Dijet azimuthal correlations in p-p and p-Pb collisions at forward LHC calorimeters

Based on arXiv:2210.06613
M. Abdullah Al-Mashad, A. van Hameren, H. Kakkad, P. Kotko, K. Kutak, P. van Mechelen, S. Sapeta
**ITMD**

**ITMD** = small x Improved Transverse Momentum Dependent factorization

- accounts for saturation
- correct gauge structure i.e. uses gauge links to define TMD's
- takes into account kinematical effects – the whole phase space is available at LO
- is implemented in MC event generator KaTie, LxJet
- valid in region $p_T > Q_s$, $k_T$ can be any. $p_T$ is hard final state momentum, $k_T$ is inbalance

\[
\frac{d\sigma^{pA \rightarrow \text{dijets}+X}}{d^2 P_t d^2 k_t dy_1 dy_2} = \frac{\alpha_s^2}{(x_1 x_2 s)^2} \sum_{a,c,d} x_1 f_{a/p}(x_1) \frac{1}{1 + \delta_{cd}} \sum_{i=1}^{2} K_{ag^{*} \rightarrow cd}(P_t, k_t) \Phi_{ag^{*} \rightarrow cd}^{(i)}(x_2, k_t)
\]

(one of representations of the ITMD formula)

**Generic structure:** transverse momentum enters hard factors and gluon distributions

**Gluton distribution depends on color flow**

P. Kotko, K. Kutak, C. Marquet, E. Petreska, S. Sapeta, A. van Hameren, JHEP 1509 (2015) 106

P. Kotko, K. Kutak, C. Marquet, E. Petreska, S. Sapeta, A. van Hameren JHEP 12 (2016) 034
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See also:

T. Altinoluk, C. Marquet, P. Taels, JHEP 06 (2021) 085

For developments for massive final states
p – A (dilute-dense) forward-forward di-jets

It originated from the aim to provide predictions for forward-forward jet production at the LHC

From: Piotr Kotko
LxJet
Formula for TMD gluons and gauge links

\[ \mathcal{F}(x, k_T) = 2 \int \frac{d\xi^- d^2 \xi_T}{(2\pi)^3} e^{ixP^+ \xi^- - i\vec{k}_T \cdot \vec{\xi}_T} \left\langle P \right| \text{Tr} \left\{ \hat{F}^{i+}(0) \hat{F}^{i+}(\xi^+ = 0, \xi^- \tilde{\xi}_T) \right\} \left| P \right\rangle \]

Valid for large transversal momentum and was obtained in a specific gauge.

Similar diagrams with 2, 3, ..., gluon exchanges. All this need to be resummed.

From S. Sapeta

\[ \mathcal{F}(x, k_T) = 2 \int \frac{d\xi^- d^2 \xi_T}{(2\pi)^3} e^{ixP^+ \xi^- - i\vec{k}_T \cdot \vec{\xi}_T} \left\langle P \right| \text{Tr} \left\{ \hat{F}^{i+}(0) \mathcal{U}_{C_1} \hat{F}^{i+}(\xi) \mathcal{U}_{C_2} \right\} \left| P \right\rangle \]

Hard part defines the path of the gauge link

\[ \mathcal{U}^{[C]}(\eta; \xi) = \mathcal{P} \exp \left[ -ig \int_C dz \cdot A(z) \right] \]

C.J. Bomhof, P.J. Mulders, F. Pijlman
Eur.Phys.J. C47 (2006) 147-162
The saturation problem: suppressing gluons below $Q_s$

Originally formulated in coordinate space
Balitsky '96, Kovchegov '99

Fit AAMQS '10

NLO accuracy
Balitsky, Chirilli '07

and solved
Lappi, Mantysaari '15

Kinematic corrections
Iancu et al

Solved $b$ dependent
Stasto, Golec-Biernat '02

with kinematic corrections and $b$
Cepila, Contreras, Matas '18

The momentum space BK equation for dipole gluon density

\[ \mathcal{F} = \mathcal{F}_0 + K \otimes \mathcal{F} - \frac{1}{R^2} V \otimes \mathcal{F}^2 \]

hadron's radius

solution of Balitsky-Kovchegov directly for dipole gluon density

Kwiecinski, Kutak '02
Nikolaev, Schafer '06

Fit to $F_2$ data
KK. Sapeta '12

Accounts for kinematical constraint,
Nonsingular parts of splitting function, running coupling
The ITMD factorization for di-jets

The color structure is separated from kinematic part of the amplitude by means of the color decomposition.

The TMD gluon distributions are derived for the color structures following

P. Kotko, K. Kutak, C. Marquet, E. Petreska, S. Sapeta, A. van Hameren, JHEP 1509 (2015) 106

A. van Hameren, P. Kotko, K. Kutak, C. Marquet, E. Petreska, JHEP 12 (2016) 034

Formalism implemented in Monte Carlo programs KaTie by A. van Hameren

gauge invariant amplitudes with \( k_t \) and TMDs

Example for \( g^* g \to g g \)

\[
\frac{d\sigma_{pA \to ggX}}{d^2 P_t d^2 k_t dy_1 dy_2} = \frac{\alpha_s^2}{(x_1 x_2 s)^2} x_1 f_{g/p}(x_1, \mu^2) \sum_{i=1}^{6} F_{gg}^{(i)} H_{gg \to gg}^{(i)}
\]
Improved Transverse Momentum Dependent Factorization

The same gauge link and as in TMD’s
Fabio Dominguez, Bo-Wen Xiao, Feng Yuan
Phys.Rev.Lett. 106 (2011) 022301

F. Dominguez, C. Marquet, Bo-Wen Xiao, F. Yuan
Phys.Rev. D83 (2011) 105005

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F. Dominguez, C. Marquet, Bo-Wen Xiao, F. Yuan
Phys.Rev. D83 (2011) 105005

P. Kotko, K. Kutak, C. Marquet, E. Petreska, S. Sapeta, A. van Hameren, JHEP 1509 (2015) 106
Plots of ITMD gluons

All gluons can be calculated from the dipole one. KS gluon used.

Kotko, K.K, Marquet, Petreska, Sapeta, van Hameren JHEP 1612 (2016) 034

Standard HEF gluon density

The other densities are flat at low $k_t \rightarrow$ less saturation

Not negligible differences at large $k_t \rightarrow$ differences at small angles
Expansion in distance - parameter entering as argument Wilson lines appearing in generic CGC amplitude i.e. amplitude for propagation in strong color field of target

Wandzura-Wilczek approximation ITMD neglects higher genuine twist contributions i.e. hard gluon exchanges between the target and the amplitude, while it resums all kinematic twist
In collinear physics at LO for $2 \rightarrow 2$ we get delta function since the colliding partons do not carry transverse momentum. Adding more jet we get some improvement $2 \rightarrow 3$, $2 \rightarrow 4$. The unobserved partons can be soft and can introduce large logs. Note: $k_t$ factorization also smears the delta function but takes into account also low $x$ effects.

\[ p_t \gg k_t \]

\[ L \sim \ln^2 \frac{p_t^2}{k_t^2} \]

Leading jet and associated jet – in forward jet scenario this can be linked to $k_t$ of incoming parton.
Depending on the choice of scale the collinear pdf can be put in front of the integral or kept under the integral. We consider both options. For the unfactorized case we use

\[
\frac{d\sigma^{pA\rightarrow j_1j_2+X}}{d^2P_T d^2k_T dy_1 dy_2} = \sum_{a,c,d} x_p f_{a/p} (x_p, \mu) \sum_{i=1}^{2} \mathcal{K}^{(i)}_{a\rightarrow cd} (P_T, k_T; \mu) \Phi^{(i)}_{a\rightarrow cd} (x_A, k_T)
\]

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\]

\[
\times \int db_T b_T J_0 (b_T k_T) f_{a/p} (x_p, \mu_b) \tilde{\Phi}^{(i)}_{a\rightarrow cd} (x_A, b_T) e^{-S_{a\rightarrow cd} (\mu, b)}
\]

\[\mu_b = 2 e^{-\gamma_E} / b_* \quad b_* = b_T / \sqrt{1 + b_T^2 / b_{\text{max}}^2}\]
Azimuthal angle dependence – parton level

Visible differences especially for ALICE FoCal between p-p and p-Pb results.
Lower pt cut and more forward rapidities.
Not large differences between to approaches to account for Sudakov form factor.

For earlier results see
A. Hameren, P. Kotko, K. Kutak, S. Sapeta
Phys.Lett. B795 (2019) 511-515
Azimuthal angle dependence – adding correction factor

![Graphs showing azimuthal angle dependence with correction factors applied for different pT intervals and y ranges.](image-url)
Nuclear modification ratio

Visible suppression in both ATLAS and ALICE kinematical setup. Correction factor effectively cancels. Strong saturation signal.

\[ R_{p-Pb} = \frac{\frac{d\sigma^{p+Pb}}{d\mathcal{O}}}{\frac{A}{d\mathcal{O}} \frac{d\sigma^{p+p}}{d\mathcal{O}}} \]
BACKUP
The ITMD factorization for jets

Formalism implemented in Monte Carlo programs KaTie by A. van Hameren and LxJet by P. Kotko

\[ \frac{d\sigma^{pA \rightarrow ggX}}{d^2P_t d^2k_t dy_1 dy_2} = \frac{\alpha_s^2}{(x_1 x_2 s)^2} x_1 f_{g/p}(x_1, \mu^2) \sum_{i=1}^{6} F_{gg}^{(i)} H_{gg \rightarrow gg}^{(i)} \]

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