Precision Higgs measurements

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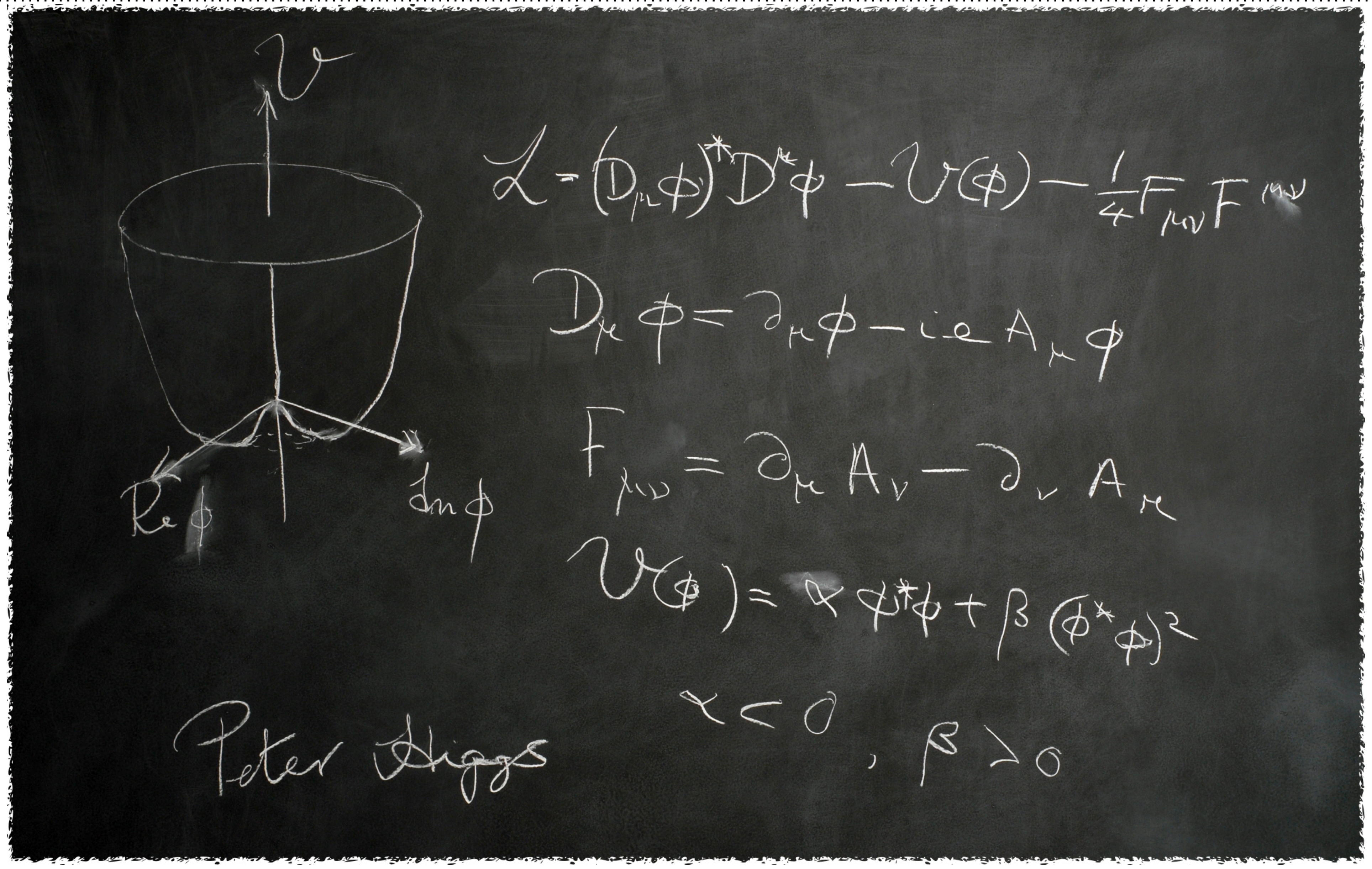
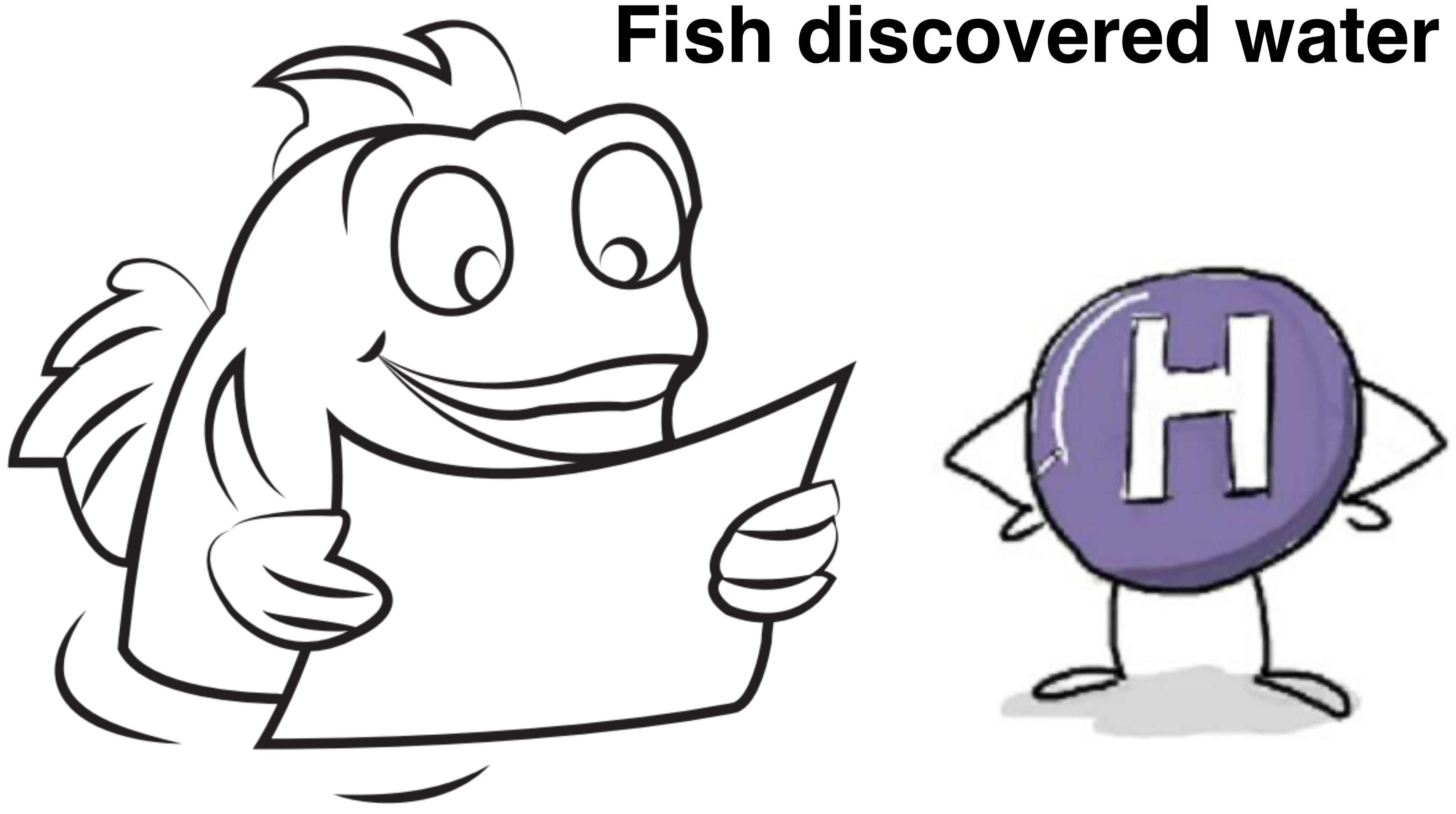
Introduction

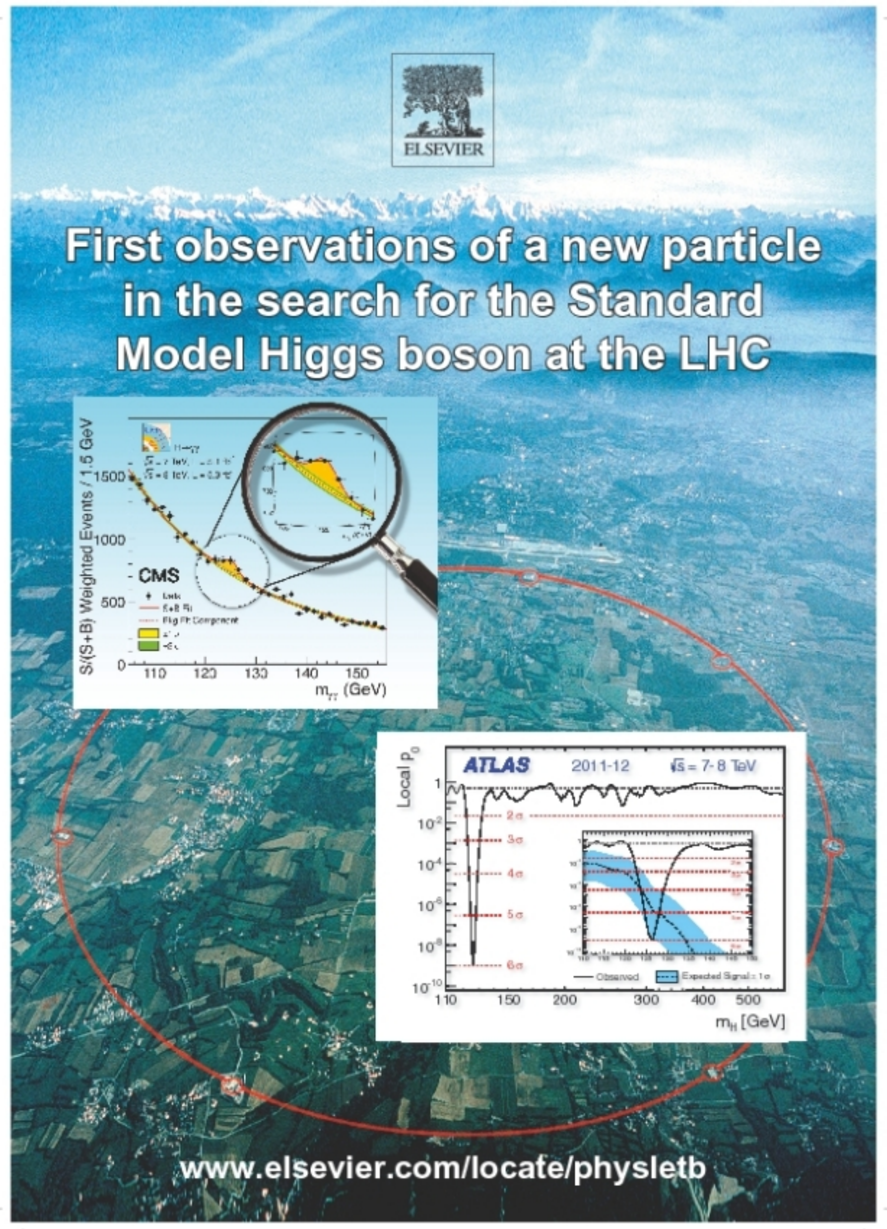
- Precision Higgs measurements are important
  - **Higgs boson has a fundamental role in the SM**. We need best experimental & theory knowledge on its properties to address many important physics questions
  - In the lack of direct discoveries, precision Higgs measurements could be **portal to new physics**
- LHC has rich Higgs precision physics programs, **with significant contributions from Chinese groups!**
- Will focus on new results released since CLHCP 2021, in particular those just released at Higgs 2022!
  - Still not able to cover everything interesting due to limited time. Sorry if your favorites are missing!





Fish discovered water

2012: Higgs boson discovery



2013 Nobel Prize

- Last missing piece of SM found. Opened a new era in particle physics!

2022: 10th anniversary of discovery

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A detailed map of Higgs boson interactions by the ATLAS experiment ten years after the discovery

The ATLAS Collaboration

ATLAS Nature paper

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A portrait of the Higgs boson by the CMS experiment ten years after the discovery

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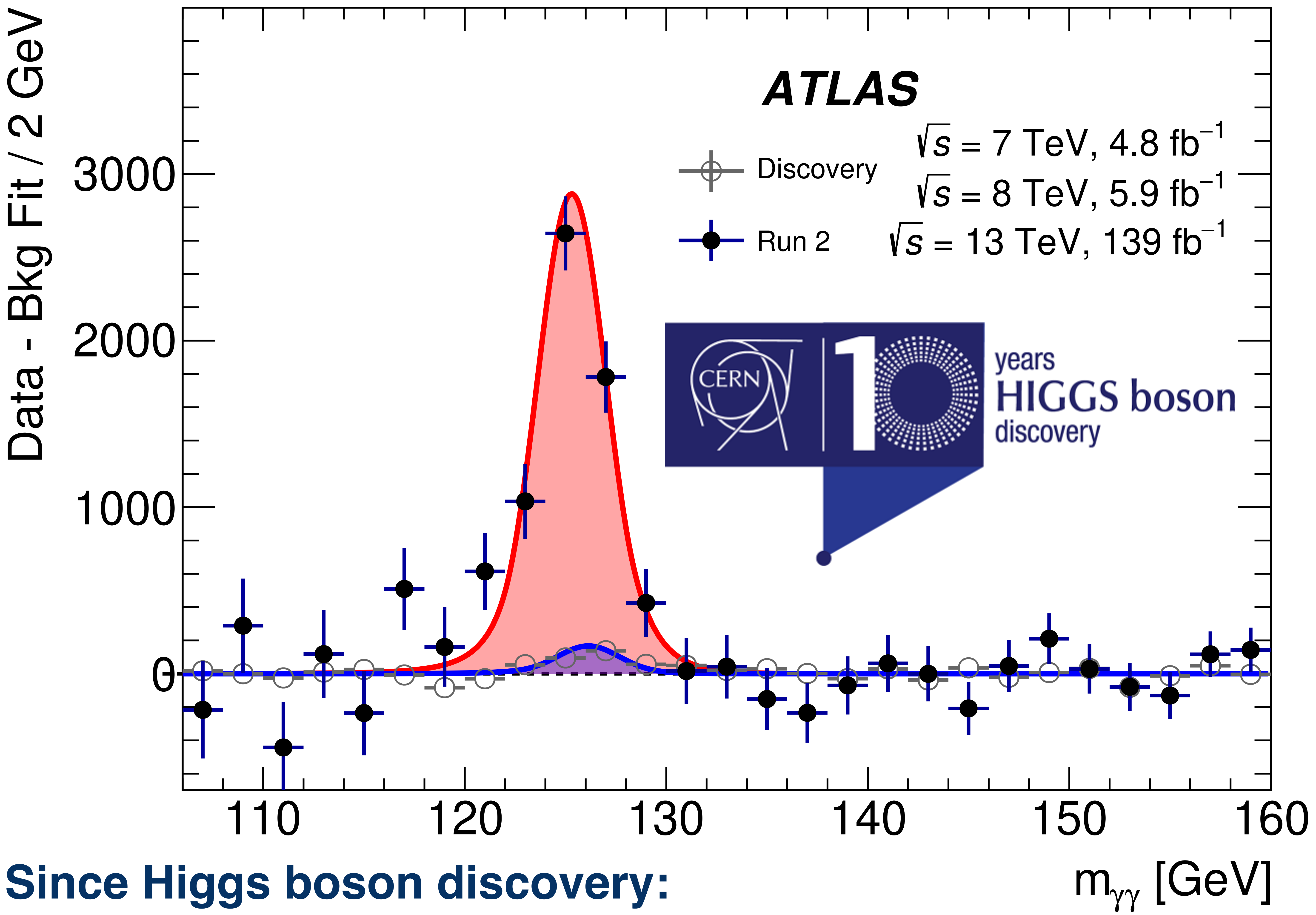


Since Higgs boson discovery:

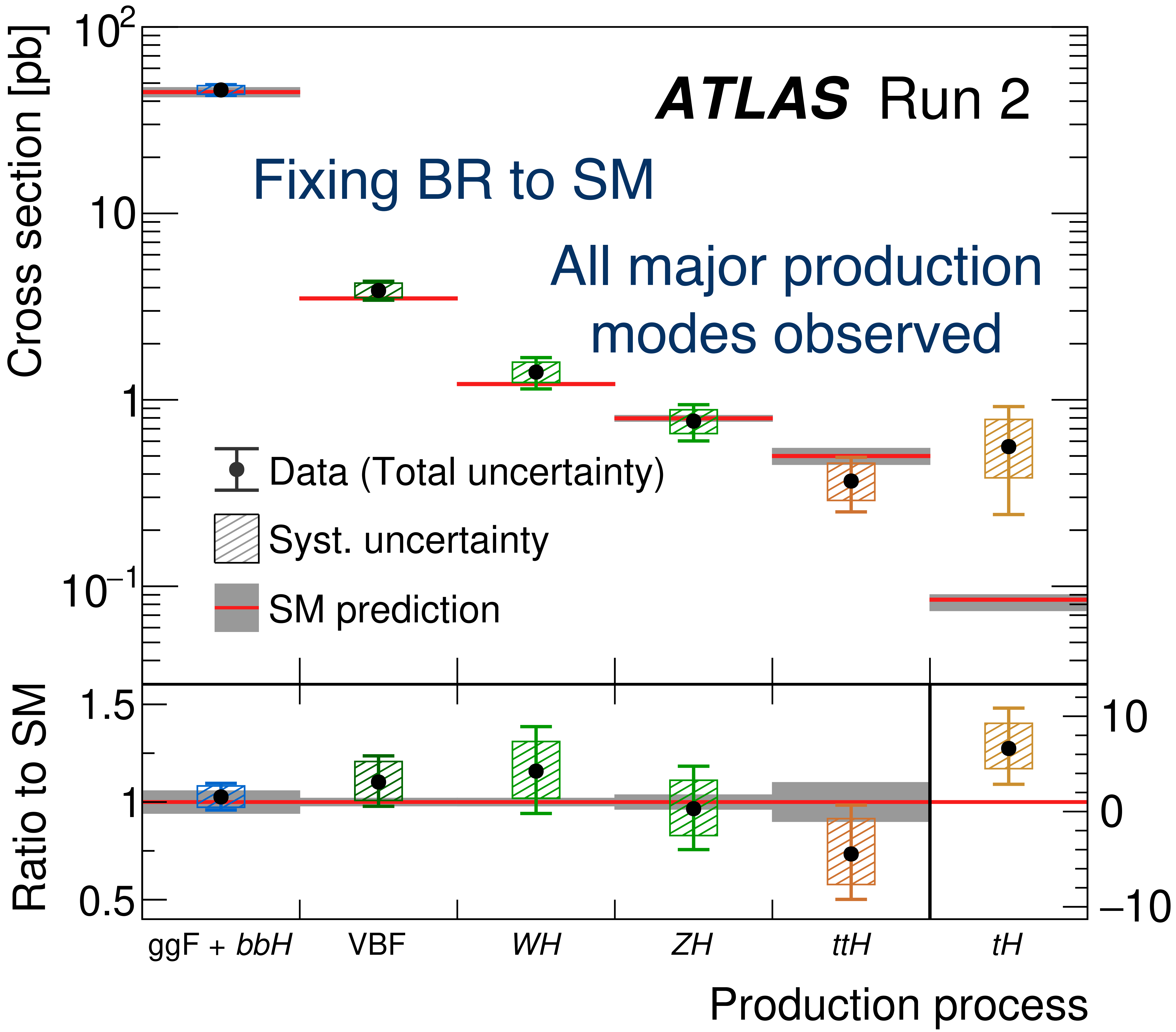
- Many, many more Higgs bosons accumulated
- Significant progress on both theory and experimental sides

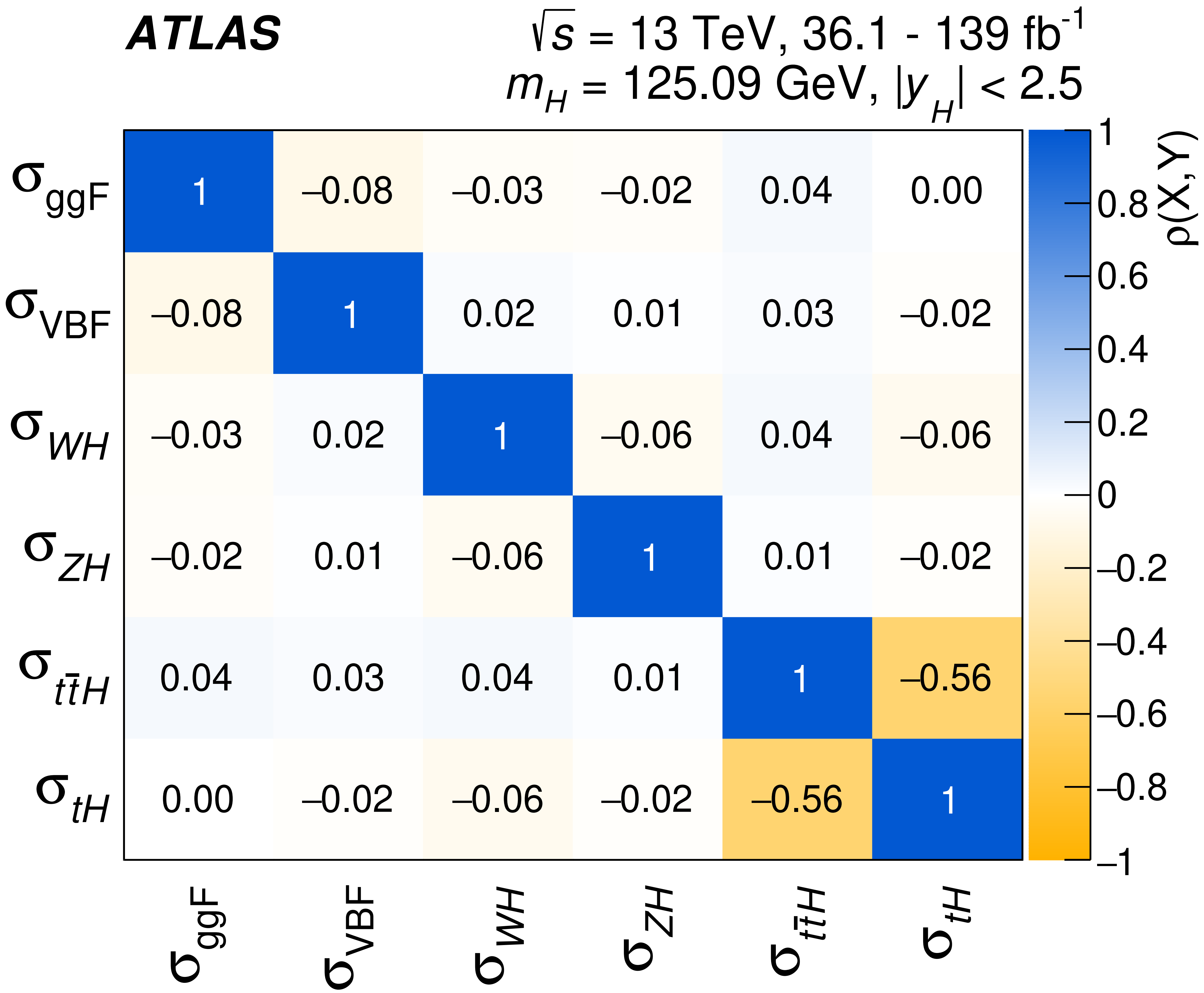
Inclusive signal strength

ATLAS $\mu = 1.05 \pm 0.06 = 1.05 \pm 0.03(\text{stat.}) \pm 0.03(\text{exp.}) \pm 0.02(\text{bkg. th.}) \pm 0.04(\text{sig. th.})$

CMS $\mu = 1.002 \pm 0.057 = 1.002 \pm 0.029(\text{stat.}) \pm 0.033(\text{syst.}) \pm 0.036(\text{sig. th.})$

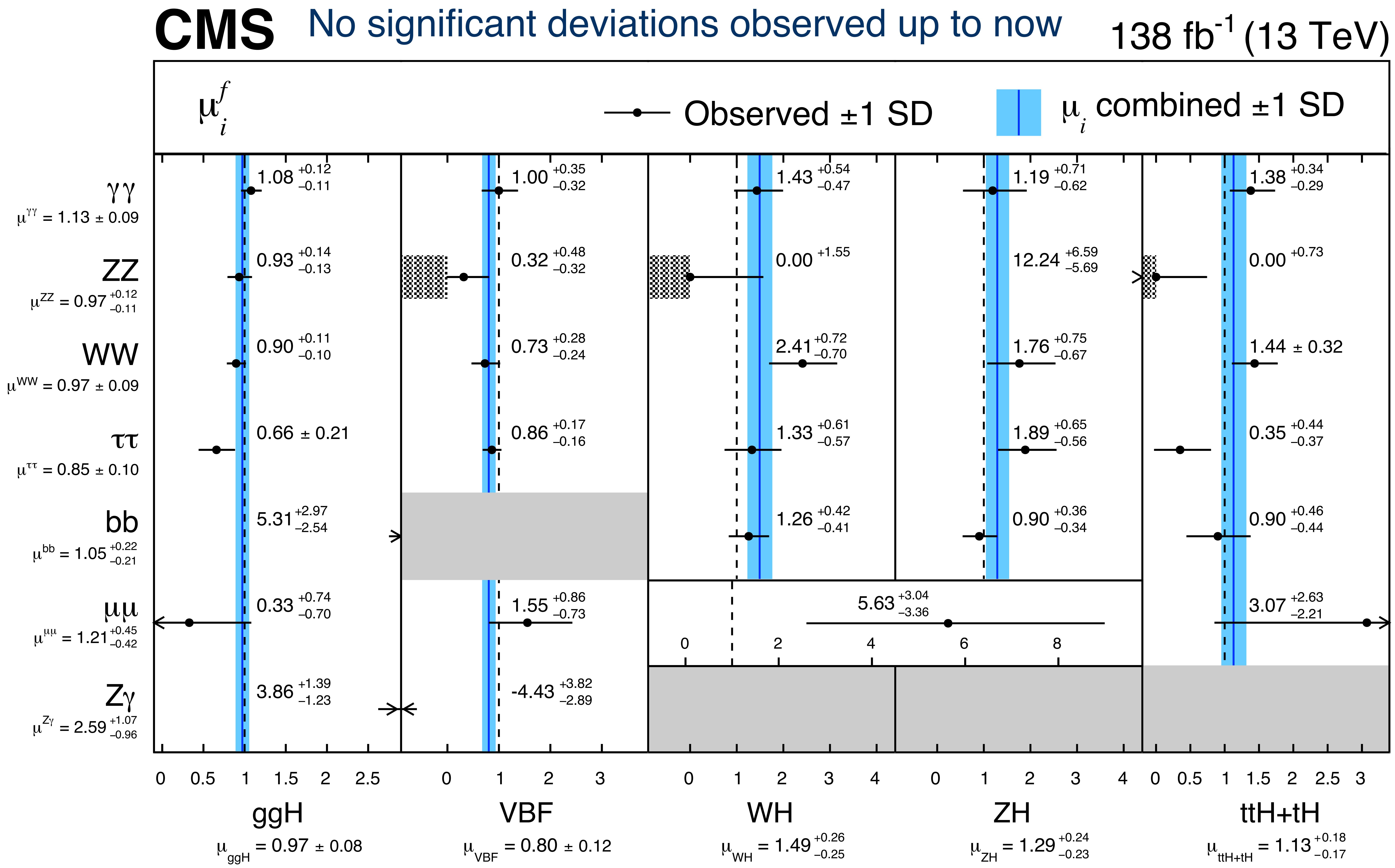
All major production modes @LHC observed





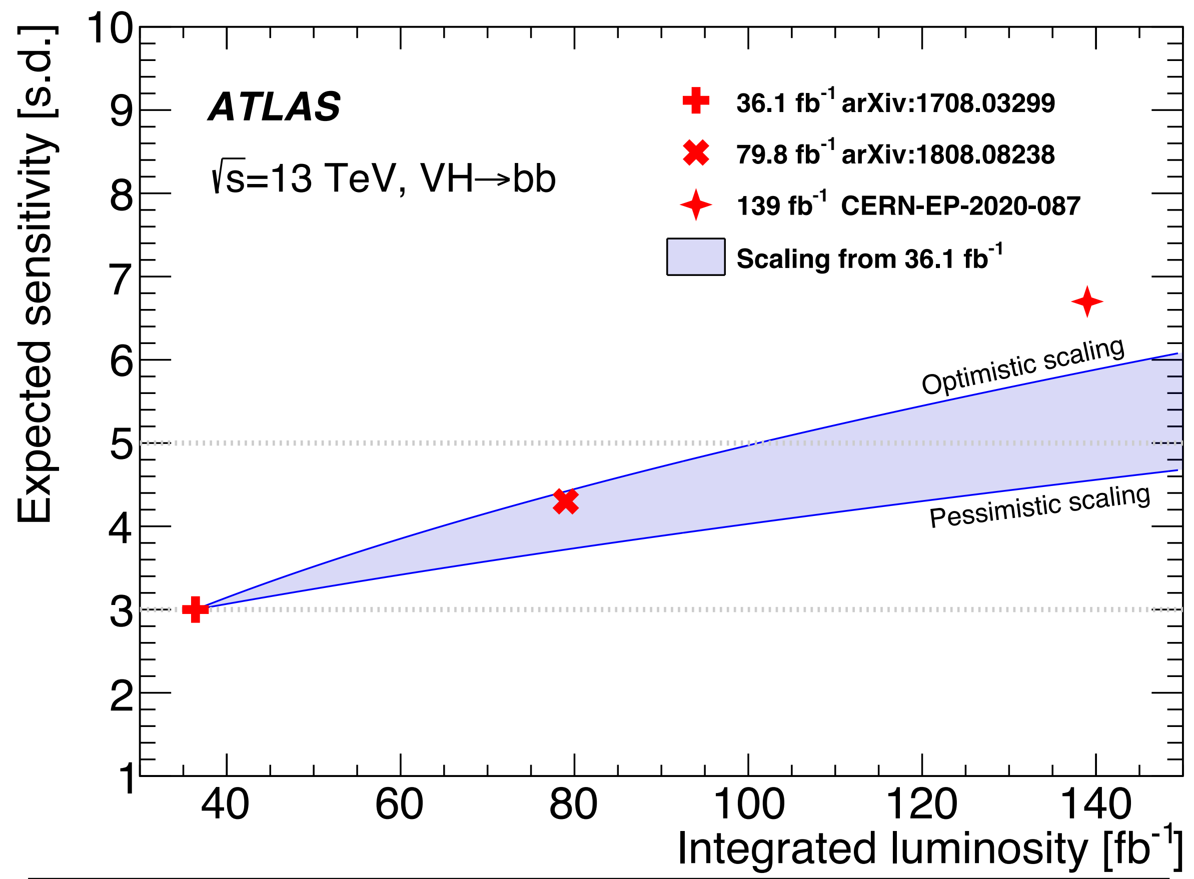
- σ(ggF) measured with ~7% precision, approaching 5% uncertainty on N³LO calculation in QCD
- VBF precision 15%, ~20% for σ(WH/ZH) and σ(ttH)
- Probing tH mode: interesting for BSM scenario

Higgs boson productions x decays



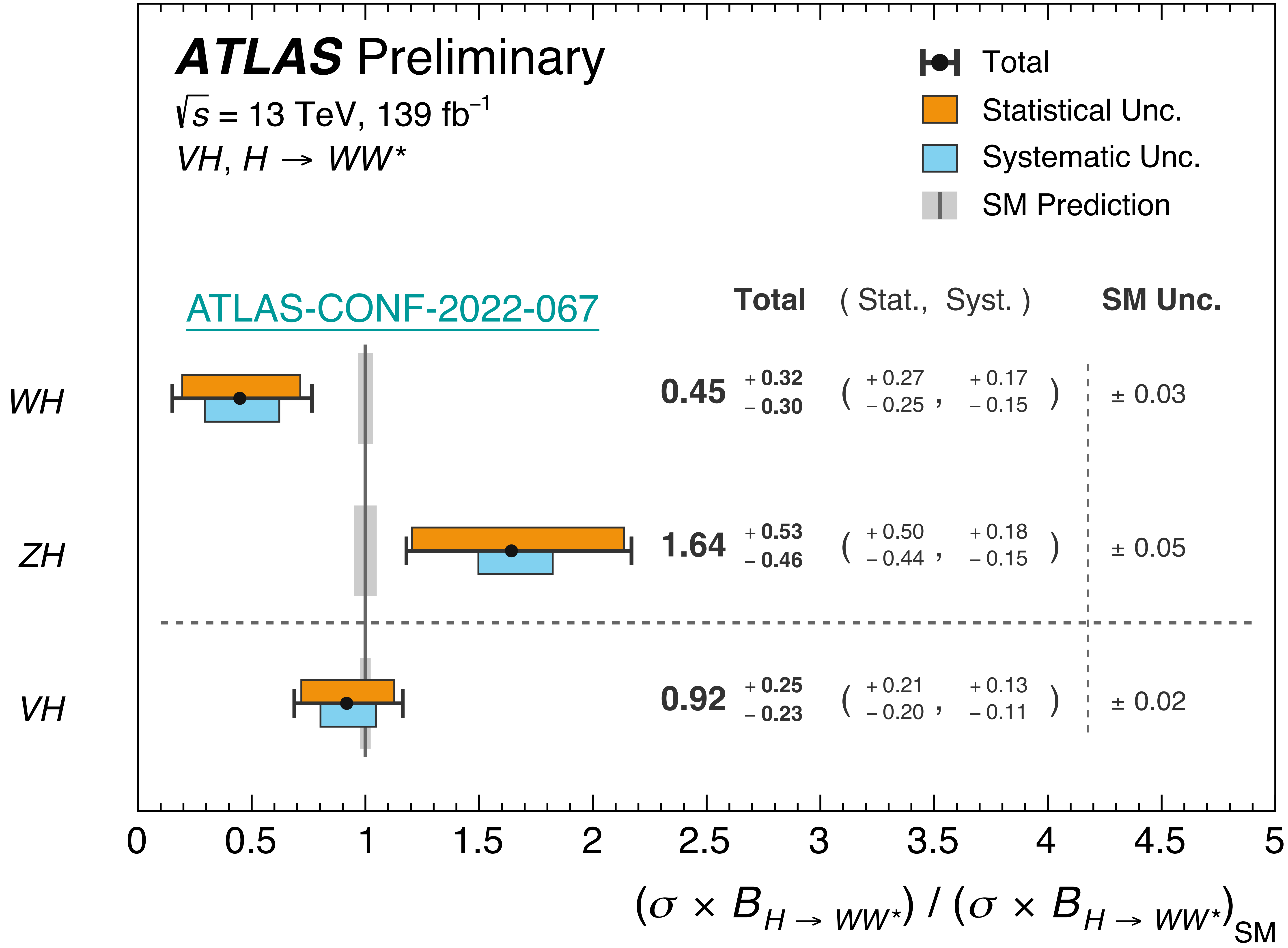
	ggH	VBF	WH	ZH	ttH+tH
γγ	1.08 $^{+0.12}_{-0.11}$	1.00 $^{+0.35}_{-0.32}$	1.43 $^{+0.54}_{-0.47}$	1.19 $^{+0.71}_{-0.62}$	1.38 $^{+0.34}_{-0.29}$
ZZ	0.93 $^{+0.14}_{-0.13}$	0.32 $^{+0.48}_{-0.32}$	0.00 $^{+1.55}$	12.24 $^{+6.59}_{-5.69}$	0.00 $^{+0.73}$
WW	0.90 $^{+0.11}_{-0.10}$	0.73 $^{+0.28}_{-0.24}$	2.41 $^{+0.72}_{-0.70}$	1.76 $^{+0.75}_{-0.67}$	1.44 ± 0.32
ττ	0.66 ± 0.21	0.86 $^{+0.17}_{-0.16}$	1.33 $^{+0.61}_{-0.57}$	1.89 $^{+0.65}_{-0.56}$	0.35 $^{+0.44}_{-0.37}$
bb	5.31 $^{+2.97}_{-2.54}$		1.26 $^{+0.42}_{-0.41}$	0.90 $^{+0.36}_{-0.34}$	0.90 $^{+0.46}_{-0.44}$
μμ	0.33 $^{+0.74}_{-0.70}$	1.55 $^{+0.86}_{-0.73}$	5.63 $^{+3.04}_{-3.36}$ (VH)		3.07 $^{+2.63}_{-2.21}$
Zγ	3.86 $^{+1.39}_{-1.23}$	-4.43 $^{+3.82}_{-2.89}$			

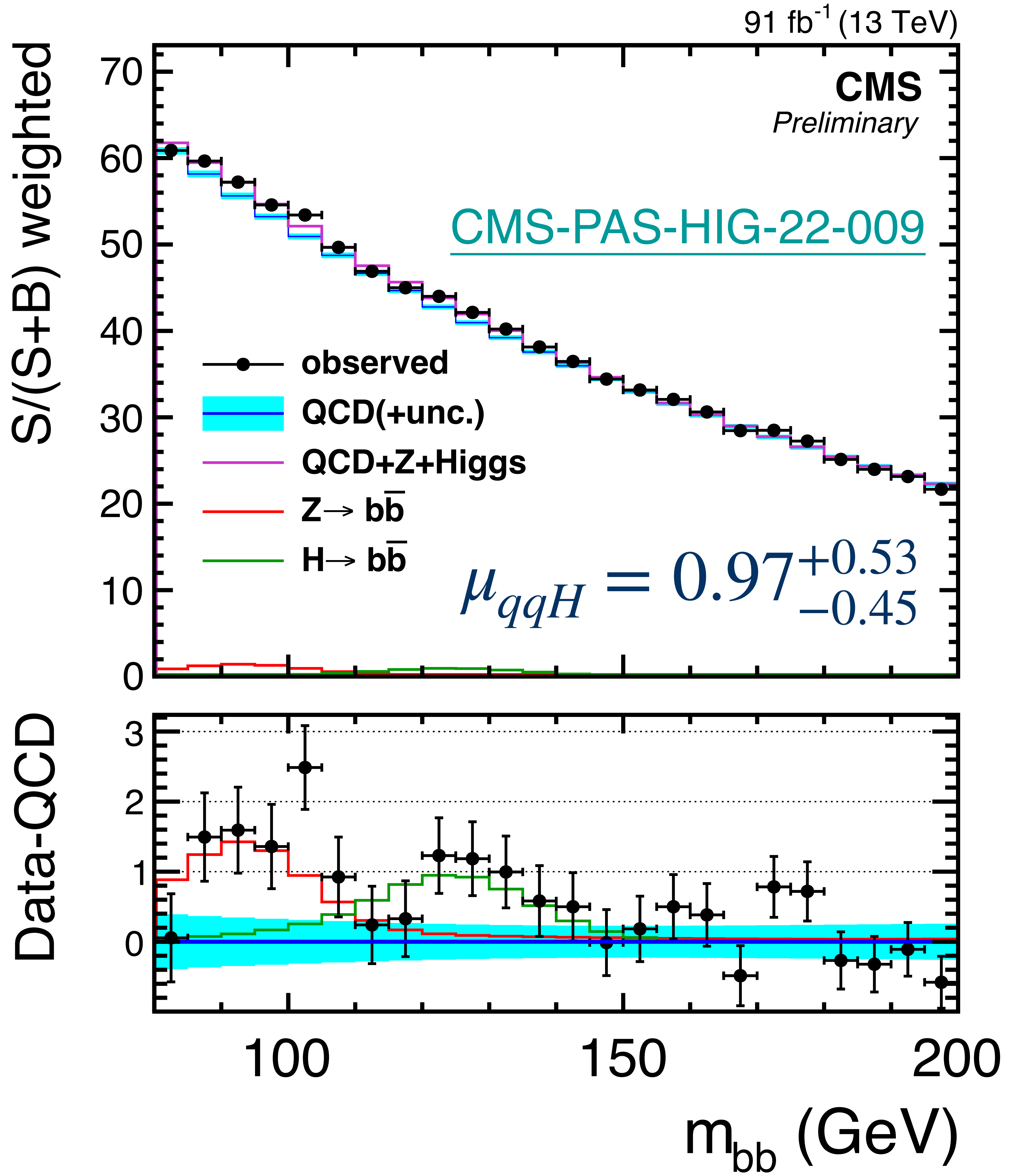
- Good coverage of production and decay channels by LHC measurements
- Significant progresses in analyses. Many “impossibles” in the past now become possible



Projected vs. actual sensitivity of ATLAS VH(bb)

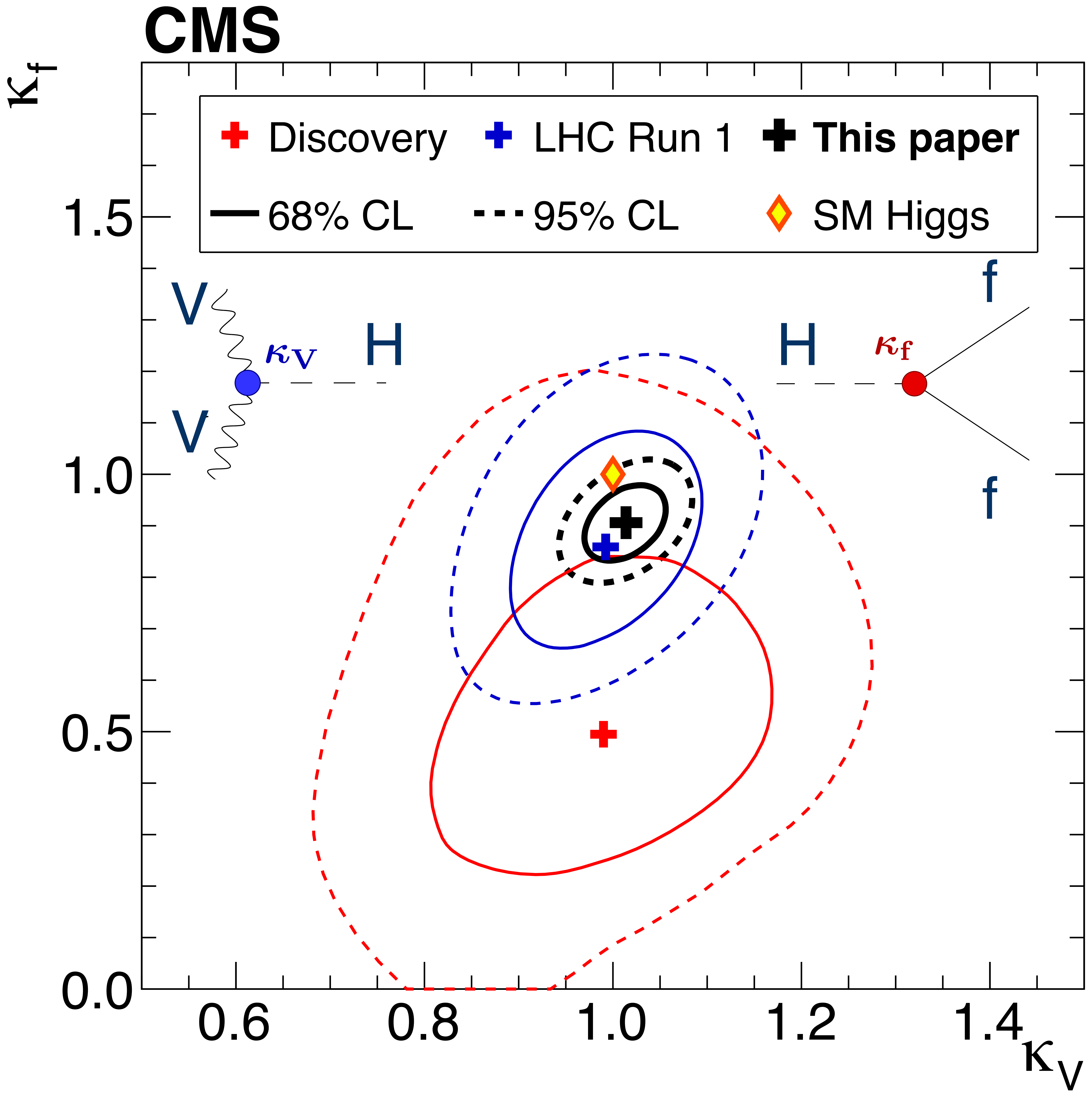
Complete the measurement matrix

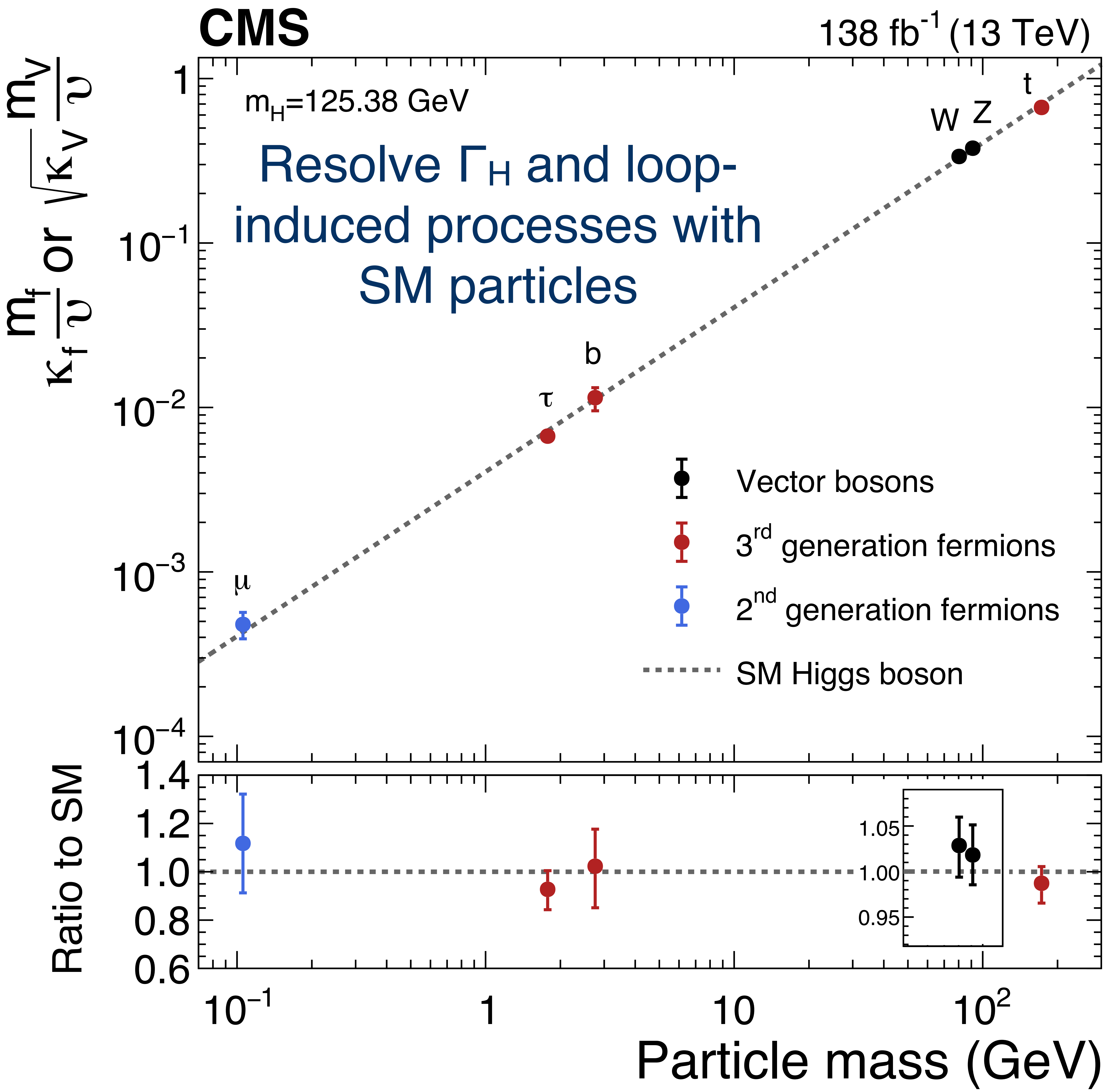




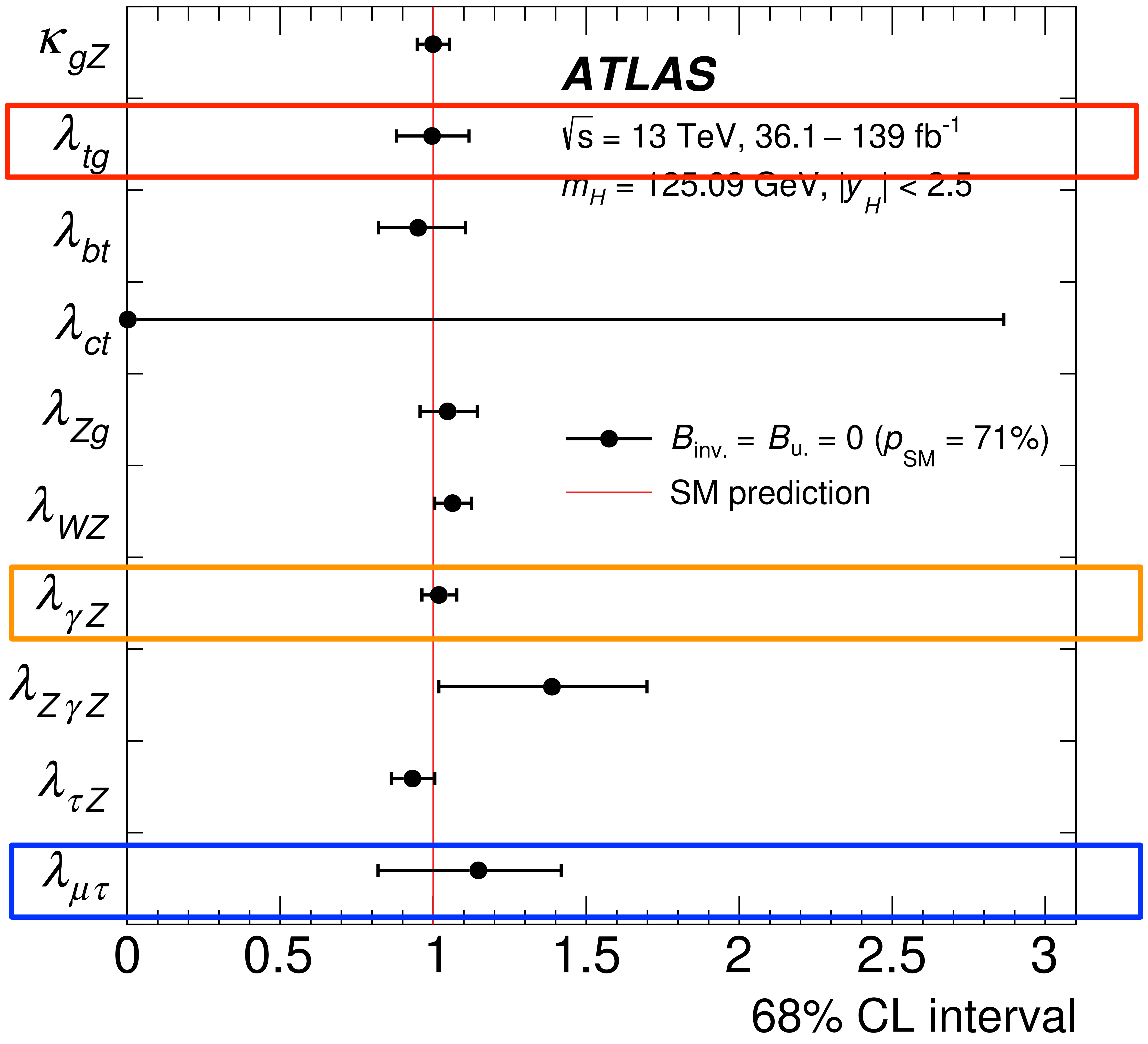
- ATLAS VH, H→WW: 4.6σ
- CMS VBF, H→bb: 2.4σ

Coupling strength tests

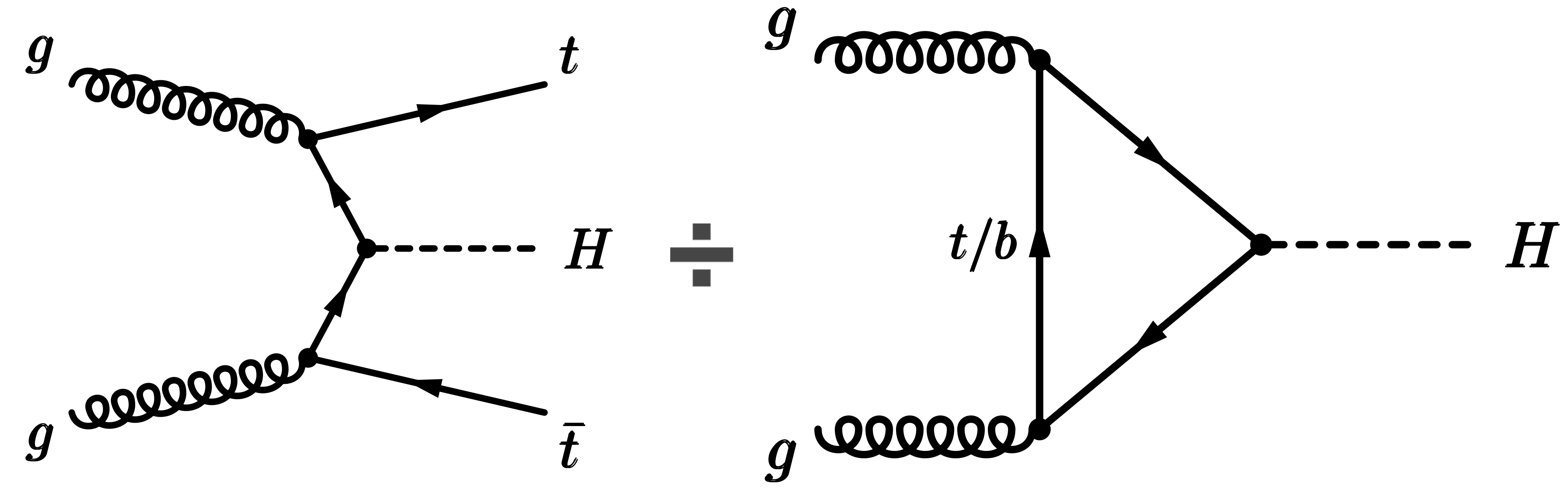




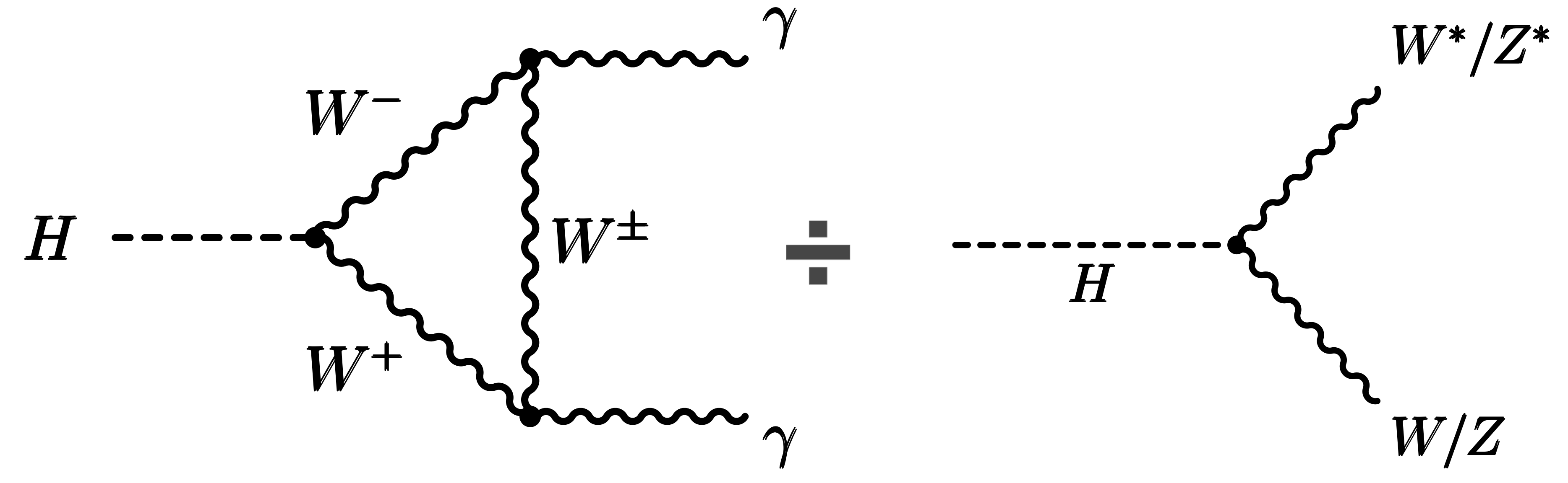
Ratios of coupling strengths



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

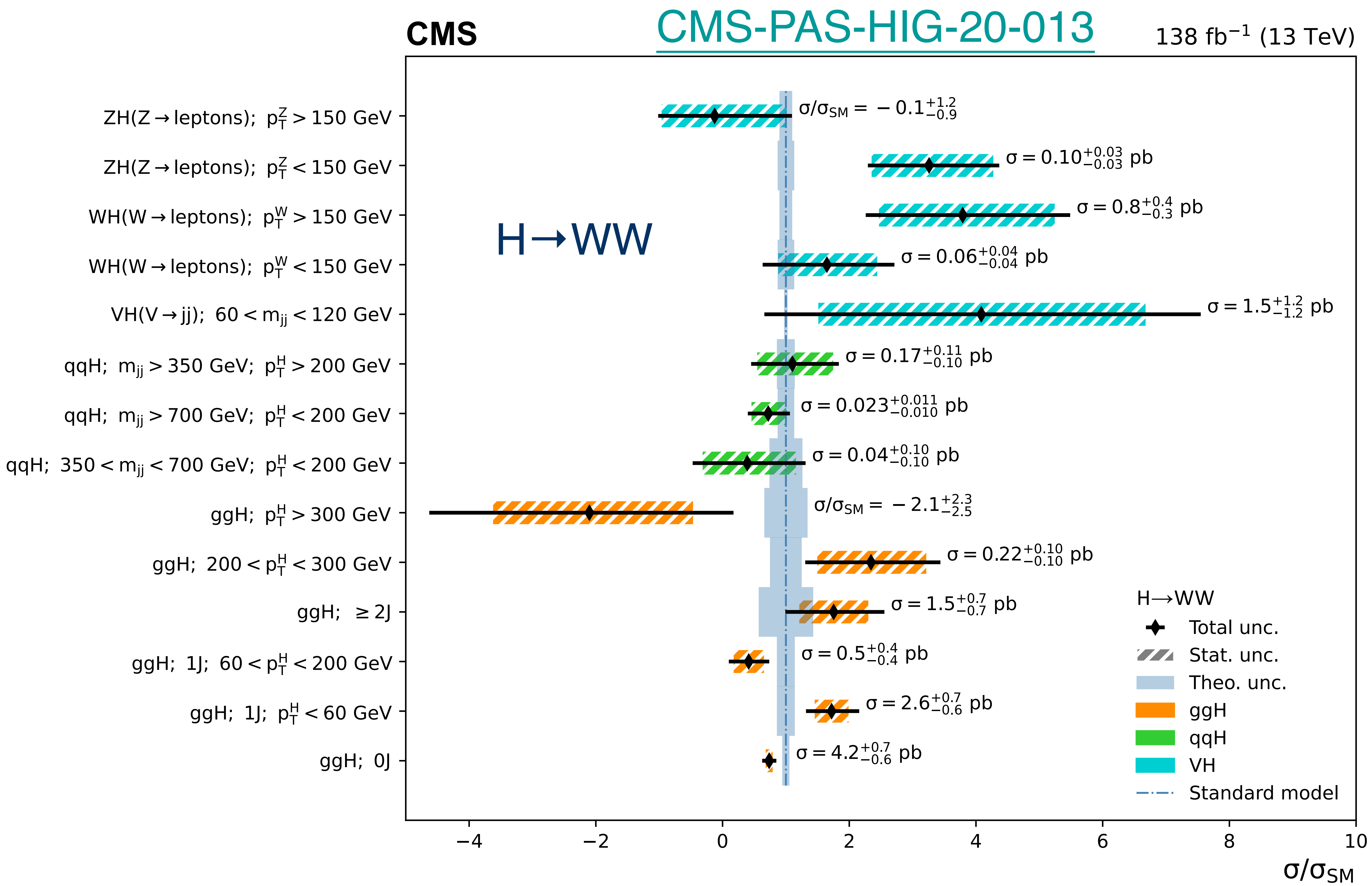


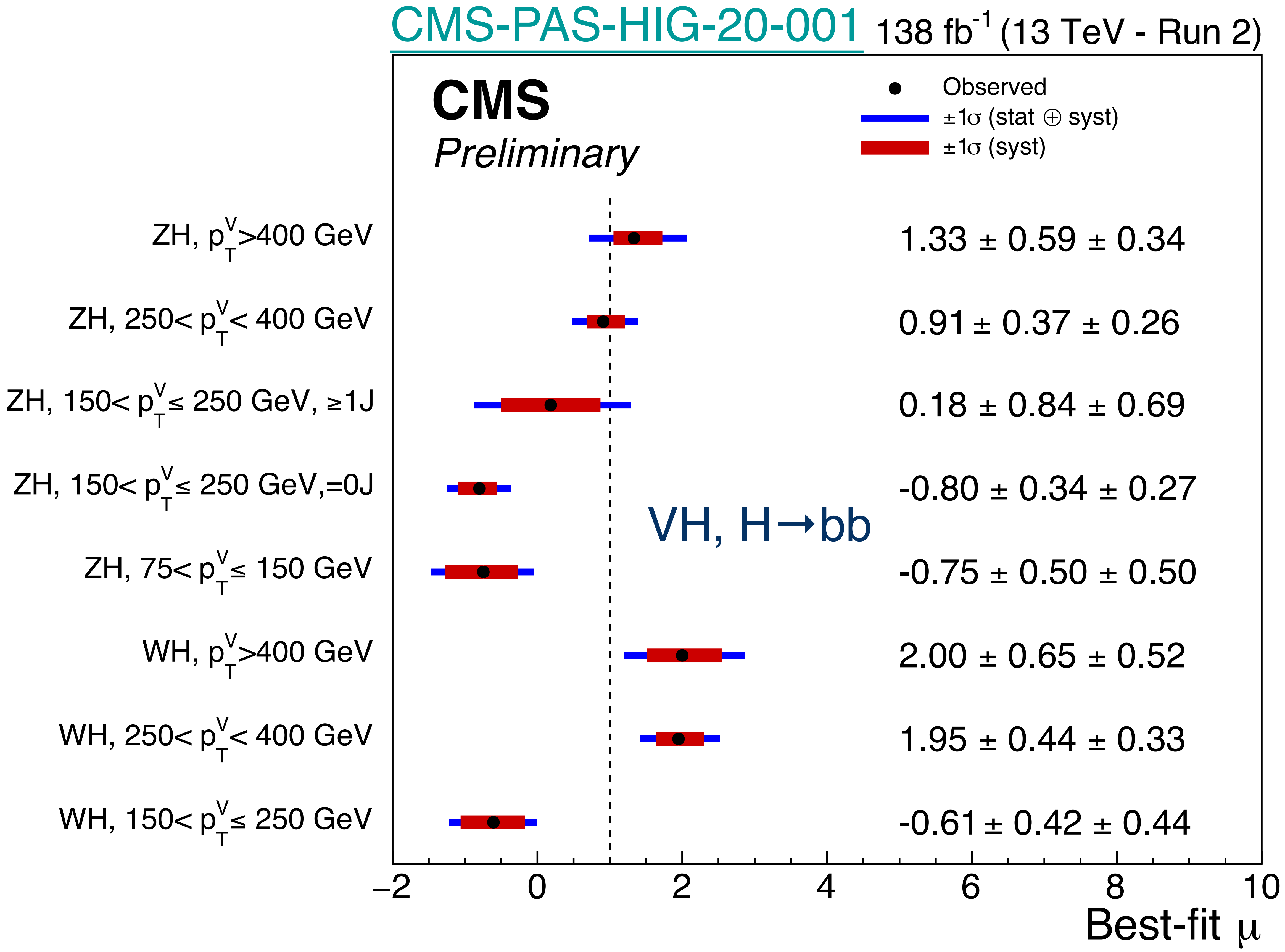
$$\lambda_{\gamma Z} = \frac{\kappa_\gamma}{\kappa_Z}$$



- 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**

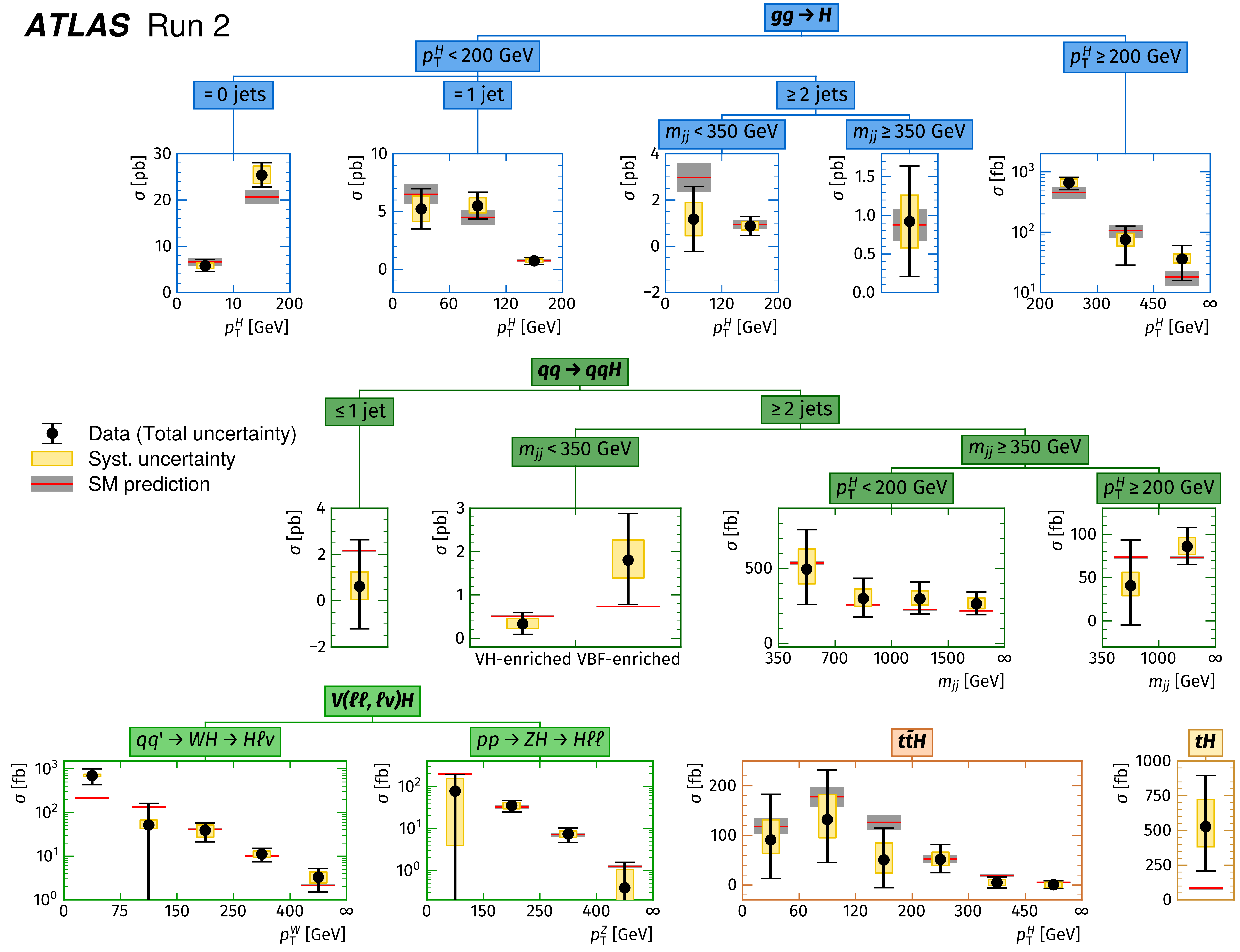
Simplified Template cross-section (STXS) measurements

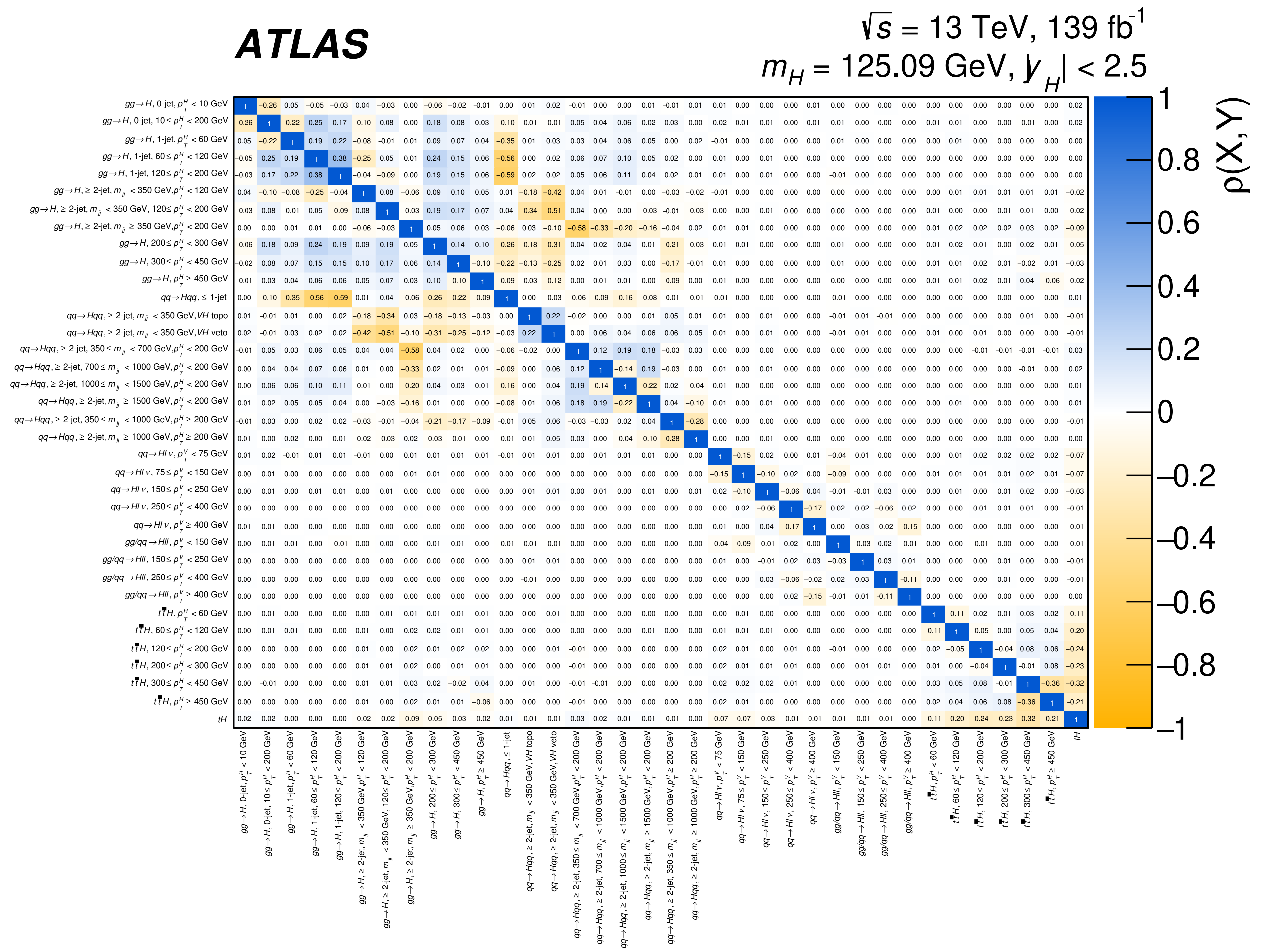




- STXS: split inclusive Higgs boson MC template into various phase-space regions (truth bins)
  - Truth bins match experimental selection. **Reduce model dependence from aggressive extrapolations**
  - Still allow **powerful analysis techniques** (e.g. machine learning) within each truth bin. Model dependence remains on decay side in channels like H→ZZ→4l H→WW→lνlν and in truth bins

Simplified Template cross-section (STXS) measurements



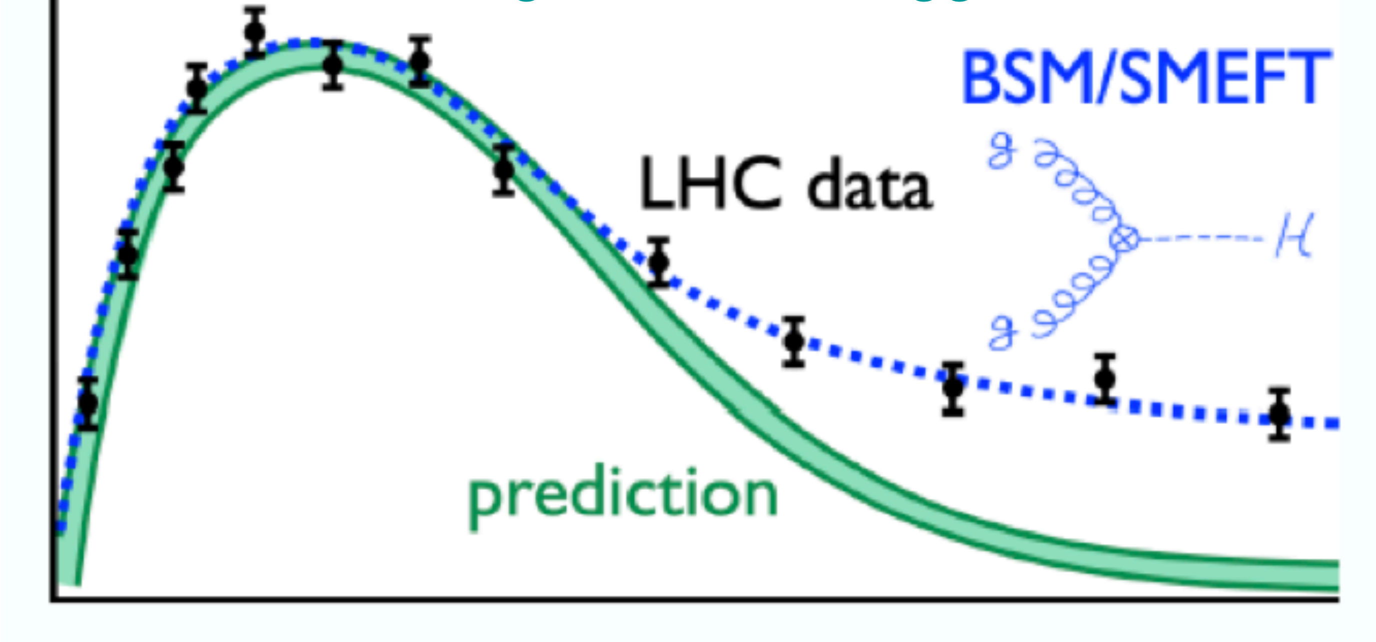


- **STXS is designed for combination**: uniform truth bin definitions across channels, and between ATLAS and CMS
- When understanding/interpreting STXS results, do not forget correlation matrix!
- STXS framework will keep evolving in Run 3
  - **Crucial for experimentalists to participate in the development**

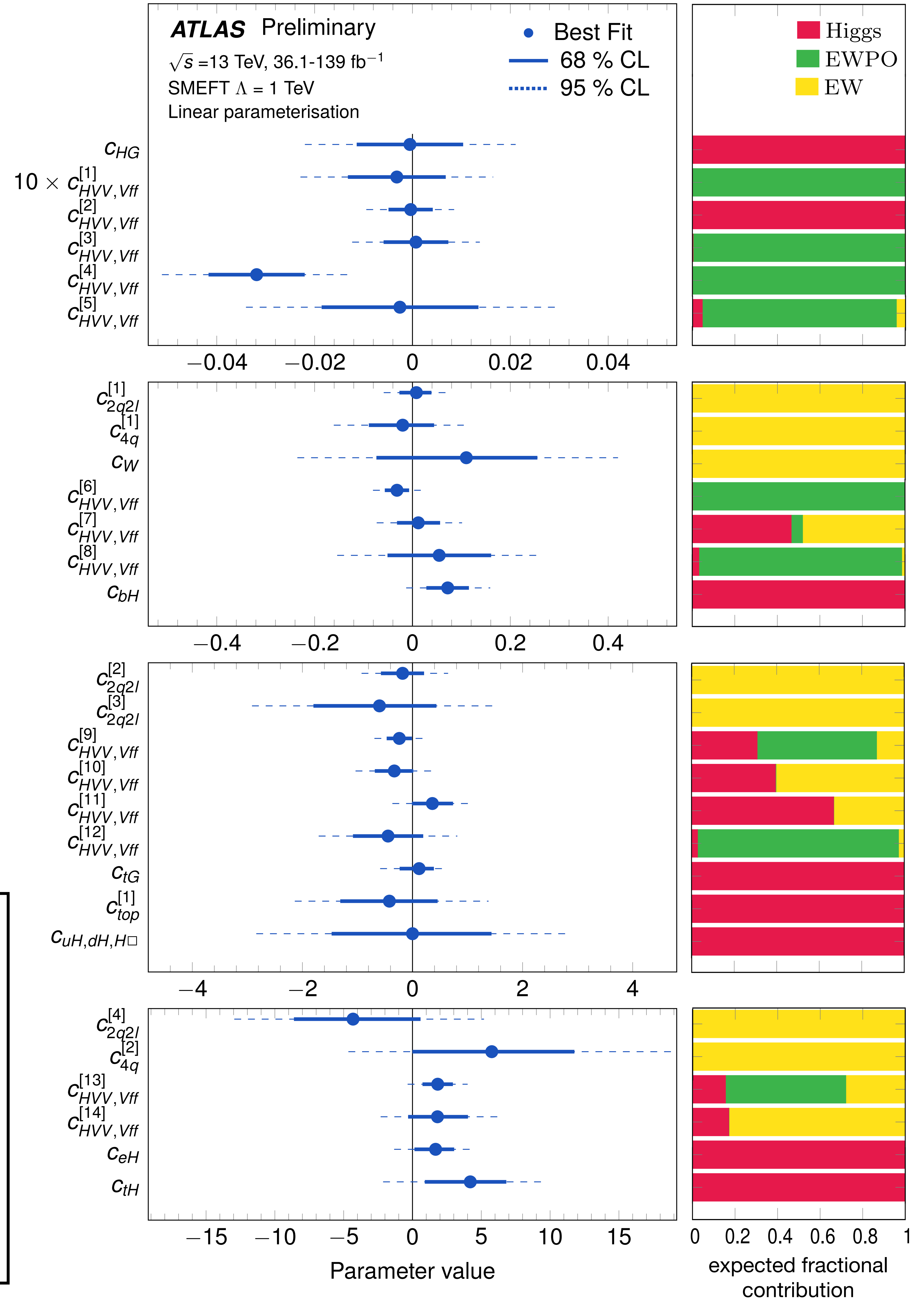
EFT interpretation of STXS measurements

- **HEP discoveries are often enabled by higher collision energy**
- **However, we will not have a machine with much higher energy than LHC in the coming decades**
  - If new physics is beyond LHC reach, it will most likely manifest itself as deviations in SM precision measurements
- STXS measurements are natural candidates for EFT interpretations from Higgs sector
  - Need to combine with EW and Top measurements to get full picture
  - Physics observables have similar dependence on EFT different operators → introduces degeneracy among Wilson coefficients…

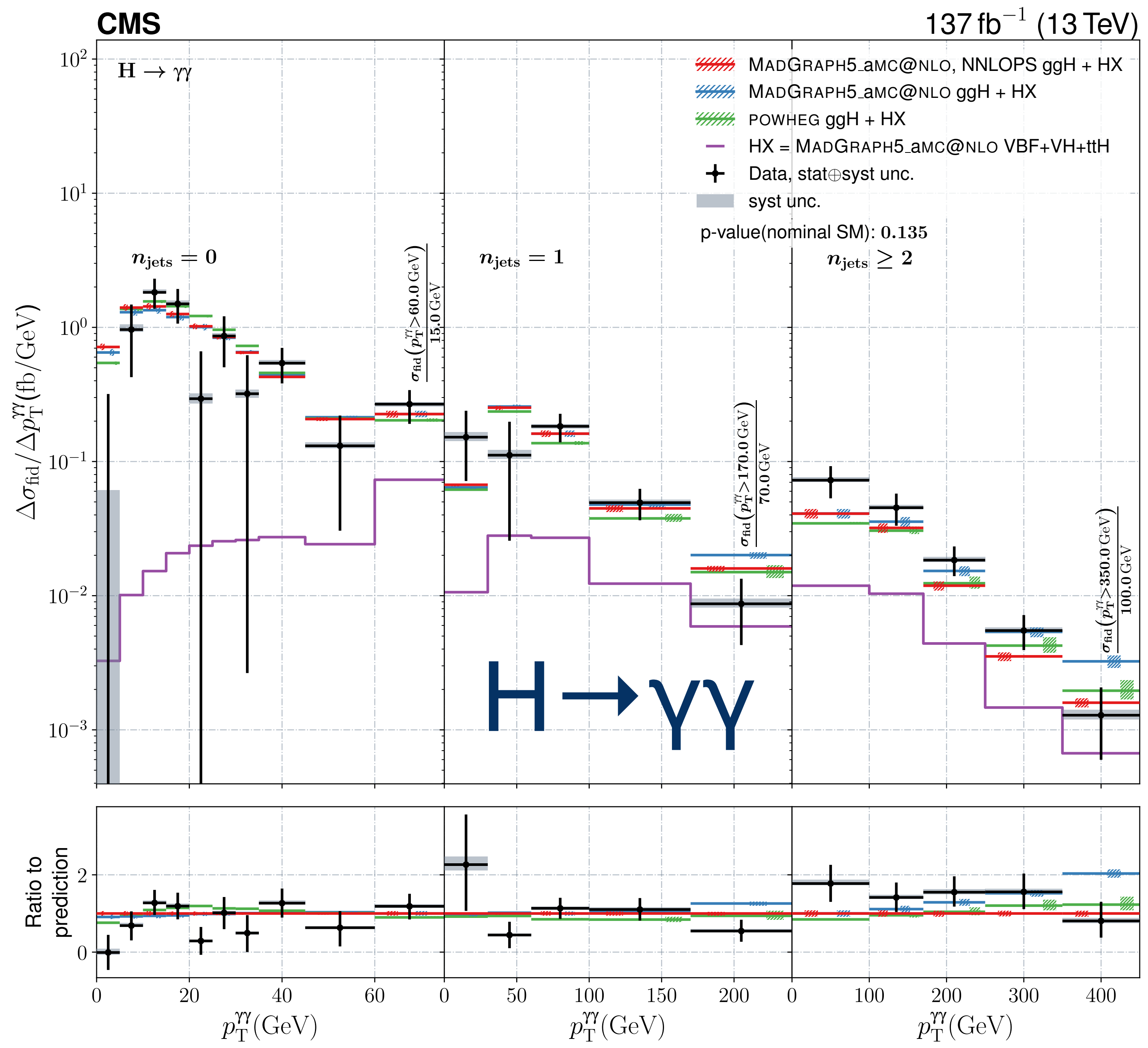
G. Zanderighi's talk at Higgs 2022



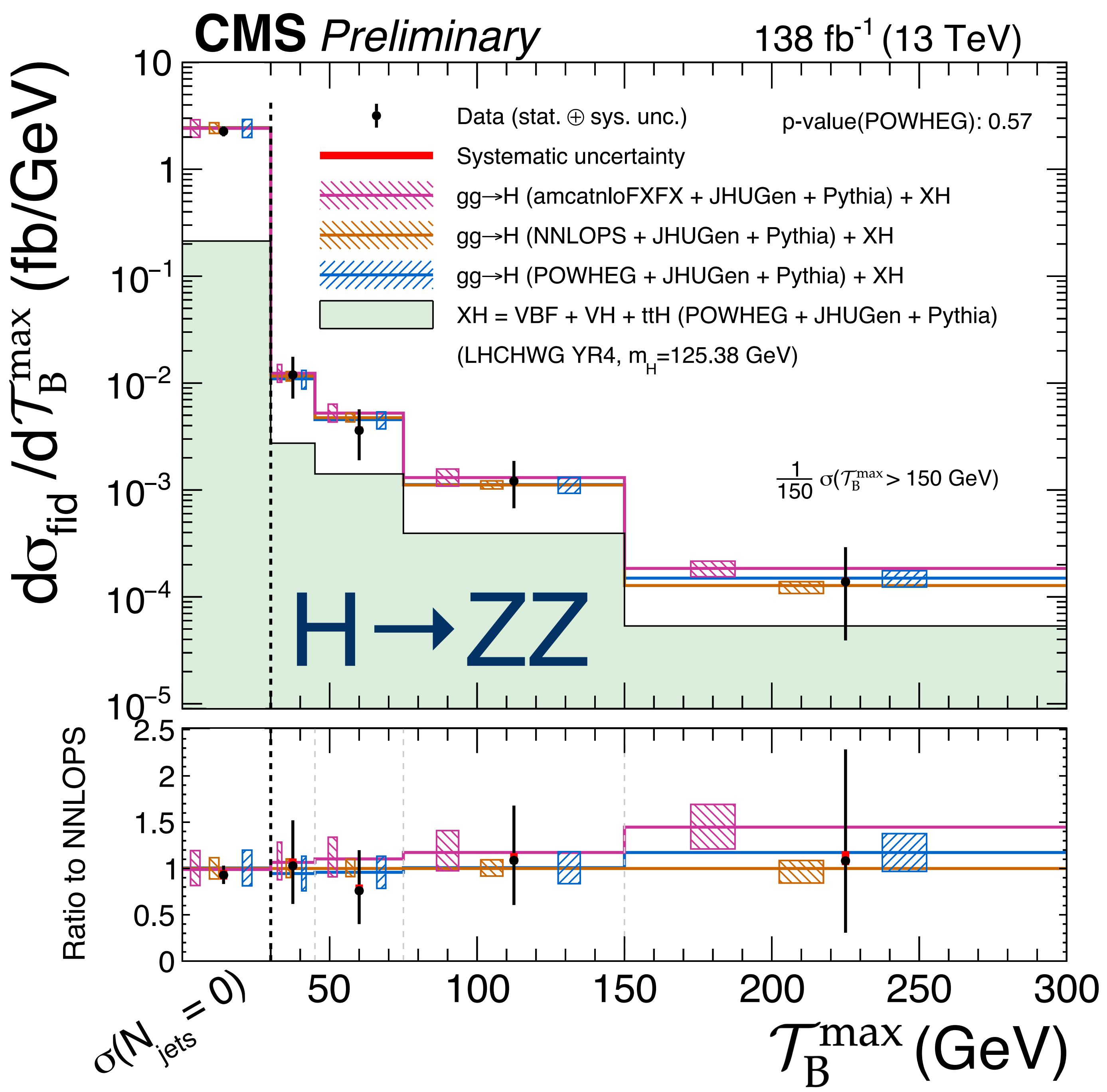
- ATLAS Higgs + ATLAS EW + LEP/SLC EW
- Certain Wilson coef. are added up linearly from diagonalizing correlation matrix
- Only tension from $A_{FB}^{(b,c)}$ in EW precision data



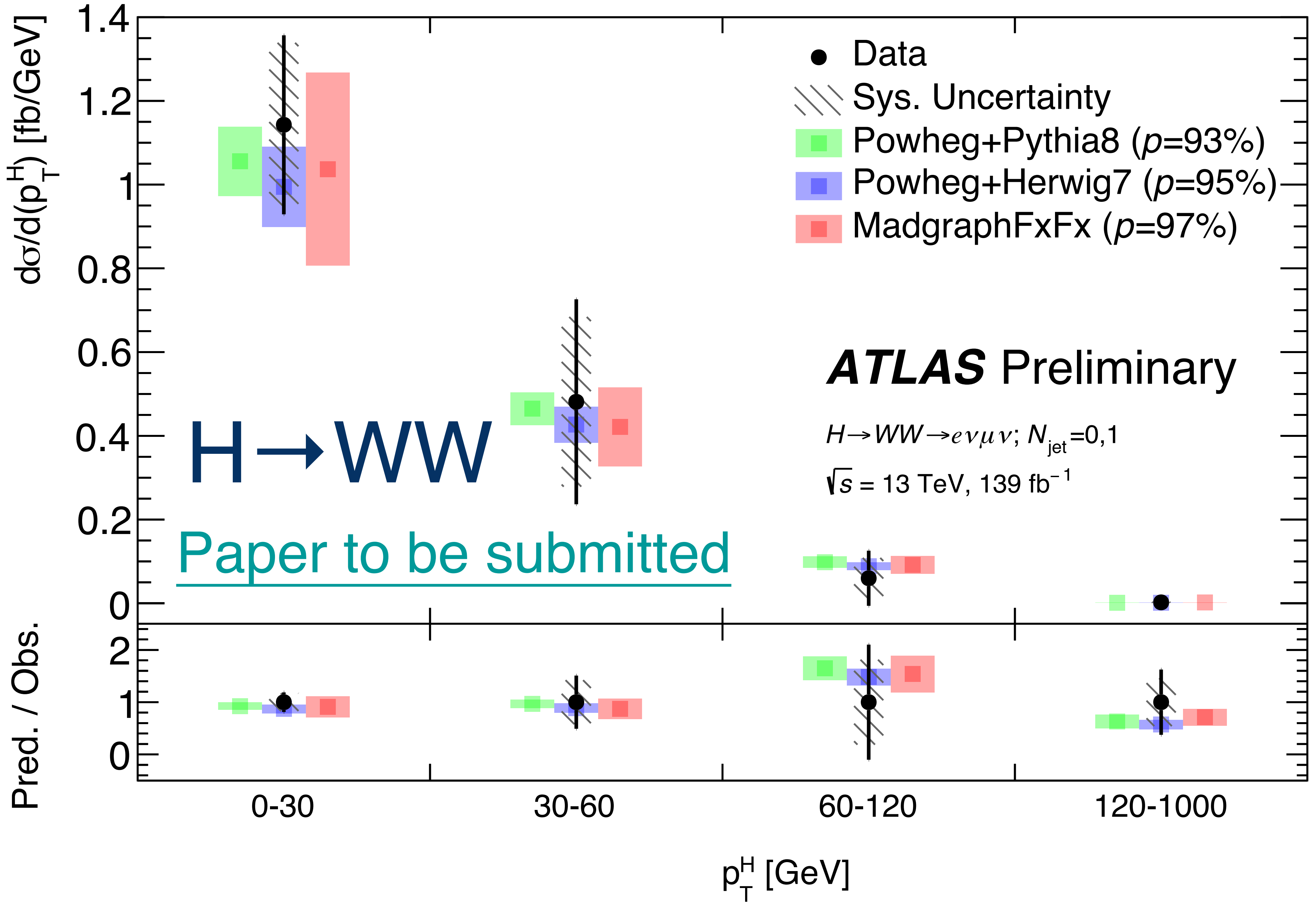
Fiducial differential cross-section measurements



[arXiv:2208.12279]

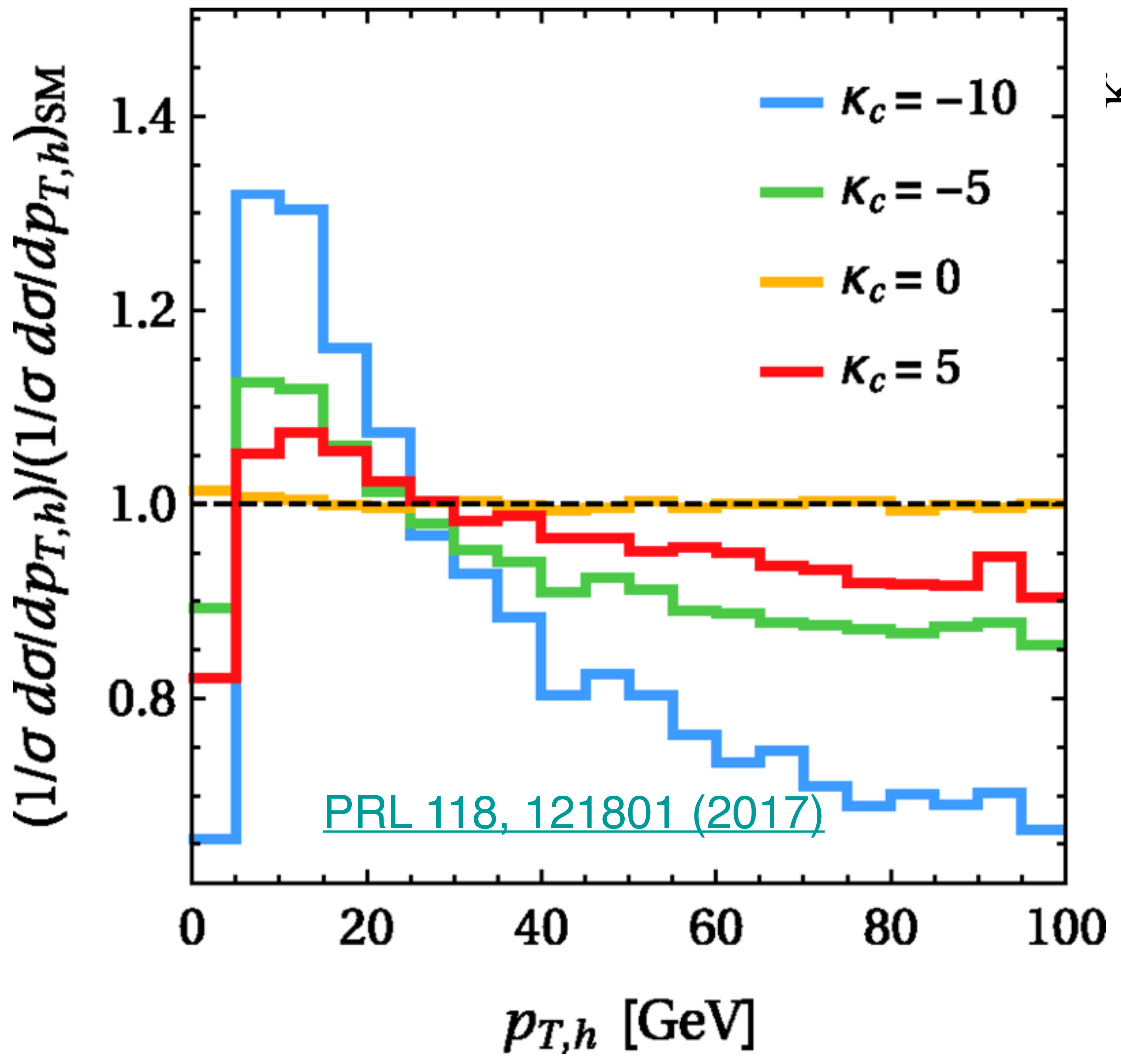


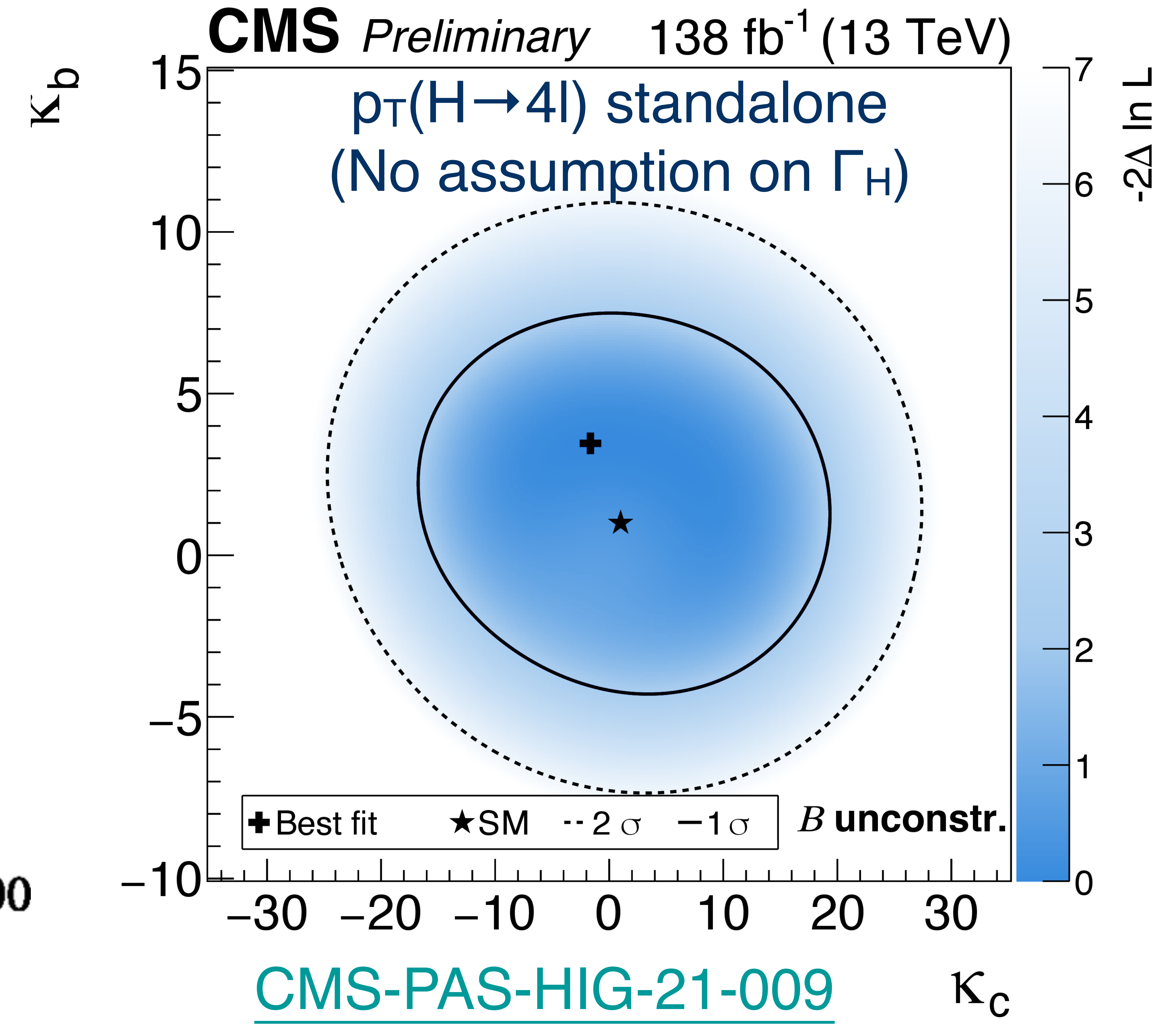
[CMS-PAS-HIG-21-009]

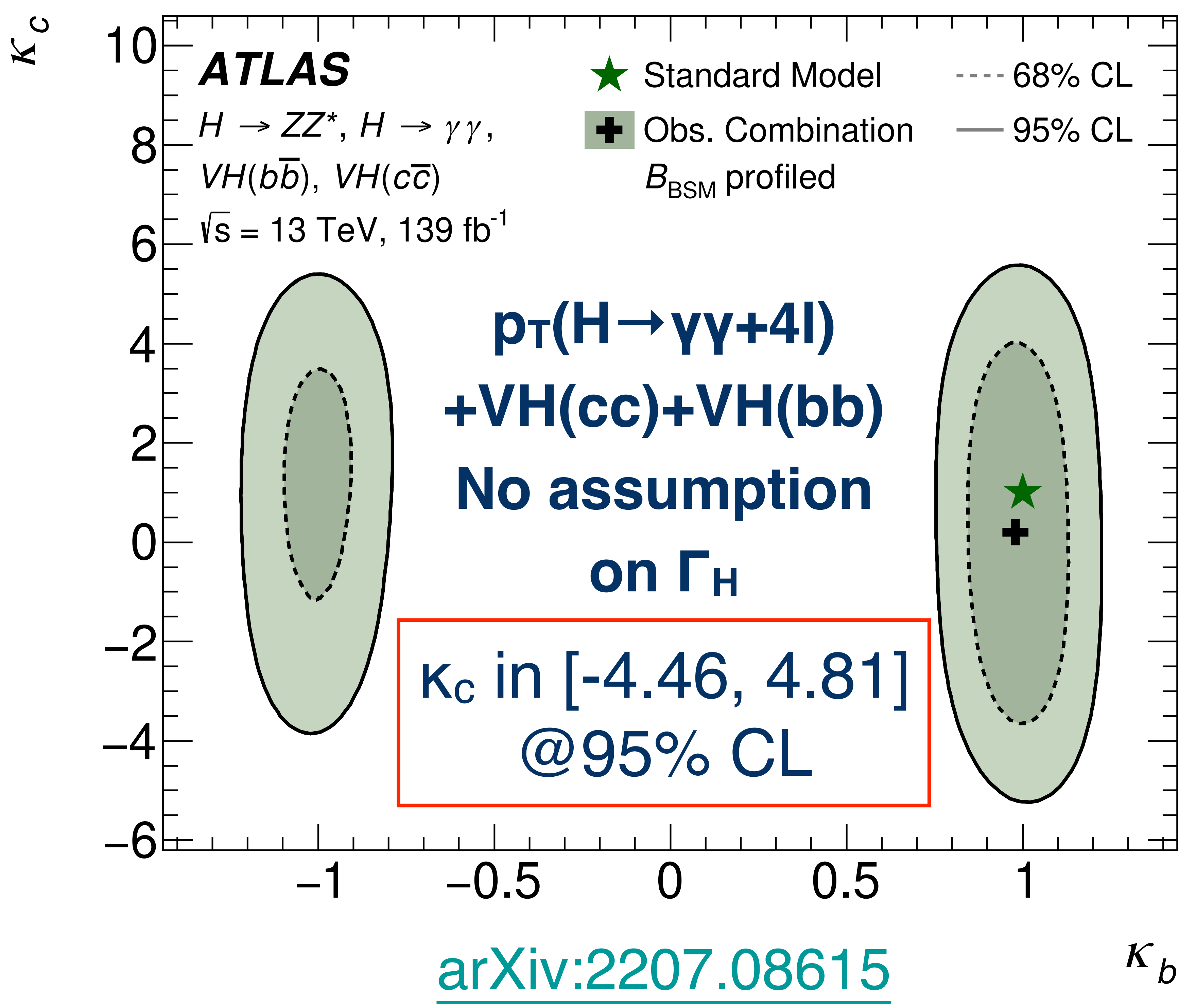


- High-precision channels (γγ and 4l) start exploring 2D measurement & advanced variables that better test theory calculations. Also contributions from other channels e.g. WW
  - Rapidity weighted observable $\mathcal{T}_B^j = m_T^j e^{-|y_j - Y_H|}$ to test QCD resummation
  - Useful inputs for theory. Can be used in various interpretations (EFT, self-coupling…)

Use Higgs boson p_T to constrain charm Yukawa coupling

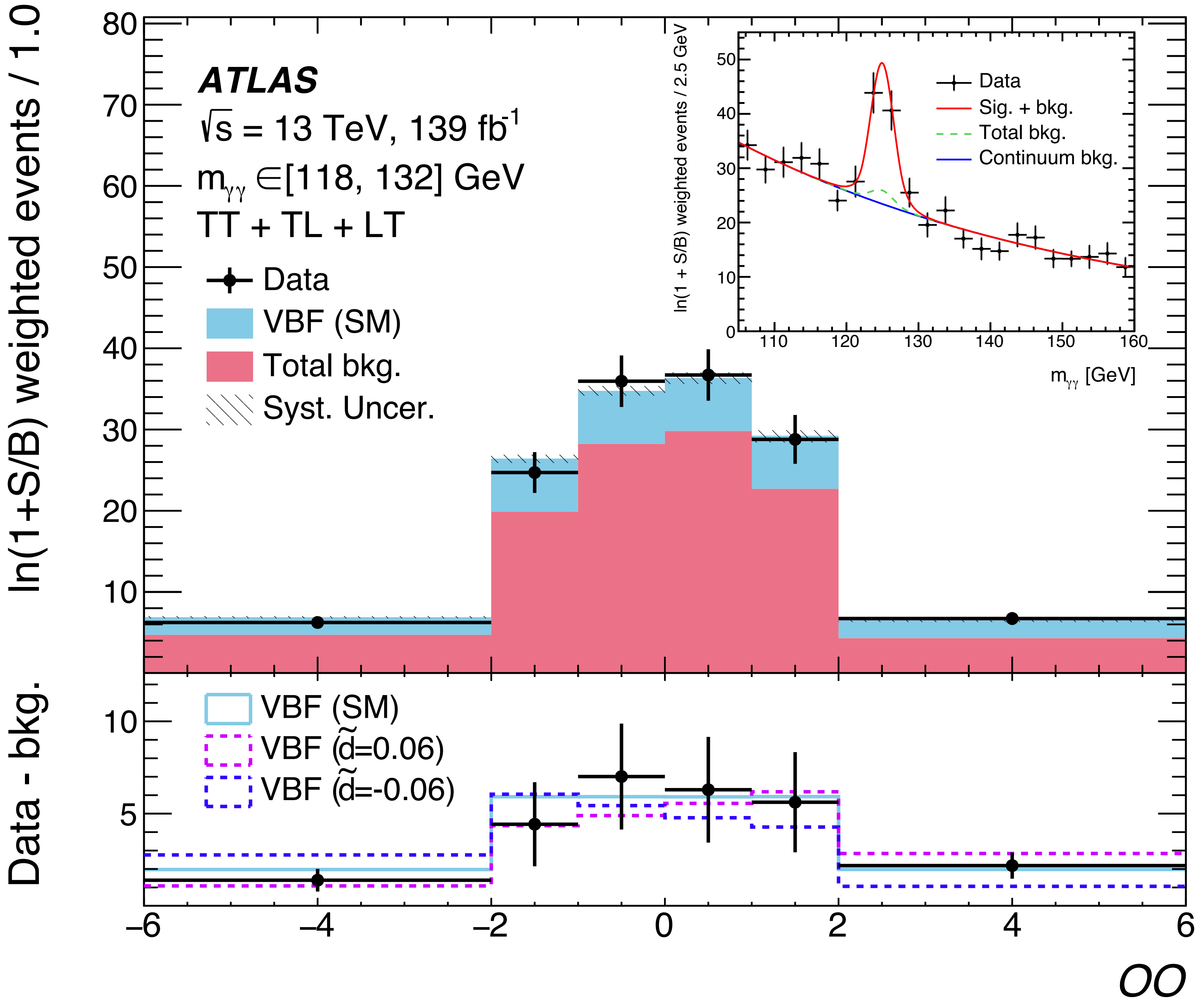


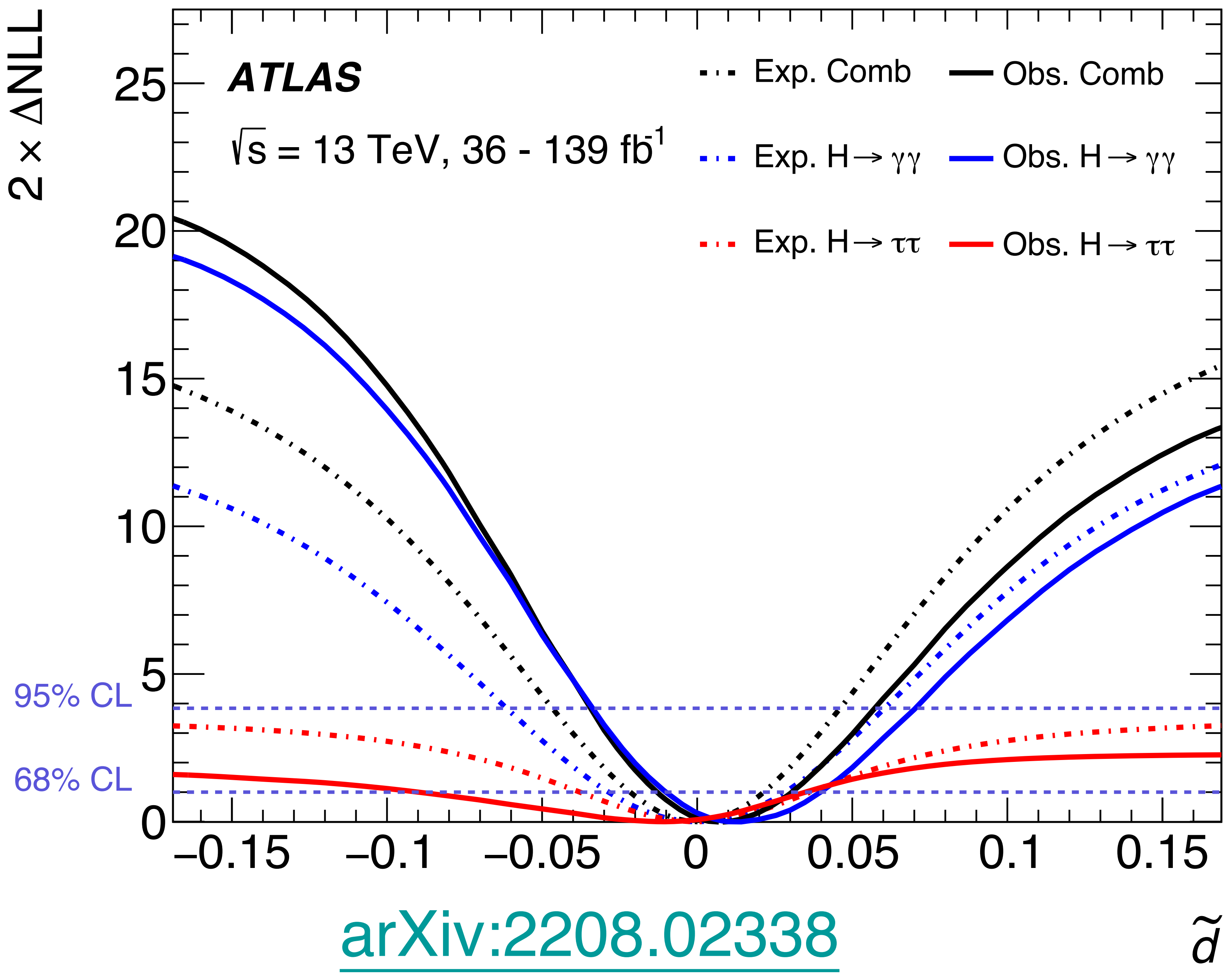




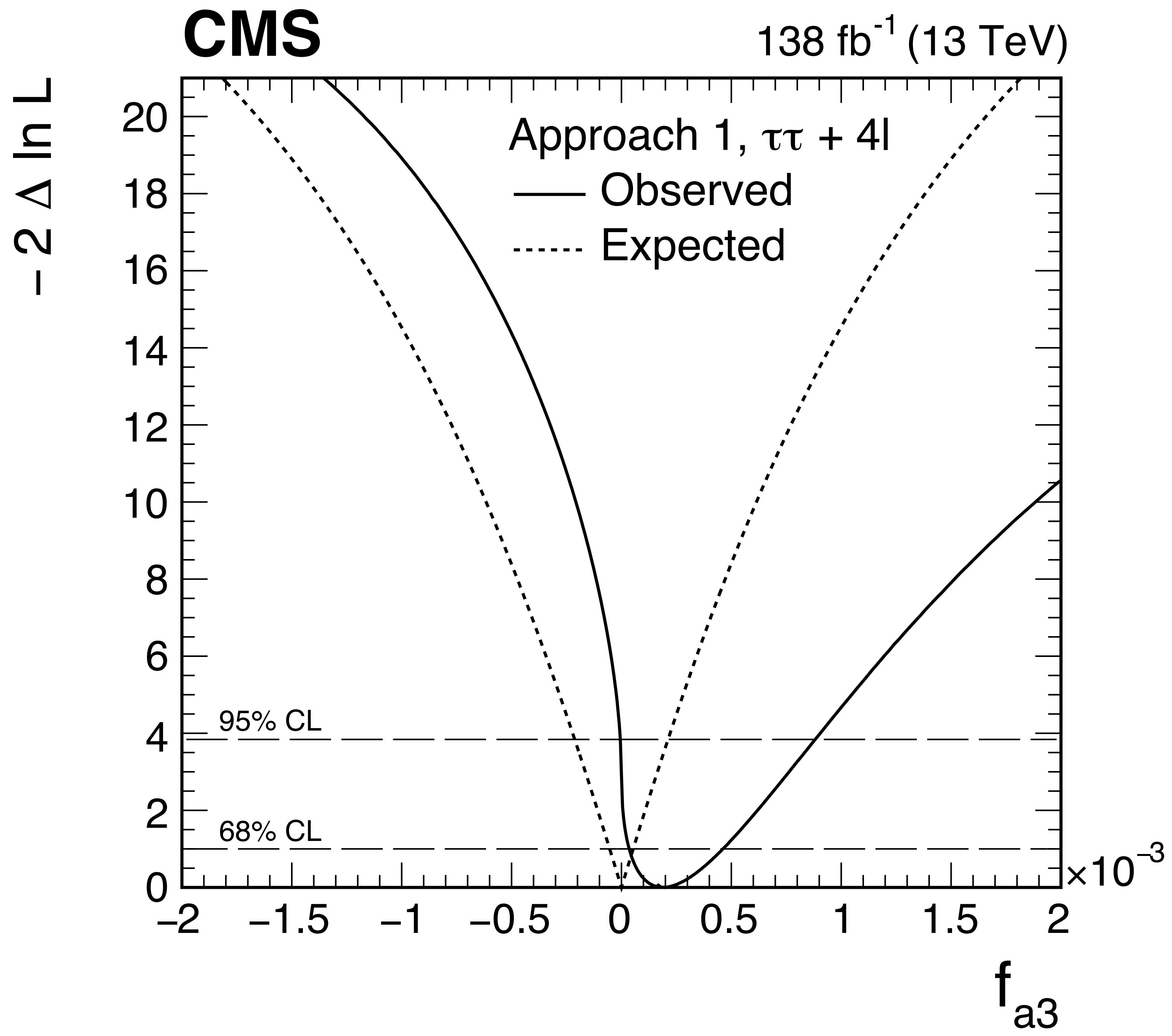
- **Higgs boson p_T** provide **indirect** constraint on charm Yukawa coupling that is comparable to direct VH, H→cc search
- Combination of the **indirect** and **direct** results **allows reducing model dependence** of direct search, and **yields better sensitivity** ($|\kappa_c|<8.5$ @95% CL from ATLAS VH(cc))

HVV CP study in VBF, H→γγ channel

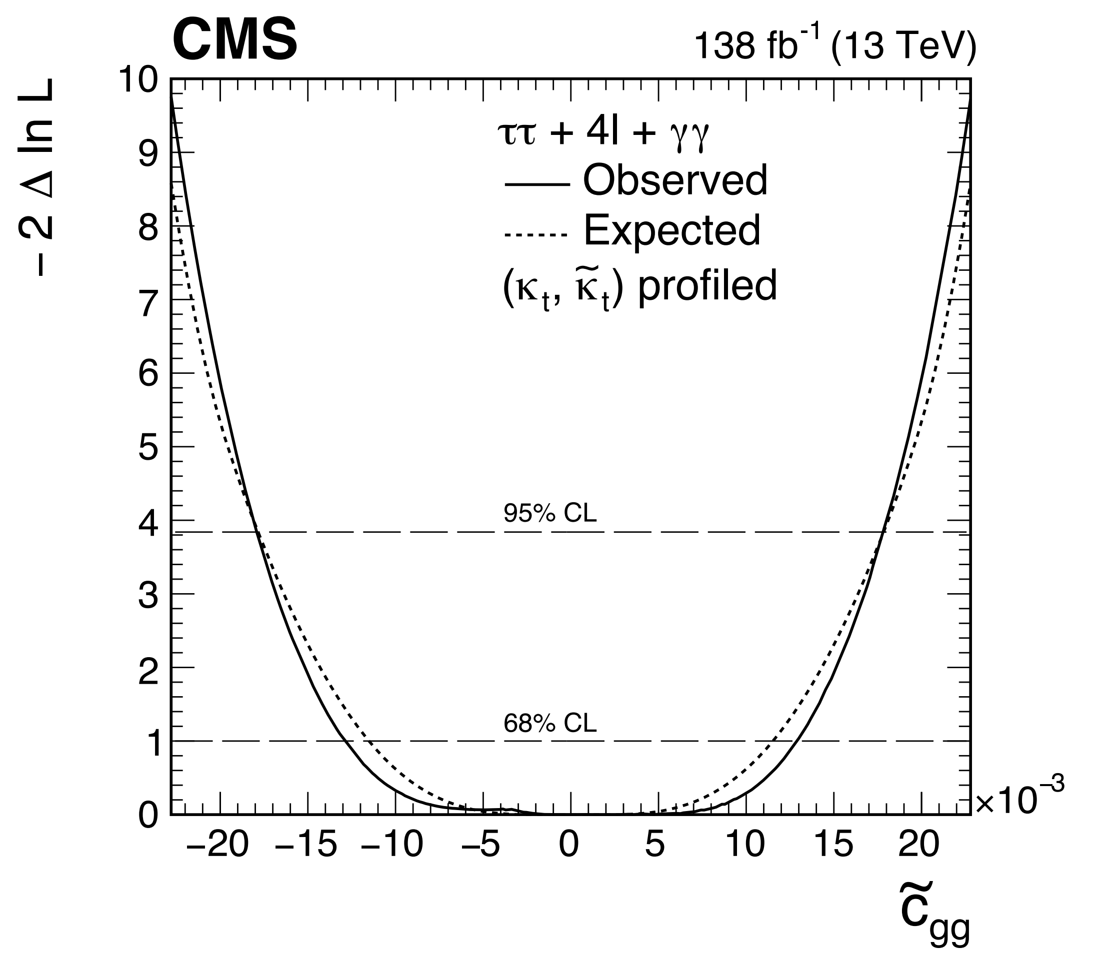




[arXiv:2208.02338](https://arxiv.org/abs/2208.02338)



- Based on **shape info** of **optimal observable** $OO = 2Re(\mathcal{M}^*_{SM}\mathcal{M}_{CP-odd})/|\mathcal{M}_{SM}|^2$
- Two interpretations: $\tilde{d} = -(m_W^2/\Lambda^2)c_{W\tilde{W}}$ from HISZ basis, and $c_{H\tilde{W}}$ from Warsaw basis (**x5 better** than directly fitting diff. xs. $\Delta\Phi(jj)$ etc.)
- HVV CP can be explored in many channels. Interesting to explore their combinations
  - $\tilde{d}$ VBF H→γγ+ττ combination from this work. Also see CMS ττ+4l in [arXiv:2205.05120](https://arxiv.org/abs/2205.05120)

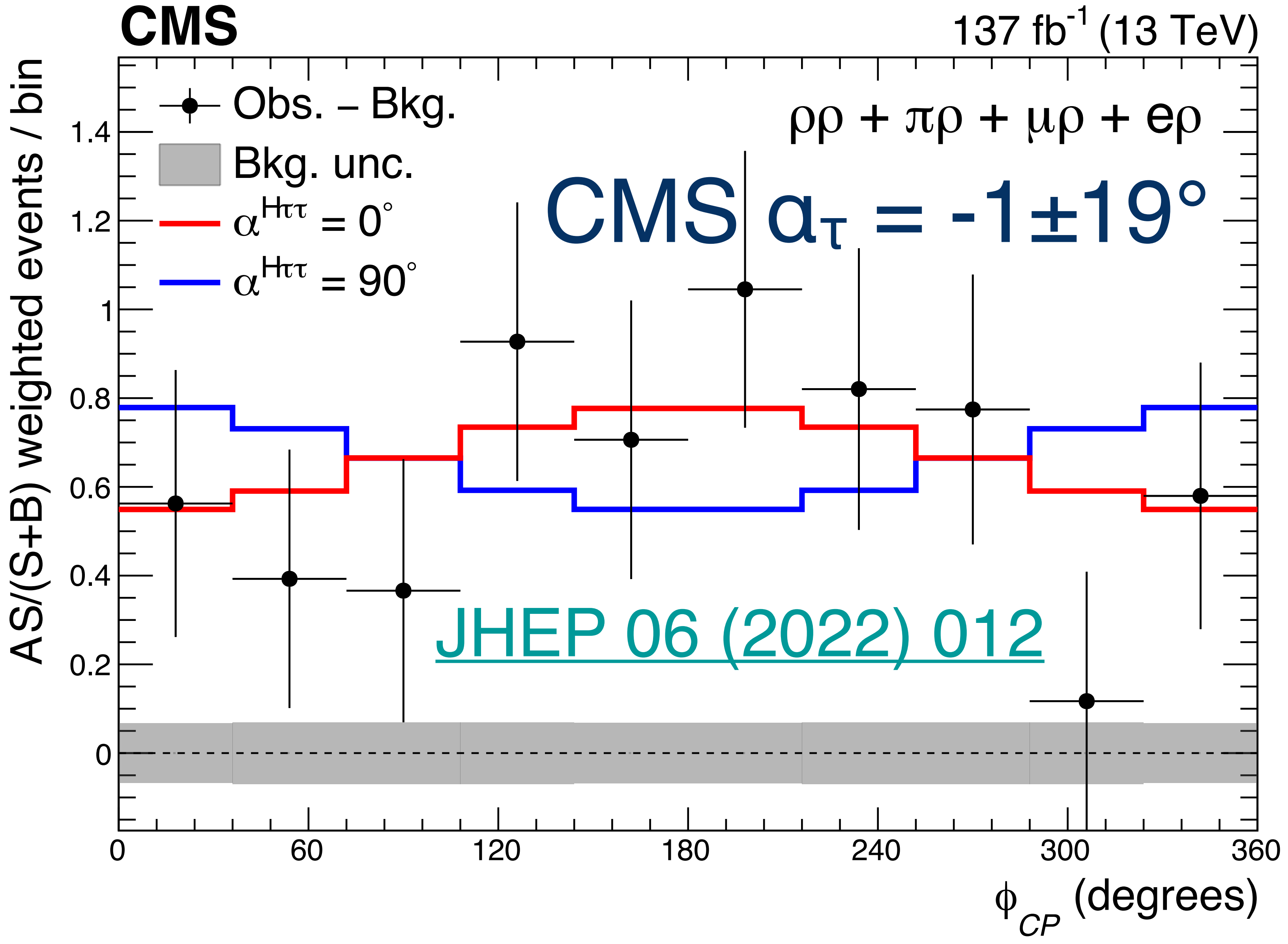


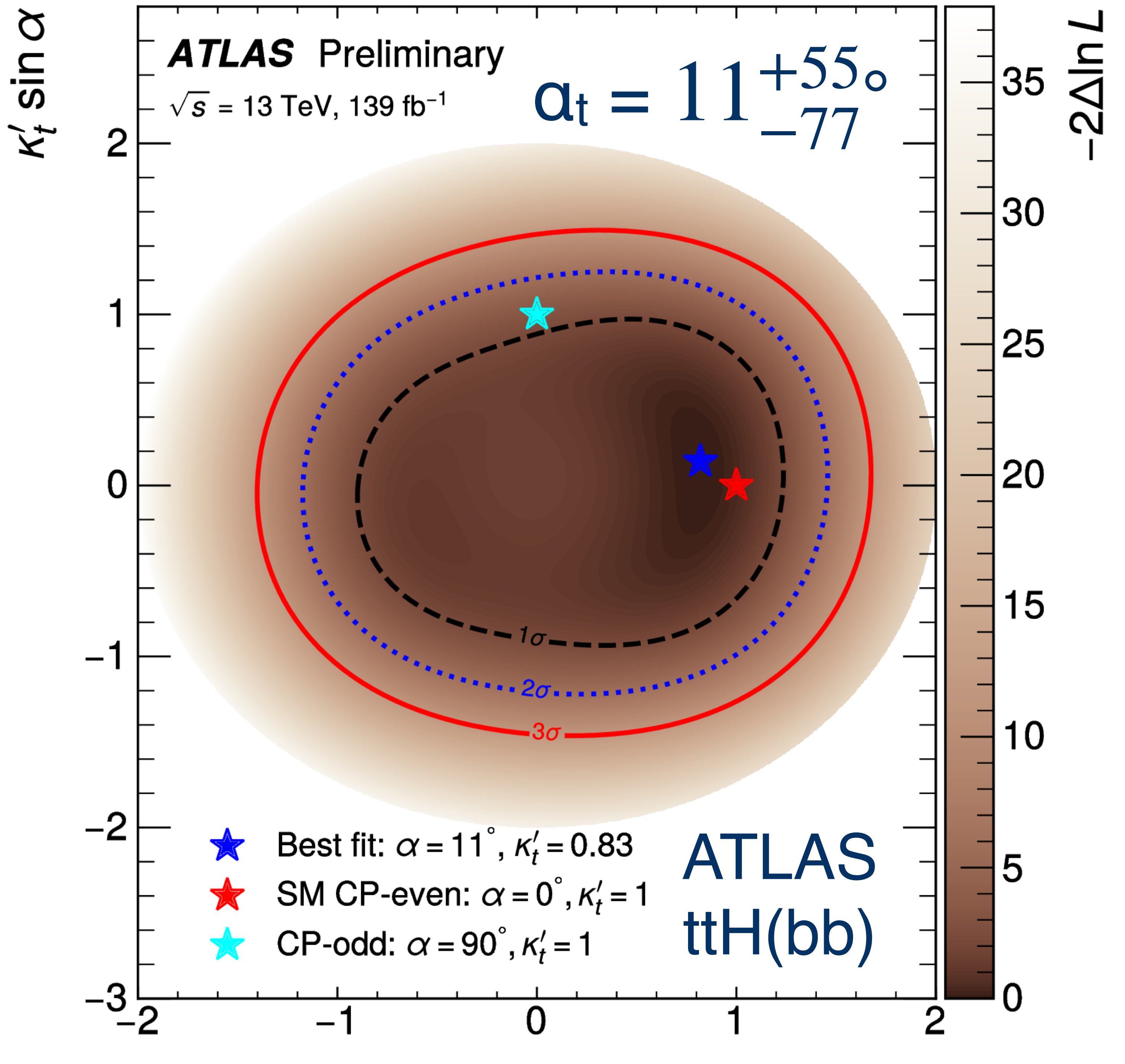
CP study in Yukawa couplings

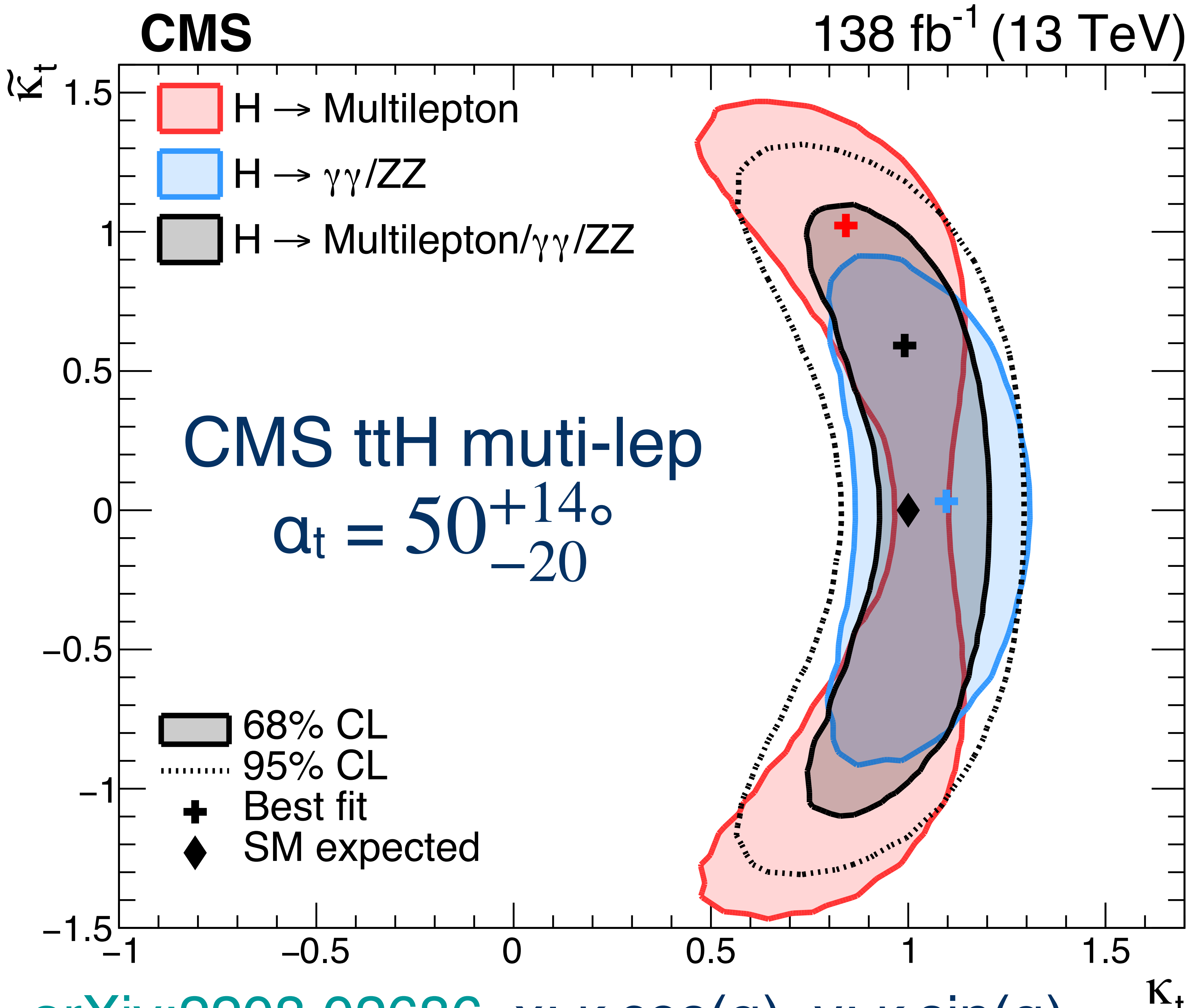
- Yukawa coupling Lagrangian involving CP mixing:

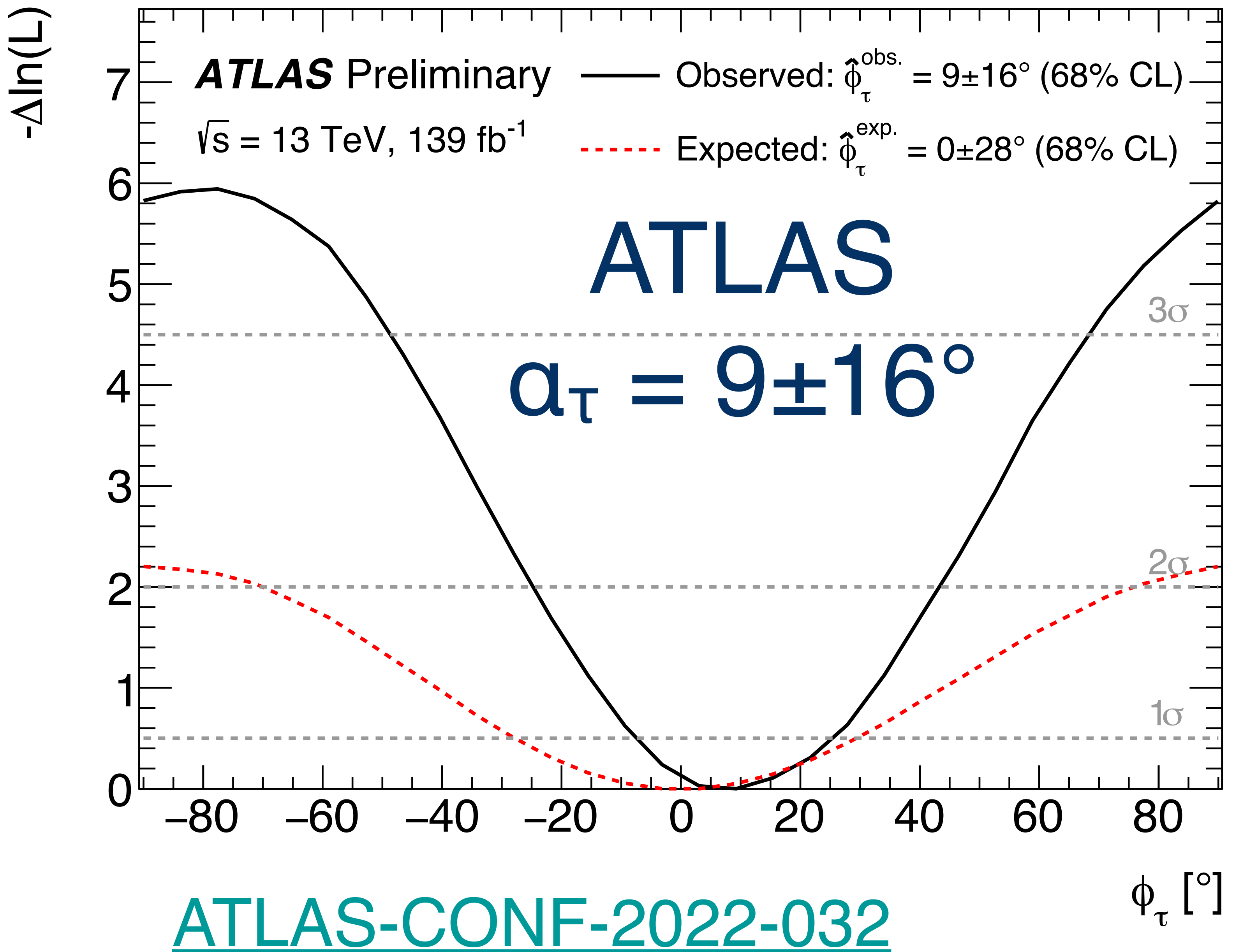
$$\mathscr{L}_f = -\frac{m}{v}\kappa_f(\cos(\alpha)\bar{f}f + i\sin(\alpha)\bar{f}\gamma_5 f)H$$

- Can perform **direct measurement of α** in top (using ttH/tH) and tau (using H→ττ) Yukawa couplings at LHC (κ_f is floating)







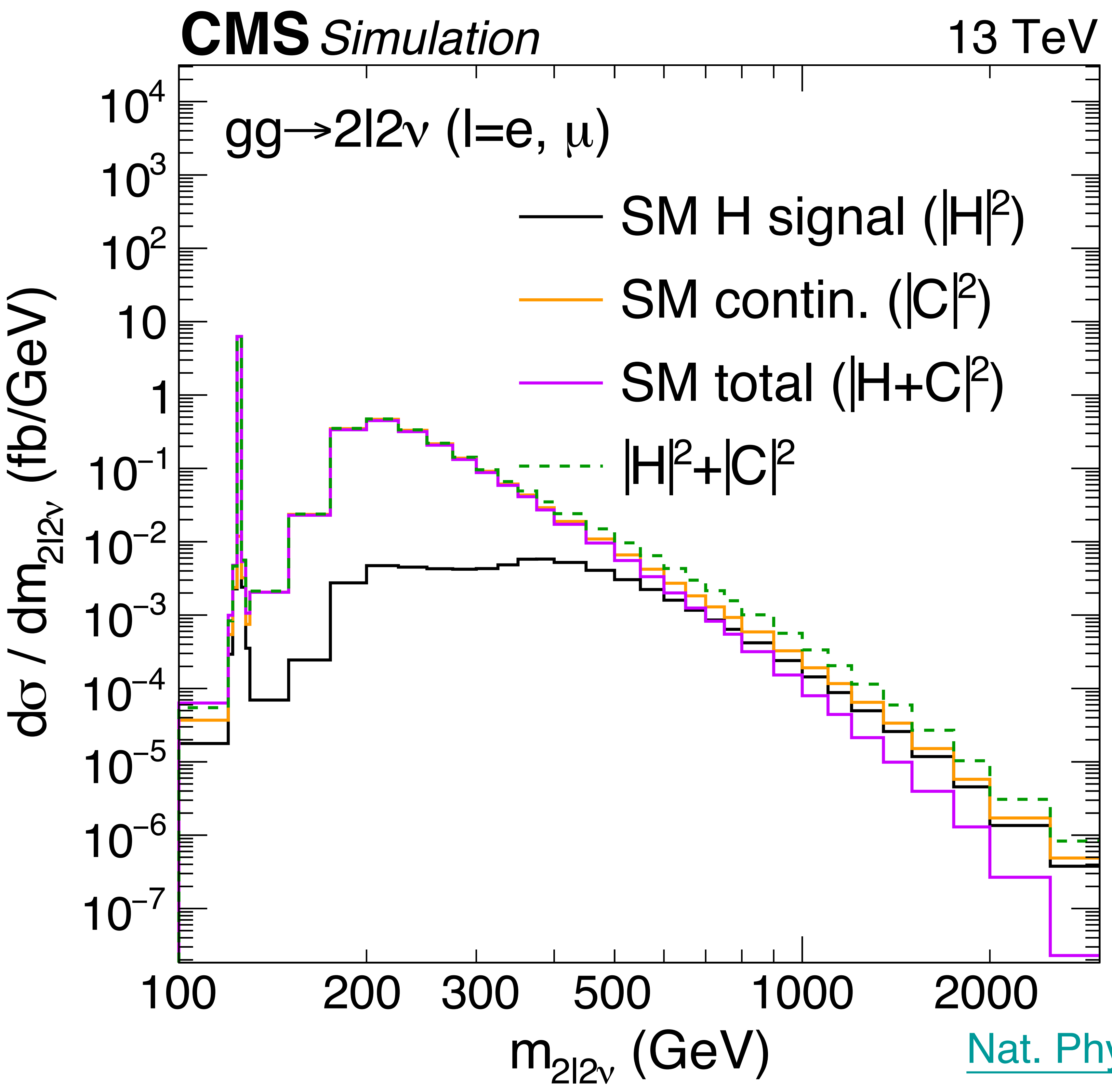


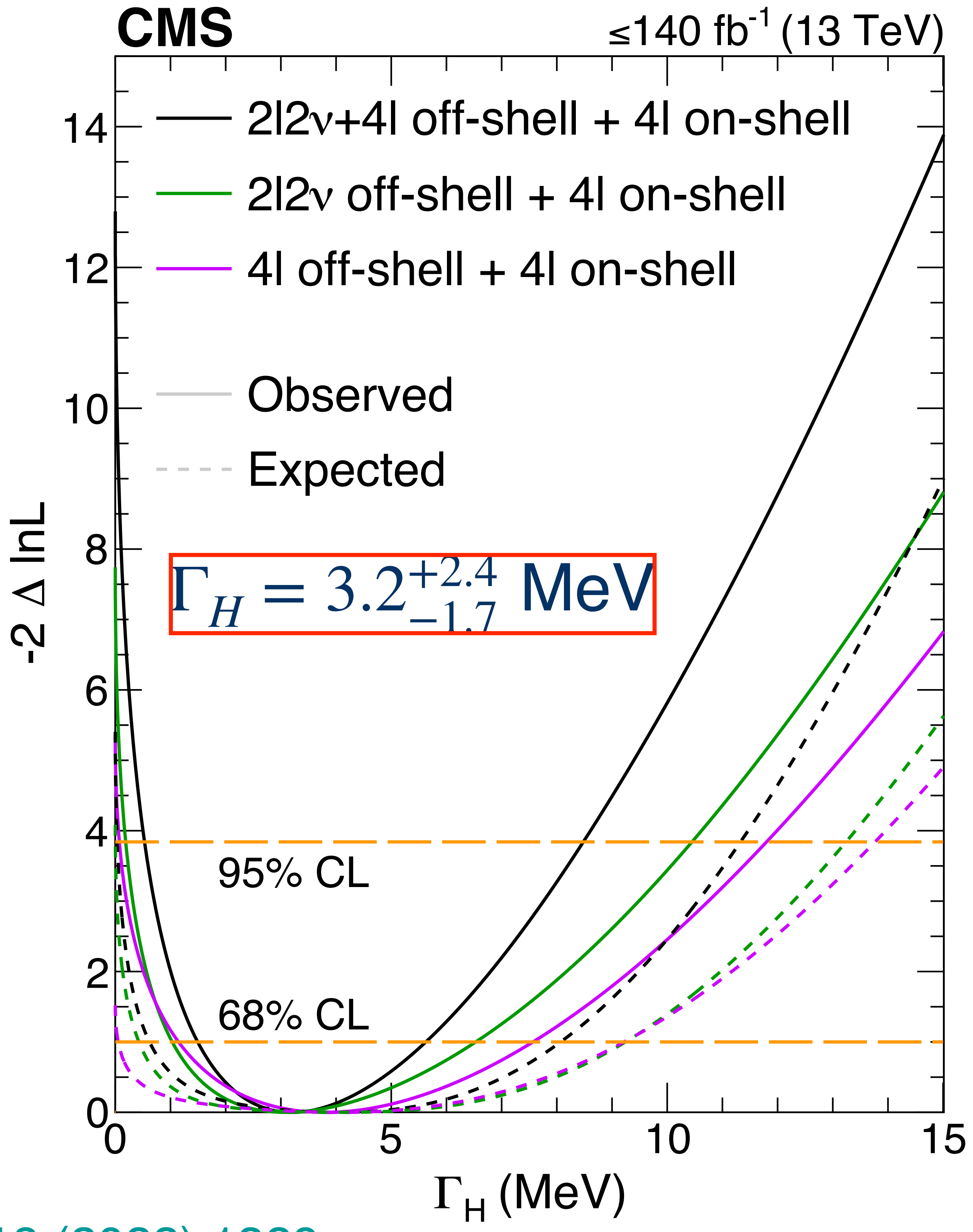
ATLAS-CONF-2022-016

arXiv:2208.02686, x: $\kappa_t\cos(\alpha)$, y: $\kappa_t\sin(\alpha)$

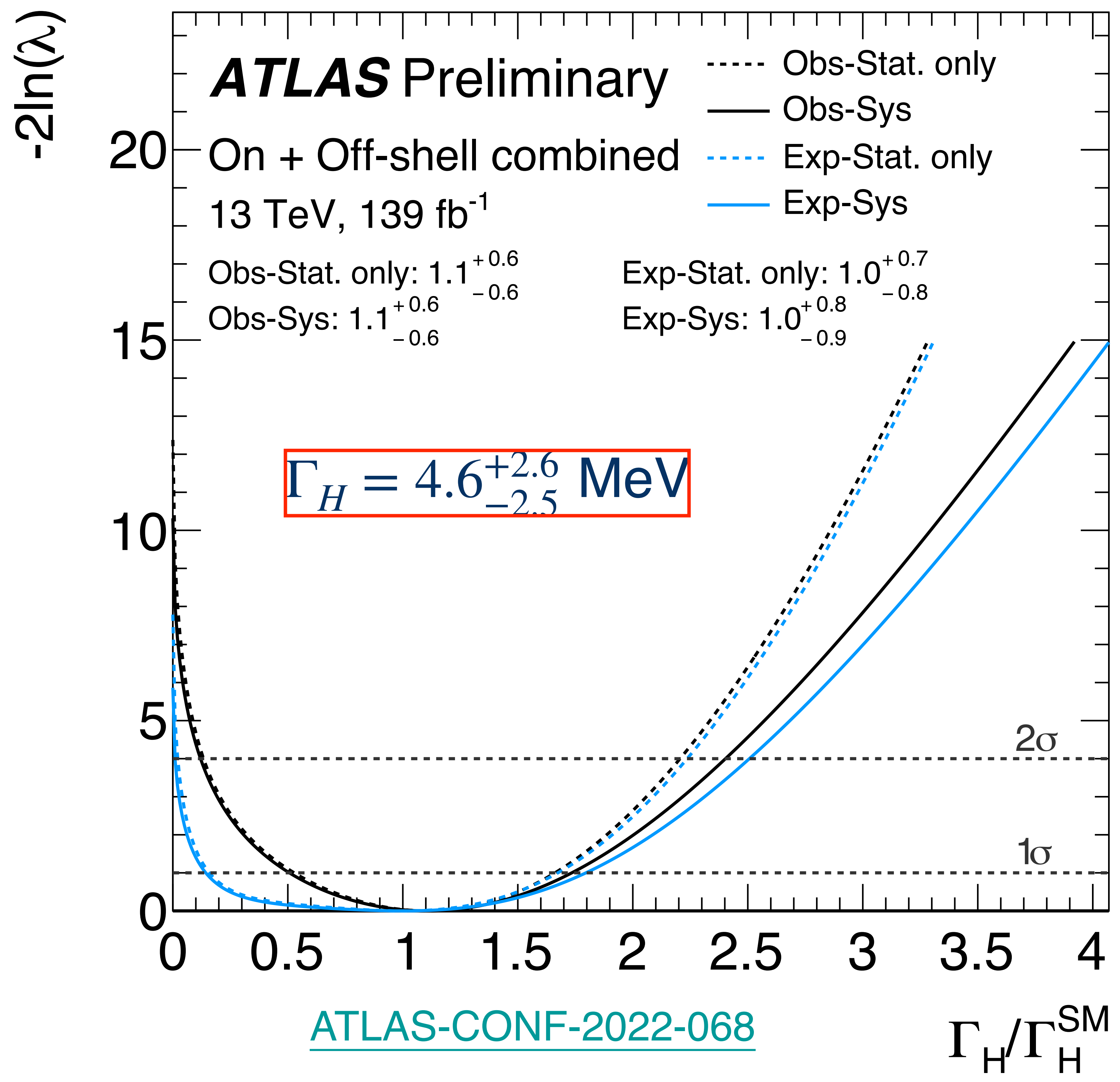
ATLAS-CONF-2022-032

Off-shell measurements





Nat. Phys. 18 (2022) 1329

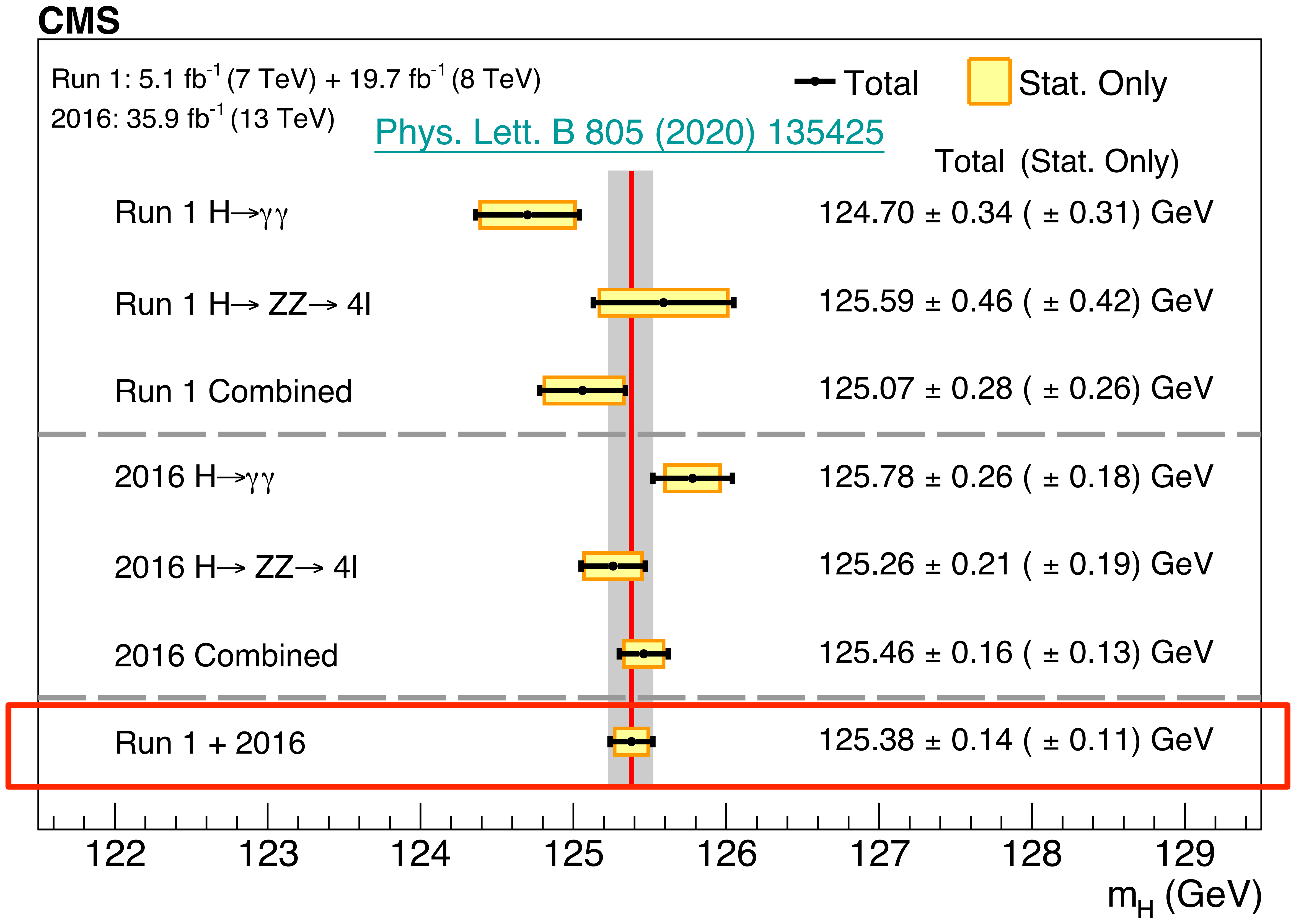


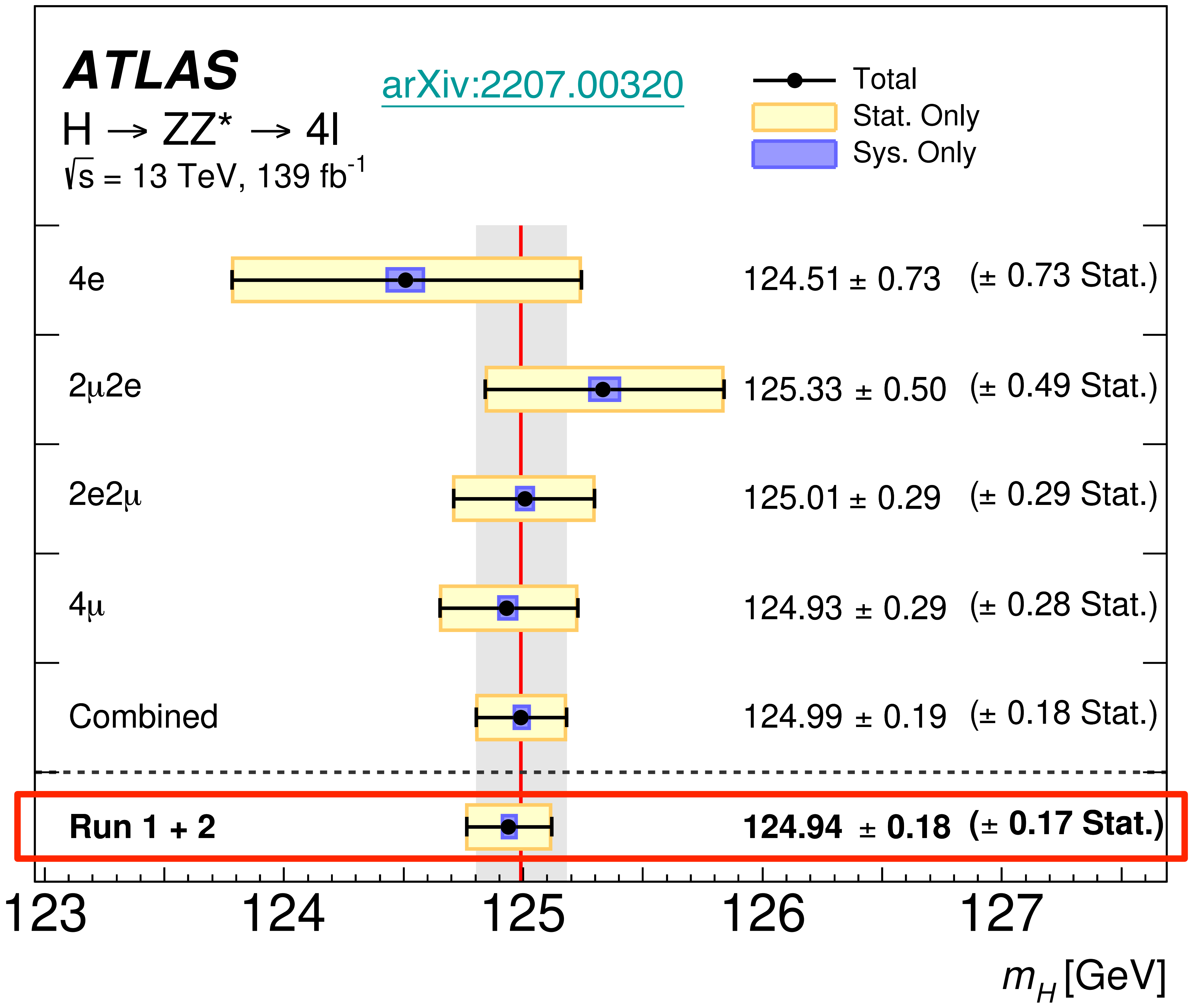
ATLAS-CONF-2022-068

- Explore large contribution of Higgs boson to high mass gg→ZZ and VBF ZZ, can constrain Γ_H by comparing on-shell/off-shell
- Both ATLAS and CMS have established **evidence** of Higgs boson off-shell production, and obtained competitive constraint on Γ_H

Could be interesting to have an ATLAS-CMS combination!

Higgs boson mass measurement

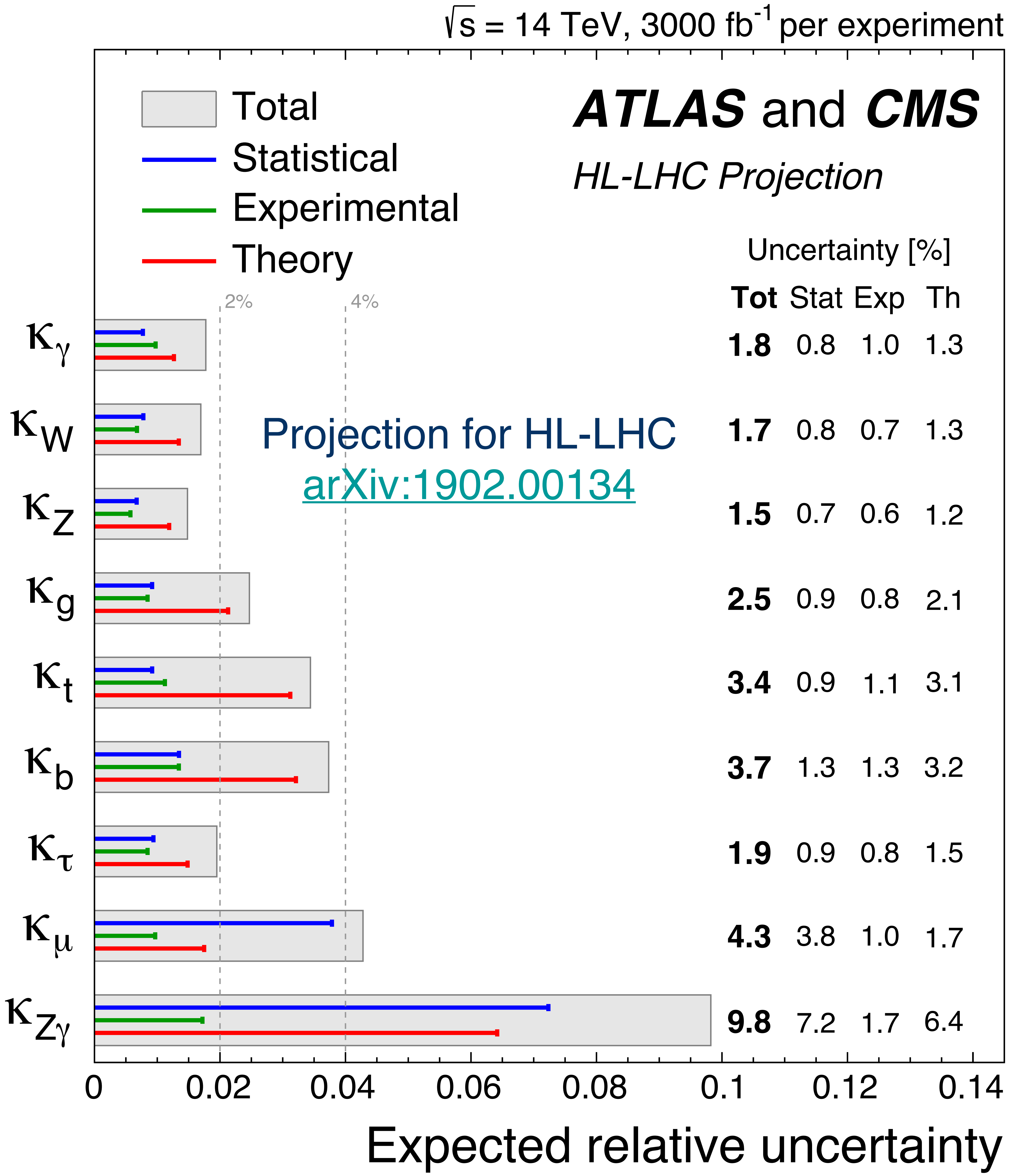




- Free parameter of SM. Measurement mainly an experimental effort in 4l and γγ
  - 4l channel still driven by limited stats, while γγ channel start to be limited by syst.
- **0.1% precision achieved.** Not a limiting factor for most Higgs boson property studies

Conclusions

- Study Higgs boson at LHC is not easy!
  - Only O(0.1%) of Higgs bosons produced at LHC are accessible in analyses
- Still, with Run 1+2 data, we managed to achieve
  - **O(10%)** precision for rate measurements
  - **0.1%** precision of Higgs boson mass
  - **O(50%)** precision on total width from off-shell
  - Constraint of CP violation in Higgs sector, EFT…
- Run 3 is perfect time for further improving precision & trying out new ideas!
- **x20 larger Higgs boson sample at HL-LHC!**

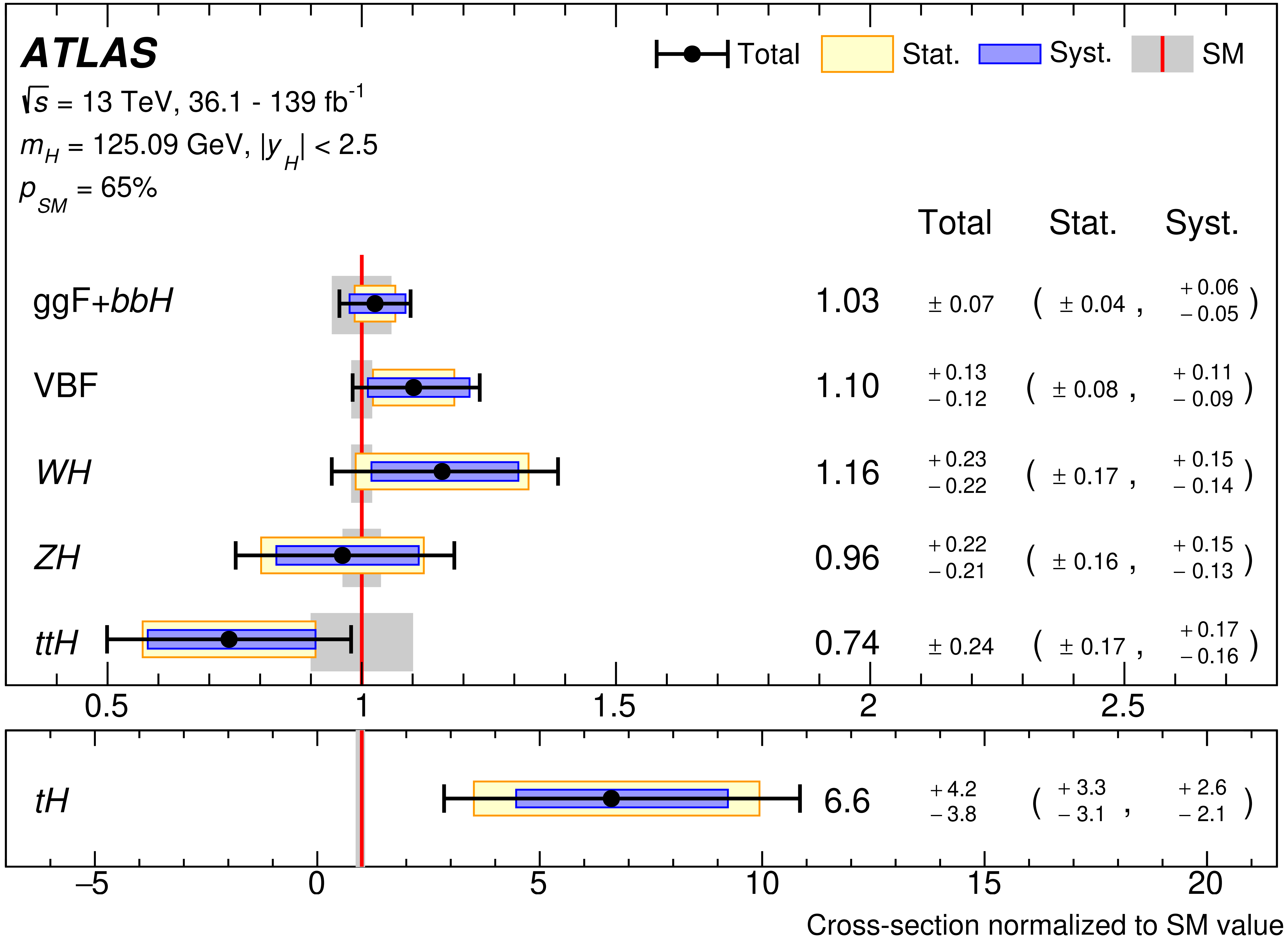


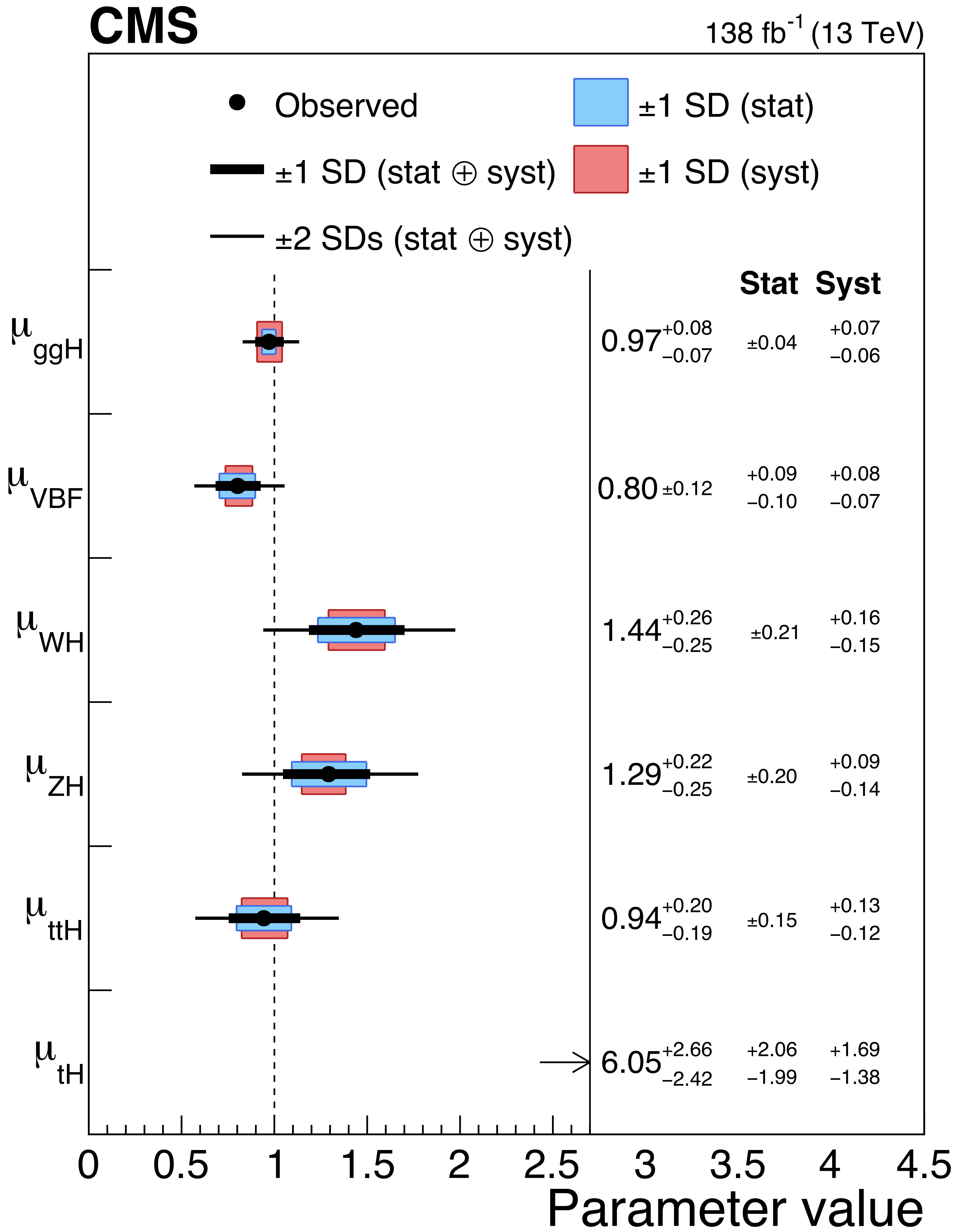
Backup

Inputs for ATLAS Nature combination

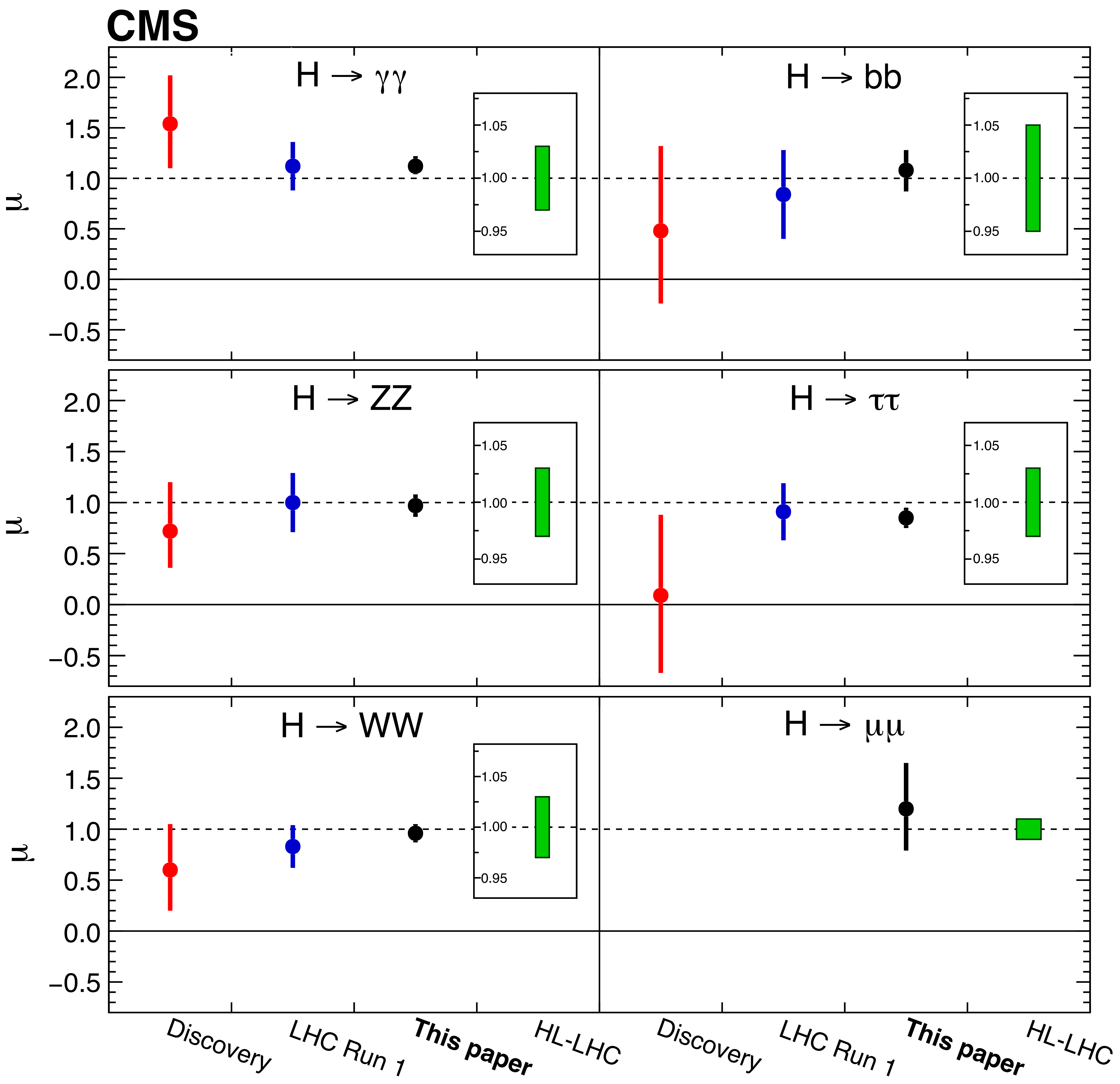
Decay mode	Targeted production processes	$\mathcal{L}$ [fb^{-1}]	Ref.	Fits deployed in
$H \to \gamma\gamma$	ggF, VBF, $WH, ZH, t\bar{t}H, tH$	139	[31]	All
$H \to ZZ$	ggF, VBF, $WH + ZH, t\bar{t}H + tH$	139	[28]	All
	$t\bar{t}H + tH$ (multilepton)	36.1	[39]	All but fit of kinematics
$H \to WW$	ggF, VBF	139	[29]	All
	WH, ZH	36.1	[30]	All but fit of kinematics
	$t\bar{t}H + tH$ (multilepton)	36.1	[39]	All but fit of kinematics
$H \to Z\gamma$	inclusive	139	[32]	All but fit of kinematics
$H \to b\bar{b}$	WH, ZH	139	[33, 34]	All
	VBF	126	[35]	All
	$t\bar{t}H + tH$	139	[36]	All
	inclusive	139	[37]	Only for fit of kinematics
$H \to \tau\tau$	ggF, VBF, $WH + ZH, t\bar{t}H + tH$	139	[38]	All
	$t\bar{t}H + tH$ (multilepton)	36.1	[39]	All but fit of kinematics
$H \to \mu\mu$	ggF + $t\bar{t}H + tH$, VBF + $WH + ZH$	139	[40]	All but fit of kinematics
$H \to c\bar{c}$	$WH + ZH$	139	[41]	Only for free-floating κ_c
$H \to$ invisible	VBF	139	[42]	κ models with $B_{u.}$ & $B_{inv.}$
	ZH	139	[43]	κ models with $B_{u.}$ & $B_{inv.}$

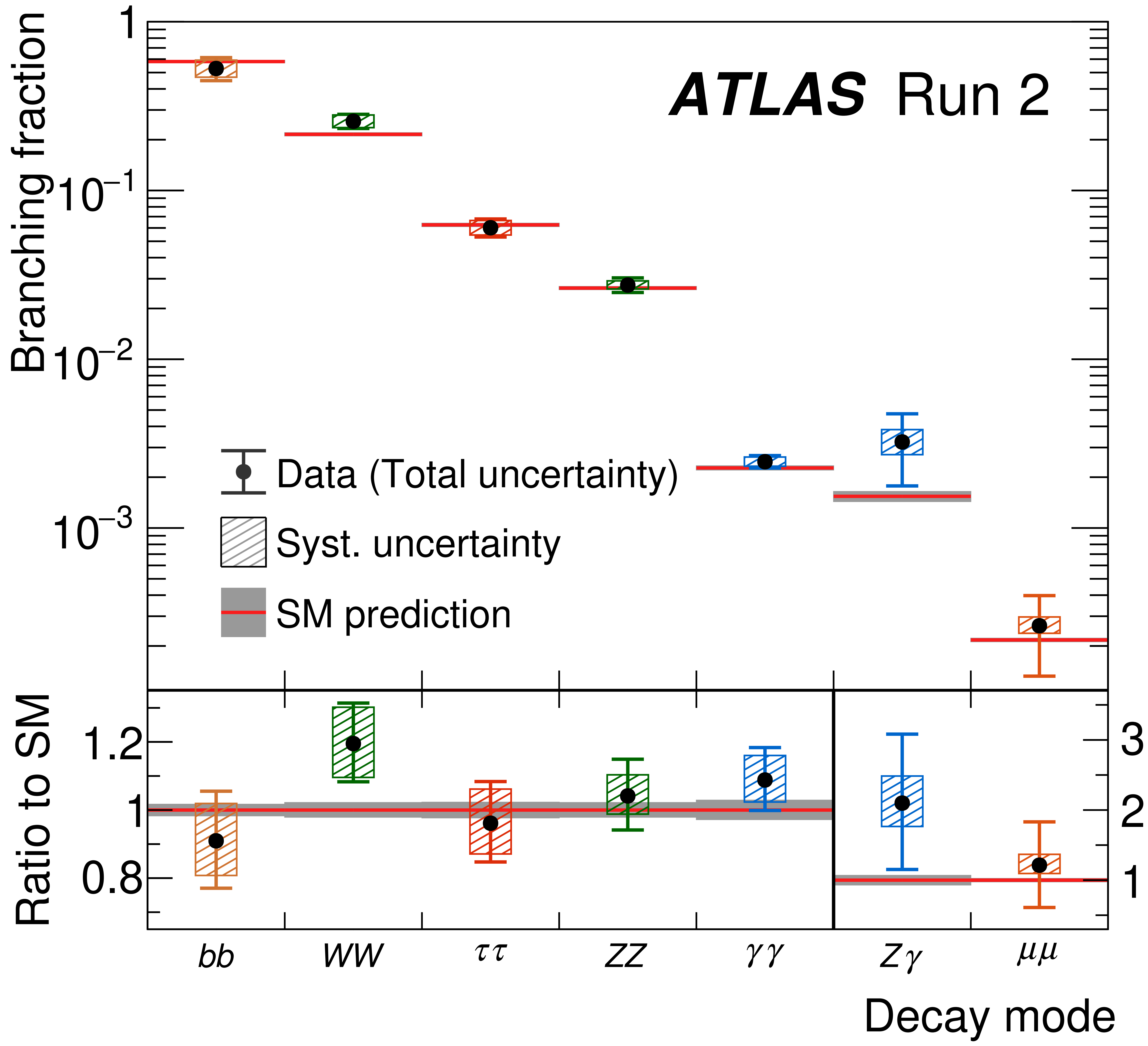
Higgs boson productions ATLAS vs. CMS



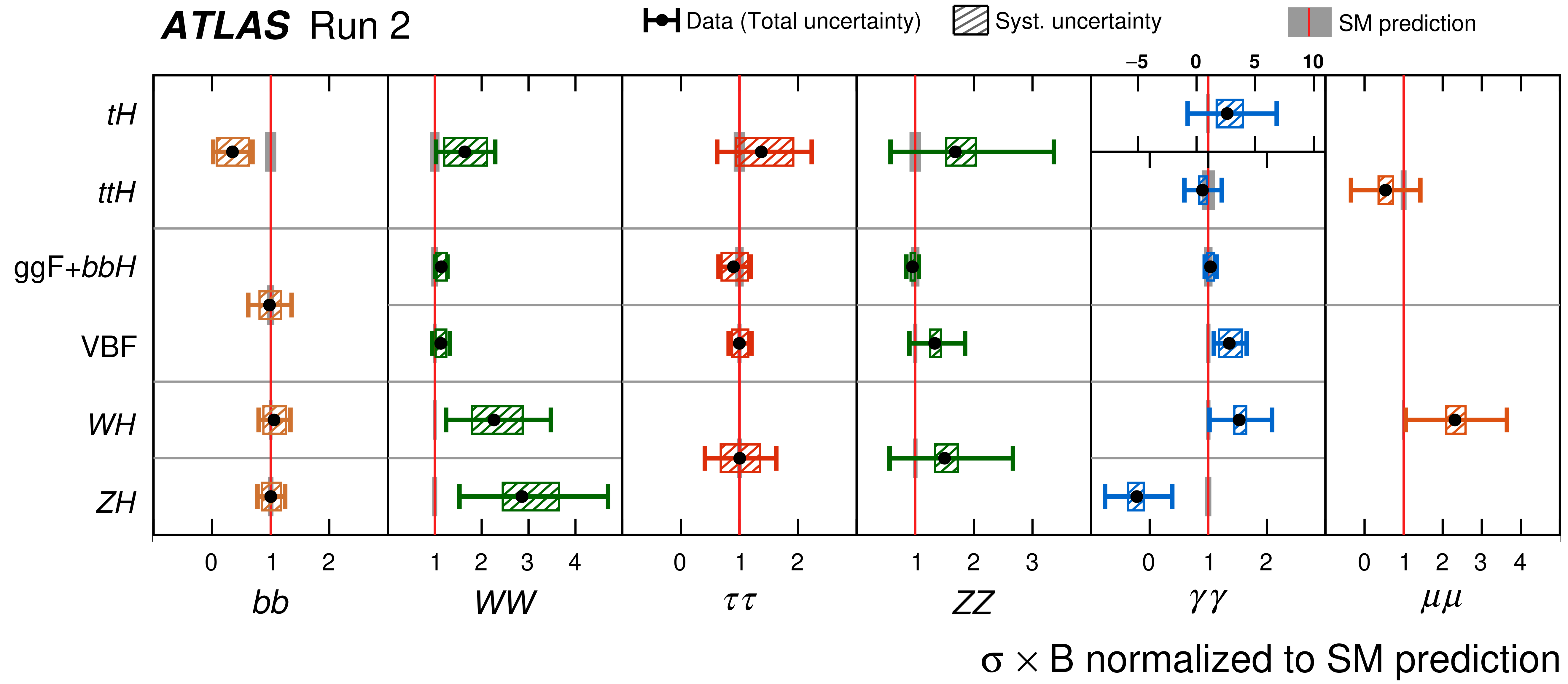


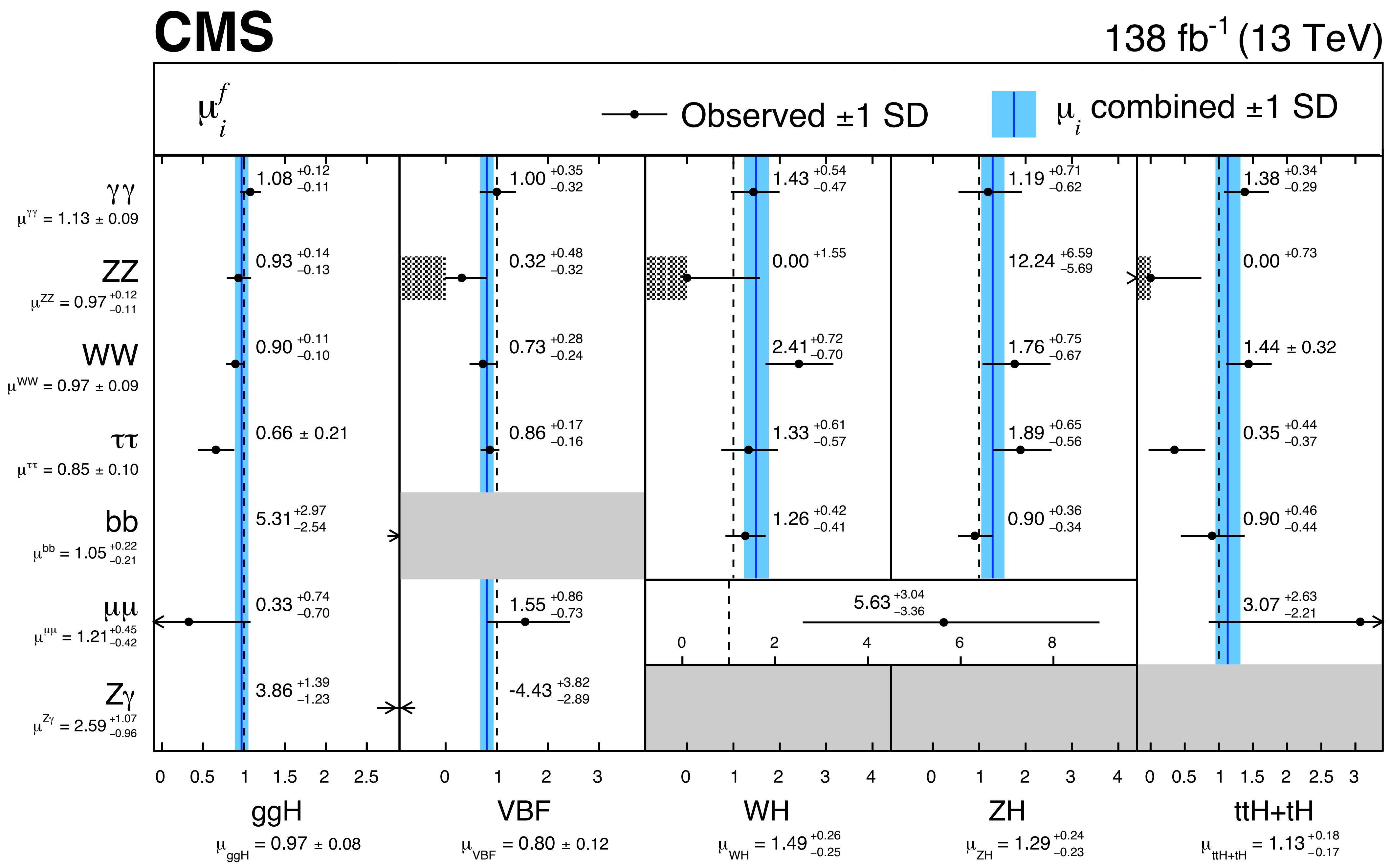
Higgs boson decays ATLAS vs. CMS





Prod×decay ATLAS vs. CMS





CMS ttH multi-lepton CP 1D likelihood scan