Transverse-momentum distributions of W and Z bosons at the Tevatron and at the LHC

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Based on a collaboration with:
G. Bozzi, S. Catani, D. de Florian & M. Grazzini

Outline

Motivations

The study of Drell-Yan lepton pair production is well motivated:

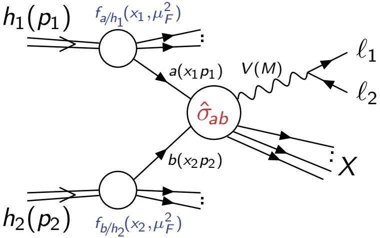
- Large production rates and clean experimental signatures:
  - Important for detector calibration.
  - Possible use as luminosity monitor.
- Transverse momentum distributions needed for:
  - Precise prediction for M_W.
  - Beyond the Standard Model analysis.
- Test of perturbative QCD predictions.
- Constrain for fits of PDFs.

State of the art: fixed order calculations

Historically the Drell-Yan process [Drell,Yan('70)] was the first application of parton model ideas developed for deep inelastic scattering.

- QCD corrections:
  - Total cross section known up to NNLO ($\mathcal{O}(\alpha_S^2)$) [Hamberg,Van Neerven,Matsuura('91)], [Harlander,Kilgore('02)]
  - Rapidity distribution known up to NNLO [Anastasiou,Dixon,Melnikov,Petriello('03)]
  - Fully exclusive NNLO calculation completed [Melnikov,Petriello('06)], [Catani,Cieri,de Florian,G.F., Grazzini('09)]
  - Vector boson transverse-momentum distribution known up to NLO ($\mathcal{O}(\alpha_S^2)$) [Ellis et al.('83)],[Arnold,Reno('89)], [Gonsalves et al.('89)]
- Electroweak correction are know at $\mathcal{O}(\alpha)$ [Dittmaier et al.('02)],[Baur et al.('02)] [Carloni Calame, Montagna,Nicrosini,Vicini('06)]

The Drell-Yan q_T distribution



$$h_1(p_1) + h_2(p_2) \;\rightarrow\; V(M) + X \;\rightarrow\; \ell_1 + \ell_2 + X$$

where $\quad V = \gamma^*, Z^0, W^\pm \quad$ and $\quad \ell_1 \ell_2 = \ell^+ \ell^-, \ell \nu_\ell$

According to the QCD factorization theorem:

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

The standard fixed-order QCD perturbative expansions gives:

$$\int_0^{Q_T^2} dq_T^2 \frac{d\hat{\sigma}_{q\bar{q}}}{dq_T^2} \sim 1 + \alpha_S \left[c_{12} \log^2(M^2/Q_T^2) + c_{11} \log(M^2/Q_T^2) + c_{10}(Q_T) \right]$$
$$+ \alpha_S^2 \left[c_{24} \log^4(M^2/Q_T^2) + \cdots + c_{21} \log(M^2/Q_T^2) + c_{20}(Q_T) \right] + \mathcal{O}(\alpha_S^3)$$

Fixed order calculation theoretically justified only in the region $q_T \sim M_V$

For $q_T \to 0$, $\alpha_S^n \log^m(M^2/q_T^2) \gg 1$: need for resummation of logarithmic corrections

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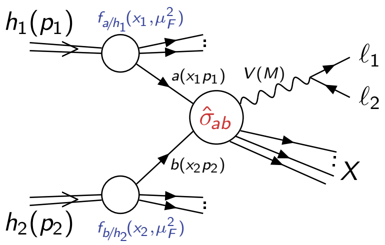

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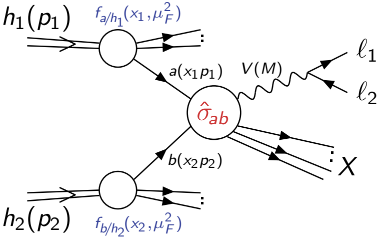

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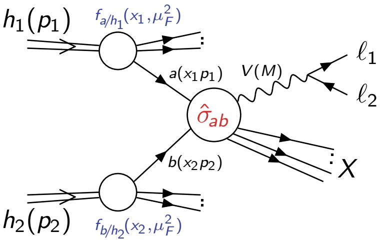

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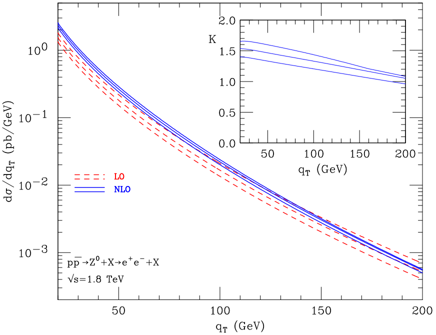
Fixed order results: q_T spectrum of Drell-Yan e^+e^- pairs at $\sqrt{s} = 1.8\ TeV$



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- Factorization and renormalization scale variations:
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  $q_T \sim m_Z : LO \pm 25\%, NLO \pm 8\%$
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$$K(q_T) = \frac{d\sigma/dq_{T\,NLO}(\mu_F, \mu_R)}{d\sigma/dq_{T\,LO}(\mu_F = \mu_R = m_Z)}$$

  $K \sim 1.1$ at $q_T \sim 200\ GeV$ up to
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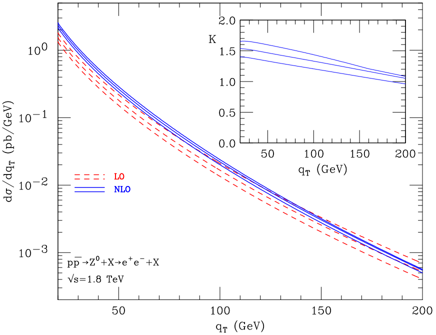

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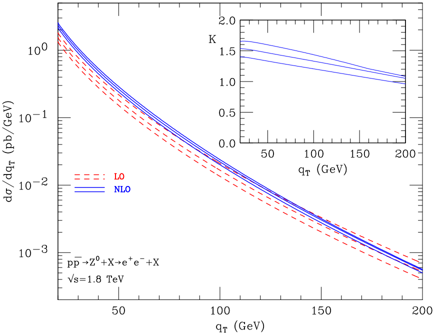

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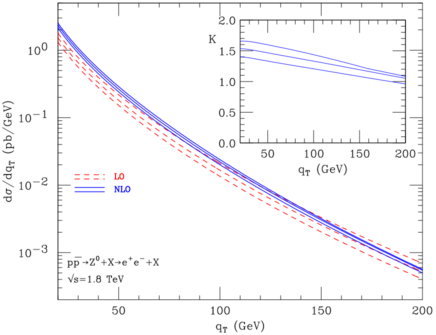

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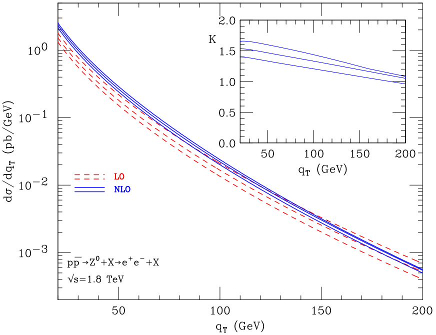

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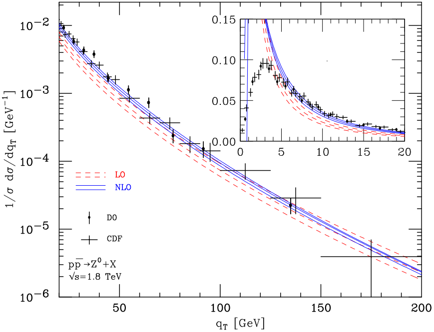

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  D0 data: $75\ GeV < M^2 < 105\ GeV$, $\sigma_{tot} = 221 \pm 11\ pb$ [D0 Collaboration ('00)]
- Good agreement between NLO results and data up to $q_T \sim 20\ GeV$.
- In the small q_T region ($q_T \lesssim 20\ GeV$) LO and NLO result diverges to $+\infty$ and $-\infty$ (accidental partial agreement at $q_T \sim 5 - 7\ GeV$): need for resummation.

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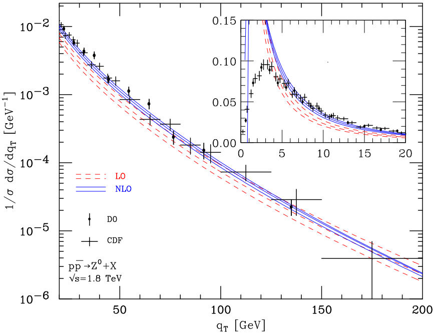

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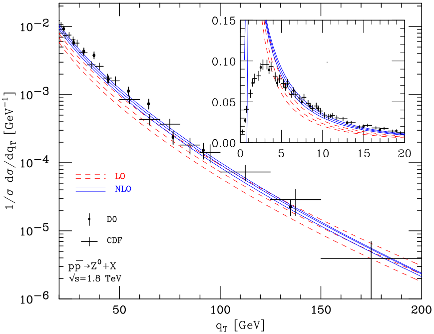

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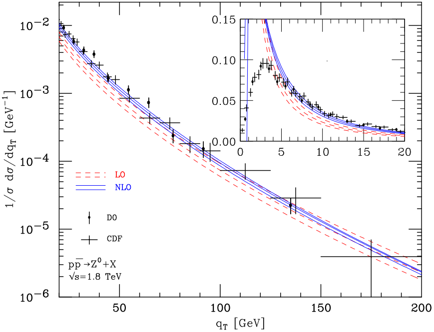

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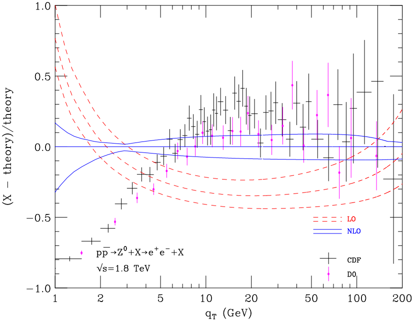

- Percentage difference between data and theory:

$$\frac{(d\sigma/dq_T)_X - (d\sigma/dq_T)_{NLO}(\mu_F = \mu_R = m_Z)}{(d\sigma/dq_T)_{NLO}(\mu_F = \mu_R = m_Z)}$$

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- Relative difference between LO and NLO: very large at low q_T, $\sim 40-50\%$ at intermediate q_T, small only at large q_T ($q_T \gtrsim m_Z$).
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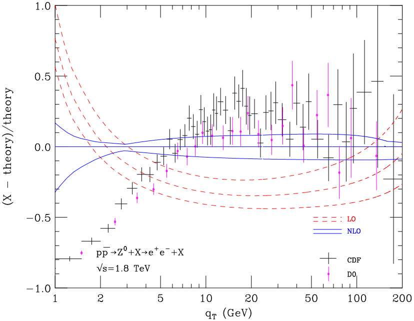

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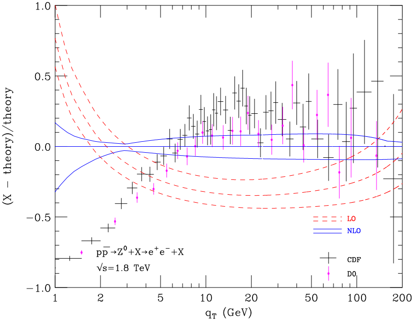

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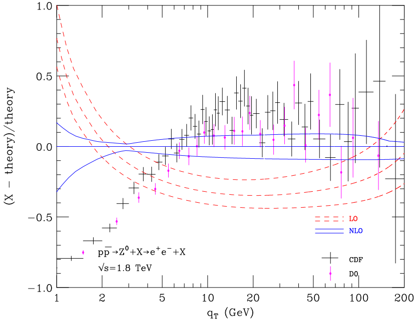

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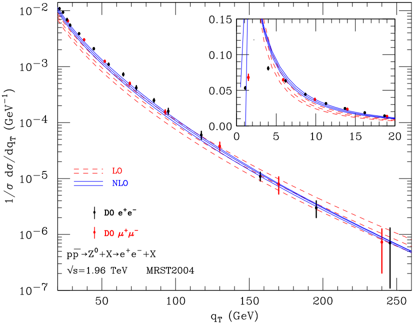

- D0 data normalized to 1: [D0 Coll.('08,'10)].
- Normalization reduces only marginally fixed order scale variations.
- Factorization and renormalization scale variations: $\mu_F = \mu_R = m_Z$, $m_Z/2 \leq \mu_F, \mu_R \leq 2m_Z$, $1/2 \leq \mu_F/\mu_R \leq 2$.
  LO and NLO scale variations bands overlap only for $q_T > 60\ GeV$
- Good agreement between NLO results and data up to $q_T \sim 20\ GeV$.
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In the small q_T region ($q_T \lesssim 20\ GeV$) effects of soft-gluon resummation are essential.
At Tevatron 90% of the $W^{\pm}$ and Z^0 are produced with $q_T \lesssim 20\ GeV$

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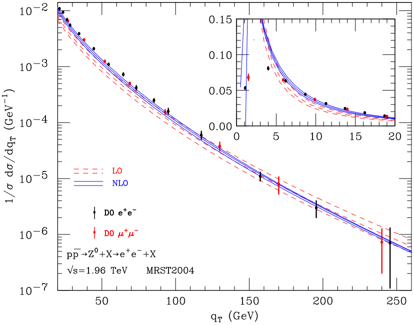

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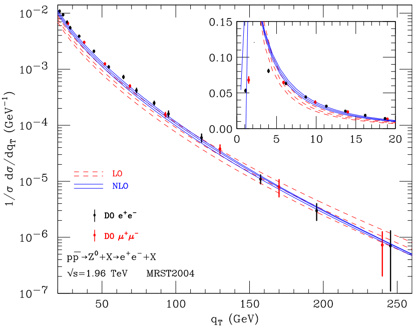
At Tevatron 90% of the $W^\pm$ and Z^0 are produced with $q_T \lesssim 20\ GeV$

Fixed order results: q_T spectrum of Drell-Yan l^+l^- pairs at $\sqrt{s} = 1.96\ TeV$



- D0 data normalized to 1: [D0 Coll.('08,'10)].
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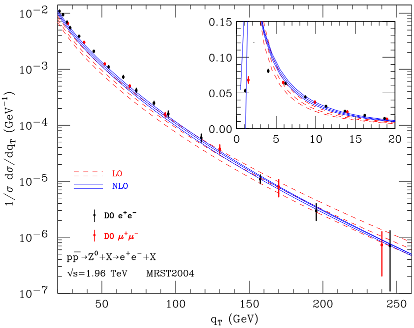

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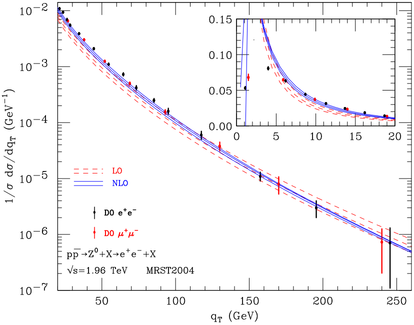

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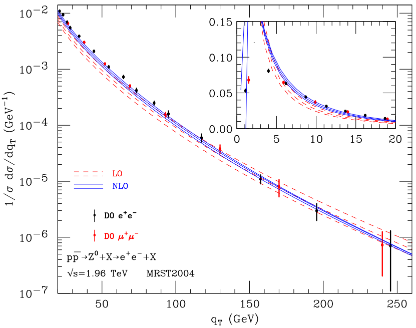

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State of the art: transverse-momentum resummation

- The method to perform the resummation of the large logarithms of q_T is known
  [Dokshitzer,Diakonov,Troian ('78)], [Parisi,Petronzio('79)], [Kodaira,Trentadue('82)],[Altarelli et al.('84)], [Collins,Soper,Sterman('85)], [Catani,de Florian,Grazzini('01)]
- Various phenomenological studies of the vector boson transverse momentum distribution exist
  [Balasz,Qiu,Yuan('95)],[Balasz,Yuan('97)],[Ellis et al.('97)], [Kulesza et al.('02)]
- Recently various results for transverse momentum resummation in the framework of Effective Theories appeared [Gao,Li,Liu('05), Idilbi,Ji,Yuan('05), Mantry,Petriello('10), Becher,Neubert('10)].

DY q_T resummation at NNLL+NLO:

Bozzi,Catani,G.F.,de Florian, Grazzini arXiv:1007.2351

- We have applied for Drell-Yan transverse-momentum distribution the resummation formalism developed by [Catani,de Florian, Grazzini('01)] already applied for the case of Higgs boson production [Bozzi,Catani,de Florian, Grazzini('03,'06,'08)].
- We have performed the resummation up to NNLL+NLO. It means that our complete formula includes:
  - NNLL logarithmic contributions to all orders;
  - NNLO corrections (i.e. $\mathcal{O}(\alpha_S^2)$) at small q_T;
  - NLO corrections (i.e. $\mathcal{O}(\alpha_S^2)$) at large q_T;
  - NNLO result for the total cross section (upon integration over q_T).
- We have implemented the calculation in a numerical code DYqT (a public version of it will be available in the near future).

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Transverse momentum resummation

$$\frac{d\hat{\sigma}_{ab}}{dq_T^2} = \frac{d\hat{\sigma}_{ab}^{(res)}}{dq_T^2} + \frac{d\hat{\sigma}_{ab}^{(fin)}}{dq_T^2};$$

The finite component $\left(\lim_{Q_T\to 0}\int_0^{Q_T^2} dq_T^2 \left[\frac{d\hat{\sigma}_{ab}^{(fin)}}{dq_T^2}\right]_{f.o.} = 0\right)$ ensure to reproduce the fixed order calculation at large q_T

Resummation holds in impact parameter space:

$$\frac{d\hat{\sigma}_{ab}^{(res)}}{dq_T^2} = \frac{M^2}{\hat{s}} \int_0^\infty db\, \frac{b}{2} J_0(bq_T)\, \mathcal{W}_{ab}(b, M), \qquad q_T \ll M \Leftrightarrow Mb \gg 1, \quad \log M^2/q_T^2 \gg 1 \Leftrightarrow \log Mb \gg 1$$

In the Mellin moments space we have the exponentiated form:

$$\mathcal{W}_N(b,M) = \mathcal{H}_N(\alpha_S) \times \exp\left\{\mathcal{G}_N(\alpha_S, L)\right\} \qquad \text{where} \qquad L \equiv \log\left(\frac{M^2 b^2}{b_0^2}\right), \quad b_0 = 2e^{-\gamma_E}$$

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The q_T resummation formalism

The main distinctive features of the formalism we are using are [Catani,de Florian, Grazzini('01)], [Bozzi,Catani,de Florian, Grazzini('03,'06,'08)]:

- Resummation performed at partonic cross section level: PDF evaluated at $\mu_F \sim M$: no PDF extrapolation in the non perturbative region, study of renormalization and factorization scale dependence as in fixed-order calculations.
- Possible to make prediction without introducing non perturbative effects: Landau singularity of the QCD coupling regularized using a *minimal prescription* [Laenen,Sterman,Vogelsang('00)],[Catani et al.('96)].
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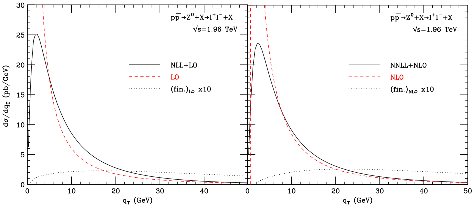
Resummed results: q_T spectrum of Drell-Yan l^+l^- pairs at $\sqrt{s} = 1.96\ TeV$



- Left side: NLL+LO result compared with fixed LO result.
  Resummation cure the fixed order divergence at $q_T \to 0$.
- Right side: NNLL+NLO result compared with fixed NLO result.
- The q_T spectrum is slightly harder at NNLL+NLO accuracy than at NLL+LO accuracy.
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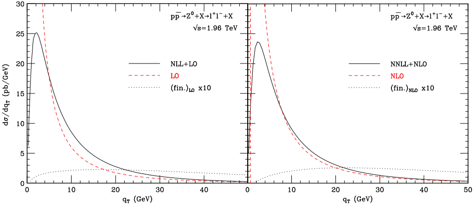

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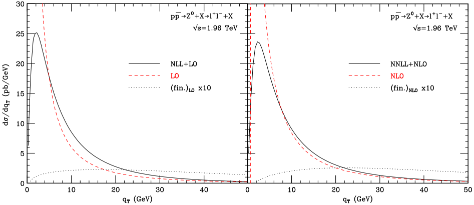

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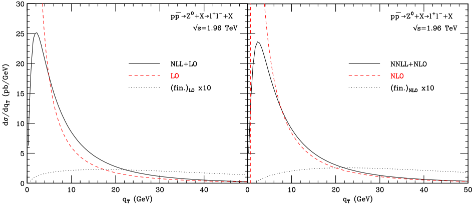

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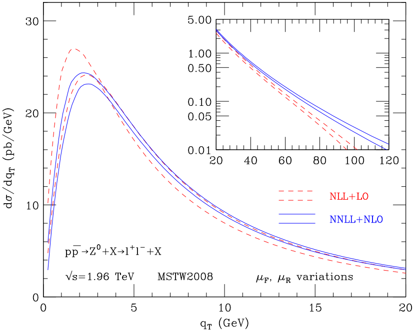

- Our calculation implements $\gamma^* Z$ interference and finite-width effects. Here we use the narrow width approximation (differences within 1% level).
- Uncertainty bands obtained by performing renormalization and factorization scale variations: $m_Z/2 \le \{\mu_F, \mu_R\} \le 2m_Z$, $0.5 \le \mu_F/\mu_R \le 2$ with $Q = m_Z/2$.
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- Suppression of NLL+LO result in the large-q_T region ($q_T \gtrsim 60$ GeV) (strong dependence from the resummation scale, see next plot).

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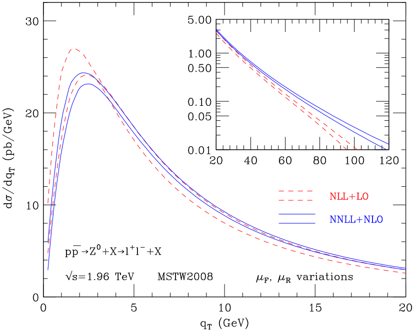

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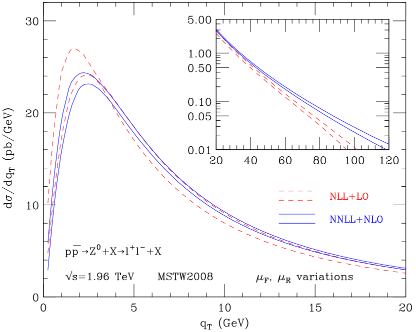

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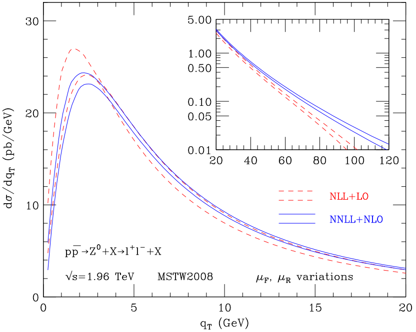

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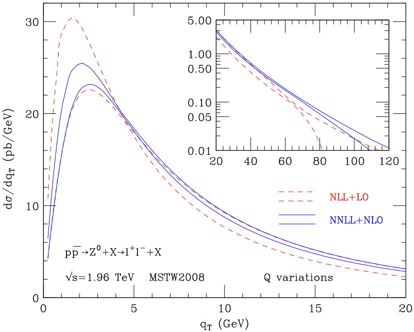

- Uncertainty bands obtained by performing resummation scale variations (estimate of higher-order logarithmic contributions): $m_Z/4 \leq Q \leq m_Z$ with $\mu_F = \mu_R = m_Z$.
- The resummation scale dependence at NNLL+NLO (NLL+LO) is about $\pm 5\%$ ($\pm 12\%$) around the peak and $\pm 5\%$ ($\pm 16\%$) in the $q_T \gtrsim 20\ GeV$ region and it is larger than the renormalization and factorization scale dependence.
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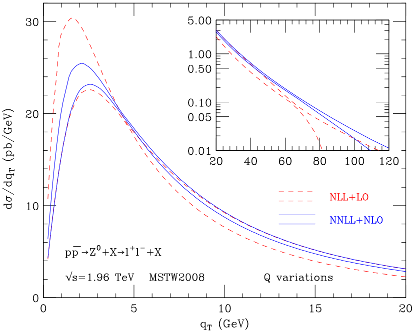

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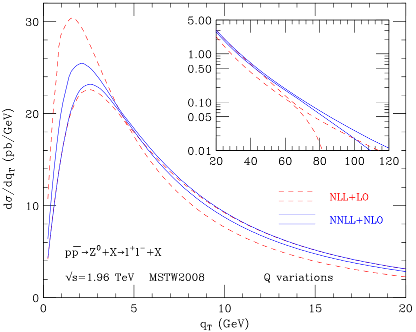

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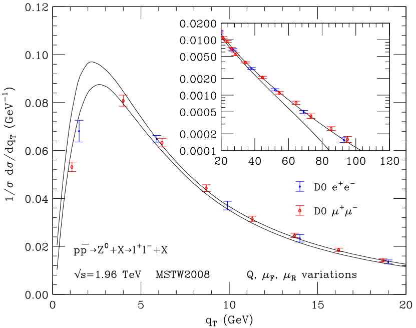

- D0 data compared with our NNLL+NLO result.
- The NNLL+NLO band obtained varying μ_R, μ_F, Q independently: $m_Z/2 \le \{\mu_F, \mu_R, 2Q\} \le 2m_Z$ with the constraints $0.5 \le \{\mu_F/\mu_R, Q/\mu_R\} \le 2$ which avoid large logarithmic contributions ($\sim \ln(\mu_F^2/\mu_R^2)$, $\ln(Q^2/\mu_R^2)$) in the evolution of the parton densities and in the the resummed form factor.
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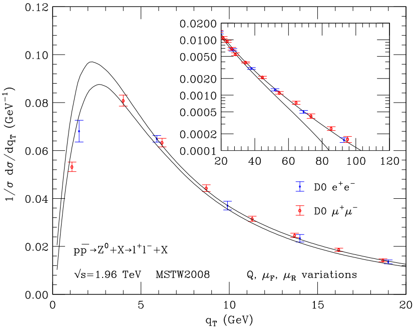

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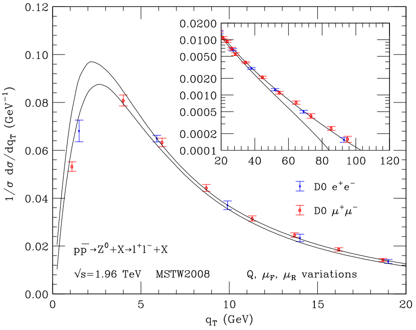

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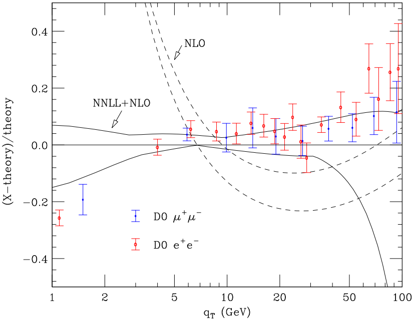

- Fractional difference with respect to the reference result: NNLL+NLO, $\mu_R = \mu_F = 2Q = m_Z$.
- NNLL+NLO scale dependence is $\pm 6\%$ at the peak, $\pm 5\%$ at $q_T = 10\ GeV$ and $\pm 12\%$ at $q_T = 50\ GeV$. For $q_T \geq 60\ GeV$ the resummed result looses predictivity.
- At large values of q_T, the NLO and NNLL+NLO bands overlap.
  At intermediate values of transverse momenta the scale variation bands do not overlap: we added the NLO curve with $\mu_F = m_Z/4$.
  The resummation improve 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+NLO band.
- The effect of the new result for the coefficient $A^{(3)}$ which appears in the NNLL $g^{(3)}$ function [Becher,Neubert('10)] is small (within the perturbative uncertainties).

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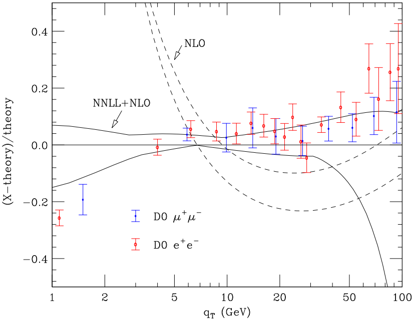

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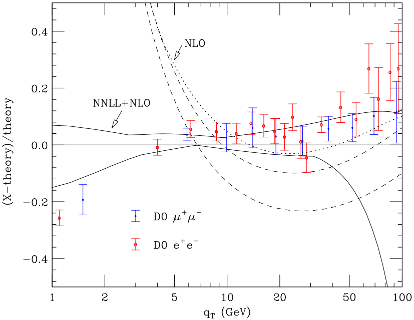
Resummed results: q_T spectrum of Drell-Yan l^+l^- pairs at $\sqrt{s} = 1.96$ TeV



- Fractional difference with respect to the reference result: NNLL+NLO, $\mu_R = \mu_F = 2Q = m_Z$.
- NNLL+NLO 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+NLO bands overlap.
  At intermediate values of transverse momenta the scale variation bands do not overlap: we added the NLO curve with $\mu_F = m_Z/4$.
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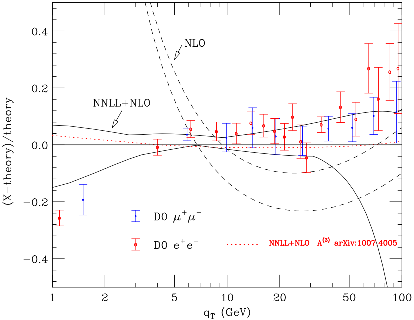

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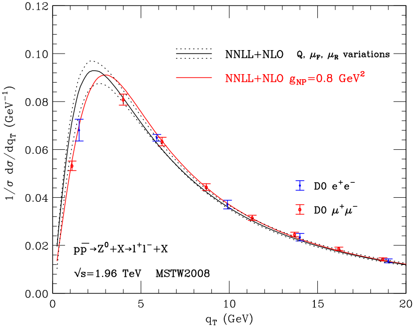
Non perturbative effects: q_T spectrum of Drell-Yan l^+l^- pairs at $\sqrt{s}=1.96$ TeV



- Up to now result in a complete perturbative framework.
- Non perturbative effects parametrized by a NP form factor $S_{NP} = \exp\{-g_{NP} b^2\}$:

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

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

- With NP effects the q_T spectrum is harder.
- Quantitative impact of such NP effects is comparable with perturbative uncertainties.

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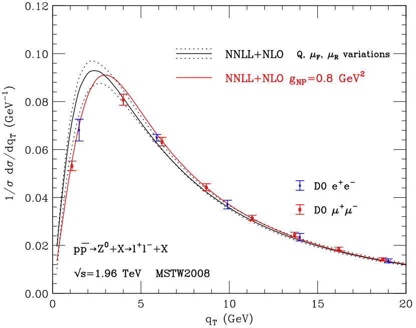

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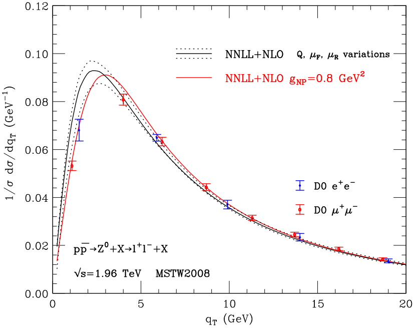

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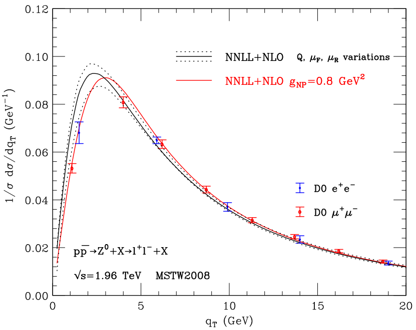

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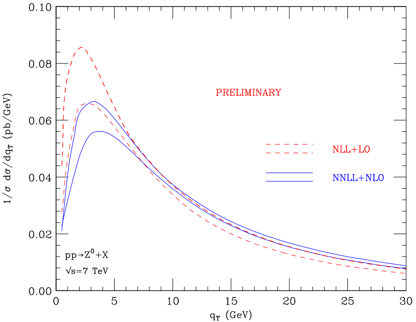
Resummed results: q_T spectrum of Drell-Yan e^+e^- pairs for LHC at $\sqrt{s}=7\ TeV$



- Uncertainty bands obtained varying μ_R, μ_F, Q independently: $m_Z/2 \leq \{\mu_F, \mu_R, 2Q\} \leq 2m_Z$ with the constraints $0.5 \leq \{\mu_F/\mu_R, Q/\mu_R\} \leq 2$ which avoid large logarithmic contributions ($\sim \ln(\mu_F^2/\mu_R^2)$, $\ln(Q^2/\mu_R^2)$) in the evolution of the parton densities and in the the resummed form factor.
- The scale dependence at NNLL+NLO (NLL+LO) is about $\pm 9\%$ ($\pm 13\%$) around the peak and $\pm 4\%$ ($\pm 11\%$) in the $q_T \gtrsim 20\ GeV$ region and it is larger than the one at the Tevatron.
- Going from the NLL+LO to the NNLL+NLO calculation the resummation scale dependence is strongly reduced.

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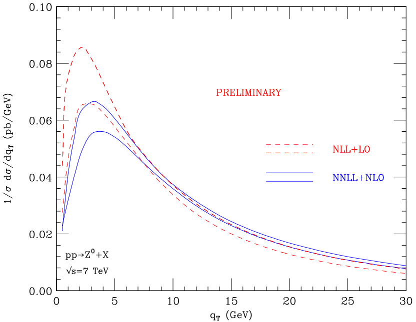

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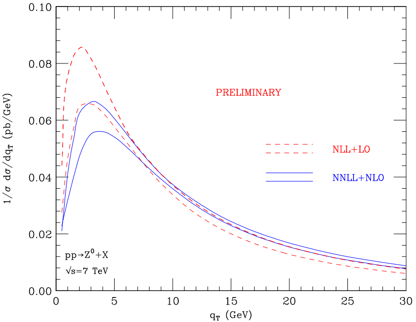

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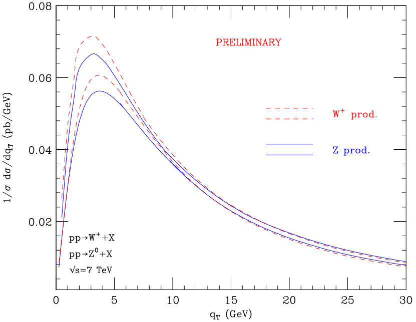
comparison between the Z and the W shape.



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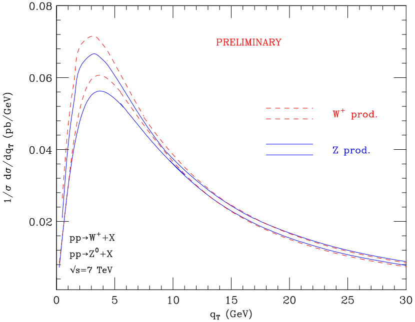

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Conclusions and Perspectives

- We have presented a study on transverse momentum distribution of Drell-Yan lepton pairs produced in hadronic collisions.
- We have compared LO and NLO fixed order prediction to Tevatron data finding good agreement down to transverse momenta of the order $q_T \sim 20\ GeV$.
- We have applied the q_T-resummation formalism developed in [Catani,de Florian, Grazzini('01)], [Bozzi,Catani,de Florian, Grazzini('06)] performing the resummation up to NNLL+NLO.
  It means NNLL resummation, NNLO corrections at small q_T; NLO corrections at large q_T; σ_{TOT} at NNLO (upon integration over q_T).
- A public version of our code DYqT will be available in the near future.
- The size of the scale uncertainties is considerably reduced in going from NLL+LO to NNLL+NLO accuracy.
- The NNLL+NLO results (without the inclusion of any non-perturbative effects) are consistent with the experimental data in a wide region of transverse momenta and improve the agreement of the NLO results with the data at small and intermediate values of q_T.
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