Z transverse-momentum distribution

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Motivations

Vector boson production is a benchmark process in hadron collider physics.
The transverse-momentum q_T distributions important for:

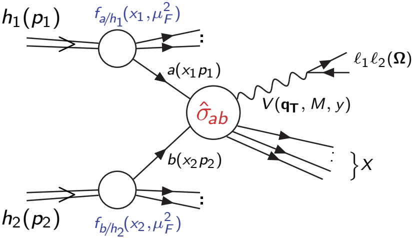
- Constraints of PDFs.
- M_W measurement $\rightarrow$ see M. Boonekamp and F. Piccinini talks.
- Beyond the Standard Model analyses.
- Perturbative QCD studies.

The above reasons and precise experimental data demands for accurate theoretical predictions $\Rightarrow$ computation of higher-order QCD corrections.

Drell–Yan q_T distribution

$$\mathbf{h_1(p_1) + h_2(p_2) \;\to\; V + X \;\to\; \ell_1 + \ell_2 + X}$$

where $\quad V = Z^0/\gamma^*, W^{\pm}$



QCD factorization formula:

$$\frac{d\sigma}{d^2\mathbf{q_T}\, dM^2\, dy\, d\mathbf{\Omega}} = \sum_{a,b} \int_0^1 dx_1 \int_0^1 dx_2\, f_{a/h_1}(x_1, \mu_F^2)\, f_{b/h_2}(x_2, \mu_F^2)\, \frac{d\hat{\sigma}_{ab}}{d^2\mathbf{q_T}\, dM^2\, d\hat{y}\, d\mathbf{\Omega}}(\hat{s}; \alpha_S, \mu_R^2, \mu_F^2).$$

Fixed-order perturbative expansion reliable

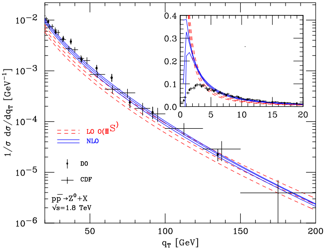
only for $q_T \sim M$. When $q_T \ll M$:

$$\int_0^{q_T^2} d\bar{q}_T^2 \frac{d\hat{\sigma}_{q\bar{q}}}{d\bar{q}_T^2} \sim 1 + \alpha_S \left[c_{12} L_{q_T}^2 + c_{11} L_{q_T} + \cdots \right]$$

$$+ \alpha_S^2 \left[c_{24} L_{q_T}^4 + \cdots + c_{21} L_{q_T} + \cdots \right] + \mathcal{O}(\alpha_S^3)$$

with $\alpha_S^n L_{q_T}^m \equiv \alpha_S^n \log^m(M^2/q_T^2) \gg 1$.

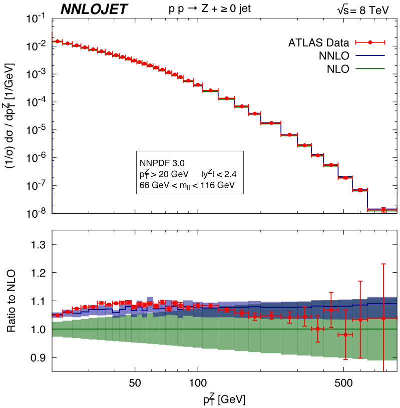
Resummation of logarithmic corrections needed.



State of the art: DY q_T distribution

- At large q_T: fixed-order analytical calculations available at $\mathcal{O}(\alpha_S^2)$ [Arnold,Reno('89)], [Gonsalves et al.('89)]. Vector boson plus jet (parton level MC) computations at $\mathcal{O}(\alpha_S^3)$ [Gehrmann-De Ridder et al.('15)][Boughezal et al.('15)].
- At small q_T: method to resum large q_T logarithms is known [Parisi,Petronzio('79)], [Kodaira,Trentadue('82)],[Collins,Soper,Sterman('85)],[Catani,de Florian, Grazzini('01)],[Bozzi et al.('06,'08)],[Catani,Grazzini('11)],[Catani et al.('13)].
- Results for q_T resummation by using Soft Collinear Effective Theory methods, resummation in direct-space and transverse-momentum dependent (TMD) factorization [Gao et al.('05)],[Idilbi et al.('05)],[Mantry,Petriello('10,'11)], [Becher et al.('11)],[Echevarria et al.('12,'13,'15)],[Chiu et al.('12)], [Dokshitzer et al.('78)],[Ellis et al.('97)],[Monni et al.('16)], [Roger,Mulders('10)],[Collins('11)],[Collins,Rogers('13)],[D'Alesio et al.('14)].
- Effective q_T-resummation can be obtained with Parton Shower algorithms (NNLO+PS [Hoeche,Li,Prestel('14)], [Karlberg,Re,Zanderighi('14)]).
- QCD/EW corrections implemented in POWHEG [Barze et al.('12,'13)].

NNLO QCD predictions at large q_T



Normalized Z q_T spectrum ($q_T > 20\ GeV$).

- ATLAS data ($\sqrt{s} = 8\ TeV$) [1512.02192] (2.8% luminosity uncertainty not shown).
- NNLO (i.e.$\mathcal{O}(\alpha_S^3)$) QCD predictions [G.-De Ridder, Gehrmann, Glover, Huss, Morgan('15)]. NNLO correction positive (∼6-8%) and reduce scale dependence (factor 2 around $\mu = \sqrt{M^2 + q_T^2}$).

In the small q_T region effects of soft-gluon resummation are essential

At the LHC 90% of the $W^\pm$ and Z^0 are produced with $q_T \lesssim 20\ GeV$

$\mathbf{q_T}$ resummation in QCD

$$\frac{d\hat{\sigma}}{d^2\mathbf{q_T}\, dM^2\, d\hat{y}\, d\mathbf{\Omega}} = \left[d\hat{\sigma}^{(res)}\right] + \left[d\hat{\sigma}^{(fin)}\right];$$

$$\int dq_T^2 \frac{d\hat{\sigma}^{(res)}}{dq_T^2} \overset{q_T\to 0}{\sim} \sum \alpha_S^n \log^m \frac{M^2}{Q_T^2}$$

$$\int dq_T^2 \frac{d\hat{\sigma}^{(fin)}}{dq_T^2} \overset{q_T\to 0}{\sim} 0$$

Resummation holds in impact parameter space: $q_T \ll M \Leftrightarrow Mb \gg 1$, $\log M/q_T \gg 1 \Leftrightarrow \log Mb \gg 1$

$$\left[d\hat{\sigma}^{(res)}\right] = \frac{d\hat{\sigma}^{(0)}}{d\mathbf{\Omega}} \frac{1}{\hat{s}} \int \frac{d^2\mathbf{b}}{4\pi^2} e^{i\mathbf{b}\cdot\mathbf{q_T}}\, \mathcal{W}(b, M, \hat{y}, \hat{s}),$$

In the *double* Mellin space ($z_{1,2} = e^{\pm\hat{y}} M/\sqrt{\hat{s}}$) we have:

$$\mathcal{W}_{(N_1,N_2)}(b,M) = \mathcal{H}_{(N_1,N_2)}(\alpha_S) \times \exp\left\{\mathcal{G}_{(N_1,N_2)}(\alpha_S, \widetilde{L})\right\}$$

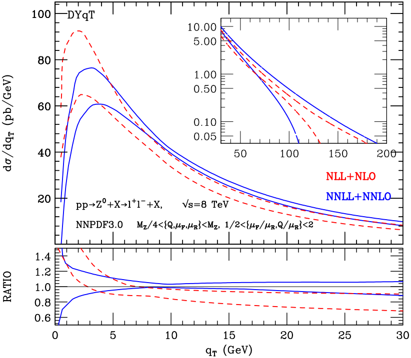
with $\widetilde{L} \equiv \log(Q^2 b^2 + 1)$ ($Q \sim M$ is the resummation scale)

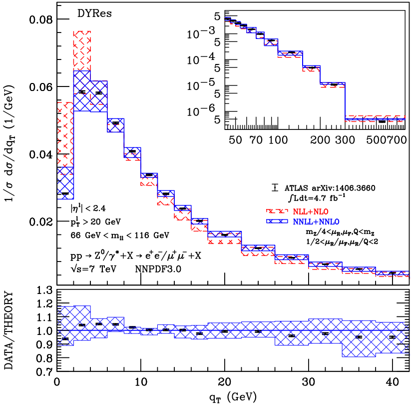
$$\mathcal{G}(\alpha_S, \widetilde{L}) = \widetilde{L}\, g^{(1)}(\alpha_S \widetilde{L}) + g^{(2)}(\alpha_S \widetilde{L}) + \frac{\alpha_S}{\pi} g^{(3)}(\alpha_S \widetilde{L}) + \cdots \qquad \mathcal{H}(\alpha_S) = 1 + \frac{\alpha_S}{\pi}\mathcal{H}^{(1)} + \left(\frac{\alpha_S}{\pi}\right)^2 \mathcal{H}^{(2)} + \cdots$$

LL ($\sim\alpha_S^n \widetilde{L}^{n+1}$): $g^{(1)}$, ($\hat{\sigma}^{(0)}$); NLL ($\sim\alpha_S^n \widetilde{L}^{n}$): $g^{(2)}$, $\mathcal{H}^{(1)}$; NNLL ($\sim\alpha_S^n \widetilde{L}^{n-1}$): $g^{(3)}$, $\mathcal{H}^{(2)}$;

Resummed (N)NLL/(N)NLO result at small q_T *matched* with fixed (N)LO (i.e. $\alpha_S(\alpha_S^2)$) "finite" part at large q_T: *uniform accuracy* for $q_T \ll M$ and $q_T \sim M$.

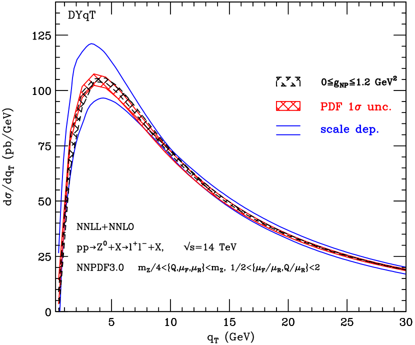
q_T spectrum of the Z boson





NLL+NLO and NNLL+NNLO Z q_T spectrum at the LHC at $\sqrt{s} = 7/8$ TeV with DYqT/DYRes [Bozzi et al. ('11)], [Catani et al. ('15)] public codes. Extension to N^3LL+NNLO (with NNLO matching at large q_T) possible.

PDF uncertainties and NP effects



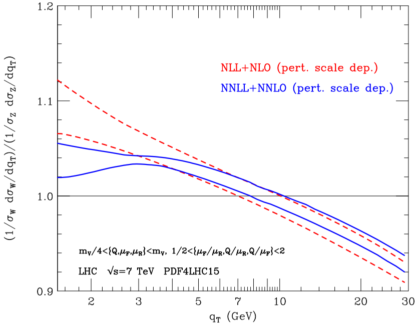
NNLL+NNLO result for Z q_T spectrum at the LHC. Perturbative scale dependence, PDF uncertainties and impact of NP effects.

- PDF uncertainty is smaller than the scale uncertainty and it is approximately independent on q_T (around the 3% level).
- Non perturbative *intrinsic* k_T effects parametrized by a NP form factor $S_{NP} = \exp\{-g_{NP} b^2\}$ with $0 < g_{NP} < 1.2\ GeV^2$:

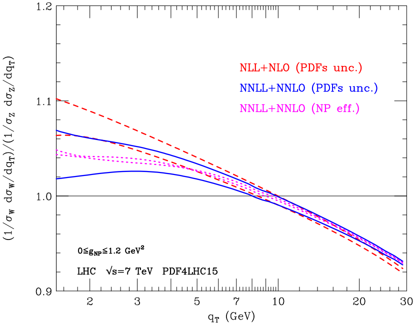
$$\exp\{\mathcal{G}_N(\alpha_S, \widetilde{L})\} \quad \rightarrow \quad \exp\{\mathcal{G}_N(\alpha_S, \widetilde{L})\}\, S_{NP}$$

- NP effects increase the hardness of the q_T spectrum at small values of q_T.
- NNLL+NNLO result with NP effects very close to perturbative result except for $q_T < 3GeV$ (i.e. below the peak).

W/Z ratio: the q_T spectrum



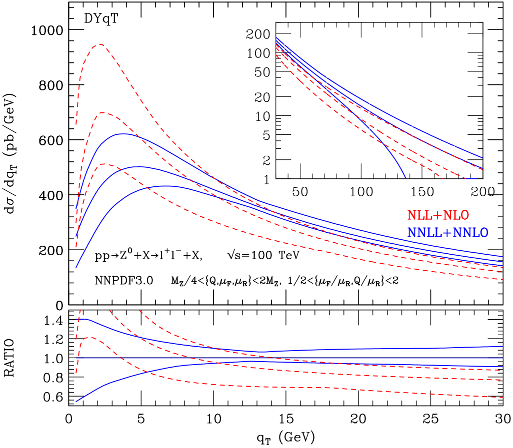
Correlated $(\mu^W/M_W = \mu^Z/M_Z)$ scale variations gives reasonable estimate of pert. uncertainty.



PDF uncertainty dominates at very small q_T ($q_T \lesssim 5\, GeV$).

Non trivial interplay of perturbative and NP effects.

q_T spectrum of the Z boson at 100 TeV

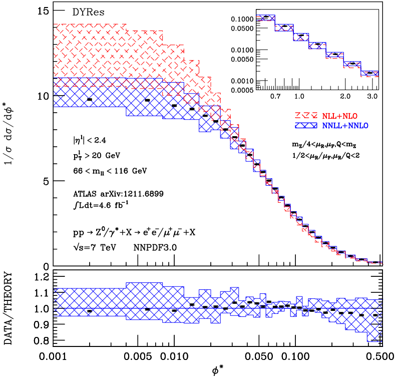


NLL+NLO and NNLL+NNLO Z q_T spectrum in pp collisions at $\sqrt{s} = 100$ TeV

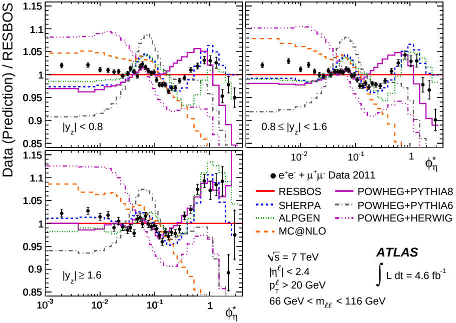
[Mangano et al.('16)].

Back up slides

ϕ^* spectrum of Z boson: theory vs ATLAS data

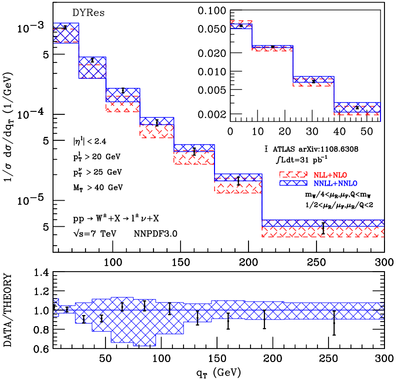


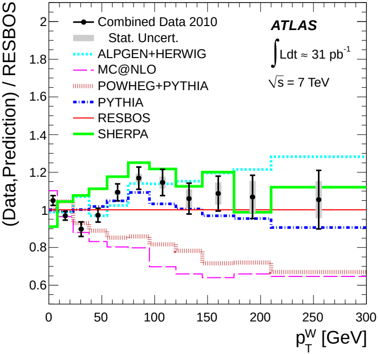
NLL+NLO and NNLL+NNLO bands for Z/γ^* ϕ^* spectrum compared with ATLAS data.



MC generators results and ATLAS data ratio to ResBos.

q_T spectrum of W: theory vs ATLAS data

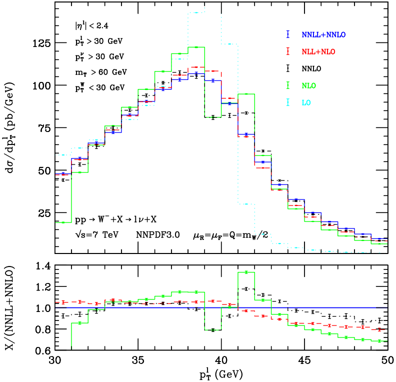


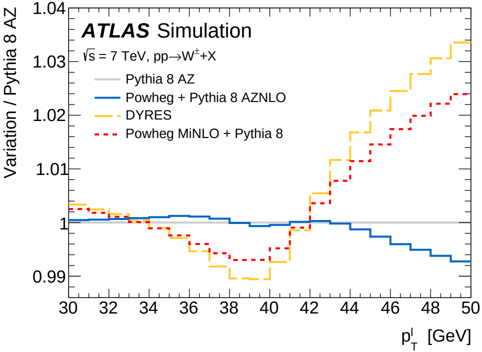


NLL+NLO and NNLL+NNLO bands for $W^{\pm}$ q_T spectrum compared with ATLAS data.

MC generators results and ATLAS data ratio to ResBos.

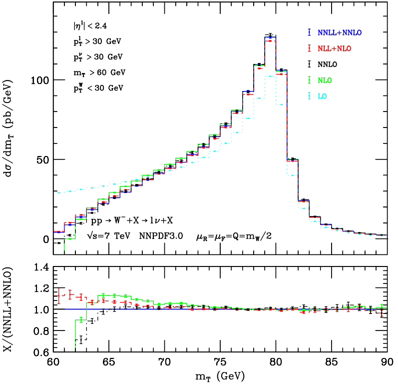
Lepton p_T distributions from W decay

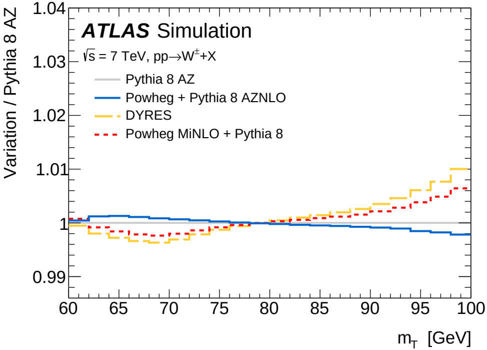




Ratios of the lepton p_T normalised distribution obtained using Powheg+Pythia 8 AZNLO, DYRES and Powheg MiNLO+Pythia 8 to the distribution obtained using PYTHIA 8 AZ.

Transverse-mass distributions from W decay





Ratios of the m_T normalised distribution obtained using Powheg+Pythia 8 AZNLO, DYRES and Powheg MiNLO+Pythia 8 to the distribution obtained using PYTHIA 8 AZ.

Idea of (analytic) resummation

Idea of large logs (Sudakov) resummation: reorganize the perturbative expansion by all-order summation.

$\alpha_S L^2$	$\alpha_S L$	$\cdots$	$\cdots$	$\cdots$	$\mathcal{O}(\alpha_S)$
$\alpha_S^2 L^4$	$\alpha_S^2 L^3$	$\alpha_S^2 L^2$	$\alpha_S^2 L$	$\cdots$	$\mathcal{O}(\alpha_S^2)$
$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$
$\alpha_S^n L^{2n}$	$\alpha_S^n L^{2n-1}$	$\alpha_S^n L^{2n-2}$	$\cdots$	$\cdots$	$\mathcal{O}(\alpha_S^n)$
dominant logs	next-to-dominant logs	$\cdots$	$\cdots$	$\cdots$	$\cdots$

- Ratio of two successive rows $\mathcal{O}(\alpha_S L^2)$: fixed order expansion valid when $\alpha_S L^2 \ll 1$.
- Ratio of two successive columns $\mathcal{O}(1/L)$: resummed expansion valid when $1/L \ll 1$.

Soft gluon exponentiation

Sudakov resummation feasible when:
dynamics AND kinematics factorize
$\Rightarrow$ exponentiation.

- Dynamics factorization: general propriety of QCD matrix element for soft emissions.

$$dw_n(q_1, \ldots, q_n) \simeq \frac{1}{n!} \prod_{i=1}^{n} dw_i(q_i)$$

- Kinematics factorization: not valid in general. For q_T distribution of DY process it holds in the impact parameter space (Fourier transform).

$$\int d^2\mathbf{q_T}\ \exp(-i\mathbf{b}\cdot\mathbf{q_T})\,\delta\left(\mathbf{q_T} - \sum_{j=1}^{n} \mathbf{q_{T_j}}\right) = \exp(-i\mathbf{b}\cdot\sum_{j=1}^{n}\mathbf{q_{T_j}}) = \prod_{j=1}^{n}\exp(-i\mathbf{b}\cdot\mathbf{q_{T_j}})\,.$$

- Exponentiation holds in the impact parameter space. Results have then to be transformed back to the physical space.

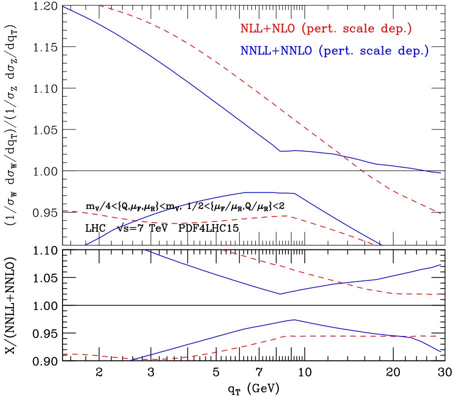
q_T resummation at NNLL+NNLO

- q_T resummation performed for Drell–Yan process up to NNLL+NNLO by using the formalism developed in [Catani,de Florian,Grazzini('01)], [Bozzi,Catani,de Florian,Grazzini('06,'08)]. We have included
  - NNLL logarithmic contributions to all orders (i.e. up to $\exp(\sim\alpha_S^n L^{n-1})$);
  - NNLO corrections (i.e. up to $\mathcal{O}(\alpha_S^2)$) at small q_T;
  - NLO corrections (i.e. up to $\mathcal{O}(\alpha_S^2)$) at large q_T;
  - NNLO result (i.e. up to $\mathcal{O}(\alpha_S^2)$) for the total cross section.
- Analytic resummation implemented in publicly available codes:

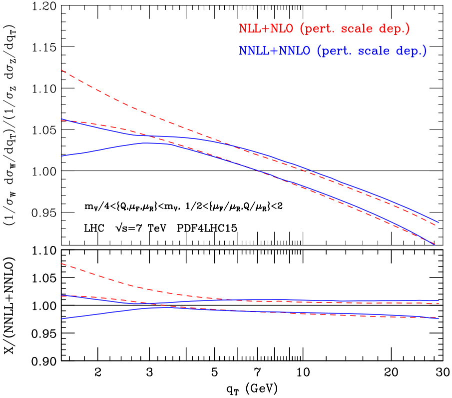
  DYqT: computes resummed q_T spectrum, inclusive over other kinematical variables [Bozzi,Catani,de Florian,G.F.,Grazzini('09,'11)]

  DYRes: computes resummed q_T spectrum and related distributions, it retains full kinematics of the vector boson and of its leptonic decay products (possible to apply arbitrary cuts on these variables, and to plot the corresponding distributions) [Catani,de Florian,G.F.,Grazzini('15)]

W/Z ratio q_T spectrum: perturbative scale uncertainty

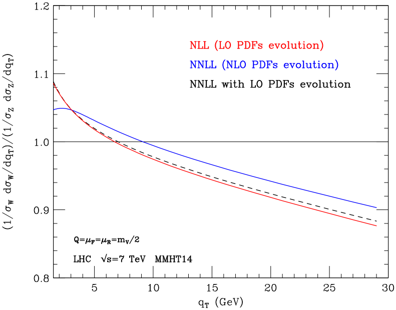


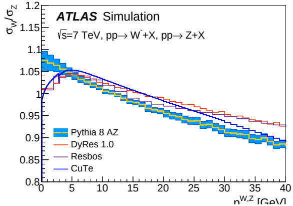
DYqT resummed predictions for the ratio of W/Z normalized q_T spectra. Uncorrelated perturbative scale variation band.

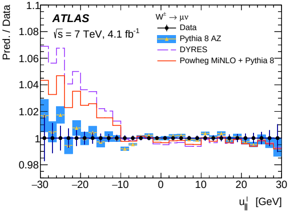


DYqT resummed predictions for the ratio of W/Z normalized q_T spectra. Correlated perturbative scale variation band.

W/Z ratio: the q_T spectrum







Left: Ratio of NNLL results for W/Z q_T spectra at the LHC, effect of PDFs evolution.
Right: Ratios of the normalised W/Z q_T spectra predicted by Pythia 8 and several resummation programs for W^+ and W^-.