Measurements of Drell-Yan transverse momentum and vector boson plus jets properties with the ATLAS detector

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DIS 2015

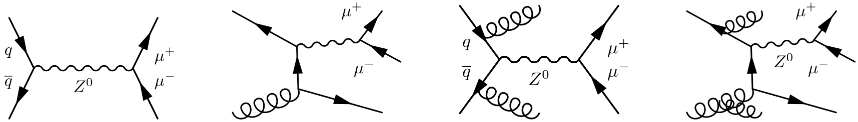
Dallas, TX

April 28, 2015

Overview

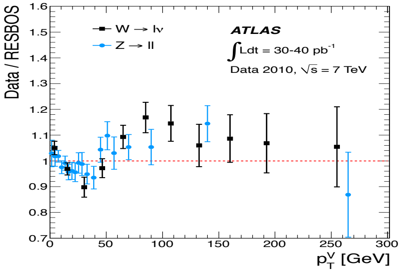
- Theoretical Motivation
- Z/γ^* Boson Transverse Momentum [arxiv:1406.3660], [JHEP09(2014)145]
- Z/γ^* Boson ϕ^*_η [arxiv:1211.6899], [Phys. Lett. B 720 (2013) 32-51]
- Production of Z Bosons with Jets [arxiv:1304.7098], [JHEP07(2013)032]
- Ratio of W and Z plus Jets [arxiv:1408.6510], [Eur. Phys. J. C (2014) 74: 3168]
- Conclusions

Theoretical Motivation



P_T^Z/ϕ^*_η Measurement:

- The dynamical effects of the strong interaction can be studied by measuring the transverse momentum or ϕ^*_η of the Z/γ^* boson
- Transverse momentum is imparted to the Z/γ^* boson from the radiation of partons as the Z recoils from the hadronic system
- This measurement is an ideal test of perturbative QCD (pQCD) calculations
- Can also test QCD predictions re-summed to all perturbative orders of α_s complemented with Parton Showers (PS)
- Good modelling of the transverse momentum of vector bosons is crucial for precise measurement of the W P_T hence the W mass



[arxiv:1108.6308v2], [Phys.Rev.D 85 (2012) 012005]

Vector Boson plus Jets Measurement:

- Production of vector (Z and W) bosons in association with jets can be used to test pQCD and Monte Carlo (MC) generators based on LO or NLO matrix elements matched to a PS
- The ratio of $W+$ jets and $Z+$ jets provides a more precise test of pQCD since some experimental uncertainties are significantly reduced

Z/γ^* Boson Transverse Momentum

Measurement:

$q\bar{q} \rightarrow Z/\gamma^* \rightarrow l^+l^-, \quad l = e, \mu$

2011, 4.7 fb^{-1}, $\sqrt{s} = 7$ TeV

Fiducial volume:

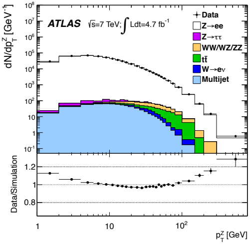
- $66 < M_{ll} < 116$ GeV
- $p_T^l > 20$ GeV
- $|\eta^l| < 2.4$

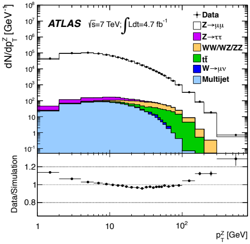
Background:

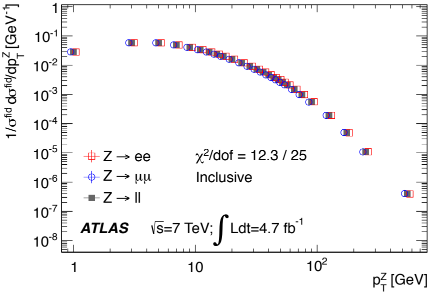
- Multi-jet background dominates at low P_T^Z, estimated from data using isolation distributions
- Electroweak and top quark backgrounds estimated using MC

Systematics:

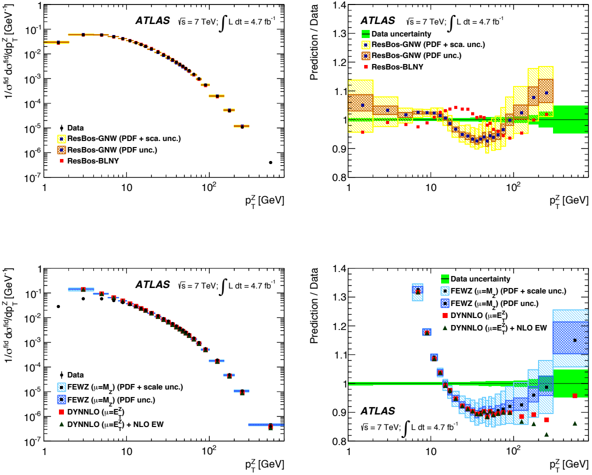
- e-channel: Dominated by energy modelling
- μ-channel: Dominated by muon selection efficiency







Comparison with QCD Predictions



QCD Predictors:

ResBos:

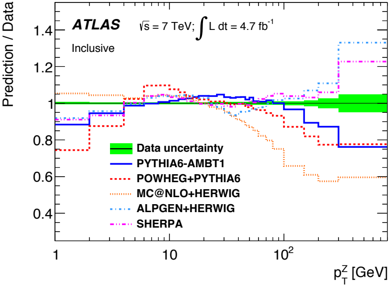
- **Res**ummation module for **Bos**ons
- NNLL resummation at low P_T^Z
- $\mathcal{O}(\alpha_s) + \mathcal{O}(\alpha_s^2)$ in pQCD
- **Result:** Describes the P_T^Z spectrum well over the entire range

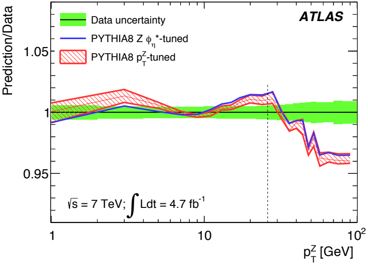
FEWZ:

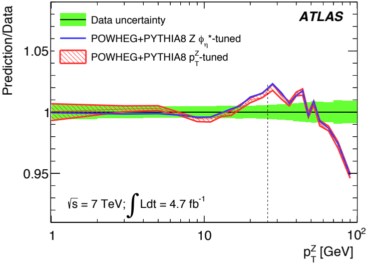
- **F**ully **E**xclusive **W**, **Z** Production through NNLO in pQCD
- $\mathcal{O}(\alpha_s^2)$ in pQCD
- **Result:** Struggles at low P_T^Z, 10% discrepancy to data in central region

DYNNLO:

- **Drell-Yan** at **NNLO**
- $\mathcal{O}(\alpha_s^2)$ in pQCD
- Variable renormalization scale $\mu_r(E_T^Z)$
- **Result:** Struggles at low P_T^Z, 10% discrepancy with data at central region





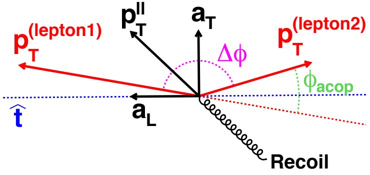


Comparison with MC Generators:

- **Result:** POWHEG+PYTHIA (NLO+PS+UE) generators agree with the data best over the entire range
- **Result:** MC@NLO (NLO+PS+UE), ALPGEN (Multi-Leg-LO+PS+UE), and SHERPA (Multi-Leg-LO+PS) show significant discrepancies at low and high values of P_T^Z
- PYTHIA8 and POWHEG+PYTHIA8 generators were tuned to probe sensitivity of generator parameters to the measurement
- The parton shower model parameters were tuned
- **Result:** Tuned predictions are in agreement with data within 2% for $P_T^Z < 50$ GeV

Z/γ^* Boson ϕ^*_η

The observable ϕ^*_η probes low P_T^Z with excellent experimental precision.

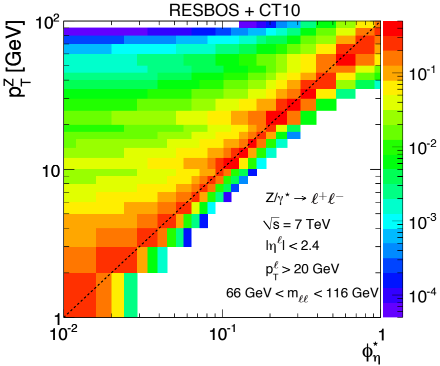


$$\phi^*_\eta = \tan\left(\frac{\phi_{acop}}{2}\right)\sin(\theta^*)$$

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

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

ϕ^*_η depends only on the directions of the two leptons, which are typically measured better than their momenta.



Correlation matrix between ϕ^*_η and P_T^Z variables, at Born level. The RESBOS prediction with the CT10 PDF set has been used.

Note: Values $0 < \phi^*_\eta < 1$ probes $P_T^Z \sim 100$ GeV

Z/γ^* Boson ϕ^*_η

Measurement:

$q\bar{q} \to Z/\gamma^* \to l^+l^-, \quad l = e, \mu$

2011, 4.7 fb^{-1}, $\sqrt{s} = 7$ TeV

Fiducial volume:

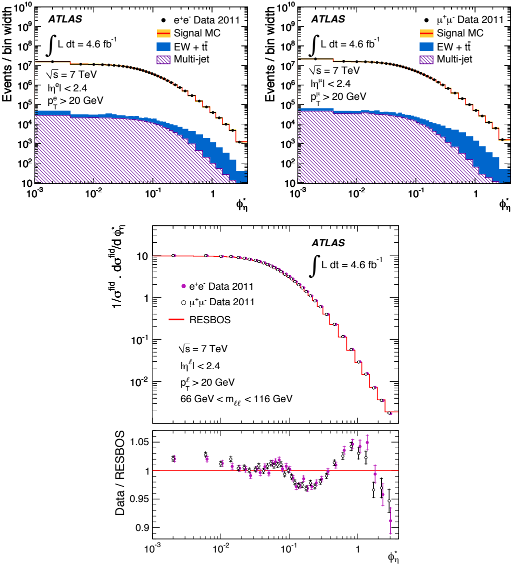
- $66 < M_{ll} < 116$ GeV
- $p_T^l > 20$ GeV
- $|\eta^l| < 2.4$

Background:

- Multi-jet background dominates at low ϕ^*_η
- Template fit data driven method for multi-jet background
- Electroweak and top quark estimated using MC

Systematics:

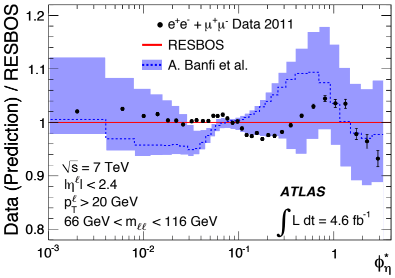
- e-channel: Dominated by the limited MC statistics
- μ-channel: Dominated by the limited MC statistics

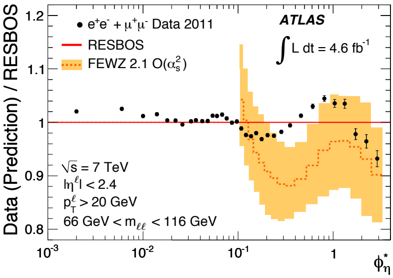


Z/γ^* Boson ϕ^*_η

RESBOS Baseline Comparisons:

- For $\phi^*_\eta < 0.1$, the difference between data and RESBOS is about 2% increasing to about 5% for larger values of ϕ^*_η
- **Note:** The PDF uncertainty on the RESBOS prediction ranges from 4-6% which is within the data measurement





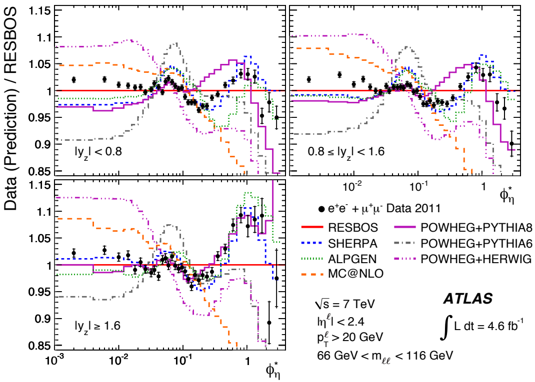
- NNLL resummation matched to NLO prediction from A. Banfi et al. [arxiv:1205.4760]
- **Result:** A. Banfi's prediction is mostly consistent with the measurement though the uncertainty on the prediction is sizable

- NLO FEWZ calculation
- **Result:** Since fixed order pQCD (without resummation) was not expected to give a good prediction at low-ϕ^*_η, the FEWZ prediction was not shown there

Z/γ^* Boson ϕ^*_η

- Ratio of differential cross-sections from data/prediction to RESBOS shown for several $|y_Z|$ regions
- Comparison is made for several Monte Carlo generators
- **Result:** SHERPA and ALPGEN describe the data well for $\phi^*_\eta > 0.1$ but encounter some problems for $\phi^*_\eta < 0.1$
- **Result:** MC@NLO fails to describe the data for $\phi^*_\eta > 0.1$ but for $\phi^*_\eta < 0.1$, results were within 4-7%
- **Result:** POWHEG+PYTHIA8 are within 5% of data over the entire range
- **Result:** POWHEG+PYTHIA6 and POWHEG+HERWIG PS tunings were changed but resulted in worse descriptions than POWHEG+PYTHIA8

RESBOS Baseline Comparisons:



- **RESBOS:** NNLL resummation + $\mathcal{O}(\alpha_s) + \mathcal{O}(\alpha_s^2)$ in pQCD
- **PYTHIA:** LO + PS
- **SHERPHA:** LO with up to 5 additional hard partons + PS
- **ALPGEN:** LO with up to 5 additional hard partons (with HERWIG (PS) and JIMMY (UE))
- **MC@NLO:** NLO (with HERWIG (PS) and JIMMY (UE))
- **POWHEG:** NLO

Z+Jets Events

Measurement:

$Z + jets \rightarrow l^{+}l^{-} + jets, \quad l = e, \mu$

2011, 4.7 fb^{-1}, $\sqrt{s} = 7$ TeV

Fiducial volume:

- $66 < M_{ll} < 116$ GeV
- $p_T^l > 20$ GeV
- $|\eta^l| < 2.4$

Jet selection:

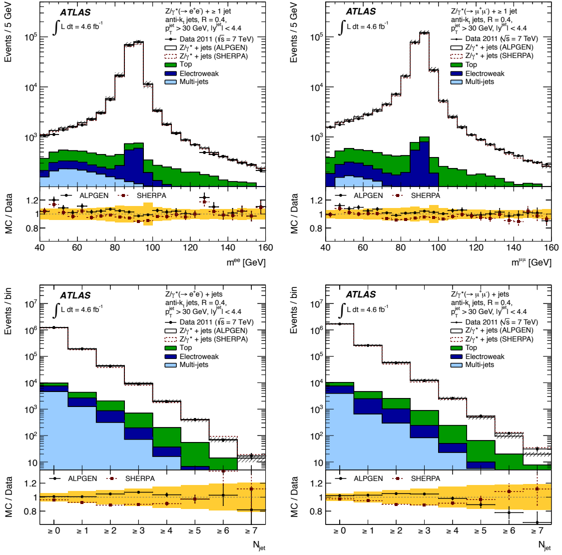
- $p_T^j > 30$ GeV
- $|y^j| < 4.4$
- $\Delta R^{lj} > 0.5$

Background:

- Multi-jet and $t\bar{t}$ estimated using data driven techniques
- EW estimated using MC

Systematics:

- Dominated by the jet energy scale

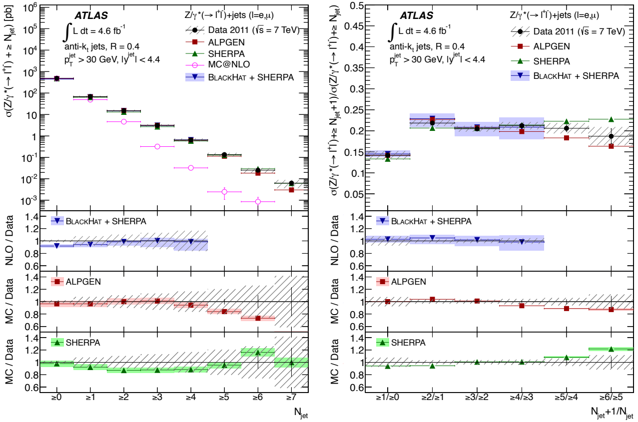


Z+Jets Events

Comparisons to MC Generators:

"Staircase" scaling

- Cross-sections for dressed leptons and particle jets unfolded to fiducial volume
- Cross-section as a function of inclusive jet multiplicities **(left)** and ratio of inclusive jet multiplicities **(right)**
- BLACKHAT(NLO) + SHERPA + CT10
- ALPGEN 2.13 + HERWIG + JIMMY + CTEQ6L1
- SHERPA 1.4.1 + MEnloPS + CT10
- MC@NLO agrees only for at most ≥ 1 jet (one parton from NLO real emission), otherwise HERWIG PS fails to model jet multiplicities



Result: Good description of the data is obtained by using fixed order NLO calculations and multi-leg MC + PS

Z+Jets Events

Staircase scaling:

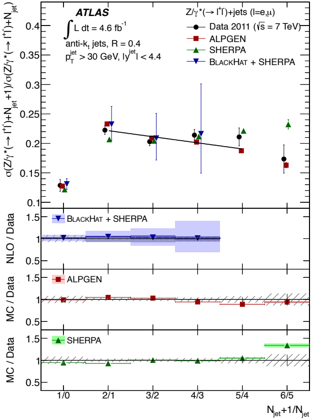
- Staircase scaling expected when no major kinematic cuts are applied
- Jet rate $\sigma^n \sim \exp^{-bn}$
- Ratio $\sigma^{n+1}/\sigma^n \sim$ constant

Poisson scaling:

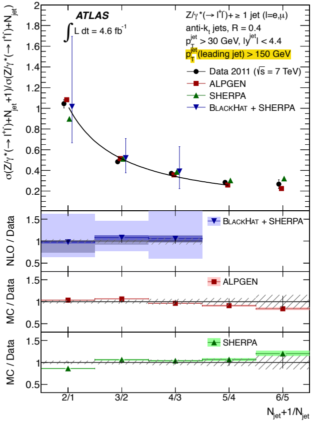
- Expected when jet acceptance cut is much larger than the hard process scale
- Emerges when the difference in energy scale between the leading jet and other jets is large
- Jet rate $\sigma^n \sim \text{Poisson}(n|\mu_n)$
- Exclusive ratio $\sigma^{n+1}/\sigma^n \sim \mu_n/(n+1)$

- Jet multiplicity ratios are expected to follow one of two benchmark patterns
- Its behaviour can be used to extrapolate the jet rate to higher multiplicities

Staircase scaling



Poisson scaling



Ratio $R = (W + jet)/(Z + jet)$

- Sensitive to the differences between W+jets and Z+jets events
- Large amount of cancellation of experimental uncertainties and non-pQCD effects

Measurement:

$$W + jets \to l\nu + jets, \quad Z/\gamma^* + jets \to l^+l^- + jets, \quad l = e, \mu$$

$$2011,\ 4.7\ \text{fb}^{-1},\ \sqrt{s} = 7\ \text{TeV}$$

Lepton	**W Boson**	**Z Boson**	**Jet**
$p_T^l > 25$ GeV	$M_T > 40$ GeV	$66 < M_{ll} < 116$ GeV	$p_T^j > 30$ GeV
$\lvert\eta^l\rvert < 2.5$	$P_T^W > 25$ GeV	$\Delta R_{ll} > 0.2$	$\lvert\eta^l\rvert < 4.4$
			$\Delta R_{lj} > 0.5$

Background:

- Multi-jet and $t\bar{t}$: Data driven template fits
- Electroweak: Monte Carlo

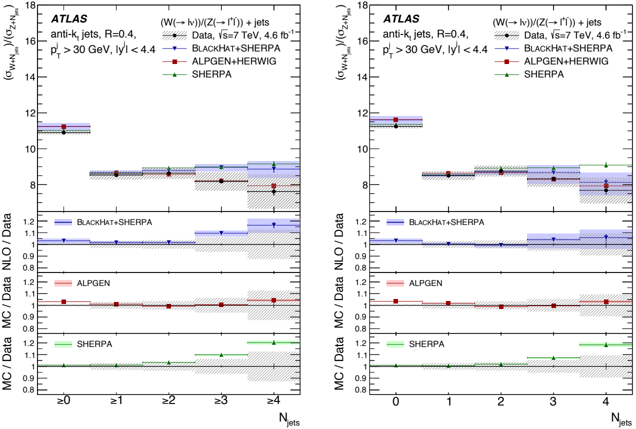
Systematics:

- Jet energy resolution
- Jet energy scale
- Multi-jet background

Ratio $R = (W + jet)/(Z + jet)$

Comparisons to MC Generators:

- Ratio of combined cross-sections unfolded to the fiducial volume
- Ratio as a function of inclusive **(left)** and exclusive **(right)** jet multiplicities
- BLACKHAT(NLO) + SHERPA + CT10
- ALPGEN 2.13 + HERWIG + JIMMY + CTEQ6L1
- SHERPA 1.4.1 + MEnloPS + CT10
- MC@NLO agrees only for at most ≥ 1 jet (one parton from NLO real emission), otherwise HERWIG PS fails to model jet multiplicities



Result: Good description of the data is obtained by using fixed order NLO calculations and multi-leg MC + PS

Conclusions

- A wide variety of vector boson plus jets measurements have been made at the LHC with the ATLAS detector
- Such measurements provide stringent tests of perturbative QCD and our ability to model it
- In general, comparisons made with generators were good especially those with NLO calculations and Multi-Leg Monte Carlo with Parton Shower modelling
- Many ATLAS 8 TeV analyses on this topic are in very mature stages
- At 13 TeV, new kinematic phase spaces will be available to be tested leading to an enhanced understanding of QCD