Measurements of Multi-boson Production at 13 TeV with ATLAS

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Overview

- Result of 4 years of work resulting in 1 thesis and 2 papers:
  - Measurements of $Z\gamma$ production arXiv
  - Measurements of $Z\gamma\gamma$ production arXiv


Motivation

The Standard Model

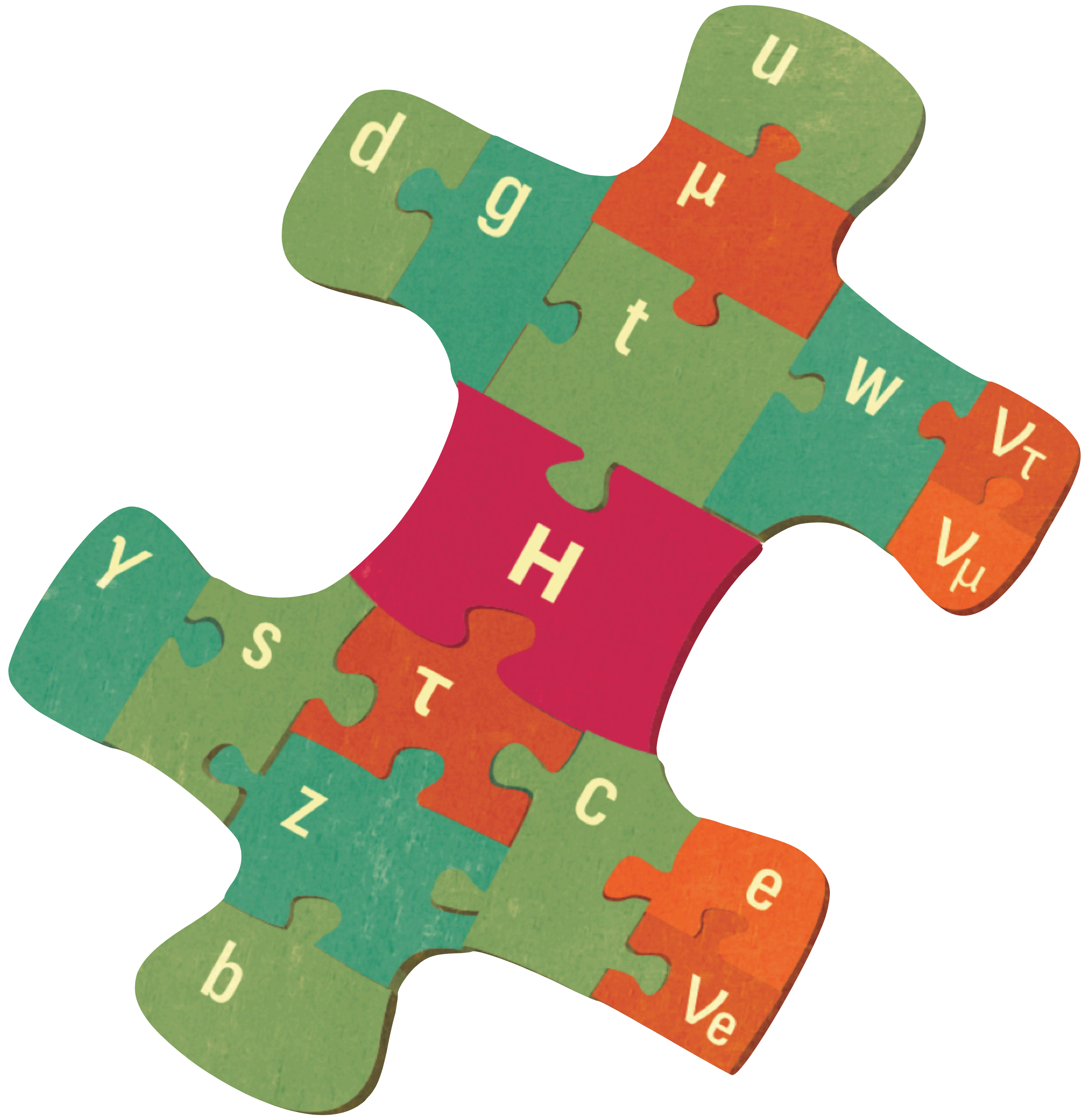


Image shamelessly stolen from: https://www.nobelprize.org/uploads/2018/06/popular-physicsprize2013-1.pdf

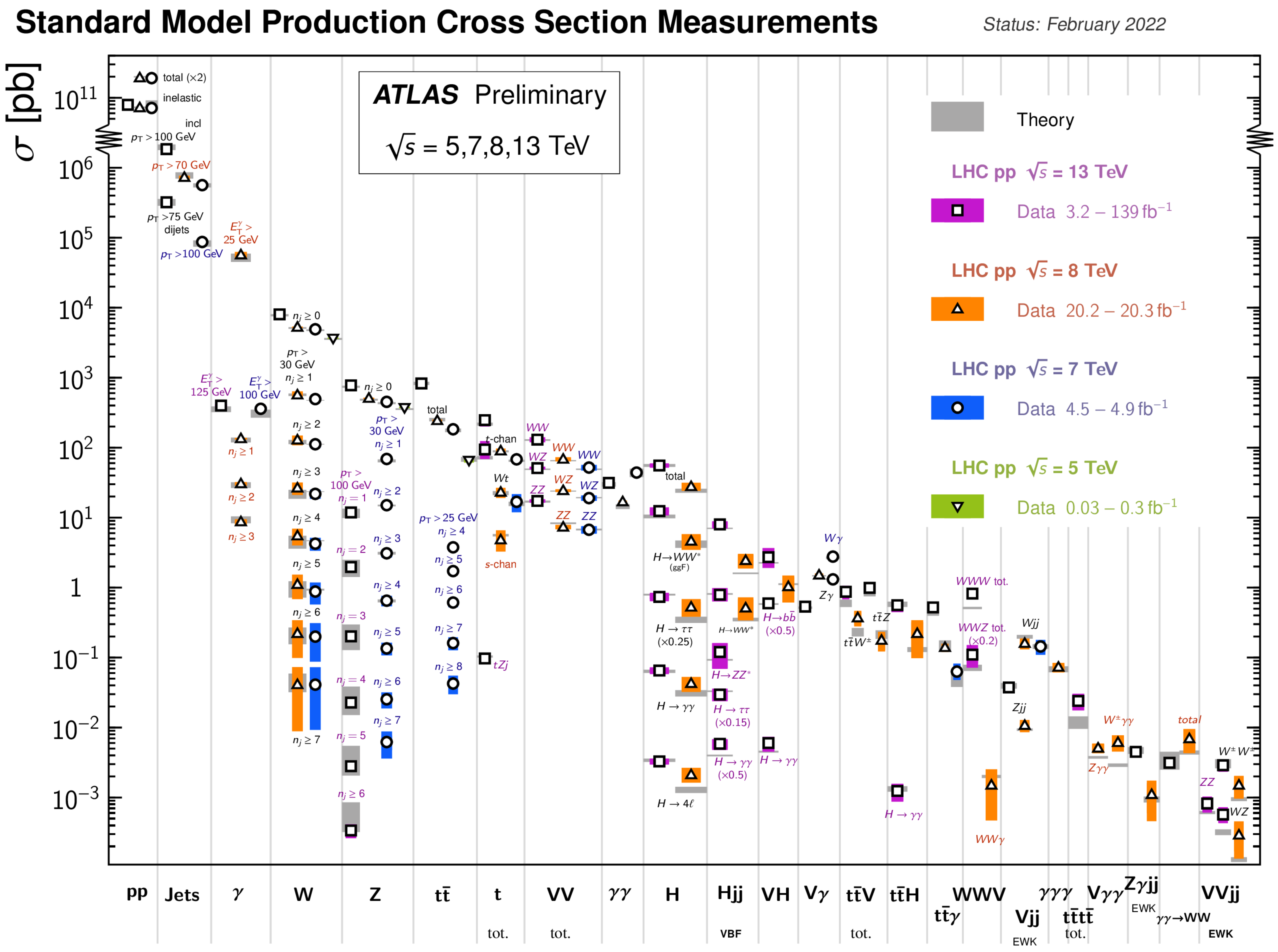
The future of the Particle Physics

Searches or Measurements?

Measuring the Standard Model

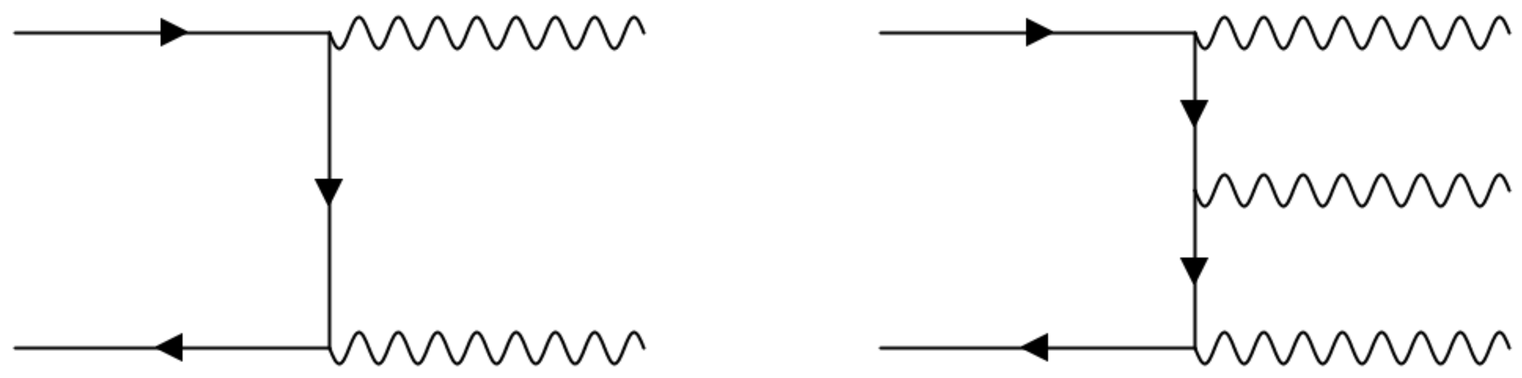
- What can we measure?
  - Free-parameters (masses, couplings etc.)
  - Cross-sections
    - Fiducial - for strongest comparative power
    - Differential - for probing areas of interest (modelling, new physics)
  - Other observables
  - Compare to state of the art predictions at NNLO/N3LO in QCD and NLO in EWK

The Standard Model at the LHC

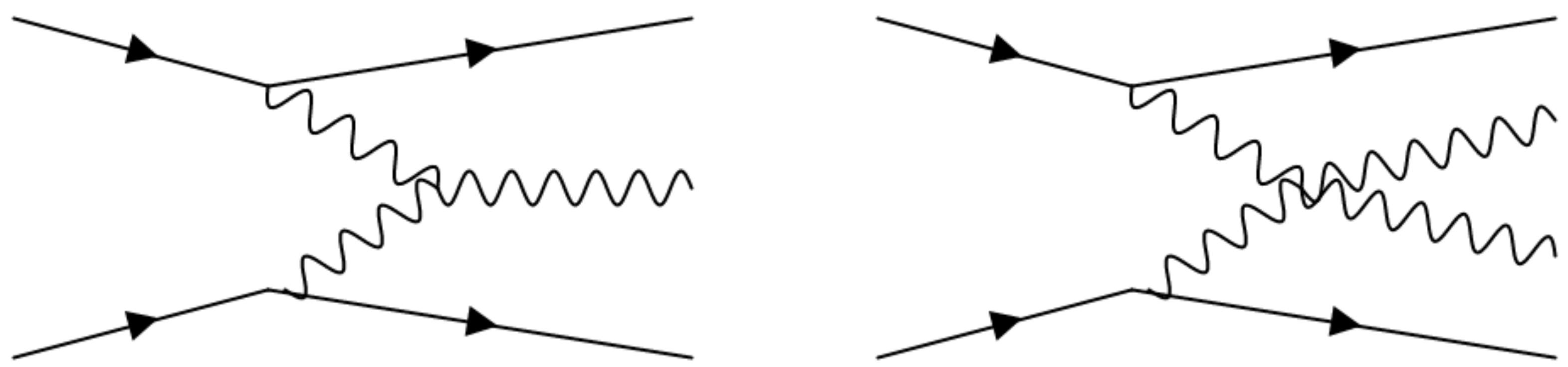


EW multi-boson processes

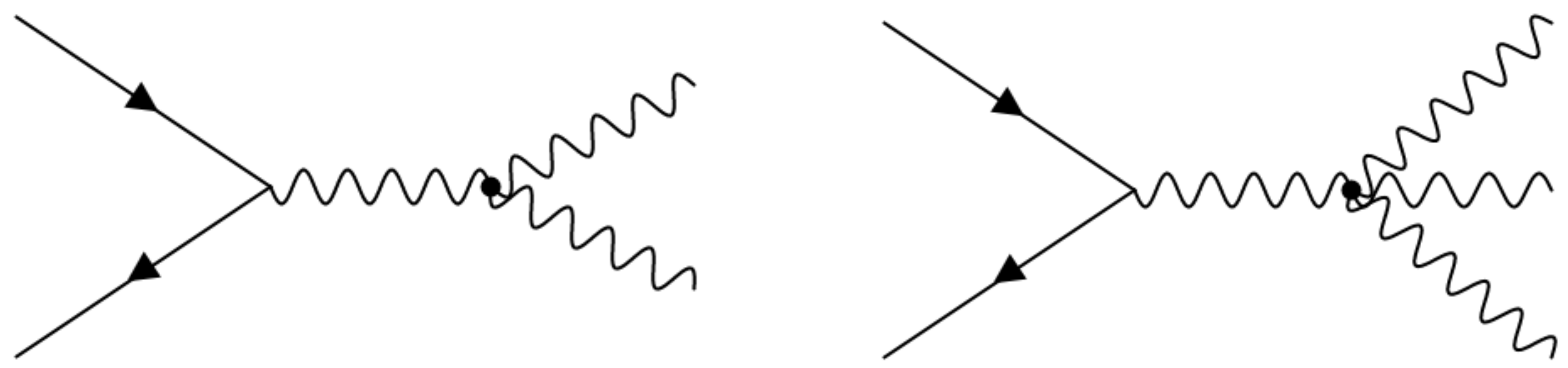
- Processes involving Z, W or γ bosons



LO production



Exclusive VBF/VBS production

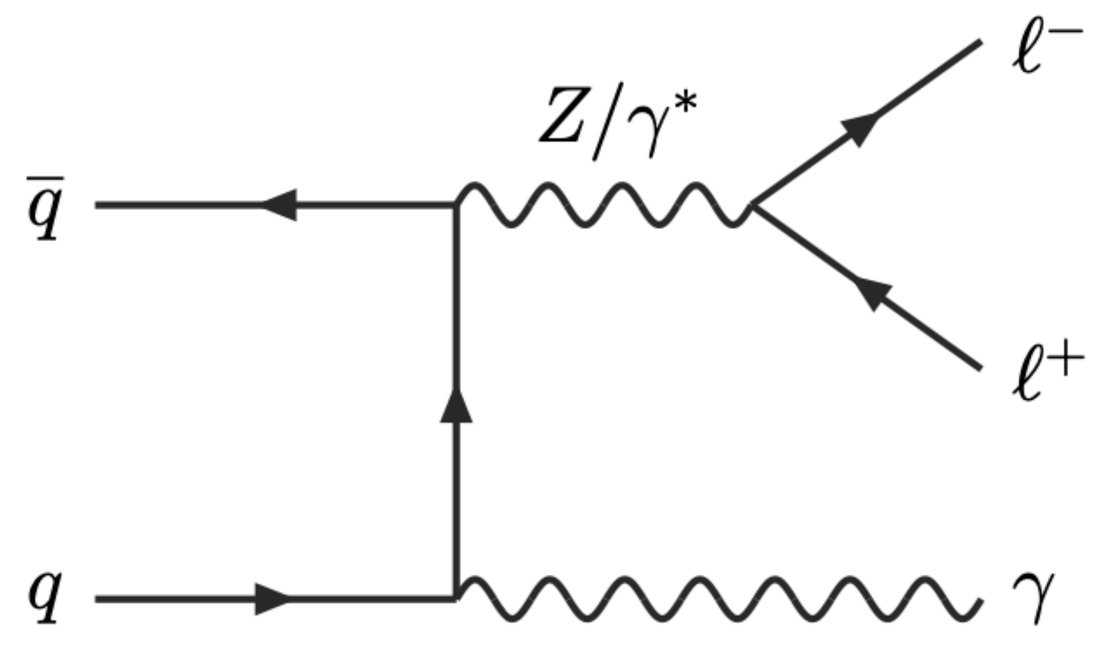


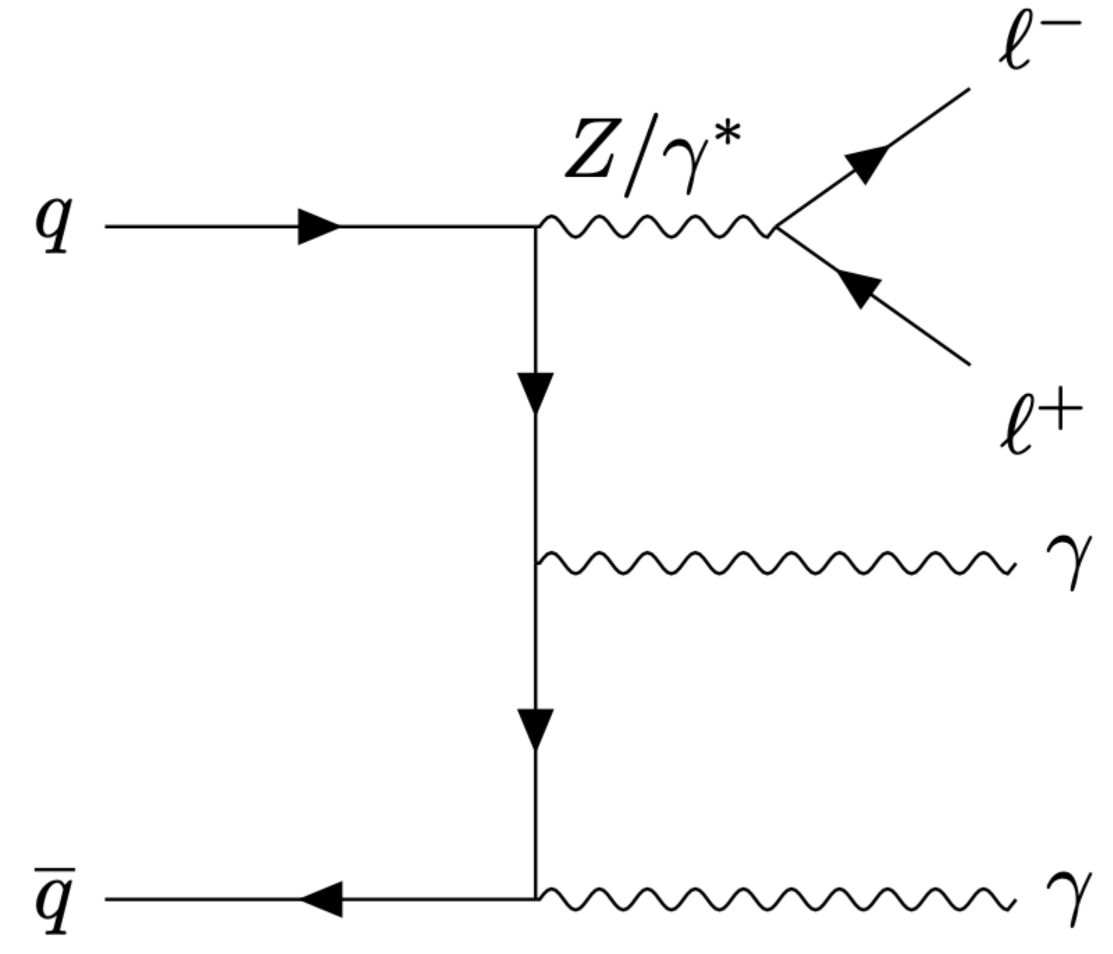
Production via TGC/QGC

- Tests of EW sector of SM
- Indirect/direct probe of non-Abelian couplings
- Constrain new physics effects via anomalous TGC/QGCs
- Improve understanding of SM backgrounds to rarer/forbidden process (e.g. Higgs & heavy resonances)

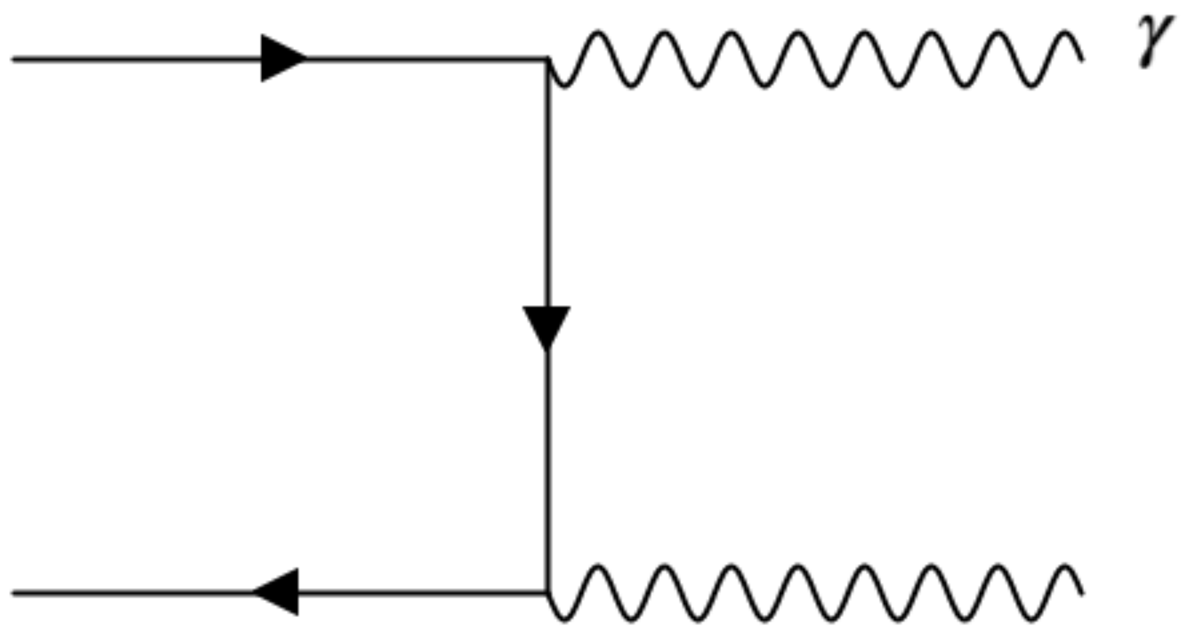
Introduction

- This talk covers the measurements of $Z\gamma$ and $Z\gamma\gamma$
- Both analyses:
  - Use the full LHC Run 2 proton-proton dataset, 139 fb^{-1}
  - Use the $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ channels
  - Select events with photons produced via Initial-state radiation (ISR)

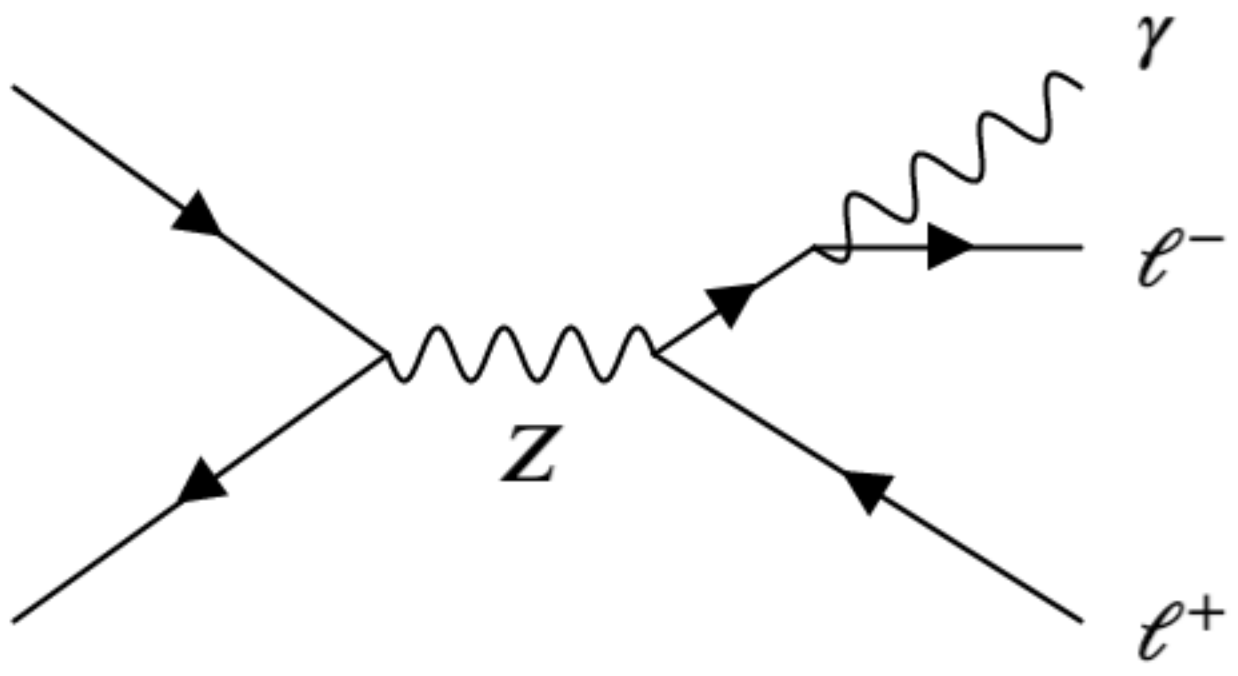




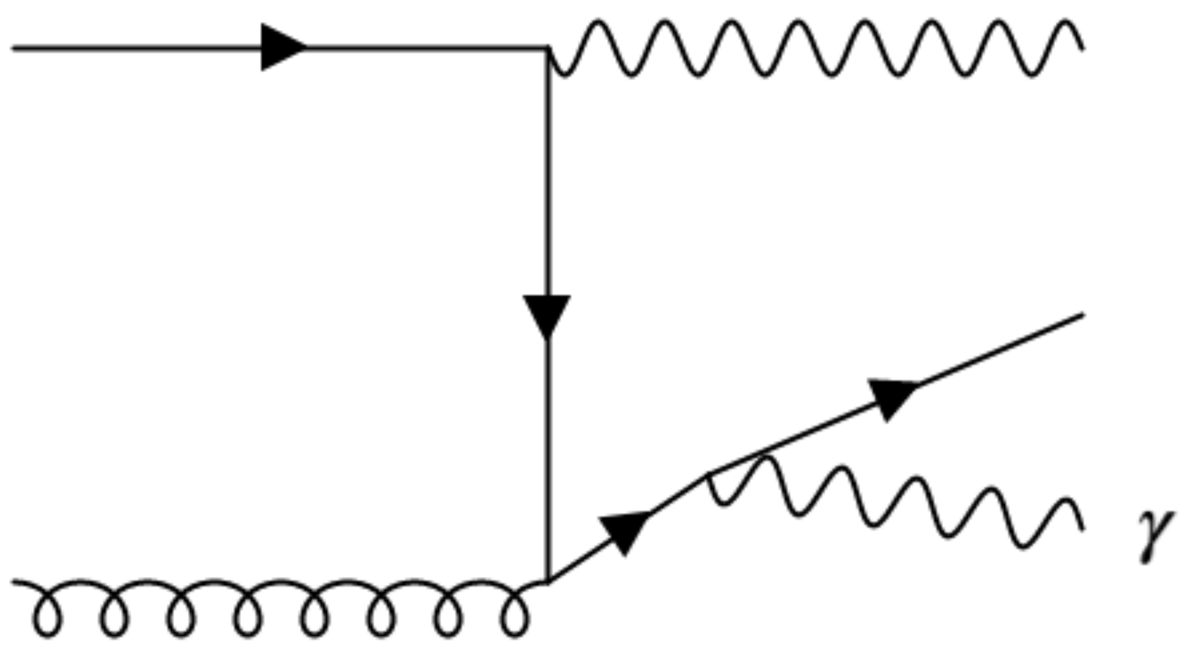
Photon production mechanisms



Initial-state radiation (ISR)



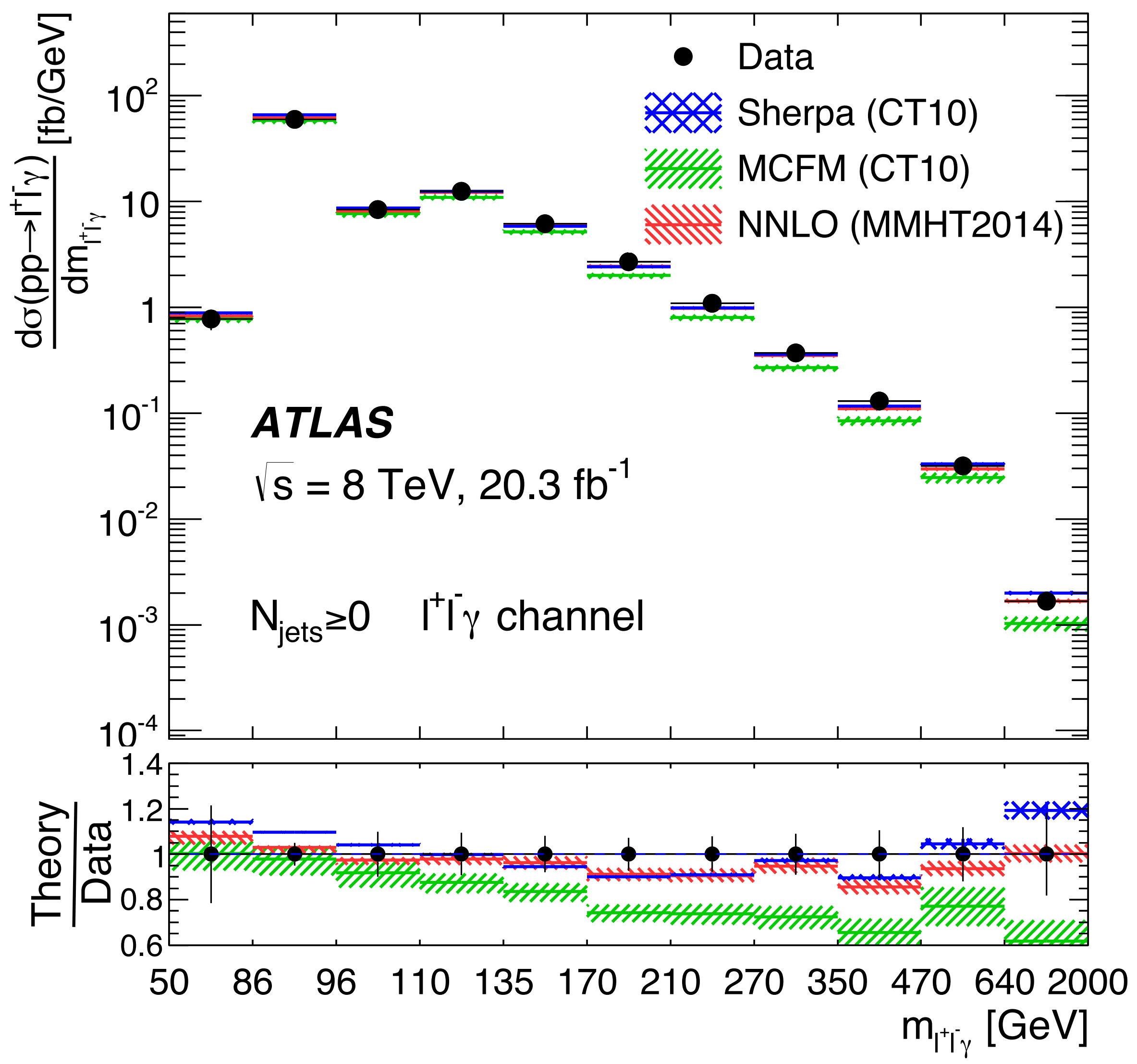
Final-state radiation (FSR)



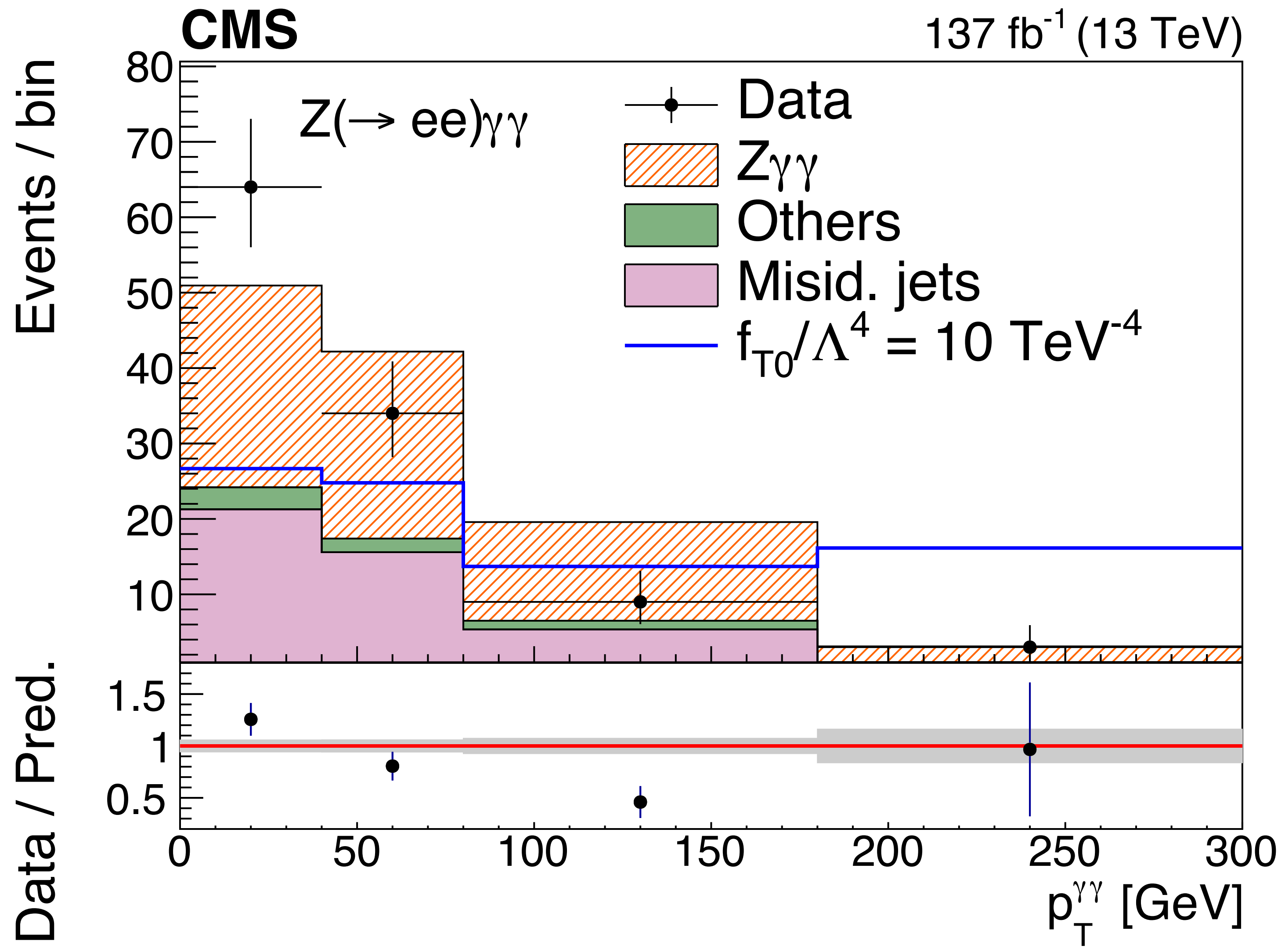
Parton fragmentation

Previous measurements

- Measurements of both $Z\gamma$ and $Z\gamma\gamma$ made by ATLAS and CMS in Run 1 (8 TeV)
- $Z\gamma\gamma$ measured by CMS in Run 2 (13 TeV)



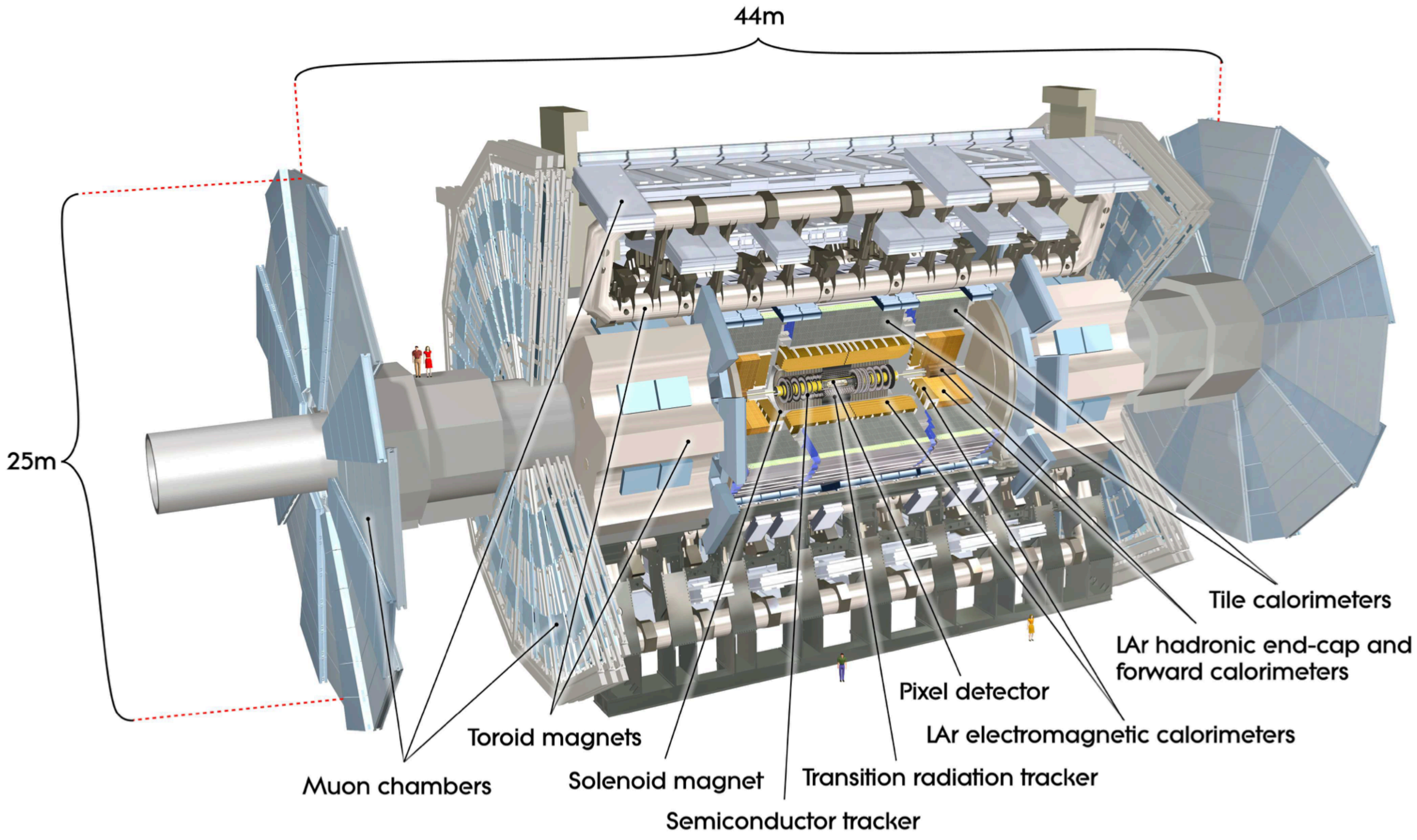
ATLAS 8 TeV Zγ(γ)



CMS 13 TeV Zγγ

Analysis Methods

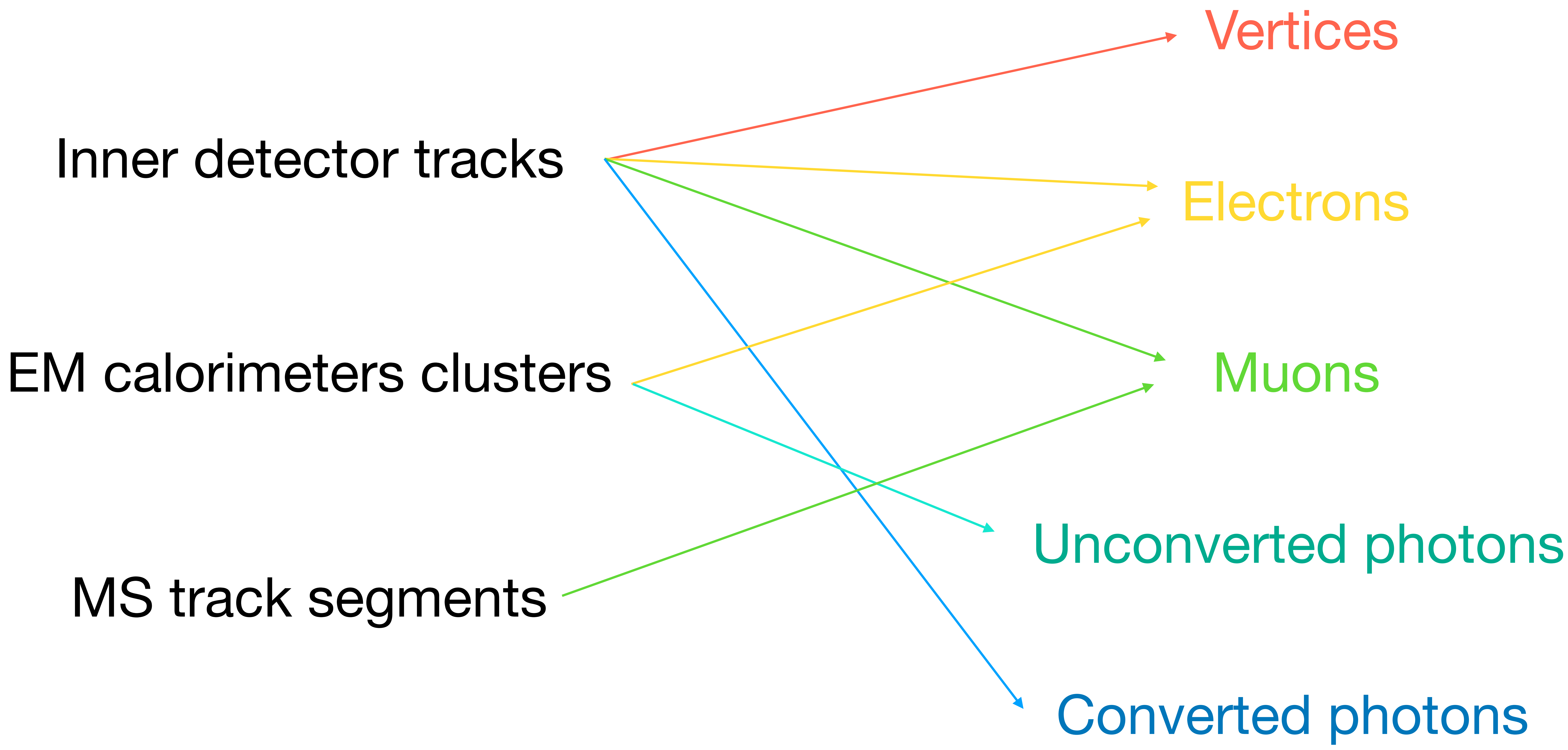
The ATLAS detector



Triggers

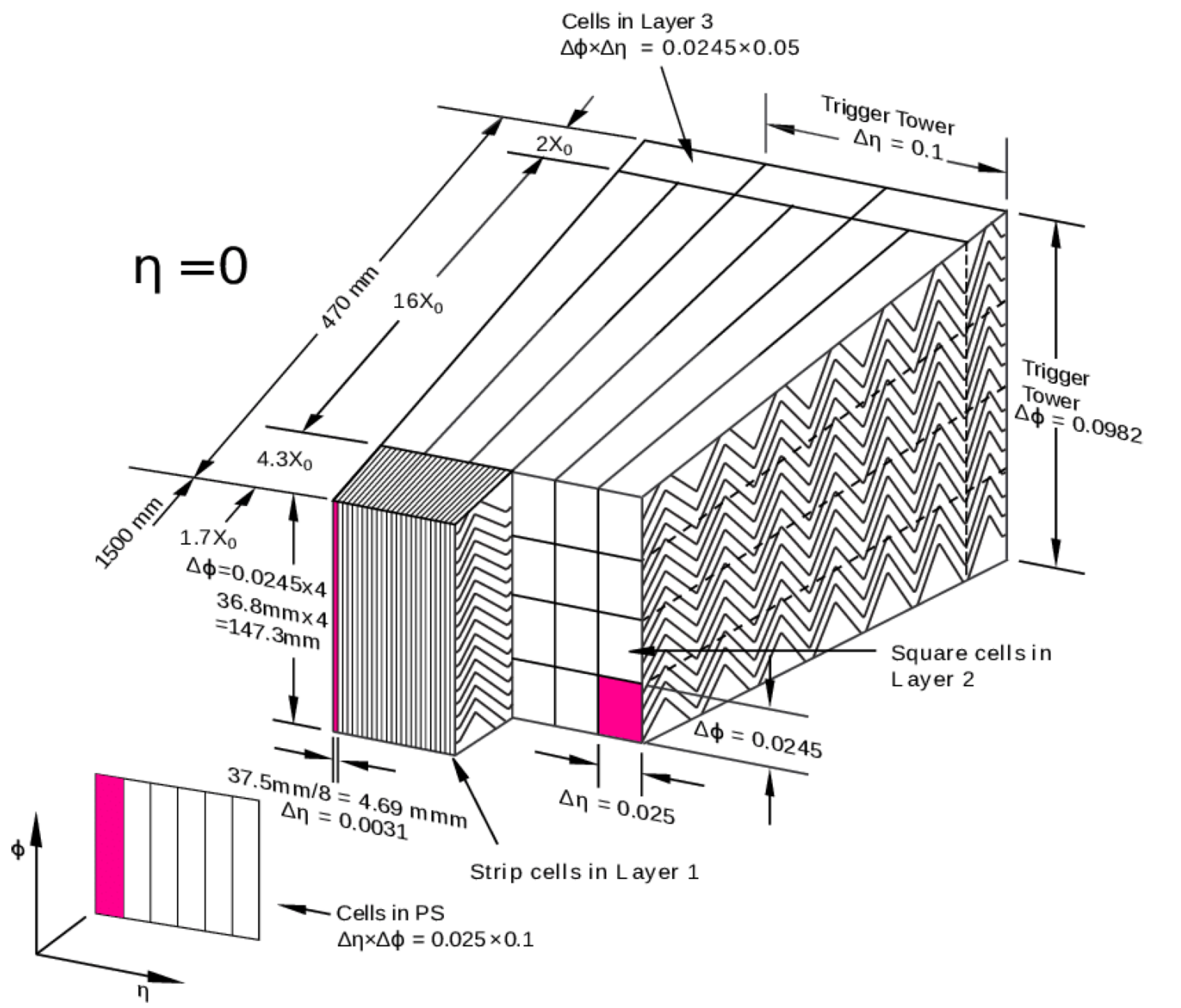
- Lowest unprescaled p_T thresholds (26 GeV) - maximise number of events
  - **Electron** - Large E_T measurements in ECAL selected in hardware trigger, then combined with tracks in software trigger (also shower shapes)
  - **Muon** - coincidences in muon trigger chambers in hardware trigger, matched to inner detector tracks in software trigger
- No trigger on photons

Particle reconstruction



Photon identification and isolation

- **Identification**
  - Shower shape variables to select collimated deposits with small leakage into HCAL
  - Use fine granularity of strip layer to resolve double peak typical of $\pi^0 \rightarrow \gamma\gamma$ decays
- **Isolation**
  - Put constraints on nearby activity in calorimeter and tracking systems
- These two conditions can be exploited to constrain fake photon backgrounds



Fiducial cross-section measurements

Defined by selection criteria

Estimated from simulation or data-driven methods

$$\sigma_{fid} = \frac{N_{data} - N_{bkg}}{C \times L}$$

Detector-level to fiducial-level correction factor from simulation

Total integrated luminosity

- For differential measurements C is replaced by unfolding

Effective field theories

- General approach to constraining new physics, no specific model being tested

- Add higher dimension (d>4) operators ($\mathcal{O}_i^d$) to SM Lagrangian which are suppressed by new physics scale Λ

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_{d>4} \sum_i \frac{f_i^d}{\Lambda^{d-4}} \mathcal{O}_i^d$$

- f_i^d are Wilson coefficients, the coupling strength of the EFT operators

$Z\gamma$ measurement

Selections

Electrons

- $p_T > 30, 25$ GeV
- $|\eta| < 2.47$ excl. $1.37 < |\eta| < 1.52$
- PV consistency
- ID and isolation criteria

Muons

- $p_T > 30, 25$ GeV
- $|\eta| < 2.5$
- PV consistency
- ID and isolation criteria

Photons

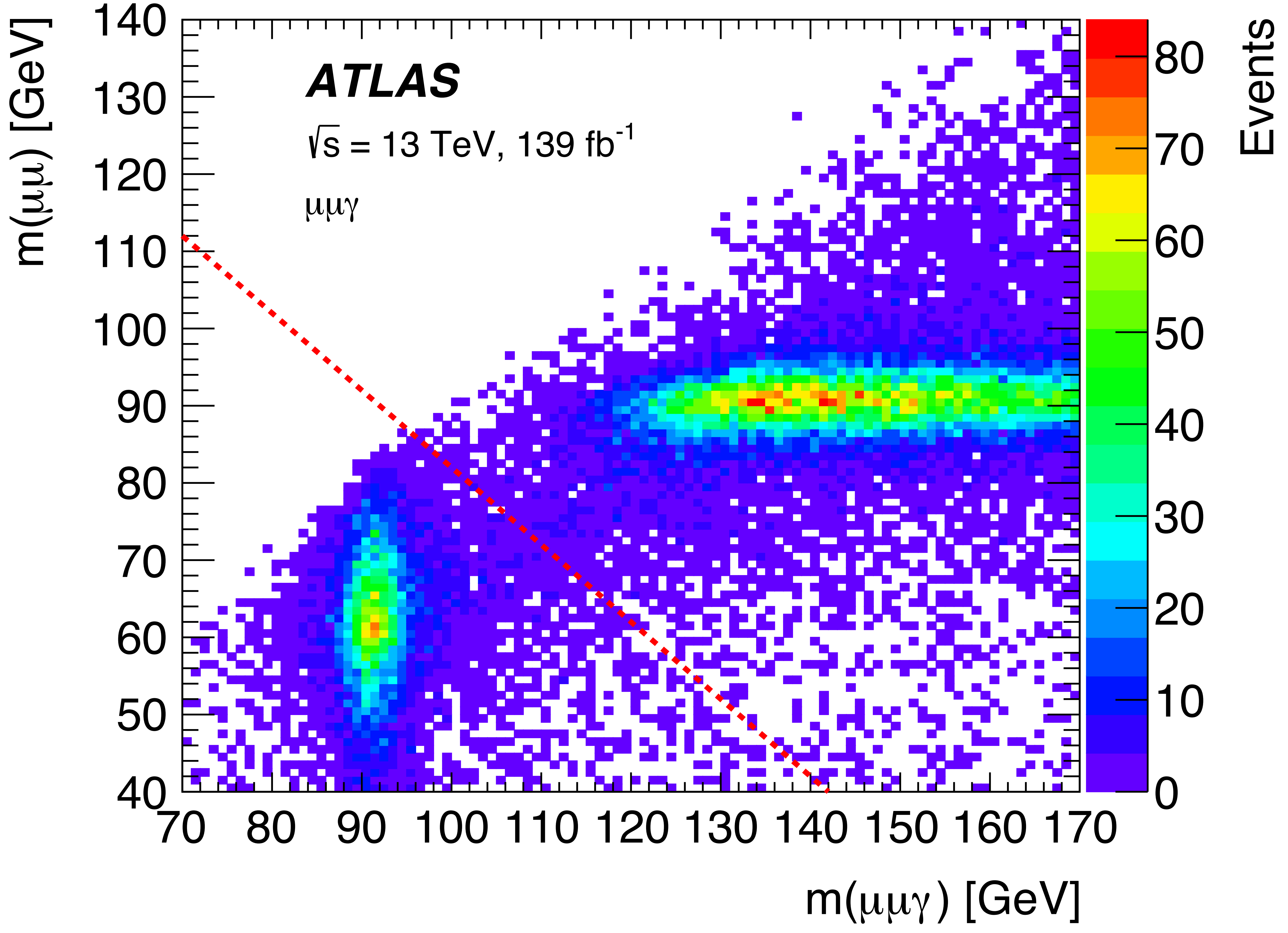
- $p_T > 30$ GeV
- $|\eta| < 2.47$ excl. $1.37 < |\eta| < 1.52$
- ID and isolation criteria

Event

- $m_{\ell\ell} > 40$ GeV
- $\Delta R(\ell, \gamma) > 0.4$
- $m_{\ell\ell} + m_{\ell\ell\gamma} > 2m_Z$

- Select ~95000 events in signal region

FSR rejection



Background summary

Fake photon background (10%)

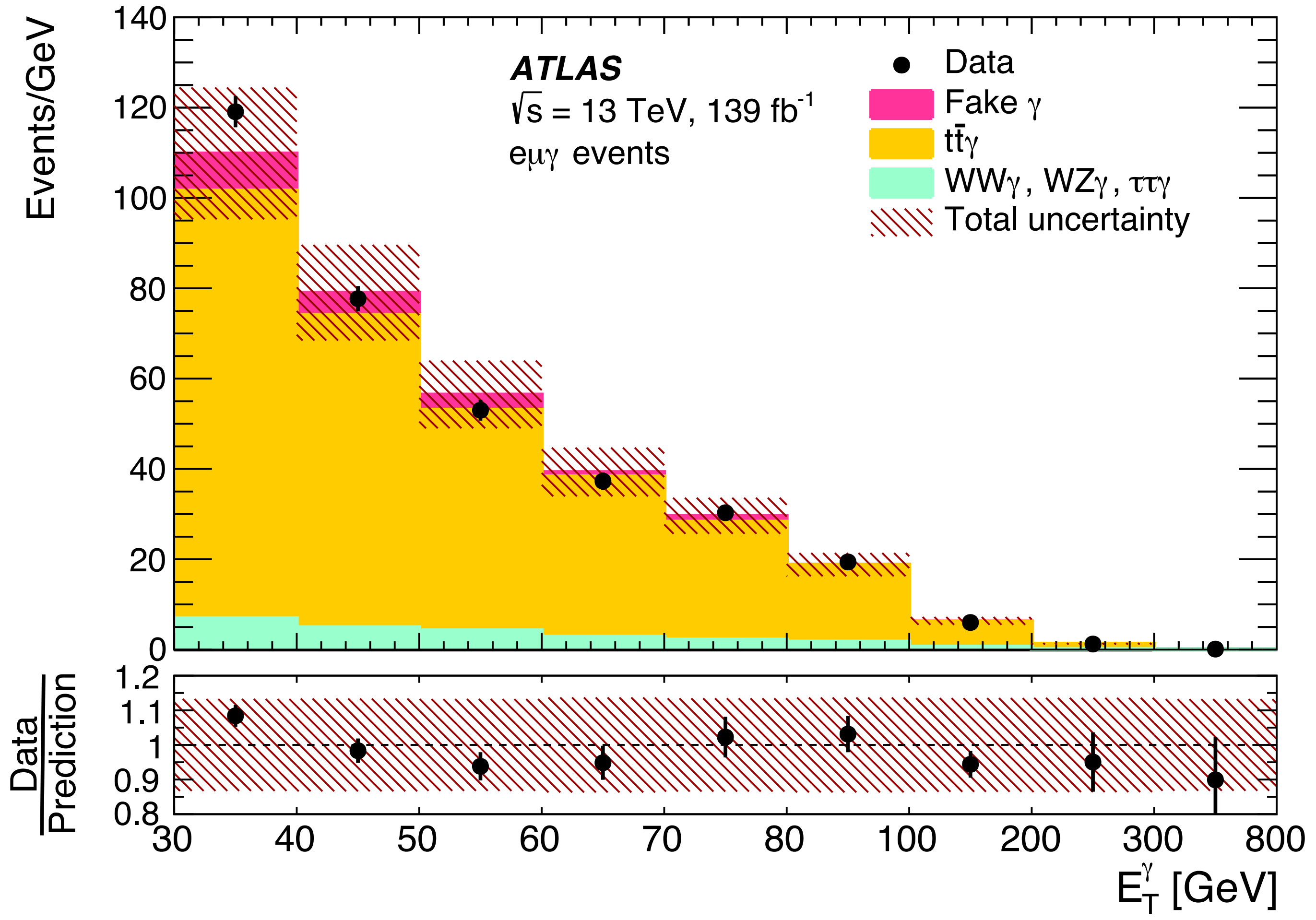
- Jets misidentified as photons
- Data-driven method

Pile-up background (2.5%)

- Z and γ from separate pp interactions
- Data-driven method

Top background (3.8%)

- Constrain normalisation in $e\mu\gamma$ CR
- Shapes from simulation



Multi-boson (1%)

- $WZ, ZZ, WW\gamma, Z(\rightarrow \tau\tau)\gamma$
- Directly from simulation

Fake photon background

- $j \to \gamma$ fake rates poorly modelled by simulation
- Define jet-enriched CRs (B, C & D) by inverting photon ID/isolation cuts to constrain fake background
- For each region: $N^X_{data} = c_X N^A_{sig} + N^X_{fakes} + N^X_{bkg}$
- c_X signal leakage fractions, taken from simulation

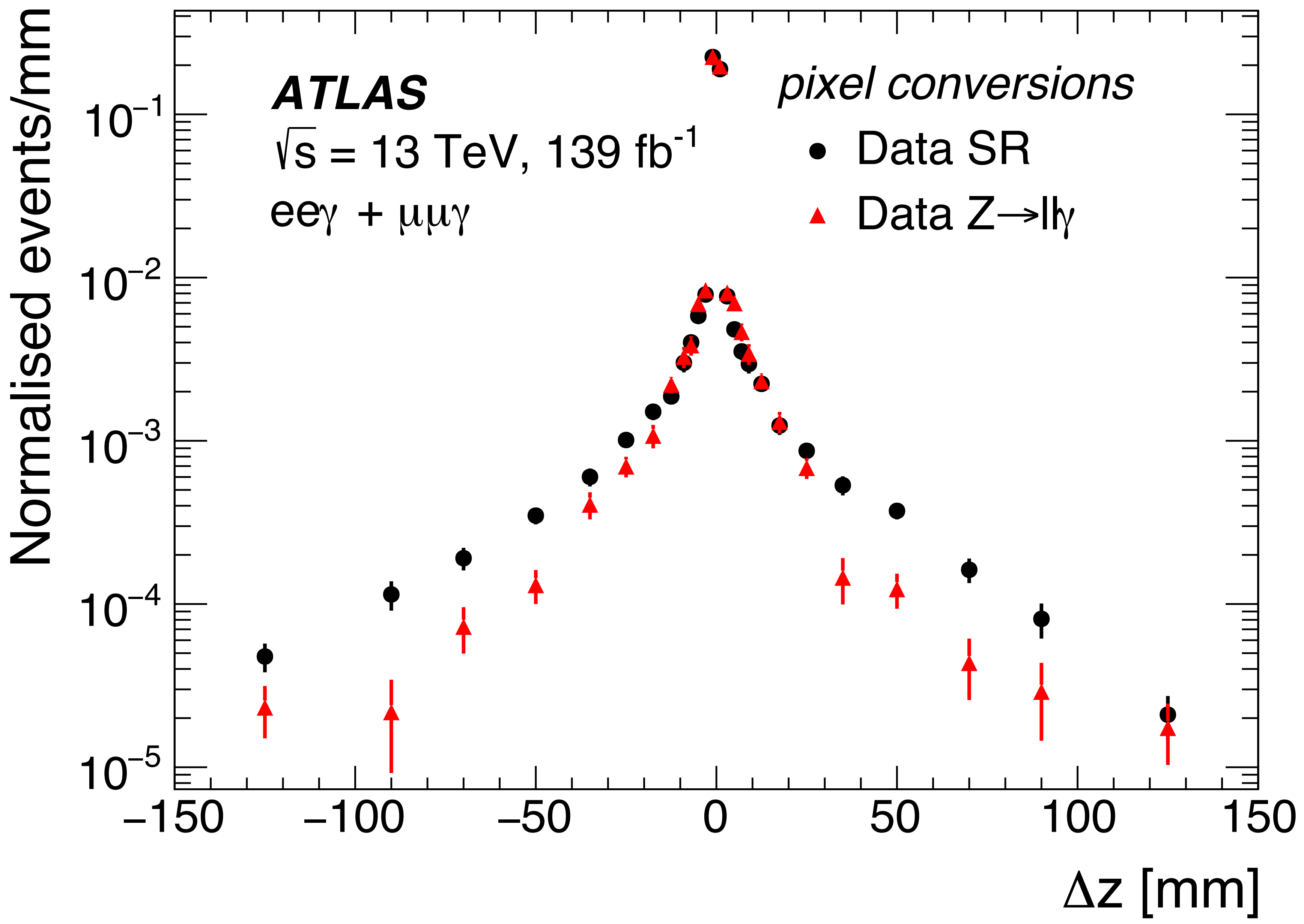
$$\frac{N^A_{fakes}}{N^C_{fakes}} = R\frac{N^B_{fakes}}{N^D_{fakes}}$$

- R accounts for ID/isolation correlation, determined from simulation
- Systematic uncertainties to account for MC inputs (R and c_X)

A Pass isolation Pass identification	**B** Fail isolation Pass identification
C Pass isolation Fail identification	**D** Fail isolation Fail identification

Pile-up background

- No tracking information for unconverted photons
- ~30 pp collisions per event, sometimes photon may originate from different interaction than Z
- $\Delta z = z_{PV} - z_{\gamma}$
- Pixel conversions: photons which convert within pixel volume (R_{conv} < 125mm, δz~0.2mm)

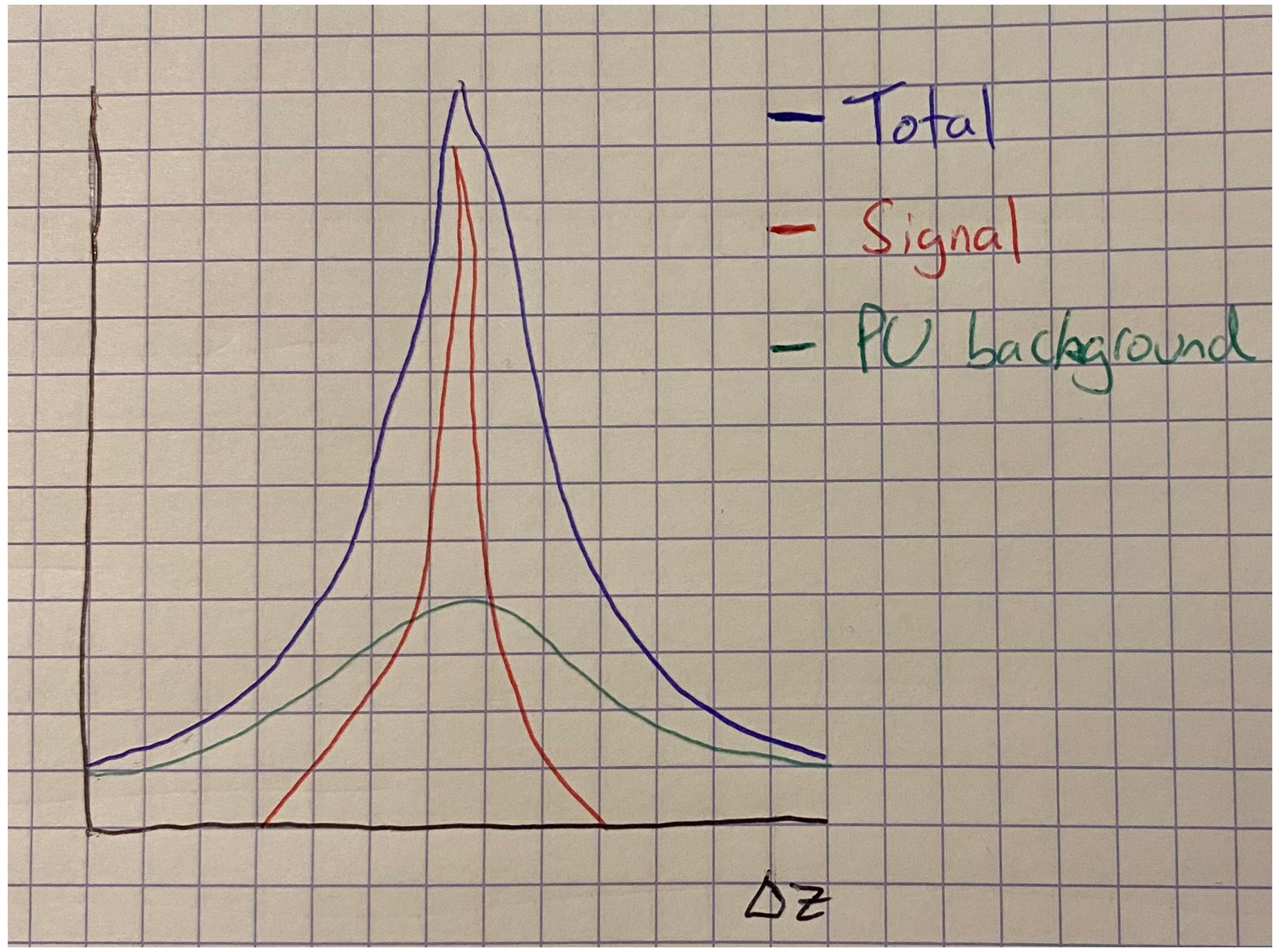


Pile-up background

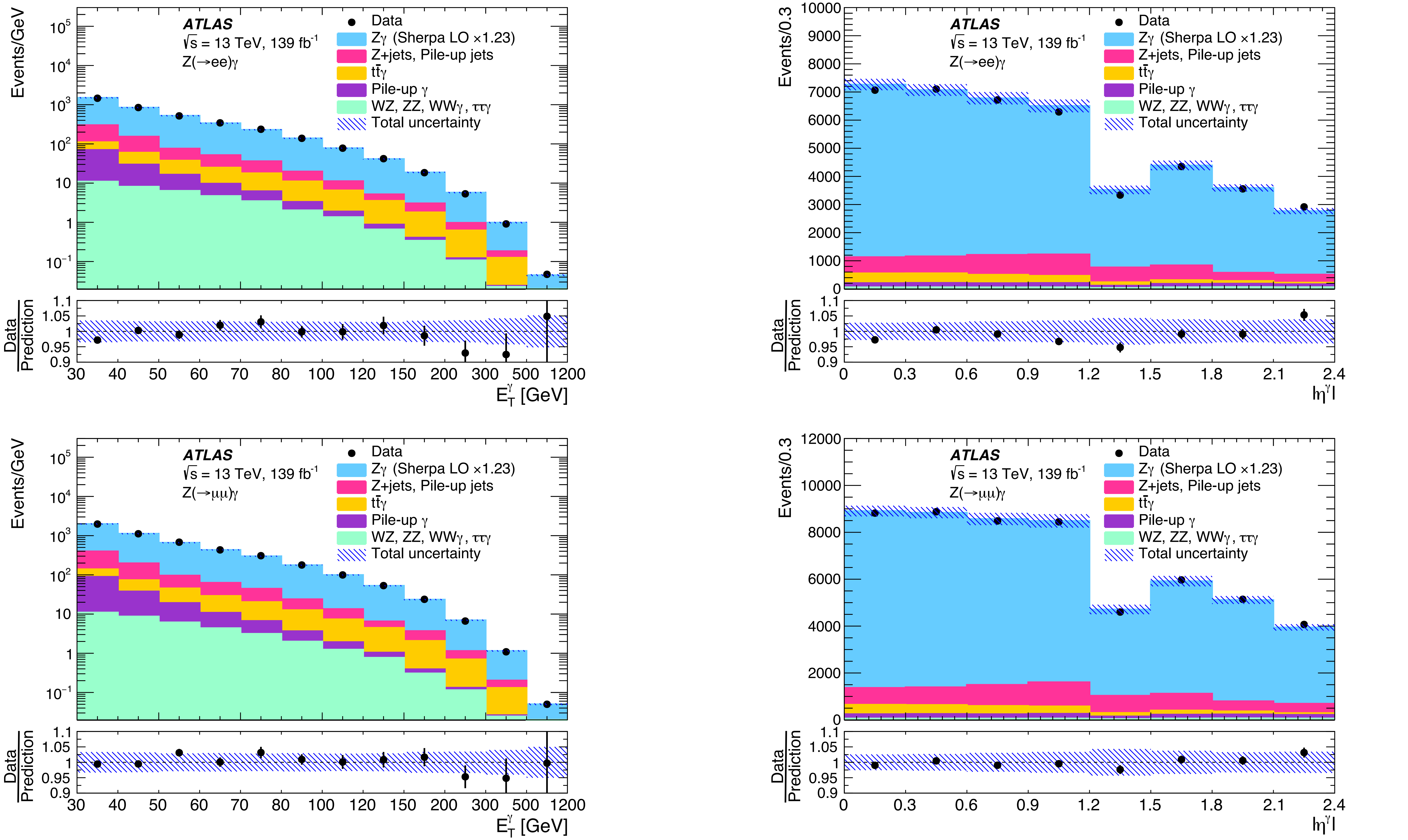
- Two components to Δz distribution
  - Single pp processes (signal) & pile-up overlay background
- PV z distribution, gaussian with width 35mm
  - Pile-up width from convolution of two gaussians →width 50mm (green)
- Measure fraction in tails then expand to full range using Gaussian behaviour

$$f_{PU} = \frac{N^{|\Delta z|>50mm}_{data,pixel-conv} - F \times N^{|\Delta z|>50mm}_{signalMC,pixel-conv}}{N_{data,pixel-conv} \times 0.32},$$

- Account for jet contribution using photon purity from single-photon data
- Total fraction: $2.5 \pm 0.5\ \%$



Detector-level distributions



Cross-section measurements

- Each channel unfolded separately, then combined accounting for correlated systematics

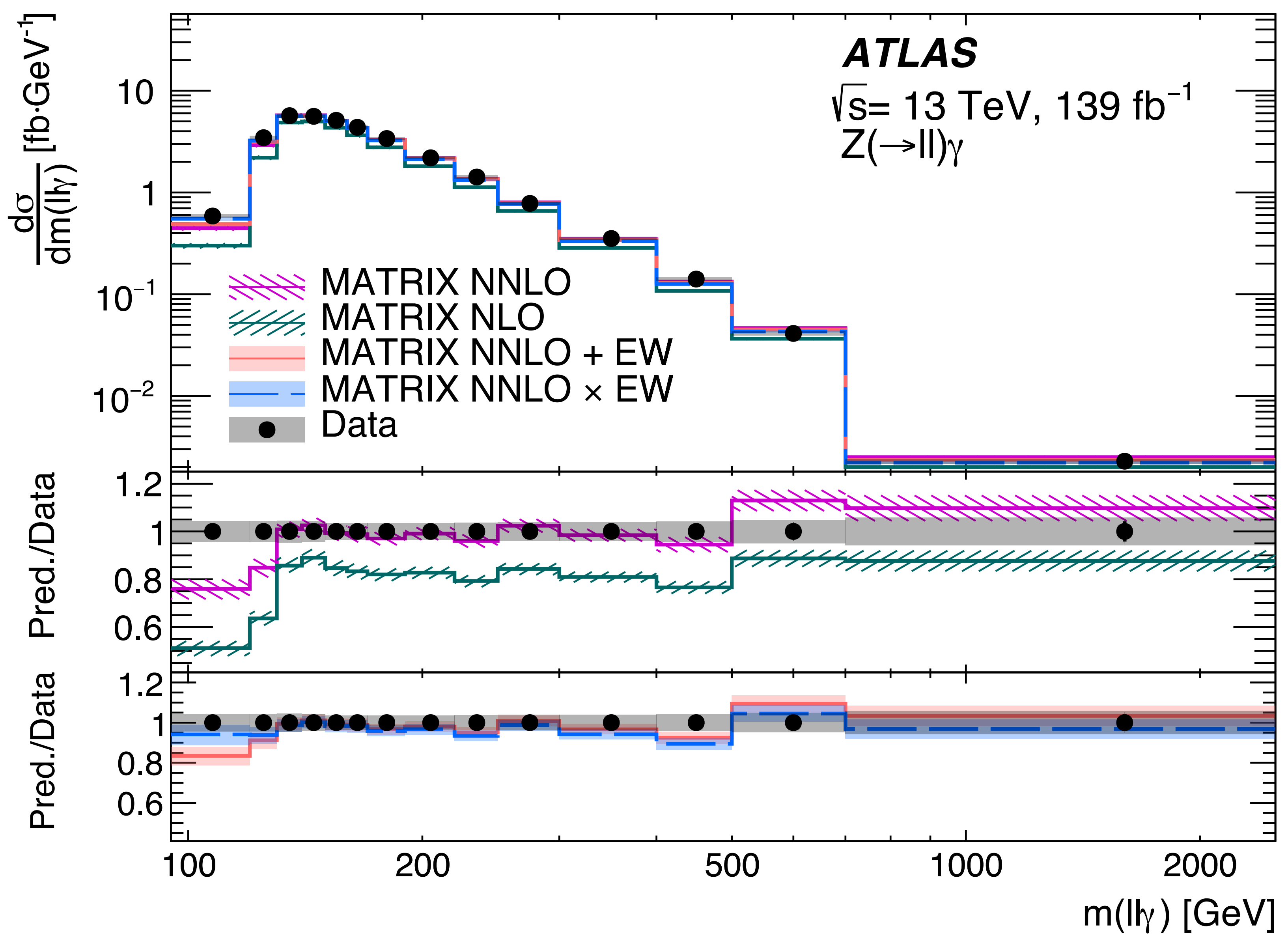
- Integrated cross-section measured with precision of 3%

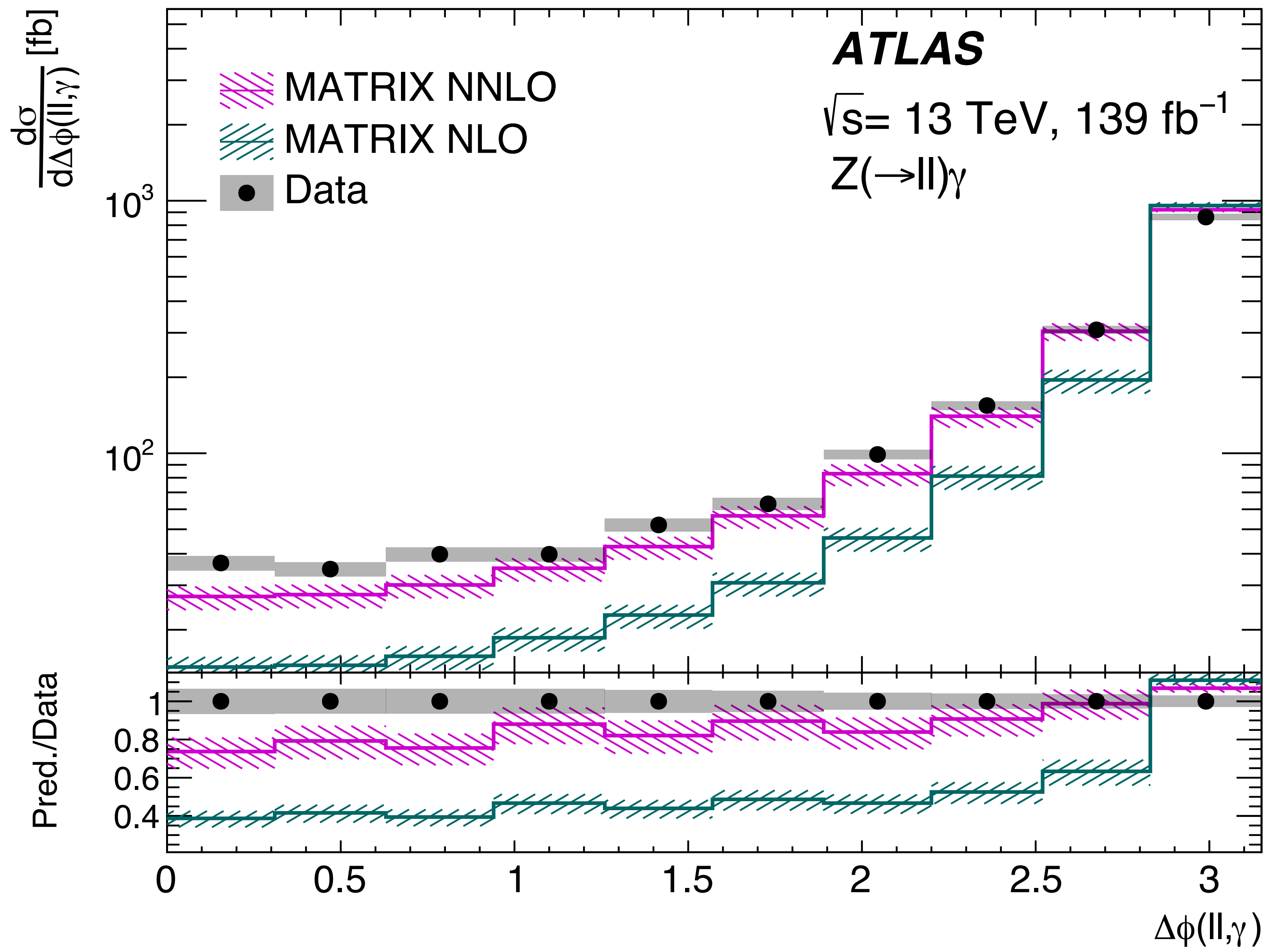
$$\sigma_{fid}^{Z(\rightarrow \ell\ell)\gamma} = 533.7 \pm 2.1(\text{stat.}) \pm 12.4(\text{syst.}) \pm 9.1(\text{lumi.})\ \text{fb}$$

- Dominant systematics from fake photon background and electron identification efficiency

- Differential cross-sections measured as a function of E_T^γ, $|\eta^\gamma|$, $m_{\ell\ell\gamma}$, $p_T^{\ell\ell\gamma}$, $p_T^{\ell\ell\gamma}/m_{\ell\ell\gamma}$ and $\Delta\phi(\ell\ell,\gamma)$

- Distributions provide precise probes of QCD modelling, compared to fixed-order calculations from MATRIX





Conclusions

- $Z(\rightarrow \ell\ell)\gamma$ was measured for the first time at 13 TeV
- Measured for the first time in a novel phase space, dominated by ISR production of photons
- Extremely precise measurement, 3% integrated cross-section
- Differential measurements provide excellent probe of QCD modelling and highlight importance of NNLO QCD and NLO EWK corrections

$Z\gamma\gamma$ measurement

Selections

Electrons

- $p_T > 30, 20$ GeV
- $|\eta| < 2.47$ excl. $1.37 < |\eta| < 1.52$
- PV consistency
- ID and isolation criteria

Muons

- $p_T > 30, 20$ GeV
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Photons

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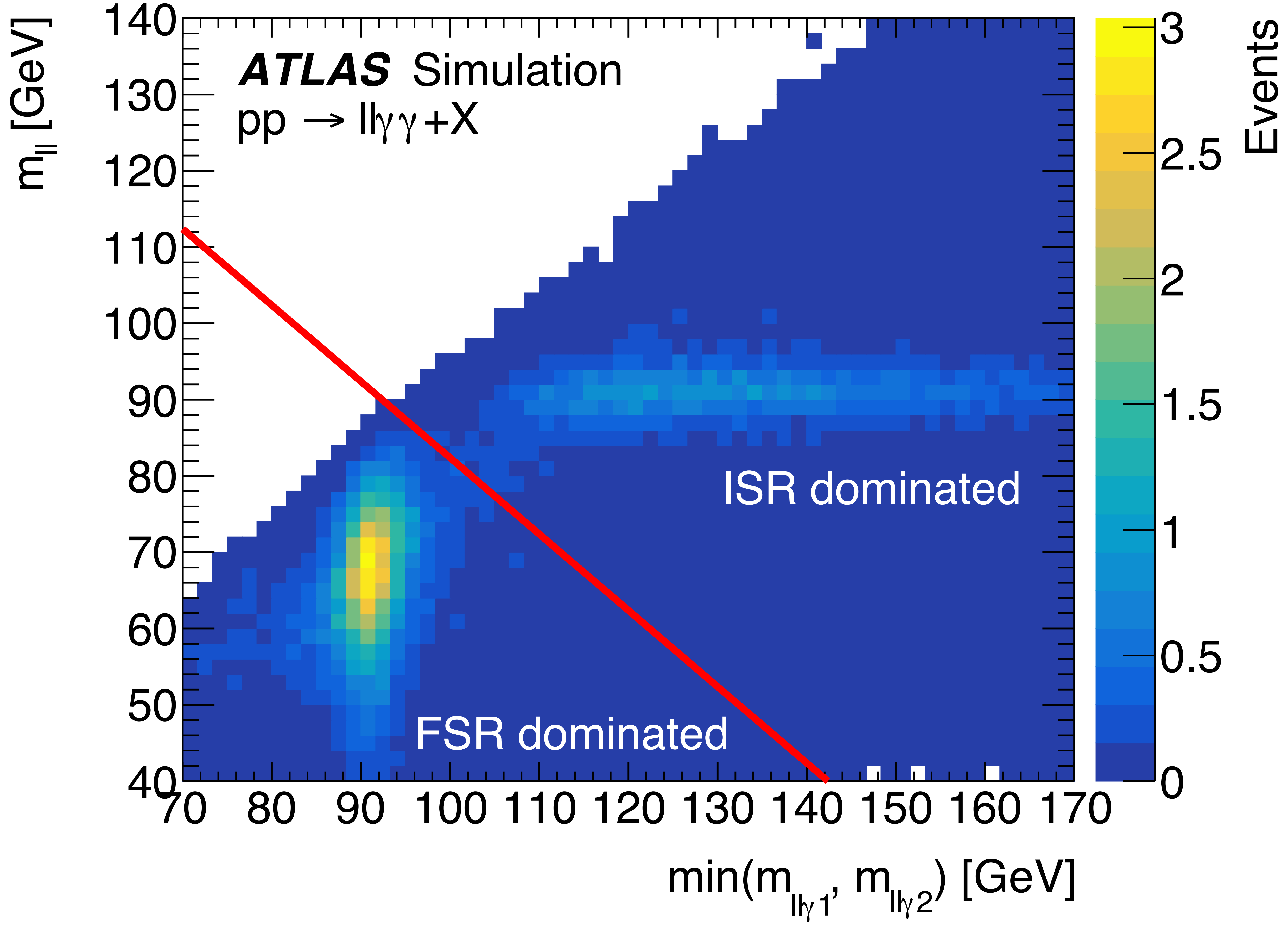
- ID and isolation criteria

Event

- $m_{\ell\ell} > 40$ GeV
- $\Delta R(\ell, \gamma) > 0.4$
- $m_{\ell\ell} + \min(m_{\ell\ell\gamma 1}, m_{\ell\ell\gamma 2}) > 2m_Z$

- Select ~320 events in signal region

FSR removal



ATLAS Simulation
pp → llγγ+X
ISR dominated
FSR dominated
m_ll [GeV]
min(m_llγ1, m_llγ2) [GeV]
Events
140
130
120
110
100
90
80
70
60
50
40
70 80 90 100 110 120 130 140 150 160 170
0 0.5 1 1.5 2 2.5 3

Background summary

Fake photon background (20%)

- Jets misidentified as photons
- Data-driven method

Top background (5%)

- Constrain normalisation in $e\mu\gamma\gamma$ CR
- Shapes from simulation

Pile-up background (3%)

- Two contributions: $Z + \gamma\gamma$, $Z\gamma + \gamma$
- Overlay simulation at fiducial level
- “Fold” to detector-level using signal simulation

Multi-boson (2%)

- $ZZ \to \ell\ell\ell\ell$, $WZ\gamma \to \ell\nu\ell\ell\gamma$, $Z(\to \ell\ell)H(\to \gamma\gamma)$
- From simulation

Fake photon backgrounds

A	B
Pass isolation Pass identification	Fail isolation Pass identification
C	**D**
Pass isolation Fail identification	Fail isolation Fail identification

- Three background processes to consider: $Z\gamma j$, $Zj\gamma$ and Zjj
- Categorise each photon candidate as A, B, C or D → 16 regions
- Map contributions of each process into 4 regions (AA, AB, BA, BB) with 4x4 matrix:

$$\begin{pmatrix} N^{AA} \\ N^{AB} \\ N^{BA} \\ N^{BB} \end{pmatrix} = \begin{pmatrix} \epsilon_1\epsilon_2 & \epsilon_1 f_2 & f_1\epsilon_2 & f_1 f_2 \\ \epsilon_1(1-\epsilon_2) & \epsilon_1(1-f_2) & f_1(1-\epsilon_2) & f_1(1-f_2) \\ (1-\epsilon_1)\epsilon_2 & (1-\epsilon_1)f_2 & (1-f_1)\epsilon_2 & (1-f_1)f_2 \\ (1-\epsilon_1)(1-\epsilon_2) & (1-\epsilon_1)(1-f_2) & (1-f_1)(1-\epsilon_2) & (1-f_1)(1-f_2) \end{pmatrix} \begin{pmatrix} W_{Z\gamma\gamma} \\ W_{Z\gamma j} \\ W_{Zj\gamma} \\ W_{Zjj} \end{pmatrix}.$$

$$\epsilon_1 = \frac{N_{AA}^{sig}}{N_{AA}^{sig} + N_{BA}^{sig}}$$

Photon isolation efficiency (from signal simulation)

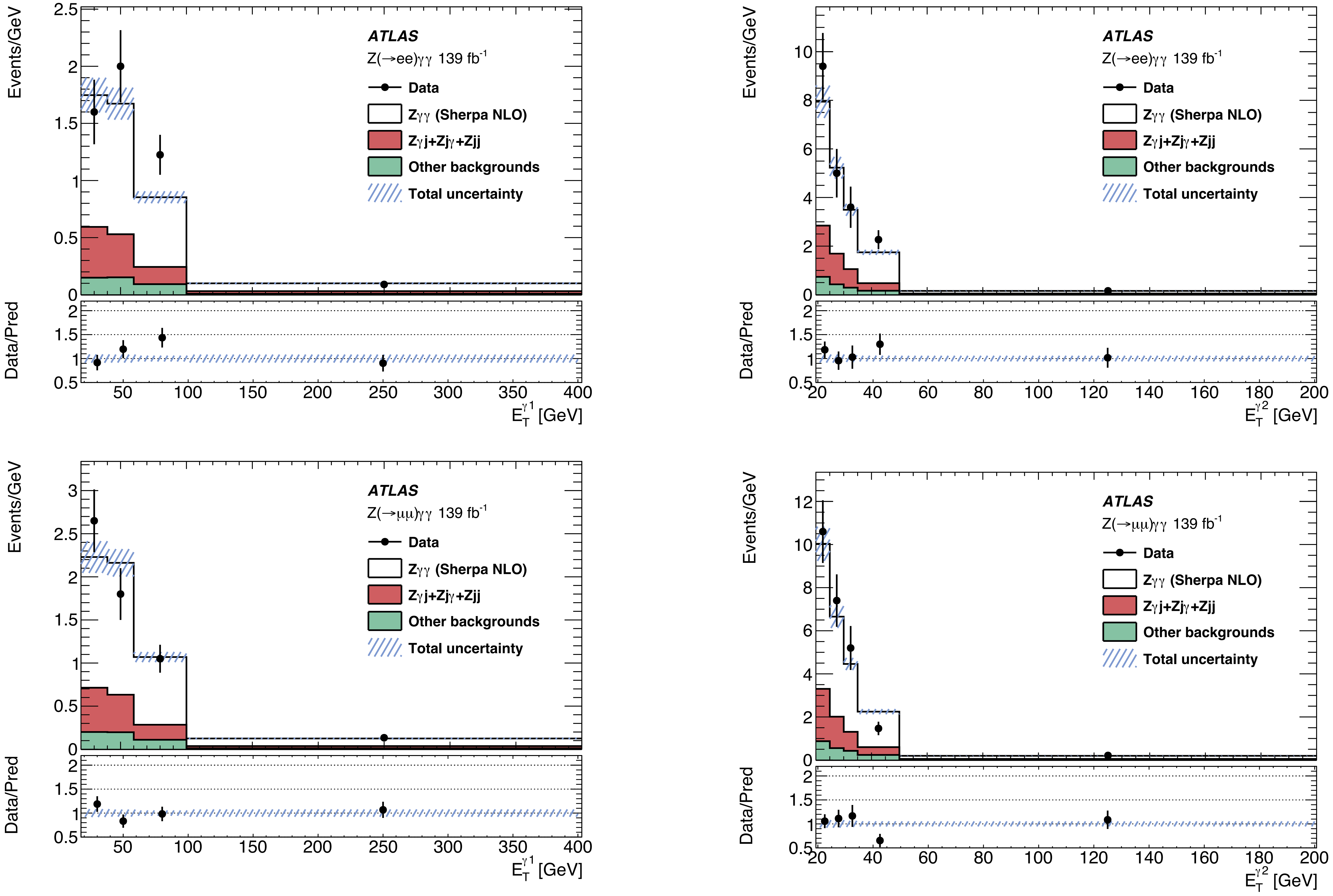
$$f_1 = \frac{(N_{CA} - c_{CA}N_{AA}^{sig})R_1}{(N_{CA} - c_{CA}N_{AA}^{sig})R_1 + N_{DA} - c_{DA}N_{AA}^{sig}}$$

Jet isolation fake rate (from data with signal leakage subtracted)

Fake photon backgrounds

- Data-driven method gives background normalisations
  - $Z\gamma j : 8.2 \pm 2.6\,\%\,, Zj\gamma : 9.1 \pm 2.3\,\%\,, Zjj : 2.8 \pm 1.1\,\%$
- Shapes taken from simulation using truth-level matching to select fake photon process
- Systematics to account for:
  - Choice of control regions
  - Parameters from simulation
  - Isolation efficiency dependence on p_T^γ
  - Shape uncertainties for the templates from simulation

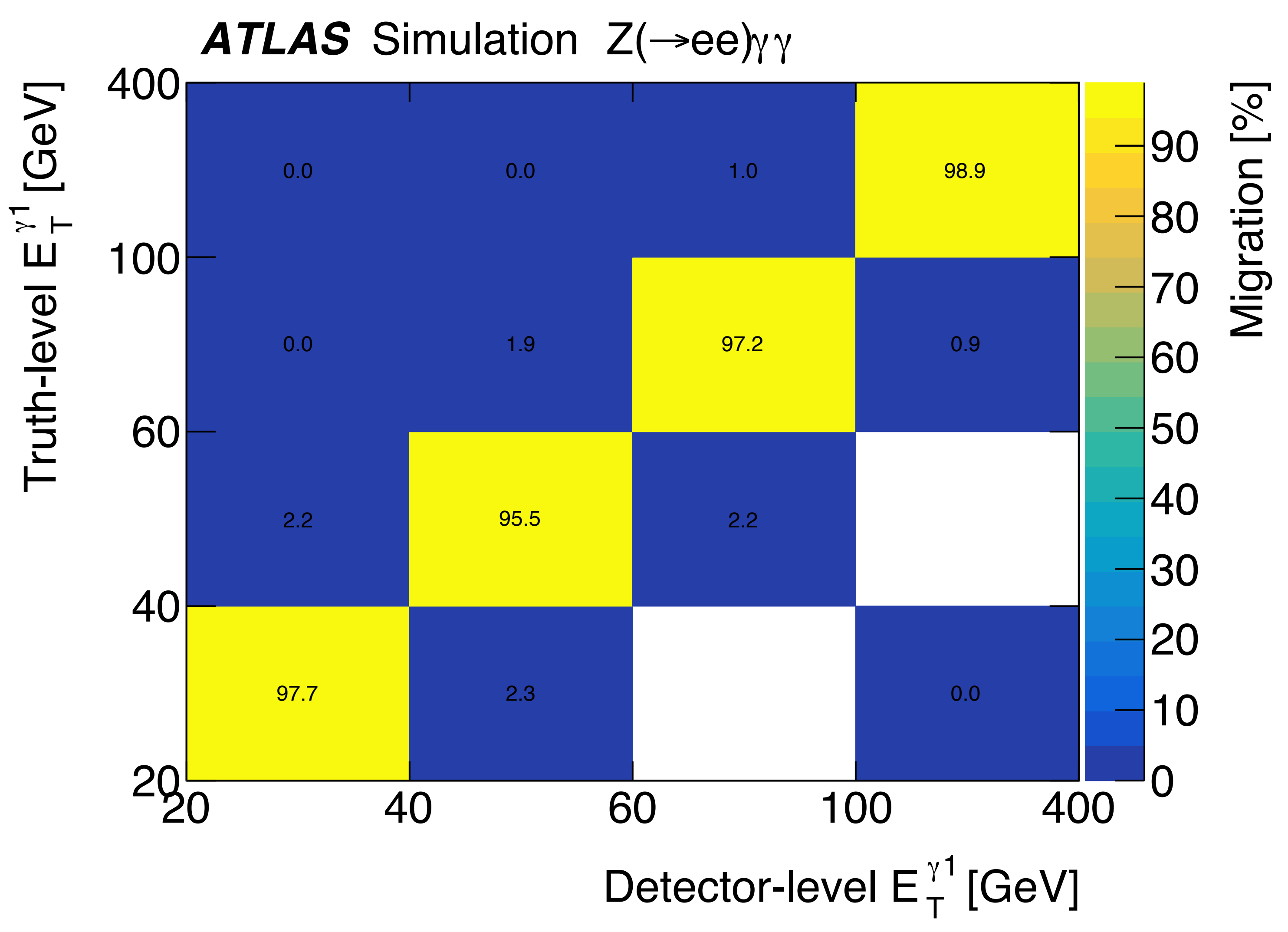
Detector-level distributions

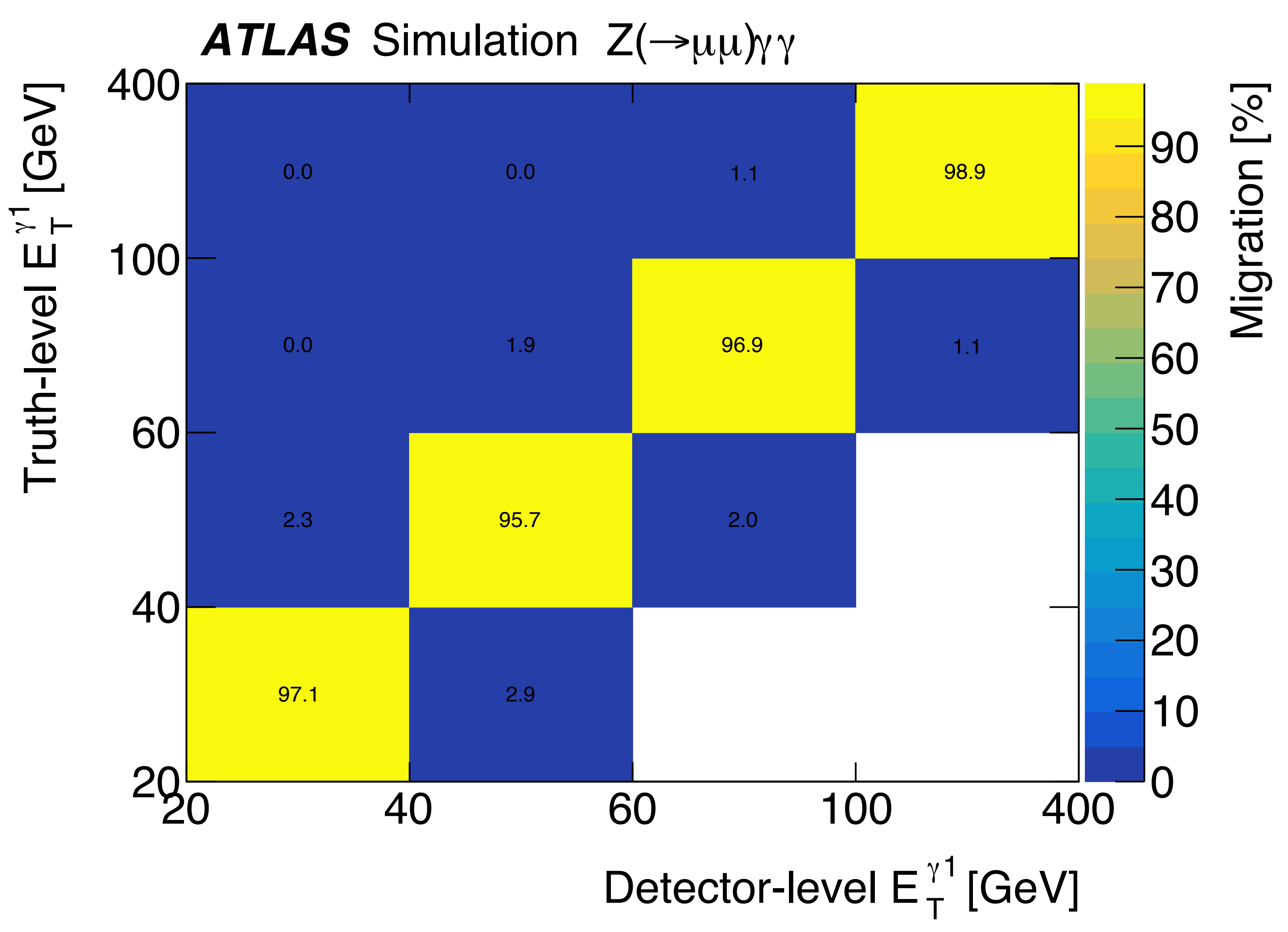


- Binning optimised in order to have sufficient number of events to unfold

Unfolding

- Iterative Bayesian unfolding
- Migrations small, typically <5% per bin
- Unfolded separately in each channel
- Channels combined after unfolding, accounting for correlated uncertainties



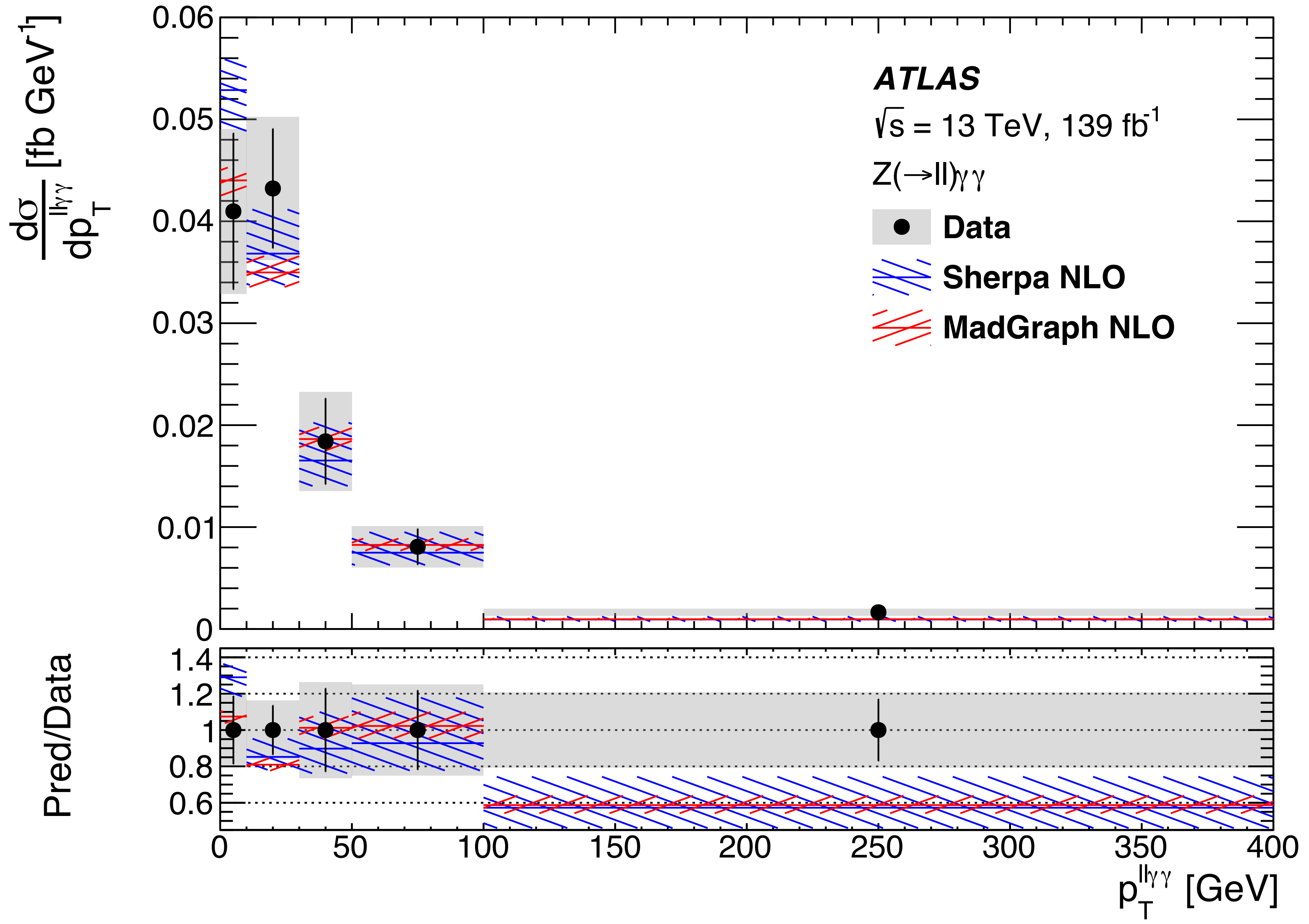


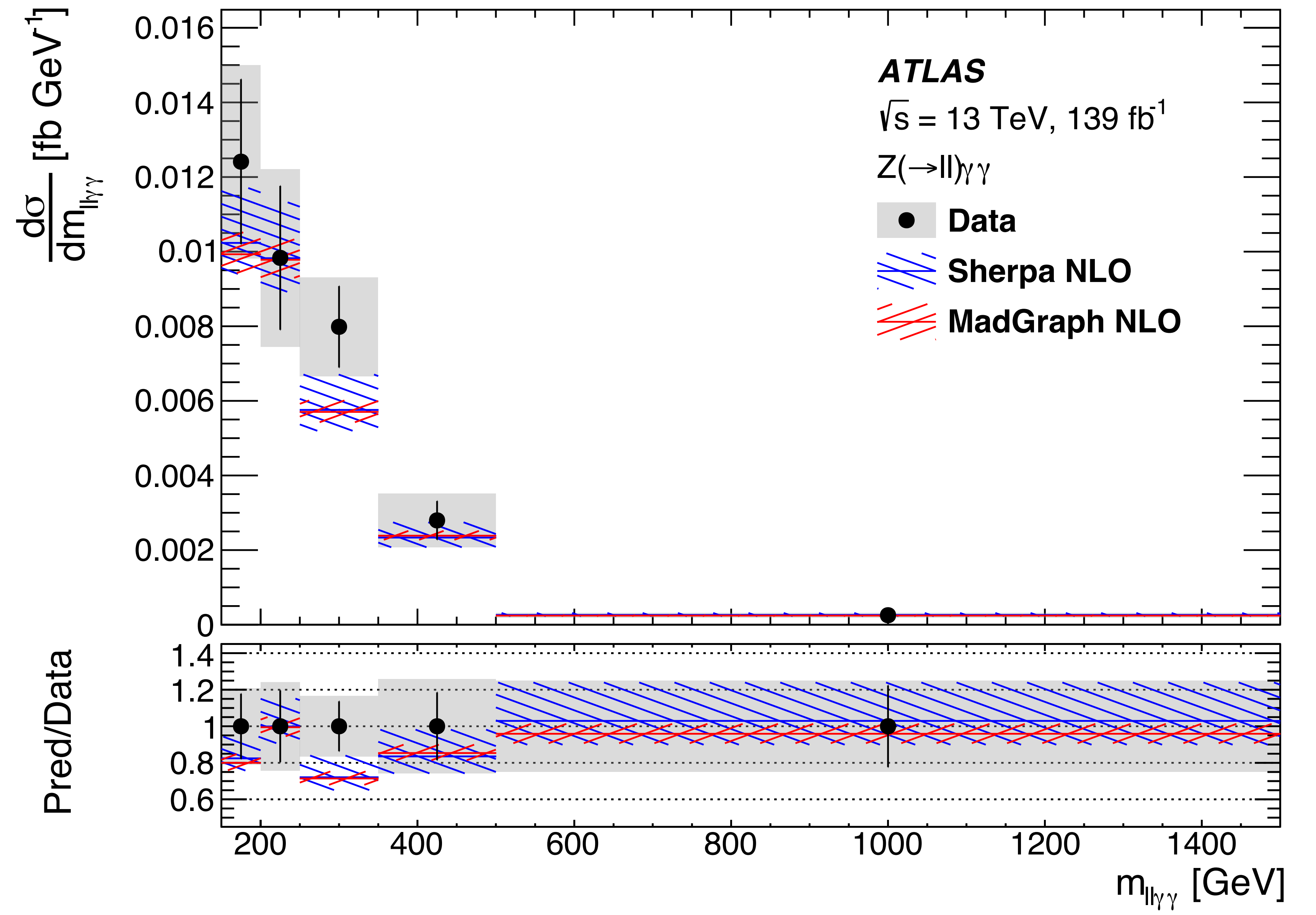
Cross-section measurements

- Integrated fiducial cross-section measured with a precision of 12%

$$\sigma_{fid}^{Z(\to\ell\ell)\gamma\gamma} = 2.45 \pm 0.20(\text{stat.}) \pm 0.22(\text{syst. + lumi.})\ \text{fb}$$

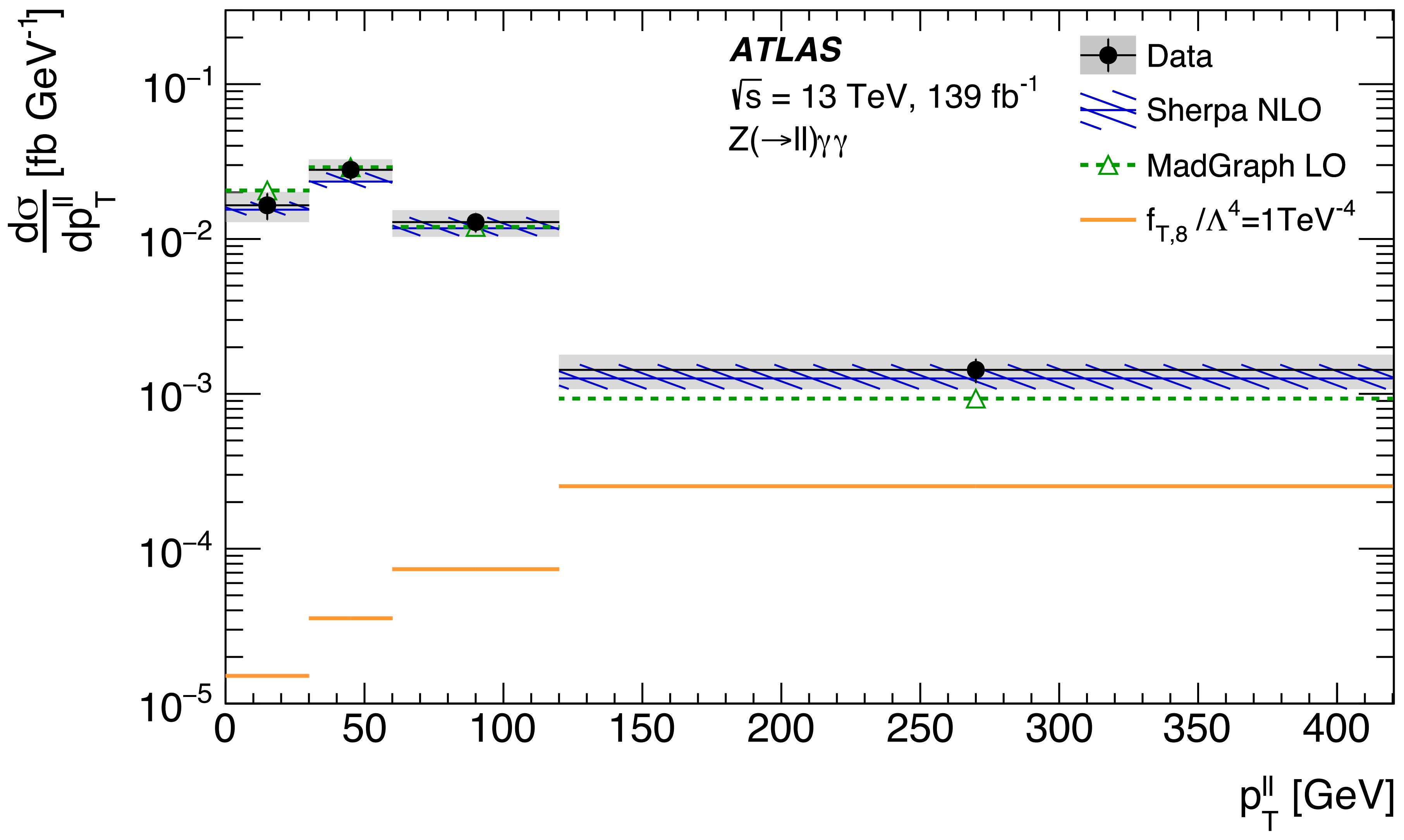
- Dominant uncertainties from data statistics and fake photon background
- Differential cross-sections measured as a function of $E_T^{\gamma 1}$, $E_T^{\gamma 2}$, $p_T^{\ell\ell}$, $p_T^{\ell\ell\gamma\gamma}$, $m_{\gamma\gamma}$ and $m_{\ell\ell\gamma\gamma}$
- Sherpa NLO@0j + LO@1,2j, Madgraph NLO@0,1j
- Data described well by the predictions in most regions, except high $p_T^{\ell\ell\gamma\gamma}$

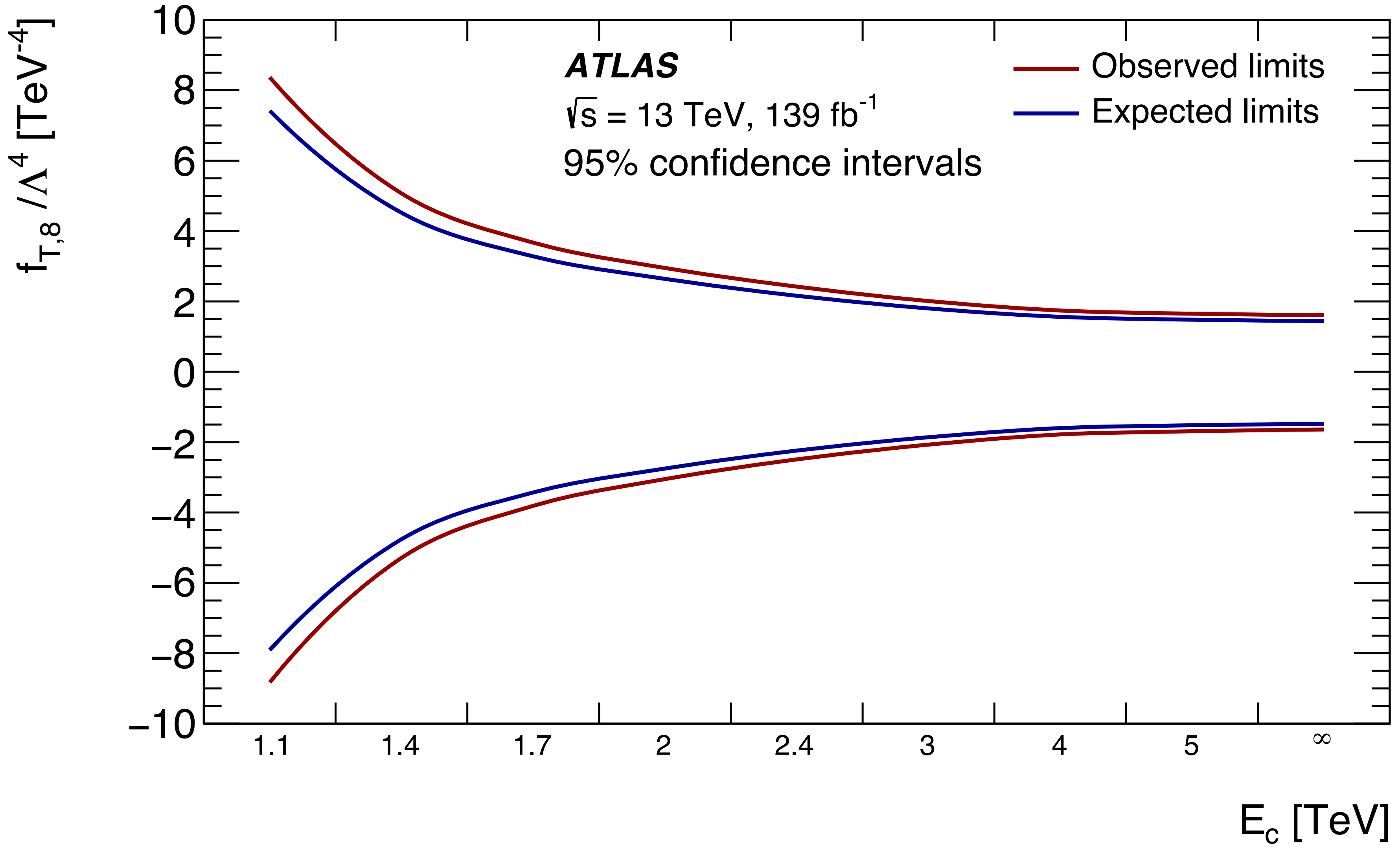




EFT interpretation

- $p_T^{\ell\ell}$ is the most sensitive variable measured
- Limits placed on 8 Wilson coefficients characterising anomalous aQGCs
- Limits improved by ~2 orders of magnitude w.r.t 8 TeV analyses
- Limits restricted by binning which was optimised for cross-section measurements, not EFT interpretation





Conclusions

- $Z(\rightarrow \ell\ell)\gamma\gamma$ measured by ATLAS at 13 TeV
- First measurements of purely ISR process
- Differential cross-sections measured for the first time
- Dimension-8 Wilson coefficient limits greatly improved w.r.t. 8 TeV analysis

Summary

Summary

- A plethora of SM processes are being measured at the LHC
  - Two results from ATLAS presented
- LHC Run 2 dataset allows for extremely precise measurements, which demand more precise and accurate predictions for comparison
- Also allows for measurements of rarer processes
- The SM remains steadfast and highly consistent!
  - Measurements allow us to place limits on new physics
- Run 3/HL-LHC will allow us to further drive precision