Transverse-momentum resummation for Drell-Yan lepton pair production at NNLL accuracy

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Outline

Motivations

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

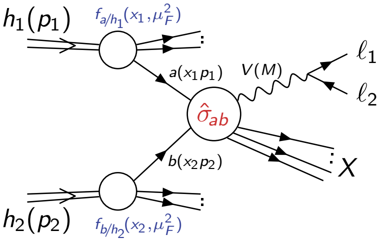
- Large production rates and clean experimental signatures:
  - Important for detector calibration.
  - Possible use as luminosity monitor.
- Transverse momentum distributions needed for:
  - Precise prediction for M_W.
  - Beyond the Standard Model analysis.
- Test of perturbative QCD predictions.
-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

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:

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

The standard fixed-order QCD perturbative expansions gives:

$$\int_{Q_T^2}^{\infty} dq_T \frac{d\hat{\sigma}_{q\bar{q}}}{dq_T^2} \;\sim\; \alpha_S\left[c_{12}\log^2(M^2/Q_T^2) + c_{11}\log(M^2/Q_T^2) + c_{10}(Q_T)\right]$$

$$+\alpha_S^2\left[c_{24}\log^4(M^2/Q_T^2) + \cdots + c_{21}\log(M^2/Q_T^2) + c_{20}(Q_T)\right] + \mathcal{O}(\alpha_S^3)$$

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

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

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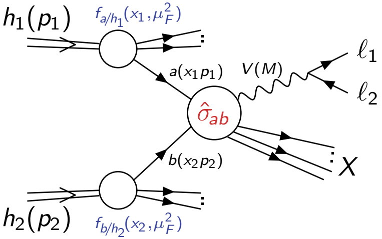

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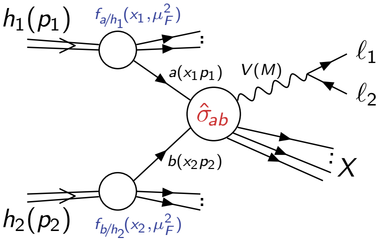

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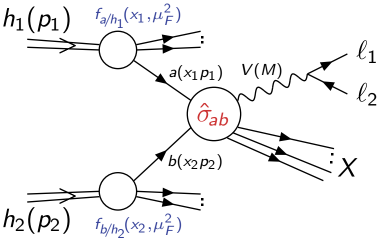

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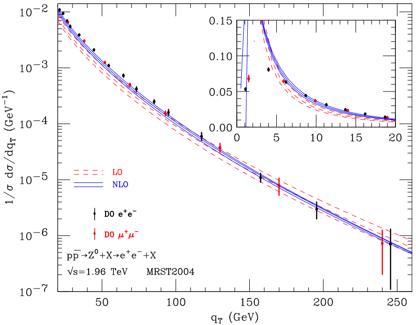
Fixed order results: q_T spectrum of Drell-Yan l^+l^- pairs at $\sqrt{s} = 1.96\ TeV$



- D0 data normalized to 1: [D0 Coll.('08,'10)]
- Factorization and renormalization scale variations: $\mu_F = \mu_R = m_Z$, $m_Z/2 \le \mu_F, \mu_R \le 2m_Z$, $1/2 \le \mu_F/\mu_R \le 2$.
  LO and NLO scale variations bands overlap only for $q_T > 60\ GeV$
- Good agreement between NLO results and data up to $q_T \sim 20\ GeV$.
- 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.

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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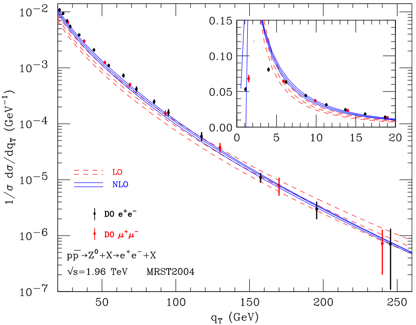

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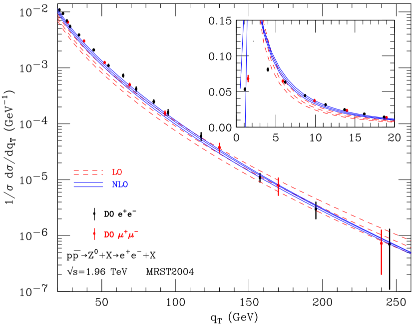

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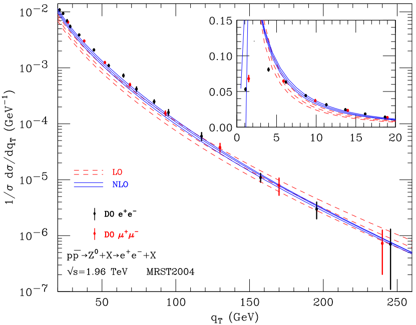

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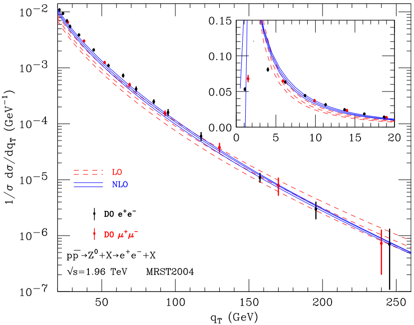

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State of the art: transverse-momentum resummation

- The method to perform the resummation of the large logarithms of q_T is known [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)].
- In this study we apply 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)].

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:

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

$$\mathcal{G}_N(\alpha_S,L) = L\, g^{(1)}(\alpha_S L) + g_N^{(2)}(\alpha_S L) + \frac{\alpha_S}{\pi} g_N^{(3)}(\alpha_S L) + \cdots; \qquad \mathcal{H}_N(\alpha_S) = \sigma^{(0)}(\alpha_S, M)\left[1 + \frac{\alpha_S}{\pi}\mathcal{H}_N^{(1)} + \left(\frac{\alpha_S}{\pi}\right)^2 \mathcal{H}_N^{(2)} + \cdots\right]$$

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Using the recently computed function $\mathcal{H}_N^{(2)}$, we have performed the resummation up to NNLL matched with the NLO calculation.

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

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Resummation holds in impact parameter space:

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$q_T \ll M \Leftrightarrow Mb \gg 1$, $\log M^2/q_T^2 \gg 1 \Leftrightarrow \log Mb \gg 1$

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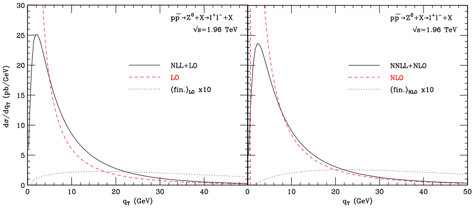
Resummed results: q_T spectrum of Drell-Yan l^+l^- pairs at $\sqrt{s} = 1.96\ TeV$



- 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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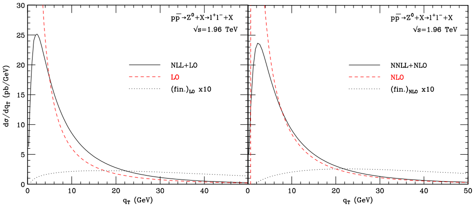

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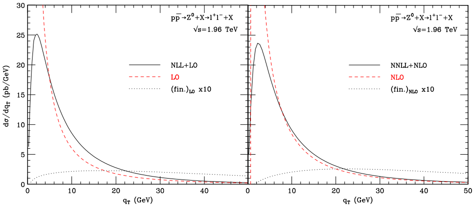

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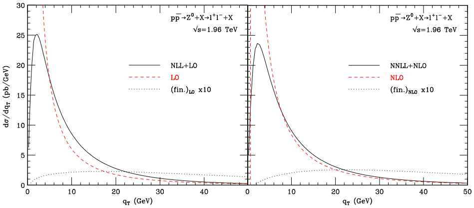

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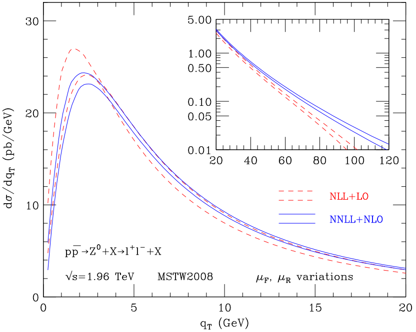

- Our calculation implements $\gamma^* Z$ interference and finite-width effects. Here we use the narrow width approximation (differences within 1% level).
- Uncertainty bands obtained by performing renormalization and factorization scale variations: $m_Z/2 \le \{\mu_F, \mu_R\} \le 2m_Z$, $0.5 \le \mu_F/\mu_R \le 2$ with $Q = m_Z/2$.
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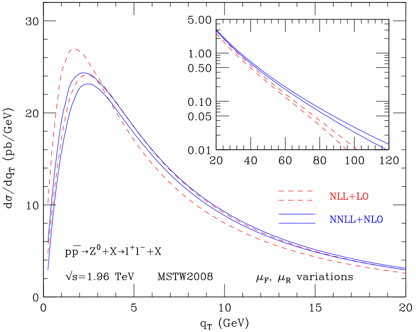

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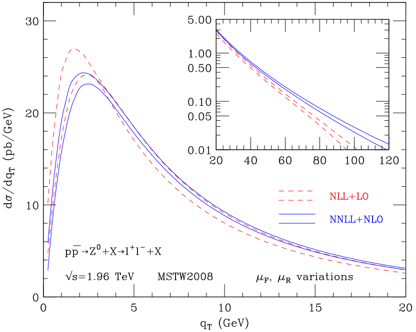

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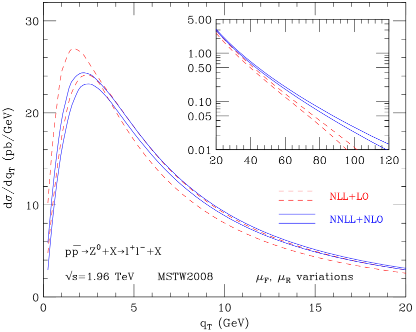

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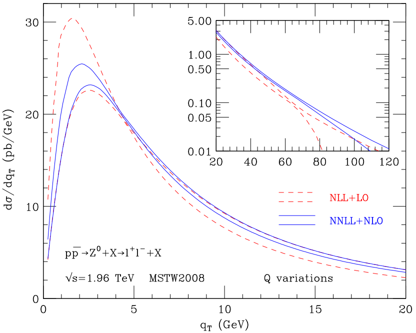

- Uncertainty bands obtained by performing resummation scale variations (estimate of higher-order logarithmic contributions): $Q = m_Z/2, \quad m_Z/4 \leq Q \leq m_Z$ with $\mu_F = \mu_R = m_Z$.
- The resummation scale dependence at NNLL+NLO (NLL+LO) is about $\pm5\%$ ($\pm12\%$) around the peak and $\pm5\%$ ($\pm16\%$) in the $q_T \gtrsim 20\ GeV$ region and it is larger than the renormalization and factorization scale dependence.
- Going from the NLL+LO to the NNLL+NLO calculation the resummation scale dependence is reduce by roughly a factor 2 in the wide region $5\ GeV \lesssim q_T \lesssim 50\ GeV$.

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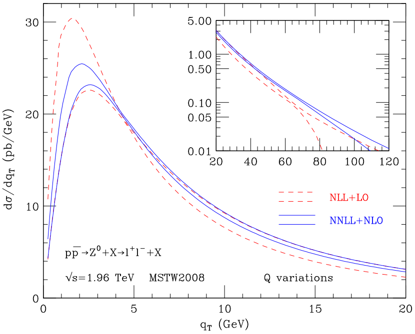

- Uncertainty bands obtained by performing resummation scale variations (estimate of higher-order logarithmic contributions): $Q = m_Z/2$, $m_Z/4 \leq Q \leq m_Z$ with $\mu_F = \mu_R = m_Z$.
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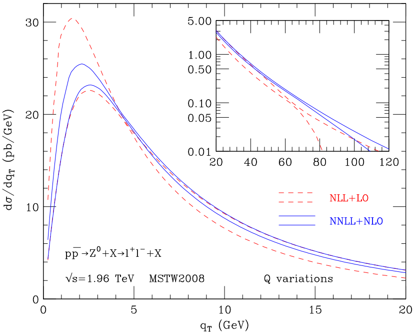

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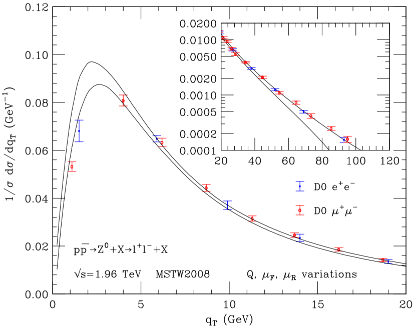

- D0 data compared with our NNLL+NLO result.
- The NNLL+NLO band obtained varying μ_R, μ_F, Q independently: $m_Z/2 \leq \{\mu_F, \mu_R, 2Q\} \leq 2m_Z$ with the constraints $0.5 \leq \{\mu_F/\mu_R, Q/\mu_R\} \leq 2$ which avoid large logarithmic contributions ($\sim \ln(\mu_F^2/\mu_R^2)$, $\ln(Q^2/\mu_R^2)$) in the evolution of the parton densities and in the the resummed form factor.
- Good agreement between experimental data and theoretical resummed predictions (without any model for non-perturbative effects). The perturbative uncertainty of the NNLL+NLO results is comparable with the experimental errors.

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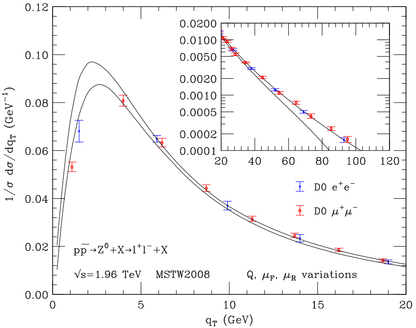

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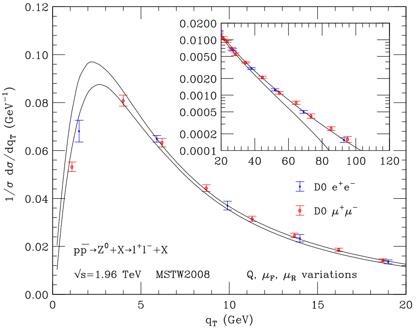

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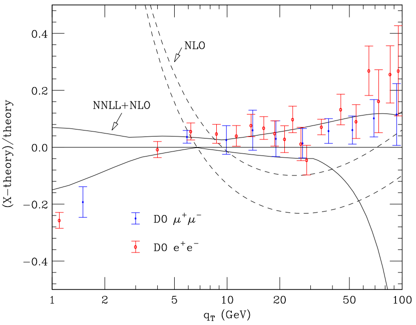

- Fractional difference with respect to the reference result: NNLL+NLO, $\mu_R = \mu_F = 2Q = m_Z$.
- NNLL+NLO scale dependence is $\pm 6\%$ at the peak, $\pm 5\%$ at $q_T = 10\ GeV$ and $\pm 12\%$ at $q_T = 50\ GeV$. For $q_T \geq 60\ GeV$ the resummed result looses predictivity.
- At large values of q_T, the NLO and NNLL+NLO bands overlap.
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  In the small-q_T region, the NLO result is theoretically unreliable and the NLO band deviates from the NNLL+NLO band.
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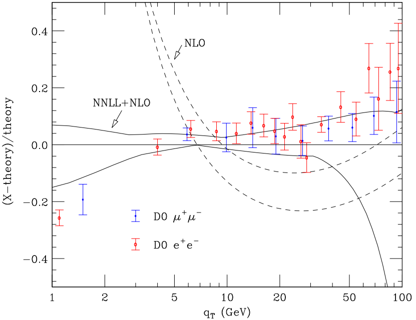

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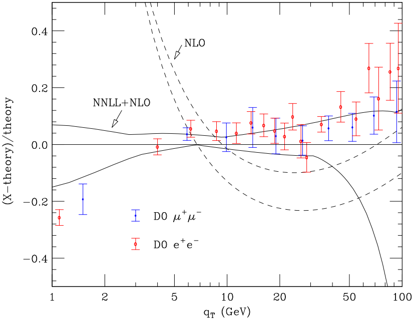

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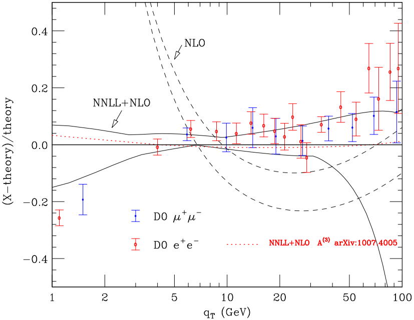

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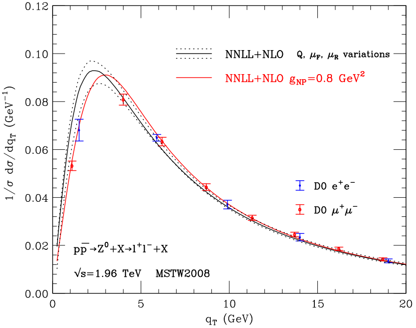
Non perturbative effects: q_T spectrum of Drell-Yan l^+l^- pairs at $\sqrt{s}=1.96$ TeV



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

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

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

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

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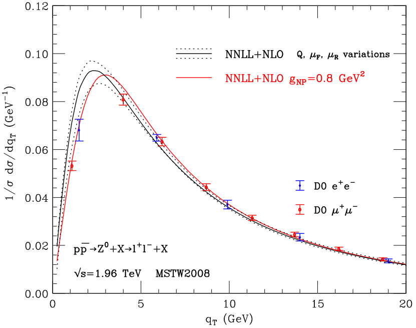

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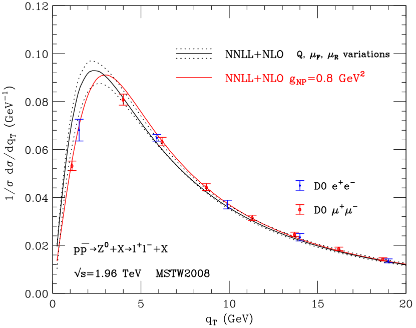

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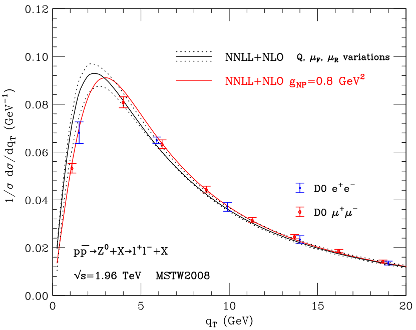

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- We have presented a study on transverse momentum distribution of Drell-Yan lepton pairs produced in hadronic collisions.
- We have compared LO and NLO fixed order prediction to Tevatron data finding good agreement down to transverse momenta of the 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, implementing the calculation in a numerical code.
- A public version of our code DYqT will be available in the near future.
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