Measurement of Higgs Boson mass and width with LHC run2 data at the ATLAS experiment

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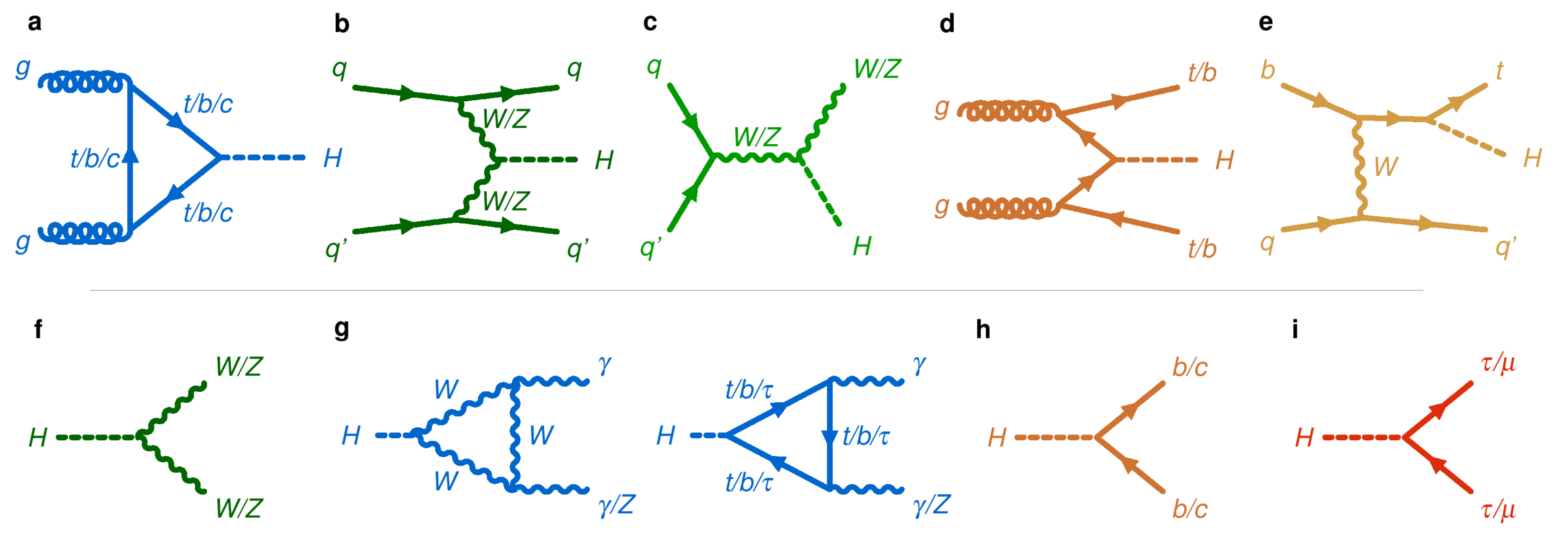
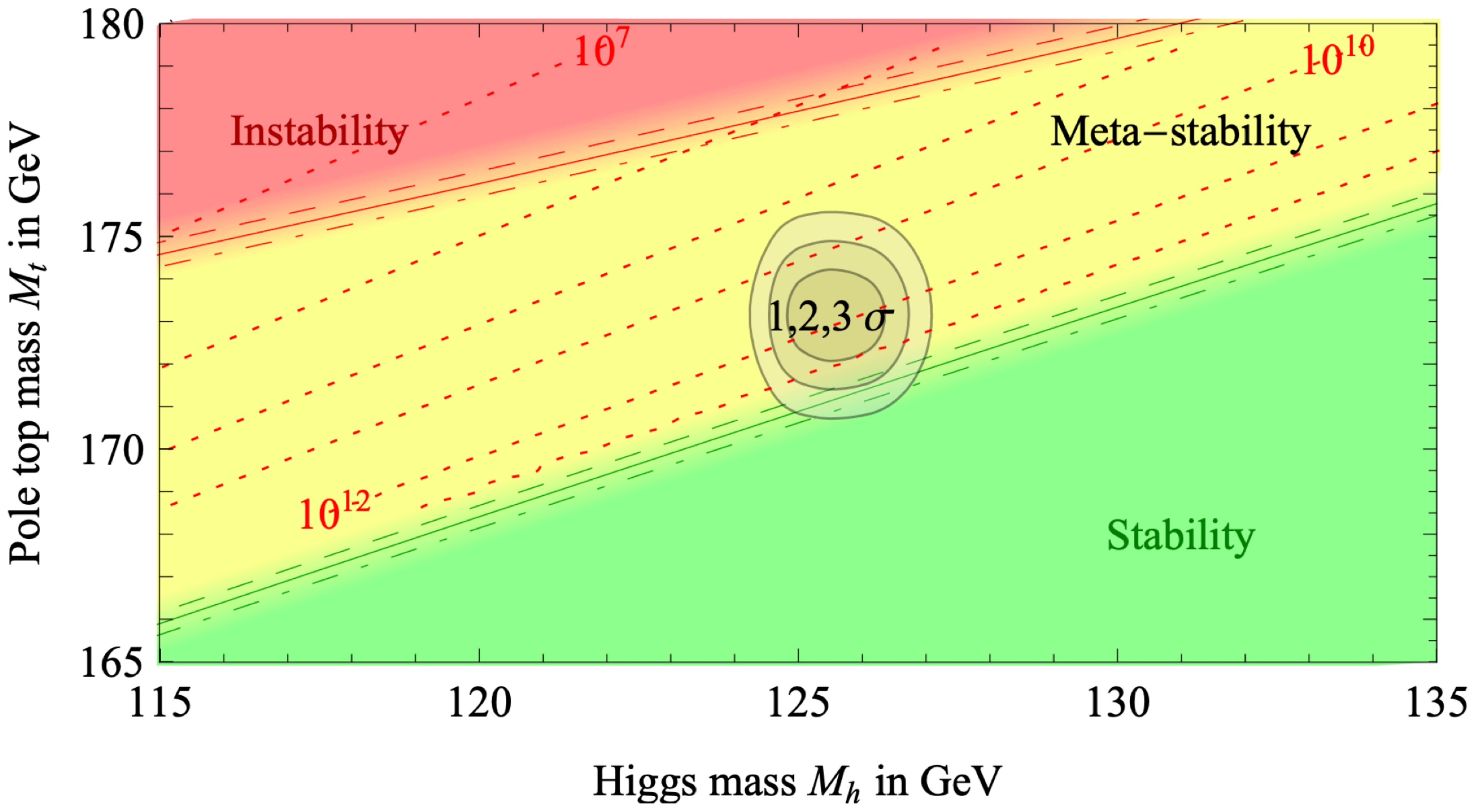
CLHCP, November 16th, 2023

Introduction

Higgs mass m_H:

- Fundamental parameter of the Standard Model
- Related to various physics topics:
  - Higgs production rates & decay branching ratios
  - Electroweak vacuum stability
  - SM internal consistency
- **NOT** predicted by theory





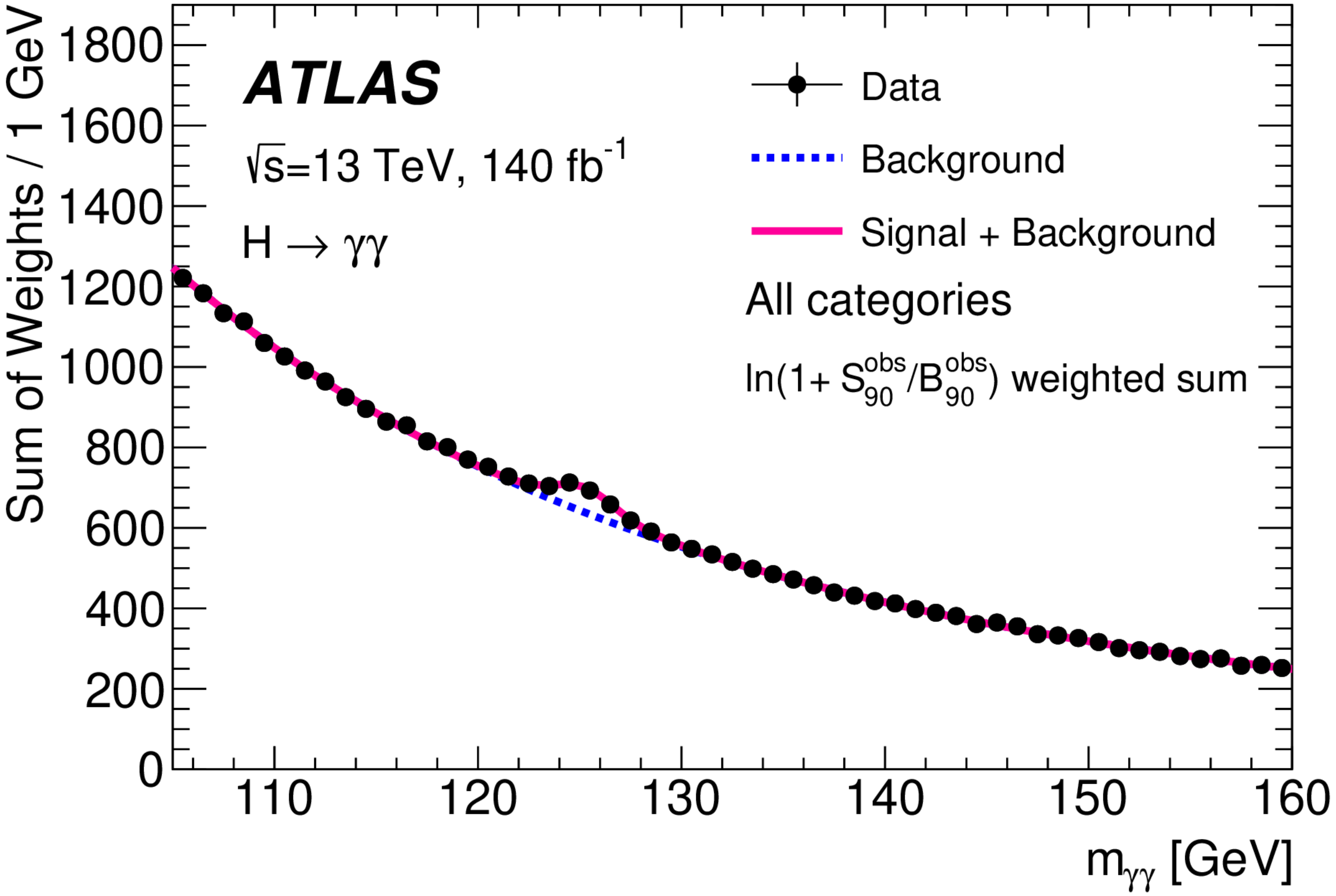
Higgs width Γ_H:

- Related to origin of flavor/electroweak symmetry breaking
- Predicted by theory
- Deviation from predicted value will indicate new physics

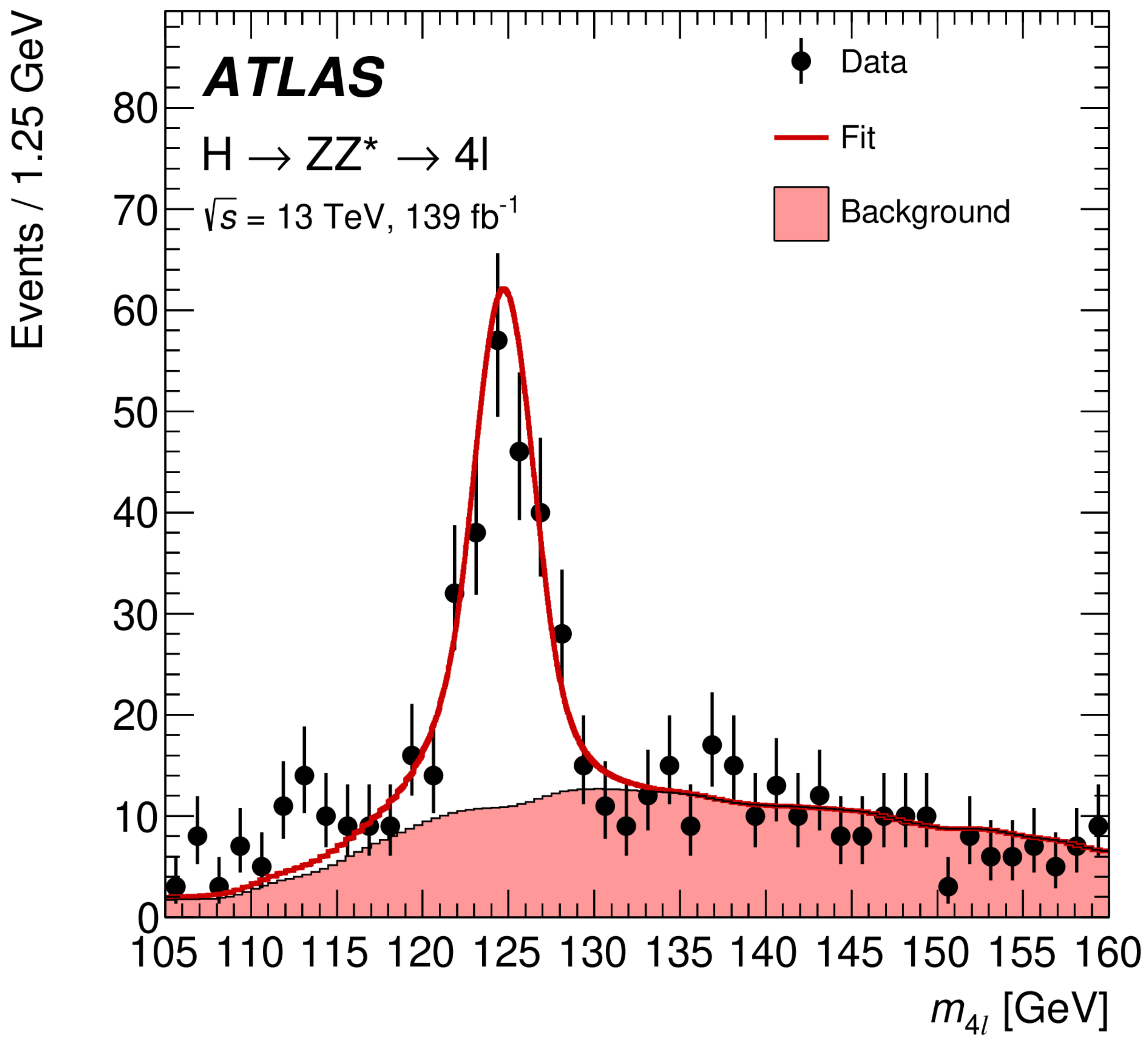
Precise measurement for Higgs mass and width is important

Higgs mass measurement

Higgs decay channels with the best resolution: $H \to \gamma\gamma$ and $H \to ZZ^* \to 4l$



Run2 $H \to \gamma\gamma$, accepted by PLB



Run2 $H \to ZZ^* \to 4l$, Phys. Lett. B 843 (2023) 137880

Run2 individual analysis highlights

$H \to \gamma\gamma$:

- New linearity fit method to estimate energy scale
- Improved photon reconstruction algorithm
- Optimized categorization strategy

$\to m_H = 125.17 \pm 0.11(\text{stat.}) \pm 0.09(\text{syst.})$

$H \to ZZ^* \to 4l$:

- Improved muon momentum calibration
- Neural Network for signal background separation
- Per-event invariant mass resolution of 4l system

$\to m_H = 124.99 \pm 0.18(\text{stat.}) \pm 0.04(\text{syst.})$

- Do a combination to bring better statistical power → better precision

Input channels for combination

- 4 Input channels: (Run1, Run2)×($H \to \gamma\gamma$, $H \to ZZ^* \to 4l$)

Parameter of Interest (POI) in each input channel

	$H \to ZZ^* \to 4l$	$H \to \gamma\gamma$
Run1	m_H+1 global μ	m_H+2μ (ggF+ttH,VBF+VH)
Run2	m_H+4μ (4e, 4μ, 2e2μ, 2μ2e)	m_H+14μ (1 per category)

- Among them, only correlate Higgs boson mass m_H between each analysis
- In run2 analysis, each category has a different signal strength

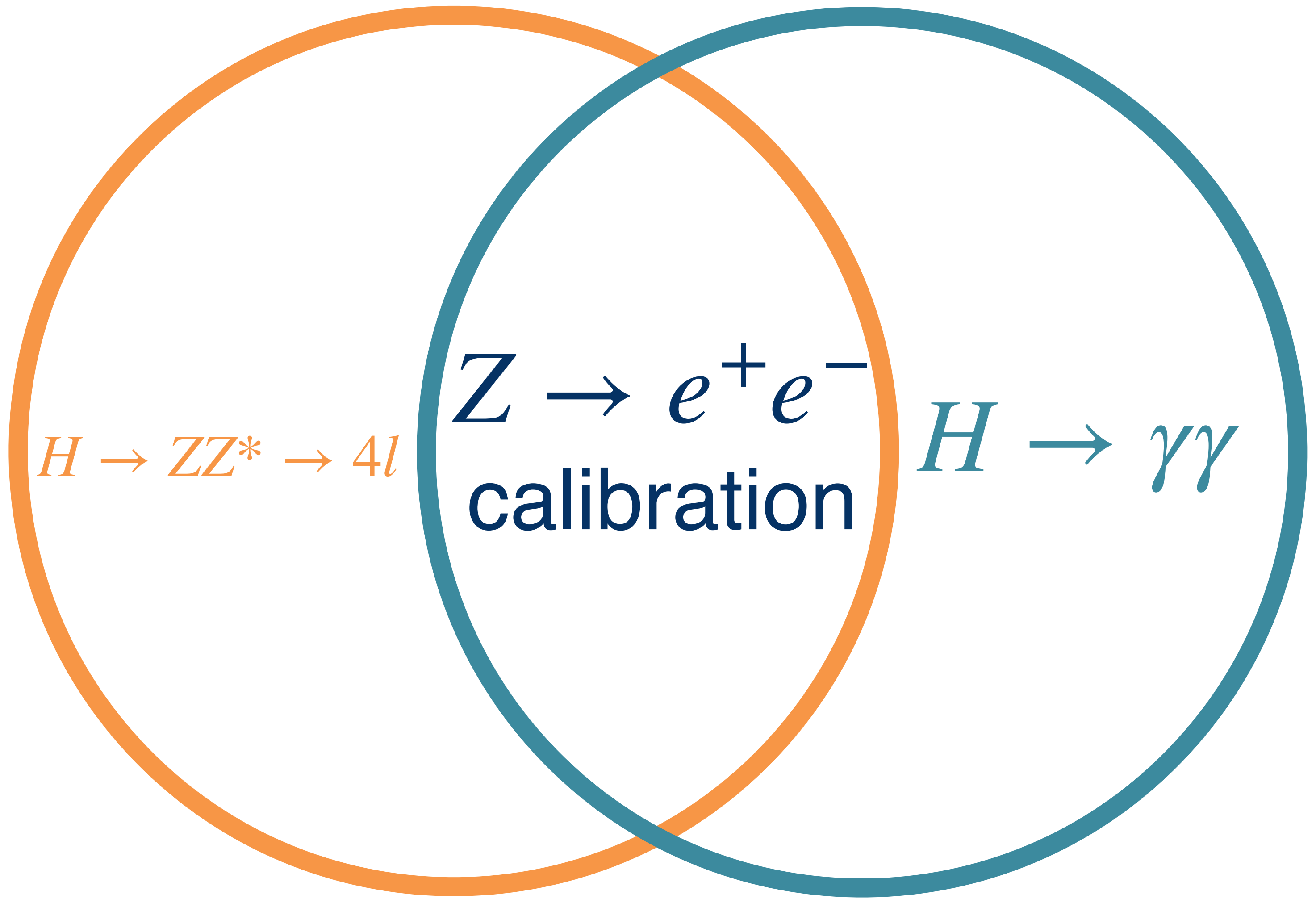
$\to$ Reduce model-dependency

Systematic uncertainty correlation scheme

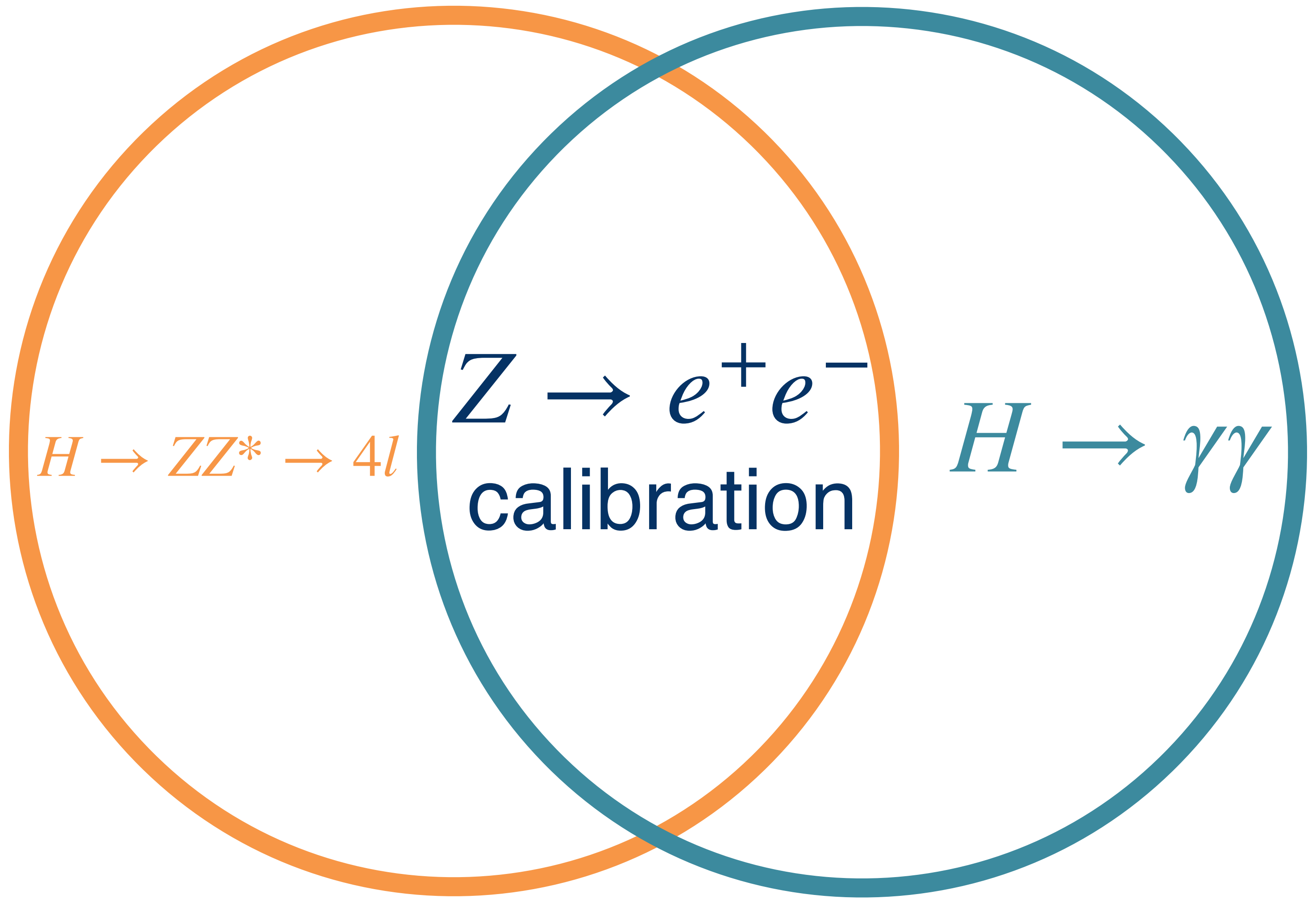
Different individual analysis can share systematic uncertainties from same source

→ Need to correlate them properly

Run2



Run1+Run2



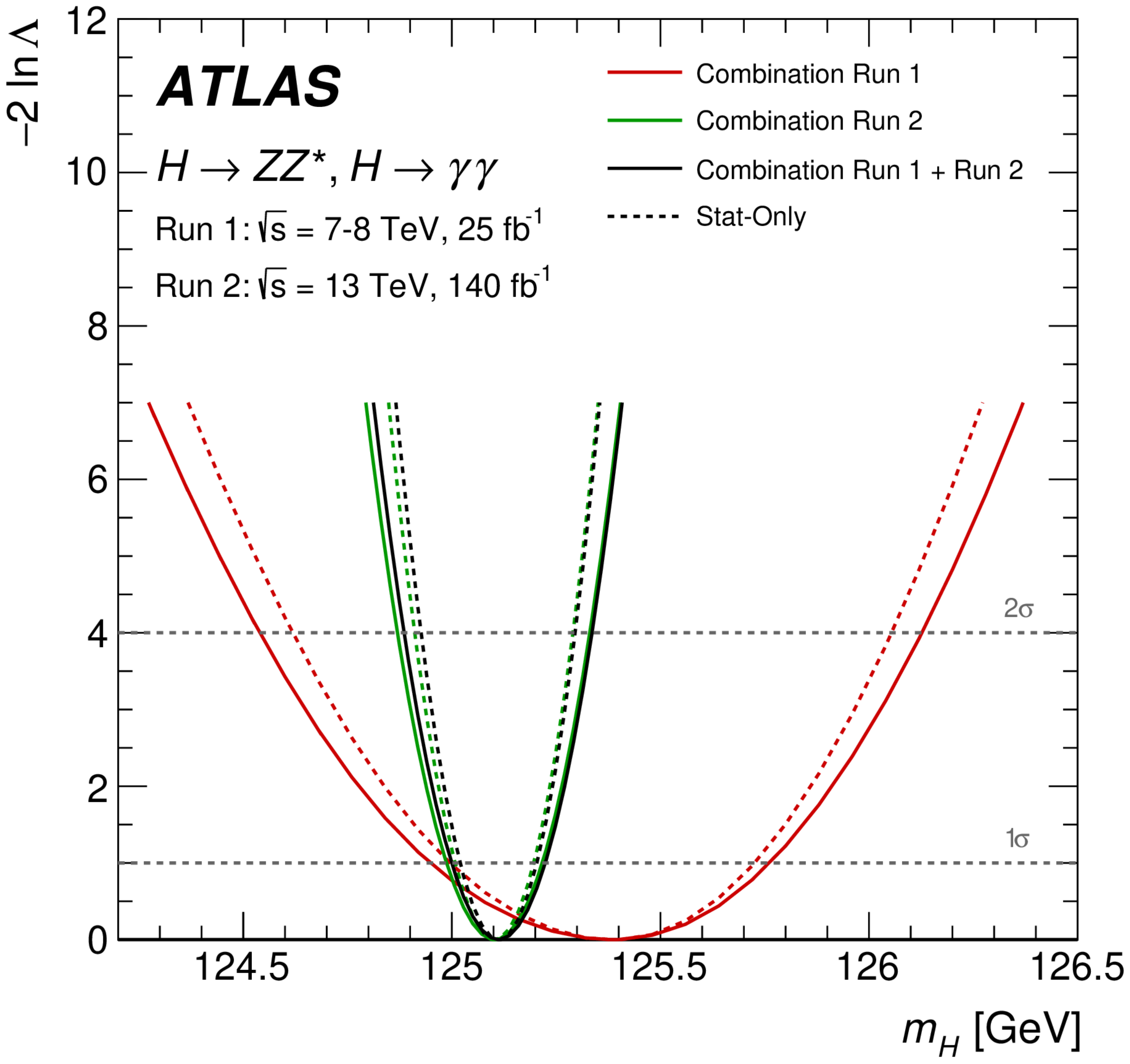
- E_T independent $Z \to e^+e^-$ calibration is shared for e/γ energy scale
- Many other e/γ calibration uncertainties not correlated due to new linearity fit in Run2 $H \to \gamma\gamma$ analysis

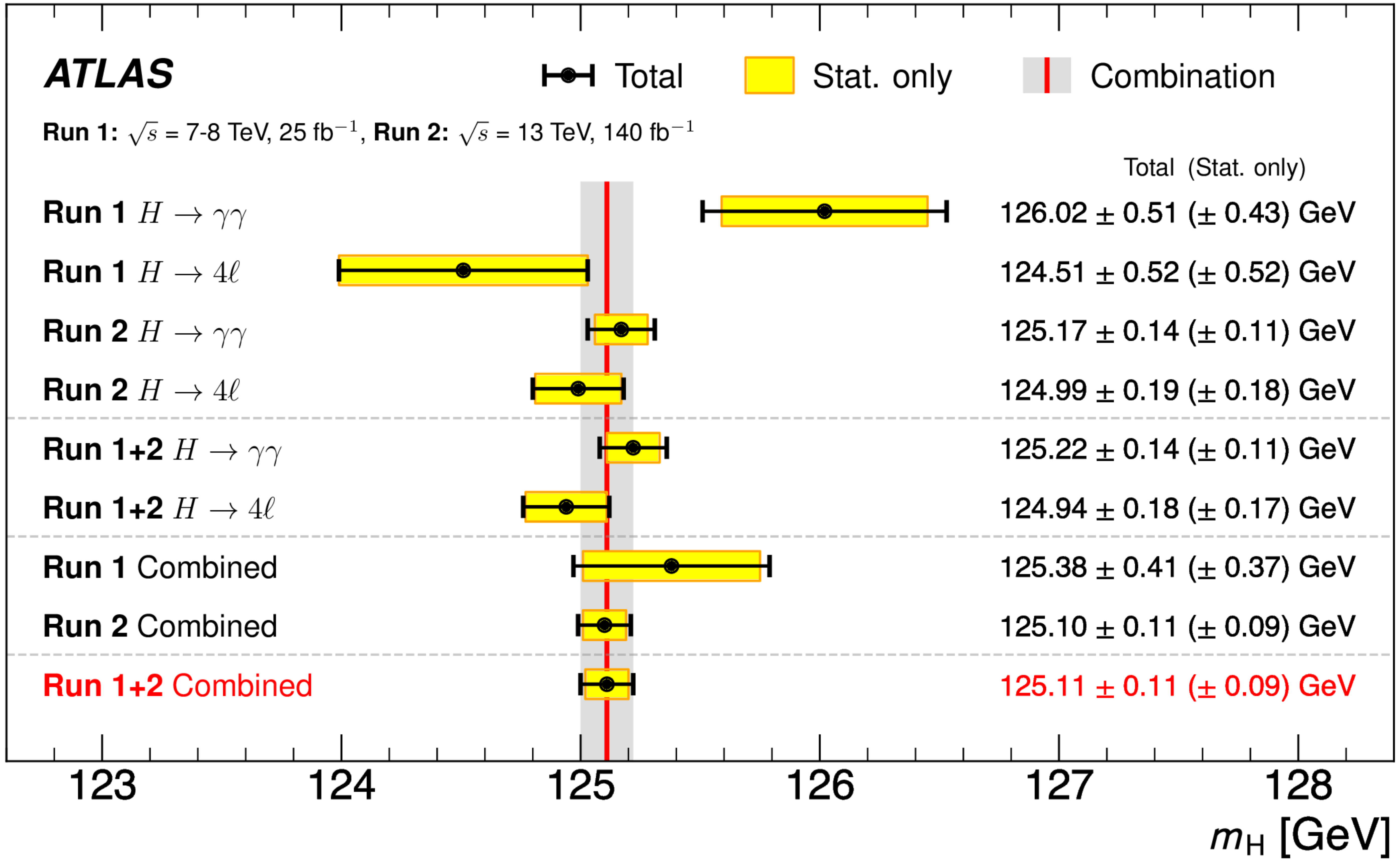
Higgs mass results

By combining all 4 individual analysis: Accepted by PRL

$m_H = 125.11 \pm 0.11 = 125.11 \pm 0.09(\text{stat.}) \pm 0.06(\text{syst.})$ GeV

→ Precision better than 1 per mille: The most precise result up to date!





Uncertainty decomposition

The impact from different sources of systematic uncertainty:

Source	Systematic uncertainty on m_H [MeV]
e/γ E_T-independent $Z \to ee$ calibration	44
e/γ E_T-dependent electron energy scale	28
$H \to \gamma\gamma$ interference bias	17
e/γ photon lateral shower shape	16
e/γ photon conversion reconstruction	15
e/γ energy resolution	11
$H \to \gamma\gamma$ background modelling	10
Muon momentum scale	8
All other systematic uncertainties	7

→ Help to identify the direction of future improvement

Higgs width measurement

- Theoretical prediction: 4.1 MeV → too small compared to detector resolution at LHC
- Use an indirect method to measure Higgs width
  - For Higgs production and decay: $i \rightarrow H \rightarrow f$

Differential cross-section: $$\frac{d\sigma}{dm^2} = \frac{g_i^2 g_f^2}{(m^2 - m_H^2)^2 + m_H^2 \Gamma^2}$$

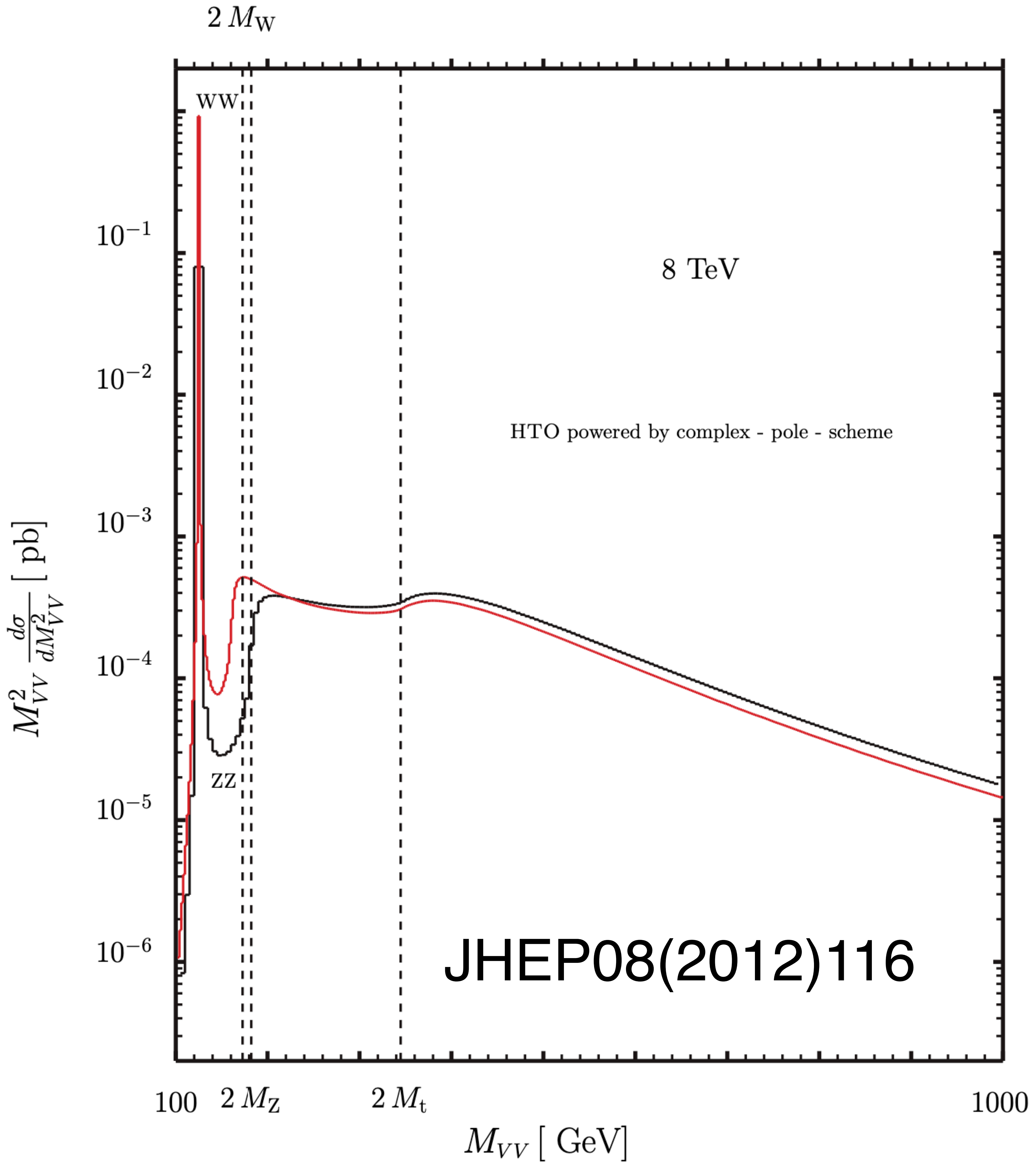
For on-shell measurements: $$\sigma \propto \frac{g_i^2 g_f^2}{m_H \Gamma}$$

For off-shell measurements: $$\frac{d\sigma}{dm^2} \propto \frac{g_i^2 g_f^2}{(m^2 - m_H^2)^2}$$

Take a ratio → $$\frac{\sigma_{offshell}}{\sigma_{onshell}} \propto \Gamma_H$$

- $H \rightarrow ZZ$ channel
  - Can measure both on-shell and off-shell Higgs production

→ Suitable to measure Higgs width!



JHEP08(2012)116

Analysis overview: $4l$ final state

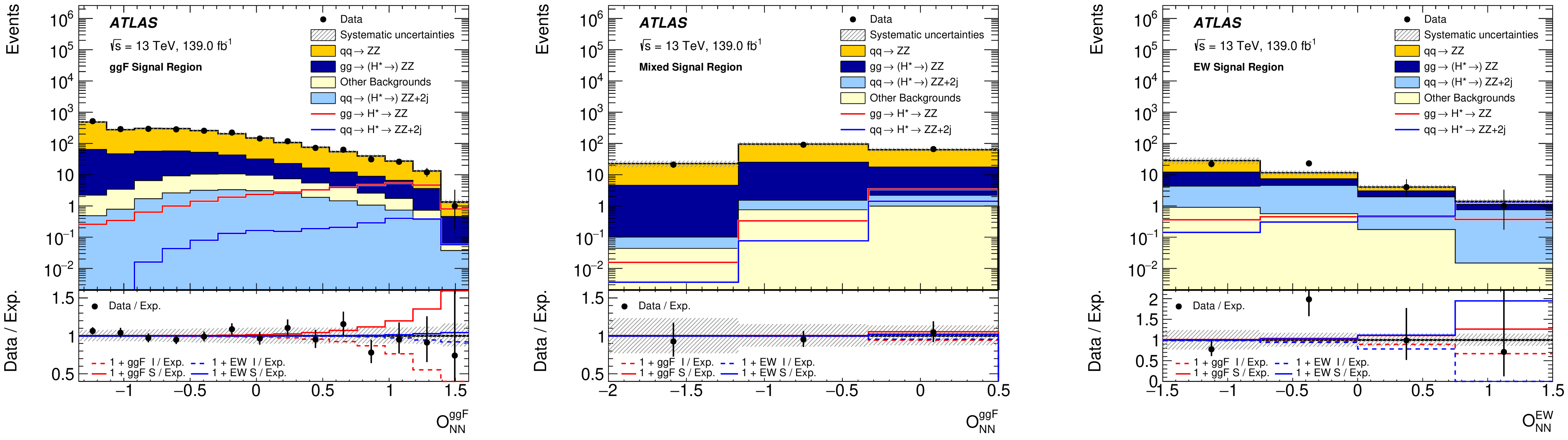
Advantage:

- Clean signal
- Fully reconstructable

Main background: $q\bar{q} \rightarrow ZZ$

	Control region			Signal region		
Mass range	$180 < m_{4l} < 220$ GeV			$m_{4l} > 220$ GeV		
Categorization	Jet multiplicity			Production mode		
	0 jet	1 jet	>=2 jets	ggF	EW	Mixed

- A multi-class dense Neural Network is used to maximize sensitivity in each signal region



Analysis overview: $2l2\nu$ final state

Advantage:

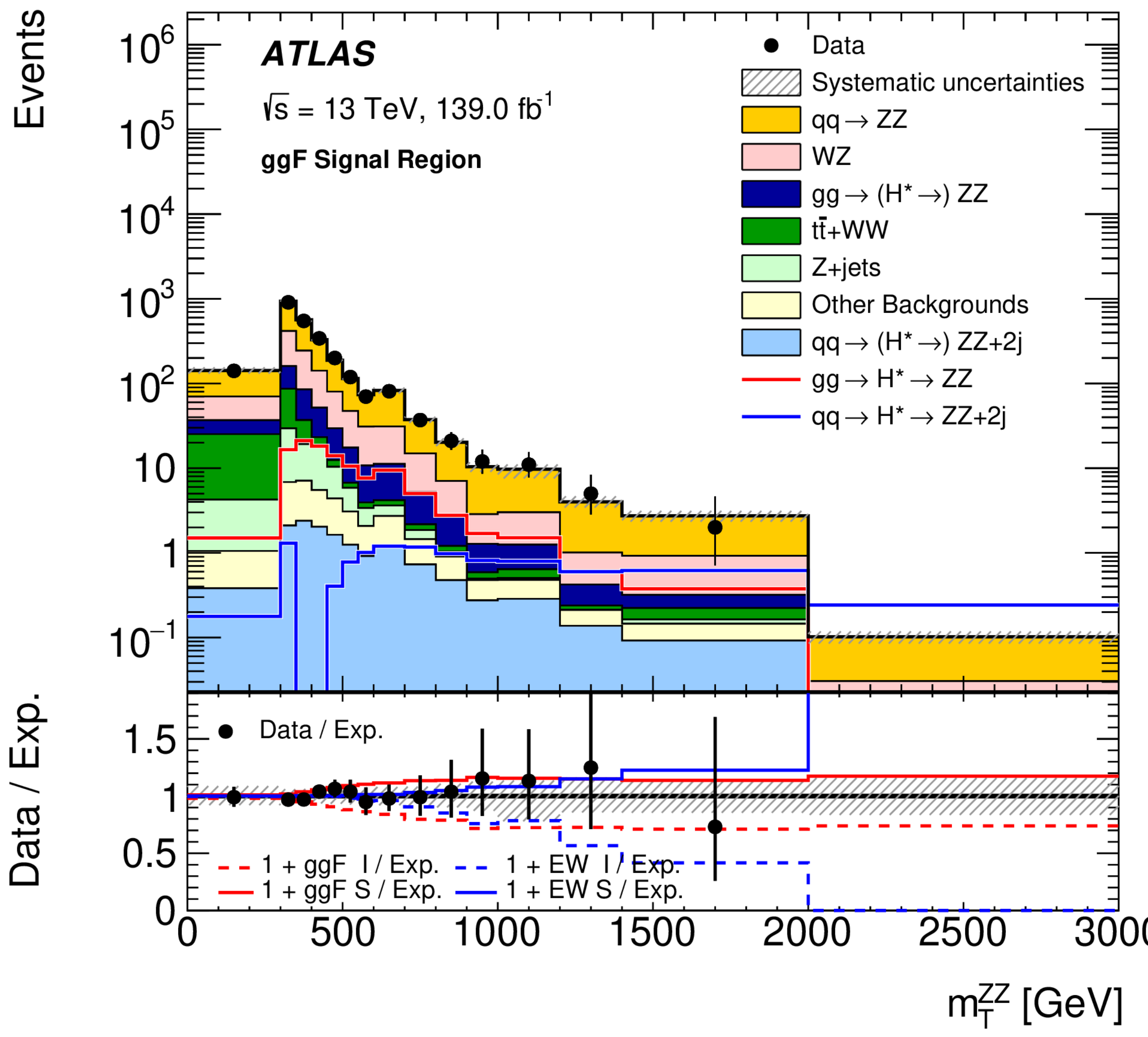
- Six times higher branching ratio

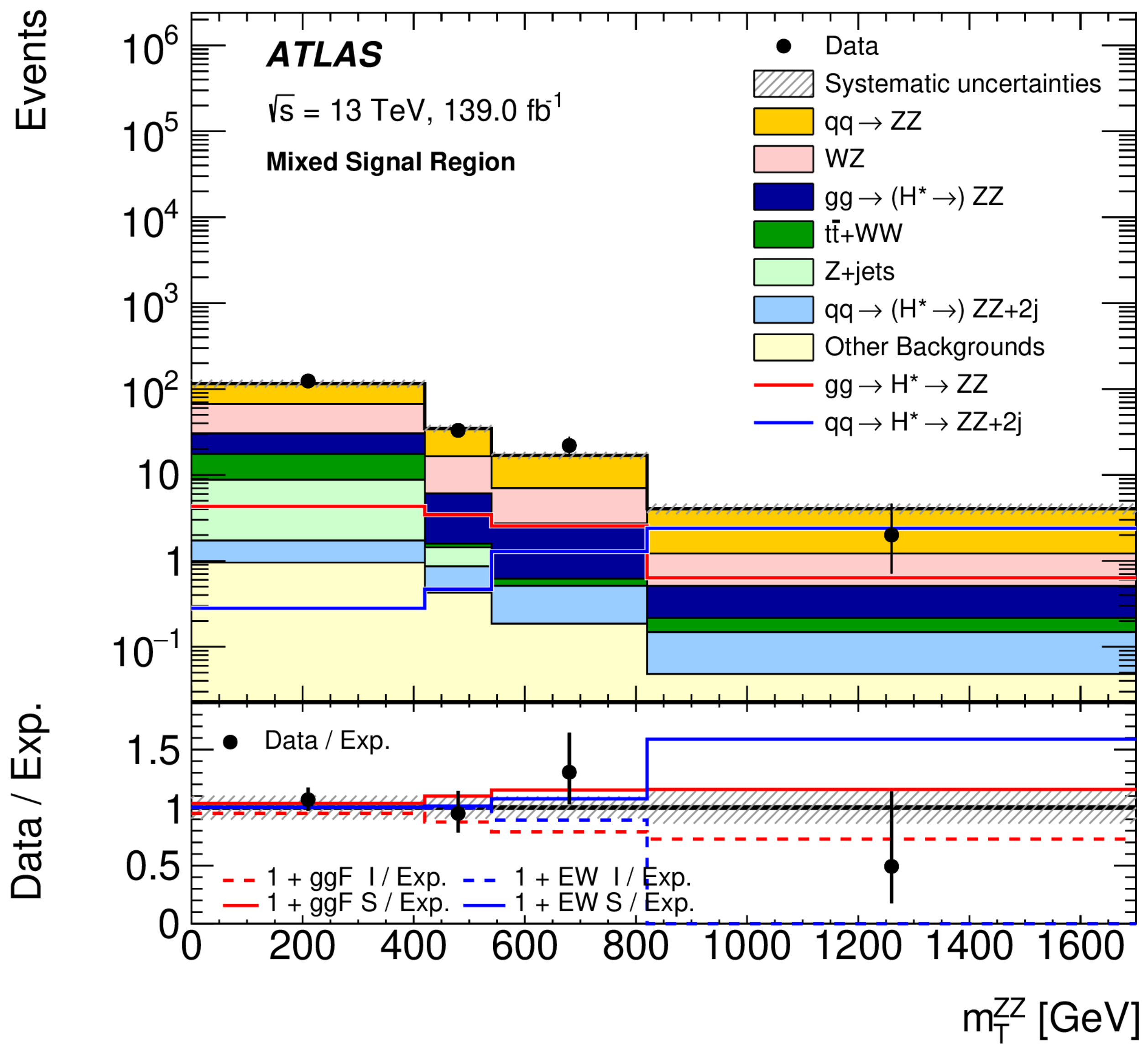
More background:

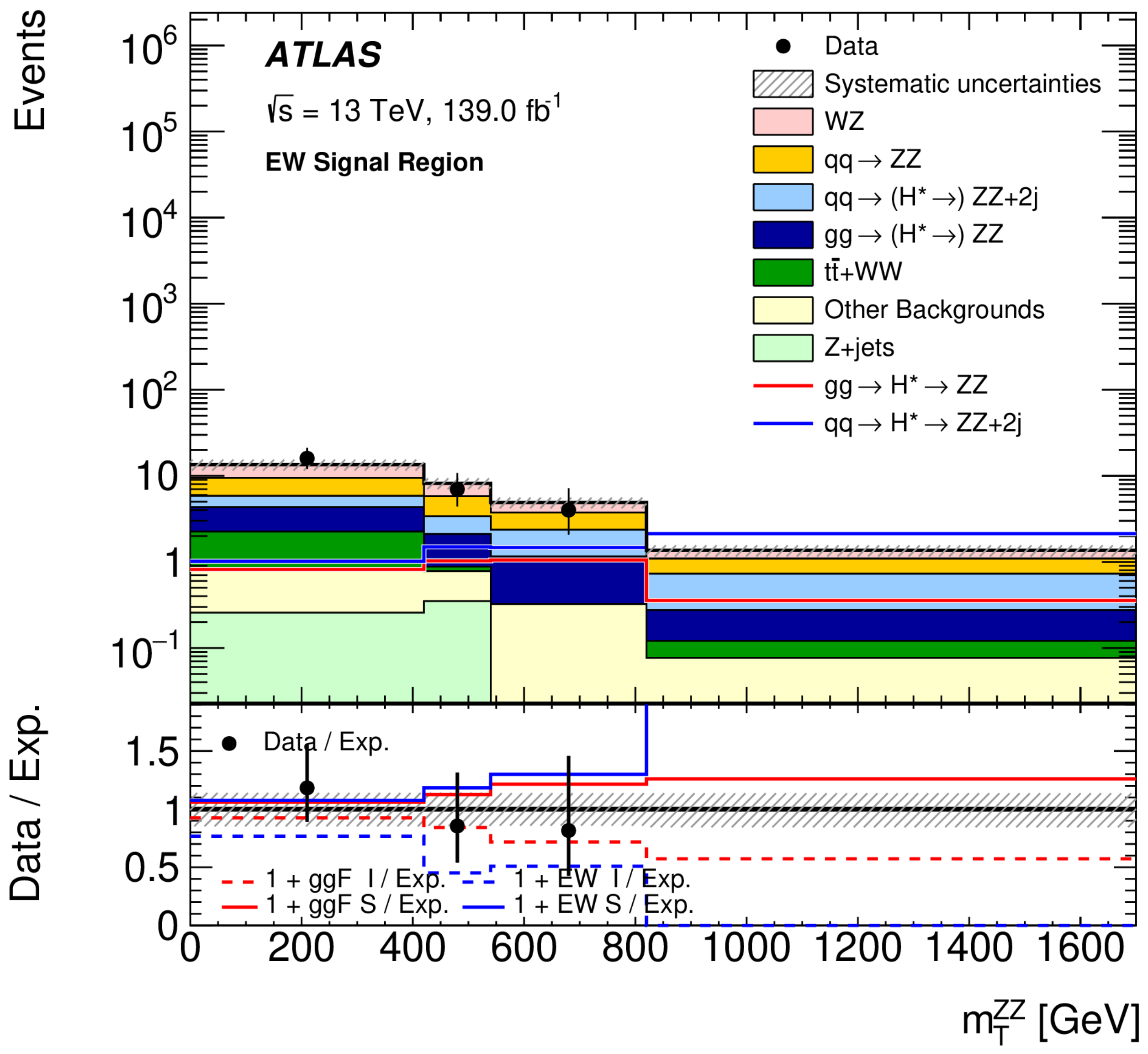
- $q\bar{q} \to ZZ, WZ, WW/\text{top}, Z + \text{jets}\ldots$

	Control region	Signal region
Categorization	Designed for each background process	Same as in 4l final state

- Final observable: transverse mass of ZZ system m_T^{ZZ}



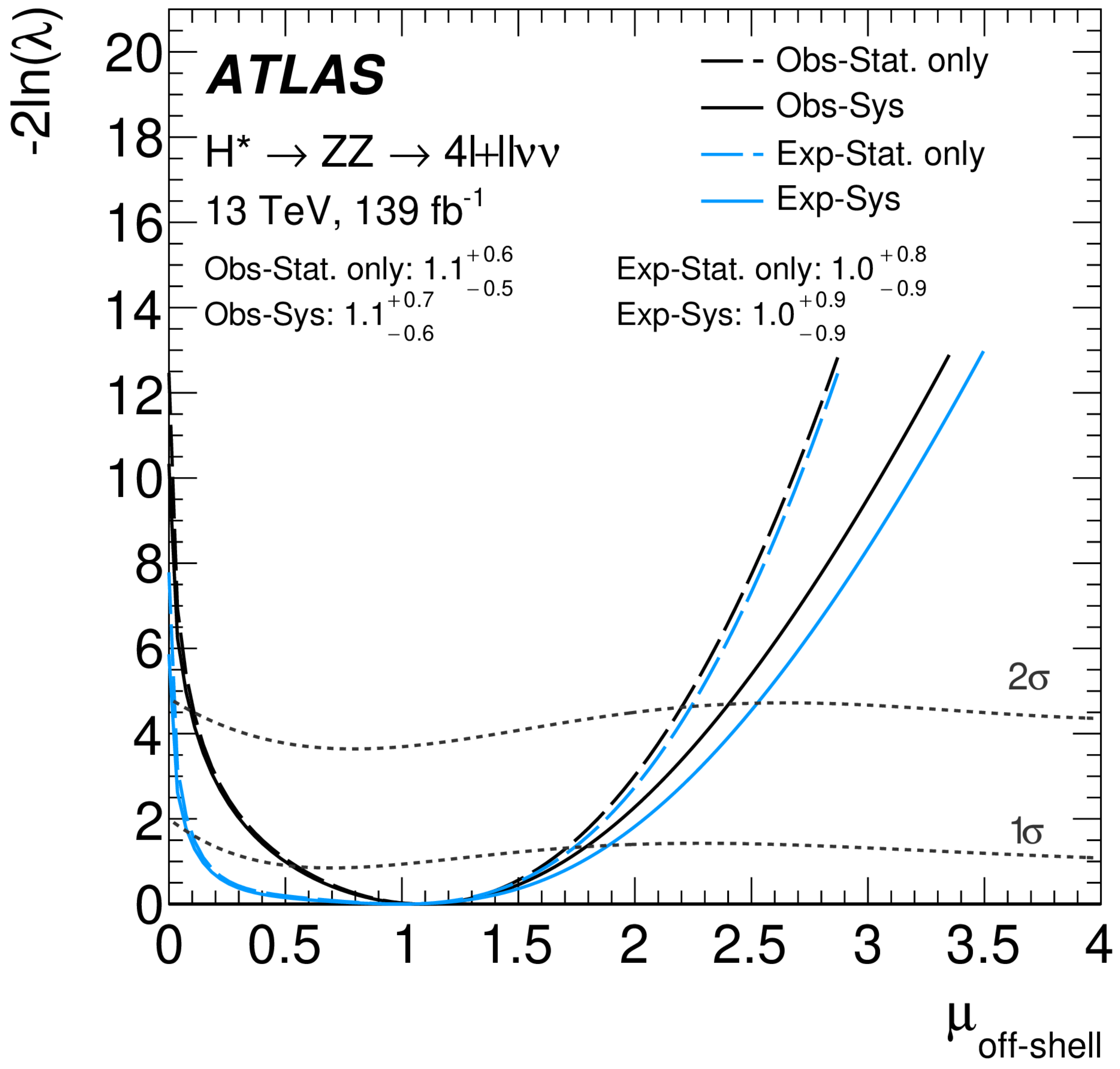




Higgs width results

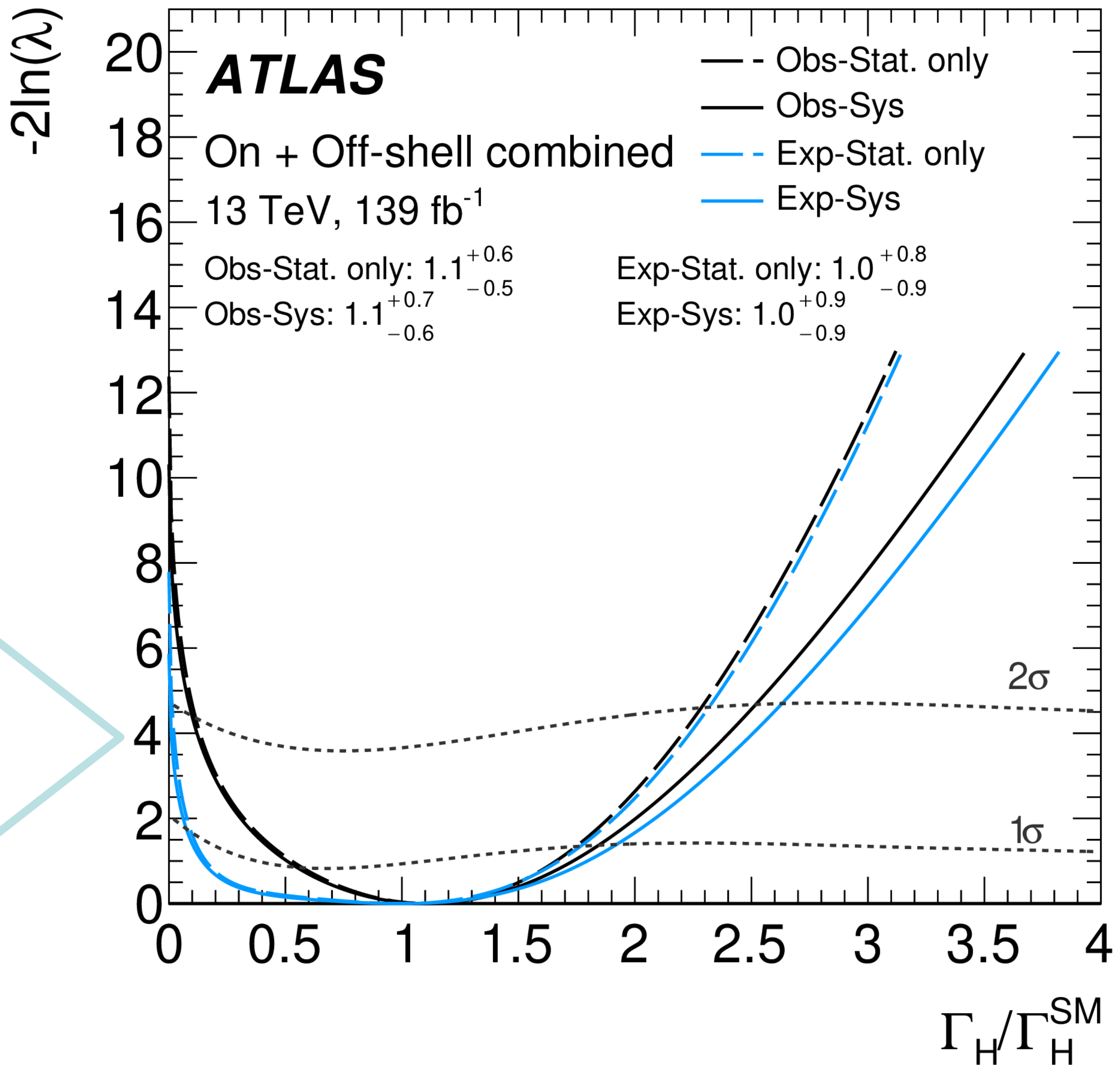
- Simultaneous fit to the combination of $4l$ and $2l2\nu$ final states
- Assumes $\kappa_{V,on-shell} = \kappa_{V,off-shell}$, $\kappa_{g,on-shell} = \kappa_{g,off-shell}$

Published on PLB



Combined with measurement of the on-shell signal strength

Eur. Phys. J. C 80 (2020) 957



Off-shell signal strength: $\mu_{off-shell} = 1.1^{+0.7}_{-0.6}$

Background-only hypothesis: rejected at 3.3σ

→ Evidence of off-shell Higgs boson production

total Higgs Boson width:

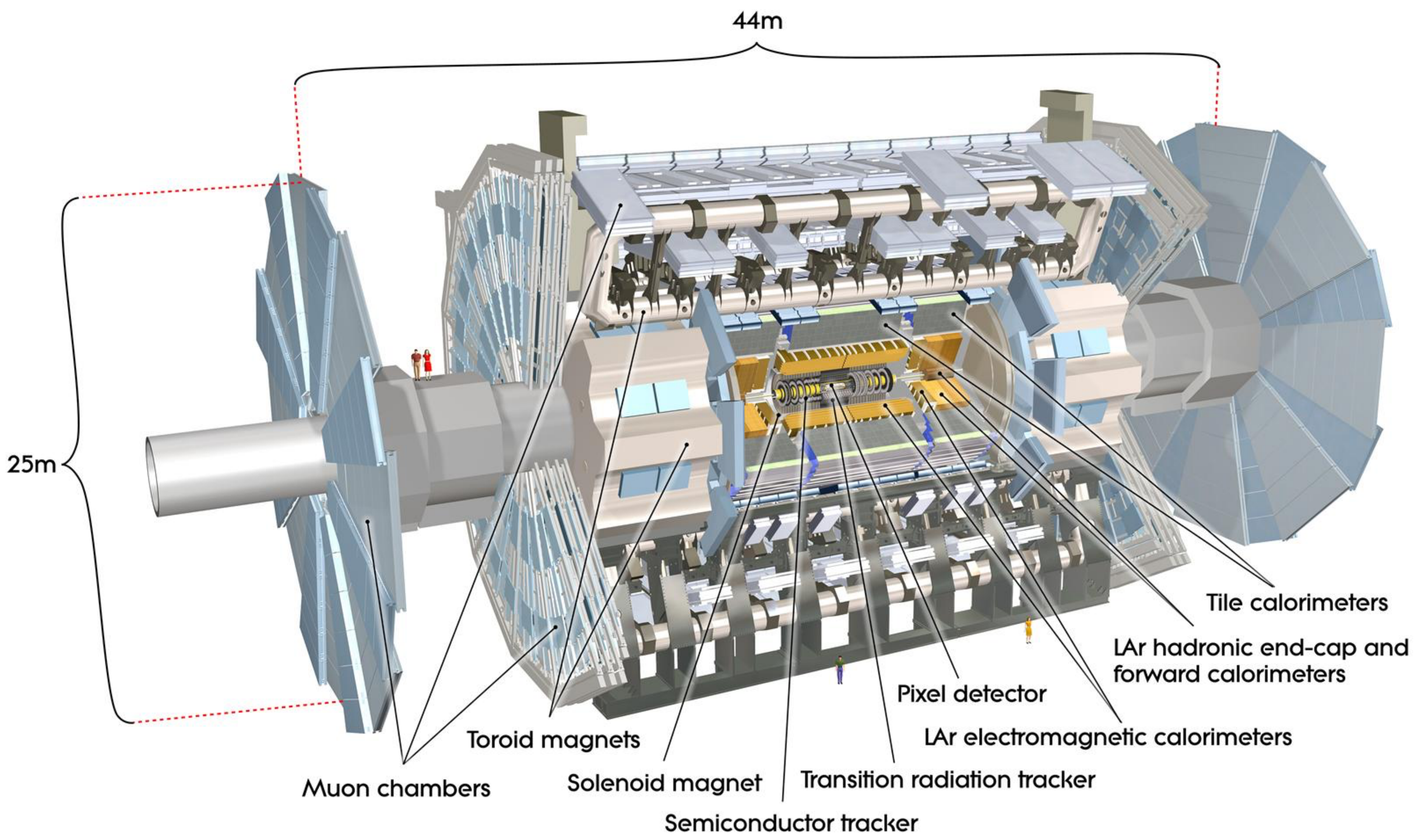
$\Gamma_H = 4.5^{+3.3}_{-2.5}$ MeV

Summary

- Higgs Boson mass is measured from a combination of run1 and run2 data in $H \to \gamma\gamma$ and $H \to ZZ^* \to 4l$ channels in ATLAS experiment: $m_H = 125.11 \pm 0.11$ GeV, which is the most precise measurement up to date
- Higgs Boson width is measured from Higgs off-shell production and ZZ leptonic decay channels with ATLAS run2 data: $\Gamma_H = 4.5^{+3.3}_{-2.5}$ MeV
- Next steps:
  - Higgs mass: discuss on a LHC combination
  - Higgs width: HL-LHC projection ~ 17% accuracy(Snowmass 2021)

Back up

ATLAS experiment



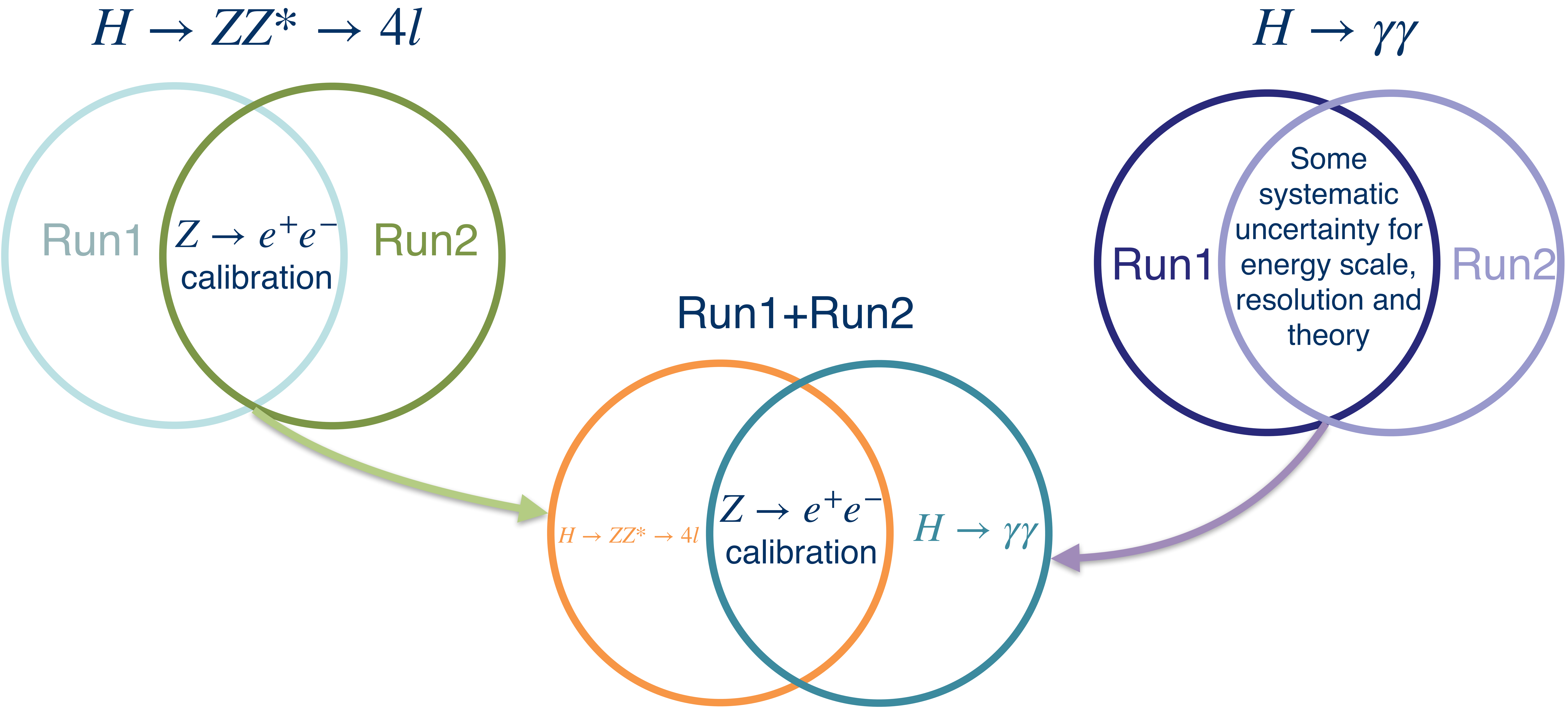
- Large Hadron Collider (LHC)
  - The largest and highest energy particle collider in the world
  - Proton beams collide at center-of-mass energy up to 13.6 TeV

  → Suitable to study Higgs boson physics

- A Toroidal LHC Apparatus (ATLAS)
  - Largest particle detector in the world
  - Inner solenoid + outer toroidal magnetic field
  - Various sub-detectors to measure and reconstruct particle information

Systematic uncertainty correlation scheme

Different input individual analysis can share systematic uncertainties from same source
$\rightarrow$ Need to correlate them properly



Systematic uncertainty correlation scheme

- $H \to \gamma\gamma$ Run1+Run2: Correlate some NPs for energy scale, resolution and theoretical uncertainties

  - Energy scale systematics uncertainties:

    ATLAS_EG_SCALE_ZEESYST ↔ ATLAS_EM_ES_Z

    ATLAS_PH_SCALE_CONVRADIUS ↔ ATLAS_EM_ConvRadius

  - Resolution systematics uncertainties:

    ATLAS_EG_RESOLUTION_MATERIAL_RUN1_RUN2 ↔ ATLAS_EM_mRes_MAT

    ATLAS_EG_RESOLUTION_SAMPLINGTERM ↔ ATLAS_EM_mRes_ST

    ATLAS_EG_RESOLUTION_ZSMEARING ↔ ATLAS_EM_mRes_CT

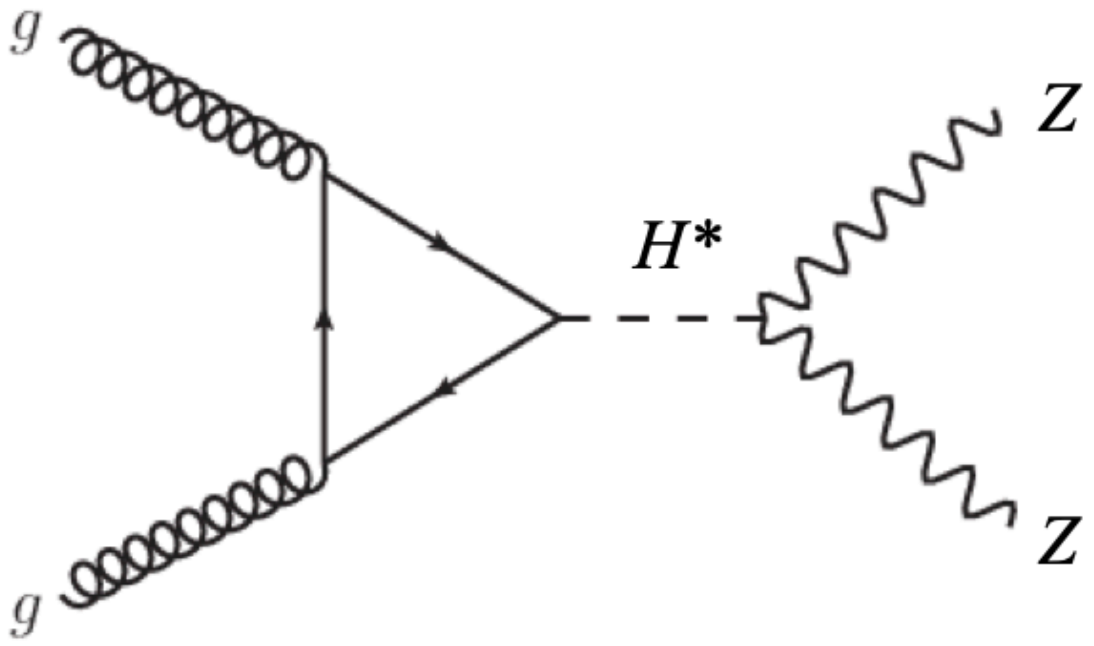
  - Theoretical uncertainties:

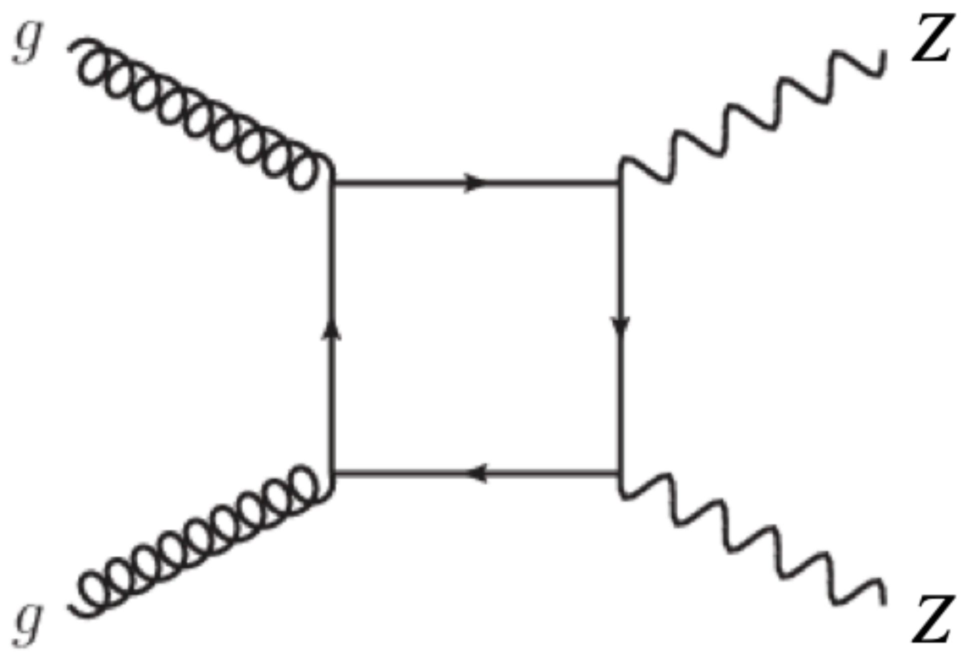
    ATLAS_QCDscale_ggH ↔ ATLAS_QCDscale_ggH

    ATLAS_QCDscale_VBF ↔ ATLAS_QCDscale_qqH

    ATLAS_QCDscale_ttH ↔ ATLAS_QCDscale_ttH

ZZ interference

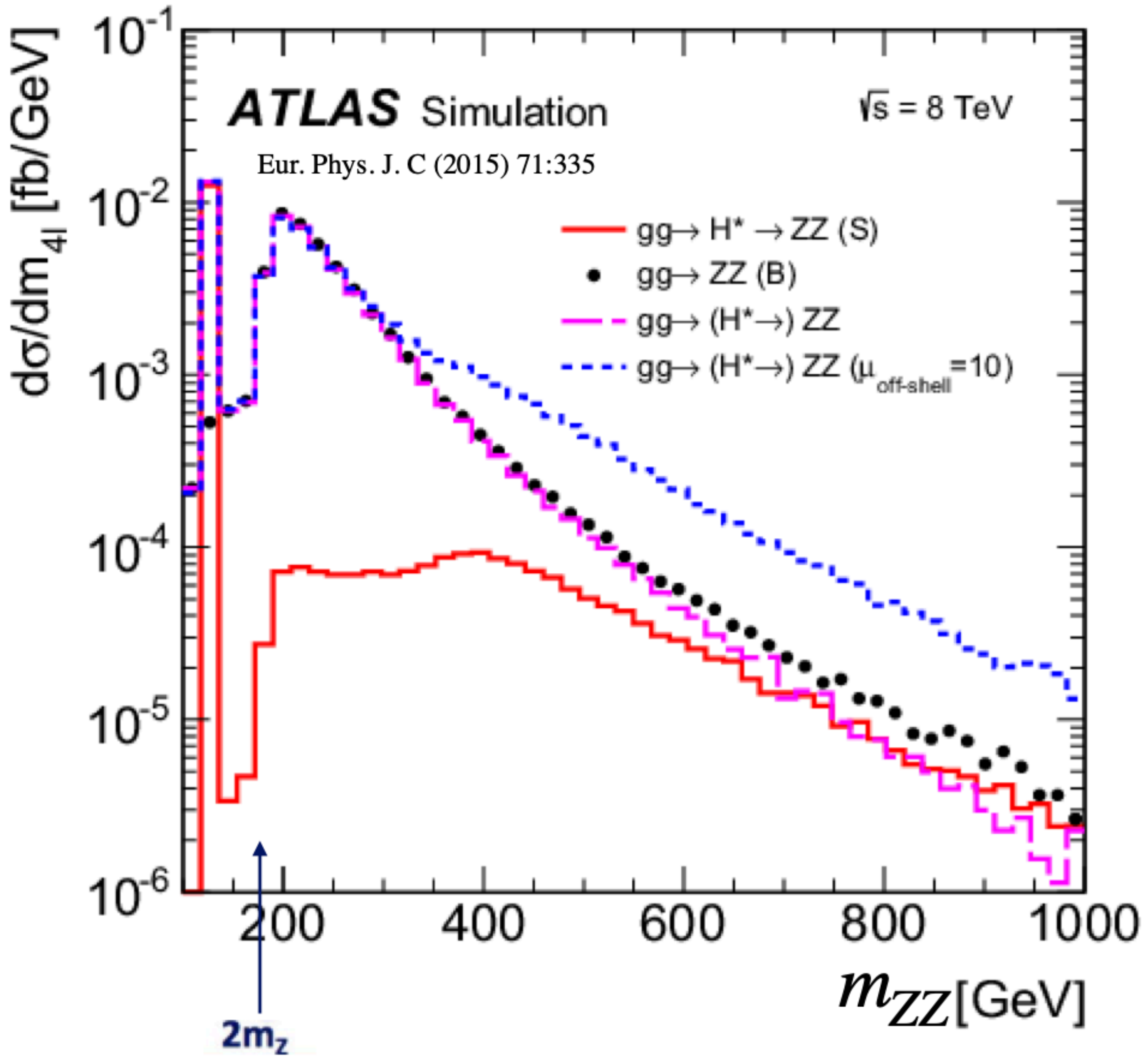


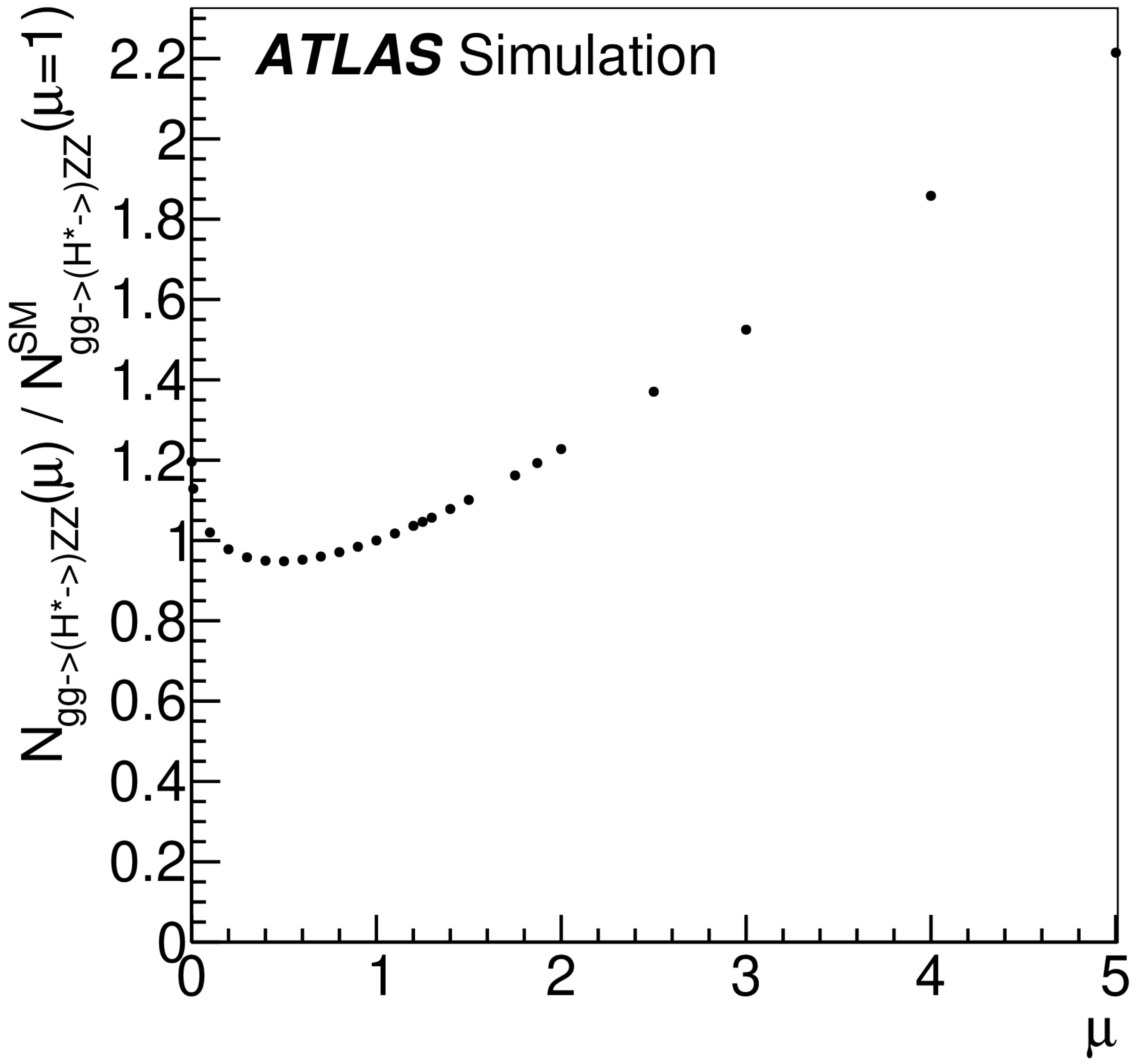


Cannot be distinguished, interference exists

Total number of events:

$$N = \mu S + \sqrt{\mu} I + B$$





yields

$4l$ channel

Process	ggF SR	Mixed SR	EW SR
$gg \to (H^* \to)ZZ$	341 ± 117	42.5 ± 14.9	11.8 ± 4.3
$gg \to H^* \to ZZ$	32.6 ± 9.07	3.68 ± 1.03	1.58 ± 0.47
$gg \to ZZ$	345 ± 119	43.0 ± 15.2	11.9 ± 4.4
$qq \to (H^* \to)ZZ + 2j$	23.2 ± 1.0	2.03 ± 0.16	9.89 ± 0.96
$qq \to ZZ$	1878 ± 151	135 ± 23	22.0 ± 8.3
Other backgrounds	50.6 ± 2.5	1.79 ± 0.16	1.65 ± 0.16
Total expected (SM)	2293 ± 209	181 ± 29	45.3 ± 10.0
Observed	2327	178	50

$2l2\nu$ channel

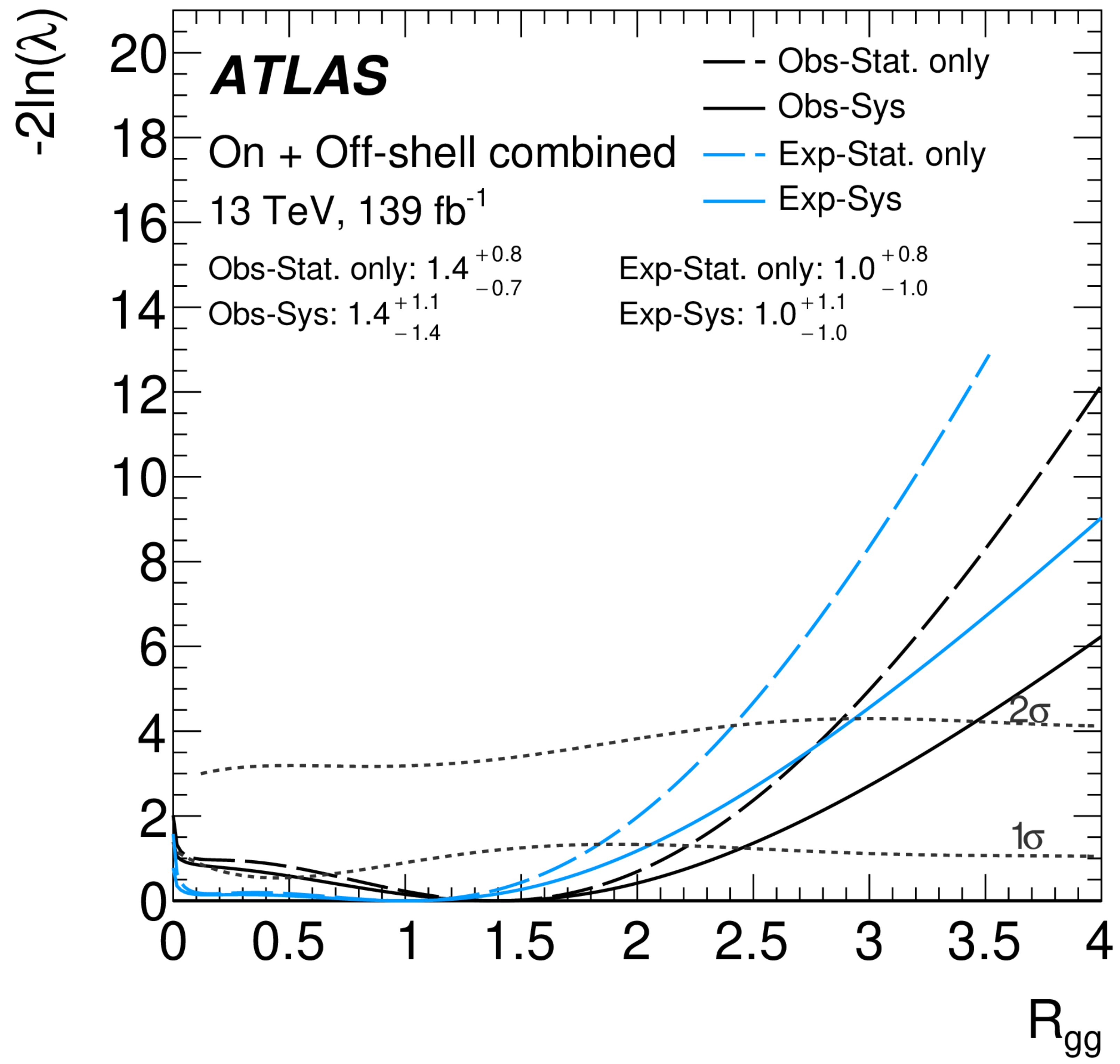
Process	ggF SR	Mixed SR	EW SR
$gg \to (H^* \to)ZZ$	210 ± 53	19.7 ± 4.9	4.29 ± 1.10
$gg \to H^* \to ZZ$	111 ± 26	10.9 ± 2.5	3.26 ± 0.82
$gg \to ZZ$	251 ± 66	23.4 ± 6.2	5.31 ± 1.46
$qq \to (H^* \to)ZZ + 2j$	14.0 ± 3.0	1.63 ± 0.17	4.46 ± 0.50
$qq \to ZZ$	1422 ± 112	80.4 ± 11.9	7.74 ± 2.99
WZ	678 ± 54	51.9 ± 6.9	7.89 ± 2.50
Z+jets	62.3 ± 24.3	7.51 ± 6.94	0.62 ± 0.54
Non-resonant-$\ell\ell$	106 ± 39	9.17 ± 2.73	1.55 ± 0.42
Other backgrounds	22.6 ± 5.2	1.62 ± 0.25	1.40 ± 0.10
Total expected (SM)	2515 ± 165	172 ± 17	28.0 ± 4.1
Observed	2496	181	27

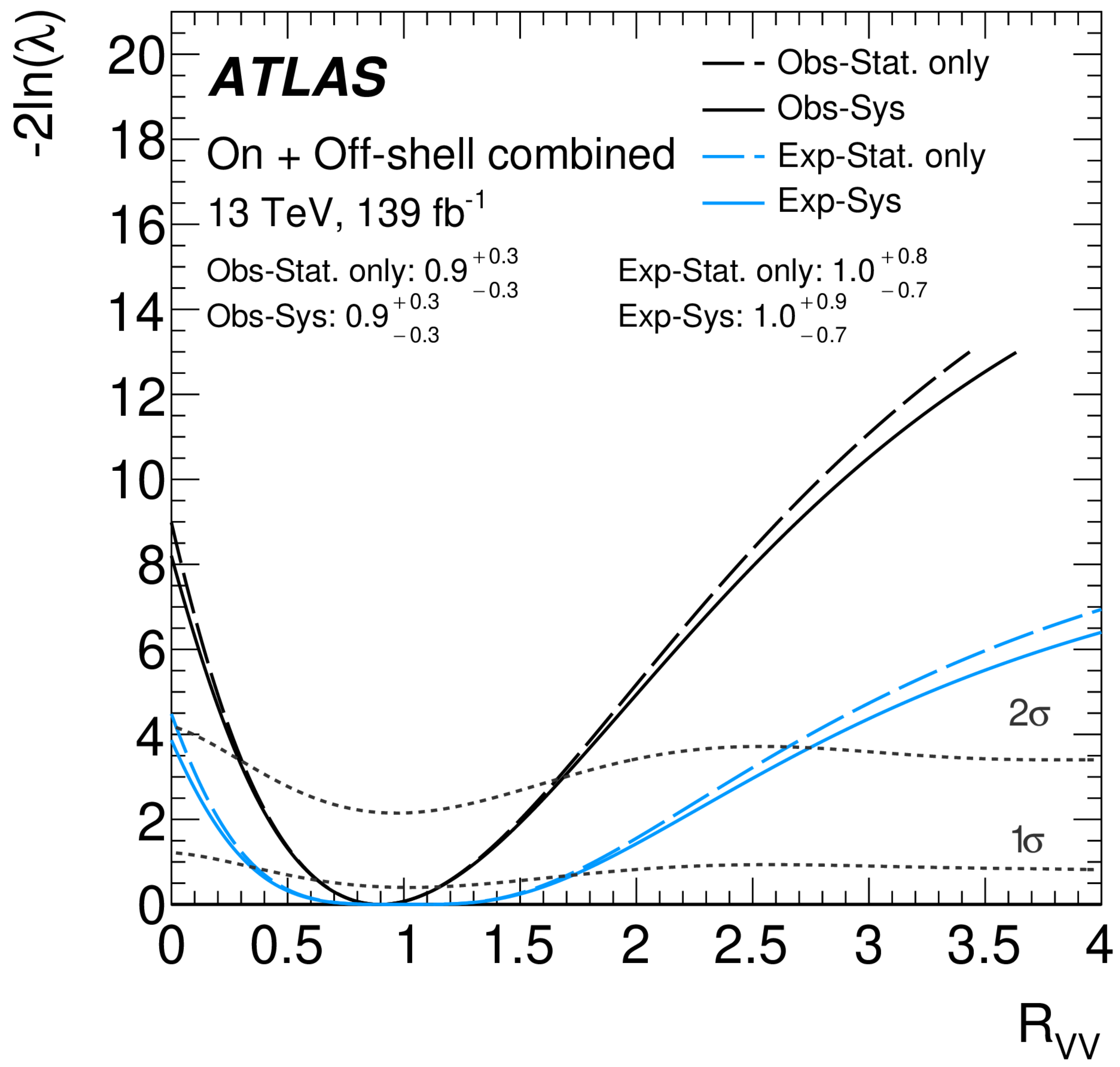
Systematic uncertainty impact

Systematic Uncertainty Fixed	$\mu_{\text{off-shell}}$ value at which $-2\ln\lambda(\mu_{\text{off-shell}}) = 4$
Parton shower uncertainty for $gg \to ZZ$ (normalisation)	2.26
Parton shower uncertainty for $gg \to ZZ$ (shape)	2.29
NLO EW uncertainty for $qq \to ZZ$	2.27
NLO QCD uncertainty for $gg \to ZZ$	2.29
Parton shower uncertainty for $qq \to ZZ$ (shape)	2.29
Jet energy scale and resolution uncertainty	2.26
None	2.30

- Fix Higgs width to Standard Model prediction

→ Measure the ratio of on-shell and off-shell coupling modifiers





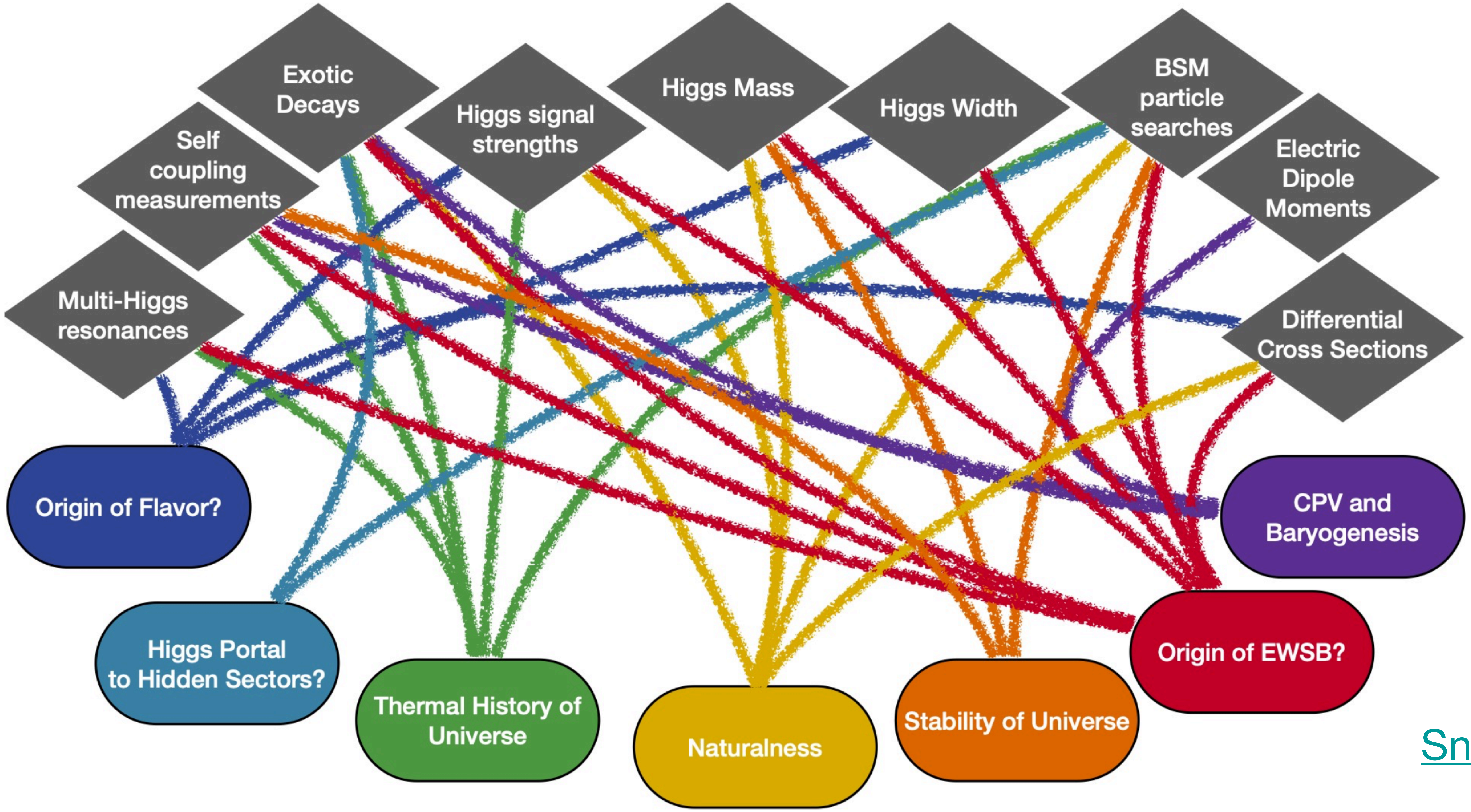
$$R_{gg} = \frac{\kappa^2_{g,off-shell}}{\kappa^2_{g,on-shell}}$$

$$R_{VV} = \frac{\kappa^2_{V,off-shell}}{\kappa^2_{V,on-shell}}$$

Introduction

Higgs Boson properties play an important role in answering the big questions
- Among them: Higgs mass and width are the most basic properties

→ Precise measurement of them in the experiment will help to solve the puzzles



Snowmass 2021