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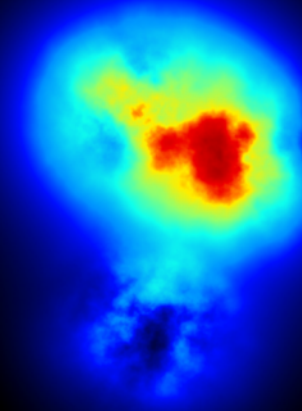
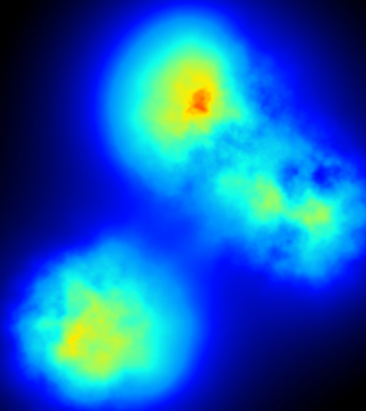
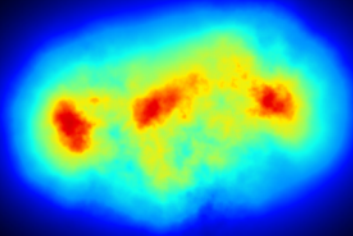
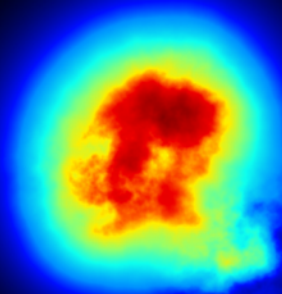
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NATIONAL LABORATORY

EVIDENCE OF PROTON SHAPE FLUCTUATIONS FROM DIFFRACTION

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Brookhaven National Laboratory



June 26, 2017

Synergies of pp and pA Collisions with an Electron-Ion Collider
Brookhaven National Laboratory

Introduction

Fundamental questions:

How are gluons distributed spatially in the proton?

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

Diffraction 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

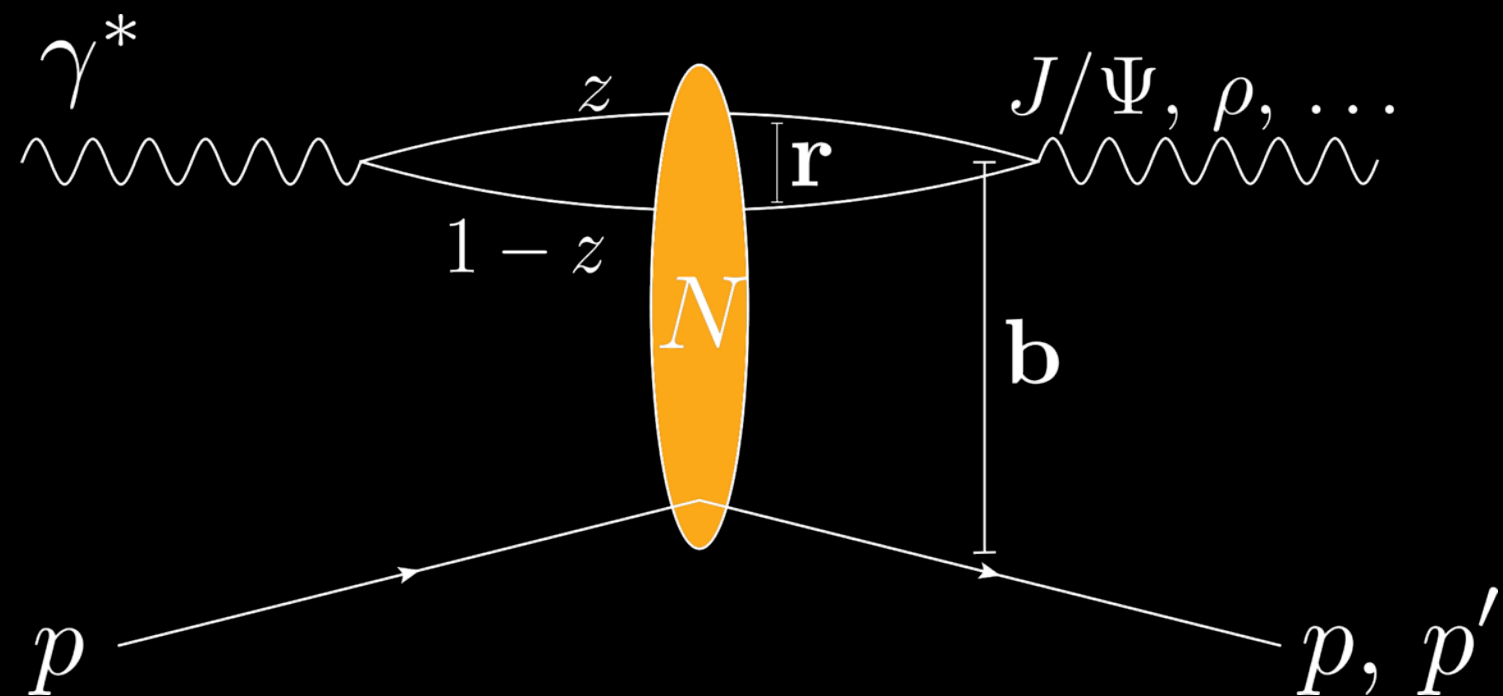
No exchange of
color charge
→ Large rapidity gap

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

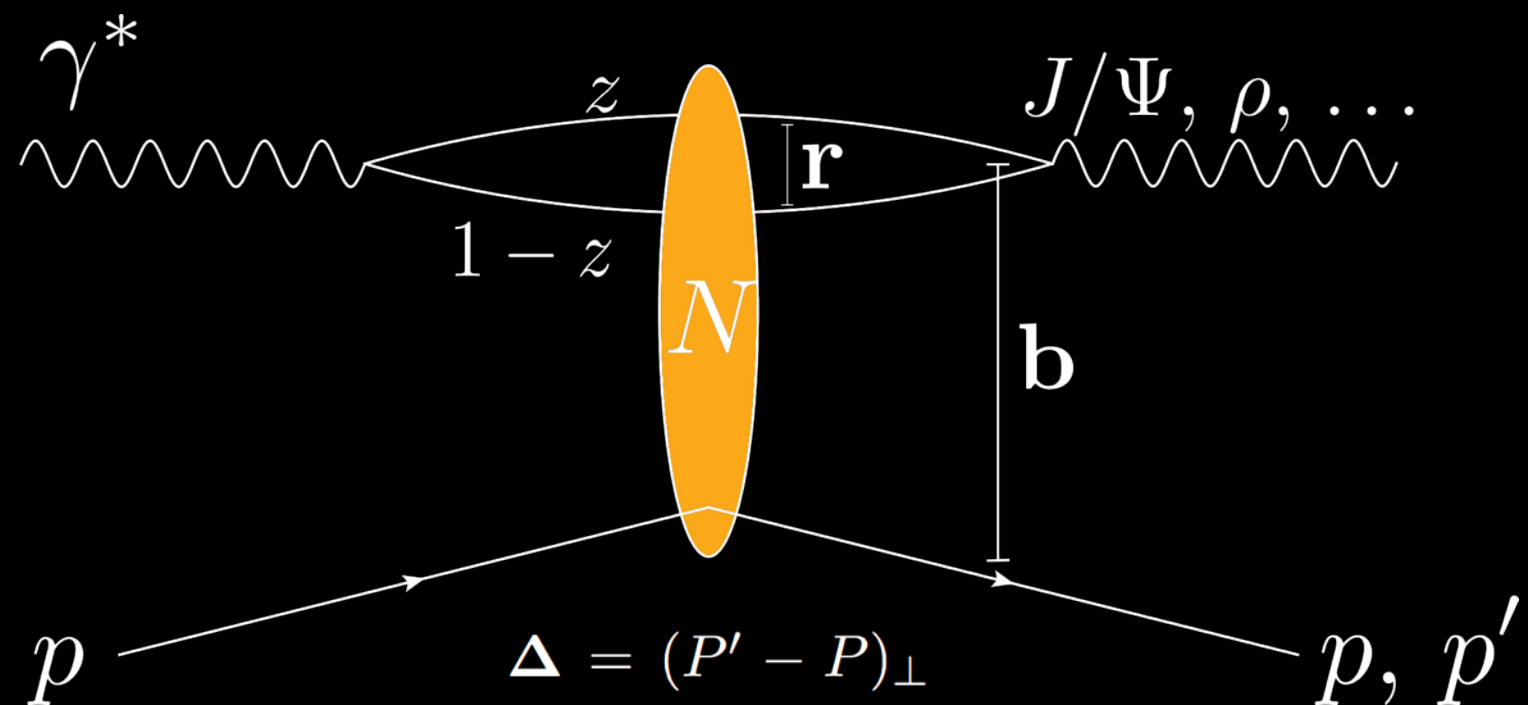
Diffractive eigenstates are color dipoles
at fixed r_T and b_T

see

M. L. Good and W. D. Walker

Phys. Rev. 120 (1960) 1857.

Scattering amplitude



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

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

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

INCOHERENT DIFFRACTION:
TARGET BREAKS UP

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

SENSITIVE TO FLUCTUATIONS!

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

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

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

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:

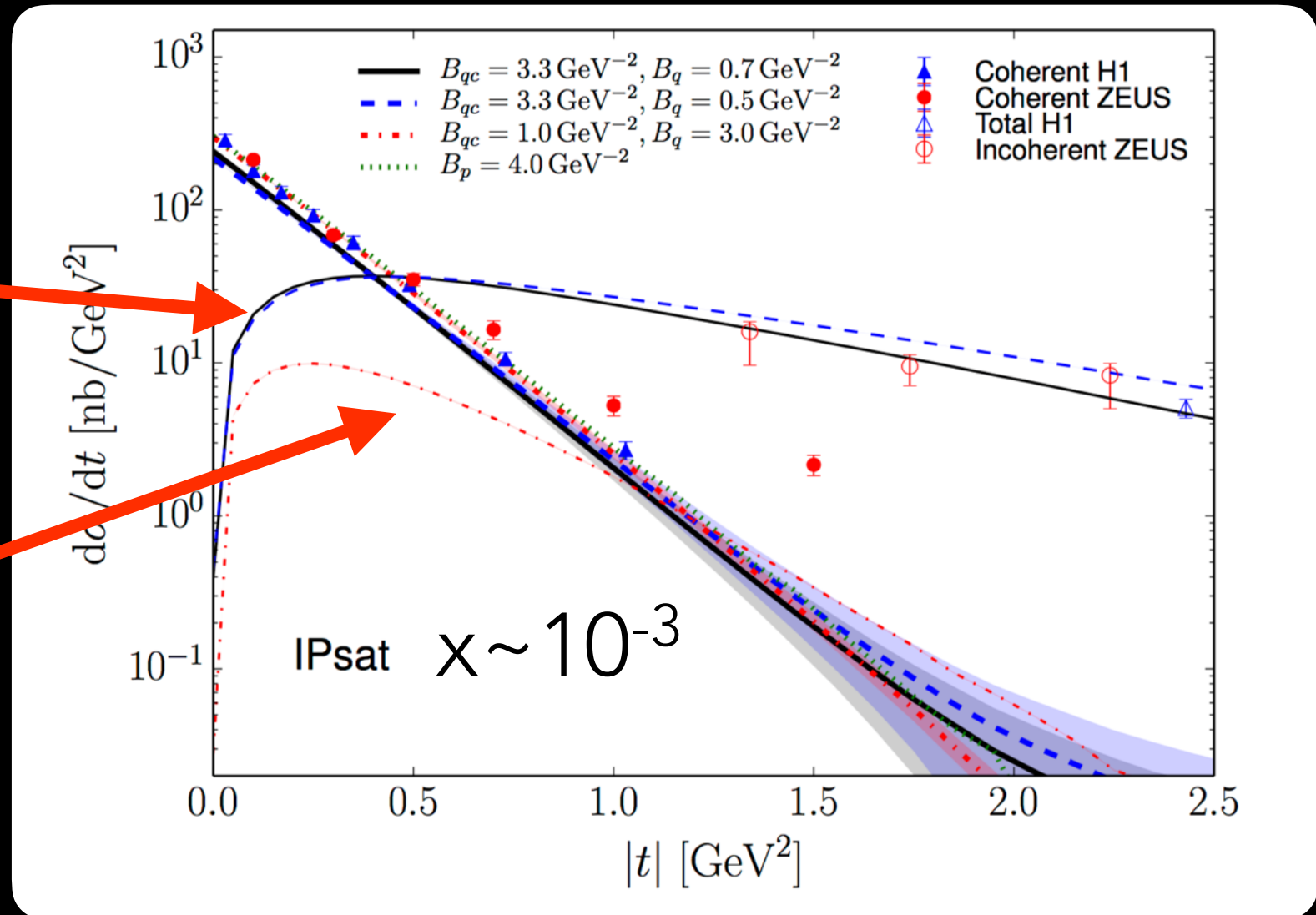
$$T_p(\vec{b}) = \sum_{i=1}^3 T_q(\vec{b} - \vec{b}_i)$$

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

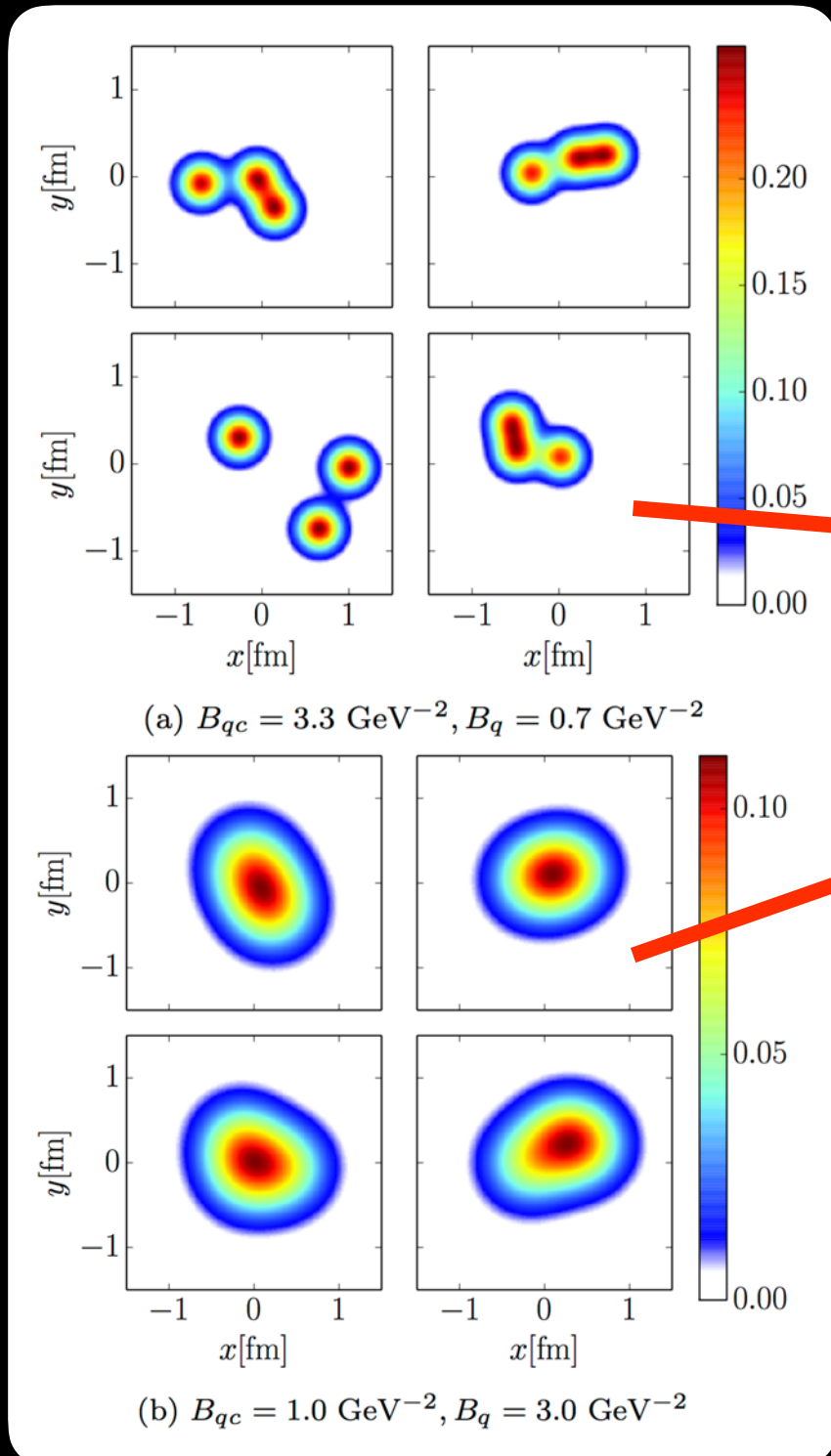
where the positions $\vec{b}_i$ are sampled from a Gaussian with width B_{qc}

J/ψ production from fluctuating proton

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

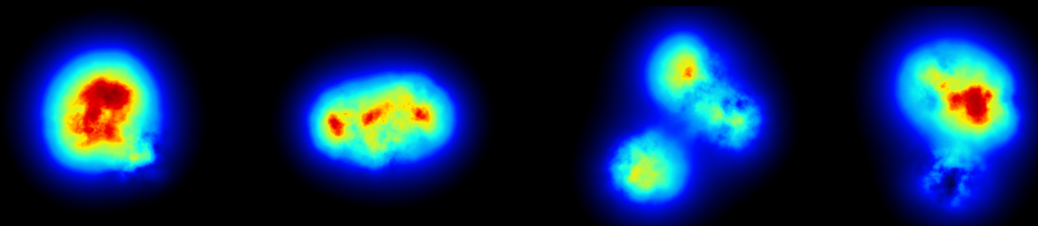
Sample color charges $\rho(x, \vec{b})$ from distribution with variance $\sim Q_s^2(x, \vec{b})$

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:



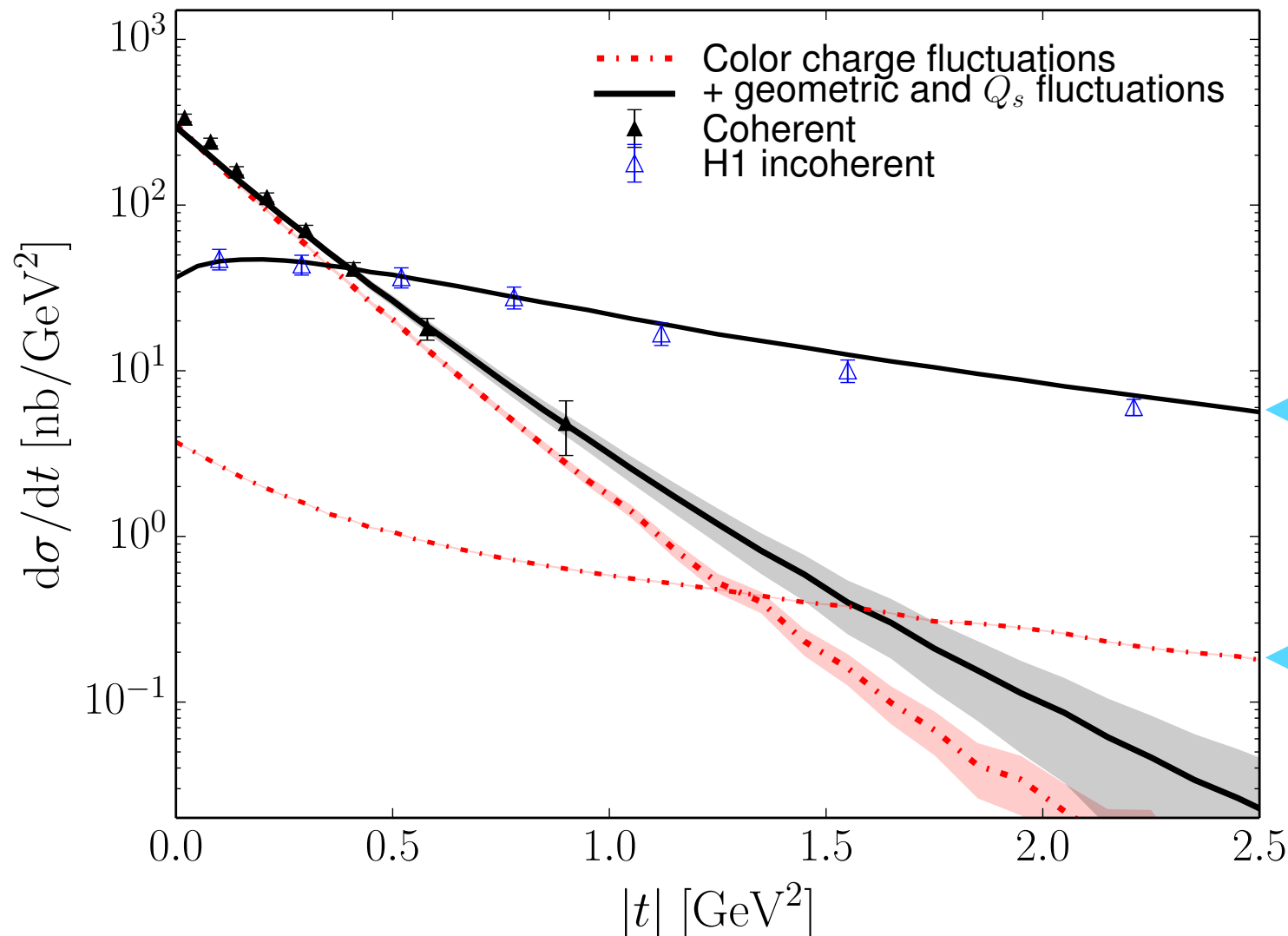
IP-Glasma results

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

Geometric + color charge fluctuations

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

Wilson lines



tuned shape
fluctuations

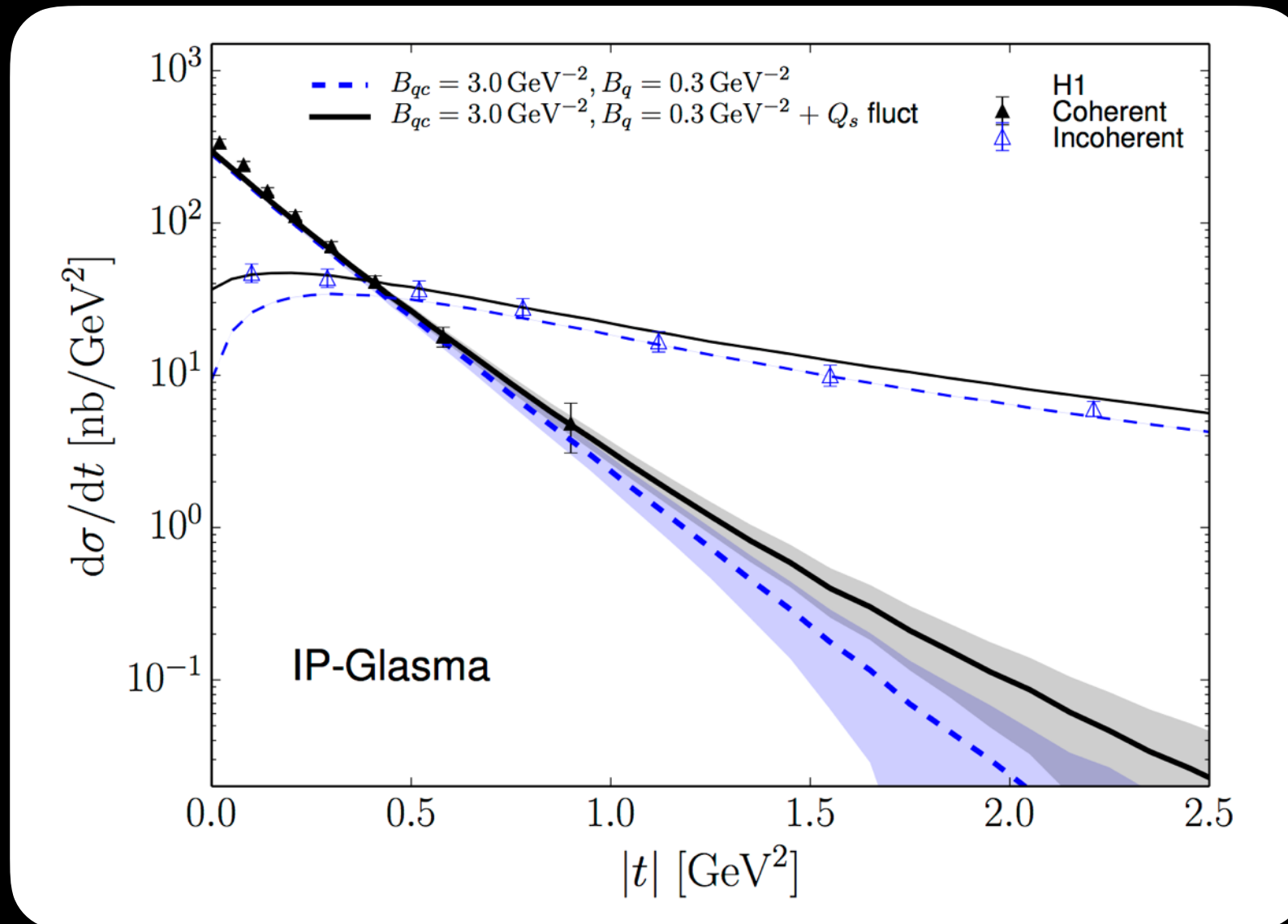
round proton

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

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



$\sigma=0.5$

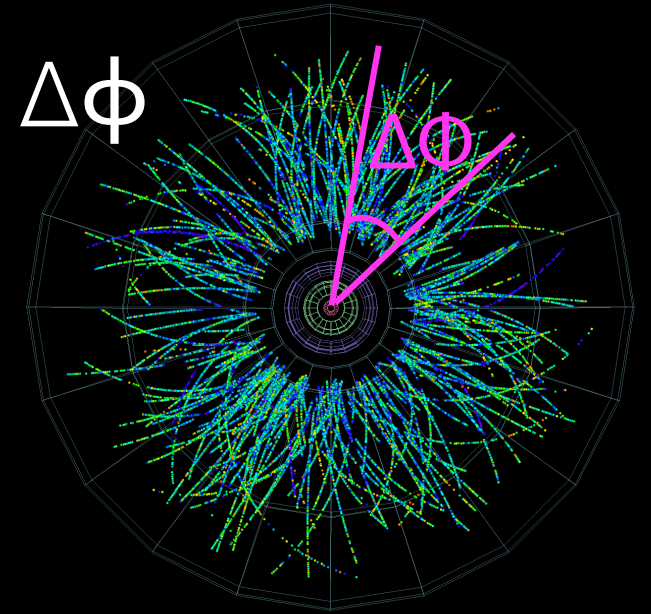
Experimental data: H1 collaboration, JHEP 1005 (2010) 032

Effect on p+A collisions: Correlations

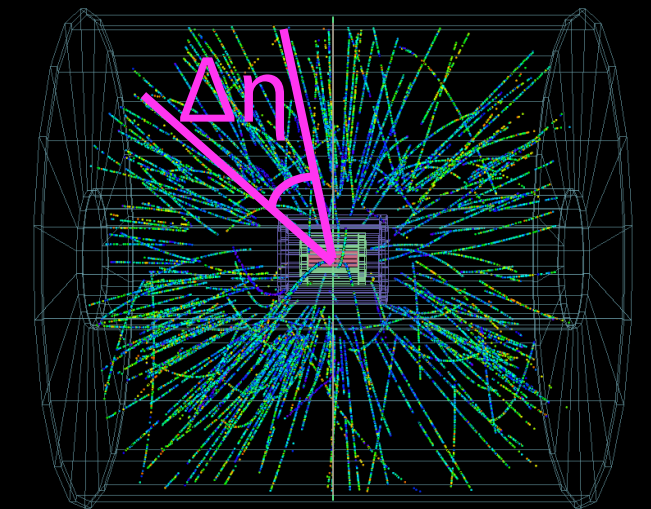
2-particle correlation as a function of $\Delta\eta$ and $\Delta\phi$

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

$\Delta\phi$: DIFFERENCE IN AZIMUTHAL ANGLE



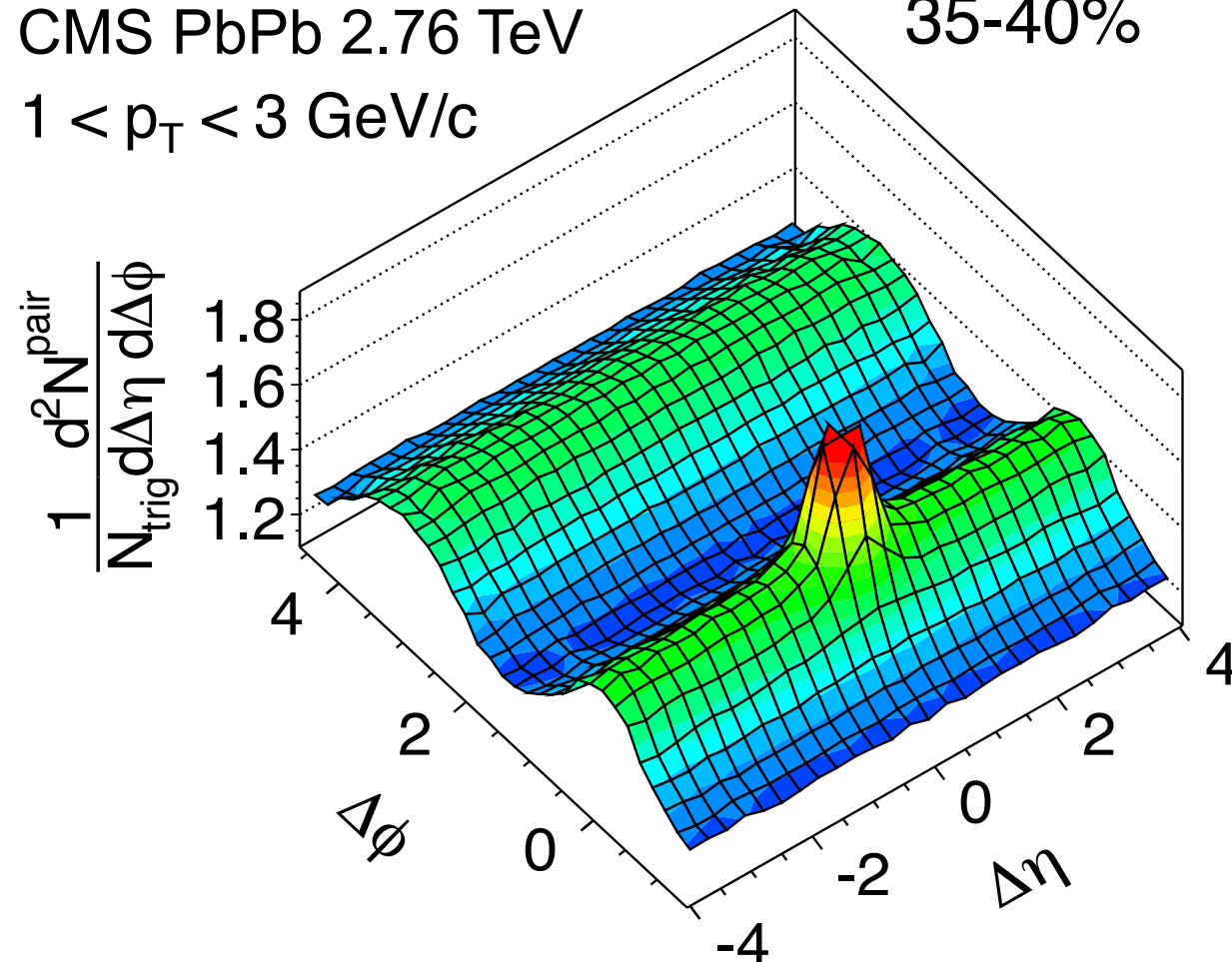
$\Delta\phi$: DIFFERENCE
IN AZIMUTHAL ANGLE



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

CMS PbPb 2.76 TeV
 $1 < p_T < 3$ GeV/c

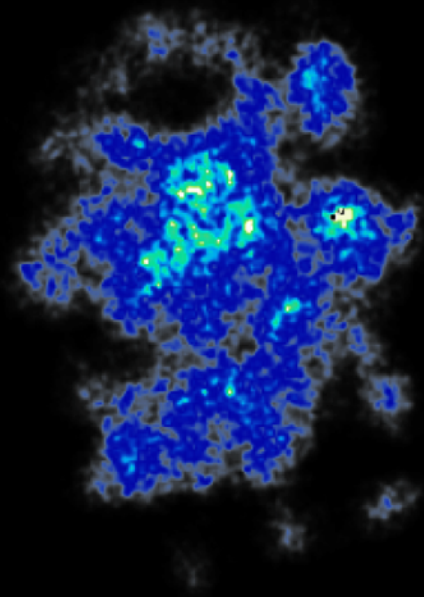
35-40%



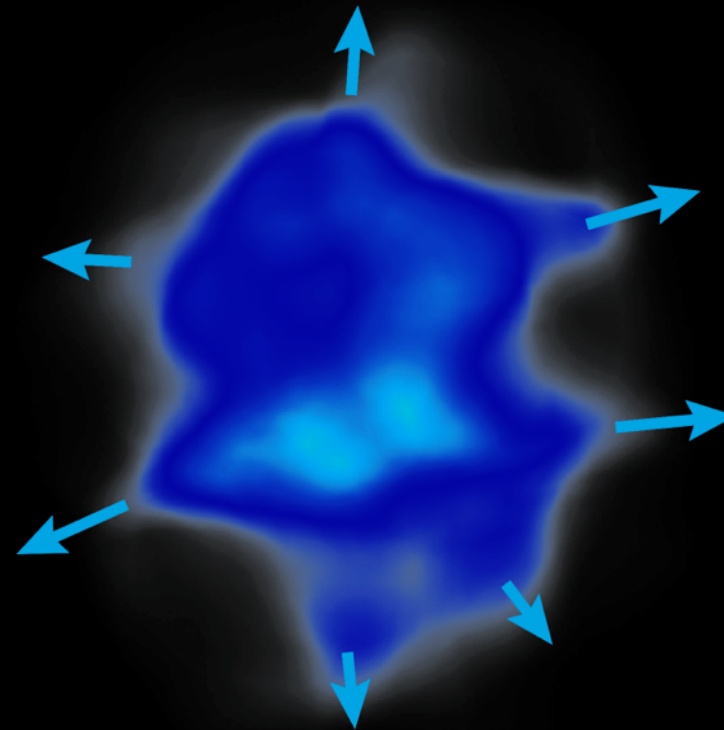
CMS COLL., EUR. PHYS. J. C72 (2012)

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



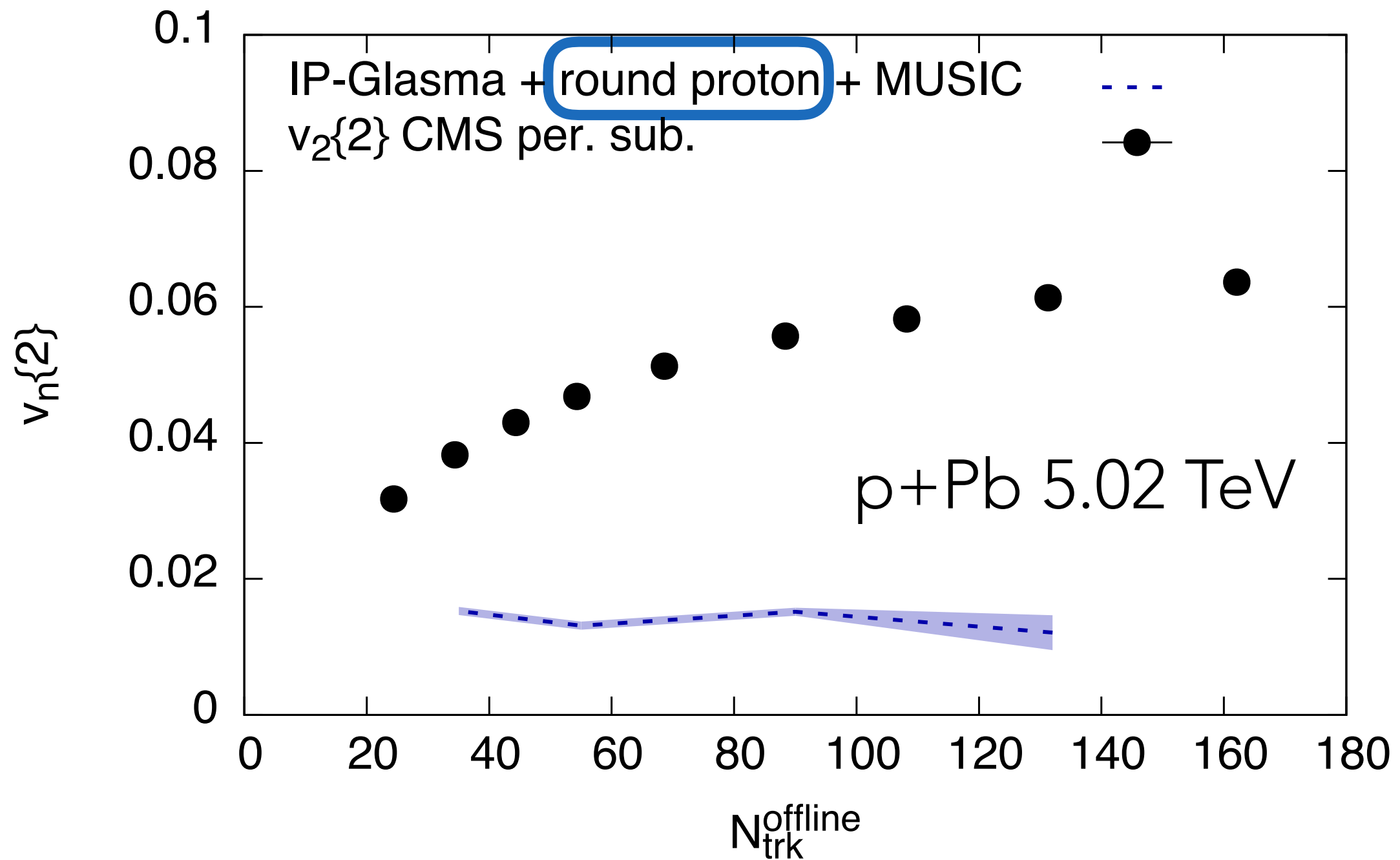
Initial energy density
distribution



Hydrodynamic
expansion

IP-Glasma+MUSIC (hydrodynamics) results

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

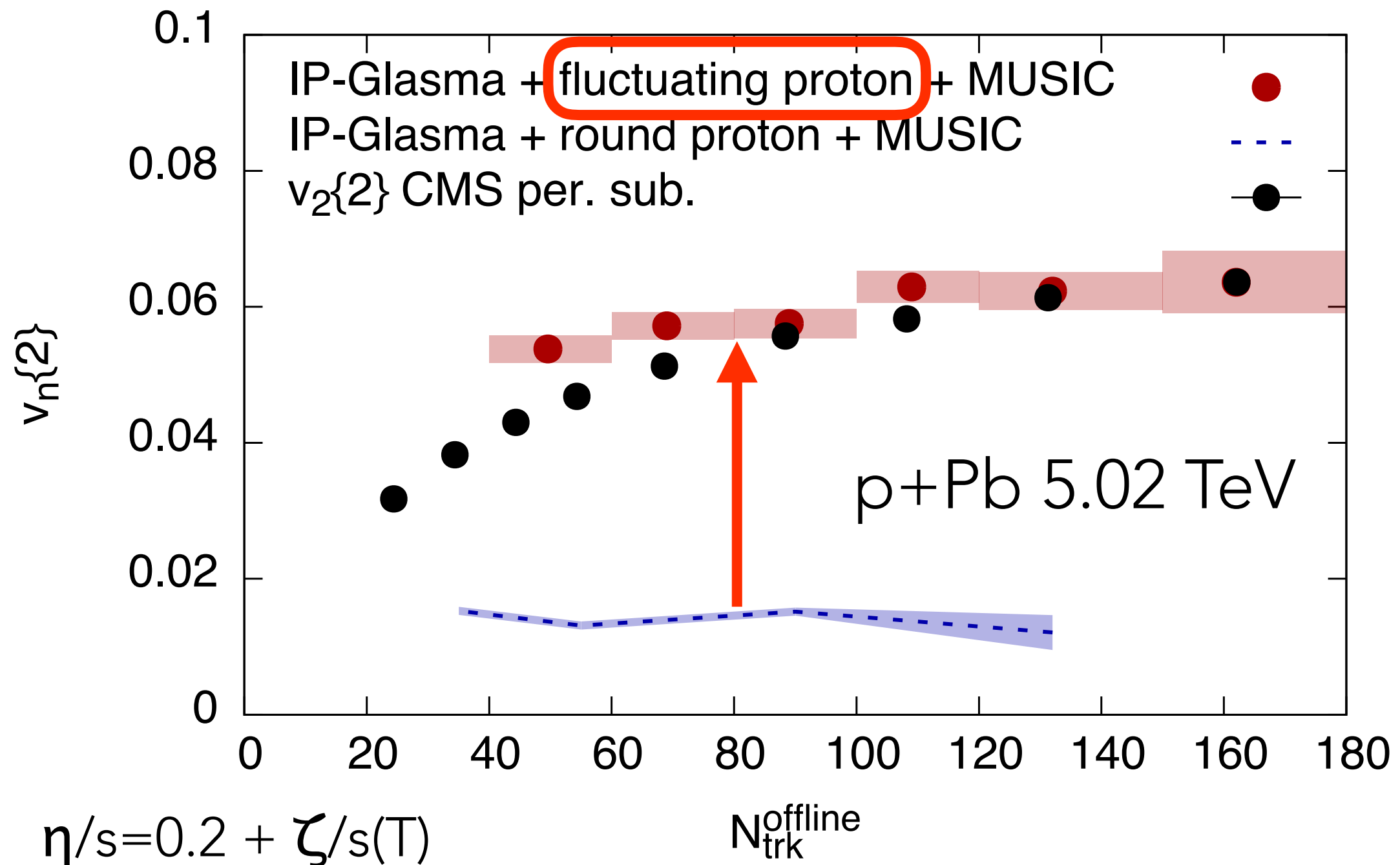


Experimental data: CMS Collaboration, Phys.Lett. B724, 213 (2013)

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



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:

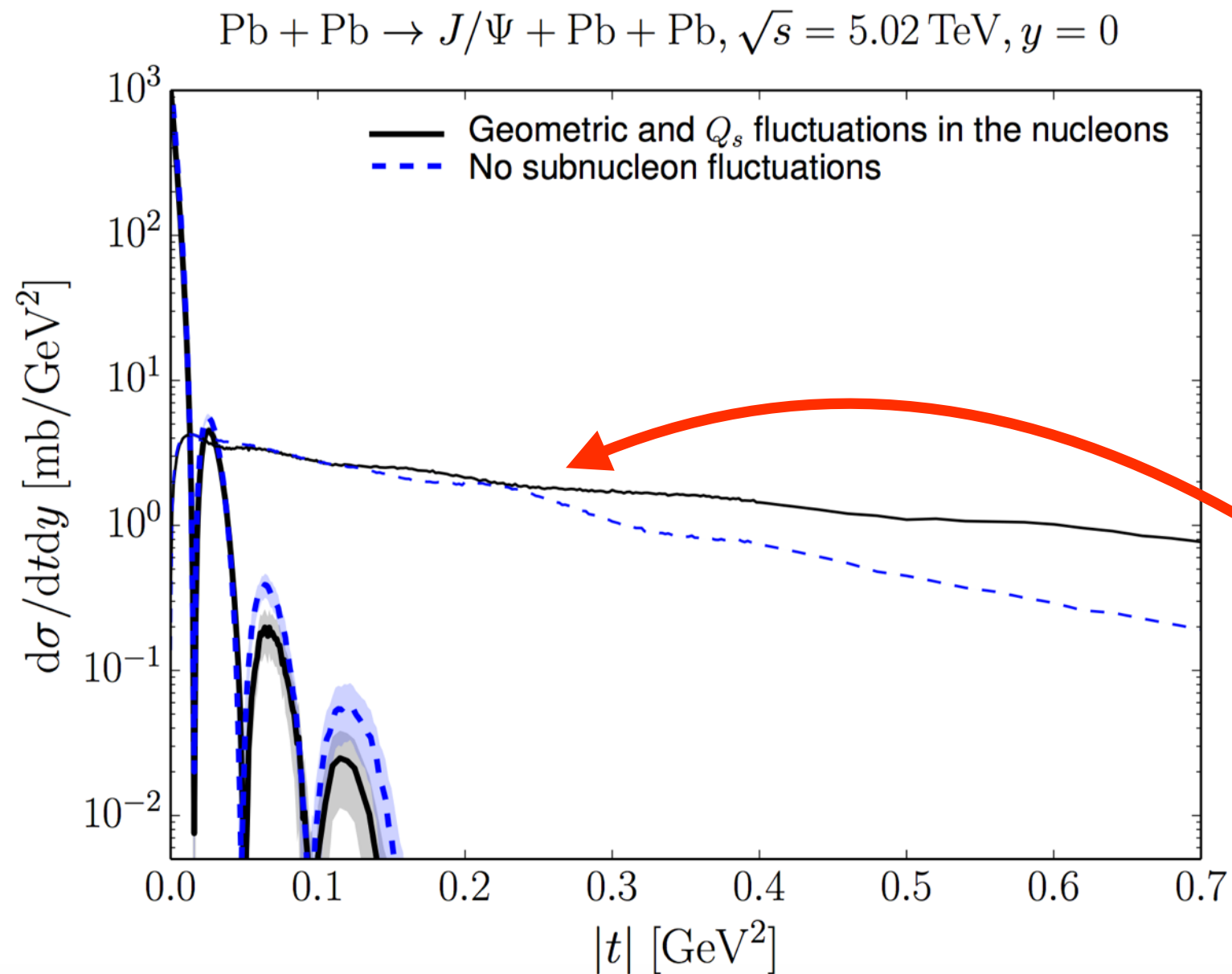
Sample nucleon positions from Woods-Saxon

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



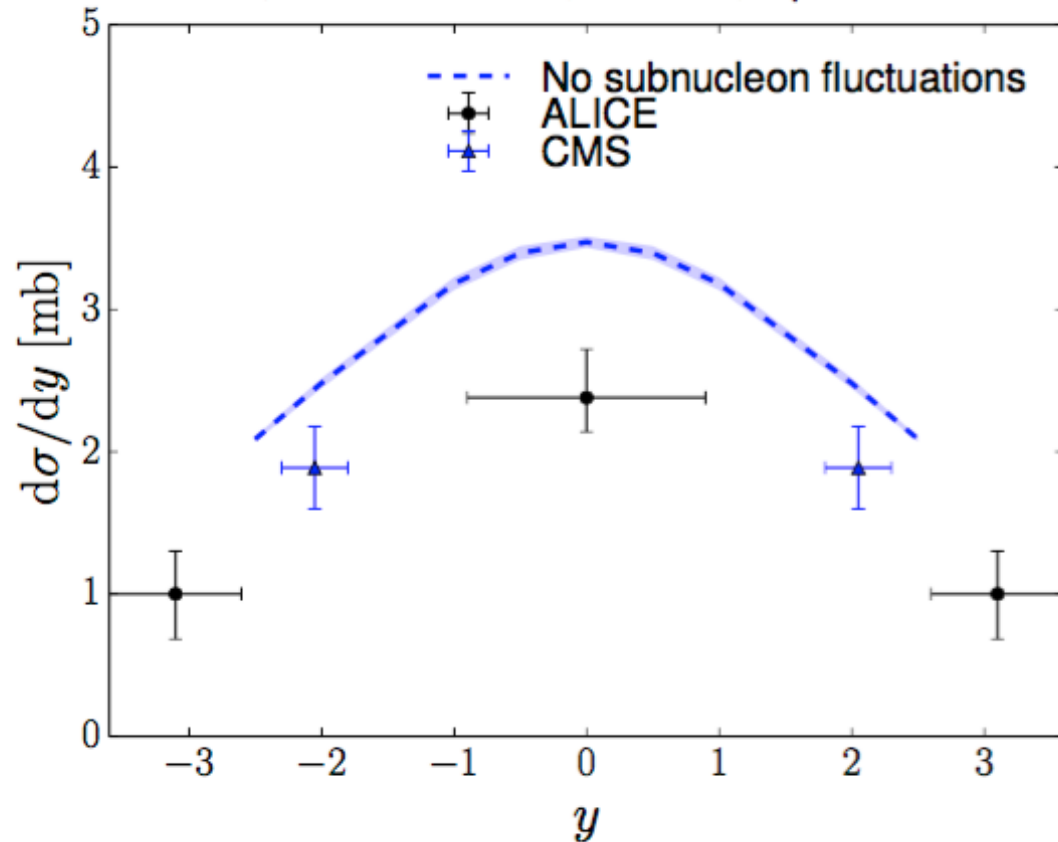
- Small $|t|$: fluctuations of nucleon positions
- Large $|t|$: fluctuations at subnucleon scale
- **Incoherent slope changes** at $|t| \approx 0.25$ GeV² $\rightarrow$ 0.4 fm which is size of hot spots

Coherent: thick lines
Incoherent: thin lines

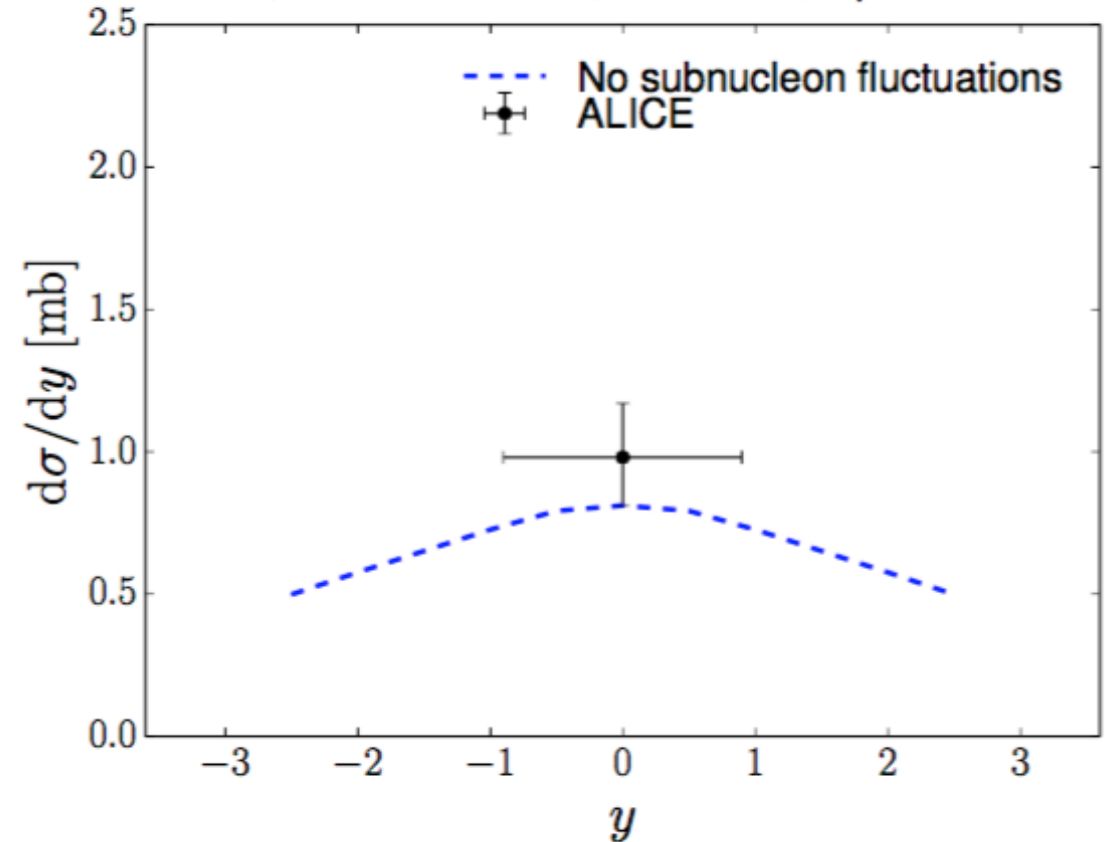
LHC data - no subnucleonic fluctuations

H. Mäntysaari, B. Schenke, arXiv:1703.09256

$\text{Pb} + \text{Pb} \rightarrow J/\Psi + \text{Pb} + \text{Pb}$ (coherent), $\sqrt{s_{NN}} = 2760 \text{ GeV}$



$\text{Pb} + \text{Pb} \rightarrow J/\Psi + \text{Pb} + \text{Pb}^*$ (incoherent), $\sqrt{s_{NN}} = 2760 \text{ GeV}$

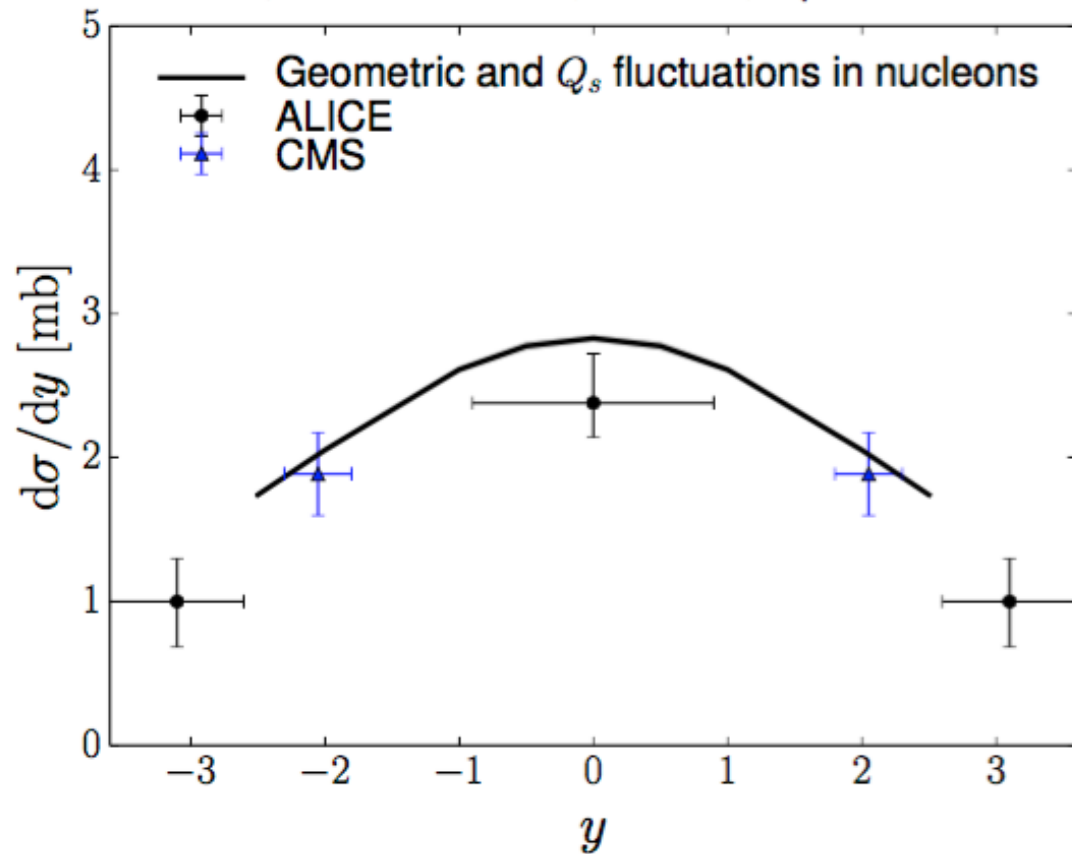


- Only fluctuations of nucleon positions
- Coherent cross section overestimated, incoherent underestimated
- ~ 20-30% normalization uncertainty from the J/Ψ wave function

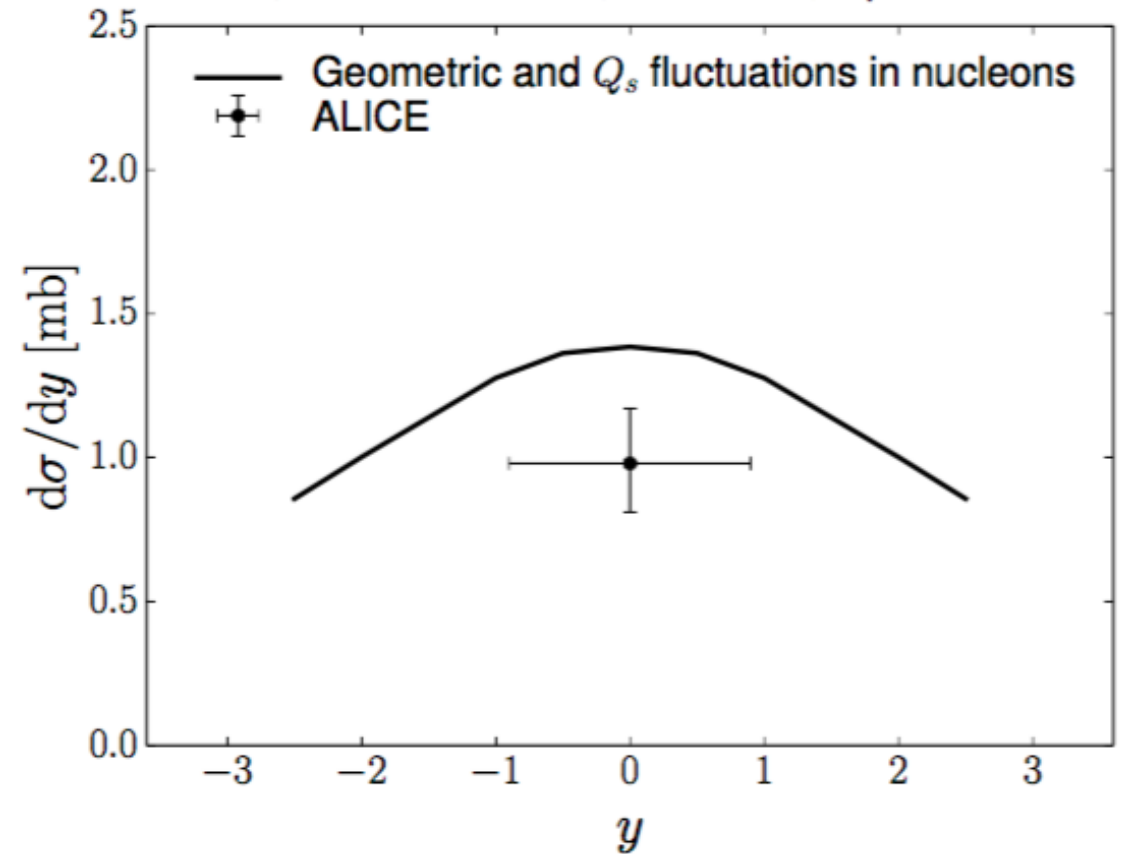
LHC data - with subnucleonic fluctuations

H. Mäntysaari, B. Schenke, arXiv:1703.09256

Pb + Pb $\rightarrow J/\Psi$ + Pb + Pb (coherent), $\sqrt{s_{NN}} = 2760$ GeV



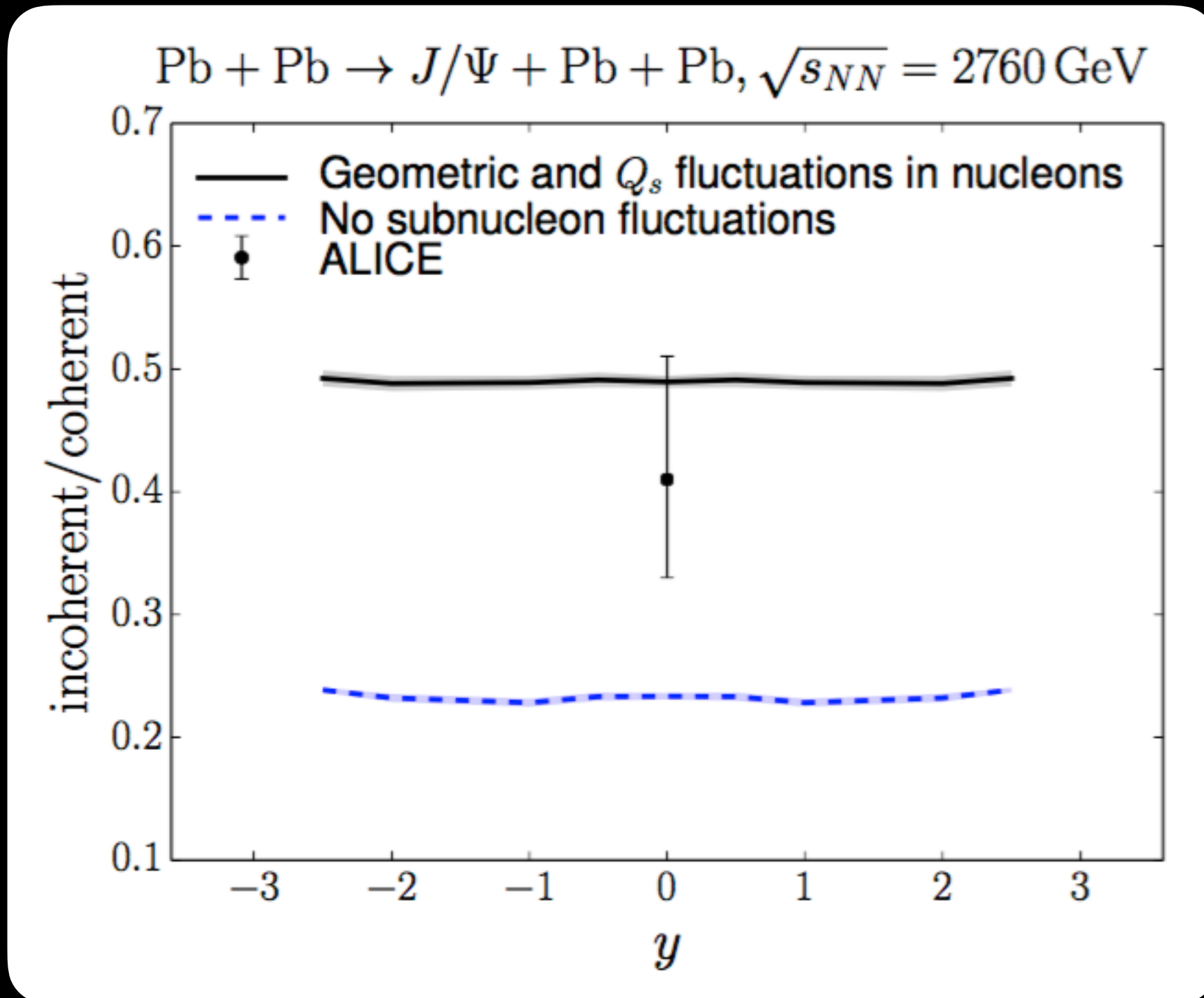
Pb + Pb $\rightarrow J/\Psi$ + Pb + Pb* (incoherent), $\sqrt{s_{NN}} = 2760$ GeV



- 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



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

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

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. Mäntysaari, Eur. Phys. J. C 73, 2307 (2013)

Langevin formulation

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

$\boldsymbol{\xi}$ is Gaussian noise with zero average and

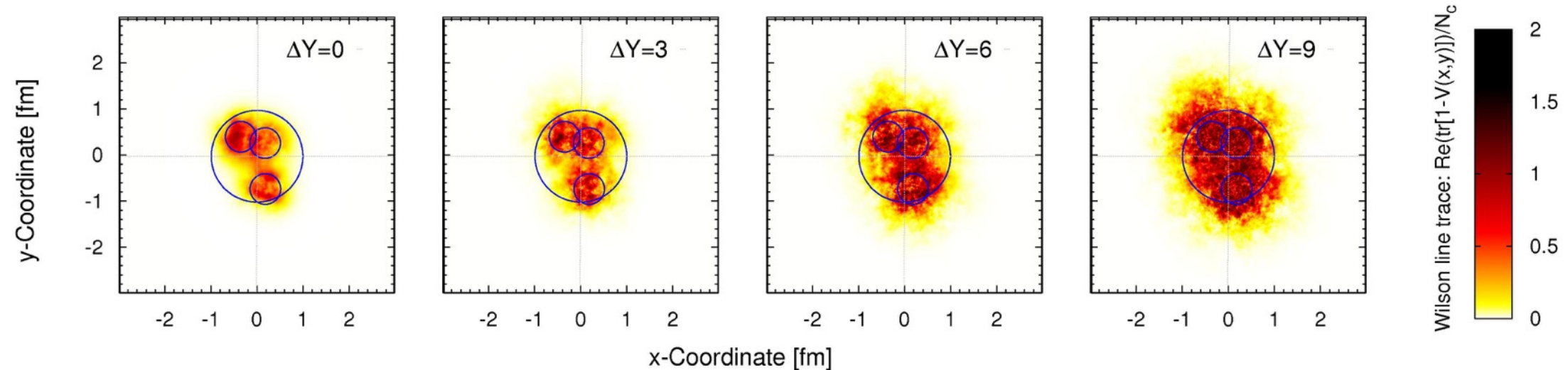
$$\langle \xi_{\mathbf{x},i}^a(Y) \xi_{\mathbf{y},j}^b(Y') \rangle = \delta^{ab} \delta^{ij} \delta_{\mathbf{xy}}^{(2)} \delta(Y - Y')$$

The JIMWLK Kernel is modified to avoid infrared tails:

$$K_{\mathbf{x}-\mathbf{z}}^{\text{mod}} = m |\mathbf{x} - \mathbf{z}| K_1(m |\mathbf{x} - \mathbf{z}|) \frac{\mathbf{x} - \mathbf{z}}{(\mathbf{x} - \mathbf{z})^2}$$

Shape evolution of the proton

decreasing x , increasing energy



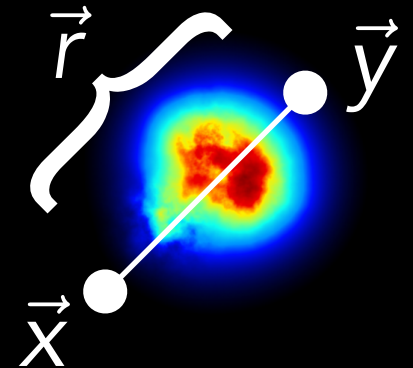
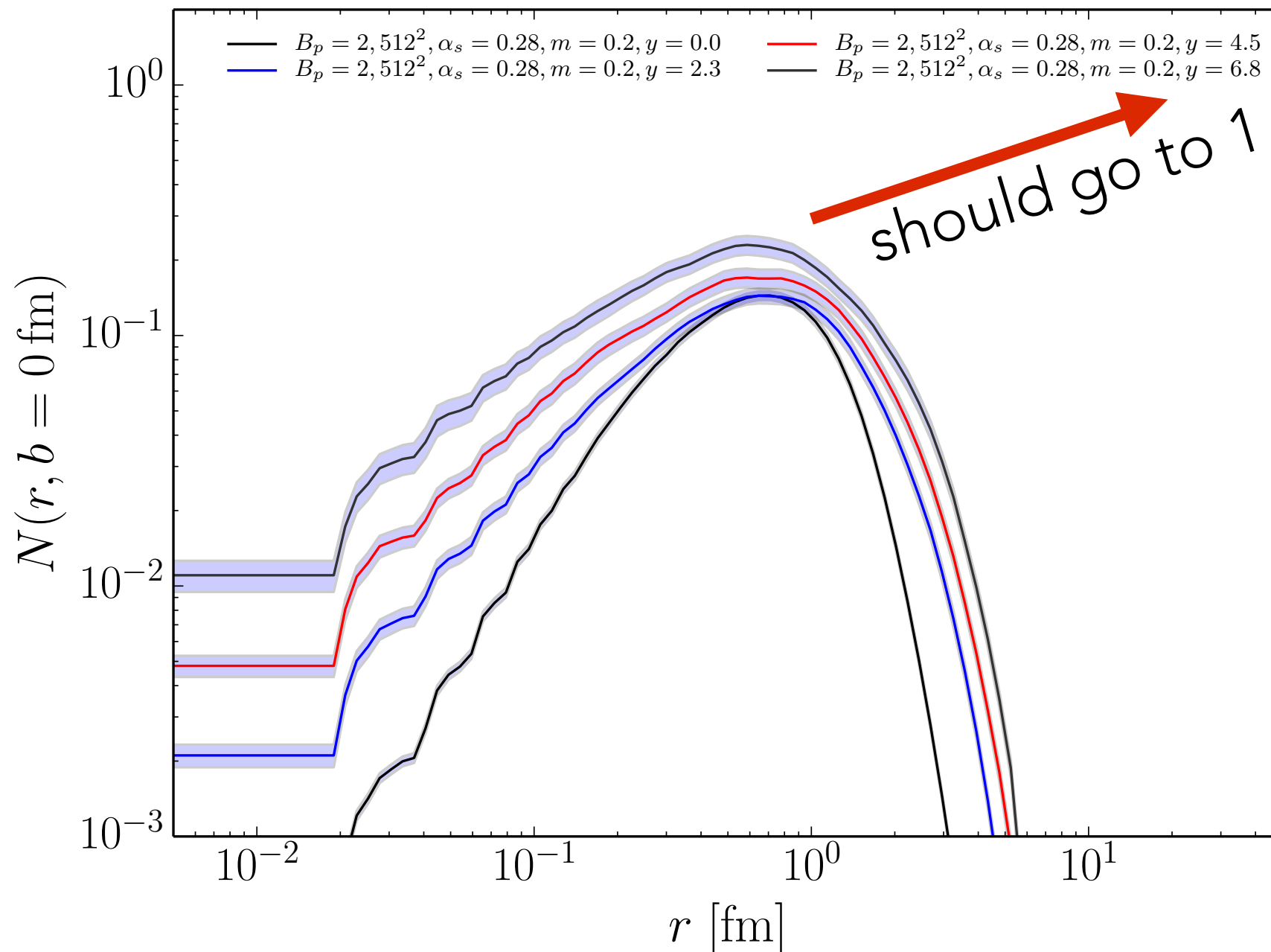
S. Schlichting, B. Schenke, Phys. Lett. B739, 313-319 (2014)

Proton grows with increasing x
Growth is linear with Y when infrared regulator is used
Froissart bound not violated

Large r is an issue for finite system

H. Mäntysaari, B. Schenke, in preparation

Dipole amplitude

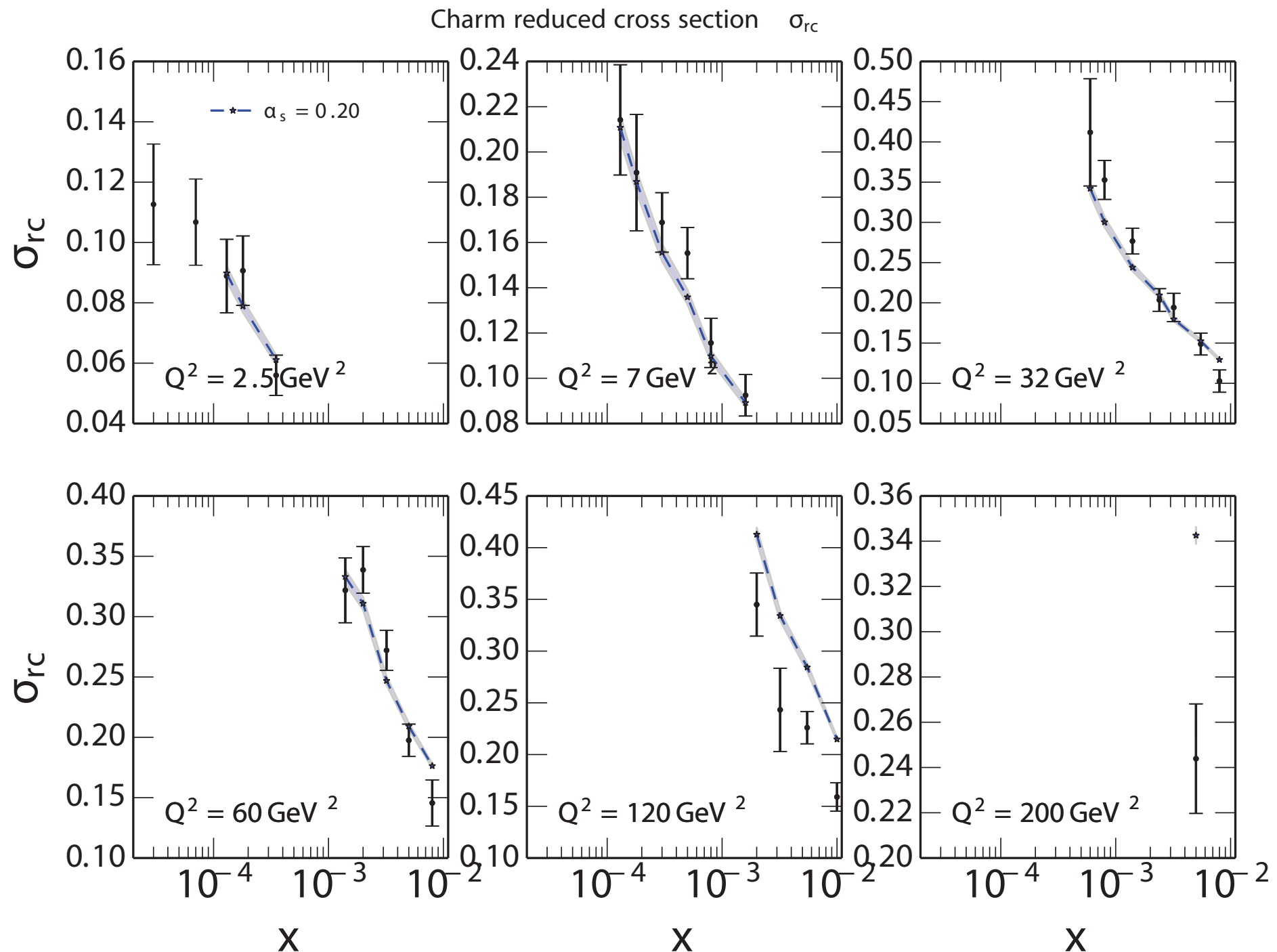


$$\text{Tr} V(\vec{x}) V^\dagger(\vec{y}) / N_c$$

see also e.g. Berger and Stasto, Phys.Rev. D83 (2011) 034015

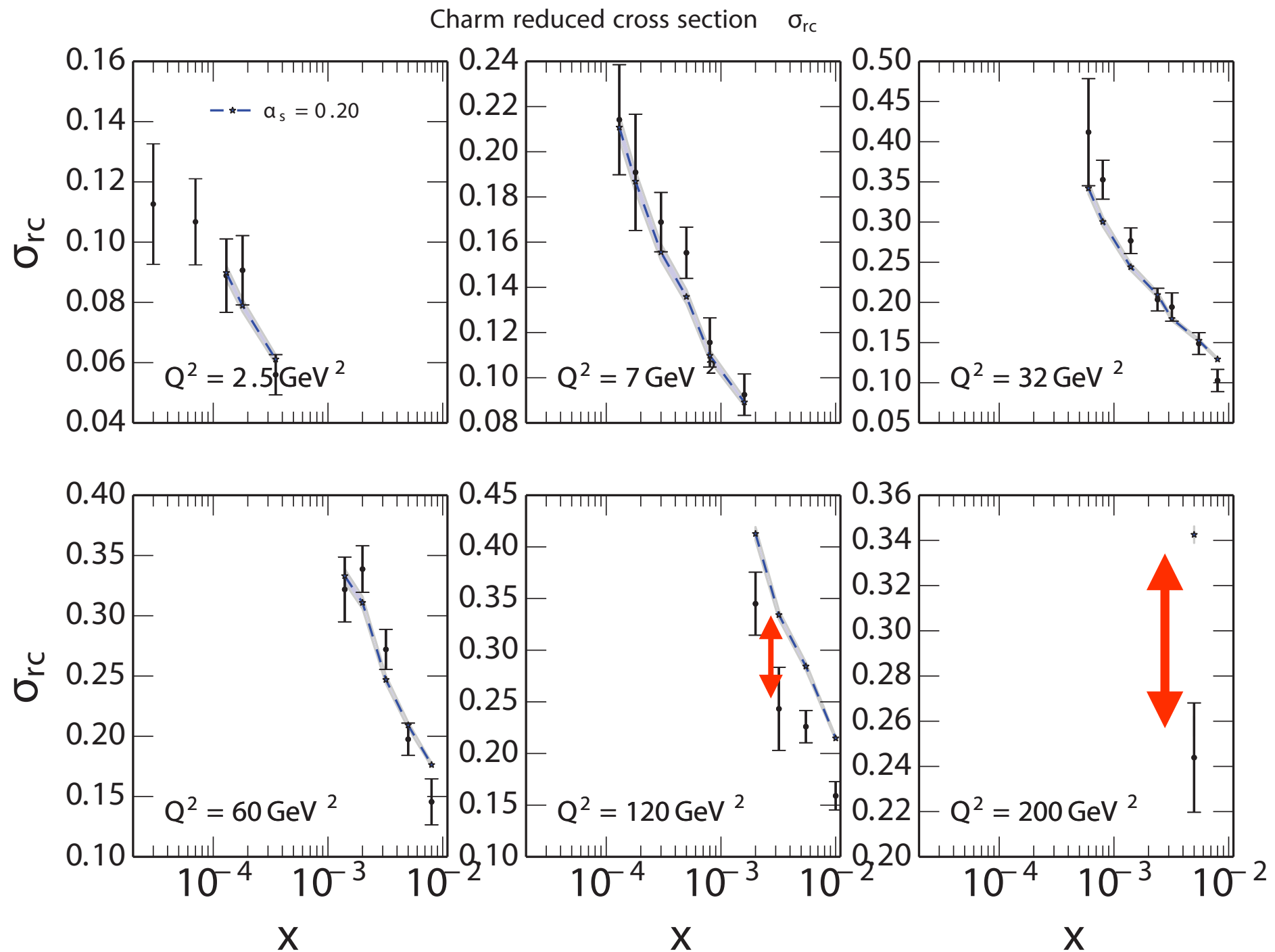
F_{2c} not sensitive to large r

H. Mäntysaari, B. Schenke, in preparation



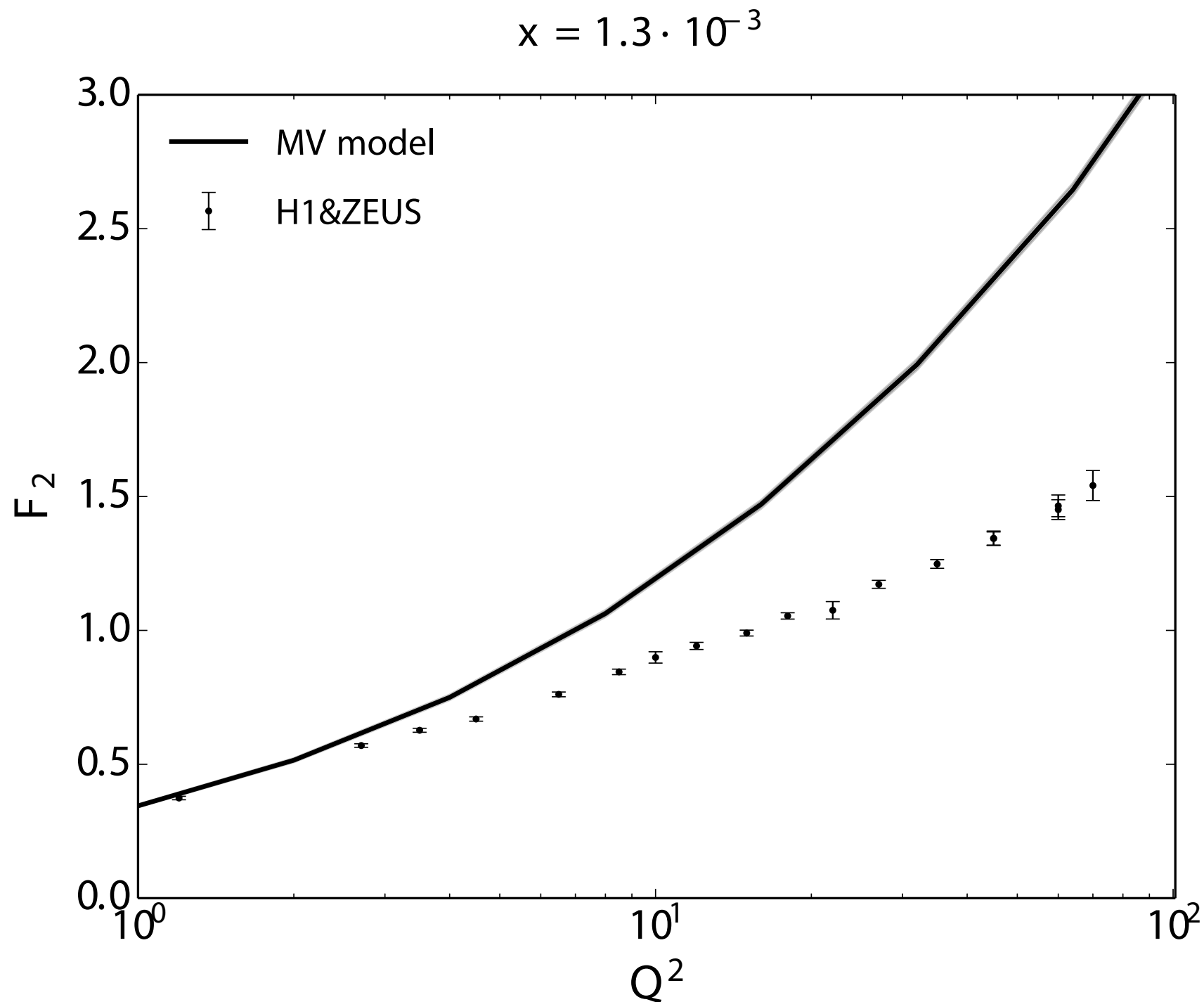
F_{2c} not sensitive to large r

H. Mäntysaari, B. Schenke, in preparation



Another issue: Q^2 dependence of F_2 and F_{2c}

H. Mäntysaari, B. Schenke, in preparation



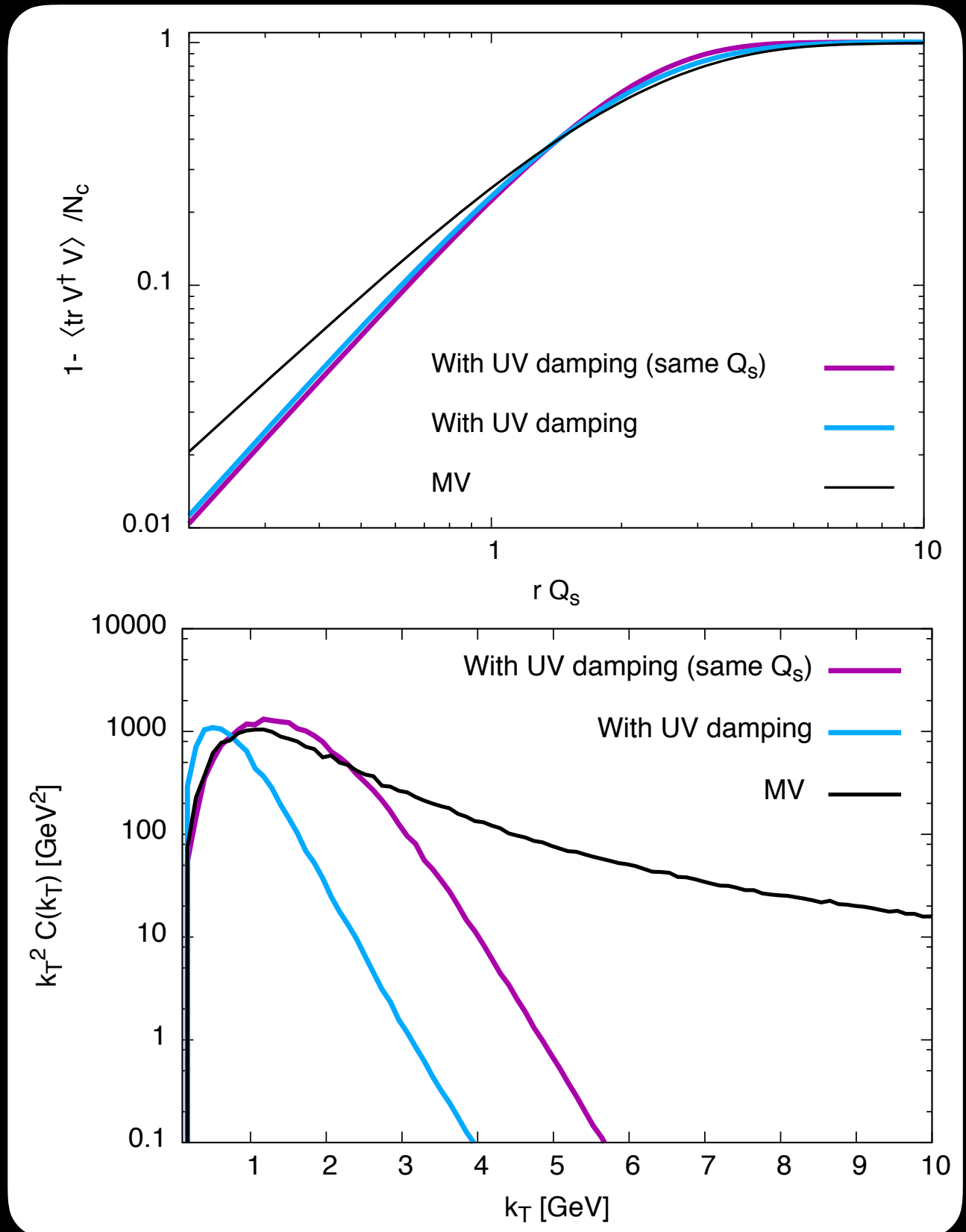
Modifying MV - changing the large k_T tails

H. Mäntysaari, B. Schenke, in preparation

Introduce a UV cutoff:
Filter out high frequency
modes in the color charge
distribution using FT with
 $\exp(-\# k_T)$

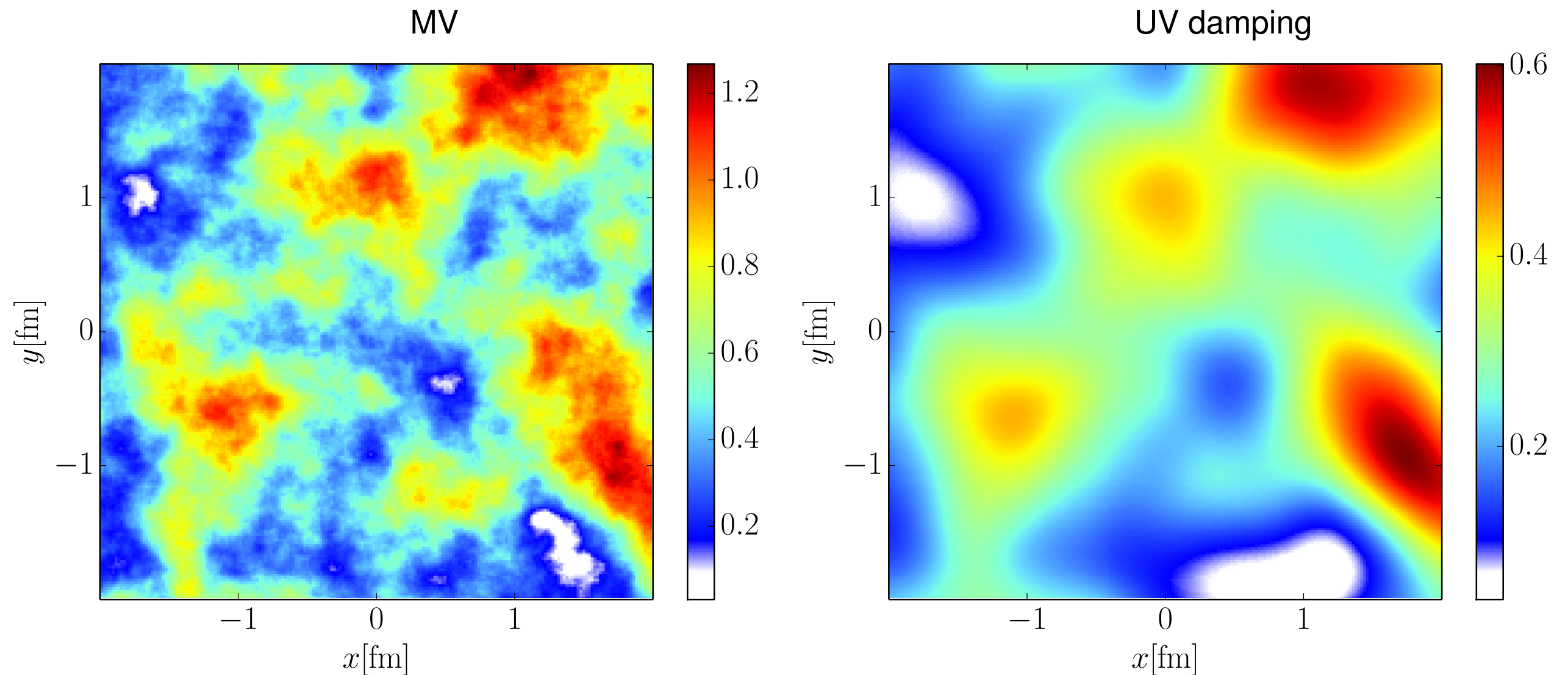
Has similar effect as
anomalous dimension
in AAMQS

J. L. Albacete, N. Armesto, J.G. Milhano,
P. Quiroga Arias, C.A. Salgado
Eur.Phys.J. C71 (2011) 1705



Modifying MV - changing the large k_T tails

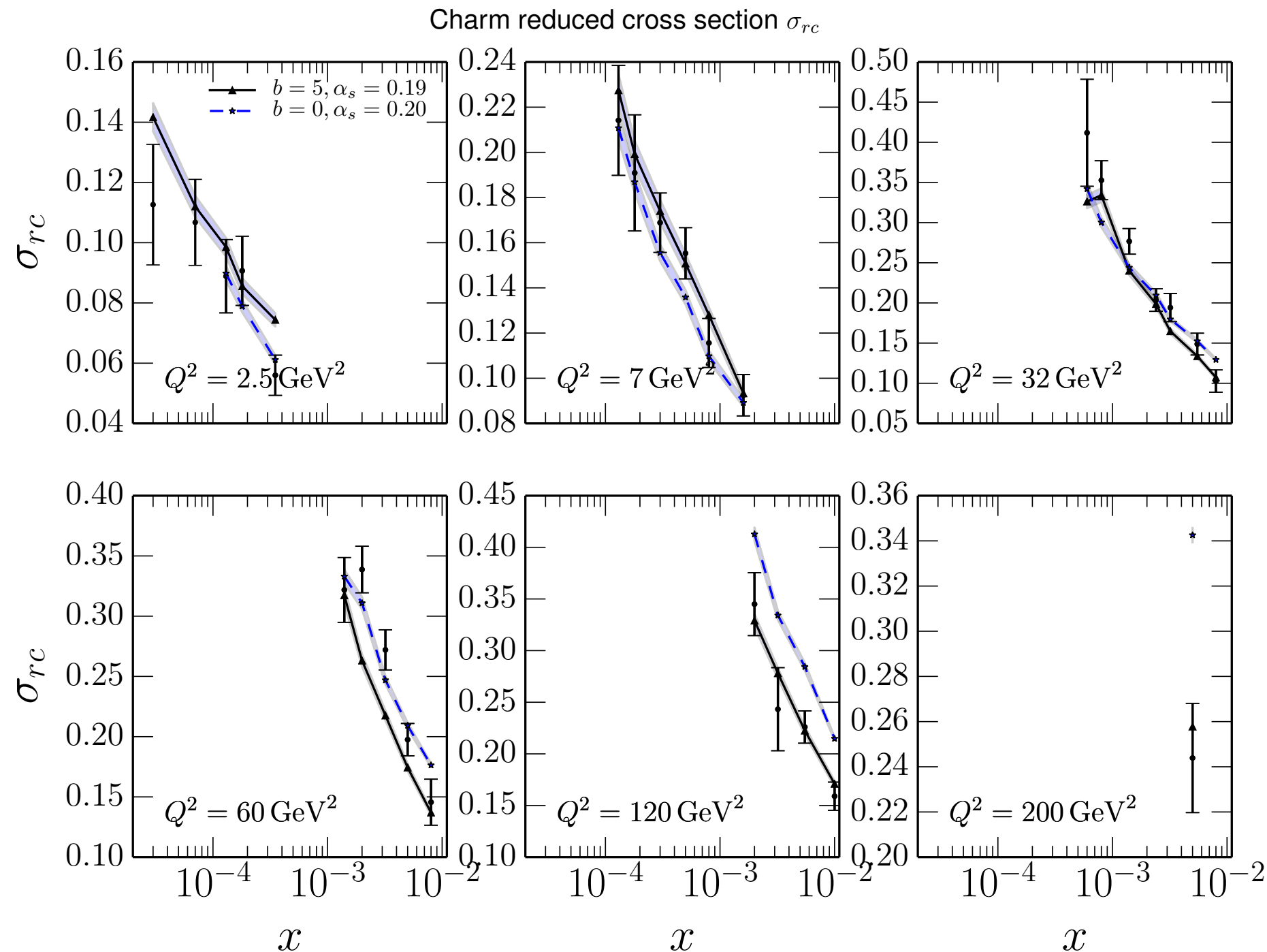
H. Mäntysaari, B. Schenke, in preparation



$$\text{Re}[\text{Tr}(1 - V(\vec{x}))]/N_c$$

F_{2c} with UV cutoff in MV model

H. Mäntysaari, B. Schenke, in preparation

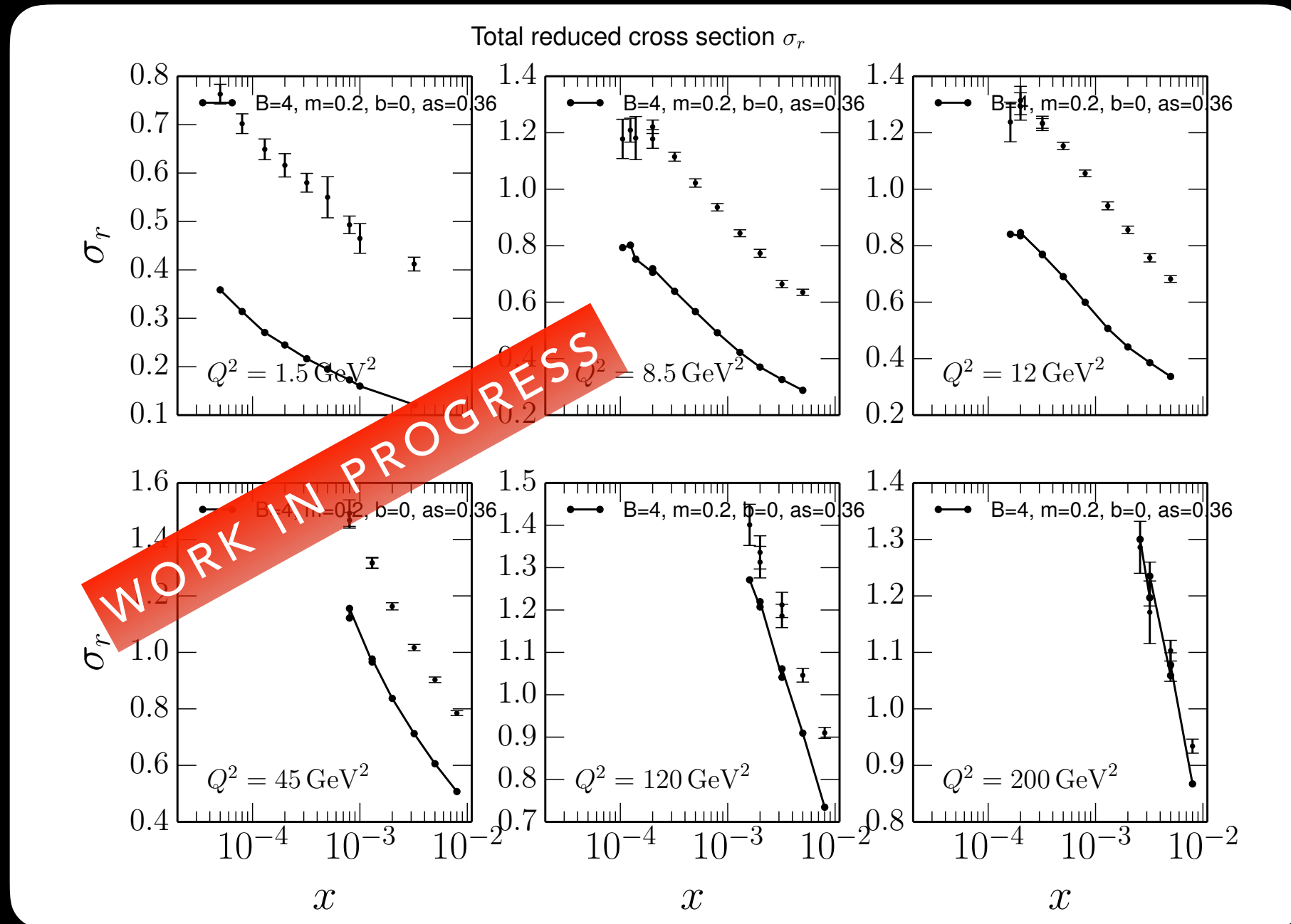


solid:
with UV cut

dashed:
w/o UV cut

F_2 underestimated when fitting to charm F_{2c}

H. Mäntysaari, B. Schenke, in preparation



Difference must come from large r dipoles

Working on model to reintroduce large- r contribution

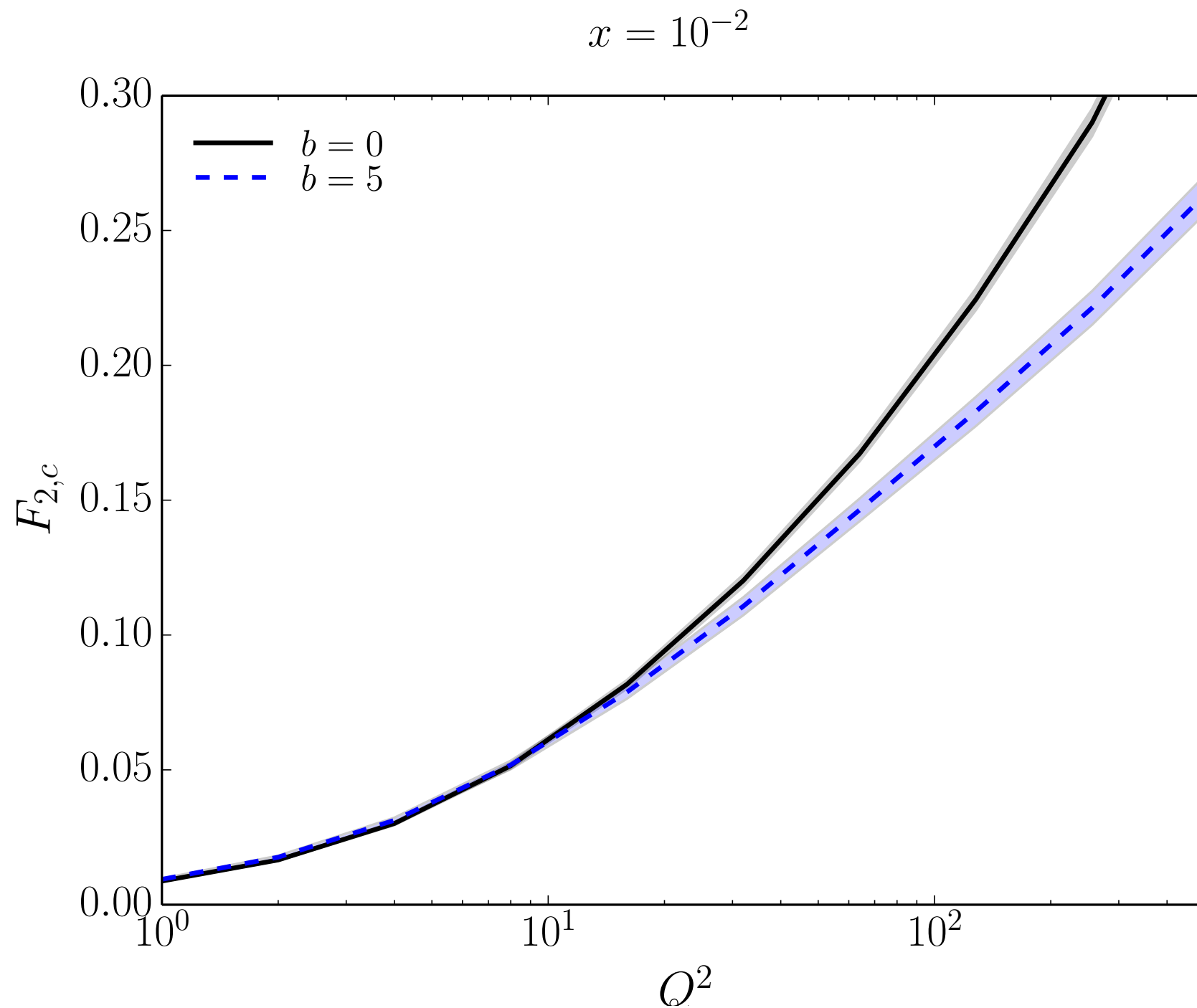
Summary

- Shape fluctuations of the proton's gluon distribution are needed to describe incoherent diffractive vector meson data from HERA in the dipole picture
- 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
- Latest: Go from IPsat to explicit JIMWLK evolution and describe F_2 and diffractive data - Modification of MV initial condition necessary - Deal with large dipole contribution

BACKUP

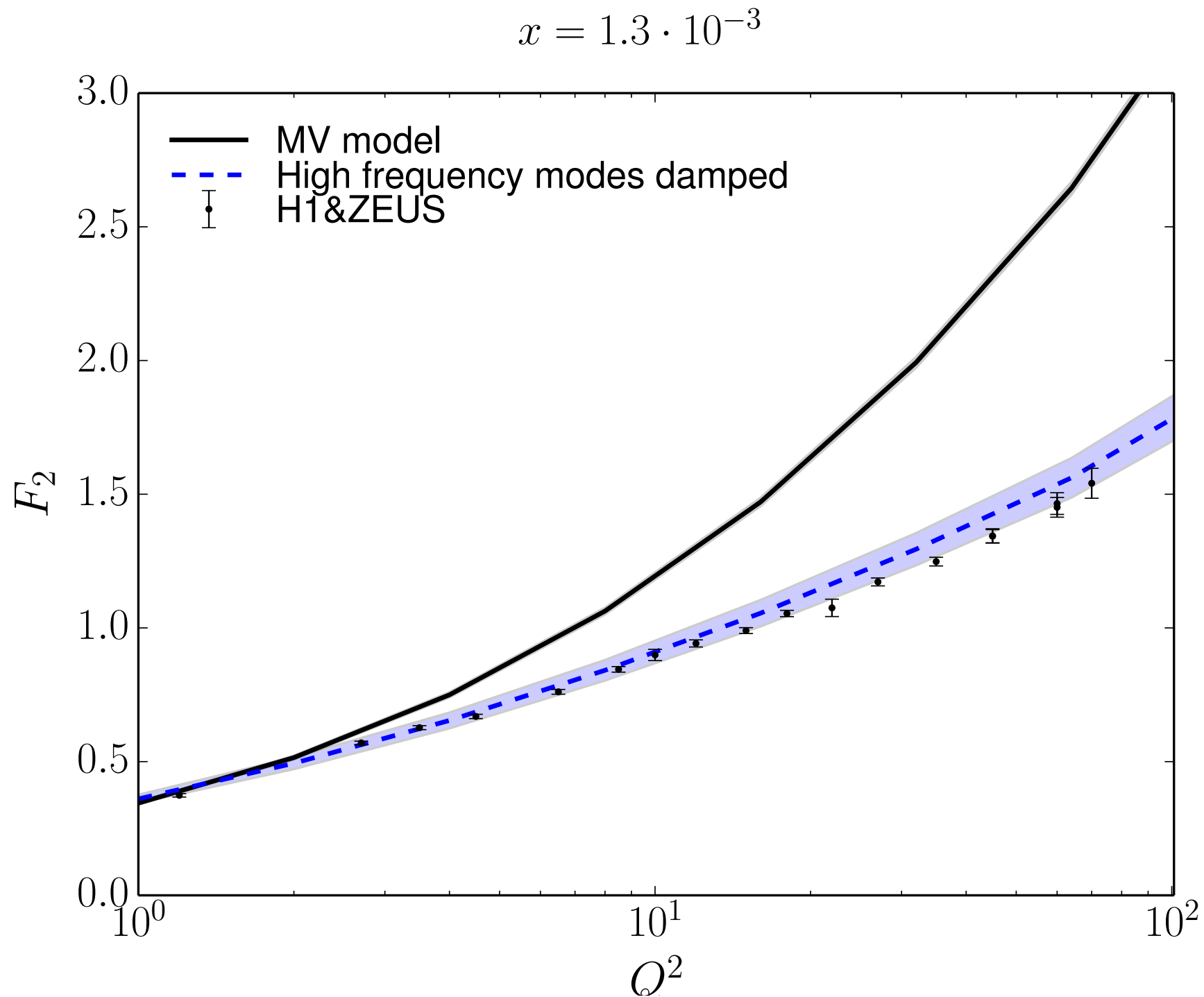
Q^2 dependence of $F_{2,c}$

H. Mäntysaari, B. Schenke, in preparation



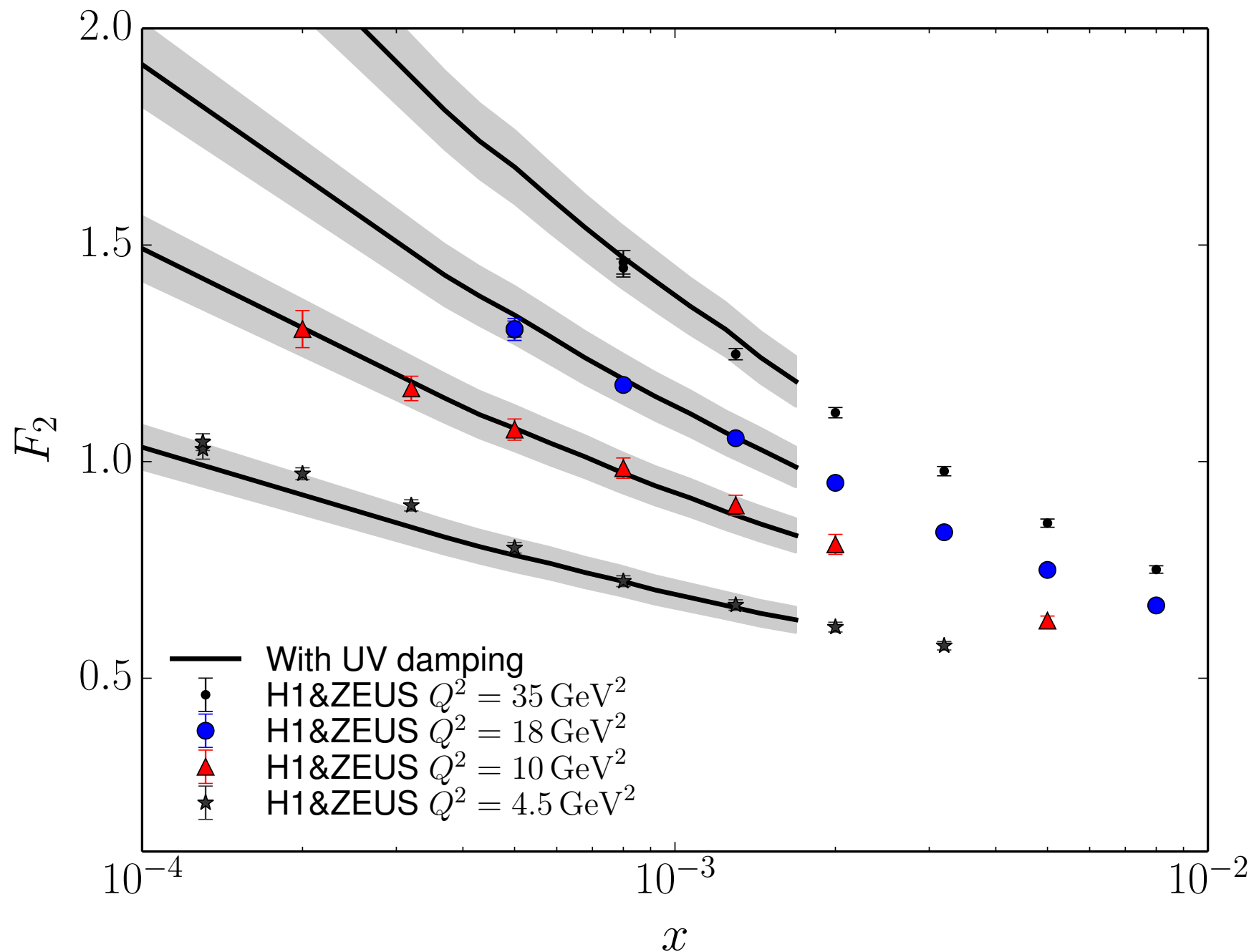
Q^2 dependence of F_2

H. Mäntysaari, B. Schenke, in preparation



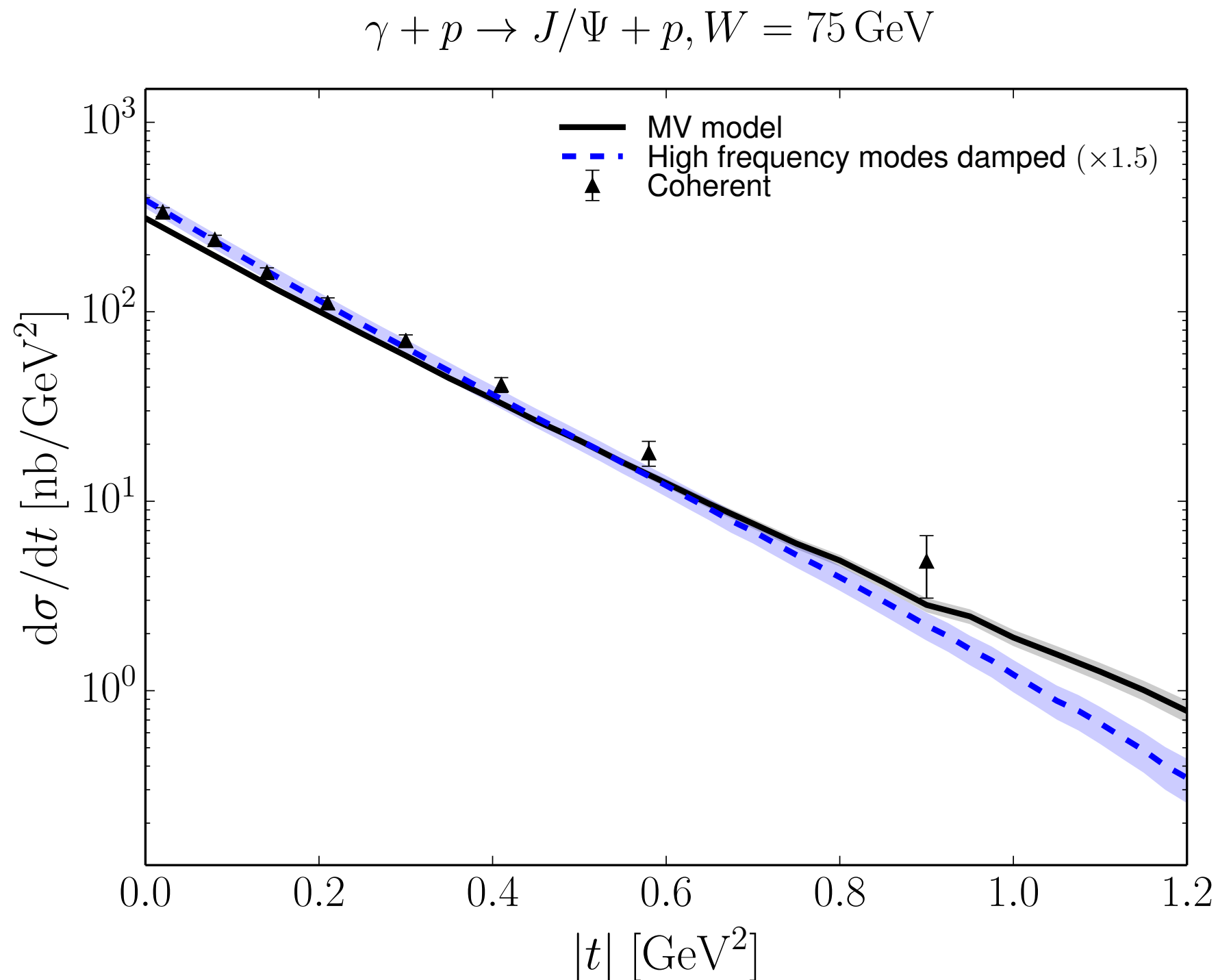
x dependence of F_2 from JIMWLK

H. Mäntysaari, B. Schenke, in preparation



Proton size constrained by diffractive data

H. Mäntysaari, B. Schenke, in preparation



Why a variance?

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

Simple model: Target particle $\rightarrow$ average optical potential

beam particle $\nearrow$ $|B\rangle = \sum_k C_k |\psi_k\rangle$ $\nwarrow$ linear comb. of diffractive eigenstates

Imaginary part of scattering amplitude $\nearrow$ $\text{Im}T |\psi_k\rangle = A_k |\psi_k\rangle$ $\nwarrow$ 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:

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

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

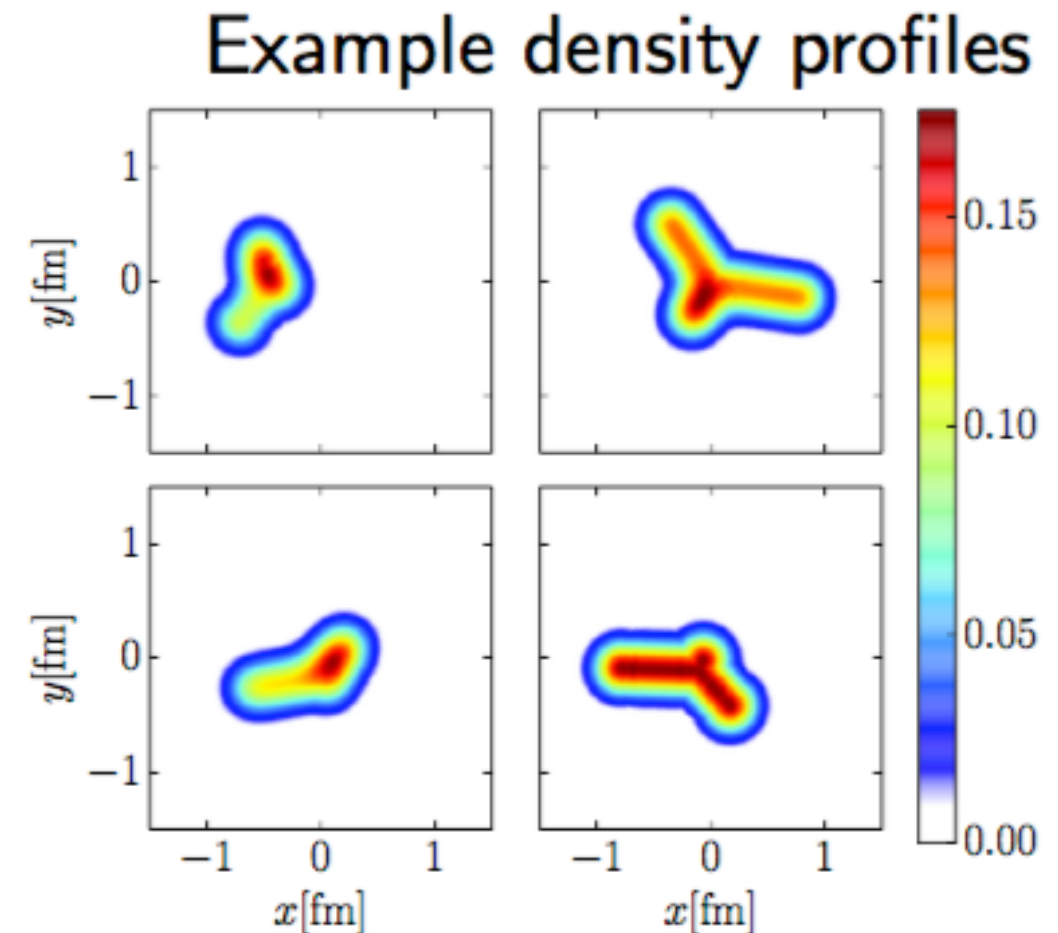
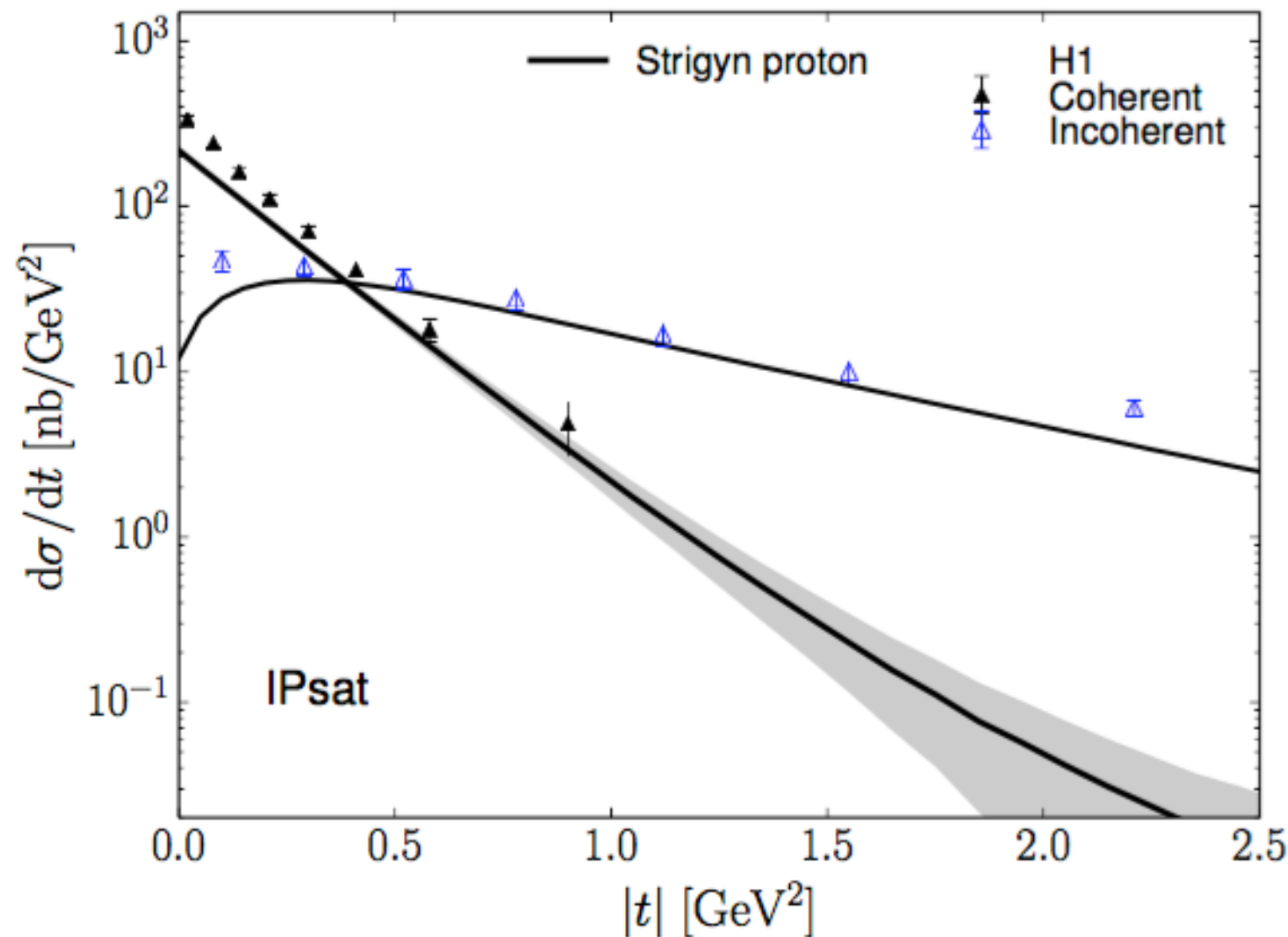
Elastic cross section: $\frac{d\sigma_{\text{el}}}{d^2\vec{b}} = \langle A \rangle^2$

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

Lumpiness matters, not details of the density profile

3 valence quarks that are connected by "color flux tubes":

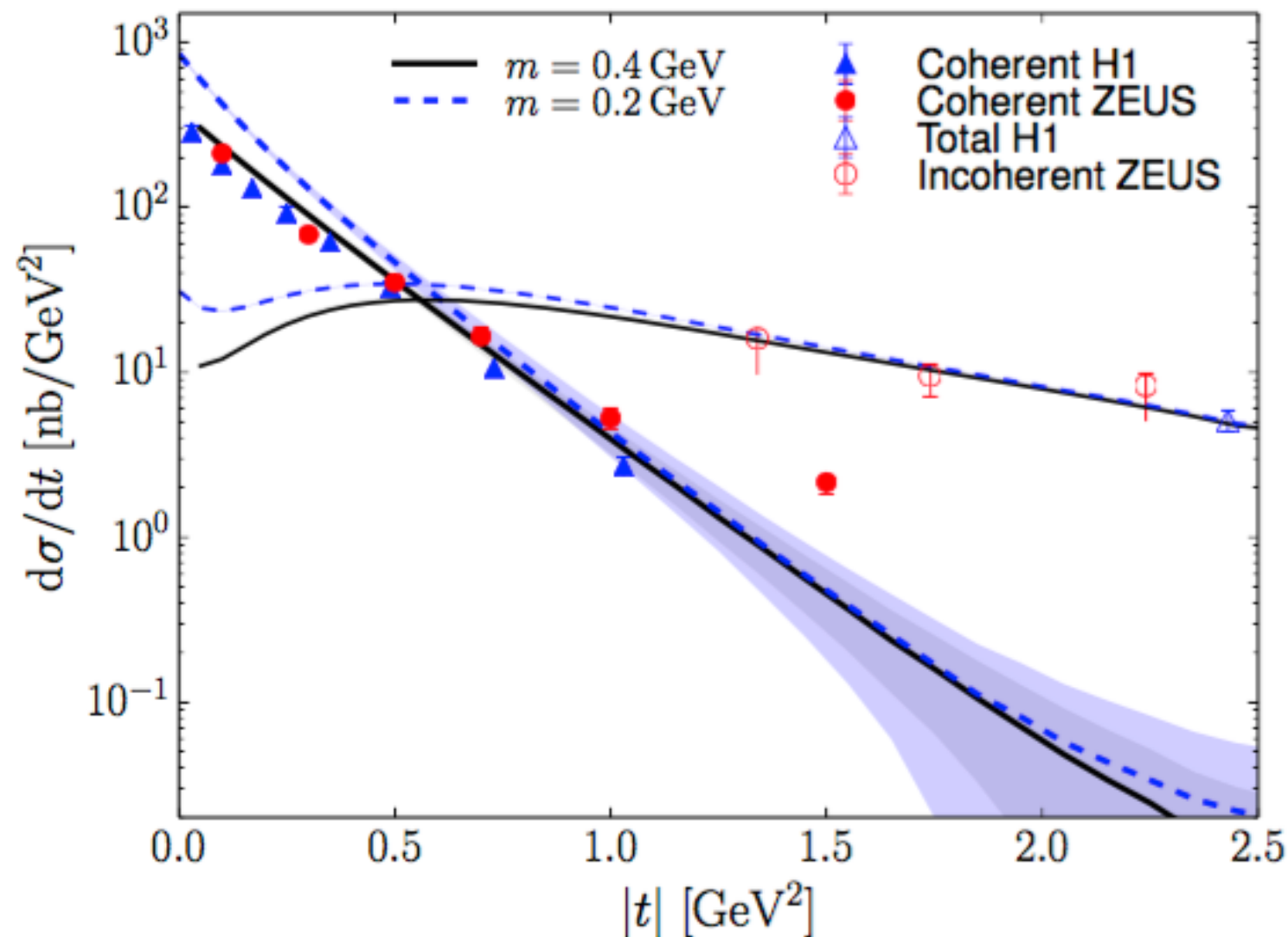
Gaussian tubes connecting quarks. Also good description of the data



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

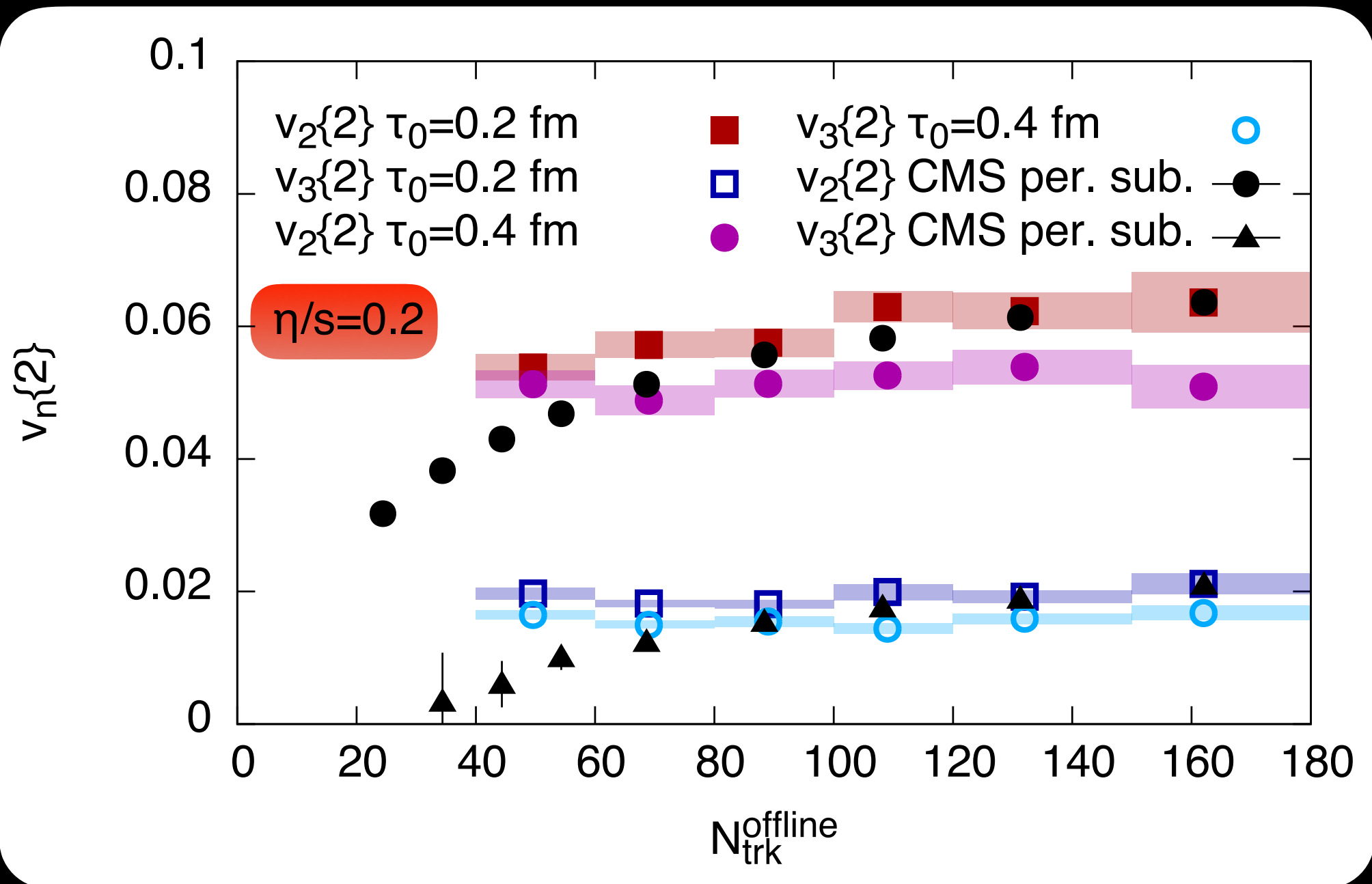


IP-Glasma: IR cutoff $m \sim \Lambda_{\text{QCD}}$ to regulates long distance coulomb tails

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

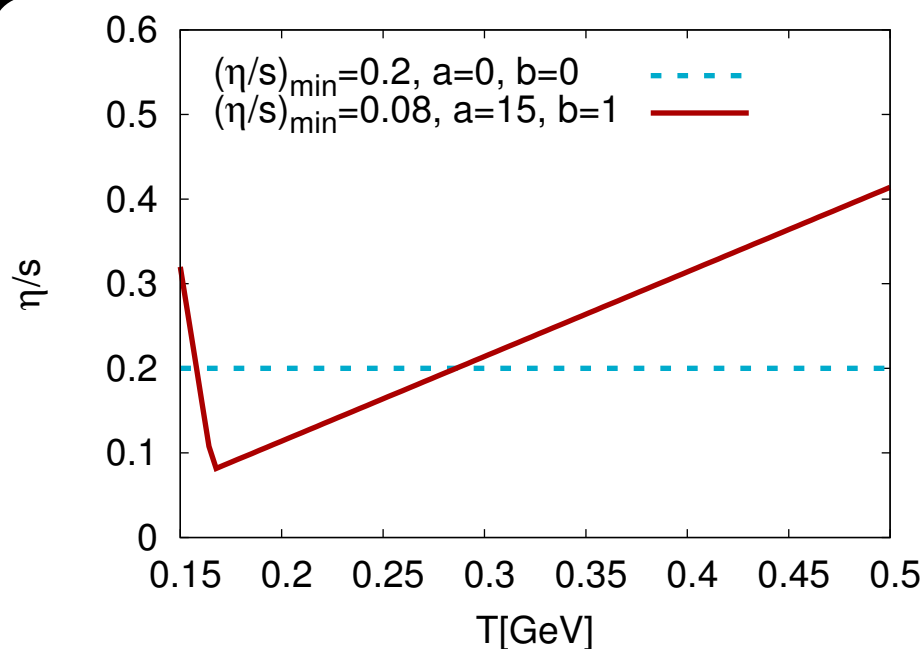
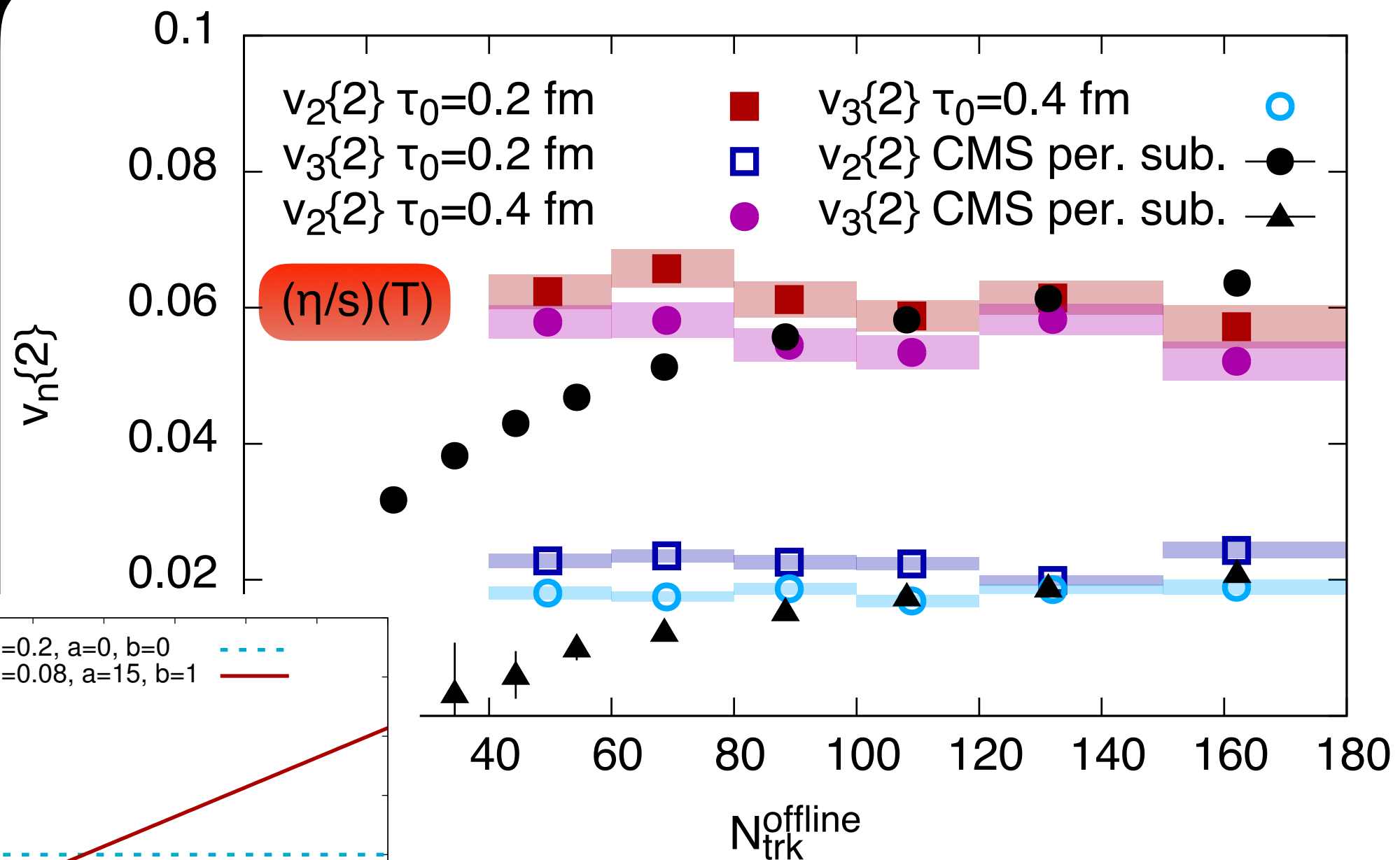
Integrated anisotropic flow

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



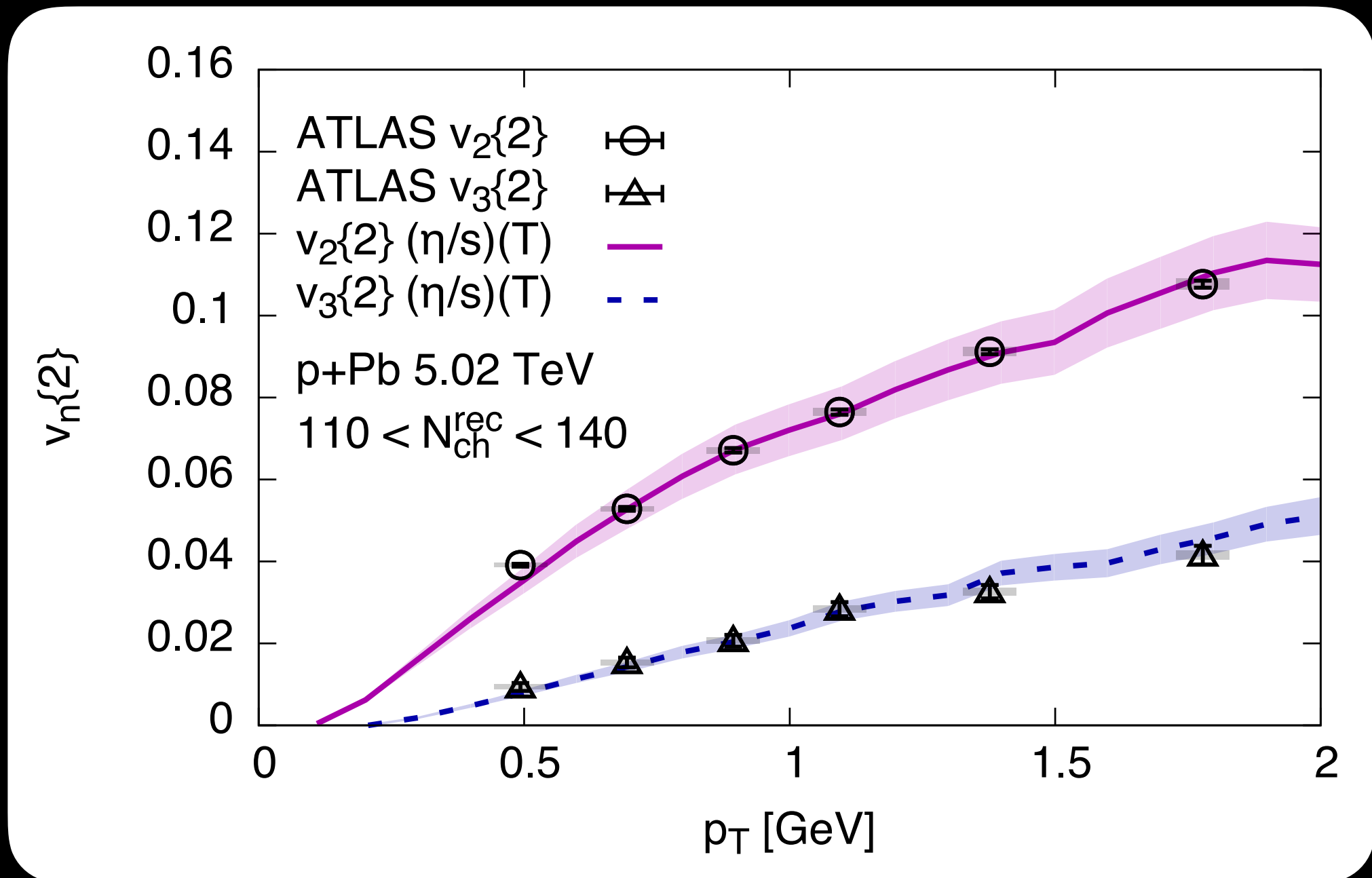
Integrated anisotropic flow

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



p_T -differential anisotropic flow

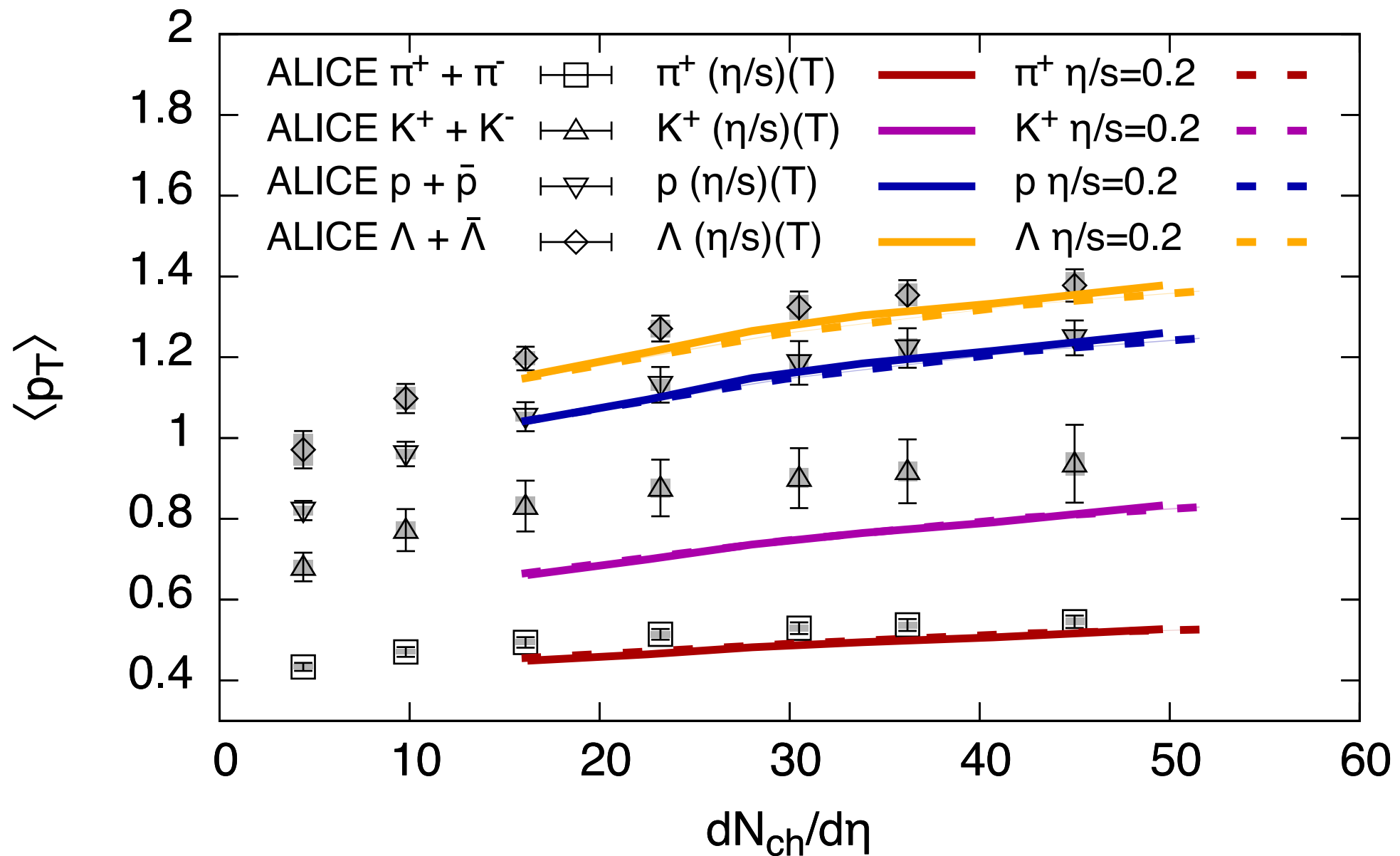
H. Mäntysaari, B. Schenke, C. Shen, P. Tribedy, arXiv:1705.03177



$\tau_0 = 0.4$ fm

Identified particle mean p_T

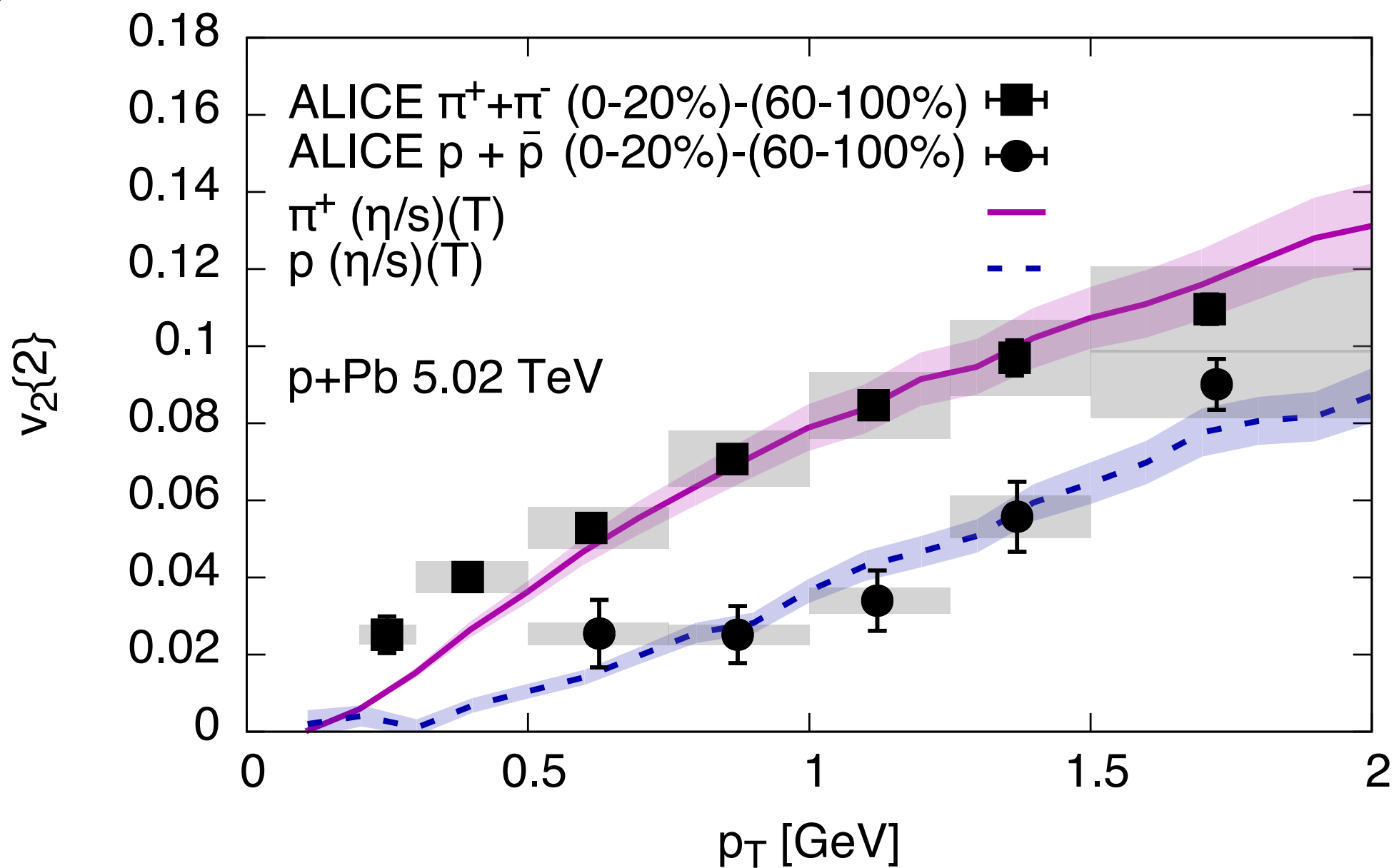
H. Mäntysaari, B. Schenke, C. Shen, P. Tribedy, arXiv:1705.03177



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

Identified particle flow

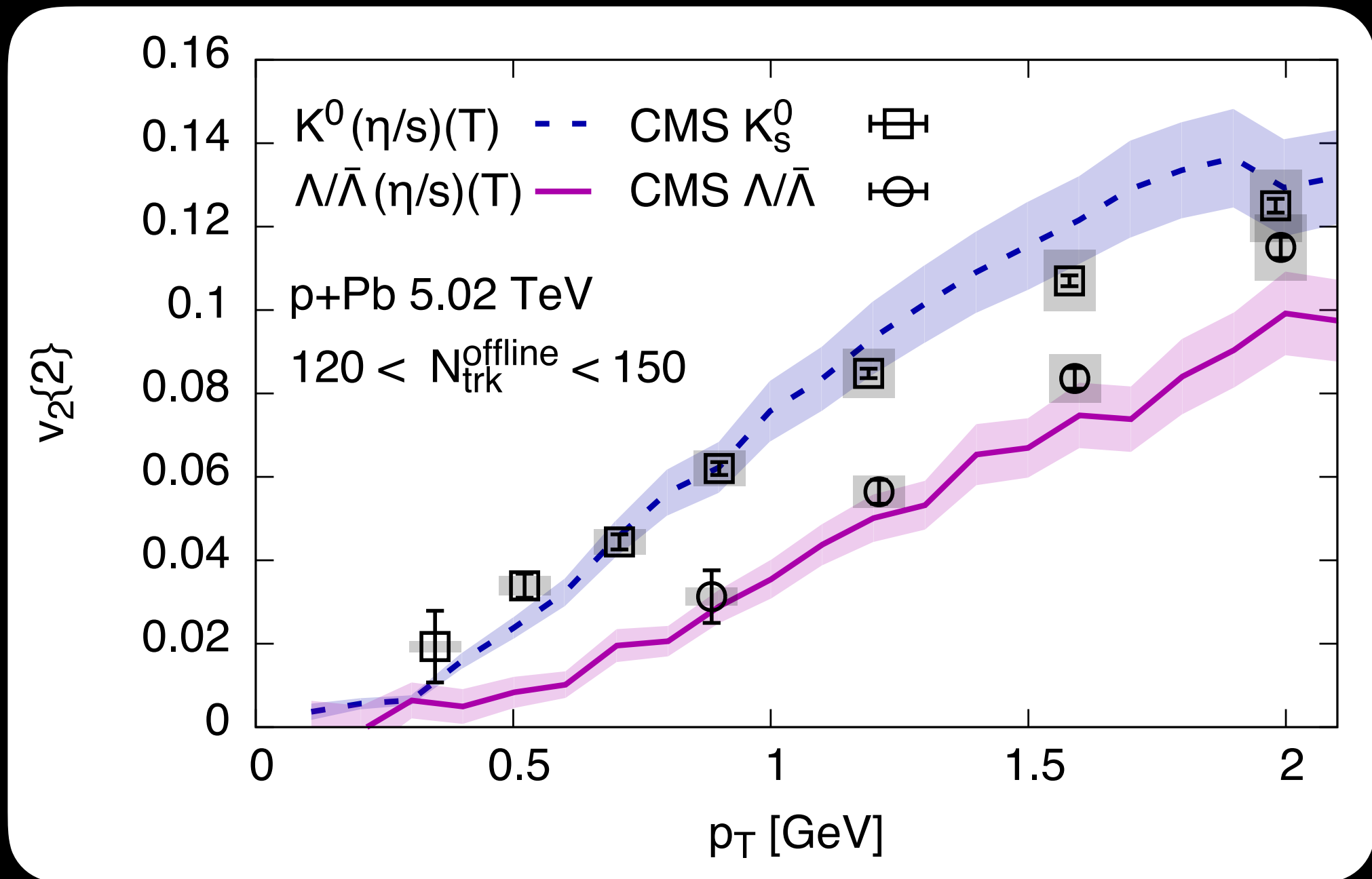
H. Mäntysaari, B. Schenke, C. Shen, P. Tribedy, arXiv:1705.03177



$\tau_0 = 0.4$ fm

Identified particle flow

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



$\tau_0=0.4$ fm

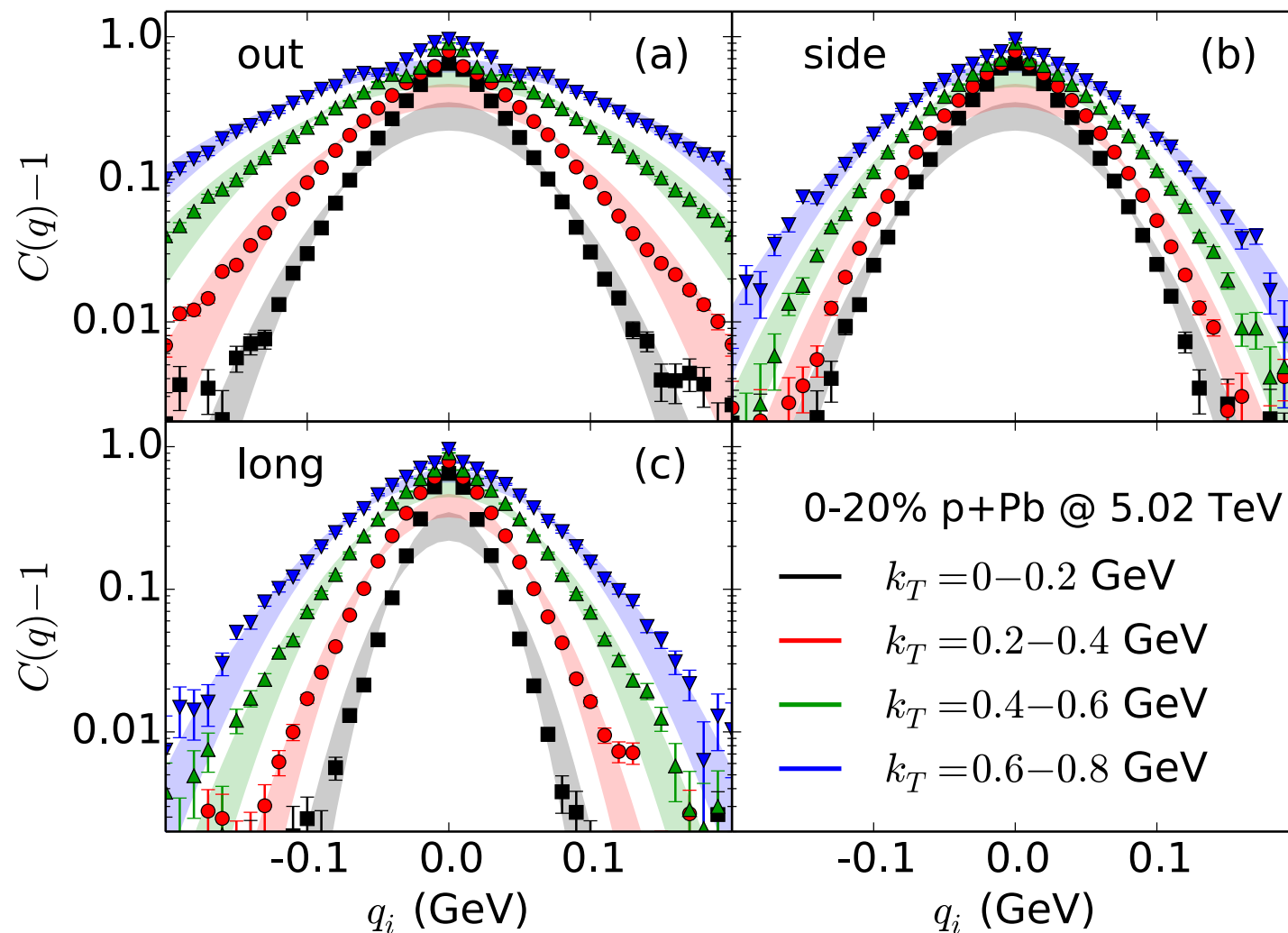
HBT radii

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

$$C(\mathbf{q}) = 1 + \frac{\frac{1}{\langle N_{\text{pair}} \rangle} \langle \sum_{ij} \cos(\mathbf{q}_{ij} \cdot \mathbf{x}_{ij}) \rangle}{\frac{1}{\langle N_{\text{mix pair}} \rangle} \langle N_{\text{mix pair}}(\mathbf{q}) \rangle}$$

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)

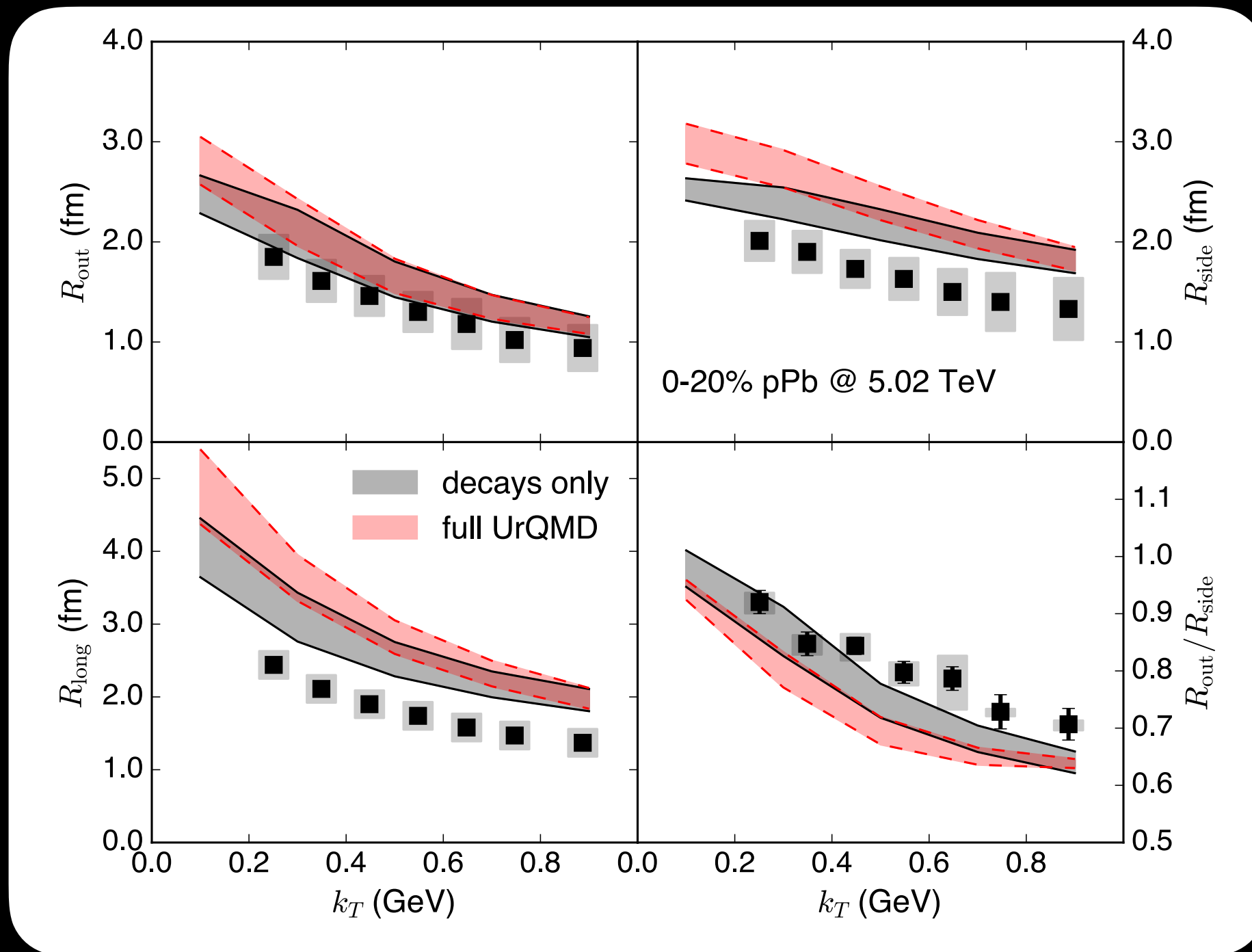
G. Bertsch, M. Gong, and M. Tohyama

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)

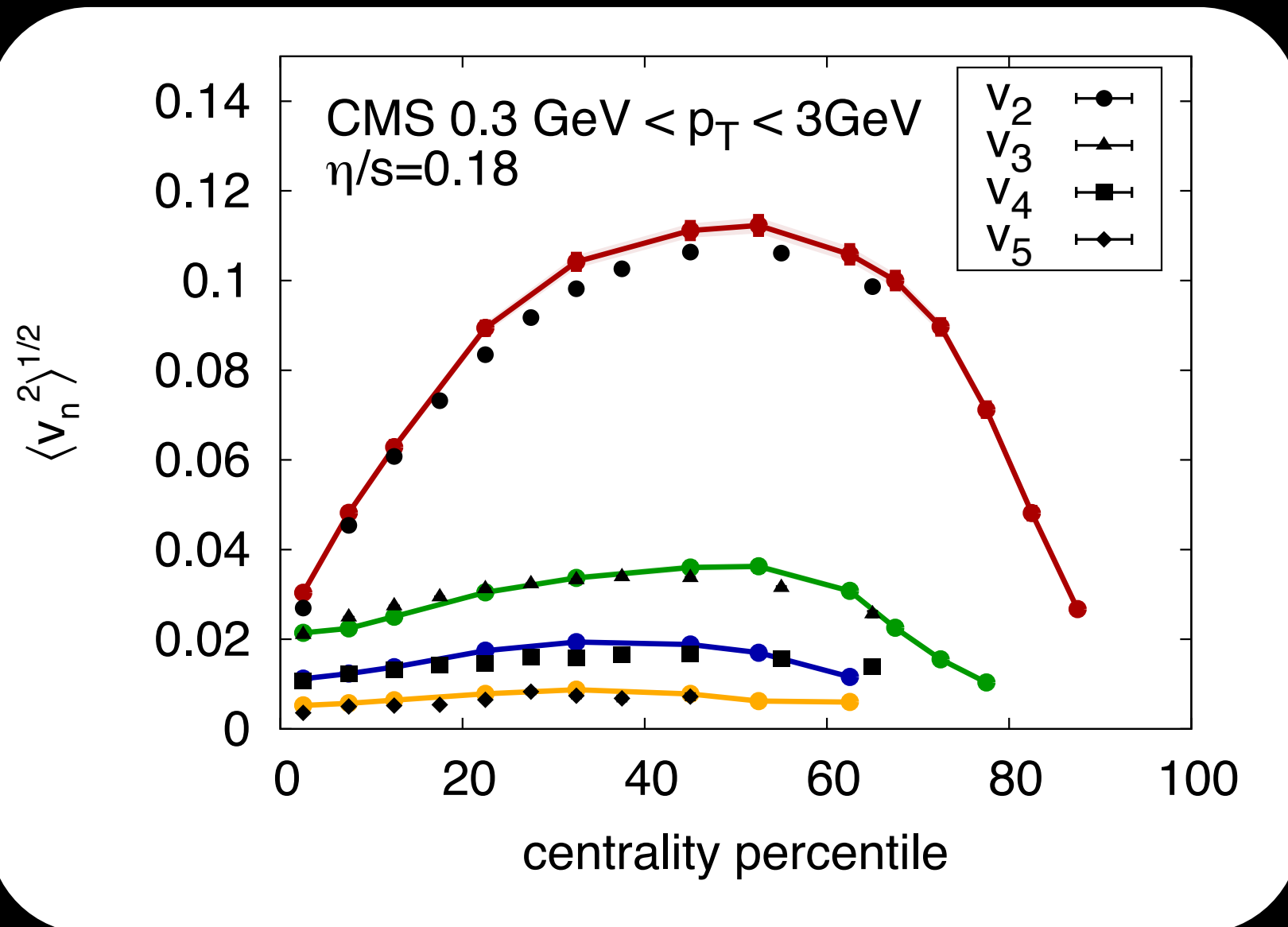
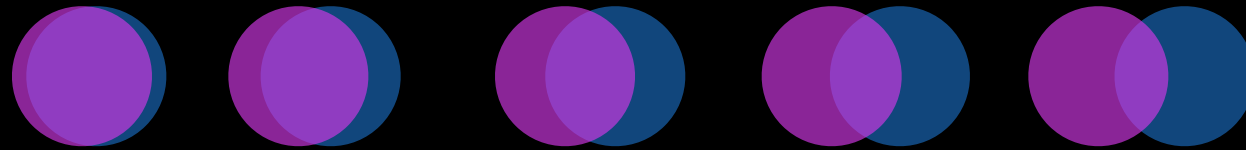


$\tau_0 = 0.4$ fm $(\eta/s)(T)$

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)

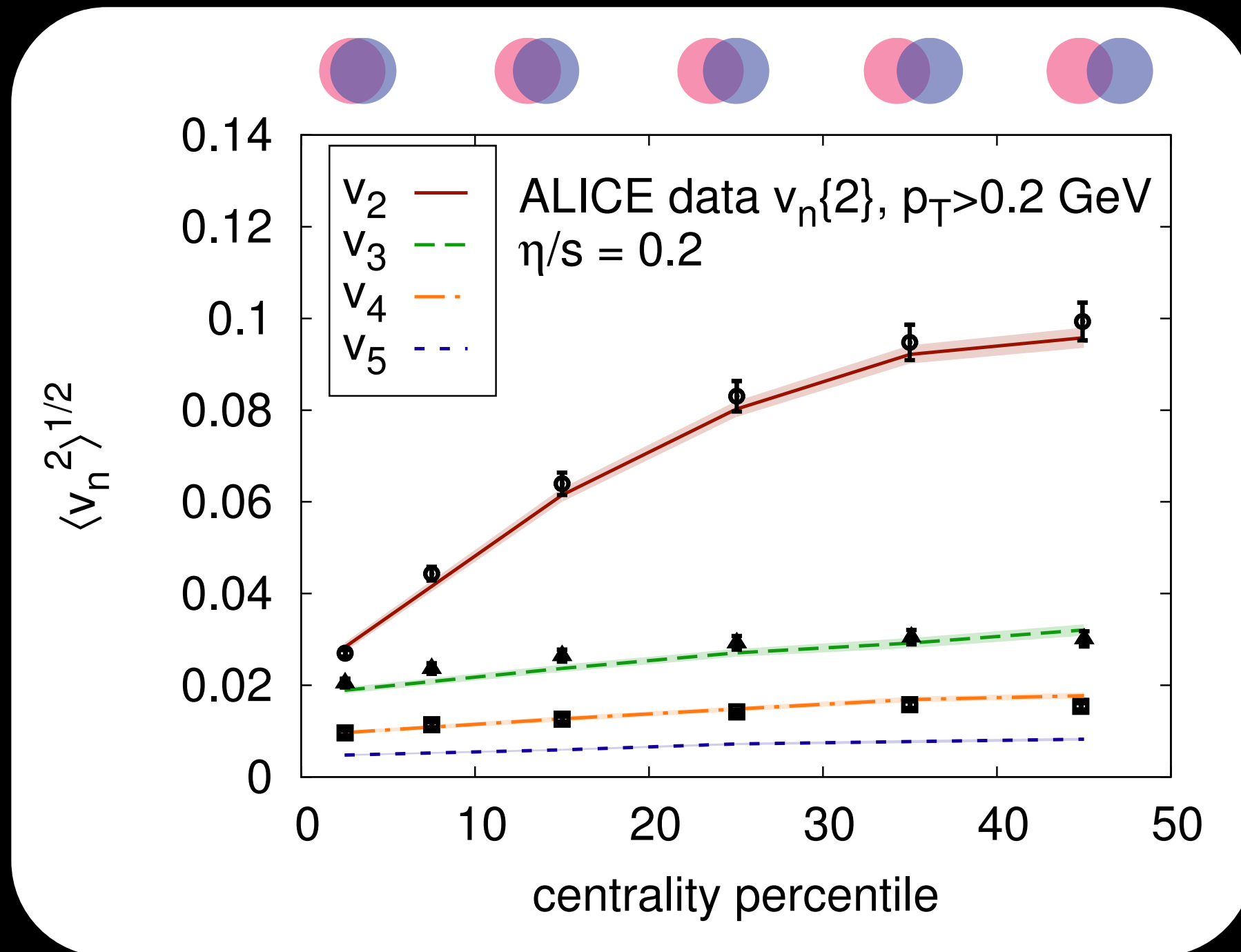
B. Schenke, R. Venugopalan, Phys.Rev.Lett. 113 (2014) 102301



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)