Higgs couplings and properties

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On behalf of the ATLAS and CMS collaborations

34th Rencontres de Blois | 15 May 2023

CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

Introduction

The H(125) - SM Higgs boson

- Special place in the SM of particle physics - the only fundamental spin-0 particle in the SM
- Responsible for the mass generation for the vector bosons (spontaneous symmetry breaking) and the fermions (Yukawa interaction)
- Discovered in 2012 at the LHC, 11 years later:

➡ Observed couplings with vector bosons, 3rd generation fermions, evidence for the 2nd generation

➡ Higgs precision measurements

➡ Probing the production of HH

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi} \not{D} \psi + h.c. + \bar{\psi}_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

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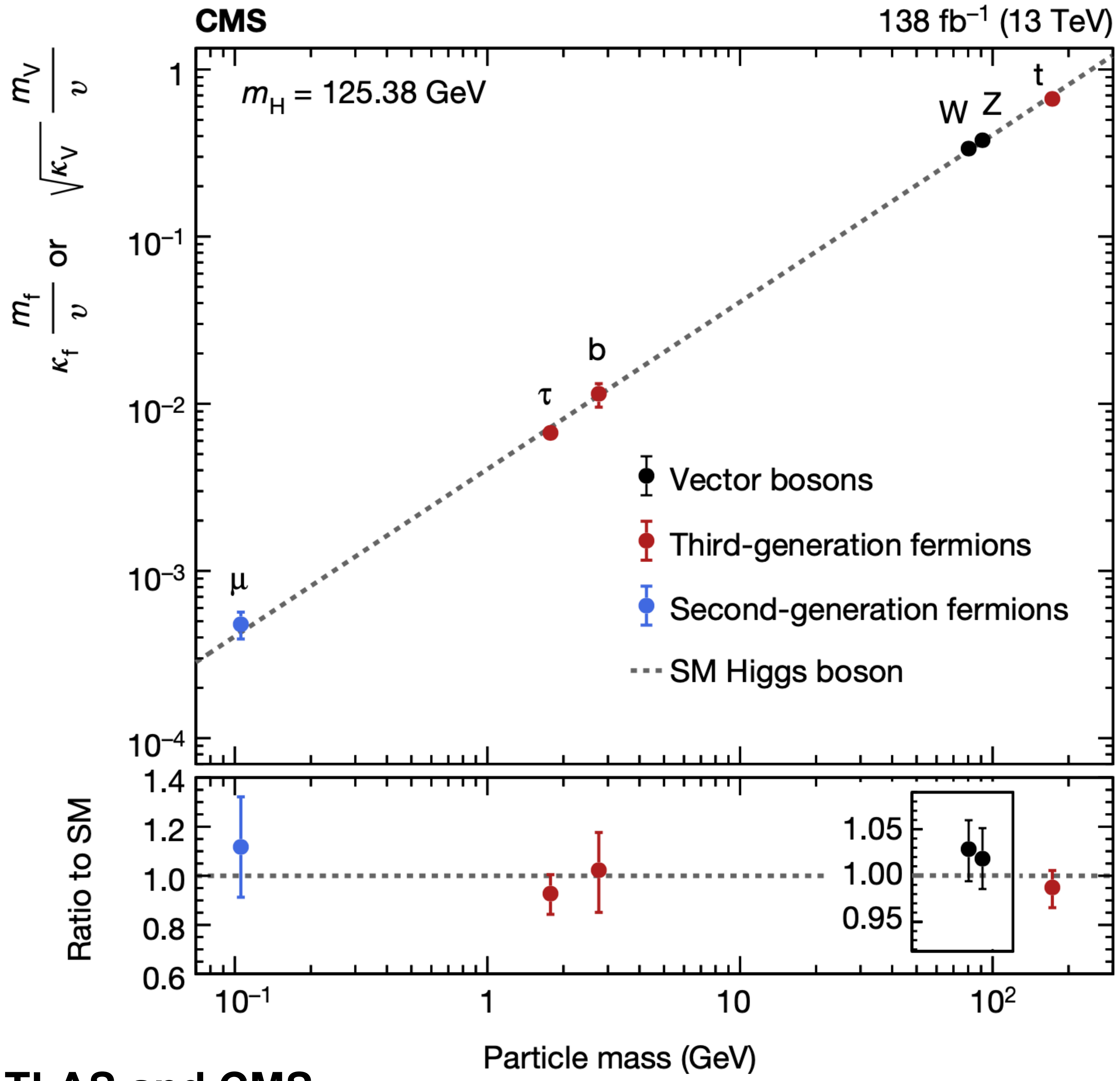


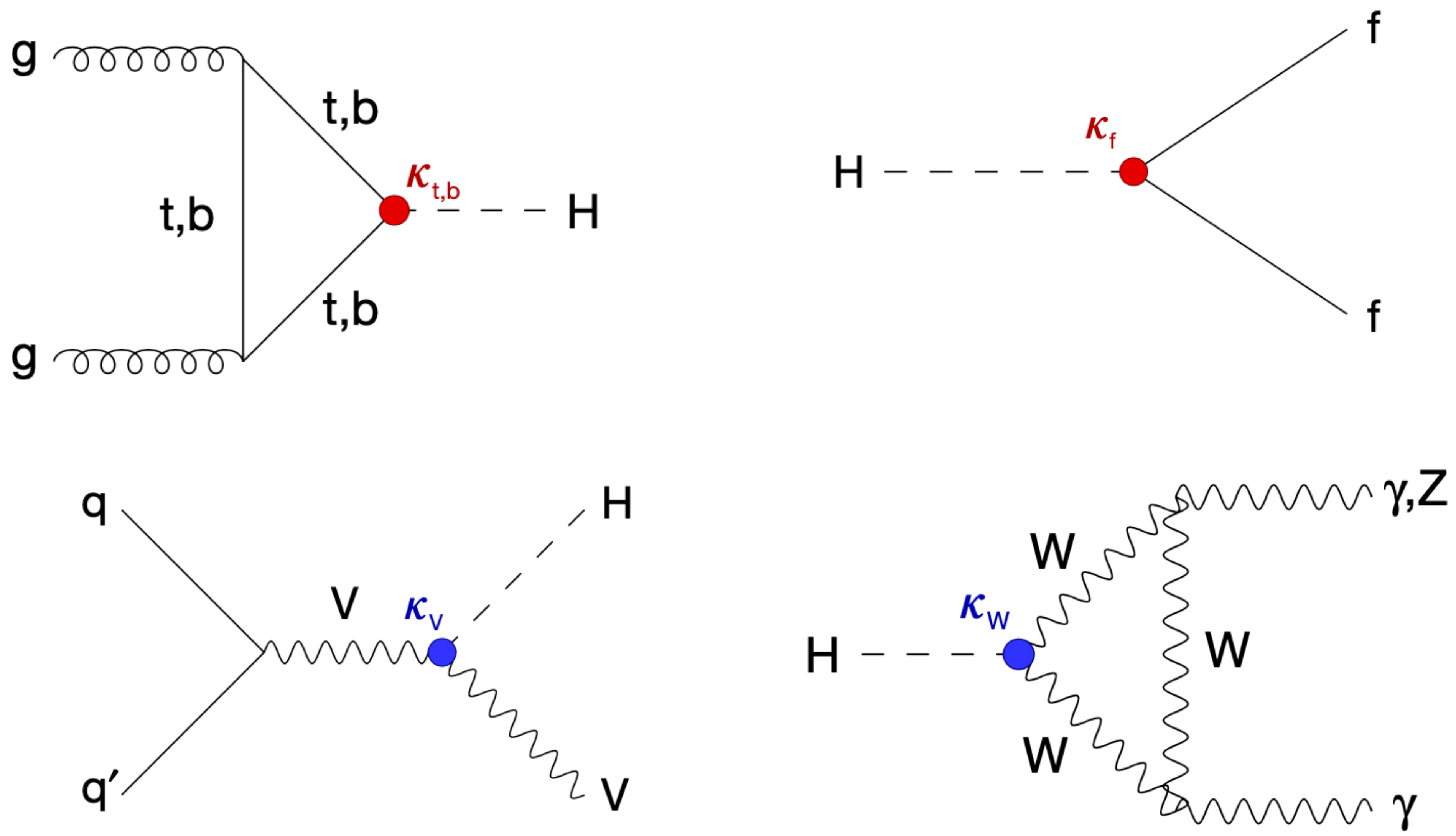
Nature 607, 60–68 (2022)

This talk: summary of Run 2 measurements from ATLAS and CMS

Overview

I. Yukawa term, couplings with vector bosons:

- Measure BR, κ - framework, CP-structure, cross sections (fiducial, Simplified Template cross section)

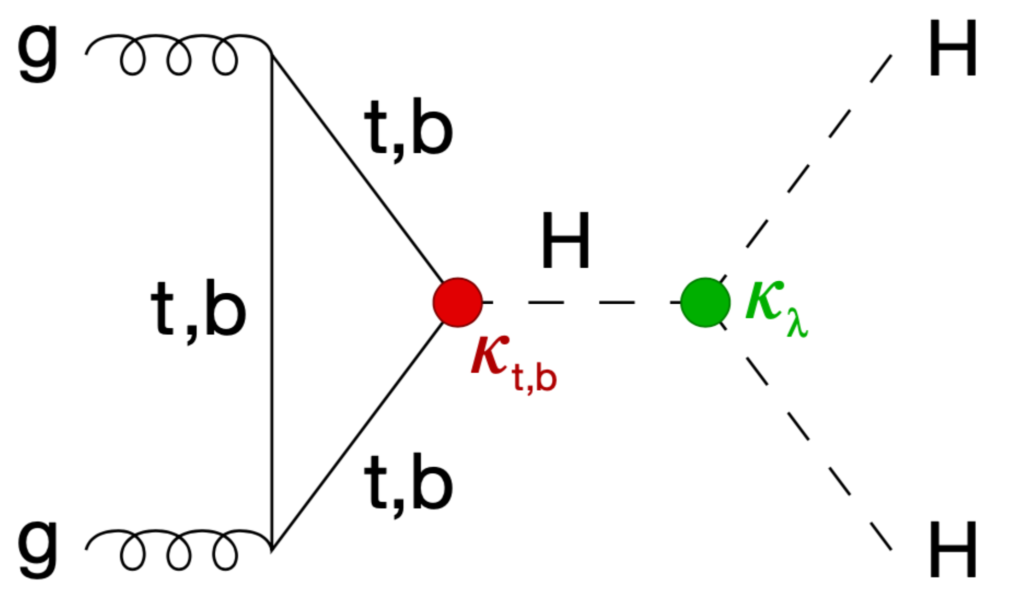


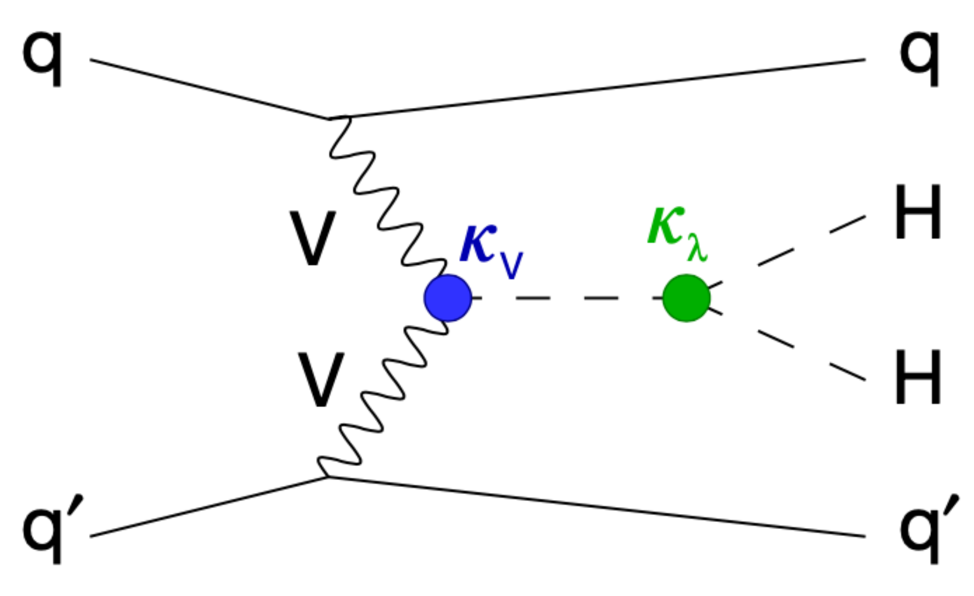
$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\Psi} \not{D} \psi + h.c. + \bar{\Psi}_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

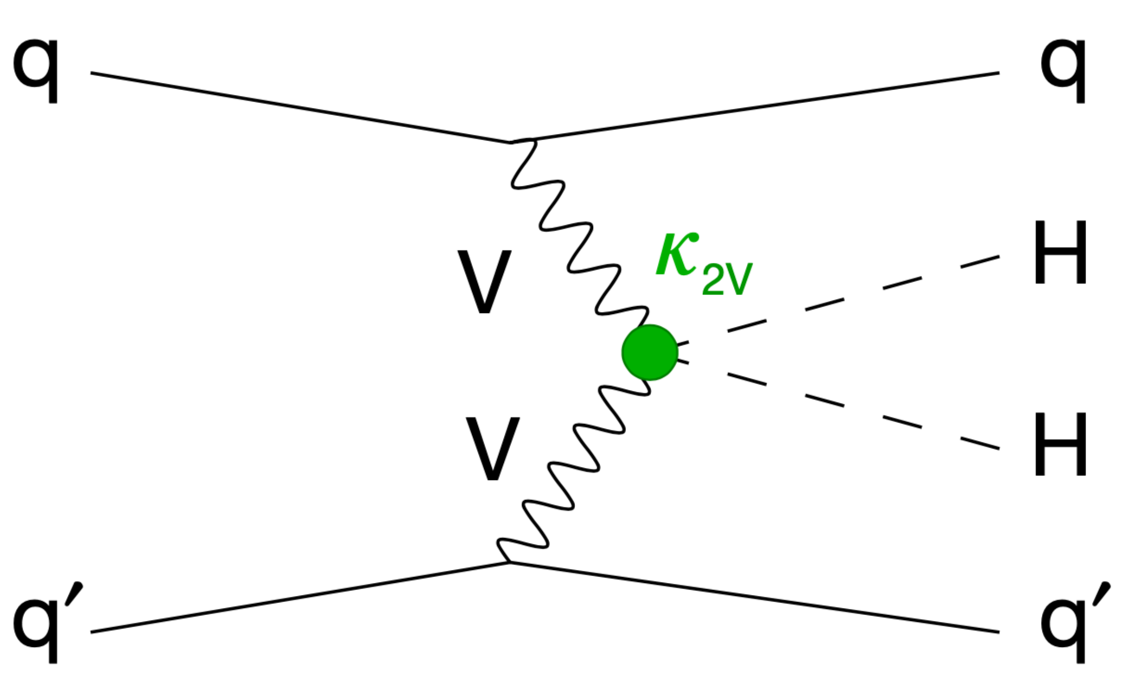
Overview

II. Higgs potential: Higgs mass, self-interaction

- Limits on HH production cross section, intervals for κ_λ, κ_{2V}







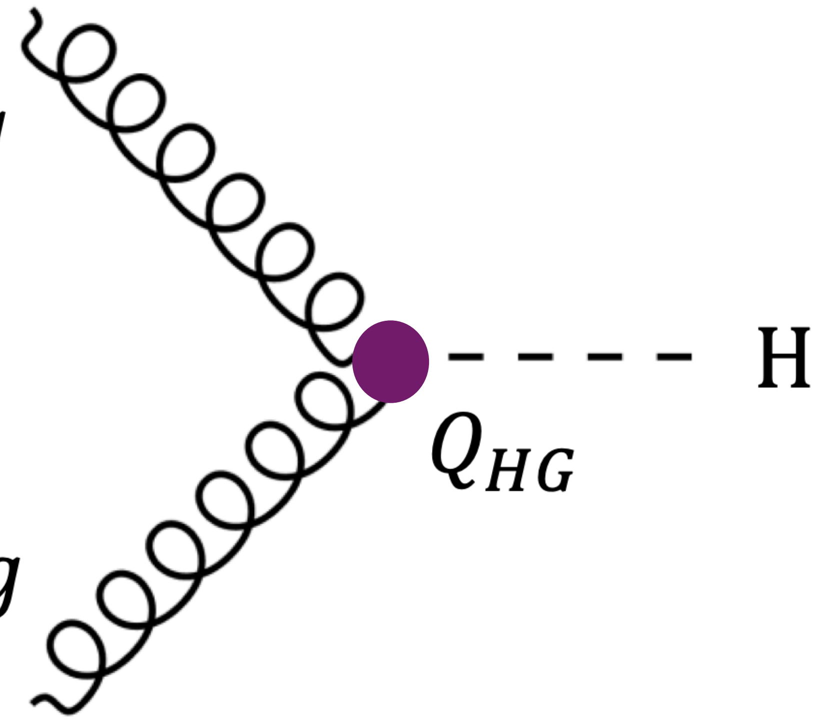
$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi} \not{D} \psi + h.c. + \bar{\psi}_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

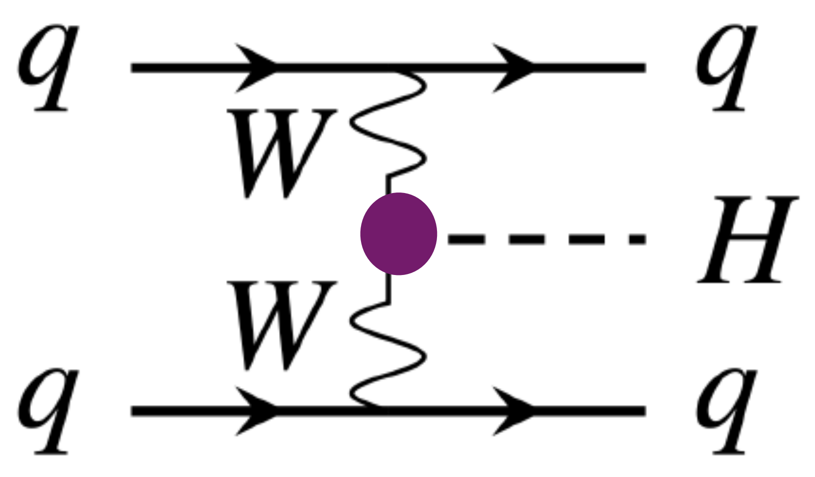
$$V(\phi) = \frac{1}{2} m_H^2 \phi^2 + \lambda \nu \phi^3 + \frac{1}{4} \lambda \phi^4$$

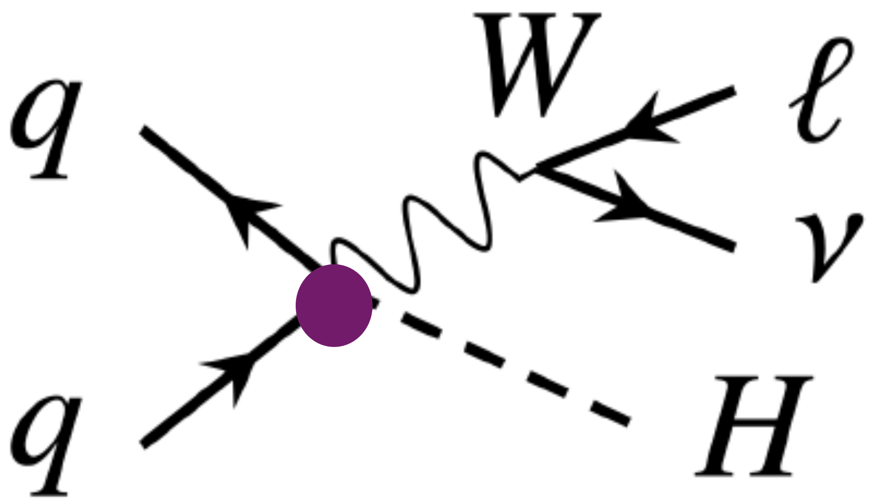
Overview

III. Search for the signs of BSM through the EFT formalism (e.g. SMEFT)

- Introduce contact interactions and model them as additional terms in $\mathscr{L} \propto \frac{1}{\Lambda^2}$ (d=6),
  → measure c_i modifying effective vertices:







$$
\begin{aligned}
\mathcal{L} = & -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\
& + i \bar{\psi} \not{D} \psi + h.c. \\
& + \bar{\psi}_i y_{ij} \psi_j \phi + h.c. \\
& + |D_\mu \phi|^2 - V(\phi) \\
& + \sum \frac{c_i}{\Lambda^2} O_i^{d=6} + \sum \frac{c_i}{\Lambda^4} O_i^{d=8} + \ldots
\end{aligned}
$$

Overview

I. Yukawa term, couplings with vector bosons:

- Measure BR, κ - framework, CP-nature, cross sections (fiducial, Simplified Template cross section)

II. Higgs potential: Higgs mass, self-interaction

- Limits on HH production cross section, intervals for κ_λ, κ_{2V}

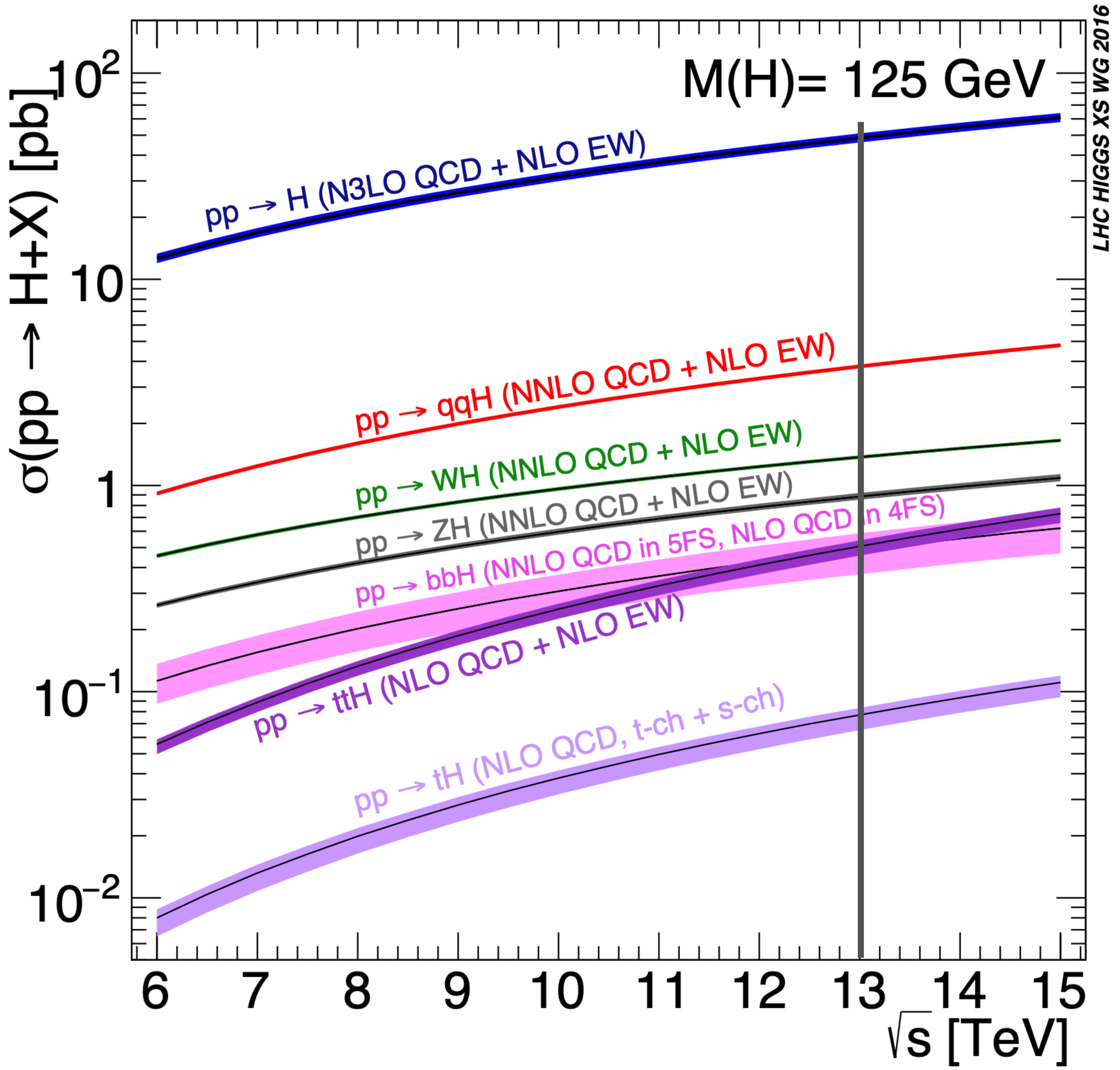
III. Search for the signs of BSM through the EFT formalism (e.g. SMEFT)

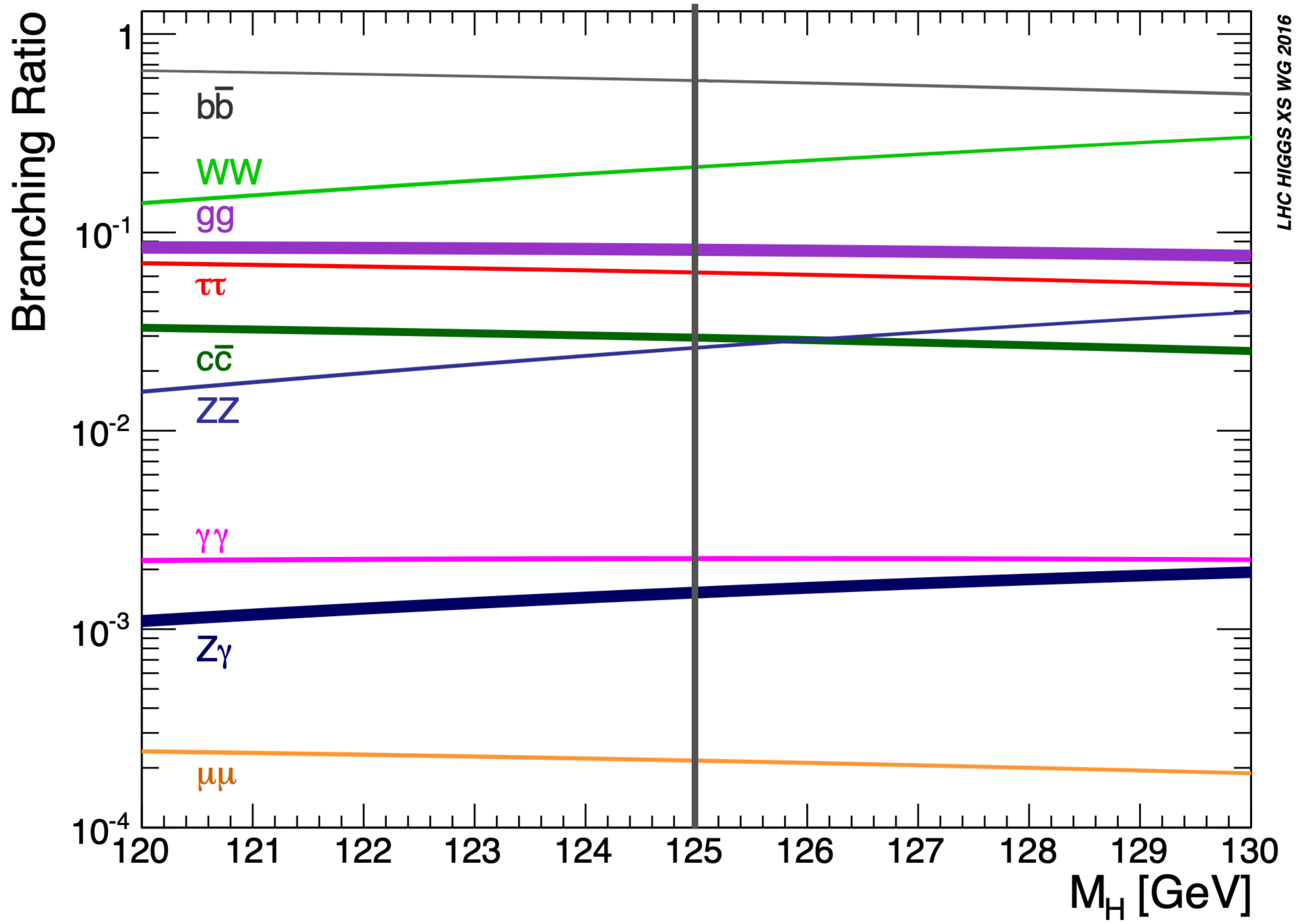
- Introduce contact interactions and model them as additional terms in $\mathscr{L} \propto \frac{1}{\Lambda^2}$ (d=6), $\rightarrow$ measure c_i

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\psi} \not{D} \psi + h.c. + \bar{\psi}_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi) + \sum \frac{c_i}{\Lambda^2} O_i^{d=6} + \sum \frac{c_i}{\Lambda^4} O_i^{d=8} + \ldots$$

SM Higgs production and decay

Production modes and decay channels of H(125) at pp 13 TeV @LHC.





- Best sensitivity achieved by balancing large couplings in the initial (final) state with clear signatures in the final (initial) state.
- Taking car of complicated backgrounds (final states with jets)
- Gain sensitivity from new analysis and jet-tagging methods (ML)

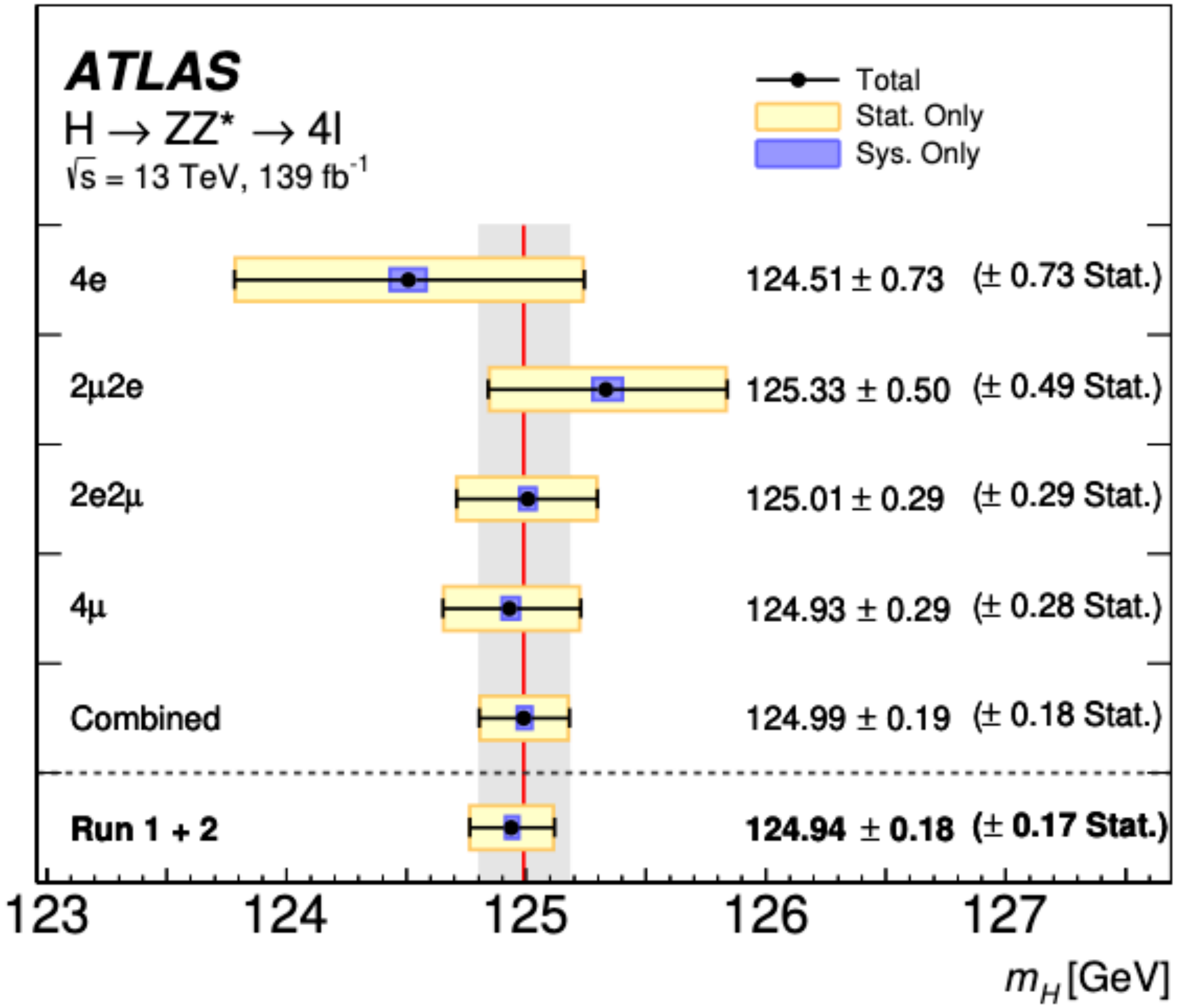
Higgs boson properties

Higgs mass measurement

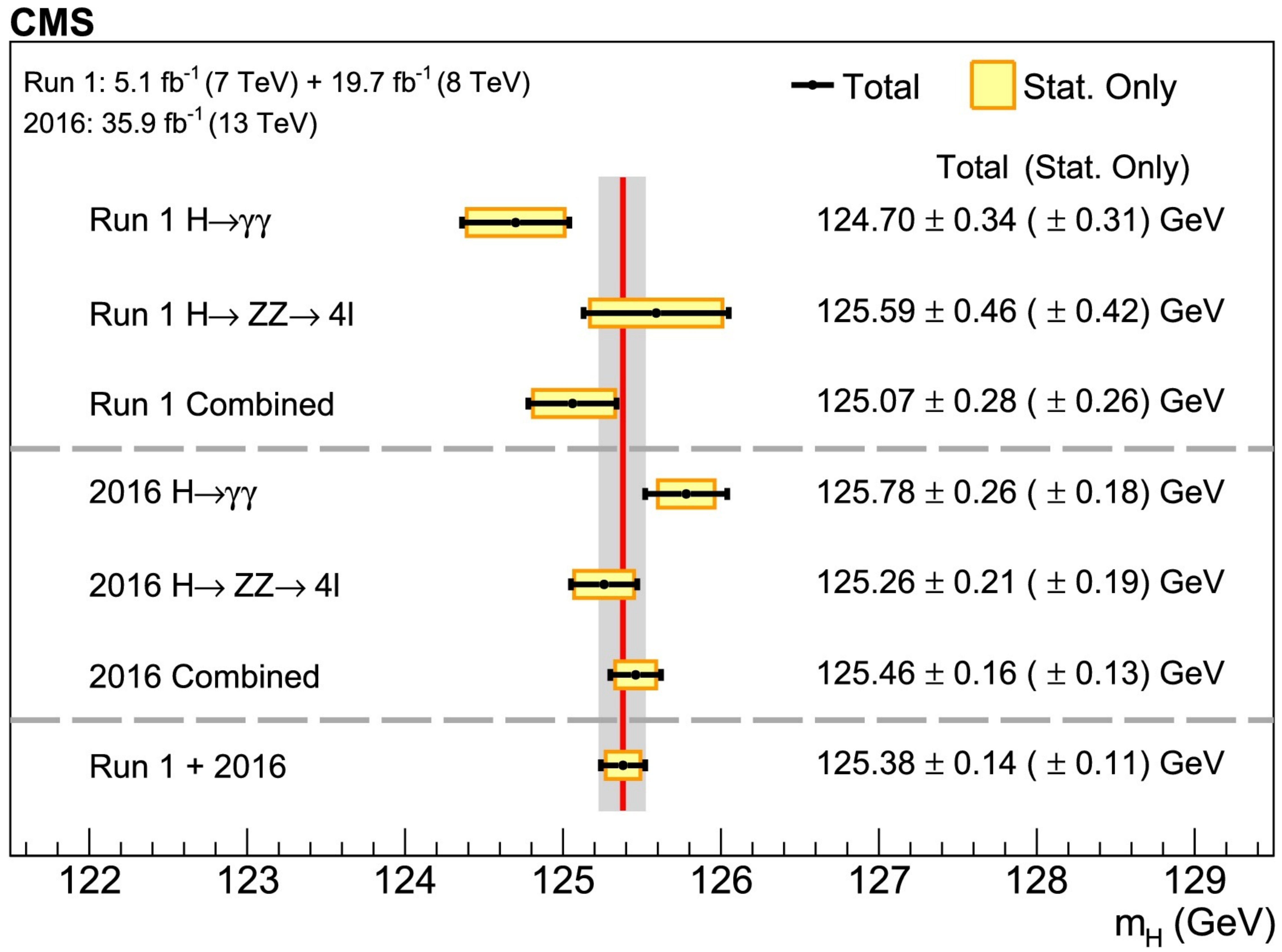
Most precise channel: H $\rightarrow ZZ \rightarrow 4l$ final state

ATLAS: Combined Run 2 + Run 1 measurement

[arxiv:2207.00320]



CMS: Combined H $\rightarrow ZZ \rightarrow 4l$ with $H \rightarrow \gamma\gamma$



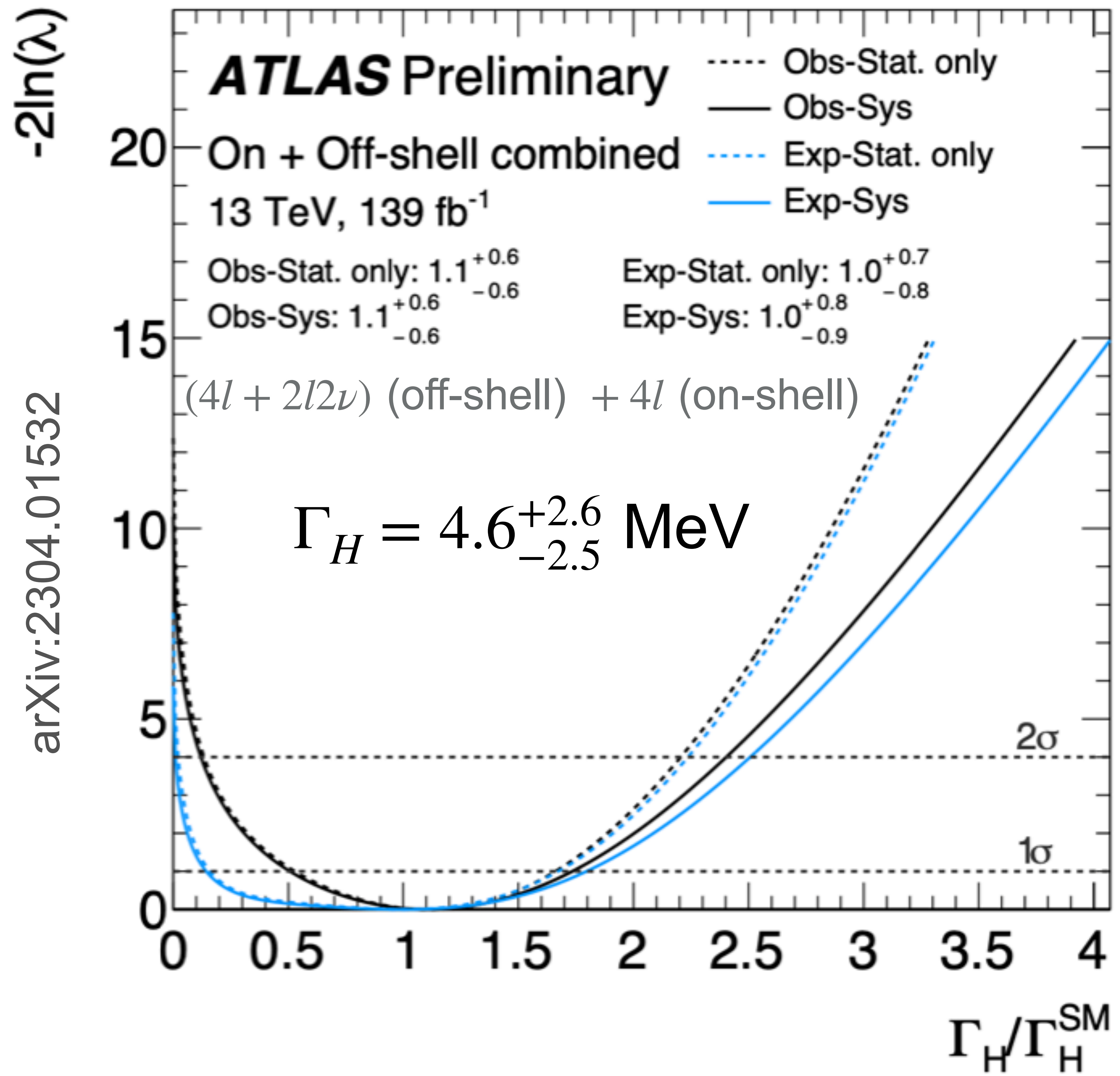
Phys. Lett. B 805 (2020) 135425

Similar sensitivity with partial Run 2 + Run 1
(stay tuned for the full Run 2 update)

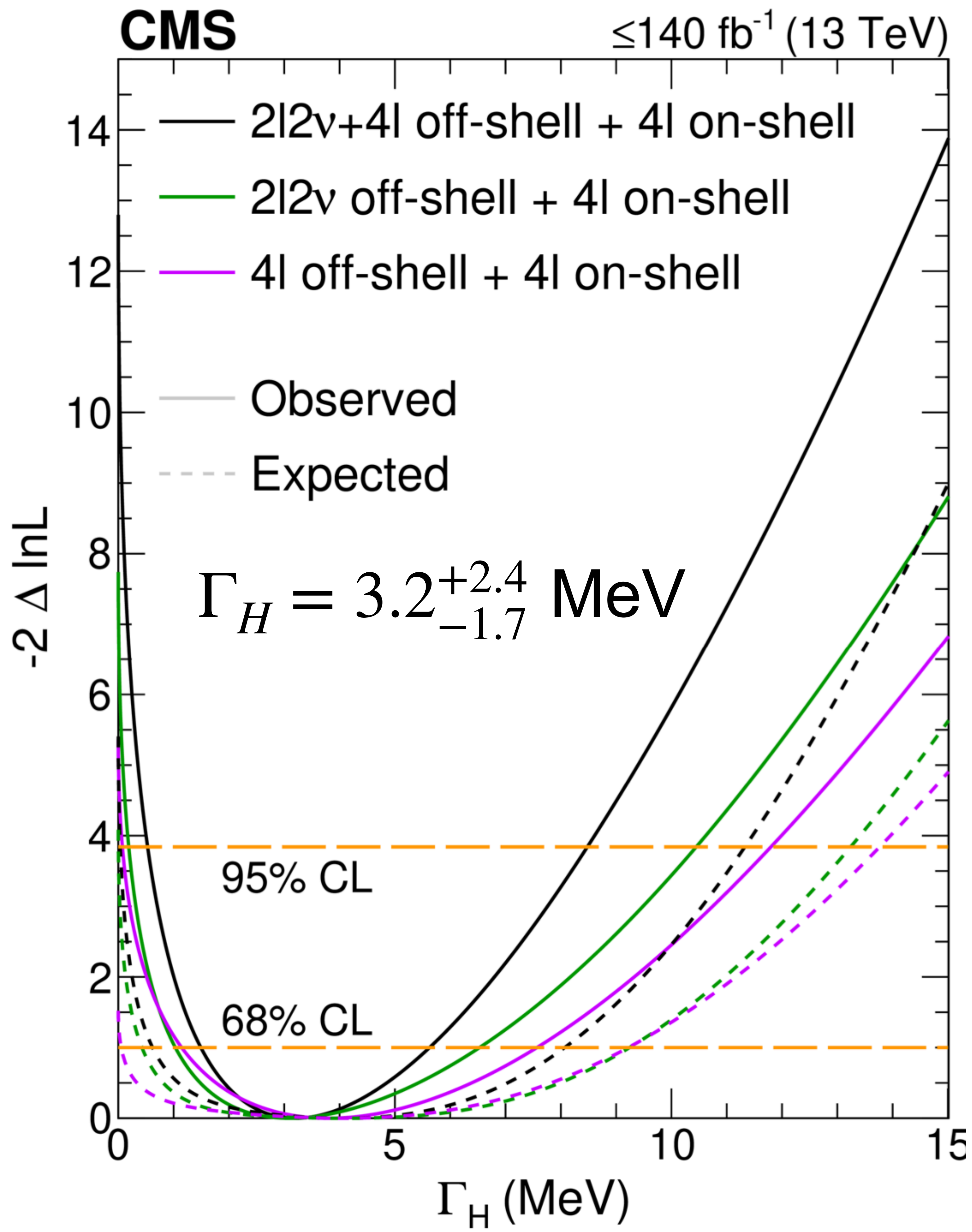
Higgs width measurements

Can be accessed through the ratio of on-shell and of-shell production cross sections:

$$\sigma^{\text{on-shell}} \propto \frac{g_p^2 g_d^2}{\Gamma_H} \propto \mu_p \Rightarrow \sigma^{\text{off-shell}} \propto g_p^2 g_d^2 \propto \mu_p \Gamma_H$$



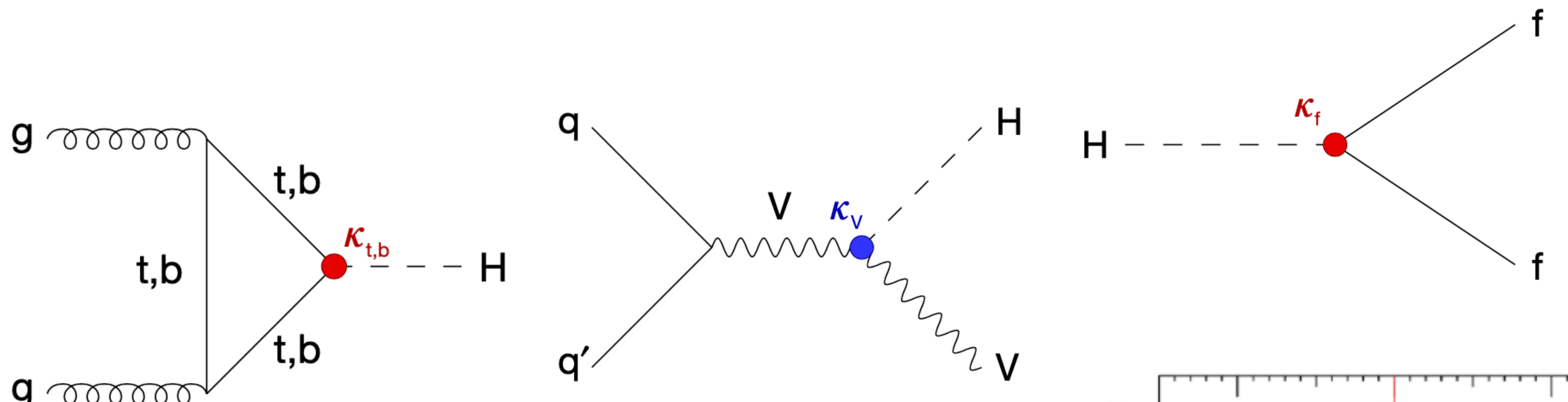
arXiv:2304.01532



Nat. Phys. 18, 1329–1334 (2022)

Higgs couplings measurements

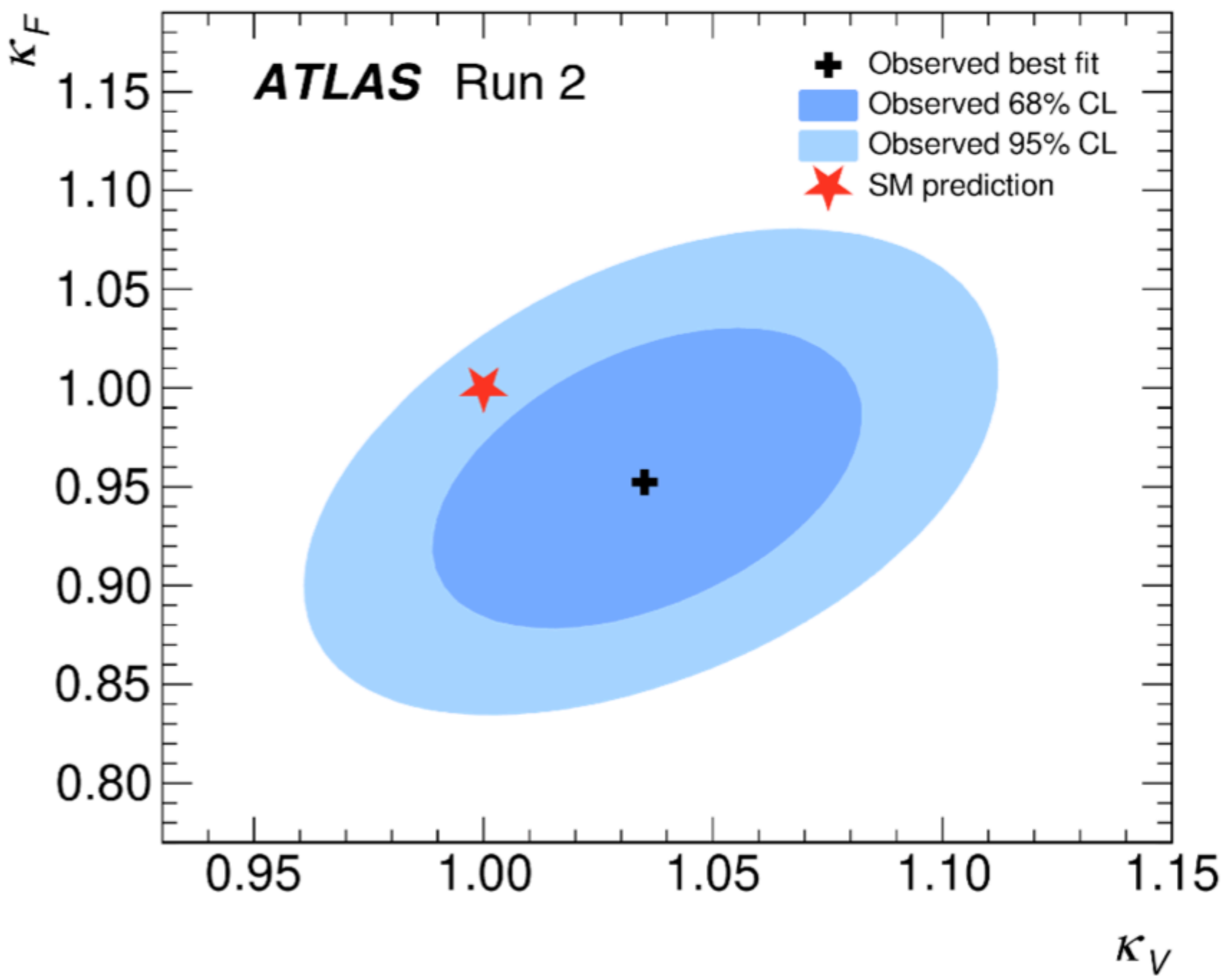
Couplings summary from ATLAS

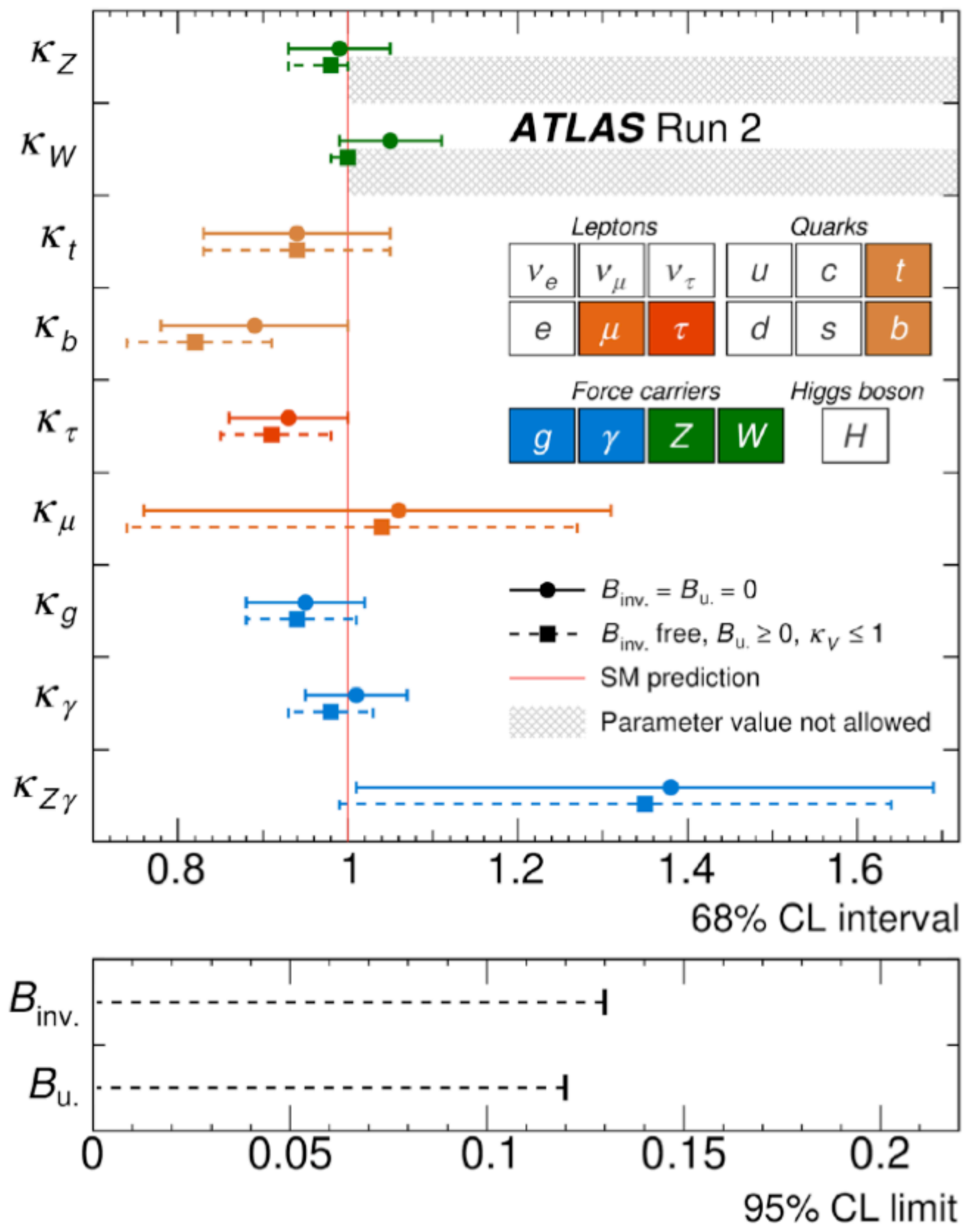


Nature 607, 52–59 (2022)

- Full Run 2 for all single Higgs production and decay channels
- Summarised in [Nature 607, 52–59 (2022)]
  - Precision of 10-12 % for H → γγ, ZZ, W±W∓, τ+τ− couplings
  - Production processes: ttH, WH, ZH individually observed
- Inclusive sensitivity:

$$\mu = \frac{(\sigma \times B)^{obs}}{(\sigma \times B)^{exp}} = 1.05 \pm 0.06$$

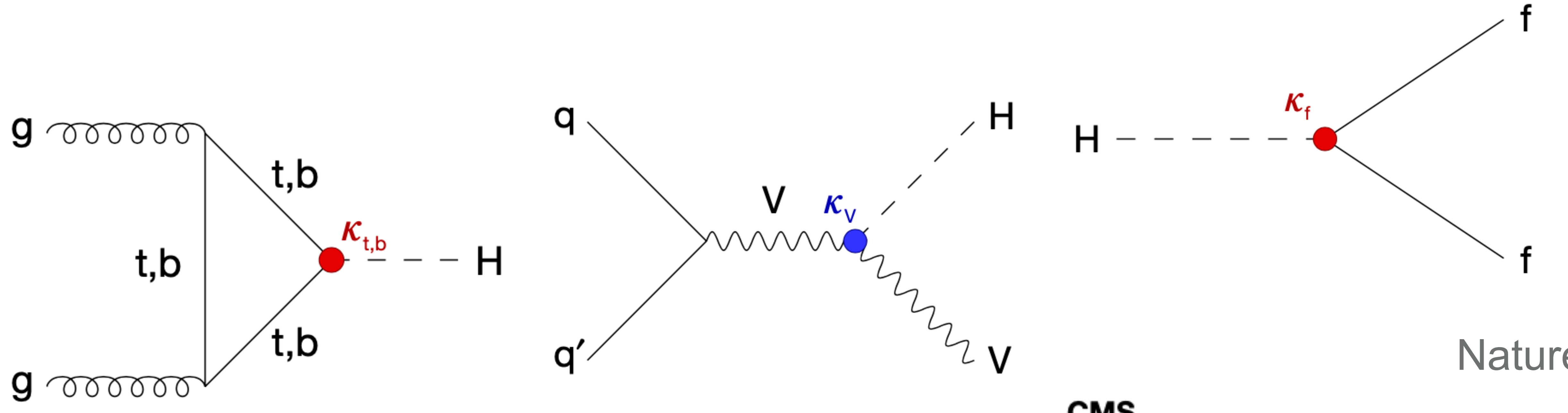




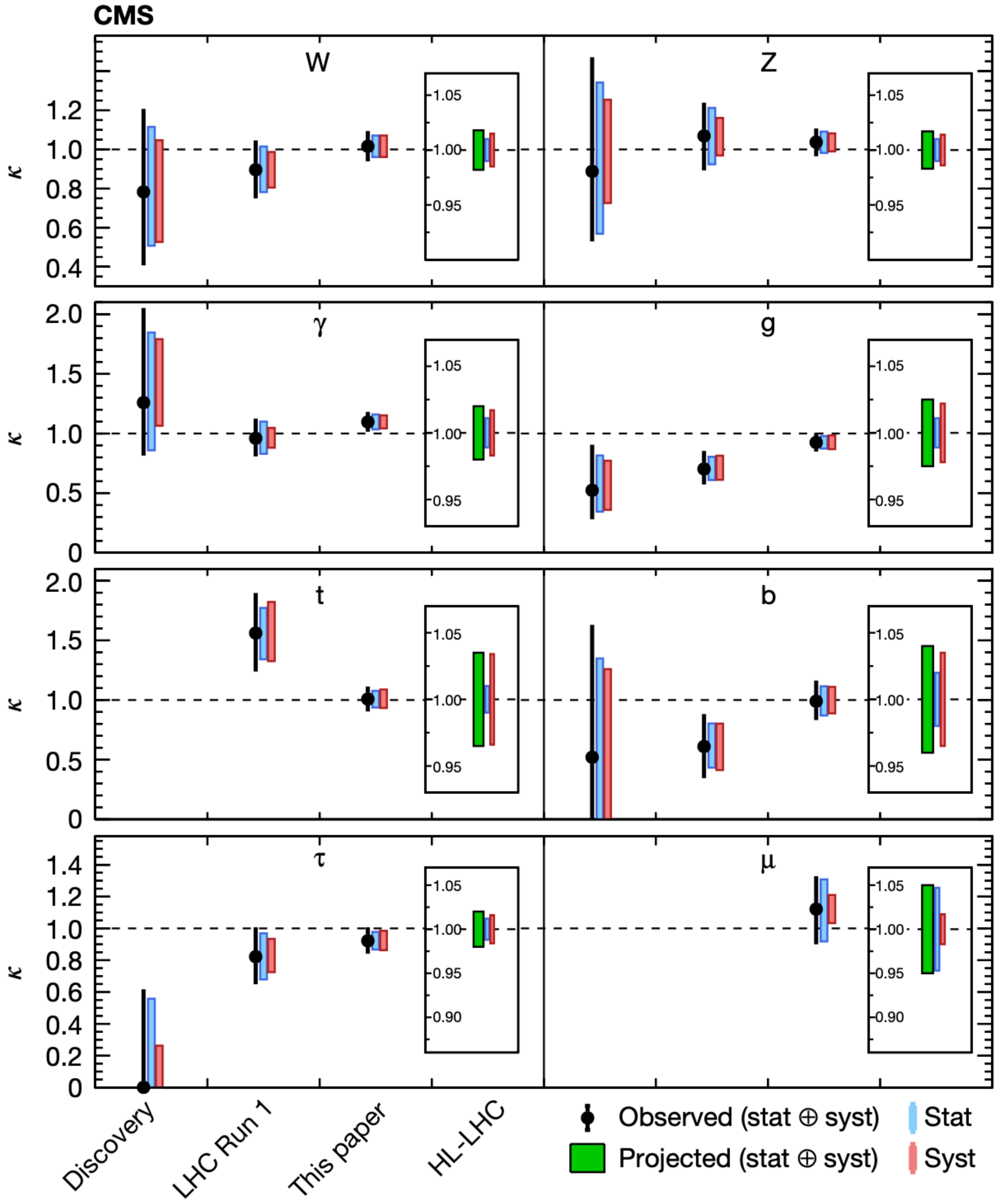
Couplings summary from CMS

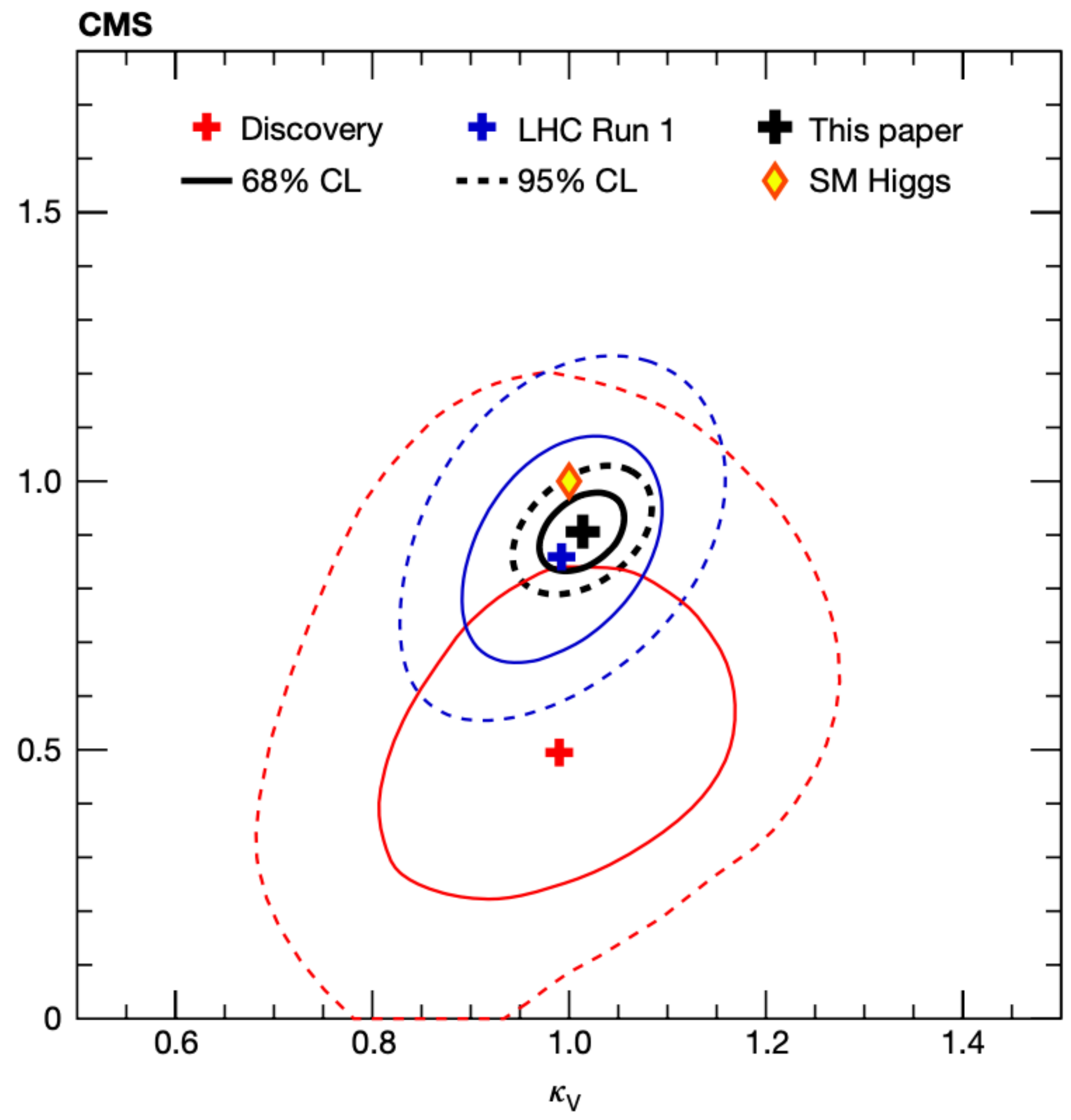
- Full Run 2 for majority of single Higgs production and decay channels
- Summarised in [Nature 607, 60–68 (2022)]
  - Precision of 10-12 % for H → γγ, ZZ, $W^{\pm}W^{\mp}$, $\tau^{+}\tau^{-}$ couplings
  - Evidence of $H \rightarrow \mu\mu$ decay
- Inclusive sensitivity:

$$\mu = \frac{(\sigma \times B)^{obs}}{(\sigma \times B)^{exp}} = 1.002 \pm 0.057$$



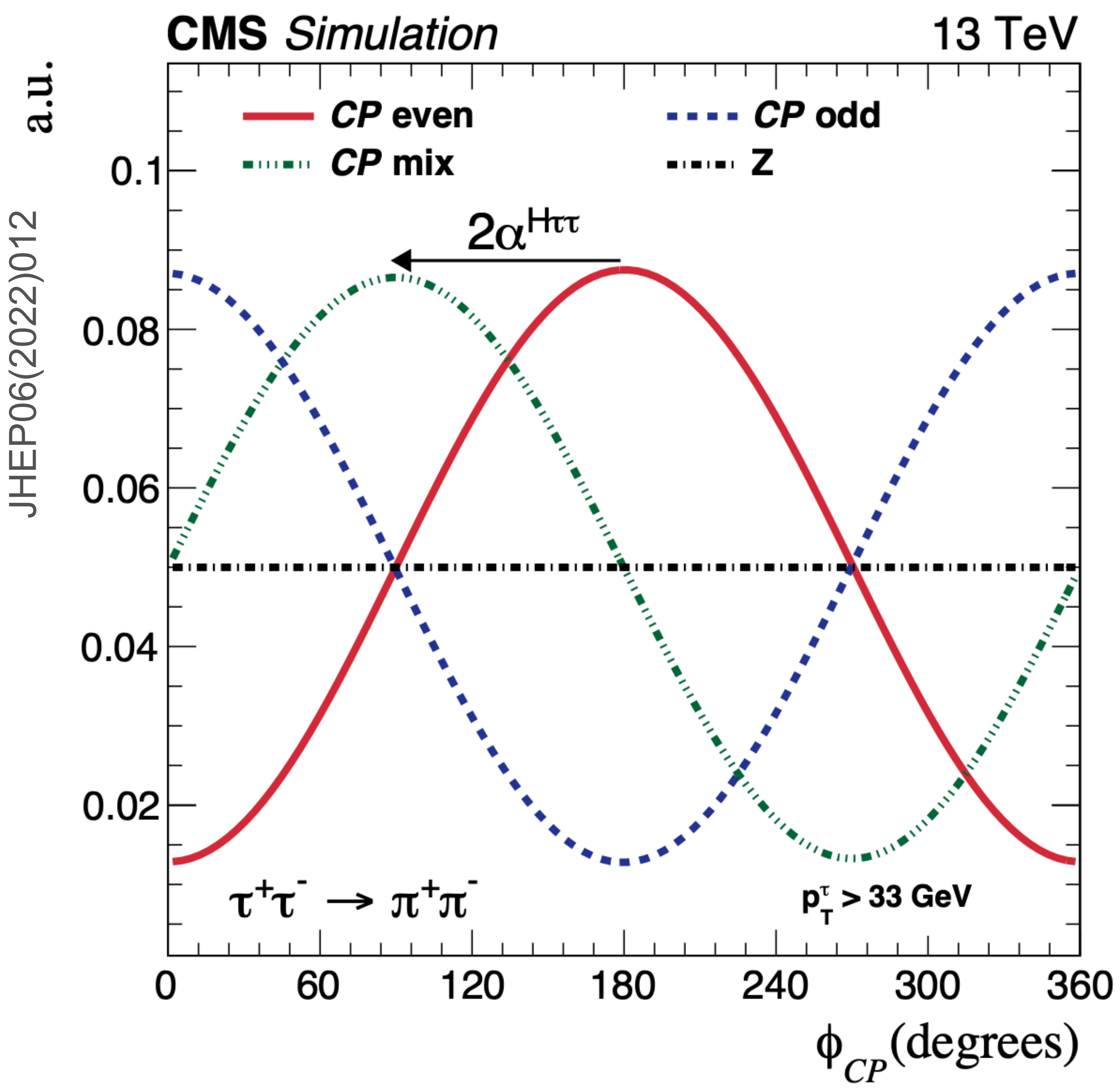
Nature 607, 60–68 (2022)

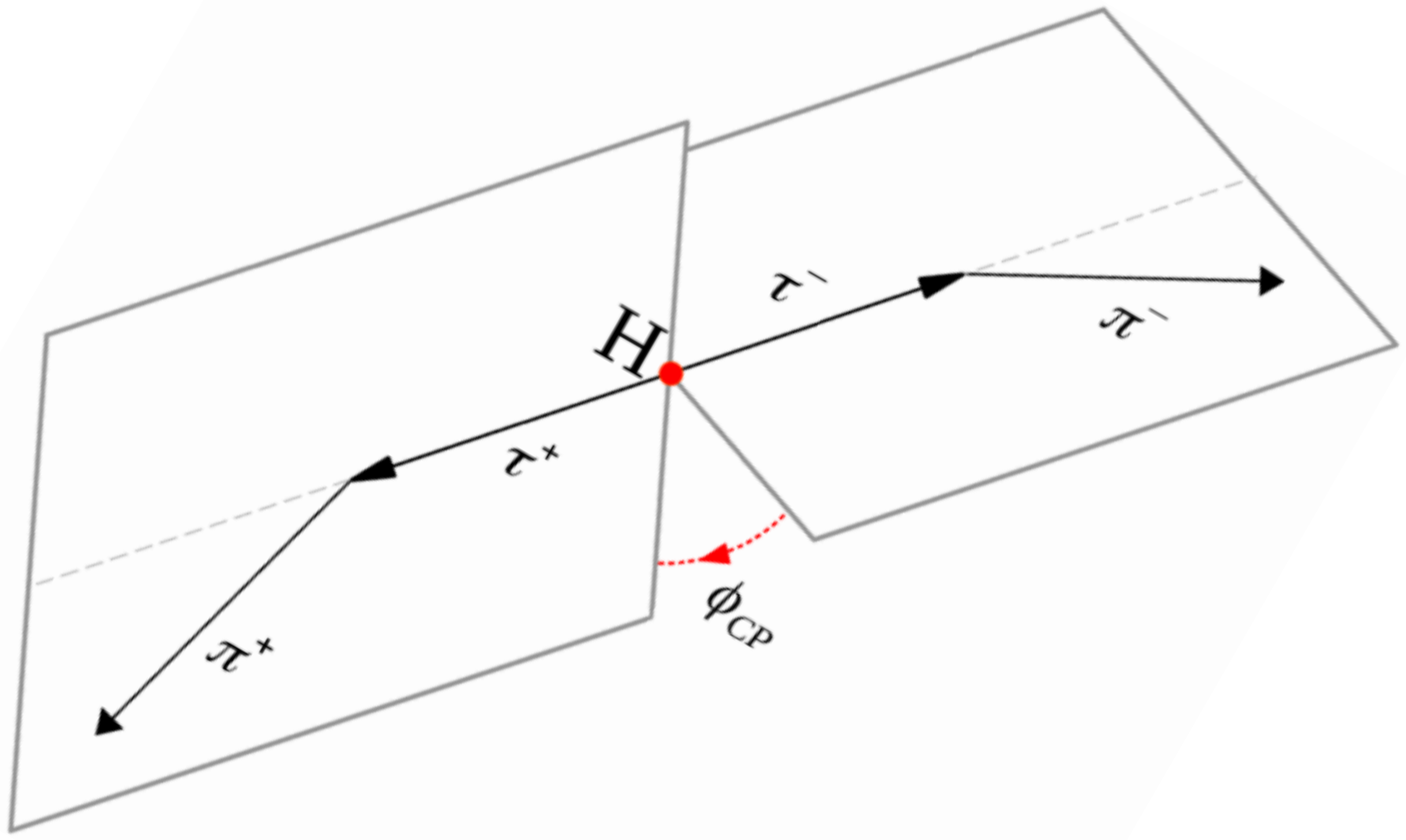




Higgs CP ($H \to \tau\tau$)

Parametrise CPV with effective Yukawa Interaction : $\mathscr{L}_{ffH} = \kappa_f' y_f \phi \bar{\psi}_f(\cos\alpha + i\gamma_5 \sin\alpha)\psi_f$





- Neural network based τ reconstruction
- Additional MVA (BDT) for classification
- Observable: ϕ_{CP} X BDT to improve sensitivity to CP-odd vs. CP-even

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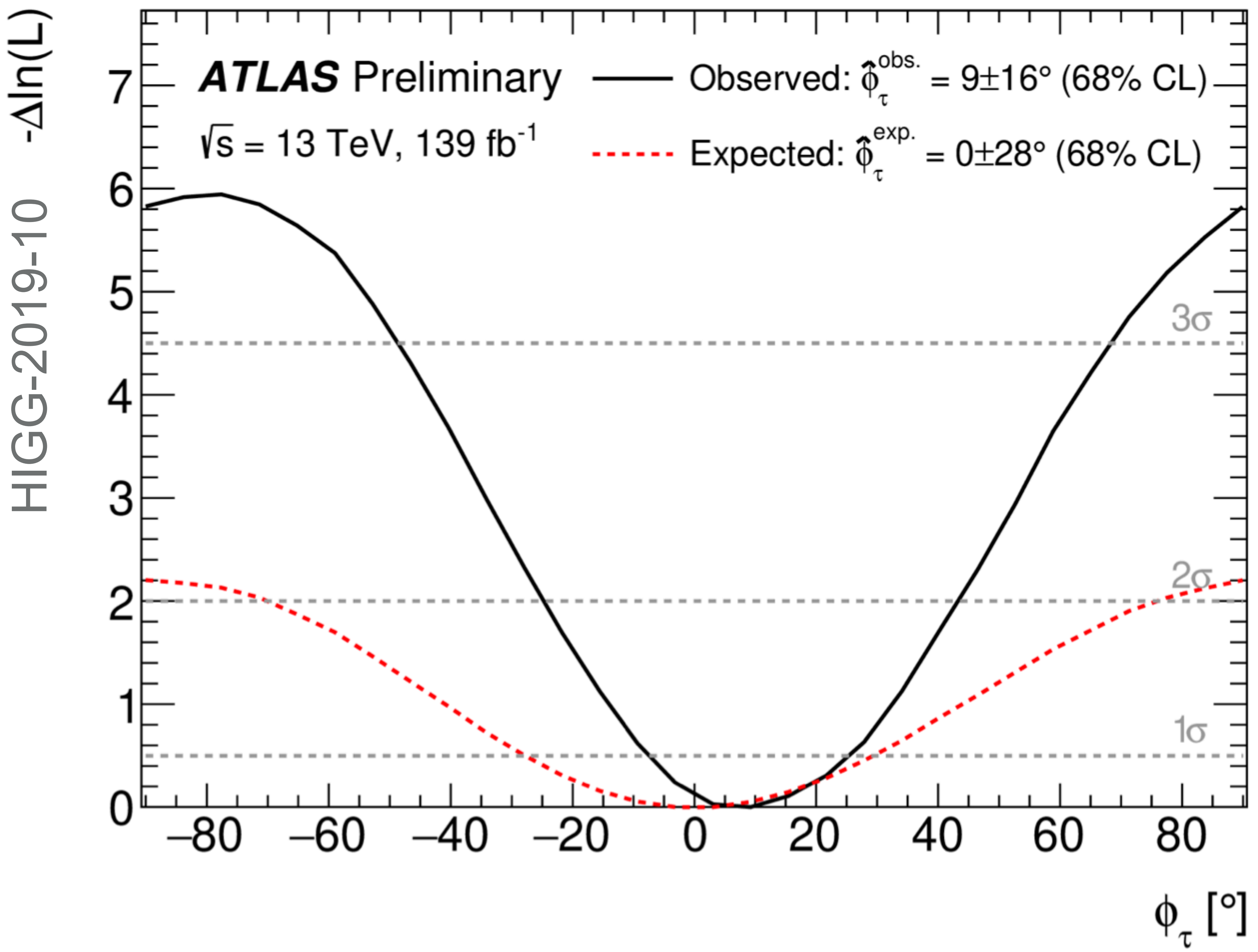
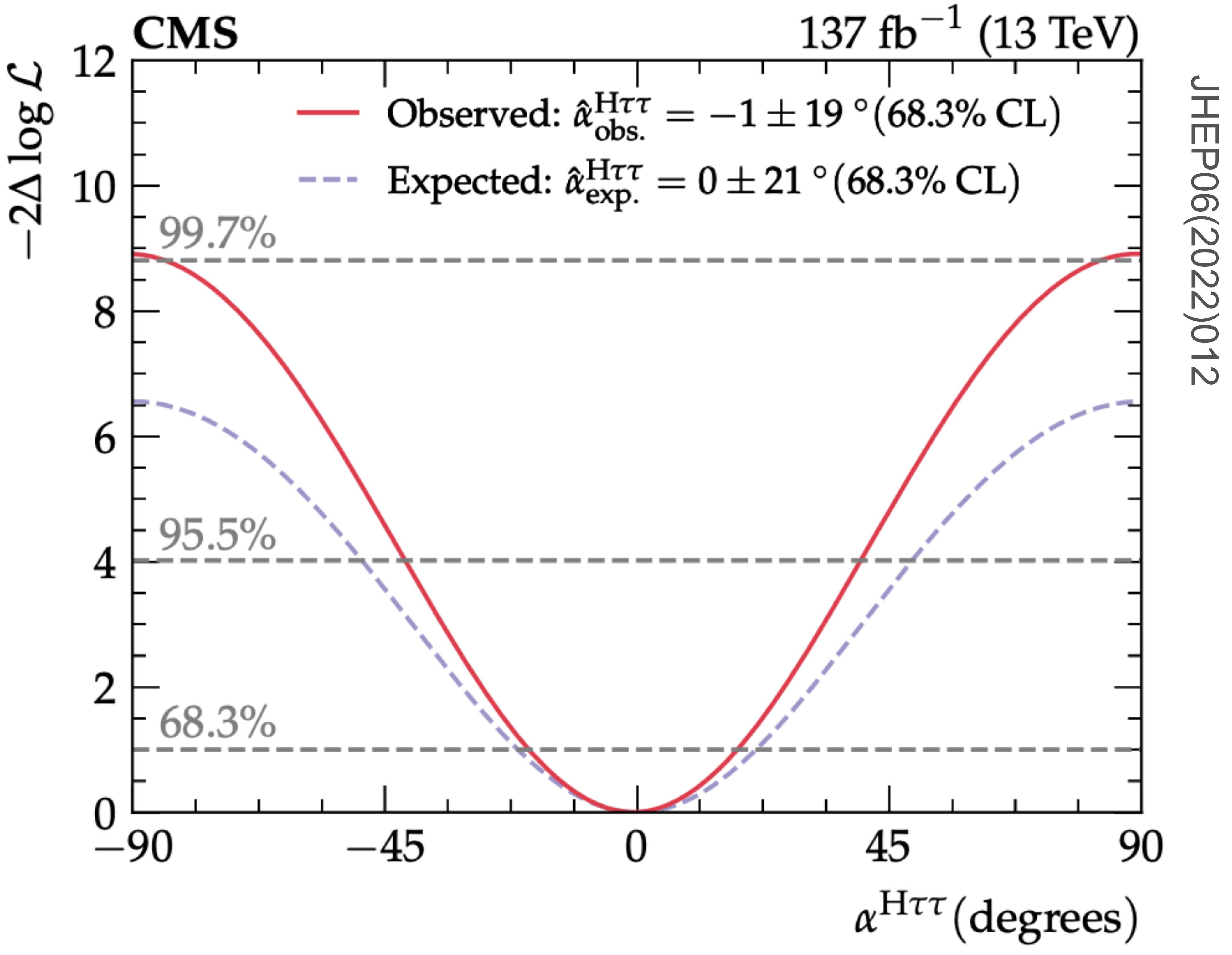




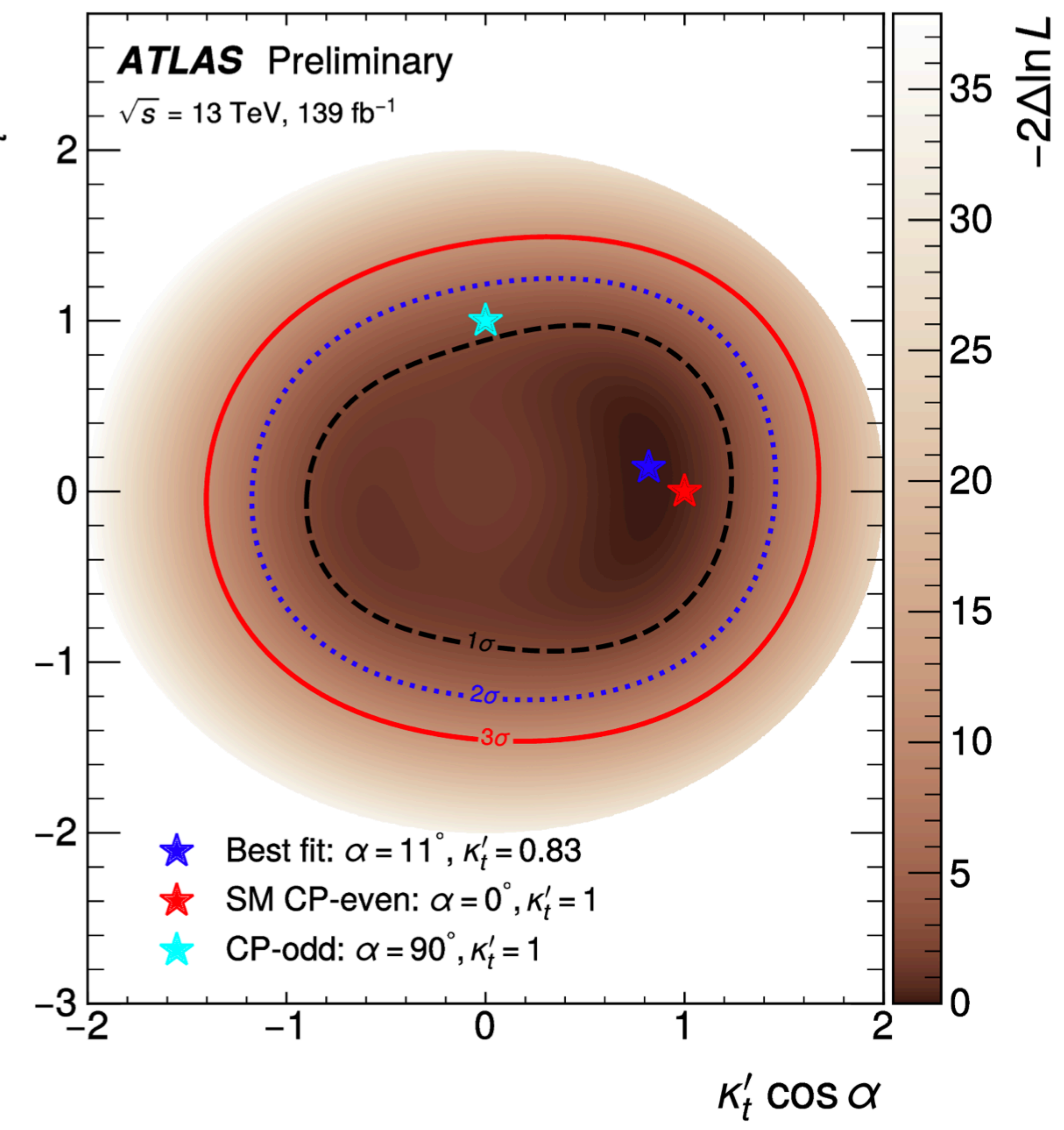
Compatible with CP-even hypothesis

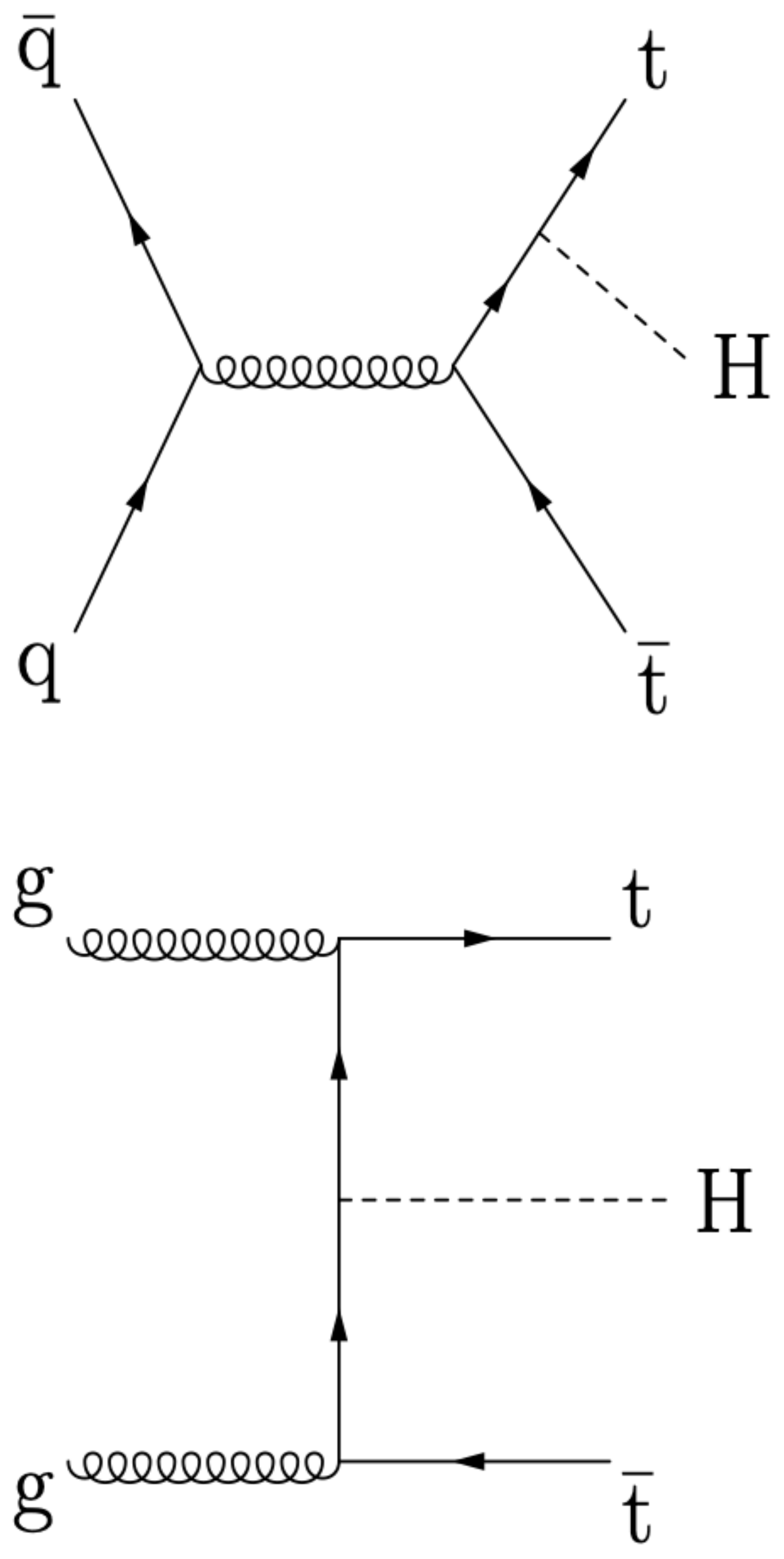
Higgs CP (H→ff)

Parametrise effective CPV with effective Yukawa Interaction : $\mathscr{L}_{ffH} = \kappa_f' y_f \phi \bar{\psi}_f (\cos\alpha + i\gamma_5 \sin\alpha)\psi_f$

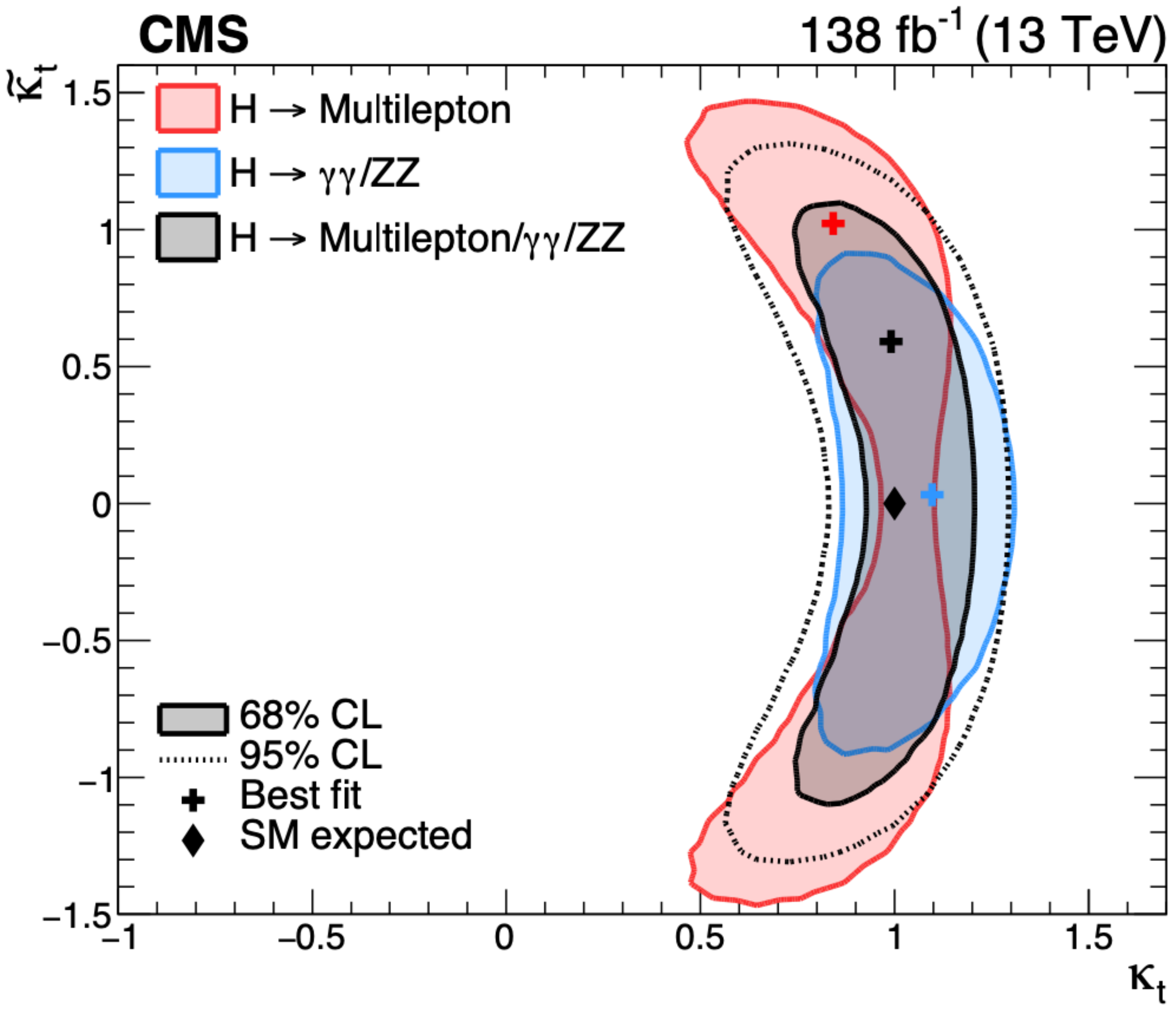
CPV in $t\bar{t}H \rightarrow b\bar{b}$

arXiv:2303.05974





CPV in $t\bar{t}H \rightarrow$ multilepton



arXiv:2208.02686

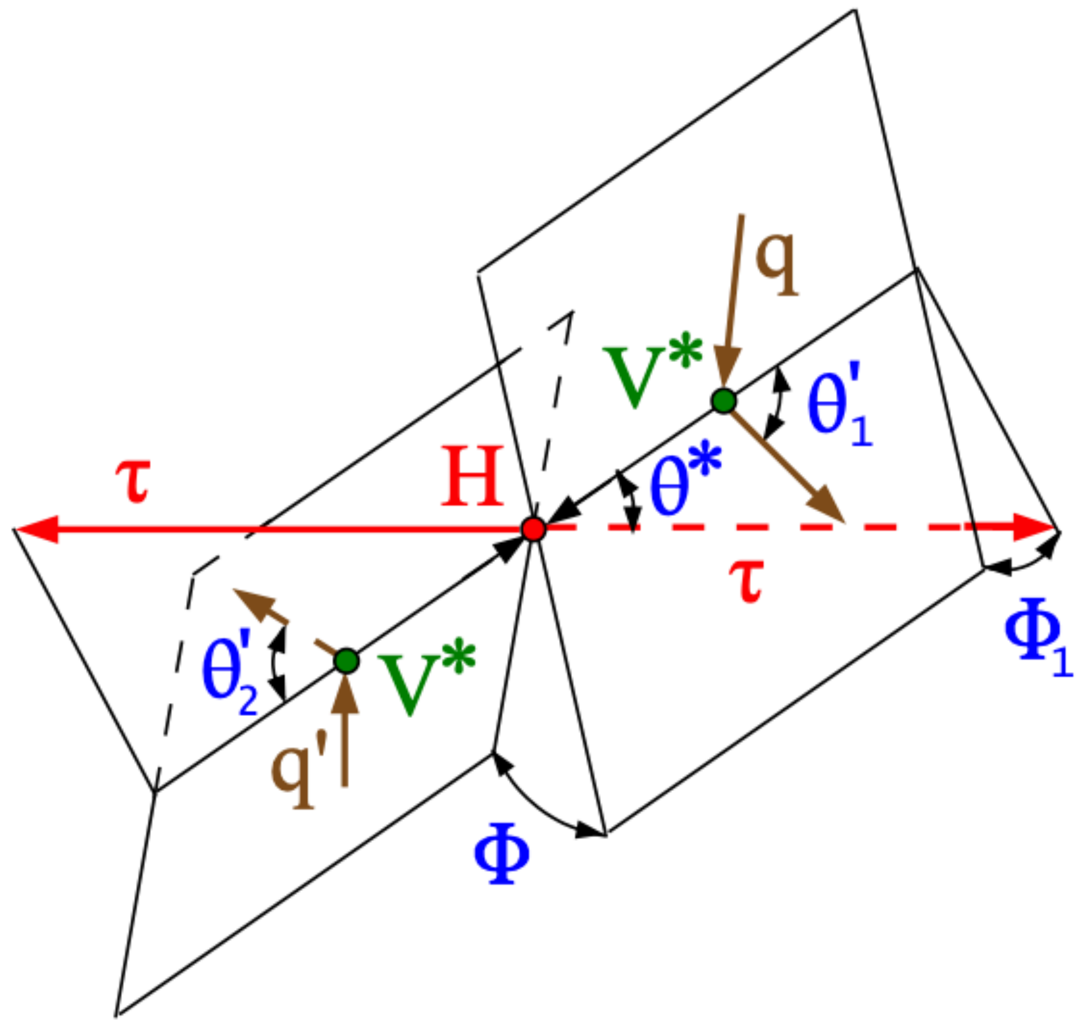
Compatible with CP-even hypothesis

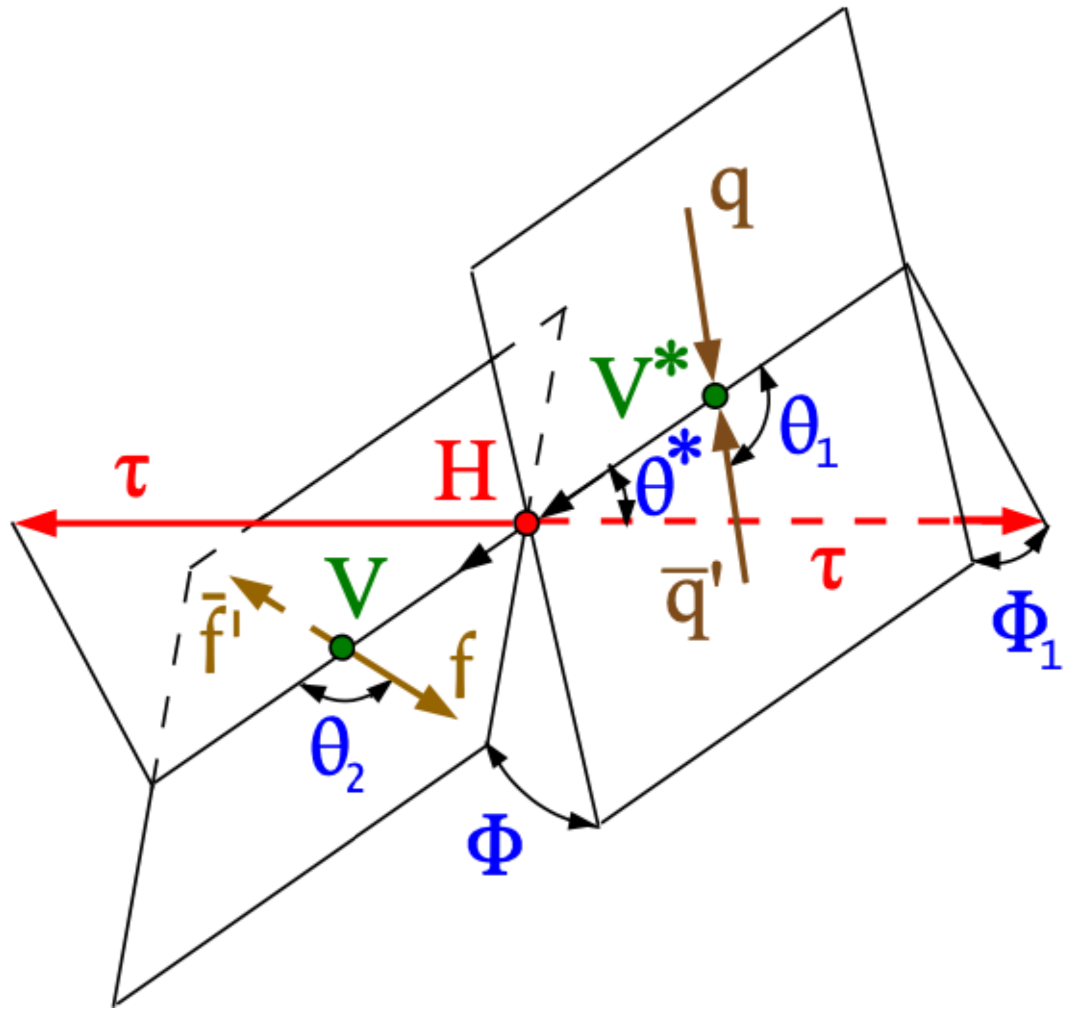
CPV in HVV couplings

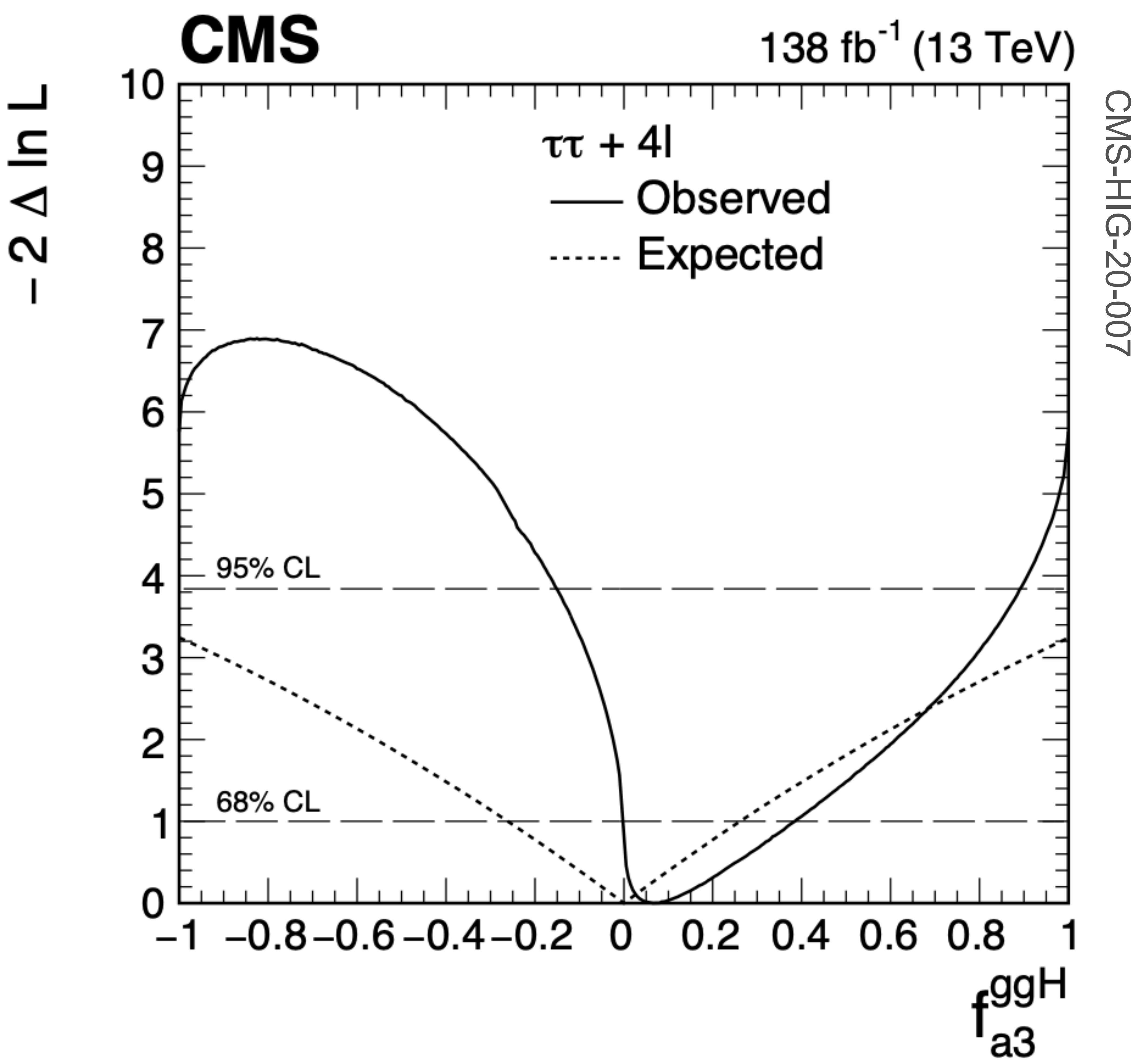
$$\mathcal{A}(\mathrm{HVV}) \sim \left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_1^2 + \kappa_2^{\mathrm{VV}} q_2^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2} \right] m_{\mathrm{V}1}^2 \epsilon_{\mathrm{V}1}^* \epsilon_{\mathrm{V}2}^* + a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2)\mu\nu} + a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2)\mu\nu},$$

$$f_{a3} = \frac{|a_3|^2\sigma_3}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + |\kappa_1|^2\sigma_{\Lambda 1} + |\kappa_1^{Z\gamma}|^2\sigma_{\Lambda 1}^{Z\gamma}} \,\mathrm{sgn}\left(\frac{a_3}{a_1}\right)$$

MELA observable: use event kinematics,
➡results in significant improvement in sensitivity







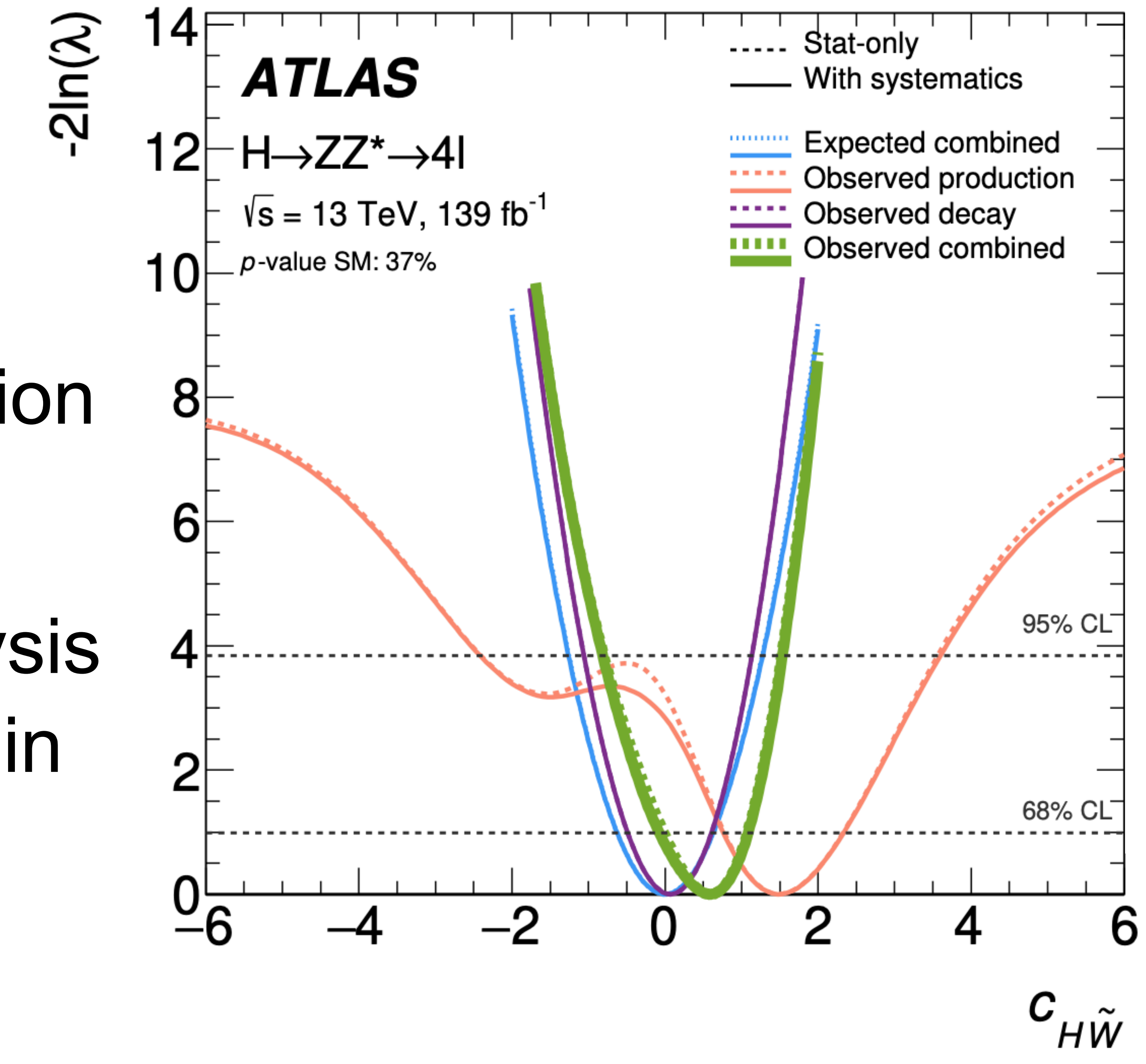
Higgs CP (SMEFT)

- Parametrise CP-odd effects by expanding the SM with dim6 SMEFT operators

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2} O_i^{(6)}$$

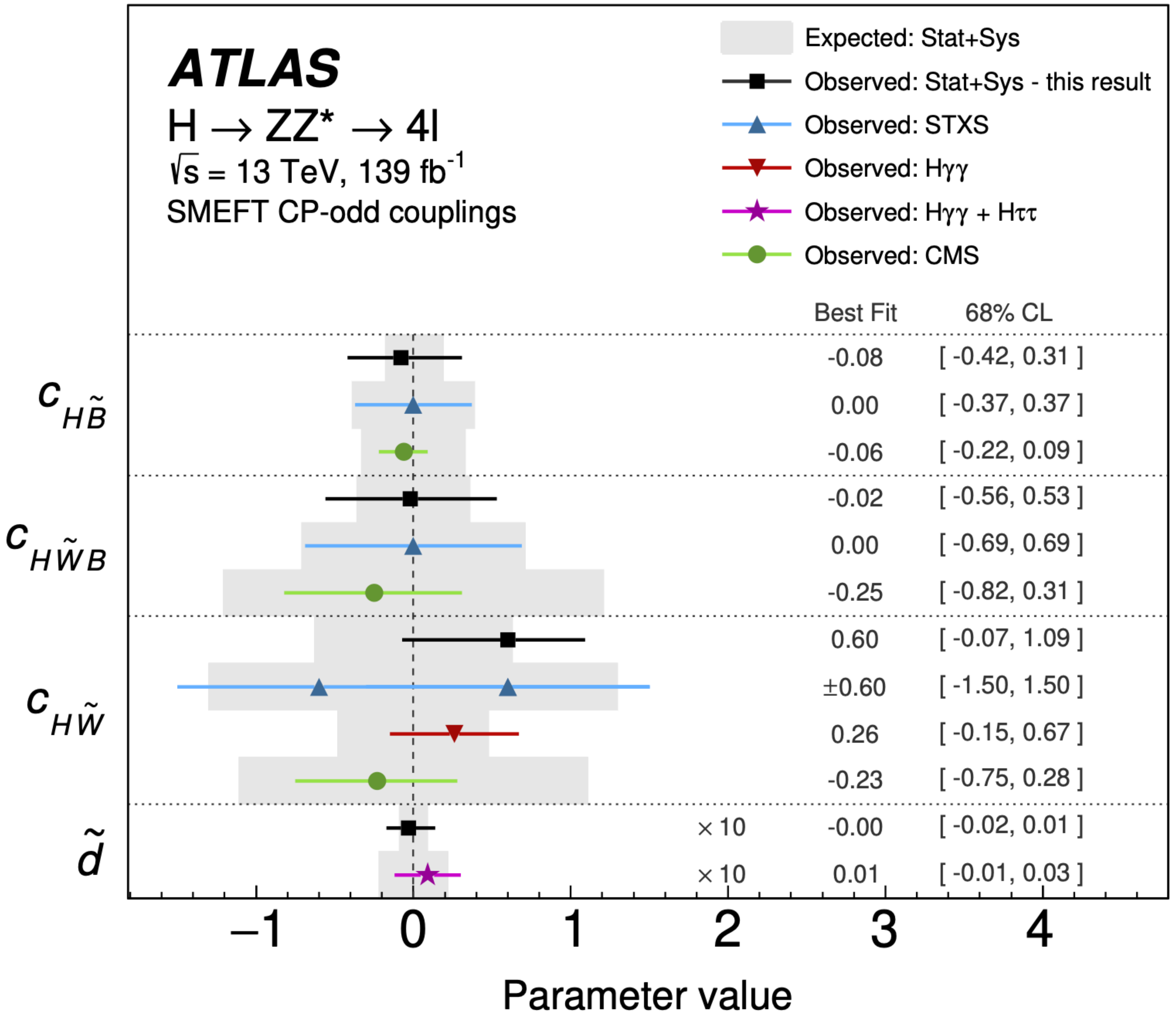
- Optimal observable constructed based on the BSM/SM matrix element ratio (back up)
- SMEFT is considered for production and decay processes
- Results from H → ZZ* → 4l analysis combined with the measurement in H → $\tau\tau$ channel

Operator	Structure	Coupling
	Warsaw Basis	
$O_{\Phi\tilde{W}}$	$\Phi^\dagger\Phi\tilde{W}^I_{\mu\nu}W^{\mu\nu I}$	$c_{H\tilde{W}}$
$O_{\Phi\tilde{W}B}$	$\Phi^\dagger\tau^I\Phi\tilde{W}^I_{\mu\nu}B^{\mu\nu}$	$c_{H\tilde{W}B}$
$O_{\Phi\tilde{B}}$	$\Phi^\dagger\Phi\tilde{B}_{\mu\nu}B^{\mu\nu}$	$c_{H\tilde{B}}$
	Higgs Basis	
$O_{hZ\tilde{Z}}$	$hZ_{\mu\nu}\tilde{Z}^{\mu\nu}$	$\tilde{c}_{zz}$
$O_{hZ\tilde{A}}$	$hZ_{\mu\nu}\tilde{A}^{\mu\nu}$	$\tilde{c}_{z\gamma}$
$O_{hA\tilde{A}}$	$hA_{\mu\nu}\tilde{A}^{\mu\nu}$	$\tilde{c}_{\gamma\gamma}$



(b) $c_{H\tilde{W}}$

arXiv:2304.09612



Cross section measurements and interpretations

Cross section measurements

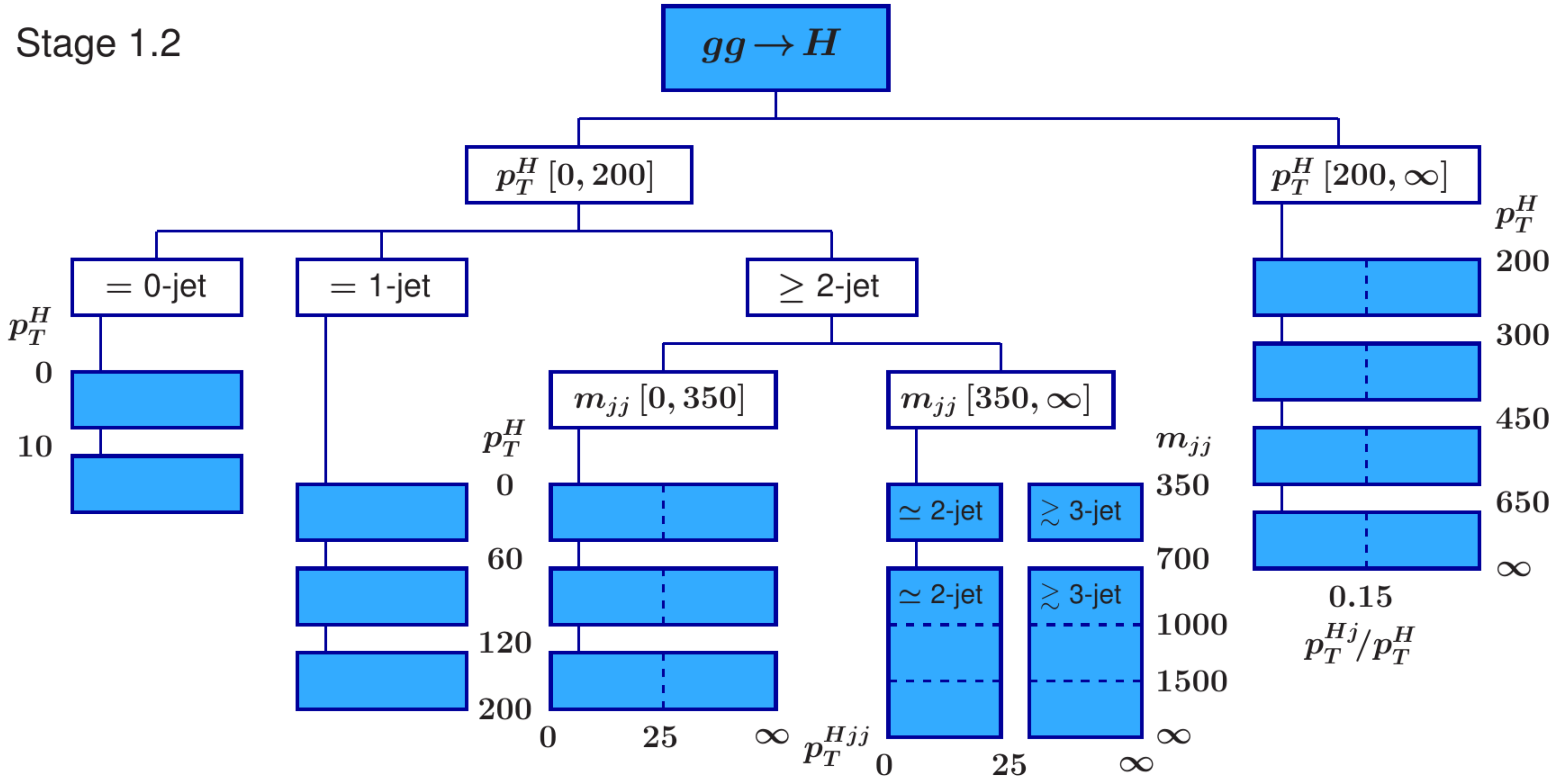
I. Fiducial differential measurements
- Define fiducial region to minimise acceptance effects ($A \approx 1$), i.e. try to match experimental selection
- Differential: Unfolded to particle level kinematical variables p_T^H, m_{jj} …

$$\sigma = \frac{N^{reco}}{(A \times \epsilon)\ L}$$

II. Simplified template cross section (STXS)
- Aim to separate BSM sensitive region
- Reduce the dependence on theory
- Bins based on kinematic variables

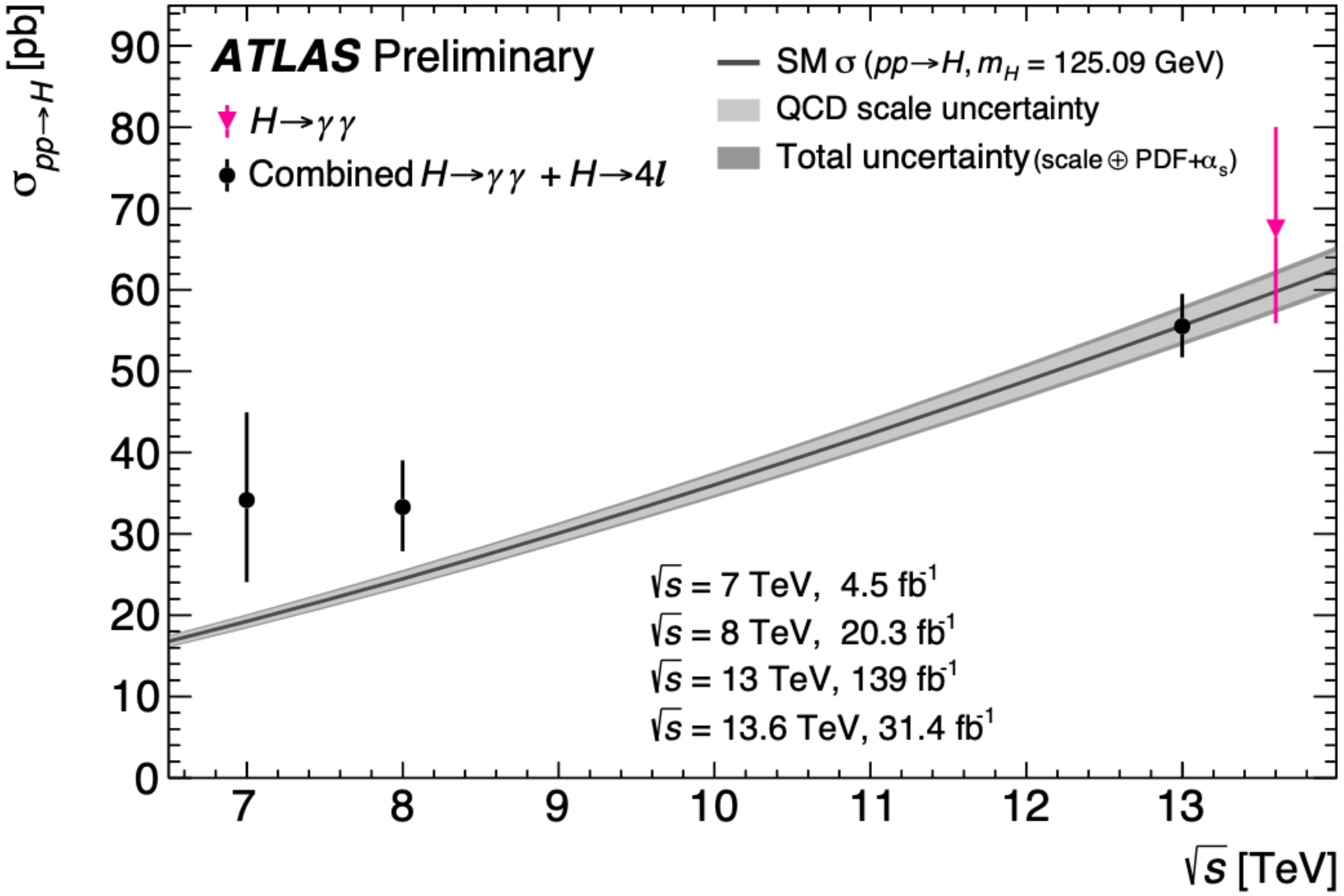
  N_{jets}, p_T^H, m_{jj} - ggF, VBF, ttH

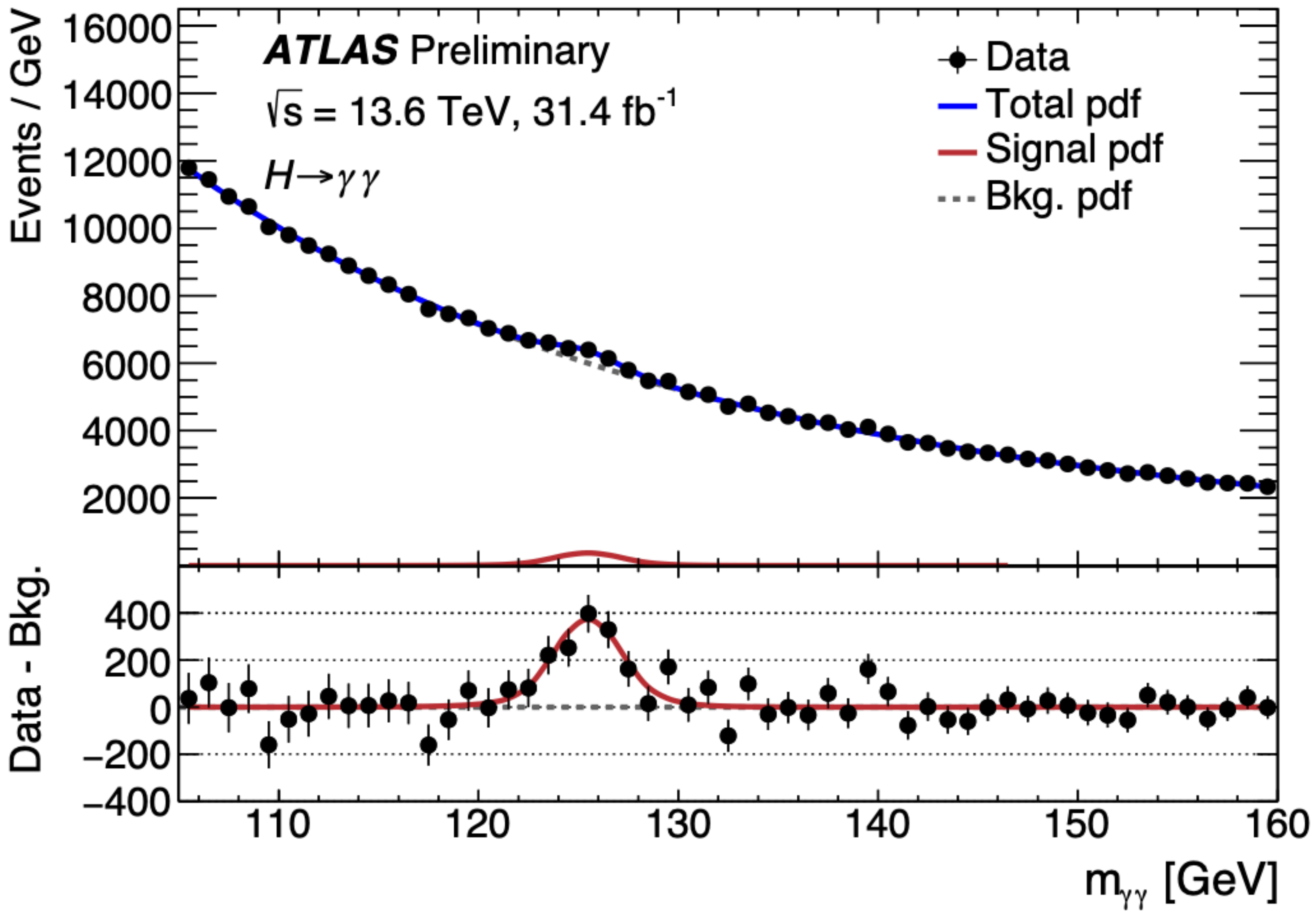
  N_{jets}, p_T^V - VH



H → $\gamma\gamma$ @13.6 TeV

New: First Higgs measurement @13.6 TeV from ATLAS inclusive cross-section measurement in H → $\gamma\gamma$ channel

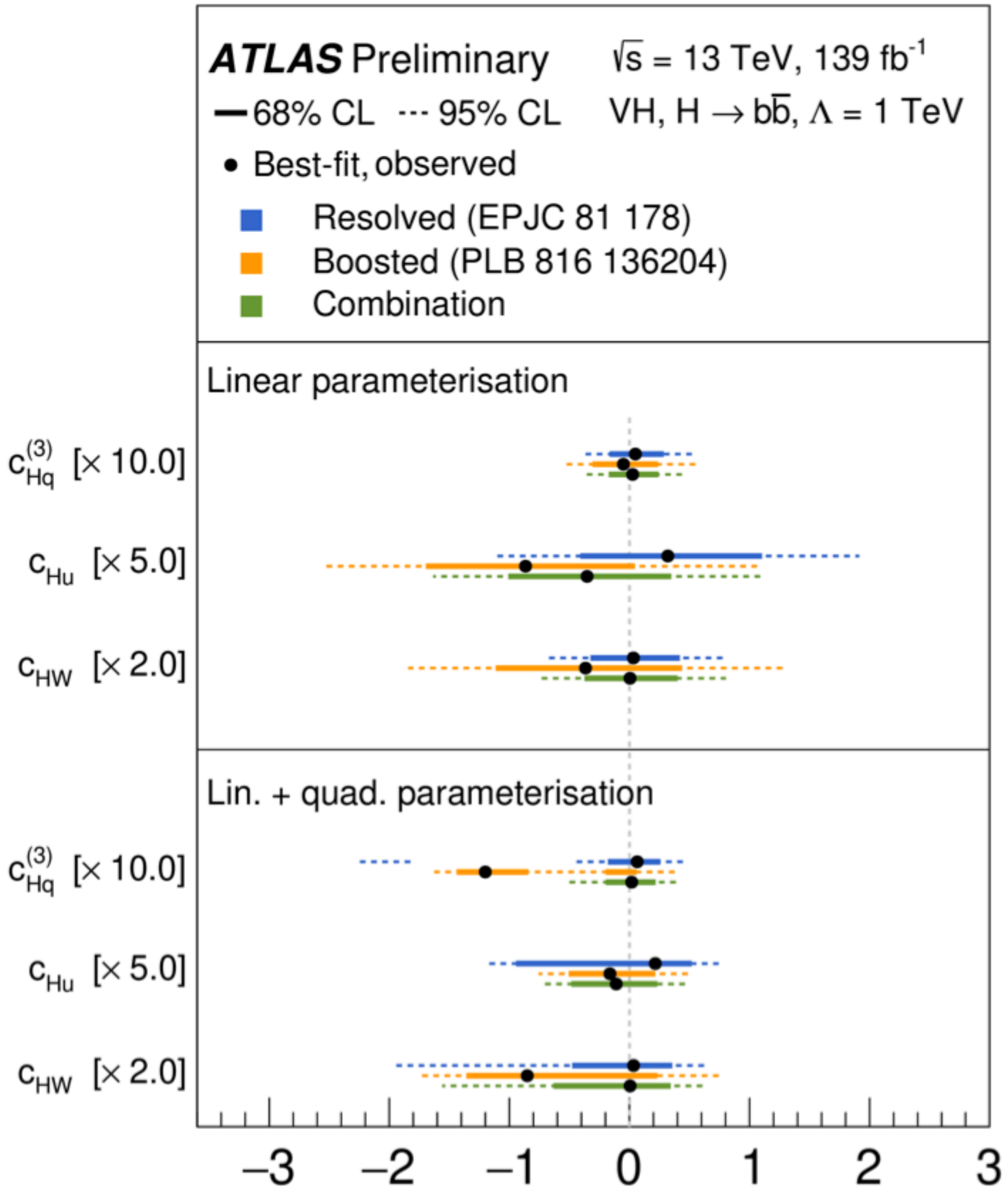




ATLAS-CONF-2023-003

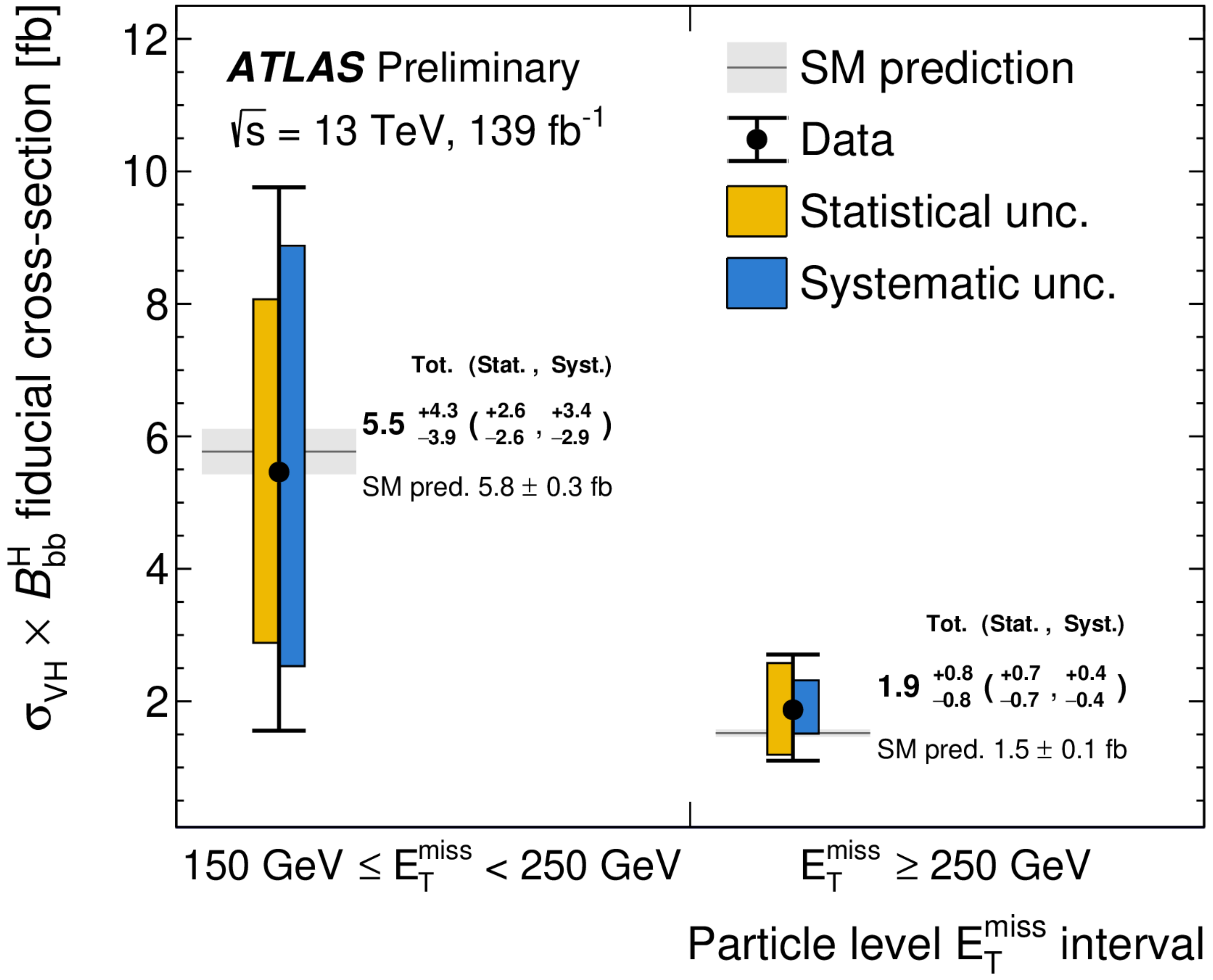
Source	Uncertainty [%]
Statistical uncertainty	14.0
Systematic uncertainty	10.9
Photon trigger and selection efficiency	6.7
Background modelling (spurious signal)	6.0
Photon energy scale & resolution	5.5
Luminosity	2.2
Pile-up modelling	1.1
Higgs boson mass	0.1
Theoretical (signal) modelling	<0.1
Total	17.7

H → b$\bar{b}$ final state

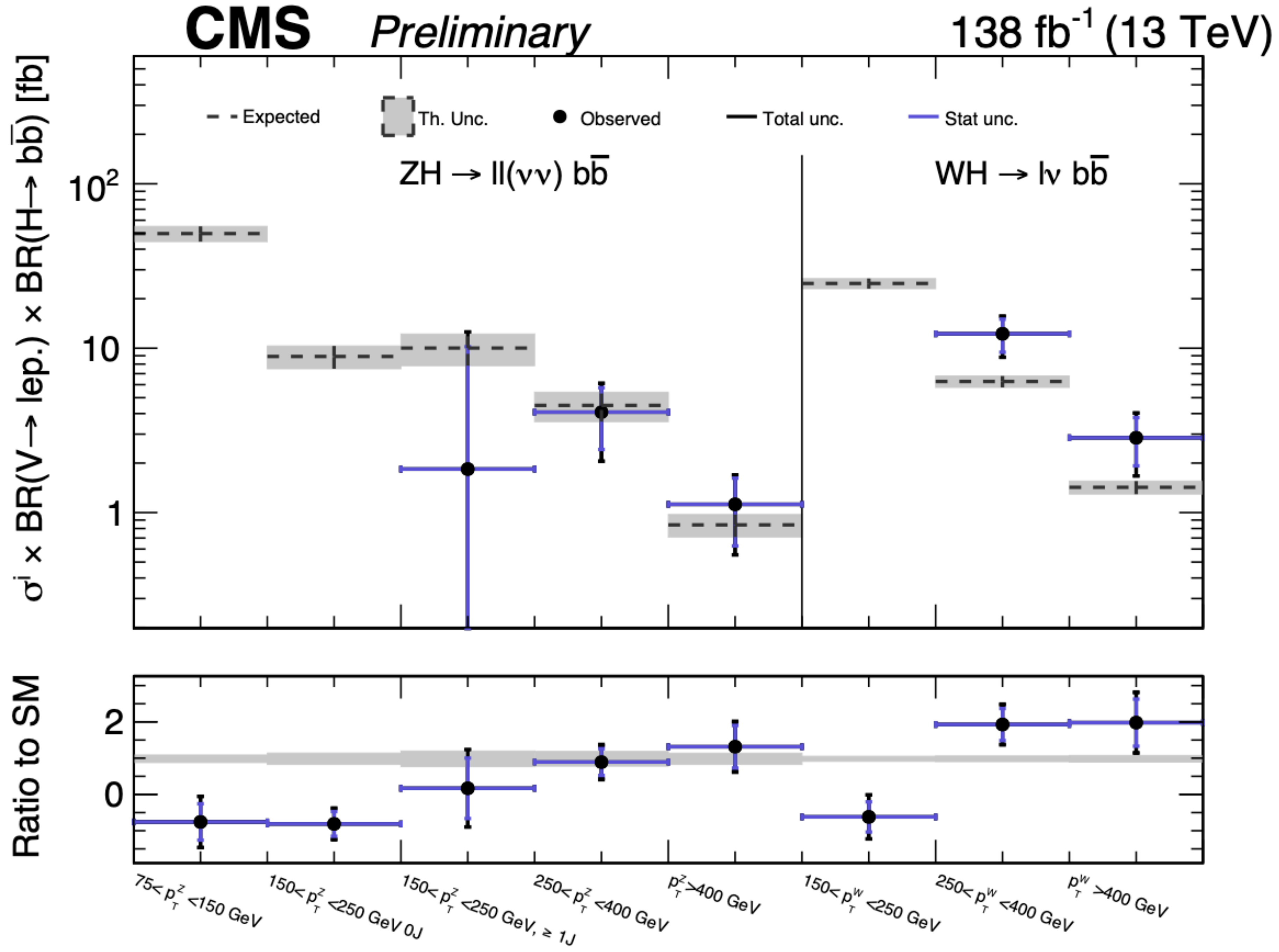


ATLAS-CONF-2021-051

ATLAS-CONF-2022-015



CMS-HIG-20-001



Latest status of the measurements in the VH → b$\bar{b}$ channel:

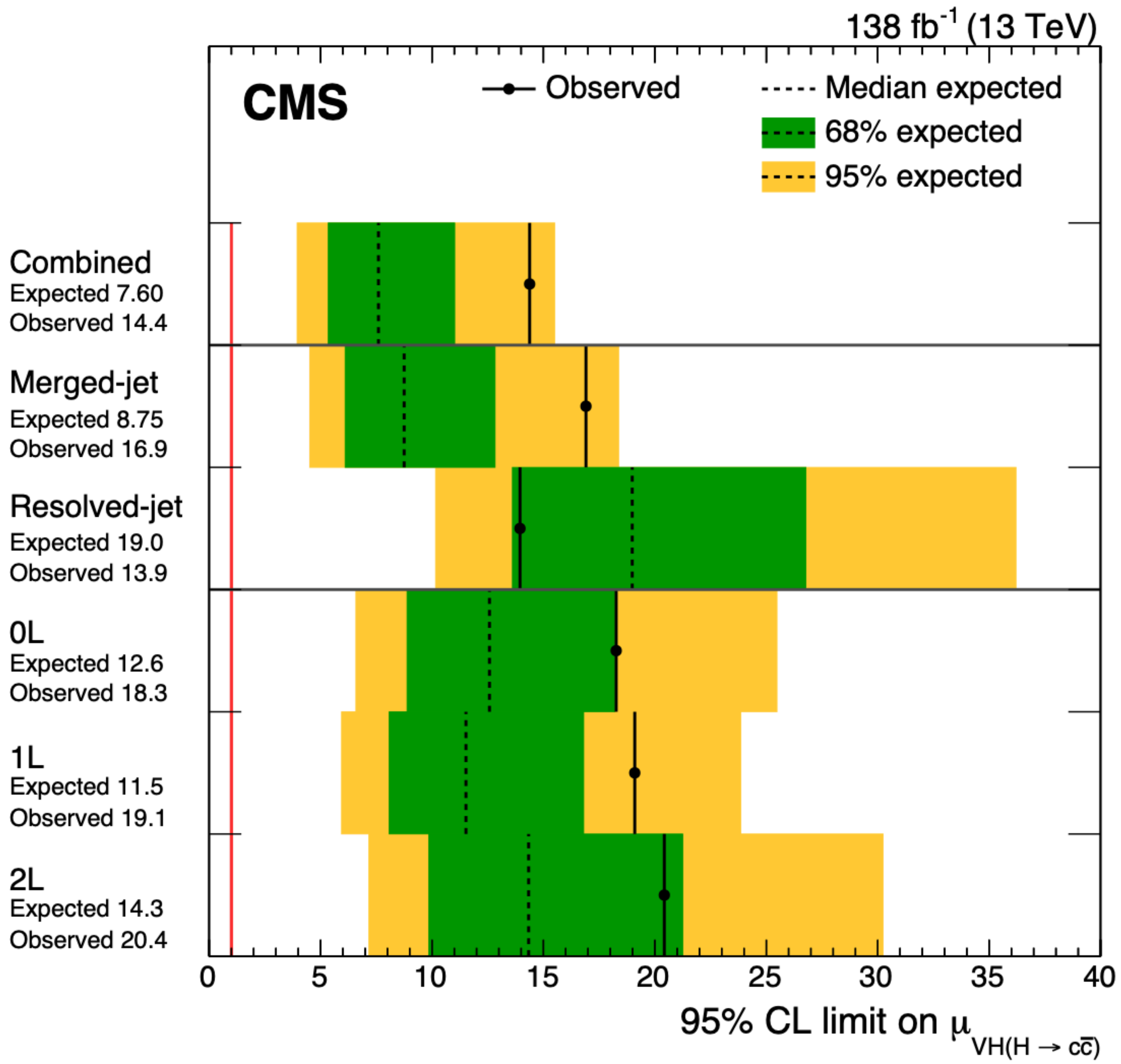
- ATLAS: V(H → b$\bar{b}$) fiducial, H → b$\bar{b}$ resolved + boosted combination (SMEFT)
- CMS: released full Run 2 STXS results

H → $c\bar{c}$ final state

- Low H → $c\bar{c}$ BR and challenging to reconstruct
- V(leptons)H production produces a cleaner signature due to the lepton in final state
- Challenging backgrounds: V+jets and VH → $b\bar{b}$
- Relies on c-tagging algorithms
- Analysis includes resolved and merged-jet topologies in CMS
- Leading limit on κ_c from CMS :

$$1.1 < |\kappa_c| < 5.5 \; (|\kappa_c| < 3.4)$$

CMS-HIG-21-008



H → c$\bar{c}$ final state

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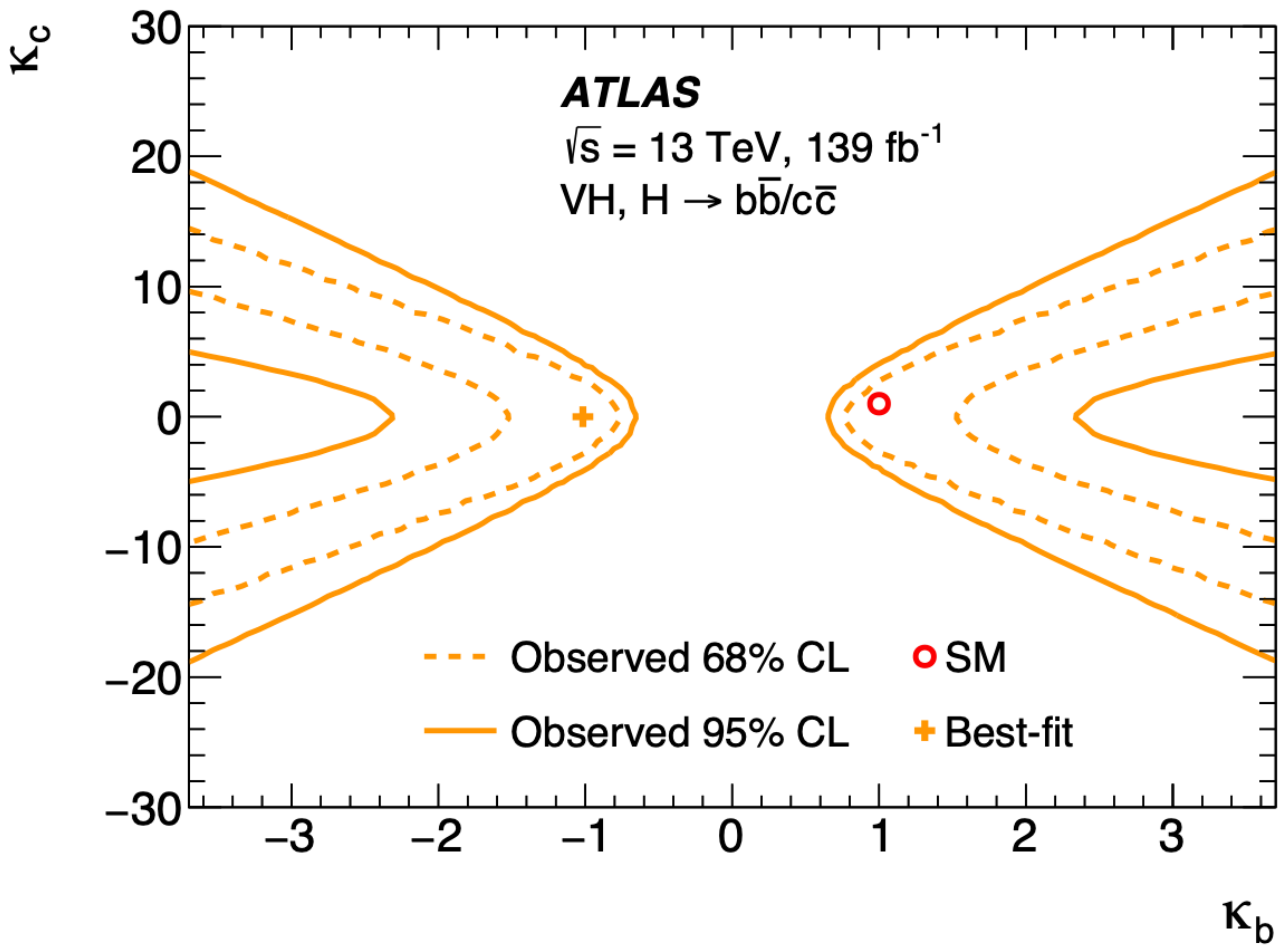
$$1.1 < |\kappa_c| < 5.5 \ (|\kappa_c| < 3.4)$$

- ATLAS: $\kappa_c < 8.5\ (12.4)$ at 95%

✳ Combined with VH → b$\bar{b}$

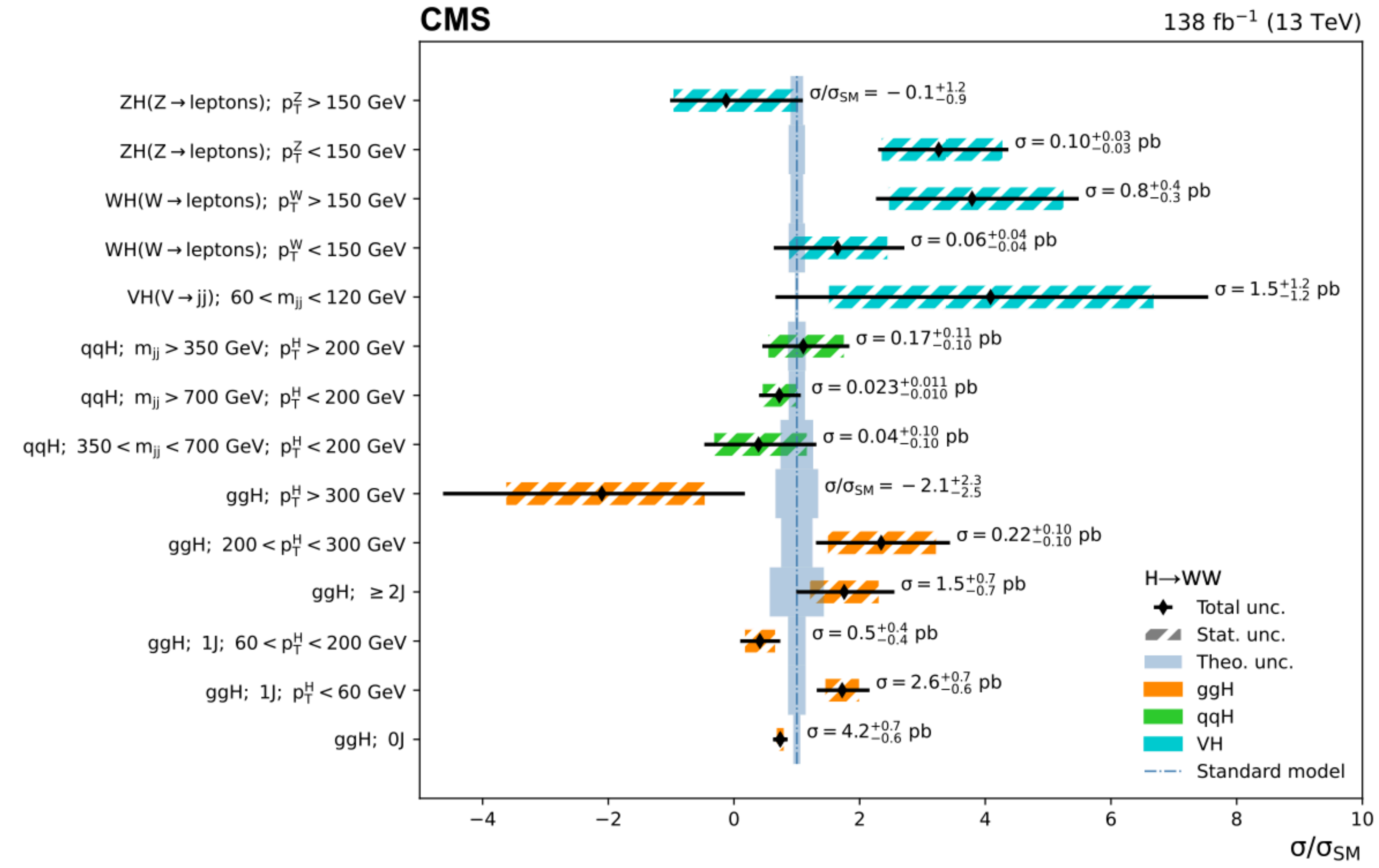
arXiv:2201.11428

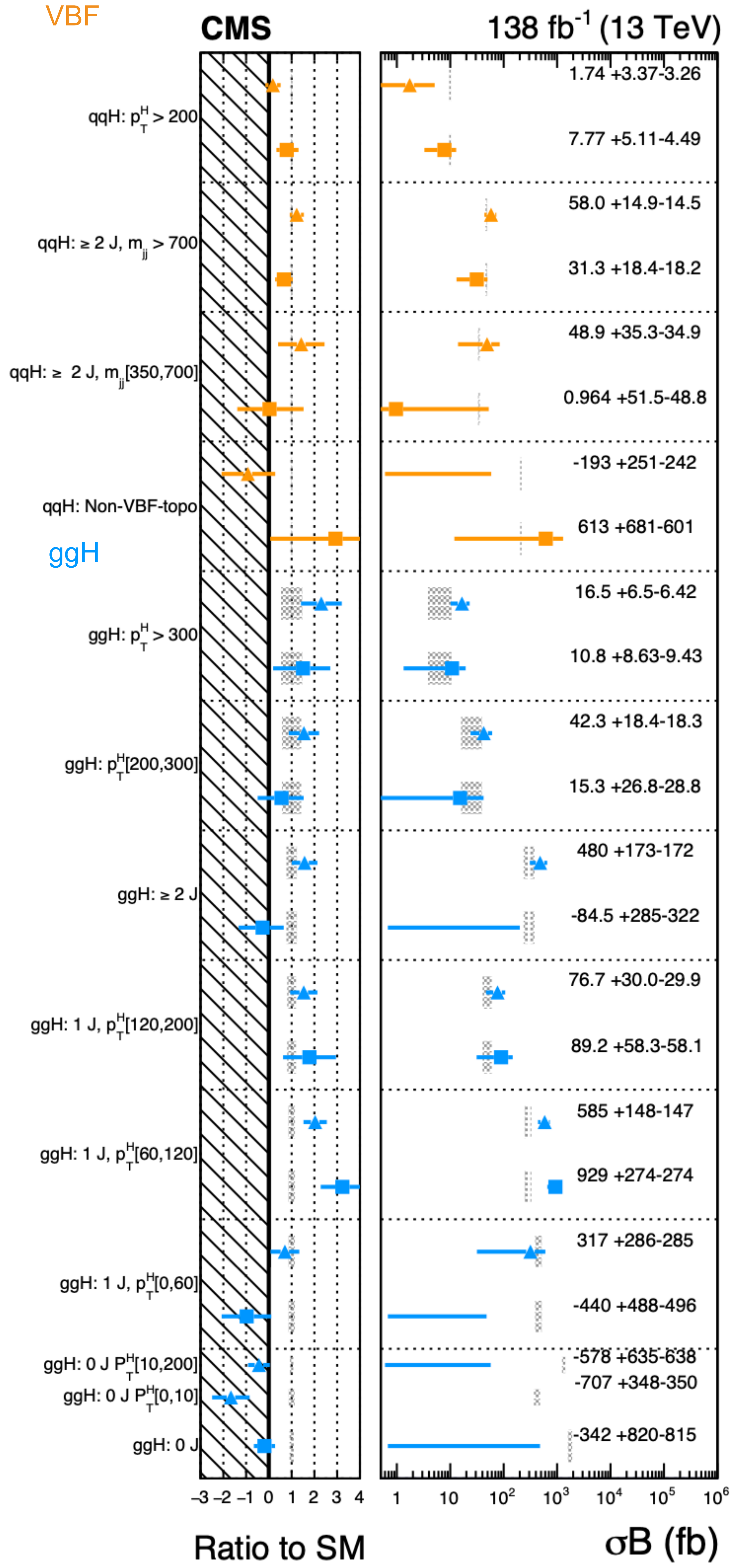


STXS in H→WW and H → $\tau\tau$

- VBF and ggH cross sections measured in STXS 1.2 scheme
- H→WW cut based categorisation
- H → $\tau\tau$ DNN multi-classifier reduced correlations between STXS bins, improved sensitivity

[arXiv:2204.12957]





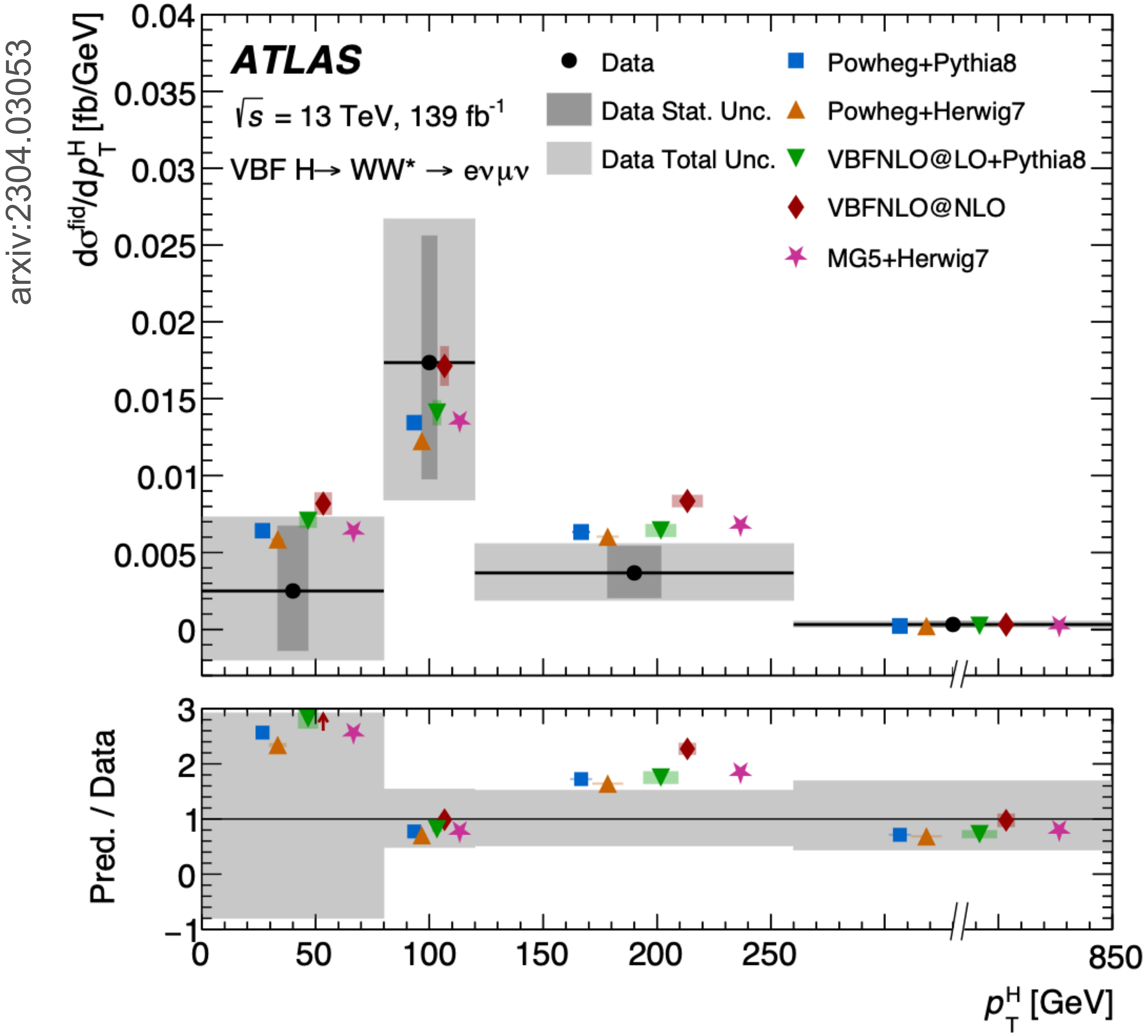
[arXiv:2206.09466]

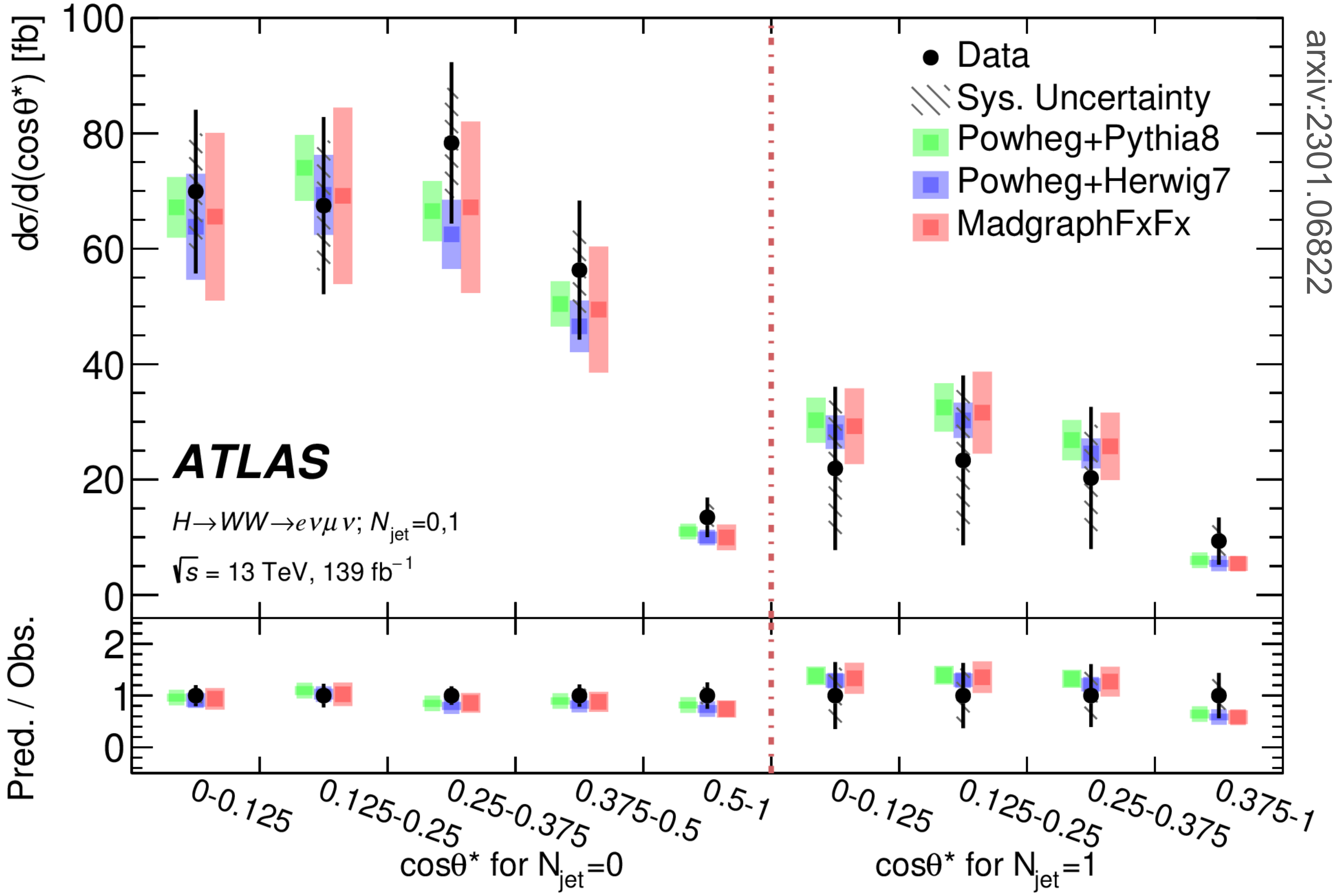
H→WW final state

Differential measurements

VBF Run 2 differential analysis, Powheg, Madgraph predictions. SMEFT interpretation

ggF Run 2 differential analysis, targeting many observables, compared with Pythia8, Herwig

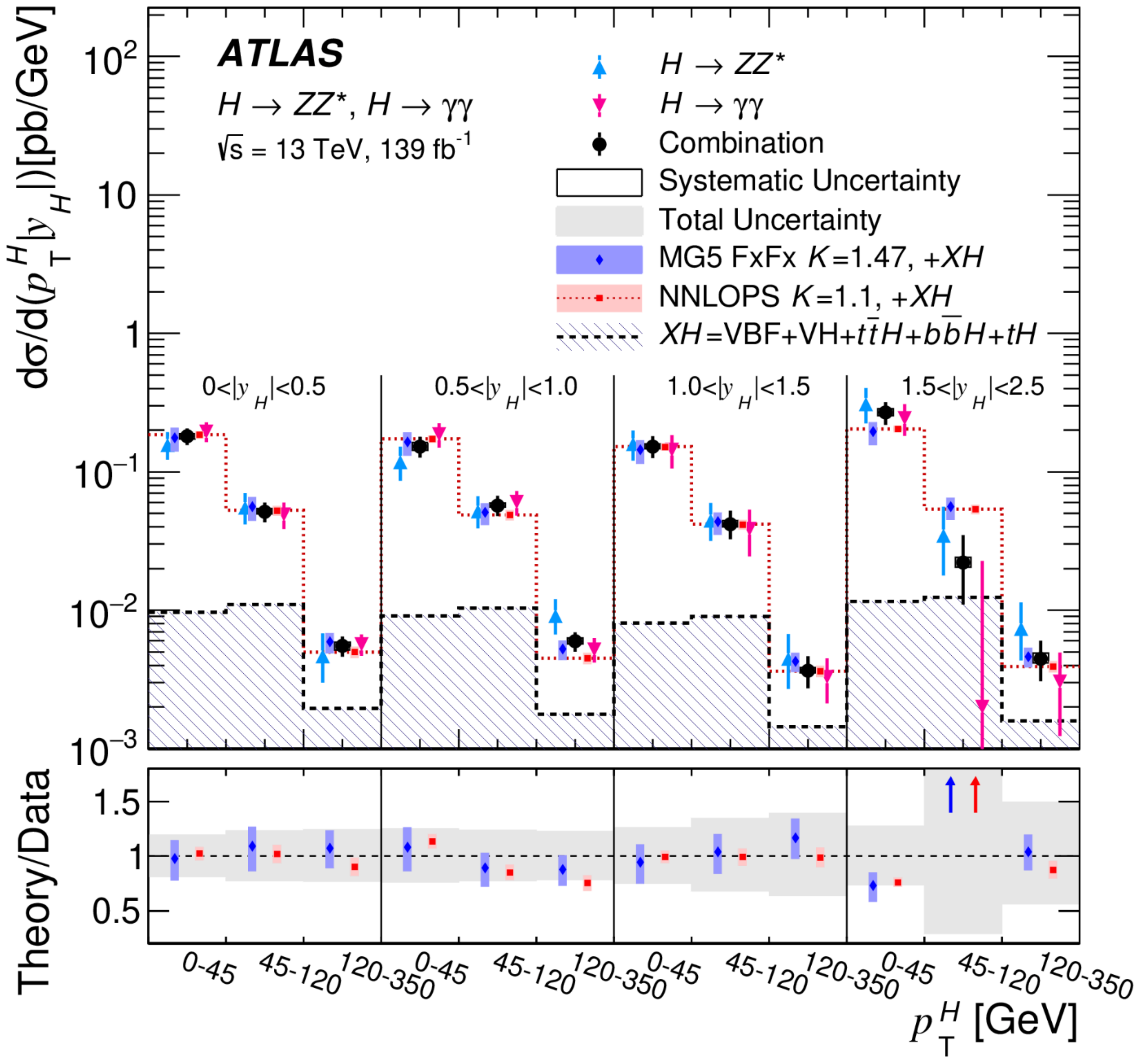


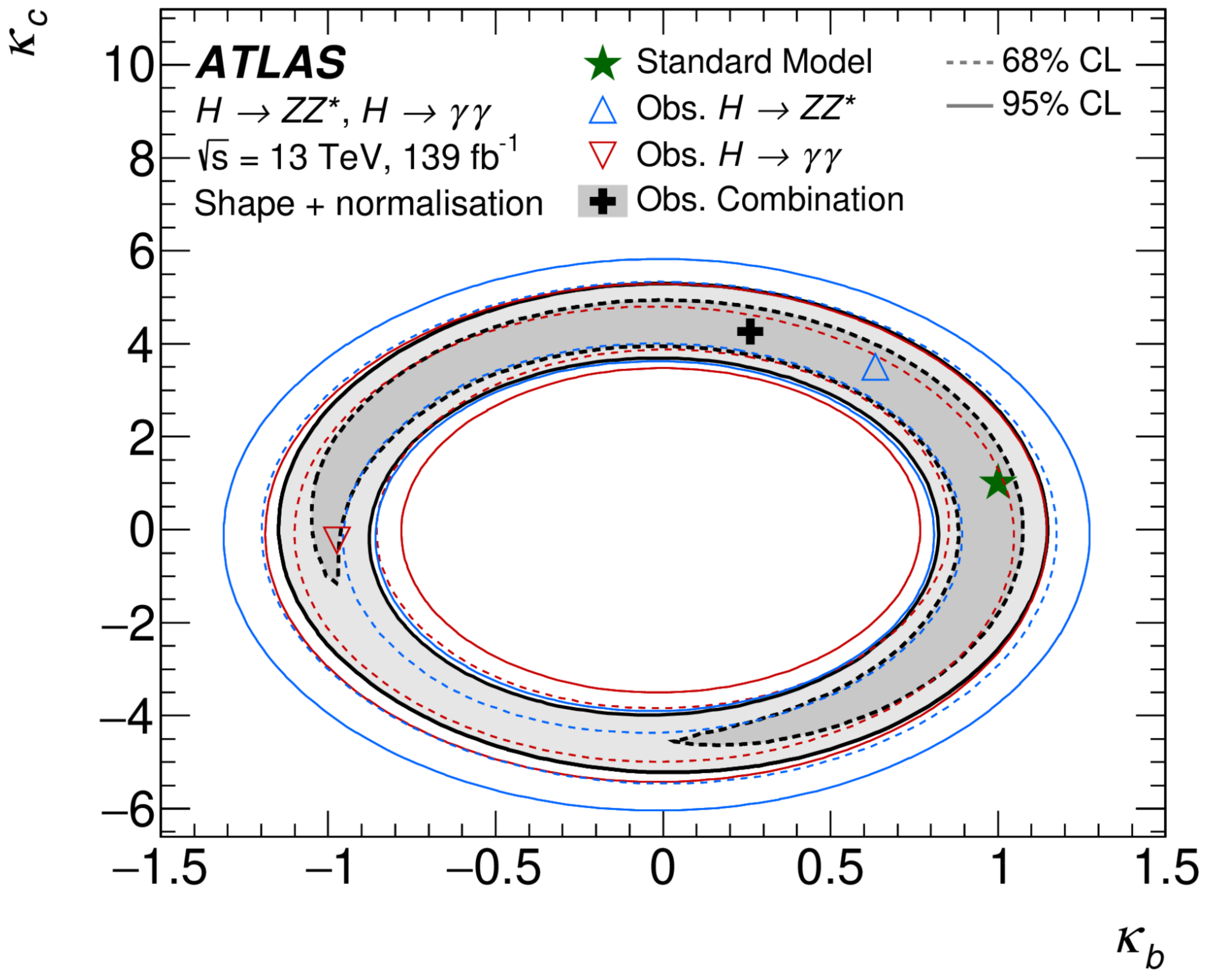


H → $\gamma\gamma$, ZZ final states (ATLAS)

- Combinations of differential H → $\gamma\gamma$ and ZZ analyses, compared with different generators.
- Constraints in κ_c vs. κ_b plane are extracted

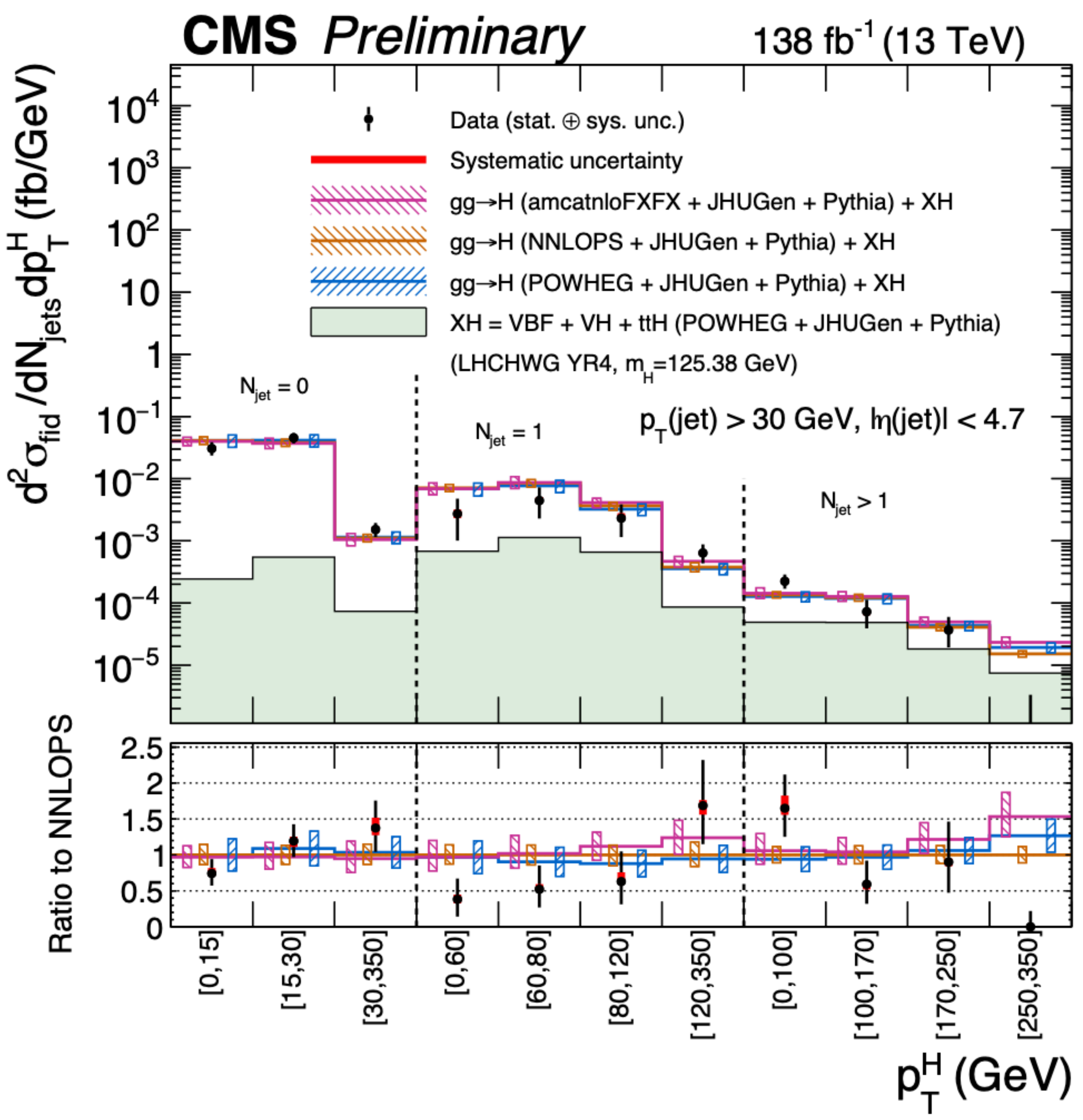
[HIGG-2022-04]

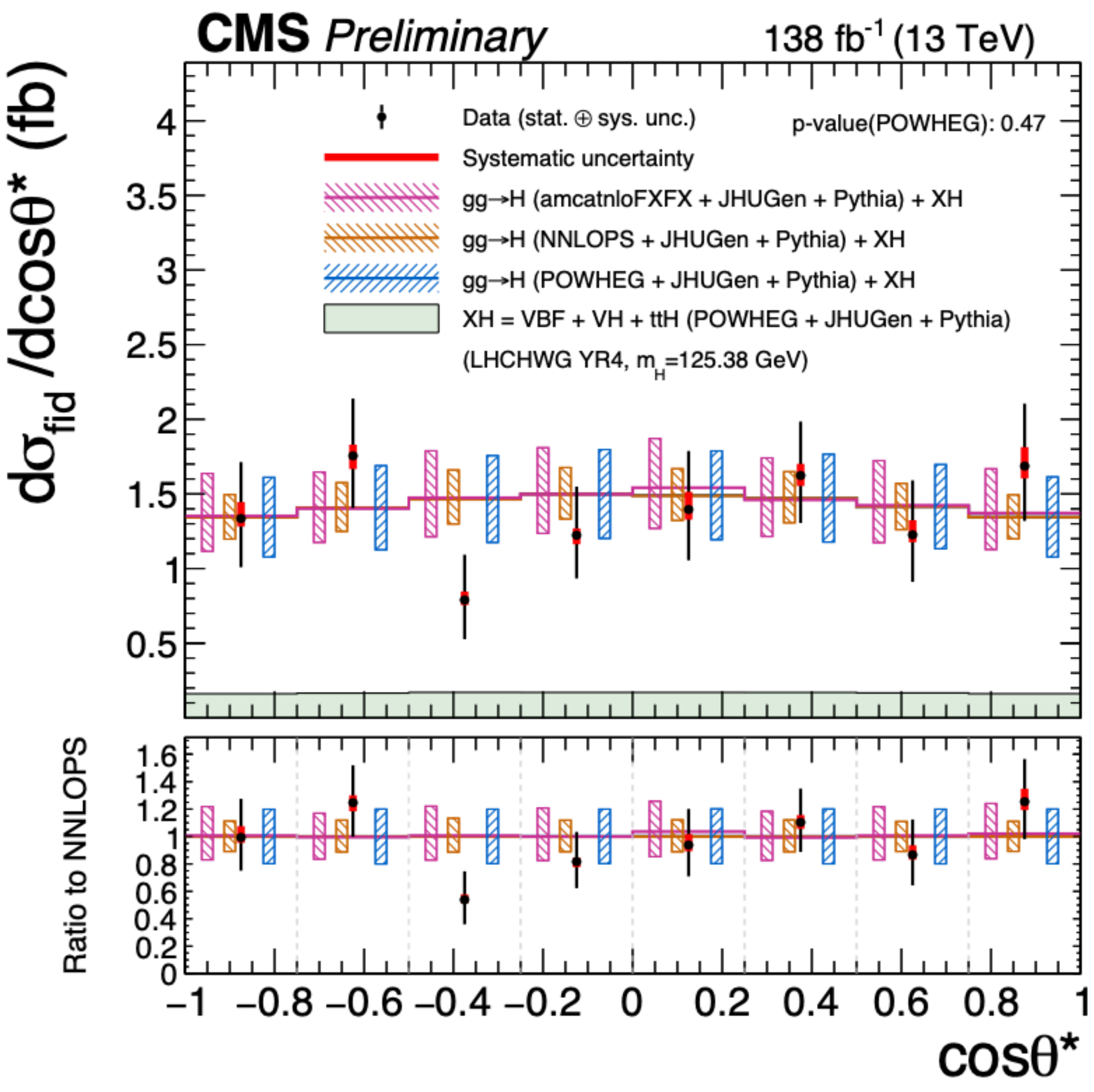




H→ZZ final state (CMS)

CMS-HIG-21-009





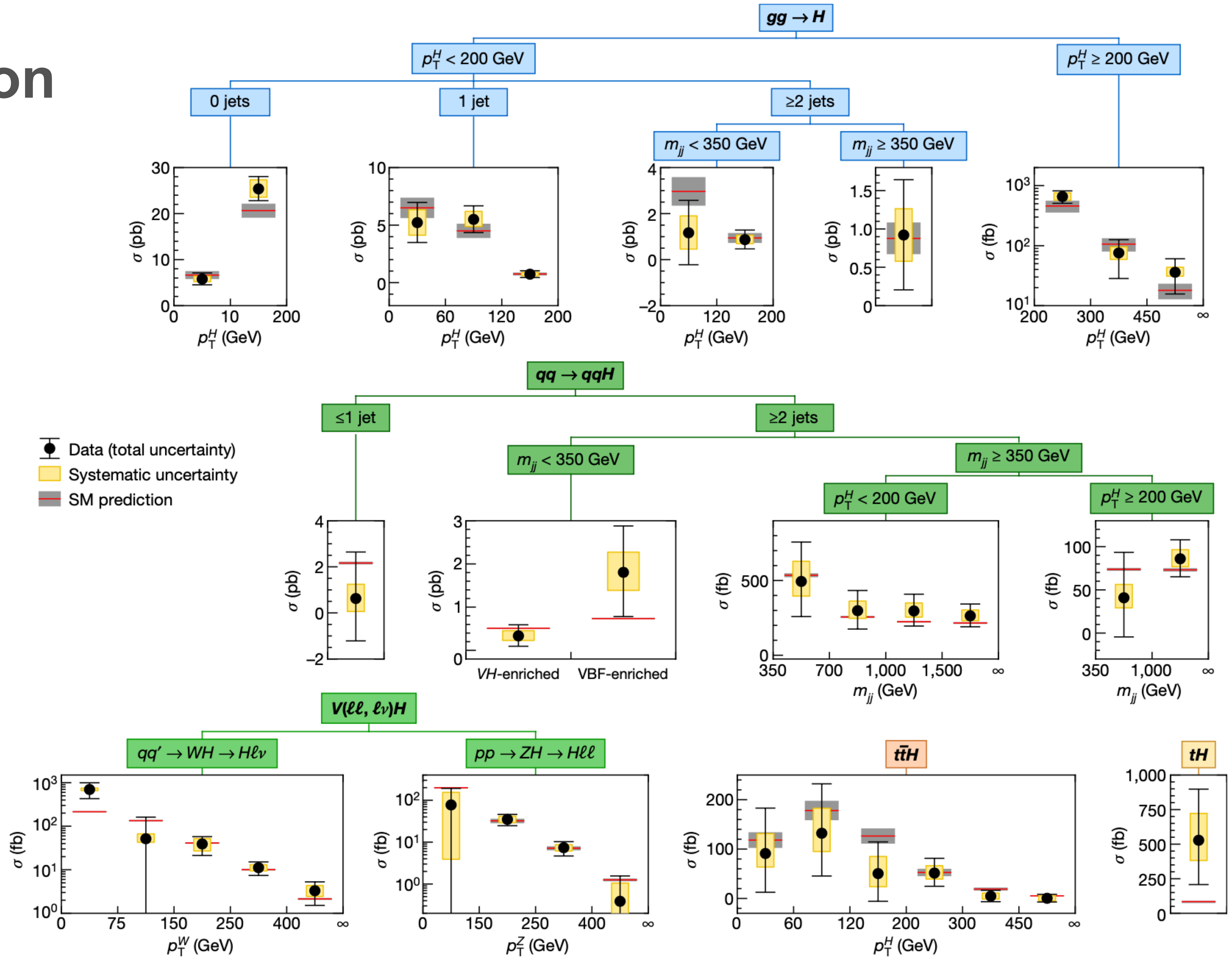
ggF Run 2 differential measurement in kinematical observables, angular distributions and ME observables

Compared with different predictions: generators, parton shower models

STXS combination

Nature 607, 52–59 (2022)

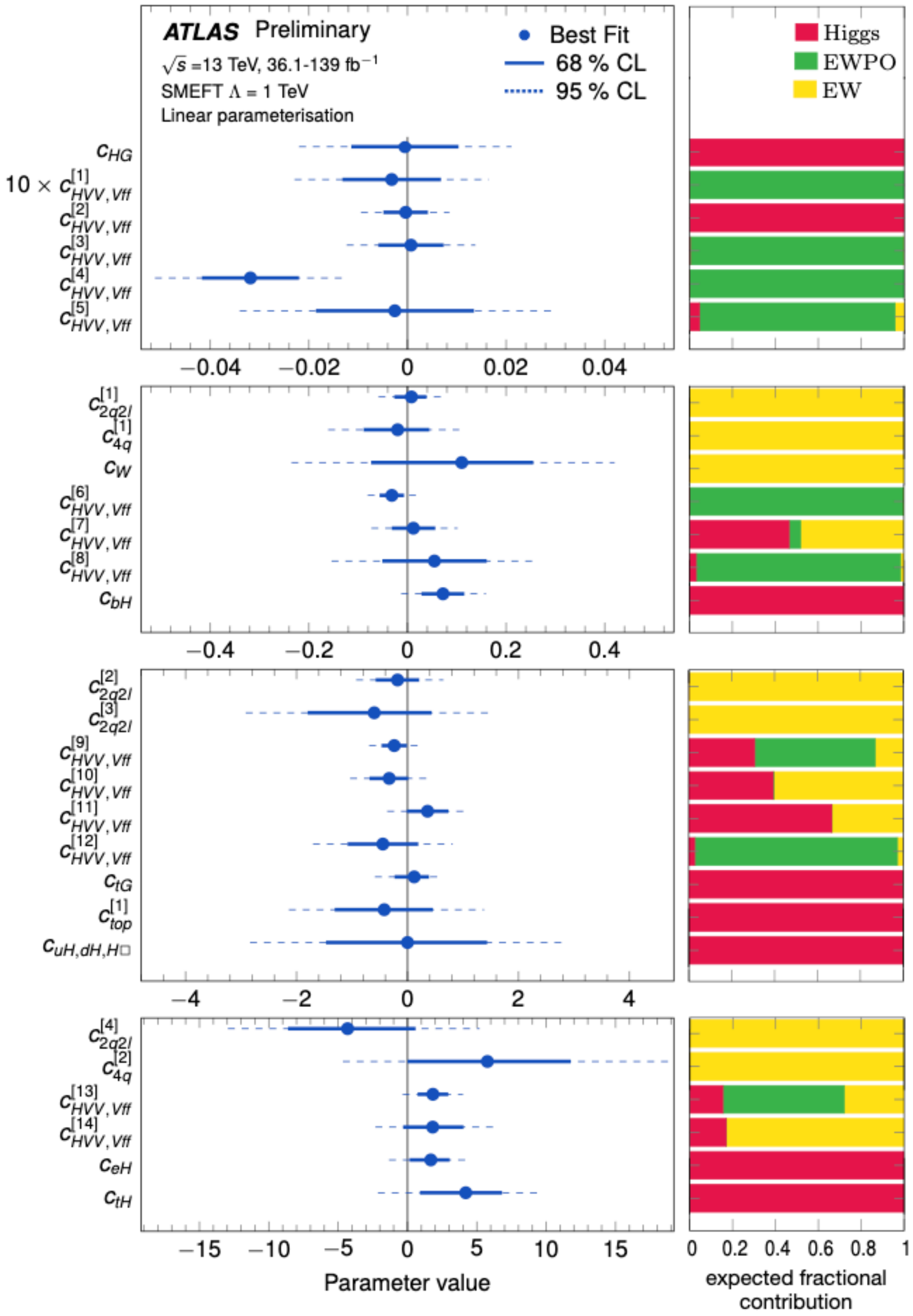
Run 2 combination of STXS in different Higgs final states measurements



Towards global fits

- SMEFT combination including
  - Higgs STXS
  - EWK measurements
  - EWPO (LEP)
- Complementarity of different observables
- Constrained 6 operators
- + 18 linear combinations

Observable	Measurement	Prediction	Ratio
Γ_Z [MeV]	2495.2 ± 2.3	2495.7 ± 1	0.9998 ± 0.0010
R^0_ℓ	20.767 ± 0.025	20.758 ± 0.008	1.0004 ± 0.0013
R^0_c	0.1721 ± 0.0030	0.17223 ± 0.00003	0.999 ± 0.017
R^0_b	0.21629 ± 0.00066	0.21586 ± 0.00003	1.0020 ± 0.0031
$A^{0,\ell}_{FB}$	0.0171 ± 0.0010	0.01718 ± 0.00037	0.995 ± 0.062
$A^{0,c}_{FB}$	0.0707 ± 0.0035	0.0758 ± 0.0012	0.932 ± 0.048
$A^{0,b}_{FB}$	0.0992 ± 0.0016	0.1062 ± 0.0016	0.935 ± 0.021
σ^0_{had} [pb]	41488 ± 6	41489 ± 5	0.99998 ± 0.00019

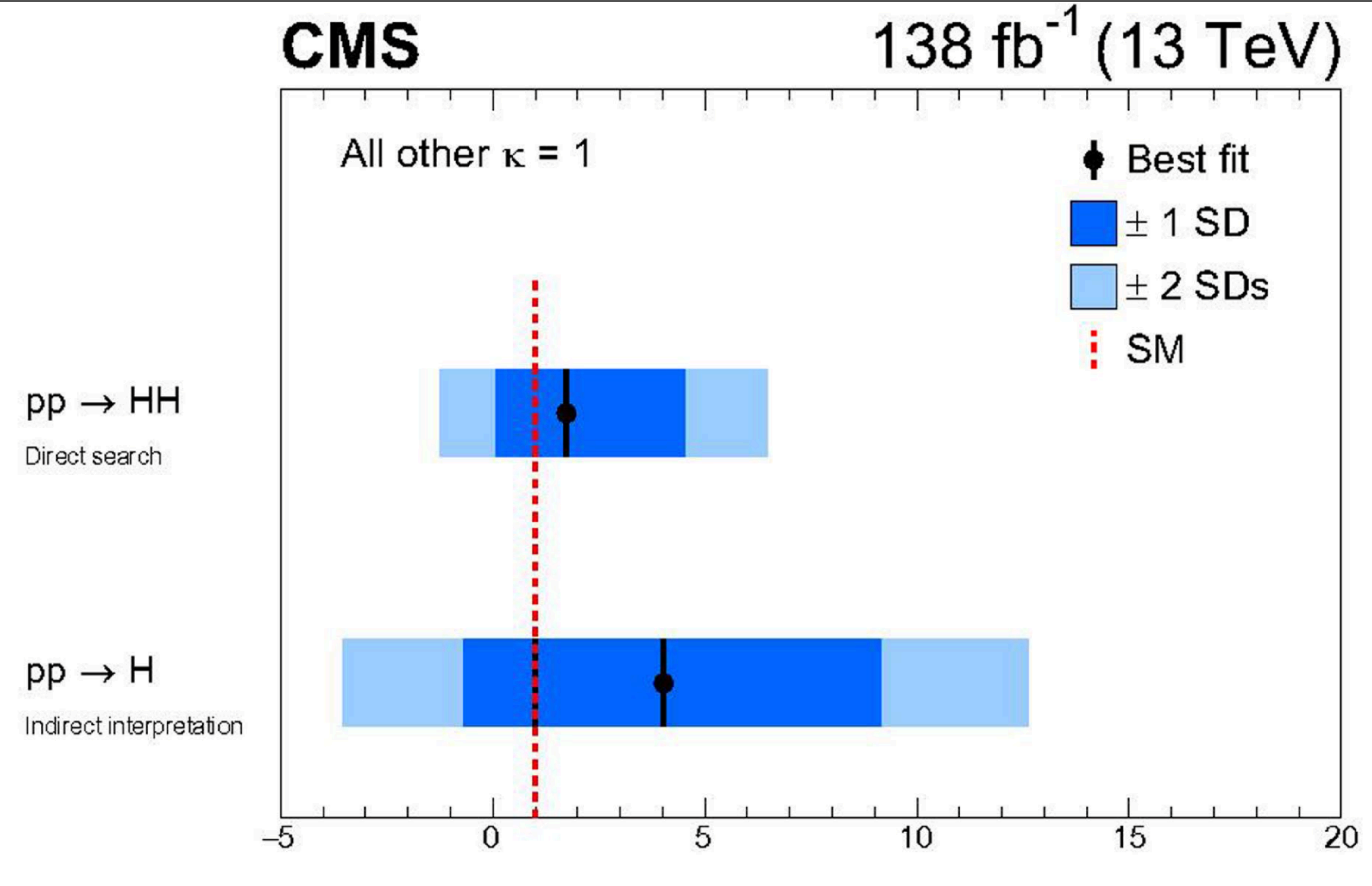


ATL-PHYS-PUB-2022-037

Higgs potential: di-Higgs is essential

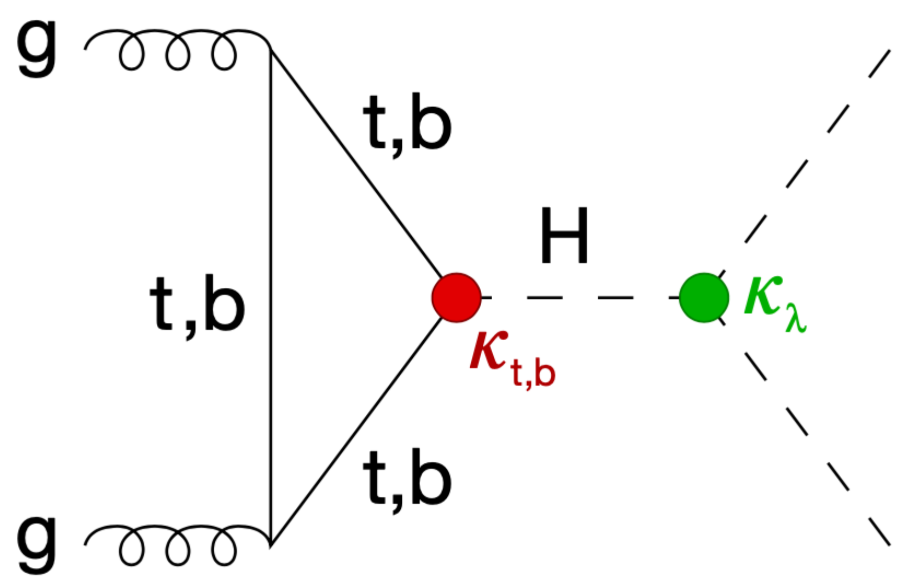
$$V(\phi) = \frac{1}{2}m_H^2\phi^2 + \lambda\nu\phi^3 + \frac{1}{4}\lambda\phi^4$$

$$\kappa_\lambda = \frac{\lambda}{\lambda_{SM}}$$

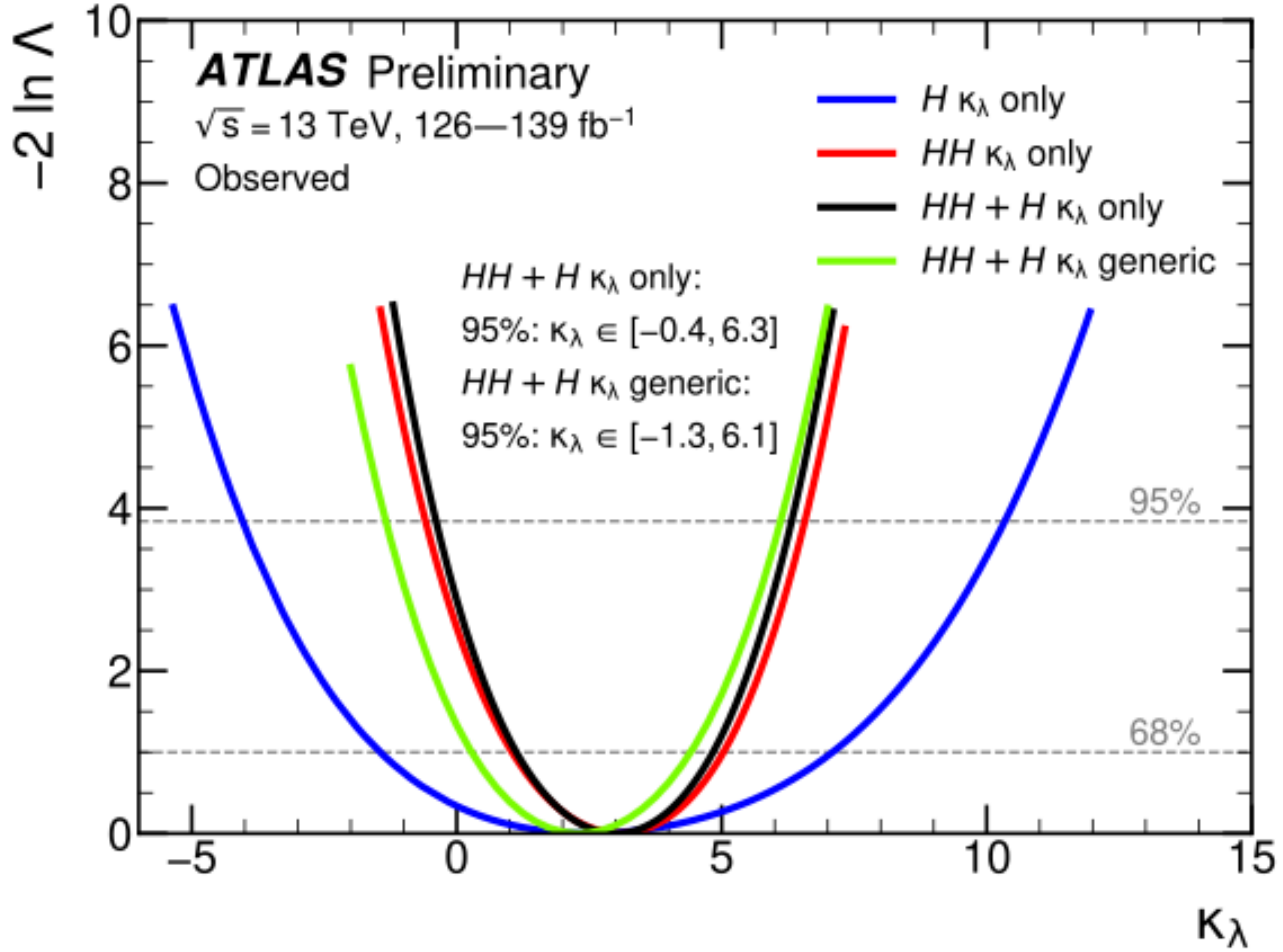


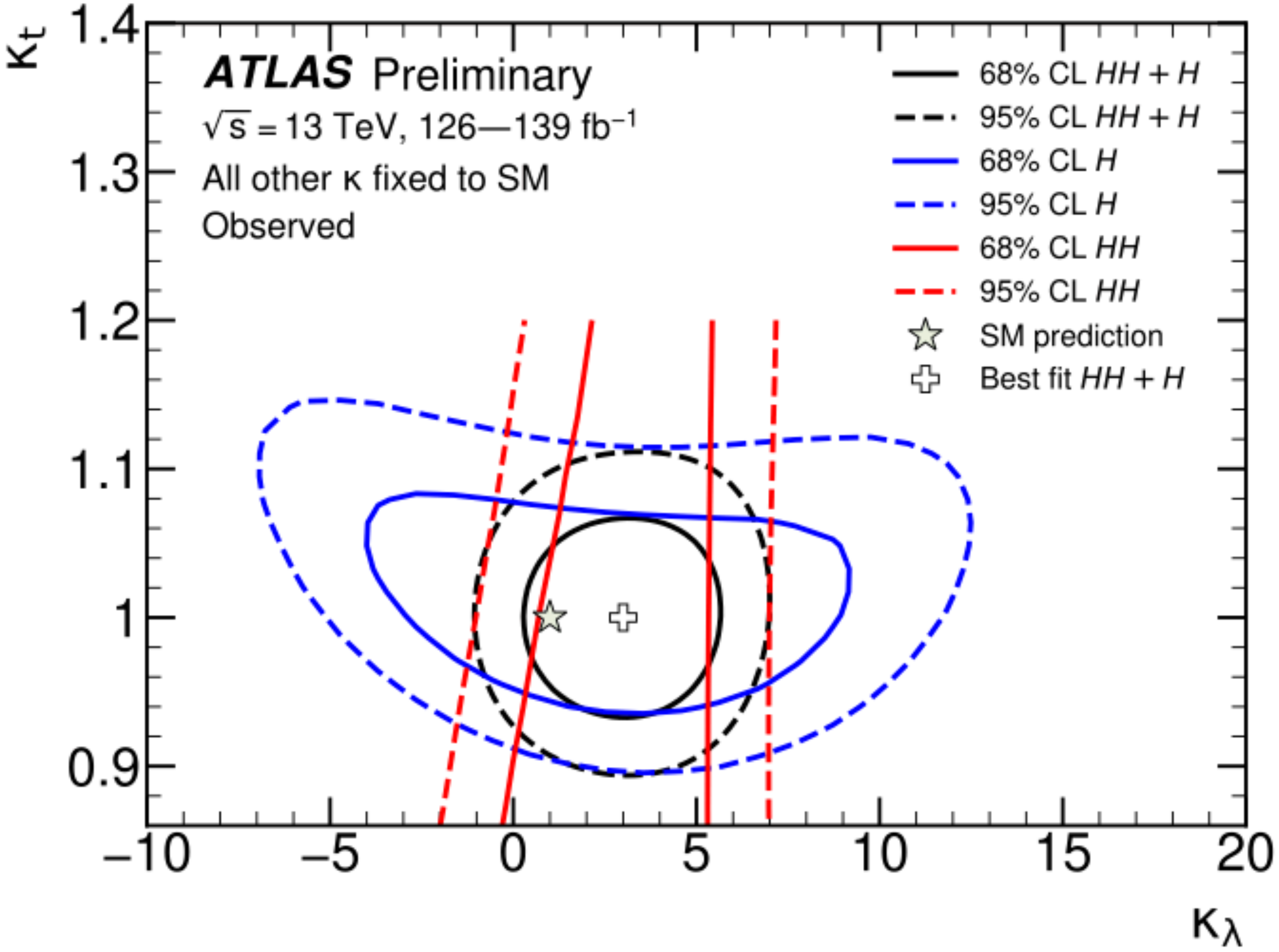
Nature 607, 60–68 (2022)

κ_λ from di-Higgs production



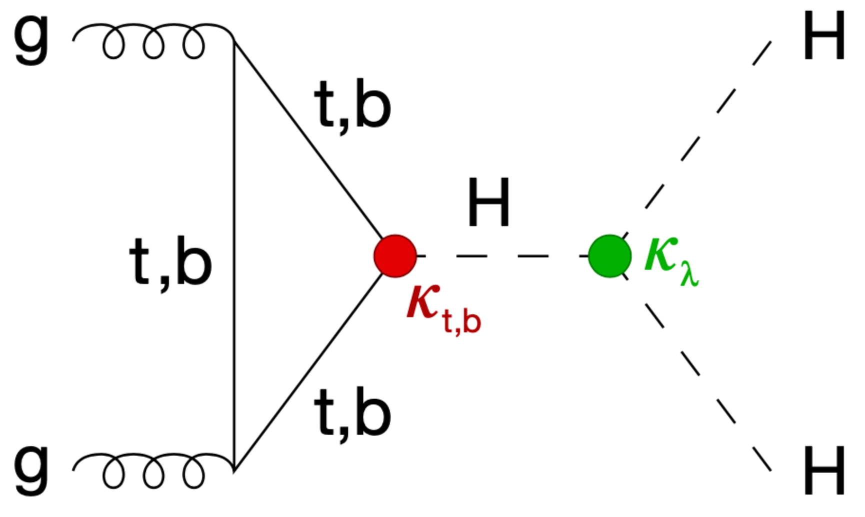
Significant improvement wrt. projection studies in di-Higgs analyses, due to the analyses techniques and particle identification. Combination of $HH \rightarrow b\bar{b}b\bar{b}$, $b\bar{b}\tau\tau$, $b\bar{b}\gamma\gamma$ with single Higgs measurements to extract the constraints on Higgs self coupling (+ κ_λ vs. κ_t)





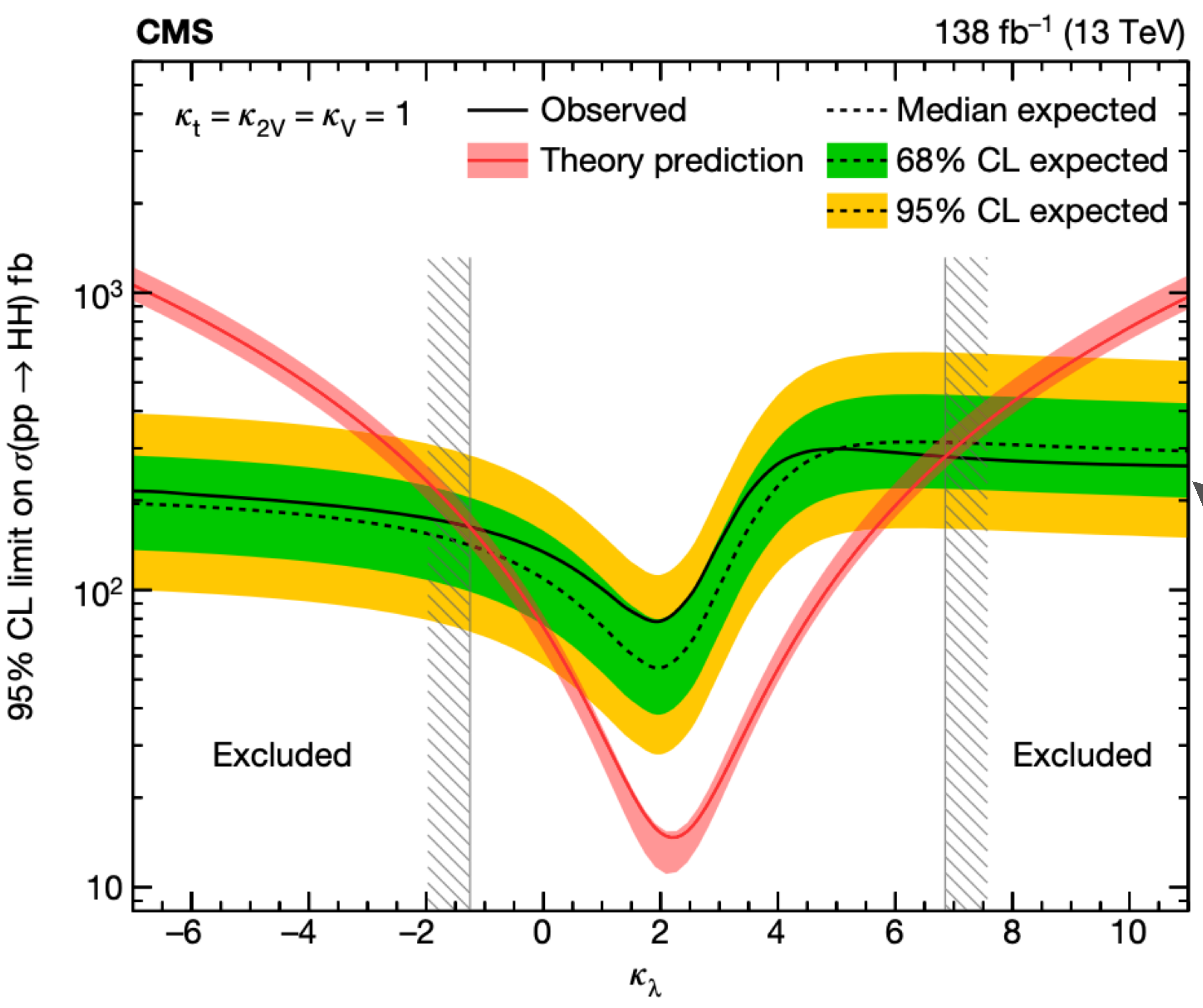
arxiv:211.01216

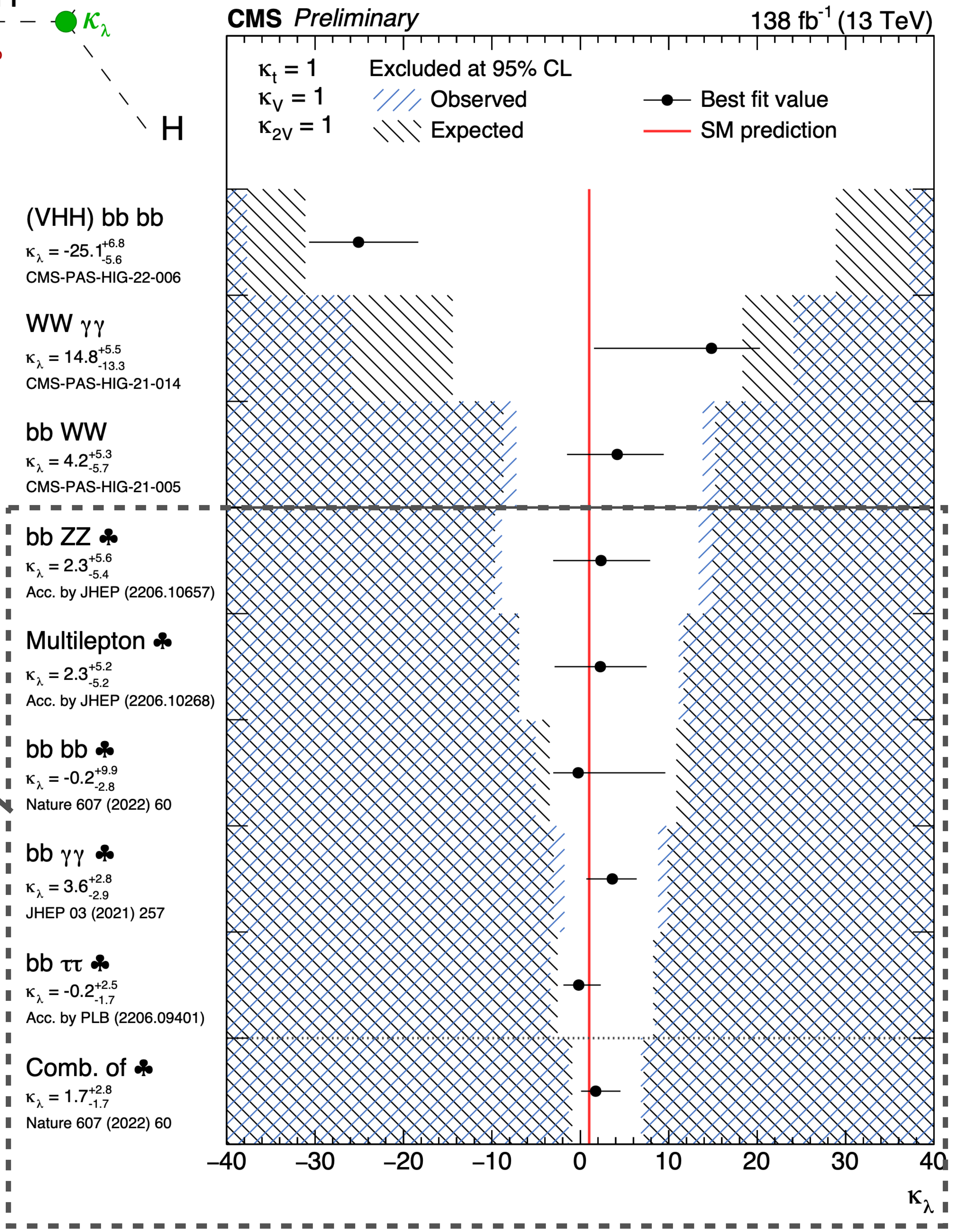
HH production at CMS



Multiple final states are already being probed:

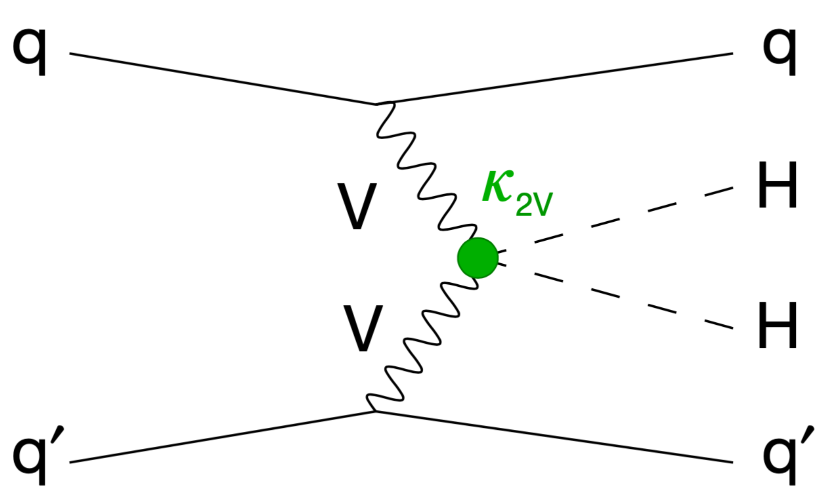
Nature 607, 60–68 (2022)



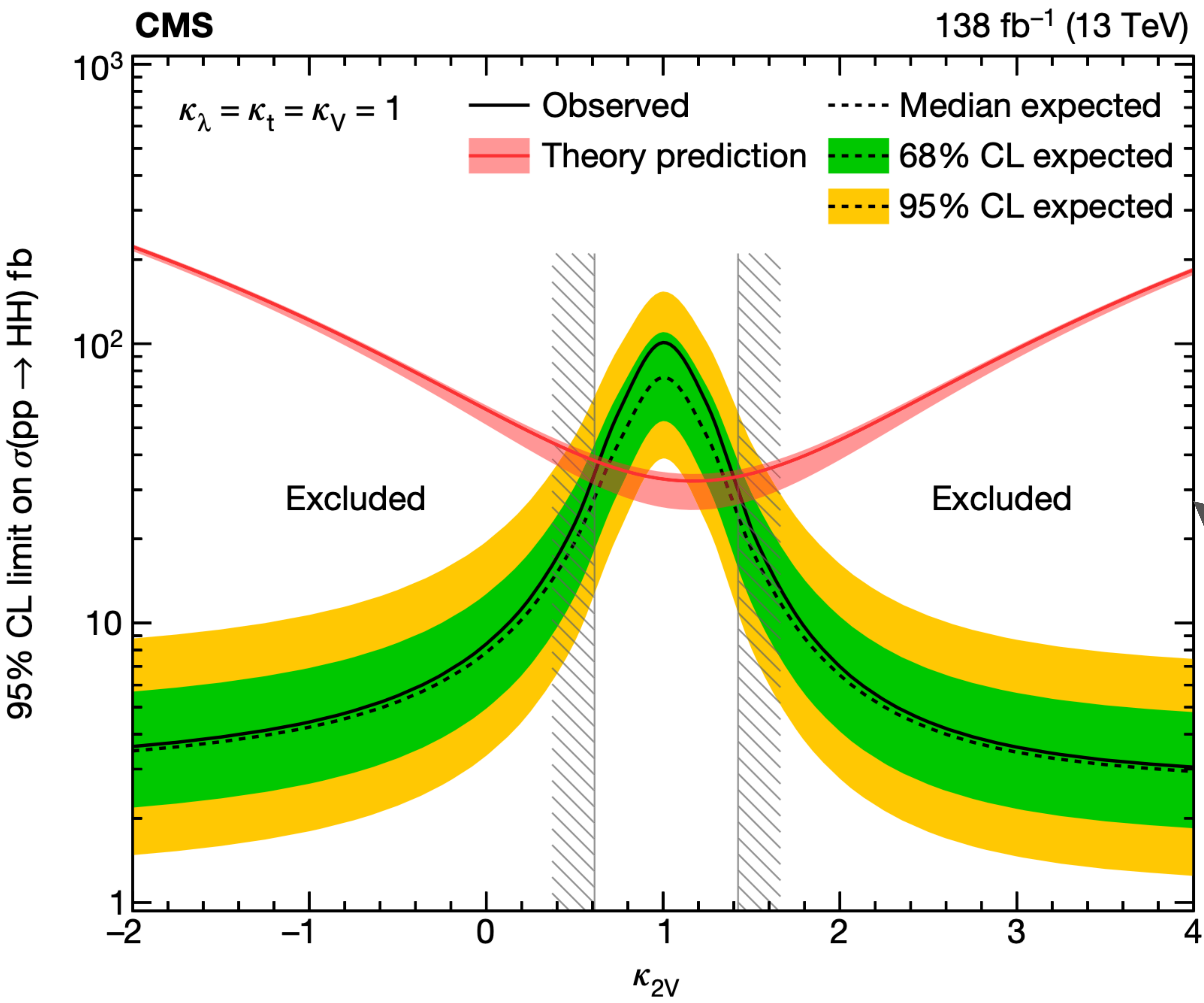


HH production at CMS

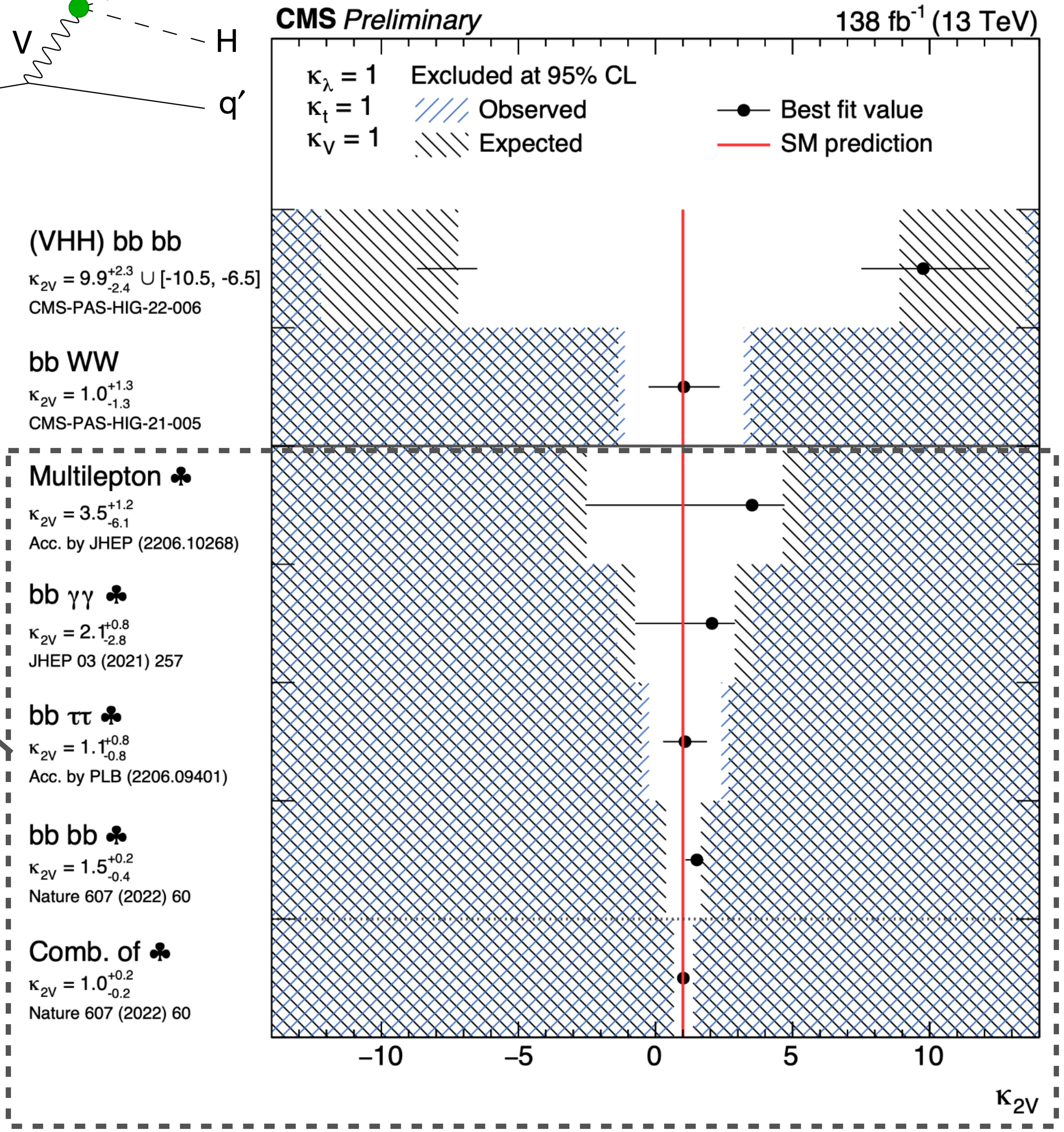
Multiple final states are already being probed:



Nature 607, 60–68 (2022)

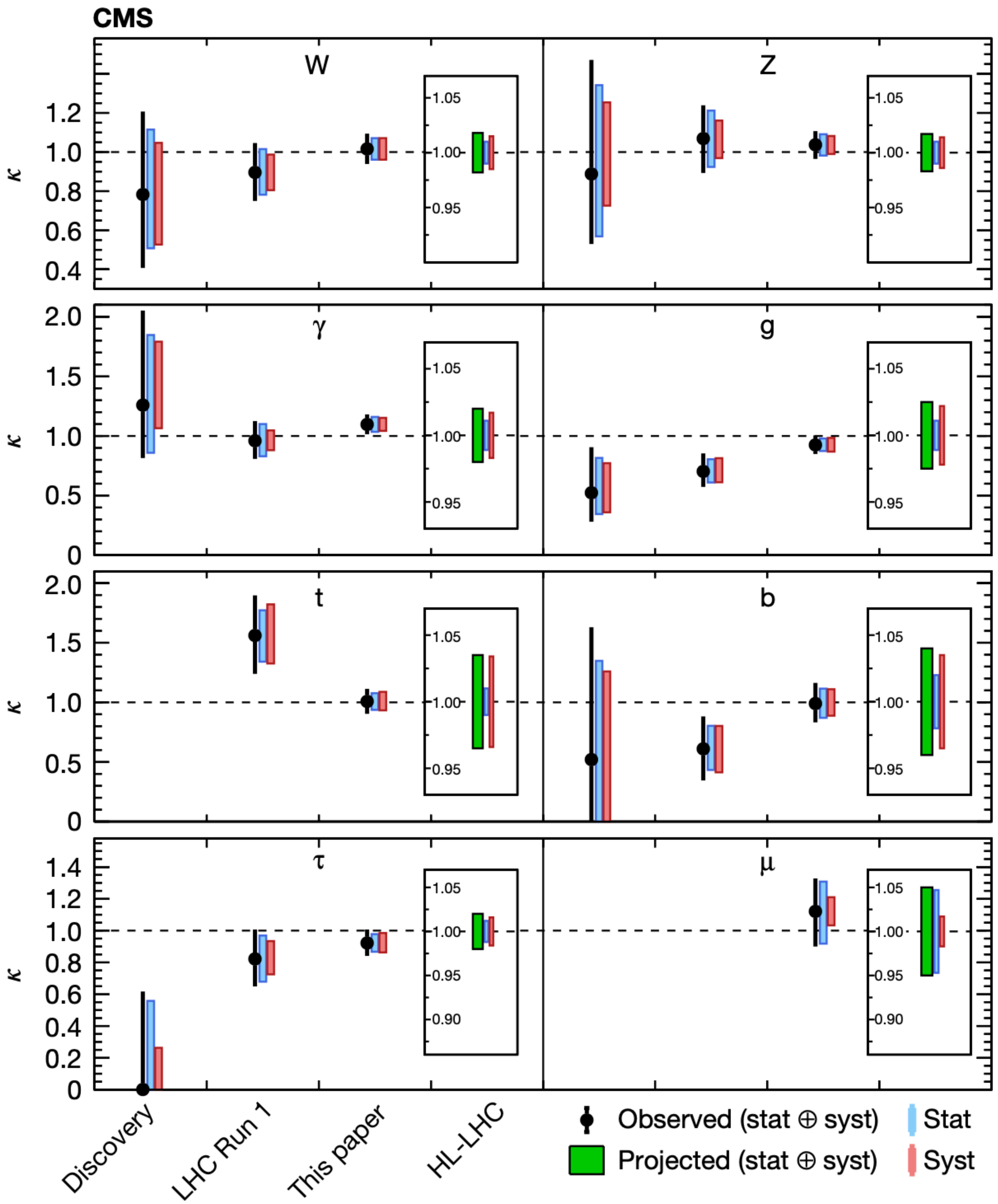


$\kappa_{2V} = 0$ excluded at 6.6 s.d.



Summary

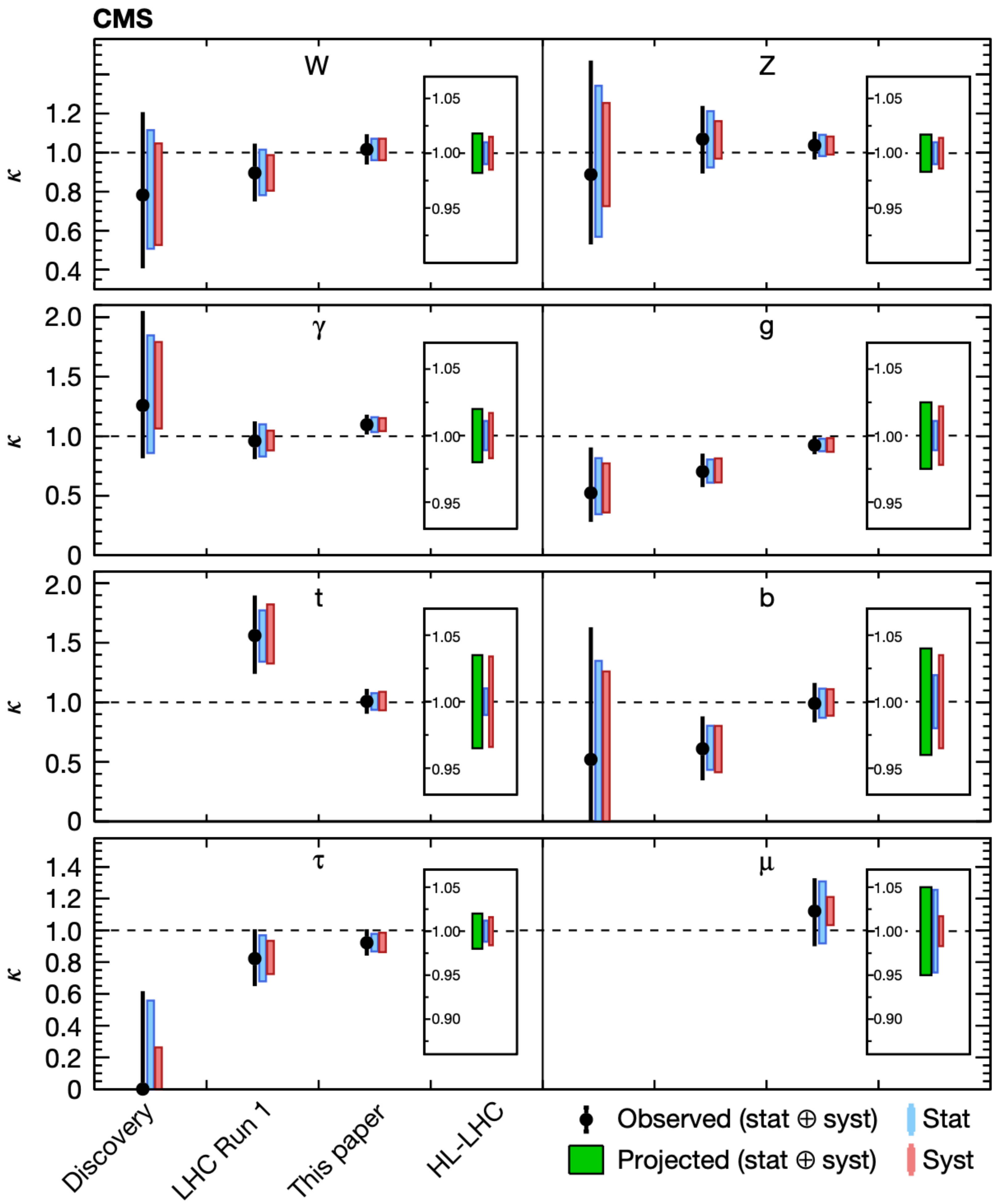
- Highlights from Run 2 SM Higgs measurements are presented
- Inclusive signal strength is measured with 6% accuracy
- Couplings with bosons and 3rd generation fermions are established with precision ~10%
- Differential and STXS measurements are published for the majority of channels
    - Stress-testing the precision with SMEFT (backup)
- HH is being explored, many final states, sensitivity exceeding expectations from conservative projections
- Run 3 is ongoing, first Higgs measurement from ATLAS $\sqrt{s} = 13.6$ TeV
- **Next 10 years promise significant progress**

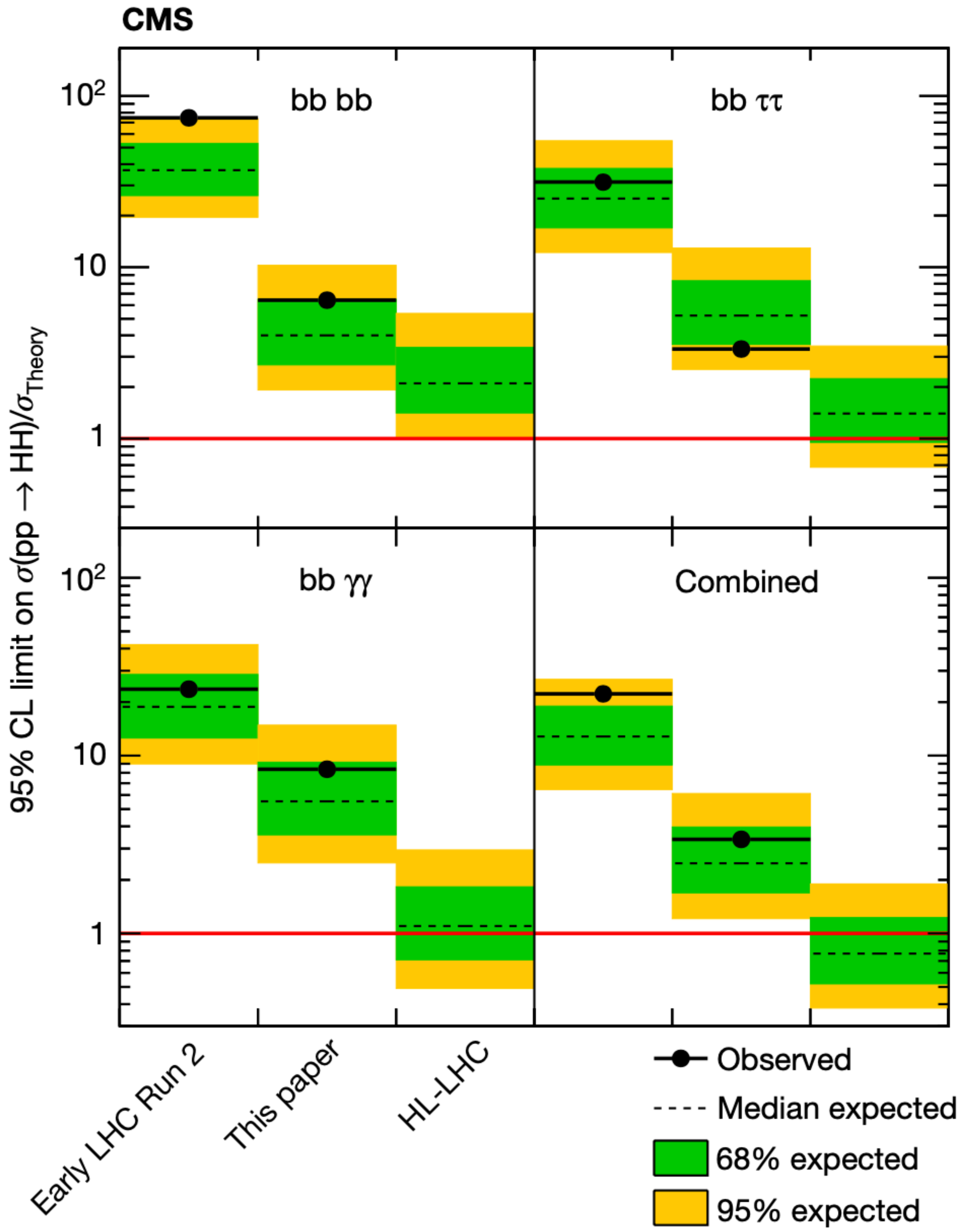


Backup

Projections

Run 1, Run 2, HL-LHC





Higgs CP (SMEFT)

arXiv:2304.09612

- Parametrise CP-odd effects by expanding the SM with dim6 SMEFT operators

Operator	Structure	Coupling
Warsaw Basis		
$O_{\Phi\tilde{W}}$	$\Phi^\dagger\Phi\tilde{W}^I_{\mu\nu}W^{\mu\nu I}$	$c_{H\widetilde{W}}$
$O_{\Phi\tilde{W}B}$	$\Phi^\dagger\tau^I\Phi\tilde{W}^I_{\mu\nu}B^{\mu\nu}$	$c_{H\widetilde{W}B}$
$O_{\Phi\tilde{B}}$	$\Phi^\dagger\Phi\tilde{B}_{\mu\nu}B^{\mu\nu}$	$c_{H\widetilde{B}}$
Higgs Basis		
$O_{hZ\tilde{Z}}$	$hZ_{\mu\nu}\tilde{Z}^{\mu\nu}$	$\tilde{c}_{zz}$
$O_{hZ\tilde{A}}$	$hZ_{\mu\nu}\tilde{A}^{\mu\nu}$	$\tilde{c}_{z\gamma}$
$O_{hA\tilde{A}}$	$hA_{\mu\nu}\tilde{A}^{\mu\nu}$	$\tilde{c}_{\gamma\gamma}$

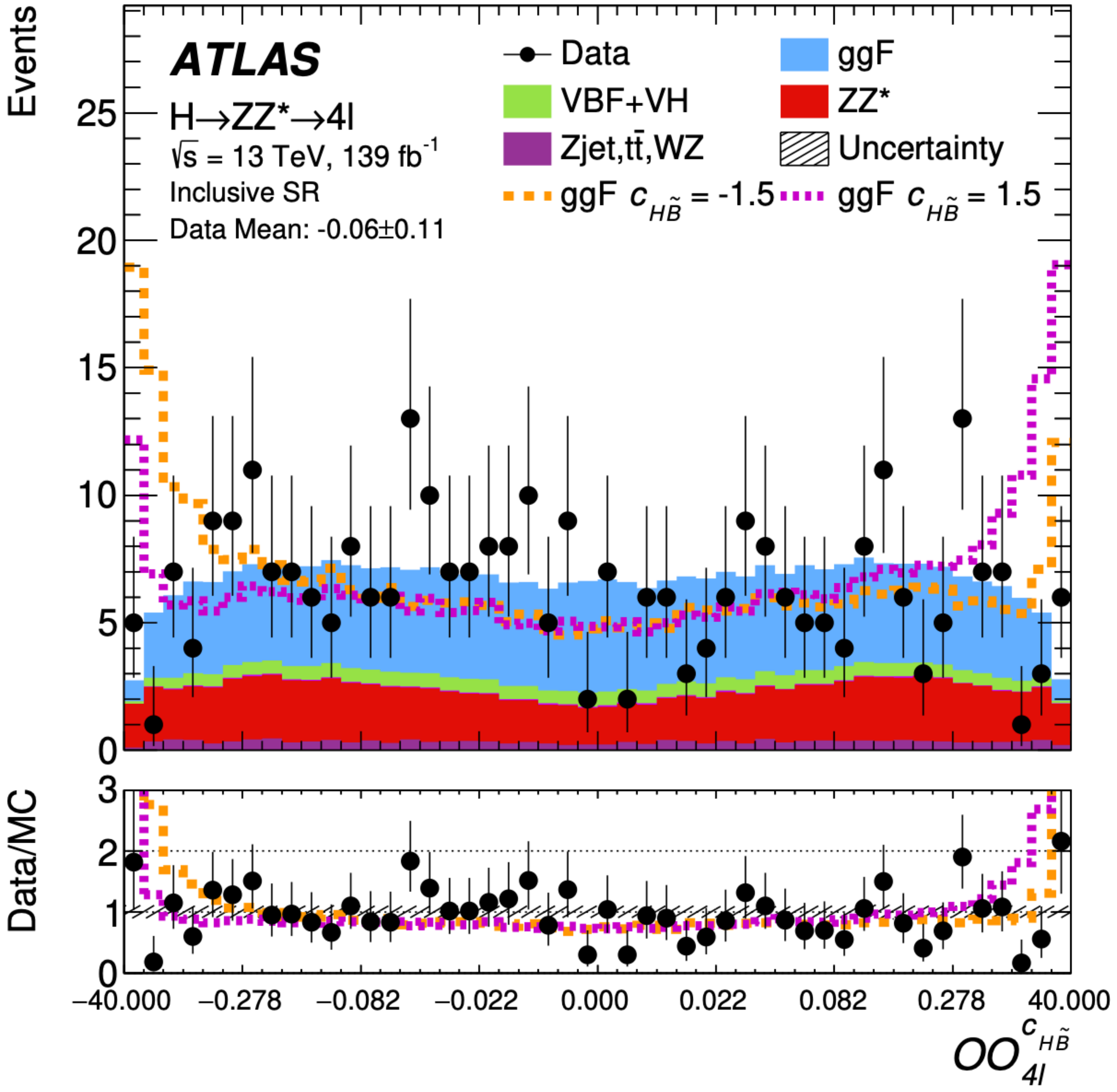
- $$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2} O_i^{(6)}$$

$$|\mathcal{M}|^2 = \left|\mathcal{M}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{M}_{\text{BSM},i}\right|^2$$

$$= |\mathcal{M}_{\text{SM}}|^2 + 2\sum_i \frac{c_i}{\Lambda^2}\Re\left(\mathcal{M}^*_{\text{SM}}\mathcal{M}_{\text{BSM},i}\right) + \sum_i\sum_j \frac{c_i c_j}{\Lambda^4}\Re\left(\mathcal{M}^*_{\text{BSM},i}\mathcal{M}_{\text{BSM},j}\right)$$

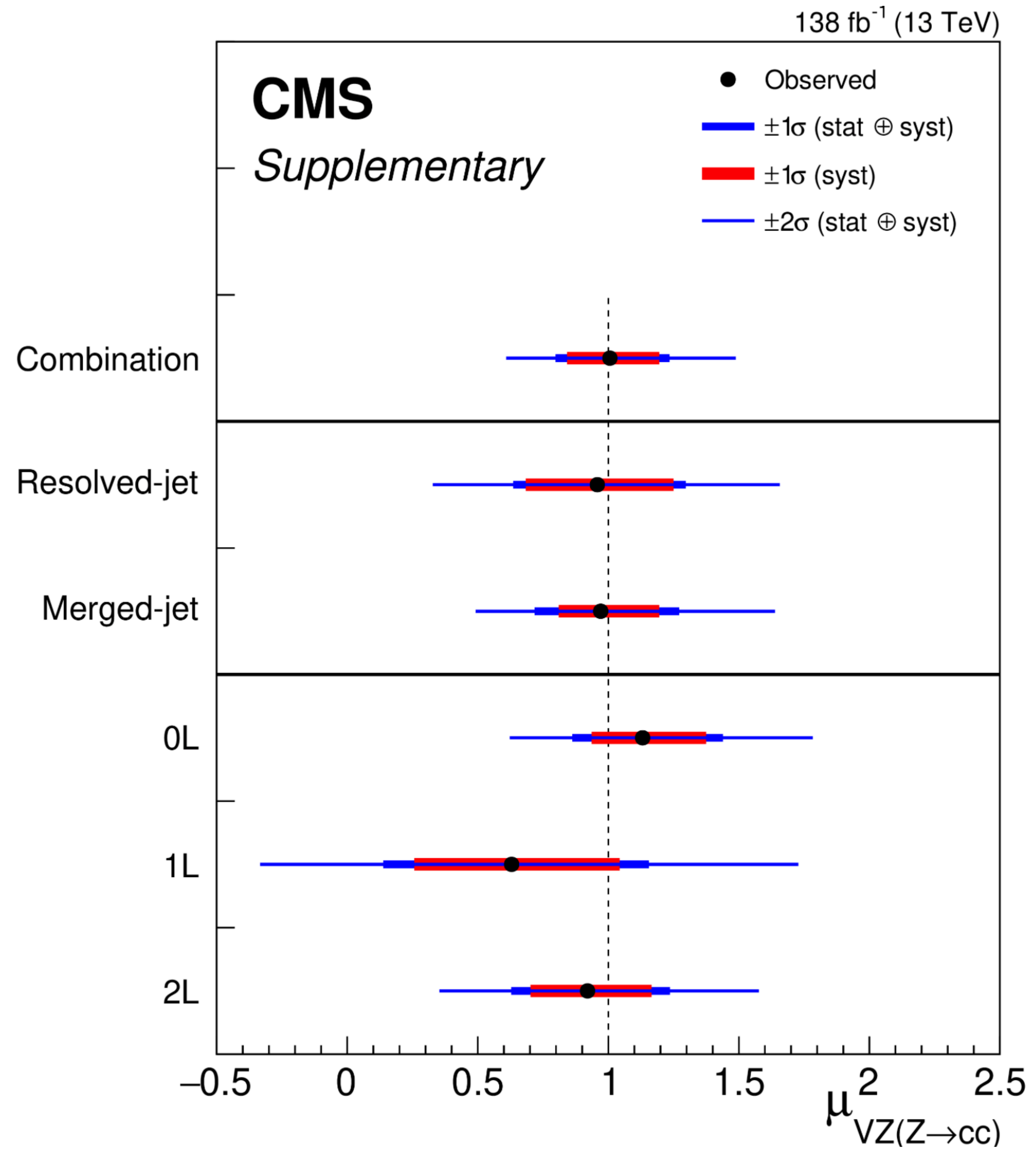
- Optimal observable constructed based on the BSM/SM matrix element ratio:

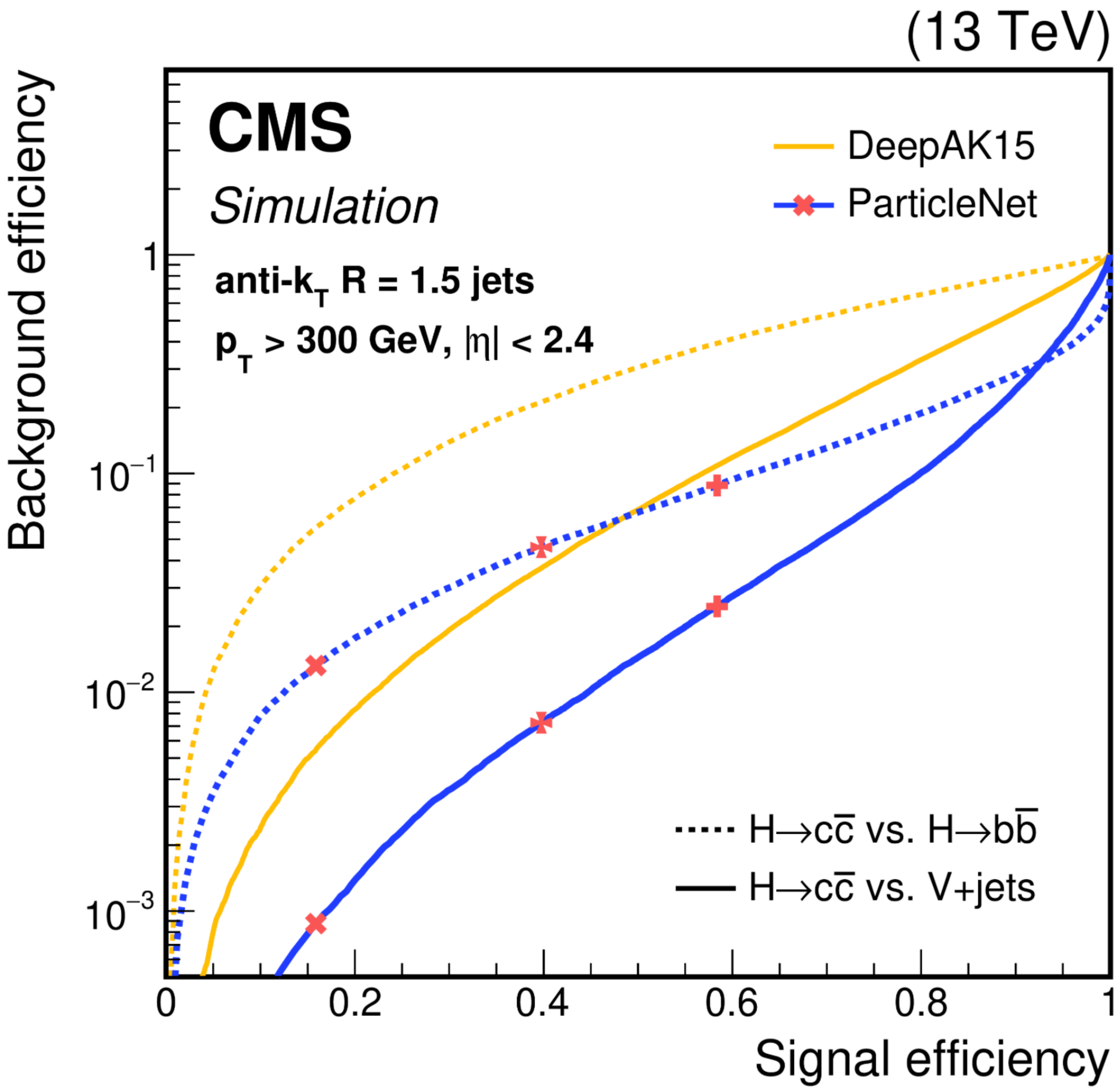
$$OO = \frac{2\Re\left(\mathcal{M}^*_{\text{SM}}\mathcal{M}_{\text{BSM}}\right)}{|\mathcal{M}_{\text{SM}}|^2}$$



$H \to c\bar{c}$ final state c-tagging

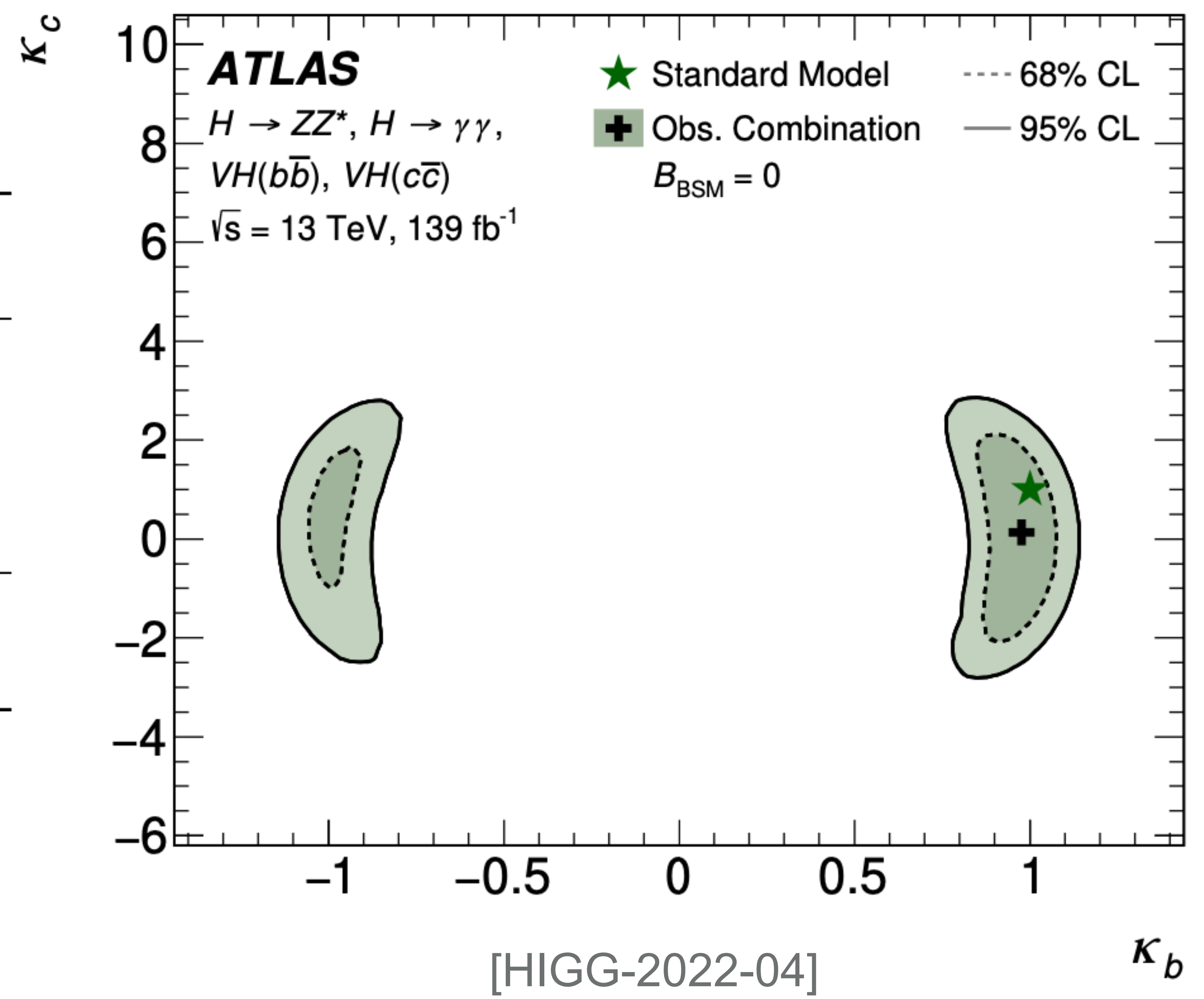
CMS-HIG-21-008





H → $\gamma\gamma$, ZZ final states

Channel	Parameter	Observed 95% confidence interval	Expected 95% confidence interval
$H \to ZZ^* \to 4\ell$	κ_b	$[-1.8,\ 6.4]$	$[-3.3,\ 9.3]$
	κ_c	$[-7.7,\ 18.3]$	$[-12.3,\ 19.2]$
$H \to \gamma\gamma$	κ_b	$[-3.5,\ 10.2]$	$[-2.5,\ 8.0]$
	κ_c	$[-12.6,\ 18.3]$	$[-10.1,\ 17.3]$
Combined	κ_b	$[-2.0,\ 7.4]$	$[-2.0,\ 7.4]$
	κ_c	$[-8.6,\ 17.3]$	$[-8.5,\ 15.9]$



[HIGG-2022-04]

arxiv:2304.03053

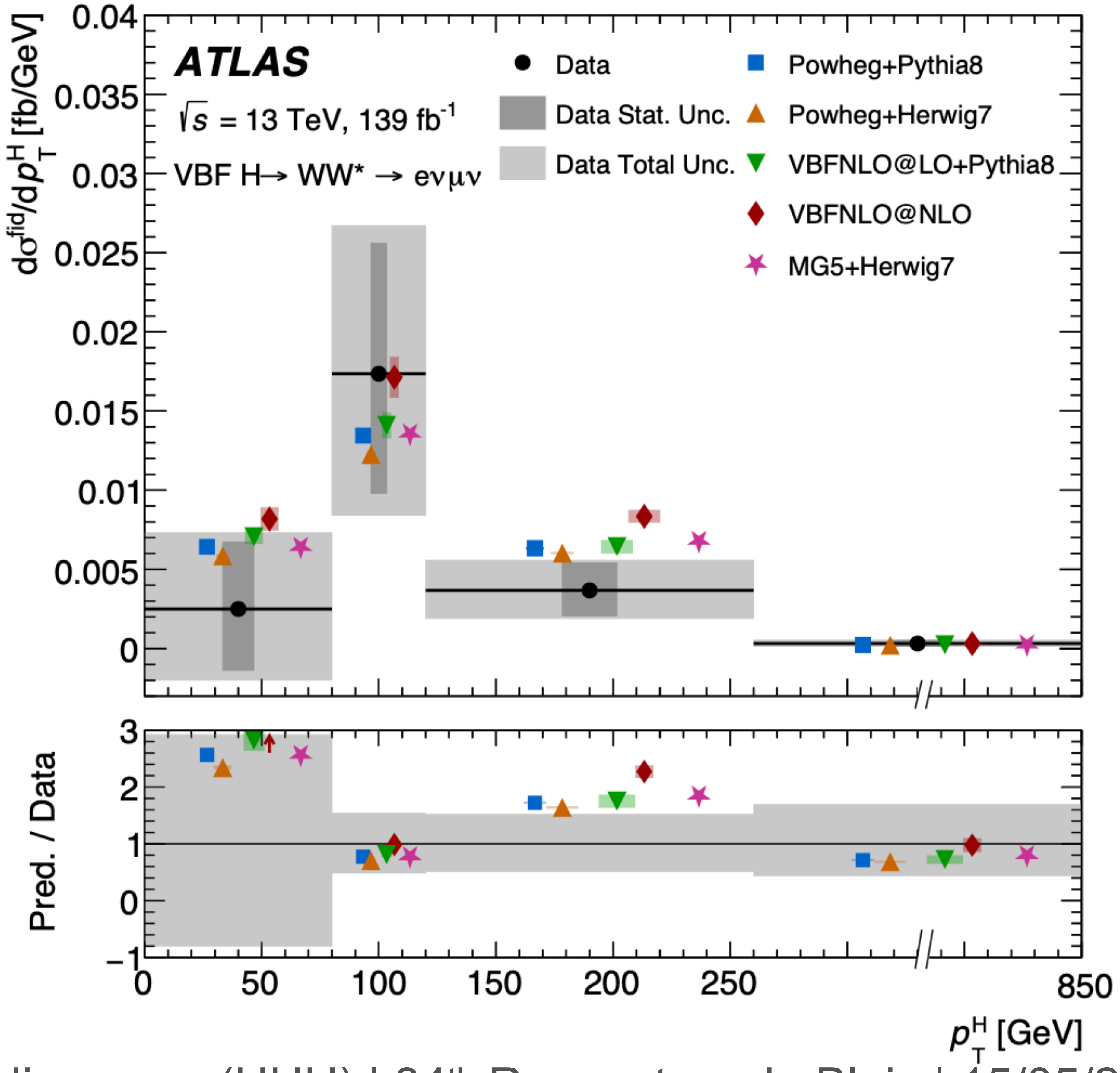
H→WW final state

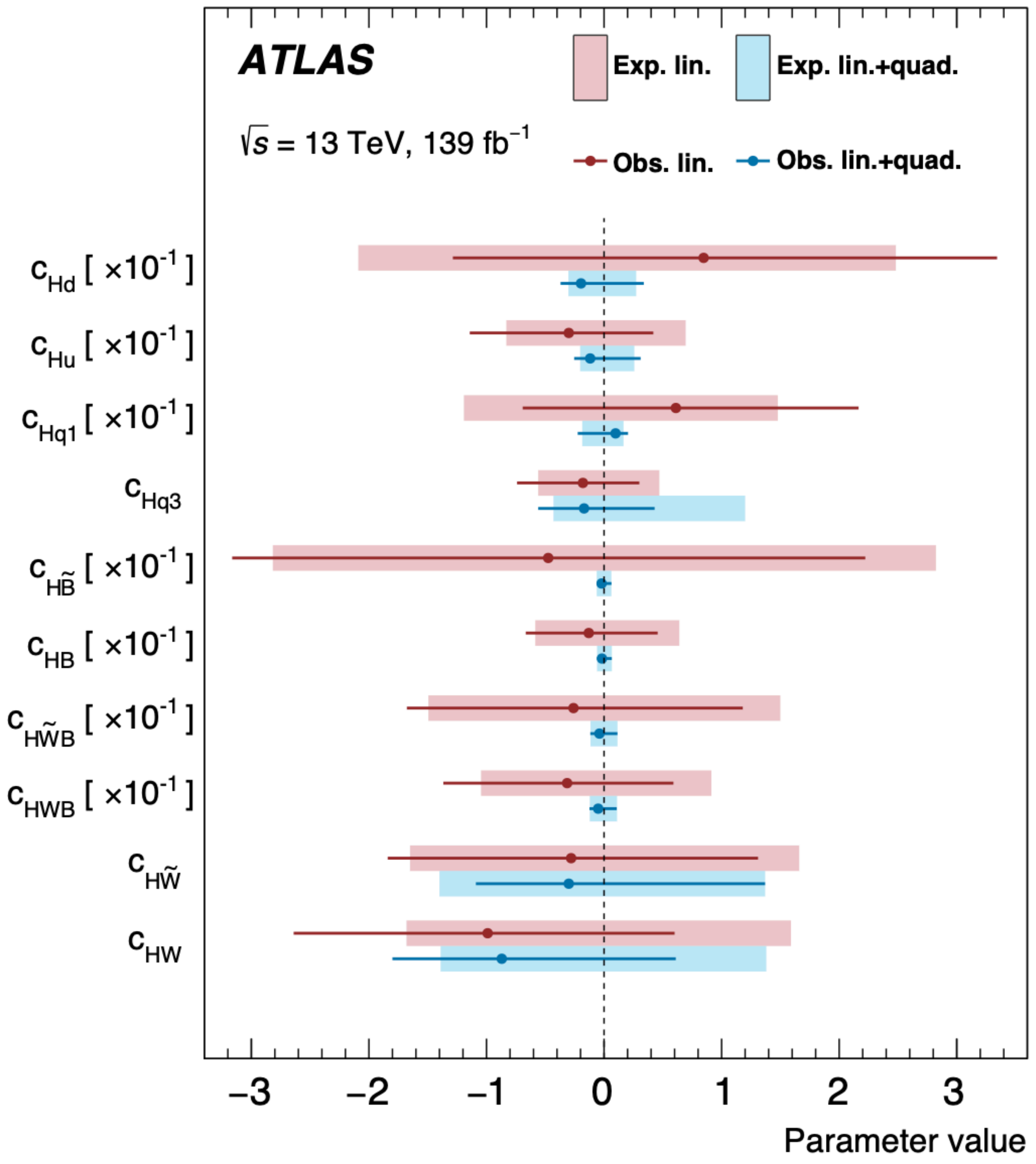
Differential VBF

VBF Run 2 differential analysis, Powheg, Madgraph predictions.

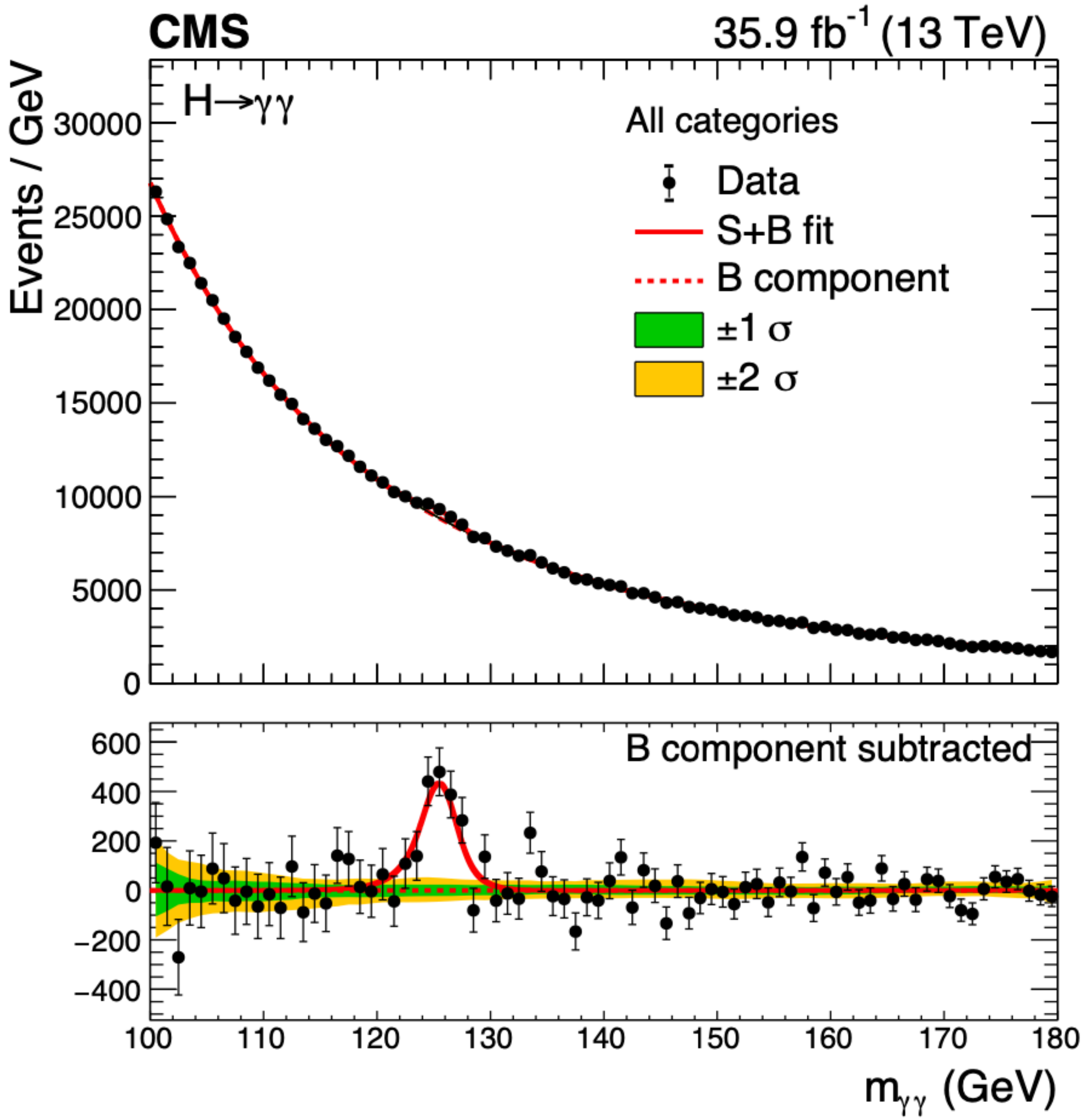
SMEFT interpretation, including CP-odd operators

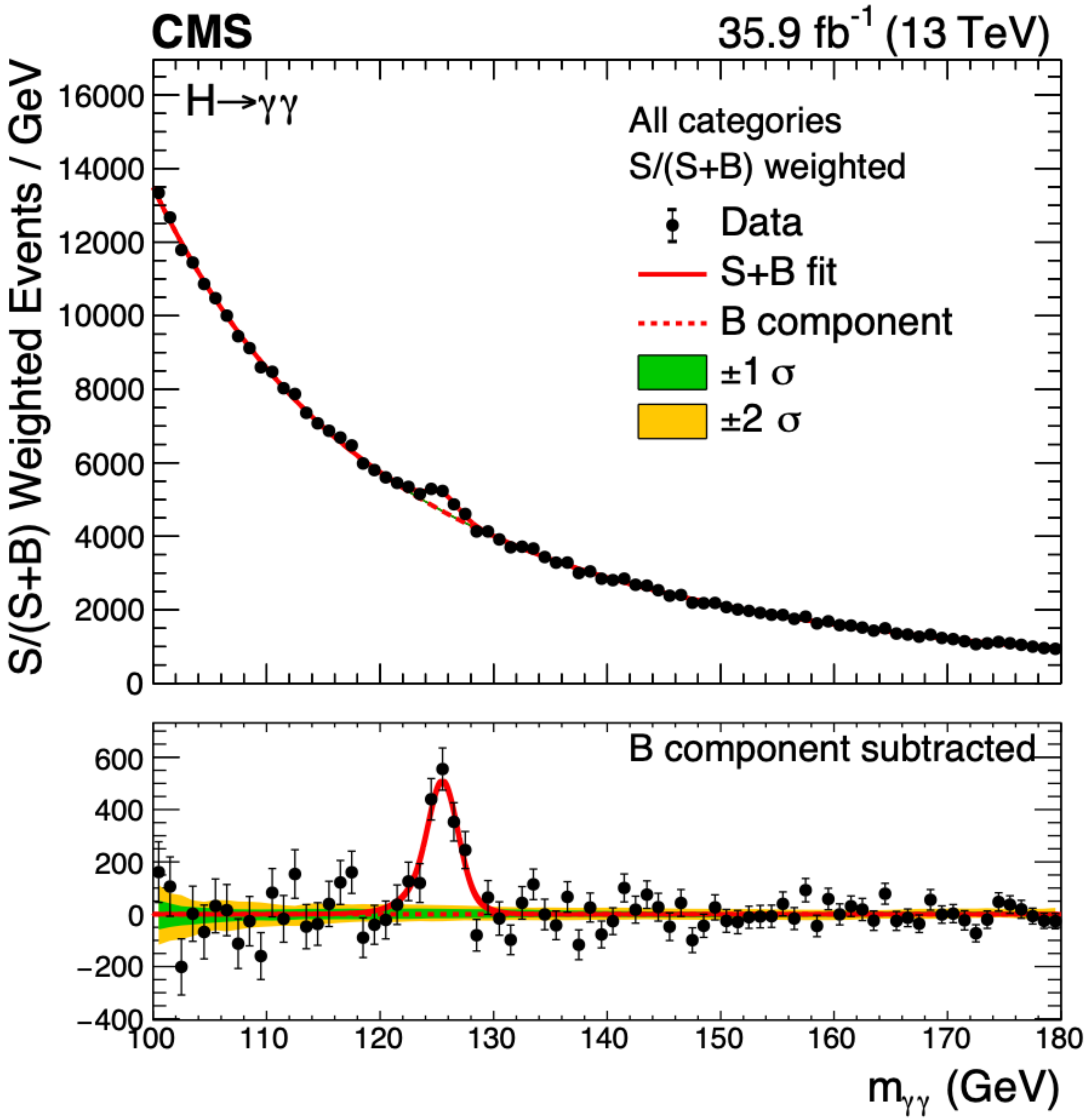
$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^2} O_i^{(6)}$$





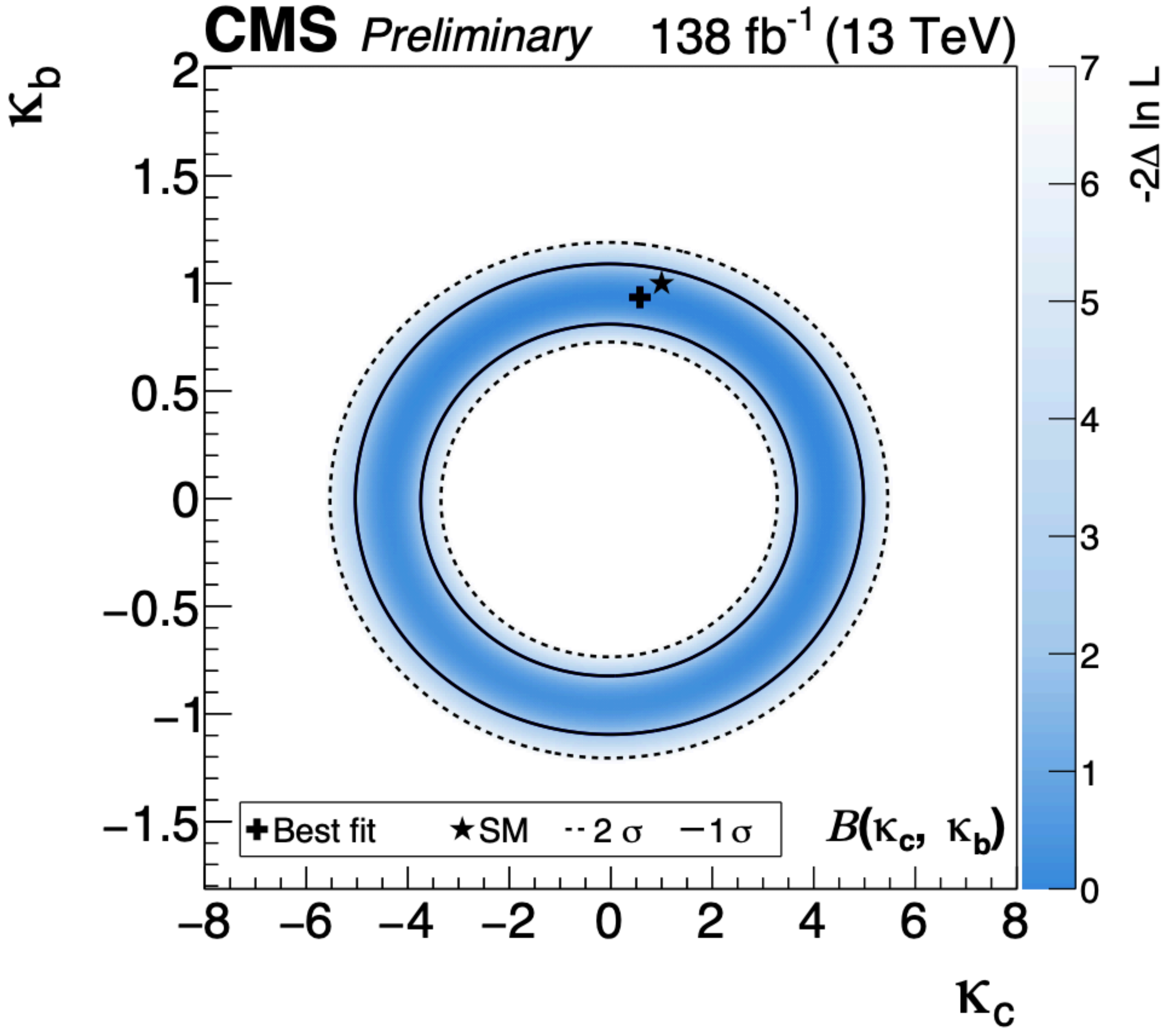
CMS H $\rightarrow \gamma\gamma$ mass measurement

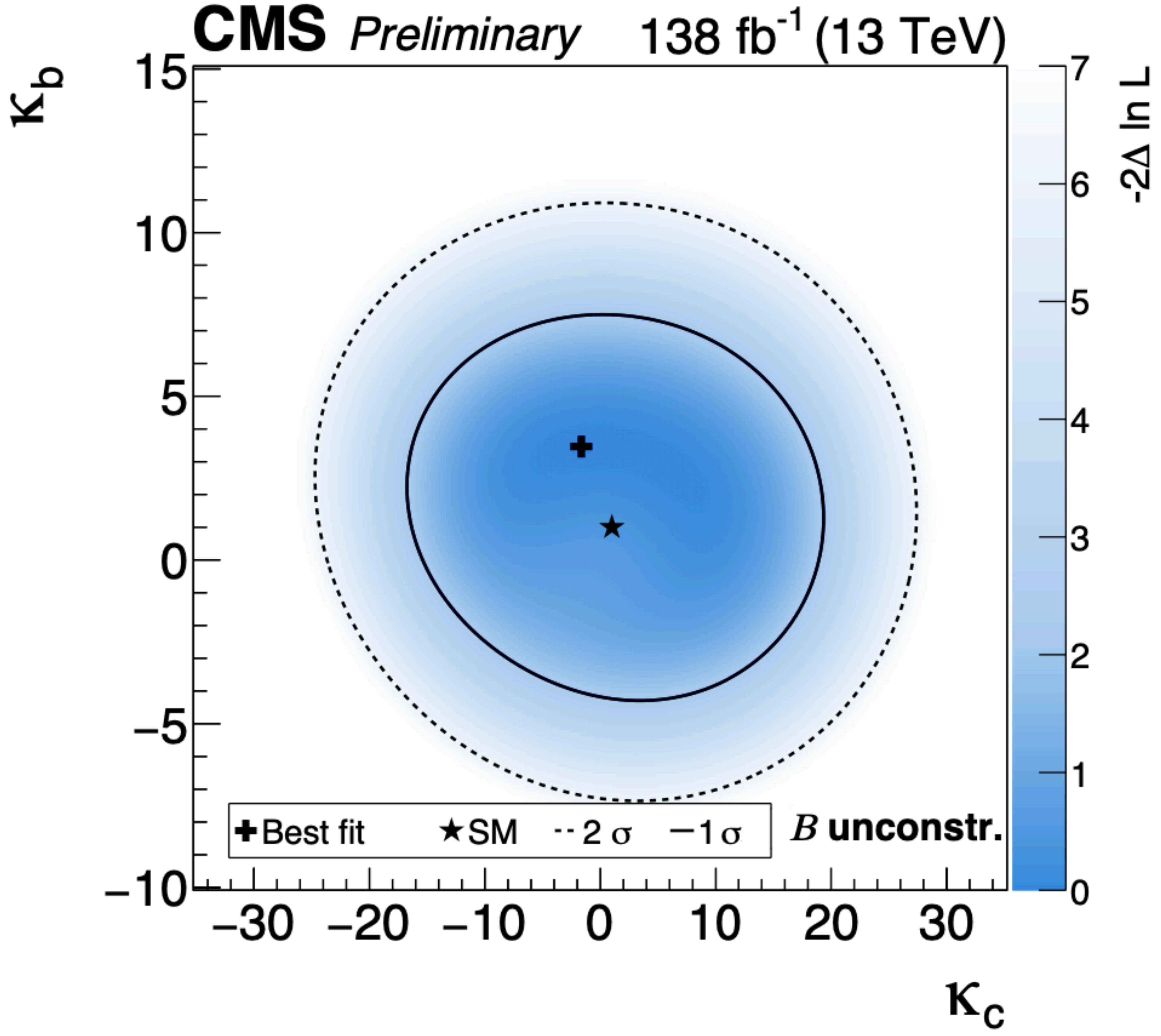




H→ZZ final state

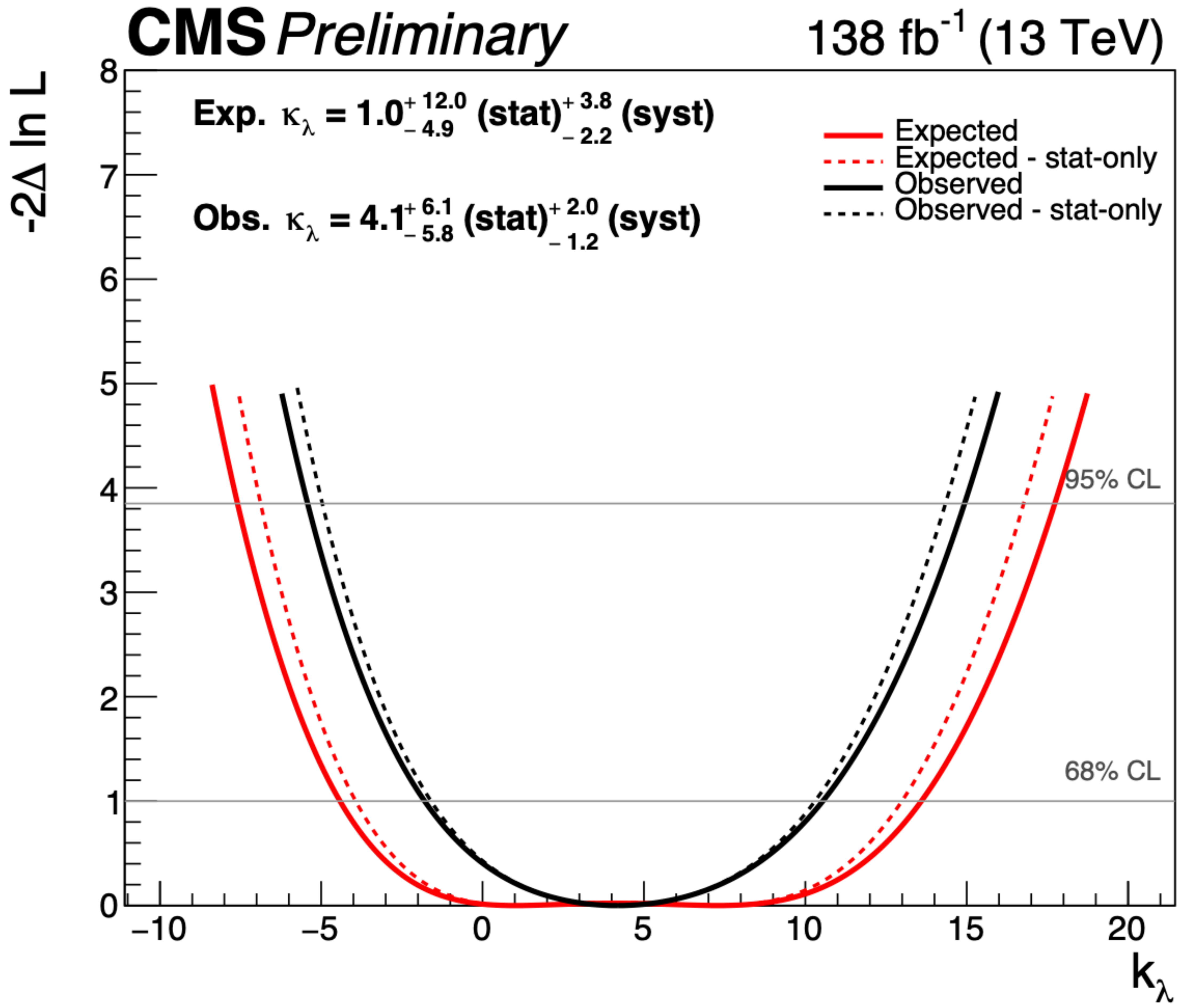
CMS-HIG-21-009

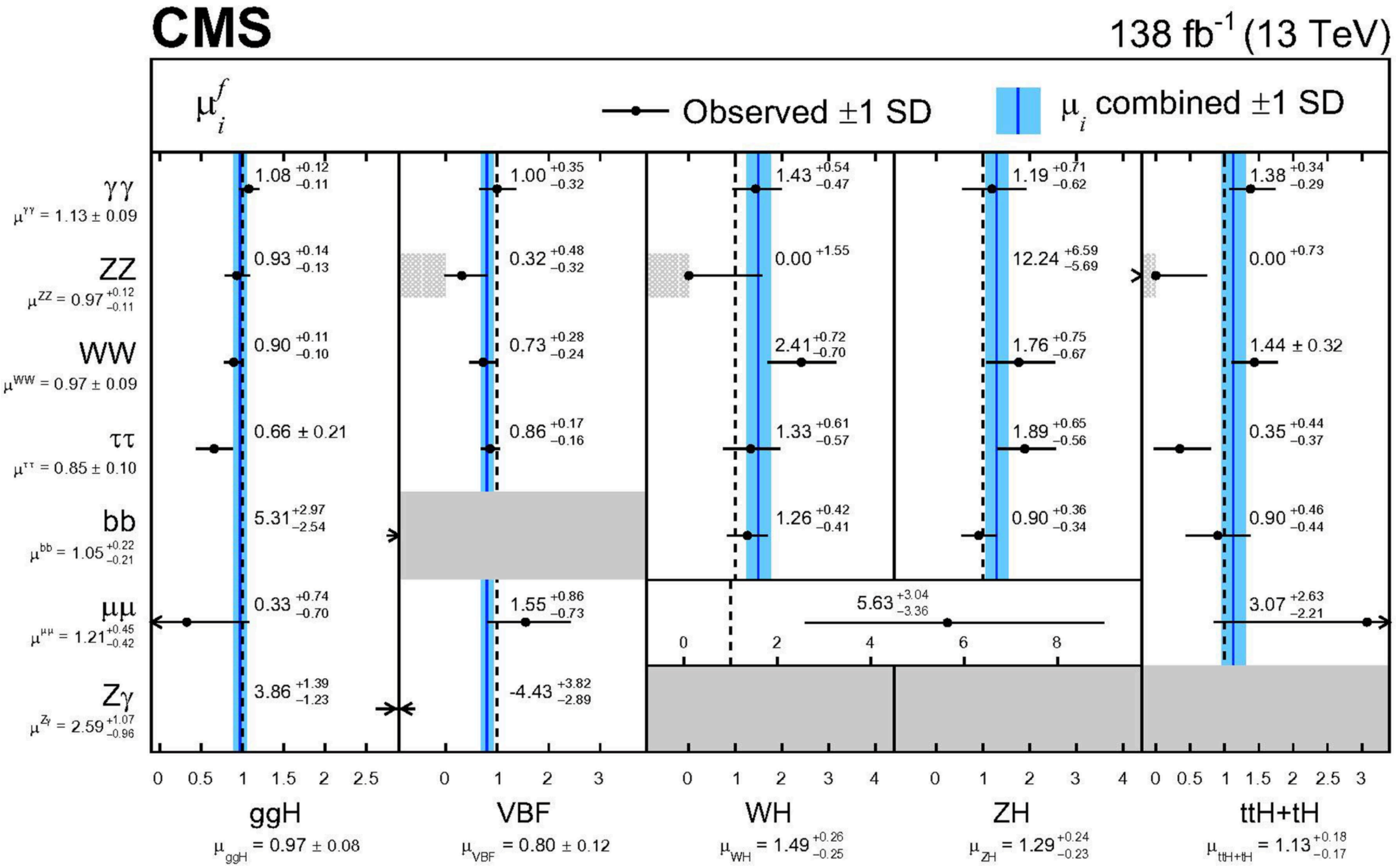




H→ZZ final state

CMS-HIG-21-009




CMS
138 fb-1 (13 TeV)
μ_i^f
Observed ±1 SD
μ_i combined ±1 SD
γγ
μ^γγ = 1.13 ± 0.09
ZZ
μ^ZZ = 0.97 +0.12 −0.11
WW
μ^WW = 0.97 ± 0.09
ττ
μ^ττ = 0.85 ± 0.10
bb
μ^bb = 1.05 +0.22 −0.21
μμ
μ^μμ = 1.21 +0.45 −0.42
Zγ
μ^Zγ = 2.59 +1.07 −0.96
1.08 +0.12 −0.11
0.93 +0.14 −0.13
0.90 +0.11 −0.10
0.66 ± 0.21
5.31 +2.97 −2.54
0.33 +0.74 −0.70
3.86 +1.39 −1.23
1.00 +0.35 −0.32
0.32 +0.48 −0.32
0.73 +0.28 −0.24
0.86 +0.17 −0.16
1.55 +0.86 −0.73
-4.43 +3.82 −2.89
1.43 +0.54 −0.47
0.00 +1.55
2.41 +0.72 −0.70
1.33 +0.61 −0.57
1.26 +0.42 −0.41
5.63 +3.04 −3.36
1.19 +0.71 −0.62
12.24 +6.59 −5.69
1.76 +0.75 −0.67
1.89 +0.65 −0.56
0.90 +0.36 −0.34
1.38 +0.34 −0.29
0.00 +0.73
1.44 ± 0.32
0.35 +0.44 −0.37
0.90 +0.46 −0.44
3.07 +2.63 −2.21
ggH
μ_ggH = 0.97 ± 0.08
VBF
μ_VBF = 0.80 ± 0.12
WH
μ_WH = 1.49 +0.26 −0.25
ZH
μ_ZH = 1.29 +0.24 −0.23
ttH+tH
μ_ttH+tH = 1.13 +0.18 −0.17