Dijet azimuthal correlations in p-p and p-Pb collisions at forward LHC calorimeters

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NCN

Based on
arXiv:2210.06613
M. Abdullah Al-Mashad, A. van Hameren,
H. Kakkad, P. Kotko, K. Kutak, P. van Mechelen, S. Sapeta

ITMD

ITMD = small x Improved Transverse Momentum Dependent factorization

- accounts for saturation
- correct gauge structure i.e. uses gauge links to define TMD's
- takes into account kinematical effects – the whole phase space is available at LO
- is implemented in MC event generator KaTie
- valid in region $p_T > Q_s$, k_T can by any. p_T is hard final state momentum, k_T is inbalance

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

(one of reprezentations of the ITMD formula)

Generic structure: transverse momentum enters hard factors and gluon distributions gluon distribution depends on color flow

P. Kotko K. Kutak , C. Marquet , E. Petreska , S. Sapeta, A. van Hameren, JHEP 1509 (2015) 106

P. Kotko, K. Kutak, C. Marquet, E. Petreska, S. Sapeta, A. van Hameren JHEP 12 (2016) 034

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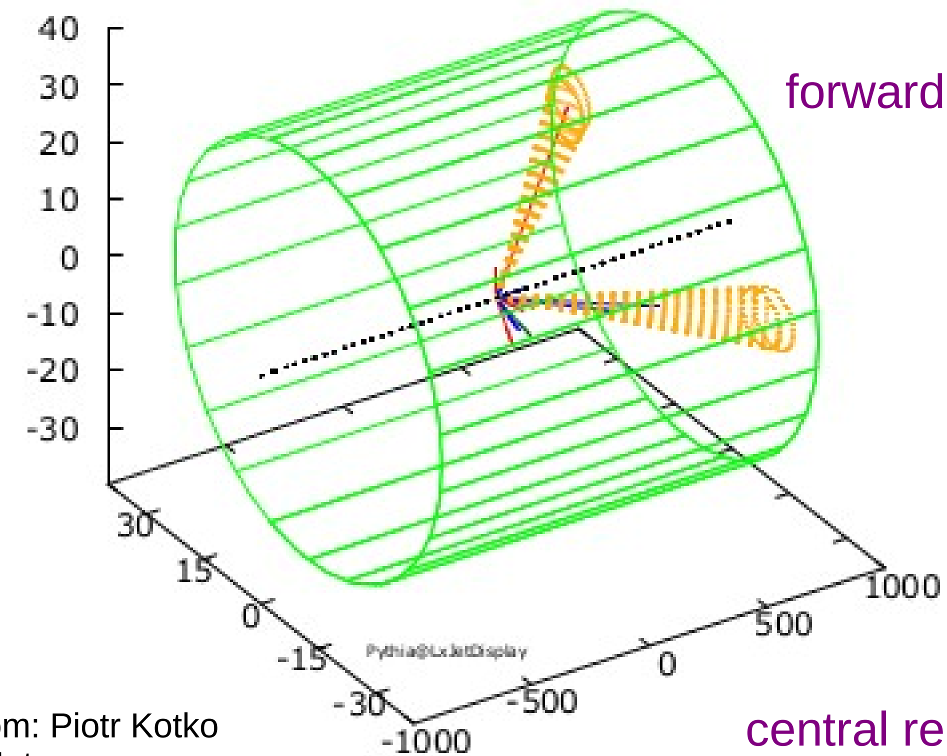
See also:
T. Altinoluk, C. Marquet, P. Taels JHEP 06 (2021) 085
For developments for massive final states

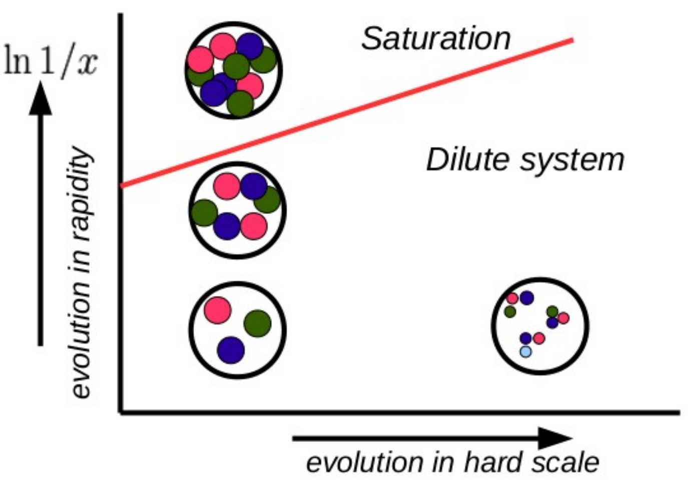
p – A (dilute-dense) forward-forward di-jets



forward region

central region

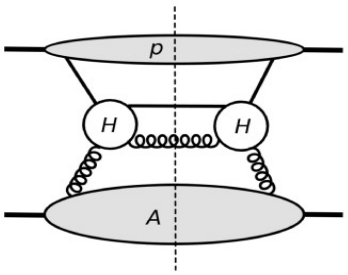
From: Piotr Kotko
LxJet

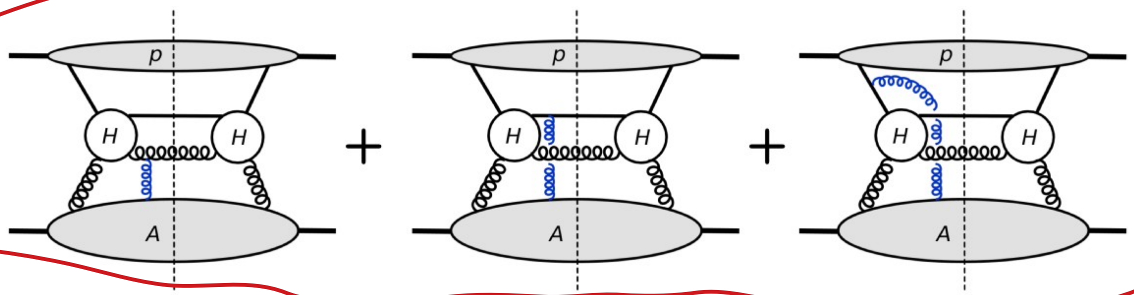


It originated from the aim to provide predictions for forward-forward jet production at the LHC

Formula for TMD gluons and gauge links

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





Valid for large transversal momentum and was obtained in a specific gauge

From *S. Sapeta*

similar diagrams with 2,3,….gluon exchanges. All this need to be resummed

C.J. Bomhof, P.J. Mulders, F. Pijlman Eur.Phys.J. C47 (2006) 147-162

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

Hard part defines the path of the gauge link $\mathcal{U}^{[C]}(\eta;\xi) = \mathcal{P}\exp\left[-ig\int_C \mathrm{d}z\cdot A(z)\right]$

The saturation problem: supressing gluons below Q_s

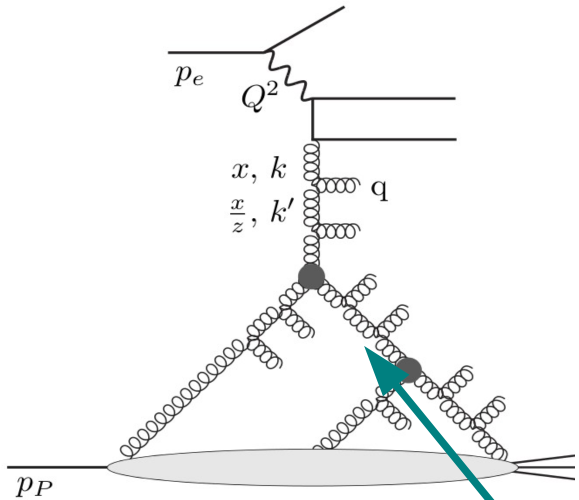
Originally formulated in coordinate space
Balitsky '96, Kovchegov '99

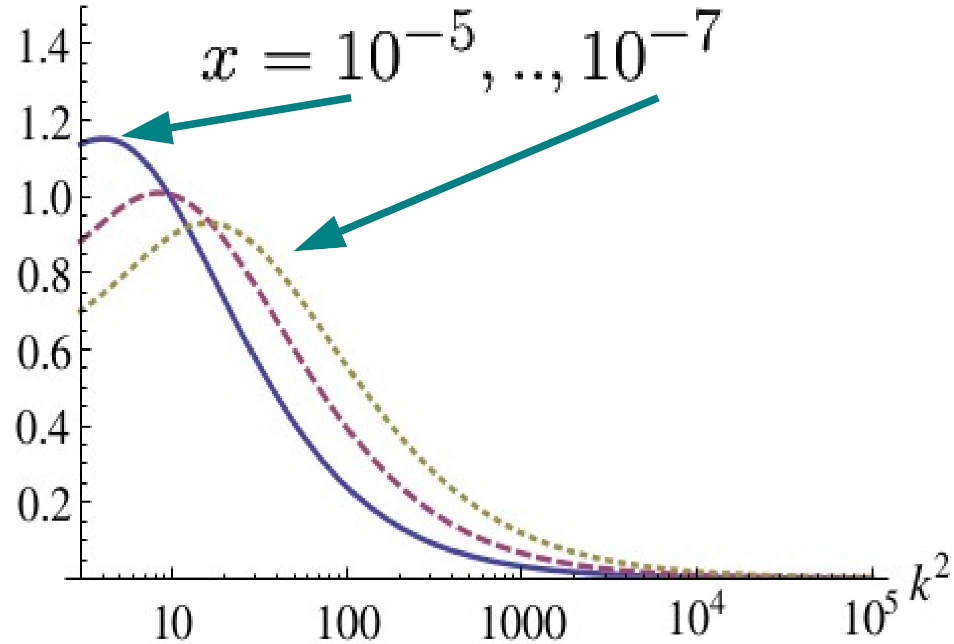
Fit AAMQS '10

NLO accuracy
Balitsky, Chirilli '07

and solved
Lappi, Mantysaari '15

Kinematic corrections
Iancu at el





Solved b dependent
Stasto, Golec-Biernat '02

with kinematic corrections and b
Cepila, Contrares, Matas '18

solution of Balitsky-Kovchegov directly for dipole gluon density

Kwiecinski, Kutak '02
Nikolaev, Schafer '06

The momentum space BK equation for dipole gluon density

$$\mathcal{F} = \mathcal{F}_0 + K \otimes \mathcal{F} - \frac{1}{R^2} V \otimes \mathcal{F}^2$$

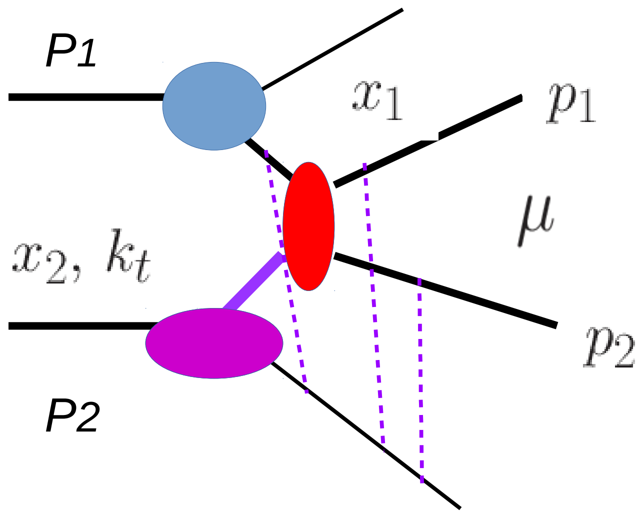
hadron's radius

Fit to F_2 data
KK. Sapeta '12

Accounts for kinematical constraint,

Nonsingular parts of splitting function, running coupling

The ITMD factorization for di-jets



- The color structure is separated from kinematic part of the amplitude by means of the color decomposition.
- The TMD gluon distributions are derived for the color structures following

P. Kotko K. Kutak , C. Marquet , E. Petreska , S. Sapeta, A. van Hameren,
JHEP 1509 (2015) 106

A. van Hameren, P. Kotko, K. Kutak, C. Marquet, E. Petreska
JHEP 12 (2016) 034

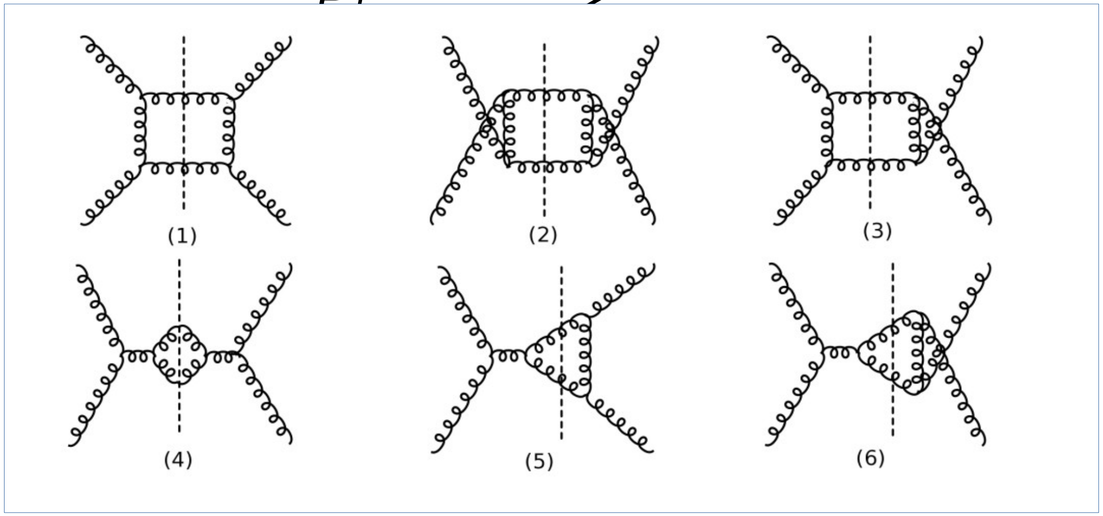
Formalism implemented in Monte Carlo programs KaTie by A. van Hameren

gauge invariant amplitudes with k_t and TMDs

Example for g* g → g g

$$\frac{d\sigma^{pA\to ggX}}{d^2P_t d^2k_t dy_1 dy_2} = \frac{\alpha_s^2}{(x_1 x_2 s)^2}\, x_1 f_{g/p}(x_1,\mu^2) \sum_{i=1}^{6} \mathcal{F}_{gg}^{(i)} H_{gg\to gg}^{(i)}$$

Improved Transverse Momentum Dependent Factorization



from

F. Dominguez, C. Marquet,
Bo-Wen Xiao, F. Yuan
Phys.Rev. D83 (2011) 105005

The same gauge link and as in TMD 's

Fabio Dominguez, Bo-Wen Xiao, Feng Yuan
Phys.Rev.Lett. 106 (2011) 022301

F. Dominguez, C. Marquet, Bo-Wen Xiao, F. Yuan
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P. Kotko K. Kutak , C. Marquet , E. Petreska , S. Sapeta,
A. van Hameren, JHEP 1509 (2015) 106

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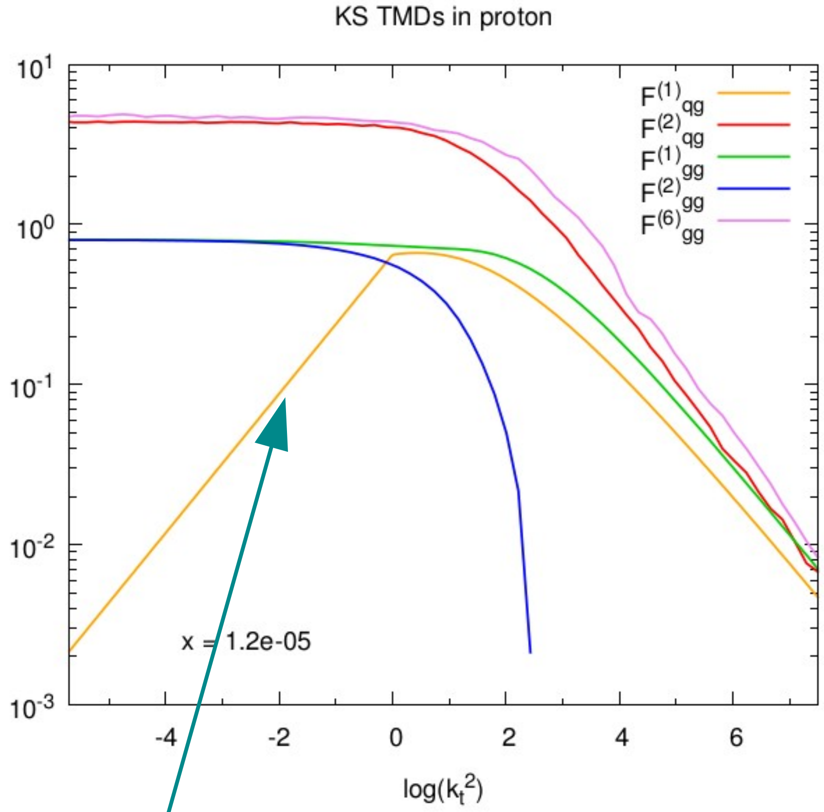
Plots of ITMD gluons



All gluons can be calculated from the dipole one. KS gluon used.

Kotko, K.K, Marquet, Petreska, Sapeta, van Hameren JHEP 1612 (2016) 034

Standard HEF gluon density

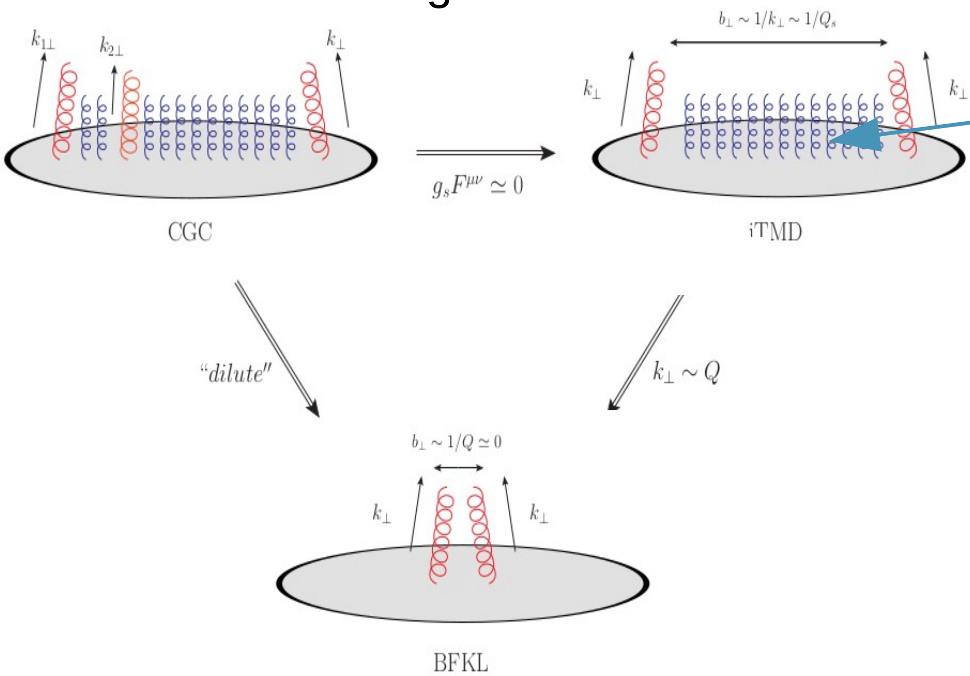
The other densities are flat at low k_t → less saturation

Not negligible differences at large k_t → differences at small angles

ITMD from CGC

T. Altinoluk, R. Boussarie, P. Kotko JHEP 1905 (2019) 156
T. Altinoluk, R. Boussarie, JHEP10(2019)208

Expansion in distance - parameter entering as argument Wilson lines appearing in generic CGC amplitude i.e. amplitude for propagation in strong color field of target



Multiple soft emissions

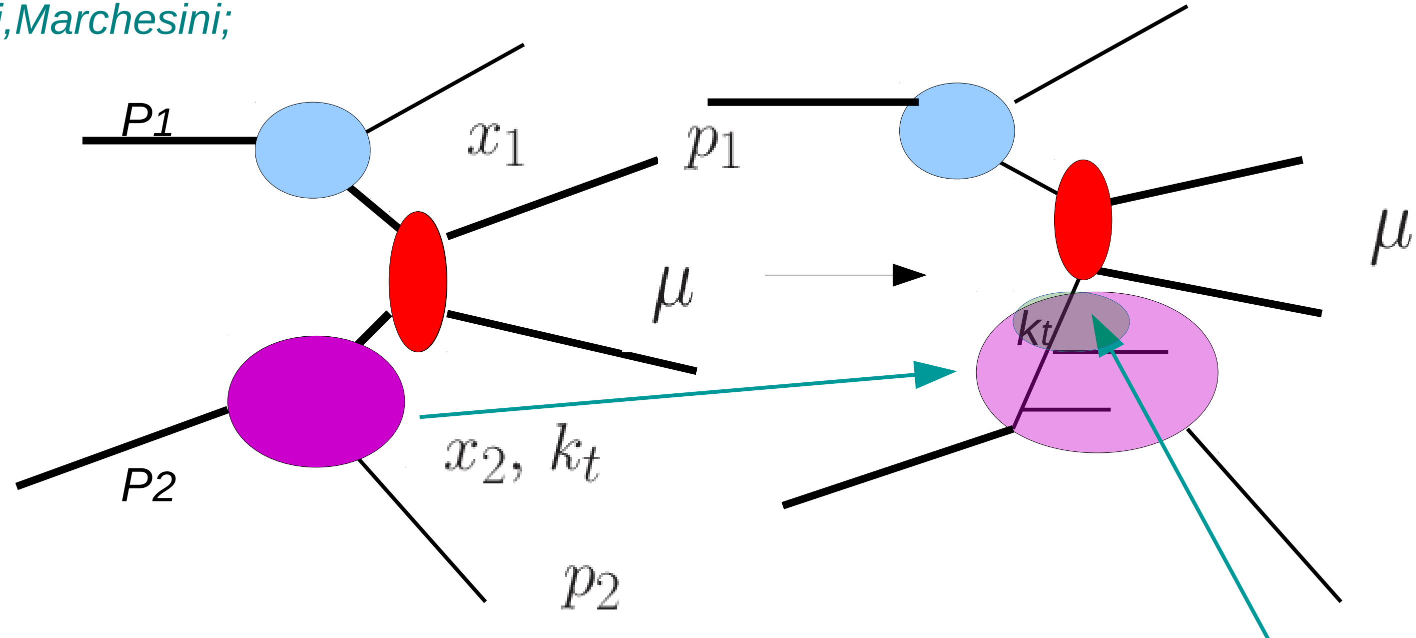
from R. Boussarie
Initial Stages 2019

Wandzura-Wilczek approximmation ITMD neglects higher genuine twist contributions i.e. hard gluon exchanges between the target and the amplitude, while it resums all kinematic twist

Other relevant effects – Sudakov form factor in ISR

The relevance in low x physics at linear level rcognized by:
Catani, Ciafaloni, Fiorani, Marchesini; Kimber, Martin, Ryskin; Collins, Jung

Survival probability of the gap without emissions



If hard scale is larger than kt the phase space opens for hard scale reusmmation

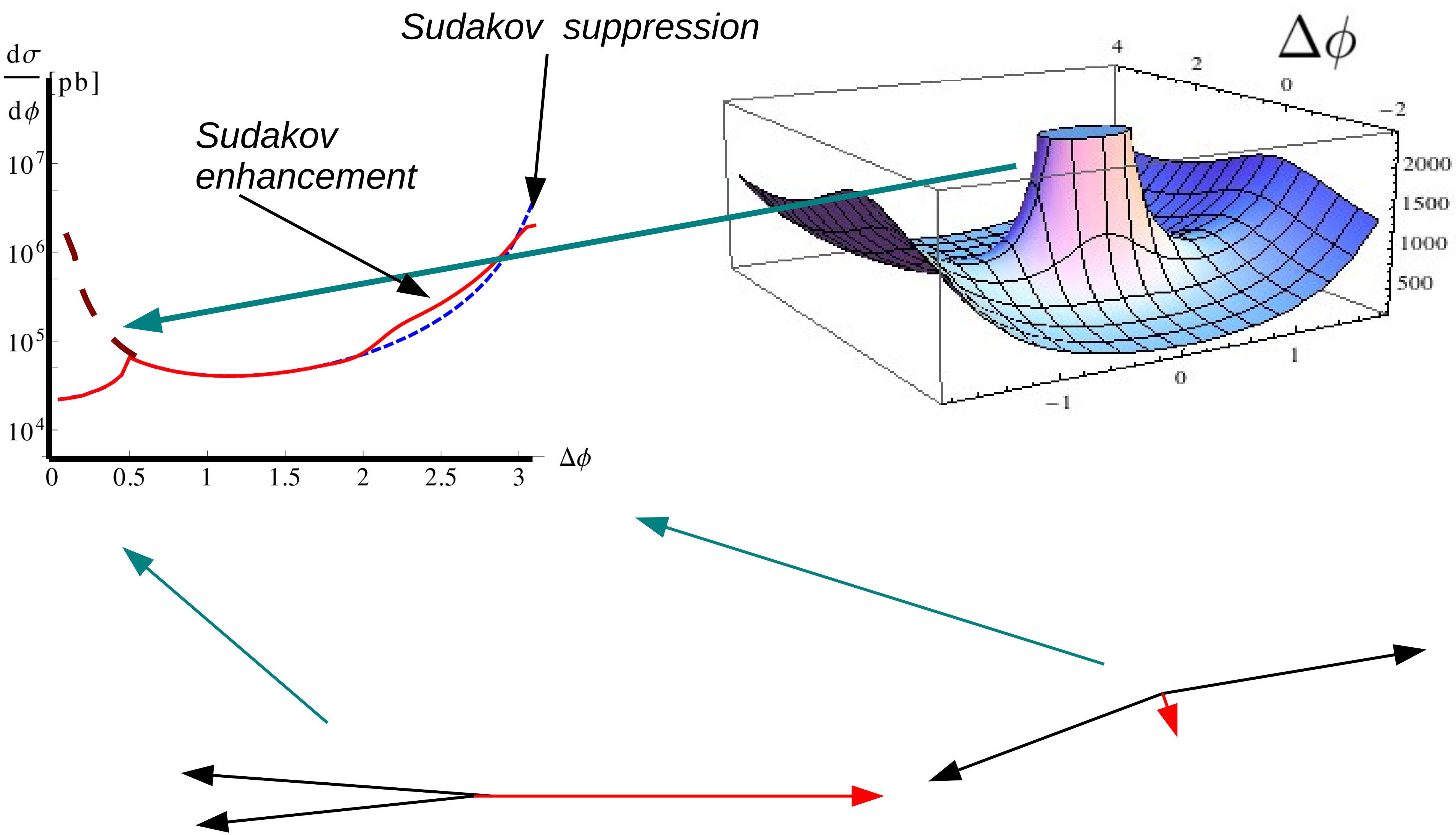
Survival probability of the gap without emissions

Mueller, Xiao, Yuan '12
Mueller, Xiao, Yan '13
Van Hameren, Kotko, Kutak, Sapeta '14
Xiao, Yuan, Zhou '17
Zhou' 16
Kutak '14

Other relevant effects – Sudakov form factor

Divergence regularized by jet algorithm

K.K '14



ITMD +Sudakov

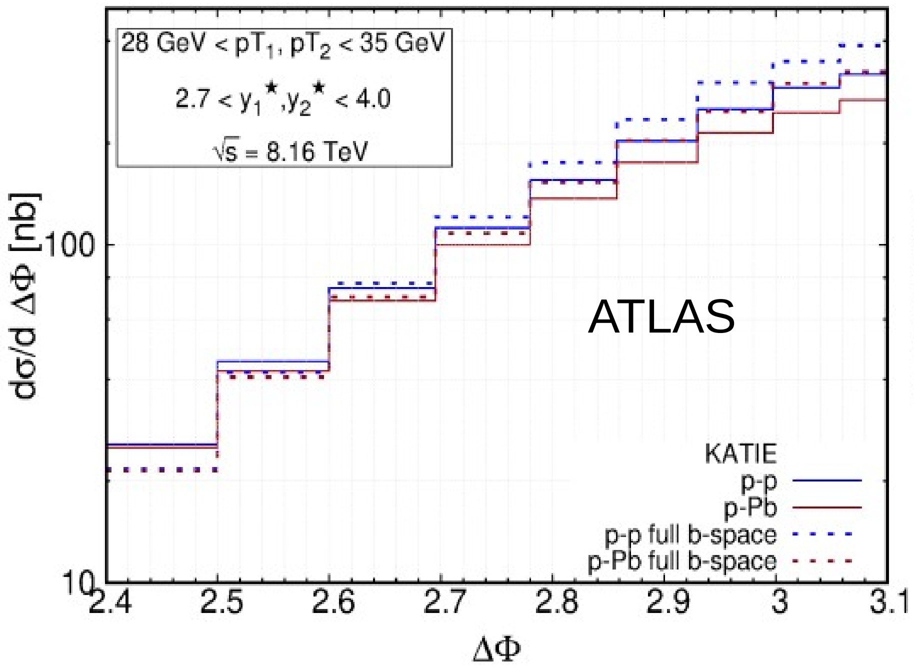
$$\frac{d\sigma^{\mathrm{pA}\to j_1 j_2+X}}{d^2P_T d^2k_T dy_1 dy_2} = \sum_{a,c,d} x_{\mathrm{p}} f_{a/\mathrm{p}}(x_{\mathrm{p}},\mu) \sum_{i=1}^{2} \mathcal{K}^{(i)}_{ag^*\to cd}(P_T,k_T;\mu)\,\Phi^{(i)}_{ag\to cd}(x_{\mathrm{A}},k_T)$$

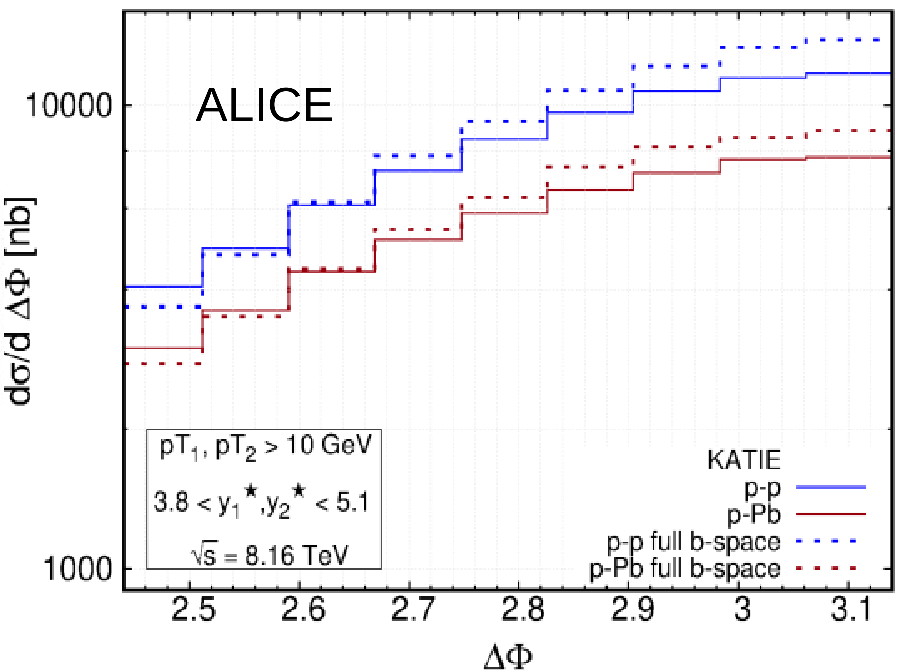
$$\frac{d\sigma^{\mathrm{pA}\to j_1 j_2+X}}{d^2P_T d^2k_T dy_1 dy_2} = \sum_{a,c,d} x_{\mathrm{p}} \sum_{i=1}^{2} \mathcal{K}^{(i)}_{ag^*\to cd}(P_T,k_T;\mu)$$

$$\times \int db_T b_T J_0(b_T k_T) f_{a/\mathrm{p}}(x_{\mathrm{p}},\mu_b)\,\widetilde{\Phi}^{(i)}_{ag\to cd}(x_{\mathrm{A}},b_T)\,e^{-S^{ag\to cd}(\mu,b_\perp)}$$

Depending on the choice of scale the collinear pdf can be put in front of the integral or kept under the integral. We consider both options and call them factorized and unfactorized. The Sudakov is at DLL accuracy.

Azimuthal angle dependence – parton level



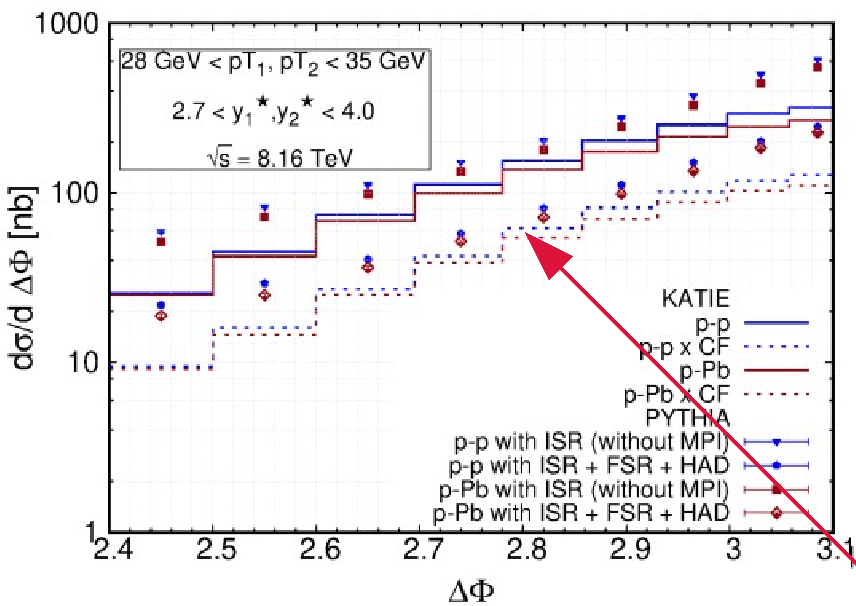


Visible differences especially for ALICE FoCal between p-p and p-Pb results.
Lower pt cut and more forward rapidities.
Not large differences between to approaches to account for Sudakov form factor.

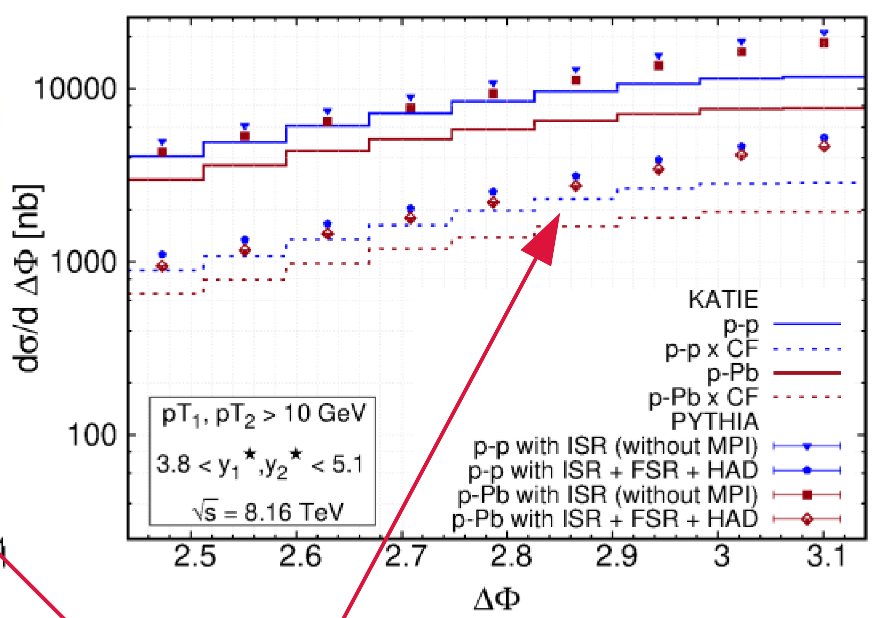
For earlier results see

A. Hameren, P. Kotko, K. Kutak, S. Sapeta
Phys.Lett. B795 (2019) 511-515

Azimuthal angle dependence – adding correction factor



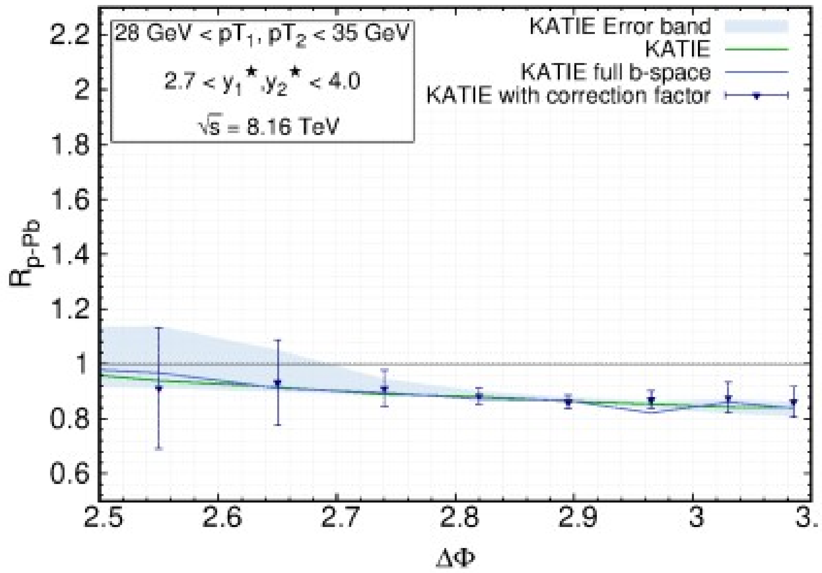
ATLAS



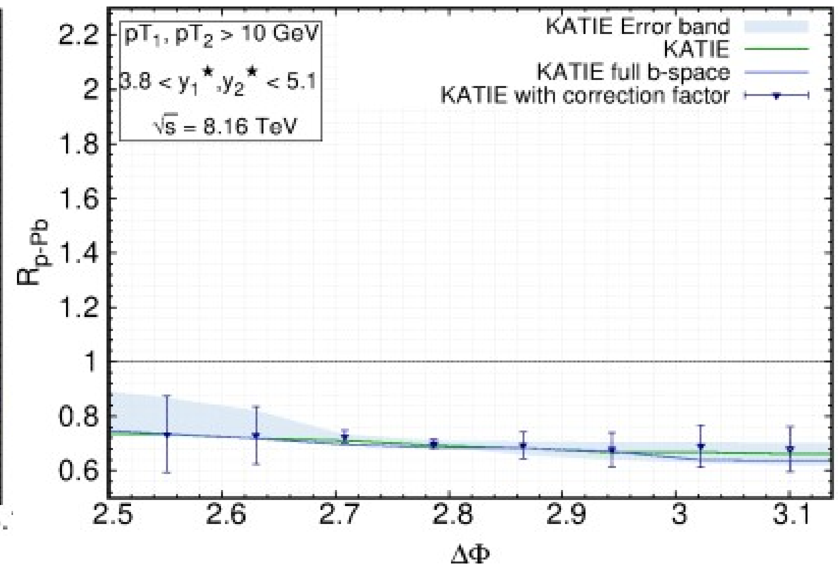
ALICE

“Corrected” parton level
PYTHIA and KATIE

Nuclear modification ratio



ATLAS



ALICE

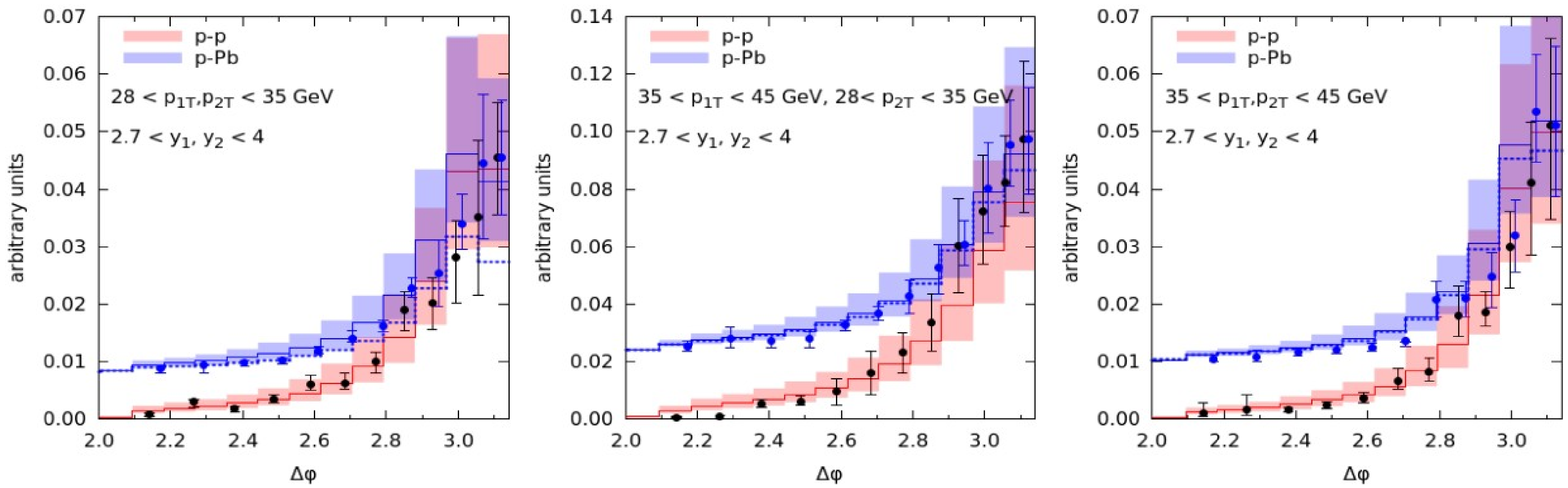
Visible suppression in both ATLAS and ALICE kinematical setup.
Correction factor effectively cancels. Strong saturation signal.

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

Signature of saturation in forward-forward dijets

ATLAS 1901.10440

van Hameren, Kotko, Kutak, Sapeta '19

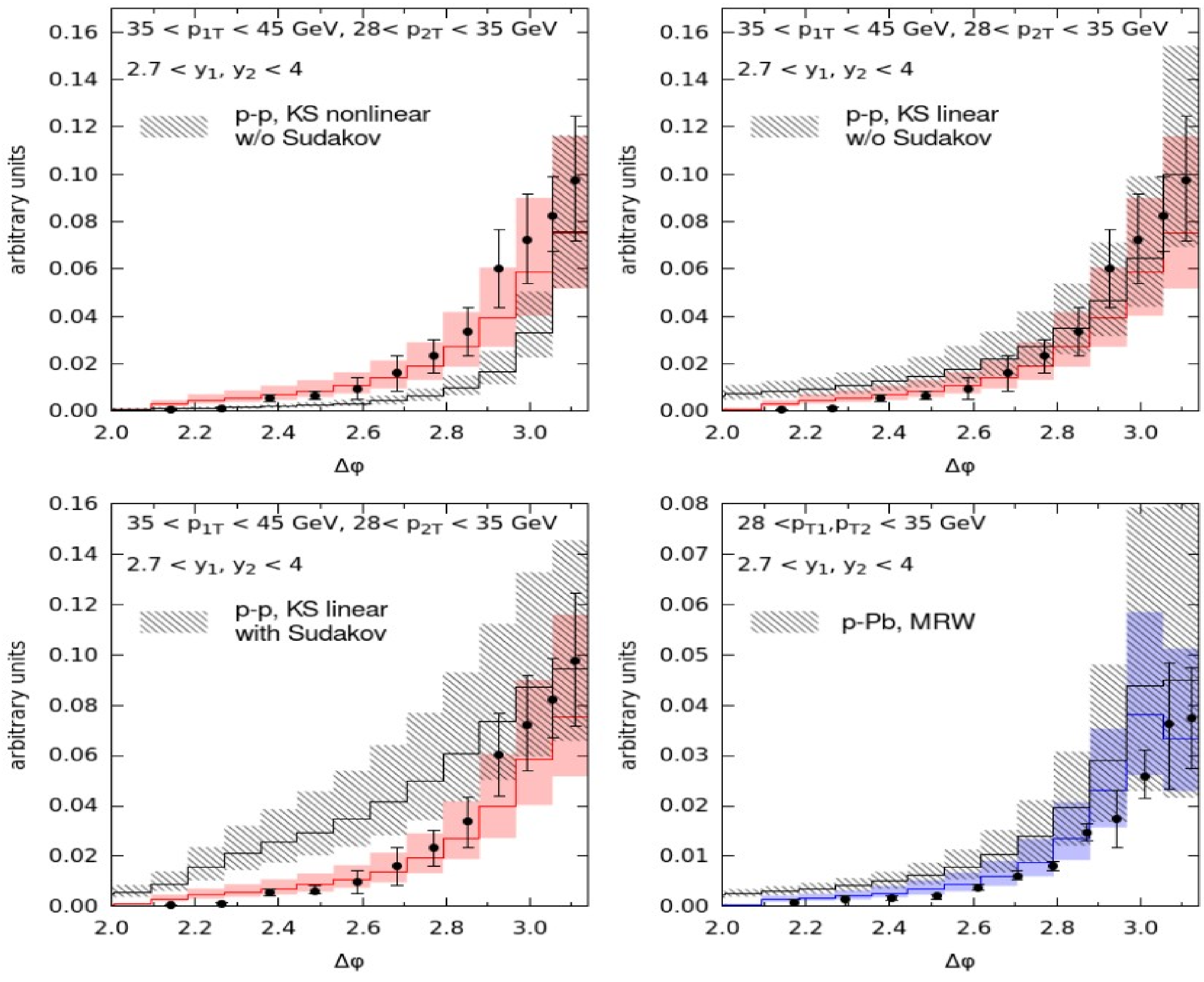


Data: number of dijets normalized to number of single inclusive jets. We can not calculate that.
We can compare shapes.

Procedure: fit normalization to p-p data. Use that both for p-p and p-Pb. Shift p-Pb data

The procedure allows for visualization of broadening

Other possible scenarios



Backup

Azimuthal angle dependence – adding correction factor