ACCESSING THE GLUON CONTENT OF PROTONS AND NUCLEI IN ULTRA PERIPHERAL COLLISIONS

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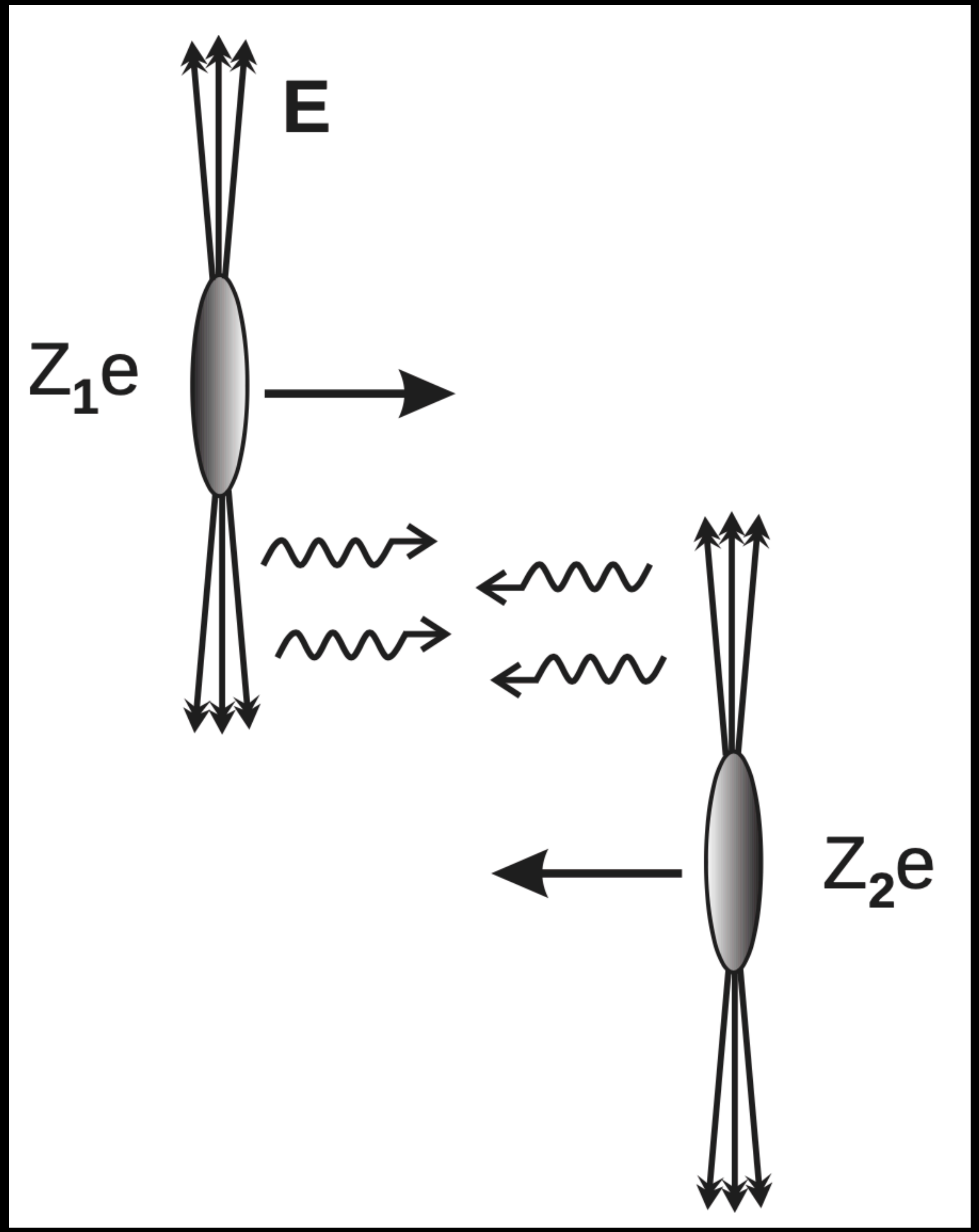
Ultraperipheral collisions (UPC)

- At an impact parameter $|b_T| > 2R_A$ nuclei are photon sources
- Photons are quasi-real $Q^2 = 0$
- High energy $\gamma + \gamma$, $\gamma + p$, $\gamma + A$ at RHIC and LHC
- Focus on $\gamma + p$ and $\gamma + A$ and study diffractive production of vector mesons:

  At small x target is mostly gluons

$$\frac{d\sigma^{\gamma^* A \to VA}}{dt} \propto \left[xg(x, Q^2)\right]^2$$ (gluon distribution squared)



Ultraperipheral collisions (UPC)

C. A. Bertulani, S. R. Klein and J. Nystrand, Ann. Rev. Nucl. Part. Sci. 55 (2005) 271

Higher energy in $\gamma + p$ than at HERA

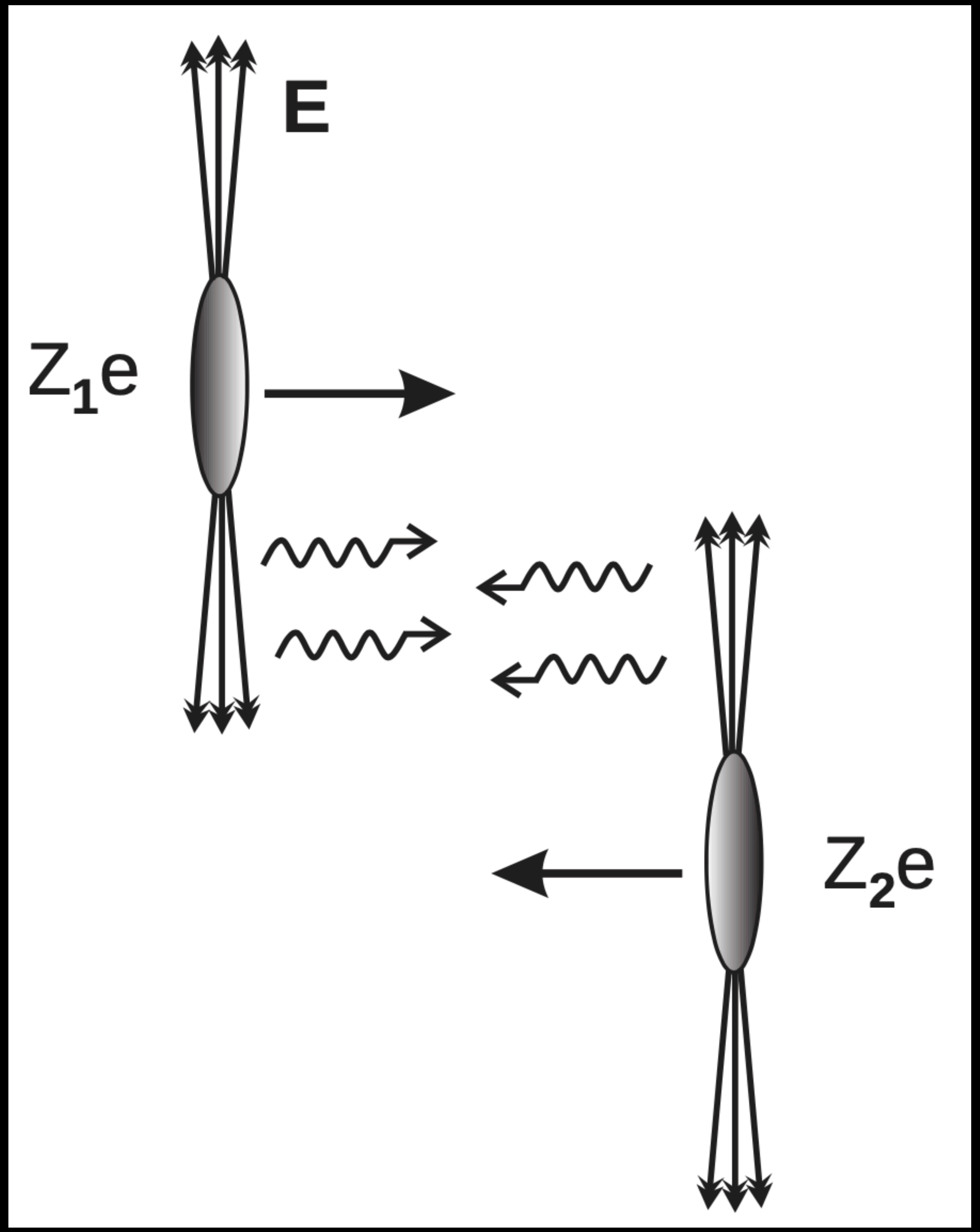
Can study $\gamma A \to VA$ even before the EIC is built

Cross section is convolution of photon flux n^{A_1} from nucleus A_1 and γA_2 cross section (and vice versa):

$$\frac{d\sigma^{AA\to J/\psi AA'}}{dt} = n^{A_2}(\omega_2)\,\sigma^{\gamma A_1}(y) + n^{A_1}(\omega_1)\,\sigma^{\gamma A_2}(-y)$$

y is the rapidity of the J/ψ

$\omega_{1/2}$ are the photon energies



$\gamma^* A$ cross section - the same as in e+A collisions

Coherent diffraction:

Target stays intact

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

Incoherent diffraction:

Target breaks up

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

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

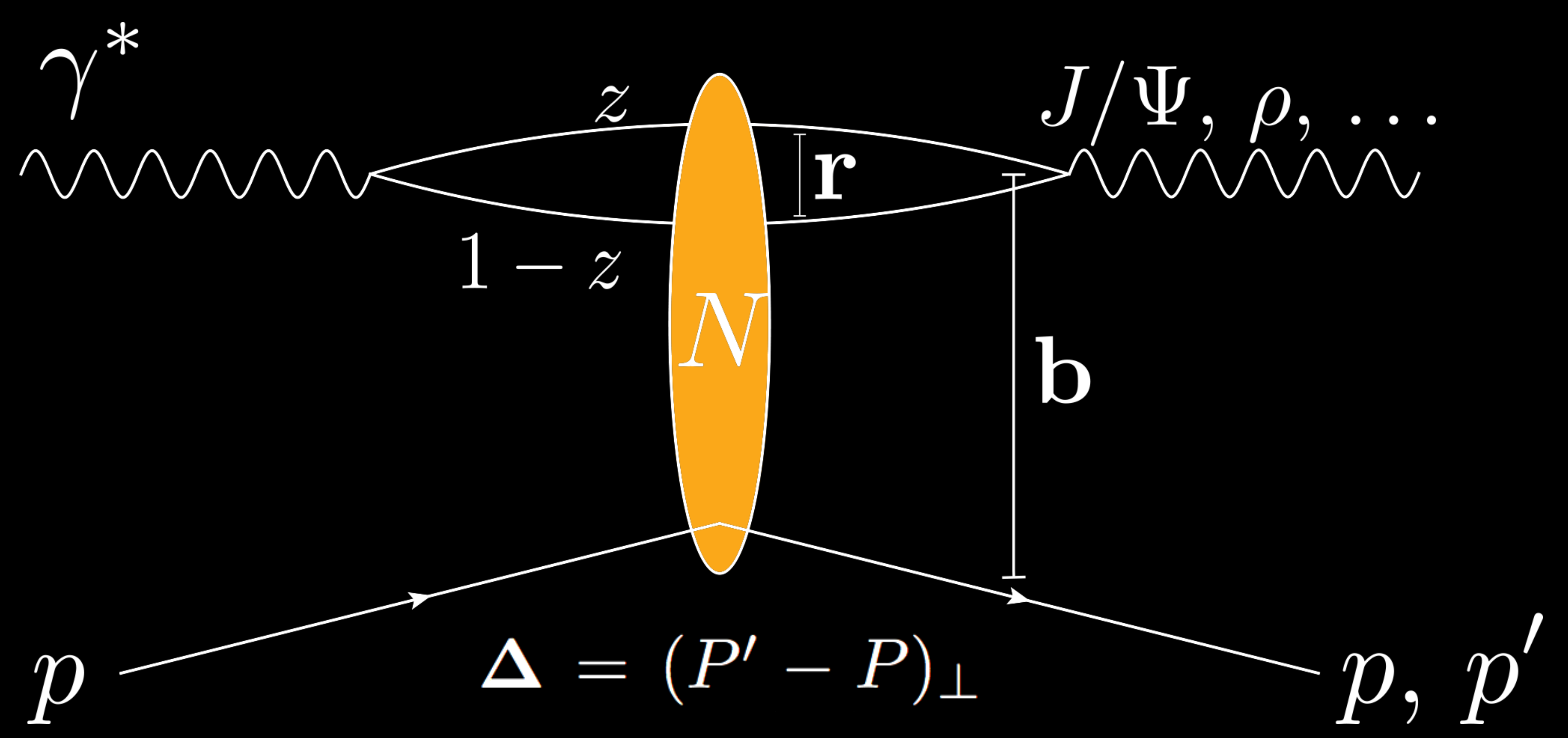
A. Kovner and U. A. Wiedemann, Phys. Rev. D64 (2001) 114002

Dipole picture: Scattering amplitude

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

High energy factorization:

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



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

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

Modeling the dipole amplitude

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

IPSat model:

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

Proton targets: parameters $\mu_0^2, C, xg(x, \mu_0^2), B_{\mathrm{p}}$(in T) fixed by HERA data

Scale dependence of xg obtained from DGLAP evolution

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

Alternatively, use fluctuating proton structure

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

Modeling the dipole amplitude - heavy nuclei

For a heavy ion target use an independent scattering approximation

H. Kowalski and D. Teaney, Phys. Rev. D68 (2003) 114005
T. Lappi and H. Mäntysaari, Phys. Rev. C83 (2011) 065202
H. Mäntysaari, B. Schenke, Phys.Lett.B 772 (2017) 832-838

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

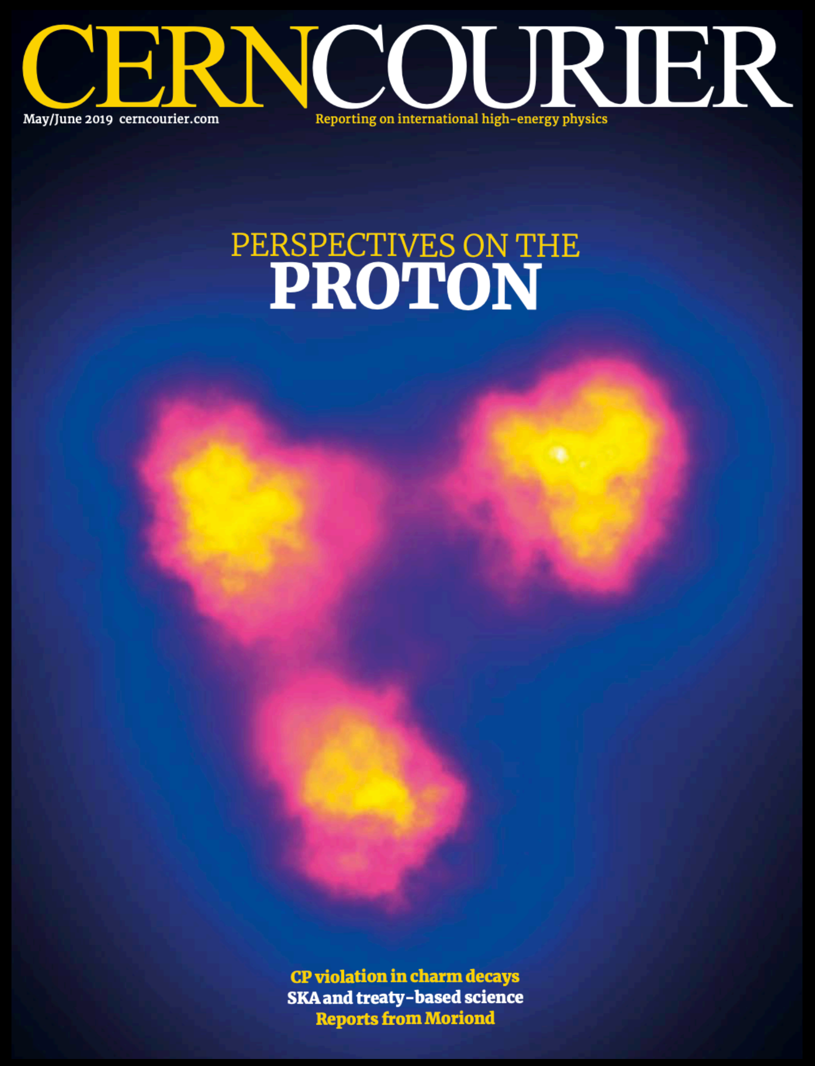
[1 – N] is the probability not to scatter off an individual nucleon

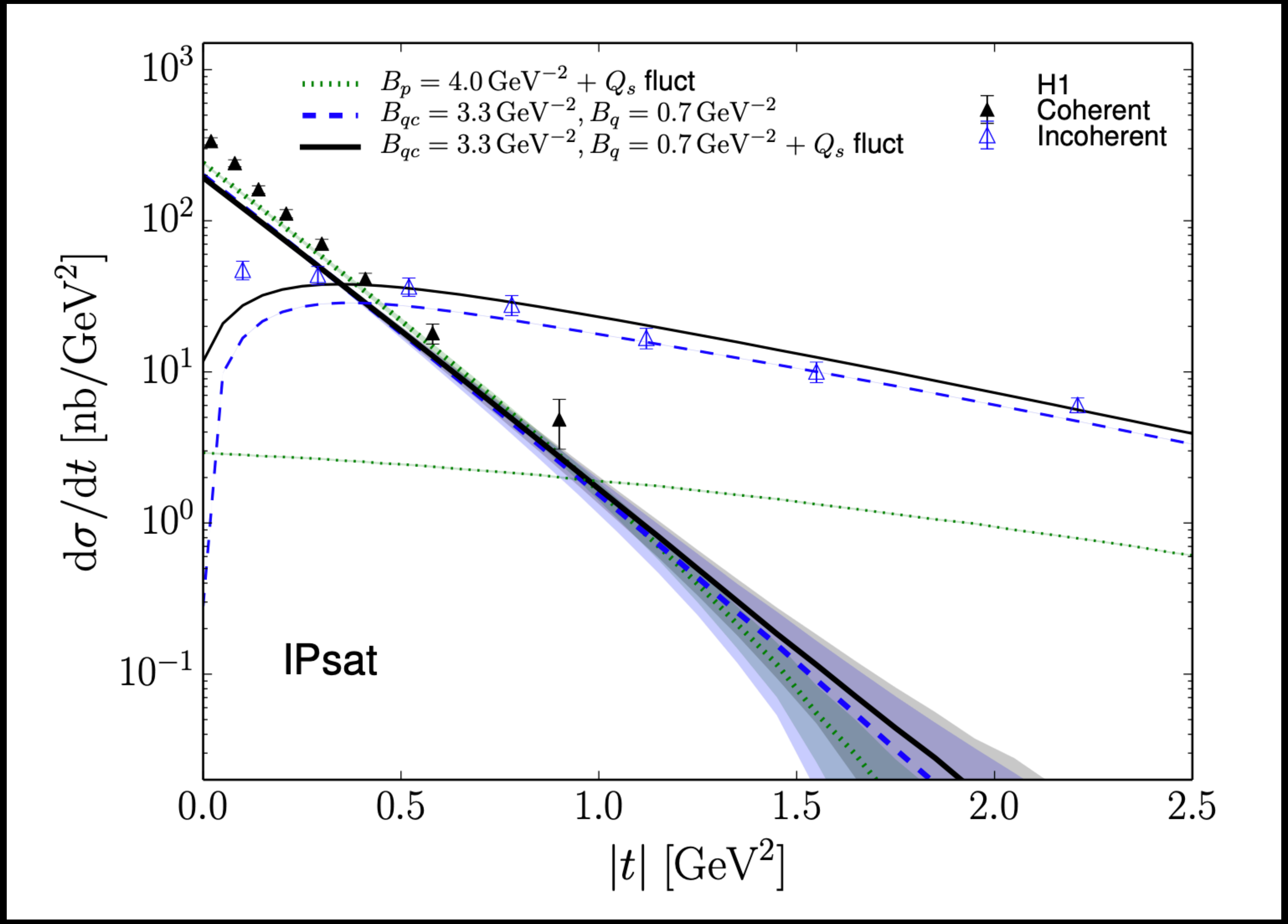
thus $\prod_i (1 - N_i)$ is the probability not to scatter off the entire nucleus.

e+p collisions to constrain parameters

Before we study J/ψ production in Pb+Pb UPCs at LHC we fix parameters in e+p collisions at HERA

H. Mäntysaari, B. Schenke, Phys.Rev. D94 (2016) 034042

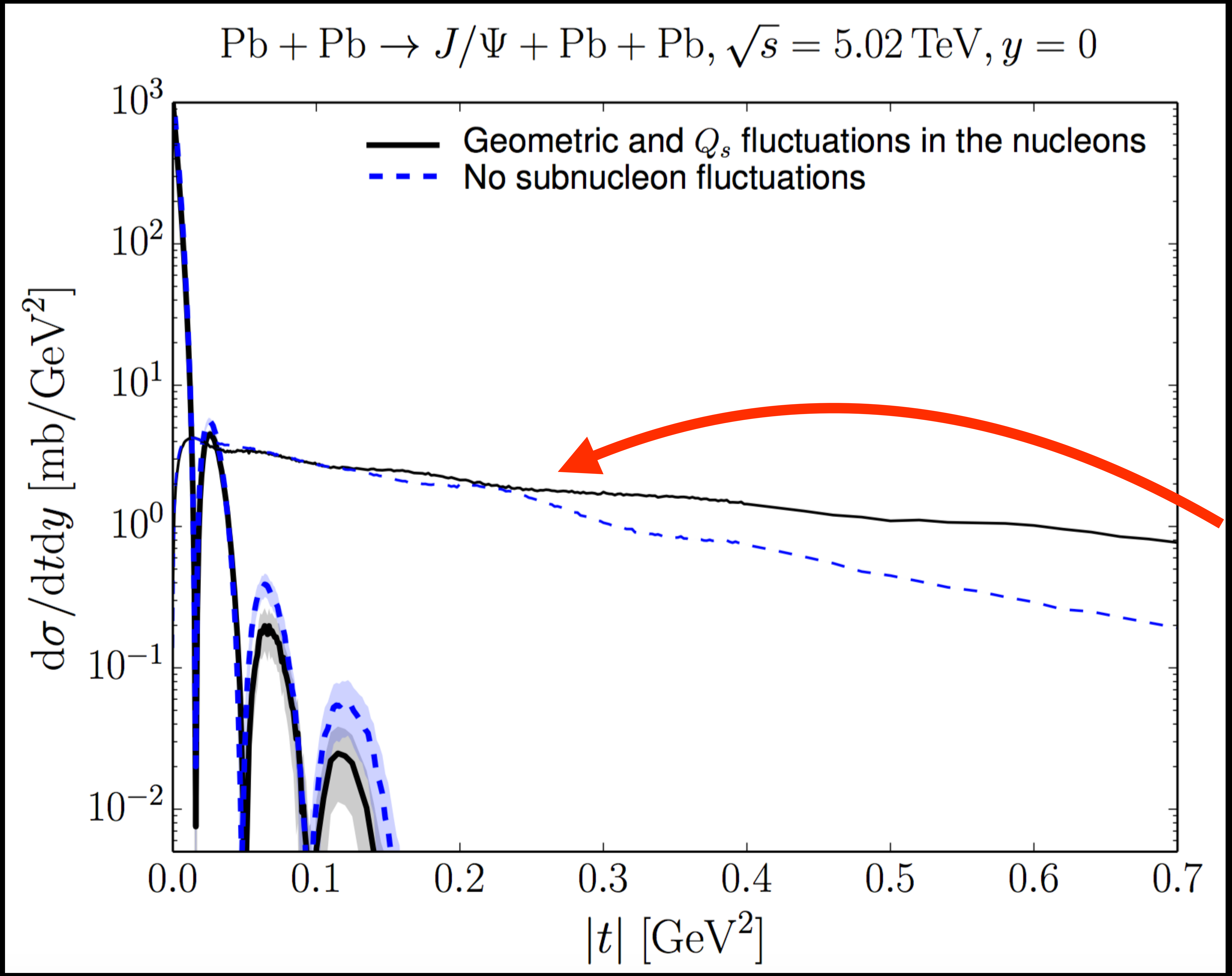




Data: H1 collaboration, Eur. Phys. J. C73 (2013) no. 6 2466

J/ψ in Pb+Pb UPCs

H. Mäntysaari, B. Schenke, Phys.Lett.B 772 (2017) 832-838, arXiv:1703.09256

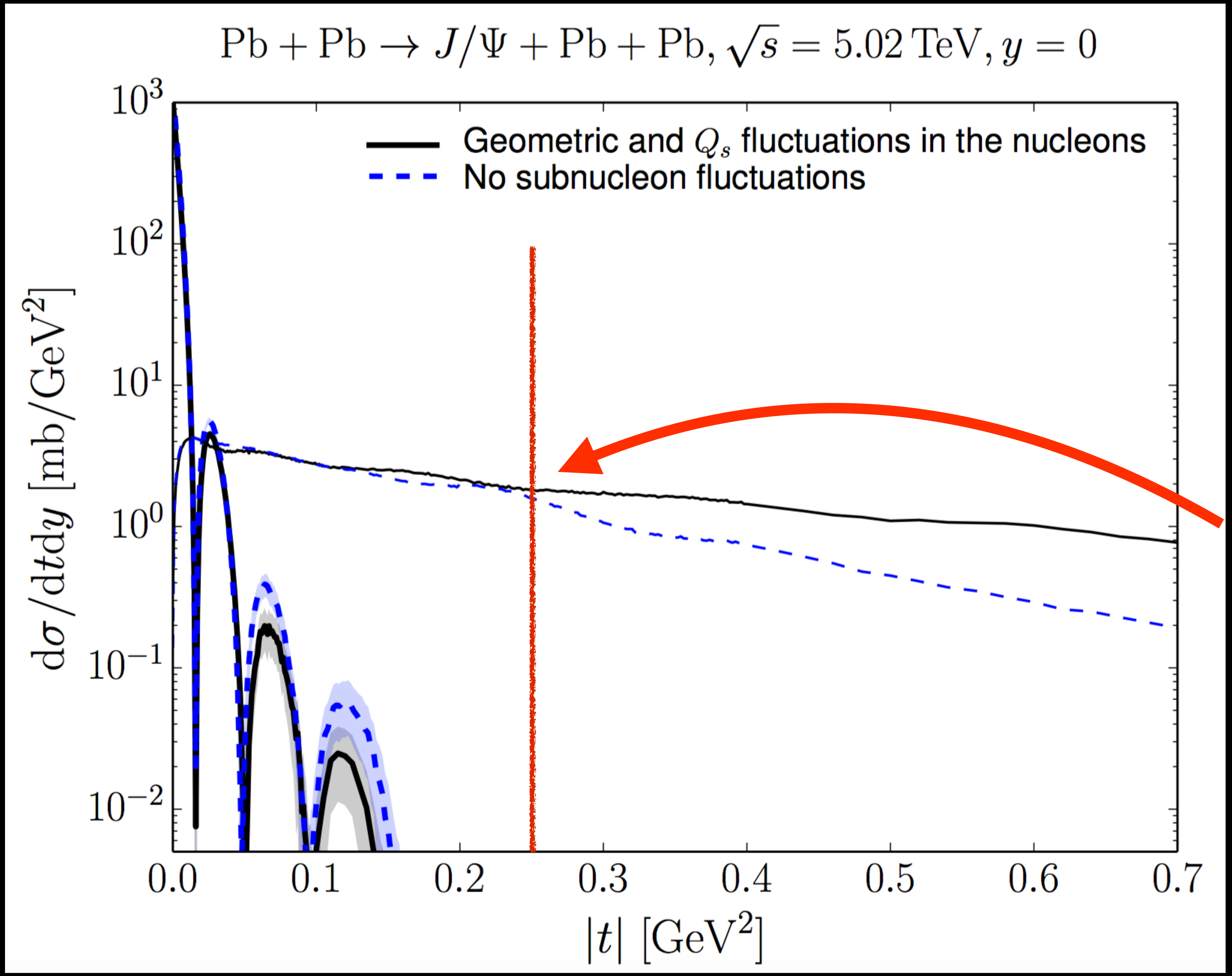


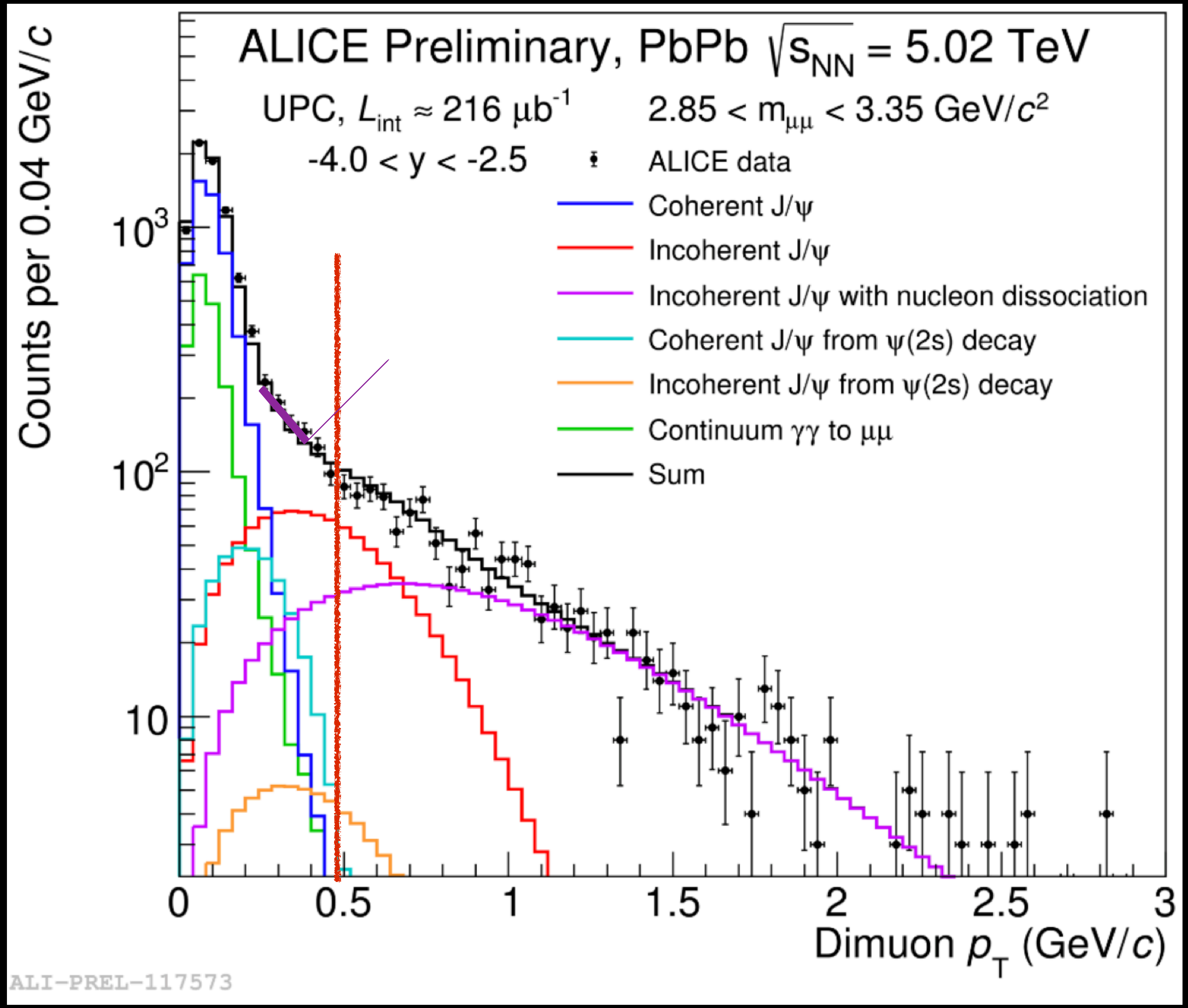
Coherent: thick lines
Incoherent: thin lines

- Small |t|: fluctuations of nucleon positions
- Large |t|: fluctuations at subnucleon scale
- Incoherent slope changes at $|t| \approx 0.25\,\mathrm{GeV}^2 \to 0.4\,\mathrm{fm}$ which is size of hot spots

J/ψ in Pb+Pb UPCs: Subnucleonic fluctuations

H. Mäntysaari, B. Schenke, Phys.Lett.B 772 (2017) 832-838, arXiv:1703.09256

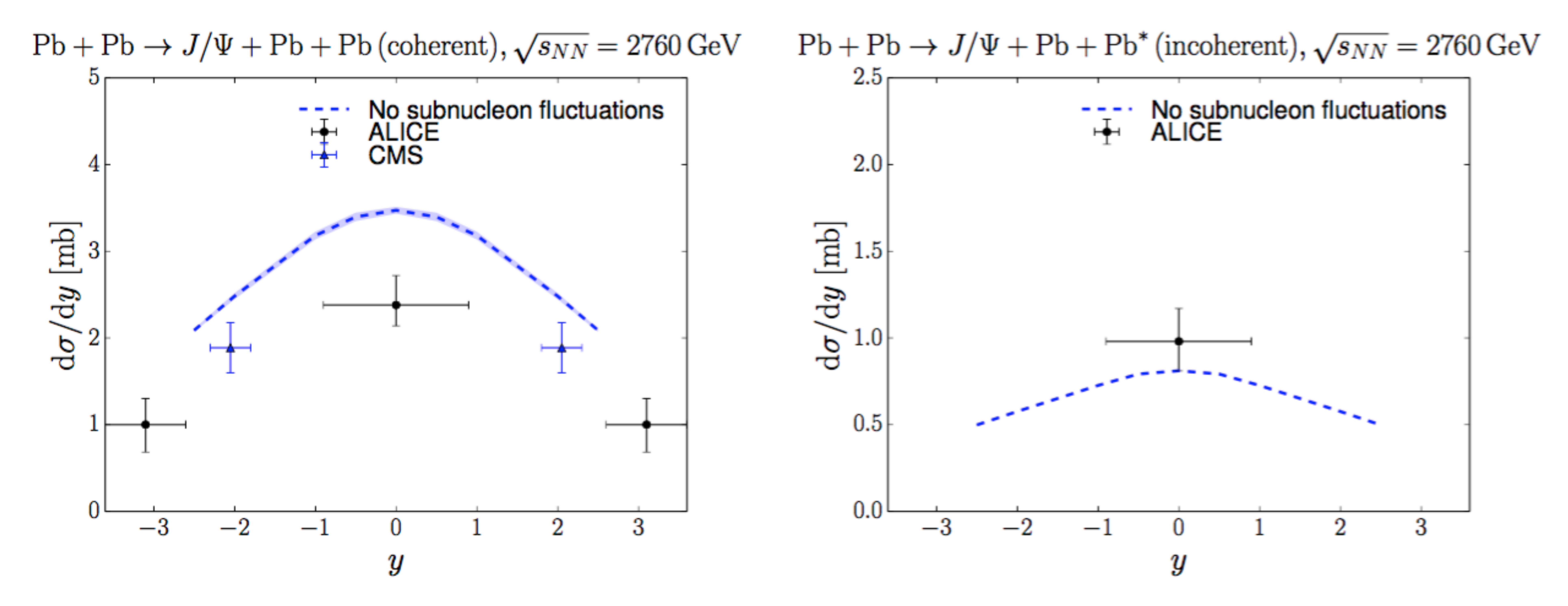




Coherent: thick lines
Incoherent: thin lines

LHC data - no subnucleonic fluctuations

H. Mäntysaari, B. Schenke, Phys.Lett.B 772 (2017) 832-838, arXiv:1703.09256

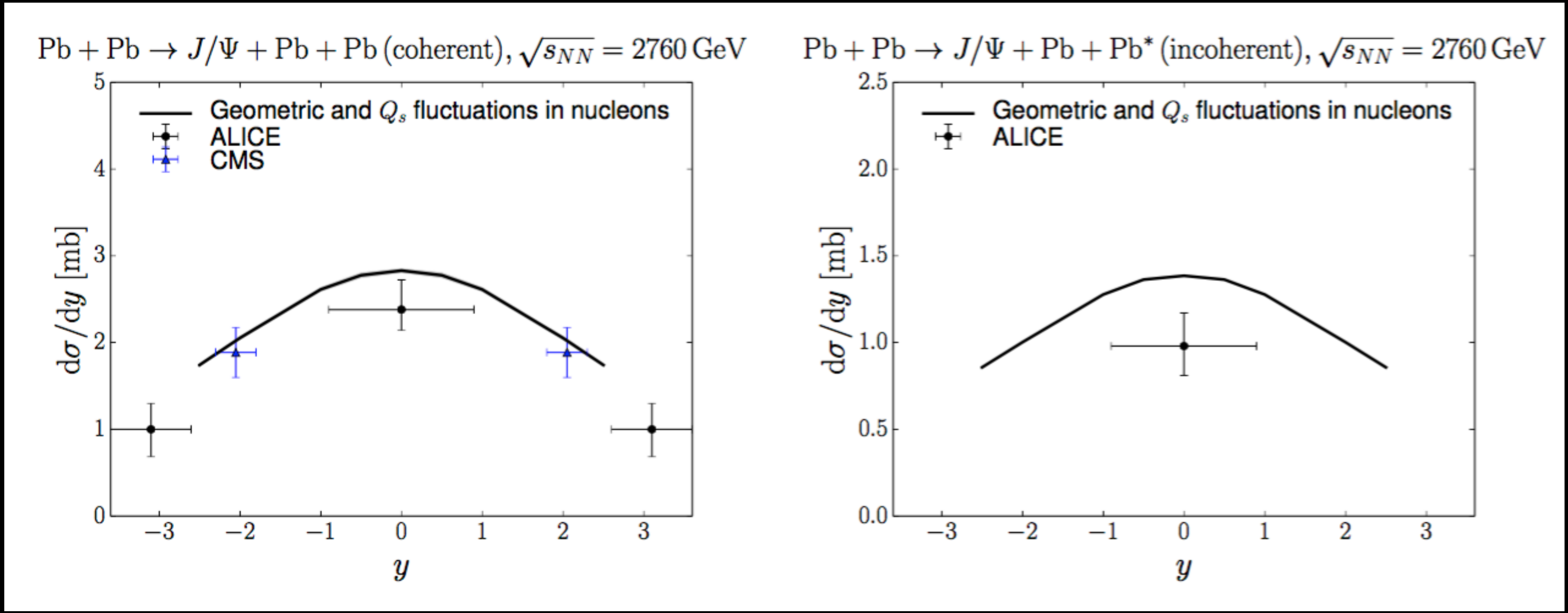


ALICE Collaboration, Eur. Phys. J. C73 (2013) 2617
ALICE Collaboration, Phys. Lett. B718 (2013) 1273
CMS Collaboration, Phys.Lett.B 772 (2017) 489-511

- Only fluctuations of nucleon positions
- Coherent cross section overestimated, incoherent underestimated
- ~20-30% normalization uncertainty from the J /Ψ wave function

LHC data - with subnucleonic fluctuations

H. Mäntysaari, B. Schenke, Phys.Lett.B 772 (2017) 832-838, arXiv:1703.09256

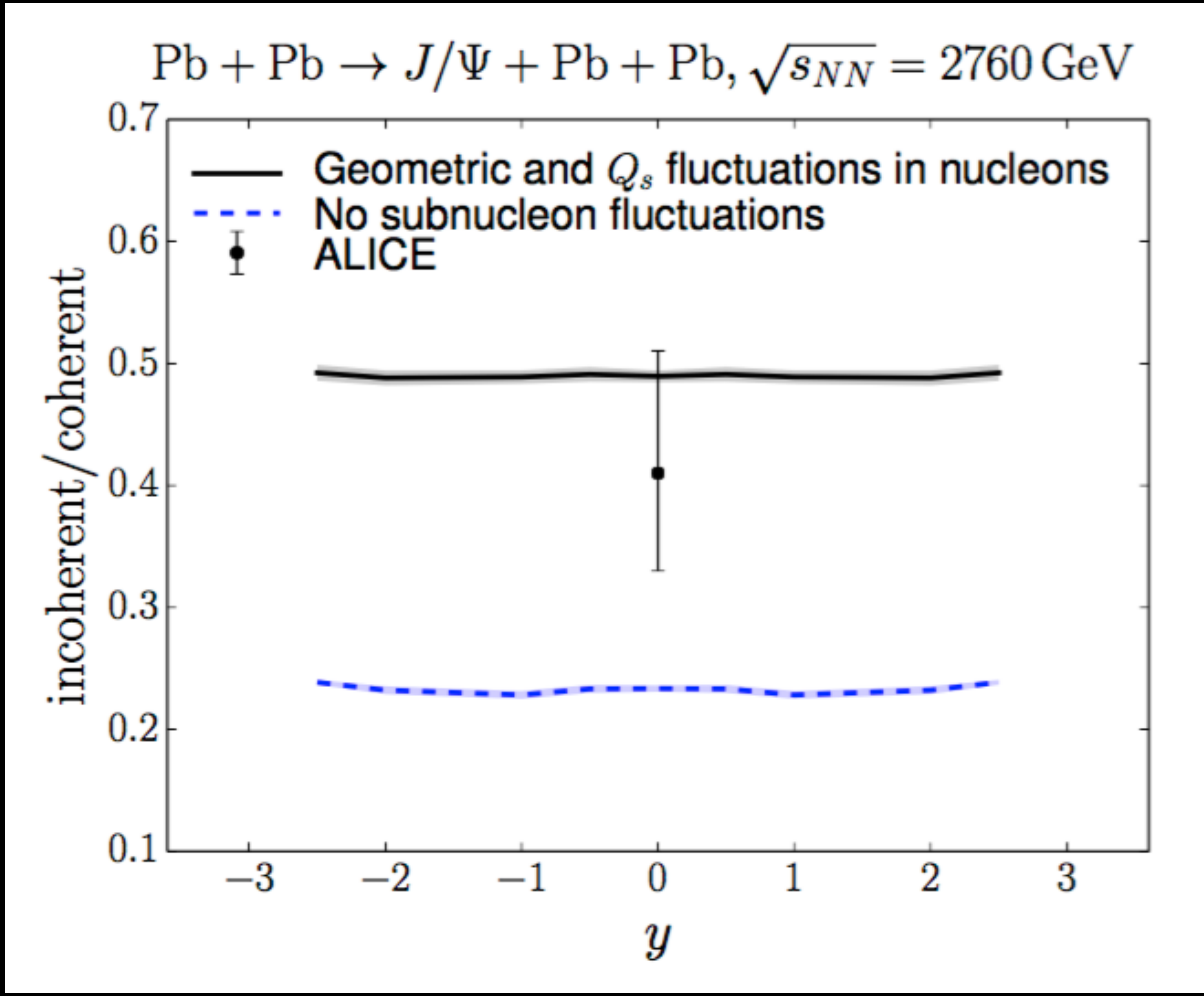


- Same subnucleonic fluctuations as used for protons earlier
- Both cross sections slightly above the data
- ~20-30% normalization uncertainty from the J /Ψ wave function

ALICE Collaboration, Eur. Phys. J. C73 (2013) 2617
ALICE Collaboration, Phys. Lett. B718 (2013) 1273
CMS Collaboration, Phys.Lett.B 772 (2017) 489-511

Ratio incoherent/coherent cross sections

H. Mäntysaari, B. Schenke, Phys.Lett.B 772 (2017) 832-838, arXiv:1703.09256



Color Glass Condensate formalism

H. Mäntysaari, B. Schenke, Phys.Rev.D 98 (2018) 3, 034013

Besides IPSat we can compute the dipole amplitude from Wilson lines 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.D 98 (2018) 3, 034013

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 $\tilde{m}$

Dipole amplitude: $N(\vec{r}, x_{\mathbb{P}}, \vec{b}) = N(\vec{x} - \vec{y}, x_{\mathbb{P}}, (\vec{x} + \vec{y})/2) = \mathrm{Tr}\, V(\vec{x}) V^\dagger(\vec{y})/N_c$

Evolution is done using the Langevin formulation of the JIMWLK equations

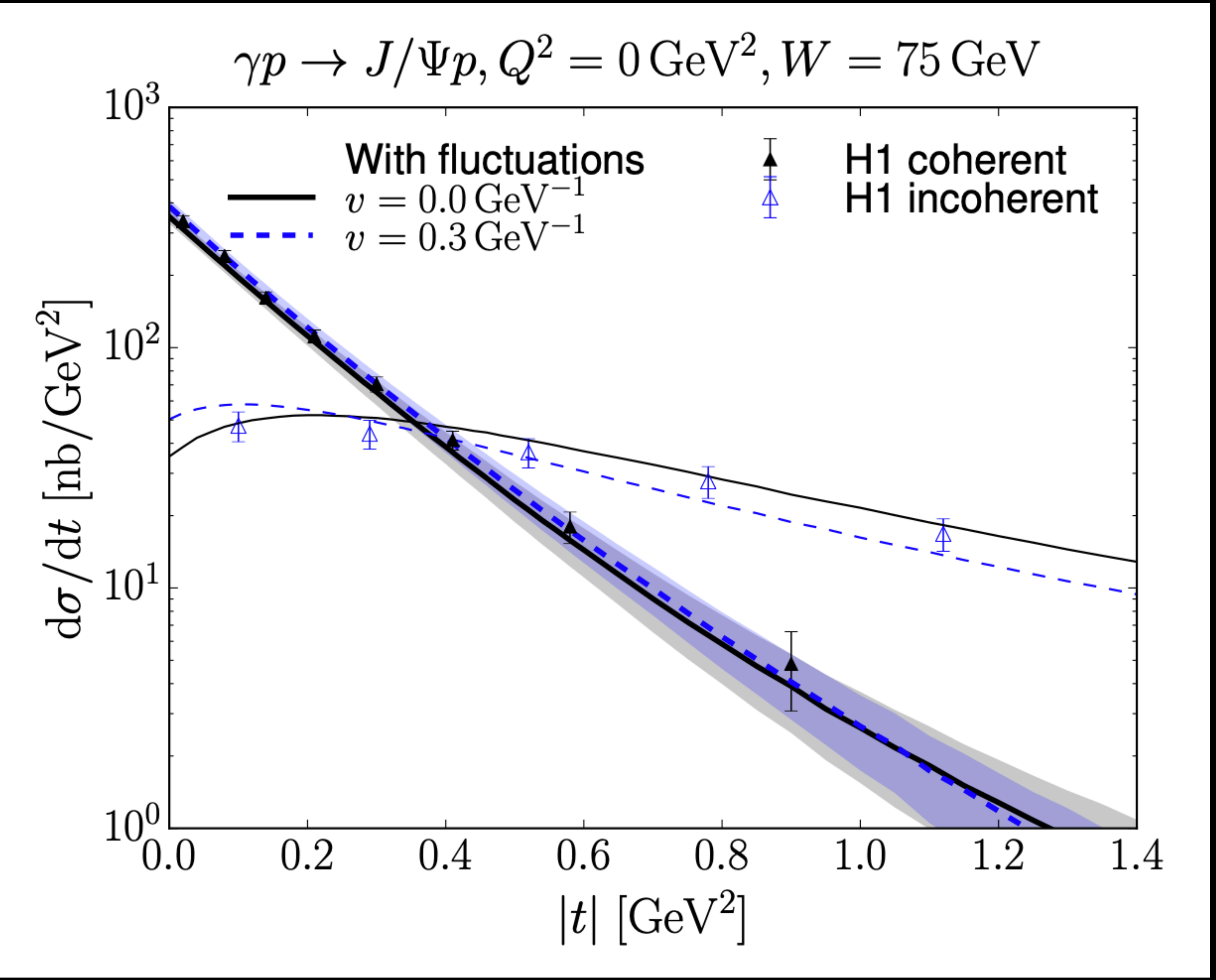
K. Rummukainen and H. Weigert Nucl. Phys. A739 (2004) 183; T. Lappi, H. Mäntysaari, Eur. Phys. J. C73 (2013) 2307

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

Constrain parameters in e+p again

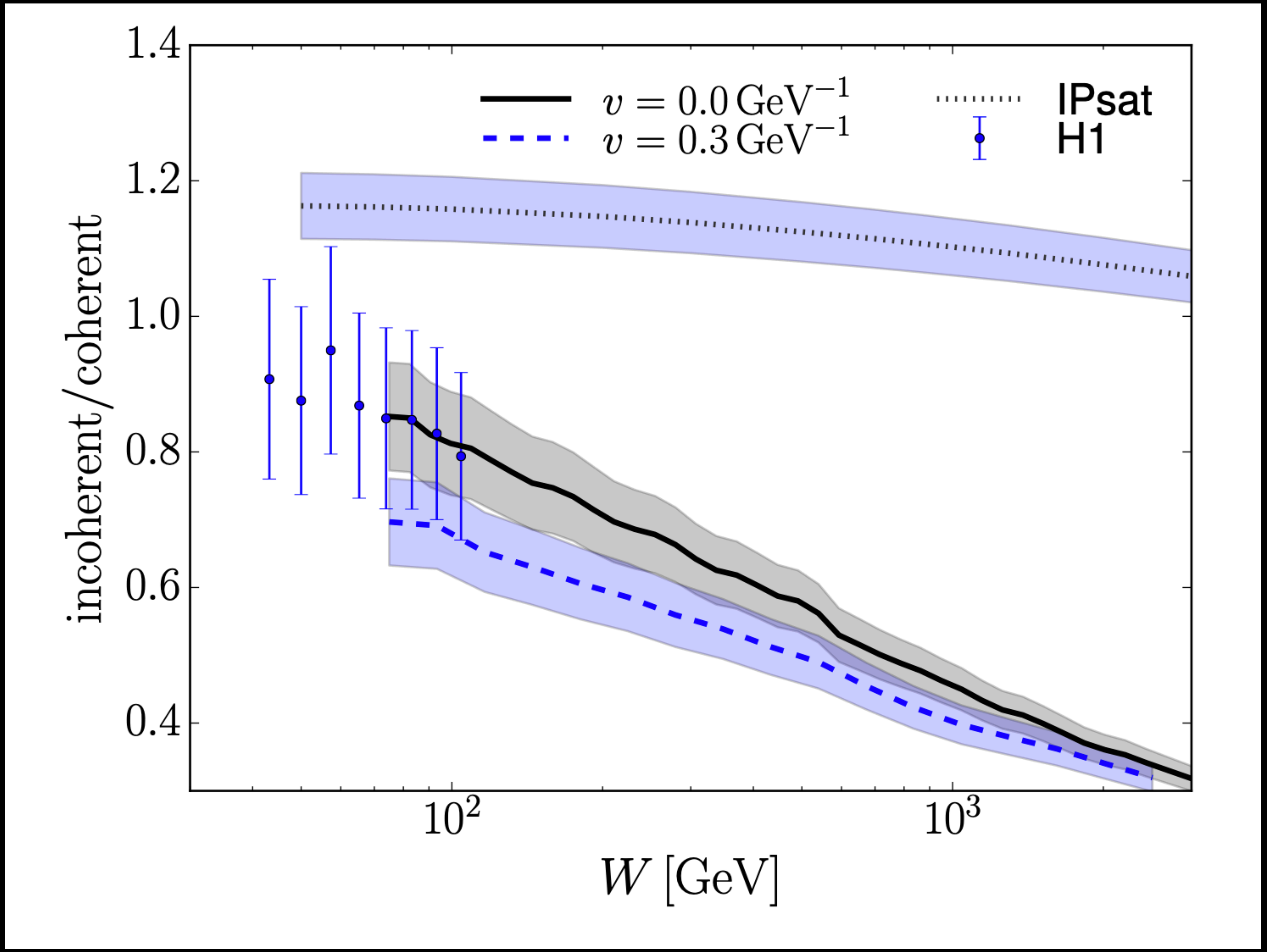
H. Mäntysaari, B. Schenke, Phys.Rev.D 98 (2018) 3, 034013

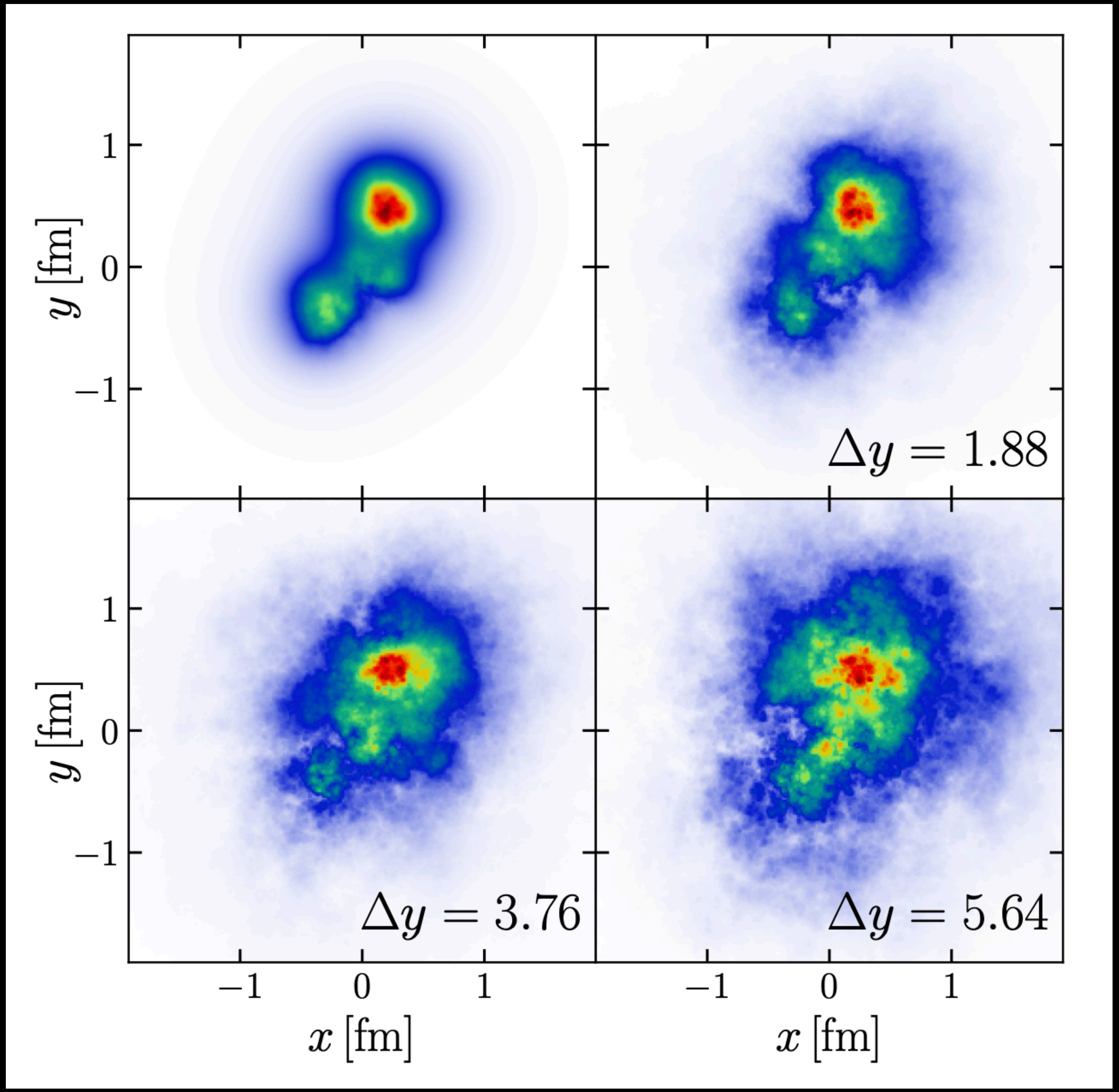


H1 collaboration, Eur. Phys. J. C73 (2013) no. 6 2466

Energy evolution - JIMWLK

H. Mäntysaari, B. Schenke, Phys.Rev.D 98 (2018) 3, 034013

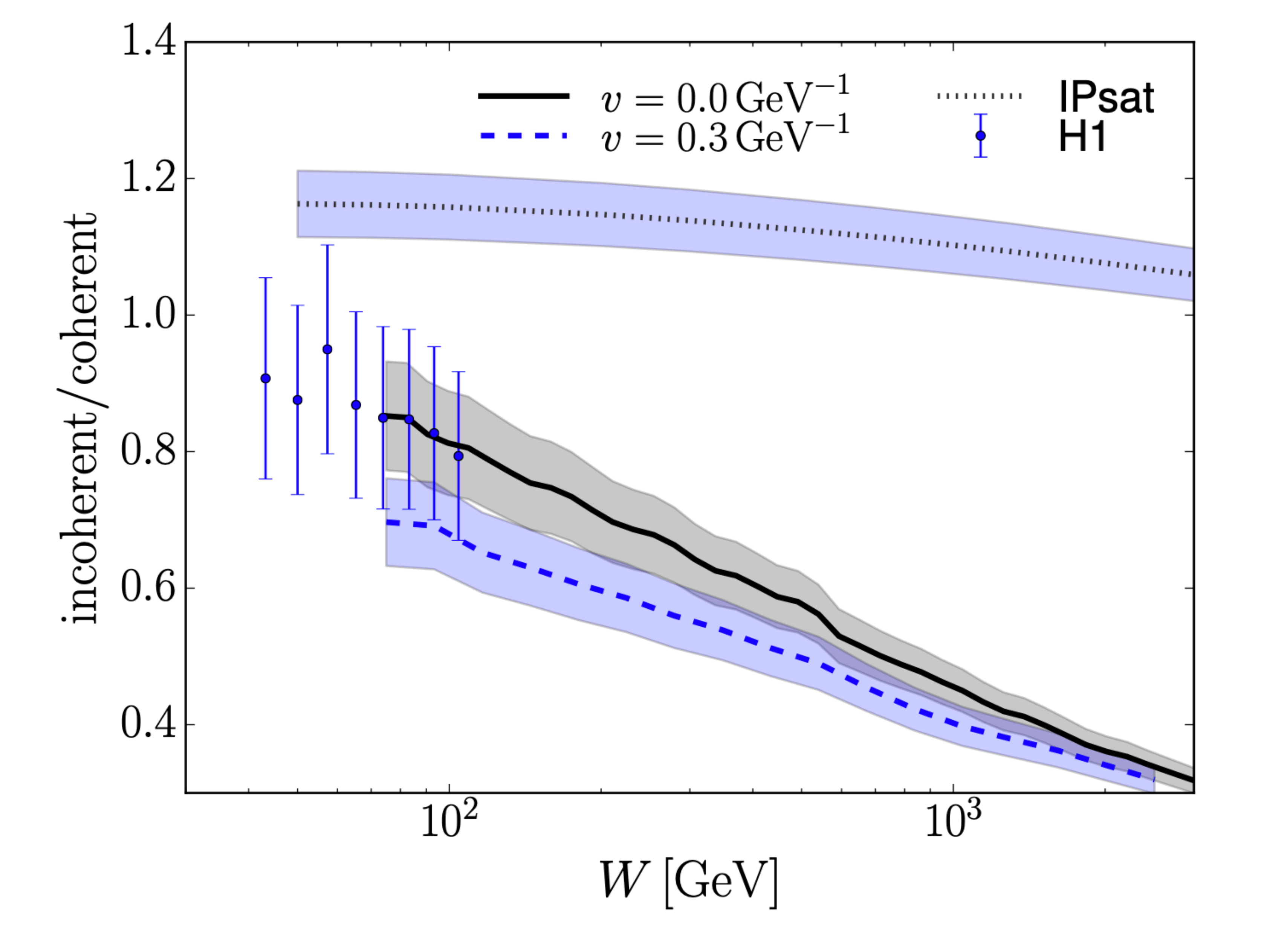


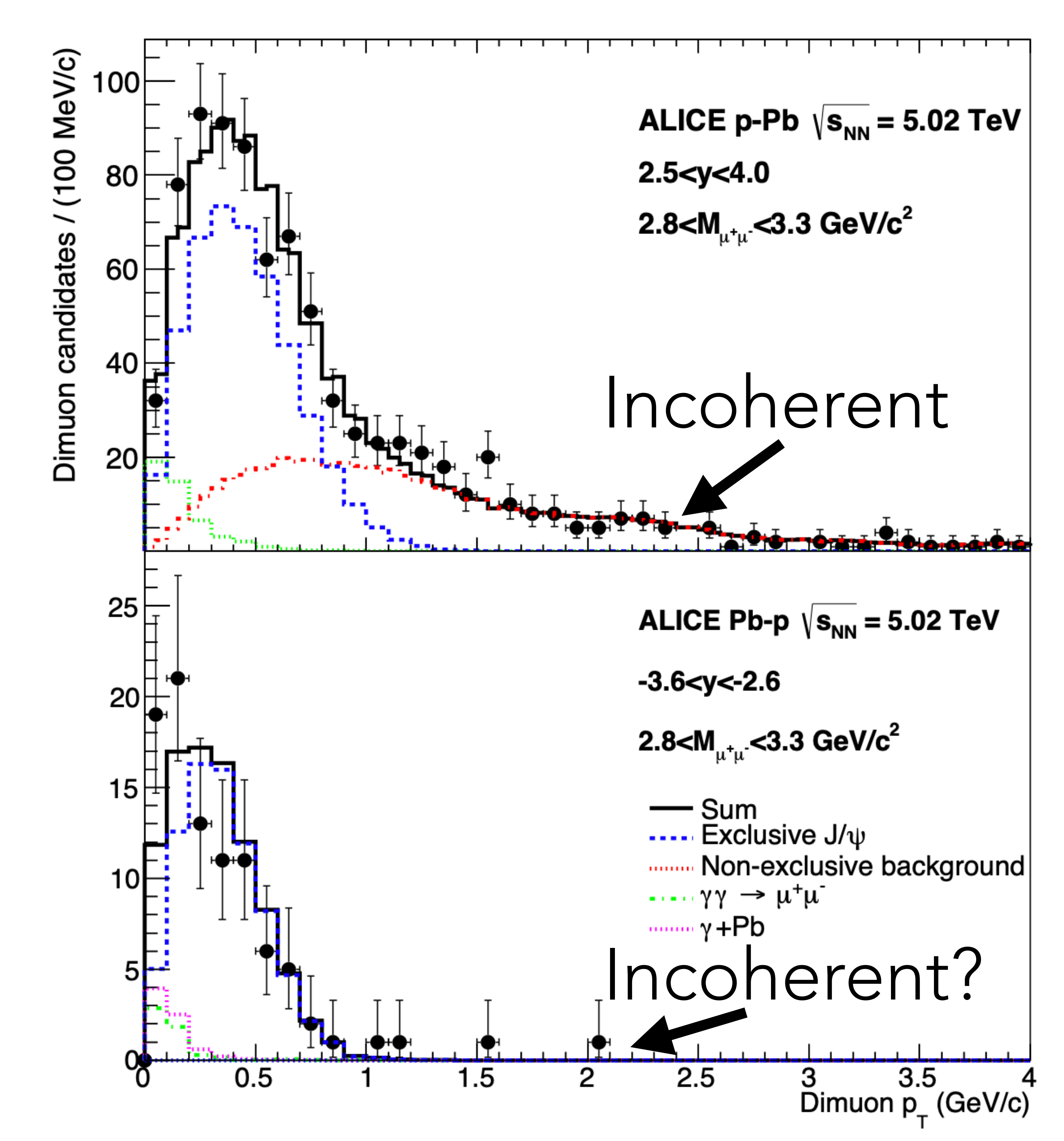


H1 collaboration, Eur. Phys. J. C73 (2013) no. 6 2466

Energy evolution - JIMWLK

H. Mäntysaari, B. Schenke, Phys.Rev.D 98 (2018) 3, 034013



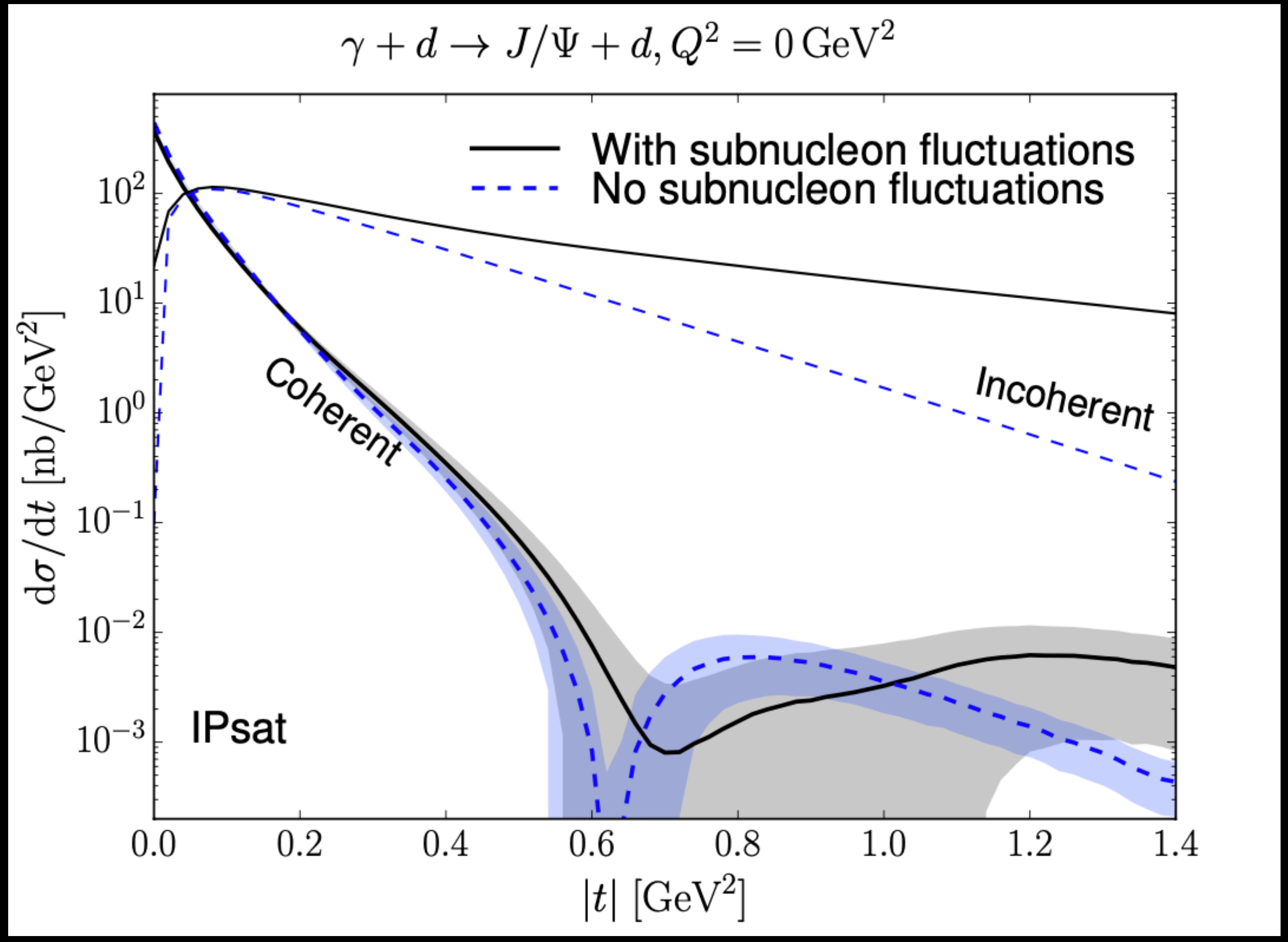


ALICE: arXiv:1406.7819 and 1809.03235

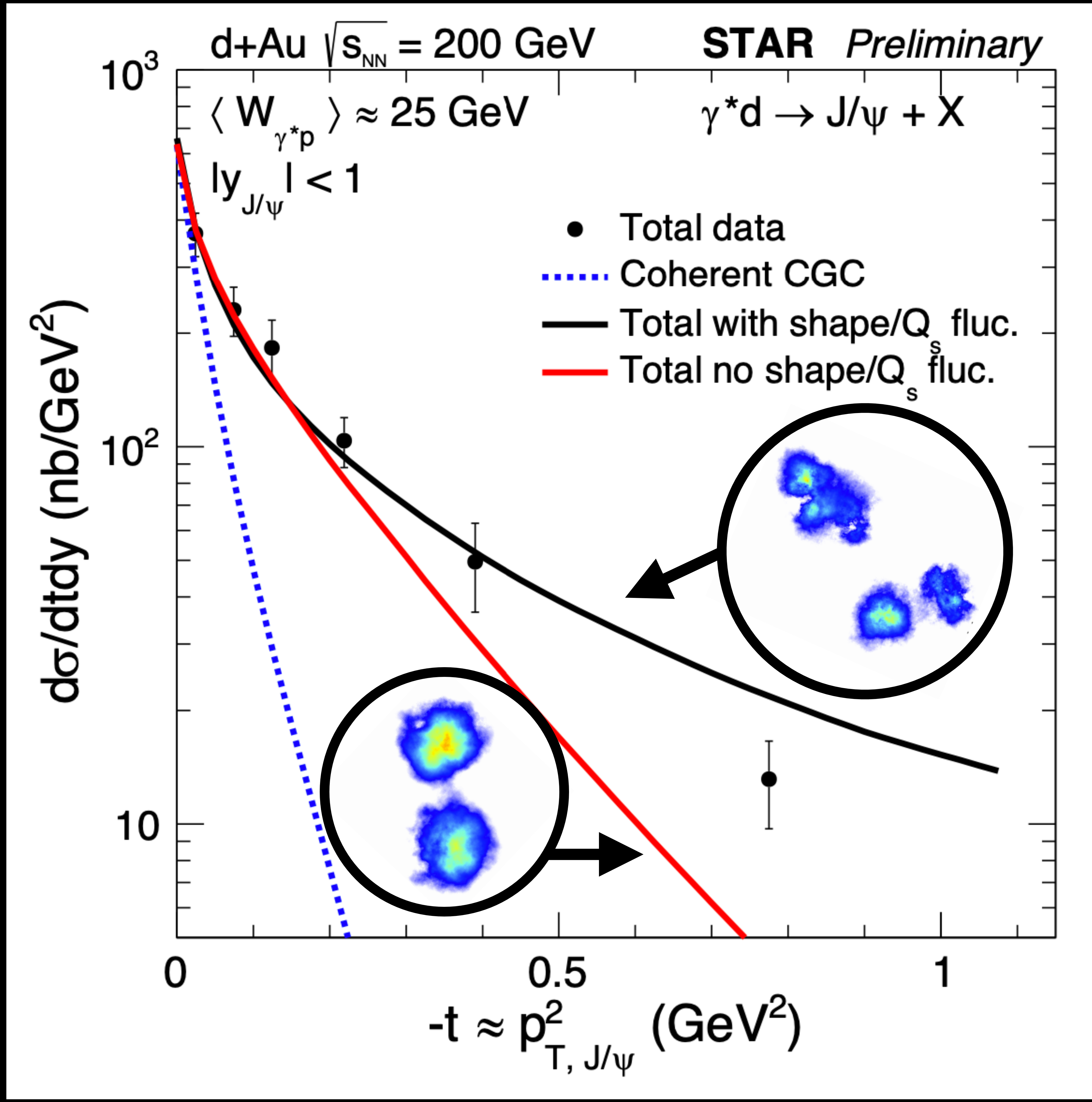
Qualitatively compatible with LHC data: Small incoherent cross section in high-energy γp scattering

Photoproduction of J/ψ in d+Au collisions at STAR

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



Can also access details of deuteron wave function



STAR Collaboration at Hard Probes 2020
arXiv:2009.04860

Substructure: large effect on incoherent at $|t| \gtrsim 0.25\mathrm{GeV}^2$ (as in Pb)

STAR data favors substructure

Summary and Outlook

- Ultra peripheral collisions: Study J/Ψ production in γ + A and γ + p
- Coherent and incoherent diffraction at small x provide information on spatial gluon distribution
- Nucleon substructure has a significant effect on the incoherent cross section at $|t| \gtrsim 0.25\,\mathrm{GeV}^2$
- Incoherent increases more slowly than coherent cross section with increasing energy. Hints at that also seen in LHC data at high W in γ + p
- γ + d collisions at RHIC: Substructure fluctuations needed to describe the observed $|t|$ dependence!
- Next: Go to NLO. A lot of recent progress: e.g. H. Mäntysaari, J. Penttala, arXiv:2104.02349