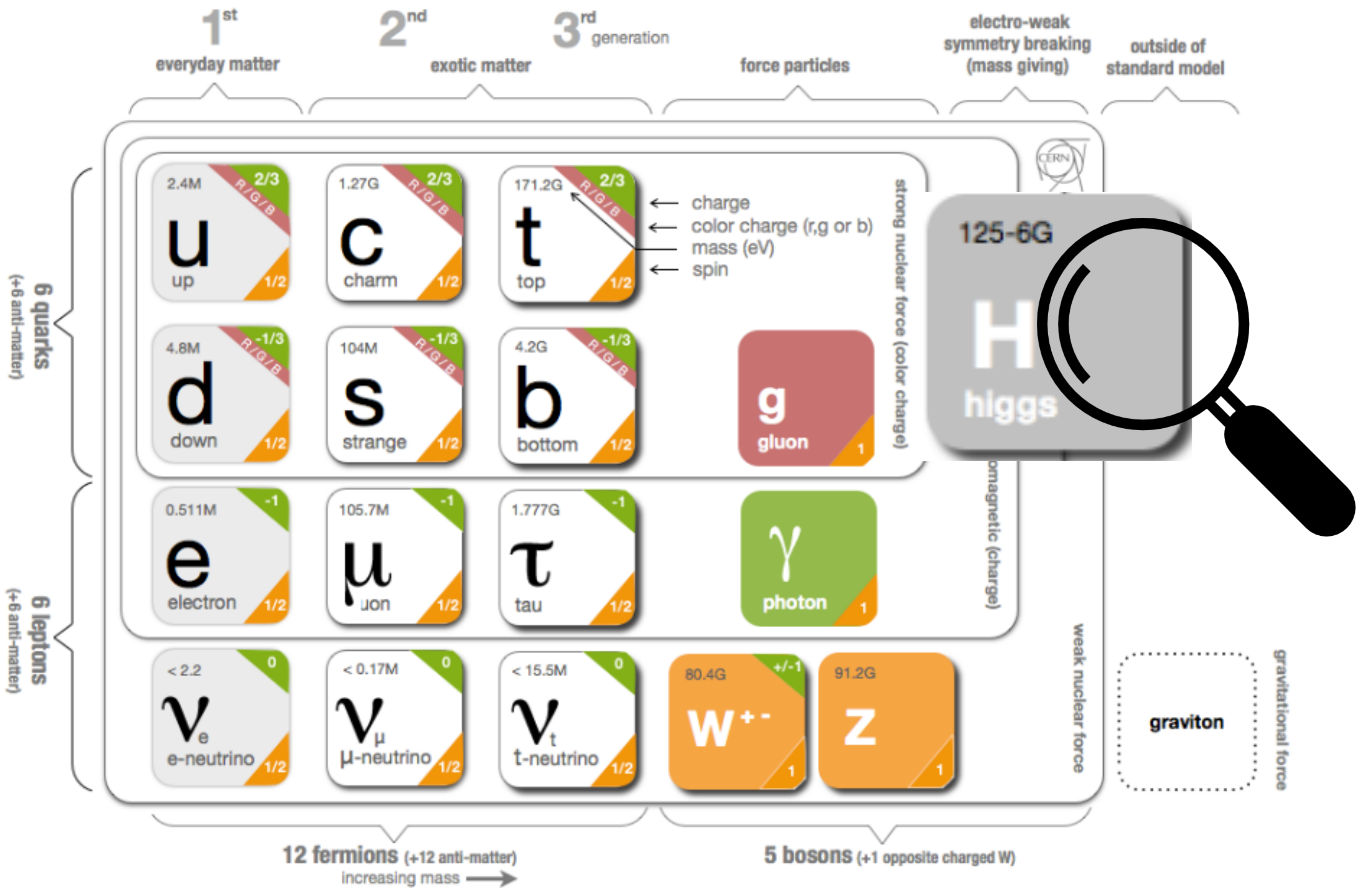
Measurements of Higgs boson mass, width, and CP with the ATLAS detector

Luca Franco (Nikhef and Radboud University)
On behalf of the ATLAS collaboration

PIC 2024, October 23rd 2024

Introduction



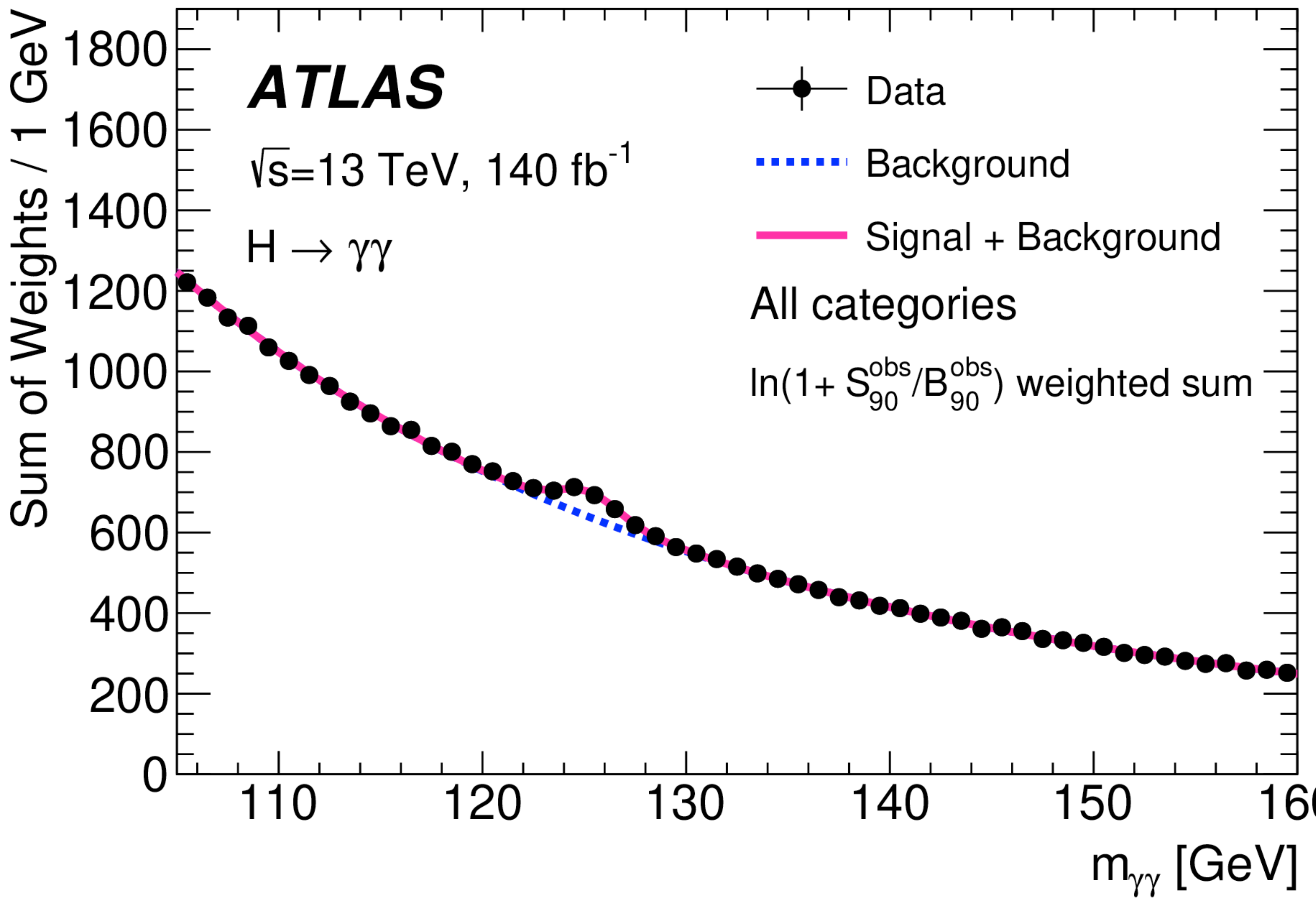
- **Mass m_H** (free parameter of the Standard Model (SM))
  - Strength of interaction with other SM particles depends on m_H
  - Stability of our universe (via the Higgs potential) depends on m_H
- **Decay width Γ_H**
  - New physics can alter its value both directly (new final states) and indirectly (virtual particles in the loop)
- **Charge-Parity (CP) state**
  - Predicted to be pure CP-even in the SM
  - CP-odd components in the couplings might explain baryon asymmetry of the universe

Phys. Lett. B 847 (2023) 138315

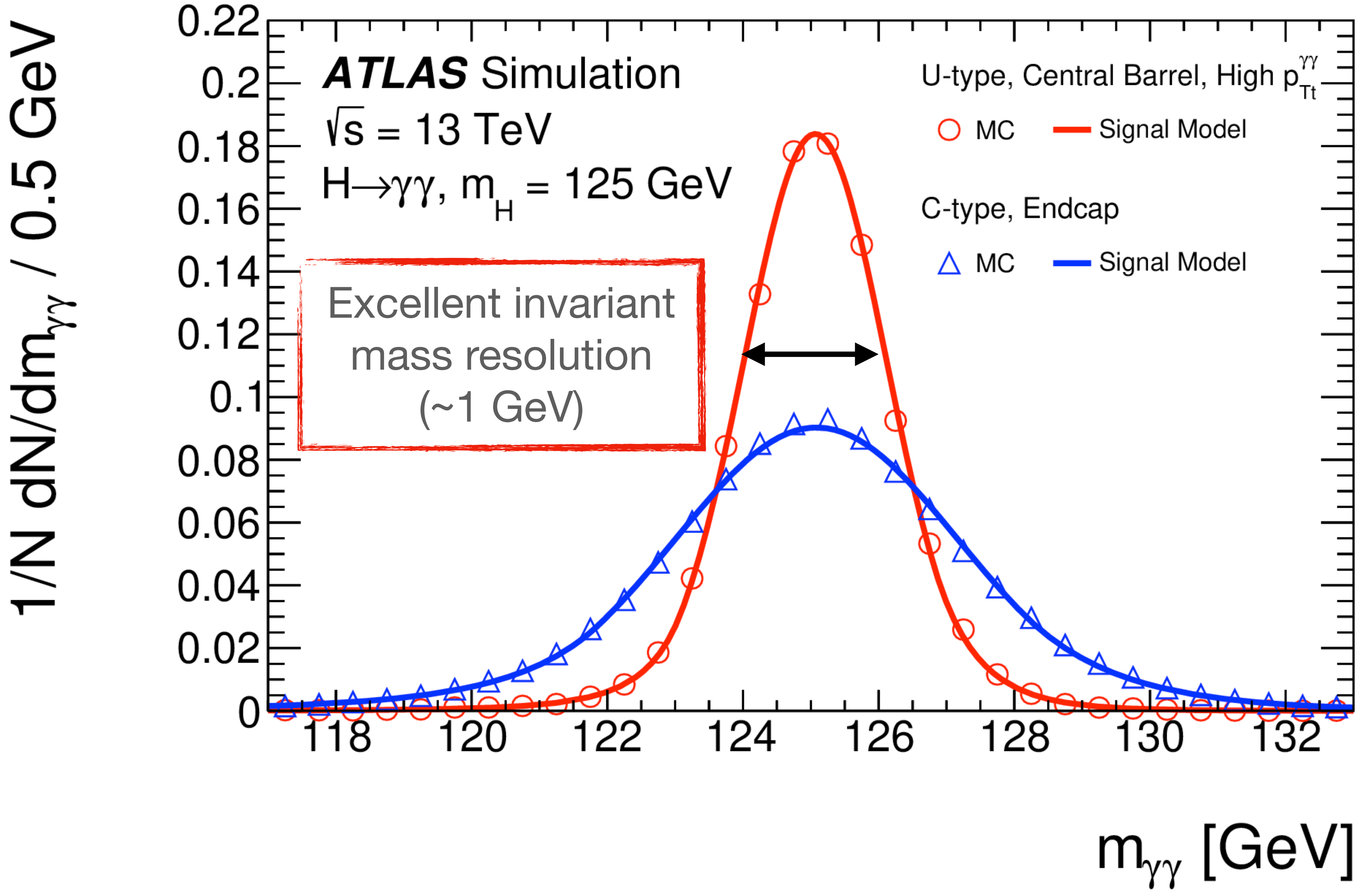
H→γγ mass

Mass

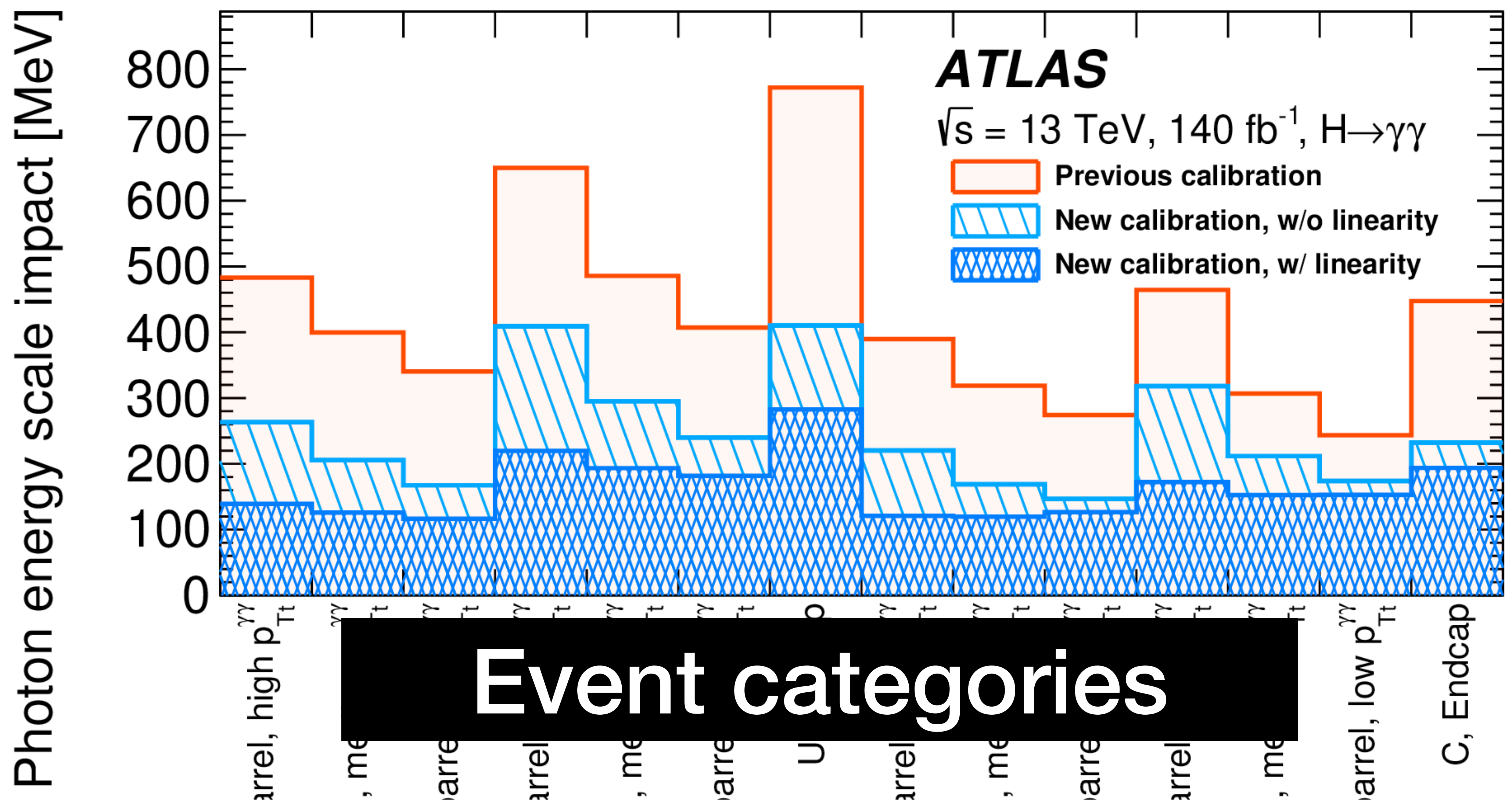
- Select events with two "good quality" photons
- Classify events into 14 categories according to the properties of the two photons (conversion status, position of energy cluster, …)
- Model signal and background using analytic functions
- Simultaneous fit of $m_{\gamma\gamma}$ data in each category



Peak position depends on m_H (and photon energy scale systematics!)



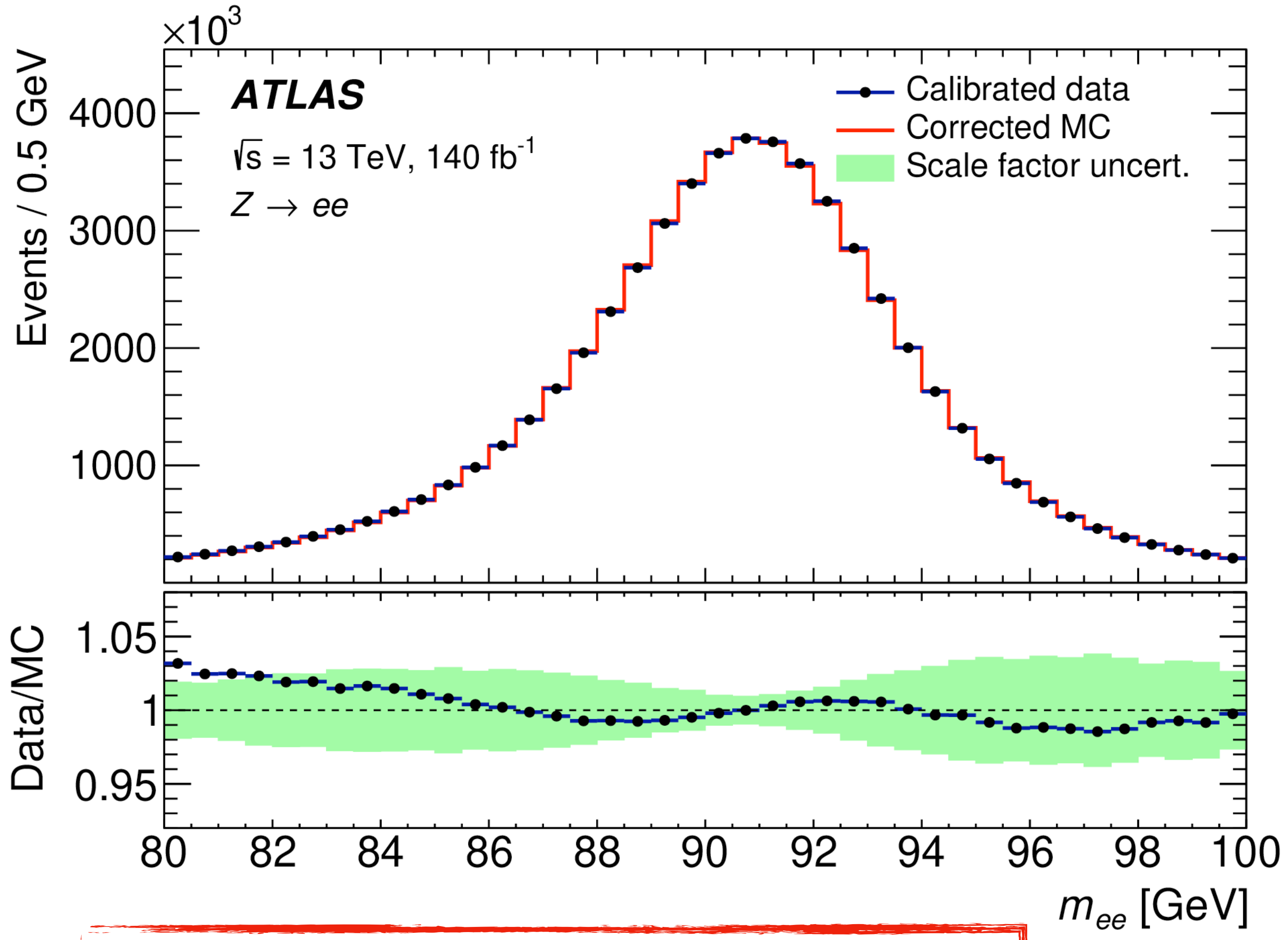
Systematic uncertainty x4 smaller thanks to new calibration



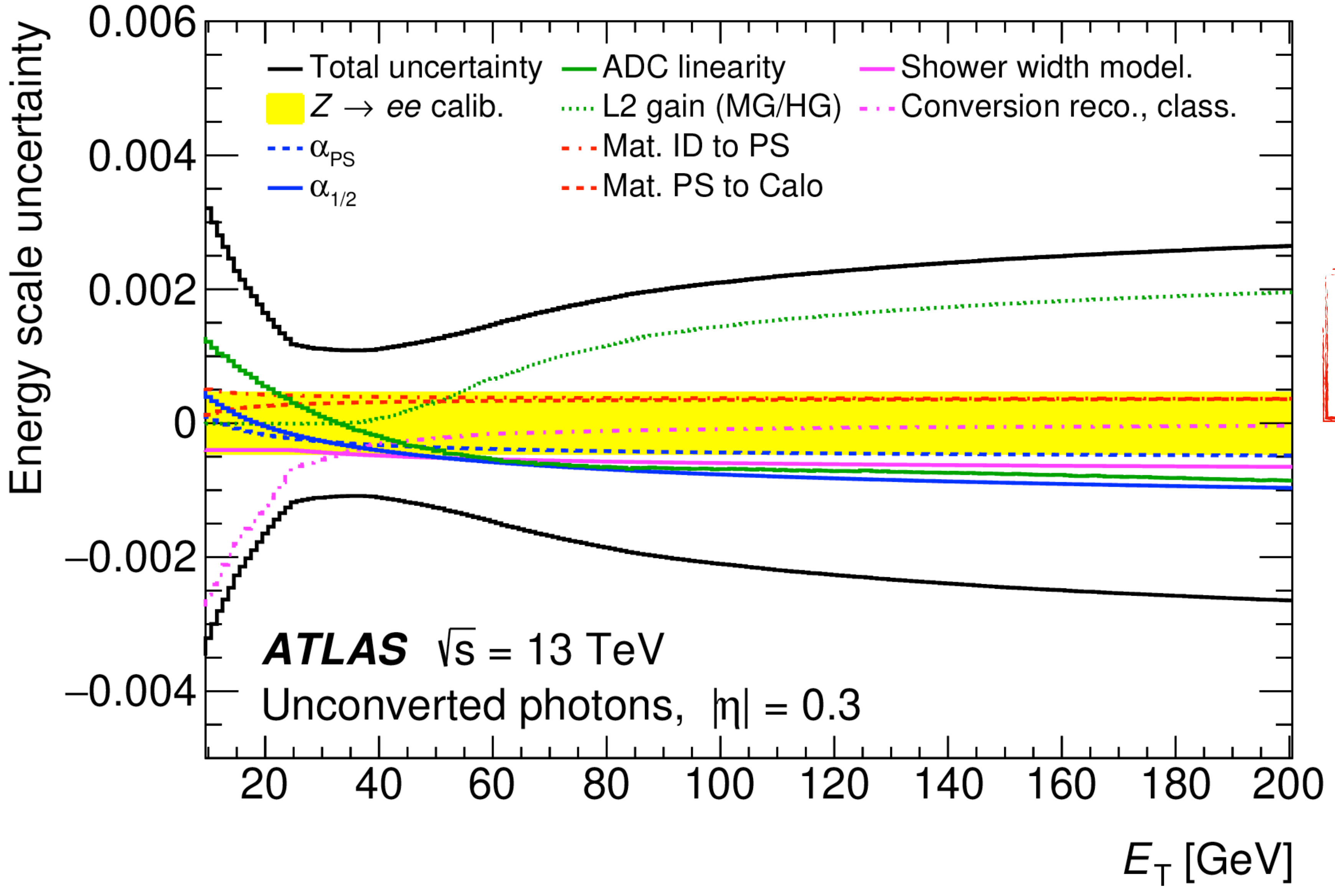
JINST 19 (2024) P02009

Intermezzo: photon energy calibration

- New ATLAS calibration based on full run 2 data
  - improved descriptions of the calorimeter electronics' response
  - enhanced calibration of energy response in longitudinal layers of the calorimeter
  - improved measurement of lateral energy leakage from e/γ clusters



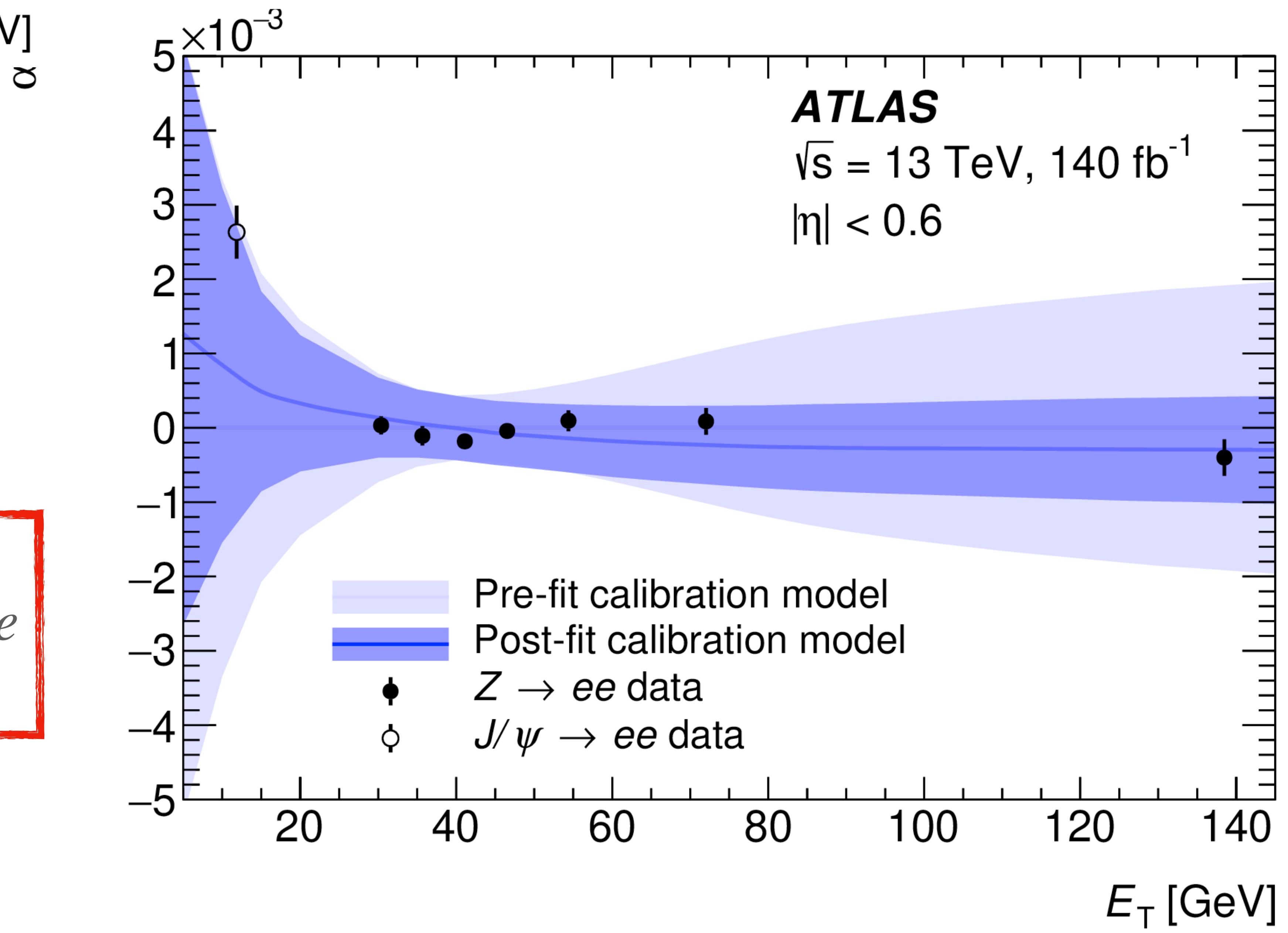
Z→ee as standard candle for calibration



0.2% average precision for H→γγ-like photons

- Novel approach: energy linearity
  - Introducing E_T dependence of the e/γ energy scale
  - Calibration uncertainties further constrained using Z→ee measurements

Full calibration model validated using $J/\Psi \rightarrow ee$ and $Z \rightarrow ll\gamma$ decays



(Image: ATLAS Collaboration/CERN)

$H \rightarrow \gamma\gamma$ candidate event

Phys. Rev. Lett. 131 (2023) 251802 ← Editors' suggestion

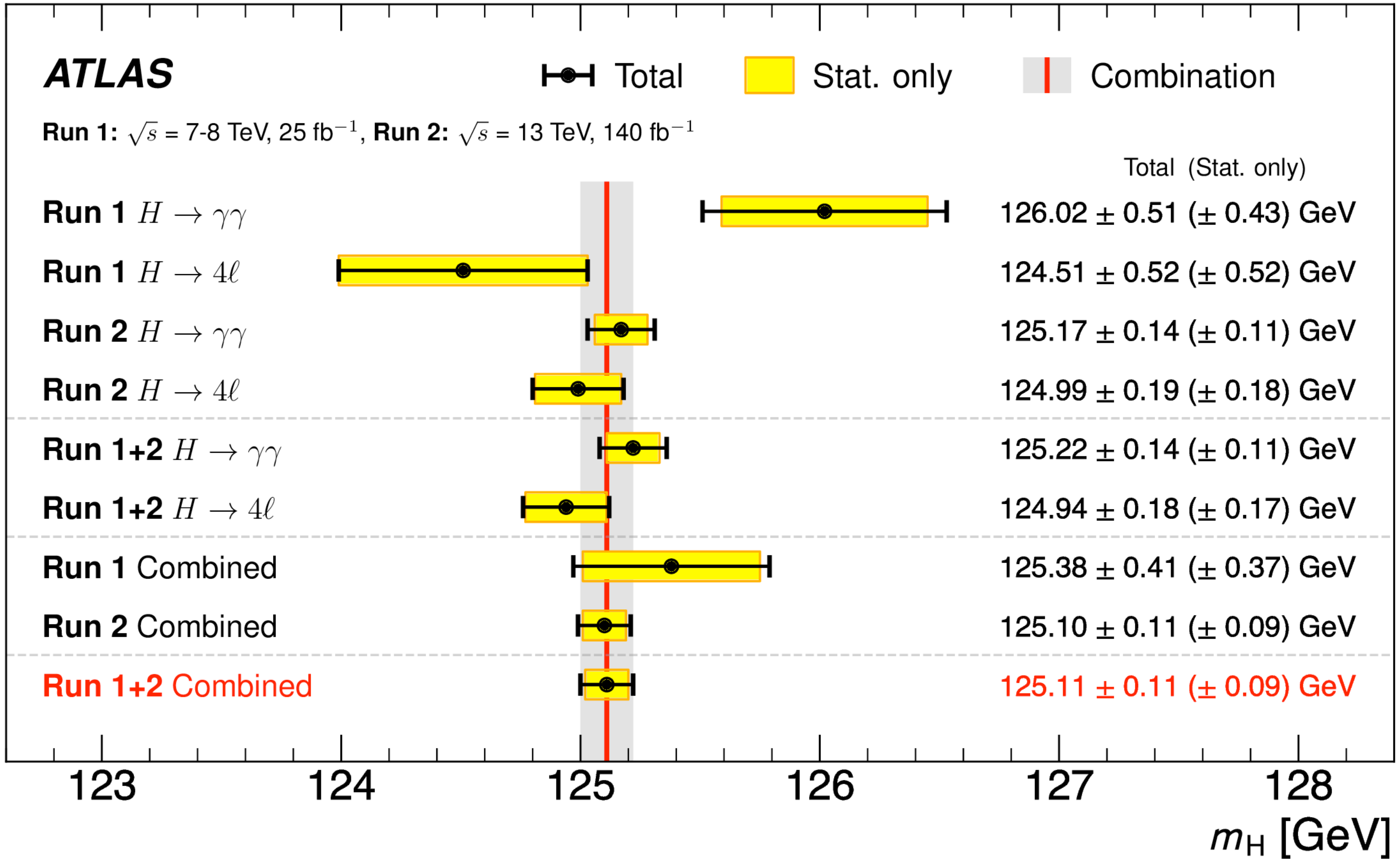
H→γγ + H→4ℓ combination

Mass

- Combining m_H measurements from the two channels with best mass resolution
- Combining with old results from run 1
- Unprecedented precision thanks to ATLAS commitment to understanding the detector and its performance

125.11 ± 0.11 (± 0.09) GeV

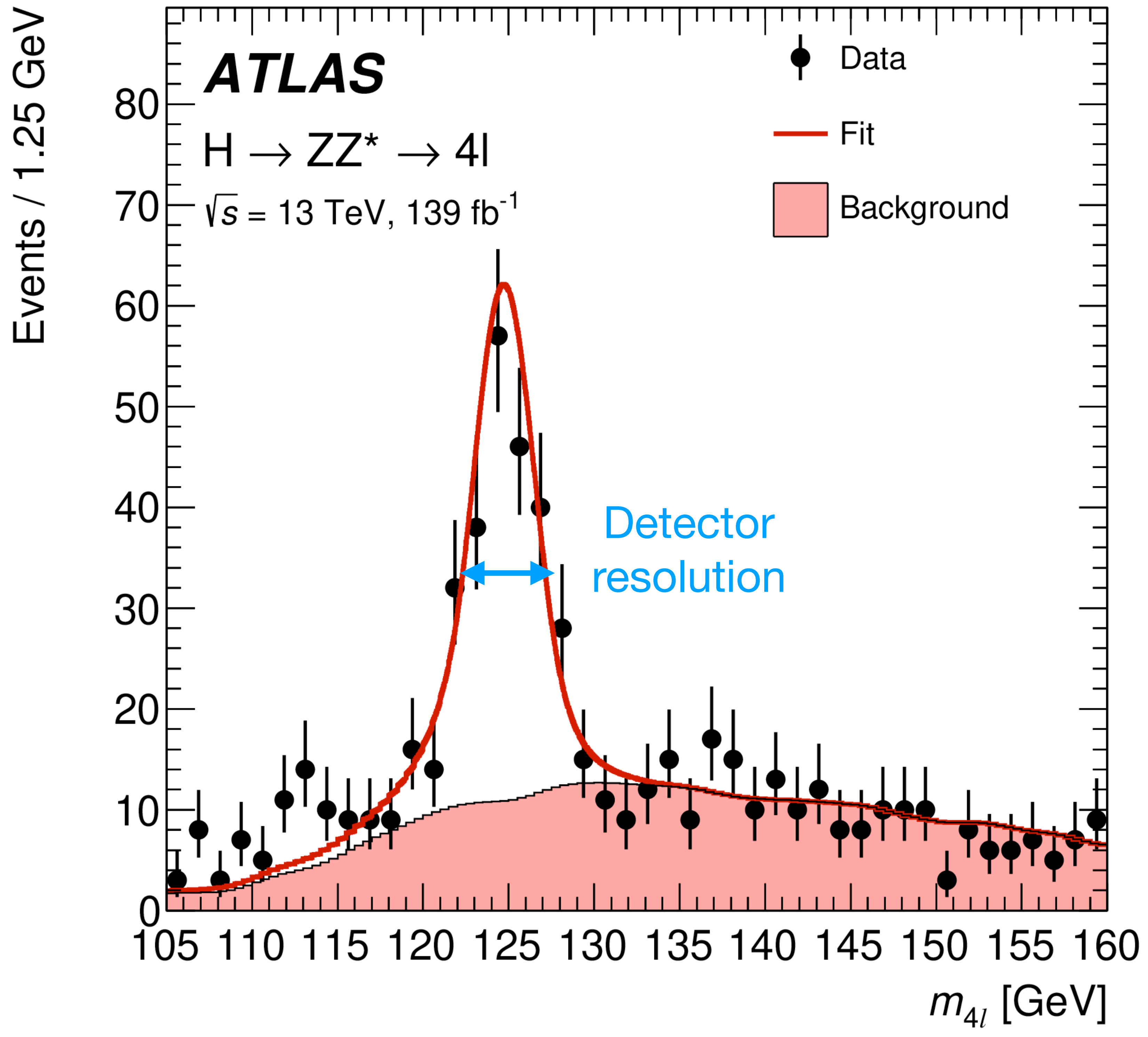
Ultimate precision on $\boldsymbol{m_H}$ *is < 0.1% !*

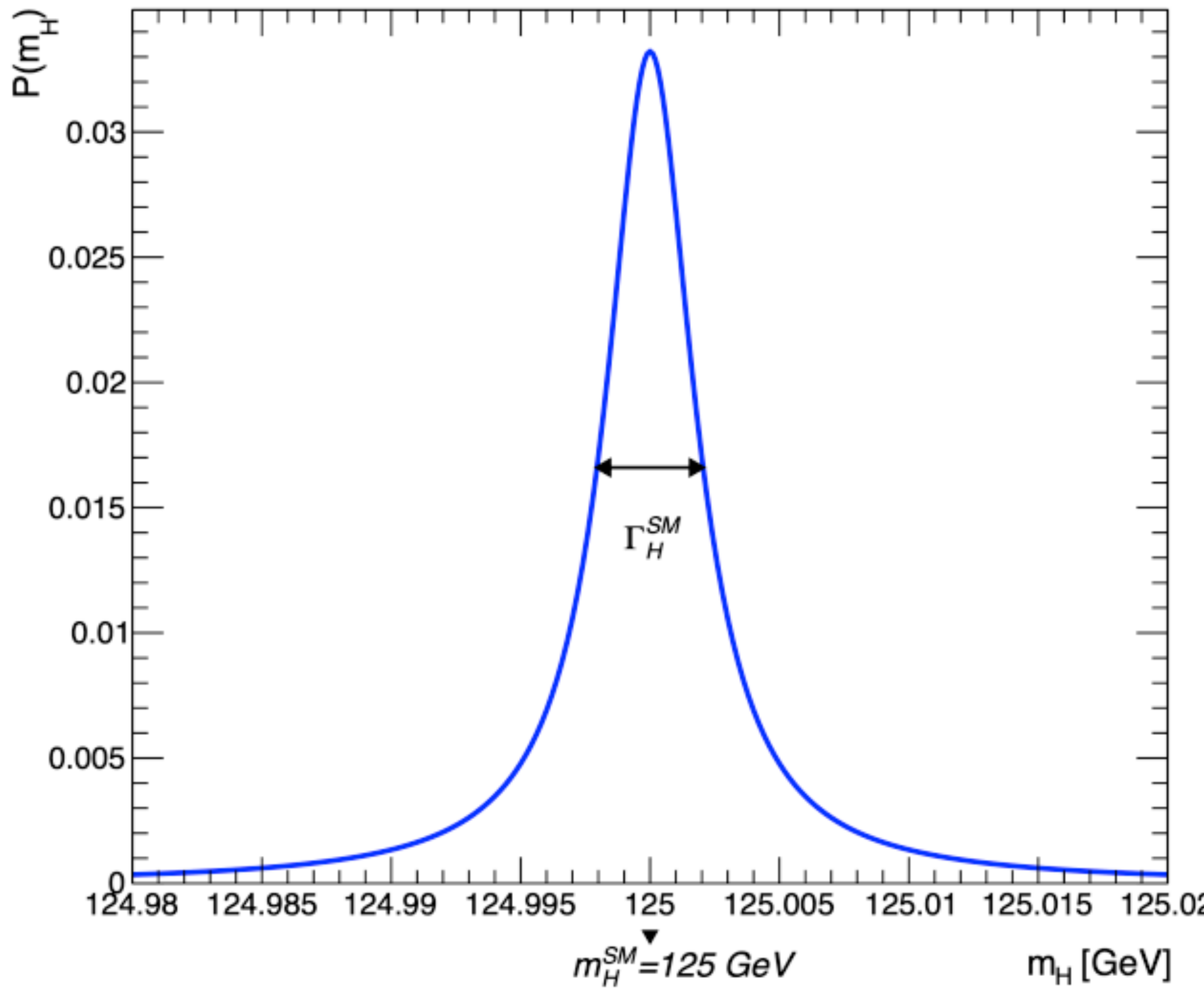


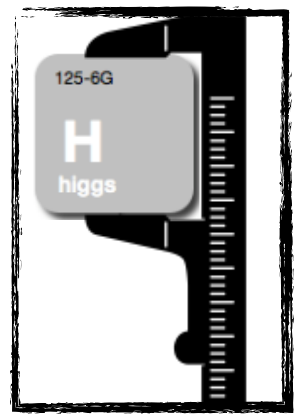
Higgs decay width

- The SM predicts a very narrow width Γ_H = 4.07 MeV
- Direct measurement? Experimental resolution O(1) GeV

~10^3 gap!!!

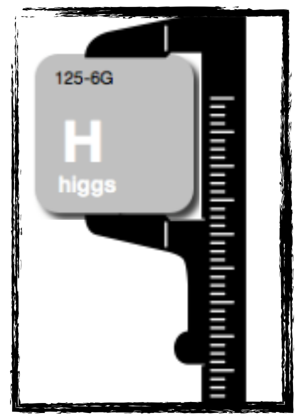






$$\frac{d\sigma_{pp\to H\to ZZ}}{dM_{4l}^2} \sim \frac{g_{Hgg}^2 g_{HZZ}^2}{(M_{4l}^2 - m_H^2)^2 + m_H^2\Gamma_H^2}$$

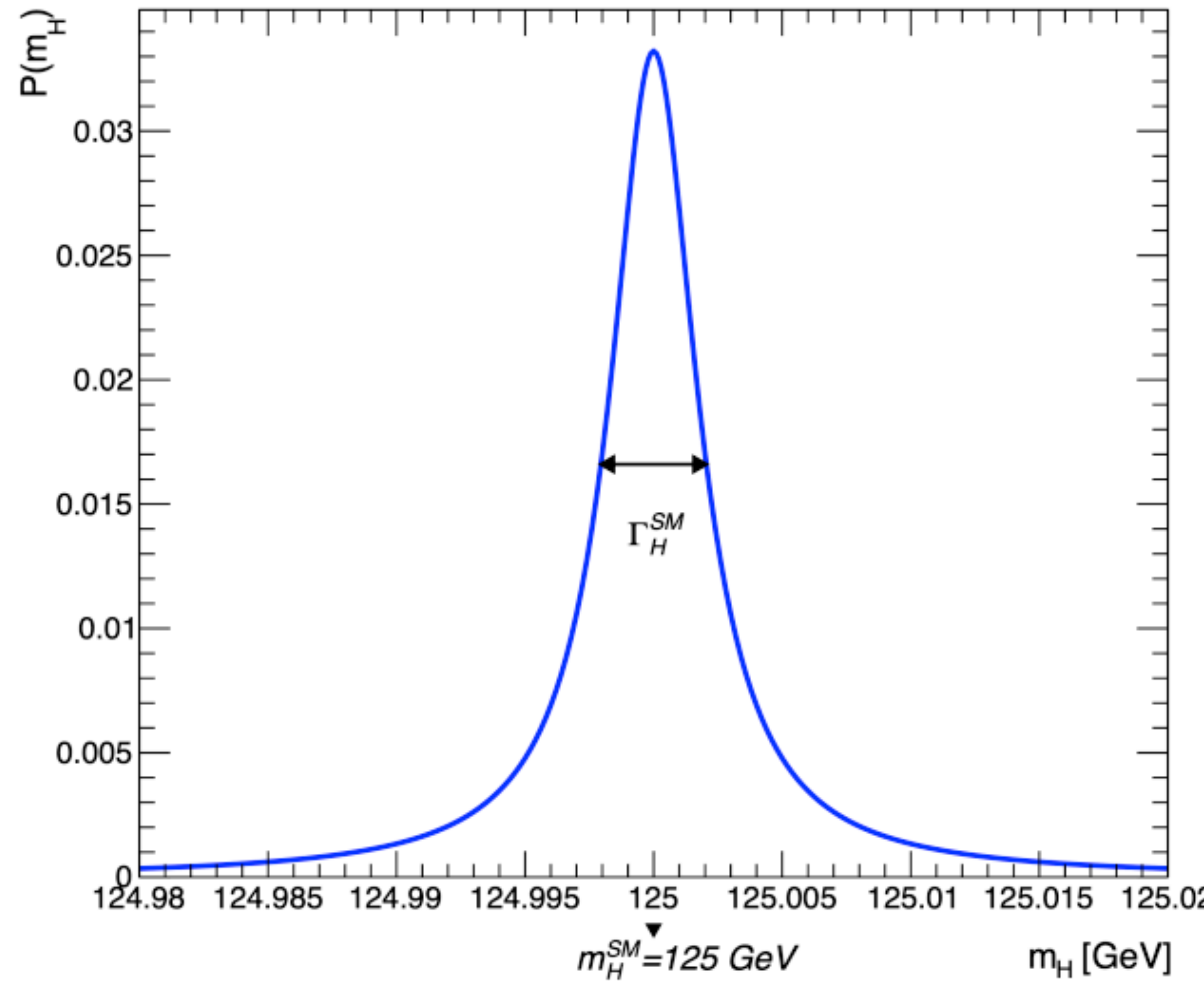
Higgs decay width



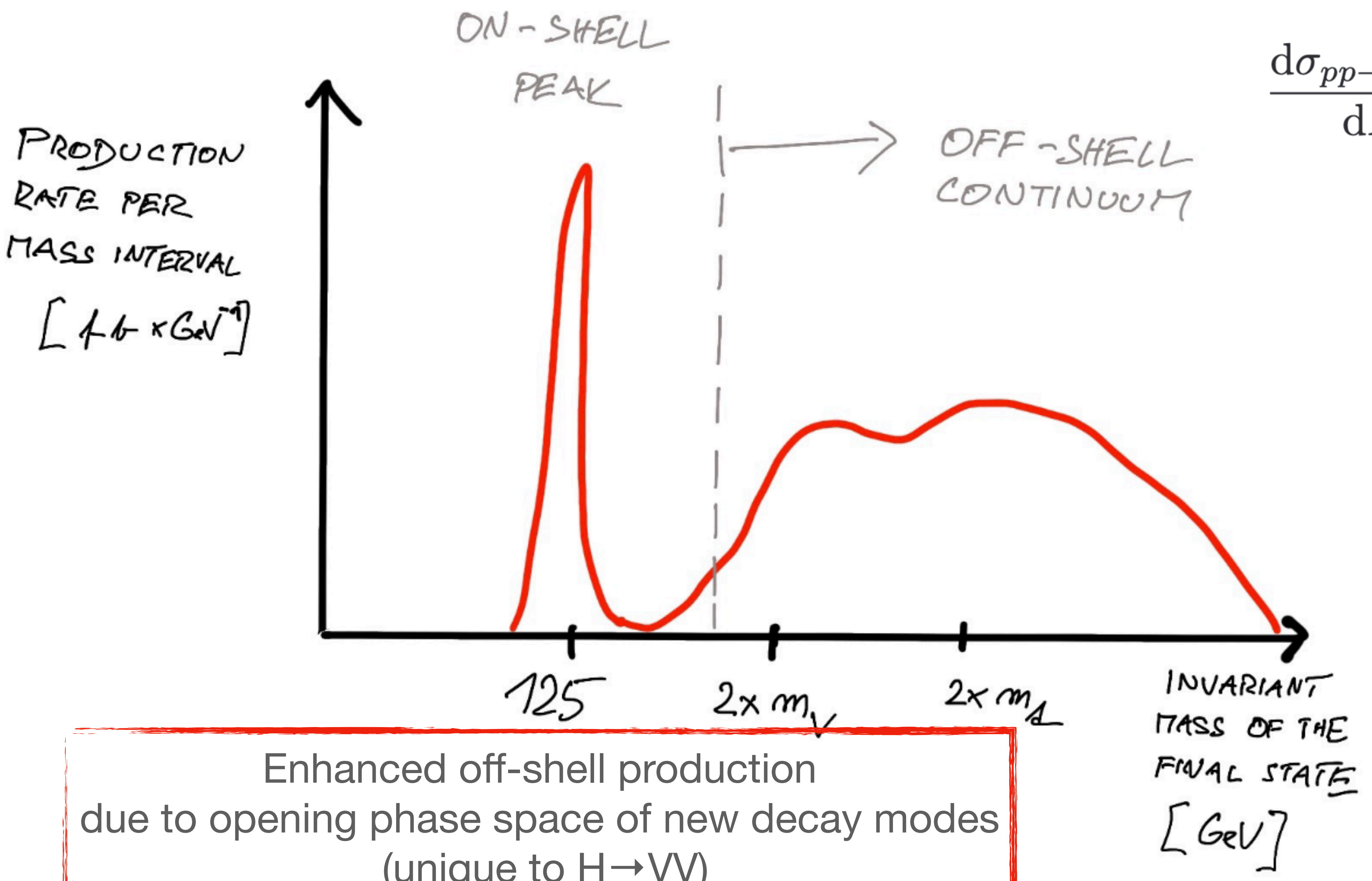
Width

- The SM predicts a very narrow width Γ_H = 4.07 MeV
- Direct measurement? Experimental resolution O(1) GeV
- Indirect approach: exploit off-shell Higgs production

~10^3 gap!!!



$$\frac{\mathrm{d}\sigma_{pp\to H\to ZZ}}{\mathrm{d}M_{4l}^2} \sim \frac{g_{Hgg}^2 g_{HZZ}^2}{(M_{4l}^2 - m_H^2)^2 + m_H^2\Gamma_H^2}$$



Enhanced off-shell production
due to opening phase space of new decay modes
(unique to H→VV)

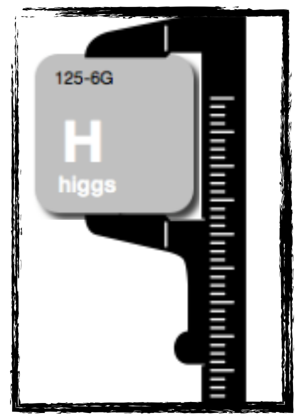
$$\sigma^{\text{on-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{\text{ggH}} g^2_{\text{HZZ}}}{m_H \Gamma_H}$$

$$\sigma^{\text{off-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{\text{ggH}} g^2_{\text{HZZ}}}{m^2_{ZZ}}$$

…assuming same strength of the on-shell and off-shell effective couplings…

$$\frac{\mu_{\text{offshell}}}{\mu_{\text{onshell}}} \propto \Gamma_H$$

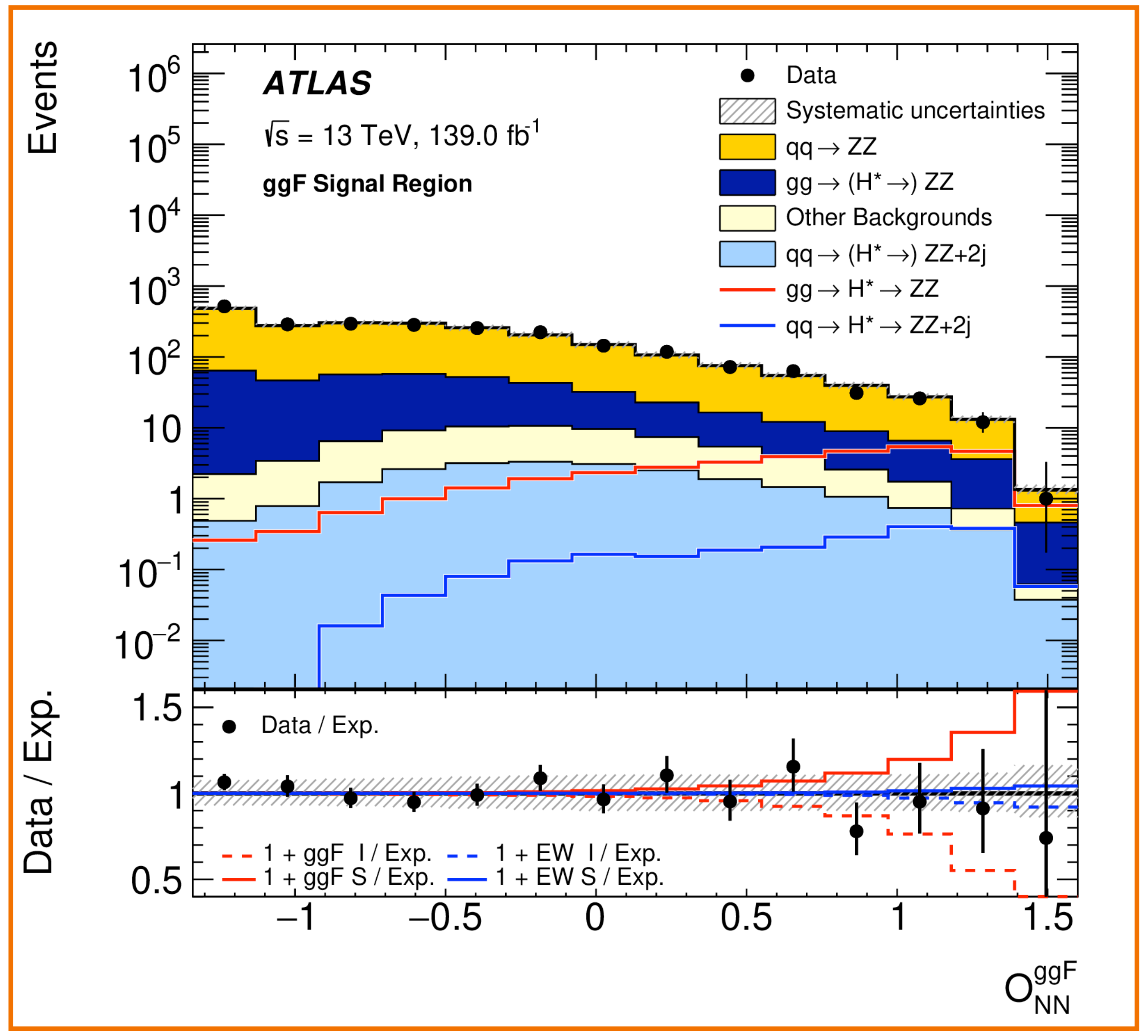
JHEP 08 (2012) 116,
Phys. Rev. D 88 (2013) 054024,
JHEP 04 (2014) 060,
Phys. Rev. D 89 (2014) 053011

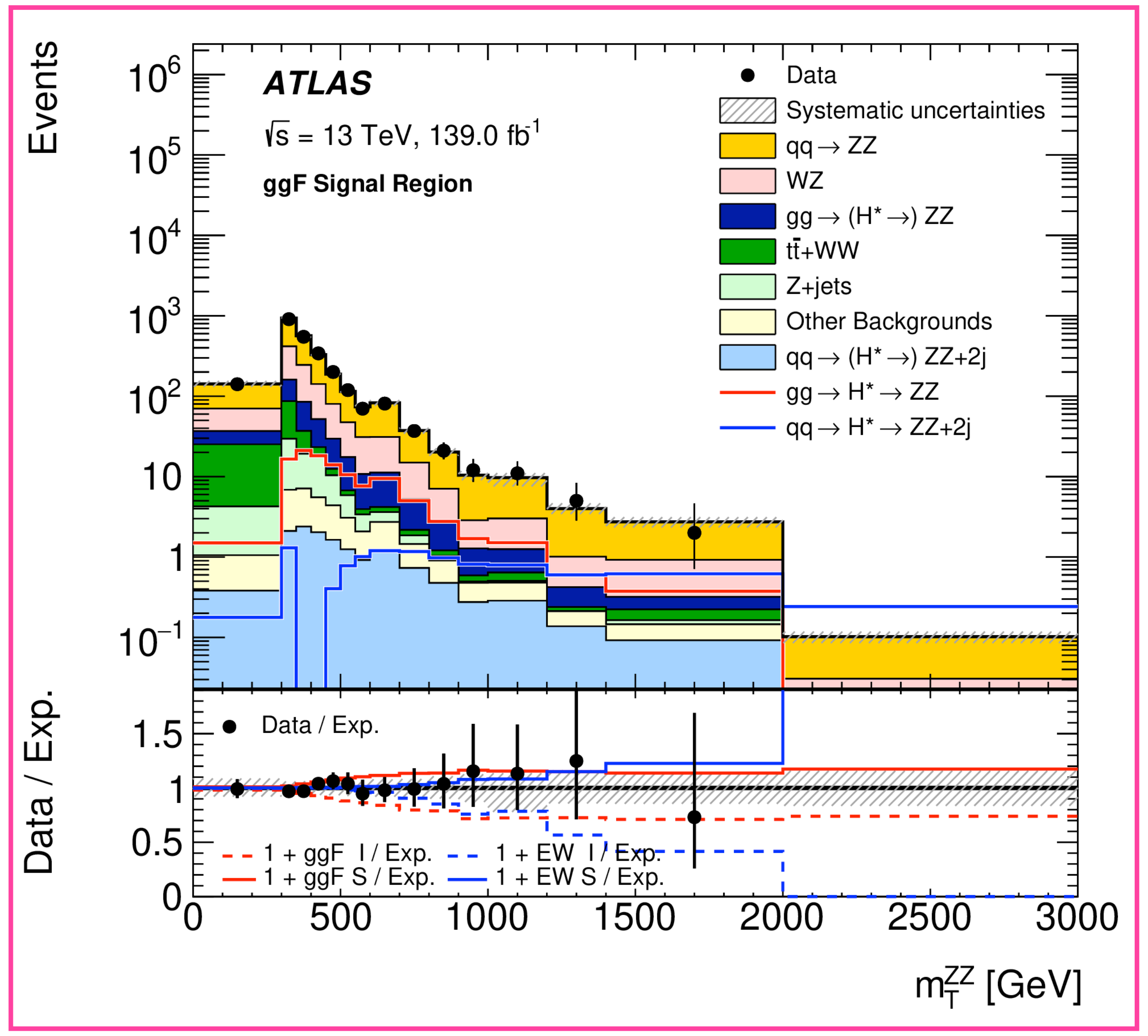


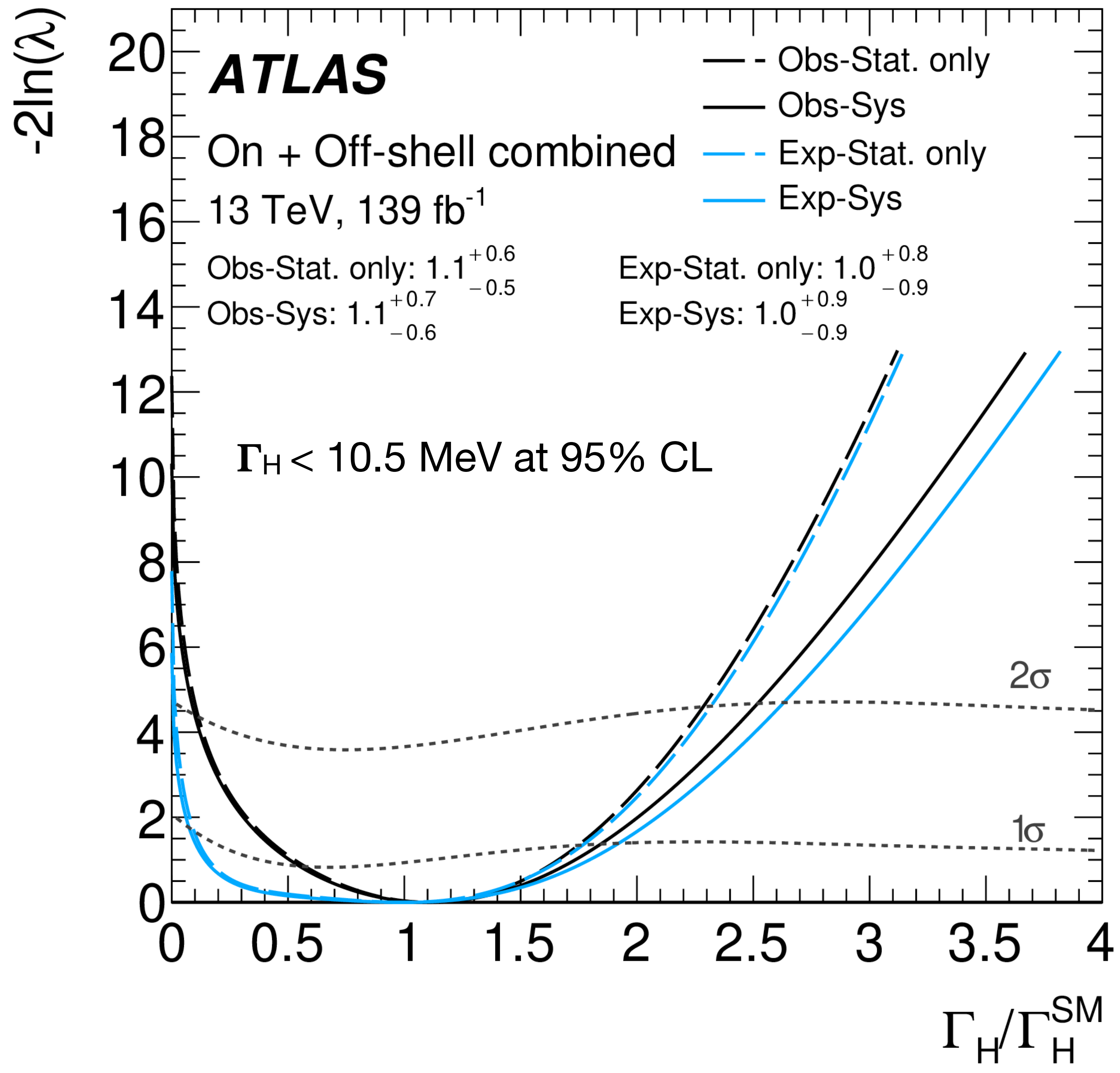
Width

H→ZZ On/Off-shell

- Performed in two channels:
  - 4ℓ final state, where the **output of neural networks (O_{NN})** , used to enhance Higgs signal, is fitted
  - 2ℓ2ν final state, where the **transverse mass of the ZZ system** is fitted $$m_T^{ZZ} \equiv \sqrt{\left[\sqrt{m_Z^2 + (p_T^{\ell\ell})^2} + \sqrt{m_Z^2 + (E_T^{miss})^2}\right]^2 - \left|\vec{p}_T^{\,\ell\ell} + \vec{E}_T^{miss}\right|^2}$$
- Uncertainty from theoretical modelling of signal and backgrounds is the dominant systematic





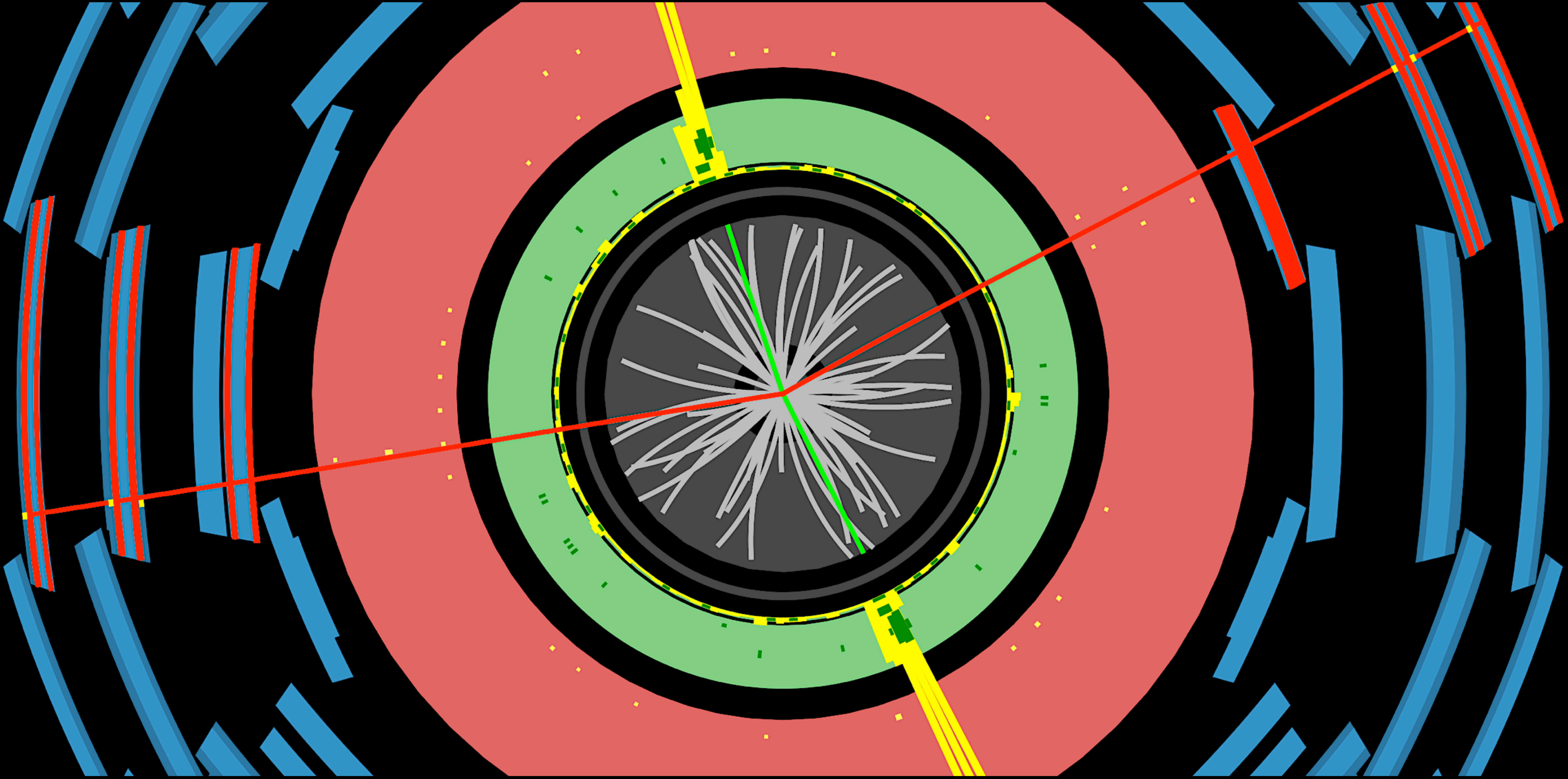


$$4.5^{+3.3}_{-2.5}\ \text{MeV}$$

First direct measurement of Γ_H with ATLAS!

(And 3.3σ evidence of Higgs off-shell production)

H→4ℓ candidate event



arXiv:2407.10631

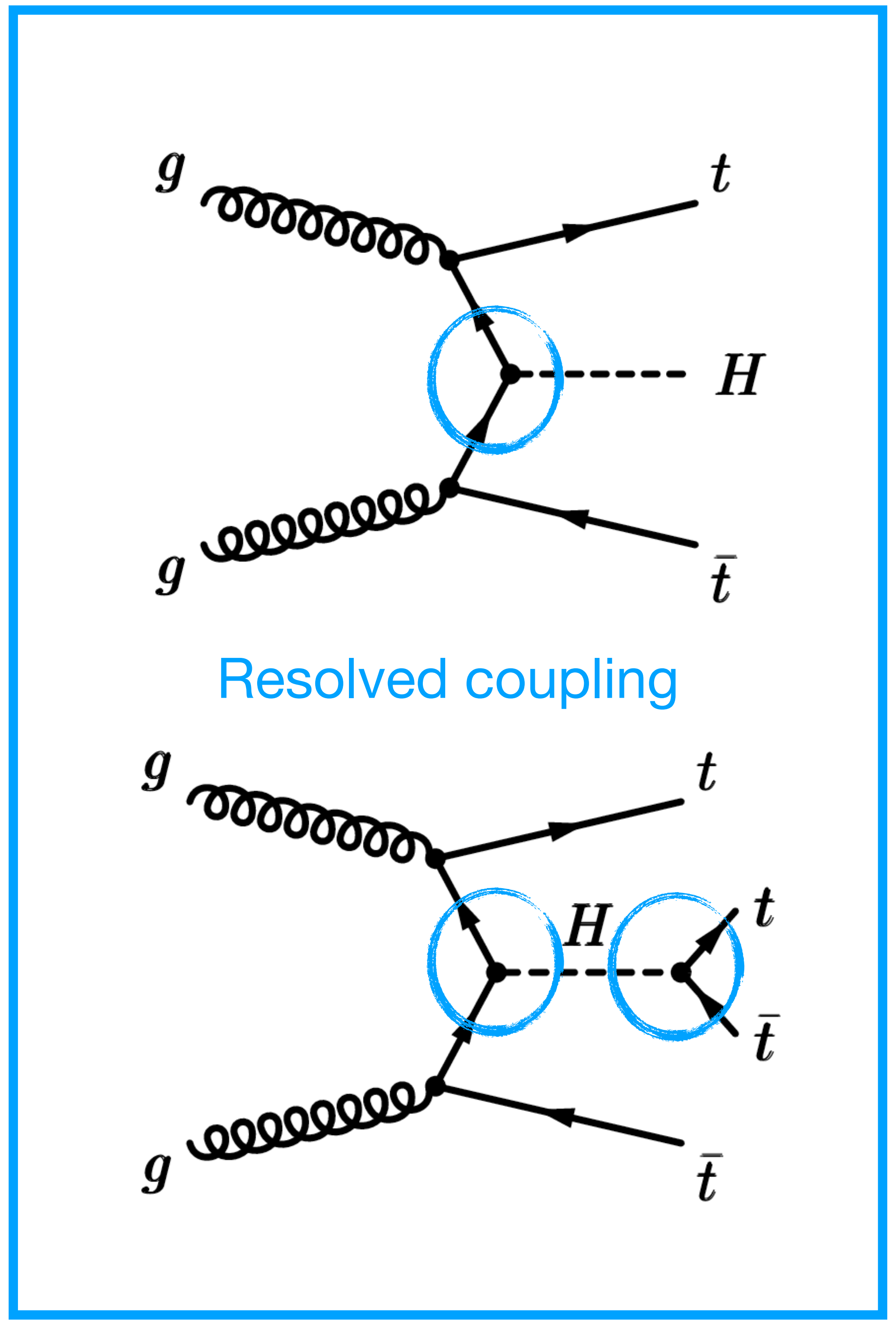
Combination of ttH + Higgs-mediated tttt

Width

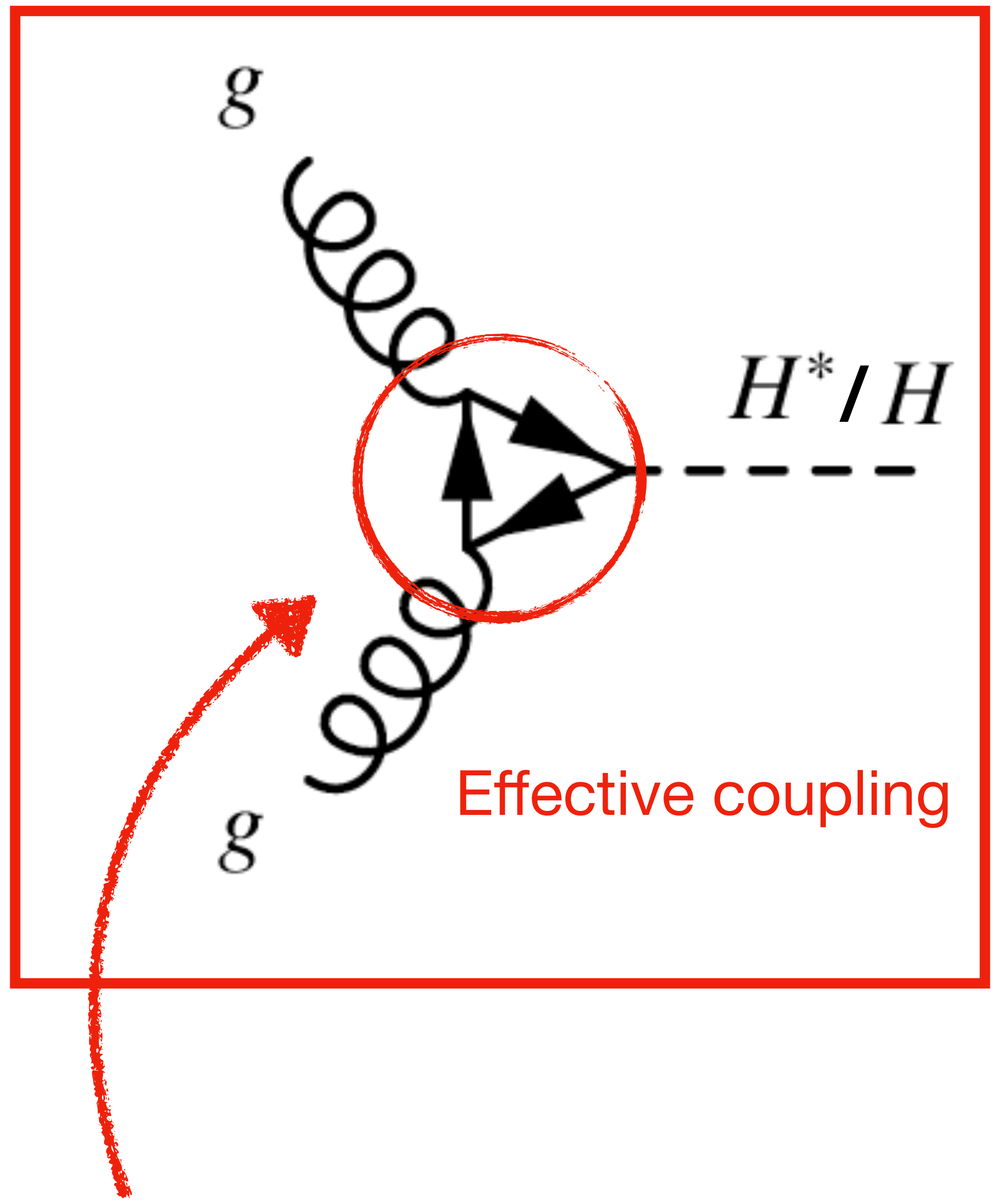
This method

On-shell

Off-shell



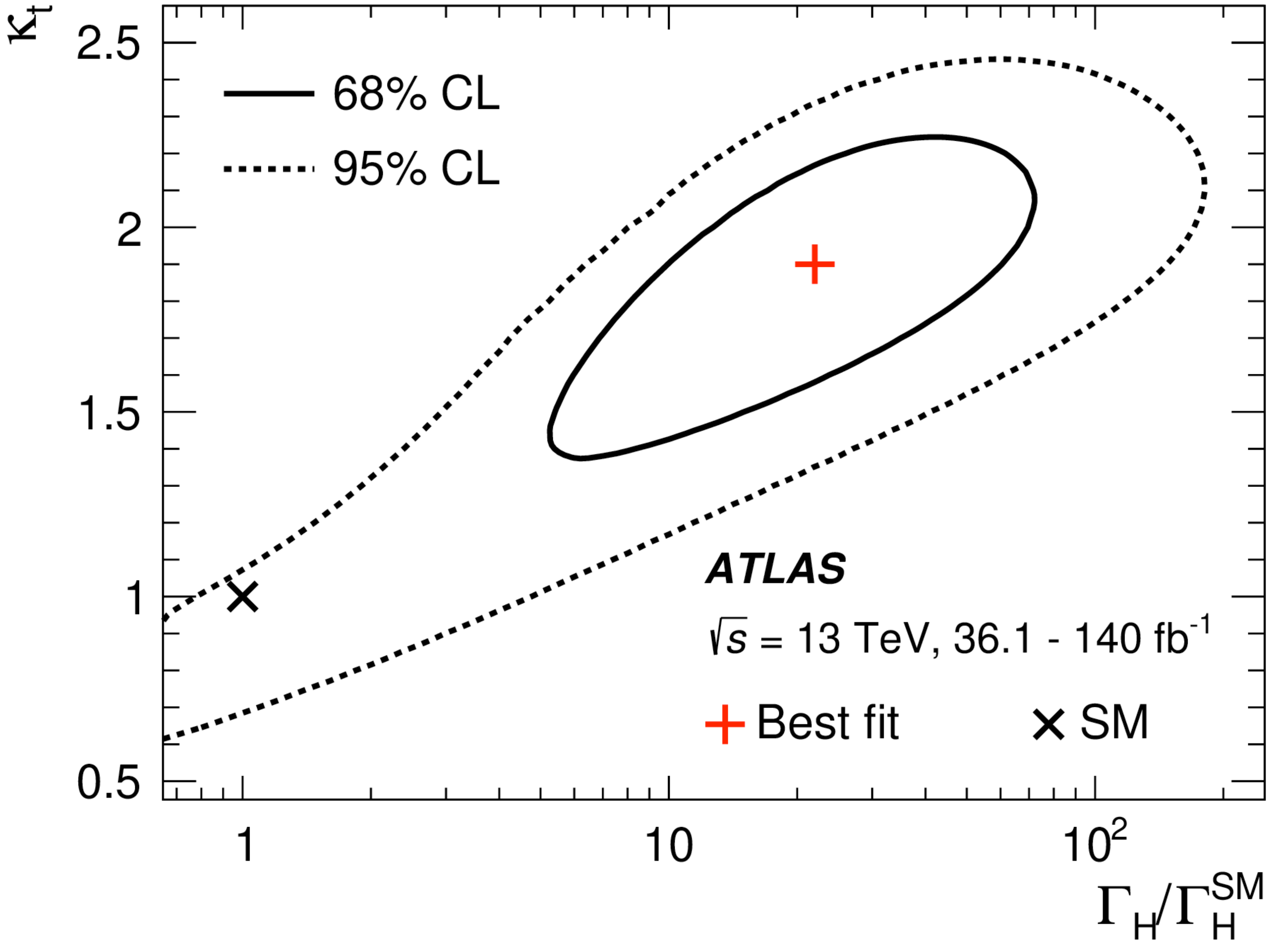
Other methods (based on ggH)



Unknown particles may enter the loop and spoil the assumption

$$\frac{\mu_{\text{offshell}}}{\mu_{\text{onshell}}} \propto \Gamma_H$$

2σ tension w.r.t. SM prediction (caused by 1.8σ tension in tttt measurement)

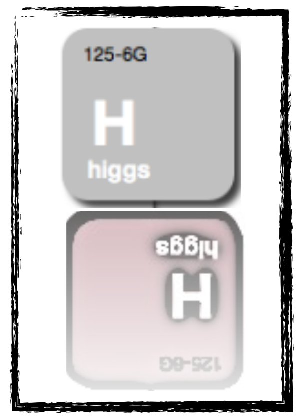


$$\Gamma_H < 160\,(55)\ \text{MeV}\ \ @\,95\,\%\,\text{CL}$$

First constraint on Γ_H using processes involving the top-Yukawa coupling!

JHEP 05 (2024) 105

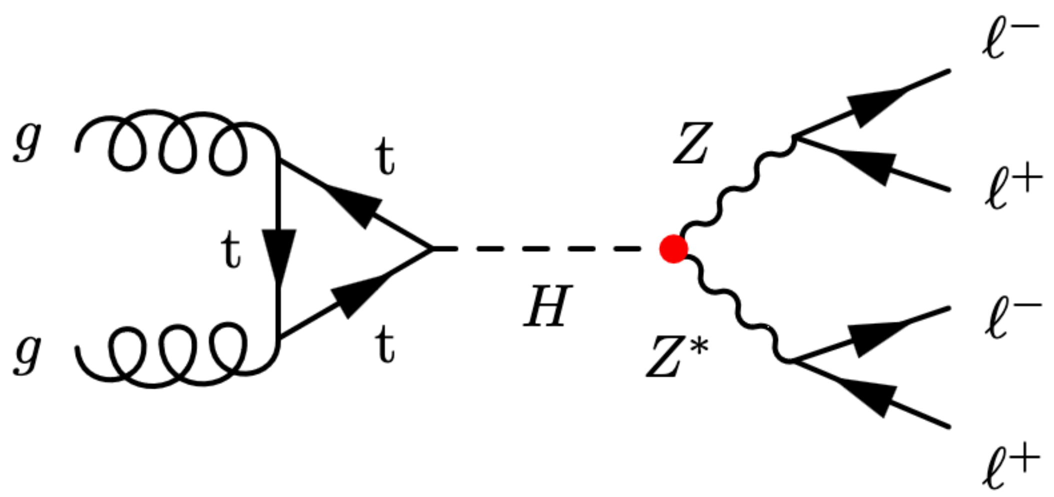
H→ZZ*→4ℓ CP



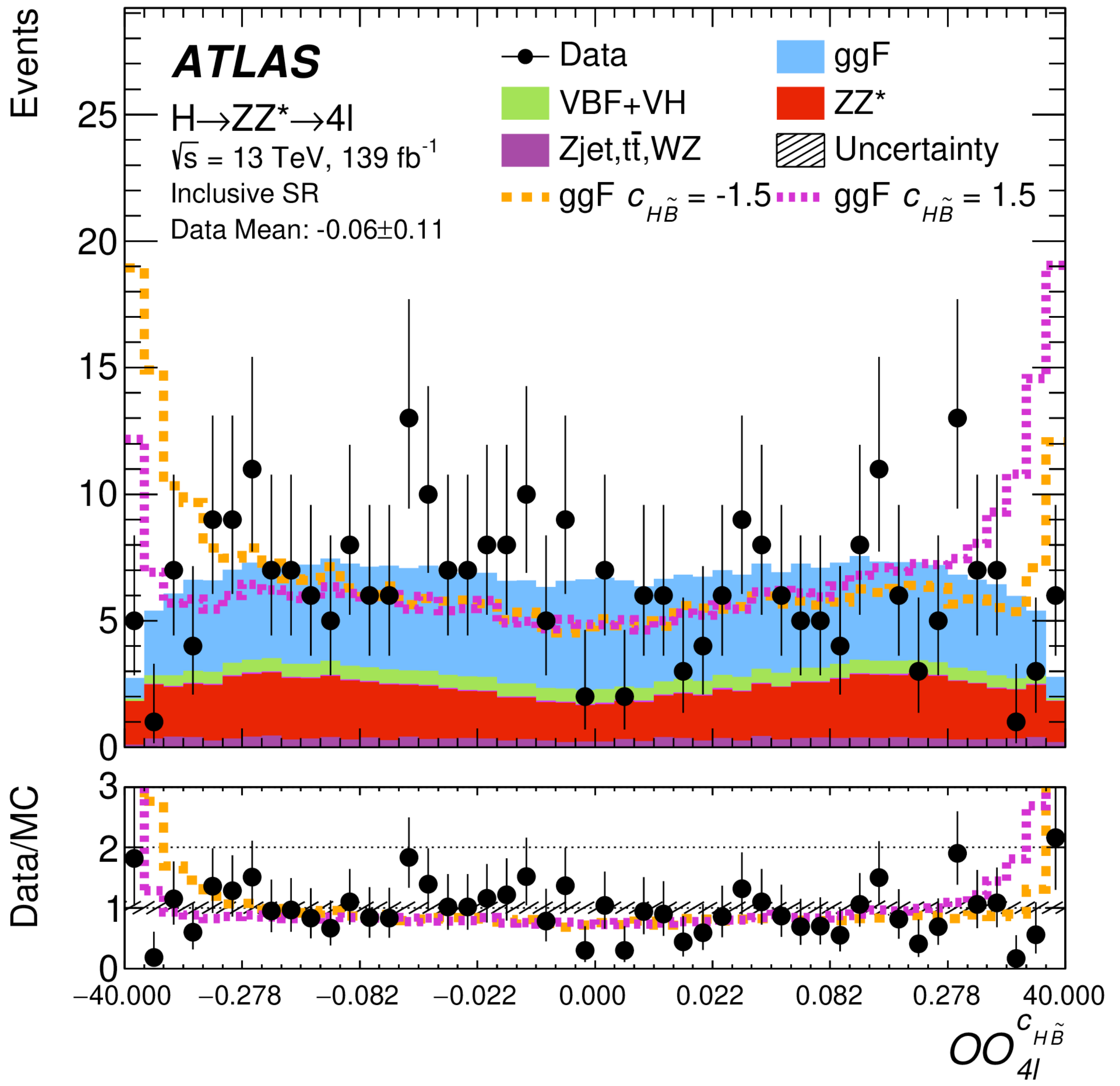
$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2} O_i^{(6)}$$

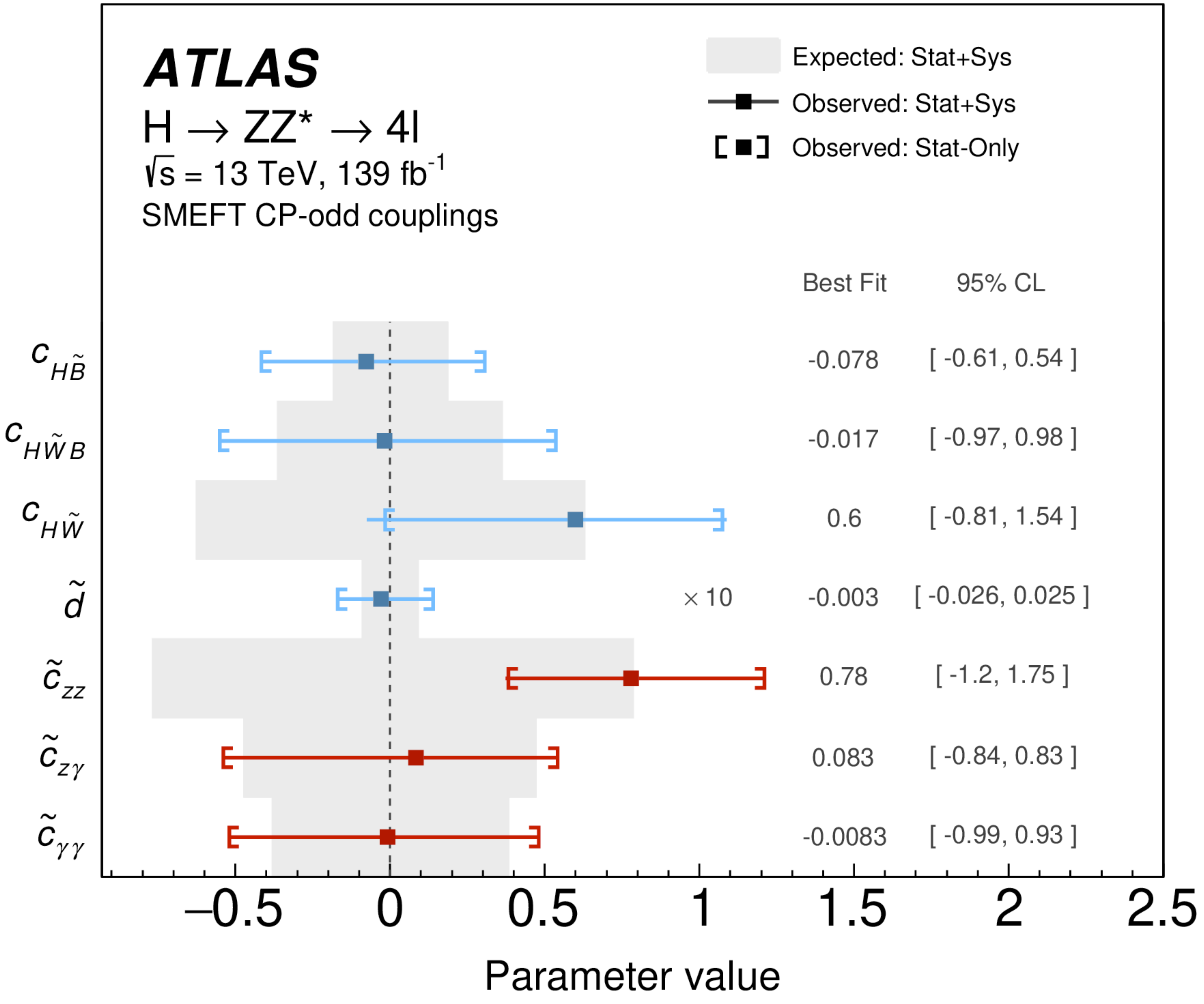
- Possible sources of CP-violation can be represented by effective couplings
- Constraints on Wilson coefficients related to dim-6 CP-odd operators
- Two bases considered: **Warsaw** and **Higgs mass eigenstates**
- Optimal observables (OO) sensitive to anomalous CP-odd couplings

Coupling on decay side



OOs on production side considered too, via Vector Boson Fusion (VBF)





Precision limited by statistics:
Impact of systematics (exper. and theor.) is <5%

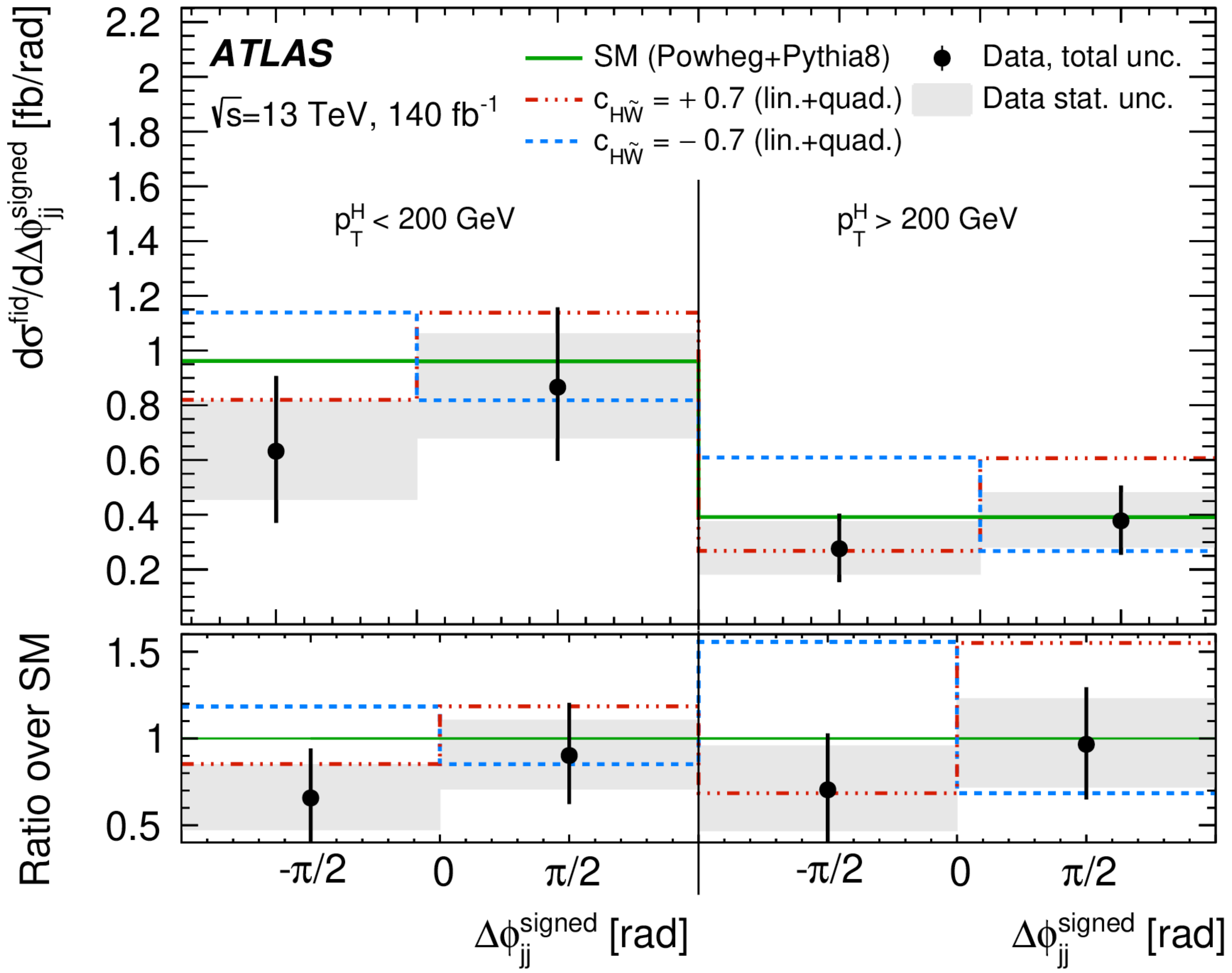
VBF H→ττ CP

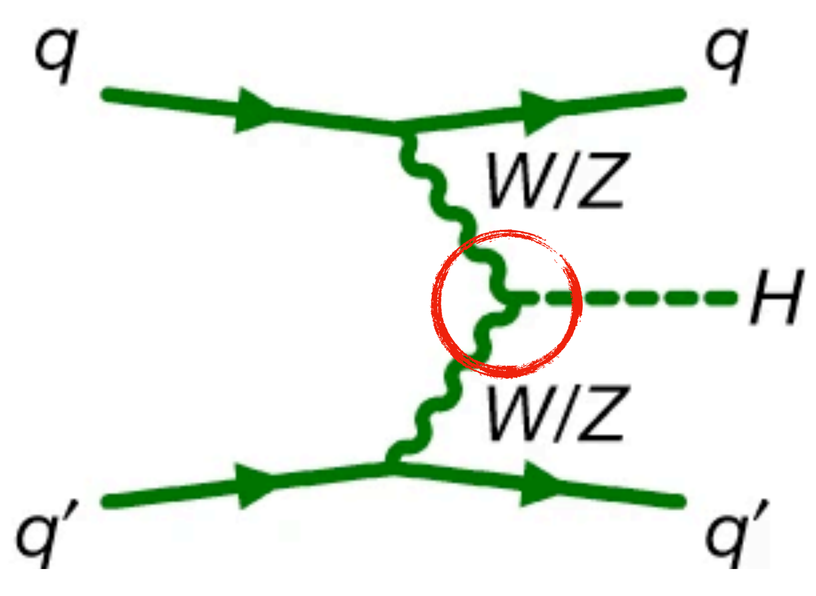
CP nature of Yukawa couplings investigated too (see back-up)

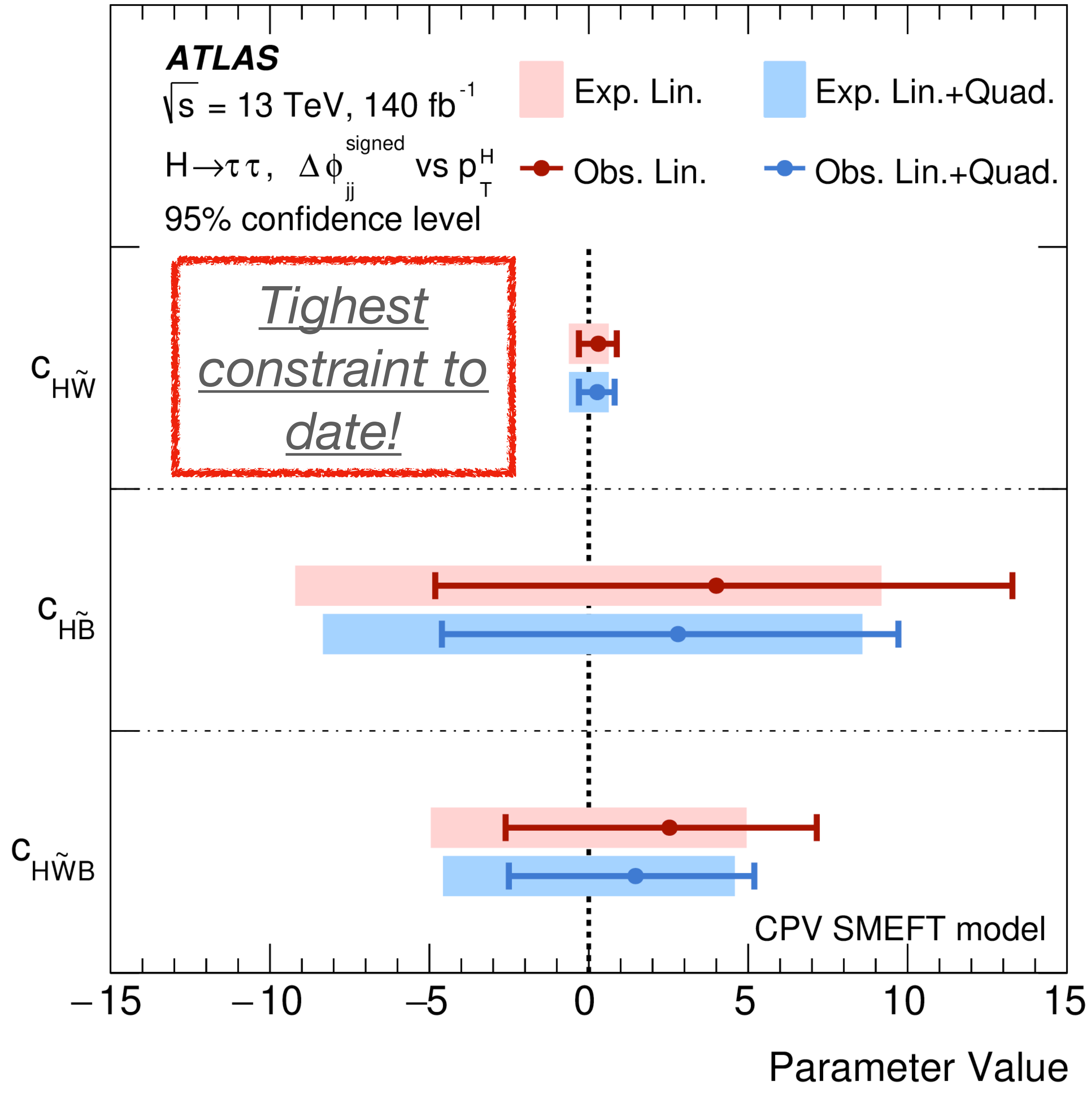
CP

- Interpretation of differential cross-section measurements via SMEFT approach
- CP-odd operators can intervene in the HVV coupling → studied through VBF production
- 2D distributions of $\Delta\phi_{jj}^{\mathrm{signed}}$ vs p_T^H are asymmetrical for non-zero CP-odd couplings

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



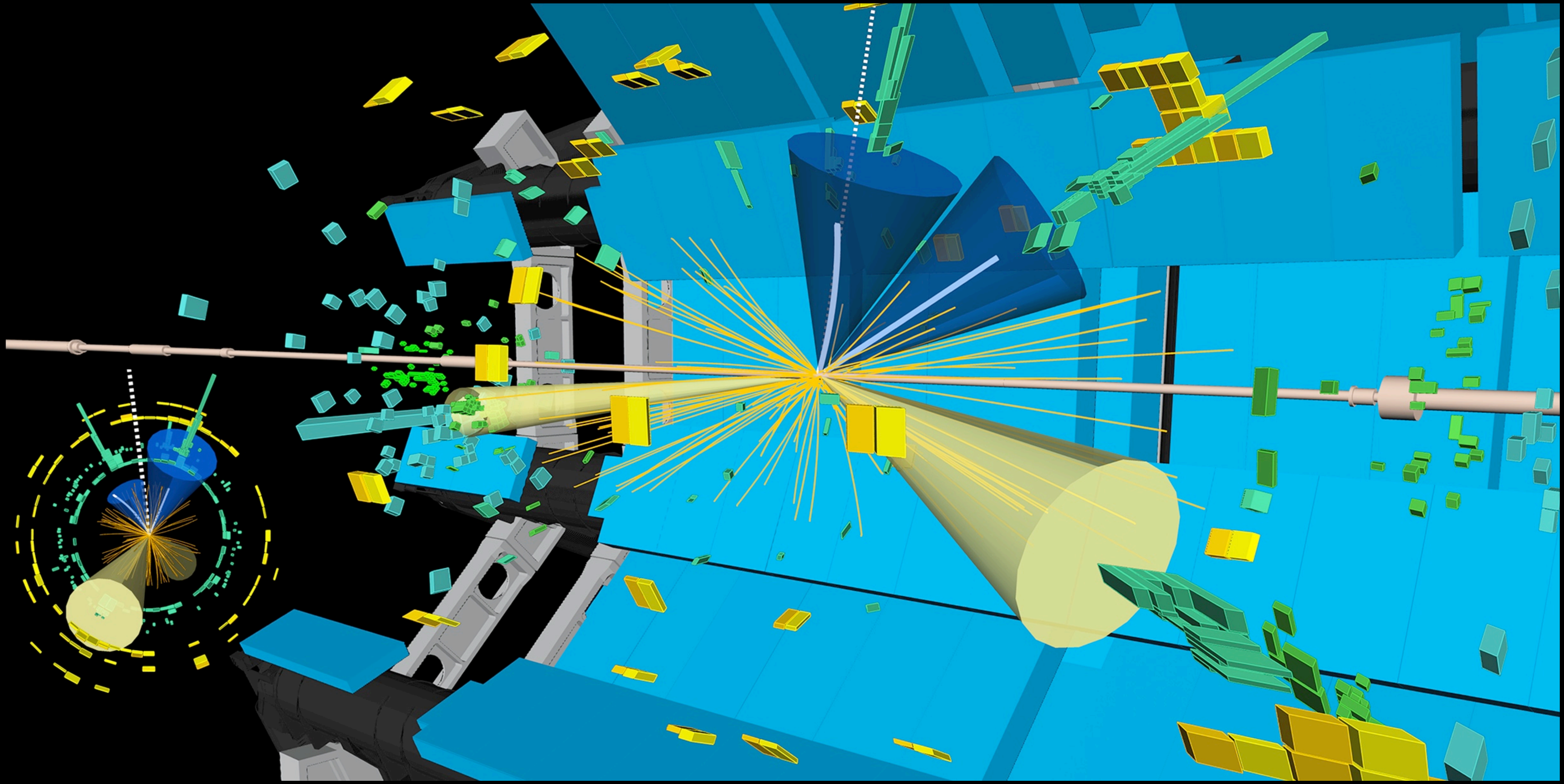




Tighest constraint to date!

(Image: ATLAS Collaboration/CERN)

H→ττ+2j candidate event



Conclusions

- ATLAS has measured the properties of the Higgs boson exploiting 140 fb^{-1} of pp collisions at $\sqrt{s}$=13 TeV (in some cases combining with data from run 1)
  - The mass, a free parameter of the theory, is now known with very high precision (per mill level):

$$m_H = 125.11 \pm 0.11 \text{ GeV}$$

  - The decay width is difficult to measure at the LHC, nonetheless it's been constrained (using different methods):

$$\Gamma_H < 10.5\ (10.9)\ \text{MeV} @ 95\,\%\ \text{CL}$$

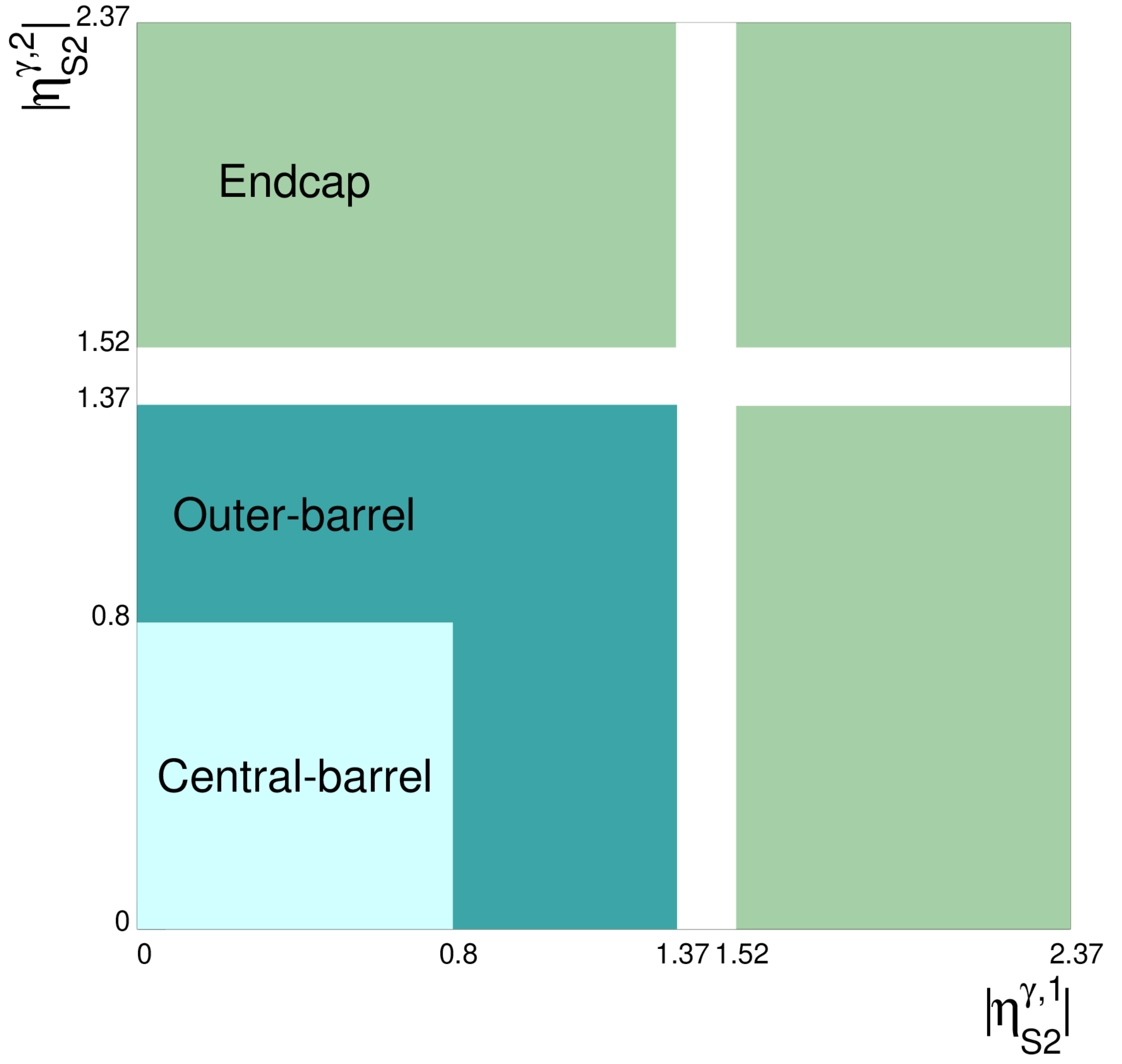
  - CP-odd contributions to the couplings have not been completely ruled out (yet) with our data
- Some of these measurements are statistically limited and will be significantly updated with the upcoming dataset of run 3

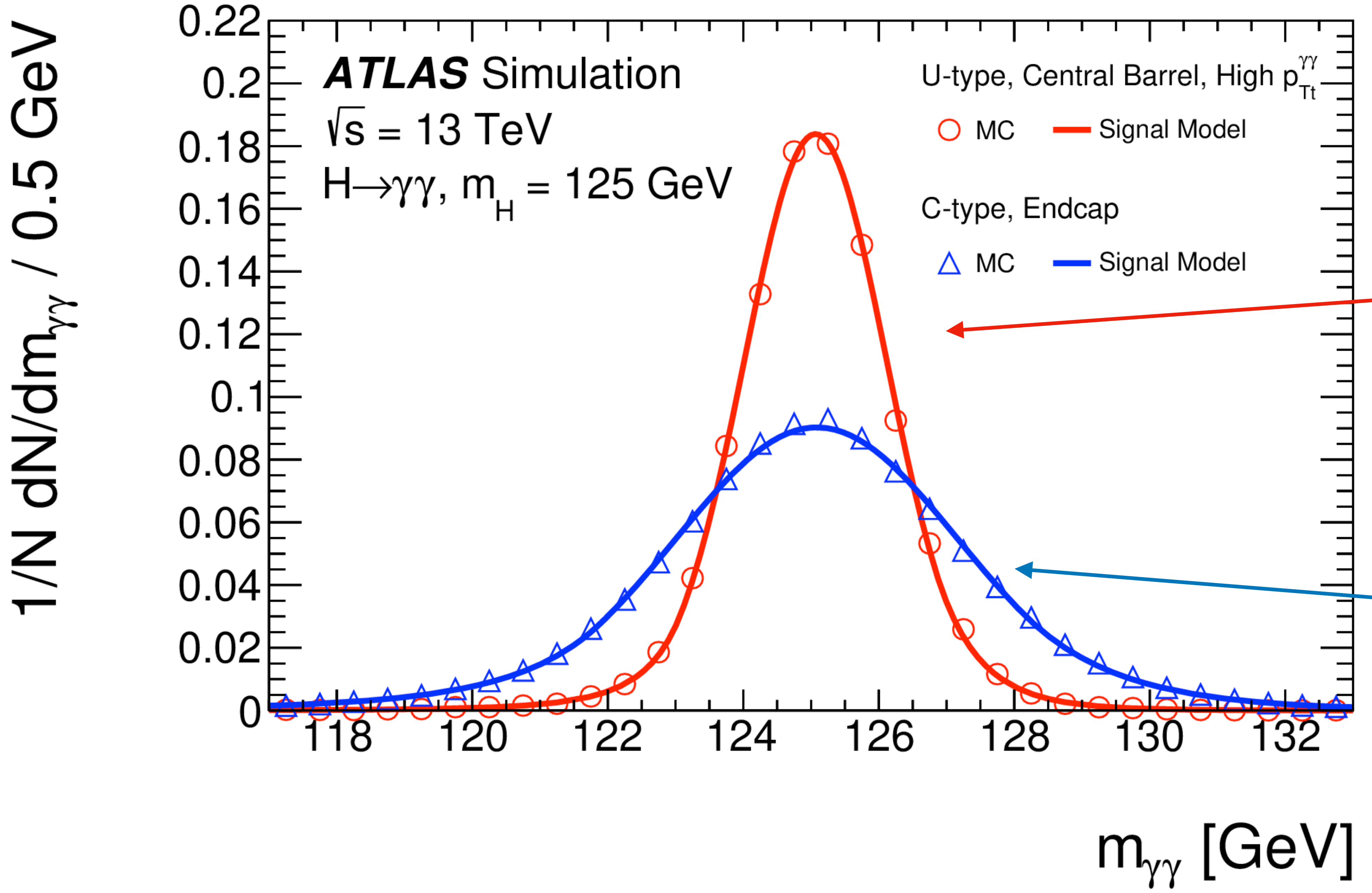
Back-up

H→γγ mass: event categories

- Selected diphoton events are split into 14 mutually exclusive categories
  - At least one converted $\gamma \to e^+e^-$ candidate (C-type) or only unconverted candidates (U-type)
  - Position of the associated photon energy cluster: central-barrel, outer-barrel or endcap
  - Magnitude of the $p_T^{\gamma\gamma}$ component orthogonal to the thrust axis $\hat{t}$: low, medium or high

$$p_{\mathrm{Tt}}^{\gamma\gamma} = |\vec{p}_{\mathrm{T}}^{\gamma\gamma} \times \hat{t}| \qquad \hat{t} = (\vec{p}_{\mathrm{T}}^{\gamma 1} - \vec{p}_{\mathrm{T}}^{\gamma 2})/|\vec{p}_{\mathrm{T}}^{\gamma 1} - \vec{p}_{\mathrm{T}}^{\gamma 2}|$$





Categorization minimizes total expected uncertainty on m_H

Best resolution

Worst resolution

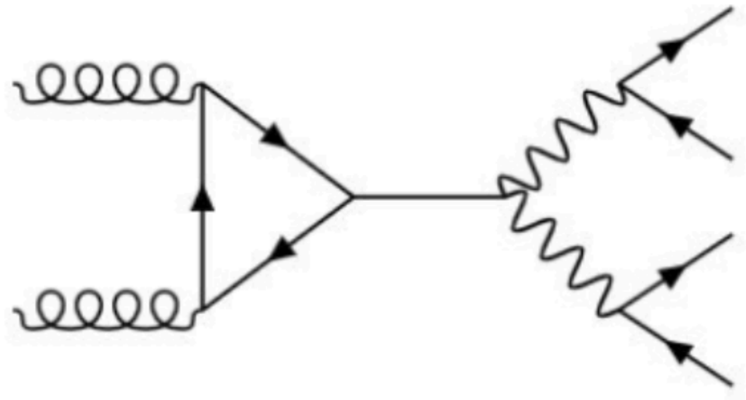
Category	$\sigma_{68}^{\gamma\gamma}$ [GeV]
U, Central-barrel, high $p_{\mathrm{Tt}}^{\gamma\gamma}$	1.10
U, Central-barrel, medium $p_{\mathrm{Tt}}^{\gamma\gamma}$	1.38
U, Central-barrel, low $p_{\mathrm{Tt}}^{\gamma\gamma}$	1.47
U, Outer-barrel, high $p_{\mathrm{Tt}}^{\gamma\gamma}$	1.24
U, Outer-barrel, medium $p_{\mathrm{Tt}}^{\gamma\gamma}$	1.52
U, Outer-barrel, low $p_{\mathrm{Tt}}^{\gamma\gamma}$	1.75
U, Endcap	1.90
C, Central-barrel, high $p_{\mathrm{Tt}}^{\gamma\gamma}$	1.17
C, Central-barrel, medium $p_{\mathrm{Tt}}^{\gamma\gamma}$	1.51
C, Central-barrel, low $p_{\mathrm{Tt}}^{\gamma\gamma}$	1.68
C, Outer-barrel, high $p_{\mathrm{Tt}}^{\gamma\gamma}$	1.44
C, Outer-barrel, medium $p_{\mathrm{Tt}}^{\gamma\gamma}$	1.82
C, Outer-barrel, low $p_{\mathrm{Tt}}^{\gamma\gamma}$	2.10
C, Endcap	2.23
Inclusive	1.82

H→ZZ off shell: analysis strategy

Width

- Analyses performed in three signal regions

ggF Signal region

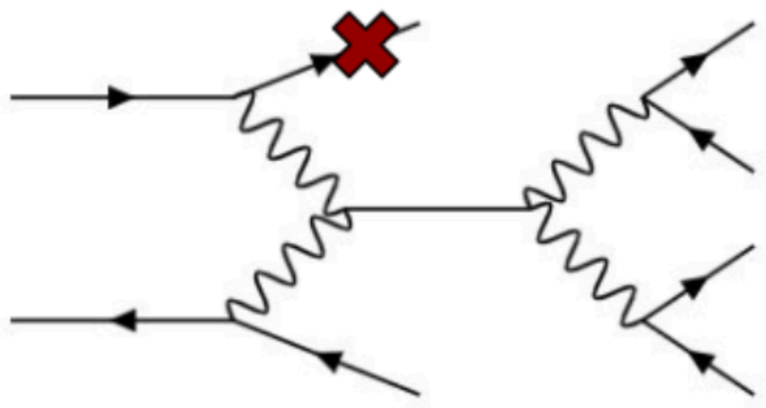


$n_{\text{jets}} = 0$

$n_{\text{jets}} = 1$ and $\eta_j < 2.2$

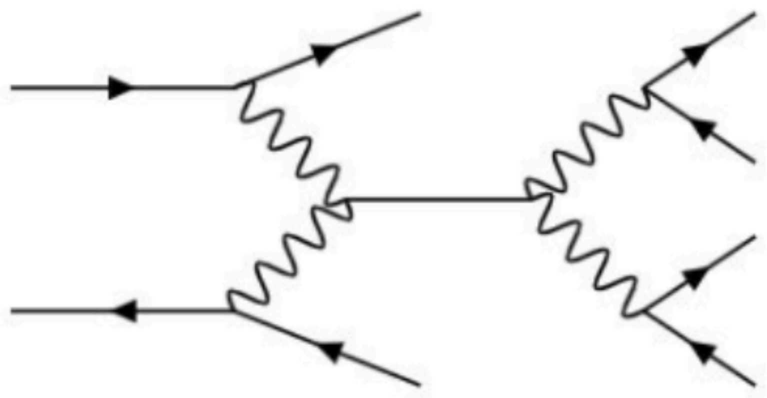
$n_{\text{jets}} \geq 2$ and $\Delta\eta_{jj} < 4.0$

1 jet mixed signal region



$n_{\text{jets}} = 1$ and $\eta_j \geq 2.2$

EW signal region



$n_{\text{jets}} \geq 2$ and $\Delta\eta_{jj} \geq 4.0$

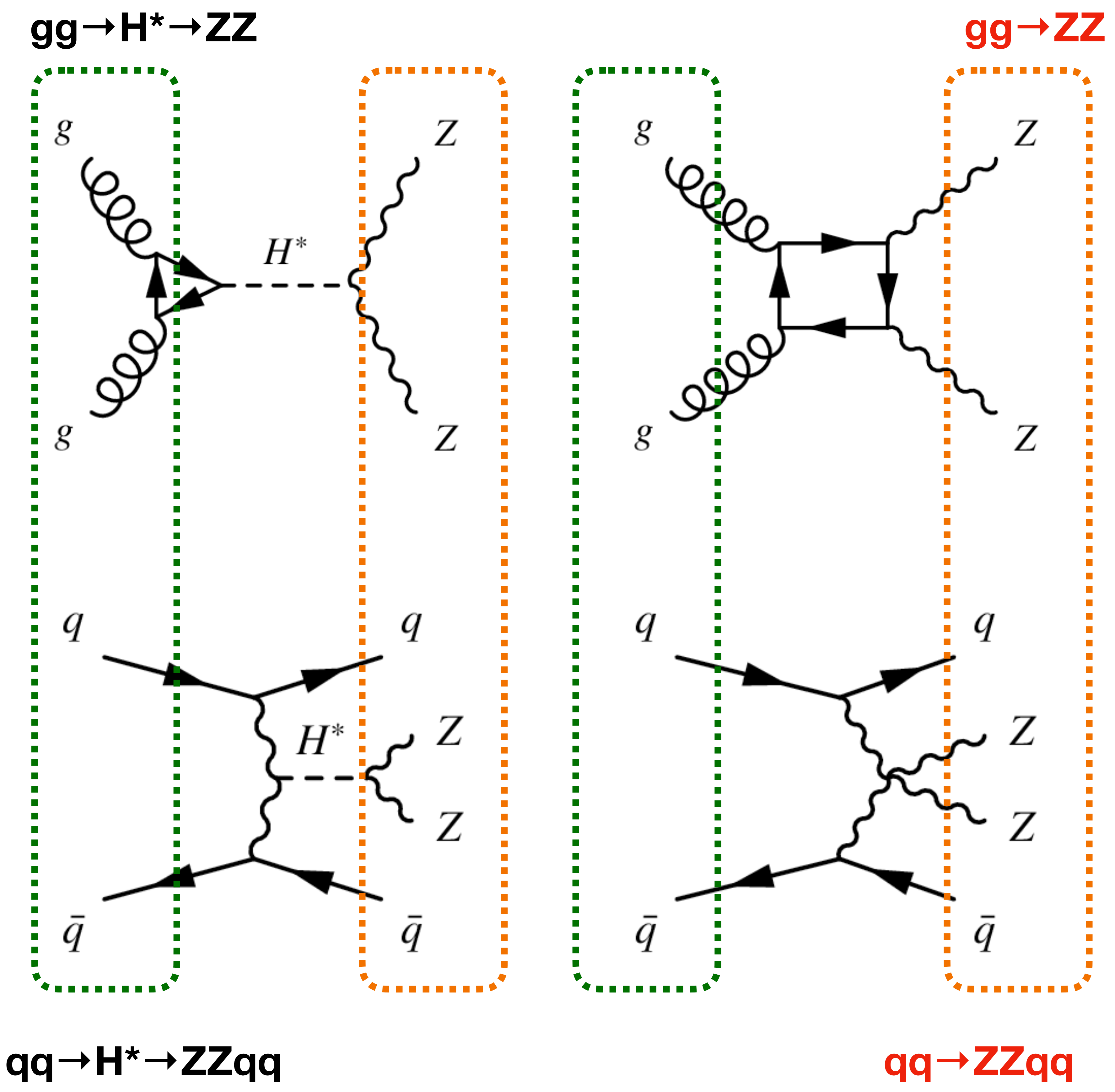
- **Interference** component parametrised separately from **signal** and **background**

$$\nu^{\text{ggF}}(\mu^{\text{ggF}}_{\text{off-shell}}, \boldsymbol{\theta}) = \mu^{\text{ggF}}_{\text{off-shell}} \cdot n^{\text{ggF}}_{\text{S}}(\boldsymbol{\theta}) + \sqrt{\mu^{\text{ggF}}_{\text{off-shell}}} \cdot (n^{\text{ggF}}_{\text{SBI}}(\boldsymbol{\theta}) - n^{\text{ggF}}_{\text{S}}(\boldsymbol{\theta}) - n^{\text{ggF}}_{\text{B}}(\boldsymbol{\theta})) + n^{\text{ggF}}_{\text{B}}(\boldsymbol{\theta})$$

H→ZZ off shell: interference

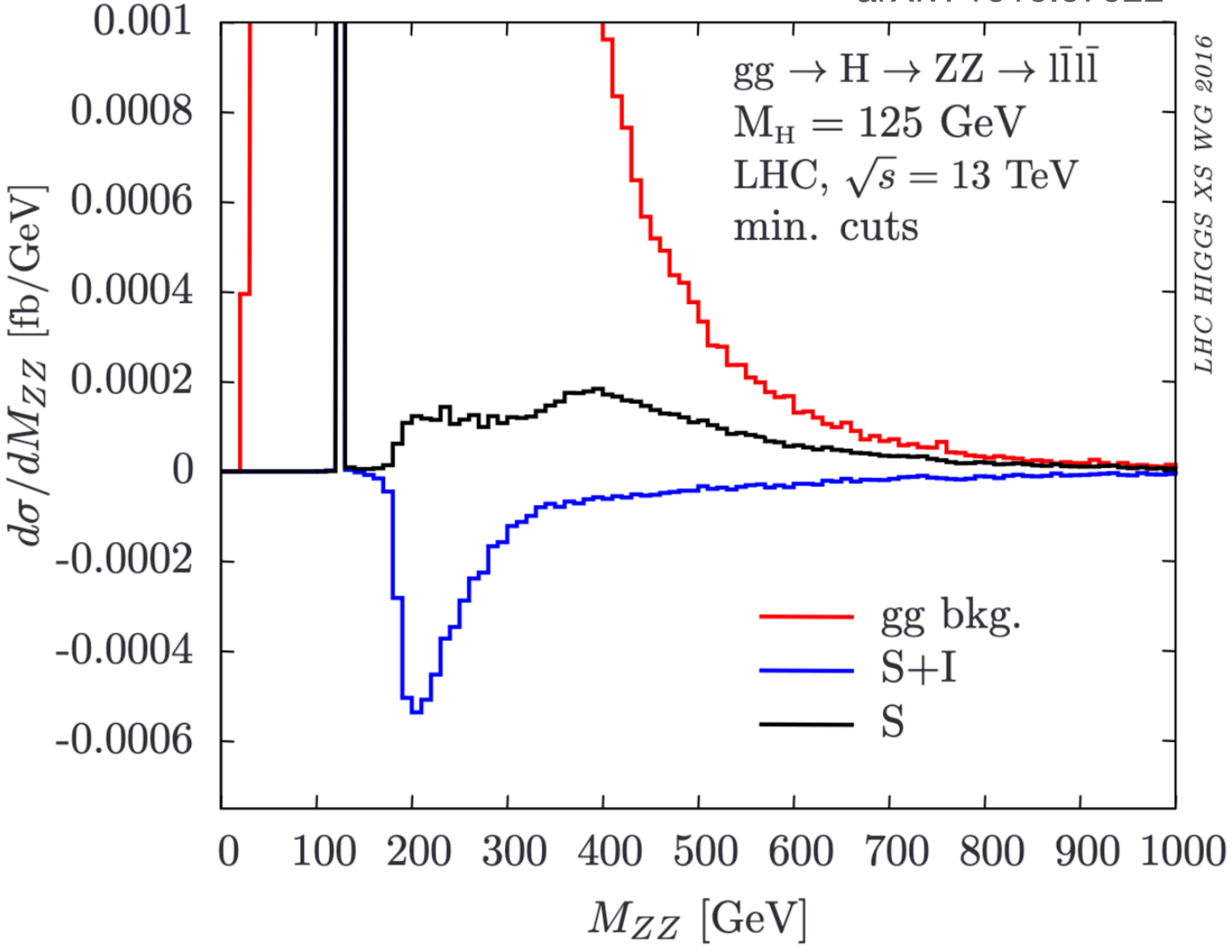
Width

- **Signal** and **background** have same **initial** and **final** state
- **Negative interference** in the off-shell region with destructive effects on the cross-section

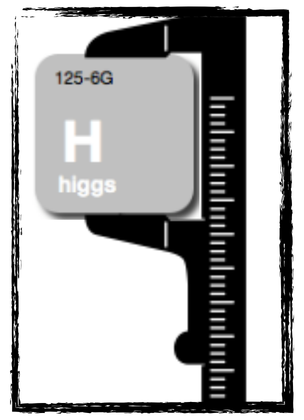


In the ATLAS analysis, three regions are defined to target the production modes: ggF, EW and mixed.

arXiv: 1610.07922



ttH+4top width: details



Width

Systematic uncertainty	Impact on 95% CL upper limit on Γ_H Expected [%]	Impact on 95% CL upper limit on Γ_H Observed [%]
Theory	37	33
$t\bar{t}t\bar{t}$ production	25	13
Higgs boson production/decay	5	6
Other processes	10	16
Experimental	2	2
Jet flavour tagging	2	1
Jet and missing transverse energy	< 1	< 1
Leptons and photons	< 1	< 1
All other systematic uncertainties	< 1	< 1

Target processes		Reference
Off-shell measurement		
$pp \to t\bar{t}t\bar{t}$		[26]
On-shell measurement		
Production	Decay	
ggF, VBF, WH, ZH, $t\bar{t}H$, tH	$H \to \gamma\gamma$	[31]
$t\bar{t}H + tH$	$H \to b\bar{b}$	[32]
WH, ZH	$H \to b\bar{b}$	[33, 34]
VBF	$H \to b\bar{b}$	[35]
ggF, VBF, $WH + ZH$, $t\bar{t}H + tH$	$H \to ZZ$	[36]
ggF, VBF	$H \to WW$	[37]
WH, ZH	$H \to WW$	[38]
ggF, VBF, $WH + ZH$, $t\bar{t}H + tH$	$H \to \tau\tau$	[39]
ggF+ $t\bar{t}H + tH$, VBF+ $WH + ZH$	$H \to \mu\mu$	[40]
Inclusive	$H \to Z\gamma$	[41]

H→ZZ CP

CP

Possible sources of CP-violation can be represented by effective couplings

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

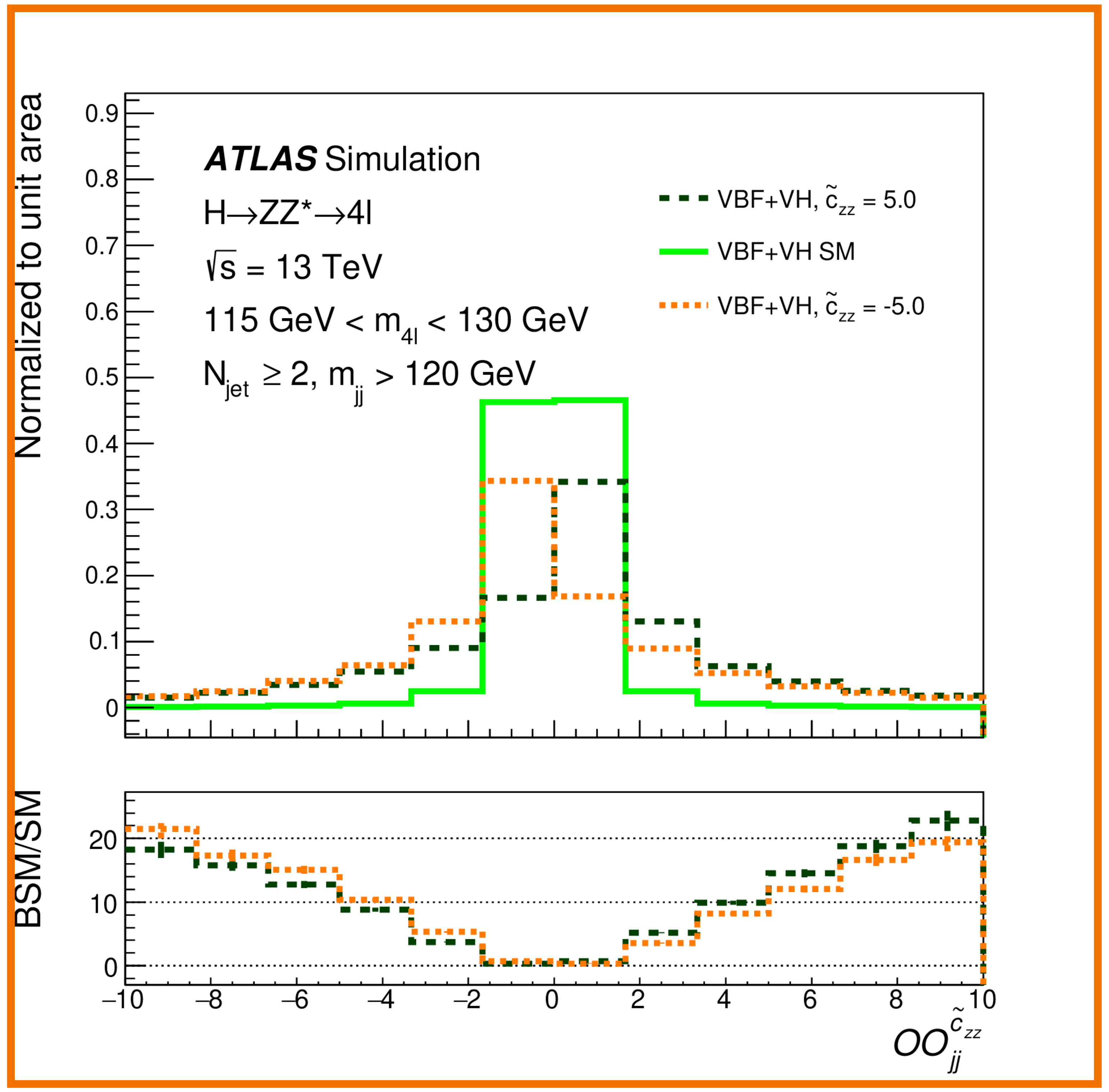
$$\mathcal{M}_{\text{Mix}}(\boldsymbol{c}) = \mathcal{M}_{\text{SM}} + \mathcal{M}_{\text{BSM}}(\boldsymbol{c})$$

$$\implies |\mathcal{M}_{\text{Mix}}(\boldsymbol{c})|^2 = |\mathcal{M}_{\text{SM}}|^2 + 2\Re(\mathcal{M}_{\text{SM}}\mathcal{M}^*_{\text{BSM}}(\boldsymbol{c})) + |\mathcal{M}_{\text{BSM}}(\boldsymbol{c})|^2$$

CP-even

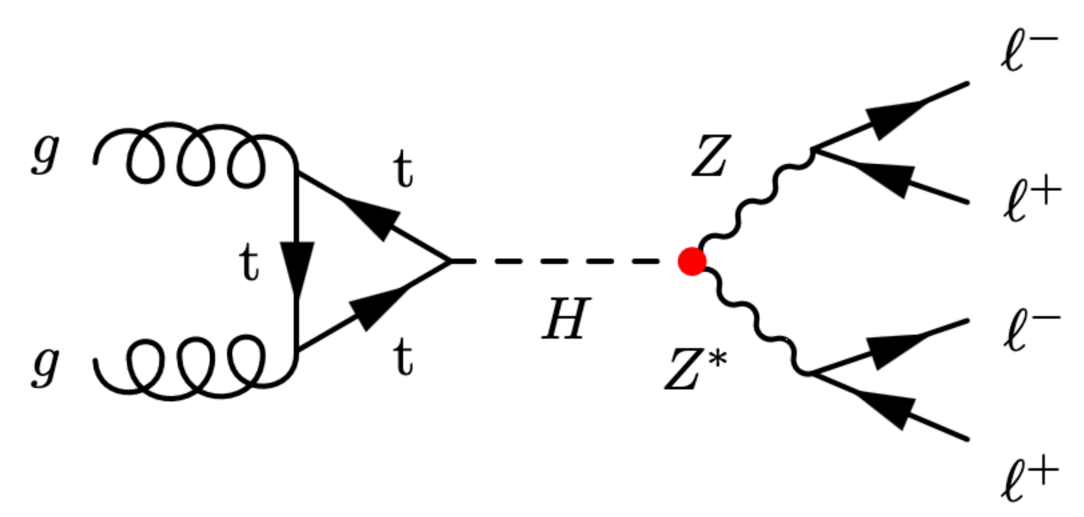
CP-odd

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

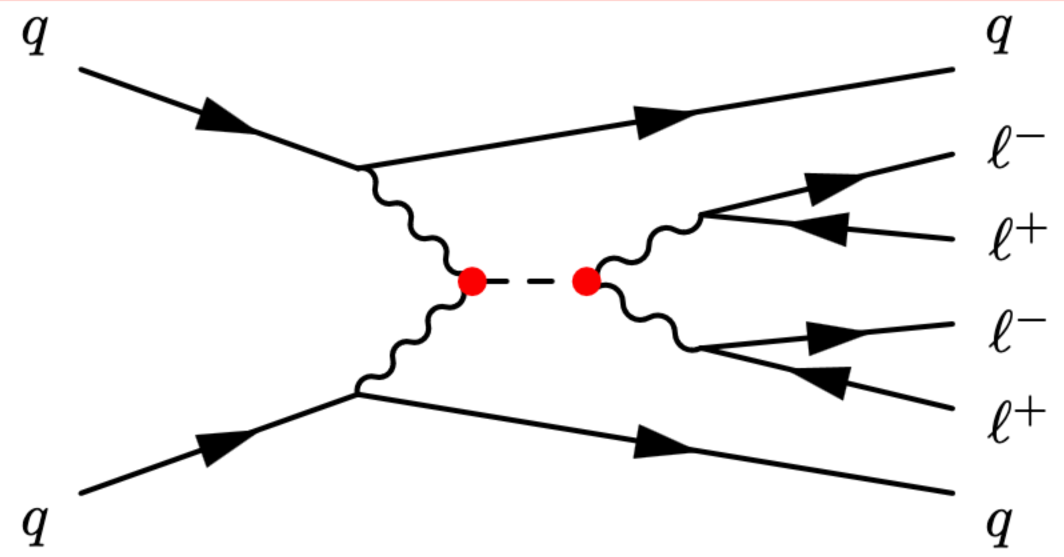


Symmetric for CP-even (SM)
Asymmetric for CP-odd (BSM)

Coupling on decay side



Coupling on both production and decay side

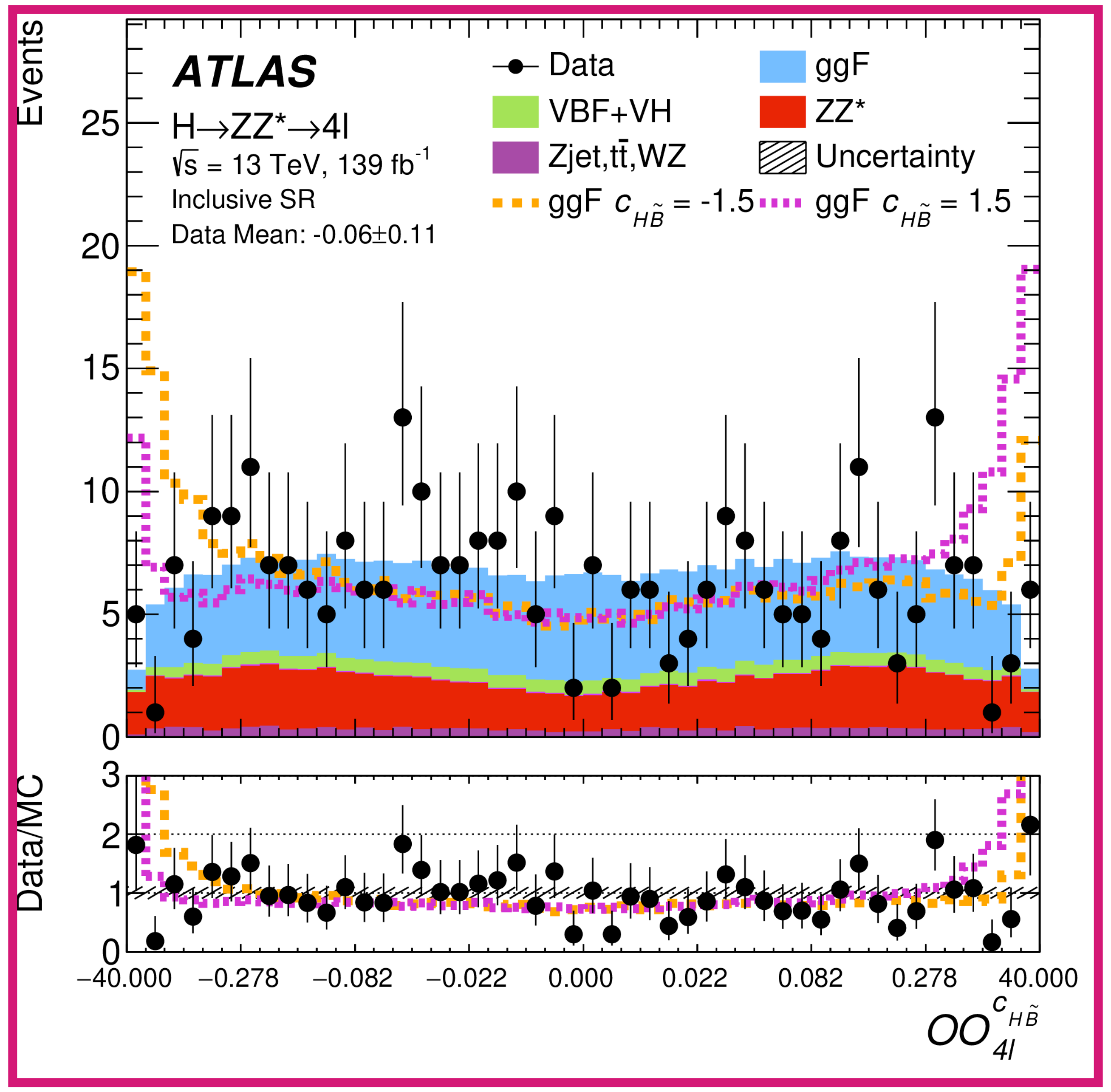


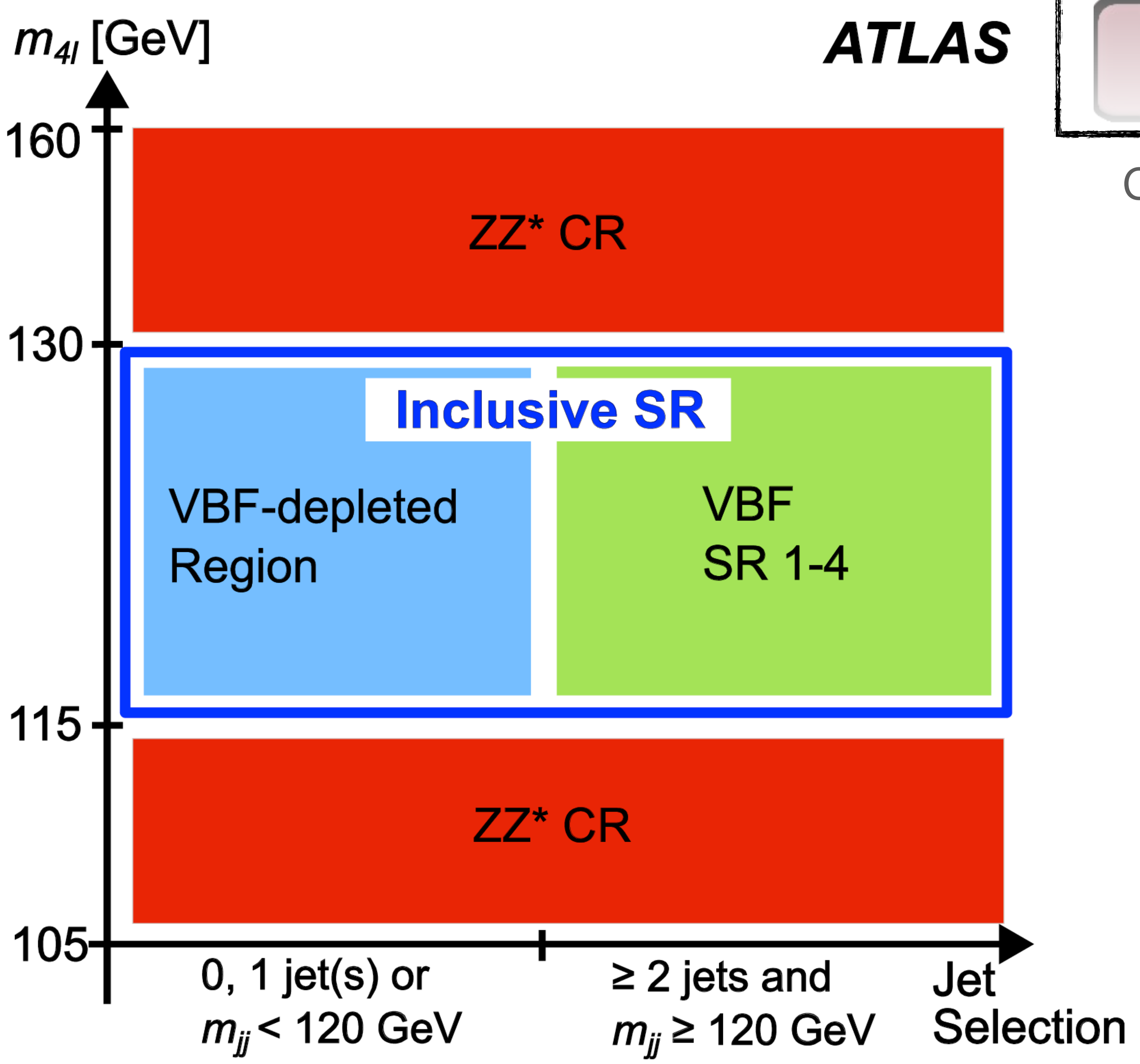
Optimal observables (OO)

- Production OO → 2-jets variable
- Decay OO → 4l variable

H→ZZ CP: analysis strategy

- Decay-only fit:
  - Decay-level OO in the Inclusive SR
- Production-only fit:
  - VBF-depleted region to estimate ggF normalization
  - Production-level OO in VBF SR 1-4
- Combined fit:
  - Decay-level OO in VBF-depleted region
  - Production-level OO in VBF SR 1-4





CP

- ZZ* CR to estimate bkg normalisation
- Morphing method to perform a shape-only analysis

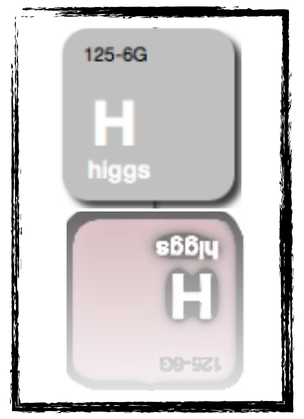
H→ZZ CP: results

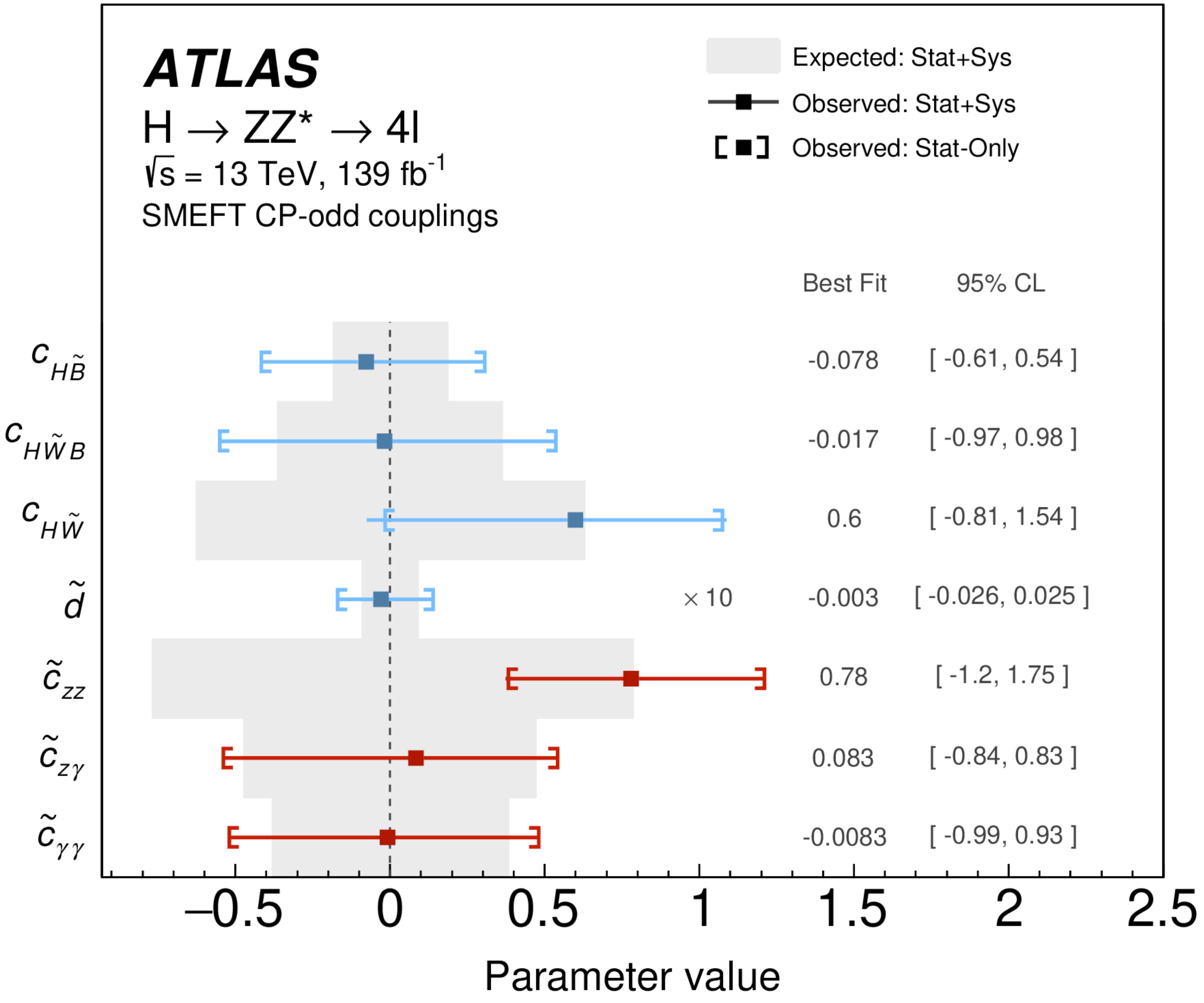
- Constraints on Wilson coefficients related to dim-6 CP-odd operators
- Two bases considered: **Warsaw** and **Higgs mass eigenstates**
- Sensitive to only CP-odd couplings - i.e. not CP-even quadratic terms, nor CP-even couplings
- No uncertainties on the normalisation of the processes (data-driven)
- All results are compatible with the SM expectation of pure CP-even couplings

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

$\tilde{d}$ single BSM CP-odd coupling

Precision limited by statistics:
Impact of systematics (exper. and theor.) is <5%





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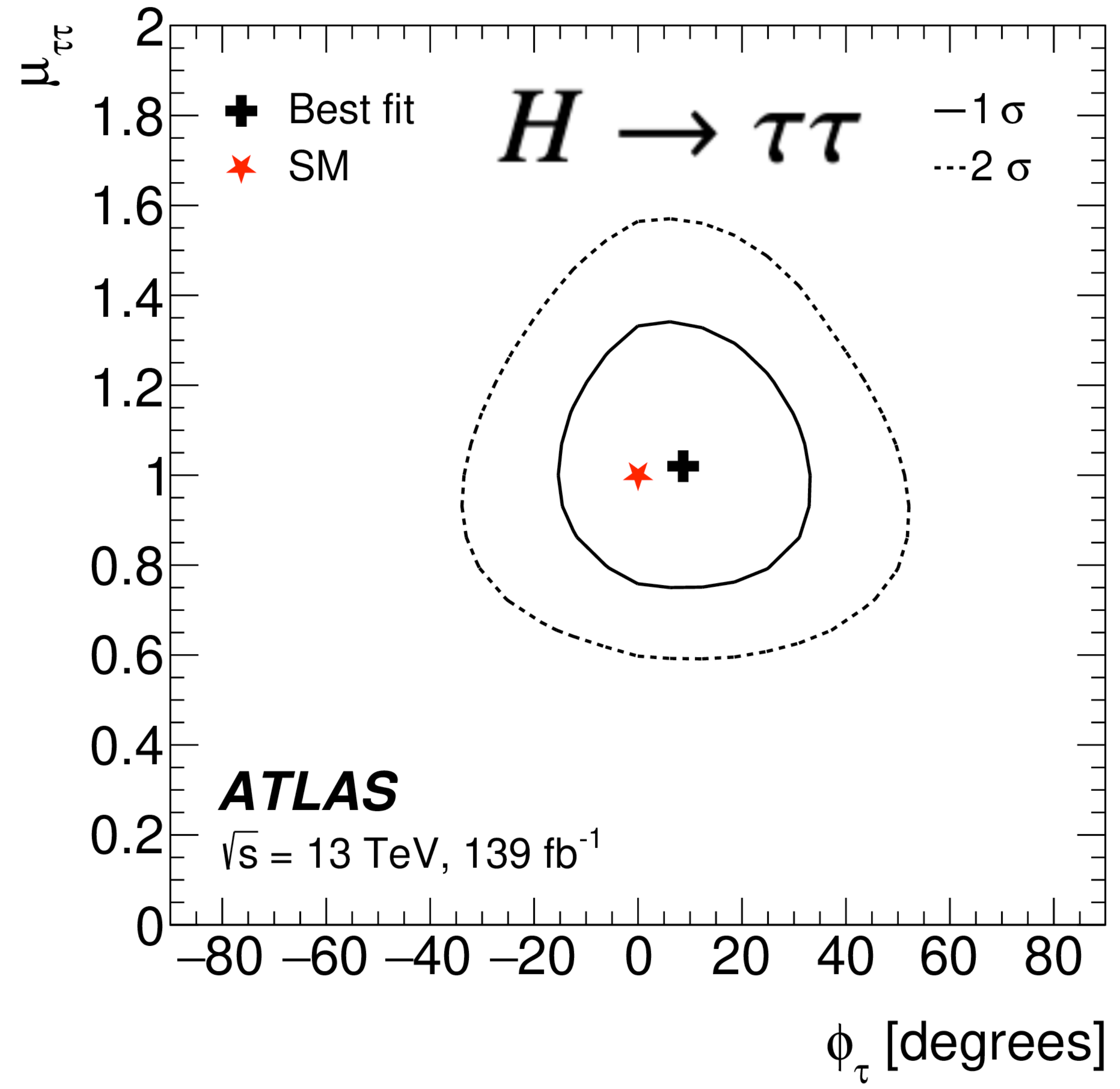
CP

CP nature of Yukawa couplings

$$\mathscr{L}_{ffH} = \kappa'_f y_f \phi \bar{\psi}_f (\cos\alpha + i\gamma_5 \sin\alpha)\psi_f$$

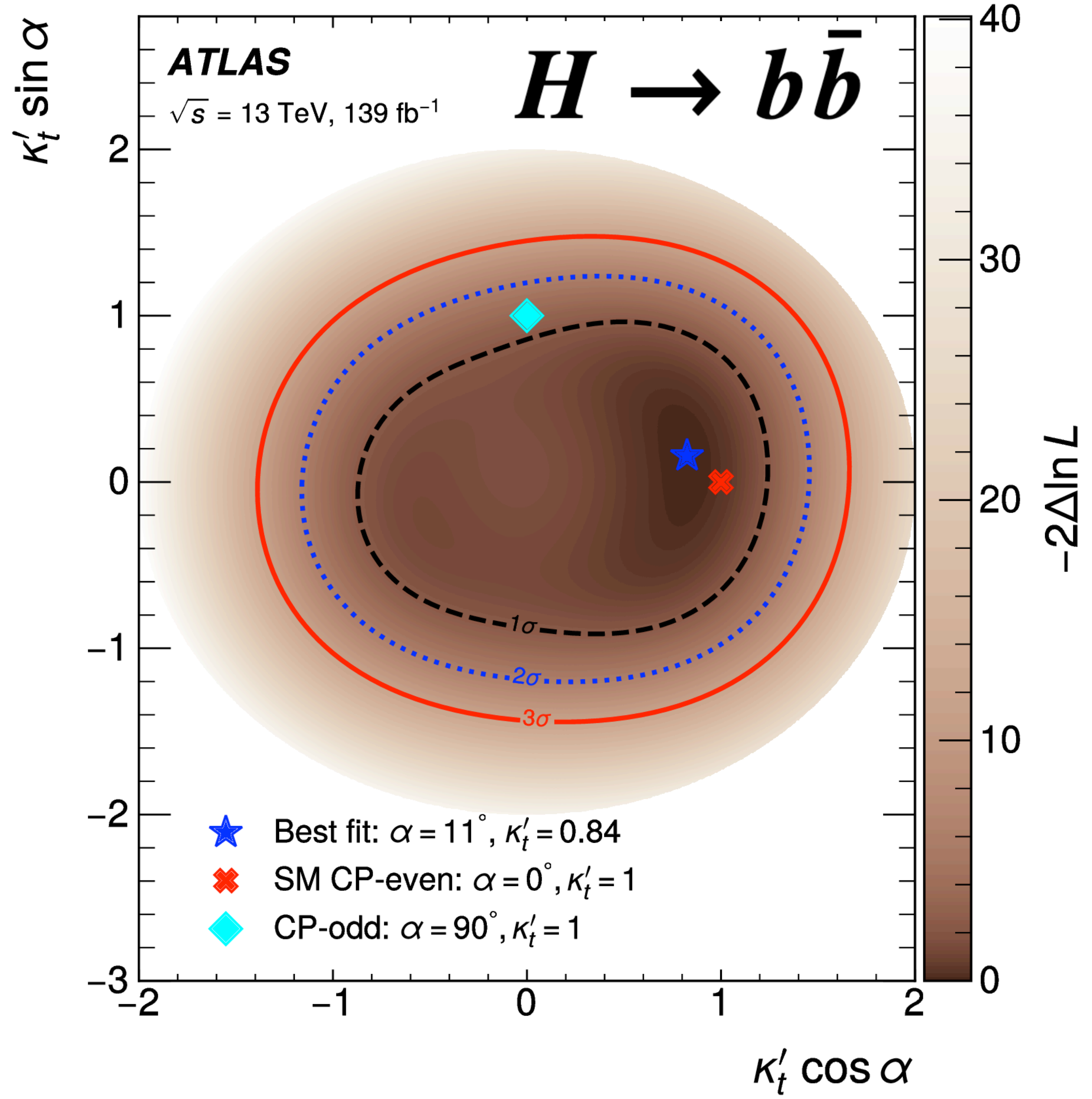
Coupling strength   CP-mixing angle



ϕ_τ is $9° \pm 16°$

And pure CP-odd hypothesis excluded at 3.4σ

- H→bb produced in association with top quarks (ttH and tH)
  - CP-sensitive observables rely on characteristics of the ttH topology for CP-odd production
- Interactions with tau-leptons in H→ττ
  - CP-sensitive observables rely on the geometry of the visible τ decay products



$$\alpha = 11^{\circ}{}^{+52°}_{-73°}$$

And pure CP-odd hypothesis excluded at 1.2σ