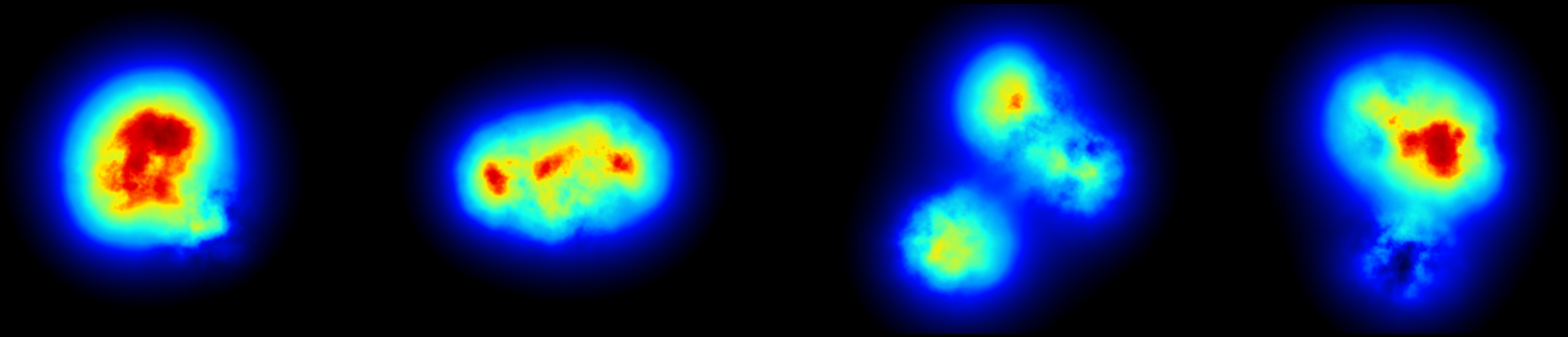
SUBNUCLEONIC FLUCTUATIONS, DIFFRACTION, AND SMALL-X EVOLUTION

Björn Schenke
Brookhaven National Laboratory



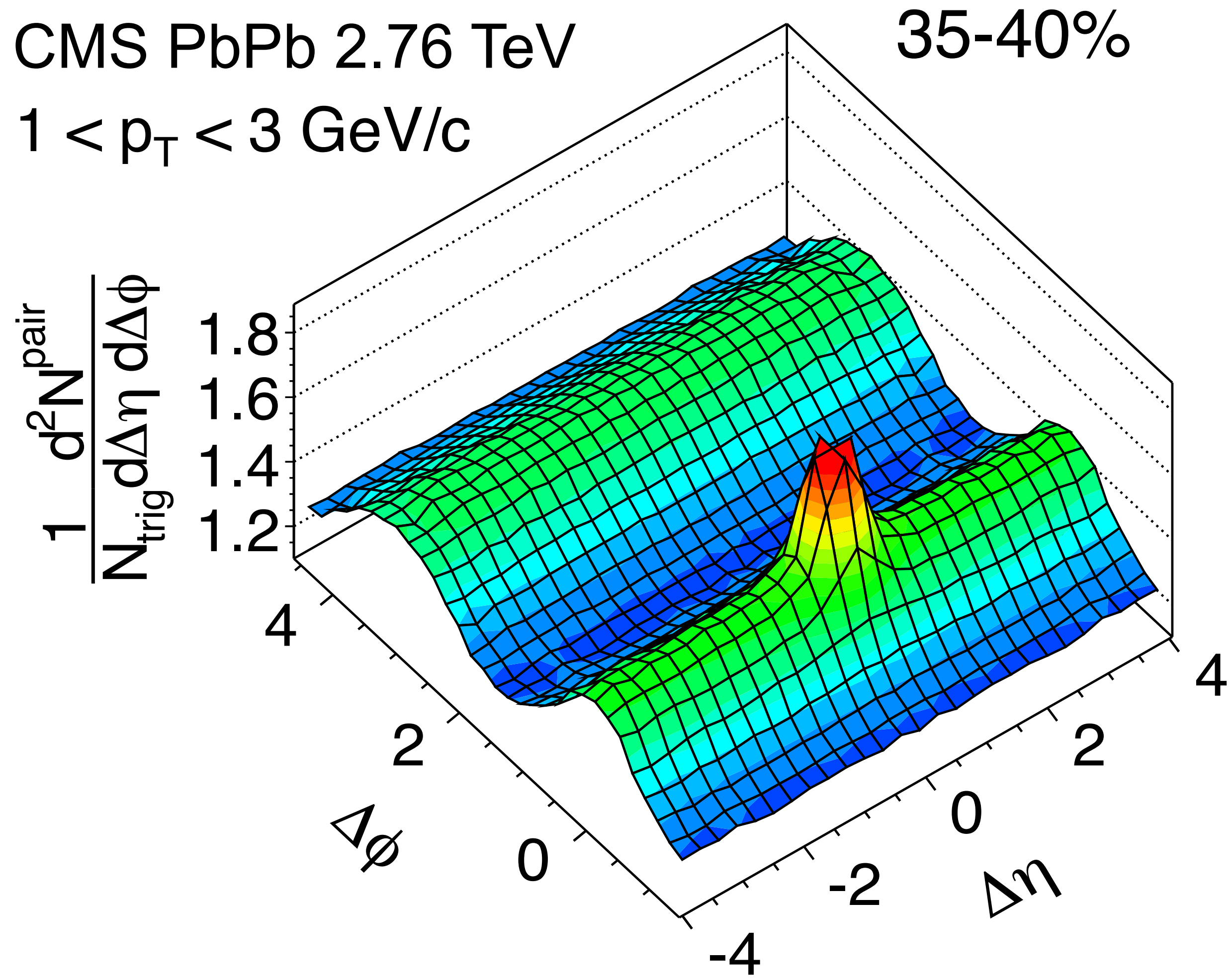
April 26, 2017
Saturation: Recent Developments, New Ideas and Measurements
RBRC Workshop

Introduction: Multi-particle correlations

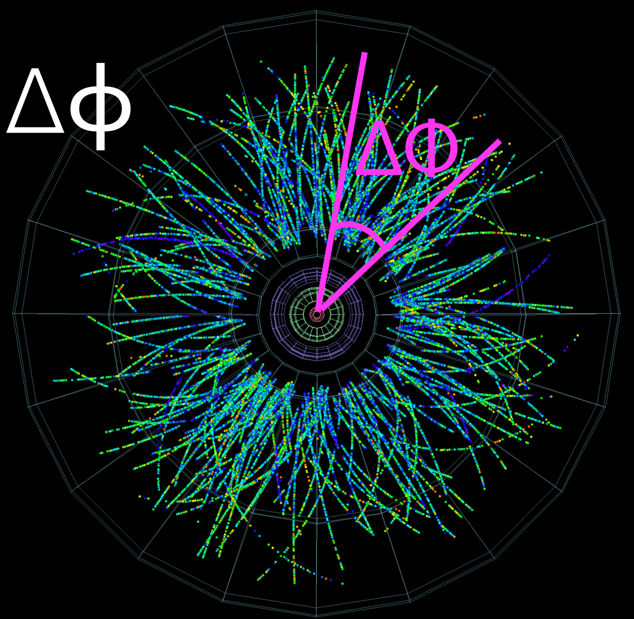
2-particle correlation as a function of $\Delta\eta$ and $\Delta\phi$

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

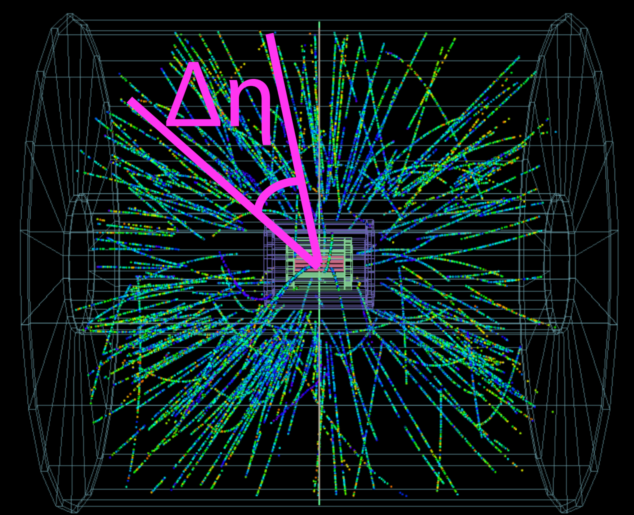
$\Delta\Phi$: DIFFERENCE IN AZIMUTHAL ANGLE



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



$\Delta\Phi$: DIFFERENCE IN AZIMUTHAL ANGLE

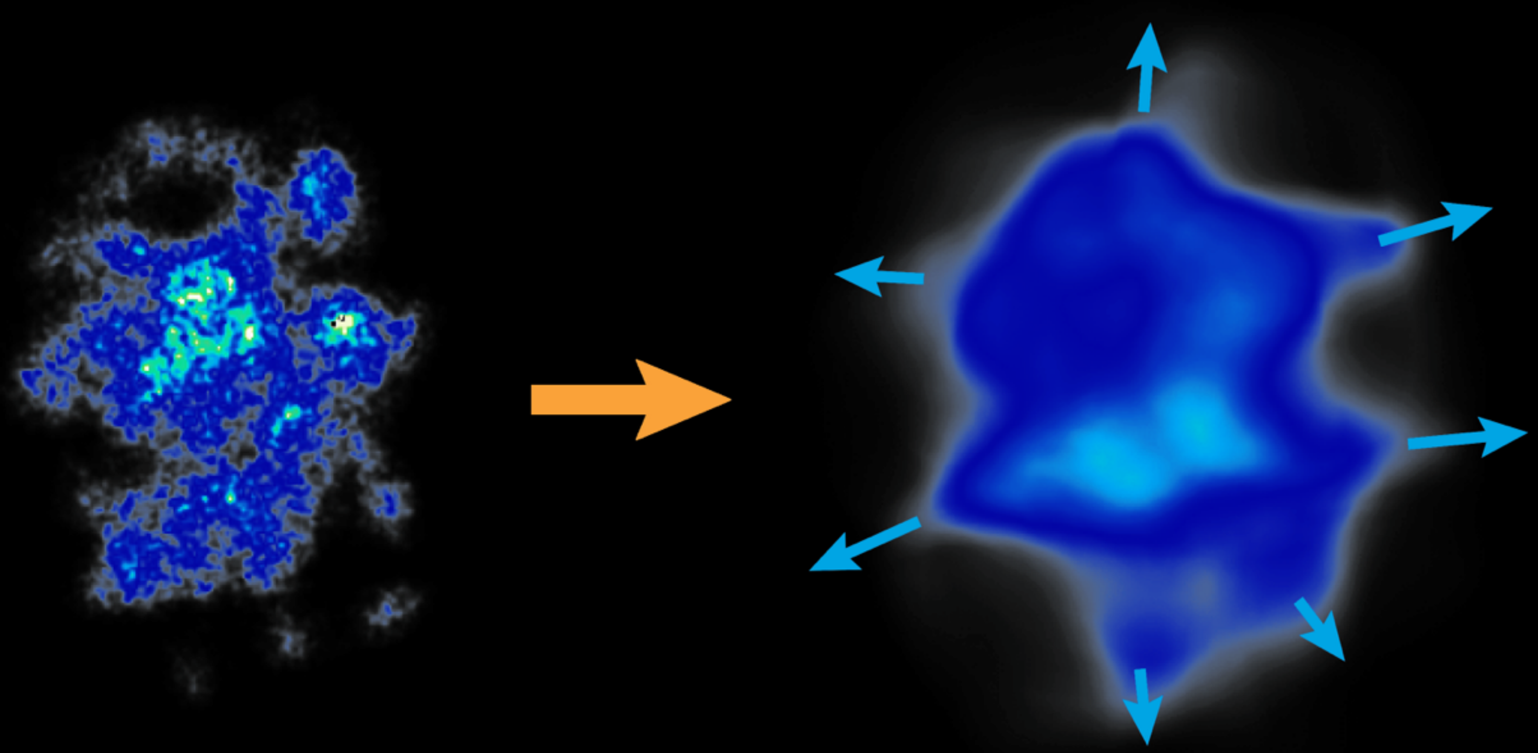


$\Delta\eta$: DIFFERENCE IN PSEUDO-RAPIDITY

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

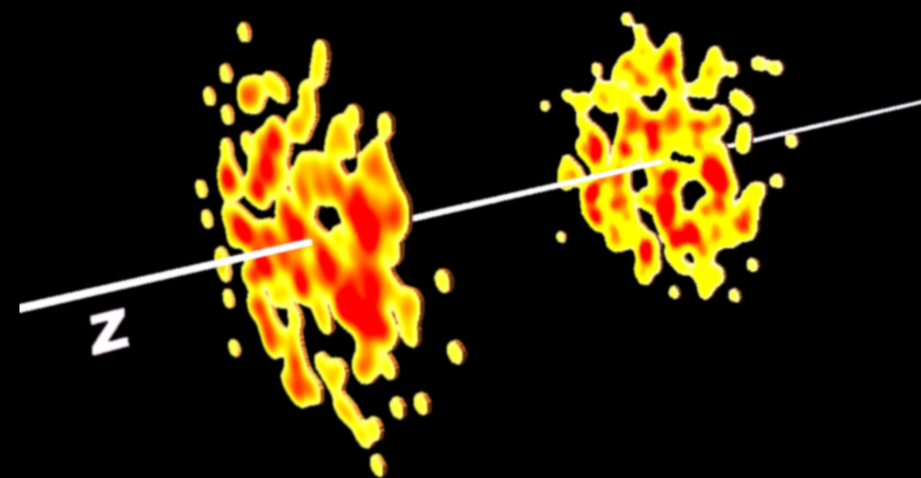
Hydrodynamic expansion

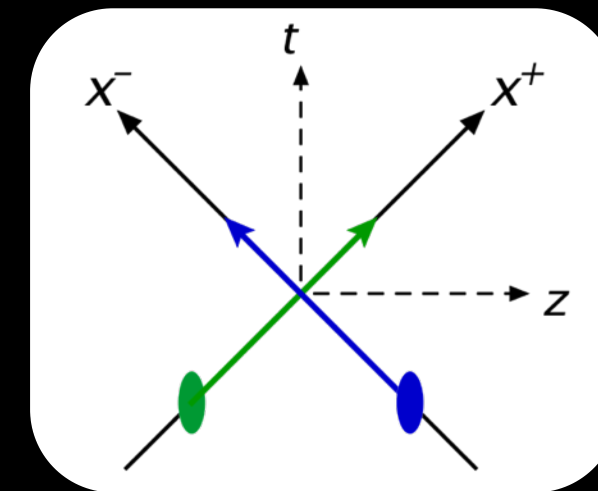
IP-Glasma initial state

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

Particle production governed by the **Yang Mills equations**

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





Incoming currents

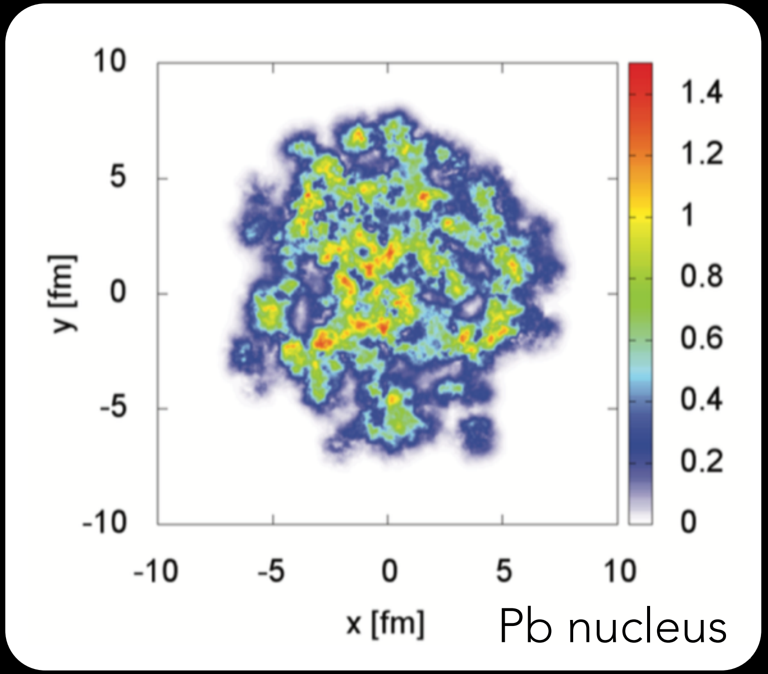
How to determine the incoming currents J^ν:

- IP-Sat model: Parametrize energy and spatial dependence of deep inelastic cross section - fit parameters to HERA data
  Kowalski, Teaney, Phys.Rev. D68 (2003) 114005
- → energy and position dependent saturation scale $Q_s(x, \vec{x})$
- Sample nucleons and color charges $\rho(\vec{x})$ with density ~ $Q_s(x, \vec{x})$

IP-Glasma initial state

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

Trace of Wilson lines



Pb nucleus

Fields before the collision:

$$A^i_{(1)}(\vec{x}) = -\frac{i}{g} V_{(1)}(\vec{x}) \partial_i V^\dagger_{(1)}(\vec{x})$$ with Wilson lines:

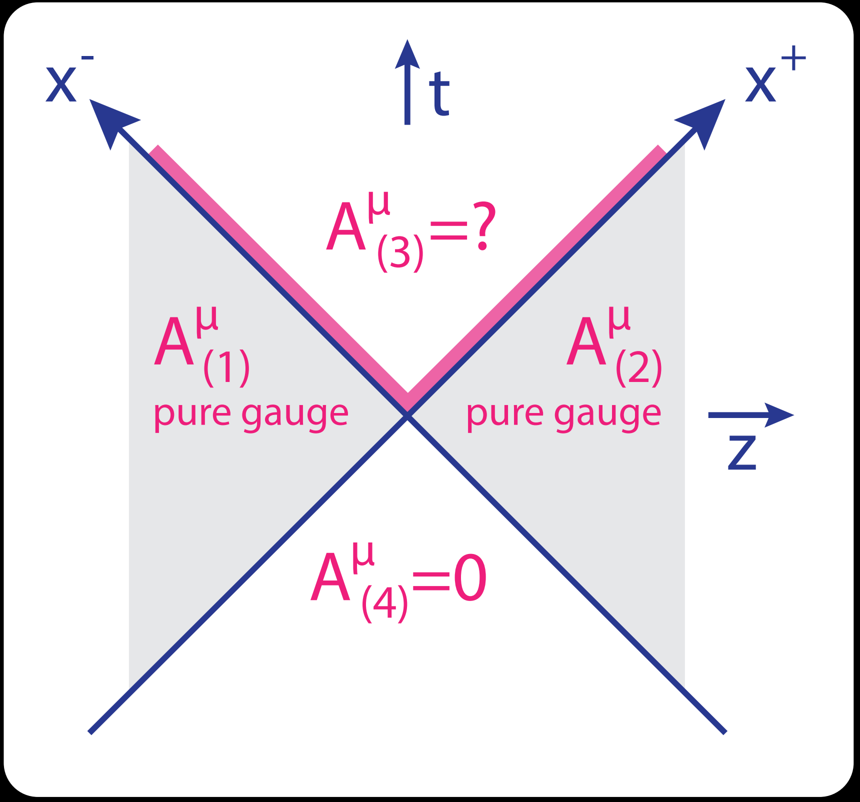
$$V_{(1)}(\vec{x}) = P\exp\left(-ig \int dx^- \frac{\rho_{(1)}(x^-, \vec{x})}{\nabla^2 + m^2}\right)$$

Fields after the collision:

$$A^i_{(3)}|_{\tau=0^+} = A^i_{(1)} + A^i_{(2)}$$

$$A^\eta_{(3)}|_{\tau=0^+} = \frac{ig}{2}[A^i_{(1)}, A^i_{(2)}]$$

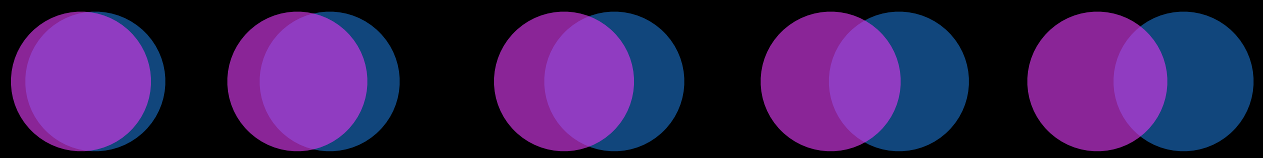
Kovner, McLerran, Weigert, Phys. Rev. D52, 6231 (1995)
Krasnitz, Venugopalan, Nucl.Phys. B557 (1999) 237

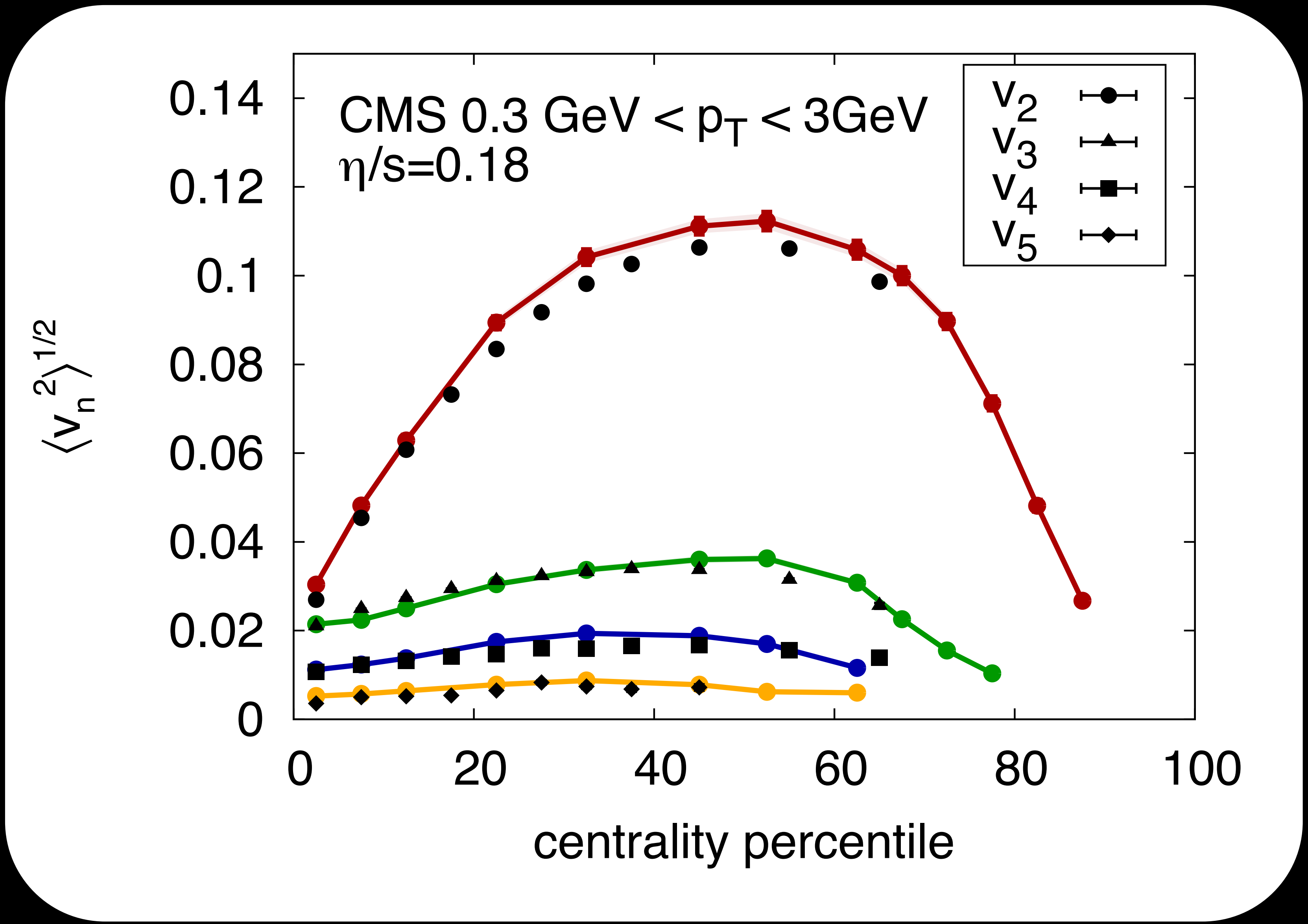


Fields in Schwinger gauge

Heavy ions: v_n from IP-Glasma initial state and MUSIC hydrodynamics

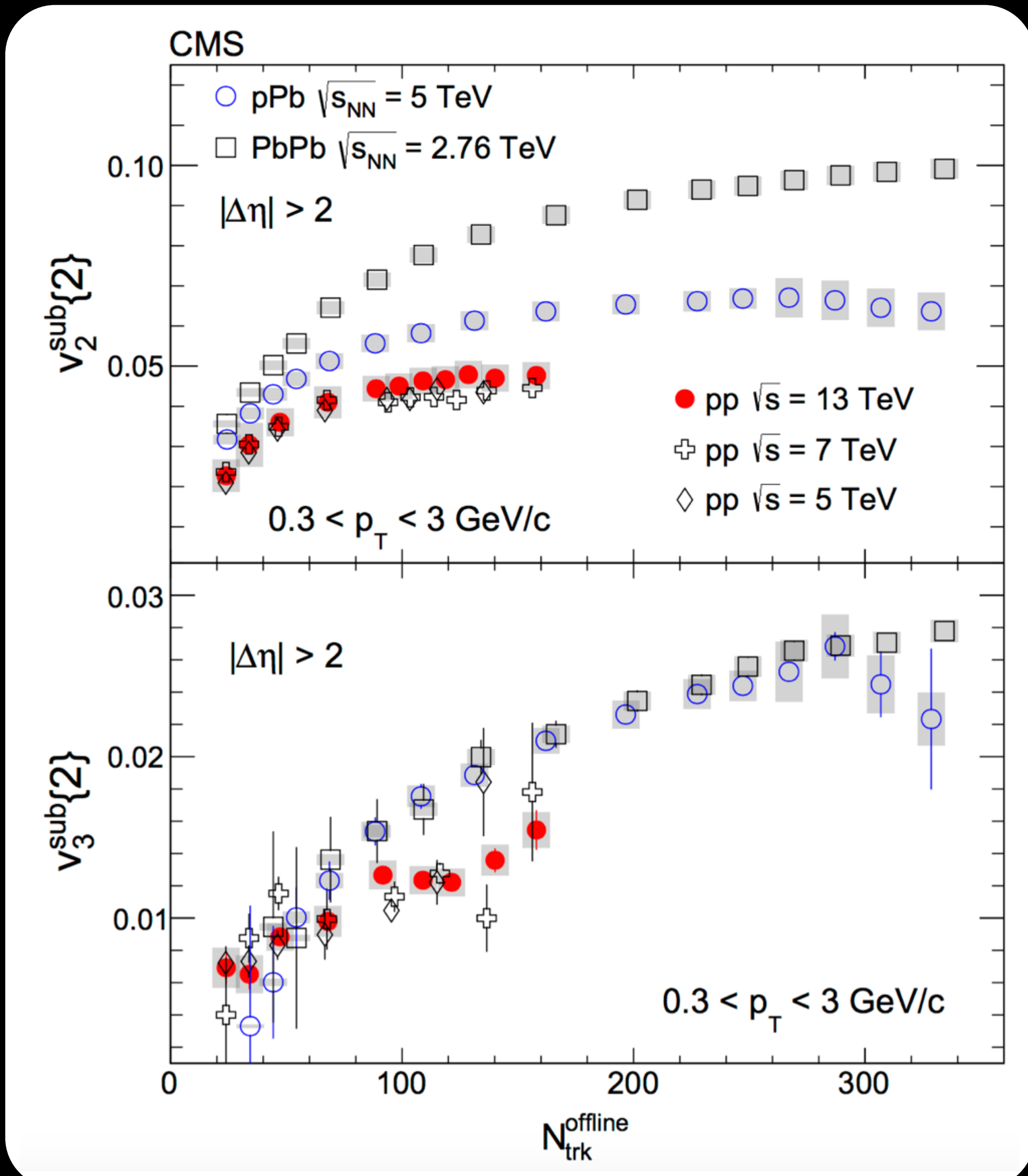
C.Gale, S.Jeon, B.Schenke, P.Tribedy, R.Venugopalan, Phys.Rev.Lett. 110, 012302 (2013)
B. Schenke, R. Venugopalan, Phys.Rev.Lett. 113 (2014) 102301





CMS Collaboration, PRC 87(2013) 014902

v_n in p+p, p+Pb, Pb+Pb Collisions



CMS Collaboration, Phys.Lett. B765 (2017) 193-220

see also:

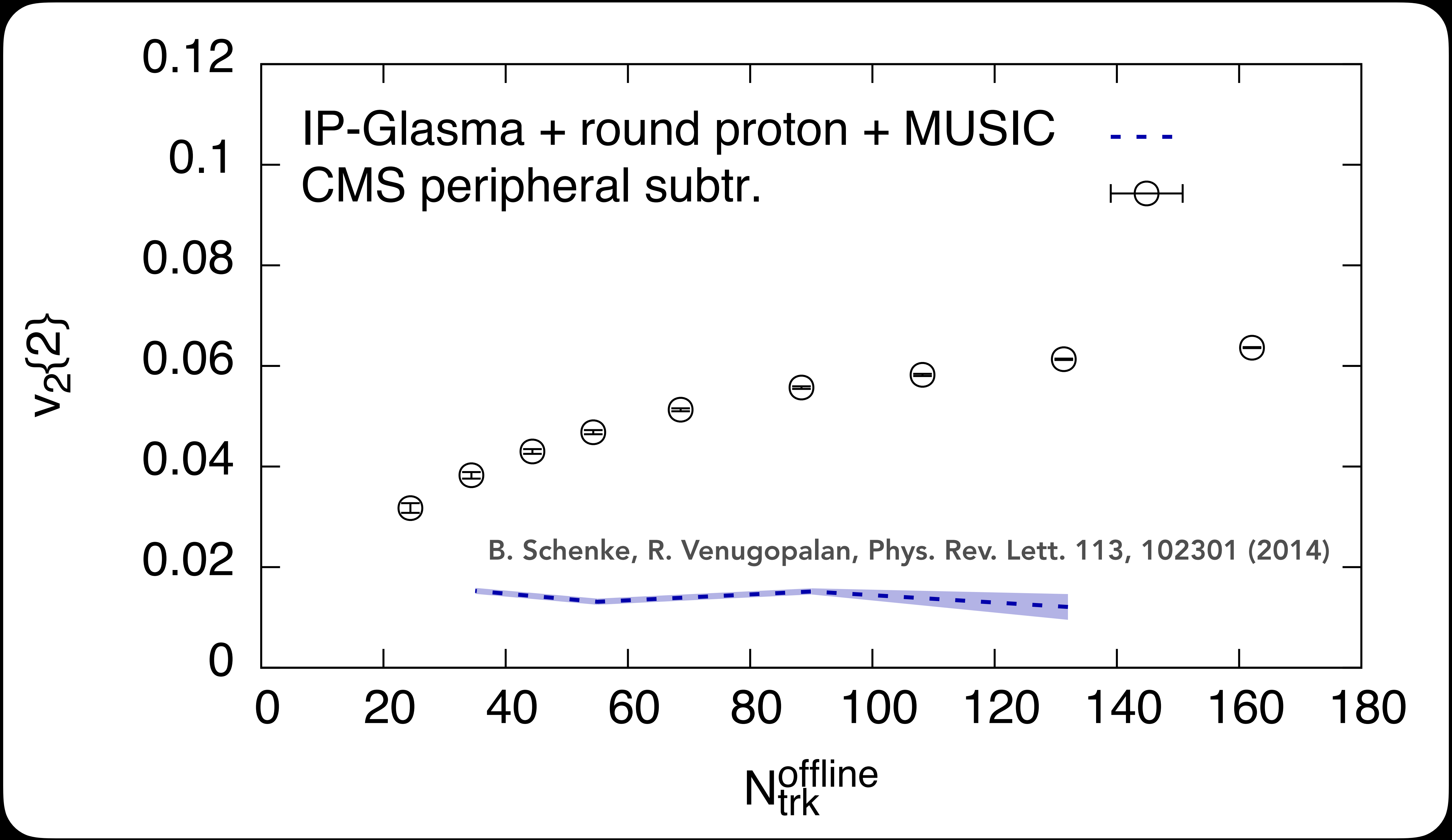
ALICE CollABORATION
Phys. Lett. B719 (2013) 29-41; Phys. Rev. C 90, 054901

ATLAS CollABORATION
Phys. Rev. Lett. 110, 182302 (2013); Phys. Rev. C 90.044906 (2014)

CMS CollABORATION Phys.Rev.Lett. 115, 012301 (2015)

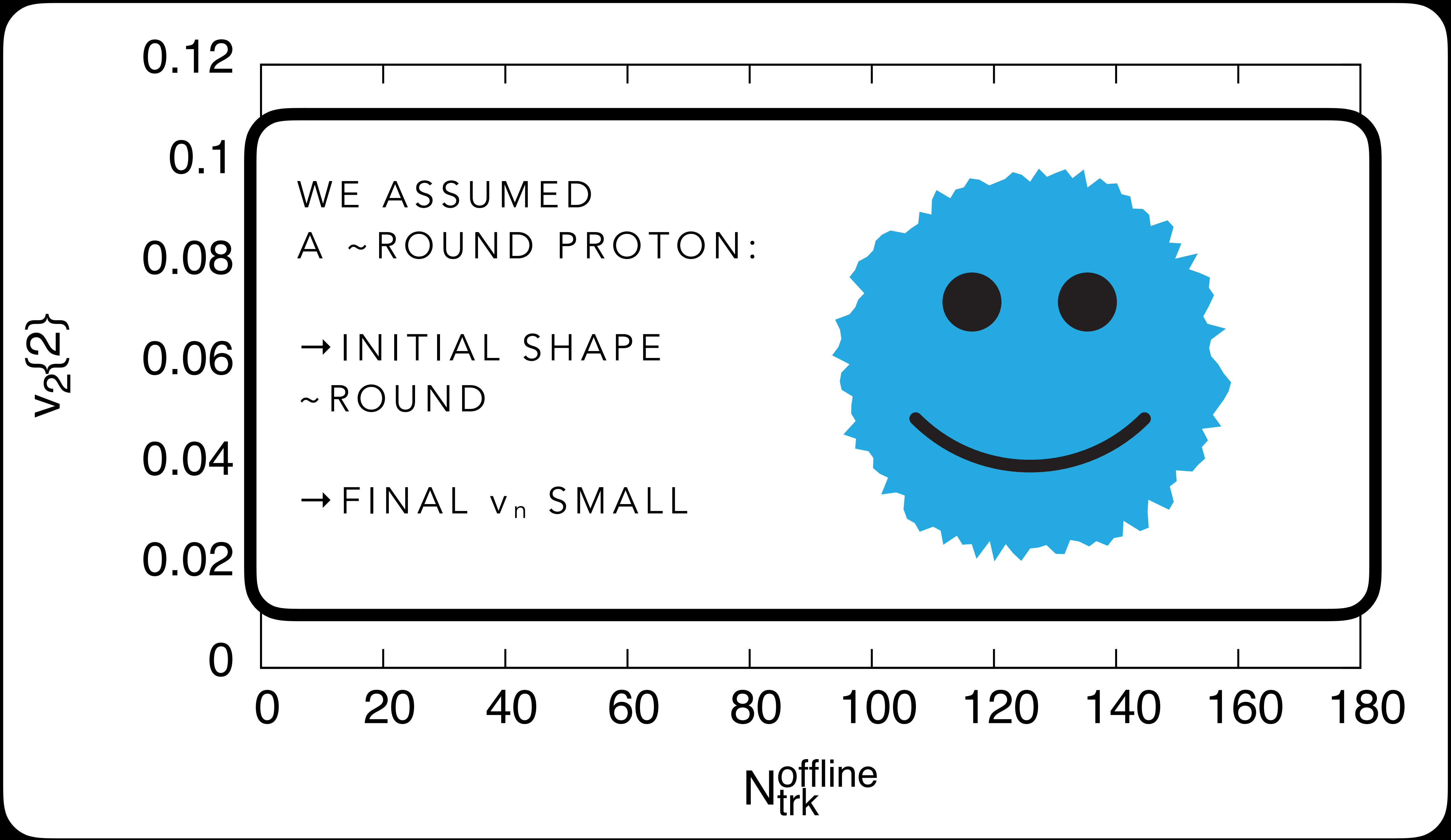
IP-Glasma+MUSIC results

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



IP-Glasma+MUSIC results

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



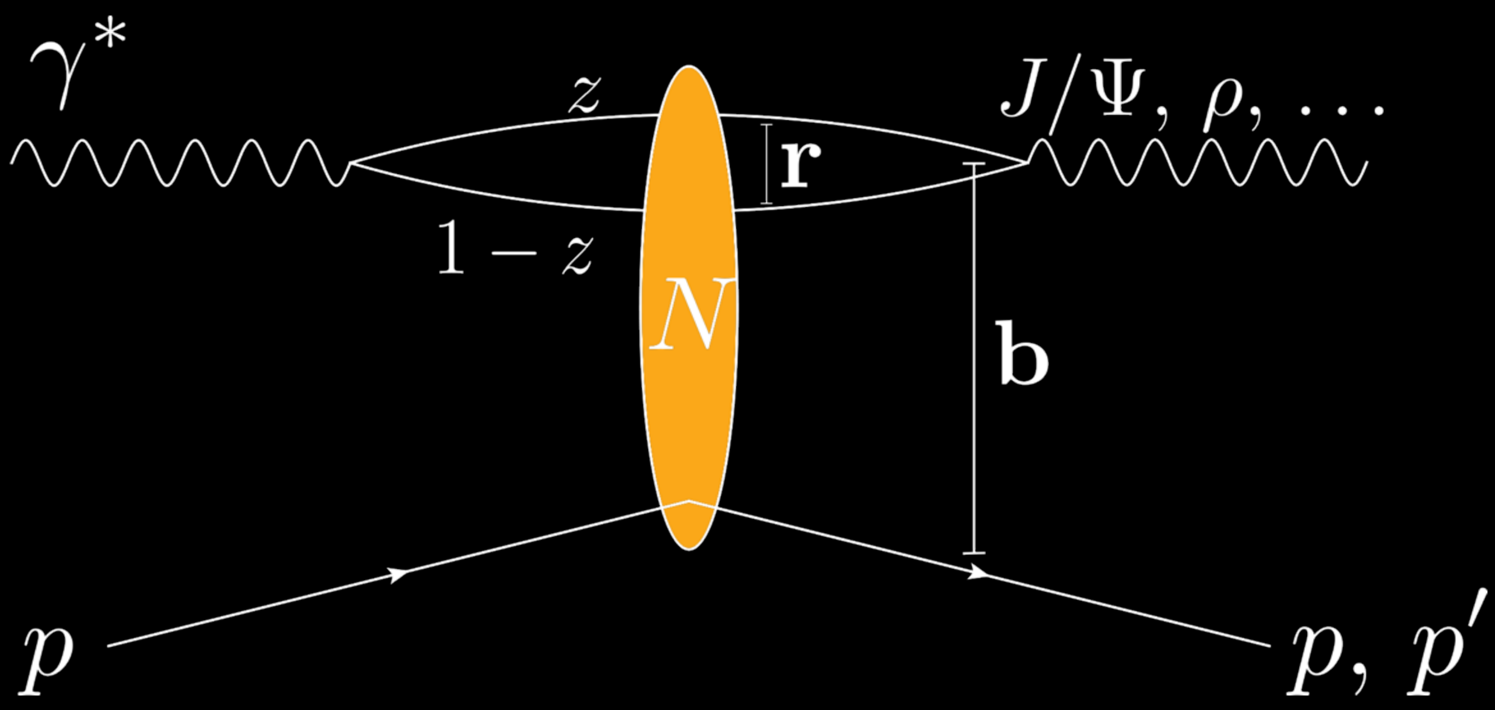
THEORY FRAMEWORK REQUIRES ADDITIONAL PROTON SHAPE FLUCTUATIONS

HOW TO CONSTRAIN THEM?

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:

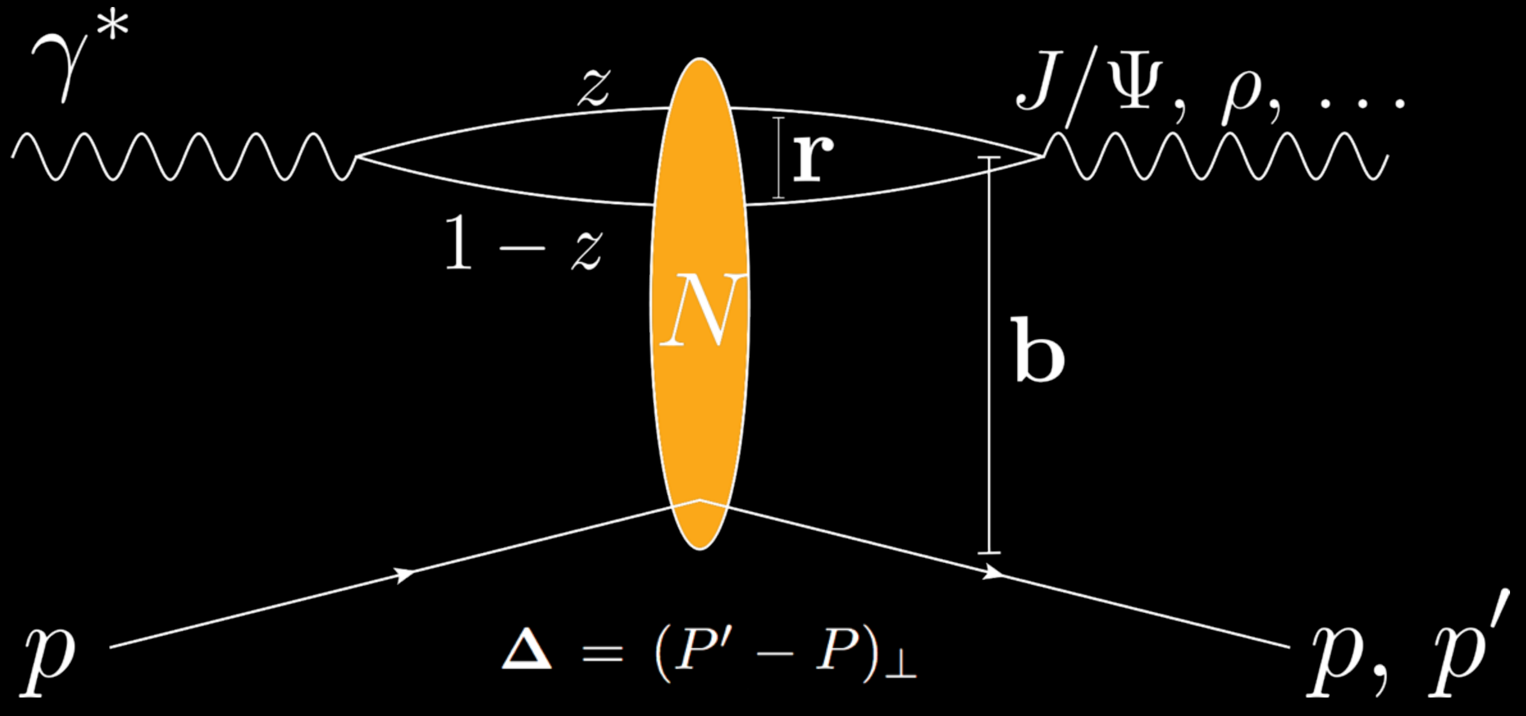
Proton breaks up, Sensitive to shape fluctuations

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

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

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

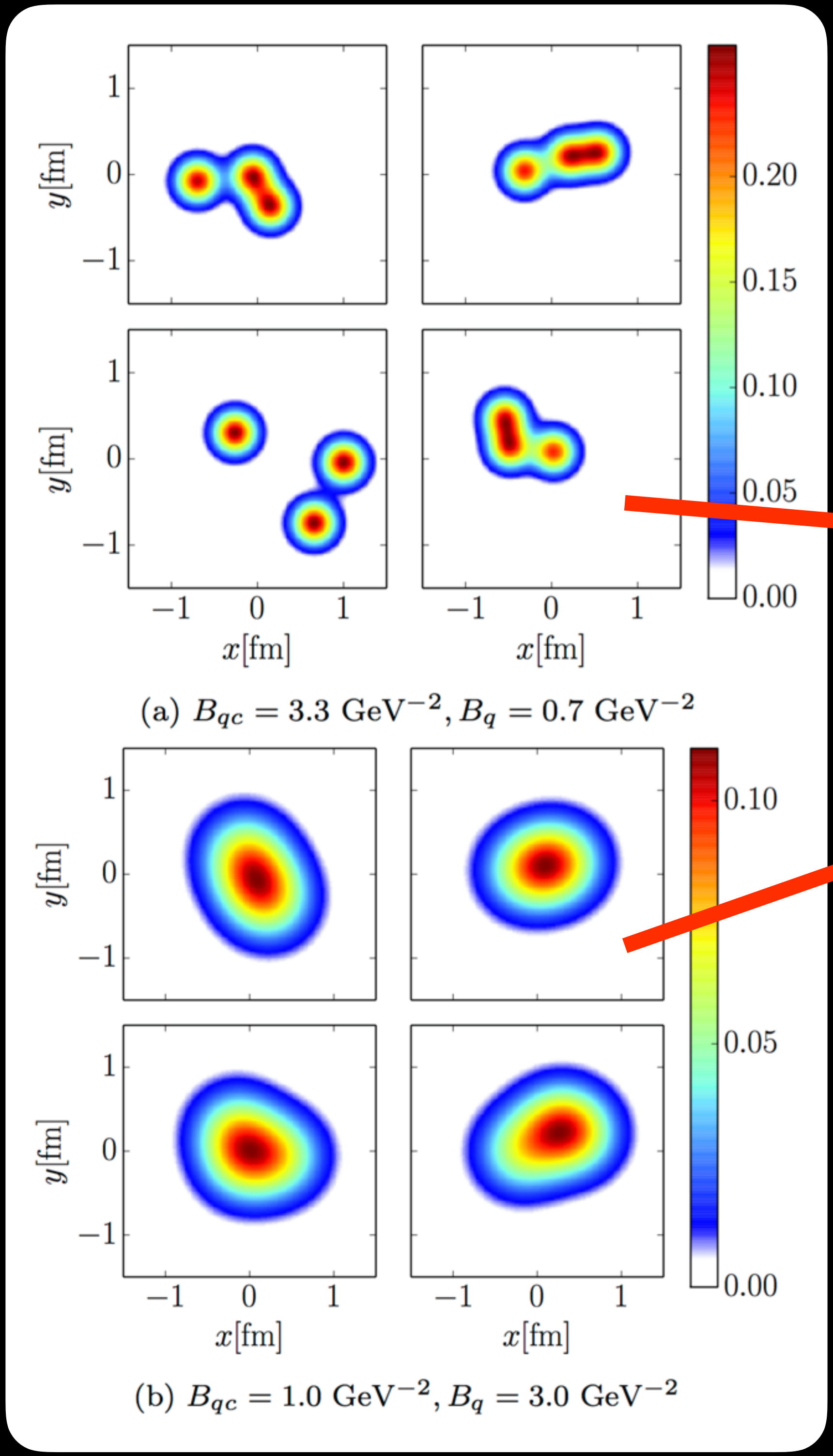
Y. V. KOVCHEGOV
AND L. D. MCLERRAN
PHYS. REV. D60 (1999) 054025

A. KOVNER AND
U. A. WIEDEMANN
PHYS. REV. D64 (2001) 114002

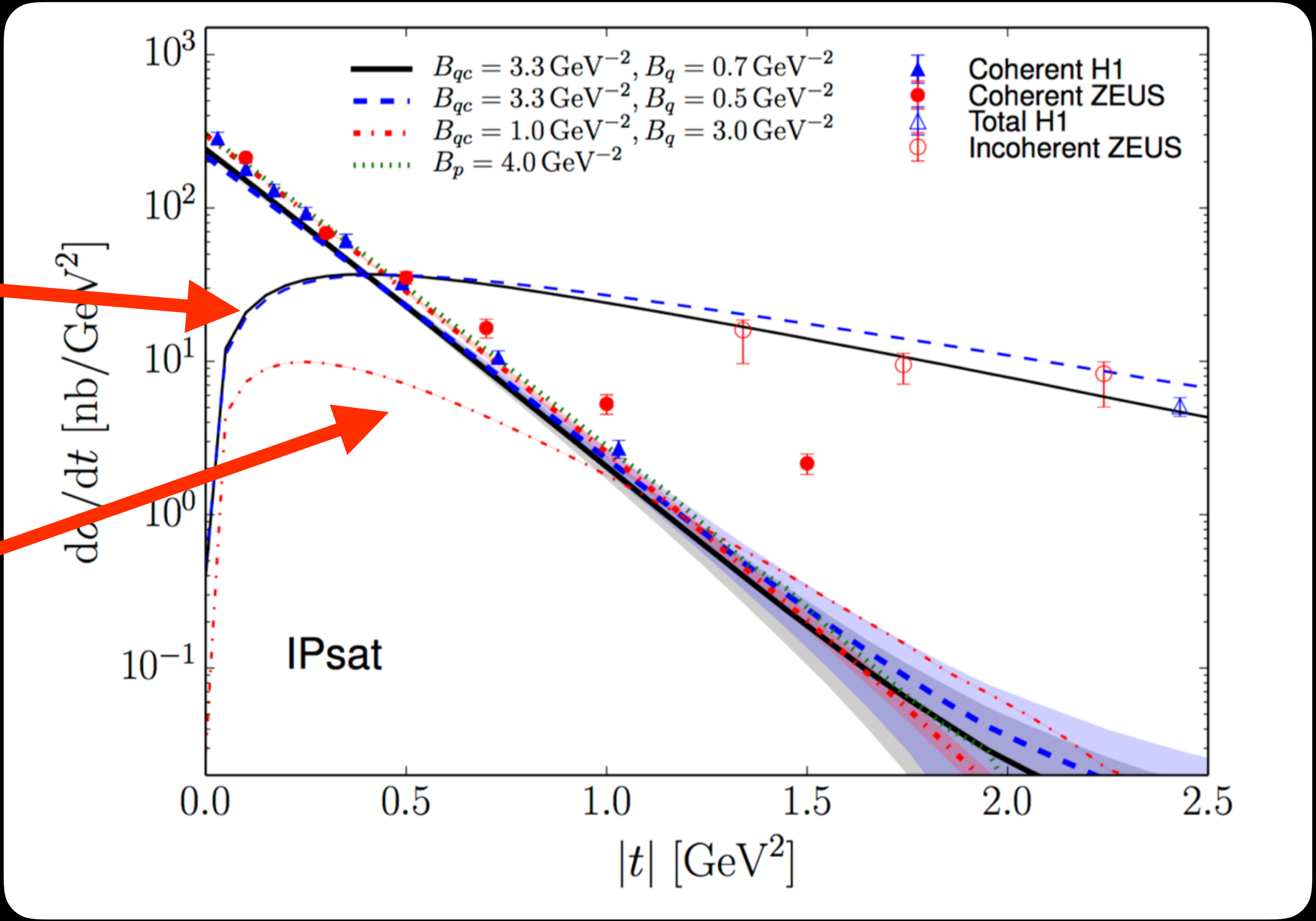
SENSITIVE TO FLUCTUATIONS!

Introduce geometric fluctuations

Assume 3 valence quark-like hot spots



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

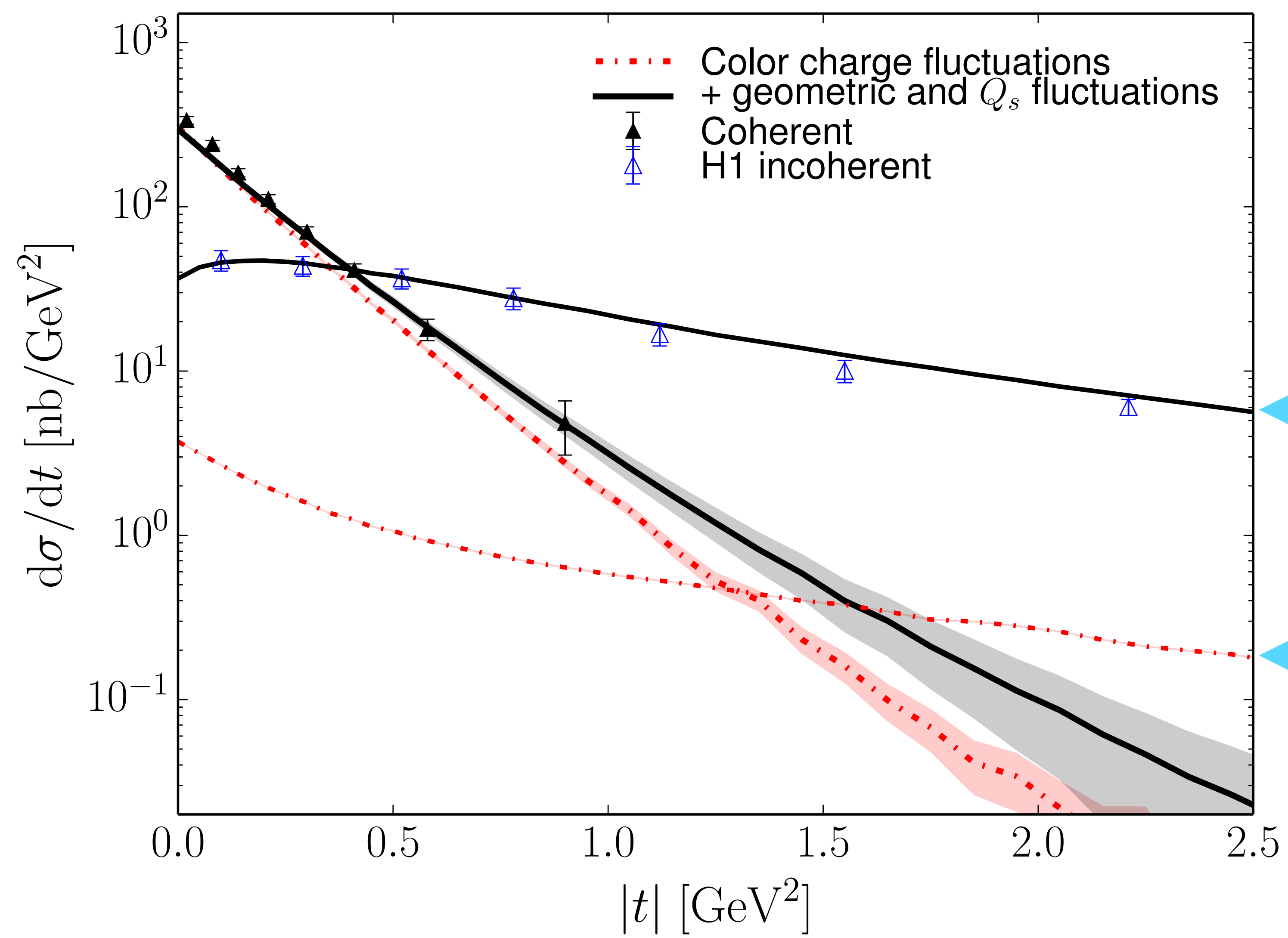
IP-Glasma calculation

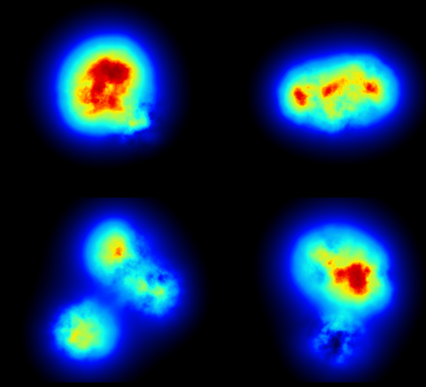
H. Mäntysaari, B. Schenke, Phys. Rev. Lett. 117 (2016) 052301; Phys.Rev. D94 (2016) 034042

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

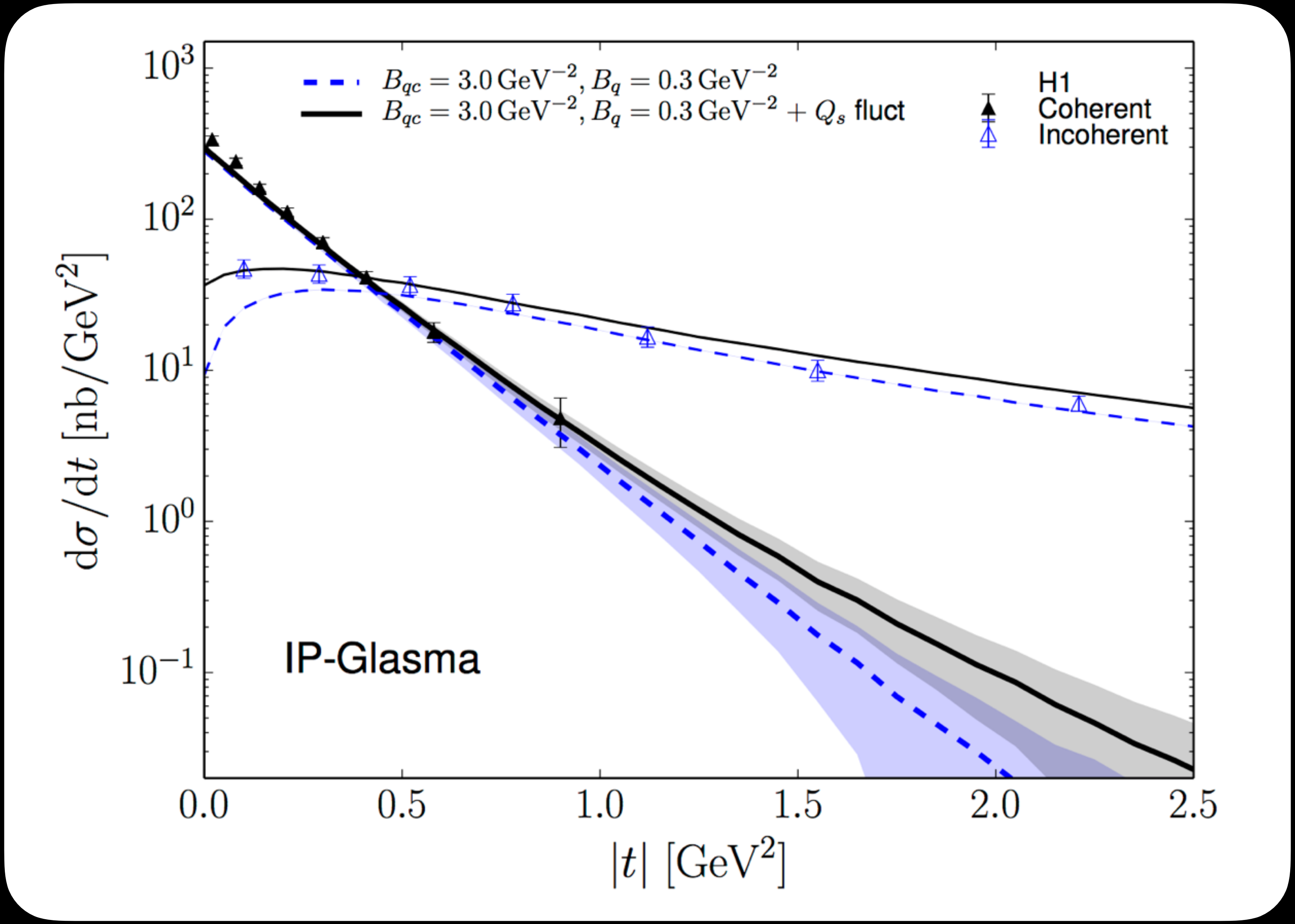
round proton

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

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

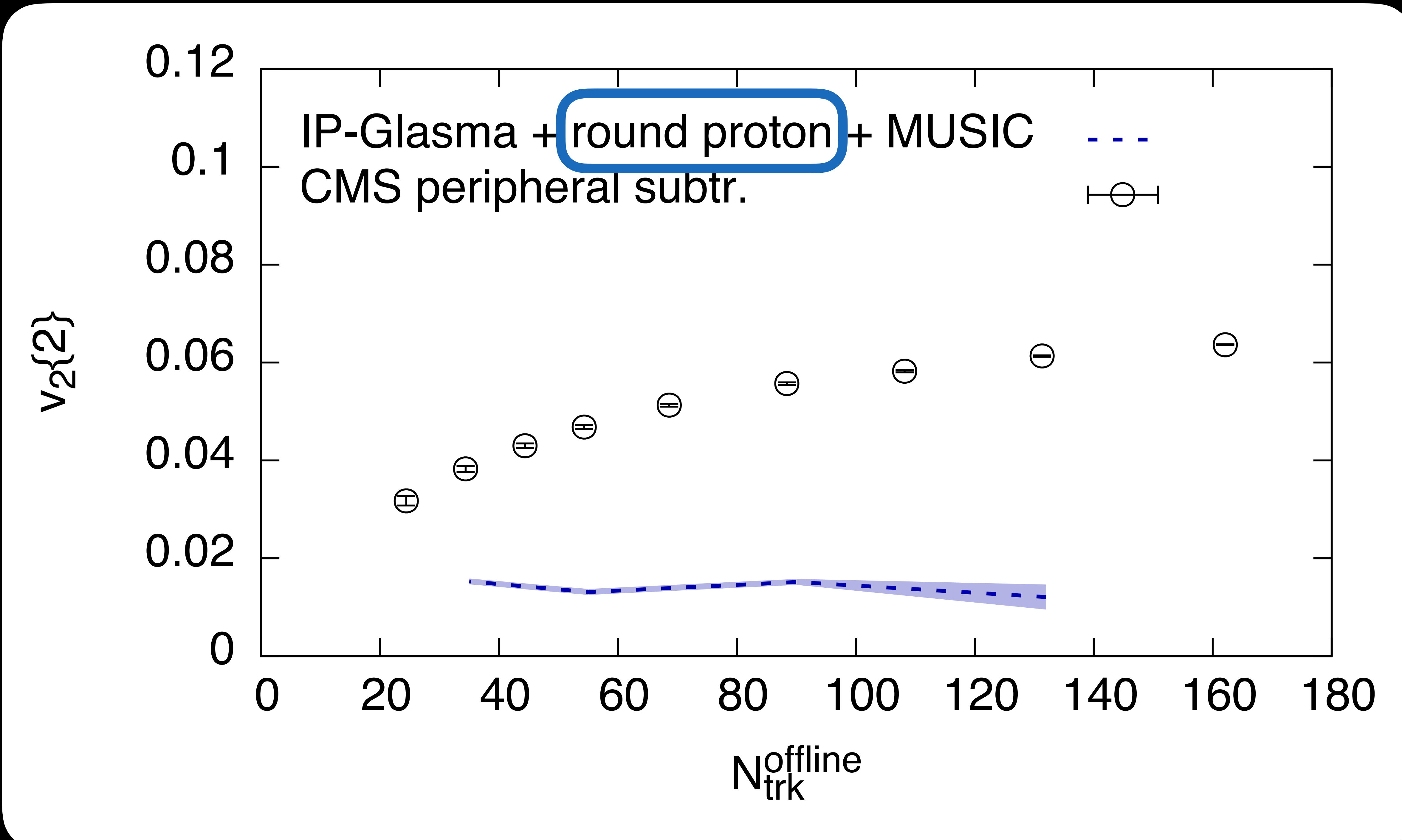


σ=0.5

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

Let's compare to p+Pb data again…

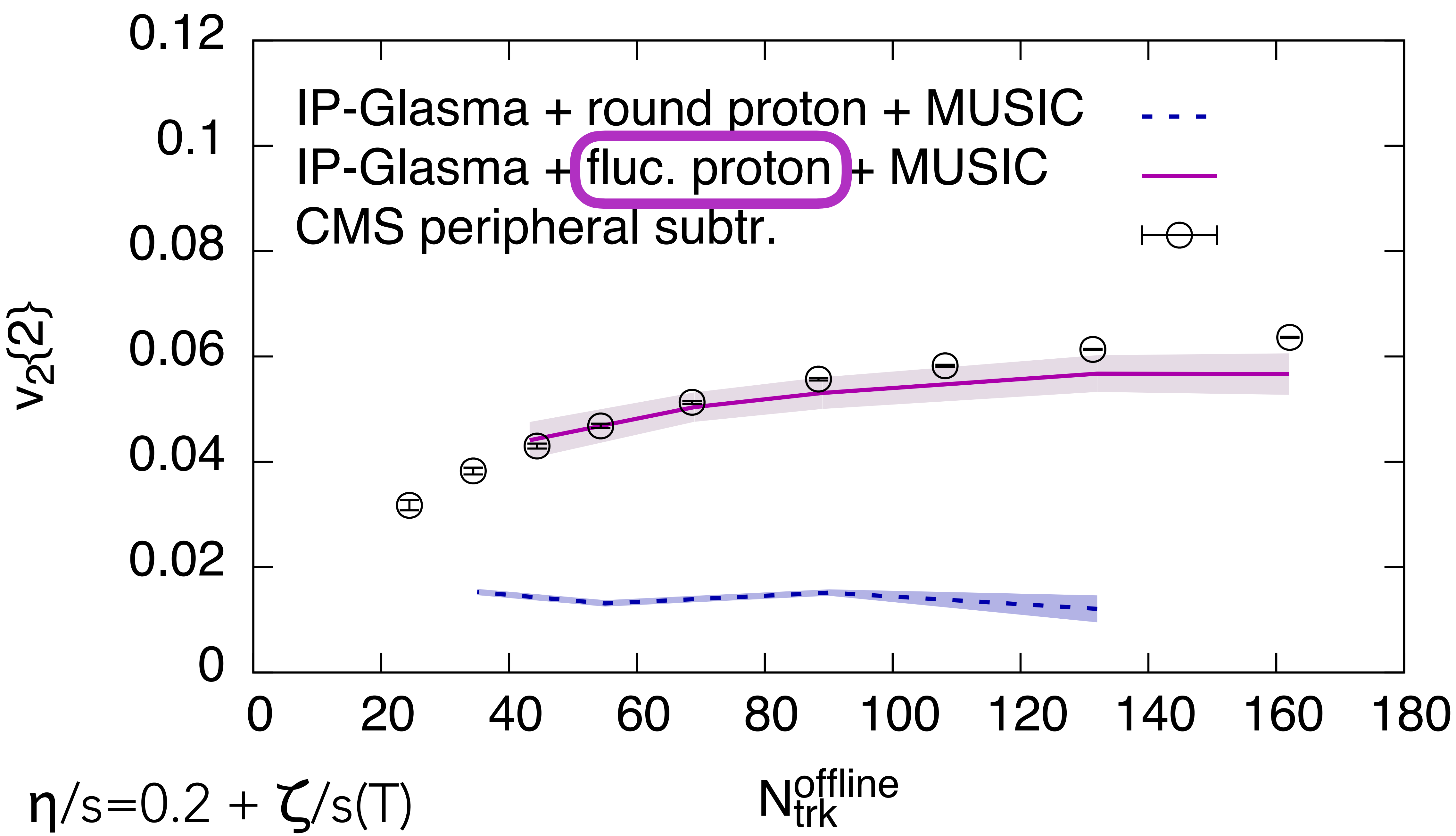
B. Schenke, R. Venugopalan, Phys. Rev. Lett. 113, 102301 (2014)



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

Effect of proton shape fluctuations

B. Schenke, R. Venugopalan, Phys. Rev. Lett. 113, 102301 (2014)
H. Mäntysaari, P. Tribedy, B. Schenke, C. Shen, in preparation (2017)



η/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:

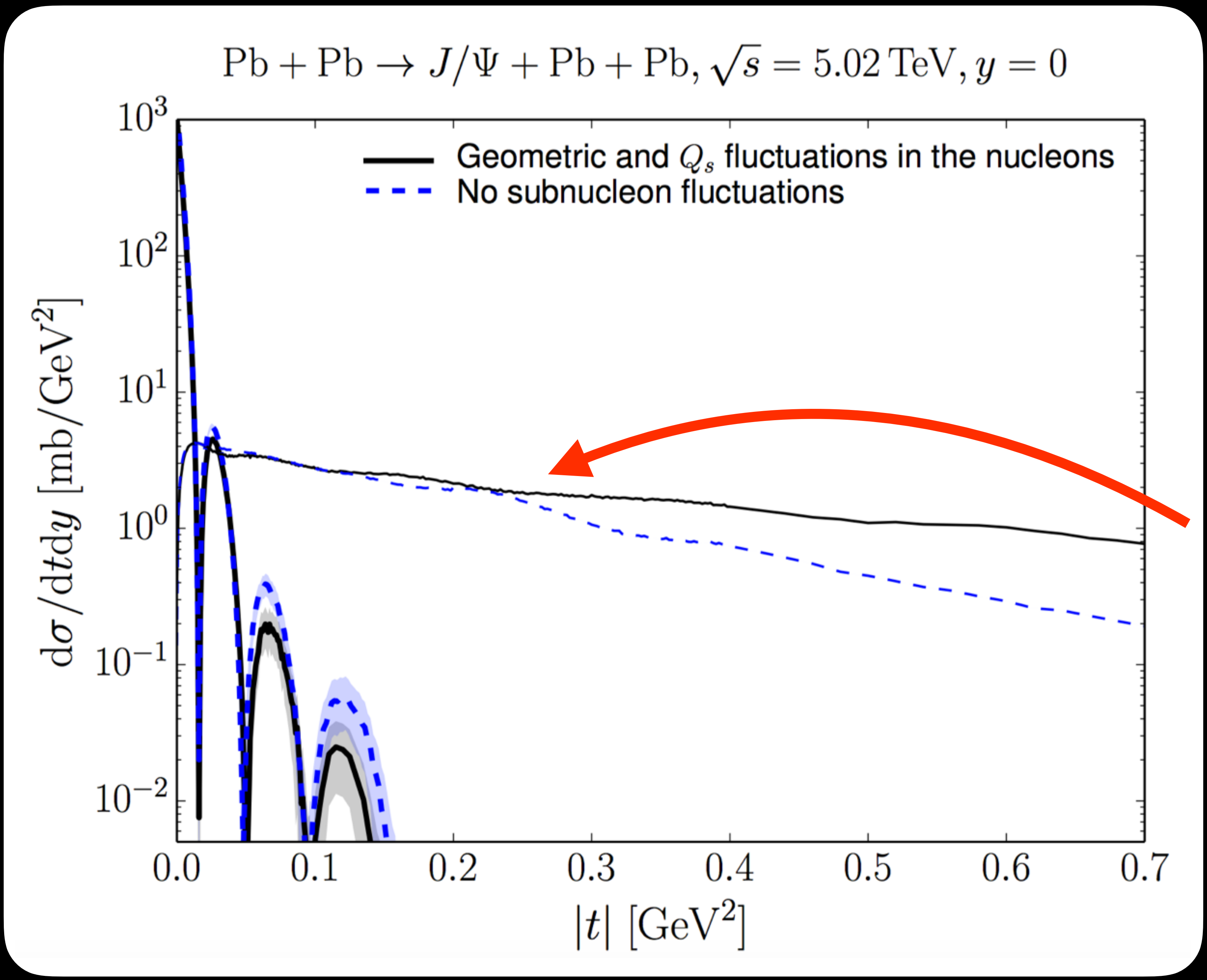
Sample nucleon positions from Woods-Saxon

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

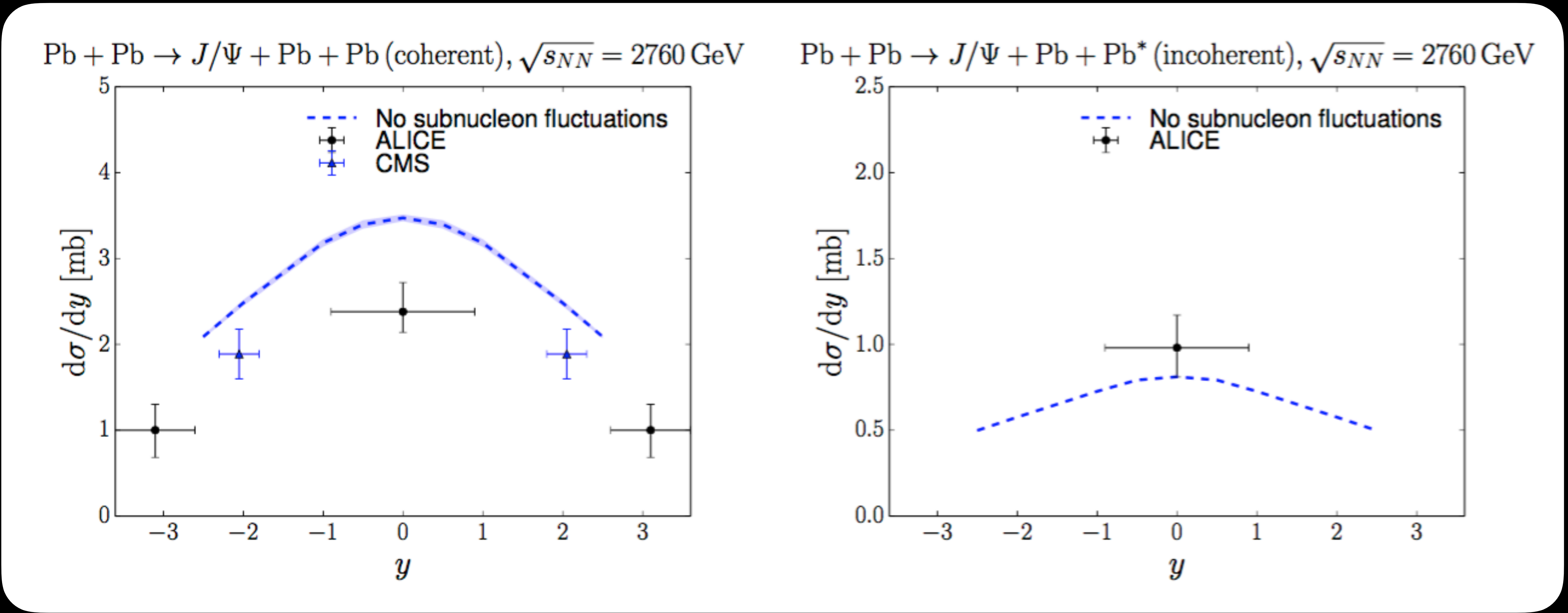


- Small |t|: fluctuations of nucleon positions
- Large |t|: fluctuations at subnucleon scale
- Incoherent slope changes at $|t| \approx 0.25$ GeV^2 → 0.4 fm which is size of hot spots

Coherent: thick lines
Incoherent: thin lines

LHC data - no subnucleonic fluctuations

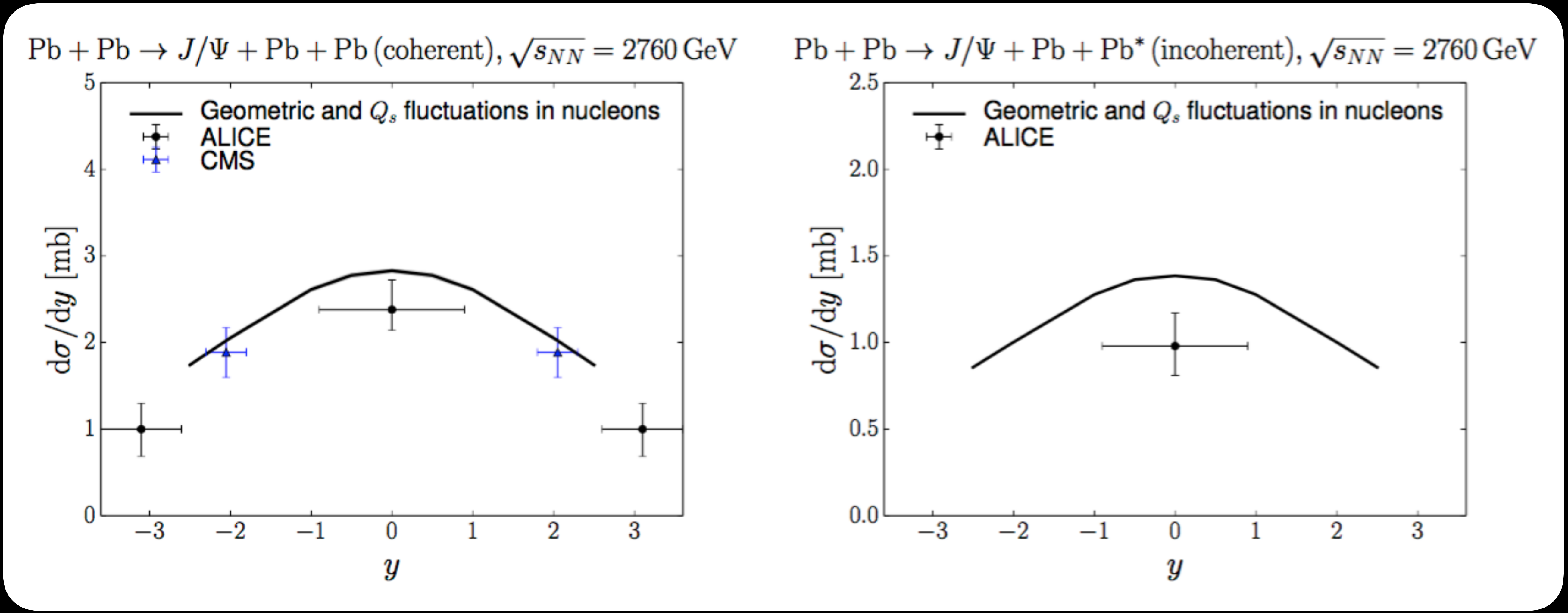
H. Mäntysaari, B. Schenke, arXiv:1703.09256



- 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

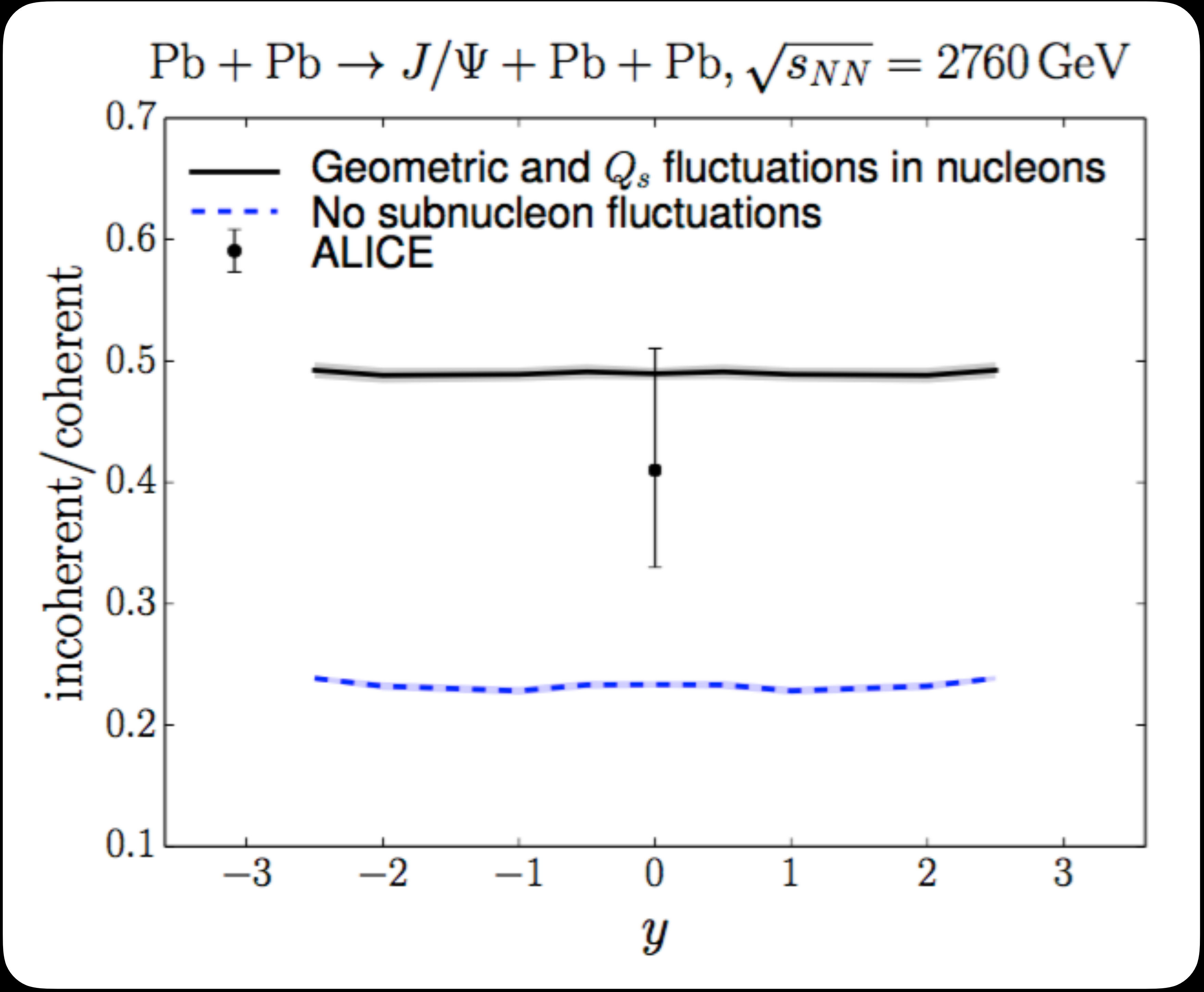
H. Mäntysaari, B. Schenke, arXiv:1703.09256



- 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



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

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

ξ is Gaussian noise with zero average and

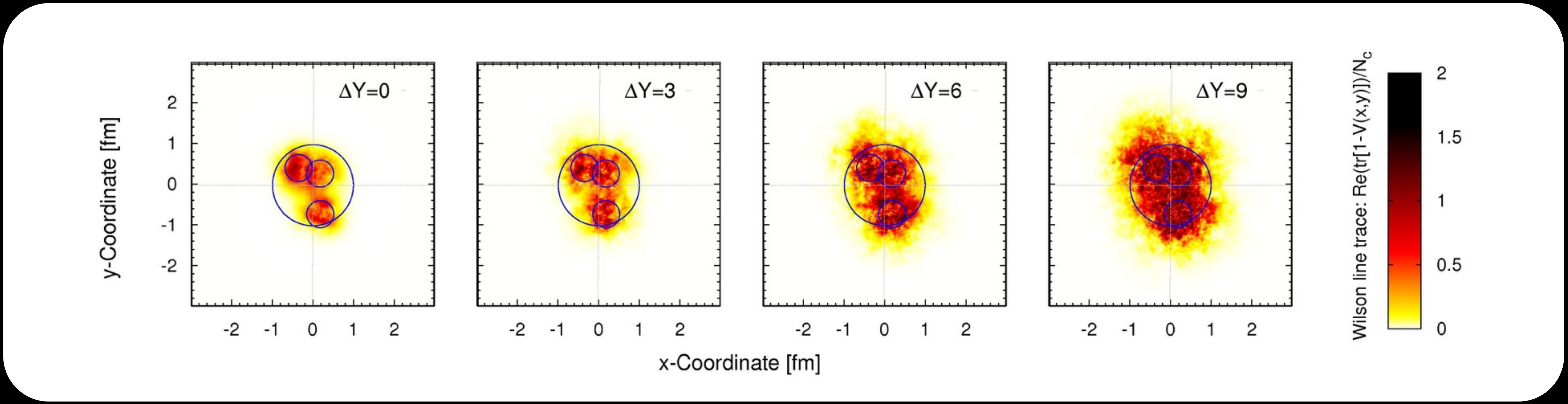
$$\left\langle \xi^{a}_{\mathbf{x},i}(Y)\xi^{b}_{\mathbf{y},j}(Y')\right\rangle = \delta^{ab}\delta^{ij}\delta^{(2)}_{\mathbf{xy}}\delta(Y-Y')$$

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)

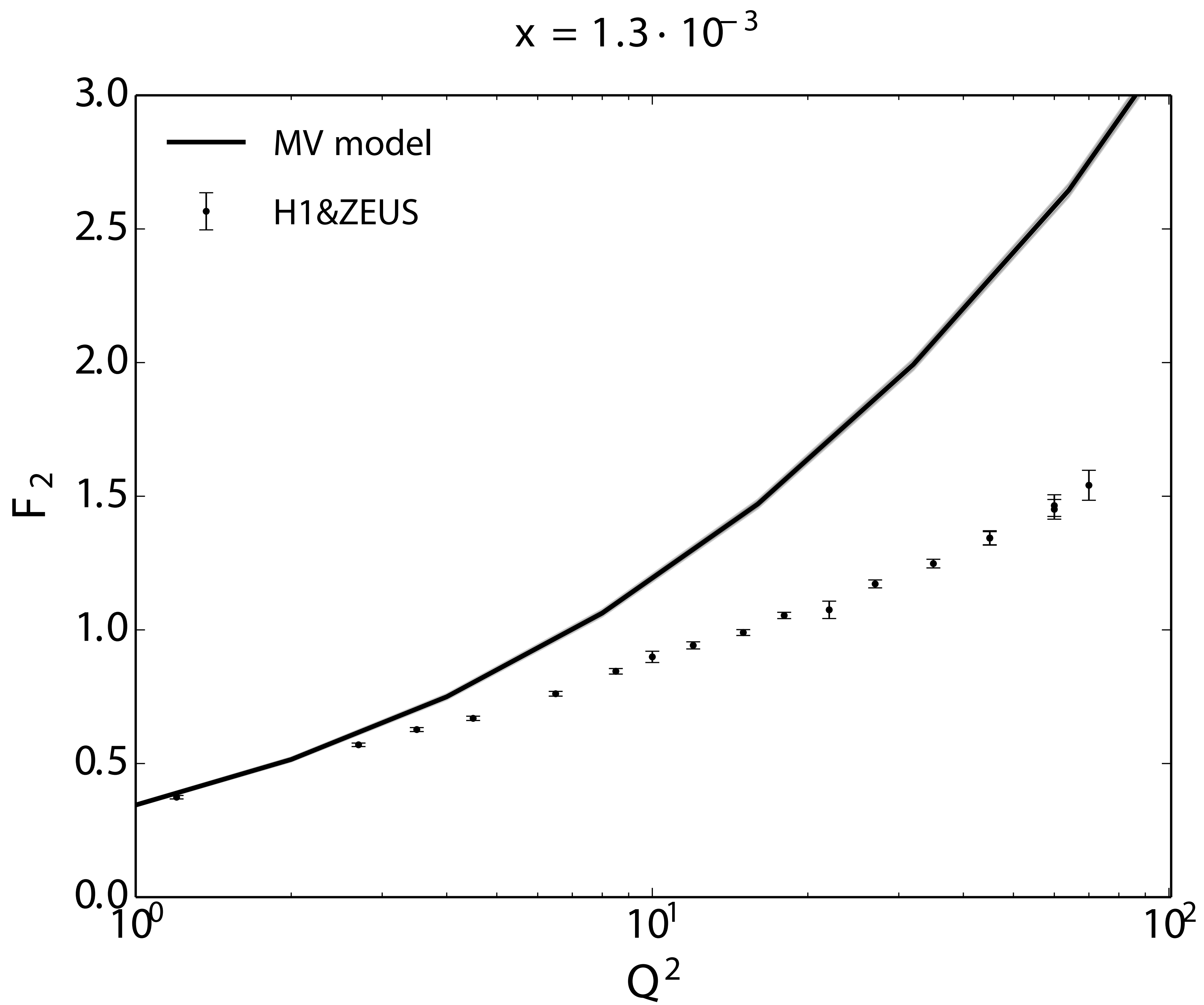
Proton grows with increasing x

Growth is linear with Y when infrared regulator is used

Froissart bound not violated

Q^2 dependence of F_2

H. Mäntysaari, B. Schenke, in preparation



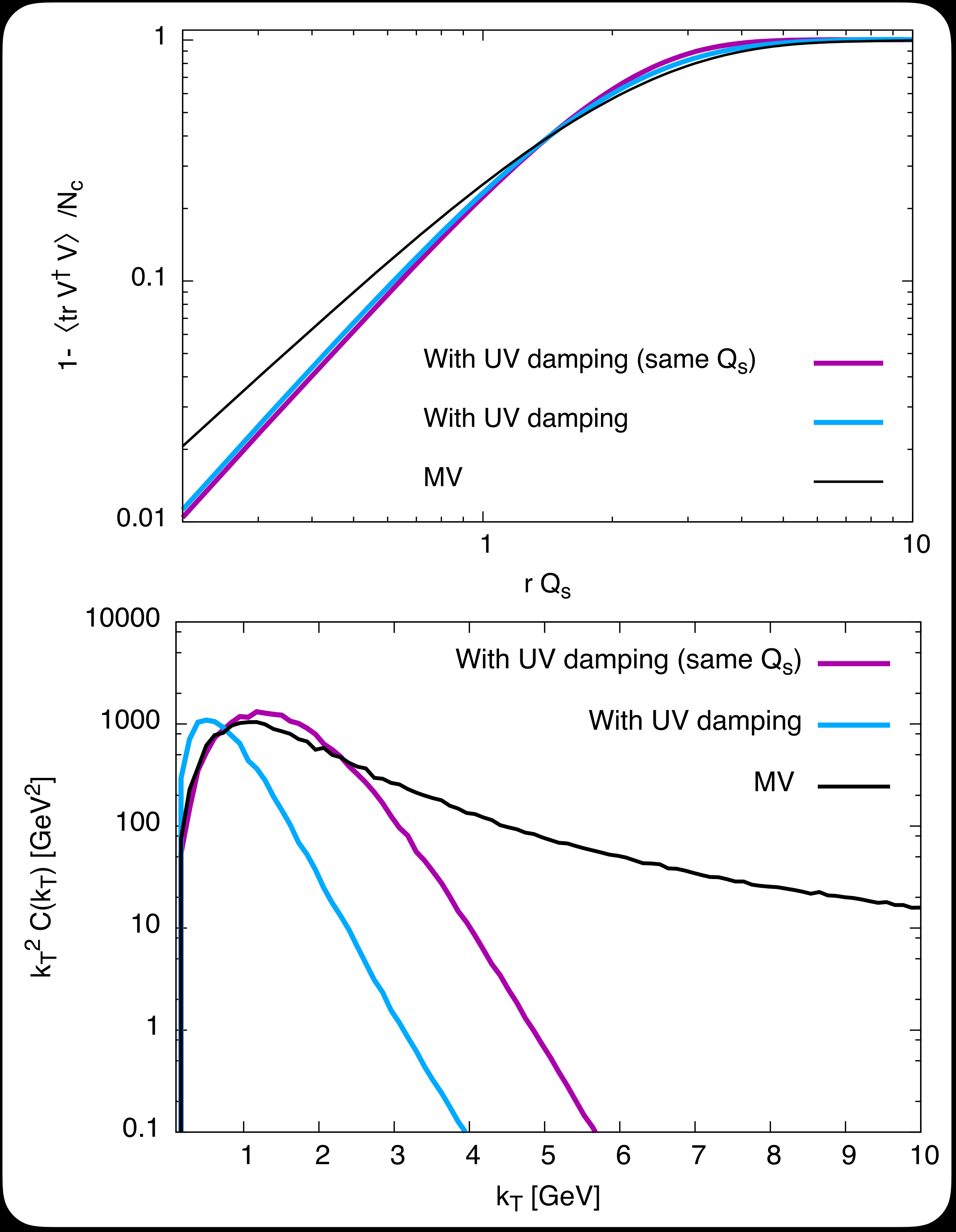
Modifying MV - changing the large k_T tails

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)

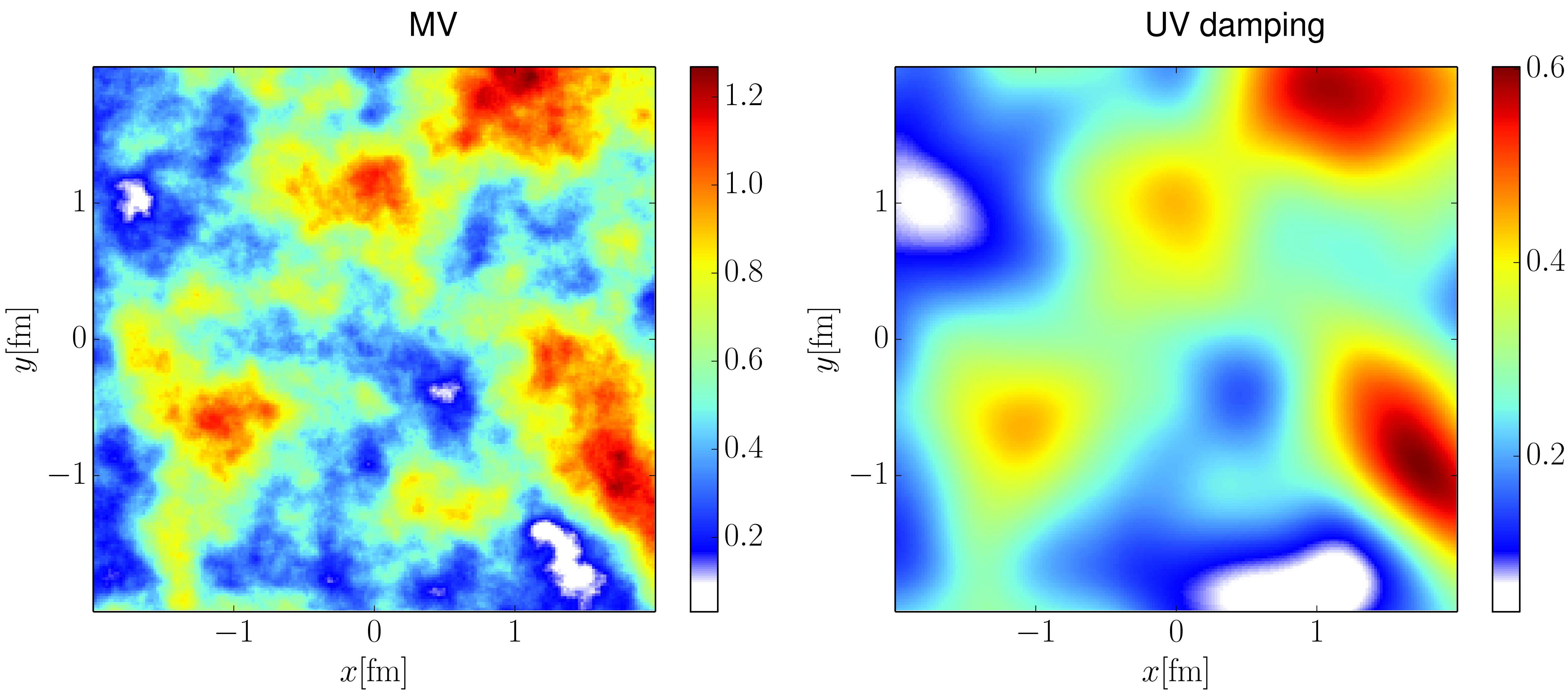
Has similar effect as anomalous dimension in AAMQS

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

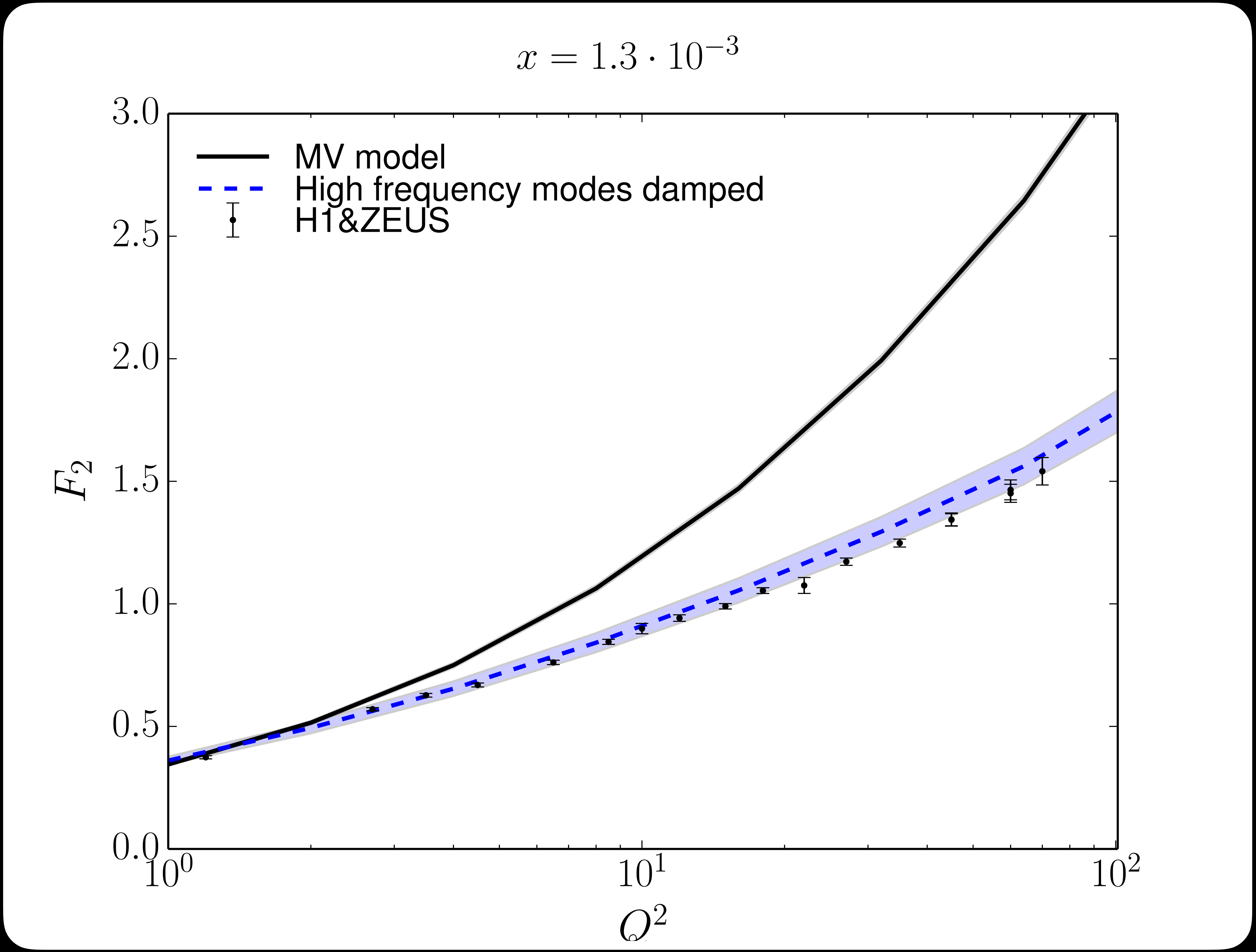
H. Mäntysaari, B. Schenke, in preparation



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

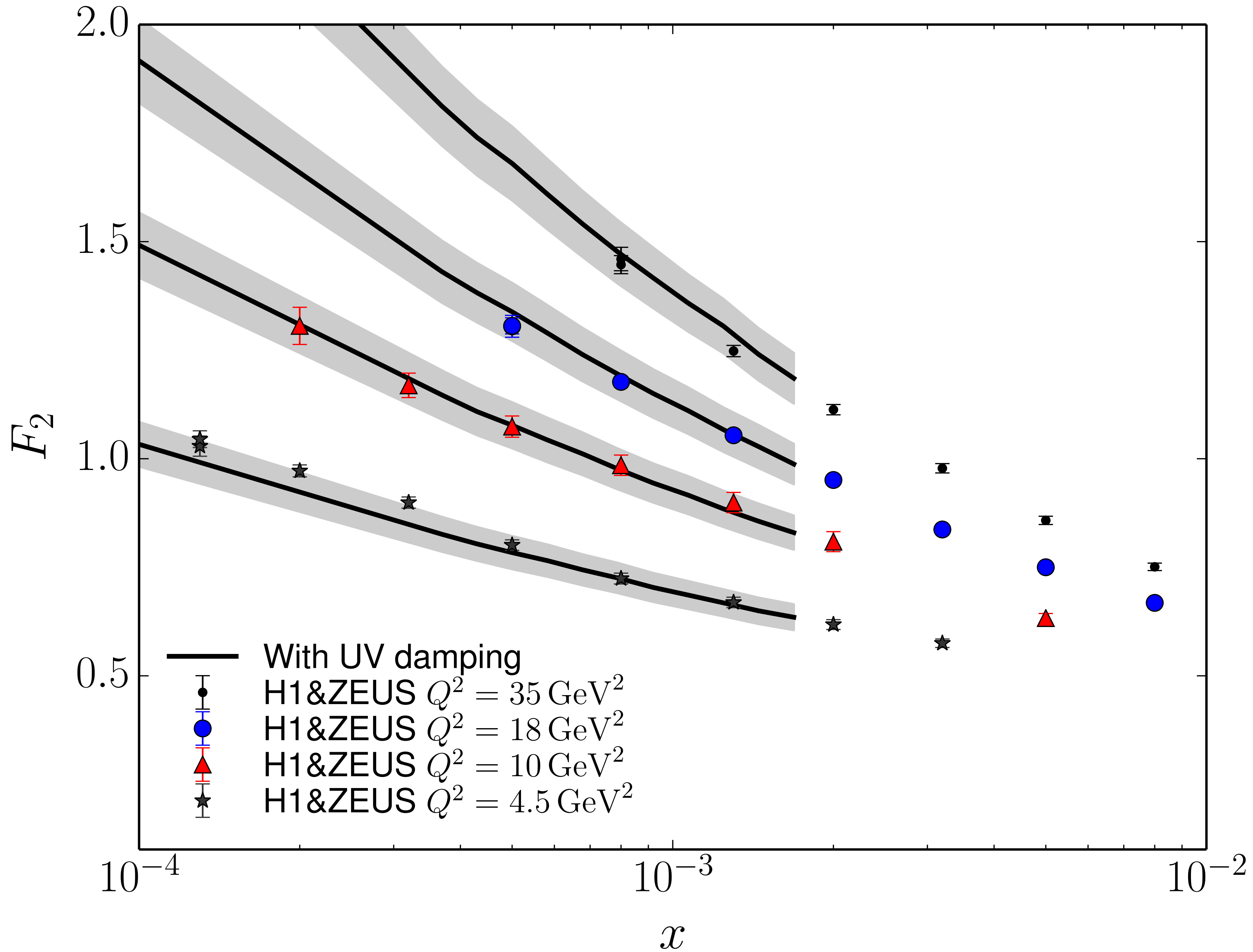
Q^2 dependence of F_2

H. Mäntysaari, B. Schenke, in preparation



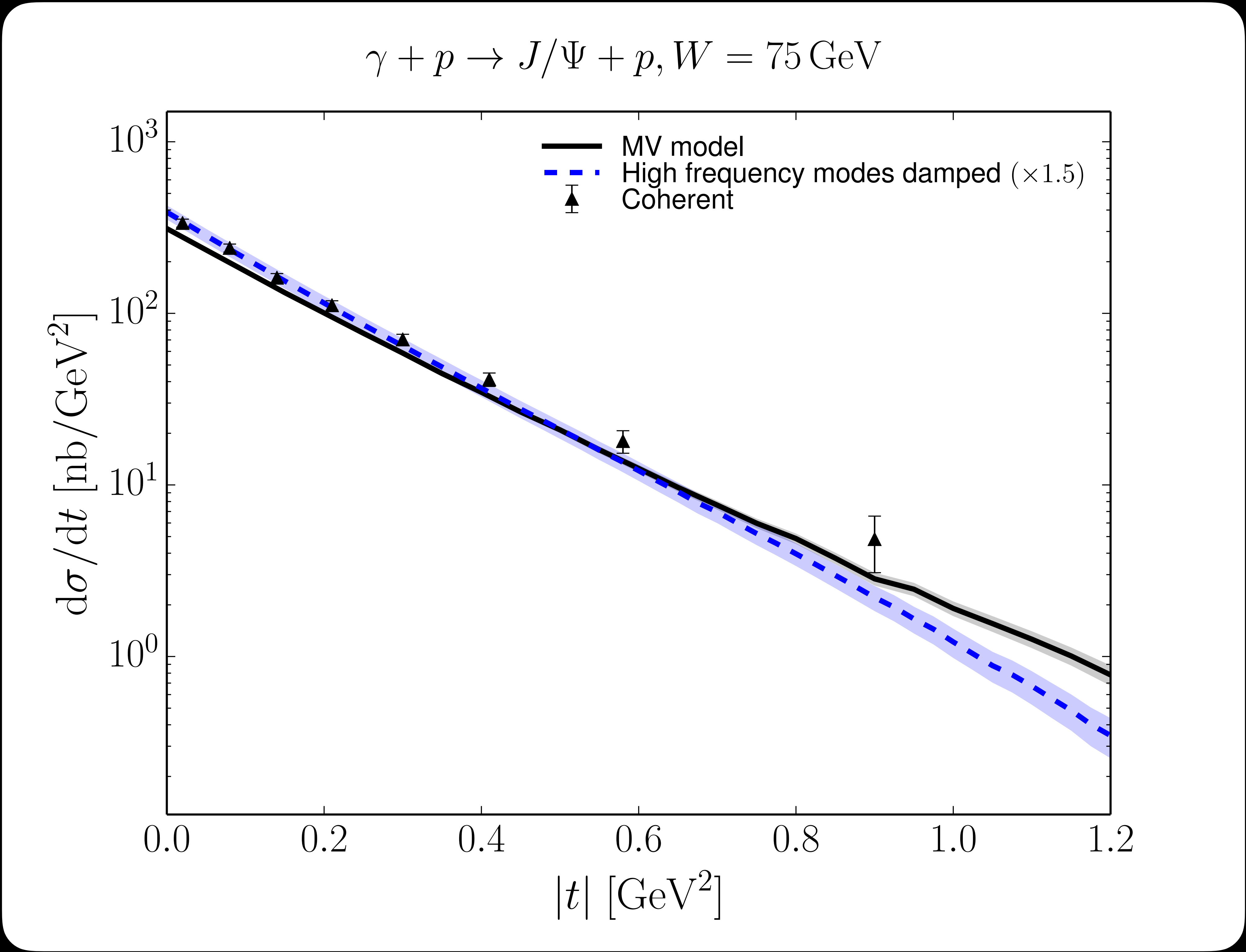
x dependence of F_2 from JIMWLK

H. Mäntysaari, B. Schenke, in preparation



Proton size constrained by diffractive data

H. Mäntysaari, B. Schenke, in preparation



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:

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

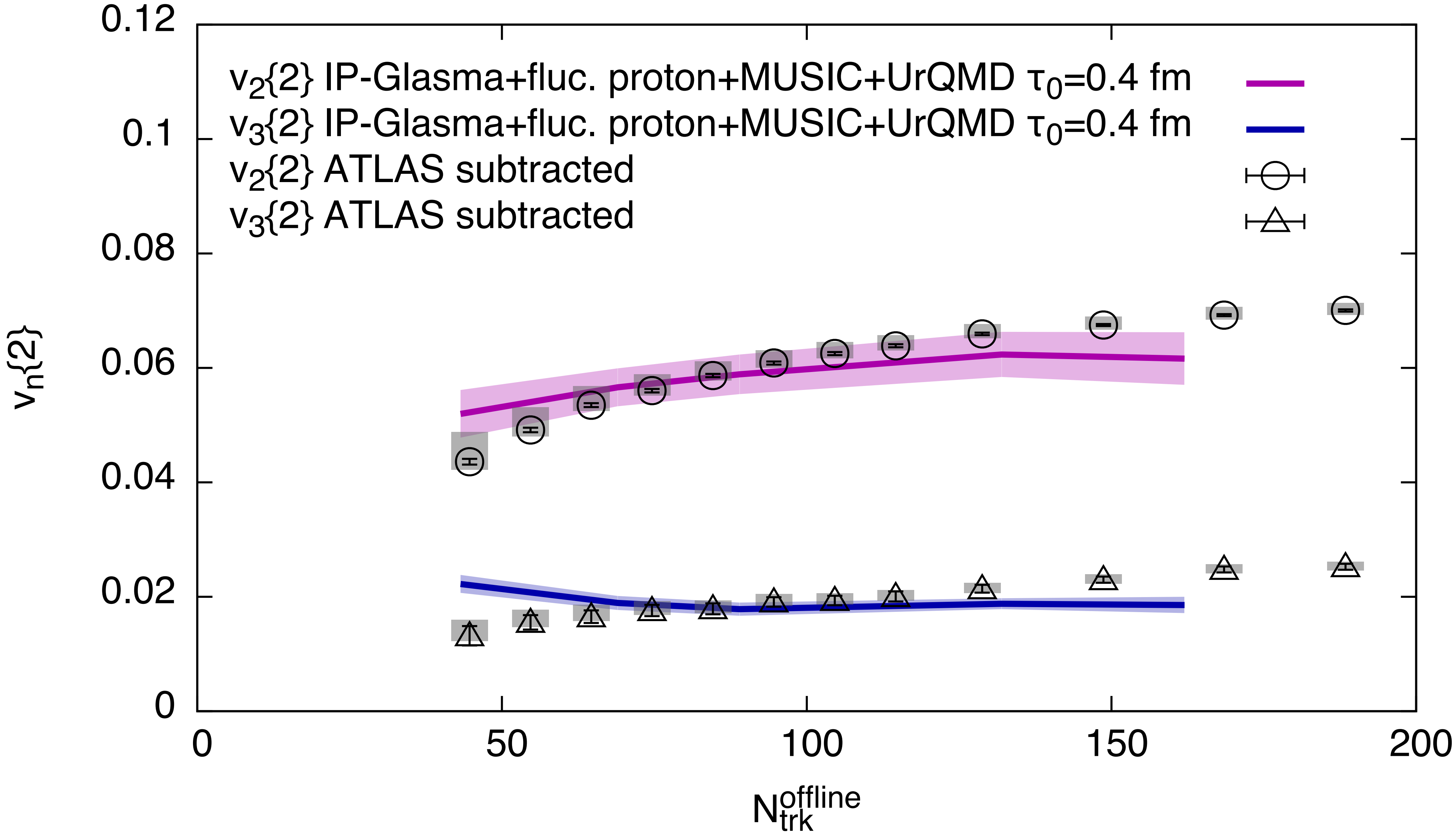
Average over absorption coefficients, weighted according to their probability of occurrence in the particle B

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

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

Elliptic and triangular flow

H. Mäntysaari, P. Tribedy, B. Schenke, C. Shen, in preparation (2017)

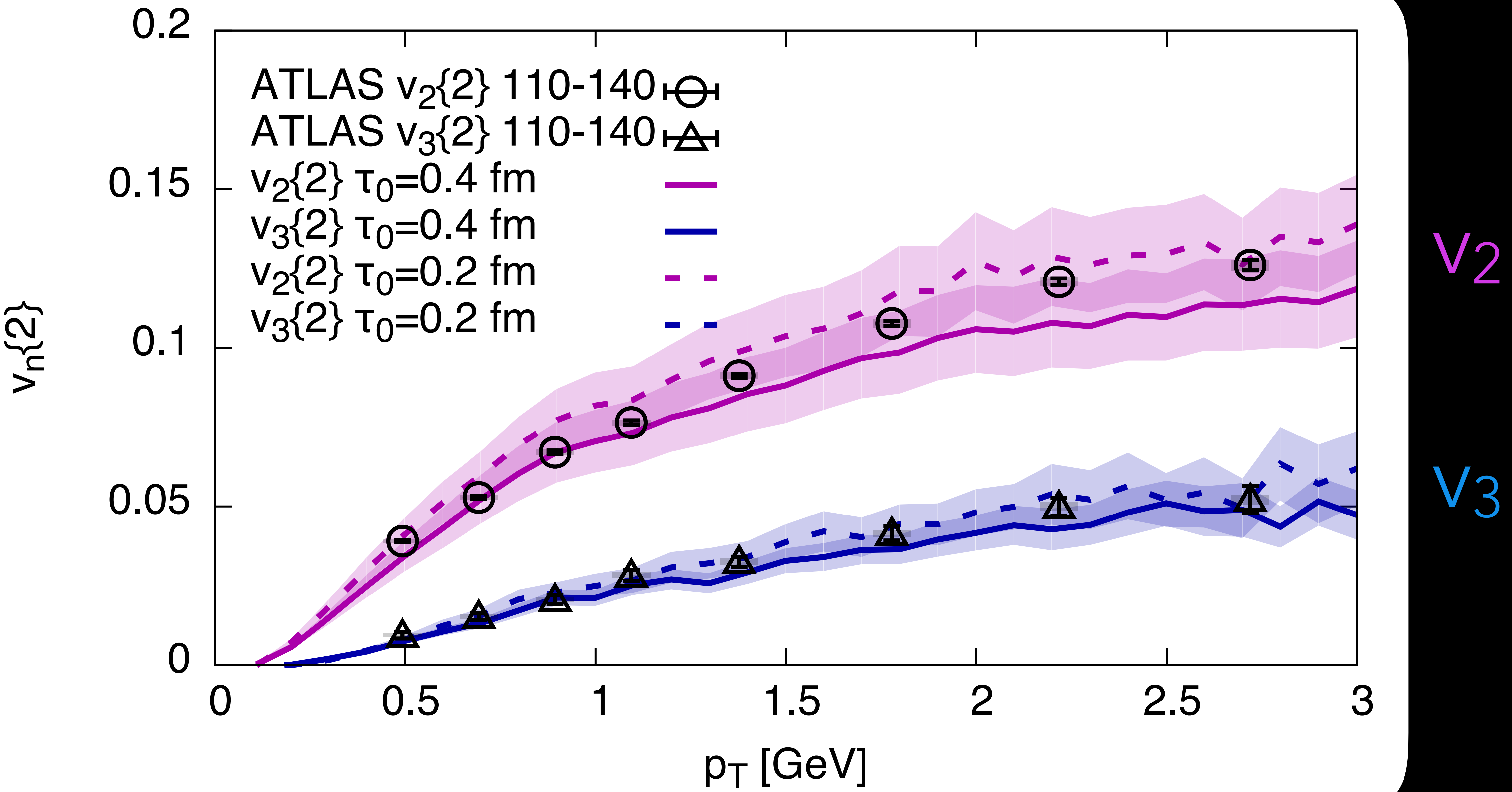


ATLAS Collaboration, Phys.Rev. C90 (2014) 044906

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

Transverse momentum dependence

H. Mäntysaari, P. Tribedy, B. Schenke, C. Shen, in preparation (2017)



ATLAS Collaboration, Phys.Rev. C90 (2014) 044906

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

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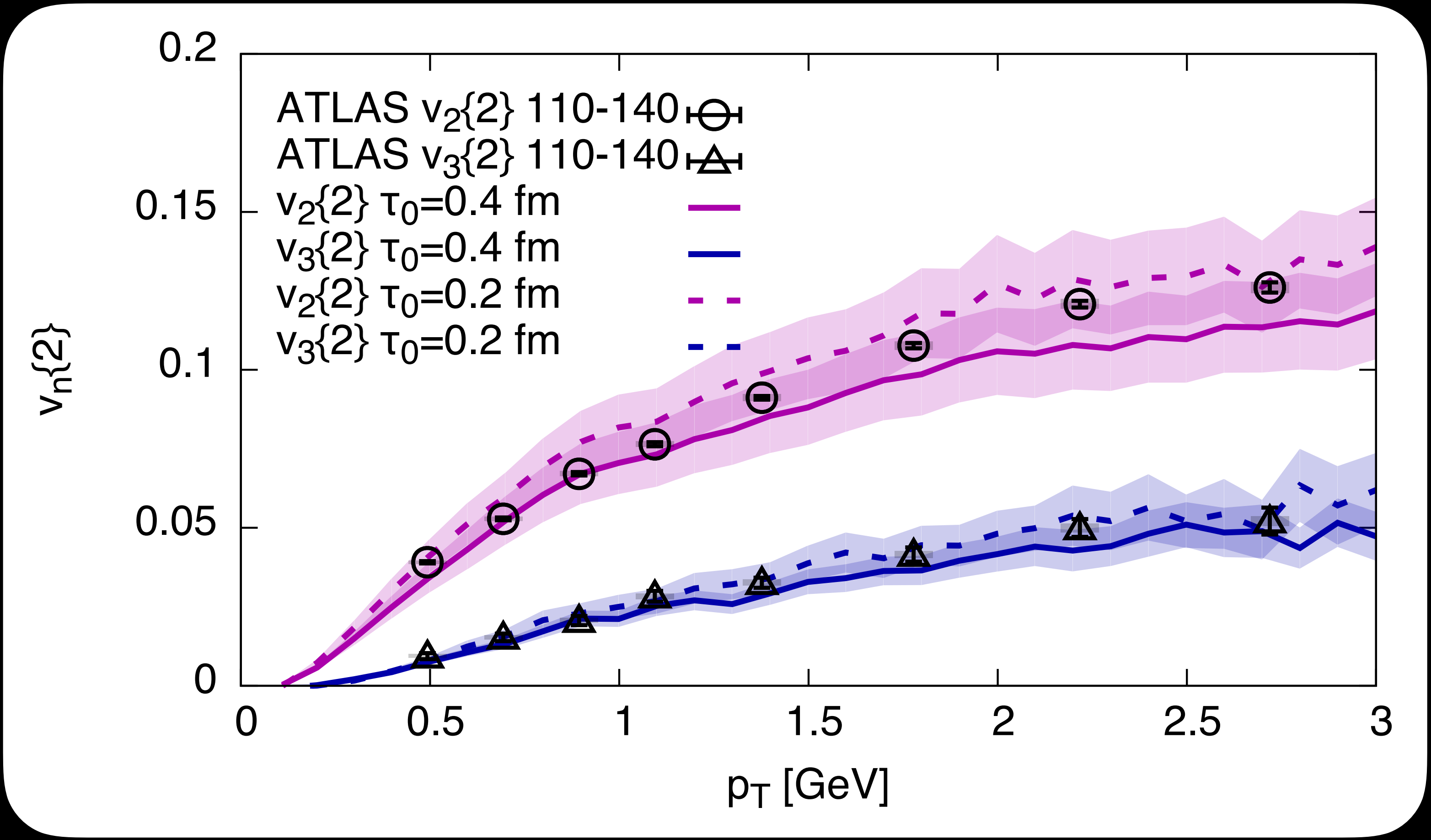


v_2

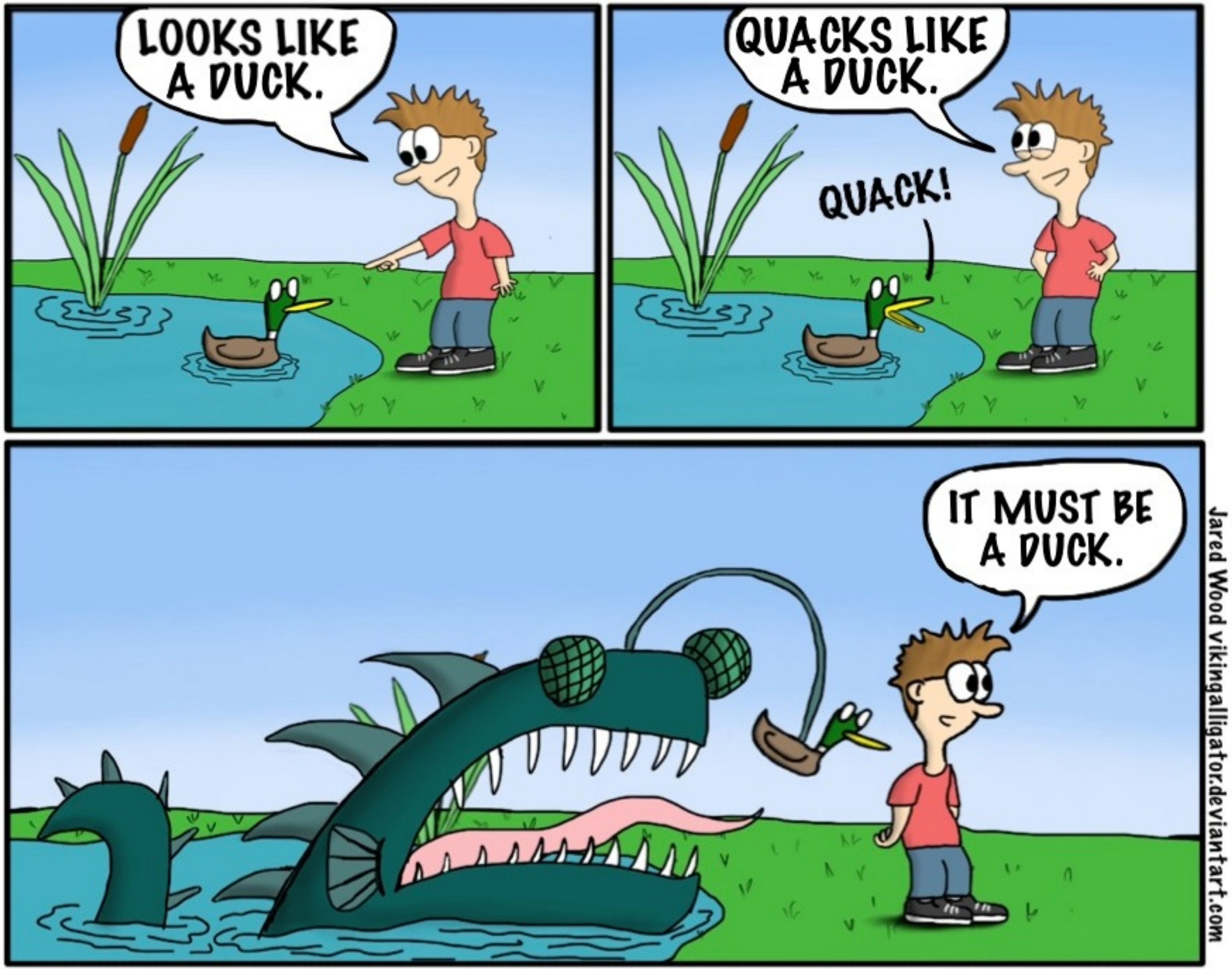
v_3

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

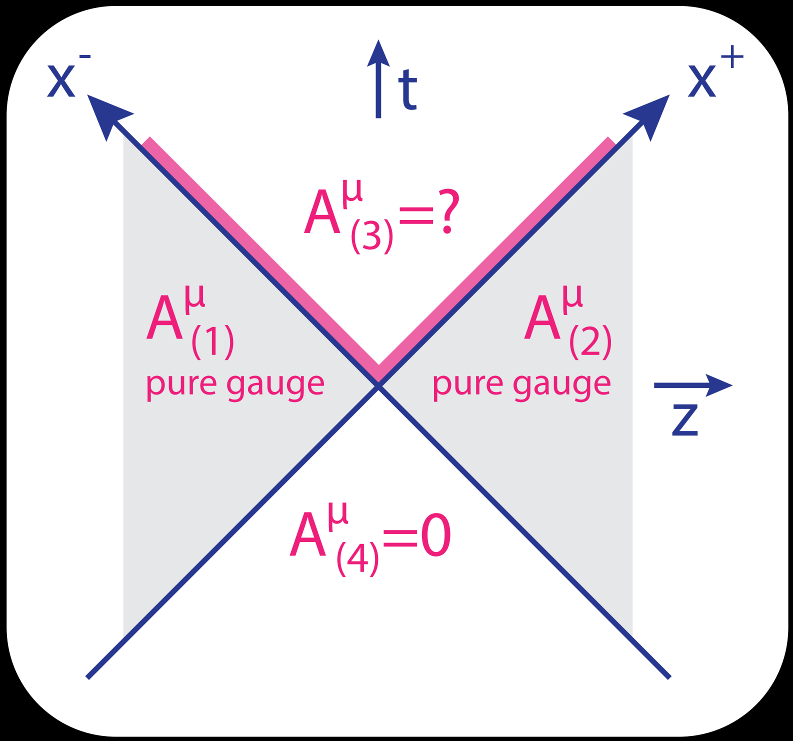
ATLAS Collaboration, Phys.Rev. C90 (2014) 044906

Fair warning: Strong dependence on whether initial shear stress tensor is included and the relaxation time. Viscous corrections can be very large

OTHER EXPLANATIONS



Backing up to the calculation of initial gluon fields



$$A^i_{(3)}|_{\tau=0^+} = A^i_{(1)} + A^i_{(2)}$$
$$A^\eta_{(3)}|_{\tau=0^+} = \frac{ig}{2}[A^i_{(1)}, A^i_{(2)}]$$

Now compute gluon momentum distributions from the fields in Coulomb gauge

Next we analyze the momentum distribution of the produced gluons

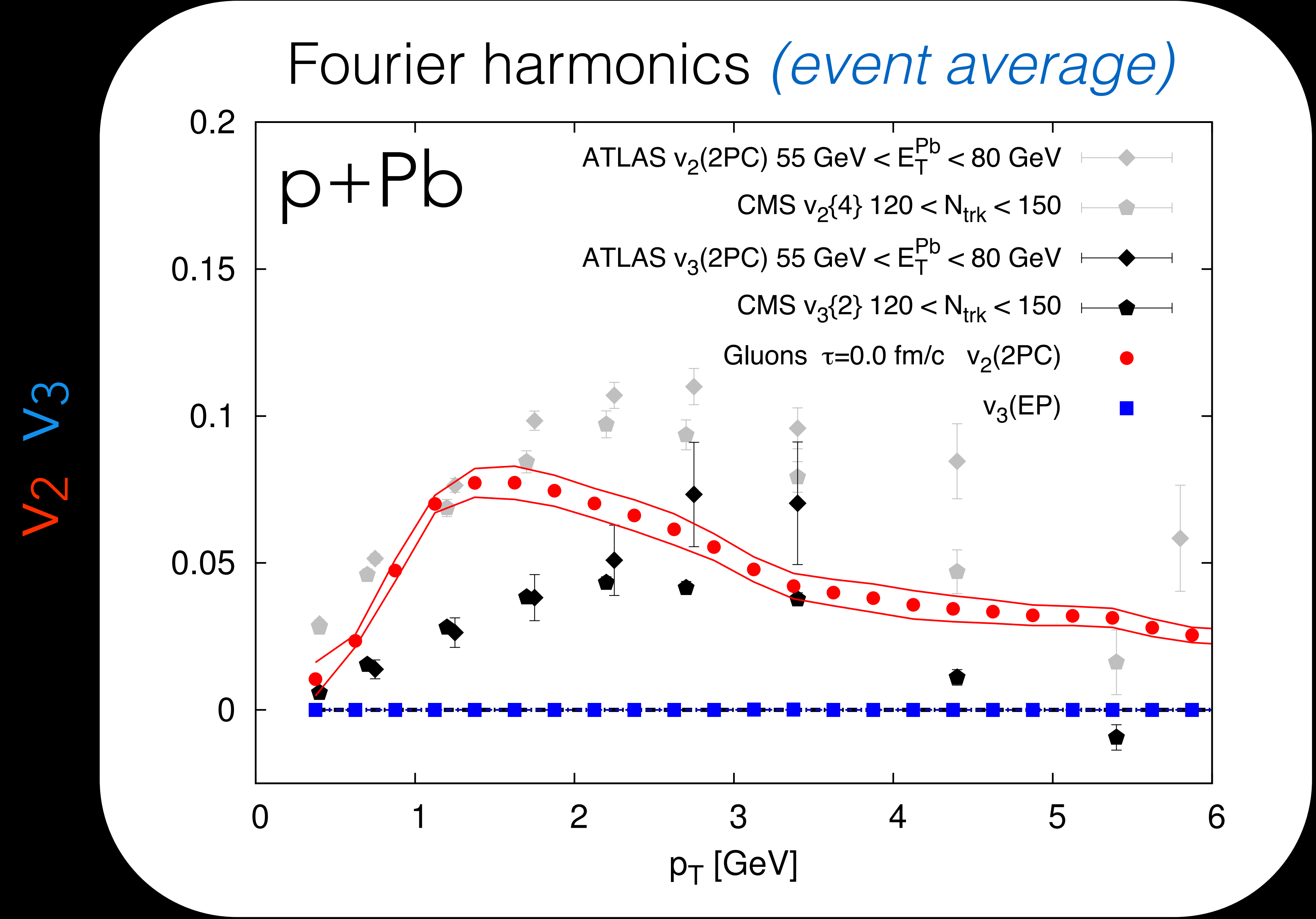
There is NO hydrodynamics in what follows, just Yang-Mills

Correlations from the initial state

Schenke, Schlichting, Venugopalan, Phys. Lett. B747, 76-82 (2015)

τ=0.0 fm/c

gluons



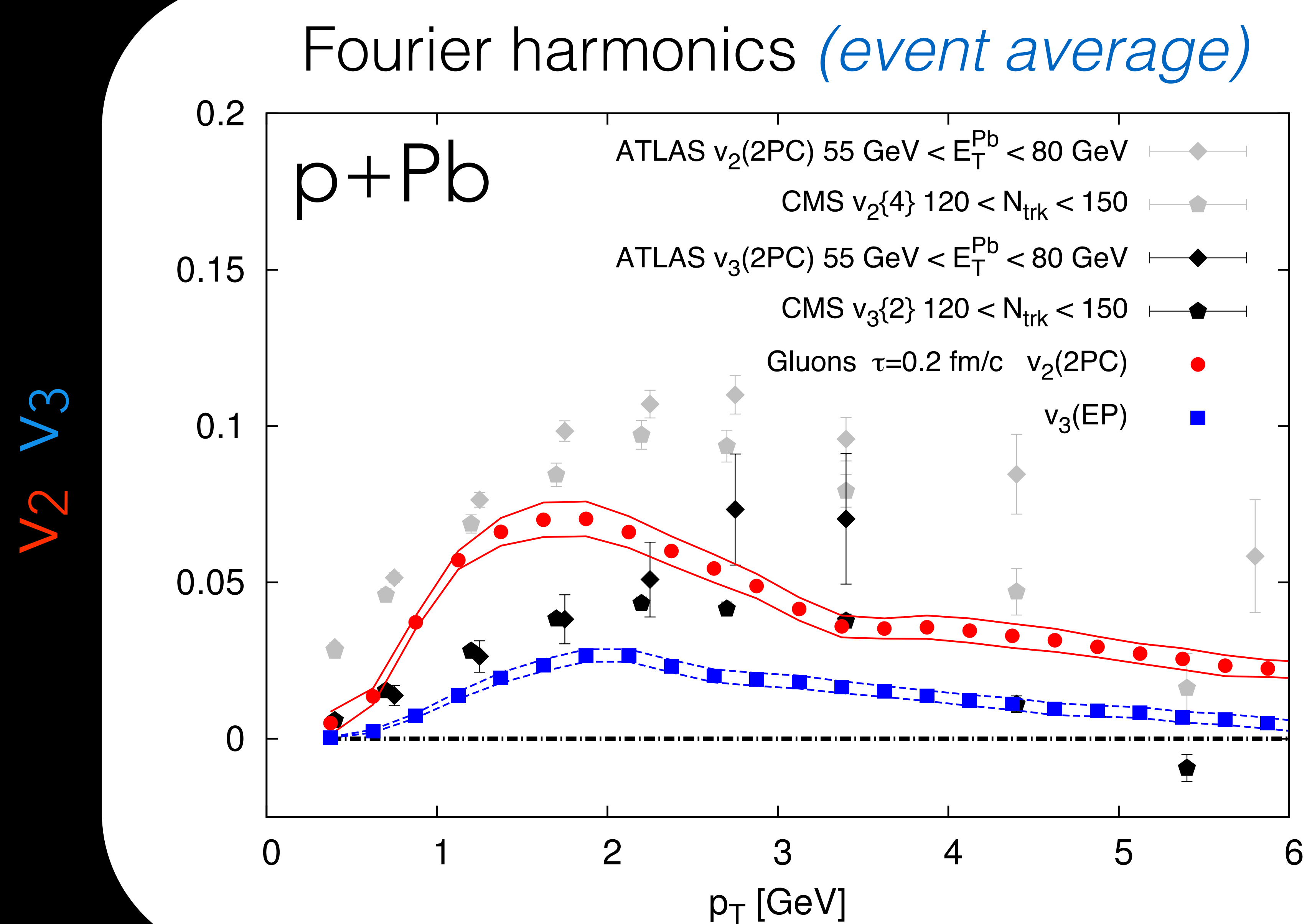
Significant v_2 at time 0

No odd harmonics for gluons without final state interactions

Correlations from the initial state

Schenke, Schlichting, Venugopalan, Phys. Lett. B747, 76-82 (2015)

τ=0.2 fm/c
gluons

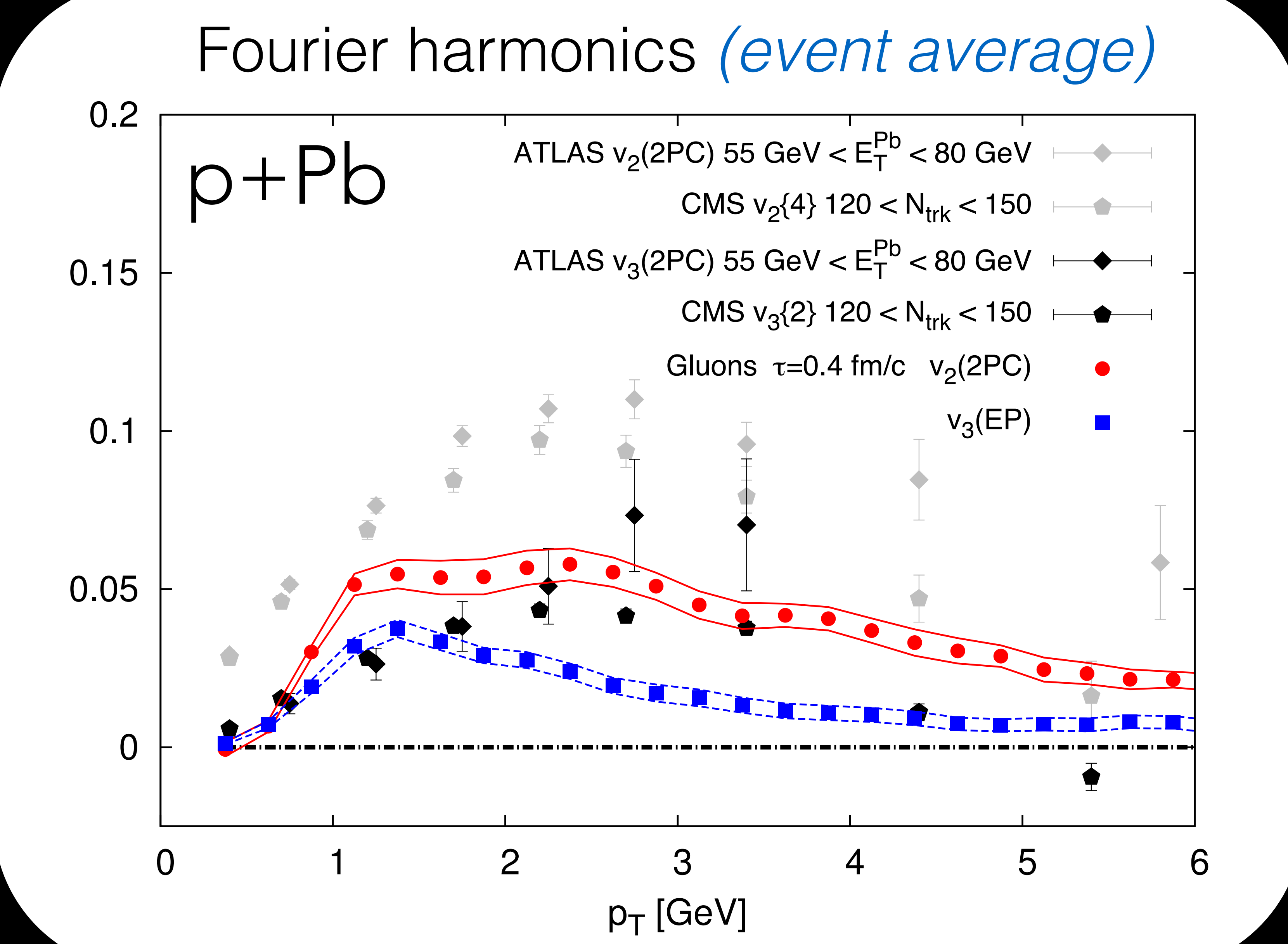


Correlations from the initial state

Schenke, Schlichting, Venugopalan, Phys. Lett. B747, 76-82 (2015)

$\tau = 0.4$ fm/c
gluons

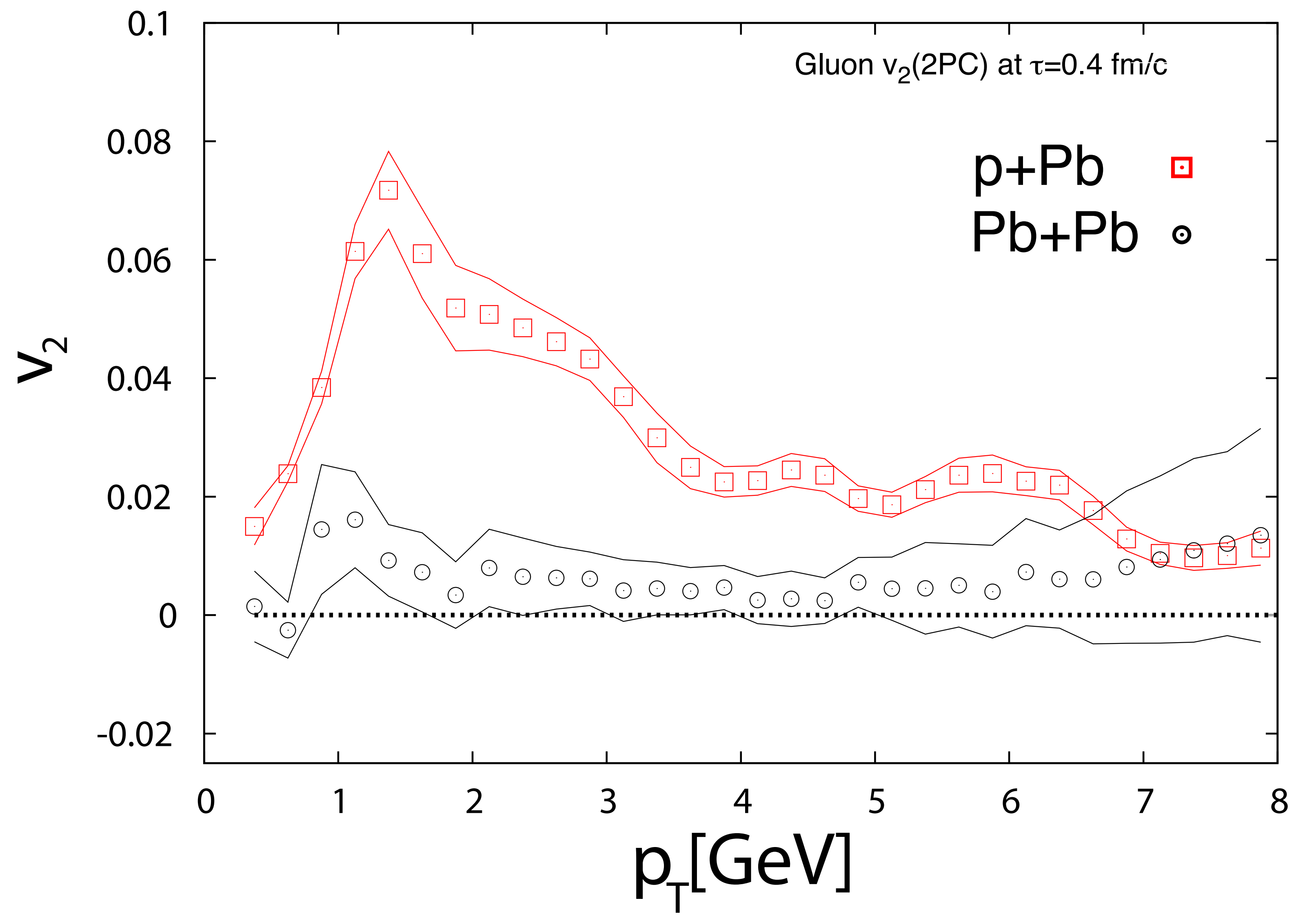
v_2 v_3

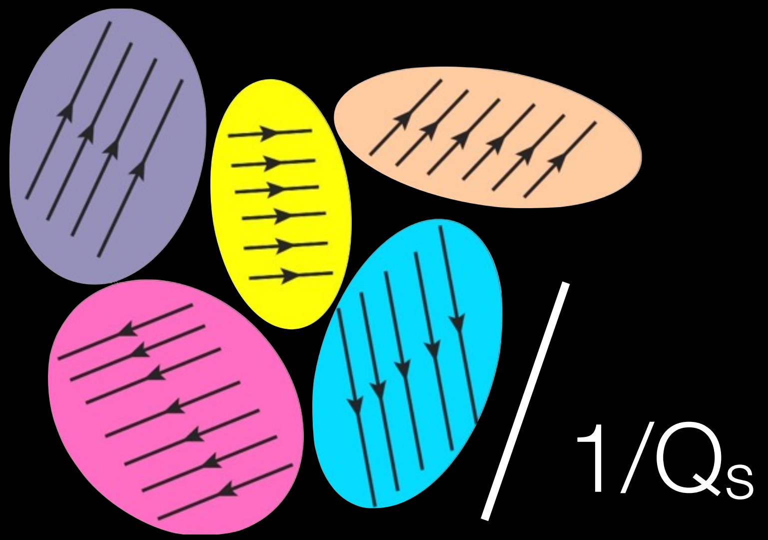


Odd harmonics generated by pre-equilibrium dynamics

Interpretation and system size dependence

Schenke, Schlichting, Venugopalan, Phys. Lett. B747, 76-82 (2015)





Pb+Pb not described in initial state picture. Reason:

Gluons produced from many uncorrelated color field domains

Collective flow in the final state is needed

Many calculations, different approximations

- **Glasma graph approximation:** only two gluon exchange and Gaussian statistics of color charge fluctuations
- **Non-linear Gaussian approximation:** Multi-gluon exchanges and Gaussian statistics
- **Numerical solution:** Solves Yang-Mills equations exactly as we did, includes multiple-gluon exchange, “rescattering”
- Some go beyond classical approximation by including **JIMWLK** evolution which will introduce some non-Gaussian correlations

They all find anisotropies without any hydrodynamics

Some are compared in

T. Lappi, B. Schenke, S. Schlichting, R. Venugopalan, JHEP 1601 (2016) 061

See the review article

K. Dusling, W. Li, B. Schenke, Int. J. Mod. Phys. E25, 1630002 (2016)

So what do we see?

1. Initial momentum correlations

or

2. A reflection of the initial geometry mediated by final state effects?

Observables to tell the difference

- Different collision systems
- Mass ordering
- Odd harmonics
- Beam energy dependence
- Jet quenching
- Electromagnetic probes
- Sign change of $c_2\{4\}$
- Multi particle (>2) cumulants

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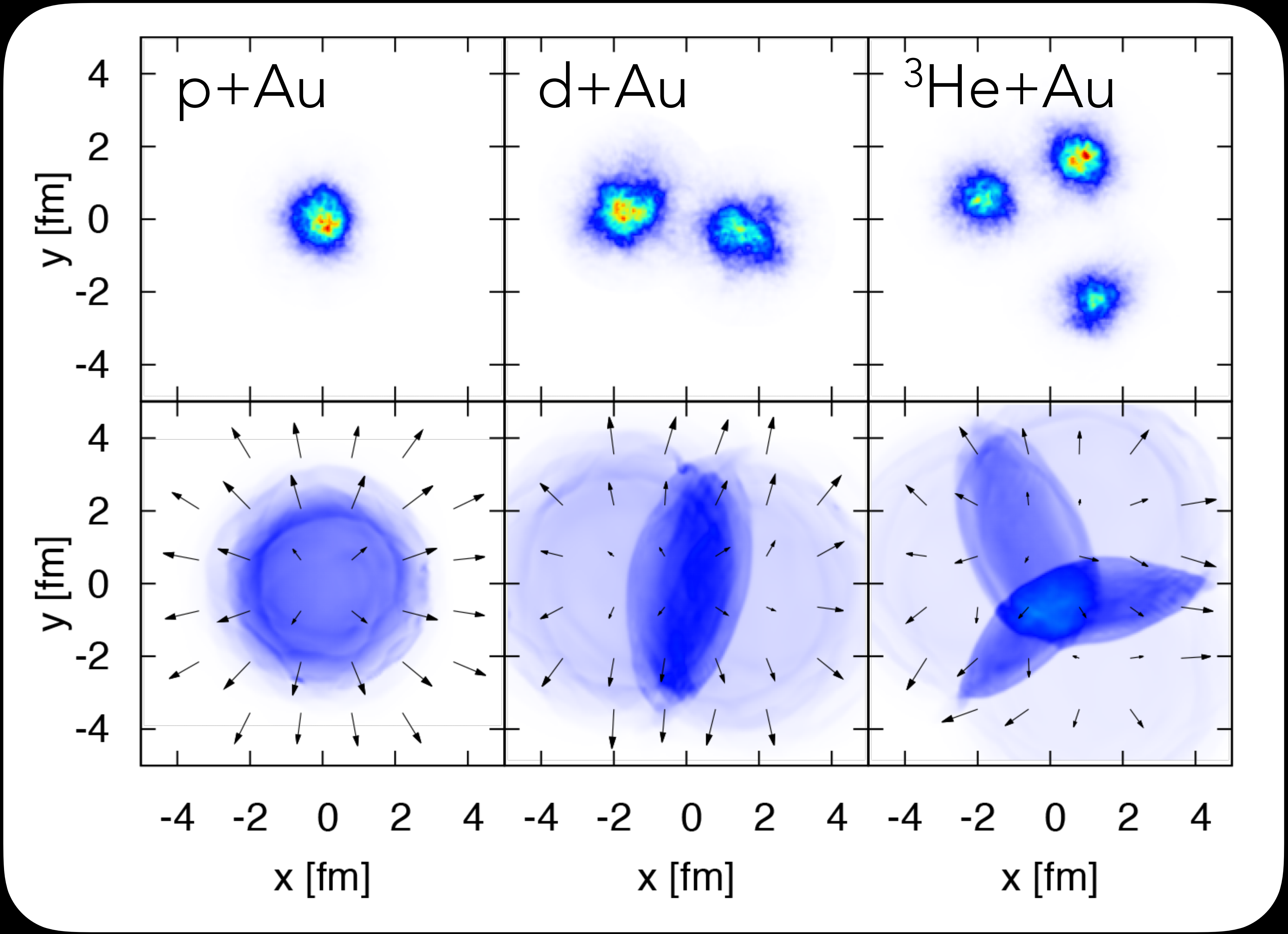
RHIC to the rescue: Different small systems

Different initial shapes lead to different flow harmonics



Different small systems

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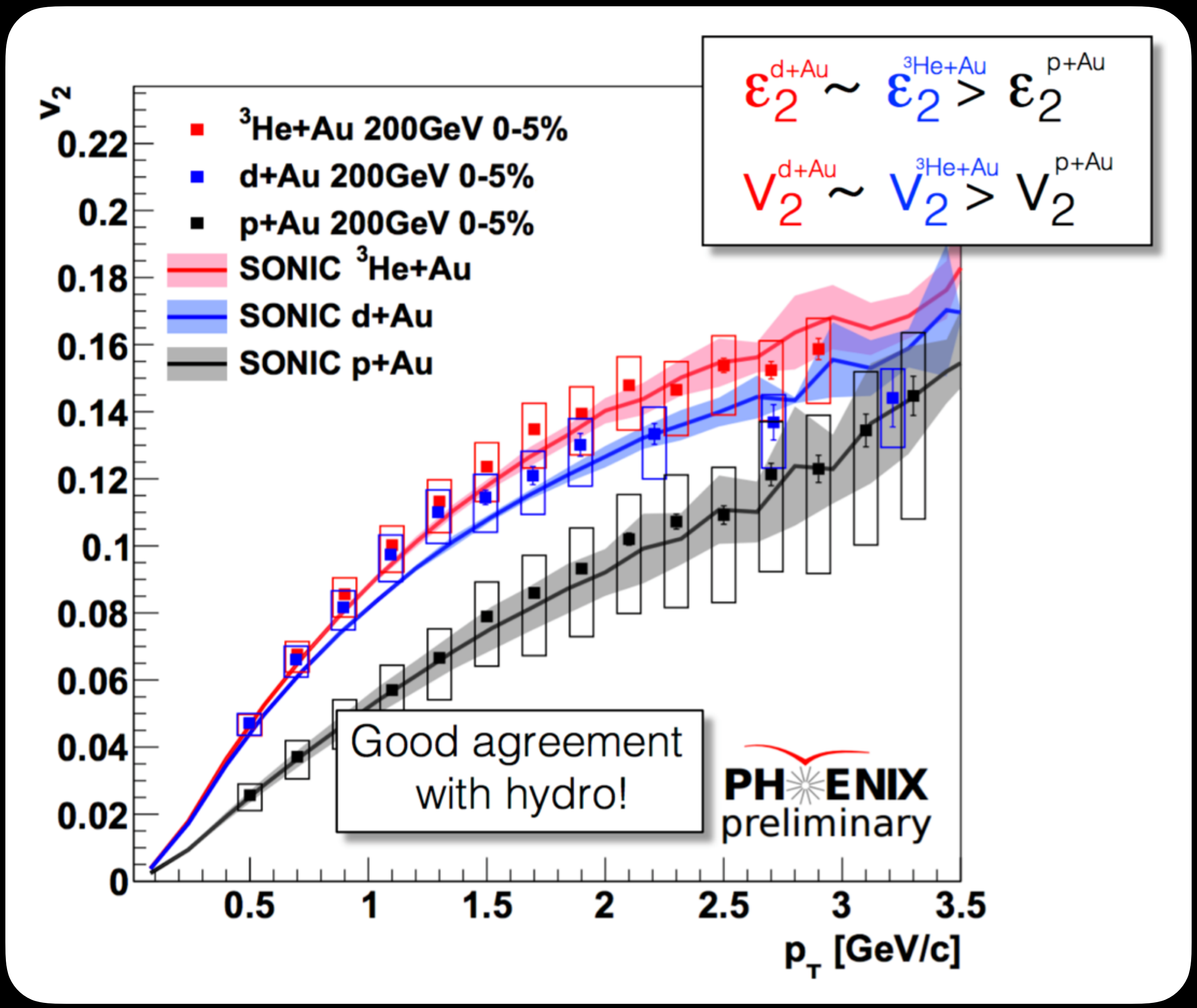
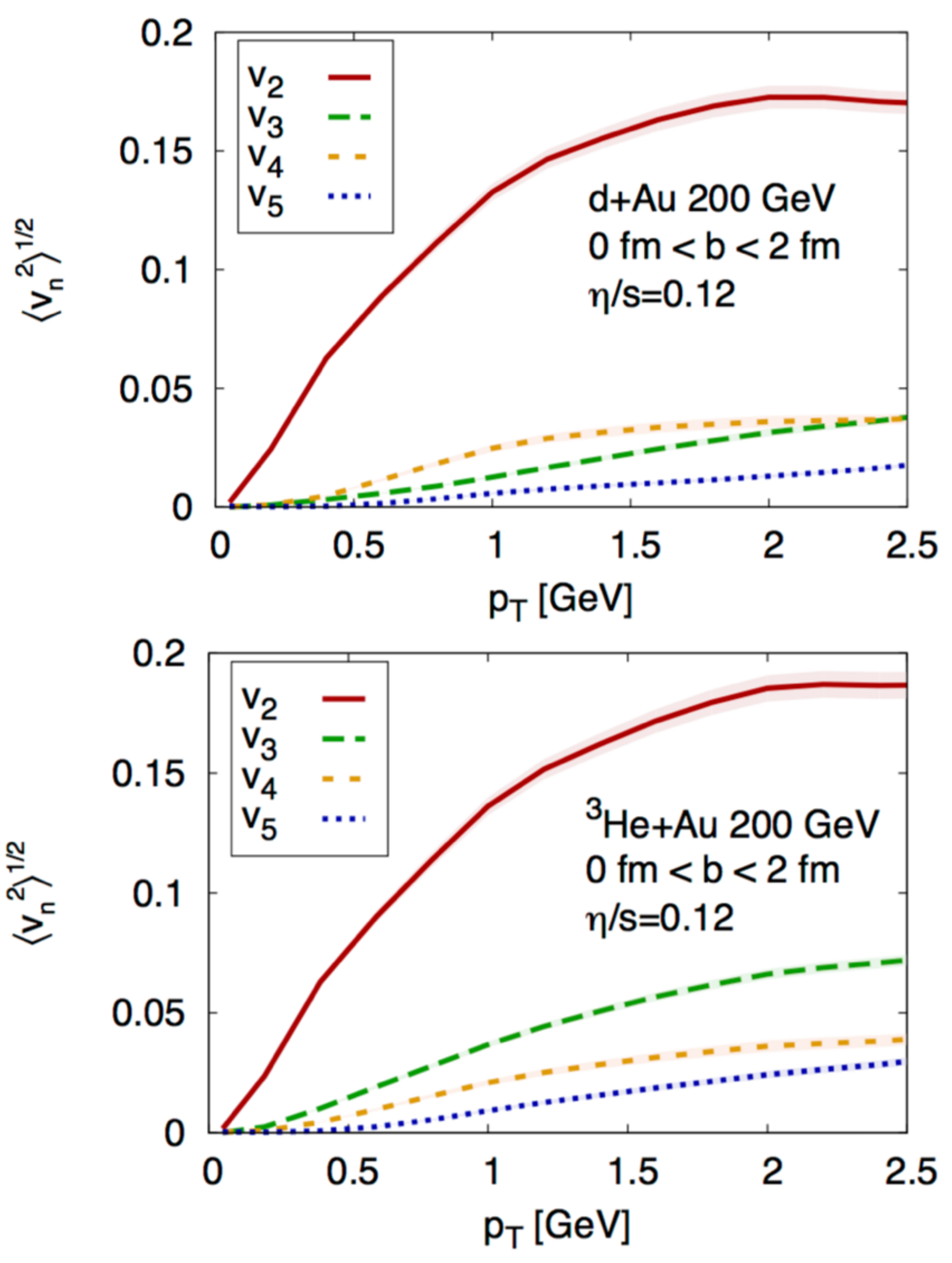


from Javier Orjuela-Koop
for the PHENIX Collaboration
at Initial Stages 2016

d+Au: PHENIX Collaboration, Phys.Rev.Lett. 114 (2015) 192301
^{3}He+Au: PHENIX Collaboration, Phys. Rev. Lett. 115, 142301 (2015)
P. Romatschke, Eur. Phys. J. C 75 (2015) 305

d+Au ^{3}He+Au Hydro Predictions

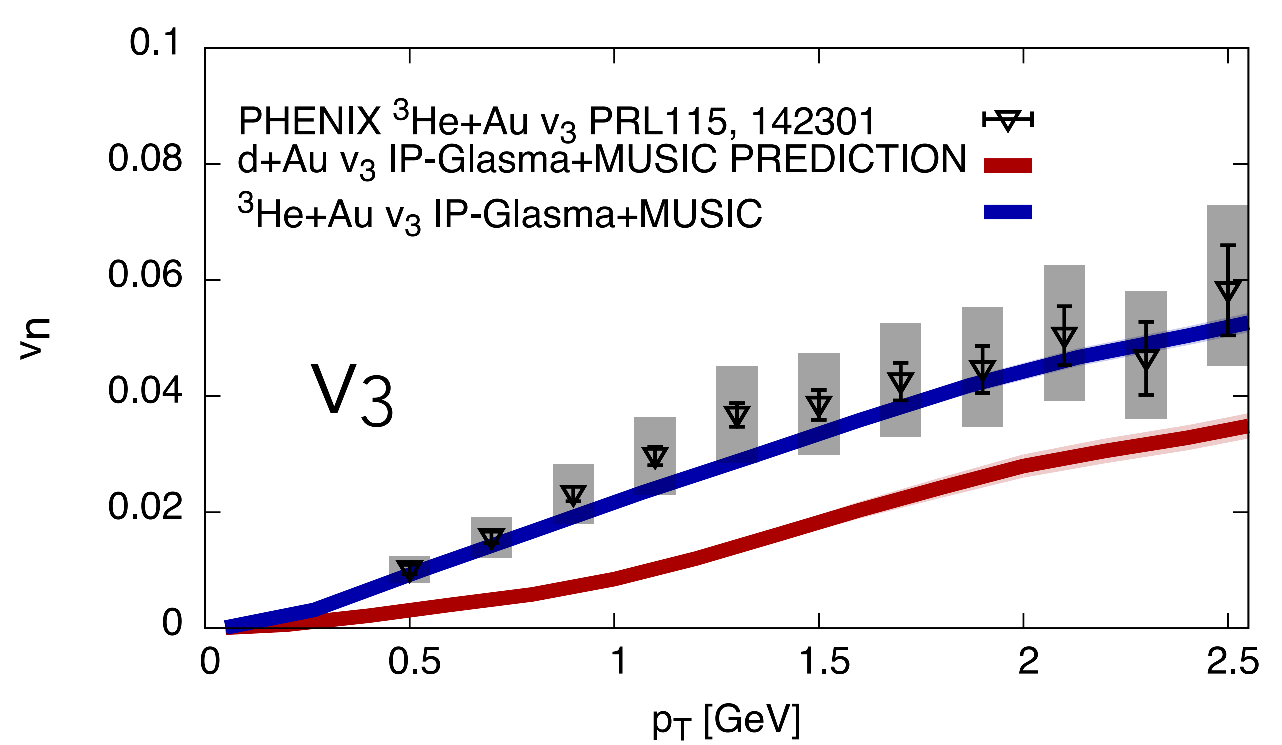


Left: Initial prediction for d+Au and ^{3}He+Au with **η**/s=0.12

Bottom: adjusted calculation with **η**/s=0.18

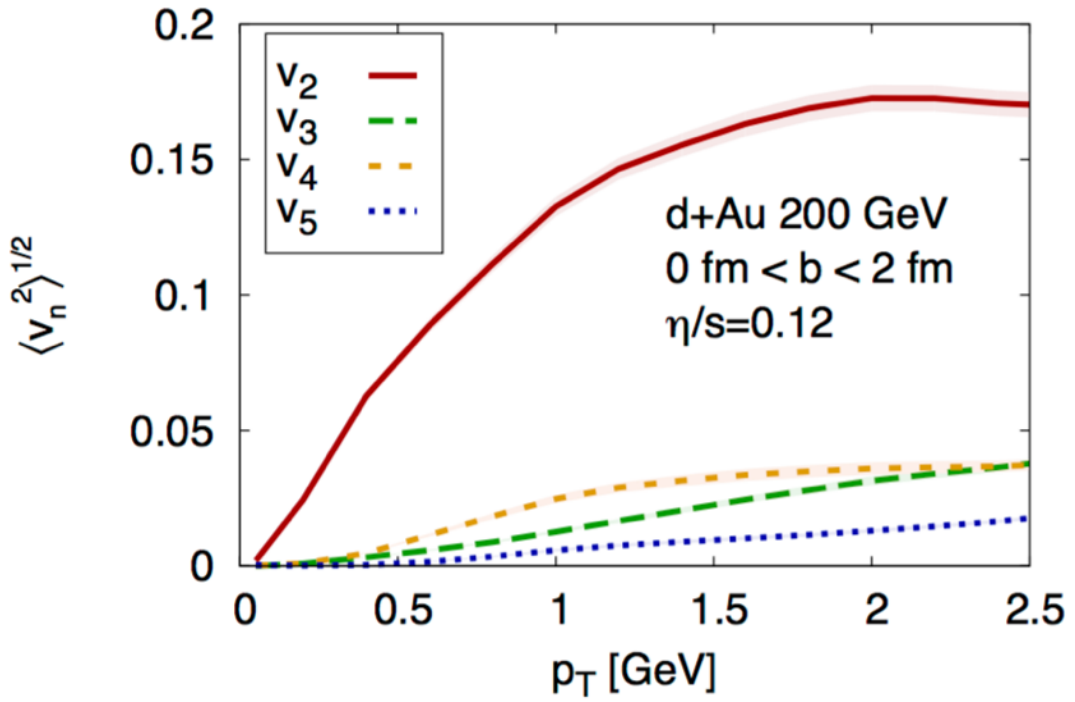
d+Au v_3 is a true prediction

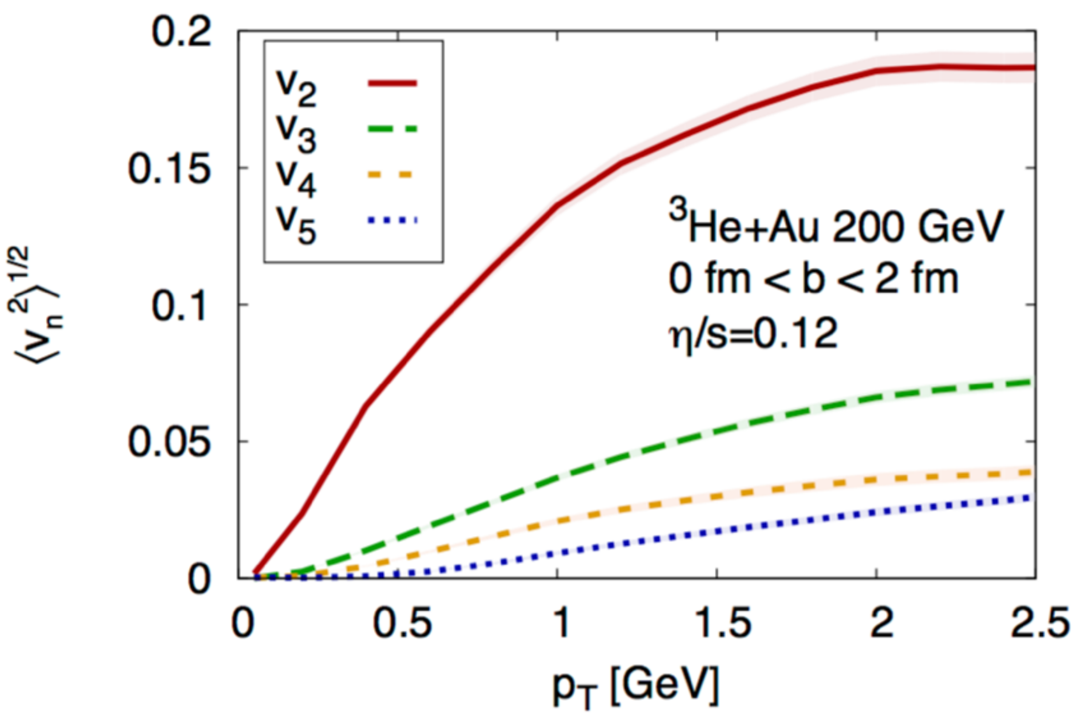
(shown @2015 RHIC&AGS Users' Meeting)



B. Schenke and R. Venugopalan, Nucl. Phys. A 931 (2014) 1039

d+Au ^{3}He+Au Hydro Predictions





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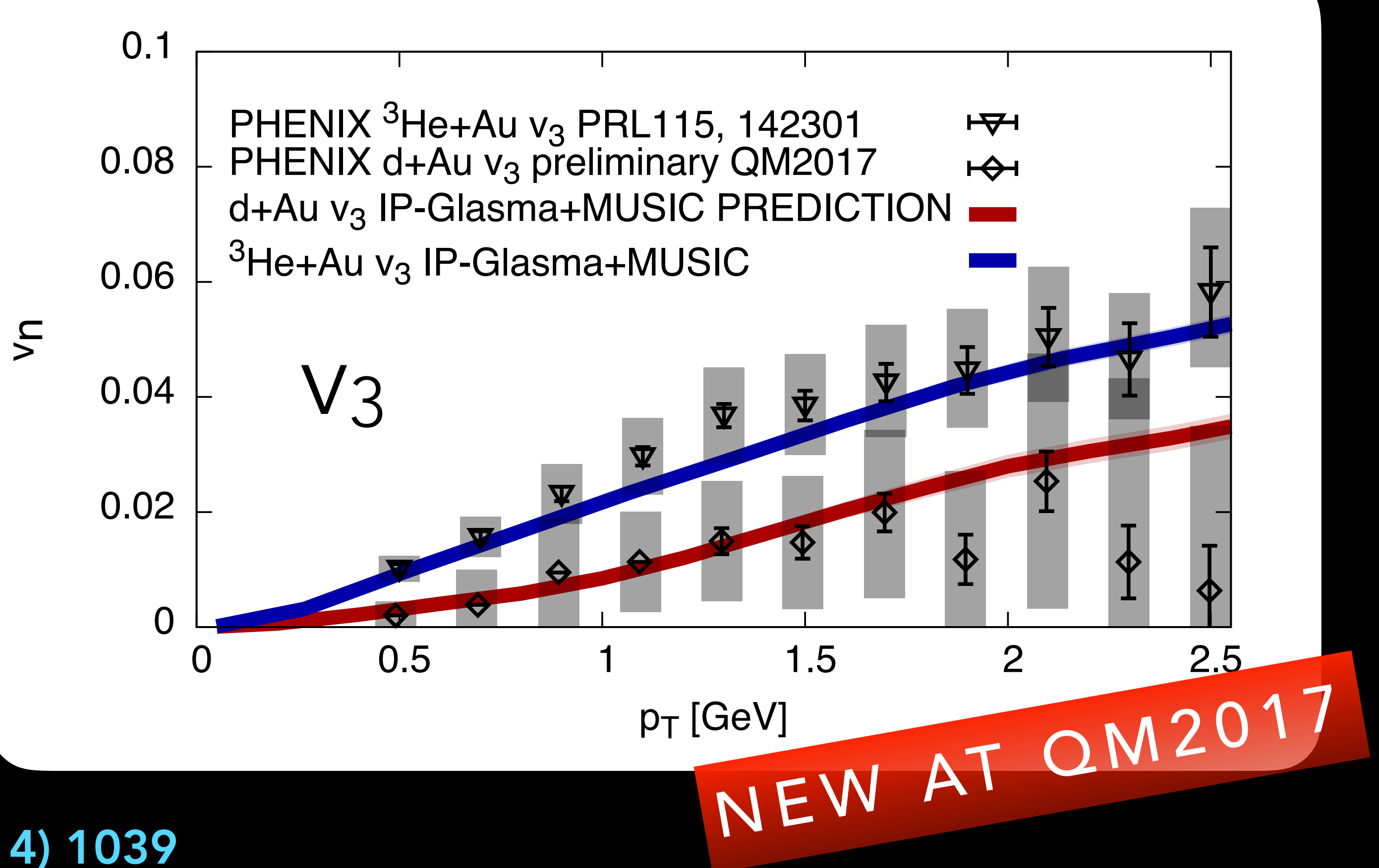

B. Schenke and R. Venugopalan, Nucl. Phys. A 931 (2014) 1039

Initial state picture

So far there is no initial state calculation comparing different small collision systems

There is no correlation between the harmonics and the initial global eccentricities

B. Schenke, S. Schlichting, R. Venugopalan, Phys. Lett. B747, 76-82 (2015)

L. McLerran, V. Skokov, arXiv:1611.09870

Difference must have a different origin:
Different multiplicities in the 0-5% bin?