EXCLUSIVE Q-QBAR PHOTOPRODUCTION AND PROTON STRUCTURE

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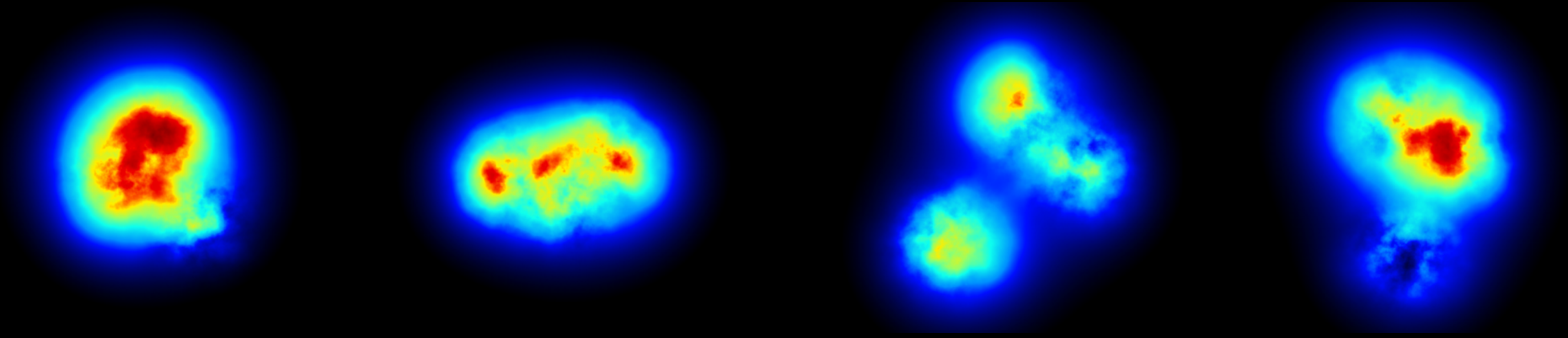


May 24, 2017
PHOTON 2017
CERN

Introduction

Fundamental questions:

How are gluons distributed spatially in the proton?

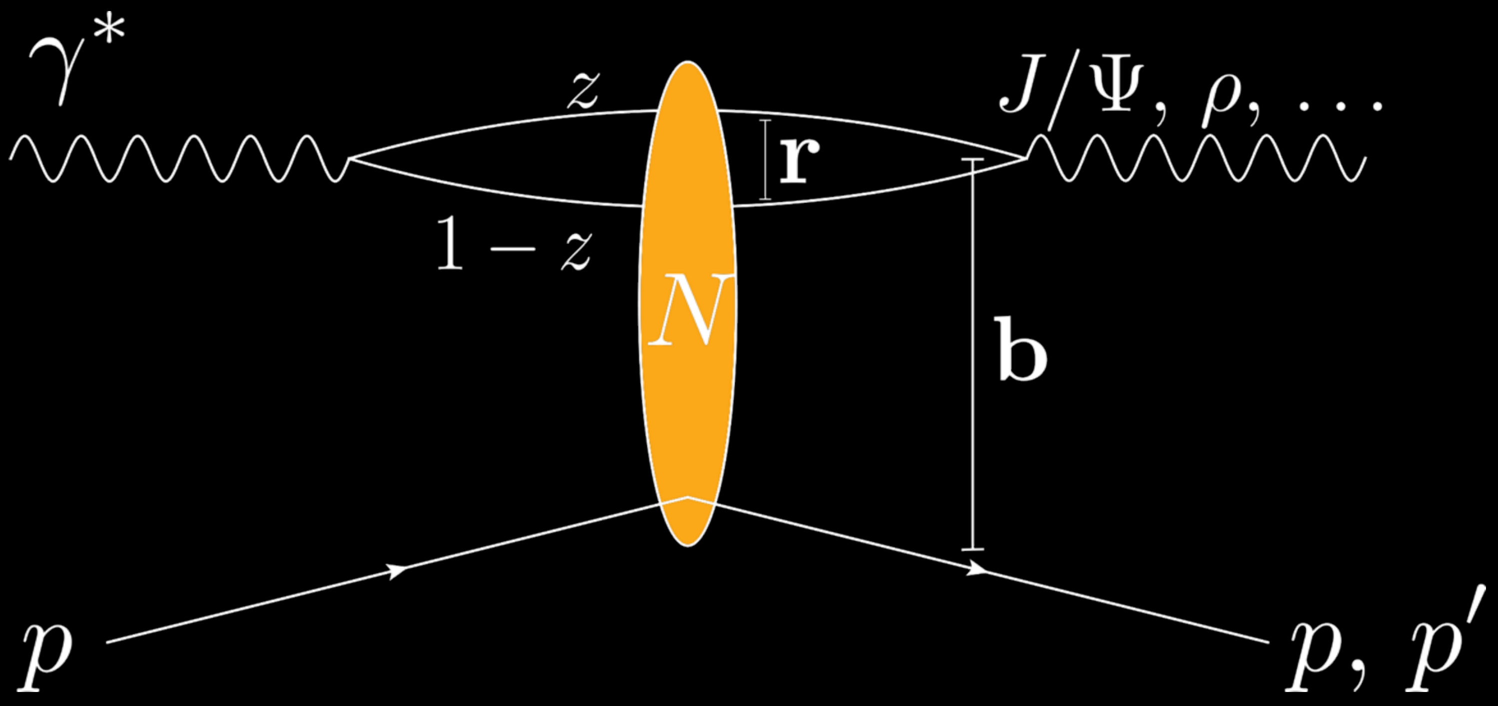
Do we have access to the fluctuating shape of the proton?

Diffractive J/Ψ production in e+p provides access

… so do proton + heavy ion collisions

Diffractive J/Ψ production

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:

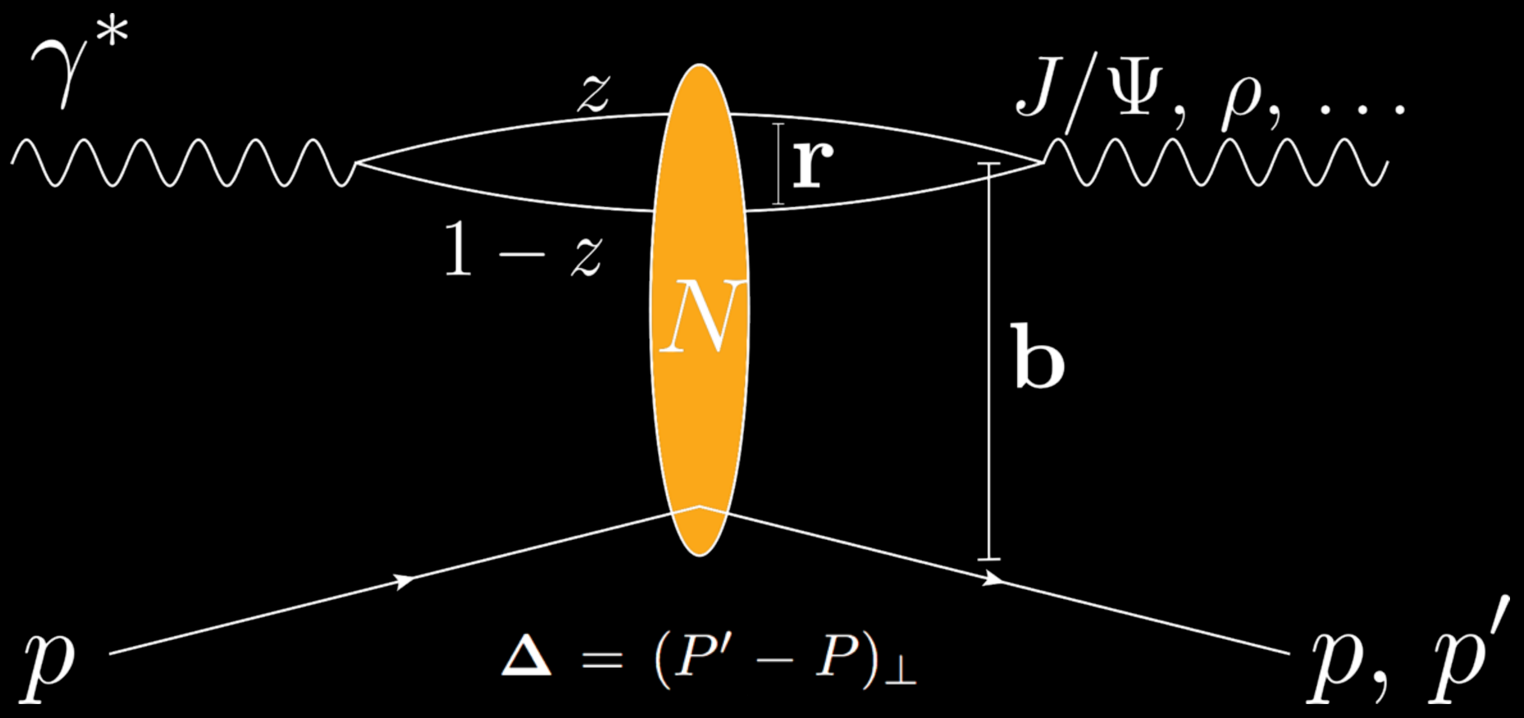
Proton breaks up, Sensitive to shape fluctuations

CGC Framework J/Ψ production

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

Diffractive eigenstates are color dipoles at fixed r_T and b_T

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



Scattering amplitude

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

Dipole amplitude N determined in IPsat or IP-Glasma

Averaging over the target

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

COHERENT DIFFRACTION:

TARGET STAYS INTACT

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

INCOHERENT DIFFRACTION:

TARGET BREAKS UP

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

SEE
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

SENSITIVE TO FLUCTUATIONS!

IPsat model

Kowalski, Teaney, Phys.Rev. D68 (2003) 114005

Parametrize the dipole amplitude as

$$N(\vec{r}, x, \vec{b}) = 1 - \exp[-F(\vec{r}, x, \vec{b})]$$

with $$F(\vec{r}, x, \vec{b}) = \frac{\pi^2}{2N_c}\vec{r}^2\alpha_s(\mu^2)xg(x,\mu^2)T_p(\vec{b})$$

gluon density including DGLAP to scale $\mu^2 = 4/\vec{r}^2 + \mu_0^2$

impact parameter dependence

Saturation scale: $Q_s^2(x,\vec{b}) = 2/r_s^2(x,\vec{b})$

with r_s defined via $N(\vec{r}_s, x, \vec{b}) = 1 - e^{1/2}$

Geometric fluctuations in the IPsat model

Kowalski, Teaney, Phys.Rev. D68 (2003) 114005

All parameters are fit to HERA DIS data

Thickness function $T_p(\vec{b})$ normally assumed to be Gaussian

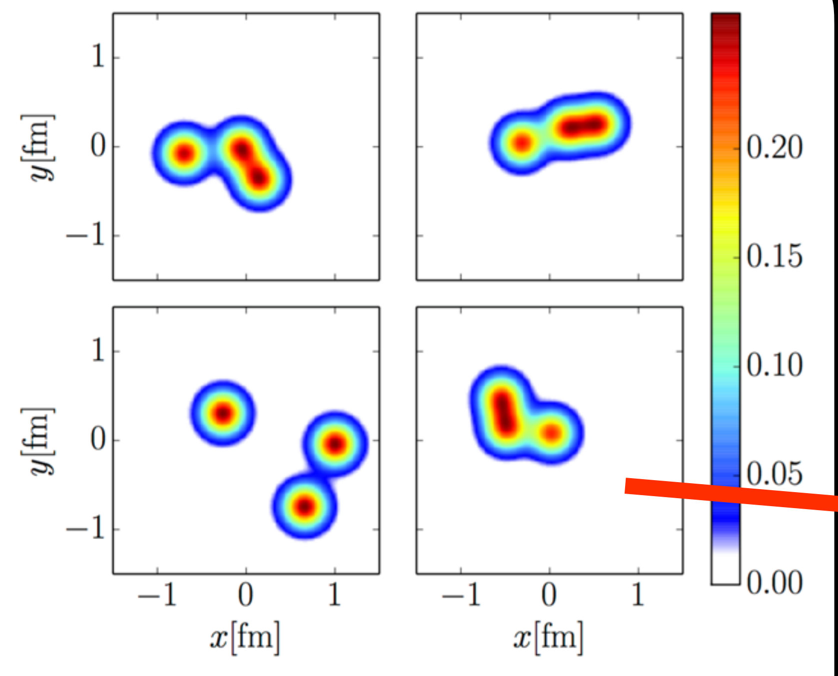
Here we introduce a substructure to the proton by defining:

$$T_p(\vec{b}) = \sum_{i=1}^{3} T_q(\vec{b} - \vec{b}_i)$$

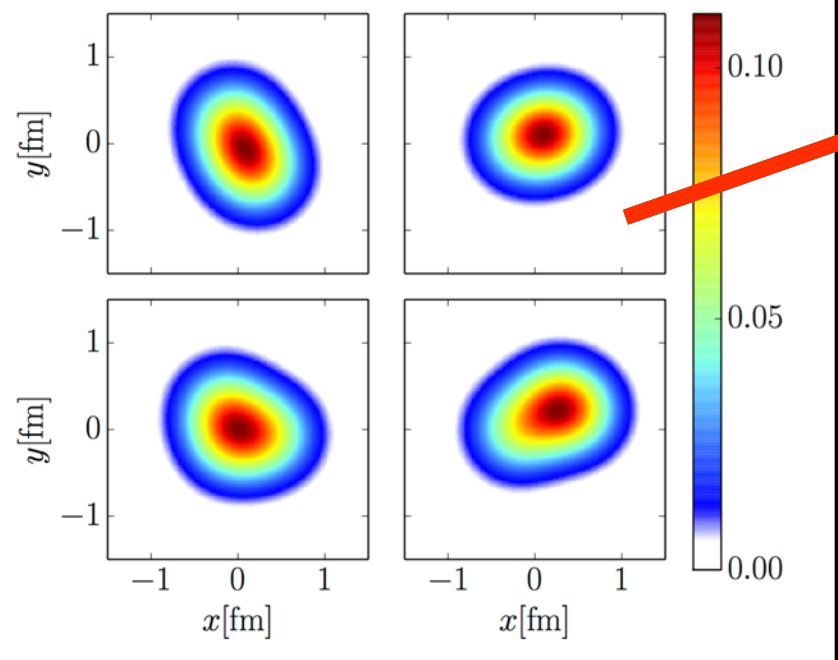
with $T_q(\vec{b}) \sim e^{-b^2/2B_q}$

where the positions $\vec{b}_i$ are sampled from a Gaussian with width B_{qc}

J/Ψ production from fluctuating proton

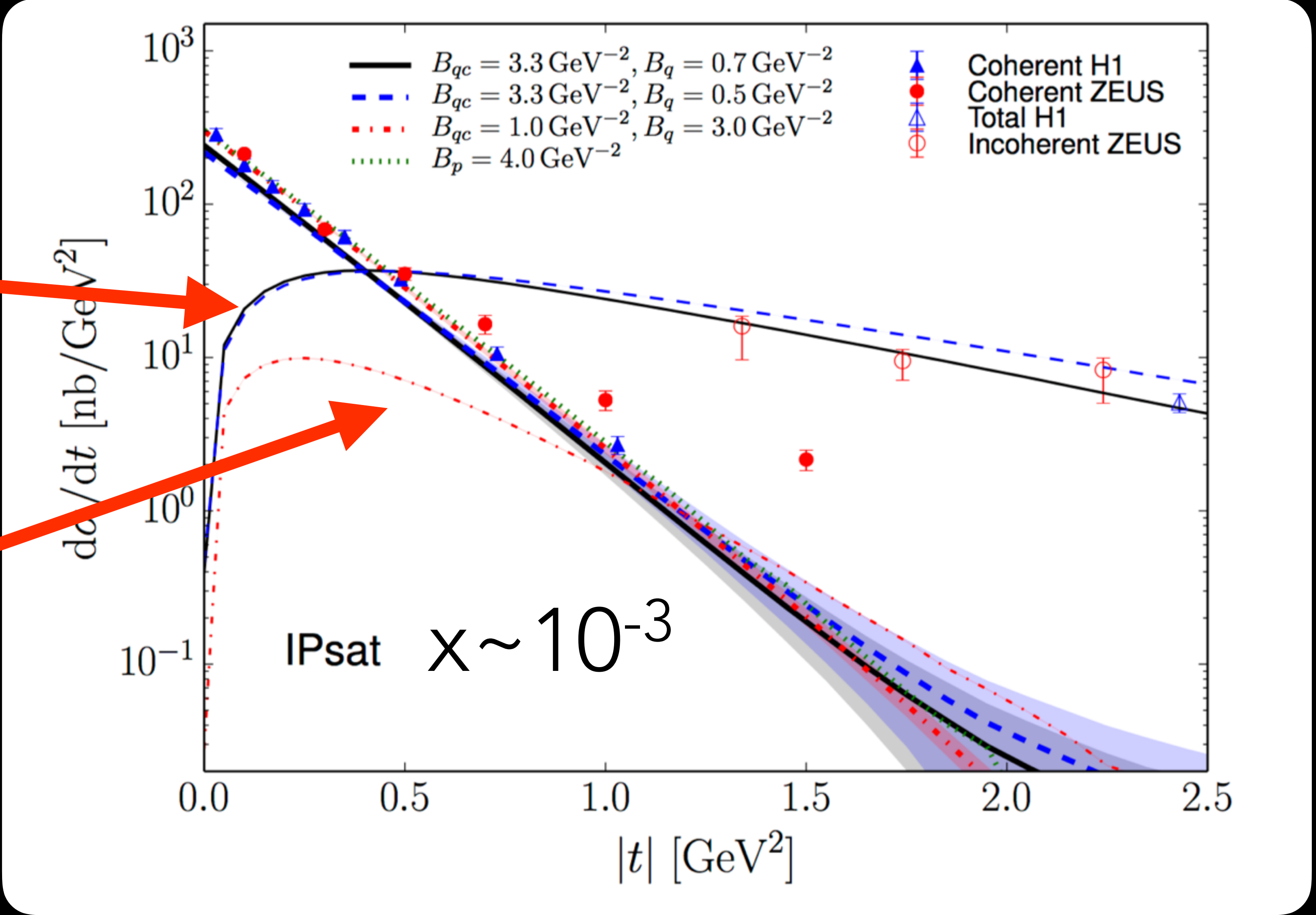


(a) $B_{qc} = 3.3\ \mathrm{GeV}^{-2}, B_q = 0.7\ \mathrm{GeV}^{-2}$



(b) $B_{qc} = 1.0\ \mathrm{GeV}^{-2}, B_q = 3.0\ \mathrm{GeV}^{-2}$

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

IP-Glasma model

B.Schenke, P.Tribedy, R.Venugopalan, PRL108, 252301 (2012), PRC86, 034908 (2012)

Take $Q_s^2(x,\vec{b})$ from IPsat for a given geometry

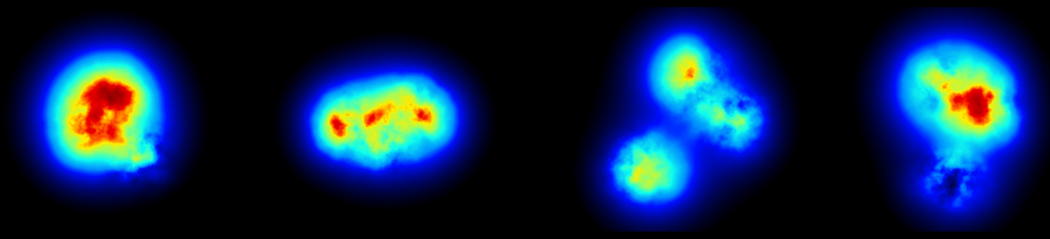
Sample color charges $\rho(x,\vec{b})$ from distribution with variance ~ $Q_s^2(x,\vec{b})$

Gluon fields in the proton follow from Yang-Mills eqs.

$$A^i(\vec{b}) = -\frac{i}{g} V(\vec{b}) \partial_i V^\dagger(\vec{b})$$

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

Traces of Wilson lines:



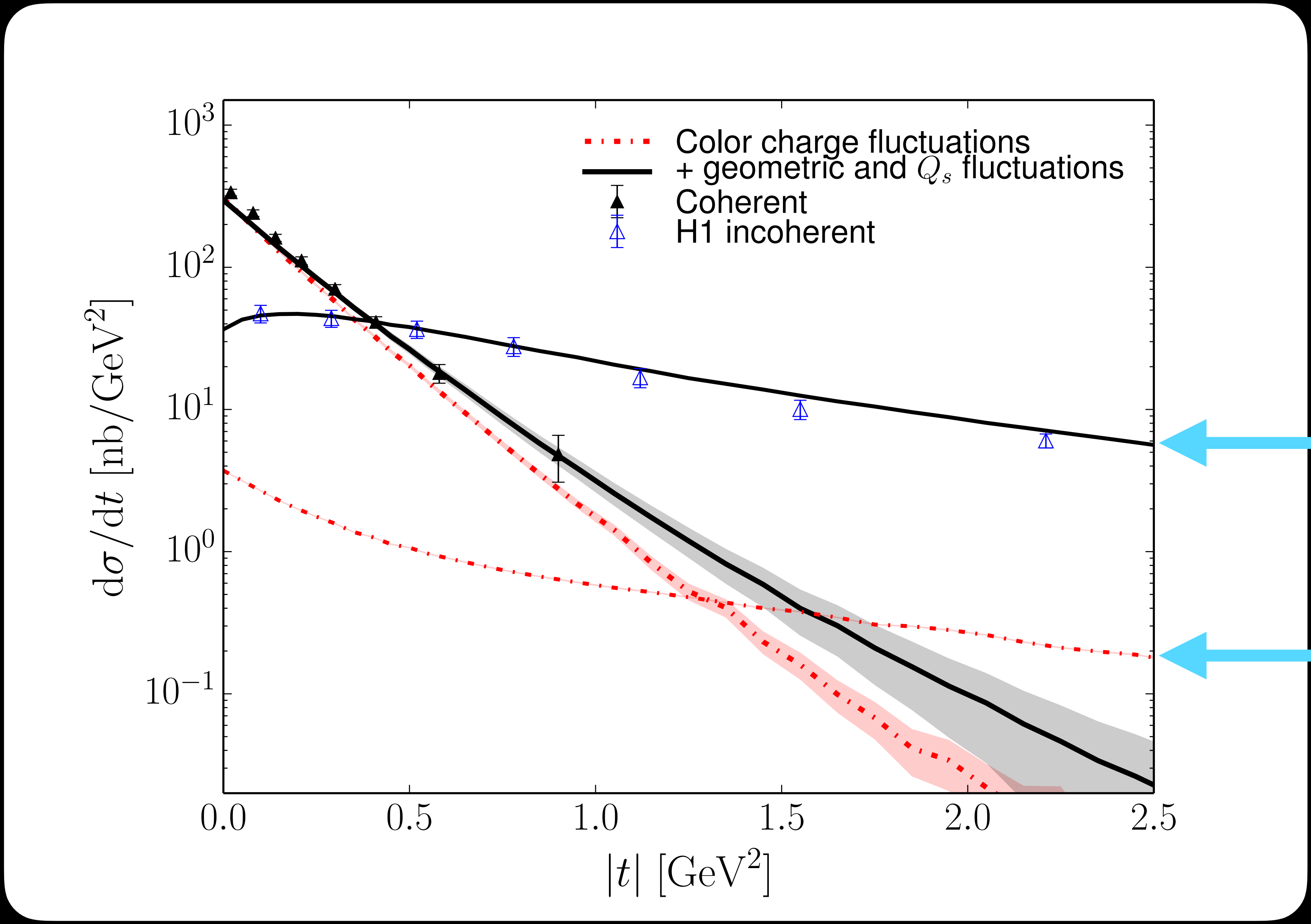
IP-Glasma results

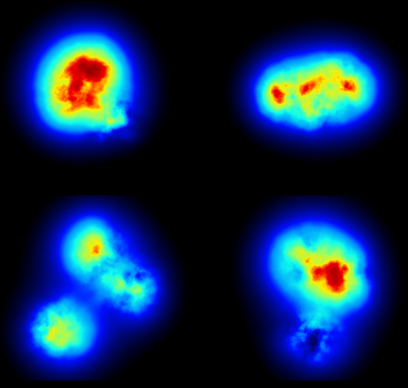
H. Mäntysaari, B. Schenke, Phys. Rev. Lett. 117 (2016) 052301; Phys.Rev. D94 (2016) 034042

Geometric + color charge fluctuations

Wilson lines

Dipole amp.: $N(\vec{r}, x_{\mathbb{P}}, \vec{b}) = N(\vec{x} - \vec{y}, x_{\mathbb{P}}, (\vec{x} + \vec{y})/2) = 1 - \mathrm{Tr}\, V(\vec{x}) V^{\dagger}(\vec{y})/N_c$





tuned shape fluctuations

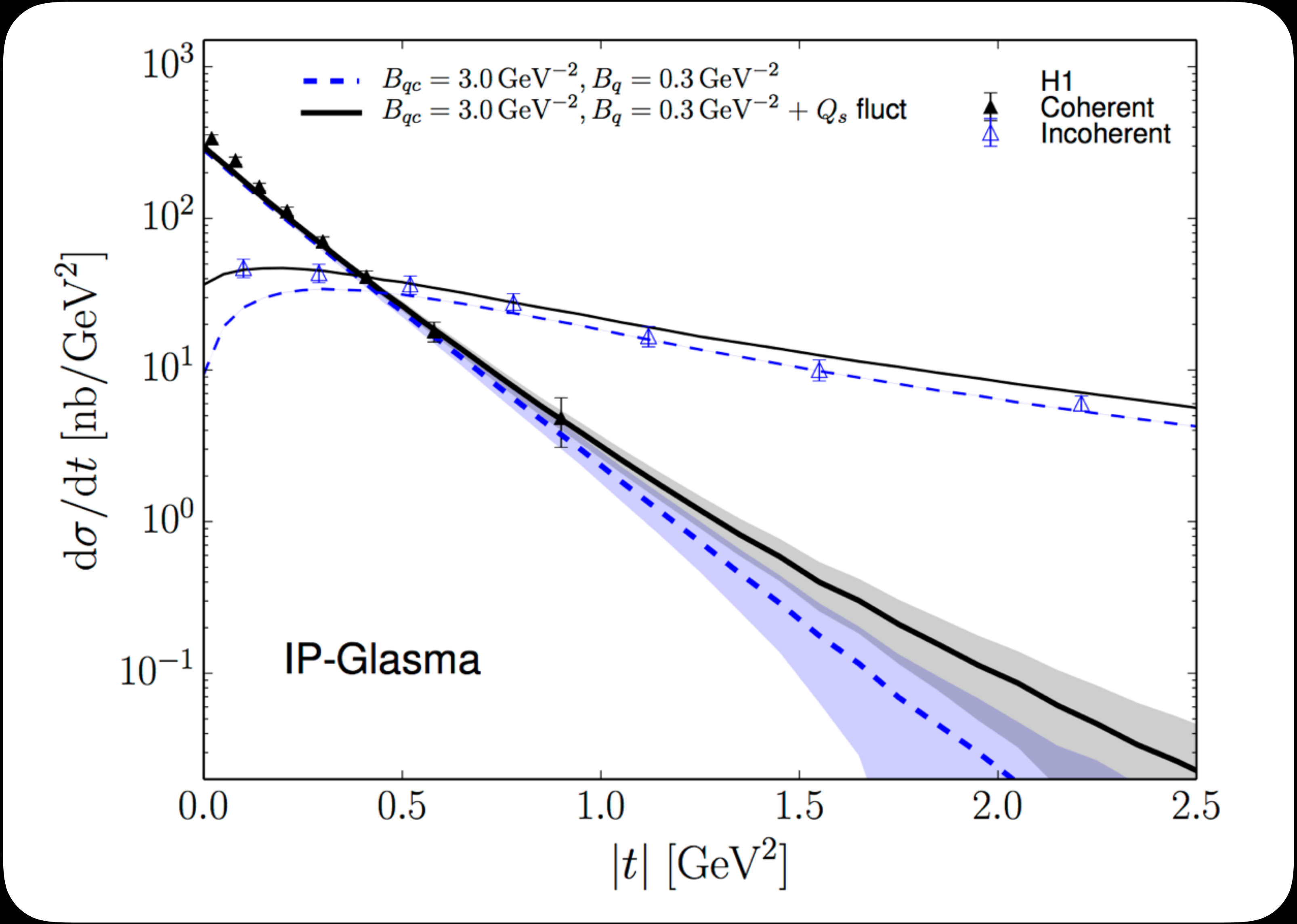
round proton

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

Effect of Q_S fluctuations

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

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



σ=0.5

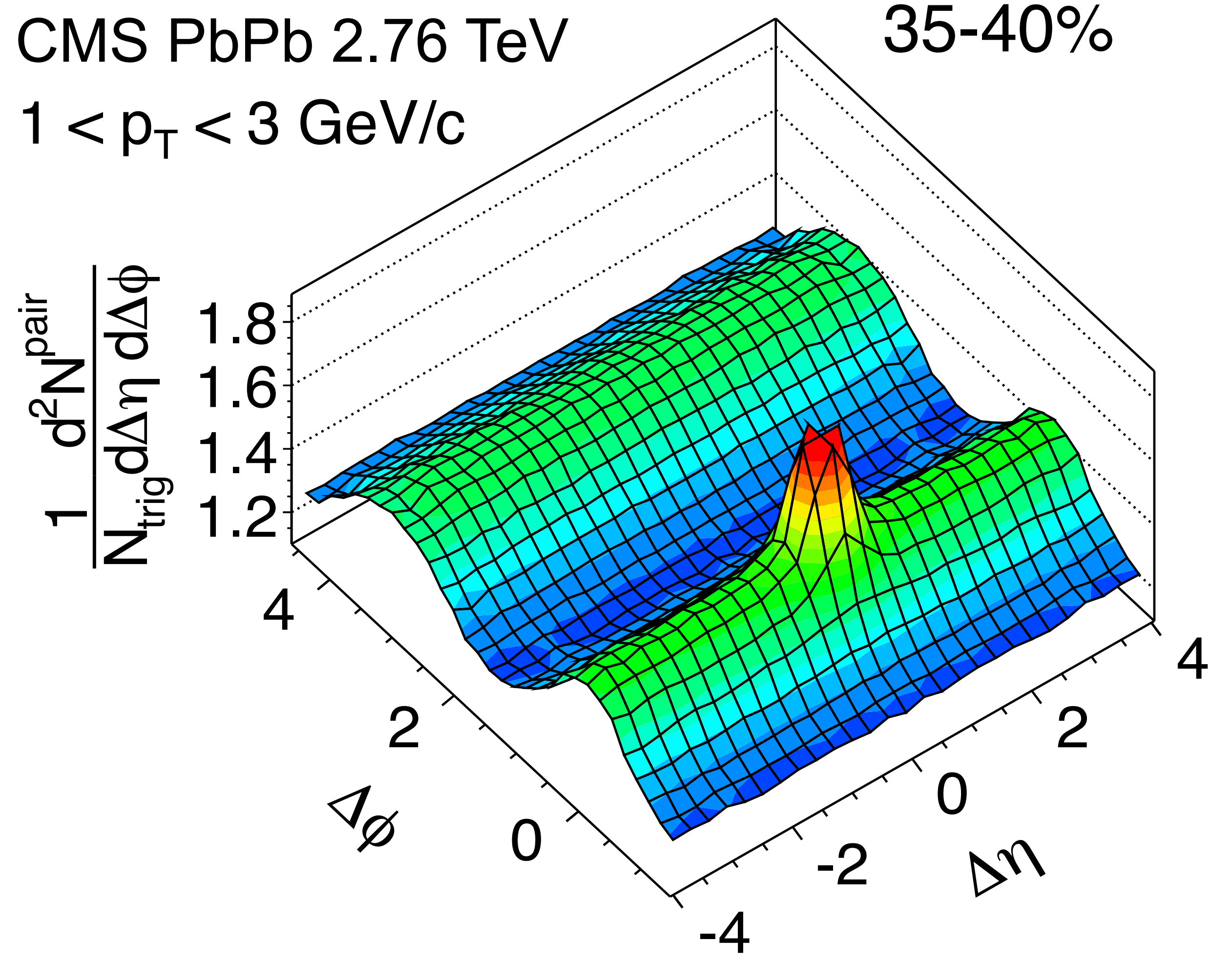
Experimental data: H1 collaboration, JHEP 1005 (2010) 032

Effect on p+A collisins: Correlations

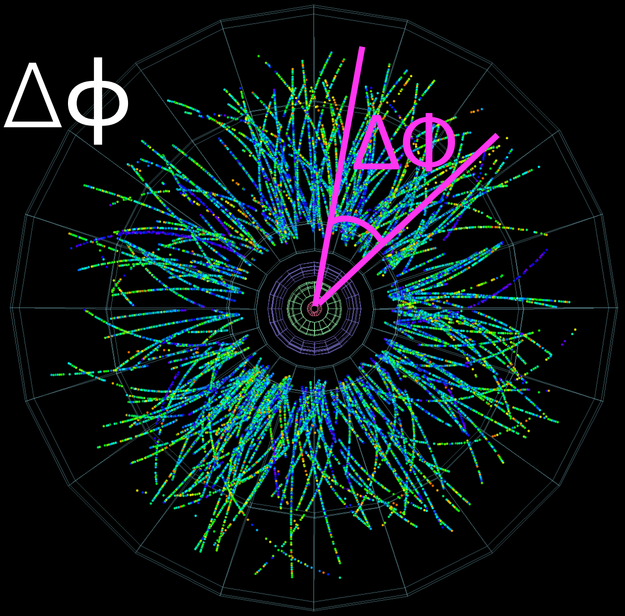
2-particle correlation as a function of $\Delta\eta$ and $\Delta\phi$

$\Delta\eta$: DIFFERENCE IN PSEUDO-RAPIDITY

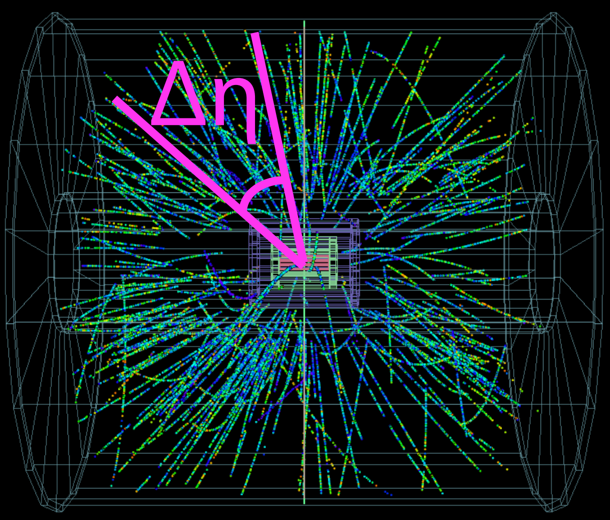
$\Delta\Phi$: DIFFERENCE IN AZIMUTHAL ANGLE



CMS COLL., EUR. PHYS. J. C72 (2012)



$\Delta\Phi$: DIFFERENCE IN AZIMUTHAL ANGLE

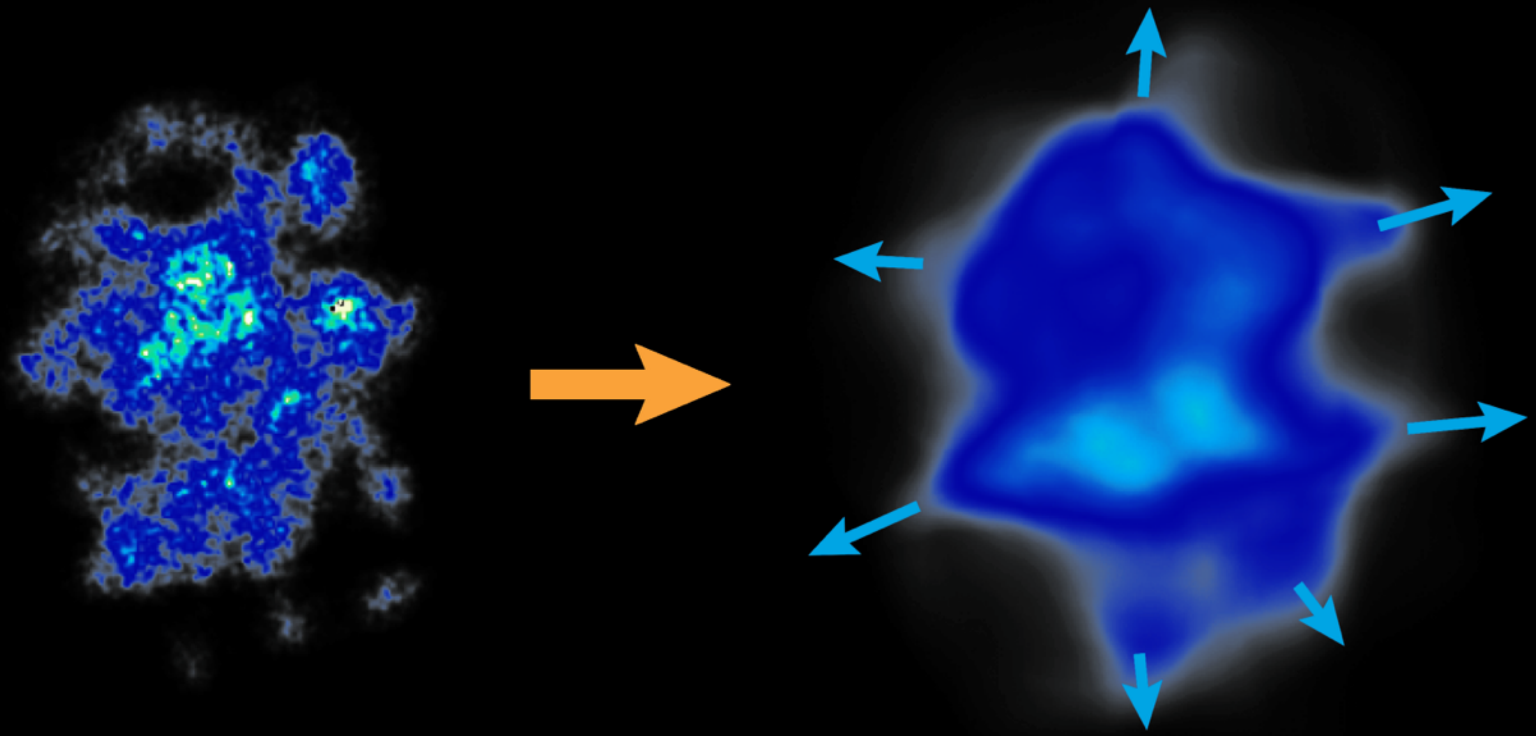


$\Delta\eta$: DIFFERENCE IN PSEUDO-RAPIDITY

Event Displays: © 2012 CERN, ALICE

Interpretation: Strong final state effects

- Long range $\Delta\eta$ correlations emerge from early times (causality)
- Azimuthal structure formed by the medium response to the fluctuating initial transverse geometry

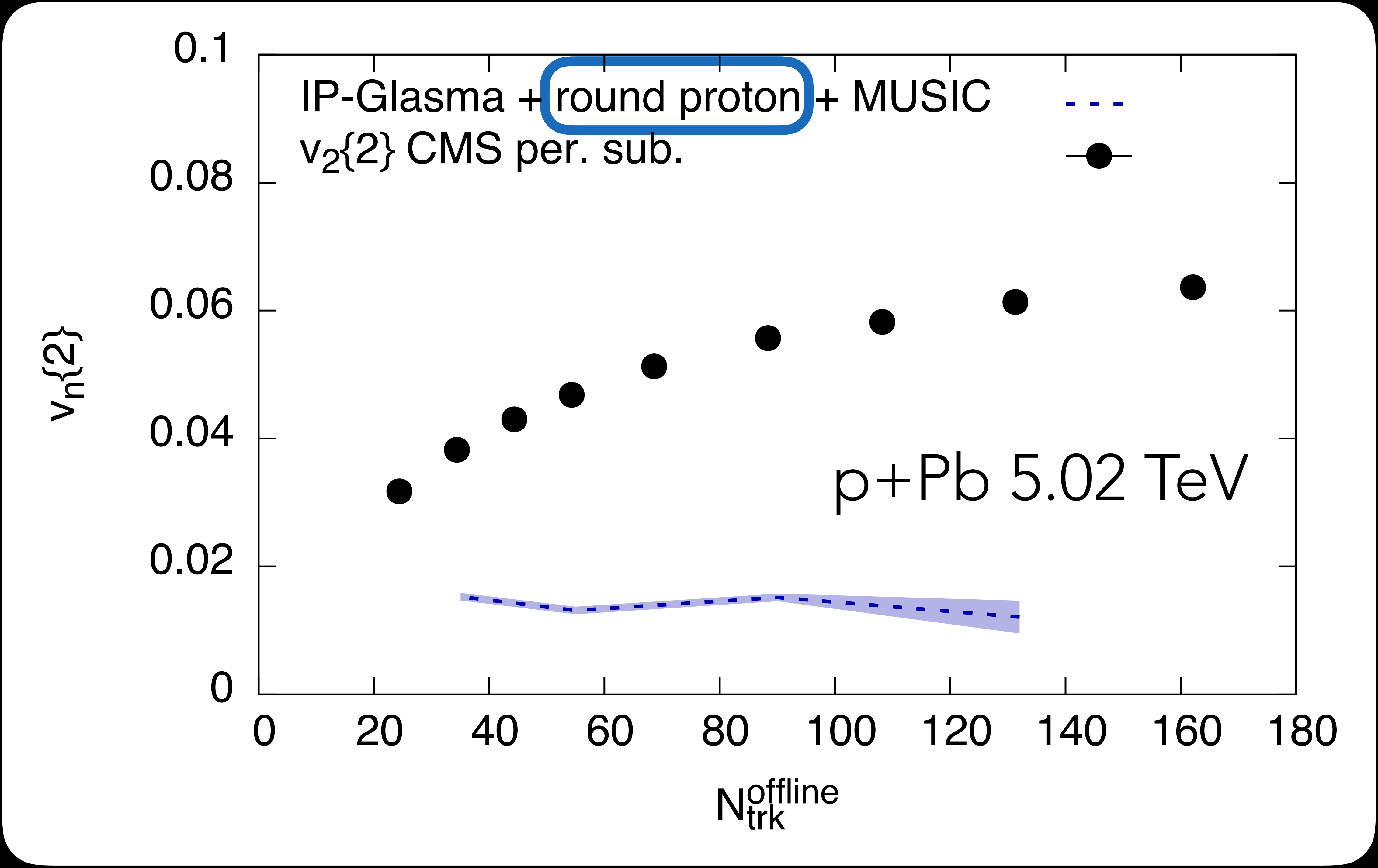


Initial energy density distribution

Hydrodynamic expansion

IP-Glasma+MUSIC (hydrodynamics) results

B. Schenke, R. Venugopalan, Phys. Rev. Lett. 113, 102301 (2014)

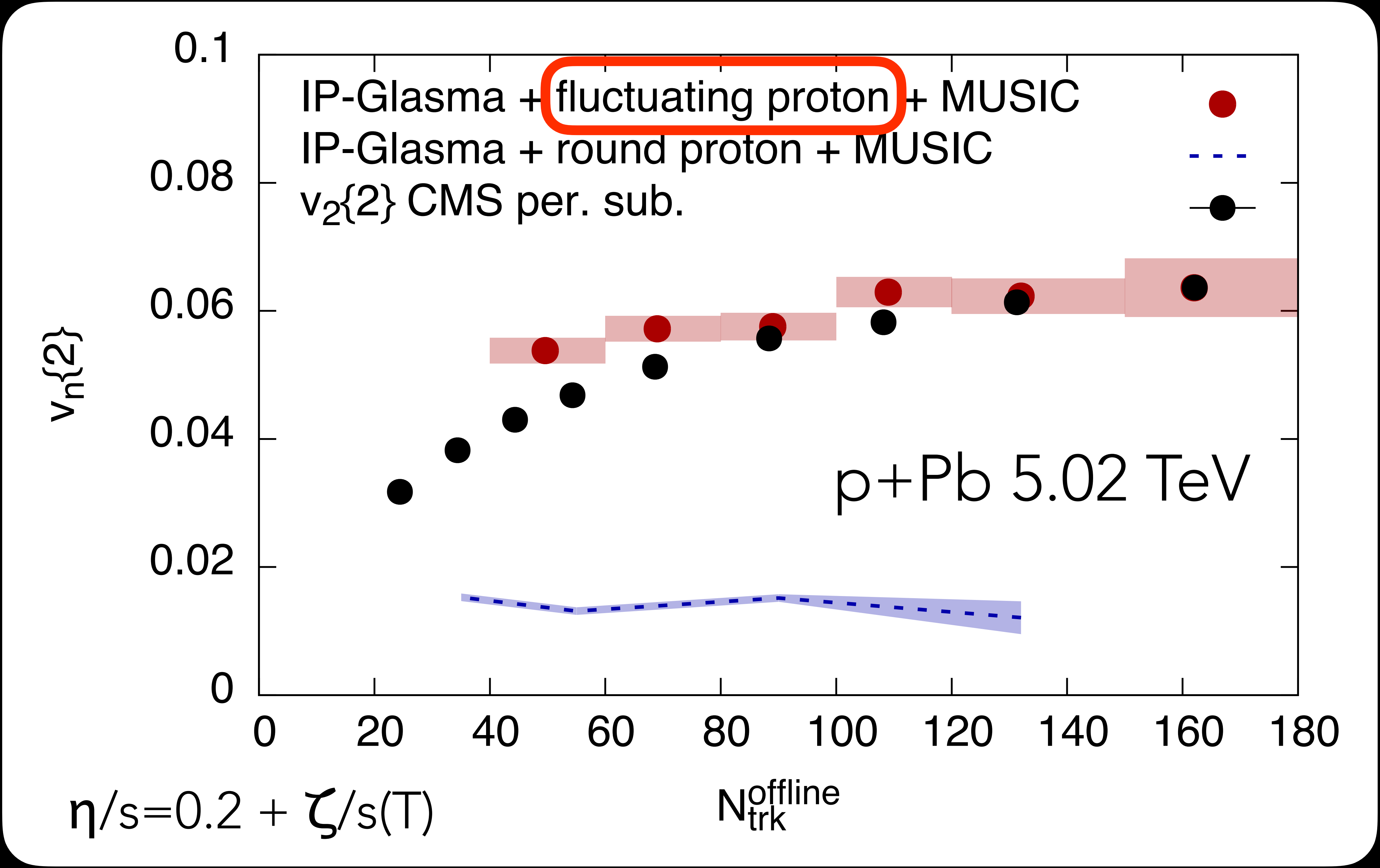


Experimental data: CMS Collaboration, Phys.Lett. B724, 213 (2013)

IP-Glasma+MUSIC (hydrodynamics) results

B. Schenke, R. Venugopalan, Phys. Rev. Lett. 113, 102301 (2014)

H. Mäntysaari, B. Schenke, C. Shen, P. Tribedy, arXiv:1705.03177



$\eta/s=0.2 + \zeta/s(T)$

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

Subnucleonic fluctuations in large nuclei

H. Mäntysaari, B. Schenke, arXiv:1703.09256

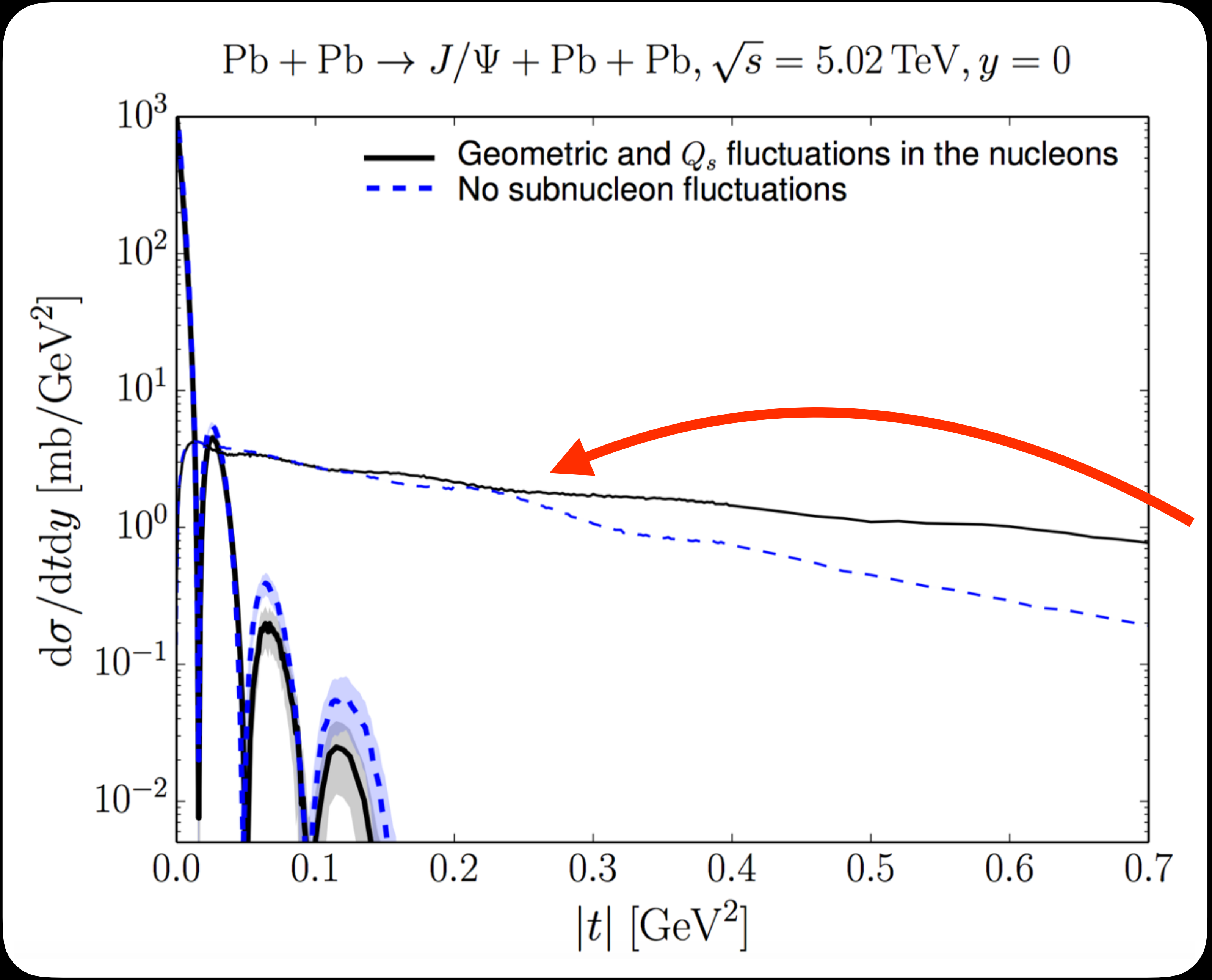
UltraPeripheral heavy ion Collisions (UPC)
At $|b_T| > 2R_A$ one nucleus acts as a photon source

Two sources of fluctuations:
Sample nucleon positions from Woods-Saxon
Sample constituent quark structure for each nucleon

We use the IPsat model for this analysis

Subnucleonic fluctuations in large nuclei

H. Mäntysaari, B. Schenke, arXiv:1703.09256

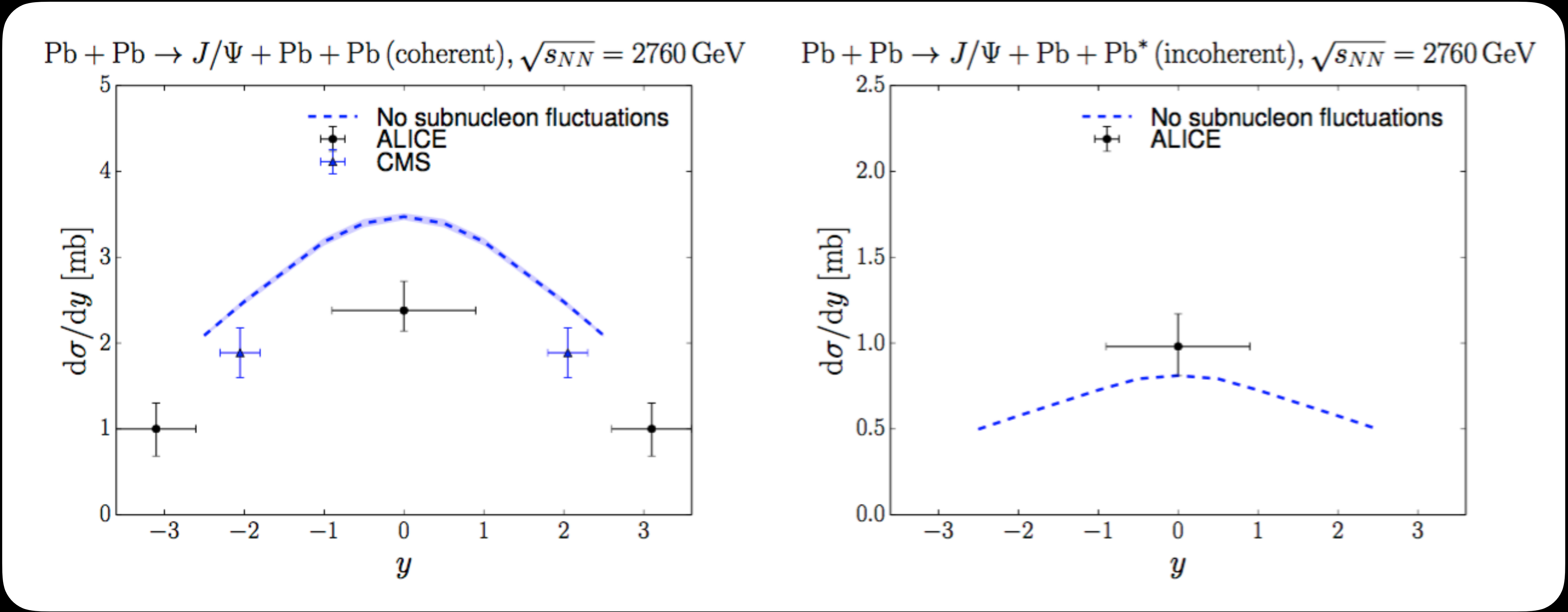


- Small |t|: fluctuations of nucleon positions
- Large |t|: fluctuations at subnucleon scale
- Incoherent slope changes at |t| ≈ 0.25 GeV^2 → 0.4 fm which is size of hot spots

Coherent: thick lines
Incoherent: thin lines

LHC data - no subnucleonic fluctuations

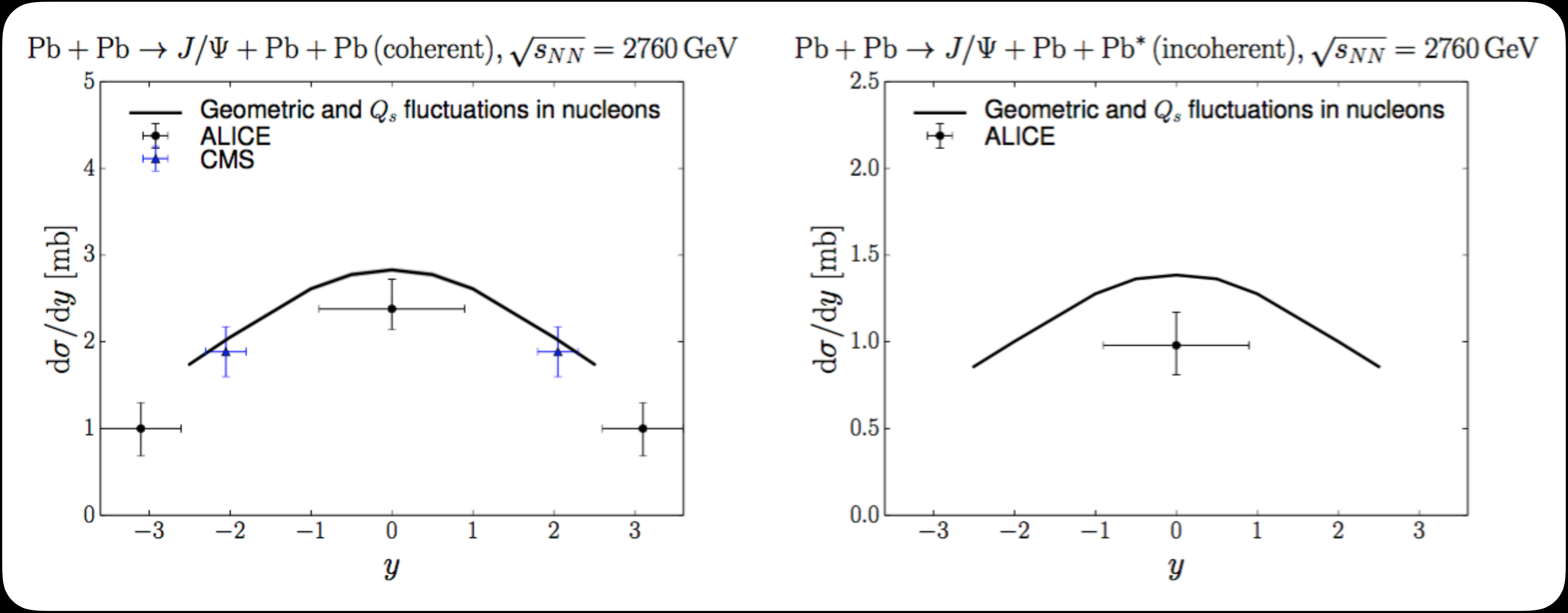
H. Mäntysaari, B. Schenke, arXiv:1703.09256



- 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

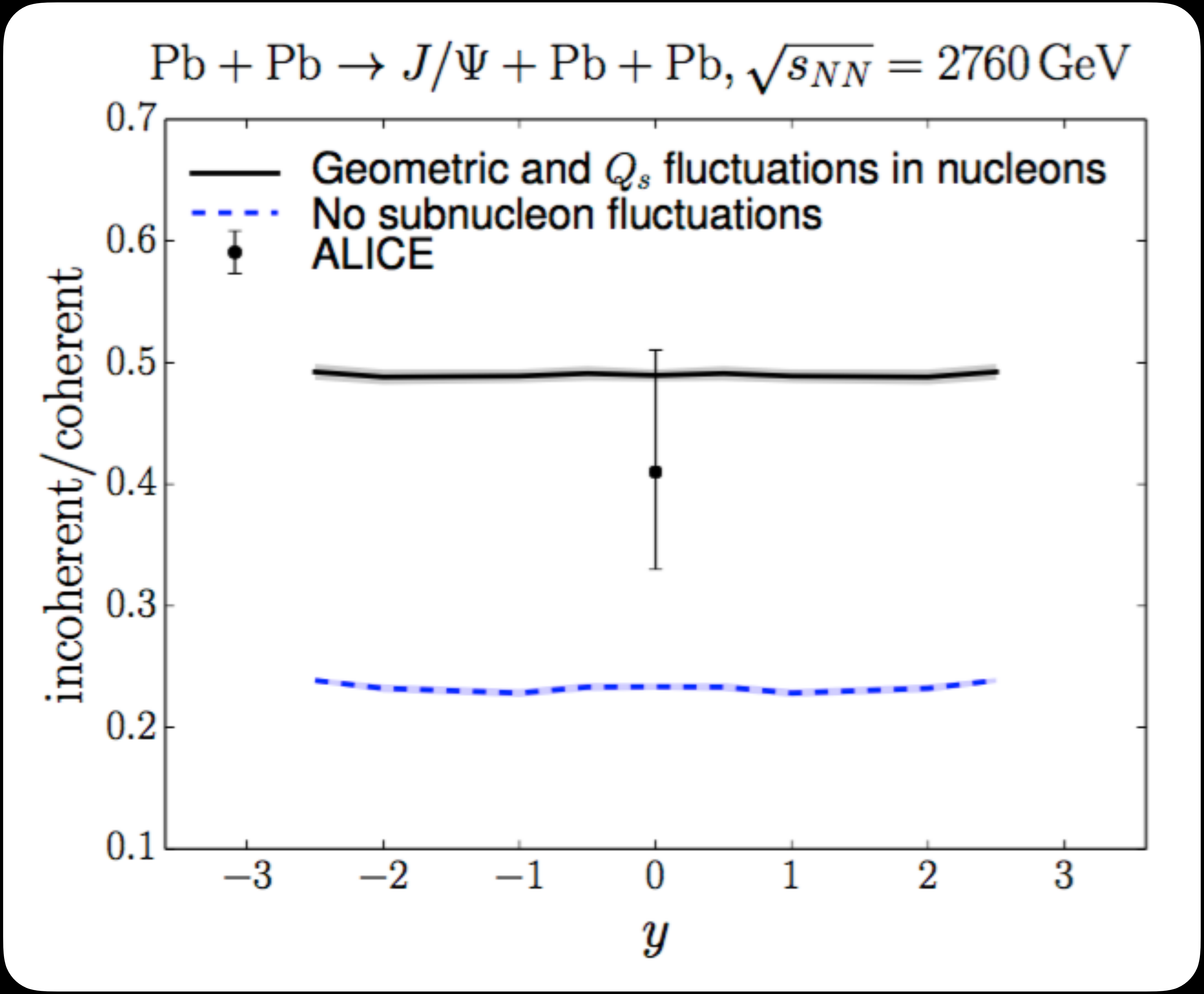
H. Mäntysaari, B. Schenke, arXiv:1703.09256



- 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

Ratio incoherent/coherent cross sections

H. Mäntysaari, B. Schenke, arXiv:1703.09256



Summary

- Shape fluctuations of the proton's gluon distribution are needed to describe incoherent diffractive vector meson data from HERA

- Constrained fluctuating proton shape compatible with anisotropic flow in p+Pb collisions

- Sub-nucleonic fluctuations also affect incoherent diffractive cross section in ultra-peripheral A+A collisions

- Next step: Go from IPsat to explicit JIMWLK evolution and describe F_2 and diffractive data - Modification of MV initial condition necessary

BACKUP

Why a variance?

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

Simple model: Target particle → average optical potential

$$|B\rangle = \sum_k C_k|\psi_k\rangle$$

beam particle

linear comb. of diffractive eigenstates

$$Im T|\psi_k\rangle = A_k|\psi_k\rangle$$

Imaginary part of scattering amplitude

Probability for ψ_k to interact with target

$$\langle B|B\rangle = \sum_k |C_k|^2 = 1$$

Why a variance?

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

Total diffractive cross section:

$$\frac{d\sigma_{\rm diff}}{d^2\vec{b}} = \sum_k |\langle\psi_k|ImT|B\rangle|^2 = \sum_k |C_k|^2 A_k^2 = \langle A^2\rangle$$

Elastic scattering amplitude:

$$\langle B|ImT|B\rangle = \sum_k |C_k|^2 A_k = \langle A\rangle$$

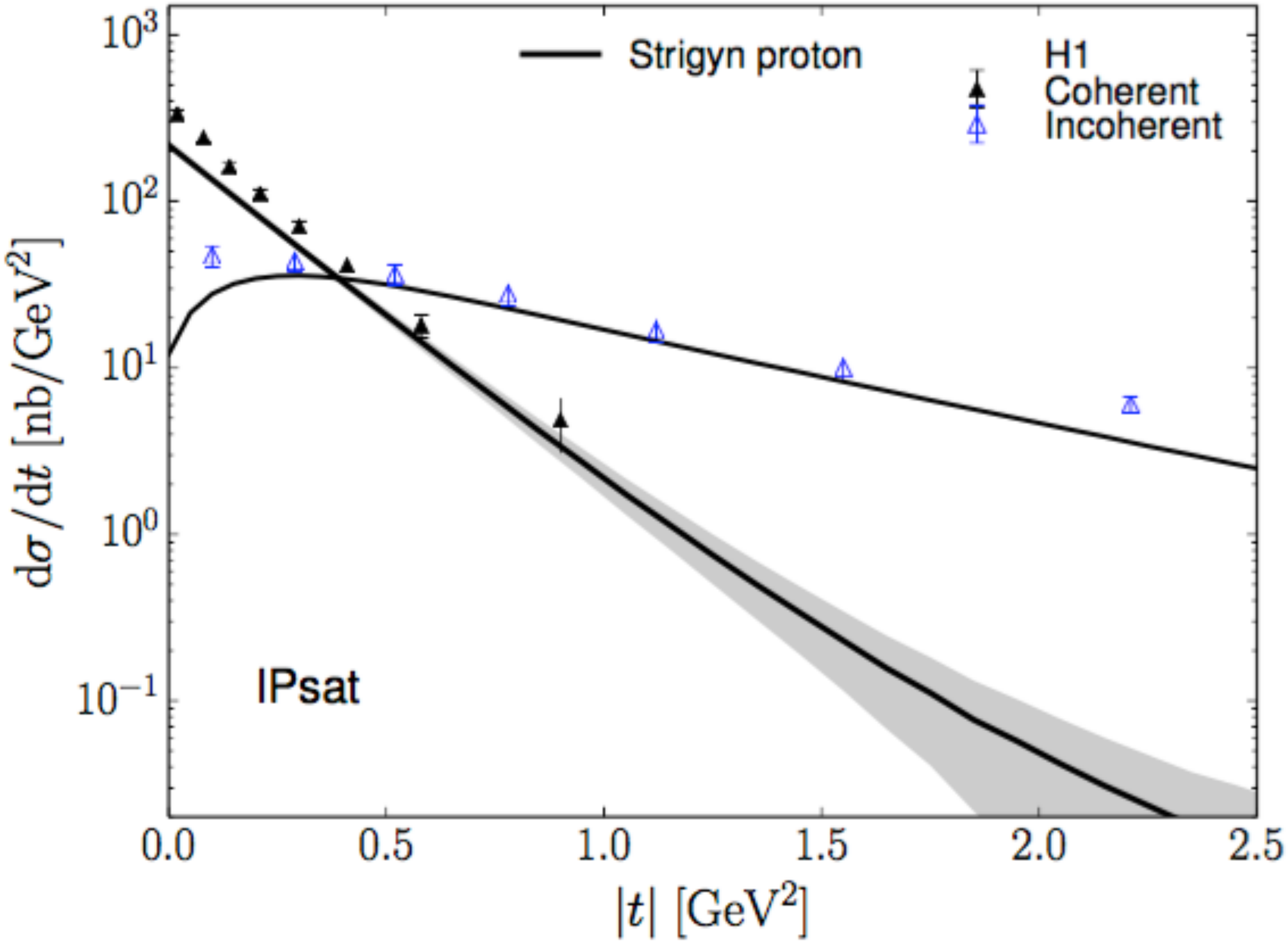
Average over absorption coefficients, weighted according to their probability of occurrence in the particle B

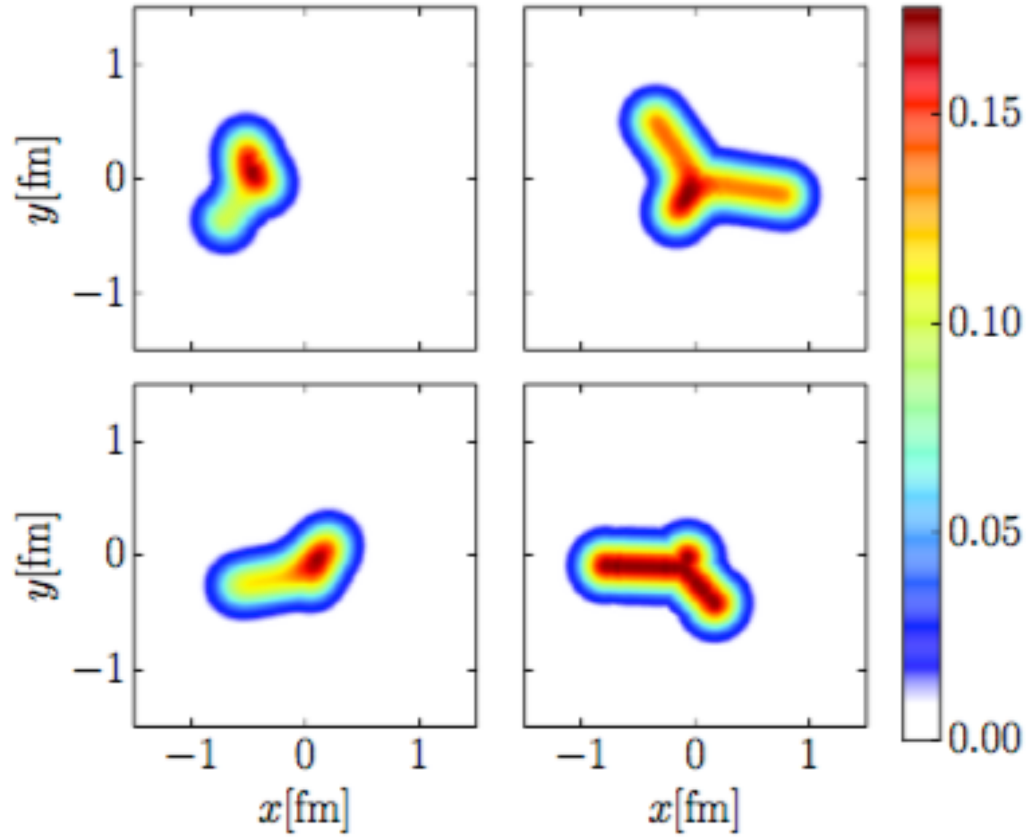
Elastic cross section: $$\frac{d\sigma_{\rm el}}{d^2\vec{b}} = \langle A\rangle^2$$

Inelastic diffractive cross section: $$\frac{d\sigma_{\rm inel}}{d^2\vec{b}} = \langle A^2\rangle - \langle A\rangle^2$$

Lumpiness matters, not details of the density profile

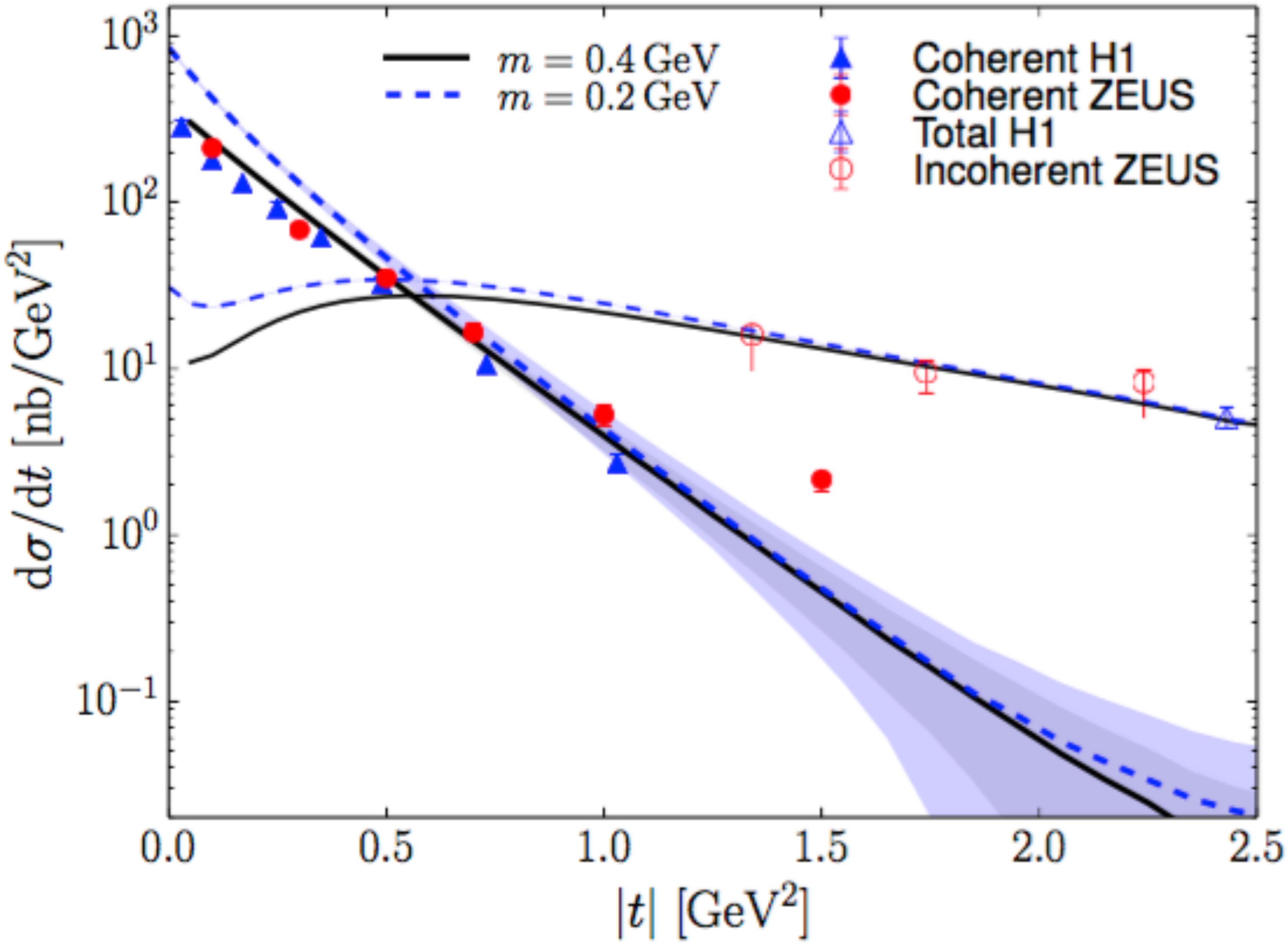
3 valence quarks that are connected by "color flux tubes":
Gaussian tubes connecting quarks. Also good description of the data




Example density profiles

H.M, B. Schenke, PRD94 034042
Flux tubes implementation following results from hep-lat/0606016, used also e.g. in 1307.5911

Insensitivity on infrared cutoff

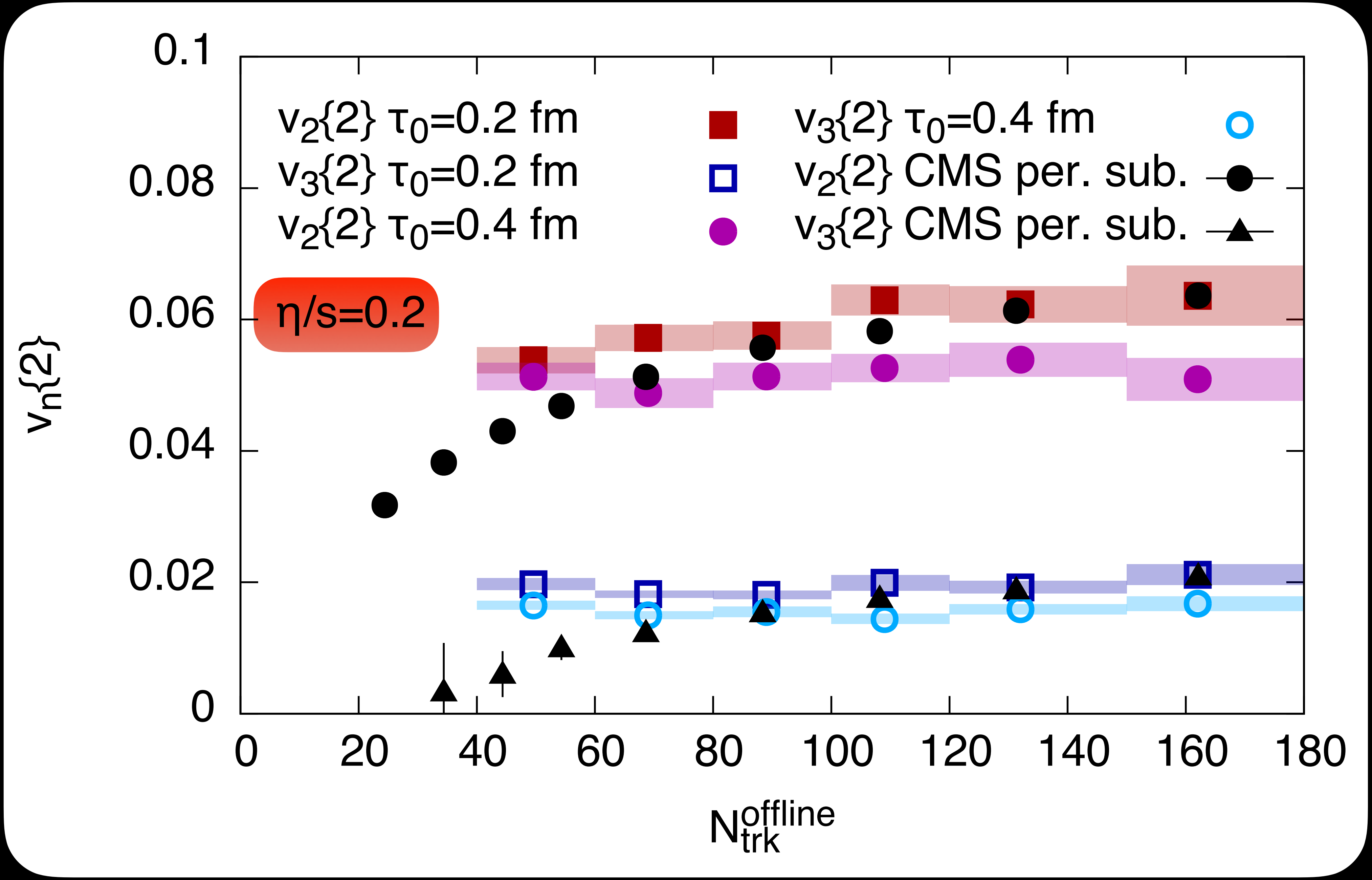


IP-Glasma: IR cutoff *m* ∼ Λ_{QCD} to regulates long distance coulomb tails

- Proton size depends on *m*
- No sensitivity at large $|t|$

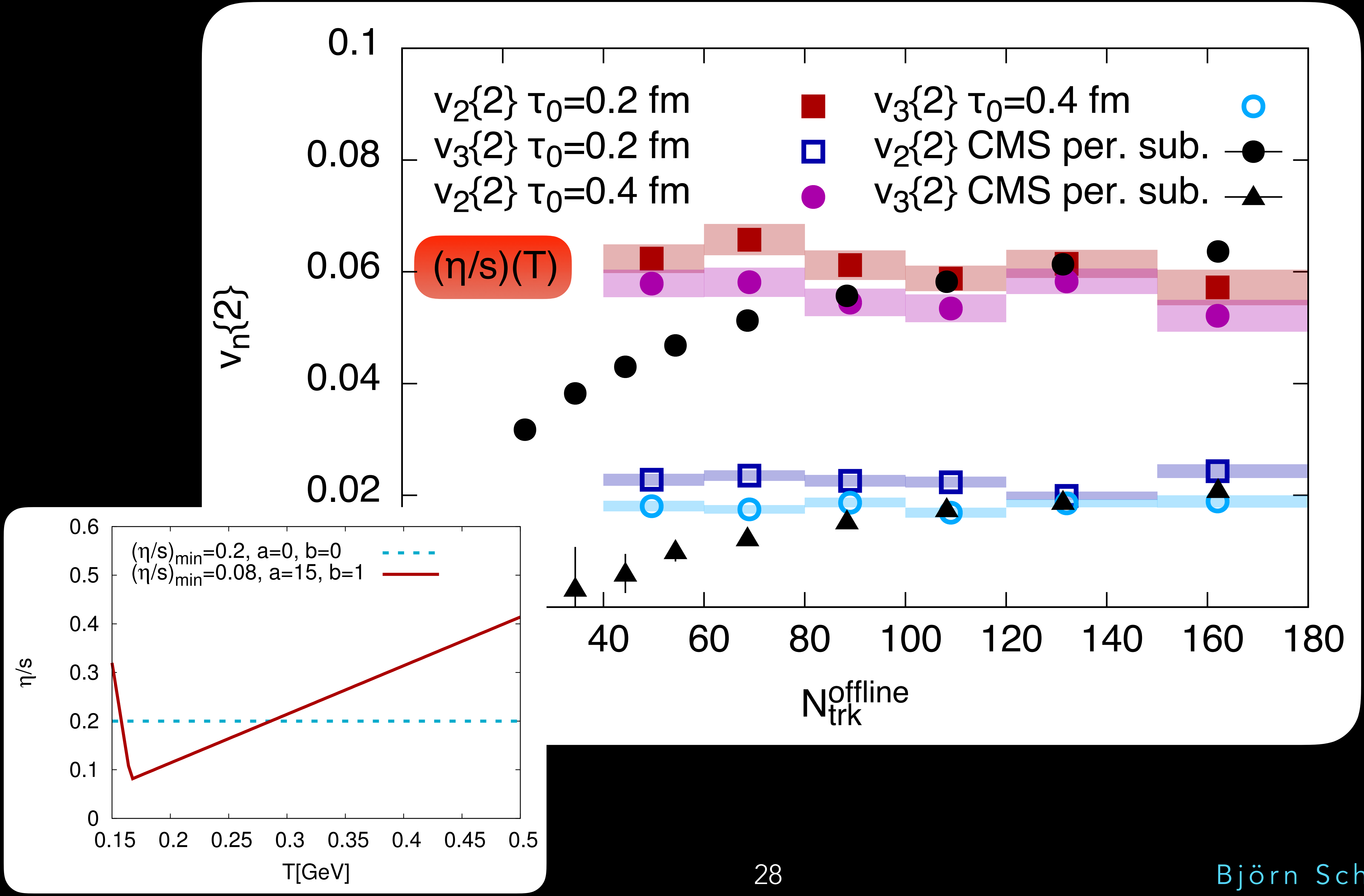
Integrated anisotropic flow

H. Mäntysaari, B. Schenke, C. Shen, P. Tribedy, arXiv:1705.03177



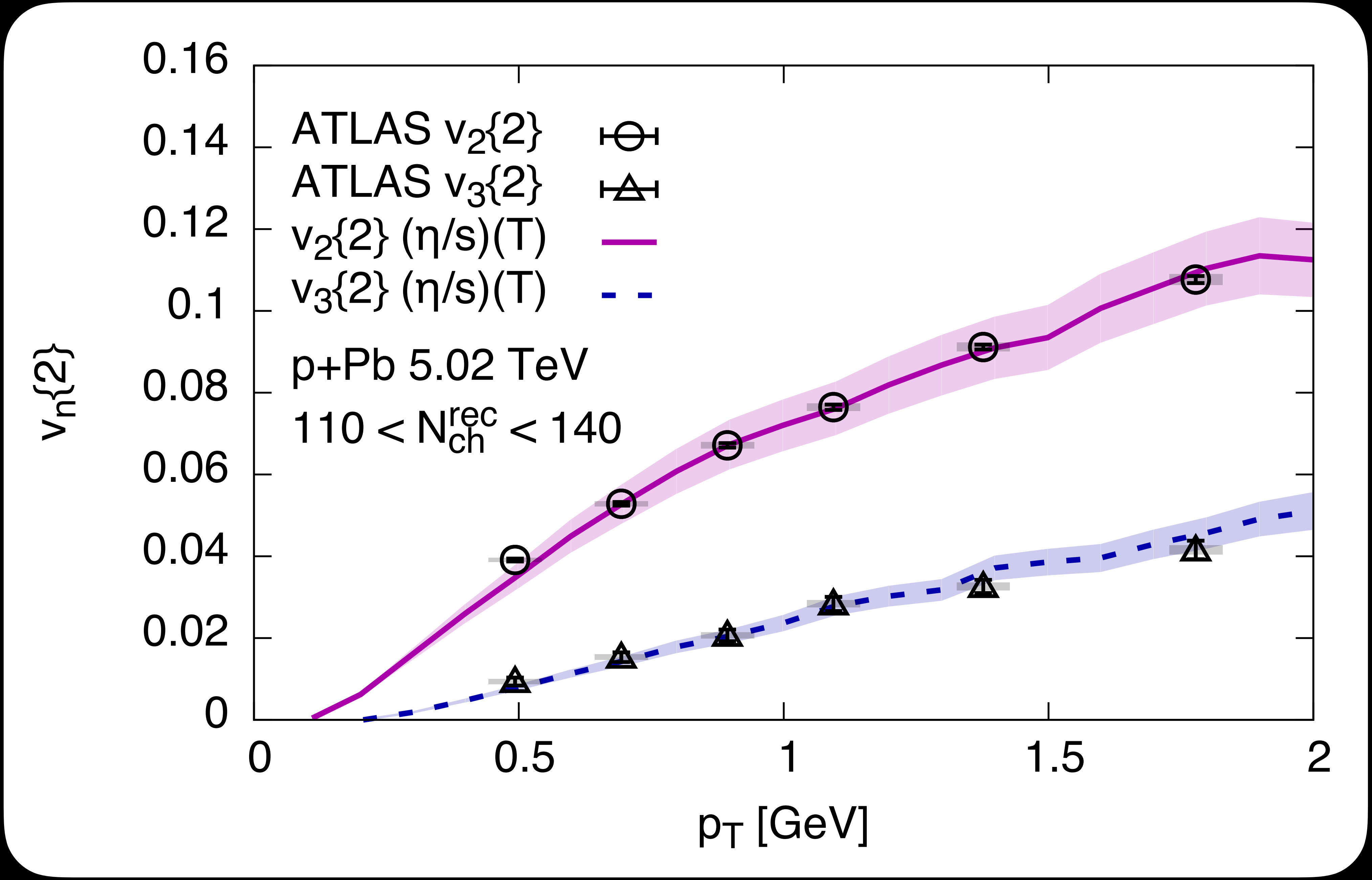
Integrated anisotropic flow

H. Mäntysaari, B. Schenke, C. Shen, P. Tribedy, arXiv:1705.03177



p_T-differential anisotropic flow

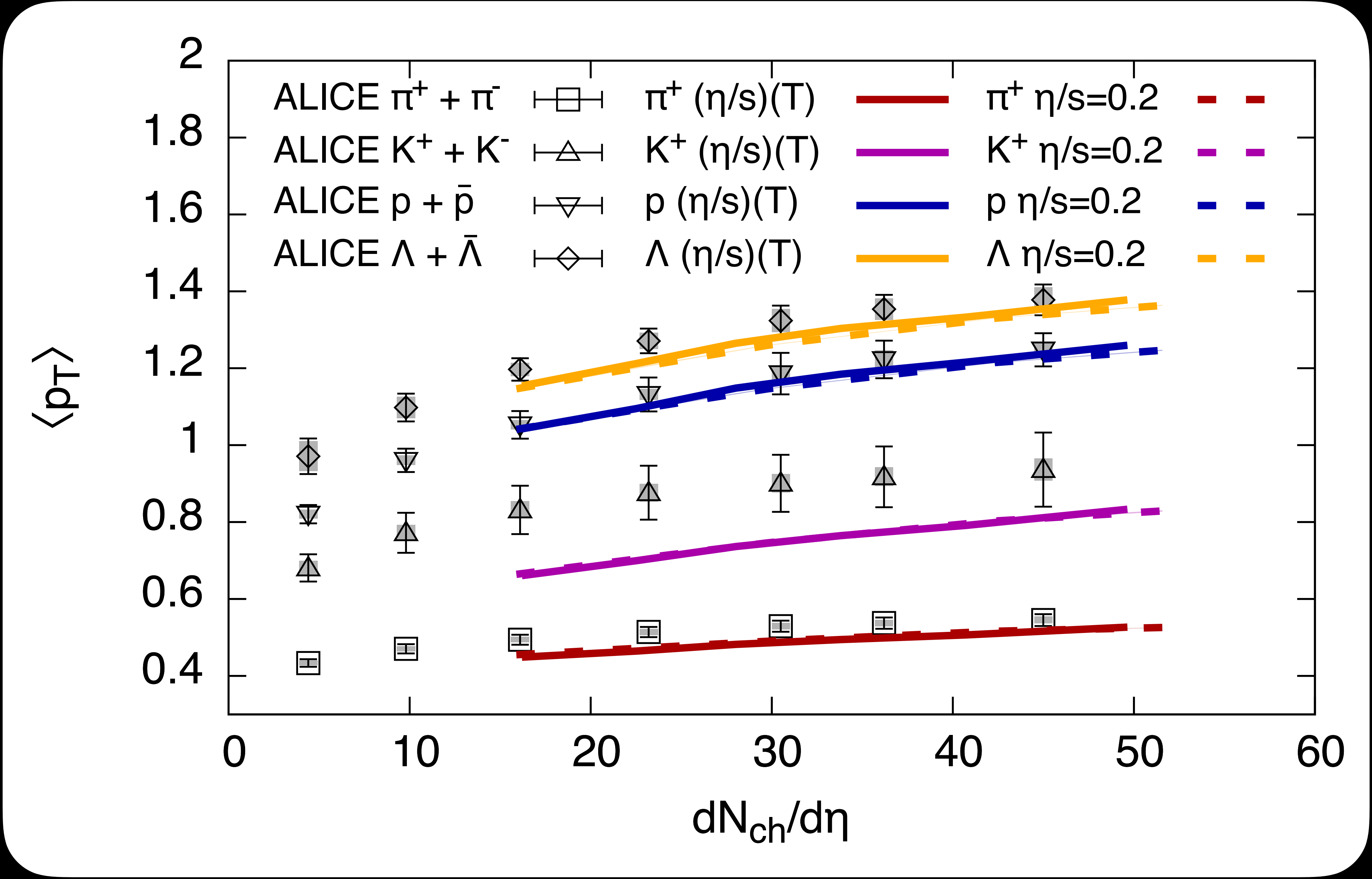
H. Mäntysaari, B. Schenke, C. Shen, P. Tribedy, arXiv:1705.03177



τ_0=0.4 fm

Identified particle mean p_T

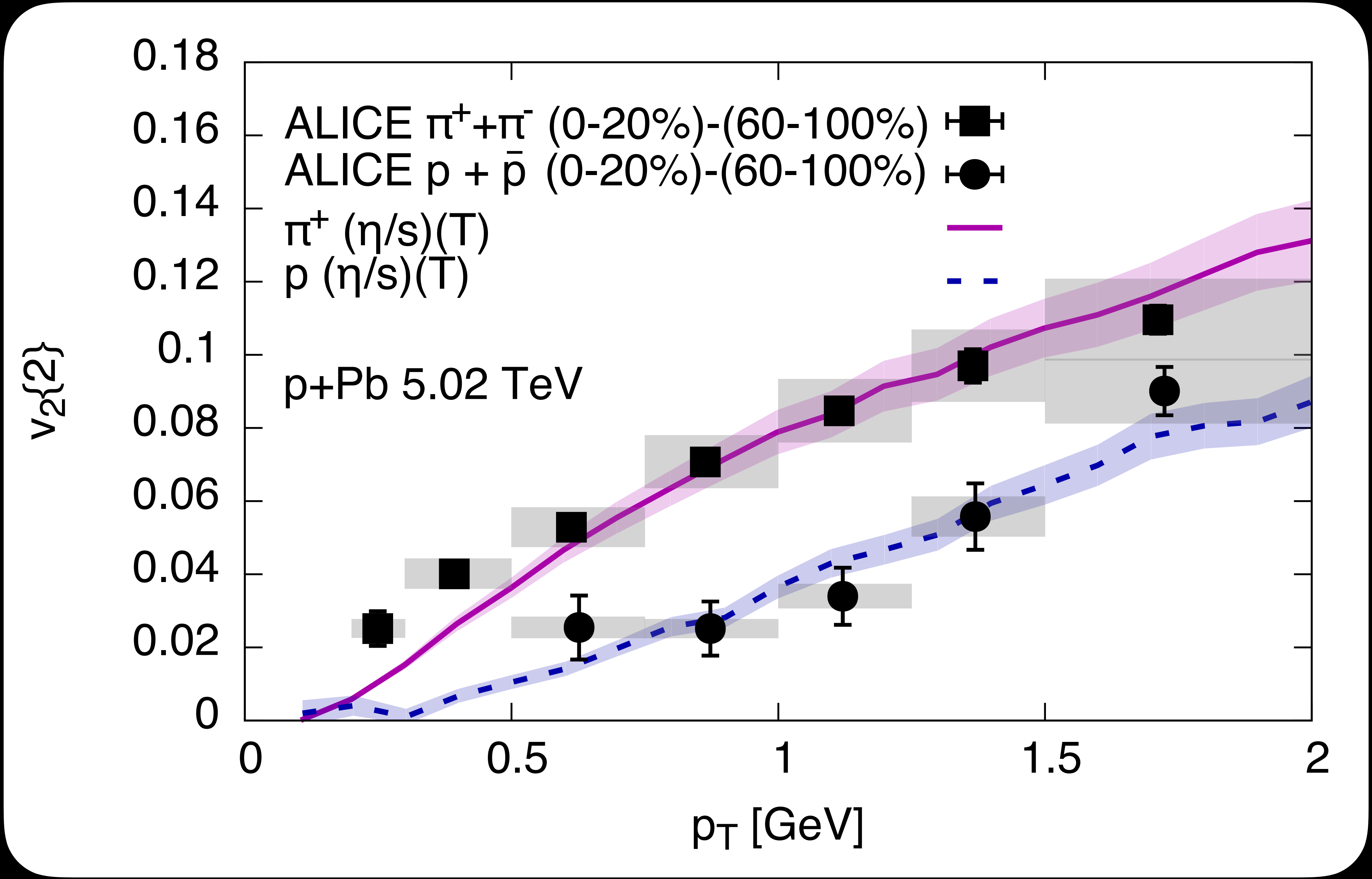
H. Mäntysaari, B. Schenke, C. Shen, P. Tribedy, arXiv:1705.03177



Experimental data: ALICE Collaboration, Phys. Lett. B728, 25 (2014)

Identified particle flow

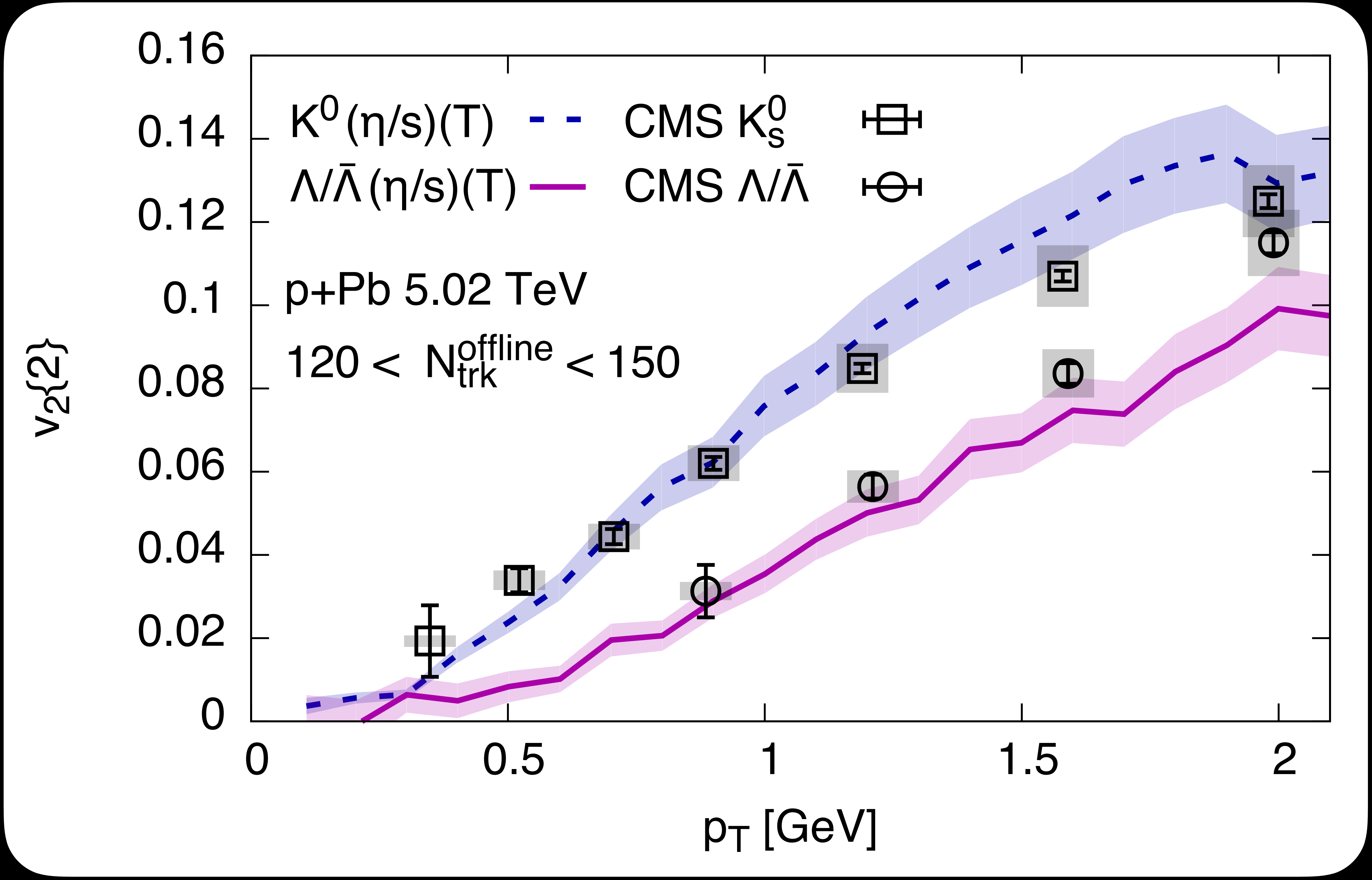
H. Mäntysaari, B. Schenke, C. Shen, P. Tribedy, arXiv:1705.03177



τ_0=0.4 fm

Identified particle flow

H. Mäntysaari, B. Schenke, C. Shen, P. Tribedy, arXiv:1705.03177

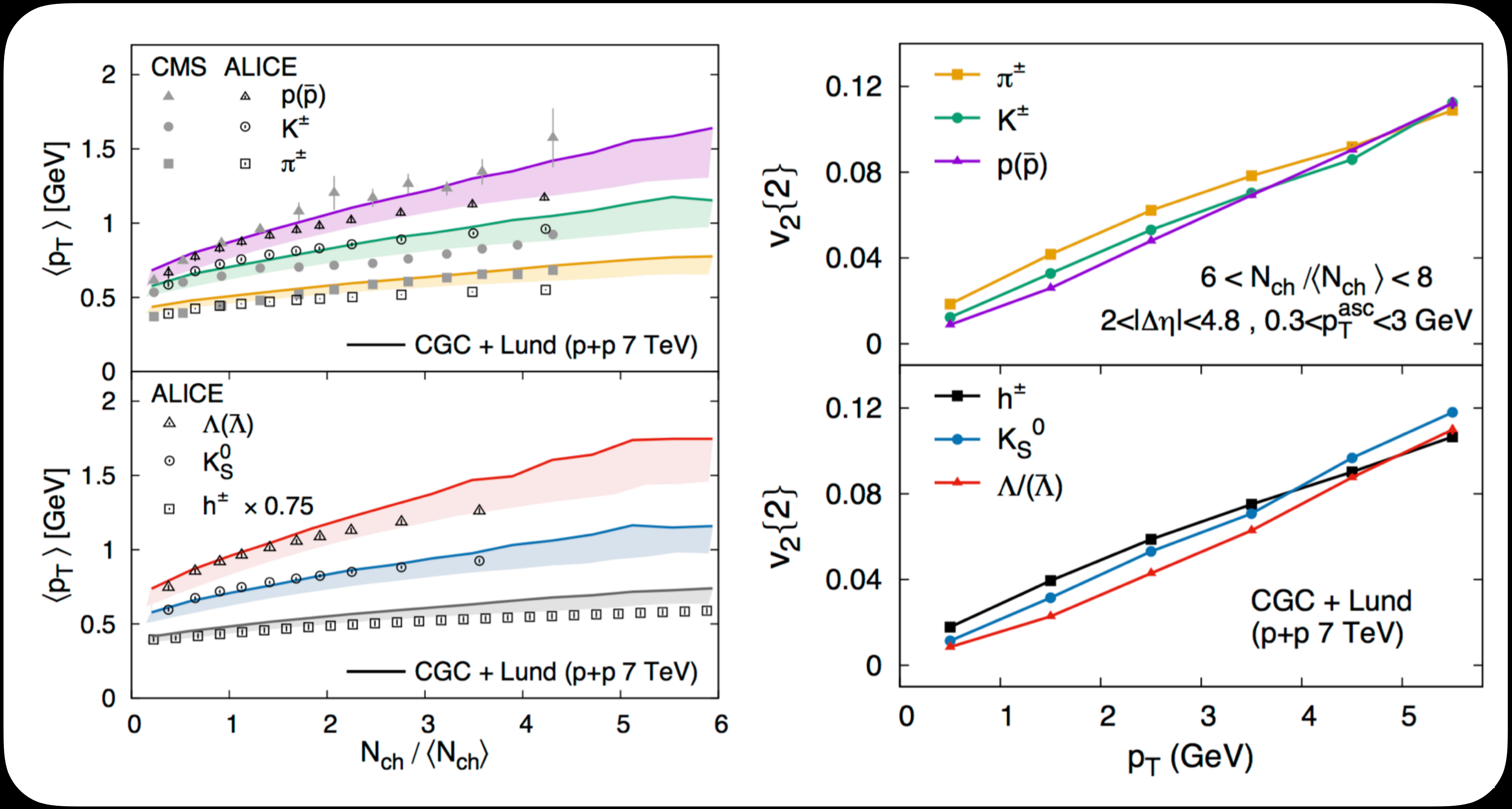


τ_0=0.4 fm

Mass ordering w/o hydrodynamics

B. Schenke, S. Schlichting, P. Tribedy, R. Venugopalan, Phys. Rev. Lett. 117, 162301 (2016)

Yang-Mills initial state + Lund fragmentation



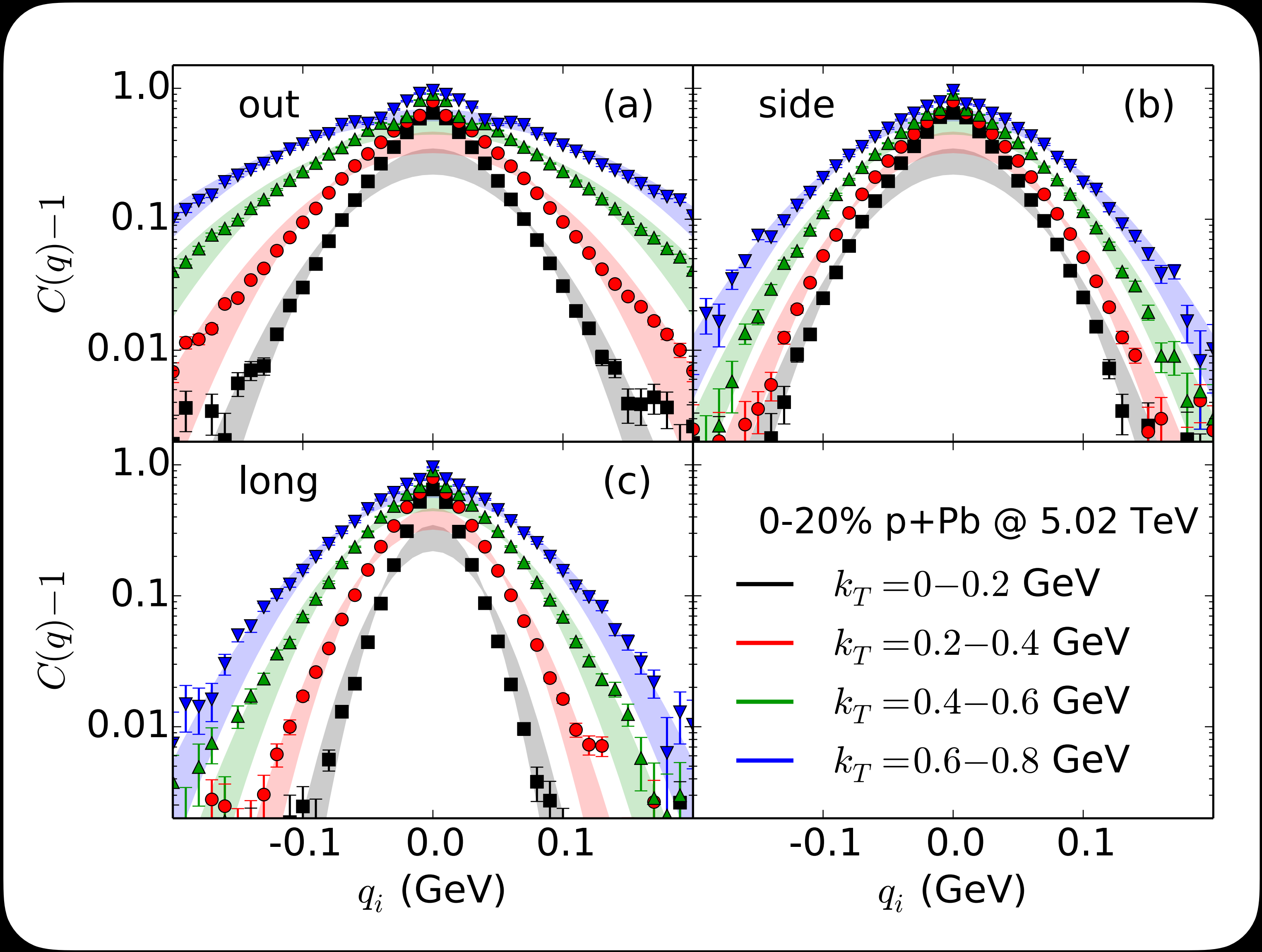
Emission from common boosted source

HBT radii

H. Mäntysaari, B. Schenke, C. Shen, P. Tribedy, arXiv:1705.03177

$$C(\mathbf{q}) = 1 + \frac{\frac{1}{\langle N_{\mathrm{pair}}\rangle}\langle \sum_{ij} \cos(q_{ij}\cdot x_{ij})\rangle}{\frac{1}{\langle N_{\mathrm{mix\,pair}}\rangle}\langle N_{\mathrm{mix\,pair}}(q)\rangle}$$

M. A. Lisa, S. Pratt, R. Soltz, and U. Wiedemann,
Ann. Rev. Nucl. Part. Sci. 55, 357 (2005)
R. Hanbury Brown and R. Q. Twiss
Nature 178, 1046 (1956)



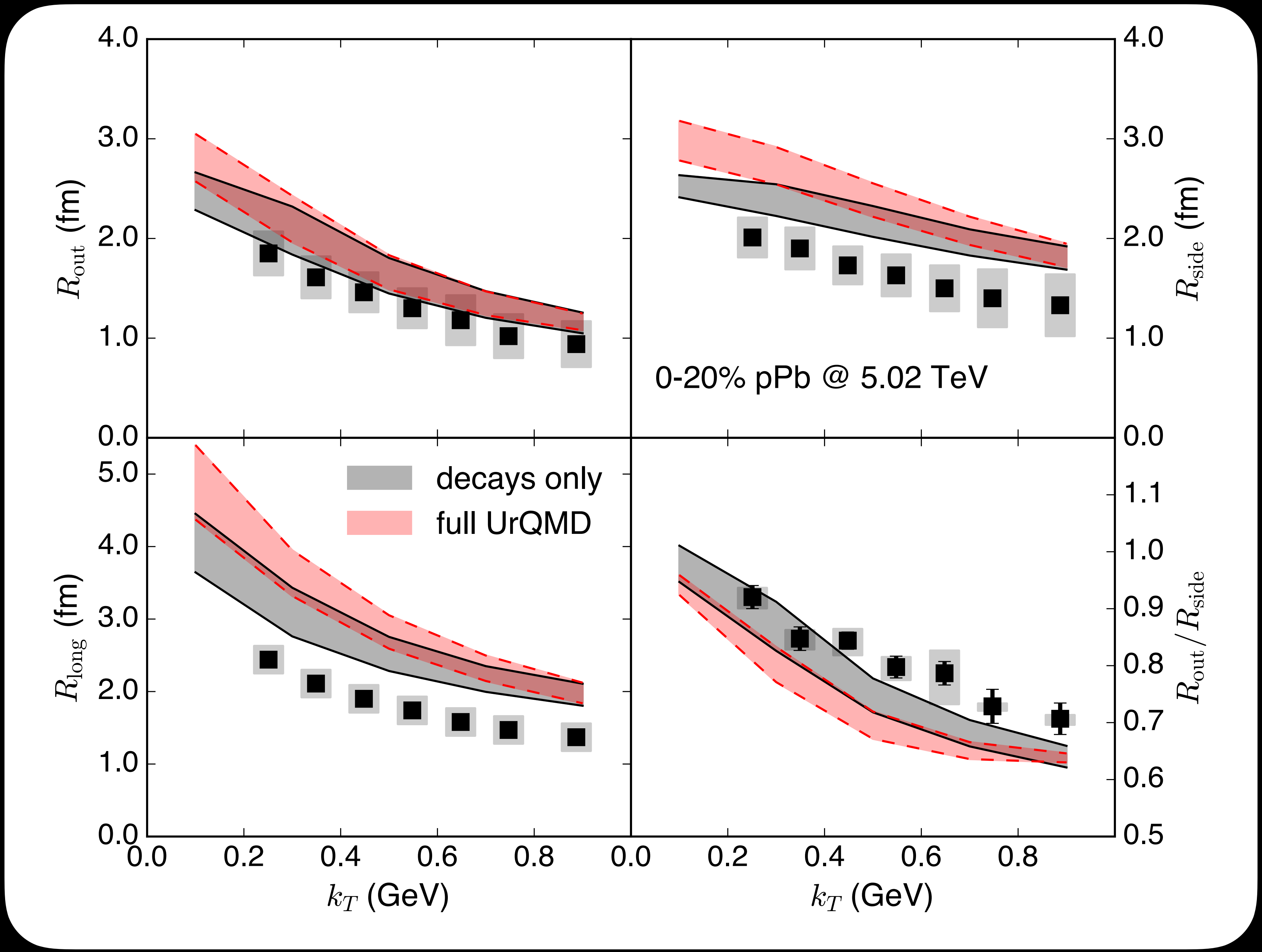
Fit to the Pratt-Bertsch parameterization in the longitudinally co-moving system

S. Pratt, Phys. Rev. D33, 1314 (1986)
G. Bertsch, M. Gong, and M. Tohyama
Phys. Rev. C37, 1896 (1988).

HBT radii

H. Mäntysaari, B. Schenke, C. Shen, P. Tribedy, arXiv:1705.03177

Data: ALICE Collaboration, J. Adam et al. (ALICE), Phys. Rev. C91, 034906 (2015)



τ_0=0.4 fm $(\eta/s)(T)$

JIMWLK evolution

Replace parametrized x-dependence by renormalization group equation for x-dependence of probability distribution of Wilson lines

$$\partial_y W_y[V(\vec{x})] = \mathcal{H} W_y[V(\vec{x})]$$

with the JIMWLK Hamiltonian

$$\mathcal{H} = -\frac{1}{2}\frac{\alpha_s}{\pi^2}\int_{\vec{x}\vec{y}\vec{z}} \frac{\delta}{\delta A^{c+}(\vec{x})}\Big[(1 - V^\dagger(\vec{x})V(\vec{z}))^{ca}(1 - V^\dagger(\vec{y})V(\vec{z}))^{ba}$$
$$\times \frac{(\vec{x}-\vec{z})\cdot(\vec{y}-\vec{z})}{(\vec{x}-\vec{z})^2(\vec{y}-\vec{z})^2}\frac{\delta}{\delta A^{b+}(\vec{y})} W_y[V]\Big]$$

J. Jalilian-Marian, A. Kovner, A. Leonidov, 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)

Numerical JIMWLK implementation

H. Weigert, Nucl. Phys. A 703, 823 (2002).
T. Lappi and H. Mantysaari, Eur. Phys. J. C 73, 2307 (2013)

Langevin formulation

$$V_{\mathbf{x}}(Y+dY) = \exp\left\{-i\frac{\sqrt{\alpha_s dY}}{\pi}\int_{\mathbf{z}} K_{\mathbf{x}-\mathbf{z}}\cdot(V_{\mathbf{z}}\xi_{\mathbf{z}}V_{\mathbf{z}}^{\dagger})\right\}$$
$$\times V_{\mathbf{x}}(Y)\exp\left\{i\frac{\sqrt{\alpha_s dY}}{\pi}\int_{\mathbf{z}} K_{\mathbf{x}-\mathbf{z}}\cdot\xi_{\mathbf{z}}\right\}$$

ξ is Gaussian noise with zero average and

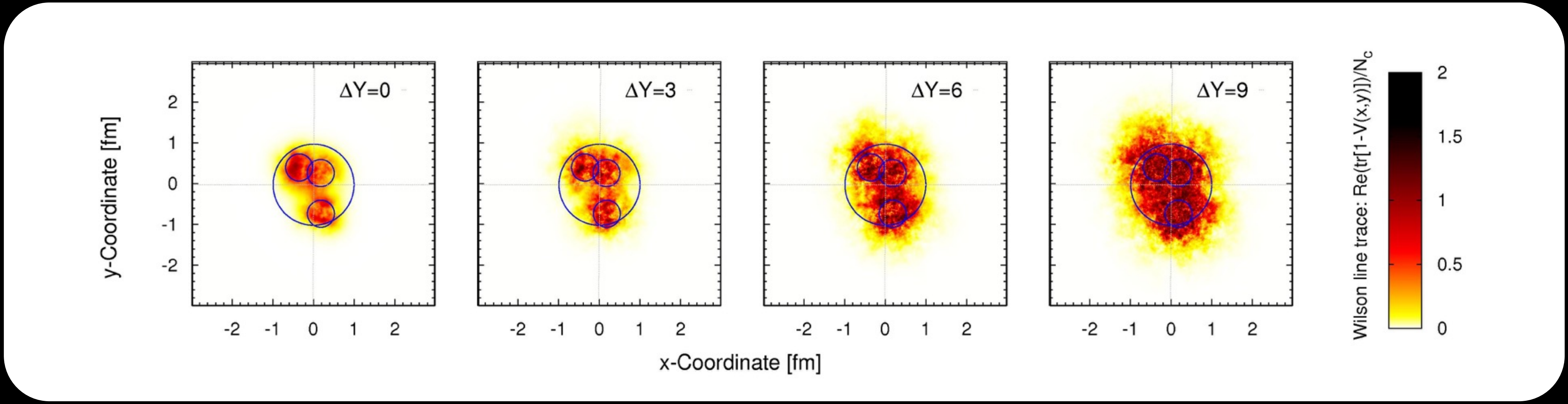
$$\langle \xi^a_{\mathbf{x},i}(Y)\xi^b_{\mathbf{y},j}(Y')\rangle = \delta^{ab}\delta^{ij}\delta^{(2)}_{\mathbf{x}\mathbf{y}}\delta(Y-Y')$$

The JIMWLK Kernel is modified to avoid infrared tails:

$$K^{\mathrm{mod}}_{\mathbf{x}-\mathbf{z}} = m|\mathbf{x}-\mathbf{z}|K_1(m|\mathbf{x}-\mathbf{z}|)\frac{\mathbf{x}-\mathbf{z}}{(\mathbf{x}-\mathbf{z})^2}$$

Shape evolution of the proton

decreasing x, increasing energy



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

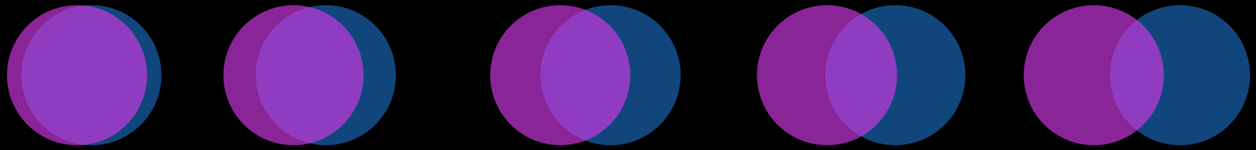
Proton grows with increasing x

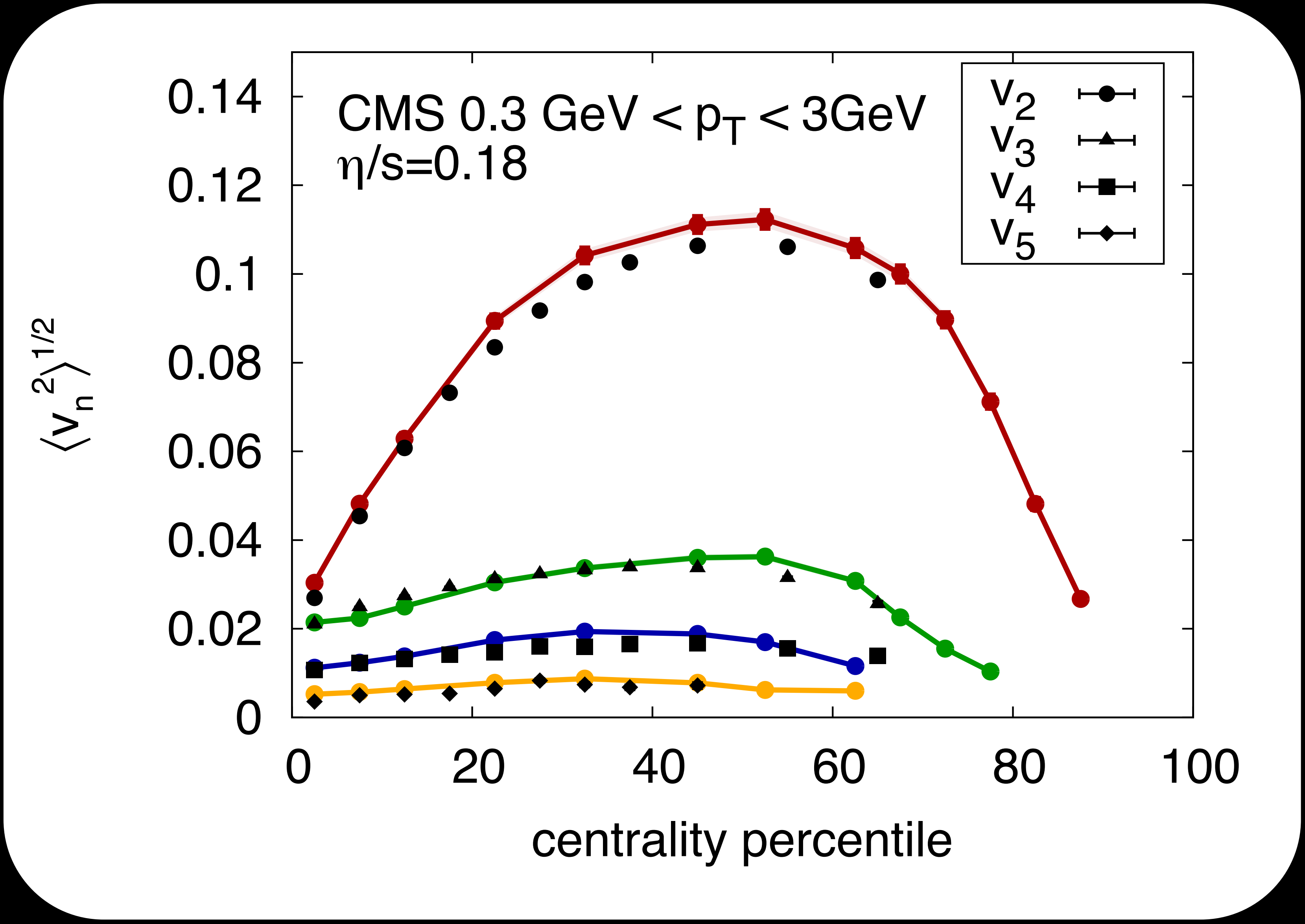
Growth is linear with Y when infrared regulator is used

Froissart bound not violated

Flow harmonics v_n from IP-Glasma initial state and MUSIC hydrodynamics

C.Gale, S.Jeon, B.Schenke, P.Tribedy, R.Venugopalan, Phys.Rev.Lett. 110, 012302 (2013)
B. Schenke, R. Venugopalan, Phys.Rev.Lett. 113 (2014) 102301

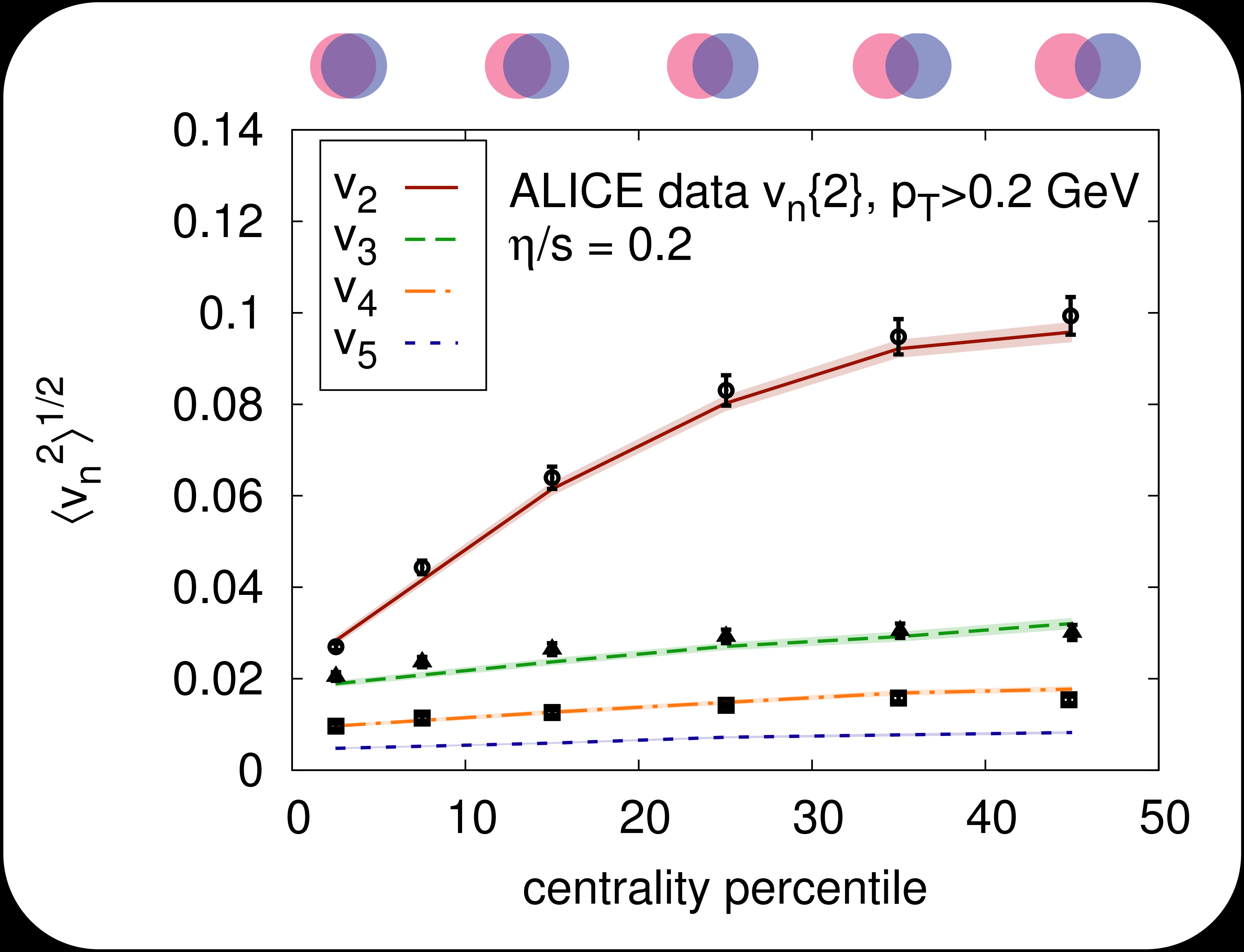




CMS Collaboration, PRC 87(2013) 014902

COMPARISON OF THEORY TO EXPERIMENT

C. GALE, S. JEON, B.SCHENKE, P.TRIBEDY, R.VENUGOPALAN, PRL110, 012302 (2013)



Quantitative description of the experimental data!

EXP. DATA: ALICE COLLABORATION, PHYS. REV. LETT. 107, 032301 (2011)