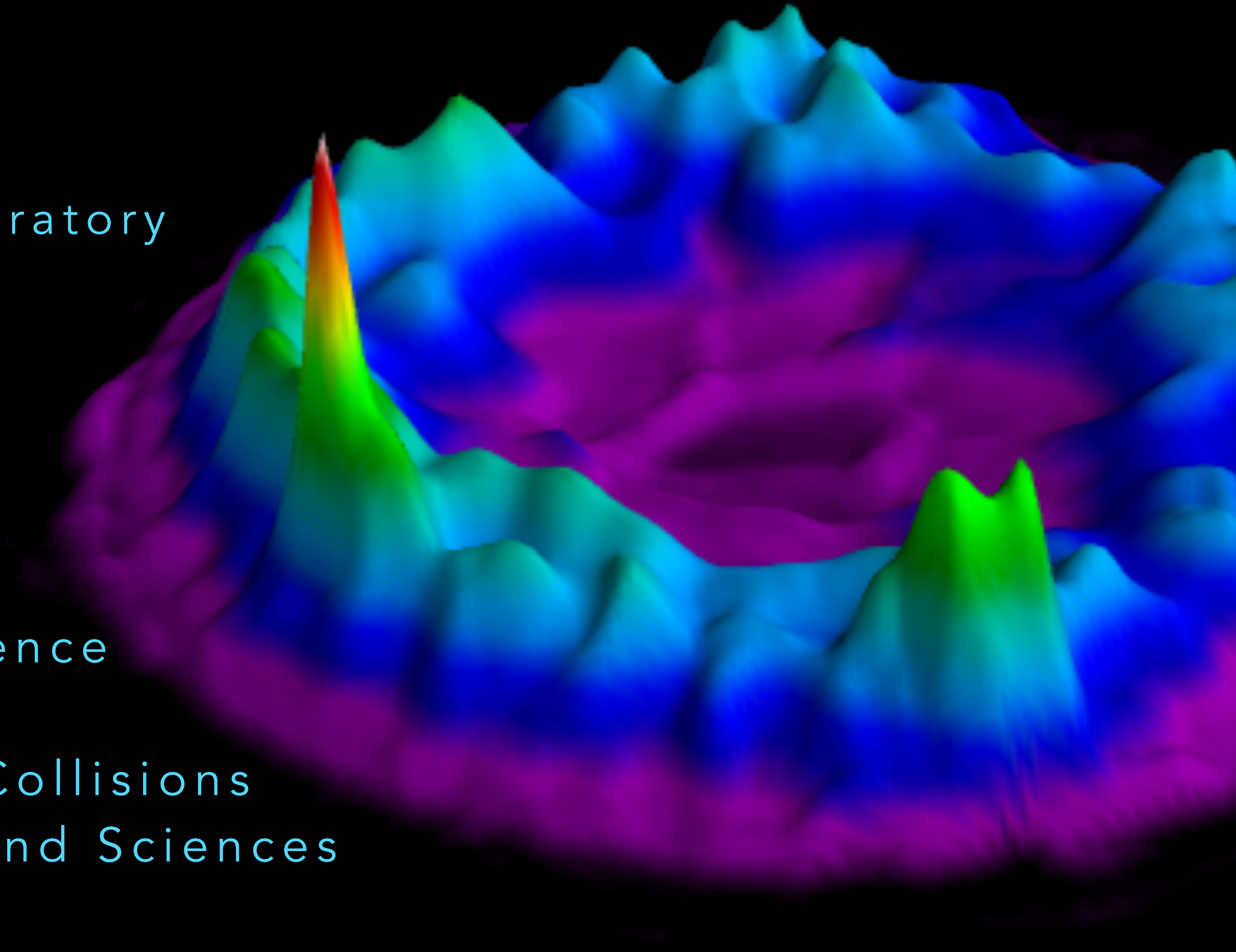
PROTON SHAPE FLUCTUATIONS AND THEIR EFFECT ON FLOW IN p+A COLLISIONS

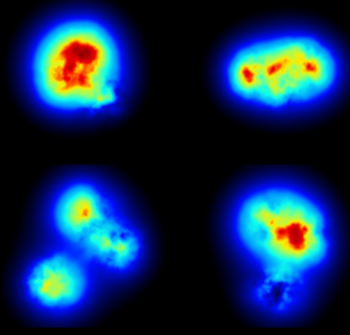


Björn Schenke
Brookhaven National Laboratory

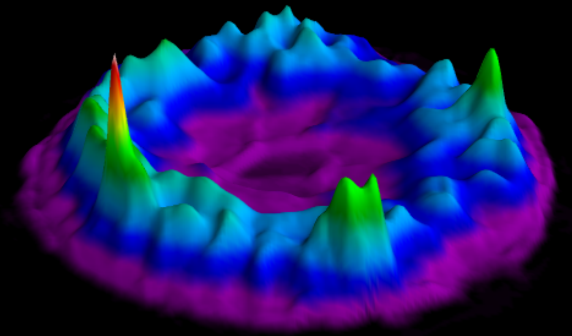
September 18, 2017
4th International Conference
on the Initial Stages
in High-Energy Nuclear Collisions
Polish Academy of Arts and Sciences

Outline

① Constraining proton shape fluctuations using diffraction



② Hydrodynamics in p+A with fluctuating protons



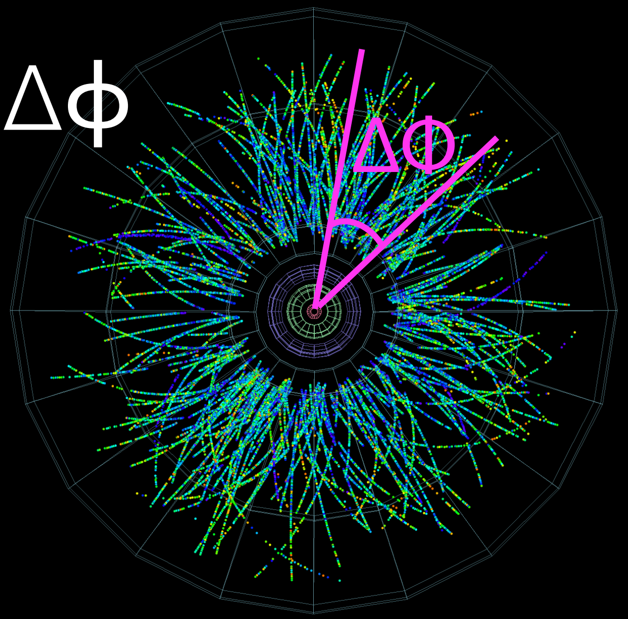
③ Initial + final state momentum correlations: Assessing their relative importance with IP-Glasma + parton cascade (BAMPS)

Introduction: Multi-particle correlations

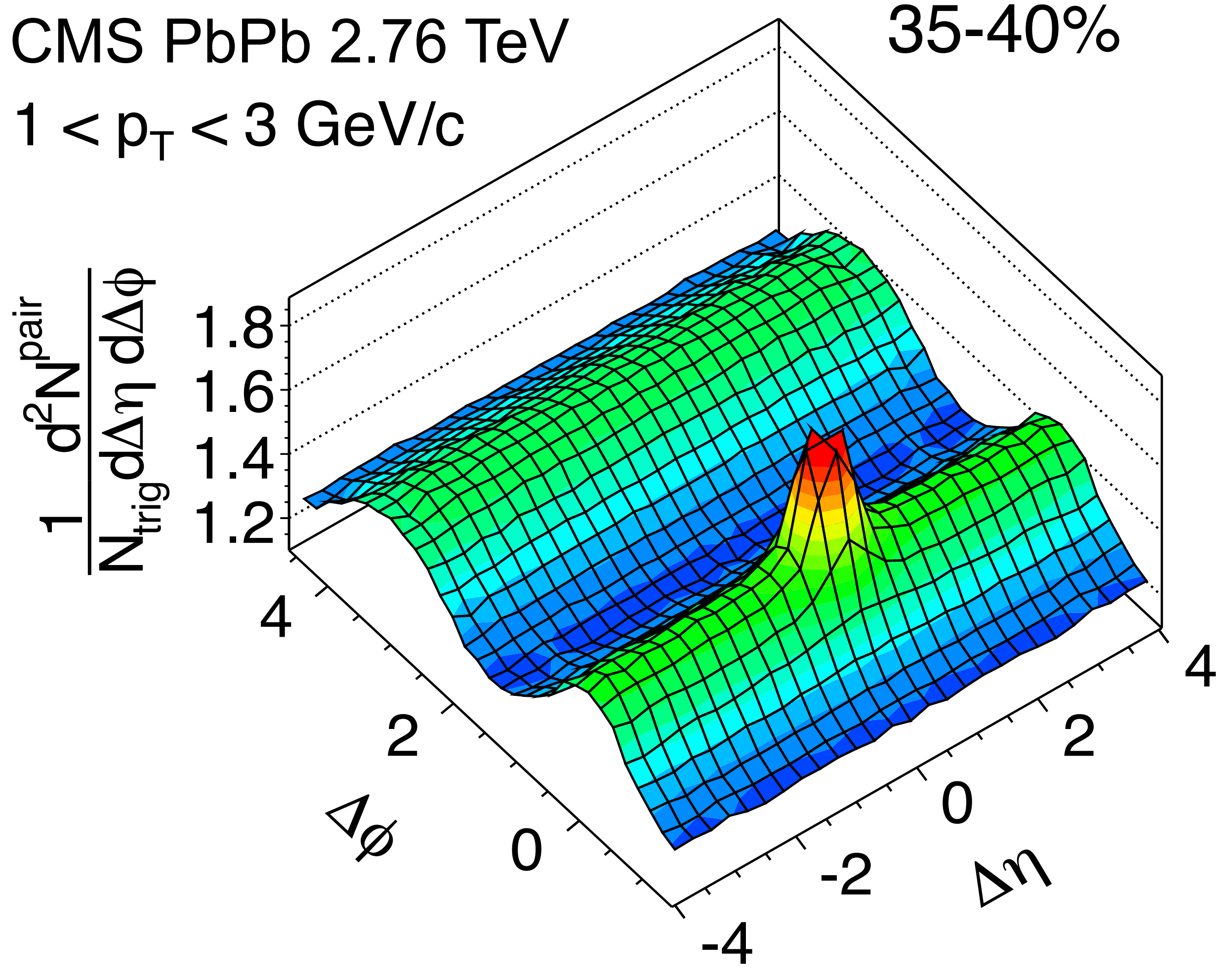
2-particle correlation as a function of Δη and Δϕ

Δη: DIFFERENCE IN PSEUDO-RAPIDITY

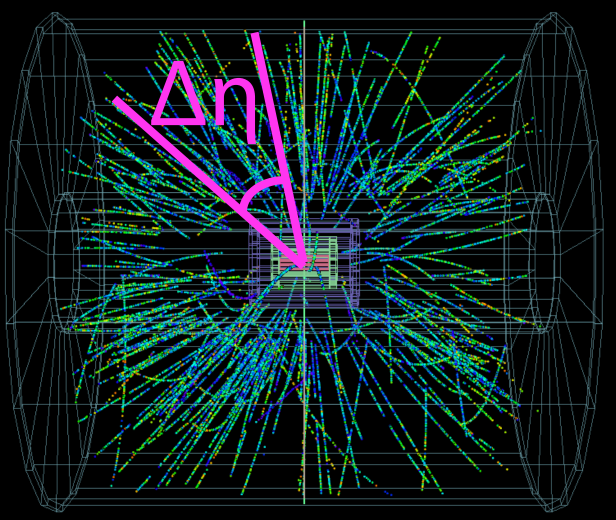
ΔΦ: DIFFERENCE IN AZIMUTHAL ANGLE



ΔΦ: DIFFERENCE
IN AZIMUTHAL ANGLE



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

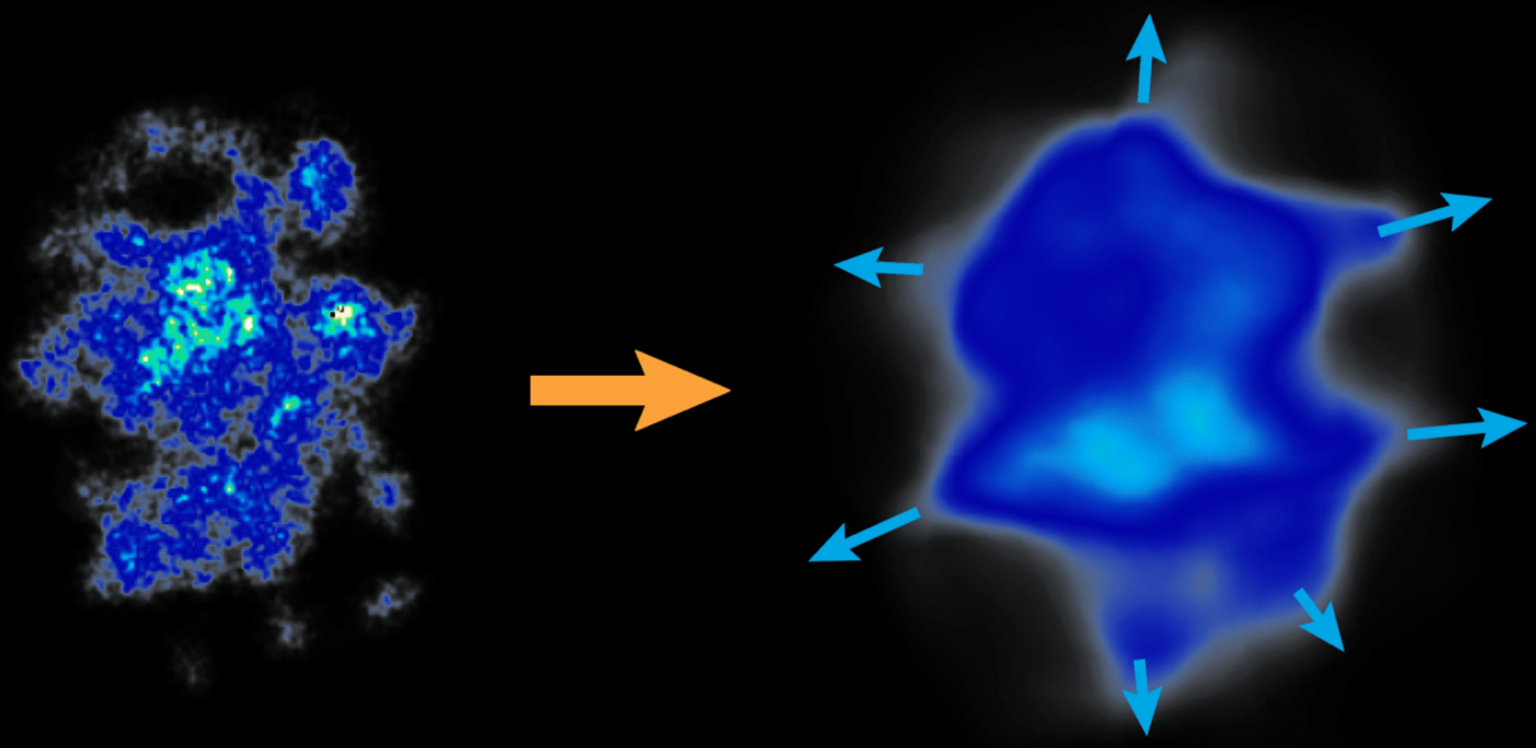


Δη: DIFFERENCE
IN PSEUDO-RAPIDITY

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

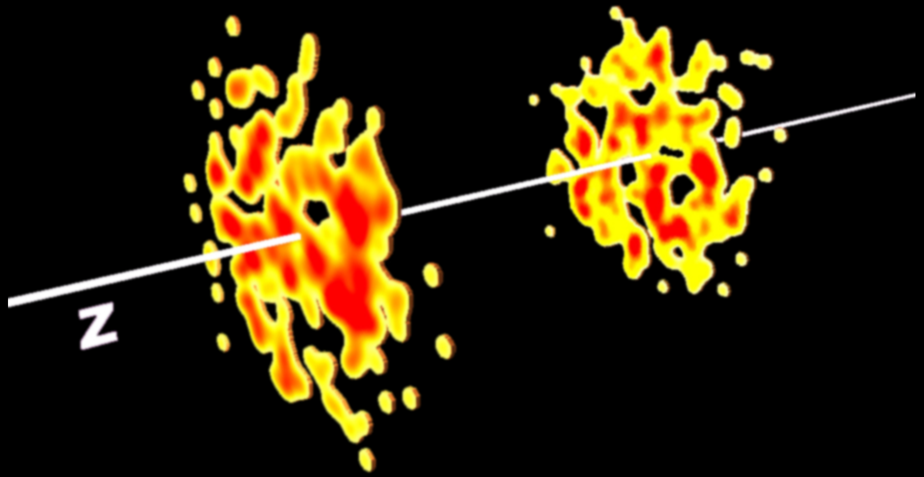
Hydrodynamic expansion

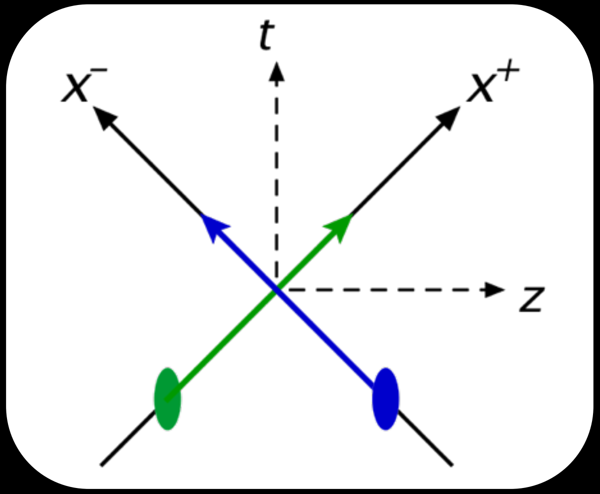
IP-Glasma initial state

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

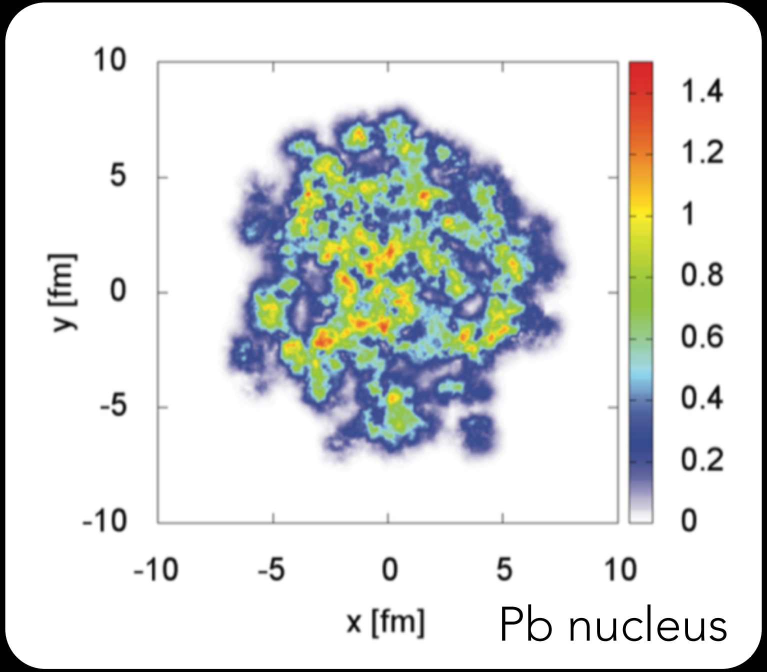
How to determine the incoming currents J^ν:

- 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:

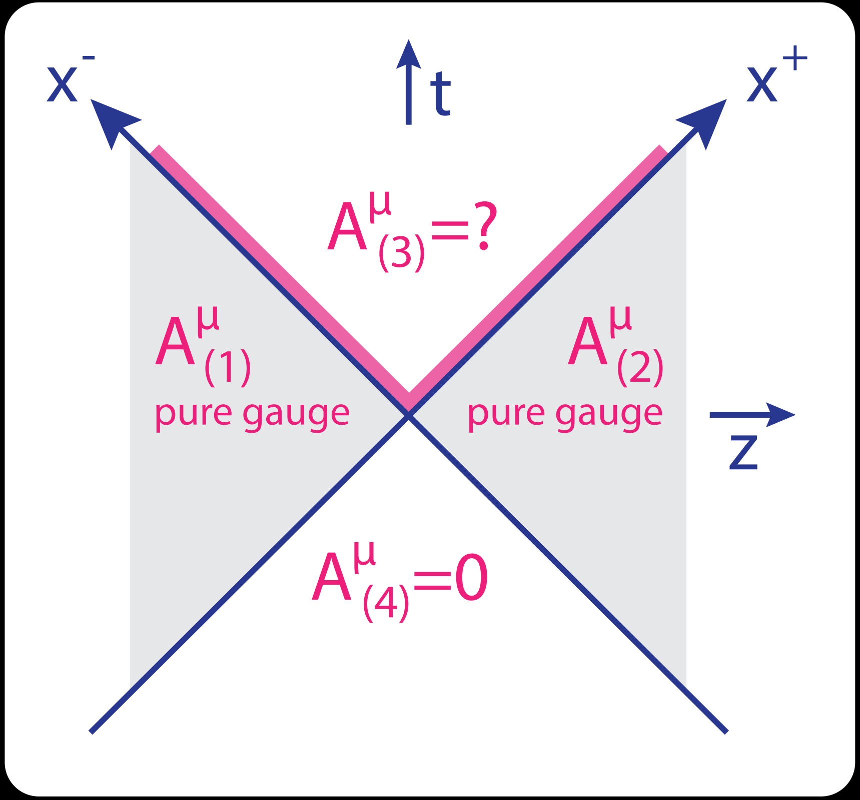
$$V_{(1)}(\vec{x}) = P\exp\left(-ig\int dx^- \frac{\rho_{(1)}(x^-,\vec{x})}{\nabla^2+m^2}\right)$$

Fields after the collision:

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

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

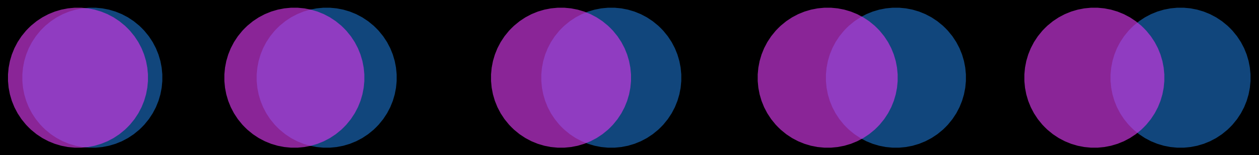
Kovner, McLerran, Weigert, Phys. Rev. D52, 6231 (1995)
Krasnitz, Venugopalan, Nucl.Phys. B557 (1999) 237

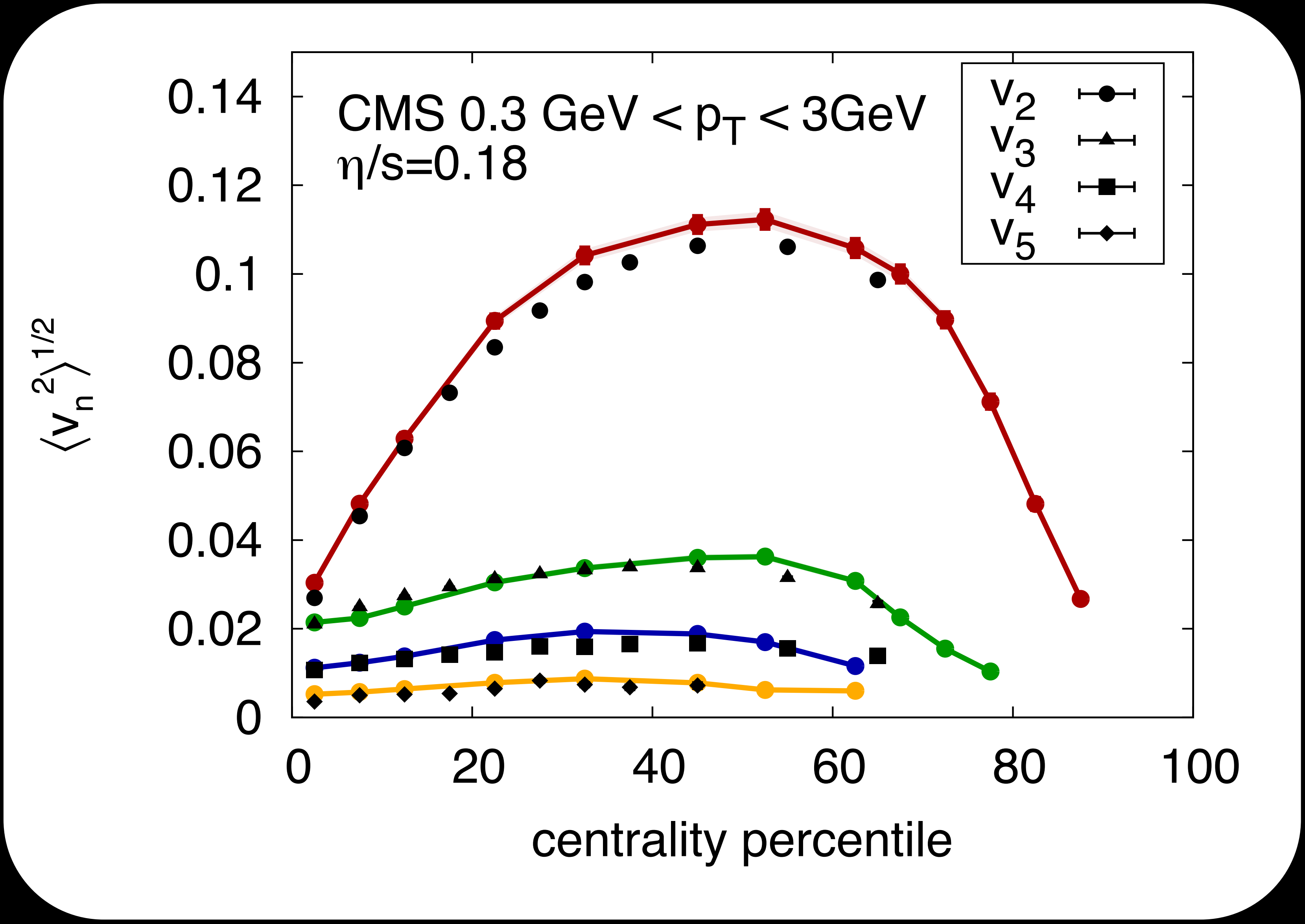


Fields in Schwinger gauge

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

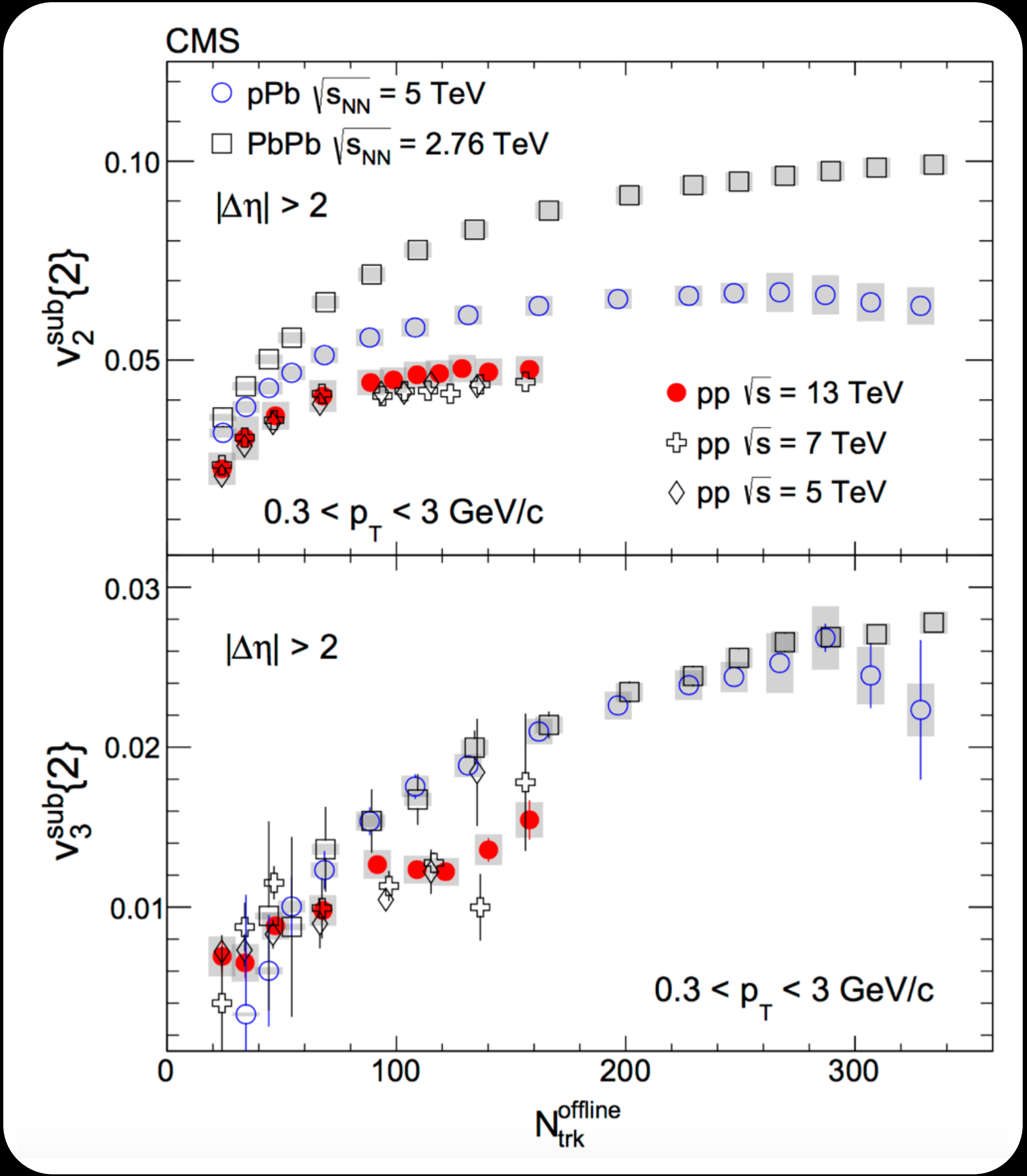
C.Gale, S.Jeon, B.Schenke, P.Tribedy, R.Venugopalan, Phys.Rev.Lett. 110, 012302 (2013)
B. Schenke, R. Venugopalan, Phys.Rev.Lett. 113 (2014) 102301





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:

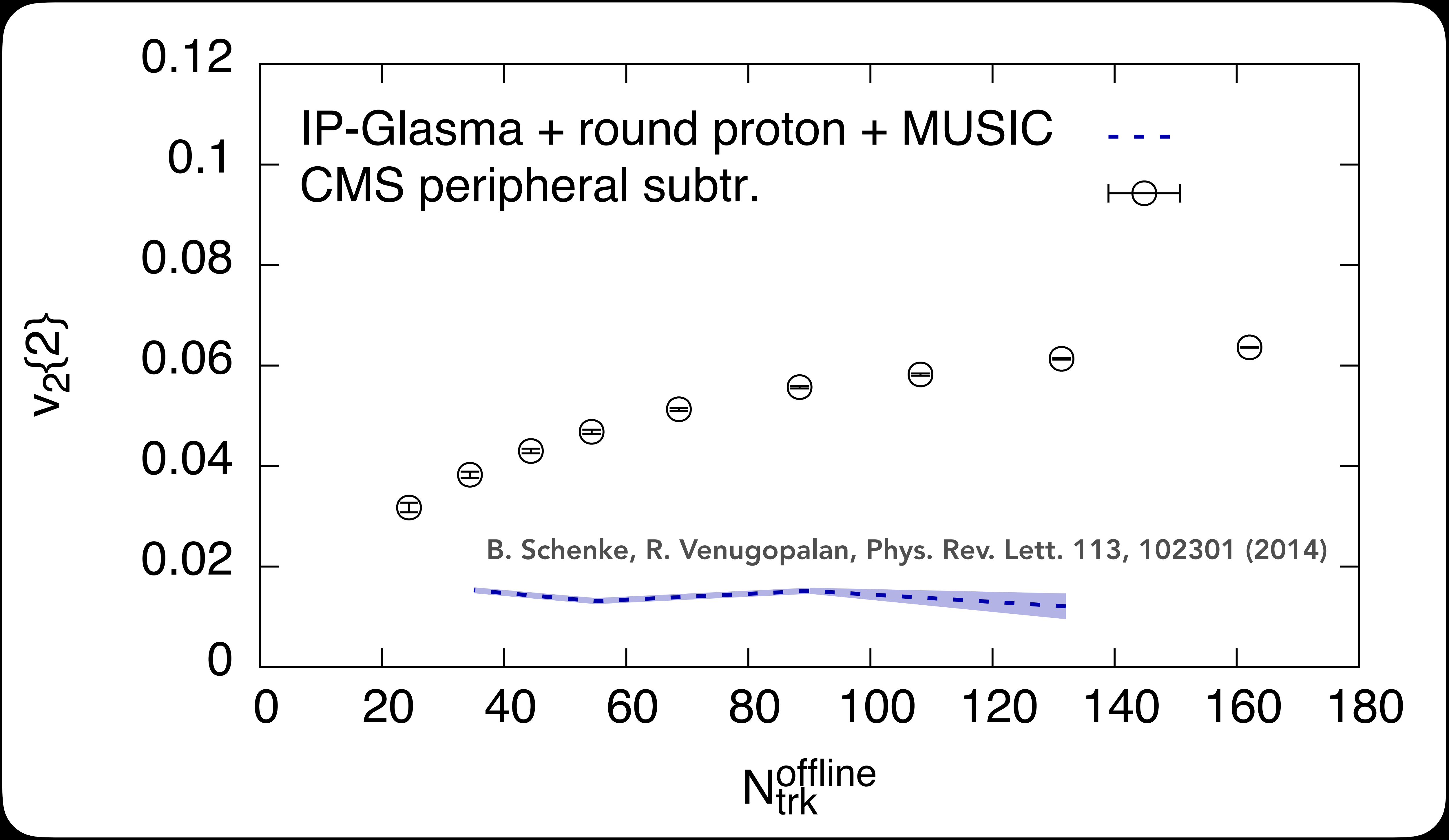
ALICE CollABORATION
Phys. Lett. B719 (2013) 29-41; Phys. Rev. C 90, 054901

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

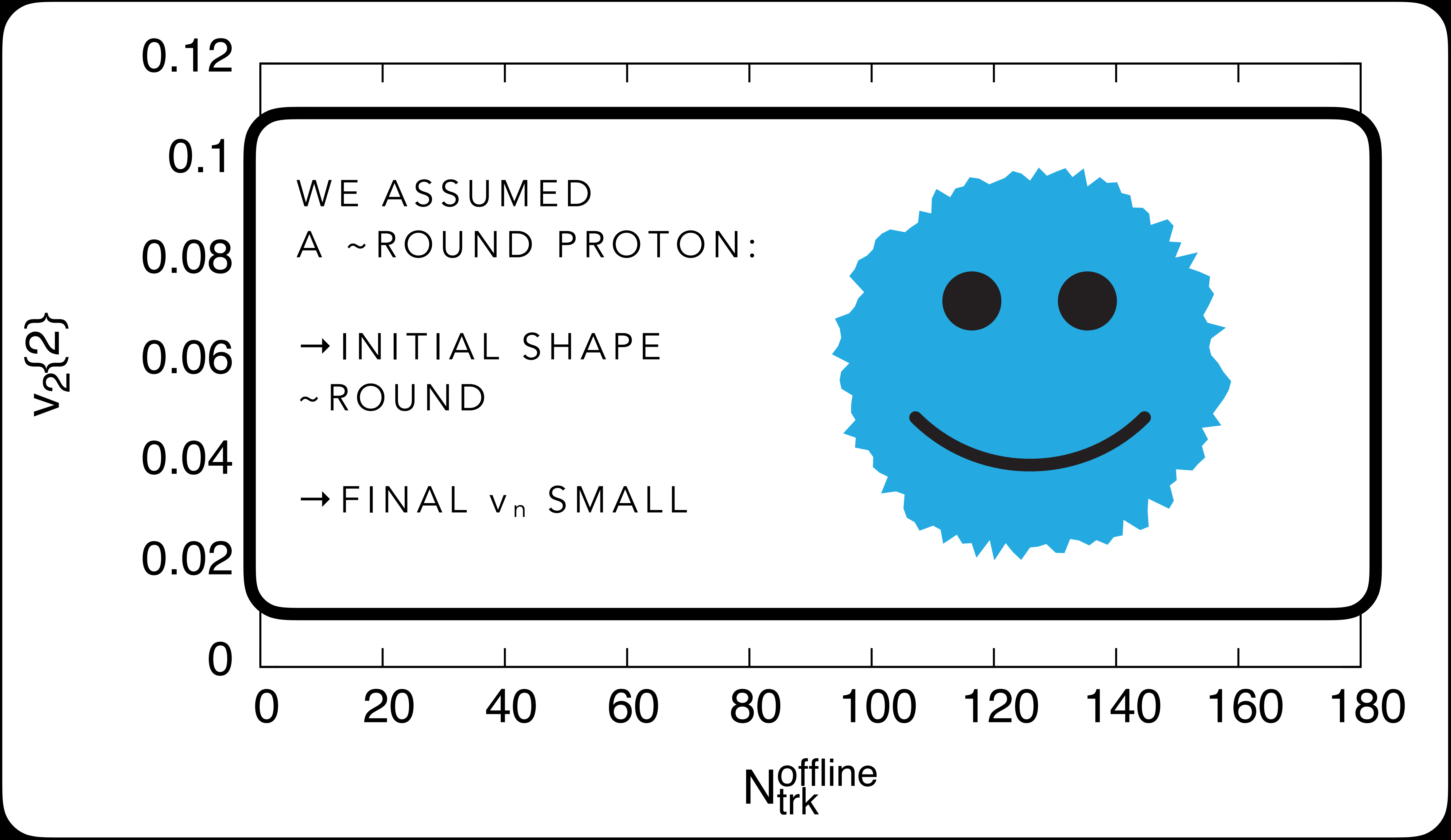
Experimental data: CMS Collaboration, Phys.Lett. B724, 213 (2013)



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

IP-Glasma+MUSIC results

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



WE ASSUMED
A ~ROUND PROTON:

→INITIAL SHAPE
~ROUND

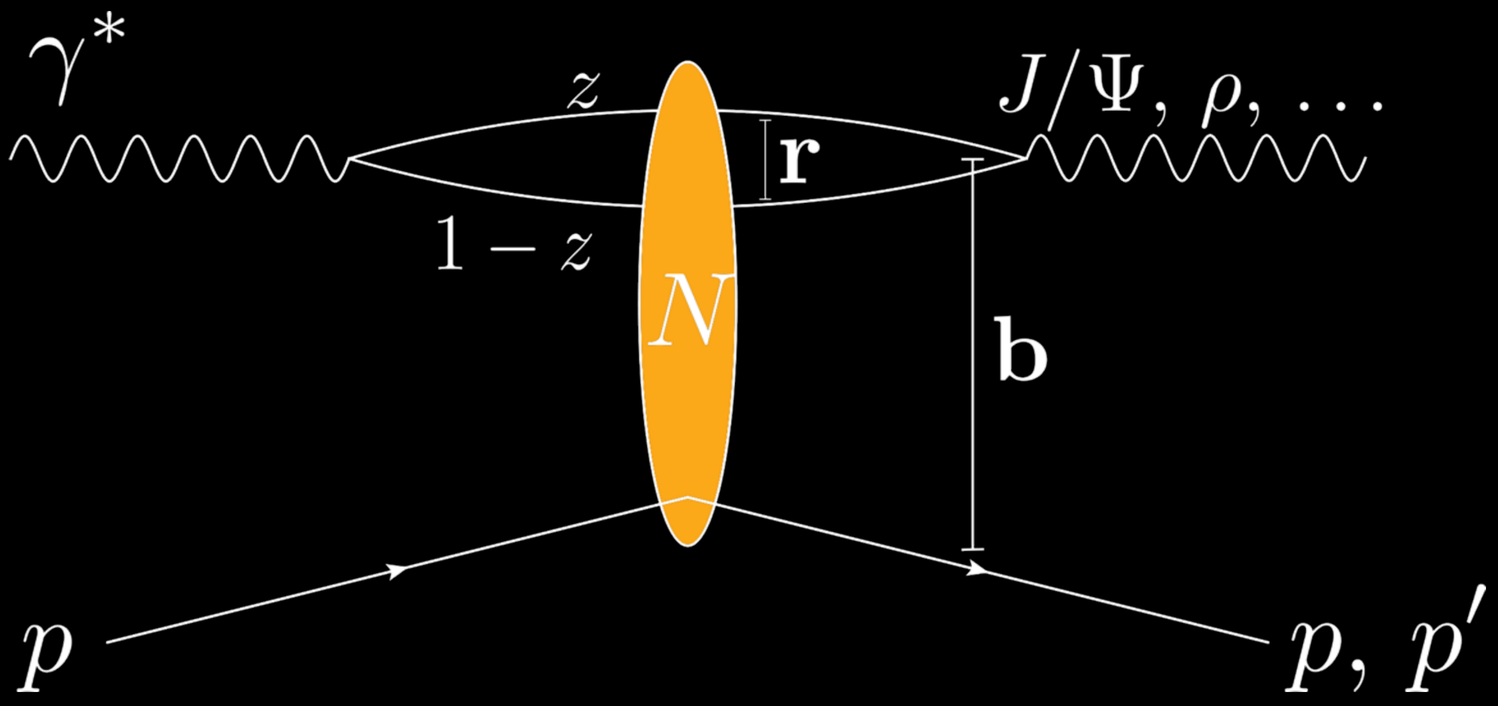
→FINAL v_n SMALL

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:

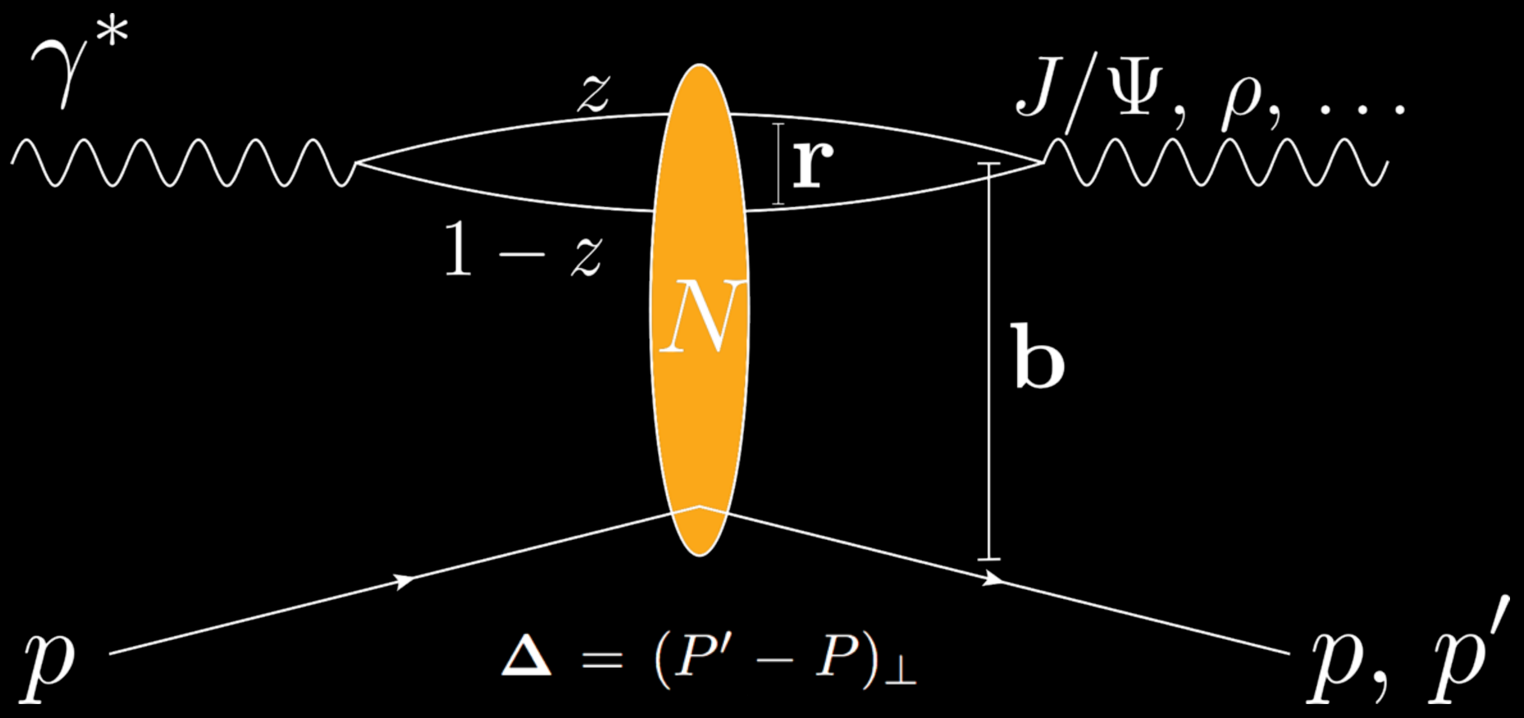
Proton breaks up, Sensitive to shape fluctuations

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:

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

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

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

INCOHERENT DIFFRACTION:

TARGET BREAKS UP

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

SEE
H. I. MIETTINEN
AND J. PUMPLIN
PHYS. REV. D18 (1978) 1696

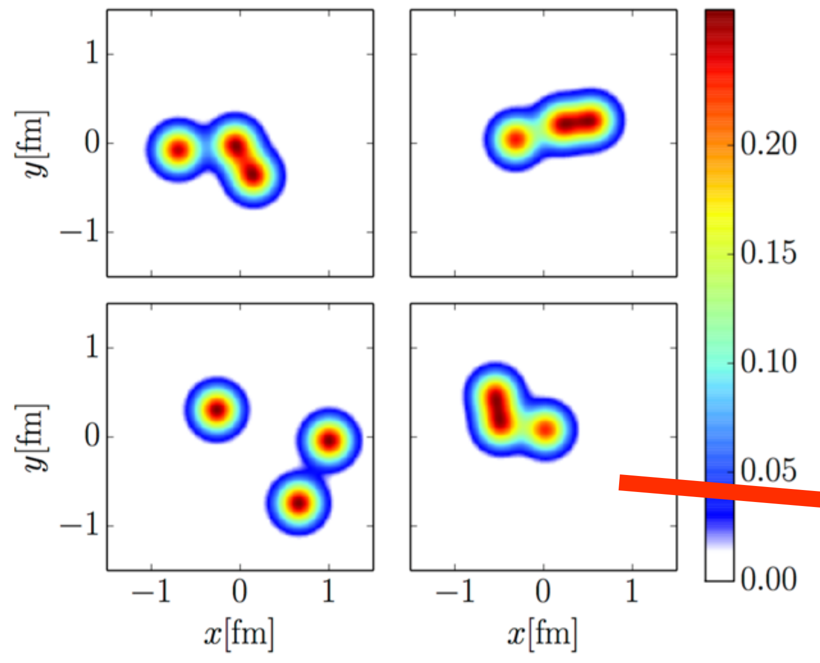
Y. V. KOVCHEGOV
AND L. D. MCLERRAN
PHYS. REV. D60 (1999) 054025

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

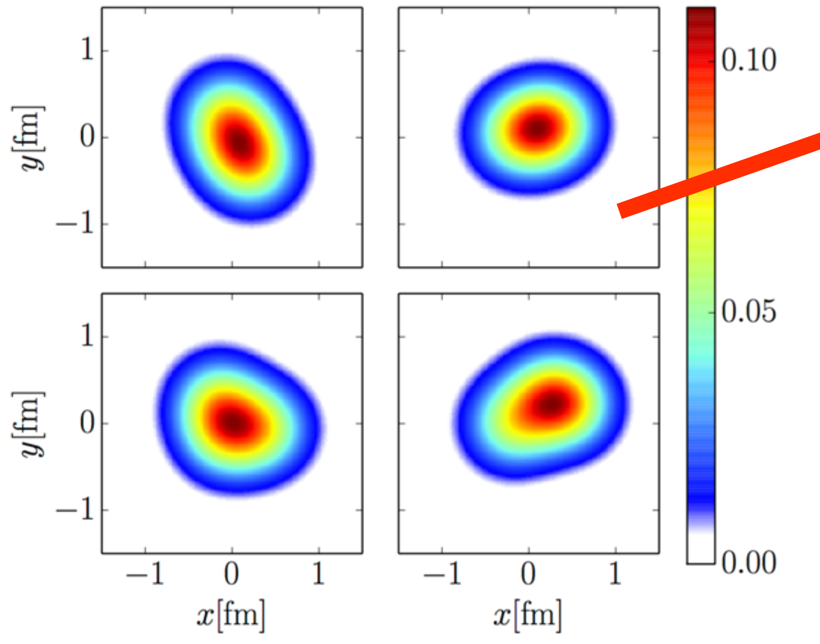
SENSITIVE TO FLUCTUATIONS!

Introduce geometric fluctuations

Assume 3 valence quark-like hot spots

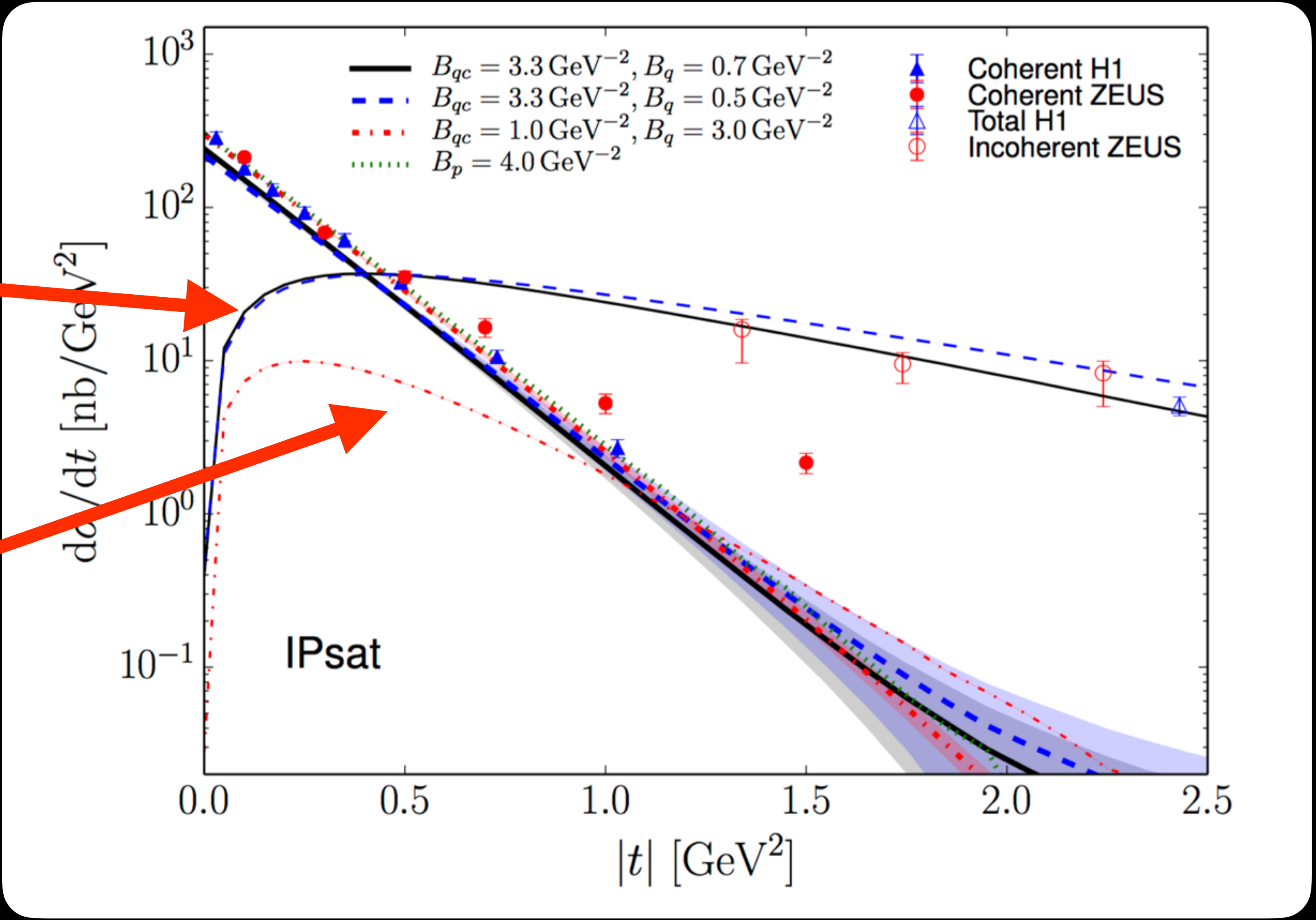


(a) $B_{qc} = 3.3\ \mathrm{GeV}^{-2}, B_q = 0.7\ \mathrm{GeV}^{-2}$



(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

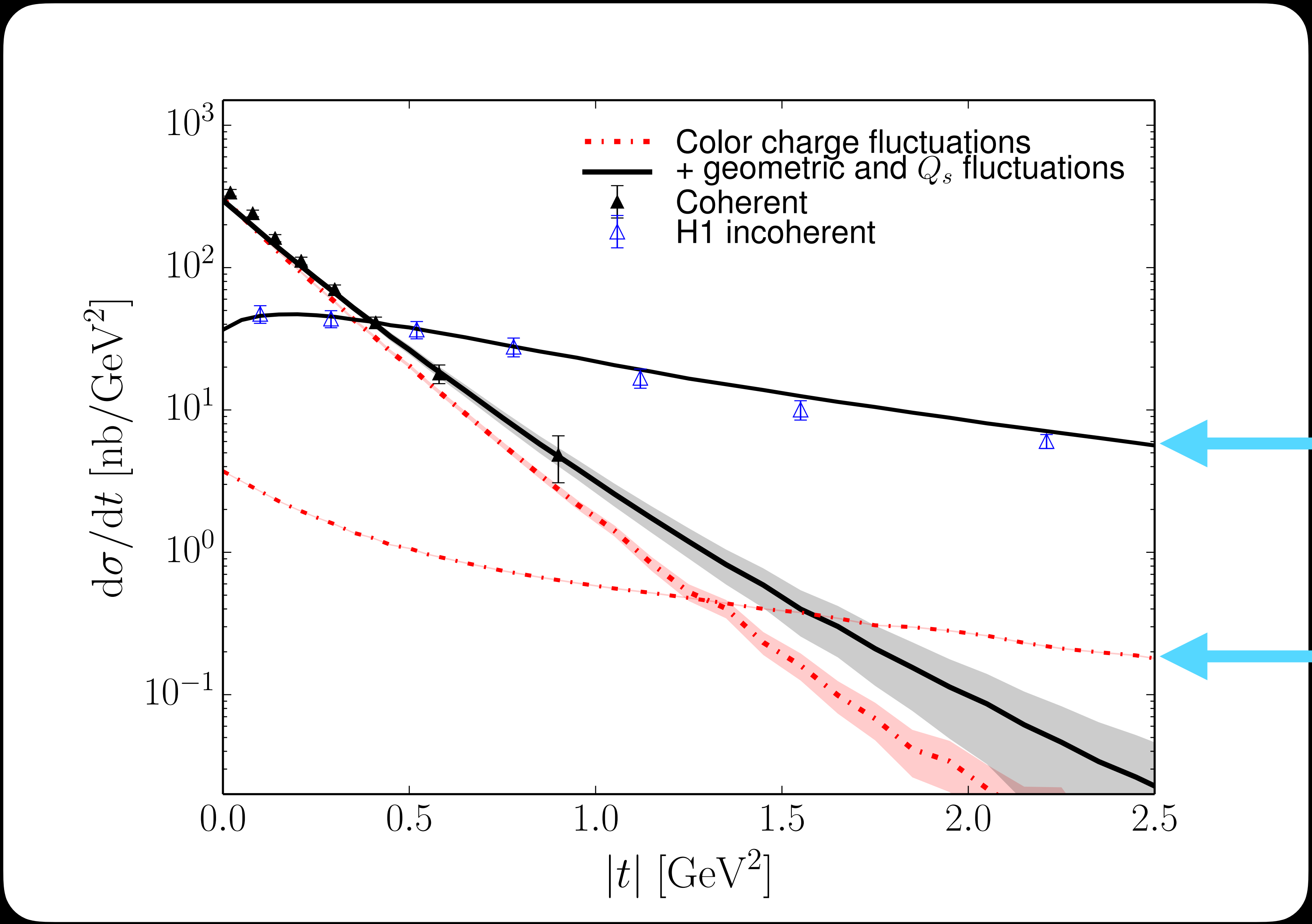
IP-Glasma calculation

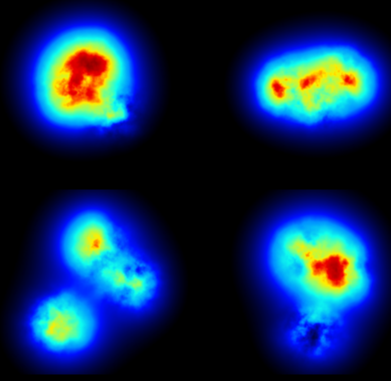
H. Mäntysaari, B. Schenke, Phys. Rev. Lett. 117 (2016) 052301; Phys.Rev. D94 (2016) 034042

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

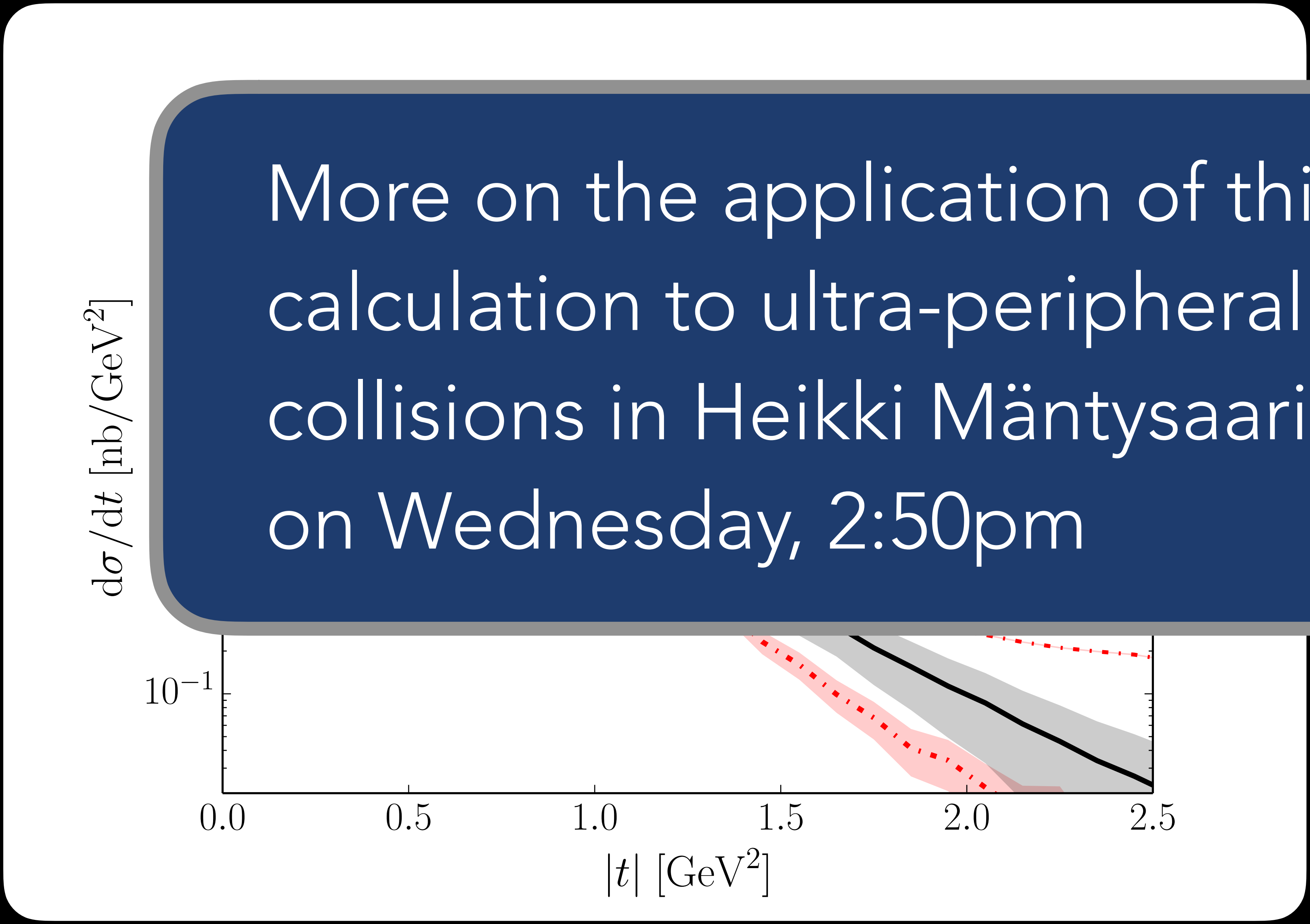
IP-Glasma calculation

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

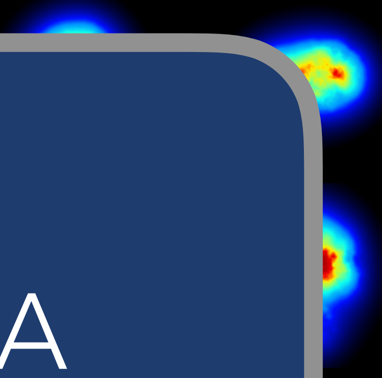
Geometric + color charge fluctuations

Wilson lines

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



More on the application of this calculation to ultra-peripheral A+A collisions in Heikki Mäntysaari's talk on Wednesday, 2:50pm



ape

ons

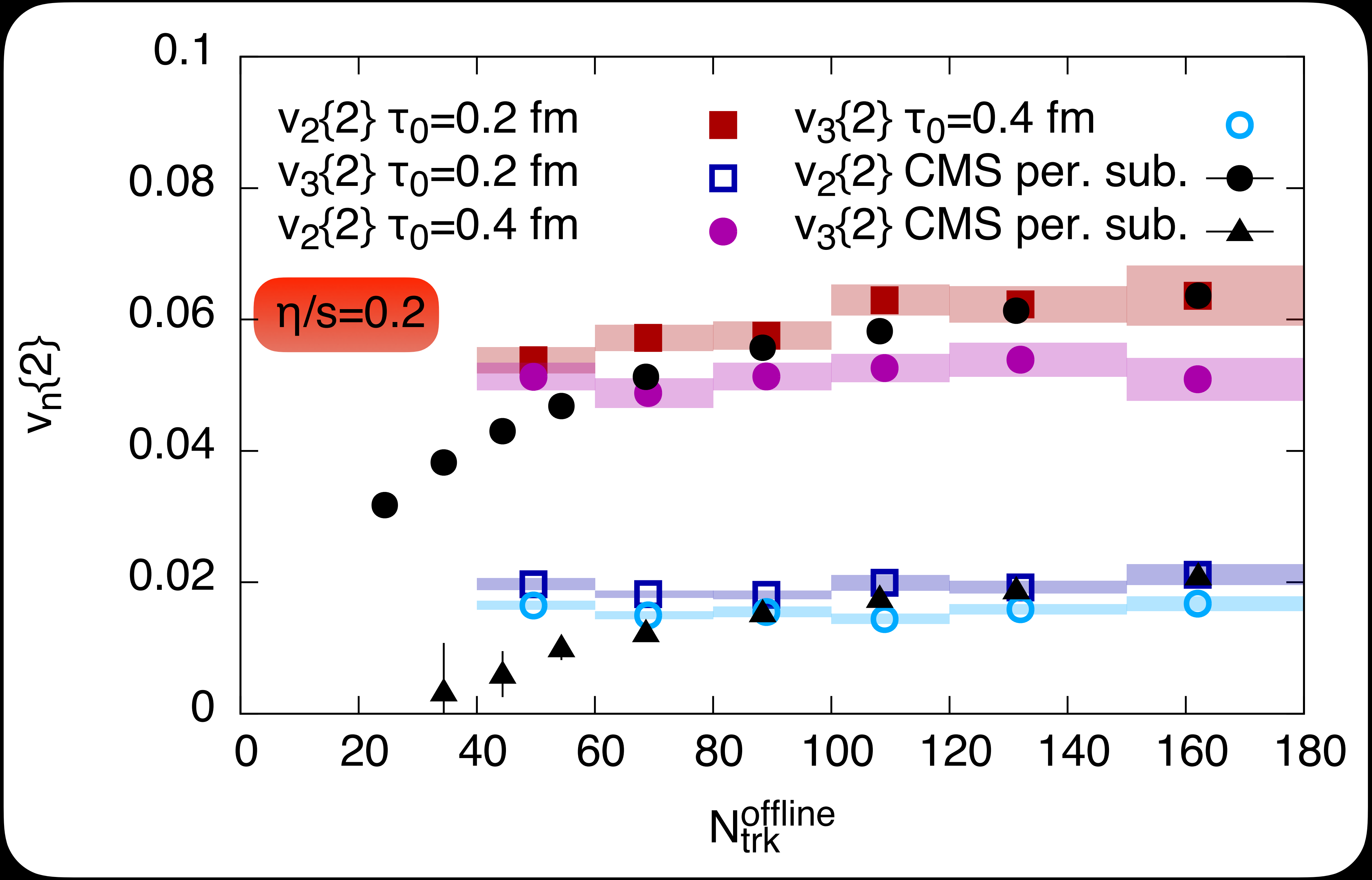
round proton

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

NOW USE CONSTRAINED FLUCTUATING PROTONS IN IP-GLASMA+HYDRO+URQMD FRAMEWORK

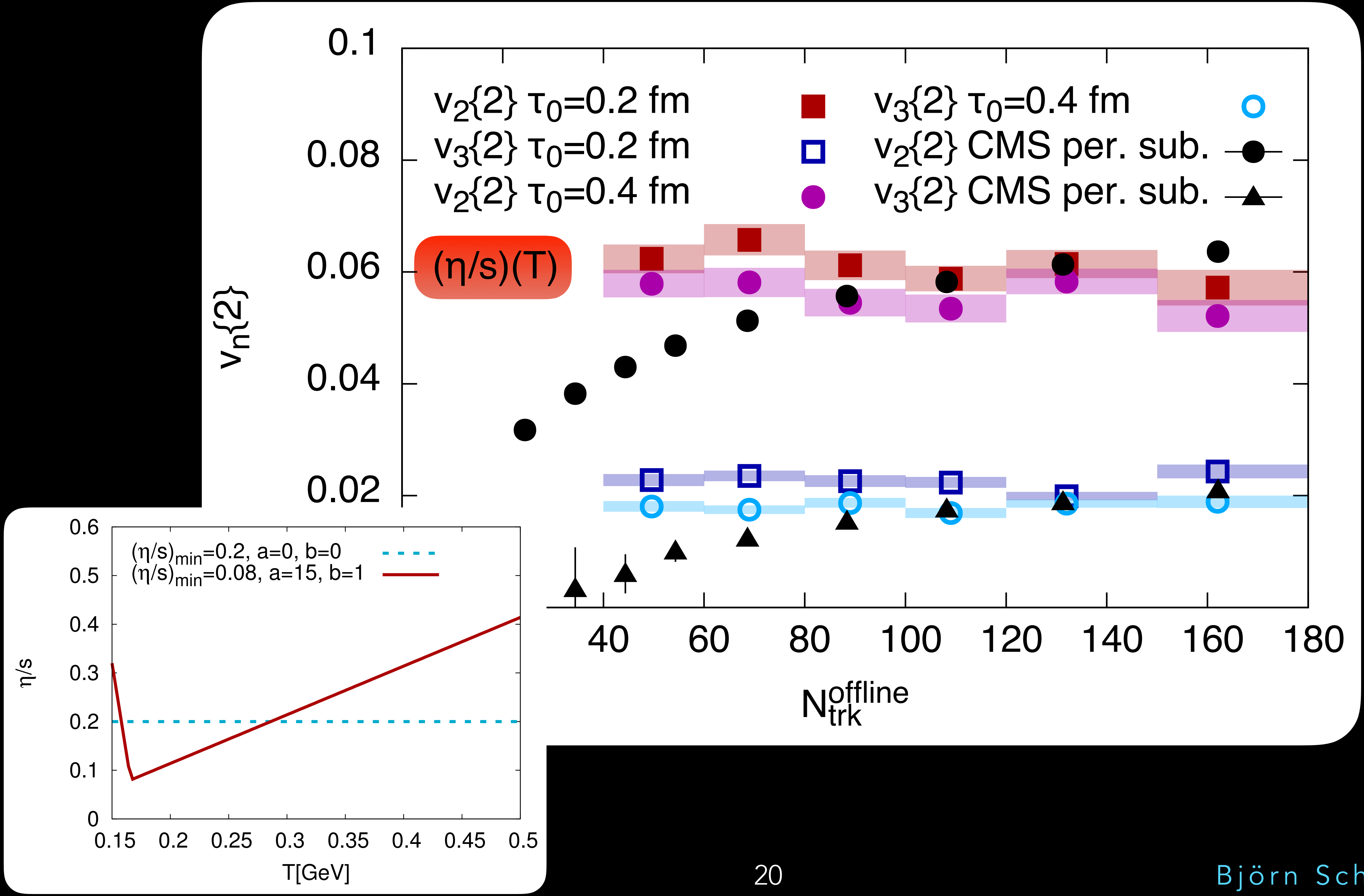
Integrated anisotropic flow

H. Mäntysaari, B. Schenke, C. Shen, P. Tribedy, Phys. Lett. B772, 681–686 (2017)



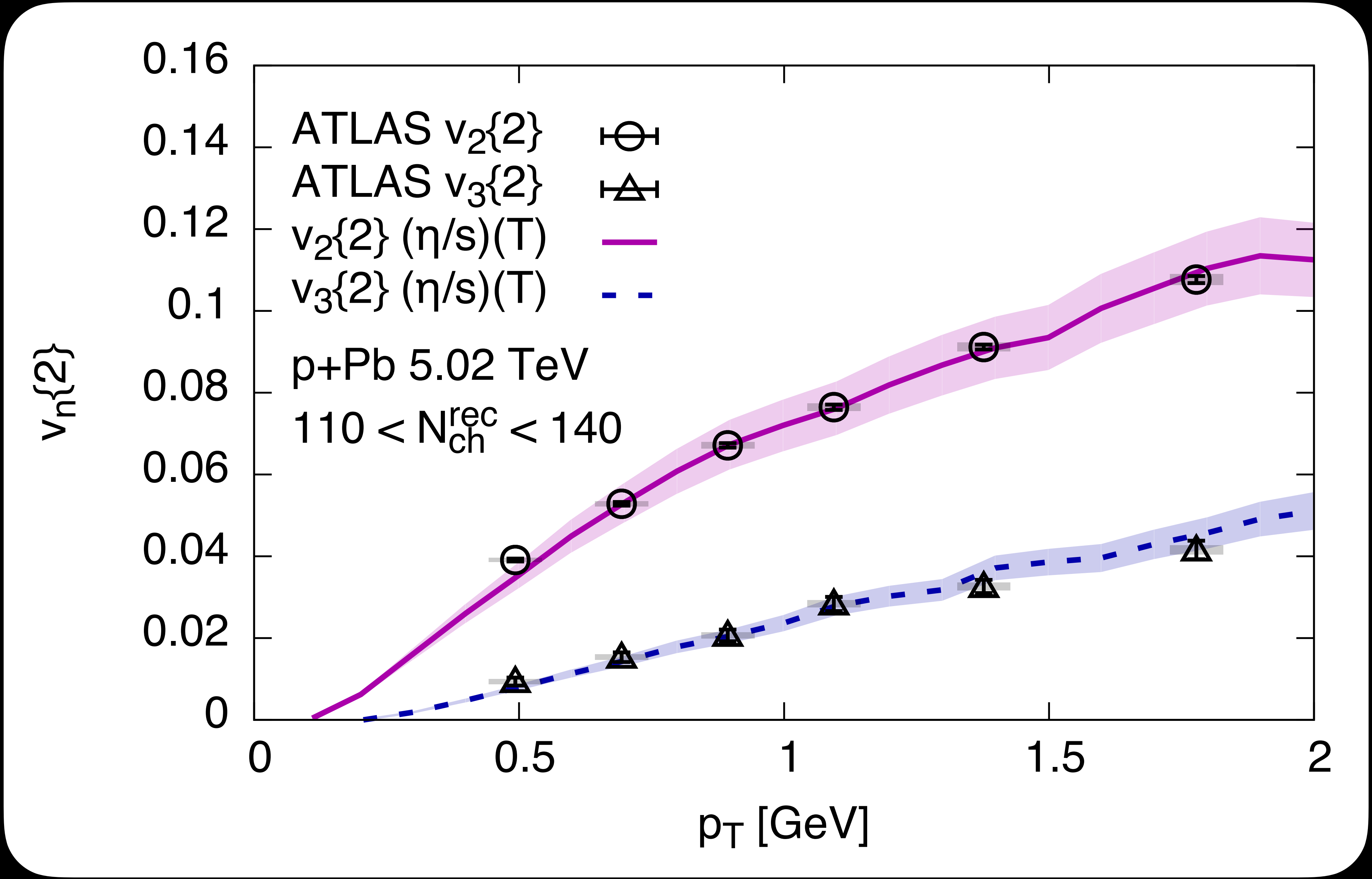
Integrated anisotropic flow

H. Mäntysaari, B. Schenke, C. Shen, P. Tribedy, Phys. Lett. B772, 681–686 (2017)



p_T-differential anisotropic flow

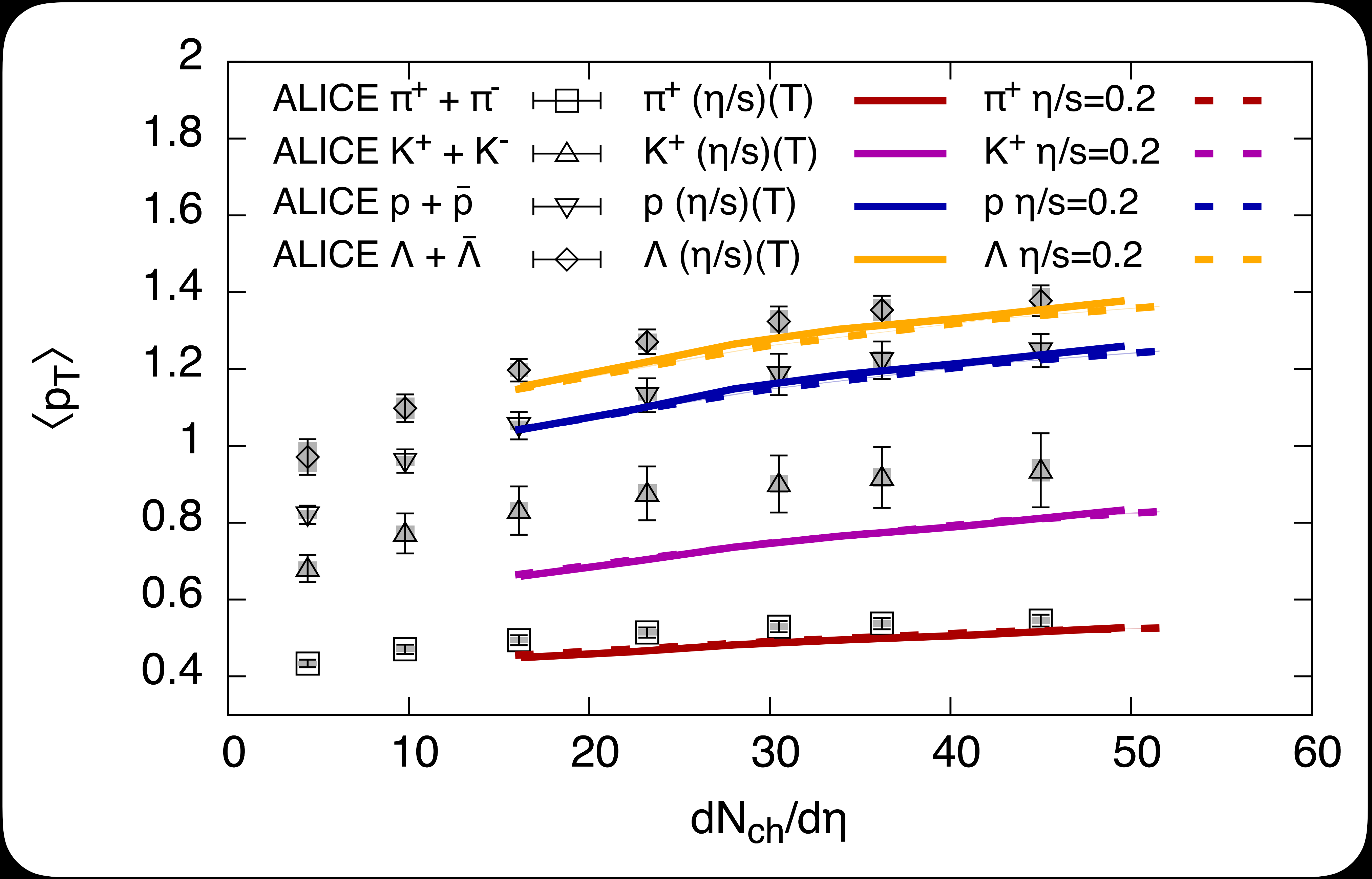
H. Mäntysaari, B. Schenke, C. Shen, P. Tribedy, Phys. Lett. B772, 681–686 (2017)



τ_0=0.4 fm

Identified particle mean p_T

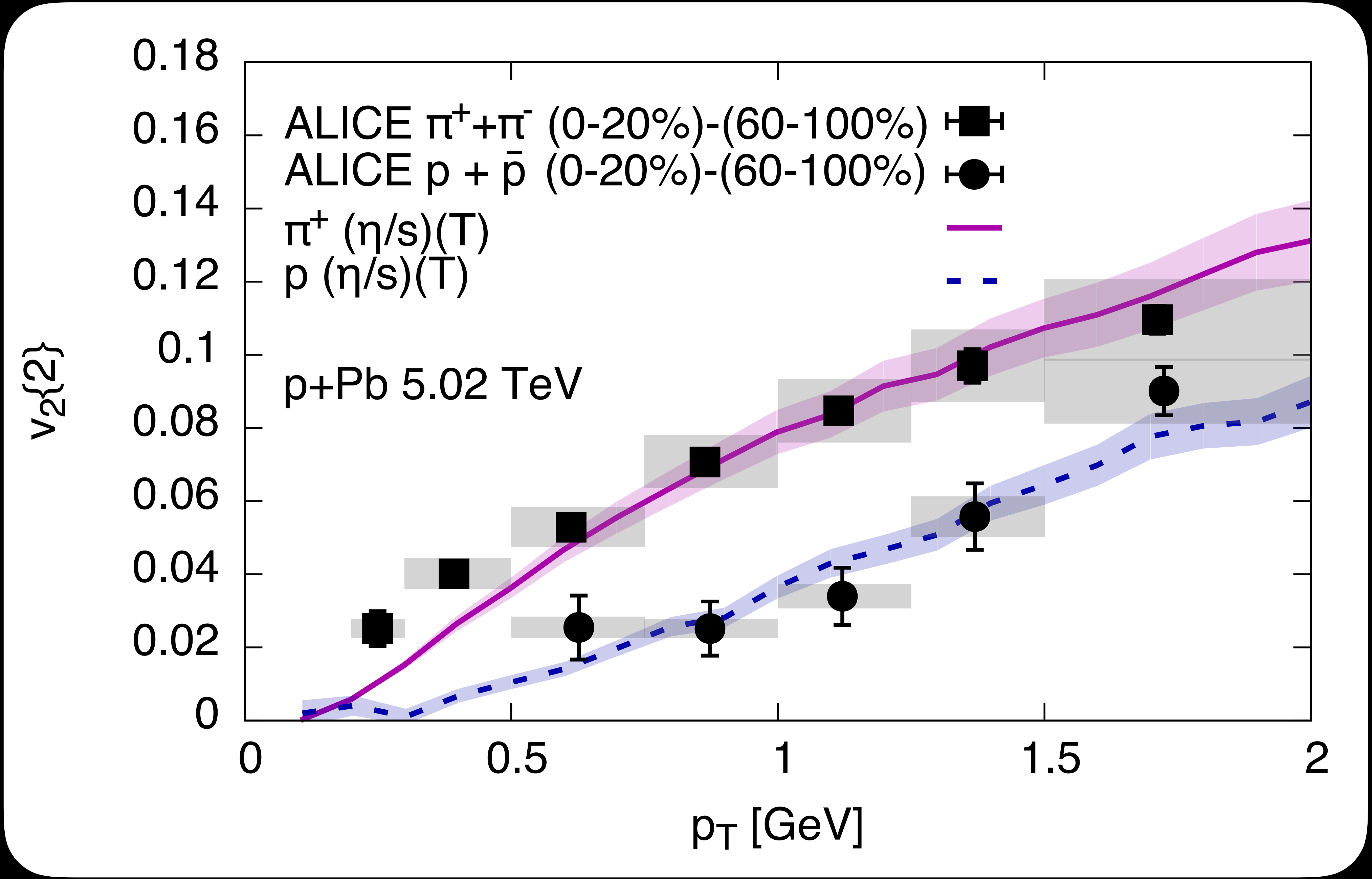
H. Mäntysaari, B. Schenke, C. Shen, P. Tribedy, Phys. Lett. B772, 681–686 (2017)



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

Identified particle flow

H. Mäntysaari, B. Schenke, C. Shen, P. Tribedy, Phys. Lett. B772, 681–686 (2017)



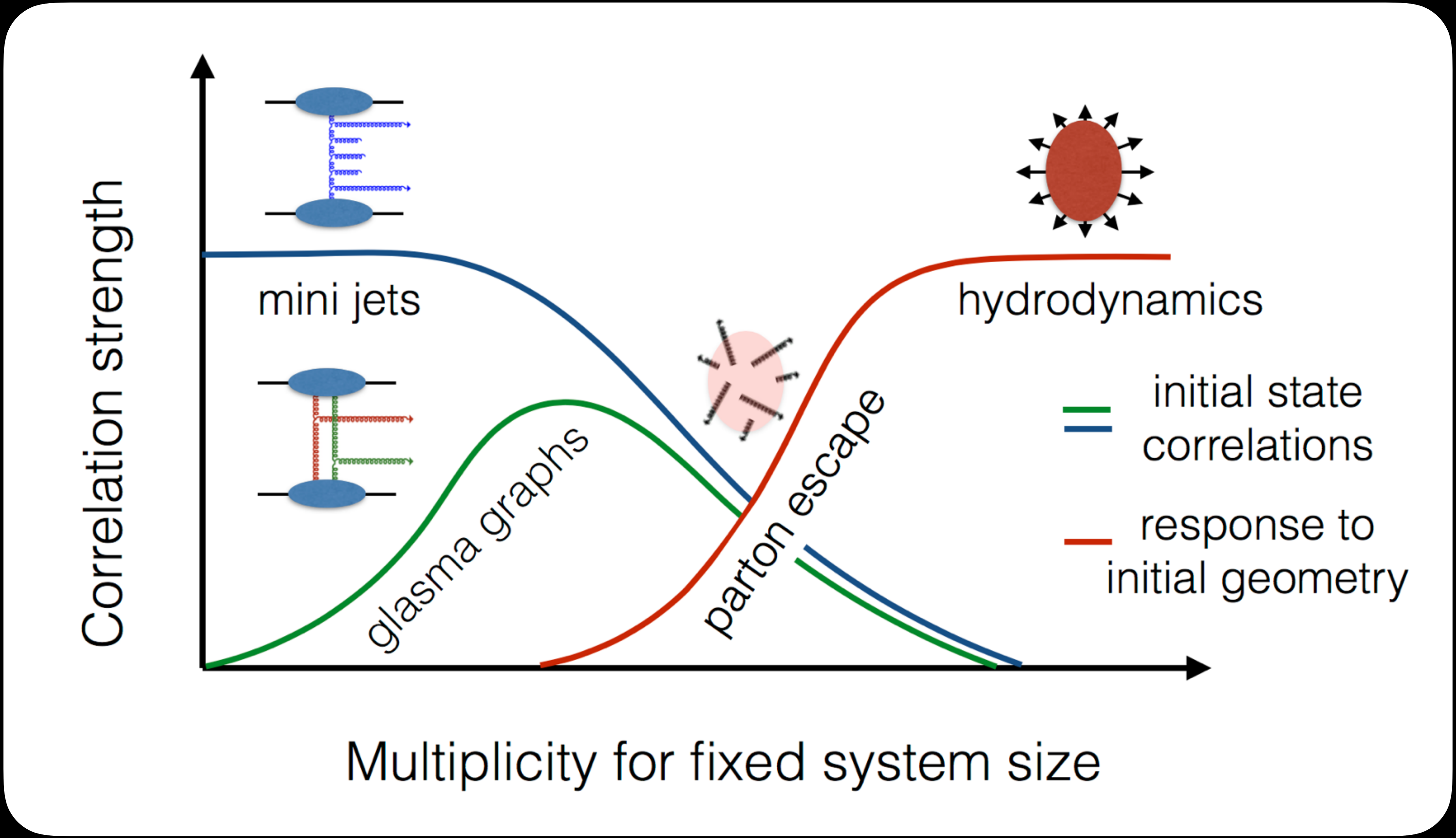
τ_0=0.4 fm

THERE’S ONE MORE THING…

WHAT ABOUT INITIAL MOMENTUM CORRELATIONS?

INTRODUCING THE
FIRST COMBINED
INITIAL+FINAL STATE
FRAMEWORK

FOR SEVERAL YEARS WE HAVE DRAWN PLOTS LIKE THIS: S. Schlichting, Quark Matter 2015



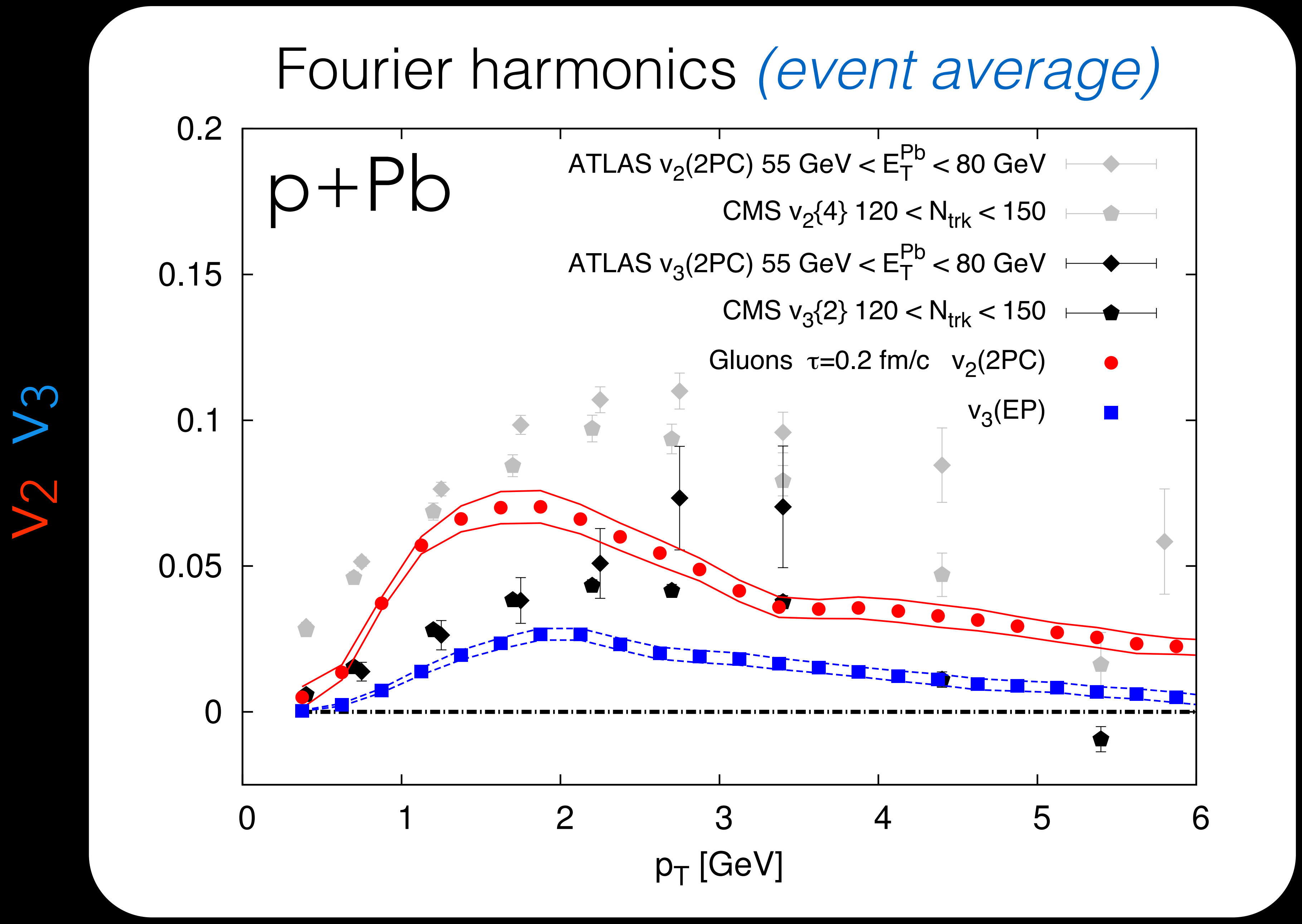
Now we can **calculate** the relative contribution of "glasma graphs" and final state effects

Reminder: Initial state correlations

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

$\tau = 0.2$ fm/c

gluons



At early times IP-Glasma (CGC) produces non-zero v_n

IP-Glasma + parton cascade

M. Greif, C. Greiner, B. Schenke, S. Schlichting, Z. Xu, arXiv:1708.02076

- Using hydrodynamics erases the initial state correlations from the IP-Glasma
- To keep them, we use a microscopic model, the parton cascade BAMPS Z.Xu, C. Greiner, PRC71, 064901 (2005)

IP-Glasma → $\frac{dN_g}{dy\,d^2x_T\,d^2p_T}$ Wigner Distribution → sample gluons → run BAMPS (pQCD)

smear → Husimi Distribution

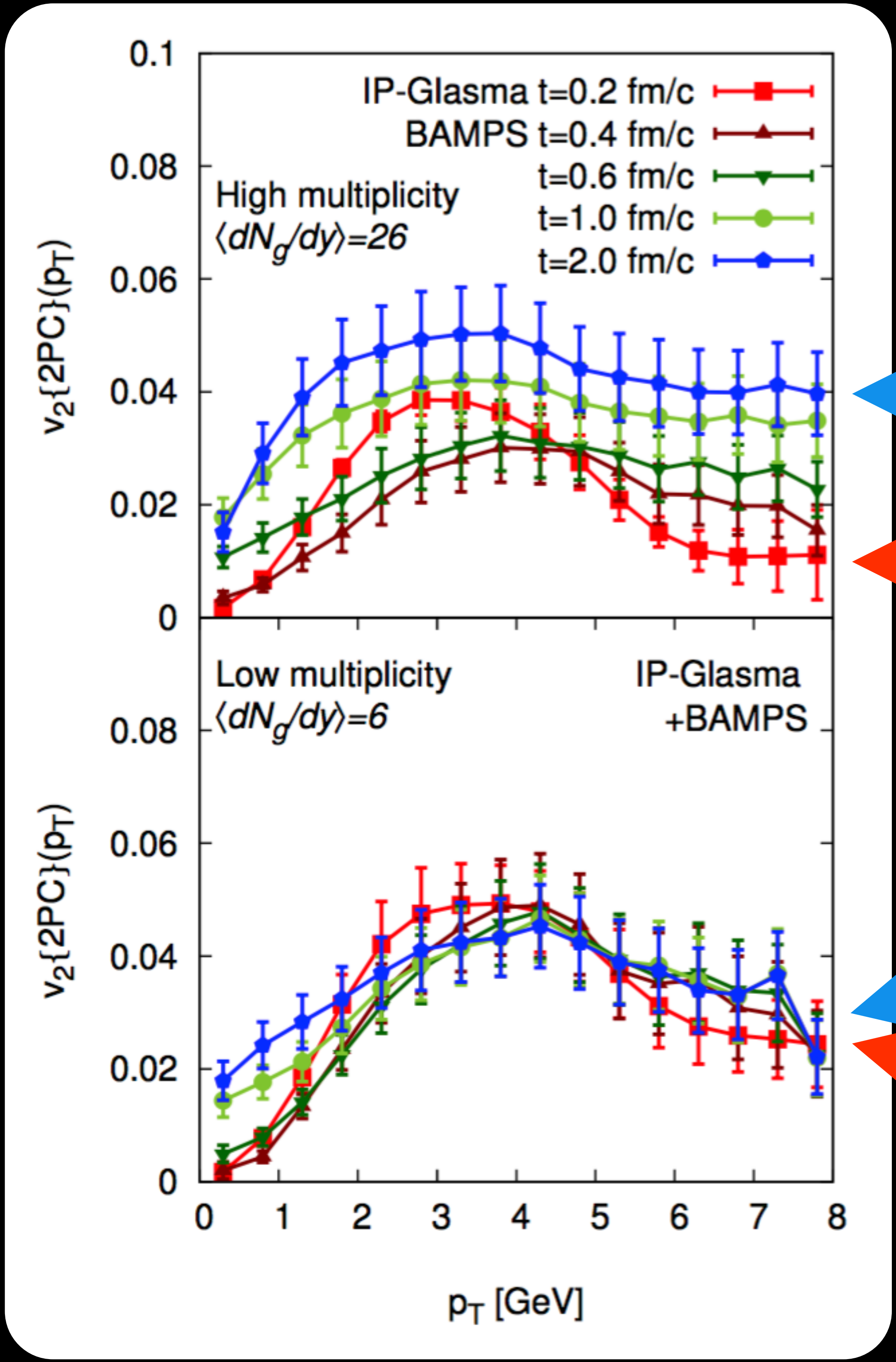
⇒ study momentum anisotropy as function of time

Time evolution of v_2

M. Greif, C. Greiner, B. Schenke, S. Schlichting, Z. Xu, arXiv:1708.02076

high multiplicity

low multiplicity



final v_2 (2fm)

initial v_2 (0.2fm)

final v_2 (2fm)

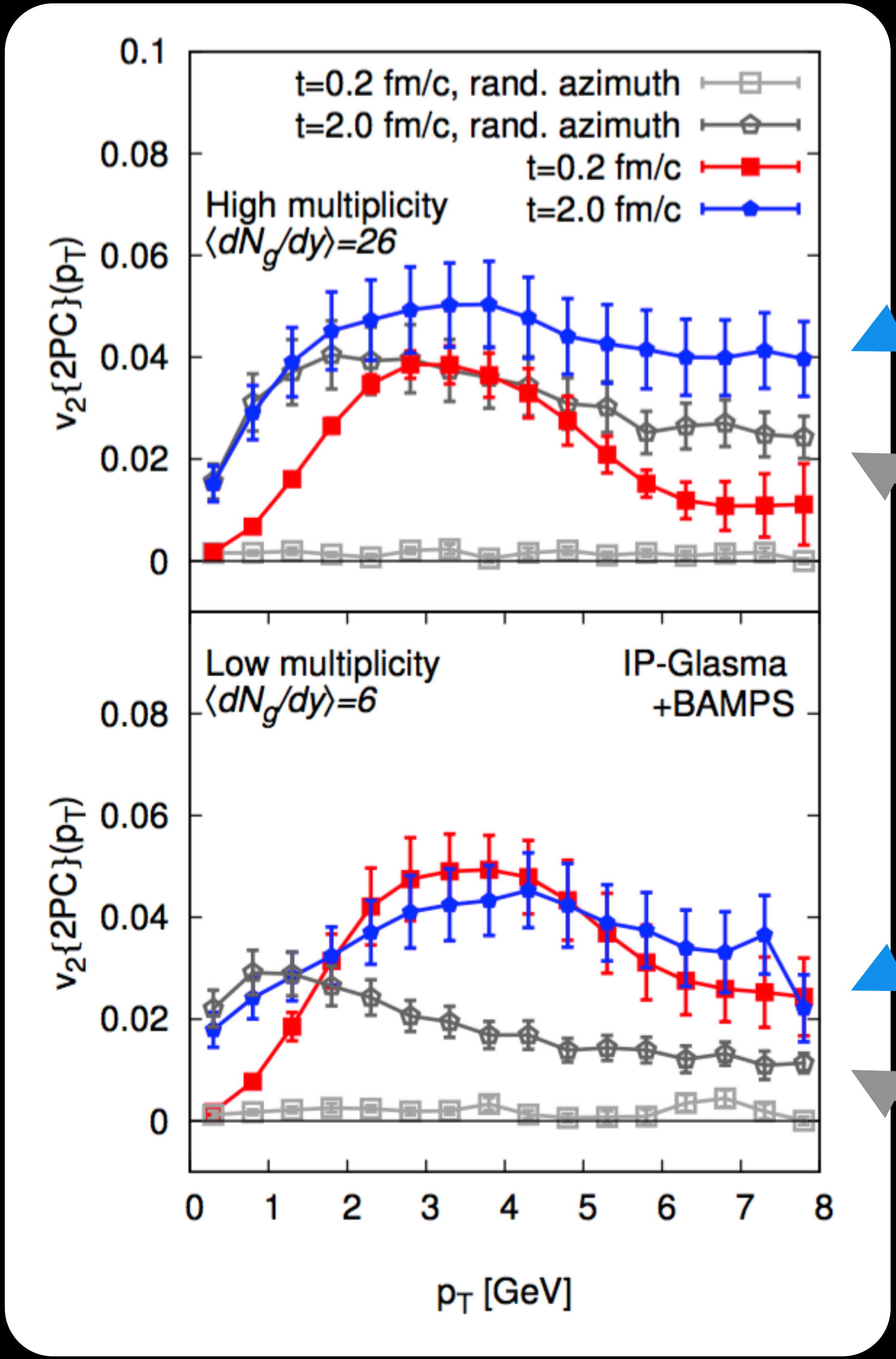
initial v_2 (0.2fm)

Effect of initial correlations on final v_2

M. Greif, C. Greiner, B. Schenke, S. Schlichting, Z. Xu, arXiv:1708.02076

high multiplicity

low multiplicity



with initial corr.

without initial corr.

with initial corr.

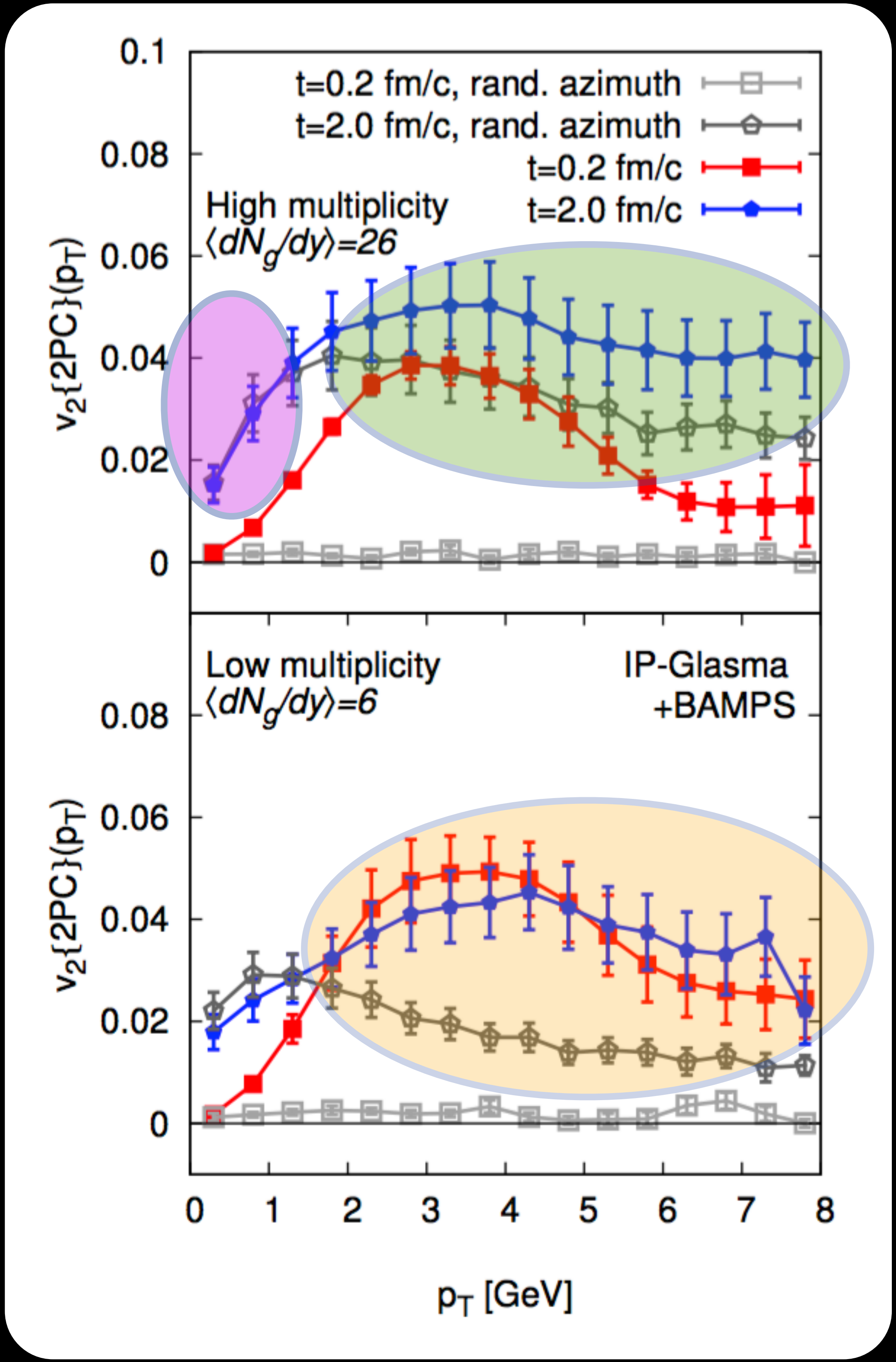
without initial corr.

Effect of initial correlations on final v_2

M. Greif, C. Greiner, B. Schenke, S. Schlichting, Z. Xu, arXiv:1708.02076

high multiplicity

low multiplicity



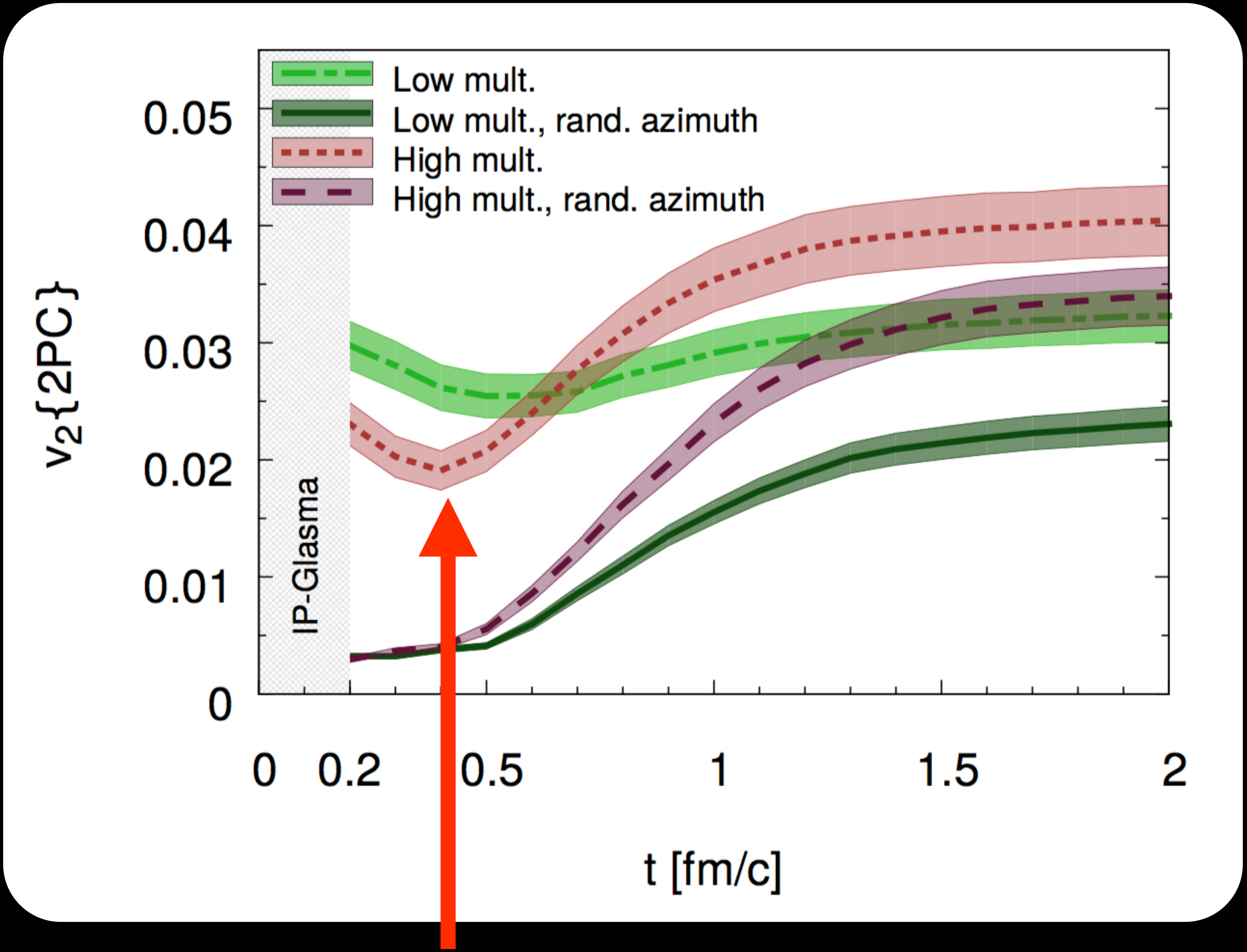
🟣 negligible effect at small p_T and high multiplicity

🟠 significant effect at p_T >2 GeV and low multiplicity

🟢 significant effect at p_T >3 GeV and high multiplicity

Evolution of integrated v_2

M. Greif, C. Greiner, B. Schenke, S. Schlichting, Z. Xu, arXiv:1708.02076



Both high and low multiplicity integrated v_2 are affected by initial correlations

First, initial correlation is reduced then final state correlation built up

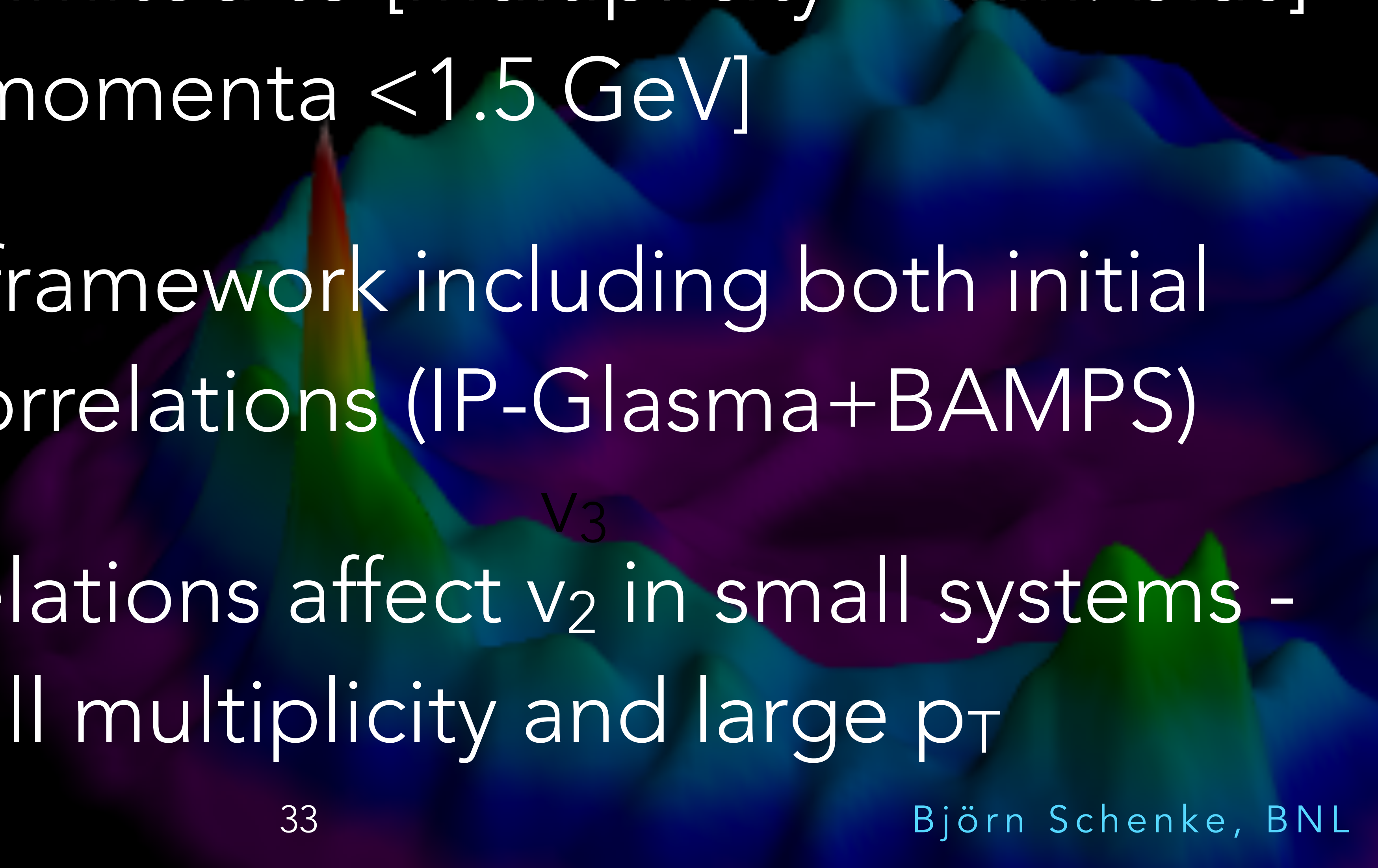
Summary

- Small system momentum anisotropy well described in hydrodynamic framework when proton fluctuations are included

- Hydrodynamics limited to [multiplicity > min. bias] and [transverse momenta <1.5 GeV]

- Introduced first framework including both initial and final state correlations (IP-Glasma+BAMPS)

- Initial state correlations affect v_2 in small systems - dominate at small multiplicity and large p_T



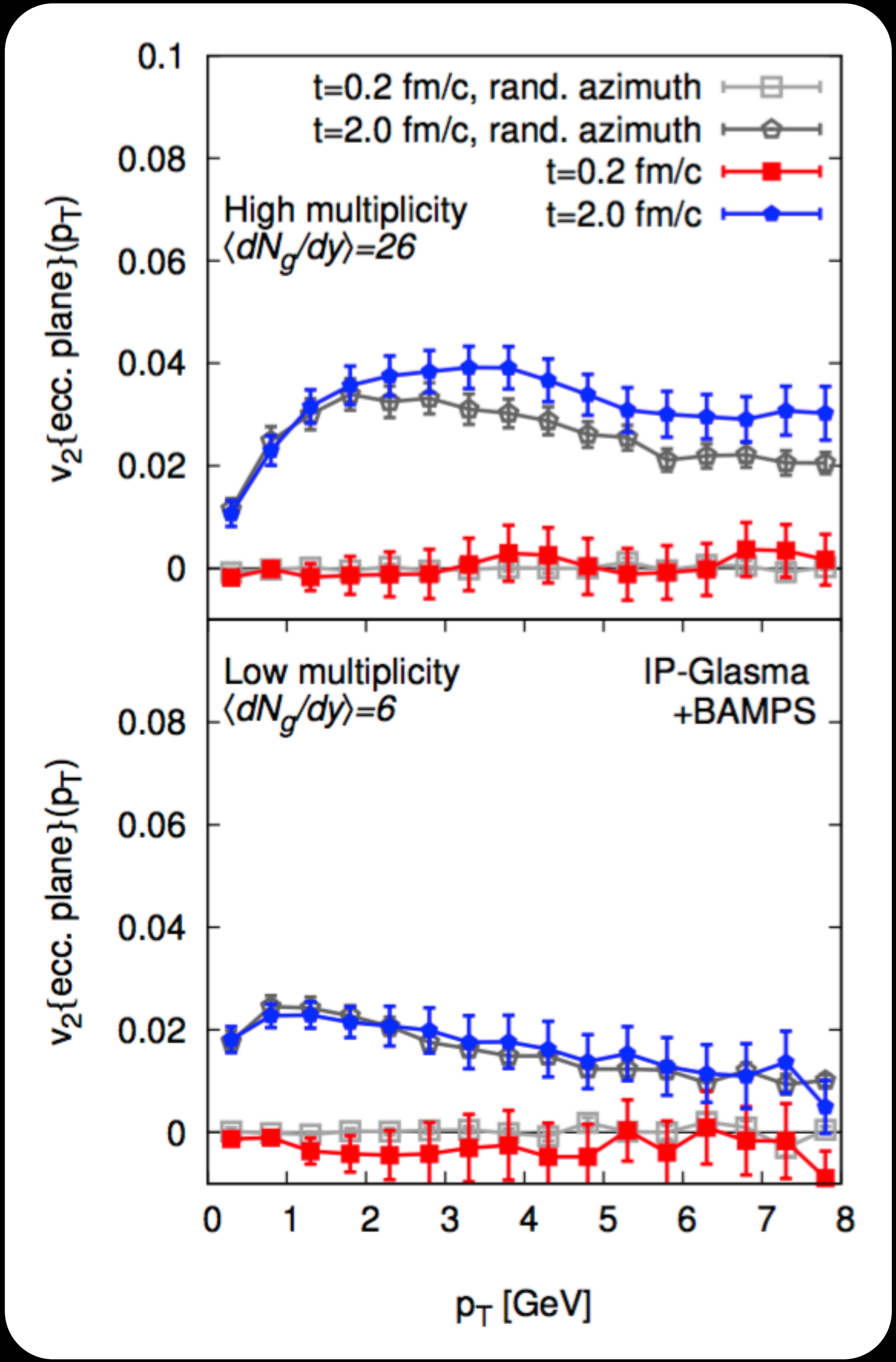
BACKUP

v_2 relative to the eccentricity plane

M. Greif, C. Greiner, B. Schenke, S. Schlichting, Z. Xu, arXiv:1708.02076

high multiplicity

low multiplicity



initial state contribution not correlated with geometry

Final state v_2 relative to the ecc. plane only weakly affected by initial state correlations

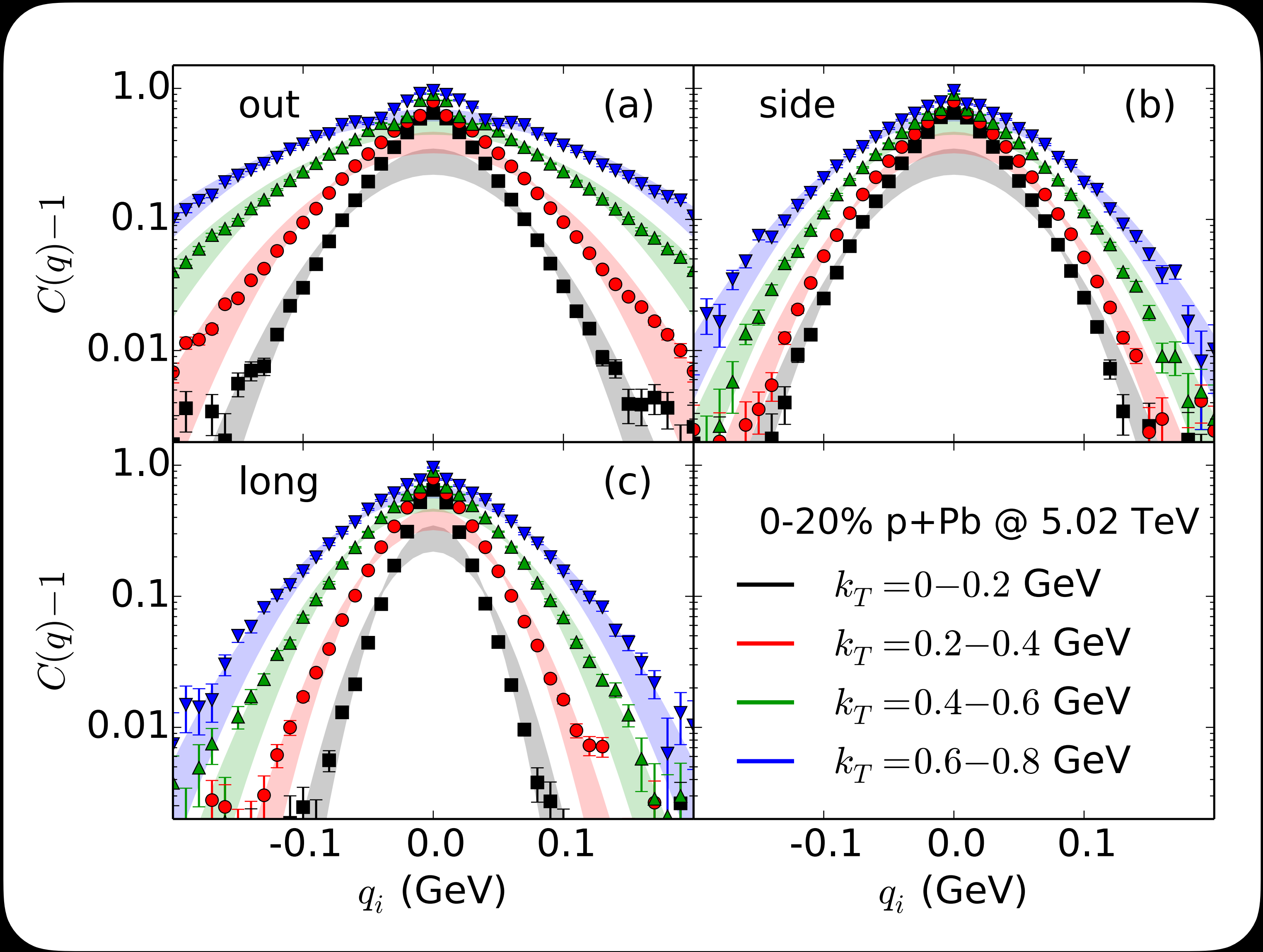
HBT radii

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)



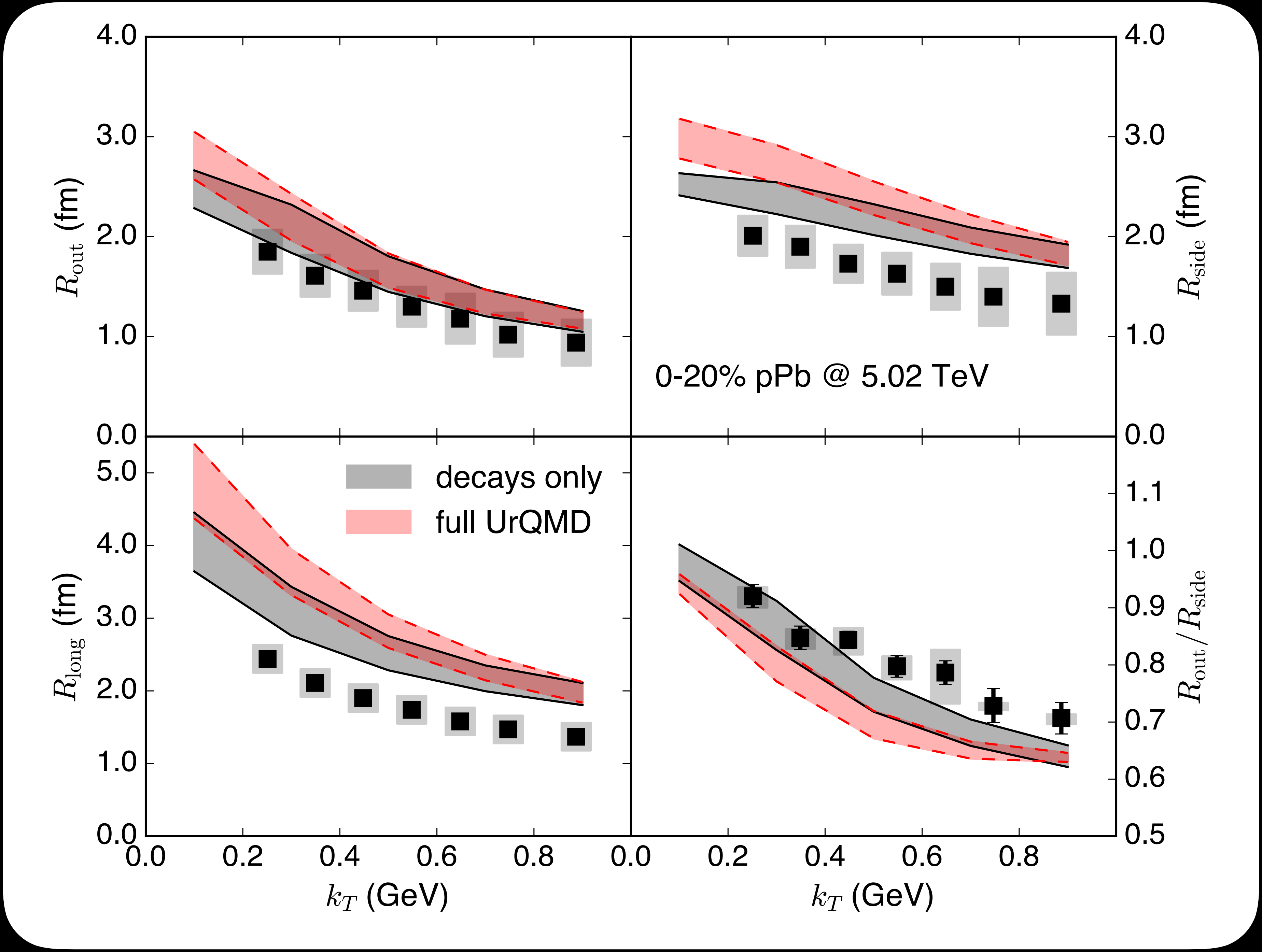
Fit to the Pratt-Bertsch parameterization in the longitudinally co-moving system

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)

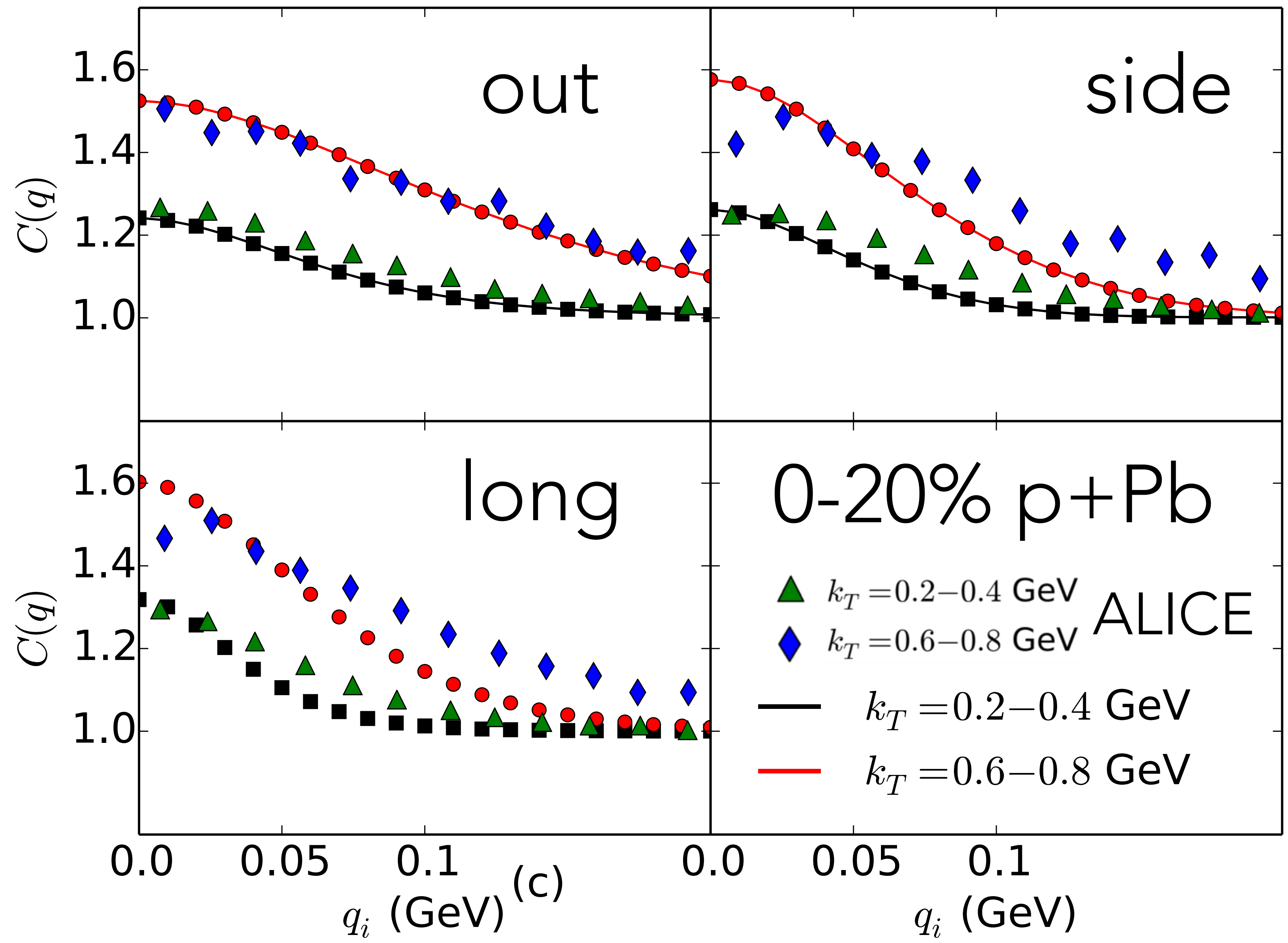


τ_0=0.4 fm (η/s)(T)

HBT radii

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

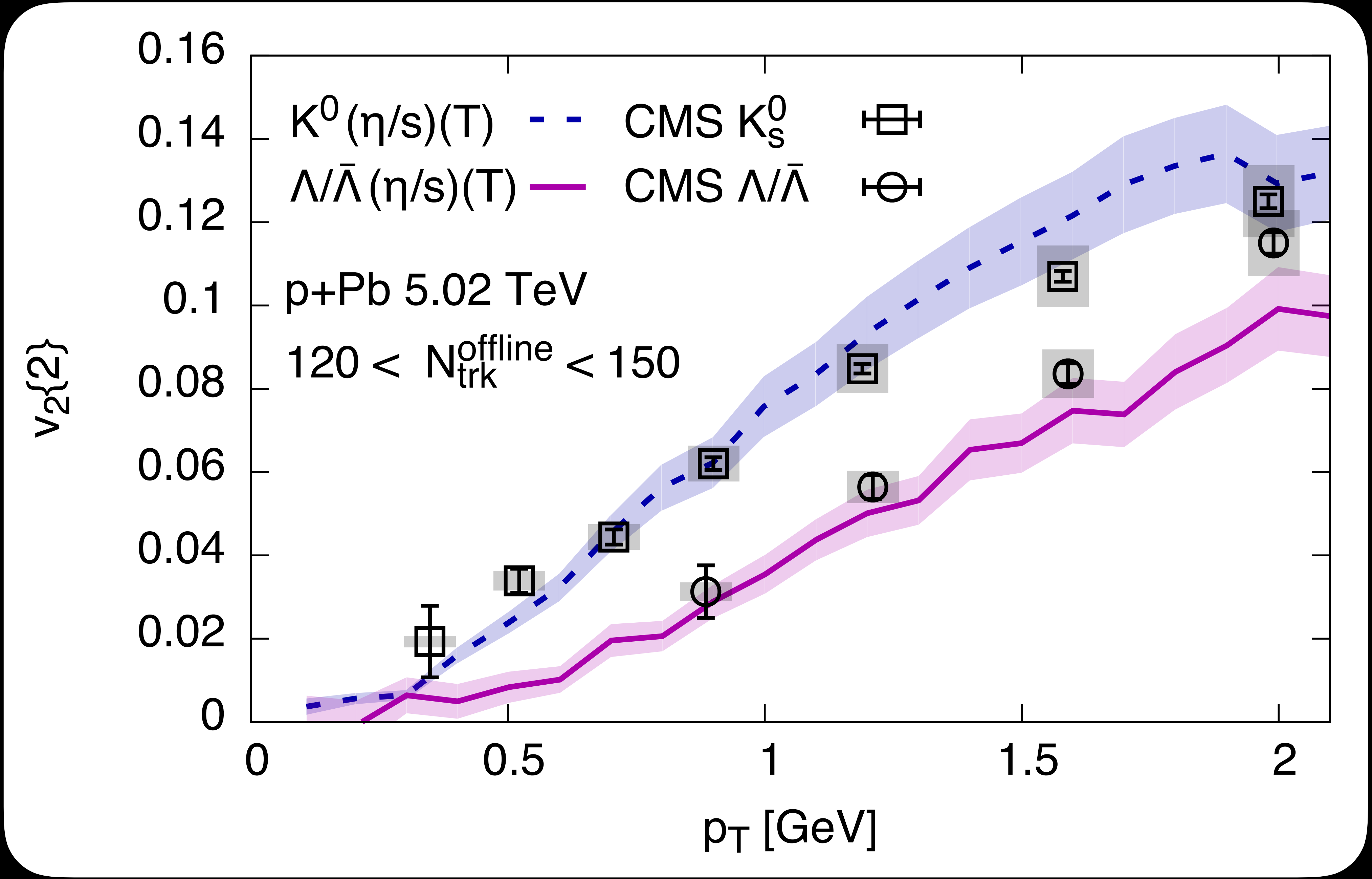
Data: ALICE Collaboration, J. Adam et al. (ALICE), Phys. Rev. C91, 034906 (2015)



τ_0=0.4 fm (η/s)(T)

Identified particle flow

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

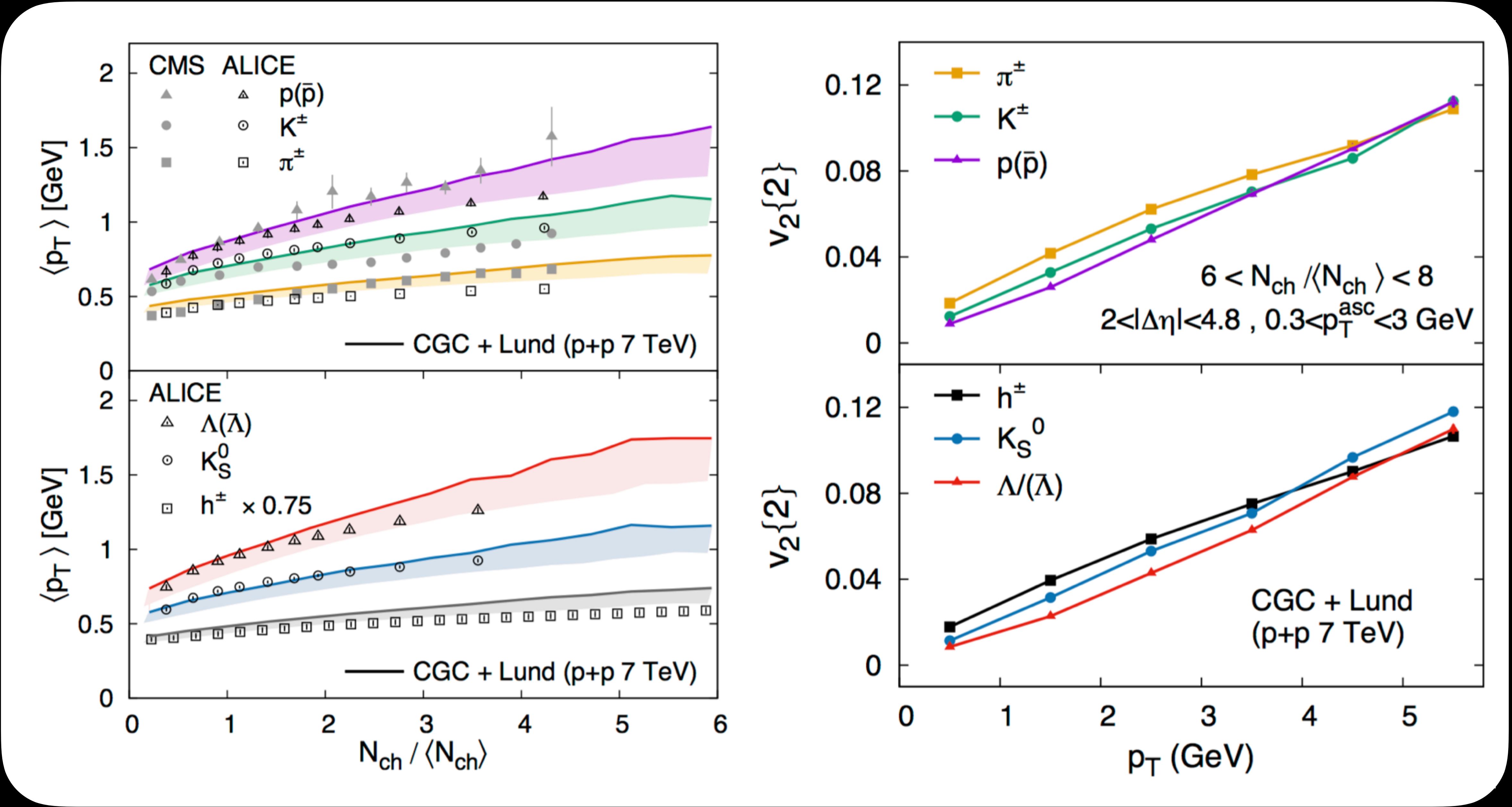


τ_0=0.4 fm

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

Significance of initial state in small systems

Lifetime in small systems is shorter than in typical A+A events

Details of the initial state matter more:

- Initial/switching time
- Initial flow
- Initial viscous stress tensor
- Possibly the details of matching

Viscous stress in the initial state

We have always neglected the initial $\pi^{\mu\nu}$ from the IP-Glasma

But of course it is there - in p+A it likely matters

There is also u^{η}, flow in the rapidity direction

Finally one can define bulk stress as $\Pi = \frac{\varepsilon}{3} - P$ using P from the EoS in hydrodynamics to match to all components of the CYM $T^{\mu\nu}$

The last two parts have a small effect.

$\pi^{\mu\nu}$ from the IP-Glasma

Determine ε and u^μ from

$$\varepsilon u^\nu = u_\mu T^{\mu\nu}$$

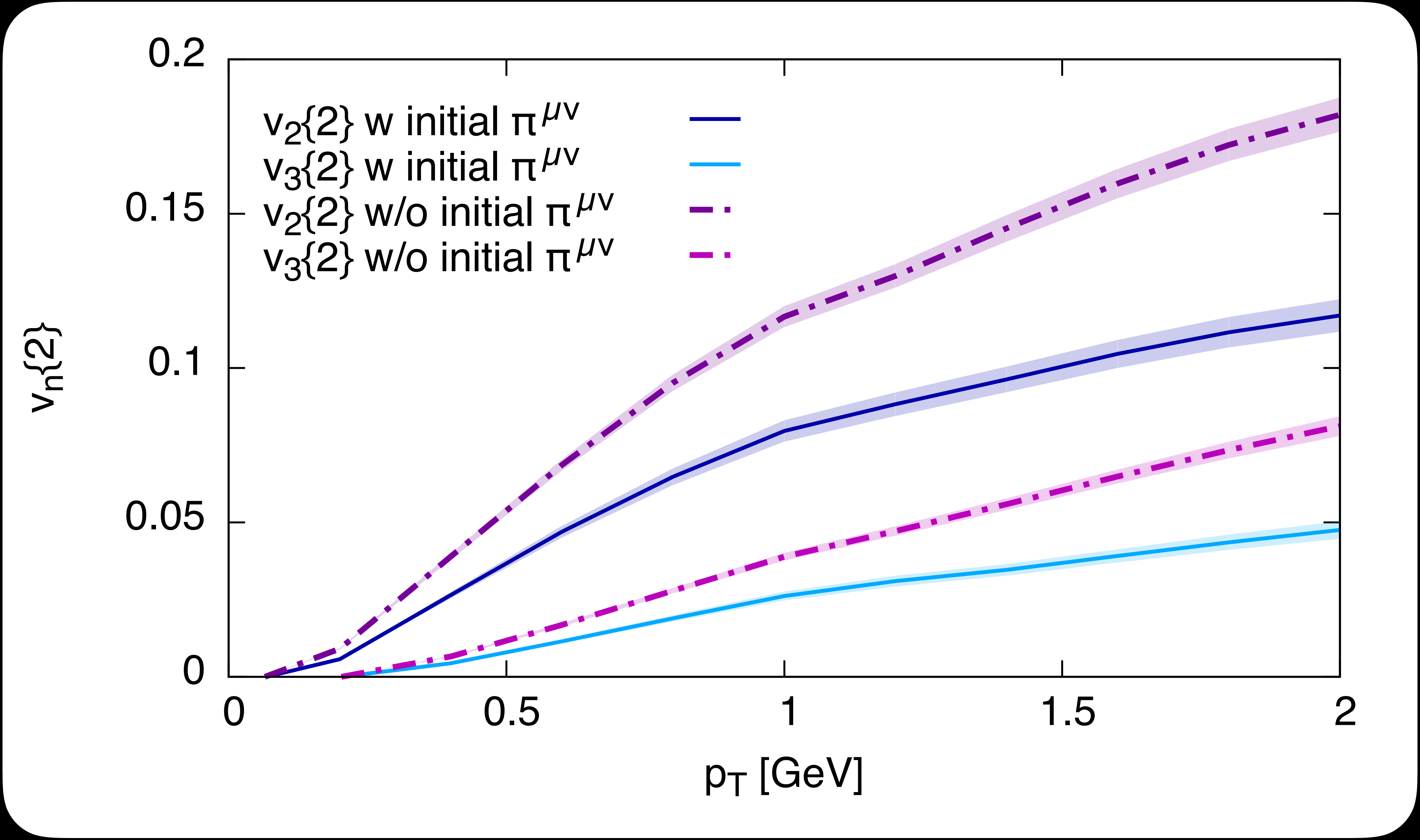
then, using P=ε/3

(it would be, had we reached isotropy in the CYM system):

$$\pi^{\mu\nu} = T^{\mu\nu}_{\mathrm{CYM}} - \frac{4}{3}\varepsilon u^\mu u^\nu + \frac{\varepsilon}{3} g^{\mu\nu}$$

This is potentially quite large

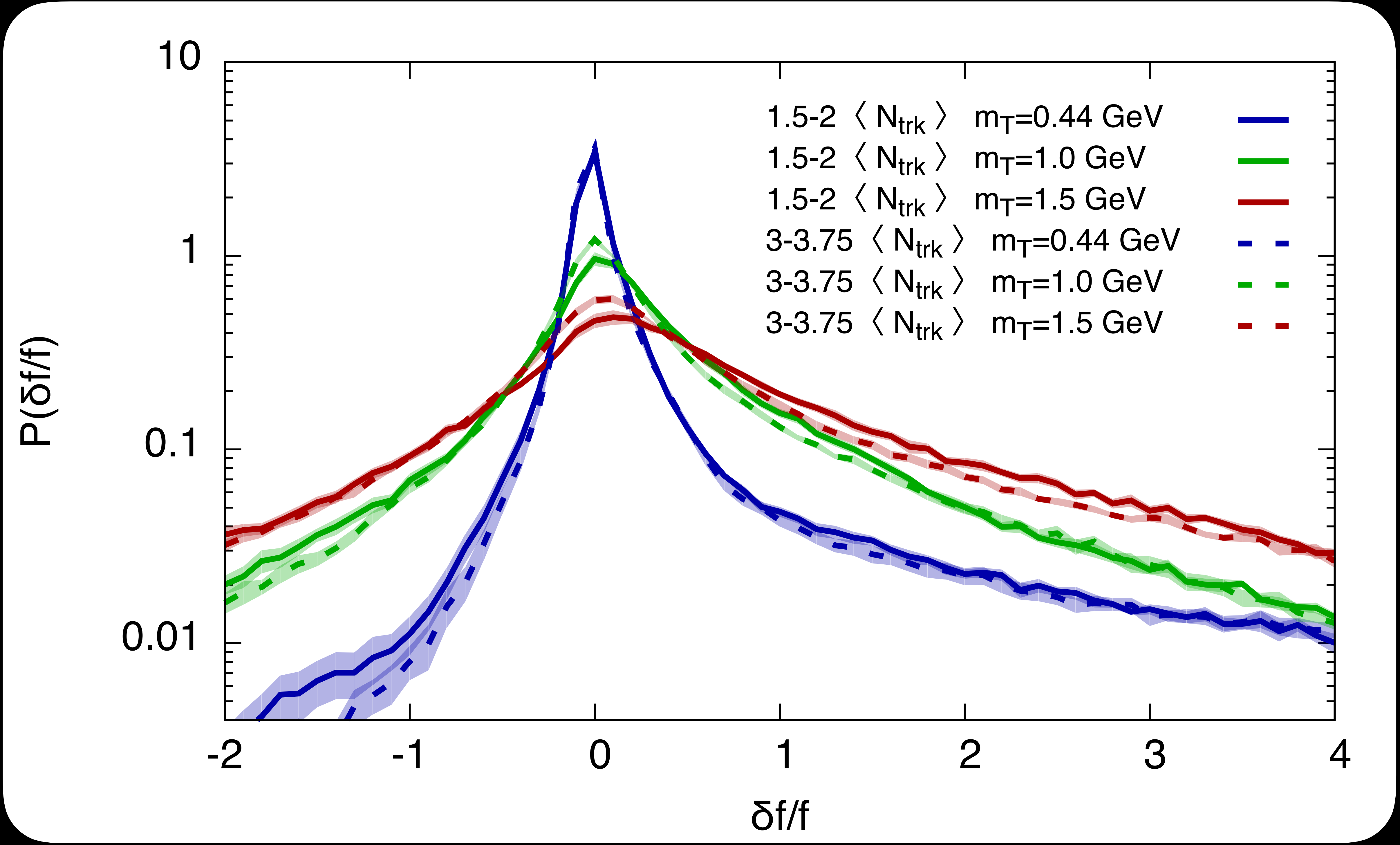
Effect of initial $\pi^{\mu\nu}$ from the IP-Glasma



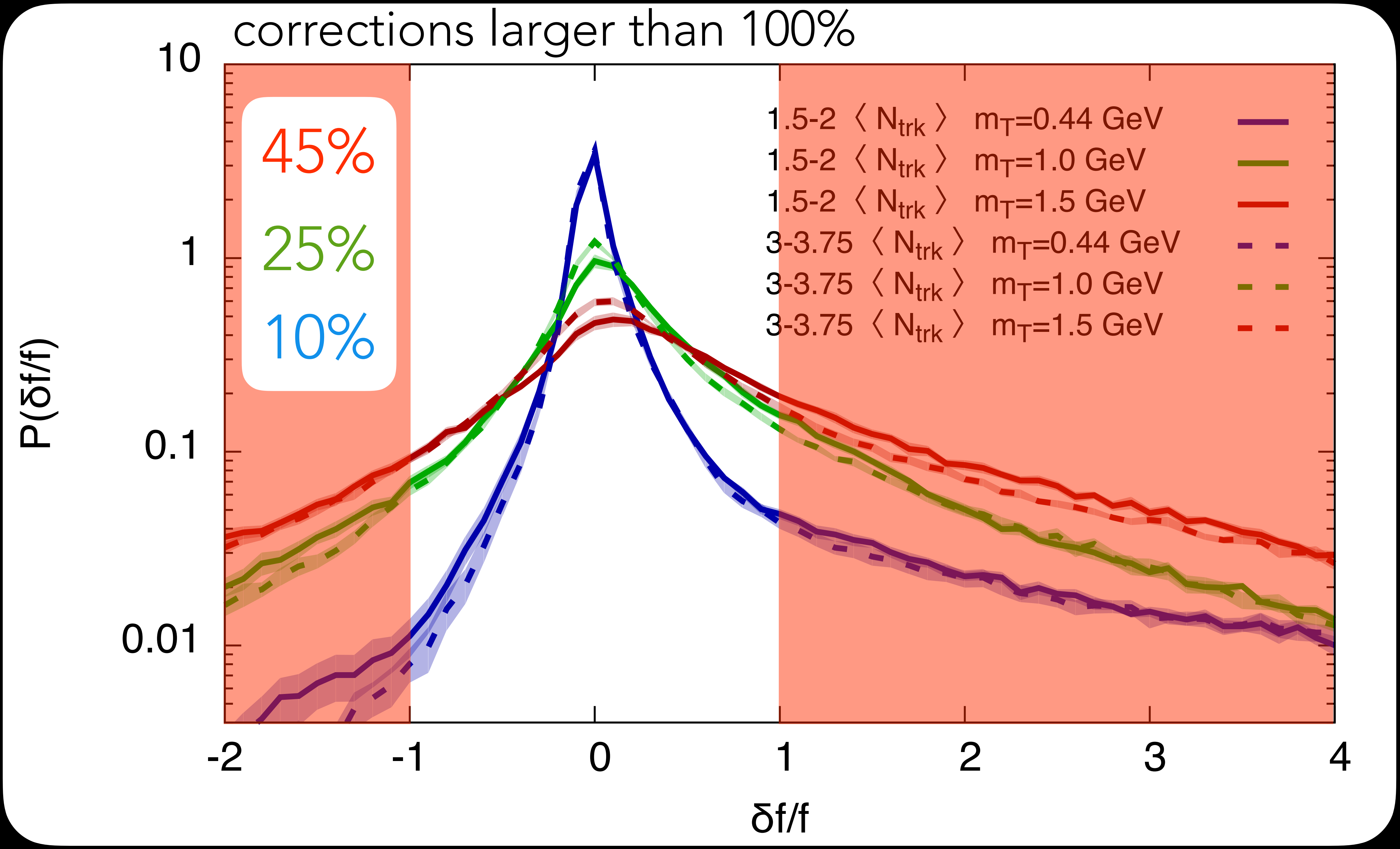
τ_0=0.4 fm η/s=0.2 $\tau_\pi = 5\frac{\eta}{\varepsilon + P}$

Björn Schenke, BNL

Histogram of δf/f on the switching surface

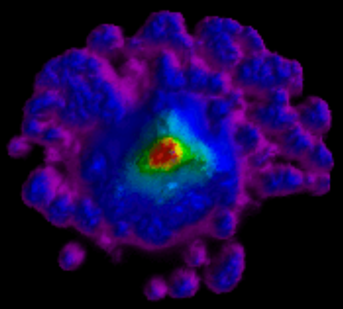


Histogram of δf/f on the switching surface

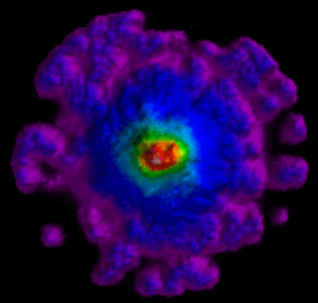


Temperature profile without bulk viscosity

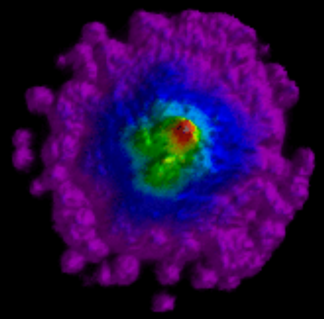
~1⟨N⟩



~2⟨N⟩

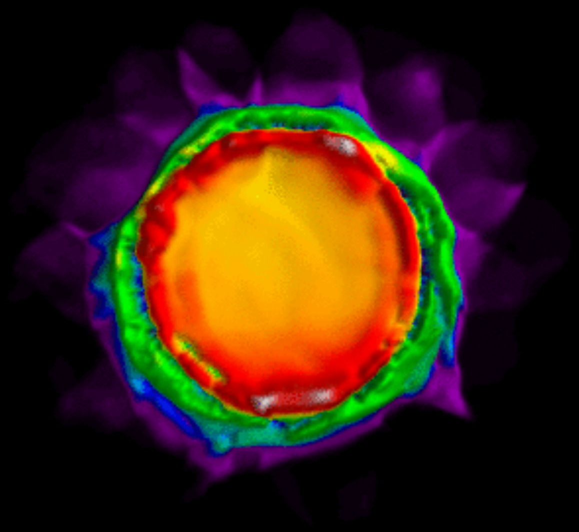


~3⟨N⟩



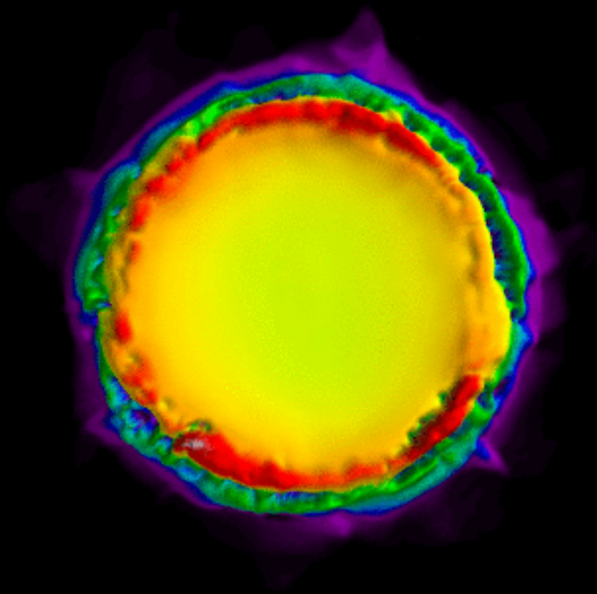
Temperature profile without bulk viscosity

$\sim 1\langle N\rangle$



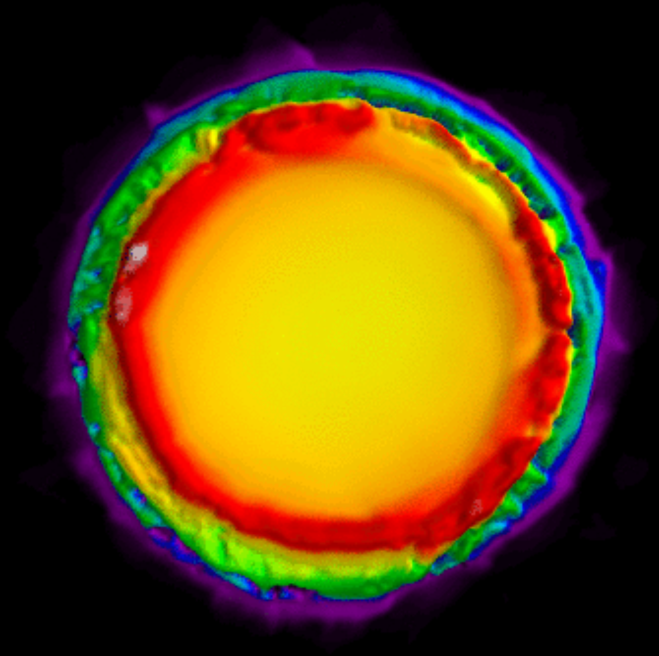
2.55 fm

$\sim 2\langle N\rangle$



3.6 fm

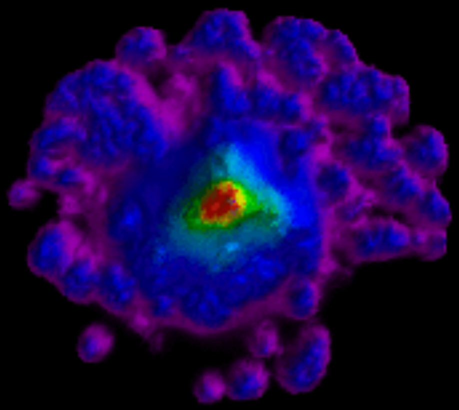
$\sim 3\langle N\rangle$



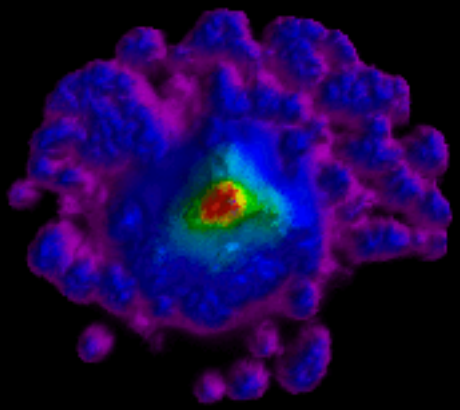
4.2 fm

Effect of Bulk viscosity

w/o bulk viscosity

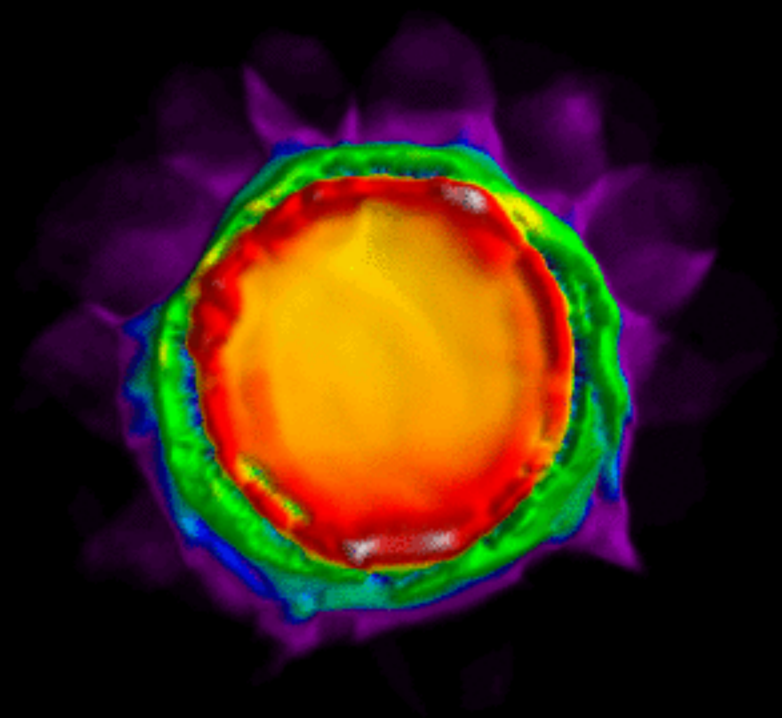


with bulk viscosity



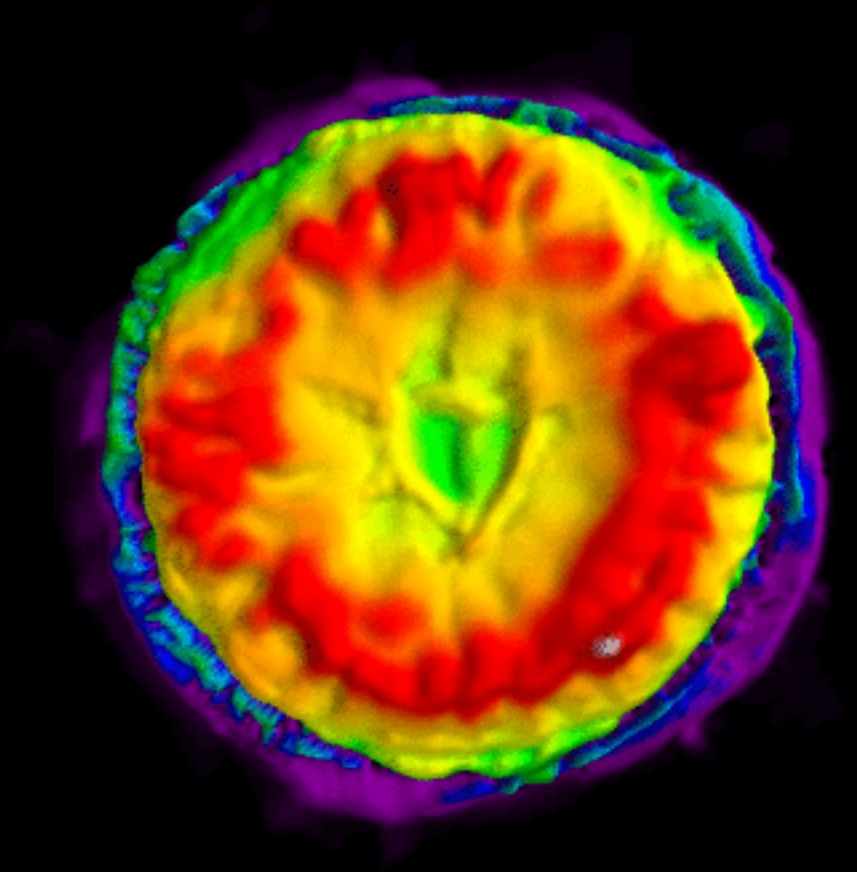
Effect of Bulk viscosity

w/o bulk viscosity



2.55 fm

with bulk viscosity



4.65 fm

Relativistic fluid dynamics

- Effective theory for the long wavelength modes, valid for a strongly interacting system

- Basic equations: **energy and momentum conservation**

$$\partial_\mu T^{\mu\nu} = 0 \quad \text{with} \quad T^{\mu\nu} = (\overset{\substack{\text{energy density}\\ \downarrow}}{\varepsilon} + P)\underset{\substack{\uparrow\\ \text{flow velocity}}}{u^\mu} u^\nu - \overset{\substack{\text{pressure}\\ \downarrow}}{P} g^{\mu\nu} + \underset{\substack{\uparrow\\ \text{viscous correction}}}{\Pi^{\mu\nu}}$$

- + constituent equations for $\Pi^{\mu\nu}$
(contains shear viscosity η and bulk viscosity ζ, possibly heat conductivity and higher order transport coefficients)

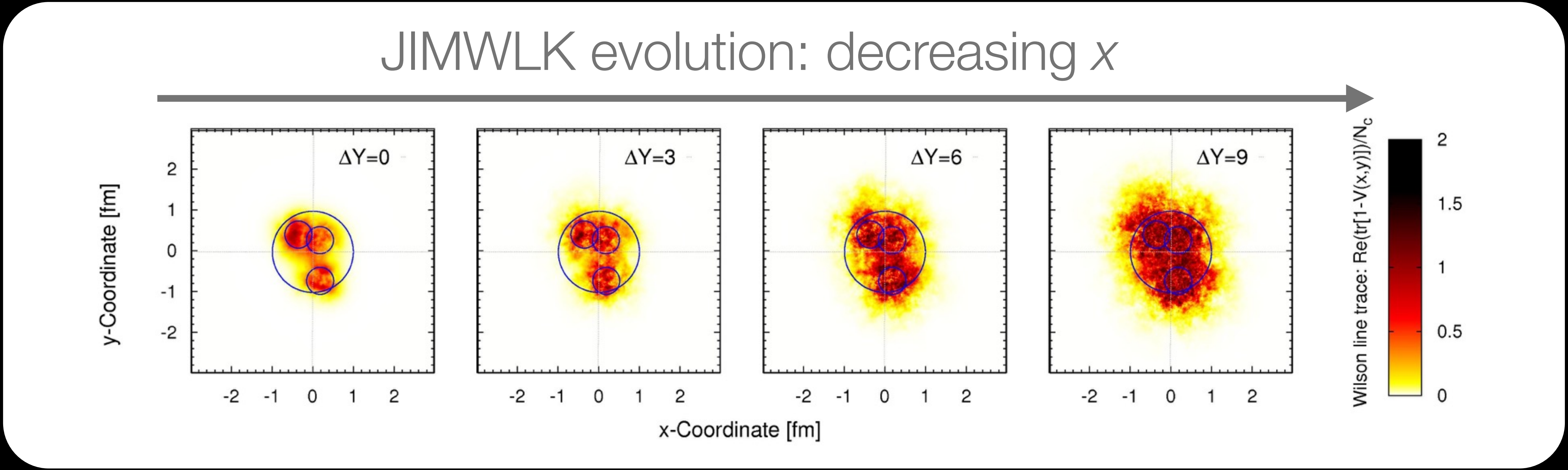
- Equation of state $P(\varepsilon)$ relates pressure to energy density (lattice)

JIMWLK evolution of the proton

Working on calculations relevant to a future EIC:

H. Mäntysaari, B. Schenke, work in progress

- Diffraction - more on proton and nuclear shape and fluctuations
- Small-x evolution of structure functions etc.
- Interesting fundamental questions and input for heavy in program

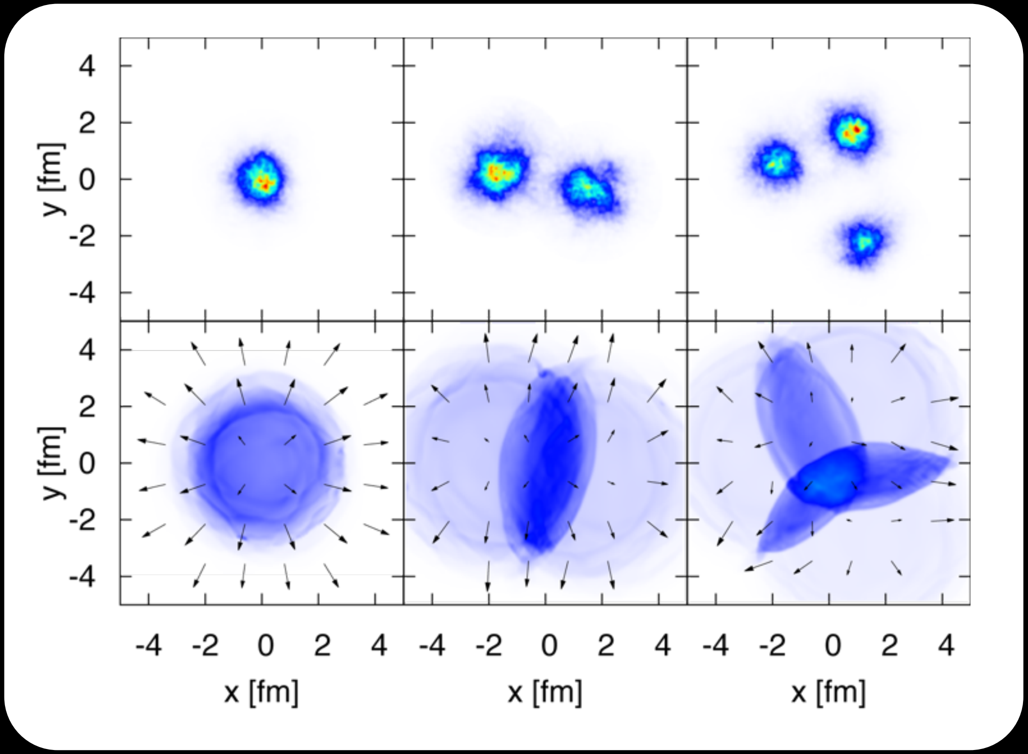


S. Schlichting, B. Schenke, Phys. Lett. B739, 313-319 (2014)

Even at small x the proton is not a sphere of gluons

HOW TO DISTINGUISH "FLOW" FROM AN "INITIAL STATE" SCENARIO

- **^{3}He+Au, d+Au:** Systematics of flow in different systems Explained by hydrodynamics. Initial state: no calculation



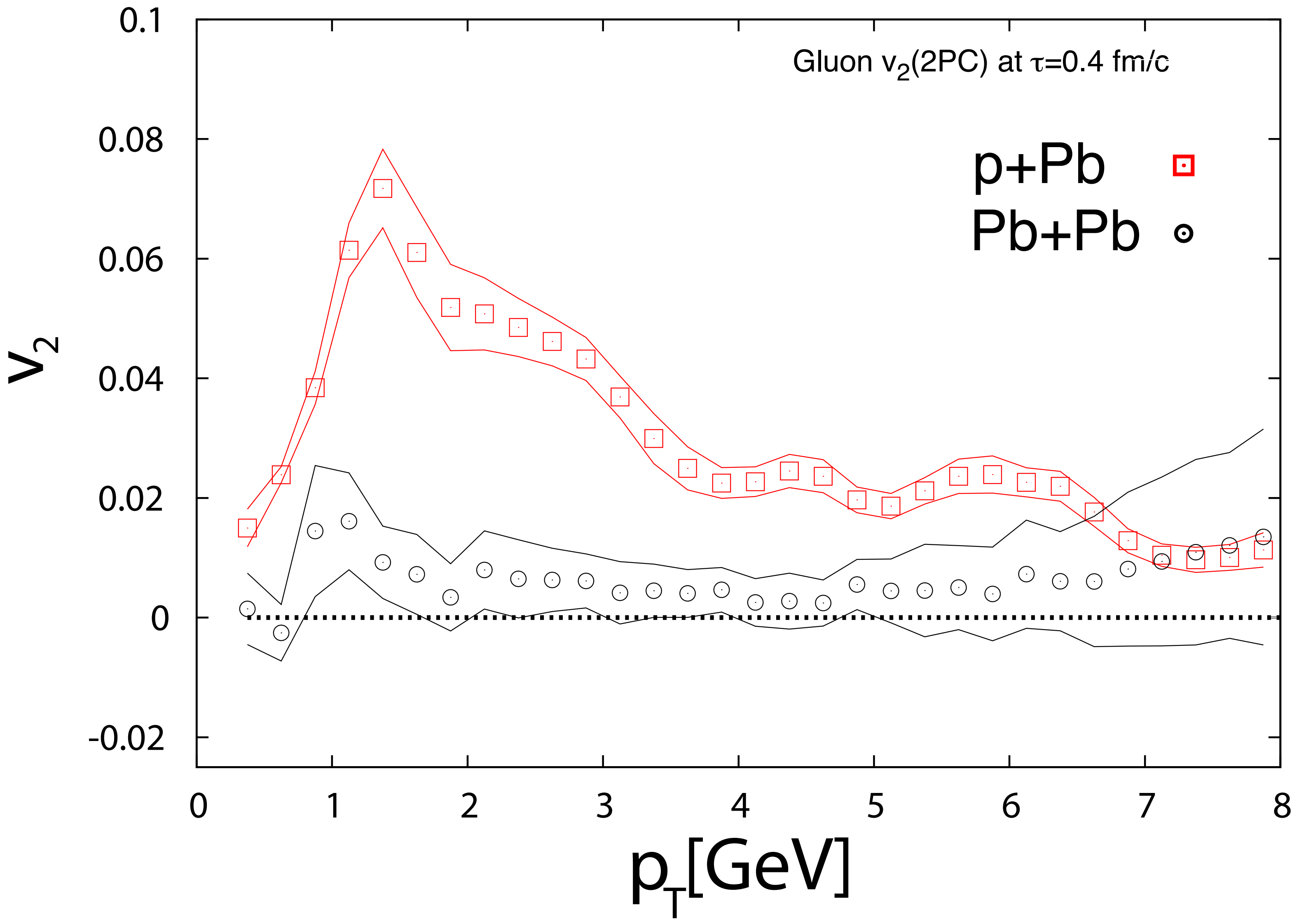
MEASUREMENT:
PHENIX COLLABORATION
PRL 114, 192301 (2015)
PRL 115, 142301 (2015

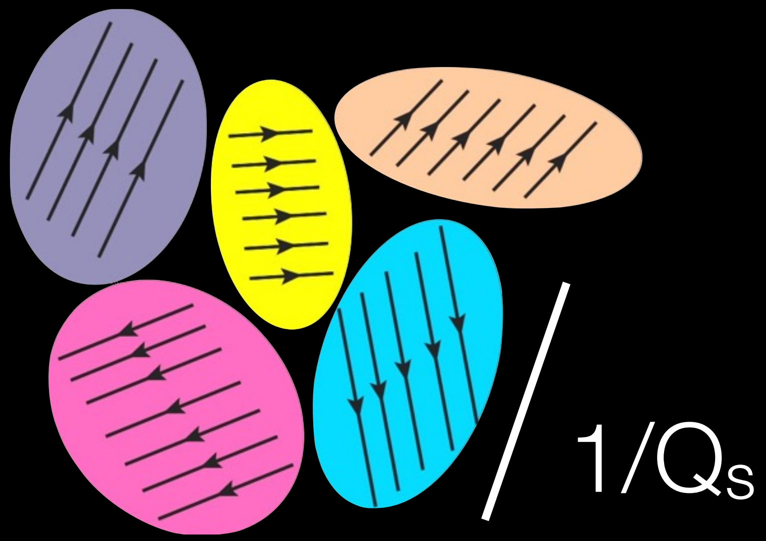
CALCULATIONS:
BOZEK, BRONIOWSKI, PLB739 (2014) 308
NAGLE ET AL, PRL113 (2014)
BOZEK, BRONIOWSKI, PLB747 (2015) 135
SCHENKE, VENUGOPALAN, NPA931 (2014) 1039
ROMATSCHKE, EUR. PHYS. J. C75 (2015) 305

- Higher order cumulants: Data shows that **$v_2\{4\}\approx v_2\{6\}\approx v_2\{8\}$ …** Natural in hydrodynamics but not a unique feature

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

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

$$ImT\,|\psi_k\rangle = A_k |\psi_k\rangle$$

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