(N)NLL+(N)NLO QCD predictions and QED FSR for a novel variable which probes the low p_T^Z domain

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Cracow, 16 May 2012

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Contents

(Data analysis is in the official ATLAS procedure for the approval of results and is not allowed to present in public.)

p_T^Z theoretical predictions (1/2)

- High p_T^Z ($>\sim$ 30 GeV)
  - Fixed order perturbative QCD predictions (like FEWZ)

    $\rightarrow$ Test pQCD
- Low p_T^Z ($<\sim$ 30 GeV):
  - Resummation of leading logarithms to all orders in α_S (like RESBOS).
  - OR modeling by parton shower generators (like PYTHIA).

    $\rightarrow$ Tune Monte Carlo models

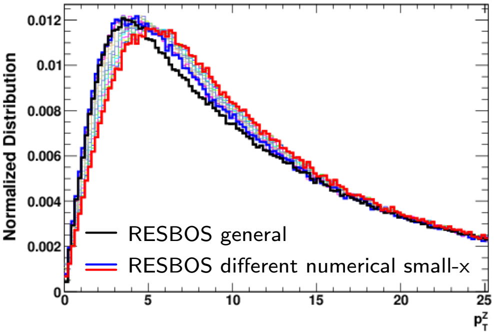
$\rightarrow$ This measurement helps to improve the modelling of W boson production needed for a precise measurement of the W mass.

p_T^Z theoretical predictions (2/2)

The small-x broadening effect was studied in Phys.Rev.D72:033015,2005: The resummed form factor may need to be modified for processes involving a small-x parton in the initial state.

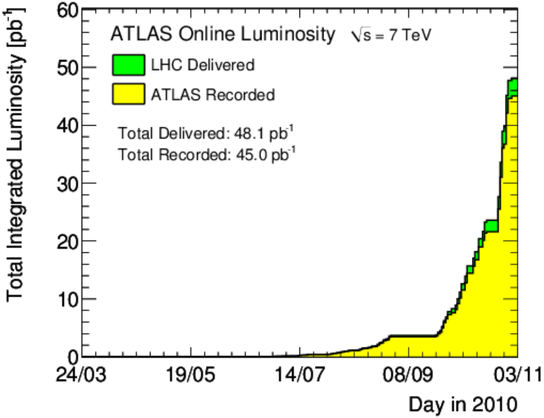
→ Lead to a wider p_T^Z distribution of Z bosons with large rapidity.

→ Interesting to be tested at LHC 7 TeV.



2010 ATLAS data at $\sqrt{s} = 7$ TeV proton-proton collisions

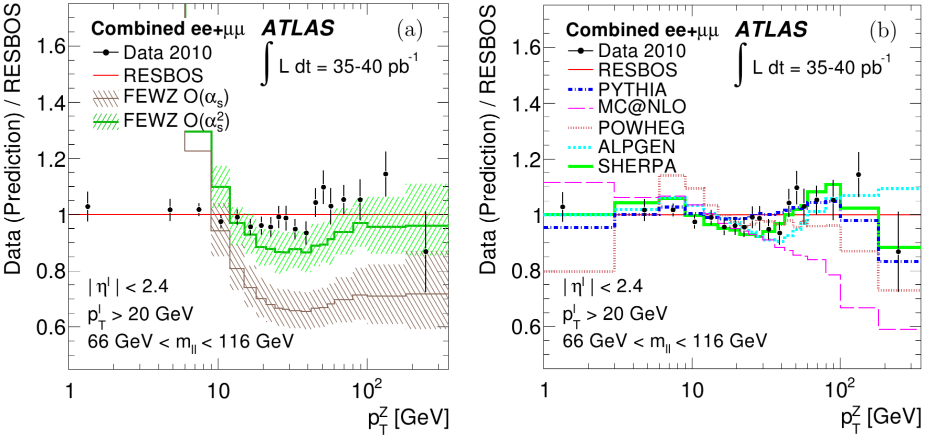
- p_T^Z distribution was measured using:
  $Z/\gamma^* \to e^+e^-$
  $Z/\gamma^* \to \mu^+\mu^-$
  $\int Ldt = 35 - 40$ pb^{-1}
- Fiducial region:
  $|\eta^l| < 2.4$
  $p_T^l > 20$ GeV
  (In electron channel - Energy by calorimetery, direction by tracker)
  66 GeV $< m_{ll} <$ 116 GeV



$\to$ 8923 $Z/\gamma^* \to e^+e^-$ and 15060 $Z/\gamma^* \to \mu^+\mu^-$ candidates

Comparison with theoretical predictions and MC generators

Phys.Lett.B 705 (2011) 415-434



Main systematic uncertainties

p_T^Z (GeV)	stat. (%)	syst. (%)
0 - 3	3.3	4.7
3 - 6	2.4	3.3
6 - 9	2.7	2.3
9 - 12	3.1	2.4
12 - 15	3.3	2.7
15 - 18	3.9	3.0
18 - 21	4.4	3.3
21 - 24	4.8	3.6
24 - 27	5.5	3.8
27 - 30	6.5	4.0

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Systematic uncertainties in electron channel:

- Energy scale: 0.2% – 4.4%.
- Unfolding: 2.0% – 4.2%.
- Efficiencies: 1.0% – 3.2%.
- Background: 1.4%
- Pileup: 0.3%
- MC statistics: 0.4% – 3.6%
- QED final state radiation: 0.6%

Why new variables?

Phys.Lett.B 705 (2011) 415-434

Main systematic uncertainties of the p_T^Z measurement:

- Energy scale: $0.2\% - 4.4\%$.
- Unfolding: $2.0\% - 4.2\%$.

$\Longrightarrow$

Optimize new variables which:

- is less susceptible to the effects of experimental resolution.

- probes the same physical effects as p_T^Z.

A novel variable definition

p_T — Eur.Phys.J.C71:1600,2011

$\downarrow$

a_T

$\downarrow \; \frac{\Delta a_T/M}{a_T/M} = \left(\frac{\Delta a_T}{a_T} - \frac{1}{2}\right) \frac{\Delta p_T^{(1)}}{p_T^{(1)}}$

a_T/M

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

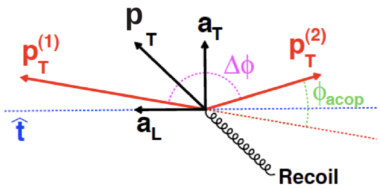
$a_T/M \approx \tan(\phi_{acop}/2)\sin(\theta^*)$

$\downarrow$

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

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

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



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

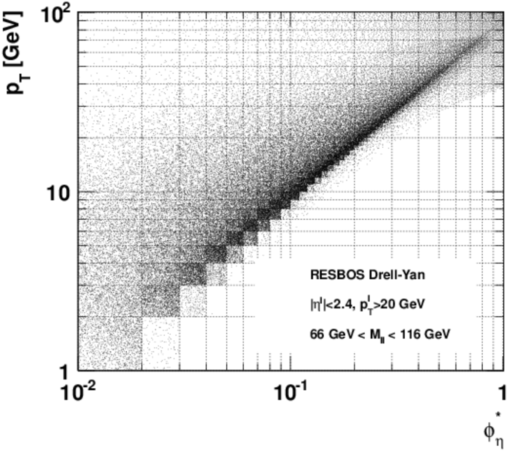
- θ^* is the scattering angle of the leptons relative to the beam direction in the dilepton rest frame.

- θ^* is commonly evaluated in the Collins Soper frame and susceptible to the effects of lepton momentum resolution.

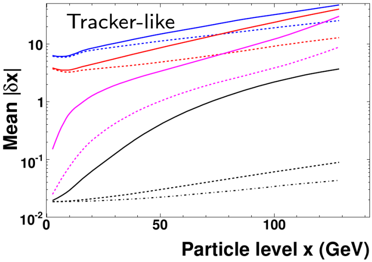
- θ_η^* is an alternative way to measure of the scattering angle that is based entirely on the measured track directions.

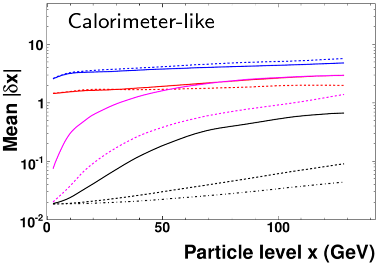
Correlation

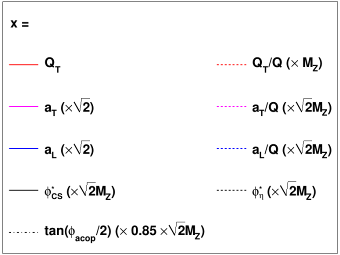
Evident correlation between p_T^Z and ϕ_η^*



Resolution







Eur.Phys.J.C71:1600,2011

Mean resolution of each candidate variable for the optimization as a function of that candidate using PYTHIA re-weighted to RESBOS for DØ.

Purity

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ATLAS p_T^Z purity $\sim 60\% - 90\%$ with 19 bins in $[0 - 350]$ GeV

Phys.Rev.Lett.106:122001,2011

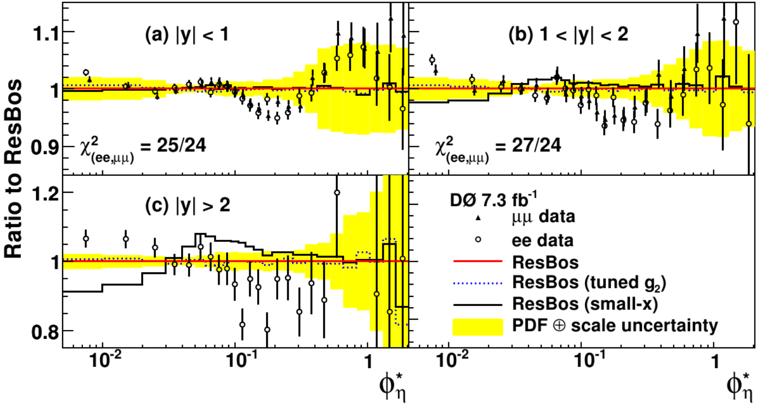
$D\emptyset$ ϕ^*_η purity $\sim 92\% - 98\%$ with 29 bins in $[0 - 4.749]$

$\rightarrow$ simplify unfolding procedure

$\rightarrow$ smaller systematic uncertainty due to unfolding is expected

DØ results

Phys.Rev.Lett.106:122001,2011



Conclusion:

1. A QCD prediction is unable to describe the detailed shape of the ϕ_η^* distribution.
2. The small-x broadening effect is strongly disfavored.

FEWZ

- FEWZ program:
  - QCD calculation at NLO ($\mathcal{O}(\alpha_S)$) or NNLO ($\mathcal{O}(\alpha_S^2)$) for high p_T^Z predictions.
  - No resummation for the emission of soft and collinear gluons in the low p_T^Z region.
  - PDF and α_S uncertainties calculated automatically.
  - QCD renormalization (μ_R) and fractorization (μ_F) scales initialized independently.
- The ϕ_η^* prediction using FEWZ:
  - The prediction with $\mu_R = \mu_F = M_Z$, NNLO PDF MSTW2008.
  - The theoretical uncertainty: $\sigma = \sqrt{\sigma^2_{PDF\_\alpha_S} + \sigma^2_{QCDscale}}$.
  - QCD scale uncertainty from scale variations by a factor of 2 with $1/2 \leq \mu_R/\mu_F \leq 2$.

RESBOS

- RESBOS program:

  - QCD calculation at NNLO for high p_T^Z predictions.

  - NNLL Resummation for the emission of soft and collinear gluons in the low p_T^Z region.

  - PDF uncertainties calculable.

  - Input grid with fixed QCD renormalization (μ_R) and factorization (μ_F) scales.

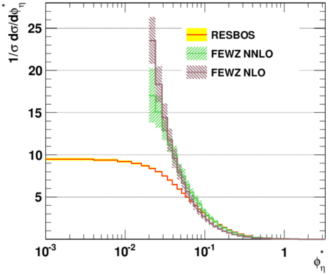
- The ϕ_η^* prediction using RESBOS:

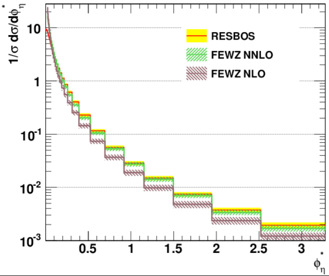
  - NLO PDF CTEQ6.6.

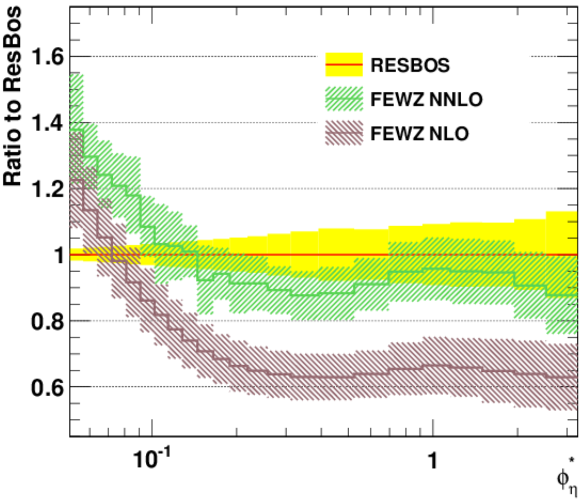
  - The theoretical uncertainty: $\sigma = \sqrt{\sigma_{PDF}^2 + \sigma_{QCDscale}^2}$.

  - No input grid for different choices of QCD scale → QCD scale uncertainty is extrapolated from FEWZ.

FEWZ and RESBOS comparison







Systematic uncertainties of ϕ^*_η measurement

- Energy scale and resolution (negligible)
- Unfolding
- Efficiencies
- Background
- Pileup
- MC statistics
- PDF
- Tracking
- QED final state radiation (studied by Z. WAS, L. DI CIACCIO): expected to give one of the highest contribution (0.6% in Phys.Lett.B 705 (2011) 415-434)

Monte Carlo generators used for QED FSR study

- PHOTOS 2.5 - interfaced with the ATLAS simulation

  (approximations for the calculations of the first and second order matrix elements to describe QED FSR)

- KKMC

  (a second order QED matrix element)

- SANC

  (one loop electroweak and QCD radiative corrections to high energy processes)

QED FSR systematic uncertainty: Methodology

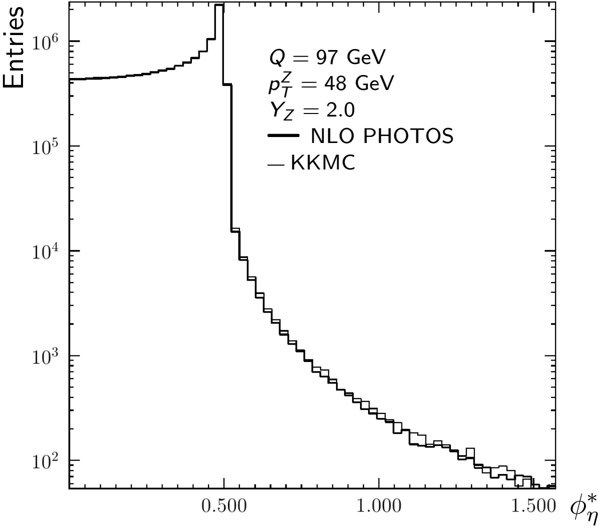
QED final state radiation can change the true level (or generated) fiducial cross section in the electron channel by about -5% and in the muon channel by about -3%.

The systematic uncertainty due to QED FSR is estimated by comparing:

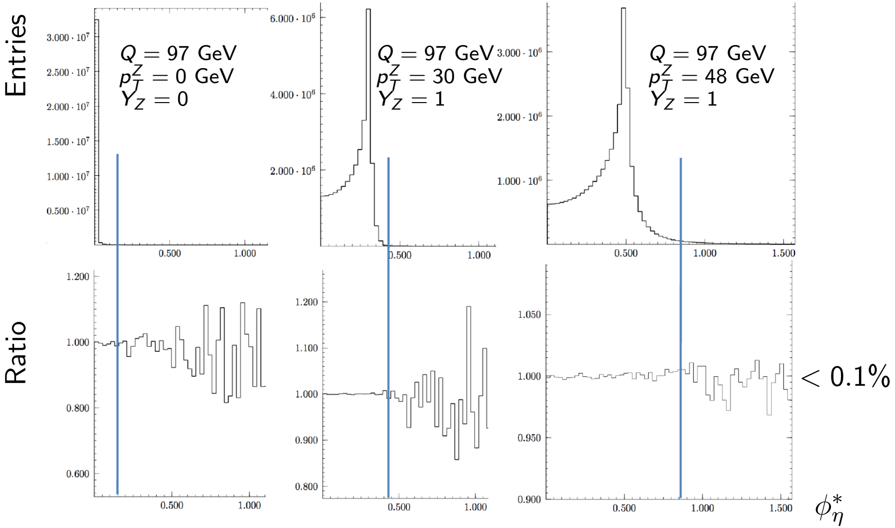
- ϕ_η^* differential distributions for fixed values of: Q, p_T^Z, Y_Z for $Z \to ee$ and $Z \to \mu\mu$
- Integrated cross-sections in each Q, p_T^Z, Y_Z bin

in PHOTOS with KKMC and SANC.

Examples of PHOTOS and KKMC comparison (1/2)



Examples of PHOTOS and KKMC comparison (2/2)



QED FSR systematic uncertainty study: First results

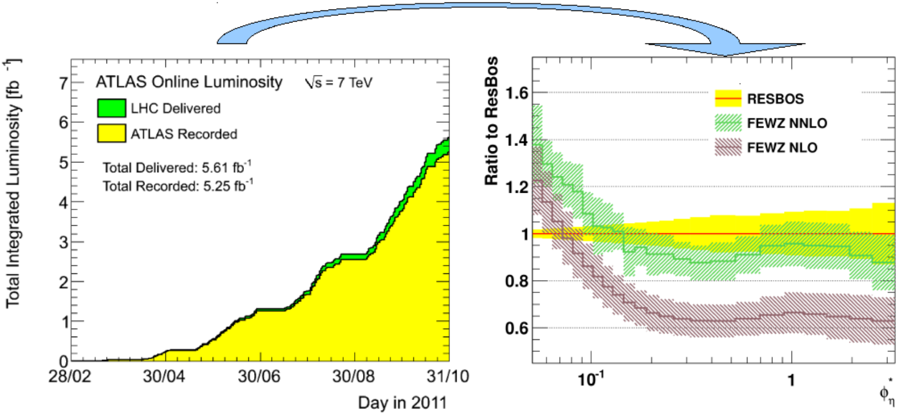
Comparison of PHOTOS with KKMC and SANC:

- PHOTOS and KKMC: $\sim 0.1\%$
- PHOTOS and SANC (multiple-photon mode):

  - Charged current ($\sim 0.1\%$)

  - Neutral current (is going on...)

2011 ATLAS data at $\sqrt{s} = 7$ TeV proton-proton collisions



Expected statistic uncertainty: $\sim 0.5\%$

Conclusion

- Theoretical predictions for ϕ_η^* measurement at $\sqrt{s} = 7$ TeV are presented.
- QED FSR systematic uncertainty estimation is going on and will be finalized in near future.
- Analysis of ϕ_η^* measurement using 2011 ATLAS data is being finalized and will be ready soon.

References

1. FEWZ:

   Comput.Phys.Commun.182:2388-2403,2011

   arXiv:1201.5896v1

   www.hep.anl.gov/fpetriello/FEWZ_2.1.tar.gz

2. RESBOS:

   Phys.Rev.D56:5558-5583,1997

   http://hep.pa.msu.edu/resum/

3. PHOTOS:

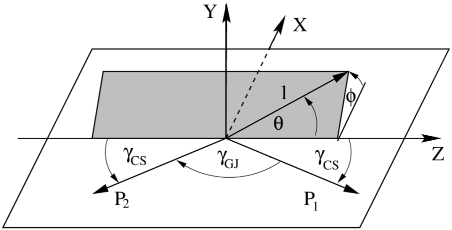
   http://annapurna.ifj.edu.pl/ wasm/phi-star.html

Thank you for your attention!

Backup

Collins Soper frame (CS)

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.

RESBOS resummation with non-perturbative functions

1. No small-x: The resummed cross section for the process AB->VX is calculated as:

$$\frac{d\sigma_{AB}}{dQ^2\,dy\,dQ_T^2} \approx \int \frac{d^2 b}{(2\pi)^2} e^{i\vec{q}_T\cdot\vec{b}}\, \widetilde{W}_{AB}(b,\ldots) + Y$$

$$\widetilde{W}_{AB}(b,Q,x_A,x_B) = \widetilde{W}_{AB}^{pert}(b_*,Q,x_A,x_B)\, e^{-S_{NP}^{BLNY}(b,Q,b_*)}$$

Where the non-perturbative Sudakov function has the BLNY (Brock-Landry-Nadolsky-Yuan) parametrization:

$$S_{NP}^{BLNY}(b,Q,b_*) = [0.21 + 0.68\ln(\frac{Q}{3.2\,GeV}) - 0.126\ln(100\,x_A x_B)]\,b^2$$

2. Small-x: The new form of resummed form factor:

$$\widetilde{W}_{AB}(b) = \widetilde{W}_{AB}^{pert}(b_*,Q,x_A,x_B)\, e^{-S_{NP}^{BLNY}(b,Q,b_*)}\, e^{-\rho(x_A)b^2 - \rho(x_B)b^2}$$

One choice of ρ(x):

$$\rho(x) = c_0\left(\sqrt{\frac{1}{x^2} + \frac{1}{x_0^2}} - \frac{1}{x_0}\right)$$

c_0 controls the magnitude of the broadening for a given x,
x_0 is a characteristic value of x below which ρ(x) becomes non-negligible.

MC generators

- PYTHIA: the hard scattering process is calculated in leading order approximation and the higher order corrections are approximated with a parton shower approach.
- ALPGEN: LO MC generator which implements the exact matrix element LO calculation for multi-partonic final states.
- SHERPA: account for multijet production through multi-parton tree-level matrix elements merged with the parton shower.
- MC@NLO: full NLO calculations of rates for QCD processes during the hard scattering.
- POWHEG: a prescription for interfacing NLO QCD calculations with parton shower generators, can be interfaced with any modern shower generator such as HERWIG and PYTHIA.