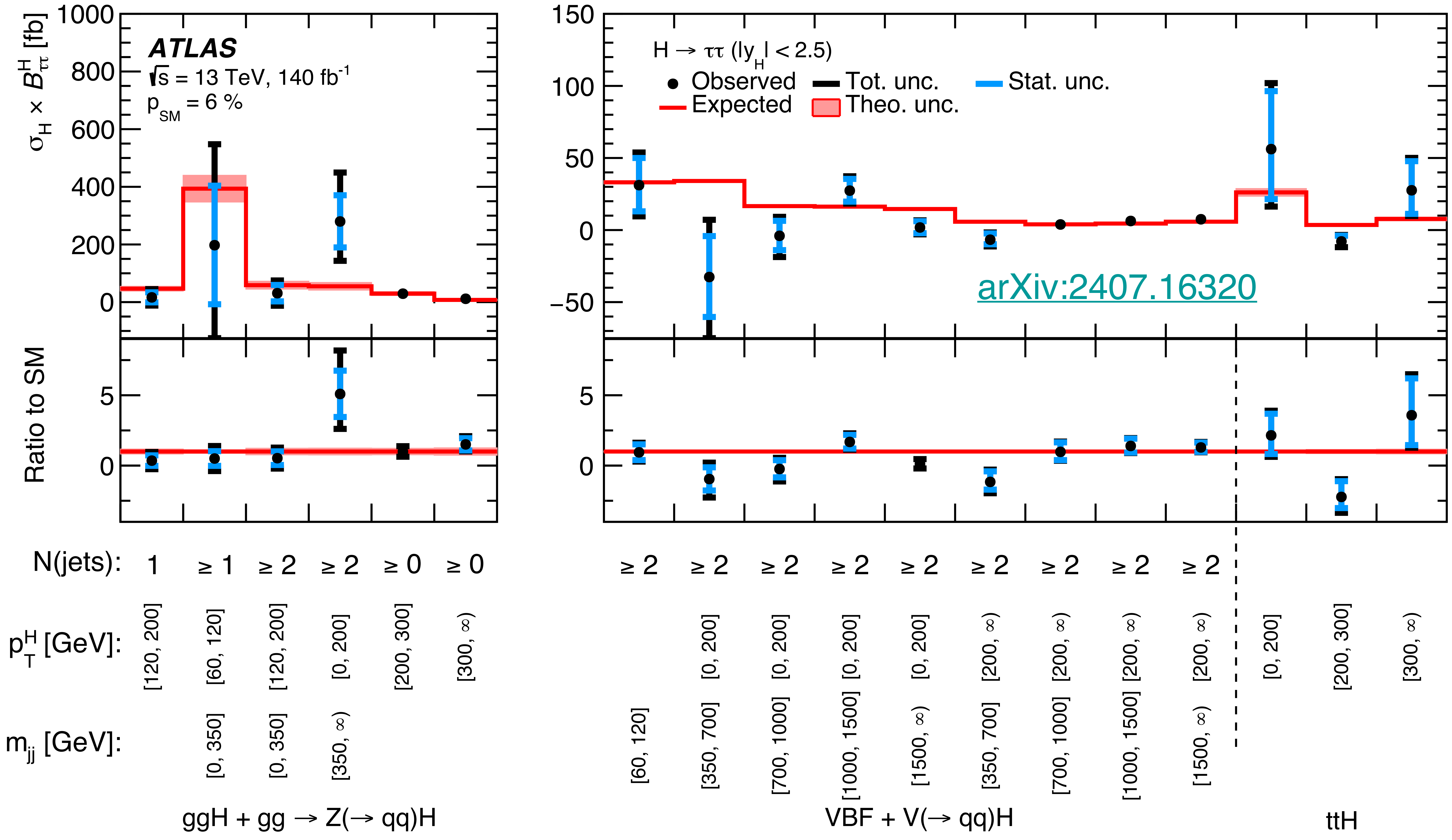


Resolved

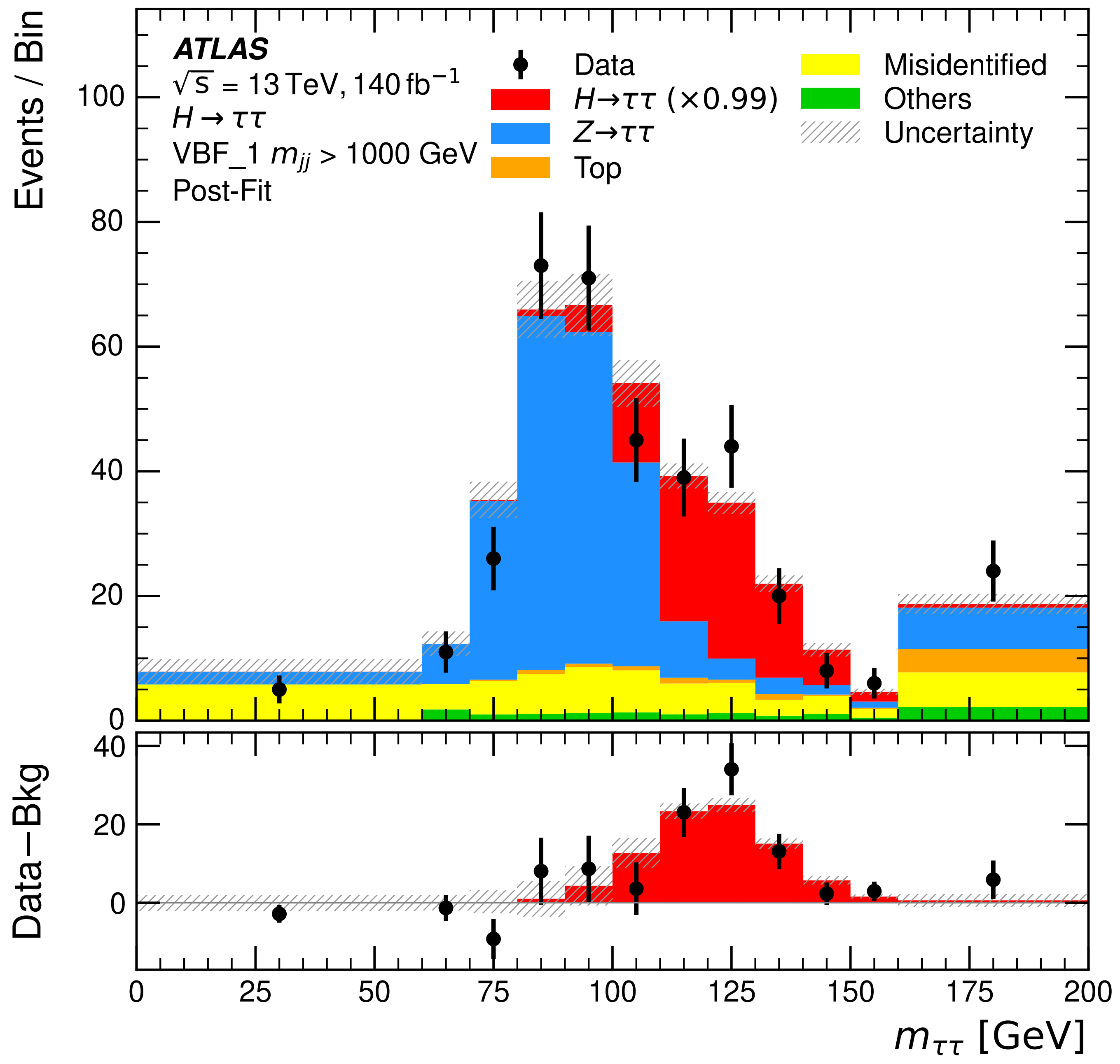


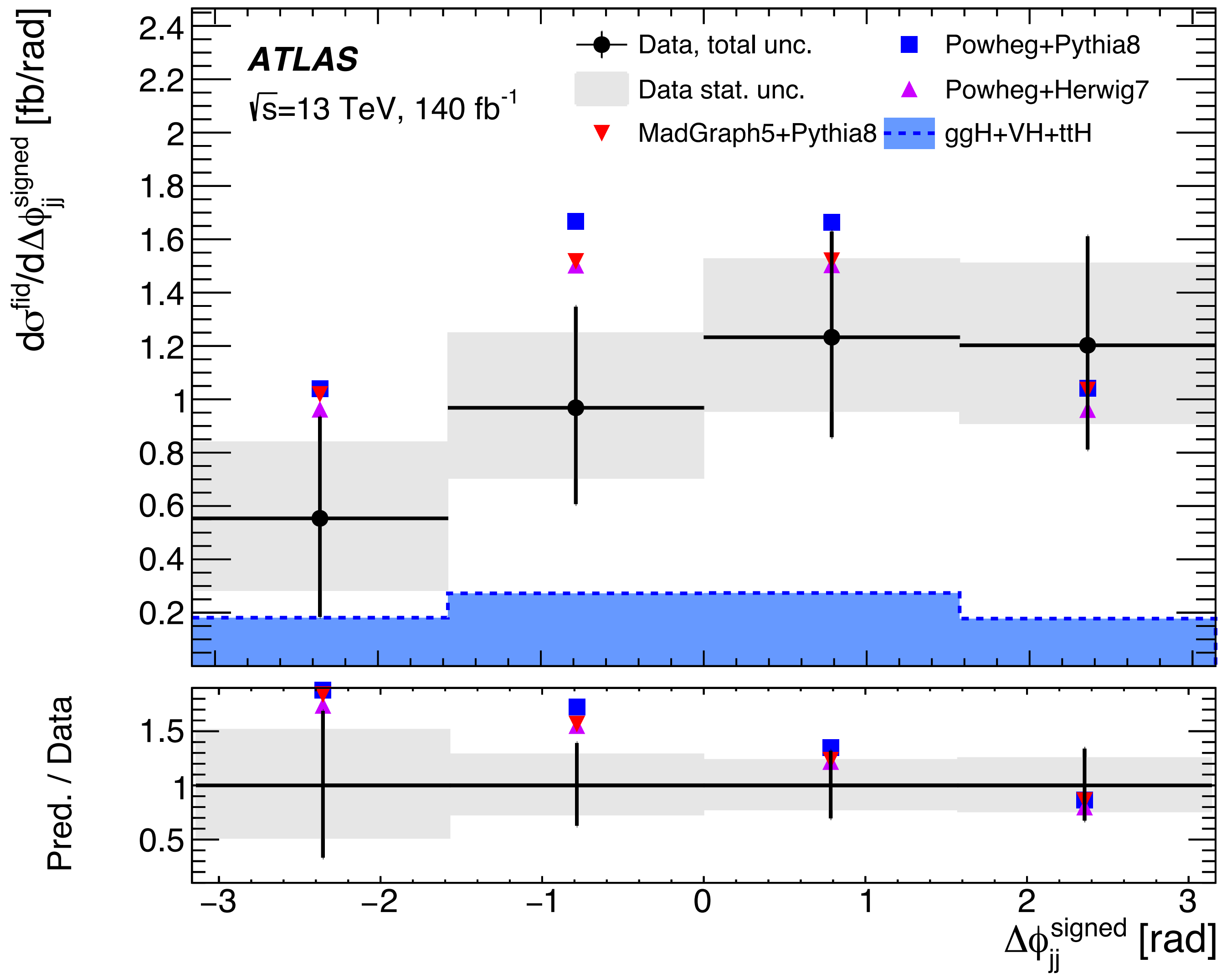
Boosted

STXS/diff. XS measurement: H→ττ



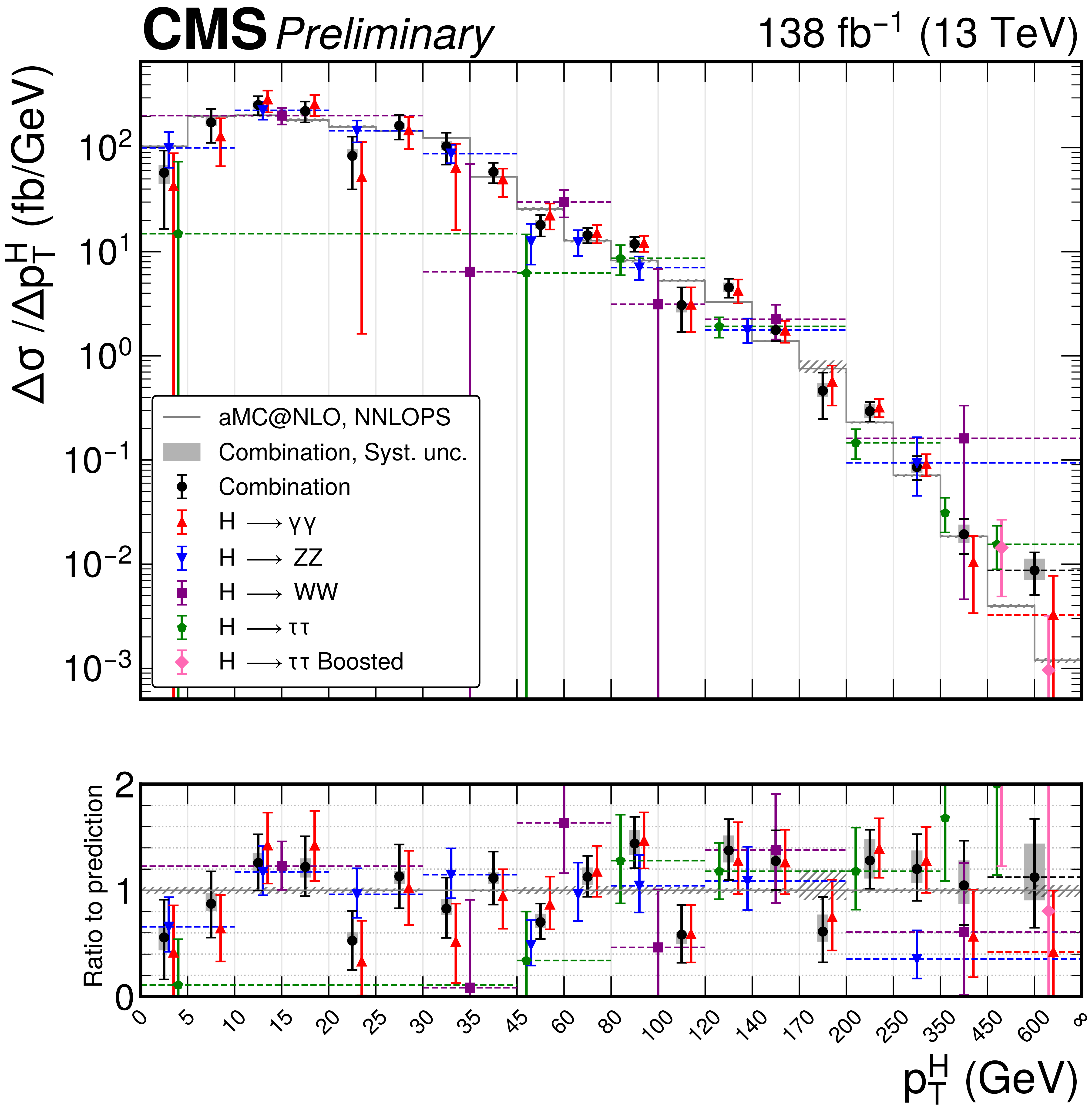
arXiv:2407.16320

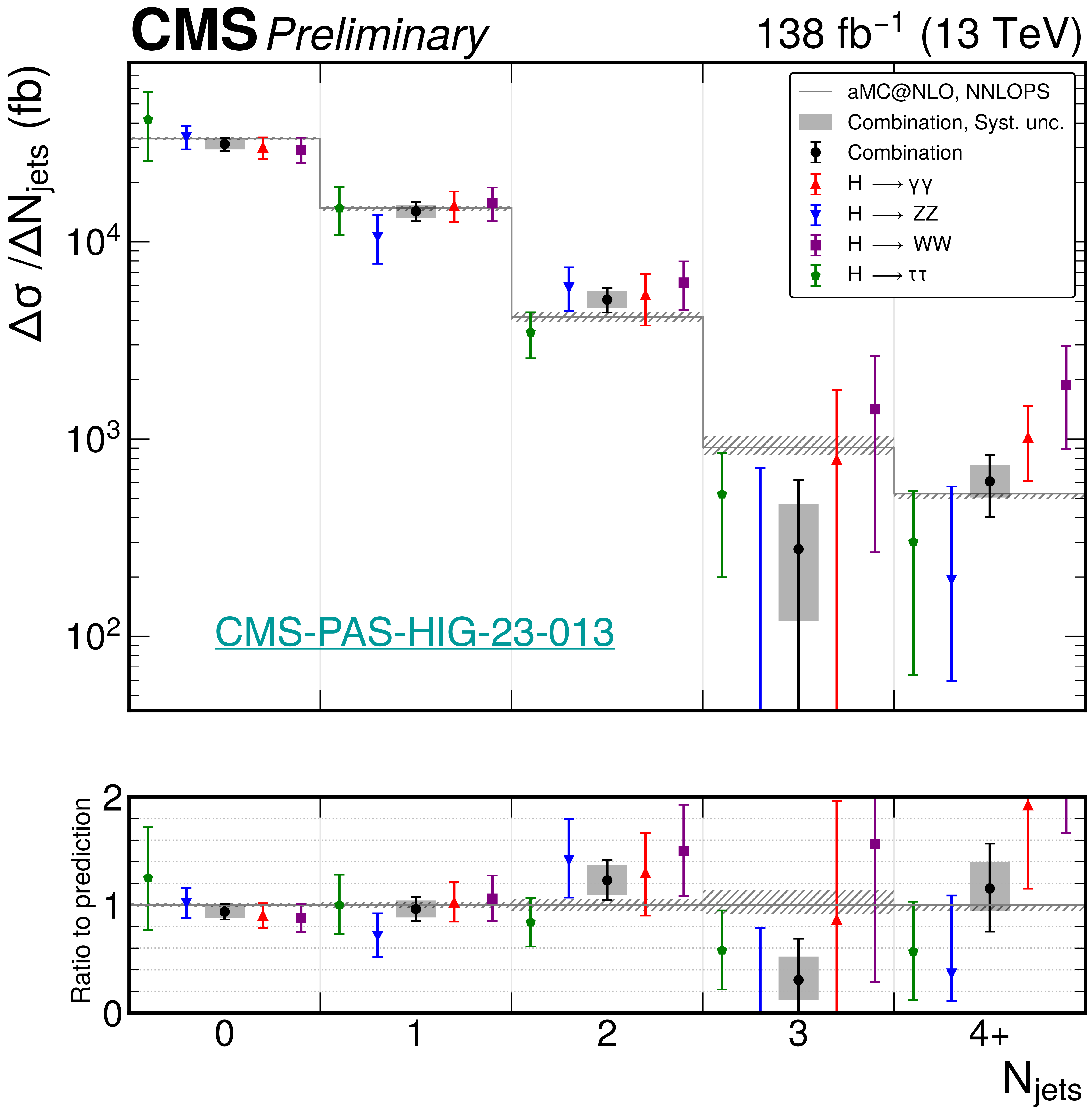




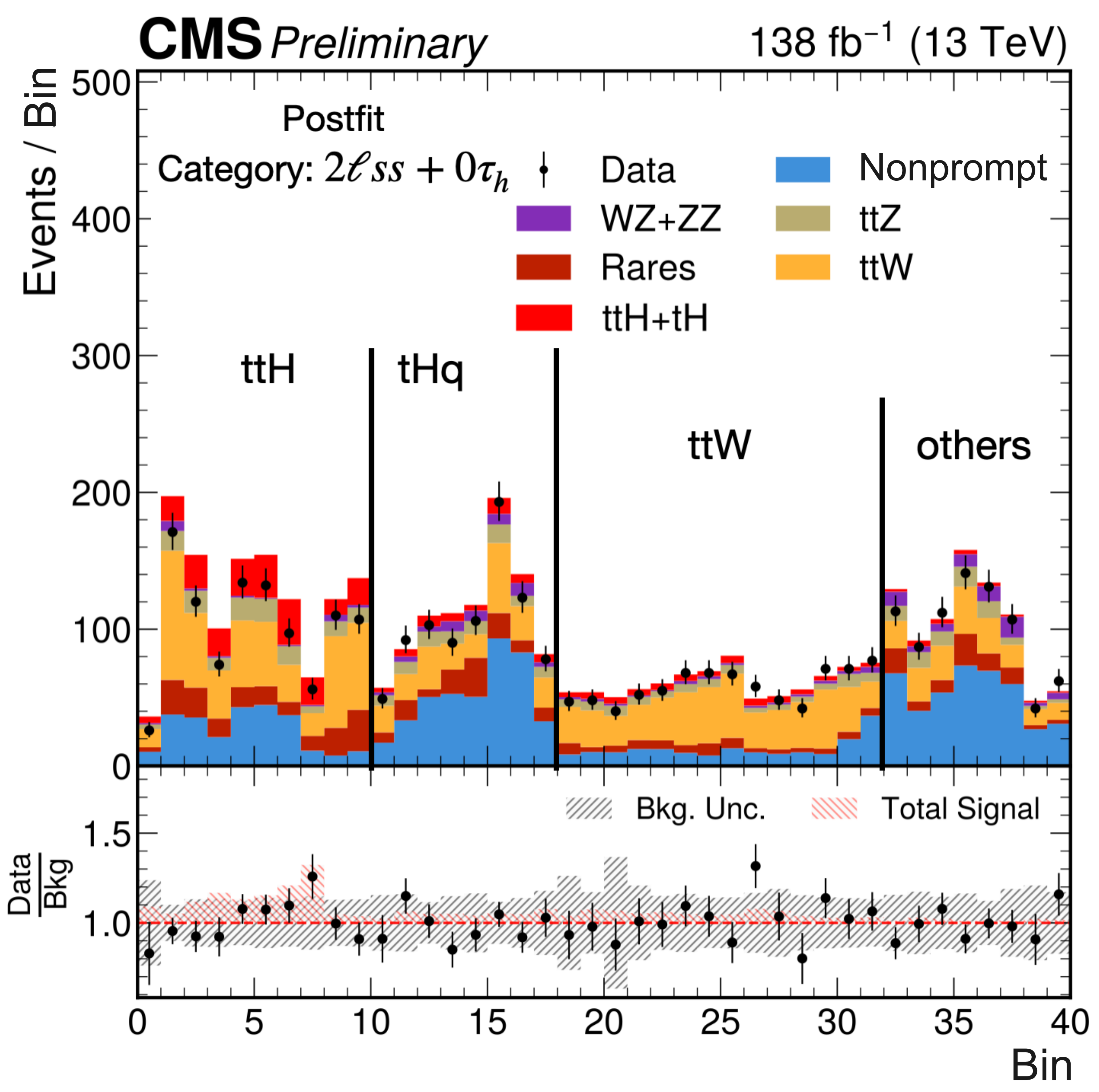
- Powerful channel for probing VBF

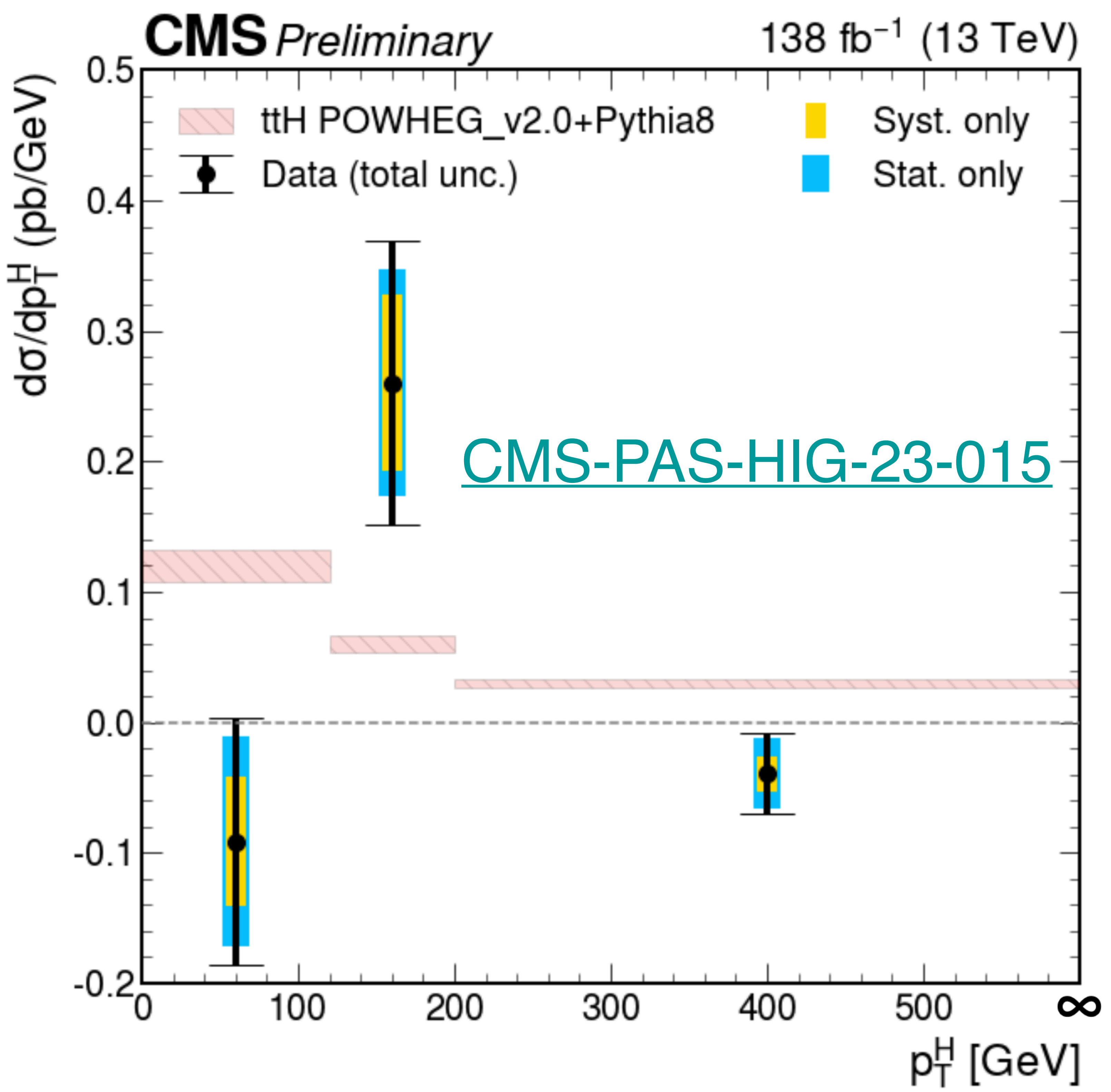
Diff. XS measurement: full phase-space combination

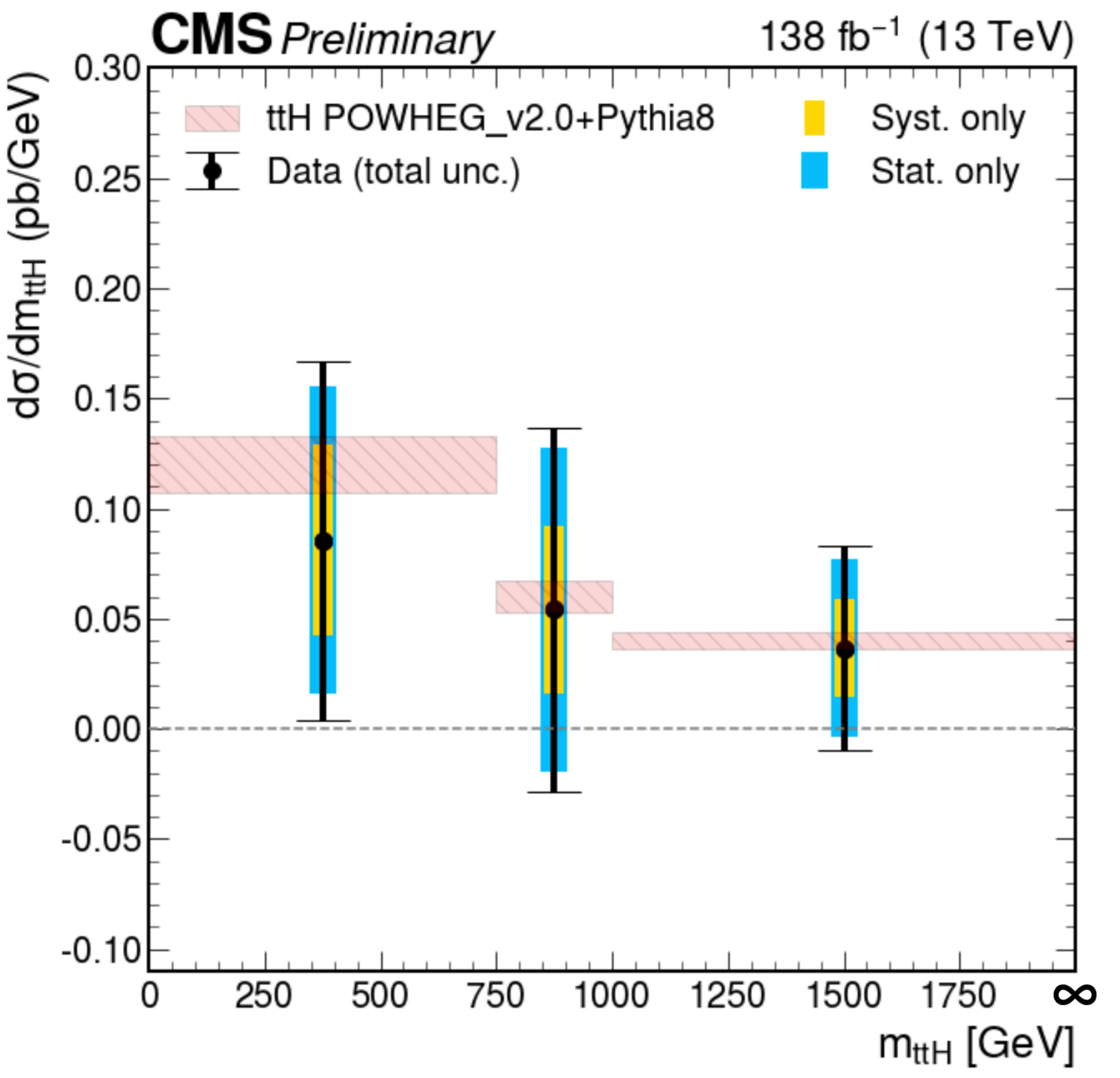




Diff. XS measurement: ttH multi-lepton



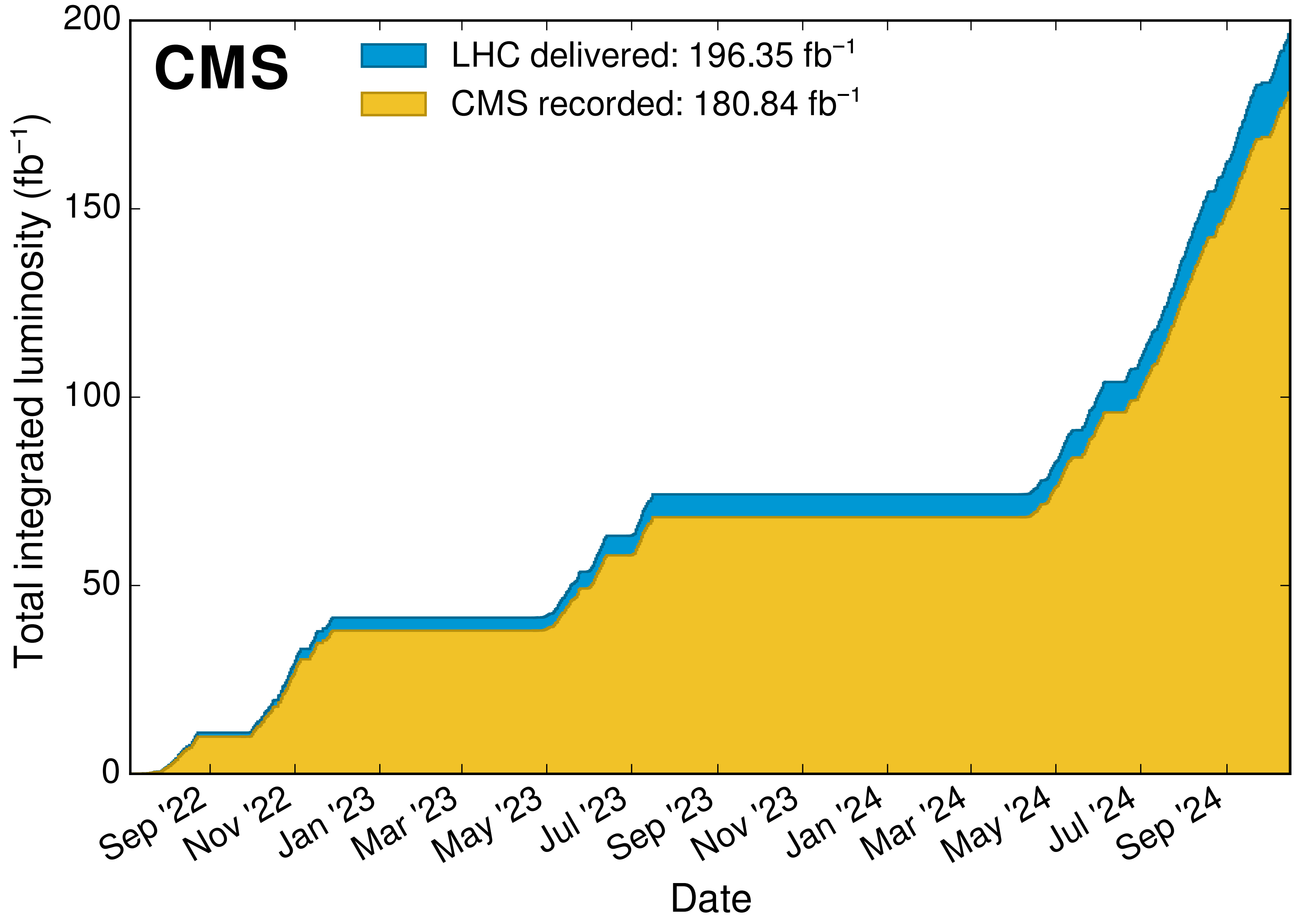


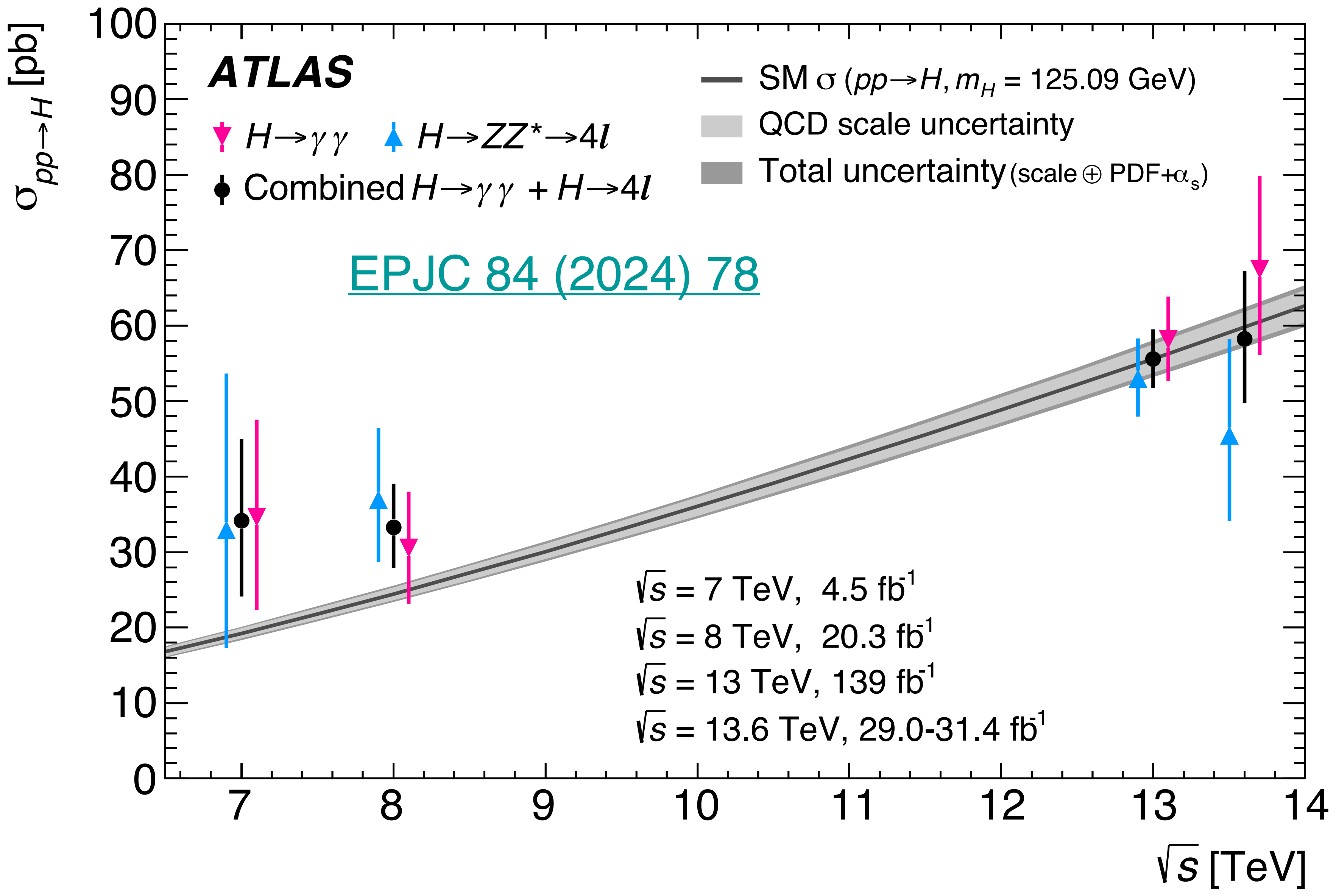


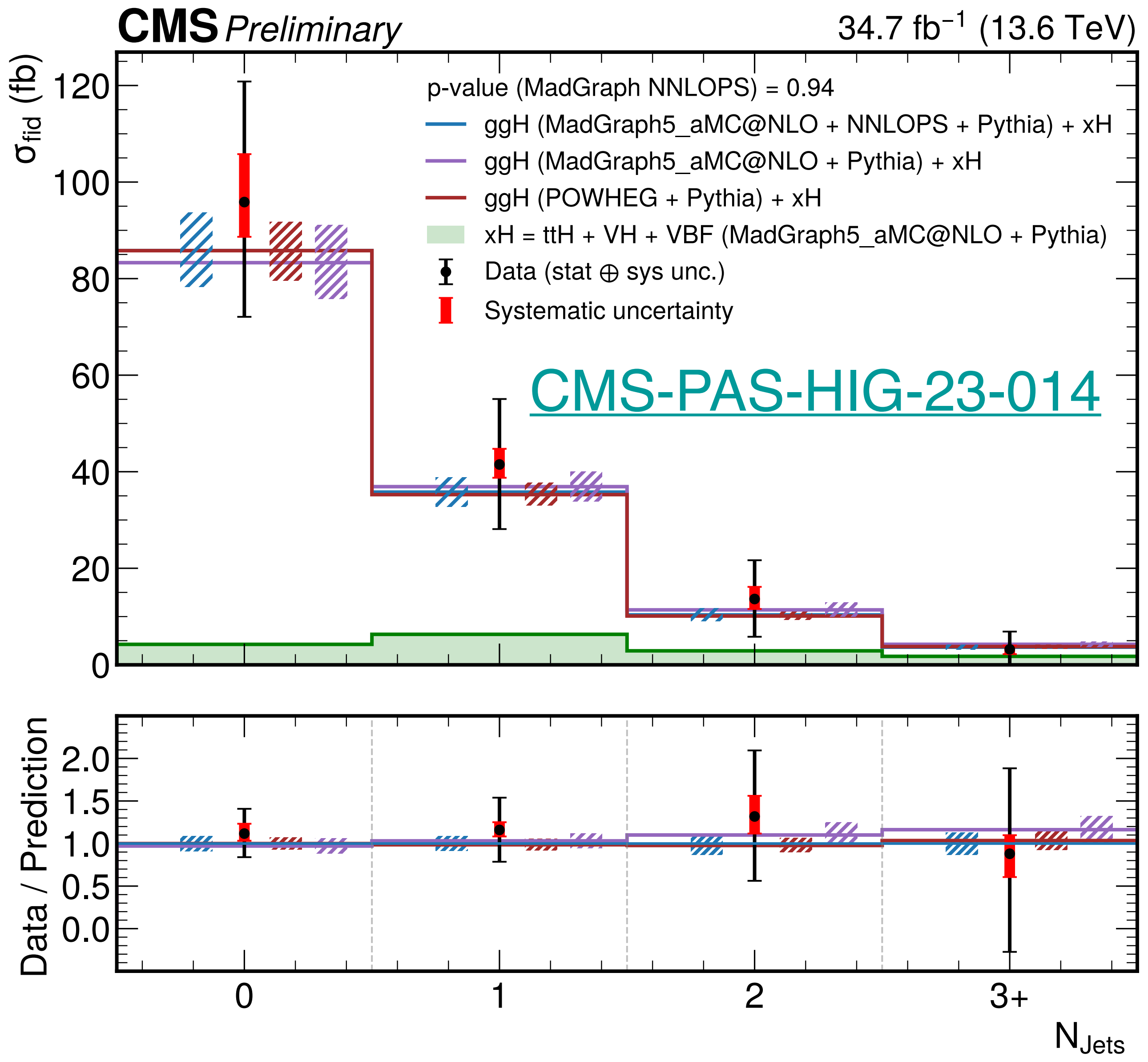
- Use DNN to separate ttH/tH signal from background (at inevitable cost of model dependence)
- Measurement still limited by statistics

Diff. XS measurement: Run 3 measurements

- **Run 3 @13.6 TeV** goes well. Dataset already larger than Run 2
  - Will hopefully reach ~250 fb^{-1} by Summer 2026: x3 stats
- First Higgs boson measurements based on 2022 data done by both ATLAS and CMS







Conclusions

- With **Run 2 data** (+ Run 1), we have
  - **0.09%** precision on Higgs boson mass
  - **~50%** precision on Γ_H from off-shell
  - **~10%** precision on production xs
- First Run 3 results available
- $\times$**20** larger Higgs boson sample at HL-LHC: improve precision by **~5**
- **Higgs boson precision measurements at LHC & beyond will decide the future of our field**

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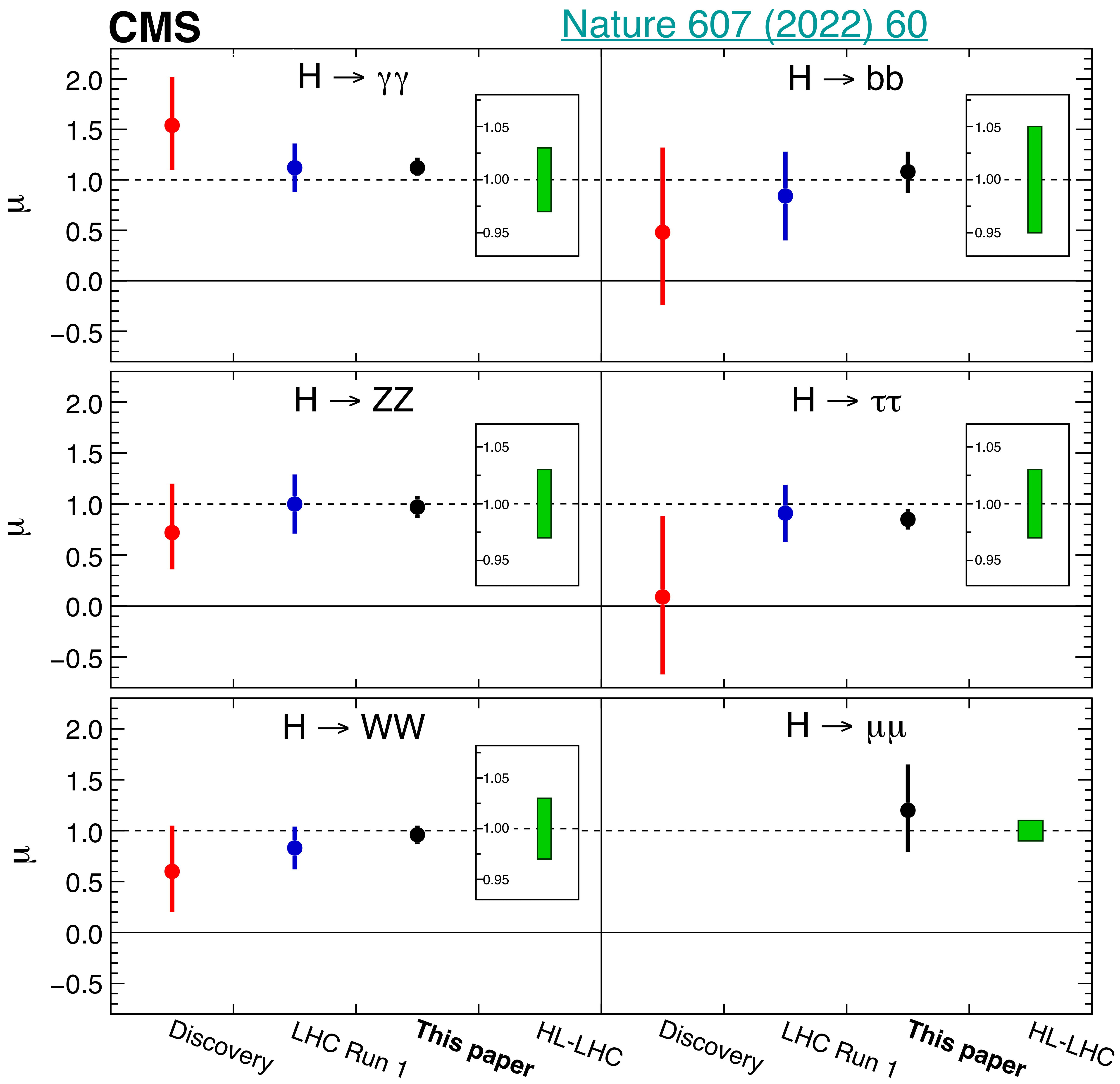
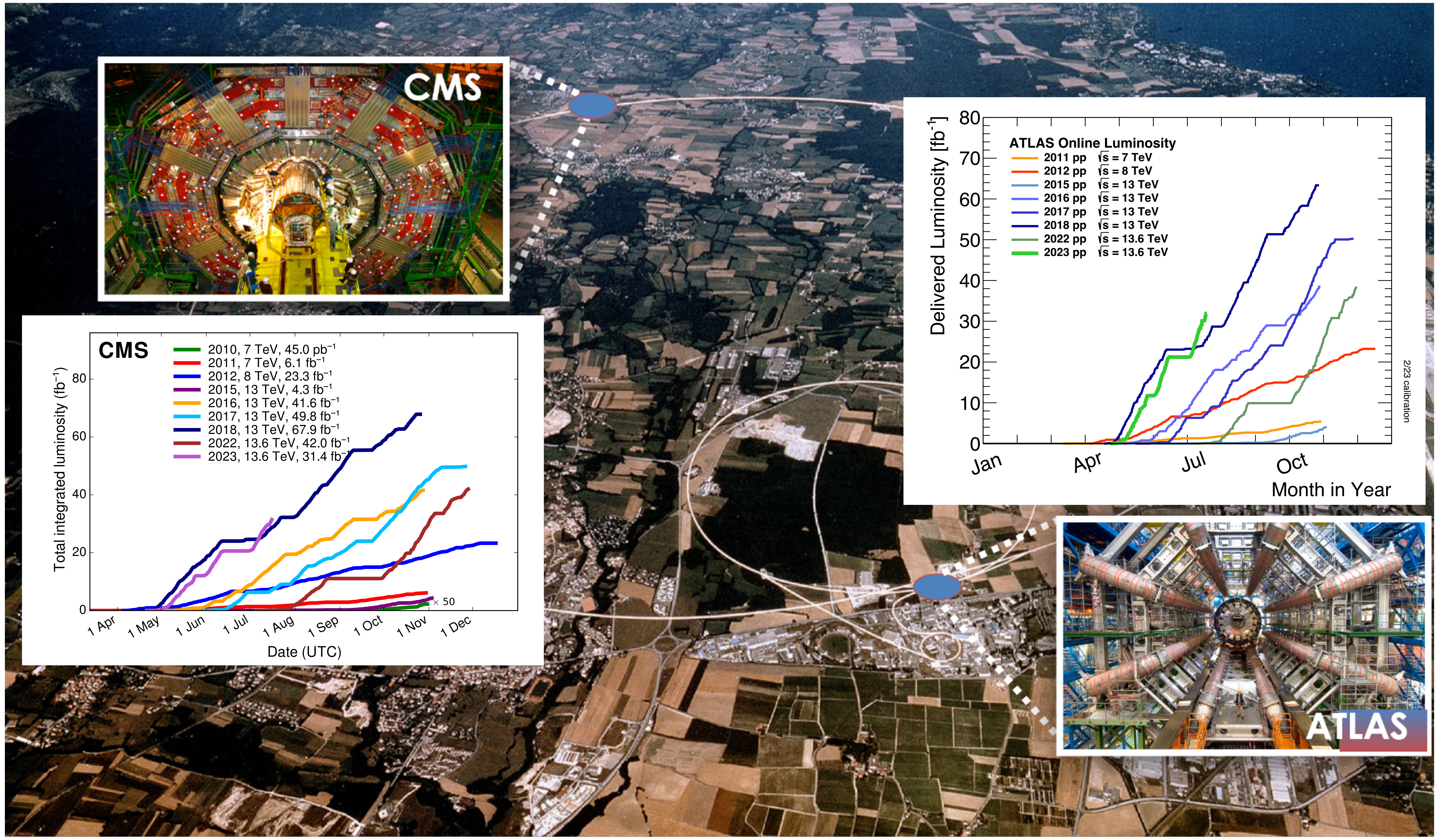
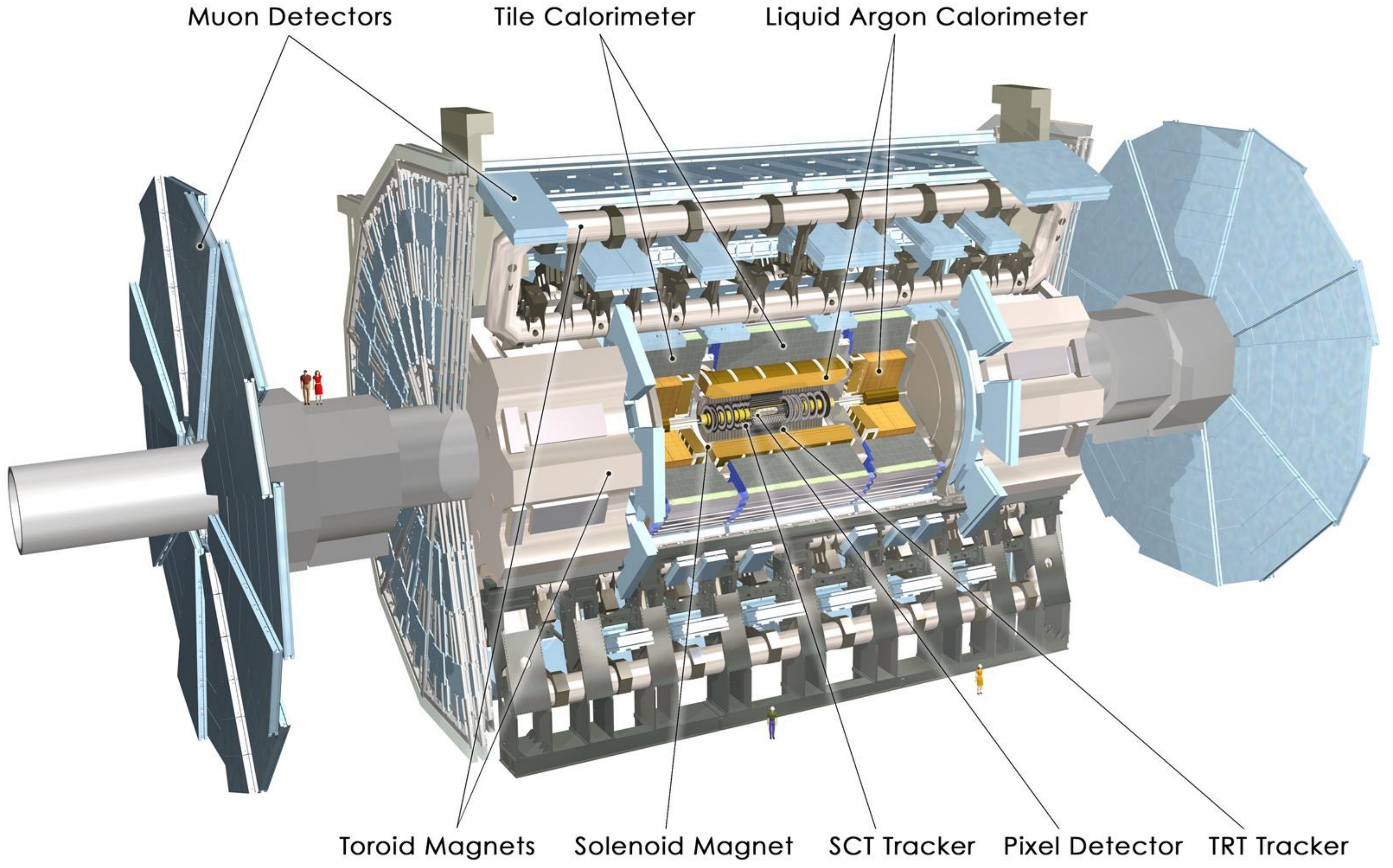
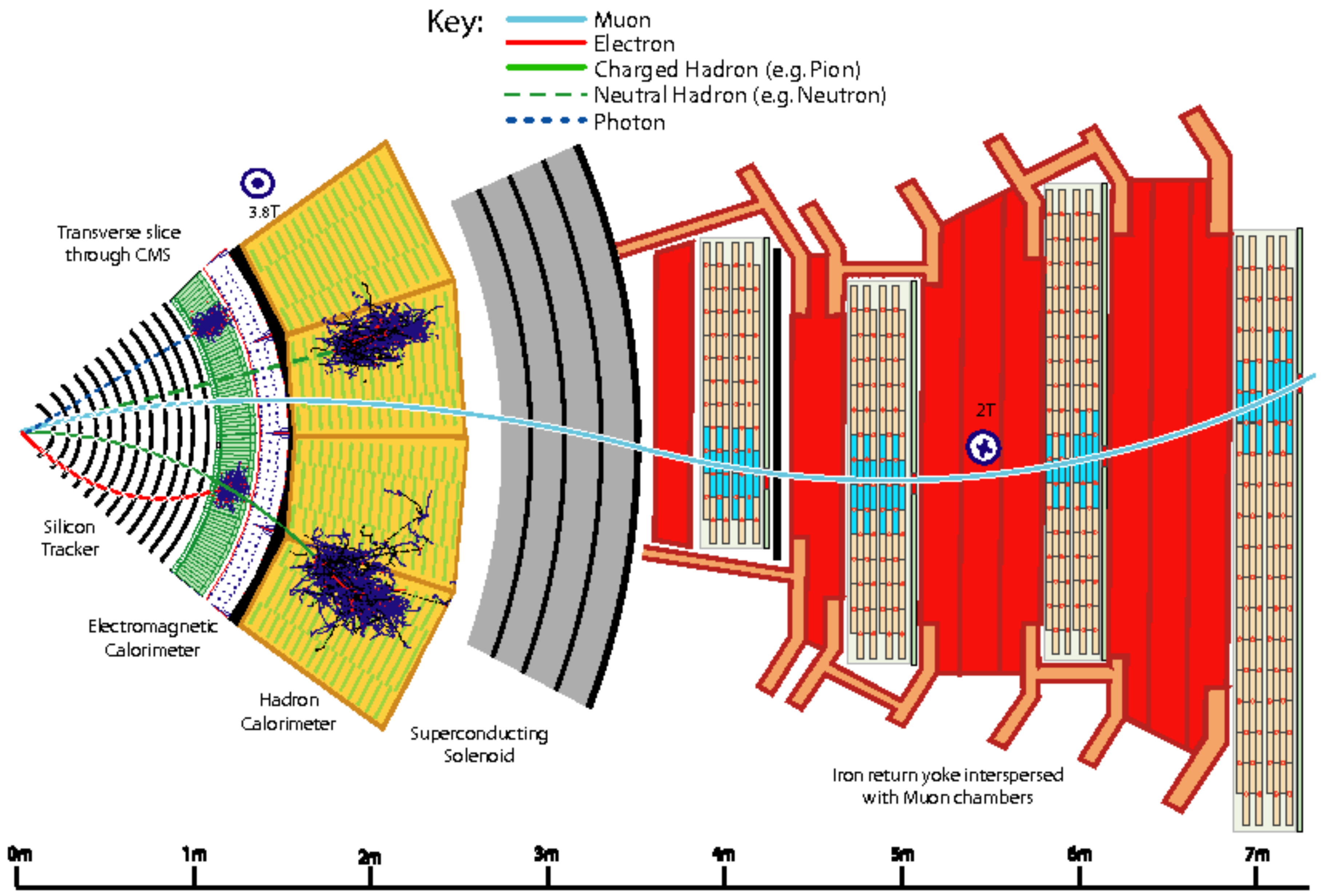


Backup

ATLAS and CMS experiments at LHC

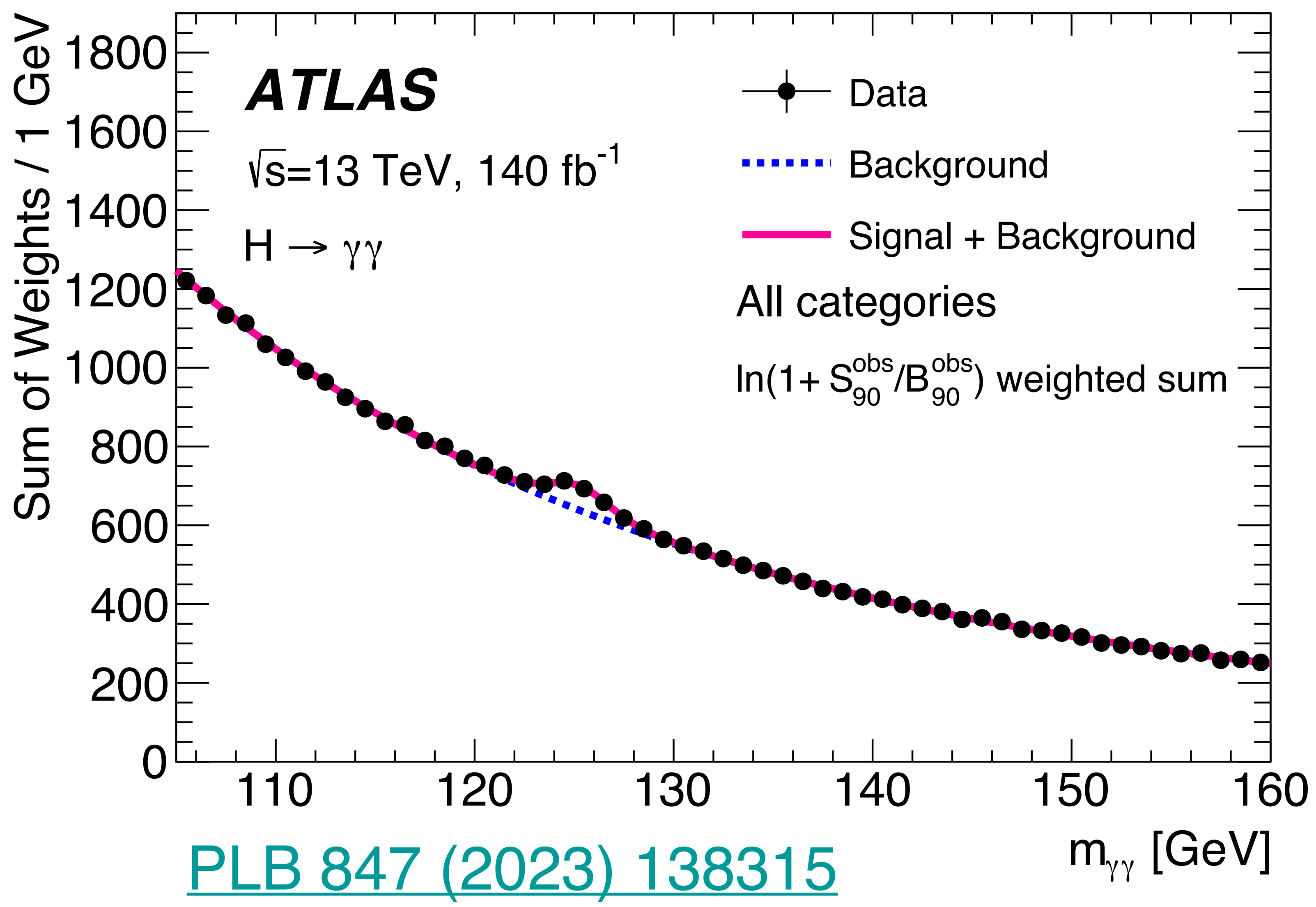




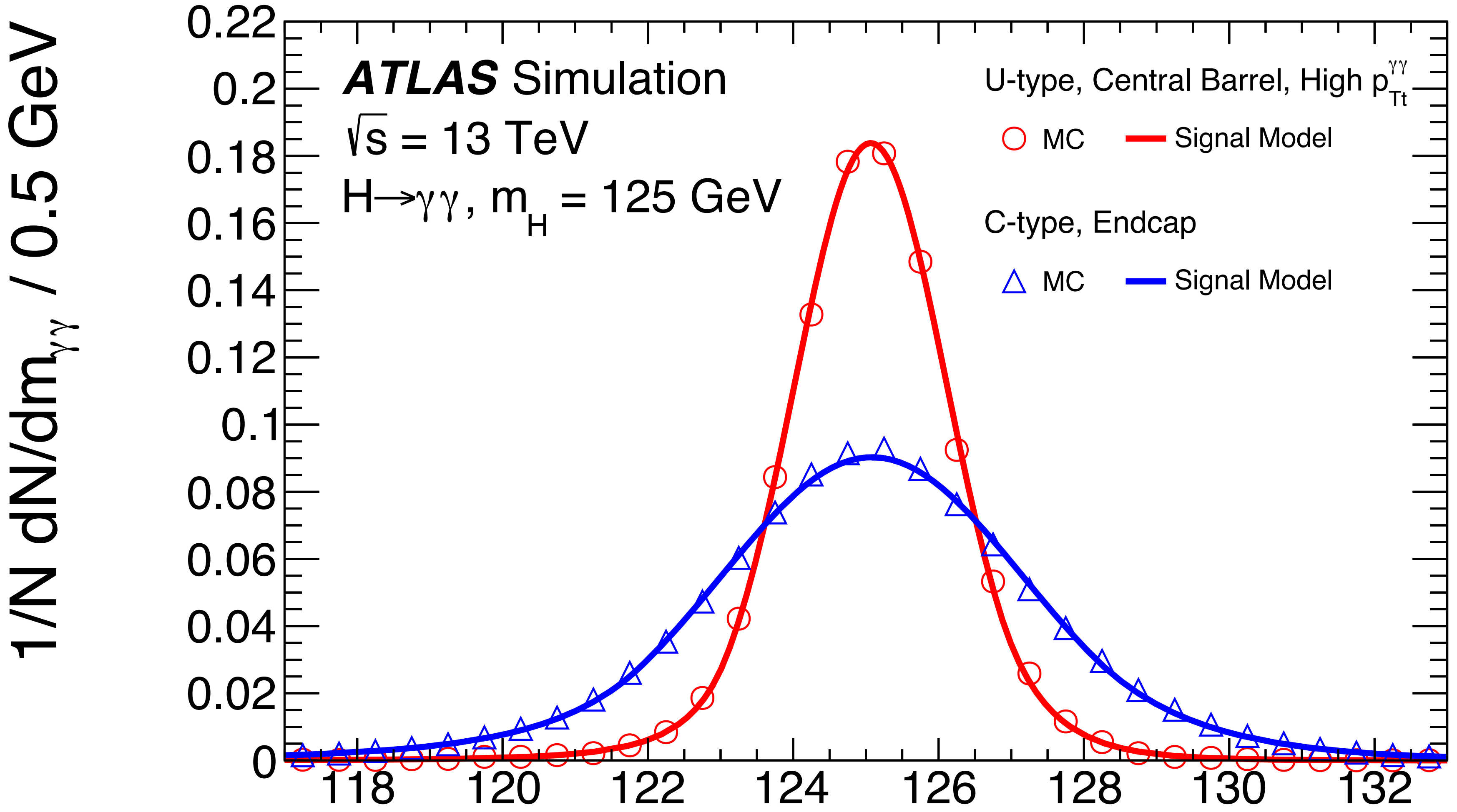


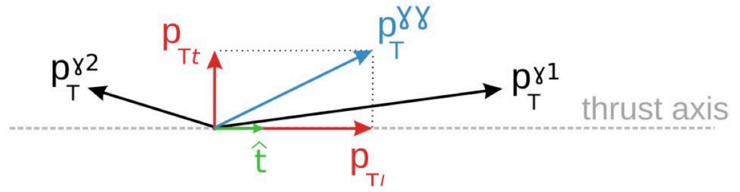
- At $\sqrt{s}$ = 13 TeV during LHC Run 2 (2015-2018), about **56000** Higgs bosons were produced in every fb^{-1} of p-p collision data
- Only selecting **O(0.1%)** for physics analyses due to various challenges: trigger, reconstruction and identification inefficiency…

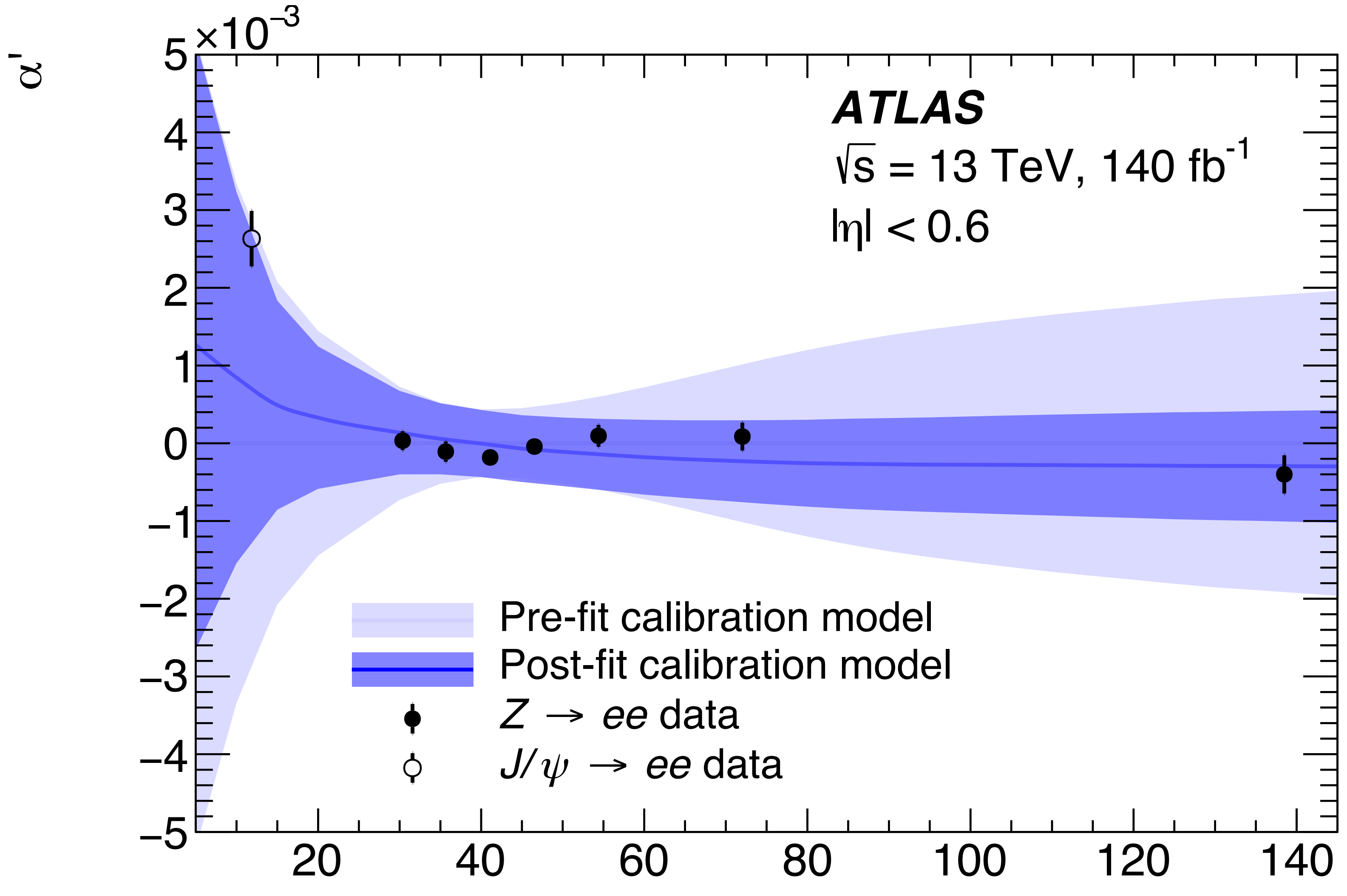
Measurement in H→γγ channel



PLB 847 (2023) 138315







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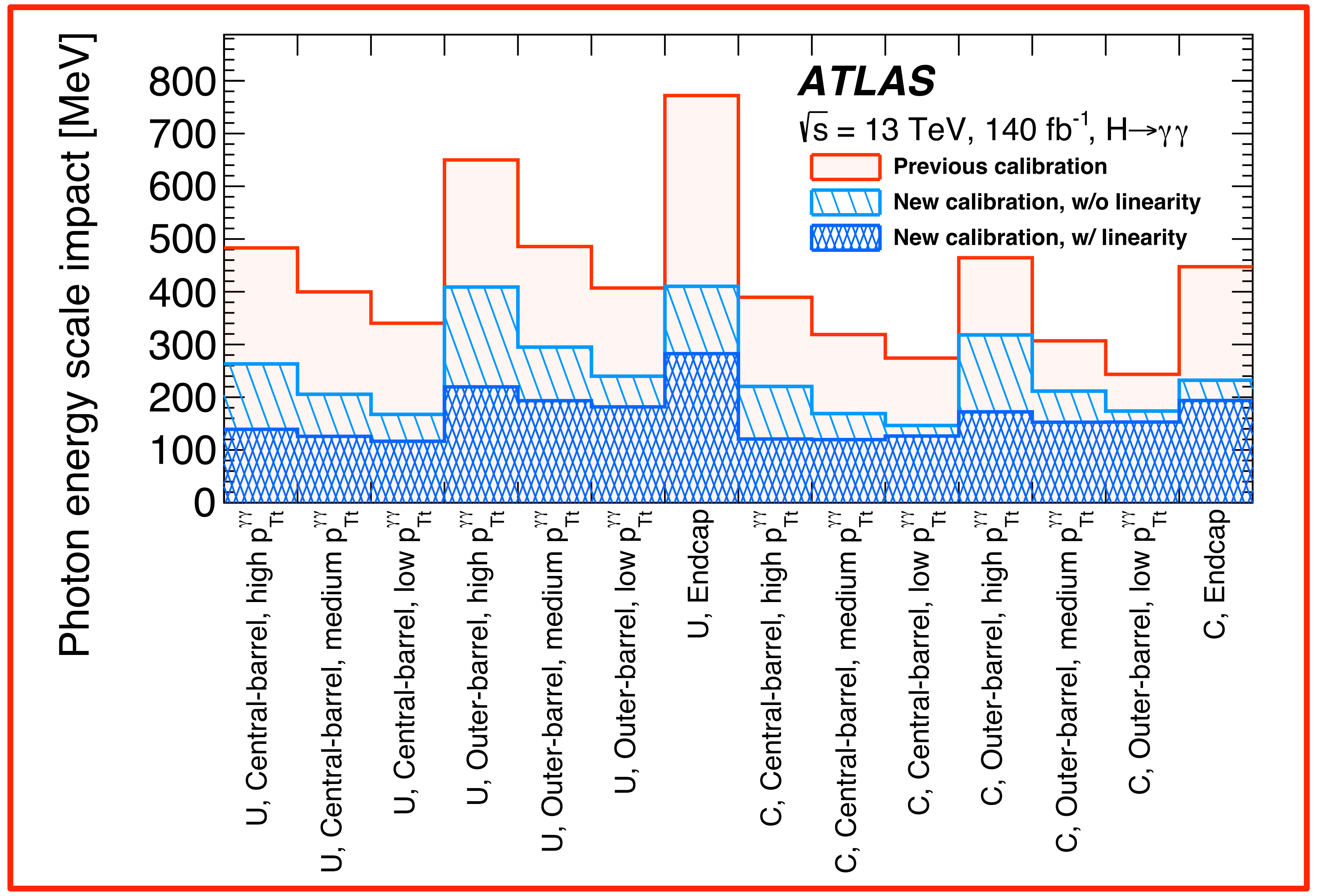
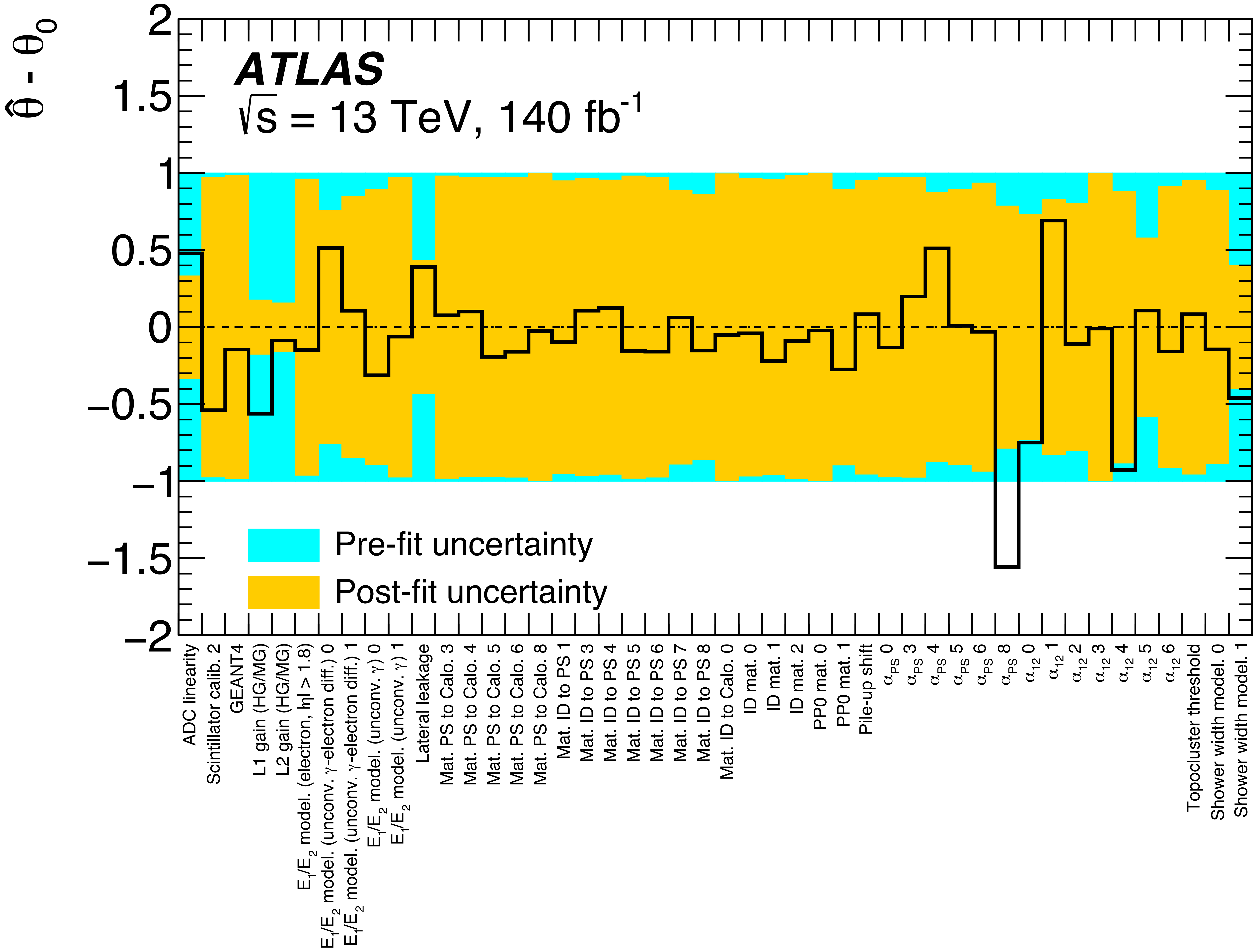
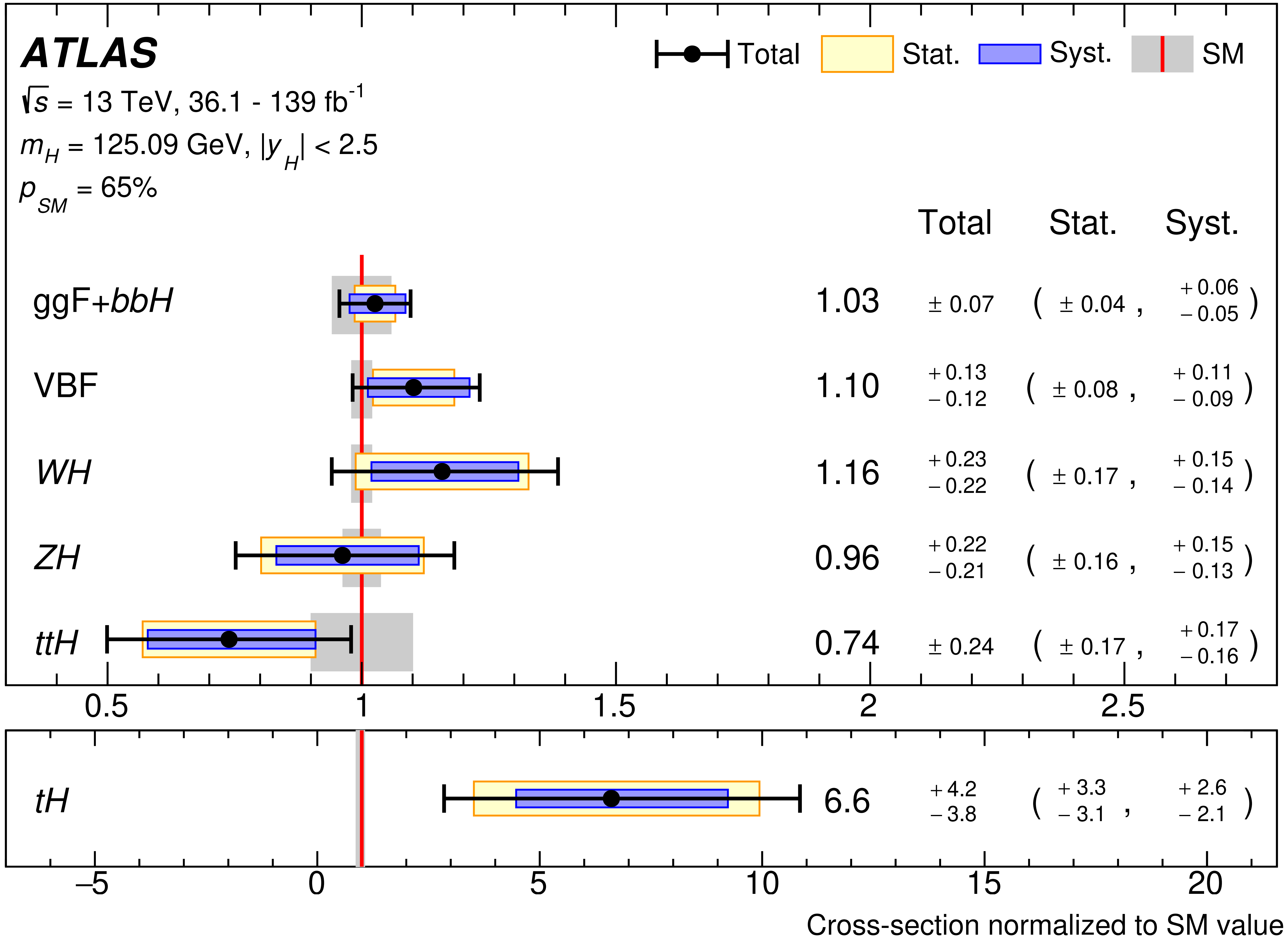
- Categorization by detector region, γ conversion type, and p_{Tt} improves total uncert. by **17%** compared with inclusive case
- Reduction of syst uncertainty by **factor of 4** compared with previous iteration based on partial Run 2 data
  - Improved photon energy scale calibration (and also E resolution)
  - Better constraint of E_T dependent e→γ extrapolation uncertainty using Z→ee data ("linearity fit")

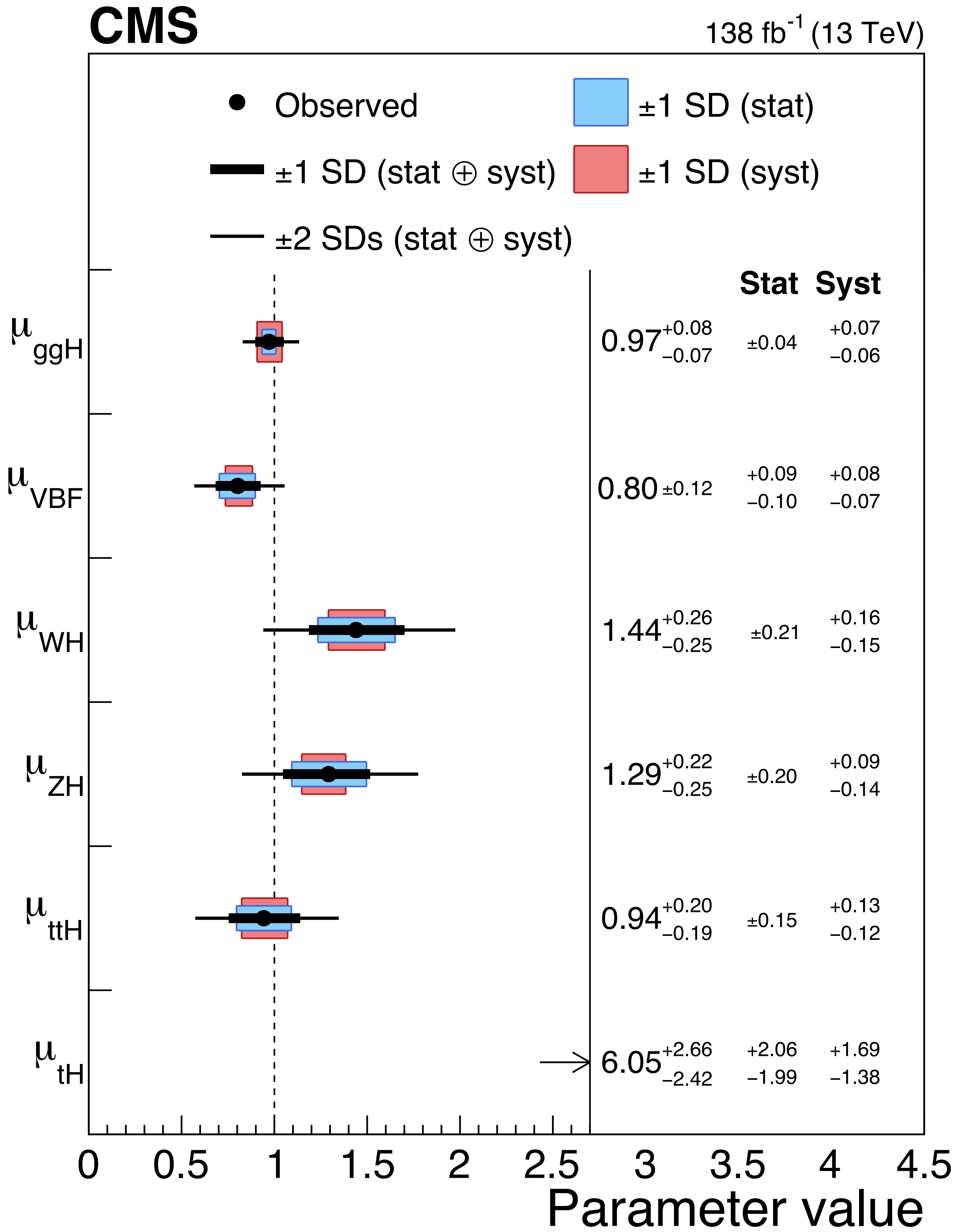


Reduction of e/γ energy scale syst from linearity fit

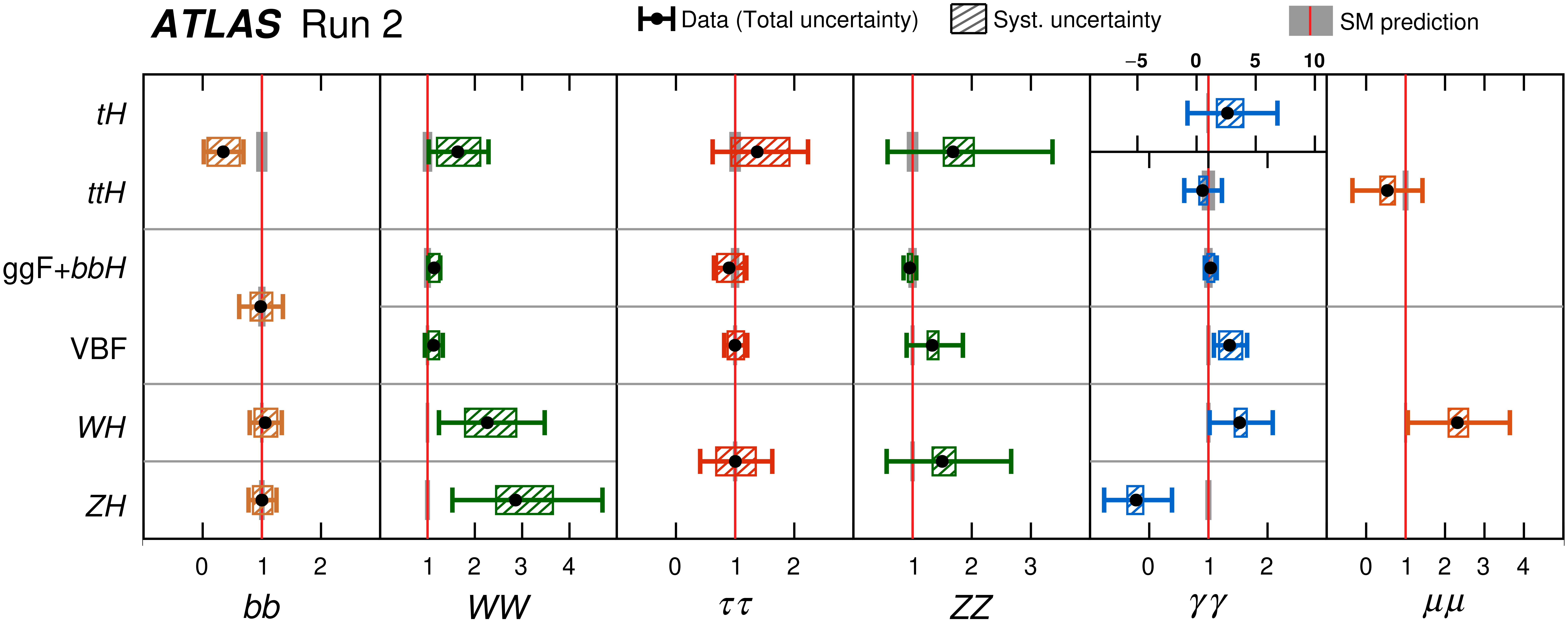


Higgs boson productions ATLAS vs. CMS





Production cross-section times decay BR



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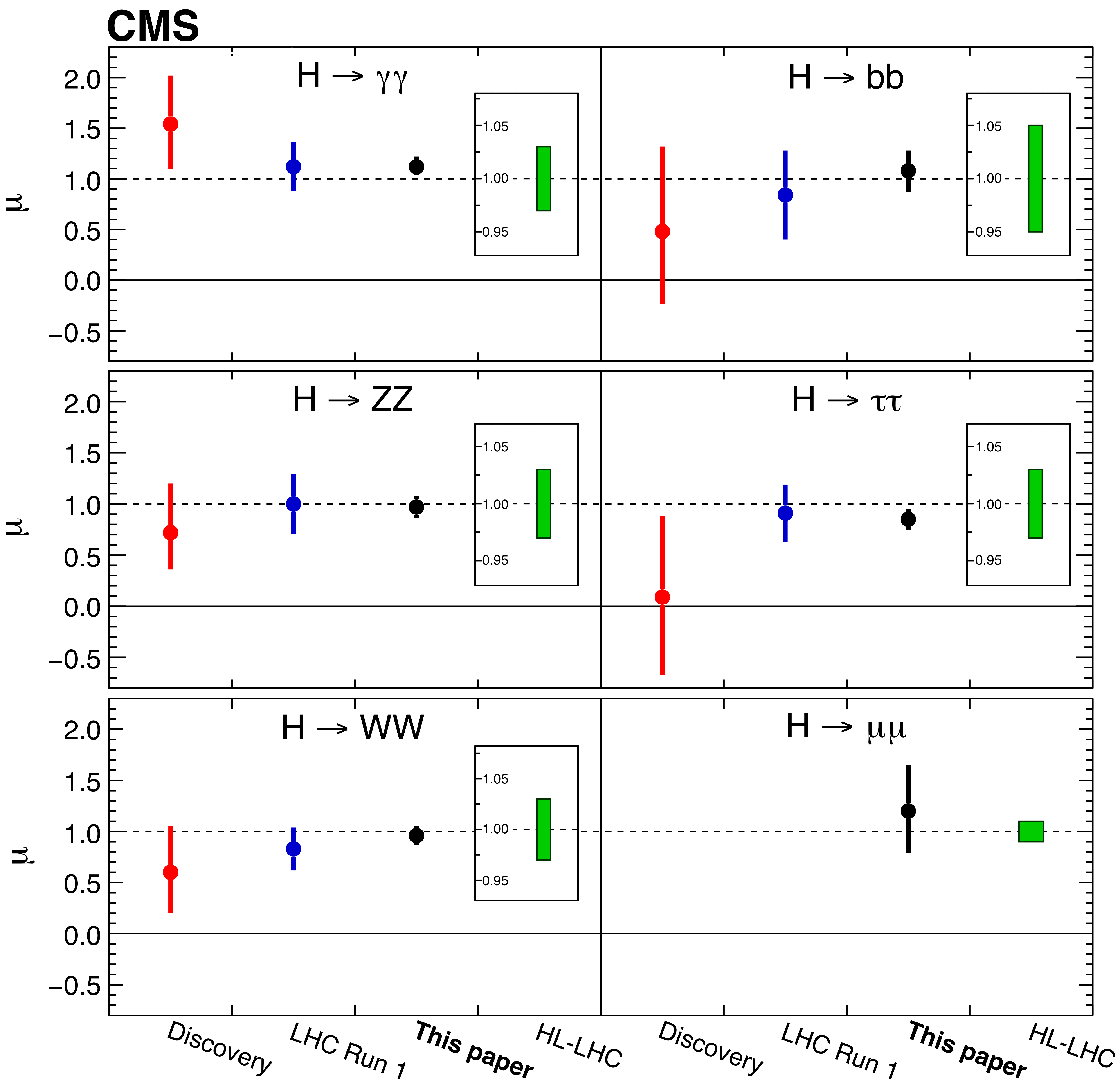
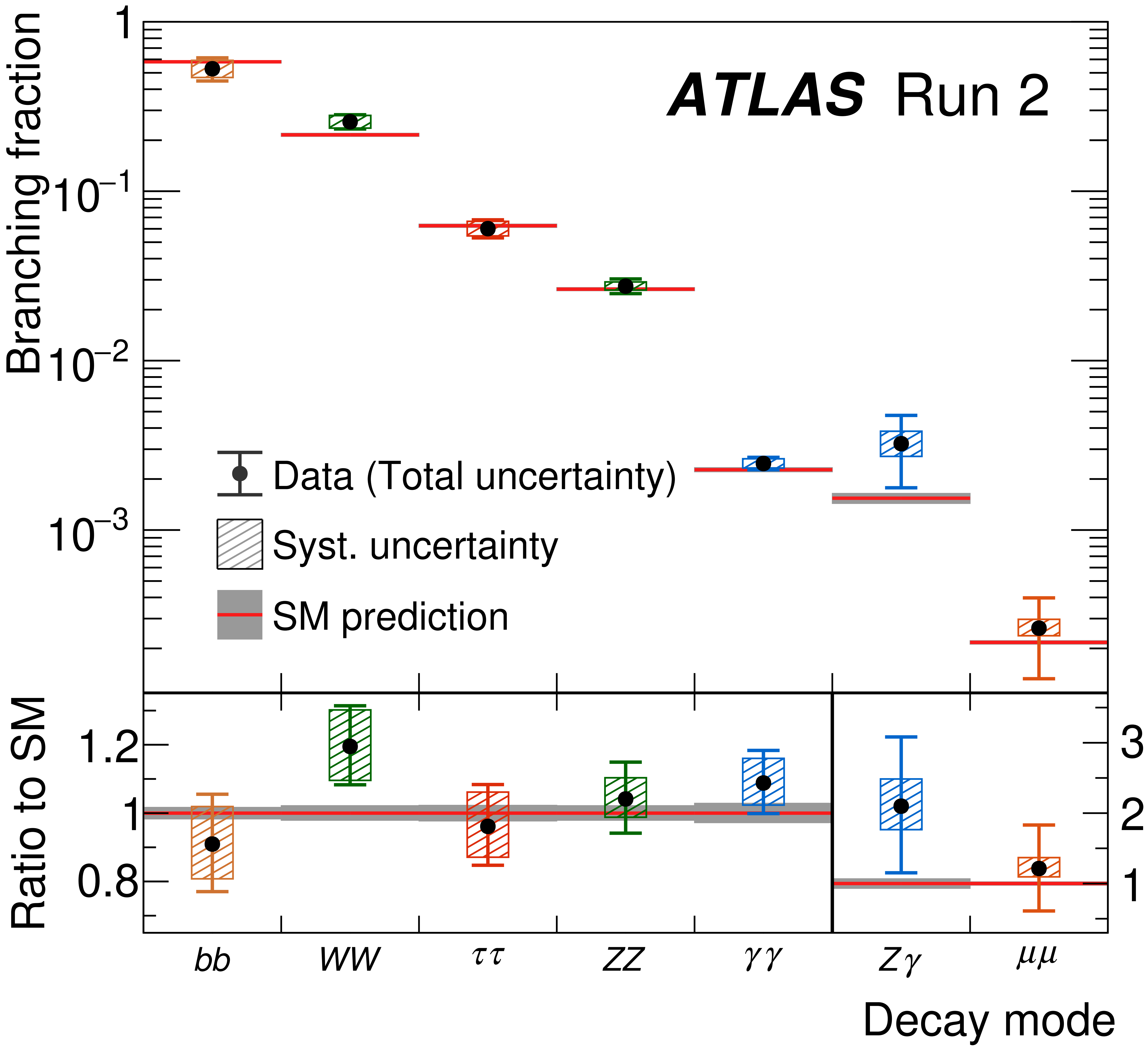
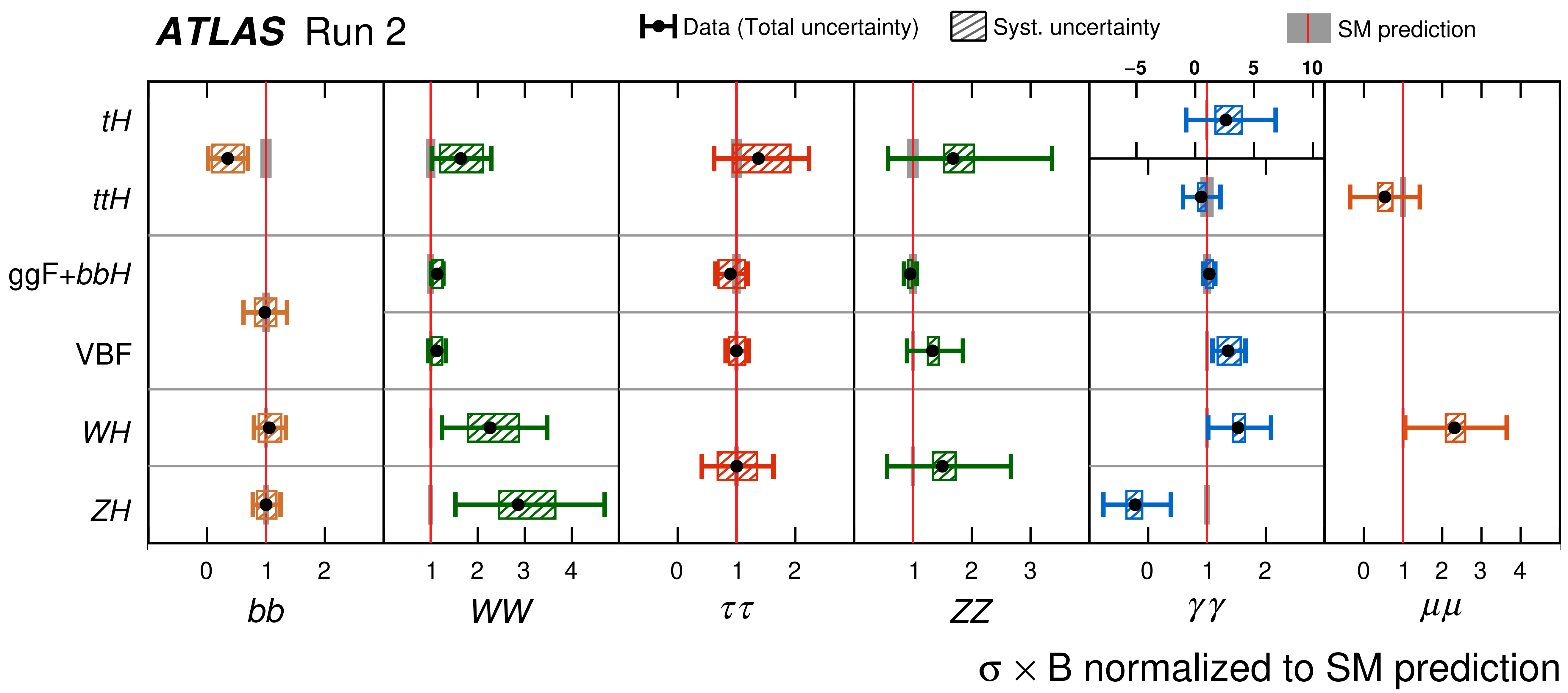
- Interesting combination of production & decay still to be explored: see our joker talk!

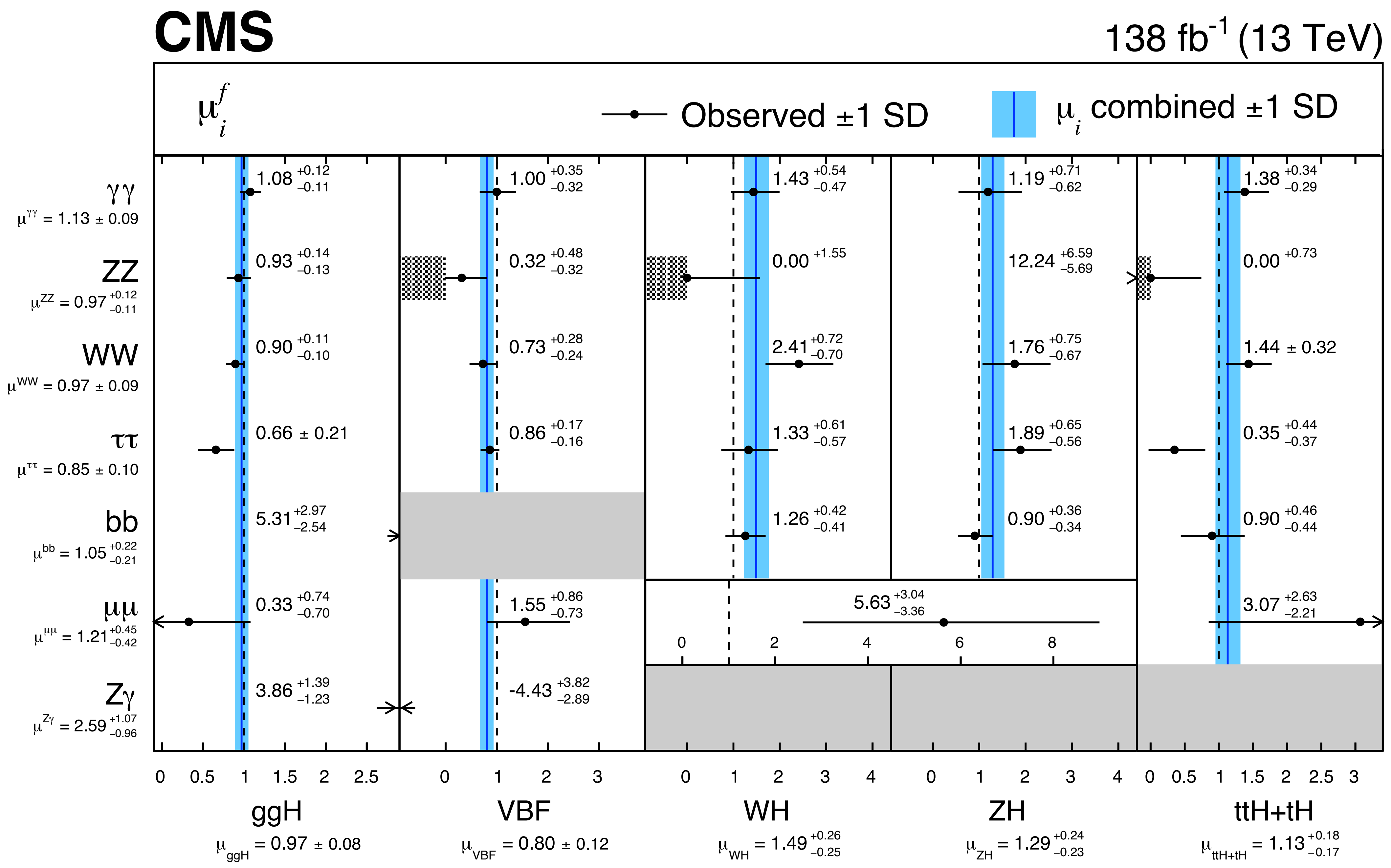
Higgs boson decays ATLAS vs. CMS



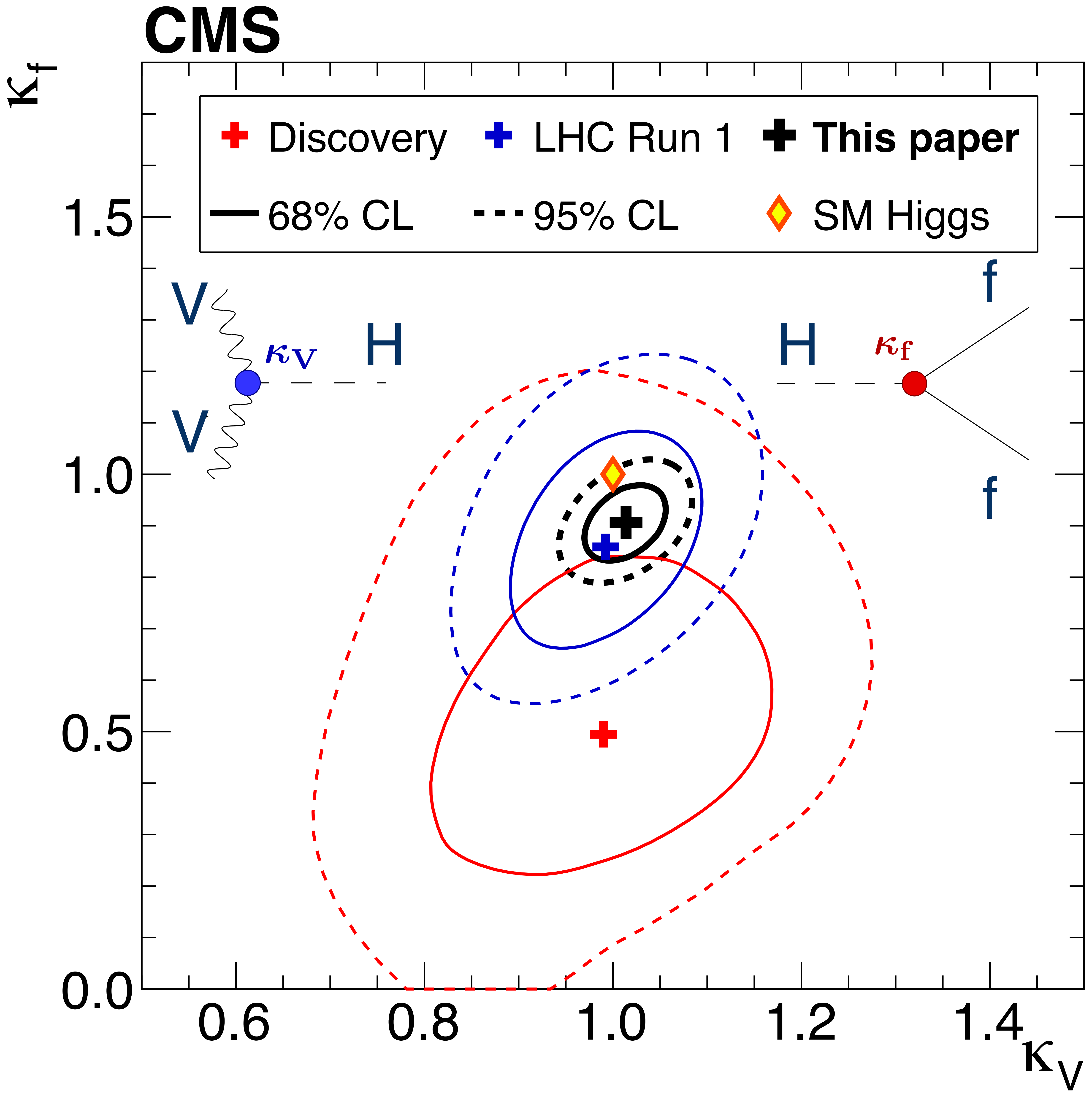


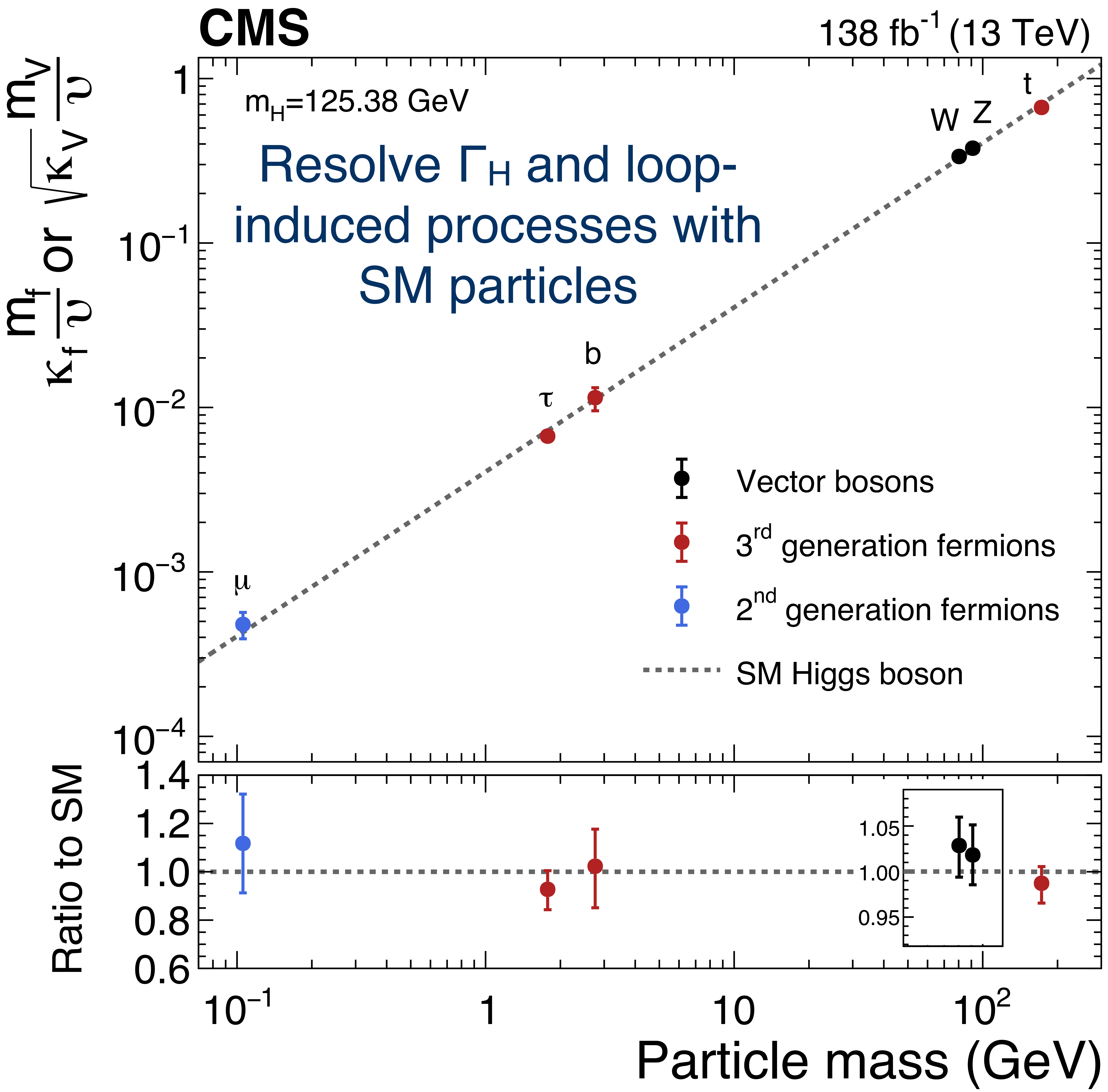
Prod×decay ATLAS vs. CMS



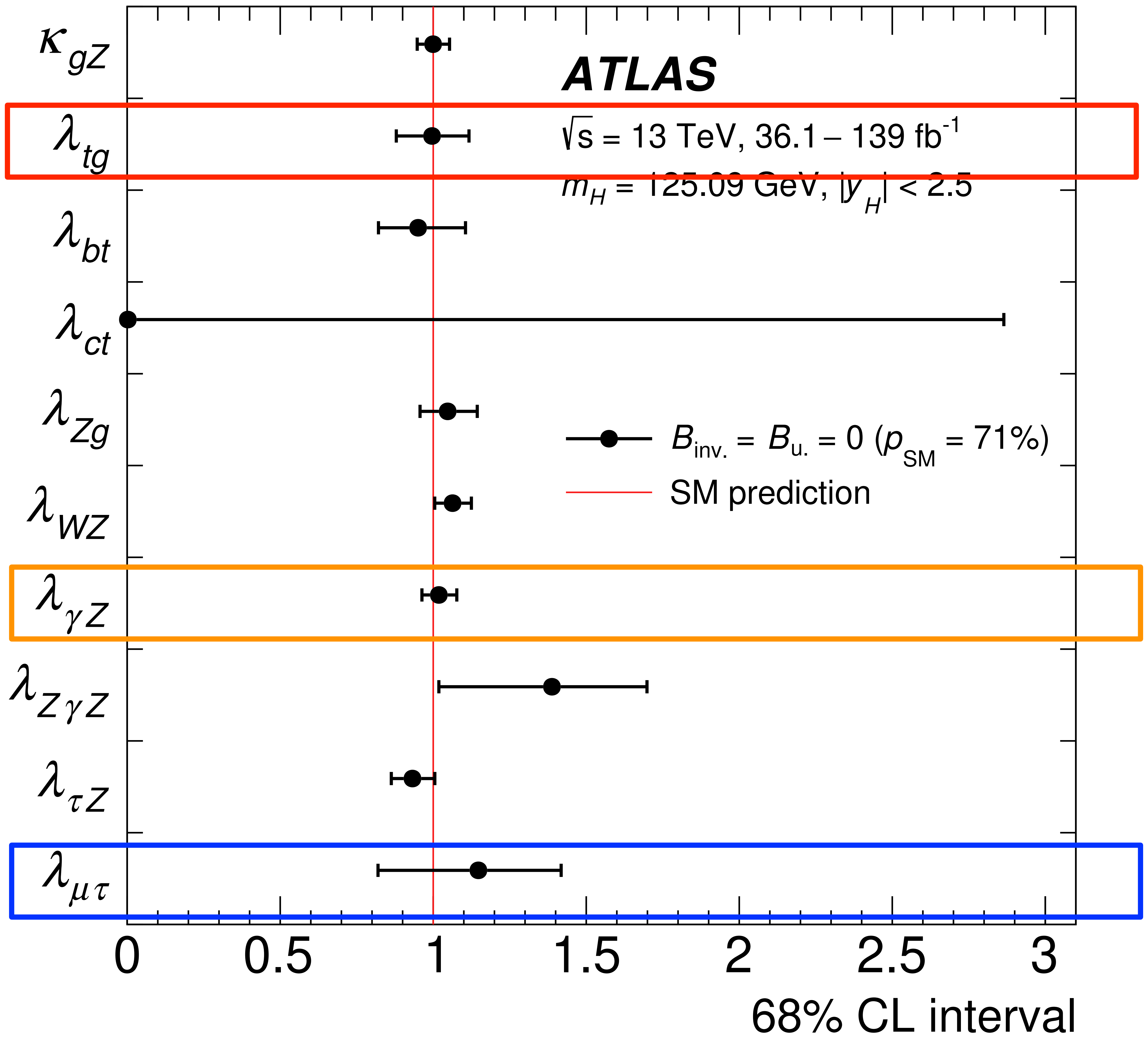


Coupling strength tests

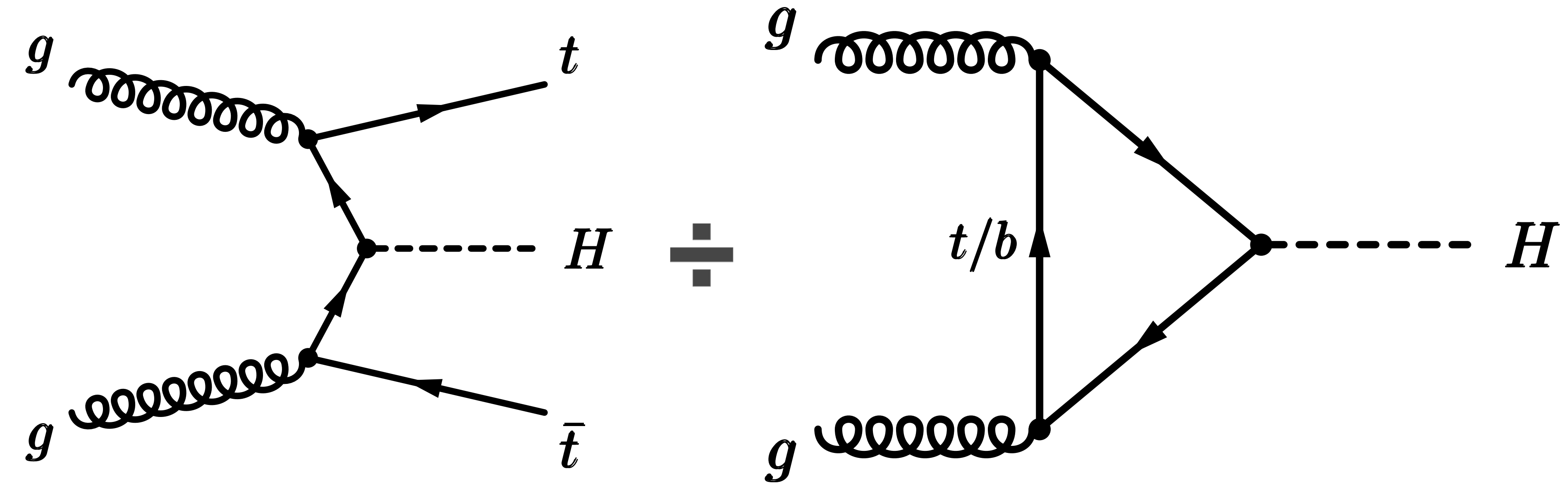




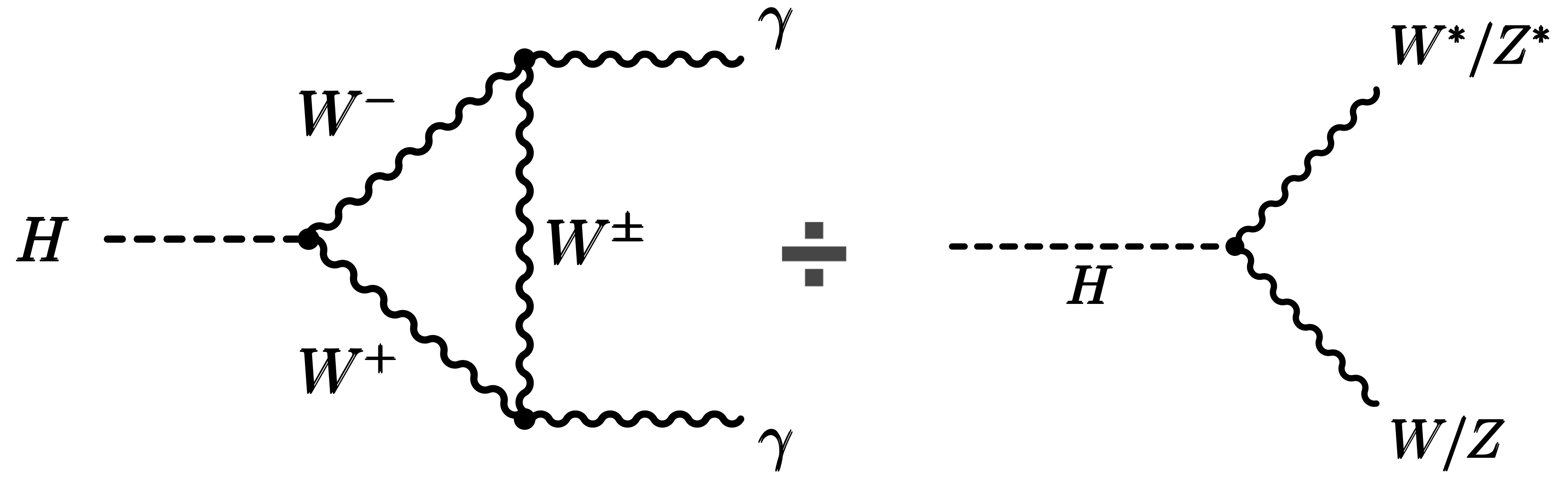
Ratios of coupling strengths



$\lambda_{tg} = \dfrac{\kappa_t}{\kappa_g}$

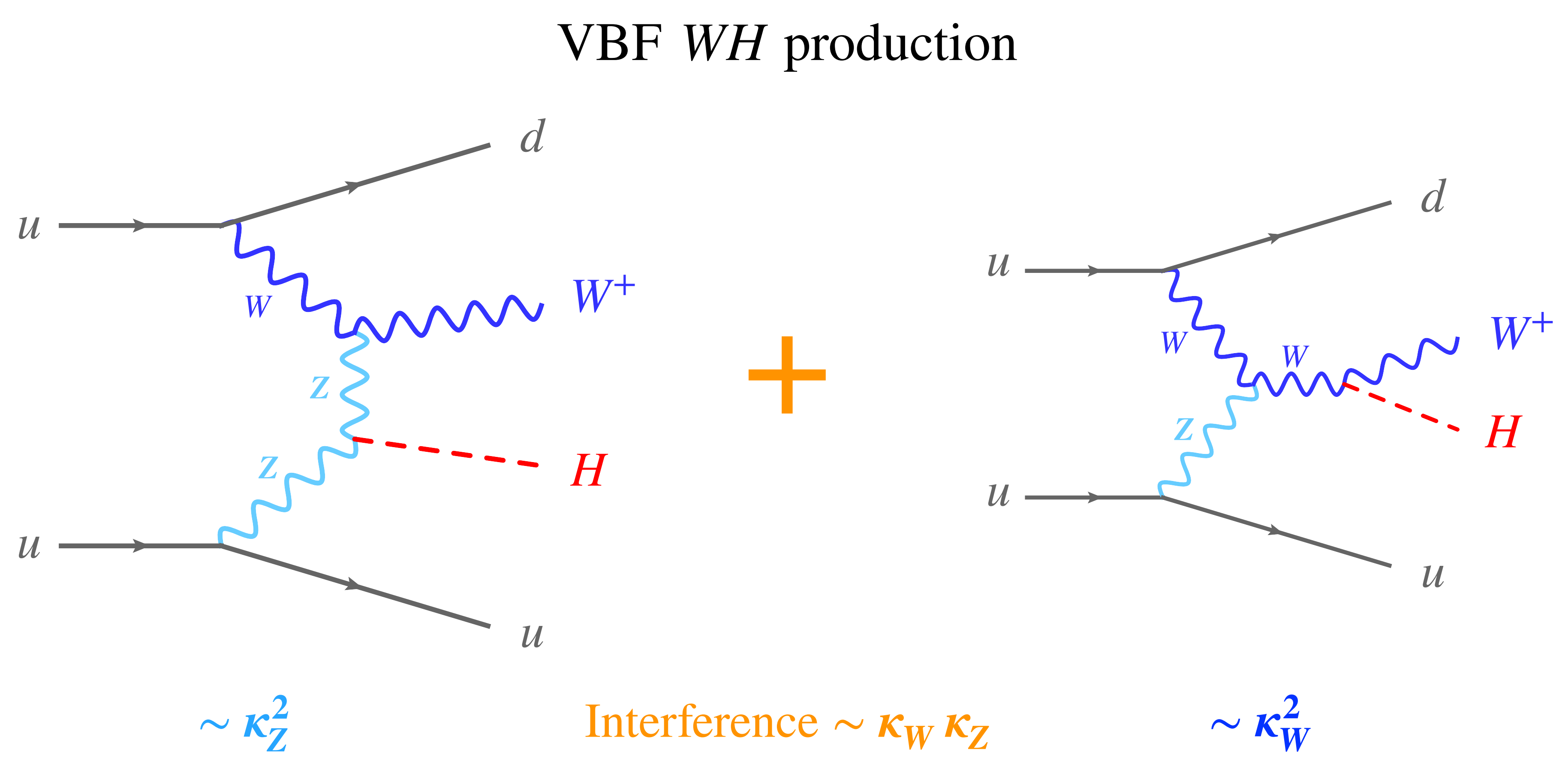


$\lambda_{\gamma Z} = \dfrac{\kappa_\gamma}{\kappa_Z}$

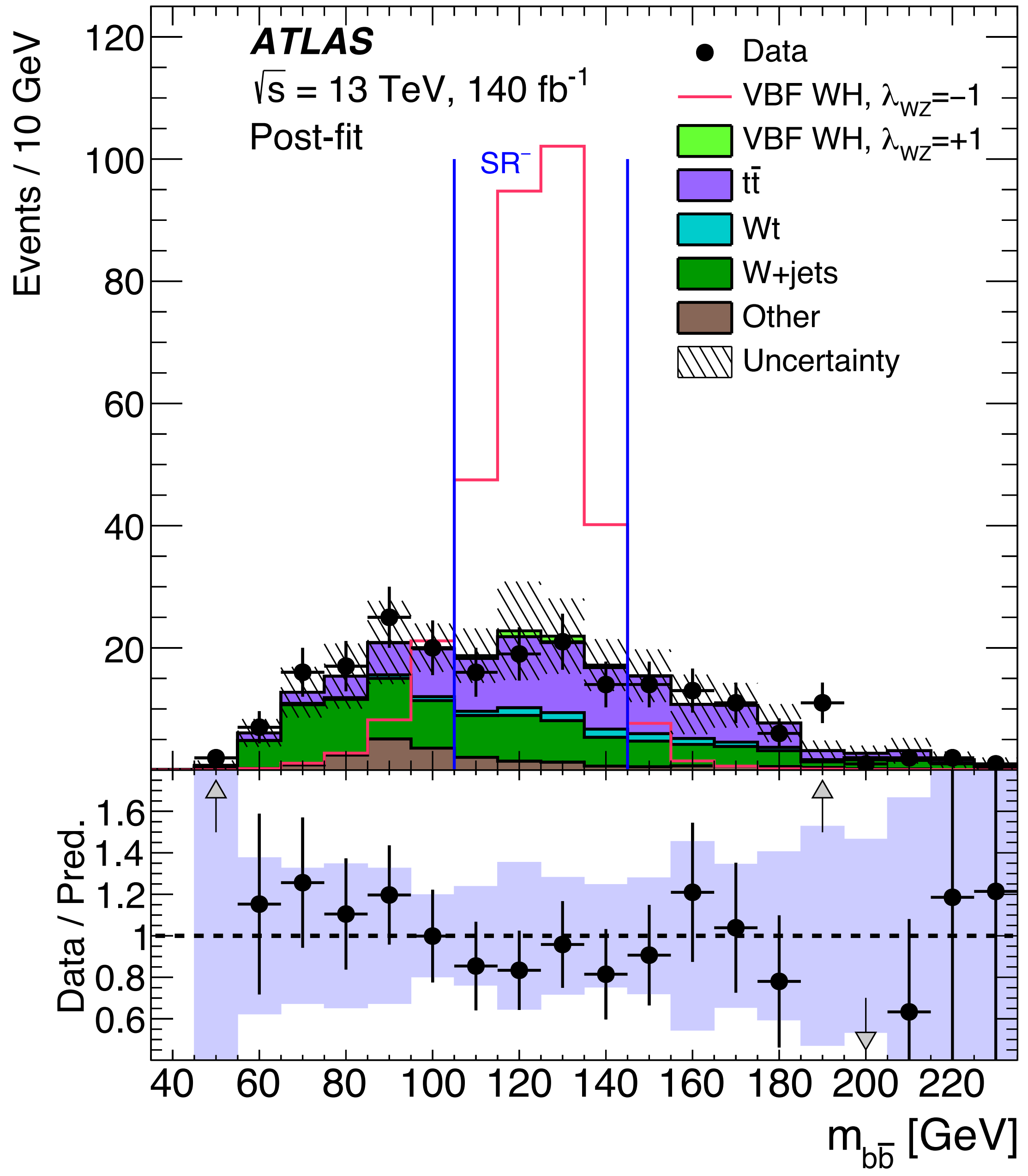


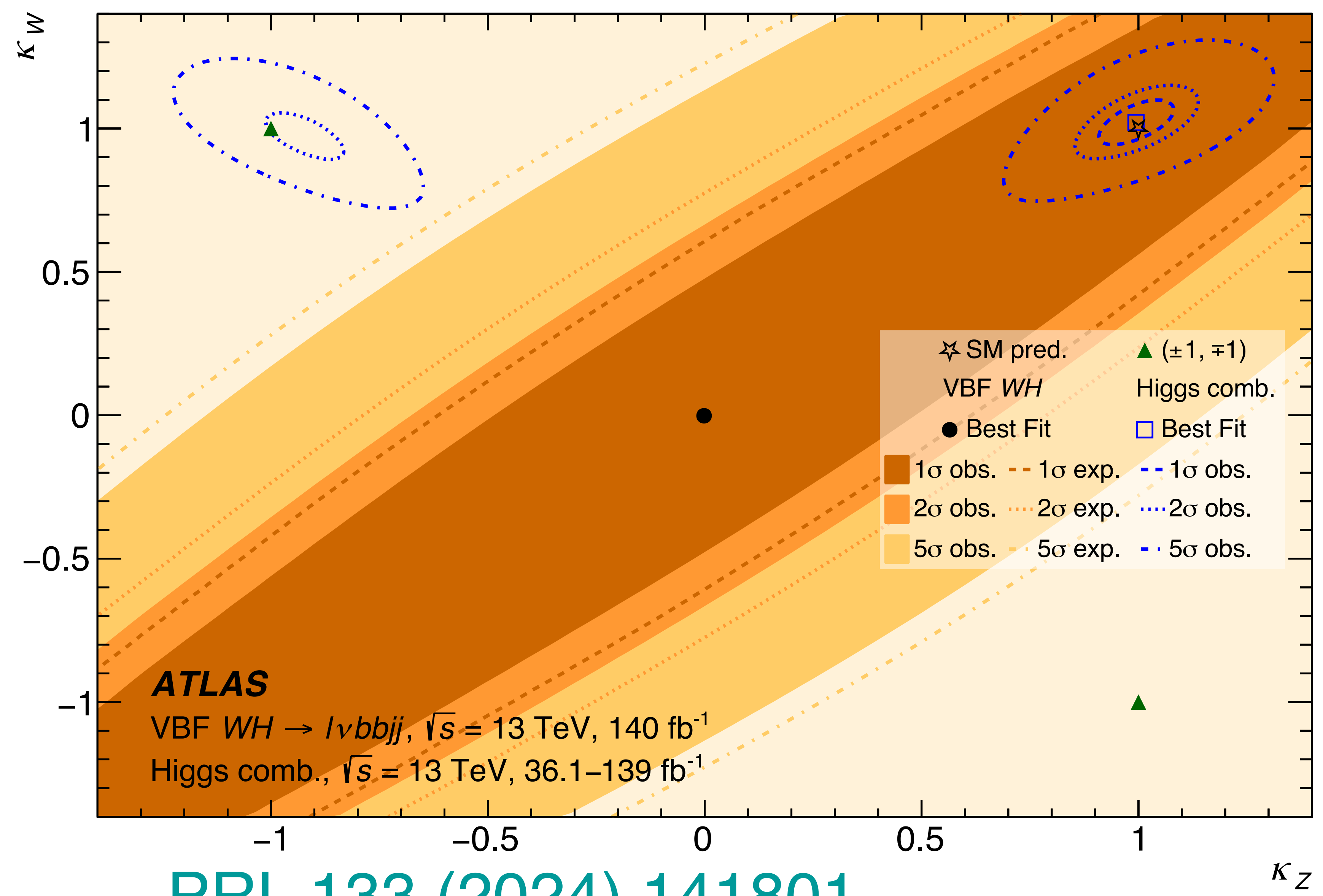
- LHC experiments cannot directly constrain Higgs boson total width. **Ratios are what we could measure best @LHC!**
- Explore new physics in **ggF**/**H→γγ** loops, and **3rd vs. 2nd generation Yukawa couplings**

Determine relative sign between κ_W and κ_Z



$$\sigma_{\mathrm{VBF},WH} \propto \kappa_Z^2|\mathcal{M}_Z|^2 + \kappa_W^2|\mathcal{M}_W|^2 - 2\,\kappa_Z\kappa_W\,\Re[\mathcal{M}_Z^\dagger\mathcal{M}_W]$$
$$= \kappa_Z^2|\mathcal{M}_Z|^2 + \kappa_W^2|\mathcal{M}_W|^2 - 2\,\kappa_Z^2\lambda_{WZ}\,\Re[\mathcal{M}_Z^\dagger\mathcal{M}_W]$$





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- $\lambda_{WZ} = \kappa_W/\kappa_Z$ is an important validation for **custodial symmetry**
- For the first time, **the sign of λ_{WZ}** is determined to be **consistent with SM** with WH→lvbb counting analysis in VBF topology
  - Negative sign of λ_{WZ} excluded by **>8σ**