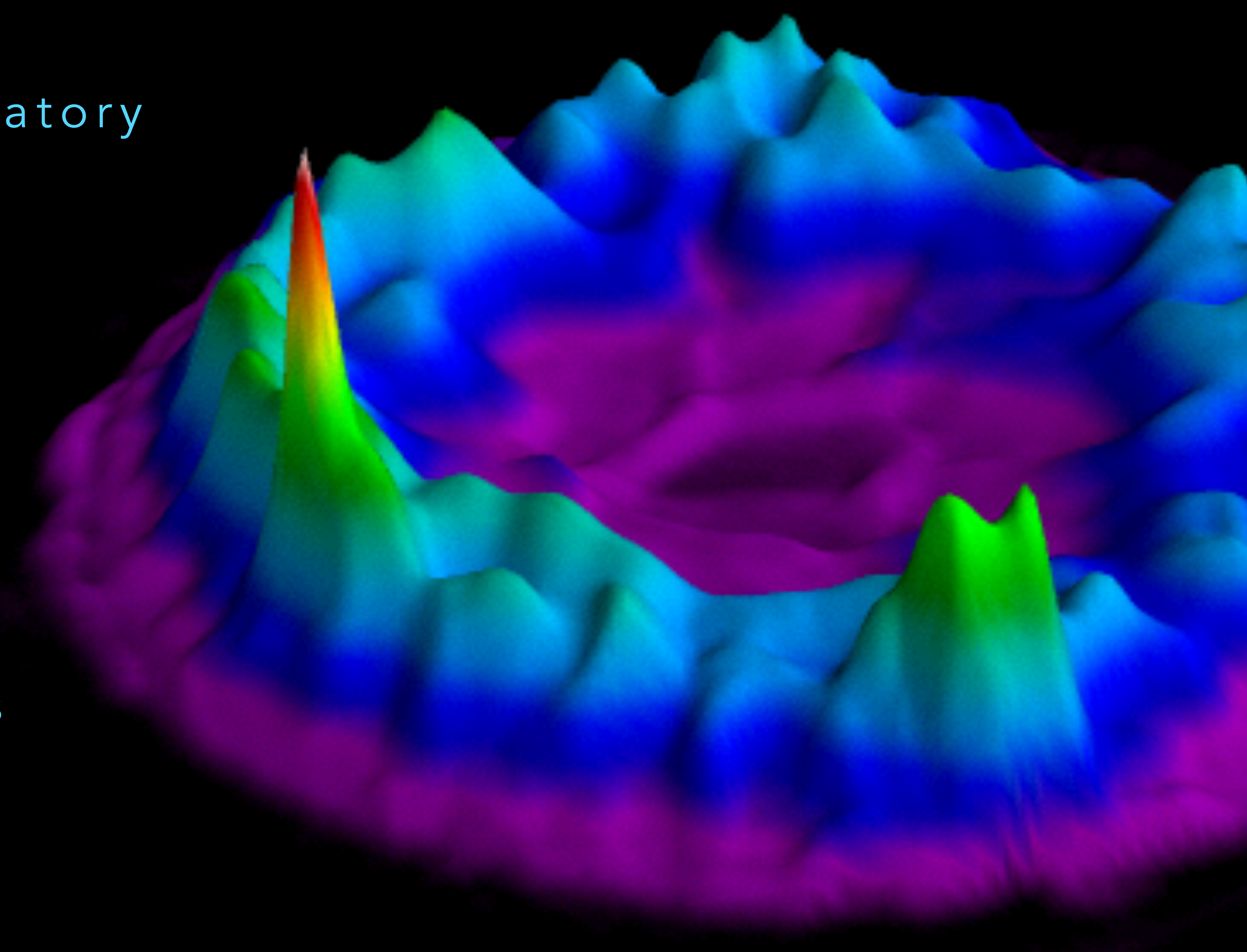
U.S. DEPARTMENT OF ENERGY | Office of Science

BROOKHAVEN NATIONAL LABORATORY

IMPRINTS OF THE PROTON SHAPE IN p+Pb COLLISIONS

Björn Schenke
Brookhaven National Laboratory



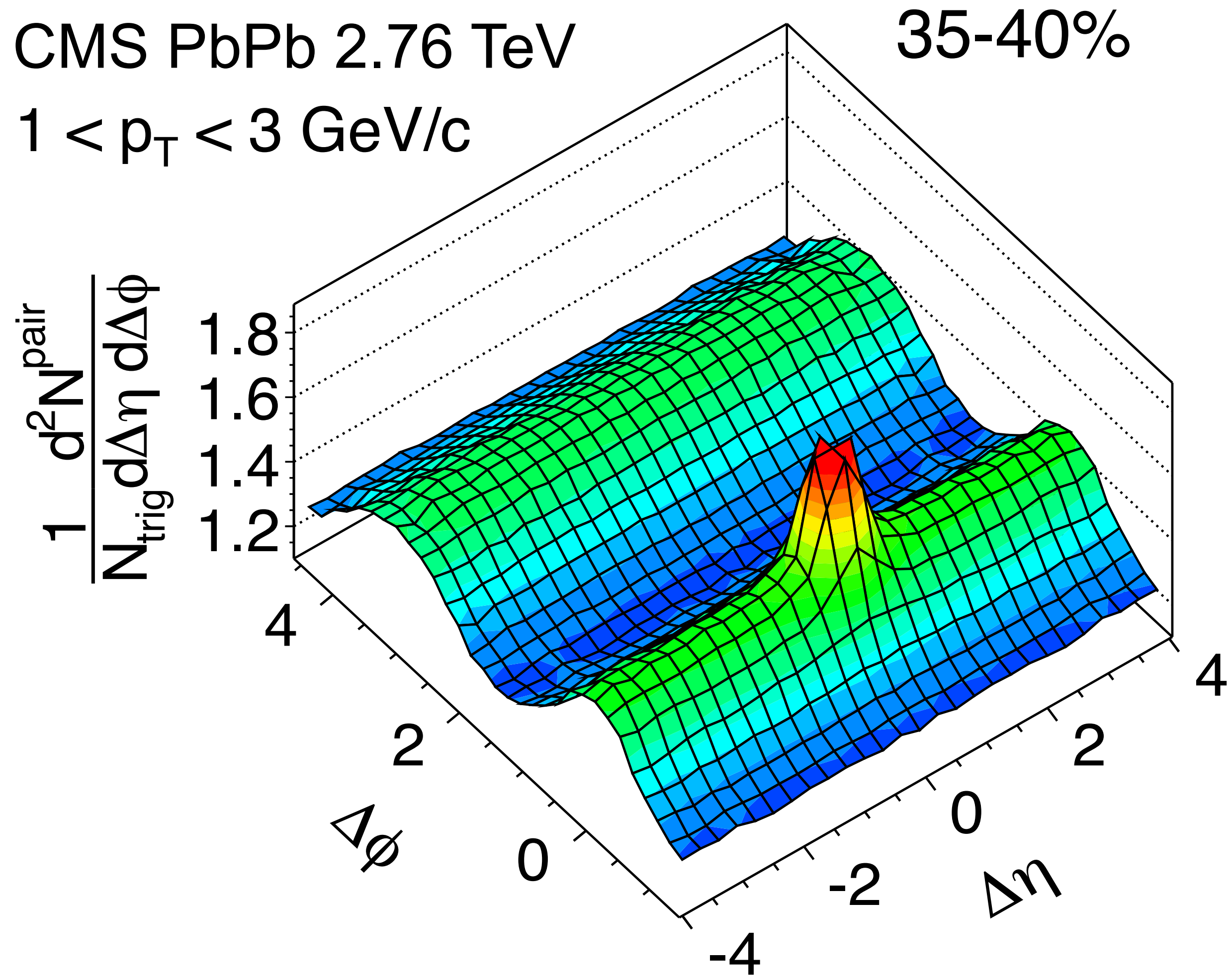
May 10, 2017
Workshop on Collectivity in Small Collision Systems
Niels Bohr Institute
University of Copenhagen

Introduction: Multi-particle correlations

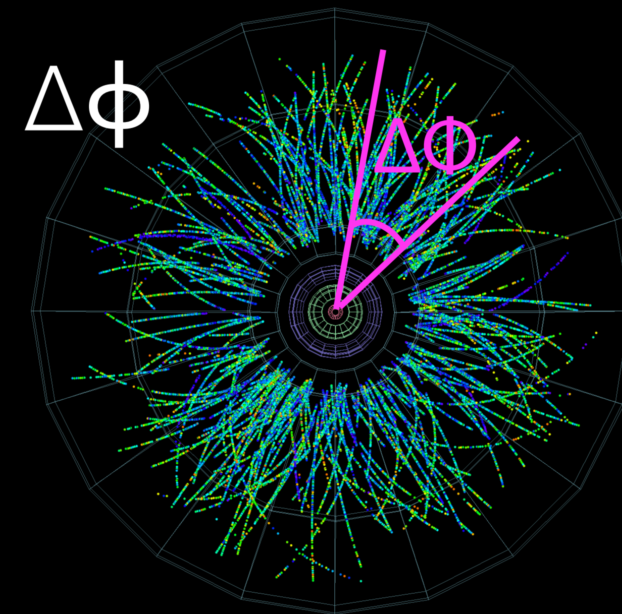
2-particle correlation as a function of Δη and Δϕ

ΔΗ: DIFFERENCE IN PSEUDO-RAPIDITY

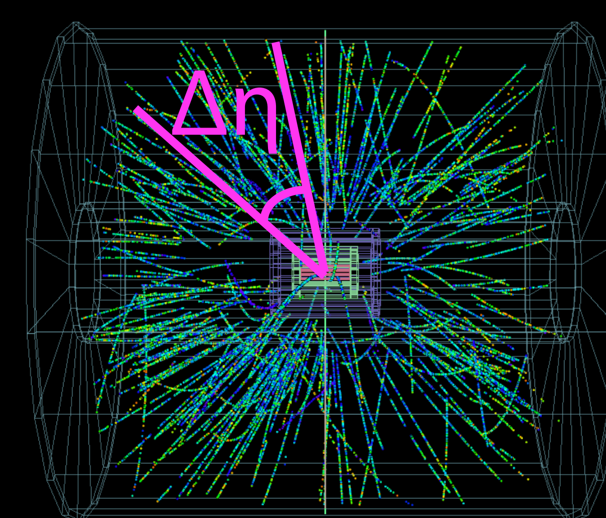
ΔΦ: DIFFERENCE IN AZIMUTHAL ANGLE



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



ΔΦ: DIFFERENCE IN AZIMUTHAL ANGLE

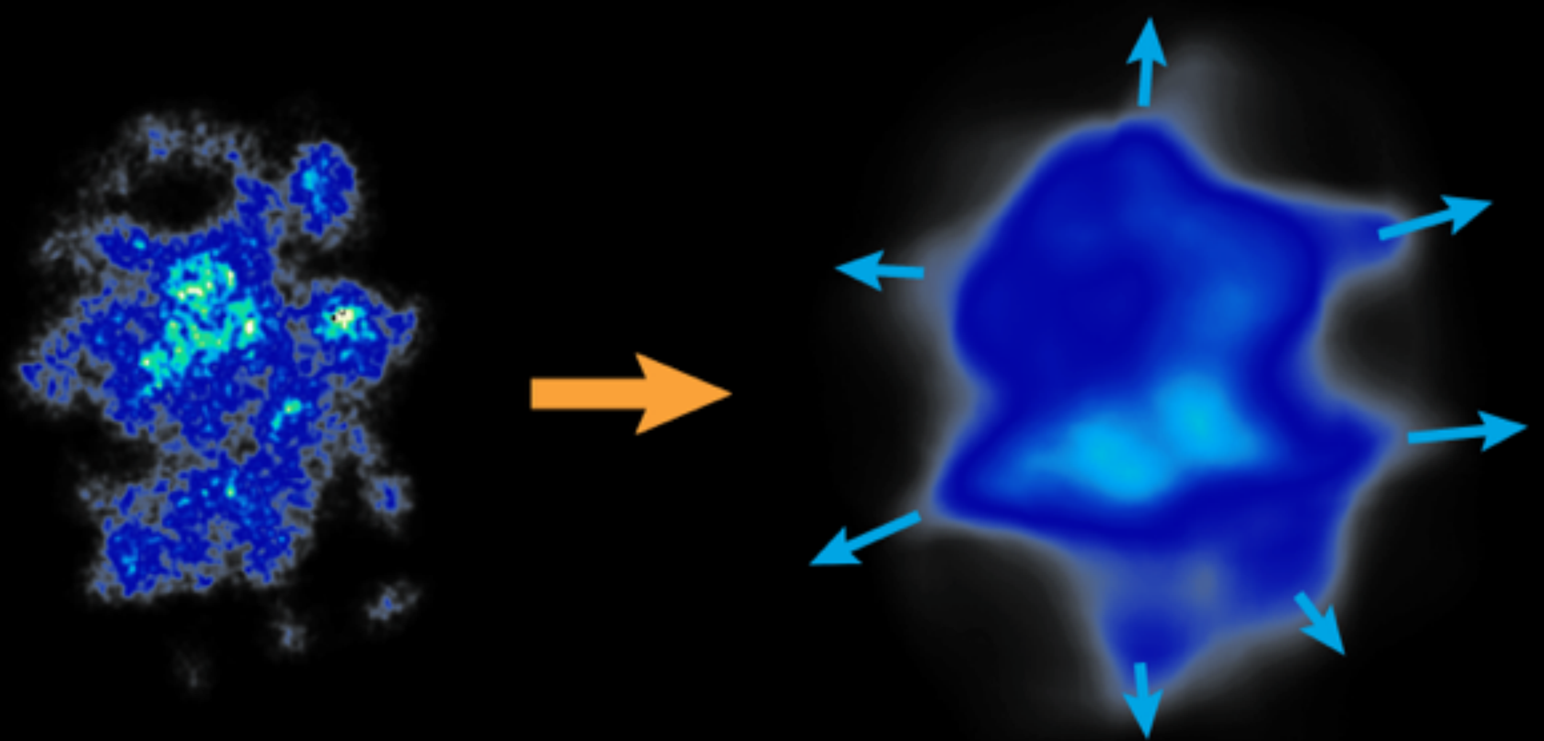


Δη: DIFFERENCE IN PSEUDO-RAPIDITY

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

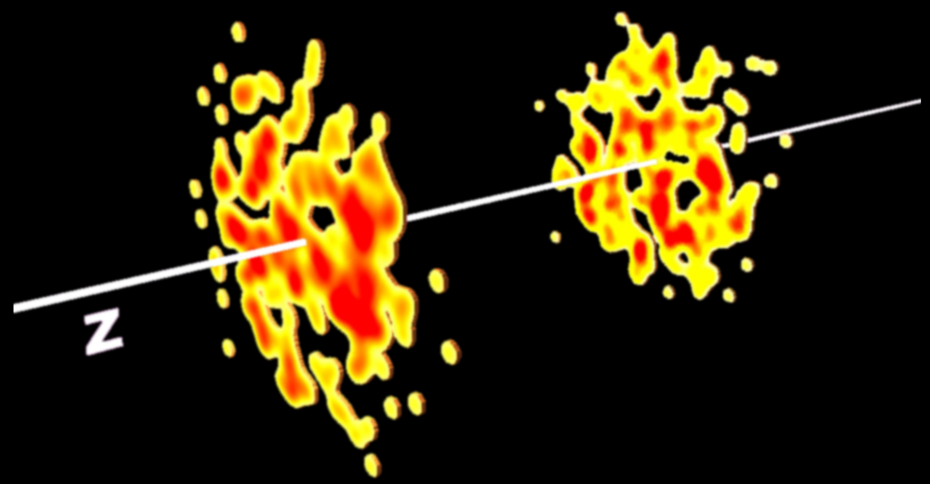
Björn Schenke, BNL

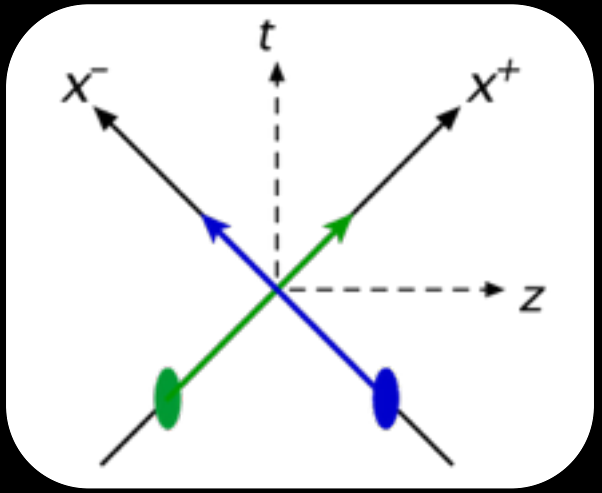
IP-Glasma initial state

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

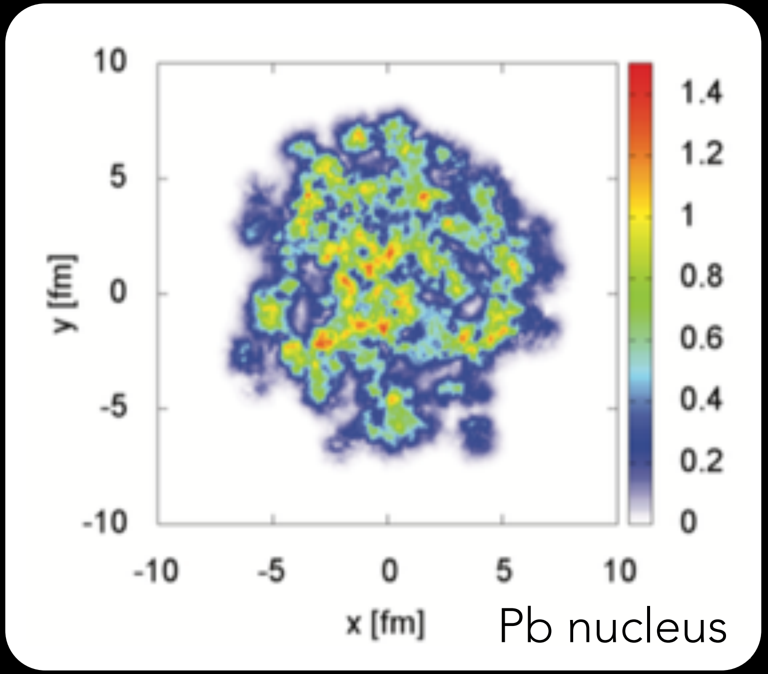
B.Schenke, P.Tribedy, R.Venugopalan, PRL108, 252301 (2012)
PRC86, 034908 (2012)

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:

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

Trace of Wilson lines

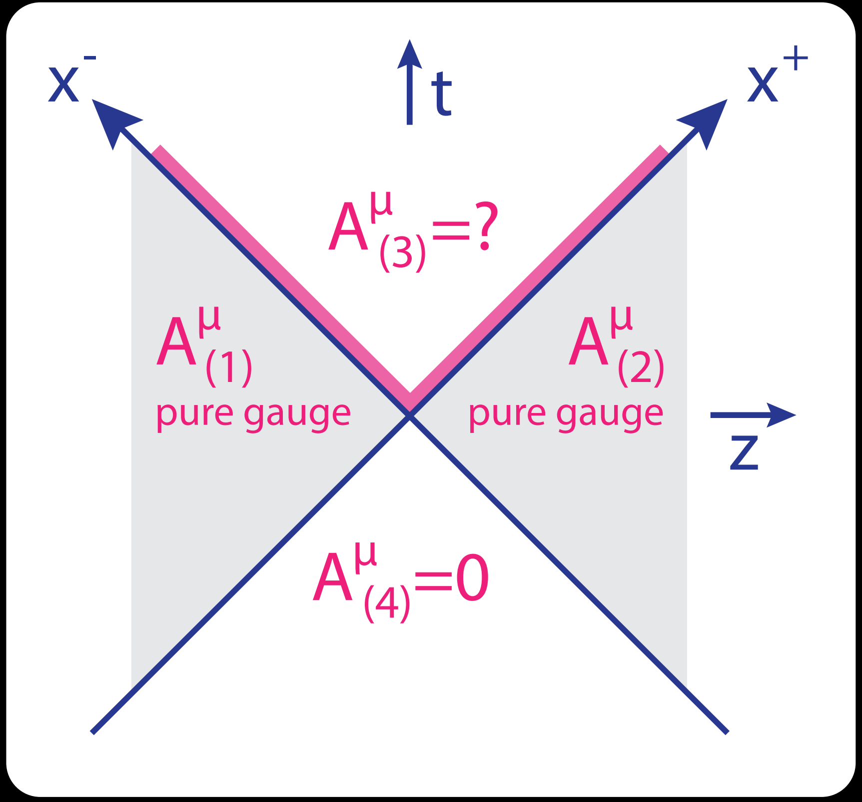


Fields after the collision:

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

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

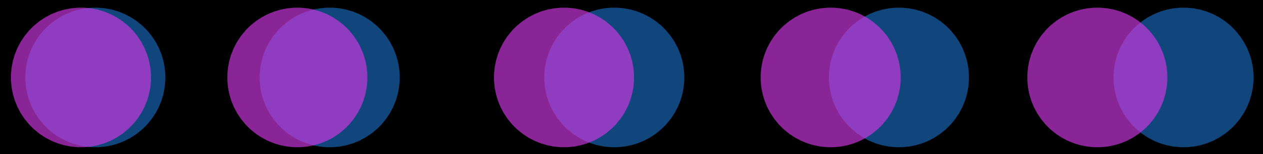
Kovner, McLerran, Weigert, Phys. Rev. D52, 6231 (1995)
Krasnitz, Venugopalan, Nucl.Phys. B557 (1999) 237

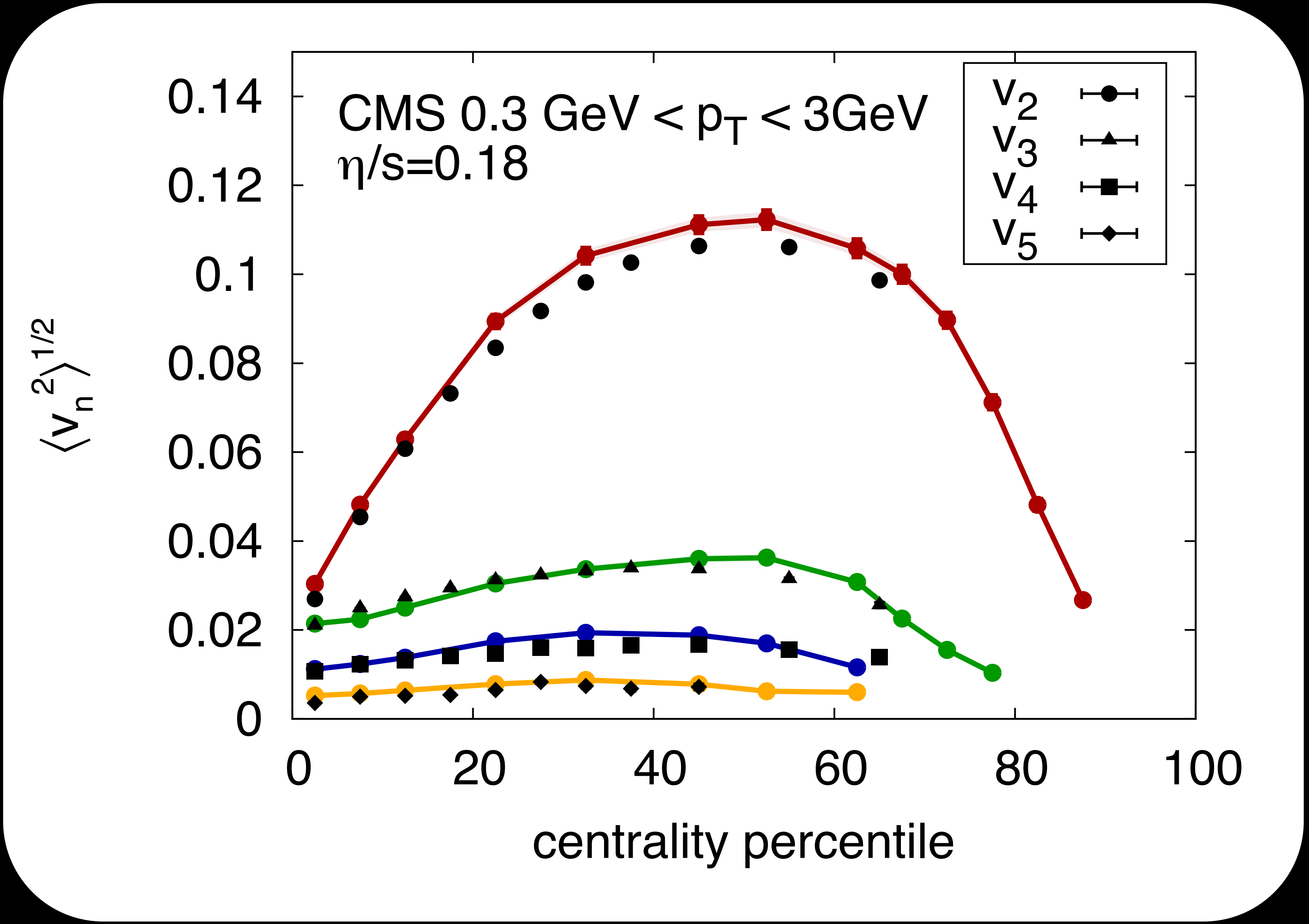


Fields in Schwinger gauge

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

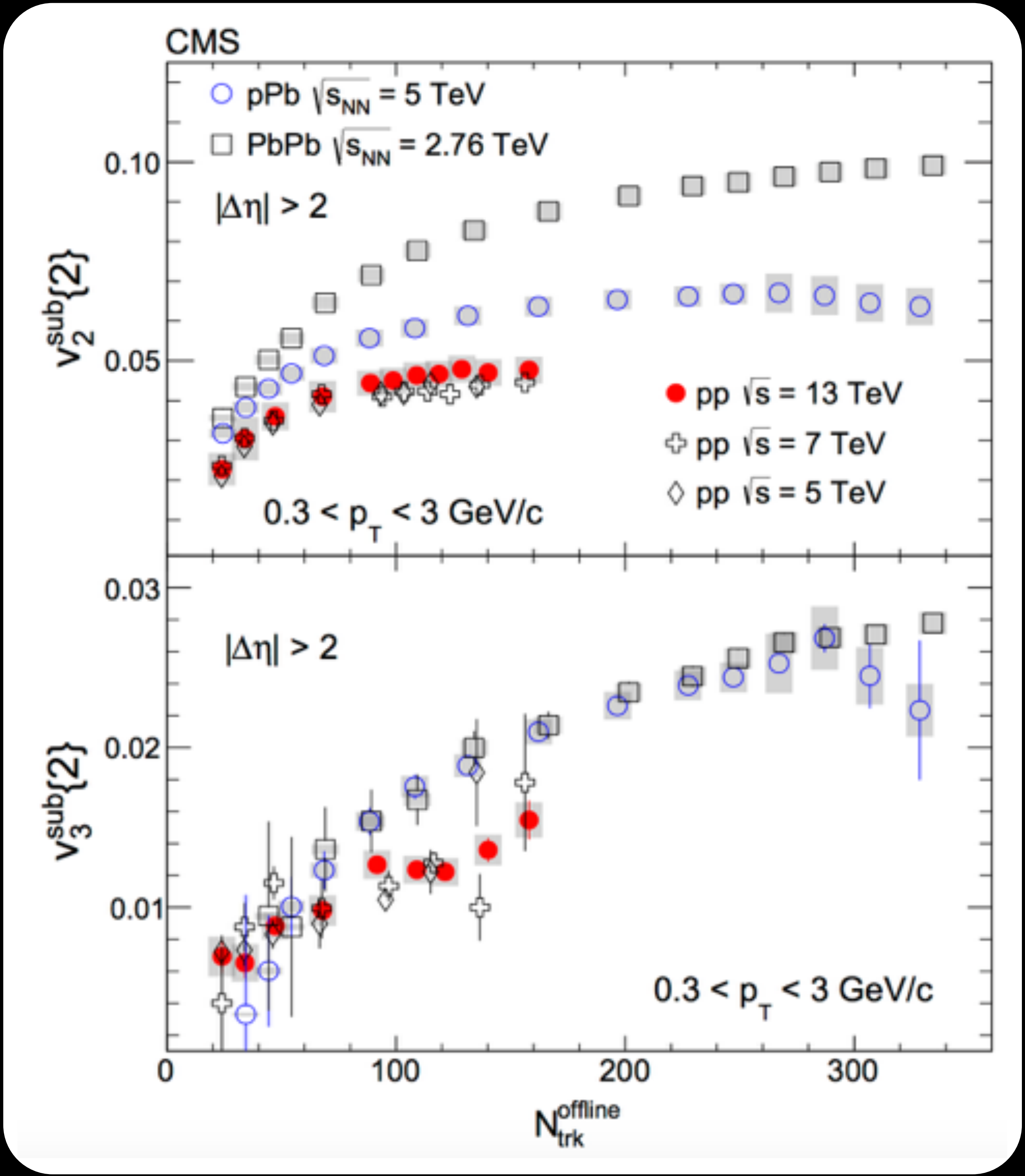
C.Gale, S.Jeon, B.Schenke, P.Tribedy, R.Venugopalan, Phys.Rev.Lett. 110, 012302 (2013)
B. Schenke, R. Venugopalan, Phys.Rev.Lett. 113 (2014) 102301





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:

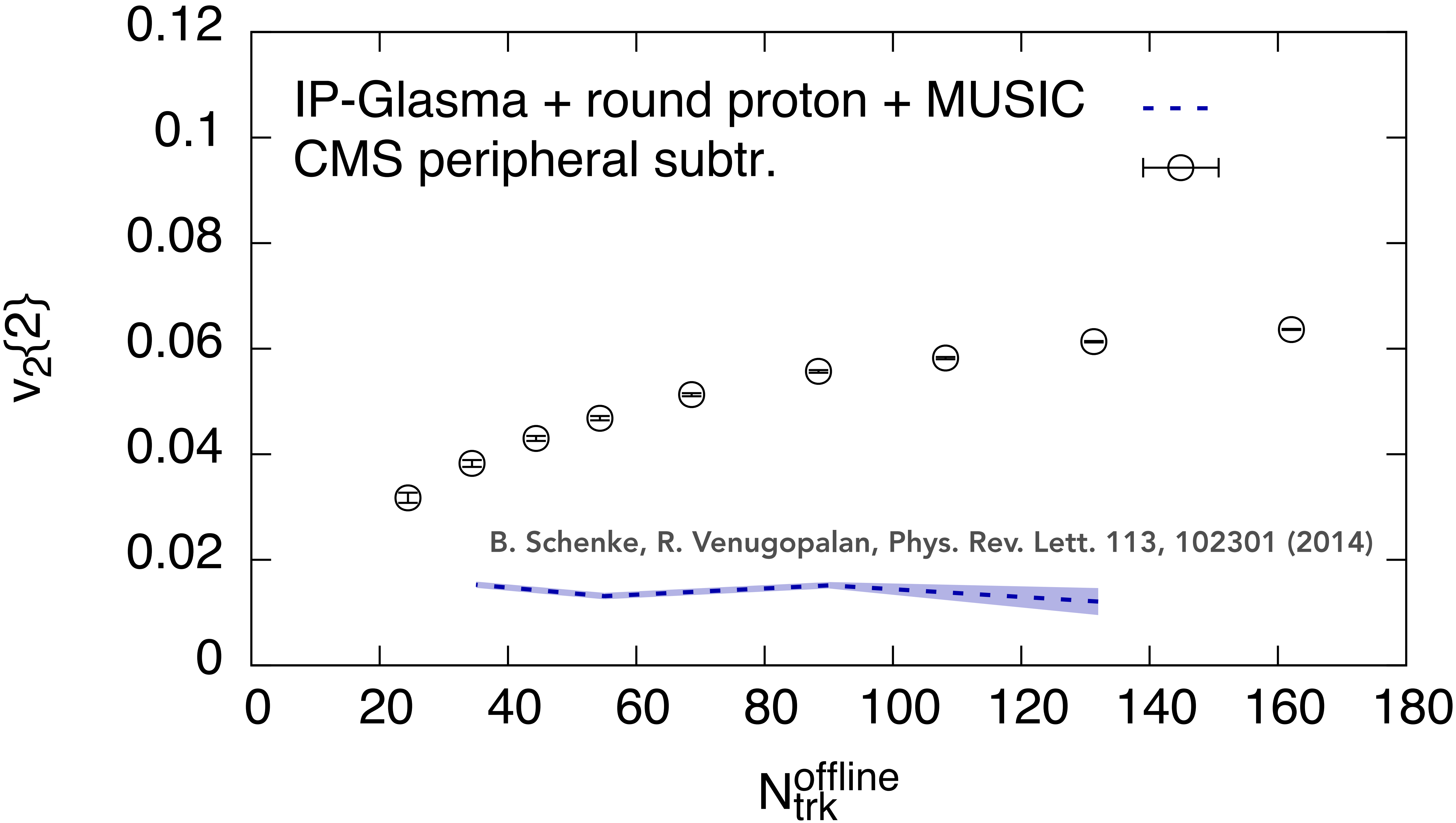
ALICE CollABORATION
Phys. Lett. B719 (2013) 29-41; Phys. Rev. C 90, 054901

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

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

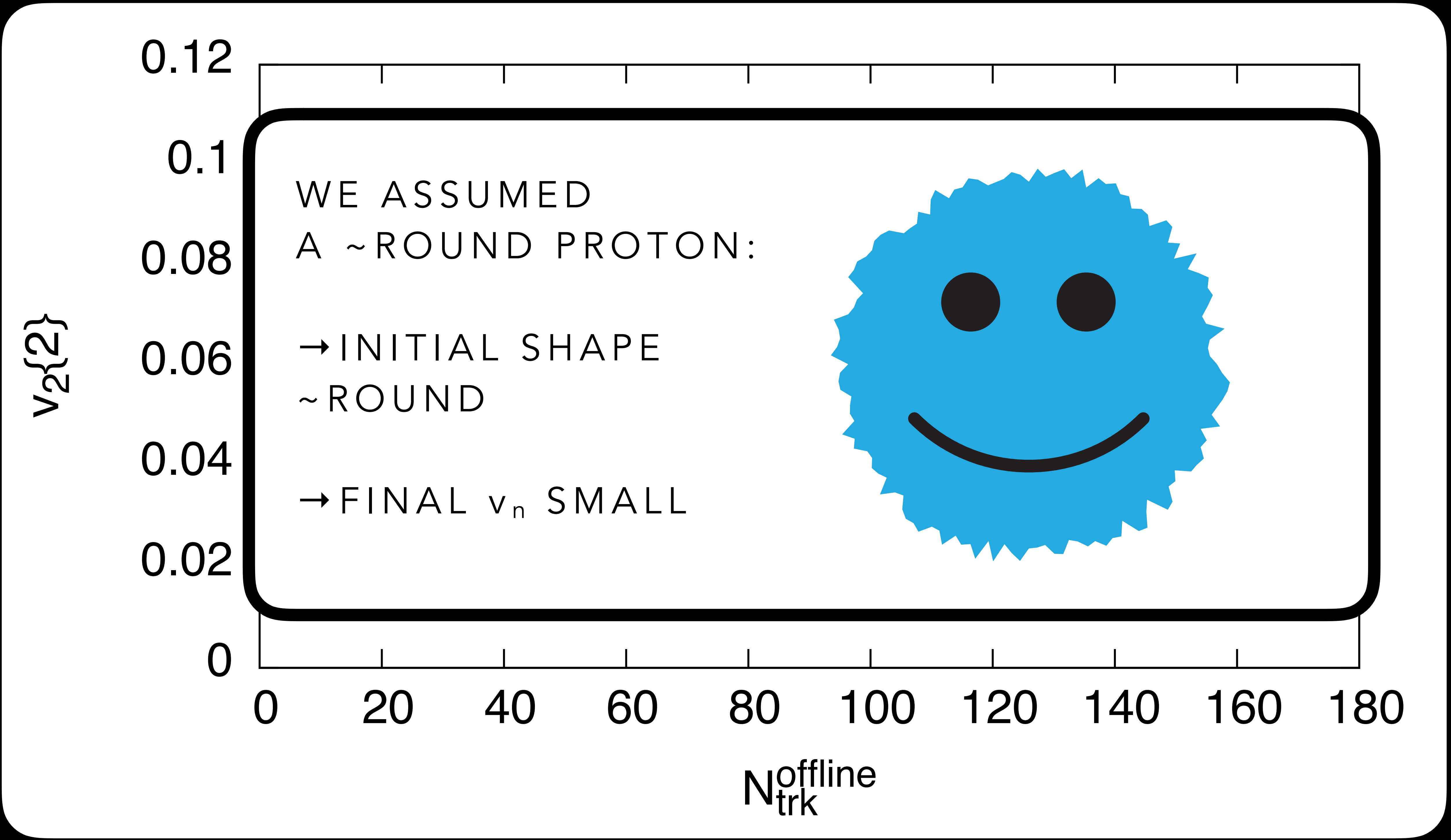
IP-Glasma+MUSIC results

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



IP-Glasma+MUSIC results

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



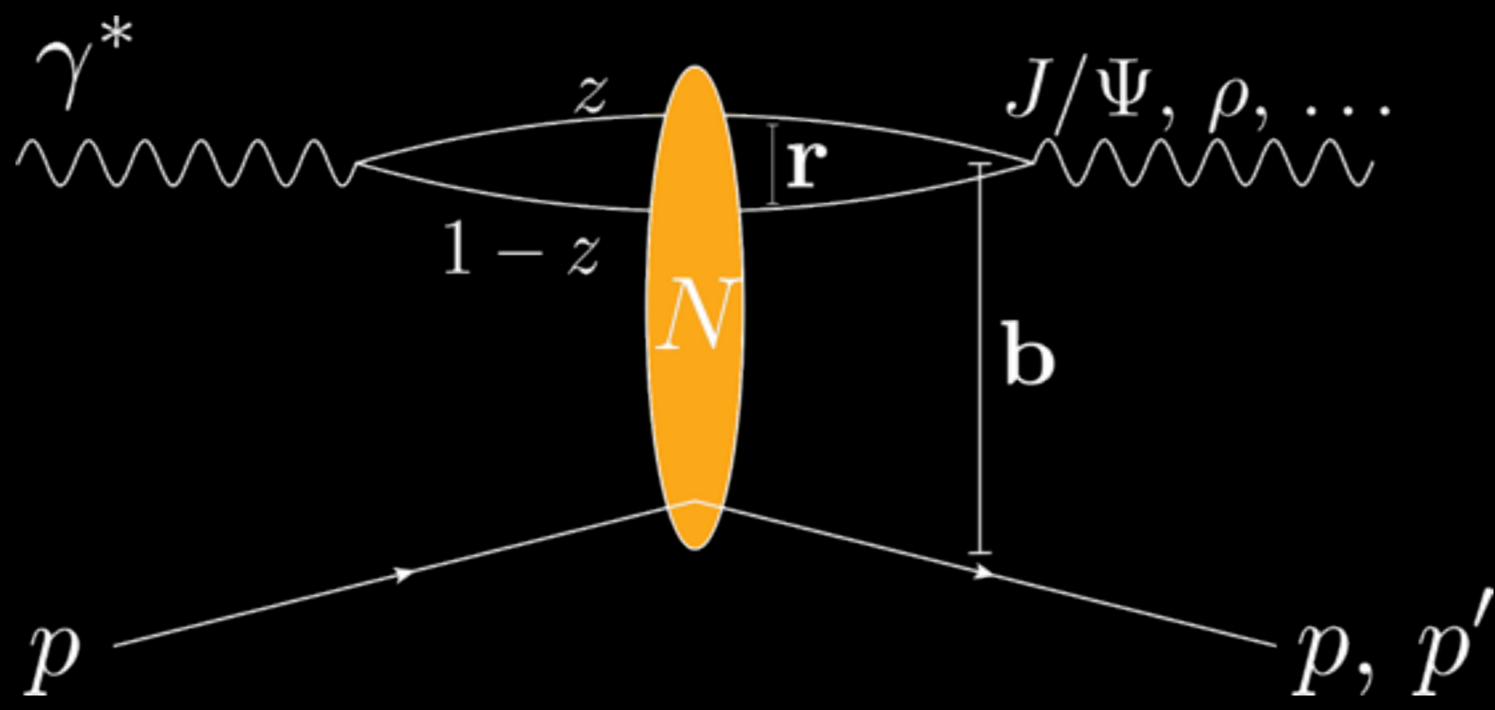
THEORY FRAMEWORK REQUIRES ADDITIONAL PROTON SHAPE FLUCTUATIONS

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:

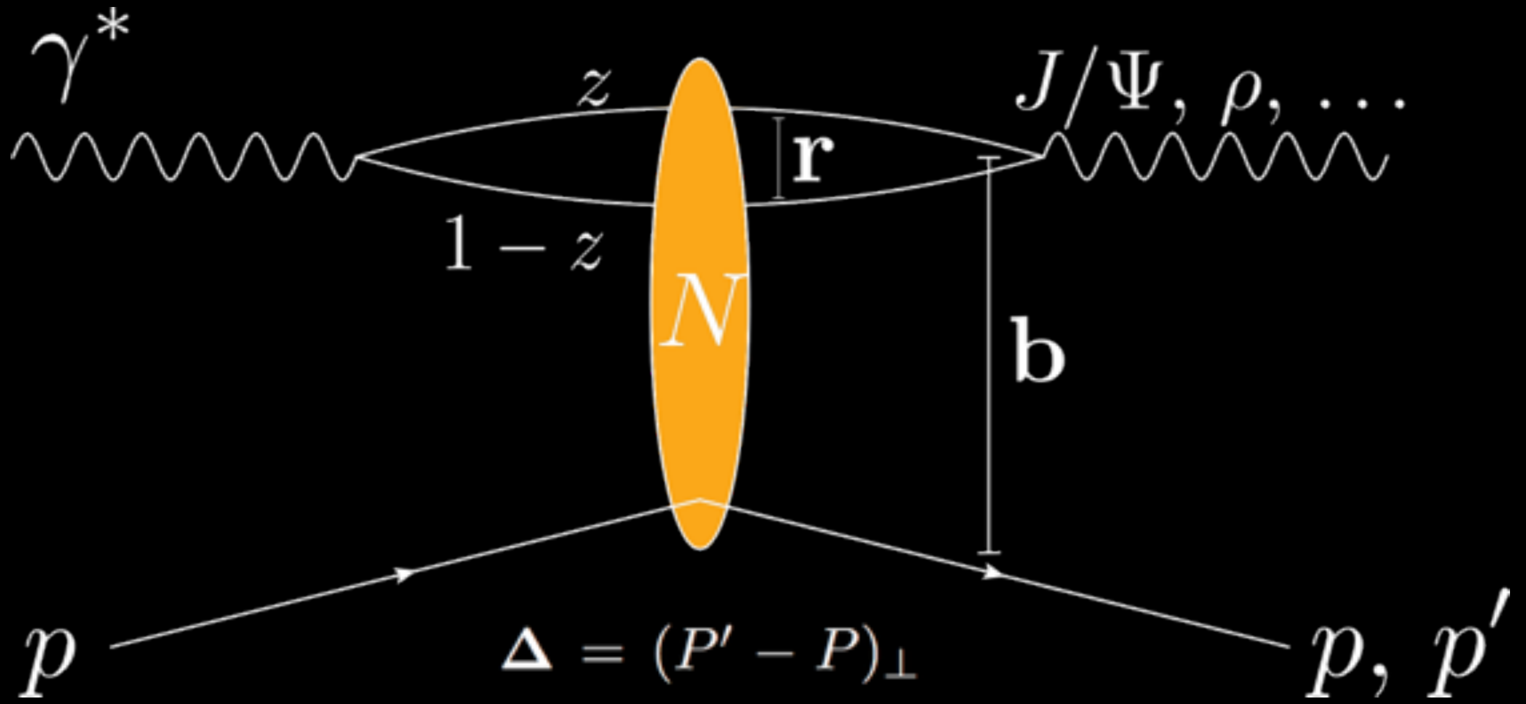
Proton breaks up, Sensitive to shape fluctuations

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

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

INCOHERENT DIFFRACTION:
TARGET BREAKS UP

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

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

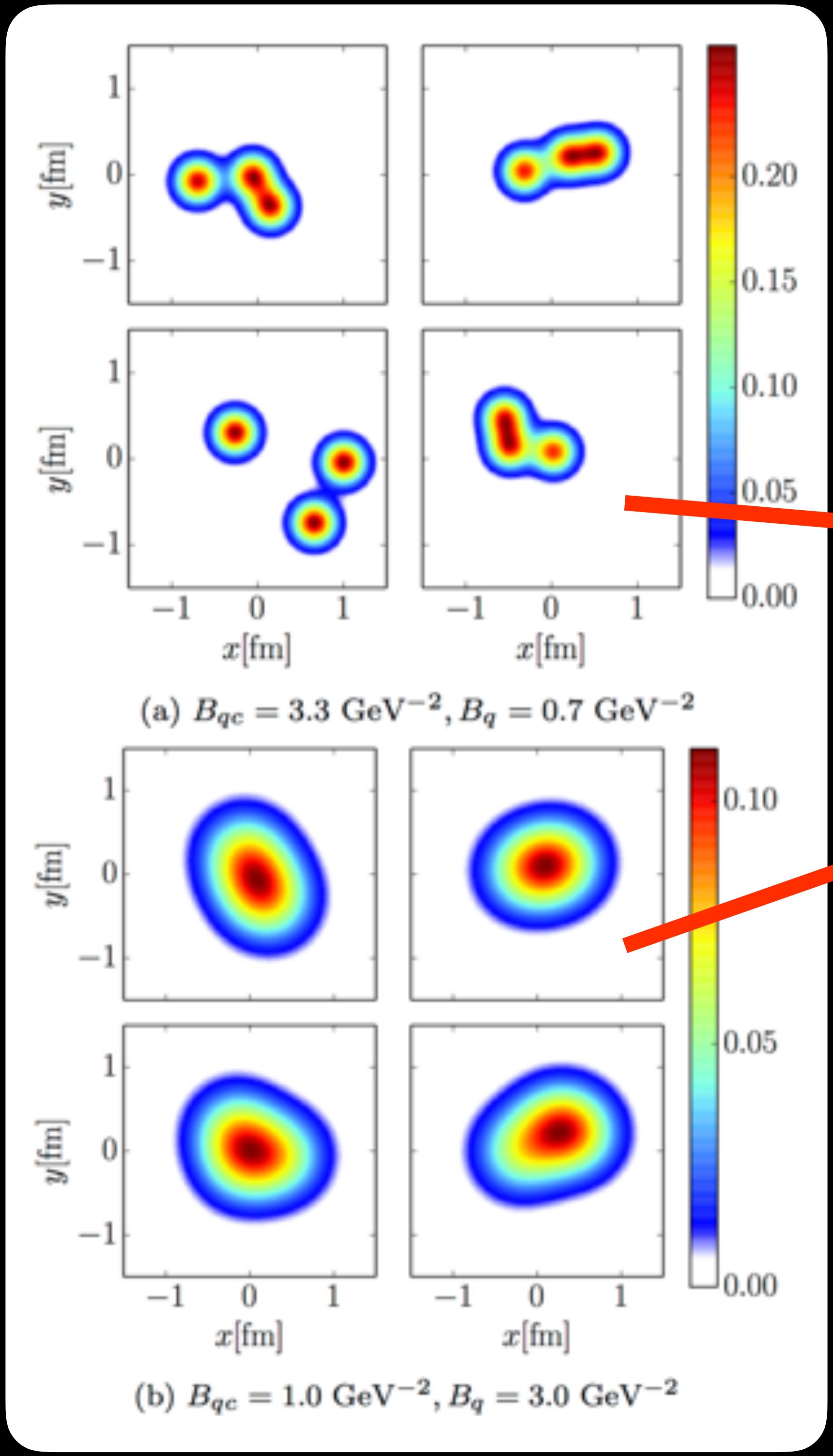
Y. V. KOVCHEGOV
AND L. D. MCLERRAN
PHYS. REV. D60 (1999) 054025

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

SENSITIVE TO FLUCTUATIONS!

Introduce geometric fluctuations

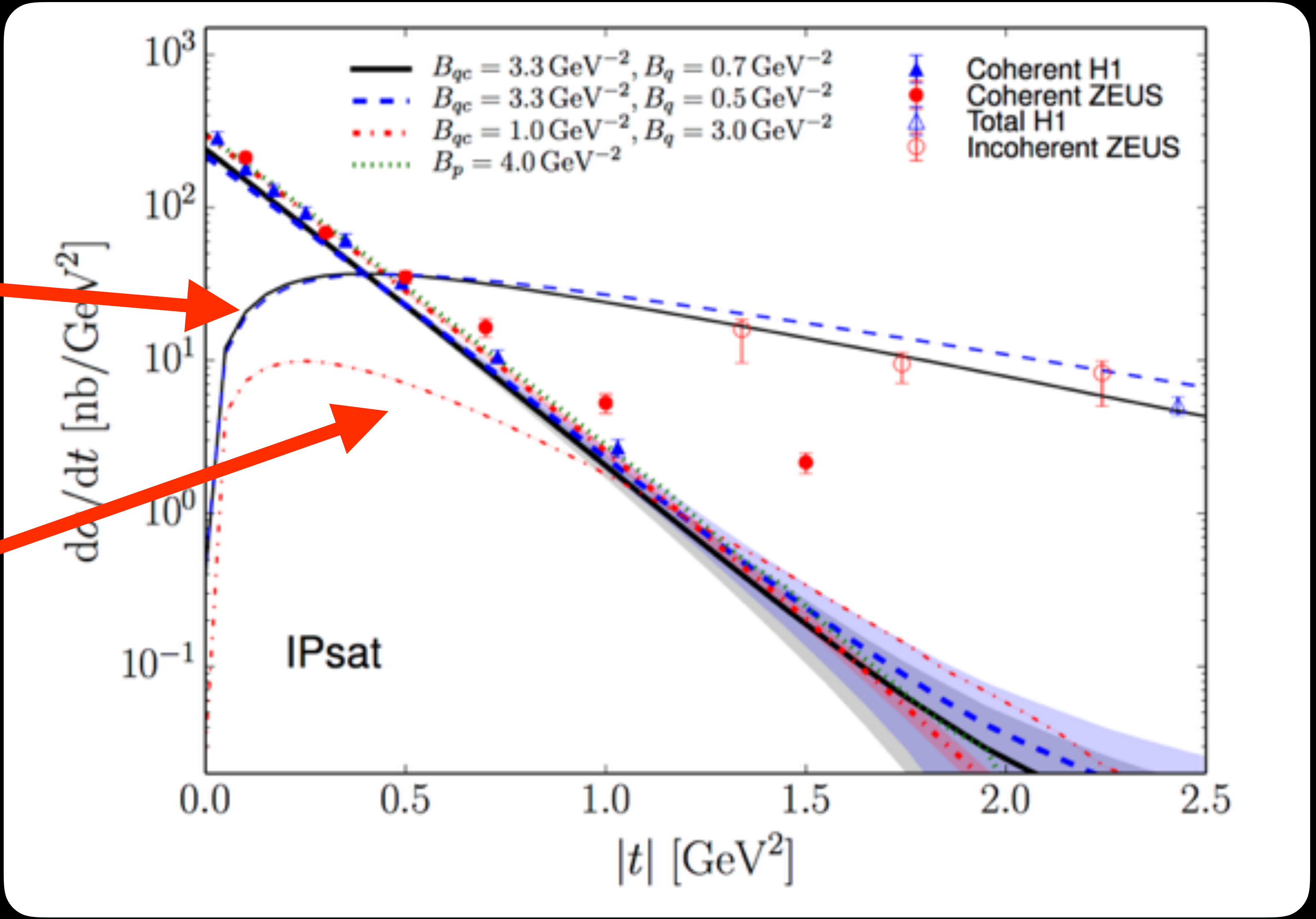
Assume 3 valence quark-like hot spots



(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

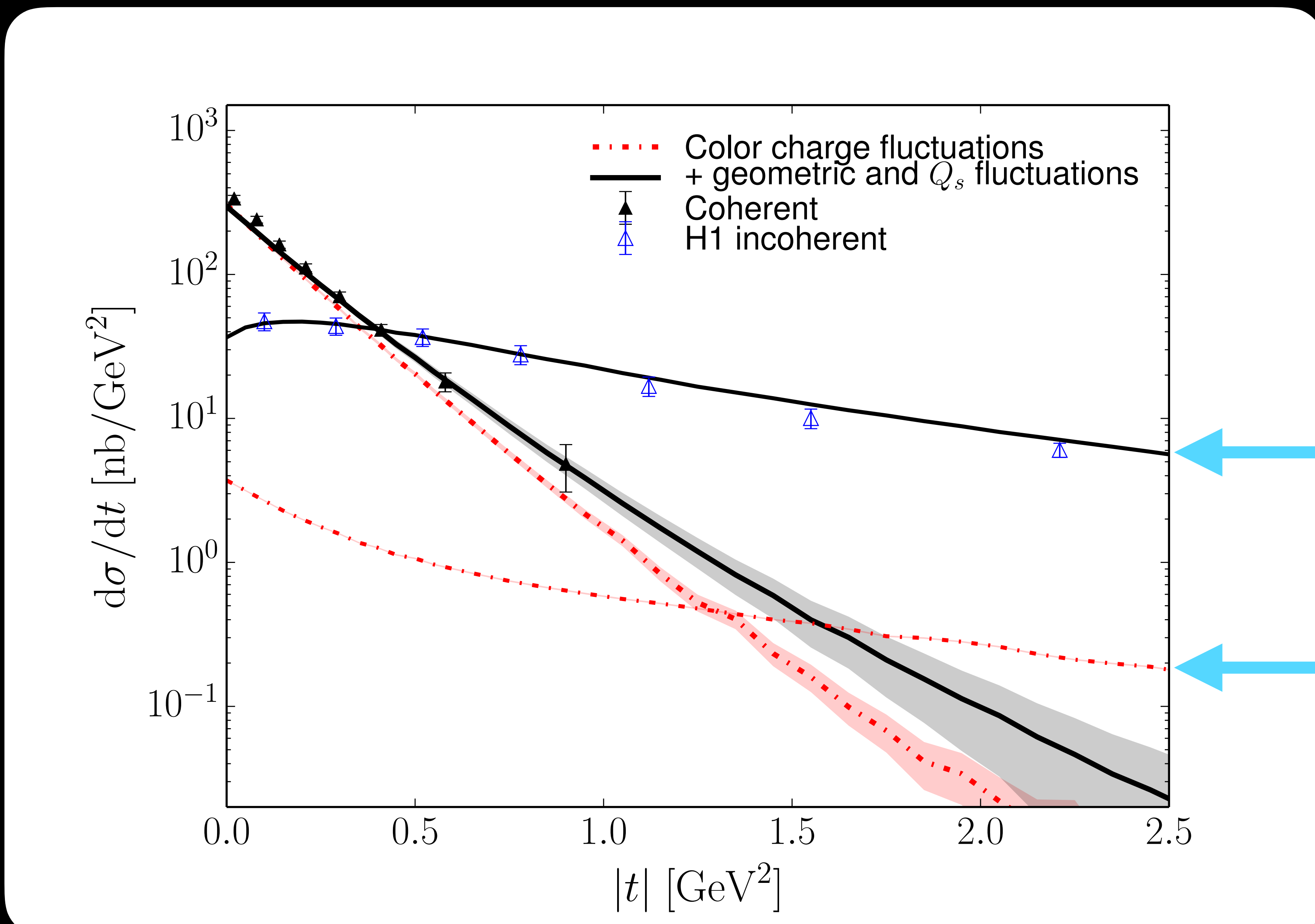
IP-Glasma calculation

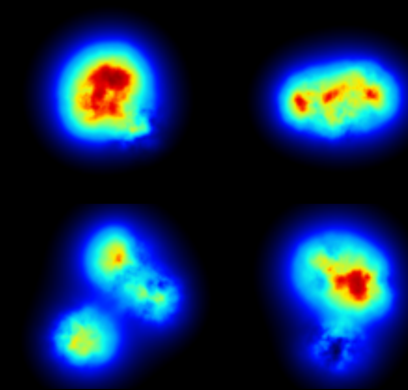
H. Mäntysaari, B. Schenke, Phys. Rev. Lett. 117 (2016) 052301; Phys.Rev. D94 (2016) 034042

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

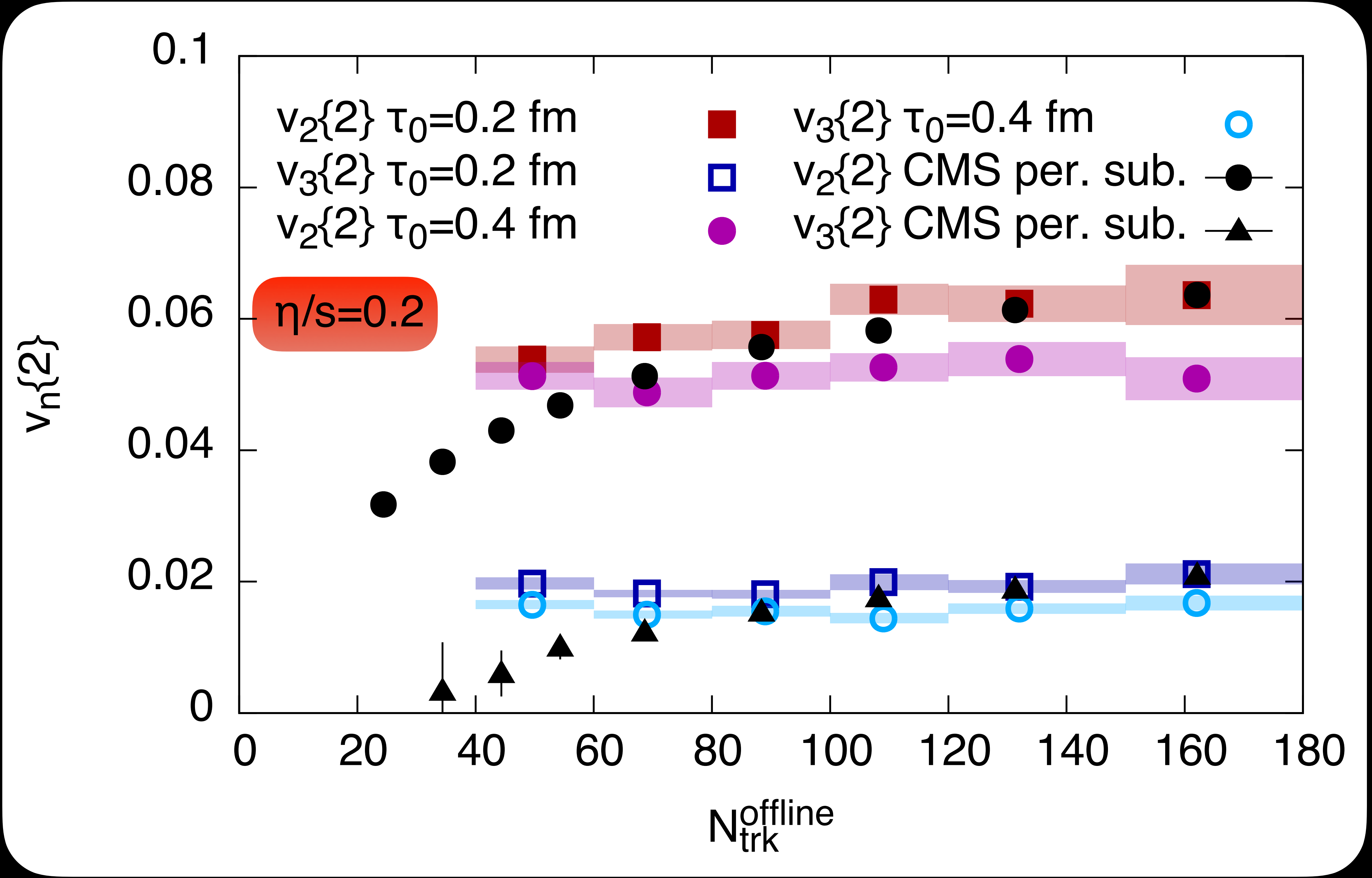
round proton

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

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

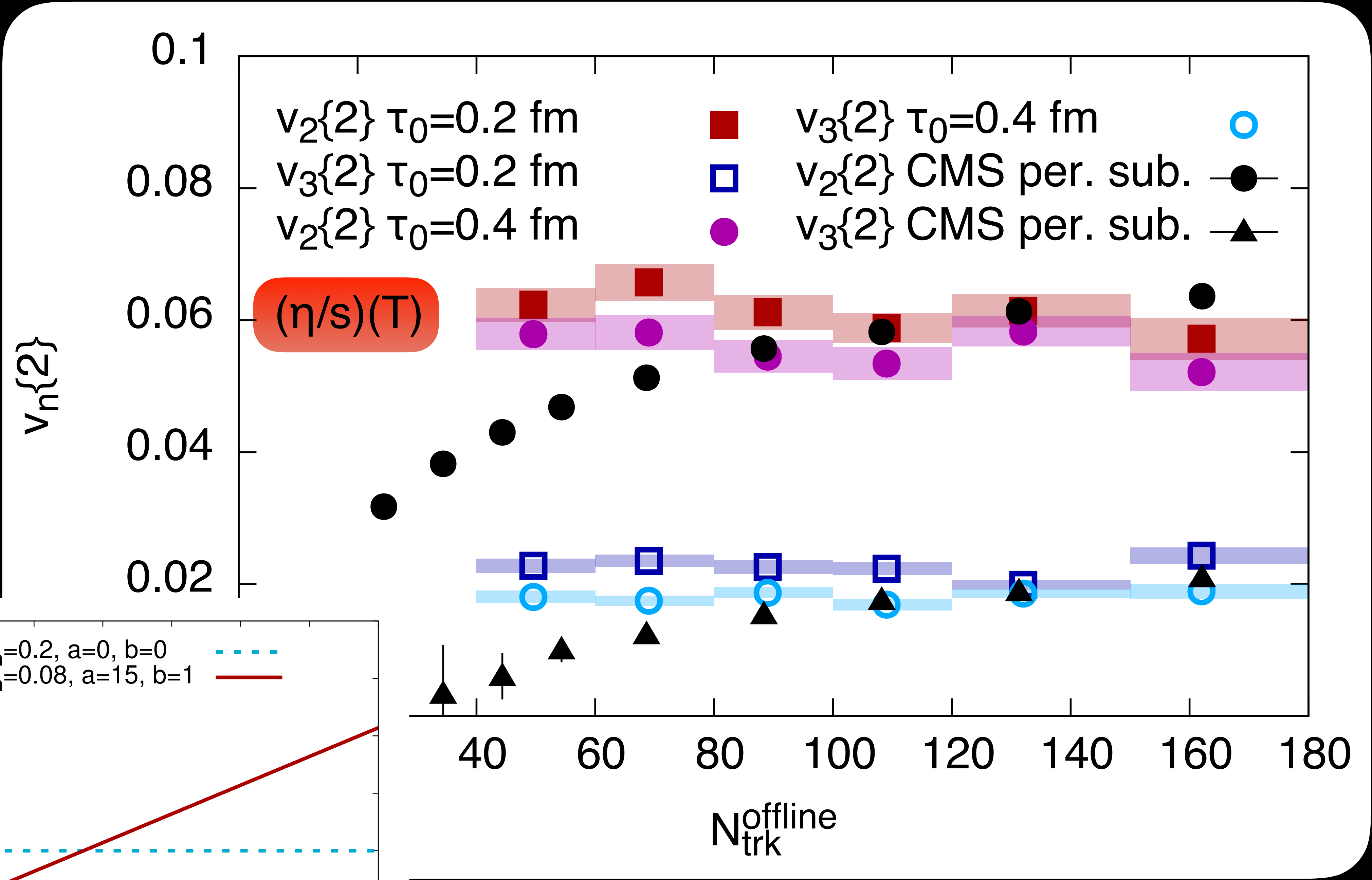
Integrated anisotropic flow

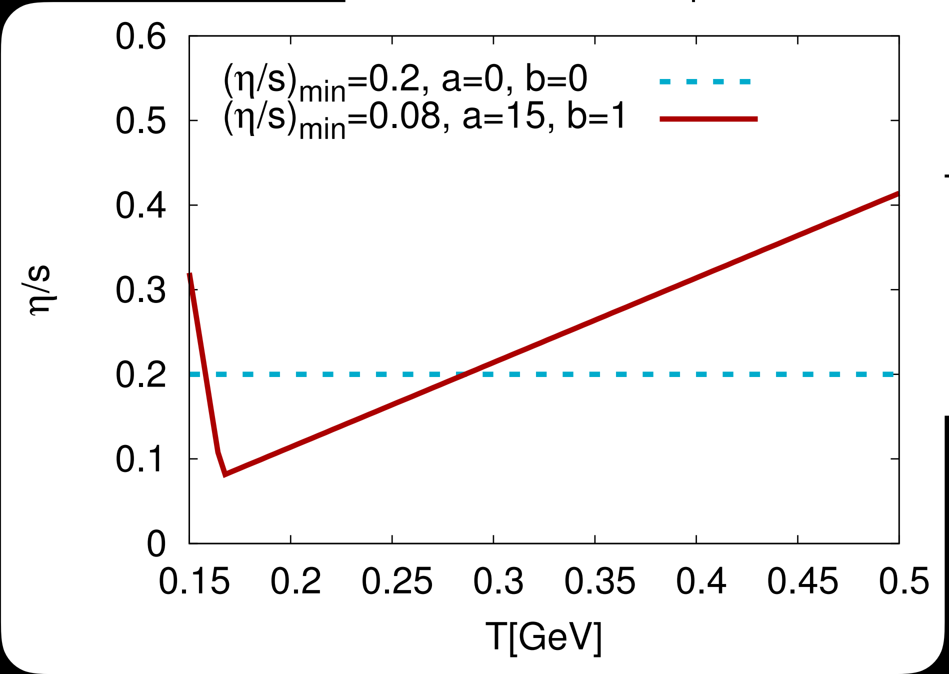
H. Mäntysaari, B. Schenke, C. Shen, P. Tribedy, arXiv:1705.03177



Integrated anisotropic flow

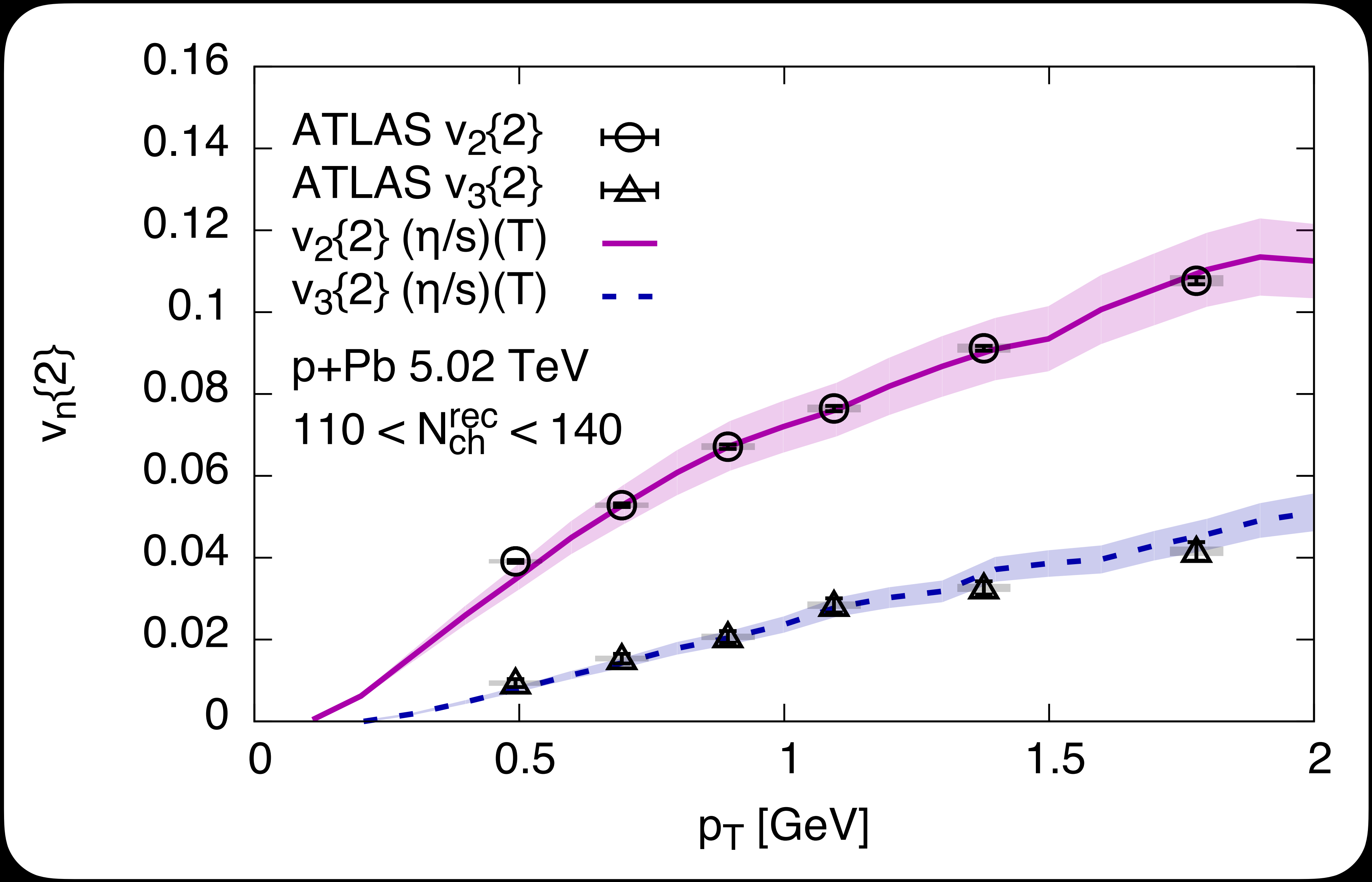
H. Mäntysaari, B. Schenke, C. Shen, P. Tribedy, arXiv:1705.03177





p_T-differential anisotropic flow

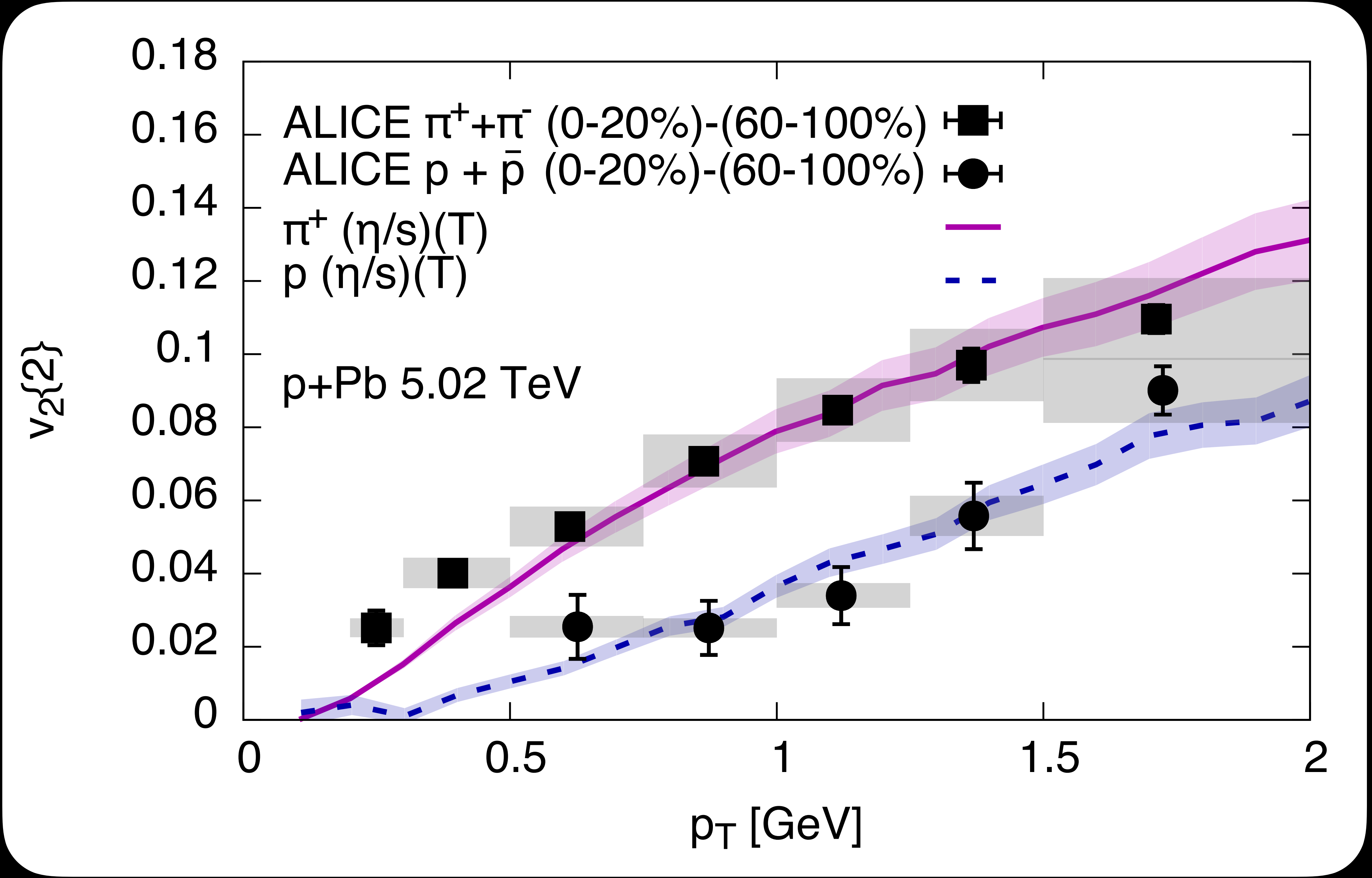
H. Mäntysaari, B. Schenke, C. Shen, P. Tribedy, arXiv:1705.03177



τ_0=0.4 fm

Identified particle flow

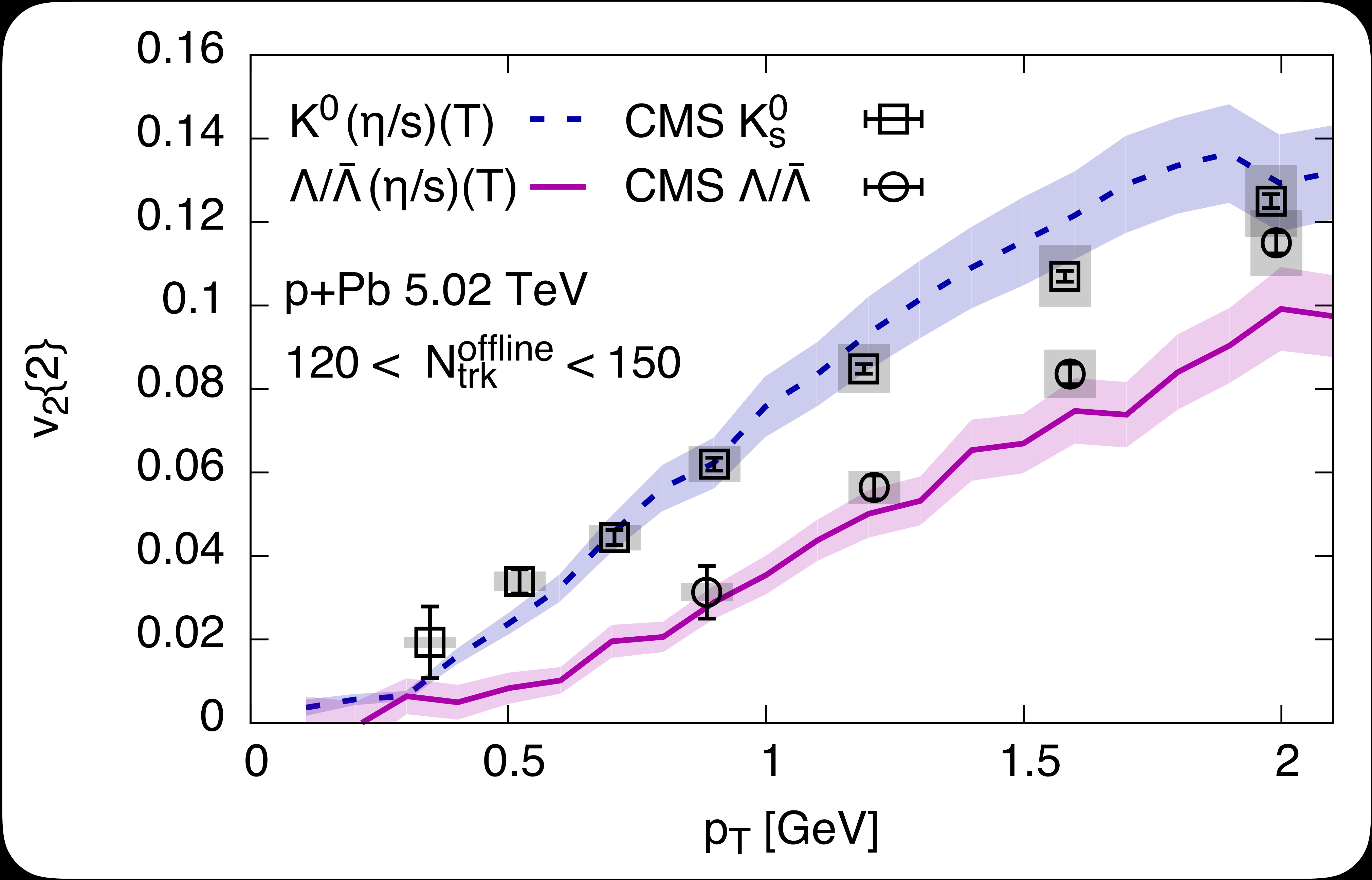
H. Mäntysaari, B. Schenke, C. Shen, P. Tribedy, arXiv:1705.03177



τ_0=0.4 fm

Identified particle flow

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

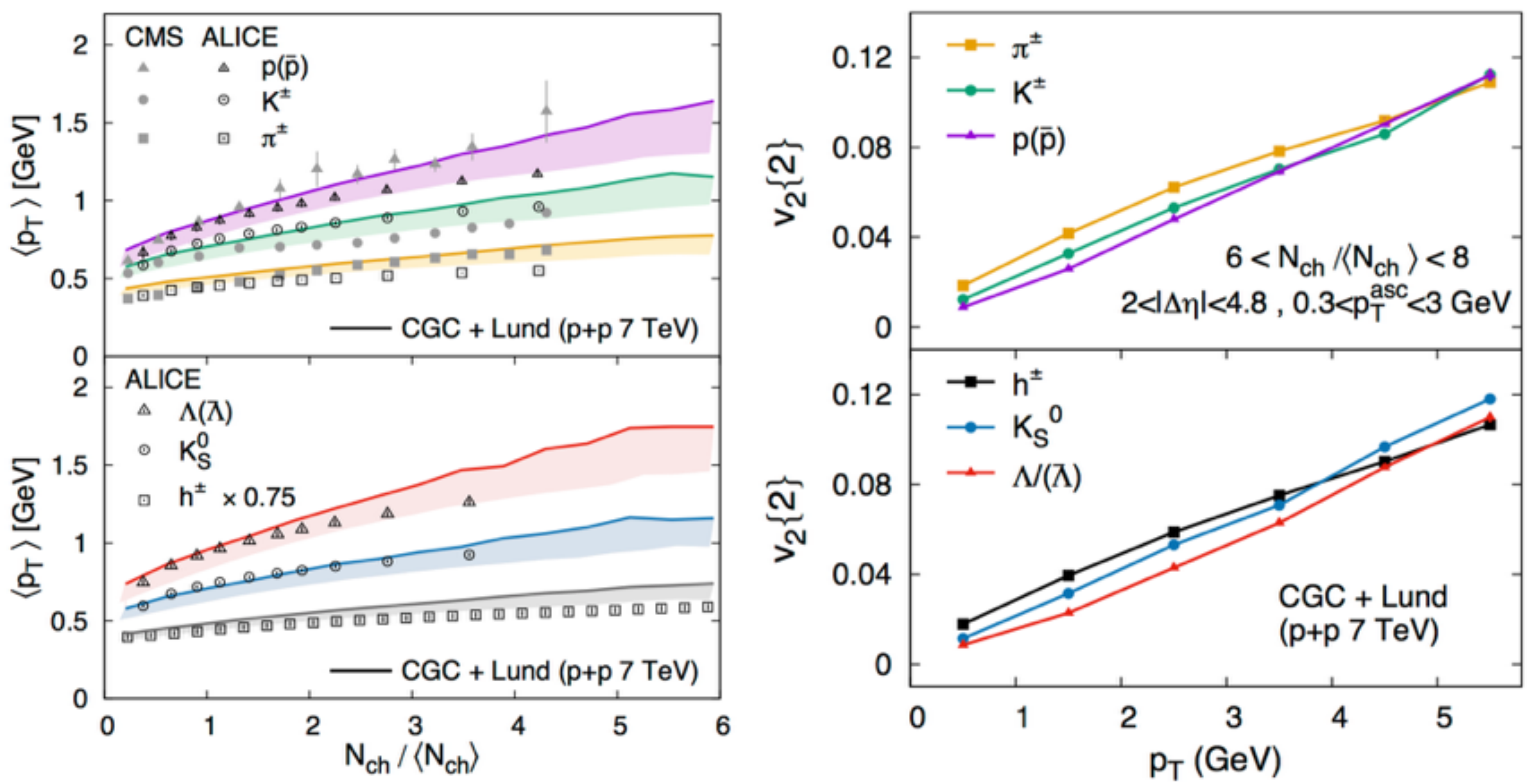


τ_0=0.4 fm

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



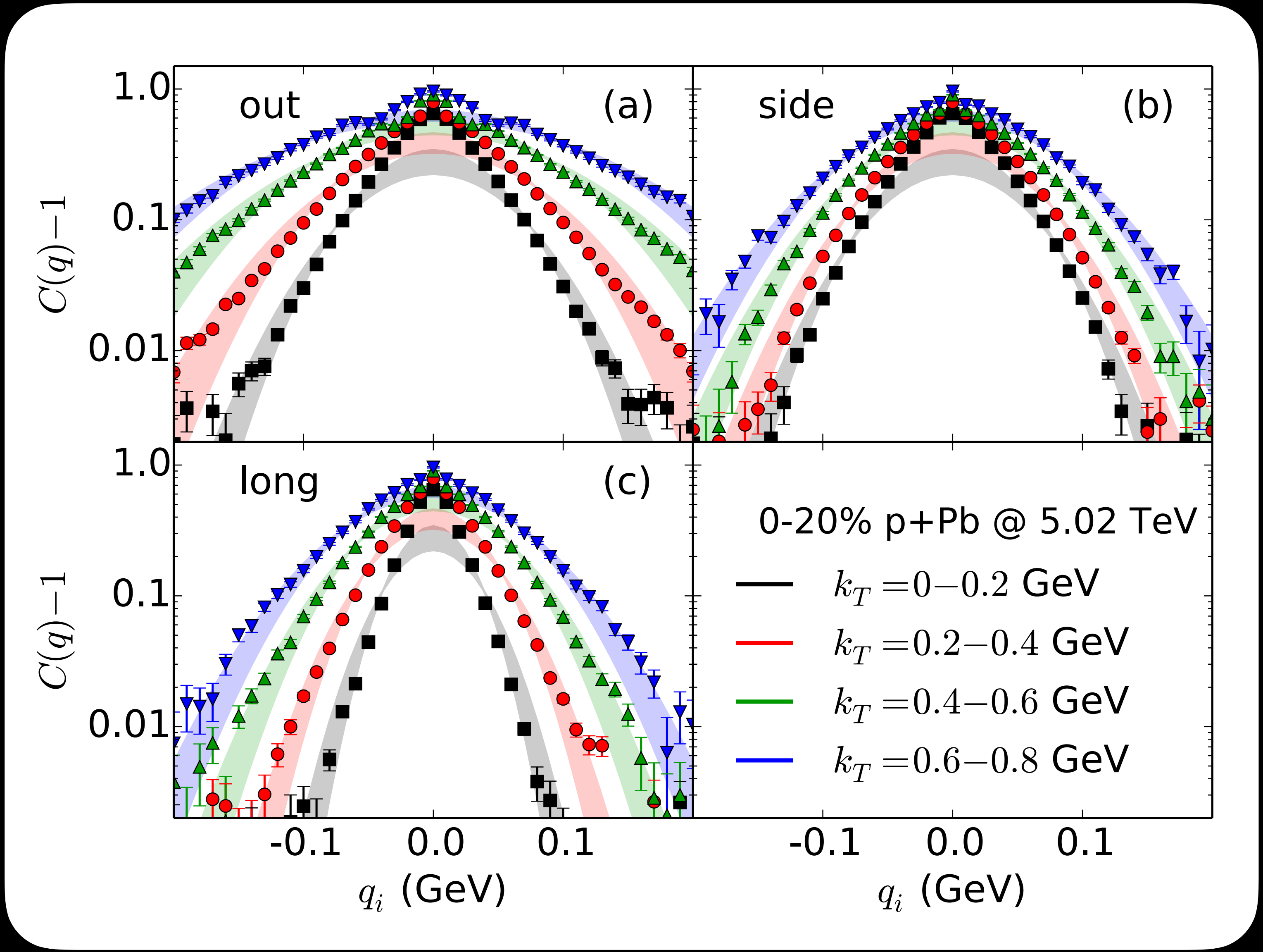
Emission from common boosted source

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)



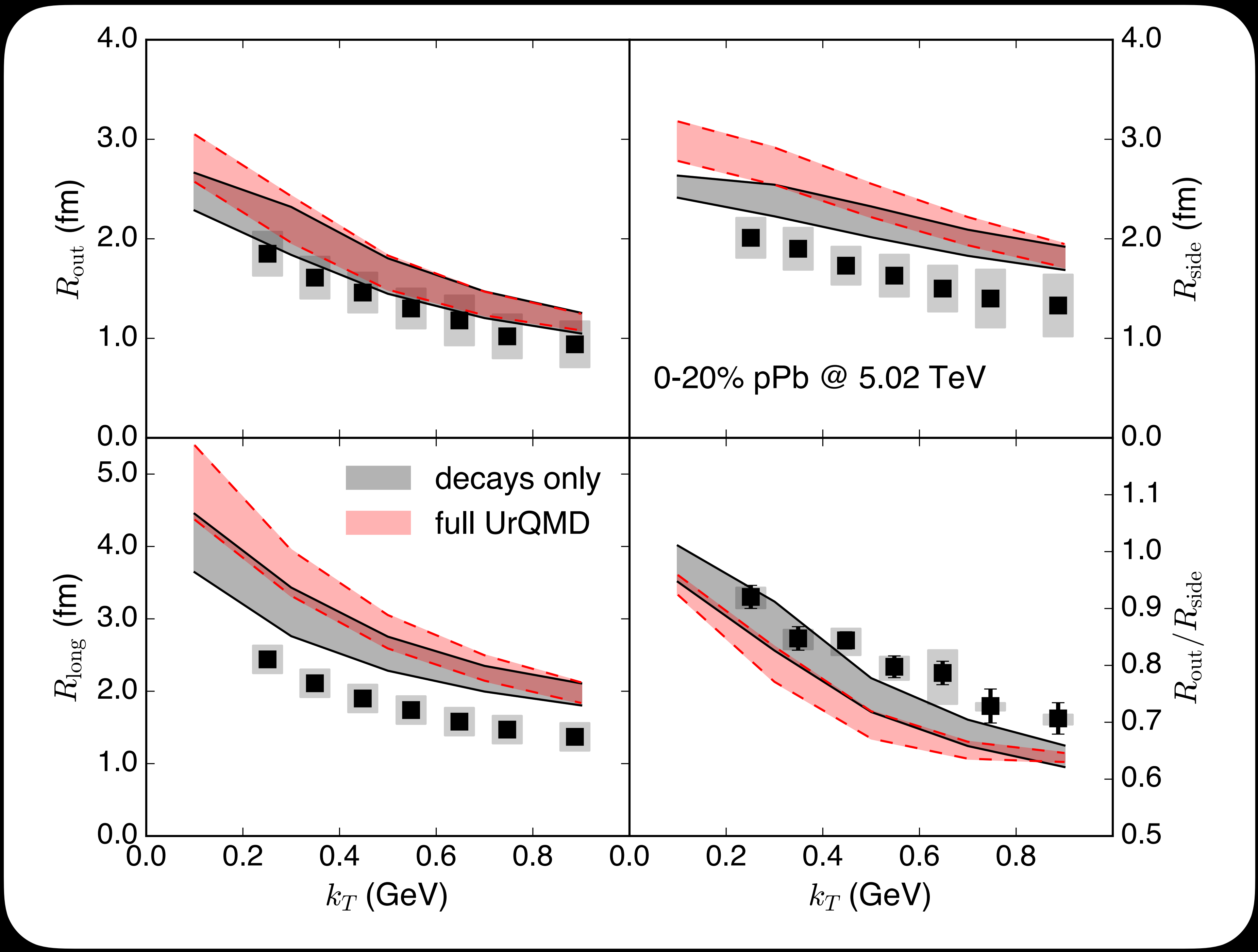
Fit to the Pratt-Bertsch parameterization in the longitudinally co-moving system

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 $(\eta/s)(T)$

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

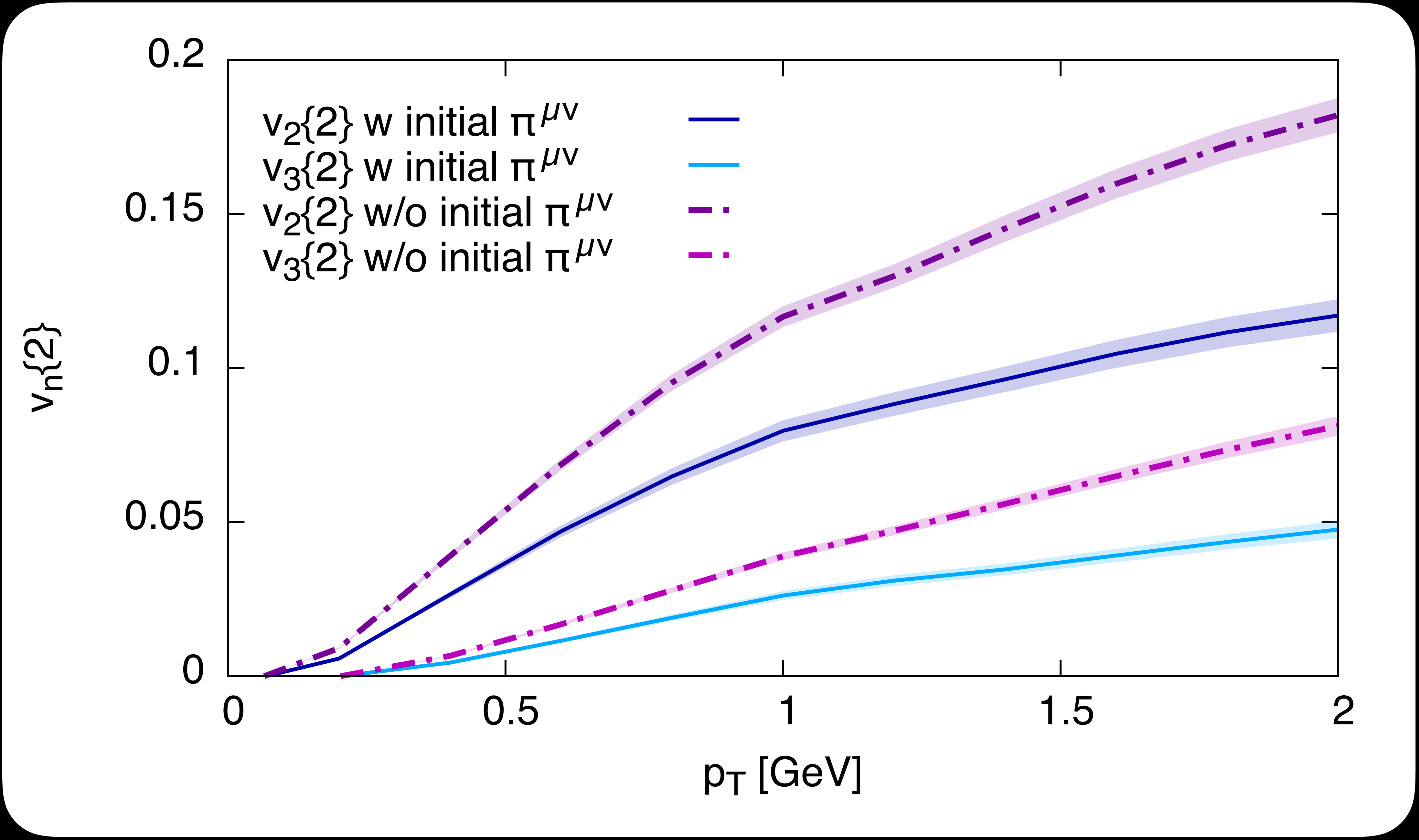
$$\varepsilon u^\nu = u_\mu T^{\mu\nu}$$

then, using P=**ε**/3
(it would be, had we reached isotropy in the CYM system):

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

This is potentially quite large

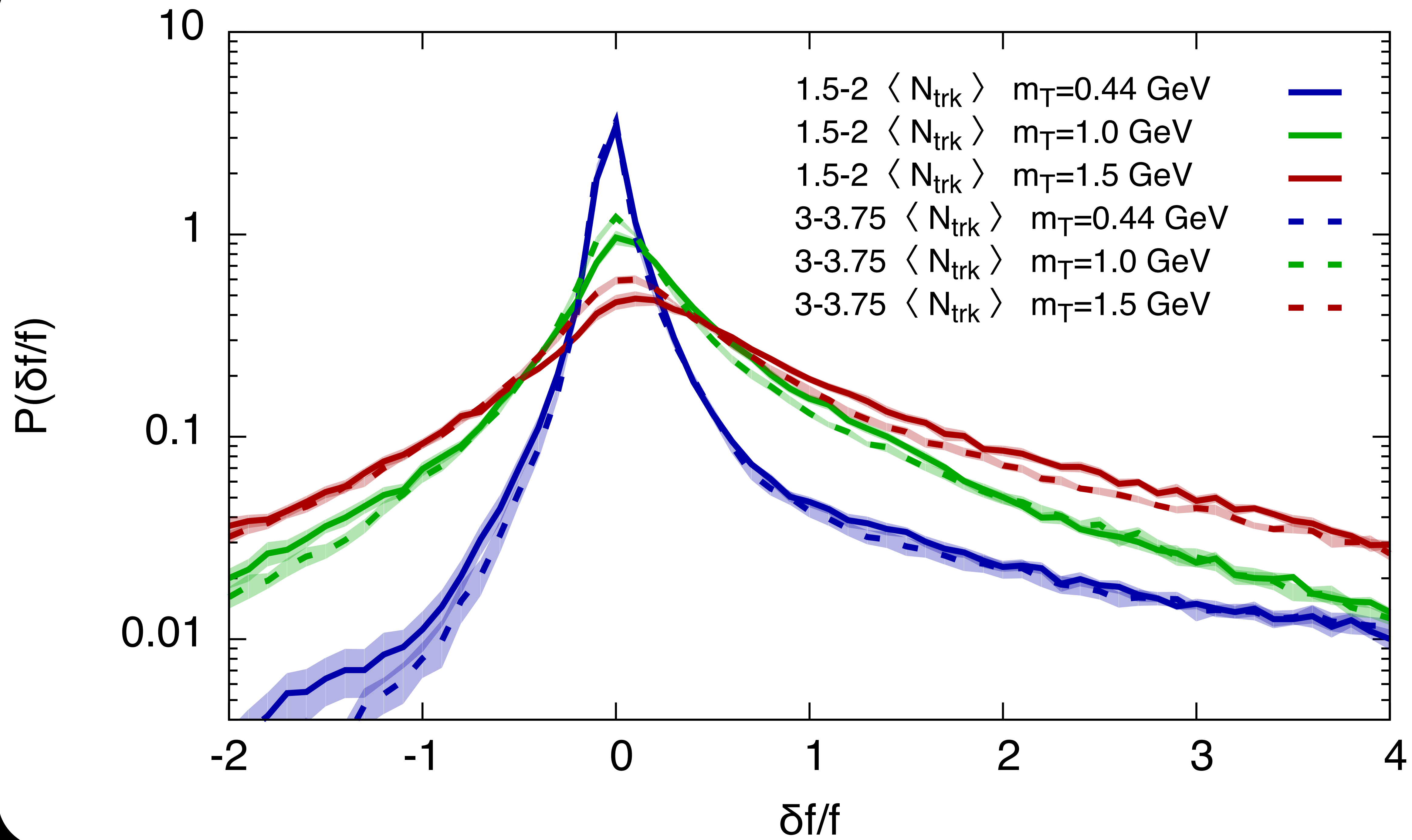
Effect of initial $\pi^{\mu\nu}$ from the IP-Glasma



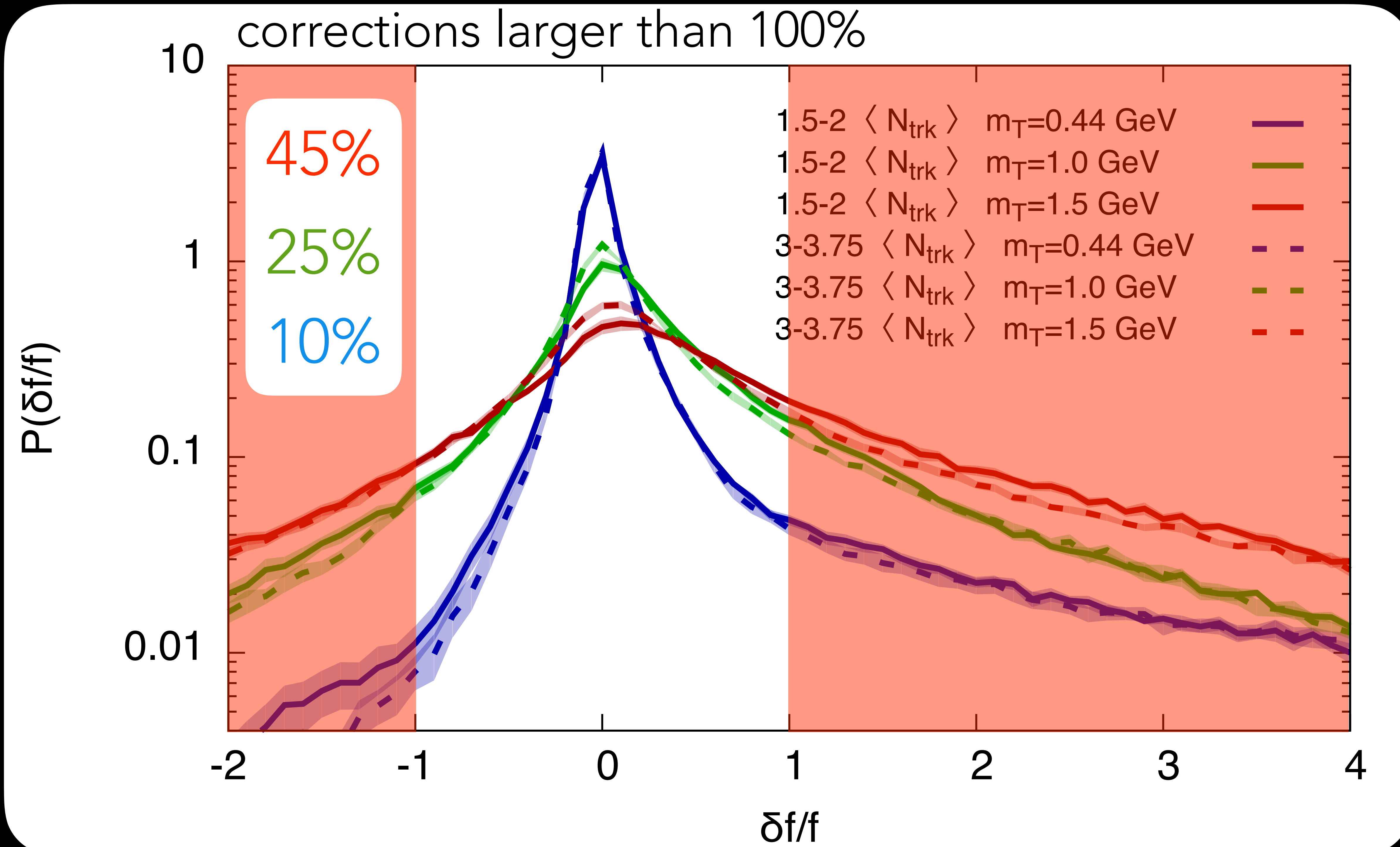
τ_0=0.4 fm η/s=0.2 $\tau_\pi = 5\frac{\eta}{\varepsilon + P}$

Björn Schenke, BNL

Histogram of δf/f on the switching surface



Histogram of δf/f on the switching surface



Summary

- Small systems well described in hydrodynamic framework when proton fluctuations are included

- Initial non-equilibrium stage matters and needs improved treatment

- Viscous corrections at p_T>1 GeV are large

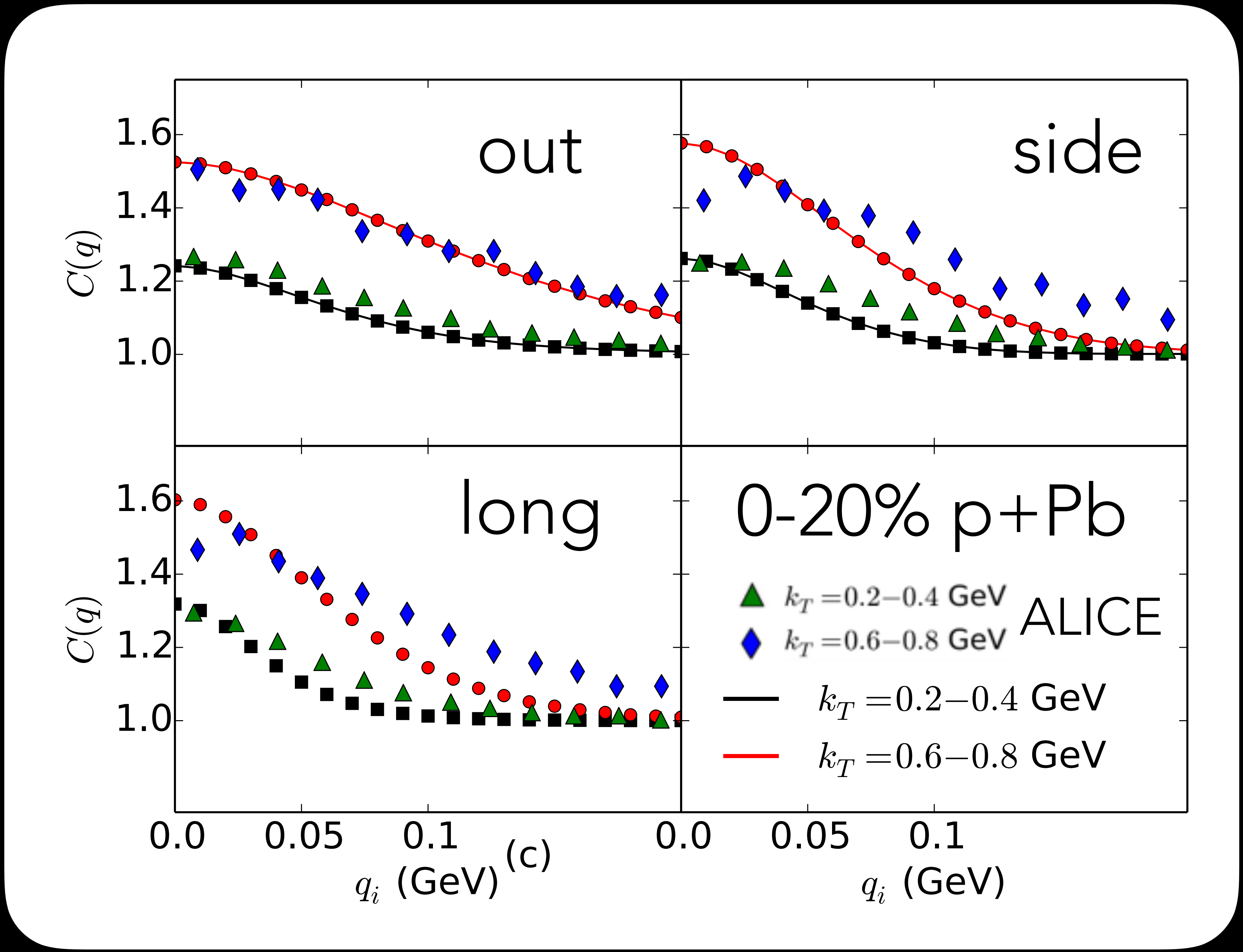
- Future: higher statistics + more observables could be used to constrain fluctuating (energy dependent) shape of the proton

BACKUP

HBT radii

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

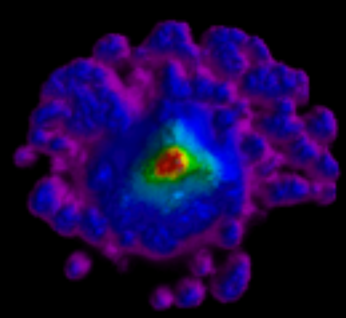
Data: ALICE Collaboration, J. Adam et al. (ALICE), Phys. Rev. C91, 034906 (2015)



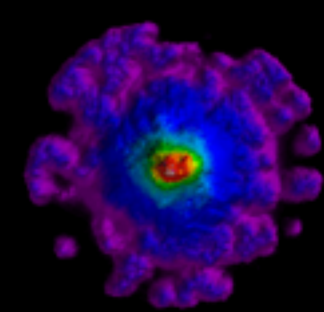
τ_0=0.4 fm (η/s)(T)

Temperature profile without bulk viscosity

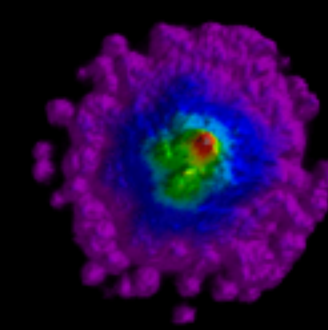
$\sim 1\langle N\rangle$



$\sim 2\langle N\rangle$

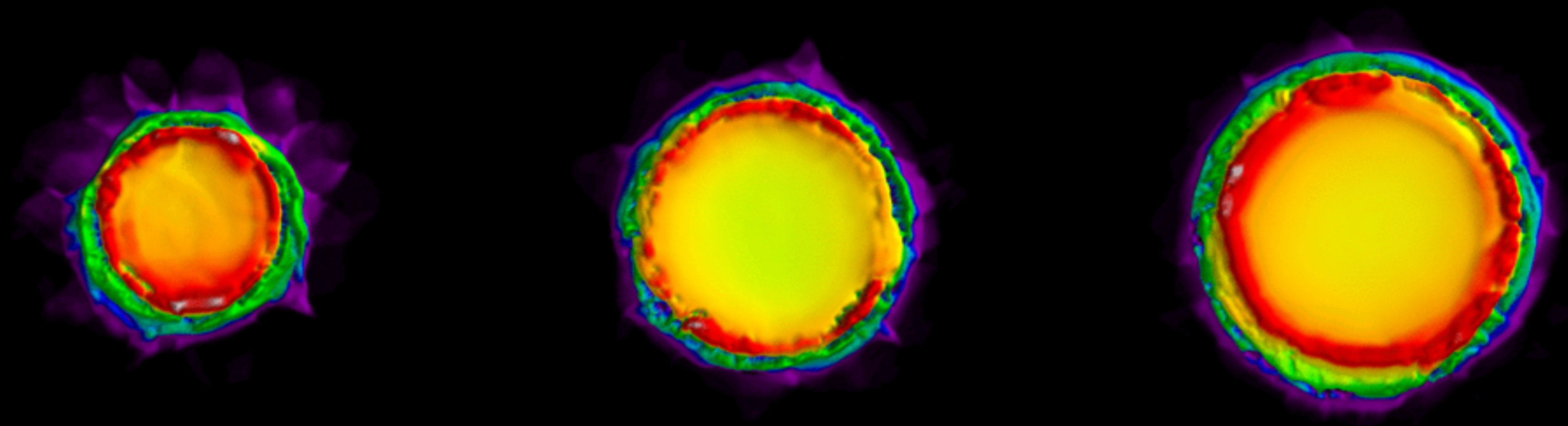


$\sim 3\langle N\rangle$



Temperature profile without bulk viscosity

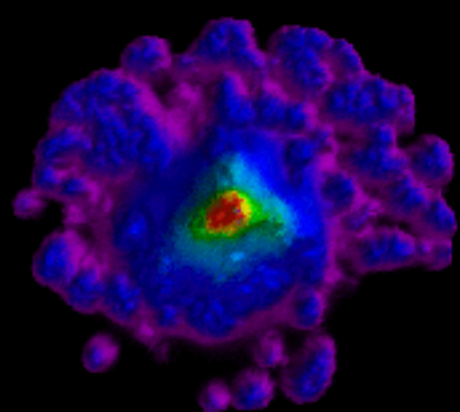
~1⟨N⟩	~2⟨N⟩	~3⟨N⟩



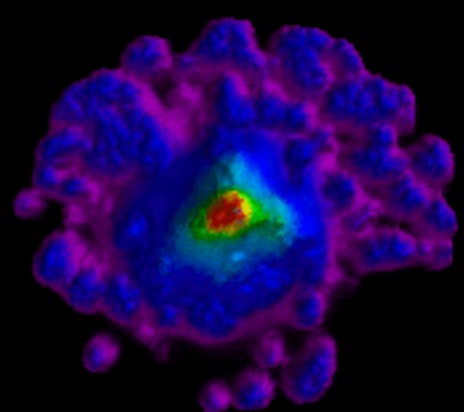
2.55 fm	3.6 fm	4.2 fm

Effect of Bulk viscosity

w/o bulk viscosity

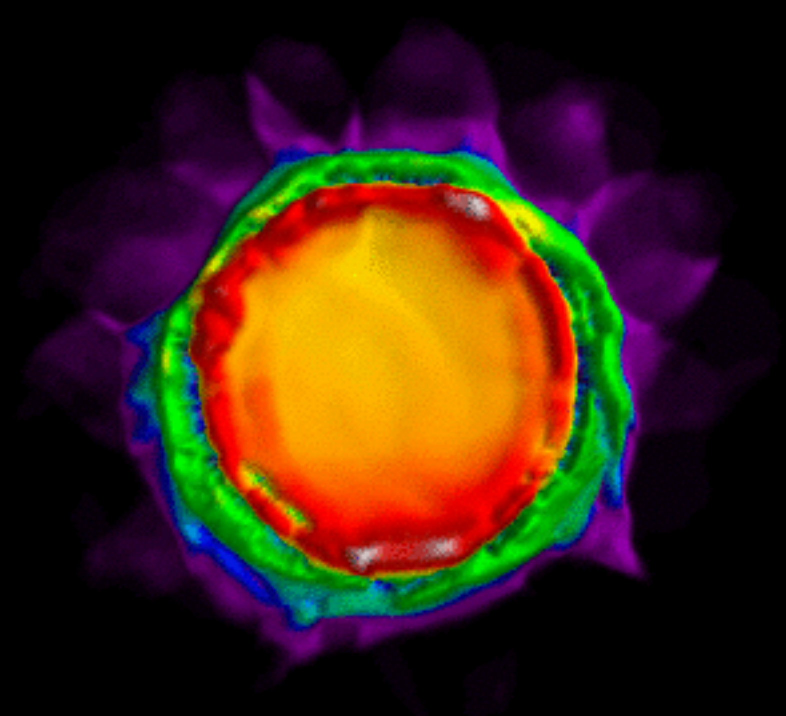


with bulk viscosity



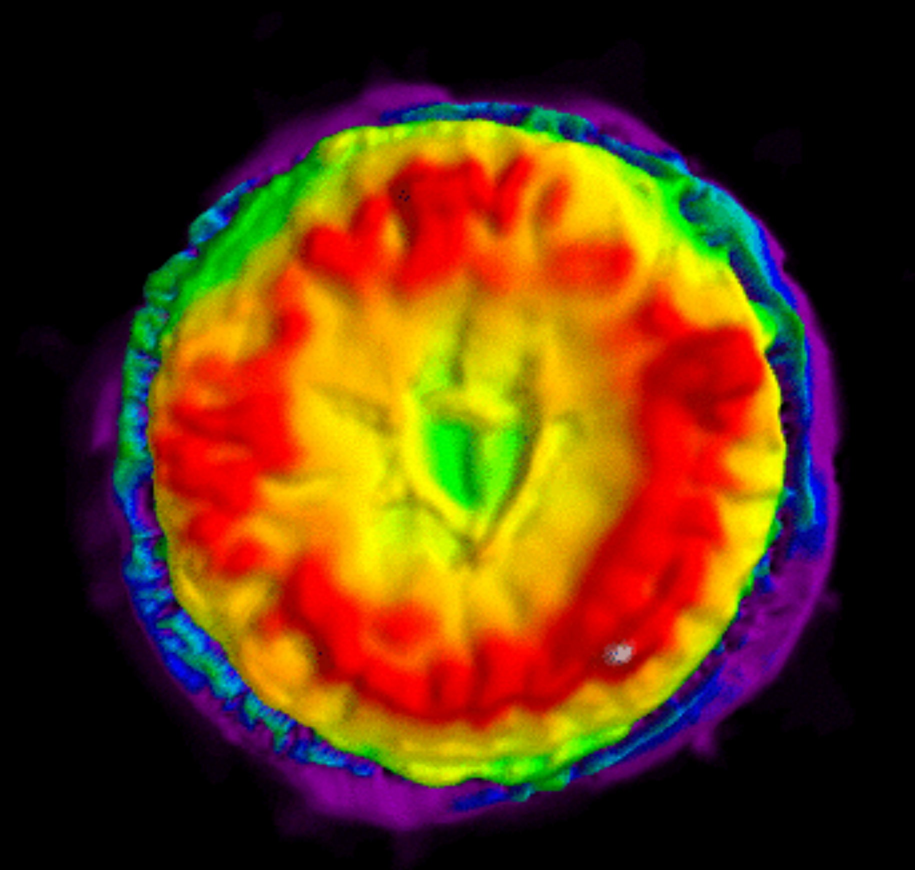
Effect of Bulk viscosity

w/o bulk viscosity



2.55 fm

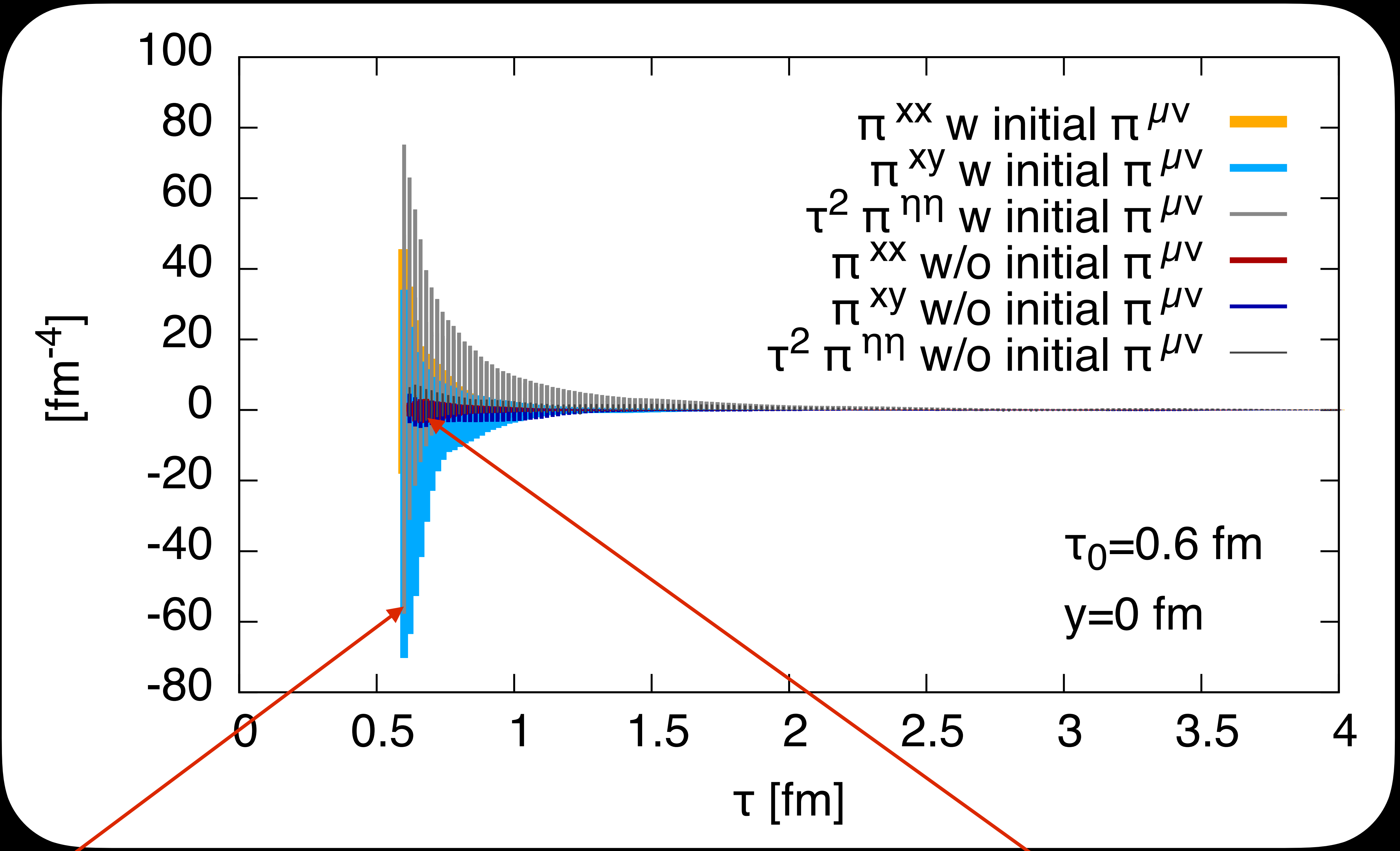
with bulk viscosity



4.65 fm

EVOLUTION OF $\pi^{\mu\nu}$

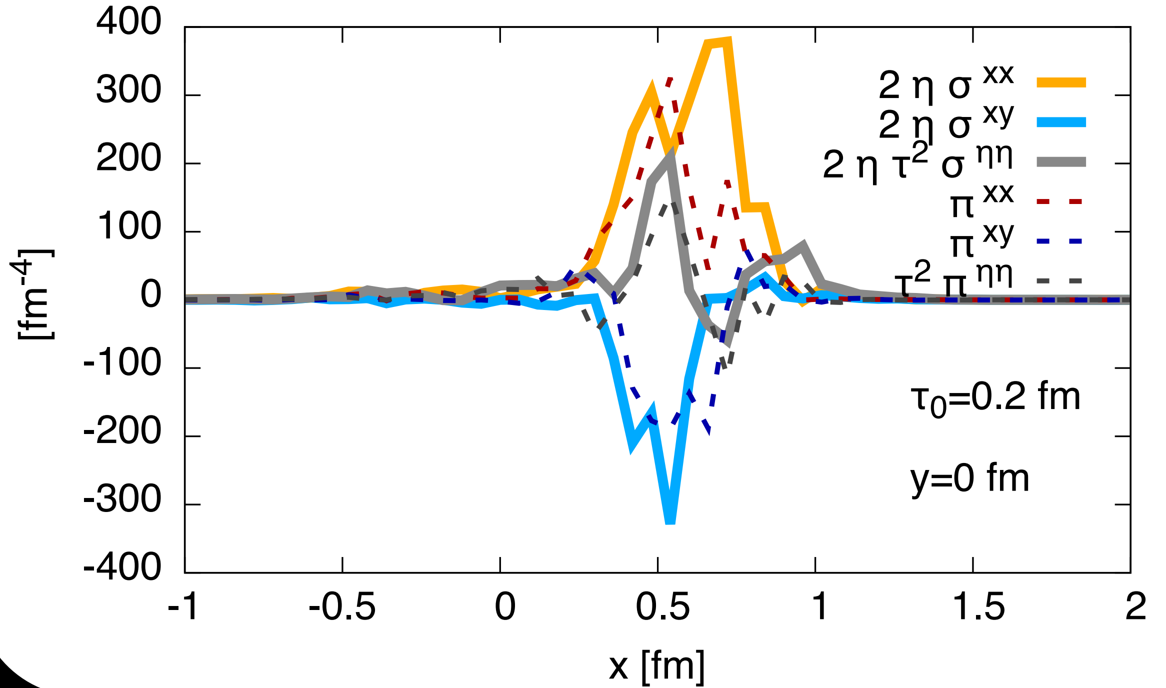
$\eta/s = 0.1$ and T dependent ζ/s

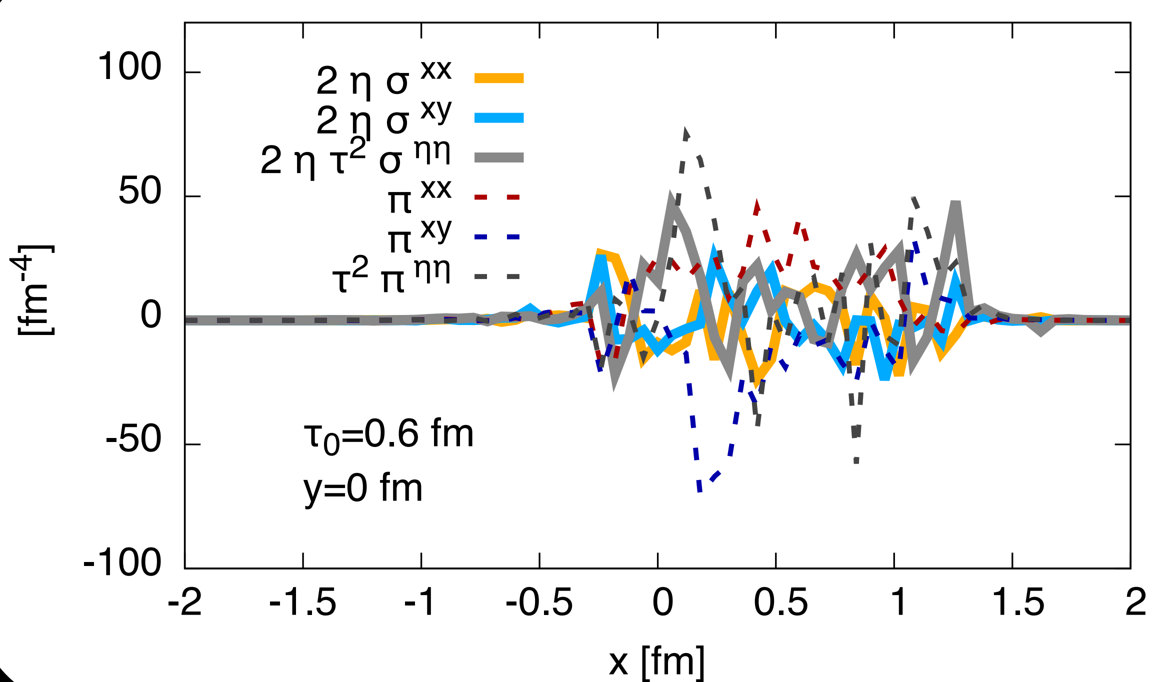


with initial $\pi^{\mu\nu}$

without initial $\pi^{\mu\nu}$

INITIAL IP-GLASMA $\pi^{\mu\nu}$ COMPARED TO INITIAL NAVIER-STOKES VALUE

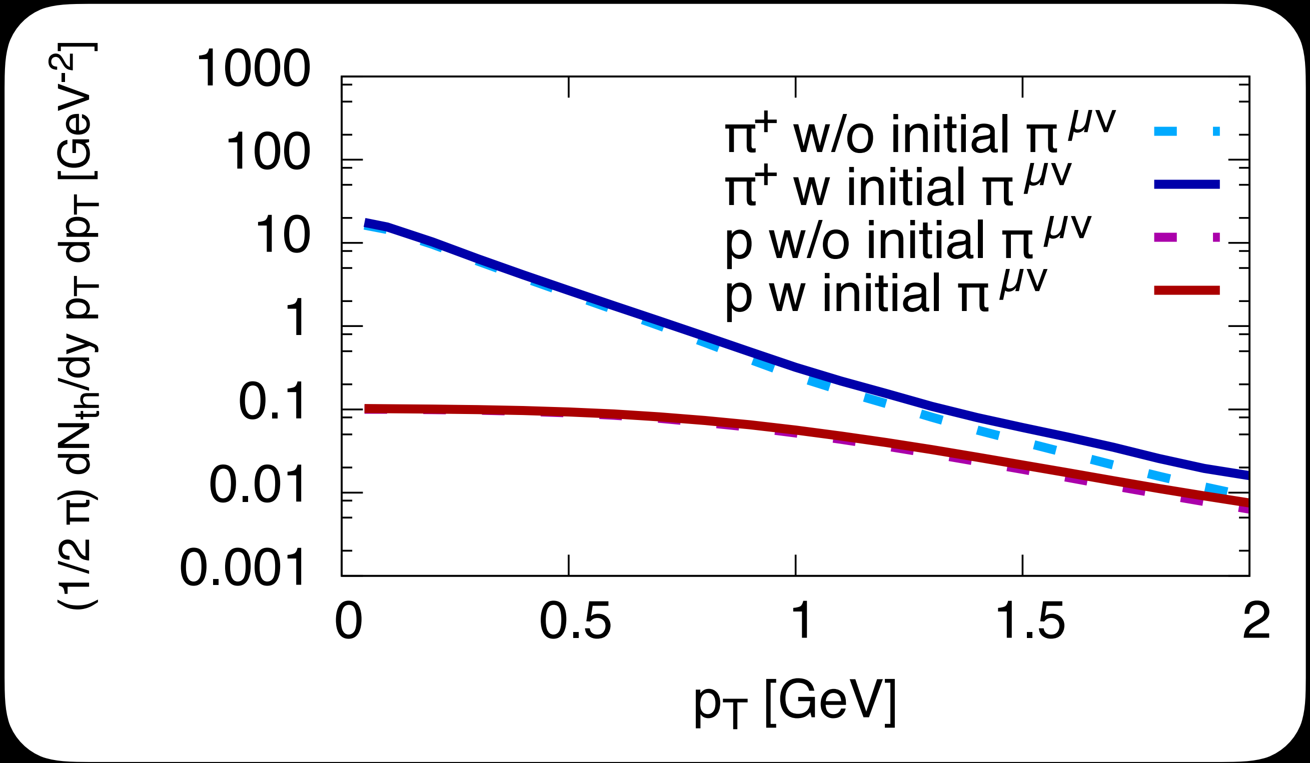


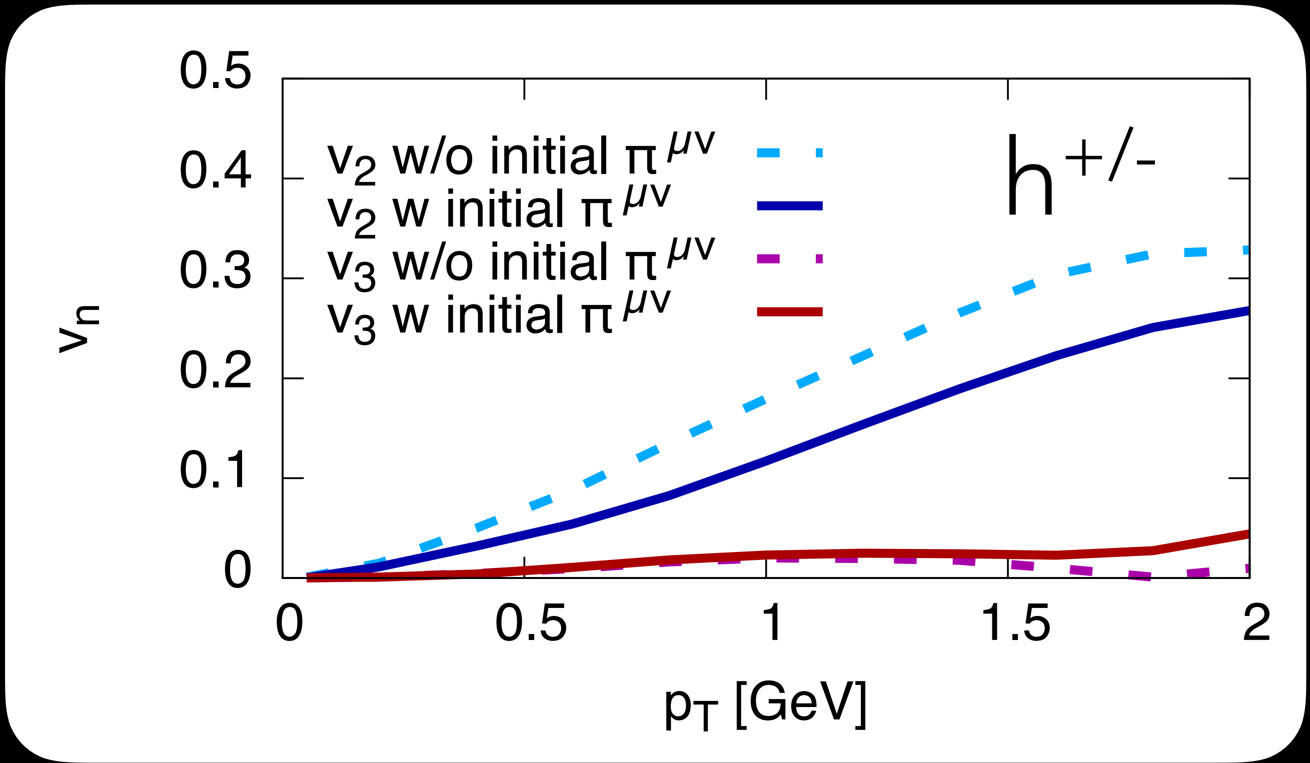


$$\sigma^{\mu\nu} = \nabla^{(\mu} u^{\nu)} - \frac{1}{3}\Delta^{\mu\nu}\nabla_\alpha u^\alpha$$

Similar magnitude for $\eta/s = 0.1$

EFFECT OF INITIAL $\pi^{\mu\nu}$





Testing in just one event:

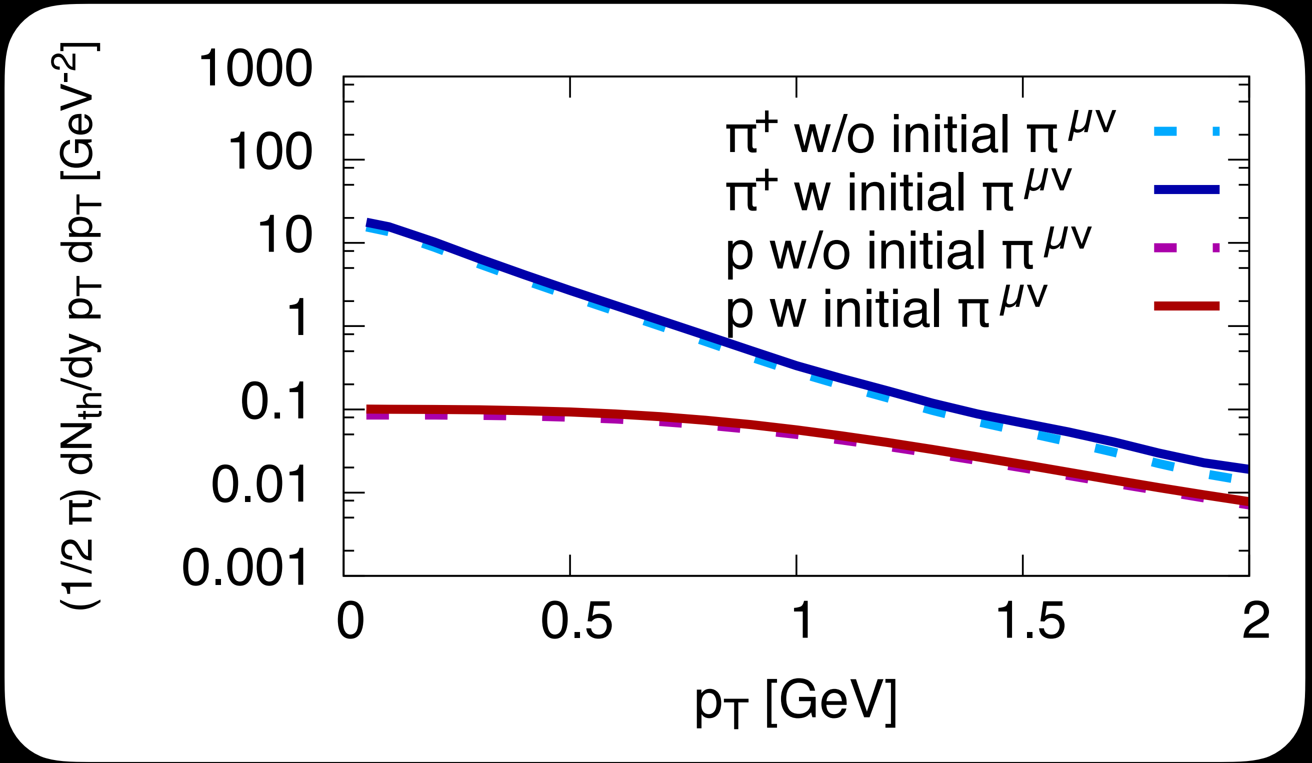
- more entropy production
- different viscous effects

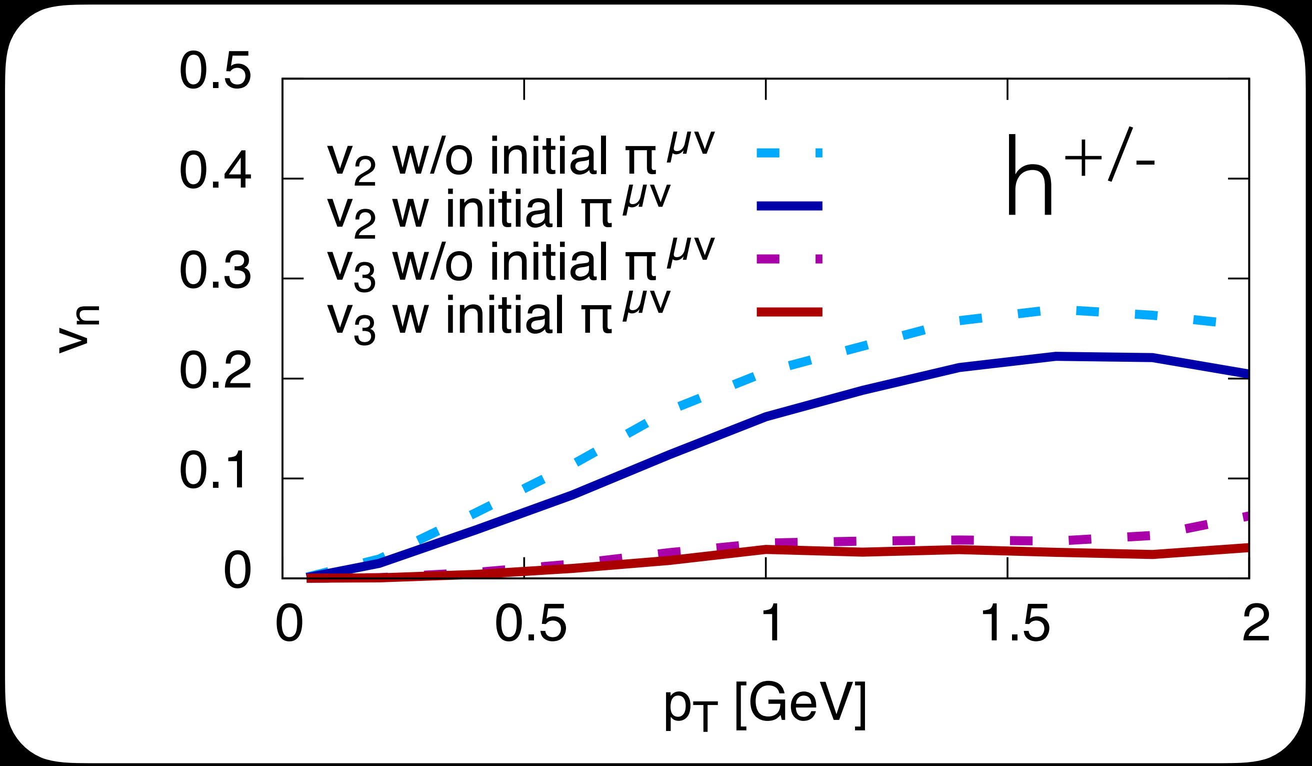
- initial $\pi^{\mu\nu}$ reduces v_2

$$\tau_\pi = 3\frac{\eta}{\varepsilon + P}$$

τ_0=0.6 fm

EFFECT OF INITIAL $\pi^{\mu\nu}$





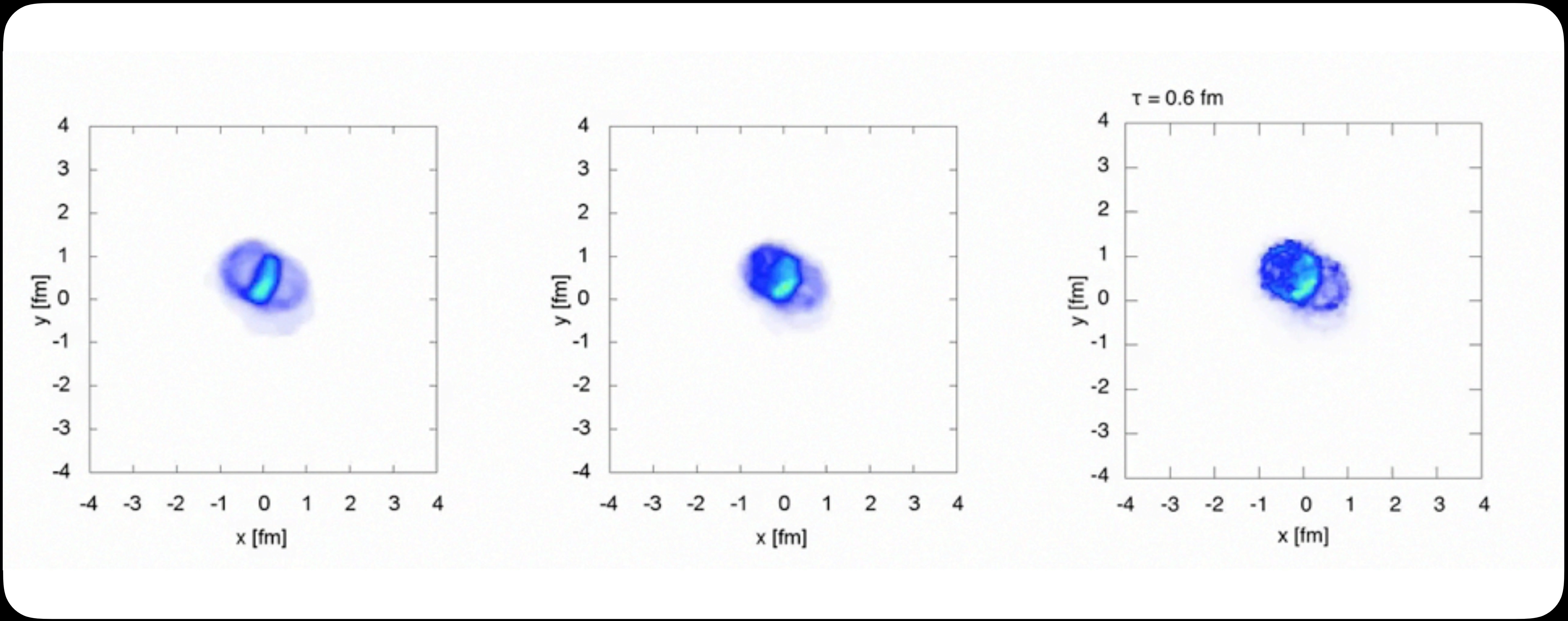
Testing in just one event:

- more entropy production
- different viscous effects

- initial $\pi^{\mu\nu}$ reduces v_2

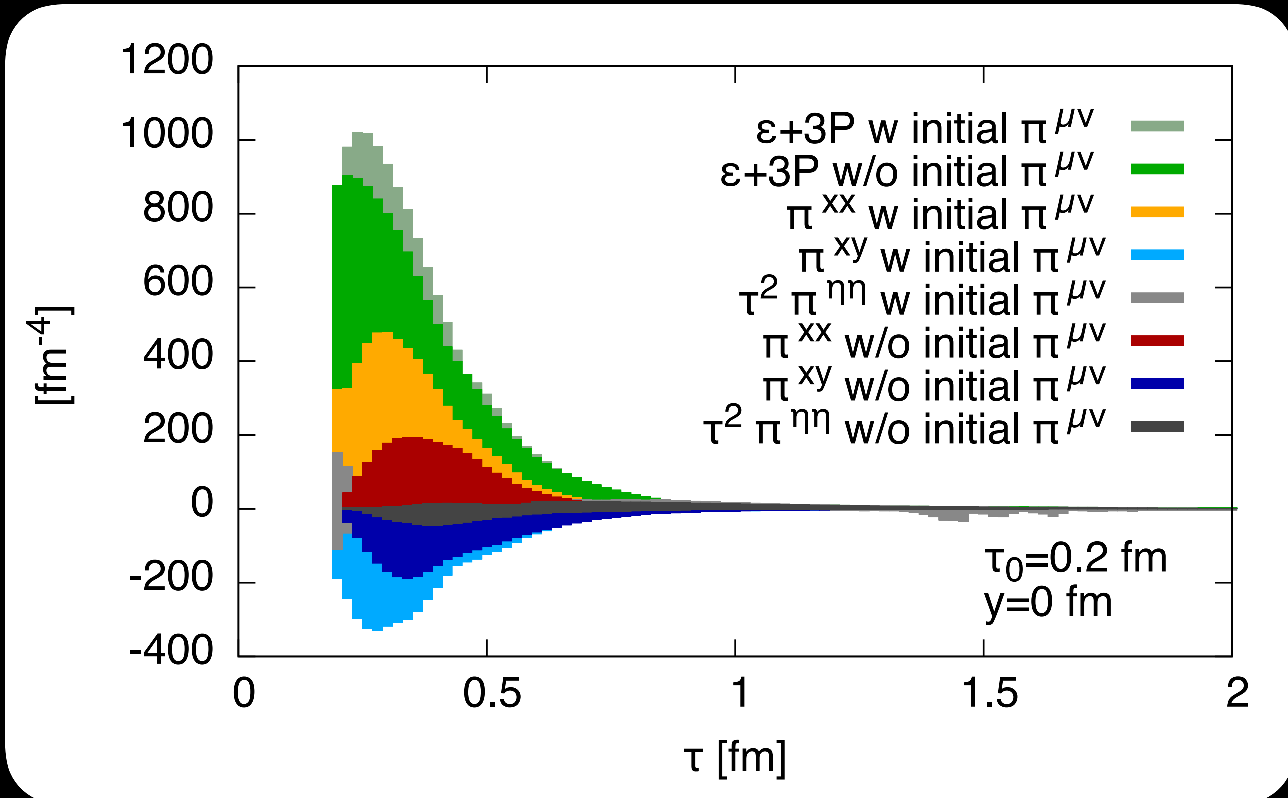
$$\tau_\pi = 3\frac{\eta}{\varepsilon + P} \qquad \tau_0 = 0.4\ \text{fm}$$

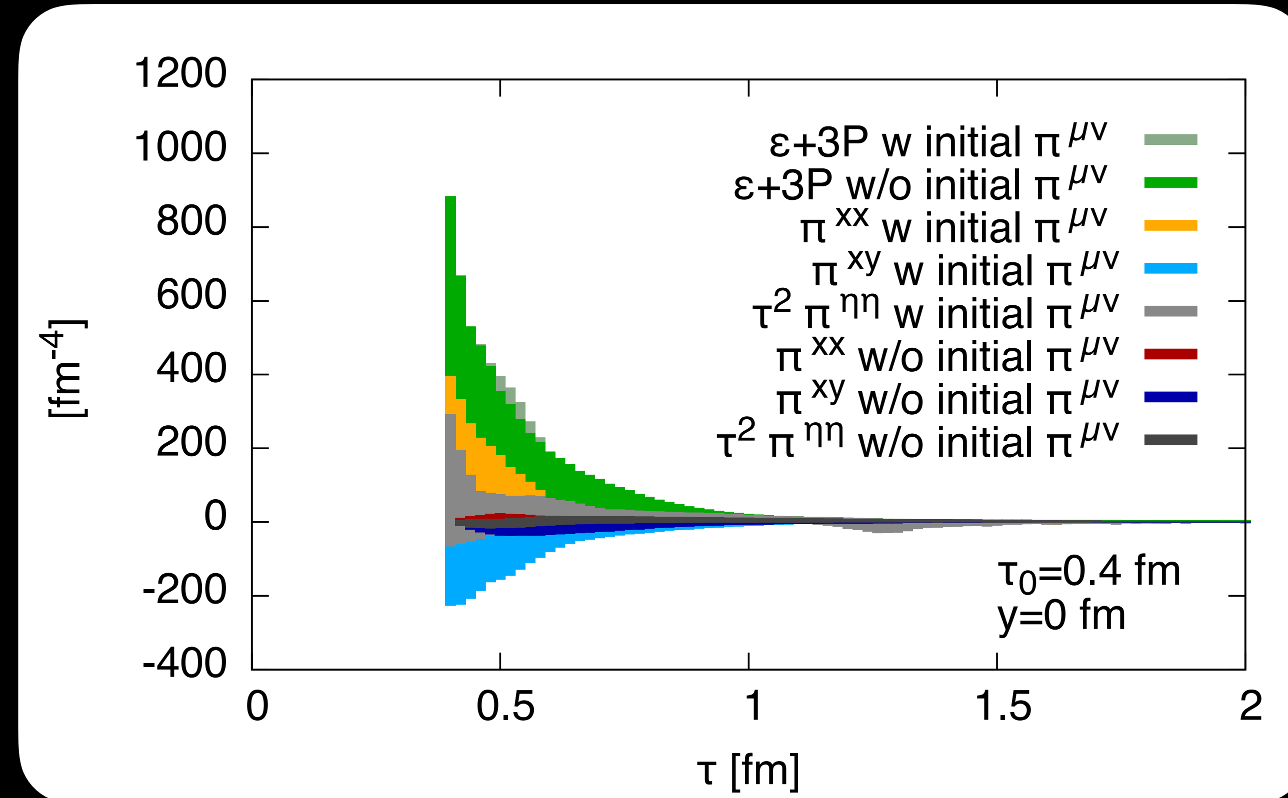
EFFECT OF SWITCHING TIME



τ_0=0.2 fm τ_0=0.4 fm τ_0=0.6 fm

EVOLUTION OF $\pi^{\mu\nu}$

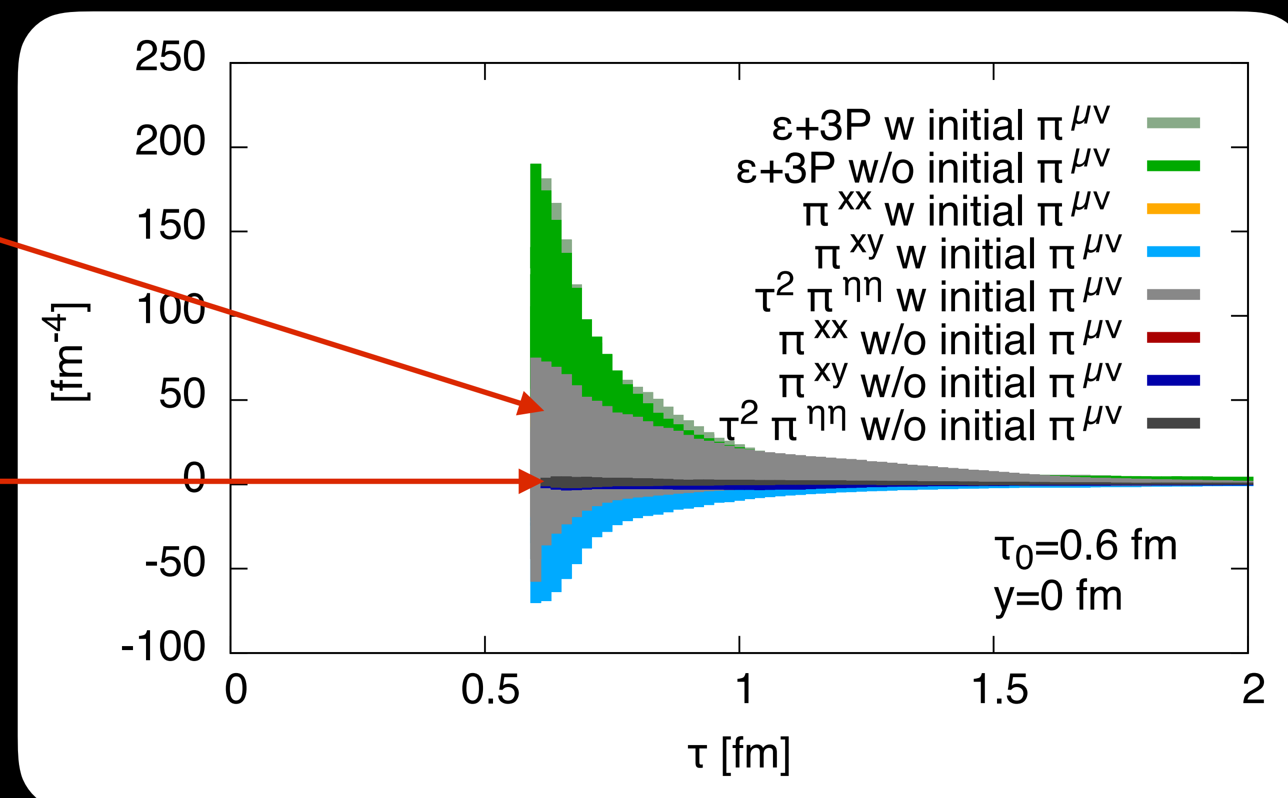




$$\tau_\pi = 5\frac{\eta}{\varepsilon + P}$$

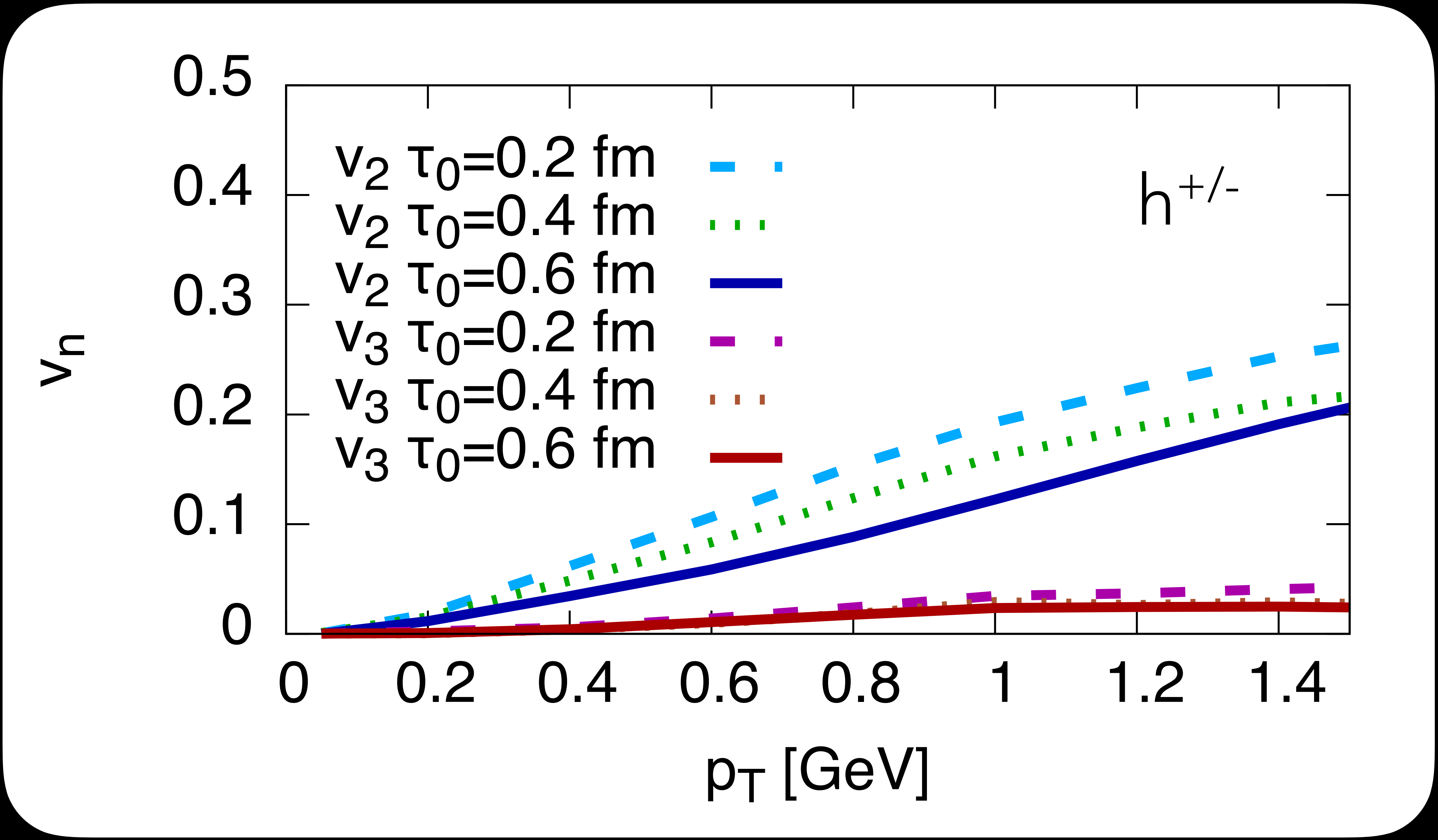
with initial $\pi^{\mu\nu}$

without initial $\pi^{\mu\nu}$



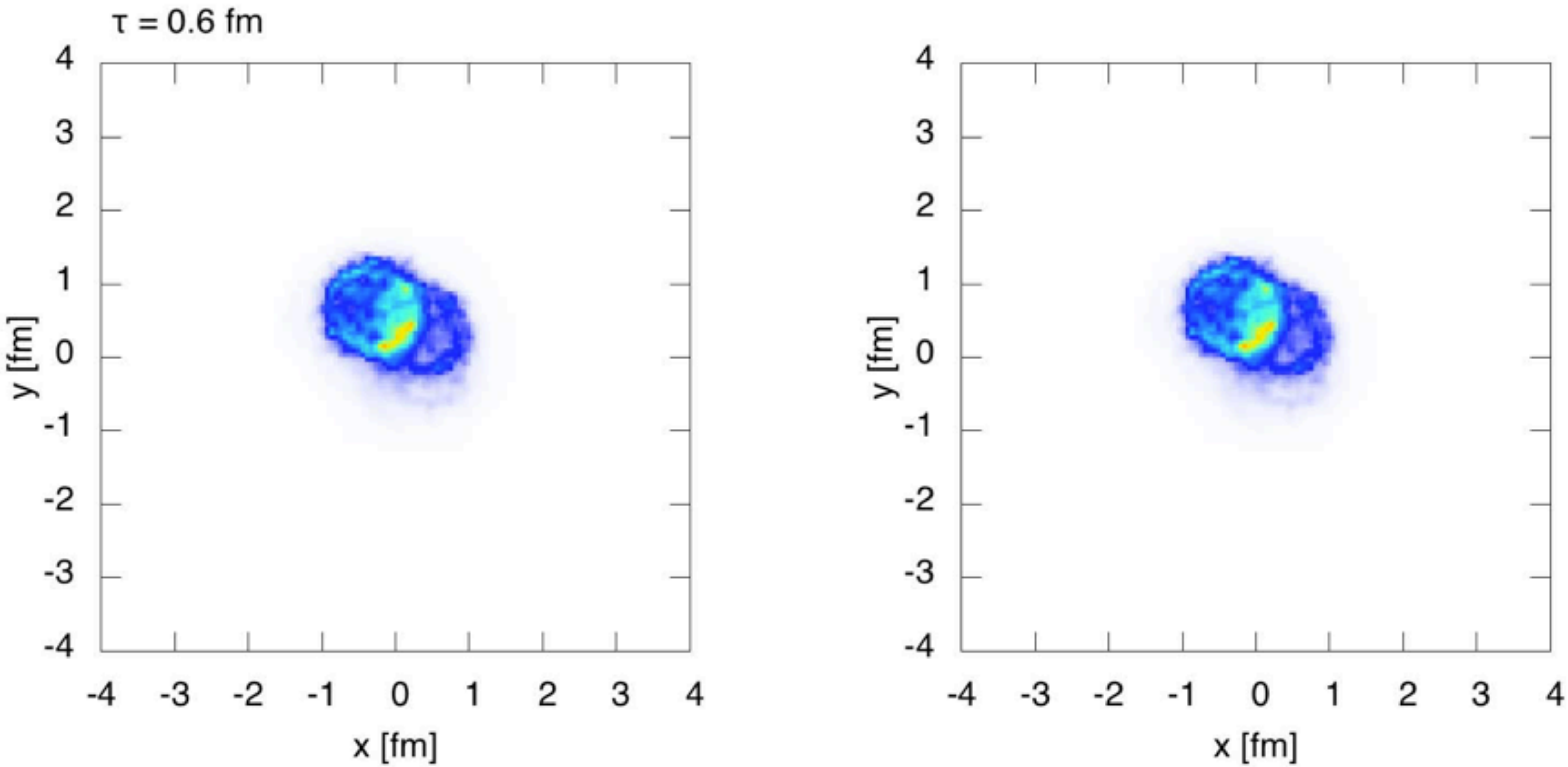
T dependent **η**/s and **ζ**/s

EFFECT OF SWITCHING TIME

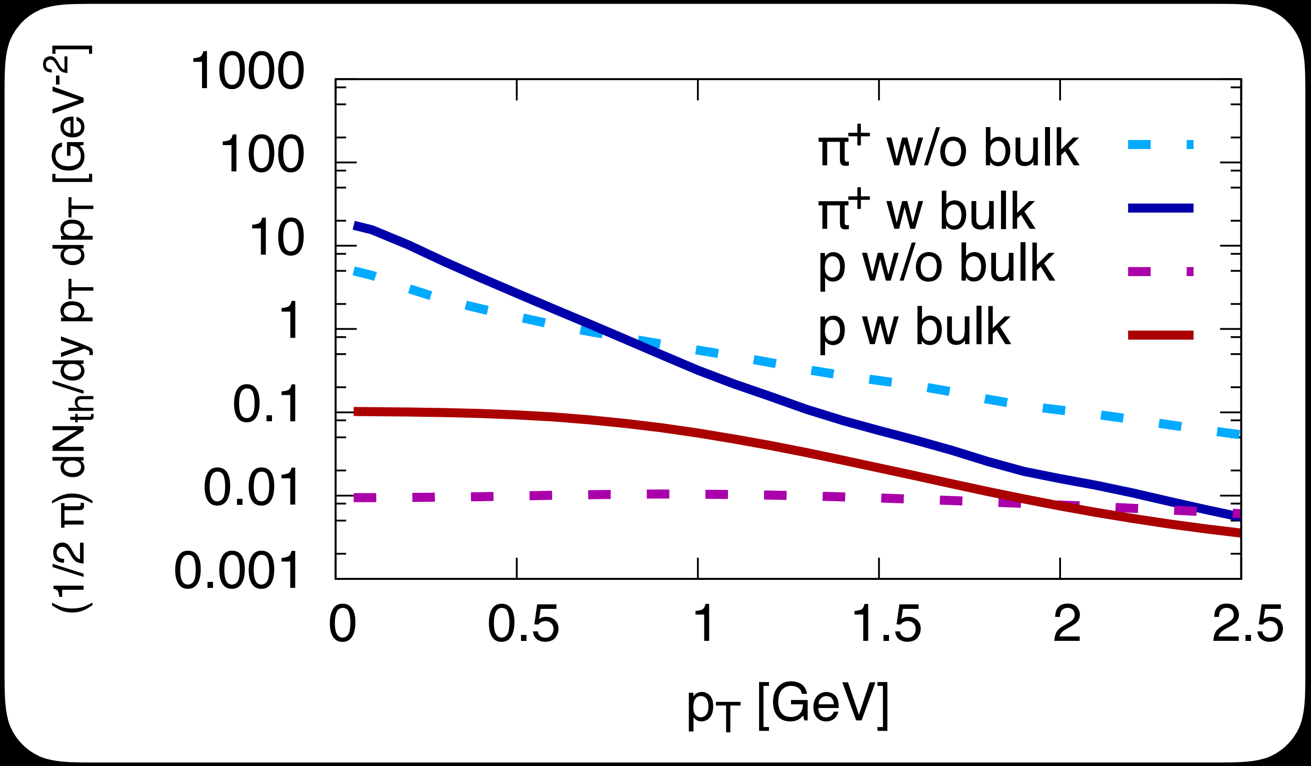


more hydro → larger v_n

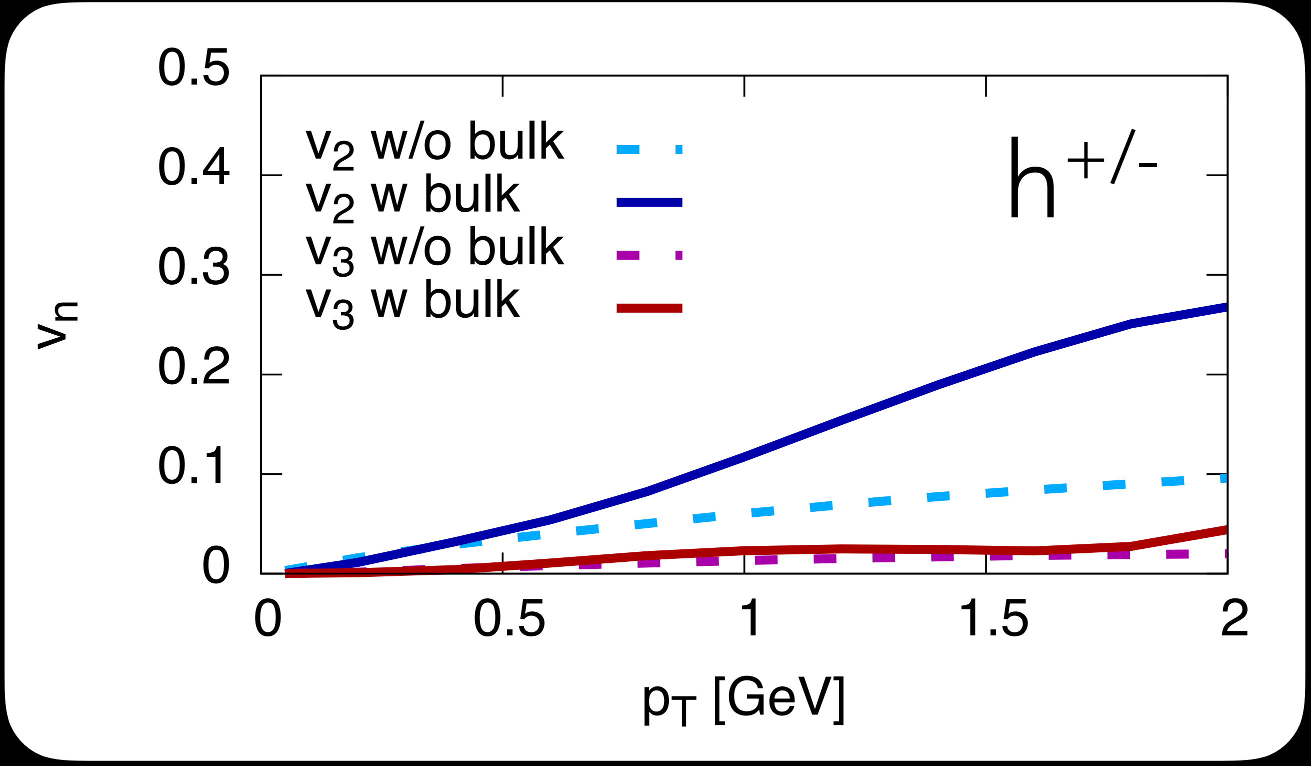
EFFECT OF BULK VISCOSITY



EFFECT OF BULK VISCOSITY

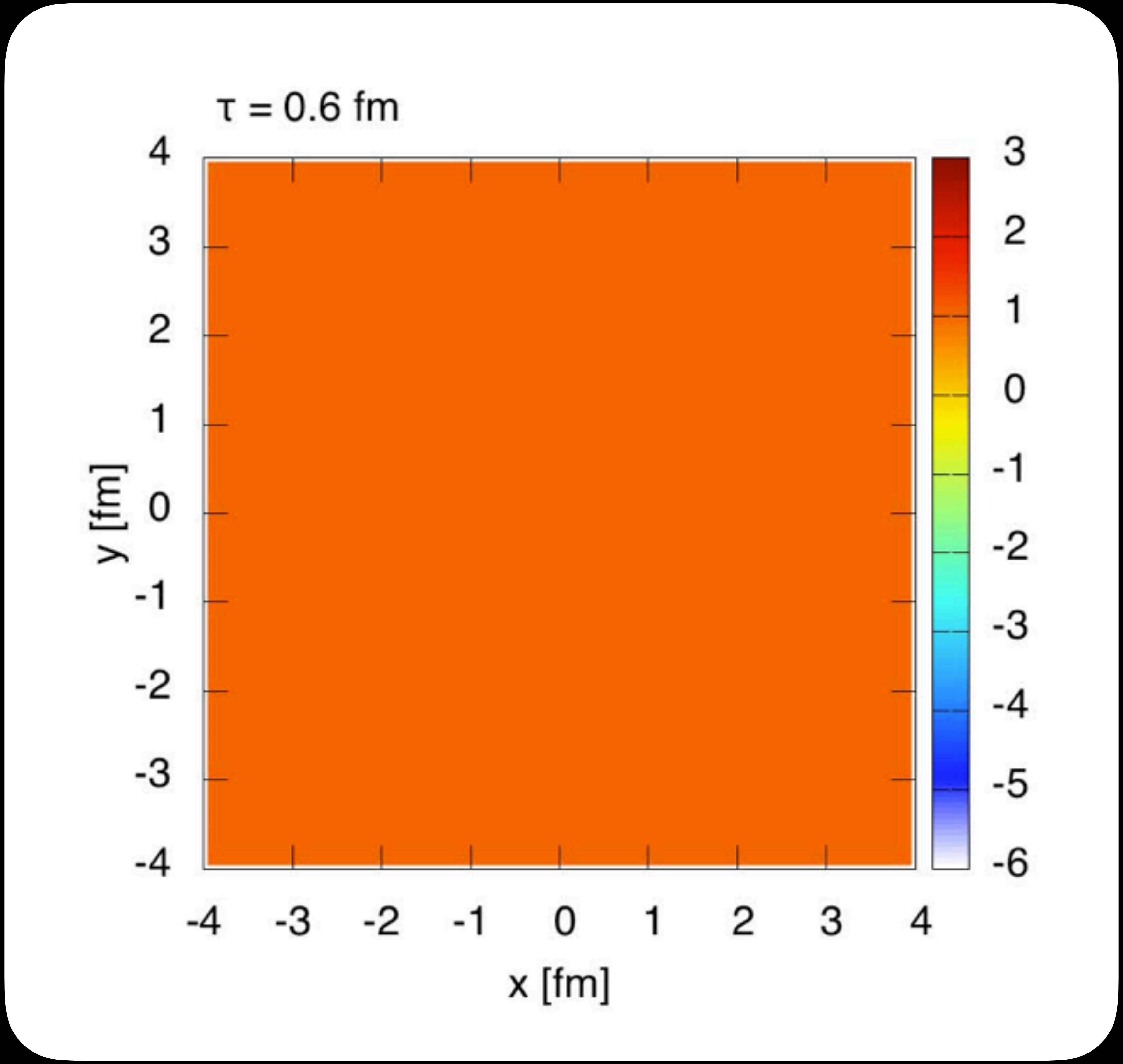


Spectra become significantly steeper (decreased radial flow)

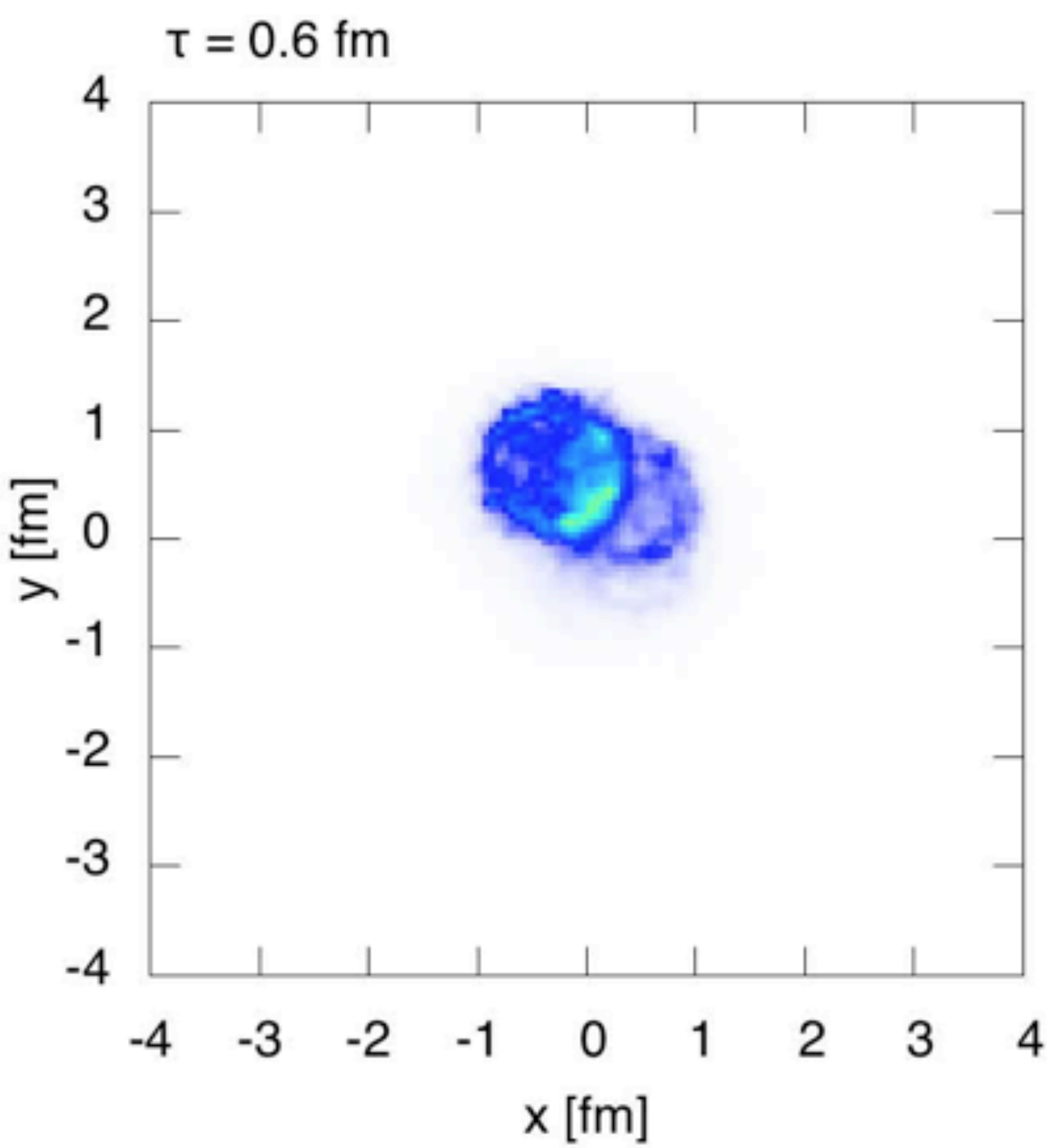


v_n are increased likely mainly due to the steeper spectra

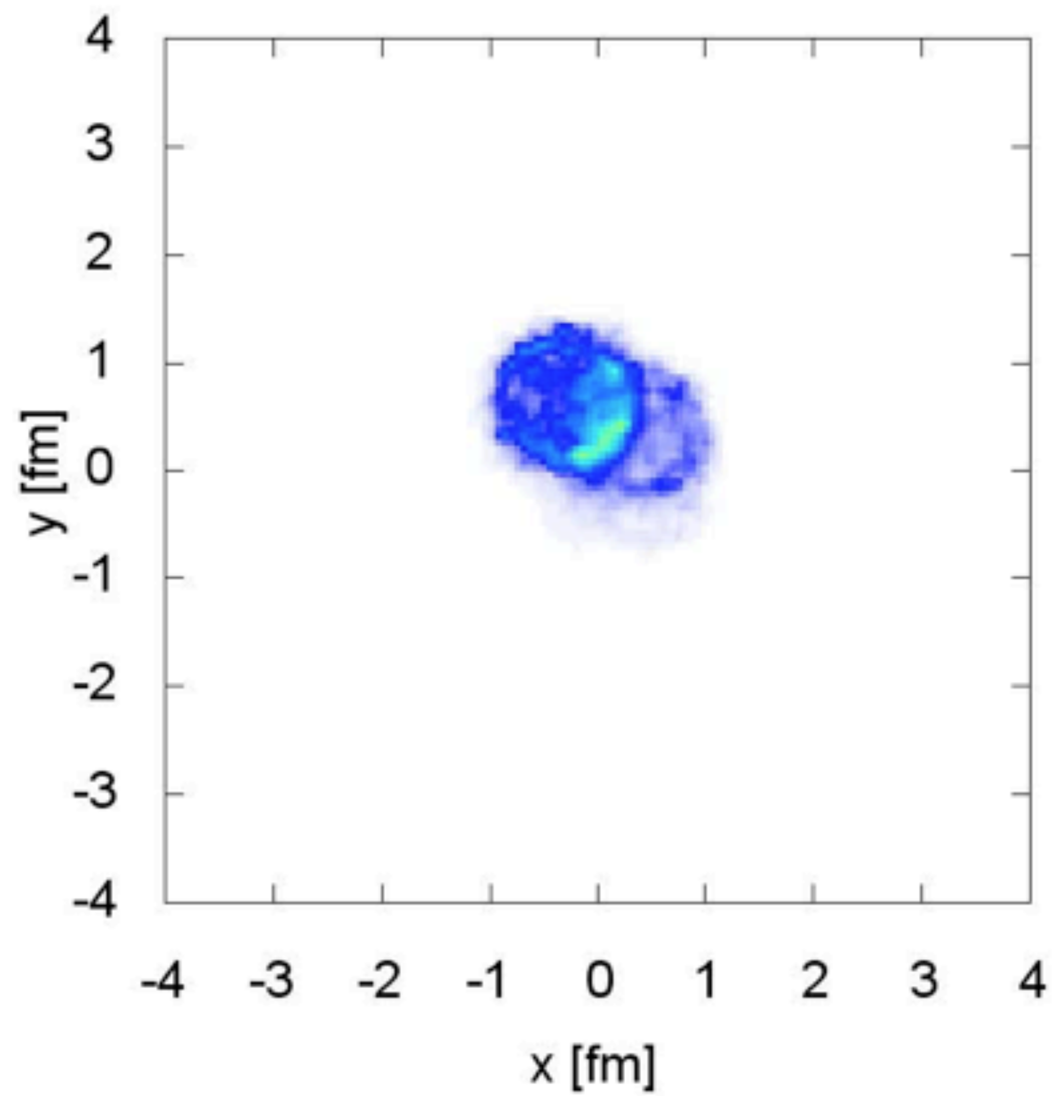
EFFECTIVE PRESSURE 1+Π/P



EFFECT OF INITIAL u^μ

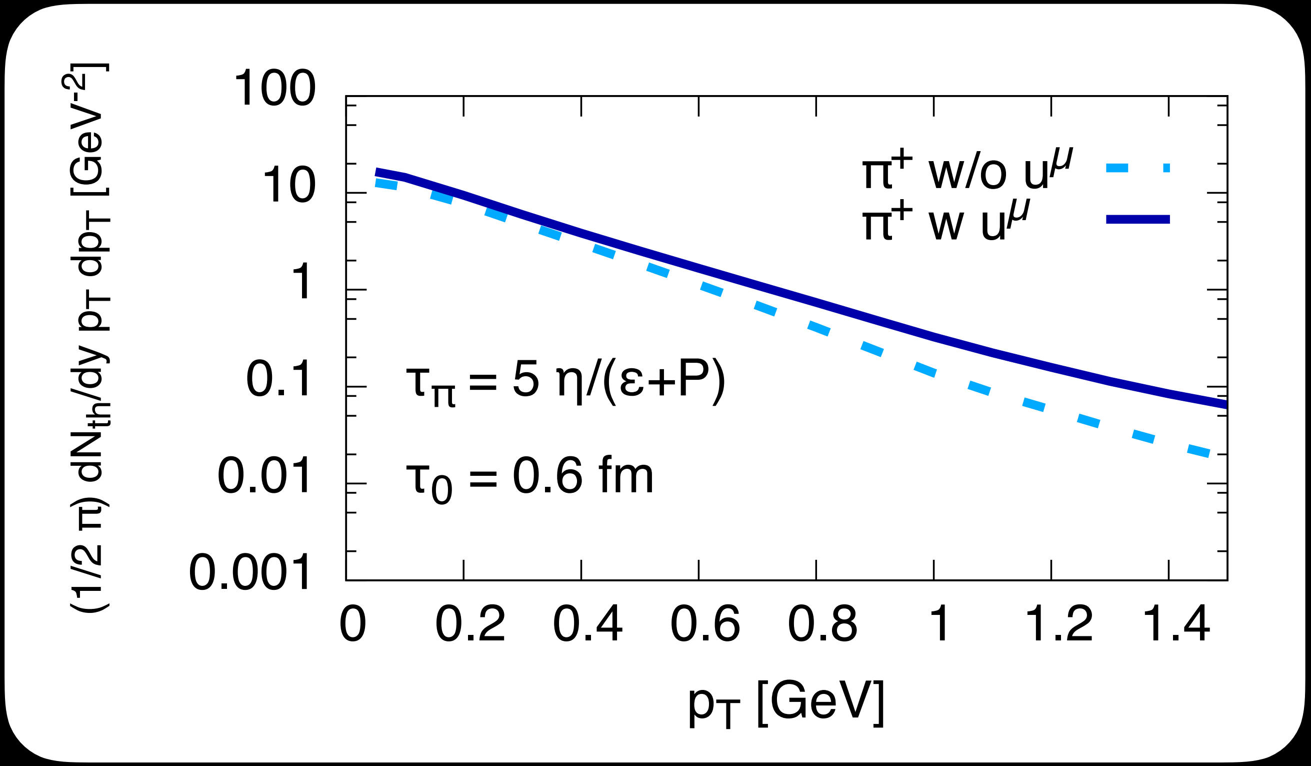


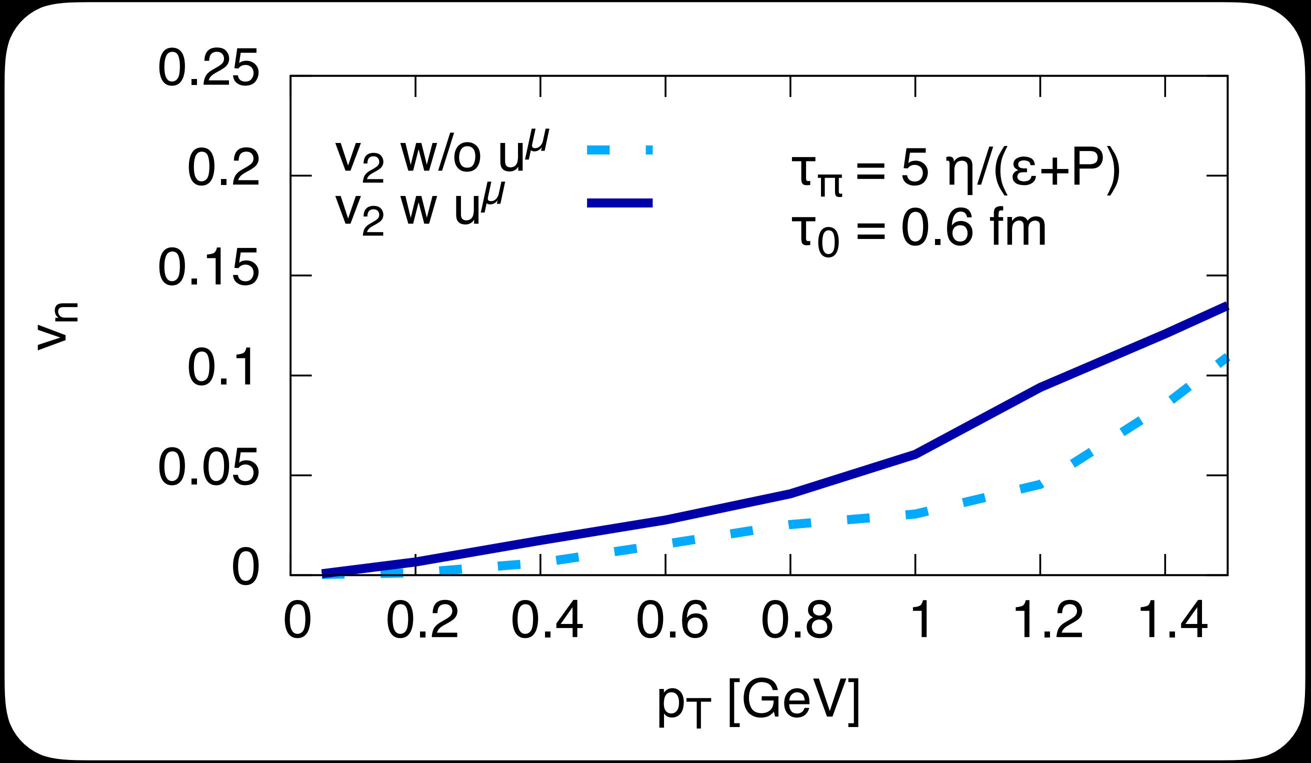
w/o initial flow



w initial flow

EFFECT OF INITIAL u^{μ} (with initial $\pi^{\mu\nu}$)





Harder spectra

τ_0=0.6 fm: $\sqrt{\langle u^{x2}\rangle} = 0.47$

$\sqrt{\langle u^{y2}\rangle} = 0.53$

$\sqrt{\langle (\tau u^{\eta})^2\rangle} = 0.14$

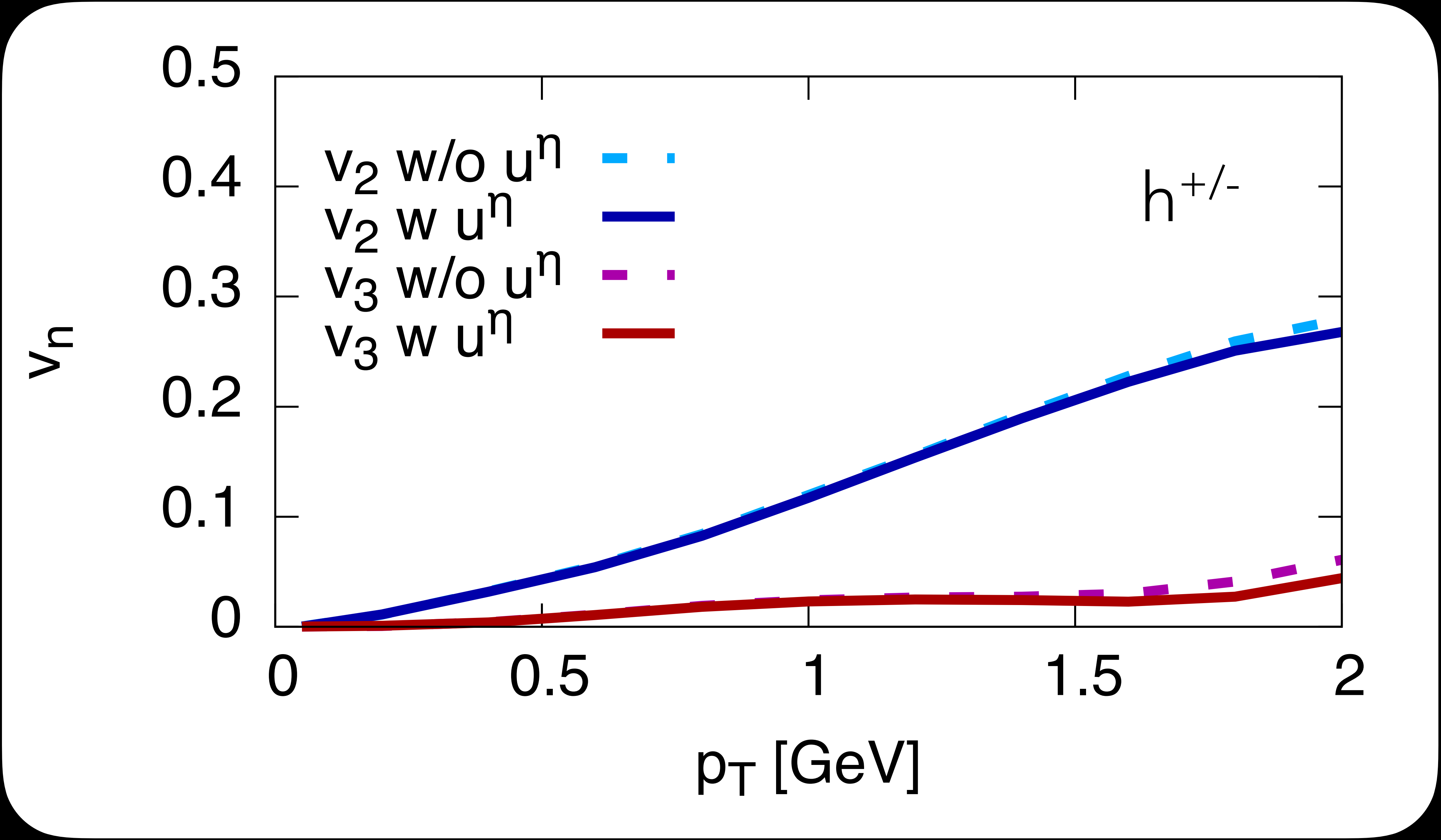
τ_0=0.2 fm: $\sqrt{\langle u^{x2}\rangle} = 0.38$

$\sqrt{\langle u^{y2}\rangle} = 0.41$

$\sqrt{\langle (\tau u^{\eta})^2\rangle} = 0.53$

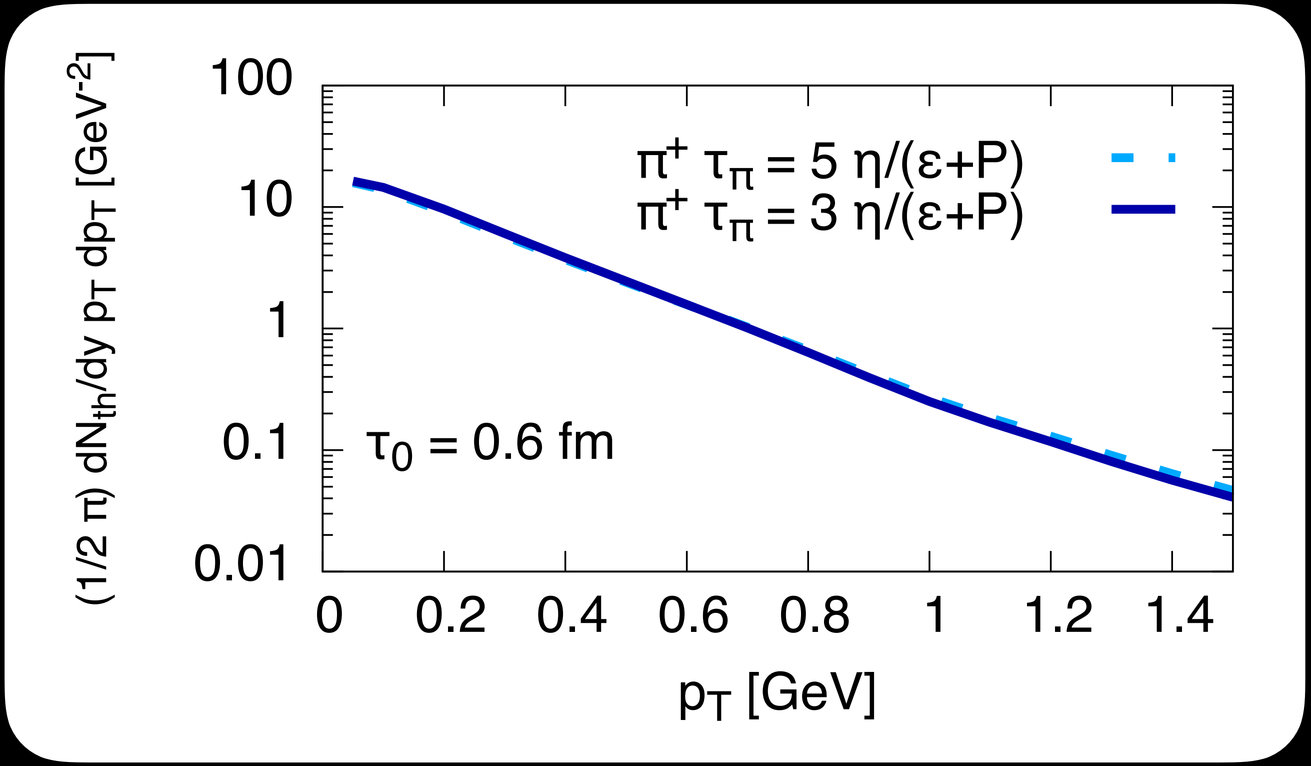
Less v_2

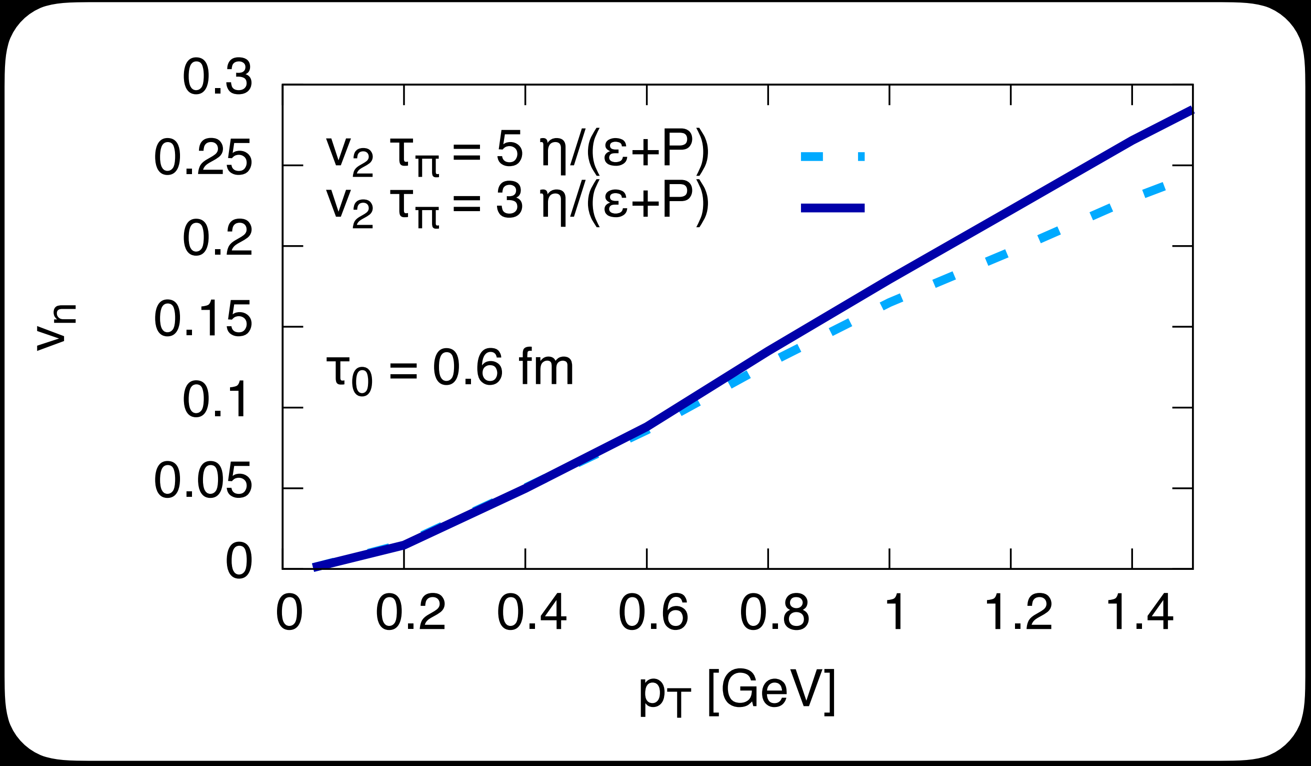
EFFECT OF INITIAL u^η



small effect: with u^η a little more suppression of v_n as one would expect

EFFECT OF RELAXATION TIME

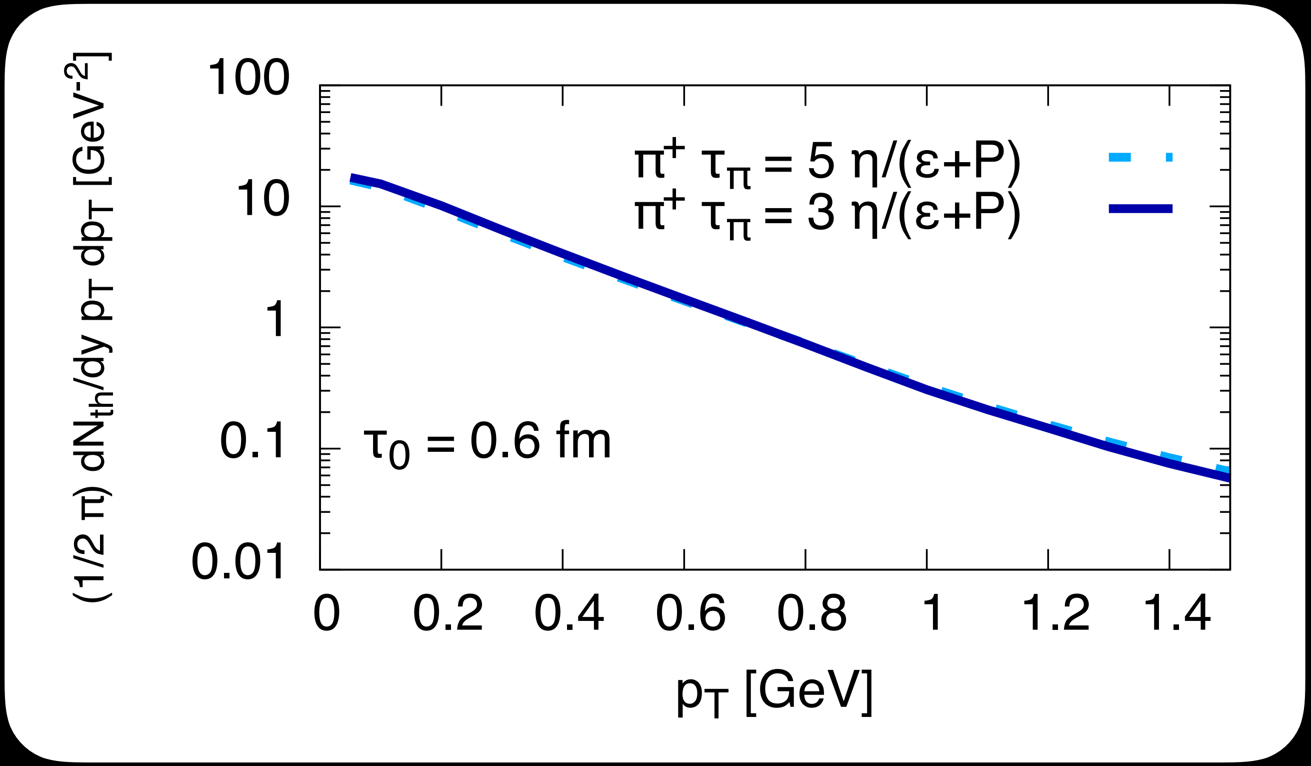




Weak effect when not including initial $\pi^{\mu\nu}$

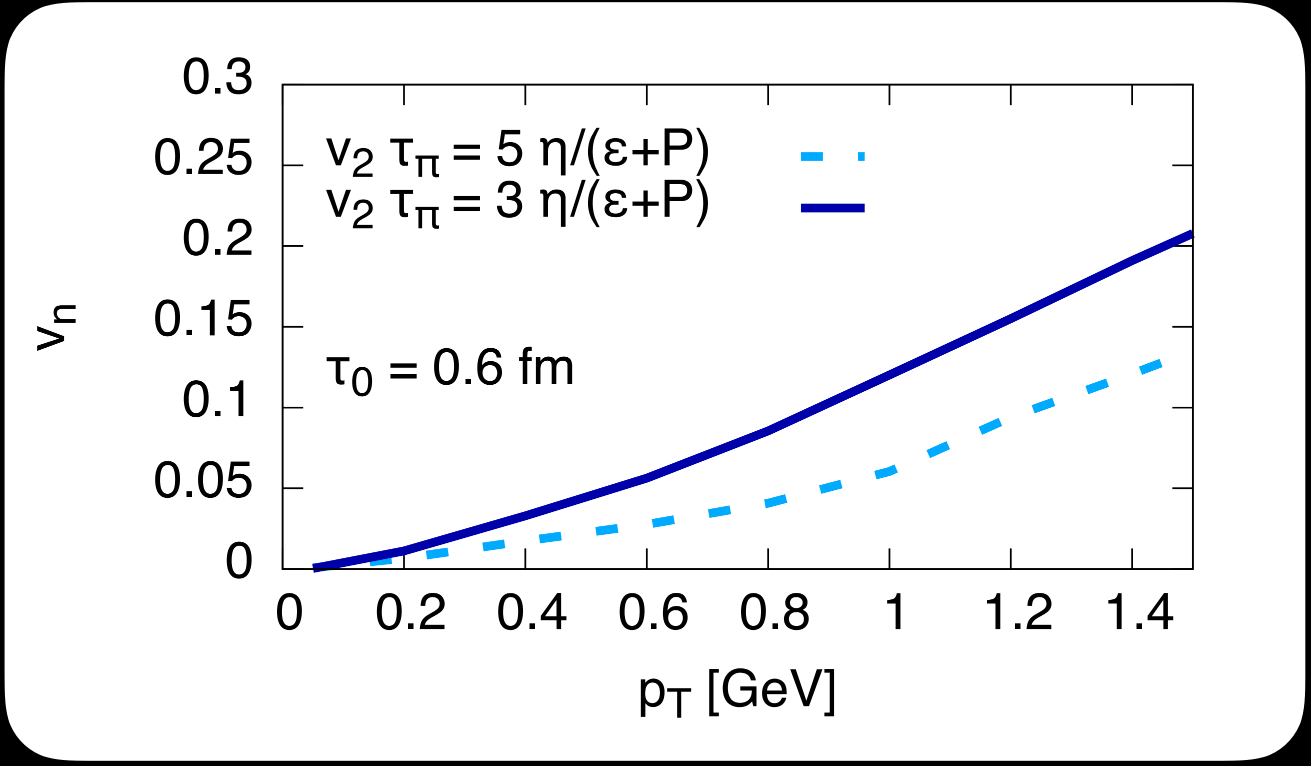
w/o initial $\pi^{\mu\nu}$

EFFECT OF RELAXATION TIME



With initial $\pi^{\mu\nu}$ surprisingly large effect on v_2

probably a **δ**f effect



with initial $\pi^{\mu\nu}$

Relativistic fluid dynamics

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

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

$$\partial_\mu T^{\mu\nu} = 0 \quad \text{with} \quad T^{\mu\nu} = (\varepsilon + P) u^\mu u^\nu - P g^{\mu\nu} + \Pi^{\mu\nu}$$

energy density (ε), pressure (P), flow velocity (u^μ), 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)

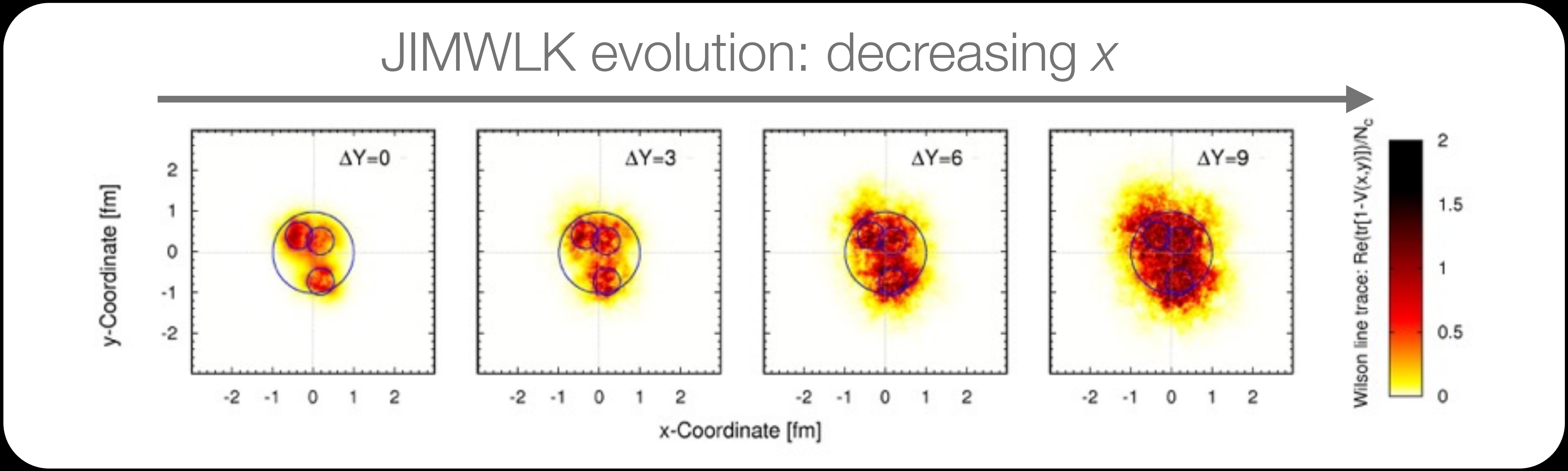
- Equation of state $P(\varepsilon)$ relates pressure to energy density (lattice)

JIMWLK evolution of the proton

Working on calculations relevant to a future EIC:

H. Mäntysaari, B. Schenke, work in progress

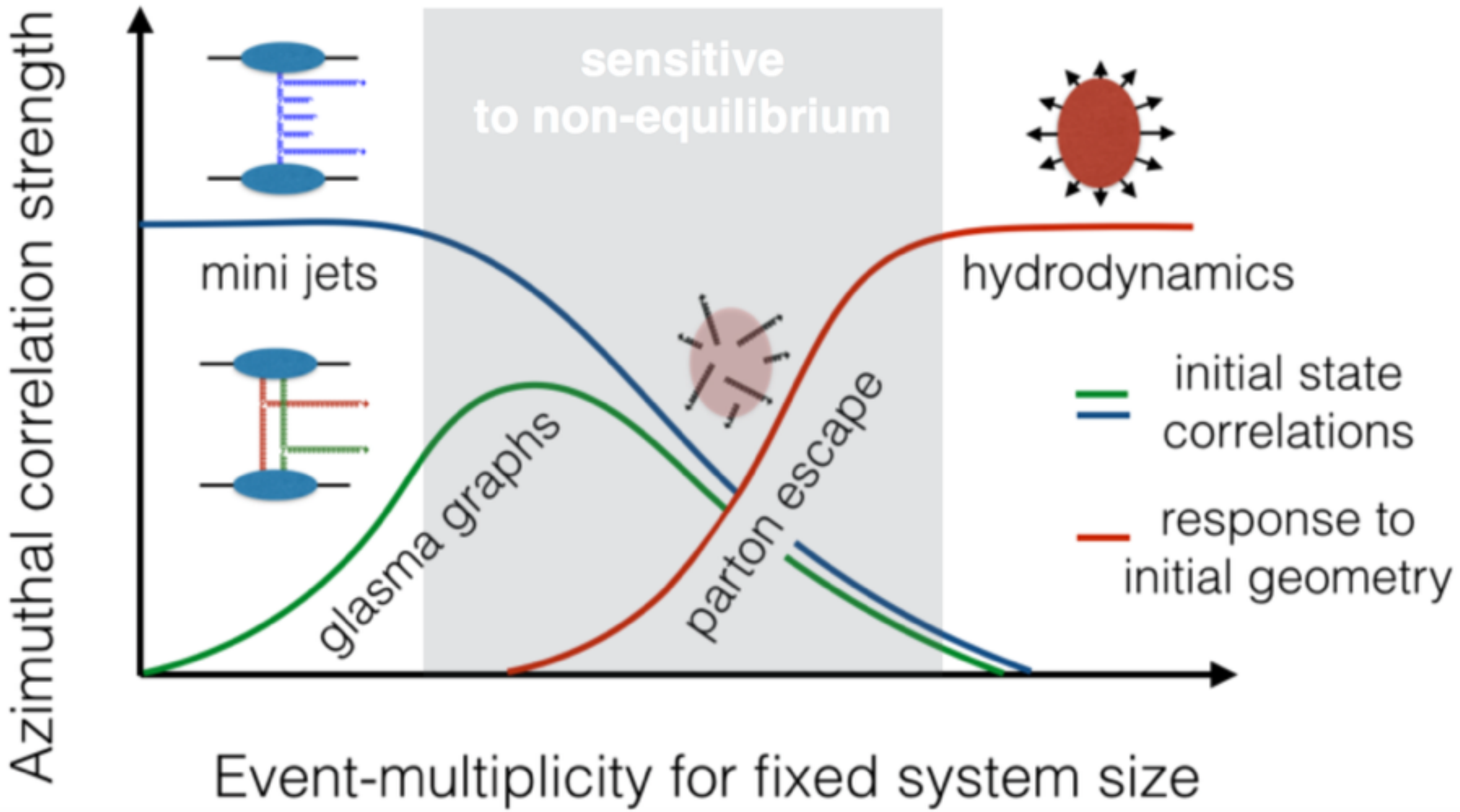
- Diffraction - more on proton and nuclear shape and fluctuations
- Small-x evolution of structure functions etc.
- Interesting fundamental questions and input for heavy in program



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

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

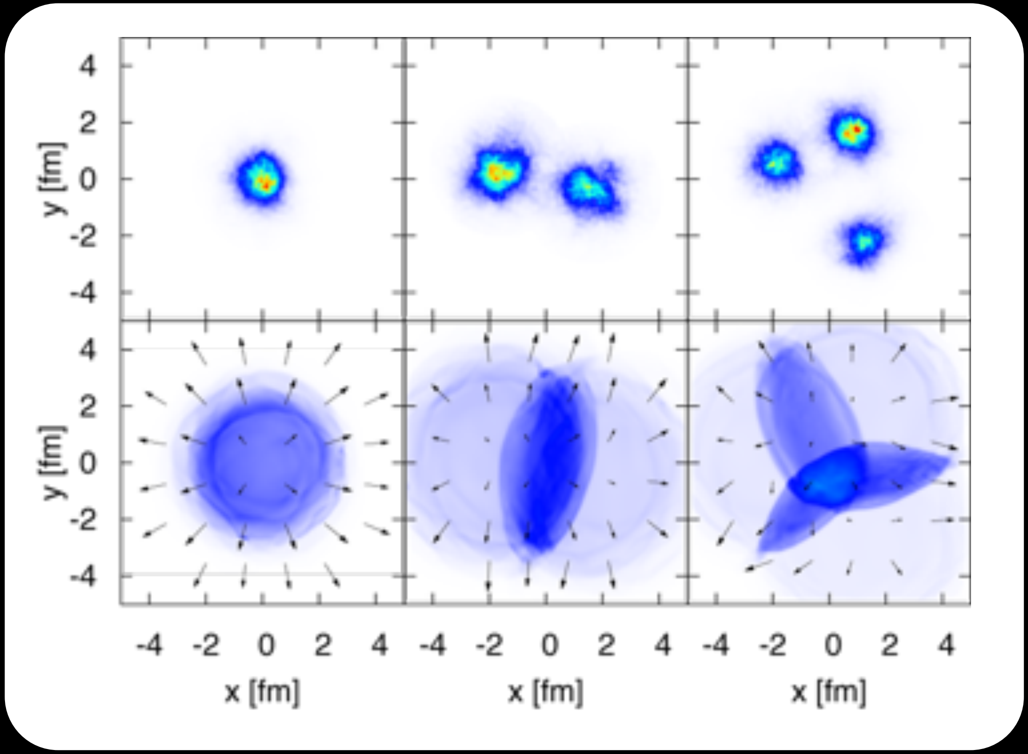
COMPLETE PICTURE



S. SCHLICHTING, QUARK MATTER PROCEEDINGS, ARXIV:1601.01177

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

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

- **Mass splitting of mean p_T and v_n:** (probably not good)
  Natural in any situation where particles are produced from a common boosted source: e.g. fluid cell, strings

- **$c_2\{4\}$ turning positive** as multiplicity increases
  could mean collectivity sets in but also alternative explanations
  DUMITRU, MCLERRAN, SKOKOV, PHYS.LETT. B743 (2015) 134-137

- **HBT**: Relative radii in p+p, p+Pb and Pb+Pb: Data favors description that yields similar radii in p+p and p+Pb
  ALICE COLLABORATRION, PHYS. LETT. B 739 (2014) 139-151

MANY CALCULATIONS OF RIDGE EFFECT FROM INITIAL STATE

Many different calculations using different approximations exist Dumitru, Dusling, Fernandez-Fraile, Gavin, Gelis, Jalilian-Marian, Kovchegov, Lappi, McLerran, Dominguez, Marquet, McLerran, Moschelli, Schenke, Schlichting, Skokov, Venugopalan, Wu, …

They all find a ridge 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)

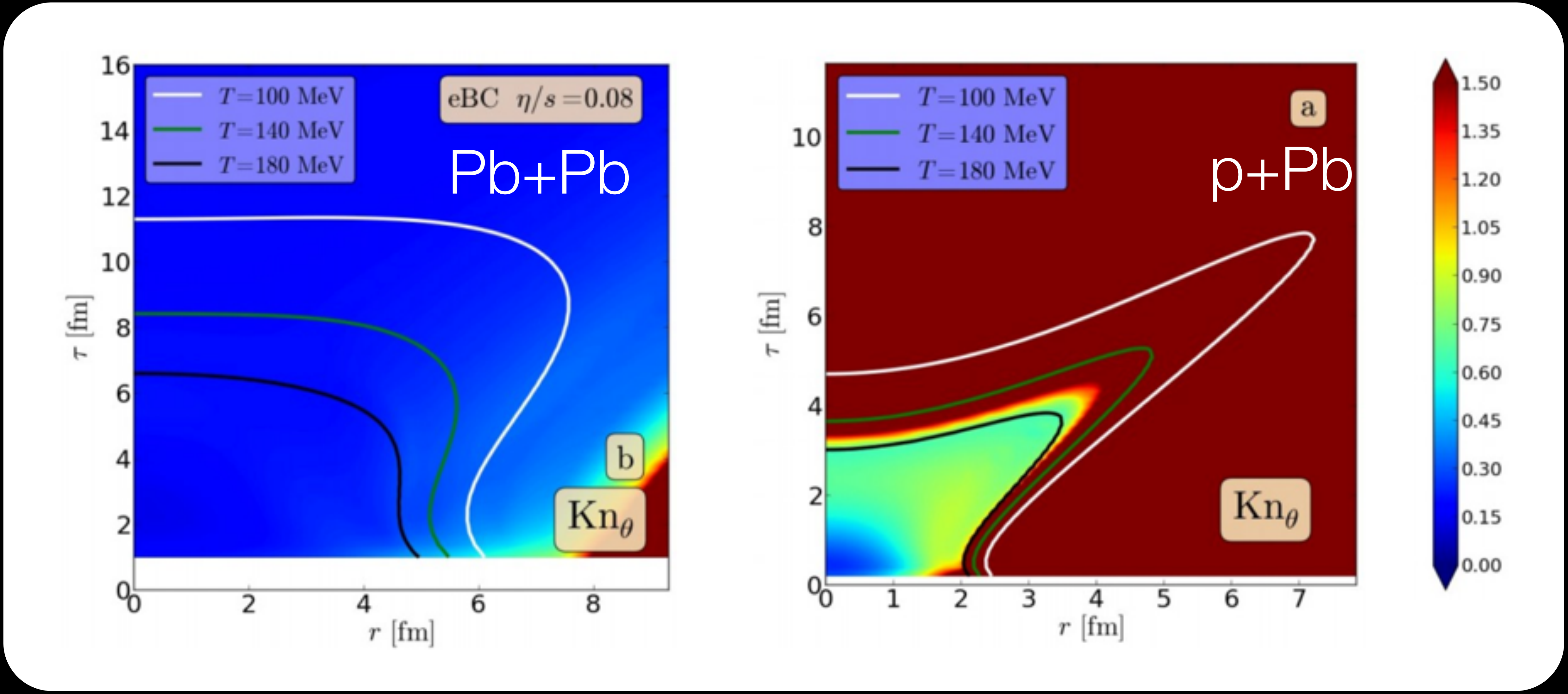
MANY CALCULATIONS OF RIDGE EFFECT FROM INITIAL STATE

T. LAPPI, B. SCHENKE, S. SCHLICHTING, R. VENUGOPALAN, JHEP 1601 (2016) 061

1. Dilute-dense limit:
   - **Glasma graph approximation** Dumitru, Dusling, Fernandez-Fraile, Gavin, Gelis, Kovchegov, Jalilian-Marian, Lappi, McLerran, Moschelli, Venugopalan, …
     two gluon exchange (not more) and Gaussian statistics of color charges (MV model) - closer to dilute-dilute limit
   - **Nonlinear Gaussian approximation** Dominguez, Marquet, Wu; Lappi, Schenke, Schlichting, Venugopalan
     resums multiple gluon exchanges, neglects non-Gaussianities
   - **JIMWLK evolution** Lappi, Phys.Lett. B744 (2015) 315-319
     introduces non-Gaussianities via evolution
     Color Domain Model A. Dumitru, A.V. Giannini, L. McLerran, V. Skokov
     introduces additional non-Gaussian correlations (like the ones introduced by JIMWLK evolution (small) or intrinsic four point correlations of significant magnitude)
2. Dense-dense limit:
   - **Classical Yang-Mills calculation** Schenke, Schlichting, Venugopalan
     includes multiple-gluon exchange, “rescattering”

PROBLEM WITH HYDRODYNAMICS

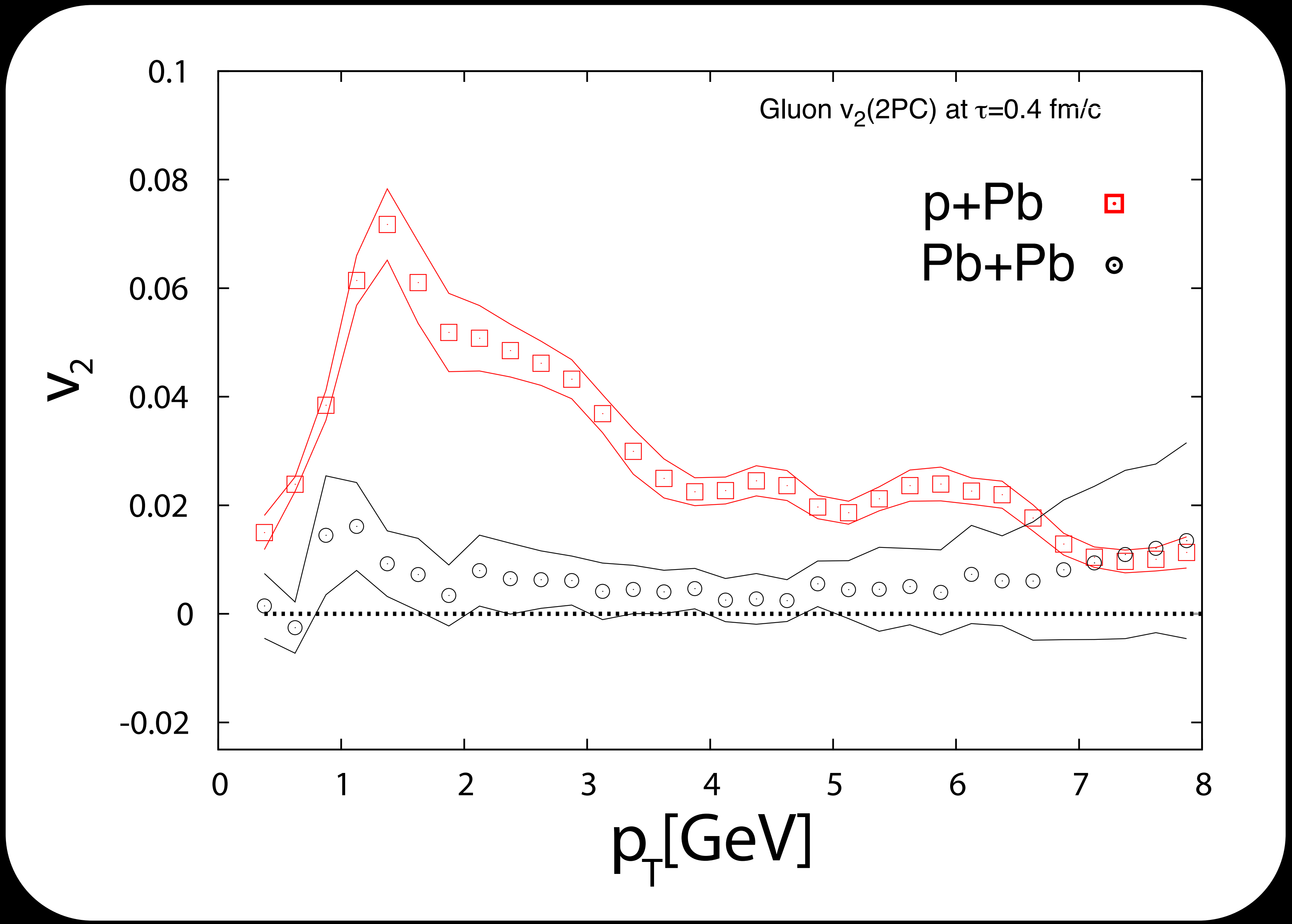
Knudsen number: ratio of a microscopic to a macroscopic scale
Small Knudsen number means hydrodynamics is valid



H. NIEMI, G.S. DENICOL, E-PRINT: ARXIV:1404.7327

SENSITIVITY TO SYSTEM SIZE

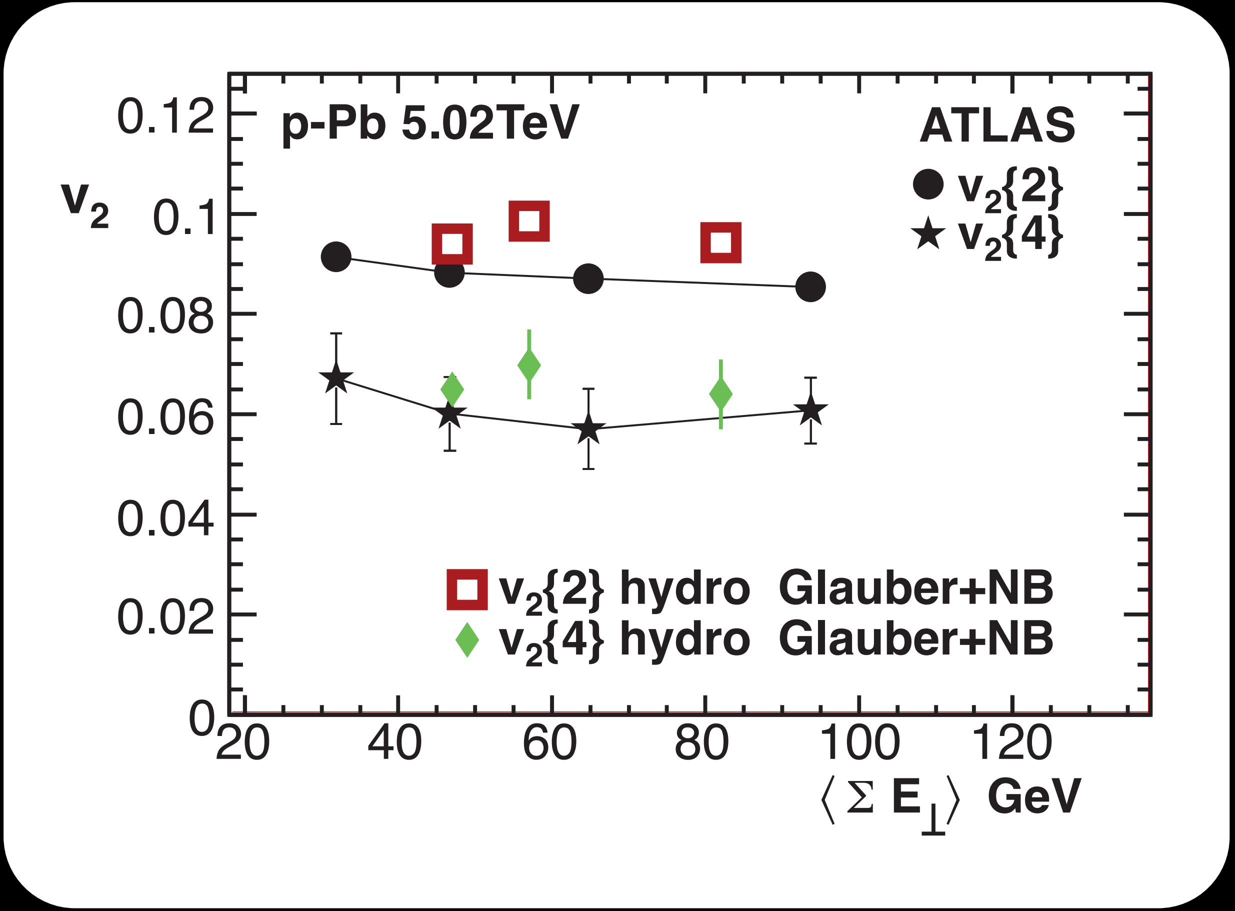
SCHENKE, SCHLICHTING, VENUGOPALAN, PHYS. LETT. B747, 76-82 (2015)



Pb+Pb not described in initial state picture. Reason:
Gluons produced from many uncorrelated color field domains

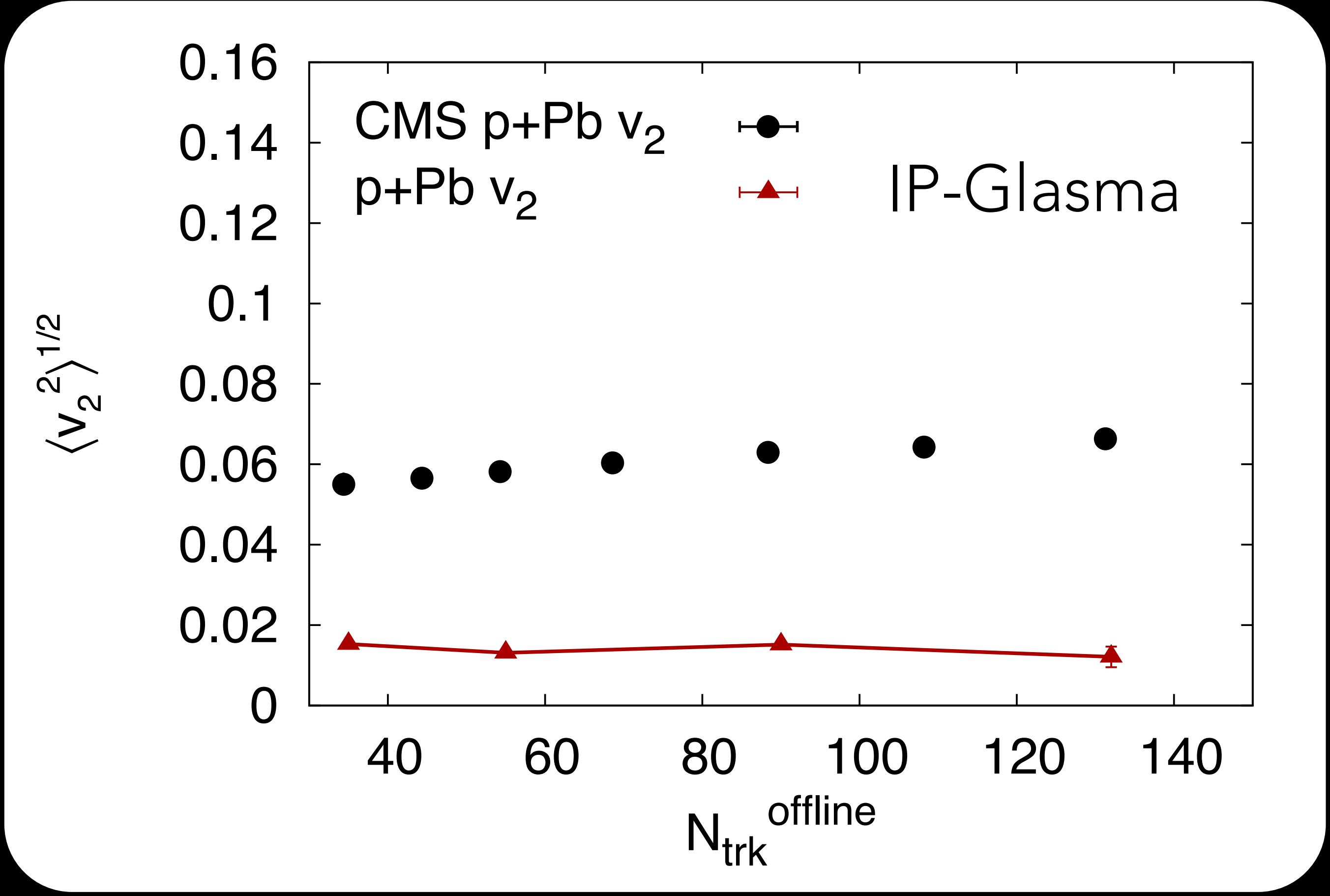
STRONG FINAL STATE EFFECTS IN SMALL SYSTEMS? EVEN HYDRODYNAMICS?

Simple initial state + hydro works



BOZEK, BRONIOWSKI
PRC88 (2013) 014903

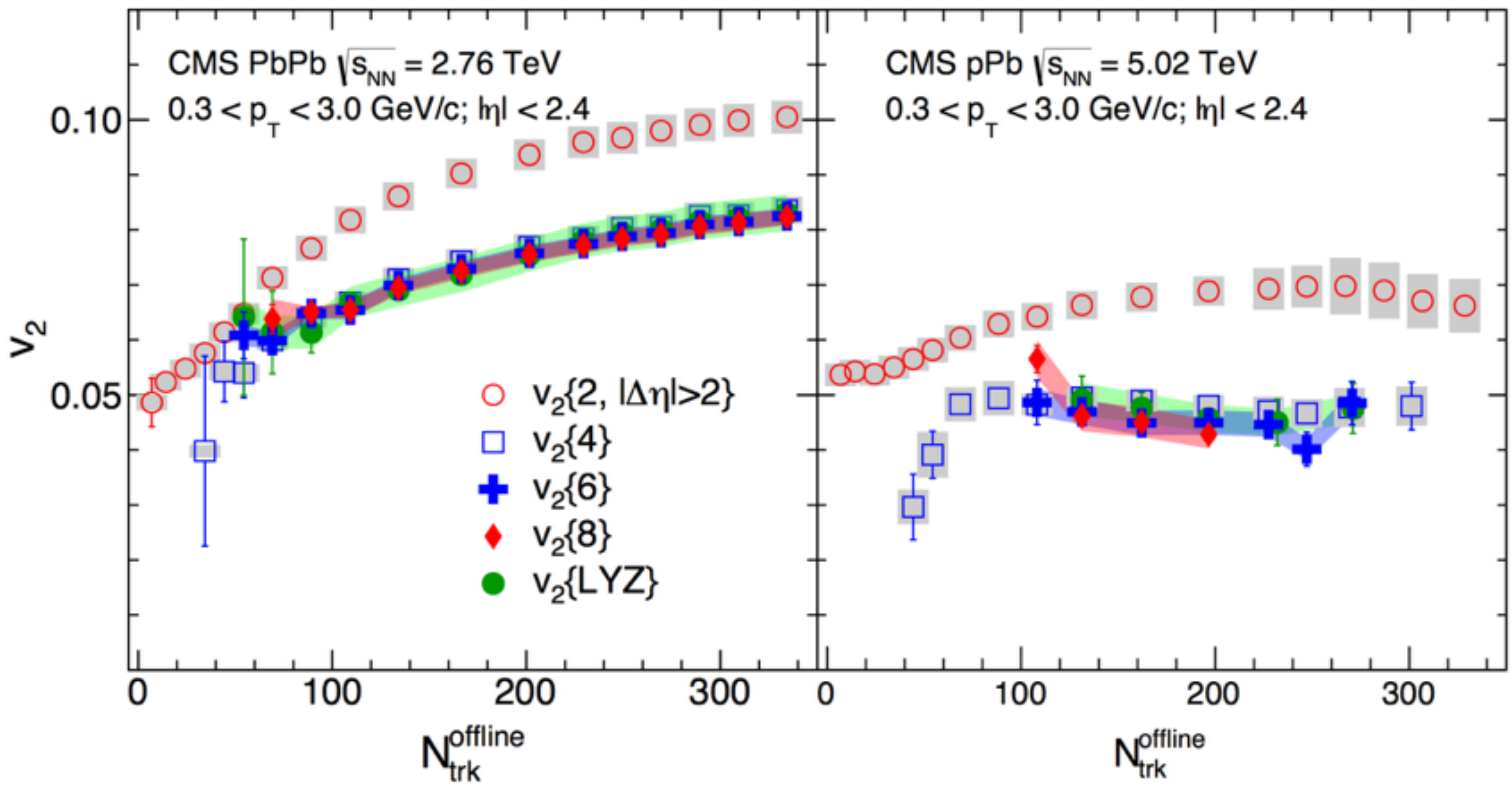
Calculation I showed before does not work in p+Pb



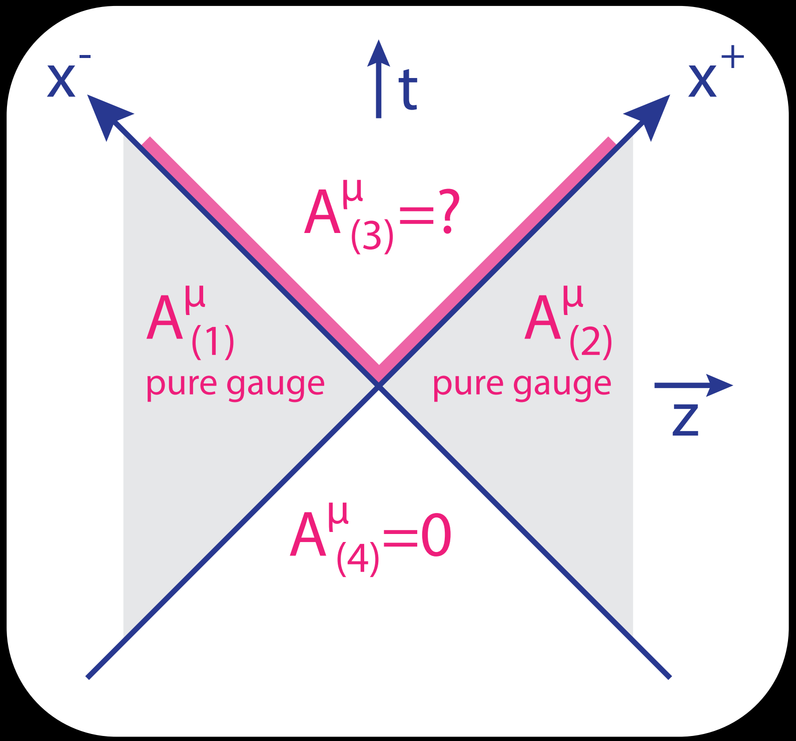
SCHENKE, VENUGOPALAN
PRL113 (2014) 102301

OTHER CALCULATIONS: KOZLOV, LUZUM, DENICOL, JEON, GALE; WERNER, GUIOT, KARPENKO, PIEROG; ROMATSCHKE, ...

v_2 IN p+Pb COLLISIONS
MULTI-PARTICLE CORRELATIONS



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

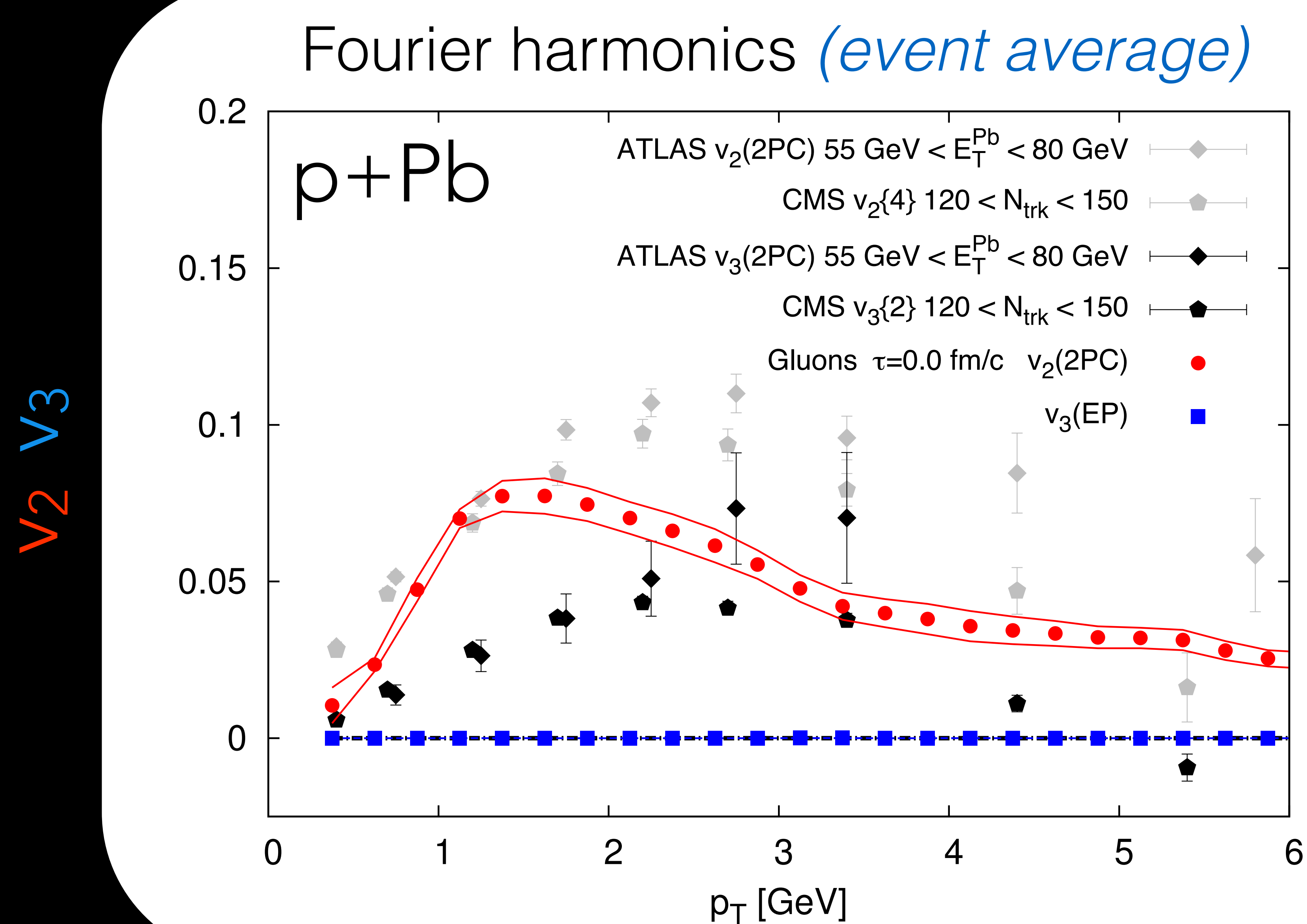
Next we analyze the momentum distribution of the produced gluons

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

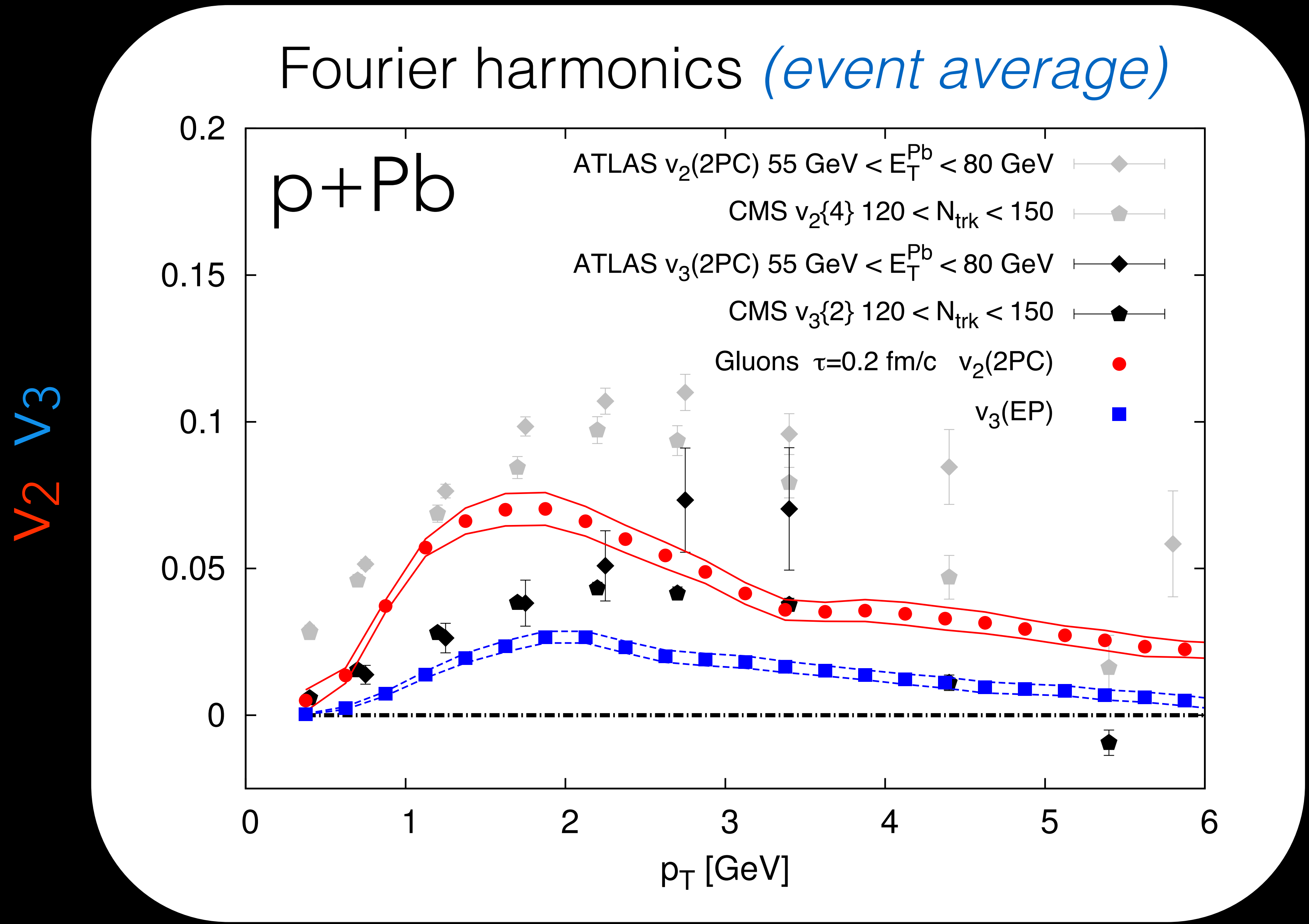
No odd harmonics for gluons without final state interactions

Correlations from the initial state

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

$\tau = 0.2$ fm/c

gluons

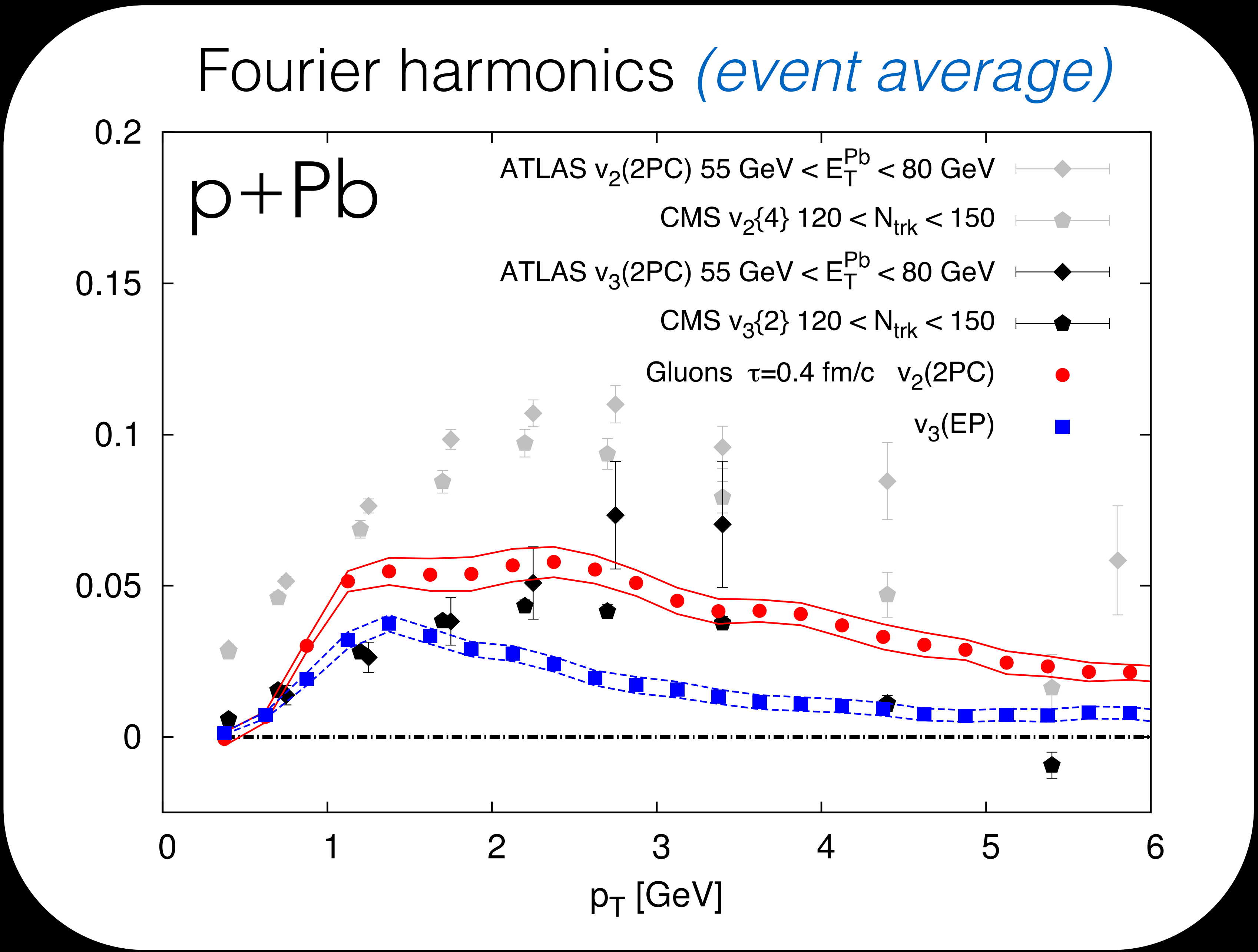


Correlations from the initial state

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

$\tau = 0.4$ fm/c
gluons

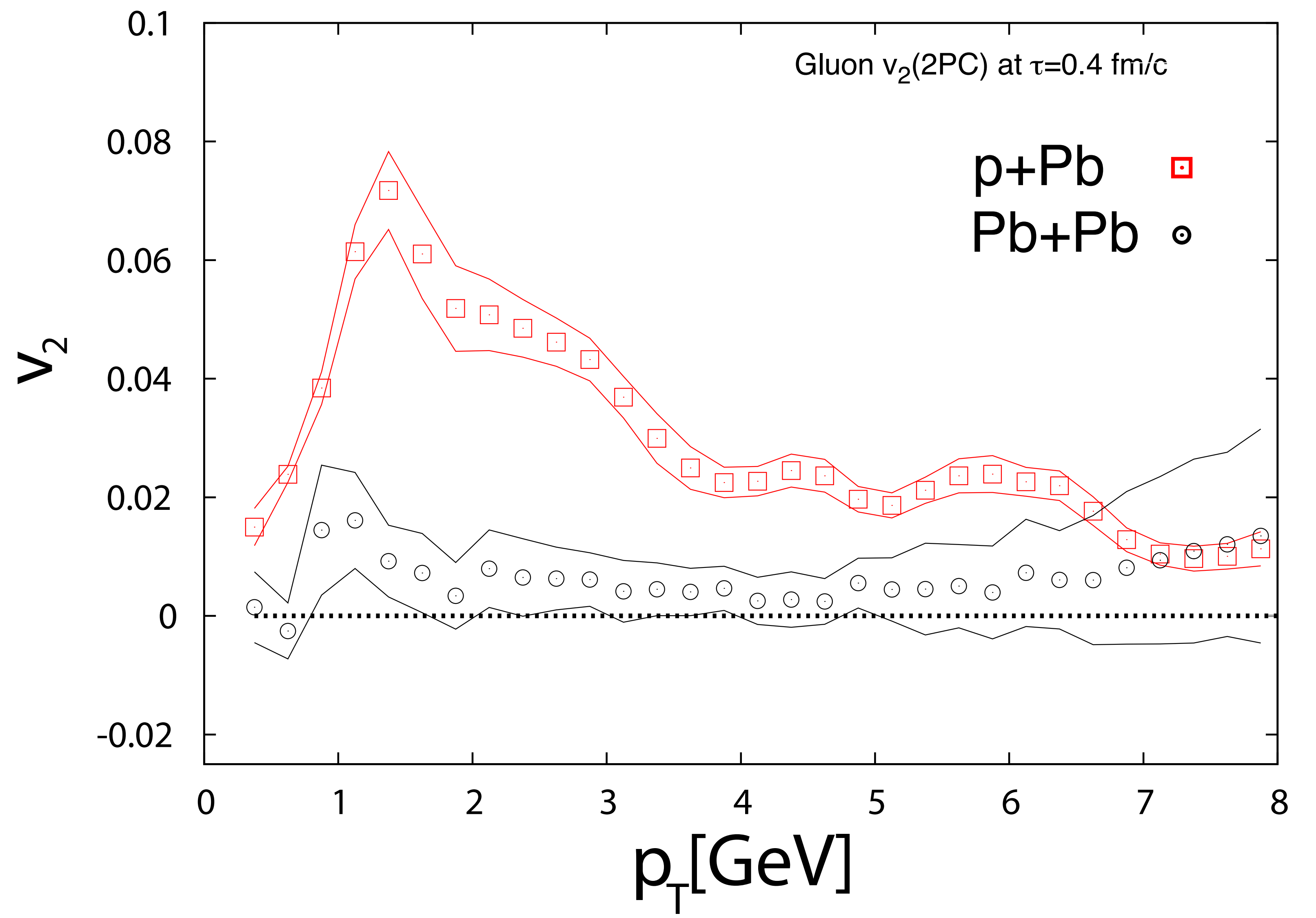
v_2 v_3

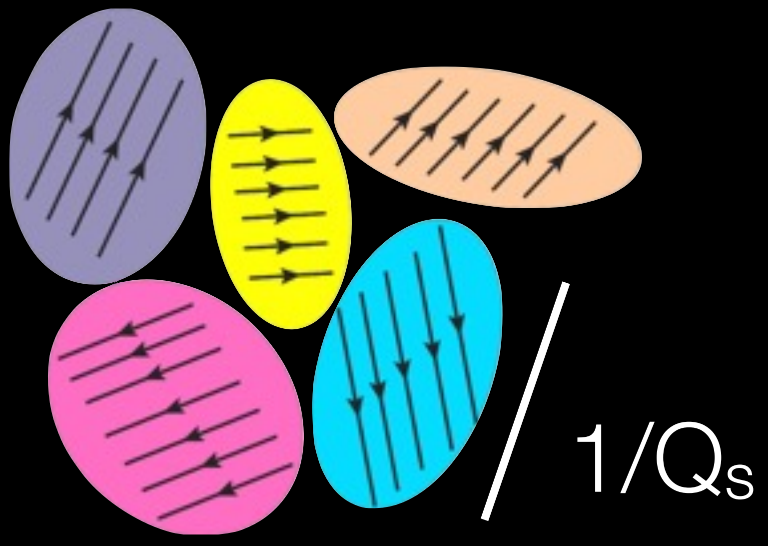


Odd harmonics generated by pre-equilibrium dynamics

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

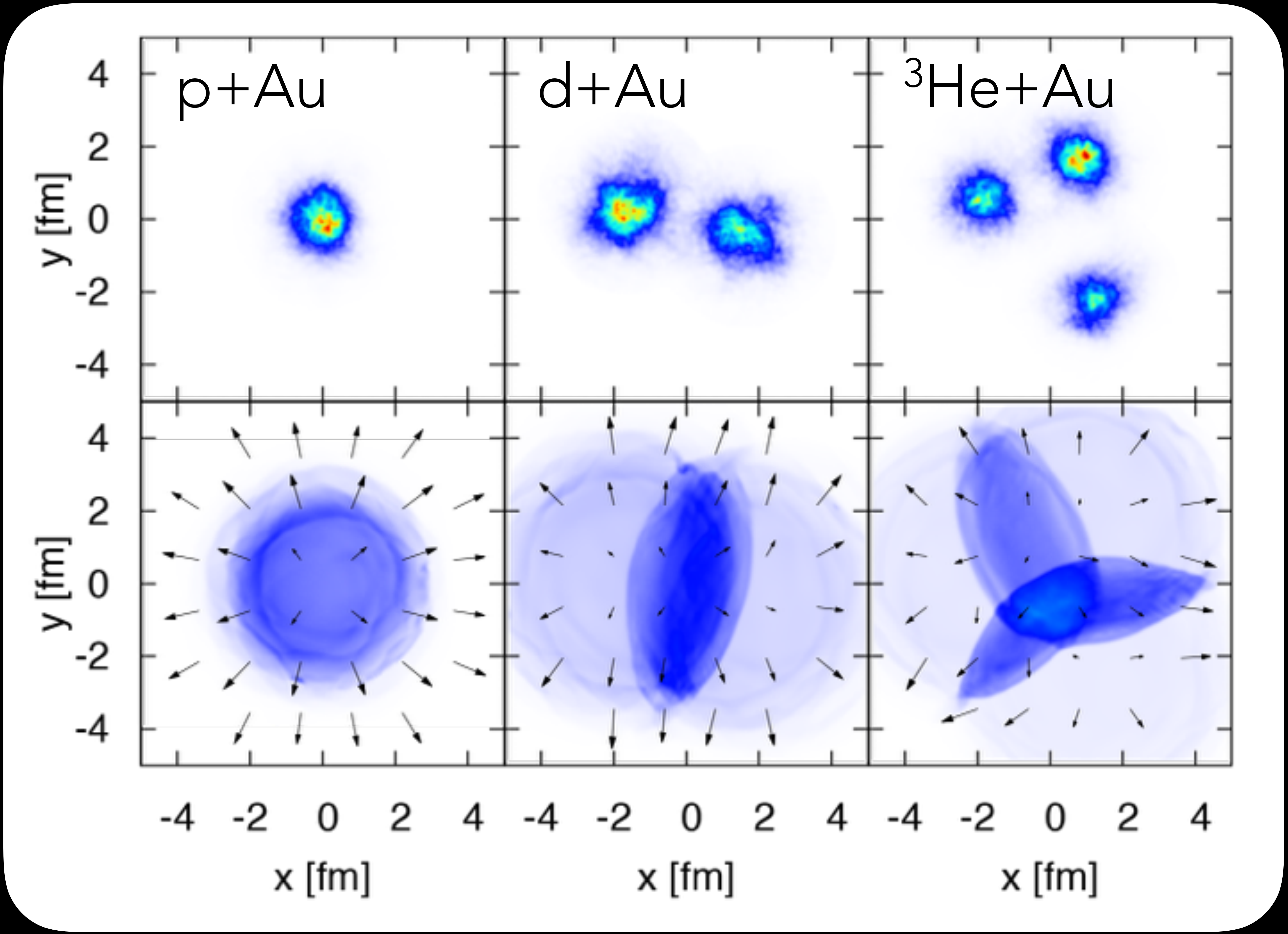
- Different collision systems
- Mass ordering
- Odd harmonics
- Beam energy dependence
- Jet quenching
- Electromagnetic probes
- Sign change of $c_2\{4\}$
- Multi particle (>2) cumulants

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

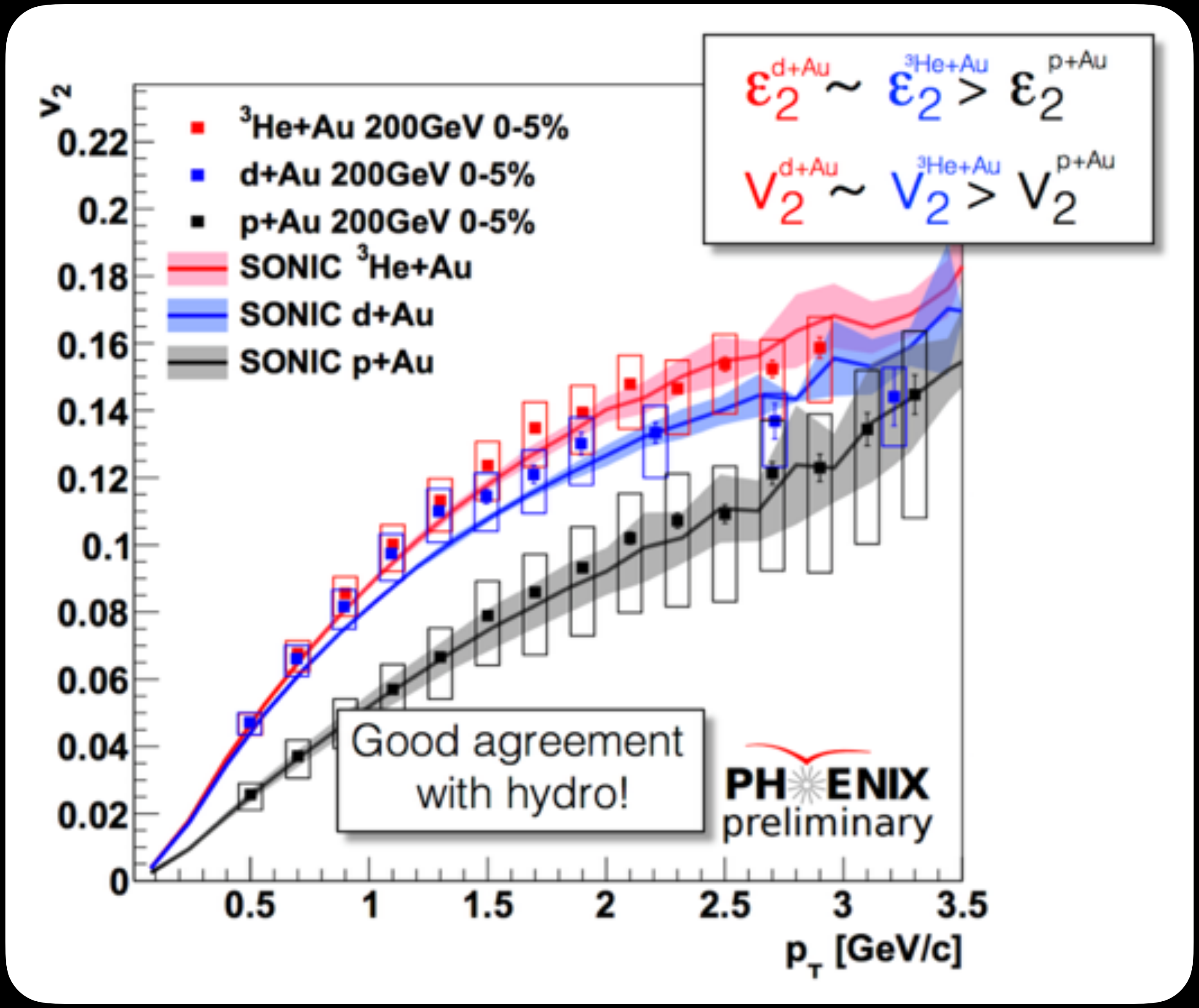
RHIC to the rescue: Different small systems

Different initial shapes lead to different flow harmonics



Different small systems

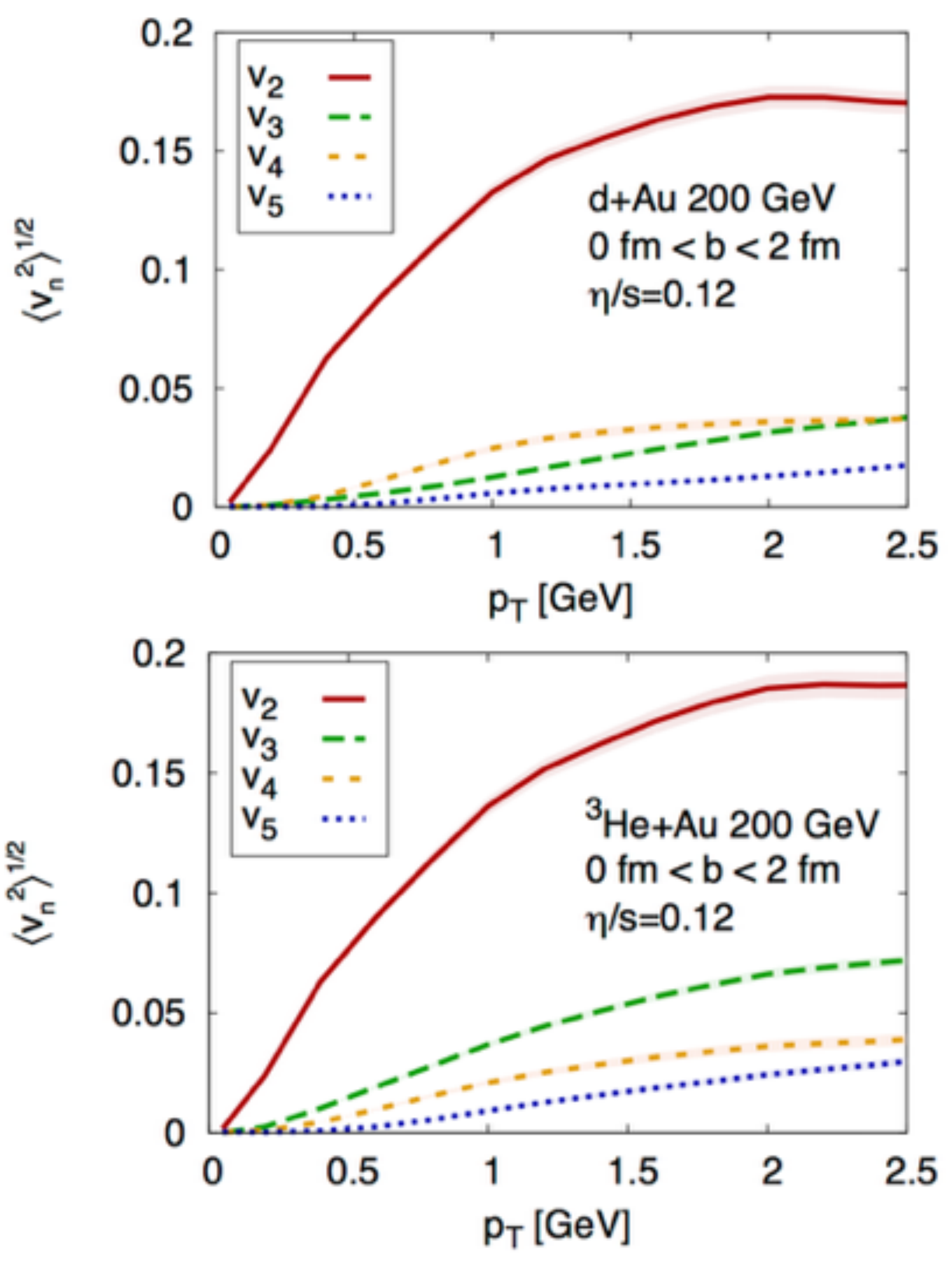
Different initial shapes lead to different flow harmonics



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

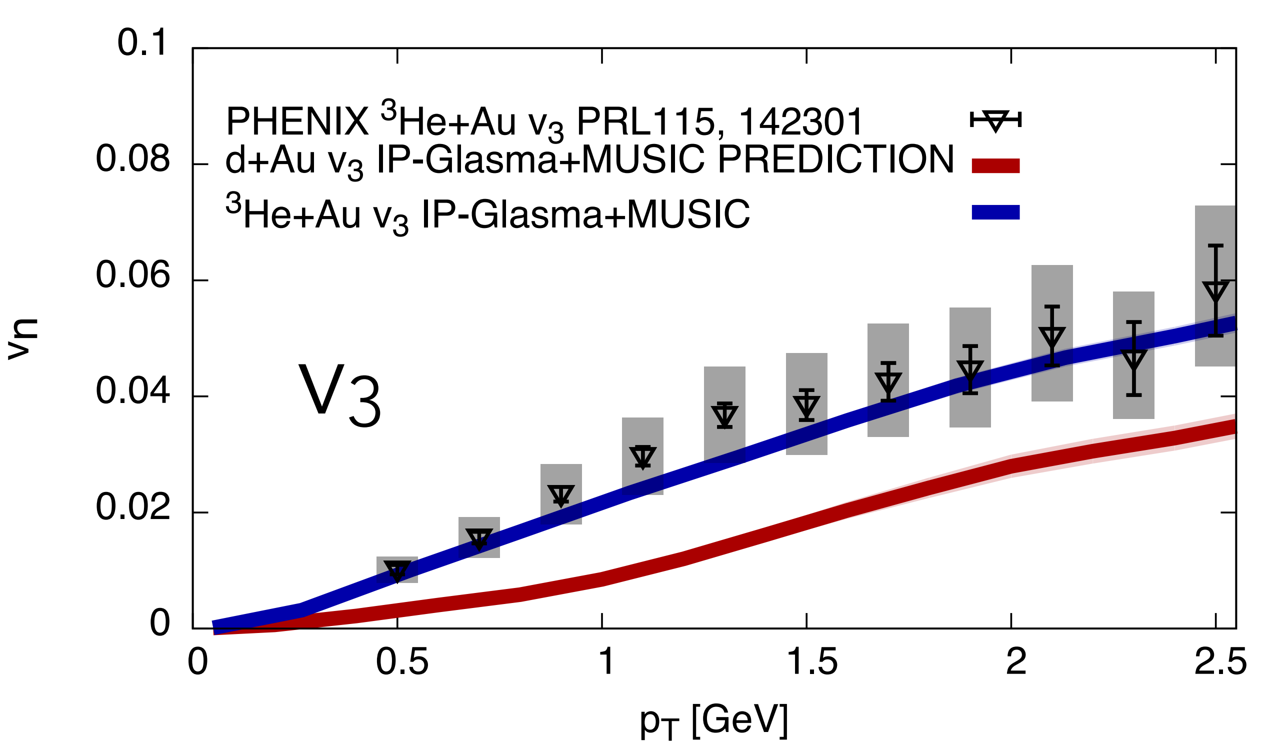


Left: Initial prediction for d+Au and ^{3}He+Au with $\eta/s=0.12$

Bottom: adjusted calculation with $\eta/s=0.18$

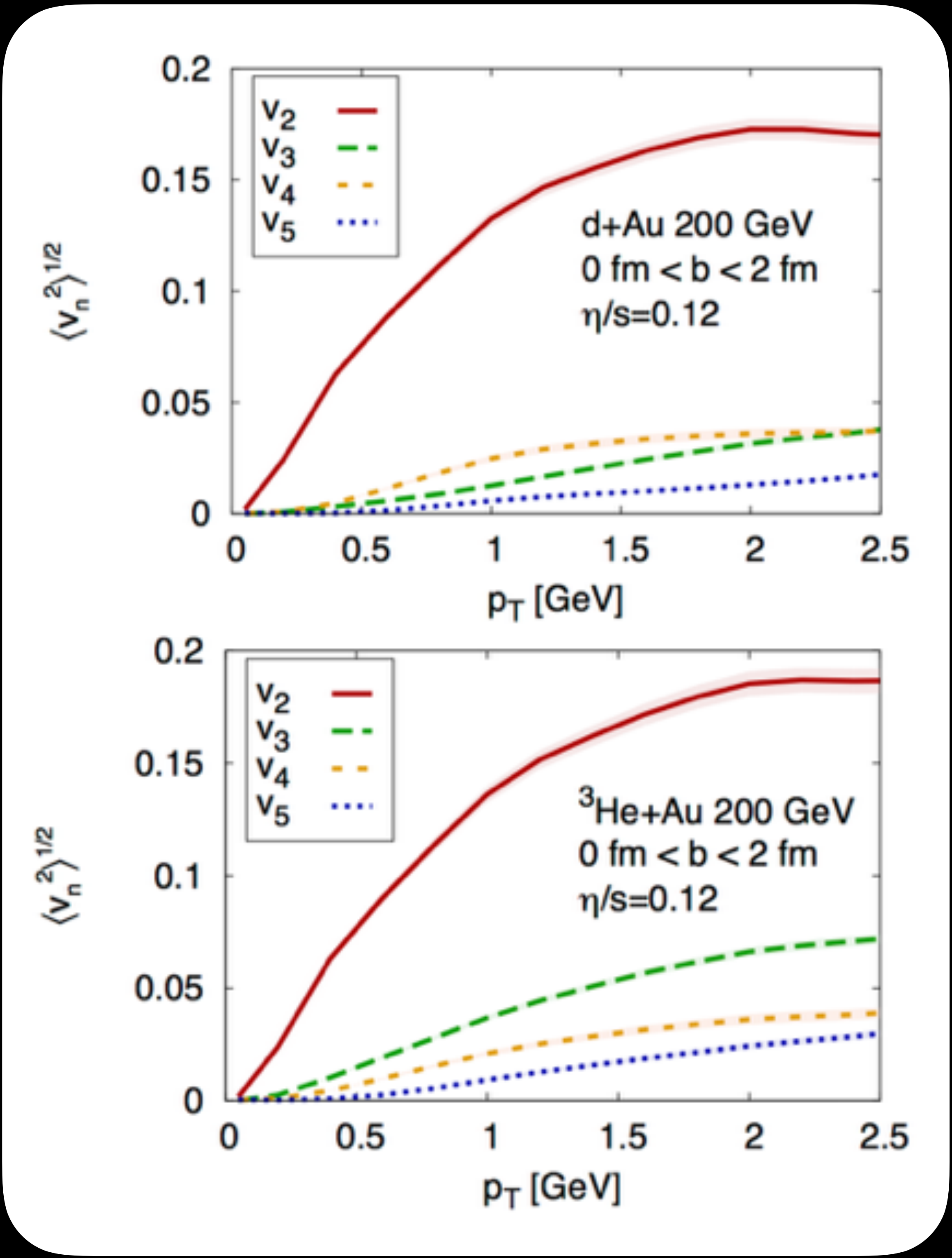
d+Au v_3 is a true prediction

(shown @2015 RHIC&AGS Users' Meeting)



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

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

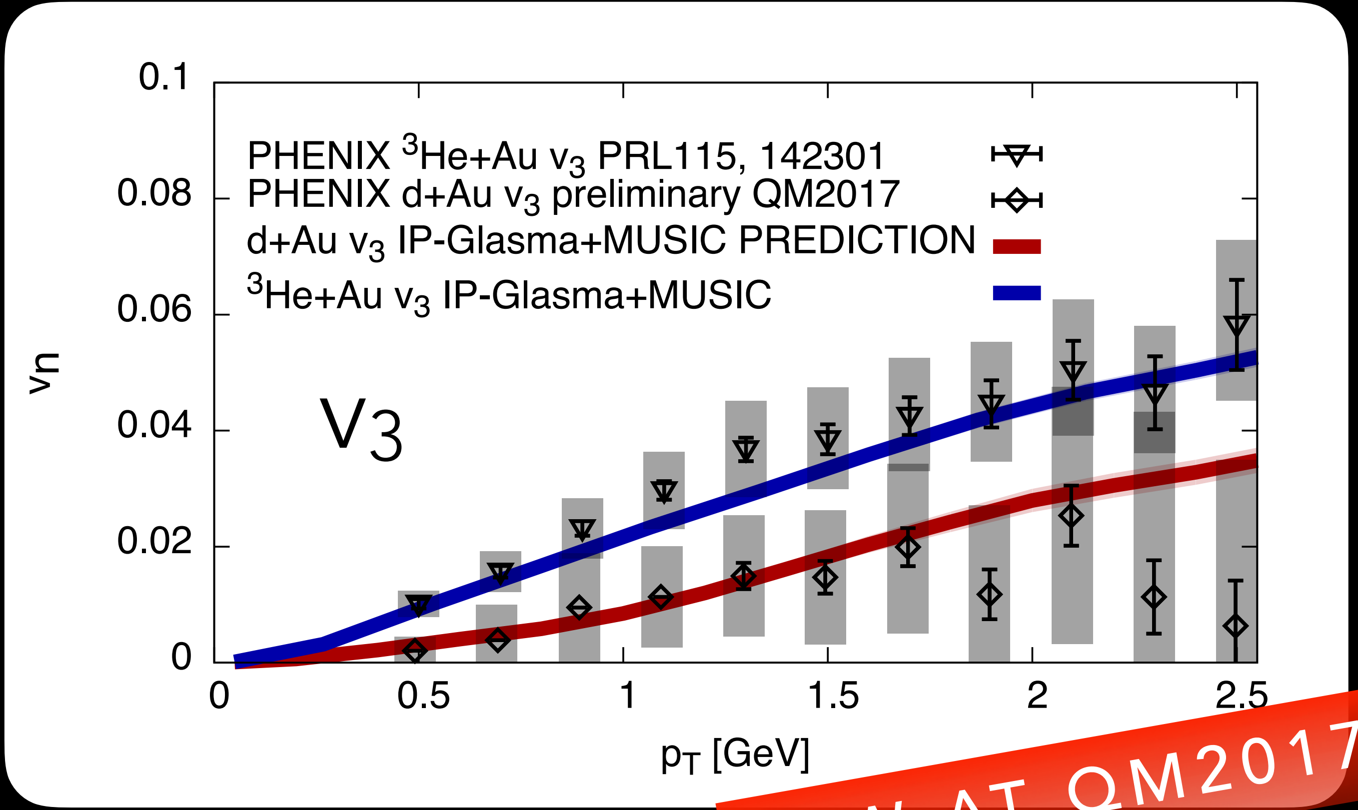


Left: Initial prediction for d+Au and ^{3}He+Au with $\eta/s=0.12$

Bottom: adjusted calculation with $\eta/s=0.18$

d+Au v_3 is a true prediction

(shown @2015 RHIC&AGS Users' Meeting)



NEW AT QM2017

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?