Measurement of the Z boson transverse momentum: direct and using ϕ^*_η variable with ATLAS

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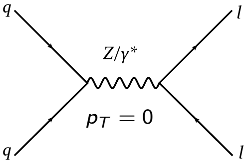
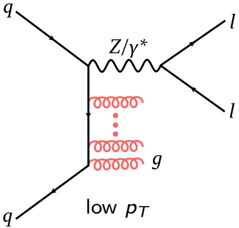
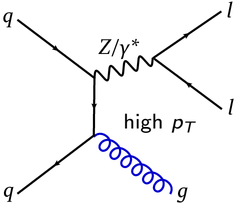
Z boson production at LHC

In hadron collisions at TeV energies the vector bosons W and Z/γ^* are produced with **non-zero** momentum transverse to the beam axis, due to

- Intrinsic momentum;
- radiation of quarks and gluons from the initial state partons.





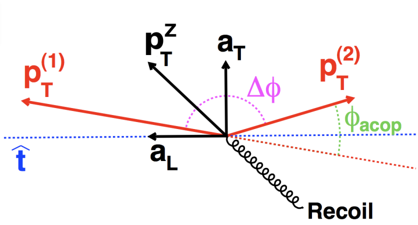


Test of QCD predictions

- Low p_T: emission of soft gluons.
  Resummed calculations:
  soft qluon resummation technique or parton showers.
- High p_T: hard parton emission.
  Fixed order pQCD calculations.

Improve modeling of W boson production for
W mass measurement: Monte Carlo tuning.

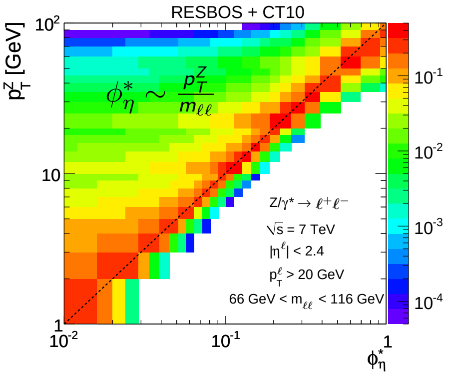
p_T and ϕ^*_η variables



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

$$\phi_{acop} \equiv \pi - \Delta\phi$$

$$cos\theta^*_\eta \equiv tanh[\frac{\eta^- - \eta^+}{2}]$$



- ϕ^*_η depends exclusively on the direction of the two leptons track, which are better measured than their momenta;
- the reduced systematic uncertainties and better resolution are achievable with the ϕ^*_η variable in the low p_T region.

Data selection

$Z\ \phi^*_\eta$ Selection

$4.6\ \text{fb}^{-1}\ \sqrt{s} = 7$ TeV 2011

Electrons	Muons
$p_T^{e_1} > 25$ GeV, $p_T^{e_2} > 20$ GeV	$p_T^{\mu} > 20$ GeV
$\lvert\eta\rvert < 2.4$	$\lvert\eta\rvert < 2.4$
excl. $1.37 < \lvert\eta\rvert < 1.52$	
$Z/\gamma^* \to \ell^+\ell^-$	
$66 < m_{\ell\ell} < 116$ GeV	
Opposite charge	

$Z\ p_T$ Selection

35(40) $\text{pb}^{-1}\ \sqrt{s} = 7$ TeV 2010

Electrons	Muons
$p_T^{e} > 20$ GeV	$p_T^{\mu} > 20$ GeV
$\lvert\eta\rvert < 2.4$	$\lvert\eta\rvert < 2.4$
excl. $1.37 < \lvert\eta\rvert < 1.52$	
$Z/\gamma^* \to \ell^+\ell^-$	
$66 < m_{\ell\ell} < 116$ GeV	
Opposite charge	

Phys.Lett. B720 (2013) 32-51

Phys.Lett. B705 (2011) 415-434

Number of collected events:

	$Z\ \phi^*_\eta$	$Z\ p_T$
e^+e^-	$1.22 \cdot 10^6$	8923
$\mu^+\mu^-$	$1.69 \cdot 10^6$	15060

Fiducial region:

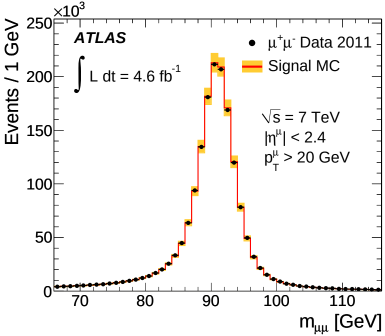
$66 < m_{\ell\ell} < 116$ **GeV**

$\lvert\eta\rvert < 2.4$

$p_T^l > 20 GeV$

Monte Carlo simulation

- Signal MC:
  - LO: Pythia
  - NLO: Powheg + Pythia
  - NLO: Mc@nlo
- p_T^Z reweighting: ResBos
- EW background:
  - Pythia: $W \to l\nu$
  - Mc@nlo: $t\bar{t}$
  - Herwig: WW, WZ, ZZ
- QED FSR: Photos.



Control plot: The observed dielectron invariant mass distribution compared to simulation. The shaded band is the total systematic uncertainty on the MC prediction.

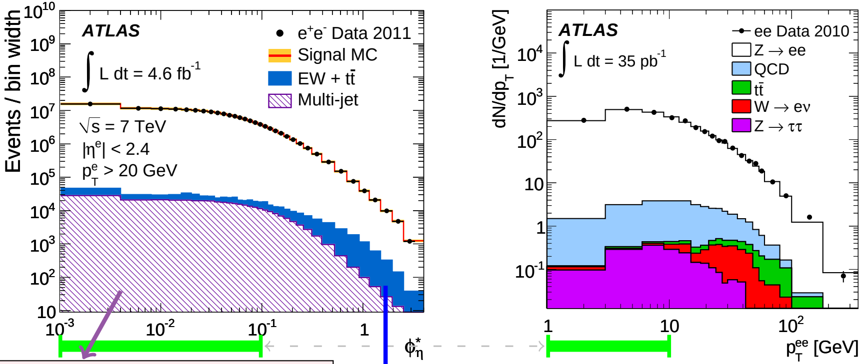
The Monte-Carlo simulation is corrected for differences with respect to the data

- in the lepton reconstruction and identification efficiencies;
- in energy (momentum) resolution.

The particle-level dilepton mass $m_{\ell\ell}$ and ϕ^*_η are defined:

"bare"	final-state leptons after FSR;
"dressed"	leptons with radiated photons within a cone of $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.1$;
"Born"	final-state leptons before FSR.

Background estimation



At low Z ϕ^*_η/p_T:
the background is dominated by **multijet** production: jet is falsely identified as a primary e or μ.

At high Z ϕ^*_η/p_T:
the main background arises from $t\bar{t}$ production.

The total fraction of background events:

	Z ϕ^*_η	Z p_T
electron channel	$(0.61 \pm 0.31)\%$	$(1.5 \pm 0.6)\%$
muon channel	$(0.56 \pm 0.28)\%$	$(0.4 \pm 0.28)\%$

Z p_T: Systematic uncertainties

The systematic uncertainties have been evaluated as a function of Z p_T.
In the cross-section dominated region, $p_T < 30$ GeV:

	e^+e^- channel [%]	$\mu^+\mu^-$ channel [%]
Bin-by-bin correlated		
Background	0.7	0.3
Identification efficiency	**2.1**	0.3
Unfolding procedure	**1.4**	**1.4**
Energy resolution	0.5	0.3
Trigger efficiency	negl.	0.3
Pile-up	0.3	0.1
Bin-by-bin uncorrelated		
MC sample statistics	0.7	0.4
QED FSR	0.6	0.6

The systematic uncertainties are added quadratically to obtain
the total systematic uncertainty: $\sim$ 3%
The uncertainties are higher for $p_T > 30$ GeV.

Z ϕ^*_η: Systematic uncertainties

$\phi^*_\eta < 0.5$

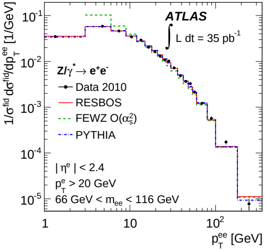
	e^+e^- channel [%]	$\mu^+\mu^-$ channel [%]
Bin-by-bin correlated		
Background	0.1	0.1
Tracking resolution	0.1-0.2	0.1-0.2
Unfolding procedure	0.1	0.1
Energy/momentum scale and resolution	0.1	0.03
Identification efficiency	0.05	0.03
Trigger efficiency	0.04	0.02
Pile-up	0.05	0.05
Bin-by-bin uncorrelated		
MC sample statistics	0.1-0.2	0.1-0.2
Tracking bias	0.1	0.1
QED FSR	0.3	0.3

The total systematic uncertainty on each data point is formed by adding the individual contribution in quadrature.
The total systematic uncertainty is up to 0.5%
The uncertainties for $\phi^*_\eta > 0.5$ are higher.

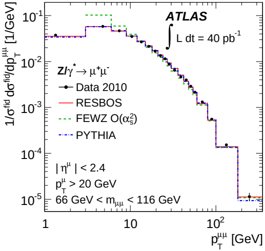
Electron and muon data are combined using χ^2 minimization method.

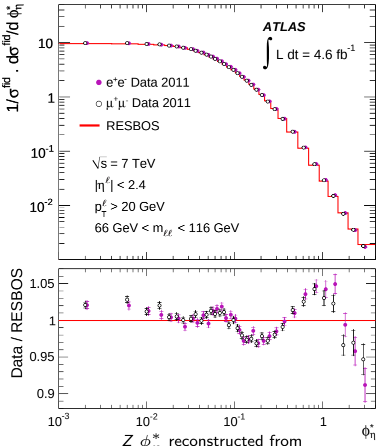
[Eur. Phys. J. C 63 (2009) 625,JHEP 01 (2010) 109]

Z p_T reconstructed from "**Born**" electrons



Z p_T reconstructed from "**Born**" muons





Z ϕ^*_η reconstructed from "**Born**" electrons and muons

Good consistency between electron and muon data for both measurements:

Z ϕ^*_η: $\chi^2/n_{dof} = 33.2/34$

Z p_T: $\chi^2/n_{dof} = 17.0/19$

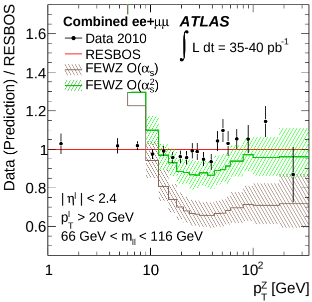
Z p_T Cross Section

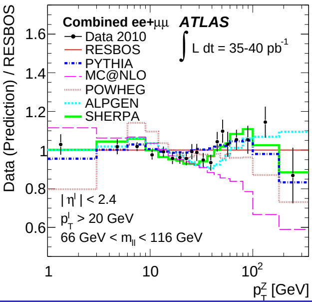
The differential cross section $\frac{1}{\sigma}\frac{d\sigma}{dp_T^Z}$ is measured in the p_T^Z range from 0 to 350 GeV divided into 19 bins.

- ResBos shows good agreement with the data: $\chi^2/n_{dof} = 21.7/19$;
- Fewz v2.0 with MSTW2008 PDF.
  Uncertainties: **at NLO:** $\sim 10\%$
  at NNLO: $\sim 8\%$
  scale variation $0.5 \leq \mu_R, \mu_F \leq 2$ around the nominal scale $\mu_R = \mu_F = m_Z$ + PDF error.

  NNLO Fewz predictions undershoot the data by $\sim 10\%$ which is compartible to the size of the scale uncertainty.

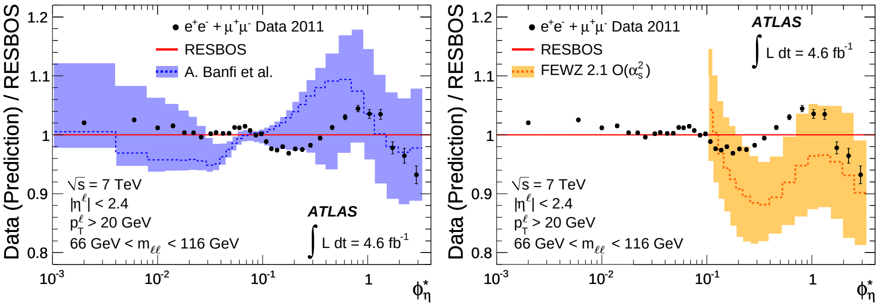
- LO multi-leg generators Alpgen and Sherpa give a good description of the entire measured spectrum;
- LO Pythia describes the measurement well;
- NLO generators Mc@nlo and Powheg+Pythia deviate from the data at low and high p_T^Z.





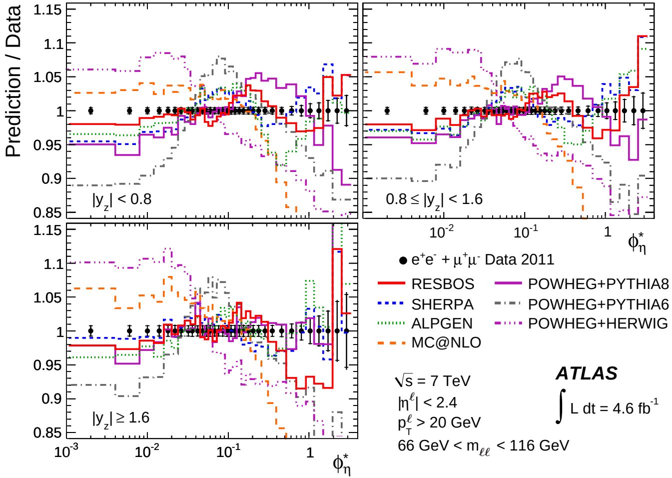
$Z\ \phi^*_\eta$ Cross Section

The differential cross section $\frac{1}{\sigma}\frac{d\sigma}{d\phi^*_\eta}$ is measured in 34 ϕ^*_η bins up to $\phi^*_\eta \sim 3$.



- RESBOS describes the data very well with discrepancy up to 5%, which is lower than RESBOS systematic uncertainty due to the propagation of PDF eigenvectors sets, which amounts to 4% for $\phi^*_\eta < 0.1$ and 6% above;
- FEWZ v2.1 predictions calculated at NNLO using CT10 PDF.
  Uncertainties: varying renormalization and factorization scales by factor of 2 up and down around the nominal scale m_Z; varying α_s + PDF uncertainty;
- Calculation by A.Banfi *et al.*: NNLL resummation matched to fixed order MCFM.
  Uncertainties: varying ressumation, renormalization and factorization scales + PDF uncertainty.

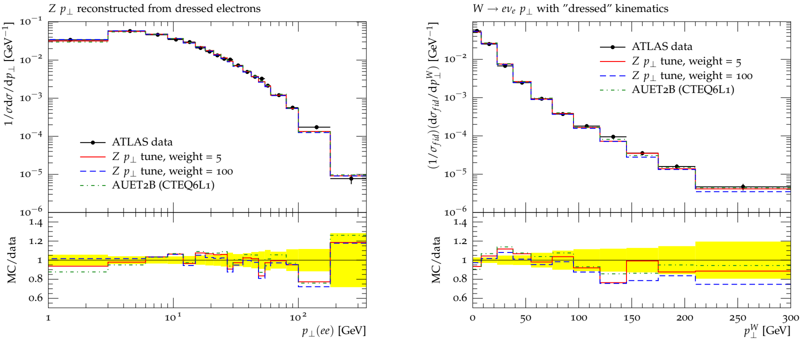
$Z\ \phi^*_\eta$ Double-differential Cross Section



Similar behaviour for all rapidity ranges:

- SHERPA and ALPGEN provide a good description of the spectra;
- POWHEG+PYTHIA8 describes the data better than POWHEG+PYTHIA6 and POWHEG+HERWIG;
- MC@NLO doesn't properly describe the data for $\phi^*_\eta > 0.1$.

The cross section is also measured **double-differentially** as a function of ϕ^*_η in 3 bins of Z boson rapidity for both e^+e^- and $\mu^+\mu^-$. Combination χ^2: $\chi^2/n_{dof} = 118/102$.



- Z p_T data were added to AUET2B PYTHIA6 tune to describe Z transverse momentum spectra, as well as W p_T distribution; ATL-PHYS-PUB-2011-015
- improved description of the spectra is important for W **mass measurement**.

Rivet analyses (http://rivet.hepforge.org/):

- Z p_T: *ATLAS_2011_S9131140*;
- W p_T: *ATLAS_2011_I925932*.

Summary

- Measurements of Z boson transverse momentum have been perfomed, directly and using the novel technique;
- Measurements are compared to different MC models and QCD predictions;
- Precision of the Z ϕ^*_η measurement is typically better by one order of magnitude than present theoretical predictions;
- Valuable to constrain further QCD predictions;
- Tuning of Monte Carlo generators to measured Z boson transverse momentum will allow to reduce systematical uncertainty for W mass measurement.

Backup Slides

Uncertainties due to QED FSR

- assigned to account for uncertainties due to ϕ^*_η / p_T dependent modeling of electroweak radiative corrections.

- PHOTOS vs SHERPA
  QED FSR in SHERPA based on the YSF method found to be different from PHOTOS QED FSR (in POWHEG). D. Yennie, S. Frautschi, and H. Suura. Ann.Phys.,13:379,1961

- PHOTOS vs KKMC
  PHOTOS uses approximation for the calculation of the first and second order matrix elements (ME). The prediction is compared to exact second order QED FSR ME calculations.
  Potential dependencies of ϕ^*_η / p_T were studied using sets of Z boson four-vectors with varying virtuality (Q), rapidity (y) and transverse momentum.

  KKMC - second order QED matrix element event generator S.Jadach, B.Ward, Z.Was

- PHOTOS vs SANC
  Comparison in single-photon and multi-photon modes.

  SANC is a computer system for calculating complete one-loop EW and QCD radiative corrections