Estimating saturation in dijet production in *pA* and UPC at LHC

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based on:

P.K., K. Kutak, S. Sapeta,
A. Stasto, M. Strikman,
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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

Two basic small-x Transverse Momentum Dependent (TMD) gluon distributions:

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inclusive DIS⋆ inclusive jet in pA⋆ inclusive dijet in pA	inclusive dijet in γA⋆ inclusive dijet in pA
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Constraints from data

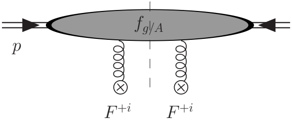
- xG_2 is well constrained from data.
- xG_1 is known from Color Glass Condensate (CGC).
- Dijets in Ultra-pheripheral Collisions (UPC) probe xG_1 directly.
- Dijets in pA collisions probe xG_1 and xG_2.

Plan

1. Introduction
    - Collinear vs TMD gluon distributions
2. Formalism for hard dijets in pA (dilute-dense) collisions
    - Generalized factorization approach
    - Proliferation of TMD gluon distributions
    - Small-x TMD gluon distributions from Gaussian approximation
    - Nuclear modification ratios for LHC
3. Dijets in UPC
    - Factorization formula with xG_1
    - Nuclear modification ratios for LHC
4. Summary

Gluon distributions

Operator definition of the collinear gluon distribution



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

$F^{+i}(x) = F_a^{+i}(x)\, t^a$ – 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:

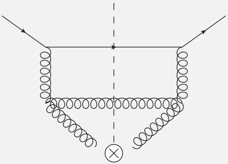
$$\mathcal{F}_{g/H}^{(C_1,C_2)}(x,k_T)=\int\frac{d\xi^- d^2\xi}{(2\pi)^3 p^+}\,e^{ixp^+\xi^- - i\vec{k}_T\cdot\vec{\xi}_T}\langle p|\,\mathrm{Tr}\Big\{F^{+i}(0,\xi_T,\xi^-)[\xi,0]_{C_1}F^{+i}(0)[0,\xi]_{C_2}\Big\}|p\rangle$$

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 on its color structure.

Gluon distributions

Example: TMD distribution for a particular diagram[1]



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

where the Wilson lines (and loops) are defined as

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

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

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

Improved small x TMD factorization (ITMD)

Factorization formula for forward dijets in pA ($\mu = \bar{p}_T \gg Q_s$)

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

$$\frac{d\sigma_{AB\to 2j+X}}{dy_1 d^2p_{T1} dy_2 d^2p_{T2}} \sim \sum_{a,c,d} f_{a/B}\left(x_B, \mu^2\right) \sum_{i=1,2} \Phi^{(i)}_{ag\to cd}\left(x_A, k_T^2, \mu^2\right) K^{(i)}_{ag\to cd}\left(k_T^2, \mu^2\right)$$

$\Phi^{(i)}_{ag\to cd}$ – small-x TMD Gluon Distributions

$K^{(i)}$ – hard factors calculated from off-shell gauge invariant amplitudes

Formula contains essential limiting cases:

1. $Q_s \ll k_T \sim \overline{p}_T$ – High Energy Factorization (HEF)/k_T-factorization
   - All $\Phi^{(i)}_{ag\to cd}$ become equal to xG_2.
   - Off-shell factors combine to appropriate Lipatov vertex.
   - Correct collinear limit (if collinear PDF is defined as integrated xG_2)
2. $k_T \sim Q_s \ll \overline{p}_T$ – leading power limit of CGC[1]
   - Off-shell factors become on-shell
   - TMD gluon distributions can be identified with color averages in CGC

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

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TMD gluon distributions:

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

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

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

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

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

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Off-shell hard factors:

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

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

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

$\hat{s},\hat{t},\hat{u}$ – 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, $\bar{s}+\bar{u}+\bar{t}=0$
.

Improved small x TMD factorization (ITMD)

Two most basic TMD distributions:

$$\langle p|\,\mathrm{Tr}\left\{F(\xi)\,\mathcal{U}^{[+]\dagger}F(0)\,\mathcal{U}^{[+]}\right\}|p\rangle \sim xG_1$$

$$\langle p|\,\mathrm{Tr}\left\{F(\xi)\,\mathcal{U}^{[-]\dagger}F(0)\,\mathcal{U}^{[+]}\right\}|p\rangle \sim xG_2$$

It is possible to choose a gauge to eliminate Wilson lines in xG_1 so that it has an interpretation as a gluon number density. This is not possible for xG_2.

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How to obtain the rest?

- Full evolution equations of the hierarchy of the operators[1,2]
- Approximations:
  - At large N_c some TMD gluon distributions are suppressed $\Rightarrow$ 5 left.
  - In the leading power limit we recover CGC and thus we may assume the Gaussian distribution of color sources known from CGC

$\Rightarrow$ All TMD gluons can be calculated from xG_2

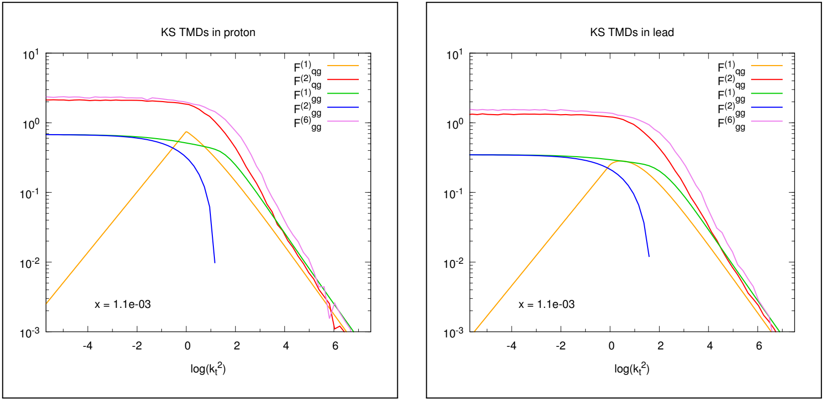
[1] I. Balitsky, A. Tarasov, JHEP 1510 (2015) 017
[2] C. Marquet, E. Petreska, C. Roiesnel, JHEP 1610 (2016) 065

Gluon distributions for ITMD

Small x TMD gluon distributions from data

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

The dipole gluon xG_2 was fitted to HERA data by Kutak and Sapeta[1] (KS) using nonlinear extension[2] of Kwiecinski-Martin-Stasto[3] (KMS) evolution equation.



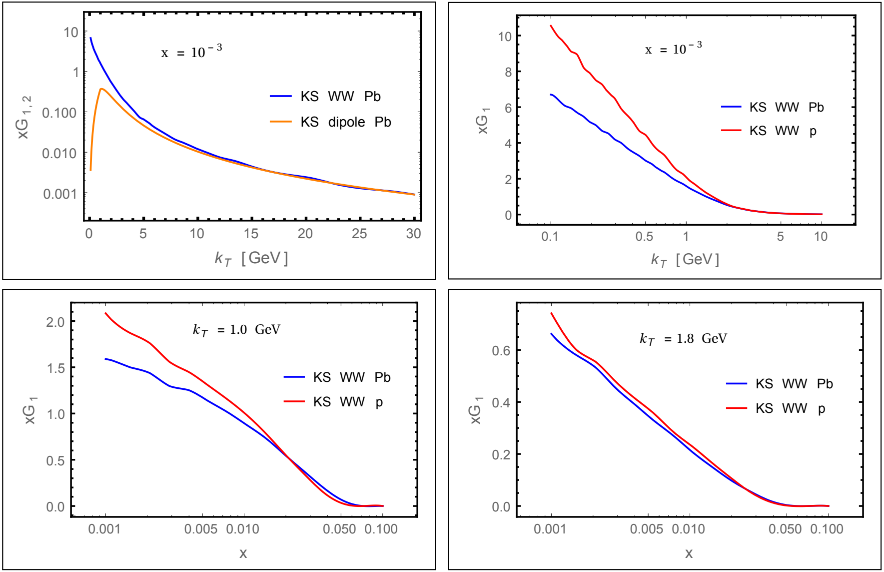
All gluons merge for large k_T (except $\mathcal{F}_{gg}^{(2)}$ which vanishes) $\Rightarrow$ correct HEF limit.

[1] K. Kutak, S. Sapeta, Phys. Rev. D 86 (2012) 094043 [2] K. Kutak, K. Kwiecinski, Eur. Phys. J. C 29 (2003) 521
[2] K. Kwiecinski, A. Martin, A. Stasto, Phys.Rev. D59 (1999) 093002

Weizsacker-Williams xG_1 from KS fit

Results for $Pb = 208$

[P.K., K. Kutak, S. Sapeta, A. Stasto, M. Strikman, Eur. Phys. J. C77 (2017) no.5, 353]



Comments on the formalism (1)

1. In practical application it is convenient to use Monte Carlo generators.
   - ITMD is perfect for such implementation due to exact momentum conservation.
   - Two independent implementations: C++ `LxJet` and the fortran program of A. van Hameren.

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[1] see eg. M. Bury, M. Deak, K. Kutak, S. Sapeta, Phys.Lett. B760 (2016) 594-601

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   - Two independent implementations: C++ `LxJet` and the fortran program of A. van Hameren.
2. At phenomenological level, the k_T dependence mimics initial state parton shower[1].
3. In the region $\bar{p}_T \gg k_T \sim Q_s$ one should resum the Sudakov logs.
   - Formally this should be done by considering a complete evolution equation for TMD gluons.
   - However, at lowest order the Sudakov form factor has a simple probabilistic interpretation.
   - This can be used to model the resummation at the Monte Carlo level[2].

[1] see eg. M. Bury, M. Deak, K. Kutak, S. Sapeta, Phys.Lett. B760 (2016) 594-601

[2] A. van Hameren, P.K., K. Kutak, S. Sapeta, Phys.Lett. B737 (2014) 335-340

Comments on the formalism (2)

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:

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

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

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

where $\langle ij\rangle = \langle k_i - | k_j + \rangle$ with spinors defined as $|k_i\pm\rangle = \frac{1}{2}\left(1 \pm \gamma_5\right) u\left(k_i\right)$.
Spinor products for off-shell states involve only longitudinal component of the off-shell momentum $\langle 1^* i\rangle = \langle p_1 i\rangle$, where $k_1 = p_1 + k_{T1}$, $k_1^2 \neq 0$, $p_1^2 = 0$.

Why the MHV form?

It turns out that also two-leg-off-shell gauge invariant amplitudes have MHV form.
It is much more general feature, not related to high energy amplitudes:
Appearance of non-light like Wilson lines in the light-front MHV Lagrangian for the Cachazo-Svrcek-Witten (CSW) method of calculating amplitudes.

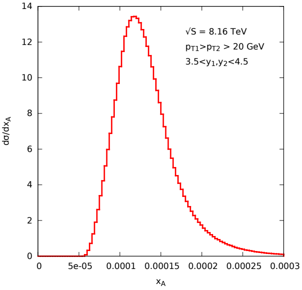
[P.K., A. Stasto, arxiv:1706.00052]

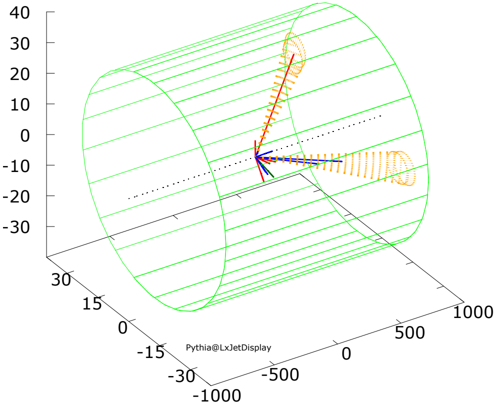
Results for dijet production in pPb at LHC

Kinematic cuts

- CM energy: $\sqrt{S} = 8.16\,\mathrm{TeV}$
- require two jets with $(\Delta\phi)^2 + (\Delta\eta)^2 > R^2, R = 0.5$
- transverse momenta cuts: $p_{T1} > p_{T2} > 20\,\mathrm{GeV}$
- rapidity cuts: $3.5 < y_1, y_2 < 4.5$

x fractions probed





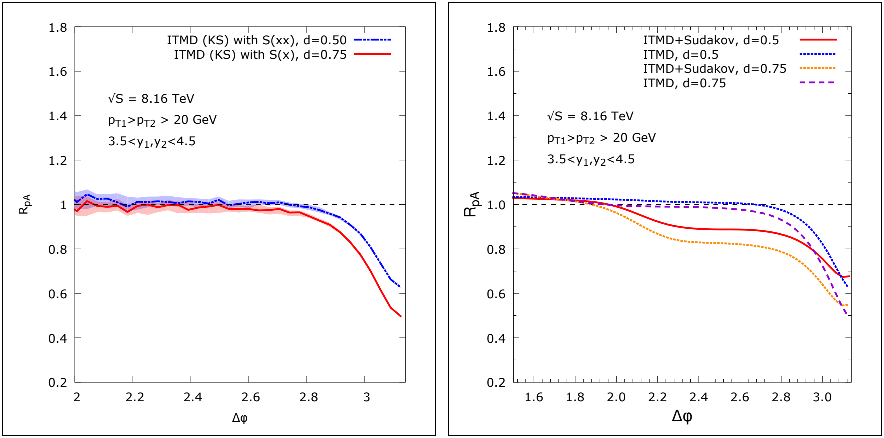
This particular PYTHIA event:

- jets with $p_{T1} \sim 27\,\mathrm{GeV}$, $p_{T2} \sim 30\,\mathrm{GeV}$
- $y > 3.5$
- 9 MPI events (not all visible; each in different color)
- jet imbalance $q_T \sim 10\,\mathrm{GeV}$

Results for dijet production in pPb at LHC

Nuclear modification ratio for azimuthal decorrelations

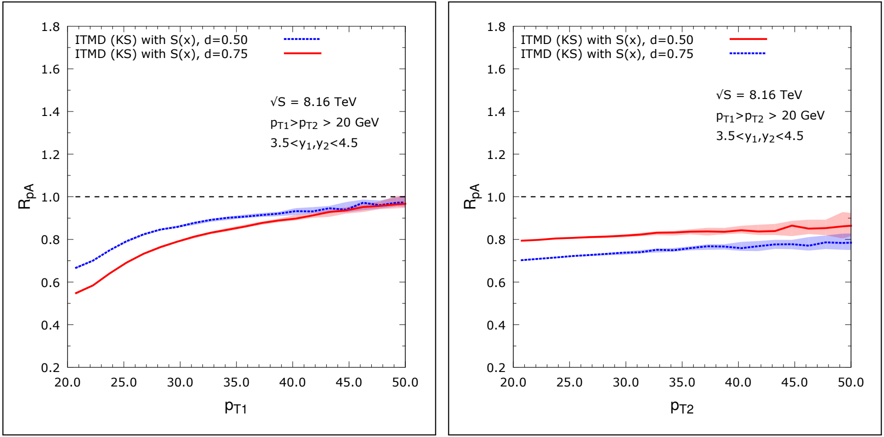
[A. van Hameren, P.K., K. Kutak, C. Marquet, E. Petreska, S. Sapeta, JHEP 1612 (2016) 034]



Results for dijet production in pPb at LHC

Nuclear modification ration for jet p_T spectra

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



ITMD for dijets in γA

Factorization formula

[P.K., K. Kutak, S. Sapeta, A. Stasto, M. Strikman, Eur. Phys. J. C77 (2017) no.5, 353]

$$\frac{d\sigma_{\gamma A\to 2j+X}}{dy_1 d^2p_{T1} dy_2 d^2p_{T2}} \sim x_A G_1\left(x_A, k_T^2, \mu^2\right) \otimes K_{\gamma g^*\to q\bar{q}}\left(k_T, \mu^2\right)$$

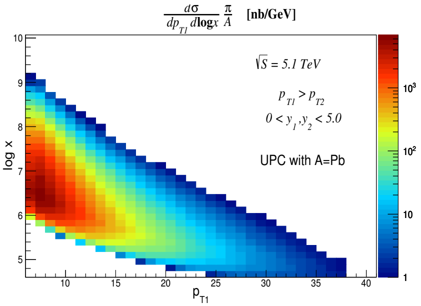
xG_1 – the Weizsacker-Williams gluon distribution
$K_{\gamma g^*\to q\bar{q}}$ – off-shell gauge invariant hard factor for the $\gamma g^* \to q\bar{q}$ process

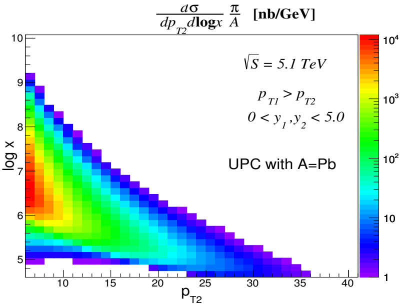
- Similar to inclusive DIS, but probes xG_1 instead of xG_2.
- For UPC one needs to convolute this with the photon flux from nucleus.
  Issue: the photon flux dies out very fast above $x_\gamma \sim 0.03$, so there is not much phase space for the asymmetric kinematics $x_A \ll x_\gamma$ which guarantees that xG_1 is probed at small x, unless we use jets with rather small p_T.

Results for dijets in UPC at LHC

Kinematic cuts

CM energy: $5.1\,\mathrm{TeV}$	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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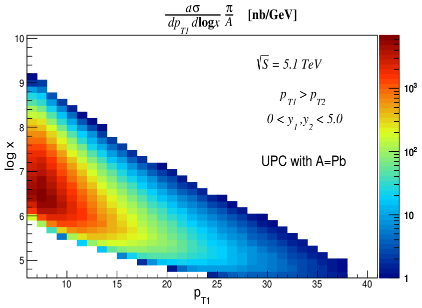

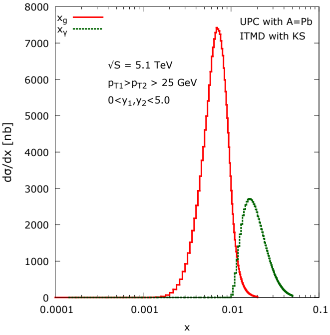

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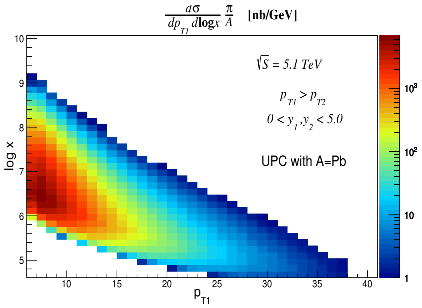

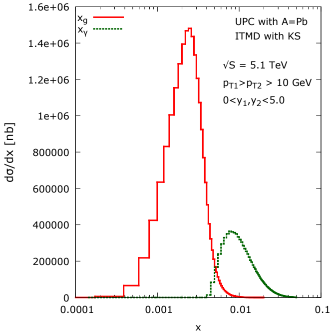

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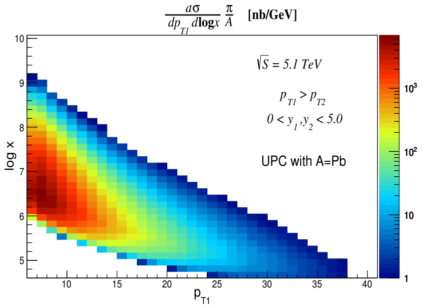
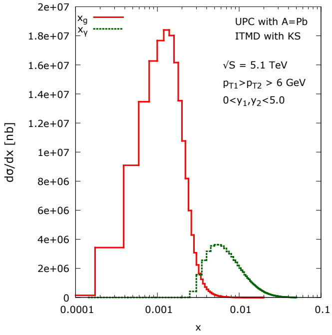
Kinematic cuts

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

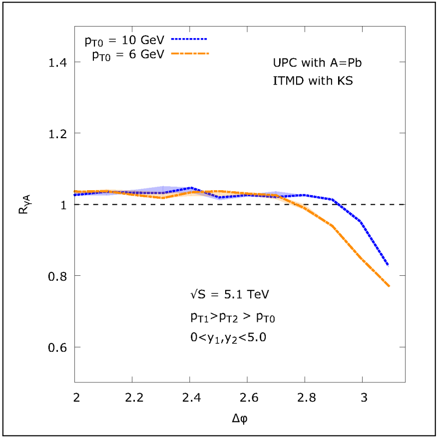


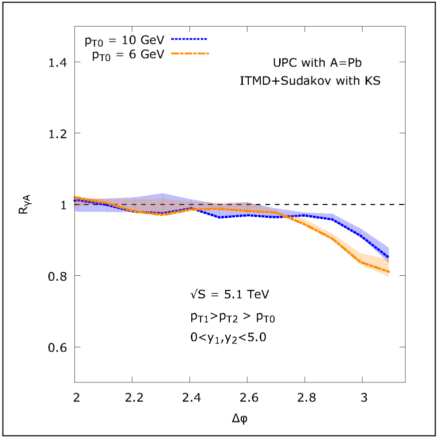


Results for dijets in UPC at LHC

Nuclear modification ration for azimuthal decorrelations

[P.K., K. Kutak, S. Sapeta, A. Stasto, M. Strikman, Eur. Phys. J. C77 (2017) no.5, 353]

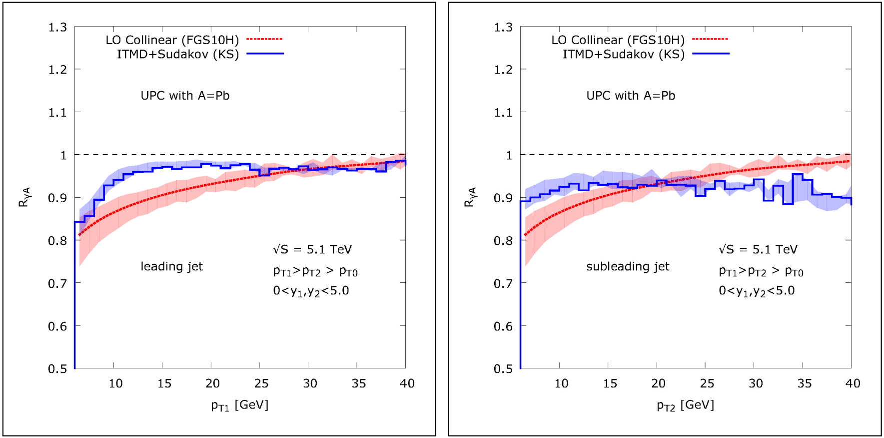




Results for dijets in UPC at LHC

Nuclear modification ratio for jet p_T spectra

[P.K., K. Kutak, S. Sapeta, A. Stasto, M. Strikman, Eur. Phys. J. C77 (2017) no.5, 353]



Conclusions

Summary

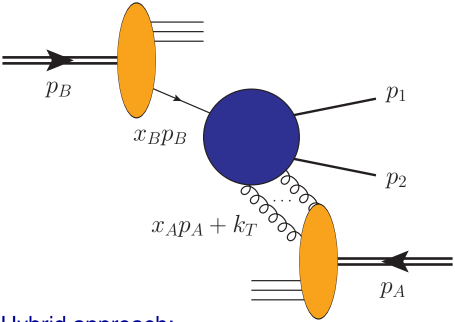
- Presented formalism is an alternative to CGC, valid when $P_T \gg Q_s$ and using small-x TMD gluon distributions.
- Dijet production in pA probes two basic gluon distributions: dipole and Weizsacker-Williams (WW).
- Direct component of dijet production in UPC probes directly WW gluon distribution.
- For practical purposes, in first approximation, all necessary gluon distributions can be obtained from the (known) dipole gluon distribution.
- At LHC, forward dijet production in pA shows about 40% of suppression due to saturation with jets $p_T > 20\,\mathrm{GeV}$.
- In forward dijets in UPC at LHC, the suppression is at most around 20% with jets $p_T > 6\,\mathrm{GeV}$.

Outlook

- We have initiated NLO program for off-shell matrix elements...

BACKUP

Dijets in *pA* collisions



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

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

Forward dijets in *pA* collisions within CGC

Example: $qA \to qg$ channel

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

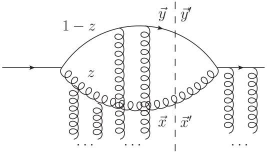
$$\frac{d\sigma_{qA\to 2j}}{d^3p_1 d^3p_2} \sim \int \frac{d^2x}{(2\pi)^2}\frac{d^2x'}{(2\pi)^2}\frac{d^2y}{(2\pi)^2}\frac{d^2y'}{(2\pi)^2}\, e^{-i\vec{p}_{T1}\cdot\left(\vec{x}_T-\vec{x}'_T\right)} e^{-i\vec{p}_{T2}\cdot\left(\vec{y}_T-\vec{y}'_T\right)} \psi^*_z\left(\vec{x}'_T-\vec{y}'_T\right)\psi_z\left(\vec{x}_T-\vec{y}_T\right)$$

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

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

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

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



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

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

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

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]

$$\mathcal{F}\left(x, k_T^2\right) = \mathcal{F}_0\left(x, k_T^2\right) + \frac{\alpha_s N_c}{\pi} \int_x^1 \frac{dz}{z} \int_{k_{T0}^2}^\infty \frac{dq_T^2}{q_T^2} \left\{ \frac{q_T^2 \mathcal{F}\left(\frac{x}{z}, q_T^2\right) \theta\left(\frac{k_T^2}{z} - q_T^2\right) - k_T^2 \mathcal{F}\left(\frac{x}{z}, k_T^2\right)}{\left|q_T^2 - k_T^2\right|} + \frac{k_T^2 \mathcal{F}\left(\frac{x}{z}, k_T^2\right)}{\sqrt{4q_T^4 + k_T^4}} \right\}$$
$$+ \frac{\alpha_s}{2\pi k_T^2} \int_x^1 dz \left\{ \left(P_{gg}(z) - \frac{2N_c}{z}\right) \int_{k_{T0}^2}^{k_T^2} dq_T^2 \mathcal{F}\left(\frac{x}{z}, q_T^2\right) + z P_{gq}(z)\, \Sigma\left(\frac{x}{z}, k_T^2\right) \right\}$$
$$- \frac{2\alpha_s^2}{R^2} \left\{ \left[\int_{k_T^2}^\infty \frac{dq_T^2}{q_T^2} \mathcal{F}\left(x, q_T^2\right) \right]^2 + \mathcal{F}\left(x, k_T^2\right) \int_{k_T^2}^\infty \frac{dq_T^2}{q_T^2} \ln\left(\frac{q_T^2}{k_T^2}\right) \mathcal{F}\left(x, q_T^2\right) \right\}$$

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 $dA^{1/3}$.

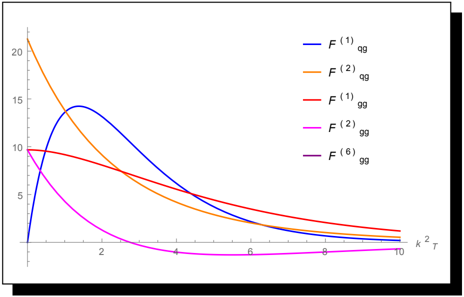
Gluon distributions: GBW model

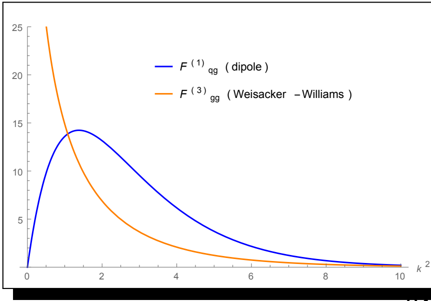
How to obtain 5 gluon distributions?

To start, we take the Golec-Biernat-Wusthoff (GBW) model:

$$xG_2\left(x,k_T^2\right)=\mathcal{F}_{qg}^{(1)}\left(x,k_T^2\right)=\frac{N_c S_\perp}{2\pi^3\alpha_s}\,\frac{k_T^2}{Q_s^2\left(x\right)}\,\exp\left(-\frac{k_T^2}{Q_s^2\left(x\right)}\right),\ Q_s\left(x\right)=Q_{s0}^2\left(\frac{x}{x_0}\right)^{\lambda}$$

Assuming Gaussian distribution of colour sources, the WW gluon $xG_1\left(x,k_T^2\right)$ can be related to $xG_2\left(x,k_T^2\right)$, hence all five gluons can be calculated analytically[1]



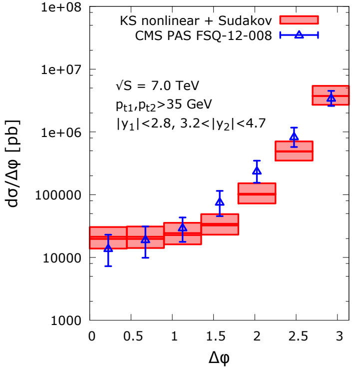


High energy factorization (HEF): $k_T \sim P_T \gg Q_s$

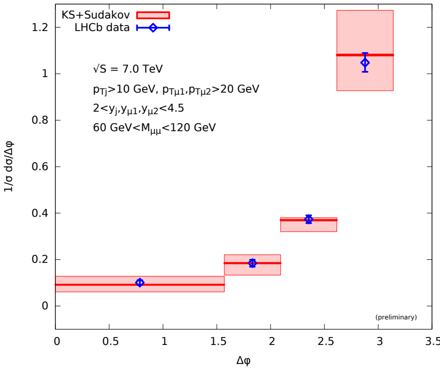
Comparison with data

[A. van Hameren, PK, K. Kutak, S. Sapeta, Phys.Lett. B737 (2014) 335-340]
[A. van Hameren, PK, K. Kutak, Phys.Rev. D92 (2015) 054007]

- central-forward dijet production



- forward Z_0+jet production



Nuclear modification ratio in UPC

Nuclear modification factor $R_{\gamma A}$

For UPC collisions we define the nuclear modification ratio as

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

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