FORWARD DIJET PRODUCTION IN SATURATION FORMALISM

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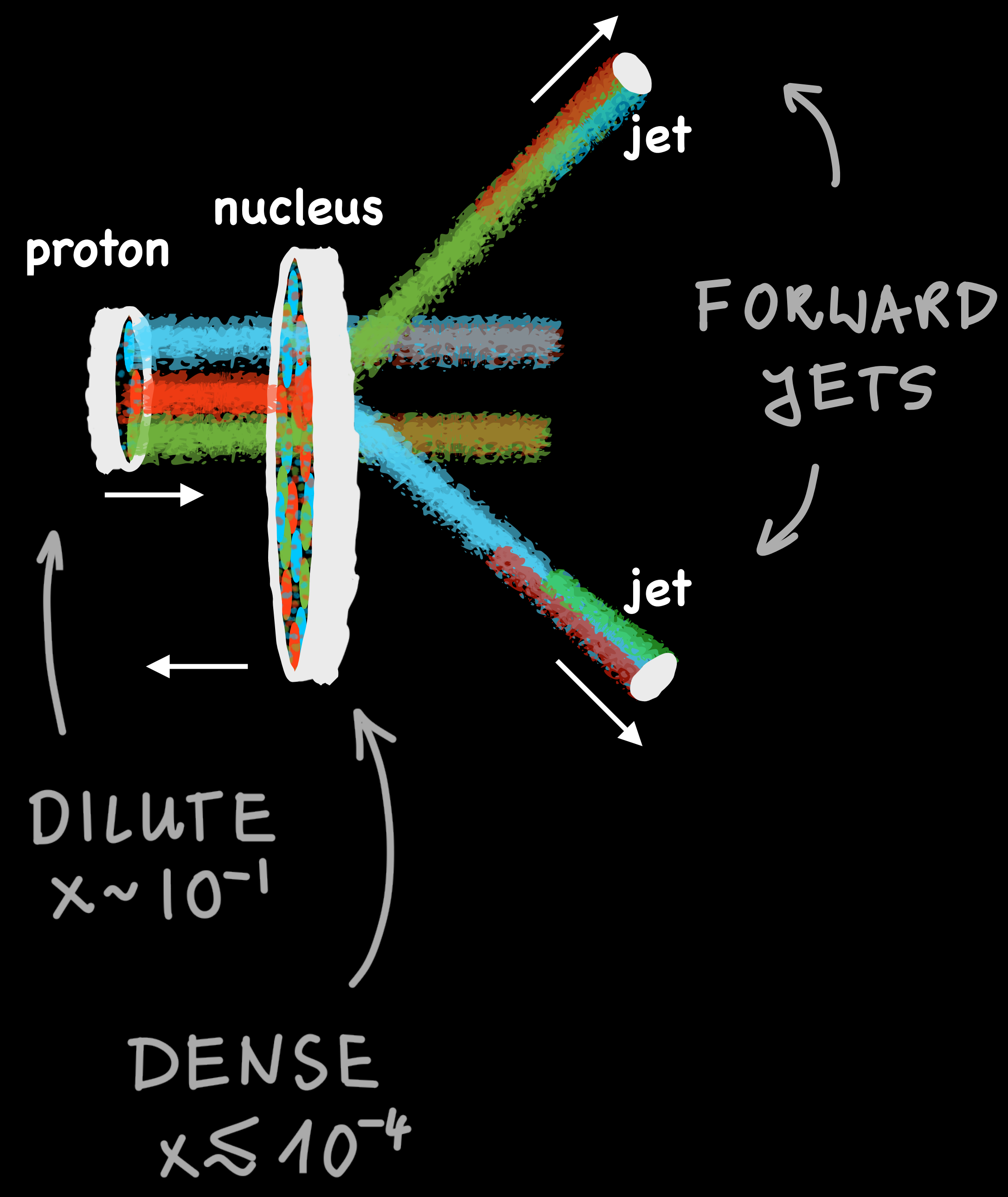
MOTIVATION

Forward dijets in dilute-dense collisions

- probing small-x regime of gluon distributions
- sensitive to nuclear effects
- sensitive to internal k_T of gluons
- sensitive to interplay between k_T of gluons and p_T of jets
- non-universality of TMD gluon distributions



PLAN

1. Framework
    - A. Small-x Improved TMD factorization (ITMD) for pA
    - B. Dilute-dense collisions in Color Glass Condensate (CGC)
    - C. TMD gluon distributions at small x
    - D. Sudakov resummation
2. Phenomenology for ATLAS and FoCal kinematics
    - A. Azimuthal dijet correlations at parton level for p-p and p-Pb
    - B. Attempts to estimate hadron-level corrections
3. Summary and Outlook

FRAMEWORK Small-x Improved TMD Factorization (ITMD)

Factorization formula for forward dijets in p-p and p-A

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

$$\frac{d\sigma_{pA\to 2j+X}}{dy_1 dy_2 d^2p_{T1} d^2p_{T2}} \sim \sum_{a,c,d} f_{a/p}(x_1,\mu) \sum_{i=1,2} K^{(i)}_{ag\to cd}(k_T)\, \Phi^{(i)}_{ag\to cd}(x_2,k_T)$$

RAPIDITY — TRANSVERSE MOMENTA — COLLINEAR PROTON PDF — GAUGE INVARIANT OFF-SHELL HARD FACTORS — TMD GLUON DISTRIBUTIONS AT SMALL-X

TWO PER CHANNEL
$(g^*q\to gq,\ g^*g\to gg,\ g^*g\to q\bar{q})$

$x_2 \ll x_1$ $\quad |\vec{p}_{T1}+\vec{p}_{T2}| = k_T$

ITMD factorization formula has been proven from the Color Glass Condensate (CGC) theory.

⇒ RESUMMATION OF KINEMATIC TWISTS AND NEGLECTING GENUINE TWISTS.

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

easy to implement in Monte Carlo

FRAMEWORK Limiting cases of Color Glass Condensate (CGC)

CGC
dilute-dense

three scales:

$Q_s \gg \Lambda_{\rm QCD}$ — saturation scale

k_T — jet transverse momentum imbalance

P_T — jet average transverse momentum

$P_T \gg k_T \sim Q_s$

TMD
GENERALIZED FACTORIZATION

leading twist

[F. Dominguez, C. Marquet, B. Xiao, F. Yuan, 2011]
[C. Marquet, E. Petreska, C. Roiesnel, 2016]
[C. Marquet, C. Roiesnel, P. Taels, 2018]
[T. Altinoluk, R. Boussarie, C. Marquet, P. Taels, 2019, 2020]
[P. Taels, T. Altinoluk, G. Beuf, C. Marquet, 2022]

$P_T \sim k_T \gg Q_s$

$P_T \gg Q_s$

ITMD
"IMPROVED" TMD factorization

all kinematic twists

[PK, K. Kutak, C. Marquet, E. Petreska, S. Sapeta, A. van Hameren, 2015]
[A. van Hameren, PK, K. Kutak, C. Marquet, E. Petreska, S. Sapeta, 2016]
[T. Altinoluk, R. Boussarie, PK, 2019]
[H. Fujii, C. Marquet, K. Wanatabe, 2020]
[T. Altinoluk, C. Marquet, P. Taels, 2021]

DILUTE
K_T-FACTORIZATION
BFKL dynamics

[S. Catani, M. Ciafaloni, F. Hautmann, 1991]
[M. Deak, F. Hautmann, H. Jung, K. Kutak, 2009]
[E. Iancu, J. Leidet, 2013]

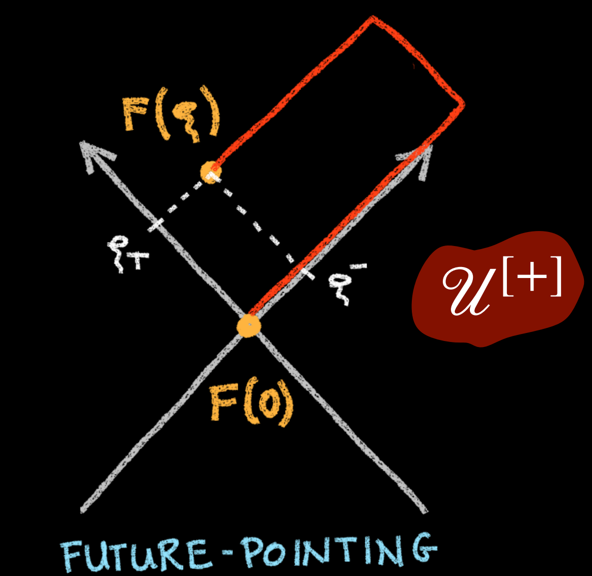
Generic operator definition

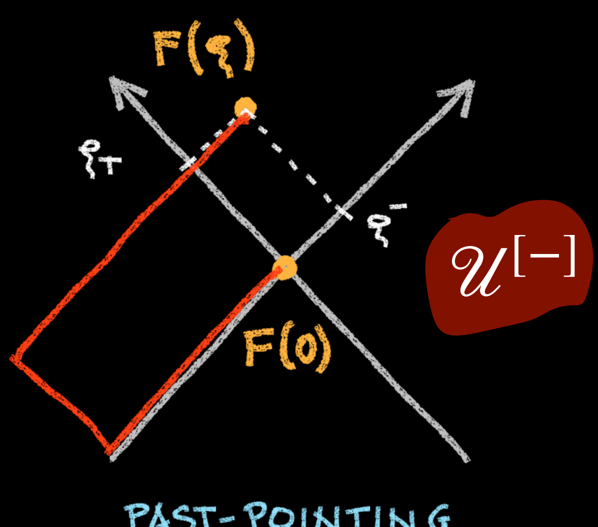
(unpolarized)

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

GLUON FIELD $\hat{F} = F_a t^a$

GAUGE LINKS in fundamental color representation





Gauge links $\mathcal{U}_{C_1}, \mathcal{U}_{C_2}$ depend on the color structure of the hard process. They are build from two basic Wilson lines:

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

$$\mathcal{U}^{[\pm]} = [0,(\pm\infty,\vec{0}_T,0)] \times [(\pm\infty,\vec{0}_T,0),(\pm\infty,\vec{\xi}_T,0)] \times [(\pm\infty,\vec{\xi}_T,0),(\xi^+,\vec{\xi}_T,0)]$$

$$[x,y] = \mathcal{P}\exp\left\{ig\int_{\overline{xy}} dz_\mu A_a^\mu(z)t^a\right\}$$

STRAIGHT LINE SEGMENT

Light-cone basis:

$$v^\pm = v^\mu n^\pm_\mu, \quad n^\pm = (1,0,0,\mp 1)$$

$$v^\mu = \frac{1}{2}v^+n^- + \frac{1}{2}v^-n^+ + v^\mu_T$$

FRAMEWORK

TMD gluon distributions

All possible operators

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

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

DIPOLE

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

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

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

in the small-x limit

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

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

WEIZSACKER -WILLIAMS

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

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

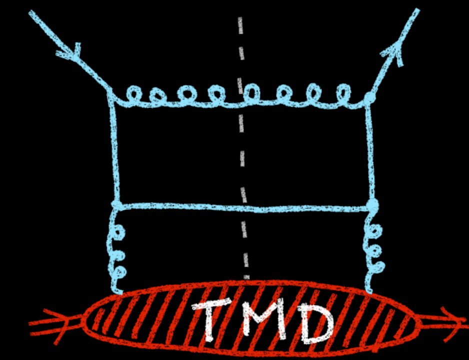
$$\mathcal{F}_{gg}^{(6)} \sim \langle P|\,\frac{\mathrm{Tr}\,\mathcal{U}^{[\Box]}}{N_c}\frac{\mathrm{Tr}\,\mathcal{U}^{[\Box]\dagger}}{N_c}\mathrm{Tr}\left[\hat{F}^{i-}(\xi)\,\mathcal{U}^{[+]\dagger}\hat{F}^{i-}(0)\,\mathcal{U}^{[+]}\right]|P\rangle$$

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

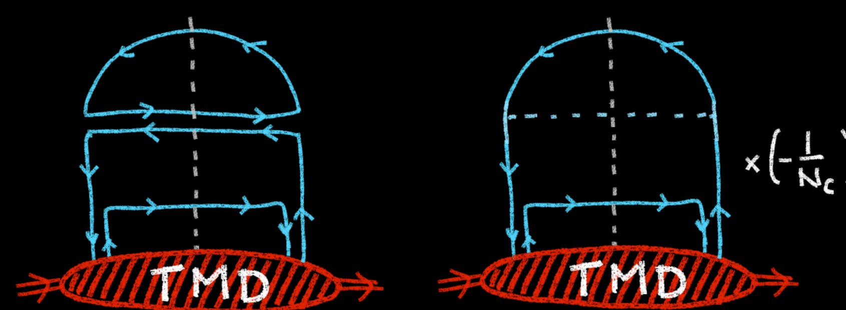
WILSON LOOP → $\mathcal{U}^{[\Box]} = \mathcal{U}^{[+]}\mathcal{U}^{[-]\dagger}$

Example

TMD gluon distribution for the following process:



Two independent color flows:



$$\rightsquigarrow \frac{N_c}{2C_F}\mathcal{F}_{qg}^{(2)} - \frac{1}{2N_cC_F}\mathcal{F}_{qg}^{(1)}$$

Gluon TMD for any multiparticle process is given by a linear combination of these "basis" TMDs.

Evolution of the TMD gluon distributions

Data-driven dipole TMD

Balitsky-Kovchegov type equation with kinematic constraint, DGLAP correction and running coupling:

[J. Kwieciński, A. Martin, A. Stasto, 1997]
[K. Kutak, J. Kwieciński, 2003]

$$\mathcal{F}^{(1)}_{qg}\left(x,k_T^2\right) = \mathcal{F}_0\left(x,k_T^2\right) + \frac{\alpha_s N_c}{\pi}\int_x^1 \frac{dz}{z}\int_{k_{T0}^2}^{\infty}\frac{dq_T^2}{q_T^2}\left\{\frac{q_T^2\mathcal{F}\left(\frac{x}{z},q_T^2\right)\theta\left(\frac{k_T^2}{z}-q_T^2\right)-k_T^2\mathcal{F}\left(\frac{x}{z},k_T^2\right)}{\left|q_T^2-k_T^2\right|}+\frac{k_T^2\mathcal{F}\left(\frac{x}{z},k_T^2\right)}{\sqrt{4q_T^4+k_T^4}}\right\}$$

$$+\frac{\alpha_s}{2\pi k_T^2}\int_x^1 dz\left\{\left(P_{gg}(z)-\frac{2N_c}{z}\right)\int_{k_{T0}^2}^{k_T^2} dq_T^2\mathcal{F}\left(\frac{x}{z},q_T^2\right)+zP_{gq}(z)\Sigma\left(\frac{x}{z},k_T^2\right)\right\}$$

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

for NUCLEUS: $R_A = A^{1/3} R_p$

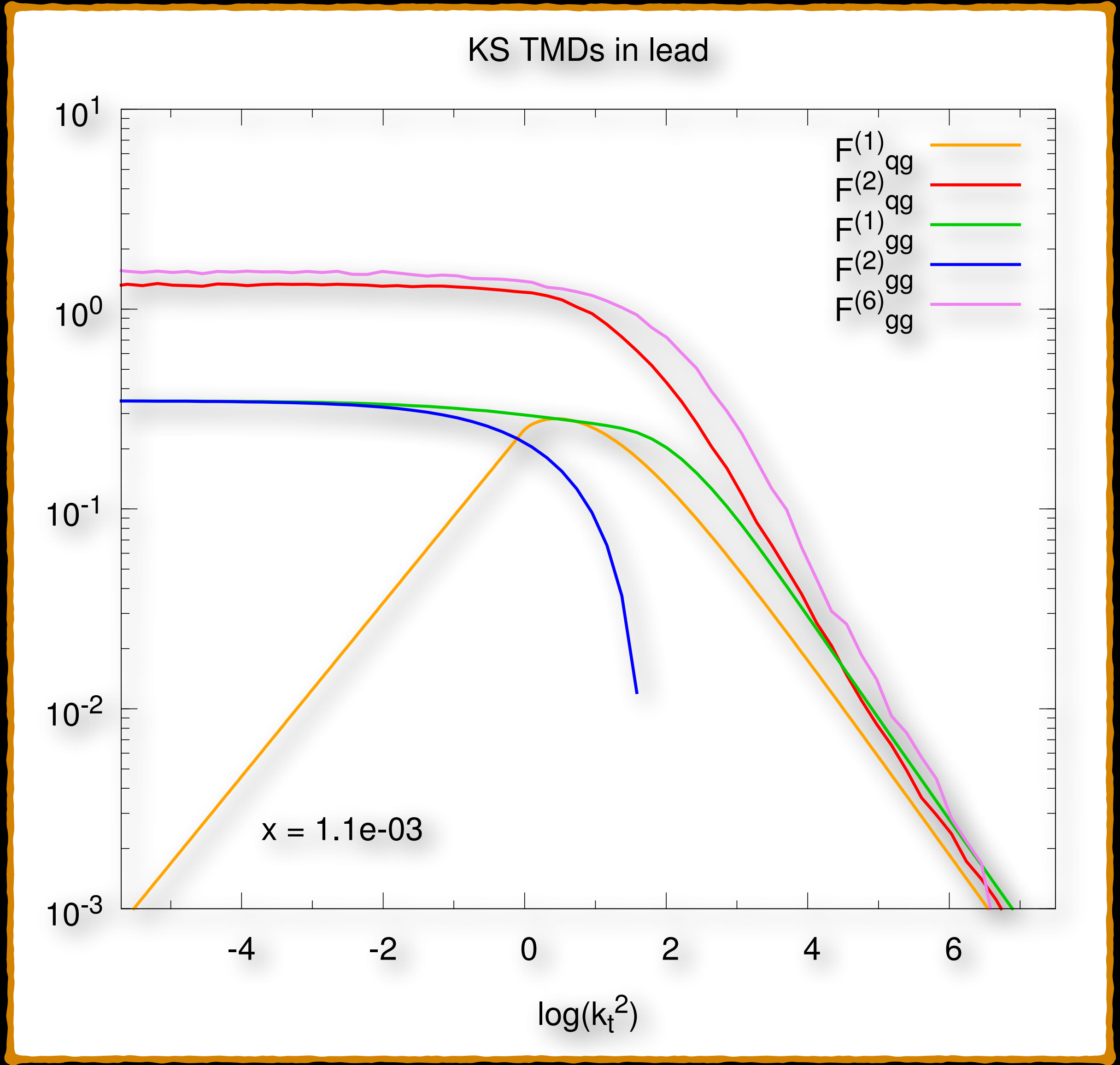
fitted to DIS HERA data

[K. Kutak, S. Sapeta, 2012]

How to get various TMD distributions?

Using CGC theory one can derive a relation between the small-x TMDs using:
(i) large N_c limit
(ii) mean field (Gaussian) approximation.

All TMDs needed for dijet production can be calculated from the dipole gluon distribution $\mathcal{F}_{qg}^{(1)}$.



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

It is possible to relax the assumptions (i) and (ii) using the JIMWLK equation.
Prove of concept:
[C. Marquet, E. Petreska, C. Roiesnel, 2016]

Improvements:
[S. Cali, K. Cichy, P. Korcyl, PK, K. Kutak, C. Marquet, 2021]

Hard scale in TMD gluon distributions

- Typical small-x evolution (BFKL, BK, JIMWLK) evolves only in energy at fixed hard scale:

$$\mathcal{F}^{(i)}_{ag}\left(x,k_T^2\right) = \mathcal{F}^{(1)}_{qg}\left(x,k_T^2,\mu=\mu_0\right), \qquad \mu_0 \sim k_T$$

- Evolution in hard scale only (at fixed x) is the DGLAP evolution:

$$f_a\left(x,\mu^2\right) = S_a(\mu^2,\mu_0^2) f_a(x,\mu_0^2) + \int_{\mu_0}^{\mu^2} \frac{dp_T^2}{p_T^2}\frac{\alpha_s(p_T^2)}{2\pi} S_a(\mu^2,p_T^2)\, P_{ba}(z) \otimes f_b\left(\frac{x}{z},p_T^2\right)$$

Sudakov form factor

$$S_a(\mu^2,\mu_0^2) = \exp\left(-\int_{\mu_0^2}^{\mu^2}\frac{dp_T^2}{p_T^2}\frac{\alpha_s(p_T^2)}{2\pi}\sum_i\int_\epsilon^{1-\epsilon} P_{ia}(z)\right)$$

- Trying to mix both types of evolution has a long history…
  - **CCFM** [M. Ciafaloni, S. Catani, F. Fiorani, G. Marchesini, 1990]
  - **KMR** [M.A. Kimber, A.D. Martin, M.G. Ryskin, 2000]
  - **CASCADE** [H. Jung, G. Salam, 2000]
  - [K. Kutak, K. Golec-Biernat, S. Jadach, M. Skrzypek, 2012]
  - [I. Balitsky, A. Tarasov, 2015]
  - [A. van Hameren, PK, K. Kutak, S. Sapeta, 2014]
  - …

- Resummation of Sudakov logs can be also done in the impact-parameter space. More general, but harder to implement in Monte Carlo.

b-space Sudakov resummation for dijets in ITMD framework

$$\frac{d\sigma_{pA\to 2j+X}}{dy_1 dy_2 d^2p_{T1} d^2p_{T2}} \sim \sum_{a,c,d} \sum_{i=1,2} K^{(i)}_{ag\to cd}(k_T,\mu) \int d^2b\, f_{a/p}(x_1,\mu_b)\, \widetilde{\Phi}^{(i)}_{ag\to cd}(x_2,\vec{b}_T)\, e^{-S^{ag\to cd}(\mu,\mu_b)}$$

F.T. of TMD gluon distributions

Sudakov factors

where

$$\mu_b = 2e^{-\gamma_E}/b_*$$

$$b_* = b_T/\sqrt{1+b_T^2/b_{T\max}^2}$$

The perturbative Sudakov factors $S^{ag\to cd}(\mu,\mu_b)$ were calculated in [A.H. Mueller, B-W. Xiao, F. Yuan, 2013]

How to apply this in Monte Carlo?

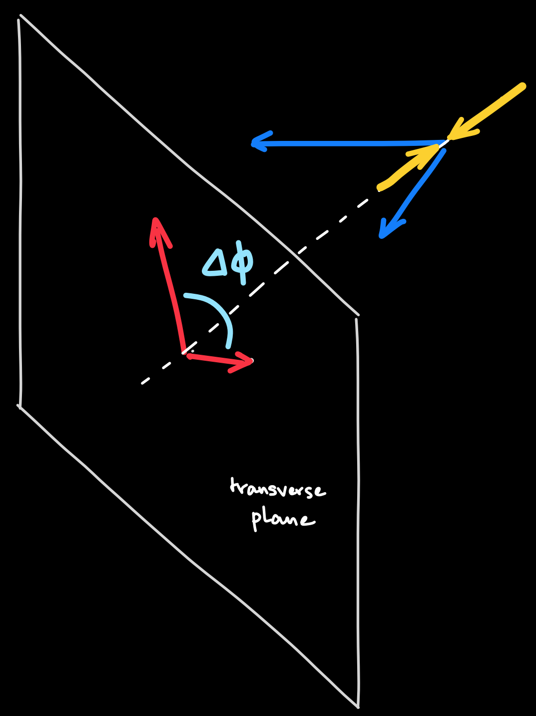
- Approach 1: ignore the b-dependence in the collinear PDF
  - the hard scale-dependent TMD distribution can be computed separately
  - missing threshold type logarithms
- Approach 2: compute the b-integral for MC generated phase space points
  - first compute the weights according to Approach 1
  - next, reweight the events using the full b-space luminosity

We test both approaches.

Kinematic setup

Overview of the computations

- azimuthal correlations between jets
- p-p and p-Pb cross sections in FoCal and ATLAS setup
- nuclear modification ratios
- ITMD framework with KS TMD gluon distributions using KaTie Monte Carlo
- both the full b-space Sudakov resummation and the approximate MC-convenient approach
- Pythia computations to estimate nonperturbative corrections

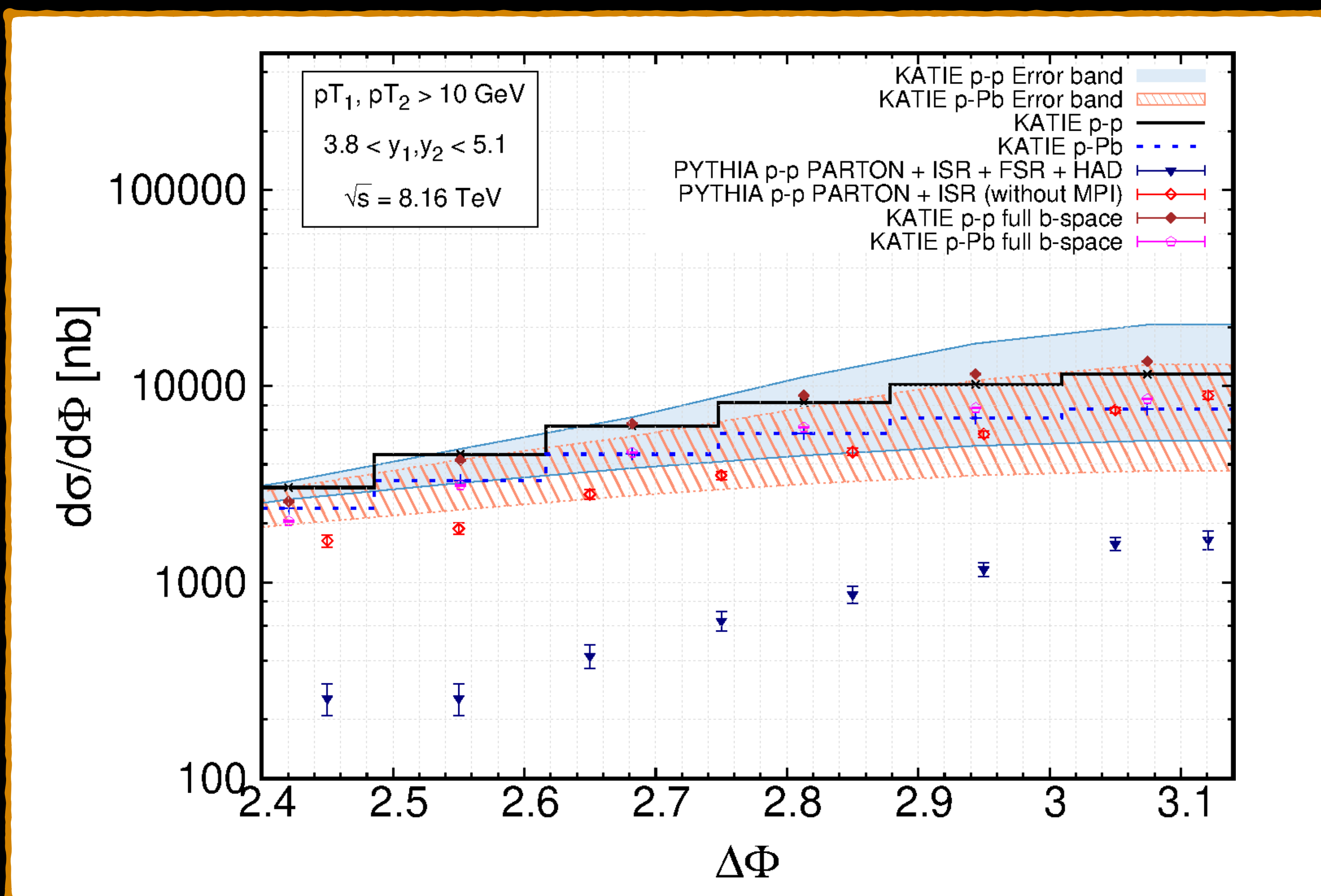


Kinematic cuts

- CM energy: $\sqrt{s} = 8.16\,\mathrm{TeV}$ per nucleon
- jet radius: $\Delta R > 0.5$

	FoCal	ATLAS
jet transverse momenta:	$p_{T1} > p_{T2} > 10\,\mathrm{GeV}$	$45\,\mathrm{GeV} > p_{T1} > p_{T2} > 28\,\mathrm{GeV}$
rapidity:	$3.8 < y_1^*, y_2^* < 5.1$	$2.7 < y_1^*, y_2^* < 4.0$

Azimuthal correlations for p-p and p-Pb



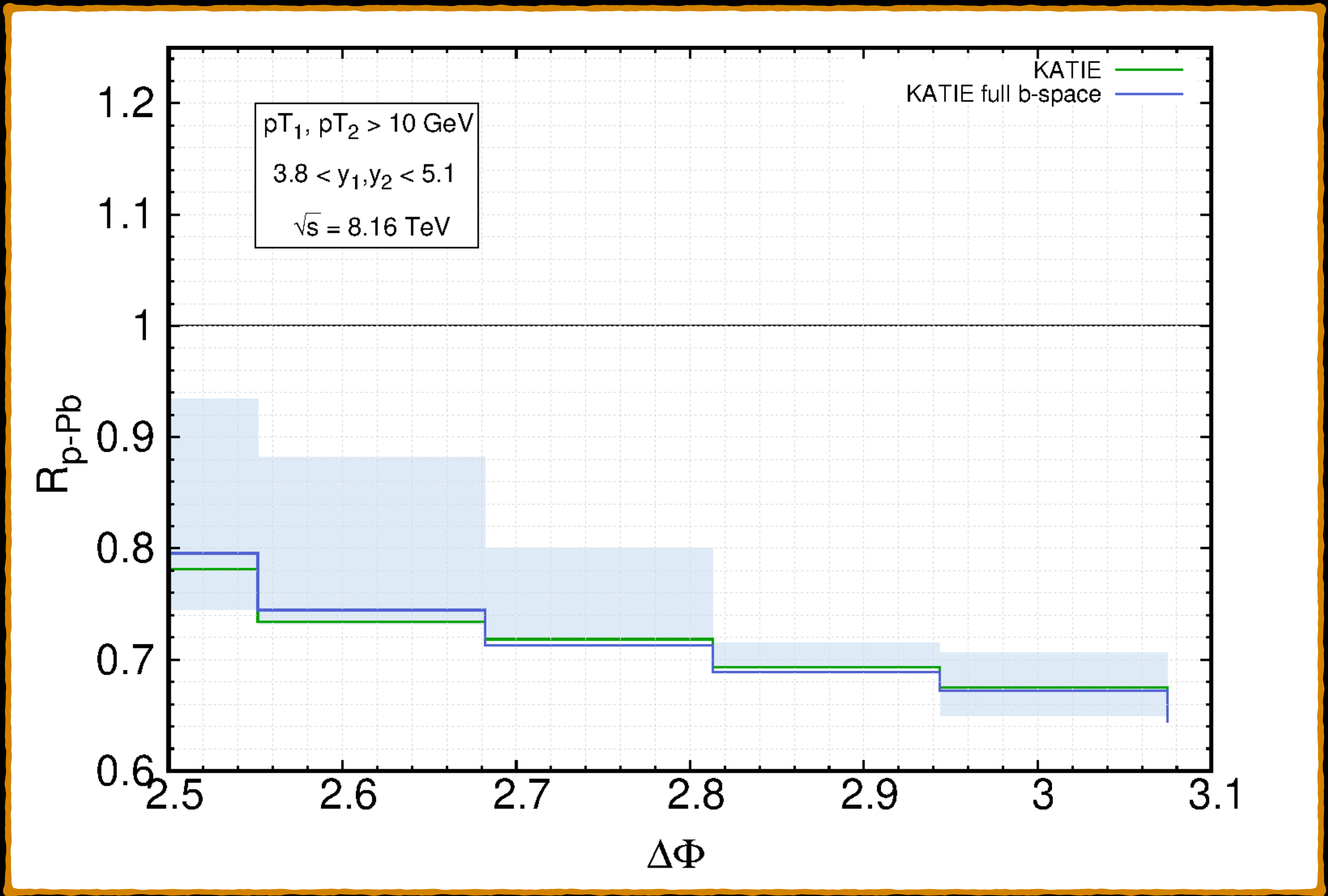
ITMD@KaTie

- large suppression of the p-Pb cross section compared to p-p
- the full b-space Sudakov resummation as well as the simplified approach are very similar
- the saturation effects do not go away when including the Sudakov resummation

lessons from Pythia:

- final state shower and nonperturbative corrections (MPI and hadronization) seem to significantly affect the spectrum
- too low p_T cut?
- can we extract nonperturbative "form factor"?

Azimuthal correlations - nuclear modification ratio



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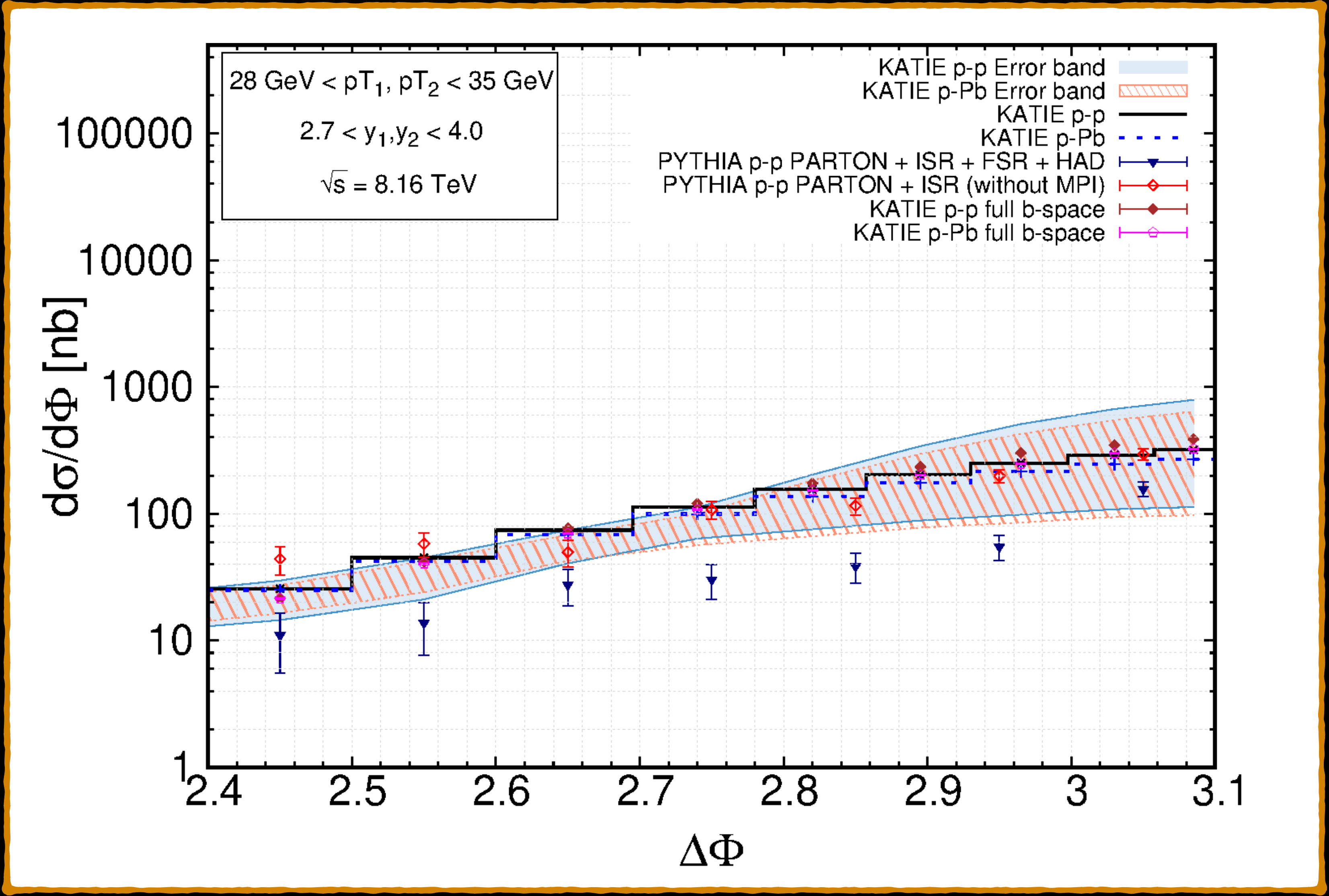

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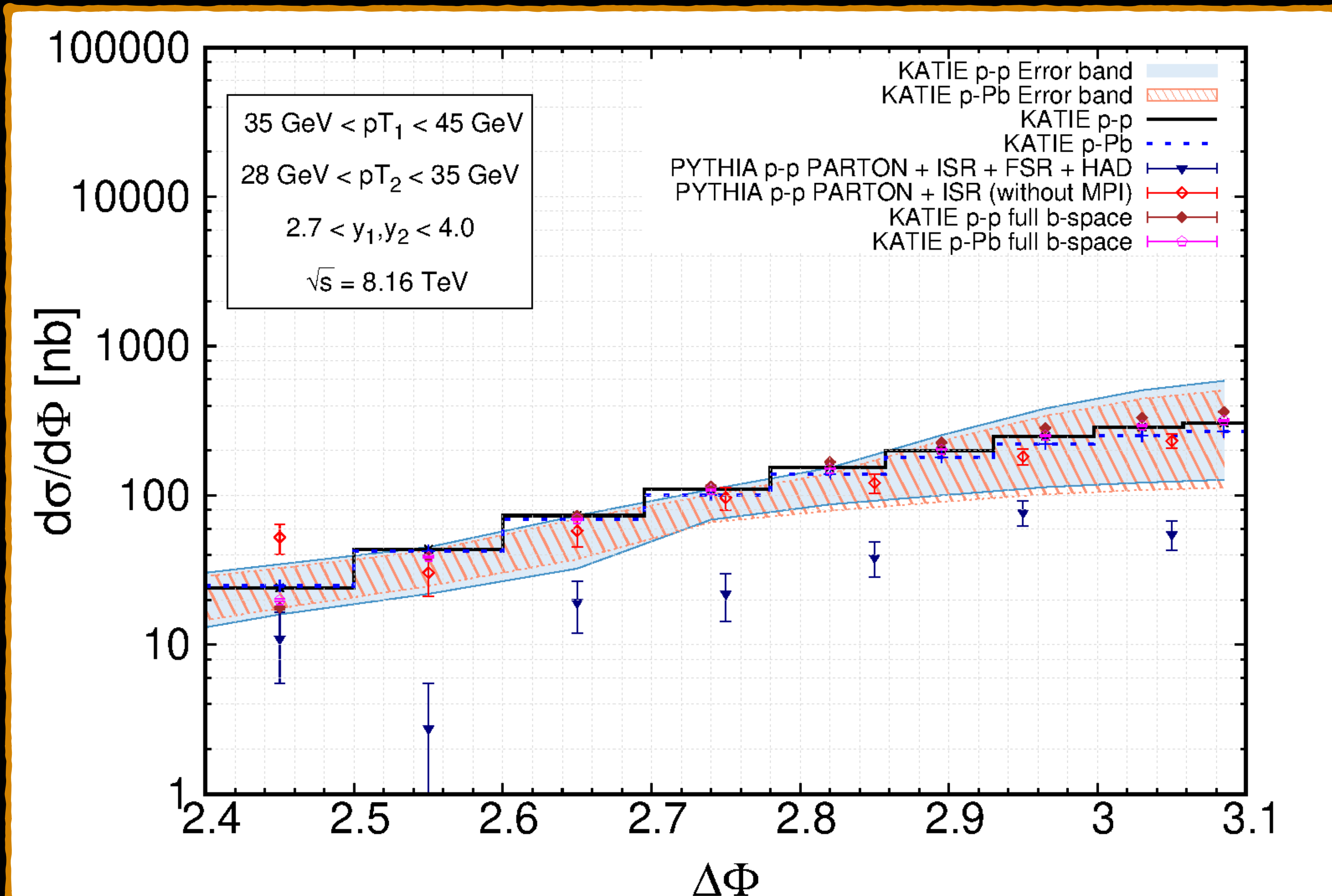

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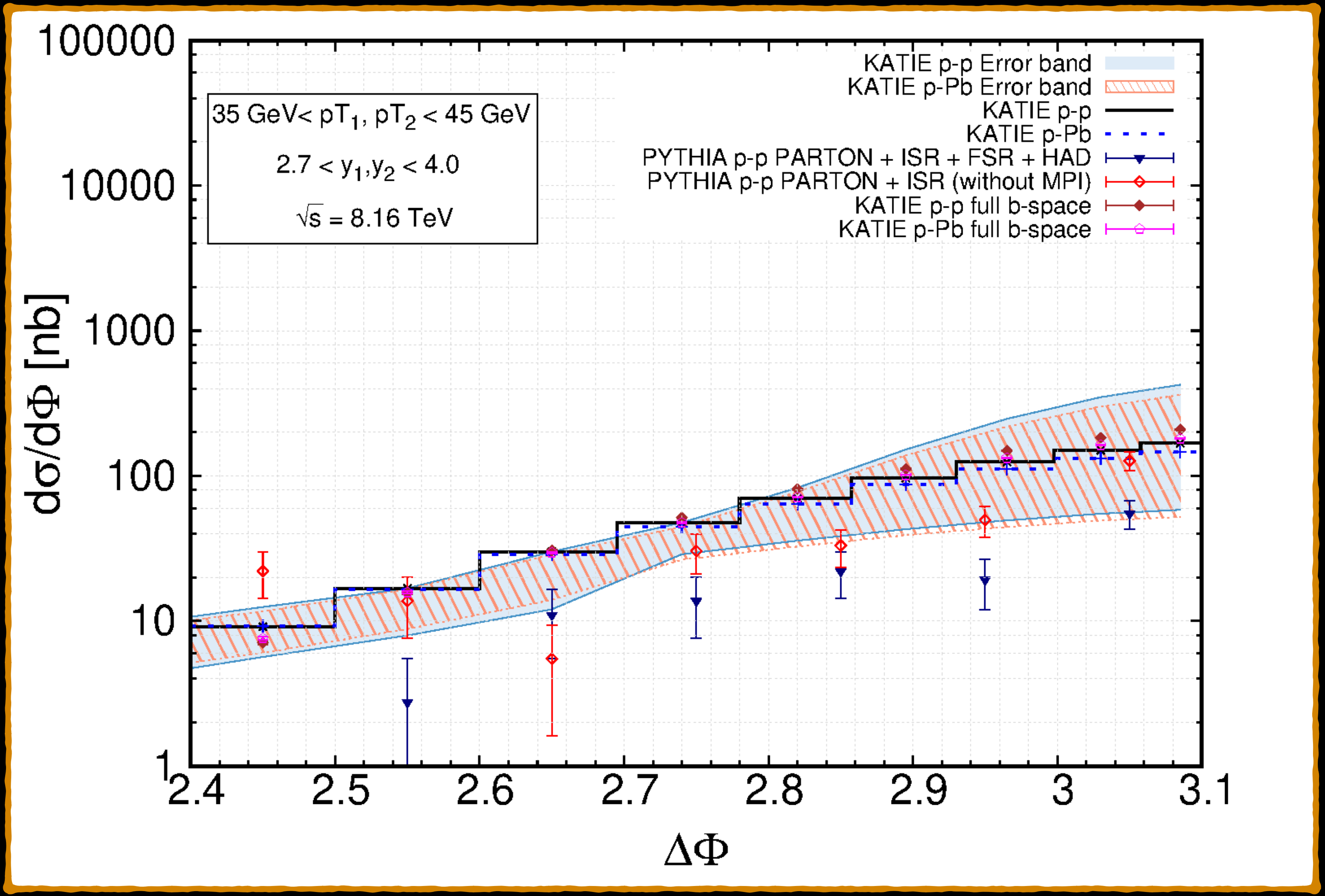

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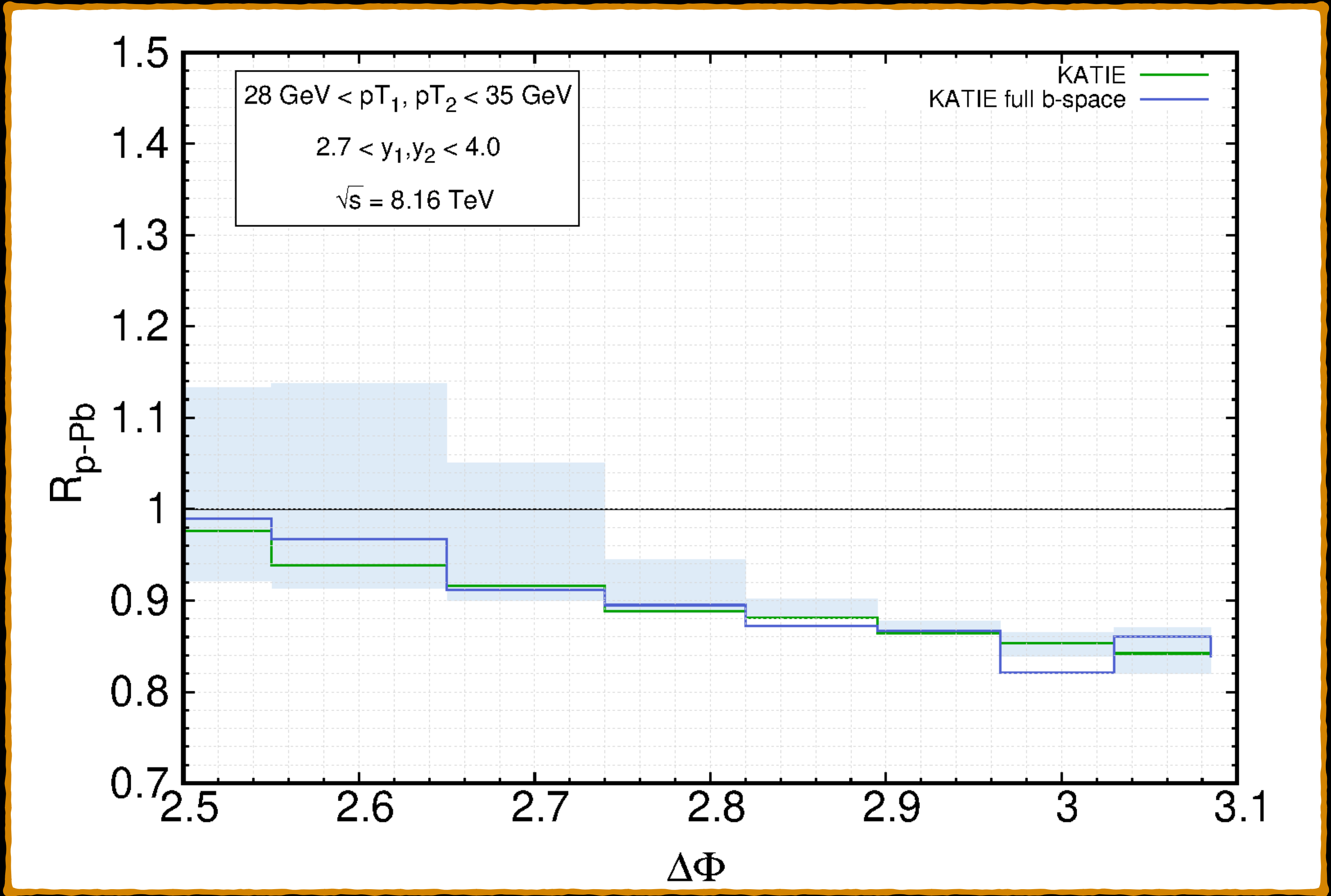
Azimuthal correlations - nuclear modification ratio



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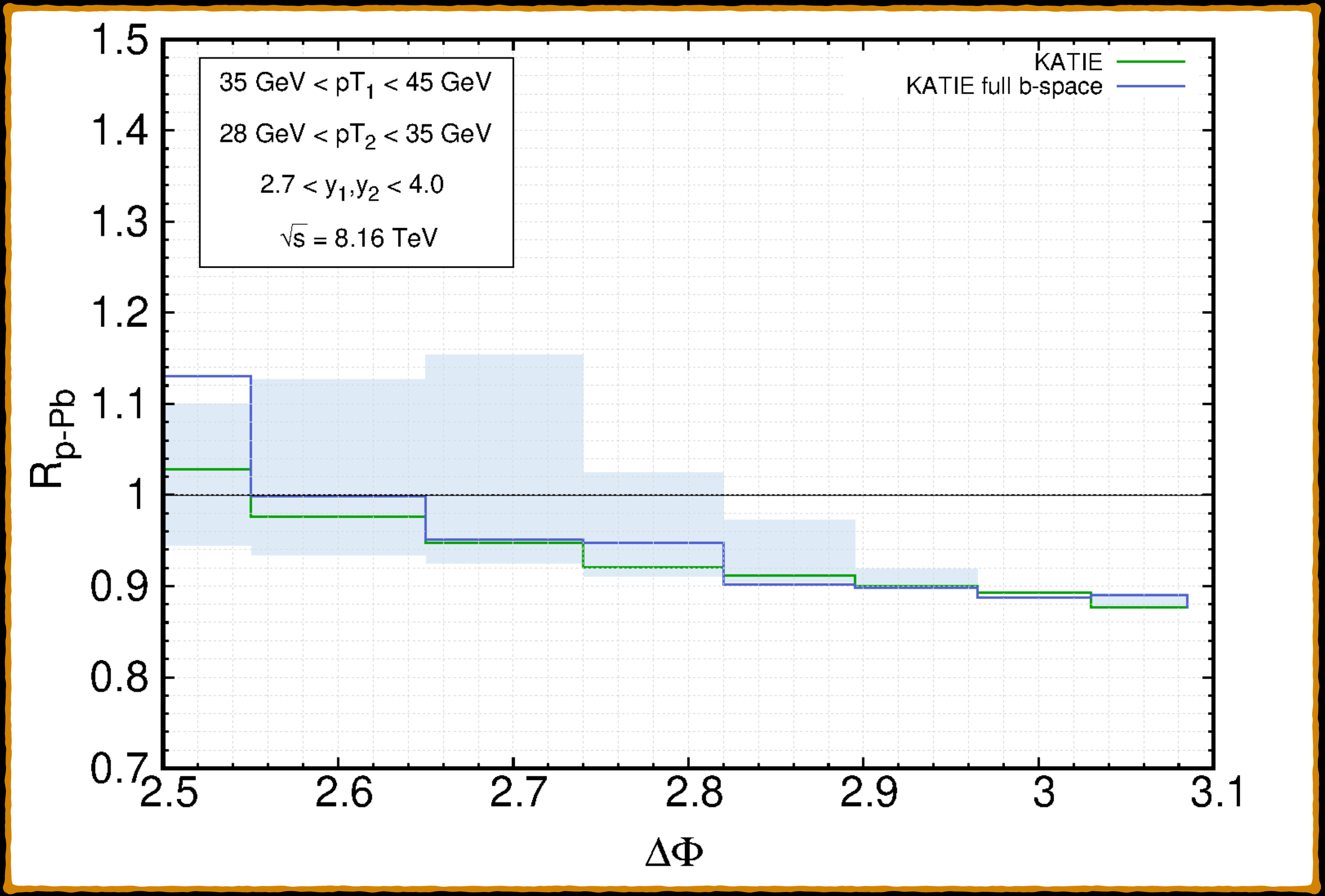

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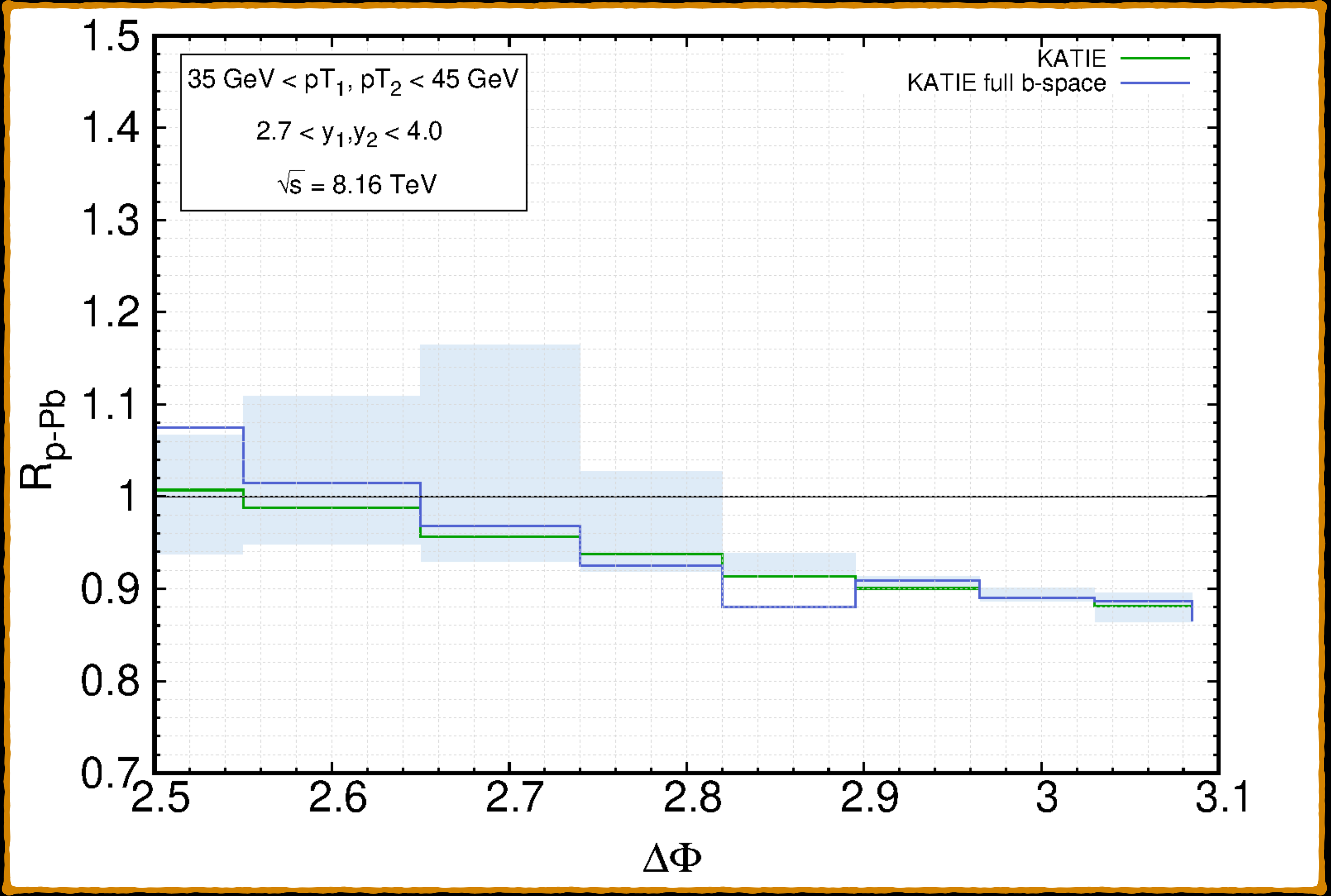

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SUMMARY

- Improved small-x TMD factorization (ITMD) is an approximation to CGC which is suitable for jet production at LHC
- ITMD has been implemented in parton level Monte Carlo programs: KaTie and LxJet
- despite proliferation of TMD gluon distributions, it is possible to calculate them with the data-driven input
- we included the Sudakov resummation in the Monte Carlo computations, including the full b-space resummation
- the Sudakov resummation is essential for a proper description of jet production

- we computed dijet azimuthal correlations for FoCal and ATLAS kinematics
- there are significant saturation effects present and they are not destroyed by the Sudakov form factors
- for the lower cuts on the jet transverse momenta the nonperturbative effects (estimated using Pythia) are large; it is important to study their dependence on the target

BACKUP

TMD gluon distributions: small-x limit

Small-x limit of TMD gluon distributions

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

$x \to 0$ limit.

Dependence on x is only via the small-x evolution equations:

- BFKL (Balitsky-Fadin-Kuraev-Lipatov).
- BK (Balitsky-Kovchegov) and modifications
- JIMWLK (Balitsky-Jalilian-Marian-Iancu-McLerran-Weigert-Leonidov-Kovner)

Correspondence to CGC

Example:

DIPOLE GLUON DISTRIBUTION

$$\mathcal{F}_{qg}^{(1)} \sim \int \frac{d^2x_T d^2y_T}{(2\pi)^4} k_T^2 e^{-i\vec{k}_T\cdot(\vec{x}_T - \vec{y}_T)} \langle \mathrm{Tr}\left[U(\vec{x}_T)U^\dagger(\vec{y}_T)\right]\rangle_x$$

WILSON LINES

AVERAGE OVER CGC COLOR SOURCES

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

$$\langle \ldots \rangle_x \to \frac{\langle \Omega | \ldots | \Omega \rangle}{\langle \Omega | \Omega \rangle}$$

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]
[C. Marquet, C. Roiesnel, P. Taels, 2018]
[Y. Kovchegov, D. Pitonyak, M. Sievert,
[T. Altinoluk, R. Boussarie, 2019]
[R. Boussarie, Y. Mehtar-Tani, 2020]

BACKUP

Dijet correlations in pA collisions

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

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

$$C_{12} = \frac{1}{N_1} \frac{dN_{12}}{d\Delta\phi}$$

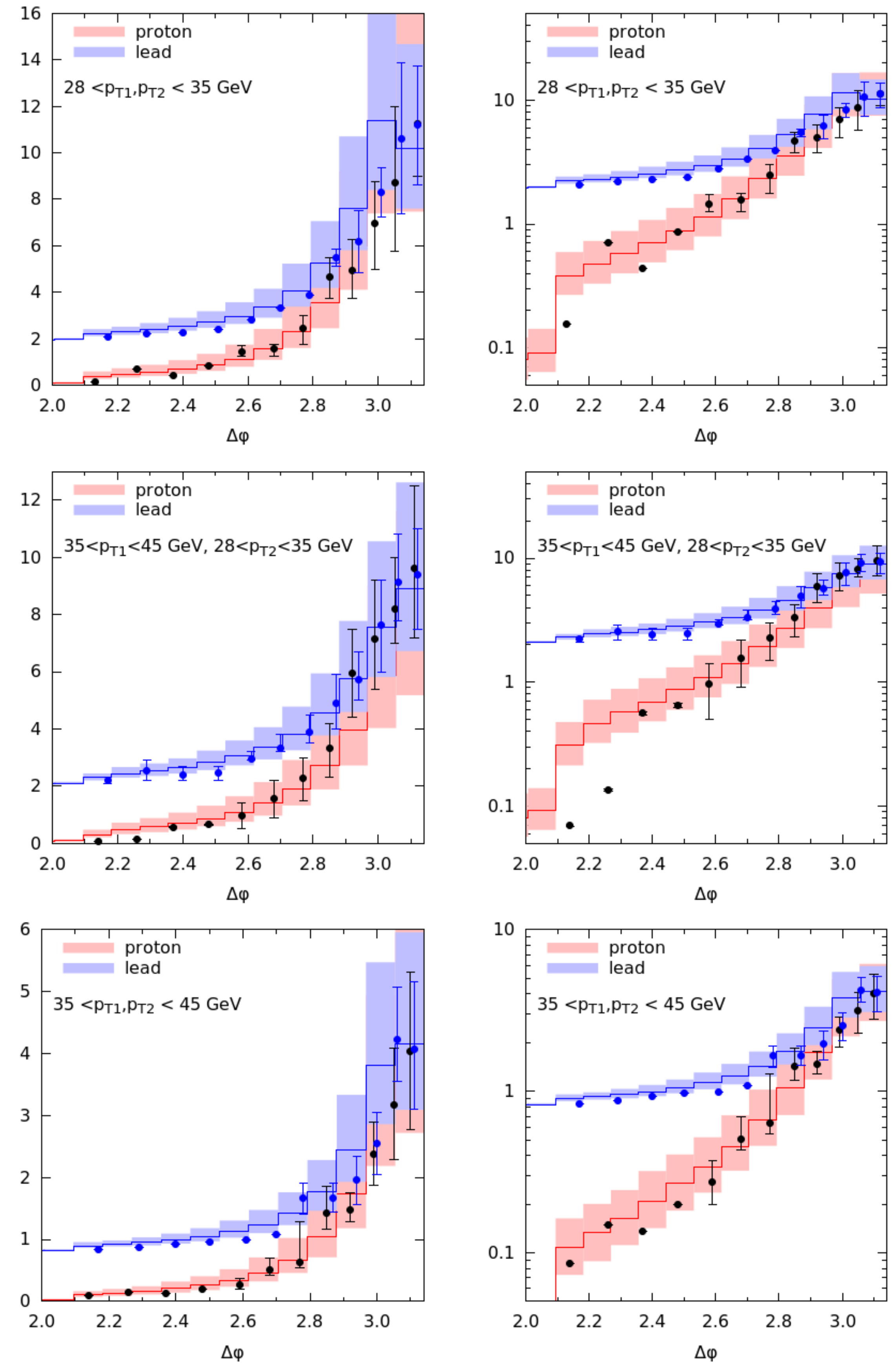
number of dijets

azimuthal angle between jets

number of leading jets

We study an interplay of saturation and Sudakov resummation vs the shape of C_{12}.

Good description of the broadening effects



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

KaTie Monte Carlo

KaTie https://bitbucket.org/hameren/katie

- parton level event generator, like ALPGEN, HELAC, MADGRAPH, etc.
- arbitrary processes within the standard model (including effective Higgs-gluon coupling) with several final-state particles.
- 0, 1, or 2 off-shell intial states.
- produces (partially un)weighted event files, for example in the LHEF format.
- requires LHAPDF. TMD PDFs can be provided as files containing rectangular grids, or with TMDlib.
- a calculation is steered by a single input file.
- employs an optimization stage in which the pre-samplers for all channels are optimized.
- during the generation stage several event files can be created in parallel.
- event files can be processed further by parton-shower program like CASCADE.
- (evaluation of) matrix elements now separately available, including C++ interface.