Sudakov effects in TMD gluon distributions and their implications on jet production

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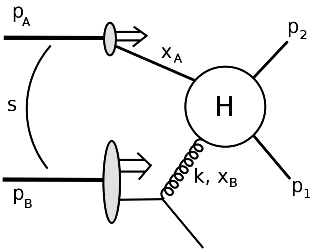
XXVIII International Workshop on Deep-Inelastic Scattering and Related Subjects
Virtual Event @ Stony Brook University, April 12-16, 2021

Forward jet production in hadronic collisions



Low x_B leads to appearance of large logarithms $\ln x_B$, which need to be resummed.

Incoming partons' energy fractions:

$$x_A = \frac{1}{\sqrt{s}} \left(|\vec{p}_{1t}|e^{y_1} + |\vec{p}_{2t}|e^{y_2}\right) , \qquad x_B = \frac{1}{\sqrt{s}} \left(|\vec{p}_{1t}|e^{-y_1} + |\vec{p}_{2t}|e^{-y_2}\right)$$

$$y_1 \sim 0,\ y_2 \gg 0 \quad \longrightarrow \quad x_A \sim 1,\ x_B \lesssim 1 \quad \text{(central-forward)}$$

$$y_1 \gg 0,\ y_2 \gg 0 \quad \longrightarrow \quad x_A \sim 1,\ x_B \ll 1 \quad \text{(forward-forward)}$$

Gluon's transverse momentum (p_{1t}, p_{2t} imbalance):

$$|\vec{k}_t|^2 = |\vec{p}_{1t} + \vec{p}_{2t}|^2 = |\vec{p}_{1t}|^2 + |\vec{p}_{2t}|^2 + 2|\vec{p}_{1t}||\vec{p}_{2t}| \cos \Delta\phi$$

Transverse momentum dependent factorization

High Energy Factorization *[Catani, Ciafaloni, Hautmann '91]* $p_t \sim k_t \gg Q_s$

$$\frac{d\sigma^{AB\to \text{dijets}+X}}{dy_1 dy_2 d^2p_{1t} d^2p_{2t}} \propto \sum_{a,c,d} x_A f_{a/A}(x_A,\mu^2)\, |\overline{\mathcal{M}_{ag^*\to cd}}|^2 \mathcal{F}_{g/B}(x_B,k_t)$$

$x_A f_{a/A}(x_A,\mu^2)$ – collinear PDF in A, suitable for $x_A \sim 1$

$|\overline{\mathcal{M}_{ag^*\to cd}}|^2$ – matrix element with off-shell incoming gluon

$\mathcal{F}_{g/B}(x_B,k_t)$ – unintegrated gluon PDF in B, suitable for $x_B \ll 1$

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Improved TMD Factorization $p_t \gg Q_s$, any k_t

[Kotko, Kutak, Marquet, Petreska, SS, van Hameren '15]

$$\frac{d\sigma^{AB\to \mathrm{dijets}+X}}{d^2P_t d^2k_t dy_1 dy_2} \propto \sum_{a,c,d} x_A f_{a/A}(x_A,\mu^2) \sum_i H^{(i)}_{ag^*\to cd} \mathcal{F}^{(i)}_{ag\to cd}(x_B,k_t)\, \frac{1}{1+\delta_{cd}}$$

$H^{(i)}_{ag\to cd}$ – hard factor of i-th type with on-shell incoming gluon

$\mathcal{F}^{(i)}_{ag\to cd}(x_B,k_t)$ – unintegrated gluon distribution of i-th type in B

$\to$ Later obtained from CGC [Altinoluk, Boussarie, Kotko '19]

Sudakov resummation

In forward jet production, besides the logarithms $\ln x$, which are resummed in TMDs, there is another class of large logarithms, namely

$$\ln \mu \qquad \text{where} \qquad \mu \sim p_{t,\text{jet}} \, .$$

Appearance of those logarithms opens phase space for soft and collinear emissions, which should also be resummed.

This resummation can be accounted for by inclusion of the Sudakov factor.

Earlier modeling of Sudakov effects

- Model 1: The survival probability model [van Hameren, Kotko, Kutak, SS '14], where the Sudakov factor of the form [Watt, Martin, Ryskin '03]

$$T_s(\mu^2, k_t^2) = \exp\left(-\int_{k_t^2}^{\mu^2} \frac{dk_t'^2}{k_t'^2}\frac{\alpha_s(k_t'^2)}{2\pi}\sum_{a'}\int_0^{1-\Delta} dz' P_{a'a}(z')\right),$$

where $\Delta = k_t/(k_t+\mu)$, is imposed at the level of the cross section

$$\sigma \sim \sum_{i\in\text{events}} \sigma_i T_s(\mu_i^2, k_{ti}^2)\Theta(\mu_i - k_{ti}) + \mathcal{W}\sum_{i\in\text{events}} \sigma_i\,\Theta(k_{ti}-\mu_i),$$

and $\mathcal{W}$ is constructed such that the total cross section is preserved.

This procedure corresponds to performing DGLAP-type evolution from the scale k_t to μ, decoupled from the small-x evolution.

Earlier modeling of Sudakov effects

- Model 2: The model with a hard scale [Kutak '14]. The Sudakov factor of the same form as above is imposed on top of the gluon distribution in such a way that, after integration of the resulting hard scale dependent gluon TMD, one obtains the same result as by integrating the original gluon distribution

$$\mathcal{F}(x,k_t^2,\mu^2) = \theta(\mu^2 - k_t^2)\,T_s(\mu^2,k_t^2)\,\frac{xg(x,\mu^2)}{xg_{hs}(x,\mu^2)}\mathcal{F}(x,k_t^2) + \theta(k_t^2-\mu^2)\mathcal{F}(x,k_t^2)\,,$$

where

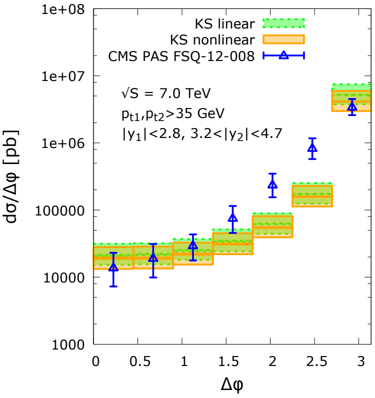
$$xg_{hs}(x,\mu^2) = \int^{\mu^2} dk_t^2\, T_s(\mu^2,k_t^2)\mathcal{F}(x,k_t^2)\,,$$

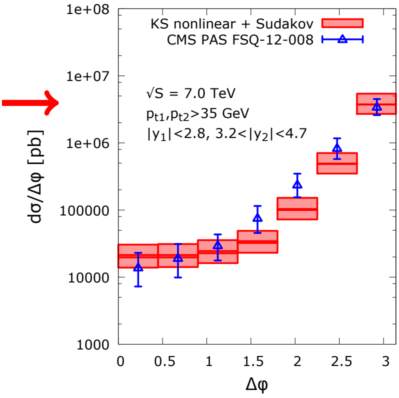
$$xg(x,\mu^2) = \int^{\mu^2} dk_t^2 \mathcal{F}(x,k_t^2)\,.$$

Earlier modeling of Sudakov effects

Those simplistic models significantly improved description of data for azimuthal decorrelations in central-forward dijet production

[van Hameren, Kotko, Kutak, SS '14]





Proper QCD Sudakov

Sudakov effects are most conveniently included in position space [Stasto, Wei, Xiao, Yuan '18]

$$\mathcal{F}_{g^*/B}^{ag\to cd}(x, q_\perp, \mu) = \frac{-N_c S_\perp}{2\pi\alpha_s} \int \frac{b_\perp db_\perp}{2\pi} J_0(q_\perp b_\perp)\, e^{-S_{\rm Sud}^{ag\to cd}(\mu, b_\perp)}\, \nabla^2_{b_\perp} S(x, b_\perp)\,,$$

where

$S_\perp$	–	transverse area of the target,
$S(x, b_\perp)$	–	dipole scattering amplitude.

We can however express the gluon with Sudakov by the gluon without Sudakov, all in momentum space

$$\mathcal{F}_{g^*/B}^{ab\to cd}(x, k_\perp, \mu) = \int db_\perp \int dk'_\perp\, b_\perp\, k'_\perp\, J_0(b_\perp\, k'_\perp)\, J_0(b_\perp\, k_\perp) \times \mathcal{F}_{g^*/B}(x, k'_\perp)\, e^{-S_{\rm Sud}^{ab\to cd}(\mu, b_\perp)}$$

For each channel, the Sudakov receives perturbative and non-perturbative contributions

$$S_{\rm Sud}^{ab\to cd}(b_\perp) = \sum_{i=a,b,c,d} S_p^i(b_\perp) + \sum_{i=a,c,d} S_{np}^i(b_\perp)\,.$$

Proper QCD Sudakov

Perturbative part [Mueller, Xiao, Yuan '13; Stasto, Wei, Xiao, Yuan '18]

$$S_p^{qg\to qg}(Q,b_\perp)=\int_{\mu_b^2}^{Q^2}\frac{d\mu^2}{\mu^2}\left[2(C_F+C_A)\frac{\alpha_s}{2\pi}\ln\left(\frac{Q^2}{\mu^2}\right)-\left(\frac{3}{2}C_F+C_A\beta_0\right)\frac{\alpha_s}{\pi}\right],$$

$$S_p^{gg\to gg}(Q,b_\perp)=\int_{\mu_b^2}^{Q^2}\frac{d\mu^2}{\mu^2}\left[4C_A\frac{\alpha_s}{2\pi}\ln\left(\frac{Q^2}{\mu^2}\right)-3C_A\beta_0\frac{\alpha_s}{\pi}\right],$$

where $\mu_b=2e^{-\gamma_E}/b_*$, and $b_*=b_\perp/\sqrt{1+b_\perp^2/b_{\max}^2}$, $b_{\max}=0.5\,\mathrm{GeV}^{-1}$.

Non-perturbative part [Sun, Isaacson, Yuan, Yuan '14; Prokudin, Sun, Yuan '15]

$$S_{np}^{qg\to qg}(Q,b_\perp)=\left(2+\frac{C_A}{C_F}\right)\frac{g_1}{2}b_\perp^2+\left(2+\frac{C_A}{C_F}\right)\frac{g_2}{2}\ln\frac{Q}{Q_0}\ln\frac{b_\perp}{b_*},$$

$$S_{np}^{gg\to gg}(Q,b_\perp)=\frac{3C_A}{C_F}\frac{g_1}{2}b_\perp^2+\frac{3C_A}{C_F}\frac{g_2}{2}\ln\frac{Q}{Q_0}\ln\frac{b_\perp}{b_*},$$

with $g_1=0.212$, $g_2=0.84$ and $Q_0^2=2.4\mathrm{GeV}^2$.

KS gluon TMD

As a basis for all the following calculations we use the nonlinear KS gluon TMD [Kutak, Sapeta '12], which:

- for $k_\perp^2 > 1$, comes from evolution of the distribution

$$\mathcal{F}^{(0)}_{g^*/B}(x, k_\perp^2) = \frac{\alpha_S(k_\perp^2)}{2\pi k_\perp^2} \int_x^1 dz P_{gg}(z) \frac{x}{z} g\left(\frac{x}{z}\right) ,$$

with the initial condition

$$xg(x) = N(1-x)^\beta (1-Dx)\,,$$

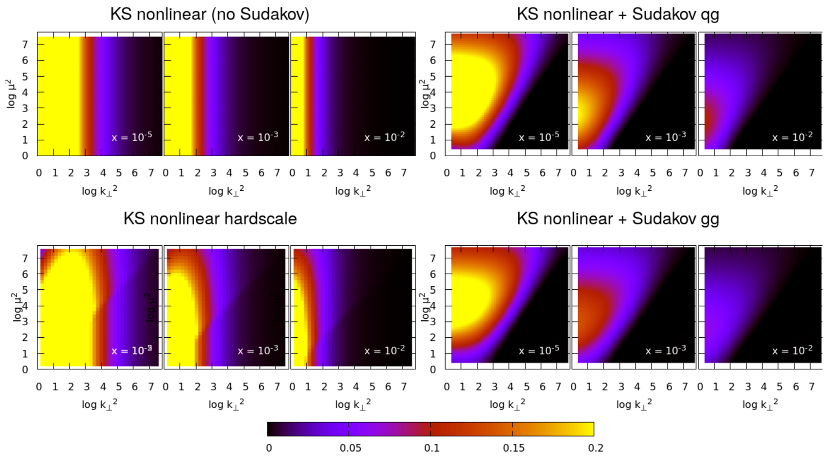
with the BK equation with kinematic constraint, non-singular DGLAP pieces and running coupling [Kwieciński, Martin, Stasto '97; Kutak, Kwieciński '03] – fitted to combined F_2 HERA data

- for $k_\perp^2 < 1$, is taken as

$$\mathcal{F}_{g^*/B}(x, k_\perp^2) = k_\perp^2 \mathcal{F}_{g^*/B}(x, 1),$$

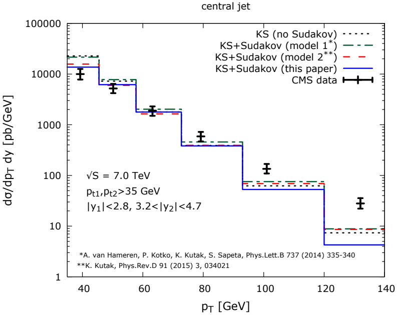
which is motivated by the shape obtained from the solution of the LO BK equation in the saturation regime [Sergey '08].

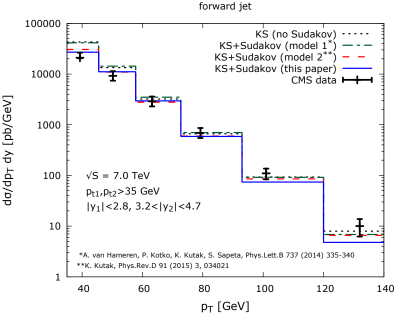
KS gluon distributions with and without Sudakov



- The new and the old gluon with Sudakov qualitatively similar
- The *qg* gluon broader than *gg* – comes from $C_A > C_F$

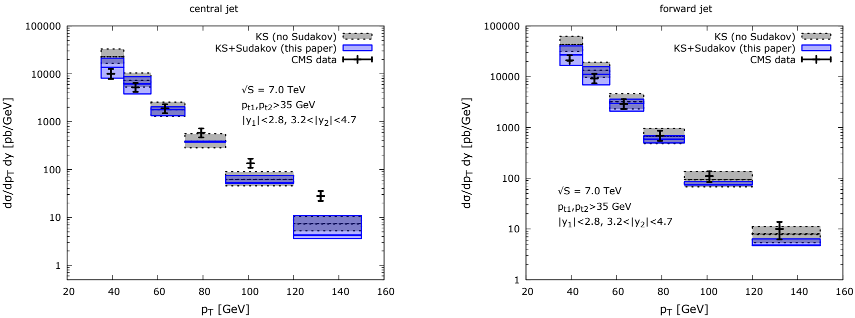
p_T spectra: predictions with and without Sudakov





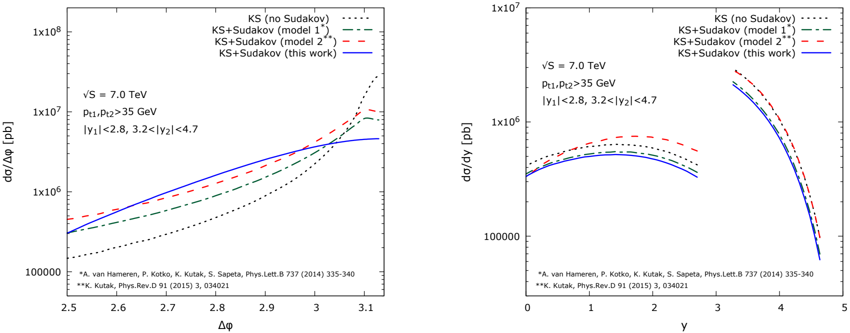
- Calculations performed with LxJet [Kotko] and KaTie [van Hameren]; $\mu_F = \mu_R = \frac{1}{2}(p_{t1} + p_{t2})$, CTEQ18 NLO collinear PDFs
- Predictions with Sudakov tend to describe data better at small p_T
- Overall picture: Sudakov effects not very strong for this observable

p_T spectra: no Sudakov vs proper QCD Sudakov



- Uncertainty estimated by the usual scale variation by factor $2^{\pm 1}$
- Good agreement with CMS data, except the tail, which is sensitive to large x, not included in our TMDs

Distributions in azimuthal distance and rapidity



- Qualitatively similar behaviour for predictions with the proper QCD Sudakov and earlier naive models: the region of small $\Delta\phi$ populated at the expense of large $\Delta\phi$ region
- In other words: suppression of the back-to-back peak and broadening of the cross section
- Convex decorrelations from earlier models vs concave from this work
- Marked differences between rapidity distributions from various versions of KS gluon

Summary

- We obtained TMD distributions which combine small-x resummation and Sudakov resummation, where the latter comes from proper QCD calculations
- We used the above TMDs to calculate p_T, $\Delta\phi$ and y distributions in central-forward dijet production
- Both the TMDs and the differential distributions are consistent with our earlier calculations based on simple modeling of Sudakov factors
- We achieved good description of CMS data for p_T distributions
- Sudakov resummation has a moderate effect on p_T spectra but sizable effect on the shapes of $\Delta\phi$