DYRes

Vector boson production at the LHC: q_T resummation and leptonic decay

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Based on:
S. Catani, D. de Florian, G. F. & M. Grazzini, arXiv:1507.06937 [hep-ph]

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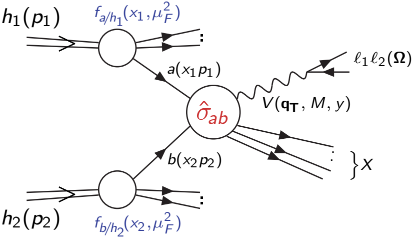
Drell–Yan $\mathbf{q_T}$ distribution



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

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.

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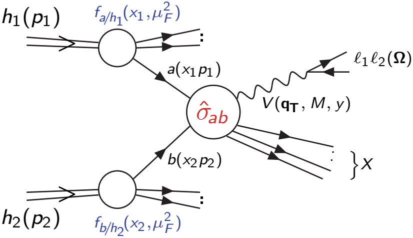

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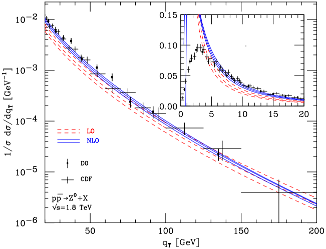

State of the art: q_T resummation

- Method to resum large q_T logarithms is known [Dokshitzer,Diakonov,Troian('78)], [Parisi,Petronzio('79)],[Curci,Greco,Srivastava('79)],[Kodaira,Trentadue('82)], [Collins,Soper('81,'82)],[Collins,Soper,Sterman('85)],[Catani,de Florian, Grazzini('01)],[Bozzi et al.('06,'08)],[Catani,Grazzini('11)],[Catani et al.('13)].
- Phenomenological studies [Altarelli et al.('84)],[ResBos:Balazs et al.('95,'97)], [Guzzi et al.('13)],[Ellis et al.('97,'98)],[Qiu et al.('01)],[Kulesza et al. ('01,'02)],[Berger et al.('02,'03)],[Landry et al.('03)],[Banfi et al.('12)].
- Results for q_T resummation by using Soft Collinear Effective Theory methods 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)], [Roger,Mulders('10)],[Collins('11)], [Collins, Rogers('13)],[D'Alesio et al.('14)].
- Effective q_T-resummation can be obtained with Parton Shower algorithms. QCD/EW DY corrections implemented in POWHEG [Barze et al.('12,'13)]. Results for NNLO+PS DY predictions obtained [Hoeche,Li,Prestel('14)], [Karlberg,Re,Zanderighi('14)].

$\mathbf{q_T}$ resummation in QCD

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

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

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

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

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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 ($\sim \alpha_S^n \widetilde{L}^{n-1}$): $g^{(3)}$, $\mathcal{H}^{(2)}$;

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q_T resummation at full NNLL

- 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 $\exp(\sim\alpha_S^n L^{n-1})$);
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- We have implemented the calculation in the publicly available codes:

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

http://pcteserver.mi.infn.it/~ferrera/dyqt.html

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

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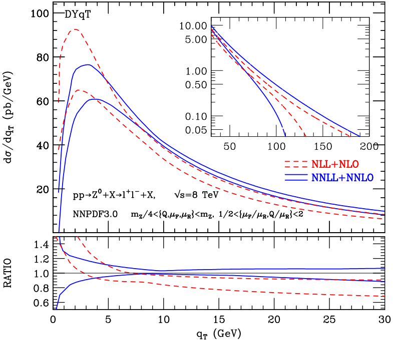
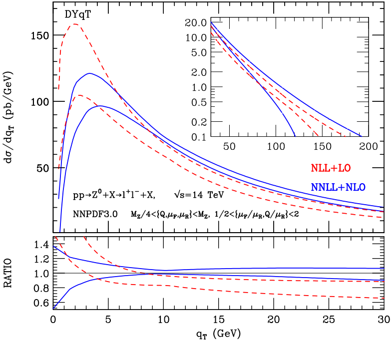
DYqT results: q_T spectrum of Z boson at the LHC

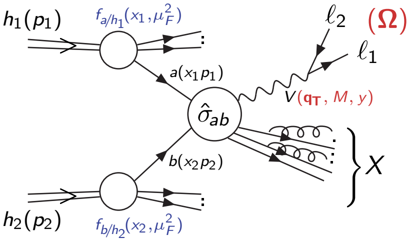




NLL+NLO and NNLL+NNLO bands for Z q_T spectrum at the LHC at $\sqrt{s} = 8$ TeV (left) and $\sqrt{s} = 14$ TeV (right).

Lower panel: ratio of the NLL+NLO and NNLL+NNLO results with respect to the NNLL+NNLO result at $\mu_F = \mu_R = Q = m_Z/2$.

DYRes: $\mathbf{q_T}$ resummation and leptonic decay



- Experiments have finite acceptance: important to provide exclusive theoretical predictions.
- Analytic resummation formalism inclusive over soft-gluon emission: not possible to apply selection cuts on final state partons.

- We have included the full dependence on the decay products variables: possible to apply cuts on vector boson and decay products.
- To construct the "finite" part we rely on the fully-differential NNLO result from the code DYNNLO [Catani,Cieri,de Florian,G.F.,Grazzini('09)].
- Calculation implemented in the code DYRes[Catani,de Florian,G.F., Grazzini('15)] which includes spin correlations, $\gamma^* Z$ interference, finite-width effects and compute distributions in form of bin histograms.
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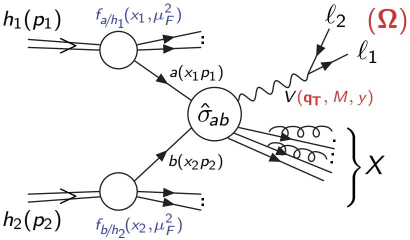

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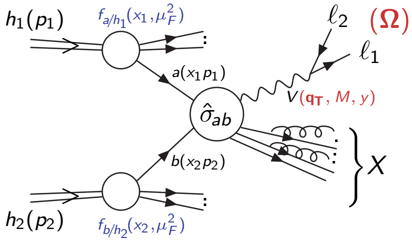

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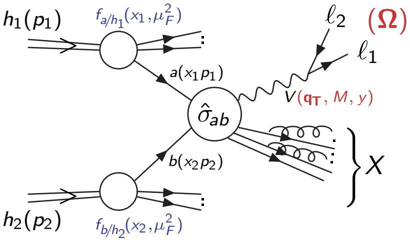

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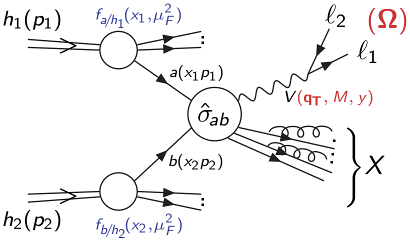

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$\mathbf{q_T}$ recoil and lepton angular distribution

- The dependence of the resummed cross section on the leptonic variable $\mathbf{\Omega}$ is

$$\frac{d\hat{\sigma}^{(0)}}{d\mathbf{\Omega}} = \hat{\sigma}^{(0)}(M^2)\ F(\mathbf{q_T}/M; M^2, \mathbf{\Omega})\ \ , \quad \text{with} \quad \int d\mathbf{\Omega}\ F(\mathbf{q_T}/M; \mathbf{\Omega}) = 1\ .$$

  the q_T dependence arise as a *dynamical* q_T-recoil of the vector boson due to *soft* and *collinear* multiparton emissions.

- This dependence cannot be *unambiguously* calculated through resummation (it is not singular)

$$F(\mathbf{q_T}/M; M^2, \mathbf{\Omega}) = F(\mathbf{0}/M; M^2, \mathbf{\Omega}) + \mathcal{O}(\mathbf{q_T}/M)\ \ ,$$

  - After the matching between *resummed* and *finite* component the $\mathcal{O}(\mathbf{q_T}/M)$ ambiguity start at $\mathcal{O}(\alpha_S^2)$ ($\mathcal{O}(\alpha_S)$) at NNLL+NNLO (NLL+NLO).
  - After integration over leptonic variable $\mathbf{\Omega}$ the ambiguity *completely cancel*.

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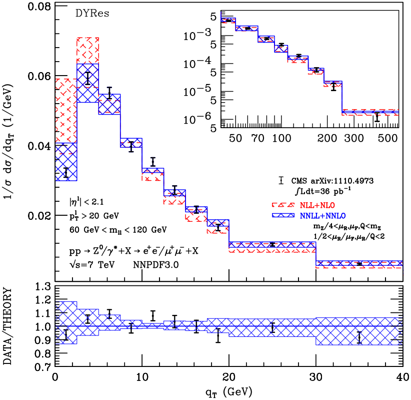
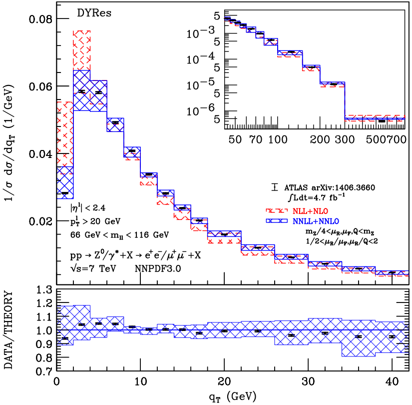
DYRes results: q_T spectrum of Z boson at the LHC

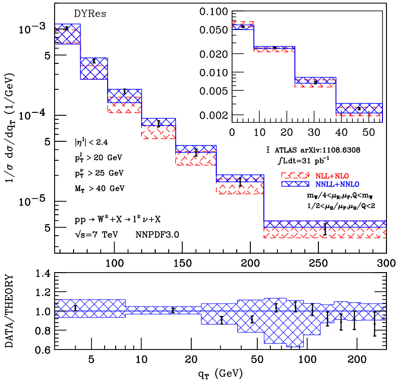


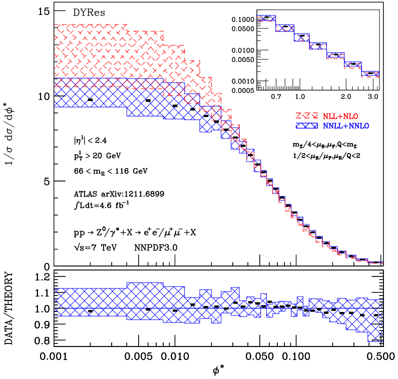


NLL+NLO and NNLL+NNLO bands for Z/γ^* q_T spectrum compared with CMS (left) and ATLAS (right) data.
Lower panel: ratio with respect to the NNLL+NNLO central value.

Program performances: for high statistic runs (i.e. few per mille accuracy on cross sections) *on a single CPU*: $\sim$ 1day at full NLL, $\sim$ 3days at full NNLL.

DYRes **results:** q_T spectrum of W and ϕ^* spectrum of Z boson at the LHC





NLL+NLO and NNLL+NNLO bands for $W^{\pm}$ q_T spectrum compared with ATLAS data.
Lower panel: ratio with respect to the NNLL+NNLO central value.

NLL+NLO and NNLL+NNLO bands for Z/γ^* ϕ^* spectrum compared with ATLAS data.
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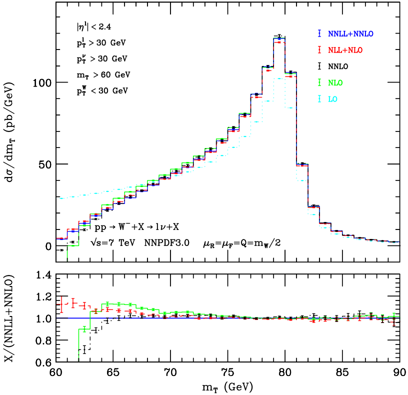
DYRes **results:** lepton kinematical distributions from W decay



Effect of q_T resummation on the transverse mass (m_T) for W^- production at the LHC. NLL+NLO and NNLL+NNLO results compared with LO, NLO and NNLO results. Lower panel: ratio between various results and NNLL+NNLO result.

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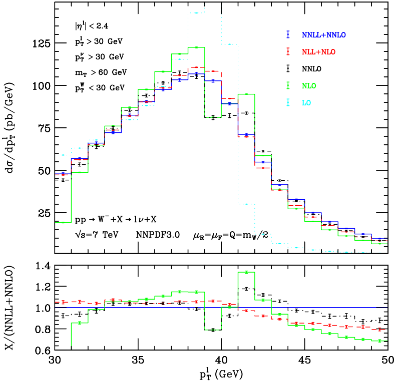
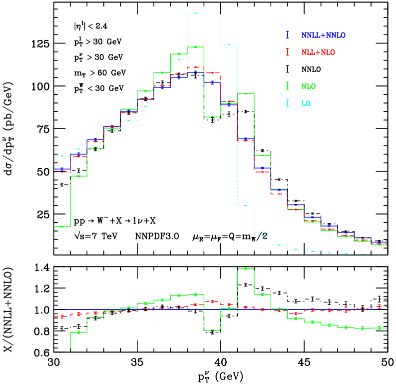
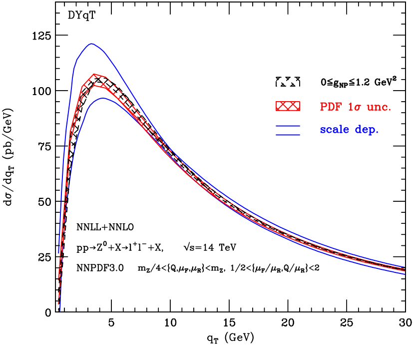




Effect of q_T resummation on lepton p_T (left) and missing p_T distribution for W^- production at the LHC. NLL+NLO and NNLL+NNLO results compared with LO, NLO and NNLO results.

Lower panel: ratio between various results and NNLL+NNLO result.

PDF uncertainties and NP effects



NNLL+NNLO result for Z q_T spectrum at the LHC at $\sqrt{s} = 14$ TeV. 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 $0 < g_{NP} < 1.2\ GeV^2$:

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

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- NNLL+NNLO result with NP effects very close to perturbative result except for $q_T < 3GeV$ (i.e. below the peak).

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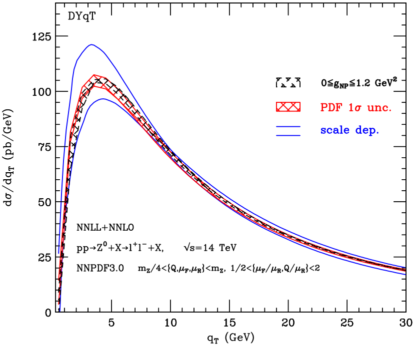

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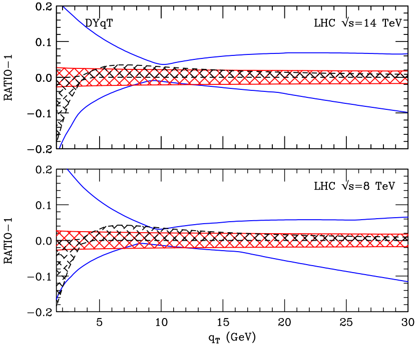

NNLL+NNLO result for Z q_T spectrum at the LHC at $\sqrt{s} = 14$ TeV (up) $\sqrt{s} = 8$ TeV (down). Perturbative scale dependence, PDF uncertainties and impact of NP effects normalized to central NNLL+NNLO prediction.

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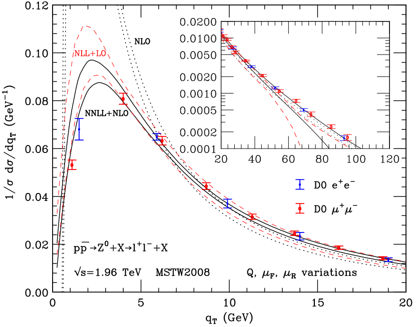
Back up slides

DYqT results: q_T spectrum of Z boson at the Tevatron



D0 data for the Z q_T spectrum compared with perturbative results.

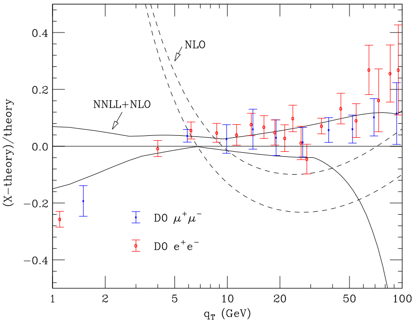
- Uncertainty bands obtained varying μ_R, μ_F, Q independently:

$$\frac{1}{2} \leq \{\mu_F/m_Z, \mu_R/m_Z, 2Q/m_Z, \mu_F/\mu_R, Q/\mu_R\} \leq 2$$

- Significant reduction of scale dependence from NLL to NNLL for all q_T.
- Good convergence of resummed results: NNLL and NLL bands overlap (contrary to the fixed-order case).
- Good agreement between data and resummed predictions (without any model for non-perturbative effects).

  The perturbative uncertainty of the NNLL results is comparable with the experimental errors.

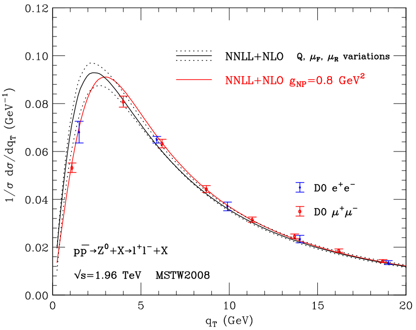
DYqT results: q_T spectrum of Z boson at the Tevatron



D0 data for the Z q_T spectrum: Fractional difference with respect to the reference result: NNLL, $\mu_R = \mu_F = 2Q = m_Z$.

- NNLL scale dependence is $\pm 6\%$ at the peak, $\pm 5\%$ at $q_T = 10\,GeV$ and $\pm 12\%$ at $q_T = 50\,GeV$. For $q_T \geq 60\,GeV$ the resummed result looses predictivity.
- At large values of q_T, the NLO and NNLL bands overlap.
  At intermediate values of transverse momenta the scale variation bands do not overlap.
- The resummation improves the agreement of the NLO results with the data.
  In the small-q_T region, the NLO result is theoretically unreliable and the NLO band deviates from the NNLL band.

Non perturbative Fermi motion effects



D0 data for the Z q_T spectrum.

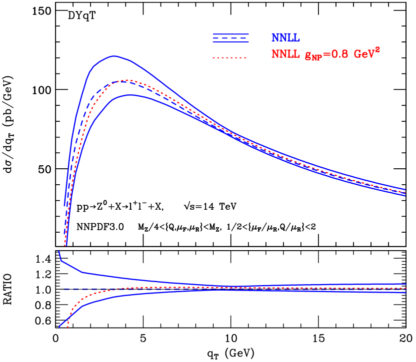
- Up to now result in a complete perturbative framework (plus PDFs).
- Non perturbative *intrinsic* k_T effects can be parametrized by a NP form factor $S_{NP} = \exp\{-g_{NP} b^2\}$:

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

$$g_{NP} \simeq 0.8\ GeV^2$$ [Kulesza et al.('02)]

- With NP effects the q_T spectrum is harder. Quantitative impact of intrinsic k_T effects is comparable with perturbative uncertainties and with non perturbative effects from PDFs.

Non perturbative Fermi motion effects



Z q_T spectrum at the LHC14.

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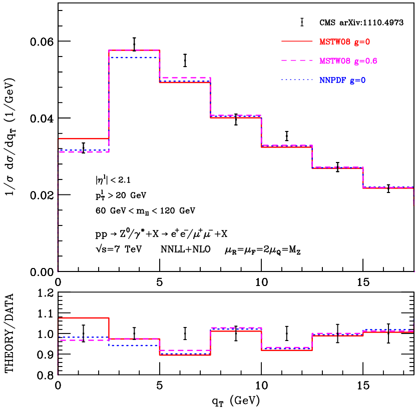
Non perturbative Fermi motion effects



CMS data for the Z q_T spectrum.

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- Non perturbative *intrinsic* k_T effects can be parametrized by a NP form factor $S_{NP} = \exp\{-g_{NP} b^2\}$:

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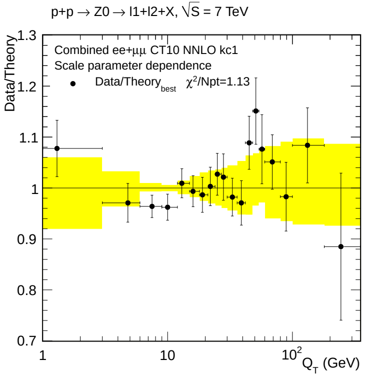
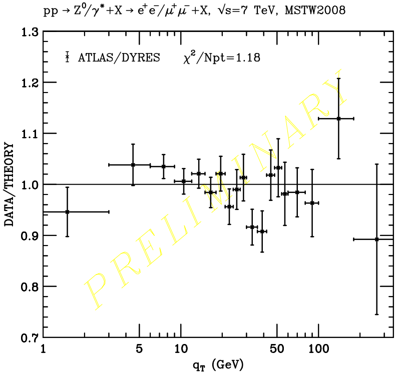
Non perturbative Fermi motion effects

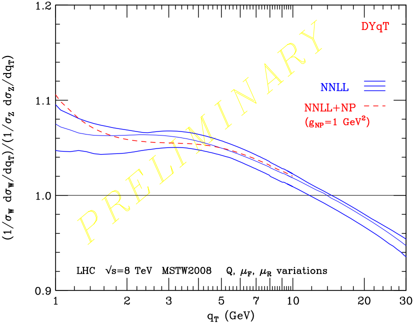


ATLAS ('11) data for the Z q_T spectrum compared with ResBos predictions with a Non Perturbative smearing parameter $g_{NP} = 1.1\,GeV^2$ [Guzzi,Nadolsky,Wang('13)].



ATLAS ('11) data for the Z q_T spectrum compared with DYRes predictions without Non Perturbative smearing ($g_{NP} = 0$).

W/Z ratio: the q_T spectrum



DYqT resummed predictions for the ratio of W/Z normalized q_T spectra.

- The use of the W/Z ratio observables substantially reduces both the experimental and theoretical systematic uncertainties [Giele,Keller('97)].
- Resummed perturbative prediction for

$$\frac{\frac{1}{\sigma_W}\frac{d\sigma_W}{dq_T}}{\frac{1}{\sigma_Z}\frac{d\sigma_Z}{dq_T}}(\mu_R,\mu_F,Q)$$

with the customary scale variation.

- NNLL perturbative uncertainty band very small: 2-5% for $1 < q_T < 2$ GeV, 1.5-2% for $2 < q_T < 30$ GeV.
- Non perturbative effects within 1% for $1.5 < q_T < 5$ GeV and negligible for $q_T > 5$ GeV.

$\mathbf{q_T}$ resummation formalism

Main distinctive features of the formalism [Catani,de Florian, Grazzini('01)], [Bozzi,Catani,de Florian, Grazzini('06,'08)]:

- Resummation performed at partonic level: PDF evaluated at $\mu_F \sim M$: no PDF extrapolation in the non perturbative region, customary study of μ_R and μ_F dependence.
- Introduction of resummation scale $Q \sim M$: variations give an estimate of the uncertainty from uncalculated logarithmic corrections.

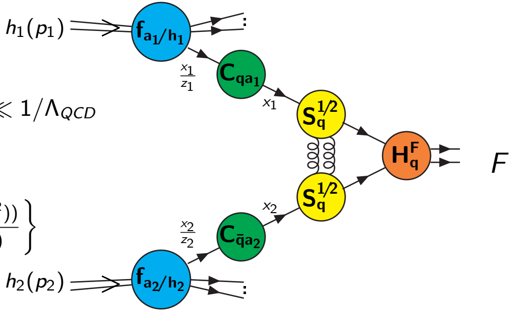
$$\ln(M^2 b^2) \to \ln(Q^2 b^2) + \ln(M^2/Q^2)$$

- No need for non perturbative models: Landau singularity of α_S regularized using *Minimal Prescription* [Laenen,Sterman,Vogelsang('00)],[Catani et al.('96)].
- Resummed effects exponentiated in a universal Sudakov form factor $\mathcal{G}_N(\alpha_S, L)$; process-dependence factorized in the hard scattering coefficient $\mathcal{H}_N(\alpha_S)$.
- Perturbative unitarity constraint:

$$\ln(Q^2 b^2) \to \widetilde{L} \equiv \ln(Q^2 b^2 + 1) \quad \Rightarrow \quad \exp\{\mathcal{G}_N(\alpha_S, \widetilde{L})\}\big|_{b=0} = 1 \;\Rightarrow\; \int_0^\infty dq_T^2 \left(\frac{d\hat{\sigma}}{dq_T^2}\right) = \hat{\sigma}^{(tot)};$$

  - avoids unjustified higher-order contributions in the small-b region.
  - recover *exactly* the total cross-section (upon integration on q_T)

Transverse-momentum resummation formula



$$M \gg \Lambda_{QCD}\ , \quad b \gg 1/M\ , \quad b \ll 1/\Lambda_{QCD}$$

$$C(\alpha_S(b_0^2/b^2)) = C(\alpha_S(M^2))$$
$$\times\ \exp\left\{ - \int_{b_0^2/b^2}^{M^2} \frac{dq^2}{q^2}\ \beta(\alpha_S(q^2))\ \frac{d \ln C(\alpha_S(q^2))}{d \ln \alpha_S(q^2)} \right\}$$

$$\frac{d\sigma_F^{(res)}}{d^2\mathbf{q_T}\ dM^2\ dy\ d\mathbf{\Omega}} = \frac{M^2}{s}\left[d\sigma^{(0)}_{q\bar{q},F}\right] H_q^F(x_1p_1, x_2p_2; \mathbf{\Omega}; \alpha_S(M^2)) \sum_{a_1,a_2} \int \frac{d^2\mathbf{b}}{(2\pi)^2}\ e^{i\mathbf{b}\cdot\mathbf{q_T}}\ S_q(M,b)$$
$$\times \int_{x_1}^1 \frac{dz_1}{z_1}\ C_{qa_1}(z_1; \alpha_S(b_0^2/b^2))\ f_{a_1/h_1}(x_1/z_1, b_0^2/b^2) \int_{x_2}^1 \frac{dz_2}{z_2}\ C_{\bar{q}\,a_2}(z_2; \alpha_S(b_0^2/b^2))\ f_{a_2/h_2}(x_2/z_2, b_0^2/b^2)$$

$$\tilde{F}_{q_f/h}(x,b,M) = \sum_a \int_x^1 \frac{dz}{z}\ \sqrt{S_q(M,b)}\,C_{q_f\,a}(z;\alpha_S(b_0^2/b^2))\ f_{a/h}(x/z, b_0^2/b^2)$$

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.