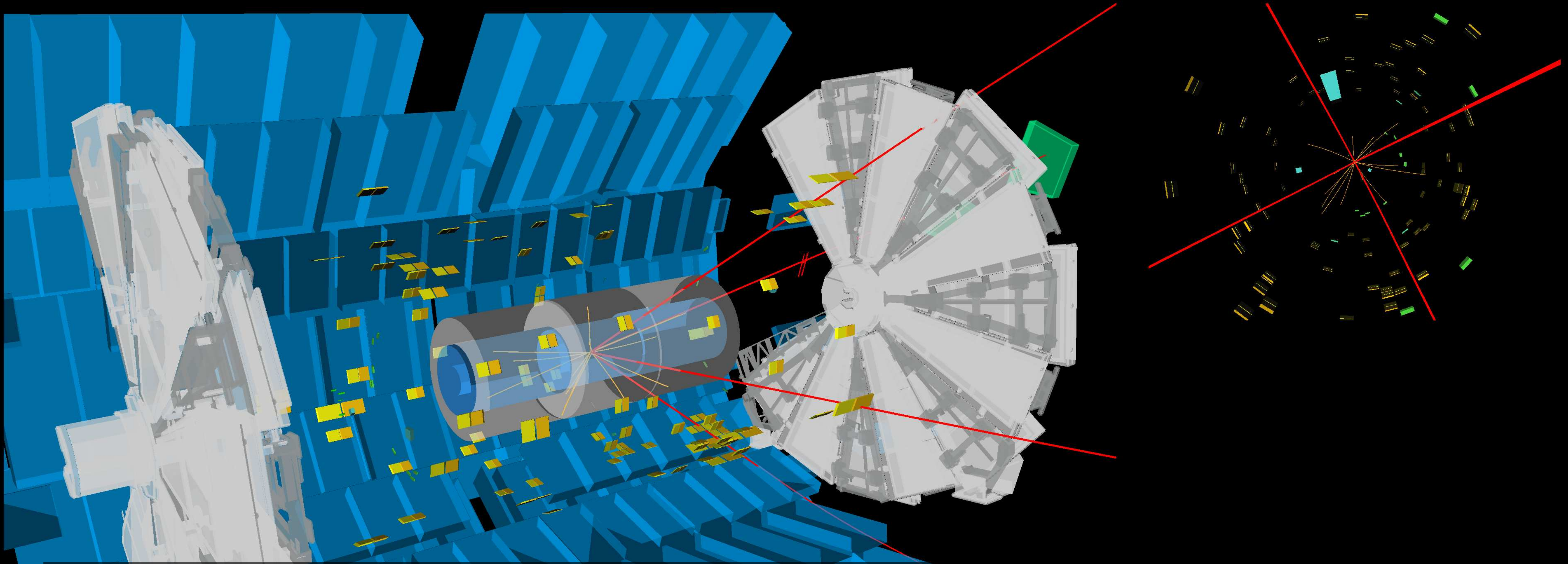


What can we still learn from studying the Higgs boson with the ATLAS Detector?

Alice Reed

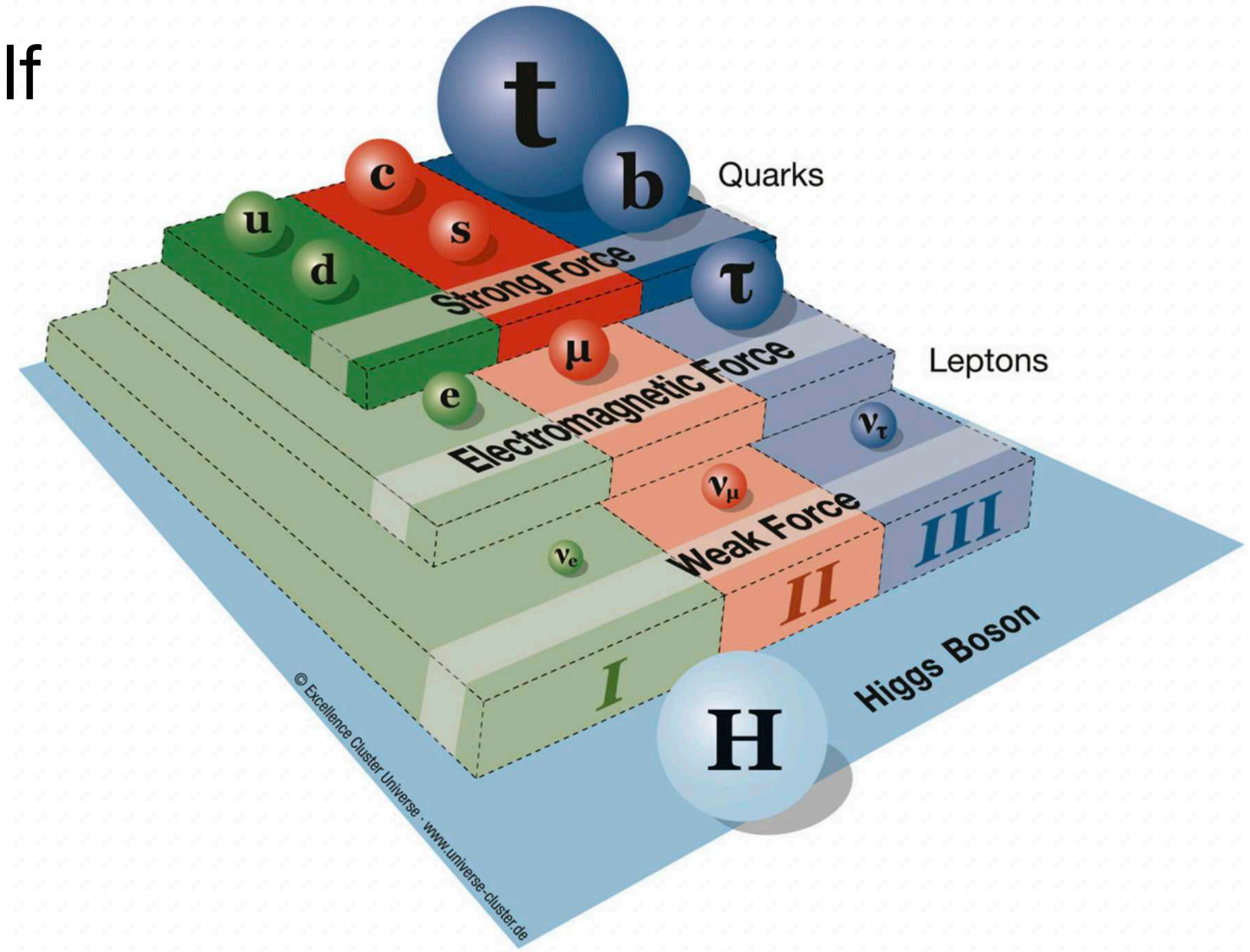
IMPRS Young Scientist Workshop - November 2023

ATLAS EXPERIMENT

Run: 437711
Event: 1155602798
2022-10-22 03:09:27 CEST

Higgs Boson Introduction

- Standard Model (SM) of particle physics describes 3 out of 4 fundamental forces and classifies all known elementary particles, including the Higgs
- Observation of a particle compatible with the SM Higgs boson announced by the ATLAS and CMS experiments at the LHC in July 2012
- The Higgs couples to all particles in the SM, including itself
- Precision measurements of Higgs properties are a **crucial test of the SM**
- Probe for physics beyond the SM:
  - Could the Higgs be composite?
  - Is *the* Higgs boson the SM higgs?
  - Does a full Higgs sector exist?



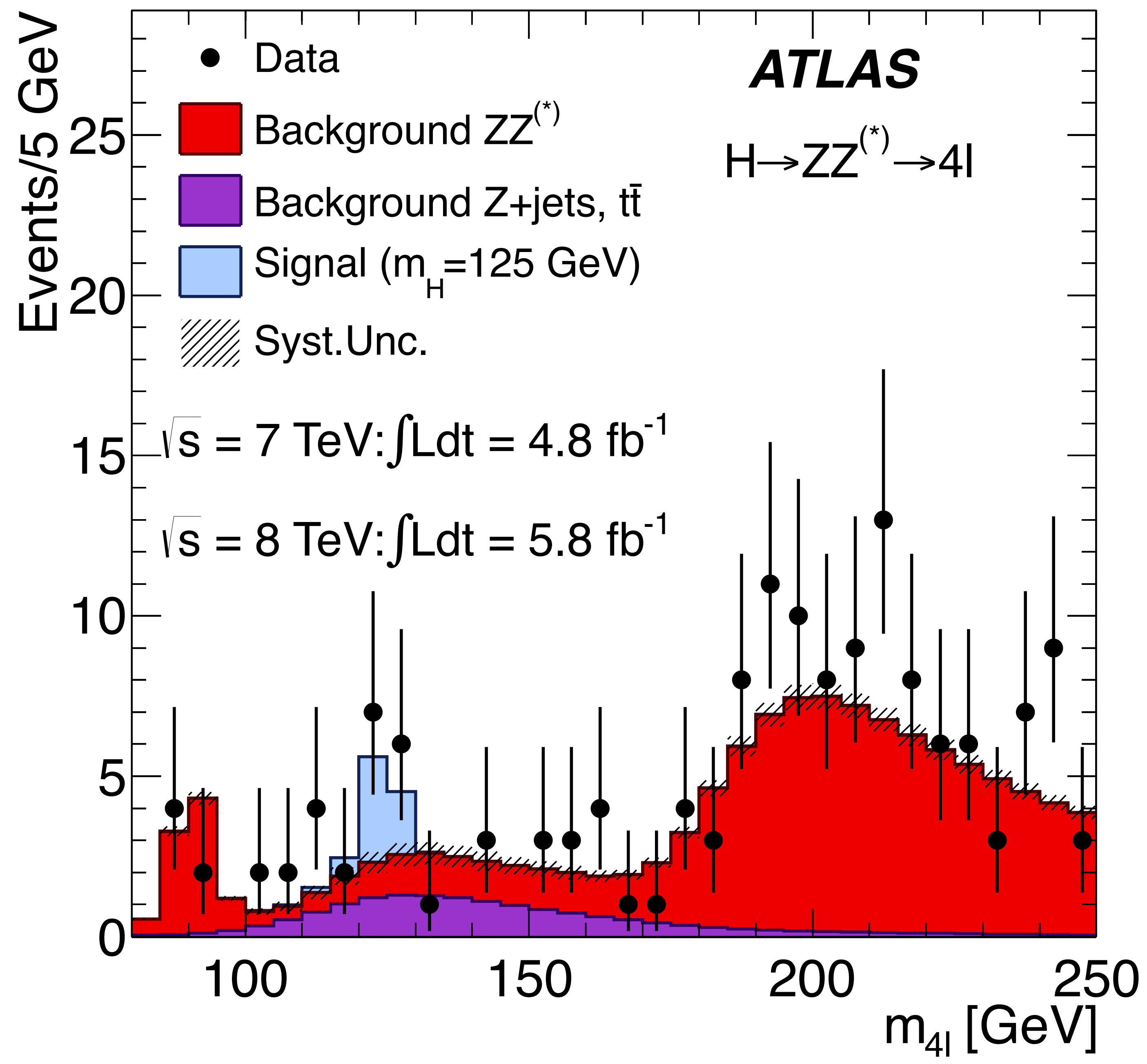
Higgs at the LHC

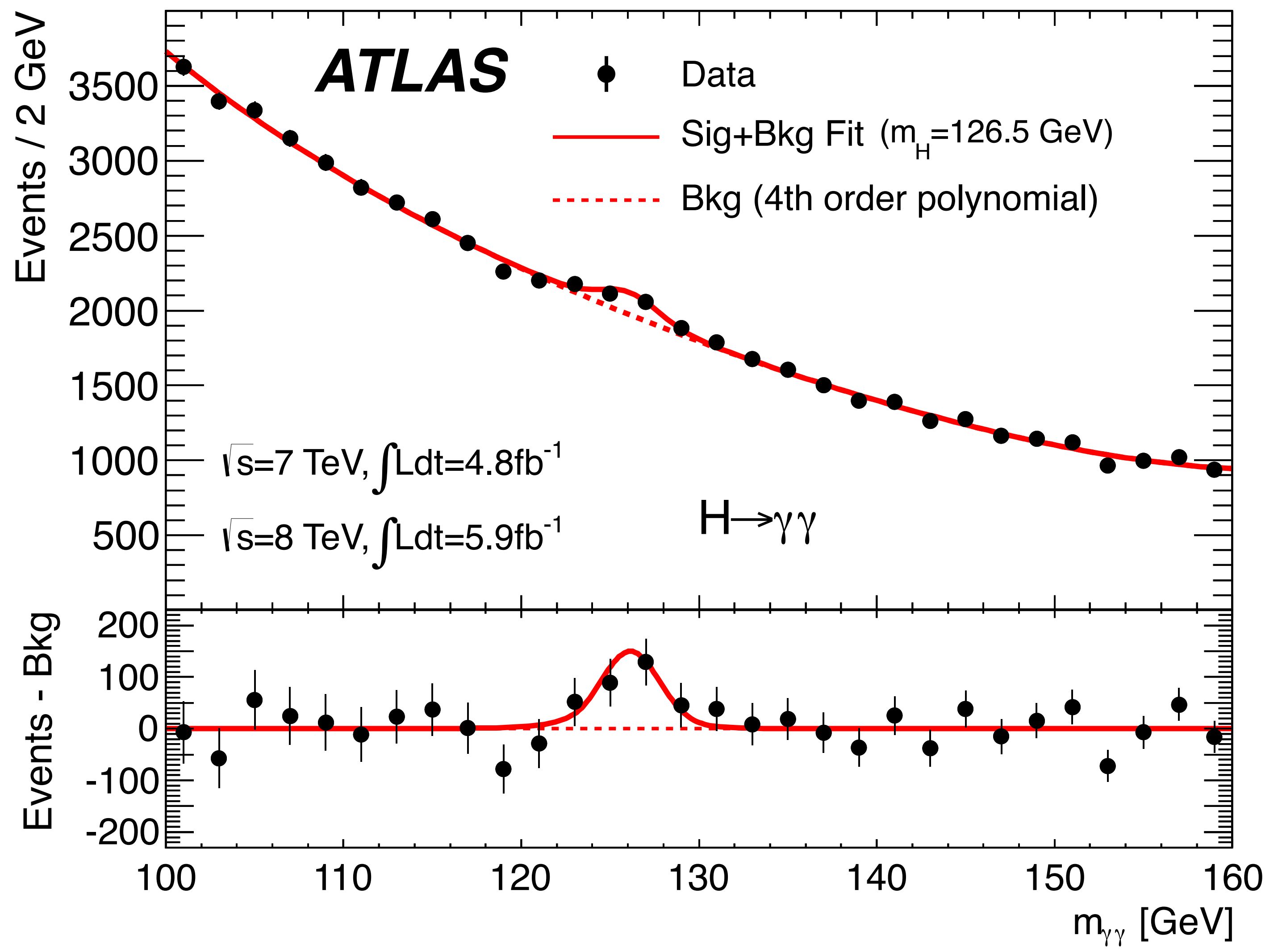
arXiv:1207.7214

- One of the physics goals for LHC → performing a search for a particle compatible with the SM Higgs boson
- Searches performed in the **H→ZZ*→4l and H→γγ channels**

  → Small branching ratio but excellent mass resolution and **high signal-to-background ratio**

- **Clear signature** allows these "golden" channels to be studied with small datasets
- Higgs properties measured during in Run 1 (2009-2013) at centre-of-mass energies of $\sqrt{s}$ = 7 TeV and 8 TeV
- Further measurements continue to be performed with 139 fb^{-1} data from Run 2 (2015-2018) at $\sqrt{s}$ = 13 TeV





Higgs Boson Property Measurements

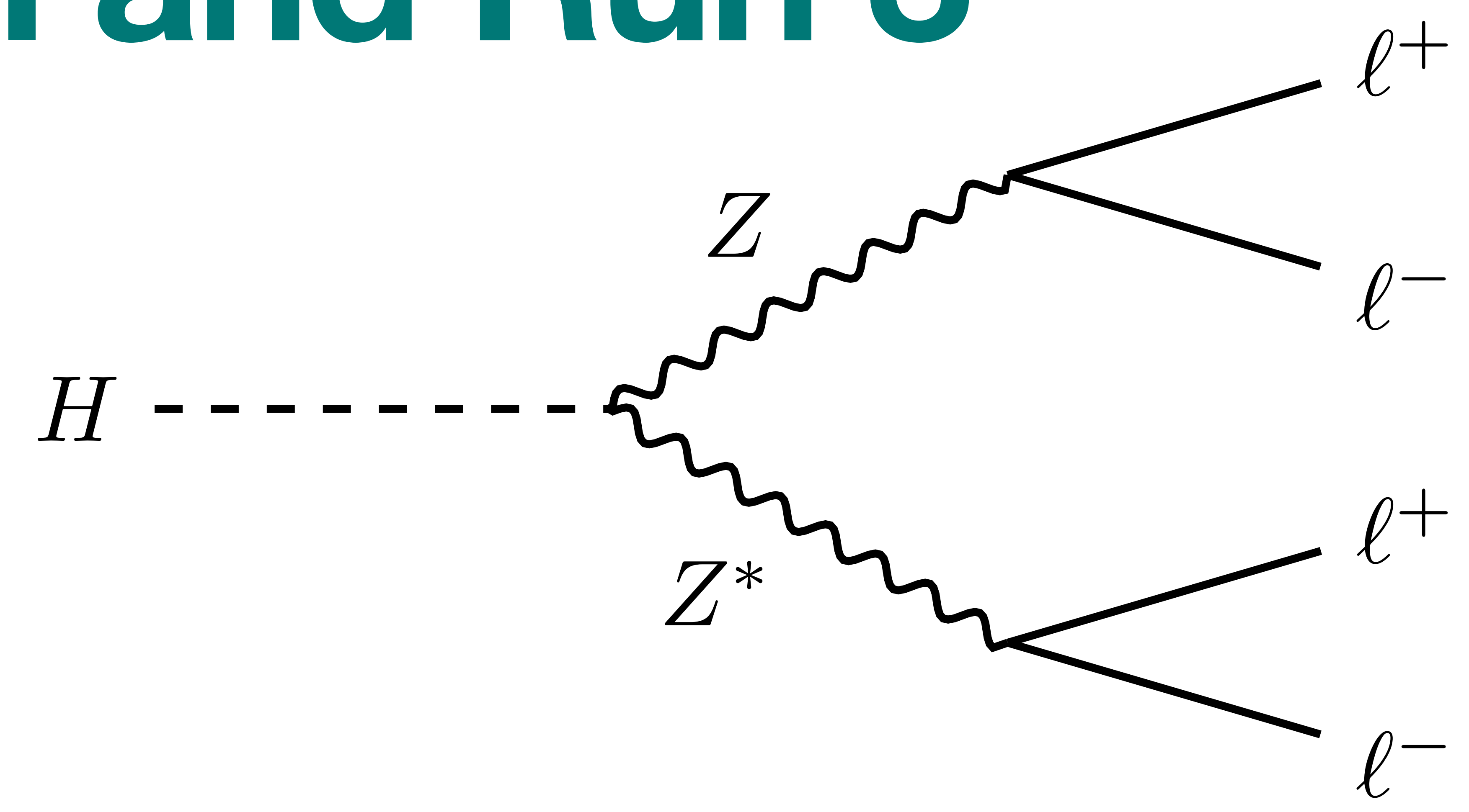
- Precision measurements of the Higgs boson test the SM and can also be used to look for deviations which could be physics beyond the Standard Model (BSM)
- Measured properties:
  - **Branching ratio** → how often the Higgs decays into different particles
  - **Mass** → parameter not predicted in the SM
  - **Width** → sets limits on the natural lifetime of the Higgs
  - **Coupling to other SM particles** → SM predicts that couplings scale with particle mass

    → puts constraints on BSM theories which often predict a different pattern in couplings
  - **Self-coupling** → coupling of the Higgs to itself is largely unconstrained

    → gives direct insight into the structure of the Higgs potential
  - **Charge and parity (CP)** → probes the matter–antimatter asymmetry in the Universe
  - **Production cross-section** → how often the Higgs is produced

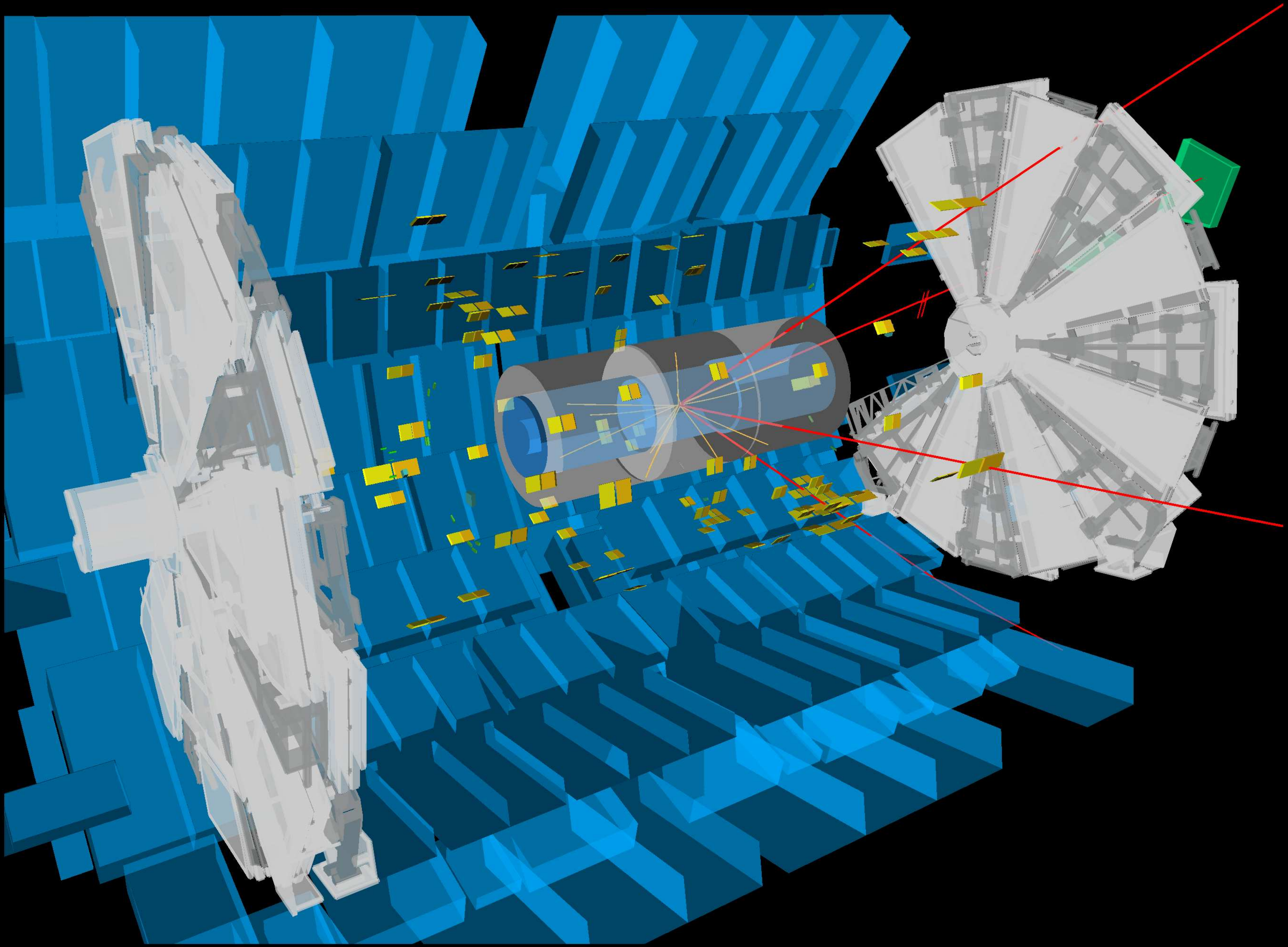
H→ZZ*→4l Decay Channel and Run 3

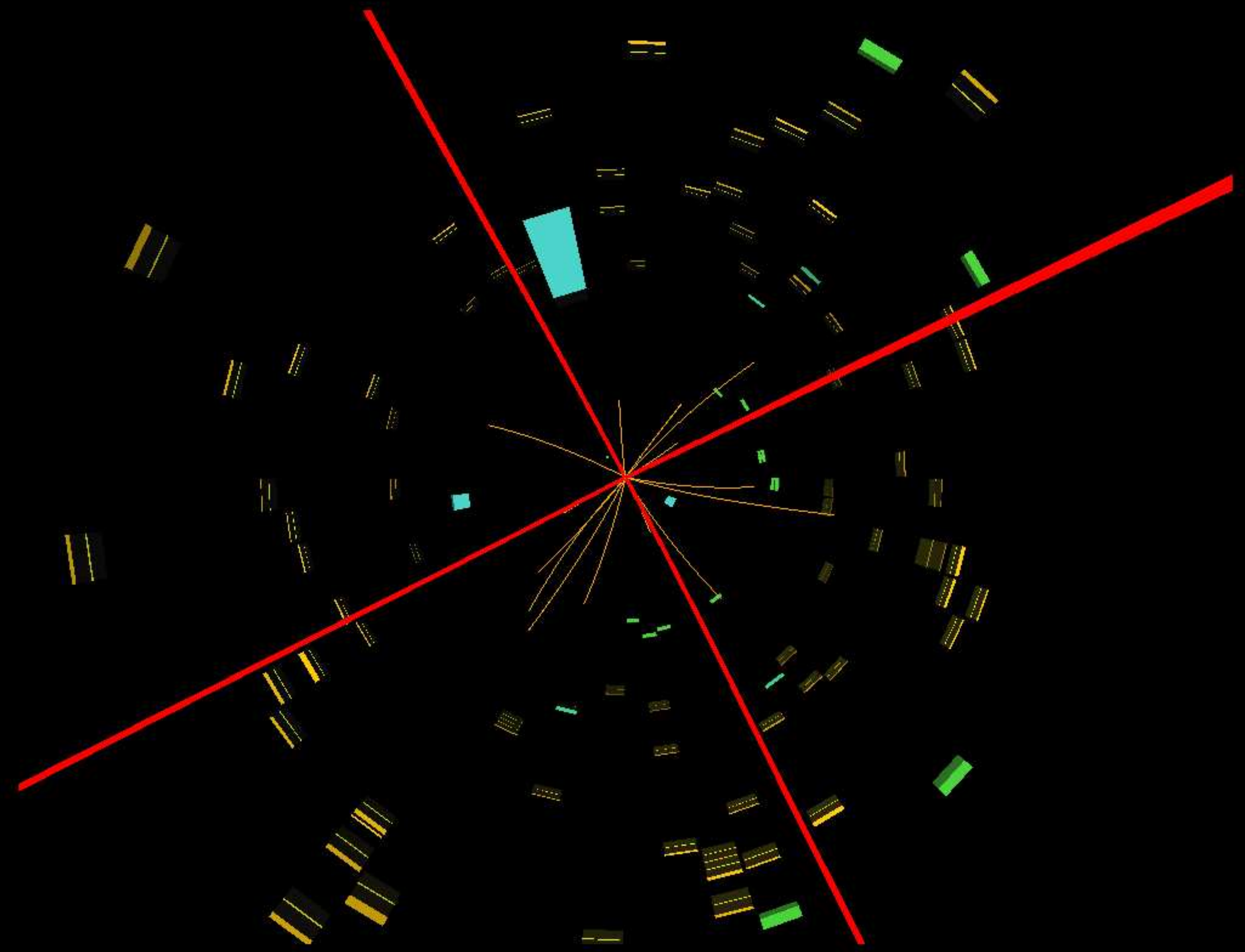
- H→ZZ*→4l channel characterised by a final state containing two pairs of oppositely charged leptons (*e* or *μ*) from the same primary vertex
- Four possible **final states: 4μ, 4e, 2e2μ, 2μ2e**



- Run 3 of the LHC began in July 2022 at an increased **centre-of-mass energy of 13.6 TeV**
- 2022 ATLAS dataset corresponds to an integrated luminosity of 29.0 fb^{-1}

- Higgs boson cross-section measurement in the H→ZZ*→4l channel is one of the **standard candles of the SM**
  - Important to measure this process at the new centre-of-mass energy
  - Re-establish measurement with upgraded detector components





4μ Higgs
candidate Event

ATLAS
EXPERIMENT

Run: 437711
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Fiducial Cross-section Measurements

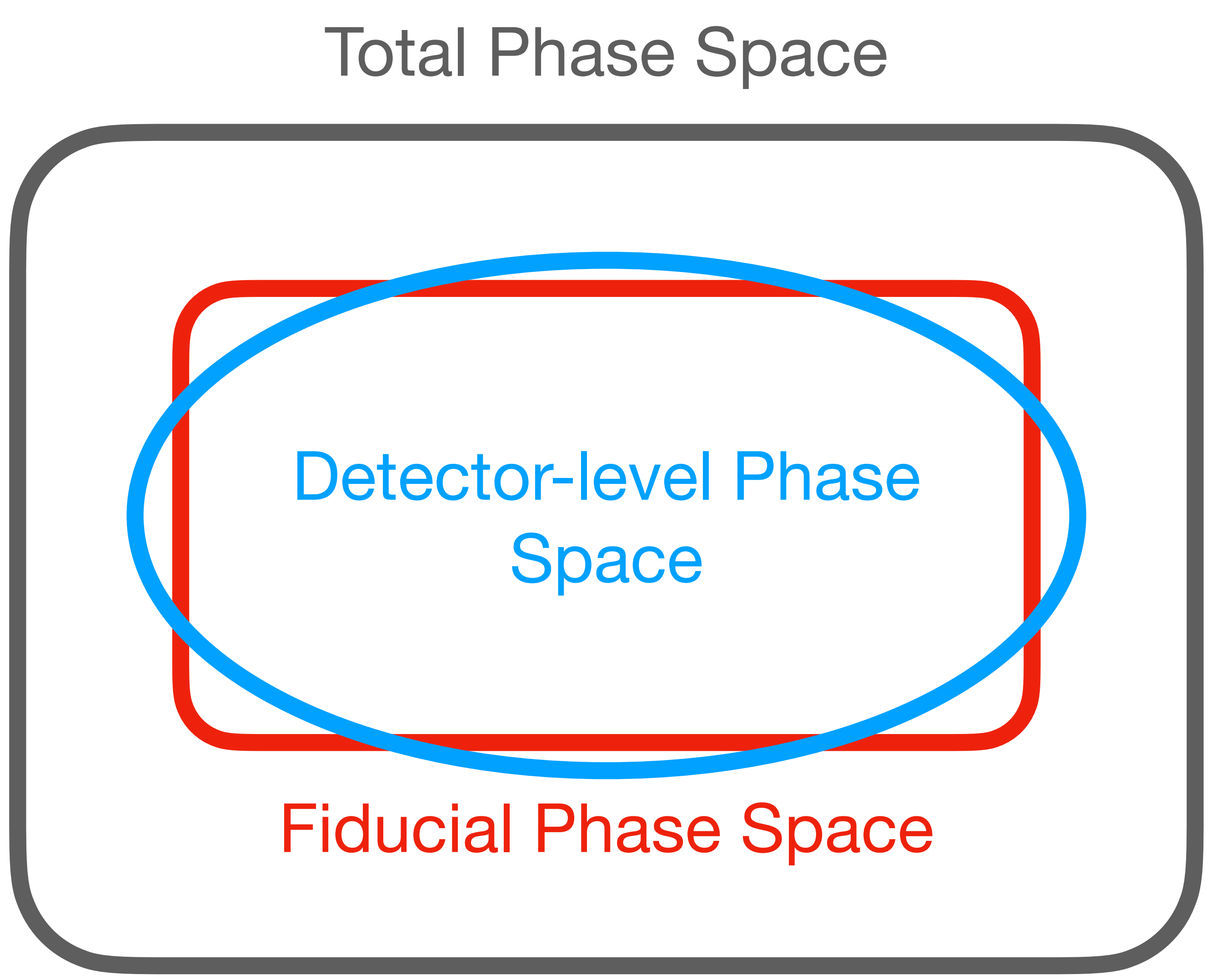
- Want to measure **total Higgs production cross-section**
- However our detector can only measure a **restricted area of phase space**
- **Aim: Minimise model-dependency** when extrapolating to total cross-section

- Define a **fiducial phase space**, which closely matches the **detector-level phase space**

$$\sigma_{\text{fid}} = \sigma_{\text{tot}} \cdot A \cdot \mathcal{B} = \text{Parameter of Interest}$$

$$A = \text{Acceptance} = N_{\text{fid}}/N_{\text{tot}}$$

$$\mathcal{B} = \text{Branching ratio}$$



- Fiducial space includes corrections for detector-level efficiency and resolution effects

Fiducial Cross-section with Run 3 Data

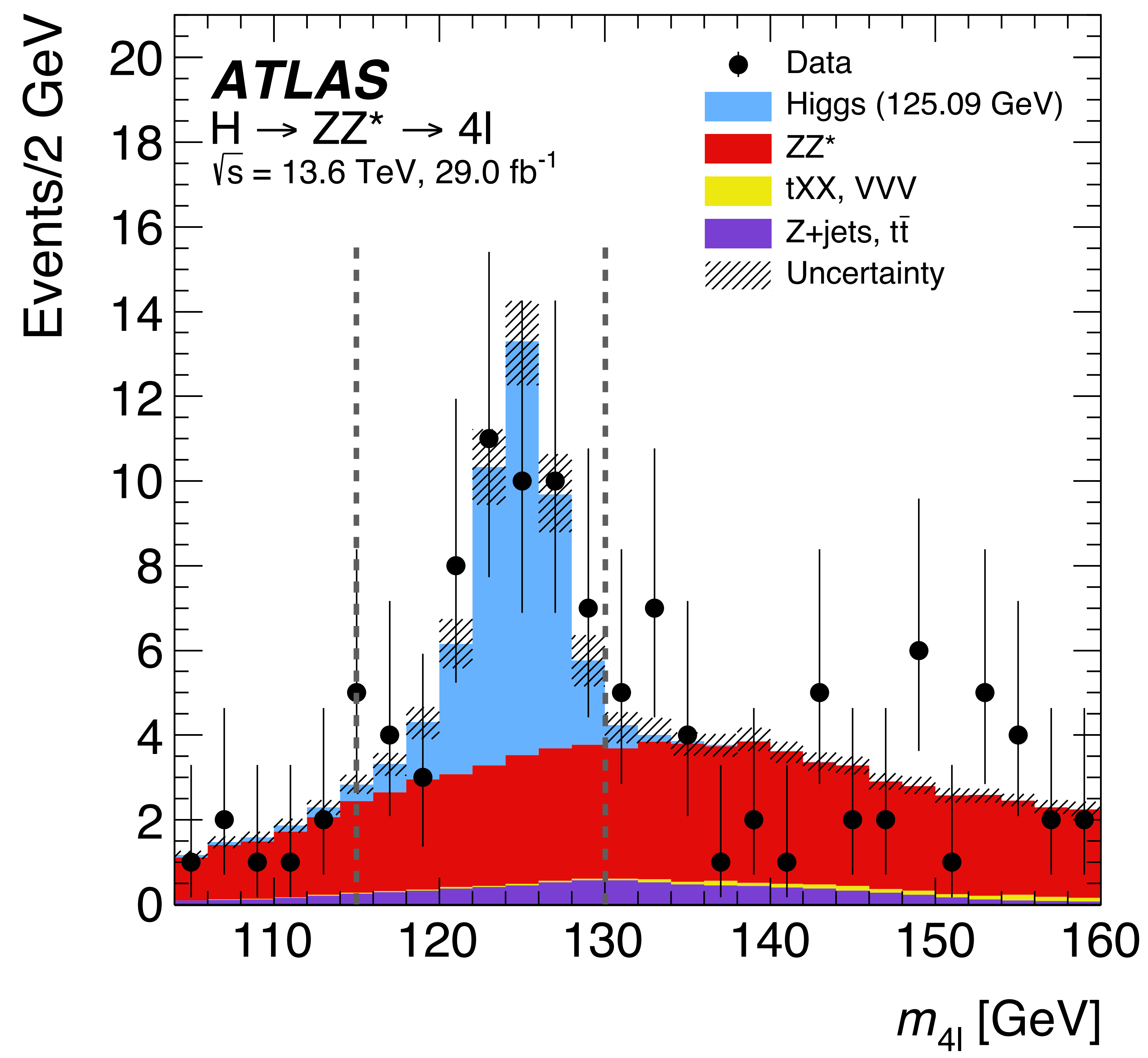
- Fiducial cross-section, σ_{fid}, is extracted using a **binned maximum-likelihood fit of the *m_{4l}* distribution** inclusively for all four-lepton final states:

$$N = \sigma_{fid} \times \mathcal{L} \times \mathcal{C}_{\mathcal{F}}$$

Number of events

Luminosity (amount of data)

Correction factor (detector efficiency…)



- Signal region: 115 - 130 GeV
- Analysis strategy closely follows the full Run 2 inclusive and differential cross-section measurement: EPJC 80 (2020) 942
- Run 3 strategy and results about to be published in EPJC: arXiv:2306.11379

$H \to 4l$ Fiducial Cross-section Results

- **Observed** number of events comparable to the **expected** signal and background yields for each of the four-lepton final states (4μ, 4e, 2e2μ, 2μ2e):

Final state	Signal SM (pre-fit)	Signal (post-fit)	ZZ^* background	Other backgrounds	Total	Observed
4μ	14.8 ± 1.0	11.3 ± 0.8	8.3 ± 0.6	1.0 ± 0.3	20.6 ± 1.0	23
$2e2\mu$	11.1 ± 0.8	8.5 ± 0.6	6.5 ± 0.4	1.0 ± 0.3	16.0 ± 0.8	13
$2\mu 2e$	7.0 ± 1.3	5.4 ± 1.0	3.2 ± 0.6	0.9 ± 0.1	9.4 ± 1.2	12
$4e$	7.4 ± 1.5	5.7 ± 1.1	3.1 ± 0.7	0.8 ± 0.2	9.6 ± 1.4	9
Total	40.3 ± 3.8	30.9 ± 2.9	21.1 ± 2.0	3.6 ± 0.7	55.6 ± 4.4	57

- **Inclusive fiducial cross-section** extracted from the m_{4l} fit:

$$\boxed{\sigma_{fid} = 2.80 \pm 0.70\ (\text{stat.}) \pm 0.21\ (\text{syst.})\ \text{fb}}$$

- In agreement with SM value:

$$\sigma_{fid,SM} = 3.67 \pm 0.19\ \text{fb}$$

→ Breakdown of uncertainties:

Source	Uncertainty [%]
Statistical uncertainty	25.1
Systematic uncertainty	7.9
Electron uncertainties	6.3
Muon uncertainties	3.8
Luminosity	2.2
ZZ^* theoretical uncertainties	0.7
Reducible background estimation	0.6
Other uncertainties	<1.0
Total	26.4

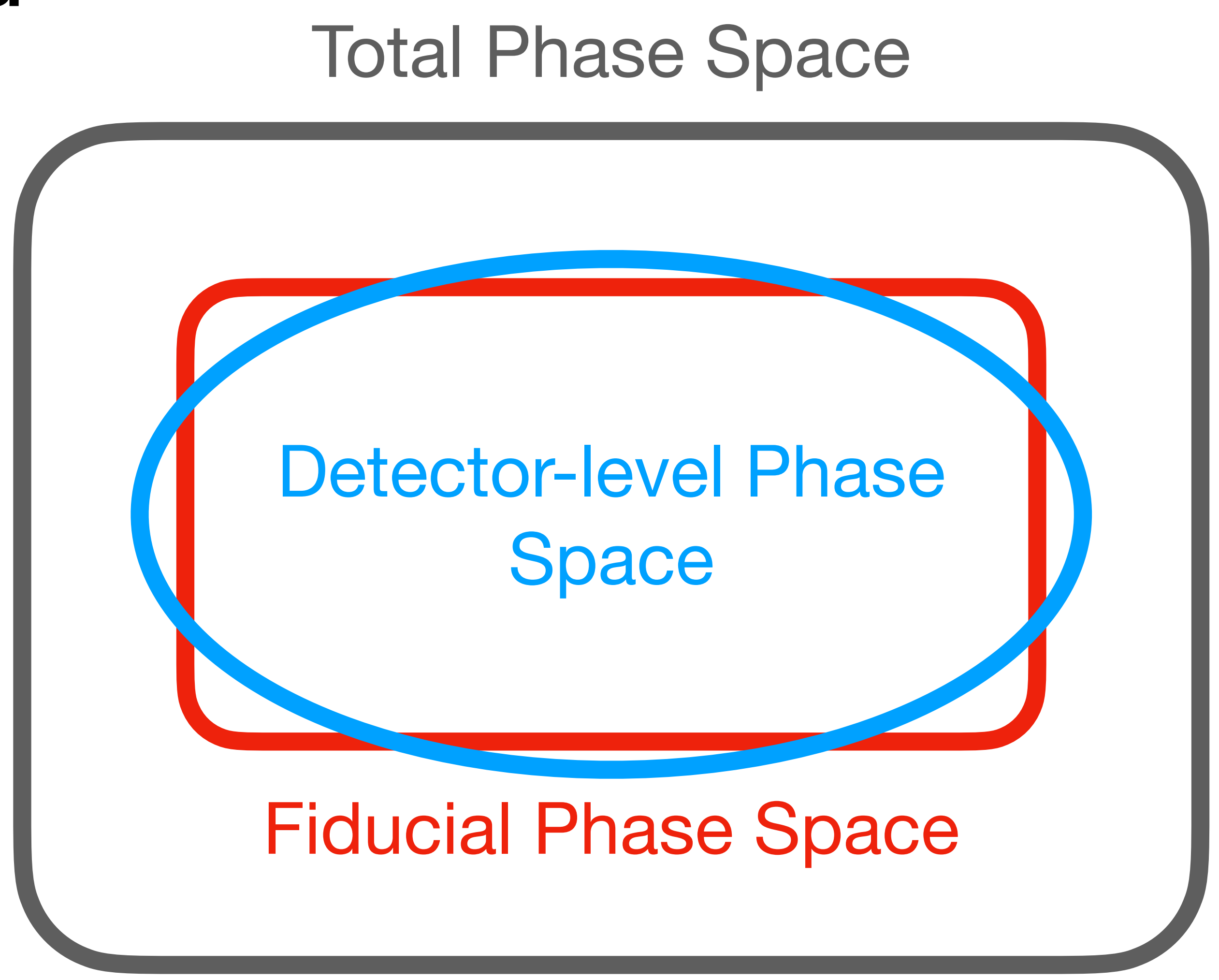
H→4l Total cross-section

- Total Higgs production cross-section in *pp* collisions extrapolated from fiducial cross-section measurement:

$$\sigma_{\text{fid}} = \sigma_{\text{tot}} \cdot A \cdot \mathcal{B} = \text{Parameter of Interest}$$

$$A = \text{Acceptance} = N_{\text{fid}}/N_{\text{tot}}$$

$$\mathcal{B} = \text{Branching ratio}$$



- Branching ratios assumed to take SM values
- Acceptance determined from simulation and then applied to fiducial cross-section determined from data
- **Total Higgs production cross-section determined for the H→4l channel:**

$$\boxed{\sigma_{(pp\to H)} = 46 \pm 12\ \text{pb}}$$

Total Cross-section Combination

- $H \to 4l$ total cross-section can be combined with the total cross-section extracted from the $H \to \gamma\gamma$ channel using similar methods:

$H \to 4l$:

$$\boxed{\sigma_{(pp \to H)} = 46 \pm 12 \text{ pb}}$$

$H \to \gamma\gamma$:

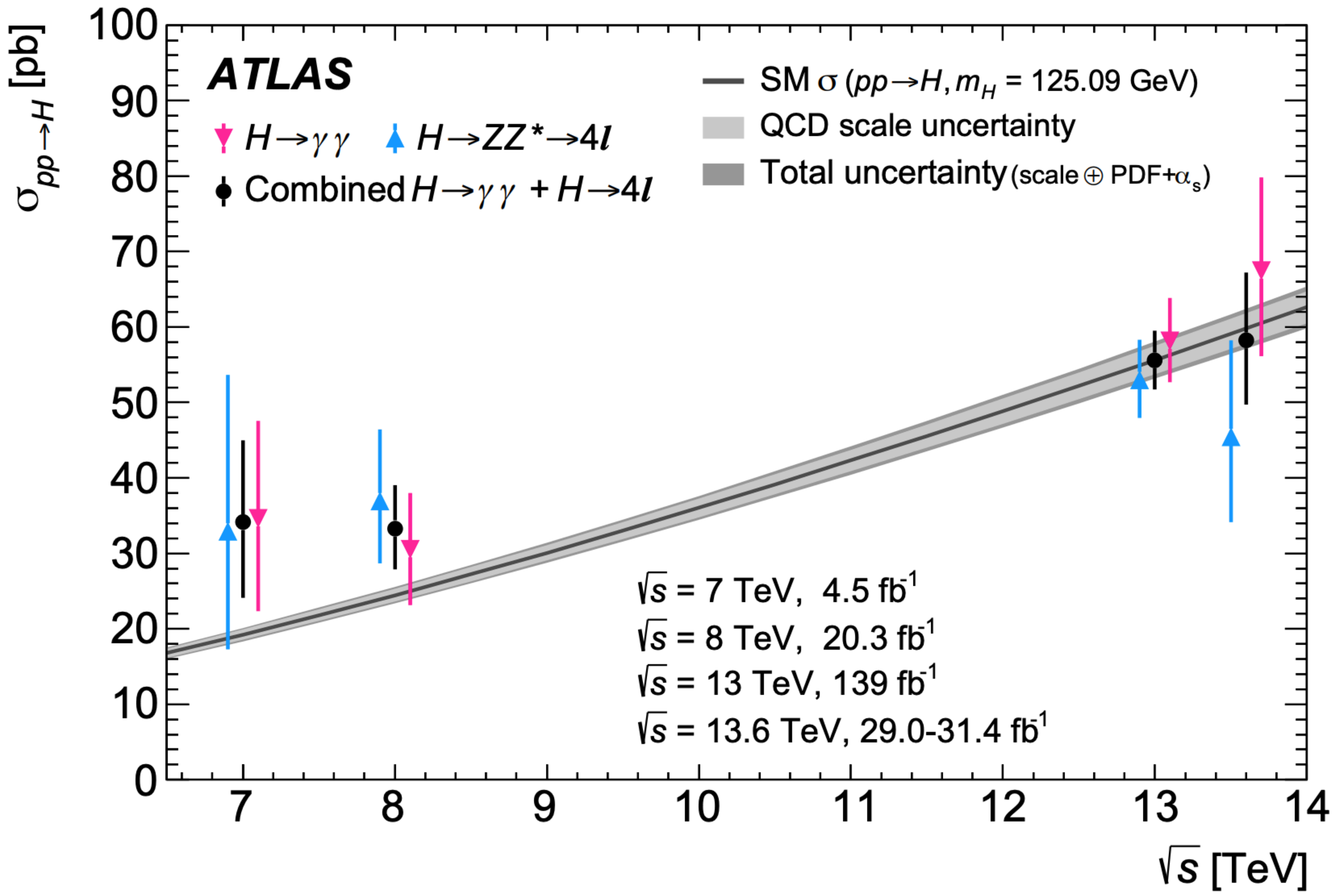
$$\boxed{\sigma_{(pp \to H)} = 67^{+12}_{-11} \text{ pb}}$$

- The two measurements are compatible with a **p-value of 20%**

- Combining the total cross-section measurements from the $H \to 4l$ and $H \to \gamma\gamma$ channels at $\sqrt{s}$ = 13.6 TeV:

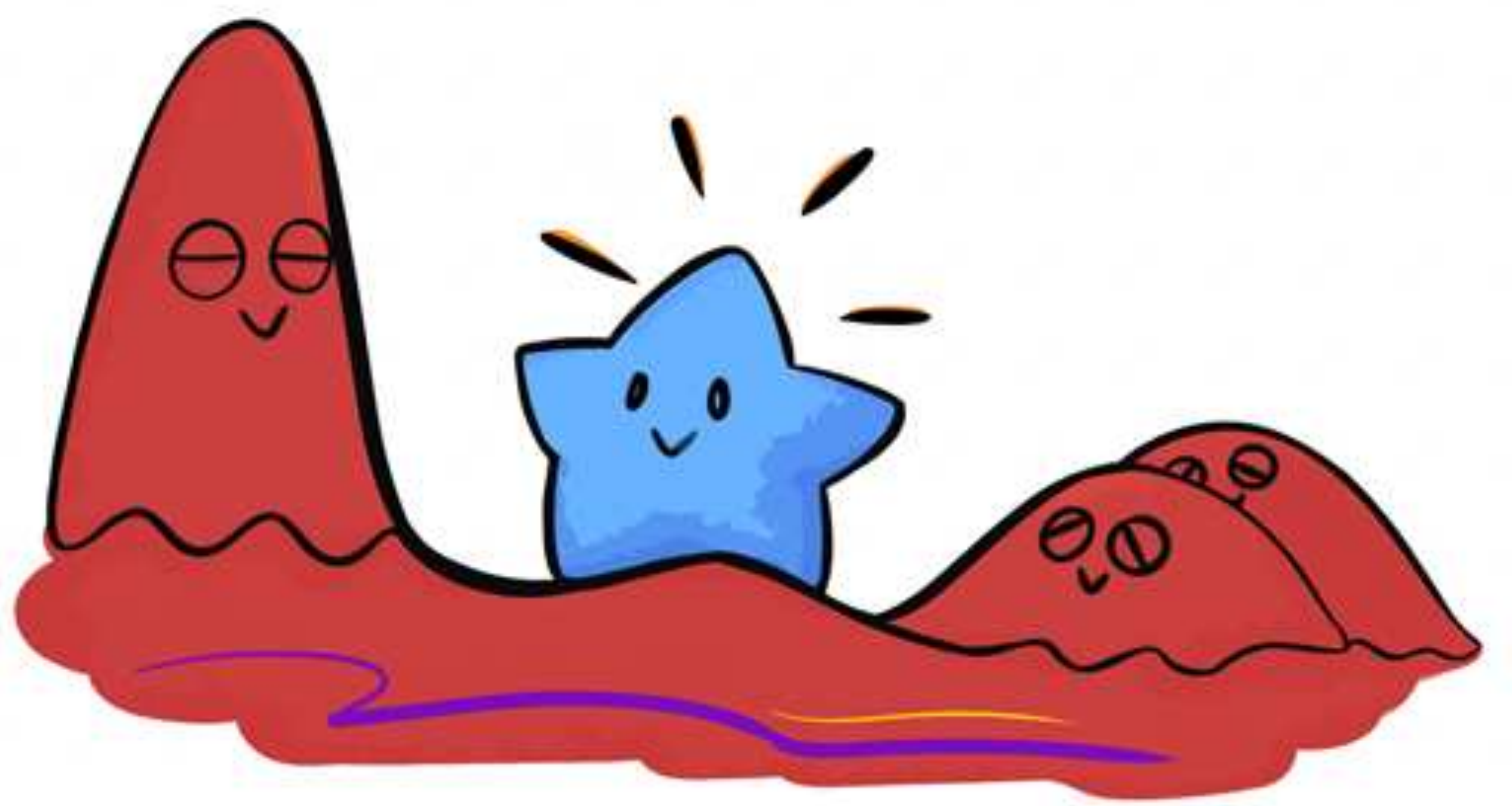
$$\boxed{\sigma_{(pp \to H)} = 58.2 \pm 7.5 \text{ (stat.)} \pm 4.5 \text{ (syst.) pb}}$$

$$(\sigma_{(pp \to H),SM} = 59.9 \pm 2.6 \text{ pb})$$



Conclusions

- 11 years after its discovery, the Higgs Boson is still relatively new and very exciting!
- Important to test if it has SM properties (or not) as precisely as possible
- Precisely measurements of the Higgs boson allows us to not only study the Higgs, but also all of the particles in the SM
- Higgs boson re-observed at $\sqrt{s}$ = 13.6 TeV and Higgs production cross-section measured in the $H \rightarrow ZZ^* \rightarrow 4l$ and $H \rightarrow \gamma\gamma$ channels at ATLAS (arXiv:2306.11379)



Thanks to Siyuan Yan (Glasgow) for the illustration!

- Continue to perform precision Higgs measurements throughout Run 3 to better understand the Higgs
- Interpret our results using effective field theories to look for BSM physics

Additional Content

Fiducial Cross-section Measurements

- **Fiducial cross-section**, σ^{fid}, for each final state, *i,* is extracted using a **binned fit of the m_{4l} distribution**, $P_i\,(m_{4l})$, according to the number of reconstructed events, N_i, in each bin, i, in the signal region:

1 bin [105,115] GeV + 15 bins in [115,130]GeV + 1 bin [130,135] GeV + 1 bin [135,160] GeV

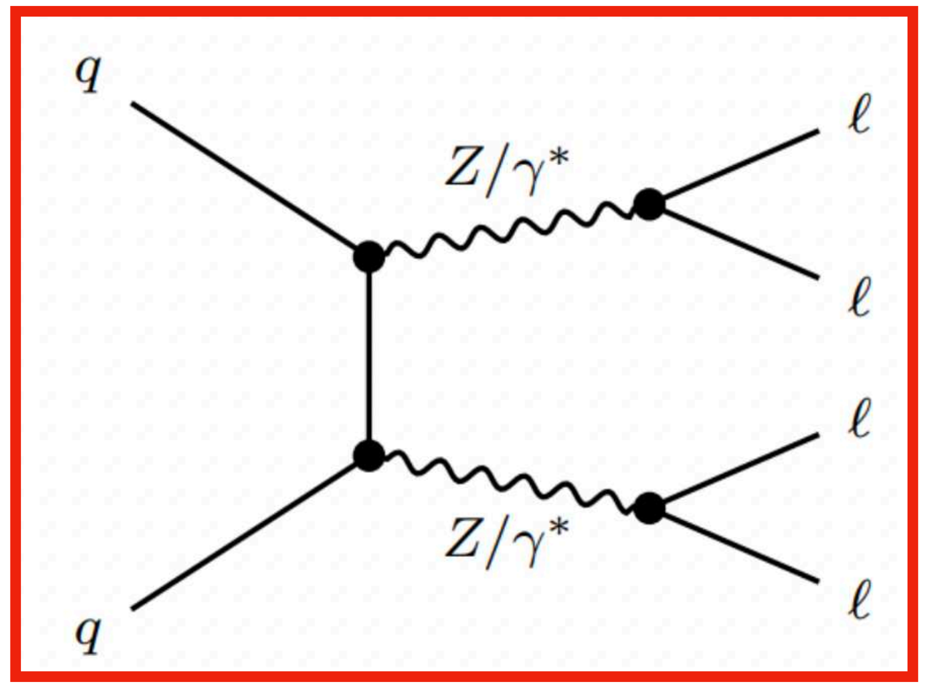
$$N_i\left(m_{4\ell}\right) = \sum_i \epsilon_i \cdot \left(1 + f_i^{\text{nonfid}}\right) \cdot \sigma_i^{\text{fid}} \cdot \mathcal{P}_i\left(m_{4\ell}\right) \cdot \mathcal{L} + N_i^{\text{bkg}}\left(m_{4\ell}\right)$$

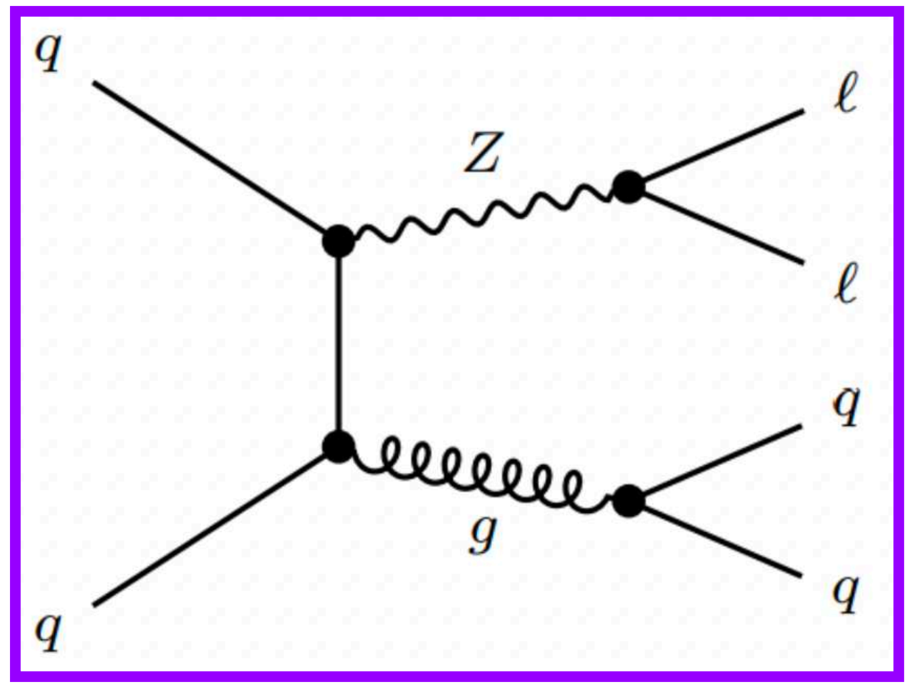
$$\sigma_i^{\text{fid}} = \sigma_i \cdot A_i \cdot \mathcal{B} = \text{Parameter of Interest}$$
$$\mathcal{P}_i\left(m_{4\ell}\right) = m_{4l}\ \text{signal shape}$$
$$N_i^{\text{bkg}}\left(m_{4\ell}\right) = \text{Background contribution}$$

Fiducial factors

$$A_i = \text{Acceptance} = N_{\text{fid}}/N_{\text{tot}}$$
$$\epsilon_i = \text{Reconstruction efficiency}$$
$$f_i^{\text{nonfid}} = \text{Fraction of events outside the fiducial region which are reconstructed in the signal region}$$

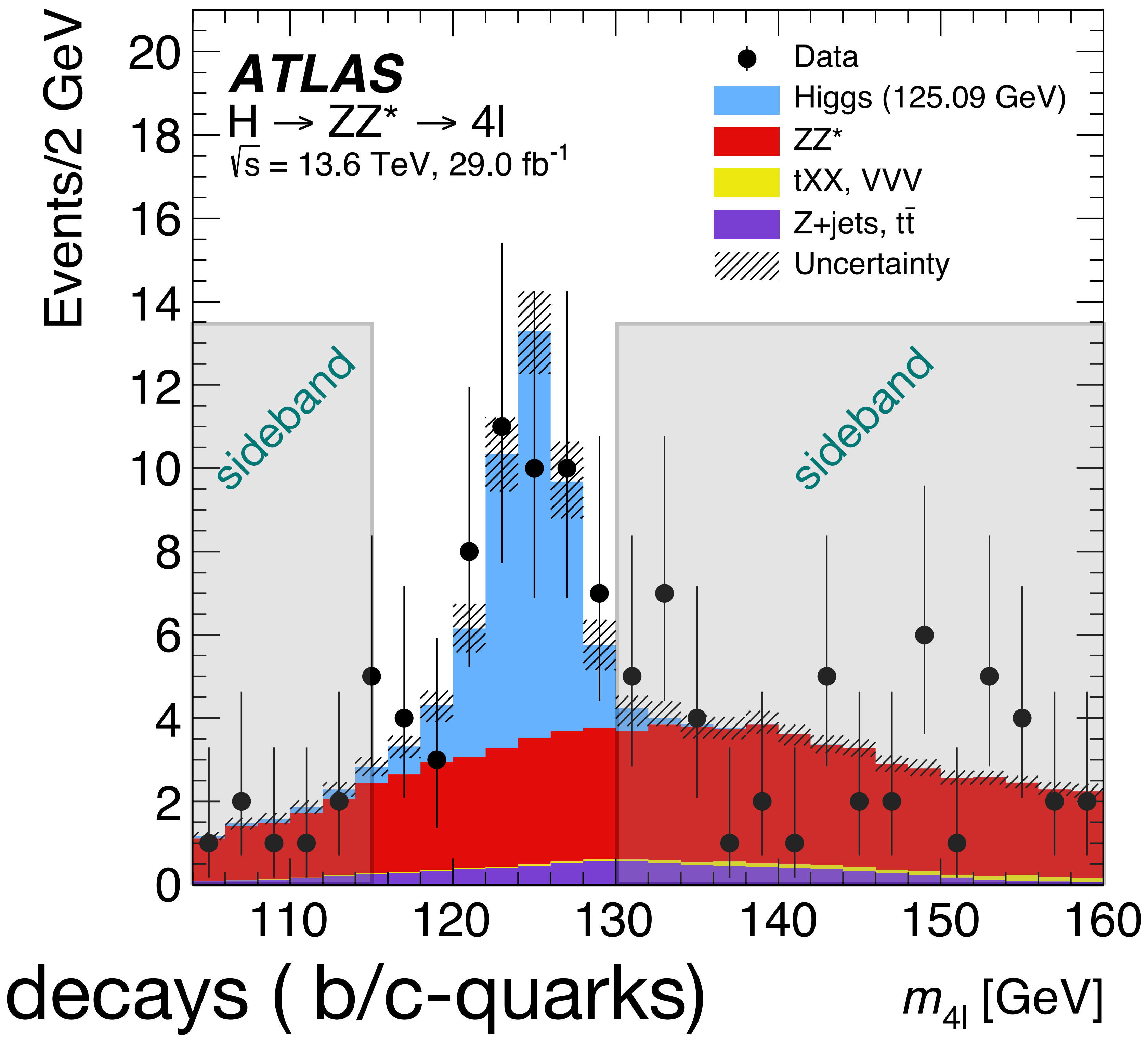
Background Estimation





Irreducible Background

- 4 prompt leptons in the final state - indistinguishable from signal
- Non-resonant ZZ* production
  - Estimated from data in two sideband regions: 105-115 and 130-160 GeV
- Triboson (ZZZ, WZZ, WWZ) & tt+ll contribution estimated from simulation (small)

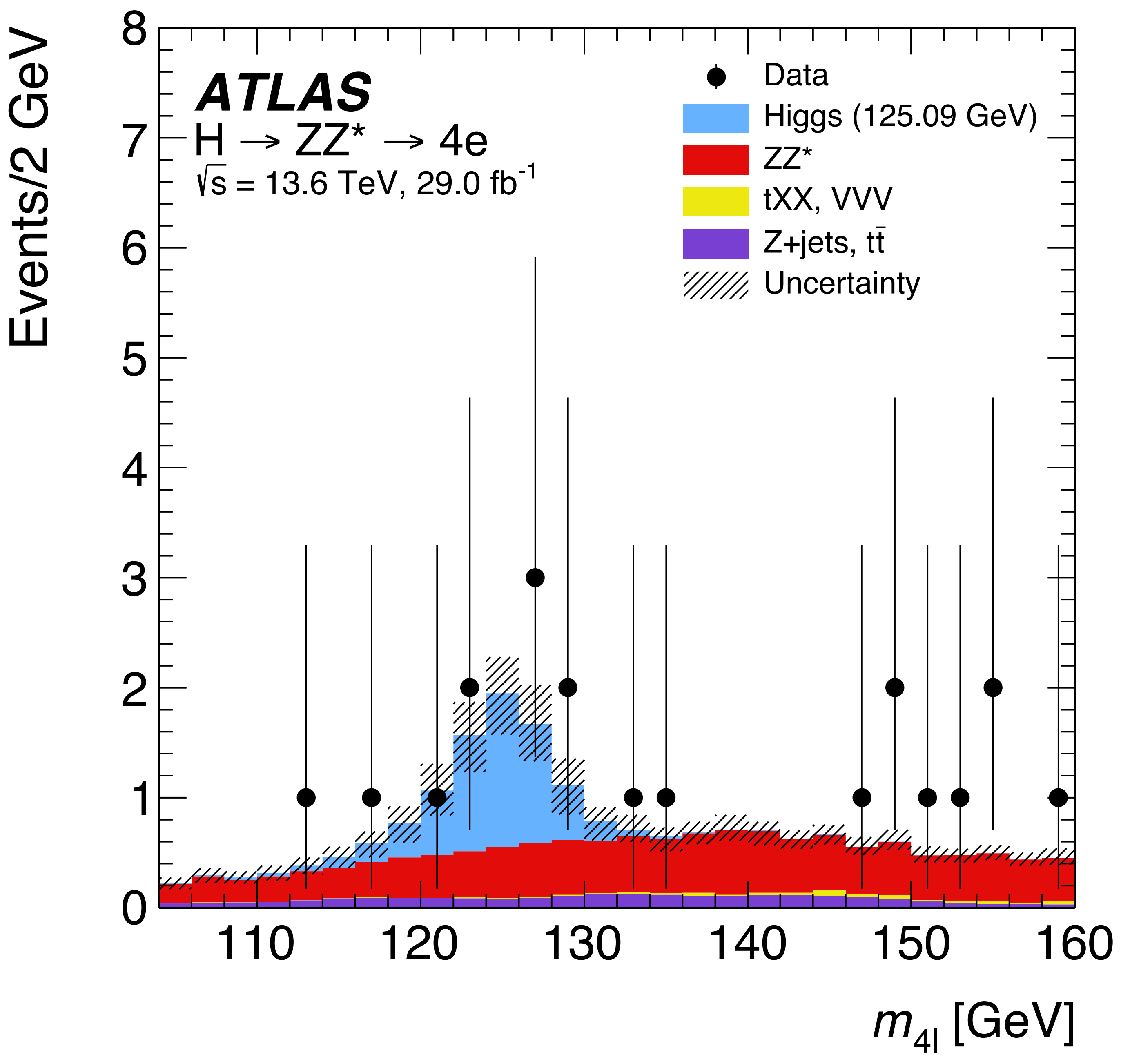


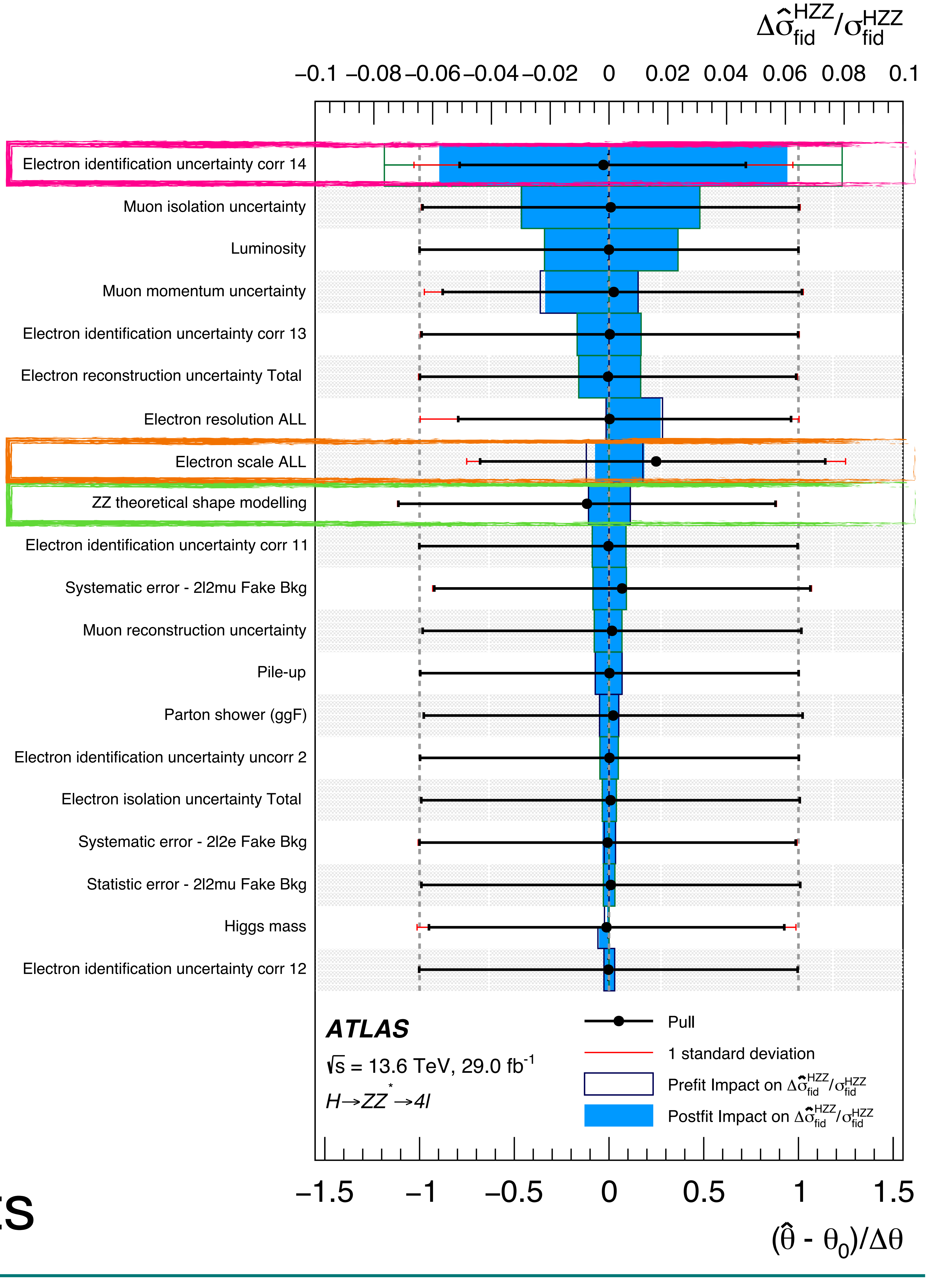
Reducible Background

- 2 real prompt leptons (Z or tt̄) and 2e or 2μ from semi-leptonic decays (b/c-quarks)
  - Different event topology allows events to be distinguished from signal
  - Data-driven estimation in control regions

Breakdown of Systematic Uncertainties

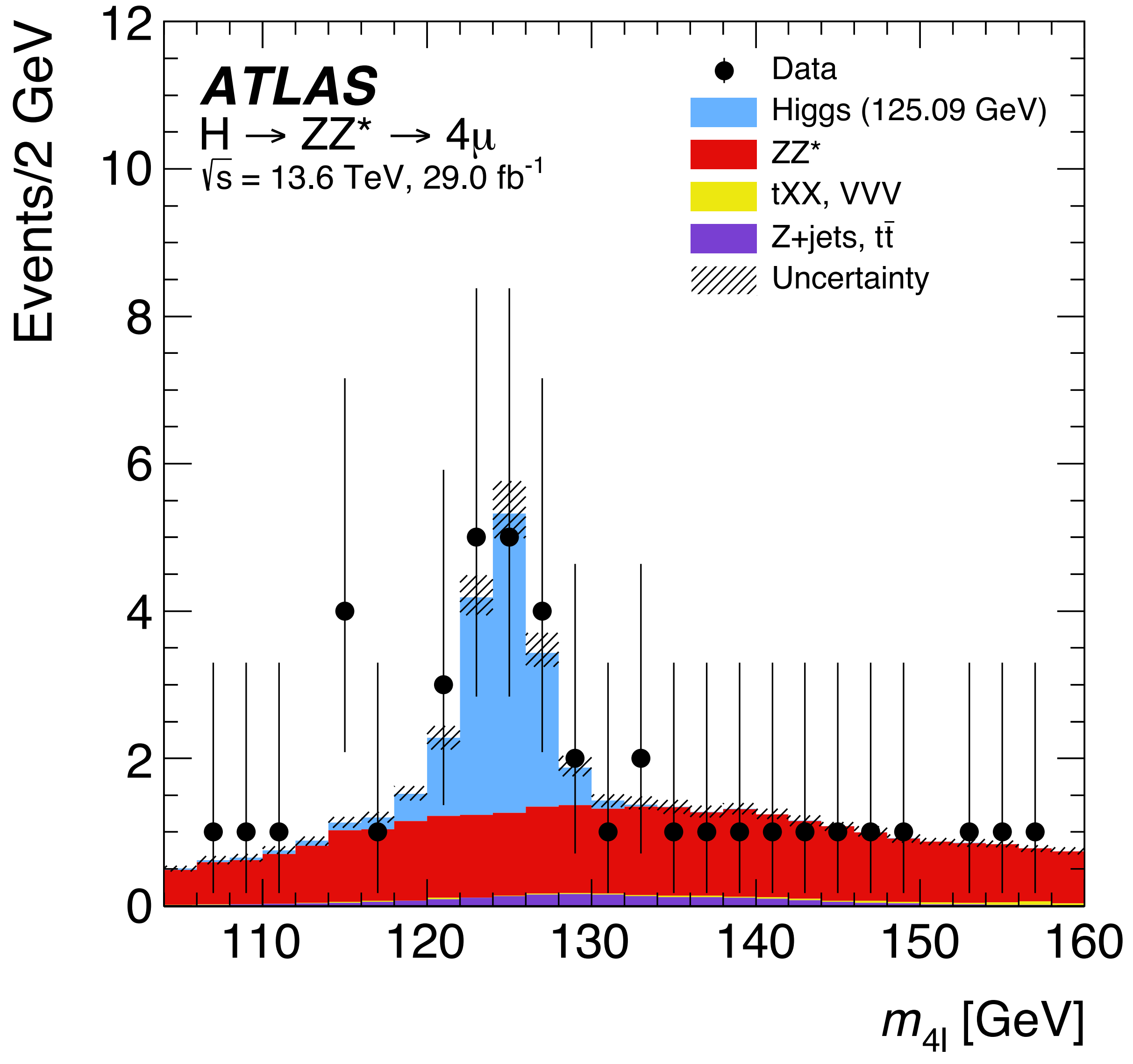
- Largest systematic uncertainty from electron identification efficiency of low p_T electrons
  - Conservative systematic unc. due to extrapolation of Run 2 identification/reconstruction calibrations to Run 3 data
- Slight pull of electron energy scale sys. due to the fluctuation of the m_{4e} dist. towards higher masses in data
- ZZ shape modelling theory unc. pulled due to the m_{4e} mass shift and a slight excess of events observed in upper m_{4l} sideband region

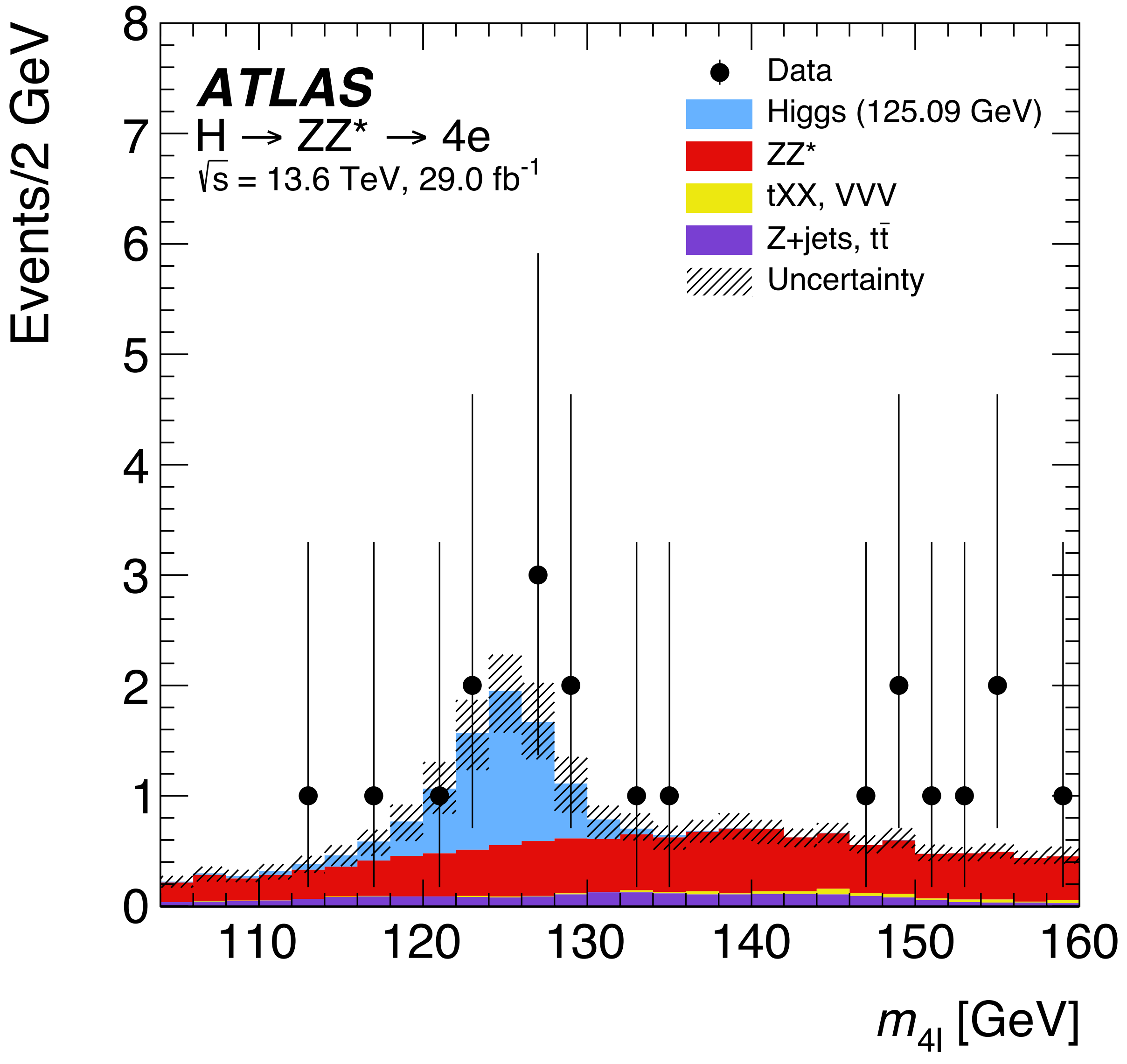


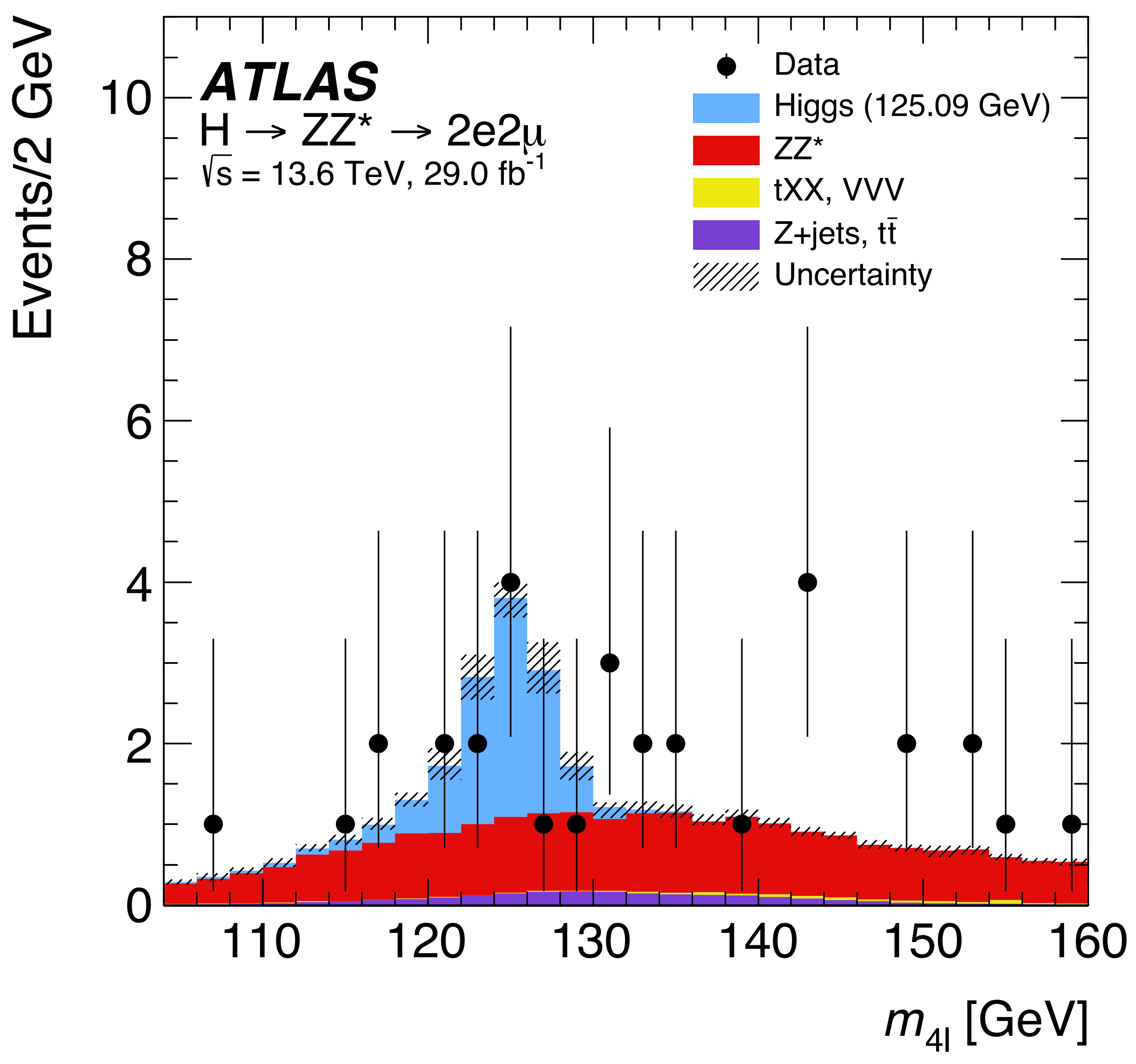


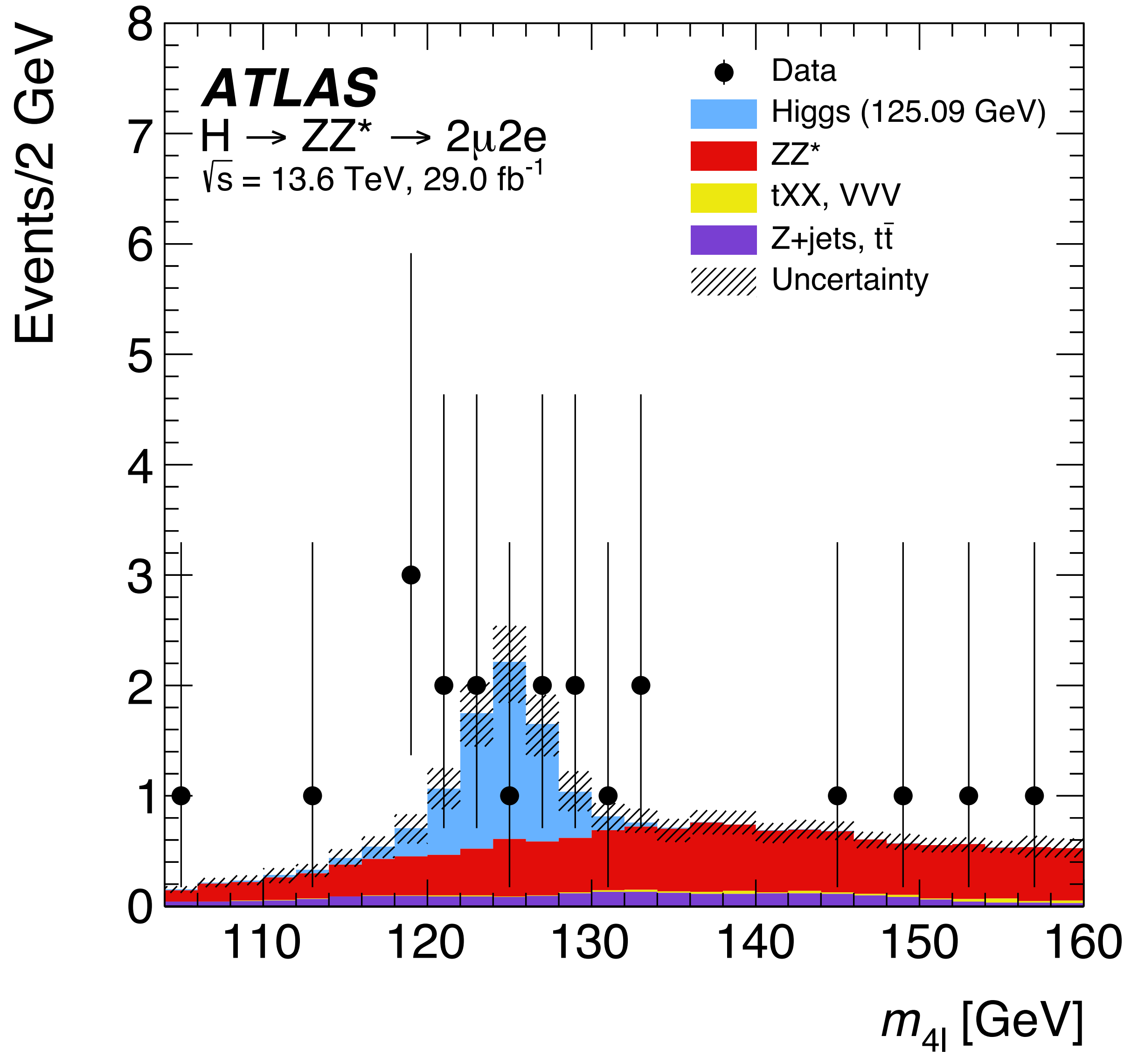
- However, these pulls do not significantly impact the final results

M4l Distributions Per-channel









Object/Event Selection and Triggers

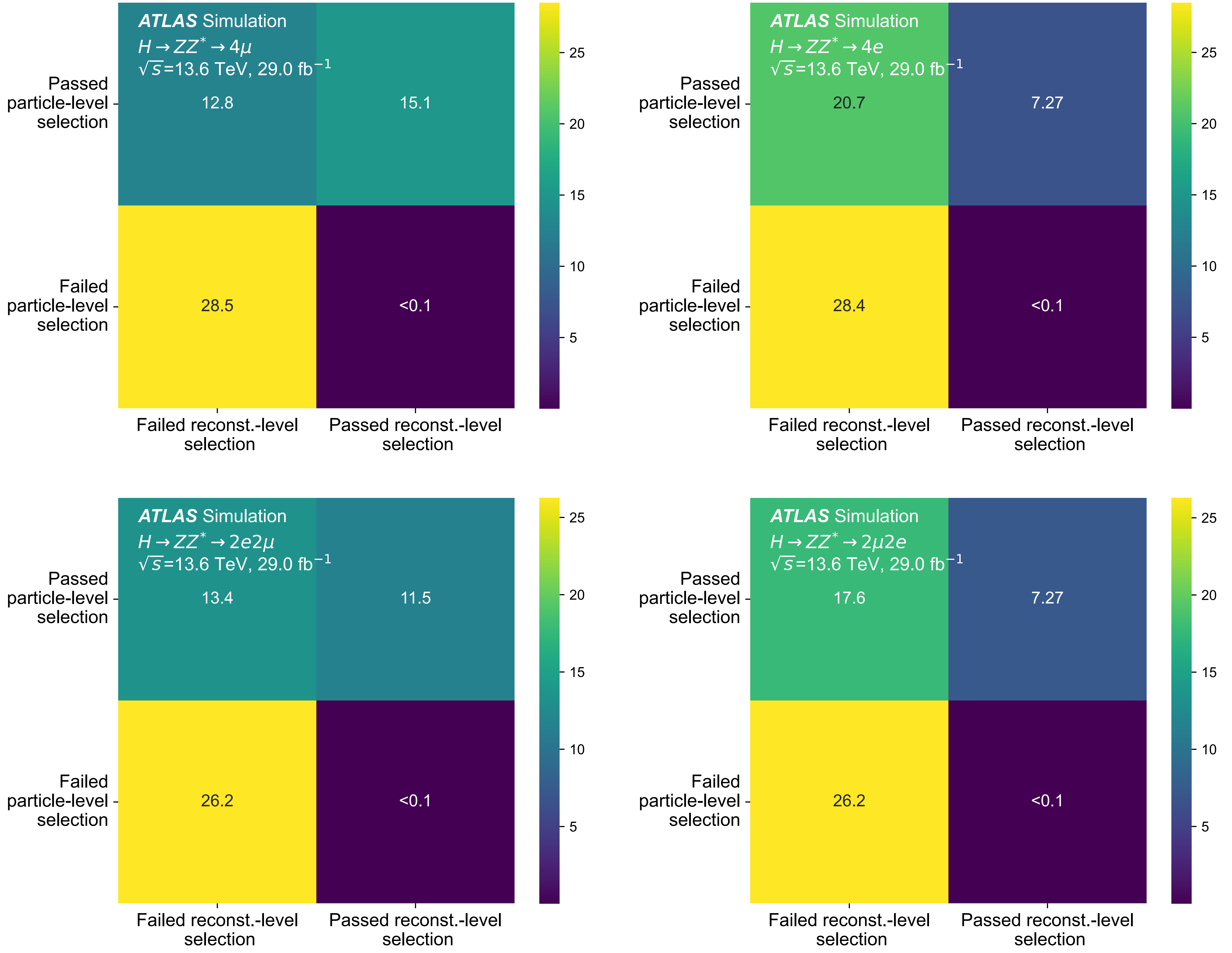
Leptons	
Muons	$p_T > 5$ GeV, $|\eta| < 2.5$
Electrons	$E_T > 7$ GeV, $|\eta| < 2.47$
Lepton selection and pairing	
Lepton kinematics	$p_T > 20, 15, 10$ GeV
Leading pair (m_{12})	SFOC lepton pair with smallest $|m_Z - m_{\ell\ell}|$
Subleading pair (m_{34})	remaining SFOC lepton pair with smallest $|m_Z - m_{\ell\ell}|$
Event selection (at most one Higgs boson candidate per channel)	
Mass requirements	50 GeV$< m_{12} <$ 106 GeV and $m_{\text{threshold}} < m_{34} <$ 115 GeV
Lepton separation	$\Delta R(\ell_i, \ell_j) > 0.1$
J/ψ veto	$m(\ell_i, \ell_j) > 5$ GeV for all SFOC lepton pairs
Impact parameter	$|d_0|/\sigma(d_0)$ <5 (3) for electrons (muons)
Mass window	105 GeV $< m_{4\ell} <$ 160 GeV
Vertex selection	$\chi^2/N_{\text{dof}} <$ 6 (9) for 4μ (other channels)
If extra lepton with $p_T > 12$ GeV	quadruplet with largest ME value

- Triggers: lowest unprescaled lepton and multi-lepton triggers available during 2022 data taking

Events in Fiducial Phase Space

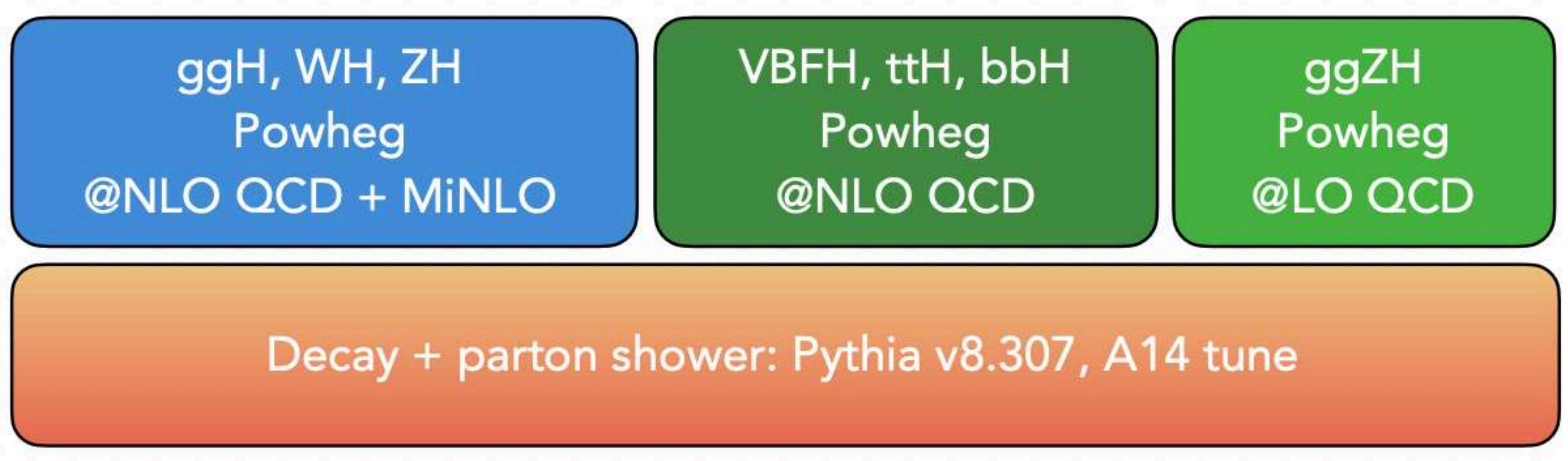
- Number of Monte Carlo signal events (normalised to the SM prediction) selected or rejected by the selections applies at:
    - reconstruction level (x-axis)
    - particle (fiducial) level (y-axis)

- Shown for each four-lepton final state



Signal and Background MC Samples

- Signal: default PDF set → PDF4LHC21



- Backgrounds:
  - qqZZ, WZ, tt+ll, VVV: Sherpa 2.2.12 MEPS@NLO
  - ttbar, ggZZ: Powheg @NLO QCD + Pythia 8

- ggZZ background sample unavailable at the time of the analysis
- qq & ggZZ summed together in fit: currently rescaling qqZZ to emulate inclusion of ggZZ
  - re-weight factor derived from run 2 samples → qqZZ scaled by $1 + \dfrac{N(ggZZ, 13\,\mathrm{TeV})}{N(qqZZ, 13\,\mathrm{TeV})}$
- Impact on fiducial cross-section of including ggZZ: < 0.3%

Systematics Ranking

- Conservative electron ID unc. 14 related to differences observed in mc20 and mc21
- Slight pull observed for electron scale due to shift of 4e dist to higher masses in data
- ZZ th. Shape modelling sys pull due to 4e shape and more data in upper m_{4l} sideband region