TMD PDFs in Drell-Yan lepton pair production at LHC

Nikolay P. Zotov
SINP MSU, Moscow, Russia

A.V. Lipatov, N.P. Zotov, arXiv:1409.0514 [hep-ph]
S.P. Baranov, A.V. Lipatov, N.P. Zotov, Phys. Rev. D **89**, 094025 (2014)

Content

- Introduction and motivation
- Theoretical framework

  - off-shell amplidudes
  - unintegrated (TMD) parton densities
- Numerical results
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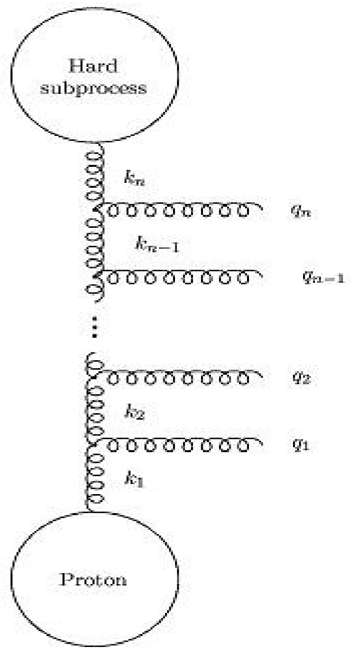
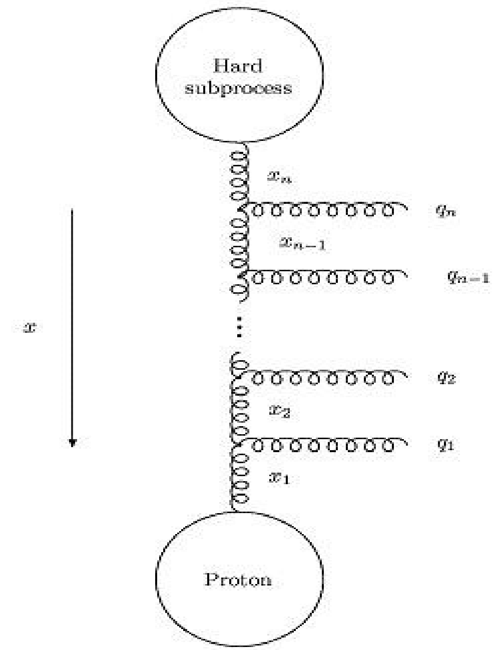
Motivation

- Drell-Yan lepton pair production is a unique process which offers high sensitivity to the parton density functions in a proton.
- It provides a major source of background to a number of processes (such as Higgs, top quark pair, W' and Z' production and other) studied at hadron colliders.
- It is used for monitoring of the collider luminosity and calibration of detectors.
- It is important to obtain within the framework of kt-factorization approach the description of measured cross sections close to the precision one, especially in the forward region, where the small-x dynamics come to the game.

Collinear & kt-factorization in QCD



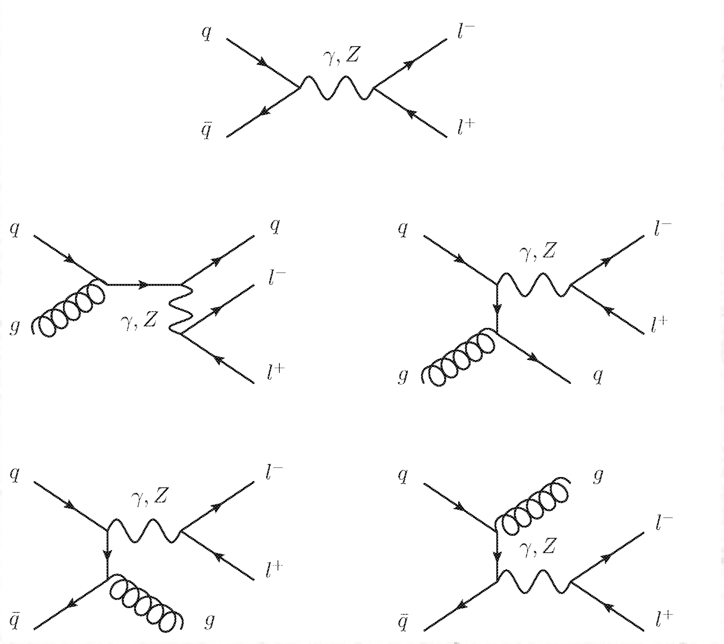
- DGLAP evolution
- resummation of the terms ~ $\ln Q^2$
- strong ordering in Q^2
- no kt of incoming partons
- on-shell hard matrix elements
- collinear QCD factorization



- 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

Inclusive Drell-Yan lepton pair production

- We used the quark-antiquark annihilation subprocess to describe inclusive Drell-Yan lepton pair production



- Contributions from last 4 diagrams are taken into account by quark-antiquark annihilation
- It is in a contrast with collinear QCD factorization where all these contributions have to be taken into account separately
- 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)

- 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

Off-shell amplitude for q*q* → Z/γ* → ll can be written as:

$$\mathcal{M}_\gamma = e_q e^2 \, \bar{v}_{s_1}(q_2)\Gamma^\mu_\gamma(q_1,q_2)u_{s_2}(q_1)\frac{g^{\mu\nu}}{\hat{s}}\bar{u}_{r_1}(p_1)\gamma^\nu v_{r_2}(p_2),$$

$$\mathcal{M}_Z = \frac{e^2}{\sin 2\theta_W}\bar{v}_{s_1}(q_2)\Gamma^\mu_Z(q_1,q_2)u_{s_2}(q_1)\left[g^{\mu\nu} - \frac{(q_1+q_2)^\mu(q_1+q_2)^\nu}{m_Z^2}\right]\times$$
$$\times\frac{1}{\hat{s} - m_Z^2 - i m_Z\Gamma_Z}\bar{u}_{r_1}(p_1)\gamma^\nu(C_V^l - C_A^l\gamma^5)v_{r_2}(p_2),$$

The relevant cross section in the kt-factorization approach reads

$$\sigma = \sum_q \int \frac{|\bar{\mathcal{M}}|^2}{16\pi\,(x_1 x_2 s)^2} f_q(x_1,\mathbf{q}_{1T}^2,\mu^2)\, f_q(x_2,\mathbf{q}_{2T}^2,\mu^2)\, d\mathbf{p}_{1T}^2 d\mathbf{q}_{1T}^2 d\mathbf{q}_{2T}^2 dy_1 dy_2 \frac{d\phi_1}{2\pi}\frac{d\phi_2}{2\pi}$$

Numerical parameters: $m_c = 1.4$ GeV, $\Lambda_{QCD} = 200$ MeV, $N_f = 4$
and the massless approximation for light quarks is applied.
Hard scale is the dilepton invariant mass.

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

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:

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

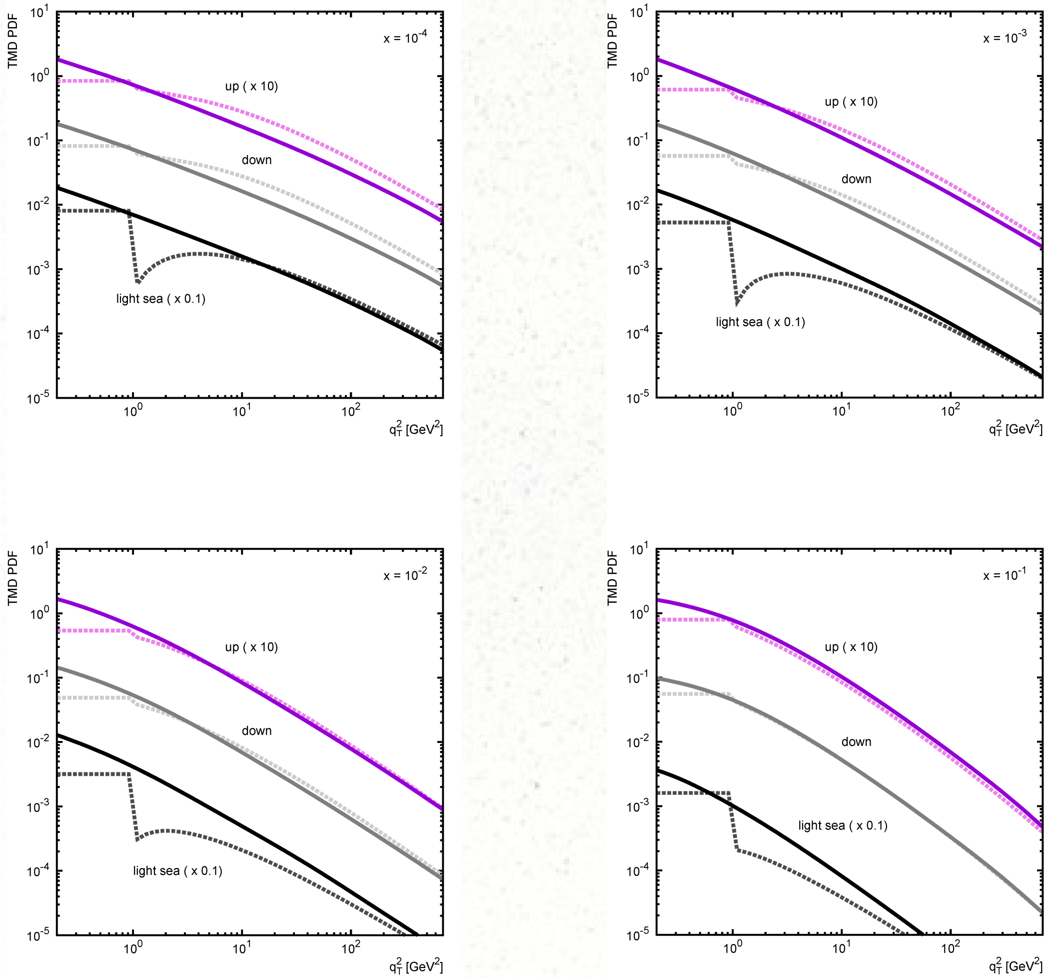
where TMD gluon-to-quark splitting function is given by

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

with **Δ = q — z****k**, and **k** and **q** are the the gluon and quark transverse momenta

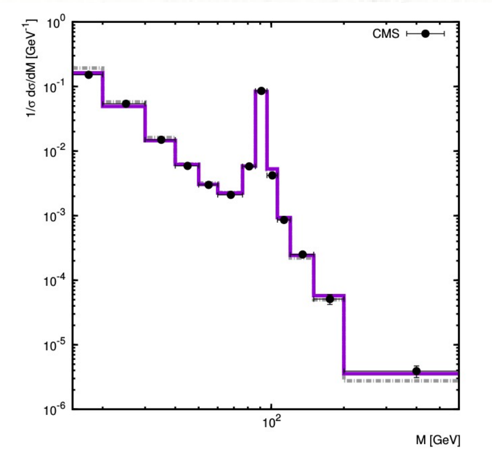
S. Catani, F. Hautmann, NPB 427, 475 (1994)
F. Hautmann, H. Jung, M. Hentschinski, NPB 865, 54 (2012)

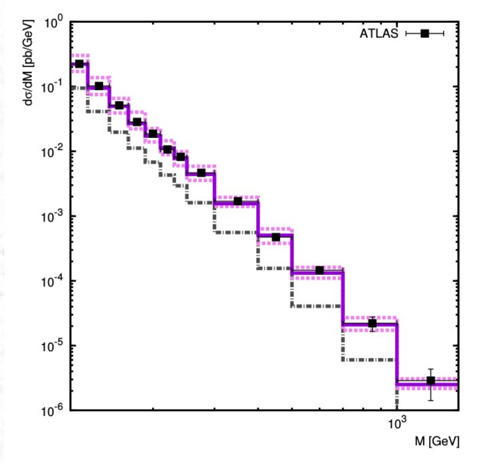
TMD parton densities in a proton

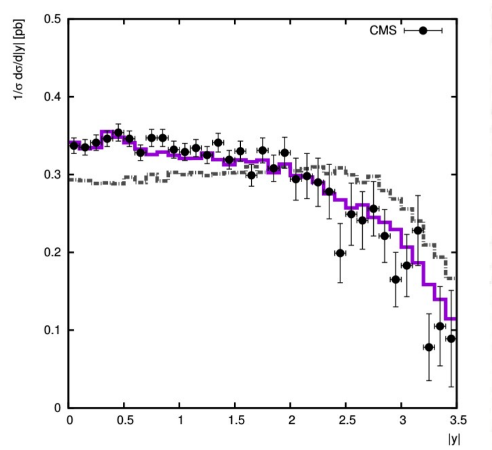


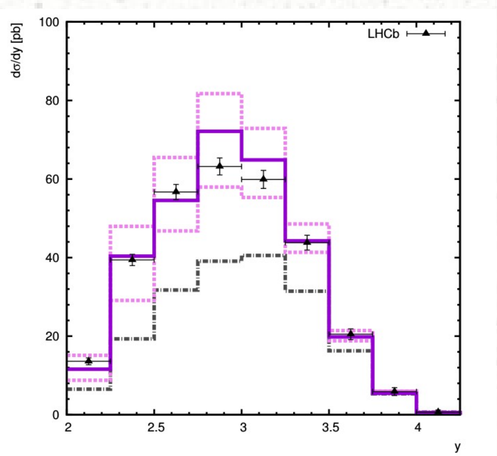
Solid lines: CCFM A0
Dashed lines: KMR

Inclusive Drell-Yan lepton pair production









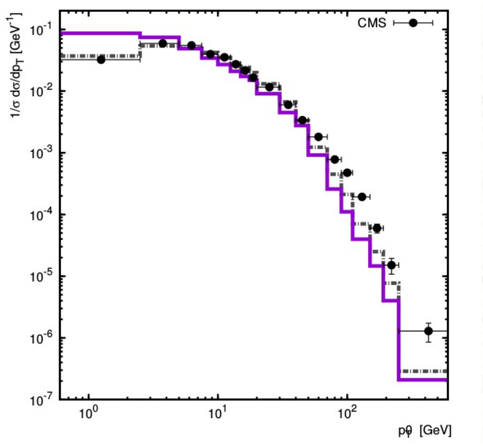
- Distribution on the dilepton invariant mass is sensitive to the normalization of the TMD quark density
- Rapidity distribution is sensitive to the both normalization and shape of the TMD quark density
- The CCFM-based predictions agree well with the LHC data in a forward region

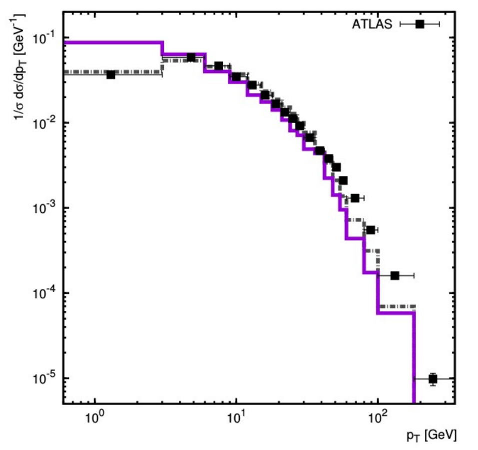
CCFM

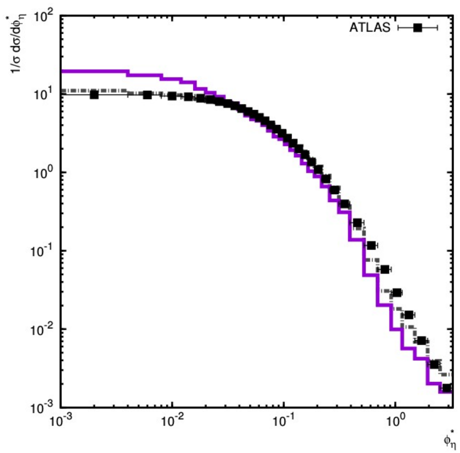
CCFM unc.

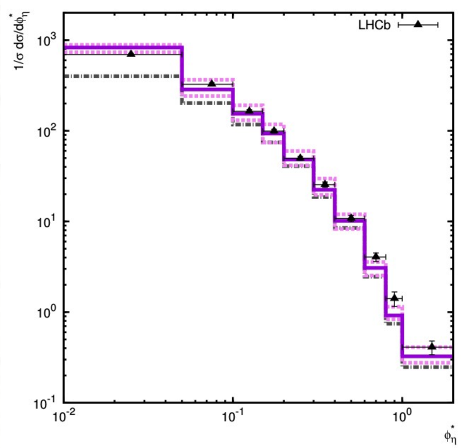
KMR

Inclusive Drell-Yan lepton pair production









- Distributions on the dilepton transverse momentum and variable ϕ_η are sensitive to the shape of the TMD quark density

$$\phi^*_\eta = \tan\left(\frac{\phi_{\rm acop}}{2}\right)\left[\cosh\left(\frac{\Delta\eta}{2}\right)\right]^{-1}$$

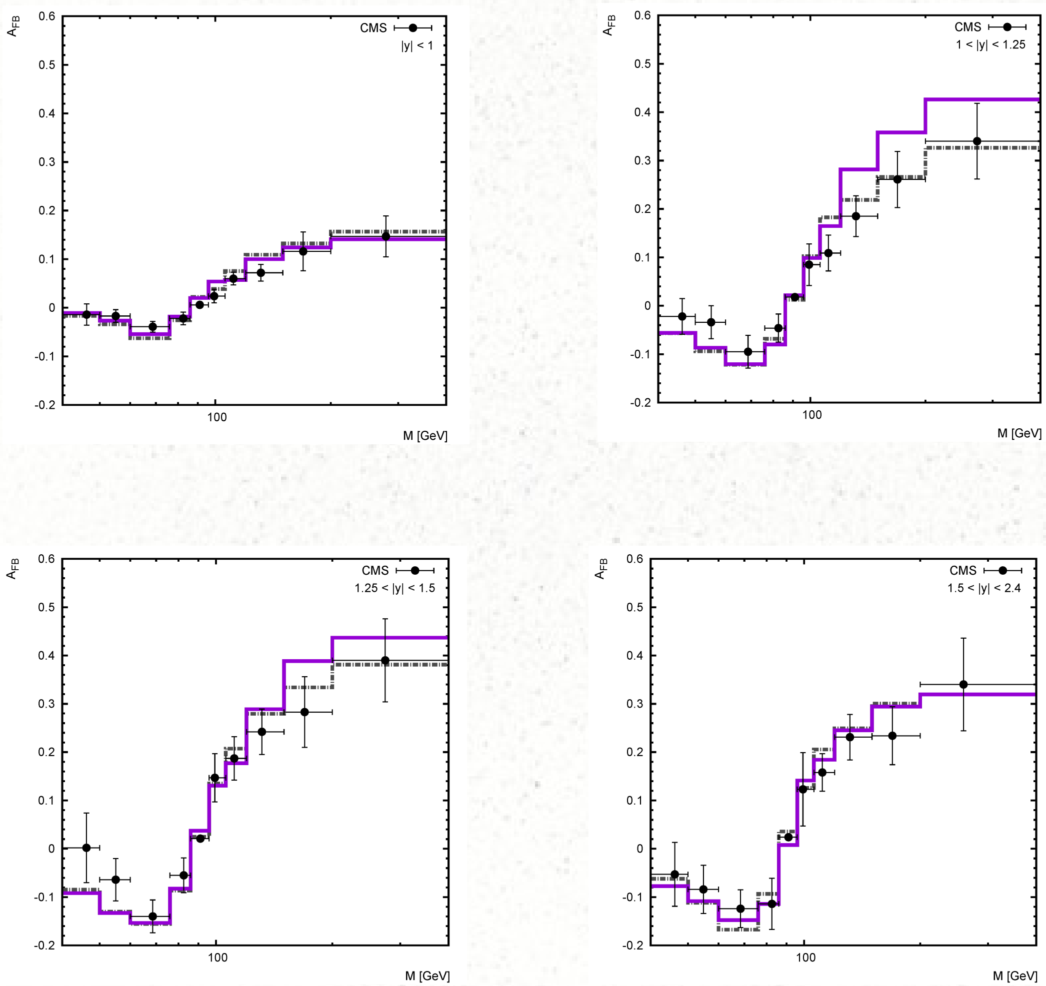
- The CCFM-based predictions agree well with the LHC data in a forward region

CCFM

CCFM unc.

KMR

Forward-backward assymetry



$$\frac{d\sigma}{d\cos\theta^*} \sim \frac{3}{8}(1+\cos^2\theta^*) + A_{\rm FB}\cos\theta^*$$

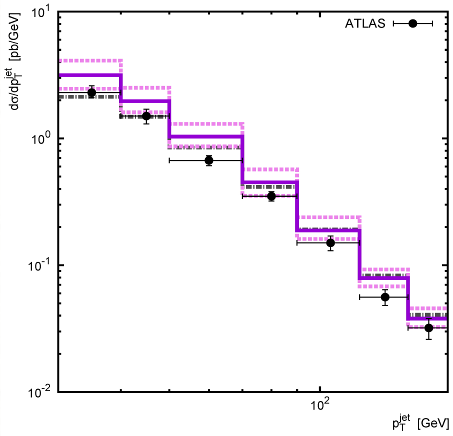
$$A_{\rm FB} = \frac{\sigma_{\rm F} - \sigma_{\rm B}}{\sigma_{\rm F} + \sigma_{\rm B}}$$

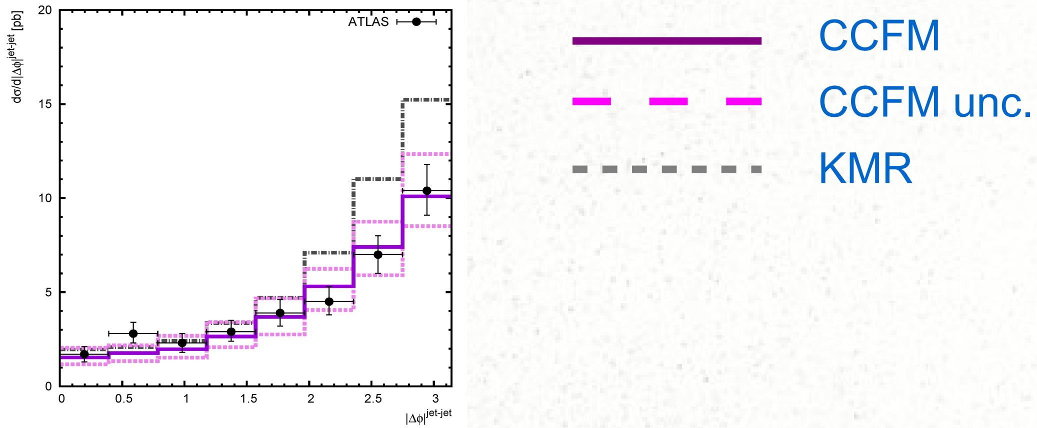
At the dilepton invariant masses near the Z boson peak, the asymmetry is small due to the small value of the lepton vector coupling. Above and below the Z boson peak, the asymmetry shows a characteristic energy dependence governed by γ*— Z interference.

CCFM

KMR

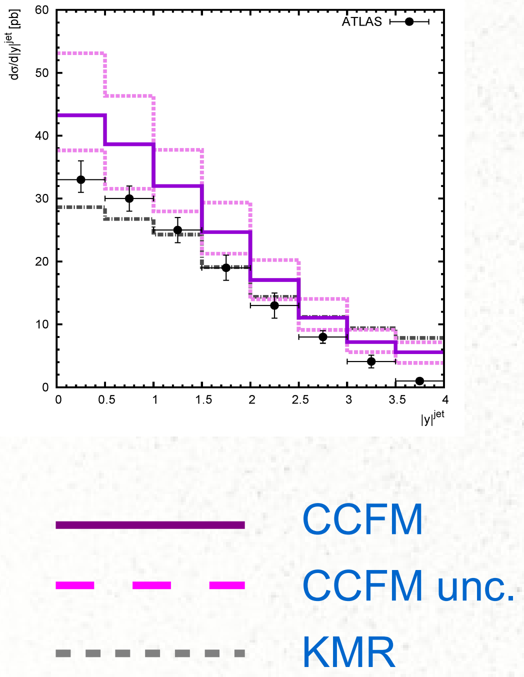
Associated Drell-Yan pair and jet(s) production





- We take into account QCD Compton subprocess qg* → Z/γ*q → ll q
- φ is the azimuthal angle between the two leading jets
- Distribution on the φ is sensitive to the normalization and shape of the TMD parton densities
- CCFM agree well with the ATLAS data

Associated Drell-Yan pair and jet(s) production



- In the kt-factorization approach, the produced lepton pair is accompanied by a number of partons radiated due to the non-collinear parton evolution.
- In our calculations, the rapidities of such partons are generated according to the phase space.
- From several jets we choose the one carrying the largest transverse energy.
- The observed disagreement in the rapidity distributions is due to our approximation for the rapidity of jets coming from the evolution ladder.
- The full hadron-level Monte-Carlo event generator (CASCADE) is needed to investigate these observables

Conclusions

- The TMD quark densities in a proton have been calculated and effects of the kt-dependent gluon-to-quark splitting function are taken into account.
- We have been obtained the full set of TMD parton densities in the framework of CCFM evolution. These TMD PDFs can be used in a phenomenological applications.
- The cross sections of inclusive and jet associated Drell-Yan lepton pair production at the LHC have been calculated. We have been demonstrated the level of sensitivity of predicted cross sections to the normalization and shape of the TMD parton densities in a proton.
- The obtained off-shell matrix elements squared will be implemented to the MC event generator CASCADE, which includes number high-energy processes and which is used by the CMS collaboration in the data analysis.