Precision Higgs boson measurements at LHC

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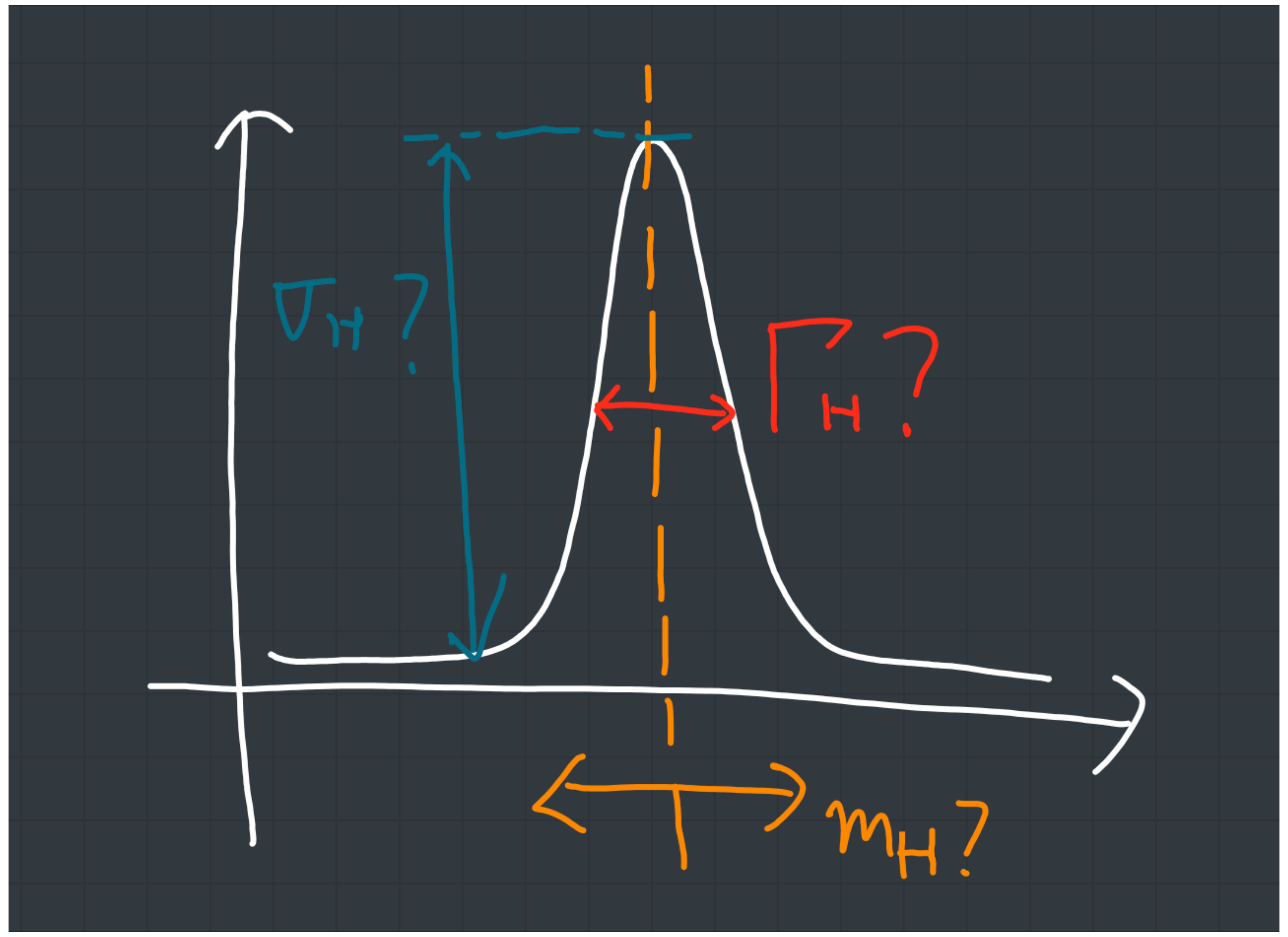
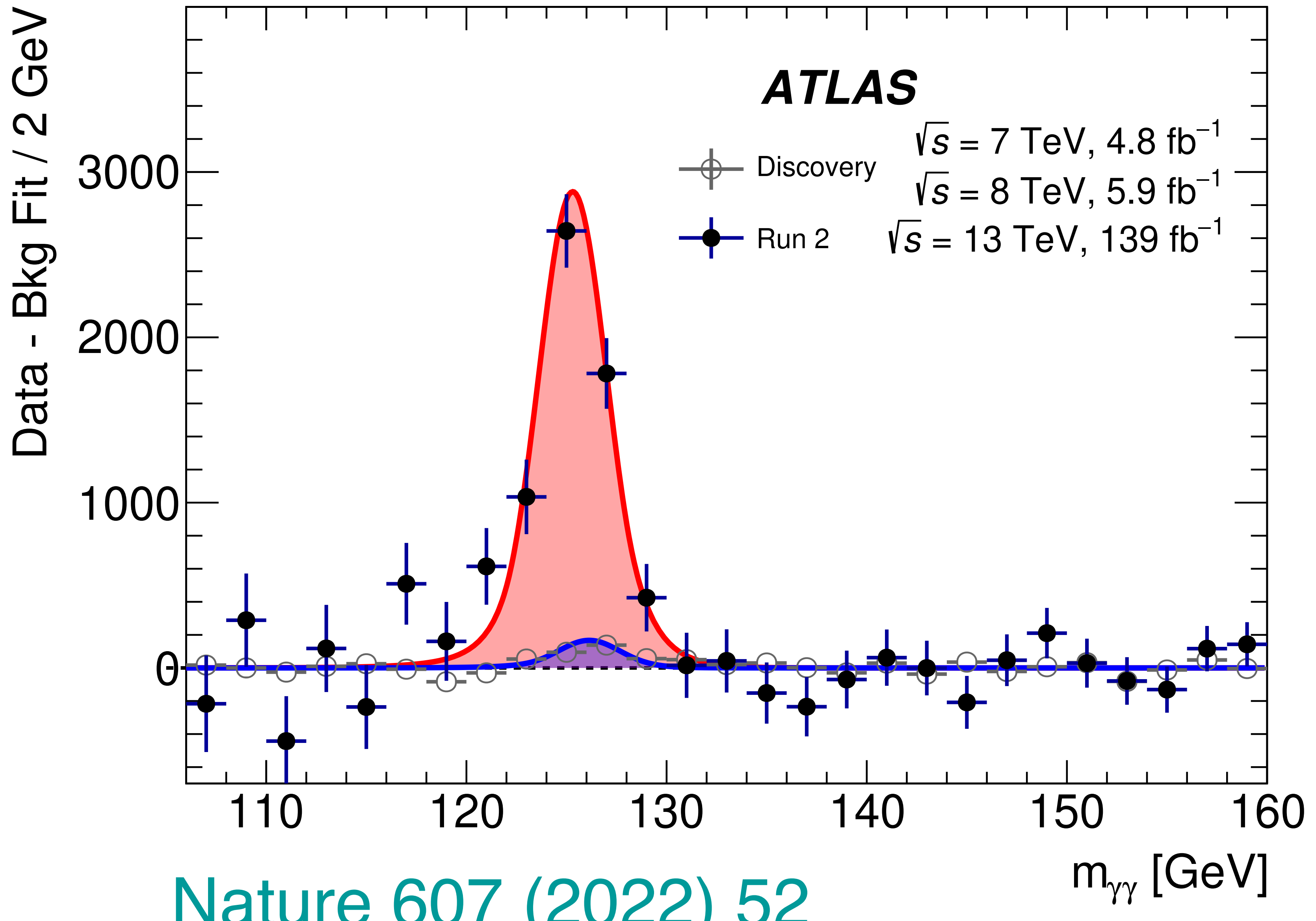
Introduction

- **Precision is important**
  - Higgs boson is fundamental. We need best knowledge on its properties
  - Precision could be portal to new physics



- With **LHC Run 2 data**, ATLAS and CMS have measured Higgs boson **mass**, **width**, and **production cross-sections** with yet a new level of precision



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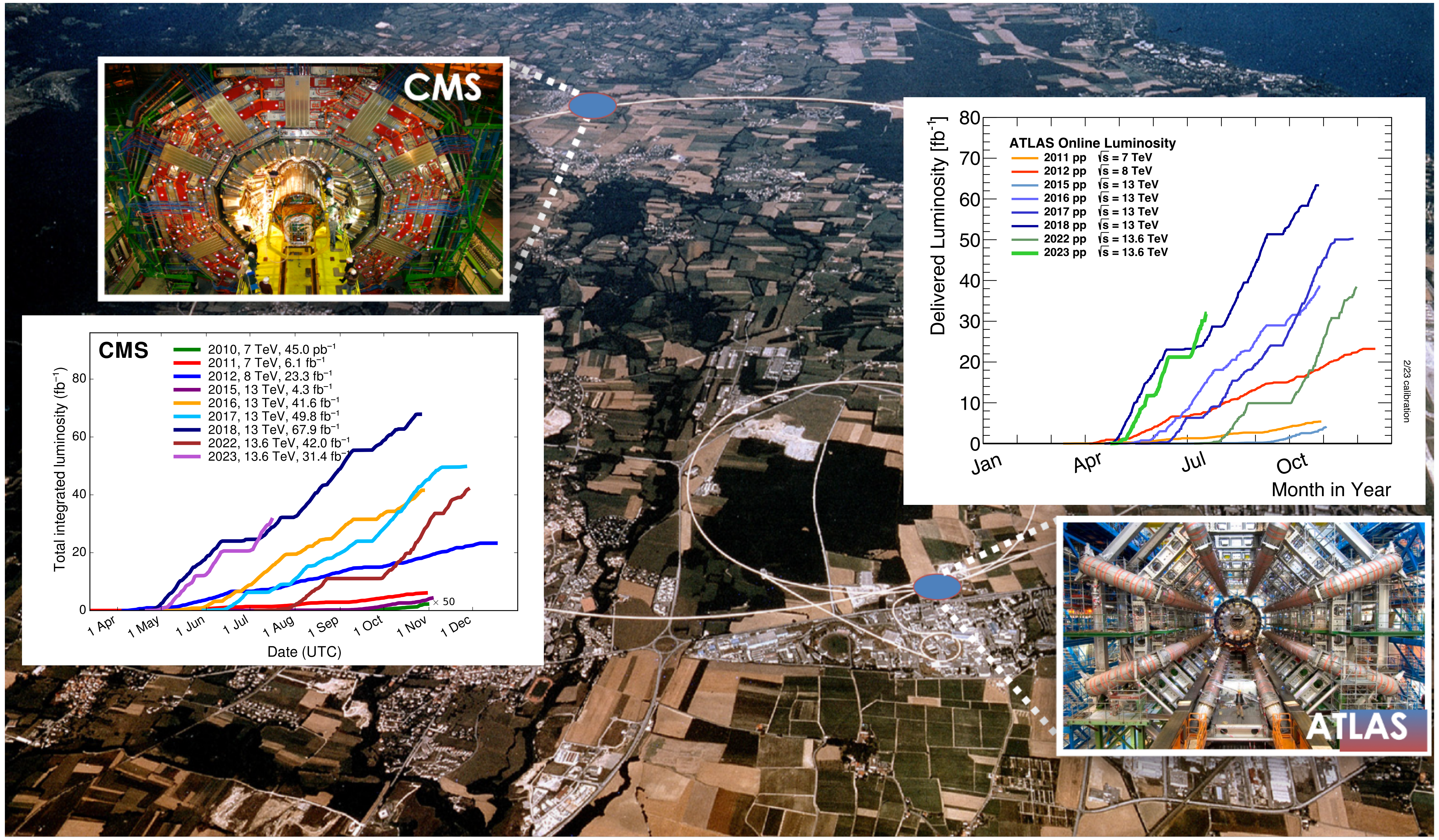
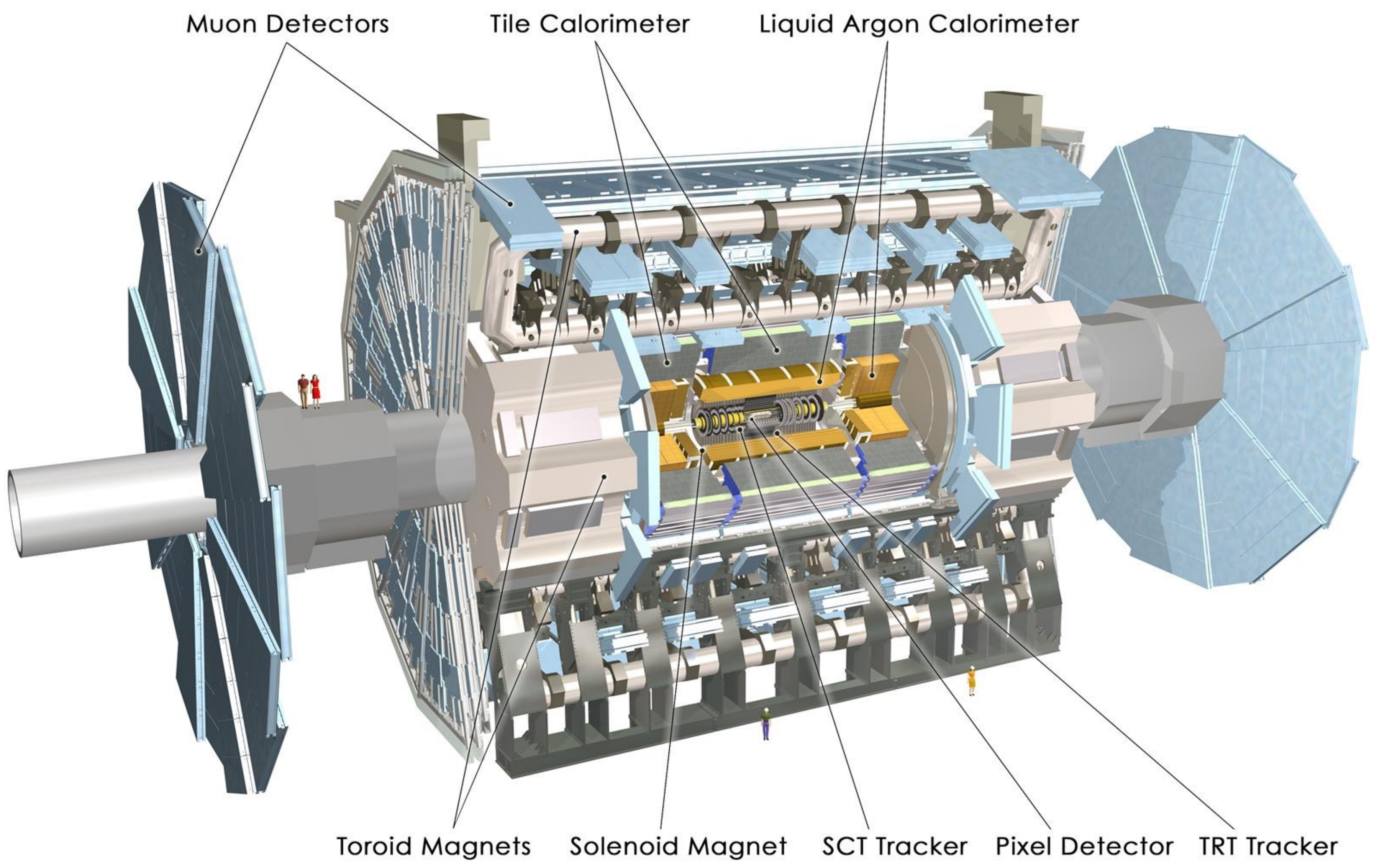
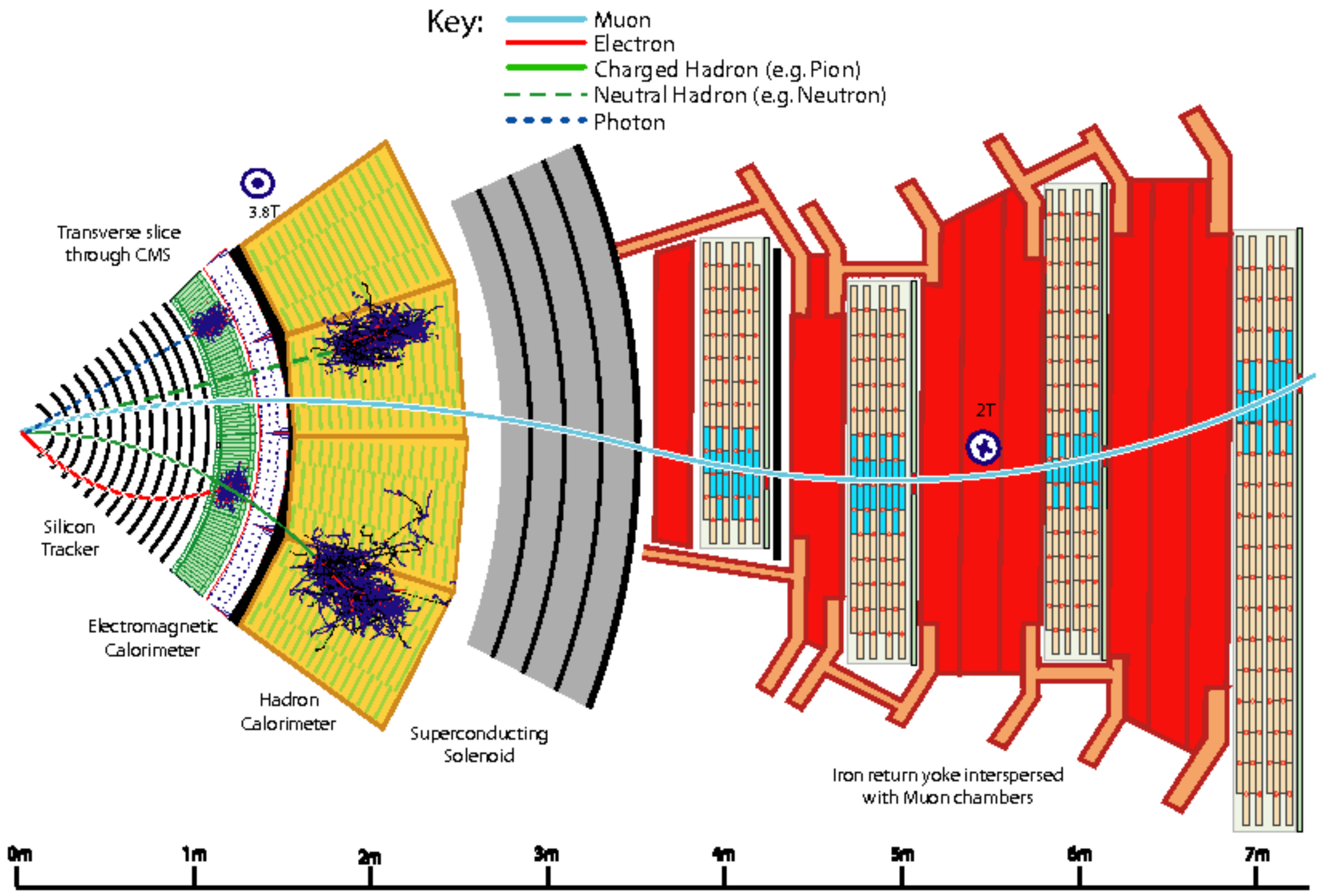
- *Will focus on results released since Higgs 2022, but still cannot cover all updates due to limited time. Sorry if your favorite topics are missing!*

ATLAS and CMS experiments at LHC

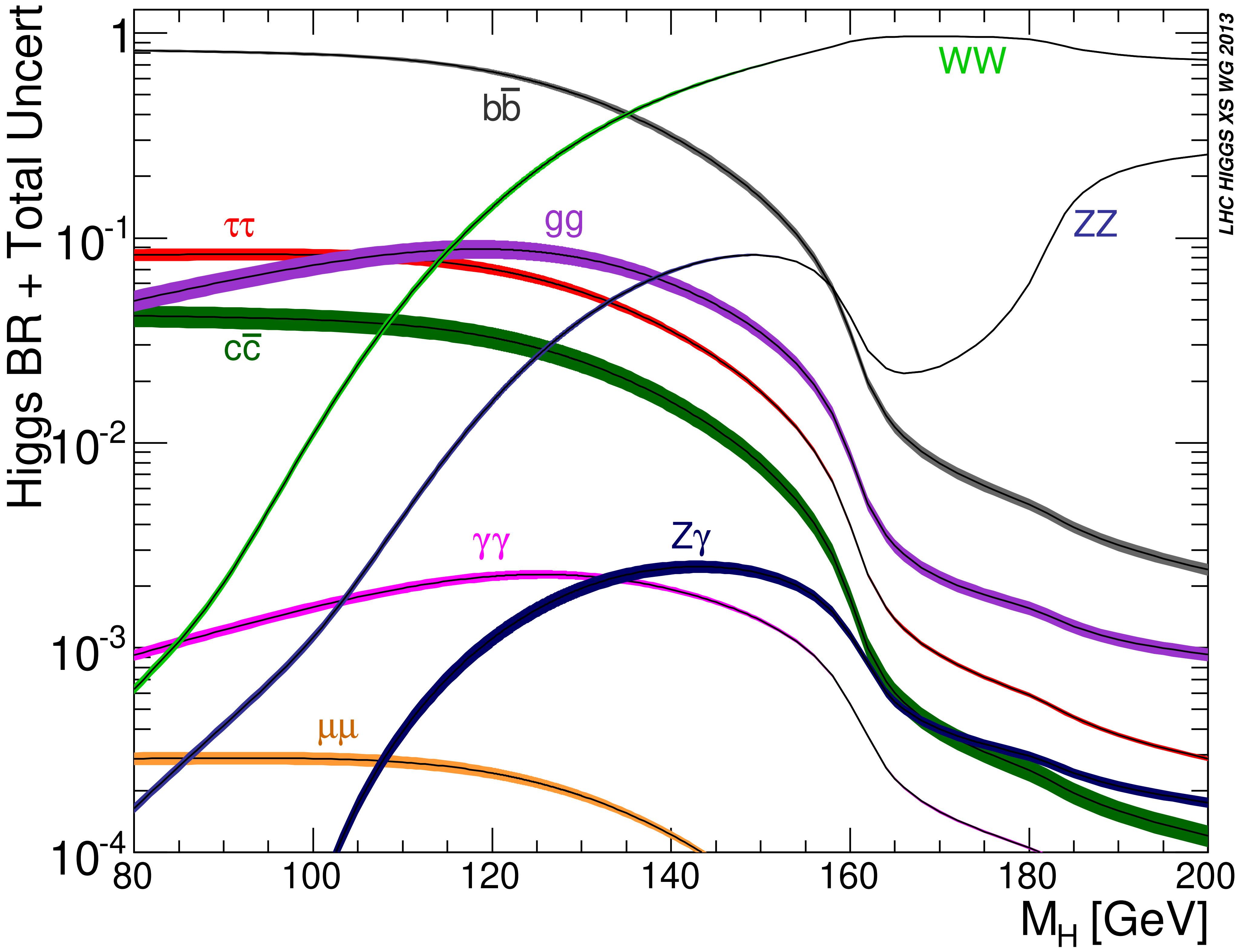




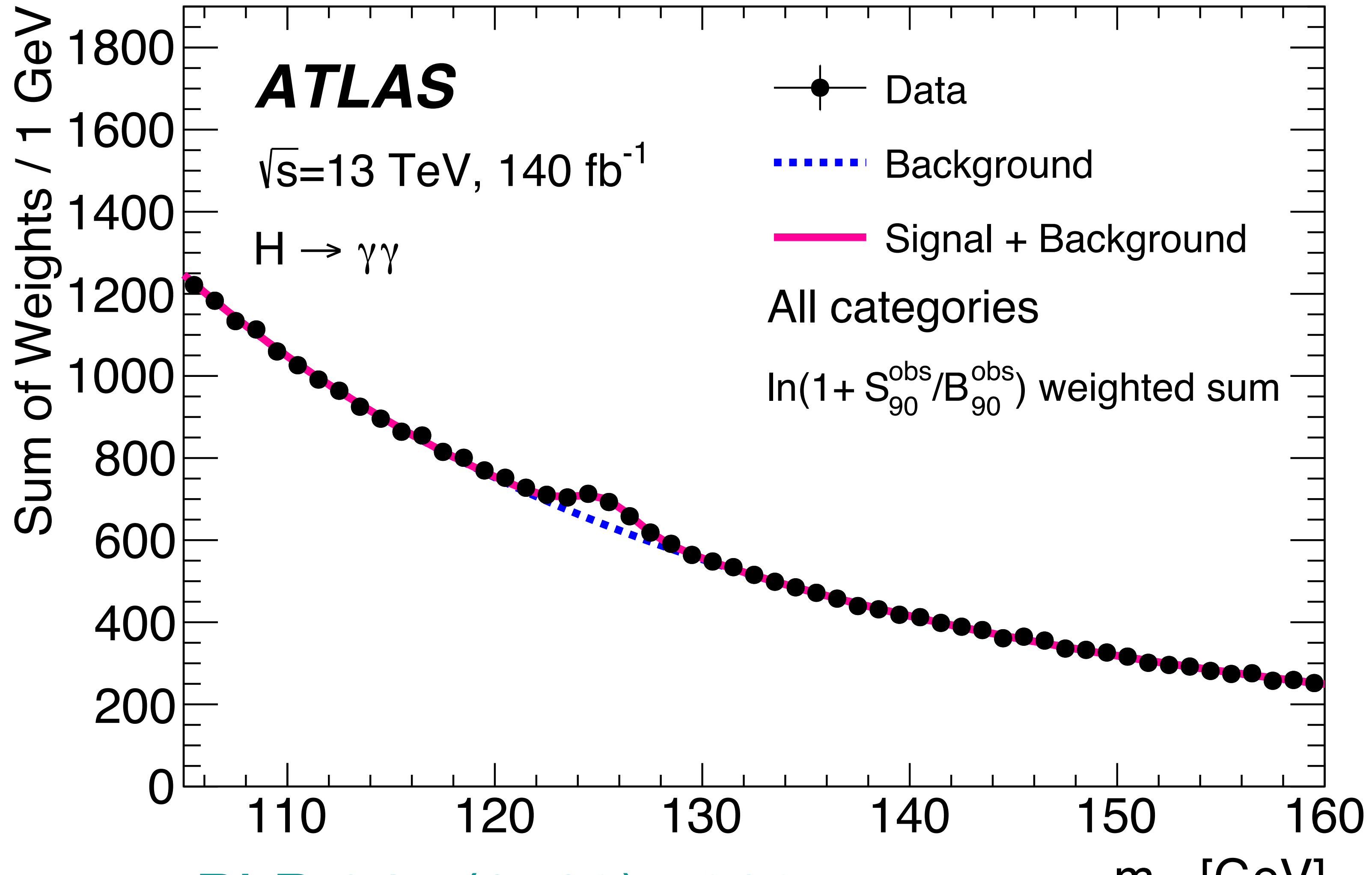


- At √s = 13 TeV during LHC Run 2 (2015-2018), about **56000** Higgs bosons were produced in every fb^{-1} of p-p collision data
- Only selecting **O(0.1%)** for physics analyses due to various challenges: trigger, reconstruction and identification inefficiency…

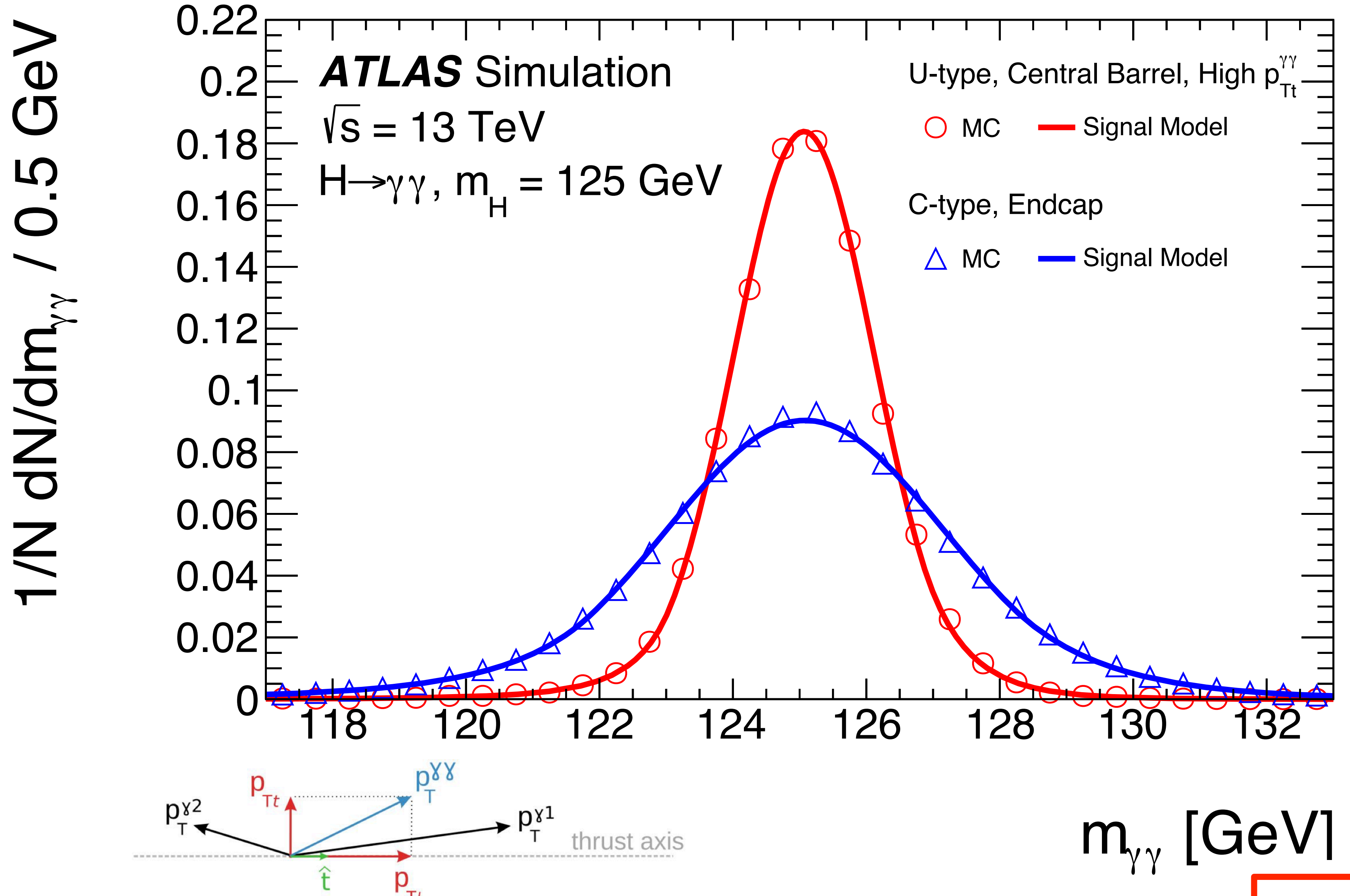
Mass measurement

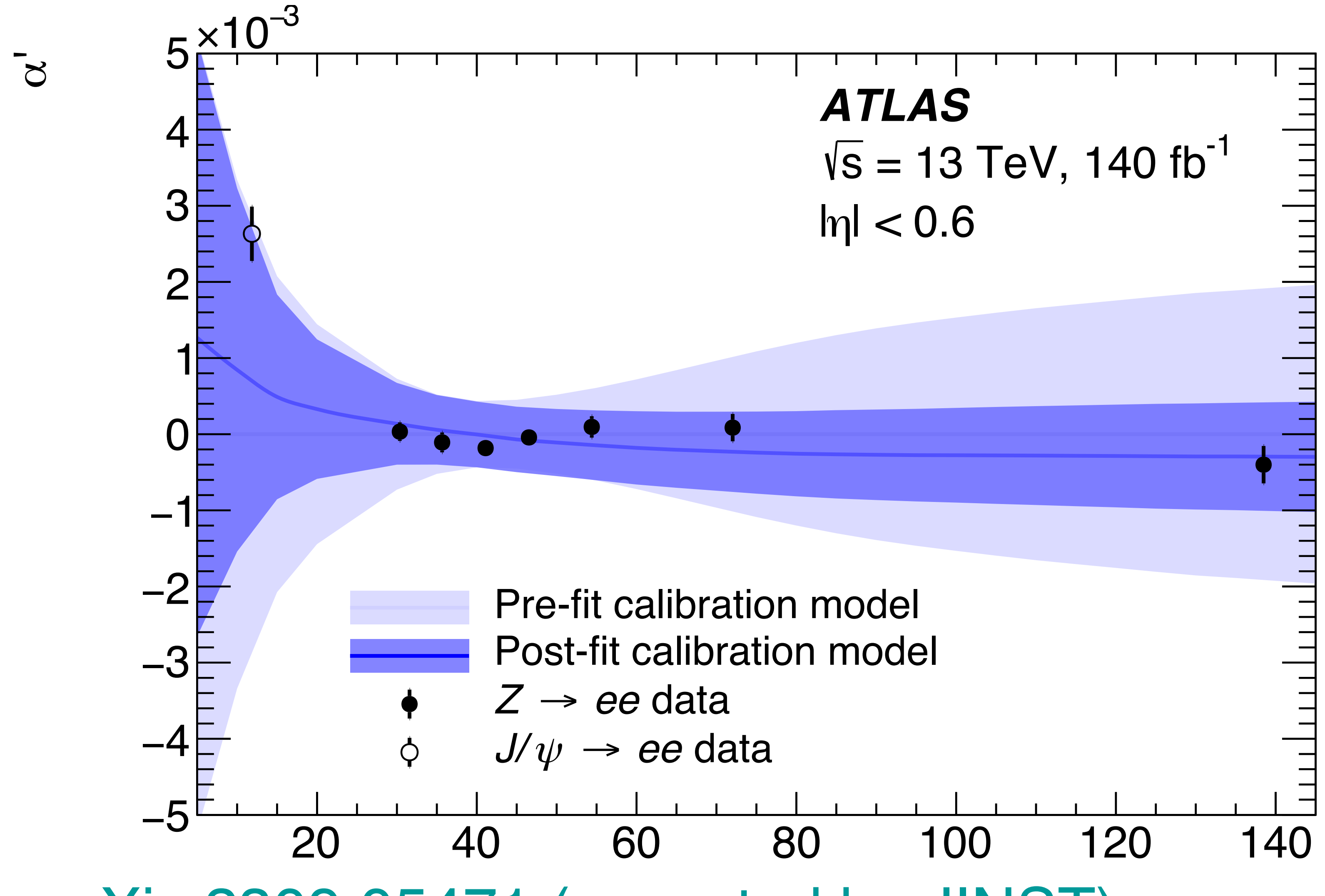


Measurement in H→γγ channel



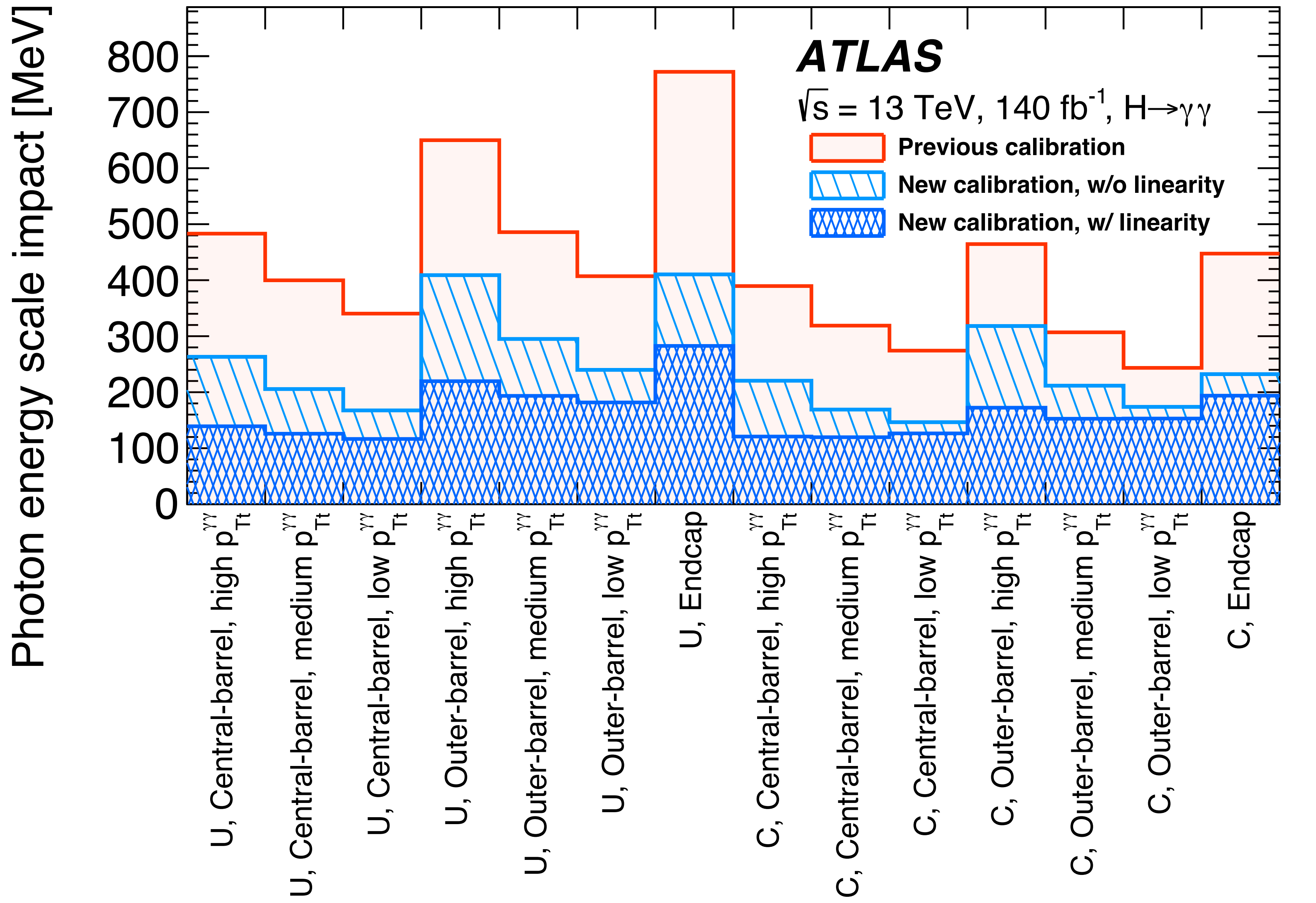
[PLB 847 (2023) 138315](#)



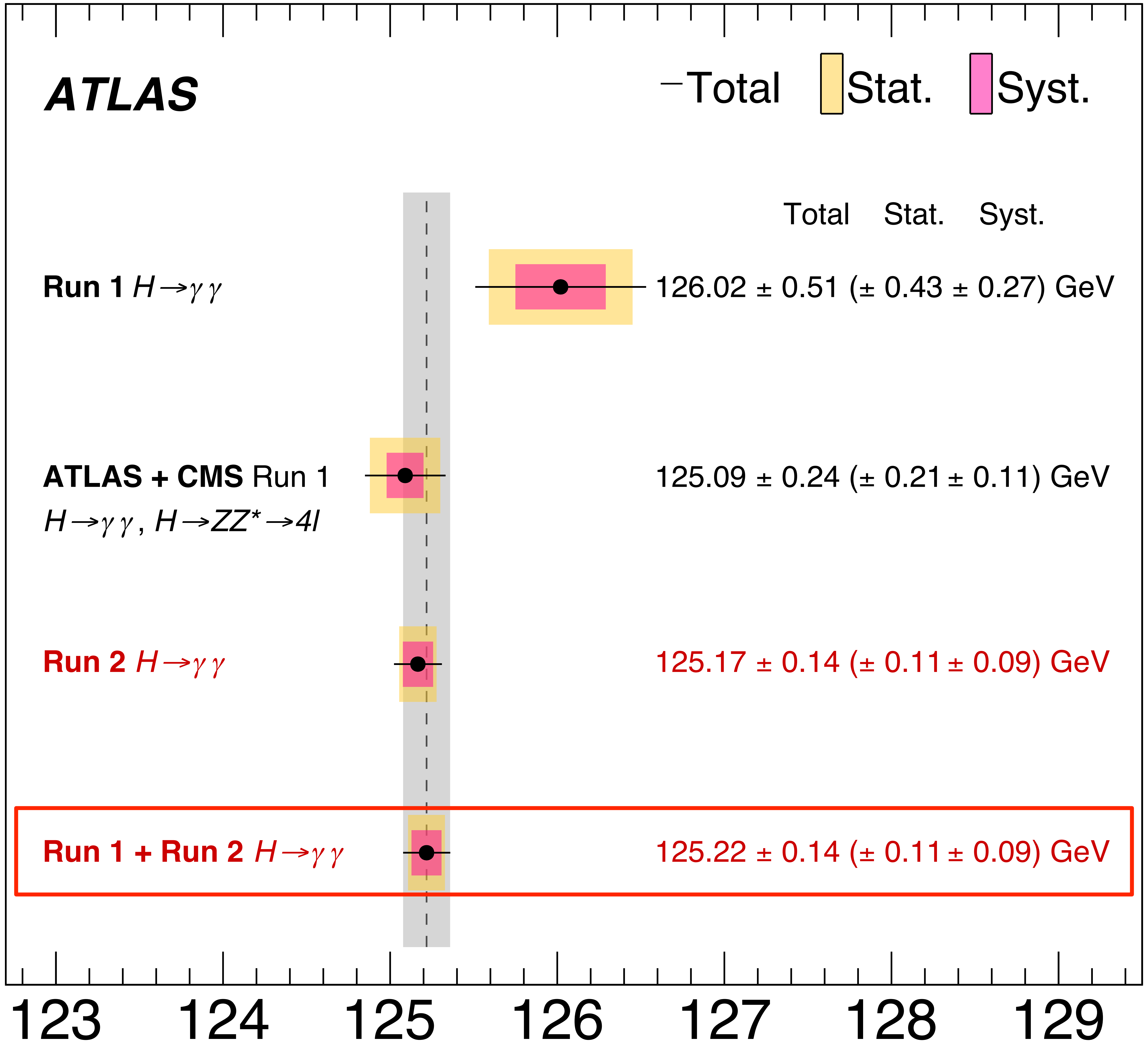


[arXiv:2309.05471 (accepted by JINST)](#) E_T [GeV]

- 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”)



H→γγ measurement results

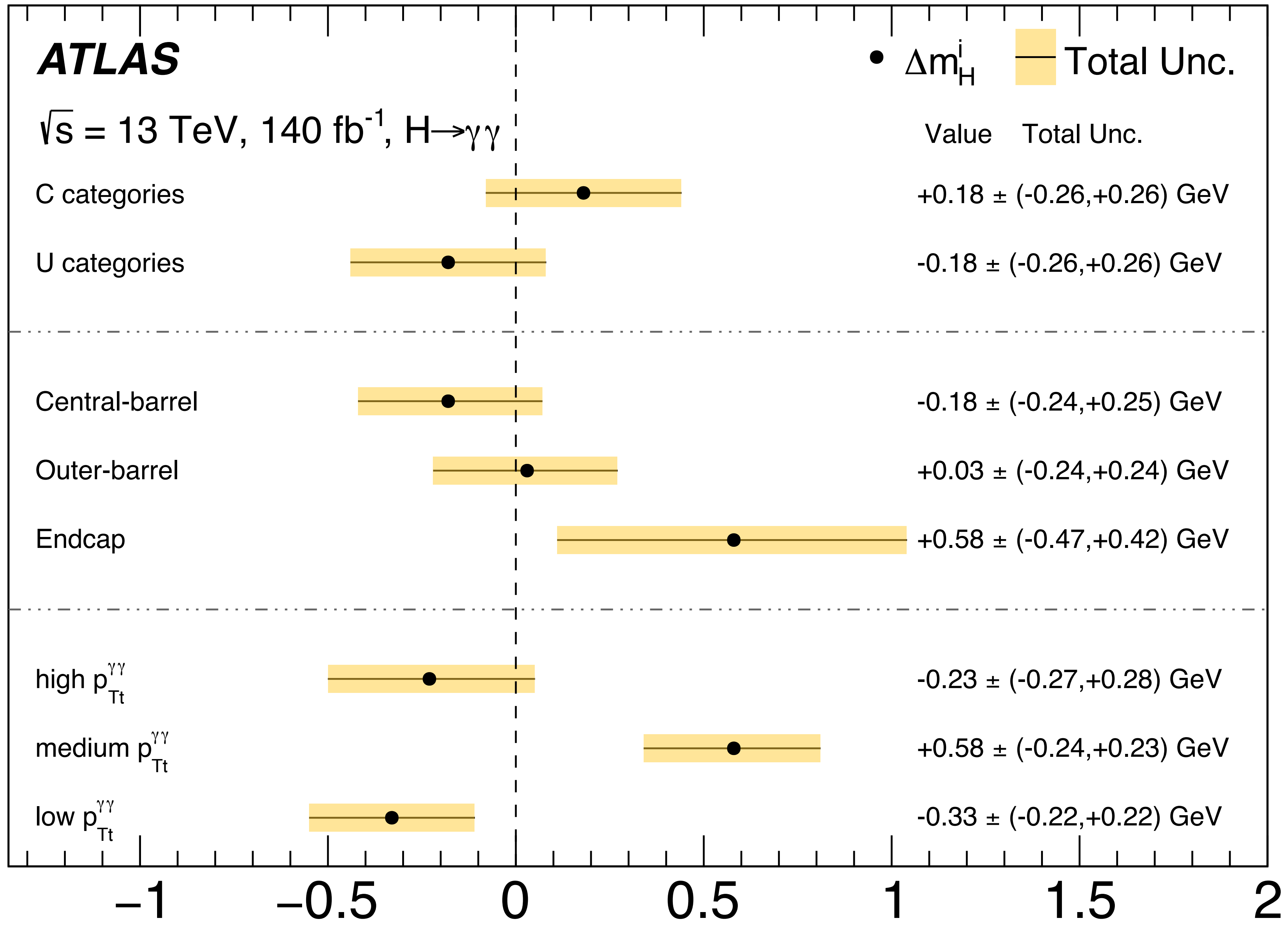


0.1% precision from a single channel!

m_H [GeV]

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



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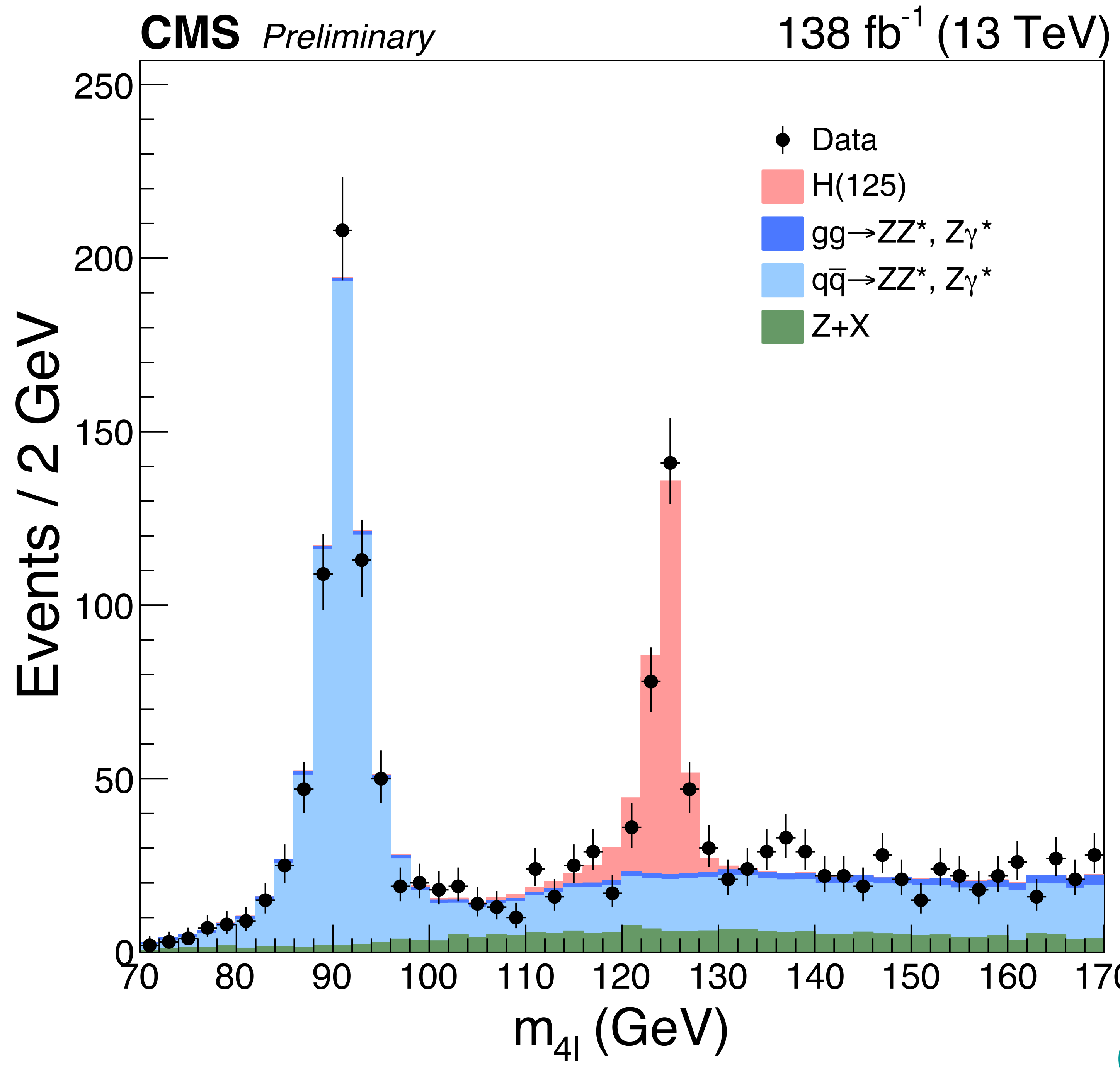
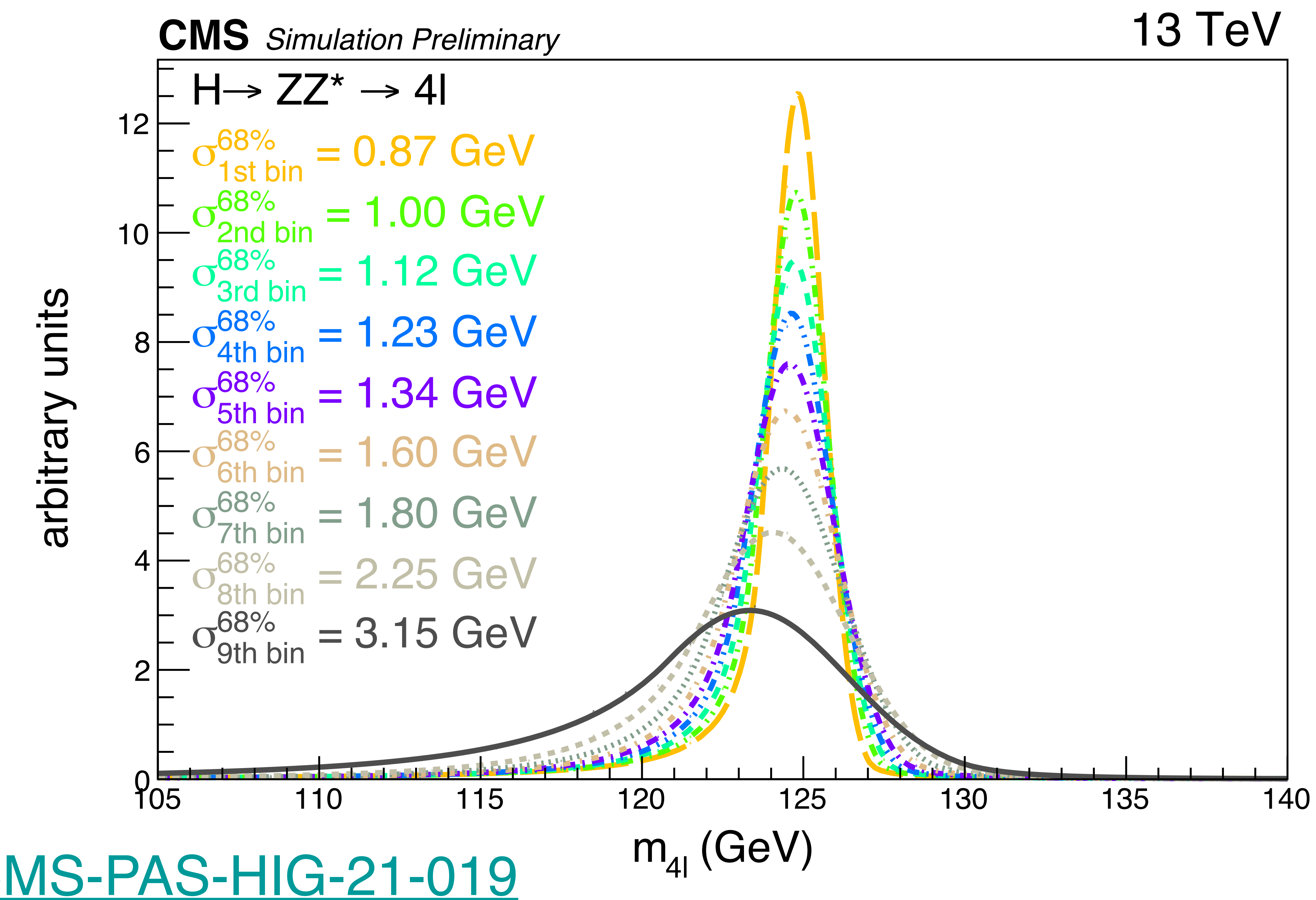
Δm_H^i [GeV]

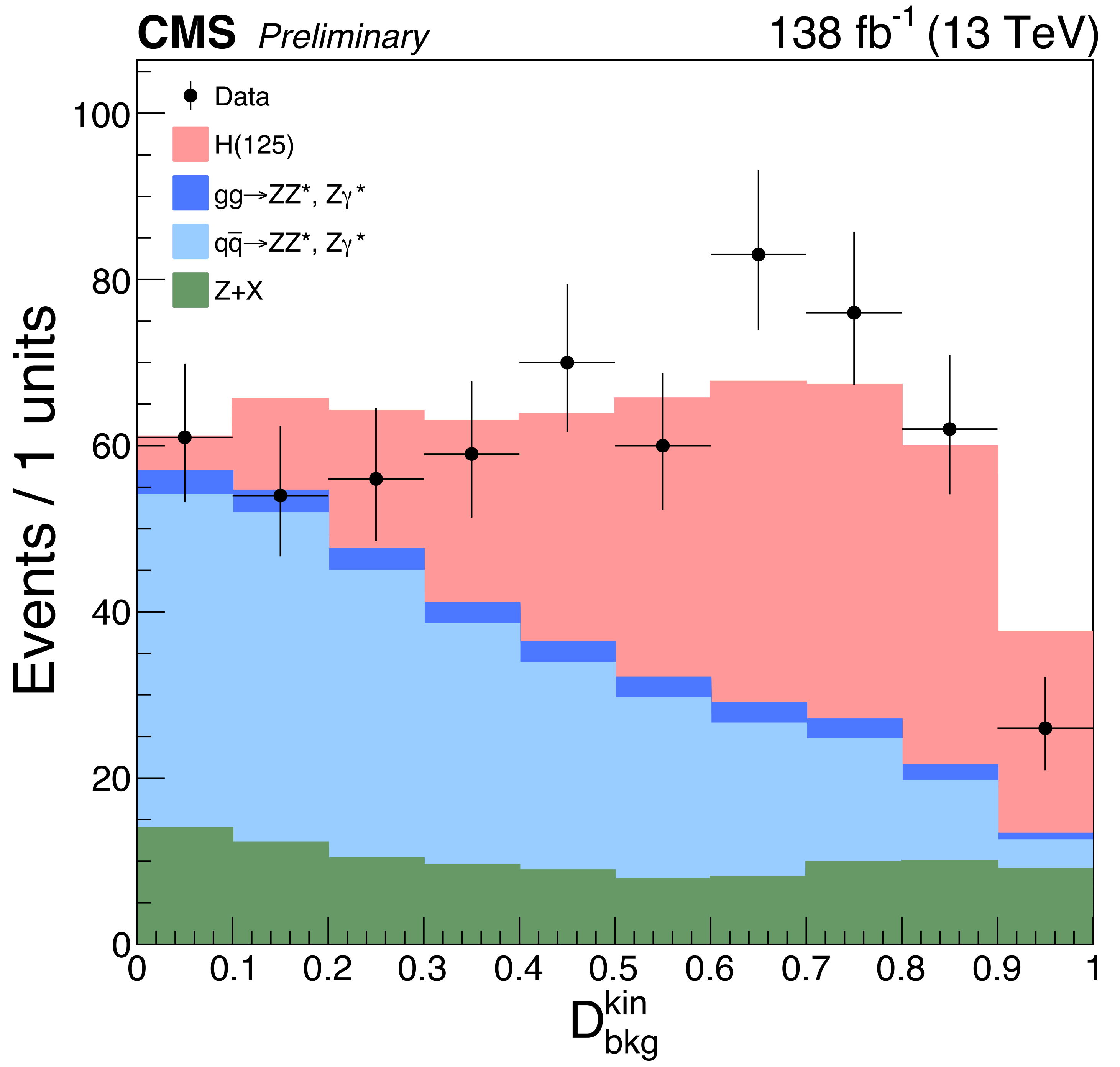
Good consistency

between conversion type, different detector regions etc.

Measurement in H→ZZ*→4l channel





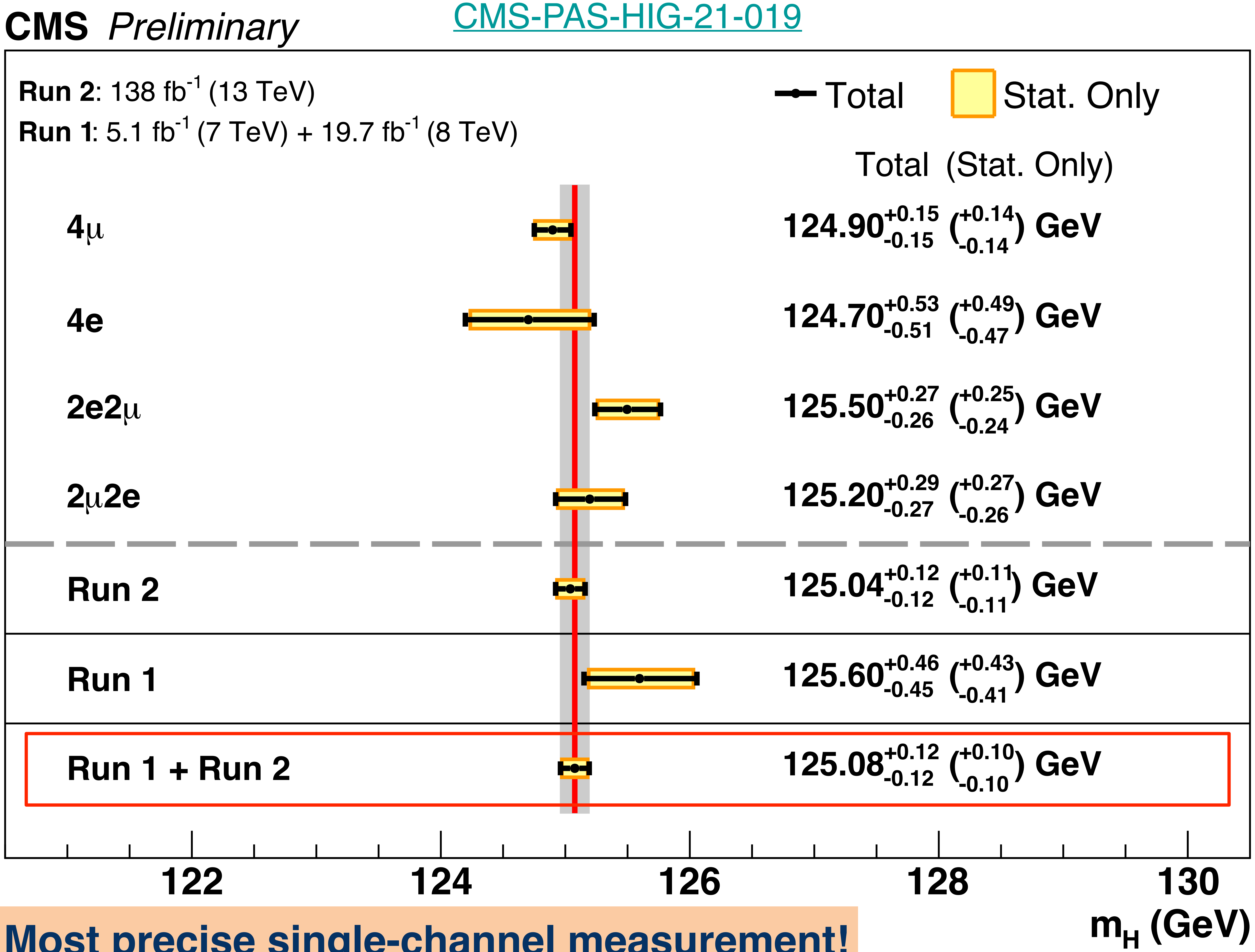


CMS-PAS-HIG-21-019

- Beam-spot constraint in muon reconstruction + kinematic fit to Z-pole for on-shell lepton-pair candidate (**+15%** improvement in precision)
- Categorization based on per-event 4l mass resolution (**+8%**)
- 2D fit of m_{4l} and matrix-element-based (MELA) discriminant (**+4%**)

H→ZZ*→4l measurement results

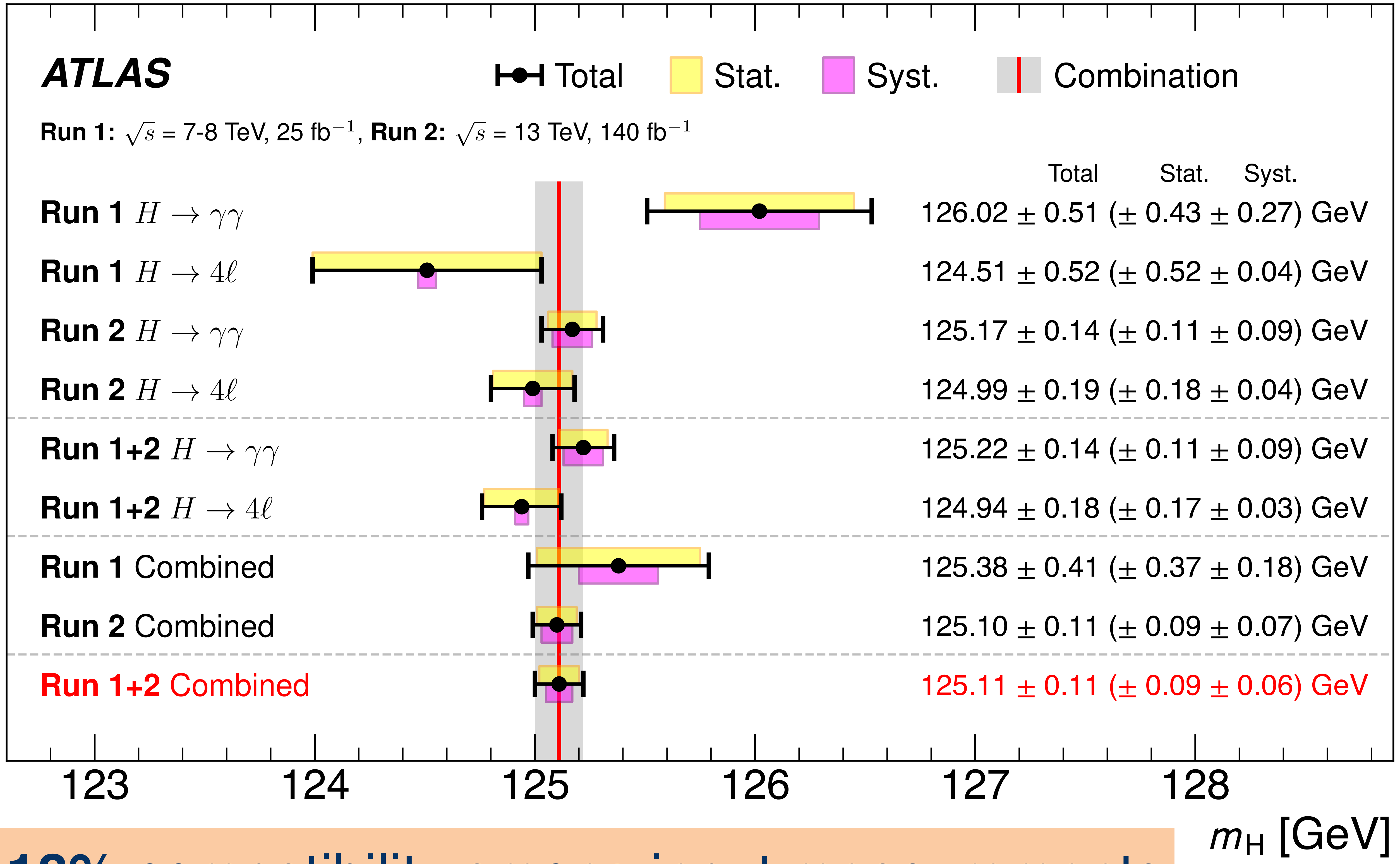
CMS-PAS-HIG-21-019



Most precise single-channel measurement!

- Measurement fully driven by data stat uncertainty
- Main syst from muon momentum and electron energy scale uncertainties
- Analysis validated with Z→4l fit as well as 1D m_H fit

Combining γγ and 4l, Run 1 and Run 2



18% compatibility among input measurements

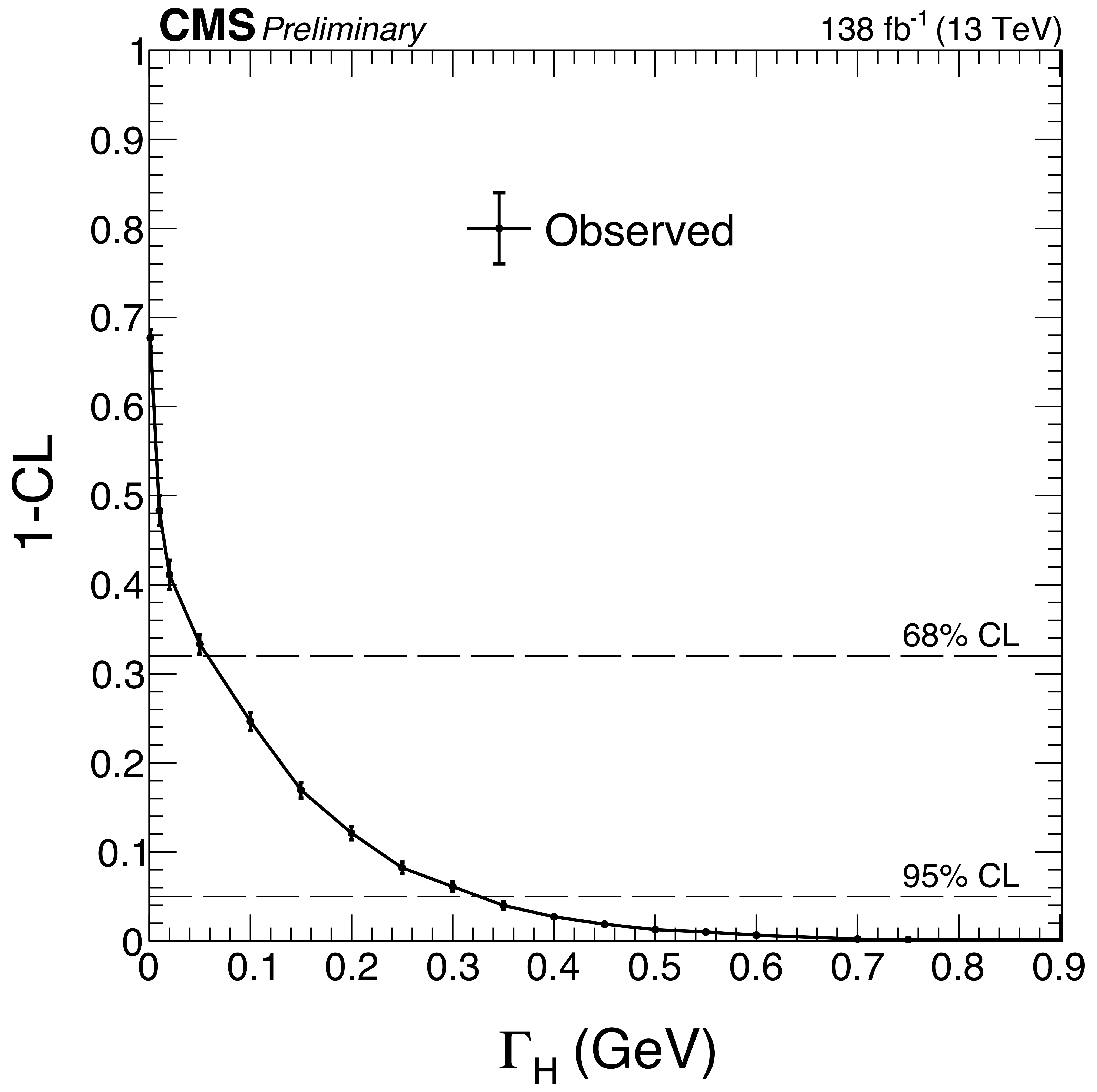
Syst. source	Impact [MeV]
Z→ee calibration	44
E_T-dep. e energy scale	28
H→γγ signal-bkg interference	17
γ lateral shower shape	16
γ conversion modeling	15
e/γ energy resolution	11
H→γγ background modeling	10
Muon momentum scale	8
Others	7

arXiv:2308.04775 (accepted by PRL)

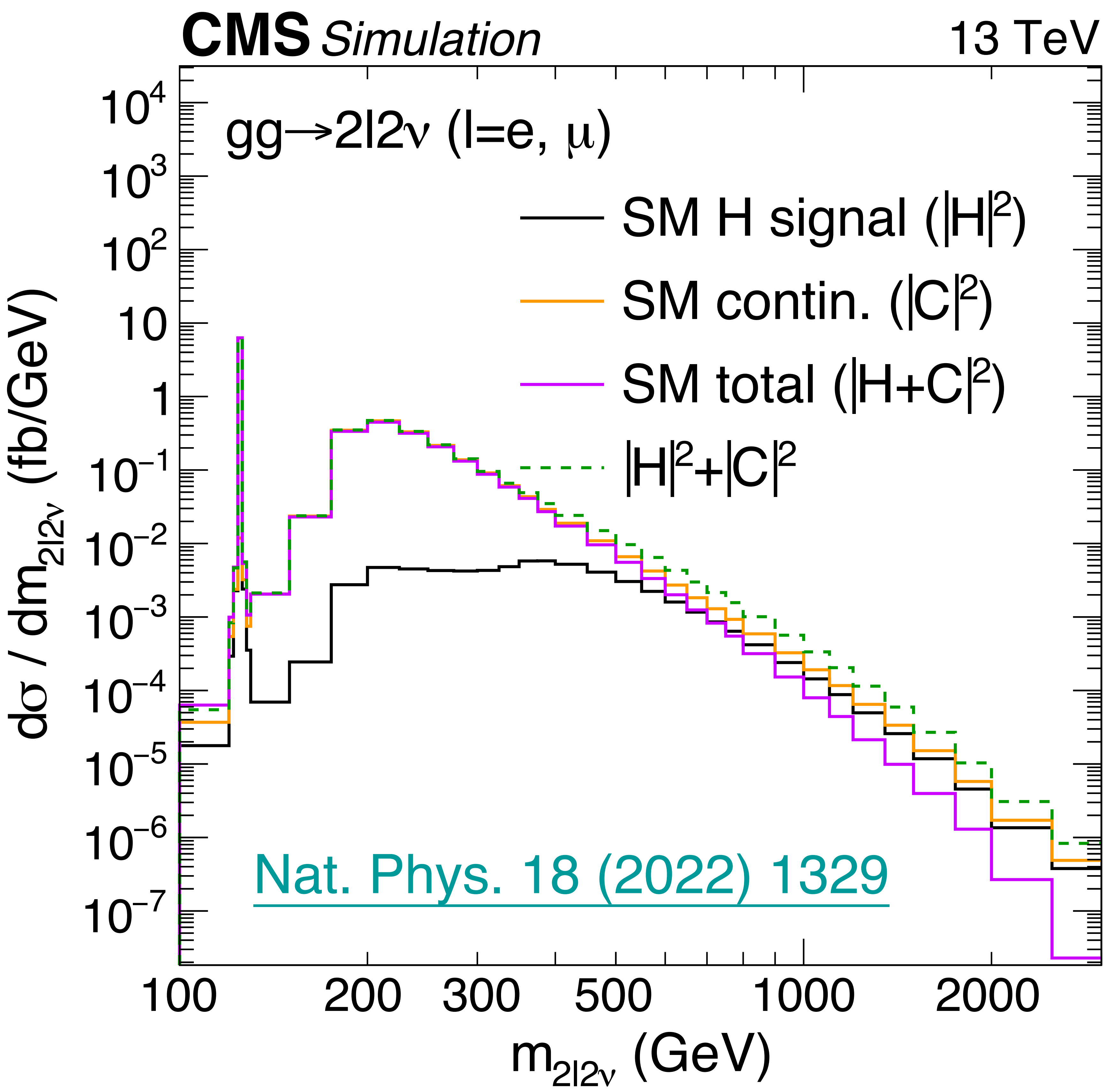
- Uncorrelate signal rates (γγ vs. 4l, Run1 vs. Run 2) to reduce model dependence
- **The most precise measurement of m_H (0.09%) up to date**
- ATLAS+CMS combination under preparation: will provide best m_H for experiment & theory

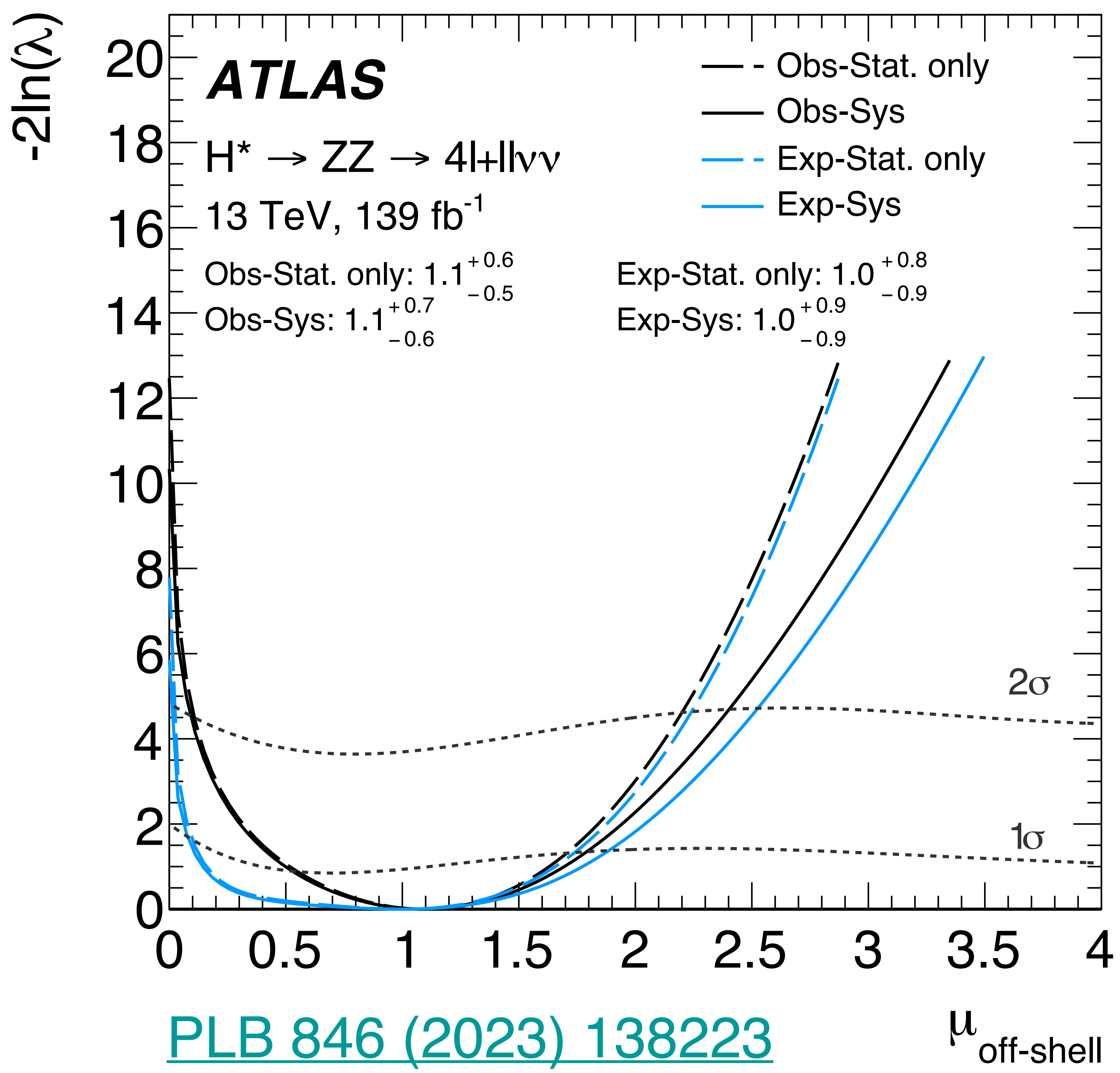
Width measurement

CMS-PAS-HIG-21-019



Off-shell measurements





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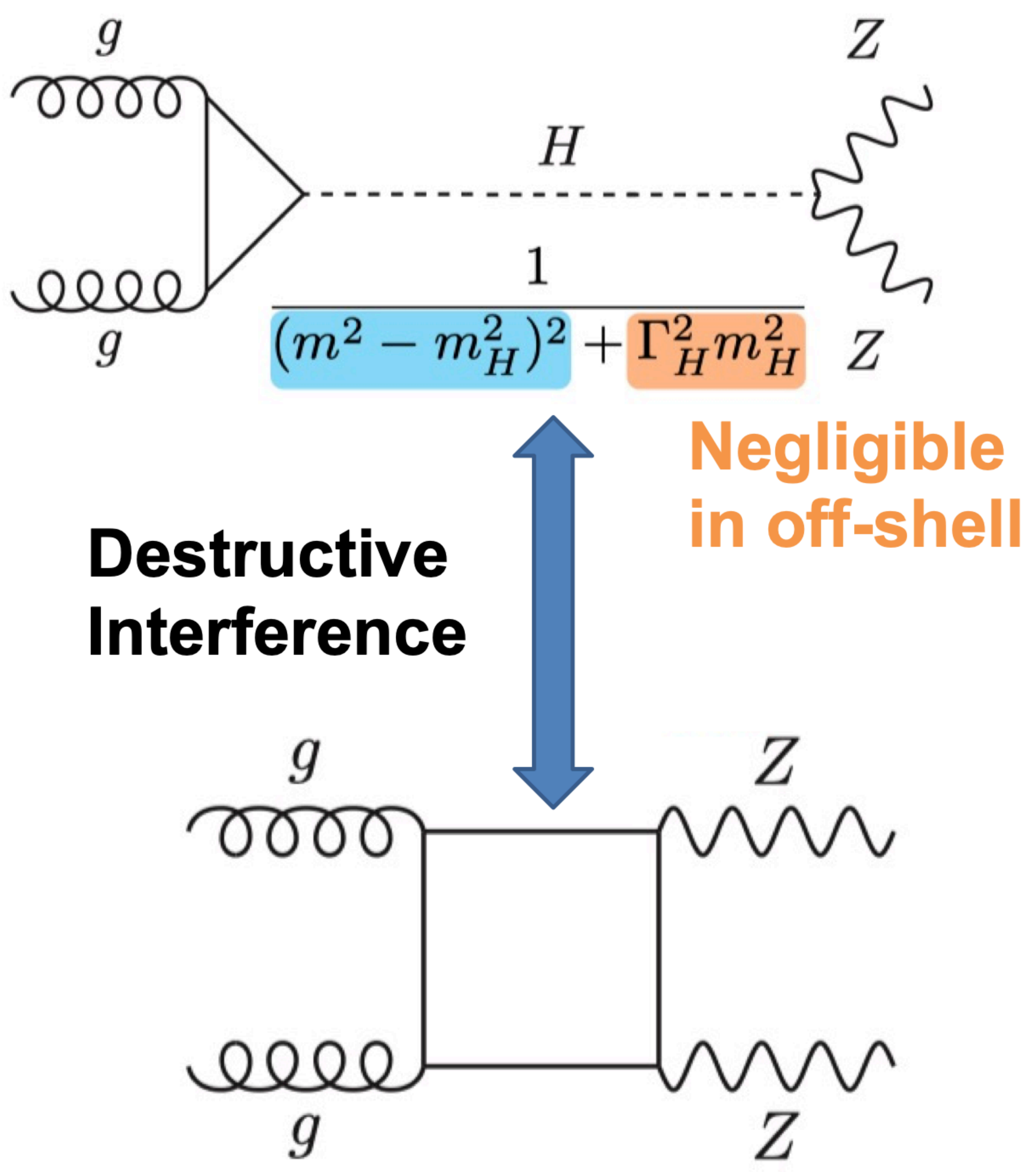
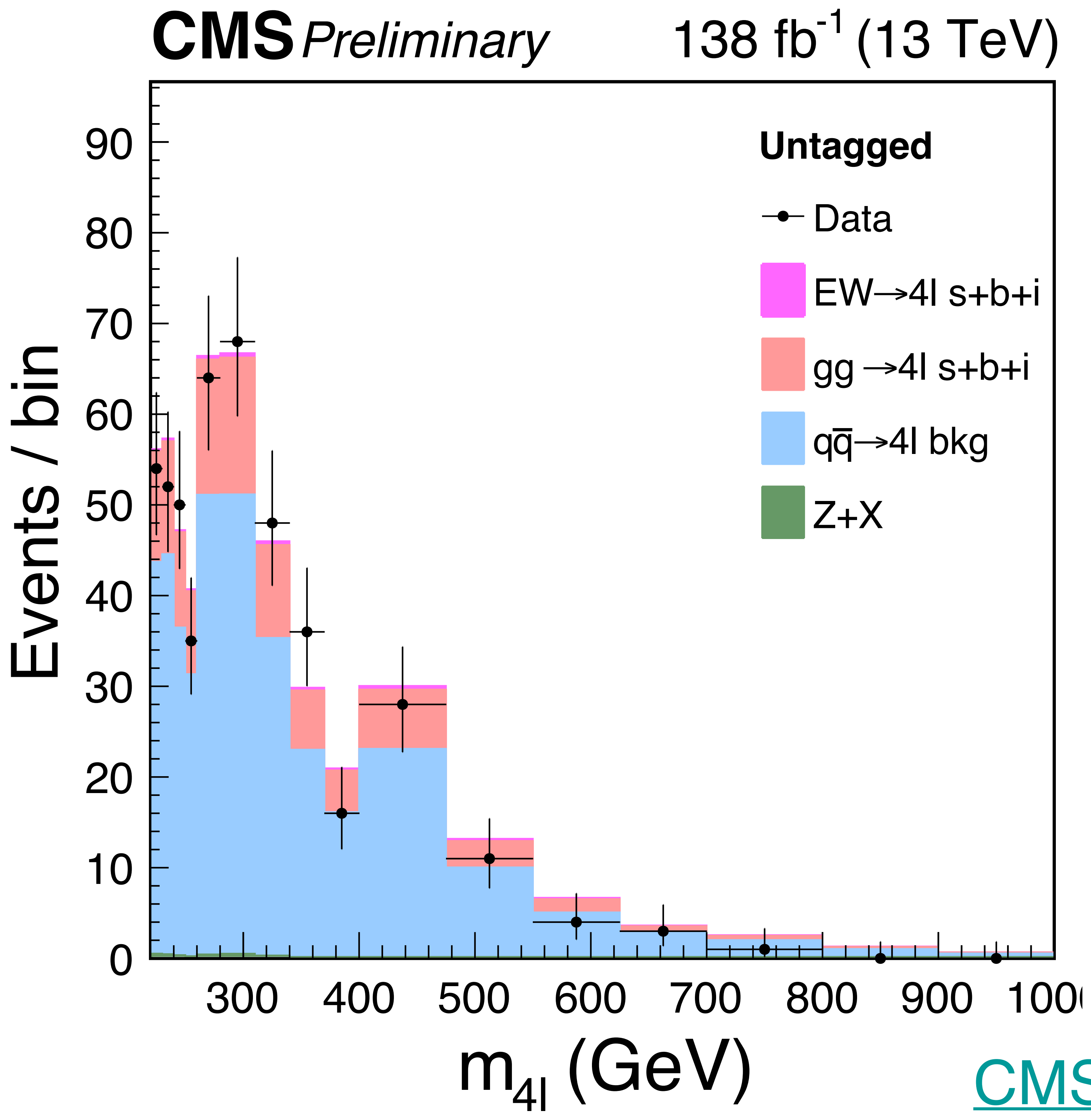
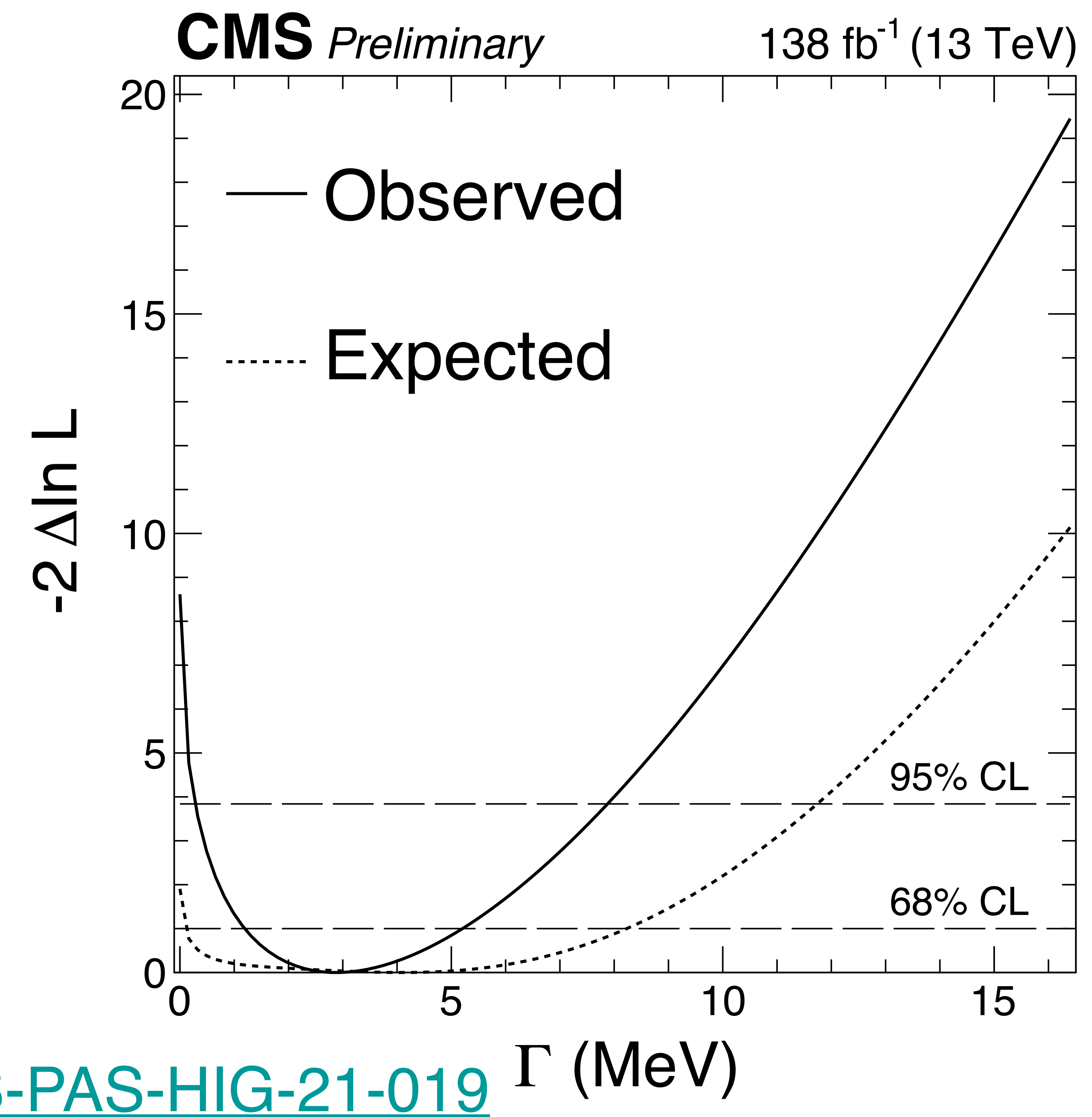


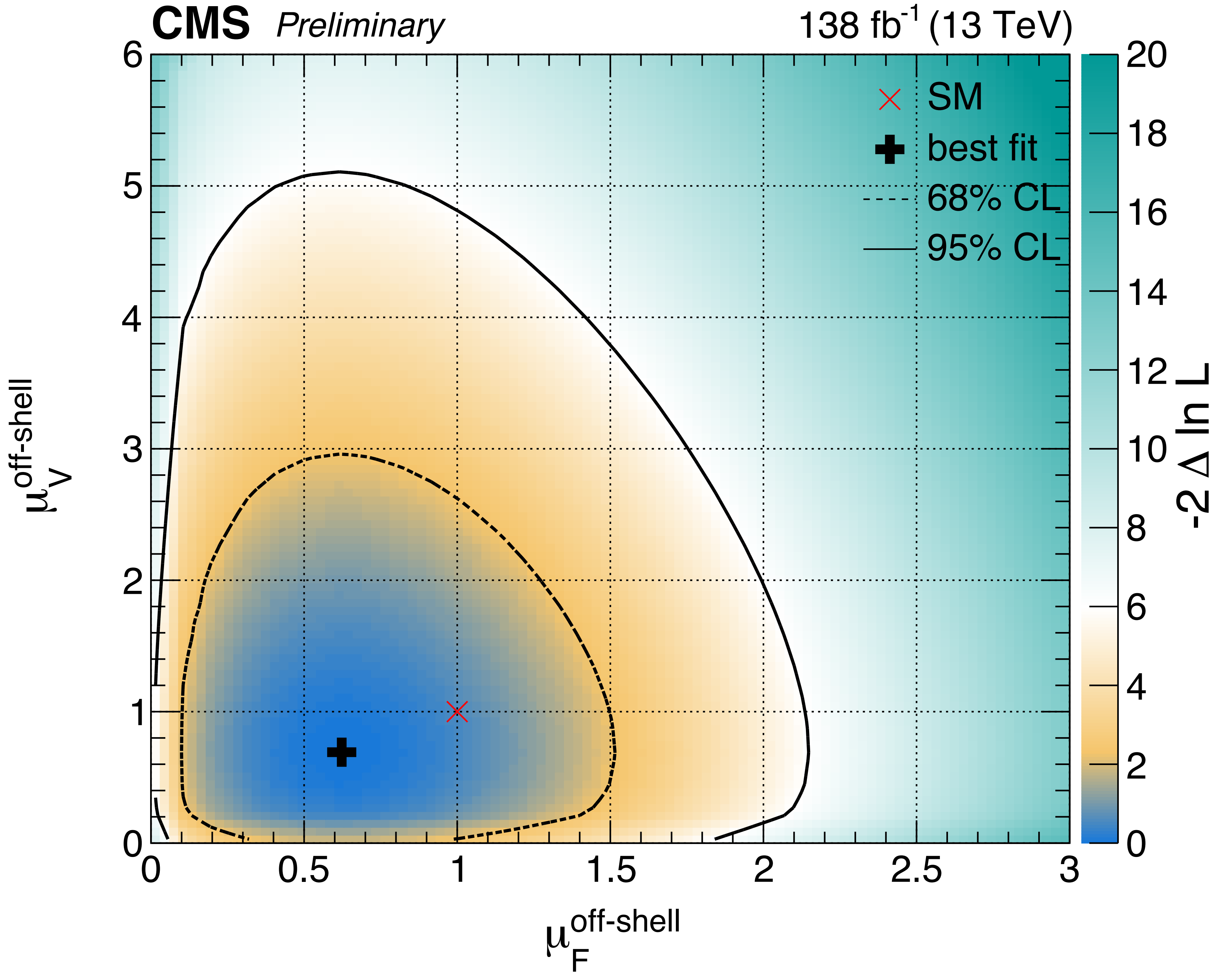
- **Evidence for off-shell production** has been claimed by both ATLAS and CMS
- By assuming identical coupling between on-shell and off-shell productions:

$$\Gamma(H) = (\mu_{\text{off-shell}}/\mu_{\text{on-shell}})\,\Gamma_{SM}(H)$$

Updated measurement in H→ZZ*→4l channel



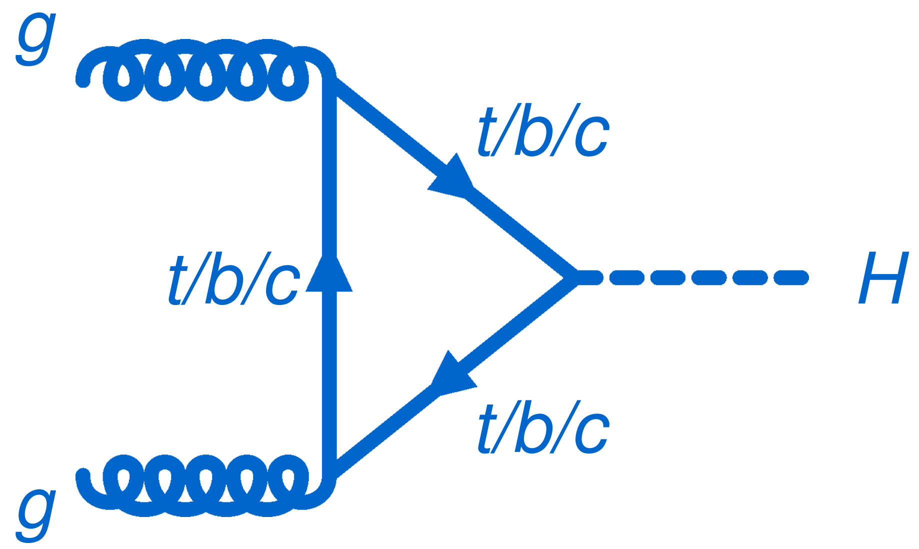




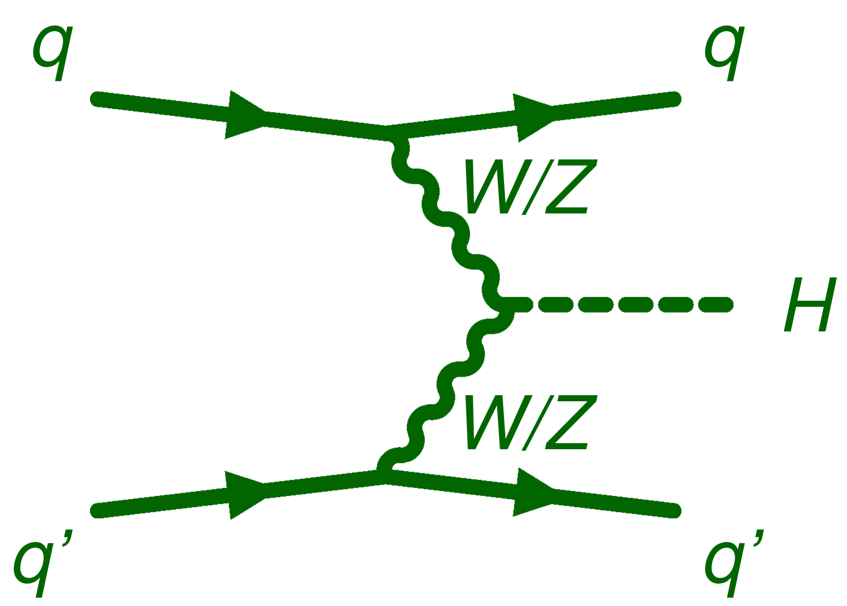
CMS-PAS-HIG-21-019

- Study off-shell ($m_{4l} > 220$ GeV) production in VBF-tagged, VH-tagged, and untagged regions
- Measured Γ(H) consistent with SM. Consistent ggF and VBF+VH off-shell signal strengths

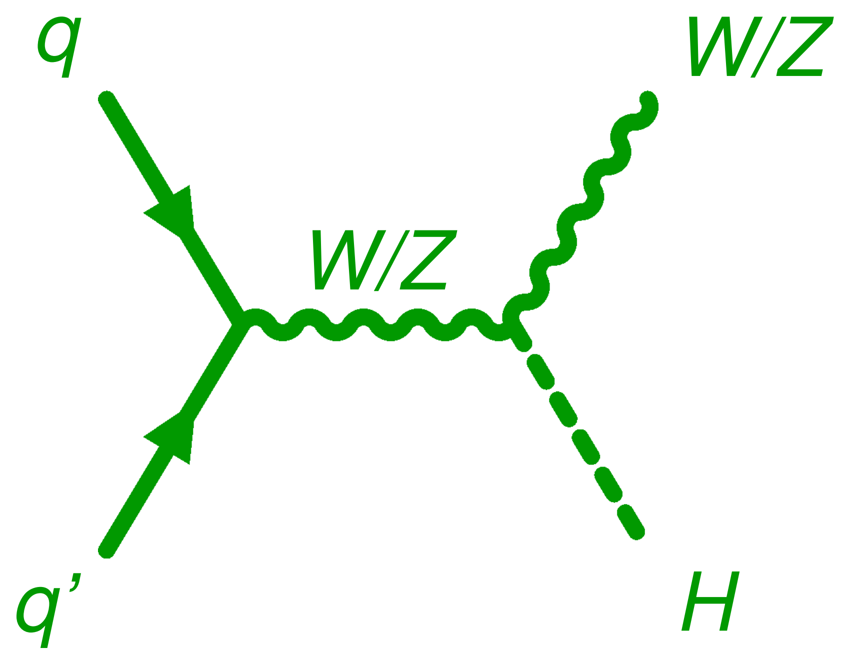
Measurement	Γ(H) [MeV]
ATLAS 4l+llνν (PLB 846 (2023) 138223)	$4.6^{+2.6}_{-2.5}$
CMS 4l+llνν (Nat. Phys. 18 (2022) 1329)	$3.2^{+2.4}_{-1.7}$
Updated CMS 4l (CMS-PAS-HIG-21-019)	$2.9^{+2.3}_{-1.7}$



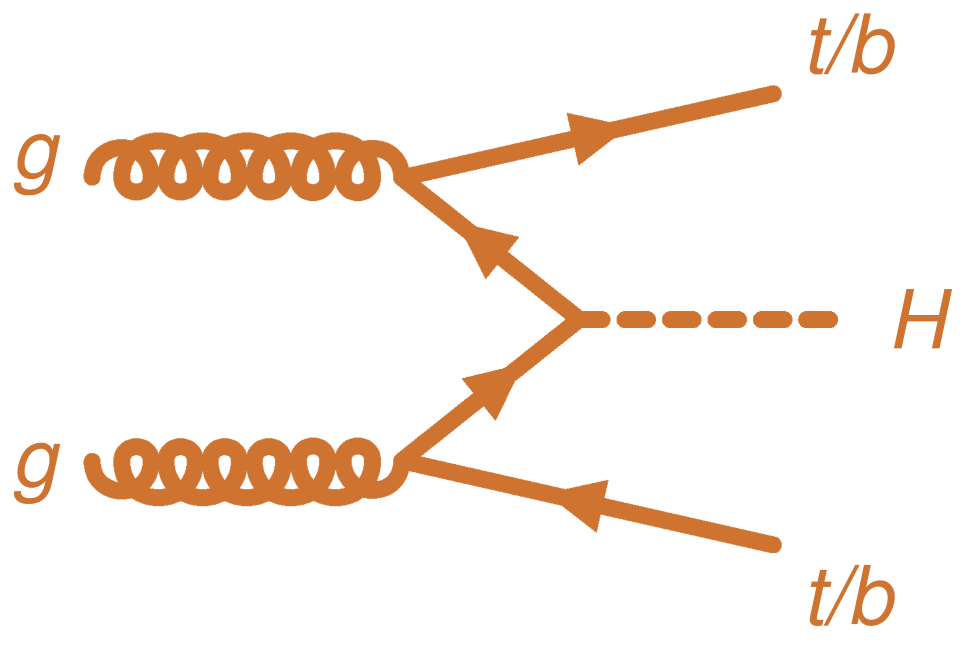
ggF (87%)



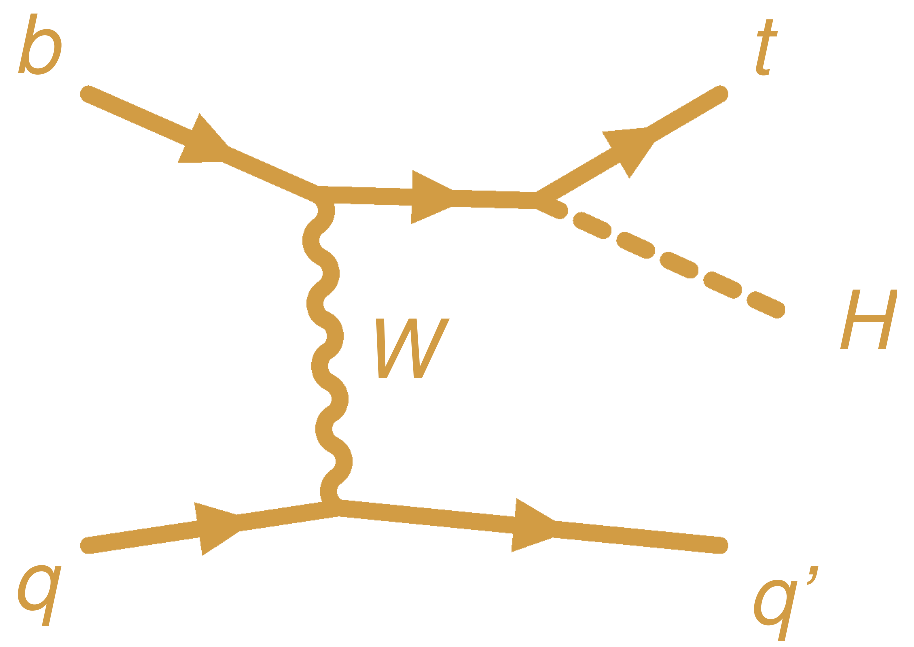
VBF (7%)



VH (4%)

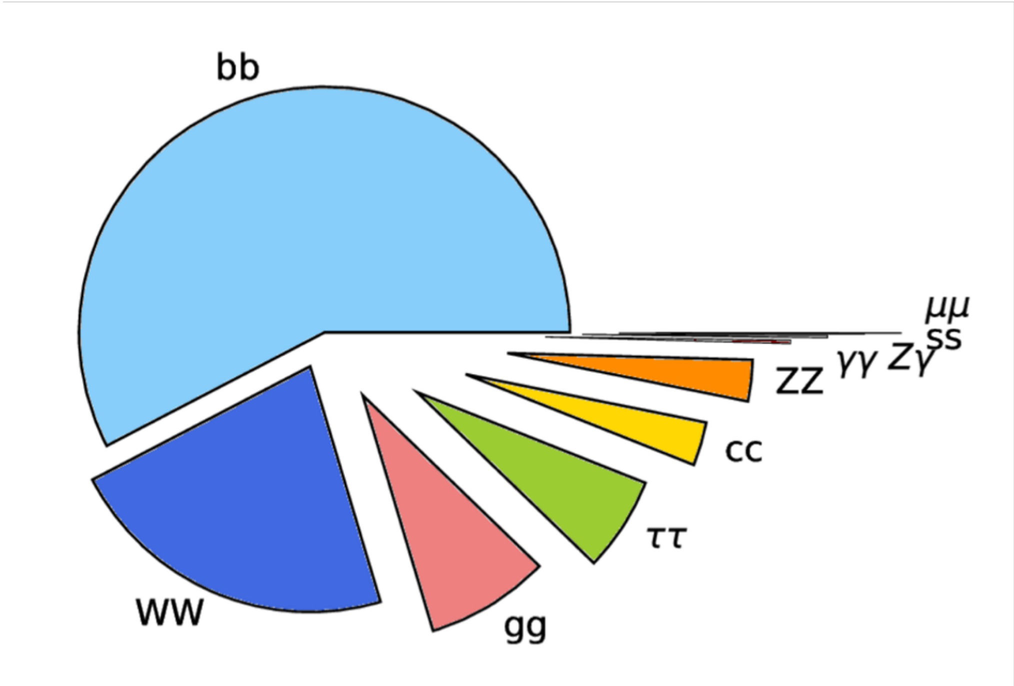


ttH/bbH (2%)

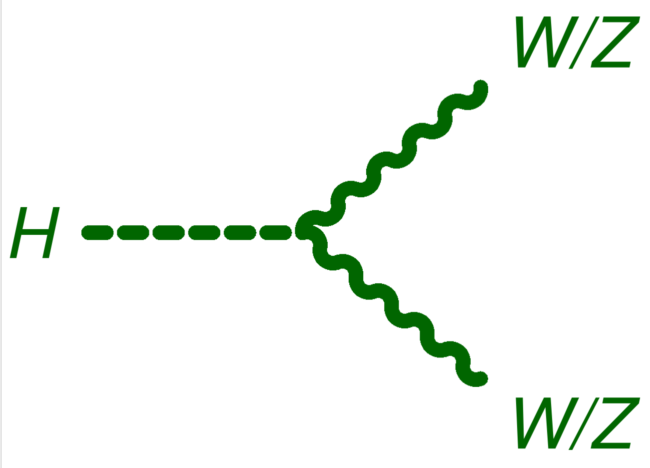


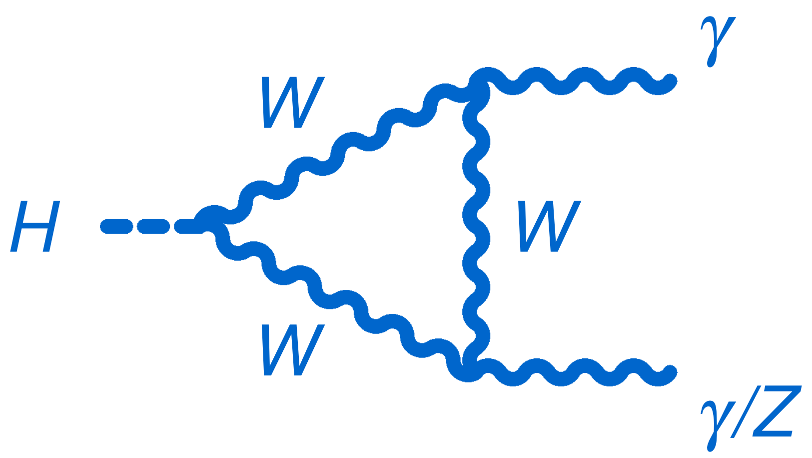
tH (0.1%)

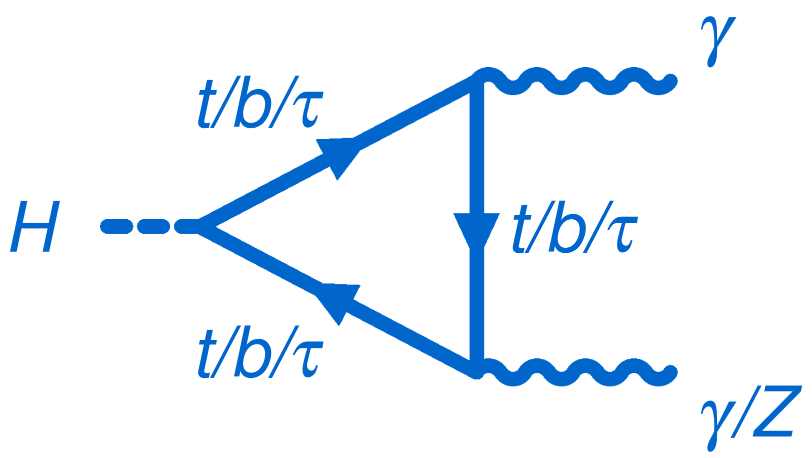
XS measurements

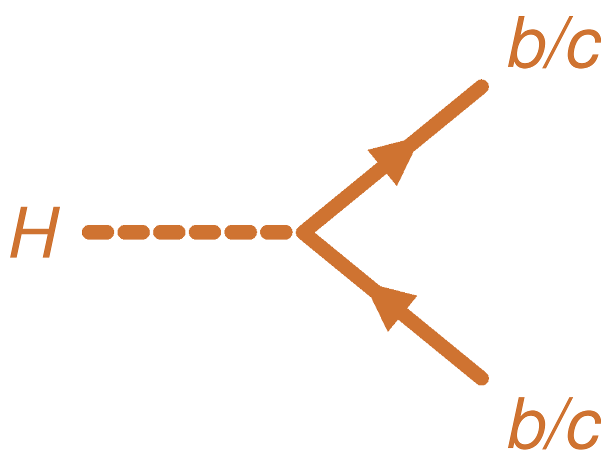


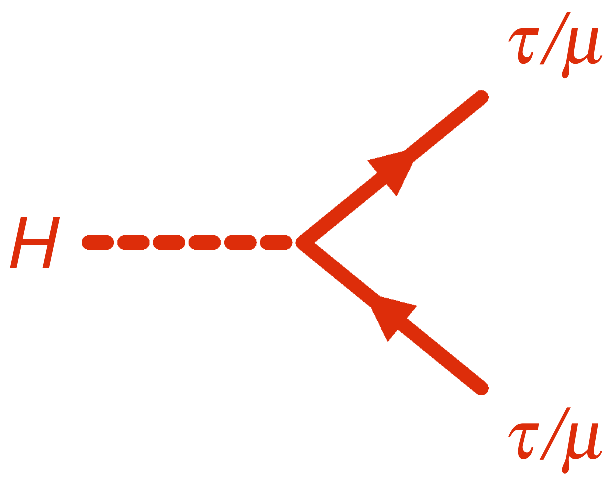
Higgs boson decay BR



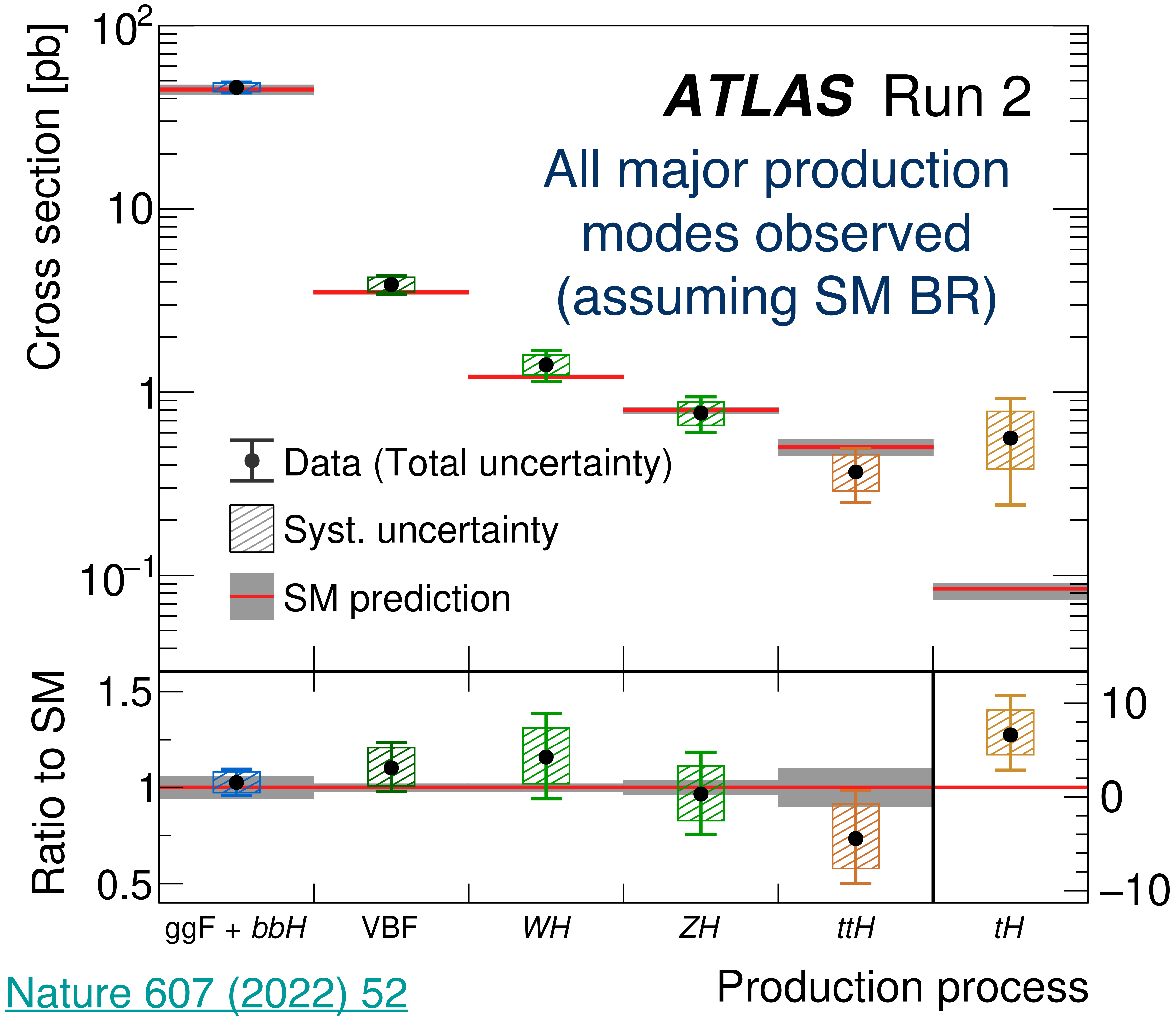








Inclusive production cross-sections



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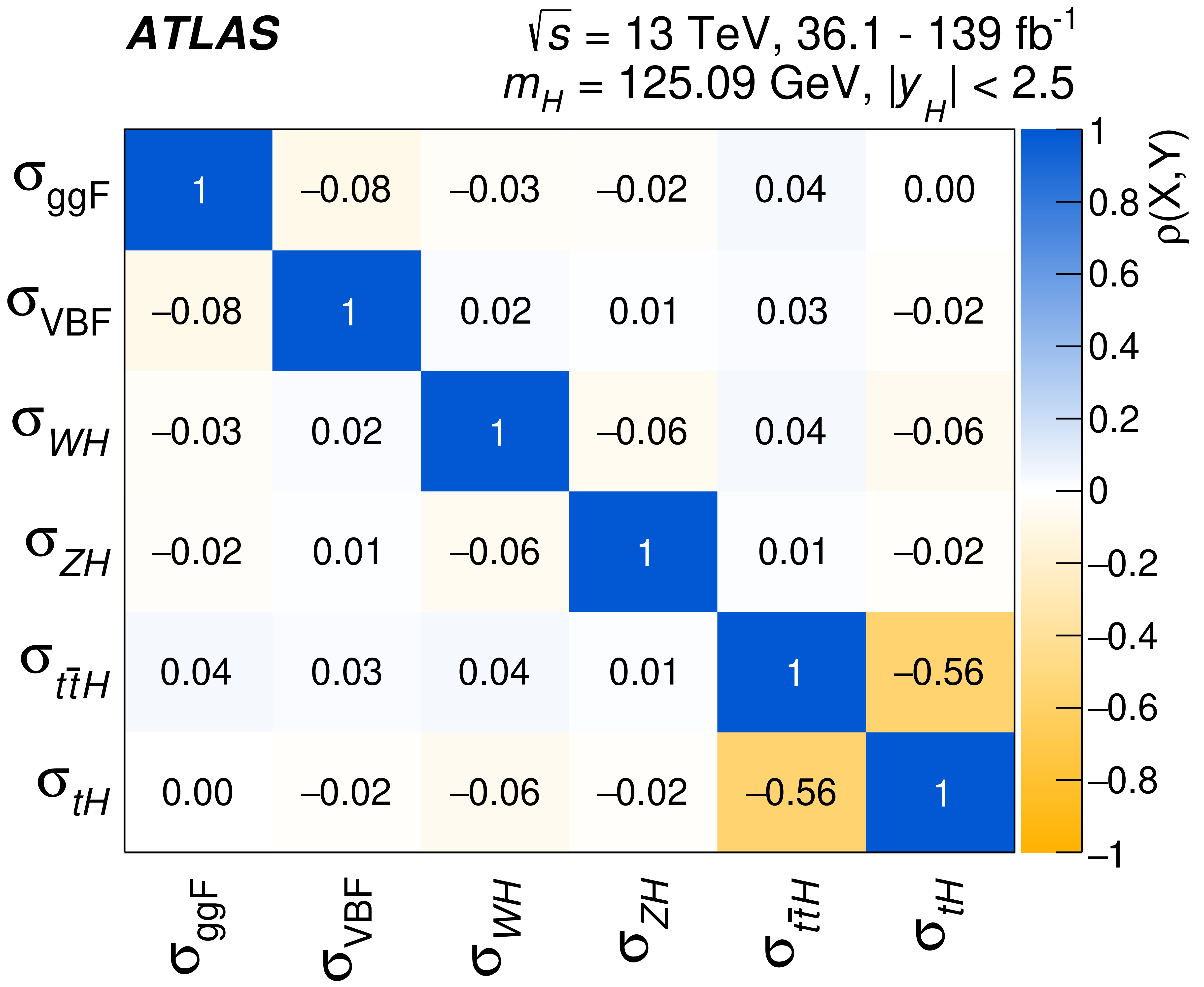
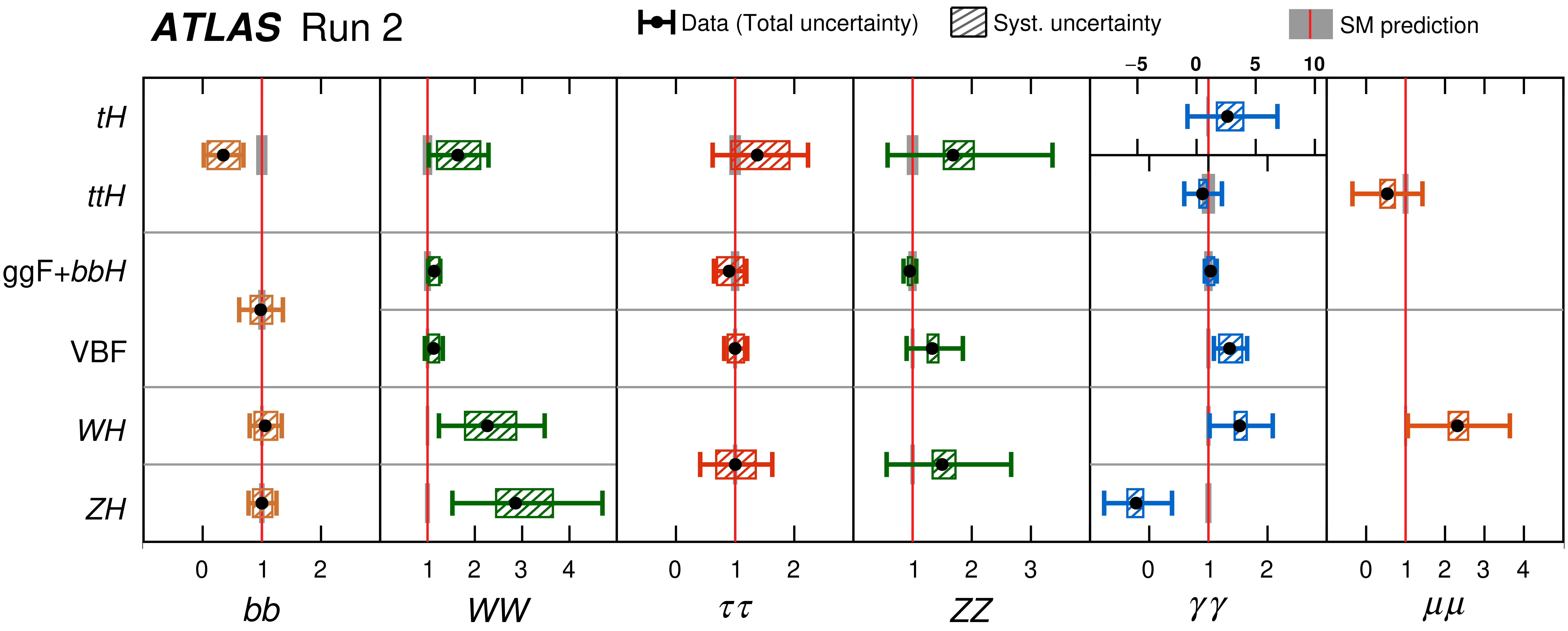


ATLAS signal strength	$\mu = 1.05 \pm 0.06 = 1.05 \pm 0.03(\text{stat.}) \pm 0.03(\text{exp.}) \pm 0.02(\text{bkg. th.}) \pm 0.04(\text{sig. th.})$
CMS signal strength	$\mu = 1.002 \pm 0.057 = 1.002 \pm 0.029(\text{stat.}) \pm 0.033(\text{syst.}) \pm 0.036(\text{sig. th.})$

Production cross-section times decay BR



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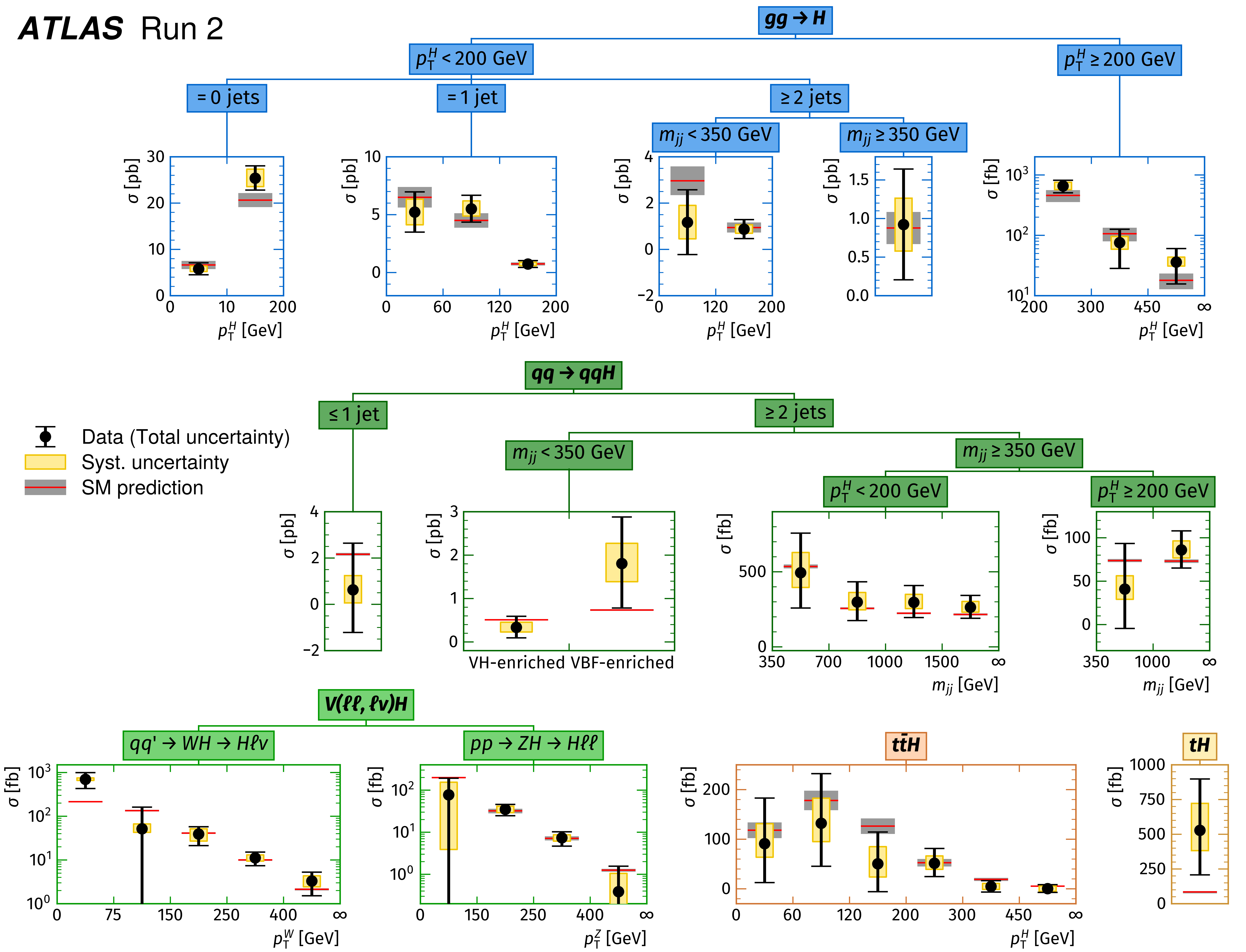
σ × B normalized to SM prediction

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

Dive into phase-space sensitive to BSM

- Inclusive measurements are not enough: **go differential to validate SM & probe potential new physics!**
- The Simplified Template XS (STXS) framework has been widely implemented in LHC Higgs "coupling" analyses
- Run 2 LHC measurements features exploring **high p_T(H) regime** etc. that are sensitive to new physics effects



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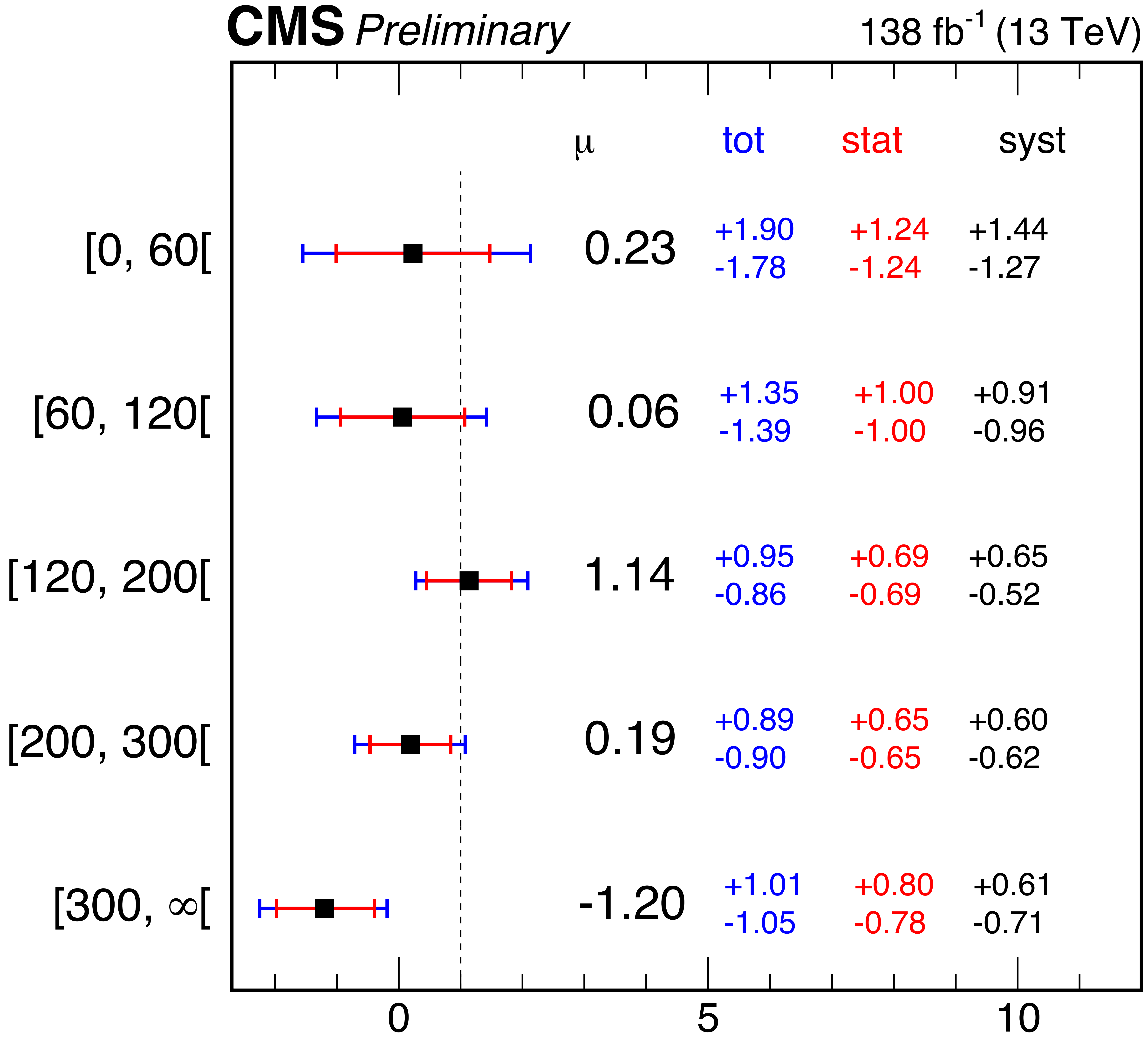
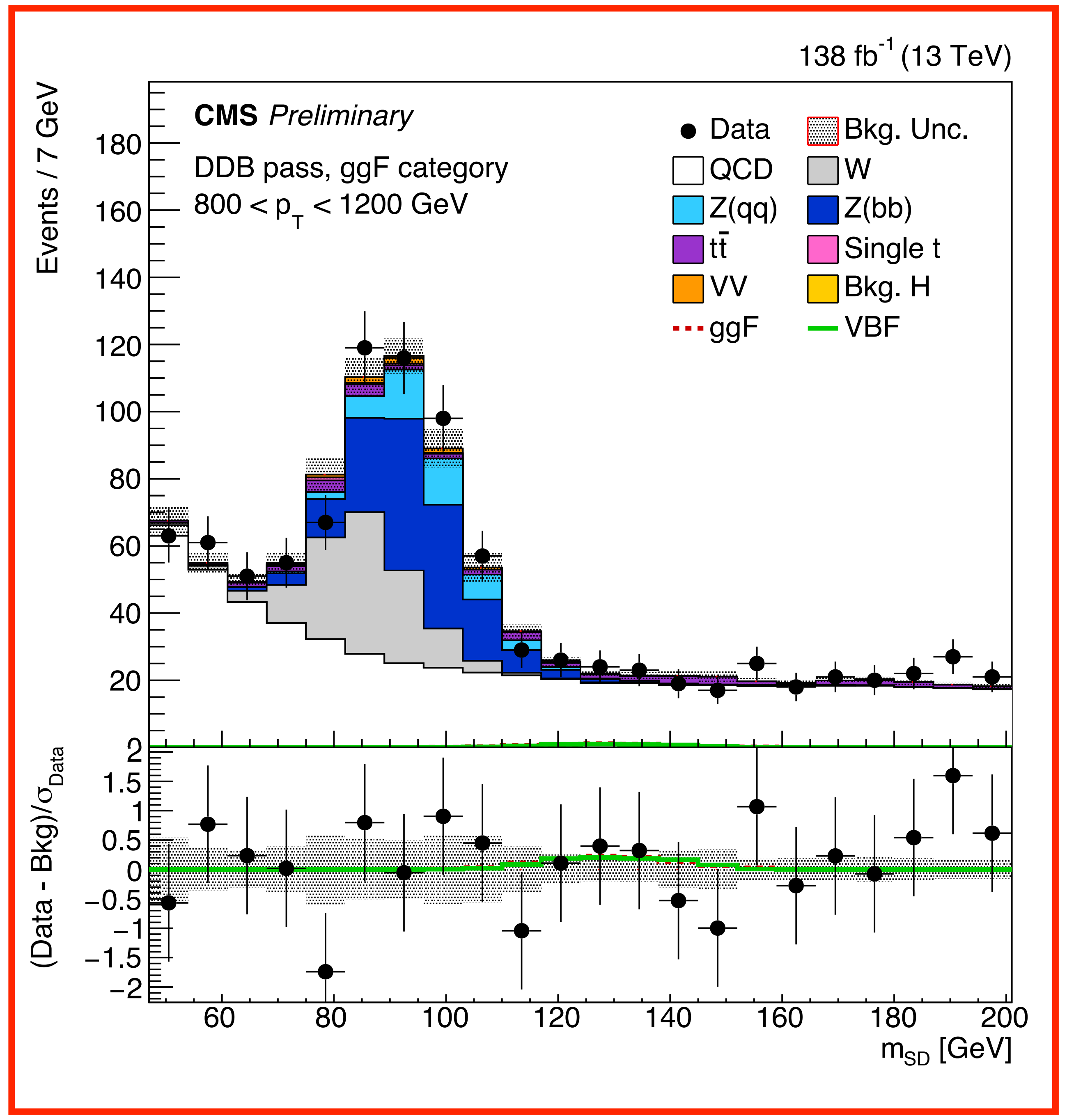


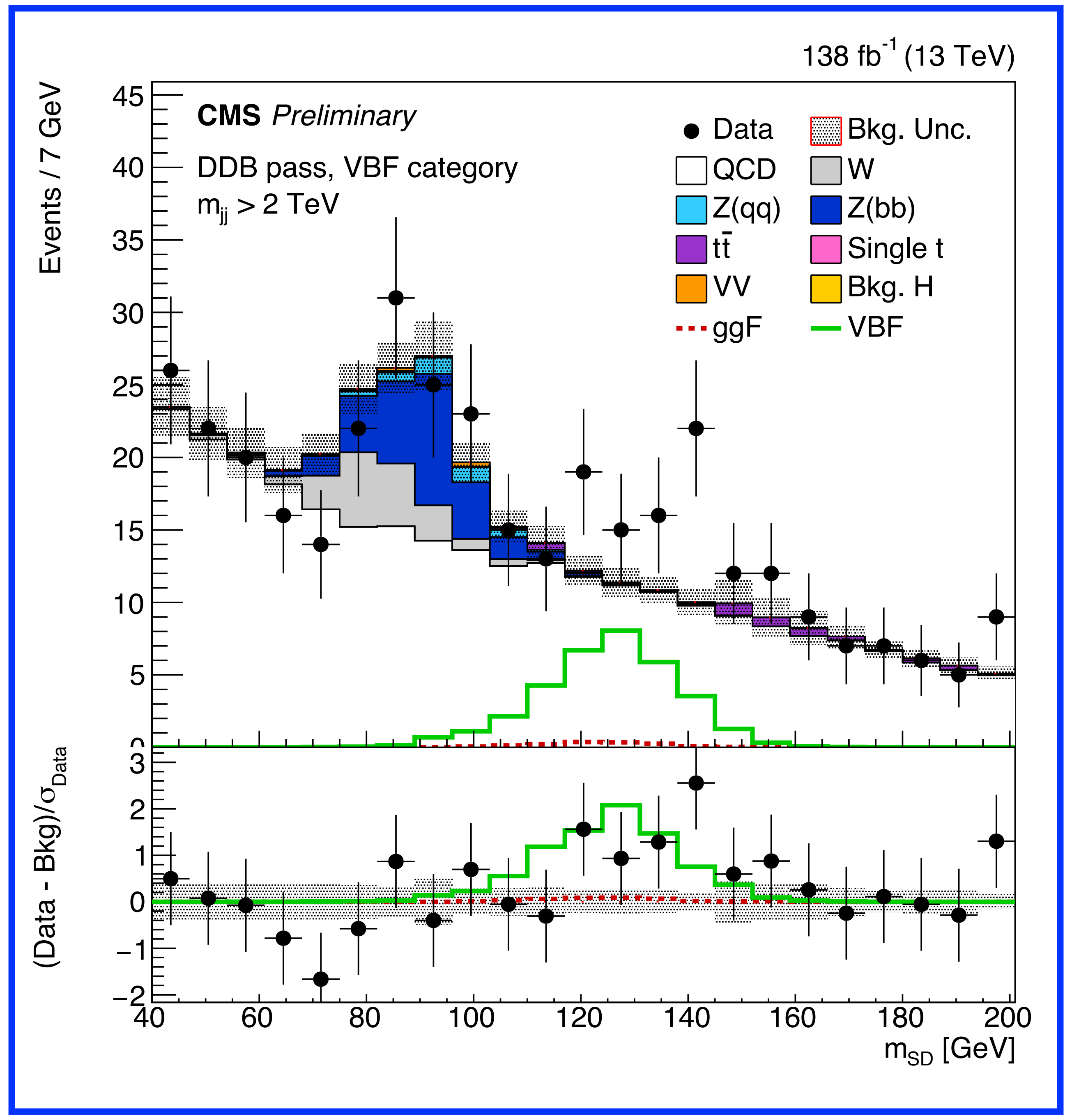
CMS-PAS-HIG-19-011

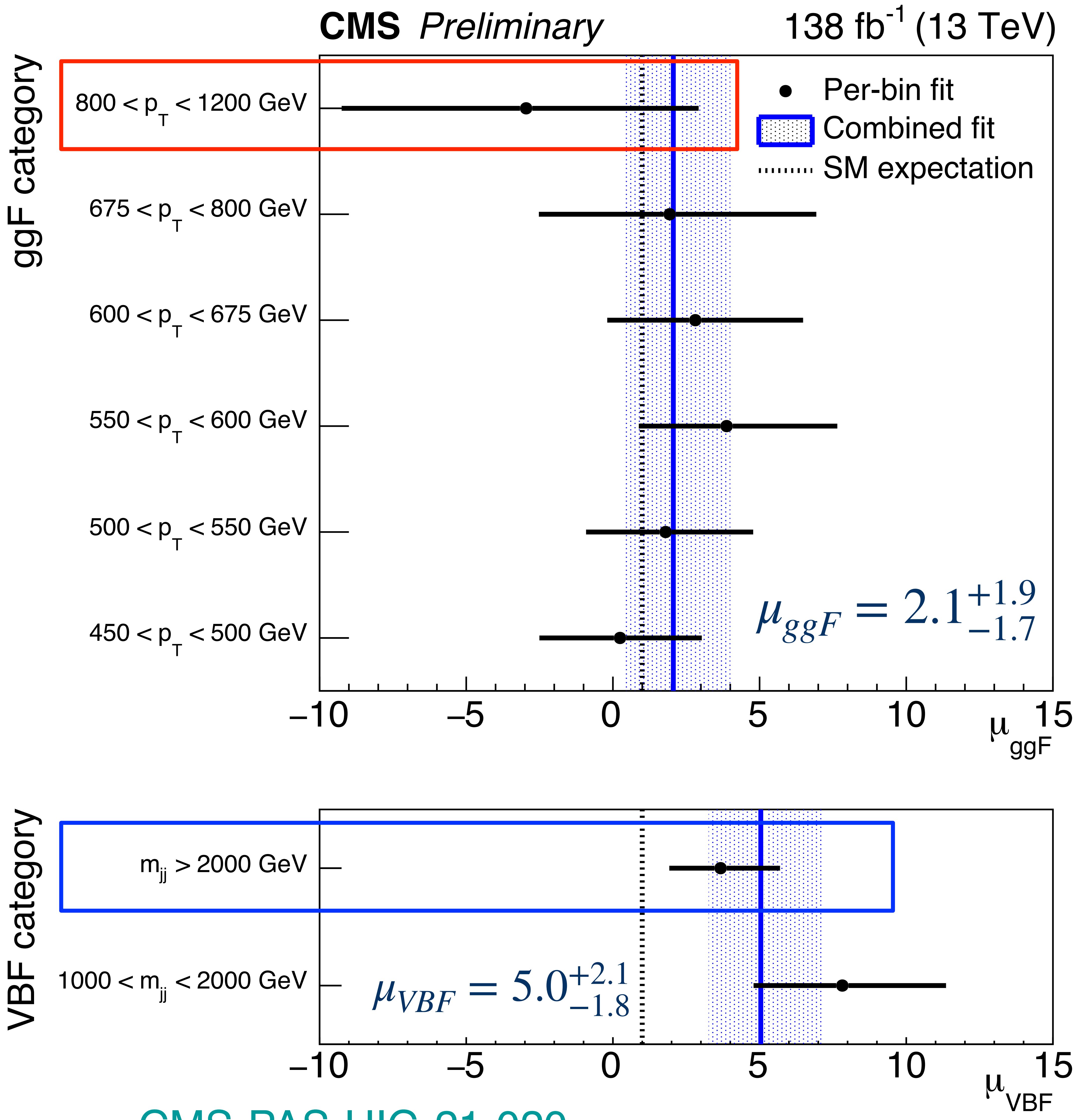
More in Chris Palmer's talk

$\hat{\mu} = \hat{\sigma}/\sigma_{SM}$

Boosted ggF/VBF, H→bb







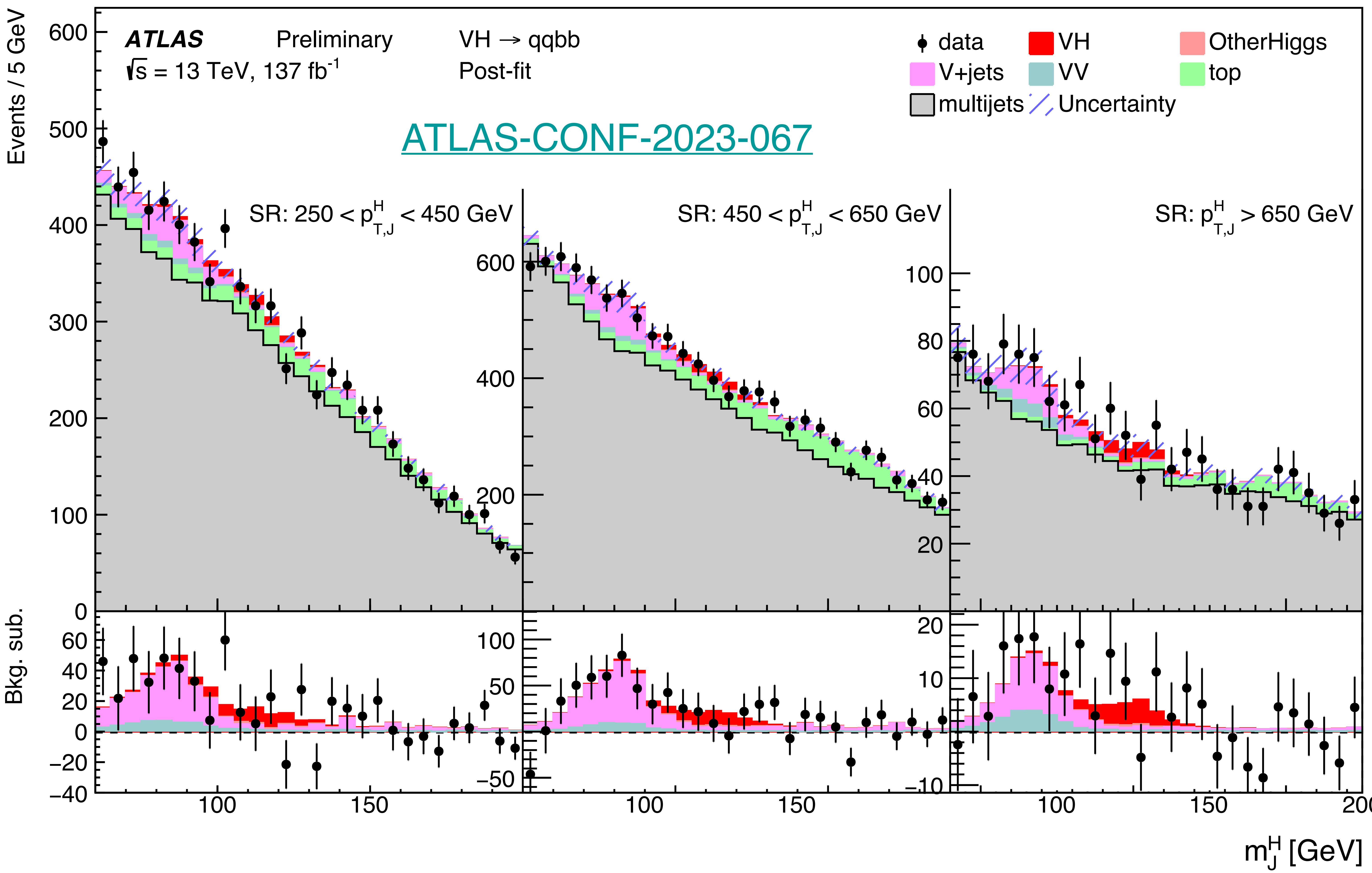
- Use boosted H(bb) reconstructed as large-R jet to explore **TeV-scale** $p_T(H)$ and m_{jj} regimes

Prod. mode	ggF	VBF
Obs. (exp.) Z_0 [σ]	1.2 (0.9)	3.0 (0.9)

CMS-PAS-HIG-21-020

Boosted VH→qqbb

- VH, H→bb traditionally studied in V(lep) channel
  - Measure in $p_T(V)$ bins for good resolution
- In boosted regime, can look into V(qq) channel by reconstructing both H and V as large-R jets
  - Measure in $p_T(H)$ bins



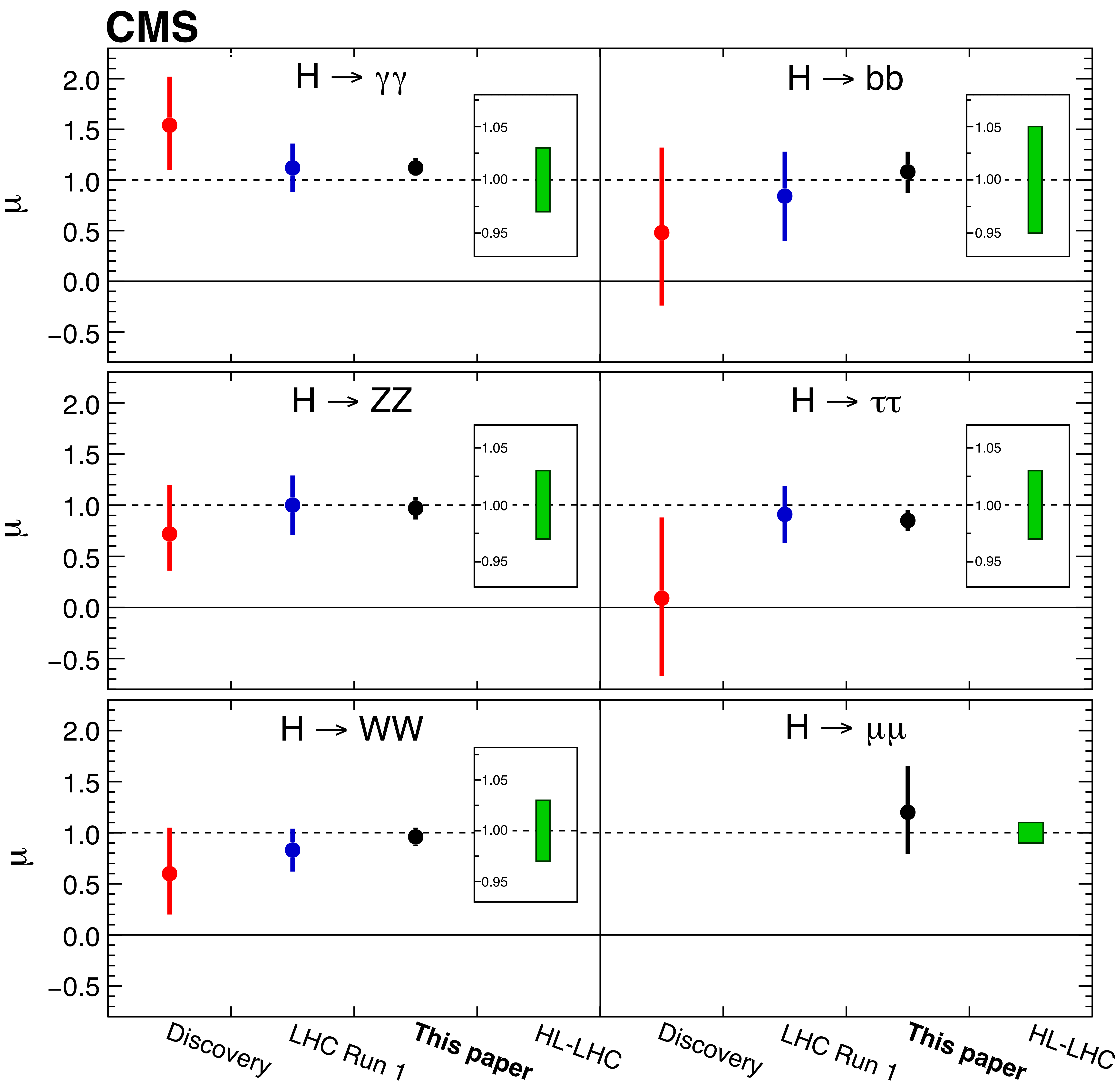
$p_H^{T,J}$ range [GeV]	[250, 450)	[450, 650)	[650, ∞)	Combined
Signal strength	$0.6^{+1.8}_{-1.7}$	$0.6^{+1.3}_{-1.2}$	$4.5^{+8.8}_{-2.7}$	$1.4^{+1.0}_{-0.9}$

Obs. $Z_0 = 1.7\sigma$

Exp. $Z_0 = 1.2\sigma$

Conclusions

- With Run 1+2 data, we have
  - **0.09%** precision on Higgs boson mass
  - **~50%** precision on Γ_H from off-shell
  - **~10%** precision on production cross-sections
- Run 3 ongoing: will hopefully **triple** the stats
  - Perfect time to explore new ideas!
- ×**20** larger Higgs boson sample at HL-LHC. Will hopefully improve precision by **~5**
  - **Higgs boson precision measurements will guide the future of our field**
  - We always do better than expected. Stay tuned!



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ATLAS references

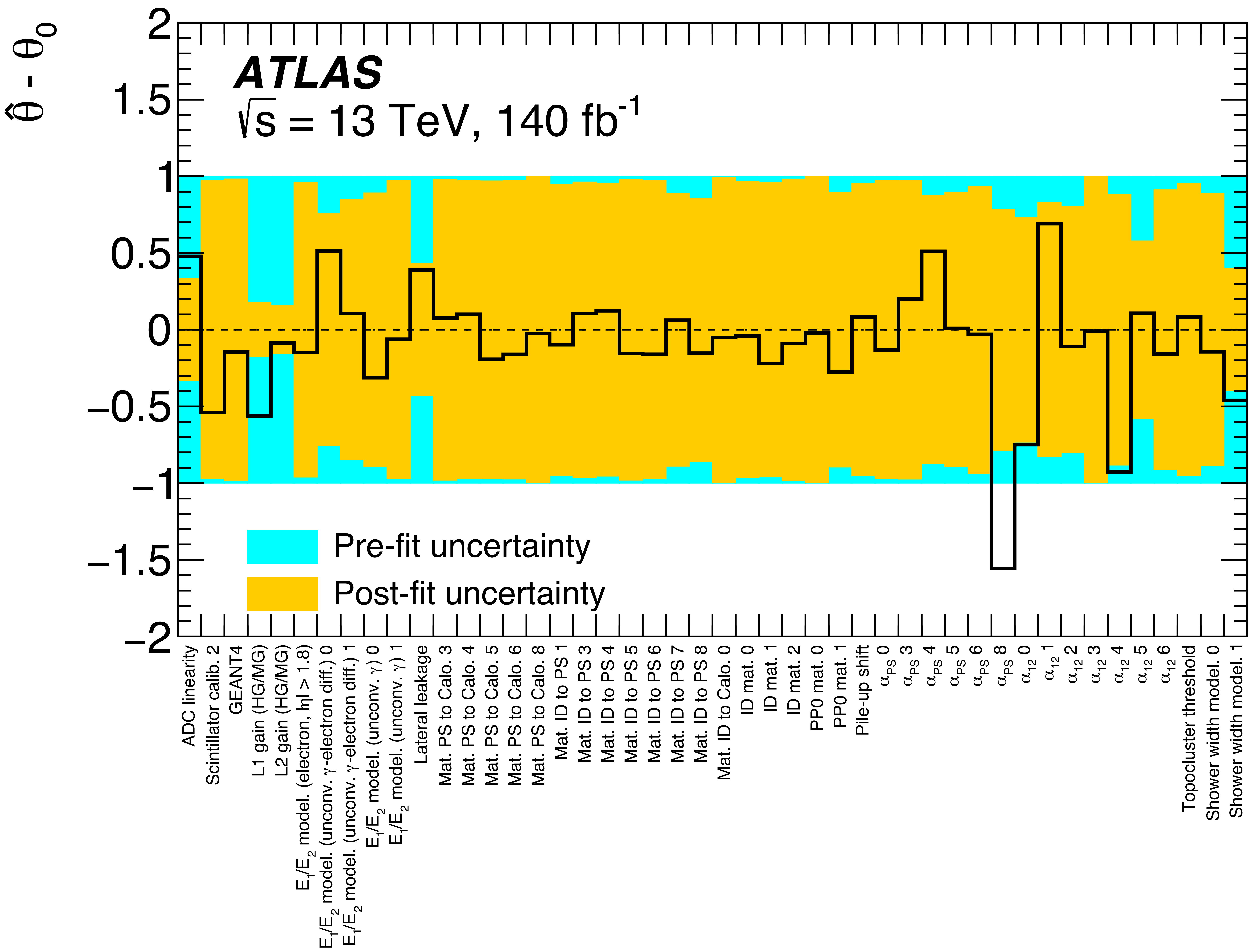
- “A detailed map of Higgs boson interactions by the ATLAS experiment ten years after the discovery”, Nature 607 (2022) 52
- “Measurement of the Higgs boson mass with $H\to\gamma\gamma$ decays in 140 fb^{-1} of $\sqrt{s}$ = 13 TeV pp collisions with the ATLAS detector”, PLB 847 (2023) 138315
- “Electron and photon energy calibration with the ATLAS detector using LHC Run 2 data”, arXiv:2309.05471 (accepted by JINST)
- “Combined measurement of the Higgs boson mass from the $H\to\gamma\gamma$ and $H\to ZZ^*\to 4\ell$ decay channels with the ATLAS detector using $\sqrt{s}$ = 7, 8 and 13 TeV pp collision data”, arXiv:2308.04775 (accepted by PRL)
- “Evidence of off-shell Higgs boson production from ZZ leptonic decay channels and constraints on its total width with the ATLAS detector”, PLB 846 (2023) 138223
- “Determining the relative sign of the Higgs boson couplings to W and Z bosons using VBF WH production with the ATLAS detector”, ATLAS-CONF-2023-057
- “Measurement of high-momentum Higgs boson production in association with a vector boson in the qqbb final state with the ATLAS detector”, ATLAS-CONF-2023-067

CMS references

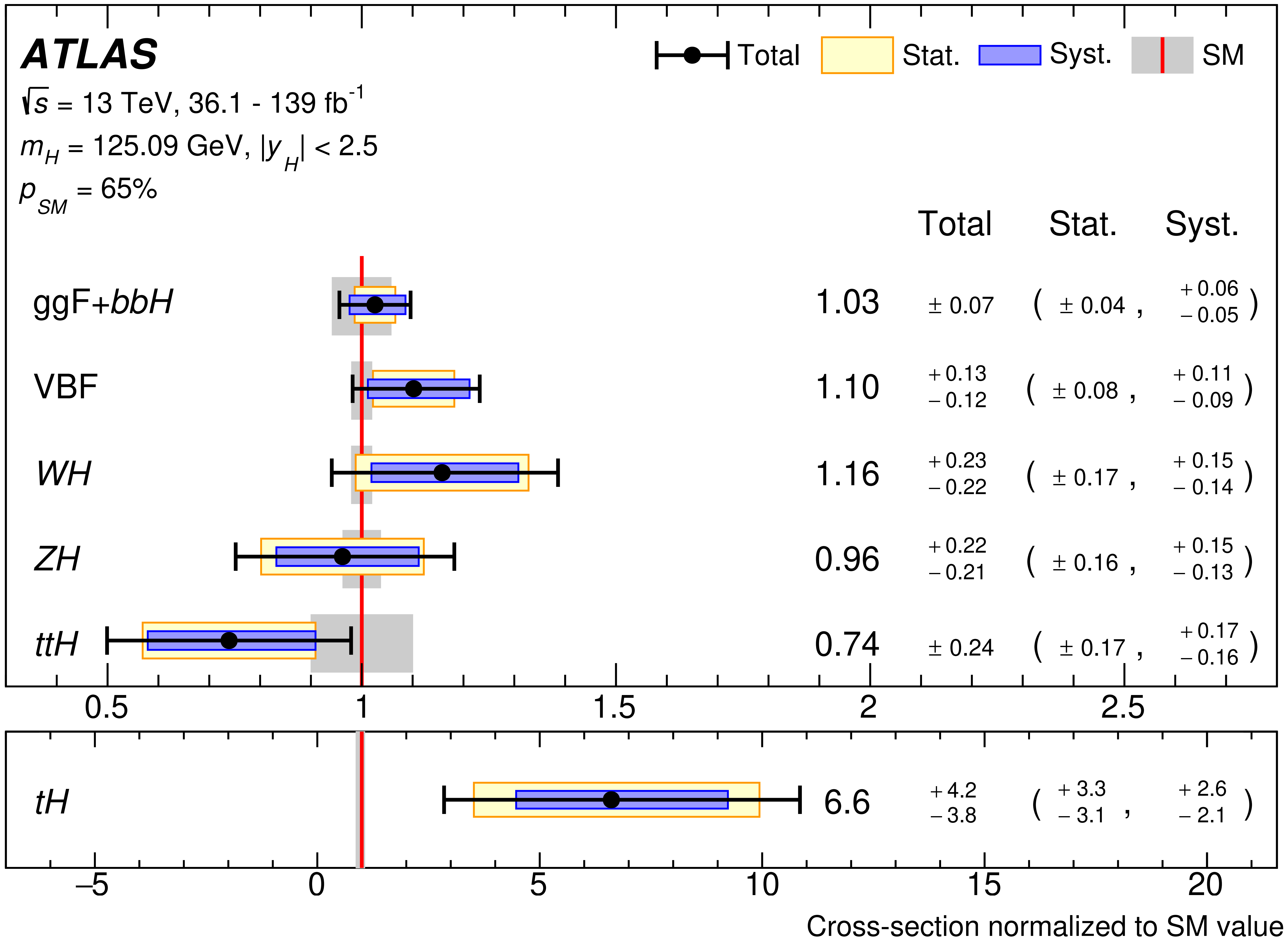
- "A portrait of the Higgs boson by the CMS experiment ten years after the discovery", Nature 607 (2022) 60
- "Measurement of the Higgs boson width and evidence of its off-shell contributions to ZZ production", Nat. Phys. 18 (2022) 1329
- "Measurement of the Higgs boson mass and width using the four leptons final state", CMS-PAS-HIG-21-019
- "Measurement of the ttH and tH production rates in the H→bb decay channel with 138 fb^{-1} of proton-proton collision data at $\sqrt{s}$ = 13 TeV", CMS-PAS-HIG-19-011
- "Search for boosted Higgs bosons produced via vector boson fusion in the H→bb decay mode using LHC proton-proton collision data at $\sqrt{s}$ = 13 TeV", CMS-PAS-HIG-21-020

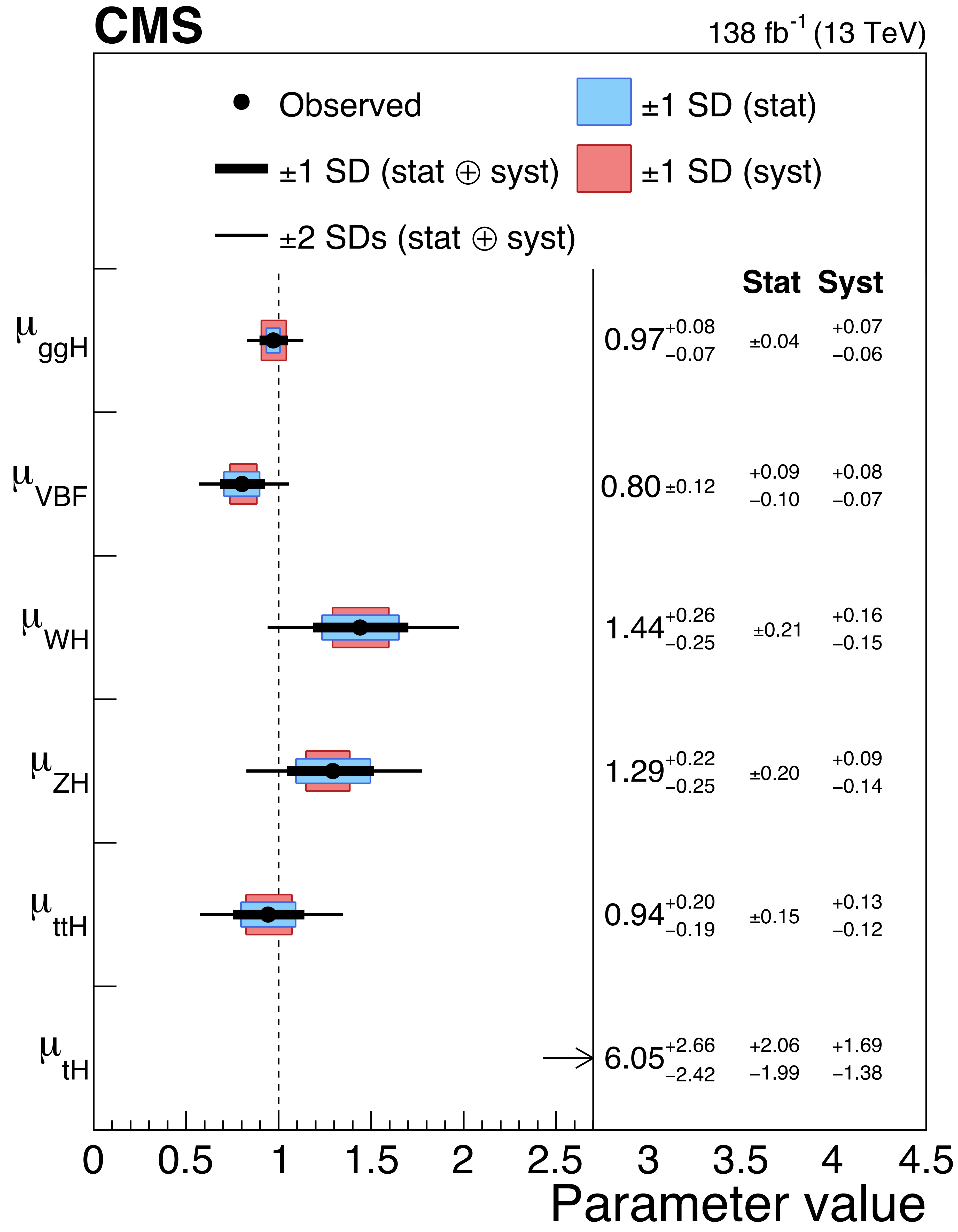
Backup

Reduction of e/γ energy scale syst from linearity fit

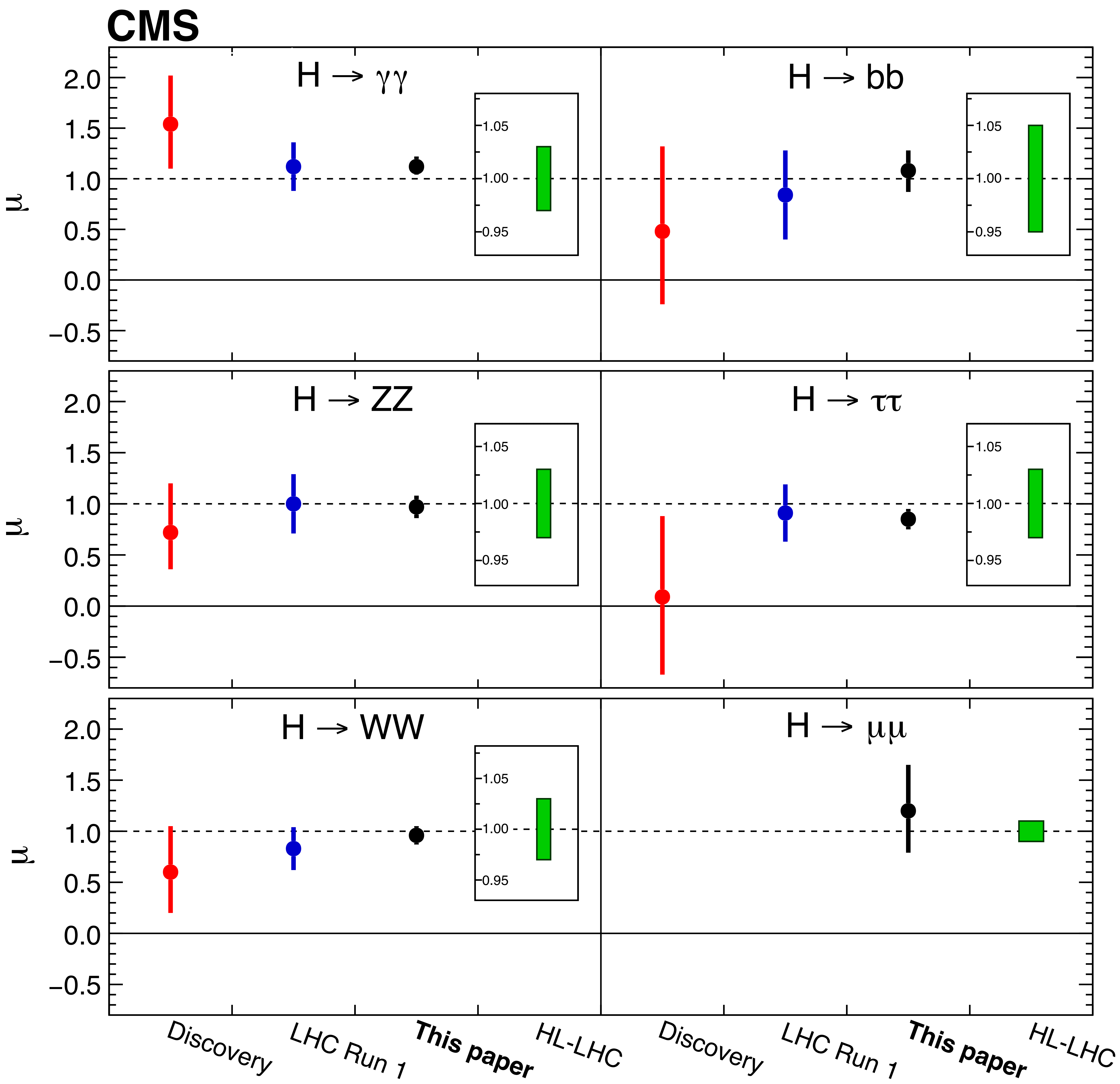


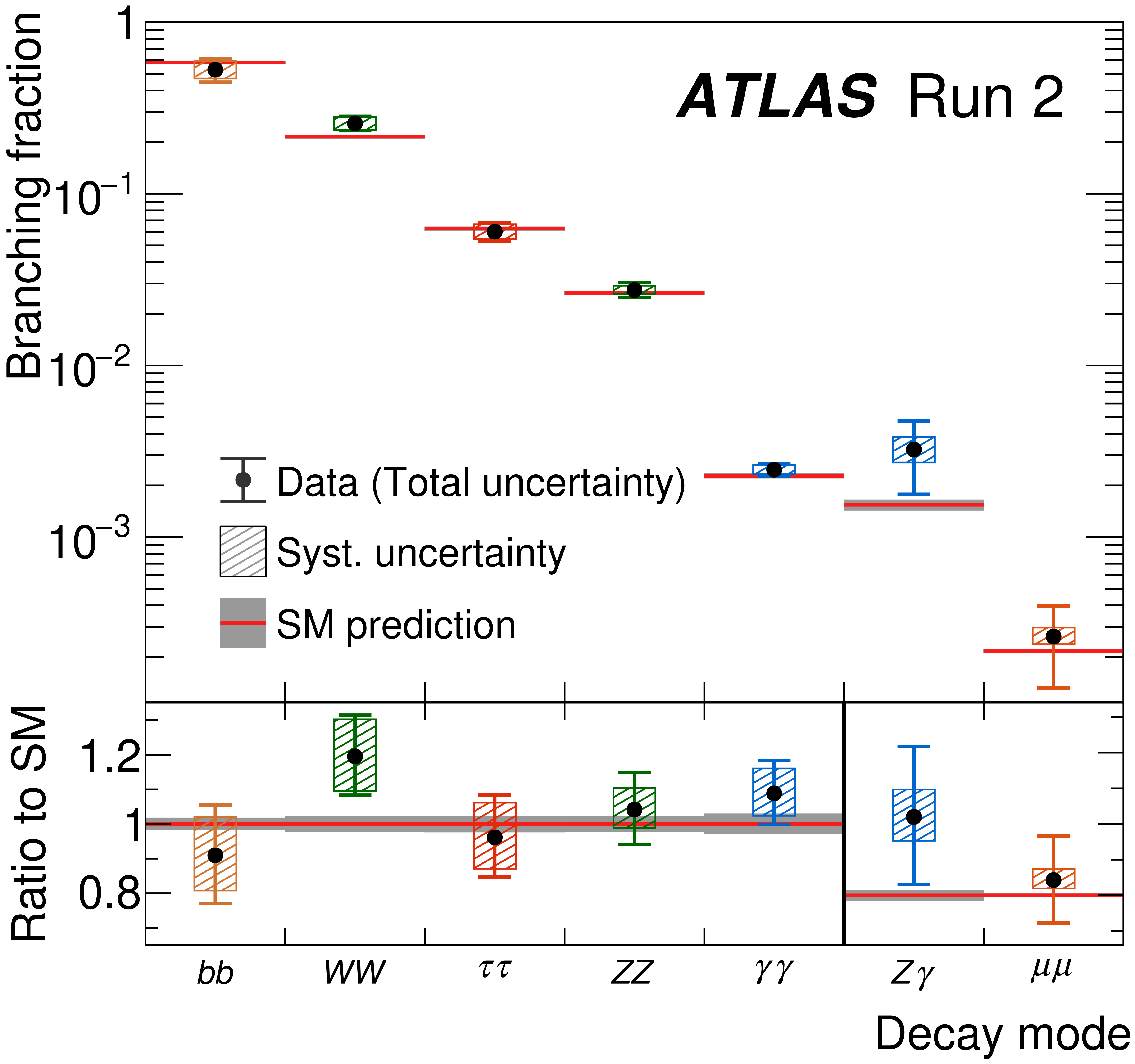
Higgs boson productions ATLAS vs. CMS



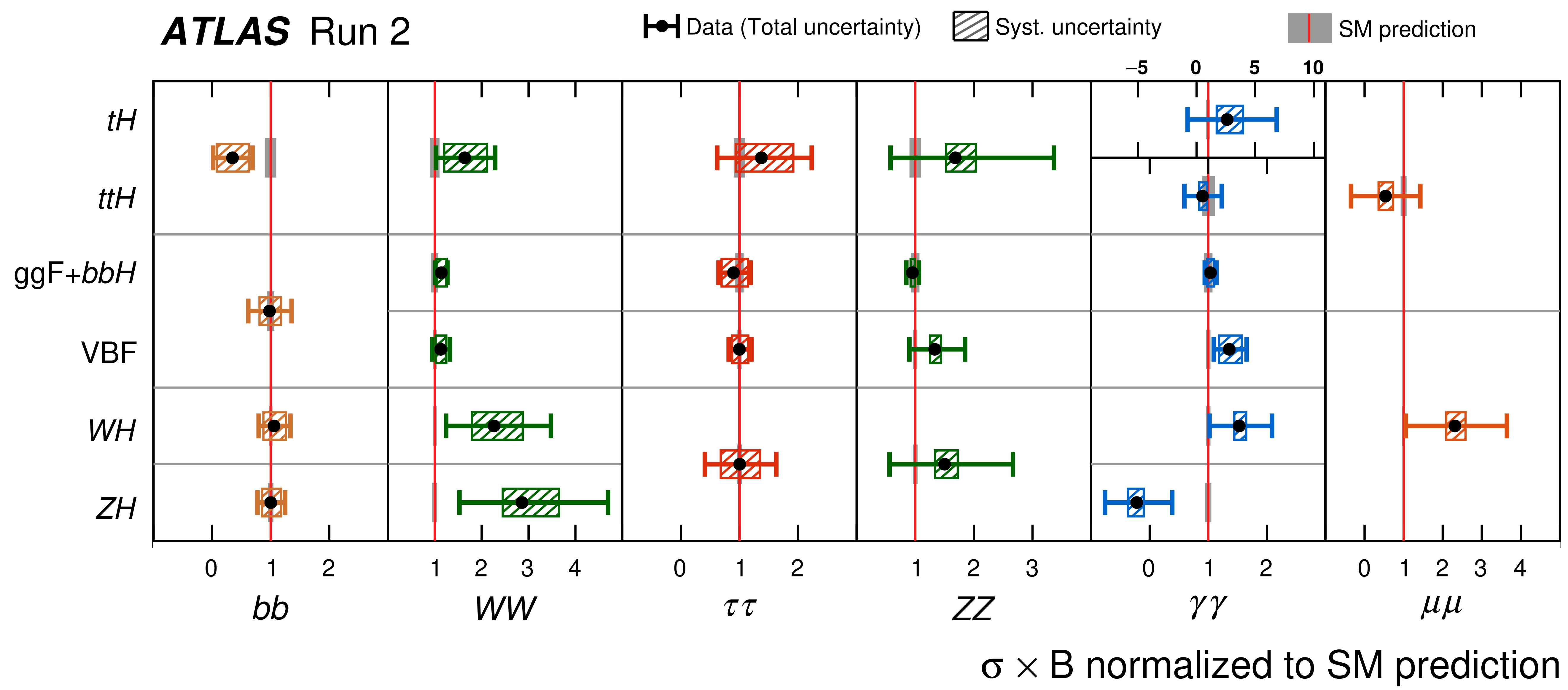


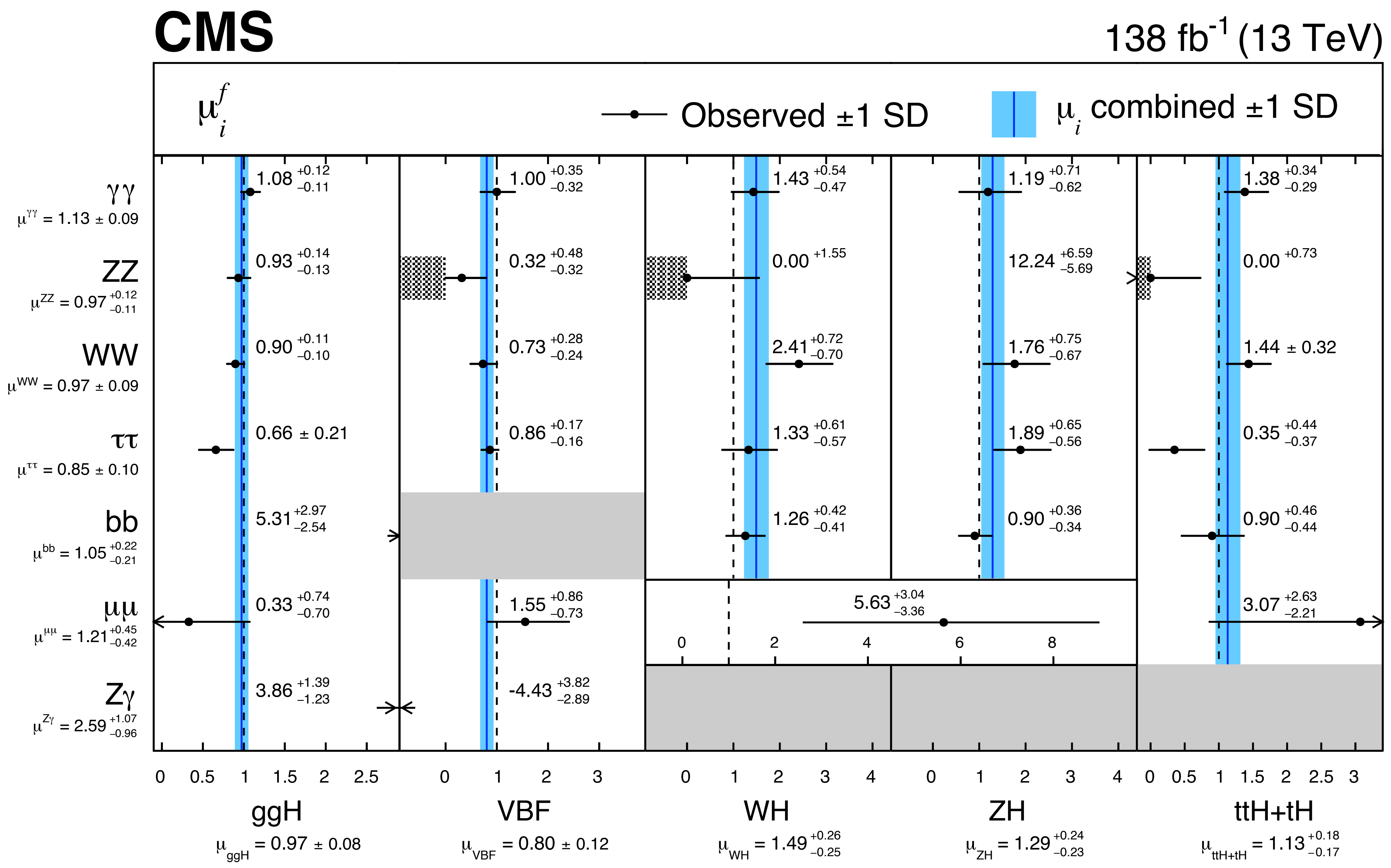
Higgs boson decays ATLAS vs. CMS



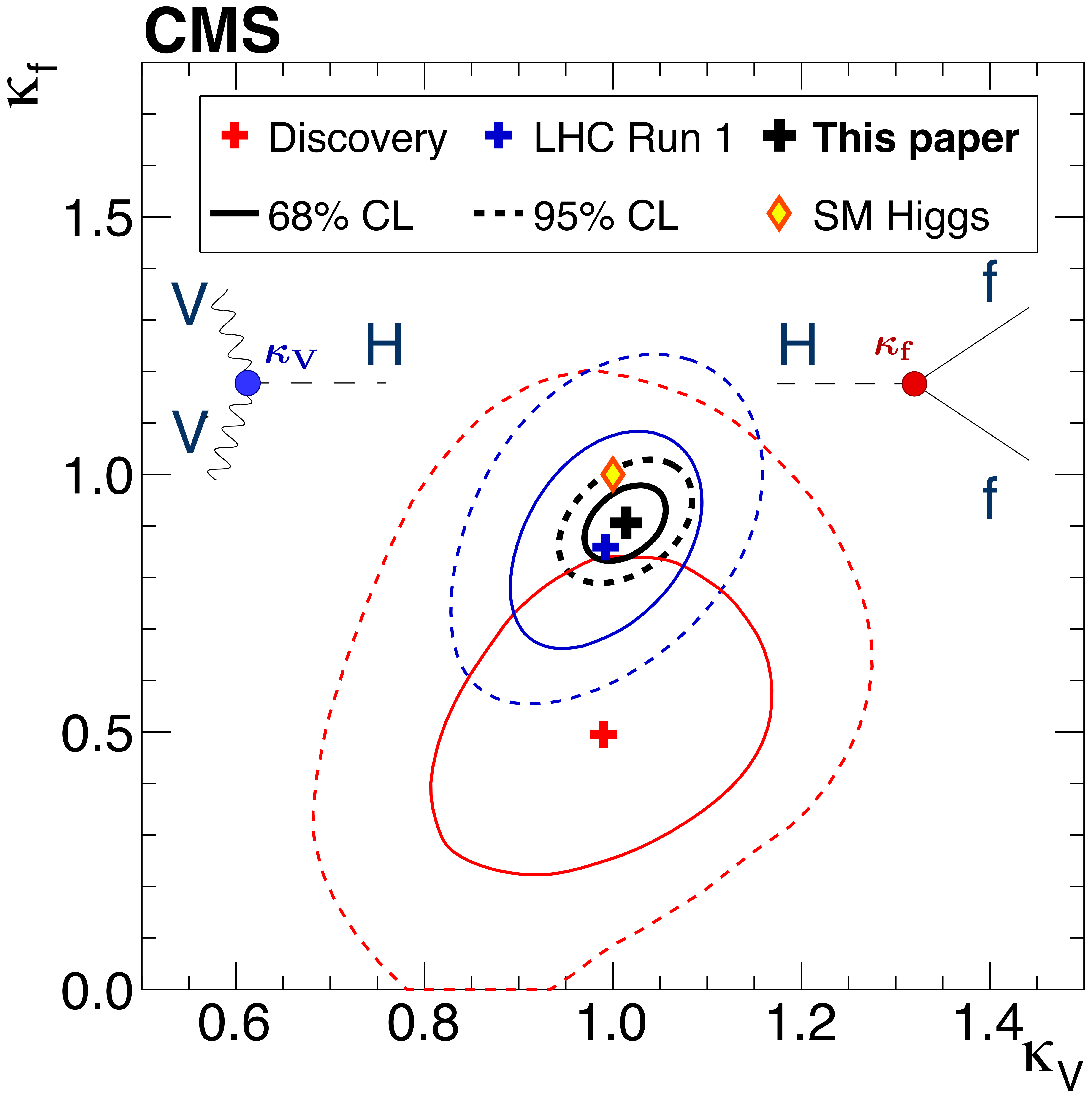


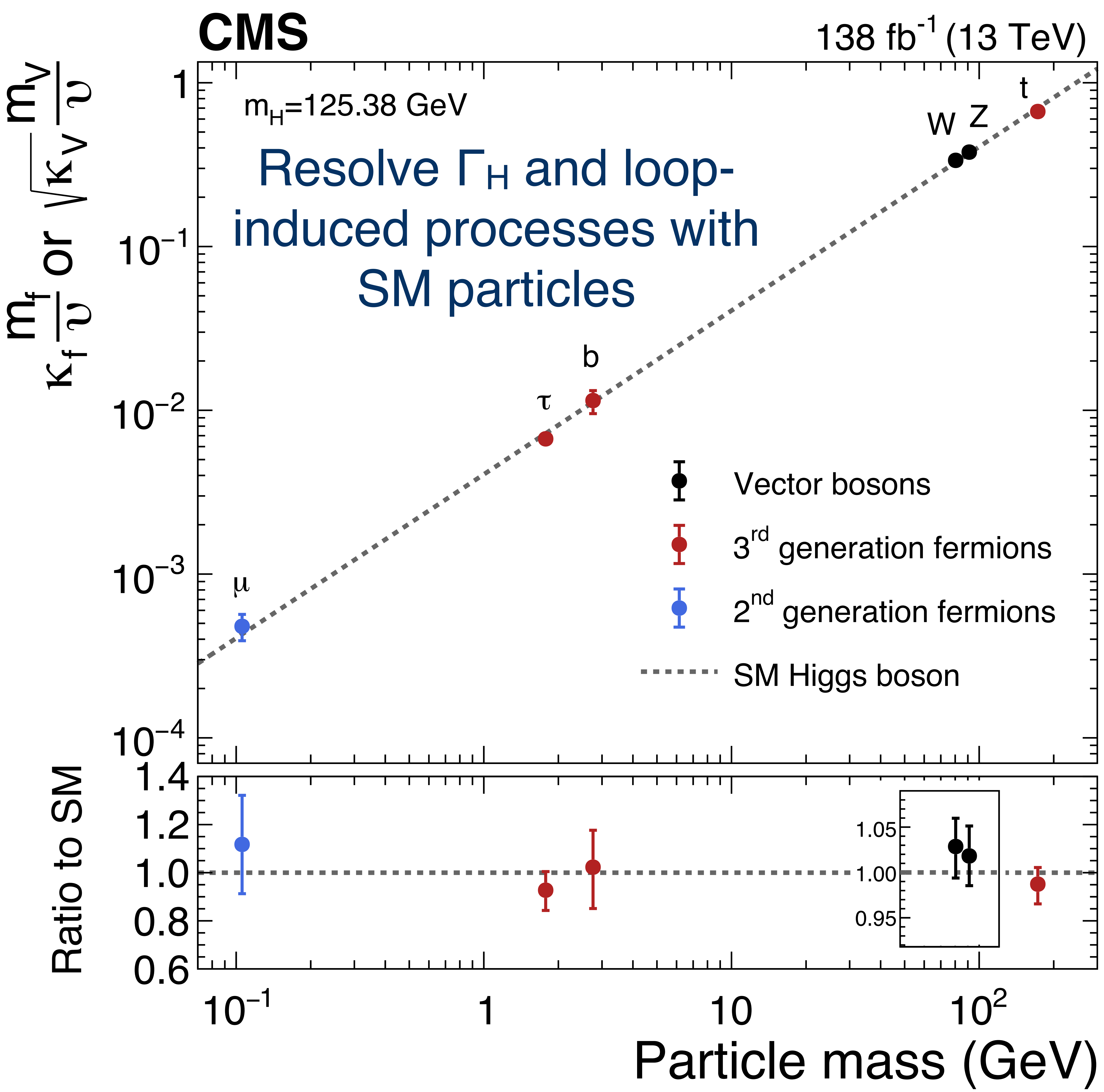
Prod×decay ATLAS vs. CMS



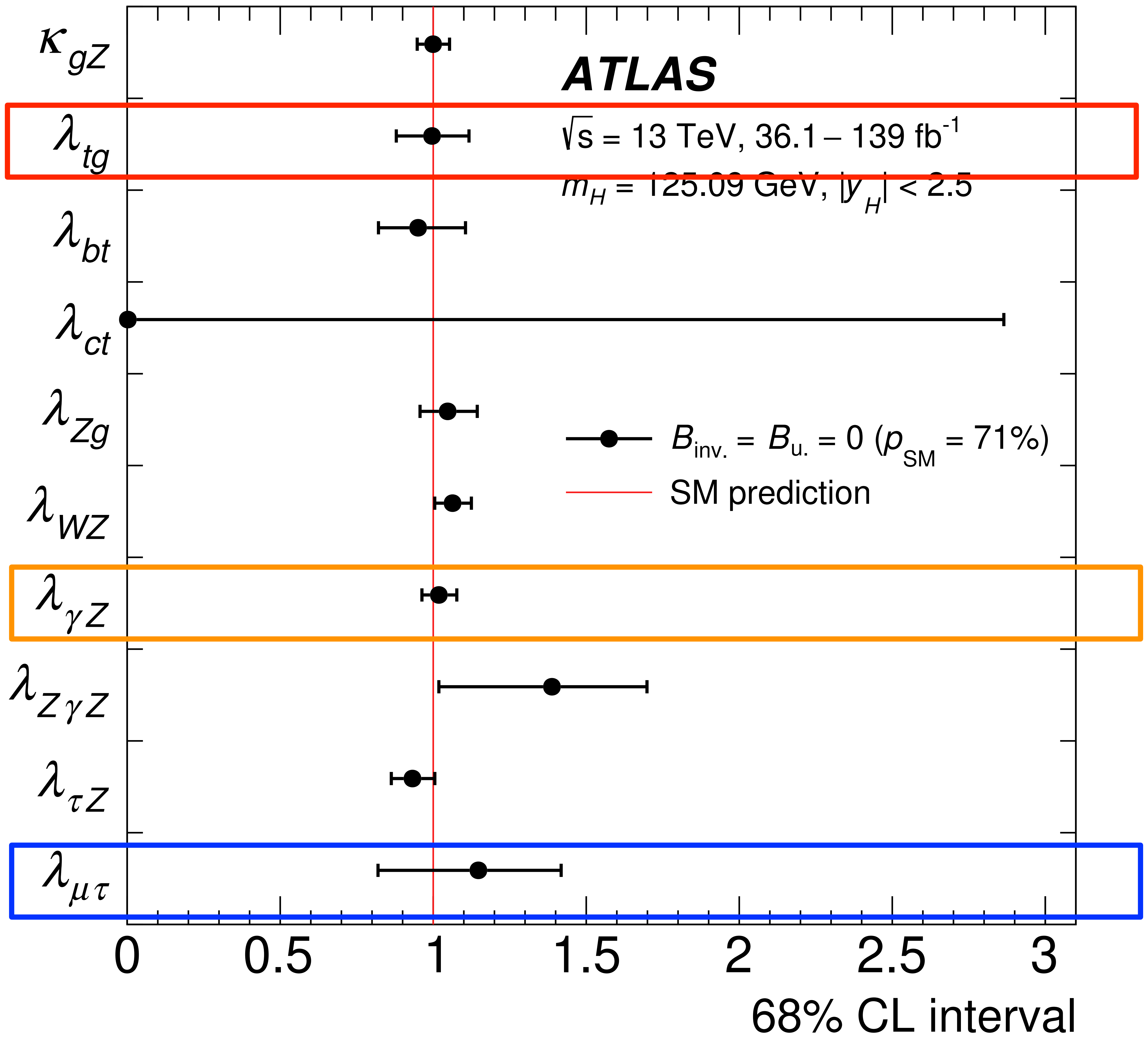


Coupling strength tests

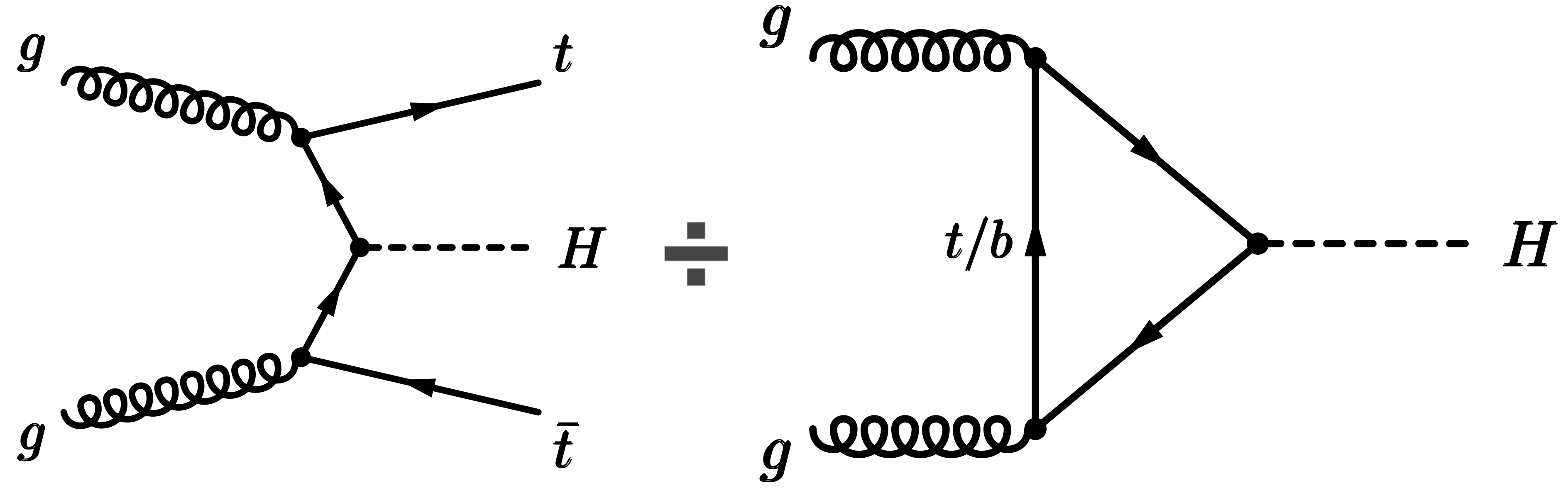




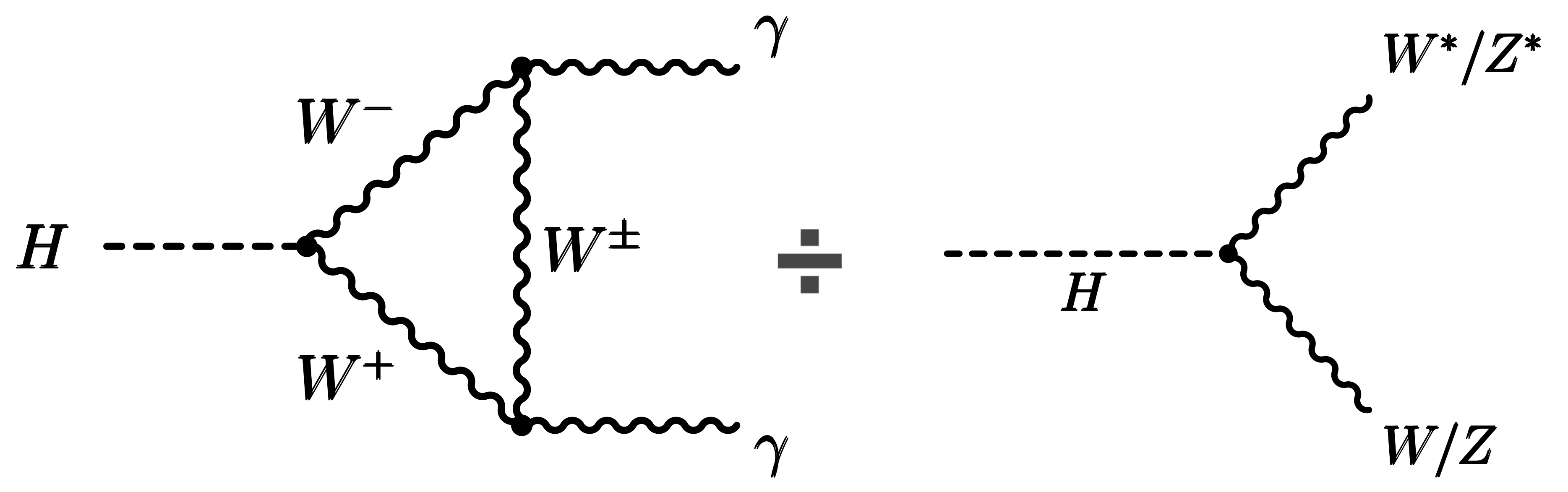
Ratios of coupling strengths



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

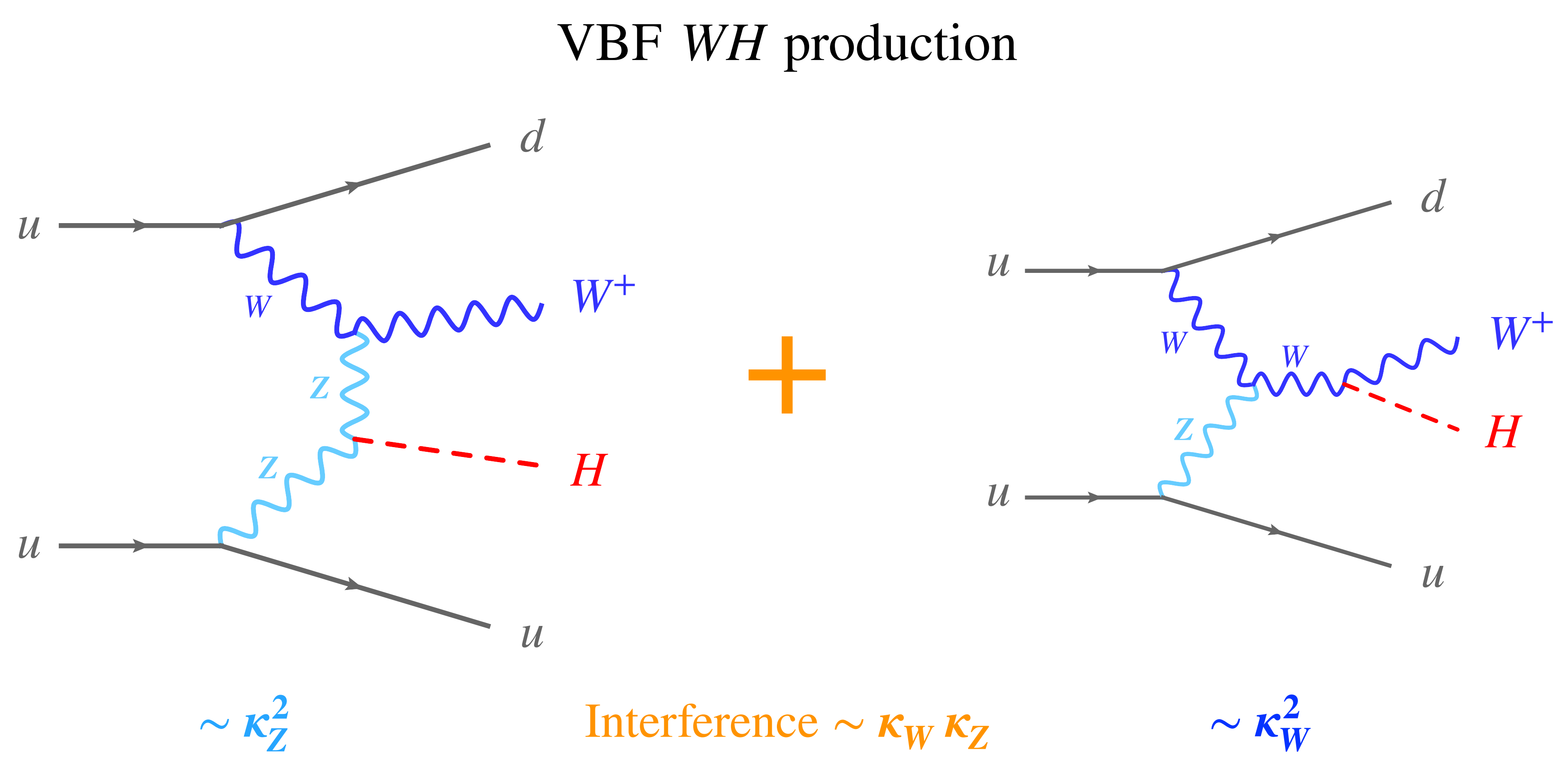


$$\lambda_{\gamma Z} = \frac{\kappa_\gamma}{\kappa_Z}$$

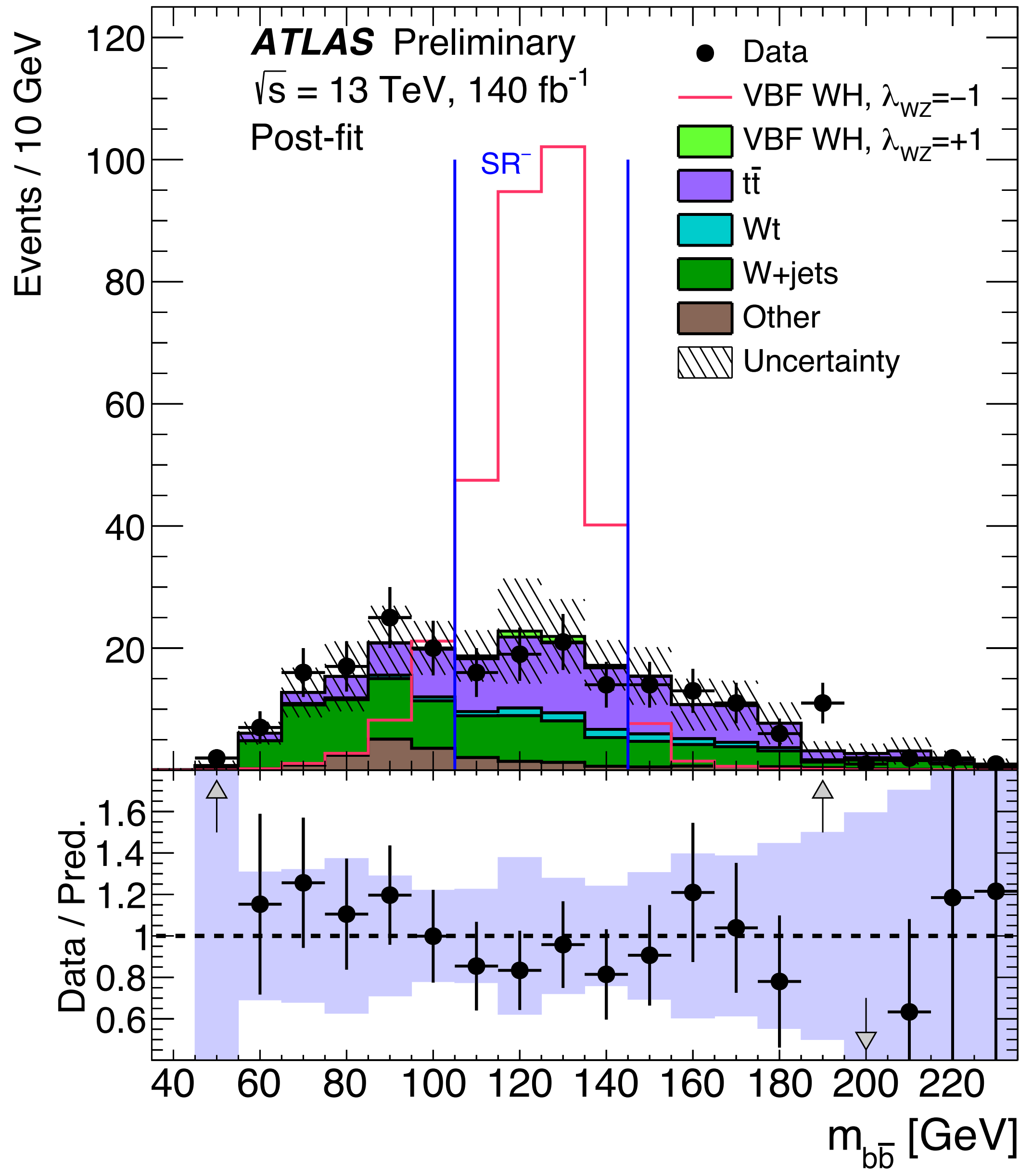


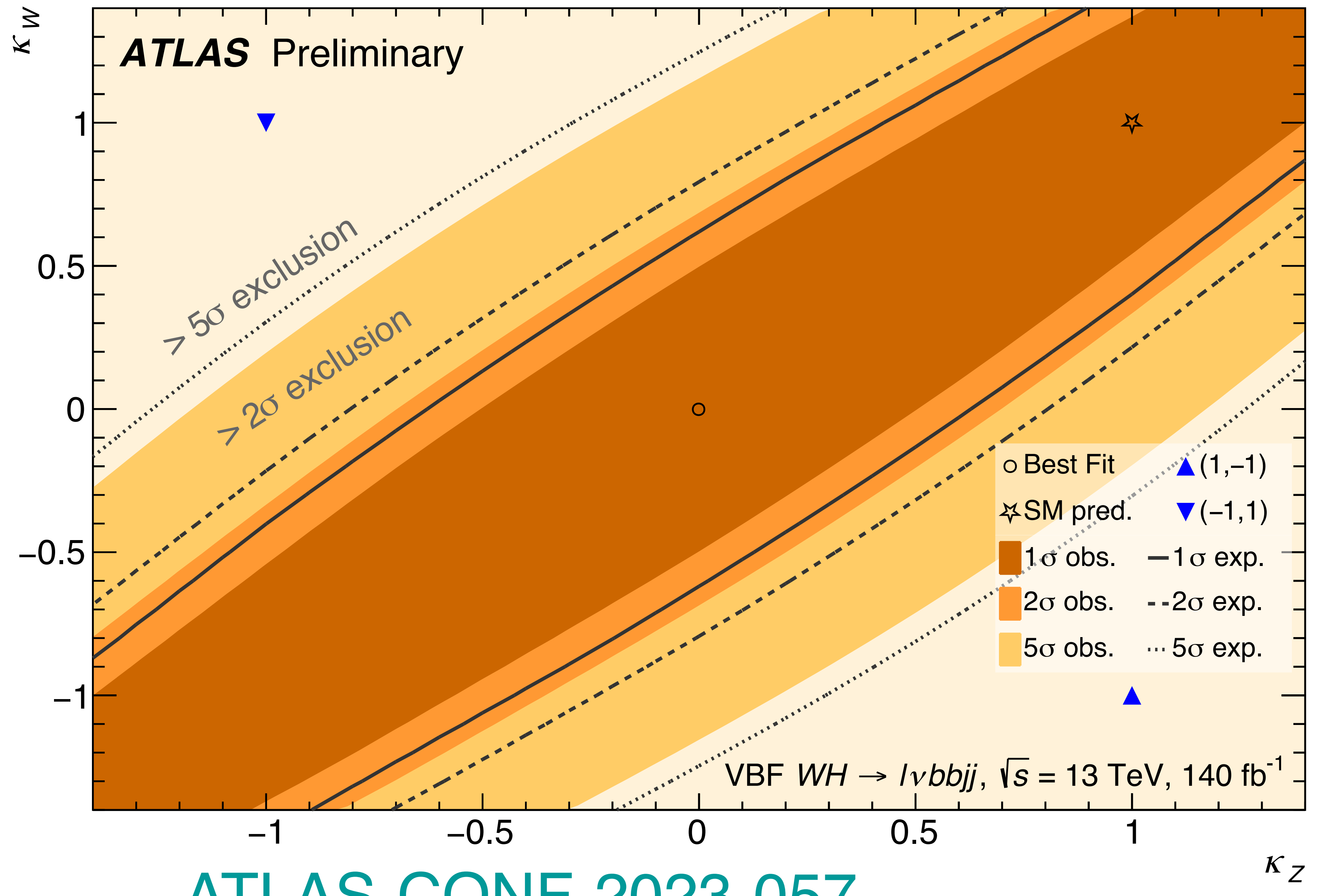
- LHC experiments cannot directly constrain Higgs boson total width. **Ratios are what we could measure best @LHC!**
- Explore new physics in **ggF**/**H→γγ** loops, and **3rd vs. 2nd generation Yukawa couplings**

Determine relative sign between κ_W and κ_Z



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





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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→lνbb counting analysis in VBF topology
  - Negative sign of λ_{WZ} excluded by **>8σ**

What can we still learn after 10 years of discovery?

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