ATLAS ϕ^*_η measurement of Z/γ^* at 7 TeV

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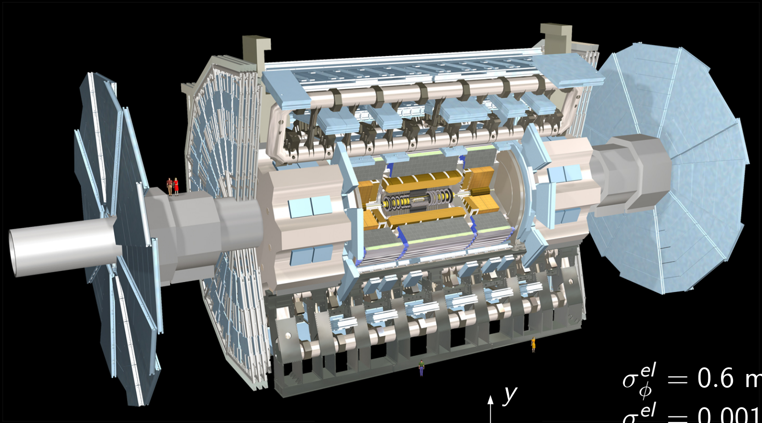
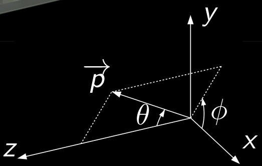
Contents

The ATLAS detector





$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

$$\sigma_\phi^{el} = 0.6 \text{ mrad}$$
$$\sigma_\eta^{el} = 0.0012$$

$$\sigma_\phi^{\mu} = 0.4 \text{ mrad}$$
$$\sigma_\eta^{\mu} = 0.001$$

p_T^Z - theoretical points of view

- High p_T^Z:
    - Fixed order perturbative QCD predictions (like FEWZ).
- Low p_T^Z:
    - Resummation of leading logarithms to all orders in α_S (+ non-perturbative parameterization like RESBOS).
    - OR modeling by parton shower generators (like PYTHIA).

→ Motivations of the p_T^Z measurement:

- Provide a test of pQCD.
- Study the low p_T^Z region where non-perturbative effects may play a role.
    - Help in improving the modelling of W boson production needed for a precise measurement of the W mass.
    - Help in understanding the low p_T spectrum of the Higgs boson.

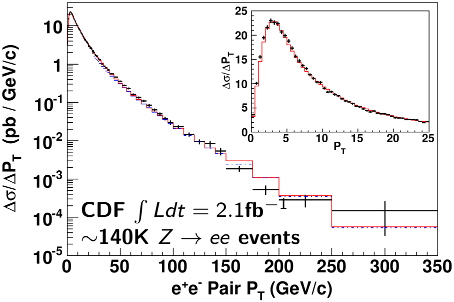
Why new variables?

The measurement at low p_T^Z is limited by the experimental resolution rather than the event statistics in particular for the electron channel.

Phys. Rev. D 86 (2012) 052010

Main systematic uncertainties of the latest p_T^Z measurement:

Calorimeter response modeling $\oplus$ Unfolding $\sim 1\%$.



$\Longrightarrow$ Optimize new variables:

- less sensitive to the effects of experimental resolution.

- probe the same physical effects as p_T^Z.

ϕ^*_η definition

$\boxed{p_T}$ Eur. Phys. J. C 71 (2011) 1600

$\downarrow$

$\boxed{a_T}$

$\downarrow$

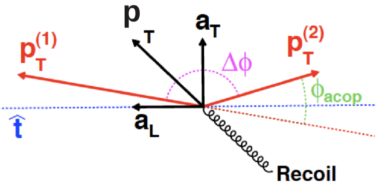
$\boxed{a_T/M}$

$\downarrow (p_T^{(1)} \approx p_T^{(2)})$

$\boxed{a_T/M \approx \tan(\phi_{acop}/2)\sin(\theta^*)}$

$\downarrow \cos(\theta^*_\eta) = \tanh(\frac{\eta^- - \eta^+}{2})$

$\boxed{\phi^*_\eta \equiv \tan(\phi_{acop}/2)\sin(\theta^*_\eta)}$



$$\hat{t} = (p_T^{(1)} - p_T^{(2)})/|p_T^{(1)} - p_T^{(2)}|$$

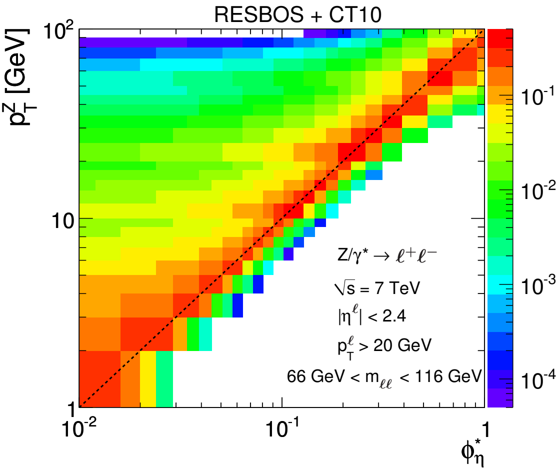
- θ^* is the scattering angle of the leptons relative to the beam direction in the dilepton rest frame and is sensitive to the effects of lepton momentum resolution.

- θ^*_η is an alternative way to estimate the scattering angle.

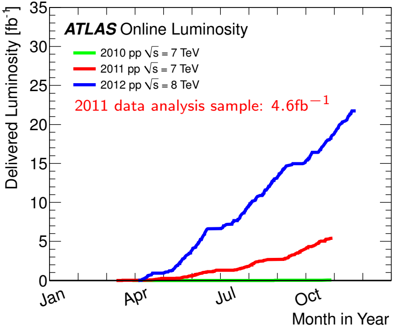
→ ϕ^*_η is based entirely on the measured track directions

Relation between p_T^Z and ϕ^*_η

Evident correlation between p_T^Z and ϕ^*_η



2011 Data and Monte Carlo samples



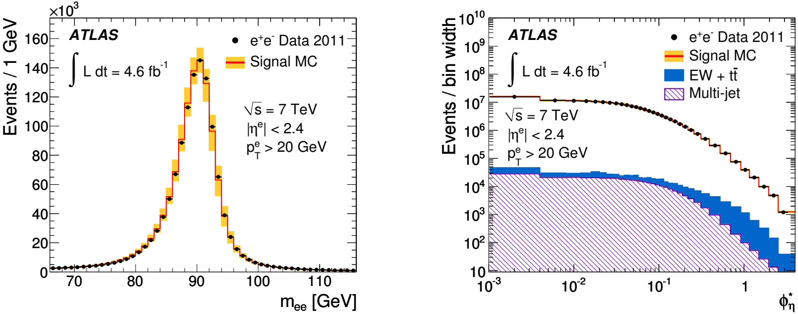
MC sample	Process
Signal	
POWHEG+PYTHIA6 (*)	$Z/\gamma^* \to \ell\ell$
EW background	
PYTHIA	$W \to \ell\nu$
PYTHIA	$Z \to \tau\tau$
MC@NLO	$t\bar{t}$
HERWIG	WW
HERWIG	ZZ
HERWIG	WZ
Multi-jet background: Data driven method	

(*) with the p_T^Z spectrum reweighted to RESBOS prediction

Event selection

Collision event selection	
Stable beams + working detectors + $\geq$ 1 good vertex + single lepton trigger	
Good lepton selection	
Electron	$p_{\mathrm{T}}^{el1} > 25$ GeV, $p_{\mathrm{T}}^{el2} > 20$ GeV $\lvert\eta_{trk}\rvert < 2.4$ excluding $1.37 < \lvert\eta_{cl}\rvert < 1.52$ Medium identification
Muon	$p_{\mathrm{T}}^{\mu 1} > 20$ GeV, $p_{\mathrm{T}}^{\mu 2} > 20$ GeV $\lvert\eta_{trk}\rvert < 2.4$ Isolated muons + impact parameter requirements
$Z/\gamma^* \to \ell\ell$ event selection	
Charge	Opposite sign
Invariant mass	66 GeV $< M_{\ell\ell} <$ 116 GeV

Selection results



	$Z \to ee$	$Z \to \mu\mu$
# events selected in data	$1.22 \cdot 10^6$	$1.69 \cdot 10^6$
Fraction of background events	$(0.61 \pm 0.31)\%$	$(0.56 \pm 0.28)\%$

Methodology of the measurement

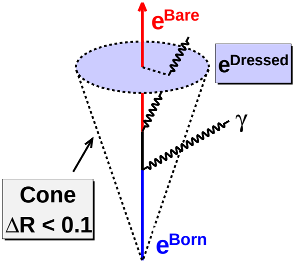
- The differential cross section: $\boxed{\frac{1}{\sigma} \cdot \frac{d\sigma}{d\phi^*_\eta}}$

- Measured within the fiducial acceptance: $p_T^{\ell 1} > 20$ GeV, $p_T^{\ell 2} > 20$ GeV, $|\eta_\ell| < 2.4$, 66 GeV $< M_{\ell\ell} <$ 116 GeV.

- Extrapolated to the acceptance: 66 GeV $< M_{\ell\ell} <$ 116 GeV.

- The reconstructed ϕ^*_η spectrum is corrected for detector and QED final state radiation (FSR) effects using an unfolding technique (bin-by-bin correction) to the underlying "true" spectrum.

- The "true" spectrum is defined at different reference points referring to the amount of QED FSR corrections considered at the generator level: "Born", "Dressed", "Bare".

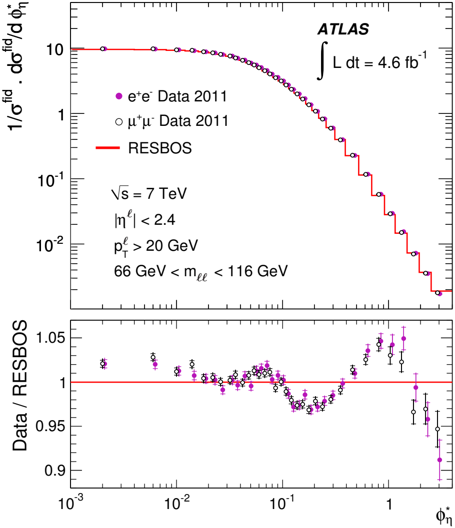


Systematic uncertainties in ϕ^*_η bins

Source	Sys. unc.
Background	$< 0.3\%$
Tracking	$< 0.3\%$
MC statistics	$0.13 - 0.9\%$
Unfolding	$< 0.1\%$
Energy/momentum scale and resolution	$< 0.1\%$
Efficiencies	$< 0.05\%$
Pile-up	$< 0.05\%$
QED final state radiation (*)	0.3%

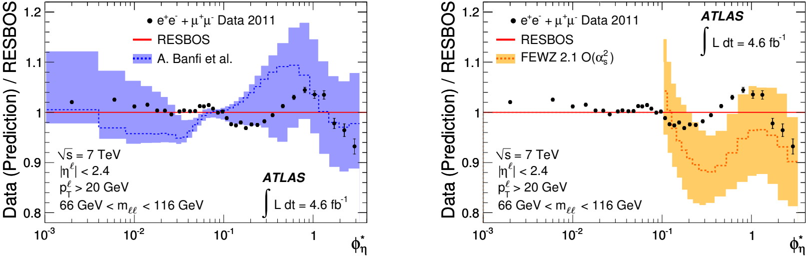
(*) ϕ^*_η is the first result in LHC where the experimental uncertainty is smaller than the QED FSR uncertainty → require dedicated work together with the theoreticians (See Z. Was's talk). Some of these studies can be found in http://annapurna.ifj.edu.pl/∼wasm/phi-star.html, CERN-THESIS-2013-001 and arXiv:1303.2220.

The fiducial differential cross section result



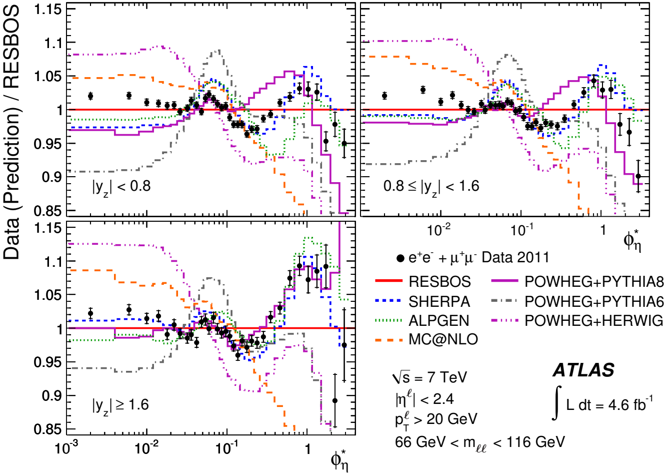
- Results of electron and muon channels were combined using a χ^2 minimisation method [Eur. Phys. J. C 63 (2009) 625, JHEP 01 (2010) 109].
- Statistic uncertainty: 0.3 – 1.6%.
- Systematic uncertainty: $\sim 0.5\%$ $\sim$ 2 times smaller than the latest p_T^Z measurement.

Comparison with QCD predictions



- Best prediction by RESBOS CT10 (Non-perturbative+NNLL+NLO-scaled to NNLO) within $2-5\%$. Full theoretical uncertainty was not supported.
- Calculation from A. Banfi *et al.* CTEQ6m (NNLL+NNLO - Phys. Lett. B 715 (2012) 152-156) agrees with data within full theoretical uncertainty (pdf+scale+resummation).
- FEWZ CT10 (NNLO) undershoots data by 10%, as already observed in Phys. Lett. B 705 (2011) 415-434.

Double differential cross section measurement



- The Differential cross section measurement as a function of ϕ_η^* is measured in 3 bins of y_Z.
- SHERPA and ALPGEN provide good descriptions.
- POWHEG+PYTHIA8 has better description than POWHEG+PYTHIA6 and POWHEG+HERWIG.
- POWHEG+HERWIG and MC@NLO (interfaced with HERWIG) give worse descriptions.

→ valuable information for the tuning of MC generators

Note: CT10 is used in all Monte Carlo samples except ALPGEN with CTEQ6L1

Conclusion

The first measurement of the ϕ^*_η spectrum of Z/γ^* bosons at $\sqrt{s} = 7$ TeV of *pp* collisions using the full 2011 ATLAS data sample corresponding with 4.6 fb^{-1} integrated luminosity.

- At low ϕ^*_η ($\phi^*_\eta < 0.1$): Data agree with RESBOS CT10 within 2%.
- At high ϕ^*_η: RESBOS CT10 provides better prediction than FEWZ CT10 and A. Banfi *et al.* CTEQ6m but can not reproduce the detailed shape of data better than 4%.
- Among MC generators: the best description by SHERPA. MC@NLO, POWHEG+HERWIG, POWHEG+PYTHIA6 underestimate the data at higher ϕ^*_η.
- The typical experimental precision ($\sim 0.5\%$) is now ten times better than the typical theoretical precision and therefore is valuable to constrain the theoretical predictions further.

THANK YOU!

Backup

Low p_T^Z calculation

Dominant contributions to the differential cross section ($Q^2 = M_Z^2$):

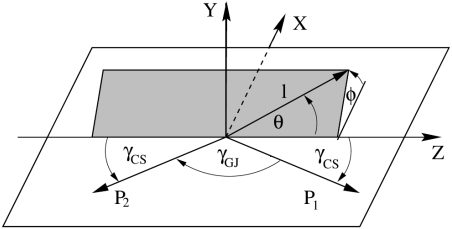
$$\frac{d\sigma}{dp_T^2} \sim \frac{\alpha_s}{p_T^2} \ln\left(\frac{Q^2}{p_T^2}\right)\left[v_1 + v_2\alpha_s \ln^2\left(\frac{Q^2}{p_T^2}\right) + v_3\alpha_s^2 \ln^4\left(\frac{Q^2}{p_T^2}\right) + \ldots\right]$$

For $p_T \to 0$, $\alpha_s \ln^2(Q^2/p_T^2)$ is large even when α_s is small

$\to$ the p_T distribution diverges.

Collins Soper Dilepton rest frame

Nucl.Phys.B582:537-570,2000



The Collins-Soper frame (in the dilepton rest frame):

When we boost from the hadron center-of-mass frame to the dilepton rest frame, the collinearity of the hadron momenta $\mathbf{P}_1$ and $\mathbf{P}_2$ is lost and they span a plane which we identify with the **X**-**Z**-plane.

We are still free to fix **Z** within this plane. In the Collins-Soper frame **Z** is chosen to bisect the angle between $\mathbf{P}_1$ and $-\mathbf{P}_2$. The angle between **Z** and $\mathbf{P}_1$ and between **Z** and $\mathbf{P}_2$ is called γ_{CS}.

θ and ϕ define the lepton direction in CS frame.

Multi-jet background: template fit

The template background sample: is selected from data requiring:
- Electron: failing the medium identification criteria (based on shower shape and track-quality variables)
- Muon: inverting the isolation requirement

Isolation = {scalar sum of p_T of tracks within $\Delta R = 0.2$ around muon $< 10\%\ p_T^\mu$}

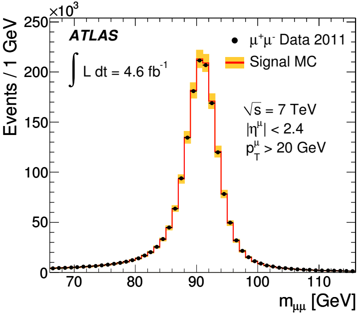
Method: using a binned likelihood fit on $Z \to ee$ mass distributions.

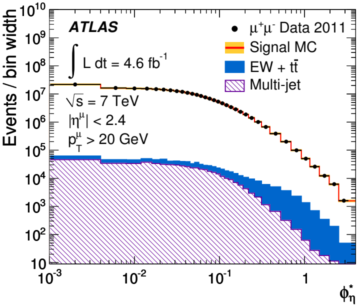
$$\mathbf{Data}(M_{ee}) = \mathbf{P_0} \cdot [\underbrace{\mathbf{Z} + \mathbf{EW}}_{}](M_{ee}) + \mathbf{P_1} \cdot \mathbf{QCD}(M_{ee})$$

$$\overset{\text{MC}}{\Downarrow} \qquad \overset{\text{from data}}{\Downarrow}$$

→ The real multi-jet background (QCD) is estimated by scaling the template background sample from data with parameter $\mathbf{P_1}$ from fitting results.

Selection results: muon channel





Bin-by-bin Correction factors

To fiducial acceptance:

$$\left(\frac{1}{\sigma}\right)_{fid}\left(\frac{\Delta\sigma_i}{\Delta\phi^*_{\eta,i}}\right)_{fid} = \frac{C}{C^i}\cdot\frac{\left(N^i_{\rm data} - N^i_{\rm bg}\right)}{\Delta\phi^*_{\eta,i}\cdot\left(N^{tot}_{\rm data} - N^{tot}_{\rm bg}\right)}$$

$$C^i = \frac{N^i_{\rm MC,rec,cuts}}{N^i_{\rm MC,gen,fid}} \quad , \quad C = \frac{N^{tot}_{\rm MC,rec,cuts}}{N^{tot}_{\rm MC,gen,fid}}$$

To full acceptance:

$$\left(\frac{1}{\sigma}\right)_{tot}\left(\frac{\Delta\sigma_i}{\Delta\phi^*_{\eta,i}}\right)_{tot} = \frac{A}{A^i}\cdot\left(\frac{1}{\sigma}\right)_{fid}\left(\frac{\Delta\sigma_i}{\Delta\phi^*_{\eta,i}}\right)_{fid}$$

$$A^i = \frac{N^i_{\rm MC,gen,fid}}{N^i_{\rm MC,gen}} \quad , \quad A = \frac{N^{tot}_{\rm MC,gen,fid}}{N^{tot}_{\rm MC,gen}}$$

QED FSR uncertainty

Compare POWHEG+PYTHIA6 (interfaced with PHOTOS ∼ 2nd QED FSR simulation) with SHERPA (YFS formalism - 1st QED FSR simulation).

→ To extract pure QED FSR effect:

$$\mathrm{QED}_{\mathrm{Bare}} = \left(\left(\frac{1}{\sigma}\right)_{fid} \left(\frac{\Delta\sigma_i}{\Delta\phi^*_{\eta\, i}}\right)_{fid} \right)_{\mathrm{Bare}} \Bigg/ \left(\left(\frac{1}{\sigma}\right)_{fid} \left(\frac{\Delta\sigma_i}{\Delta\phi^*_{\eta\, i}}\right)_{fid} \right)_{\mathrm{Born}}$$

$$\mathrm{QED}_{\mathrm{Dressed}} = \left(\left(\frac{1}{\sigma}\right)_{fid} \left(\frac{\Delta\sigma_i}{\Delta\phi^*_{\eta\, i}}\right)_{fid} \right)_{\mathrm{Dressed}} \Bigg/ \left(\left(\frac{1}{\sigma}\right)_{fid} \left(\frac{\Delta\sigma_i}{\Delta\phi^*_{\eta\, i}}\right)_{fid} \right)_{\mathrm{Born}}$$

→ To extract systematic uncertainty:

$$(\mathrm{QED}_{\mathrm{Bare}})_{\mathrm{POWHEG+PYTHIA6}} \Big/ (\mathrm{QED}_{\mathrm{Bare}})_{\mathrm{SHERPA}} - 1$$

$$(\mathrm{QED}_{\mathrm{Dressed}})_{\mathrm{POWHEG+PYTHIA6}} \Big/ (\mathrm{QED}_{\mathrm{Dressed}})_{\mathrm{SHERPA}} - 1$$

Effect of PDF on RESBOS predictions