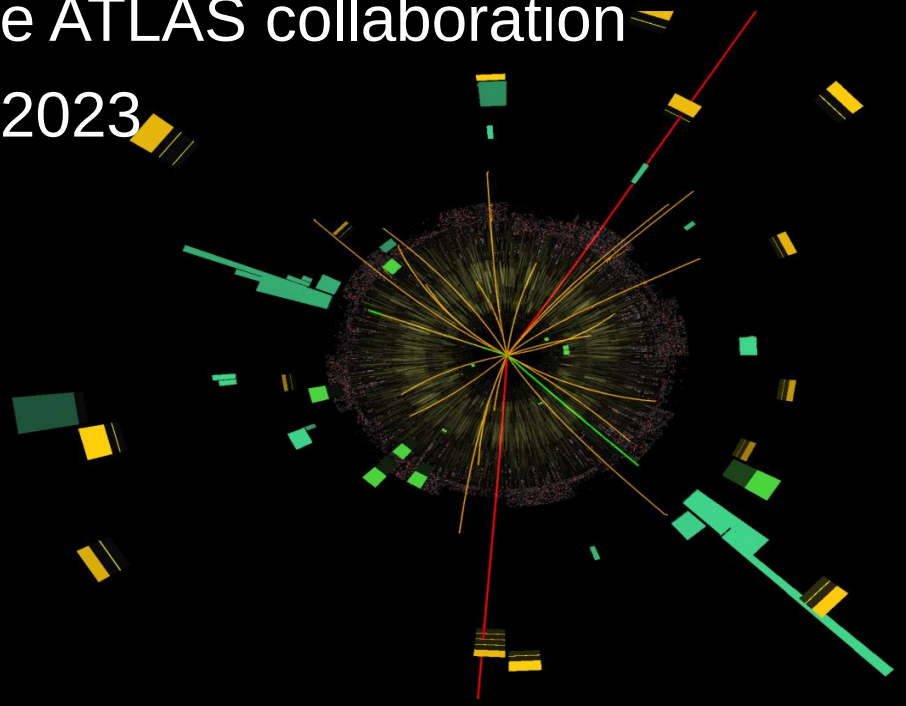
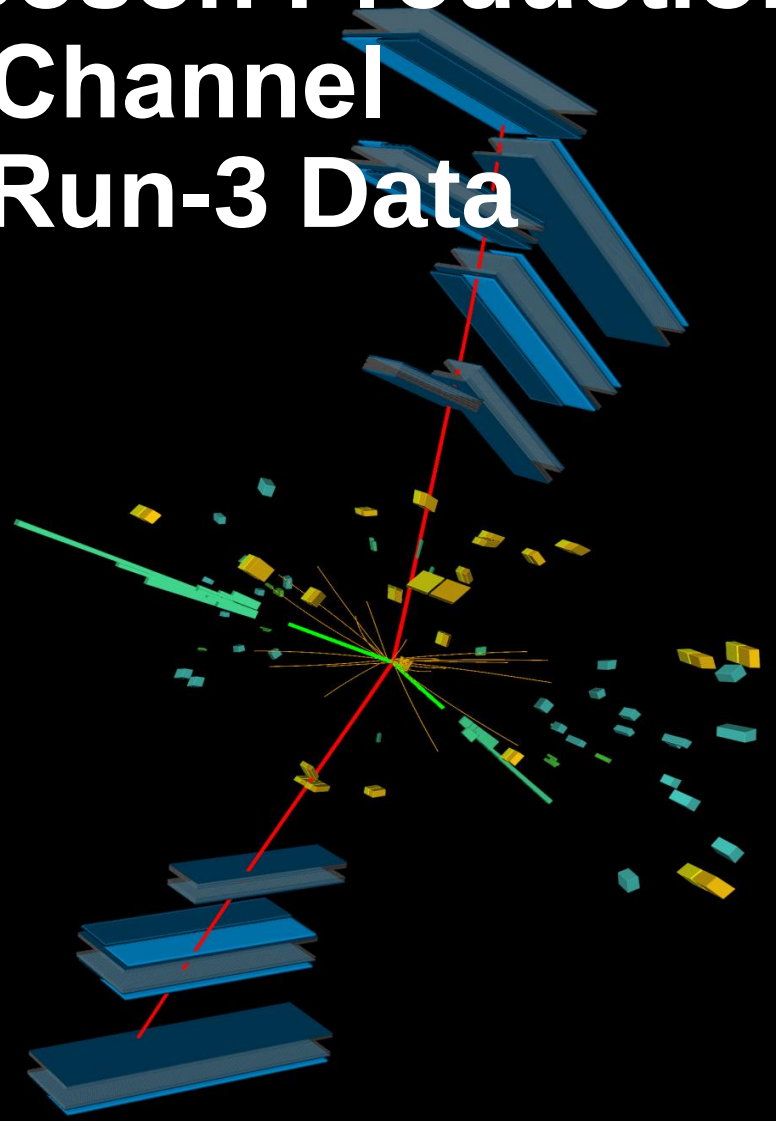
First Measurement of the Higgs Boson Production Cross-Section in the H→ZZ*→4ℓ Channel at √s = 13.6TeV using the ATLAS Run-3 Data

Xinmeng Ye

On behalf of the ATLAS collaboration

Nov 29, Higgs 2023





ATLAS EXPERIMENT

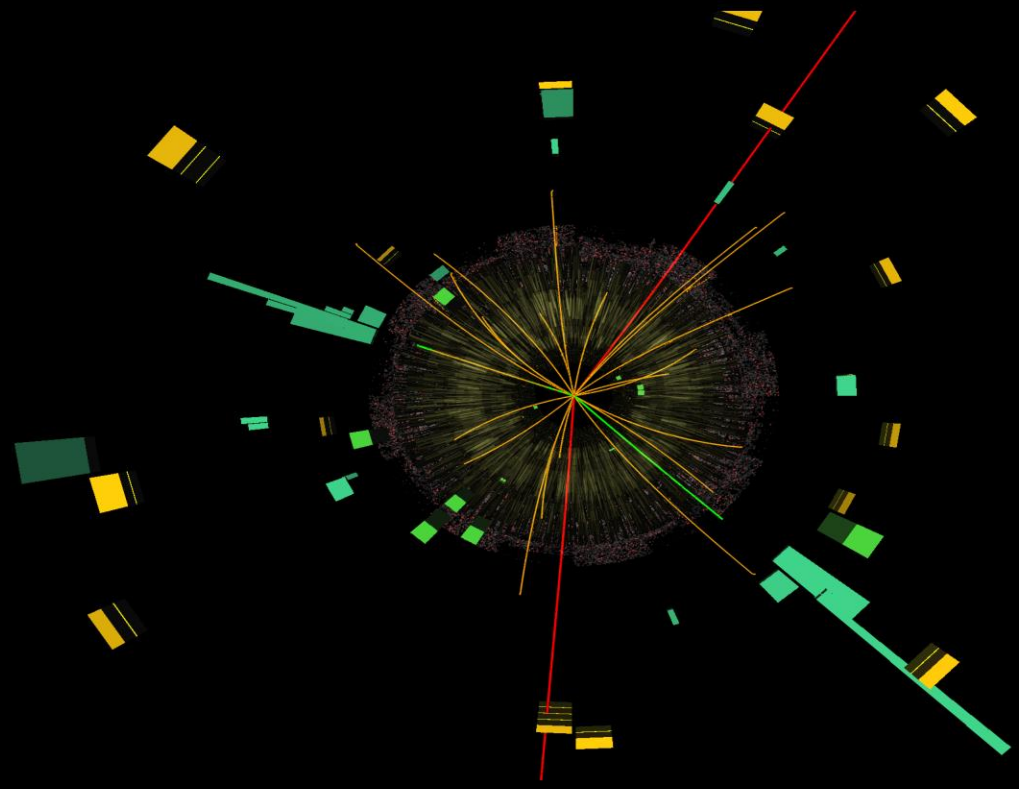
中国科学技术大学 University of Science and Technology of China

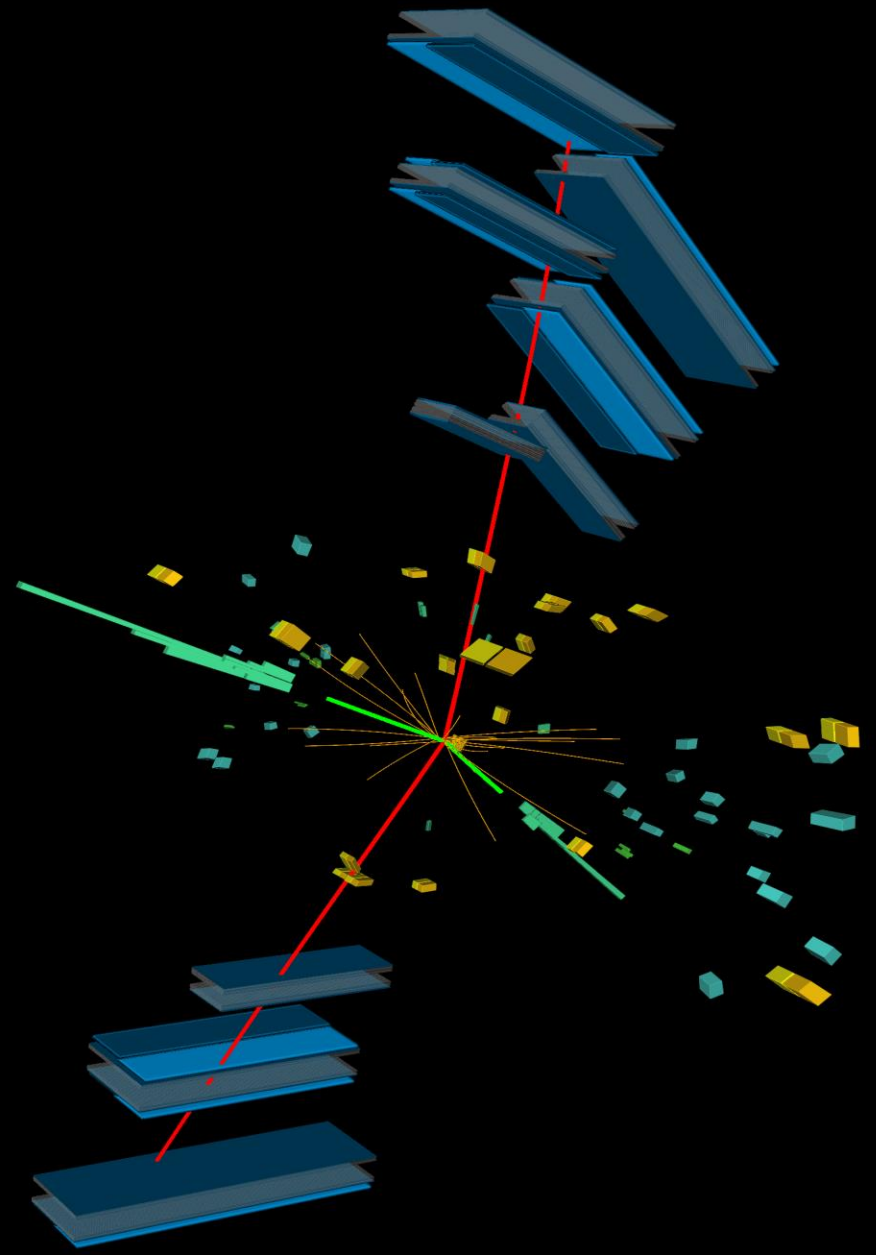
UNIVERSITY OF MICHIGAN

ATLAS EXPERIMENT

Run: 439798
Event: 2690382975
2022-11-15 01:22:07 CEST

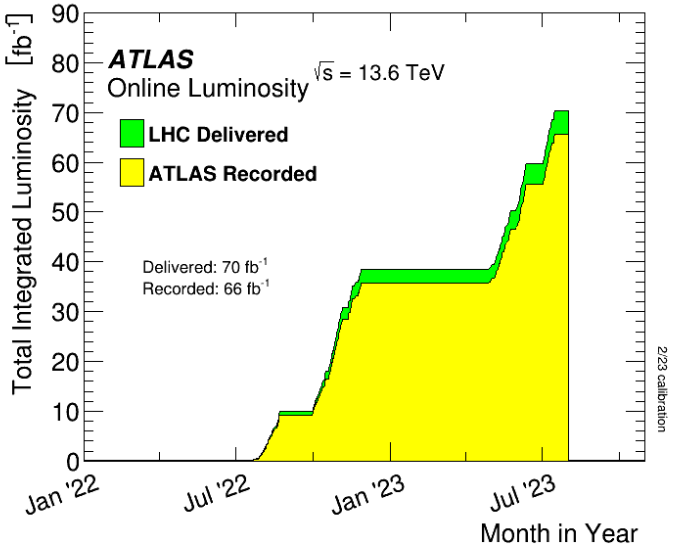
Run-3 H→2e2μ @ 13.6 TeV

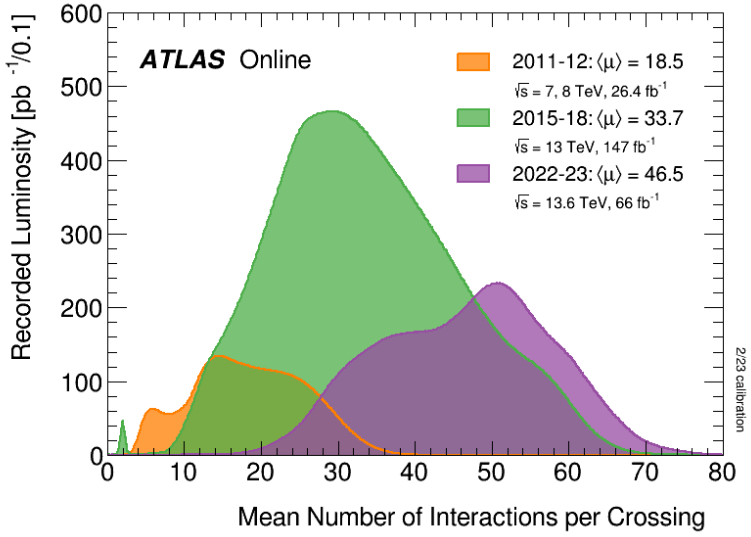




Introduction: ATLAS operation in Run-3

- Phase-I upgrade (2019-2022)
  - Muon spectrometers: New Small Wheel, BIS RPC
  - LAr calorimeter: front-end electronics
  - TDAQ

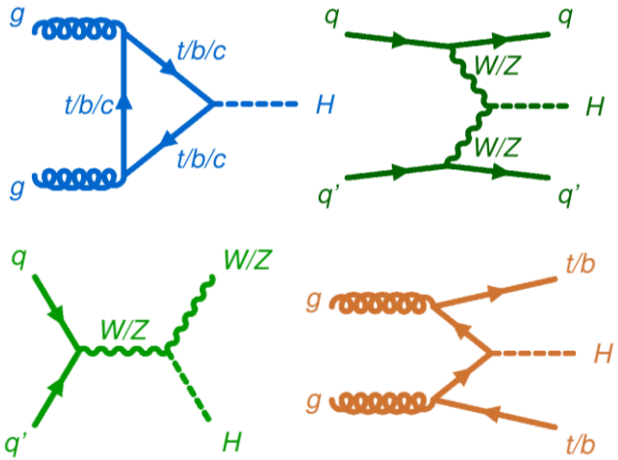


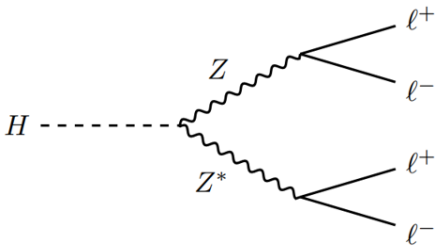


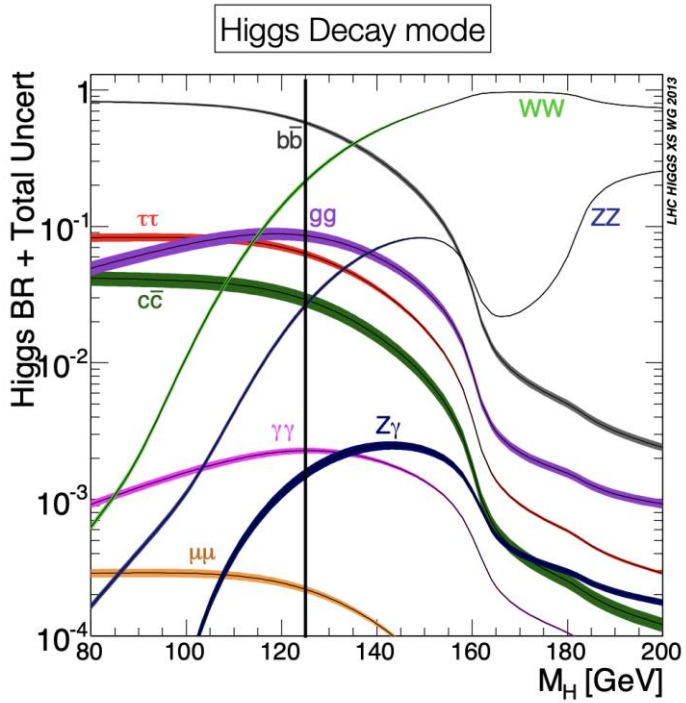
- Successful start of the Run-3 in 2022 with new *pp* energy at 13.6 TeV
- Quick measurements using early Run3 data are necessary
  - to **validate the detector performance** for basic objects
  - to **test the Standard Model predictions under an unprecedented centre-of-mass energy**

Early Run-3 H→ZZ*→4ℓ analysis

- Final states characterized by two pairs of **S**ame-**F**lavor **O**pposite-**C**harged leptons (4μ, 4e, 2e2μ, 2μ2e) from the same primary vertex
- Benefit from the clean final states with **high mass resolution and signal significance** (N_{sig}/N_{bkg}~2) despite the small branching ratio
- Experienced in Run-2 H→4ℓ studies
  - Latest Higgs combination [Nature 607, 52 (2022)]
  - H→4ℓ differential cross section [EPJC 80 (2020) 941]
  - H→γγ and H→4ℓ combined differential cross section [JHEP 05 (2023) 028]



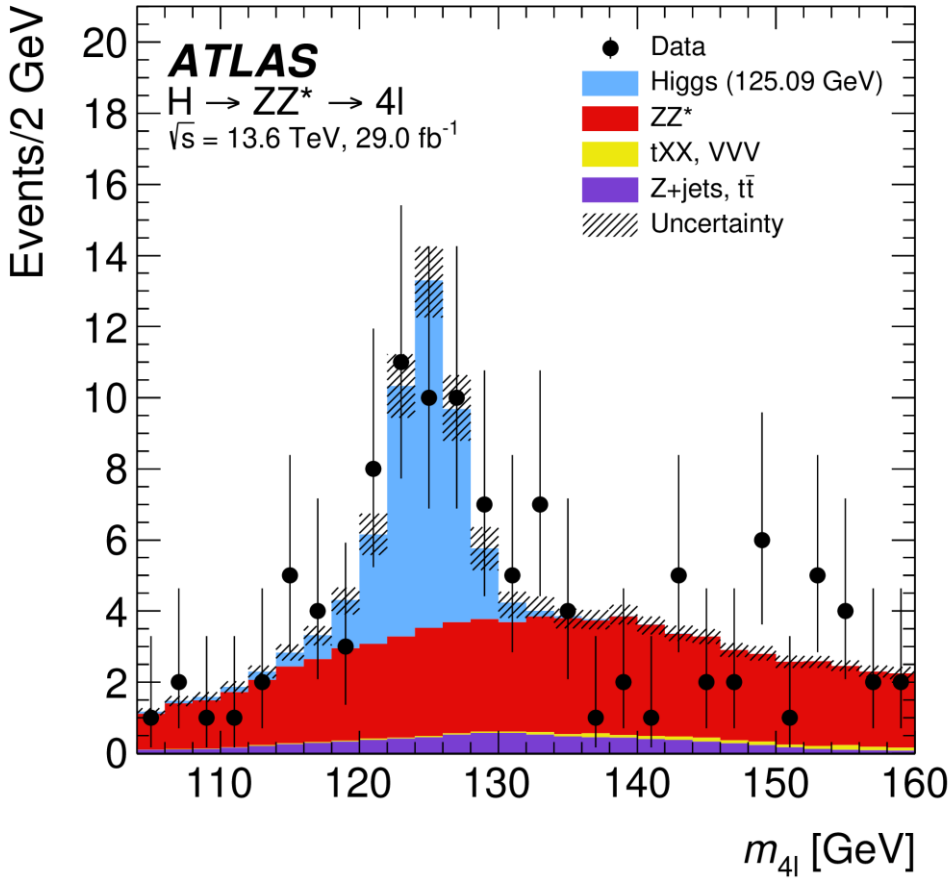




H→ZZ*→4ℓ analysis strategy in a nutshell

- Utilize ATLAS **full 2022 Run-3 dataset** corresponding to an integrated luminosity of **29.0 fb^{-1}**
  - First measurement of Higgs cross-section @ 13.6 TeV

- Lowest un-prescaled triggers with p_T threshold down to 6/7 GeV for e/μ
- Build the Higgs candidate from 2 SFOC lepton pairs with **105GeV < $m_{4\ell}$ < 160GeV**
  - **On-shell** Z boson: 50GeV < m_{12} < 106GeV
  - **Off-shell** Z boson: 12GeV < m_{34} < 115GeV
- **Fiducial cross-sections** extracted by a binned fit processed on the reconstructed 4-lepton invariant mass spectrum $m_{4\ell}$
- Paper published on EPJC [CERN-EP-2023-114]



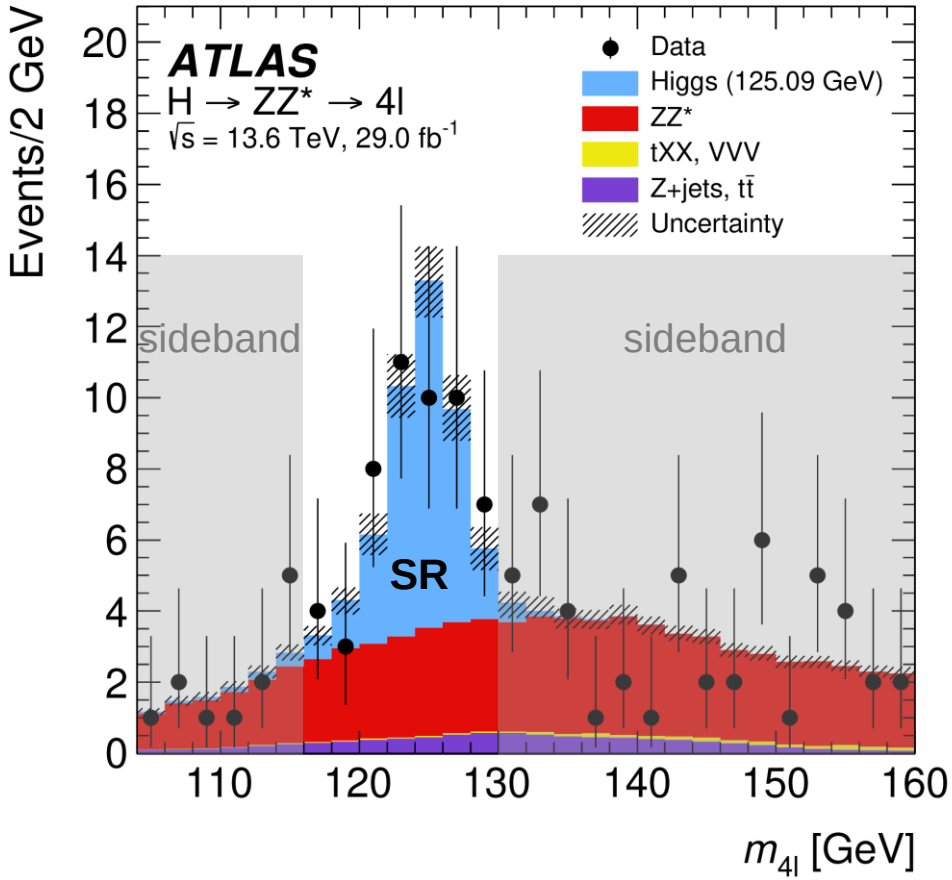
Background estimation

Irreducible background - 4 prompt lepton in the final states

- non-resonant ZZ*
  - Simultaneous extraction of the normalization factor via fit to the $m_{4\ell}$ sidebands [105,115] + [130,160] GeV
- $t\bar{t}$+$\ell\ell$ & VVV
  - Estimated from MC due to small cross-sections

Reducible background - 2 prompt leptons (Z or $t\bar{t}$) + 2 reco. leptons from heavy-flavour decays / fakes / photon conversion

- Study background in dedicated CRs orthogonal to SR defined by inverting/relaxing event selection criteria
- Expected background yields in the SR extrapolated from CRs via transfer factors



Fiducial cross-section fit

- The fiducial phase space is defined at particle-level closely following the definition of detector-level event reconstruction
- Fiducial cross-section σ_{fid} extracted inclusive for all final states (4μ, $4e$, $2e2\mu$, $2\mu2e$) using a binned fit of the m_{4l} distribution $\boldsymbol{P_i(m_{4l})}$ to the number of observed events

$$N(m_{4l}) = \mathcal{L}\sum_i \epsilon_i(1+f_i^{\text{nonfid}})\boldsymbol{\sigma_i^{\text{fid}}}\boldsymbol{P_i(m_{4l})} + N^{\text{bkg}}(m_{4l}) \qquad i = 4\mu,\ 4e,\ 2e2\mu,\ 2\mu2e$$

Parameter of Interest: $\sigma_i^{\text{fid}} = \sigma_i \cdot A_i \cdot BR_i$

m_{4l} signal shape: $P_i(m_{4l})$

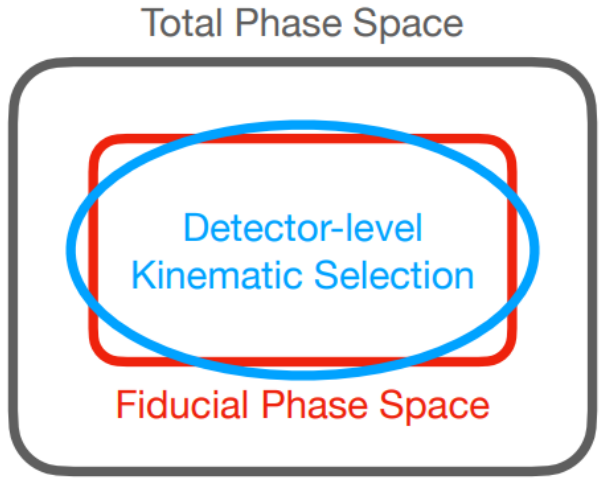
Acceptance: $A_i = N_{\text{fid}}/N_{\text{tot}}$ ~ 50%

Reconstruction efficiency: $\epsilon_i = N_{\text{reco}}/N_{\text{fid}}$ ~ 25%-50%

Fiducial leakage: $f_i^{\text{nonfid}} = (N_{\text{reco}} - N_{\text{reco\&fid}})/N_{\text{reco}}$ ~1%

fraction of events outside the fiducial region but are reconstructed in the SR

} fiducial factors



Fiducial cross-section results

- Observed number of events compared to the expected signal and background yields for each of the 4μ, 4e, 2e2μ, 2μ2e channels **in the SR (115GeV < $m_{4\ell}$ < 130GeV)**

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

- Fiducial cross-section results:

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

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

☞**In agreement with SM prediction**

Uncertainties

- Source of systematics
  - **Experimental** (e/μ performance, pile-up reweight, luminosity)
  - **Theory** (signal/background modelling)
  - **Other** (reducible backgrounds estimation)
- Uncertainties dominated by statistics
- Significantly larger e/μ uncertainties compared to Run-2 (139 fb^{-1}) H→4ℓ analysis
  - Largest impact from the electron identification efficiency - conservative uncertainty from extrapolation of Run-2 identification / reconstruction calibrations to Run-3 data

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

☞ **This analysis**

Source	Uncertainty [%]
Stat.	9
Syst.	3
Lumi.	1.7
e/μ	2
Jets	<0.5
Other	<0.5
ZZ* Th.	1
Sig. Th.	1.5
Comp.	<0.5

☞ **From Run-2 H→4ℓ paper [EPJC 80 (2020) 941]**

Total cross-section combination

- The H→ZZ*→4ℓ inclusive fiducial cross-section is extrapolated to total phase space and combined with H→γγ to get the total cross-section for pp→H
  - H→ZZ*→4ℓ [this analysis]: $\sigma(pp\to H) = 46 \pm 12$ pb
  - H→γγ [ATLAS-CONF-2023-003]: $\sigma(pp\to H) = 67^{+12}_{-11}$ pb

} **compatible with a p-value of 20%**

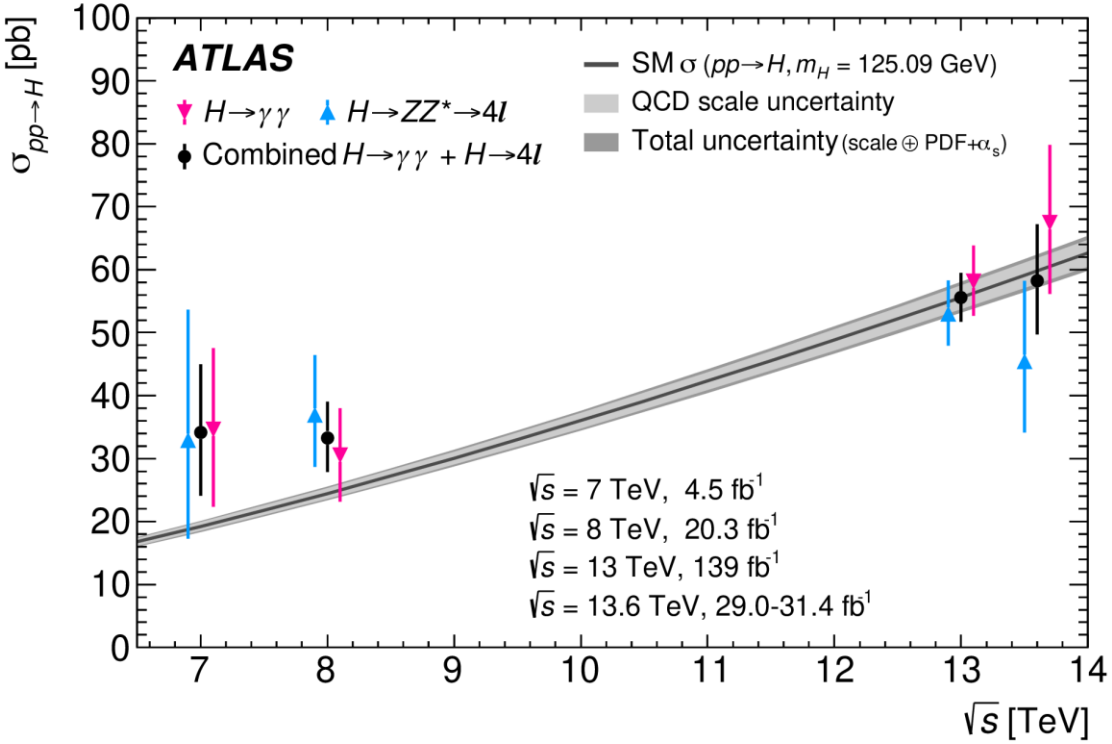
- Combined total cross-section
  - **observed**

    $\sigma(pp\to H) = 58.2 \pm 8.7$ pb

    $= 58.2 \pm 7.5\,(\text{stat.}) \pm 4.5\,(\text{syst.})$ pb
  - **expected**

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

☞ **All 3 results in agreement with SM prediction**



Summary

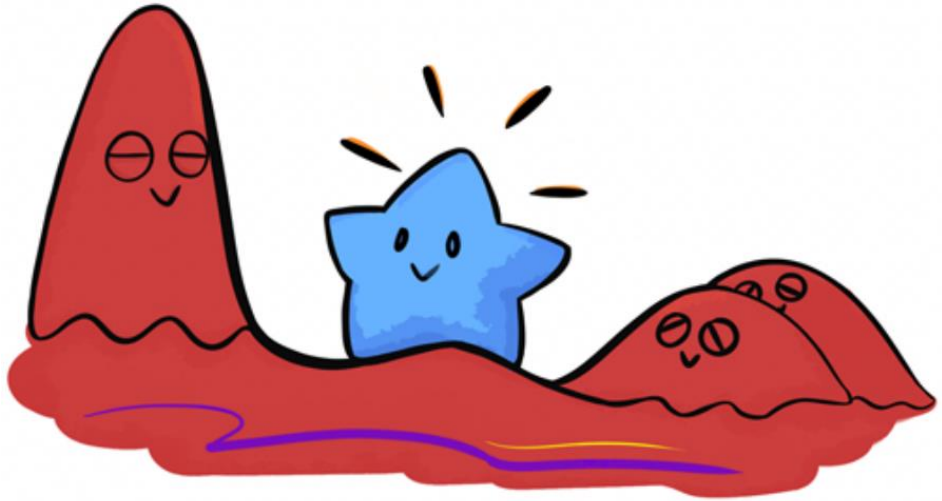
- First measurement of the Higgs boson cross-section at $\sqrt{s}$ = 13.6 TeV has been performed in the $H \to ZZ^* \to 4\ell$ and $H \to \gamma\gamma$ channels at ATLAS [CERN-EP-2023-114]

$$\sigma(pp \to H) = 58.2 \pm 8.7 \text{ pb} = 58.2 \pm 7.5 \text{ (stat.)} \pm 4.5 \text{ (syst.) pb} \quad \text{(obs.)}$$

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

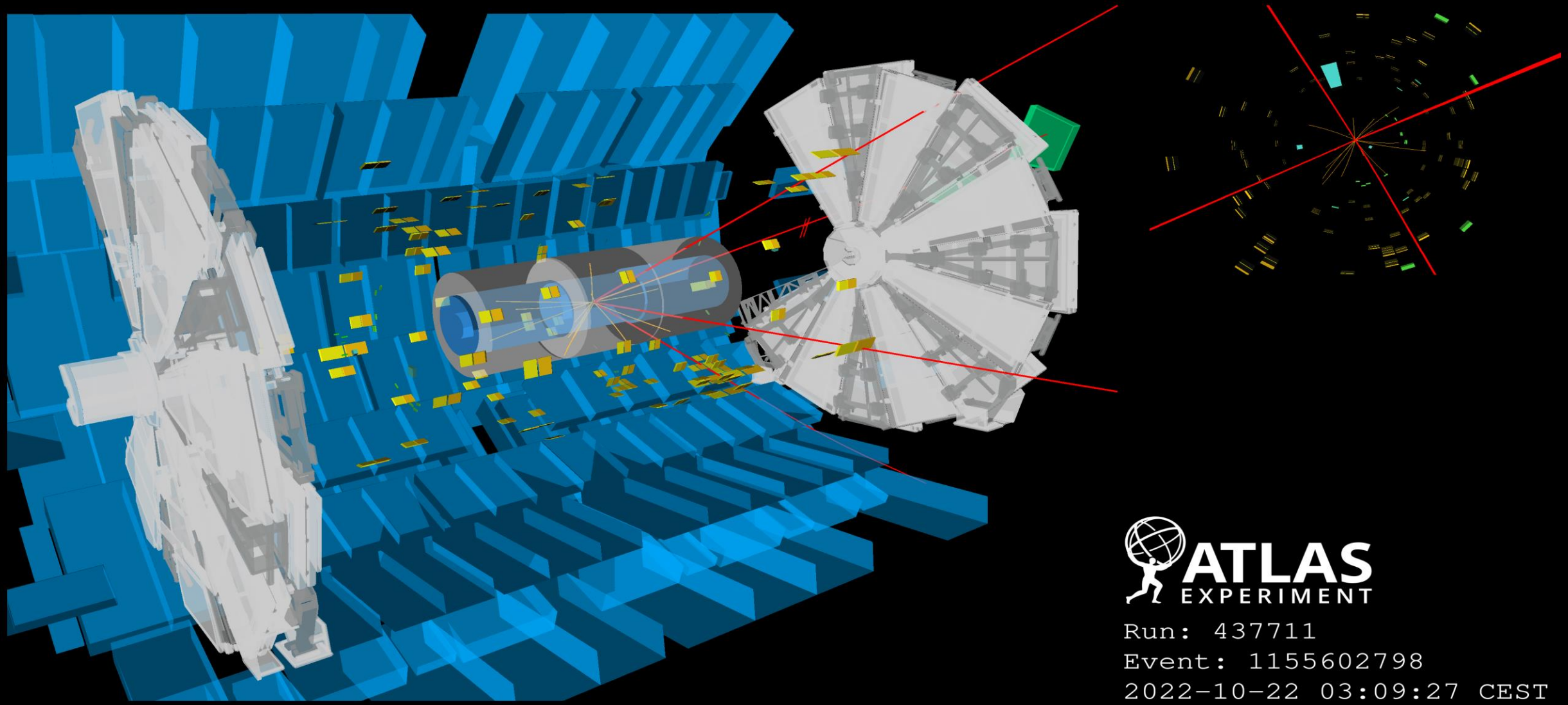
- Analysis largely constrained by the limited statistics – another 29.9 fb^{-1} of data recorded during 2023!

- Run-3 $H \to 4\ell$ differential cross-sections and coupling measurements become feasible with improved sensitivity
  - Expect improvement in the calibration of electron and muon using dedicated Run-3 campaigns



Thanks to Siyuan Yan for the illustration!

BACKUPS


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

MC samples

- 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%

Process	Generator	Showering	PDF set	σ [pb] $\sqrt{s}$ = 13.6 TeV
ggF + $b\bar{b}H$	POWHEG BOX v2 + MiNLO	PYTHIA 8.2/8.3	PDF4LHC21	52.7 ± 2.6
VBF	POWHEG BOX v2	PYTHIA 8.2/8.3	PDF4LHC21	$4.075^{+0.088}_{-0.089}$
WH	POWHEG BOX v2 + MiNLO	PYTHIA 8.2/8.3	PDF4LHC21	$1.453^{+0.029}_{-0.028}$
$q\bar{q} \to ZH$	POWHEG BOX v2 + MiNLO	PYTHIA 8.2/8.3	PDF4LHC21	$0.806^{+0.033}_{-0.029}$
$gg \to ZH$	POWHEG BOX v2	PYTHIA 8.2/8.3	PDF4LHC21	$0.136^{+0.034}_{-0.026}$
$t\bar{t}H$	POWHEG BOX v2	PYTHIA 8.2/8.3	PDF4LHC21	$0.569^{+0.040}_{-0.057}$
$\gamma\gamma, m_{\gamma\gamma} \in 90$–$175$ GeV	MADGRAPH5_aMC@NLO	PYTHIA 8.2	NNPDF3.0 NLO	-
$qq \to ZZ^*$	SHERPA 2.2.12	SHERPA	NNPDF3.0 NNLO	-
VV, VVV	SHERPA 2.2.12	SHERPA	NNPDF3.0 NNLO	-
Z + jets	SHERPA 2.2.12	SHERPA	NNPDF3.0 NLO	-
$t\bar{t}$	POWHEG BOX v2	PYTHIA 8.3	NNPDF3.0 NLO	-
$t\bar{t}W, t\bar{t}Z$	SHERPA 2.2.12	SHERPA 2.2.12	NNPDF3.0 NNLO	-

Object definition & event selection

Object definition

- Electrons:
  - E_T > 7 GeV, |η| < 2.47
  - ID: Loose+B-Layer
  - Iso: Loose VarRad
- Muons:
  - p_T > 5 GeV, |η| < 2.5
  - ID: Loose
  - ISO: PFlowLoose VarRad
- TTVA:
  - $|d_0|$ < 1mm, $d_0/\sigma(d_0)$ < 5/3 for e/μ
  - $|z_0 \sin\theta|$ < 0.5 mm
- FSR recovery
  - consider photons within |η| < 2.5
  - collinear FSR (μ only): p_T > 1 GeV, ΔR(ℓ,γ) < 0.15
  - non-collinear FSR: tight photons, p_T > 10 GeV

Event selection

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

- m_{34} dynamic cut: $m_{threshold} < m_{34} < 115$GeV
  - $m_{threshold}$ is 12 GeV for $m_{4\ell} < 140$ GeV, and rises linearly to 50 GeV for $m_{4\ell}$ = 190 GeV
- ME value calculated with MadGraph at LO

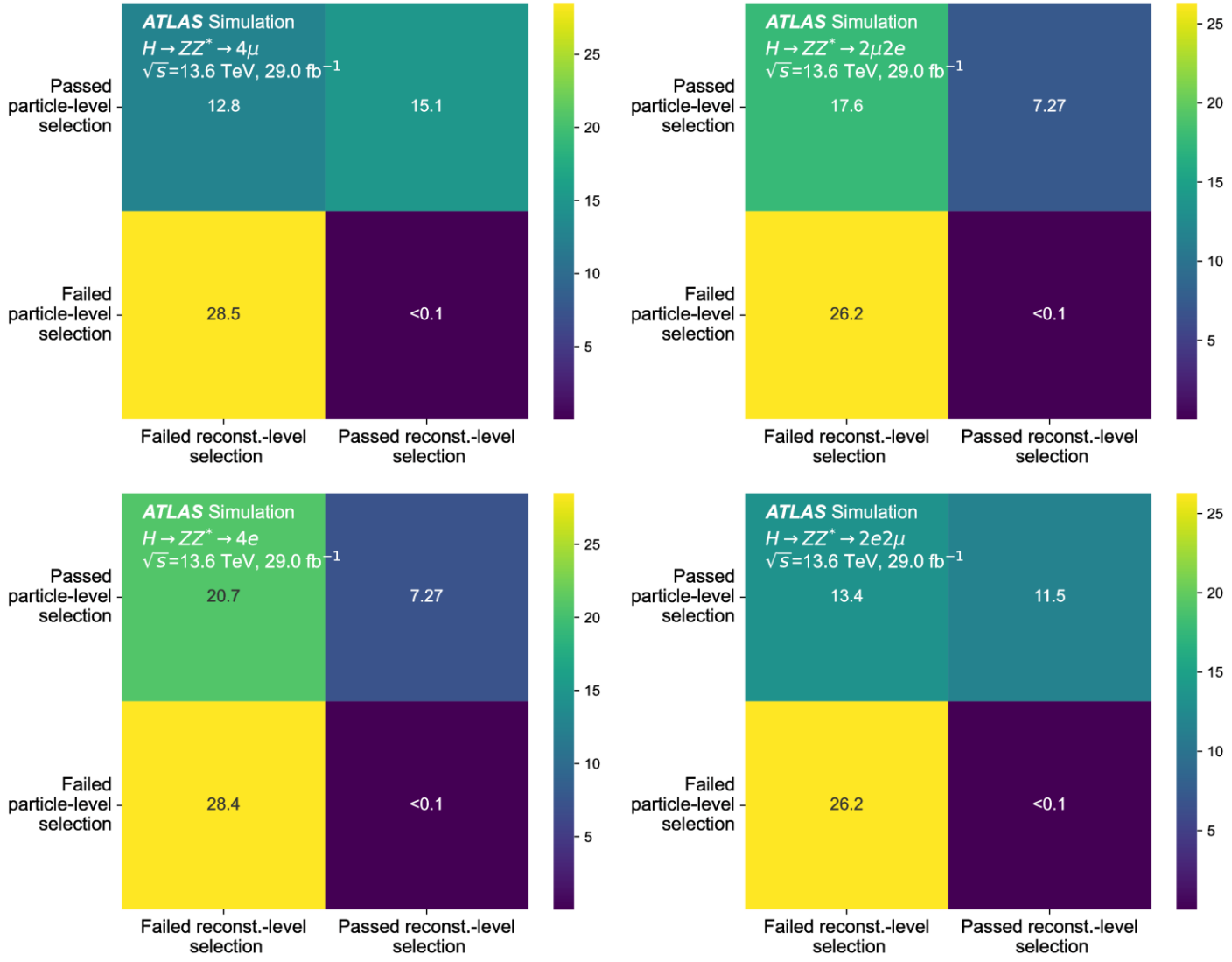
Fiducial phase-space & fiducial factors

- 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

Fiducial phase space

Leptons	
Leptons	$p_{\mathrm{T}} > 5$ GeV, $\lvert\eta\rvert < 2.7$
Lepton selection and pairing	
Lepton kinematics	$p_{\mathrm{T}} > 20, 15, 10$ GeV
Leading pair (m_{12})	SFOC lepton pair with smallest $\lvert m_Z - m_{\ell\ell}\rvert$
Subleading pair (m_{34})	remaining SFOC lepton pair with smallest $\lvert m_Z - m_{\ell\ell}\rvert$
Event selection (at most one quadruplet per event)	
Mass requirements	50 GeV$< m_{12} <$ 106 GeV and 12 GeV$< m_{34} <$ 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
Mass window	105 GeV$< m_{4\ell} <$ 160 GeV
If extra lepton with $p_{\mathrm{T}} > 12$ GeV	quadruplet with largest matrix element value



Systematic uncertainties

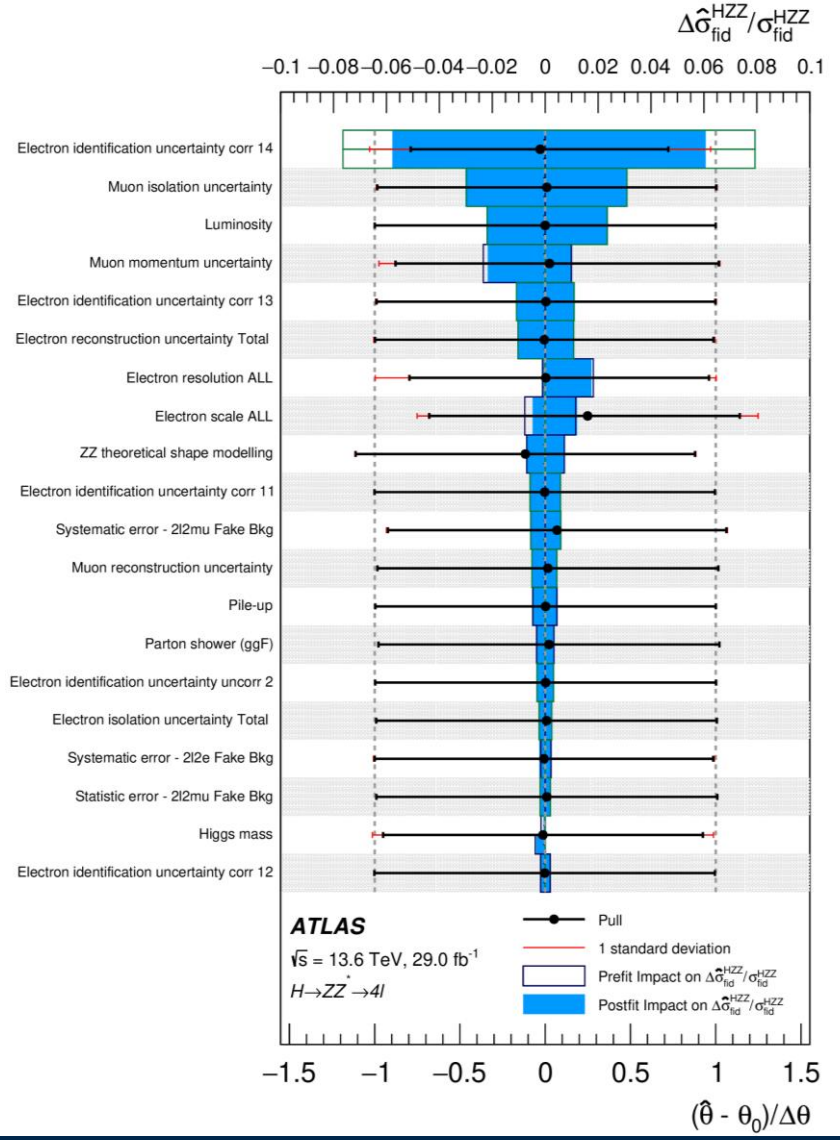
- MCP
  - reconstruction+ID, isolation, TTVA efficiency measurements
  - uncertainties from momentum smearing: muon resolution, muon scale, sagitta bias
- Egamma
  - reconstruction, isolation, ID efficiency
  - uncertainties from momentum smearing: EG Scale, EG Resolution
- Modelling
  - signal: α_s + PDF4LHC21 variations, QCD scale variations, PS modelling, signal composition, Higgs boson mass (240 MeV)
  - background: PDF & QCD scale variations, ZZ* modelling (shape variation)
- Other
  - reducible backgrounds
  - PRW
  - luminosity

Syst. correlation for total cross-section combination

- Additional modelling systematic uncertainties considered on the Acceptance
  - α_s + PDF4LHC21 variations, QCD scale variations, PS modelling
  - 2.9% uncertainty on BR(H→γγ), 2.2% on BR(H→ZZ*→4l)
- Correlation scheme
  - correlated uncertainties
    - lumi, PRW
    - EG scale/resolution
    - Higgs boson mass & BR uncertainties
    - QCD scale acceptance uncertainties
  - other uncertainties decorrelated

Systematics Ranking

- 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



m_{4l} distribution per channel