Estimating saturation effects for dijet production in UPC

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based on:

P.K., K. Kutak, S. Sapeta,
A. Stasto, M. Strikman, arXiv:1702.03063

A. van Hameren, P.K., K. Kutak,
C. Marquet, E. Petreska, S. Sapeta,
JHEP 1612 (2016) 034, JHEP 1509 (2015) 106

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Motivation

Why dijets in UPC?

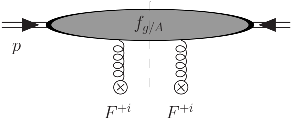
- $\gamma A \to 2\,\mathrm{jets}$ is sensitive to the Weizsacker-Williams (WW) unintegrated gluon distribution (UGD), whereas other processes like J/ψ or inclusive jets are sensitive to the dipole UGD
- $pA \to 2\,\mathrm{jets}$ is sensitive to both UGDs (directly to the dipole UGD and indirectly to WW)
- Dipole UGD for proton is relatively well constrained from HERA; this not the case for the WW UGD
- Goal: calculate nuclear modification ratios and see how much saturation one gets for dijets in UPC for the current LHC setup

Plan

1. Introduction
   - nonuniversality of TMD gluon distributions
   - two basic TMDs
   - TMD 'factorization' and relation to Color Glass Condensate (CGC) (for $pA \to 2\,\mathrm{jets}$ to see the complications)
2. Saturation approach for hard dijets in pA and γA
3. Results for dijets in UPC
4. Summary

Gluon distributions

Operator definition of collinear gluon distribution



$$f_{g/H}(x) = \int \frac{dz^-}{2\pi p^+} e^{-ixp^+z^-} \langle p|\, \mathrm{Tr}\{F^{+i}\left(0, \vec{0}_T, z^-\right) U\left(z^-, 0; \vec{0}_T\right) F^{+i}(0)\}\, |p\rangle$$

$F^{+i}(x) = F_a^{+i}(x)\, t^a$ – gluon strength tensor in fundamental representation

$U\left(z^-, 0; \vec{0}_T\right) = \mathcal{P} \exp\left[ig \int_0^{z^-} dy^- A_a^+(0, \vec{0}_T, y^-) t^a\right]$ – the Wilson line

Gluon distributions

Transverse momentum dependent (TMD) gluon distributions

The position of one of the gluon operators is off the light-cone:

$$\mathcal{F}_{g;C_1,C_2}(x,k_T) = \int \frac{d\xi^- d^2\boldsymbol{\xi}}{(2\pi)^3 p^+} e^{ixp^+\xi^- - i\vec{k}_T\cdot\vec{\xi}_T} \langle p| \,\mathrm{Tr}\left\{F^{+i}\left(0,\xi_T,\xi^-\right)[\xi,0]_{C_1} F^{+i}(0)\,[0,\xi]_{C_2}\right\}|p\rangle$$

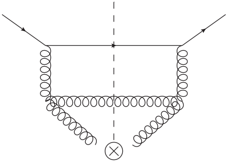
where $[\xi,0]_{C_i}$ are again Wilson lines which lie along some paths C_1 and C_2.

The structure of Wilson lines depends on the particular hard process attached to the gluon distribution, more precisely its color structure.

Gluon distributions

Example: TMD distribution for a particular subprocess in $HH \rightarrow 2\text{jets}$

[C.J. Bomhof, P.J. Mulders, F. Pijlman, Eur.Phys.J.C. 47, 147 (2006)]



$$\mathcal{F}_{g;C_1,C_2} \sim \langle p|\,\mathrm{Tr}\{F^{+i}(\xi)\,\mathcal{U}^{[+]\dagger}F^{+i}(0)\left[\frac{\mathrm{Tr}\,\mathcal{U}^{[\square]\dagger}}{N_c}\mathcal{U}^{[+]}+\mathcal{U}^{[-]}\right]\}\,|p\rangle$$

where the Wilson lines (and loops) are defined as

$$\mathcal{U}^{[\pm]} = U(0,\pm\infty;0_T)U_T(\pm\infty;0_T,\xi_T)U(\pm\infty,\xi^-;\xi_T)$$

$$\mathcal{U}^{[\square]} = \mathcal{U}^{[+]}\mathcal{U}^{[-]\dagger} = \mathcal{U}^{[-]}\mathcal{U}^{[+]\dagger}$$

Gluon distributions

Two most basic TMD distributions:

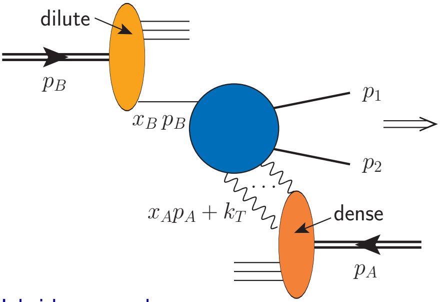
1. $$\mathcal{F}_{g;++} \sim \langle p|\,\mathrm{Tr}\left\{F(\xi)\,\mathcal{U}^{[+]\dagger} F(0)\,\mathcal{U}^{[+]}\right\}|p\rangle$$
2. $$\mathcal{F}_{g;-+} \sim \langle p|\,\mathrm{Tr}\left\{F(\xi)\,\mathcal{U}^{[-]\dagger} F(0)\,\mathcal{U}^{[+]}\right\}|p\rangle$$

It is possible to choose a gauge to eliminate Wilson lines in **1** so that it has an interpretation as a gluon number density.
This is not possible for the distribution function **2**.

Remark 1: TMD gluon distributions are defined at leading power ('leading twist').

Remark 2: TMD gluon distributions are valid at any x.
$\Rightarrow$ there is a relation to Weizsacker-Williams (WW) xG_1 and 'dipole' xG_2 gluon distributions known at small x.

Forward dijets in pA collisions within CGC



forward dijets with transverse momentum imbalance:

$$\left|\vec{p}_{T1} + \vec{p}_{T2}\right| = \left|\vec{k}_T\right| = k_T$$

asymmetric kinematics:

$$x_B \gg x_A$$

Hybrid approach:

- large-x parton in hadron B is treated as 'collinear' with standard PDFs
- small-x partons within hadron A have internal transverse momentum k_T

Three-scale problem (typically in CGC $Q_s \sim k_T \sim P_T$)

1. hard scale P_T (of the order of the average transverse momentum of jets)
2. transverse momentum imbalance k_T
3. saturation scale $\Lambda_{\mathrm{QCD}} \ll Q_s$ (increasing with energy)

Forward dijets in *pA* collisions within CGC

Example: $qA \to qg$ channel

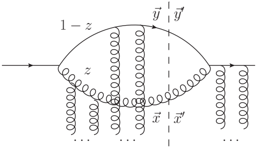
[C. Marquet, Nucl. Phys. A 796 (2007) 41]

$$\frac{d\sigma_{qA\to 2j}}{d^3p_1 d^3p_2} \sim \int \frac{d^2x}{(2\pi)^2}\frac{d^2x'}{(2\pi)^2}\frac{d^2y}{(2\pi)^2}\frac{d^2y'}{(2\pi)^2} e^{-i\vec{p}_{T1}\cdot\left(\vec{x}_T-\vec{x}'_T\right)} e^{-i\vec{p}_{T2}\cdot\left(\vec{y}_T-\vec{y}'_T\right)}\psi^*_z\left(\vec{x}'_T-\vec{y}'_T\right)\psi_z\left(\vec{x}_T-\vec{y}_T\right)$$

$$\Big\{S^{(6)}_{x_g}\left(\vec{y}_T,\vec{x}_T,\vec{y}'_T,\vec{x}'_T\right) - S^{(3)}_{x_g}\left(\vec{y}_T,\vec{x}_T,(1-z)\,\vec{y}'_T+z\vec{x}'_T\right) - S^{(3)}_{x_g}\left((1-z)\,\vec{y}_T+z\vec{x}_T,\vec{y}'_T,\vec{x}'_T\right)$$
$$-S^{(2)}_{x_g}\left((1-z)\,\vec{y}_T+z\vec{x}_T,(1-z)\,\vec{y}'_T+z\vec{x}'_T\right)\Big\}$$

$\psi_z\left(\vec{x}_T\right)$ – quark wave function

$S^{(i)}_{x_g}$ – correlators of Wilson line operators, e.g.



$$S^{(2)}_{x_g}\left(\vec{y}_T,\vec{x}_T\right) = \frac{1}{N_c}\left\langle \mathrm{Tr}\left[U\left(\vec{y}_T\right)U^\dagger\left(\vec{y}'_T\right)\right]\right\rangle_{x_g}$$

$$S^{(3)}_{x_g}\left(\vec{z}_T,\vec{y}_T,\vec{x}_T\right) = \frac{1}{2C_FN_c}\left\langle \mathrm{Tr}\left[U\left(\vec{z}_T\right)U^\dagger\left(\vec{y}_T\right)\right]\mathrm{Tr}\left[U\left(\vec{y}_T\right)U^\dagger\left(\vec{x}_T\right)\right]\right\rangle_{x_g} - S^{(2)}_{x_g}\left(\vec{z}_T,\vec{x}_T\right) \text{ etc.}$$

where $U(\vec{x}_T) = U(-\infty,+\infty;\vec{x}_T)$ and $\langle\ldots\rangle_{x_g}$ denotes the average over color sources.

CGC vs TMD

Leading power limit of CGC vs small x TMD factorization

[F. Dominguez, C. Marquet, B-W. Xiao, F. Yuan Phys.Rev. D 83 (2011) 105005]

- Take the limit $k_T \sim Q_s \ll P_T$ of CGC expressions (back-to-back dijets)
- Replace the color averages by the hadronic ME: $\langle \ldots \rangle_{x_g} \to \langle p | \ldots | p \rangle / \langle p|p \rangle$

$$\frac{d\sigma_{AB\to 2j}}{dy_1 d^2 p_{T1} dy_2 d^2 p_{T1}} \sim \sum_{a,c,d} f_{a/B}\left(x_B, P_T^2\right) \sum_i \mathcal{F}_{ag}^{(i)}\left(x_A, k_T^2\right) H_{ag\to cd}^{(i)}$$

$H^{(i)}$ – hard on-shell factors
$\mathcal{F}_{ag}^{(i)}$ – TMD gluon distributions:

$$\mathcal{F}_{qg}^{(1)} \sim \langle p_A | \,\mathrm{Tr}\{F^{+i}(\xi)\,\mathcal{U}^{[-]\dagger} F^{+i}(0)\,\mathcal{U}^{[+]}\} | p_A \rangle, \quad \mathcal{F}_{qg}^{(2)} \sim \langle p_A | \,\mathrm{Tr}\{F^{+i}(\xi)\,\frac{\mathrm{Tr}\,\mathcal{U}^{[\square]}}{N_c}\mathcal{U}^{[+]\dagger} F^{+i}(0)\,\mathcal{U}^{[+]}\} | p_A \rangle,$$

$$\mathcal{F}_{gg}^{(1)} \sim \langle p_A | \,\mathrm{Tr}\{F^{+i}(\xi)\,\frac{\mathrm{Tr}\,\mathcal{U}^{[\square]}}{N_c}\mathcal{U}^{[-]\dagger} F^{+i}(0)\,\mathcal{U}^{[+]}\} | p_A \rangle, \quad \mathcal{F}_{gg}^{(2)} \sim \frac{1}{N_c}\langle p_A | \,\mathrm{Tr}\left\{F^{+i}(\xi)\,\mathcal{U}^{[\square]\dagger}\right\} \mathrm{Tr}\left\{F^{+i}(0)\,\mathcal{U}^{[\square]}\right\} | p_A \rangle,$$

$$\mathcal{F}_{gg}^{(3)} \sim \langle p_A | \,\mathrm{Tr}\left\{F^{+i}(\xi)\,\mathcal{U}^{[+]\dagger} F^{+i}(0)\,\mathcal{U}^{[+]}\right\} | p_A \rangle, \quad \mathcal{F}_{gg}^{(4)} \sim \langle p_A | \,\mathrm{Tr}\left\{F^{+i}(\xi)\,\mathcal{U}^{[-]\dagger} F^{+i}(0)\,\mathcal{U}^{[-]}\right\} | p_A \rangle,$$

$$\mathcal{F}_{gg}^{(5)} \sim \langle p_A | \,\mathrm{Tr}\left\{F^{+i}(\xi)\,\mathcal{U}^{[\square]\dagger}\mathcal{U}^{[+]\dagger} F^{+i}(0)\,\mathcal{U}^{[\square]}\mathcal{U}^{[+]}\right\} | p_A \rangle, \quad \mathcal{F}_{gg}^{(6)} \sim \langle p_A | \,\mathrm{Tr}\left\{F^{+i}(\xi)\,\mathcal{U}^{[+]\dagger} F^{+i}(0)\,\mathcal{U}^{[+]}\right\}\left(\frac{\mathrm{Tr}\,\mathcal{U}^{[\square]}}{N_c}\right)^2 | p_A \rangle$$

Exact correspondence to the TMD factorization.

Improved TMD factorization (ITMD)

Pros and cons of the TMD factorization

- Pros: usage of gluon distributions with operator definitions
- Cons: only back-to-back region
- Cons: cannot be easily implemented in a MC event generation

We can 'improve' the TMD factorization to be valid at $P_T \gg Q_s$

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

- Use the dual decomposition of the hard sub-processes to simplify the structure: only two TMDs per channel
- Calculate the amplitudes off-shell in a gauge invariant way

$$\frac{d\sigma_{AB}}{dy_1 d^2p_{T1} dy_2 d^2p_{T1}} \sim \sum_{a,c,d} f_{a/B}\left(x_B, P_T^2\right) \sum_{i=1,2} \Phi^{(i)}_{ag\to cd}\left(x_A, k_T^2\right) K^{(i)}_{ag\to cd}\left(k_T^2\right)$$

- Two well defined limits:
  1. leading power limit of CGC when $P_T \gg k_T$ (saturation)
  2. dilute limit of CGC when $P_T \sim k_T$ (High Energy Factorization)

ITMD for $\gamma A \to 2\,\mathrm{jets}$

Similar procedure (but simpler) gives:

$$\frac{d\sigma_{\gamma A\to 2j}}{dy_1 d^2p_{T1} dy_2 d^2p_{T1}} \sim x_A G_1\left(x_A, k_T^2\right) \otimes K_{\gamma g^*\to q\bar{q}}\left(k_T\right)$$

xG_1 – the WW gluon distribution
$K_{\gamma g^*\to q\bar{q}}$ – off-shell hard factor for the $\gamma g^* \to q\bar{q}$ process

- Formula is as simple as for e.g. inclusive DIS, but probes different gluon distribution
- For UPC the problem is that the photon flux dies out very fast above $x_\gamma \sim 0.03$ for Pb, so there is not much 'space' for the asymmetric kinematics $x_A \ll x_\gamma$ at current LHC energies with reasonable p_T cuts.

Improved TMD factorization (ITMD)

How to get gluon distributions?

- At large N_c and in Gaussian approximation all distributions can be calculated from the dipole UGD, which is known from HERA
  [A. van Hameren, P.K., K. Kutak, C. Marquet, E. Petreska, S. Sapeta, JHEP 1612 (2016) 034]
- One can use JIMWLK equation to get gluon distributions from McLerran-Venugopalan (MV) model [C. Marquet, E. Petreska, C. Roiesnel, JHEP 1610 (2016) 065]
- Direct renormalization group equation of operators, valid at any x and including hard scale dependence (very complicated, in progress)
  [I. Balitsky, A. Tarasov, JHEP 1606 (2016) 164]

Important result:

All gluon distributions have universal large k_T behavior (except one which vanishes very fast).
$\Rightarrow$ ITMD formalism recovers correct linear regime of High Energy factorization.

Checked in two first approaches (and also analytically for the MV model).

The WW gluon distribution from data

Relation between xG_1 and xG_2 in gaussian approximation

$$\nabla^2_{k_T} G^{(1)}(x,k_T) = \frac{4\pi^2}{N_c S_\perp} \int \frac{d^2 q_T}{q_T^2} \frac{\alpha_s}{(k_T - q_T)^2} G^{(2)}(x,q_T)\, G^{(2)}(x,|k_T - q_T|)$$

Realistic evolution equation for xG_2

Nonlinear extension of the Kwiecinski-Martin-Stasto (KMS) evolution equation (below $xG_2 \equiv \mathcal{F}$):

[K. Kutak, K. Kwiecinski, Eur. Phys. J. C 29 (2003) 521]
[J. Kwiecinski, Alan D. Martin, A.M. Stasto, Phys.Rev. D56 (1997) 3991-4006]

$$\mathcal{F}(x,k_T^2) = \mathcal{F}_0(x,k_T^2) + \frac{\alpha_s N_c}{\pi} \int_x^1 \frac{dz}{z} \int_{k_{T\,0}^2}^{\infty} \frac{dq_T^2}{q_T^2} \left\{ \frac{q_T^2 \mathcal{F}\left(\frac{x}{z}, q_T^2\right) \theta\left(\frac{k_T^2}{z} - q_T^2\right) - k_T^2 \mathcal{F}\left(\frac{x}{z}, k_T^2\right)}{|q_T^2 - k_T^2|} + \frac{k_T^2 \mathcal{F}\left(\frac{x}{z}, k_T^2\right)}{\sqrt{4q_T^4 + k_T^4}} \right\}$$
$$+ \frac{\alpha_s}{2\pi k_T^2} \int_x^1 dz \left\{ \left(P_{gg}(z) - \frac{2N_c}{z} \right) \int_{k_{T\,0}^2}^{k_T^2} dq_T^2 \mathcal{F}\left(\frac{x}{z}, q_T^2\right) + z P_{gq}(z)\, \Sigma\left(\frac{x}{z}, k_T^2\right) \right\}$$
$$- \frac{2\alpha_s^2}{R^2} \left\{ \left[\int_{k_T^2}^{\infty} \frac{dq_T^2}{q_T^2} \mathcal{F}(x,q_T^2) \right]^2 + \mathcal{F}(x,k_T^2) \int_{k_T^2}^{\infty} \frac{dq_T^2}{q_T^2} \ln\left(\frac{q_T^2}{k_T^2}\right) \mathcal{F}(x,q_T^2) \right\}$$

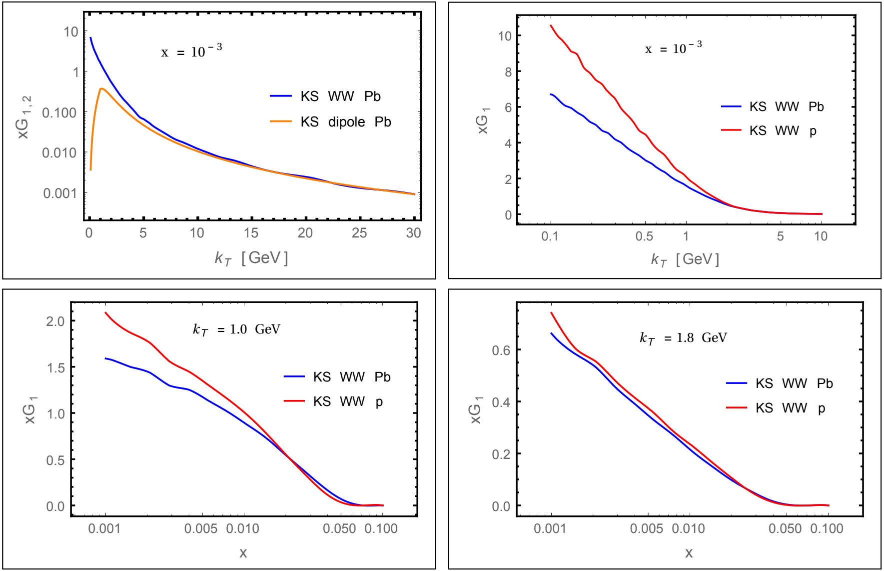
This equation was fitted to HERA data for proton by Kutak-Sapeta (KS).

[K. Kutak, S. Sapeta, Phys. Rev. D 86 (2012) 094043]

For nucleus $R_A = RA^{1/3}/\sqrt{d}$ is used so the nonlinear term is enhanced by $dA^{1/3}$.

The WW gluon distribution from data

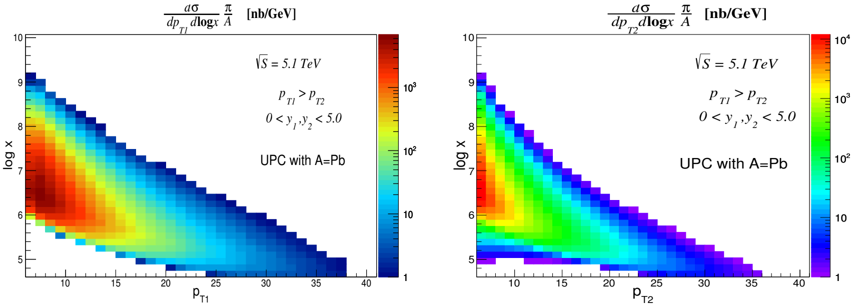
Results for $Pb = 208$ and $d = 0.5$



Results for dijets in UPC

Kinematic cuts

CM energy: 5.1 TeV	rapidity: $0 < y_1, y_2 < 5$
transverse momenta: $p_{T1} > p_{T2} > p_{T0}$, $p_{T0} = 6 \div 25\,\mathrm{GeV}$	jet algorithm: $R = 0.5$



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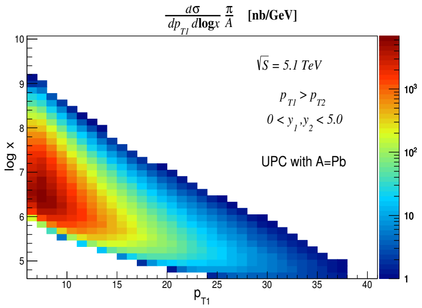

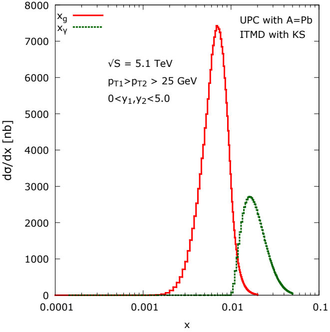

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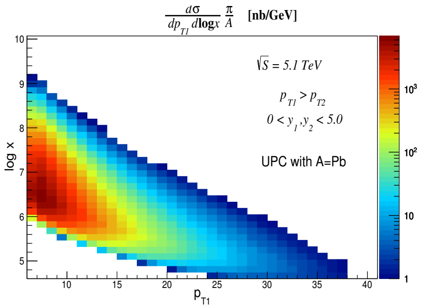

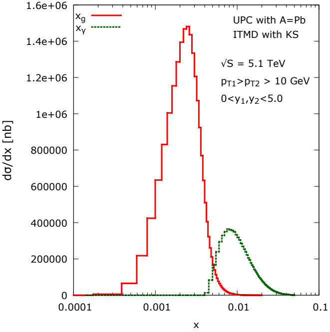

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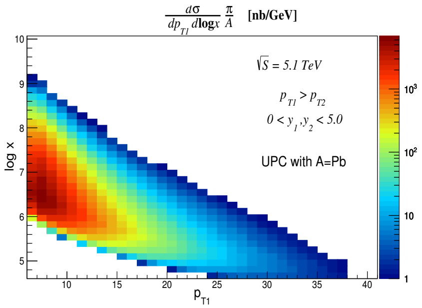
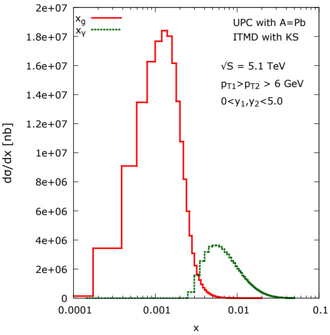




Results for dijets in UPC

Nuclear modification factor $R_{\gamma A}$

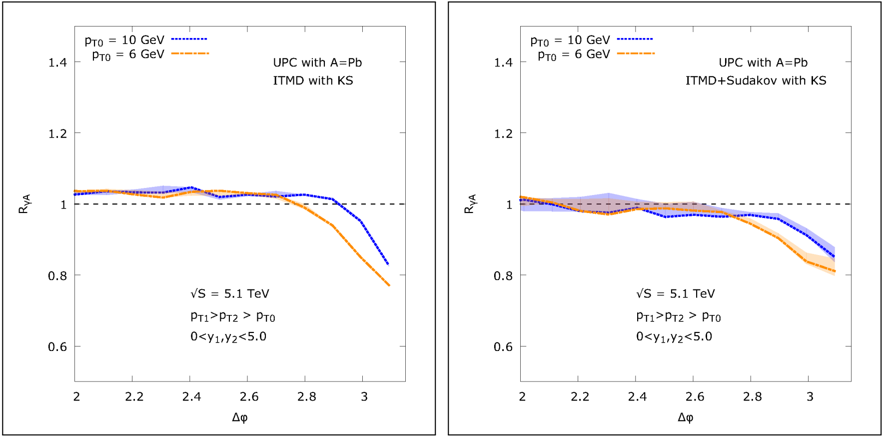
$$R_{\gamma A} = \frac{d\sigma_{AA}^{\mathrm{UPC}}}{A d\sigma_{Ap}^{\mathrm{UPC}}}$$

where $A = \mathrm{Pb}$ and the $d\sigma_{Ap}^{\mathrm{UPC}}$ is with jets going in the nucleus direction.

Results for dijets in UPC

Nuclear modification factor $R_{\gamma A}$

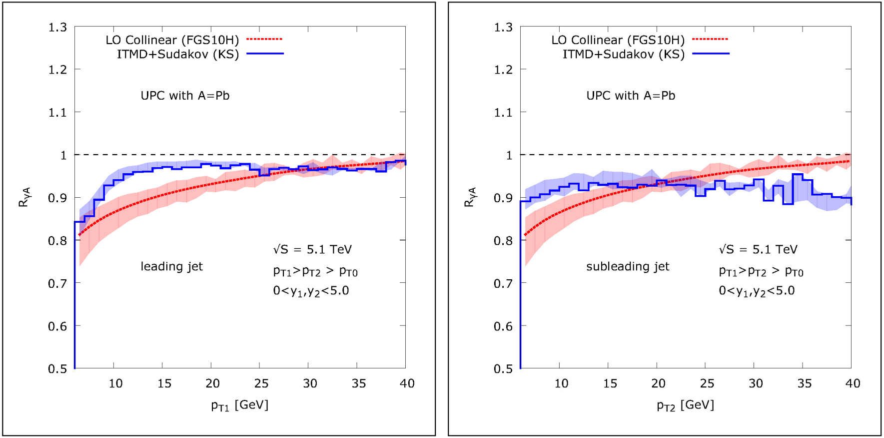
azimuthal imbalance | azimuthal imbalance with Sudakov



Results for dijets in UPC

Nuclear modification factor $R_{\gamma A}$

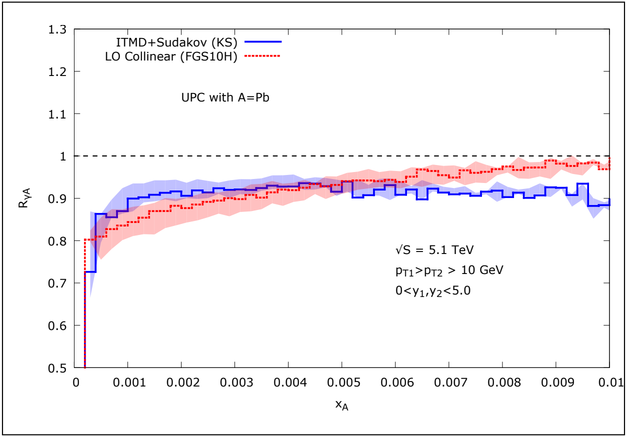
leading jet p_T | subleading jet p_T



Results for dijets in UPC

Nuclear modification factor $R_{\gamma A}$

x spectrum



Summary

- When $P_T \gg Q_s$ the CGC expressions for dijet production can be reinterpret in terms of small-x TMD gluon distributions.
  - They are not universal, but can be calculated within certain approximations
  - The language of gluon distribution has practical advantages
- Direct component of dijet production in UPC is directly sensitive to Weizsacker-Williams (WW) gluon distribution; this is the only 'true' gluon distribution at small x
- Present calculations use WW obtained from the 'dipole' gluon distribution fitted to data; no experimental information about WW is available
- Within the kinematics allowed by the present formalism the suppression factor is 10-20% depending on the transverse momentum cut
- Similar suppression is visible for leading twist shadowing, but it vanishes faster with increase of x

BACKUP

Improved TMD factorization (ITMD): $P_T \gg Q_s$

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

$$\frac{d\sigma_{AB}}{dy_1 d^2p_{T1} dy_2 d^2p_{T1}} \sim \sum_{a,c,d} f_{a/B}\left(x_B, P_T^2\right) \sum_{i=1,2} \Phi^{(i)}_{ag\to cd}\left(x_A, k_T^2\right) K^{(i)}_{ag\to cd}$$

$$\Phi^{(1)}_{qg\to gq} = \mathcal{F}^{(1)}_{qg},\ \Phi^{(2)}_{qg\to gq} = \frac{1}{N_c^2-1}\left(N_c^2\mathcal{F}^{(2)}_{qg} - \mathcal{F}^{(1)}_{qg}\right),\ \Phi^{(1)}_{gg\to q\bar{q}} = \frac{1}{N_c^2-1}\left(N_c^2\mathcal{F}^{(1)}_{gg} - \mathcal{F}^{(3)}_{gg}\right),\ \Phi^{(2)}_{gg\to q\bar{q}} = \mathcal{F}^{(3)}_{gg} - N_c^2\mathcal{F}^{(2)}_{gg}$$

$$\Phi^{(1)}_{gg\to gg} = \frac{1}{2N_c^2}\left(N_c^2\mathcal{F}^{(1)}_{gg} - 2\mathcal{F}^{(3)}_{gg} + \mathcal{F}^{(4)}_{gg} + \mathcal{F}^{(5)}_{gg} + N_c^2\mathcal{F}^{(6)}_{gg}\right),\ \Phi^{(2)}_{gg\to gg} = \frac{1}{N_c^2}\left(N_c^2\mathcal{F}^{(2)}_{gg} - 2\mathcal{F}^{(3)}_{gg} + \mathcal{F}^{(4)}_{gg} + \mathcal{F}^{(5)}_{gg} + N_c^2\mathcal{F}^{(6)}_{gg}\right)$$

$$K^{(1)}_{qg\to gq} = -\frac{\bar{u}\left(\bar{s}^2+\bar{u}^2\right)}{2\bar{t}\hat{t}\hat{s}}\left(1+\frac{\bar{s}\hat{s}-\bar{t}\hat{t}}{N_c^2\ \bar{u}\hat{u}}\right),\ K^{(2)}_{qg\to gq} = -\frac{C_F}{N_c}\ \frac{\bar{s}\left(\bar{s}^2+\bar{u}^2\right)}{\bar{t}\hat{t}\hat{u}},\ K^{(1)}_{gg\to q\bar{q}} = \frac{1}{2N_c}\ \frac{\left(\bar{t}^2+\bar{u}^2\right)\left(\bar{u}\hat{u}+\bar{t}\hat{t}\right)}{\bar{s}\hat{s}\hat{t}\hat{u}}$$

$$K^{(2)}_{gg\to q\bar{q}} = \frac{1}{4N_c^2 C_F}\ \frac{\left(\bar{t}^2+\bar{u}^2\right)\left(\bar{u}\hat{u}+\bar{t}\hat{t}-\bar{s}\hat{s}\right)}{\bar{s}\hat{s}\hat{t}\hat{u}},\ K^{(2)}_{gg\to q\bar{q}} = \frac{1}{4N_c^2 C_F}\ \frac{\left(\bar{t}^2+\bar{u}^2\right)\left(\bar{u}\hat{u}+\bar{t}\hat{t}-\bar{s}\hat{s}\right)}{\bar{s}\hat{s}\hat{t}\hat{u}},$$

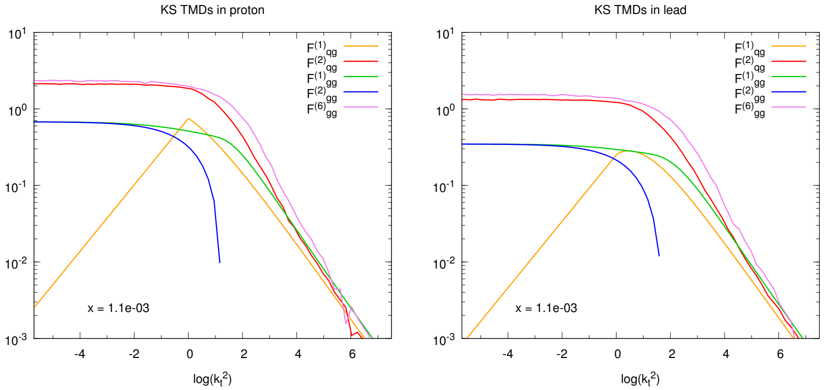
$$K^{(1)}_{gg\to gg} = \frac{N_c}{C_F}\ \frac{\left(\bar{s}^4+\bar{t}^4+\bar{u}^4\right)\left(\bar{u}\hat{u}+\bar{t}\hat{t}\right)}{\bar{t}\hat{t}\bar{u}\hat{u}\bar{s}\hat{s}},\ K^{(2)}_{gg\to gg} = -\frac{N_c}{2C_F}\ \frac{\left(\bar{s}^4+\bar{t}^4+\bar{u}^4\right)\left(\bar{u}\hat{u}+\bar{t}\hat{t}-\bar{s}\hat{s}\right)}{\bar{t}\hat{t}\bar{u}\hat{u}\bar{s}\hat{s}}$$

$\hat{s}, \hat{t}, \hat{u}$ – ordinary Mandelstam variables, $\hat{s}+\hat{t}+\hat{u} = k_T^2$

$\bar{s}, \bar{t}, \bar{u}$ off-shell momentum is replaced by its longitudinal component of off-shell momentum, $\bar{s}+\bar{u}+\bar{t} = 0$

Gluon distributions: realistic model

Five gluon distributions from KS fit

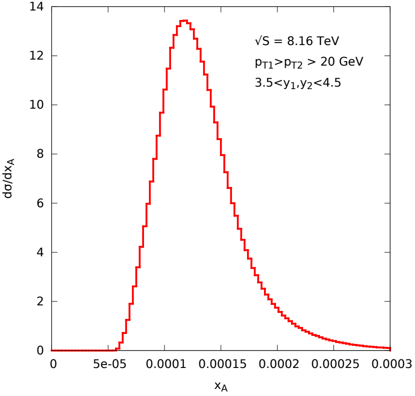


All gluons start to merge for large k_T (except $\mathcal{F}_{gg}^{(2)}$ which vanishes) $\Rightarrow$ consistent with HEF limit.

$R_{p\mathrm{Pb}}$ for azimuthal disbalance in ITMD

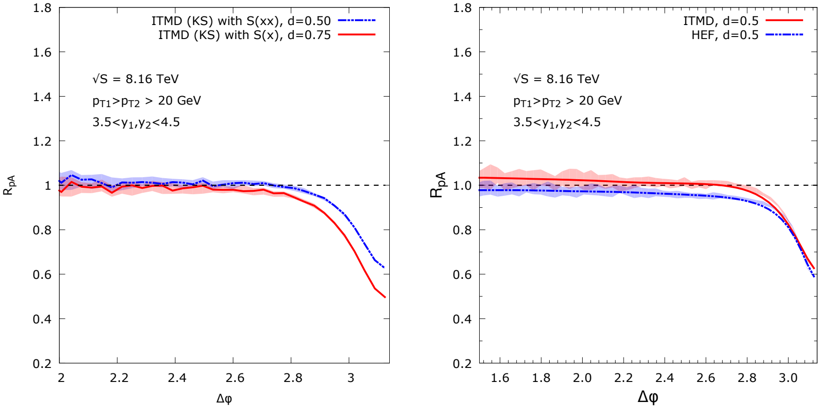
Cuts: $p_{T1} > p_{T2} > 20\,\mathrm{GeV}$, $3.5 < y_1, y_2 < 4.5$, $\sqrt{S} = 8.16\,\mathrm{TeV}$

x fractions probed:



$R_{p\mathrm{Pb}}$ for azimuthal disbalance in ITMD

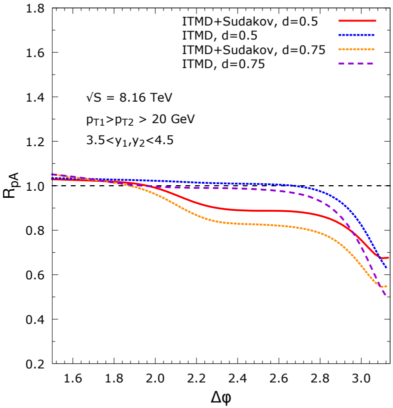
Cuts: $p_{T1} > p_{T2} > 20\,\mathrm{GeV}$, $3.5 < y_1, y_2 < 4.5$, $\sqrt{S} = 8.16\,\mathrm{TeV}$



$R_{p\mathrm{Pb}}$ for azimuthal disbalance in ITMD

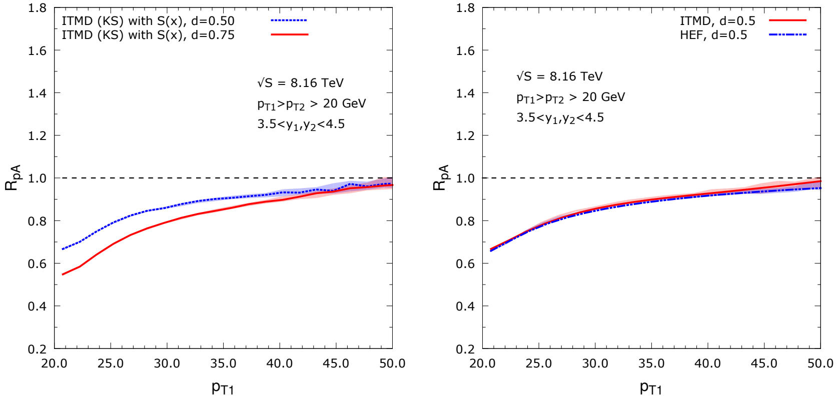
Cuts: $p_{T1} > p_{T2} > 20\,\mathrm{GeV}$, $3.5 < y_1, y_2 < 4.5$, $\sqrt{S} = 8.16\,\mathrm{TeV}$

Including Sudakov resummation (a model of):



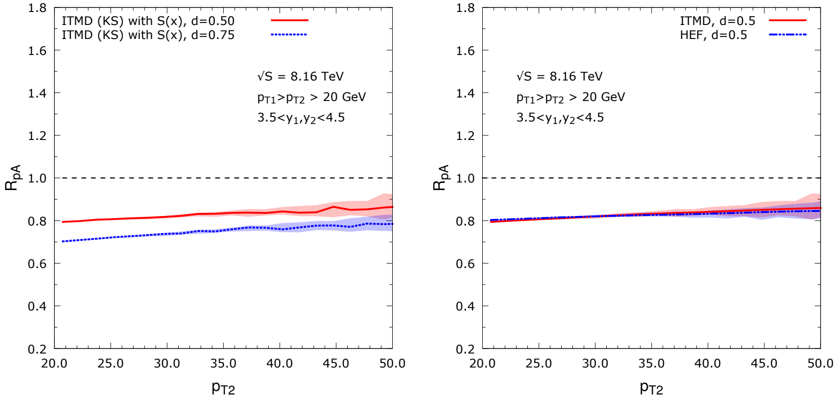
$R_{p\mathrm{Pb}}$ for p_T spectra in ITMD

leading jet spectrum:



$R_{p\mathrm{Pb}}$ for p_T spectra in ITMD

sub-leading jet spectrum:

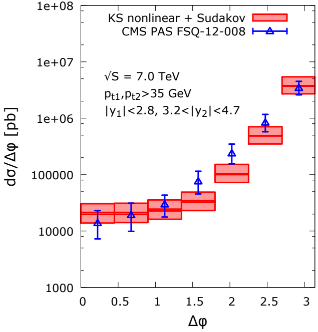


High Energy Factorization

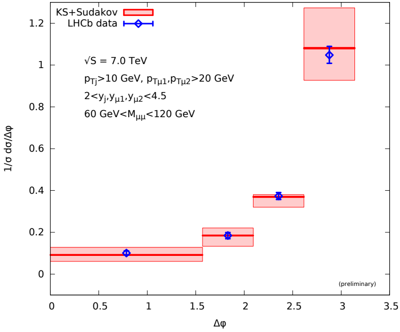
Comparison with data

In reality, the forward jets are decorrelated ⇒ decorrelations are nicely described by the High Energy Factorization. [A. van Hameren, PK, K. Kutak, S. Sapeta, Phys.Lett. B737 (2014) 335-340]

forward-central dijets



forward Z_0 + jet



We can improve TMD factorization by introducing off-shellness to the hard factors.

Constructing ITMD

Main steps

[P.K., K. Kutak, C. Marquet, E. Petreska, S. Sapeta, A. van Hameren, arXiv:150342]

- We revise the calculation of TMD gluon distributions using color decomposition of amplitudes

$$\mathcal{M}^{a_1 \dots a_N}\left(\varepsilon_1^{\lambda_1}, \dots, \varepsilon_N^{\lambda_N}\right) = \sum_{\sigma \in S_{N-1}} \mathrm{Tr}\left(t^{a_1} t^{a_{\sigma 2}} \dots t^{a_{\sigma N}}\right) \mathcal{M}\left(1^{\lambda_1}, \sigma_2^{\lambda_{\sigma 2}} \dots, \sigma_N^{\lambda_{\sigma N}}\right)$$

  a_i- color indices, $\varepsilon_i^{\lambda_i}$ - polarization vectors with helicity λ_i, S_{N-1} - set of noncyclic permutations.

  We conclude that there are only two independent TMDs $\Phi^{(i)}$, $i = 1, 2$ (being a combination of $\mathcal{F}_{qg}^{(1)}$'s) needed for each channel.

- We calculate off-shell gauge invariant color-ordered helicity amplitudes.

  Methods for gauge invariant off-shell amplitudes:

[E. Antonov, L. Lipatov, E. Kuraev, I. Cherednikov, Nucl.Phys. B721 (2005) 111-135]

[A. van Hameren, PK, K. Kutak, JHEP 1212 (2012) 029; JHEP 1301 (2013) 078]

[A. van Hameren, JHEP 1407 (2014) 138],

[PK, JHEP 1407 (2014) 128]

[A. van Hameren, M. Serino, arXiv:1504.00315]

Constructing ITMD

Color-ordered off-shell helicity amplitudes

[A. van Hameren, PK, K. Kutak, JHEP 1212 (2012) 029]

In spinor formalism, the non-zero off-shell helicity amplitudes have the form of the MHV amplitudes with certain modification of spinor products:

$$\mathcal{M}_{g^* g \to gg}\left(1^*, 2^-, 3^+, 4^+\right) = 2g^2 \rho_1 \frac{\langle 1^* 2\rangle^4}{\langle 1^* 2\rangle\langle 23\rangle\langle 34\rangle\langle 41^*\rangle}$$

$$\mathcal{M}_{g^* g \to gg}\left(1^*, 2^+, 3^-, 4^+\right) = 2g^2 \rho_1 \frac{\langle 1^* 3\rangle^4}{\langle 1^* 2\rangle\langle 23\rangle\langle 34\rangle\langle 41^*\rangle}$$

$$\mathcal{M}_{g^* g \to gg}\left(1^*, 2^+, 3^+, 4^-\right) = 2g^2 \rho_1 \frac{\langle 1^* 4\rangle^4}{\langle 1^* 2\rangle\langle 23\rangle\langle 34\rangle\langle 41^*\rangle}$$

where $\langle ij\rangle = \langle k_i - | k_j + \rangle$ with spinors defined as $|k_i \pm\rangle = \frac{1}{2}\left(1 \pm \gamma_5\right) u\left(k_i\right)$. Modified spinor products involve only longitudinal component of the off-shell momentum $\langle 1^* i\rangle = \langle p_A\, i\rangle$. Similar expressions can be derived for quarks.