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FORWARD DI-JETS IN p+A COLLISIONS IN THE ITMD FRAMEWORK

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In collaboration with Cyrille Marquet (Cyrille.Marquet@cern.ch)

OUTLINE

I. What is saturation?
   I. Gluon branching
   II. Parton distribution functions
   III. Where to look for saturation effects?
   IV. Saturation inside the nucleus
II. Di-jet events at forward rapidity
   I. Use of nuclear effects
   II. Cross section calculation
   III. Nuclear modification factor
III. Conclusions

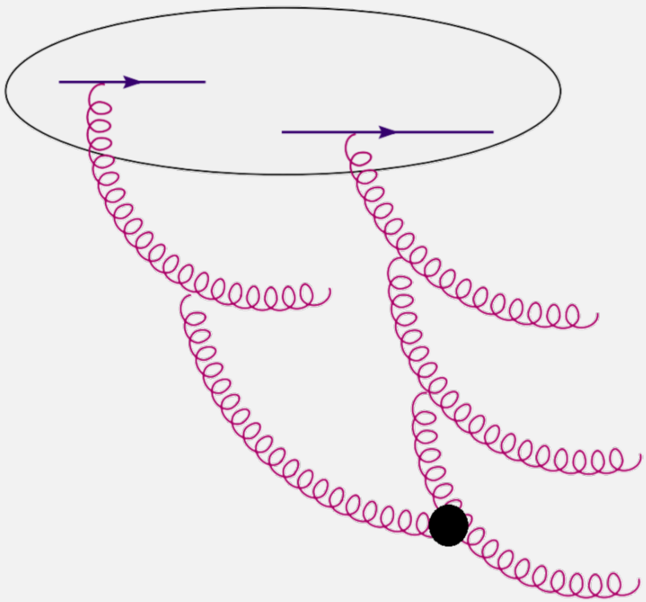
WHAT IS SATURATION?

GLUON BRANCHING

Gluon branching – The number of gluons grows as x decreases.

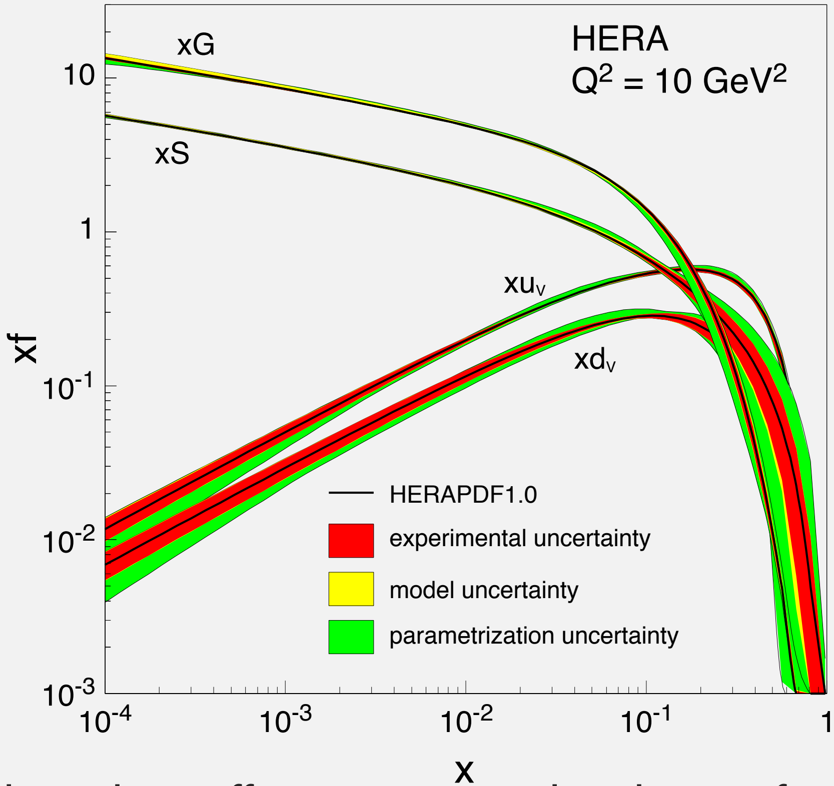
- The more gluons there are in a proton, the more they recombine.

Gluon recombination – High density of gluons can lead to overlapping of their wave functions and two gluons can merge into one.



PARTON DISTRIBUTION FUNCTIONS

- xS – Sea quark distribution
- xG – Gluon distribution
- xu_v – Valence u-quark distribution
- xd_v – Valence d-quark distribution



We can see the contribution of gluon branching effects in parton distribution functions.

Do the gluon recombination effects also contribute?

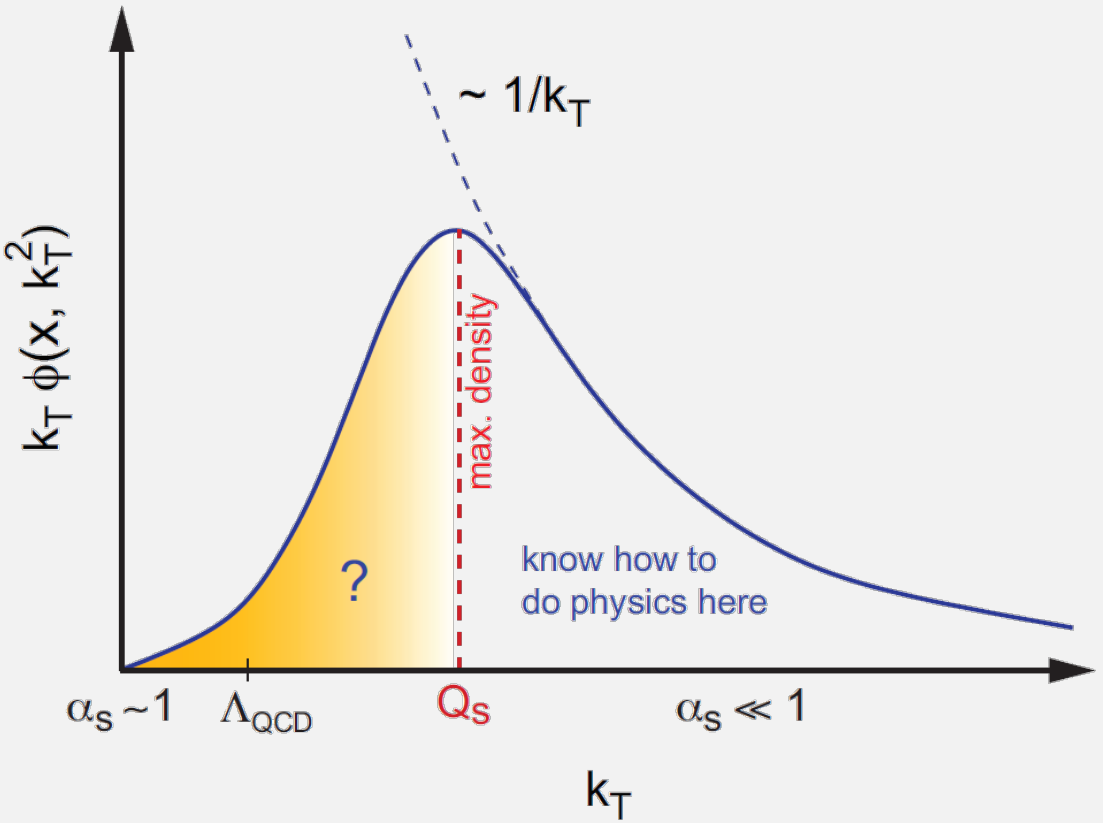
Yuri V. Kovchegov. Brief Review of Saturation Physics. Acta Phys. Polon., B45(12):2241–2256, 2014.

WHERE TO LOOK FOR SATURATION EFFECTS?

- To observe saturation effects, we need to reach low values of x.
- With a fixed collision energy, lower-x corresponds to lower values of k_t, the typical transverse momentum of the process.
- Low k_t jets can be however difficult to measure.

$$x \sim \frac{k_t}{\sqrt{s}}$$

WHERE TO LOOK FOR SATURATION EFFECTS?



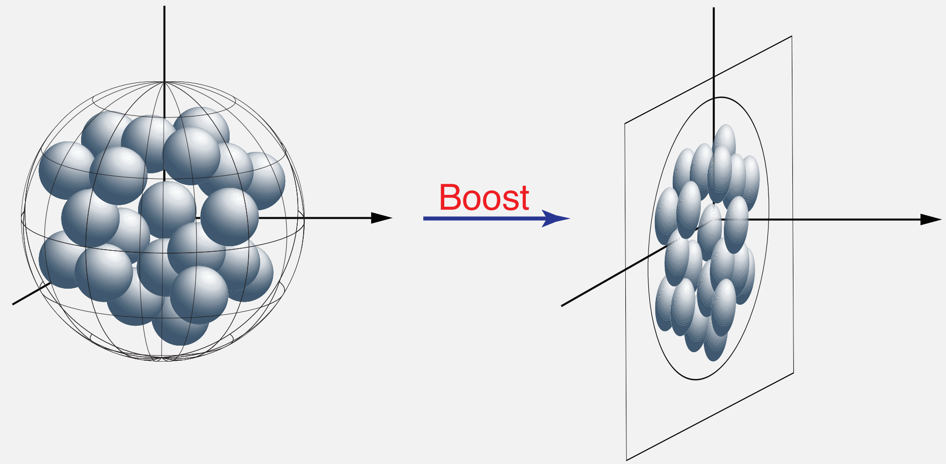
Saturation effects suppress distribution functions at low values of k_t. Maximum density is at Q_s.

Cyrille Marquet. Open questions in QCD at high parton density. Nucl.Phys. A904-905 (2013).

SATURATION INSIDE THE NUCLEUS

If we look at the influence of nuclear effects on saturation, we find out that

$$Q_{s\,A}^2 \sim A^{1/3} Q_{s\,p}^2$$



Compared to the proton case, the saturation scale inside a nucleus is larger, because of Lorentz contraction.

The goal is to use forward dijets in pA collisions to look for saturation effects in lead.

Yuri V. Kovchegov. Brief Review of Saturation Physics. Acta Phys. Polon., B45(12):2241–2256, 2014.

WHAT PROCESSES TO FOCUS ON?

STUDIED PROCESSES

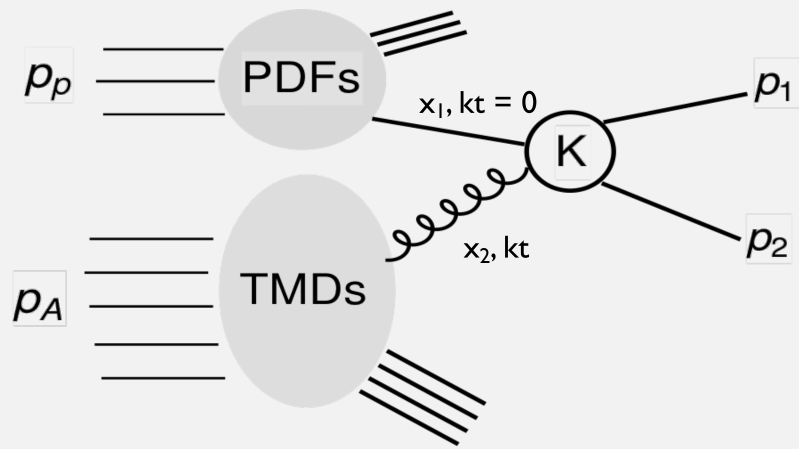
For our computation, we focused on back-to-back jets in the forward region of rapidity.

Why?

STUDIED PROCESSES

We want to reach low values of k_t.

Although p_{1t}, p_{2t} >> Q_s

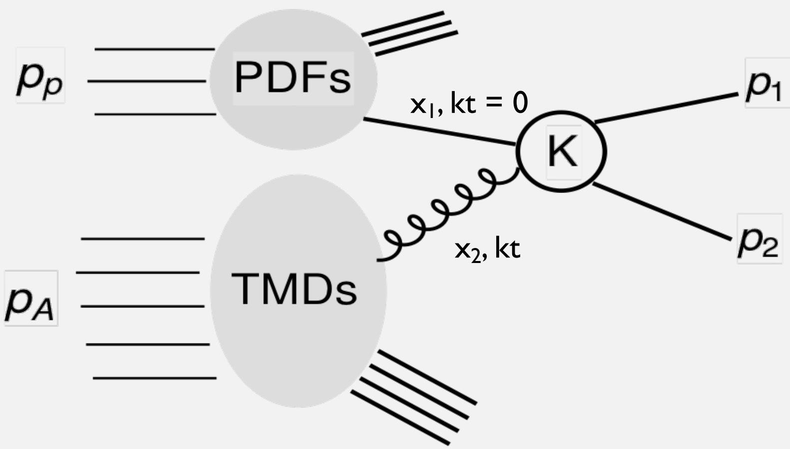


If we focus on back-to-back jets in the transverse momentum plane, we can get

$$k_t = |\vec{p}_{1t} + \vec{p}_{2t}| \text{ where } k_t \sim Q_s$$

STUDIED PROCESSES

Furthermore, it is necessary to reach the region where x_1 is large and $x_2 << 1$.



$x_2 << 1$ is necessary to detect saturation effects; large x_1 is required, because in this region of x, we can use parton distribution functions that are known with great precision from previous experiments.

STUDIED PROCESSES

For x_1 and x_2 holds:

$$x_1 = \frac{1}{\sqrt{s}} \left(|p_{1t}| e^{y_1} + |p_{2t}| e^{y_2} \right) \ , \ x_2 = \frac{1}{\sqrt{s}} \left(|p_{1t}| e^{-y_1} + |p_{2t}| e^{-y_2} \right)$$

Therefore for $y_1, y_2 \gg 1$ we obtain $x_1 \sim 1$ and $x_2 \ll 1$.

That is why we shall focus on studying back-to-back jets in the forward region in rapidity to detect saturation effects.

HOW DO WE DETERMINE WHETHER SATURATION EFFECTS ARE PRESENT?

USE OF NUCLEAR EFFECTS

We use the fact that in nuclei, the saturation scale reaches higher values than in protons.

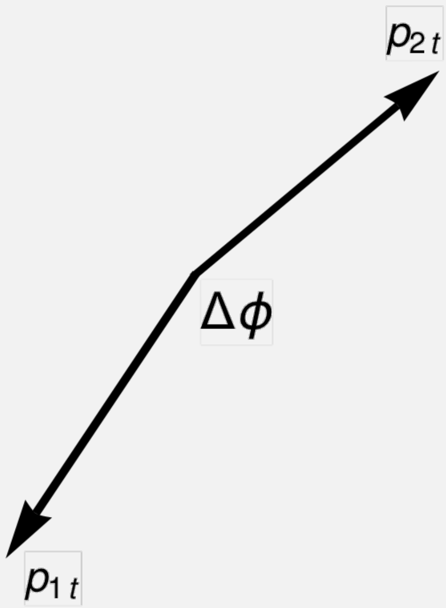
$$Q_s^2 \sim A^{1/3}$$

For the detection of saturation effects we use:

$$R_{\mathrm{pPb}} = \frac{\dfrac{d\sigma^{p+Pb}}{d\mathcal{O}}}{A\,\dfrac{d\sigma^{p+p}}{d\mathcal{O}}}$$

We look for suppression of this ratio with respect to unity.

USE OF NUCLEAR EFFECTS

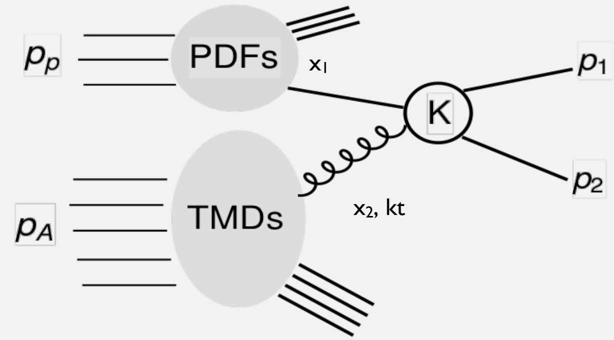


When we take a look at the nuclear modification factor with respect to the angle between the two jets, we can see the non-linear effects as a suppression at about ~180° when $p_{1t} \sim p_{2t}$.

$$R_{\mathrm{pPb}} = \frac{\dfrac{d\sigma^{p+Pb}}{d\mathcal{O}}}{A\ \dfrac{d\sigma^{p+p}}{d\mathcal{O}}}$$

HOW DO WE PREDICT THESE CROSS SECTIONS?

CROSS SECTION CALCULATION

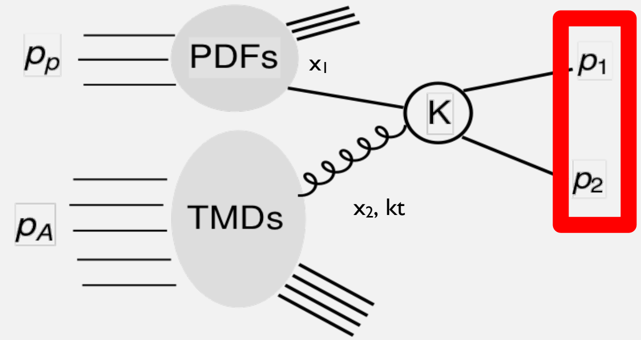


The cross section is calculated as:

$$\frac{d\sigma^{pA\to \mathrm{dijets}+X}}{d^2P_t d^2k_t dy_1 dy_2} = \frac{\alpha_s^2}{(x_1x_2s)^2}\sum_{a,c,d}\frac{x_1 f_{a/p}(x_1)}{1+\delta_{cd}}\sum_{i=1}^{2}K^{(i)}_{ag^*\to cd}(P_t,k_t)\Phi^{(i)}_{ag\to cd}(x_2,k_t)$$

A. van Hameren, P. Kotko, K. Kutak, C. Marquet, E. Petreska and S. Sapeta, JHEP 1612 (2016) 034, arXiv:1607.03121

CROSS SECTION CALCULATION



$$\frac{d\sigma^{pA\to \mathrm{dijets}+X}}{\boxed{d^2P_t d^2k_t dy_1 dy_2}} = \frac{\alpha_s^2}{(x_1 x_2 s)^2} \sum_{a,c,d} \frac{x_1 f_{a/p}(x_1)}{1+\delta_{cd}} \sum_{i=1}^{2} K^{(i)}_{ag^*\to cd}(P_t, k_t)\Phi^{(i)}_{ag\to cd}(x_2, k_t)$$

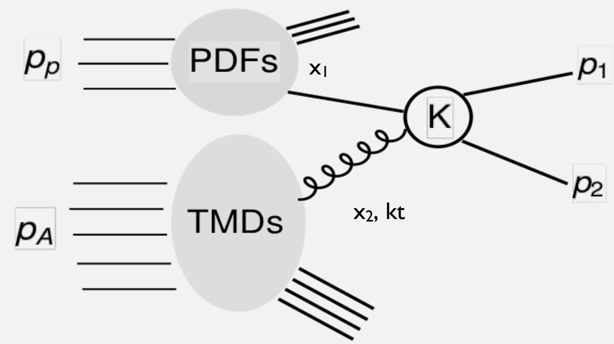
- P_t - Single jet transverse momentum, k_t - jet pair transverse momentum,

  y_1, y_2 – jet rapidities $\in$ [3.5, 4.5], p_{t1}, p_{t2} – jet momenta $\in$ [20, 250] GeV/c

$$k_t = \sqrt{p_{t1}^2 + p_{t2}^2 + 2p_{t1}p_{t2}\cos(\Delta\varphi)} \qquad \vec{P_t} = \frac{p_2^+\vec{p_1} - p_1^+\vec{p_2}}{p_1^+ + p_2^+} \qquad p_i^+ = p_{ti}e^{y_i}/\sqrt{2}$$

A. van Hameren, P. Kotko, K. Kutak, C. Marquet, E. Petreska and S. Sapeta, JHEP 1612 (2016) 034, arXiv:1607.03121

CROSS SECTION CALCULATION

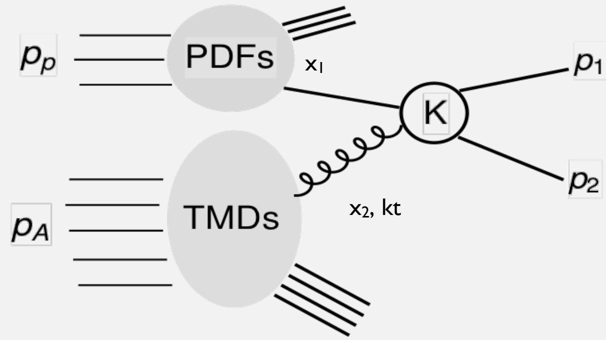


$$\frac{d\sigma^{pA\to \text{dijets}+X}}{d^2P_t d^2k_t dy_1 dy_2} = \frac{\boxed{\alpha_s^2}}{(x_1 x_2 s)^2} \sum_{a,c,d} \frac{x_1 f_{a/p}(x_1)}{1+\delta_{cd}} \sum_{i=1}^{2} K^{(i)}_{ag^*\to cd}(P_t, k_t)\Phi^{(i)}_{ag\to cd}(x_2, k_t)$$

- Running coupling – cancels in the ratio, so we fix it in our computation.

A. van Hameren, P. Kotko, K. Kutak, C. Marquet, E. Petreska and S. Sapeta, JHEP 1612 (2016) 034, arXiv:1607.03121

CROSS SECTION CALCULATION

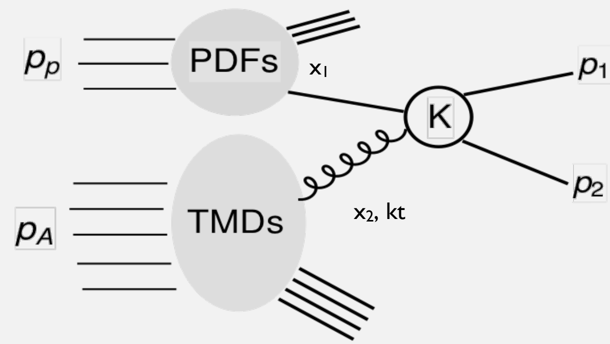


$$\frac{d\sigma^{pA\to \text{dijets}+X}}{d^2P_t d^2k_t dy_1 dy_2} = \frac{\alpha_s^2}{\boxed{x_1 x_2 s}^2} \sum_{a,c,d} \frac{x_1 f_{a/p}(x_1)}{1+\delta_{cd}} \sum_{i=1}^{2} K^{(i)}_{ag^*\to cd}(P_t,k_t)\Phi^{(i)}_{ag\to cd}(x_2,k_t)$$

- x_1 corresponds to the projectile particle, x_2 to the target particle and s is the energy of the collision.

A. van Hameren, P. Kotko, K. Kutak, C. Marquet, E. Petreska and S. Sapeta, JHEP 1612 (2016) 034, arXiv:1607.03121

CROSS SECTION CALCULATION

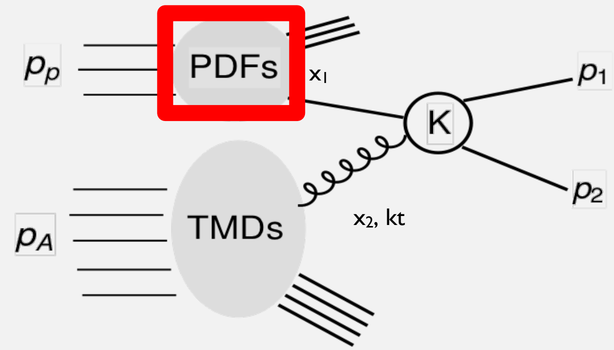


$$\frac{d\sigma^{pA\to \mathrm{dijets}+X}}{d^2P_t d^2k_t dy_1 dy_2} = \frac{\alpha_s^2}{(x_1x_2s)^2}\sum_{a,c,d}\frac{x_1 f_{a/p}(x_1)}{\boxed{1+\delta_{cd}}}\sum_{i=1}^{2}K^{(i)}_{ag^*\to cd}(P_t,k_t)\Phi^{(i)}_{ag\to cd}(x_2,k_t)$$

- The factor of ½ is included in processes with indistinguishable outgoing particles.

A. van Hameren, P. Kotko, K. Kutak, C. Marquet, E. Petreska and S. Sapeta, JHEP 1612 (2016) 034, arXiv:1607.03121

CROSS SECTION CALCULATION



1) Projectile gluon distribution

$$\frac{d\sigma^{pA\to\text{dijets}+X}}{d^2P_t d^2k_t dy_1 dy_2} = \frac{\alpha_s^2}{(x_1x_2s)^2}\sum_{a,c,d}\frac{\boxed{x_1 f_{a/p}(x_1)}}{1+\delta_{cd}}\sum_{i=1}^{2}K^{(i)}_{ag^*\to cd}(P_t,k_t)\Phi^{(i)}_{ag\to cd}(x_2,k_t)$$

Is obtained from data from previous experiments.

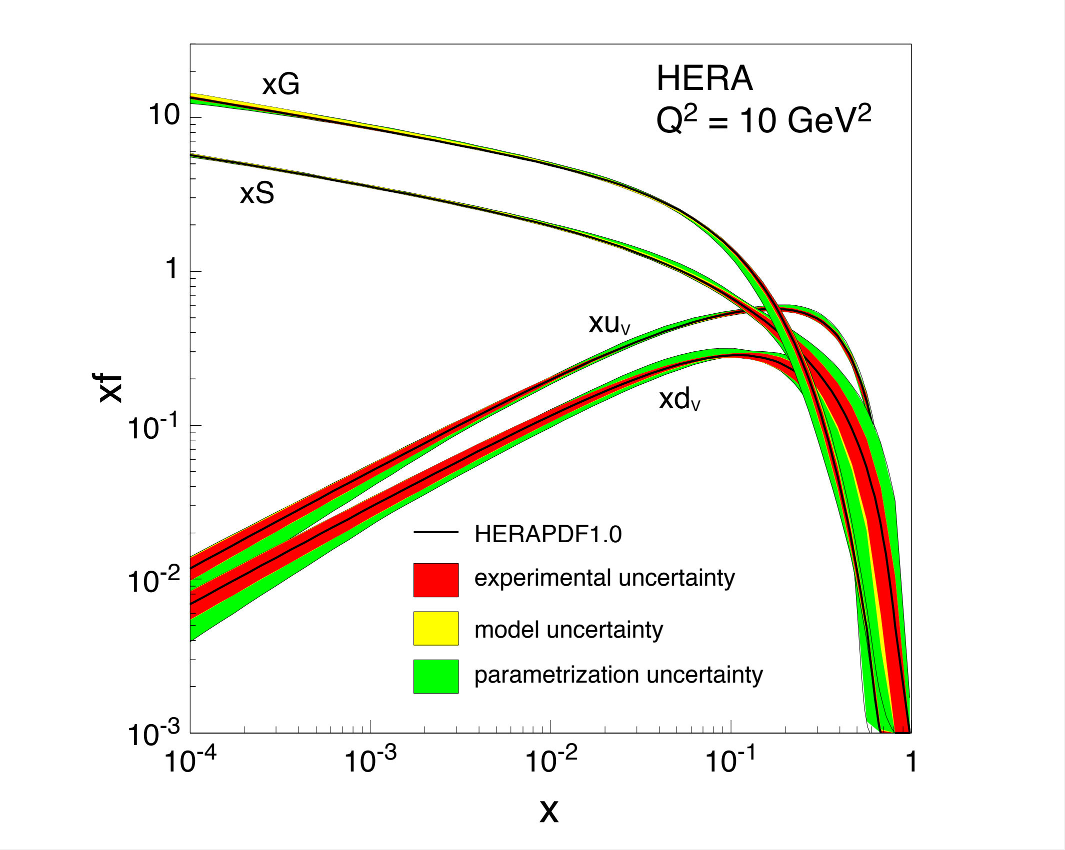
A. van Hameren, P. Kotko, K. Kutak, C. Marquet, E. Petreska and S. Sapeta, JHEP 1612 (2016) 034, arXiv:1607.03121

CROSS SECTION CALCULATION

Projectile gluon distrib

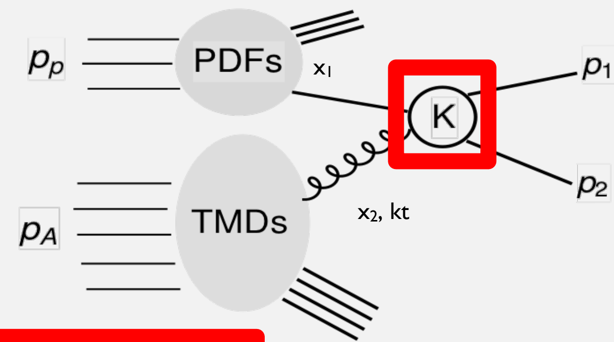
$$\frac{d\sigma^{pA\to \mathrm{dijets}+X}}{d^2P_t d^2k_t dy_1 dy_2} = \frac{\alpha}{(x_1 x} \quad k_t)$$

Is obtained from data from



A. van Hameren, P. Kotko, K. Kutak, C. Marquet, E. Petreska and S. Sapeta, JHEP 1612 (2016) 034, arXiv:1607.03121

CROSS SECTION CALCULATION



2) Matrix elements

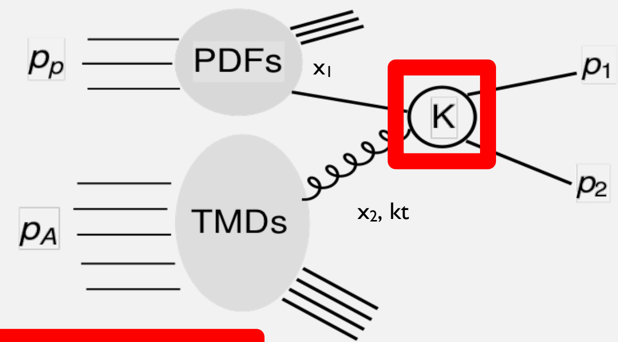
$$\frac{d\sigma^{pA\to\mathrm{dijets}+X}}{d^2P_t d^2k_t dy_1 dy_2} = \frac{\alpha_s^2}{(x_1x_2s)^2}\sum_{a,c,d}\frac{x_1 f_{a/p}(x_1)}{1+\delta_{cd}}\sum_{i=1}^{2}\boxed{K^{(i)}_{ag^*\to cd}(P_t,k_t)}\,\Phi^{(i)}_{ag\to cd}(x_2,k_t)$$

2-to-2 matrix elements with non-zero gluon k_t.

A. van Hameren, P. Kotko, K. Kutak, C. Marquet, E. Petreska and S. Sapeta, JHEP 1612 (2016) 034, arXiv:1607.03121

CROSS SECTION CALCULATION

Matrix elements



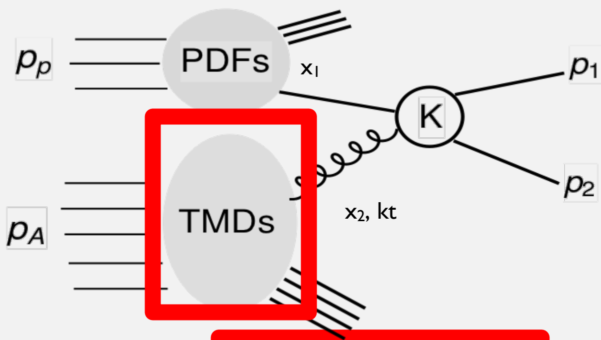
$$\frac{d\sigma^{pA\to \mathrm{dijets}+X}}{d^2P_t d^2k_t dy_1 dy_2} = \frac{\alpha_s^2}{(x_1x_2s)^2}\sum_{a,c,d}\frac{x_1 f_{a/p}(x_1)}{1+\delta_{cd}}\sum_{i=1}^{2}\boxed{K^{(i)}_{ag^*\to cd}(P_t,k_t)}\,\Phi^{(i)}_{ag\to cd}(x_2,k_t)$$

Matrix elements have been computed in:

F. Dominguez, C. Marquet, B. -W. Xiao and F. Yuan, Phys. Rev. D 83 (2011) 105005 – with zero gluon k_t.

A. van Hameren, P. Kotko, K. Kutak, C. Marquet, E. Petreska and S. Sapeta, arXiv:1607.03121 – with non-zero gluon k_t.

CROSS SECTION CALCULATION



3) Transverse momentum distributions

$$\frac{d\sigma^{pA\to \mathrm{dijets}+X}}{d^2P_t d^2k_t dy_1 dy_2} = \frac{\alpha_s^2}{(x_1x_2s)^2}\sum_{a,c,d}\frac{x_1 f_{a/p}(x_1)}{1+\delta_{cd}}\sum_{i=1}^{2}K^{(i)}_{ag^*\to cd}(P_t,k_t)\boxed{\Phi^{(i)}_{ag\to cd}(x_2,k_t)}$$

Five TMDs are needed to describe this process. These are now process dependent and not universal, unlike the usual PDFs.

For the computation, we need to undergo several substeps.

A. van Hameren, P. Kotko, K. Kutak, C. Marquet, E. Petreska and S. Sapeta, JHEP 1612 (2016) 034, arXiv:1607.03121

CROSS SECTION CALCULATION

a) Scattering amplitude

- The scattering amplitude corresponds to the cross section of the interaction of a color dipole with a nucleus. It is a solution of the Balitsky-Kovchegov equation.
- In our approach, we focus on rcBK with factorized b-dependence. (The integral over impact parameter is represented with a multiplicative factor.)

$$N_F(x, \mathbf{r}) = 1 - S_F(x, \mathbf{r})$$

CROSS SECTION CALCULATION

a) Scattering amplitude

$$\frac{\partial N(r,Y)}{\partial \ln Y} = \int d\vec{r}_1 K(\vec{r},\vec{r}_1,\vec{r}_2)(N(\vec{r}_1,Y) + N(\vec{r}_2,Y) - N(\vec{r},Y) - N(\vec{r}_1,Y)N(\vec{r}_2,Y))$$

with kernel $K(\vec{r},\vec{r}_1,\vec{r}_2) = \frac{\alpha_s(r^2)N_c}{2\pi}\left(\frac{r^2}{r_1^2 r_2^2} + \frac{1}{r_1^2}\left(\frac{\alpha_s(r_1^2)}{\alpha_s(r_2^2)} - 1\right) + \frac{1}{r_2^2}\left(\frac{\alpha_s(r_2^2)}{\alpha_s(r_1^2)} - 1\right)\right)$ where $\vec{r}_2 = \vec{r} - \vec{r}_1$

The initial condition at $x_0 = 0.01$ is $N^{MV}(r) = 1 - \exp\left(\frac{-(r^2 Q_{s0}^2)}{4}\ln\left(\frac{1}{r^2 \Lambda_{QCD}^2} + e\right)\right)$

We used $\Lambda_{QCD} = 0.241$ GeV, $Q_{s0}^2 = 0.6$ GeV^2 for lead and $Q_{s0}^2 = 0.2$ GeV^2 for protons.

I. Balitsky, Nucl. Phys. B 463, 99 (1996)
Y. V. Kovchegov, Phys. Rev. D 60, 034008 (1999)
J. L. Albacete at al, Eur.Phys.J. C71 (2011) 1705

CROSS SECTION CALCULATION

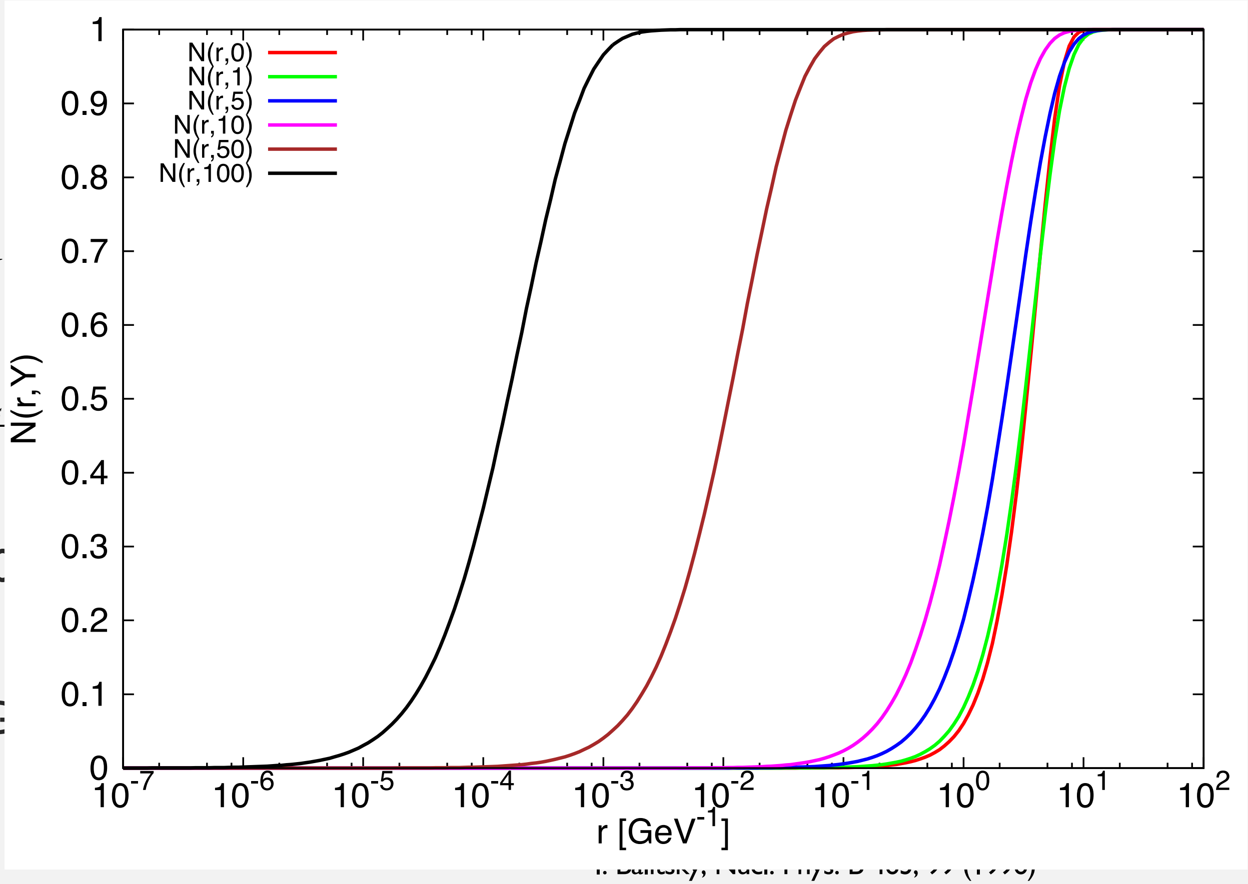
Scattering amplitude

$$\frac{\partial N(r,Y)}{\partial \ln Y} = \int d\vec{r}_1 K$$

with kernel $K(\vec{r},\vec{r}_1,\vec{r}_2) = \frac{\alpha_s}{}$

Initial condition at x_0 = 0.0

We used $\Lambda_{QCD} = 0.241$ G



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Y. V. Kovchegov, Phys. Rev. D 60, 034008 (1999)
J. L. Albacete at al, Eur.Phys.J. C71 (2011) 1705

CROSS SECTION CALCULATION

b) Fourier transform

- We transform the scattering amplitude from the coordinate space to the momentum space with the Fourier transform: $$F(x_2, k_t) = \int \frac{d^2\mathbf{r}}{(2\pi)^2} e^{-ik_t\cdot\mathbf{r}} S_F(x_2, \mathbf{r})$$

c) Compute the dipole gluon distribution and Weiszacker-Williams gluon distribution.

$$x_2 G^{(2)}(x_2, k_t) = \frac{N_c\ k_t^2\ S_\perp}{2\pi^2\alpha_s} F(x_2, k_t)$$

$$S_A(x, \mathbf{r}) = [S_F(x, \mathbf{r})]^2$$

$$x_2 G^{(1)}(x_2, k_t) = \frac{C_F}{2\alpha_s\pi^4} \int d^2b \int \frac{d^2\mathbf{r}}{\mathbf{r}^2}\ e^{-ik_t\cdot\mathbf{r}}\ [1 - S_A(x_2, \mathbf{r})]$$

A. van Hameren, P. Kotko, K. Kutak, C. Marquet, E. Petreska and S. Sapeta, JHEP 1612 (2016) 034, arXiv:1607.03121

CROSS SECTION CALCULATION

Fourier tra

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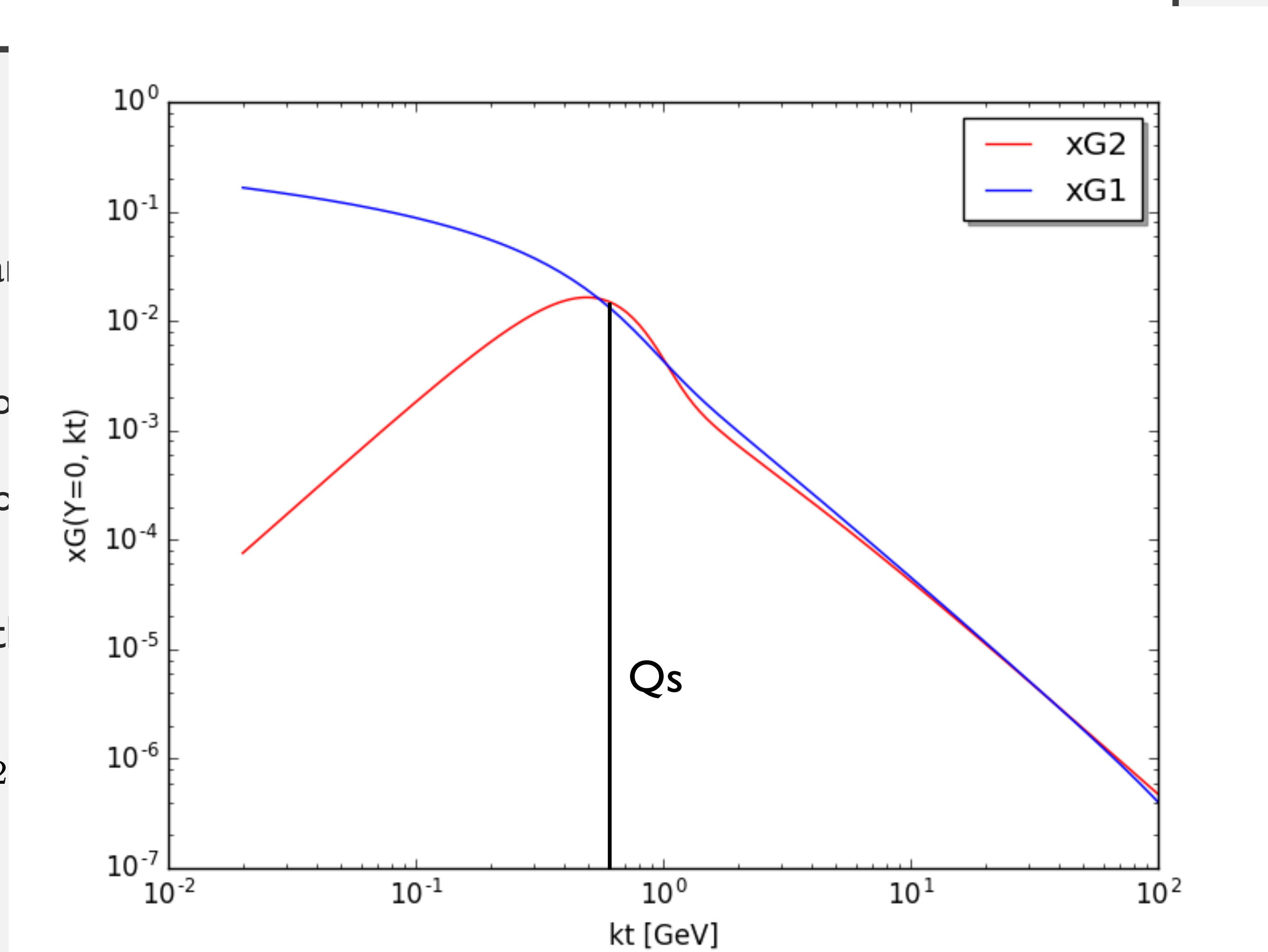
$$x_2G^{(2)}(x_2 \quad \ldots \quad r)]^2$$

$$x_2G^{(1)}(x_2$$



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CROSS SECTION CALCULATION

d) Compute the transverse momentum distributions as a convolution of the Fourier transform and the gluon distributions.

$$
\begin{aligned}
\mathcal{F}_{qg}^{(1)}(x_2,k_t) &= x_2 G^{(2)}(x_2,q_t)\,, \\
\mathcal{F}_{qg}^{(2)}(x_2,k_t) &= \int d^2q_t\, x_2 G^{(1)}(x_2,q_t) F(x_2,k_t-q_t)\,, \\
\mathcal{F}_{gg}^{(1)}(x_2,k_t) &= \int d^2q_t\, x_2 G^{(2)}(x_2,q_t) F(x_2,k_t-q_t)\,, \\
\mathcal{F}_{gg}^{(2)}(x_2,k_t) &= -\int d^2q_t\, \frac{(k_t-q_t)\cdot q_t}{q_t^2} x_2 G^{(2)}(x_2,q_t) F(x_2,k_t-q_t)\,, \\
\mathcal{F}_{gg}^{(6)}(x_2,k_t) &= \int d^2q_t d^2q'_t\, x_2 G^{(1)}(x_2,q_t) F(x_2,q'_t) F(x_2,k_t-q_t-q'_t)
\end{aligned}
$$

A. van Hameren, P. Kotko, K. Kutak, C. Marquet, E. Petreska and S. Sapeta, JHEP 1612 (2016) 034, arXiv:1607.03121

CROSS SECTION CALCULATION

Compute t … er

transform a

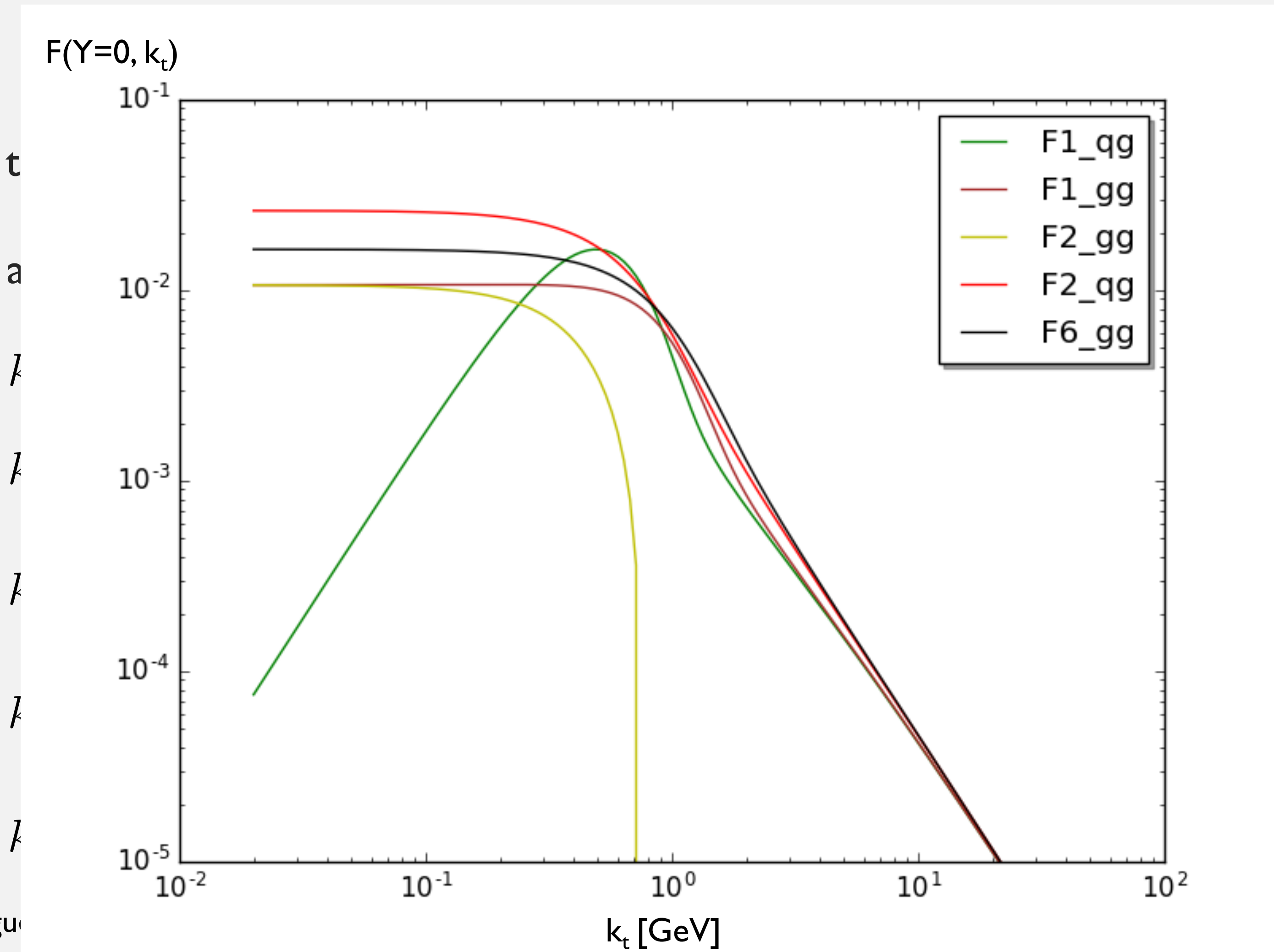
$\mathcal{F}_{qg}^{(1)}(x_2, k$

$\mathcal{F}_{qg}^{(2)}(x_2, k$

$\mathcal{F}_{gg}^{(1)}(x_2, k$

$\mathcal{F}_{gg}^{(2)}(x_2, k$

$\mathcal{F}_{gg}^{(6)}(x_2, k$



CROSS SECTION CALCULATION

e) Redefine the transverse momentum distributions in the large N_c limit as:

$$\Phi^{(1)}_{qg\to qg} = \mathcal{F}^{(1)}_{qg} \quad , \quad \Phi^{(2)}_{qg\to qg} \approx \mathcal{F}^{(2)}_{qg}$$

$$\Phi^{(1)}_{gg\to q\bar{q}} \approx \mathcal{F}^{(1)}_{gg} \quad , \quad \Phi^{(2)}_{gg\to q\bar{q}} \approx -N_c^2 \mathcal{F}^{(2)}_{gg}$$

$$\Phi^{(1)}_{gg\to gg} \approx \frac{1}{2}\left(\mathcal{F}^{(1)}_{gg} + \mathcal{F}^{(6)}_{gg}\right) \quad , \quad \Phi^{(2)}_{gg\to gg} \approx \mathcal{F}^{(2)}_{gg} + \mathcal{F}^{(6)}_{gg}$$

A. van Hameren, P. Kotko, K. Kutak, C. Marquet, E. Petreska and S. Sapeta, JHEP 1612 (2016) 034, arXiv:1607.03121

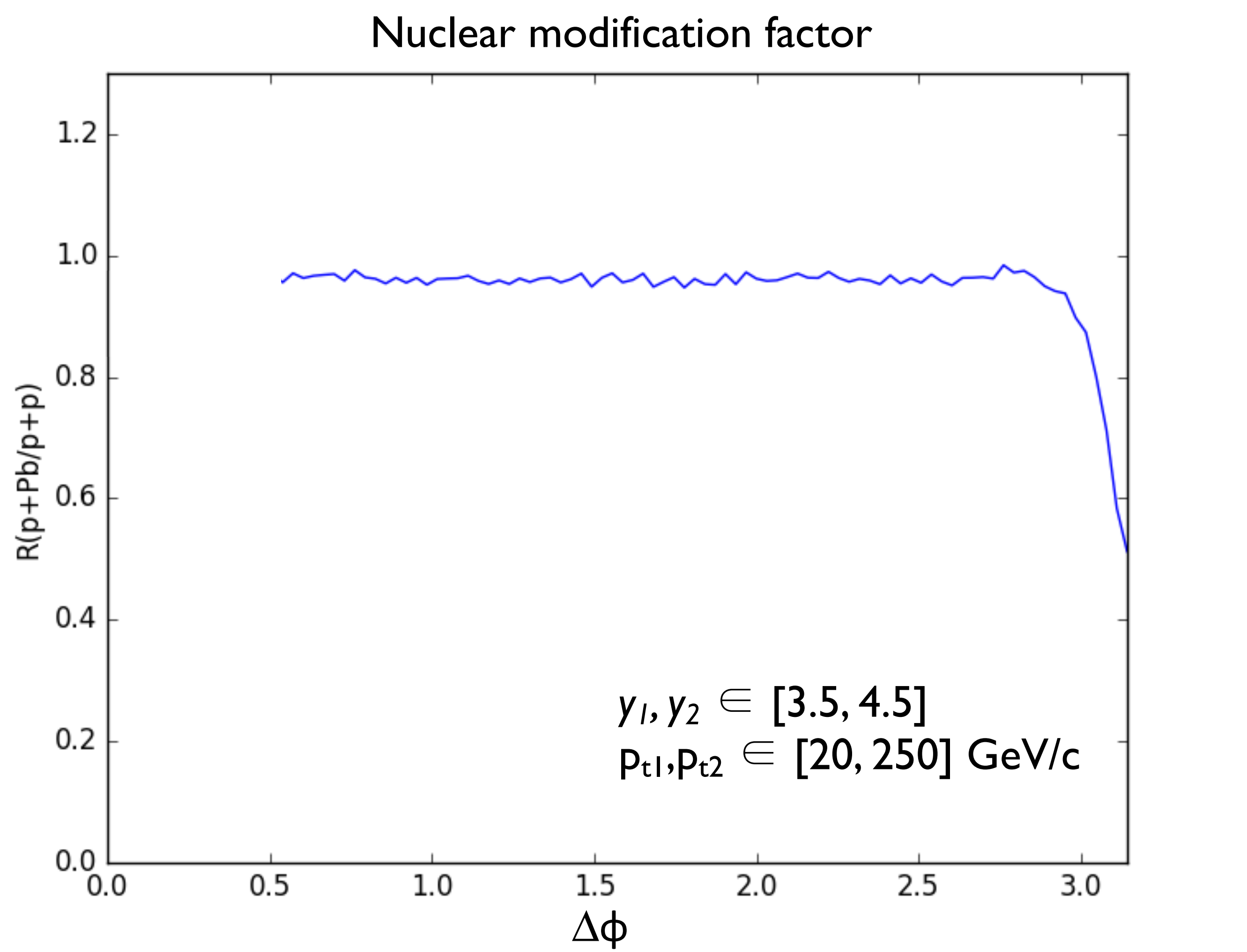
CROSS SECTION CALCULATION

$$\boxed{\frac{d\sigma^{pA\to \mathrm{dijets}+X}}{d^2P_t d^2k_t dy_1 dy_2} = \frac{\alpha_s^2}{(x_1x_2s)^2}\sum_{a,c,d}\frac{x_1 f_{a/p}(x_1)}{1+\delta_{cd}}\sum_{i=1}^{2}K^{(i)}_{ag^*\to cd}(P_t,k_t)\Phi^{(i)}_{ag\to cd}(x_2,k_t)}$$

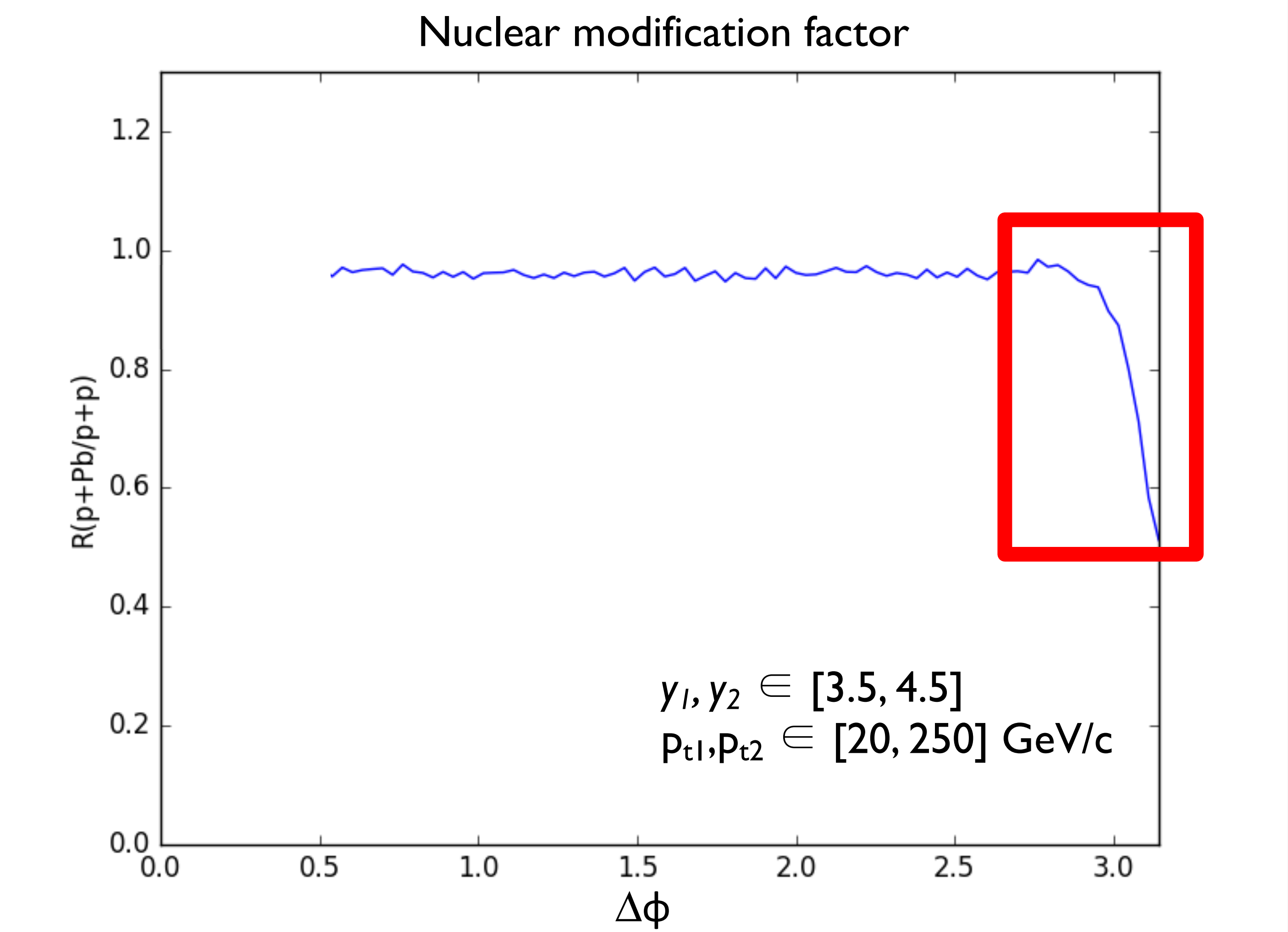
Now we can compute the cross section and from that the nuclear modification factor.

A. van Hameren, P. Kotko, K. Kutak, C. Marquet, E. Petreska and S. Sapeta, JHEP 1612 (2016) 034, arXiv:1607.03121

NUCLEAR MODIFICATION FACTOR



NUCLEAR MODIFICATION FACTOR



CONCLUSIONS

- The existence of saturation effects can be studied with the use of the nuclear modification factor in p-Pb collisions.
- Observation of the saturation effects is caused by the fact that the transverse momentum of the outgoing back-to-back jet pair is similar to the nuclear saturation scale.
- These studies are all impact parameter independent. Future incorporation of non-trivial impact parameter dependence in the scattering amplitude computation is highly desired, because it can have a major influence on the studied phenomena.
- Measurements at such forward rapidity would be desired. Is it feasible at the LHC?

THANK YOU FOR YOUR ATTENTION

MATRIX ELEMENTS

i	1	2
$K^{(i)}_{gg^*\to gg}$	$2\,\dfrac{\left(\bar{s}^4+\bar{t}^4+\bar{u}^4\right)\left(\bar{u}\hat{u}+\bar{t}\hat{t}\right)}{\bar{t}\hat{t}\bar{u}\hat{u}\bar{s}\hat{s}}$	$-\dfrac{\left(\bar{s}^4+\bar{t}^4+\bar{u}^4\right)\left(\bar{u}\hat{u}+\bar{t}\hat{t}-\bar{s}\hat{s}\right)}{\bar{t}\hat{t}\bar{u}\hat{u}\bar{s}\hat{s}}$
$K^{(i)}_{gg^*\to q\bar{q}}$	$\dfrac{1}{2N_c}\,\dfrac{\left(\bar{t}^2+\bar{u}^2\right)\left(\bar{u}\hat{u}+\bar{t}\hat{t}\right)}{\bar{s}\hat{s}\hat{t}\hat{u}}$	$\dfrac{1}{2N_c^3}\,\dfrac{\left(\bar{t}^2+\bar{u}^2\right)\left(\bar{u}\hat{u}+\bar{t}\hat{t}-\bar{s}\hat{s}\right)}{\bar{s}\hat{s}\hat{t}\hat{u}}$
$K^{(i)}_{qg^*\to qg}$	$-\dfrac{\bar{u}\left(\bar{s}^2+\bar{u}^2\right)}{2\bar{t}\hat{t}\hat{s}}$	$-\dfrac{\bar{s}\left(\bar{s}^2+\bar{u}^2\right)}{2\bar{t}\hat{t}\hat{u}}$