Dijets in pA and γA collisions in saturation formalism

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in collaboration with:

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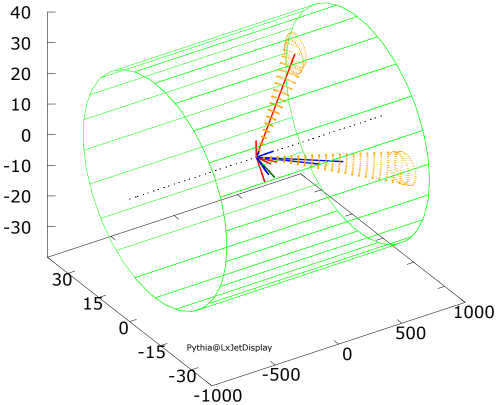
Outline

1. Theory of dijets in pA collisions in dilute-dense configuration
   - k_T-factorization ← no saturation
   - Color Glass Condensate (CGC) ← suitable for $P_T \sim Q_s$
   - leading twist limit of CGC and relation to TMD factorization
   - Improved TMD ≡ k_T-factorization with saturation (beyond leading twist)

   Features:

   - Five (5) unintegrated gluon distributions (UGDs), even at leading twist
   - In large N_c limit those UGDs can be expressed by only two UGDs:
     - dipole UGD (probed directly in inclusive particle production)
     - Weizsacker-Williams (WW) UGD (probed directly in dijets in γA)
2. UPC as a way to access (unknown) WW UGDs
3. Results for dijets in pA at 8.16 TeV (unpublished)
4. Results for dijets in UPC at 5.2 TeV (unpublished)

Dijets in dilute-dense collisions



This event (from PYTHIA):

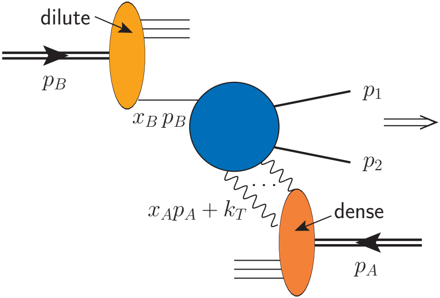
- jets with $p_{T1} \sim 27\,\mathrm{GeV}$, $p_{T2} \sim 30\,\mathrm{GeV}$
- $y > 3.5$
- 9 MPI events (not all visible; each in different color)
- jet disbalance $q_T \sim 10\,\mathrm{GeV}$

We consider collisions:

- reconstructed dijet system has the minimal p_T around $\sim 20\,\mathrm{GeV}$
- both jets are forward (in the proton direction) – rapidity y of ~ 3.5 or more

asymmetric kinematics:
one of the hadrons probed at 'small-x' (dense target); the second hadron has much larger x (dilute projectile)

Dijets in dilute-dense collisions: Hybrid approach



forward dijets with transverse momentum imbalance:

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

asymmteric kinematics:

$$x_B \gg x_A$$

- large-x parton in hadron B is treated as 'collinear' with standard PDFs
- small-x partons witin 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 $\Lambda_{\mathrm{QCD}} \ll Q_s$ (increasing with energy)

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

K_T factorized formula

[L.V. Gribov, E.M. Levin, M.G. Ryskin, Phys.Rept. 100 (1983) 1-150]
[S. Catani, M. Ciafaloni, F. Hautmann, Nucl.Phys. B366 (1991) 135-188]
[J.C. Collins, R.K. Ellis, Nucl.Phys. B360 (1991) 3-30]
[M. Deak, F. Hautmann, H. Jung, K. Kutak, JHEP 0909 (2009) 121 (hybrid)]

$$d\sigma_{AB\to 2j} = \sum_b \int dx_A dx_B \int dk_T^2 \, \mathcal{F}\left(x_A, k_T^2, \mu^2\right) f_{b/B}\left(x_B, \mu^2\right) d\hat{\sigma}_{g^* b\to 2j}\left(x_A, x_B, k_T^2, \mu^2\right)$$

$\mathcal{F}\left(x_A, k_T^2, \mu^2\right)$ – Unintegrated Gluon Distribution (UGD) evolving via BFKL, or better via extensions involving DGLAP corrections like Kimber-Martin-Ryskin (KMR), Kwiecinski-Martin-Stasto (KMS) or CCFM.

$f_{b/B}\left(x_B, \mu^2\right)$ – collinear PDF

$\hat{\sigma}_{g^* b\to 2j}$ – partonic cross section, computed with off-shell incoming gluon in a gauge invariant way. 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]
[PK, JHEP 1407 (2014) 128]
[A. van Hameren, JHEP 1407 (2014) 138]
[A. van Hameren, M. Serino, JHEP 1507 (2015) 010]

No saturation in this formalism (although one can force it by using nonlinear UGD).

Color Glass Condensate (CGC): $Q_s \sim k_T \sim P_T$

[F. Gelis, E. Iancu, J. Jalilian-Marian and R. Venugopalan, Ann. Rev. Nucl. Part. Sci. 60 (2010) 463]

Example: $qA \to qg$ channel

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

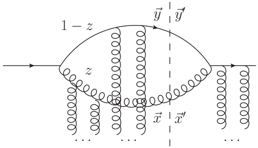
$$\frac{d\sigma_{qA\to 2j}}{d^3p_1 d^3p_2} \sim \int \frac{d^2x}{(2\pi)^2}\frac{d^2x'}{(2\pi)^2}\frac{d^2y}{(2\pi)^2}\frac{d^2y'}{(2\pi)^2} e^{-i\vec{p}_{T1}\cdot\left(\vec{x}_T-\vec{x}'_T\right)} e^{-i\vec{p}_{T2}\cdot\left(\vec{y}_T-\vec{y}'_T\right)} \psi_z^*\left(\vec{x}'_T - \vec{y}'_T\right)\psi_z\left(\vec{x}_T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

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

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

$\psi_z\left(\vec{x}_T\right)$ – 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 $U(\vec{x}_T) = U(-\infty, +\infty; \vec{x}_T)$, $U(a, b; x_T) = \mathcal{P}\exp\left[ig\int_a^b dx^+ A_a^-(x^+, x_T)t^a\right]$.

$\langle \ldots \rangle_{x_g}$ denotes the average over background color field taken typically in McLerran-Venugopalan (MV) model.

Generalized TMD factorization: $P_T \gg k_T \sim Q_s$

Leading twist formula with several process-dependent TMD gluons

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

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

$H^{(i)}$ – hard on-shell factors

$\mathcal{F}_{ag}^{(i)}$ – TMD Gluon Distributions with operator definitions:

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$H^{(i)}$ – hard on-shell factors

$\mathcal{F}_{ag}^{(i)}$ – TMD Gluon Distributions with operator definitions:

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

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

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

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

where $F^{+i}(x)$ is the gluon field in fundamental representation, the operator position ξ is off-light-cone and the Wilson lines and loops are defined as:

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

(compare: in collinear factorization the gluon PDF is $\langle p_A | \mathrm{Tr}\{F^{+i}\left(\xi^+, \vec{0}_T, 0\right) F(0)\} | p_A\rangle$)

Generalized TMD Factorization: lack of universality

Example: TMD for a particular diagram

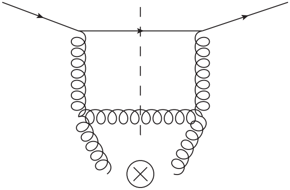
[C.J. Bomhof, P.J. Mulders, F. Pijlman, Eur.Phys.J.C. 47, 147 (2006)]

General expression for TMD gluon distribution:

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

where the Wilson lines $[\xi, 0]_{C_i}$ depend on the process.

For example:



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

Generalized TMD factorization: is it usable?

TMD factorization can be compared with the CGC results in the back-to-back limit ($k_T \ll P_T$). The emerging structures can be then identified with TMD gluon distributions.

Assumming large N_c this leads to an effective factorization:

all UGDs can be expressed by only two fundamental UGDs:

$$\mathcal{F}_{qg}^{(2)}\left(x,k_T^2\right) \sim \int \frac{d^2q_T}{q_T^2}\,\mathcal{F}_{gg}^{(3)}\left(x,q_T^2\right)\mathcal{F}_{qg}^{(1)}\left(x,|k_T-q_T|^2\right)$$

$$\mathcal{F}_{gg}^{(1)}\left(x,k_T^2\right) \sim \int \frac{d^2q_T}{q_T^2}\,\mathcal{F}_{qg}^{(1)}\left(x,q_T^2\right)\mathcal{F}_{qg}^{(1)}\left(x,|k_T-q_T|^2\right)$$

$$\mathcal{F}_{gg}^{(2)}\left(x,k_T^2\right) \sim \int \frac{d^2q_T}{q_T^2}\,\left(q_T-k_T\right)\cdot q_T\,\mathcal{F}_{qg}^{(1)}\left(x,q_T^2\right)\mathcal{F}_{qg}^{(1)}\left(x,|k_T-q_T|^2\right)$$

$$\mathcal{F}_{gg}^{(1)}\left(x,k_T^2\right) \sim \int \frac{d^2q_Td^2q'_T}{q_T^2}\,\mathcal{F}_{gg}^{(3)}\left(x,q_T^2\right)\mathcal{F}_{qg}^{(1)}\left(x,q'^2_T\right)\mathcal{F}_{qg}^{(1)}\left(x,\left|k_T-q_T-q'_T\right|^2\right)$$

1. dipole: $\mathcal{F}_{qg}^{(1)} = xG^{(2)} \sim \langle p_A|\,\mathrm{Tr}\{F(\xi)\,\mathcal{U}^{[-]\dagger}F(0)\,\mathcal{U}^{[+]}\}\,|p_A\rangle$
   appears directly in: inclusive DIS, inclusive jet in pA
2. Weizsacker-Williams (WW):
   $\mathcal{F}_{gg}^{(3)} = xG^{(1)} \sim \langle p_A|\,\mathrm{Tr}\left\{F(\xi)\,\mathcal{U}^{[+]\dagger}F(0)\,\mathcal{U}^{[+]}\right\}|p_A\rangle$
   appears directly in dijets in DIS

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]

We propose a factorization formula which has limiting cases:

1. Generalized TMD when $P_T \gg k_T$ (saturation)
2. High Energy Factorization when $P_T \sim k_T$ (jet decorrelation regime)

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

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

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

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

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

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

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

Gluon distributions: GBW model

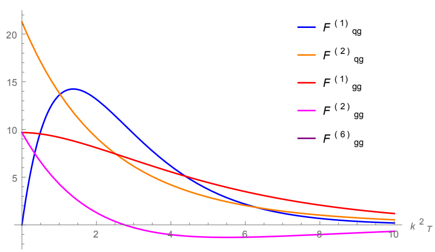
How to obtain 5 gluon distributions?

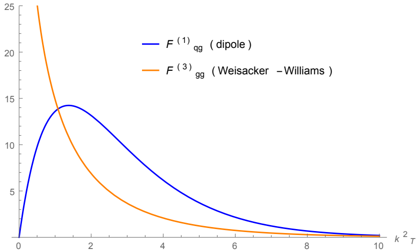
To start, we take the Golec-Biernat-Wusthoff (GBW) model:

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

Assuming gaussian dostribution 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

[E. Petreska, Proceedings, 7th International Workshop MPI@LHC 2015]





Gluon distributions: realistic model (1)

Problem: GBW model has wrong large-k_T behaviour...

Our approach: using the same assumptions as for GBW we derive 5 gluon distributions from $\mathcal{F}_{qg}^{(1)}$ evolving according to the nonlinear extension of the Kwiecinski-Martin-Stasto (KMS) evolution equation.

$\Rightarrow$ BK+running coupling+DGLAP corrections+kinematic constraint ($\mathcal{F}_{qg}^{(1)} \equiv \mathcal{F}$):

[K. Kutak, K. Kwiecinski, Eur. Phys. J. C 29 (2003) 521]

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

$$+\frac{\alpha_s}{2\pi k_T^2}\int_x^1 dz\left\{\left(P_{gg}(z)-\frac{2N_c}{z}\right)\int_{k_{T\,0}^2}^{k_T^2} dq_T^2\mathcal{F}\left(\frac{x}{z},q_T^2\right)+zP_{gq}(z)\,\Sigma\left(\frac{x}{z},k_T^2\right)\right\}$$

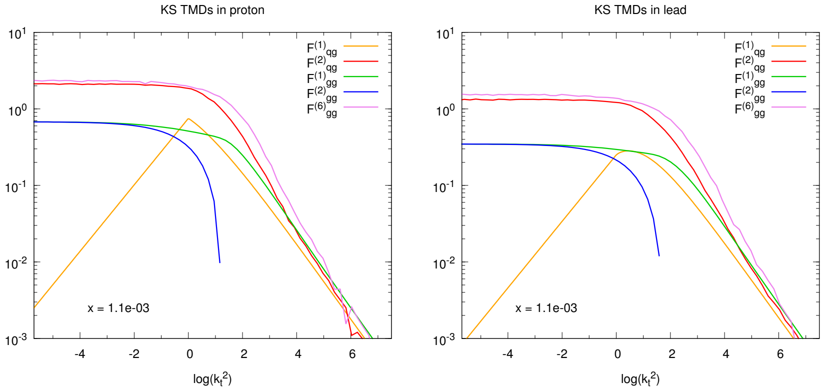
$$-\frac{2\alpha_s^2}{R^2}\left\{\left[\int_{k_T^2}^{\infty}\frac{dq_T^2}{q_T^2}\mathcal{F}\left(x,q_T^2\right)\right]^2+\mathcal{F}\left(x,k_T^2\right)\int_{k_T^2}^{\infty}\frac{dq_T^2}{q_T^2}\ln\left(\frac{q_T^2}{k_T^2}\right)\mathcal{F}\left(x,q_T^2\right)\right\}$$

This equation was fitted to HERA data for proton by Kutak-Sapeta (KS). For nucleus $R_A = RA^{1/3}$ is used and the nonlinear term is enhanced by $A^{1/3}$ (in the UGDs per nucleon). This is a crude approximation, but is enough to provide an insight to nucleus UGDs in the saturation region. We will vary R_A by a parameter d.

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

Gluon distributions: realistic model (2)

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.

Results: $R_{p\mathrm{Pb}}$ for azimuthal disbalance

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

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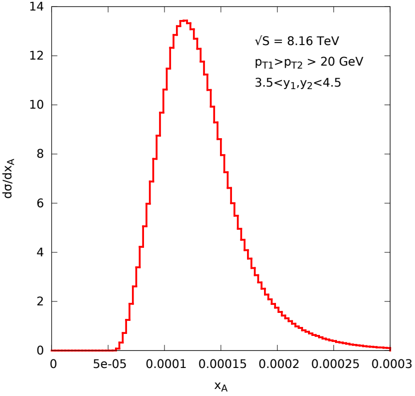
x fractions probed:



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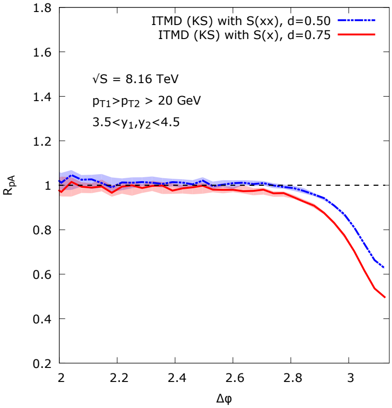
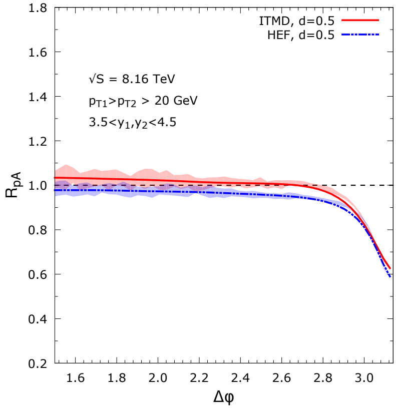
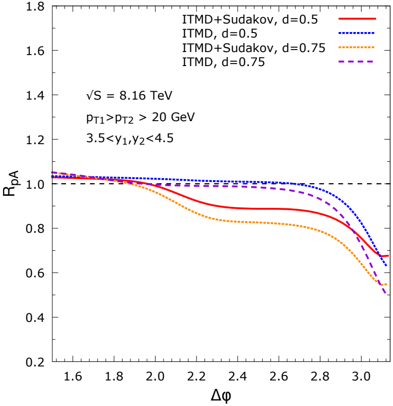




Results: $R_{p\mathrm{Pb}}$ for azimuthal disbalance

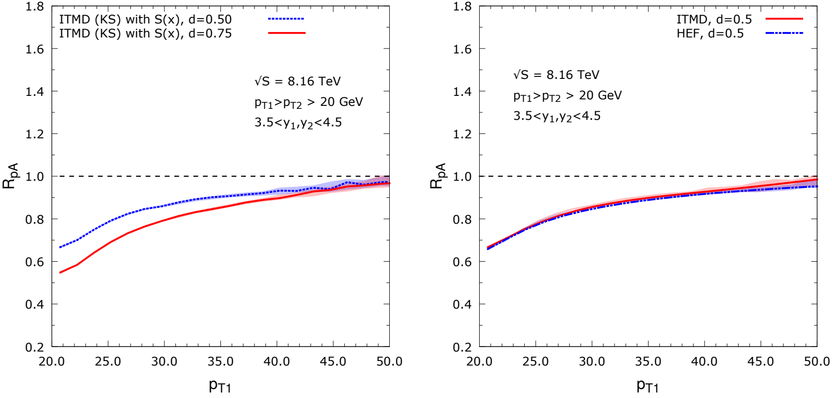
Cuts: $p_{T1} > p_{T2} > 20\,\mathrm{GeV}$, $3.5 < y_1, y_2 < 4.5$, $\sqrt{S} = 8.16\,\mathrm{TeV}$

Including Sudakov resummation (a model of):



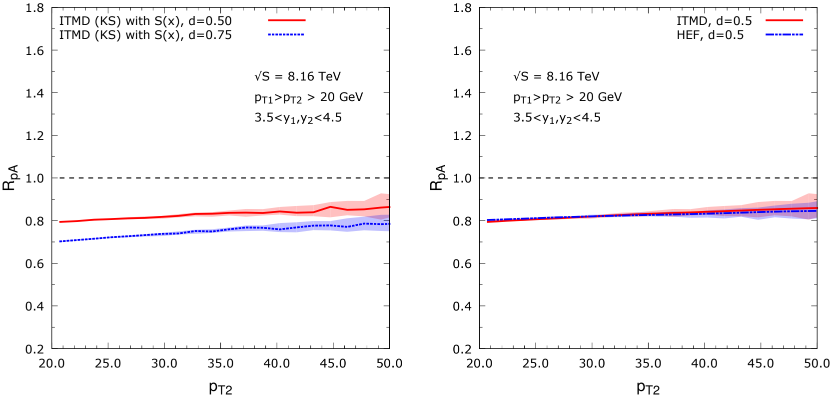
Results: p_T spectra for $R_{p\mathrm{Pb}}$

leading jet spectrum:



Results: p_T spectra for $R_{p\mathrm{Pb}}$

sub-leading jet spectrum:



WW gluon distribution issue

In general WW gluon $G^{(1)}$ and dipole gluon $G^{(2)}$ are independent.

They are related only in 'gaussian approxmiation':

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

and this is what was used before.

- the most basic process it appears directly is dijet production in γA collisions
- complicated evolution equation
- there are no fits of this gluon
- only model calculations within gaussian approximation

Can we learn about WW gluon from UPC?

ITMD for UPC

Factorization formula (direct photon)

$$d\sigma_{AB\to 2j} \sim \int d\omega \frac{dN_\gamma}{d\omega}\, G^{(1)}\left(x_A, k_T^2\right) K_{\gamma g\to q\bar{q}}$$

$\frac{dN_\gamma}{d\omega}$ – photon flux from nucleus, $\omega = x_B E_{\mathrm{Pb}}$
$K_{\gamma g\to q\bar{q}}$ – off-shell hard factor for $\gamma g^* \to q\bar{q}$ process

Formalism requires:
asymmetric kinematics
with $x_B > x_A$ and x_A small

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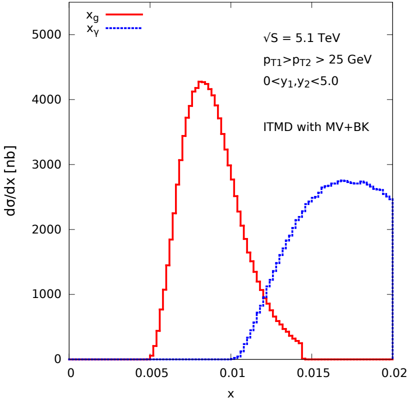

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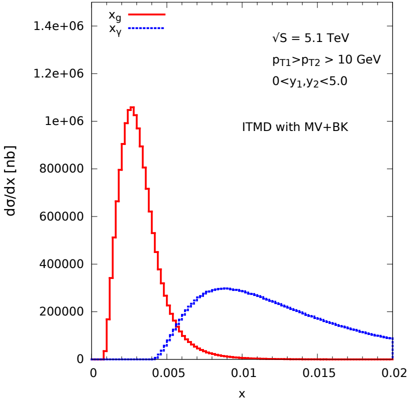

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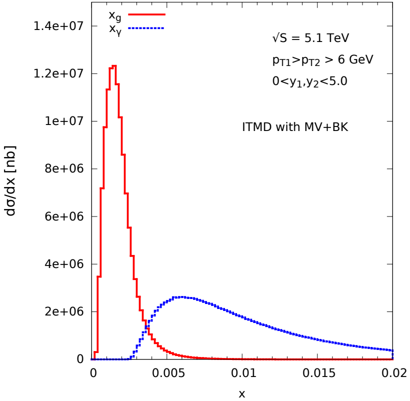
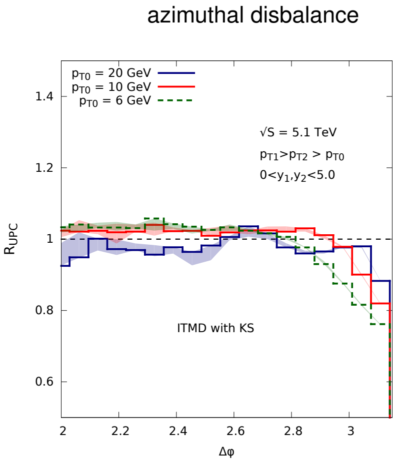
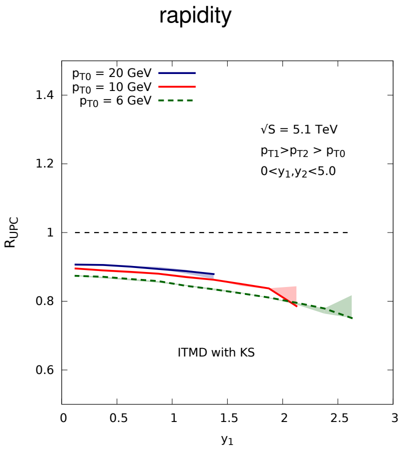


Results: R_{UPC}





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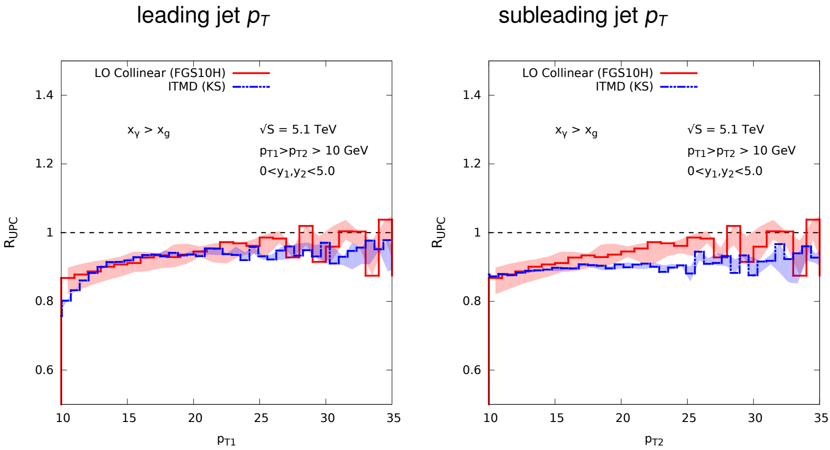

Summary & Outlook

- there is a usable approach for dijets in dilute-dense collisions in saturation formalism beyond leading twist
- it requires five unintegrated gluon distributions which at large N_c can be related to just two independent gluon distributions: $G^{(1)}$ and $G^{(2)}$
- $G^{(1)}$ is only accessible through models with however unconstrained parameters OR through the gaussian approximation from $G^{(2)}$
- first numerical results for pA and UPC in this approach
- UPC probes WW thus it a complementary process to pA collisions
- Main possible improvements:
  - use of five gluons beyond gaussian approximation (requires experimental imput to get $G^{(1)}$)
  - Sudakov-type resummation (complicated in saturation regime)
  - NLO corrections (extremely complicated...)