STUDYING SATURATION EFFECTS IN DIJET PRODUCTION AT FORWARD LHC CALORIMETERS

PIOTR KOTKO

AGH University of Science and Technology, Krakow

BASED ON 2210.06613

M.A. AL-MASHAD, A. VAN HAMEREN, H. KAKKAD,
PK, P. VAN MECHELEN, K. KUTAK, S. SAPETA

SUPPORTED BY:
NCN GRANT DEC-2020/39/O/ST2/03011

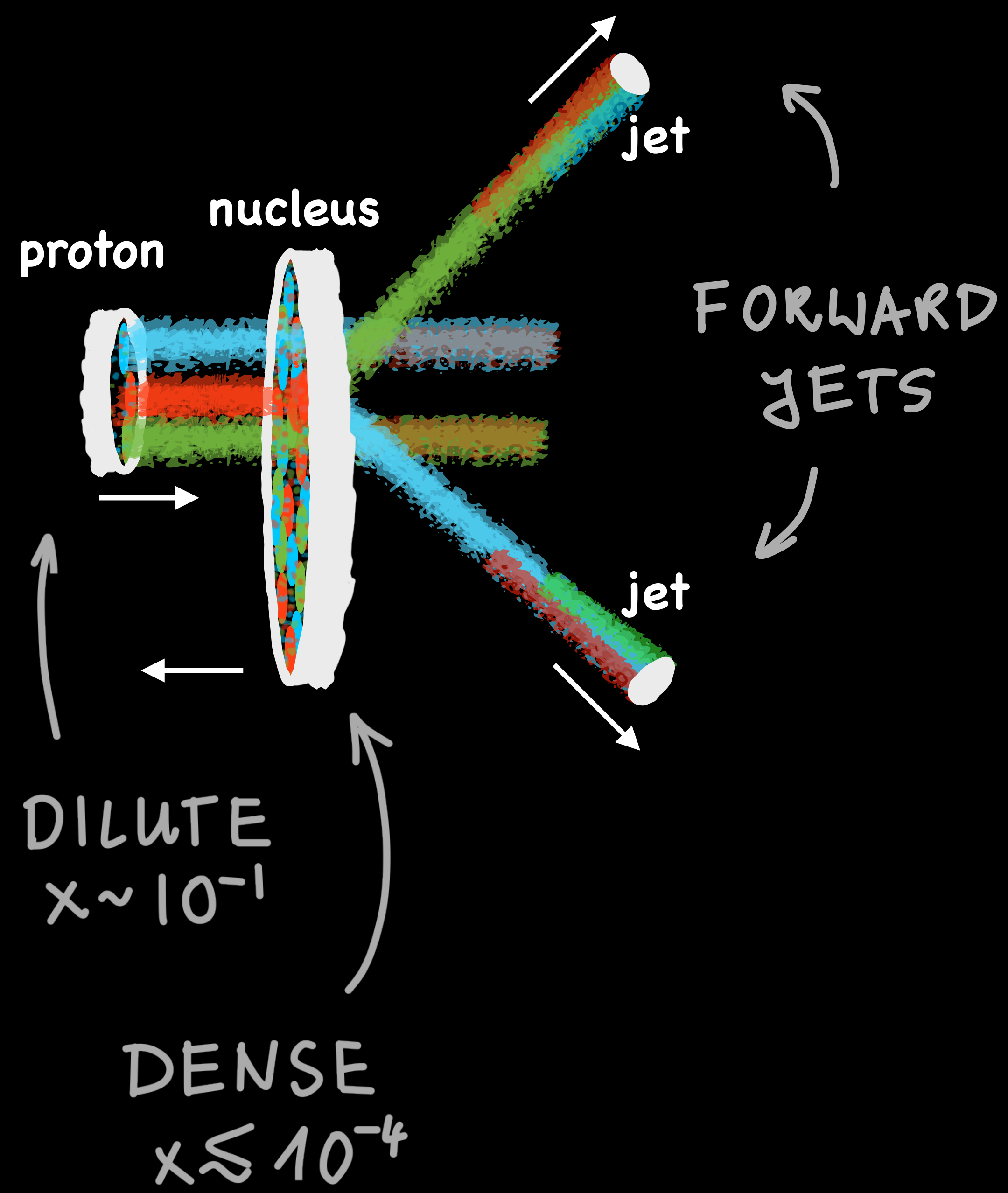
AGH

MPI@LHC 2022

MOTIVATION

Forward dijets in dilute-dense collisions

- probing small-x regime of gluon distributions
- gluon saturation
- multiple scattering
- 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 dijet production in hadron-hadron collisions
    B. Relation to 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

Limiting cases of Color Glass Condensate (CGC)

CGC

dilute-dense

three scales:

$Q_s \gg \Lambda_{\mathrm{QCD}}$ — 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]

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

$x_2 \ll x_1$

$|\vec{p}_{T1}+\vec{p}_{T2}| = k_T$

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

$\Rightarrow$ RESUMMATION OF KINEMATIC TWISTS AND NEGLECTING GENUINE TWISTS.

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

easy to implement in Monte Carlo

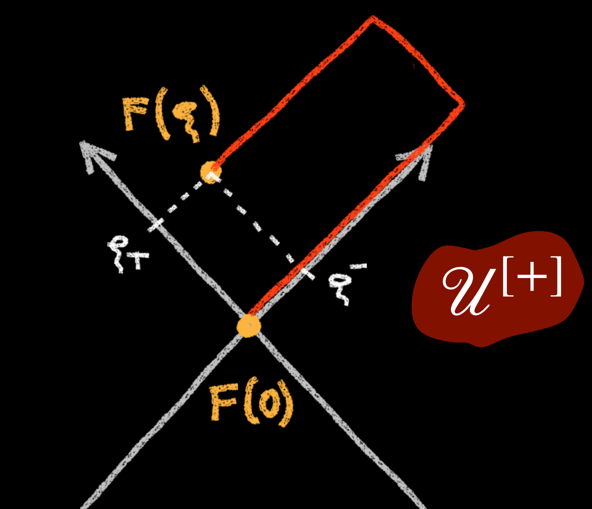
Generic operator definition

(unpolarized)

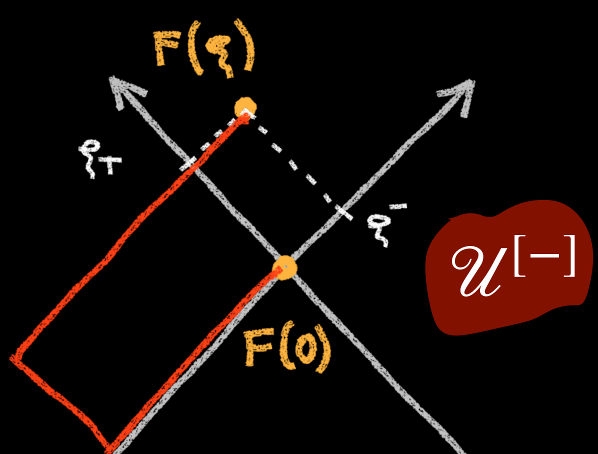
$$\mathscr{F}_g(x,k_T) = 2\int \frac{d\xi^+ d^2\xi_T}{(2\pi)^3 P^-}\, e^{ixP^-\xi^+ - i\vec{k}_T\cdot\vec{\xi}_T}\, \langle P|\,\mathrm{Tr}\left[\hat{F}^{i-}\left(\xi^+, \vec{\xi}_T, \xi^- = 0\right)\mathscr{U}_{C_1}\hat{F}^{i-}(0)\,\mathscr{U}_{C_2}\right]|P\rangle$$

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

GAUGE LINKS
in fundamental color representation



FUTURE-POINTING



PAST-POINTING

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

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

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

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

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

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

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

in the small-x limit

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

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

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

WEIZSACKER -WILLIAMS

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

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

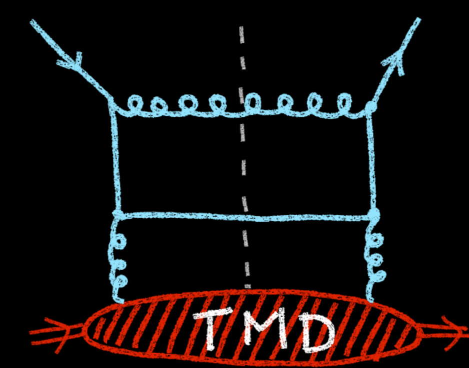
$$\mathcal{F}_{gg}^{(6)} \sim \langle P|\,\frac{\mathrm{Tr}\,\mathcal{U}^{[\Box]}}{N_c}\frac{\mathrm{Tr}\,\mathcal{U}^{[\Box]\dagger}}{N_c}\mathrm{Tr}\left[\hat{F}^{i-}(\xi)\,\mathcal{U}^{[+]\dagger}\hat{F}^{i-}(0)\,\mathcal{U}^{[+]}\right]|P\rangle$$

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

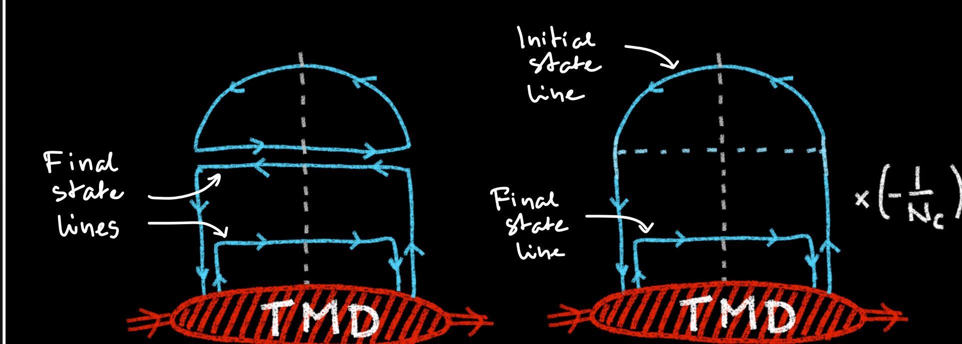
WILSON LOOP $\rightarrow$ $\mathcal{U}^{[\Box]} = \mathcal{U}^{[+]}\mathcal{U}^{[-]\dagger}$

Example

TMD gluon distribution for the 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 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]

$$\begin{aligned}\mathcal{F}^{(1)}_{qg}\left(x,k_T^2\right) = {} & \mathcal{F}_0\left(x,k_T^2\right) + \frac{\alpha_s N_c}{\pi}\int_x^1 \frac{dz}{z}\int_{k_{T0}^2}^{\infty} \frac{dq_T^2}{q_T^2}\left\{\frac{q_T^2\mathcal{F}\left(\frac{x}{z},q_T^2\right)\theta\left(\frac{k_T^2}{z}-q_T^2\right) - k_T^2\mathcal{F}\left(\frac{x}{z},k_T^2\right)}{\left|q_T^2-k_T^2\right|} + \frac{k_T^2\mathcal{F}\left(\frac{x}{z},k_T^2\right)}{\sqrt{4q_T^4+k_T^4}}\right\} \\ & + \frac{\alpha_s}{2\pi k_T^2}\int_x^1 dz\left\{\left(P_{gg}(z)-\frac{2N_c}{z}\right)\int_{k_{T0}^2}^{k_T^2} dq_T^2\mathcal{F}\left(\frac{x}{z},q_T^2\right) + zP_{gq}(z)\Sigma\left(\frac{x}{z},k_T^2\right)\right\} \\ & - \frac{2\alpha_s^2}{R^2}\underbrace{\left\{\left[\int_{k_T^2}^{\infty}\frac{dq_T^2}{q_T^2}\mathcal{F}\left(x,q_T^2\right)\right]^2 + \mathcal{F}\left(x,k_T^2\right)\int_{k_T^2}^{\infty}\frac{dq_T^2}{q_T^2}\ln\left(\frac{q_T^2}{k_T^2}\right)\mathcal{F}\left(x,q_T^2\right)\right\}}_{\text{non-linear term}}\end{aligned}$$

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

fitted to DIS HERA data

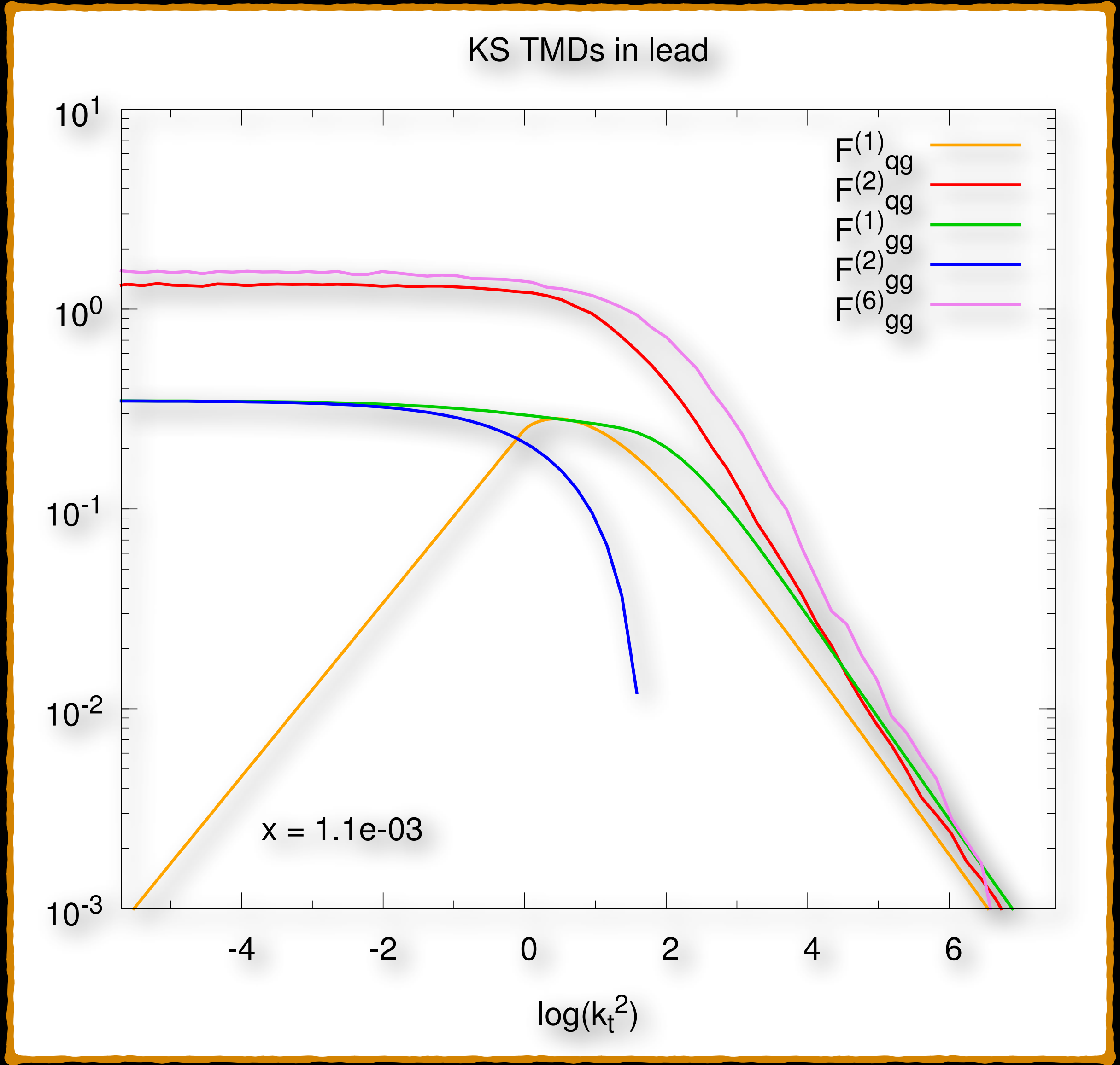
[K. Kutak, S. Sapeta, 2012]

TMD gluon distributions

How to get other 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]

Sudakov resummation

Hard scale in TMD gluon distributions

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

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

- Evolution in a hard scale (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...

$$\mathcal{F}_{ag}^{(i)}\left(x, k_T^2\right) \to \mathcal{F}_{ag}^{(i)}\left(x, k_T^2, \mu\right)$$

  - 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]
  - [M. Hentschinski, 2021]
  - ...

The b-space Sudakov resummation

In collinear/TMD factorization the Sudakov logs are consistently resummed in the impact parameter space.

Resummation in leading power CGC: [A.H. Mueller, B-W. Xiao, F. Yuan, 2013]
see also [P. Caucal, F. Salazar, B. Schenke, R. Venugopalan, 2022]

For applications see e.g.: [L. Zheng, E.C. Aschenauer, J.H. Lee, B-W. Xiao, 2014]
[A. Stasto, S-Y. Wei, B-W. Xiao, F. Yuan, 2018]
[S. Benic, O. Garcia-Montero, A. Perkov, 2022]

Resummed ITMD

$$\frac{d\sigma_{pA\to 2j+X}}{dy_1 dy_2 d^2p_{T1} d^2p_{T2}} \sim \sum_{a,c,d} \sum_{i=1,2} K^{(i)}_{ag\to cd}(k_T,\mu) \int db_T b_T\, J_0(b_T k_T) f_{a/p}(x_1,\mu_b)\, \underbrace{\widetilde{\Phi}^{(i)}_{ag\to cd}(x_2,b_T)}_{\text{F.T. of TMD gluon distributions}}\, \underbrace{e^{-S^{ag\to cd}(\mu,\mu_b)}}_{\text{Sudakov factors}}$$

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 do this in a Monte Carlo?

Monte Carlo implementation

- Approach 1: ignore the b-dependence in the collinear PDF $\mu_b \to \mu$
  - the hard scale-dependent TMD distribution can be computed separately
  - missing certain logarithms
- Approach 2: reweighing the MC events
  - first compute observables according to Approach 1
  - reweigh the events using the full b-space luminosity computed for generated phase space points

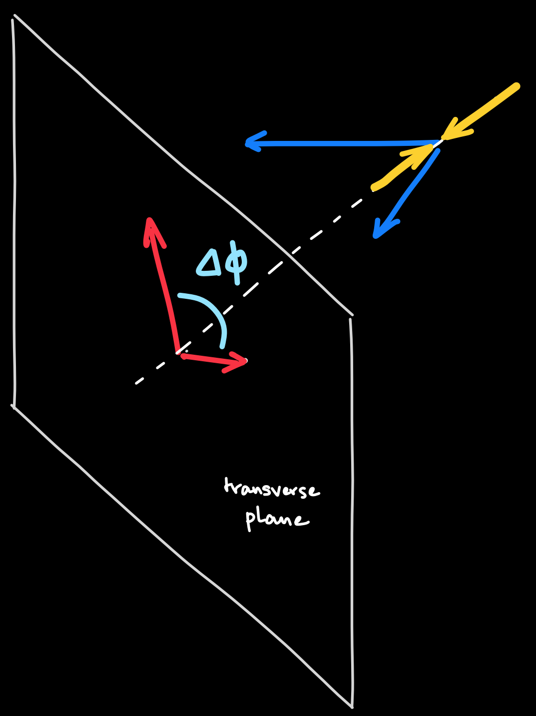
$$w(x_2, k_T, \mu) = \frac{\int db_T b_T\, J_0(b_T k_T) f_{a/p}(x_1, \mu_b)\, \widetilde{\Phi}^{(i)}_{ag\to cd}(x_2, b_T)\ e^{-S^{ag\to cd}(\mu,\mu_b)}}{\int db_T b_T\, J_0(b_T k_T)\, \widetilde{\Phi}^{(i)}_{ag\to cd}(x_2, b_T)\ e^{-S^{ag\to cd}(\mu,\mu_b)}}$$

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

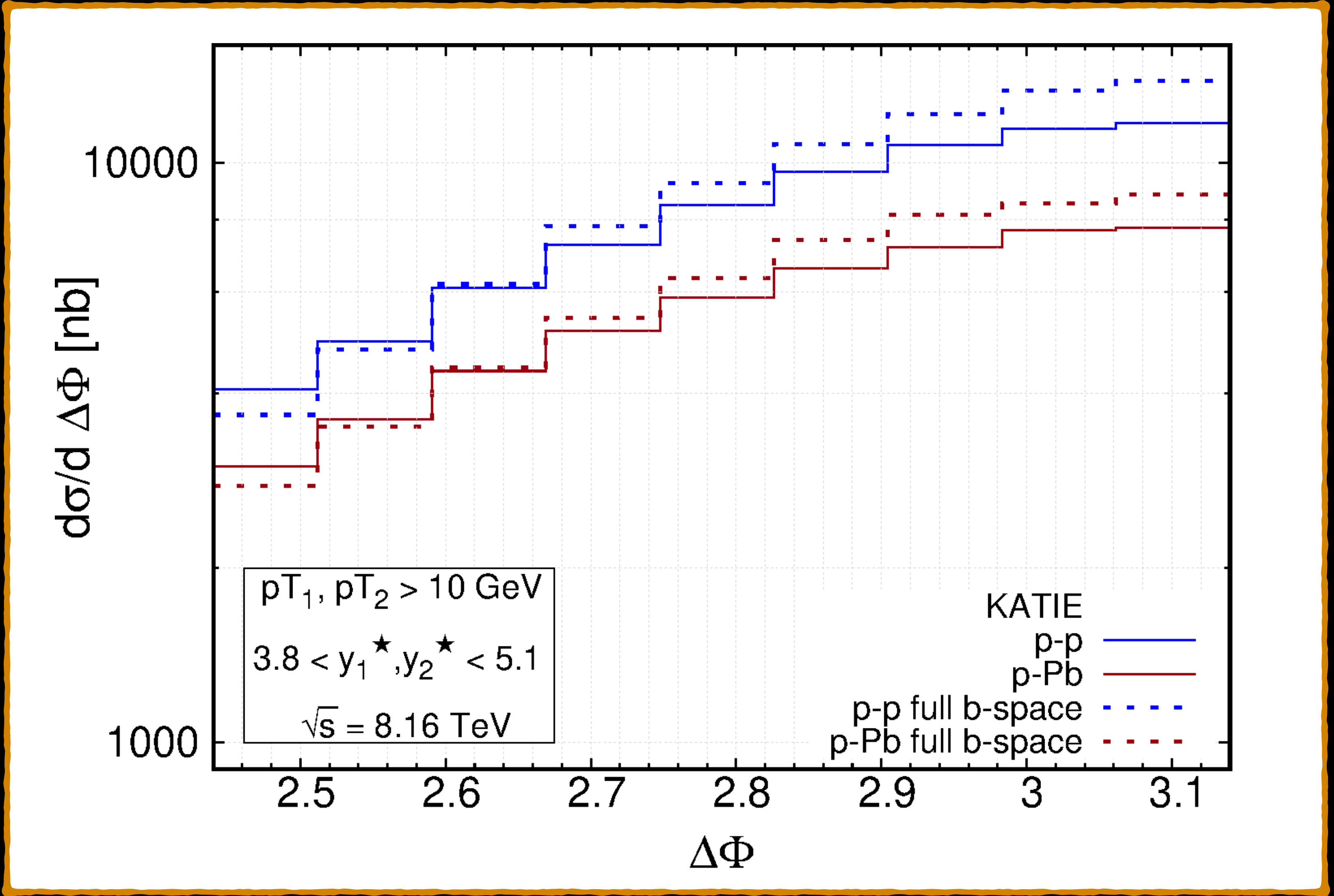


Kinematic cuts

- CM energy: $\sqrt{s} = 8.16\,\mathrm{TeV}$ per nucleon
- jet radius: $\Delta R > 0.5$
- jet transverse momenta: FoCal: $p_{T1} > p_{T2} > 10\,\mathrm{GeV}$; ATLAS: $45\,\mathrm{GeV} > p_{T1} > p_{T2} > 28\,\mathrm{GeV}$
- rapidity: FoCal: $3.8 < y_1^*, y_2^* < 5.1$; ATLAS: $2.7 < y_1^*, y_2^* < 4.0$

	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+Sudakov

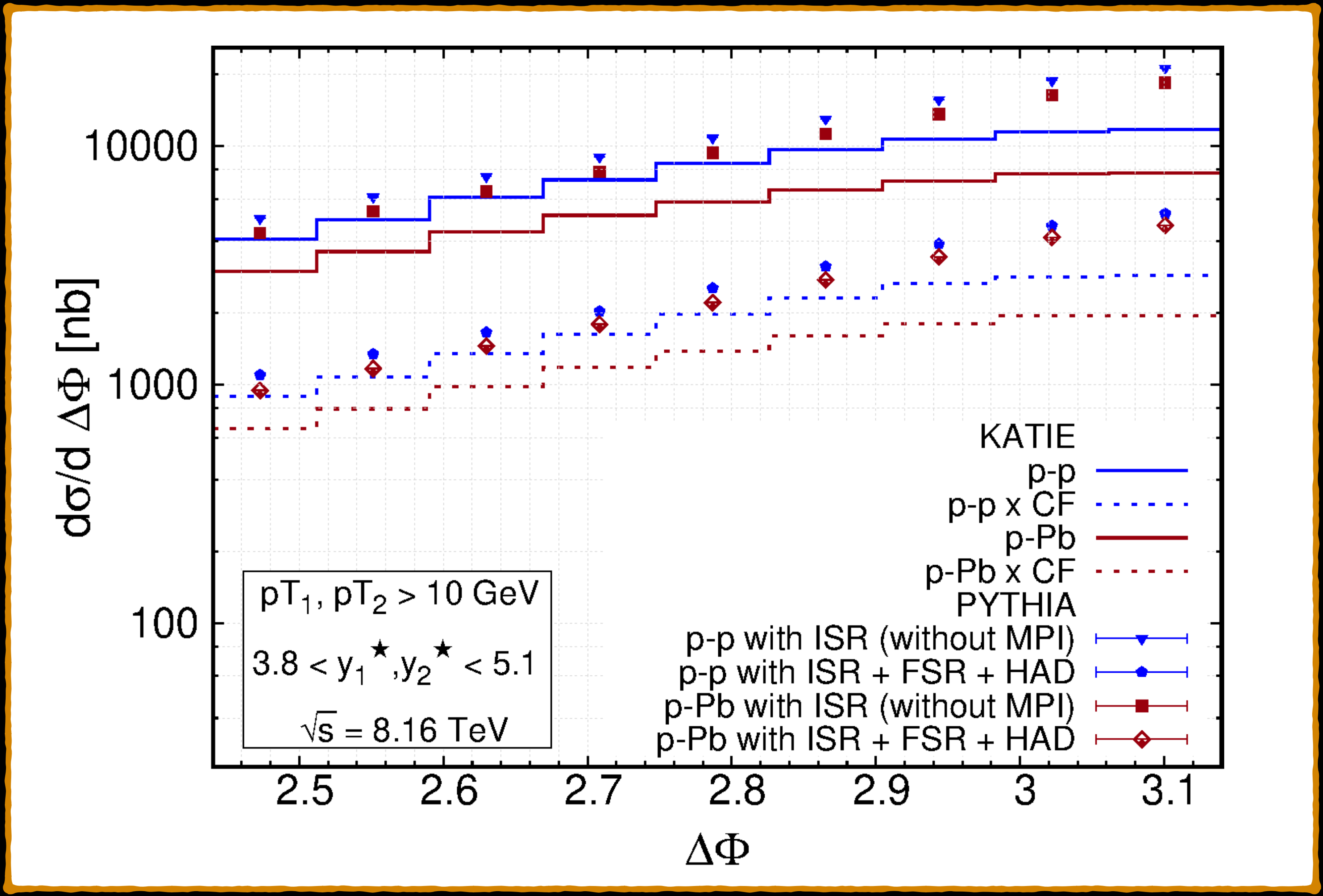
- the full b-space Sudakov resummation as well as the simplified approach are similar
- large suppression of the p-Pb cross section compared to p-p
- the saturation effects do not go away when including the Sudakov resummation

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"?

FoCal kinematics

Azimuthal correlations for p-p and p-Pb



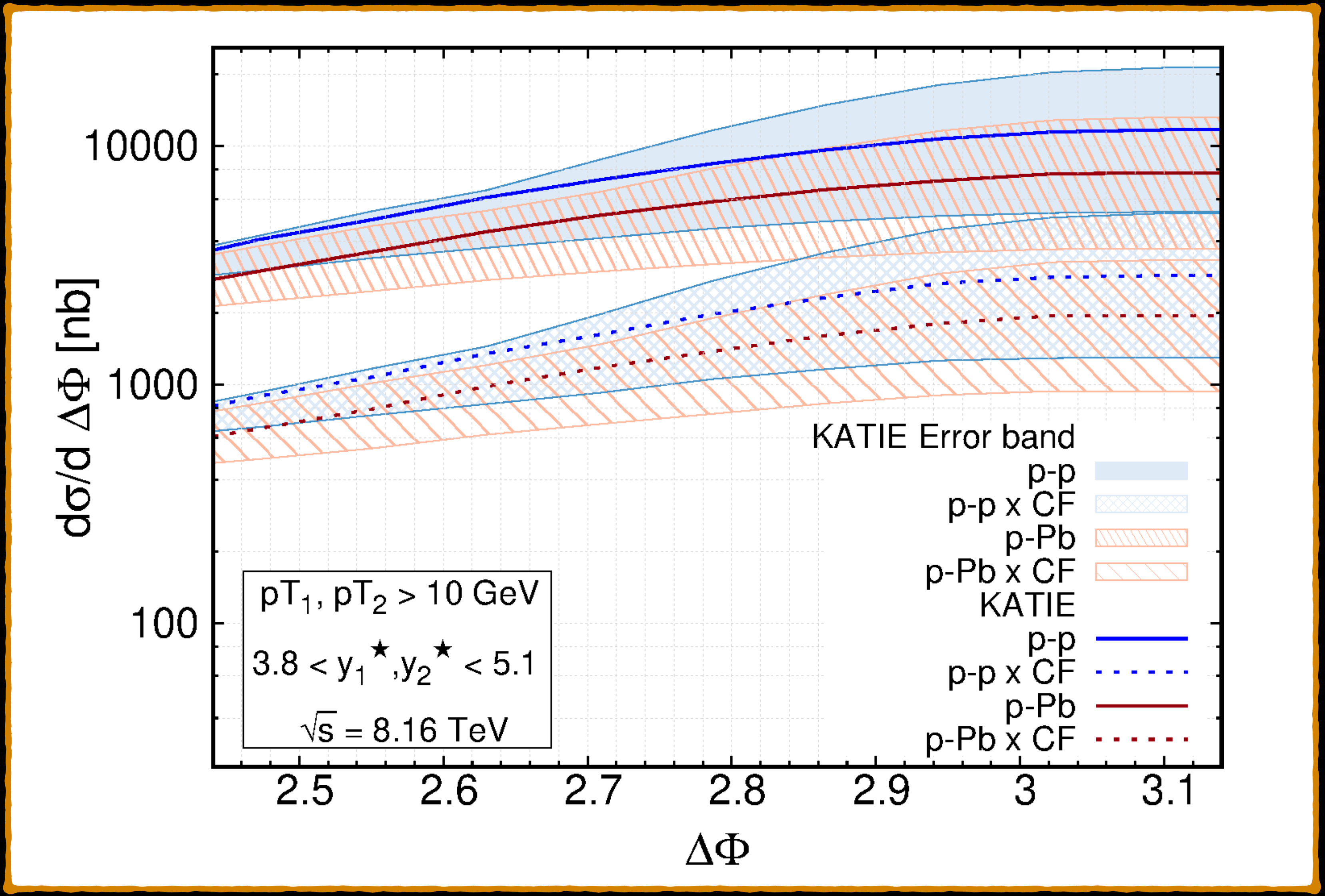
ITMD+Sudakov

- the full b-space Sudakov resummation as well as the simplified approach are similar
- large suppression of the p-Pb cross section compared to p-p
- 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 for p-p and p-Pb



ITMD+Sudakov

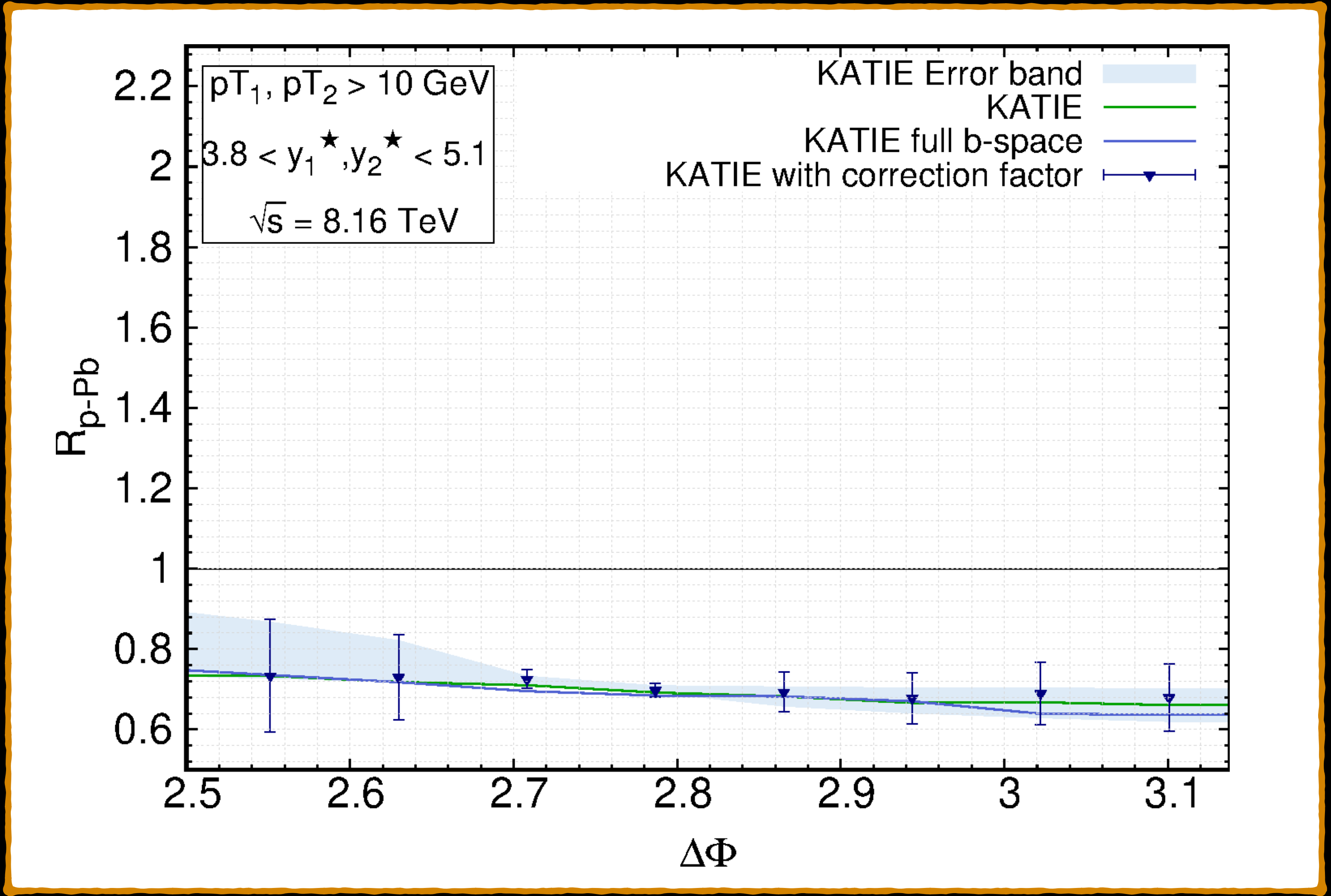
- the full b-space Sudakov resummation as well as the simplified approach are similar
- large suppression of the p-Pb cross section compared to p-p
- the saturation effects do not go away when including the Sudakov resummation

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"?

FoCal kinematics

Azimuthal correlations for p-p and p-Pb



ITMD+Sudakov

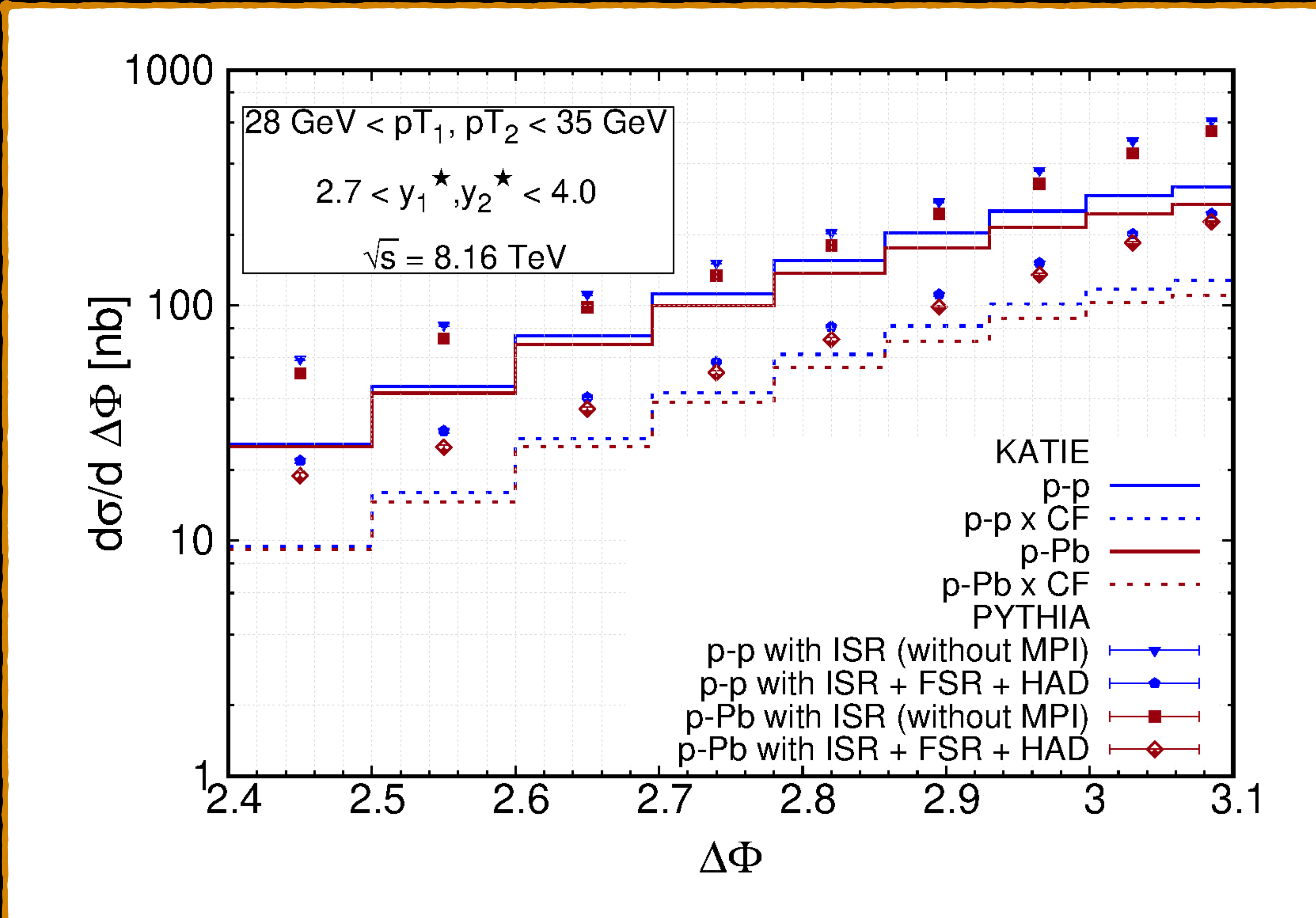
- the full b-space Sudakov resummation as well as the simplified approach are similar
- large suppression of the p-Pb cross section compared to p-p
- the saturation effects do not go away when including the Sudakov resummation

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"?

ATLAS kinematics

Azimuthal correlations for p-p and p-Pb



ITMD+Sudakov

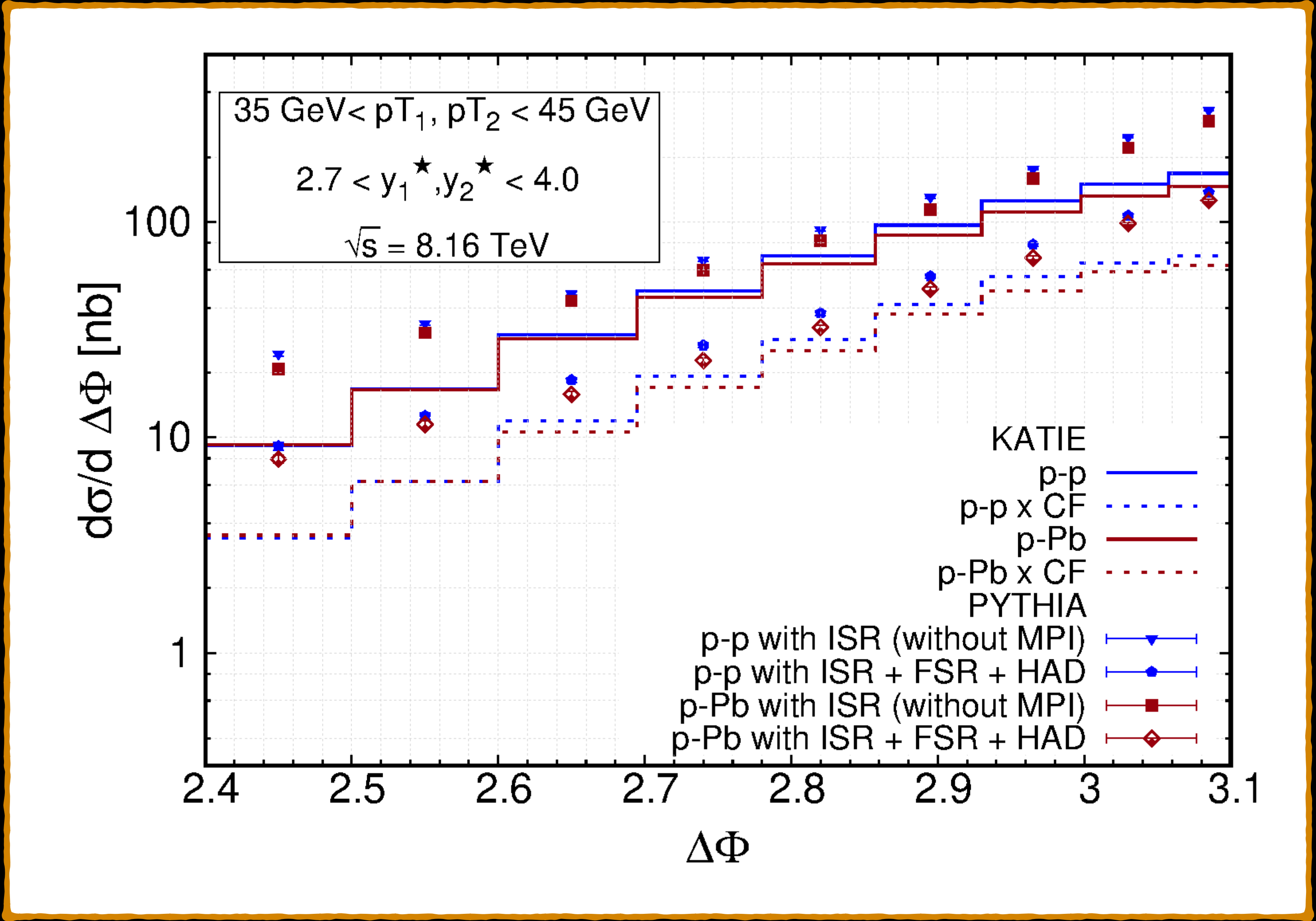
- suppression up to 20% for the lowest p_T cut
- the Sudakov resummation has the same features as for the FoCal cuts

lessons from Pythia:

- nonperturbative corrections (in particular hadronization) are milder, as one should expect due to larger p_T cut

ATLAS kinematics

Azimuthal correlations for p-p and p-Pb



ITMD+Sudakov

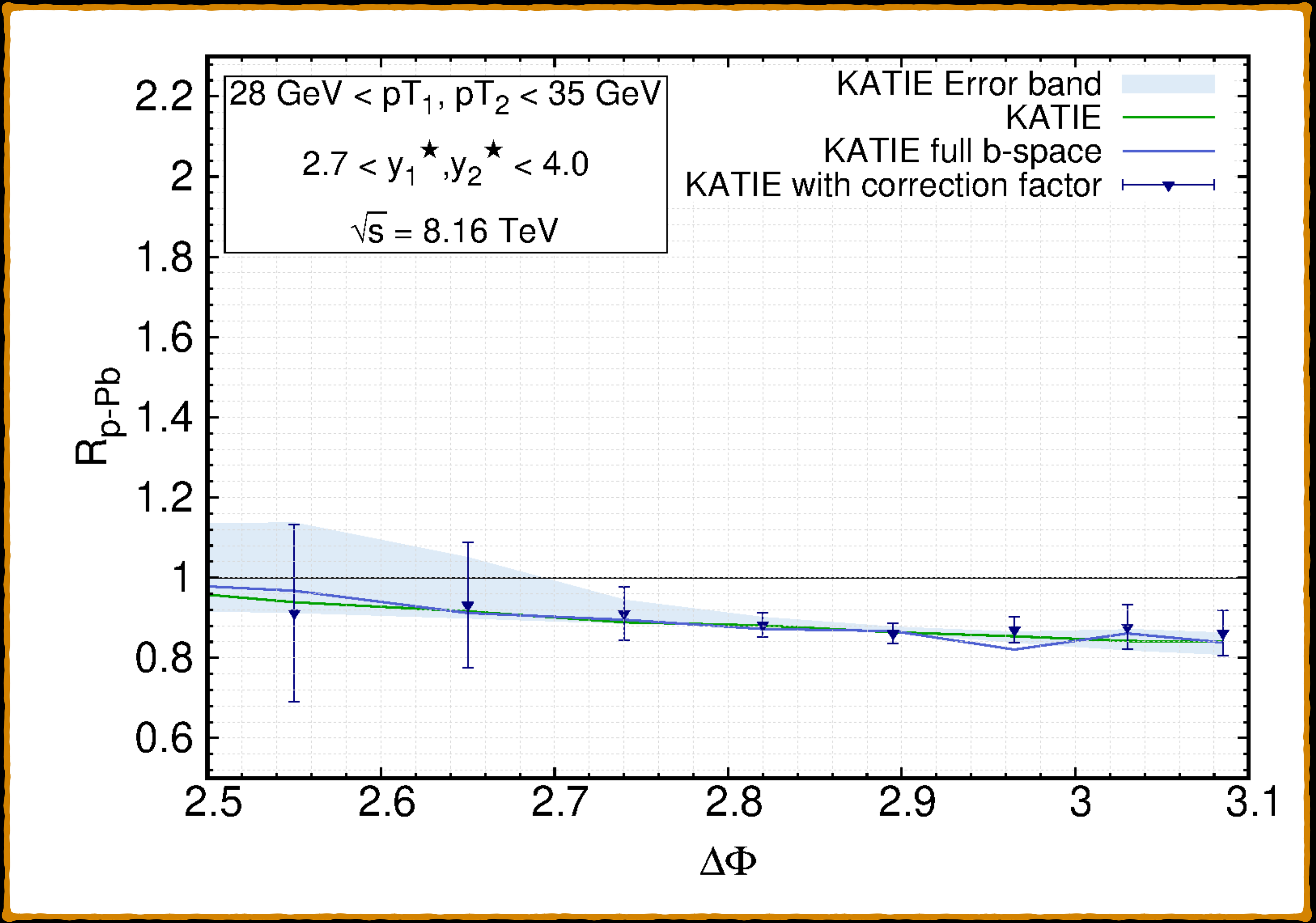
- suppression up to 20% for the lowest p_T cut
- the Sudakov resummation has the same features as for the FoCal cuts

lessons from Pythia:

- nonperturbative corrections (in particular hadronization) are milder, as one should expect due to larger p_T cut

ATLAS kinematics

Azimuthal correlations for p-p and p-Pb



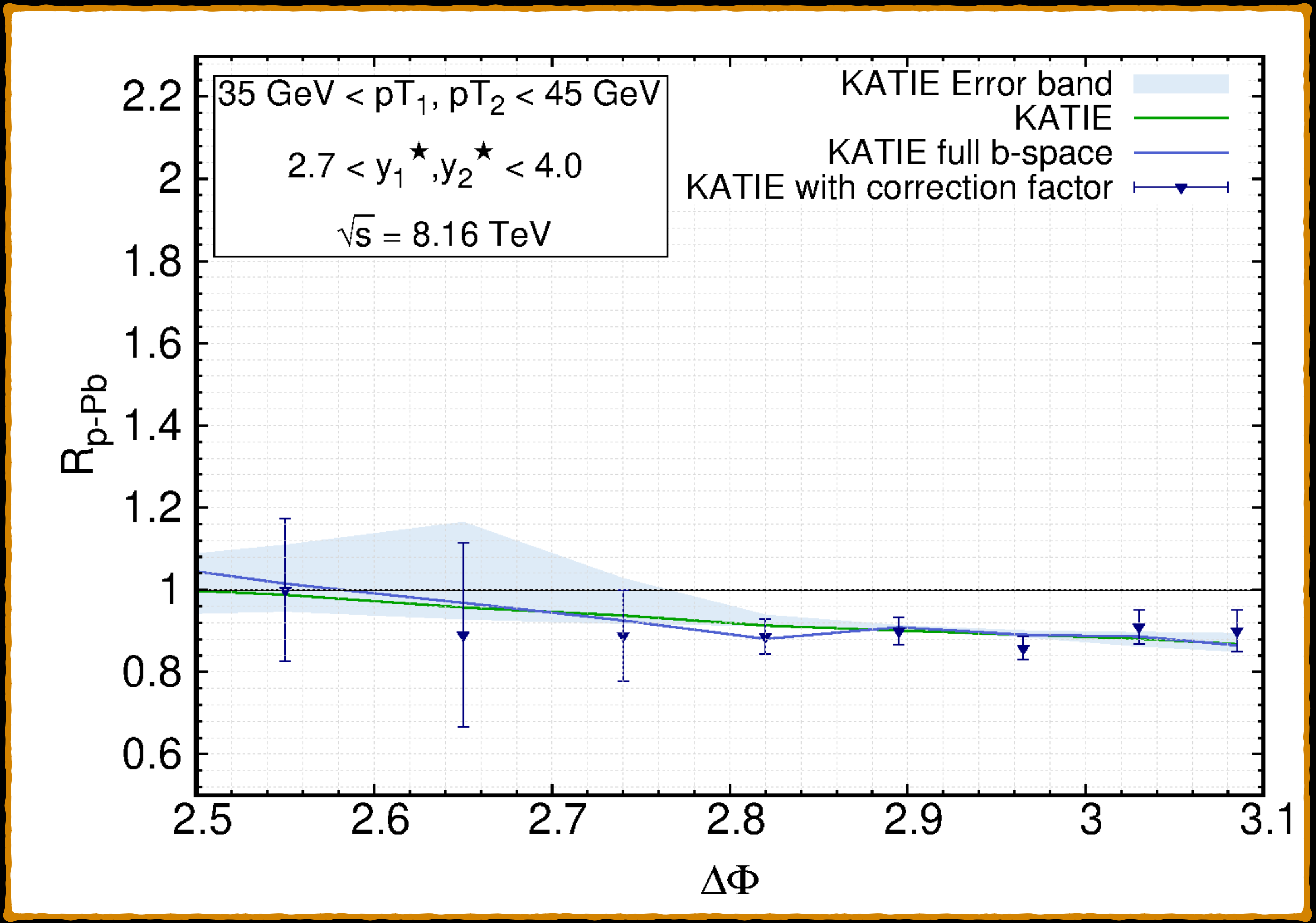
ITMD+Sudakov

- suppression up to 20% for the lowest p_T cut
- the Sudakov resummation has the same features as for the FoCal cuts

lessons from Pythia:

- nonperturbative corrections (in particular hadronization) are milder, as one should expect due to larger p_T cut

Azimuthal correlations for p-p and p-Pb



ITMD+Sudakov

- suppression up to 20% for the lowest p_T cut
- the Sudakov resummation has the same features as for the FoCal cuts

lessons from Pythia:

- nonperturbative corrections (in particular hadronization) are milder, as one should expect due to larger p_T cut

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

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: $2.7 < y_1, y_2 < 4.5$

number of dijets

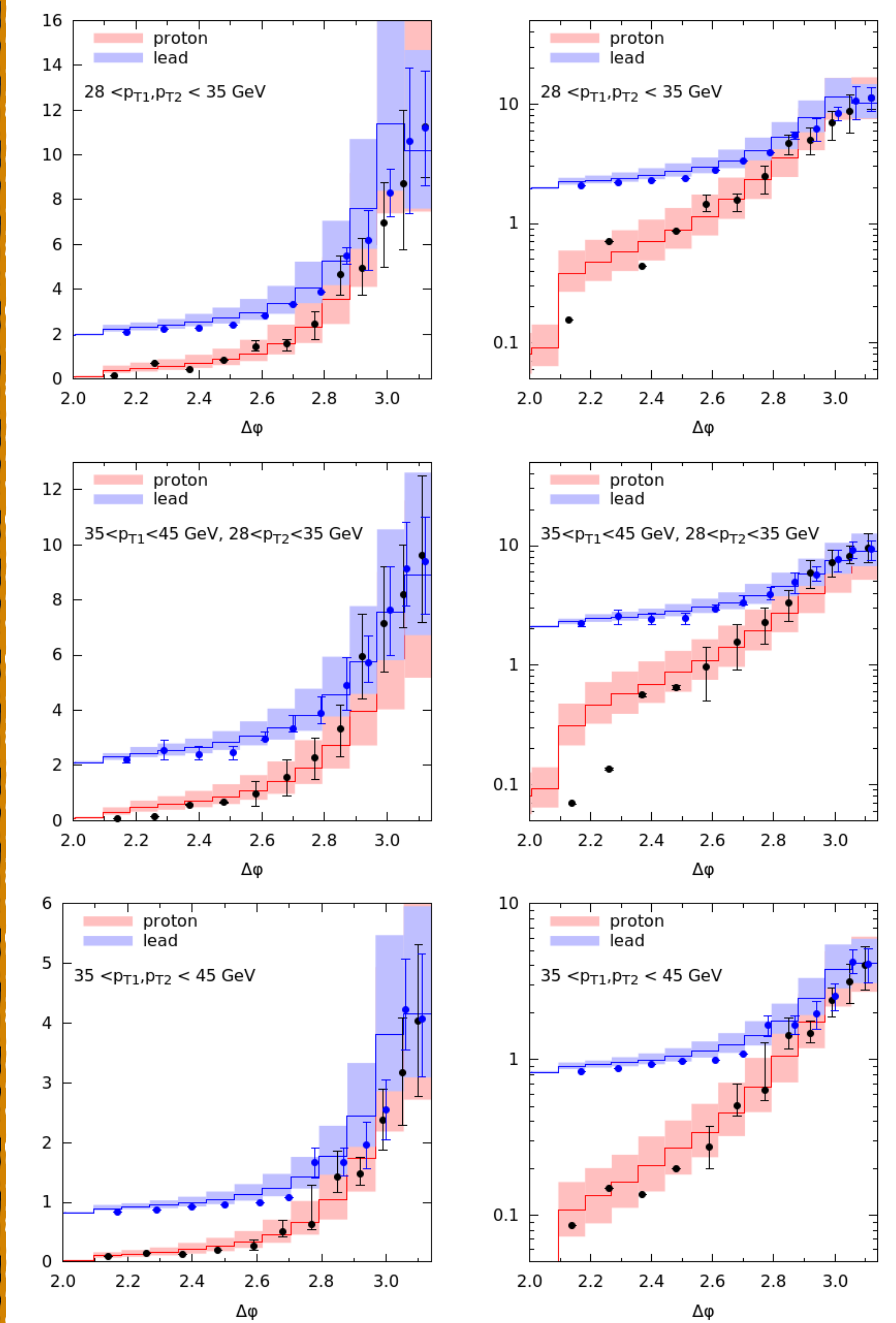
$$C_{12} = \frac{1}{N_1}\frac{dN_{12}}{d\Delta\phi}$$

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.

A. van Hameren, EIC yellow report seminar

7