# Forward trijet production and saturation

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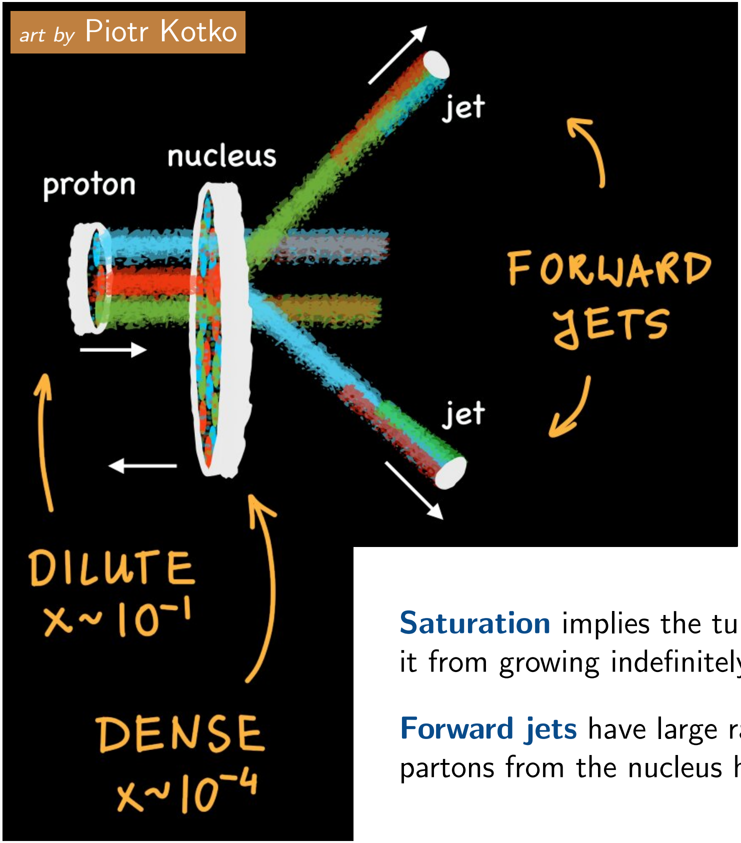
# QCD evolution, dilute vs. dense, forward jets




A dilute system carries a few high-$x$ partons contributing to the hard scattering.

A dense system carries many low-$x$ partons.

At high density, gluons are imagined to undergo recombination, and to saturate.

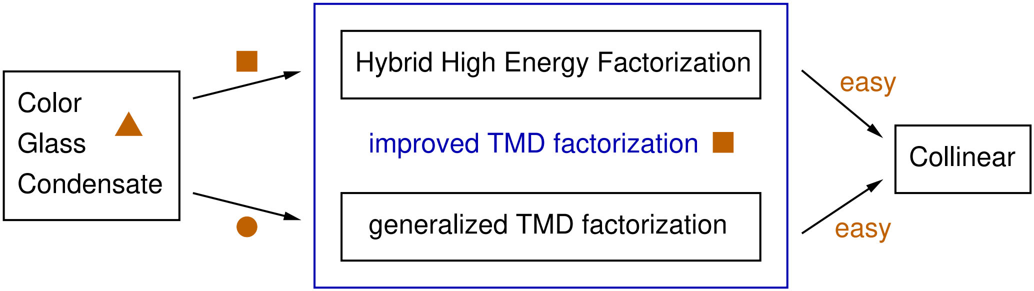
This is modeled with non-linear evolution equations, involving explicit non-vanishing $k_T$.

**Saturation** implies the turnover of the gluon density, stopping it from growing indefinitely for small $x$.

**Forward jets** have large rapidities, and trigger events in which partons from the nucleus have small $x$.

# ITMD Factorization

For forward dijet production in dilute-dense hadronic collisions




▲ McLerran, Venugopalan 1994, Iancu, Venugopalan 2003

■ Kotko, Kutak, Marquet, Petreska, Sapeta, AvH 2015, Altinoluk, Boussarie, Kotko 2019

● Dominguez, Marquet, Xiao, Yuan 2011

Model interpolating between hybrid High Energy Factorization and Generalized TMD factorization and valid for kinematical regions with hard scale $\gtrsim k_T \gtrsim$ saturation scale.
Partonic cross section $d\hat{\sigma}^{(i)}_{gb}$ **depends on color-structure** $i$,
and is calculated with **space-like initial-state gluons**.

$$d\sigma_{AB\to X} = \int dk_T^2 \int dx_A \sum_i \int dx_B \sum_y \Phi^{(i)}_{gy}(x_A, k_T, \mu)\, f_y(x_B, \mu)\, d\hat{\sigma}^{(i)}_{gy\to X}(x_A, x_B, k_T, \mu)$$

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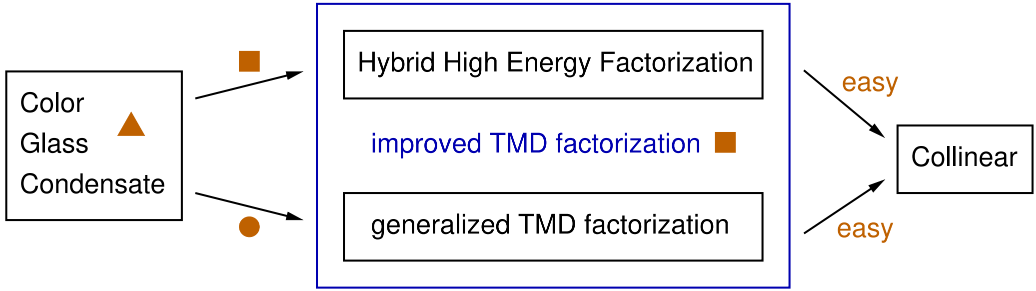


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Model interpolating between hybrid High Energy Factorization and Generalized TMD factorization and valid for kinematical regions with hard scale $\gtrsim k_T \gtrsim$ saturation scale.

ITMD formalism is fully obtained from the CGC formalism, by neglecting certain twist corrections. Antinoluk, Boussarie, Kotko 2019

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# ITMD* factorization for more than 2 jets

We want to establish a similar factorization for more than 2 jets.

However, the ITMD formalism does not account for linearly polarized gluons in unpolarized target.

Such a contribution is absent for massless 2-particle production in CGC theory, but does appear in heavy quark production (Marquet, Roiesnes, Taels 2018, Altinoluk, Marquet, Taels 2021), in the correlation limit for 3-parton final-states (Altinoluk, Boussarie, Marquet, Taels 2020), and can be concluded to be present from 3-jet formulae in CGC (Iancu, Mulian 2019).

This contribution cannot staightforwardly be formulated in terms of gauge-invariant off-shell hard scattering amplitudes

$$\sum_{i,j} \mathcal{M}_i^* \left( \frac{k_T^{(i)} k_T^{(j)}}{2|\vec{k}_T|^2} (\mathcal{F} + \mathcal{H}) + \frac{q_T^{(i)} q_T^{(j)}}{2|\vec{q}_T|^2} (\mathcal{F} - \mathcal{H}) \right) \mathcal{M}_j \quad , \quad \vec{q}_T \cdot \vec{k}_T = 0$$

$\sum_i \mathcal{M}_i k_T^{(i)}$ is gauge invariant while $\sum_i \mathcal{M}_i q_T^{(i)}$ is not. For dijets, it happens that $\mathcal{F} = \mathcal{H}$.

In the following only the manifestly gauge-invariant contribution is included, hence the designation ITMD*.

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$\sum_i \mathcal{M}$ ... $\mathcal{F} = \mathcal{H}$.

In the ... ıence the designation ITMD*.

Using the axial gauge with gluon propagator

$$\frac{-i}{K^2}\left(g^{\mu\nu} - \frac{P^\mu K^\nu + K^\mu P^\nu}{P\cdot K}\right) \qquad P^\mu \text{ hadron momentum}$$

the amplitude $\mathcal{M}$ for a process involving an off-shell gluon with momentum $xP^\mu + k_T^\mu$ can be written as

$$\mathcal{M} = k_T^\mu \mathcal{M}_\mu = -\sum_{i=1}^{2} k_T^{(i)} \mathcal{M}_i$$

where $\mathcal{M}_\mu$ is obtained from the usual Feynman graphs indeed with one gluon simply left "off-shell". The role of "polarization vector" is played by $k_T^\mu$.

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Schematic hybrid (non-ITMD) factorization fomula

$$d\sigma = \sum_{y=g,u,d,\dots} \int dx_1 d^2k_T \int dx_2 \, d\Phi_{g^*y\to n} \, \frac{1}{\text{flux}_{gy}} \, \mathcal{F}_g(x_1, k_T, \mu) \, f_y(x_2, \mu) \sum_{\text{color}} \left| \mathcal{M}^{(\text{color})}_{g^*y\to n} \right|^2$$

$$\mathcal{F}_g \sum_{\text{color}} \left| \mathcal{M}^{(\text{color})} \right|^2 = \mathcal{F}_g \sum_{i_1,i_2,\dots,i_{n+2}} \sum_{j_1,j_2,\dots,j_{n+2}} \left( \tilde{\mathcal{M}}^{i_1 i_2 \dots i_{n+2}}_{j_1 j_2 \dots j_{n+2}} \right)^* \left( \tilde{\mathcal{M}}^{i_1 i_2 \dots i_{n+2}}_{j_1 j_2 \dots j_{n+2}} \right)$$

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ITMD* formula: replace

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with (Bomhof, Mulders, Pijlman 2006; Bury, Kotko, Kutak 2018)

$$(N_c^2 - 1) \sum_{i_1,\ldots,i_n} \sum_{j_1,\ldots,j_{n+2}} \sum_{\bar{\imath}_1,\ldots,\bar{\imath}_{n+2}} \sum_{\bar{\jmath}_1,\ldots,\bar{\jmath}_{n+2}} \left( \tilde{\mathcal{M}}^{i_1 i_2 \cdots i_{n+2}}_{j_1 j_2 \cdots j_{n+2}} \right)^* \left( \tilde{\mathcal{M}}^{\bar{\imath}_1 \bar{\imath}_2 \cdots \bar{\imath}_{n+2}}_{\bar{\jmath}_1 \bar{\jmath}_2 \cdots \bar{\jmath}_{n+2}} \right)$$

$$\times 2 \int \frac{d^4\xi}{(2\pi)^3 P^+} \delta(\xi_+) \, e^{ik\cdot\xi} \left\langle P \right| \left( \hat{F}^+(\xi) \right)^{j_1}_{i_1} \left( \hat{F}^+(0) \right)^{\bar{\jmath}_1}_{\bar{\imath}_1} \left( \mathcal{U}^{[\lambda_2]} \right)_{i_2 \bar{\imath}_2} \left( \mathcal{U}^{[\lambda_2]\dagger} \right)^{j_2 \bar{\jmath}_2} \cdots$$

$$\cdots \left( \mathcal{U}^{[\lambda_{n+2}]} \right)_{i_{n+2} \bar{\imath}_{n+2}} \left( \mathcal{U}^{[\lambda_{n+2}]\dagger} \right)^{j_{n+2} \bar{\jmath}_{n+2}} \left| P \right\rangle$$

where $P$ is the light-like momentum of the hadron (with $P^- = 0$), and $k^\mu = xP^\mu + k_T^\mu$, where $\hat{F}$ is the field strenght,
and $\mathcal{U}^\pm$ is a Wilson line from $0$ to $\xi$ via a "staple-like detour" to $\pm\infty$ depending on the type and state (initial/final) of parton.

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$$\left. \cdots \left(\mathcal{U}^{[\lambda_{n+2}]}\right)_{i_{n+2}\bar{\imath}_{n+2}} \left(\mathcal{U}^{[\lambda_{n+2}]\dagger}\right)^{j_{n+2}\bar{\jmath}_{n+2}} \middle| P \right\rangle$$

where P is ... $P^\mu + k_T^\mu$,

where $\hat{F}$ is ...

and $\mathcal{U}^\pm$ is ... ling on the

type and st...

$$\tilde{\mathcal{M}}^{i_1 i_2 \ldots i_{n+2}}_{j_1 j_2 \ldots j_{n+2}} = \sum_{\sigma\in S_{n+2}} \delta^{i_1}_{j_{\sigma(1)}} \delta^{i_2}_{j_{\sigma(2)}} \cdots \delta^{i_{n+2}}_{j_{\sigma(n+2)}} \mathcal{A}_\sigma$$

Kanaki, Papadopoulos 2000; Maltoni, Paul, Stelzer, Willenbrock 2003

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Schematic hybrid (non-ITMD) factorization fomula

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ITMD* formula: replace

$$\mathcal{F}_g \sum_{\mathrm{color}} \left|\mathcal{M}^{(\mathrm{color})}\right|^2 = \mathcal{F}_g \sum_{\sigma\in S_{n+2}} \sum_{\tau\in S_{n+2}} \mathcal{A}^*_\sigma\, \mathcal{C}_{\sigma\tau}\, \mathcal{A}_\tau \quad , \quad \mathcal{C}_{\sigma\tau} = N_c^{\lambda(\sigma,\tau)}$$

with "TMD-valued color matrix"

$$(N_c^2-1) \sum_{\sigma\in S_{n+2}} \sum_{\tau\in S_{n+2}} \mathcal{A}^*_\sigma\, \tilde{\mathcal{C}}_{\sigma\tau}(x,|k_T|)\, \mathcal{A}_\tau \quad , \quad \tilde{\mathcal{C}}_{\sigma\tau}(x,|k_T|) = N_c^{\bar{\lambda}(\sigma,\tau)} \tilde{\mathcal{F}}_{\sigma\tau}(x,|k_T|)$$

where each function $\tilde{\mathcal{F}}_{\sigma\tau}$ is one of 10 functions

$$\mathcal{F}^{(1)}_{qg} \;,\; \mathcal{F}^{(2)}_{qg} \;,\; \mathcal{F}^{(3)}_{qg}$$

$$\mathcal{F}^{(1)}_{gg} \;,\; \mathcal{F}^{(2)}_{gg} \;,\; \mathcal{F}^{(3)}_{gg} \;,\; \mathcal{F}^{(4)}_{gg} \;,\; \mathcal{F}^{(5)}_{gg} \;,\; \mathcal{F}^{(6)}_{gg} \;,\; \mathcal{F}^{(7)}_{gg}$$

# ITMD* factorization for more than 2 jets

$$\mathcal{F}_{qg}^{(1)}(x,k_T) = \left\langle \mathrm{Tr}\left[\hat{F}^{i+}(\xi)\,\mathcal{U}^{[-]\dagger}\hat{F}^{i+}(0)\,\mathcal{U}^{[+]}\right]\right\rangle \quad , \quad \left\langle \cdots \right\rangle = 2\int \frac{d^4\xi\,\delta(\xi_+)}{(2\pi)^3 P^+}\, e^{ik\cdot\xi}\left\langle P\middle| \cdots \middle|P\right\rangle$$

$$\mathcal{F}_{qg}^{(2)}(x,k_T) = \left\langle \frac{\mathrm{Tr}\left[\mathcal{U}^{[\Box]}\right]}{N_c}\mathrm{Tr}\left[\hat{F}^{i+}(\xi)\,\mathcal{U}^{[+]\dagger}\hat{F}^{i+}(0)\,\mathcal{U}^{[+]}\right]\right\rangle$$

$$\mathcal{F}_{qg}^{(3)}(x,k_T) = \left\langle \mathrm{Tr}\left[\hat{F}^{i+}(\xi)\,\mathcal{U}^{[+]\dagger}\hat{F}^{i+}(0)\,\mathcal{U}^{[\Box]}\mathcal{U}^{[+]}\right]\right\rangle$$

$$\mathcal{F}_{gg}^{(1)}(x,k_T) = \left\langle \frac{\mathrm{Tr}\left[\mathcal{U}^{[\Box]\dagger}\right]}{N_c}\mathrm{Tr}\left[\hat{F}^{i+}(\xi)\,\mathcal{U}^{[-]\dagger}\hat{F}^{i+}(0)\,\mathcal{U}^{[+]}\right]\right\rangle$$

$$\mathcal{F}_{gg}^{(2)}(x,k_T) = \frac{1}{N_c}\left\langle \mathrm{Tr}\left[\hat{F}^{i+}(\xi)\,\mathcal{U}^{[\Box]\dagger}\right]\mathrm{Tr}\left[\hat{F}^{i+}(0)\,\mathcal{U}^{[\Box]}\right]\right\rangle$$

$$\mathcal{F}_{gg}^{(3)}(x,k_T) = \left\langle \mathrm{Tr}\left[\hat{F}^{i+}(\xi)\,\mathcal{U}^{[+]\dagger}\hat{F}^{i+}(0)\,\mathcal{U}^{[+]}\right]\right\rangle$$

$$\mathcal{F}_{gg}^{(4)}(x,k_T) = \left\langle \mathrm{Tr}\left[\hat{F}^{i+}(\xi)\,\mathcal{U}^{[-]\dagger}\hat{F}^{i+}(0)\,\mathcal{U}^{[-]}\right]\right\rangle$$

$$\mathcal{F}_{gg}^{(5)}(x,k_T) = \left\langle \mathrm{Tr}\left[\hat{F}^{i+}(\xi)\,\mathcal{U}^{[\Box]\dagger}\mathcal{U}^{[+]\dagger}\hat{F}^{i+}(0)\,\mathcal{U}^{[\Box]}\mathcal{U}^{[+]}\right]\right\rangle$$

$$\mathcal{F}_{gg}^{(6)}(x,k_T) = \left\langle \frac{\mathrm{Tr}\left[\mathcal{U}^{[\Box]}\right]}{N_c}\frac{\mathrm{Tr}\left[\mathcal{U}^{[\Box]\dagger}\right]}{N_c}\mathrm{Tr}\left[\hat{F}^{i+}(\xi)\,\mathcal{U}^{[+]\dagger}\hat{F}^{i+}(0)\,\mathcal{U}^{[+]}\right]\right\rangle$$

$$\mathcal{F}_{gg}^{(7)}(x,k_T) = \left\langle \frac{\mathrm{Tr}\left[\mathcal{U}^{[\Box]}\right]}{N_c}\mathrm{Tr}\left[\hat{F}^{i+}(\xi)\,\mathcal{U}^{[\Box]\dagger}\mathcal{U}^{[+]\dagger}\hat{F}^{i+}(0)\,\mathcal{U}^{[+]}\right]\right\rangle$$

# ITMD gluons

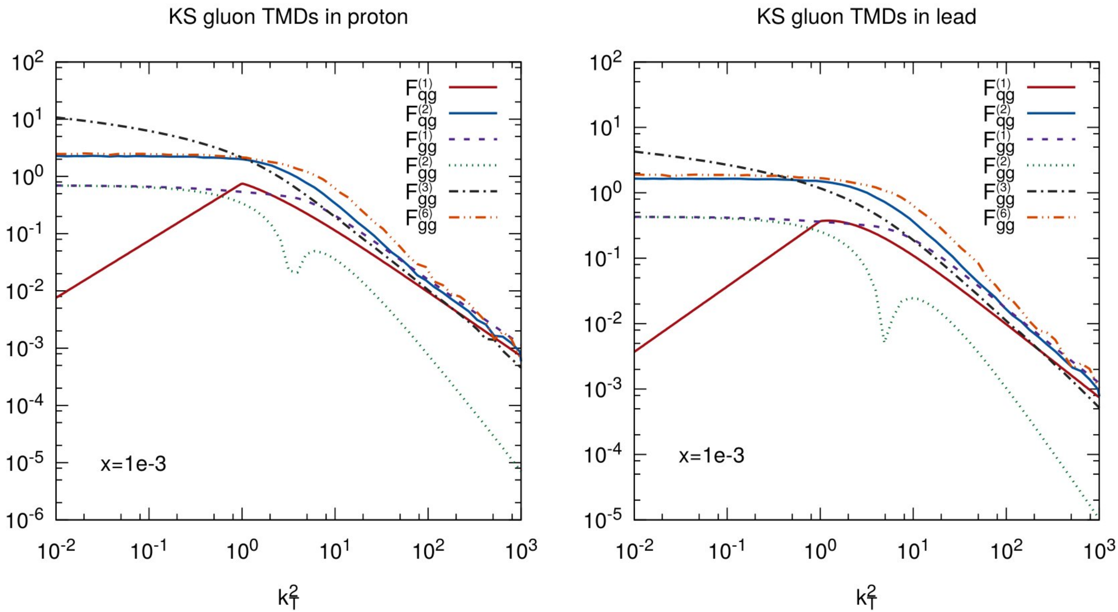
Start with dipole distribution $\mathcal{F}_{qg}^{(1)}(x, k_T) = \left\langle \mathrm{Tr}\left[\hat{F}^{i+}(\xi)\,\mathcal{U}^{[-]\dagger}\hat{F}^{i+}(0)\,\mathcal{U}^{[+]}\right]\right\rangle$ evolved via the BK equation formulated in momentum space supplemented with subleading corrections and fitted to $F_2$ data (Kutak, Sapeta 2012)

All other distribution appearing in dijet production, $\mathcal{F}_{qg}^{(2)}, \mathcal{F}_{gg}^{(1)}, \mathcal{F}_{gg}^{(2)}, \mathcal{F}_{gg}^{(6)}$, in the mean-field approximation (AvH, Marquet, Kotko, Kutak, Sapeta, Petreska 2016).

This is, at leading order in $1/N_c$. In this approximation, the same distributions suffice for trijets.

# ITMD gluons

Bury, AvH, Kotko, Kutak 2020

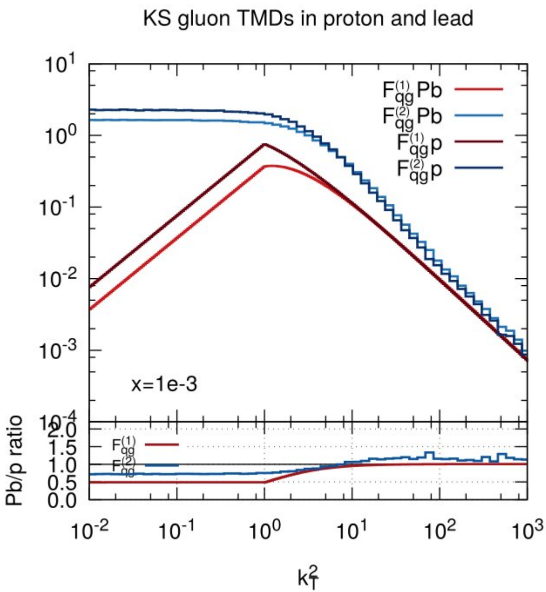


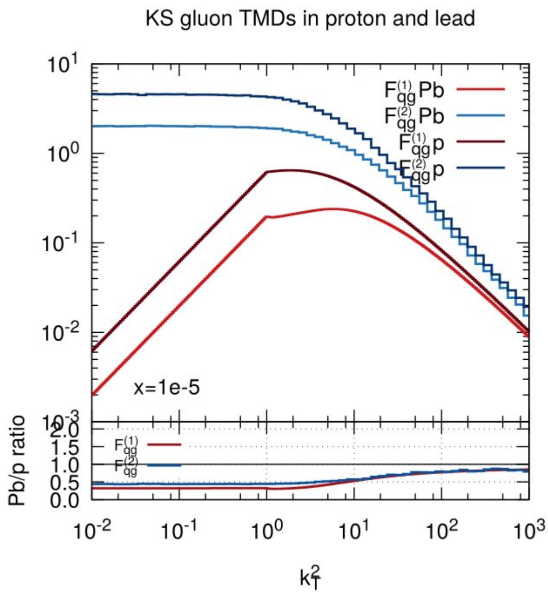

Dependence of $\mathcal{F}_{qg}^{(1)}$ on $k_T$ below 1GeV approximated by power-like fall-off. For higher values of $|k_T|$ it is a solution to the BK equation.

TMDs decrease as $1/|k_T|$ for increasing $|k_T|$, except $\mathcal{F}_{gg}^{(2)}$, which decreases faster (even becomes negative, absolute value shown here).

# ITMD gluons

Bury, AvH, Kotko, Kutak 2020




Ratio Pb/p is smaller than 1 for small $x$,
but can become larger than 1 for moderate $x$ and large $|k_T|$.

# Set up

We consider p-p and p-Pb collisions at $5.02\text{TeV}$ producing at least $3$ jets with forward rapidities $3.2 < |y_1^*, y_2^*, y_3^*| < 4.9$ in the CM frame.

Jet definition: $\Delta R > 0.5$, $p_T > 20\text{GeV}$

renormalization/factorization scale: $(p_{T\,1} + p_{T\,2} + p_{T\,3})/3$

Collinear PDFs: CTEQ10NLO from LHAPDF6

Include all partonic processes with $5$ light flavors with an (off-shell) gluon and a quark or gluon in the initial state.

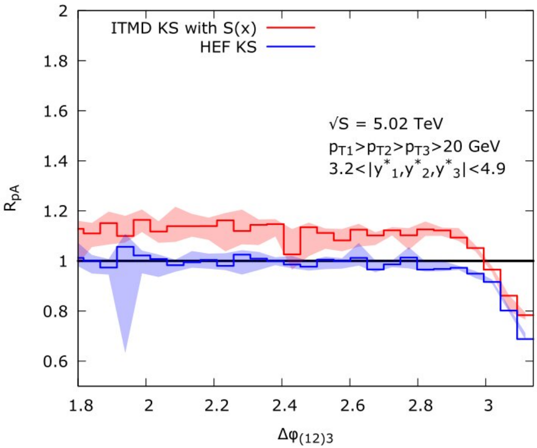
observables:
$\Delta\phi_{12}$ (angle between 2 hardest jets),
$\Delta\phi_{13}$ (angle between hardest jet and 3rd hardest jet),
$\Delta\phi_{(12)3}$ (angle between the sum of the two hardest and the 3rd hardest jet. Is sensitive to momentum inbalance)

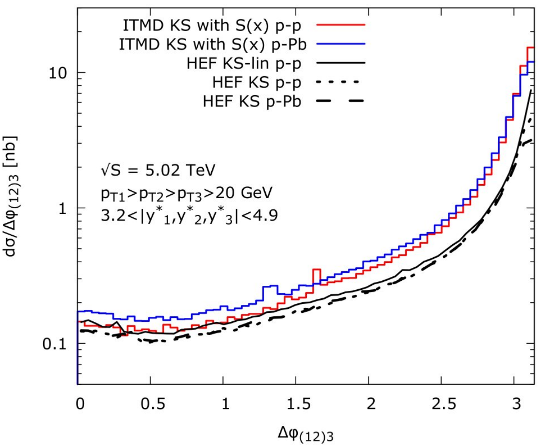
Nuclear modification ratio $R_{pA} = \dfrac{1}{A}\dfrac{d\sigma^{pPb}/d\mathcal{O}}{d\sigma^{pp}/d\mathcal{O}}$ where $A$ is the number of nucleons

Calculations performed independently with LxJet (Kotko) and KaTie (AvH 2018)

# Results






$S(x)$ refers to the $x$-dependent treatment of the nuclear target area, guaranteeing unitarity.

Saturation effect for $\Delta\phi_{(12)3} \approx \pi$, enhancement of pPb result for $\Delta\phi_{(12)3} < \pi$ due to broadening of the TMD distributions.

ITMD* normalization significantly larger than HEF, due to different shape and normalization of the extra TMDs present in ITMD* but not in HEF.

# Summary

- small-$x$ Improved TMD factorization allows to consistently include saturation effects in calculations for forward dijets
- we extended ITMD factorization to ITMD* for more than 2 jets, and performed explicit calculations for 3 jets
- we observe significant saturation effects in the nuclear modification factor for momentum inbalance-sensitive observable
- we observe significant differences between results from ITMD* and $k_T$/high-energy factorization, implying strong discriminating potential

Thank you for your attention.