DIFFRACTION AND FLUCTUATIONS IN HIGH-ENERGY SCATTERING ON LIGHT NUCLEI

BJÖRN SCHENKE, BROOKHAVEN NATIONAL LABORATORY
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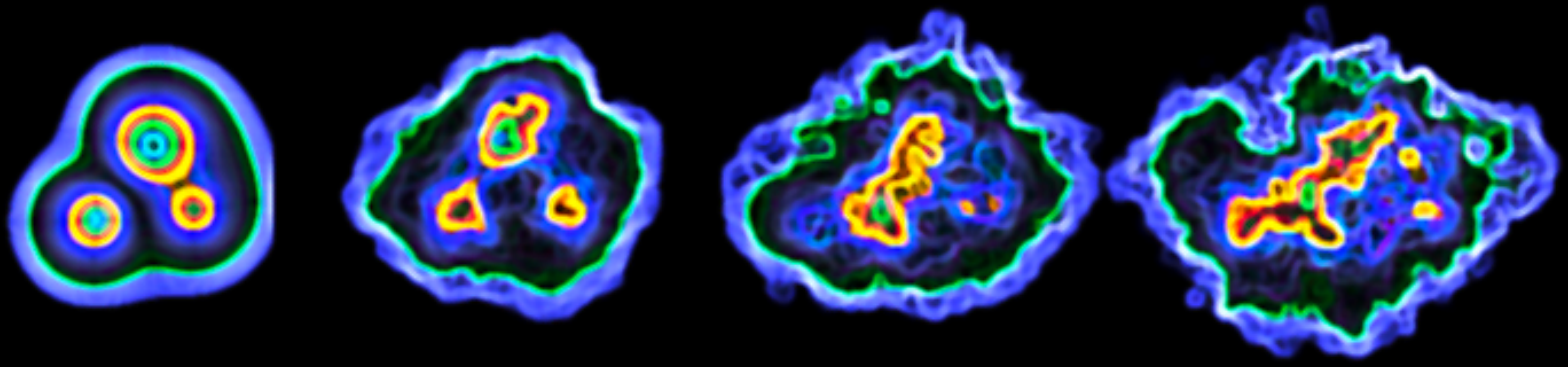


EXPLORING QCD WITH LIGHT NUCLEI AT EIC
STONY BROOK UNIVERSITY, JANUARY 24 2020

Diffractive J/Ψ production in e+p

H. Mäntysaari, B. Schenke, Phys. Rev. Lett. 117 (2016) 052301; Phys.Rev. D94 (2016) 034042

No exchange of color charge → Large rapidity gap

Coherent diffraction:

- Proton remains intact
- Sensitive to average gluon distribution in the proton

Incoherent diffraction:

- Proton breaks up
- Sensitive to fluctuations

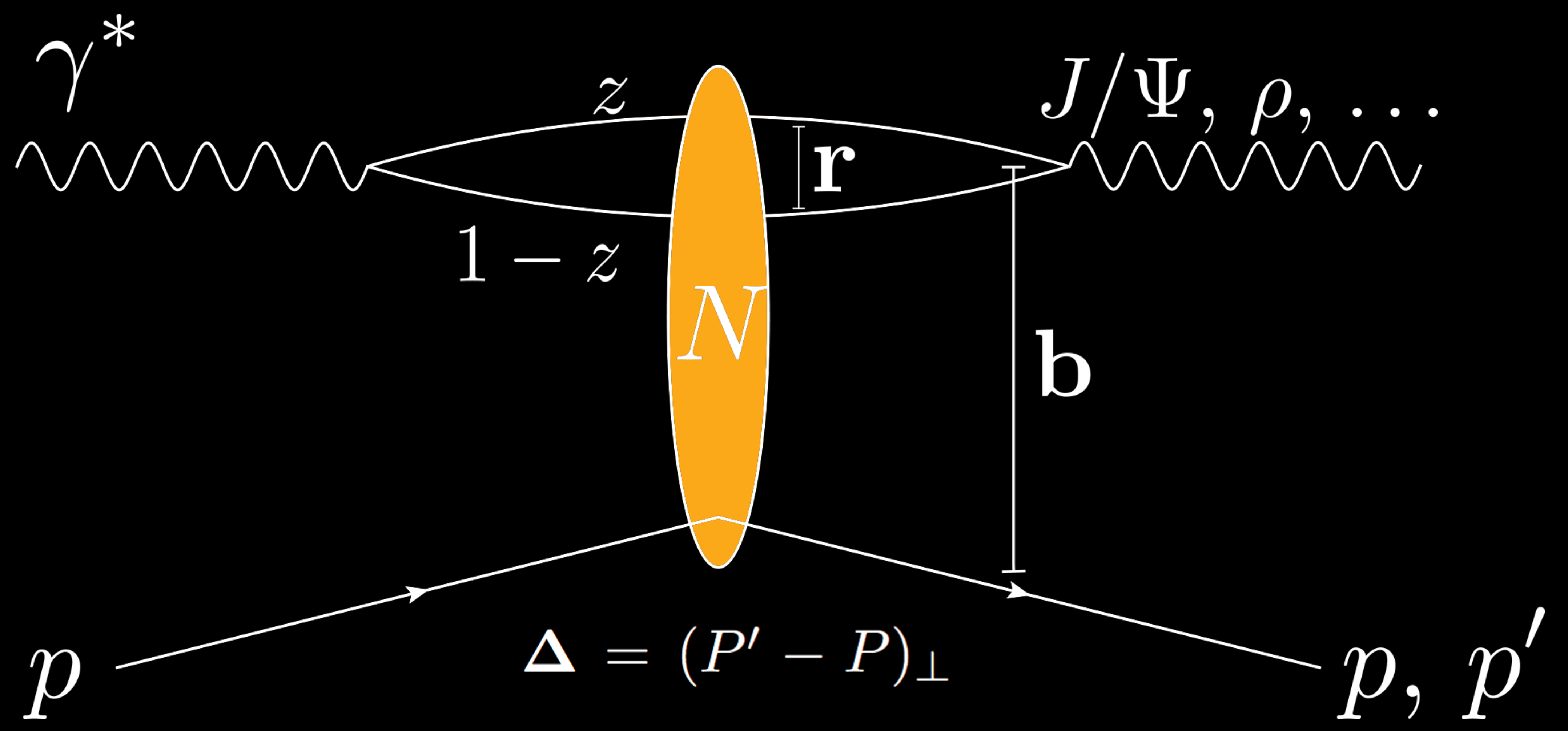
Color Glass Condensate Framework J/Ψ production

H. Mäntysaari, B. Schenke, Phys. Rev. Lett. 117 (2016) 052301; Phys.Rev. D94 (2016) 034042

Cross section is determined by the average interaction of the states that diagonalize the scattering matrix with the target

M. L. Good and W. D. Walker, Phys. Rev. 120 (1960) 1857

High energy: eigenstates are color dipoles at fixed r_T and b_T

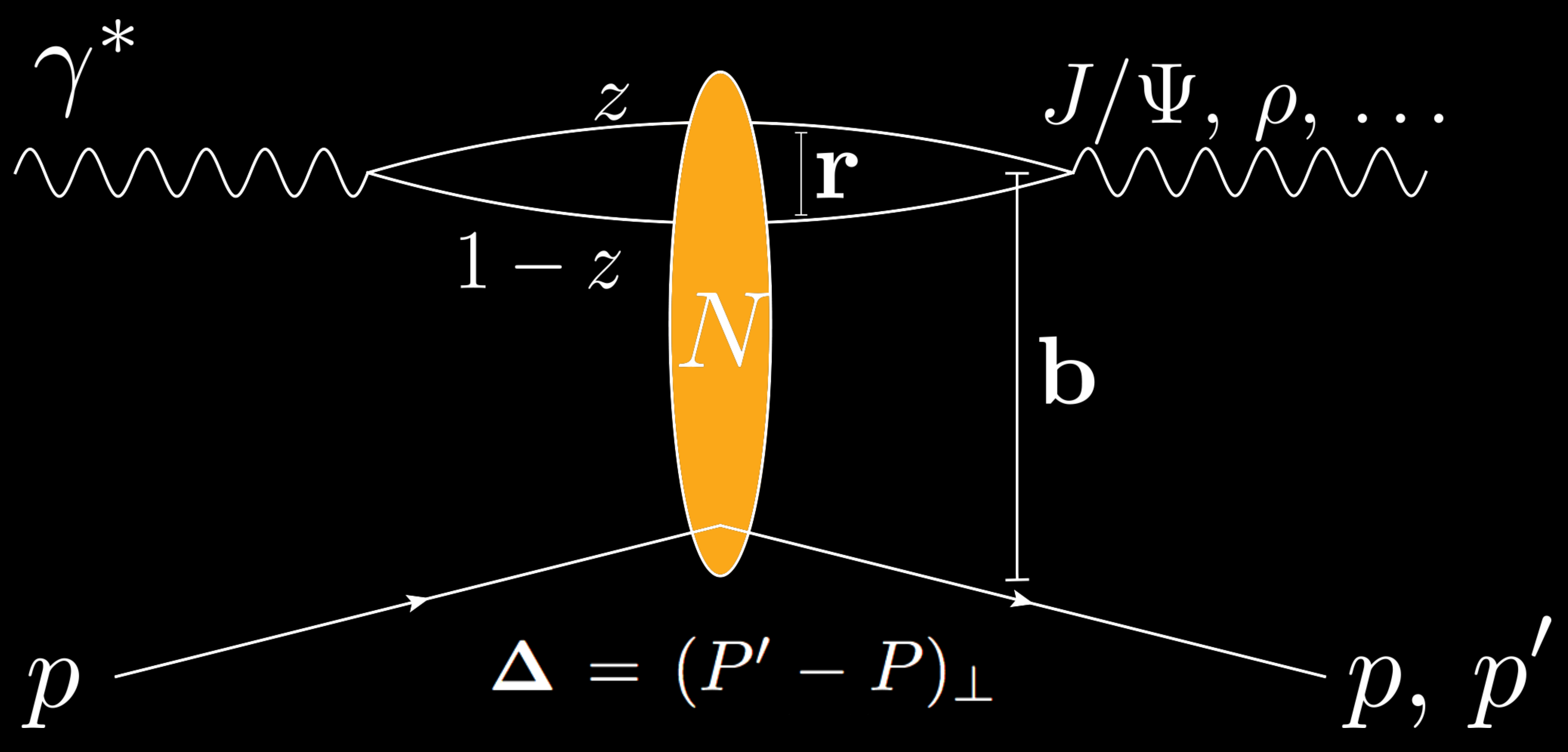


High energy factorization:

- $\gamma^* \to q\bar{q} : \psi(r, Q^2 m, z)$
- $q\bar{q}$ dipole scatters with amplitude N
- $q\bar{q} \to V : \psi^V(r, Q^2, z)$

CGC Framework: Scattering amplitude

Dipole amplitude N determined in saturation model or from Wilson lines



$$\mathcal{A} \sim \int \mathrm{d}^2 b\,\mathrm{d}z\,\mathrm{d}^2 r\,\Psi^*\Psi^V(r,z,Q^2)e^{-ib\cdot\Delta}N(r,x,b)$$

- Impact parameter ***b*** is the Fourier conjugate of transverse momentum transfer ***Δ*** → Access to spatial structure
- Total F_2: forward scattering amplitude (**Δ**=0) for V=γ (same N)

Averaging over the target

Coherent diffraction:

Target stays intact

$$\frac{d\sigma^{\gamma^* p \to Vp}}{dt} = \frac{1}{16\pi} \left| \langle \mathcal{A}^{\gamma^* p \to Vp}(x_{\mathbb{P}}, Q^2, \mathbf{\Delta}) \rangle \right|^2$$

Incoherent diffraction:

Target breaks up

$$\frac{d\sigma^{\gamma^* p \to Vp^*}}{dt} = \frac{1}{16\pi} \left(\left\langle \left| \mathcal{A}^{\gamma^* p \to Vp}(x_{\mathbb{P}}, Q^2, \mathbf{\Delta}) \right|^2 \right\rangle - \left| \langle \mathcal{A}^{\gamma^* p \to Vp}(x_{\mathbb{P}}, Q^2, \mathbf{\Delta}) \rangle \right|^2 \right)$$

Variance: Sensitive to fluctuations!

$-t \approx \mathbf{\Delta}^2$

M. L. Good and W. D. Walker, Phys. Rev. 120 (1960) 1857

H. I. Miettinen and J. Pumplin, Phys. Rev. D18 (1978) 1696

Y. V. Kovchegov and L. D. McLerran, Phys. Rev. D60 (1999) 054025

A. Kovner and U. A. Wiedemann, Phys. Rev. D64 (2001) 114002

Modeling the dipole amplitude

H. Mäntysaari, B. Schenke, Phys. Rev. Lett. 117 (2016) 052301; Phys.Rev. D94 (2016) 034042

Proton target using IPSat model:

$$N^{\mathrm{p}} = 1 - \exp[-r^2 F(x, r^2) T_{\mathrm{p}}(\vec{b})] \quad \text{with} \quad F(x, \vec{r}^2) = \frac{\pi^2}{2N_c} \alpha_s\left(\mu_0^2 + \frac{C}{r^2}\right) xg\left(x, \mu_0^2 + \frac{C}{r^2}\right)$$

Parameters $\mu_0^2, C, xg(x, \mu_0^2), B_{\mathrm{p}}$ (in T_{p}) are fixed by fitting HERA data

Scale dependence of xg obtained from DGLAP evolution

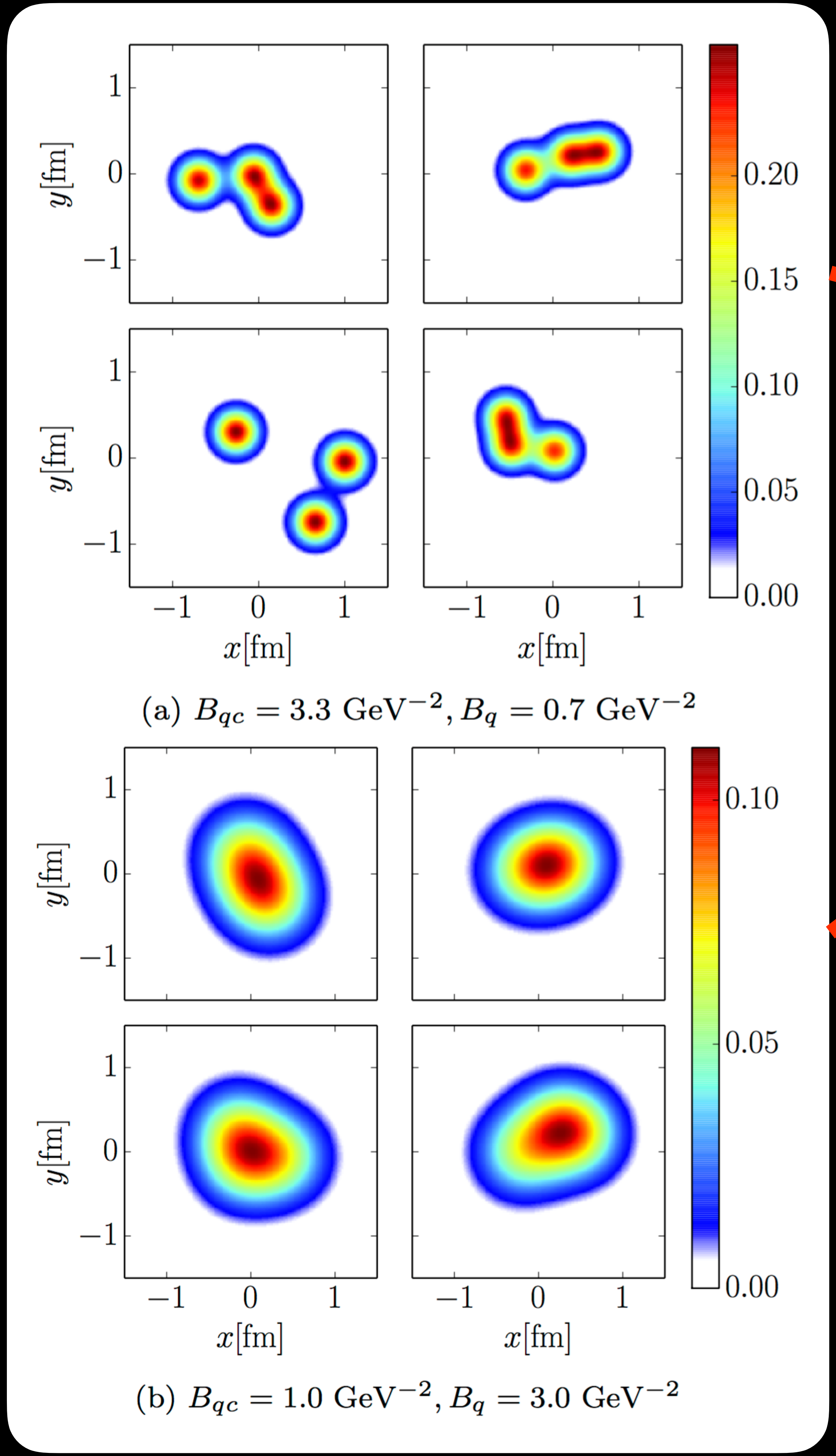
Assume a Gaussian proton shape in 2D: $T_{\mathrm{p}}(\vec{b}) = \frac{1}{2\pi B_{\mathrm{p}}} e^{-b^2/(2B_{\mathrm{p}})}$

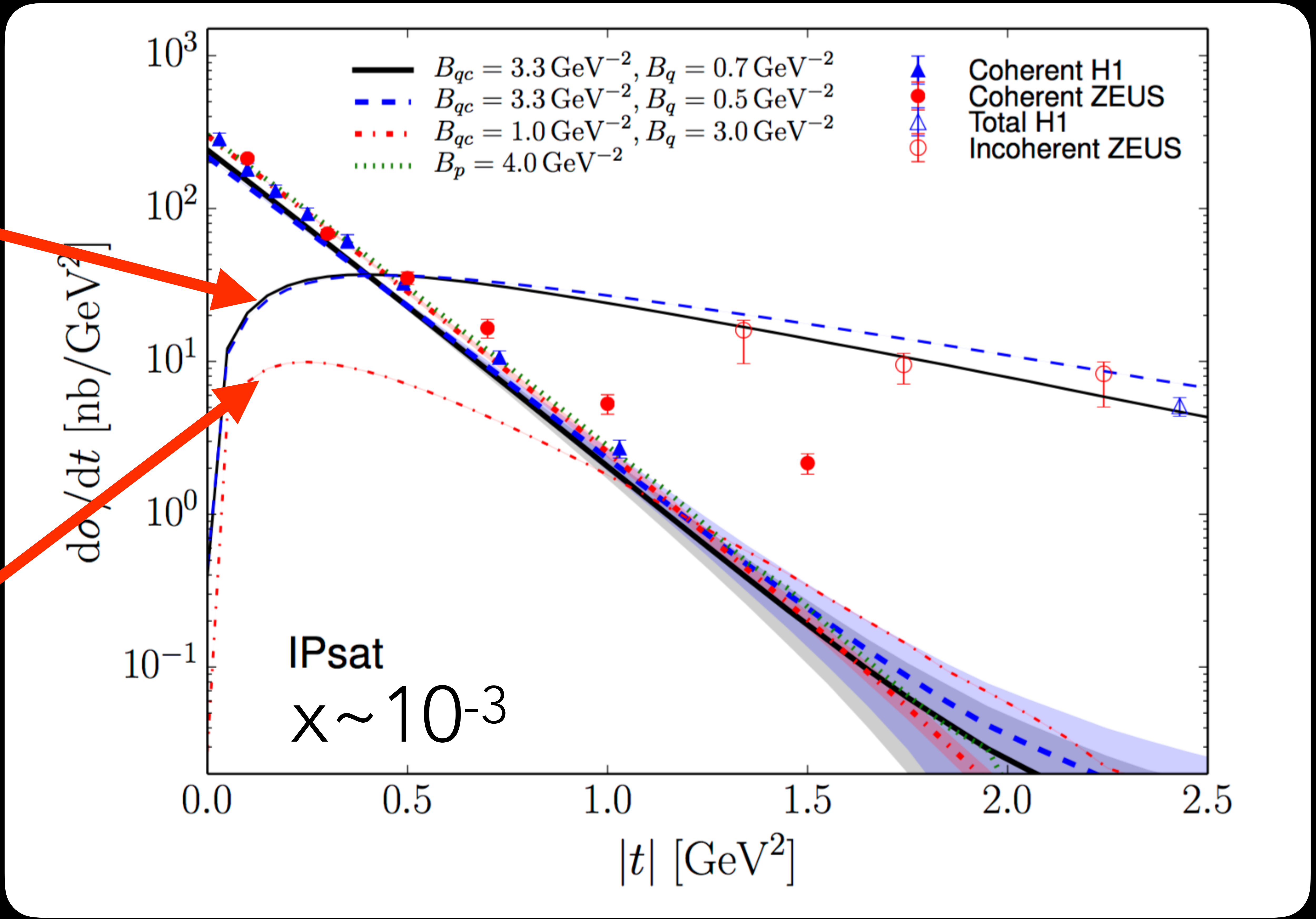
Alternatively, use fluctuating proton structure

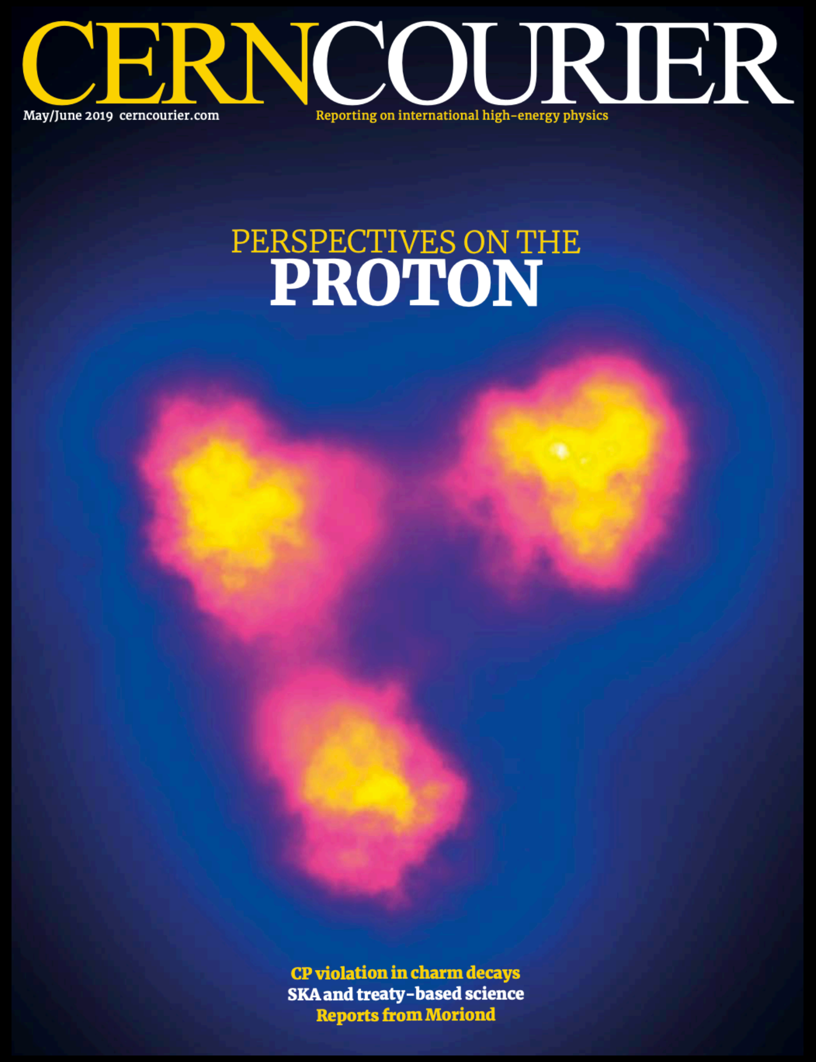
$$T_{\mathrm{p}}(\vec{b}) = \frac{1}{N_{\mathrm{q}}} \sum_{i=1}^{N_{\mathrm{q}}} T_{\mathrm{q}}(\vec{b} - \vec{b}_i) \quad \text{with } N_{\mathrm{q}} \text{ hot spots} \quad T_{\mathrm{q}}(\vec{b}) = \frac{1}{2\pi B_{\mathrm{q}}} e^{-b^2/(2B_{\mathrm{q}})}$$

Diffractive J/Ψ production in e+p collisions

H. Mäntysaari, B. Schenke, Phys. Rev. Lett. 117 (2016) 052301; Phys.Rev. D94 (2016) 034042



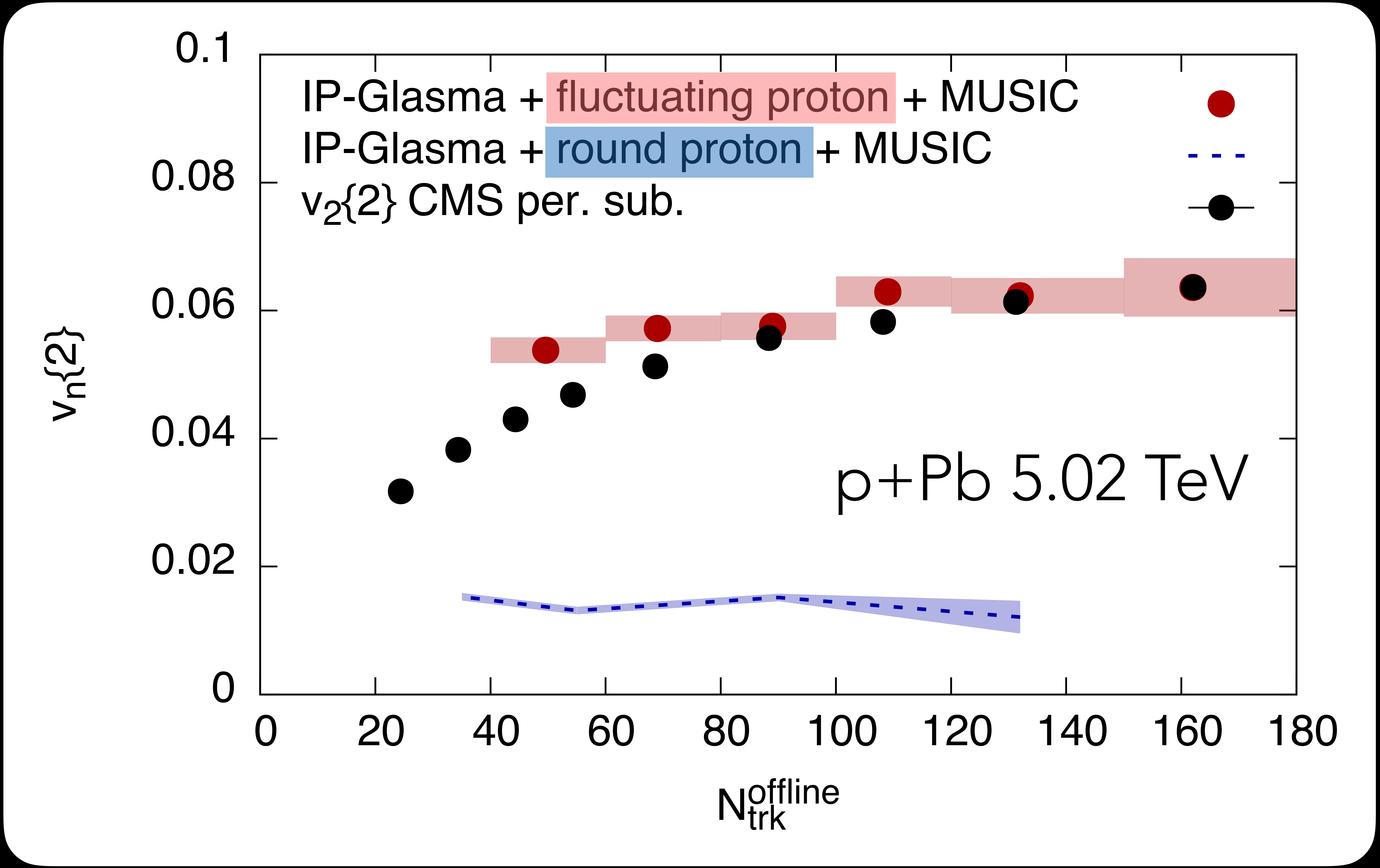




H1 collaboration, Eur. Phys. J. C46 (2006) 585; Phys. Lett. B568 (2003) 205
ZEUS collaboration, Eur. Phys. J. C24 (2002) 345; Eur. Phys. J. C26 (2003) 389

Effect of proton structure in p+A collisions

B. Schenke, R. Venugopalan, Phys. Rev. Lett. 113, 102301 (2014)
H. Mäntysaari, B. Schenke, C. Shen, P. Tribedy, Phys.Lett. B772 (2017) 681-686



Anisotropic flow in p+A depends on initial shape of the fireball

Round proton projectile leads to almost isotropic expansion and small v_2

Experimental data:
CMS Collaboration
Phys.Lett. B724, 213 (2013)

IP-Glasma=CGC initial state; MUSIC=fluid dynamics

Diffractive J/Ψ production in e+A collisions

H. Mäntysaari, B. Schenke, Phys. Rev. C101, 015203 (2020)

- Structure of light ions (d and ^{3}He) at small x
- Diffractive scattering and dipole model (IPSat and CGC)
- Energy evolution (JIMWLK)
- Results - Predictions for the Electron Ion Collider

Geometry: Nucleon distributions

H. Mäntysaari, B. Schenke, Phys. Rev. C101, 015203 (2020)

Nucleon distributions:

- Deuteron wave function:
  - Argonne v18 (AV18) R. B. Wiringa, V. G. J. Stoks and R. Schiavilla, Phys. Rev. C51 (1995) 38 `www.phy.anl.gov/theory/research/density2`
  - Hulthen:

$$\phi_{\mathrm{pn}}(d_{\mathrm{pn}}) = \frac{1}{\sqrt{2\pi}} \frac{\sqrt{ab(a+b)}}{b-a} \frac{e^{-ad_{\mathrm{pn}}} - e^{-bd_{\mathrm{pn}}}}{d_{\mathrm{pn}}}$$

$$a = 0.228\mathrm{fm}^{-1}$$
$$b = 1.18\mathrm{fm}^{-1}$$

see M. L. Miller, K. Reygers, S. J. Sanders, P. Steinberg, Ann. Rev. Nucl. Part. Sci. 57 (2007) 205

- ^{3}He wave function:
  - AV18+UIX J. Carlson and R. Schiavilla, Rev. Mod. Phys. 70 (1998) 743

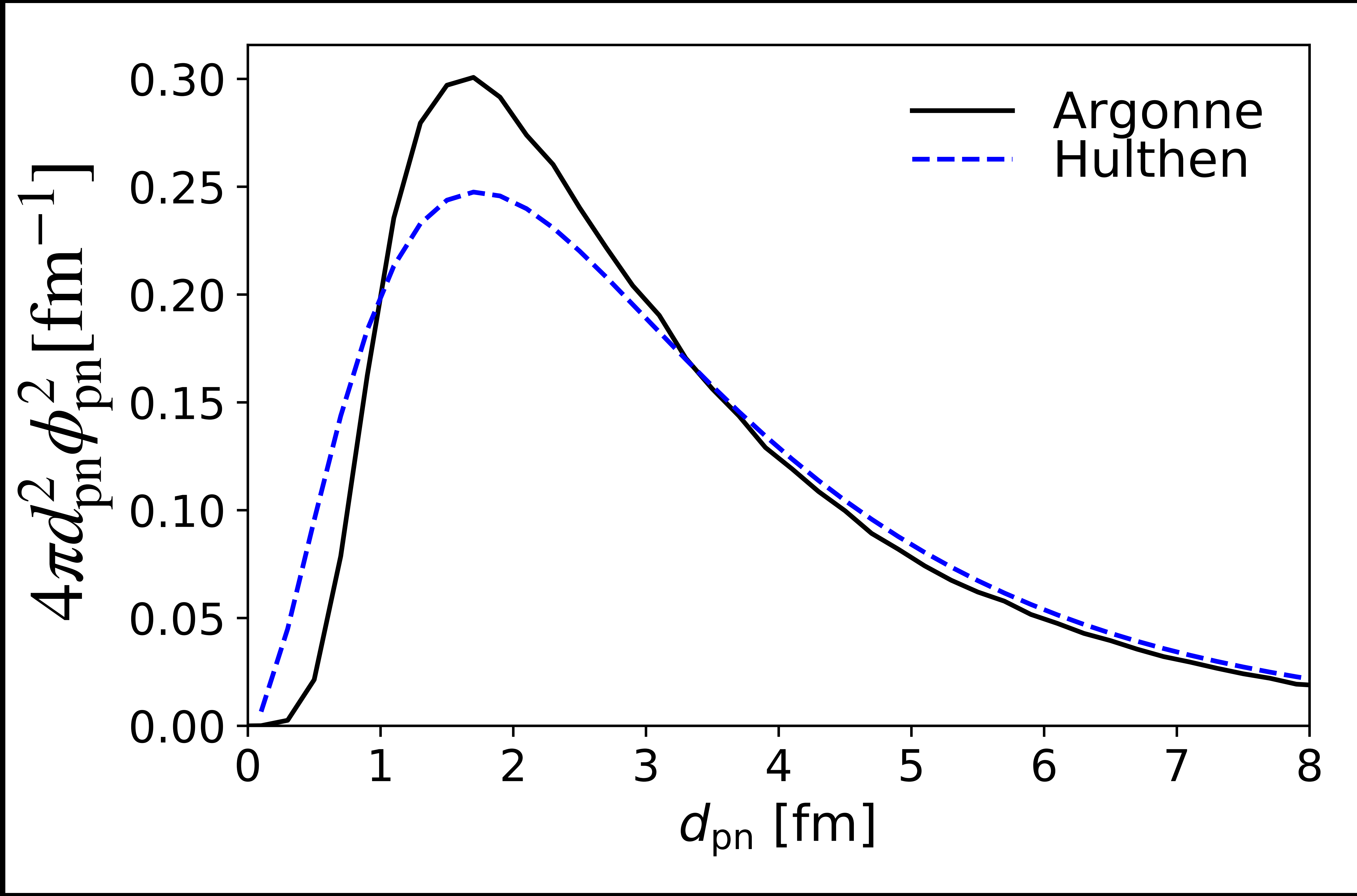
    same configurations as available in PHOBOS MC-Glauber

    C. Loizides, J. Nagle and P. Steinberg, arXiv:1408.2549

Geometry: Nucleon distributions

H. Mäntysaari, B. Schenke, Phys. Rev. C101, 015203 (2020)

Deuteron size distributions



We need the gluon distribution

Assumption:
Small x gluon structure follows the large x nucleon structure

Dipole amplitude in e+A scattering

H. Mäntysaari, B. Schenke, Phys. Rev. C101, 015203 (2020)

$$N^{\mathrm{A}}(\vec{r}, \overrightarrow{b}, x) = 1 - \prod_{i=1}^{A}\left[1 - N^{\mathrm{p}}(\vec{r}, \overrightarrow{b} - \overrightarrow{b}_i, x)\right]$$

This is equivalent to summing up the density profiles of the nucleons

We also fluctuate the normalization of Q_s^2 in each hot spot according to

$$P(\ln(Q_s^2/\langle Q_s^2\rangle) = \frac{1}{\sqrt{2\pi\sigma}}\exp\left[-\frac{\ln^2(Q_s^2/\langle Q_s^2\rangle)}{2\sigma^2}\right]$$

with $\sigma = 0.65$ for IPSat

Color Glass Condensate formalism

H. Mäntysaari, B. Schenke, Phys. Rev. C101, 015203 (2020)

Besides IPSat we also compute the dipole amplitude using the MV model and JIMWLK evolution (with the geometry as in IPSat)

Sample (local Gaussian) color charges with zero mean and

$$\langle \rho^a \rho^b \rangle \sim \delta^{ab} \delta^{(2)}(\vec{x} - \vec{y}) \delta(x^- - y^-) Q_s^2(\vec{x})$$

where Q_s at the initial x_0 is obtained from IPSat

MV model: L. D. McLerran and R. Venugopalan, Phys. Rev. D49 (1994) 2233

JIMWLK: J. Jalilian-Marian, A. Kovner, A. Leonidov, and H. Weigert, Nucl. Phys. B504, 415 (1997), Phys. Rev. D59, 014014 (1999)

E. Iancu, A. Leonidov, and L. D. McLerran, Nucl. Phys. A692, 583 (2001)

E. Ferreiro, E. Iancu, A. Leonidov, and L. McLerran, Nucl. Phys. A703, 489 (2002)

A. H. Mueller, Phys. Lett. B523, 243 (2001)

Color Glass Condensate formalism

H. Mäntysaari, B. Schenke, Phys. Rev. C101, 015203 (2020)

From color charges we obtain Wilson lines at the initial $x_0 = 0.01$

$$V(\vec{x}) = P\exp\left(-ig\int dx^{-}\frac{\rho(x^{-},\vec{x})}{\vec{\nabla}^2+\tilde{m}^2}\right)$$

from solution of Yang-Mills equations, with regulator $\tilde{m} = 0.4\,\mathrm{GeV}$

Evolution is done using the Langevin formulation of the JIMWLK equations

K. Rummukainen and H. Weigert Nucl. Phys. A739 (2004) 183; T. Lappi, H. Mäntysaari, Eur. Phys. J. C73 (2013) 2307

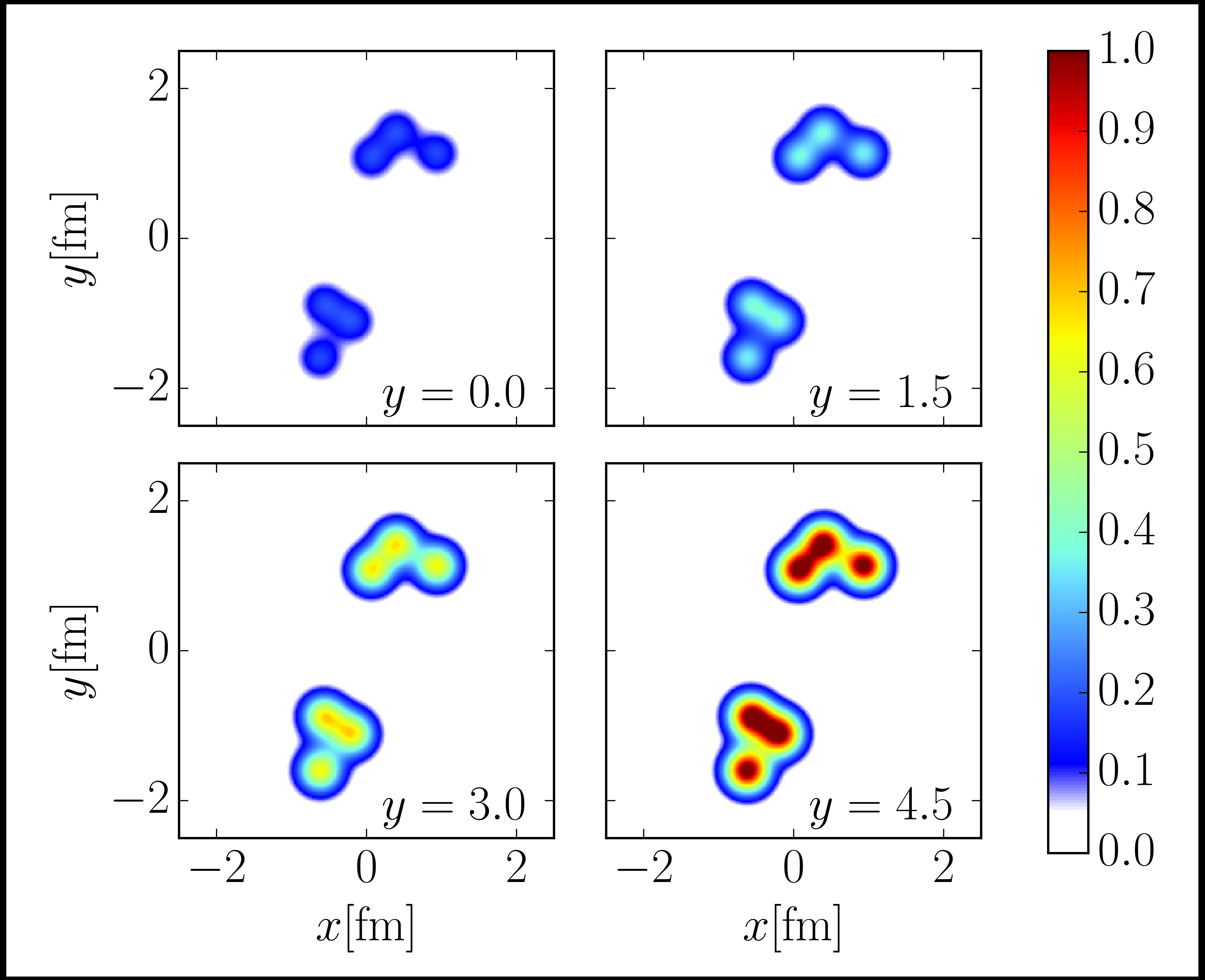
Long distance tales are tamed by imposing a regulator in the JIMWLK kernel, *m*=0.2 GeV (params. constrained by HERA VM + charm structure fct. data)

S. Schlichting, B. Schenke, Phys.Lett. B739 (2014) 313-319

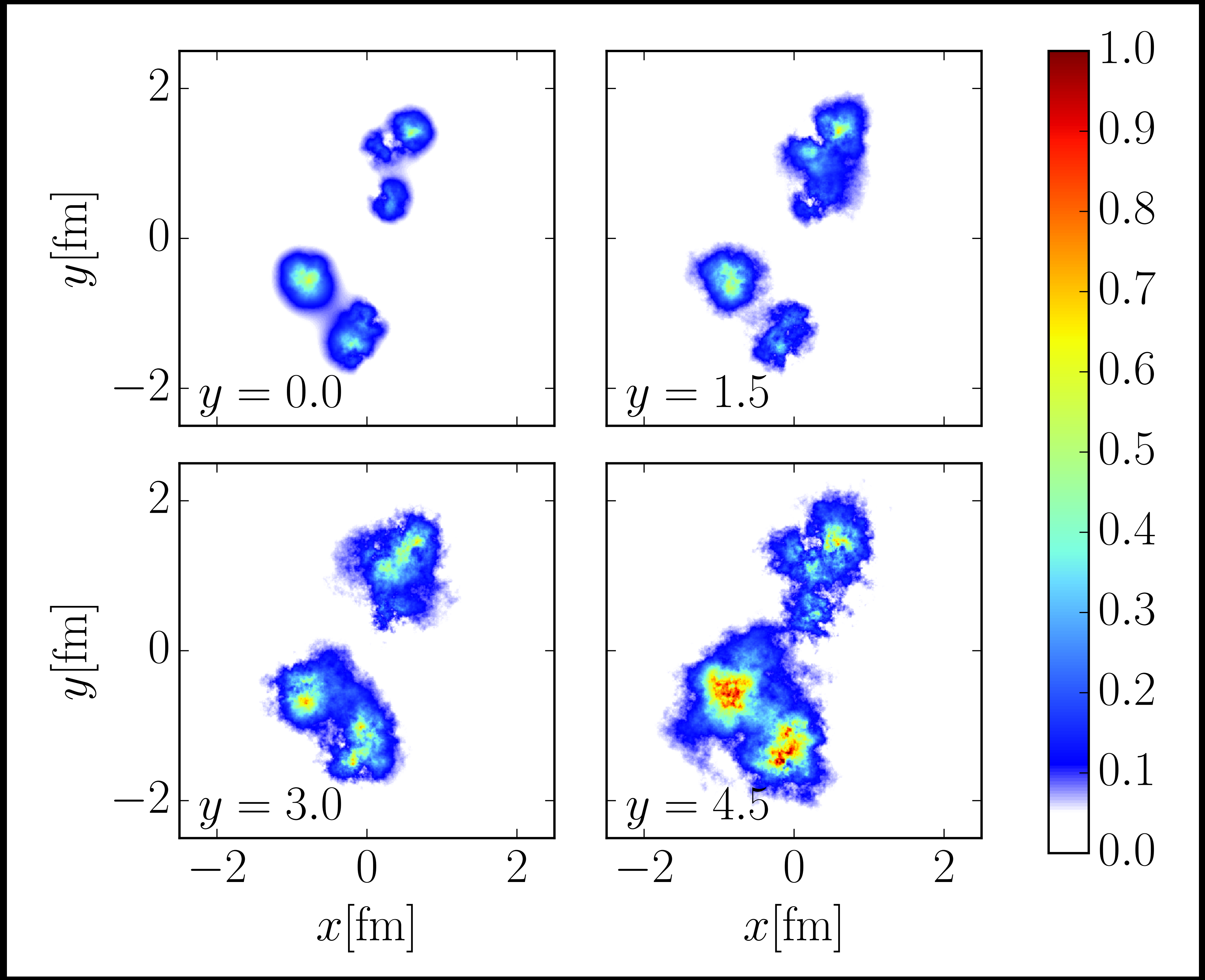
Energy evolution (deuterons)

H. Mäntysaari, B. Schenke, Phys. Rev. C101, 015203 (2020)

IPSat - only normalization changes



CGC - nucleus grows as well



We plot $1 - \mathrm{Re}[\mathrm{tr}(V(\vec{x})]/N_c$

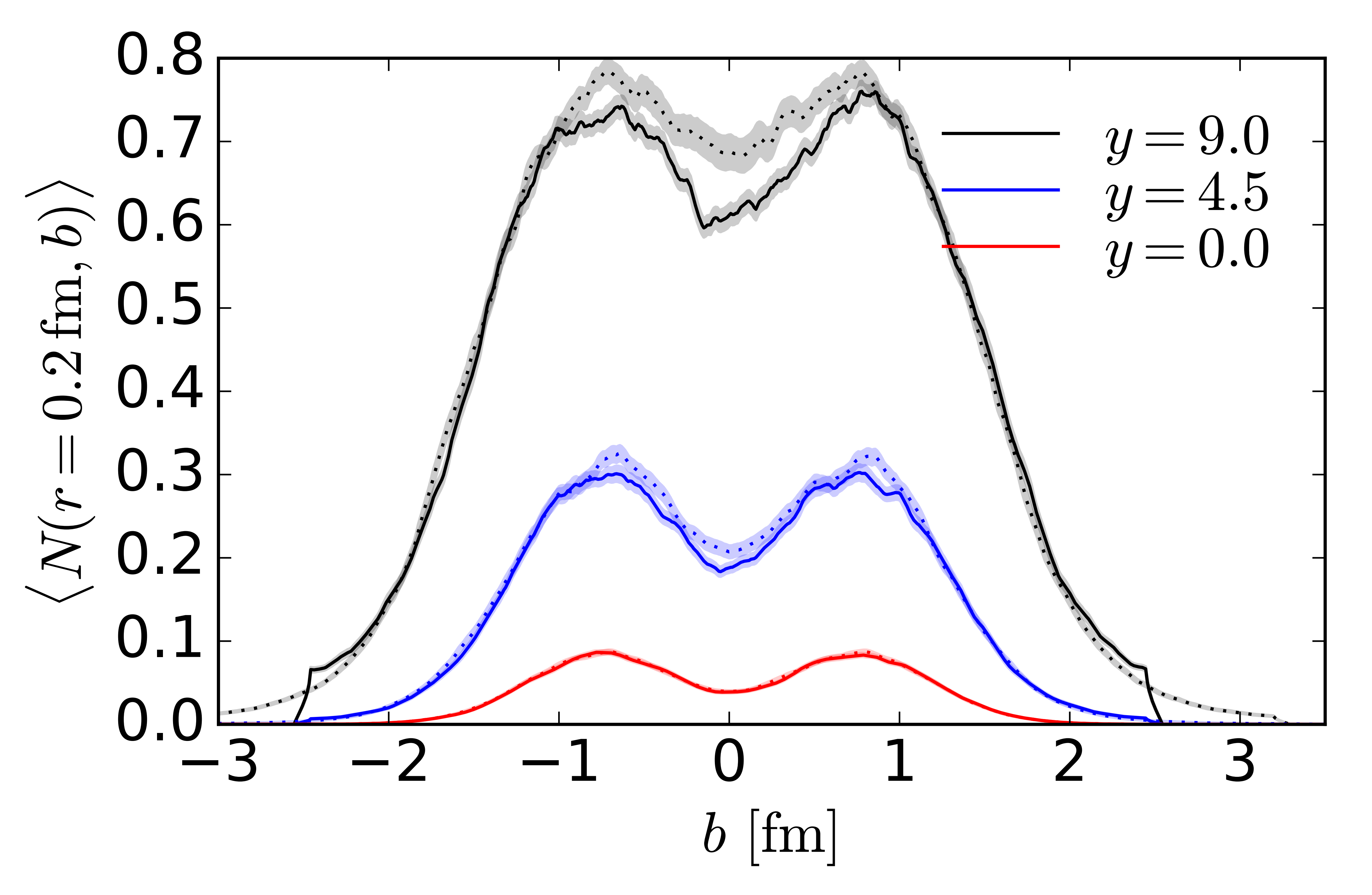
Saturation effects

H. Mäntysaari, B. Schenke, Phys. Rev. C101, 015203 (2020)

Comparing evolution of a deuteron (solid) to two individual nucleons (dotted)

The effect is only visible after substantial evolution

$d_{\mathrm{pn}} = 1.5\ \mathrm{fm}$



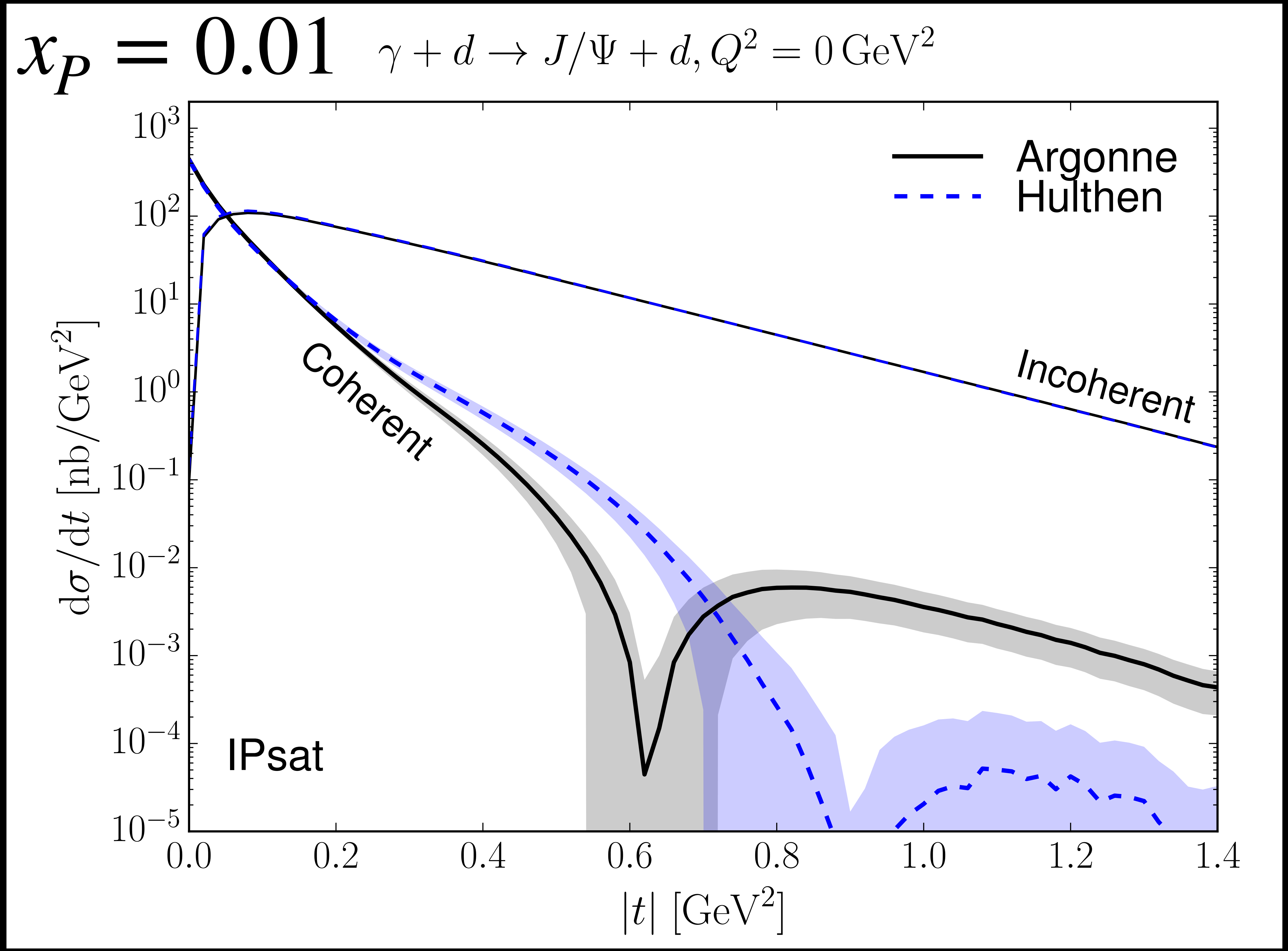
Predictions for the EIC: Effect of deuteron wave function

H. Mäntysaari, B. Schenke, Phys. Rev. C101, 015203 (2020)

J/Ψ production for $\sqrt{s} = 140\sqrt{Z/A}\,\mathrm{GeV}$

such that x_P can reach down to 10^{-4} to 10^{-3}

$$x_P = \frac{Q^2 + M_V^2 - t}{Q^2 + W^2 - m_N^2}$$



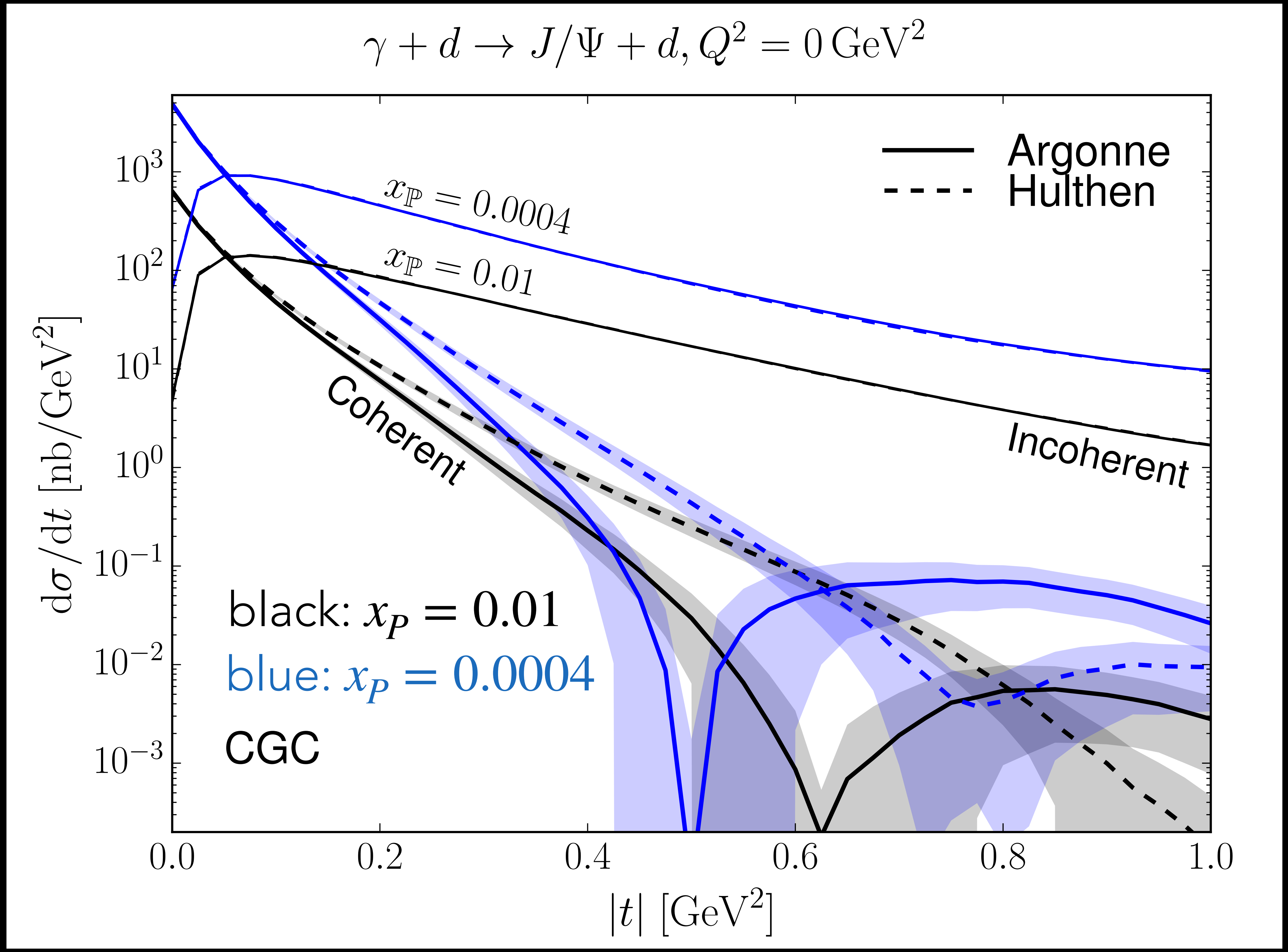
Differences appear at $|t| \gtrsim 0.3\,\mathrm{GeV}^2$
(Long distance behavior is similar)

The two wave functions result in similar rms sizes of the deuteron

Difference in dip position must come from the different average impact parameter profile.

Predictions for the EIC: Small-x evolution

H. Mäntysaari, B. Schenke, Phys. Rev. C101, 015203 (2020)



(no nucleon shape fluctuations)

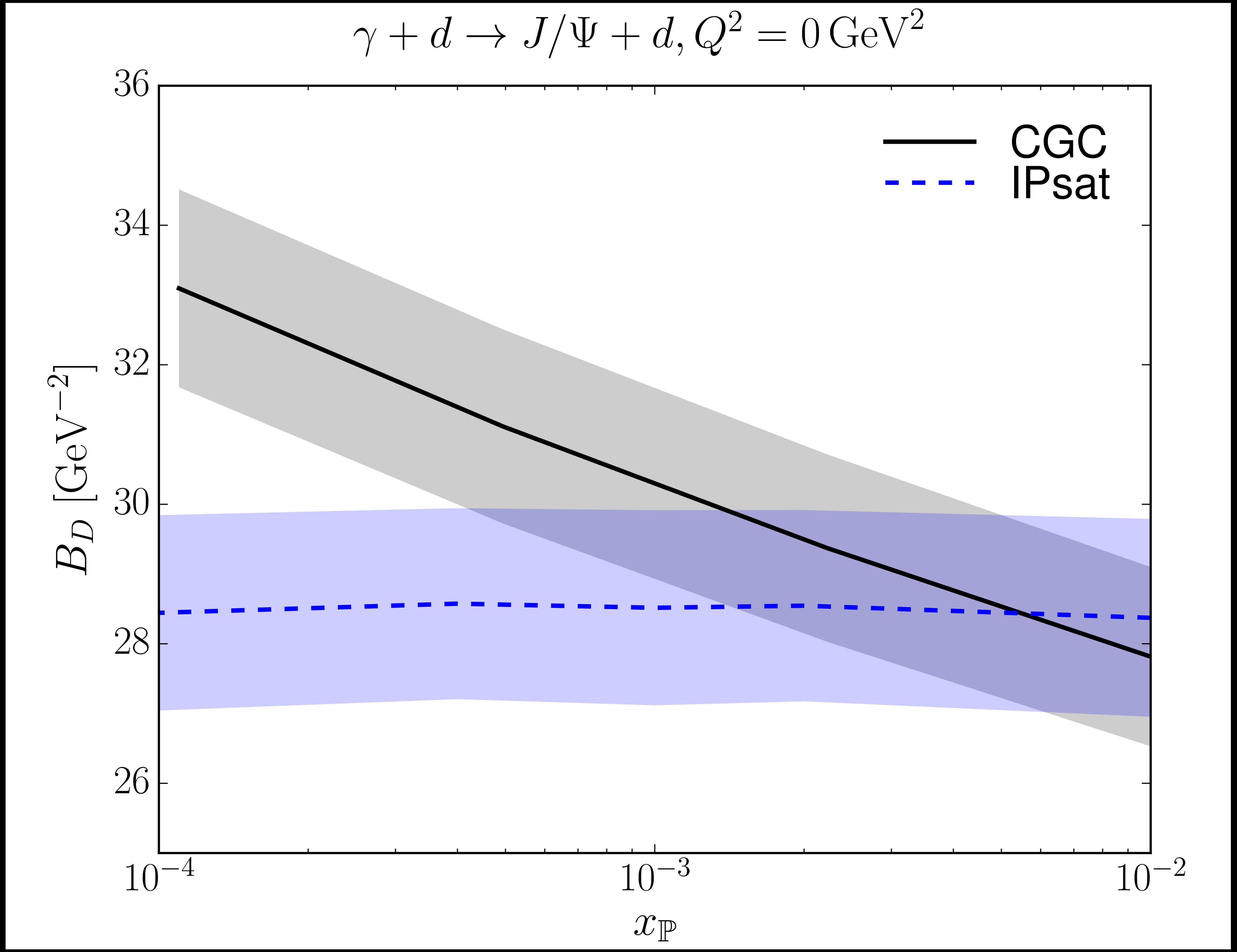
Differences between wave functions survive the JIMWLK evolution

They are not washed out at small x

Dip moves to smaller $|t|$ indicating growth of the average target size

Predictions for the EIC: Target size vs. x

H. Mäntysaari, B. Schenke, Phys. Rev. C101, 015203 (2020)

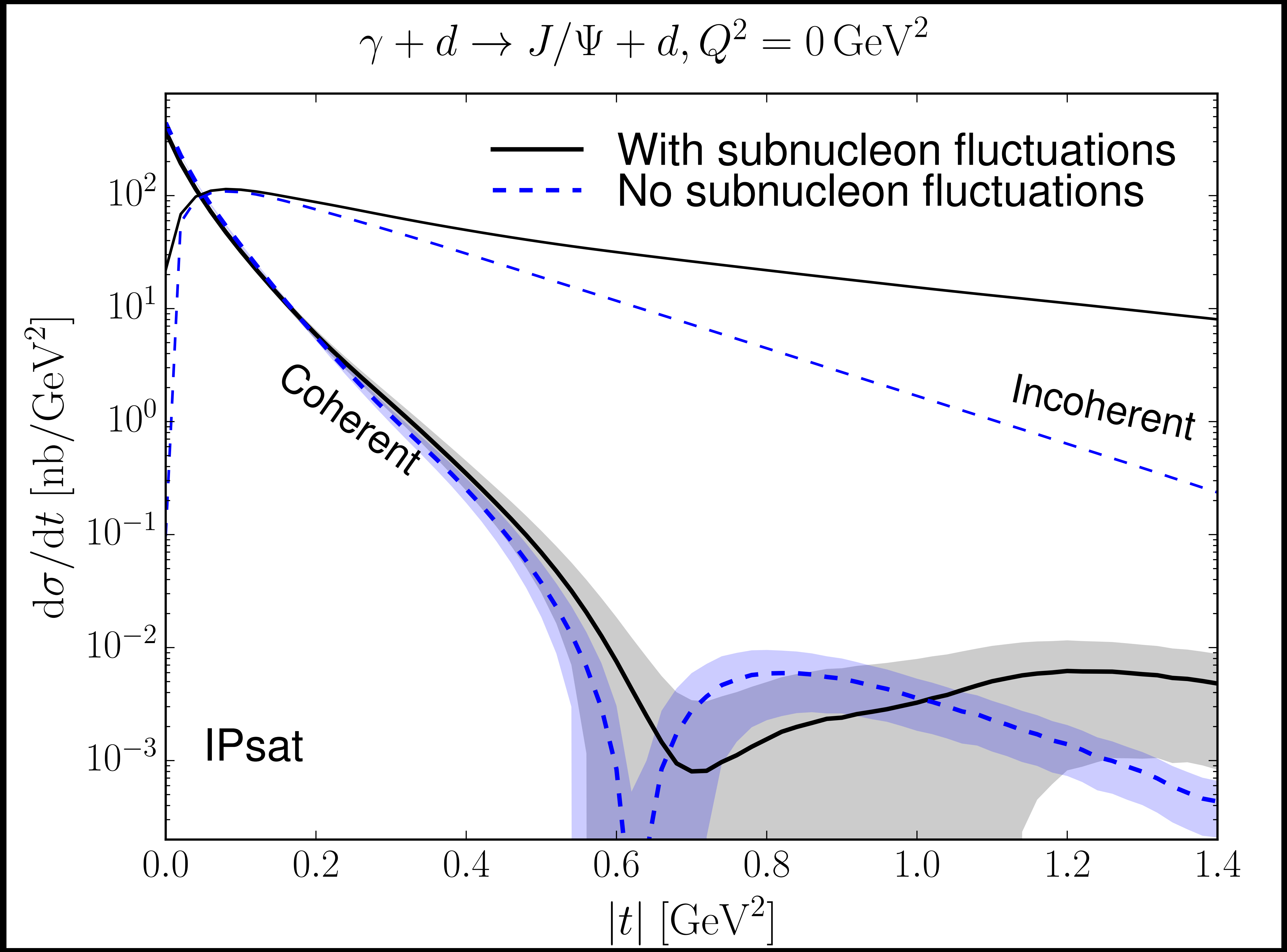


Growth of the target with decreasing x is illustrated by extracting B_D from a fit to the coherent cross section at small t using $d\sigma/dt \sim \exp(-B_D|t|)$

IPSat model does not include the growth of the target

Predictions for the EIC: Effect of nucleon shape fluctuations

H. Mäntysaari, B. Schenke, Phys. Rev. C101, 015203 (2020)



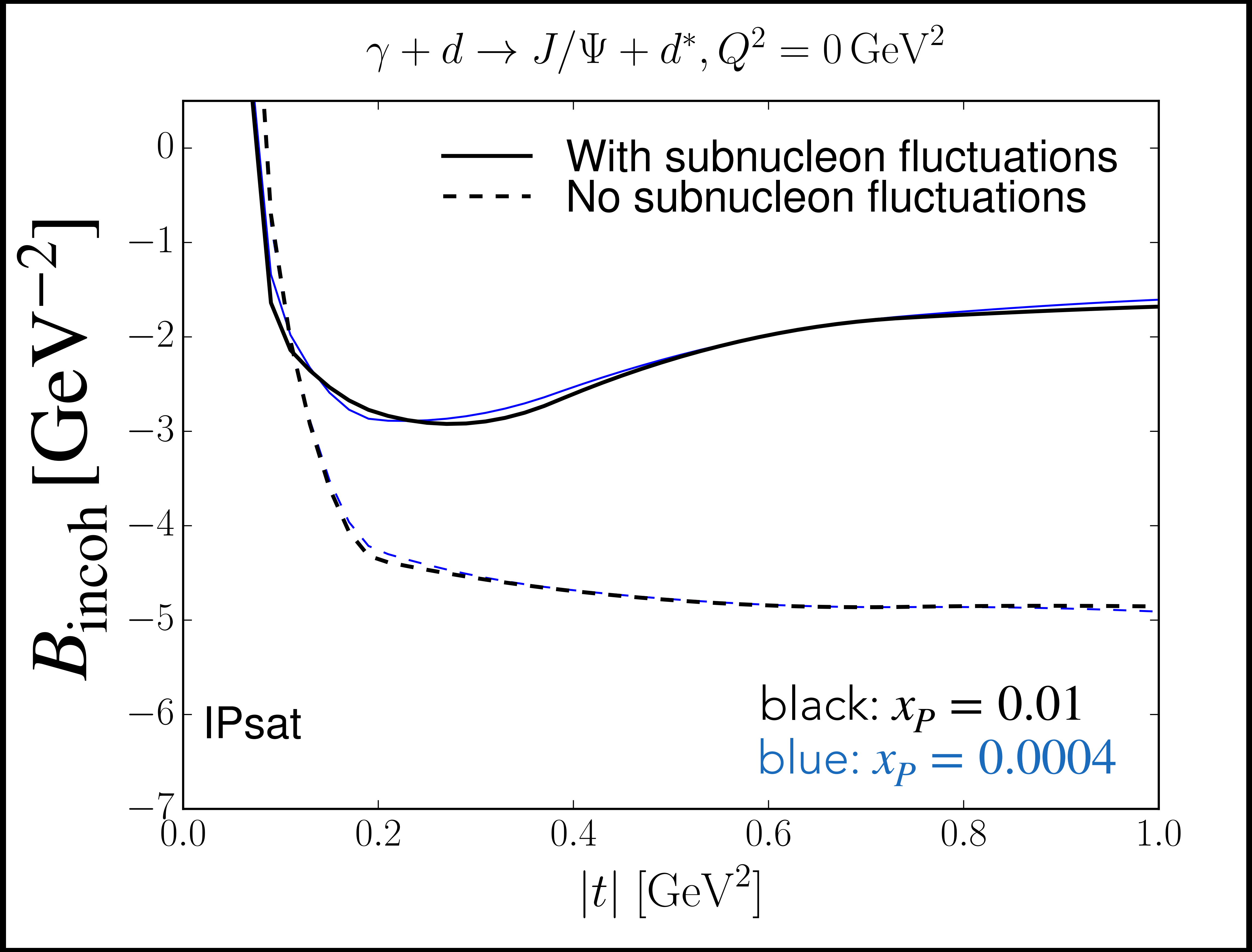
Coherent cross section unchanged (within errors) - average shape is (approximately) the same by construction

Subnucleon fluctuations increase incoherent cross section significantly for $|t| \gtrsim 0.25\,\mathrm{GeV}^2$

Lower $|t|$ are dominated by fluctuations on larger length scales

Predictions for the EIC: Slope of incoherent cross section

H. Mäntysaari, B. Schenke, Phys. Rev. C101, 015203 (2020)



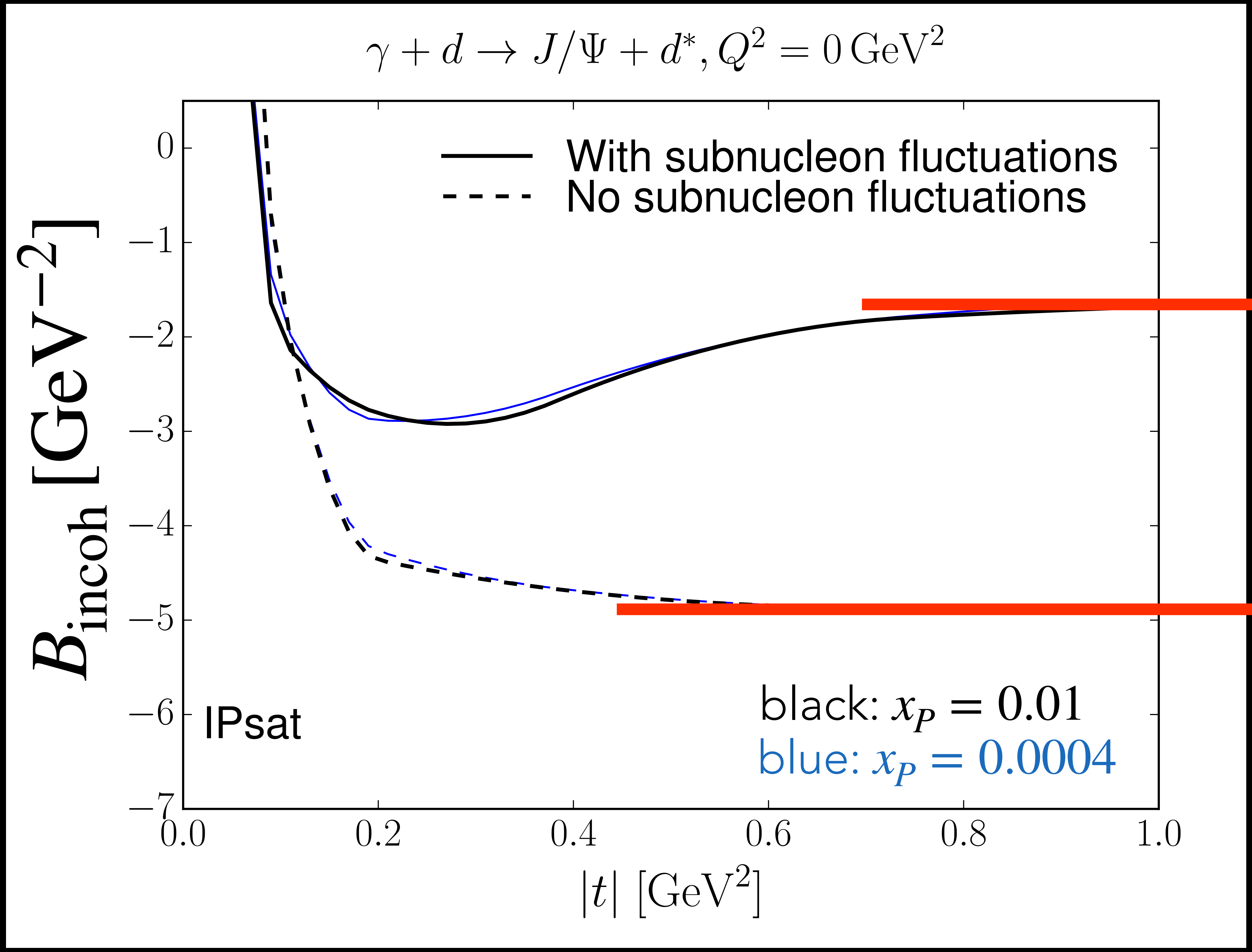
IPSat

Size of fluctuating object controls fall-off of the incoherent xsec $\sim e^{-B_{\mathrm{incoh}}|t|}$

see T. Lappi and H. Mäntysaari, Phys. Rev. C83 (2011) 065202

Predictions for the EIC: Slope of incoherent cross section

H. Mäntysaari, B. Schenke, Phys. Rev. C101, 015203 (2020)



IPSat

hot spot scale $B_q = 1\,\mathrm{GeV}^{-2}$

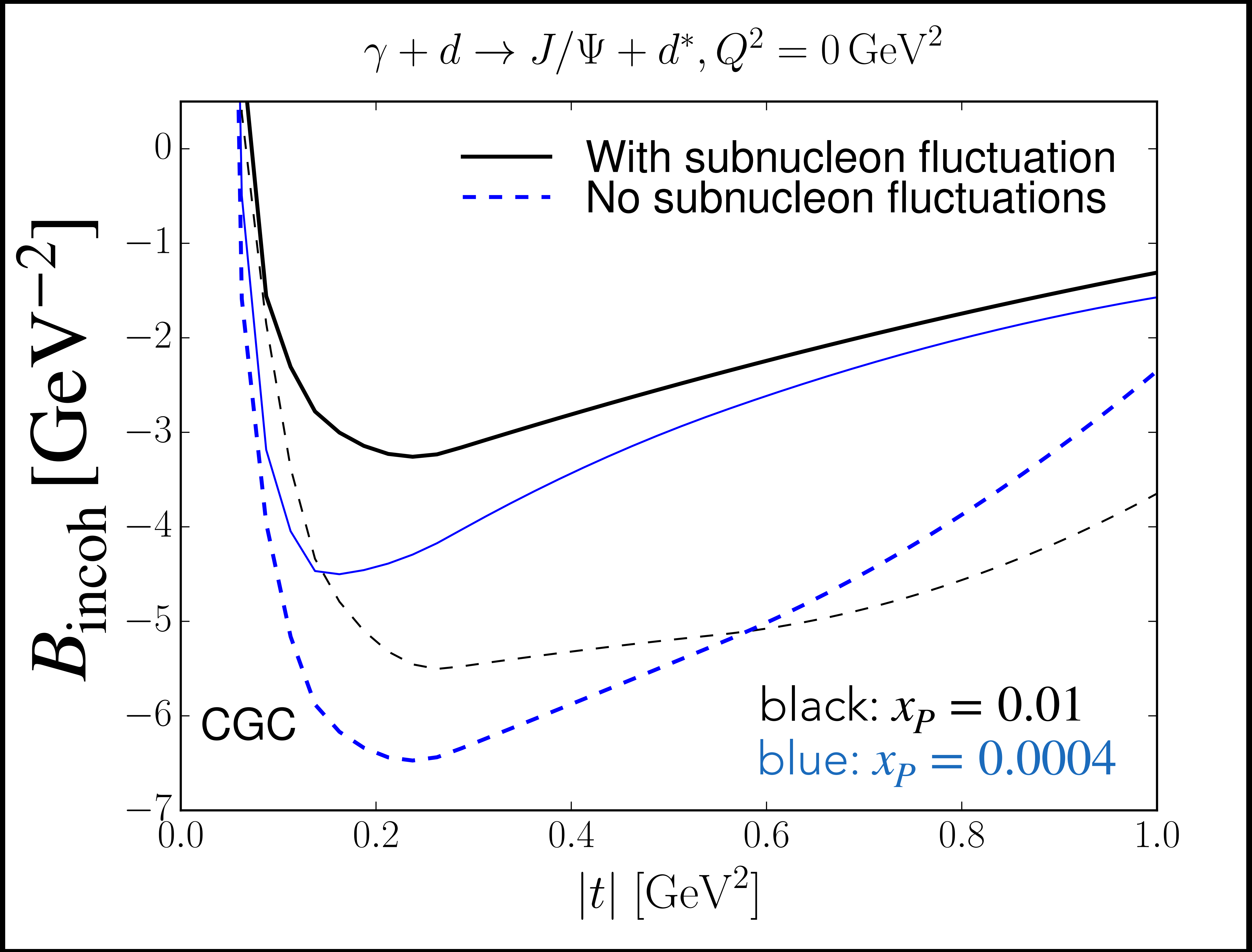
nucleon scale $B_p = 4\,\mathrm{GeV}^{-2}$

Size of fluctuating object controls fall-off of the incoherent xsec $\sim e^{B_{\mathrm{incoh}}|t|}$

see T. Lappi and H. Mäntysaari, Phys. Rev. C83 (2011) 065202

Predictions for the EIC: Slope of incoherent cross section

H. Mäntysaari, B. Schenke, Phys. Rev. C101, 015203 (2020)



CGC

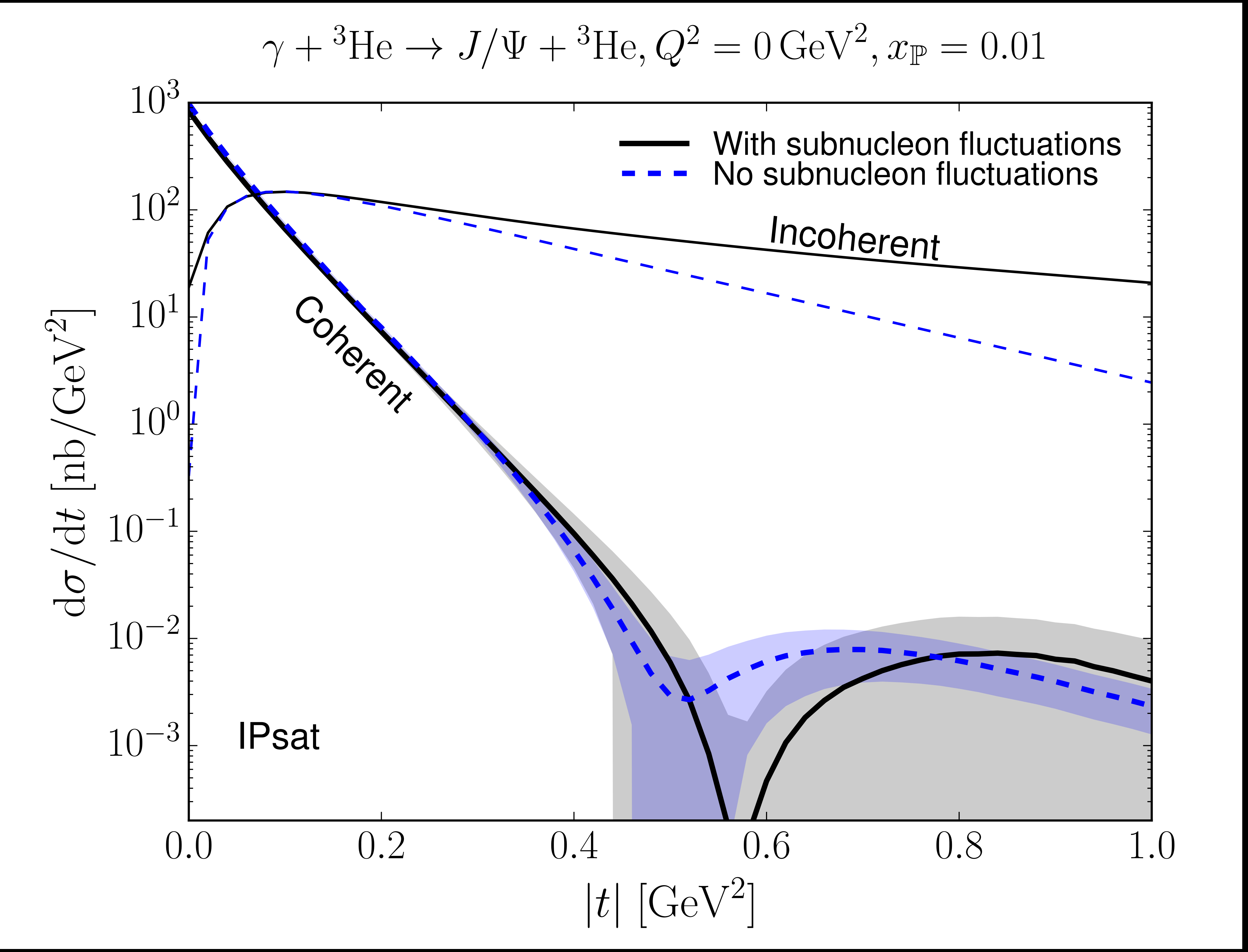
At $|t| \sim 0.2\,\mathrm{GeV}^2$ spectra become steeper with decreasing x (growth of the system and its fluctuating constituents)

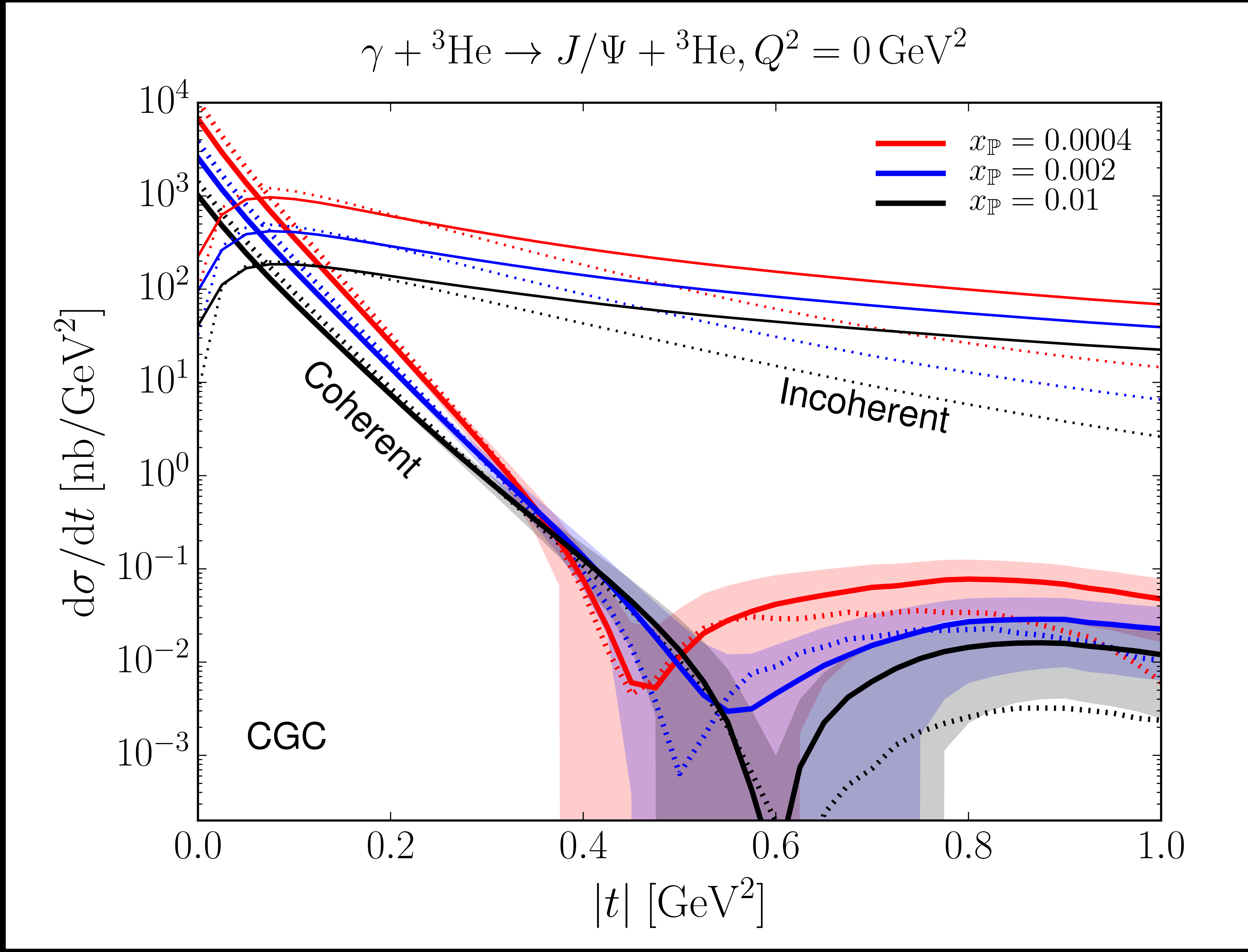
Slopes are not constant at large $|t|$
Reason: Color charge fluctuations

At smaller x color charge fluctuations happen on shorter scale $\sim 1/Q_s$ (blue dashed line crosses black dashed line)

Predictions for the EIC: Cross sections for ^{3}He targets

H. Mäntysaari, B. Schenke, Phys. Rev. C101, 015203 (2020)





Conclusions

- Diffractive J/ψ production in high energy e+A collisions can provide information on the shape and size of the gluon distribution in the nuclear target and the size scales of its fluctuating constituents

- We will be able to check the relation between spatial charge (large *x*) and small *x* gluon distributions

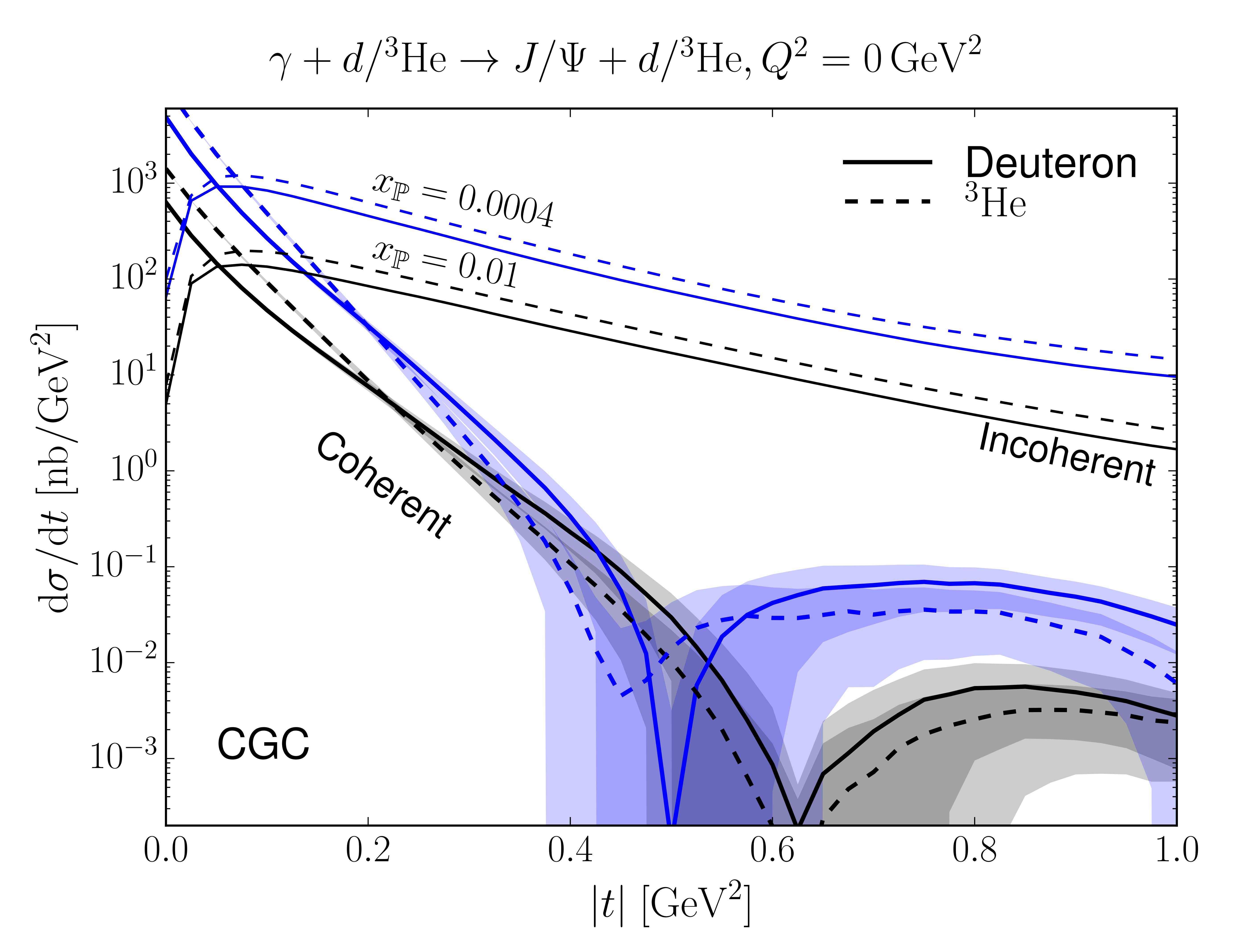
- The *x* dependence is sensitive to QCD energy evolution of the nucleus and its constituents

- The incoherent cross section becomes sensitive to subnucleon structure fluctuations for $|t| \gtrsim 0.25\,\mathrm{GeV}^2$

Backup

Predictions for the EIC: d vs. ^{3}He targets

H. Mäntysaari, B. Schenke, Phys. Rev. C101, 015203 (2020)



Björn Schenke, BNL

COLOR GLASS CONDENSATE

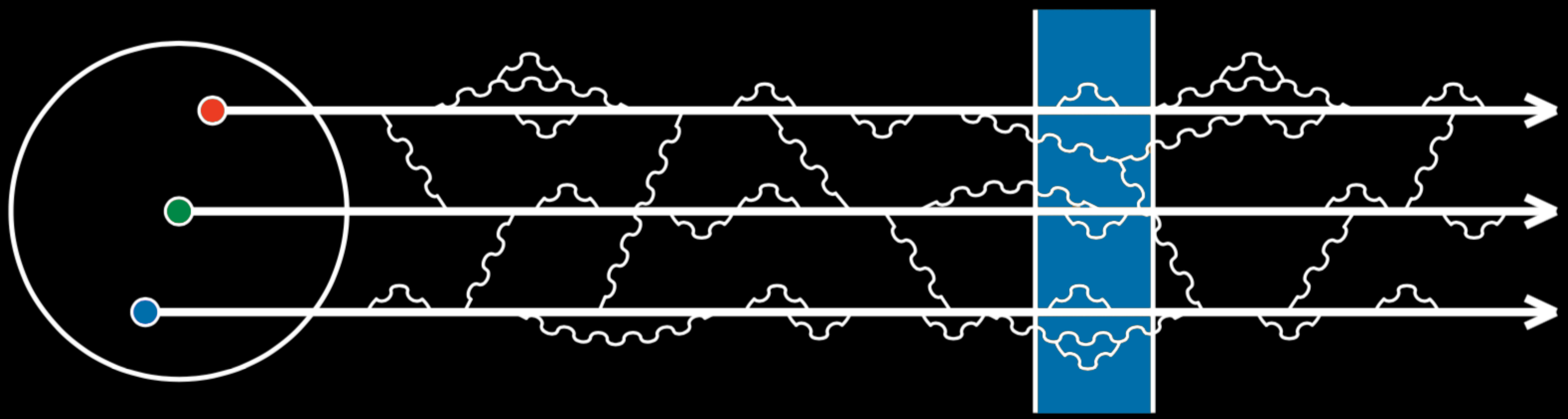


Figure from F. Gelis

Nucleon at rest:

- Complicated non-perturbative object
- Contains fluctuations at all scales smaller than its own size
- Only the fluctuations that are longer lived than the external probe participate in the interaction process
- The only role of short lived fluctuations is to renormalize the masses and couplings
- Interactions are very complicated if the constituents of the nucleon have a non trivial dynamics over time-scales comparable to those of the probe

Björn Schenke, BNL

COLOR GLASS CONDENSATE

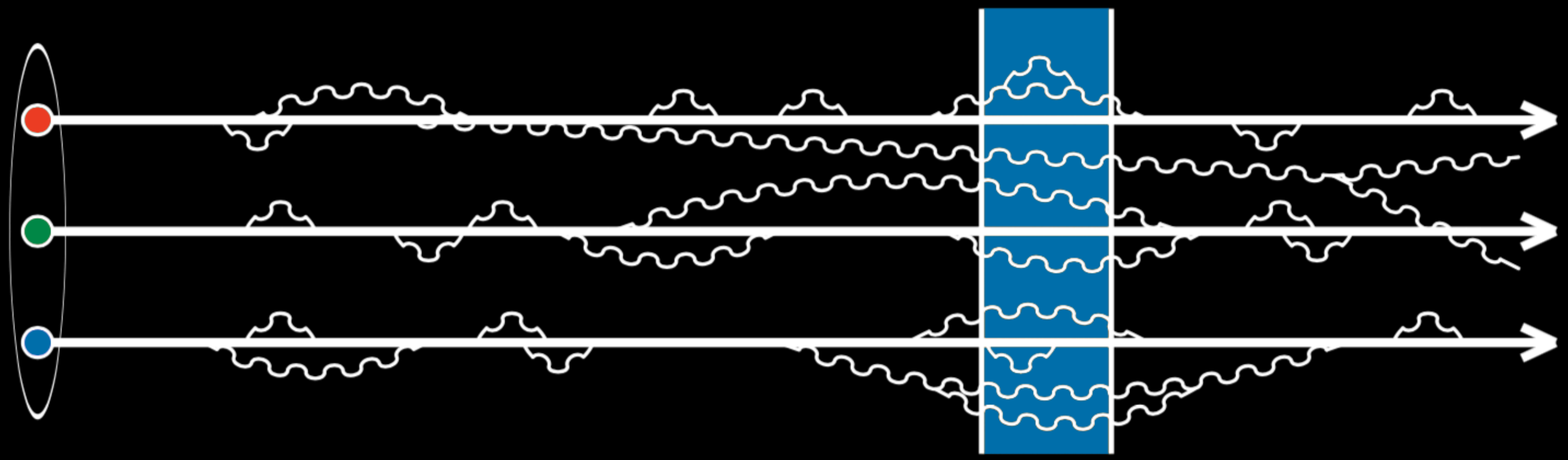


Figure from F. Gelis

Nucleon at high energy:

- Dilation of all internal time-scales of the nucleon
- Interactions among constituents now take place over time-scales longer than the characteristic time-scale of the probe → The constituents behave as if they were free
- Many fluctuations live long enough to be seen by the probe. Nucleon appears denser at high energy (contains more gluons)
- Pre-existing fluctuations are totally frozen over the time-scale of the probe, and act as static sources of new partons

Color Glass Condensate formalism

H. Mäntysaari, B. Schenke, Phys. Rev. C101, 015203 (2020)

From color charges we obtain Wilson lines at the initial $x_0 = 0.01$

$$V(\overrightarrow{x}) = P\exp\left(-ig\int dx^{-}\frac{\rho(x^{-},\overrightarrow{x})}{\overrightarrow{\nabla}^{2}+\tilde{m}^{2}}\right)$$

from solution of Yang-Mills equations, with regulator $\tilde{m} = 0.4\,\mathrm{GeV}$

Evolution in x uses the Langevin formulation of the JIMWLK equations

$$\frac{d}{dy}V(\overrightarrow{x}) = V(\overrightarrow{x})(it^{a})\left[\int d^{2}z\,\varepsilon^{ab,i}_{\overrightarrow{x},\vec{z}}\,\xi_{\vec{z}}(y)^{b}_{i} + \sigma^{a}_{\overrightarrow{x}}\right]$$

with random noise ξ and coefficient $\varepsilon^{ab,i}_{\overrightarrow{x},\vec{z}} = \left(\frac{\alpha_s}{\pi}\right)^{\frac{1}{2}} K^{i}_{\overrightarrow{x}-\vec{z}}[1 - V^{\dagger}(\overrightarrow{x})V(\vec{z})]^{ab}$

Color Glass Condensate formalism

H. Mäntysaari, B. Schenke, Phys. Rev. C101, 015203 (2020)

The kernel is given by $K^i_{\vec{x}} = \dfrac{x^i}{x^2}$

To regulate long distance tales we make the replacement

$$K^i_{\vec{x}} \to m|\vec{x}|K_1(m|\vec{x}|)\frac{x^i}{x^2}$$

Modified Bessel function K_1 suppresses contributions at distances $\gtrsim 1/m$

We use m=0.2 GeV