Measurements of Higgs boson properties with the ATLAS detector

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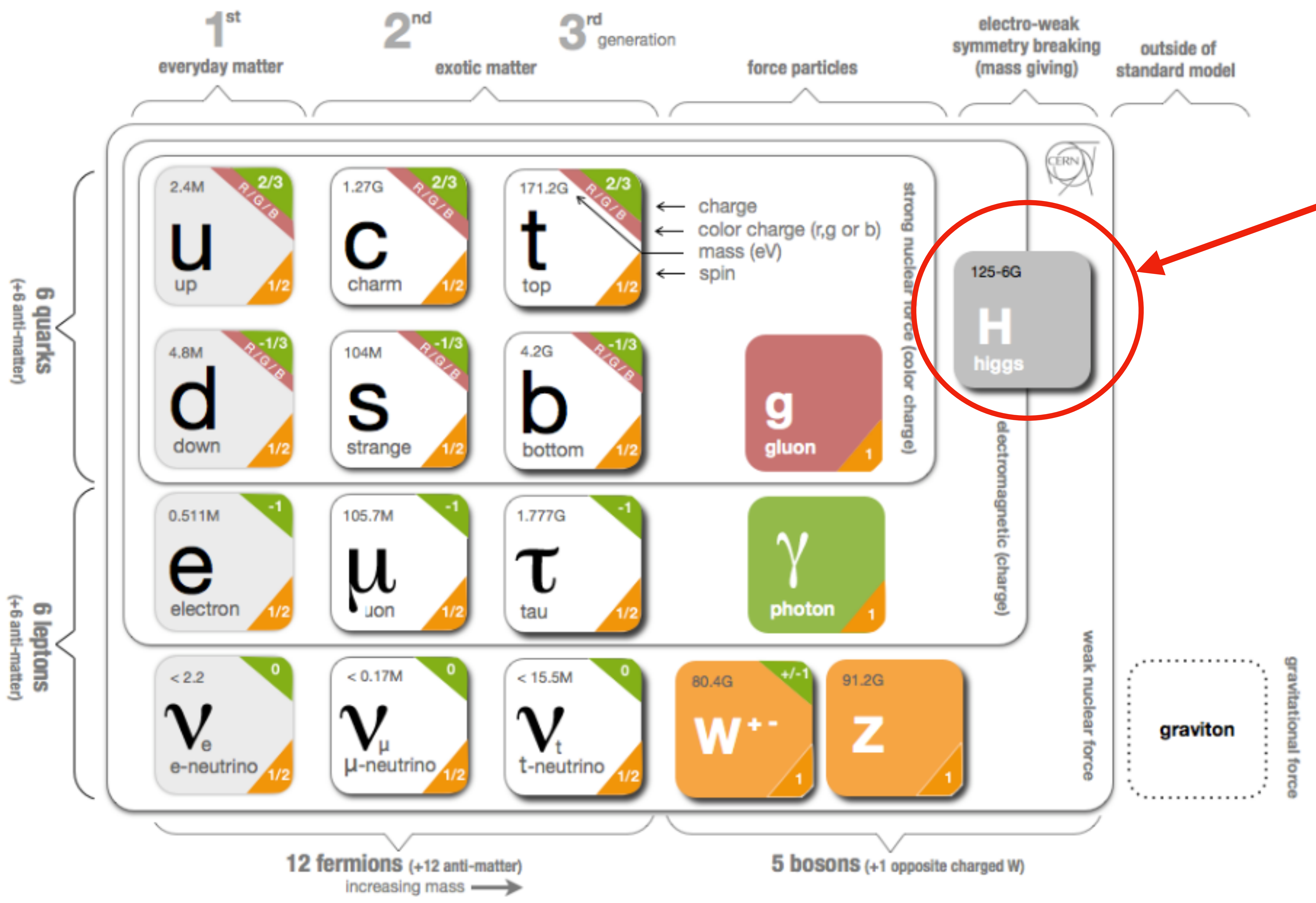
On behalf of the ATLAS collaboration

PHENO 2023 - May 9th 2023

Introduction

The Higgs boson in the Standard Model (SM) of particle physics

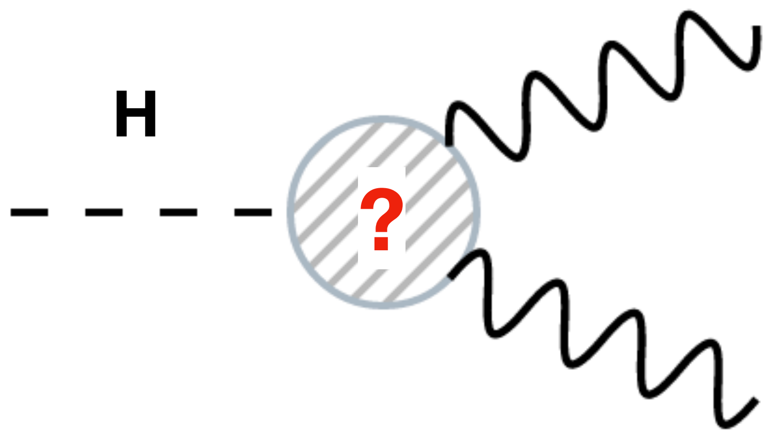


Higgs-like particle discovered at the LHC in 2012:

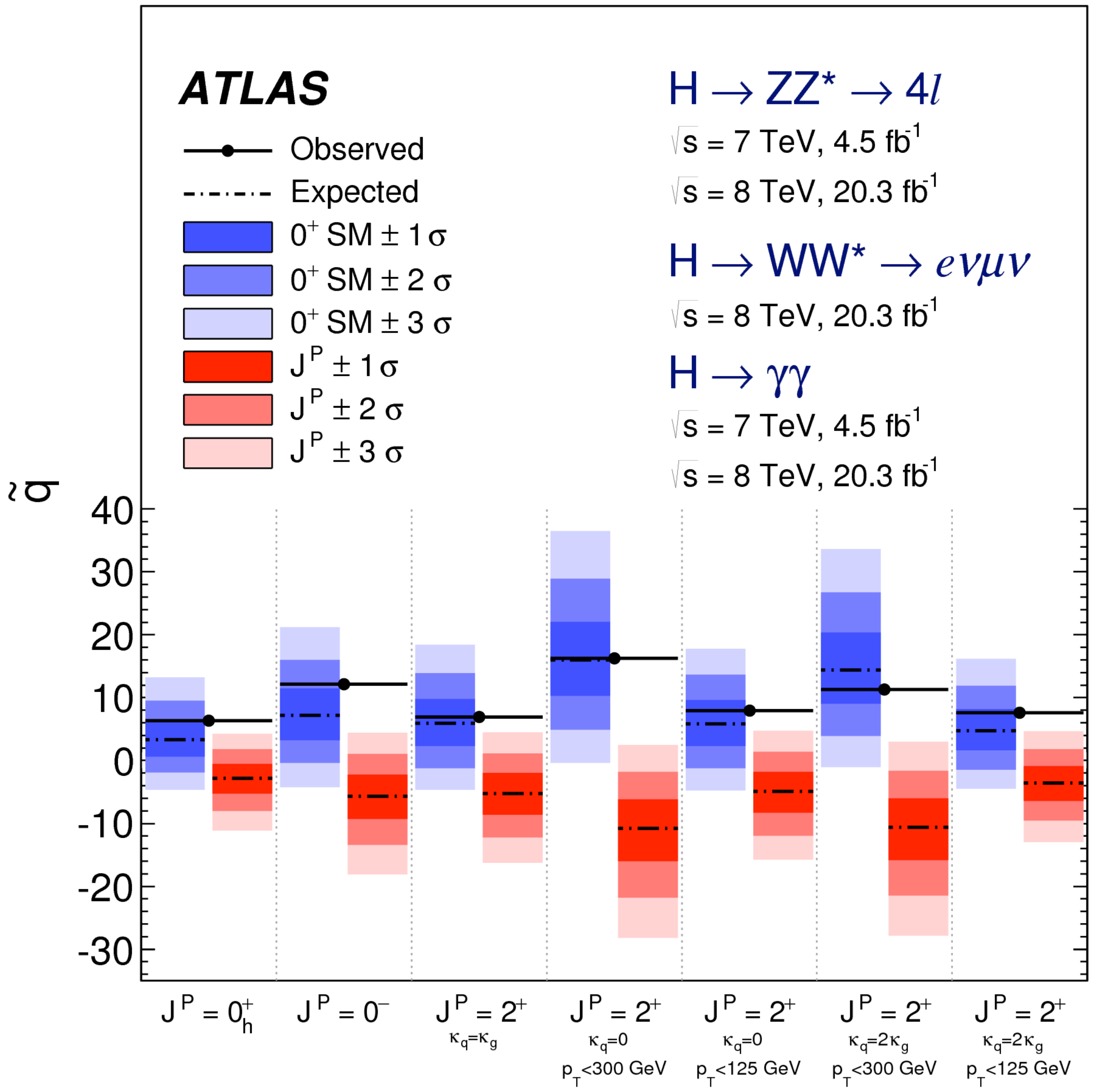
- How large is its *mass* (m_H)?
- What is its decay *width* (Γ_H)?
- And its *CP/spin* state?

Higgs properties: mass, width, CP/spin

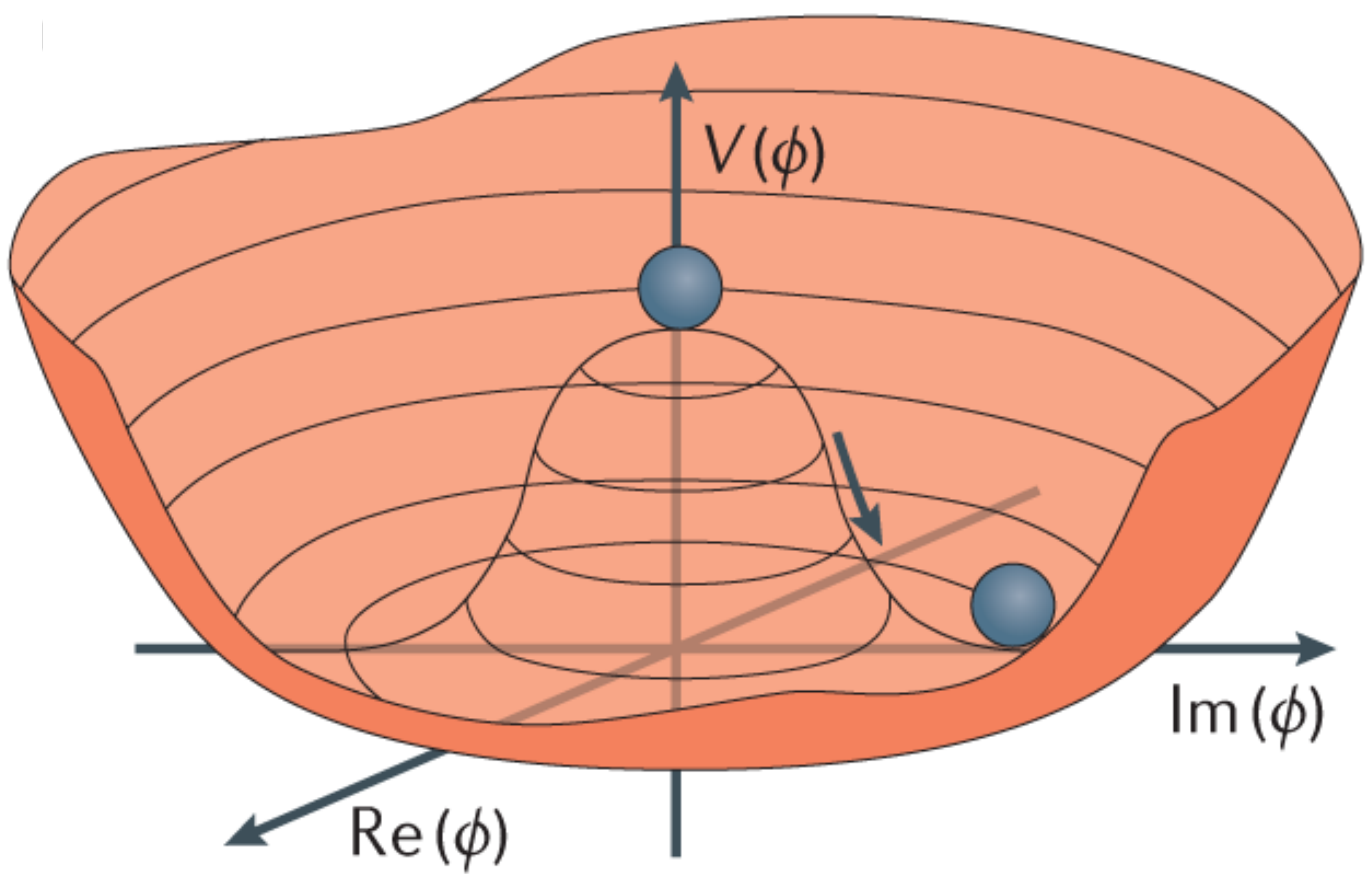
- The Higgs boson is unstable: the larger its **width**, the faster it decays
  - New physics can alter its value both directly (new final states) and indirectly (virtual particles in the loop)



- Predicted to be **spin 0 and CP-even** $J^{CP}=0^{++}$
  - Pure CP-odd states already excluded from its observed decays
  - CP admixture couplings could potentially explain baryon asymmetry of the universe



The Higgs potential

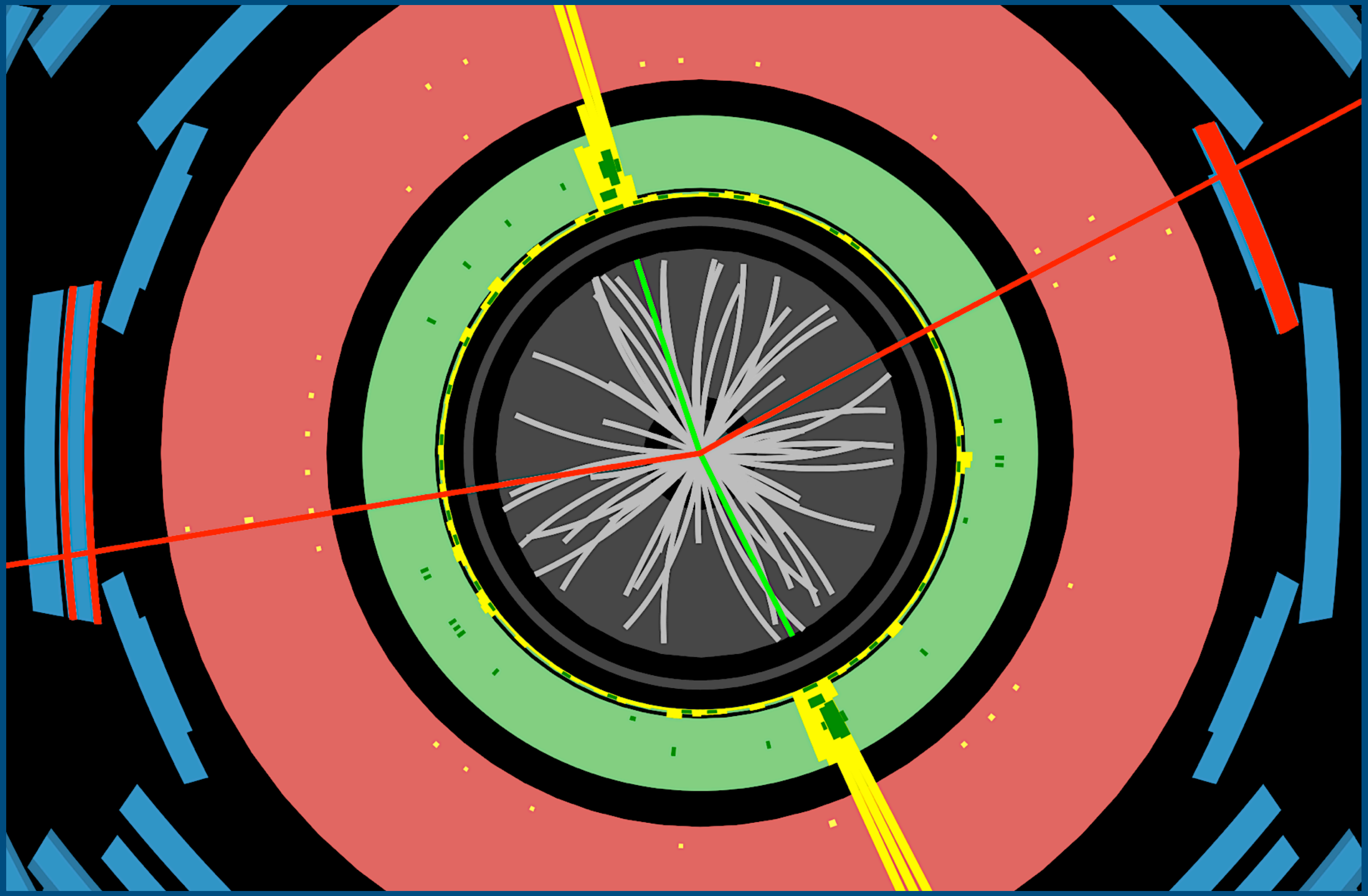


$$V(\phi) \propto \frac{1}{2} m_H^2 \phi^2 + O(\phi^3)$$

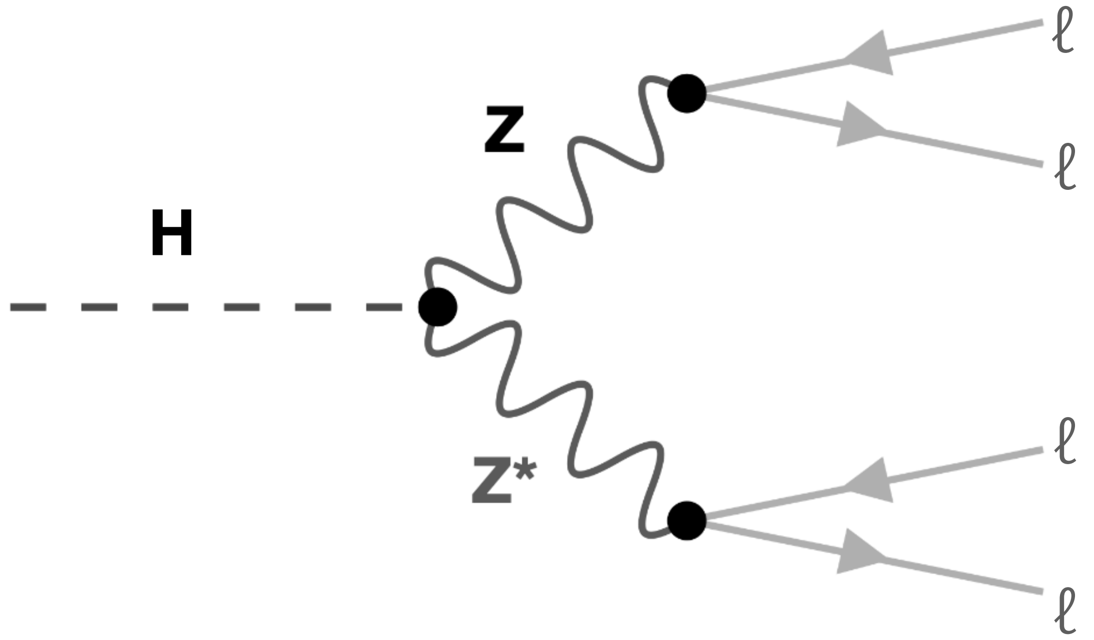
- **Mass** not predicted by the theory! It determines:
  - Strength of interaction with other SM particles
  - Shape of the Higgs potential (together with the VEV)

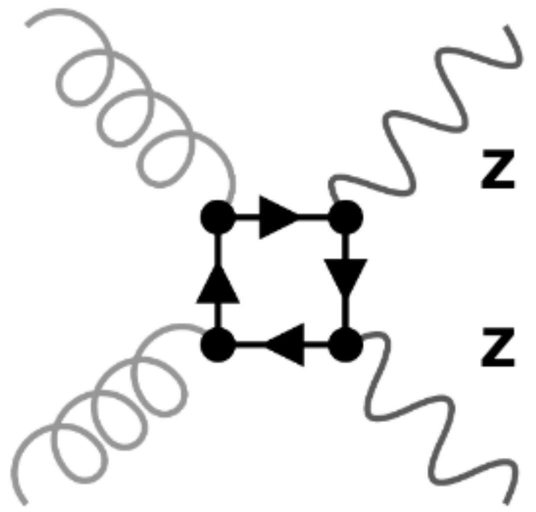
H→ZZ(*)

- **Measurement of the mass (arXiv:2207.00320)**
- **Constraint on the width (arXiv:2304.01532)**

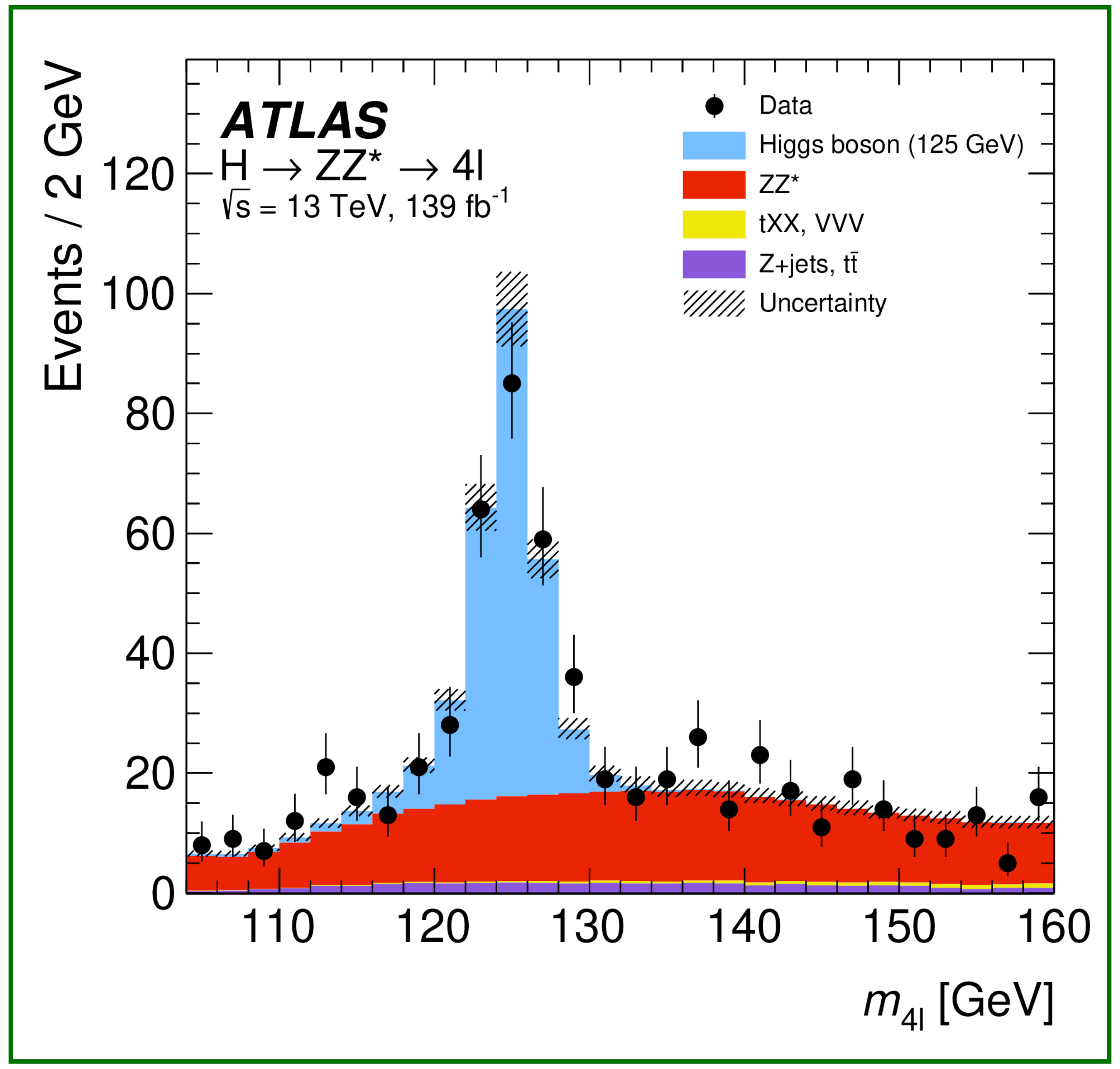


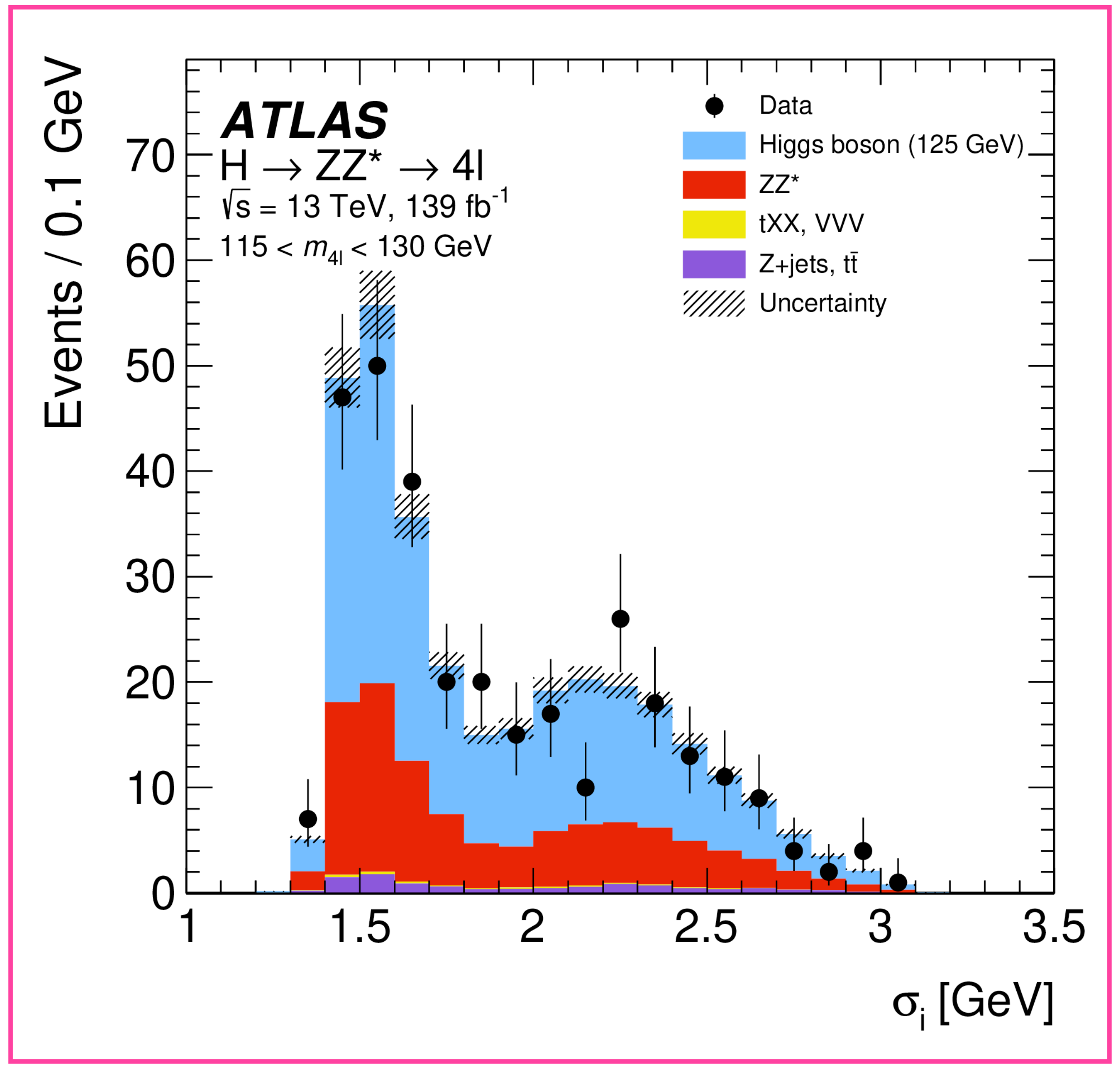
m_H measurement in H→ZZ*→4ℓ (ℓ=e, μ): method

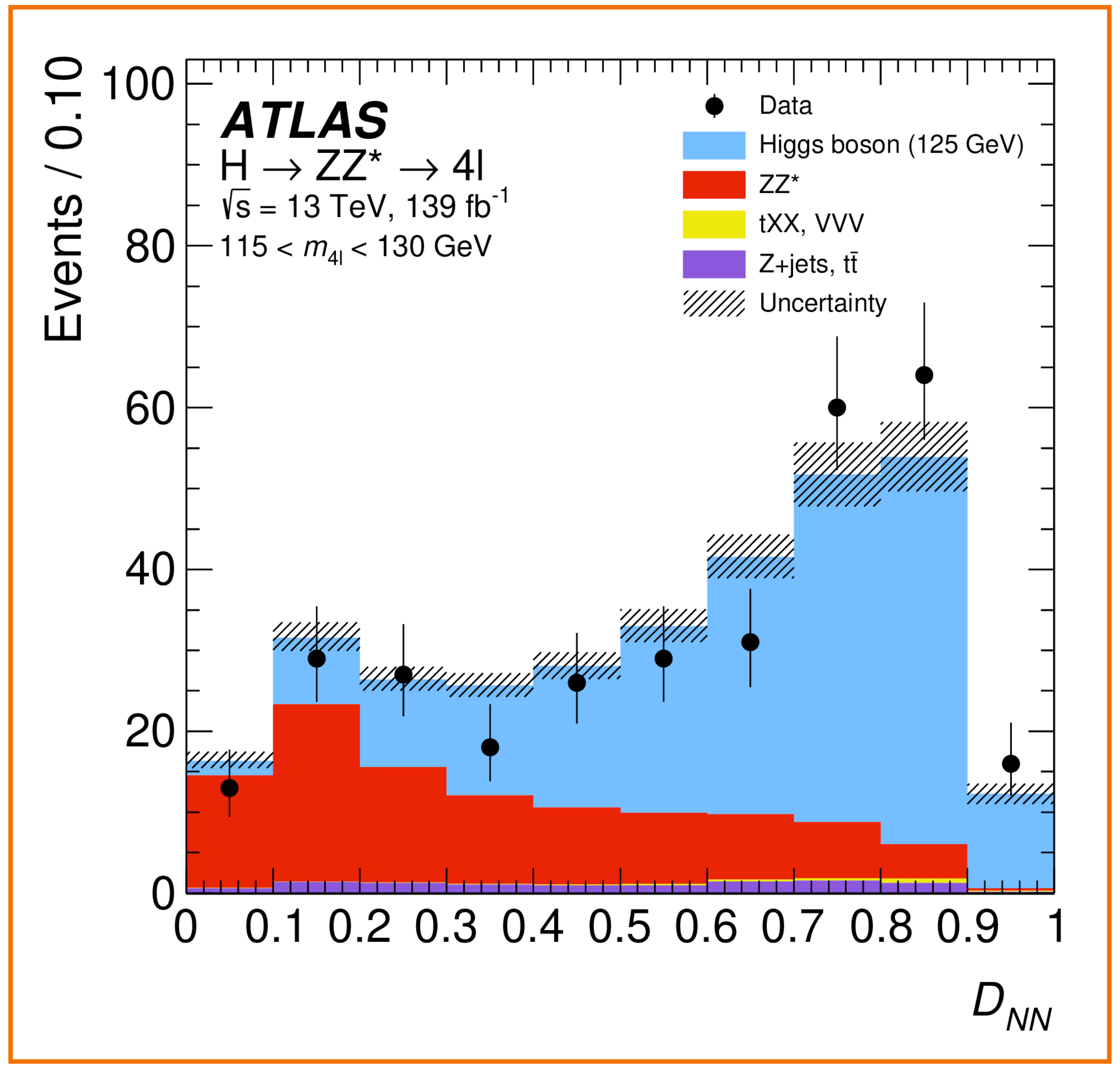




- Performed in 4 channels (4**μ**, 2**μ**2e, 2e2**μ**, 4e)
- **Deep Neural Network (D_{NN})** separates signal and main non-resonant ZZ background
- Uncertainty on m_H further constrained using **per-event resolution σ_i**
- 2-dimensional PDF to fit the signal $\mathcal{P}(m_{4\ell}|D_{NN},\sigma_i,m_H)\cdot\mathcal{P}(D_{NN}|m_H)$

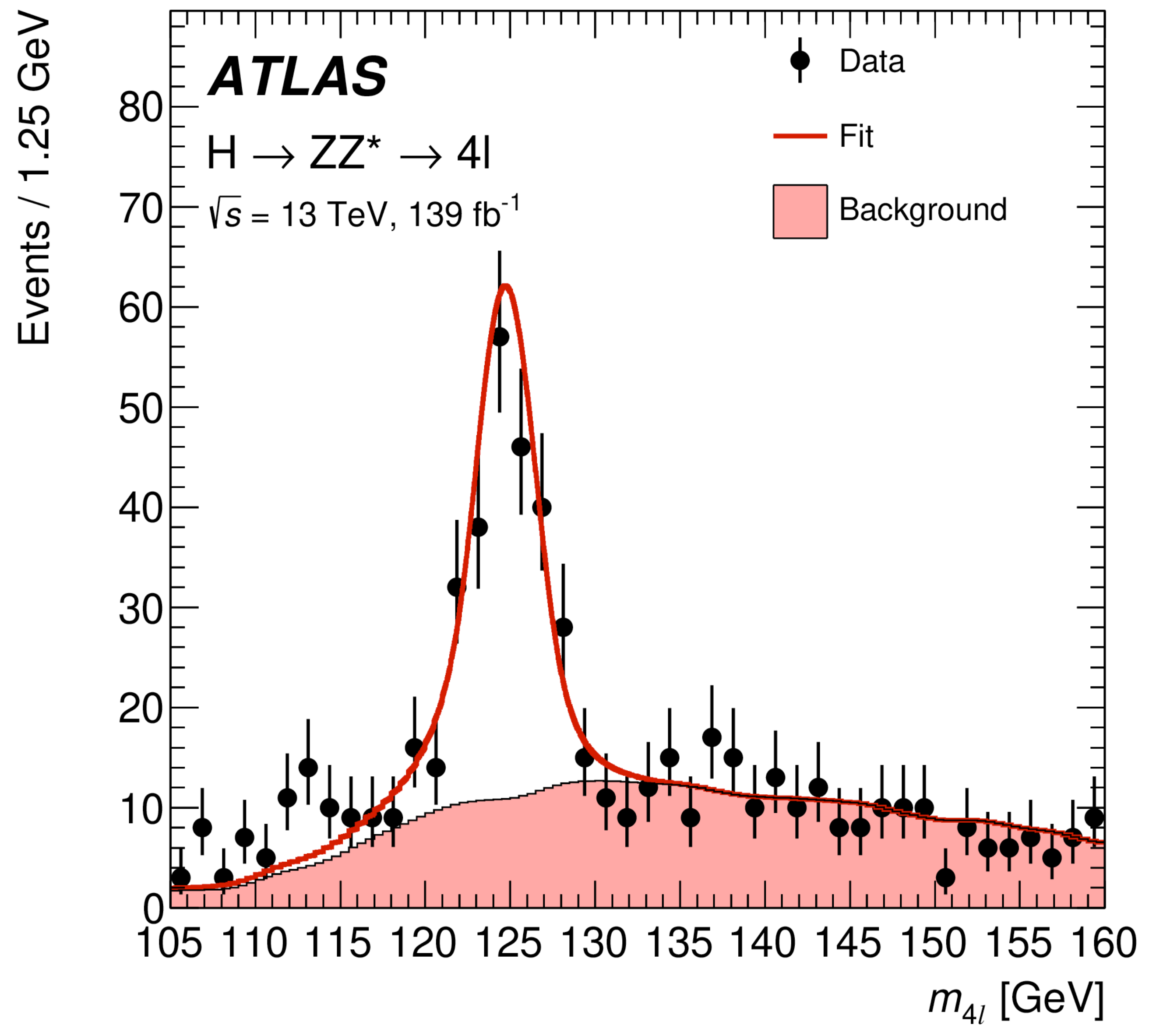


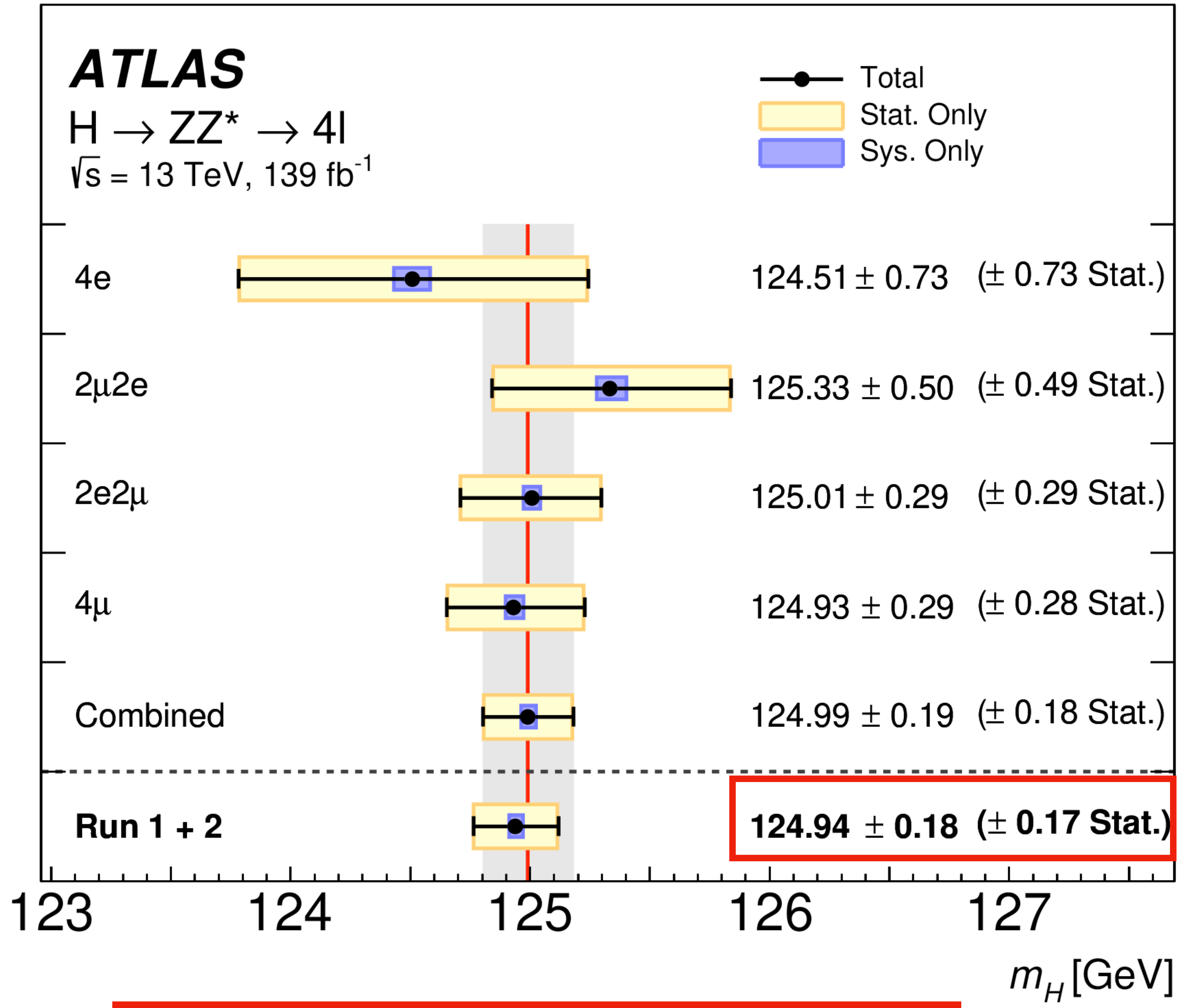




m_H measurement in H→ZZ*→4ℓ (ℓ=e, μ): results

- The most precise Higgs measurement → and will improve with more data!
- Systematics under control → uncertainties related to muon and electron reconstruction ~ O(10) MeV





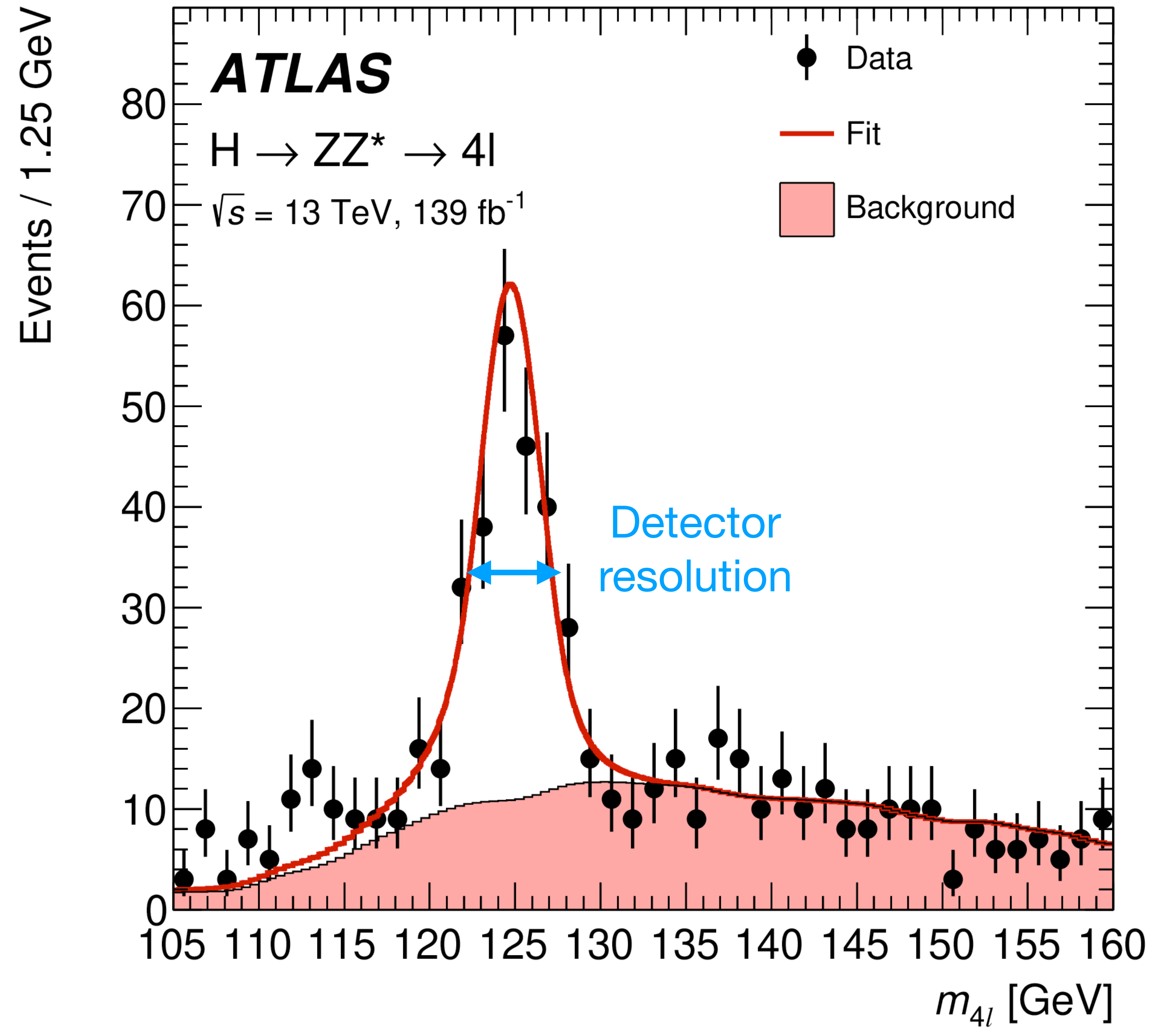
124.94 ± 0.18 (± 0.17 Stat.)

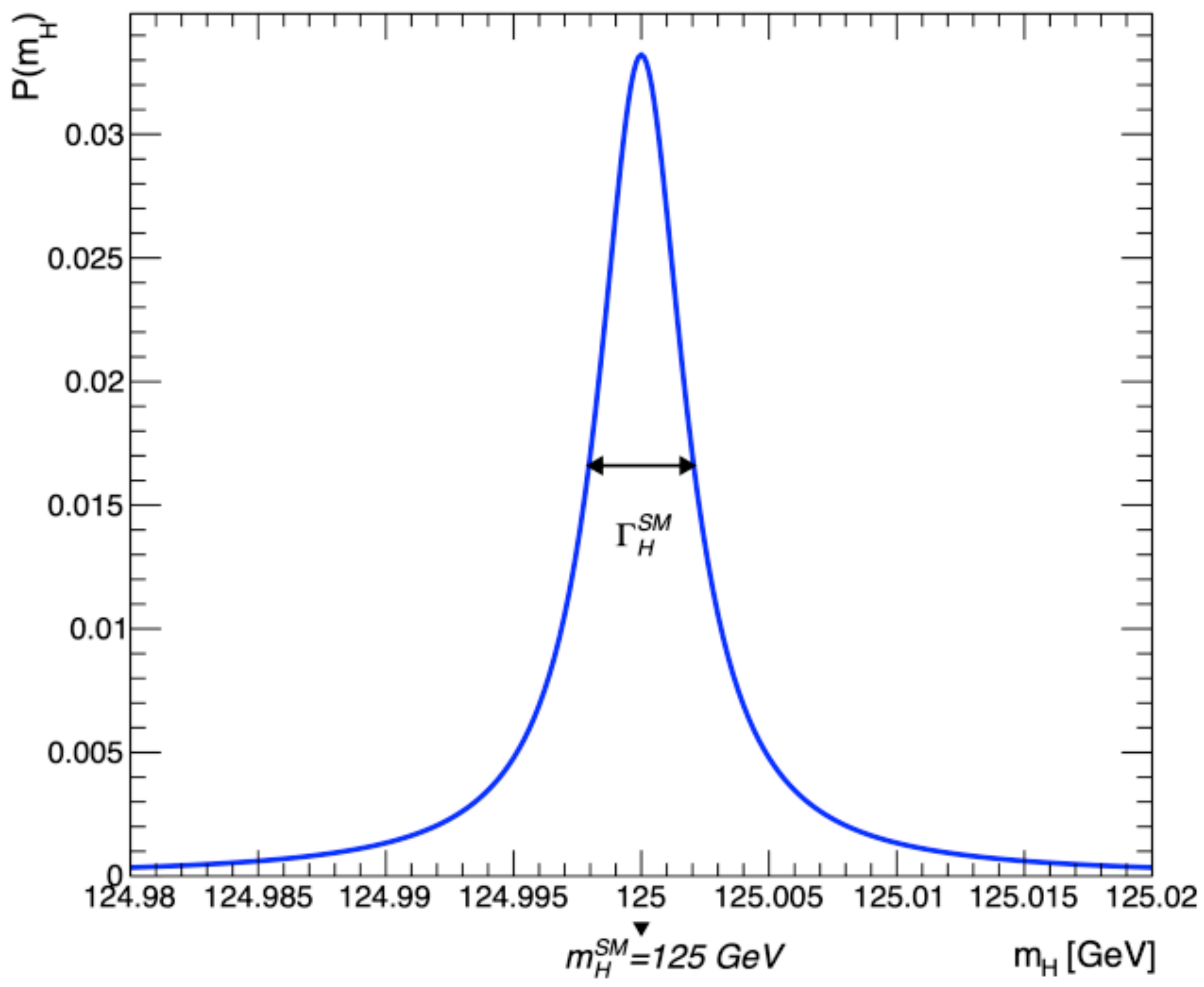
Very high precision!

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!!!



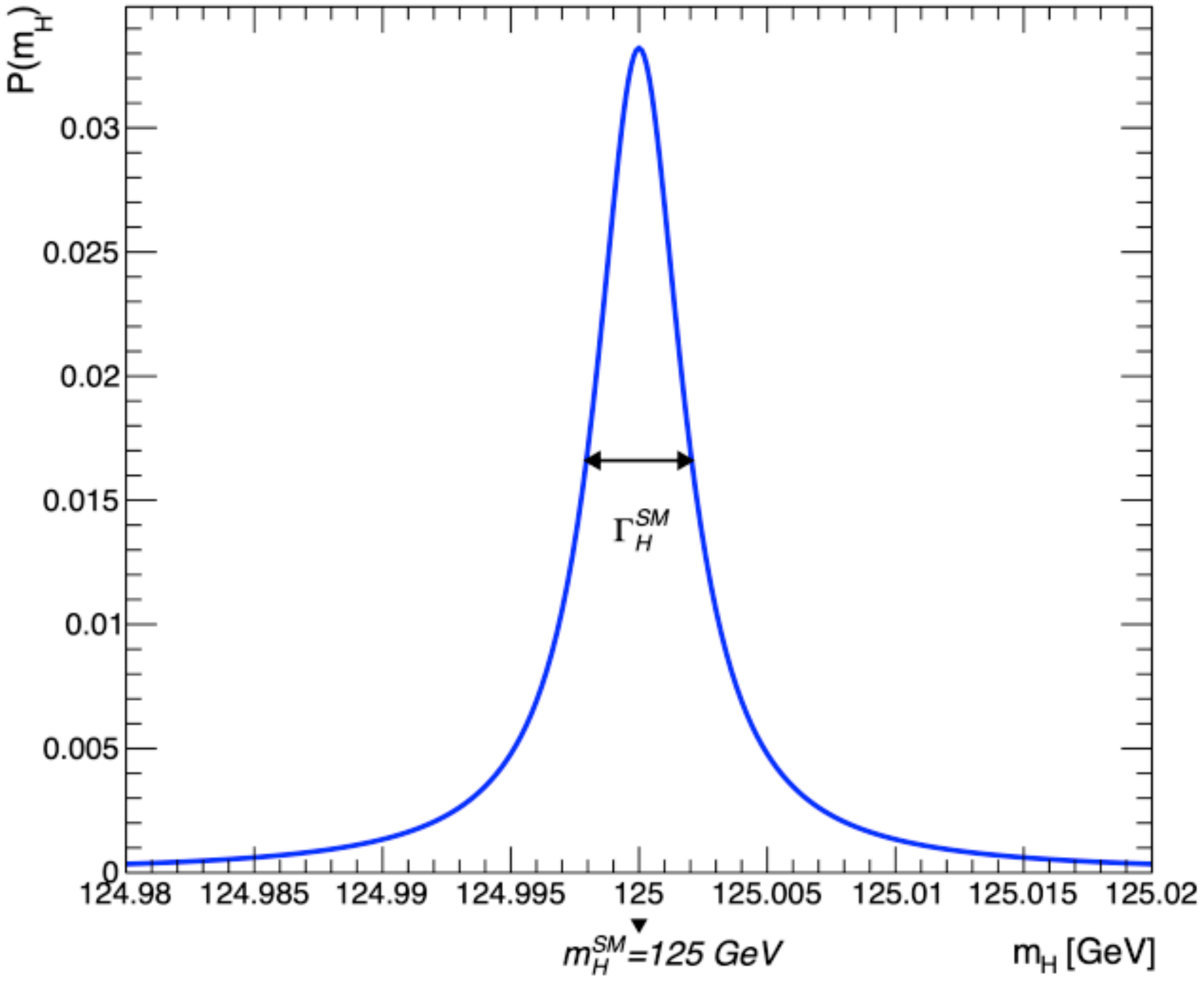


$$\frac{d\sigma_{pp\to H\to ZZ}}{dM_{4l}^2} \sim \frac{g_{Hgg}^2 g_{HZZ}^2}{(M_{4l}^2 - m_H^2)^2 + m_H^2\Gamma_H^2}$$

Higgs decay width

- 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!!!



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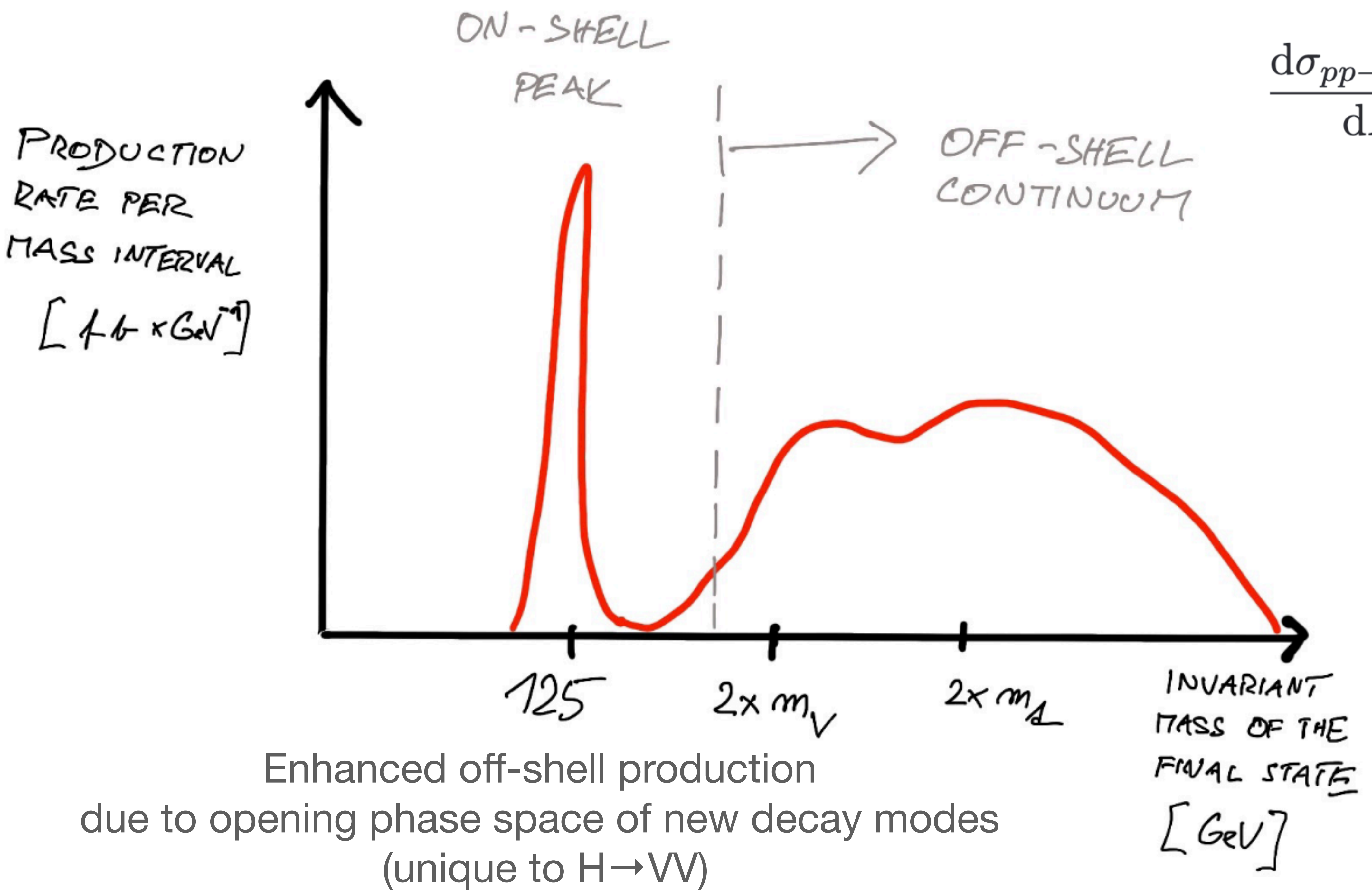


Enhanced off-shell production
due to opening phase space of new decay modes
(unique to H→VV)

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

$$\sigma_{gg\to H\to ZZ}^{\text{off-shell}} \sim \frac{g_{\text{ggH}}^2 g_{\text{HZZ}}^2}{m_{ZZ}^2}$$

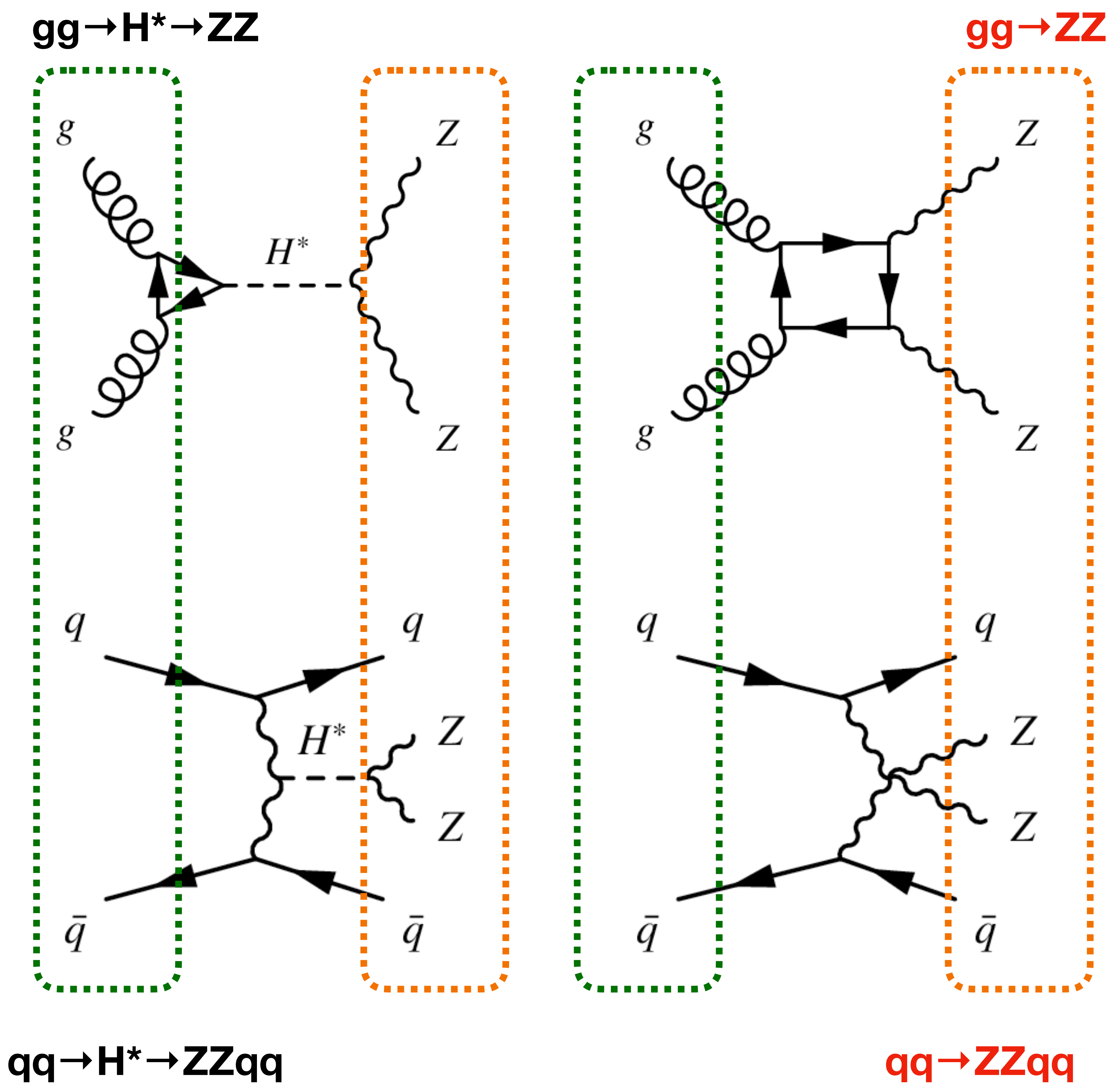
…assuming same strength of the on-shell and off-shell effective couplings…

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

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

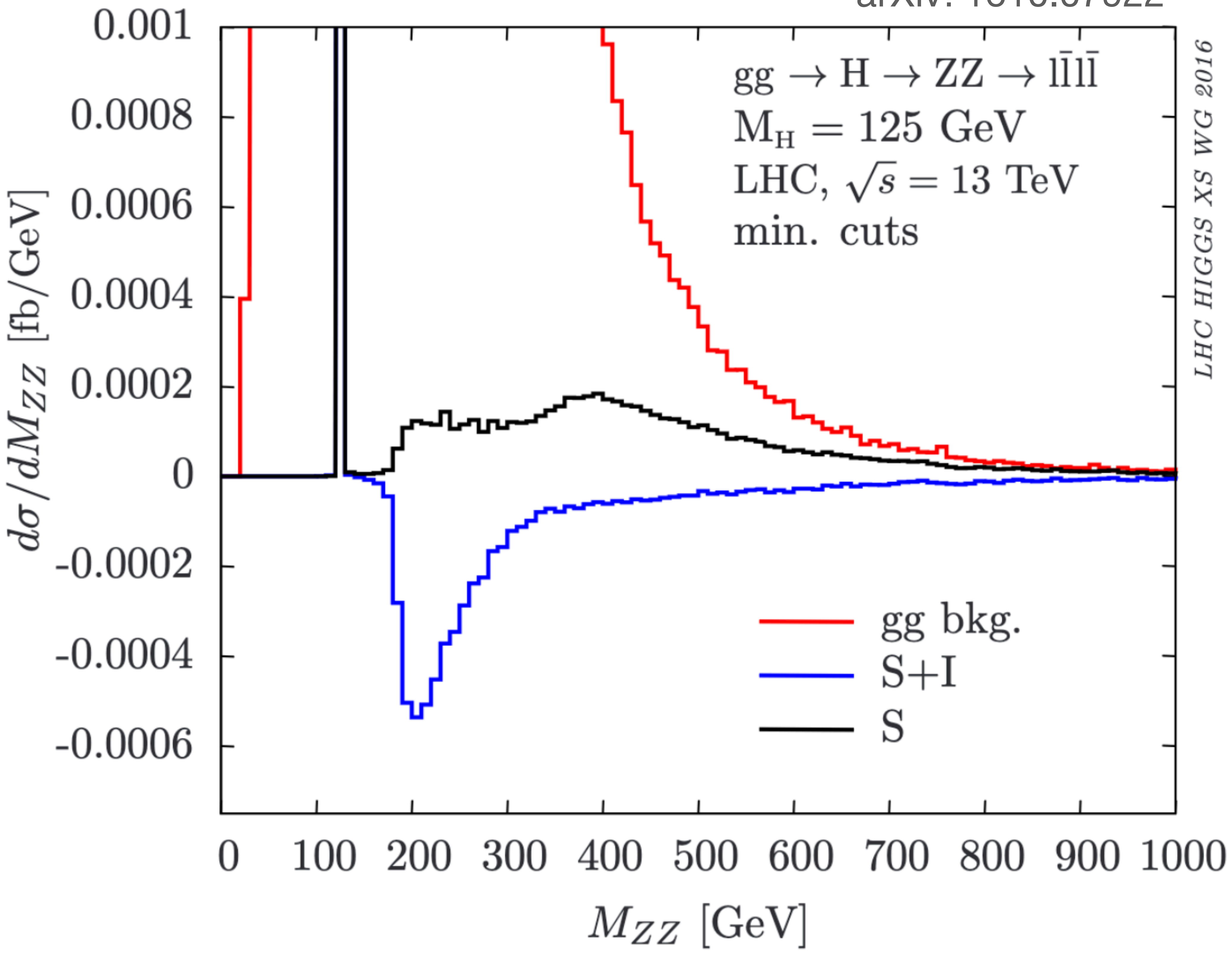
Interference

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



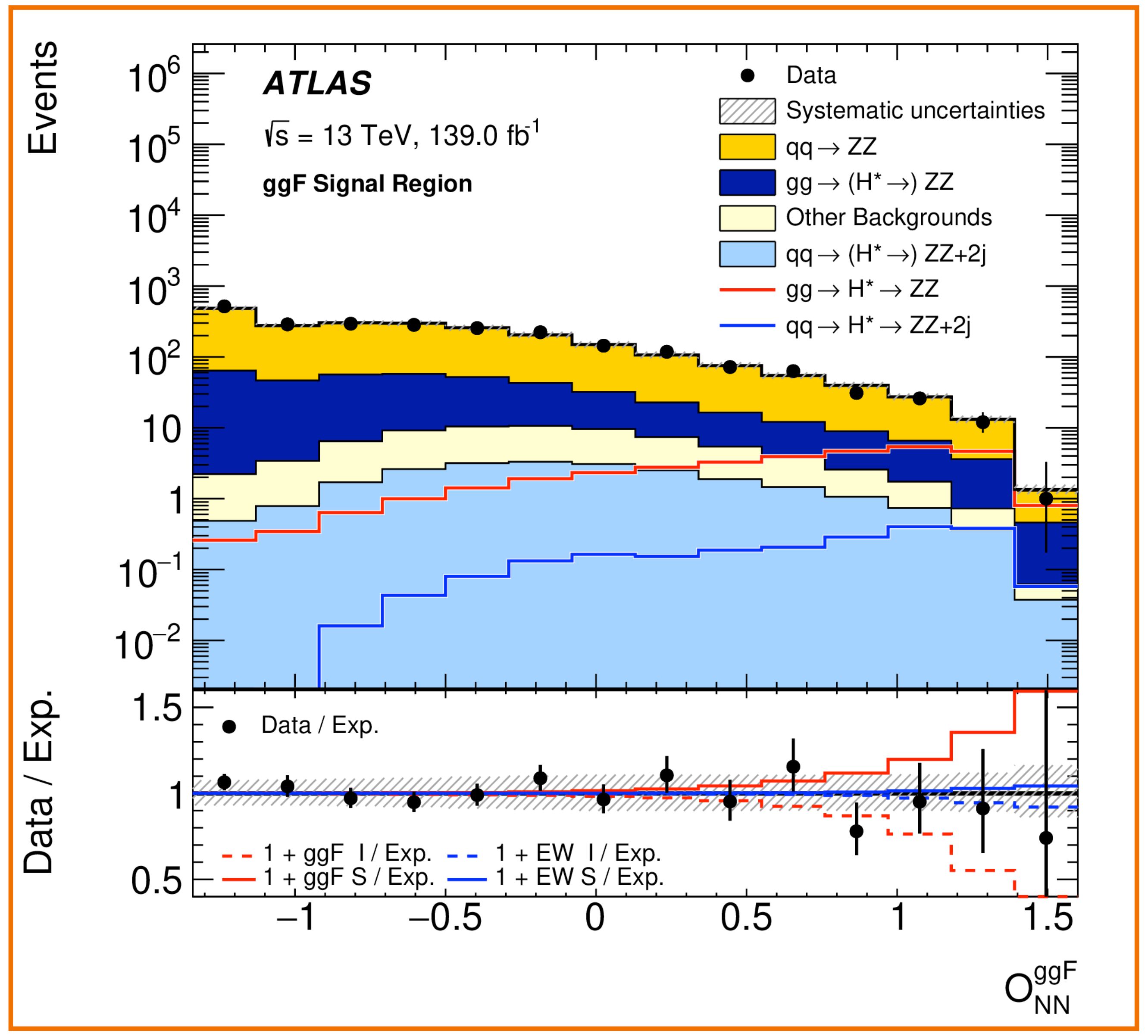
In the ATLAS analysis, three regions are defined to target the production modes: ggF, EW and mixed.

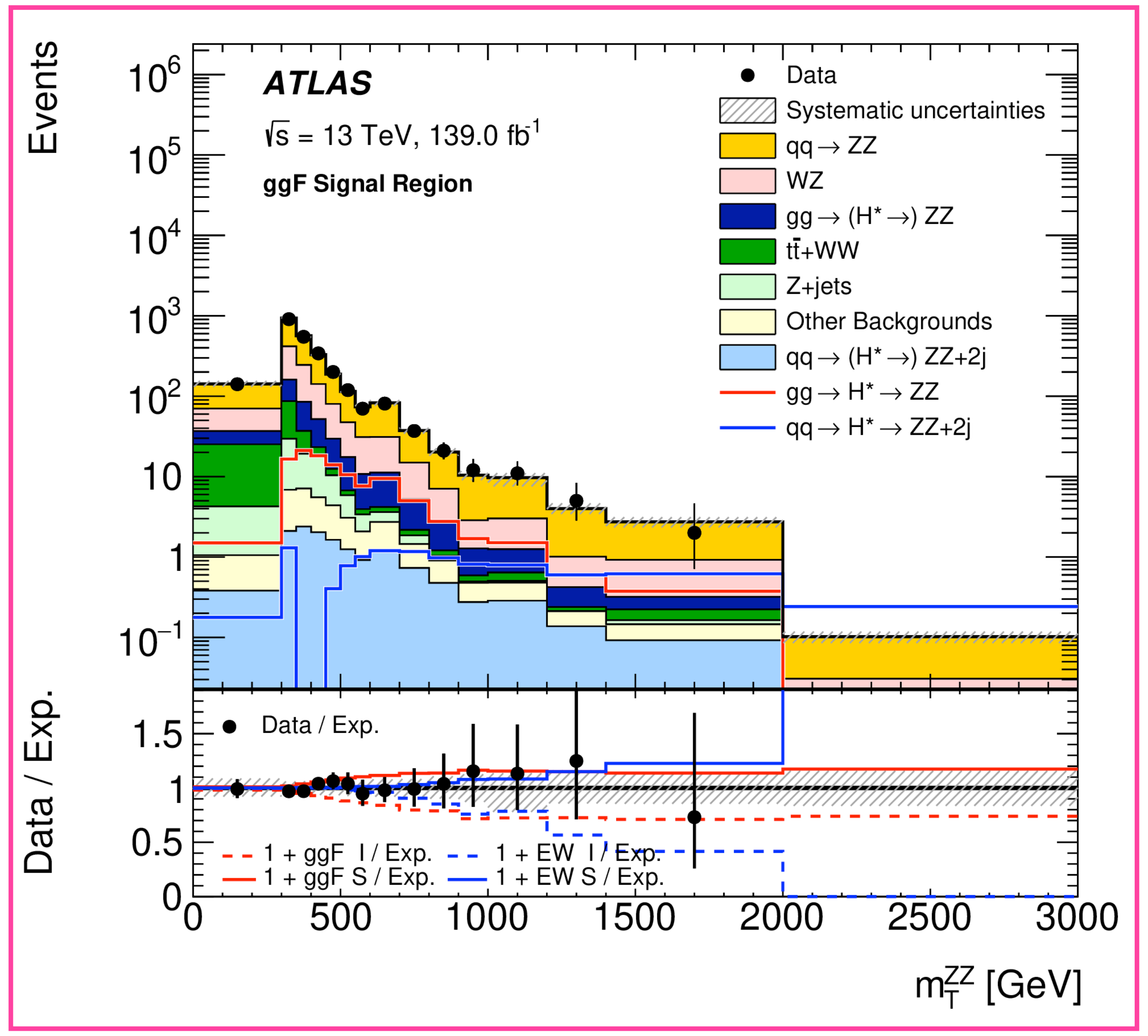
arXiv: 1610.07922

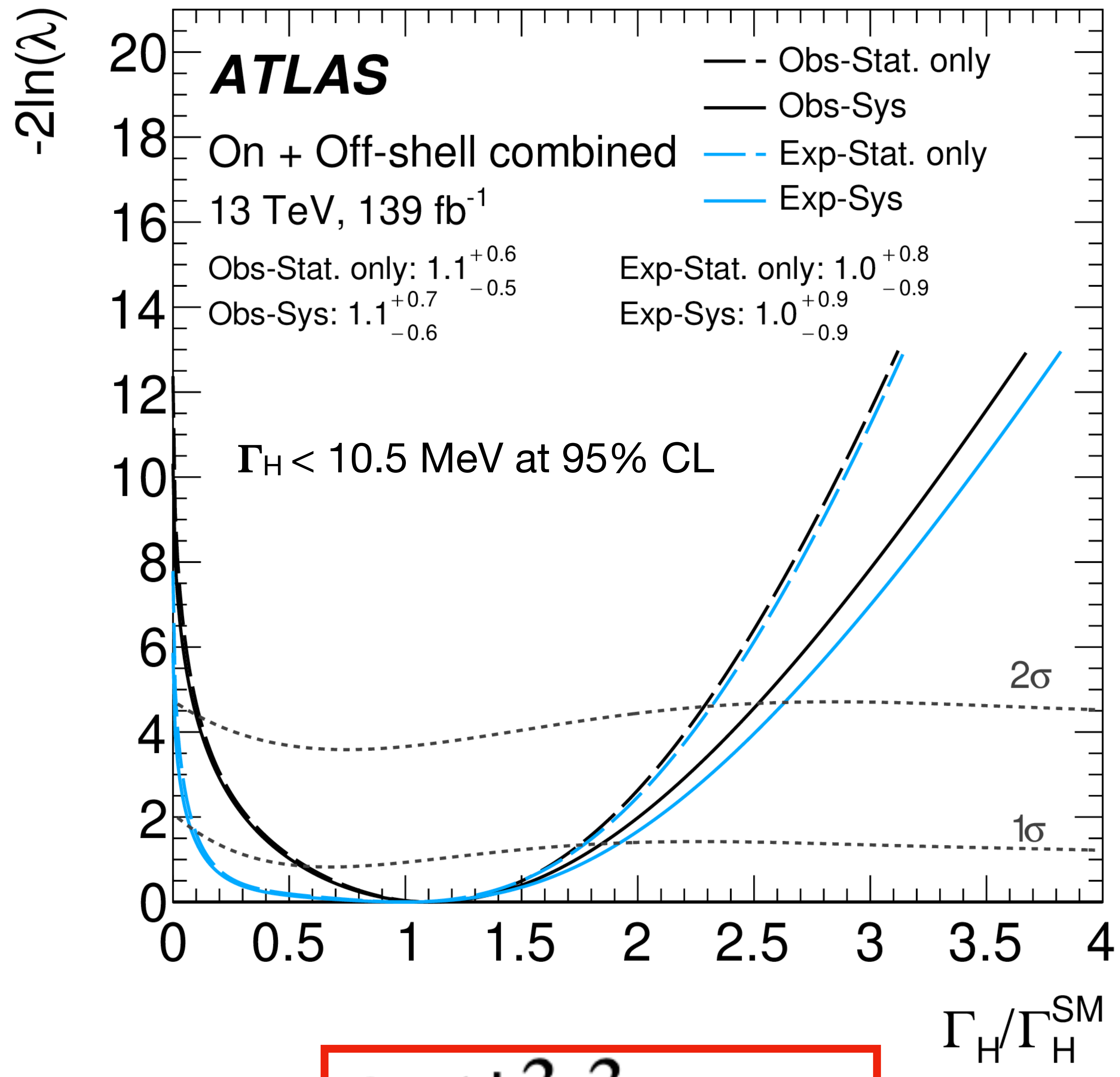


Γ_H measurement in H*→ZZ: results

- 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







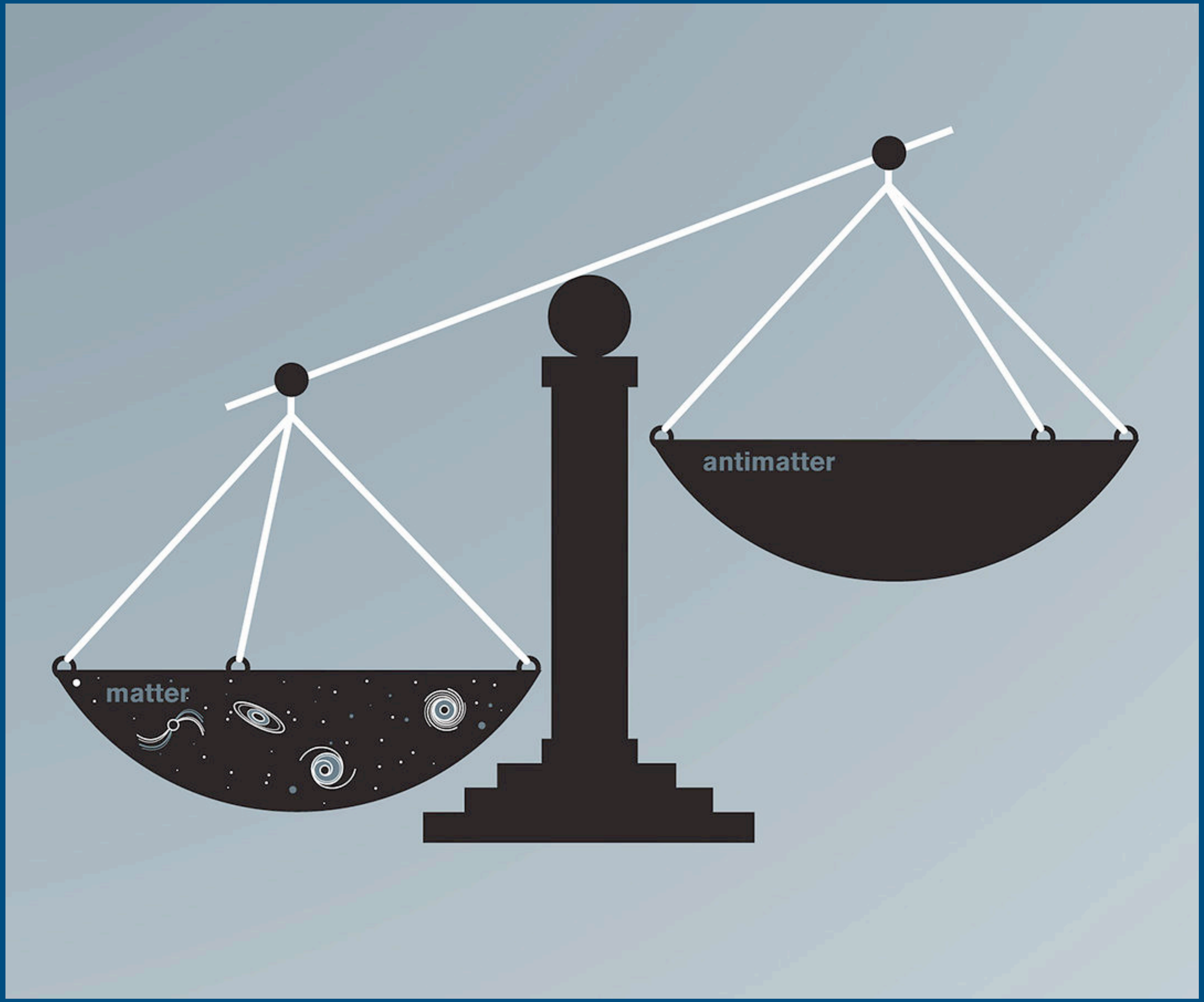
$$4.5^{+3.3}_{-2.5}\ \text{MeV}$$

First direct measurement of Γ_H with ATLAS!

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

CP measurements

- H→bb (arXiv:2303.05974)
- H→ττ (arXiv:2212.05833)
- H→ZZ*→4ℓ (arXiv:2304.09612)
- VBF H→γγ (arXiv:2208.02338)

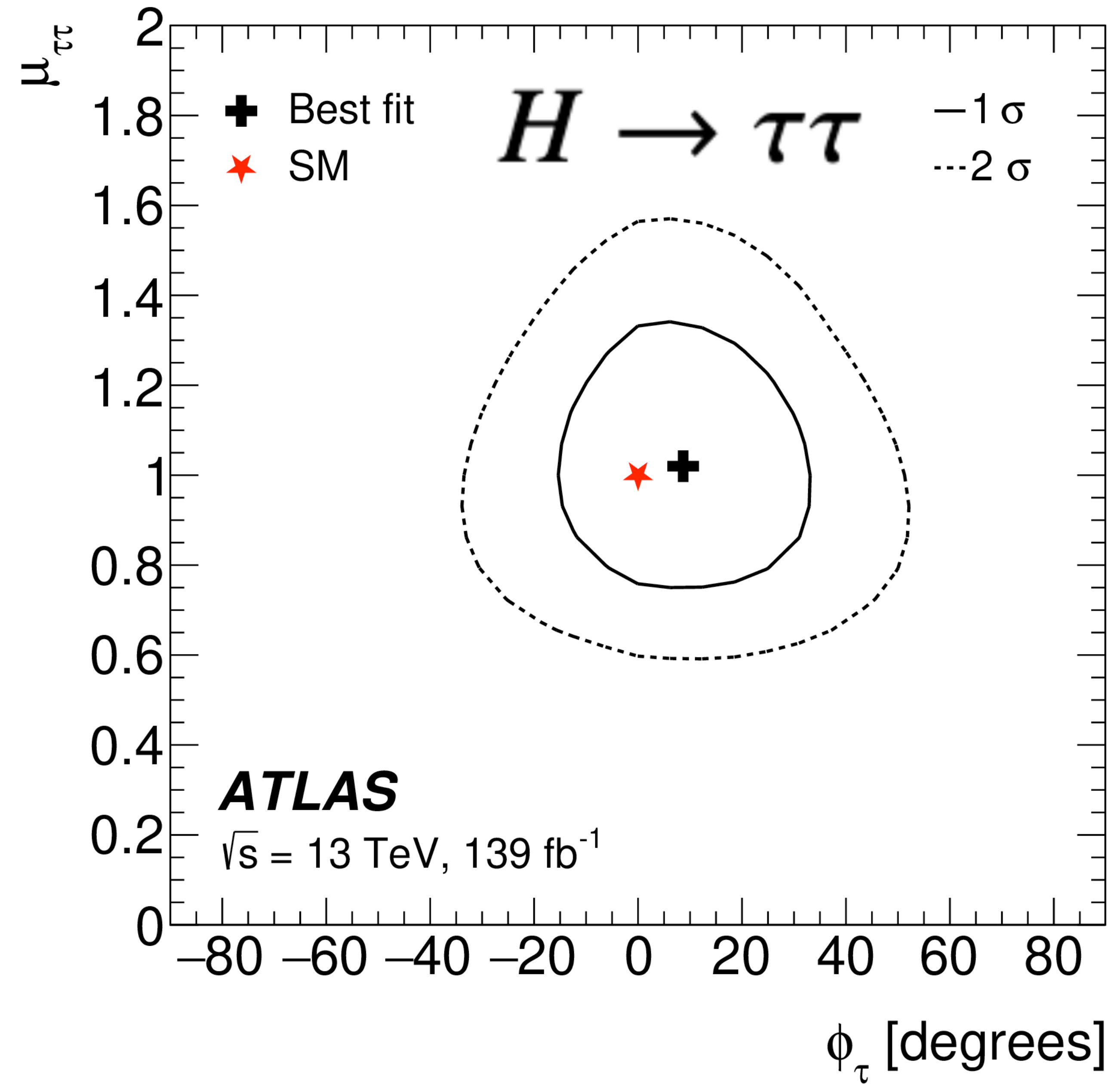


CP nature of Yukawa couplings

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

Coupling strength

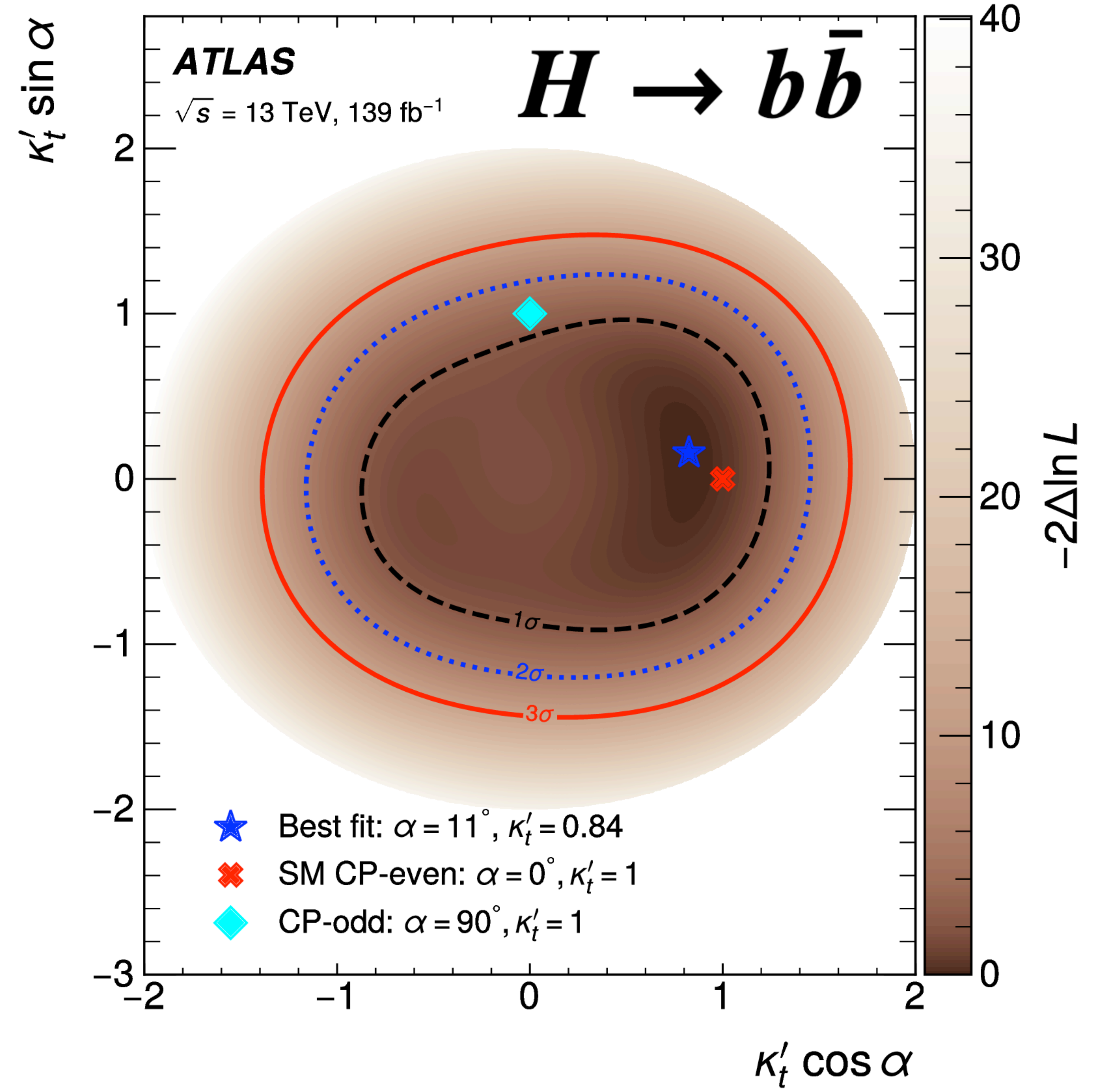
CP-mixing angle



ϕ_τ is 9° ± 16°

And pure CP-odd hypothesis excluded at 3.4σ

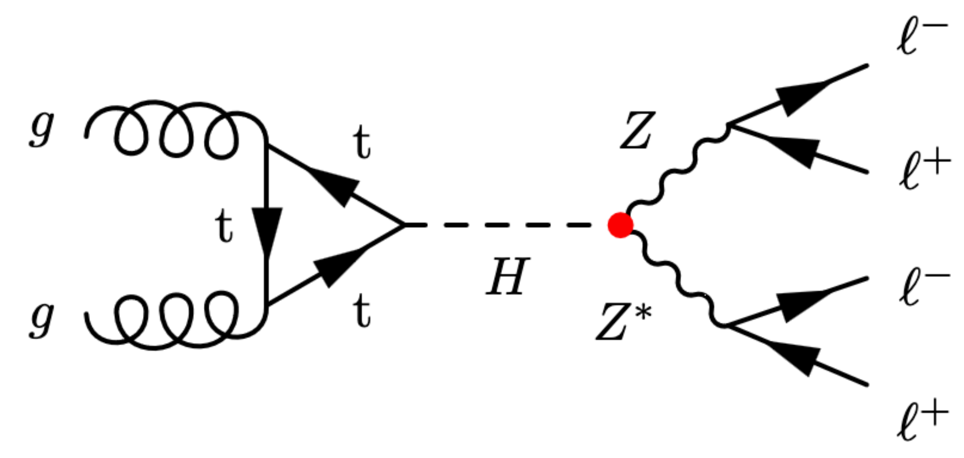
- H→bb produced in association with top quarks (ttH and tH)
  - CP-sensitive observables rely on characteristics of the ttH topology for CP-odd production
- Interactions with tau-leptons in H→ττ
  - CP-sensitive observables rely on the geometry of the visible τ decay products



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

And pure CP-odd hypothesis excluded at 1.2σ

CP nature of HVV



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

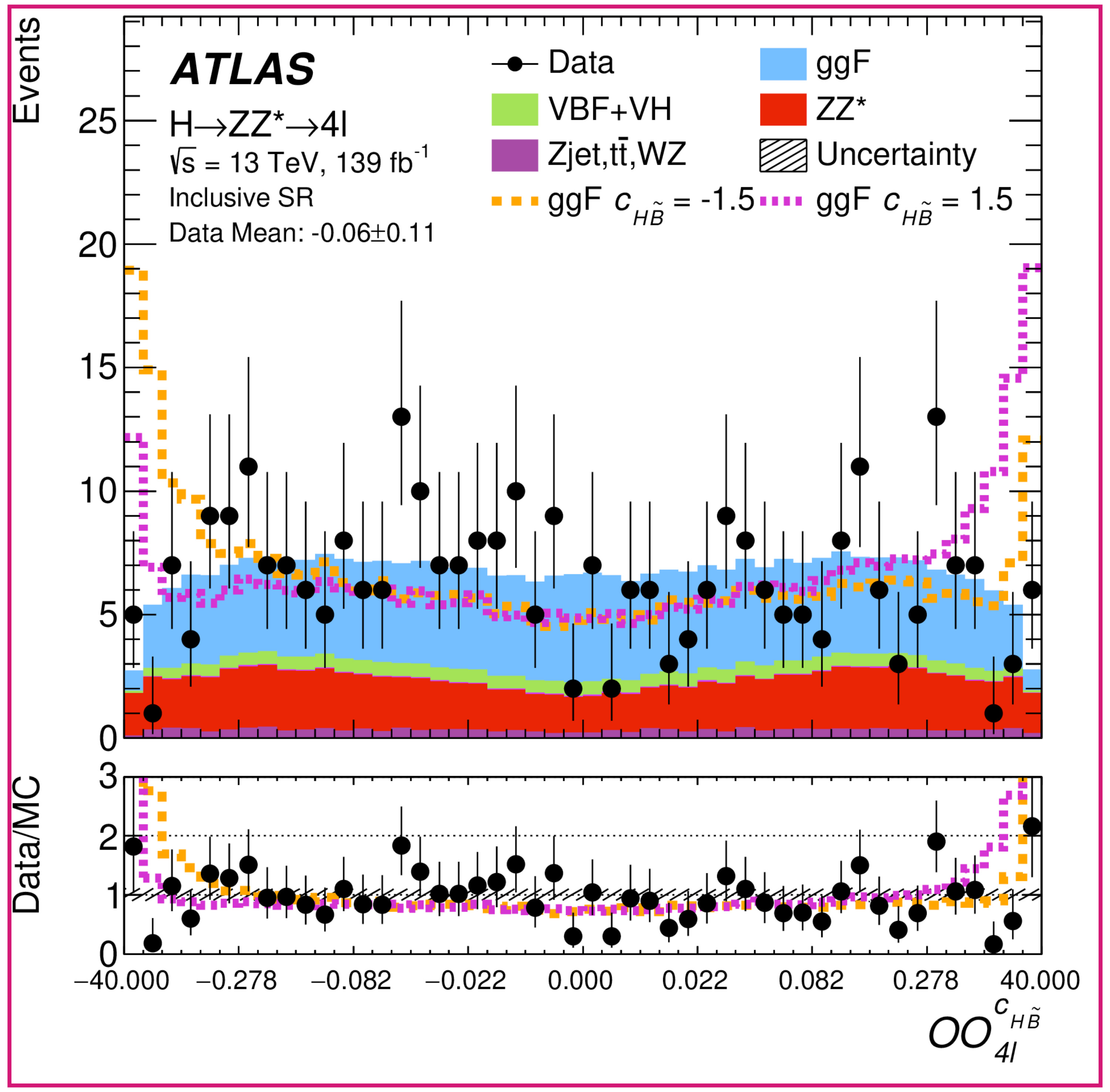
$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2} O_i^{(6)}$$

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

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

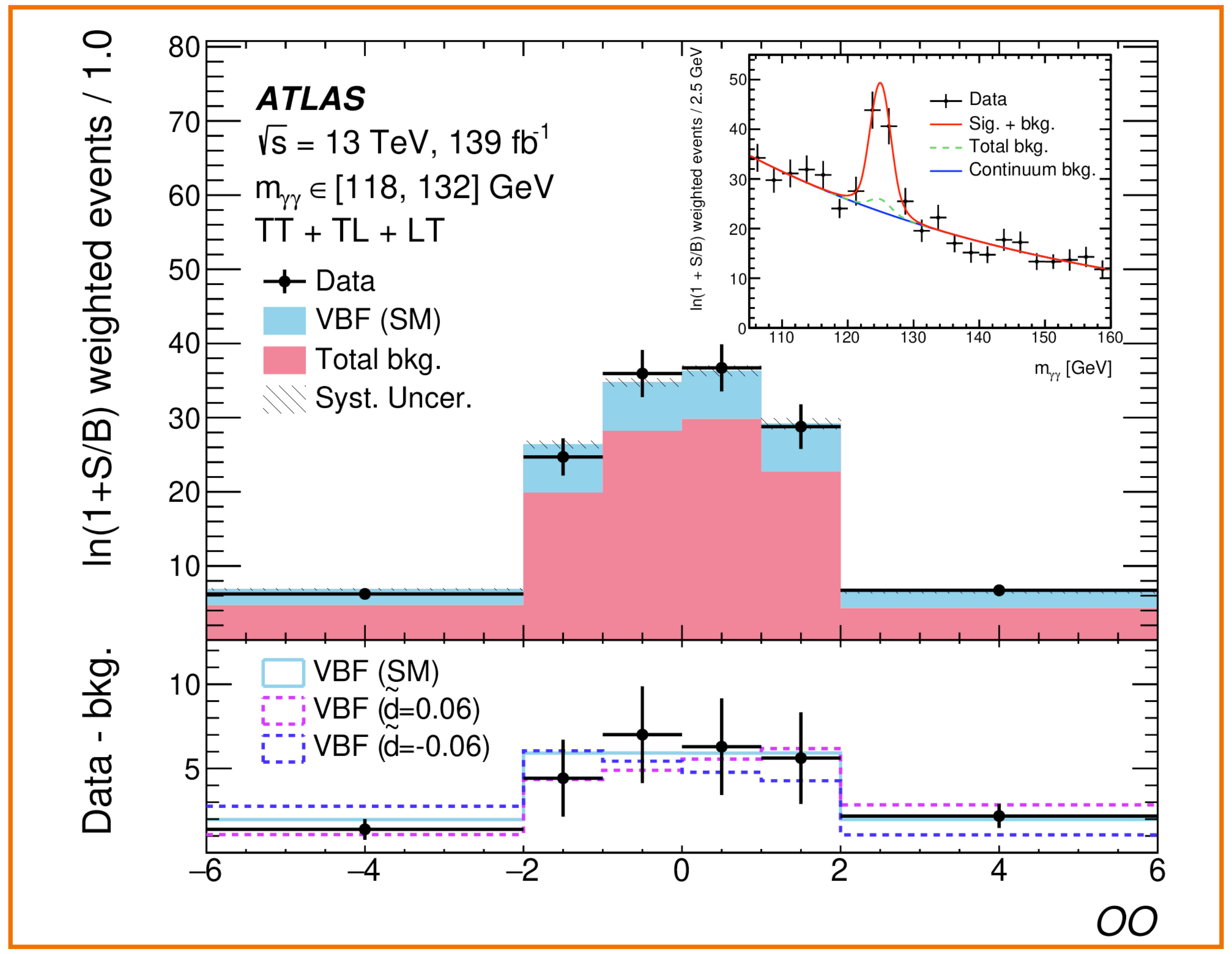
CP-even

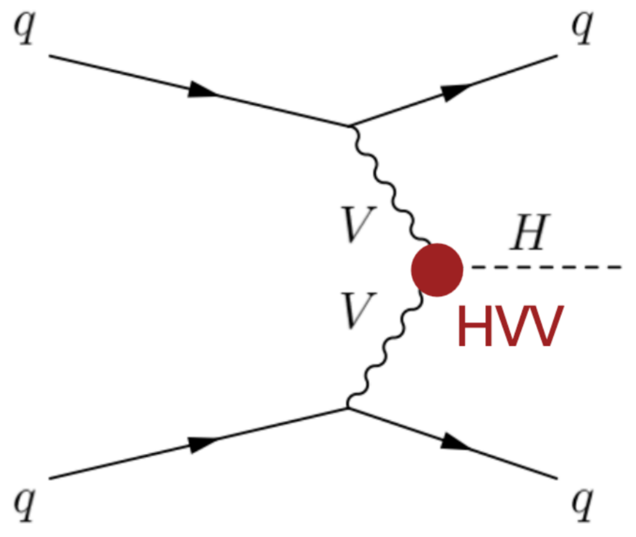
CP-odd



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

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

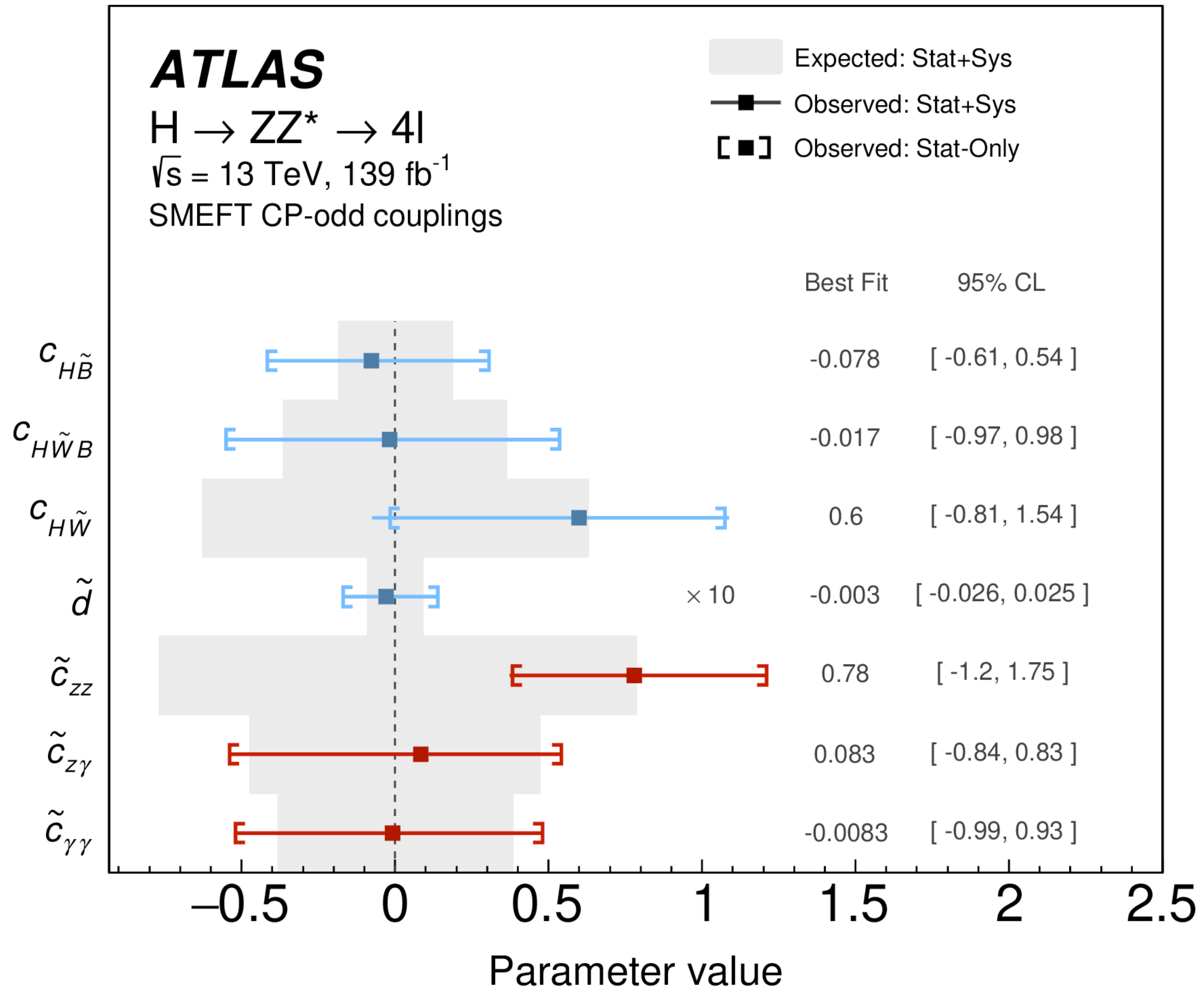




Optimal observables (OO)

- Production OO → 2-jets kinematics, used in VBF H→γγ and H→ZZ*
- Decay OO → 4l decay kinematics, used in H→ZZ*

CP nature of HVV: results



VBF $H \to \gamma\gamma$

	68% (exp.)	68% (obs.)
$\tilde{d}$ (inter. only)	[−0.027, 0.027]	[−0.011, 0.036]
$\tilde{d}$ (inter.+quad.)	[−0.028, 0.028]	[−0.010, 0.040]
$\tilde{d}$ from $H \to \tau\tau$	[−0.038, 0.036]	[−0.090, 0.035]
Combined $\tilde{d}$	[−0.022, 0.021]	[−0.012, 0.030]
$c_{H\tilde{W}}$ (inter. only)	[−0.48, 0.48]	[−0.16, 0.64]
$c_{H\tilde{W}}$ (inter.+quad.)	[−0.48, 0.48]	[−0.15, 0.67]

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		
$O_{hZ\tilde{Z}}$	$hZ_{\mu\nu}\tilde{Z}^{\mu\nu}$	$\tilde{c}_{zz}$
$O_{hZ\tilde{A}}$	$hZ_{\mu\nu}\tilde{A}^{\mu\nu}$	$\tilde{c}_{z\gamma}$
$O_{hA\tilde{A}}$	$hA_{\mu\nu}\tilde{A}^{\mu\nu}$	$\tilde{c}_{\gamma\gamma}$

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

- 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
- All results are compatible with the SM expectation of pure CP-even couplings

Conclusions

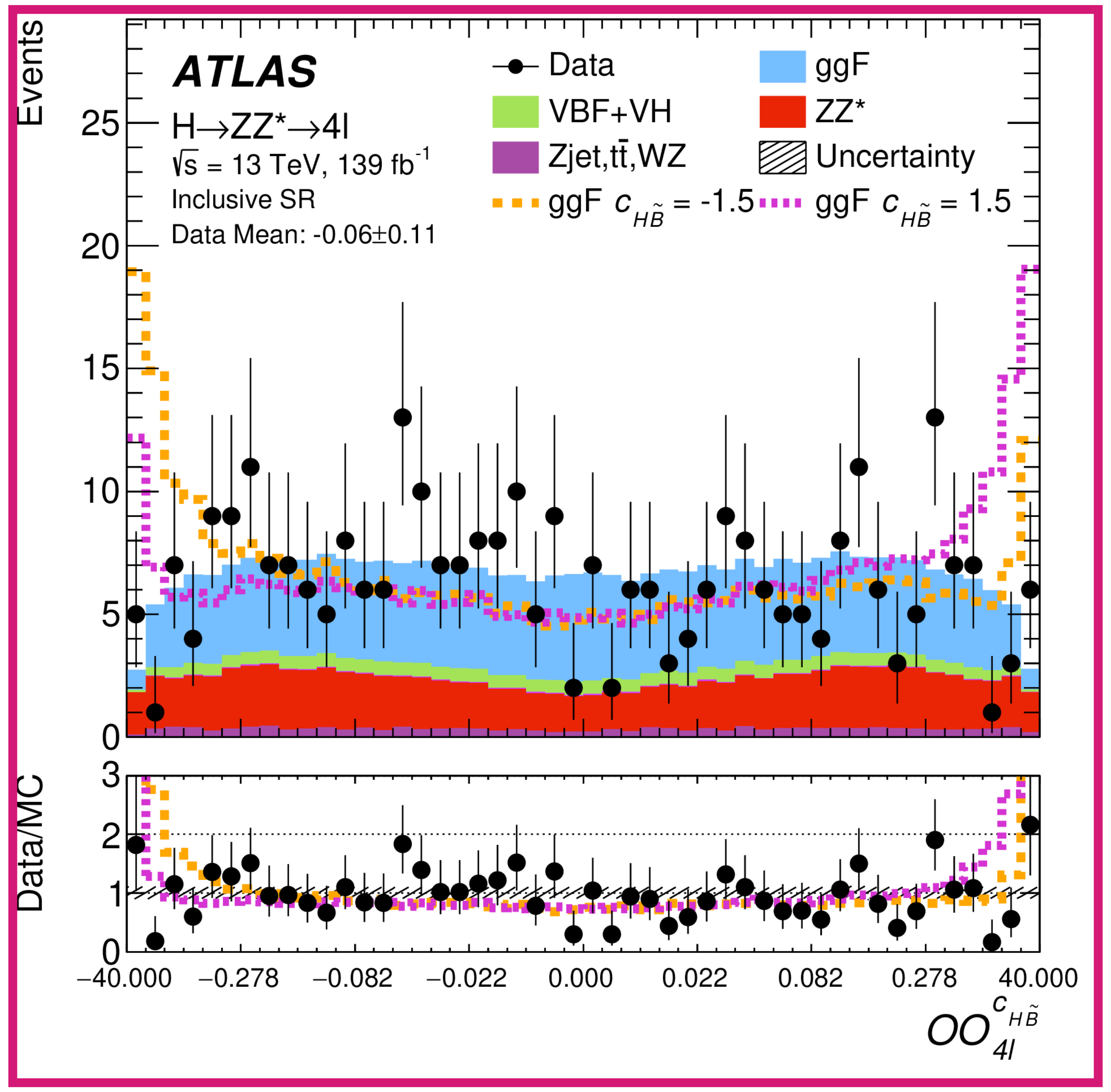
- 10 years after the discovery, Higgs boson's properties are investigated with great detail:
  - Mass is measured with the extremely high precision of ~0.1%!
  - Width is constrained to be less than 2.6 times the SM prediction
  - Search for small CP-odd couplings remain compatible with SM
- All results were obtained with the full Run 2 dataset collected by the ATLAS detector
- Exciting developments expected in the future with more data coming from the LHC, so

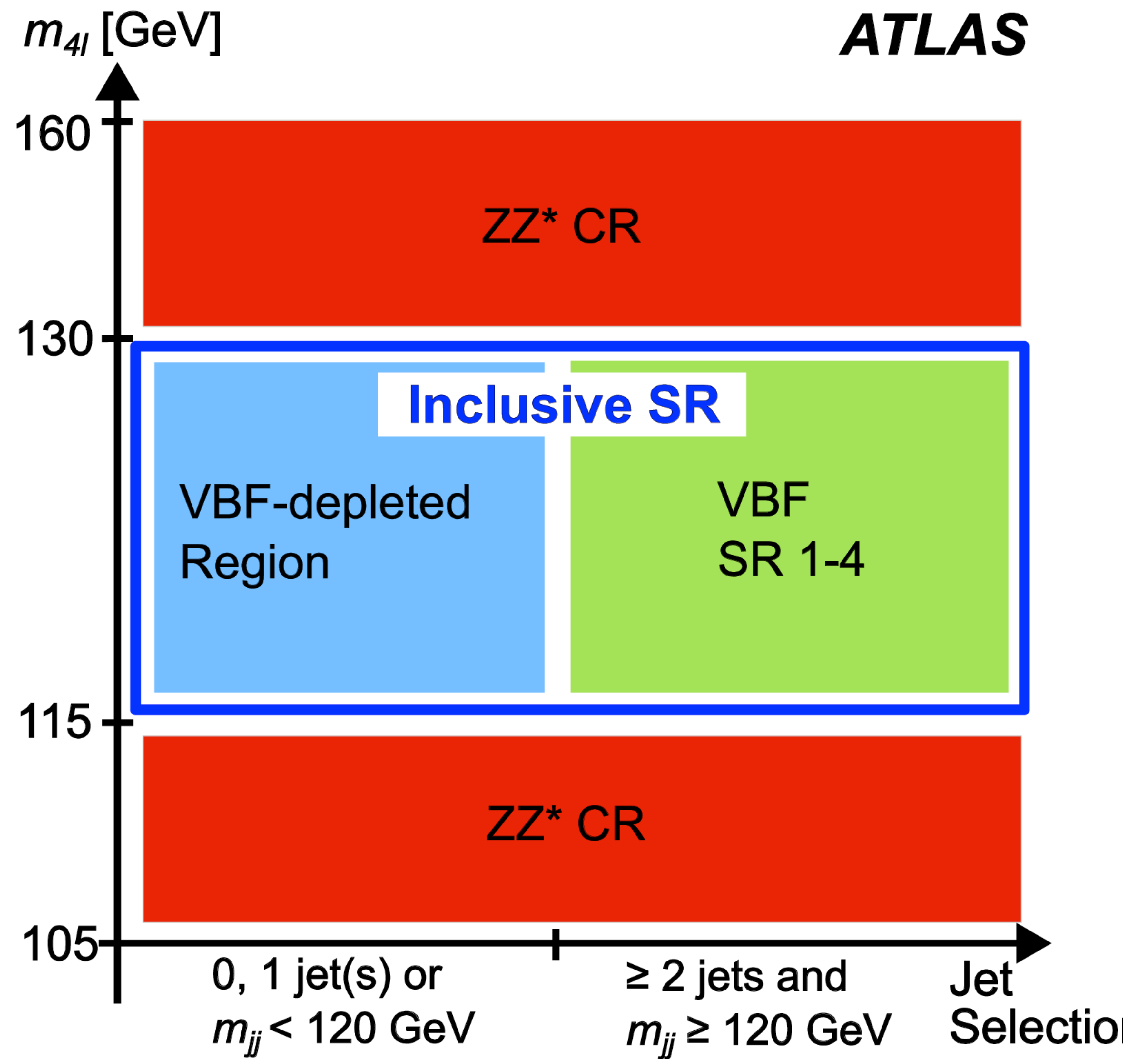
stay tuned!

Back-up

HZZ 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



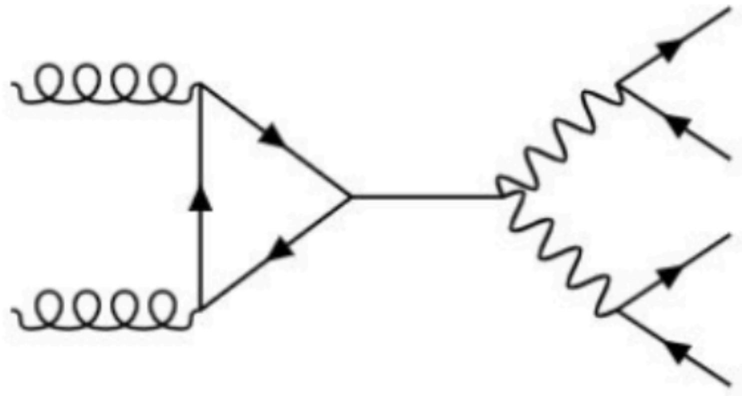


- ZZ* CR to estimate bkg normalisation
- Morphing method to perform a shape-only analysis

HZZ off shell: analysis strategy

- Analyses performed in three signal regions

ggF Signal region

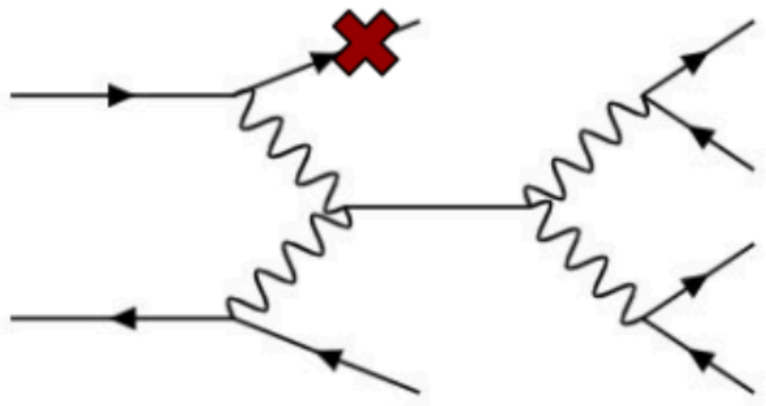


$n_{\text{jets}} = 0$

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

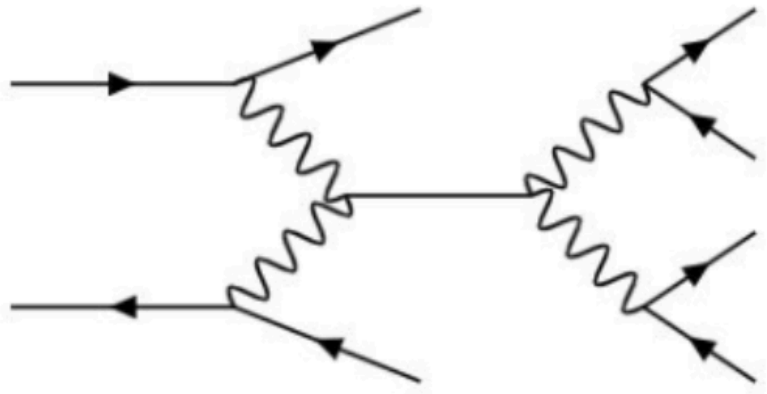
$n_{\text{jets}} \geq 2 \text{ and } \Delta\eta_{jj} < 4.0$

1 jet mixed signal region



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

EW signal region



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

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

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