

Measurement of the transverse momentum of the Z boson and NLO MC tuning

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on behalf of the ATLAS collaboration



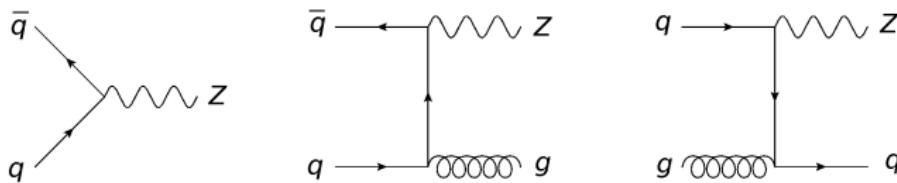
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The Z boson transverse momentum distribution

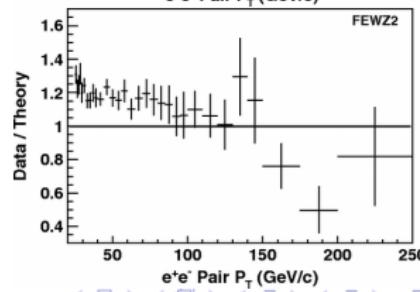
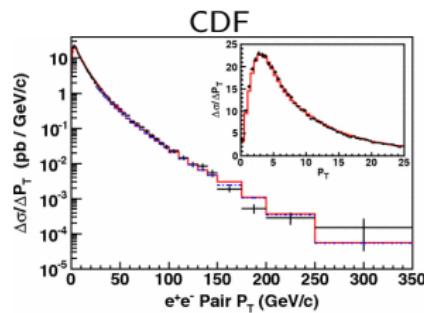
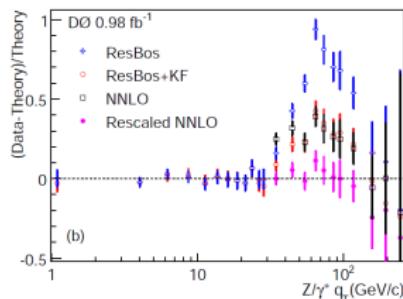
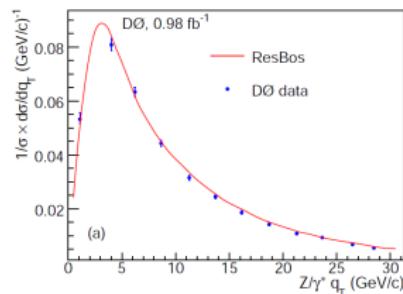
- In hadronic collisions, Z/γ^* bosons (Z from now on) are produced with non-zero transverse momentum, due to the intrinsic transverse momentum of the partons inside the proton, and hard (and soft) emission of additional partons.



- The resulting transverse momentum distribution (p_T^Z) is an excellent probe of the dynamics of QCD:
 - The low p_T part of the spectrum is dominated by the emission of soft partons → **Parton shower models and analytic resummation**.
 - The high p_T region is dominated by hard parton emissions → **Perturbative QCD, PDFs**.
- The decay into leptons ($Z \rightarrow e^+e^-$ and $Z \rightarrow \mu^+\mu^-$) provides a precise signal with very low background → **Test of theoretical calculations, improve precision of phenomenological parameters**.

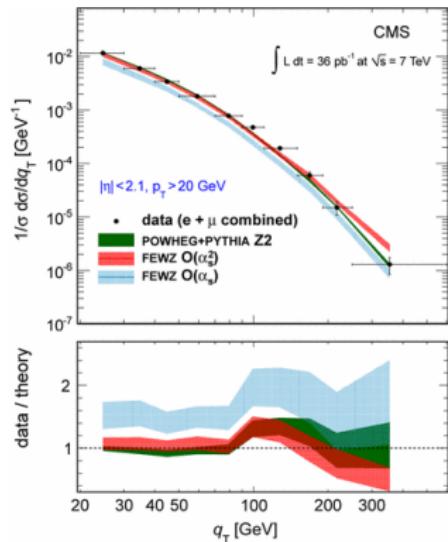
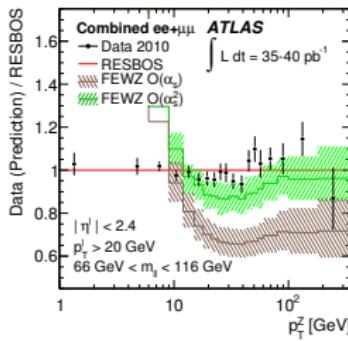
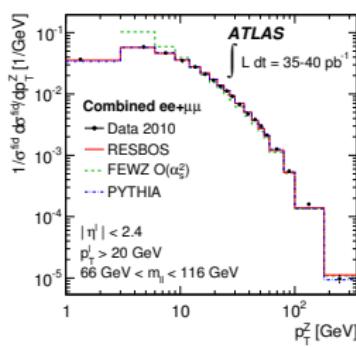
Previous measurements

- D0 (2008), 0.98 fb^{-1} @ $\sqrt{s} = 1.96 \text{ TeV}$. Up to 260 GeV, precision of 3 % to 30 %.
- CDF (2012), 2.1 fb^{-1} @ $\sqrt{s} = 1.96 \text{ TeV}$, electron channel. Up to 350 GeV, precision of 2 % to 35 % +5.8 % (from luminosity), high granularity (~ 80 bins).
- In this and following slides, showing example plots with comparisons to predictions.



Previous measurements

- ATLAS (2011), $35\text{-}40 \text{ pb}^{-1}$ @ $\sqrt{s} = 7 \text{ TeV}$. Up to 350 GeV, precision of 2 % to 15 %.
- CMS, 36 pb^{-1} @ $\sqrt{s} = 7 \text{ TeV}$. Up to 600 GeV, precision of 3 % to 30 %.
- Recent CMS measurement, 18 pb^{-1} @ $\sqrt{s} = 8 \text{ TeV}$, muon channel. Up to 600 GeV, precision of 4 % to 50 % (reduced instantaneous luminosity sample, small number of multiple collisions).

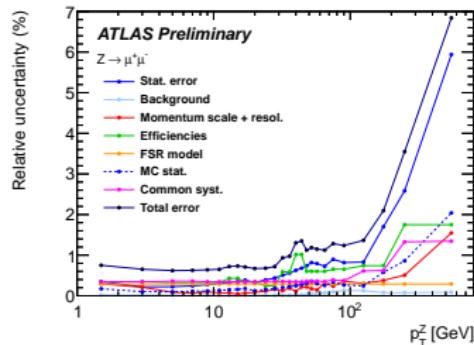


Overview of the new ATLAS p_T^Z measurement

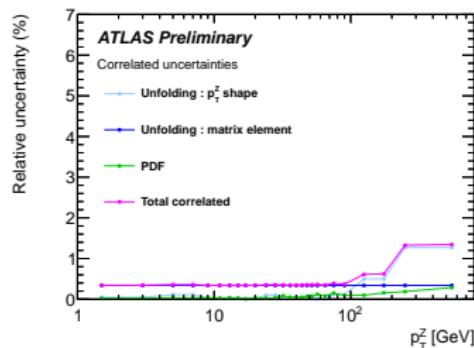
- We present for the first time an updated ATLAS measurement, done using 4.7 fb^{-1} at $\sqrt{s} = 7 \text{ TeV}$.
 - Exploit high statistics, reaching better precision and larger p_T^Z range with respect to ATLAS previous measurement.
 - 26 bins, up to 800 GeV.
 - 2 GeV granularity for p_T^Z below 20 GeV.
- The measurement is done within the fiducial volume:
 - $p_T(l) > 20 \text{ GeV}$
 - $66 \text{ GeV} < M_{ll} < 116 \text{ GeV}$
 - $|\eta| < 2.4$
- Combining electron and muon channel unfolded measurements.
- The available statistics allowed us to perform the measurement inclusive in Z boson rapidity (y^Z), and also independently in three y^Z bins (y^Z): [0, 1], [1, 2], [2, 2.4].
 - Different kinematic regions are explored.

Uncertainties for the individual channels

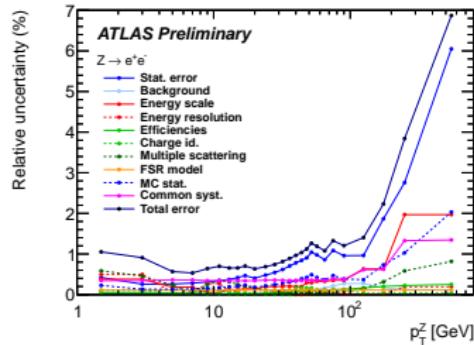
Muon channel



Correlated across channels

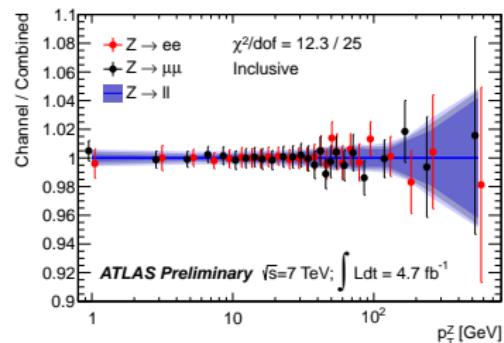
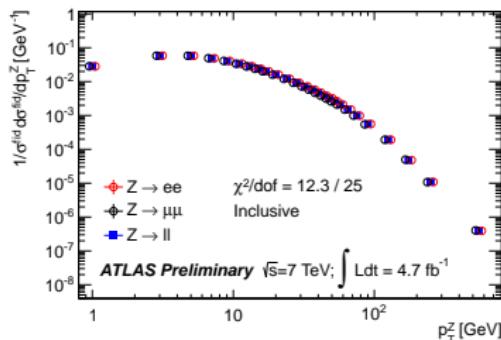


Electron channel



- Dominant uncertainties:
 - ee: energy scale and resolution, unfolding.
 - $\mu\mu$: efficiencies, unfolding.
- Statistical errors dominate above 100 GeV.

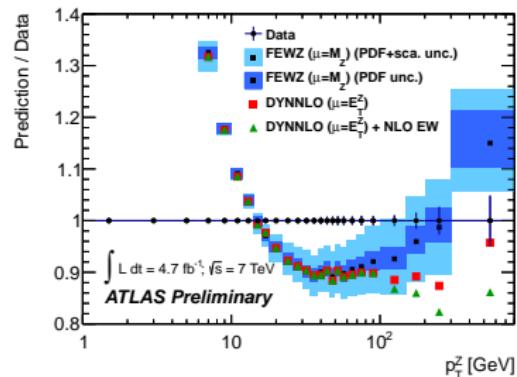
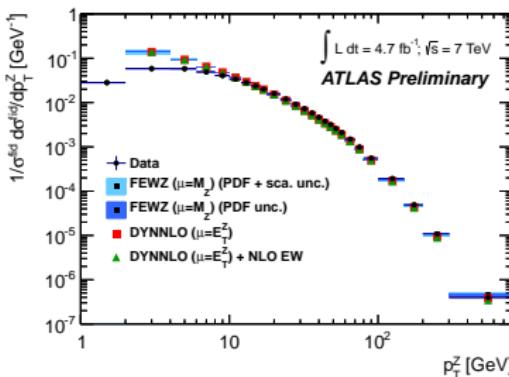
Combined result



- Precision of 0.5 % - 1.1 % up to 150 GeV, rising up to 5 % near the end of the spectrum.
- In the rapidity bins, the precision reached is of the order of 0.5 % - 6 %, 0.5 % - 9 % and 1 % - 40 %.

Comparisons to QCD predictions (1/3)

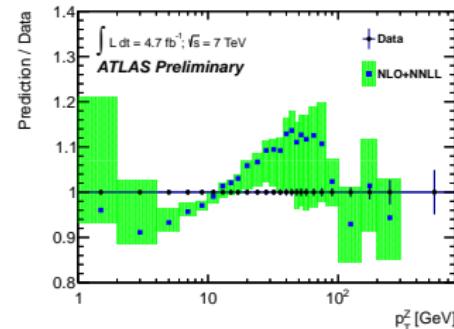
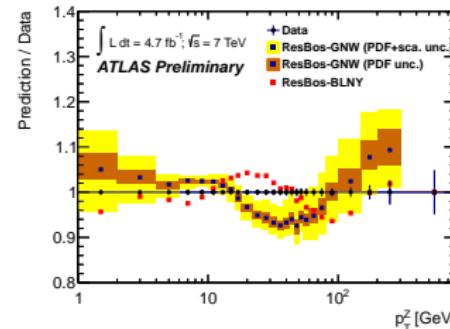
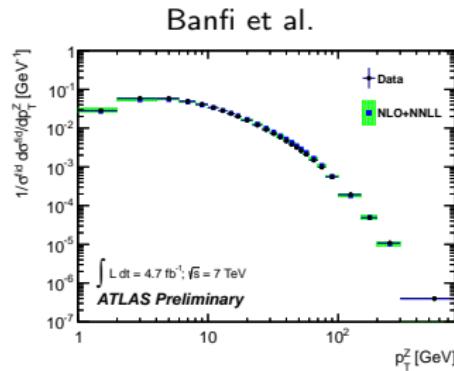
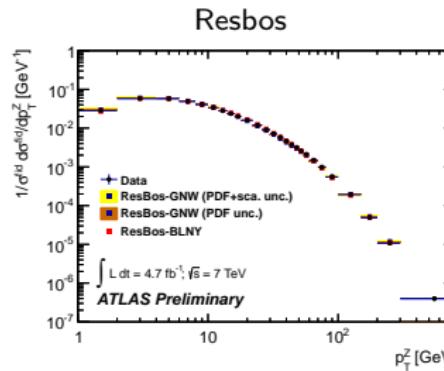
- Perturbative QCD up to NNLO in α_s (FEWZ and DYNNLO).



- Agreement within 10 % to 20 % starting from 20 GeV.
- Ratio to data is improved when including dynamic scale ($\mu = E_T^Z = \sqrt{(p_T^Z)^2 + (m_Z)^2}$) and NLO EW corrections in the calculation (the ratio flattens).

Comparisons to QCD predictions (2/3)

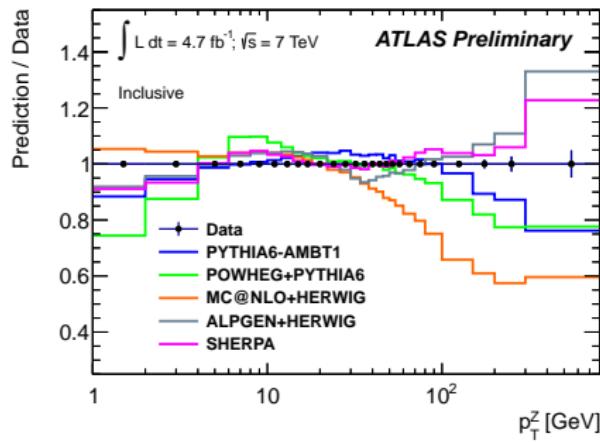
- Perturbative QCD matched to resummed calculations.



- Agreement within 10 % to 15 % across the p_T^Z spectrum.

Comparisons to QCD predictions (3/3)

- MC generators incorporating parton showers.



- At low p_T , the description is dominated by the parton shower tuning: different levels of agreement.
- At high p_T , (PYTHIA) LO and NLO generators underestimate the data, and LO multi leg generators overestimate it.

Tuning of MC parton shower models

- Motivation:

- Determine the sensitivity of the measured p_T^Z cross section to parton shower parameters.
- Exploit the high precision of the p_T^Z and the complementary $Z\phi_\eta^*$ measurements to constrain the parton shower models ($Z\phi_\eta^*$ is discussed in next slide).

- Tuning parameters:

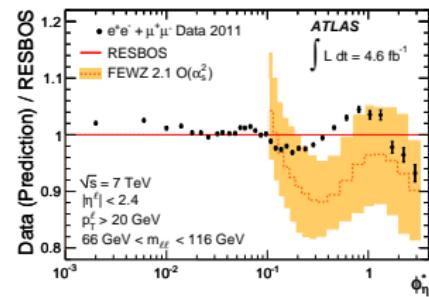
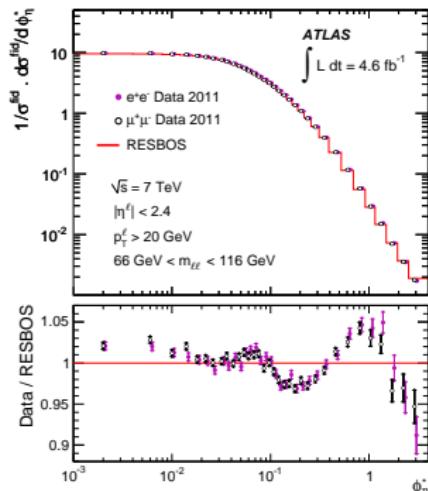
- Primordial k_T : transverse motion of partons inside the proton.
- ISR $\alpha_s^{ISR}(M_Z)$: strong coupling constant used in the evolution of the parton shower.
- ISR cut-off: parton shower lower p_T cut-off.

- Strategy:

- Tuning PYTHIA8 (LO) standalone and POWHEG+PYTHIA8 (NLO).
- Tunes are done in the low p_T^Z region ($p_T^Z < 26$ GeV and $Z\phi_\eta^* < 0.29$).
- Study sensitivity of observables with separate tunes.
- Main tune use observables: $p_T^Z(\mu\mu) + Z\phi_\eta^*(ee)$ (uncorrelated data).

Parentheses: $Z \phi_\eta^*$

- $Z \phi_\eta^*$ variable (Banfi, Wyatt, et al.): $Z \phi_\eta^* \equiv \tan\left(\frac{\pi - \Delta\phi_{12}}{2}\right) \sin\theta^*$
- Depends only on angular measurements: \rightarrow good precision.
- At low p_T : $Z \phi_\eta^* \approx \frac{p_T^Z}{m_{ll}}$ \rightarrow probe of p_T^Z .
- Measured in Tevatron, ATLAS and LHCb.
- Example: ATLAS measurement: 4.7 fb^{-1} @ $\sqrt{s} = 7 \text{ TeV}$, precision of 0.3 % to 1.7 %.

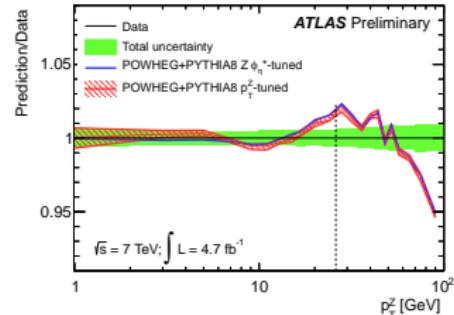
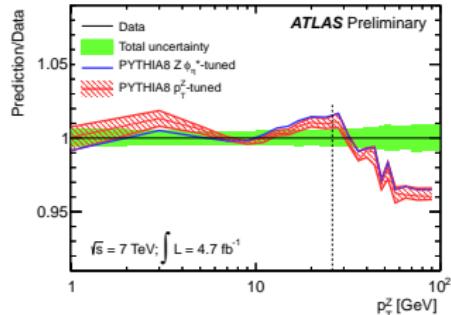


Sensitivity of observables

- Separate tuning to p_T^Z and $Z \phi_\eta^*$.

	PYTHIA8		POWHEG+PYTHIA8	
	p_T^Z	ϕ_η^*	p_T^Z	ϕ_η^*
Primordial k_T [GeV]	1.74 ± 0.03	1.73 ± 0.03	1.75 ± 0.03	1.75 ± 0.04
ISR $\alpha_s^{ISR}(M_Z)$	0.1233 ± 0.0003	0.1238 ± 0.0002	0.118 (fixed)	0.118 (fixed)
ISR cut-off [GeV]	0.66 ± 0.14	0.58 ± 0.07	2.06 ± 0.12	1.88 ± 0.12
χ^2_{min}/dof	23.9/19	59.9/45	18.5/20	68.2/46

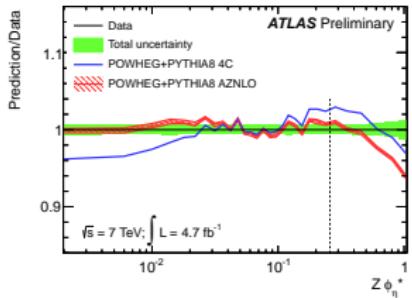
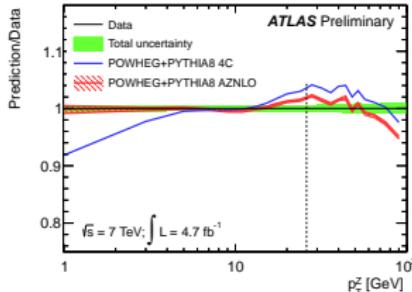
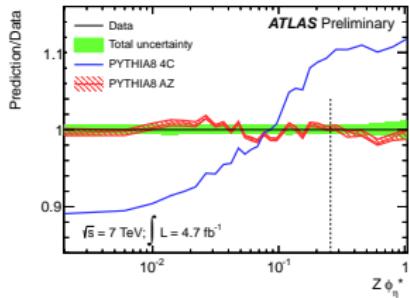
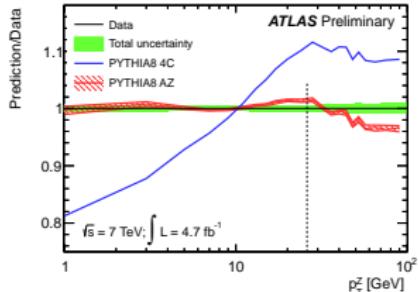
- Compatibility test:



- The observables have the same sensitivity and are compatible.

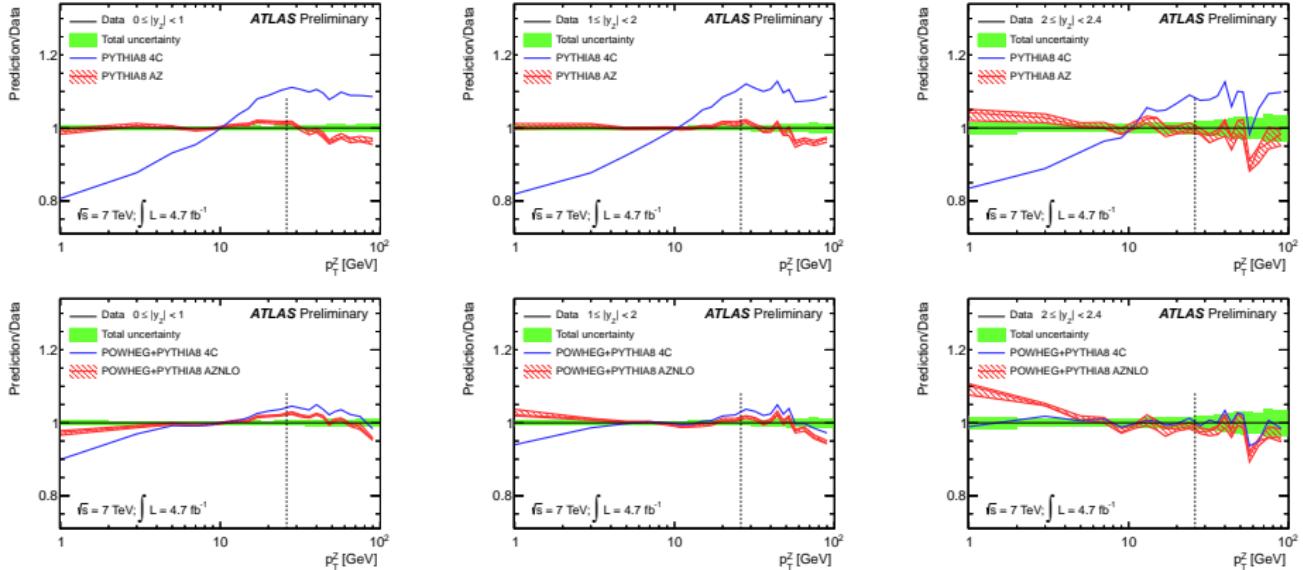
Tuning results

Tune Name	PYTHIA8	POWHEG+PYTHIA8	Base tune
AZ	AZNLO	4C	
Primordial k_T [GeV]	1.71 ± 0.03	1.75 ± 0.03	2.0
ISR $\alpha_s^{ISR}(M_Z)$	0.1237 ± 0.0002	0.118 (fixed)	0.137
ISR cut-off [GeV]	0.59 ± 0.08	1.92 ± 0.12	2.0
χ^2_{min}/dof	45.4/32	46.0/33	-



- Level of agreement goes from 10 % - 20 % to 2 %.

Consistency of models and tuning across y^Z bins



- The inclusive tune provides an accurate description of the different rapidity bins in the case of PYTHIA8, while the agreement is not that good in the case of POWHEG+PYTHIA8.

Conclusions

- We have presented a new ATLAS measurement of the Z boson transverse momentum spectrum in the electron and muon channels using 4.7 fb^{-1} of LHC proton-proton collision data @ 7 TeV.
- The large integrated luminosity allows a fine granularity in p_T^Z with a typical uncertainty on the combined result better than 1 % for $p_T^Z < 100 \text{ GeV}$, rising to 5 % in the end of the spectrum.
- The normalized cross section is compared to different QCD models and generator predictions, with different levels of agreement. The unprecedented precision of the measurement makes it very valuable to constrain the models (and look for improvement!).
- The measurement is used in combination with $Z\phi_\eta^*$ to perform a tuning of parton shower parameters, for standalone PYTHIA8 and POWHEG+PYTHIA8. The tuned predictions are in agreement with the data at the 2 % level for p_T^Z below 50 GeV.

