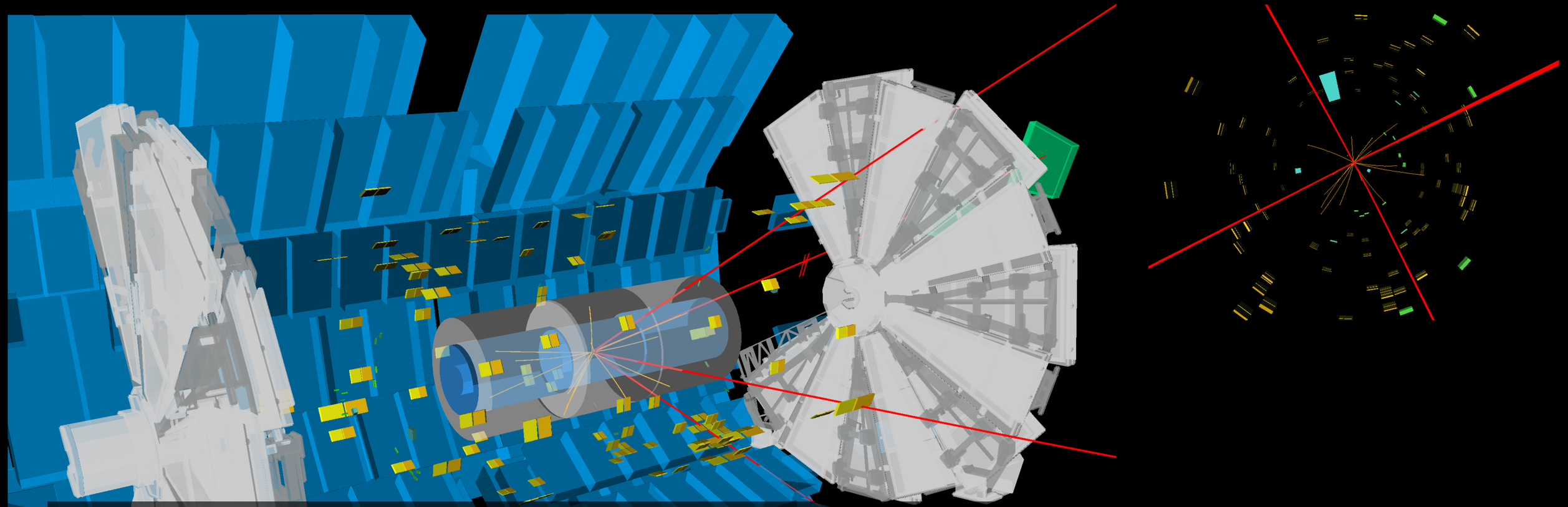


First Measurement of the Higgs Boson Production Cross-Section at $\sqrt{s}$=13.6 TeV in the $H \rightarrow ZZ^* \rightarrow 4l$ channel with the ATLAS Detector

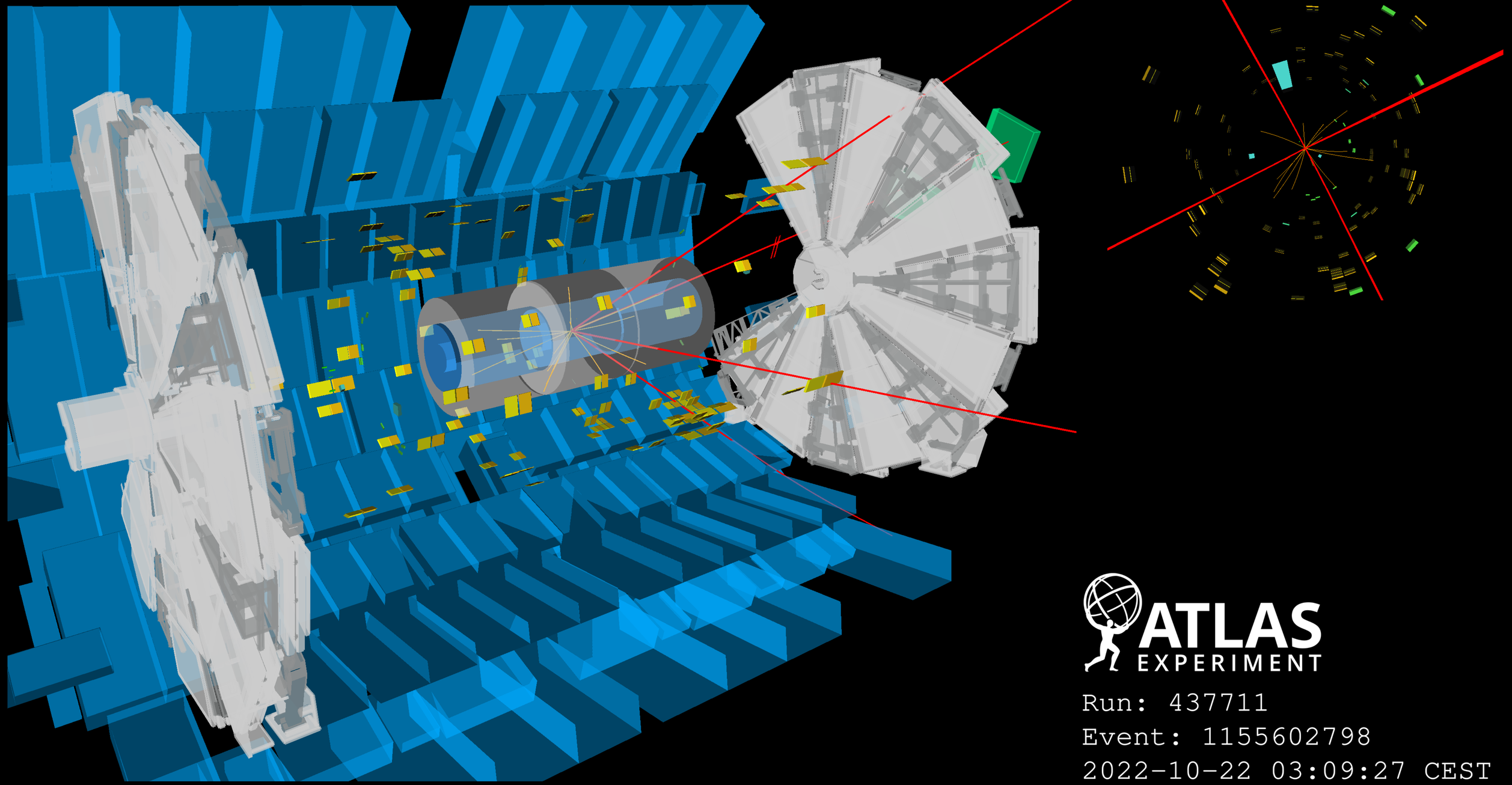
Alice Reed

On behalf of the ATLAS Collaboration

Higgs Hunting - 11 September 2023

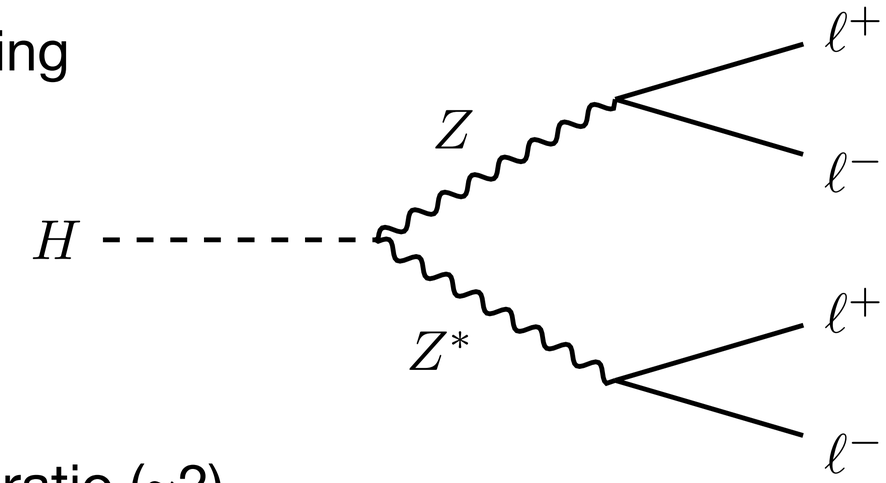
ATLAS EXPERIMENT

MAX-PLANCK-INSTITUT FÜR PHYSIK


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

Higgs Boson and the H→ZZ*→4l Channel

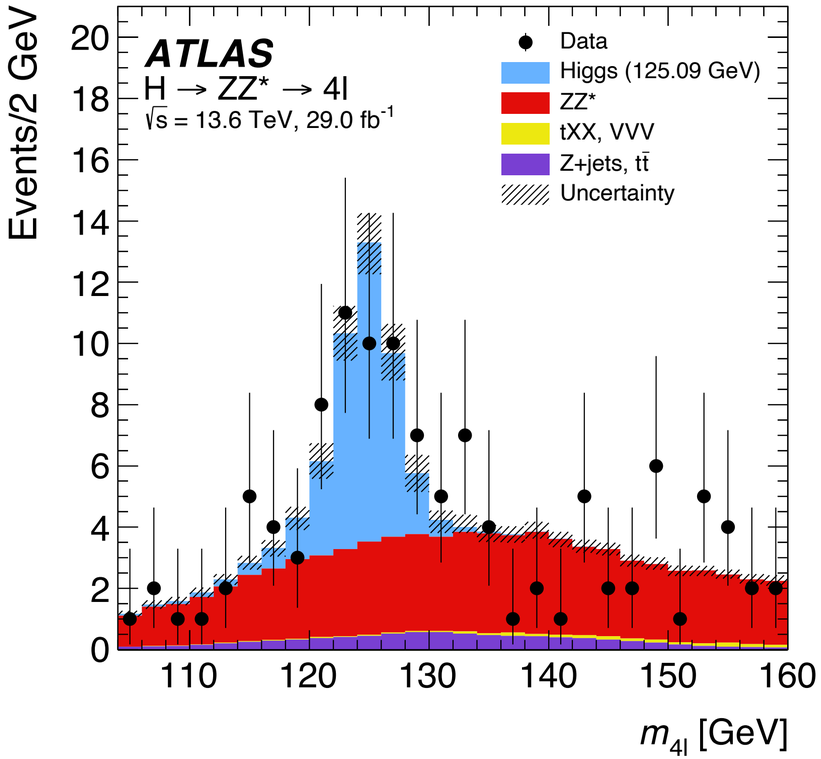
- The Higgs boson couples to all known fundamental particles, including itself
- Precision measurements of Higgs properties are a **crucial test of the SM**
- H→ZZ*→4l channel characterised by a final state containing two pairs of oppositely charged leptons from the same primary vertex
- Four possible **final states: 4μ, 4e, 2e2μ, 2μ2e**



- Excellent mass resolution and high signal-to-background ratio (~2)
- Despite a small branching ratio, this **clear signature** allows the channel to be studied with small datasets

Fiducial Cross-section with Run 3 Data

- 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 an upgraded detector
- Analysis strategy closely follows the full Run 2 inclusive and differential cross-section measurement: EPJC 80 (2020) 942
- **Fiducial cross-section extracted by fitting the invariant mass (m_{4l})** spectrum in the mass window 105-160 GeV

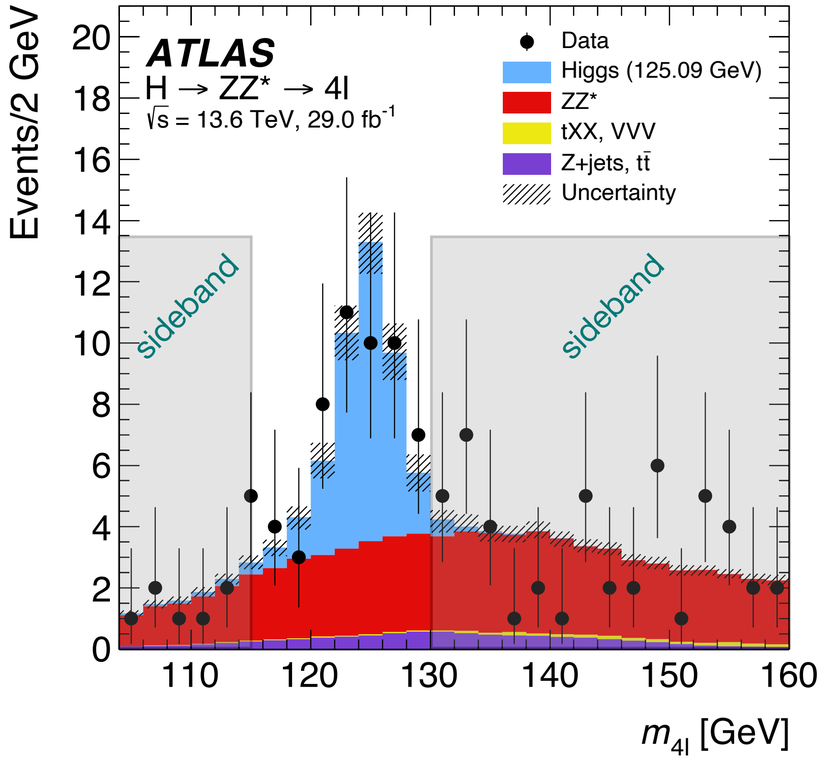


→ **Paper submitted to EPJC!**

Background Estimation

Irreducible Background

- 4 prompt leptons in the final state
- Non-resonant ZZ* production
  - Floating normalisation factor extracted from the m_{4l} **sideband regions** during the m_{4l} fit
- Triboson (ZZZ, WZZ, WWZ) & tt+ll contribution estimated from simulation (small)



Reducible Background

- 2 real prompt leptons (Z or $t\bar{t}$) and 2e or 2μ from semi-leptonic decays (b/c-quarks)
  - Control Regions (CRs) defined by inverting/relaxing event selection criteria
  - Data-driven estimation in CRs extrapolated to the Signal Region

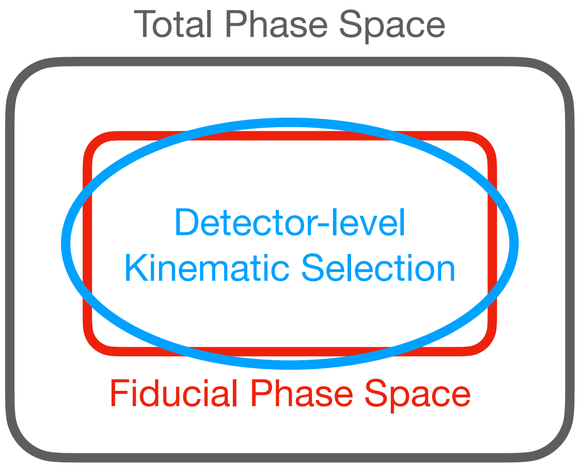
Fiducial Cross-section Measurements

- Aim: **Minimise model-dependent** acceptance extrapolations on the cross-section measurement
- Define a fiducial phase space, which closely matches the detector-level kinematic selection

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

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

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



- Includes corrections for detector-level efficiency and resolution effects
- Fiducial cross-section, σ_{fid}, is extracted using a **binned fit of the m_{4l} distribution** inclusively for all four-lepton final states

H→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
$2\mu2e$	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:

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

- 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

Total Cross-section Combination

- H→4l and H→γγ fiducial cross-sections extrapolated to the total Higgs boson production cross-section in *pp* collisions assuming SM values for the fiducial acceptance and branching ratio:

H→4l:

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

H→γγ:

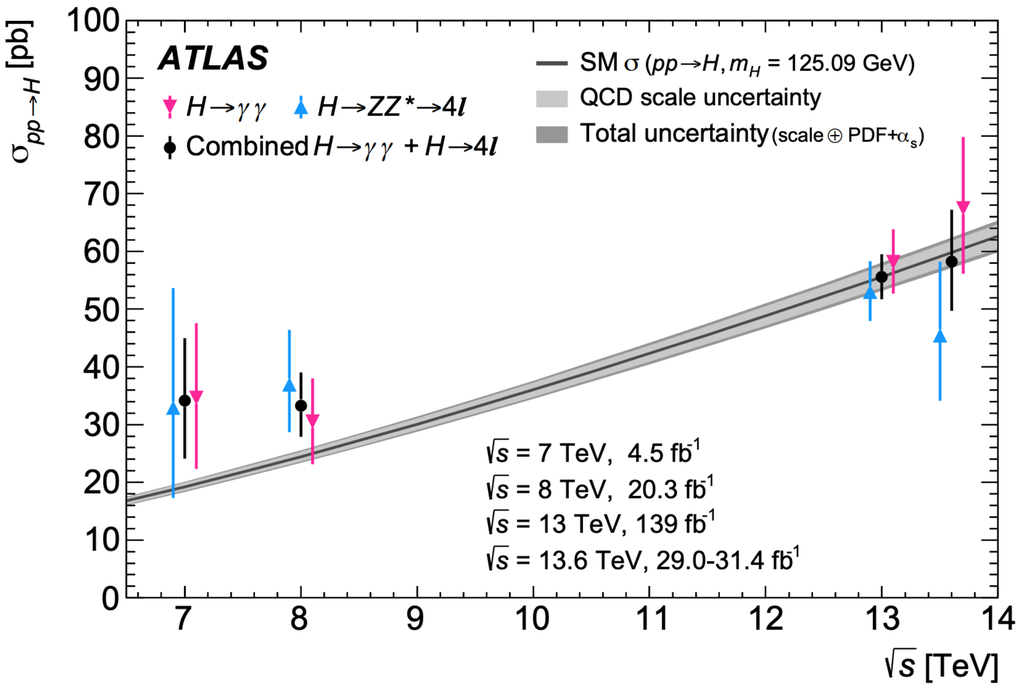
$\sigma_{(pp\to H)} = 67\ ^{+12}_{-11}$ pb

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

- Combining the total cross-section measurements from the H→4l and H→γγ channels at √s = 13.6 TeV:

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

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

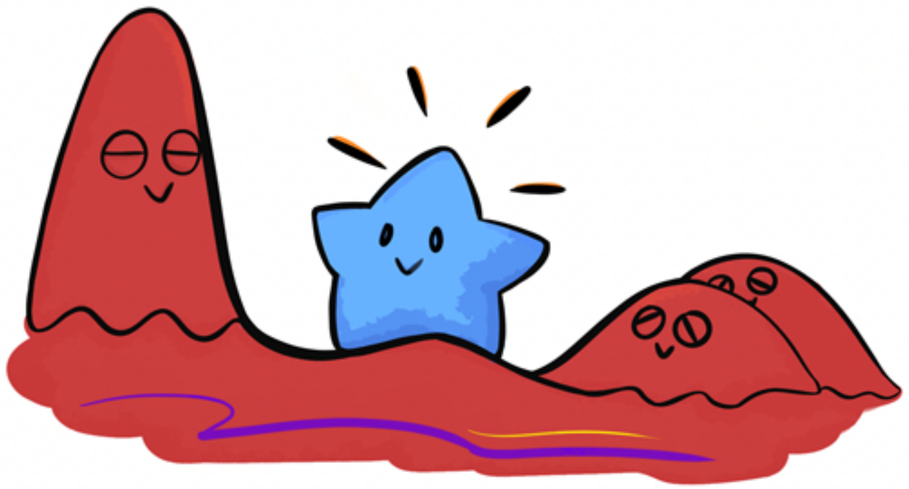


Conclusions

- First measurement of the Higgs boson cross-section at $\sqrt{s}$ = 13.6 TeV has been performed in the $H \to ZZ^* \to 4l$ and $H \to \gamma\gamma$ channels at ATLAS (submitted to EPJC)

$$\sigma_{(pp \to H)} = 58.2 \pm 8.7 \text{ pb} \qquad (\sigma_{(pp \to H),SM} = 59.9 \pm 2.6 \text{ pb})$$

- Early Run 3 data from 2022 is statistically limited
  → more statistics will of course improve sensitivity



Thanks to Siyuan Yan for the illustration!

- Systematic uncertainties will become relevant with more data
  - This calls for improvements in electron and muon calibrations using dedicated Run 3 campaigns
    → coming soon!

Backup

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

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

$\sigma_i^{\text{fid}} = \sigma_i \cdot A_i \cdot \mathcal{B}$ = Parameter of Interest

$\mathcal{P}_i\left(m_{4\ell}\right) = m_{4l}$ signal shape

$N_i^{\text{bkg}}\left(m_{4\ell}\right)$ = Background contribution

Fiducial factors

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

ϵ_i = Reconstruction efficiency

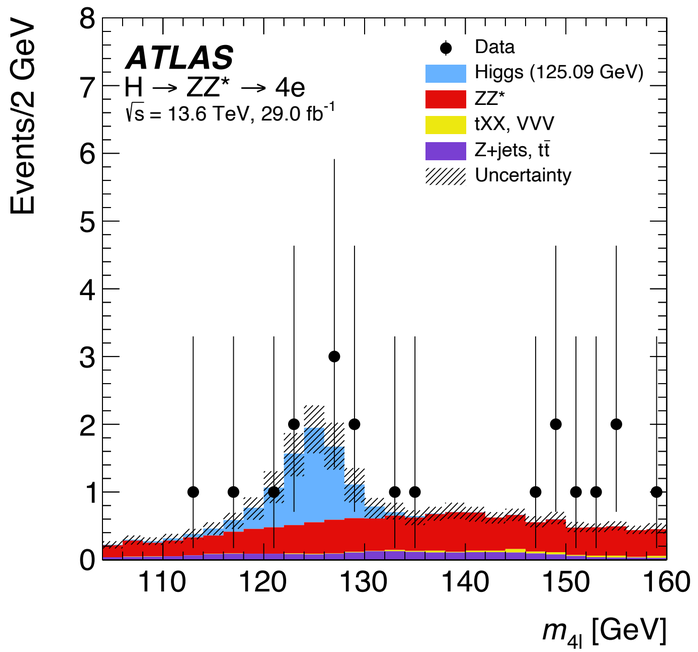
f_i^{nonfid} = Fraction of events outside the fiducial region which are reconstructed in the signal region

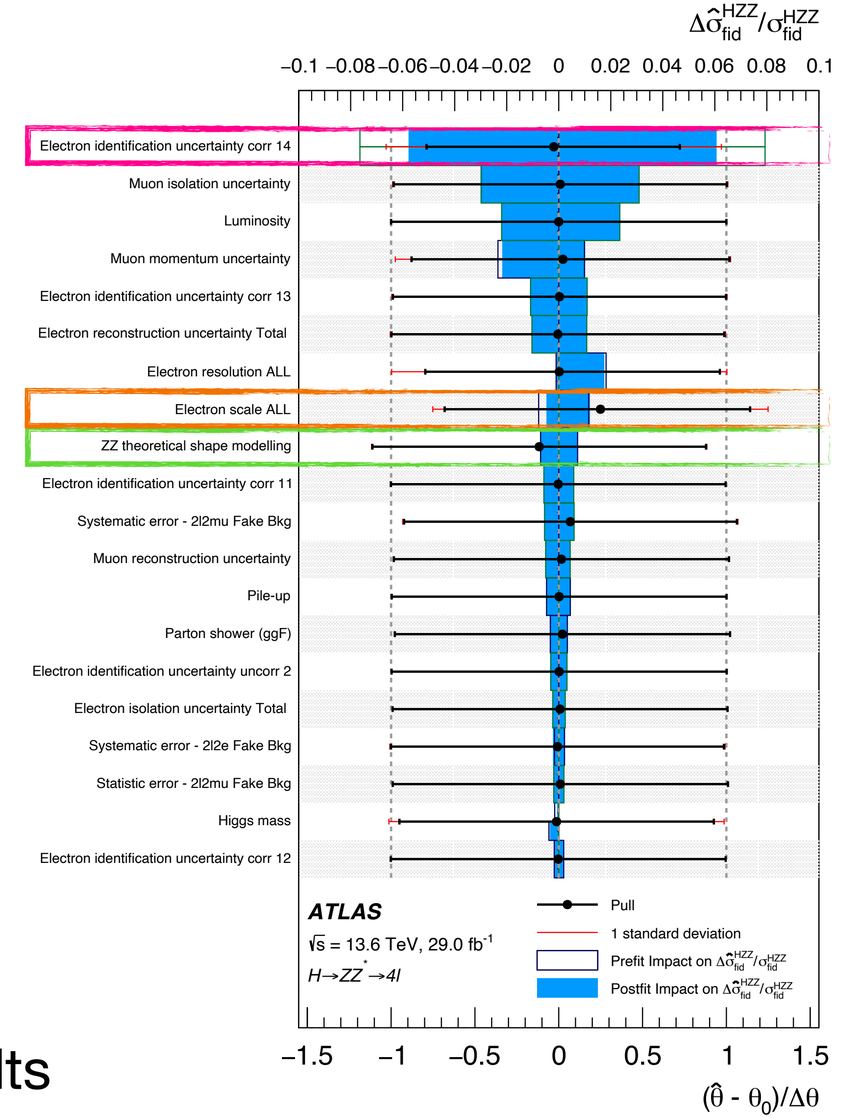
Breakdown of Systematic Uncertainties

- 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

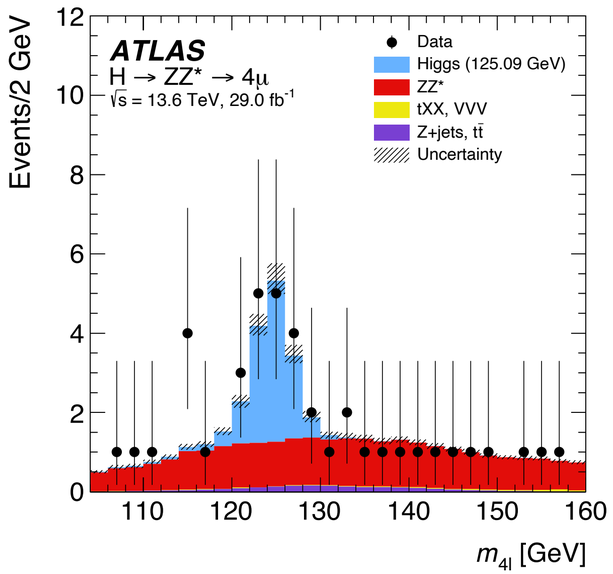
- ZZ shape modelling theory unc. pulled due to the m_{4e} mass shift and a slight excess of events observed in upper m_{4l} sideband region

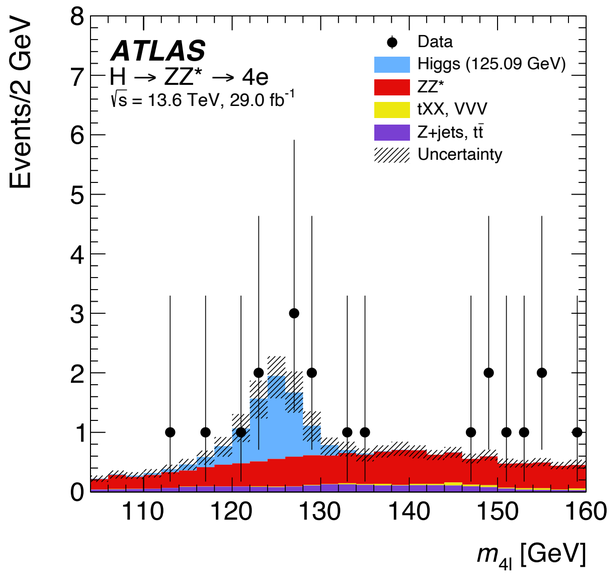


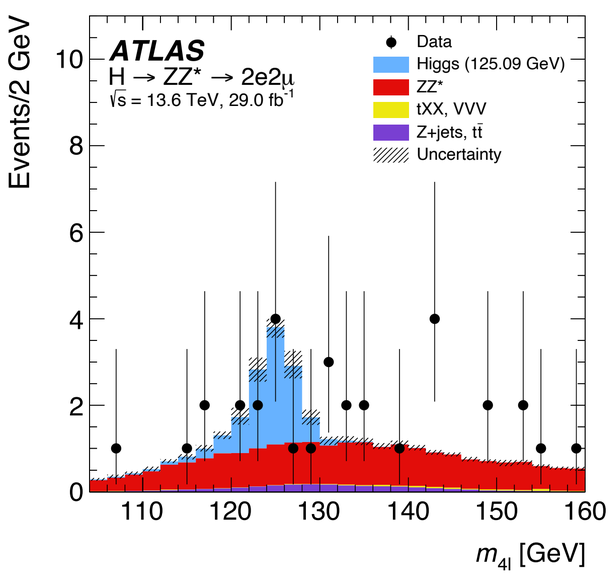


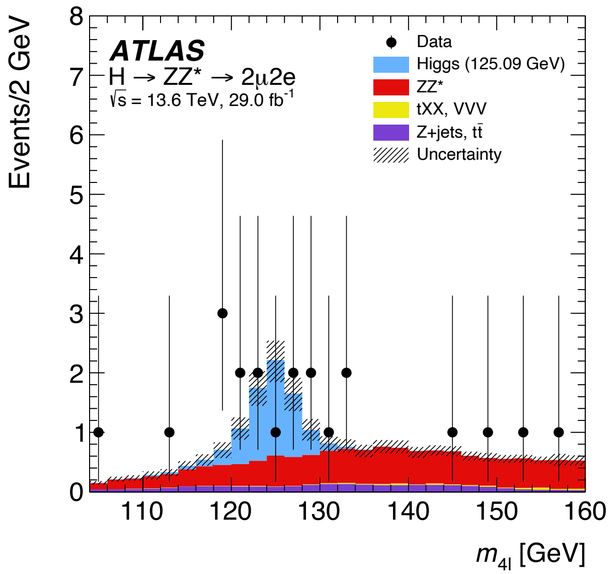
- However, these pulls do not significantly impact the final results

M4l Distributions Per-channel



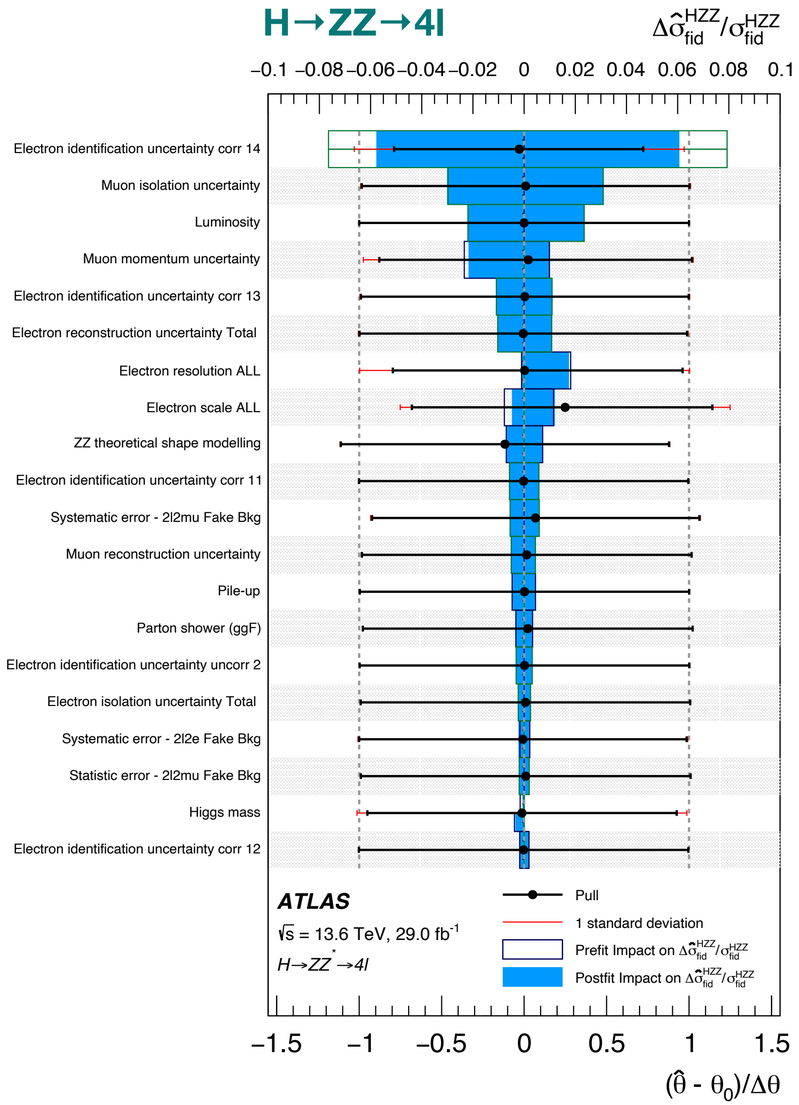


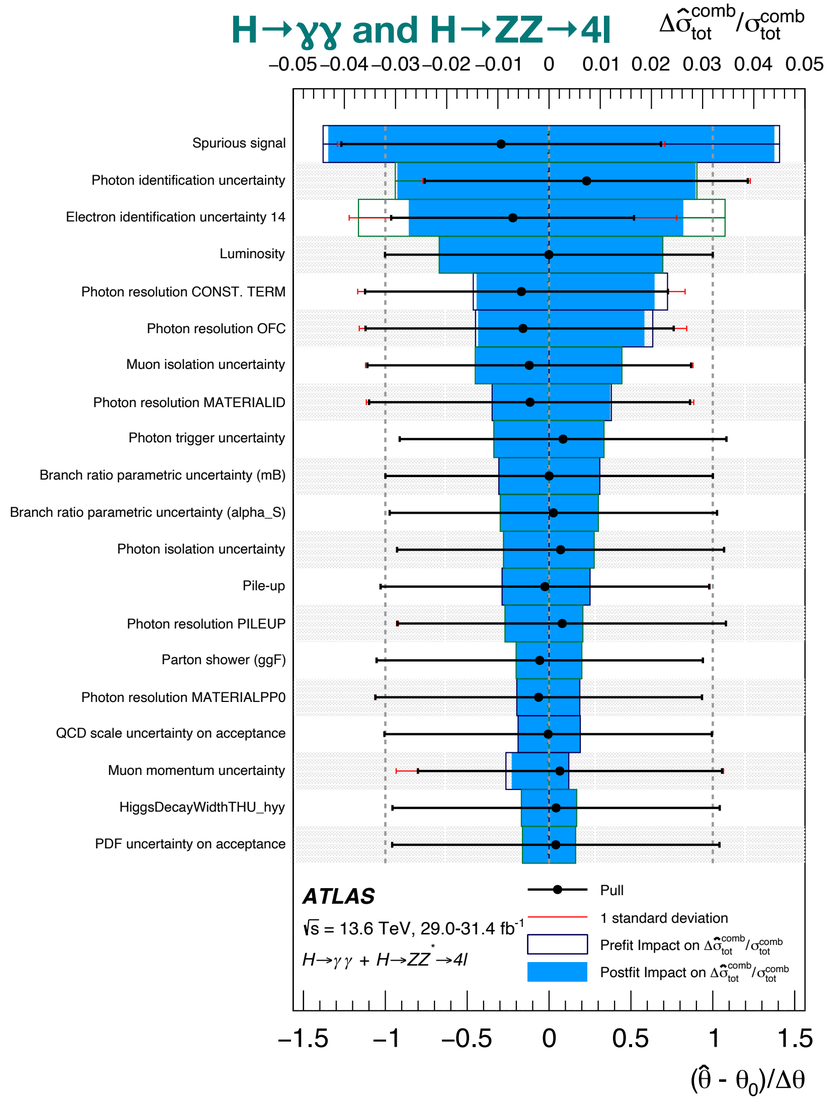




Systematics Ranking

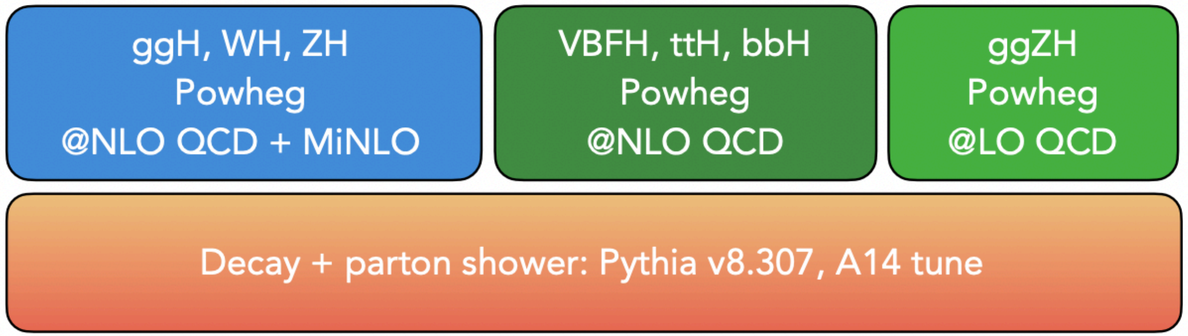
- Conservative electron ID unc. 14 related to differences observed in mc20 and mc21
- Slight pull observed for electron scale due to shift of 4e dist to higher masses in data
- ZZ th. Shape modelling sys pull due to 4e shape and more data in upper m_{4l} sideband region





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 $1 + \frac{N(ggZZ, 13\,\text{TeV})}{N(qqZZ, 13\,\text{TeV})}$
- Impact on fiducial cross-section of including ggZZ: < 0.3%

Object Definitions

- Follows full Run 2 HZZ differential cross-section measurement - EPJC 80 (2020) 942
- Working points updated to latest run 3 recommendations available
  - Electrons: $E_T > 7$ GeV, $|\eta| < 2.47$, ID: Loose+B-layer, ISO: Loose VarRad
  - Muons: $p_T > 5$ GeV, $|\eta| < 2.5$, ID: Loose, ISO: PFlowLoose VarRad
  - TTVA cuts: $|d0| < 1$mm, $d0/\sigma(d0) < 5$ (3) for electrons (muons), $|z0 \sin\theta| < 0.5$ mm
  - FSR recovery: - consider photons within $|\eta|$
    - collinear FSR (μ only): $p_T > 1$ GeV, $\Delta R(l,\gamma) < 0.15$
    - non-collinear FSR: tight photons, $p_T > 10$ GeV

Event Selection and Triggers

- Follows full Run 2 HZZ differential cross-section measurement - EPJC 80 (2020) 942

- Lepton p_T thresholds: 20, 15, 10 GeV
- 2 Z-bosons (m_{12}, m_{34}) with m_{ll} in [12-120] GeV
- If extra leptons found, ME-based selection of best pairs
- Very loose 4-lepton vertex compatibility cut:
  - 4mu: $\chi^2 < 6$, other channels: $\chi^2 < 9$
- m_{12} in [50, 106] GeV
- m_{34} dynamic cut: $m_{THR} < m_{34} < 115$GeV
  - $m_{THR} = 12$ GeV at $m_{4l} < 140$ GeV, rising linearly to 50 GeV @ $m_{4l} = 190$GeV
- $m_{(l+l-)} > 5$GeV
- $\Delta R(ll) > 0.1$ for all lepton pairs

- 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