New tests for high energy factorization in Drell-Yan lepton pair production

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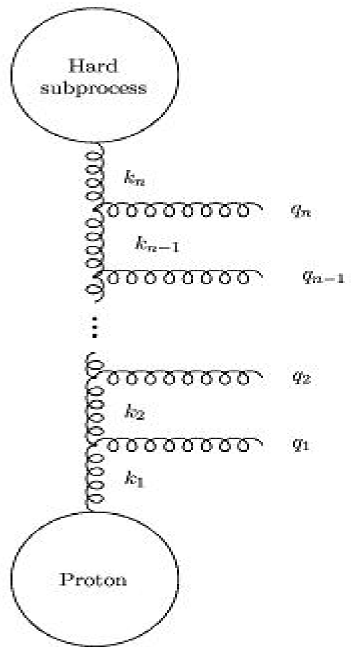
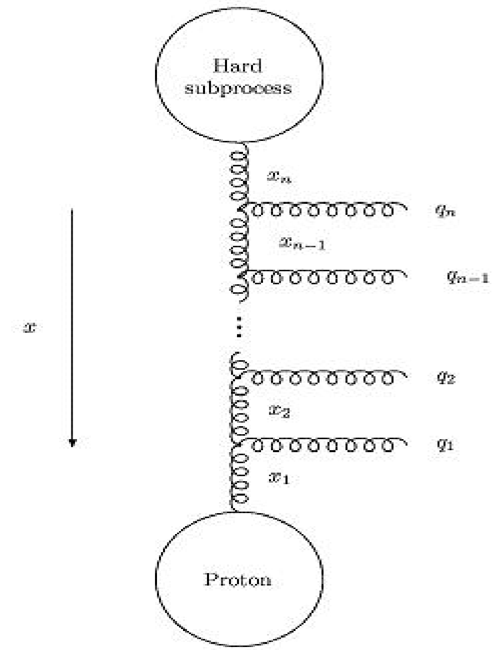
Collinear & kt-factorization in QCD



- DGLAP evolution
- resummation of the terms ~ $\ln Q^2$
- strong ordering in Q^2
- no kt of incoming partons
- on-shell hard matrix elements
- collinear QCD factorization

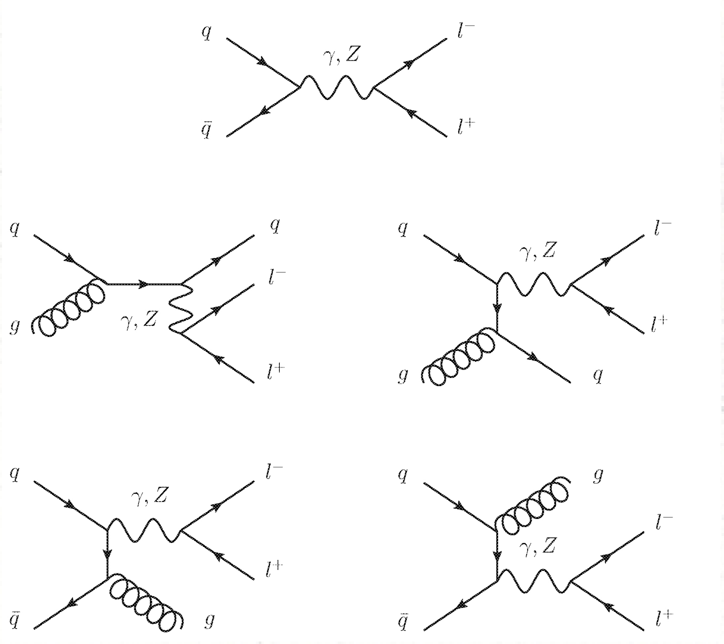


- BFKL or CCFM evolution
- resummation of the terms ~ $\ln 1/x$
- no ordering in kt
- non-zero kt of incoming partons
- unintegrated (TMD) parton densities
- off-shell hard matrix elements
- kt-factorization

Drell-Yan lepton pair production at high energies

- Major source of background to a number of SM processes and processes beyond the SM (Higgs, W'/Z' etc)
- Previously, we have used the quark-antiquark annihilation and QCD Compton subprocesses

A.V. Lipatov, M.A. Malyshev, N.P. Zotov, JHEP 12, 117 (2011)



Contributions from last diagrams are taken into account by quark-antiquark annihilation

On-shell hard matrix elements and KMR uPDFs have been applied

An additional K-factor was included:

$$K = \exp\left[C_F \frac{\alpha_s(\mu^2)}{2\pi}\pi^2\right]$$

A.Kulesza. W.J. Stirling, NPB 555, 279 (1999)

But we need CCFM-evolved partons for MC generator CASCADE which widely used by the CMS collaboration

off-shell amplitude for q*q* → Z/γ* → ll

- Effective quark-to-photon vertex for reggeized quarks

  L.N. Lipatov, M.I. Vyazovsky, NPB 597, 399 (2001)
  A.V. Bogdan, V.S. Fadin, NPB 740, 36 (2006)

$$\Gamma_\gamma^\mu(k_1,k_2)=\gamma^\mu-\hat{k}_1\frac{P_1^\mu}{P_1\cdot k_2}-\hat{k}_2\frac{P_2^\mu}{P_2\cdot k_1}$$

  where k_1 , k_2 , P_1 and P_2 are the initial quarks and protons 4-momenta

- Ward identity is satisfied: $\Gamma_\gamma^\mu(k_1,k_2)(k_1+k_2)_\mu=0$

- Effective reggeized quark-to-Z boson vertex is constructed in a similar way:

$$\Gamma_Z^\mu(k_1,k_2)=\Gamma_\gamma^\mu(k_1,k_2)(g_V-g_A\gamma^5)$$

  where g_V and g_A are usual vector and axial quark to Z boson coupling constants

off-shell amplitude for $q^*q^* \to Z/\gamma^* \to ll$

- Simple small-x approximation to calculate partonic amplitudes involving initial off-shell quarks has been proposed

  S.P. Baranov, A.V. Lipatov, N.P. Zotov, PRD 81, 094034 (2010)

  In this prescription, the initial off-shell quark is considered as the internal line in the «extended» diagram. At small x, in the zero mass limit this results in the special form of off-shell quark spin density matrix:

$$\sum u(k)\bar{u}(k) = xP$$

  where k and P are the off-shell quark and beam 4-momenta.

- In this way, gauge invariance is achieved in the small-x limit, where high-energy factorization is valid

TMD parton densities in a proton

- CCFM-evolved gluon distributions are available: H. Jung, arXiv: hep-ph/0411287
- Valence quark densities have been proposed:

  M. Deak, K. Kutak, H. Jung, Progress in High Energy Physics 2, 168 (2008)

- Sea quark densities can be calculated from gluon ones if we restrict to the case where gluon-to-quark splitting occurs in the last evolution step:

$$Q^{\rm sea}\left(x, \frac{\mathbf{\Delta}^2}{\mu^2}, \frac{\mu_F^2}{\mu^2}\right) = \int\limits_x^1 \frac{dz}{z} \int d\boldsymbol{k}^2\, \Theta\left(\mu_F^2 - \frac{\mathbf{\Delta}^2 + z(1-z)\boldsymbol{k}^2}{1-z}\right) \frac{1}{\mathbf{\Delta}^2}\frac{\alpha_s}{2\pi} P_{qg}\left(z, \boldsymbol{k}^2, \mathbf{\Delta}^2\right) \mathcal{G}\left(\frac{x}{z}, \boldsymbol{k}^2, \mu^2\right)$$

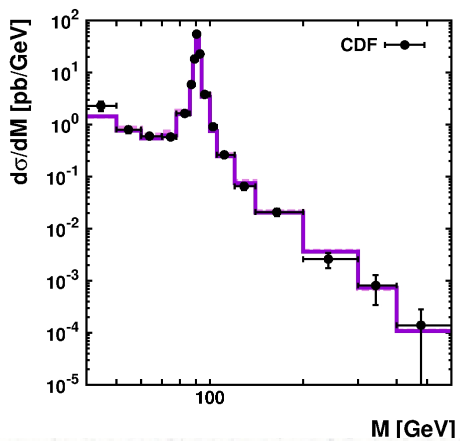
where TMD gluon-to-quark splitting function is given by

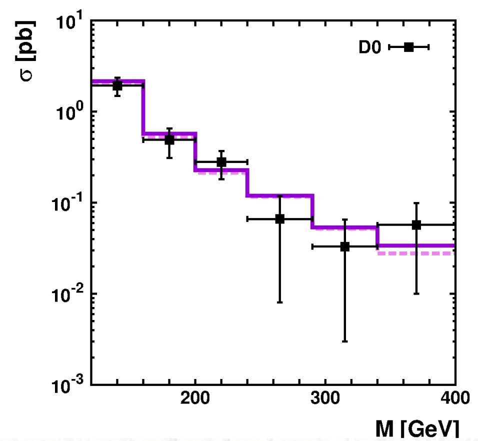
$$P_{qg}\left(z, \boldsymbol{k}^2, \mathbf{\Delta}^2\right) = T_R \left(\frac{\mathbf{\Delta}^2}{\mathbf{\Delta}^2 + z(1-z)\boldsymbol{k}^2}\right)^2 \left[(1-z)^2 + z^2 + 4z^2(1-z)^2\frac{\boldsymbol{k}^2}{\mathbf{\Delta}^2}\right]$$

with $\mathbf{\Delta} = \mathbf{q} - z\mathbf{k}$, and $\mathbf{k}$ and $\mathbf{q}$ are the the gluon and quark transverse momenta

S. Catani, F. Hautmann, NPB 427, 475 (1994)
F. Hautmann, H. Jung, M. Hentschinski, NPB 865, 54 (2012)

Effective vertex vs. small-x approximation

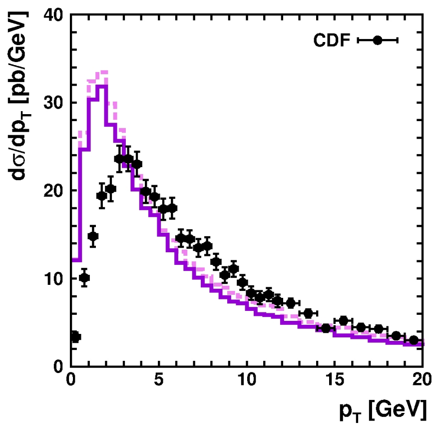


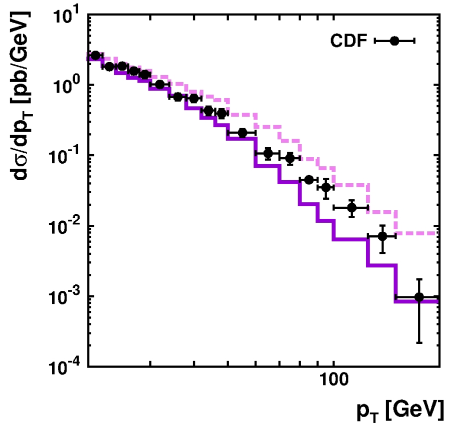


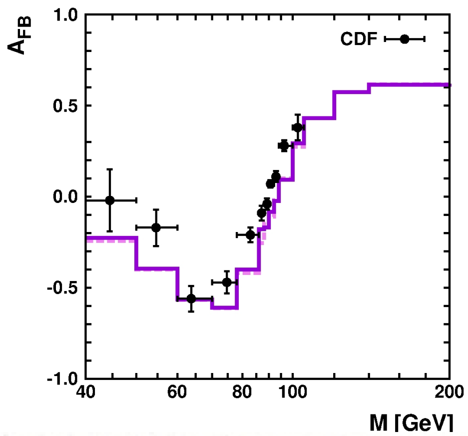
CCFM-evolved partons
no theta-function applied

effective vertex

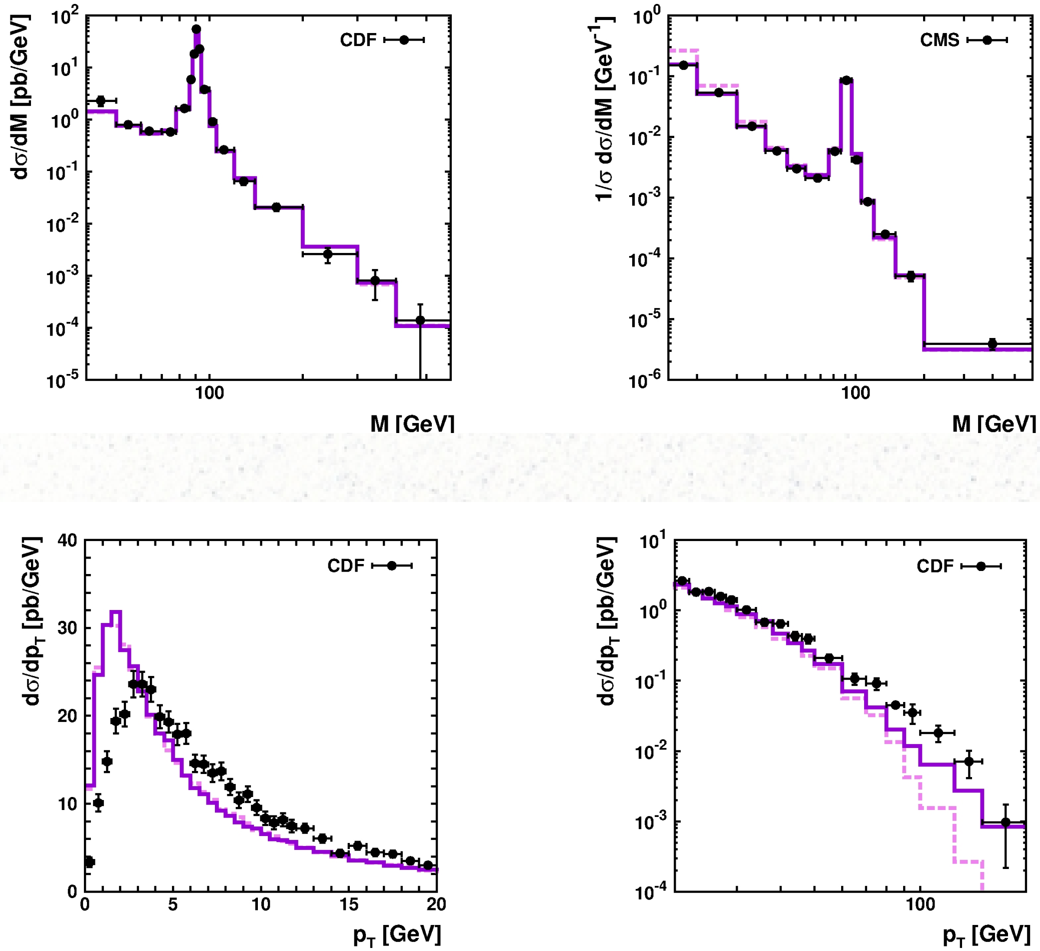
small-x approximation







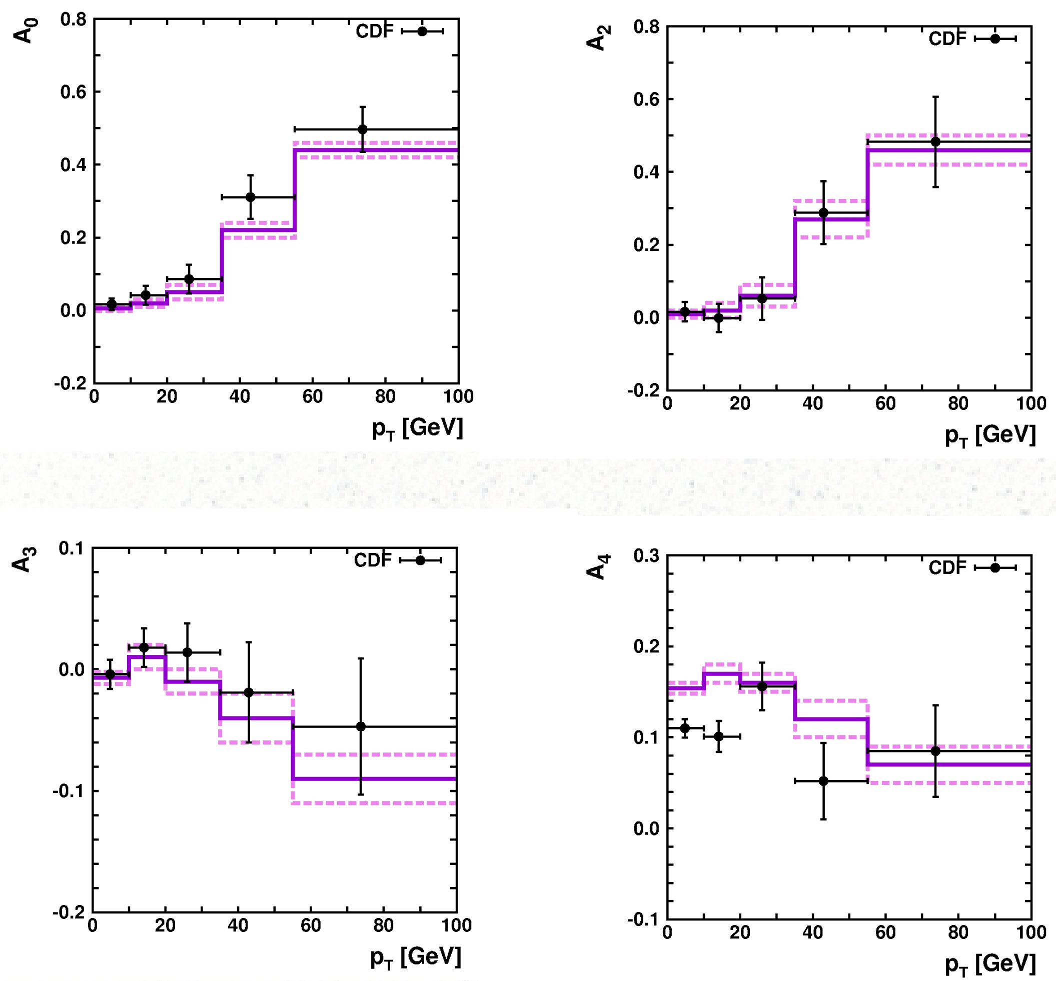
Our numerical predictions vs. Tevatron & LHC data



CCFM without theta-function

CCFM with theta-function

Angular distributions in Drell-Yan pair production



KMR

fit unc.

$$\frac{d\sigma}{d\cos\theta} \sim 1 + \cos^2\theta + \frac{1}{2} A_0 (1 - 3\cos^2\theta) + A_4 \cos\theta$$

$$\frac{d\sigma}{d\varphi} \sim 1 + \beta_3 \cos\varphi + \beta_2 \cos 2\varphi$$

$$\beta_3 = \frac{3\pi}{16} A_3 \qquad \beta_2 = \frac{A_2}{4}$$

Lam-Tung relation: $A_0 = A_2$

collinear QCD prediction:
flat behaviour of A_3

Phys. Rev. D **53**, 011201 (2001)

Conclusions

- We considered an important processes of Drell-Yan lepton pair production in the framework of kt-factorization QCD approach
- Our consideration was based on the gauge-invariant amplitude of quark annihilation subprocess (involving Z-boson exchange) and CCFM-evolved TMD PDFs in a proton
- We introduced TMD sea quarks and investigate the dependence of our predictions on the gluon-to-quark splitting function
- We have obtained a reasonable agreement of our numerical predictions and the Tevatron and LHC data taken by the D0, CDF and CMS collaborations
- Furher investigations of Drell-Yan process at the LHC are in progress