DIJET PRODUCTION AT EIC

AND INTERPLAY OF SUDAKOV AND SATURATION EFFECTS IN WEIZSACKER-WILLIAMS TMD GLUON DISTRIBUTION

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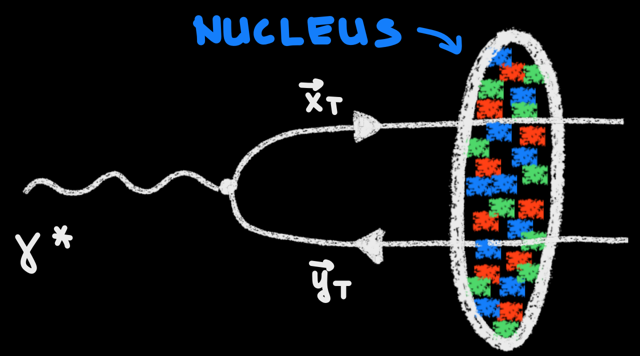
DIS 2021

INTRODUCTION Jet/hadron production in γA collisions at small x

Dipole scattering off a color field of nucleus within the Color Glass Condensate (CGC)



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

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

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

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

$$\times\left\{1+S_x^{(4)}\left(\vec{x}_T,\vec{y}_T;\vec{y}'_T,\vec{x}'_T\right)-S_x^{(2)}\left(\vec{x}_T,\vec{y}_T\right)-S_x^{(2)}\left(\vec{y}'_T,\vec{x}'_T\right)\right\}$$

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

(dipole)

⇓

dipole TMD gluon distribution

$$\mathscr{F}_{qg}^{(1)}(x,k_T)$$

$$S_x^{(4)} \sim \left\langle \mathrm{Tr}U(\vec{x}_T)U^\dagger(\vec{x}'_T)U(\vec{y}'_T)U^\dagger(\vec{y}_T)\right\rangle_x$$

(quadrupole)

⇓

Weizsäcker-Williams TMD gluon distribution

$$\mathscr{F}_{gg}^{(3)}(x,k_T)$$

accessible in
DIJET PRODUCTION

TMD gluon distributions

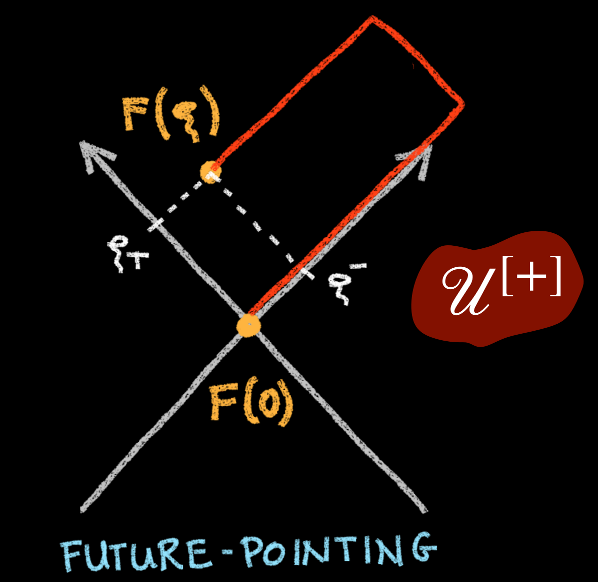
Generic operator definition

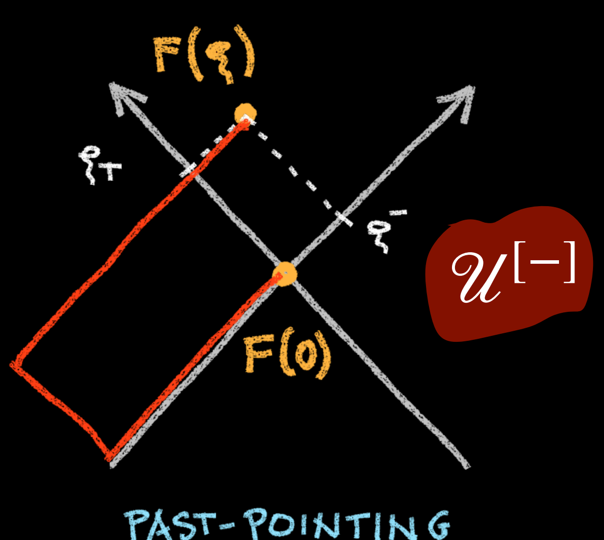
(unpolarized)

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

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

GAUGE LINKS in fundamental color representation





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]

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

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

STRAIGHT LINE SEGMENT

Light-cone basis:

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

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

INTRODUCTION TMD gluon distributions

All possible operators

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

(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)

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

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

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

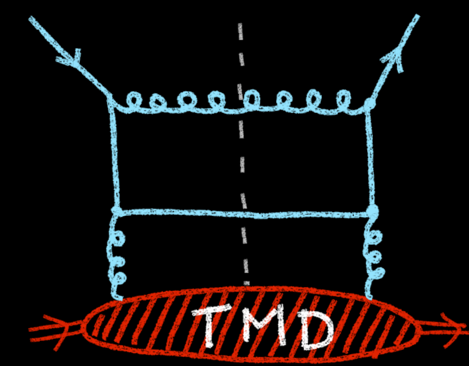
$$\mathcal{F}_{gg}^{(7)} \sim \langle P|\,\frac{\mathrm{Tr}\,\mathcal{U}^{[\Box]}}{N_c}\mathrm{Tr}\left[\hat{F}^{i-}(\xi)\,\mathcal{U}^{[\Box]\dagger}\mathcal{U}^{[+]\dagger}\hat{F}^{i-}(0)\,\mathcal{U}^{[+]}\right]|P\rangle$$

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

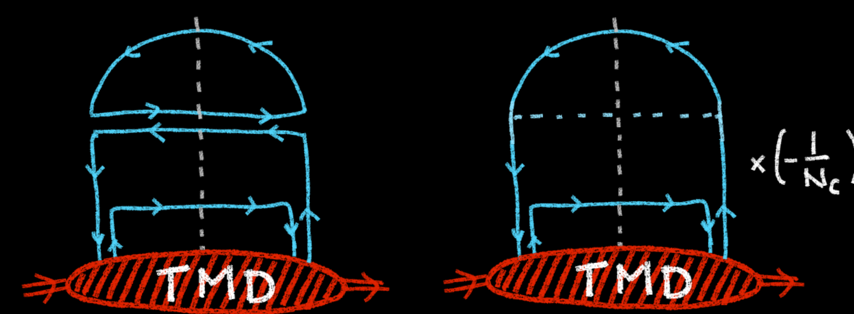
[M. Bury, PK , K. Kutak, 2018]

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.

FRAMEWORK

Small-x improved TMD Factorization (ITMD*)

Factorization for $P_T \gg Q_s$

average p_T of jets — saturation scale

[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]
[PK, K. Kutak, S. Sapeta, A. Stasto, M. Strikman, 2017]
[T. Altinoluk, R. Boussarie, PK, 2019]

see also: [T. Altinoluk, R. Boussarie, 2019]
[H. Fujii, C. Marquet, K. Wanatabe, 2020]
[T. Altinoluk, C. Marquet, P. Taels, 2021]

- resummation of kinematic twists
- only leading genuine twist (no hard MPIs)
- no linearly polarized gluons (assume $Q^2/P_T^2 \ll 1$)

$$d\sigma_{\gamma^* A \to 2j+X} \sim \int \frac{dx}{x} \int d^2k_T \, \mathscr{F}^{(3)}_{gg}(x, k_T, \mu) \, d\sigma_{\gamma^* g^* \to j_1 j_2}(x, k_T, \mu)$$

Weizsacker-Williams TMD with Sudakov resummation — off-shell matrix elements

Implemented in KaTie Monte Carlo
[A. van Hameren]

Related studies for dijet/dihadron at EIC

Back-to-back regime using MV model + Sudakov

[L. Zheng, E.C. Aschenauer, J.H. Lee, B-W. Xiao, 2014]

Full CGC calculations (no Sudakov)

[A. Dumitru, V. Skokov, 2018]
[H. Mantysaari, N. Mueller, F. Salazar, B. Schenke, 2019]
[F. Salazar, B. Schenke, 2020]

Obtaining the Weizsacker-Williams TMD

1. 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]

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

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

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

fitted to DIS HERA data

[K. Kutak, S. Sapeta, 2012]

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

2. Weizsacker-Williams TMD with Sudakov resummation

At large N_c limit and Gaussian approximation:

[A. Mueller, B-W. Xiao, F. Yuan, 2013]

$$\mathcal{F}^{(3)}_{gg}(x,k_T,\mu) = \frac{C_F}{2\pi^4\alpha_s}\int d^2b\int\frac{d^2r}{r_T^2}\,e^{-i\vec{k}_T\cdot\vec{r}_T}\left[1-S_F^2(x,r_T)\right]e^{\mathbf{S}(\mu,r_T)}$$

dipole

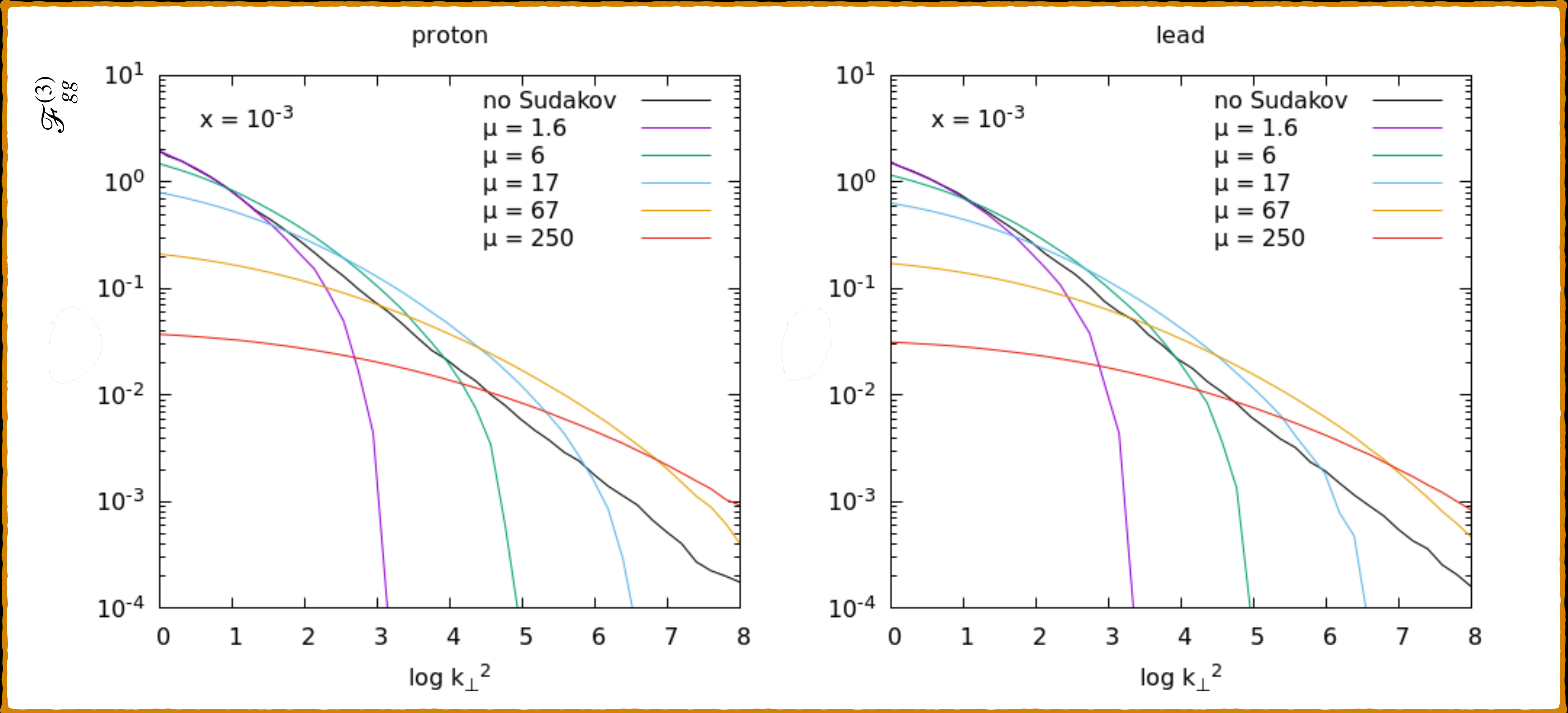
Sudakov factor

$$S_F(x,r) = \frac{2\pi^2\alpha_s}{N_c S_\perp}\int\frac{d^2k_T}{k_T^2}\,e^{i\vec{k}_T\cdot\vec{r}_T}\,\mathcal{F}^{(1)}_{qg}(x,k_T)$$

$$\mathbf{S}(\mu,r_T) = -\frac{\alpha_s N_c}{4\pi}\ln^2(A\mu^2 r_T^2)$$

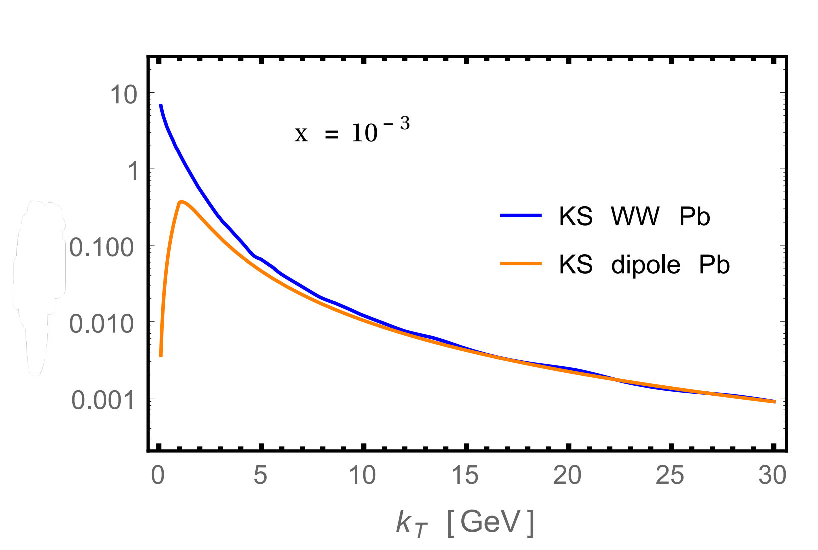
RESULTS

The Weizsacker-Williams TMD with Sudakov resummation



Weizsacker-Williams vs dipole gluon TMD distribution

different behaviour at small k_T (convergence at large k_T) →



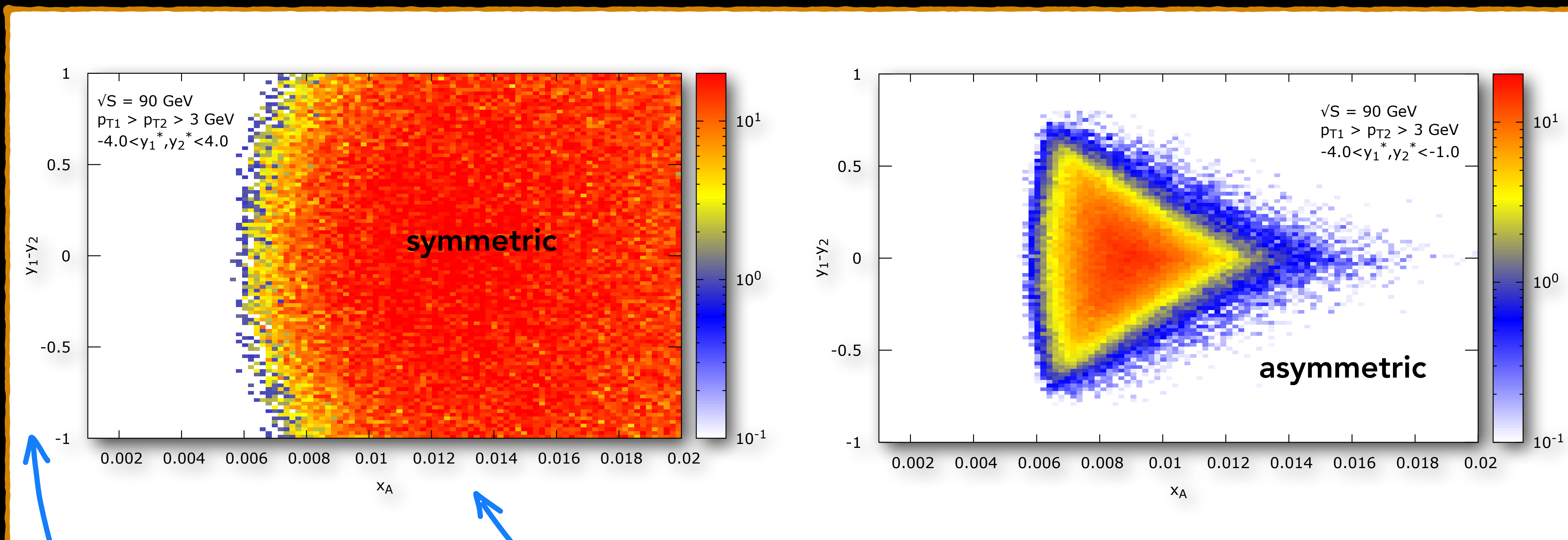
RESULTS

Kinematic setup

Cuts

- CM energy: $\sqrt{s} = 90\,\mathrm{GeV}$ (for e-p and e-Pb)
- inelasticity: $0.1 < \nu < 0.85$
- virtuality: $Q^2 > 1\,\mathrm{GeV}^2$
- jet transverse momenta: $p_{T1} > p_{T2} > 3\,\mathrm{GeV}$ (Breit frame)
- jet radius: $\Delta R > 1$ (Breit frame)
- symmetric rapidity: $-4 < y_1^*, y_2^* < 4$ (CM frame)
- asymmetric rapidity: $-4 < y_1^*, y_2^* < -1$

Symmetric vs asymmetric rapidity window



rapidity difference

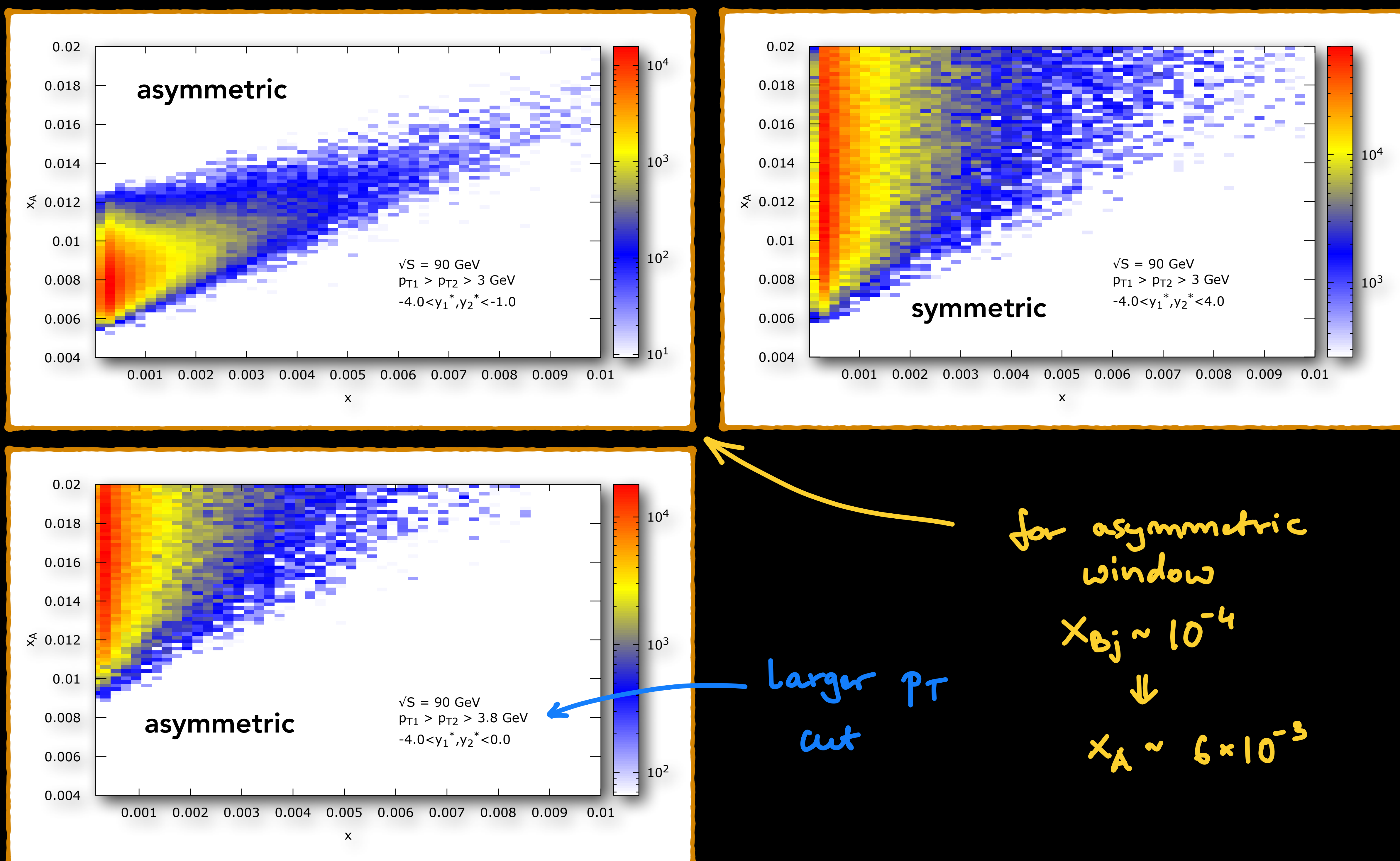
x of gluon
$x_A \neq x_{Bj}$

good focus on small x_A

RESULTS

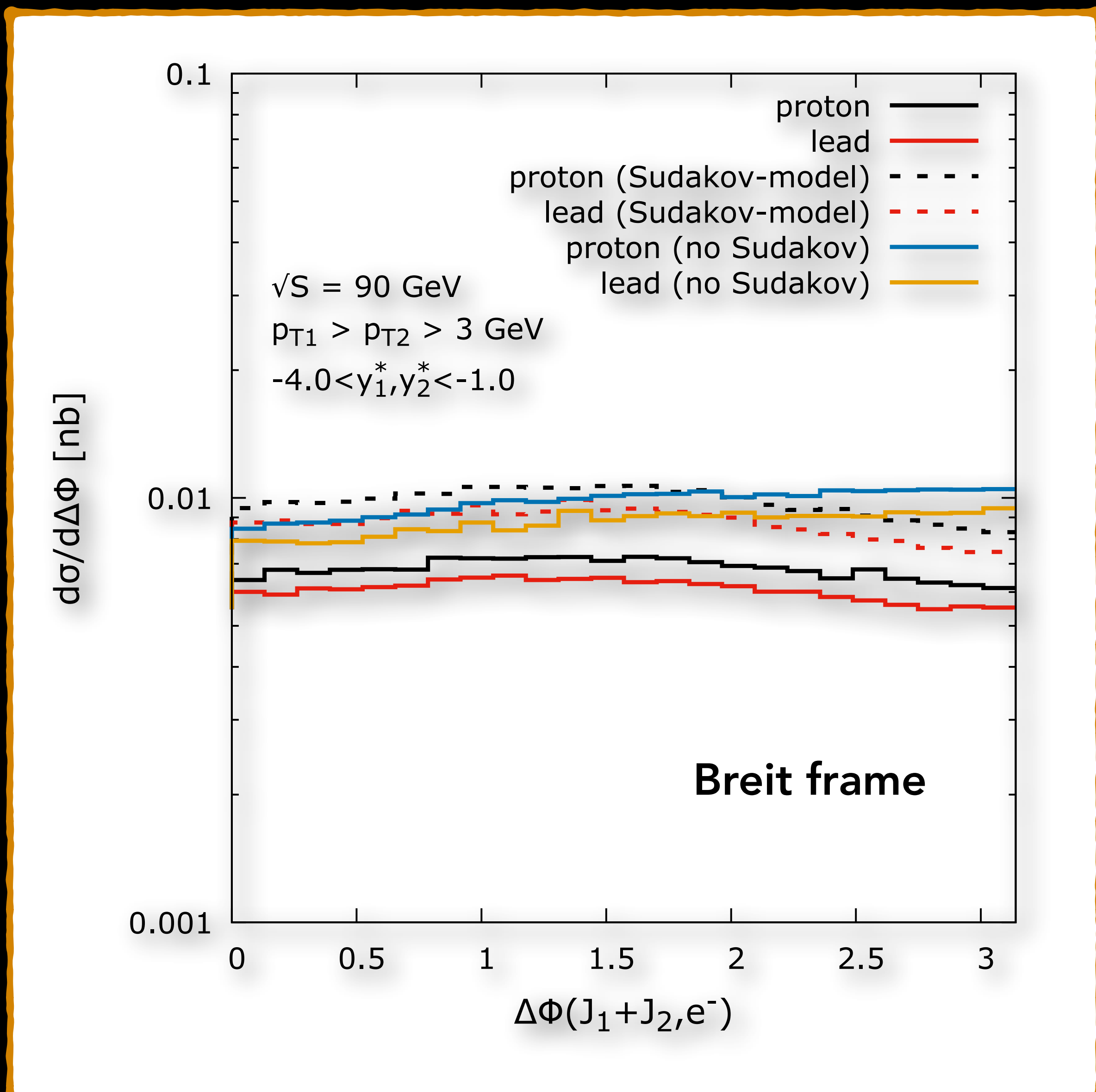
Kinematic setup

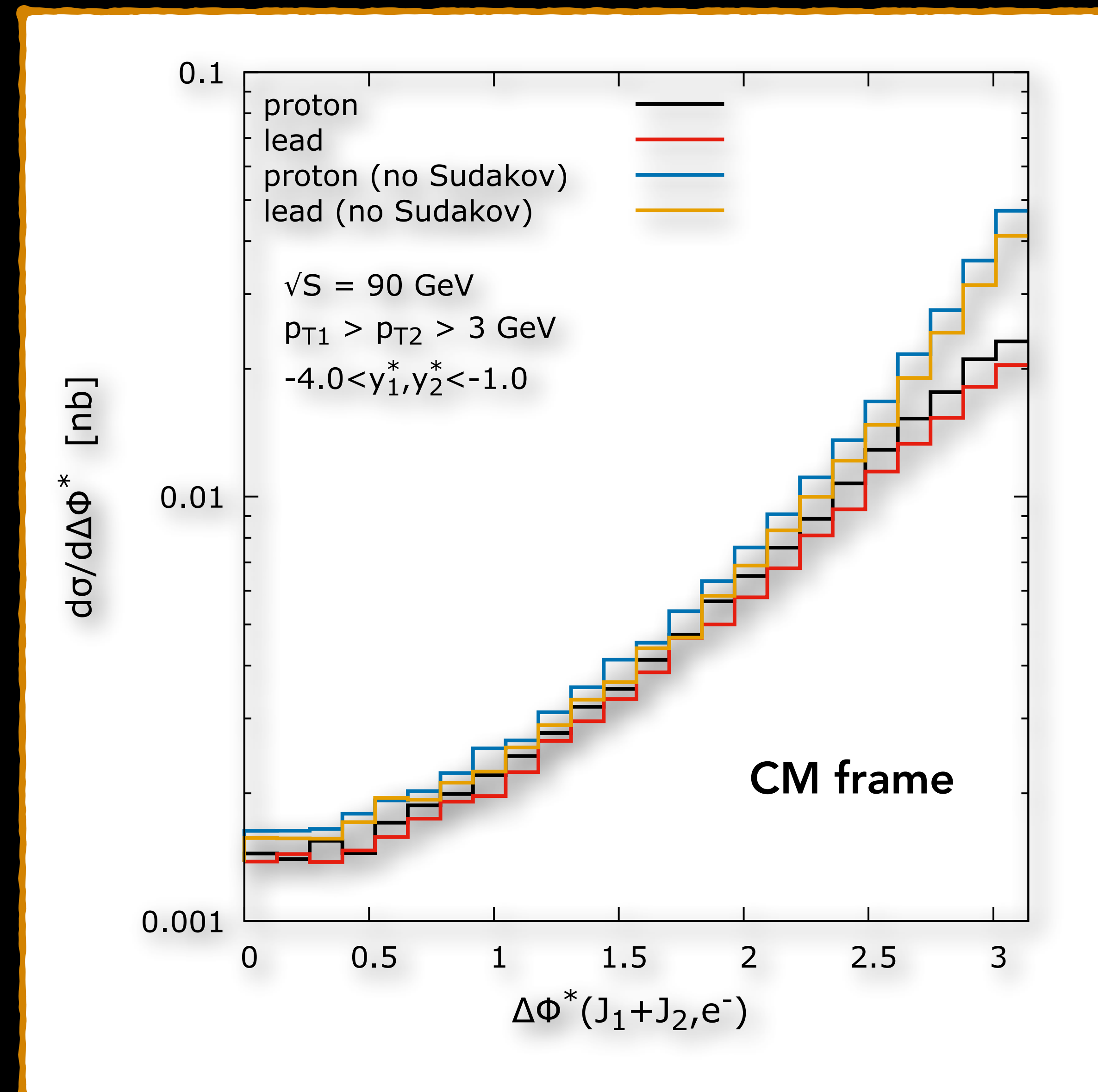
Bjorken x vs Gluon x_A



RESULTS Azimuthal correlations

Azimuthal angle between jet plane and electron $\Delta\Phi(J_1 + J_2, e^-)$





*Sudakov-model: resummation done by reweighting MC generated events via the probablility of survival given by the Sudakov factor.

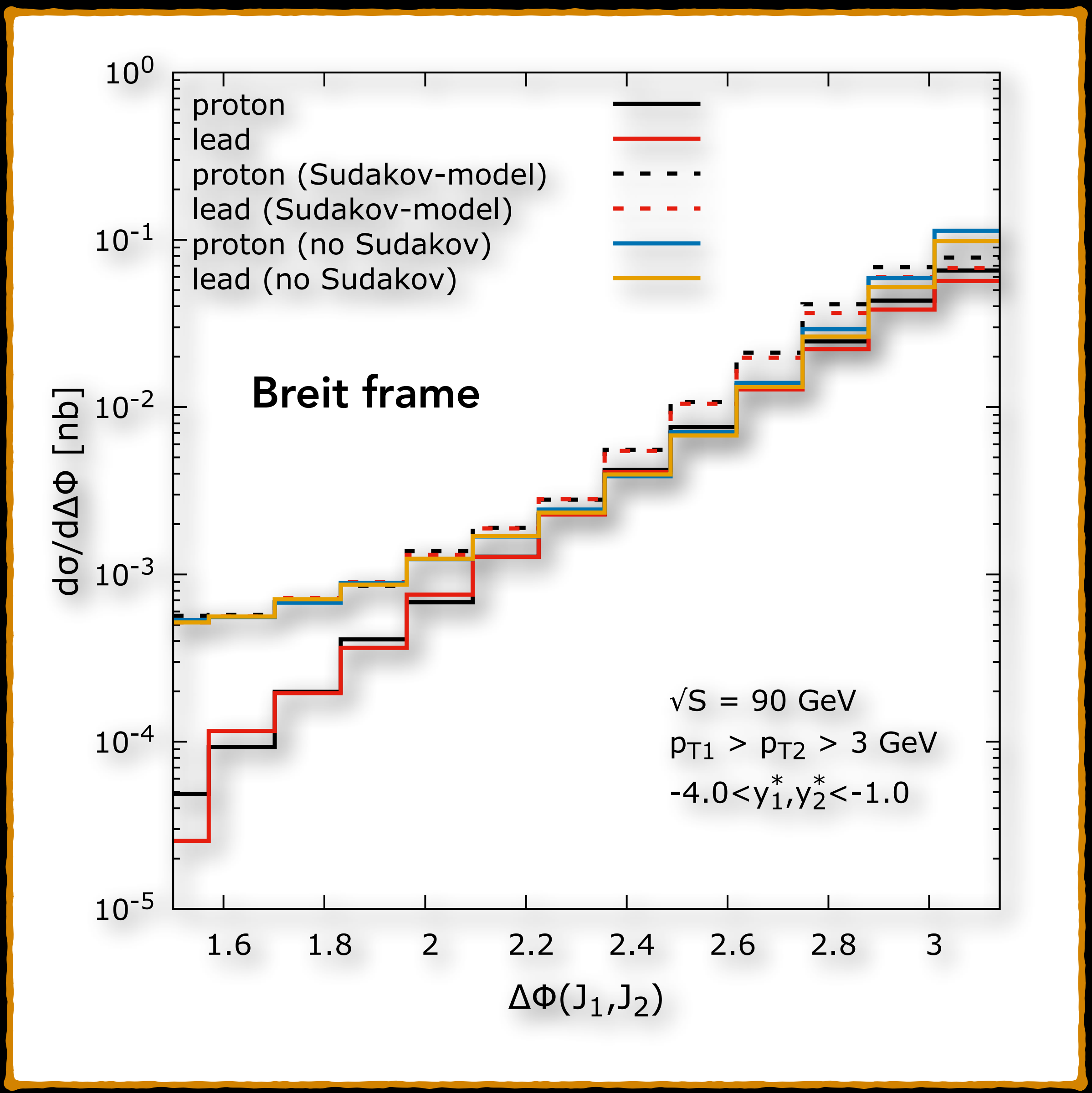
[A. van Hameren, PK, K. Kutak, S. Sapeta, 2014]

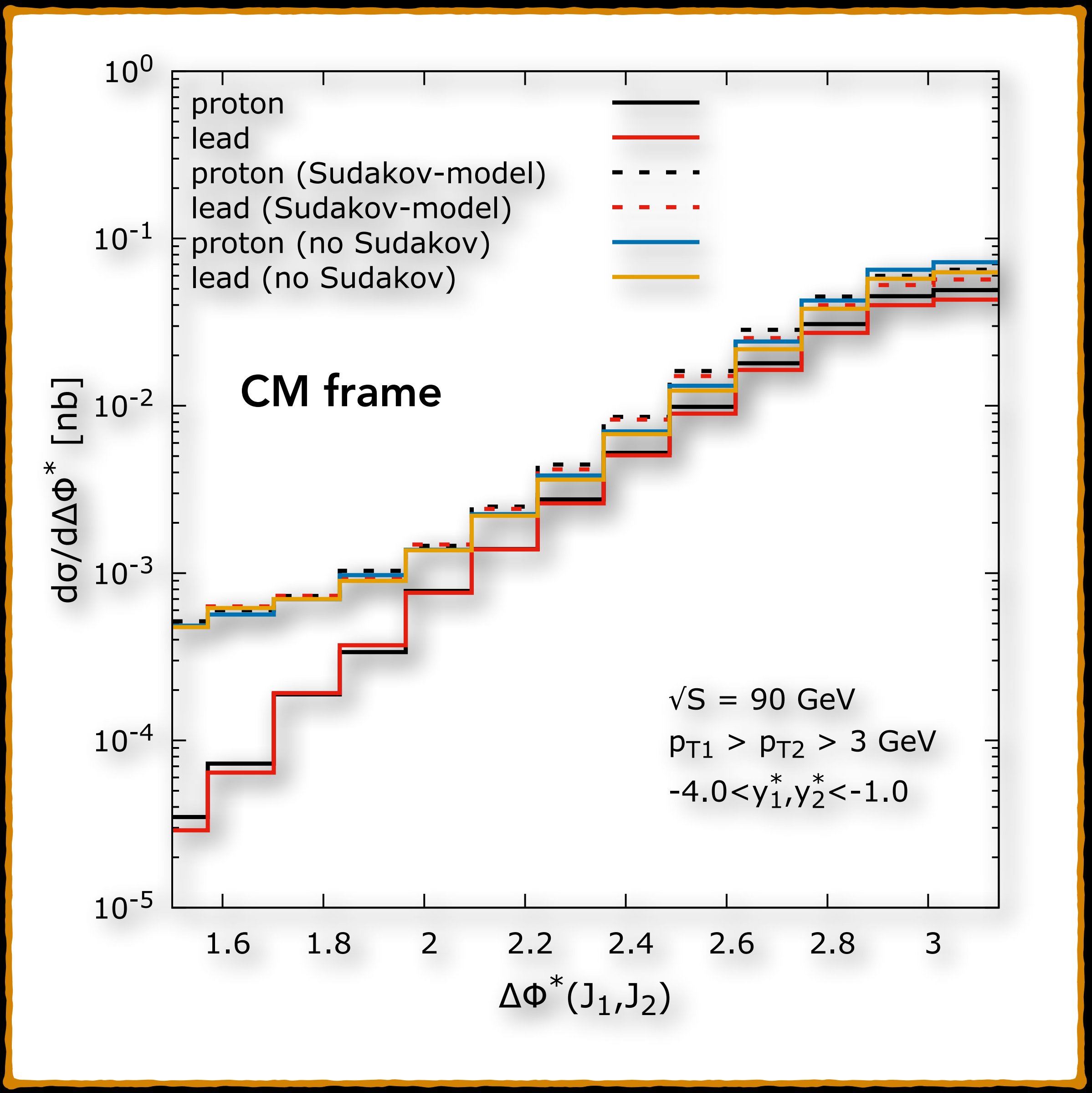
* Large Sudakov effects.
* Saturation effects: up to 15% suppression.

RESULTS

Azimuthal correlations

Azimuthal angle between the jets $\Delta\Phi(J_1, J_2)$





* Very steep distributions.
* Sudakov-model has little effect.

* Sudakov effects significant for smaller $\Delta\phi$.

SUMMARY

- New data-driven calculation for the Weizsacker-Williams TMD gluon distribution with the Sudakov resummation.
- New calculation of dijet production in the small-x region at EIC within ITMD* approach, in particular for azimuthal correlations:
  - between dijet plane and electron
  - between the jets
- Various rapidity windows and frames have been studied.

- Small p_T of jets seems to be required to access gluon $x < 10^{-3}$.
- Asymmetric rapidity window is important to focus on the small gluon x.
- Sudakov resummation changes results significantly.
- Saturation effects are up to 15% for $p_T > 3\,\mathrm{GeV}$.

- Next natural step: full NLO computation...

BACKUP

Limiting cases of CGC in dilute-dense collisions

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]
[T. Altinoluk, R. Boussarie, C. Marquet, P. Taels, 2020]

$P_T \sim k_T \gg Q_s$

$P_T \gg Q_s$

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]

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]

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 → 0

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

DIPOLE GLUON DISTRIBUTION

Example:

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

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, 2017,2018]
[T. Altinoluk, R. Boussarie, 2019]
[R. Boussarie, Y. Mehtar-Tani, 2020]

BACKUP

Dijet correlations in pA collisions in ITMD

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

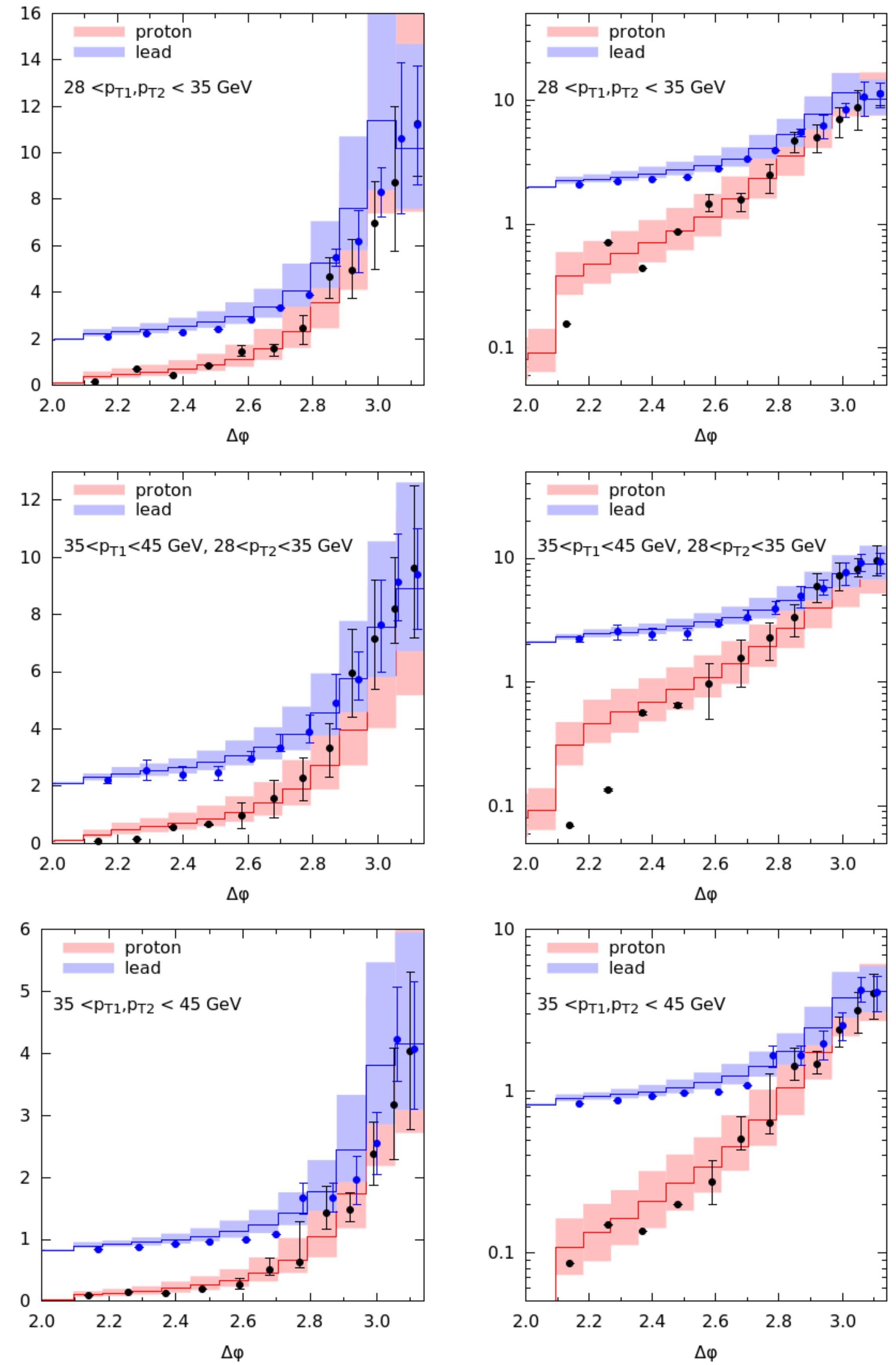
$\sqrt{S} = 5.02$ TeV   rapidity: $2.7 < y_1, y_2 < 4.5$

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

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.

A. van Hameren, EIC yellow report seminar