Drell-Yan process at forward rapidity at the LHC

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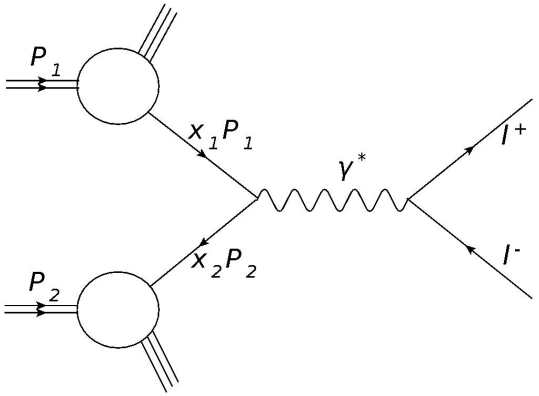
Introduction

- The Large Hadron Collider (LHC) opens a new kinematic regime at high energies.
- In this regime QCD evolution leads to fast growth of the gluon density.
- At high density novel phenomena related to saturation of gluon densities due to nonllinear QCD evolution will occur.

Drell-Yan cross section in the collinear approach

Sidney D. Drell, Tung-Mow Yan

- Drell-Yan production is a unique process which offers high sensitivity to the parton distribution in hadrons.



- In the lowest approximation, the Drell-Yan lepton pair of invariant mass $M > 1GeV$ is produced by annihilation of two quarks from the colliding hadrons:

$$q_f \bar{q}_f \rightarrow \gamma^* \rightarrow l^+ l^-$$

The LO Drell-Yan cross section

- The leading order (LO) Drell-Yan cross section is given by the quark/antiquark distributions in the colliding hadrons taken at the scale of M^2:

$$\begin{aligned}\frac{d^2\sigma^{LO}}{dM^2 dx_F} &= \frac{4\pi\alpha_{em}^2}{3N_c M^4}\frac{x_1 x_2}{x_1+x_2}\sum_f e_f^2 \\ &\times \left\{q_f(x_1,M^2)\,\bar{q}_f(x_2,M^2)+\bar{q}_f(x_1,M^2)\,q_f(x_2,M^2)\right\}\end{aligned}$$

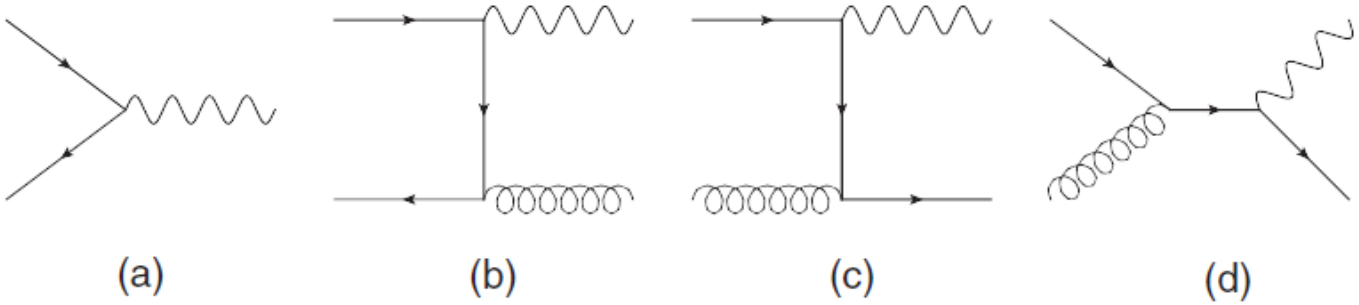
- The quark momentum fractions x_1 and x_2 are determined by the lepton pair kinematics:

$$x_1 = \frac{1}{2}\left(\sqrt{x_F^2+4\frac{M^2}{s}}+x_F\right) \qquad x_2 = \frac{1}{2}\left(\sqrt{x_F^2+4\frac{M^2}{s}}-x_F\right)$$

where $x_F = x_1 - x_2$ is the Feynman variable of the lepton pair.

The NLO Drell-Yan cross section

- In the NLO approximation, additional emission of a parton into the final state has to be taken into account.



Because of the emission, one of the quarks entering the photon vertex carries a fraction $z < 1$ of the incoming parton momentum.

- Thus, the incoming parton momentum fractions take now the form:

$$x_1 = \frac{1}{2}\left(\sqrt{x_F^2 + 4\frac{M^2}{zs}} + x_F\right) \qquad x_2 = \frac{1}{2}\left(\sqrt{x_F^2 + 4\frac{M^2}{zs}} - x_F\right)$$

- The diagrams c) and d) are enhanced in the small-x limit due to a strongly rising gluon distribution.

The NLO Drell-Yan cross section

- The NLO DY cross section is proportional to the strong coupling constant α_s:

$$\begin{aligned}\frac{d^2\sigma^{NLO}}{dM^2 dx_F} &= \frac{4\pi\alpha_{em}^2}{3N_c M^4}\frac{\alpha_s(M^2)}{2\pi}\int_{z_{min}}^{1} dz \frac{x_1 x_2}{x_1+x_2} \\ &\times \sum_f e_f^2 \Big\{ q_f(x_1, M^2)\, \bar{q}_f(x_2, M^2) D_q(z) + g(x_1, M^2) \\ &\times [q_f(x_1, M^2) + \bar{q}_f(x_2, M^2)] D_g(z) + (x_1 \leftrightarrow x_2) \Big\}\end{aligned}$$

  where the coefficient functions $D_{q,g}$ are calculated perturbatively.

- The DY cross section in the collinear approximation is the sum:

$$\frac{d^2\sigma col}{dM^2 dx_F} = \frac{d^2\sigma^{LO}}{dM^2 dx_F} + \frac{d^2\sigma^{NLO}}{dM^2 dx_F}$$

DY process in the small-x limit

- In the small-x limit the dilepton mass is much smaller than the center-of-mass energy of the colliding hadrons

$$M \ll \sqrt{s}$$

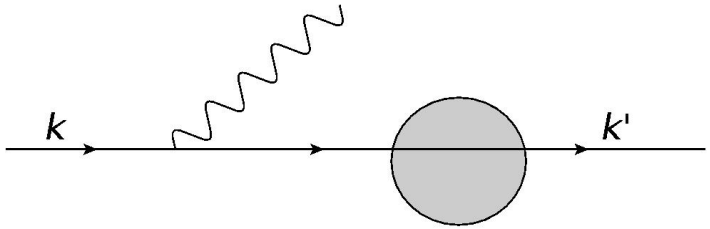
- In such a case, momentum fraction of the one of the incoming partons is very small:

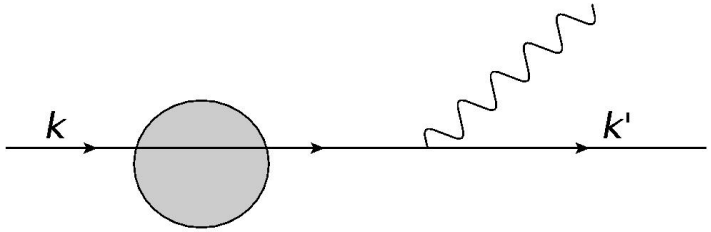
$$x_1 \sim 1 \qquad\qquad x_2 = \frac{M^2}{s\, x_1} \ll 1$$

- Particularly important is the small-x gluon since in this case the incoming quark probes potentially dense gluon fields in the target.

Target rest frame point of view

- In the rest frame of the proton target, the fast incoming quark interacts with the target gluon field, emitting the virtual photon





- The photon then decays producing a lepton pair which moves into the region of forward rapidity.

DY cross section for the forward dilepton production

- The cross section for radiation of a photon with the momentum fraction z of the fast quark is given by:

$$\sigma(qp \to \gamma^* X) = \int d^2r \; W(z, r, M^2) \; \sigma_{qq}(x_2, zr)$$

where r is the photon-quark transverse separation and W is photon wave function squared, computed perturbatively.

- The dipole cross section σ_{qq} describes the unknown interaction of the incoming quark with strong gluon fields of the target hadron.

- The final form of the DY cross section:

$$\frac{d^2\sigma^{DY}}{dM^2\, dx_F} = \frac{\alpha_{em}}{6\pi M^2} \frac{1}{x_1 + x_2} \int_{x_1}^{1} \frac{dz}{z} F_2\left(\frac{x_1}{z}, M^2\right) \sigma(qp \to \gamma^* X)$$

where F_2 is the proton structure function.

Dipole cross section models

Three models of the dipole cross section σ_{qq} with gluon saturation effects:

- GBW *(Golec-Biernat-Wüsthoff)*

$$\sigma_{qq}(x,r) = \sigma_0 \Big\{ 1 - \exp\big(- r^2 Q_s^2(x)/4 \big) \Big\}$$

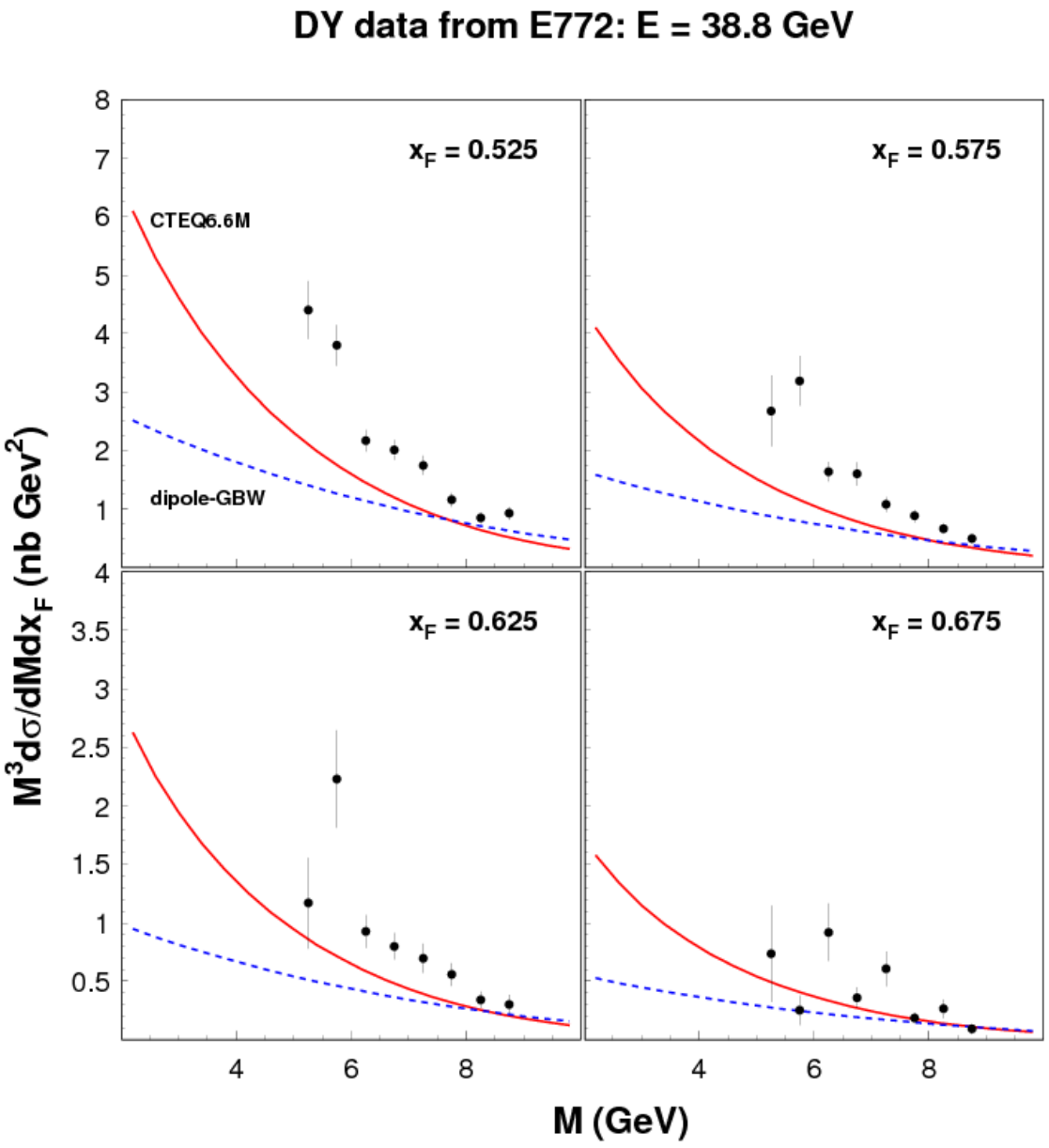
- BGKS *(Bartels-Golec-Kowalski-Sapeta)*

$$\sigma_{qq}(x,r) = \sigma_0 \Big\{ 1 - \exp\big(- \pi^2 r^2 \alpha_s(\mu^2) x g(x,\mu^2)/3\sigma_0 \big) \Big\}$$

- CGC *(Color Glass Condensate)* *E. Iancu, K. Itakura and S. Munier*

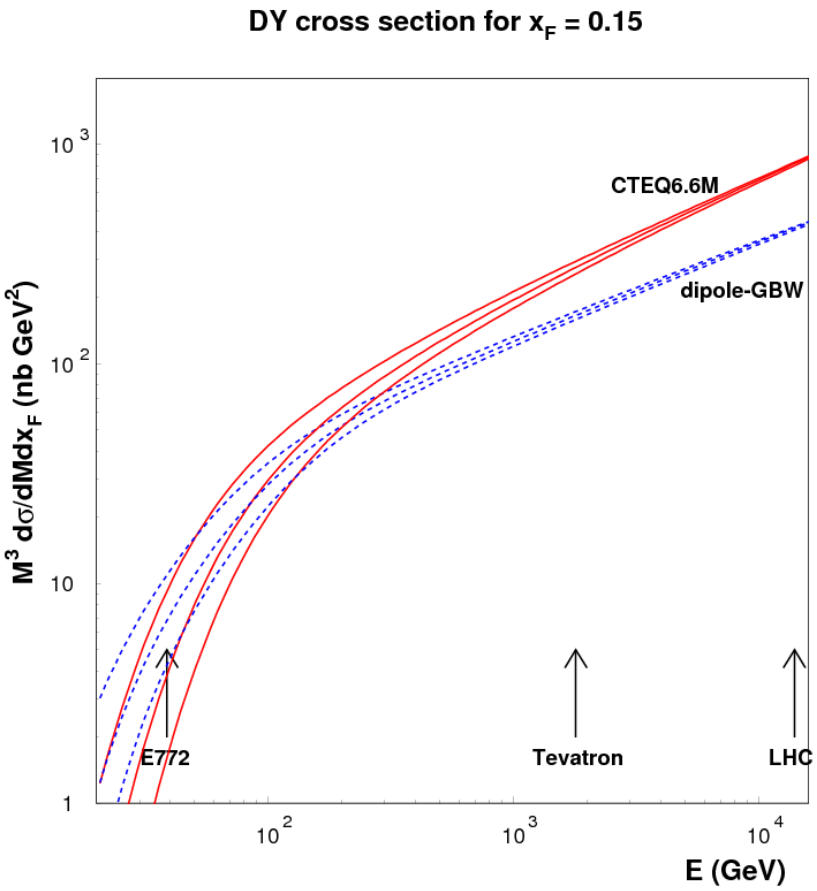
$$\sigma_{qq}(x,r) = \sigma_0 \times \begin{cases} N_0 \left(\frac{rQ_s}{2}\right)^{2\left(\gamma_s + \frac{1}{\kappa\lambda Y} \ln \frac{2}{rQ_s}\right)} & : \quad rQ_s \leq 2 \\ 1 - e^{-A \ln^2(BrQ_s)} & : \quad rQ_s > 2 \end{cases}$$

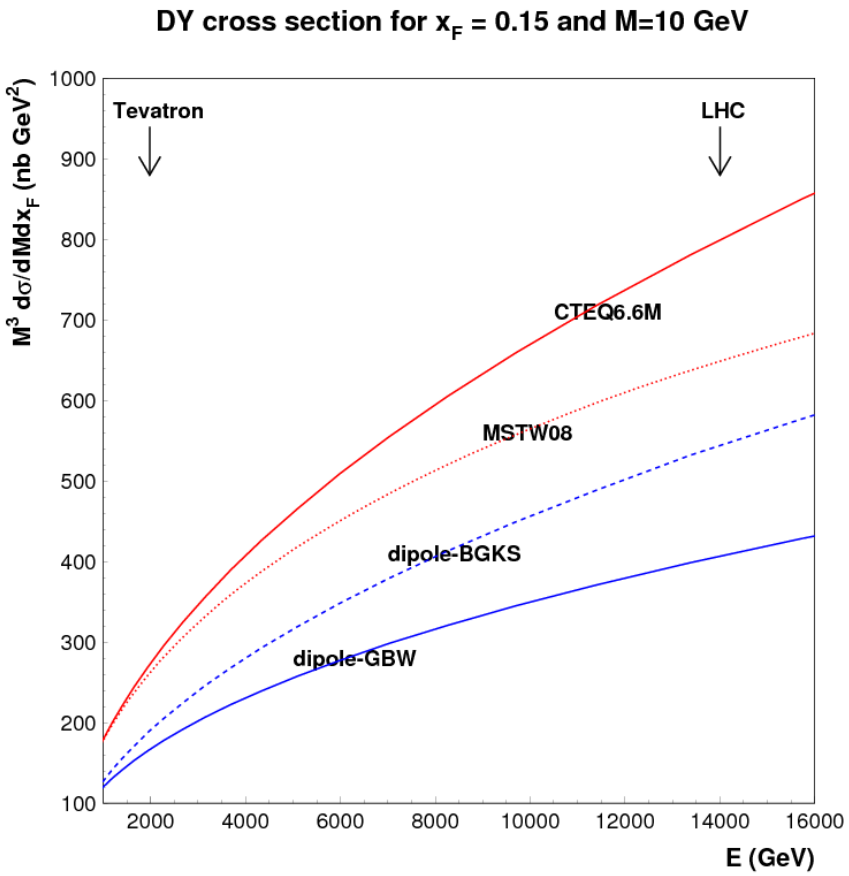
Comparison with the existing data



The E772 data are above the results from both approaches but this is not small-x data.

Predictions for the LHC





At the LHC energy, saturation effects give results which are significantly below the collinear factorization predictions.

Summary

- The analysis of the Drell-Yan process at the forward rapidity at the LHC using the dipole cross section framework with gluon saturation proves a significant suppression of the production cross section in comparison to the collinear factorization formula.
- We are looking forward to the experimental verification of this result.