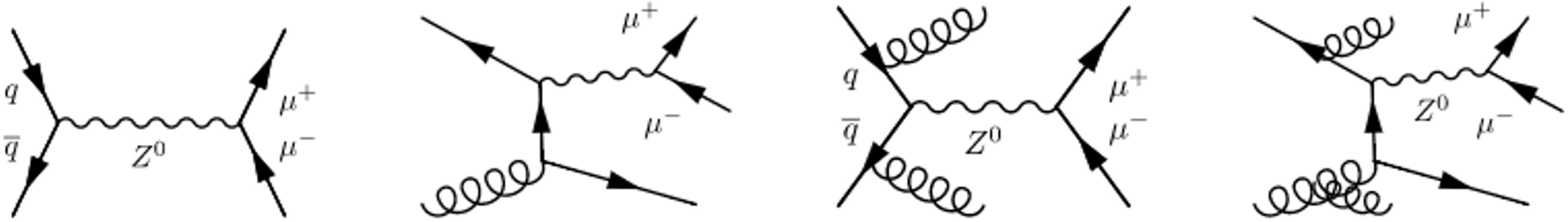
Measurement of Z boson production at ATLAS

Aleksei Ezhilov

Petersburg Nuclear Physics Institute

on behalf of ATLAS Collaboration

Introduction



(a) Leading Order (b) Next to leading order (c) Parton shower (d) Next to leading + parton shower

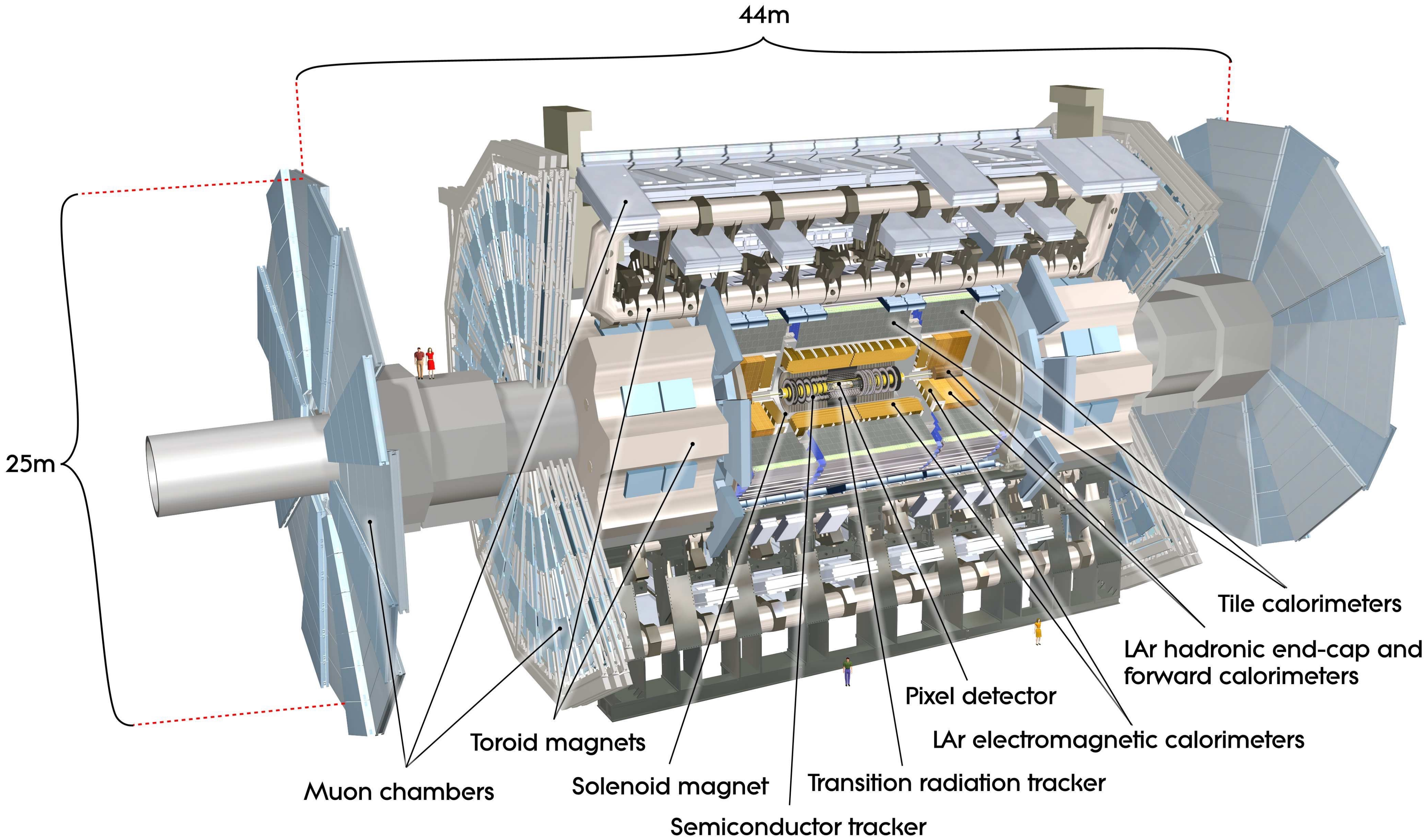
Z boson production are important:

- tests of perturbative QCD
- rapidity distributions sensitive to PDF (initial kinematics)
- input to the background predictions – used in many analysis (SM and BSM)
- constrain for p_T^W spectrum – important for W-boson mass measurements

This talk will cover:

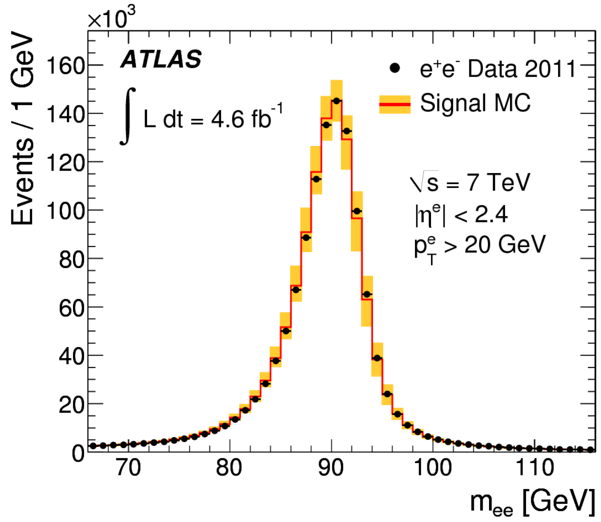
- p_T and ϕ_η^* of Drell-Yan lepton pairs at 7 TeV
[Phys. Lett. B 720 (2013) 32-51]
- p_T and ϕ_η^* of Drell-Yan lepton pairs at 8 TeV
[Eur. Phys. J. C 76 (2016) 291]
- p_T and ϕ_η^* of Drell-Yan lepton pairs at 13 TeV
[Eur. Phys. J. C 80 (2020) 616]
- Z + bjets cross-section at 13 TeV
[JHEP 07 (2020) 44]

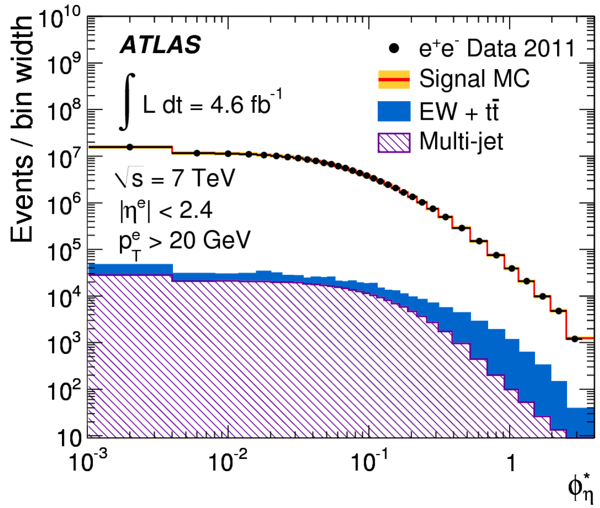
ATLAS experiment at LHC



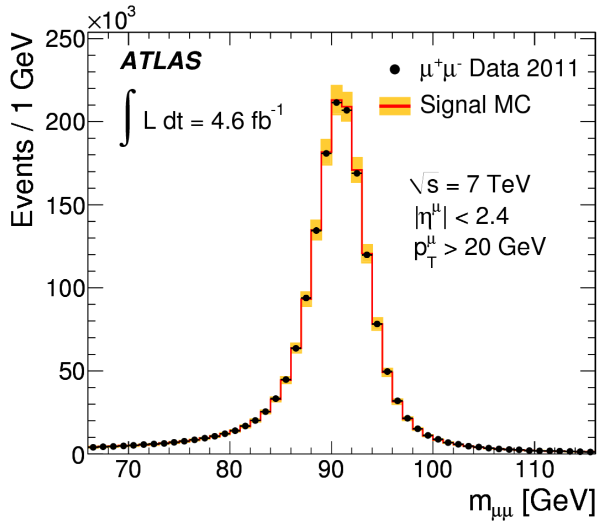
Measurement of the ϕ^*_η at 7 TeV

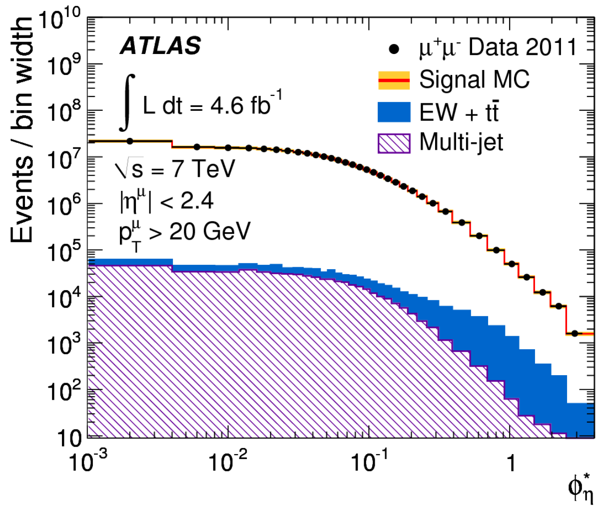
ee - channel





μμ - channel



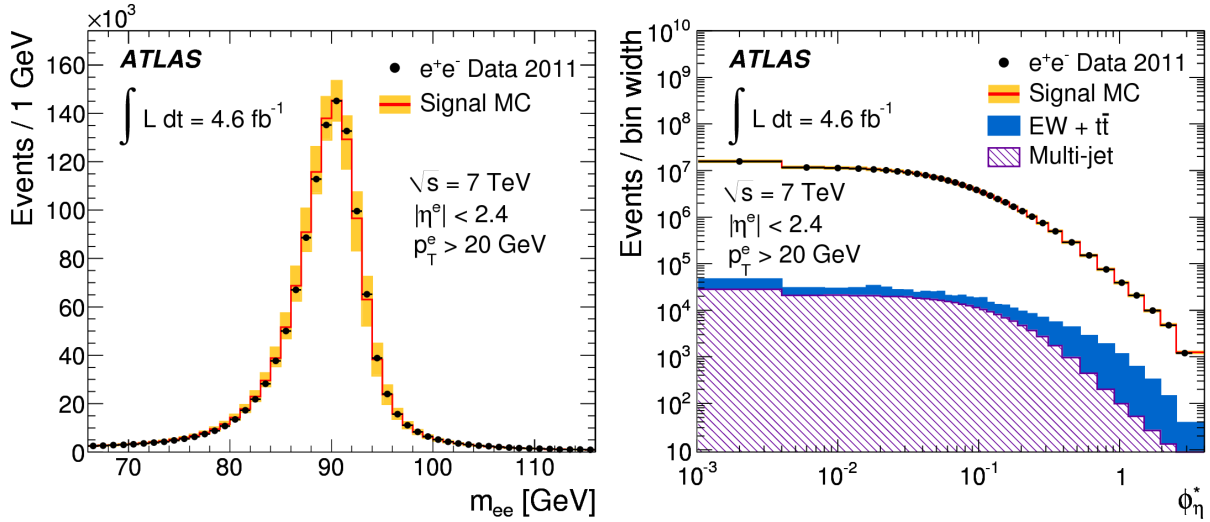


$$pp \to Z/\gamma^* \to ll(l = e, \mu)$$

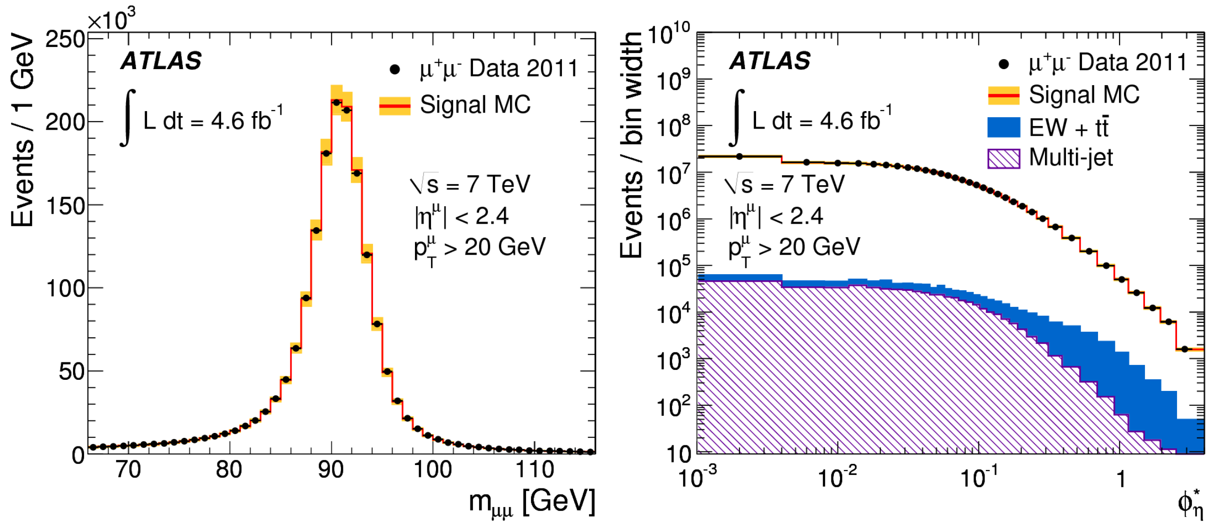
- Data collected in 2011
  ($\sqrt{s}$ = 7 TeV, $\mathcal{L}_{int}$ = 4.6 fb^{-1})
- Selections: single lepton trigger,
  - ✓ $p_T^{e\ leading} > 25$ GeV
  - ✓ $p_T^{e\ subleading} > 20$ GeV
  - ✓ $|\eta^e| < 2.4$ excluding $1.37 < |\eta^e| < 1.52$
  - ✓ $p_T^{\mu} > 20$ GeV
  - ✓ $|\eta^{\mu}| < 2.4$
  - ✓ 66 GeV $< m_{ll} <$ 116 GeV
- MC signal:
  POWHEG+PYTHIA
- Backgrounds:
  multi-jet - data-driven method
  EW and ttbar from MC

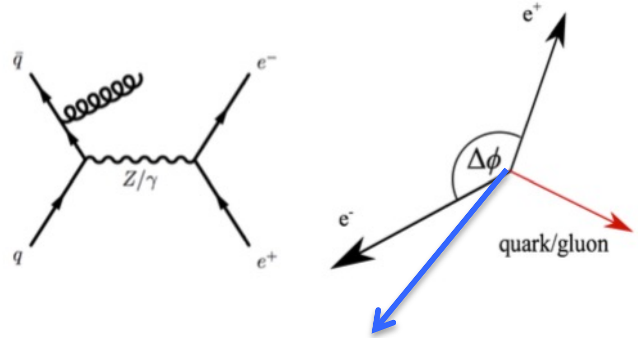
Measurement of the ϕ^*_η at 7 TeV

ee - channel



μμ - channel





$$\phi^*_\eta = \tan\left(\frac{\pi - \Delta\phi}{2}\right)\sin\theta^*_\eta$$

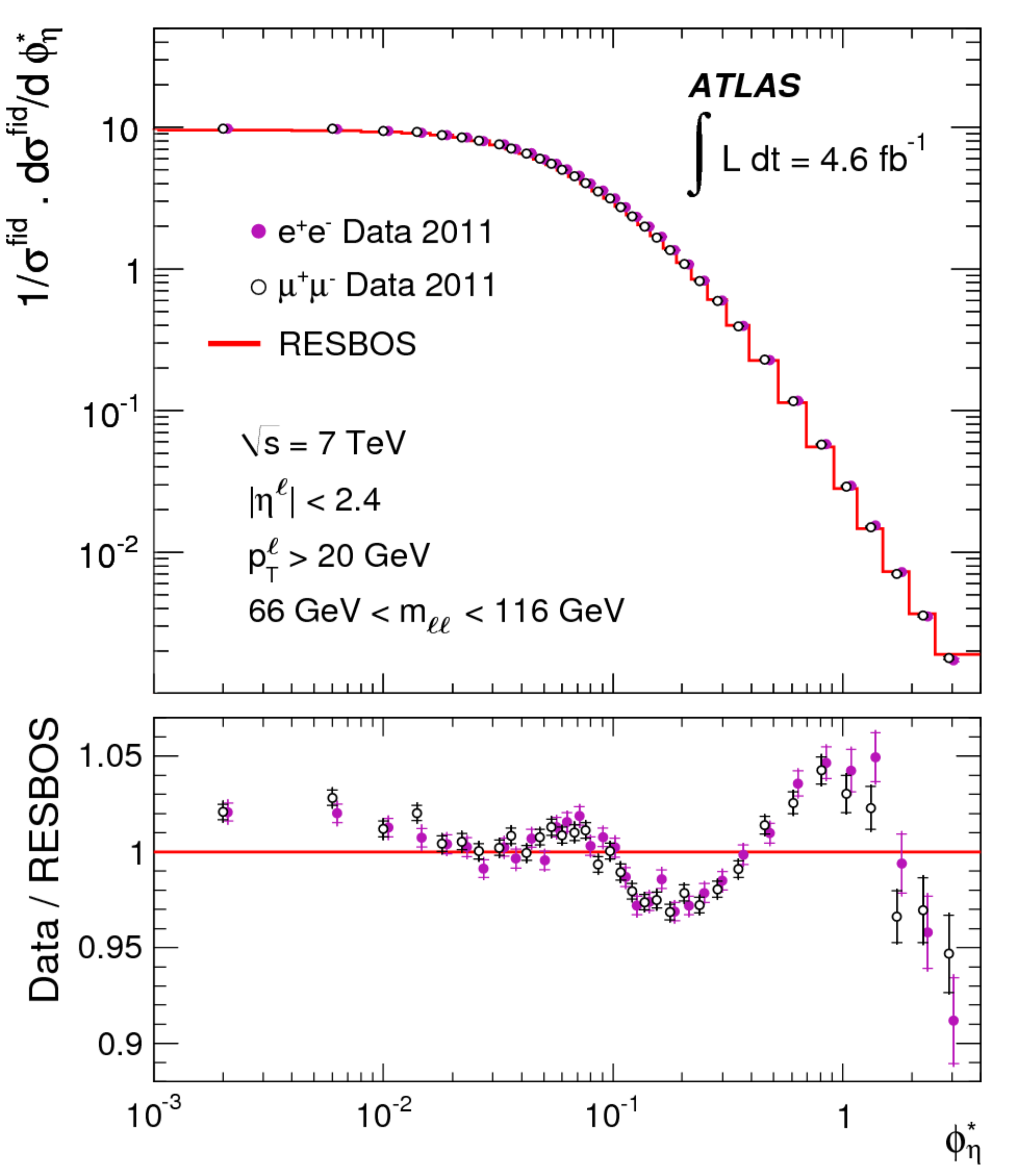
$$\theta^*_\eta = \arccos\left(\tanh\frac{\eta^- - \eta^+}{2}\right)$$

- independent for p_T calibration and resolution of the final-state leptons
- ϕ^*_η provide excellent experimental precision at low p_T^Z
- depends only on the directions of the two leptons (measured better than their momenta)

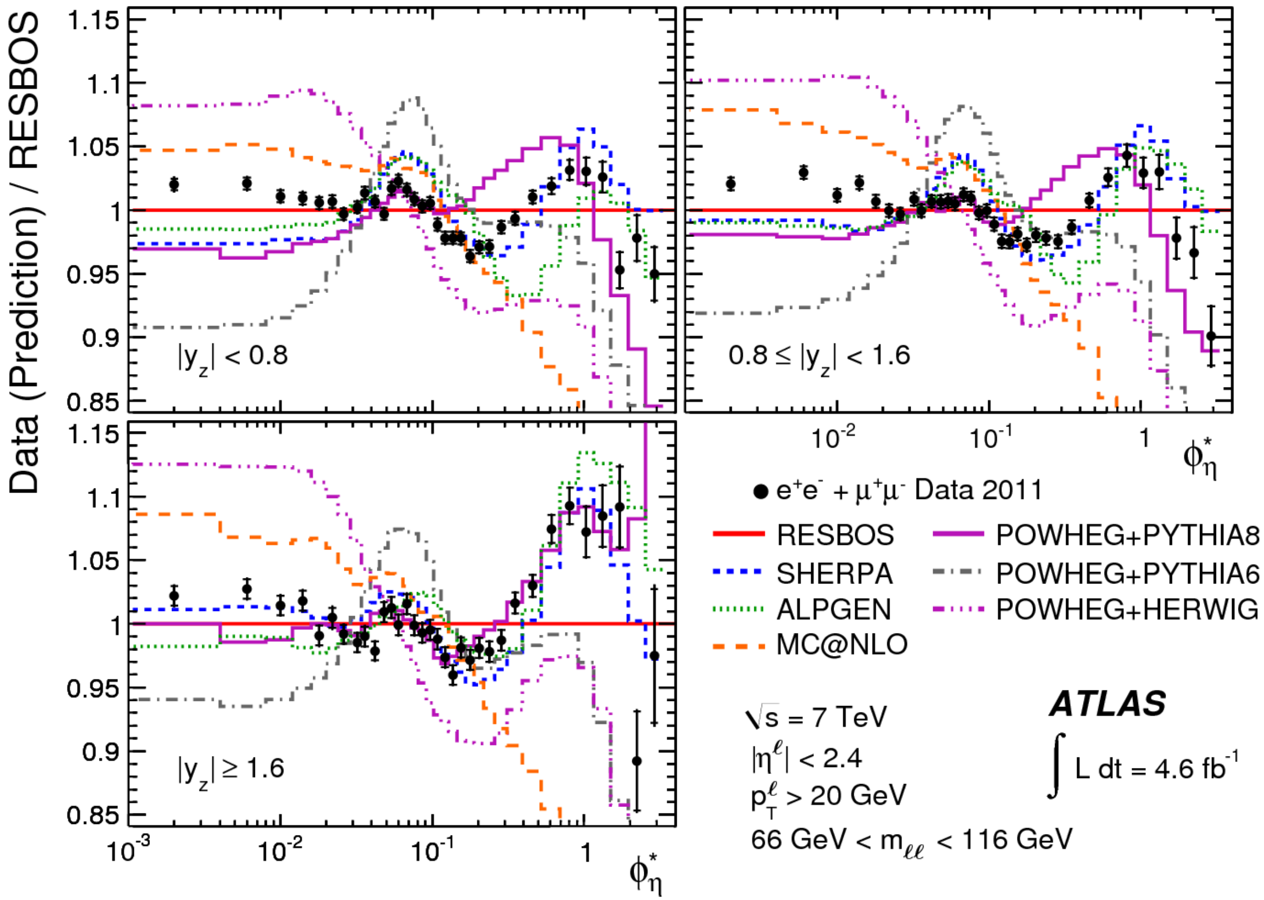
Measurement of the ϕ^*_η at 7 TeV

- Differential distributions are corrected for the detector acceptance and inefficiencies, bin-to-bin migrations using an iterative Bayesian unfolding procedure in a fiducial volume:
  $p_T^l > 20$ GeV, $|\eta^l| < 2.4$,
  66 GeV $< m_{ll} <$ 116 GeV
- The results in the individual channels are combined using χ^2 minisation
- Result: χ^2/n_{dof}=33.2/34

- Calculations using ResBos provide the best descriptions of the data (at the level of 4%).

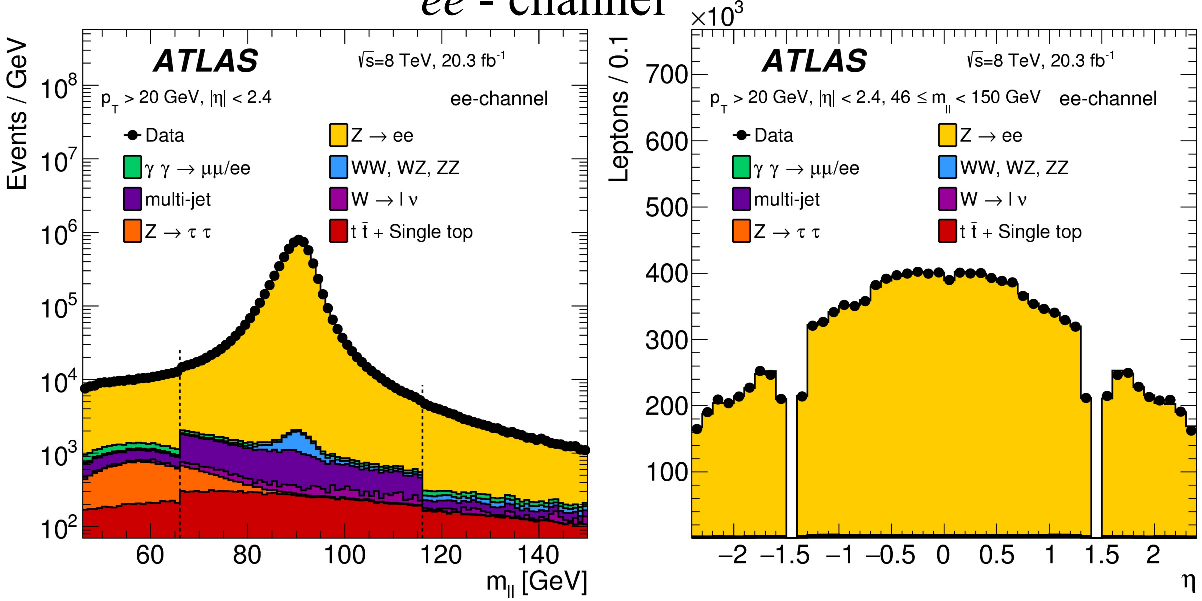


Measurement of the ϕ^*_η at 7 TeV

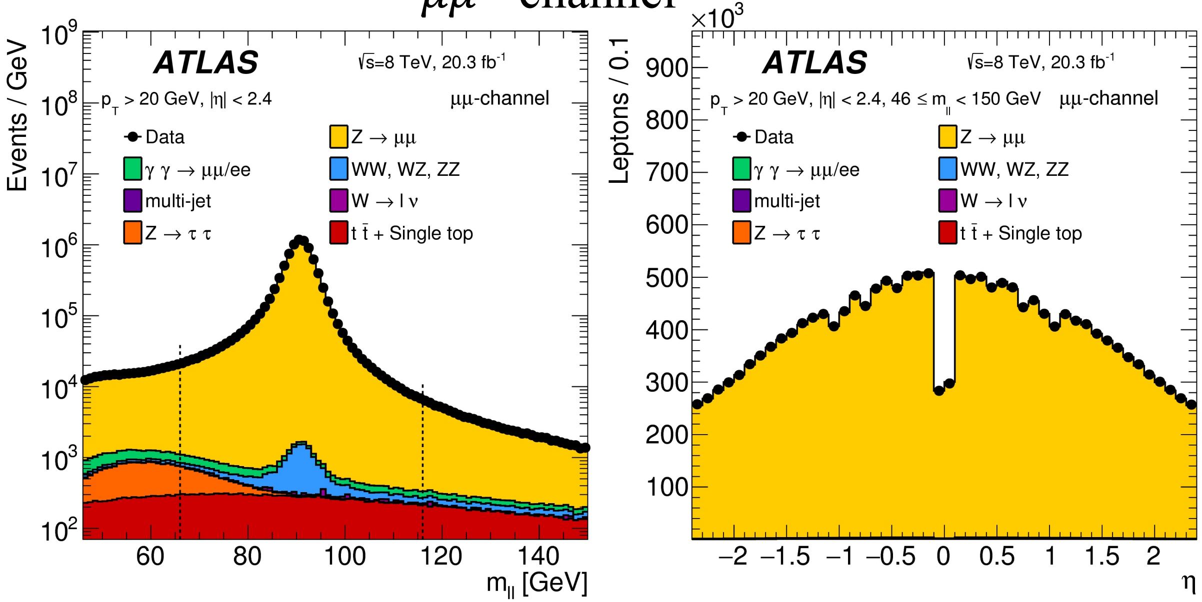


- The cross-section measurements have also been compared to predictions from different Monte Carlo generators (different PS algorithm)
- The best descriptions: Sherpa and Powheg+Pythia8
- The low ϕ^*_η part of the spectrum is better described by ResBos.
- Double differential measurements as a function of ϕ^*_η and y_Z provide valuable information for the tuning of MC generators.

ee - channel



μμ - channel

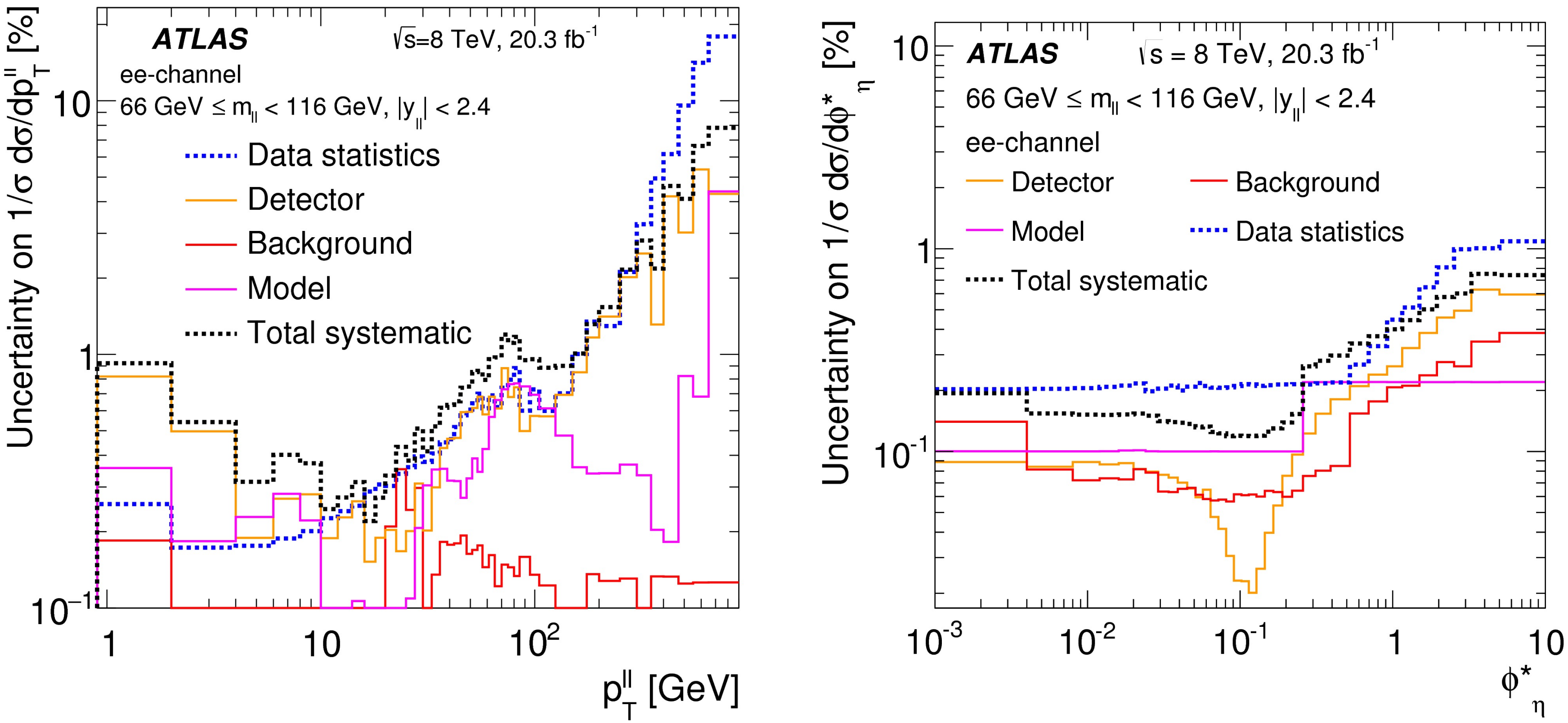


$$pp \to Z/\gamma^* \to ll(l = e, \mu)$$

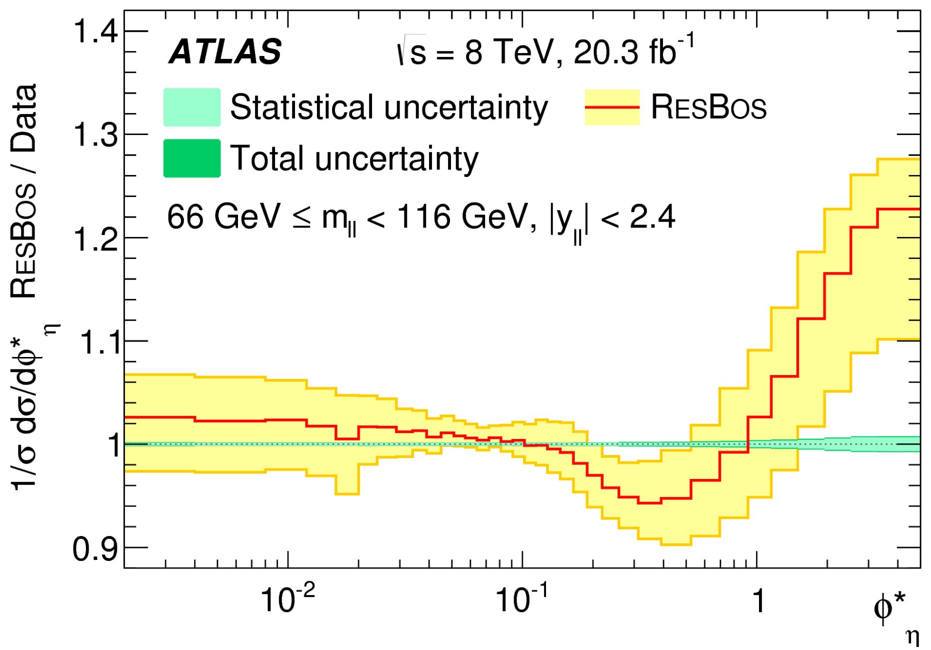
- Data collected in 2012 ($\sqrt{s} = 8$ TeV, $\mathcal{L}_{int} = 20.3$ fb^{-1})
- Selections: combination of single lepton and dilepton trigger, isolated leptons,
  - ✓ $p_T^e > 20$ GeV
  - ✓ $|\eta^e| < 2.4$ excluding $1.37 < |\eta^e| < 1.52$
  - ✓ $p_T^\mu > 20$ GeV
  - ✓ $|\eta^\mu| < 2.4$
  - ✓ 46 GeV $< m_{ll} <$ 150 GeV
- MC signal: POWHEG+PYTHIA
- Backgrounds: multi-jet - data-driven method EW and ttbar from MC

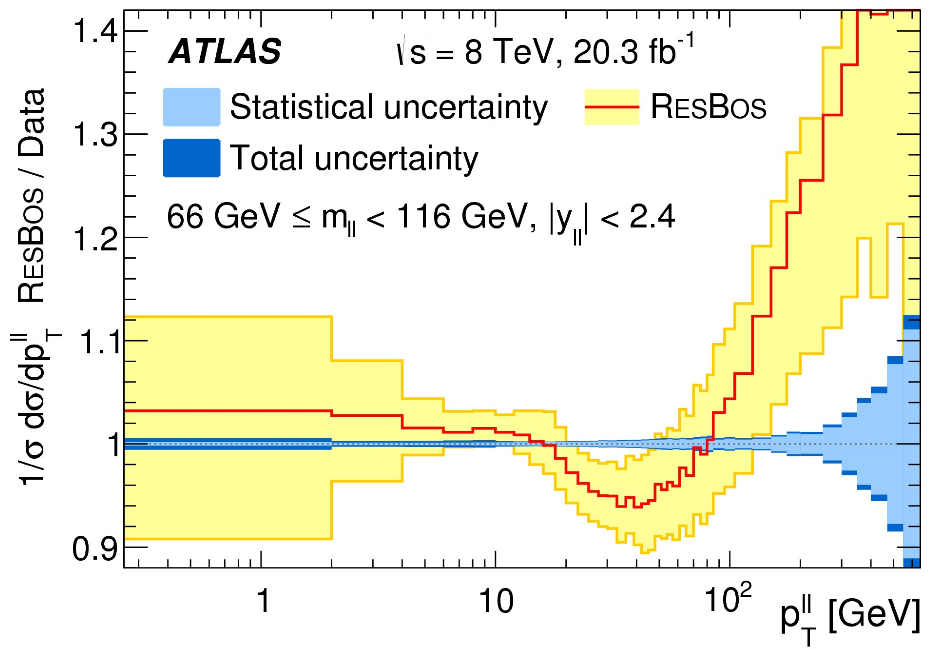
- Differential distributions are corrected for the detector acceptance and inefficiencies, bin-to-bin migrations using an iterative Bayesian unfolding procedure for p_T^{ll} and using simple bin-to-bin unfolding for ϕ^*_η in a fiducial volume:

$$p_T^l > 20 \text{ GeV}, |\eta^l| < 2.4,$$
$$66 \text{ GeV} < m_{ll} < 116 \text{ GeV}$$



- Uncertainties for unfolded results in the electron channel – lower for the ϕ^*_η





Comparison to QCD predictions

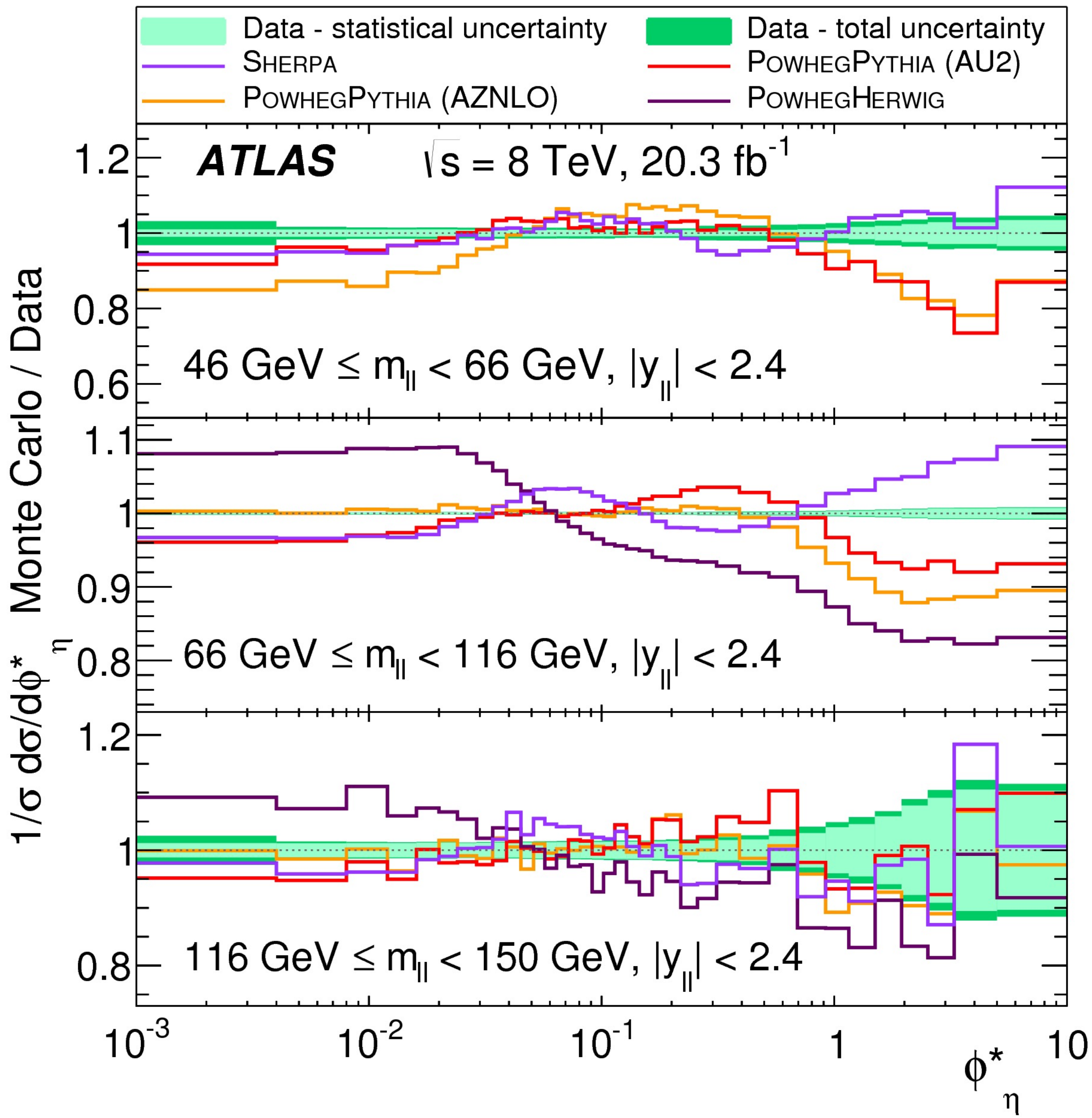
- Scale on x-axis are aligned according to the approximate relationship $\sqrt{2m_Z\phi^*_\eta} \approx p_T^{ll}$

  Finer binning in ϕ^*_η while maintaining smaller systematic uncertainties

- low and p_T^{ll} – non-perturbative effect and soft-gluon resummation dominate, the prediction from ResBos are consistent with data

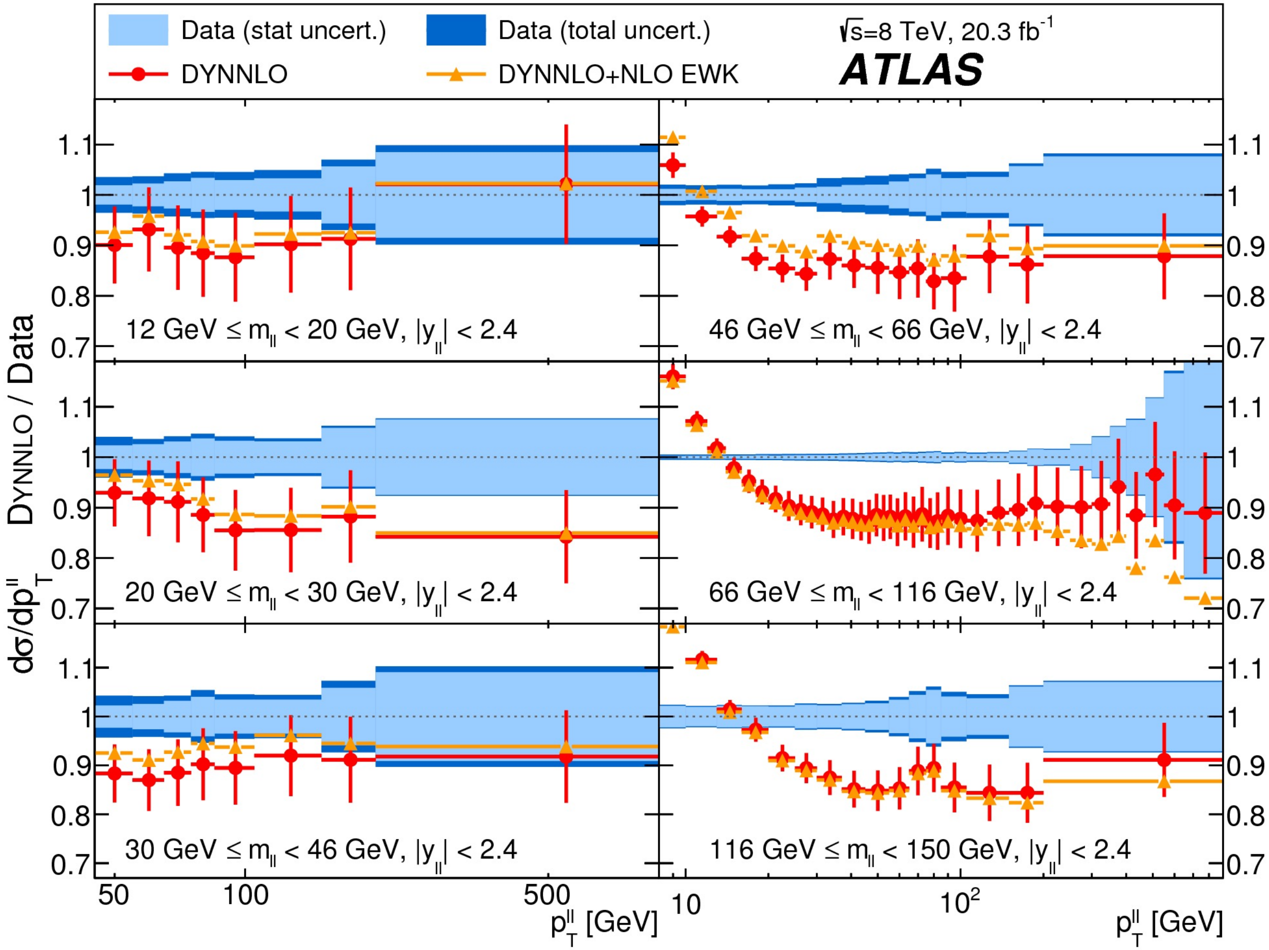
- high values of ϕ^*_η and p_T^{ll} – more sensitive to the emission of hard partons, the predictions from ResBos are not consistent with data

Comparison to parton-showers approaches



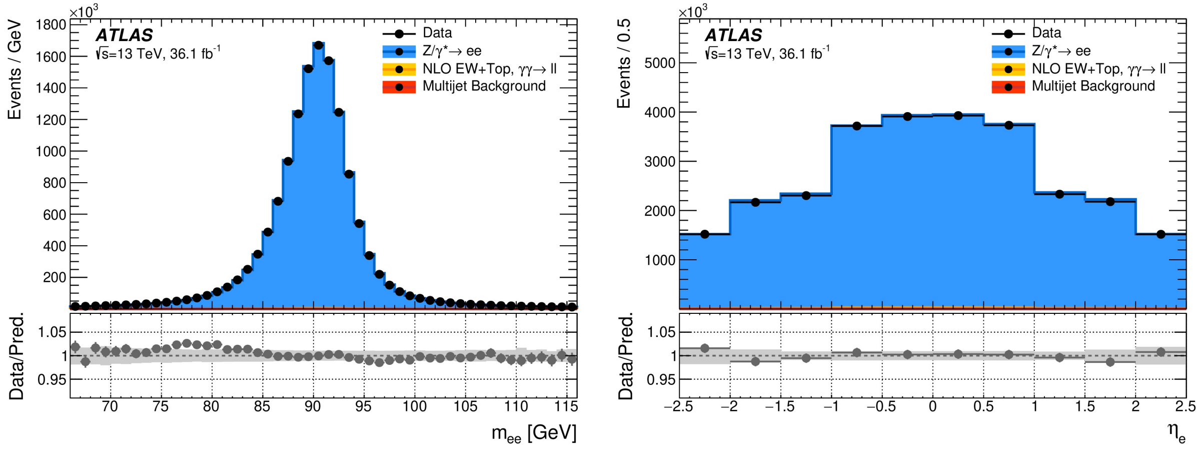
- ~10% disagreement for MC predictions vs the data for *Z*-peak mass region
- PowhegPythia(AZNLO): tuning was done in 7 TeV data (p_T < 50 GeV, Z-peak mass region)
- Differences Sherpa vs the data: ~magnitude, but of opposite sign to Powheg+Pythia vs the data

Comparison to fixed-order and electroweak corrections

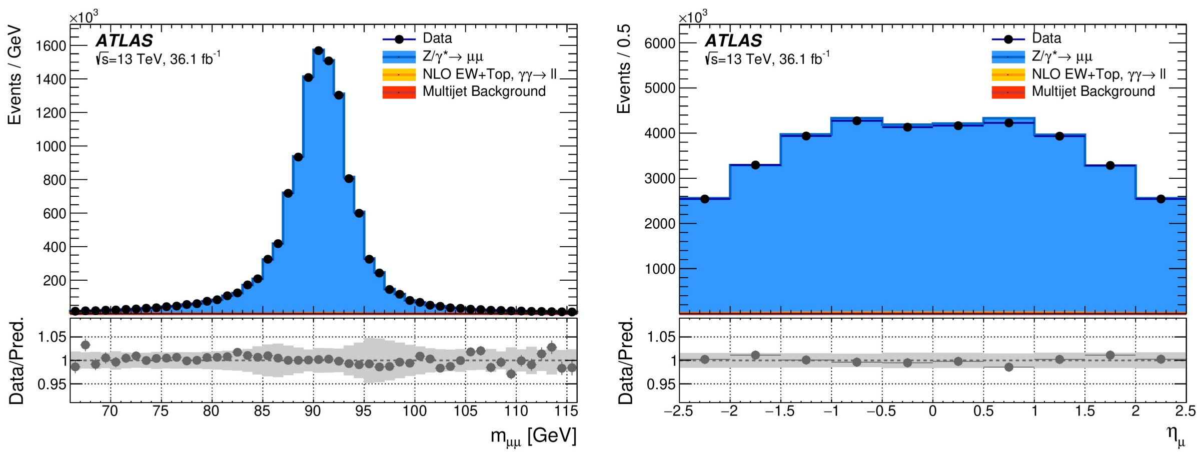


- Predictions are not expected to describe the shape of the data for low values of p_T^{ll} due to effect soft-gluon emissions
- The prediction is low by about 15% compared to the data across all m_{ll}
- No significant changes due to NLO EWK correction vs the difference between the predictions and the data

ee - channel



$\mu\mu$ - channel

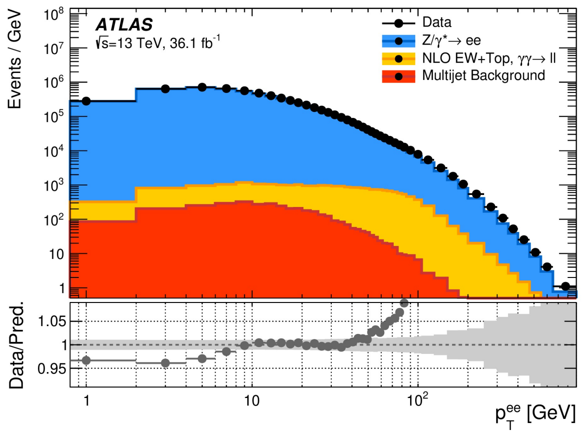


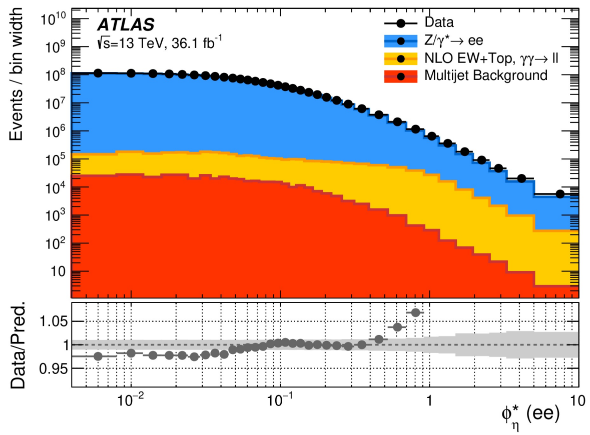
$$pp \rightarrow Z/\gamma^* \rightarrow ll(l = e, \mu)$$

- Data collected in 2015+2016 ($\sqrt{s}$ = 13 TeV, $\mathcal{L}_{int}$ = 36.1 fb^{-1})
- Selections: single lepton trigger, isolated leptons,
  - ✓ $p_T^l > 20$ GeV
  - ✓ $|\eta^e| < 2.4$ excluding $1.37 < |\eta^e| < 1.52$
  - ✓ $|\eta^\mu| < 2.5$
  - ✓ 66 GeV $< m_{ll} <$ 116 GeV
- MC signal: POWHEG+PYTHIA8
- Backgrounds: multi-jet - data-driven method; EW and ttbar from MC

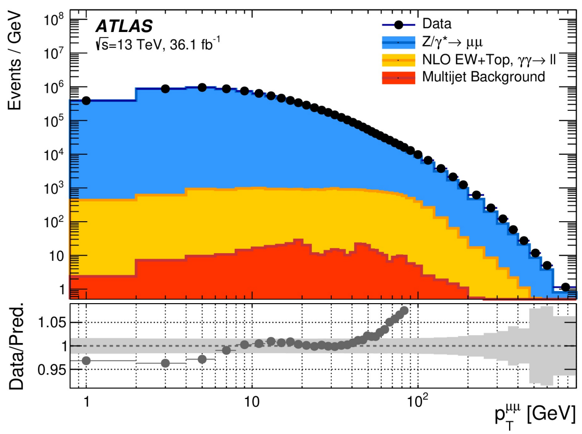
Measurement of the transverse momentum and ϕ^*_η at 13 TeV

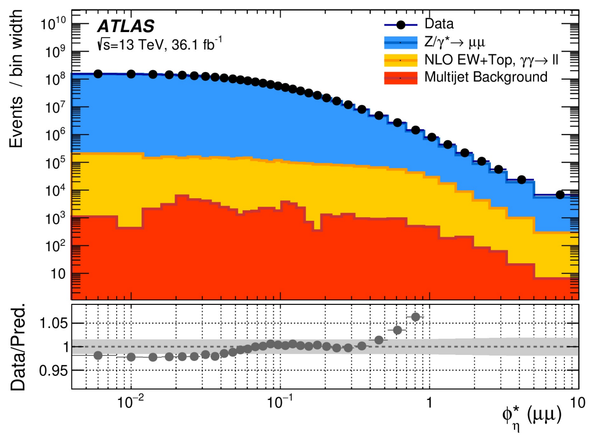
ee - channel





$\mu\mu$ - channel



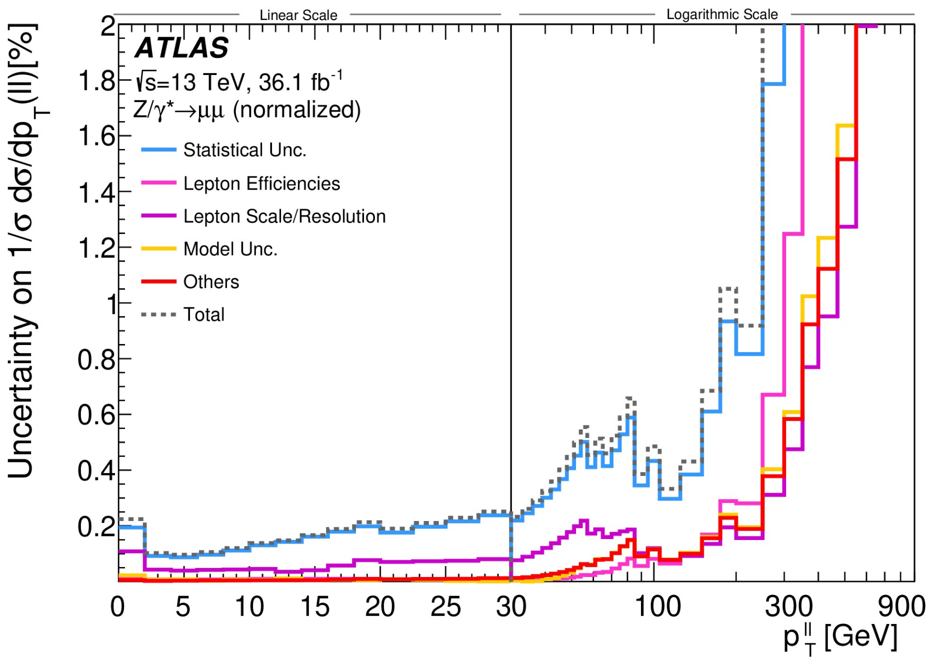


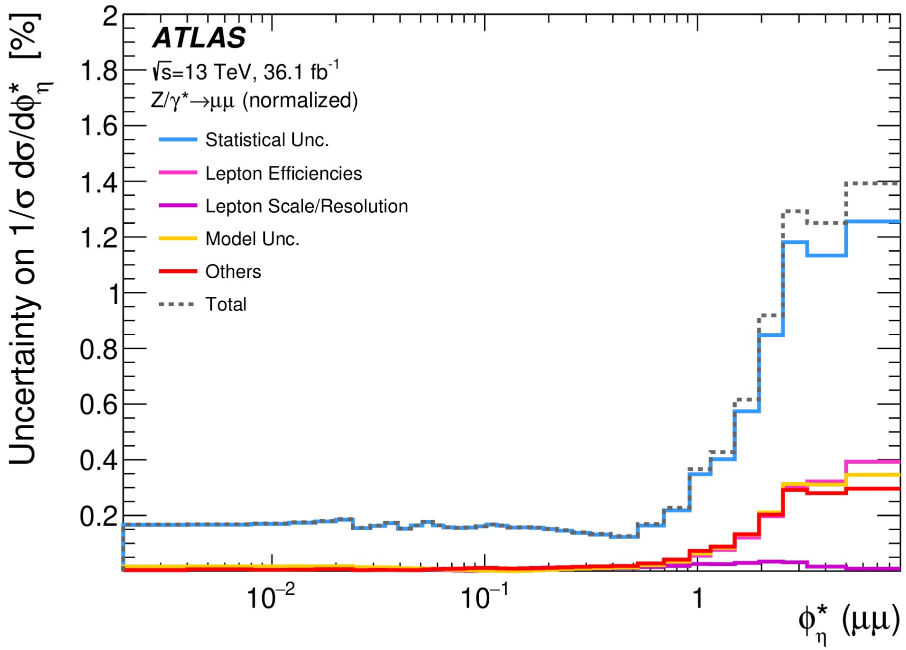
$$pp \to Z/\gamma^* \to ll(l = e, \mu)$$

- Data collected in 2015+2016 ($\sqrt{s}$ = 13 TeV, $\mathcal{L}_{int}$ = 20.3 fb^{-1})
- Selections: single lepton trigger, isolated leptons,
  - ✓ $p_T^l > 27$ GeV
  - ✓ $|\eta^e| < 2.4$ excluding $1.37 < |\eta^e| < 1.52$
  - ✓ $|\eta^\mu| < 2.5$
  - ✓ 66 GeV $< m_{ll} <$ 116 GeV
- MC signal: POWHEG+PYTHIA8
- Backgrounds:
  multi-jet - data-driven method
  EW and ttbar from MC

- Differential distributions are corrected for the detector acceptance and inefficiencies, bin-to-bin migrations using an iterative Bayesian unfolding procedure for p_T^{ll} and ϕ_η^* in a fiducial volume:

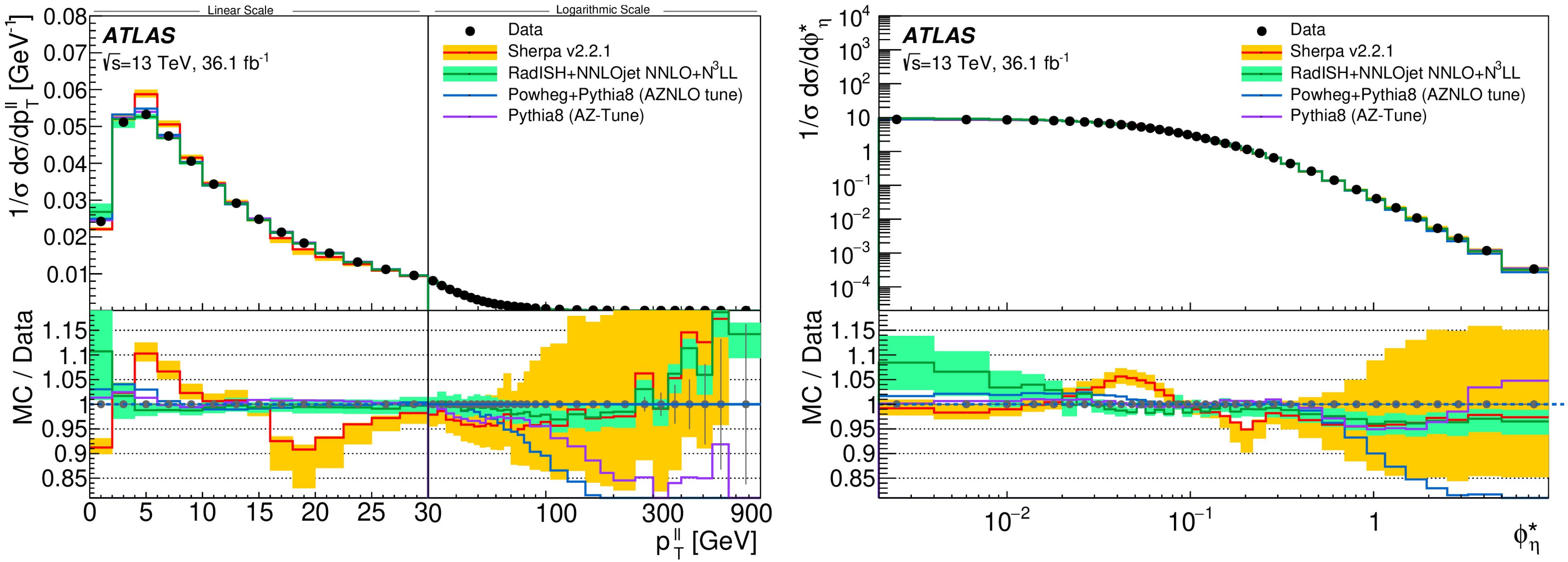
$$p_T^l > 27 \text{ GeV}, |\eta^l| < 2.5,$$
$$66 \text{ GeV} < m_{ll} < 116 \text{ GeV}$$





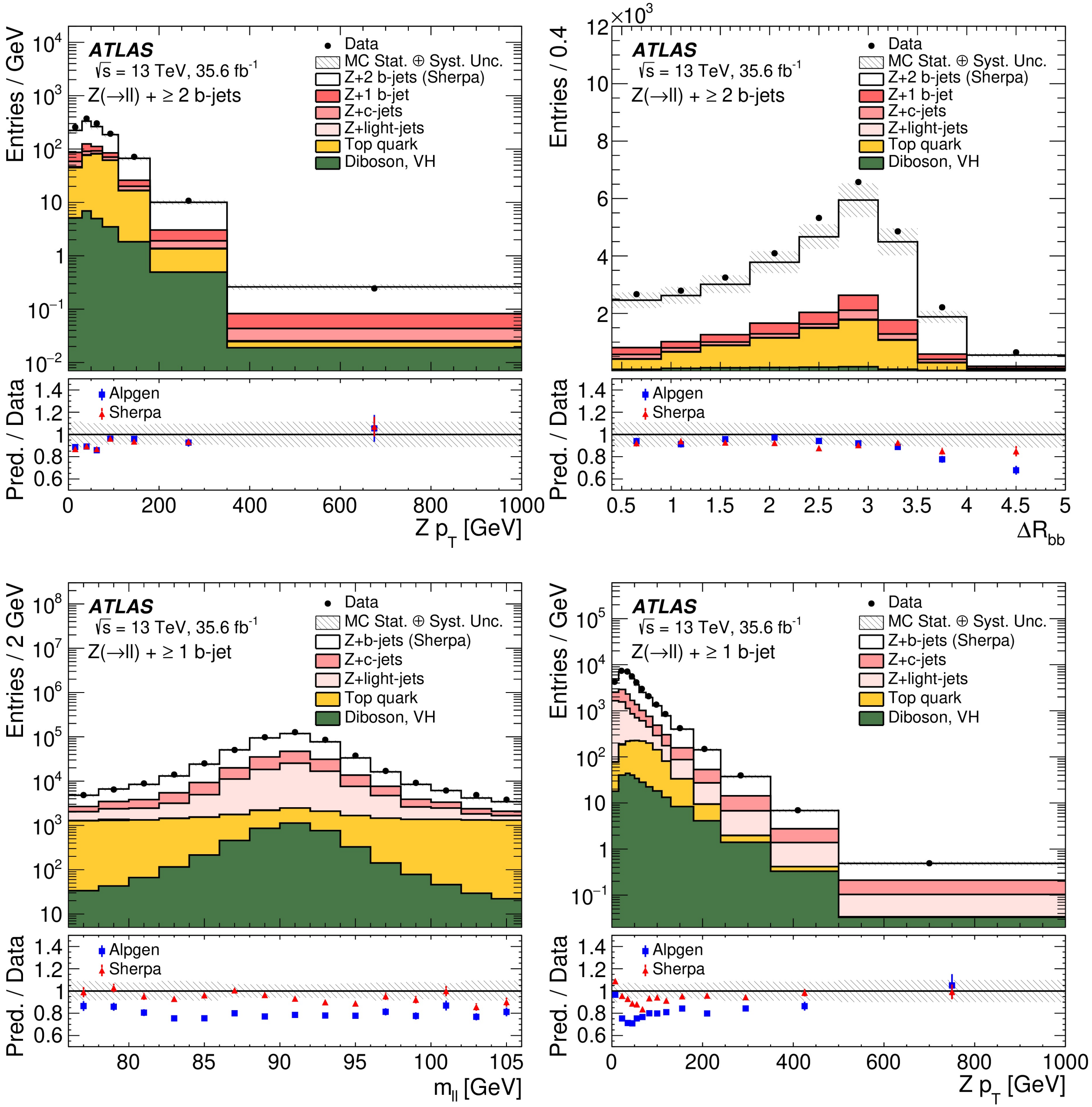
- Uncertainties for unfolded results in the muon channel – lower for the ϕ_η^*

Comparison to predictions



- Sherpa v2.2.1: NLO ME for two partons in the final state and LO ME for up to four partons (based on merging of high-order, high-multiplicity ME) – good agreement at high p_T^{ll} and ϕ_η^*
- RadISH: combines NNLO prediction of Z+jets production from NNLOjet with resummation of $\log(m_{ll}/p_T^{ll}))$ terms at N^{3}LL accuracy – prediction agrees with data for full p_T^{ll} and ϕ_η^* spectrum
- Powheg+Pythia8: NLO ME and parton shower with AZNLO tune (optimization based on 7TeV data) – describes data well at low p_T^{ll} and ϕ_η^*
- Pythia8: LO ME and parton shower with AZ tune (optimization based on 7TeV data) – describes data well at low p_T^{ll} and ϕ_η^*

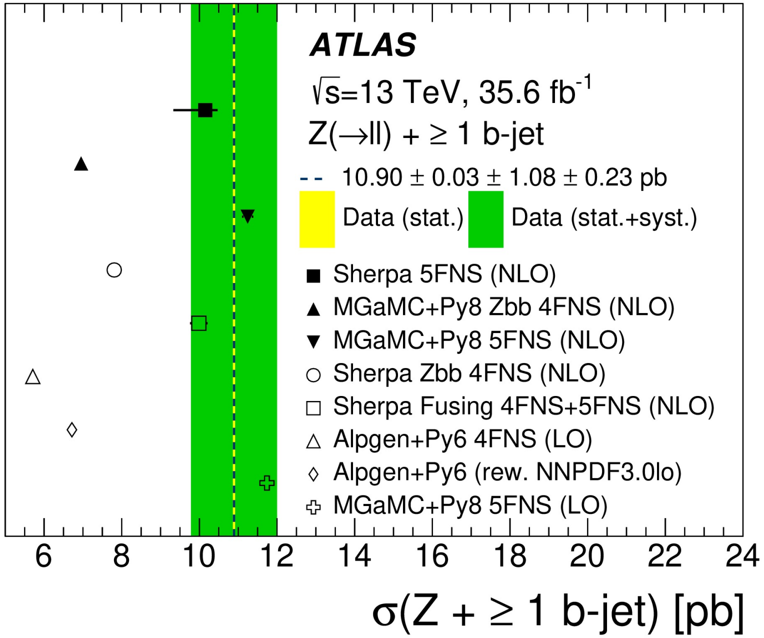
Z+bjet cross-section at 13 TeV

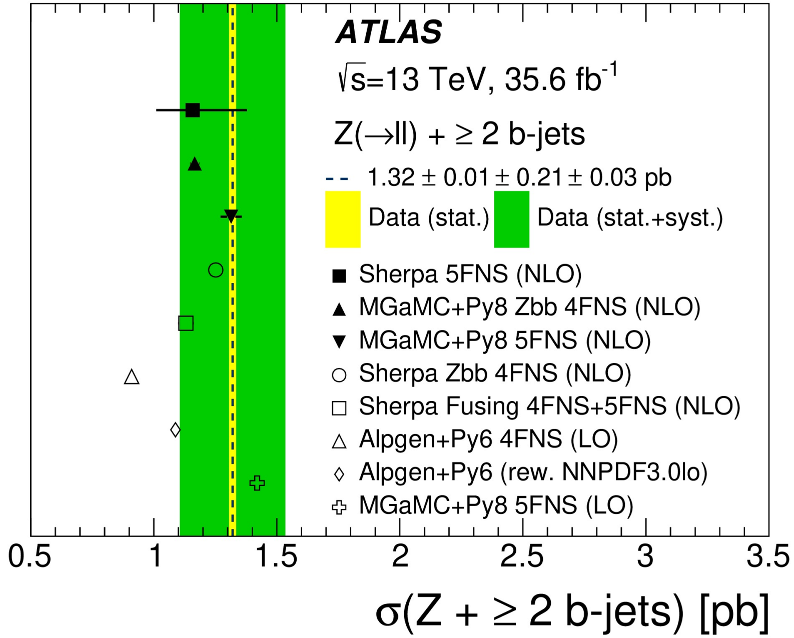


$pp \rightarrow Z/\gamma^* \rightarrow ll(l = e, \mu)$

- Data collected in 2015+2016 ($\sqrt{s}$ = 13 TeV, $\mathcal{L}_{int}$ = 36.1 fb^{-1})
- Selections: single lepton trigger, isolated leptons,
  - ✓ $p_T^l > 27$ GeV
  - ✓ $|\eta^e| < 2.4$ excluding $1.37 < |\eta^e| < 1.52$
  - ✓ $|\eta^\mu| < 2.5$
  - ✓ $p_T^{jet} > 20$ GeV
  - ✓ $|\eta^{jet}| < 2.5$
  - ✓ 76 GeV $< m_{ll} <$ 106 GeV
  - ✓ $E_T^{miss} < 60$ GeV if $p_T^{ll} < 150$ GeV
- MC signal:
  SHERPA v 2.2.1 and AlpGen
- Backgrounds:
  multi-jet - data-driven method
  EW and ttbar from MC

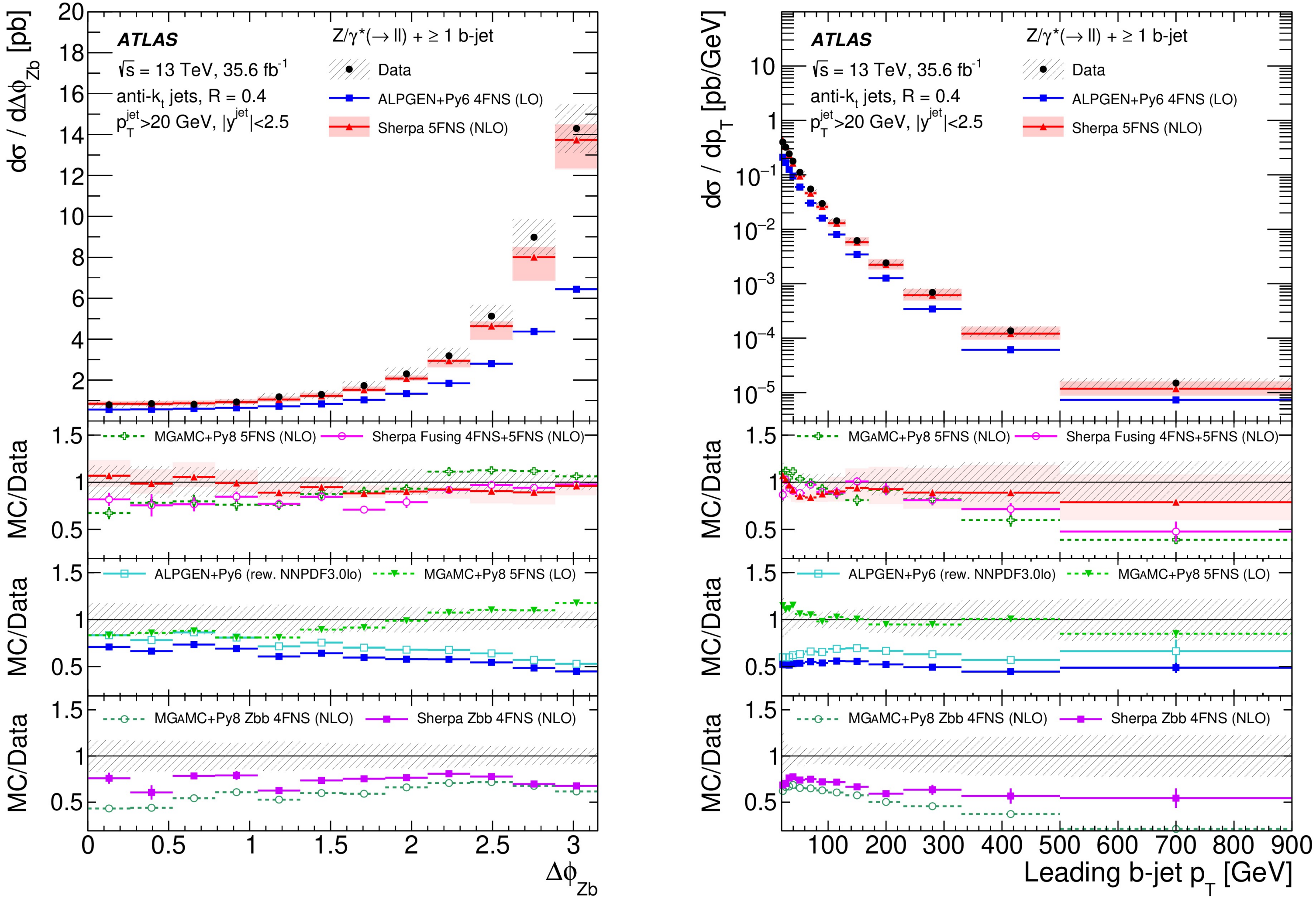
Z+bjet cross-section at 13 TeV





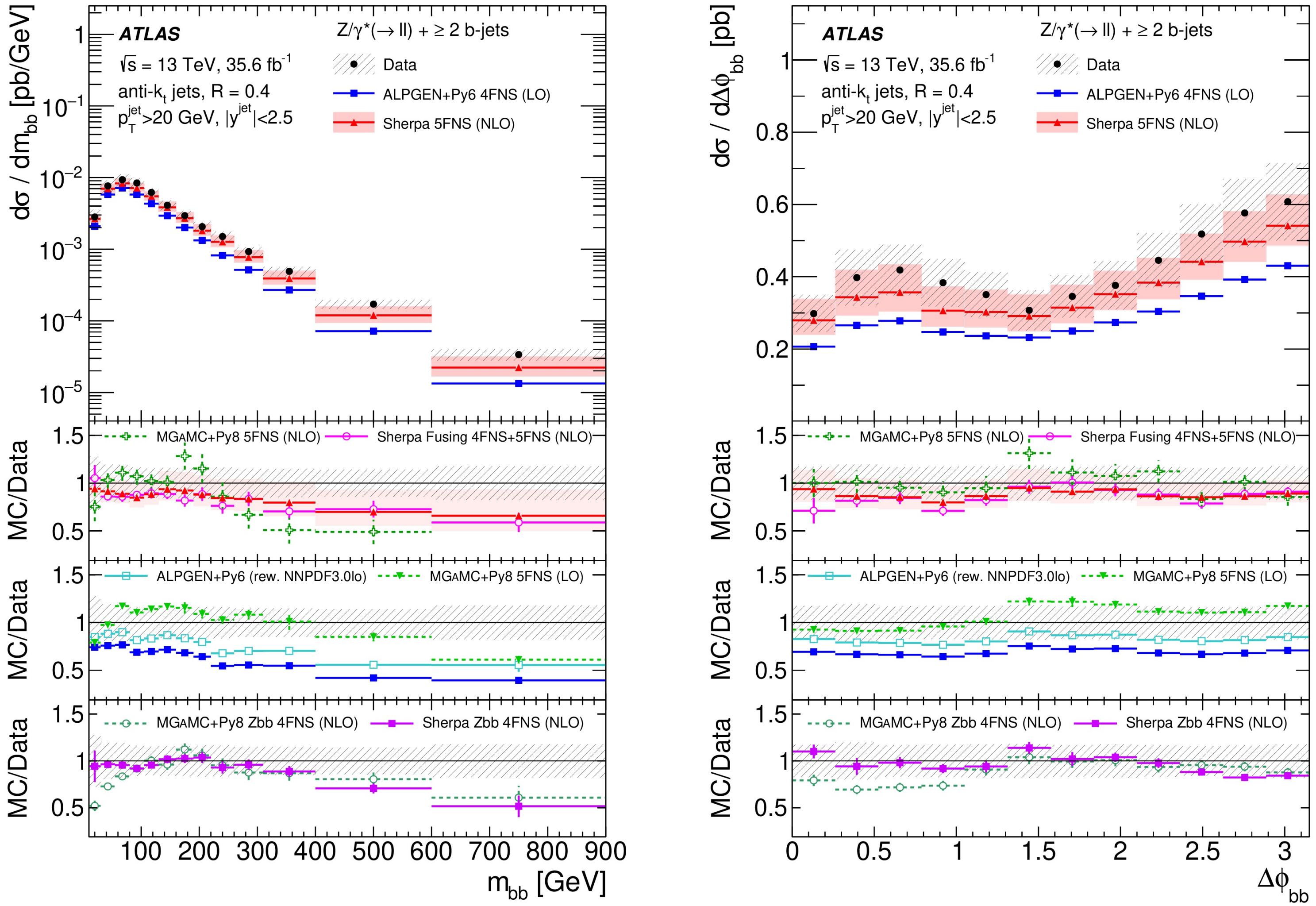
- 4FNS MC predictions are systematically lower for the inclusive one-b-jet case (Alpgen + Py6 4FNS (LO)6, Sherpa Zbb 4FNS (NLO) and MGaMC + Py8 Zbb 4FNS (NLO)).
- The 4FNS predictions agree well with data in the inclusive two-b-jet case (the LO Alpgen + Py6 4FNS (LO) underestimates the data)
- The NNPDF3.0lo PDF set in Alpgen predictions gives better agreement with data due to a higher acceptance in the fiducial region.
- The 5FNS simulations adequately predict the inclusive cross-sections for Z + ≥ 1 b-jet and Z + ≥ 2 b-jets.

Z+bjet cross-section at 13 TeV



- 4FNS predictions systematically underestimate the data
- 5FNS describe the data in most cases

Z+bjet cross-section at 13 TeV



- 4FNS predictions systematically underestimate the data
- 5FNS describe the data in most cases
- Significant difference (common to all generators) is found for large values of m_{bb}

Summary

- Main results of measurements of the ϕ_η^* and p_T^{ll} :
  - 7 TeV: Good agreement at low ϕ_η^* values for predictions from Sherpa (~2% level); double differential measurements provide valuable information for the tuning of MC generators.
  - 8 TeV (expaned the measurements at 7 TeV): the predictions from ResBos are consistent with the data within certain kinematic regions, especially at low values of ϕ_η^* and the predictions from MC generators with parton showers shows ~10% disagreement at Z-peak mass region
  - 13 TeV: Cross-sections differential in the transverse momentum of Z-boson were measured covering up to TeV-range and the combination yields the precision of 0.2% and better for $p_T^{ll} < 30$ GeV

- Main results of Z+bjet cross-section measurements:
  - the inclusive cross-sections and the differential cross-sections of several kinematic observables are measured, extending the range of jet transverse momenta to higher values
  - 5-flavour number scheme (5FNS) calculations at NLO accuracy predict the inclusive cross-sections well, while inclusive 4-flavour number scheme (4FNS) LO calculations largely underestimate the data

- Results are available in HepData and Rivet

Thanks for attention