Small-x Gluons: From HERA and the EIC to Heavy-Ion Collisions

Wenbin Zhao

Central China Normal University

见微学术沙龙, 中国科学技术大学，合肥，中国

2026.11.06

Gluons at small x

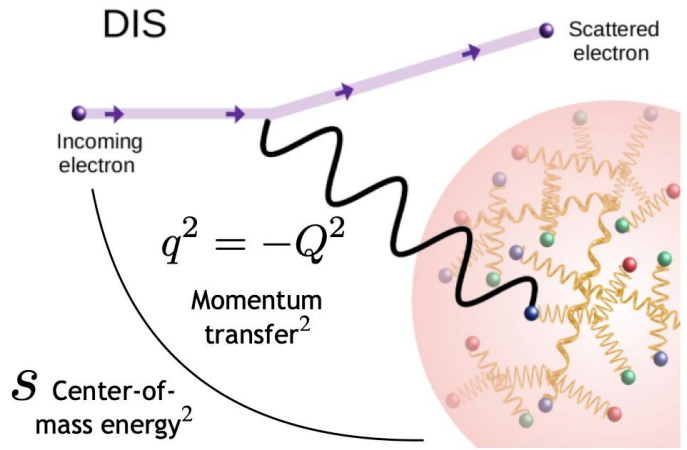
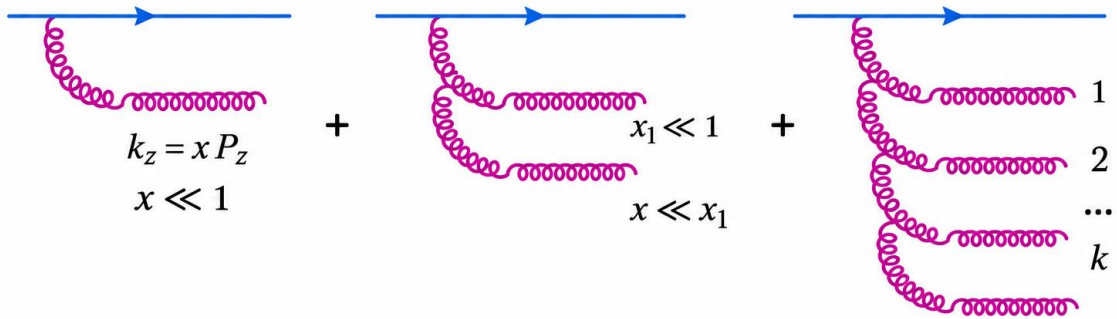
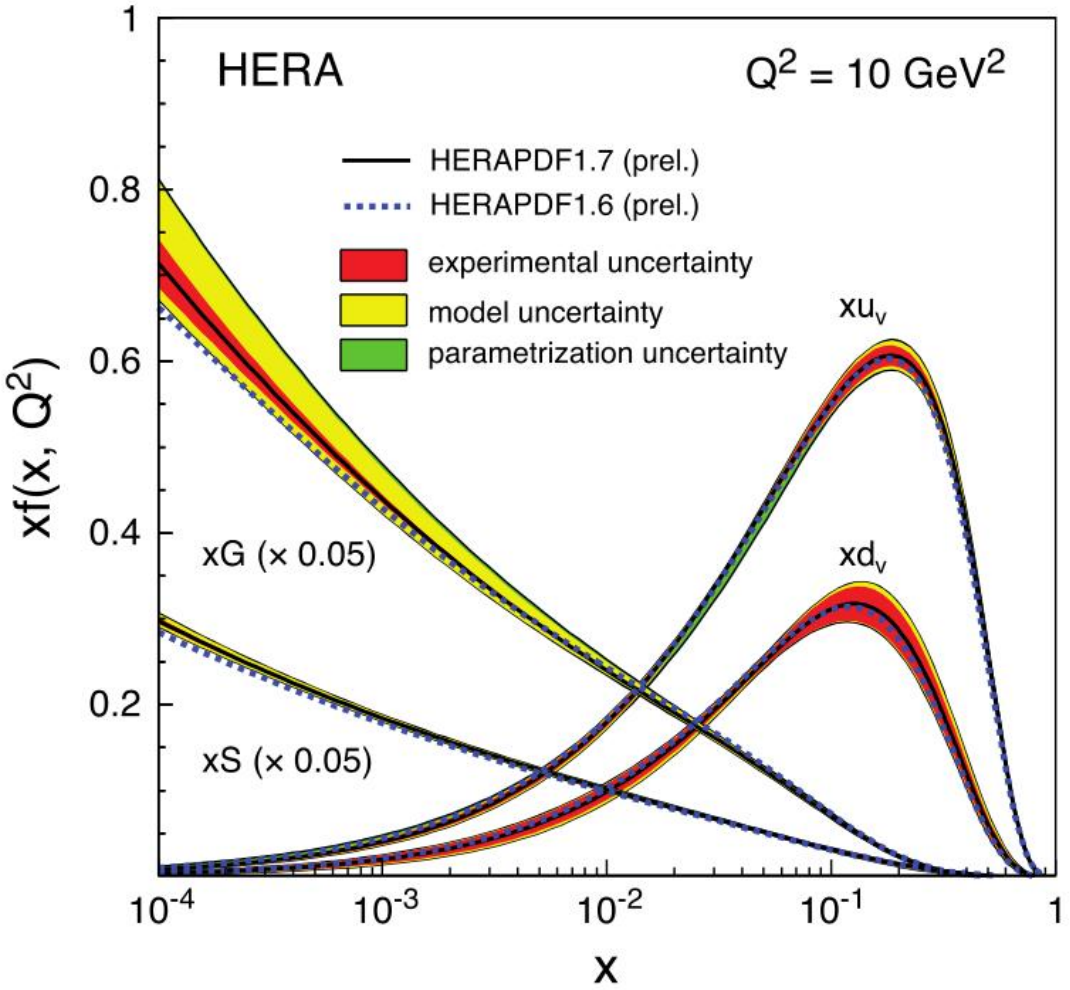


Figure (edited) from ZEUS collaboration

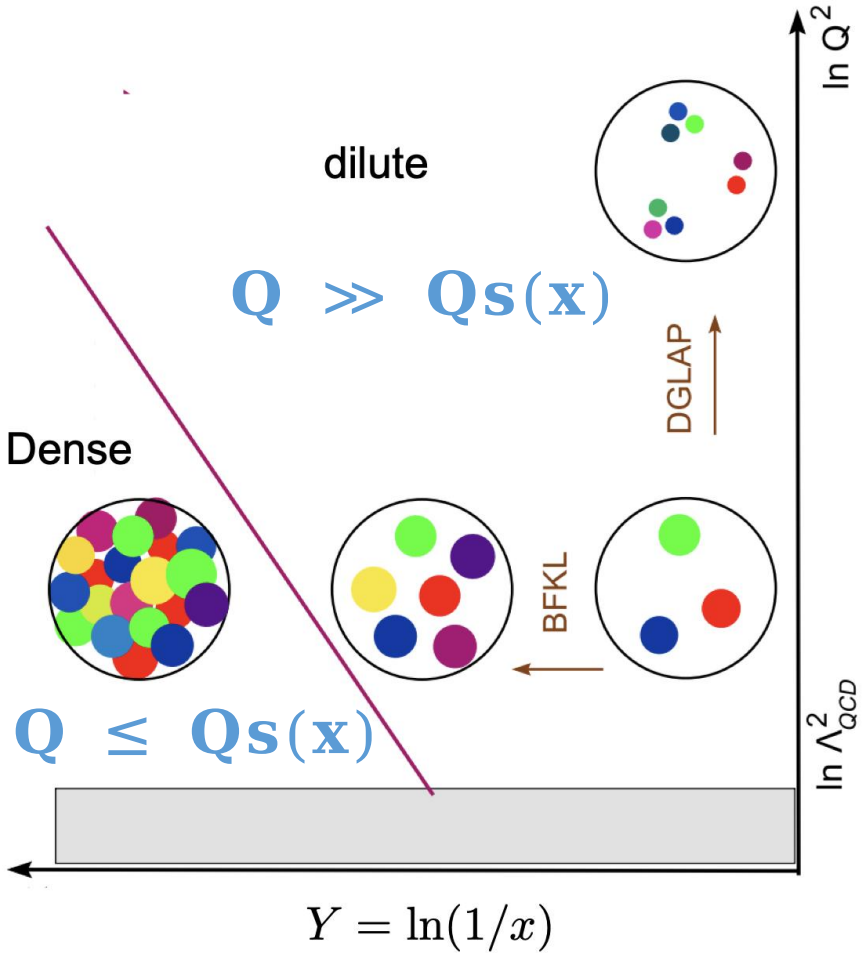
DGLAP splitting function

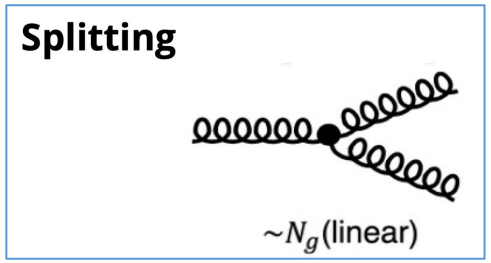
$$P_{gg}(x) \sim \frac{1}{x} \text{ for } x \to 0$$

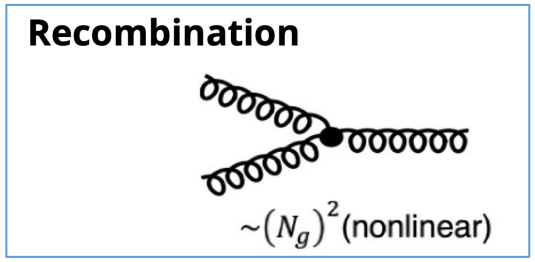




Why small-x gluons?





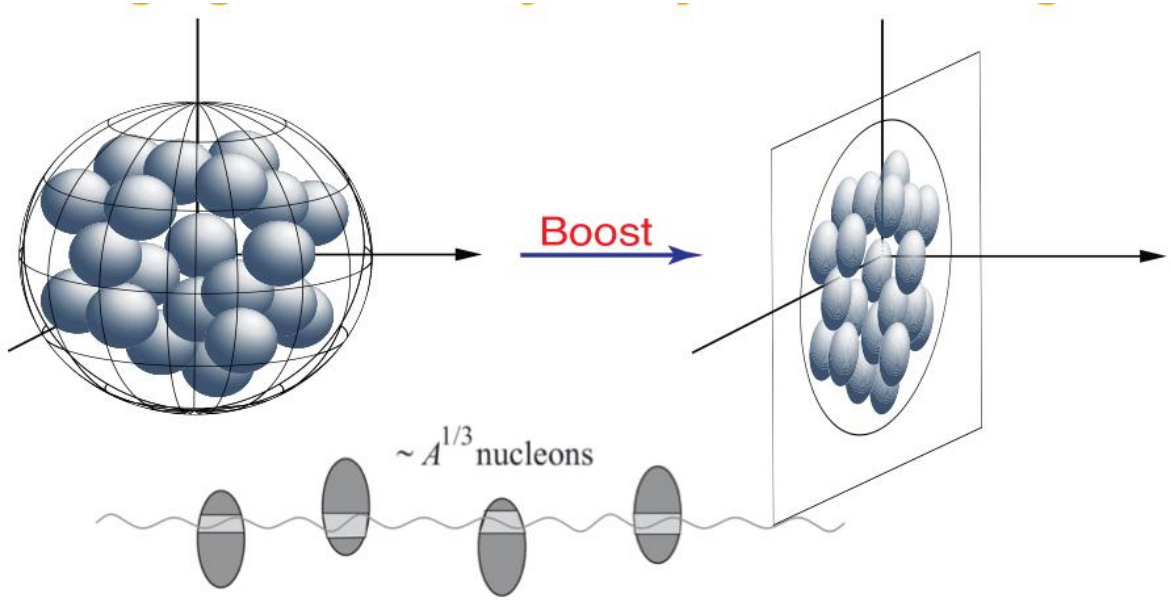


- Gluon emissions increase the density as x decreases.
- At high density, nonlinear interactions limit further growth.
- **$Qs(x)$: the onset of nonlinear dynamics**

Nuclei amplify saturation

- $Q_s^2 \propto$ gluon number per transverse area
- More nuclear matter per transverse area enhances the gluon density.

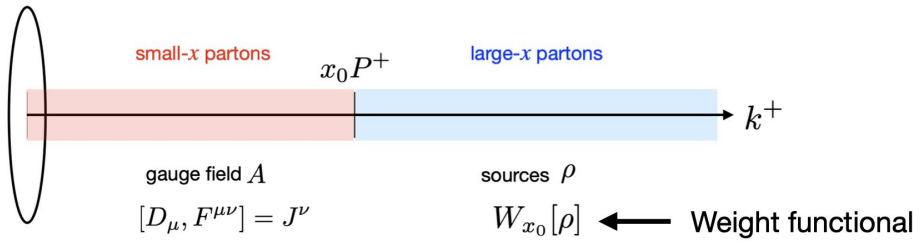
- Small x gluons (with long wave length) from different nucleons overlap with each other!
- At fixed x, saturation extends to larger momentum scales.



$$Q_{s,A}^2 \sim A^{1/3} Q_{s,p}^2$$

Color Glass Condensate in a nutshell

An effective theory of QCD at small x with strong classical fields



- **Separation of scales**

$k^+ > \Lambda^+$: sources $k^+ < \Lambda^+$: fields

Fast partons: frozen color sources ρ
Soft gluons: dynamical gauge fields A

"Glass": sources evolve slowly
on the soft-field time scale

- **Classical fields, statistical ensemble**

$$Q_s \gg \Lambda_{\rm QCD} \qquad \alpha_s(Q_s) \ll 1$$
$$f(k_\perp \lesssim Q_s) \sim 1/\alpha_s \qquad A \sim Q_s/g$$

$$[D_\mu, F^{\mu\nu}] = J^\nu[\rho]$$

$$\langle \mathcal{O} \rangle_Y = \int \mathcal{D}\rho \, W_Y[\rho] \, \mathcal{O}\big[A_{\rm cl}[\rho]\big]$$

$$\partial_Y W_Y = H_{\rm JIMWLK} \, W_Y$$

- **Quantum evolution**

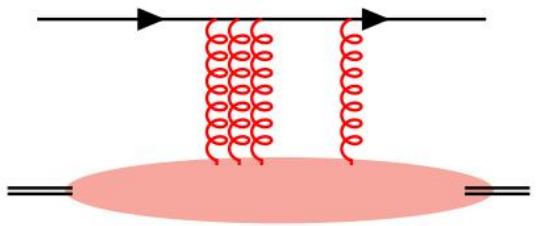
Integrate out a rapidity slice
Resum powers of αs ln(1/x)

$Y = \ln(x_0/x)$
BK: factorization of dipole correlators

The dipole amplitude connects the observables

- In the CGC, a fast quark crossing the target picks up a color rotation described by a light-like Wilson line V

$$V(\mathbf{x}) = \mathcal{P}\exp\left[ig\int_{-\infty}^{\infty} dx^+ A_a^-(x^+,\mathbf{x})\,t^a\right],$$



- Color Glass Condensate: dense gluon fields at small x
  dipole scattering amplitude (**CGC building block**)

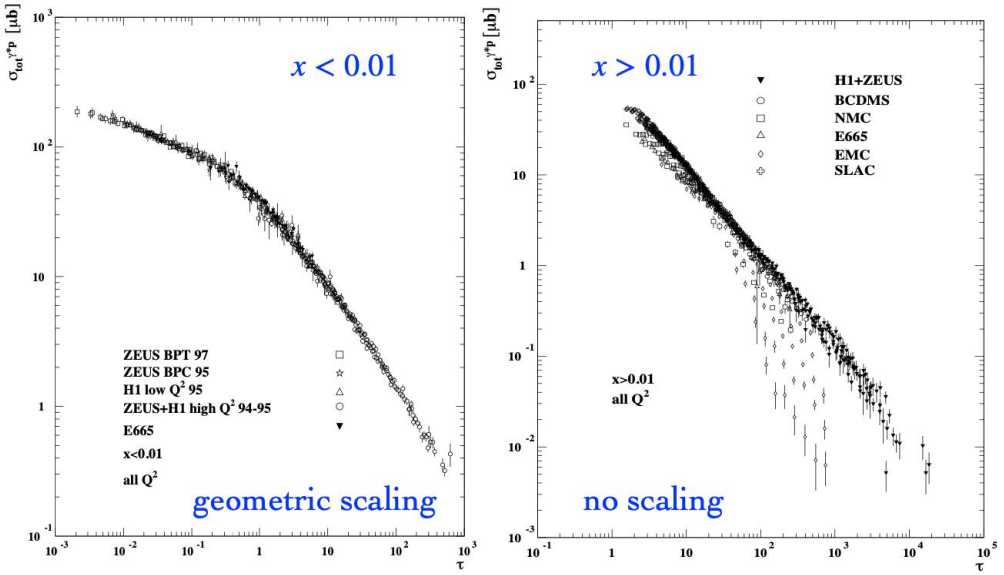
$$N(r,b;x) = 1 - \frac{1}{N_c}\langle \mathrm{Tr}\, V(\mathbf{x})V^\dagger(\mathbf{y})\rangle$$

Dipole size r Impact parameter b Wilson line V

- ✓ DIS structure functions
- ✓ Exclusive vector mesons
- ✓ Forward hadrons in DIS, pp, pA
- ✓ Small-x gluon density

Experimental status of gluon saturation

- Geometric scaling



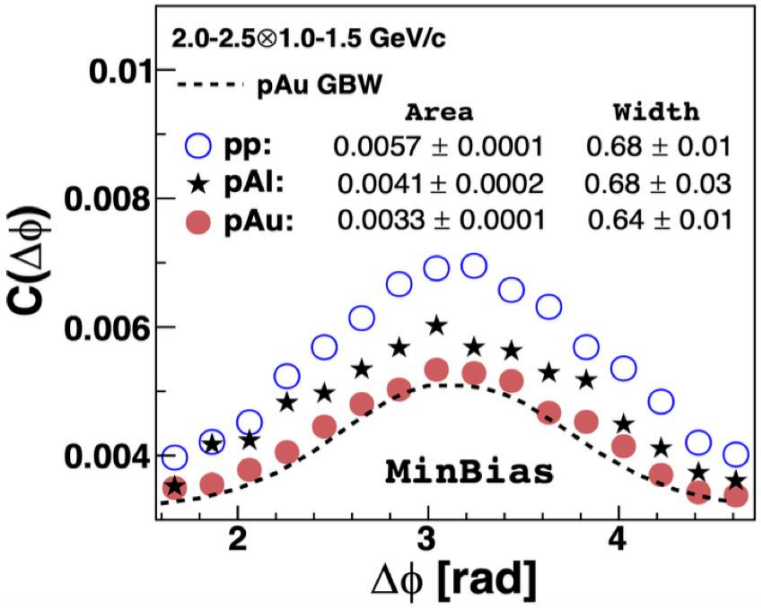
Hint of gluon saturation:

$$\sigma_{\mathrm{tot}}^{\gamma^* p}(x_{\mathrm{Bj}}, Q^2) \;\rightarrow\; \sigma_{\mathrm{tot}}^{\gamma^* p}(\tau = Q^2/Q_s^2(x_{\mathrm{Bj}}))$$

$$\text{for } x_{\mathrm{Bj}} \lesssim 0.01$$

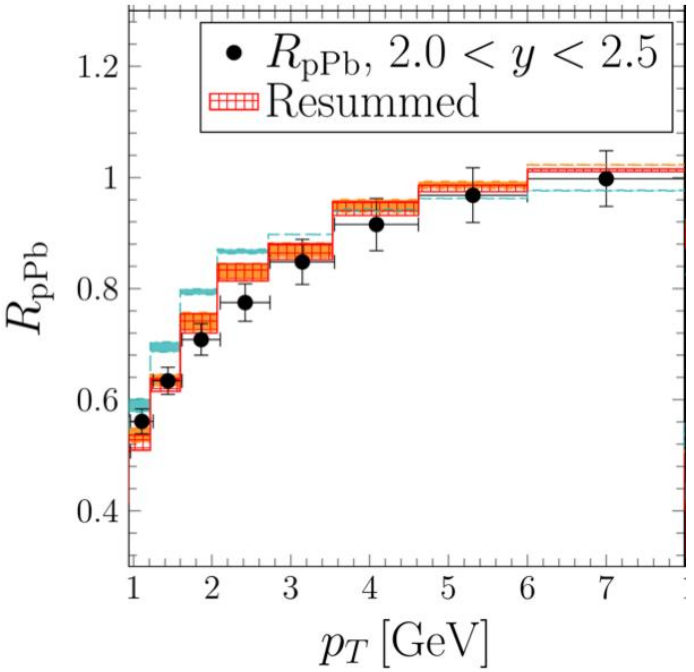
Stasto, Golec-Biernat, Kwiecinski, arXiv:hep-ph/0007192;

- Dihadron suppression at RHIC



STAR, PRL 129 (2022) 092501

- RpPb



Y. Shi, L. Wang, S. Y. Wei and B. W. Xiao, PRL 128 (2022), 202302.
LHCb data: Phys. Rev. Lett. 128, 142004 (2022).

Roadmap

I Determining the dipole

What do existing data constrain about N(r, b, x)?

II Probes in p-p/A and e-p/A

Which observables can test the small-x description?

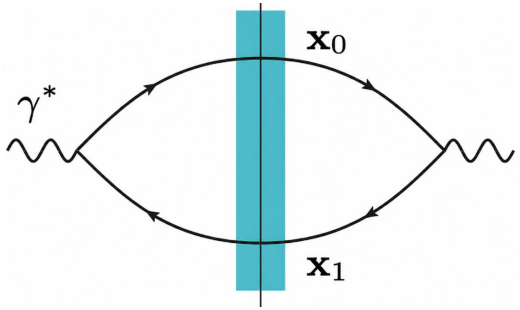
III Heavy-ion collisions

How do small-x gluon density constraints inform the initial state?

"Can one small-x gluon picture describe ep, eA, pA, and AA collisions?"

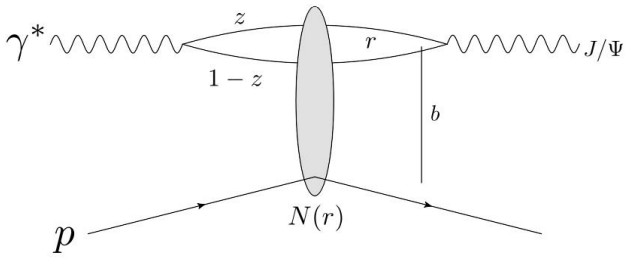
Global Extraction of the Universal Dipole Amplitude from an Unbiased Initial Condition

Universal Dipole Amplitude



$$\sigma_{T,L}^{\gamma^* p}(x,Q^2) = 2\sum_f \int d^2\mathbf{b}\, d^2\mathbf{r}\, dz \left|\Psi_{T,L}^{\gamma^*\to q\bar{q}}(\mathbf{r},Q^2,z)\right|^2 N(\mathbf{r},\mathbf{b},x),$$

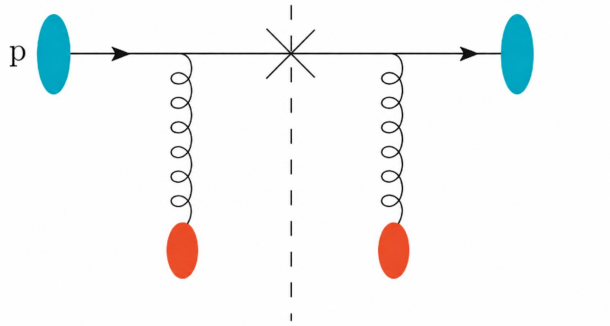
$$\sigma_{L,T}^{\gamma^* p\to\gamma^* p} \propto N(x, r_T, b)$$



$$\mathcal{A}_{T,L}^{\gamma^* p\to Vp}(x_{\mathbb{P}},Q^2,\boldsymbol{\Delta}) = 2i\int d^2\mathbf{r}\, d^2\mathbf{b}\, \frac{dz}{4\pi}\, e^{-i\left[\mathbf{b}-\left(\frac{1}{2}-z\right)\mathbf{r}\right]\cdot\boldsymbol{\Delta}} \left[\Psi_V^*\Psi_\gamma\right]_{T,L}(Q^2,\mathbf{r},z)\, N(\mathbf{r},\mathbf{b},x_{\mathbb{P}})$$

$$\frac{d\sigma^{\gamma^* A\to VA}}{d|t|} = \frac{1}{16\pi}\left|\langle\mathcal{A}\rangle_\Omega\right|^2$$

$$\frac{d\sigma^{\gamma^* A\to VA^*}}{d|t|} = \frac{1}{16\pi}\left[\left\langle|\mathcal{A}|^2\right\rangle_\Omega - \left|\langle\mathcal{A}\rangle_\Omega\right|^2\right]$$



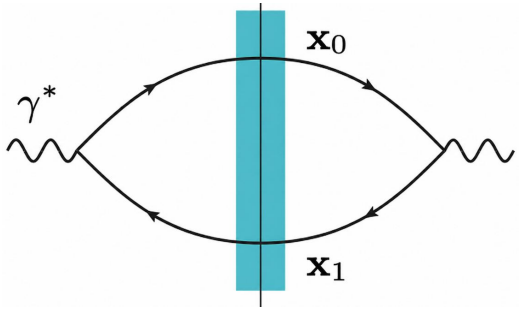
$$\frac{d\sigma^{pA\to hX}}{d^2p_\perp\, dy} = \frac{1}{(2\pi)^2}\int_{x_F}^1 \frac{dz}{z^2}\left[\sum_q x_1 q(x_1,\mu^2)\,\tilde{S}_F\left(\frac{p_\perp}{z},x_2\right) D_{h/q}(z,\mu^2)\right.$$

$$\left. + x_1 g(x_1,\mu^2)\,\tilde{S}_A\left(\frac{p_\perp}{z},x_2\right) D_{h/g}(z,\mu^2)\right]$$

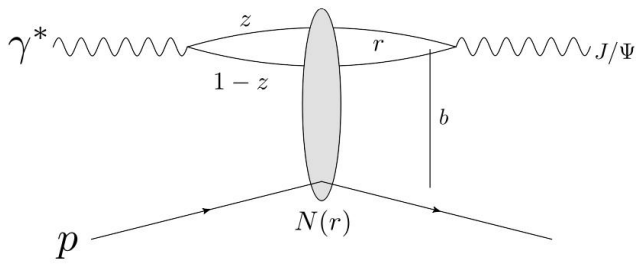
$$\sigma^{pp\to h+X} \propto S(x,k_T)$$

$$S(k_T,Y) = \int d^2\mathbf{r} e^{i\mathbf{k}_T\cdot\mathbf{r}}\left[1-N(r,Y)\right].$$

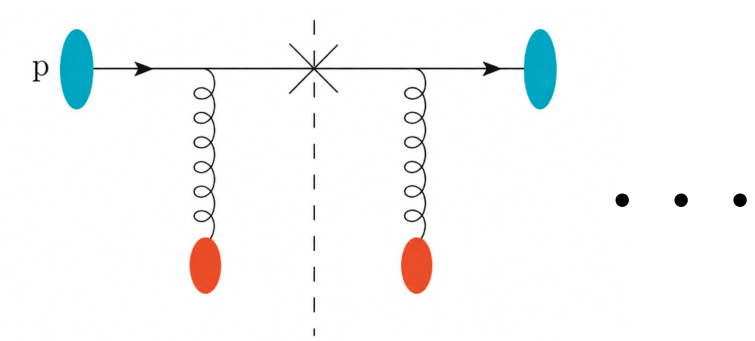
Universal Dipole Amplitude



$$\sigma_{L,T}^{\gamma^* p \to \gamma^* p} \propto N(x, r_T, b)$$



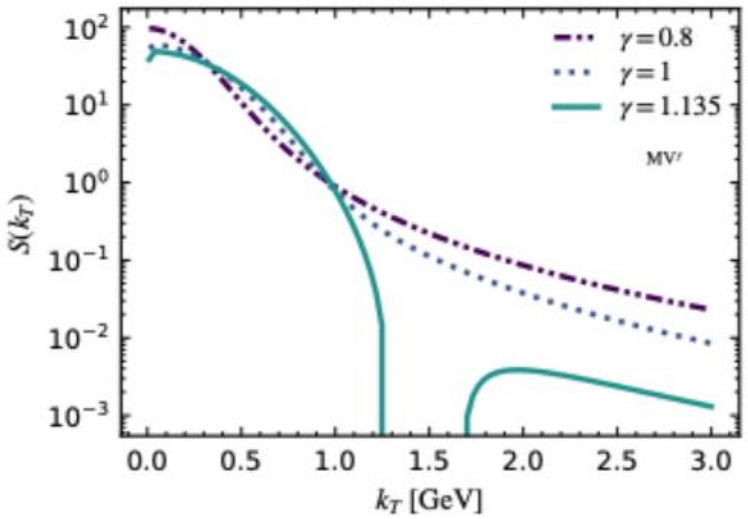
$$\sigma_{T,L}^{\gamma^* p \to V p} \propto \left| N(x, r_T, b) \right|^2$$

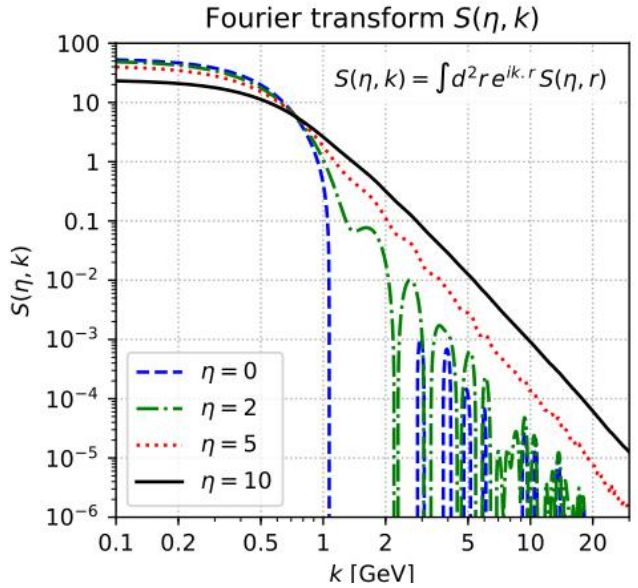


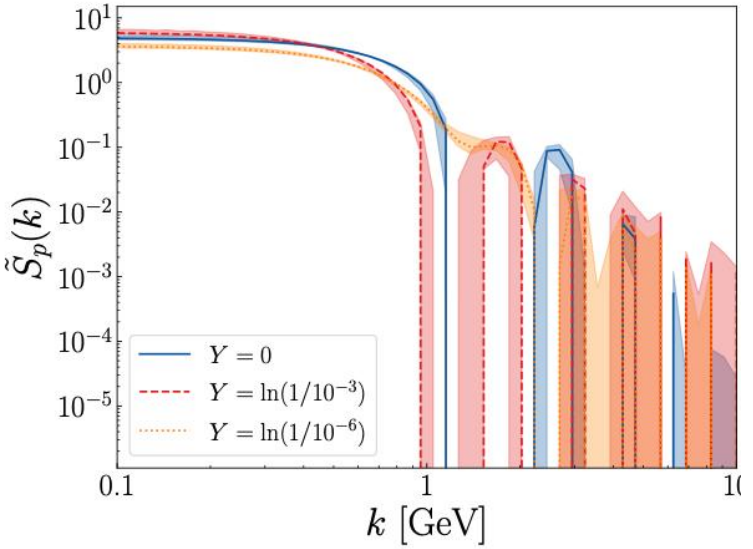
$$\sigma^{pp \to h+X} \propto S(x, k_T)$$

- The small-x dipole amplitude is **universal** across several processes.
- The dipole amplitude should be **positive** in both coordinate and momentum space.

Problem for ~ 20 Years







$$N_{\mathrm{MV}}(r) = 1 - \exp\left[-\frac{(r^2 Q_{s0}^2)^\gamma}{4} \ln\left(\frac{1}{r\Lambda} + e_c \cdot \mathrm{e}\right)\right]$$

- Using MV-type parametrization, no existing MV-type fit achieves the ep data while keeping the S(kT) positive.

References	χ^2/d.o.f. ($\sigma_r^{\mathrm{total}}$)	χ^2/d.o.f. ($\sigma_r^{c\bar{c}}$)	χ^2/d.o.f. (J/ψ)	$S(k_T) > 0$?	Universal N?
Albacete *et al.* [Albacete:2010sy] (LO BK + LO Impact Factor)	~ 1.1	~ 1.3	N/A	No	No
B. Ducloué *et al.* [Ducloue:2019jmy] (ciBK + LO Impact Factor)	~ 1.0	N/A	N/A	No	No
Casuga *et al.* [Casuga:2025etc] (KCBK + NLO Impact Factor, Bayesian)	~ 1.2	~ 2.7	N/A	No	Yes
Casuga *et al.* [Casuga:2026xxt] (NLO+NLL BK + NLO Impact Factor, Bayesian)	~ 1.2	~ 2.4	N/A	No	Yes
This work, without "$S(k_T) > 0$" constraint (ciBK + LO Impact Factor, PINN)	0.868	1.160	0.691	No	Yes
This work, with "$S(k_T) > 0$" constraint (ciBK + LO Impact Factor, PINN)	**1.48**	**1.56**	**1.13**	**Yes**	**Yes**

AAMQS: EPJC, 771 (2011), 1705;
B. Duclouw, E. Iancu, G. Soyez and D. N. Triantafyllopoulos,PLB 803 (2020), 135305
C. Casuga, H. Hanninen and H. Mantysaari, PRD 112 (2025), 034003;

Problem for ~ 20 Years

"Finding a functional form which has a **positive-definite Fourier transform** while preserving the good agreement with the HERA data would be extremely interesting, as this could open the way towards a unified description (via the dipole factorisation) of inclusive DIS and of particle production in "dilute-dense" (ep,eA, pp, pA) collisions. However, this seems to be also very challenging. At this level, it is legitimate to ask whether this difficulty solely reflects our inability to **imagine versatile enough parametrisations for the initial condition**, or it rather points towards a deeper problem"

B. Duclouw, E. Iancu, G. Soyez and D. N. Triantafyllopoulos,PLB 803 (2020), 135305

Physics-Informed Global Extraction of the Universal Dipole Amplitude

Loss function in the PINN $\mathcal{L}(\theta, \mathbf{p}) = w_1\mathcal{L}_{\text{ciBK}} + w_2\mathcal{L}_{\text{data}} + w_3\mathcal{L}_{\text{phy}},$

- $\mathcal{L}_{\text{ciBK}}$: for ciBK evolution
- $\mathcal{L}_{\text{data}}$: quantifies agreement with data
- $\mathcal{L}_{\text{phy}}$: additional physical constraints

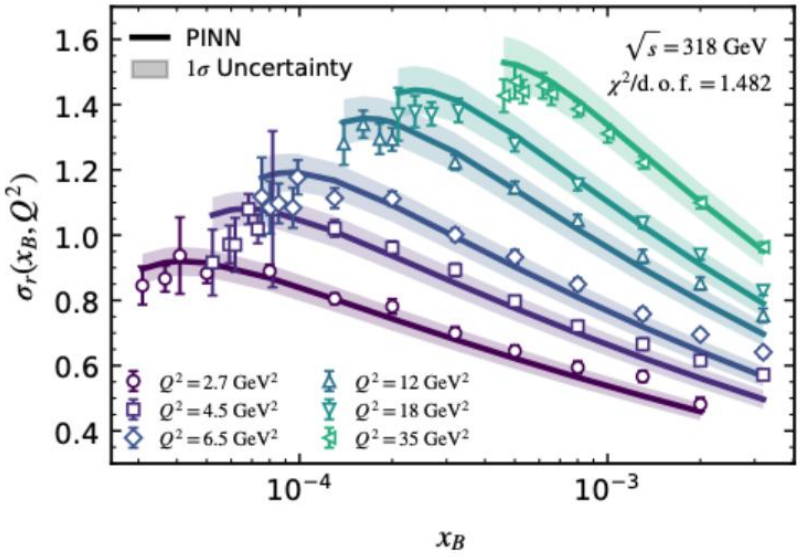
Extract **Universal, Unbiased** Dipole Amplitude

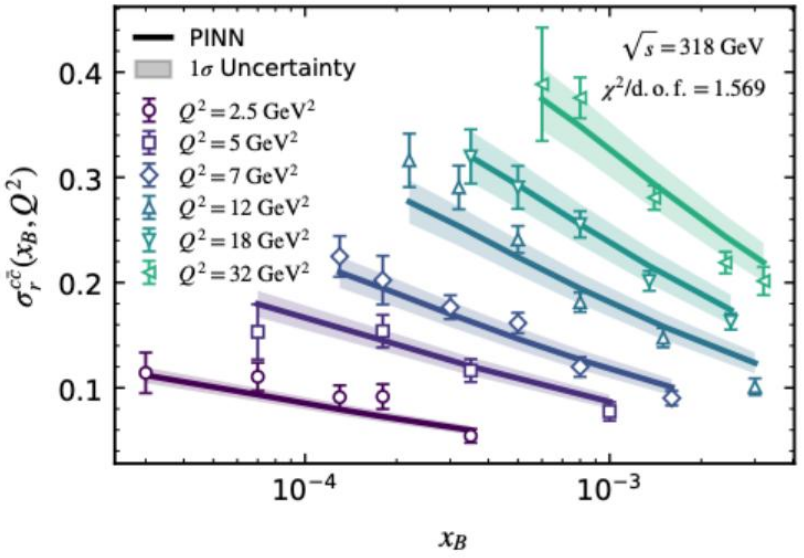
- PINN extracts a **universal** amplitude constrained by the **collinear improves BK** (ciBK).
- **Without imposing** a priori MV-type parametrization of the initial condition.

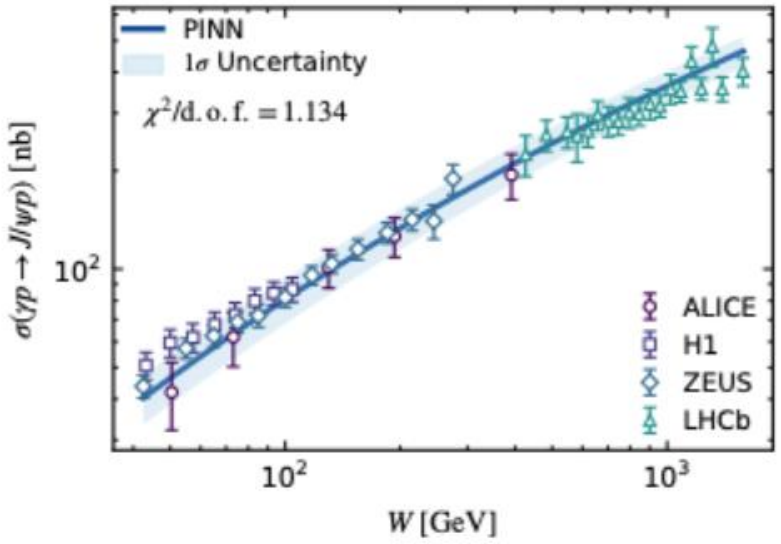
S. W. Dai, F. P. Li, L. G. Pang, G. Y. Qin, S. Y. Wei, H. Z. Zhang and W. Zhao, arXiv:2603.08008.

The dipole amplitude is available: **https://doi.org/10.5281/zenodo.18826120**

Physics-Informed Global Extraction of the Universal Dipole Amplitude







- PINN extracts an **universal** amplitude constrained by the **CiBK.**
- **Simultaneously** constrained by reduced **total** and **charm quark** DIS cross sections, exclusive **J/ψ data.**

S. W. Dai, F. P. Li, L. G. Pang, G. Y. Qin, S. Y. Wei, H. Z. Zhang and W. Zhao, arXiv:2603.08008.

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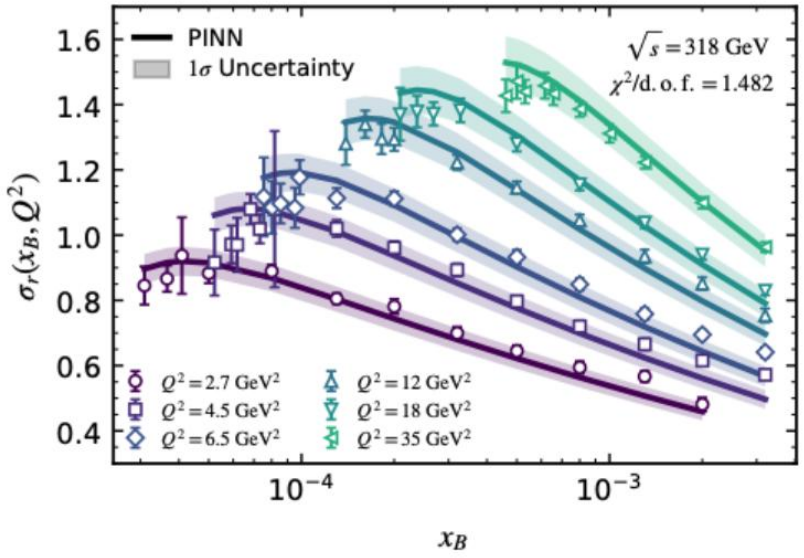
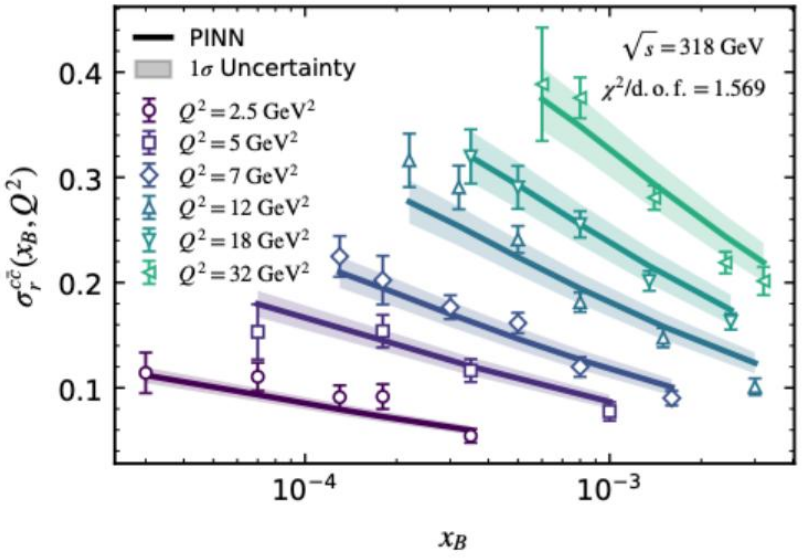
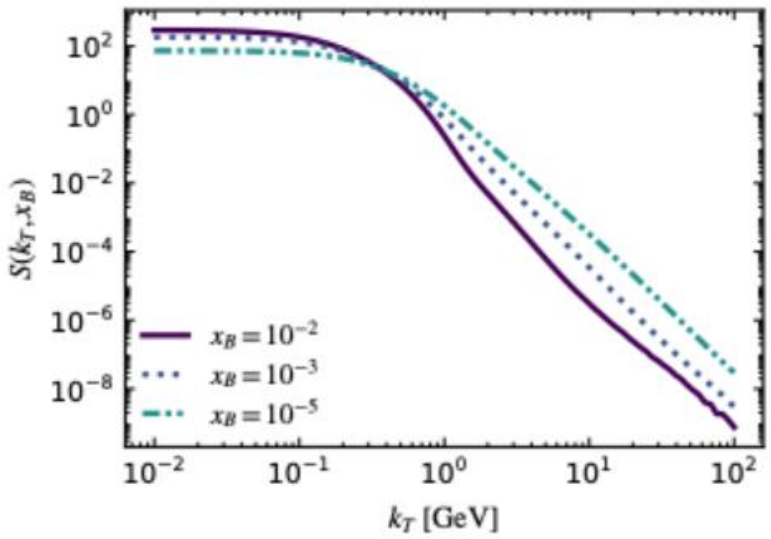
Physics-Informed Global Extraction of the Universal Dipole Amplitude





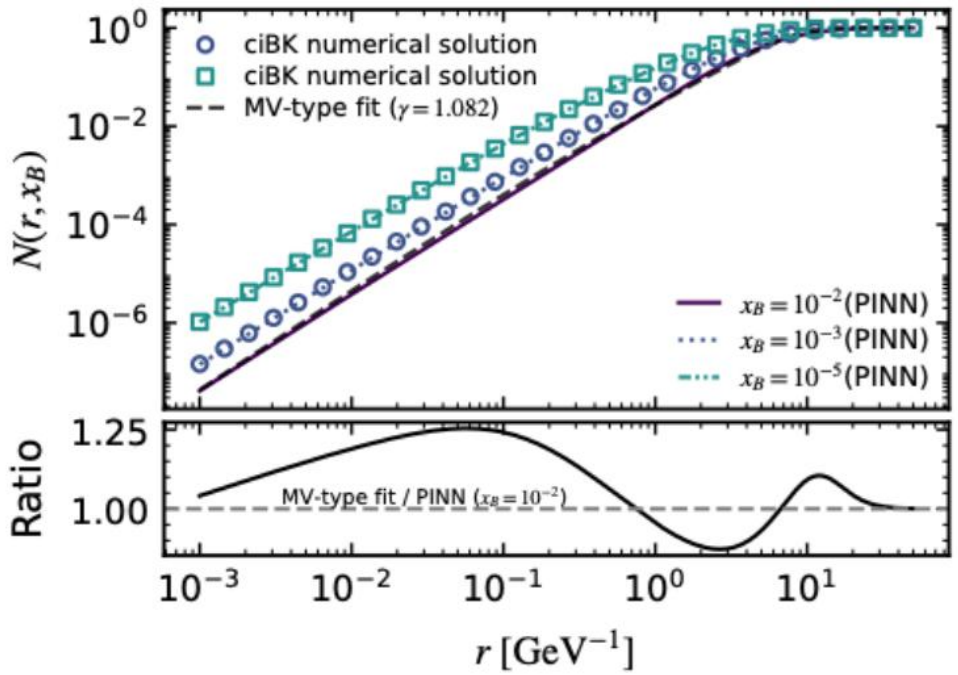


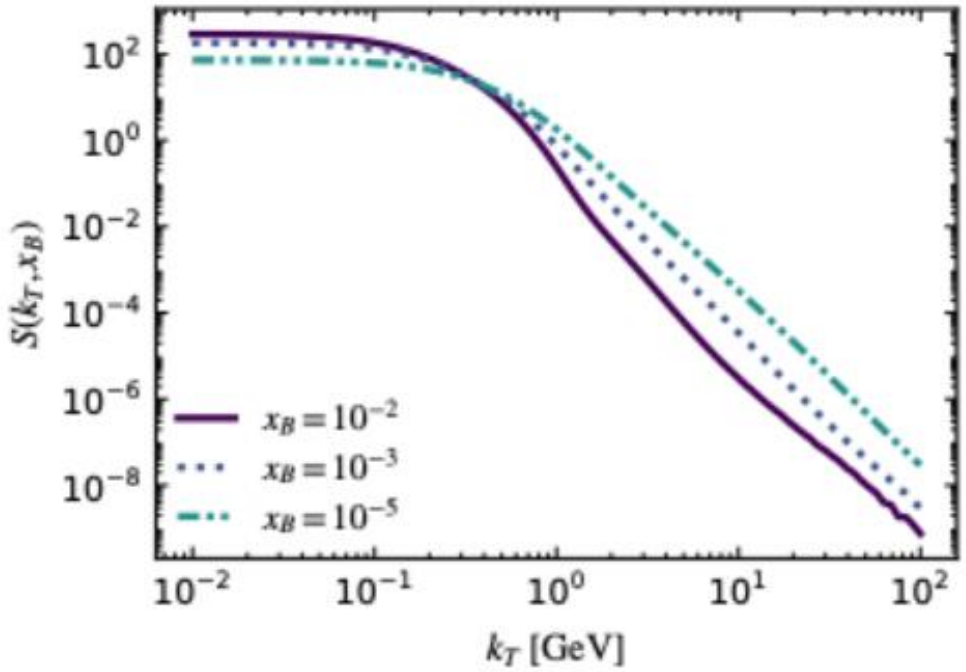
- PINN extracts an **universal** amplitude constrained by the **CiBK.**
- **Simultaneously** constrained by reduced **total** and **charm quark** DIS cross sections, exclusive **J/ψ data.**
- Keep the **positivity for the momentum-space amplitude.**

S. W. Dai, F. P. Li, L. G. Pang, G. Y. Qin, S. Y. Wei, H. Z. Zhang and W. Zhao, arXiv:2603.08008.

The dipole amplitude is available: **https://doi.org/10.5281/zenodo.18826120**

Dipole Amplitude of Proton





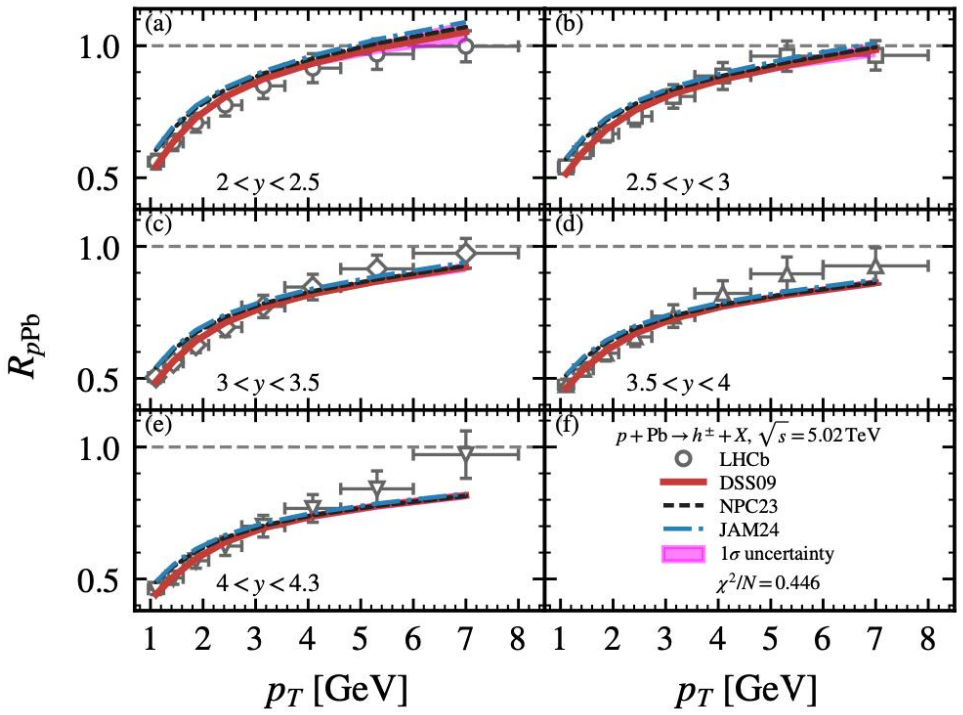
$$\text{MV-type: } N_{\text{MV}}(r) = 1 - \exp\left[-\frac{(r^2 Q_{s0}^2)^\gamma}{4} \ln\left(\frac{1}{r\Lambda} + e_c \cdot \mathrm{e}\right)\right]$$

- The MV-type fit deviates from the PINN result by up to 25% at r ~ 10^{-2}–10^{-1} GeV^{-1}: **proton needs more flexibility than MV.**

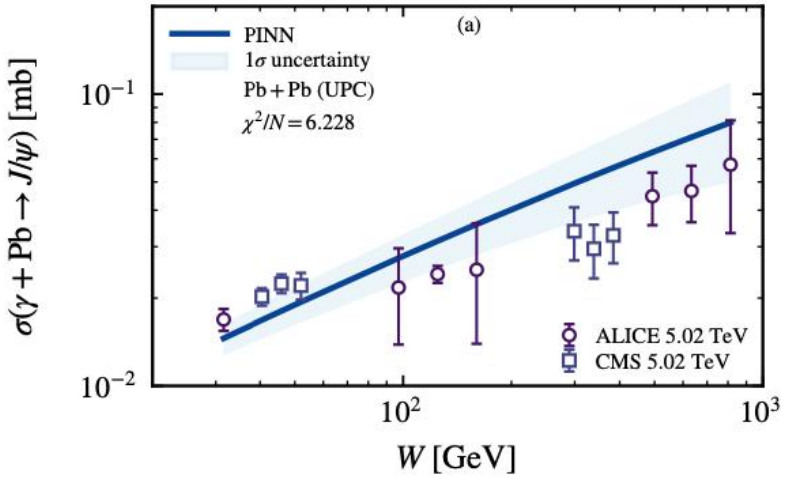
S. W. Dai, F. P. Li, L. G. Pang, G. Y. Qin, S. Y. Wei, H. Z. Zhang and W. Zhao, arXiv:2603.08008.

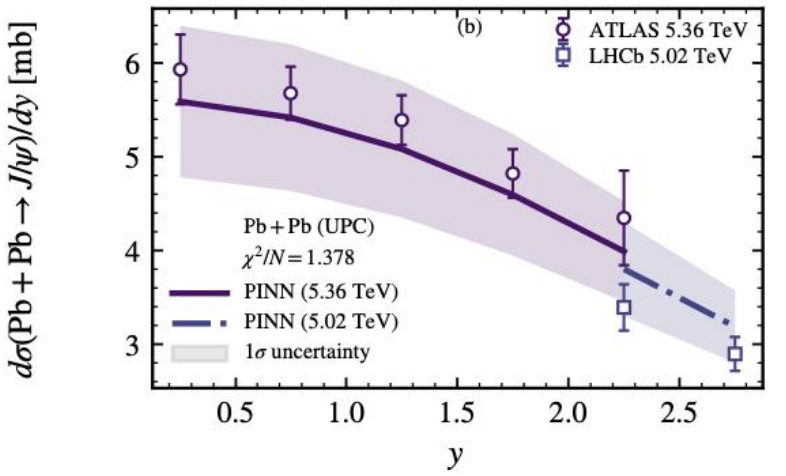
The dipole amplitude is available: https://doi.org/10.5281/zenodo.18826120

Global Extraction of the Nuclear Dipole Amplitude



$$R_{pA} = \frac{1}{A}\frac{\mathrm{d}^3\sigma^{pA}/\mathrm{d}y\,\mathrm{d}^2p_T}{\mathrm{d}^3\sigma^{pp}/\mathrm{d}y\,\mathrm{d}^2p_T}$$





- RpPb greatly **suppresses the uncertainty** from the FF and PDF.
- The only nuclear parameter, S⊥Pb, **enters both RpPb and J/ψ**
- There is some **tension** between the RpPb and J/ψ data. (EMD correction for J/ψ data?)

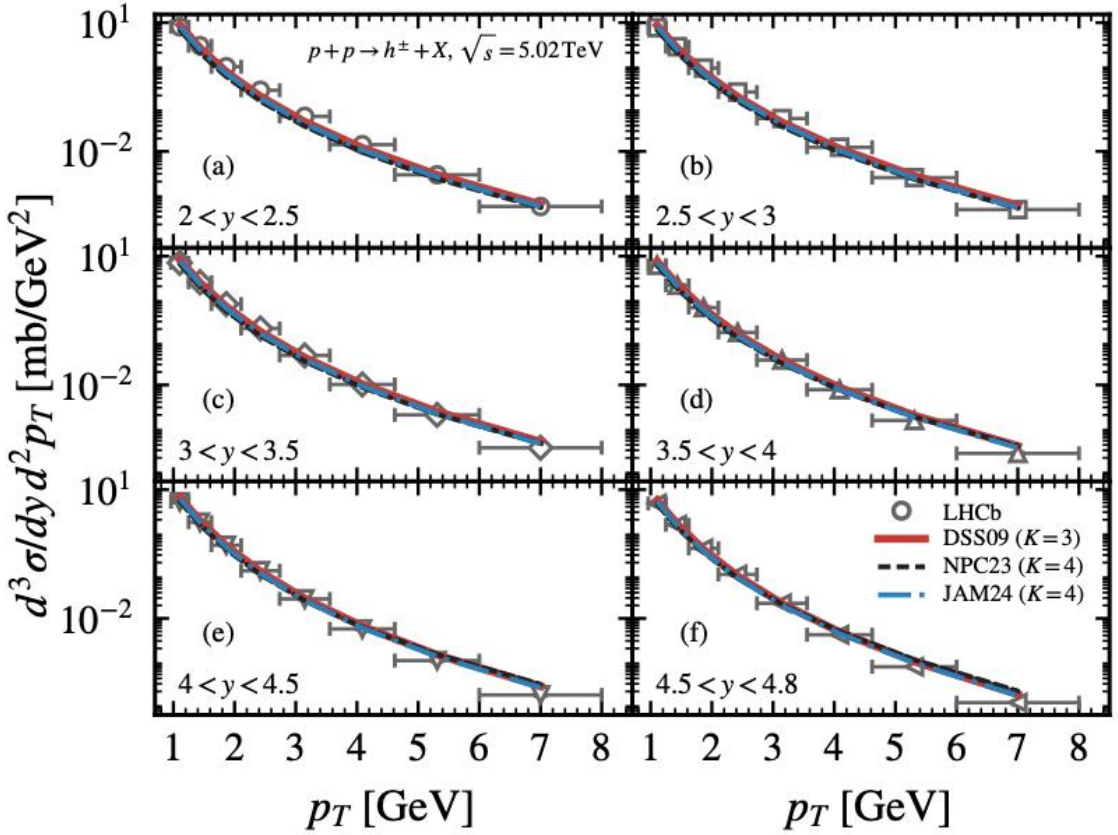
LHCb data: Phys. Rev. Lett. 128, 142004 (2022).

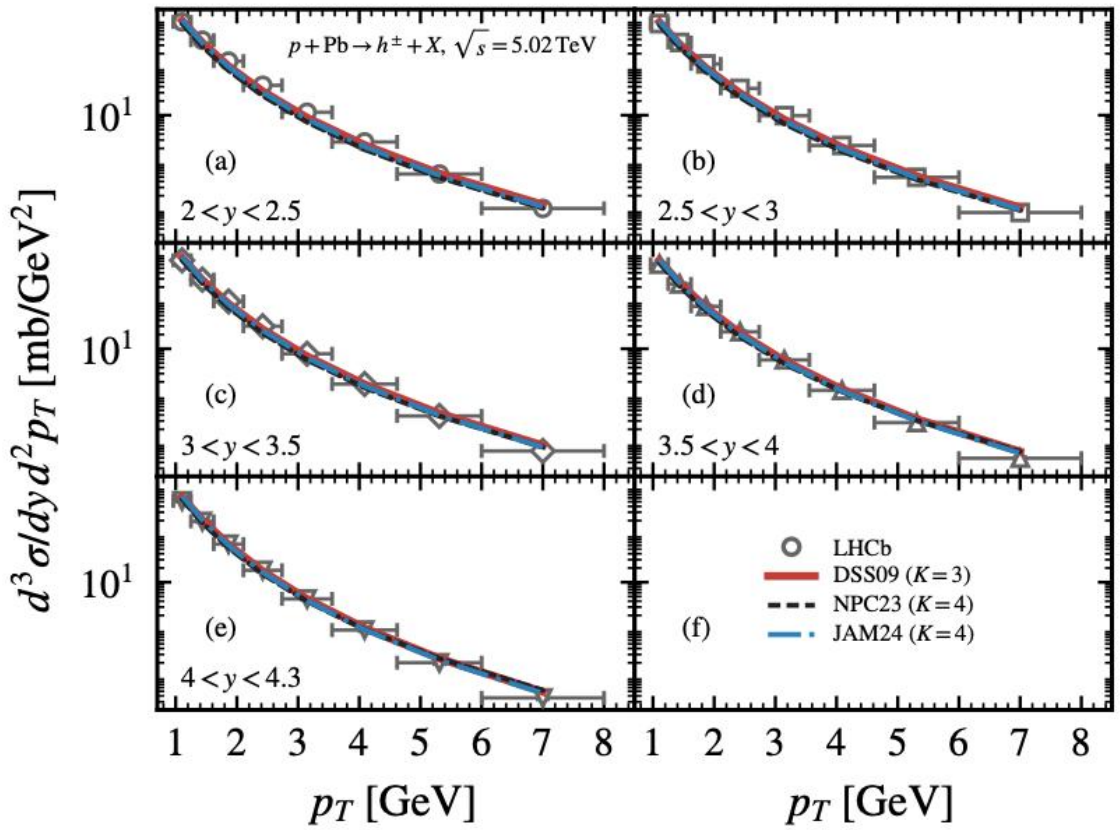
S. W. Dai, F. P. Li, H.w.Duan L. G. Pang, G. Y. Qin, S. Y. Wei, H. Z. Zhang and W. Zhao, arXiv:2603.08008; 2607.27603.

The dipole amplitude is available:

https://doi.org/10.5281/zenodo.18826120; http://dx.doi.org/10.5281/zenodo.21719195

Spectra for pp and pPb at the LHC





- Different K factor for different fragmentation functions.
- Same K factor for pp and pPb at 5.02 TeV.

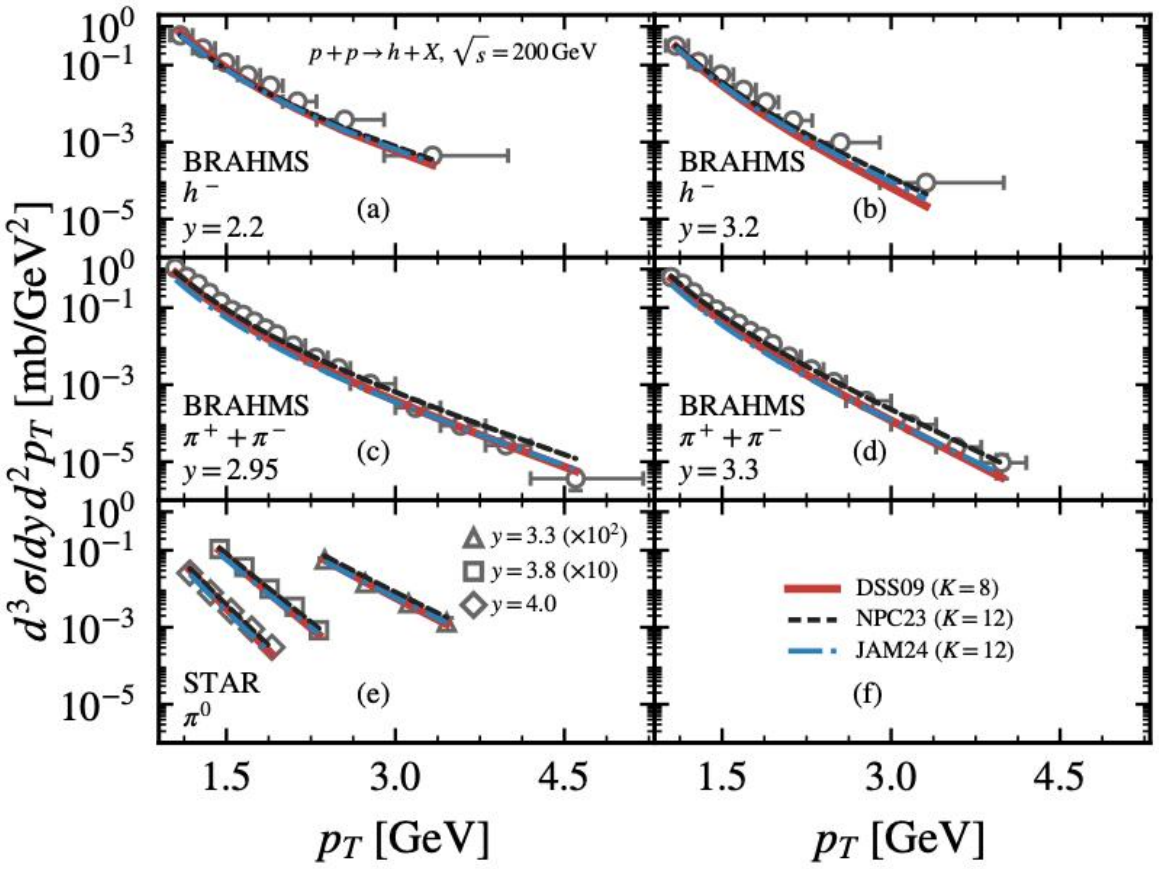
LHCb data: Phys. Rev. Lett. 128, 142004 (2022).

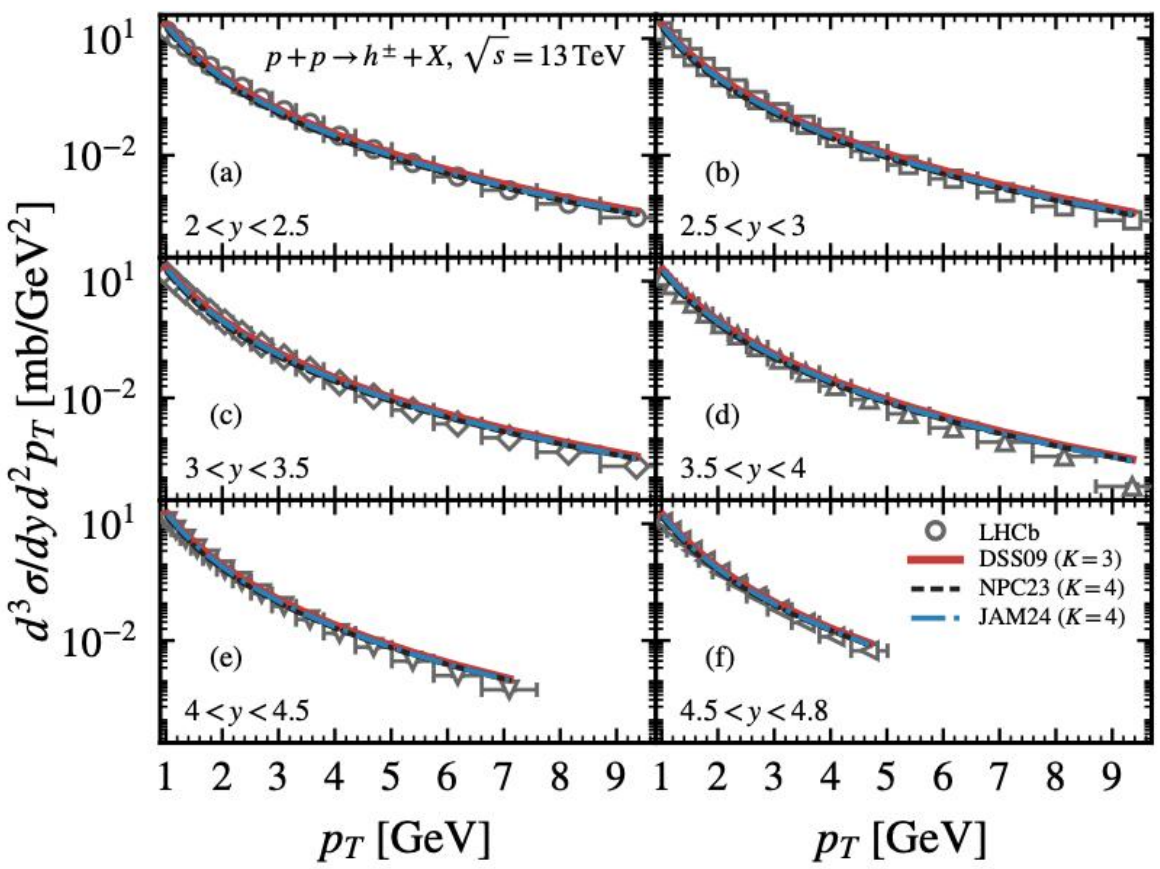
S. W. Dai, F. P. Li, H.w.Duan L. G. Pang, G. Y. Qin, S. Y. Wei, H. Z. Zhang and W. Zhao, arXiv:2603.08008; 2607.27603.

The dipole amplitude is available:

https://doi.org/10.5281/zenodo.18826120; http://dx.doi.org/10.5281/zenodo.21719195

spectra for pp at the LHC and RHIC

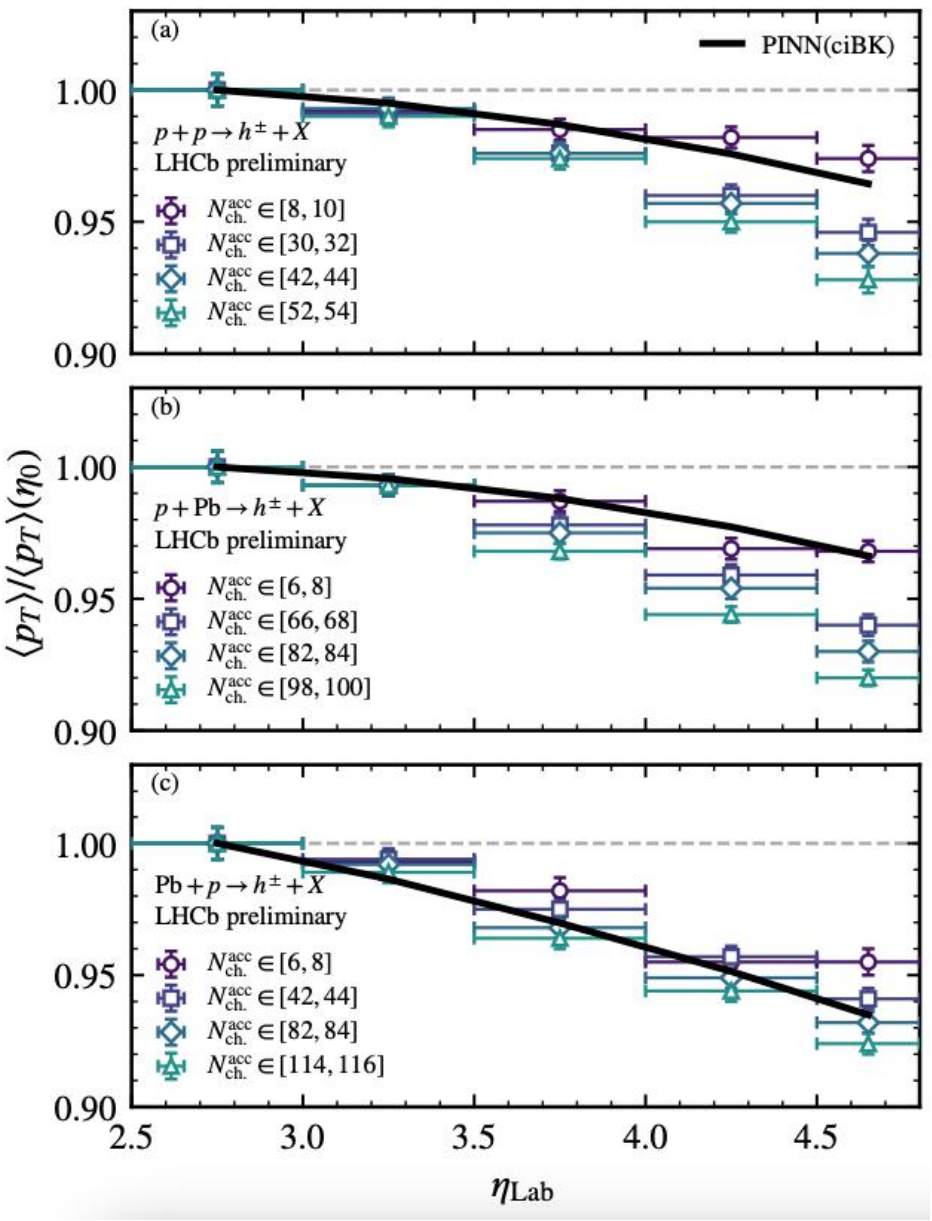




- At LO calculations, it needs different K factor at LHC and RHIC energies.

LHCb data: JHEP 01, 166 (2022); STAR data: Phys. Rev. Lett. 97, 152302; BRAHMS data: Phys. Rev. Lett. 98, 252001; 93, 242303
S. W. Dai, F. P. Li, H.w.Duan L. G. Pang, G. Y. Qin, S. Y. Wei, H. Z. Zhang and W. Zhao, arXiv:2603.08008; 2607.27603.
The dipole amplitude is available:
https://doi.org/10.5281/zenodo.18826120; http://dx.doi.org/10.5281/zenodo.21719195

Mean p_T ratio v.s. η



- Our CGC calculation of Mean p_T ratio v.s. η is **consistent** with the LHCb measurments at low Nch.
- Deviation at high Nch likely reflects final-state effects, while **low Nch results in CGC dominance.**

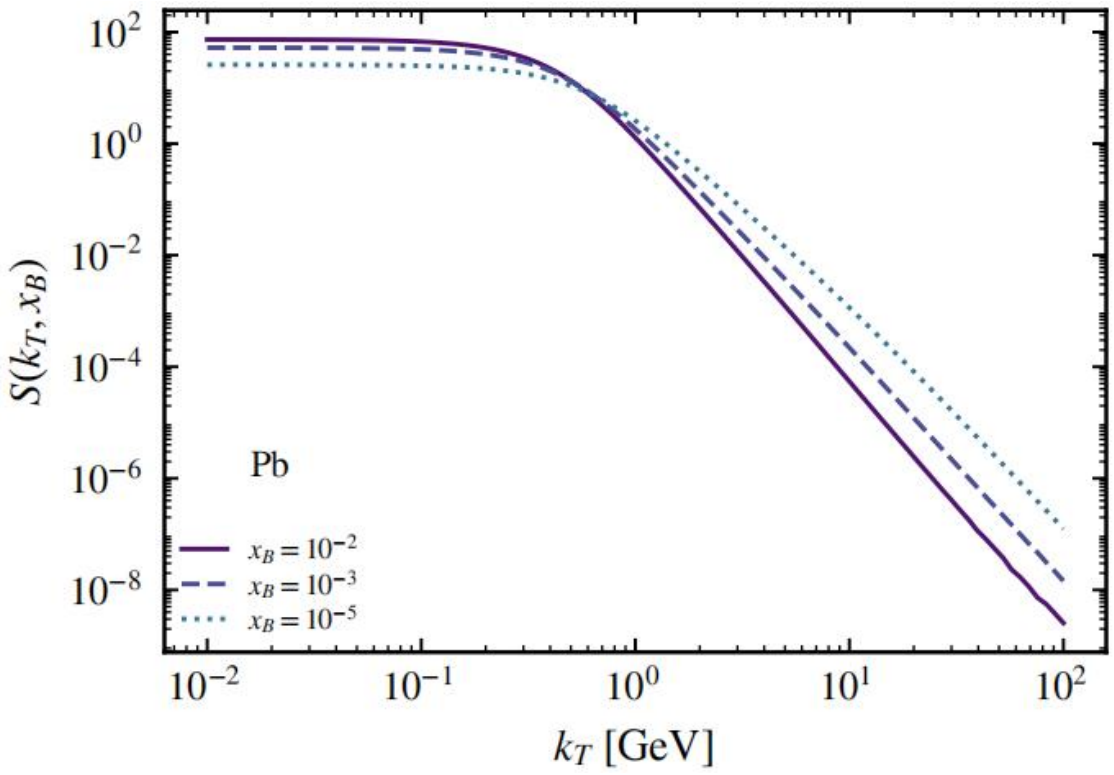
LHCb data: arXiv:2607.26783

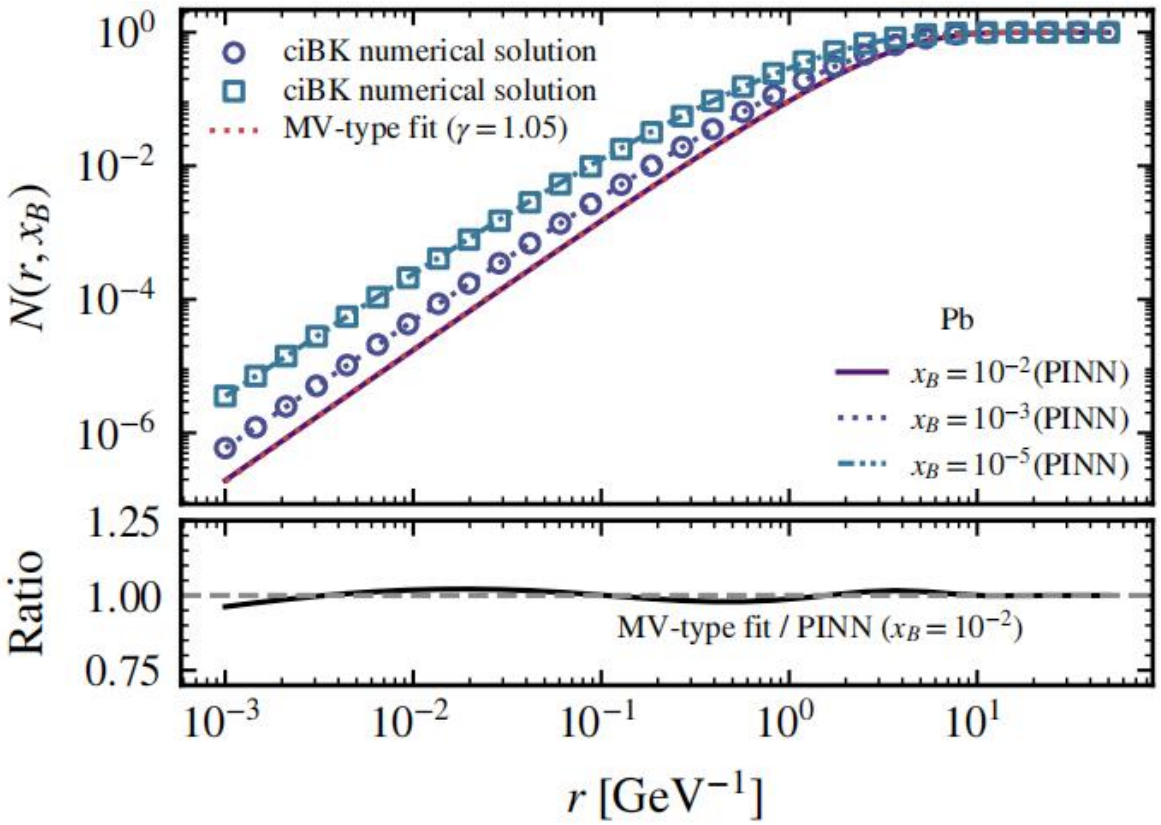
S. W. Dai, F. P. Li, H.w.Duan L. G. Pang, G. Y. Qin, S. Y. Wei, H. Z. Zhang and W. Zhao, arXiv:2603.08008; 2607.27603.

The dipole amplitude is available:

https://doi.org/10.5281/zenodo.18826120;
http://dx.doi.org/10.5281/zenodo.21719195

Dipole Amplitude of Pb





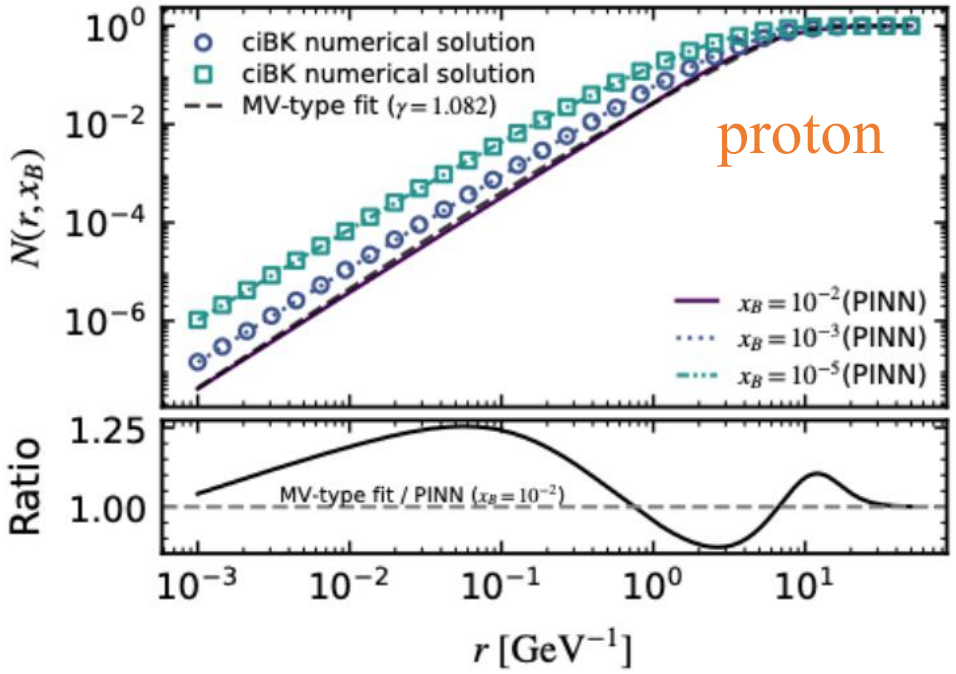
- The dipole amplitude for Pb is well behaved: S(k_T) remains positive over the entire k_T range.

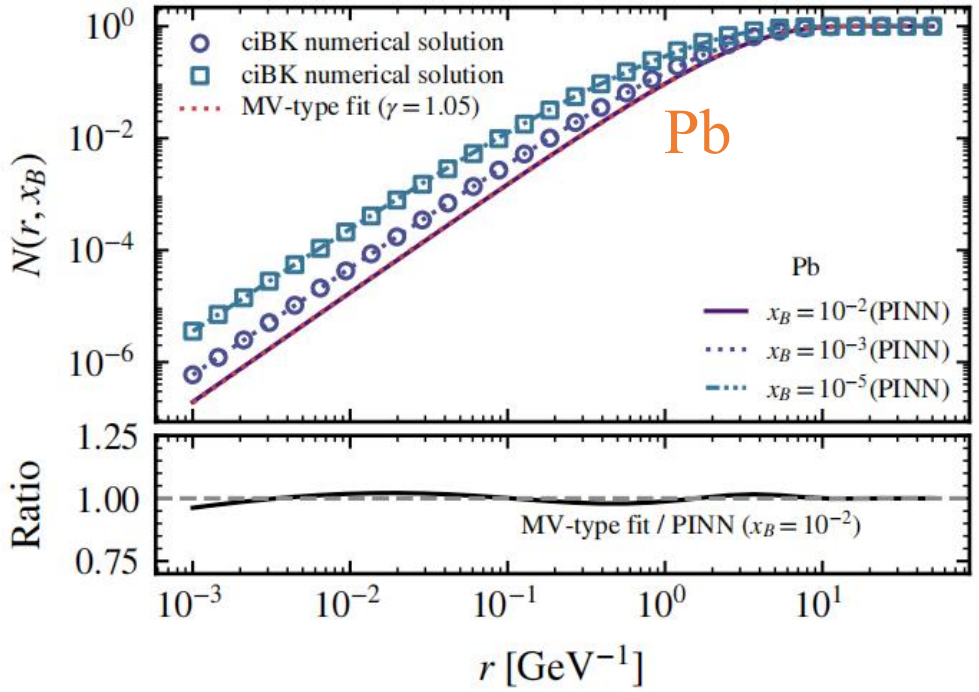
S. W. Dai, F. P. Li, H.w.Duan L. G. Pang, G. Y. Qin, S. Y. Wei, H. Z. Zhang and W. Zhao, arXiv:2603.08008; 2607.27603.

The dipole amplitude is available:

https://doi.org/10.5281/zenodo.18826120; http://dx.doi.org/10.5281/zenodo.21719195

MV-type fit





- The MV-type fit works better for Pb than for proton. (**MV model is designed for large nuclei.)**
- From the **unbiased** global fit, we obtain a ratio of $\frac{Q_{s0,Pb}^2}{Q_{s0,p}^2} \sim 3.17.$

S. W. Dai, F. P. Li, H.w.Duan L. G. Pang, G. Y. Qin, S. Y. Wei, H. Z. Zhang and W. Zhao, arXiv:2603.08008; 2607.27603.

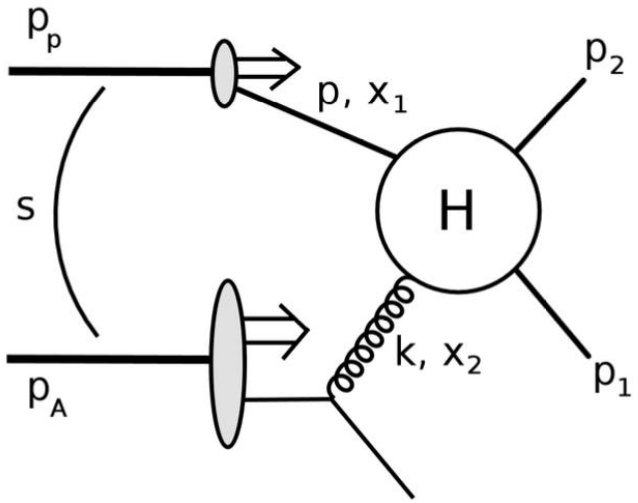
The dipole amplitude is available:

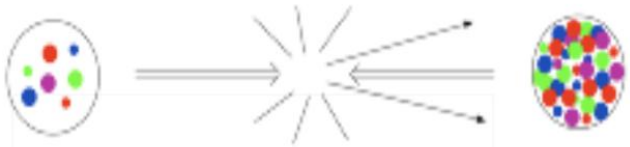
https://doi.org/10.5281/zenodo.18826120; http://dx.doi.org/10.5281/zenodo.21719195

Forward di-hadron correlations in proton-nucleus collisions

Forward di-hadrons productions (dilute-dense)

- large-x projectile (proton) on small-x target (proton or nucleus)





$$\langle k_{1t} \rangle \sim \Lambda_{QCD} \qquad \langle k_{2t} \rangle \sim Q_s(x_2)$$

$$Q_s(x_2) \gg \Lambda_{QCD}$$

so-called "dilute-dense" kinematics

Incoming partons' energy fractions:

$$x_1 = \frac{1}{\sqrt{s}} \left(|p_{1t}| e^{y_1} + |p_{2t}| e^{y_2} \right) \xrightarrow{y_1, y_2 \gg 0} x_1 \sim 1$$

$$x_2 = \frac{1}{\sqrt{s}} \left(|p_{1t}| e^{-y_1} + |p_{2t}| e^{-y_2} \right) \qquad\qquad x_2 \ll 1$$

CM (2007)

Gluon's transverse momentum (p_{1t}, p_{2t} imbalance):

$$|k_t|^2 = |p_{1t} + p_{2t}|^2 = |p_{1t}|^2 + |p_{2t}|^2 + 2|p_{1t}||p_{2t}| \cos \Delta\phi$$

prediction: modification of the k_t distribution in p+Pb vs p+p collisions

Borrow from Cyrille Marquet's slide (2020).

Color Glass Condensate Calculations

- We use the improved TMD factorization (ITMD), which resums the $\left(\frac{Q_s}{k_T}\right)^n$ and $\left(\frac{k_T}{P_T}\right)^n$.

$$\frac{d\sigma^{pA\to\text{dijets}+X}}{dy_1 dy_2 d^2p_{1t} d^2p_{2t}} = \frac{\alpha_s^2}{(x_1 x_2 s)^2} \sum_{a,c,d} x_1 f_{a/p}(x_1,\mu^2) \sum_i H^{(i)}_{ag\to cd} \mathcal{F}^{(i)}_{ag}(x_2,k_t) \frac{1}{1+\delta_{cd}},$$

$f_{a/p}$: Collinear pdf for the large-x projectile (dilute part)

$F^i_{ag}(x,k_t)$: Several gluon TMDs for small-x target (dense part)

$H^i_{ag\to cd}$: The associated hard matrix elements.

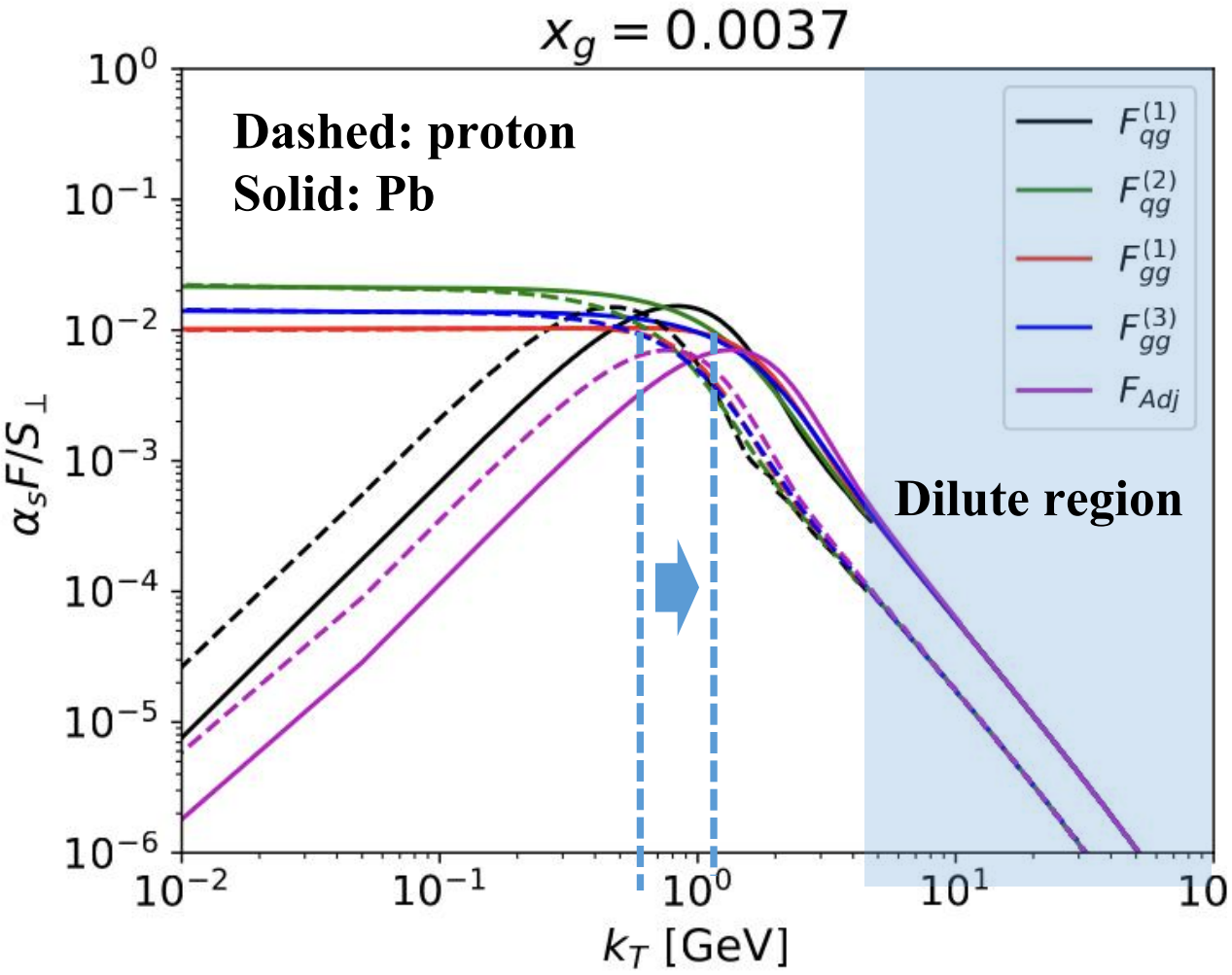
$$\frac{\mathrm{d}\sigma^{qA\to qgX}}{\mathrm{d}P.S.} = \mathcal{F}^{(1)}_{qg}(x_A,\boldsymbol{k})\mathcal{H}^{(1)}_{qg\to qg} + \mathcal{F}^{(2)}_{qg}(x_A,\boldsymbol{k})\mathcal{H}^{(2)}_{qg\to qg} \quad (2)$$

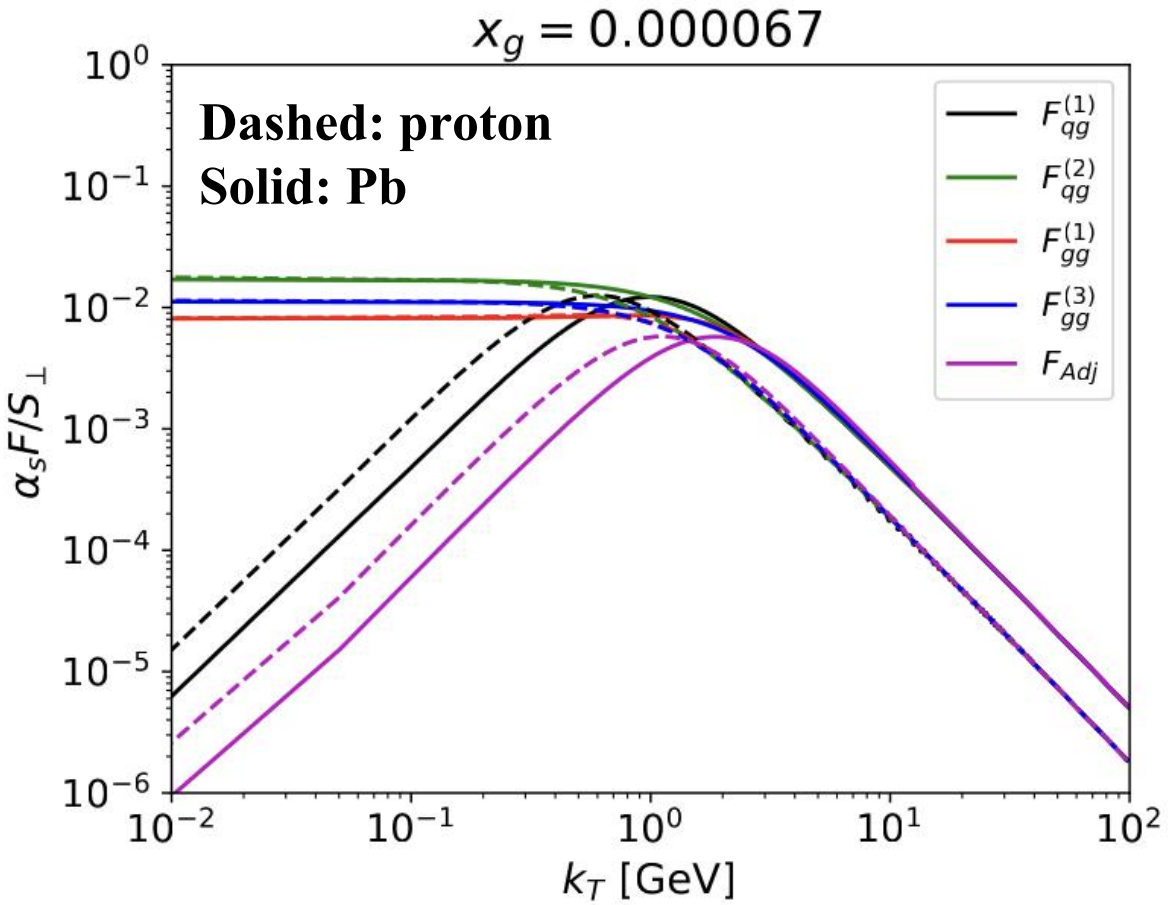
$$\frac{\mathrm{d}\sigma^{gA\to q\bar{q}X}}{\mathrm{d}P.S.} = \mathcal{F}^{(1)}_{gg}(x_A,\boldsymbol{k})\mathcal{H}^{(1)}_{gg\to q\bar{q}} + \mathcal{F}^{(2)}_{gg}(x_A,\boldsymbol{k})\mathcal{H}^{(2)}_{gg\to q\bar{q}} \quad (3)$$

$$\frac{\mathrm{d}\sigma^{gA\to ggX}}{\mathrm{d}P.S.} = (\mathcal{F}^{(1)}_{gg}(x_A,\boldsymbol{k}) + \mathcal{F}^{(3)}_{gg}(x_A,\boldsymbol{k}))\mathcal{H}^{(1)}_{gg\to gg} + (\mathcal{F}^{(2)}_{gg}(x_A,\boldsymbol{k}) + \mathcal{F}^{(3)}_{gg}(x_A,\boldsymbol{k}))\mathcal{H}^{(2)}_{gg\to gg} \quad (4)$$

P. Kotko, K. Kutak, C. Marquet, E. Petreska, S. Sapeta and A. van Hameren, JHEP09(2015)106.

Small-x gluon TMDs





- TMDs move to right from proton to nucleus.
- TMDs move to right at smaller x_g.

P. Caucal, Z. B.Kang, P. Korcyl, F. Salazar, B. Schenke, T.Stebel, R.Venugopalan and W.Zhao, [arXiv:2512.21466].

Soft gluon resummation

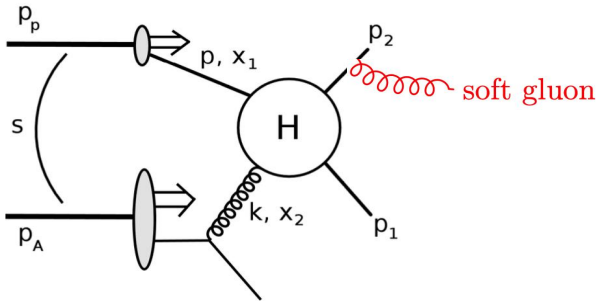
A. H. Mueller, B. W. Xiao and F. Yuan, PhysRevLett.110.082301.
P. Sun, C. P. Yuan, and F. Yuan, Phys. Rev. Lett. 113 23, (2014)
S. y. Wei, Phys. Lett. B 817, 136356 (2021)

$$\frac{d\sigma}{d^2p_{T1}d^2p_{T2}} \propto \int \frac{d^2b_\perp}{(2\pi)^2} e^{-i\vec{q}_T\cdot\vec{b}_\perp} f(x_1) \otimes F(x_2, b_\perp) \otimes H \otimes e^{-S_{\rm Sudakov}}$$

- Sudakov factors : $S_{\rm Sud}^{a+b\to c+d}(b_\perp) = \sum_{i=a,b,c,d} S_p^i(b_\perp) + \boldsymbol{C_{np}} \times \sum_{i=a,c,d} S_{np}^i(b_\perp),$

$$S_p^{q+g\to q+g}(Q, b_\perp) = \int_{\mu_b^2}^{Q^2} \frac{d\mu^2}{\mu^2}\left[2(C_F + C_A)\frac{\alpha_s}{2\pi}\ln\left(\frac{Q^2}{\mu^2}\right) - \left(\frac{3}{2}C_F + C_A\beta_0\right)\frac{\alpha_s}{\pi}\right],$$

$$S_p^{g+g\to g+g}(Q, b_\perp) = \int_{\mu_b^2}^{Q^2} \frac{d\mu^2}{\mu^2}\left[4C_A\frac{\alpha_s}{2\pi}\ln\left(\frac{Q^2}{\mu^2}\right) - 3C_A\beta_0\frac{\alpha_s}{\pi}\right].$$



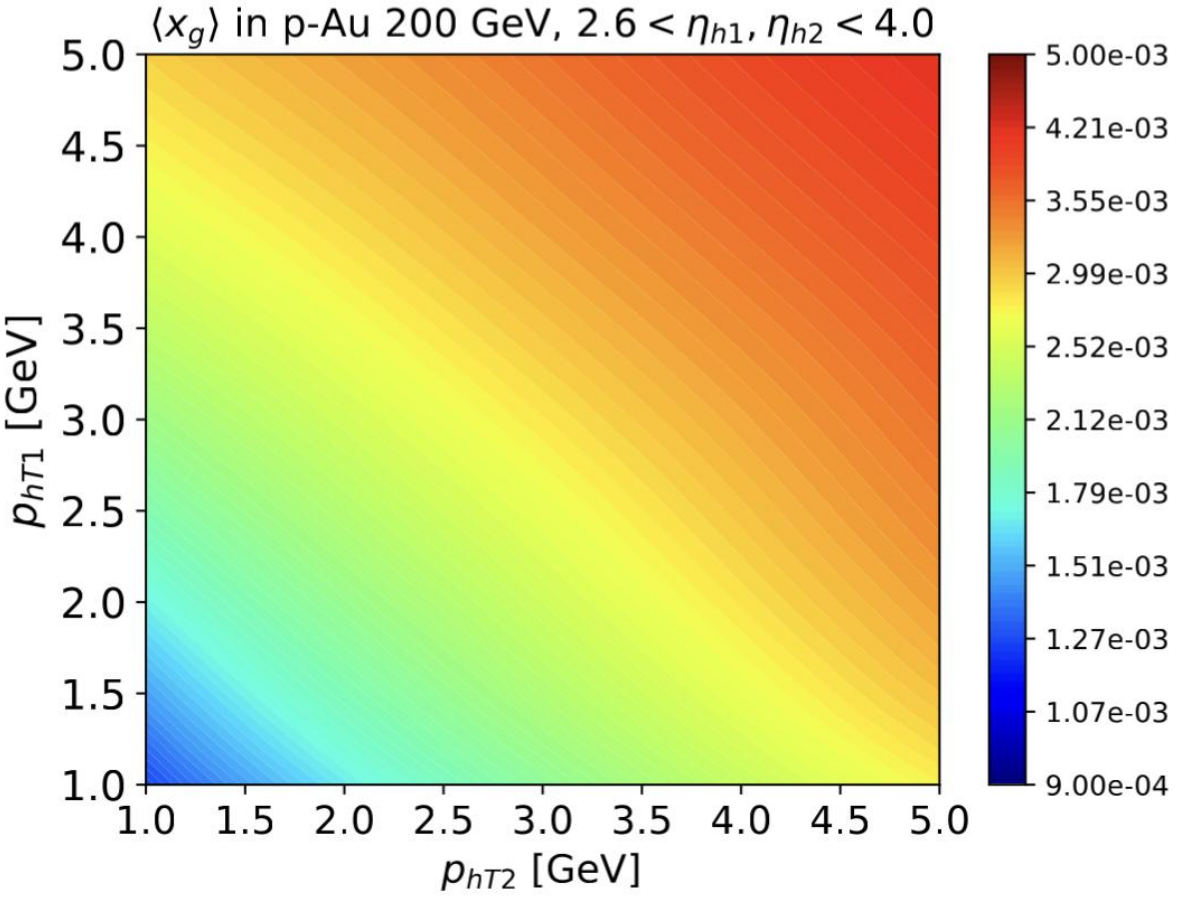
$$S_{np}^{q+g\to q+g}(Q, b_\perp) = \left(2 + \frac{C_A}{C_F}\right)\frac{g_1}{2}b_\perp^2 + \left(2 + \frac{C_A}{C_F}\right)\frac{g_2}{2}\ln\frac{Q}{Q_0}\ln\frac{b_\perp}{b_*},$$

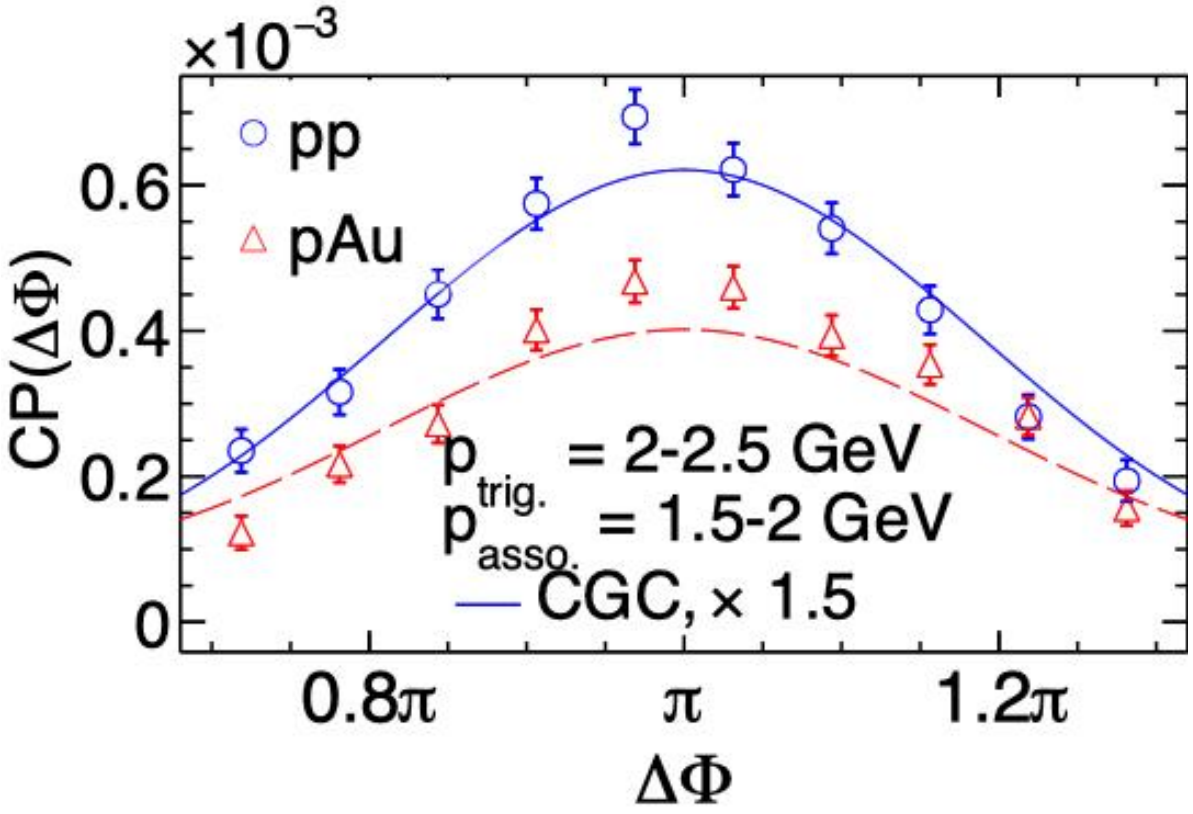
$$S_{np}^{g+g\to g+g}(Q, b_\perp) = \frac{3C_A}{C_F}\frac{g_1}{2}b_\perp^2 + \frac{3C_A}{C_F}\frac{g_2}{2}\ln\frac{Q}{Q_0}\ln\frac{b_\perp}{b_*}.$$

Using the b^*-prescription: $\beta_0 = (11 - 2n_f/3)/12$, $\mu_b = 2e^{-\gamma_E}/b_*$, and $b_* = b_\perp/\sqrt{1 + b_\perp^2/b_{\rm max}^2}$.

$\boldsymbol{C_{np}}$ as the tunable parameter (fixed by pp).

Dihadron Correlations in Forward pp and pA collisions

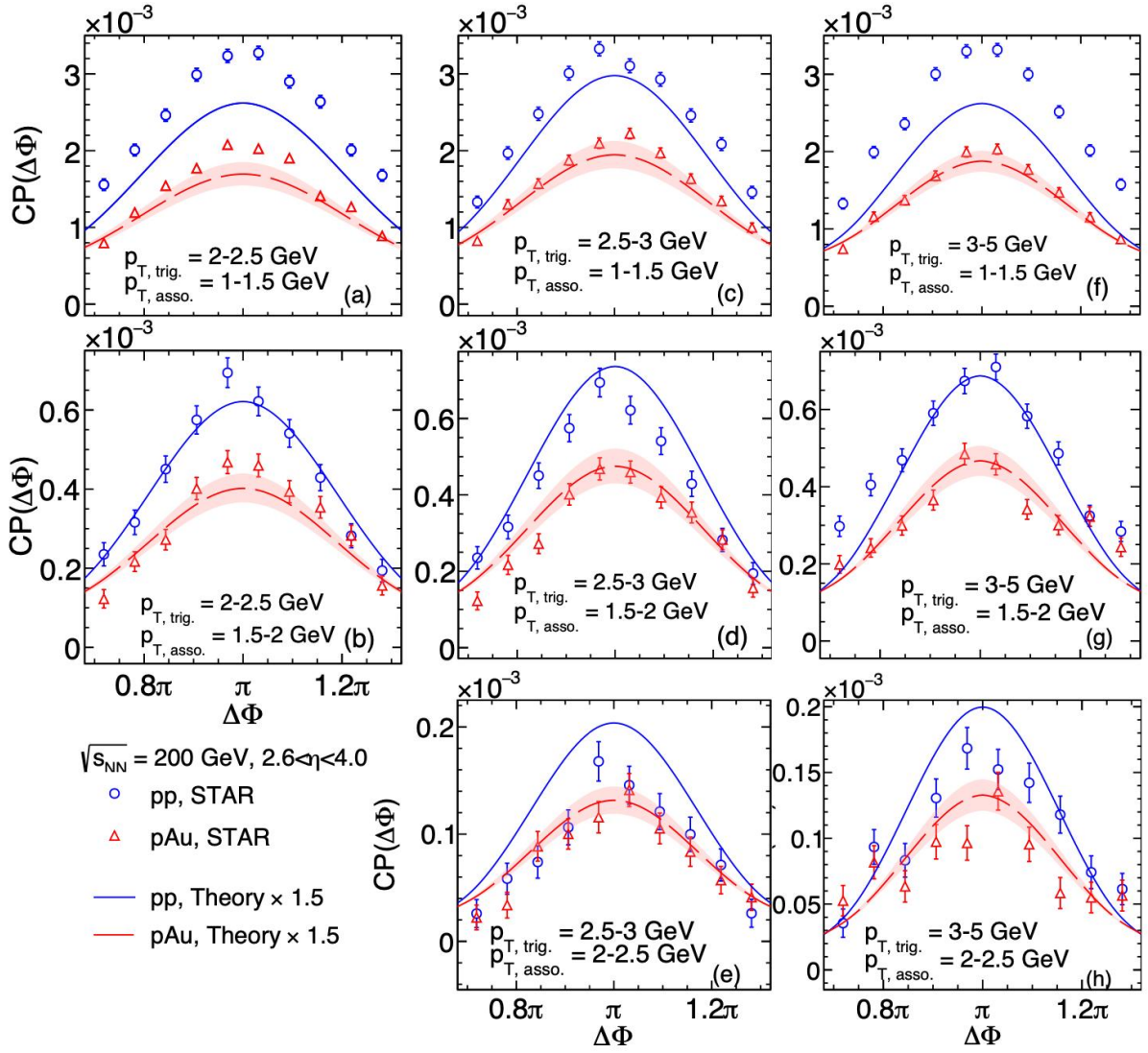




STAR data: PhysRevLett.129.092501
P. Caucal, Z. B.Kang, P. Korcyl, F. Salazar, B. Schenke, T.Stebel, R.Venugopalan and W.Zhao, [arXiv:2512.21466].

- < x_g > probed by di-hadron at STAR is small.
- CGC model reasonably describes STAR data; **pAu suppressed relative to pp.**

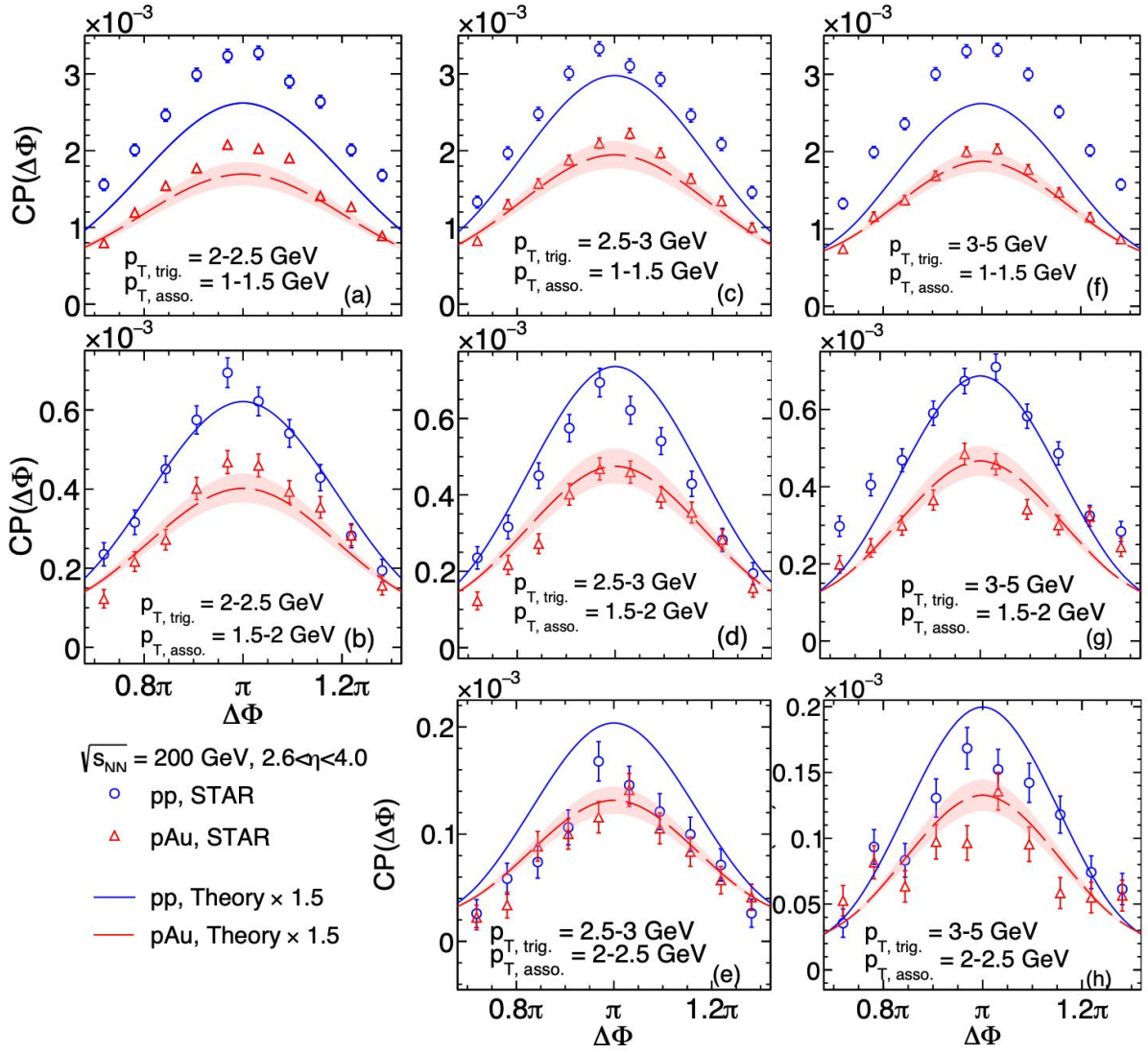
Dihadron Correlations in Forward collisions



- Overall, it's good;
- Need an **additional normalization factor**. (There are uncertainties from FF).
- The lowest $p_{T,asso}$ row is less well described.

P. Caucal, Z. B.Kang, P. Korcyl, F. Salazar, B. Schenke, T.Stebel, R.Venugopalan and W.Zhao, [arXiv:2512.21466].
STAR data: PhysRevLett.129.092501

Dihadron Correlations in Forward collisions



- Overall, it's good;
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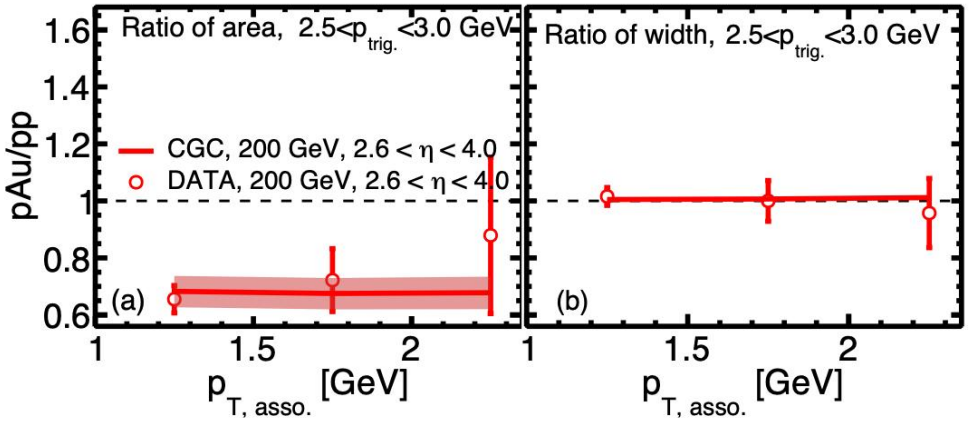


- CGC predicts very **weak p_T dependence**.
- The width ratio is very **close to 1, width is dominated by the Sudakov factor.**

P. Caucal, Z. B.Kang, P. Korcyl, F. Salazar, B. Schenke, T.Stebel, R.Venugopalan and W.Zhao, [arXiv:2512.21466].
STAR data: PhysRevLett.129.092501

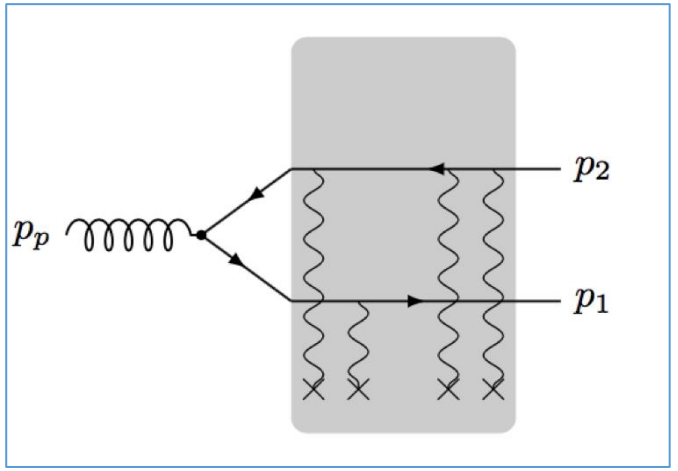
Heavy Flavour

Color Glass Condensate for Heavy Flavour

$$\frac{\mathrm{d}\sigma^{pA\to Q\bar{Q}X}}{\mathrm{d}^2\boldsymbol{k_{1\perp}}\mathrm{d}^2\boldsymbol{k_{2\perp}}\mathrm{d}y_1\mathrm{d}y_2} = x_p g(x_p,\mu^2)\int \frac{\mathrm{d}^2\boldsymbol{x}_\perp \mathrm{d}^2\boldsymbol{x}'_\perp \mathrm{d}^2\boldsymbol{y}_\perp \mathrm{d}^2\boldsymbol{y}'_\perp}{(2\pi)^6} e^{-i\boldsymbol{k_{1\perp}}\cdot(\boldsymbol{x}_\perp-\boldsymbol{x}'_\perp)} e^{-i\boldsymbol{k_{2\perp}}\cdot(\boldsymbol{y}_\perp-\boldsymbol{y}'_\perp)}$$
$$\times \psi^{g\to Q\bar{Q}}(\boldsymbol{x}_\perp-\boldsymbol{y}_\perp)\psi^{g\to Q\bar{Q},\dagger}(\boldsymbol{x}'_\perp-\boldsymbol{y}'_\perp)\left[S^{(4)}_{q\bar{q}q\bar{q}}(\boldsymbol{x}_\perp,\boldsymbol{y}_\perp,\boldsymbol{x}'_\perp,\boldsymbol{y}'_\perp;x_A)+S^{(2)}_{gg}(z\boldsymbol{x}_\perp+(1-z)\boldsymbol{y}_\perp,z\boldsymbol{x}'_\perp+(1-z)\boldsymbol{y}'_\perp;x_A)\right.$$
$$\left.-S^{(3)}(\boldsymbol{x}_\perp,z\boldsymbol{x}'_\perp+(1-z)\boldsymbol{y}'_\perp,\boldsymbol{y}_\perp;x_A)-S^{(3)}(\boldsymbol{y}'_\perp,z\boldsymbol{x}_\perp+(1-z)\boldsymbol{y}_\perp,\boldsymbol{x}'_\perp;x_A)\right]$$

- In the large Nc limit, we can have

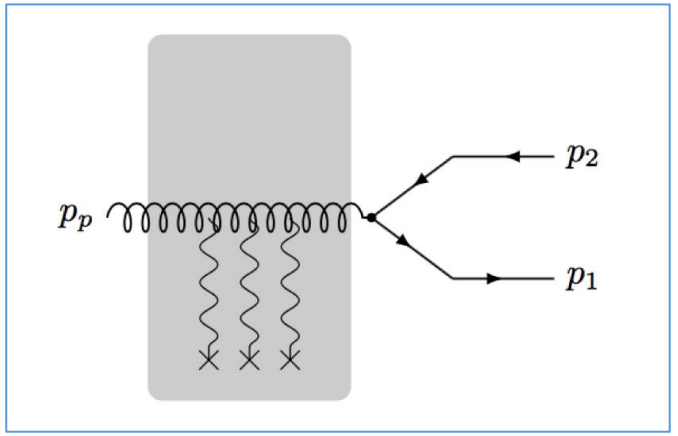
$$S^{(4)}_{q\bar{q}q\bar{q}}(\boldsymbol{x}_\perp,\boldsymbol{y}_\perp,\boldsymbol{x}'_\perp,\boldsymbol{y}'_\perp;x_A) = S^{(2)}_{q\bar{q}}(\boldsymbol{x}_\perp,\boldsymbol{x}'_\perp;x_A)S^{(2)}_{q\bar{q}}(\boldsymbol{y}'_\perp,\boldsymbol{y}_\perp;x_A)$$
$$S^{(2)}_{gg}(\boldsymbol{v}_\perp,\boldsymbol{v}'_\perp;x_A) = S^{(2)}_{q\bar{q}}(\boldsymbol{v}_\perp,\boldsymbol{v}'_\perp;x_A)S^{(2)}_{q\bar{q}}(\boldsymbol{v}'_\perp,\boldsymbol{v}_\perp;x_A)$$
$$S^{(3)}(\boldsymbol{x}_\perp,\boldsymbol{v}'_\perp,\boldsymbol{y}_\perp;x_A) = S^{(2)}_{q\bar{q}}(\boldsymbol{x}_\perp,\boldsymbol{v}'_\perp;x_A)S^{(2)}_{q\bar{q}}(\boldsymbol{v}'_\perp,\boldsymbol{y}_\perp;x_A)$$
$$S^{(3)}(\boldsymbol{y}'_\perp,\boldsymbol{v}_\perp,\boldsymbol{x}'_\perp;x_A) = S^{(2)}_{q\bar{q}}(\boldsymbol{y}'_\perp,\boldsymbol{v}_\perp;x_A)S^{(2)}_{q\bar{q}}(\boldsymbol{v}_\perp,\boldsymbol{x}'_\perp;x_A)$$



Thus

$$\frac{\mathrm{d}\sigma^{pA\to Q\bar{Q}X}}{\mathrm{d}^2\boldsymbol{k_{1\perp}}\mathrm{d}^2\boldsymbol{k_{2\perp}}\mathrm{d}y_1\mathrm{d}y_2} = S_\perp x_p g(x_p,\mu^2)\int \frac{\mathrm{d}^2\boldsymbol{l}_\perp}{(2\pi)^2}F(\boldsymbol{l}_\perp;x_A)F(\boldsymbol{K}_\perp-\boldsymbol{l}_\perp;x_A)$$
$$\int \frac{\mathrm{d}^2\boldsymbol{u}_\perp \mathrm{d}^2\boldsymbol{u}'_\perp}{(2\pi)^2}\psi^{g\to Q\bar{Q}}(\boldsymbol{u}_\perp)\psi^{g\to Q\bar{Q},\dagger}(\boldsymbol{u}'_\perp)\left[e^{-i\boldsymbol{P}_\perp\cdot\boldsymbol{u}_\perp}-e^{-i(z\boldsymbol{K}_\perp+\boldsymbol{P}_\perp-\boldsymbol{l}_\perp)\cdot\boldsymbol{u}_\perp}\right]\left[e^{i\boldsymbol{P}_\perp\cdot\boldsymbol{u}'_\perp}-e^{i(z\boldsymbol{K}_\perp+\boldsymbol{P}_\perp-\boldsymbol{l}_\perp)\cdot\boldsymbol{u}'_\perp}\right]$$

$$F(\boldsymbol{l}_\perp;x_A) = \int \frac{\mathrm{d}^2(\boldsymbol{x}_\perp-\boldsymbol{x}'_\perp)}{(2\pi)^2}e^{-i\boldsymbol{l}_\perp\cdot(\boldsymbol{x}_\perp-\boldsymbol{x}'_\perp)}S^{(2)}_{q\bar{q}}(\boldsymbol{x}_\perp,\boldsymbol{x}'_\perp;x_A)$$



F. Dominguez, C. Marquet, B. W. Xiao and F. Yuan, Phys. Rev. D 83 (2011), 105005.
C. Marquet, C. Roiesnel and P. Taels, Phys. Rev. D 97,014004 (2018).

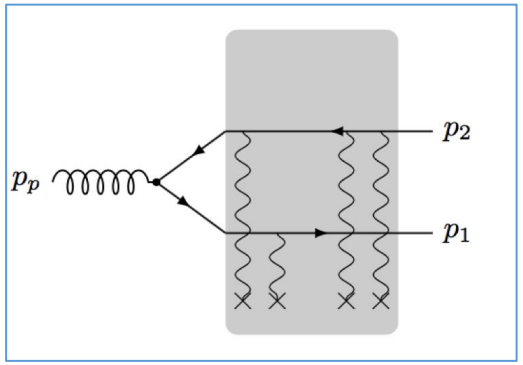
Heavy Flavour and Sudakov factor

$$\frac{\mathrm{d}\sigma^{pA\to H_1H_2X}}{\mathrm{d}^2\boldsymbol{k_{h1\perp}}\mathrm{d}^2\boldsymbol{k_{h2\perp}}\mathrm{d}y_1\mathrm{d}y_2}$$

$$= 2S_\perp \int \frac{\mathrm{d}z_{h_1}}{z_{h_1}^2} \int \frac{\mathrm{d}z_{h_2}}{z_{h_2}^2} \int \mathrm{d}^2\boldsymbol{l}_\perp \frac{[H(\boldsymbol{P}_\perp,\boldsymbol{P}_\perp) - 2H(\boldsymbol{P}_\perp + z\boldsymbol{K}_\perp - \boldsymbol{l}_\perp, \boldsymbol{P}_\perp) + H(\boldsymbol{P}_\perp + z\boldsymbol{K}_\perp - \boldsymbol{l}_\perp, \boldsymbol{P}_\perp + z\boldsymbol{K}_\perp - \boldsymbol{l}_\perp)]}{(z\boldsymbol{K}_\perp - \boldsymbol{l}_\perp)^2} \quad (315)$$

$$\times \int \frac{\mathrm{d}^2\boldsymbol{K}'_\perp}{(2\pi)^2} W(z_{h1}, z_{h2}, x_p, \boldsymbol{K}'_\perp - \boldsymbol{K}_\perp, \mu_F) (z\boldsymbol{K}'_\perp - \boldsymbol{l}_\perp)^2 F(\boldsymbol{l}_\perp; x_A) F(\boldsymbol{K}'_\perp - \boldsymbol{l}_\perp; x_A) \quad (316)$$

Unintegrated Gluon Distributions (UGD)s



where:

$$W_{(z_{h1},z_{h2},x_p,\boldsymbol{k}'_\perp-\boldsymbol{k}_\perp,\mu_F)} = \int \mathrm{d}^2\boldsymbol{b}_\perp e^{i(\boldsymbol{k}'_\perp-\boldsymbol{k}_\perp)\cdot\boldsymbol{b}_\perp} x_1 g(x_1,\mu_b^2) D_{h_1/c}(z_{h_1},\mu_b^2) D_{h_2/\bar{c}}(z_{h_2},\mu_b^2) e^{-S_{gg\to q\bar{q}}(\boldsymbol{b}_\perp,\mu_F)}$$

$$H(\boldsymbol{q_{1\perp}},\boldsymbol{q_{2\perp}}) = \int \frac{\mathrm{d}^2\boldsymbol{u}_\perp \mathrm{d}^2\boldsymbol{u}'_\perp}{(2\pi)^2} e^{-i\boldsymbol{q_{1\perp}}\cdot\boldsymbol{u}_\perp} e^{i\boldsymbol{q_{2\perp}}\cdot\boldsymbol{u}'_\perp} \psi^{g\to Q\bar{Q}}(\boldsymbol{u}_\perp) \psi^{g\to Q\bar{Q},\dagger}(\boldsymbol{u}'_\perp)$$

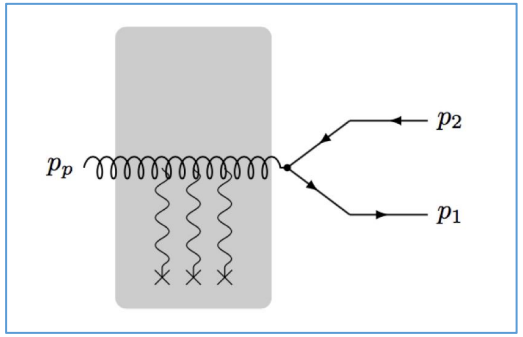
- Dead Cone effects:

$$S_{\mathrm{P}}(\boldsymbol{b},\mu^2) = \int_{\mu_b^2}^{\mu^2} \frac{\mathrm{d}\bar{\mu}^2}{\bar{\mu}^2} \frac{\alpha_s(\bar{\mu})}{2\pi} \left\{ 2C_A \ln\left(\frac{\mu^2}{\bar{\mu}^2}\right) - 2\beta_0 \right.$$

$$+ 2C_F \left[\ln\left(\frac{\mu^2}{\bar{\mu}^2}\right) - \theta(m^2-\bar{\mu}^2) \ln\left(\frac{m^2}{\bar{\mu}^2}\right) \right]$$

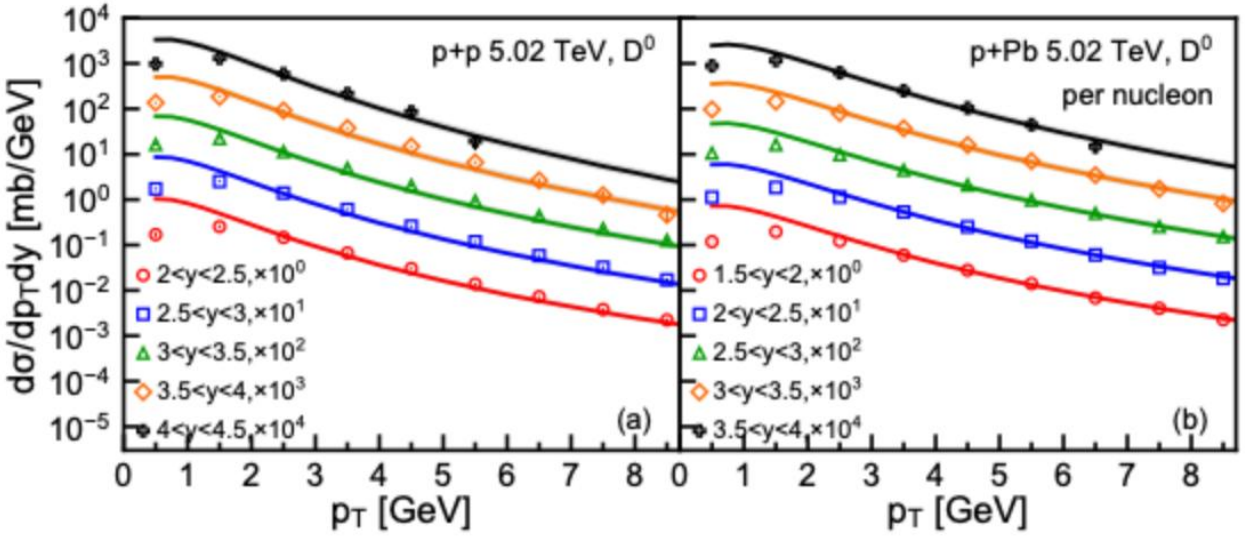
$$\left. - 2C_F \left[\frac{3}{2} - \frac{1}{2}\theta(m^2-\bar{\mu}^2) \right] \right\},$$

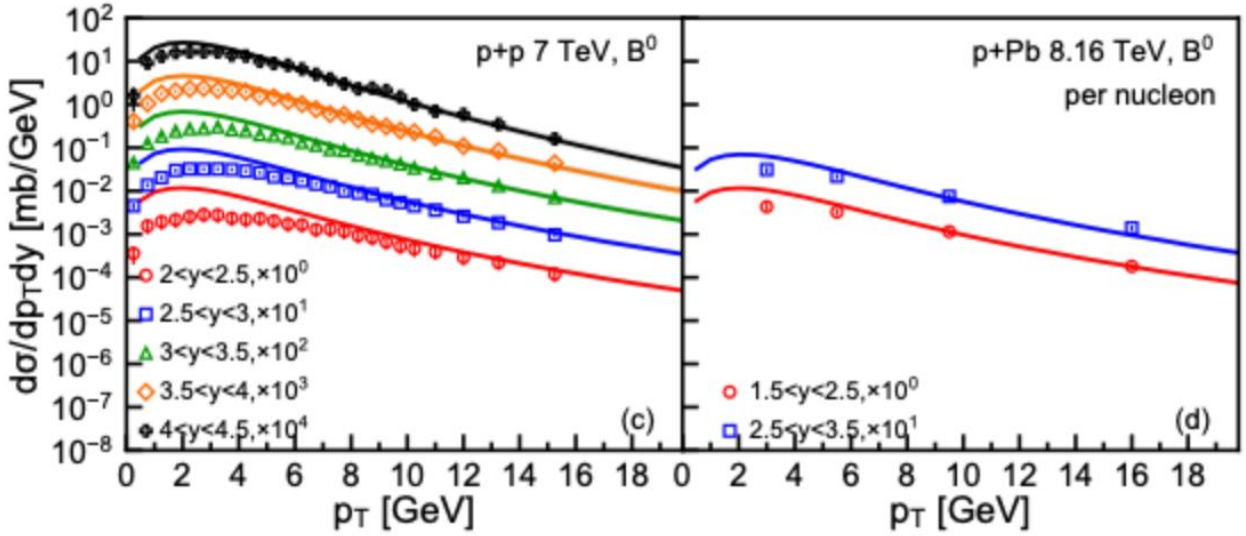
Dead Cone



C. Marquet, Y. Shi and B. W. Xiao,[arXiv:2510.18949]; W.Zhao etc.al, in progress.

Single Inclusive Heavy Flavour

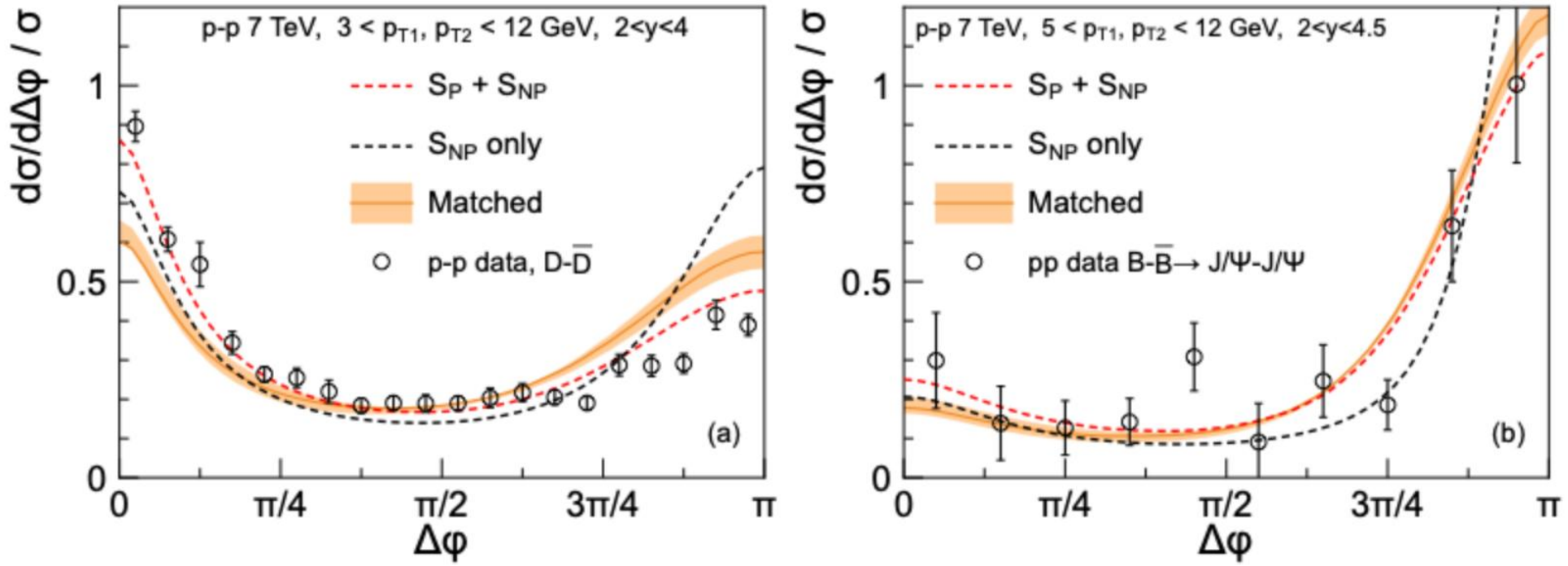




- Well describe **single inclusive** D and B spectra at the LHC.
- At low pT, current CGC overestimates the data, **needs parton shower (or Sudakov)**?

LHCb data: JHEP 06 (2017) 147, JHEP 10 (2017) 090, JHEP 08 (2013) 117, PhysRevD.99.052011
W. Zhao, etc, al. in progress.

Dihadron Correlations for Heavy Flavour

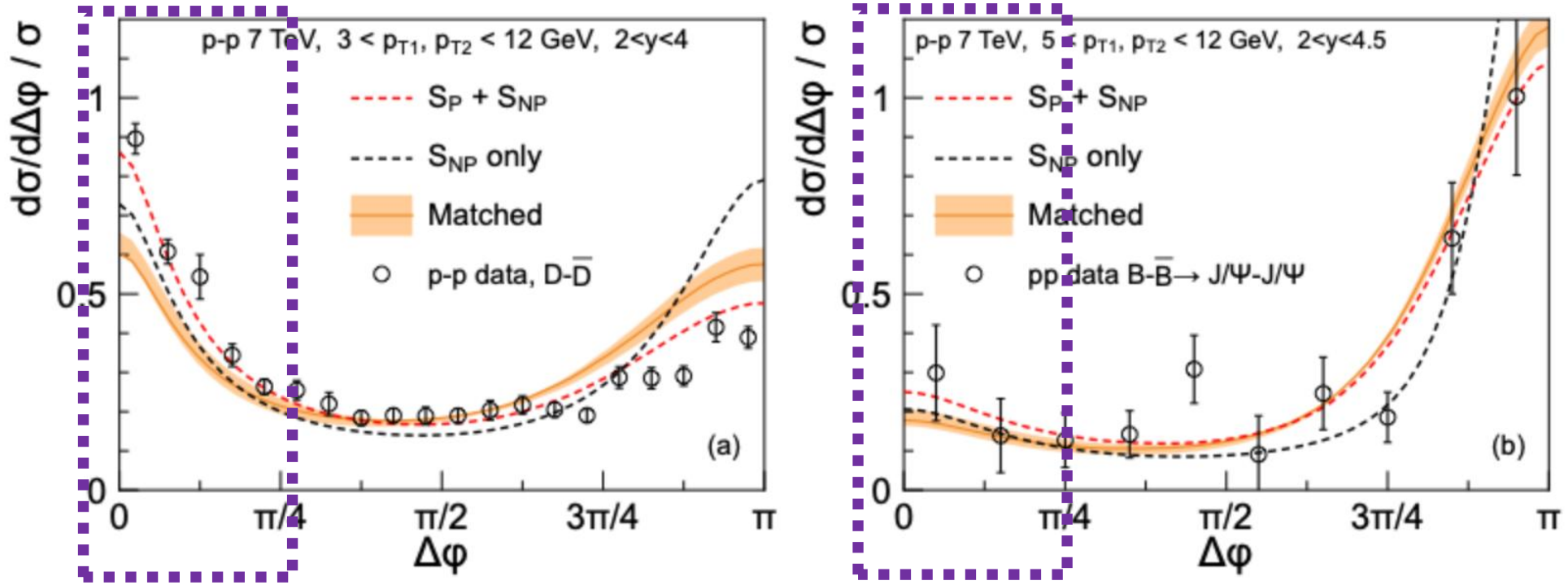


Matching Function: $G(R) = \frac{R}{R + c^2}$, $R = \frac{M^2}{K'^2}$, band is from c= 0.5, 1.0, 2.0

- Well describe the B-B and D-D correlation in p-p with **$\Delta\varphi$ from 0 to π.**

LHCb data: JHEP 06 (2012) 141, JHEP 11 (2017) 030
W. Zhao, etc, al. in progress.

Dihadron Correlations for Heavy Flavour

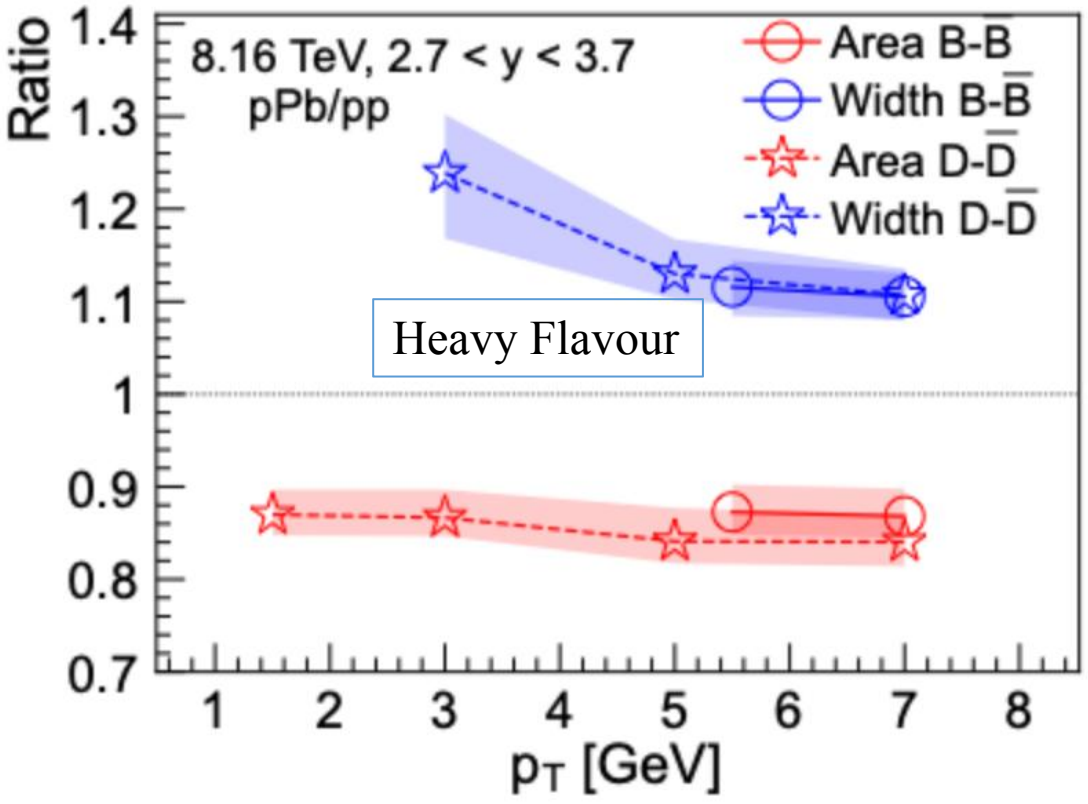


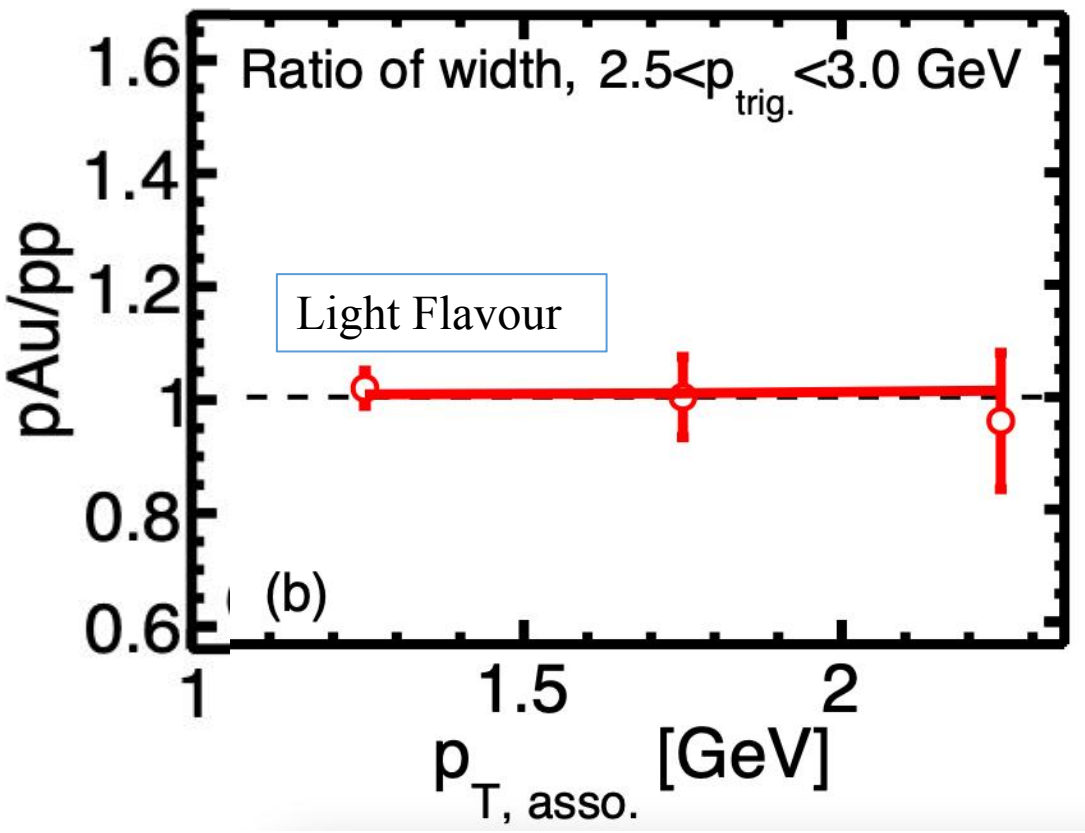
Matching Function: $G(R) = \frac{R}{R + c^2}$, $R = \frac{M^2}{K'^2}$, band is from c= 0.5, 1.0, 2.0

- Well describe the B-B and D-D correlation in p-p with **$\Delta\varphi$ from 0 to π.**
- Clean "**Dead Cone**" effects in B-B correlations.

LHCb data: JHEP 06 (2012) 141, JHEP 11 (2017) 030
W. Zhao, etc, al. in progress.

Area and Width Ratio between pPb and p-p





- Width **ratio pPb/pp >1.2** below 3 GeV bin, much larger than light hadron.
- Mostly caused by the “dead cone” effects in the Sudakov.

W. Zhao, etc, al. in progross.

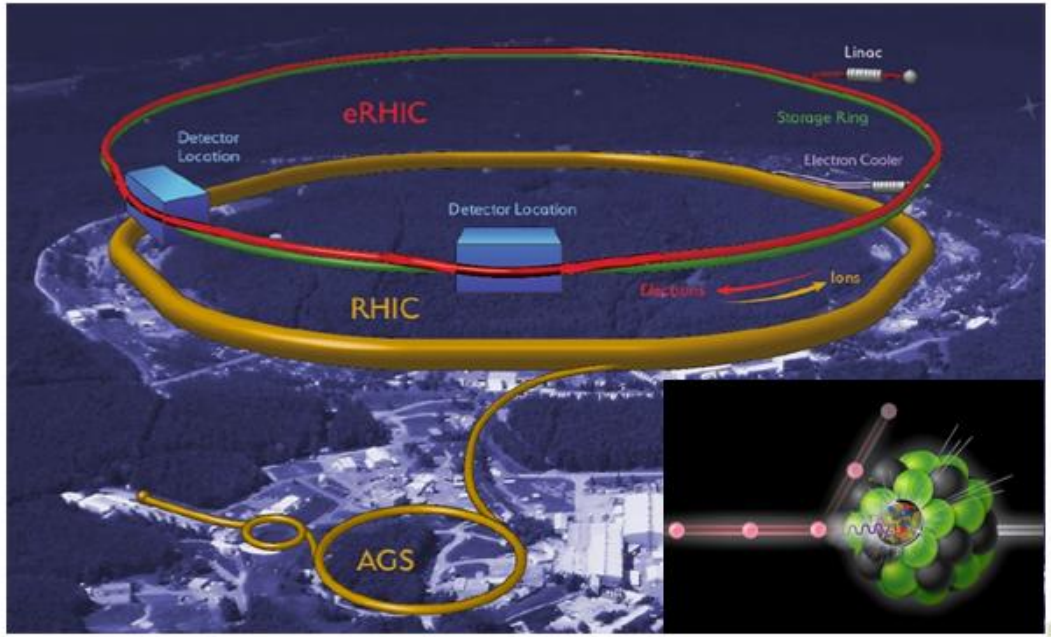
Event Generator

for Gluon Saturation Physics

Electron-Ion Collider Era

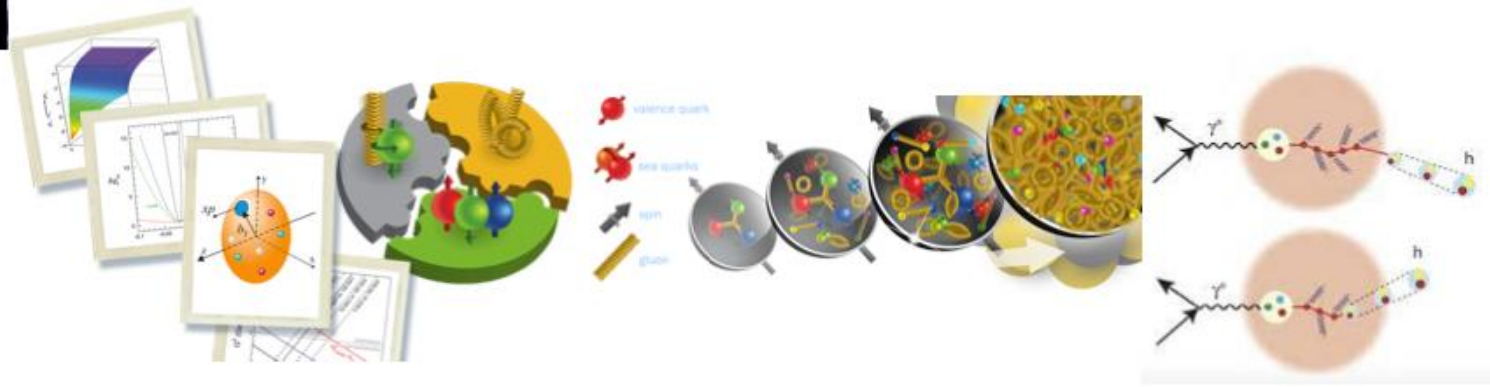
Capabilities and scientific case





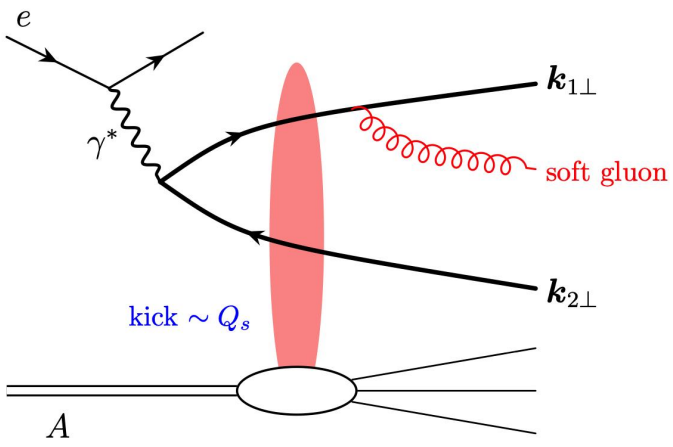
- High luminosity (high rate of collisions)
- Up to ~ 140 GeV center of mass energy
- Polarized beams of (light) ions and electrons
- Large ion species (from proton to gold)

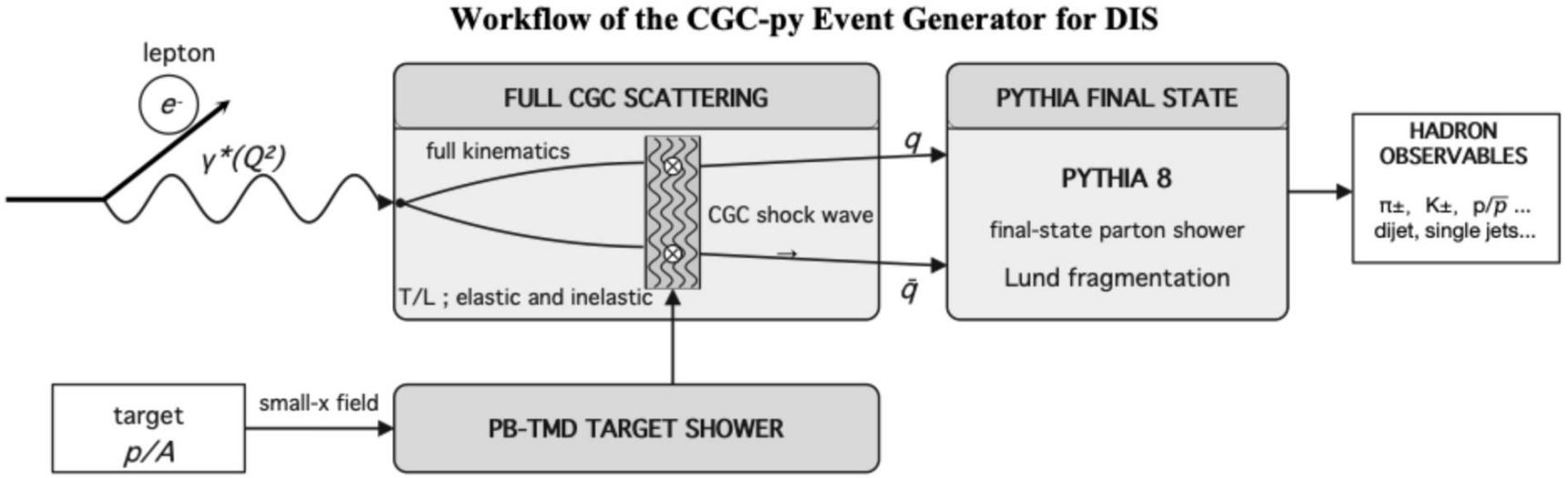
EIC goals: tomography, spin, gluon saturation, hadronization



Figures from https://www.bnl.gov/eic/science.php

Why an event generator for Small-x at DIS?

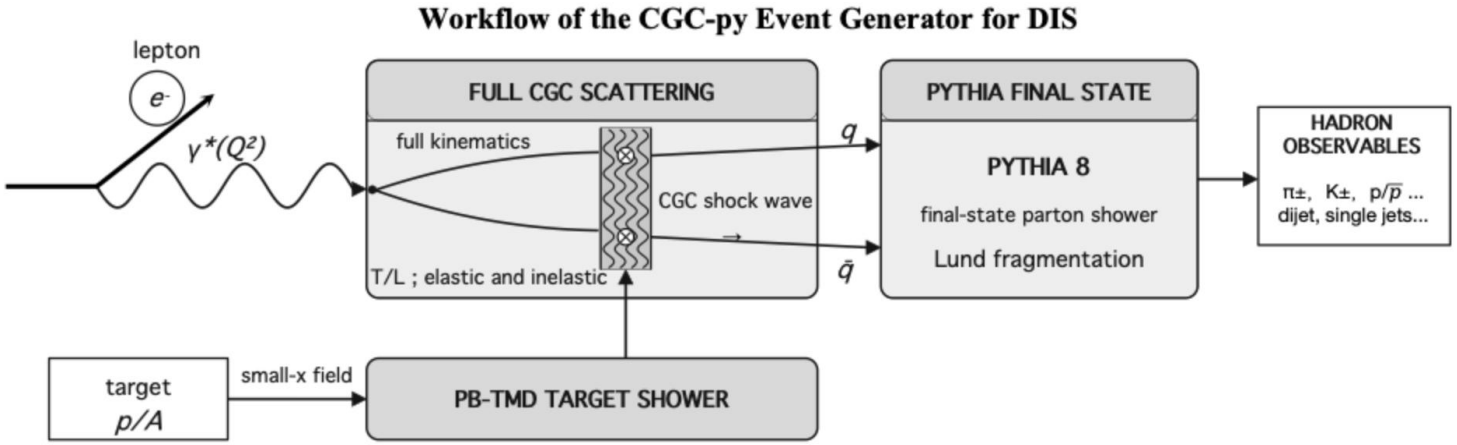




H. Duan, C. Yi, S. W. Dai, S. Y. Wei, W. Zhao and L. Zheng, [arXiv:2609.03434 [hep-ph]].

- LO CGC alone is not enough:
  - Soft/collinear radiation ⇒ Sudakov logs compete with saturation broadening
  - Needs resummation *or* a matched parton shower
- A generator coupling CGC dynamics with parton showers provides:
  - **Experiment:** realistic pseudodata and detector-level predictions for EIC *ep*/*eA*
  - **Theory:** a laboratory to test resummation and saturation against exclusive observables

CGC-py: Key Features



$$\frac{\mathrm{d}\sigma_T^{\gamma^* A}}{\mathrm{d}z\,\mathrm{d}^2\boldsymbol{k}_1\,\mathrm{d}^2\boldsymbol{k}_2} = \sum_q \frac{2N_c\alpha_{\mathrm{em}}e_q^2 S_\perp}{(2\pi)^6}\left[z^2+(1-z)^2\right]\epsilon_f^2 \int \mathrm{d}^2\boldsymbol{r}\,\mathrm{d}^2\boldsymbol{r}'\,\mathrm{d}^2\boldsymbol{b}\, e^{-\mathrm{i}(\boldsymbol{P}+z\boldsymbol{q})\cdot\boldsymbol{r}} e^{+\mathrm{i}(\boldsymbol{P}+z\boldsymbol{q})\cdot\boldsymbol{r}'} \times e^{-\mathrm{i}\boldsymbol{q}\cdot\boldsymbol{b}}\frac{\boldsymbol{r}\cdot\boldsymbol{r}'}{|\boldsymbol{r}|\,|\boldsymbol{r}'|}K_1(\epsilon_f|\boldsymbol{r}|)K_1(\epsilon_f|\boldsymbol{r}'|)\left[1+S^{(4)}-S(\boldsymbol{r})-S(\boldsymbol{r}')\right],$$

$$\frac{\mathrm{d}\sigma_L^{\gamma^* A}}{\mathrm{d}z\,\mathrm{d}^2\boldsymbol{k}_1\,\mathrm{d}^2\boldsymbol{k}_2} = \sum_q \frac{8N_c\alpha_{\mathrm{em}}e_q^2 S_\perp}{(2\pi)^6}z^2(1-z)^2Q^2 \int dd^2\boldsymbol{r}\,\mathrm{d}^2\boldsymbol{r}'\,\mathrm{d}^2\boldsymbol{b}\, e^{-\mathrm{i}(\boldsymbol{P}+z\boldsymbol{q})\cdot\boldsymbol{r}} e^{+\mathrm{i}(\boldsymbol{P}+z\boldsymbol{q})\cdot\boldsymbol{r}'} \times e^{-\mathrm{i}\boldsymbol{q}\cdot\boldsymbol{b}}K_0(\epsilon_f|\boldsymbol{r}|)K_0(\epsilon_f|\boldsymbol{r}'|)\left[1+S^{(4)}-S(\boldsymbol{r})-S(\boldsymbol{r}')\right].$$

1. Full kinematics, no back-to-back approximation

The complete LO CGC $q\bar{q}$ cross section is evaluated over the full transverse-momentum phase space (Fourier transform of the quadrupole correlator $S^{(4)}$).

2. Complete event evolution

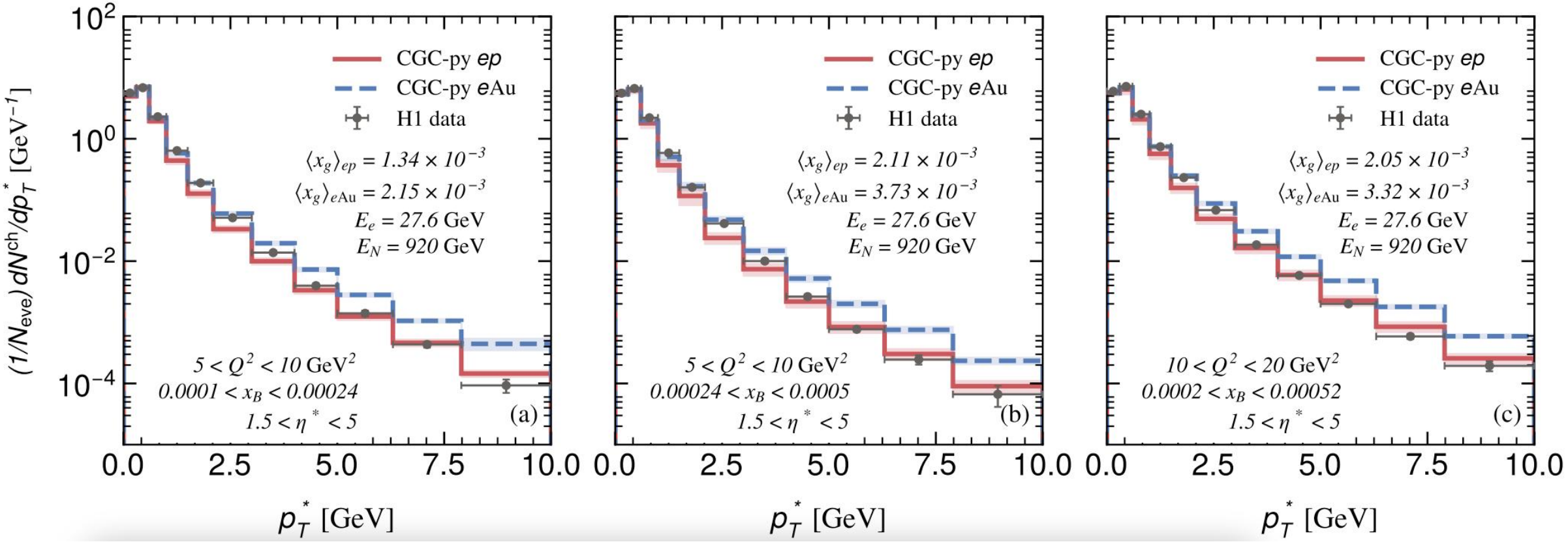
The hard process is coupled to a PB-TMD backward initial-state (target) shower, PYTHIA 8 final-state radiation and Lund string hadronization.

3. Unified single- and multi-particle observables

Dihadron (dijet) correlations and single-inclusive hadron (jet) spectra are obtained from one consistent event sample.

H. Duan, C. Yi, S. W. Dai, S. Y. Wei, W. Zhao and L. Zheng, [arXiv:2609.03434 [hep-ph]]; [arXiv:2608.18589 [hep-ph]].

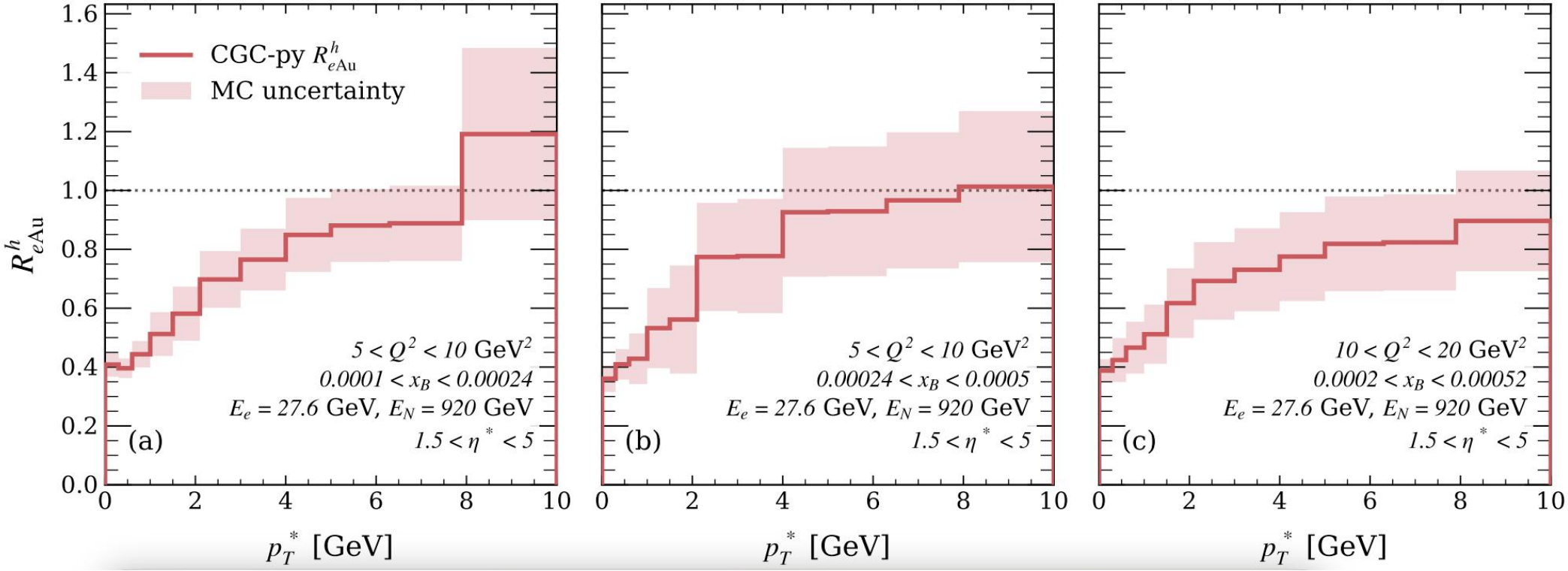
Charged-hadron spectra vs. H1 data



- Excellent description of H1 ep data over ~5 orders of magnitude.
- To our knowledge, first CGC-based generator shown to describe such data;
- eAu flatter at intermediate/high p_T

H1 data: Eur. Phys. J. C 73 (2013) 2406
H. Duan, C. Yi, S. W. Dai, S. Y. Wei, W. Zhao and L. Zheng, [arXiv:2609.03434 [hep-ph]].

Nuclear modification factor ReAu



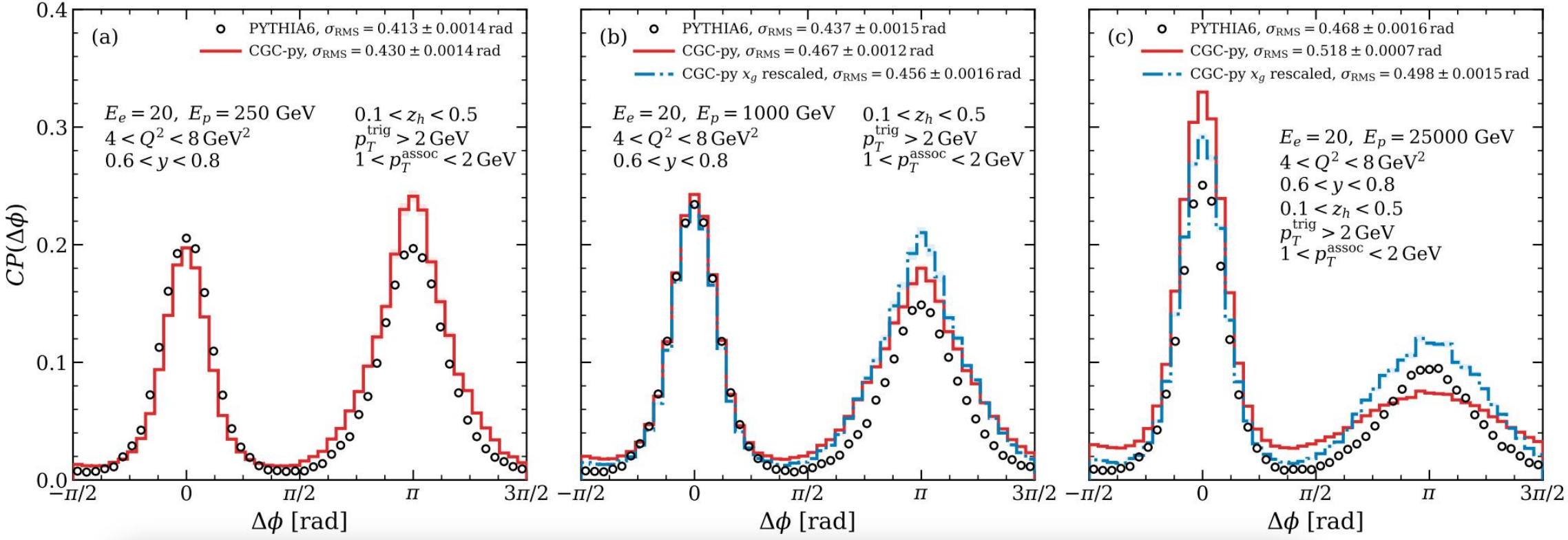
$$R^h_{eAu}(p^*_T) = \frac{S^{Au}_\perp}{A\,S^p_\perp}\frac{dN^h_{eAu}/dp^*_T}{dN^h_{ep}/dp^*_T}, \qquad \frac{S^{Au}_\perp}{AS^p_\perp} = \frac{1}{2.57}$$

S. W. Dai, F. P. Li, H.w.Duan L. G. Pang, G. Y. Qin, S. Y. Wei, H. Z. Zhang and W. Zhao, arXiv:2603.08008; 2607.27603.

- Suppression R ~ 0.4 at low p_T, rising toward unity: **saturation-driven broadening**.
- The **partonic pattern survives** ISR, FSR, and hadronization

H. Duan, C. Yi, S. W. Dai, S. Y. Wei, W. Zhao and L. Zheng, [arXiv:2609.03434 [hep-ph]].

Dihadron correlations: CGC-py vs. Pythia 6



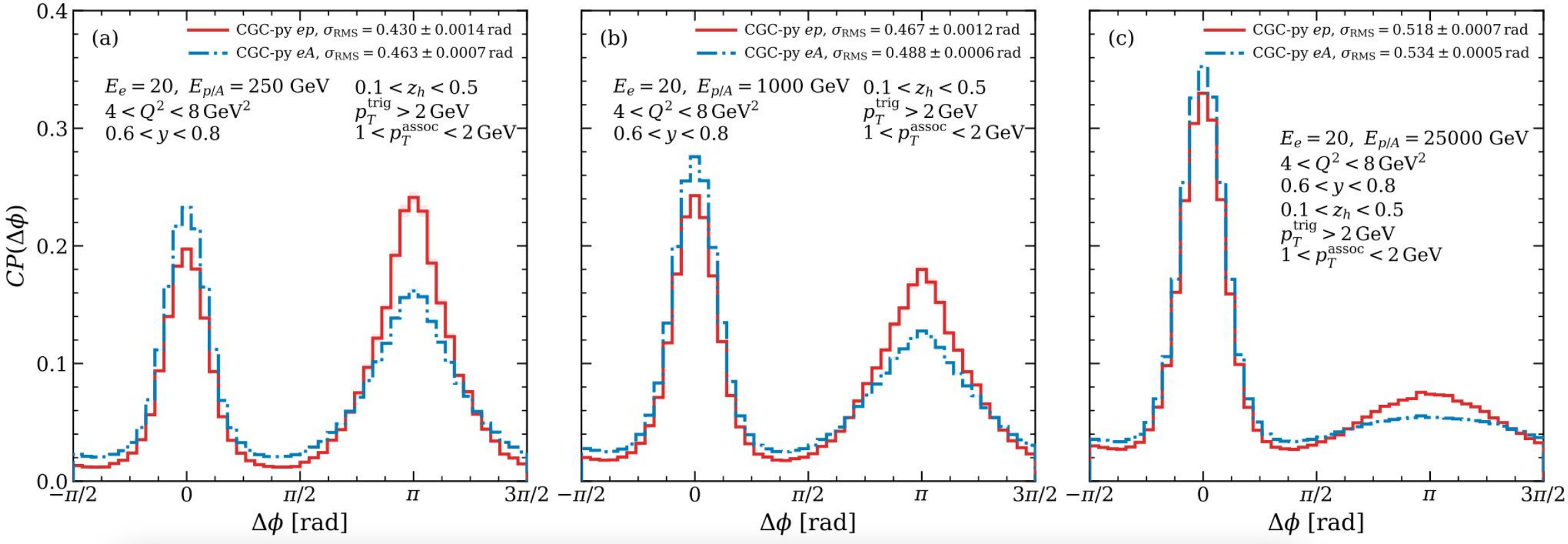
$$C_P(\Delta\phi) = \frac{1}{N_{\rm trig}} \frac{dN^{\rm pair}}{d\Delta\phi}$$

Pythia 6.428 baseline (HERA/HERMES-tuned, DGLAP only);
Zheng, Aschenauer, Lee and Xiao, Phys. Rev. D 89, (2014), 074037

- Low energies: CGC-py ≈ Pythia 6; **Highest energy: CGC-py clearly differs from Pythia 6;**
- Back-to-back area decreases with energy in both models ⇒ **Away-side suppression alone is not a unique saturation signature.**
- DIS pedestal is much smaller than in pp/pA, giving a **cleaner environment.**

H. Duan, C. Yi, S. W. Dai, S. Y. Wei, W. Zhao and L. Zheng, [arXiv:2609.03434 [hep-ph]].

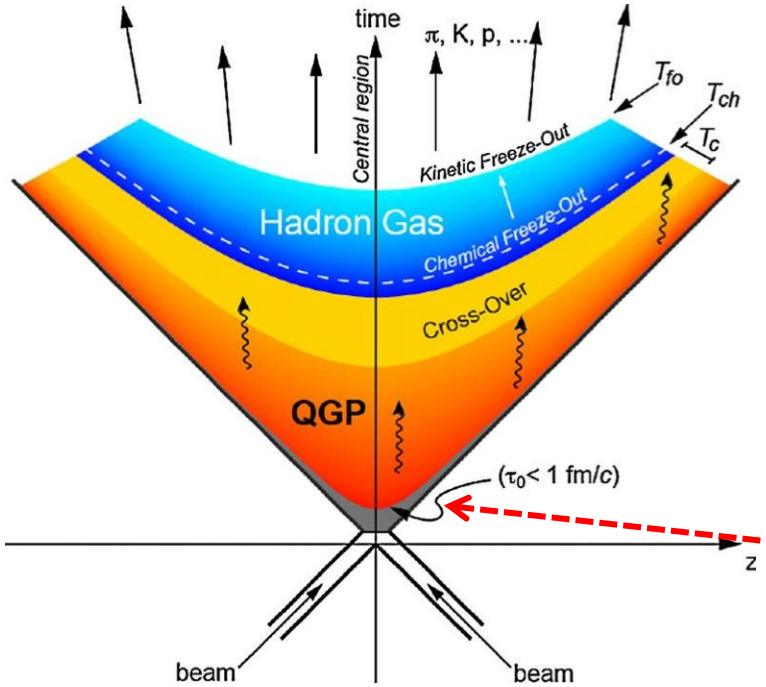
Nuclear effects: ep vs. eAu dihadrons

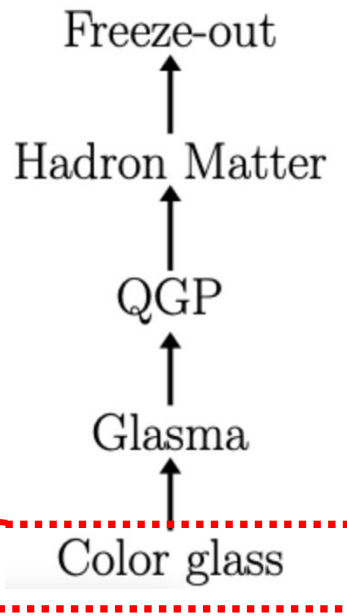


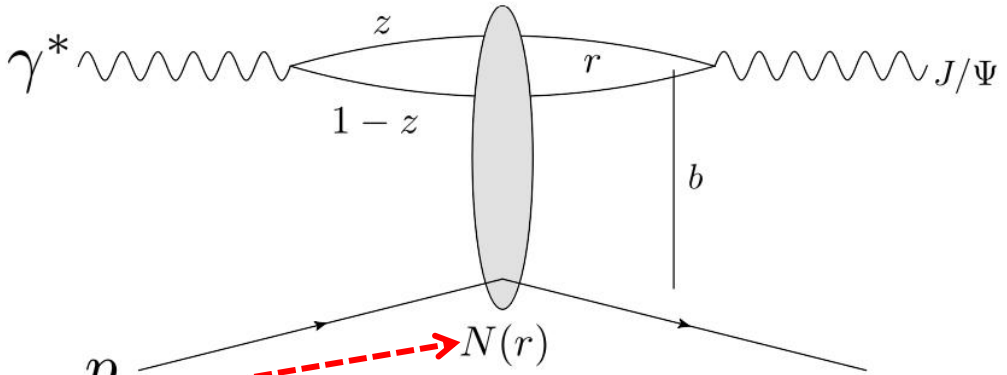
- eAu: broader away side, suppressed back-to-back yield, but effects remain **mild** at EIC energies.
- Go to the most forward kinematics (smallest xg) and use complementary probes: dijets, γ-hadron, EECs, heavy flavor. H. Duan, C. Yi, S. W. Dai, S. Y. Wei, W. Zhao and L. Zheng, [arXiv:2609.03434 [hep-ph]].

Small-x evolution in heavy-ion collisions

Heavy-ion Collisions and DIS/UPC







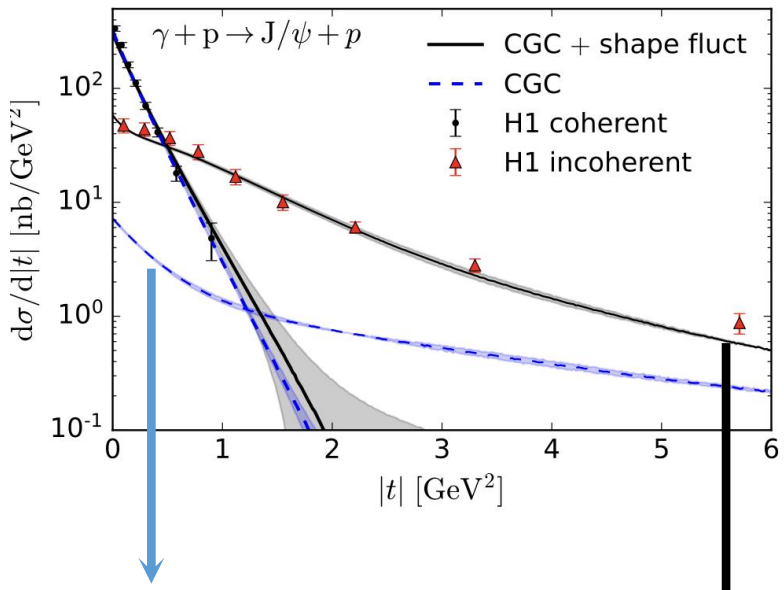
- **Heavy-ion Collisions:** High center-of-mass energies available.
- **Multi-Stage process:**

Initial state => QGP => Hadronic Scatter

- **DIS/UPC:** Pin down kinematics, clean probes of QCD dynamics.
- Collision energy is limited.

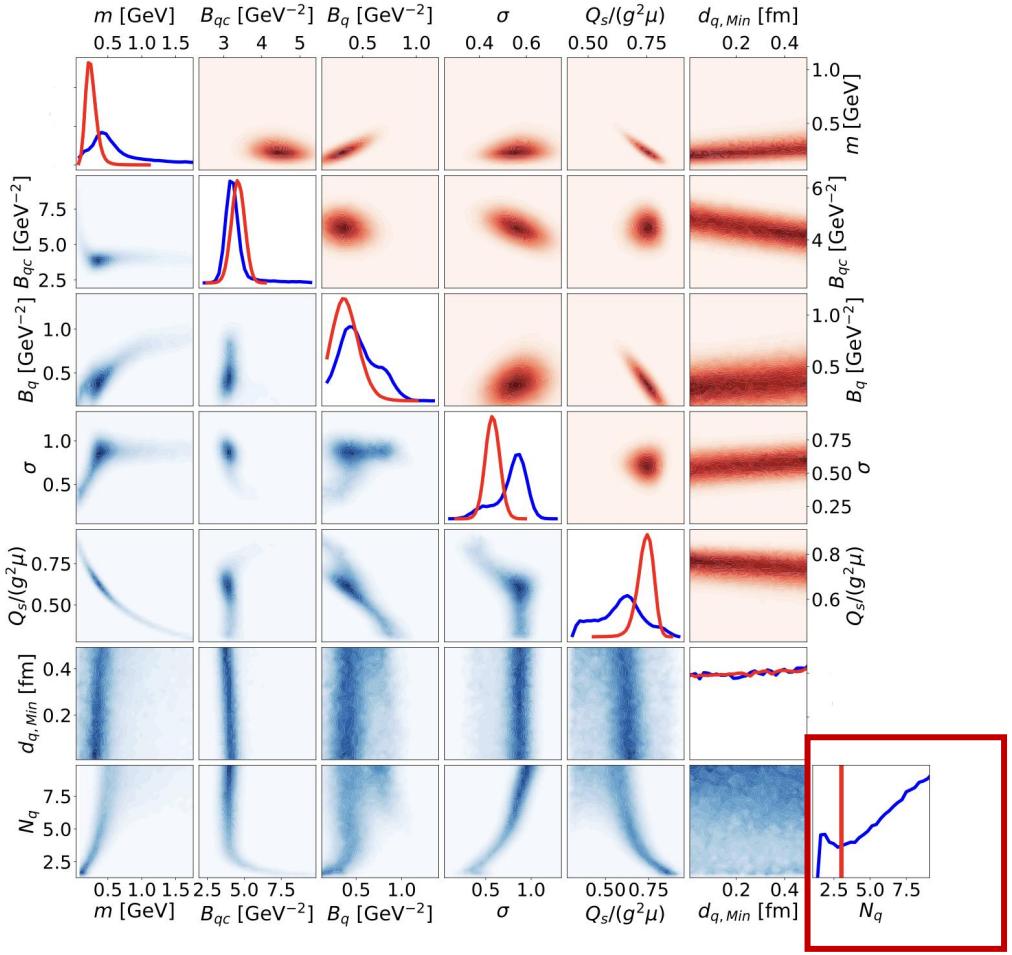
- It is the **same nucleus** at small x: probe the initial state in DIS/UPC, then apply to heavy ion simulations.

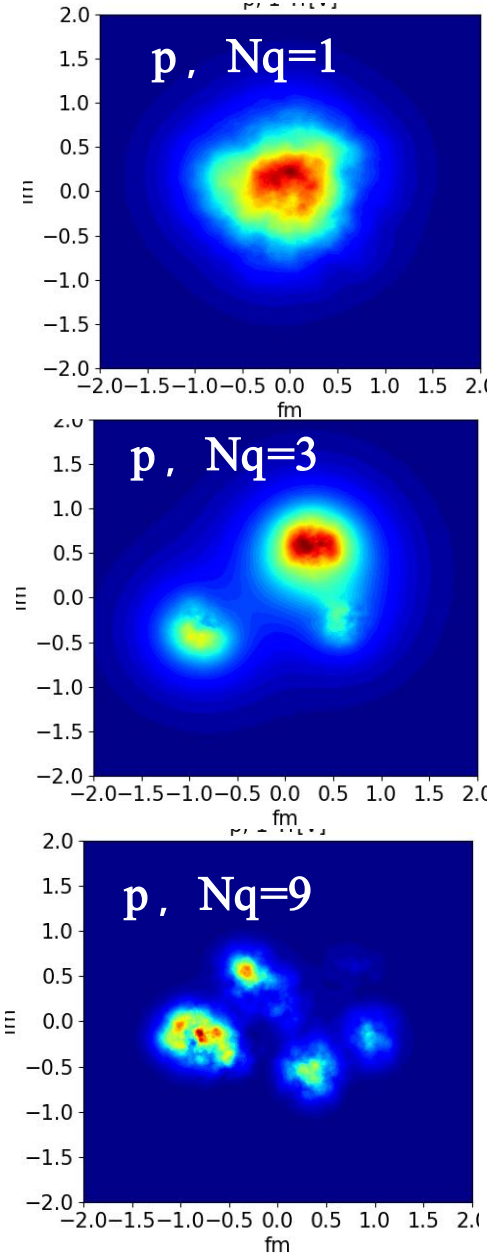
Constrain proton geometry fluctuations



No subnucleon fluctuations

With subnucleon fluctuations

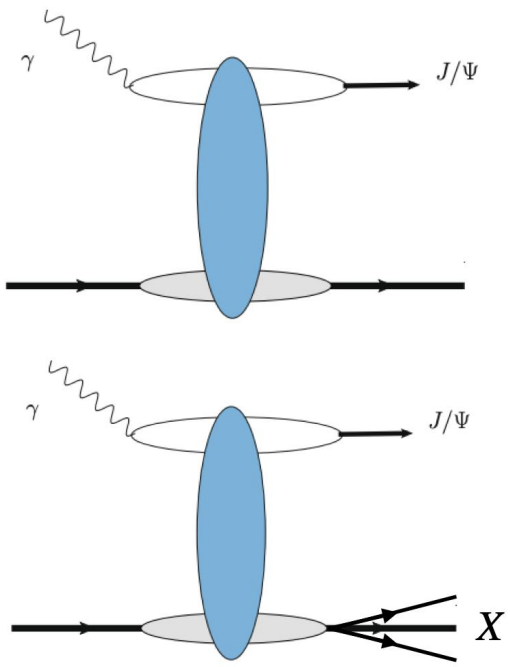


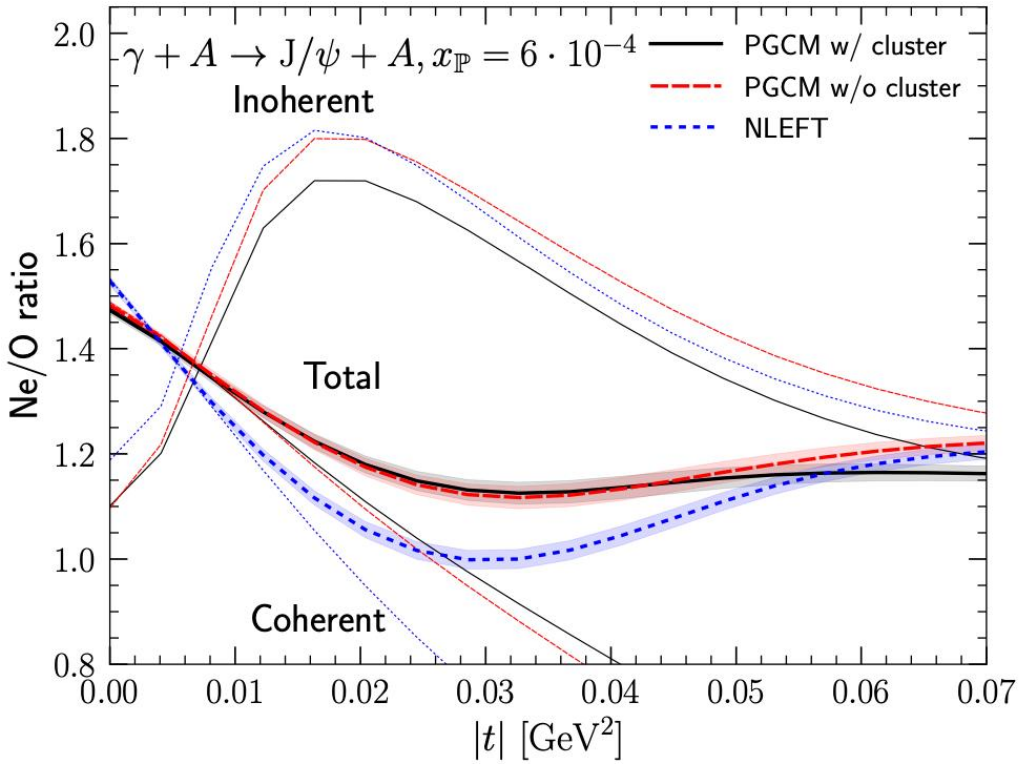


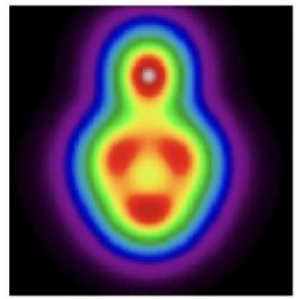
- Extract the proton geometry from the exclusive diffractive J/Psi productions in ep.
- Nq = 1 (no sub-nucleonic structure) is **excluded** by data.

H. Mäntysaari, Schenke , PhysRevLett.108.252301 , PhysRevC.86.034908 ;
H. Mäntysaari, F. Salazar and B. Schenke, Phys. Rev. D 106, 074019 (2022).
H. Mäntysaari, B.Schenke, C. Shen and W. Zhao, Phys. Lett. B 833 (2022), 137348.

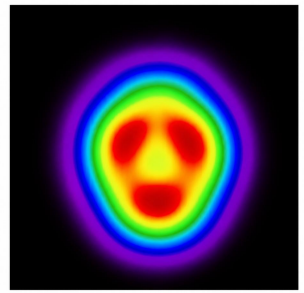
Imaging of Light Nuclei Shape in UPC/EIC







^{20}Ne

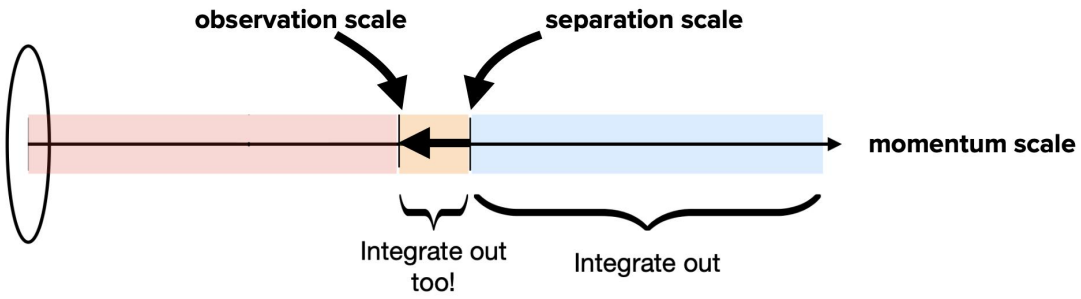


^{16}O

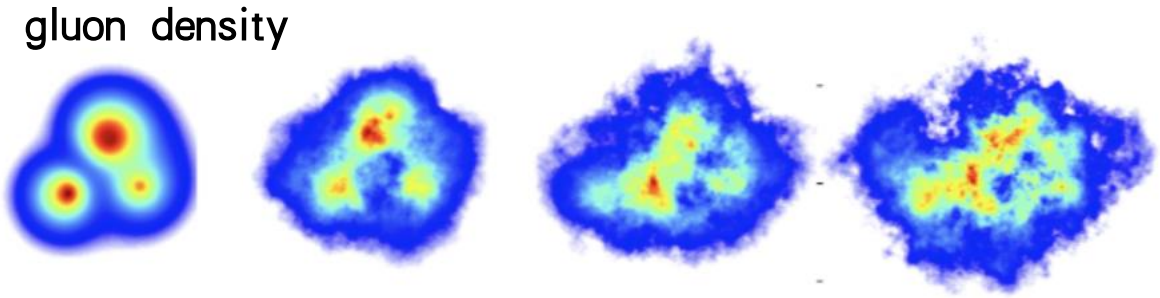
- Probing the bowling-pin shape of Ne-20 in diffractive vector meson productions.

H. Mantysaari, H. Roch, B. Schenke, C. Shen and W. Zhao, [arXiv:2605.00454 [hep-ph]].
H. Mäntysaari, B.Schenke, C. Shen and W. Zhao, PhysRevLett.131.062301.

Energy evolution of initial state



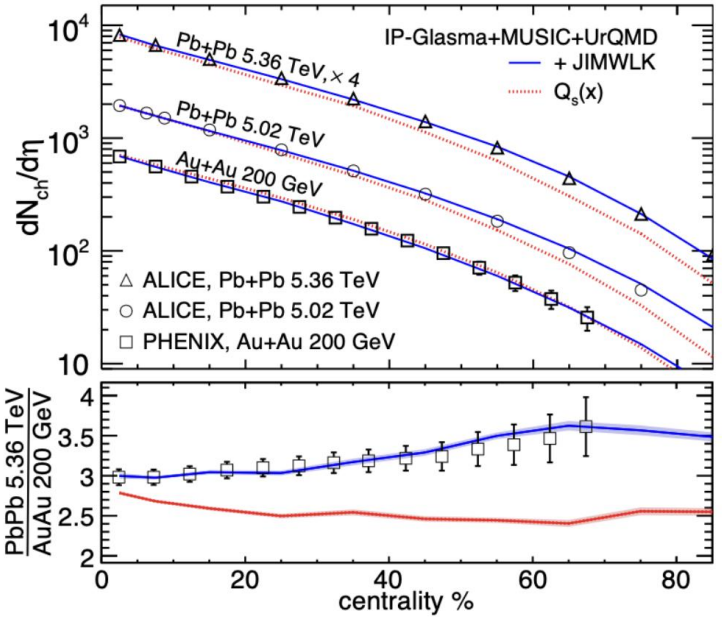
A. Morreale and F. Salazar, Universe 7, no.8, 312 (2021).

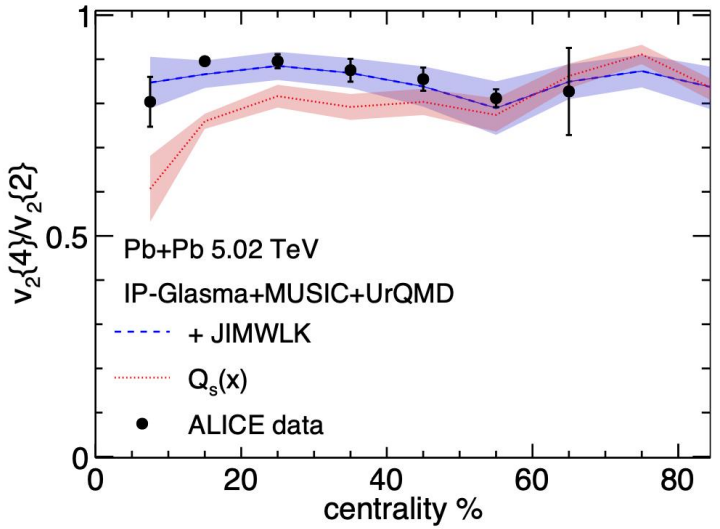


Low energy (UPC/DIS) → High energy (LHC)

- Energy evolution of the initial state is important to final state observables.

H. Mäntysaari and B. Schenke, PRD 98 (2018) 034013.
H. Mäntysaari, B. Schenke, C, Shen and W. Zhao, PRL. 135, 022302 (2025)

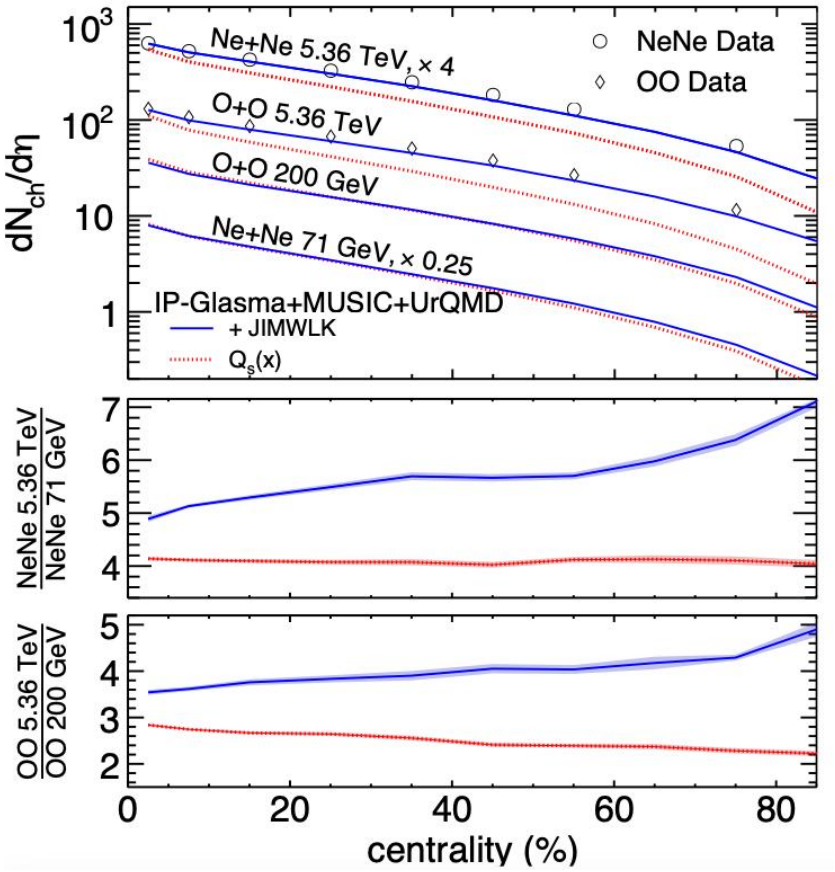


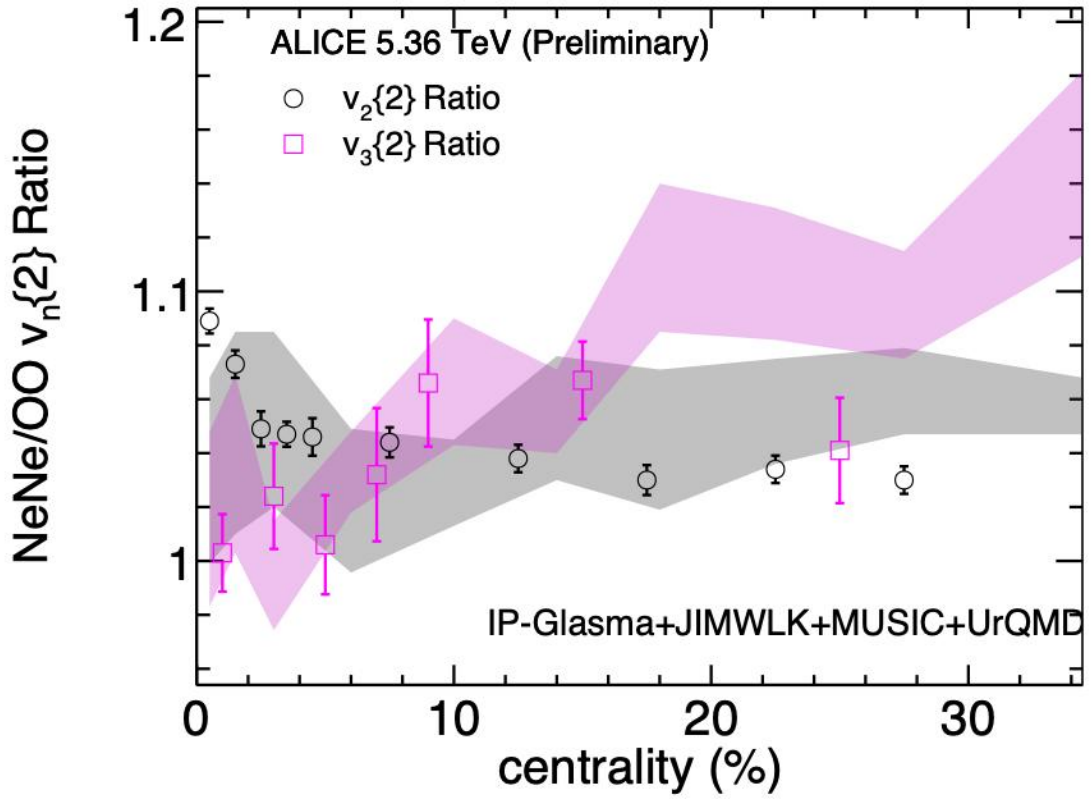


+ JIMWLK: CGC + energy evolution

$Q_s(x)$: CGC (change the $Q_s(x)$ only)

O+O and Ne+Ne





- Energy dependence of dNch/deta provides a direct signature of **small-x evolution in CGC initial state.**
- Anisotropic flow probes nuclear structure, and the Ne/O ratio reflects the **bowling-pin shape** of Ne.

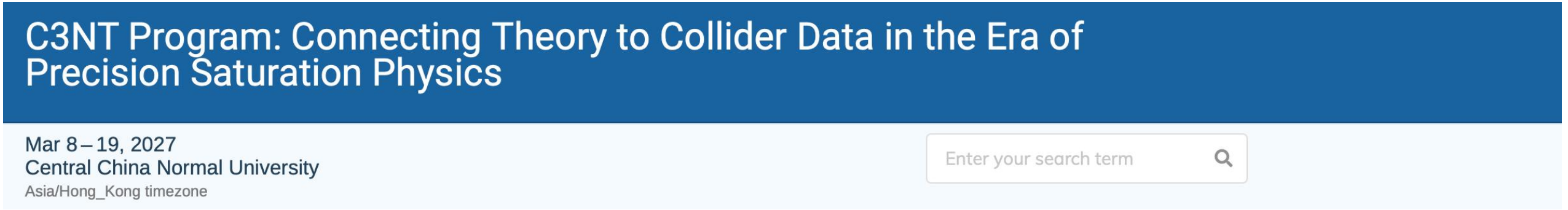
H. Mäntysaari, B. Schenke, C, Shen and W. Zhao, PRL. 135, 022302 (2025);
H. Mäntysaari, B. Schenke, C, Shen and W. Zhao, [arXiv: 2511.03588].

Summary

- **Dipole extraction:** PINN + ciBK gives **unbiased**, **Fourier-positive** proton and Pb dipoles that describe HERA total, charm, and J/ψ data.
- **Forward dihadrons:** Saturation suppresses the yield, while Sudakov effects set the width. The dead-cone effect makes **heavy flavour more sensitive**.
- **CGC-py**: A **full-kinematics** CGC event generator that describes H1 data and makes EIC predictions.
- **Heavy-ion collisions:** JIMWLK evolution shapes multiplicity, $\langle p_T \rangle$, and flow from RHIC to LHC, especially in small systems.

The same small-x gluons can be tested from ep to AA, and future precise measurements will sharpen this test.

Two-Week C3NT Program, March 08-19, 2027 in CCNU



Website: https://indico.global/event/18423

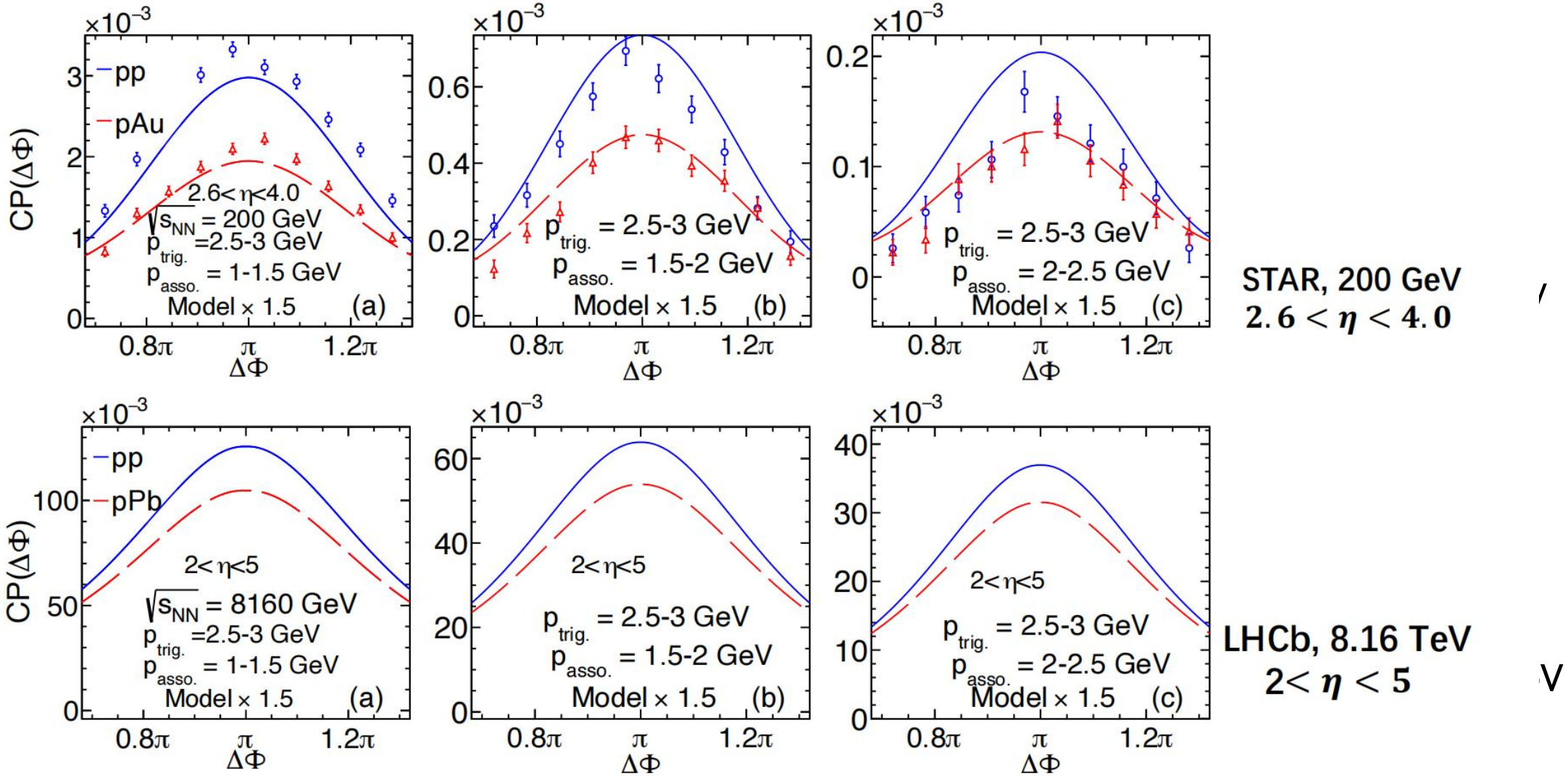
Organizers:

Bowen Xiao
Charlotte Van Hulse
Farid Salazar
Heikki Mäntysaari
Paul CAUCAL
Vladimir Skokov
Wenbin Zhao

Thank you for your attention!

Back Up

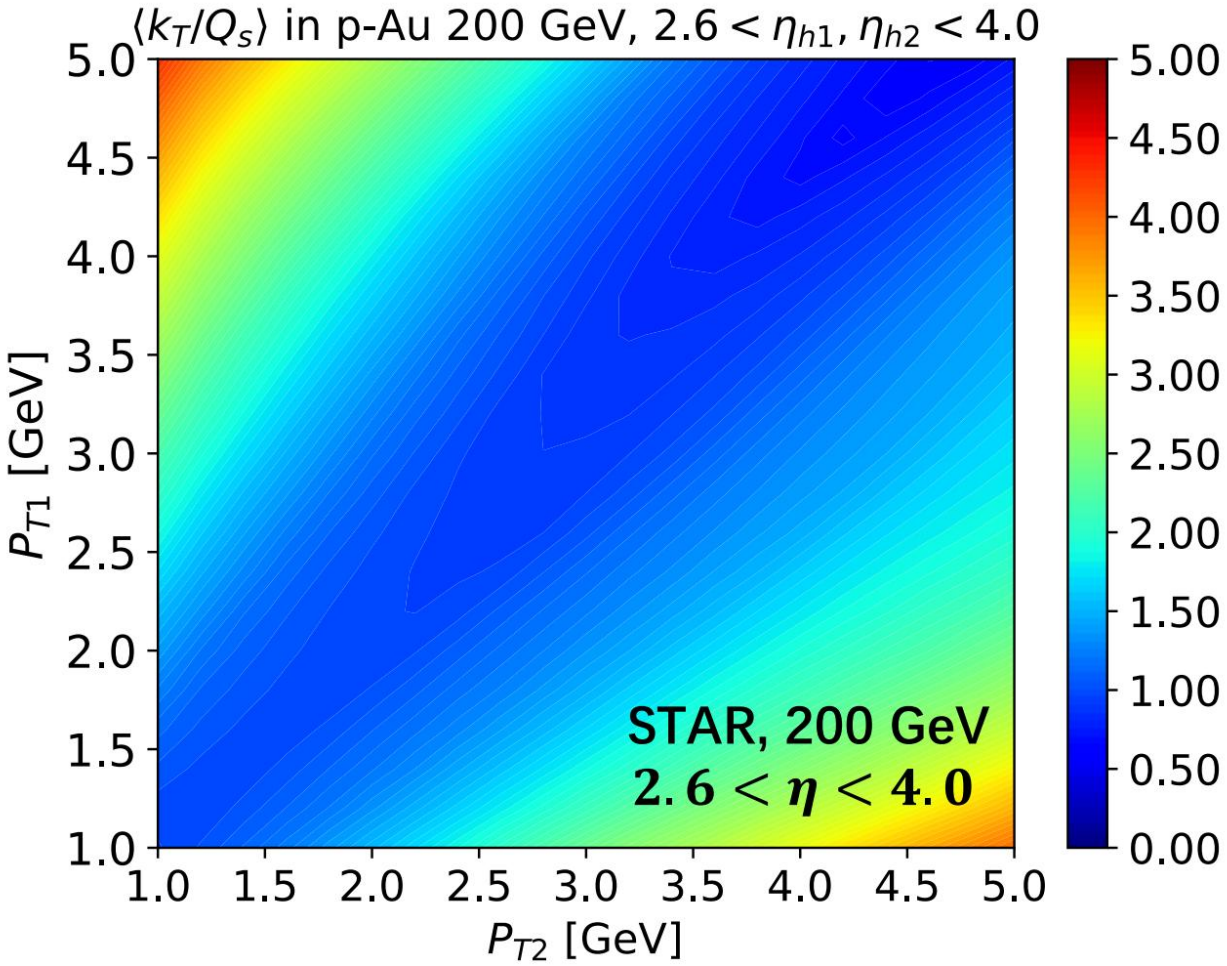
Dihadron Correlations at the LHC

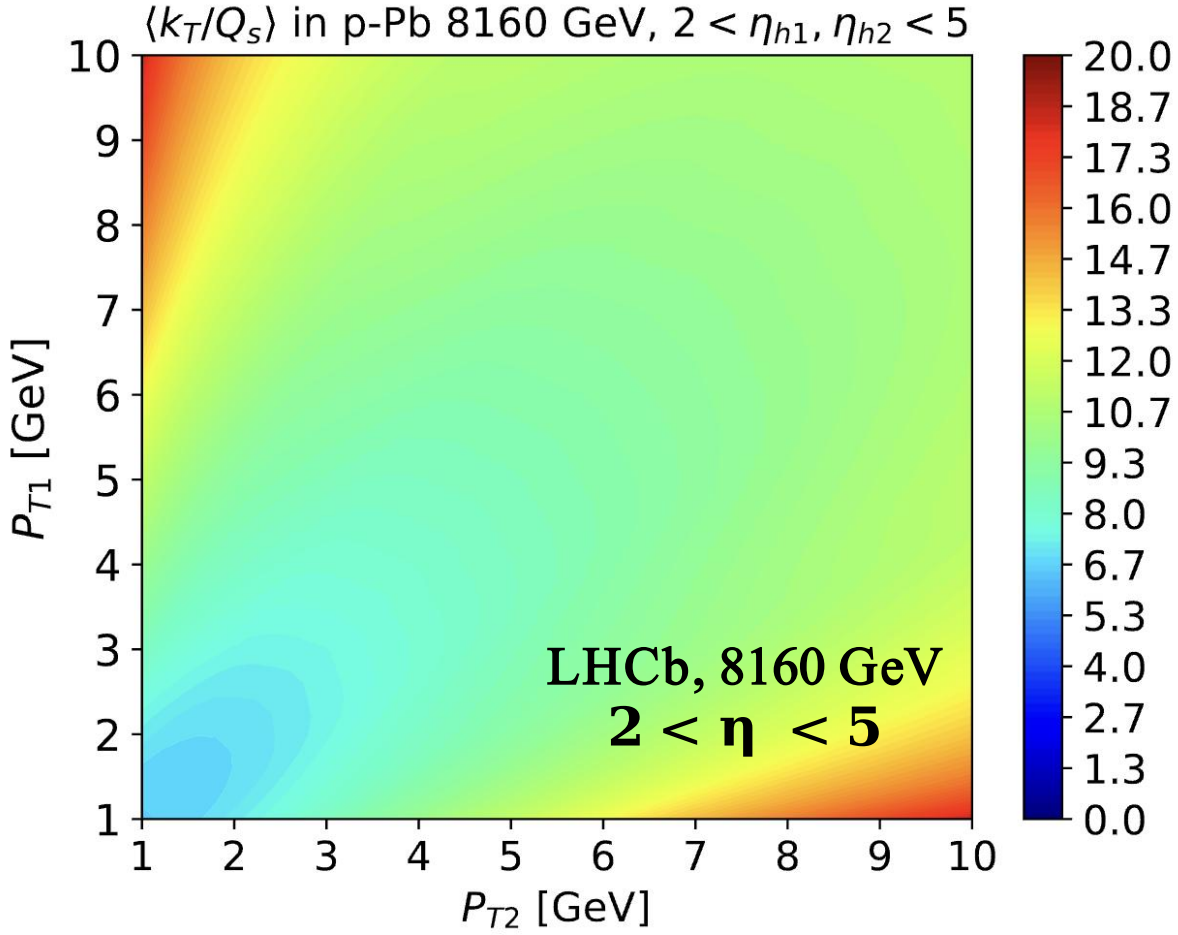


- Surprisingly, LHCb has the **smaller suppression** than STAR, even LHCb has smaller x_g .

P. Caucal, Z. B.Kang, P. Korcyl, F. Salazar, B. Schenke, T.Stebel, R.Venugopalan and W.Zhao, [arXiv:2512.21466].

$< k_T/Q_s >$ probed by STAR and LHCb

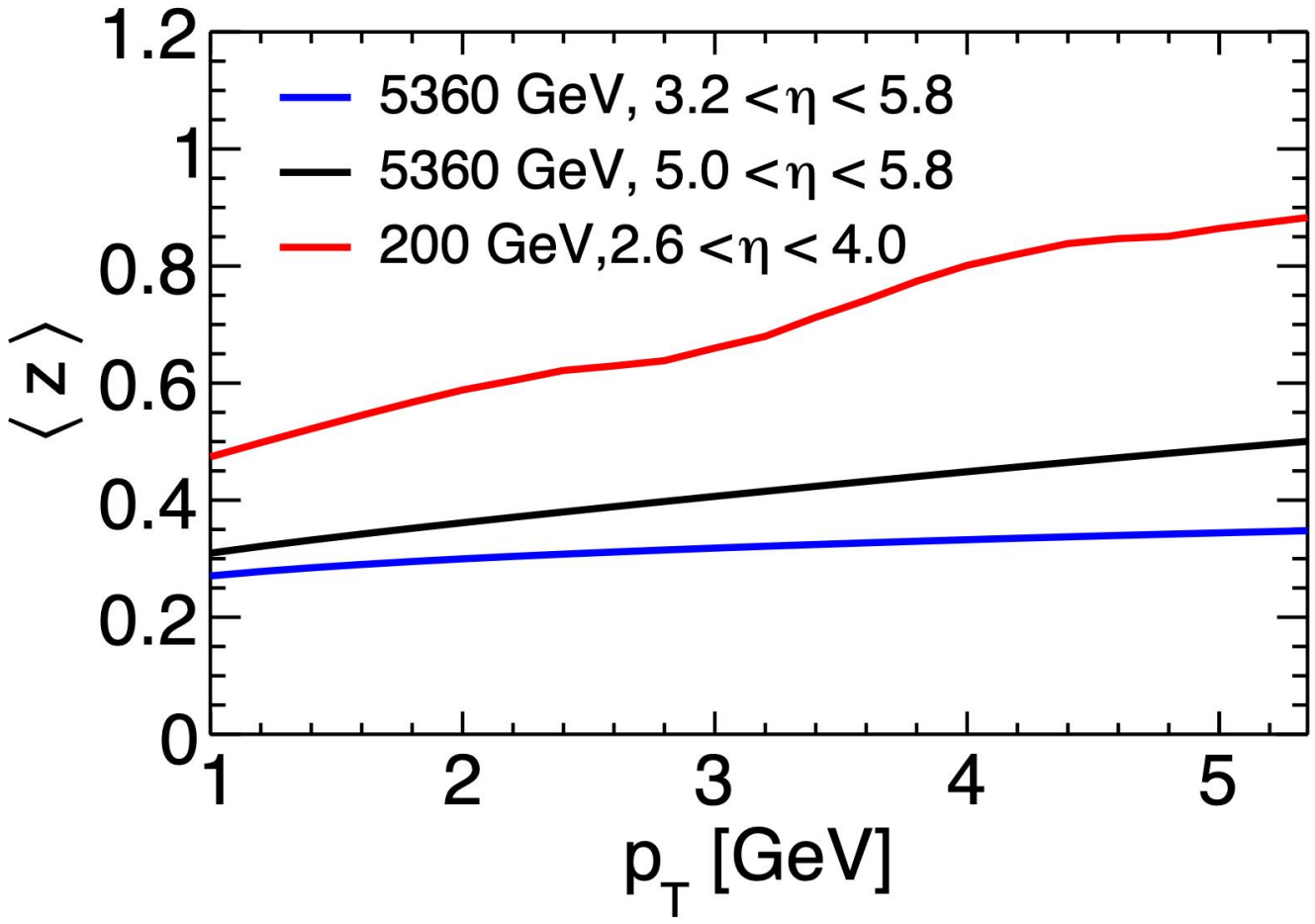




- $< k_T/Q_s >$ probed by di-hadron at **LHCb is much larger than that at STAR**, which partially explains the less saturation effects in LHCb than STAR.

P. Caucal, Z. B.Kang, P. Korcyl, F. Salazar, B. Schenke, T.Stebel, R.Venugopalan and W.Zhao, [arXiv:2512.21466].

Fragmentation fraction probed by STAR and LHC



- STAR has much **larger** $< z >$, than that at LHCb.

P. Caucal, Z. B.Kang, P. Korcyl, F. Salazar, B. Schenke, T.Stebel, R.Venugopalan and W.Zhao, [arXiv:2512.21466].

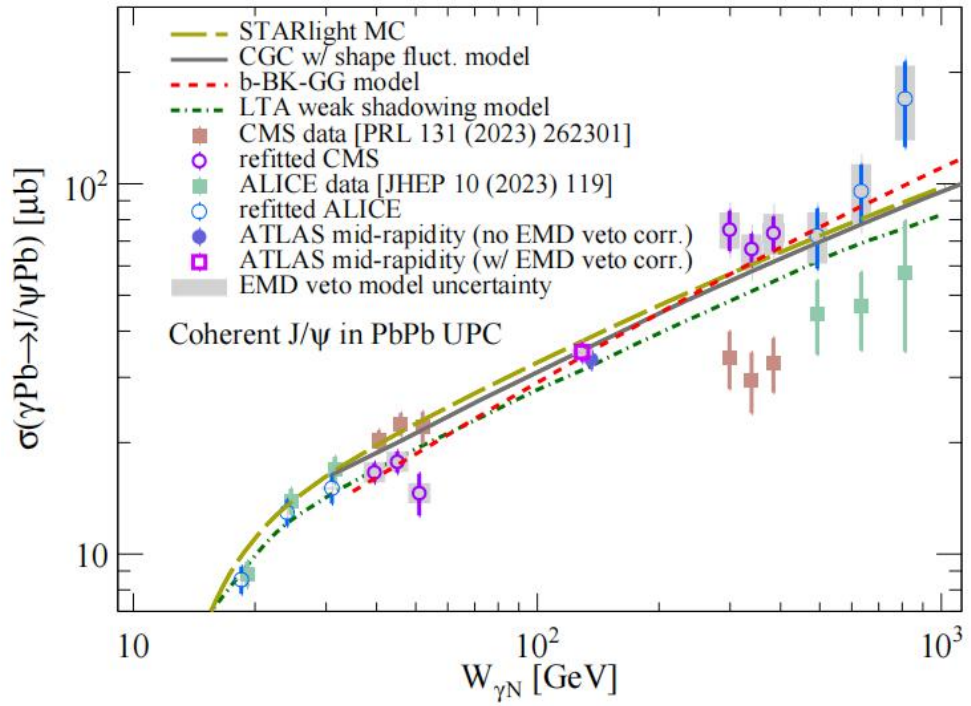
Corrections for Electromagnetic Ion Dissociation (EMD) in UPC

A First Account of the Impact of Ion Electromagnetic Dissociation on Event Exclusivity in Ultraperipheral LHC Collisions

M. Dyndal*
AGH University of Krakow, Faculty of Physics and Applied Computer Science, al. Mickiewicza 30, 30-059 Krakow, PL

L. A. Harland-Lang†
Department of Physics and Astronomy, University College London, London, WC1E 6BT, UK

[M. Dyndal and L. A. Harland-Lang, [arXiv:2604.19879]].



- EMD occurs when photon excites the ion, which de-excites by emitting particles.
- It usually forward neutrons, but at high photon energies it produces mid-rapidity hadrons.
- It can trigger the experimental exclusivity veto and reduce the J/ψ photoproduction.