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

- 1 Drell-Yan q_T distribution
- 2 Fixed order results
- 3 Transverse-momentum resummation
- Resummed results
- 5 Conclusions and Perspectives





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:

Drell-Yan q_T distribution

- 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

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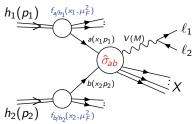
• Electroweak correction are know at $\mathcal{O}(\alpha)$ [Dittmaier et al.('02)], [Baur et al.('02)] [Carloni Calame, Montagna, Nicrosini, Vicini ('06)]



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The Drell-Yan q_T distribution

$$h_1(p_1)+h_2(p_2)
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 where $V=\gamma^*, Z^0, W^\pm$ and $\ell_1\ell_2=\ell^+\ell^-, \ell_1\nu_\ell$



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

$$\begin{split} \int_{0}^{Q_{T}^{2}} dq_{T}^{2} \, \frac{d\hat{\sigma}_{q\bar{q}}}{dq_{T}^{2}} &\sim & 1 + \alpha_{S} \bigg[c_{12} \log^{2}(M^{2}/Q_{T}^{2}) + c_{11} \log(M^{2}/Q_{T}^{2}) + c_{10}(Q_{T}) \bigg] \\ &+ \alpha_{S}^{2} \bigg[c_{24} \log^{4}(M^{2}/Q_{T}^{2}) + \dots + c_{21} \log(M^{2}/Q_{T}^{2}) + c_{20}(Q_{T}) \bigg] + \mathcal{O}(\alpha_{S}^{3}) \end{split}$$

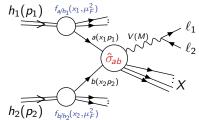
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The standard fixed-order QCD perturbative expansions gives

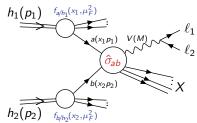
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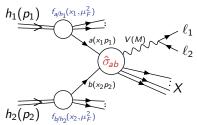
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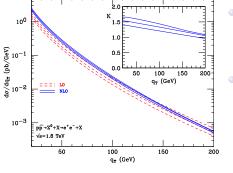
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- LO: pdf=MRST02 LO, 1-loop α_S
 NLO: pdf=MRST04 NLO, 2-loop α_S
- Factorization and renormalization scale variations: $\mu_F = \mu_R = m_Z, \quad m_Z/2 \le \mu_F, \mu_R \le 2m_Z, \\ 1/2 \le \mu_F/\mu_R \le 2. \\ q_T \sim m_Z : LO \pm 25\%, NLO \pm 8\% \\ q_T \sim 20 \ GeV : LO \pm 20\%, NLO \pm 7\%$
- q_T dependent K-factor:

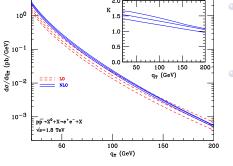
$$K(q_T) = \frac{d\sigma/dq_{TNLO}(\mu_F, \mu_R)}{d\sigma/dq_{TLO}(\mu_F = \mu_R = m_Z)}$$

 $K\sim 1.1$ at $q_T\sim 200~GeV$ up to $K\sim 1.5$ at $g_T\sim 20~GeV$

LO and NLO scale variations bands overlap only for $g_T > 70 \ GeV$



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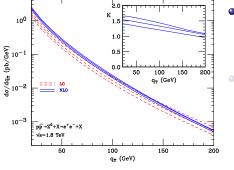
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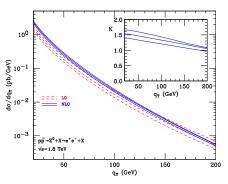
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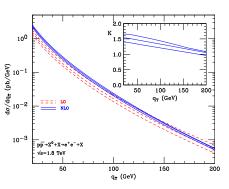


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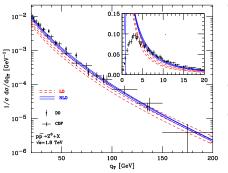
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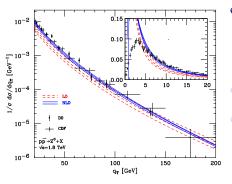
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- CDF data: $66 \ GeV < M^2 < 116 \ GeV$, $\sigma_{tot} = 248 \pm 11 \ pb$ [CDF Collaboration ('00)] D0 data: $75 \ GeV < M^2 < 105 \ GeV$, $\sigma_{tot} = 221 \pm 11 \ pb$
- Good agreement between NLO results and data up to $q_T \sim 20~GeV$.
- In the small q_T region $(q_T \lesssim 20~GeV)$ LO and NLO result diverges to $+\infty$ and $-\infty$ (accidenta partial agreement at $q_T \sim 5-7~GeV$): need for resummation.





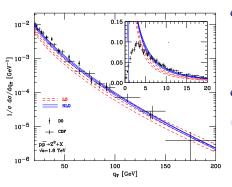


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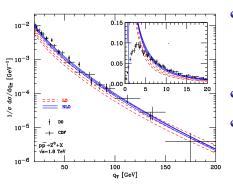


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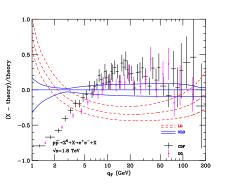
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Percentage difference between data and theory:

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

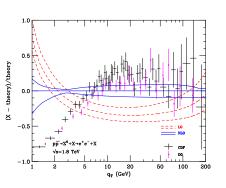
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- Relative difference between LO and NLO: very large at low q_T , $\sim 40-50\%$ at intermediate q_T ,
- Relative difference theory and data: good agreement (one standard deviation) for q_T ≥ 20 GeV,



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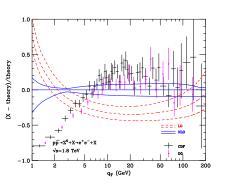
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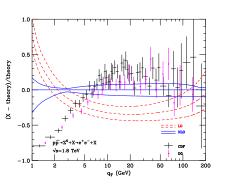
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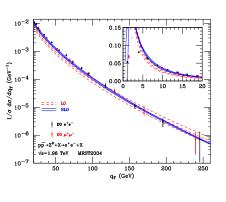
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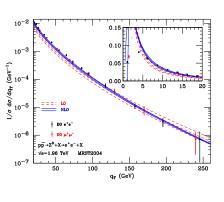


D0 data normalized to 1: [D0 Coll.('08,'10)].

- Normalization reduces only marginally fixed order scale variations.
- Factorization and renormalization scale variations: $\mu_F = \mu_R = m_Z, \qquad m_Z/2 \le \mu_F, \mu_R \le 2m_Z, \\ 1/2 \le \mu_F/\mu_R \le 2. \\ \text{LO and NLO scale variations bands overlap only}$ for $q_T > 60~\text{GeV}$
- Good agreement between NLO results and data up to $q_T \sim 20~GeV$.
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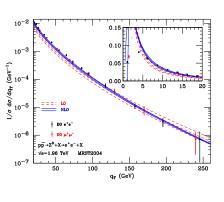
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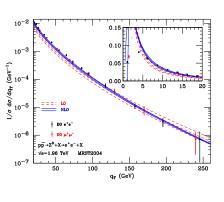
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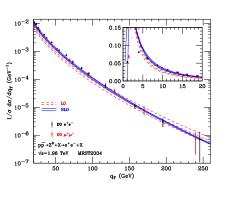
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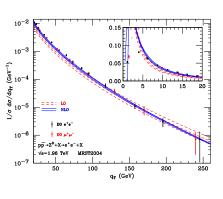
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- In the small q_T region $(q_T \lesssim 20~GeV)$ LO and NLO result diverges to $+\infty$ and $-\infty$ (accidental partial agreement at $q_T \sim 5-7~GeV$): need for resummation.

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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State of the art: transverse-momentum resummation

• The method to perform the resummation of the large logarithms of q_T is known

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[Dokshitzer, Diakonov, Troian ('78)], [Parisi, Petronzio('79)], [Kodaira, Trentadue('82)], [Altarelli et al.('84)], [Collins, Soper, Sterman('85)], [Catani, de Florian, Grazzini('01)]
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 Various phenomenological studies of the vector boson transverse momentum distribution exist

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[Balasz,Qiu,Yuan('95)],[Balasz,Yuan('97)],[Ellis et al.('97)],
[Kulesza et al.('02)]
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 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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Resummation holds in impact parameter space

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

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Challanges for precision physics at the LHC

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Challanges for precision physics at the LHC

Transverse momentum resummation

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- 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
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$$\ln\left(\frac{M^2b^2}{b_0^2}\right) \to \widetilde{L} \equiv \ln\left(\frac{Q^2b^2}{b_0^2} + 1\right)$$

- avoids unjustified higher-order contributions in the small-b region: no need for unphysical switching from resummed to fixed-order results
- allows to recover exactly the total cross-section upon integration on q_7
- variations of the resummation scale Q ~ M allows to estimate the uncertainty from uncalculated logarithmic corrections at higher orders.

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Giancarlo Ferrera 13/22

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Challanges for precision physics at the LHC

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- 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)].
- 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 constrain and resummation scale Q:

$$\ln\!\left(\!\frac{M^2b^2}{b_0^2}\!\right) \to \widetilde{L} \equiv \ln\!\left(\!\frac{Q^2b^2}{b_0^2}\!+\!1\!\right)$$

- uncertainty from uncalculated logarithmic corrections at higher orders.

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Challanges for precision physics at the LHC Paris - 16/12/2010

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- avoids unjustified higher-order contributions in the small-b region: no need for unphysical switching from resummed to fixed-order results.
- allows to recover exactly the total cross-section upon integration on q_T
- variations of the resummation scale Q ~ M allows to estimate the uncertainty from uncalculated logarithmic corrections at higher orders.

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Challanges for precision physics at the LHC Paris - 16/12/2010
Giancarlo Ferrera 13/22

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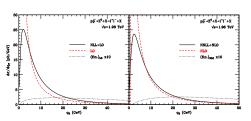
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Challanges for precision physics at the LHC



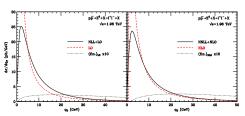
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 Resummation cure the fixed order
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- The q_T spectrum is slightly harder at NNLL+NLO accuracy than at NLL+LO accuracy
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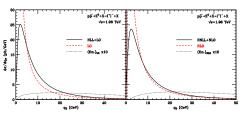
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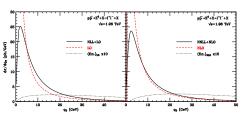
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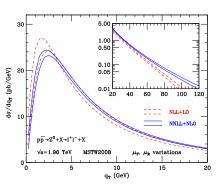
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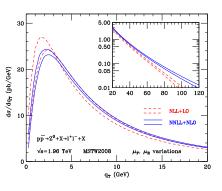
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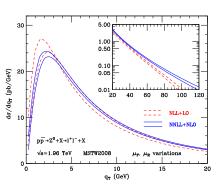


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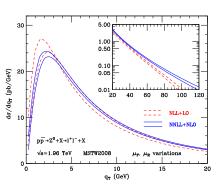
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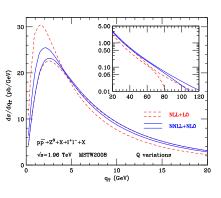


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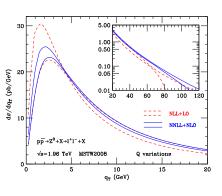


- Uncertainty bands obtained by performing resummation scale variations (estimate of higher-order logarithmic contributions): $m_Z/4 \le Q \le m_Z$ with $\mu_F = \mu_R = m_Z$.
- The resummation scale dependence at NNLL+NLO (NLL+LO) is about $\pm 5\%$ ($\pm 12\%$ around the peak and $\pm 5\%$ ($\pm 16\%$)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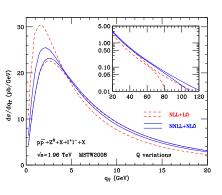
Challanges for precision physics at the LHC



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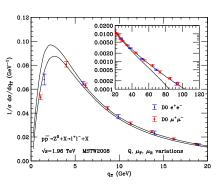
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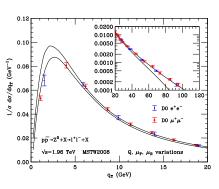
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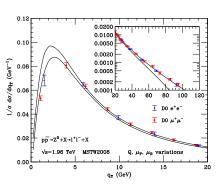
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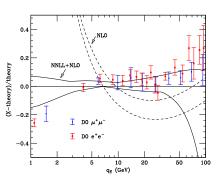


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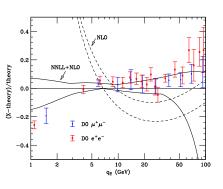




- Fractional difference with respect to the reference result: NNLL+NLO, $\mu_R = \mu_F = 2Q = m_7$.
- NNLL+NLO scale dependence is $\pm 6\%$ at the peak, $\pm 5\%$ at $q_T=10~GeV$ and $\pm 12\%$ at $q_T=50~GeV$. For $q_T\geq 60~GeV$ the resummed result looses predictivity.
- At large values of q_T , the NLO and NNLL+NLO bands overlap.

At intermediate values of transverse momenta th 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

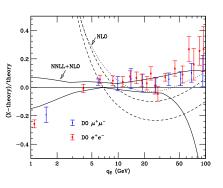
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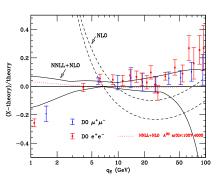
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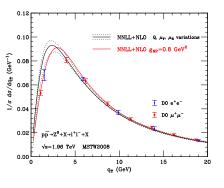


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Non perturbative effects: q_T spectrum of Drell-Yan I^+I^- pairs at $\sqrt{s}=1.96~TeV$



- Up to now result in a complete perturbative framework
- Non perturbative effects parametrized by a NP

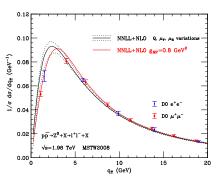
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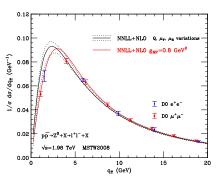
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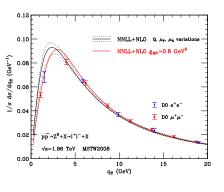
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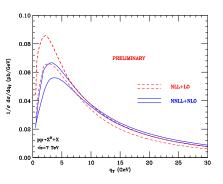
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Resummed results: q_T spectrum of Drell-Yan e^+e^- pairs for LHC at $\sqrt{s}=7$ TeV

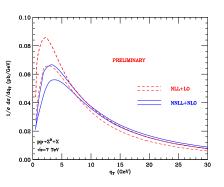


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- The scale dependence at NNLL+NLO (NLL+LO is about $\pm 9\%$ ($\pm 13\%$) around the peak and $\pm 4\%$ ($\pm 11\%$) in the $q_T \gtrsim 20~GeV$ region and it is larger than the one at the Tevatron.
- Going from the NLL+LO to the NNLL+NLO calculation the resummation scale dependence is strongly reduced.



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

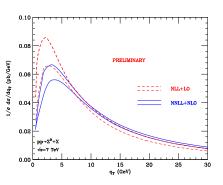


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Challanges for precision physics at the LHC Paris - 16/12/2010 Giancarlo Ferrera

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



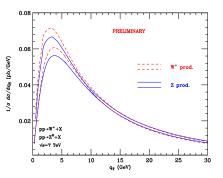
- Uncertainty bands obtained varying μ_R , μ_F , Q independently: $m_Z/2 \le \{\mu_F, \mu_R, 2Q\} \le 2m_Z$ with the constraints $0.5 \le \{\mu_F/\mu_R, Q/\mu_R\} \le 2$ which avoid large logarithmic contributions $(\sim \ln(\mu_F^2/\mu_R^2), \ln(Q^2/\mu_R^2))$ in the evolution of the parton densities and in the the resummed form factor.
- 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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comparison between the Z and the W shape.



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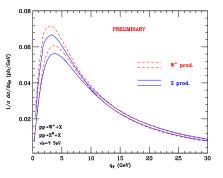
• The scale dependence at NNLL+NLO is similar from W and Z production and is larger than the one at the Tevatron.





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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 $a_T \sim 20 \ GeV$.
- 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 a_T.
- Future implementations: add the dependence on the vector boson rapidity and on the decay leptons variables.



Conclusions

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