GLUON SATURATION IN *pA* COLLISIONS AT LHC: AN OVERVIEW

PIOTR KOTKO

AGH University, Krakow

RESEARCH UNIVERSITY EXCELLENCE INITIATIVE

SUPPORTED BY:
IDUB, POB8, D21
NCN GRANT DEC-2020/39/O/ST2/03011

NATIONAL SCIENCE CENTRE POLAND

AGH

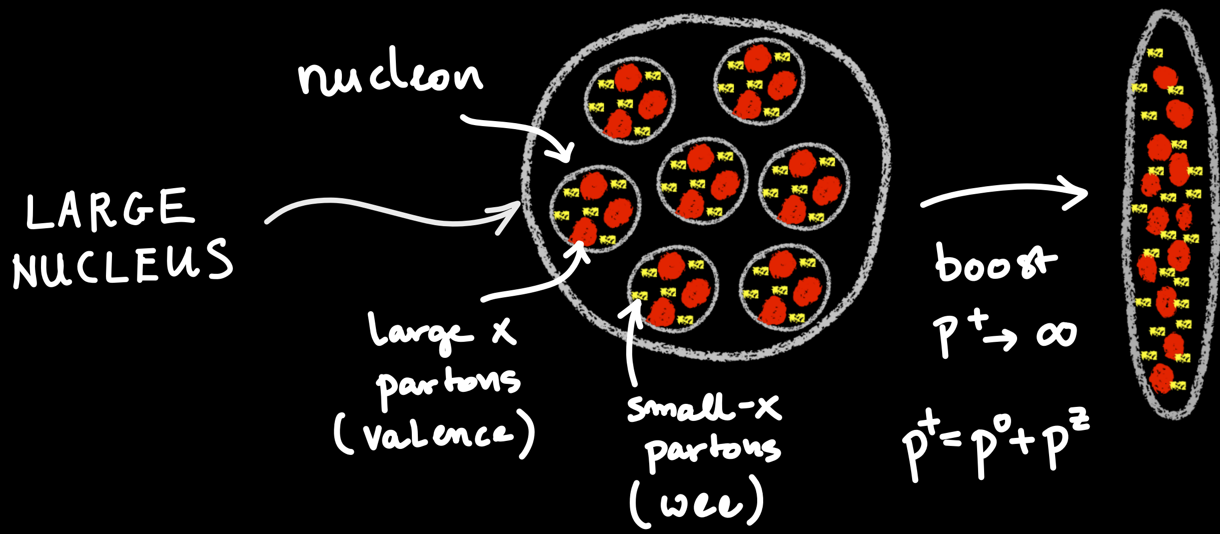
pA collisions at high luminosity LHC workshop, CERN, 4-5 July 2024

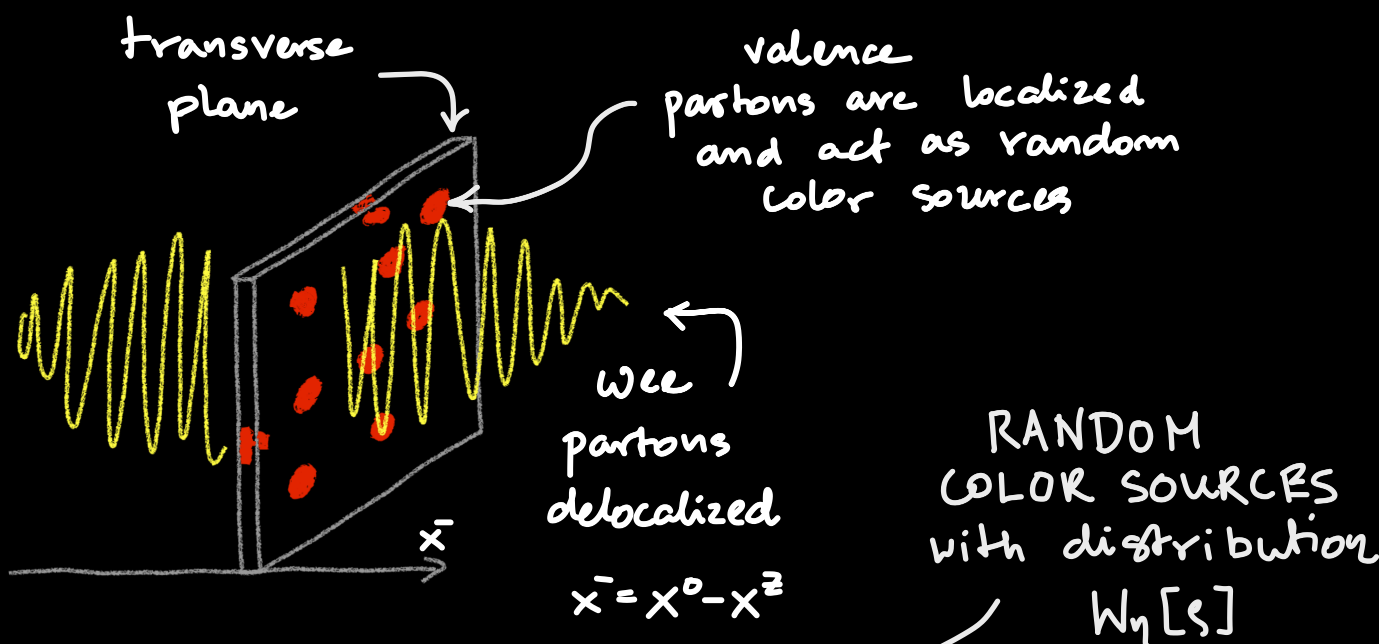
PLAN

1. Gluon saturation in Color Glass Condensate (CGC) framework
   A. CGC basic correlators
   B. TMD gluon distributions at small x
2. Dilute-dense “hybrid” approach to pA collisions
3. Phenomenological applications to selected pA processes
   A. Single inclusive hadron production
   B. Inclusive jet production
   C. Inclusive photon + jet
   D. Inclusive dijet production
4. Outlook

GLUON SATURATION (1)

Color glass condensate (CGC) in a nutshell





$$(D_\mu F^{\mu\nu})_a(x^-, \vec{x}_T) = \delta^{\nu +}\rho_a(\vec{x}_T)\delta(x^-)$$

Generating functional:

$$Z[J] = \int [d\rho] W_x[\rho] \frac{\int [dA] e^{iS[A,\rho] - iJ\cdot A}}{\int [dA] e^{iS[A,\rho]}}$$

with the effective action:

$$S[A,\rho] = -\frac{1}{4}\int d^4x F_a^{\mu\nu} F_{\mu\nu}^a + \frac{i}{gN_c}\int d^3\mathbf{x} \mathrm{Tr}\{\rho_a(\mathbf{x}) t^a V(\mathbf{x})\}$$

where $V(\mathbf{x})$ is the Wilson line:

$$V(\mathbf{x}) = \mathscr{P}\exp\{ig\int_{-\infty}^{+\infty} dy^+ A_a^-(y^+, \mathbf{x})$$

The JIMWLK equation:

$$\frac{\partial W_\eta[\rho]}{\partial \eta} = -HW_\eta[\rho]$$

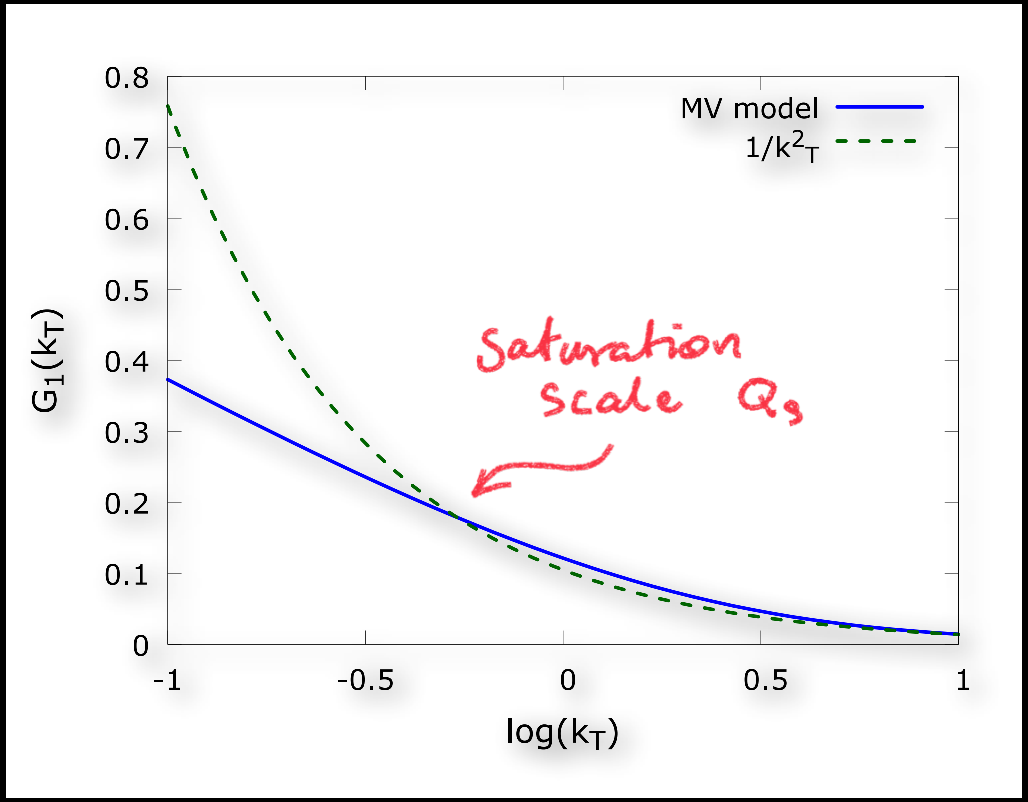
[J. Jalilian-Marian, A. Kovner, A. Leonidov, H. Weigert, 1997, 1998]
[E. Iancu, A. Leonidov, L. McLerran, 2001]

GLUON SATURATION (2)

Simplest CGC correlators

Weizsacker-Williams gluon density:

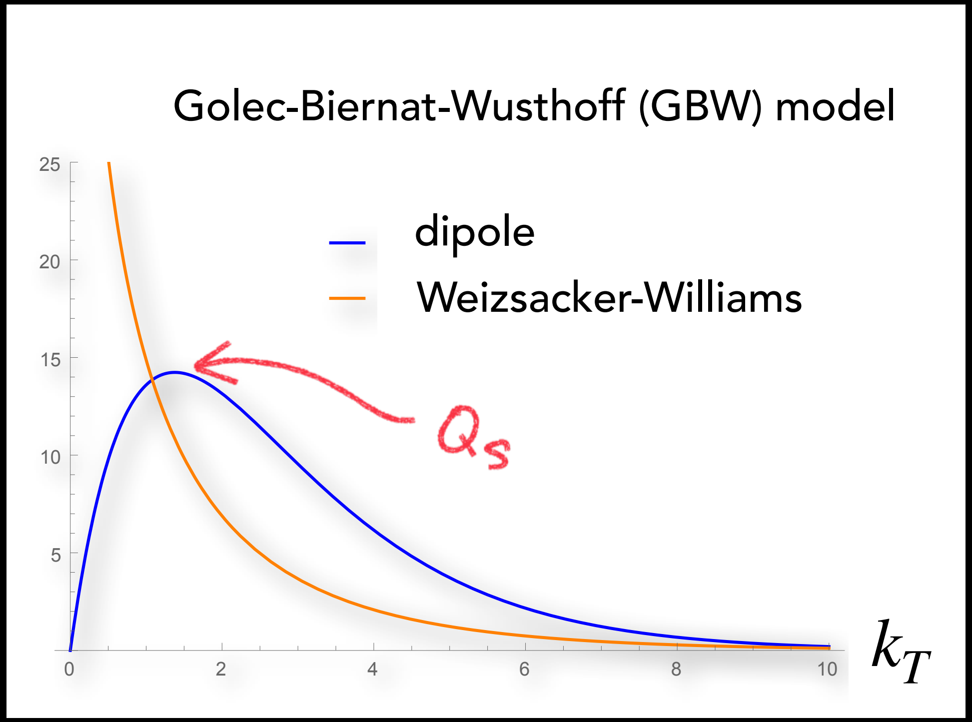
$$\int d^2b_T \int d^2r_T\, e^{i\vec{r}_T\cdot\vec{k}_T} \left\langle A_i^a(\vec{r}_T+\vec{b}_T) A_i^a(\vec{r}_T-\vec{b}_T) \right\rangle_x$$



"Dipole" gluon density:

$$\int d^2b_T \int d^2r_T\, e^{i\vec{r}_T\cdot\vec{k}_T} \left\langle \mathrm{Tr}\, U(\vec{r}_T+\vec{b}_T) U^\dagger(\vec{r}_T-\vec{b}_T) \right\rangle_x$$

where $U(\vec{x}_T) = \mathscr{P} \exp\left\{ ig \int_{-\infty}^{+\infty} dx^+\, A_a^-(x^+,\vec{x}_T)\, t^a \right\}$



- saturation tames the perturbative growth $\sim 1/k_T^2$ of gluon density
- dynamically generated saturation scale $Q_s \sim Q_0\,(x/x_0)^{-\lambda}$ that "runs" due to energy evolution equations

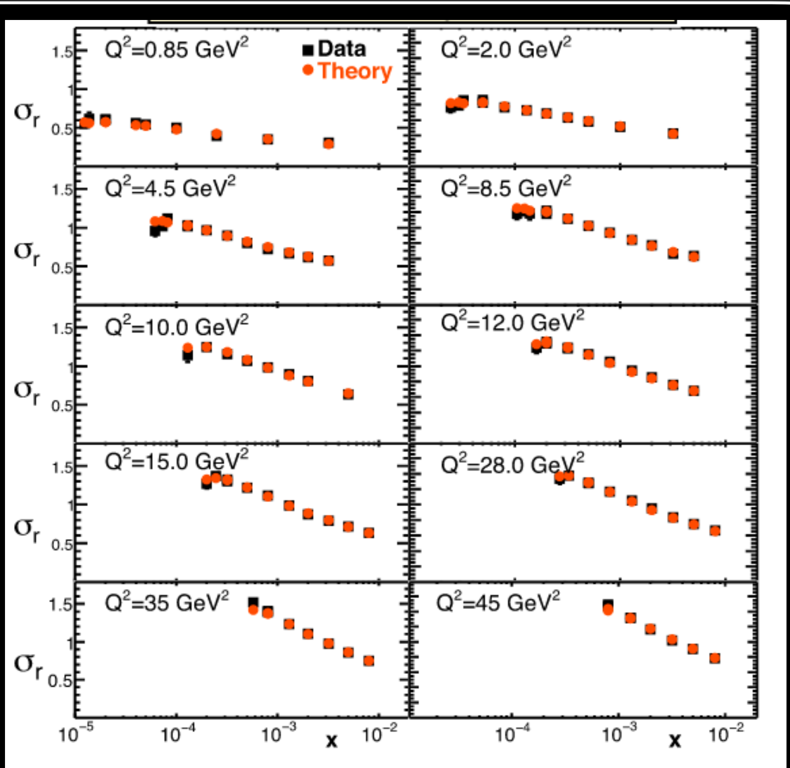
GLUON SATURATION (3)

Obtaining realistic correlators

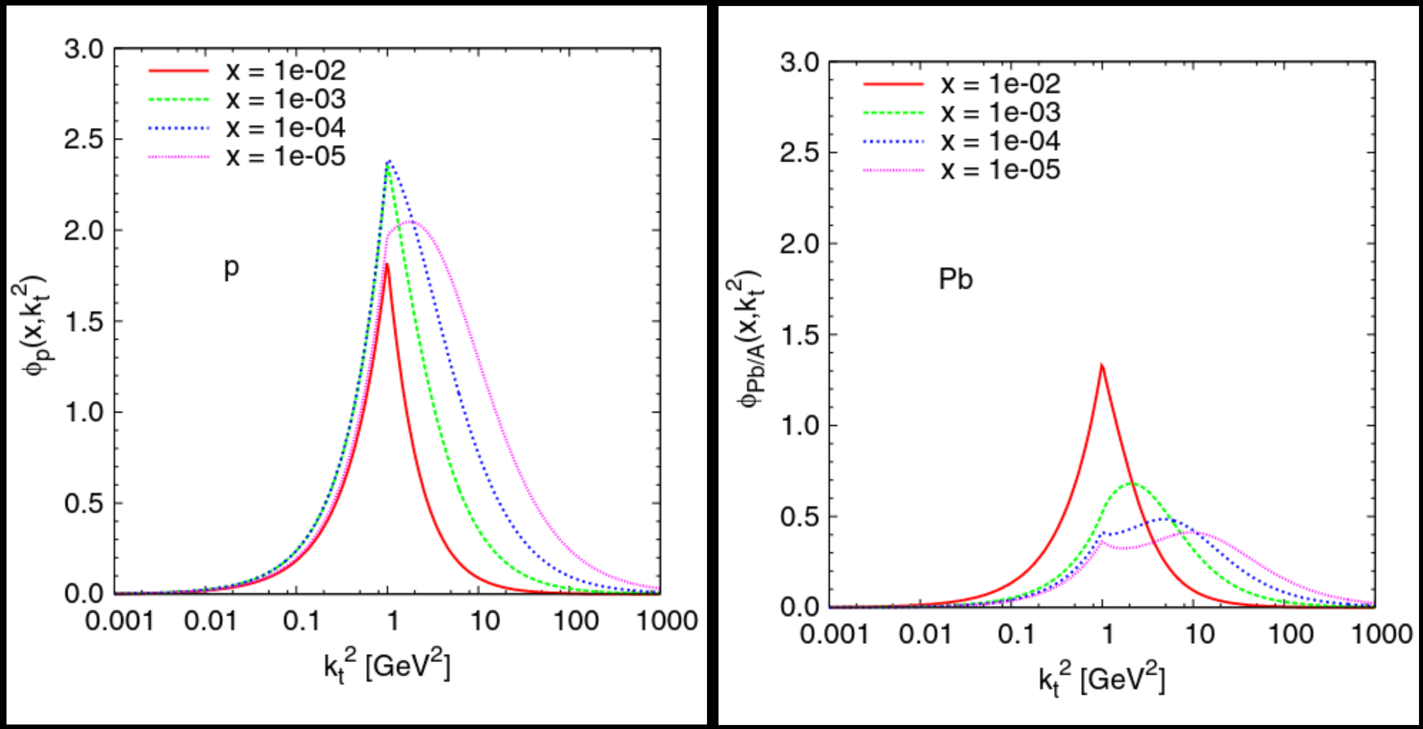
A. Fit the dipole initial condition (MV model or another), integrated over impact parameter, with x-dependence given by some type of non-linear evolution equation, to the inclusive proton DIS HERA data.

B. Compute the gluon distribution in nucleus:

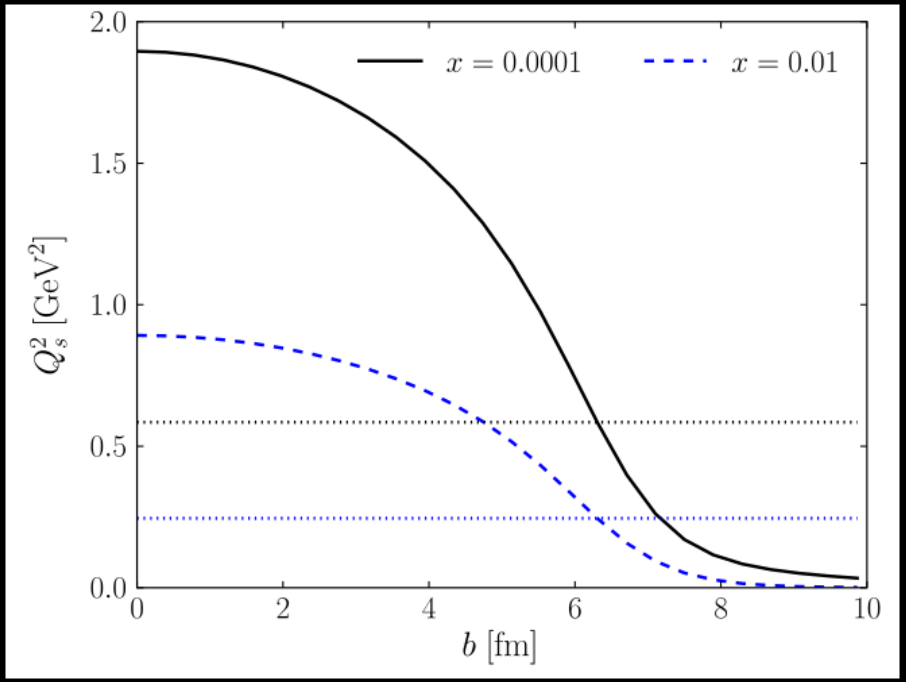
- Explicit dependence on the impact parameter (Glauber model)
- Apply the evolution equation with modified strength of the nonlinear term to the proton initial condition



[J. Albacete, N. Armesto, J.G. Milhano, P.Q. Arias, C.A. Salgado, 2011]



[K. Kutak, S. Sapeta, 2012]



[T. Lappi, H. Mantysaari, 2013]

GLUON SATURATION (4)

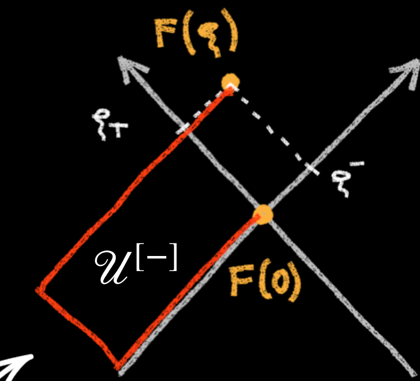
TMD gluon distributions & CGC

[C. Bomhof, P. Mulders, F. Pijlman, 2004]

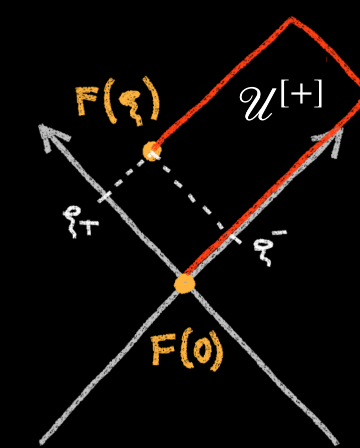
$$\mathcal{F}_{ag}^{(i)}\left(x,k_T\right) \sim \int \frac{d\xi^+ d^2\xi_T}{(2\pi)^3}\, e^{ixP^-\xi^+ - i\vec{k}_T\cdot\vec{\xi}_T} \langle P|\,\mathrm{Tr}\left[\hat{F}^{i-}\left(\xi^+,\vec{\xi}_T,\xi^-=0\right)\mathcal{U}_{C_1}\hat{F}^{i-}(0)\,\mathcal{U}_{C_2}\right]|P\rangle$$

gluon field $\hat{F}^{\mu\nu} = F_a^{\mu\nu} t^a$

gauge links made of $\mathcal{U}^{[+]}, \mathcal{U}^{[-]}$



PAST-POINTING



FUTURE-POINTING

$$\mathcal{F}_{qg}^{(1)} \sim \langle P|\,\mathrm{Tr}\left[\hat{F}^{i-}(\xi)\,\mathcal{U}^{[-]\dagger}\hat{F}^{i-}(0)\,\mathcal{U}^{[+]}\right]|P\rangle$$

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

$$\mathcal{F}_{qg}^{(3)} \sim \langle P|\,\mathrm{Tr}\left[\hat{F}^{i-}(\xi)\,\mathcal{U}^{[+]\dagger}\hat{F}^{i-}(0)\,\mathcal{U}^{[\square]}\mathcal{U}^{[+]}\right]|P\rangle$$

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

$$\mathcal{F}_{gg}^{(2)} \sim \langle P|\,\mathrm{Tr}\left[\hat{F}^{i-}(\xi)\,\mathcal{U}^{[\square]\dagger}\right]\mathrm{Tr}\left[\hat{F}^{i-}(0)\,\mathcal{U}^{[\square]}\right]|P\rangle$$

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

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

$$\mathcal{F}_{gg}^{(5)} \sim \langle P|\,\mathrm{Tr}\left[\hat{F}^{i-}(\xi)\,\mathcal{U}^{[\square]\dagger}\mathcal{U}^{[+]\dagger}\hat{F}^{i-}(0)\,\mathcal{U}^{[\square]}\mathcal{U}^{[+]}\right]|P\rangle$$

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

$$\mathcal{F}_{gg}^{(7)} \sim \langle P|\frac{\mathrm{Tr}\,\mathcal{U}^{[\square]}}{N_c}\mathrm{Tr}\left[\hat{F}^{i-}(\xi)\,\mathcal{U}^{[\square]\dagger}\mathcal{U}^{[+]\dagger}\hat{F}^{i-}(0)\,\mathcal{U}^{[+]}\right]|P\rangle$$

[M. Bury, PK , K. Kutak, 2018]

$x \to 0$

dipole

$$\frac{1}{N_c}\left\langle \mathrm{Tr}\left[U(\vec{x}_T)U(\vec{y}_T)^\dagger\right]\right\rangle_x$$

⋮

Weizsäcker-Williams

$$\left\langle \mathrm{Tr}\left[\partial_i U(\vec{x}_T)U^\dagger(\vec{y}_T)\partial_i U(\vec{y}_T)U^\dagger(\vec{x}_T)\right]\right\rangle_x$$

⋮

$$\left\langle \mathrm{Tr}\left[\partial_i U(\vec{x}_T)U^\dagger(\vec{y}_T)U(\vec{x}_T)U^\dagger(\vec{y}_T)\partial_i U(\vec{y}_T)U^\dagger(\vec{x}_T)U(\vec{y}_T)U^\dagger(\vec{x}_T)\right]\right\rangle_x$$

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

WILSON LOOP

[F. Dominguez, C. Marquet, B. Xiao, F. Yuan, 2011]

[C. Marquet, E. Petreska, C. Roiesnel, 2016]

GLUON SATURATION (4)

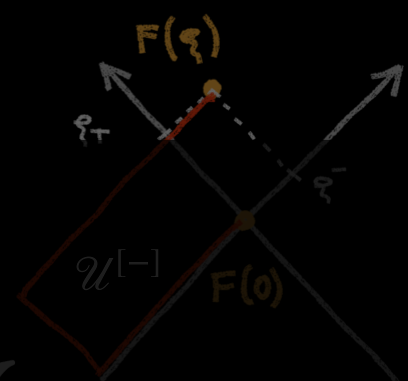
TMD gluon distributions & CGC

[C. Bomhof, P. Mulders, F. Pijlman, 2004]

$$\mathcal{F}_{qg}^{(i)}\left(x,k_T\right) \sim \int \frac{d\xi^+ d^2\xi_T}{(2\pi)^3}\, e^{ixP^-\xi^+ - i\vec{k}_T\cdot\vec{\xi}_T} \langle P|\mathrm{Tr}\left[\hat{F}^{i-}\left(\xi^+,\vec{\xi}_T,\xi^-=0\right)\mathcal{U}_{C_1}\hat{F}^{i-}(0)\,\mathcal{U}_{C_2}\right]|P\rangle$$

gluon field $\hat{F}^{\mu\nu} = F^{\mu\nu}_a t^a$

gauge links made of $\mathcal{U}^{[+]}$ $\mathcal{U}^{[-]}$



$$\mathcal{F}_{qg}^{(1)} \sim \langle P|\mathrm{Tr}\left[\hat{F}^{i-}(\xi)\,\mathcal{U}^{[-]\dagger}\hat{F}^{i-}(0)\,\mathcal{U}^{[+]}\right]|P\rangle$$

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

$$\mathcal{F}_{qg}^{(3)} \sim \langle P|\mathrm{Tr}\left[\hat{F}^{i-}(\xi)\,\mathcal{U}^{[+]\dagger}\hat{F}^{i-}(0)\,\mathcal{U}^{[\square]}\mathcal{U}^{[+]}\right]|P\rangle$$

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

$$\mathcal{F}_{gg}^{(2)} \sim \langle P|\mathrm{Tr}\left[\hat{F}^{i-}(\xi)\,\mathcal{U}^{[\square]\dagger}\right]\mathrm{Tr}\left[\hat{F}^{i-}(0)\,\mathcal{U}^{[\square]}\right]|P\rangle$$

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

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

$$\mathcal{F}_{gg}^{(5)} \sim \langle P|\mathrm{Tr}\left[\hat{F}^{i-}(\xi)\,\mathcal{U}^{[\square]\dagger}\mathcal{U}^{[+]\dagger}\hat{F}^{i-}(0)\,\mathcal{U}^{[\square]}\mathcal{U}^{[+]}\right]|P\rangle$$

$$\mathcal{F}_{gg}^{(6)} \sim \langle P|\frac{\mathrm{Tr}\,\mathcal{U}^{[\square]}}{N_c}\frac{\mathrm{Tr}\,\mathcal{U}^{[\square]\dagger}}{N_c}\mathrm{Tr}\left[\hat{F}^{i-}(\xi)\,\mathcal{U}^{[+]\dagger}\hat{F}^{i-}(0)\,\mathcal{U} \ldots\right.$$

$$\mathcal{F}_{gg}^{(7)} \sim \langle P|\frac{\mathrm{Tr}\,\mathcal{U}^{[\square]}}{N_c}\mathrm{Tr}\left[\hat{F}^{i-}(\xi)\,\mathcal{U}^{[\square]\dagger}\mathcal{U}^{[+]\dagger}\hat{F}^{i-}(0)\,\mathcal{U}^{[+]} \ldots\right.$$

[M. Bury, PK , K. Kutak, 2018]

[C. Marquet, E. Petreska, C. Roiesnel, 2016]

Small-x limit of TMD gluon distribution is intensively studied:

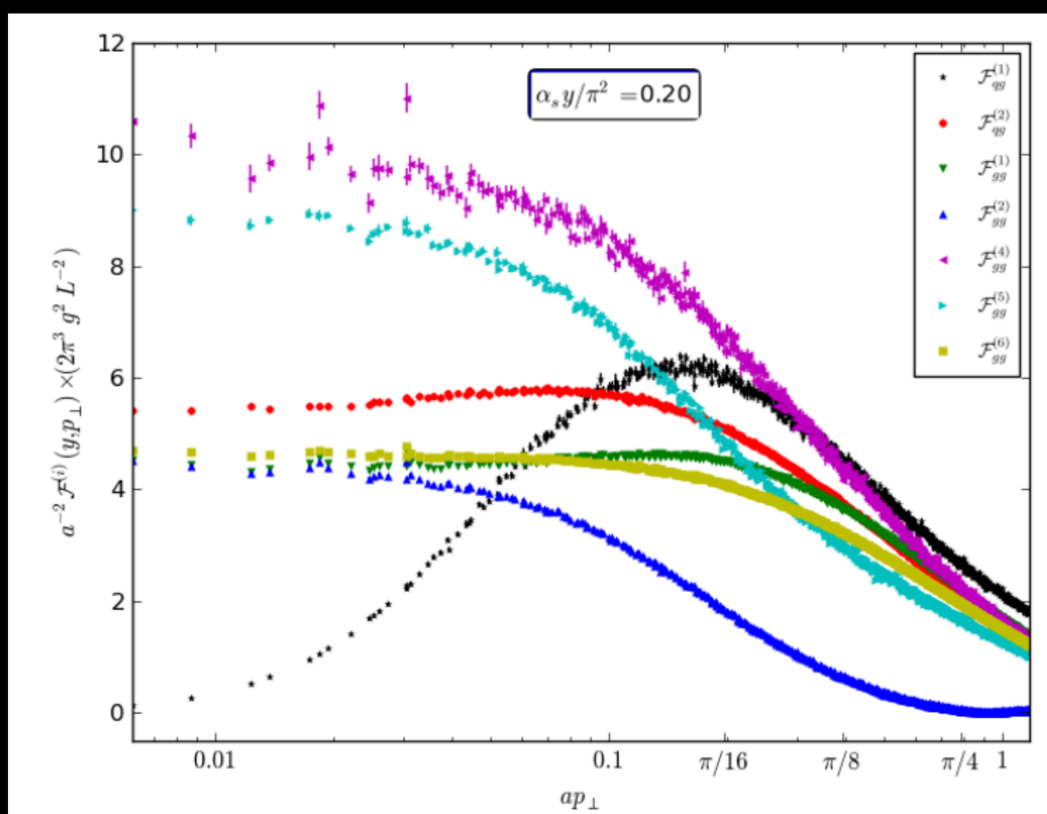
[D. Kharzeev, Y. Kovchegov, K. Tuchin, 2003]
[B. Xiao, F. Yuan, 2010]
[F. Dominguez, C. Marquet, B. Xiao, F. Yuan, 2011]
[A. Metz, J. Zhou, 2011]
[E. Akcakaya, A. Schafer, J. Zhou, 2012]
[C. Marquet, E. Petreska, C. Roiesnel, 2016]
[I. Balitsky, A. Tarasov, 2015, 2016]
[D. Boer, P. Mulders, J. Zhou, Y. Zhou, 2017]
[Y. Kovchegov, D. Pitonyak, M. Sievert, 2017,2018]
[C. Marquet, C. Roiesnel, P. Taels, 2018]
[M. Bury, PK , K. Kutak, 2018]
[T. Altinoluk, R. Boussarie, 2019]
[R. Boussarie, Y. Mehtar-Tani, 2020]

GLUON SATURATION (5)

Obtaining TMD gluon distributions at small x

Solving B-JIMWLK using lattice methods:

[K. Rummukainen, H. Weigert, 2004] [T. Lappi, 2011]
[T. Lappi, H. Mantysaari, 2013]
[T. Altinoluk, G. Beuf, M. Lublinsky, V. Skokov, 2024]



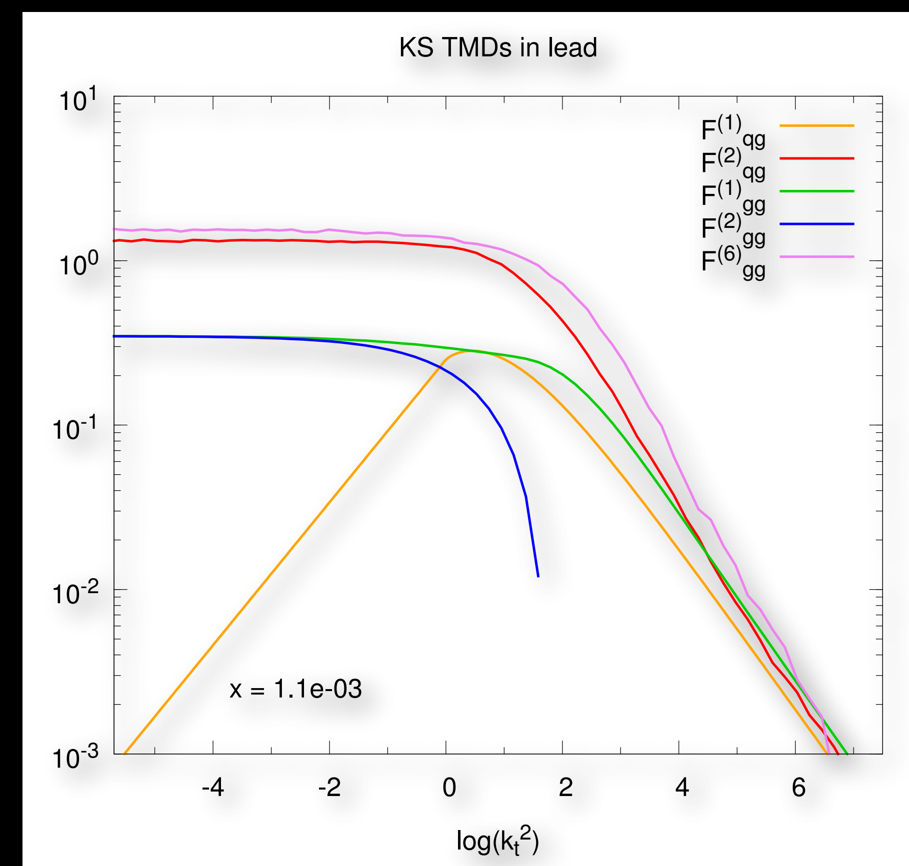
[C. Marquet, E. Petreska, C. Roiesnel, 2016]

Progress in implementing running coupling and kinematic constraint:

[S. Cali, K. Cichy, P. Korcyl, PK, K. Kutak, C. Marquet, 2021]
[P. Korcyl, L. Motyka, T. Stebel, 2024]

Suitable for phenomenology

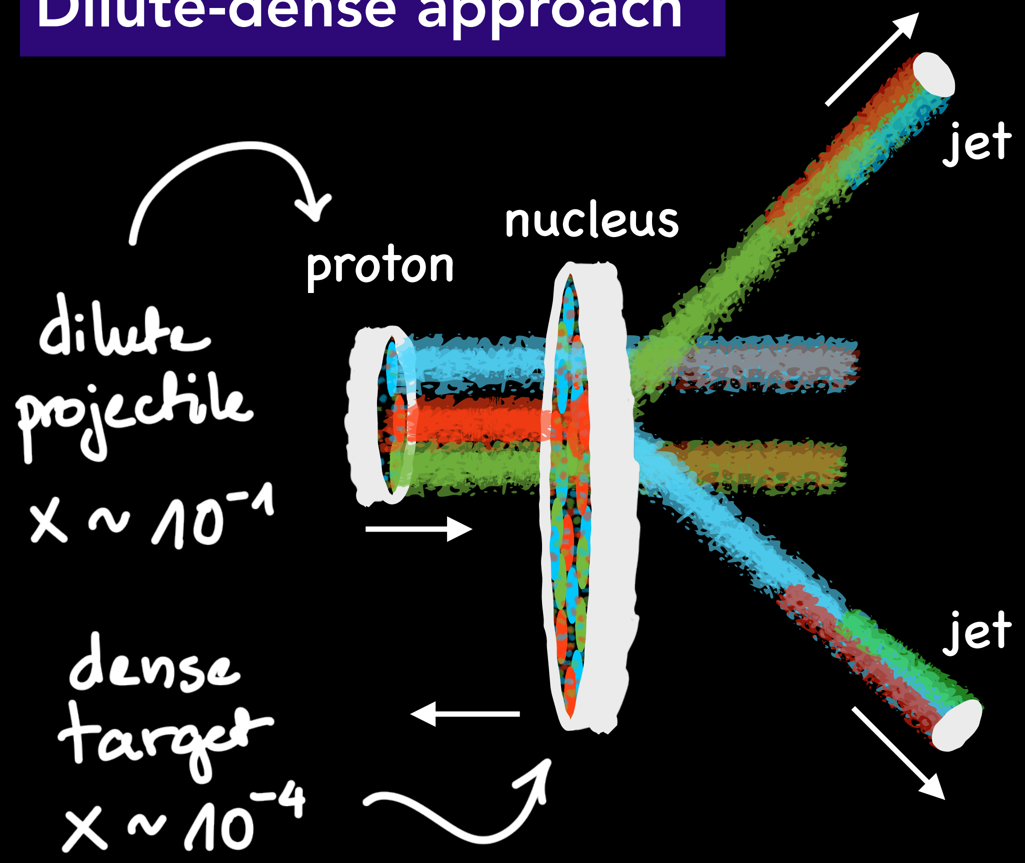
Mean field approximation based on KS fit (BK equation with DGLAP corrections):

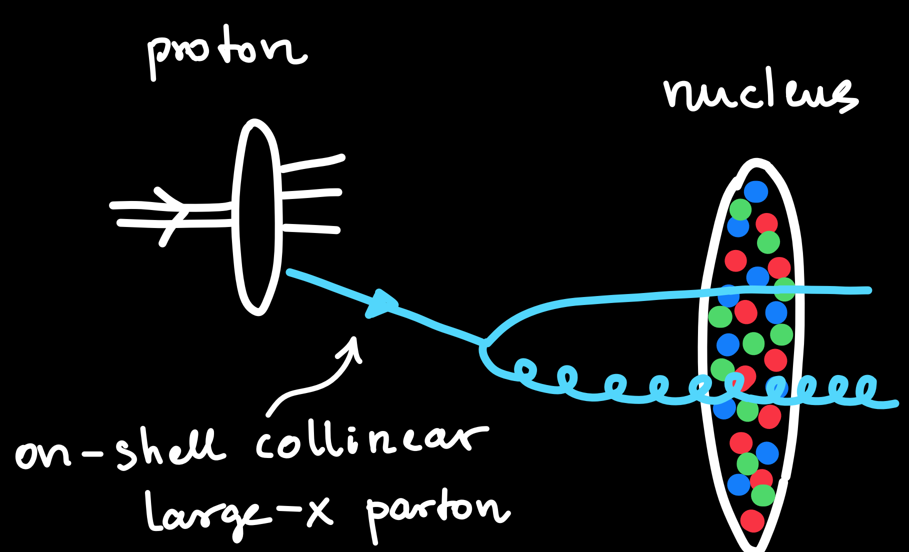


[A. Van Hameren, PK, K. Kutak, C. Marquet, E. Petreska, S. Sapeta, 2016]

COMPUTING pA PROCESSES

Dilute-dense approach





"Hybrid" factorization:

[A. Dumitru, A. Hayashigaki, J. Jalilian-Marian, 2006]

[M. Deak, F. Hautmann, H. Jung, K. Kutak, 2009]

[J.P. Blaizot, T. Lappi, Y. Mehtar-Tani, 2010]

[T. Altinoluk, A. Kovner, 2011]

[T. Altinoluk, N. Armesto, A. Kovner, M. Lublinsky, 2023]

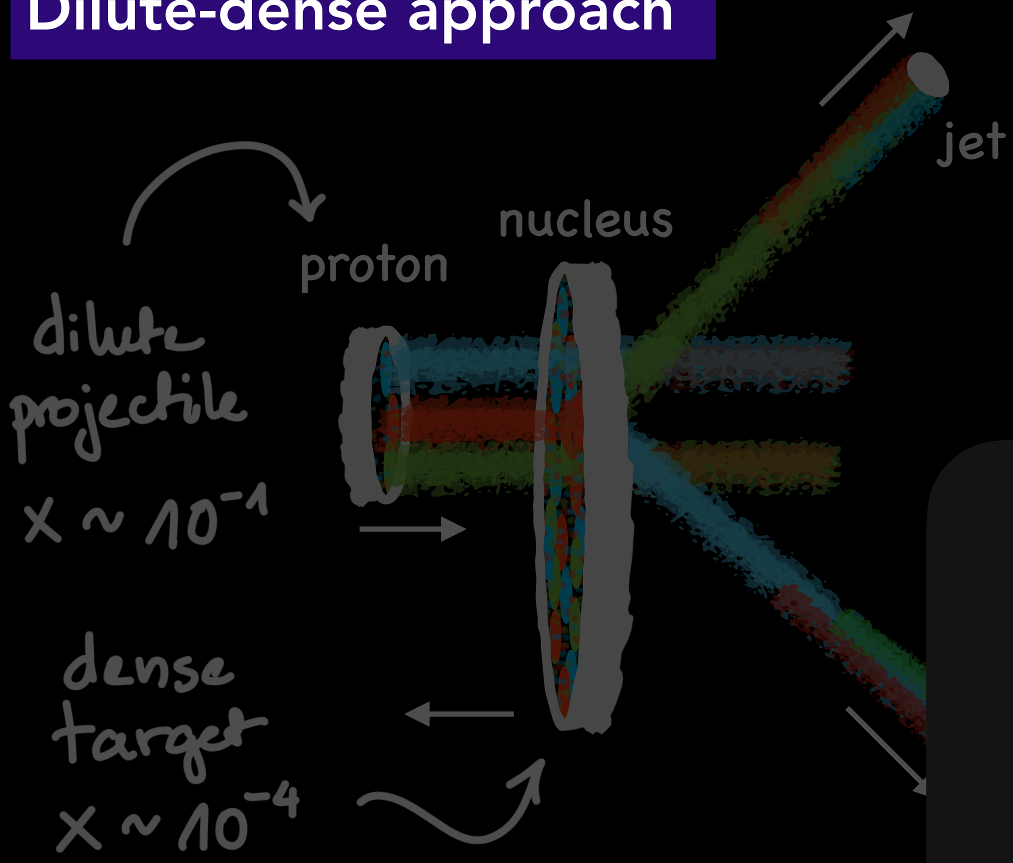
$$d\sigma_{pA} = \sum_a \int dx\, f_{a/p}(x,\mu)\, d\sigma_{aA}(x,\mu)$$

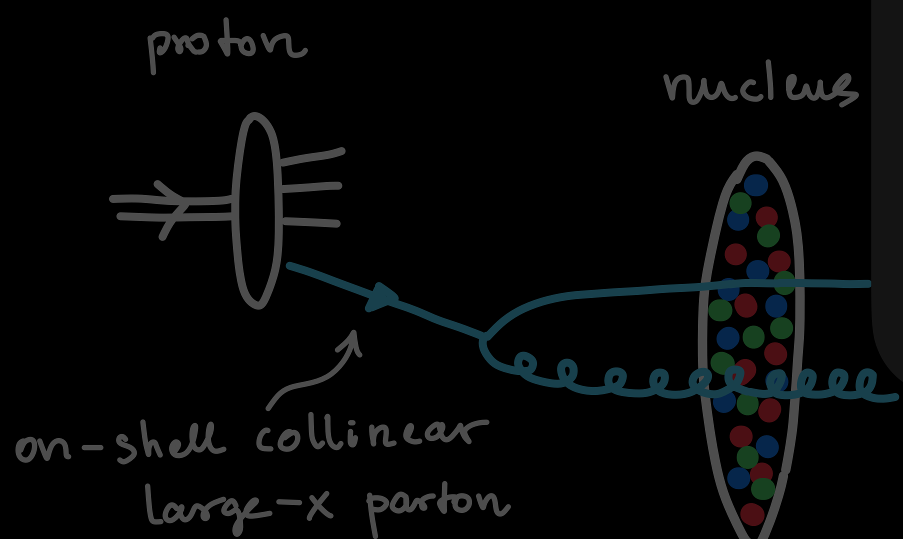
collinear PDF

The parton-nucleus cross section σ_{aA} is computed from CGC in terms of correlators of Wilson lines.

COMPUTING pA PROCESSES

Dilute-dense approach





"Hybrid" factorization:

[A. Dumitru, A. Hayashigaki, J. Jalilian-Marian, 2006]

[M. Deak, F. Hautmann, H. Jung, K. Kutak, 2009]

[J.P. Blaizot, T. Lappi, Y. Mehtar-Tani, 2010]

23]

Matching to high-p_T regime (collinear/DGLAP):

[F. Bergabo, J. Jalilian-Marian, 2023, 2024]

[T. Altinoluk, G. Beuf, J. Jalilian-Marian, 2023]

Subleading corrections in energy (next-to-eikonal):

[P. Agostini, T. Altinoluk, N. Armesto, 2024]

[P. Agostini, T. Altinoluk, N. Armesto, F. Dominguez, 2022]

[T. Altinoluk, G. Beuf, A. Czajka, A. Tymowska, 2021]

ted

es.

SINGLE INCLUSIVE HADRON PRODUCTION (1)

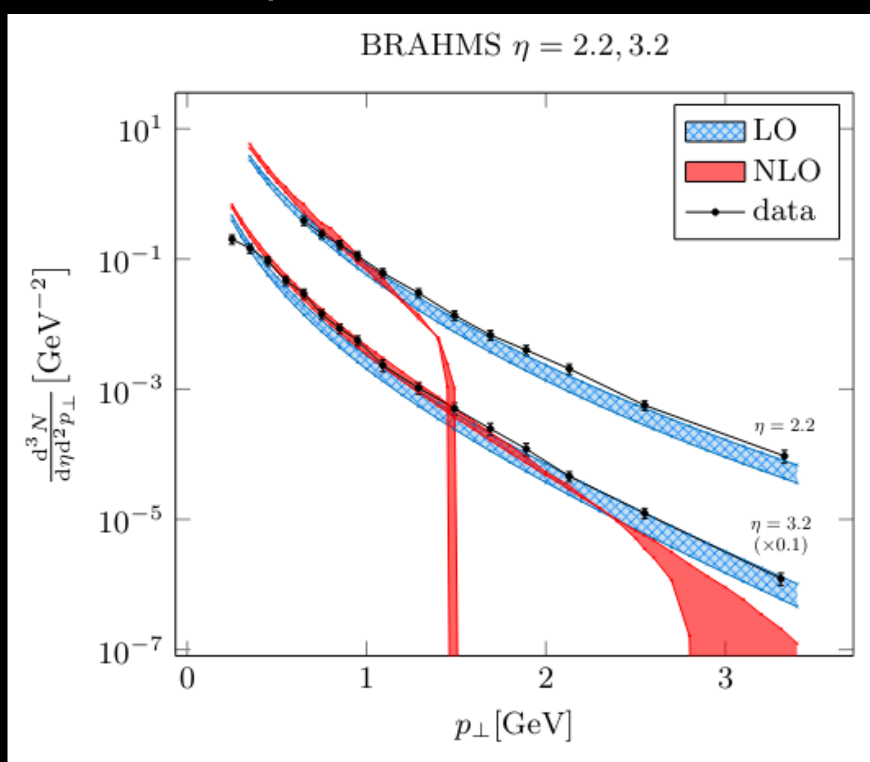
"Hybrid" factorization formula:

$$\frac{d\sigma_{pA\to j+X}}{d\mathrm{PS}} = \sum_{a,b} f_{a/p} \otimes \mathscr{H}_{a\to b} \otimes \mathscr{F}_a \otimes D_b$$

collinear PDFs | impact factors | F.T. of CGC dipole correlator | fragmentation functions

NLO catastrophe…

Inclusive π^0 production in d+Au at 200GeV



negative cross section at "large" p_T

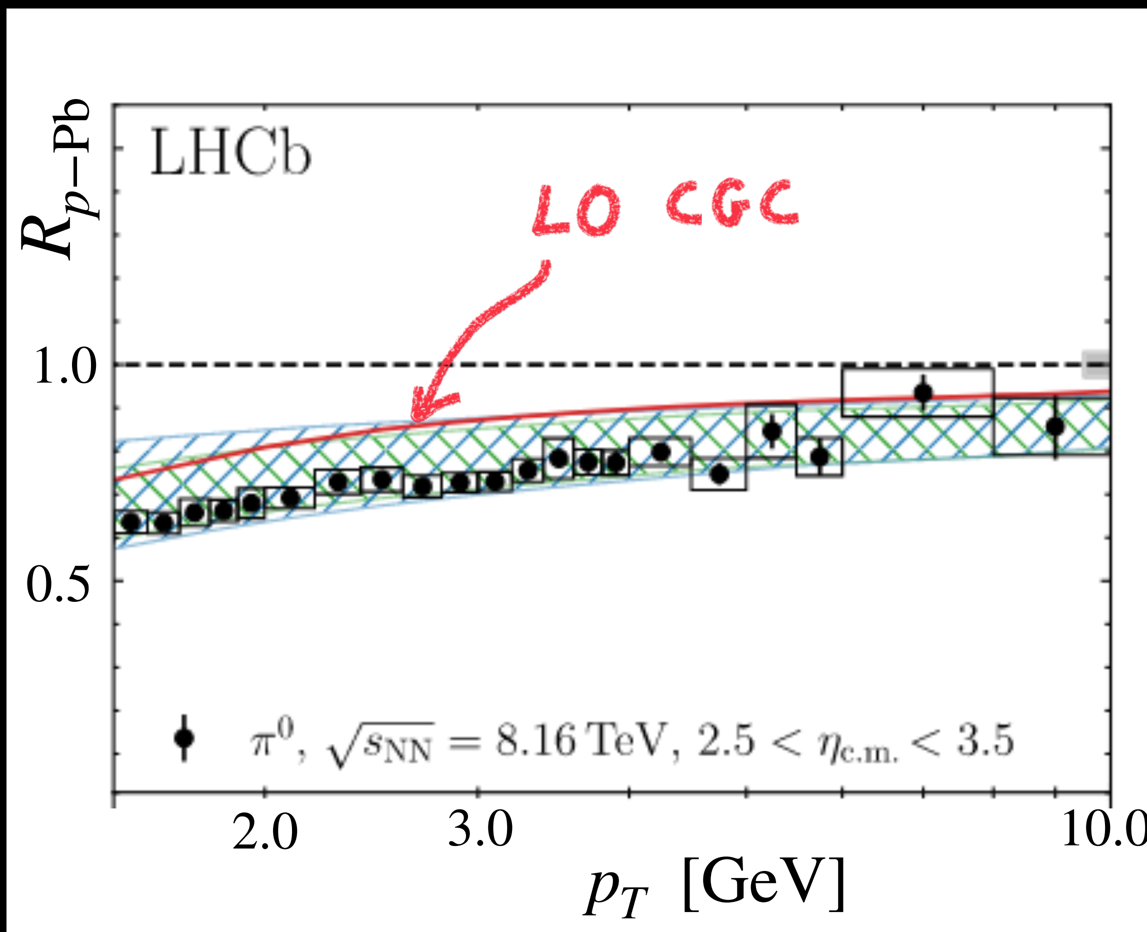
[A. Stasto, B-W. Xiao, D. Zaslavsky, 2013]
[G.A Chirilli, B.-W. Xiao, F. Yuan, 2012]

… and its resolution:

[A. Stasto, B-W. Xiao, F. Yuan, D. Zaslavsky, 2014]
[T. Altinoluk, N. Armesto, G. Beuf, A. Kovner, M. Lublinsky, 2014]
[E. Iancu, A. Mueller, D.N. Triantafyllopoulos, 2016]
[B. Ducloue, T. Lappi, Y. Zhu, 2017]
[B. Ducloue, E. Iancu, T. Lappi, A. Mueller, G. Soyez, D.N. Triantafyllopoulos, Y. Zhu, 2017]
[H-Y Liu, Z-B Kang, X. Liu, 2020]

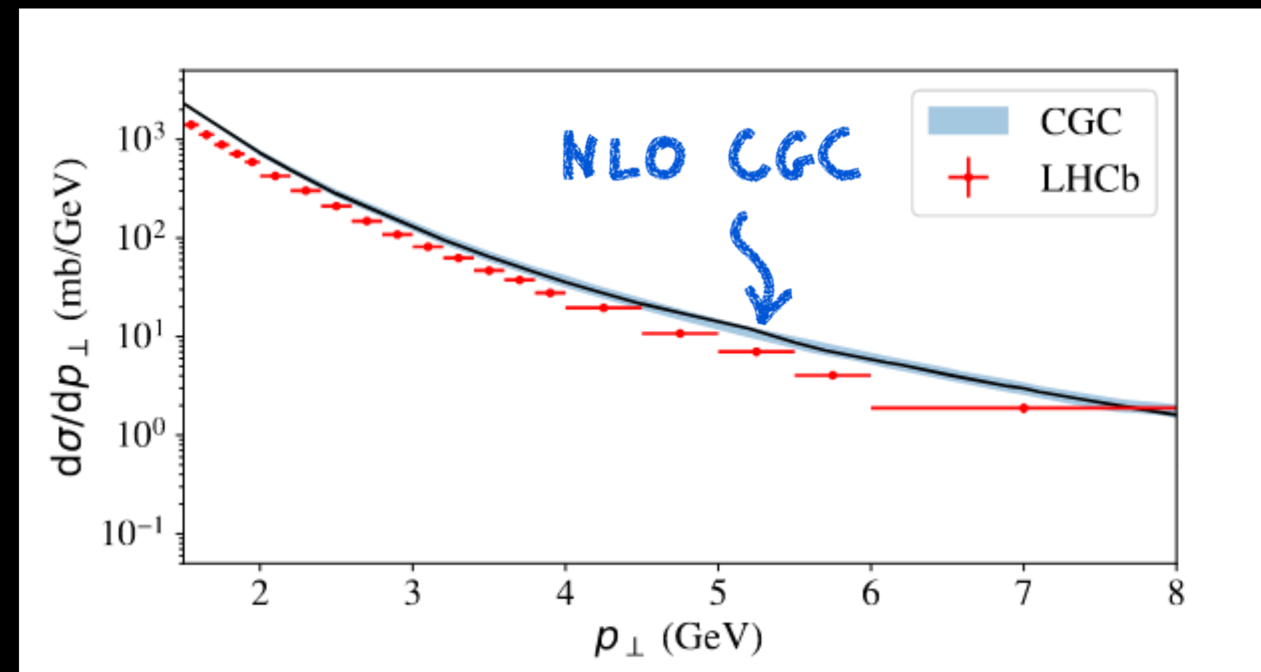
SINGLE INCLUSIVE HADRON PRODUCTION (2)

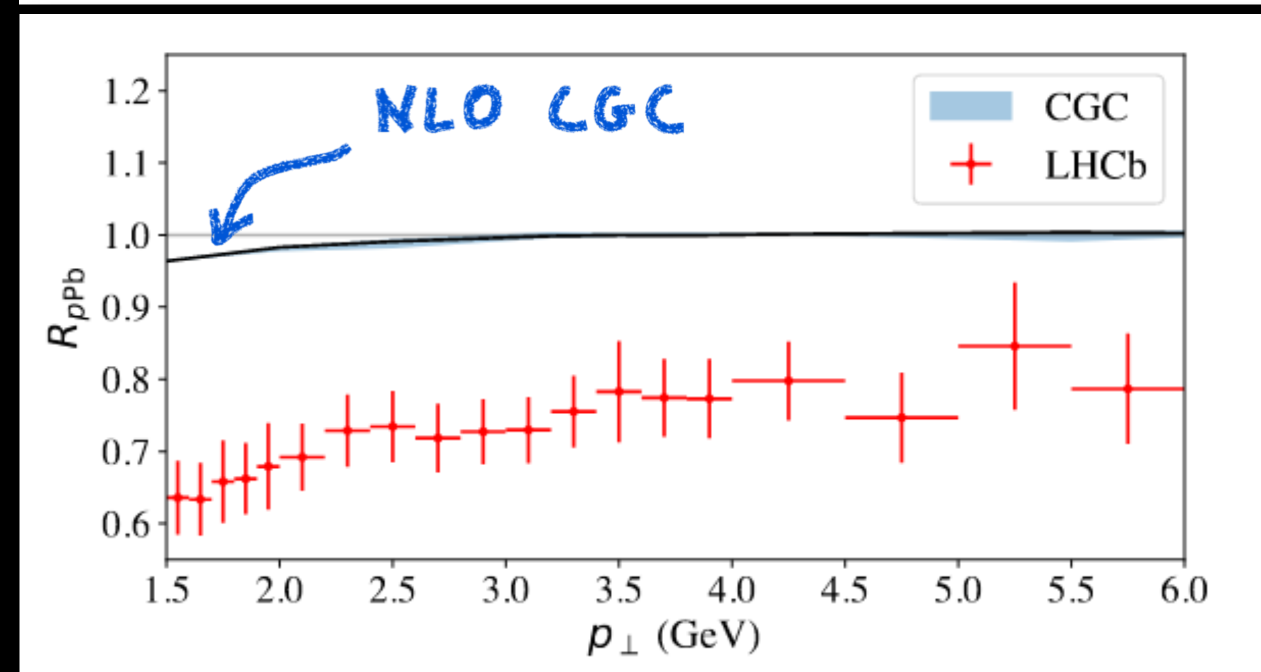
Comparison with LHCb data:



[R. Aaij (LHCb collaboration), 2023]
[T. Lappi, H. Mantysaari, 2013]

- proton: MV model + rcBK evolution fit to HERA
- nucleus: optical Glauber model

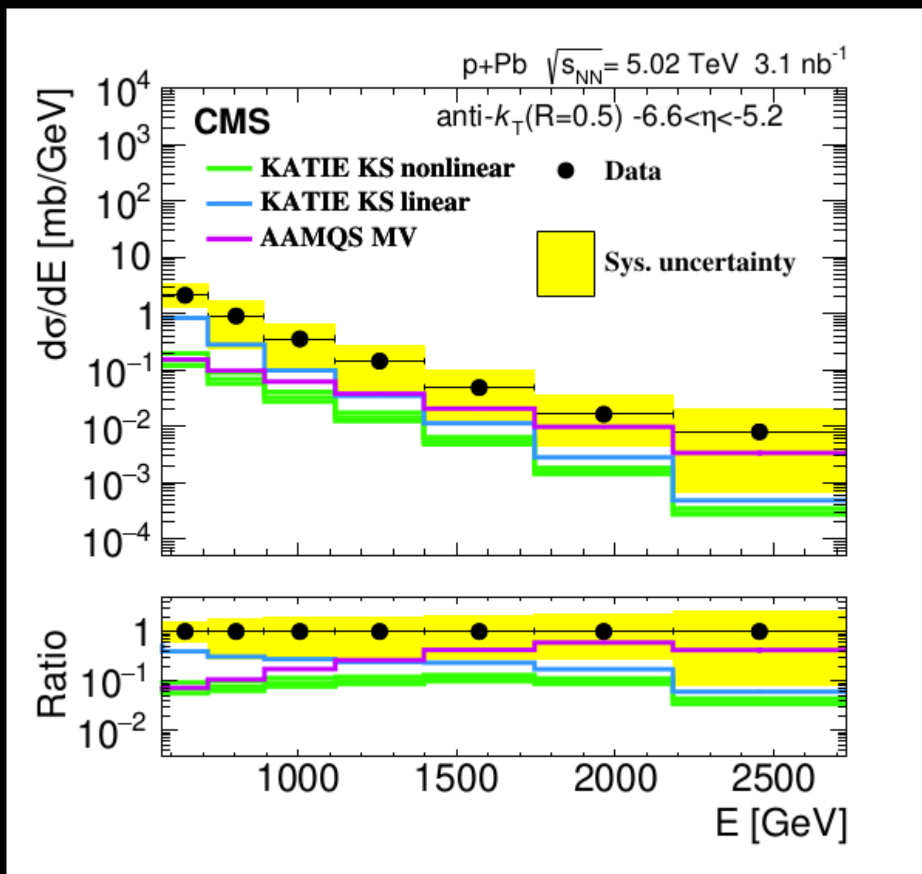




[H. Mantysaari, Y. Tawabutr, 2024]

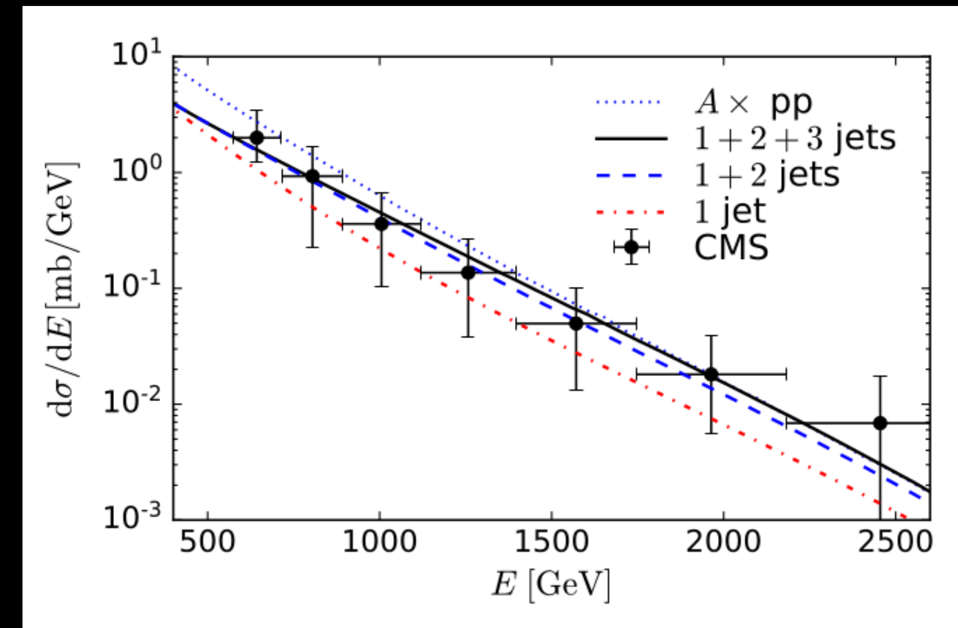
SINGLE INCLUSIVE JET PRODUCTION

Forward jet with CASTOR/CMS



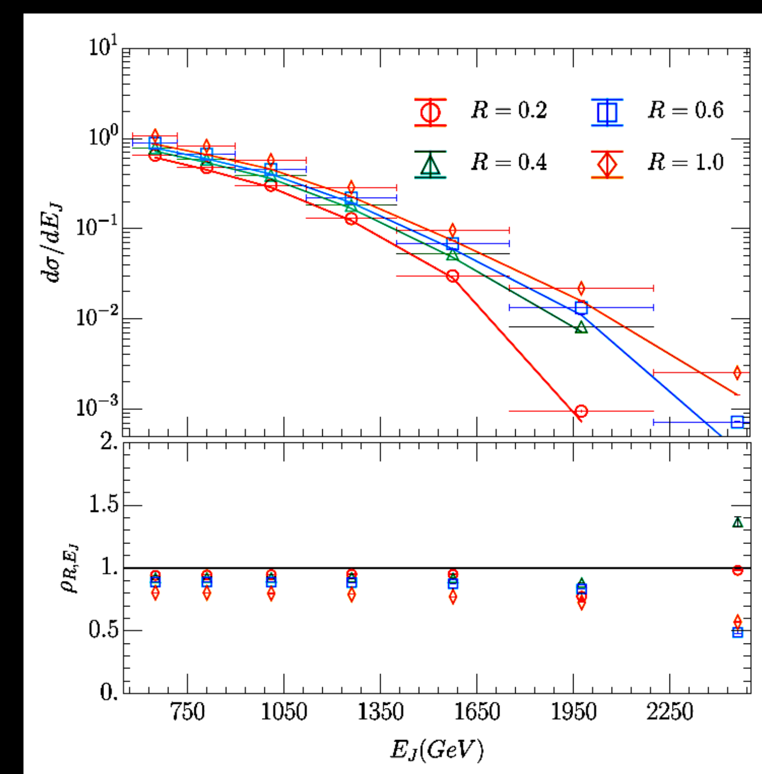
[The CMS collaboration, 2019]

LO CGC with Lappi-Mantysaari dipole amplitude + MPI



[H. Mantysaari, H. Pakkunen, 2019]

First NLO computation (but no direct comparison with data)



[H. Liu, K. Xie, Z-B Kang, X. Liu, 2022]

LO theory predictions:

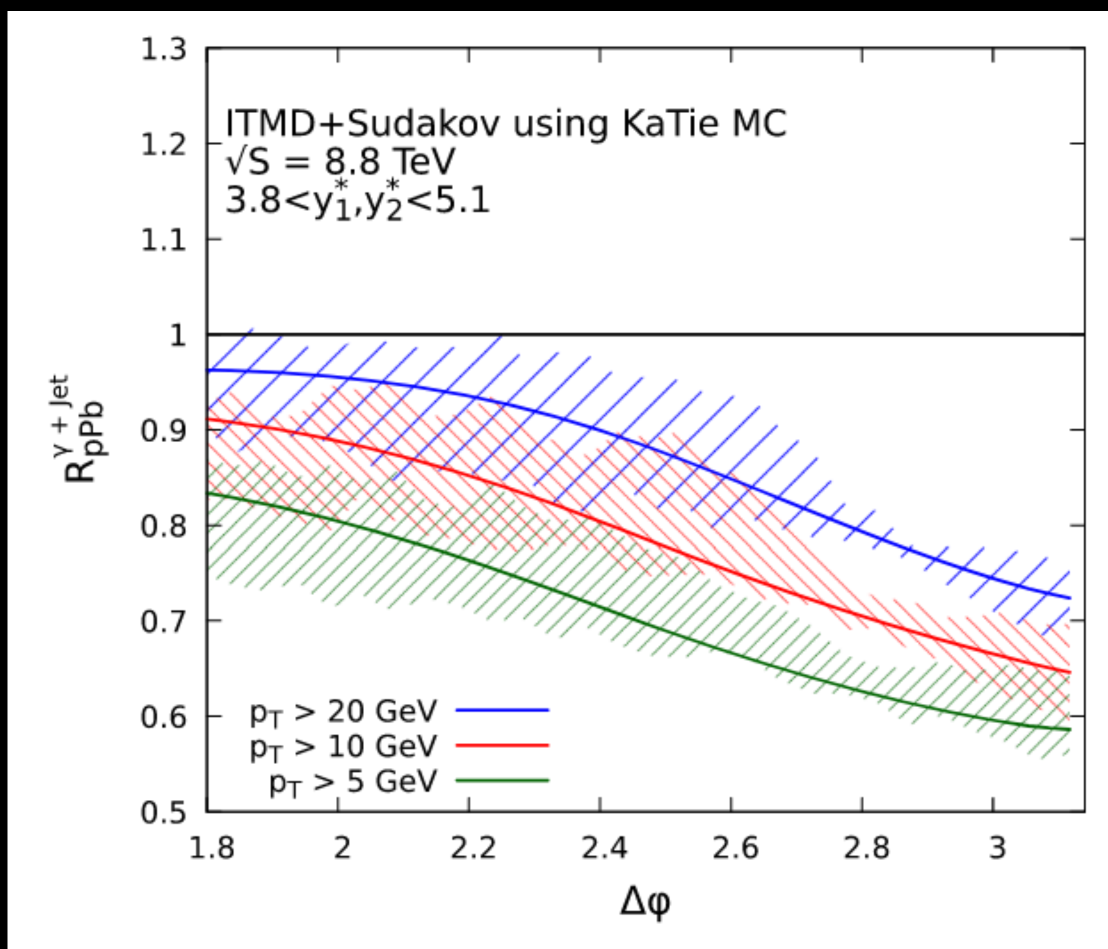
- KaTie MC (van Hameren) + Kutak-Sapeta (KS) fits of the TMD gluon distributions. [M. Bury, H. van Haevermaet, A. van Hameren, P. van Mechelen, K. Kutak, M. Serino, 2018]
- Based on Albacete-Armesto-Milhano-Quiroga-Salgado (AAMQS) dipole scattering amplitude.

[J.L. Albacete, P.G. Rodriguez, Y. Nara, 2016]

INCLUSIVE γ+JET PRODUCTION

Azimuthal correlations for FoCal/ALICE kinematics

Due to simple color flow probes solely dipole gluon distribution.



[I. Ganguli, A. van Hameren, PK, K. Kutak, 2023]

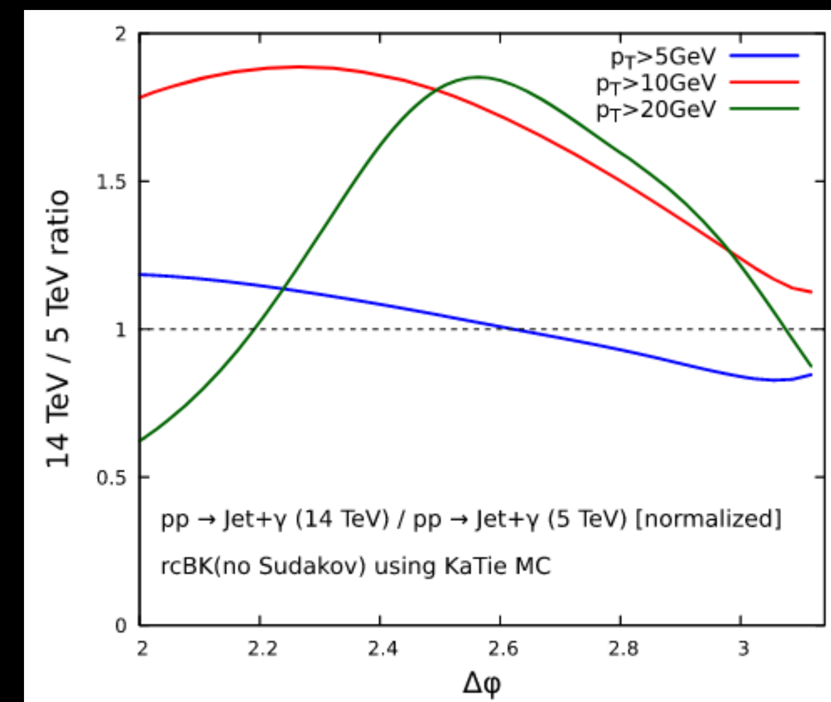
See also:

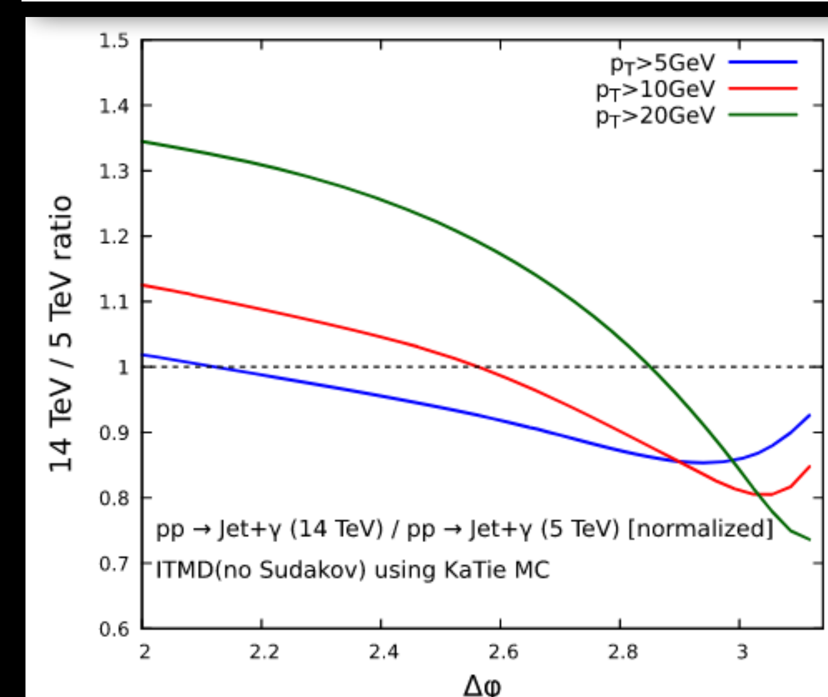
[S. Benic, O. Garcia-Montero, A. Perkov, 2022]

[J. Jalilian-Marian, 2020]

sensitive to details of the small-x evolution

Ratio of p+p cross sections for different energies





FORWARD DIJET PRODUCTION (1)

Two particle production in hybrid formalism of CGC

For example LO $q \to qg$ contribution:

$$\frac{d\sigma_{qA\to qg}}{d^3p_1 d^3p_2} \sim \int \frac{d^2x_T}{(2\pi)^2}\frac{d^2x'_T}{(2\pi)^2}\frac{d^2y_T}{(2\pi)^2}\frac{d^2y'_T}{(2\pi)^2}\, e^{-i\vec{p}_{T1}\cdot(\vec{x}_T-\vec{x}'_T)}e^{-i\vec{p}_{T2}\cdot(\vec{y}_T-\vec{y}'_T)}$$

$$\times \psi_z^*\left(\vec{x}'_T-\vec{y}'_T\right)\psi_z\left(\vec{x}_T-\vec{y}_T\right)$$

$$\times\Big\{S_x^{(6)}\left(\vec{y}_T,\vec{x}_T,\vec{y}'_T,\vec{x}'_T\right)-S_x^{(4)}\left(\vec{y}_T,\vec{x}_T,\bar{z}\vec{y}'_T+z\vec{x}'_T\right)$$

$$-S_x^{(4)}\left(\bar{z}\vec{y}_T+z\vec{x}_T,\vec{y}'_T,\vec{x}'_T\right)-S_x^{(2)}\left(\bar{z}\vec{y}_T+z\vec{x}_T,\bar{z}\vec{y}'_T+z\vec{x}'_T\right)\Big\}$$

[C. Marquet, 2007]

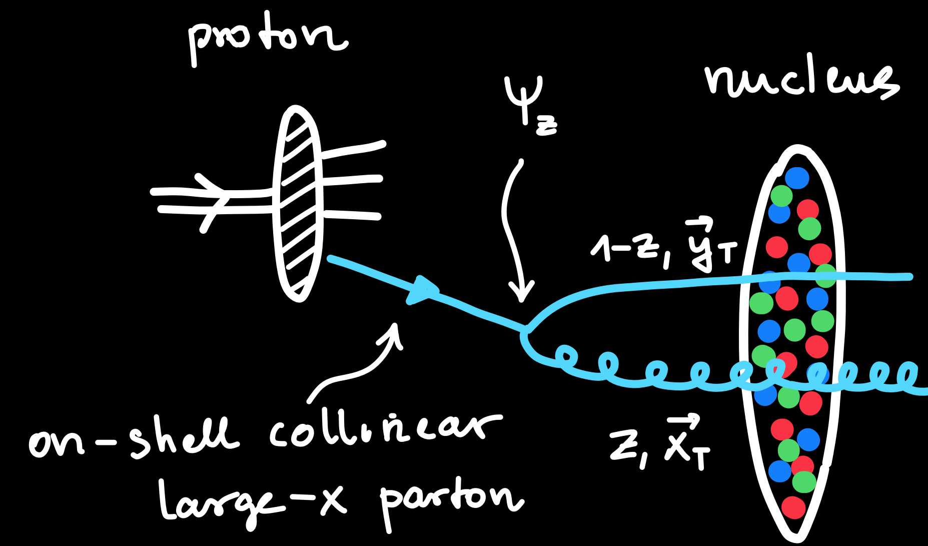
with Wilson line correlators:

$$S_x^{(2)}\left(\vec{y}_T,\vec{x}_T\right)=\frac{1}{N_c}\left\langle \mathrm{Tr}\, U(\vec{y}_T)U^\dagger(\vec{x}_T)\right\rangle_x$$

$$S_x^{(4)}\left(\vec{z}_T,\vec{y}_T,\vec{x}_T\right)=\frac{1}{2C_FN_c}\Big\langle \mathrm{Tr}\left[U(\vec{z}_T)U^\dagger(\vec{y}_T)\right]\mathrm{Tr}\left[U(\vec{y}_T)U^\dagger(\vec{x}_T)\right]\Big\rangle_x - S_x^{(2)}\left(\vec{z}_T,\vec{x}_T\right)$$

etc…

where $U(\vec{x}_T)=\mathscr{P}\exp\left\{ig\int_{-\infty}^{+\infty}dx^+\,A_a^-\left(x^+,\vec{x}_T\right)t^a\right\}$



Progress towards NLO:

- forward trijet production in pA collisions in CGC
  [E. Iancu, Y. Mulian, 2019]
- forward dijets in pA collisions in CGC: real corrections
  [E. Iancu, Y. Mulian, 2021]

FORWARD DIJET PRODUCTION (2)

Back-to-back limit & generalized TMD factorization

$\vec{r}_T = \vec{x}_T - \vec{y}_T$ $\xrightarrow{\text{F.T.}}$ $\vec{k}_T = \vec{p}_{T1} + \vec{p}_{T2}$

$\vec{b}_T = z\vec{x}_T + (1-z)\vec{y}_T$ $\quad$ $\vec{P}_T = (1-z)\vec{p}_{T1} - z\vec{p}_{T2}$

Back-to-back limit: $Q_s \ll k_T \ll P_T$

[F. Dominguez, C. Marquet, B-W Xiao, F. Yuan, 2011]

$$\frac{d\sigma_{pA\to 2j+X}}{d^3p_1 d^3p_2} = \sum_{a,c,d} f_{a/p}(x_1,\mu) \sum_i H^{(i)}_{ag\to cd}(k_T=0)\, \mathcal{F}^{(i)}_{ag}(x_2,k_T)$$

on-shell hard factors

small-x TMD gluon distributions

Saturation at leading twist!

Beyond back-to-back & improved small-x TMD factorization (ITMD)

[PK, K. Kutak, C. Marquet, E. Petreska, S. Sapeta, A. van Hameren, 2015]

Resummation of kinematic twists:

[T. Altinoluk, R. Boussarie, PK, 2019]

$$\frac{d\sigma_{pA\to 2j+X}}{d^3p_1 d^3p_2} = \sum_{a,c,d} f_{a/p}(x_1,\mu) \sum_i K^{(i)}_{ag\to cd}(k_T)\, \mathcal{F}^{(i)}_{ag}(x_2,k_T)$$

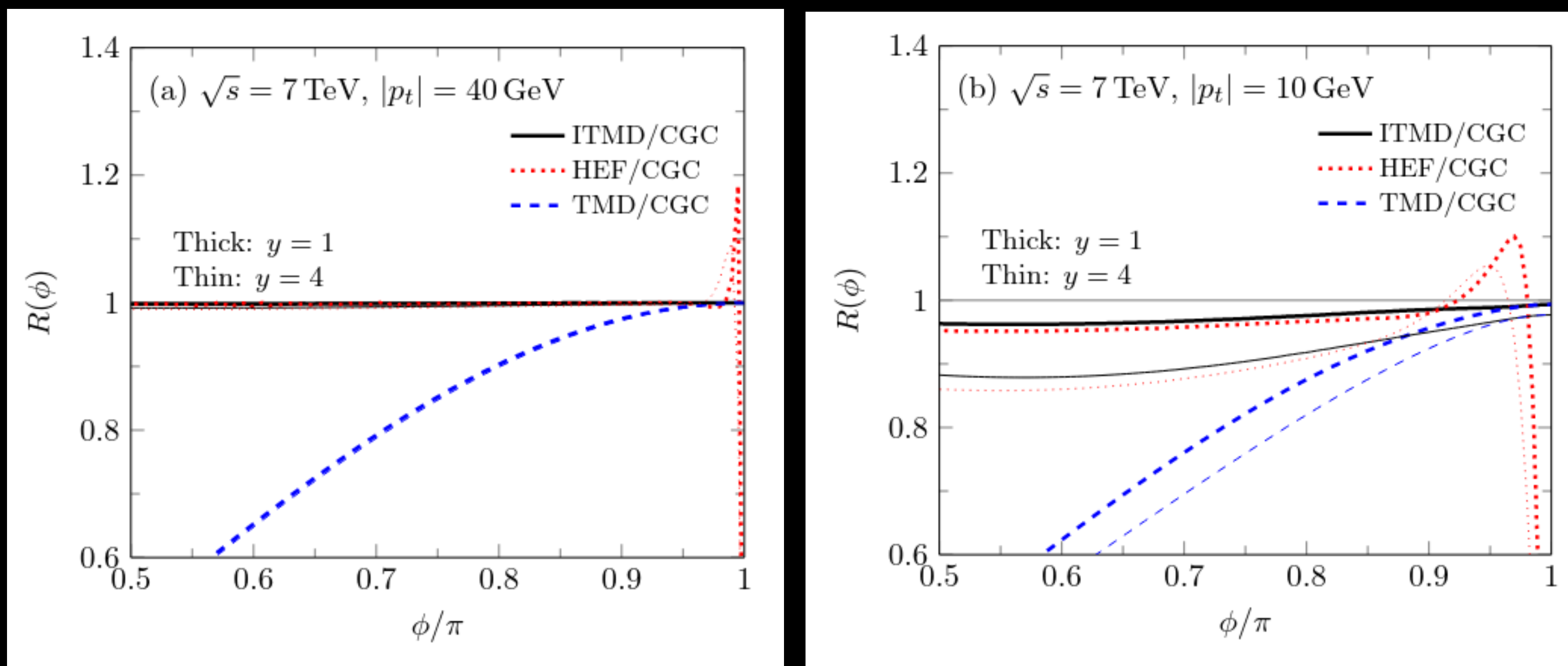
off-shell gauge invariant hard factors

Leading "genuine" twist

[A. van Hameren, PK, K. Kutak, 2012, 2013]

FORWARD DIJET PRODUCTION (3)

How good is ITMD comparing to full CGC?



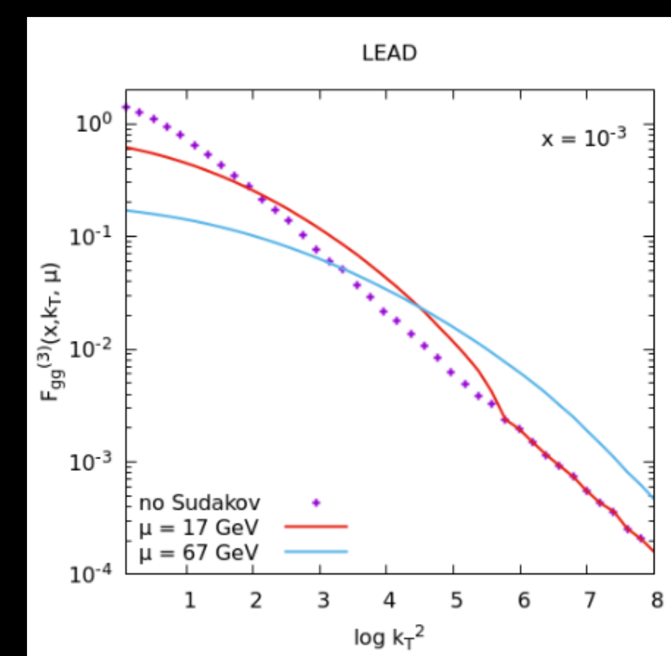
[H. Fuji, C. Marquet, K. Watanabe, 2020]

- ITMD reproduces full CGC down to moderately low p_T
- The leading twist TMD approach is good only in the back-to-back region

Further improvements

- Sudakov resummation is crucial even at moderately large p_T .

  [A. Mueller, B.-W. Xiao, F. Yuan, 2013] [A. van Hameren, P.K., K. Kutak, S. Sapeta, 2014]
  [A. Stasto, S.-Y. Wei, B.-W. Xiao, F. Yuan, 2018]
  [P. Caucal, F. Salazar, B. Schenke, R. Venugopalan, 2022]



[A. van Hameren, P.K., K. Kutak, S. Sapeta, E. Zarow, 2021]

- Automatization of NLO computations is in progress.

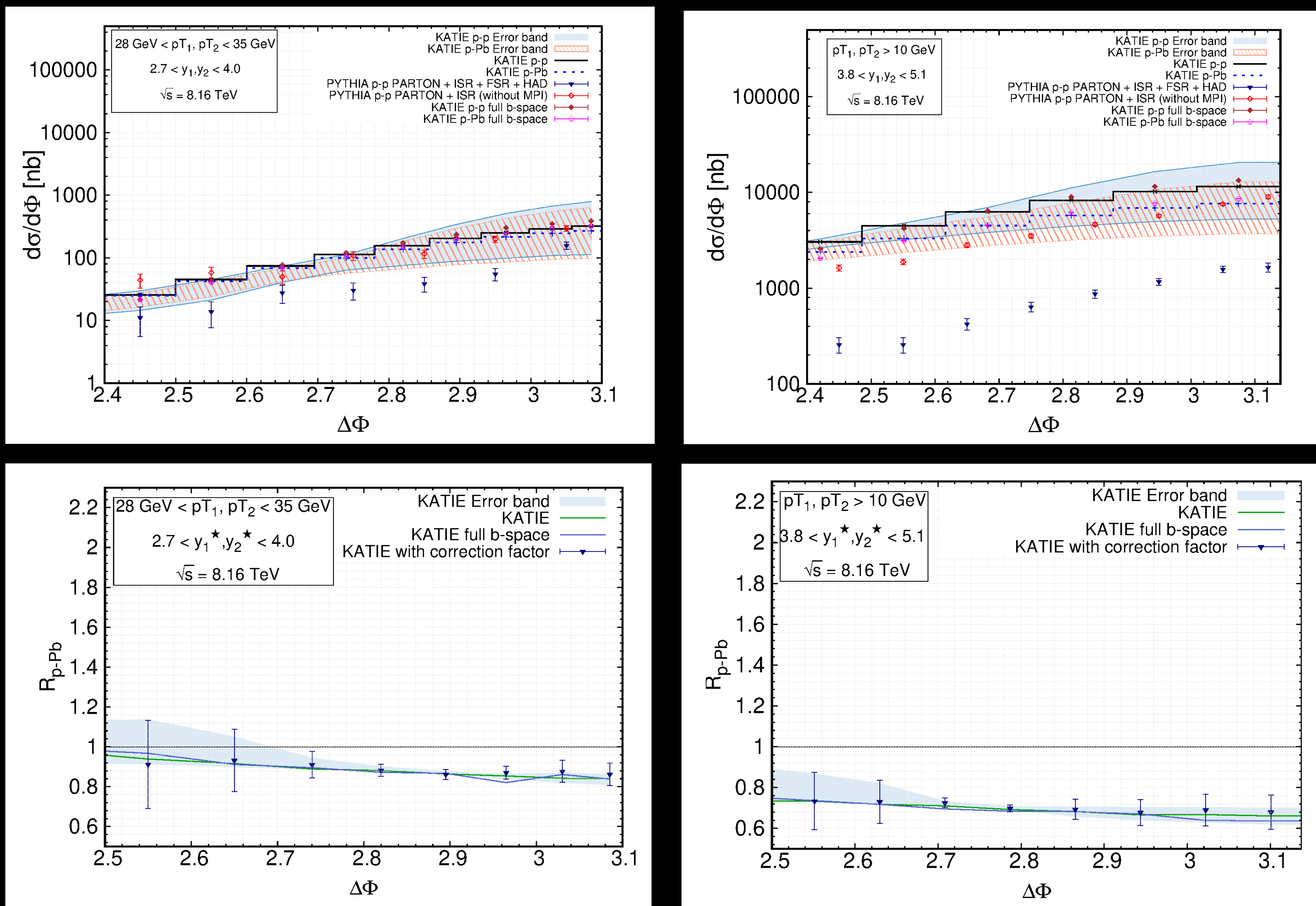
  [E. Blanco, A. van Hameren, P.K., K. Kutak, 2020]
  [E. Blanco, A. Giachino, A. van Hameren, P.K., 2023]
  [A. Giachino, A. van Hameren, G. Ziarko, 2024]

FORWARD DIJET PRODUCTION (4)

Azimuthal correlations in ATLAS & FoCal/ALICE

[M.A. Al-Mashad, A. van Hameren, H. Kakkad, P. Kotko, K. Kutak, P. van Mechelen, S. Sapeta, ArXiv:2210.06613]

ATLAS



FoCal

SUMMARY

- Understanding the k_T dependence of small-x TMD gluon distributions requires measurements of azimuthal correlations (or decorrelations) for various types of final states (and projectiles).
- However, they are very sensitive to initial state-unrelated effects (Sudakov logs), especially for jets.
- The Sudakov effects cancel, to large extent, in p+A to p+p ratio.
- Therefore measurements of R_{pA} (and not the conditional yields), as a function of various kinematic variables, is indispensable in studying possible saturation signals and discriminating it from other mechanisms.

BACKUP

BROADENING (1)

ITMD vs ATLAS data

Measurement of dijet azimuthal correlations in p+p and p+Pb. [ATLAS, Phys. Rev. C100 (2019)]

$\sqrt{S} = 5.02$ TeV   rapidity: $2.7 < y_1, y_2 < 4.5$

$$C(\Delta\phi) = \frac{1}{N_1}\frac{dN_2}{d\Delta\phi}$$

number of dijets (N_2)

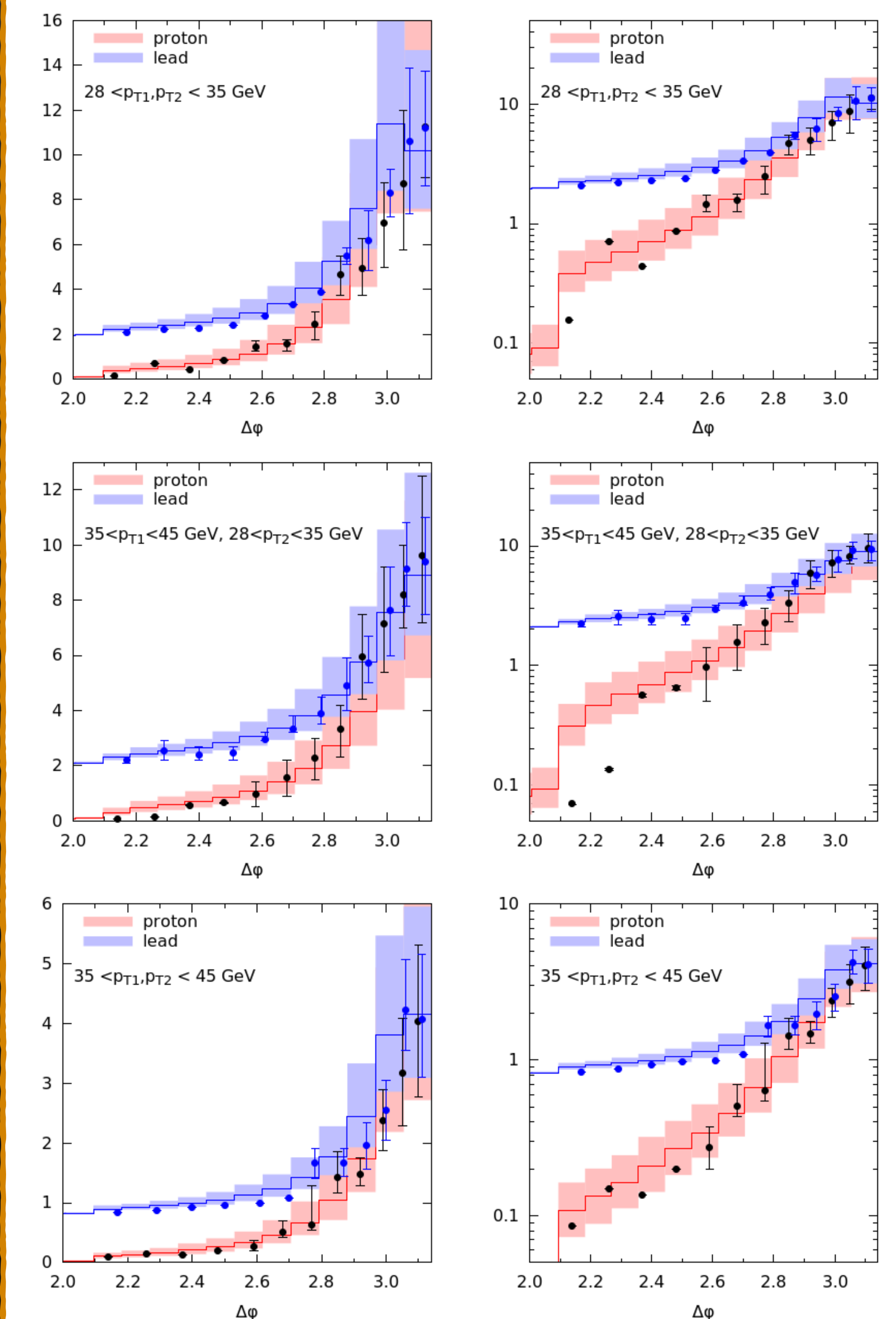
azimuthal angle between jets ($\Delta\phi$)

number of Leading jets (N_1)

We study only the <u>shape</u> of C for p+p and p+Pb.

Good description of the broadening effects.

Similar studies done at RHIC for particle production…



A. Van Hameren, P. Kotko, K. Kutak, S. Sapeta, Phys. Lett. B795 (2019) 511

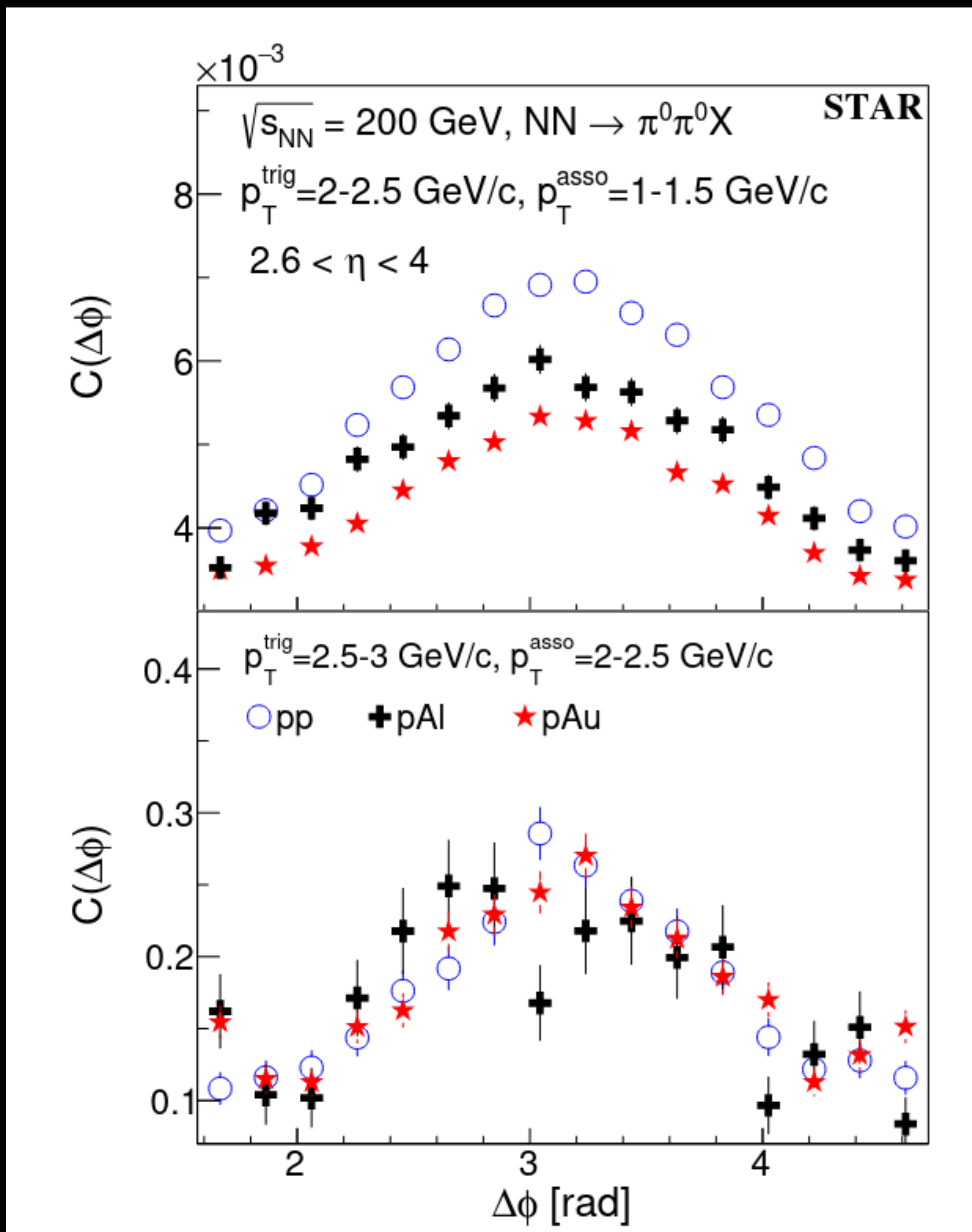
BROADENING (2)

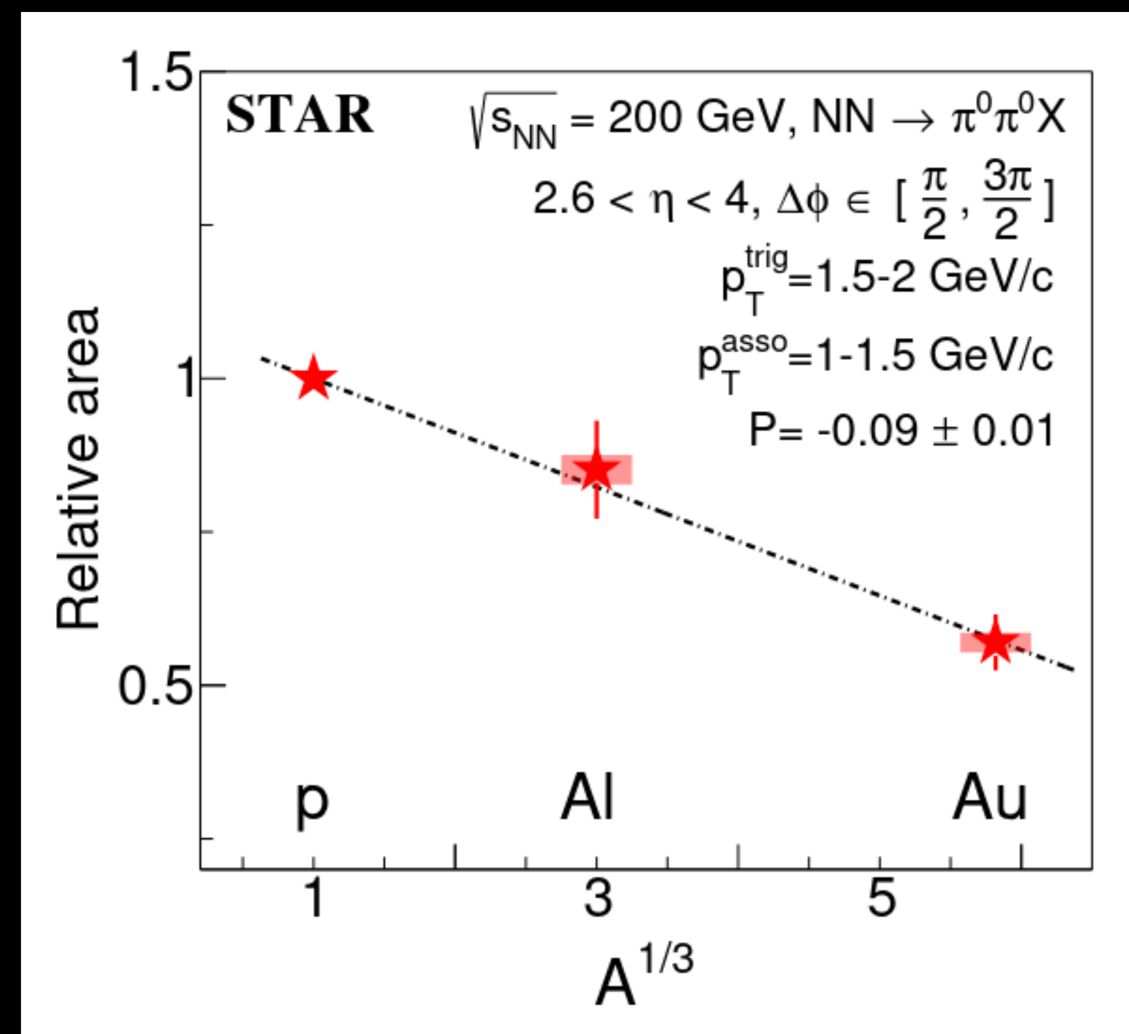
Saturation at RHIC ?

$$p + A \to \pi^0 + \pi^0 + \text{anything}$$

proton Aluminium Gold

small p_T





[STAR collaboration, 2022]