# Angular Asymmetries in High Multiplicity p+p and p+A Collisions

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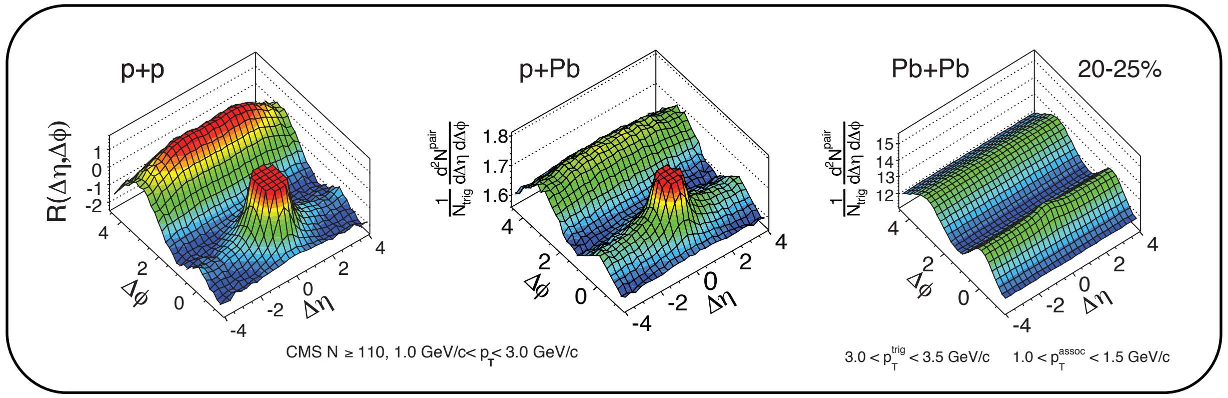
BROOKHAVEN NATIONAL LABORATORY

# Introduction

# Introduction: Small systems p+p, p+A, d+A, $^3$He+A

- High multiplicity p+p and p+Pb collisions at LHC show similar features as Pb+Pb collisions (ridge, $v_n$)
- d+Au at RHIC also seems to show similar features




- Interpretation not yet clear:
  - Initial geometry + collective effects? Fluid dynamics?
  - Initial correlations? Theory on this is developing

CMS: JHEP 1009 (2010) 091, Phys.Lett. B718 (2013) 795-814, JHEP 1107 (2011) 076 , Eur.Phys.J. C72 (2012)

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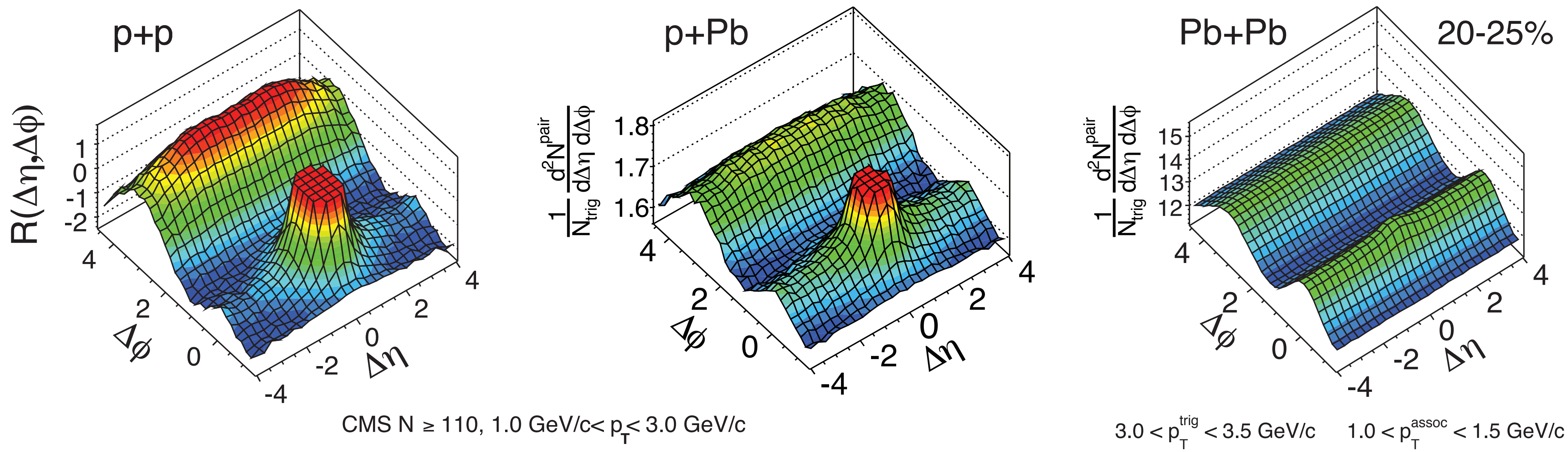



**Ridge**: Two particle correlations in pseudo-rapidity and azimuthal angle difference are long-range in pseudo-rapidity and show particular structure in azimuthal angle

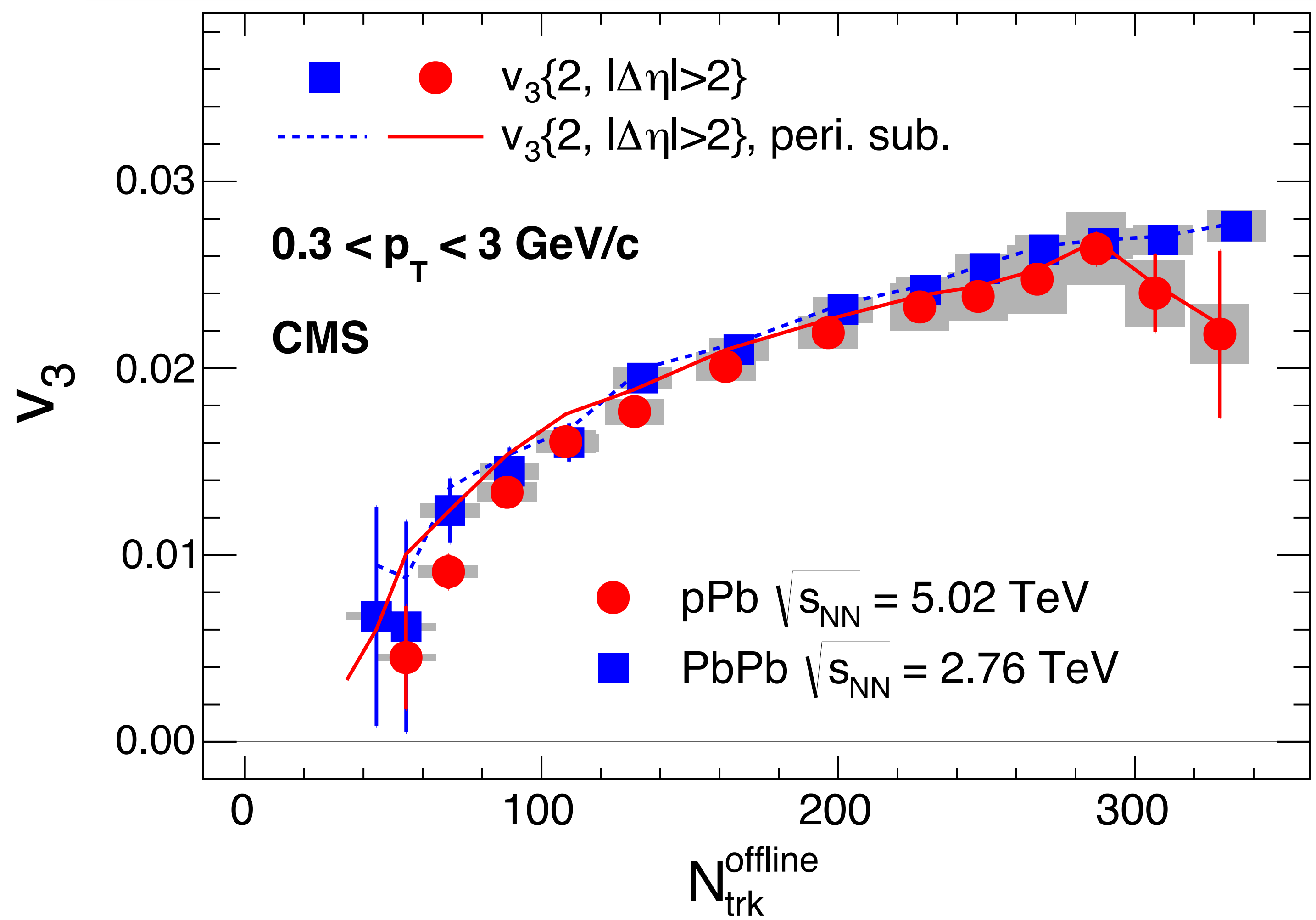
CMS: JHEP 1009 (2010) 091, Phys.Lett. B718 (2013) 795-814, JHEP 1107 (2011) 076 , Eur.Phys.J. C72 (2012)

# The experimental data was surprising:

- Similarity of experimental data in p+A and A+A collisions

CMS, Phys. Lett. B 724 (2013) 213

$$E\frac{d^3N}{dp^3} = \frac{1}{2\pi}\frac{d^2N}{p_T\,dp_T\,dy}\left(1+\sum_{n=1}^{\infty}2\underline{v_n}\cos\left[n\left(\phi-\Psi\right)\right]\right)$$




see also
ALICE Coll., Phys. Lett. B719 (2013) 29-41; Phys. Rev. C 90, 054901
ATLAS Coll., Phys. Rev. Lett. 110, 182302 (2013), Phys. Lett. B 725 (2013) 60-78 , Phys. Rev. C 90.044906 (2014);
CMS Coll., arXiv:1502.05382

Option 1:
Assume final state dominates

# Final state picture

- The initial spatial anisotropy is transformed into final state momentum distributions by final state interactions, e.g. described by hydrodynamics
- Will not describe hydrodynamics in detail here
- Will describe a successful initial state model
(it will also appear later when we discuss initial state effects)

# Initial state: IP-Glasma model

B.SCHENKE, P.TRIBEDY, R.VENUGOPALAN, PRL108, 252301 (2012), PRC86, 034908 (2012)

- IP-Sat model parametrizes saturation scale $Q_s(x, \mathbf{b})$ simple way to include impact parameter dependence
  KOWALSKI, TEANEY, PHYS.REV. D68 (2003) 114005
- Parameters are fit to HERA diffractive data
  REZAEIAN, SIDDIKOV, VAN DE KLUNDERT, VENUGOPALAN, PHYS.REV. D87 (2013) 3, 034002
- Sample nucleon positions from Woods-Saxon
- Sample color charges according to $Q_s(x, \mathbf{b})$ dist.

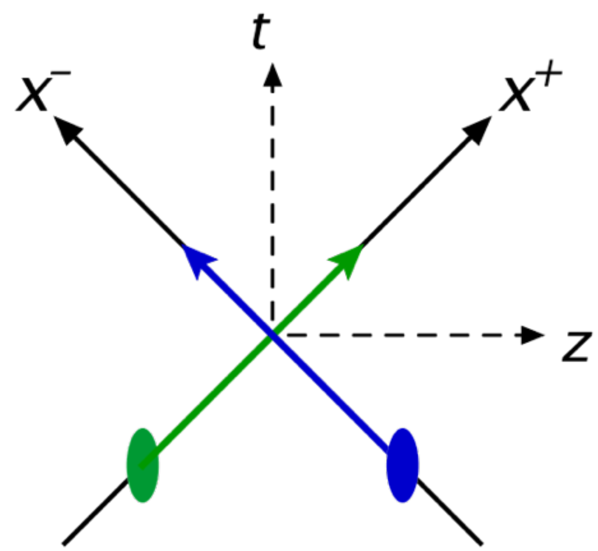
# Initial state: IP-Glasma model

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

- Moving color charges generate incoming currents

$$J_1^\mu = \delta^{\mu +} \rho_1(x^-, \mathbf{x}_T)$$

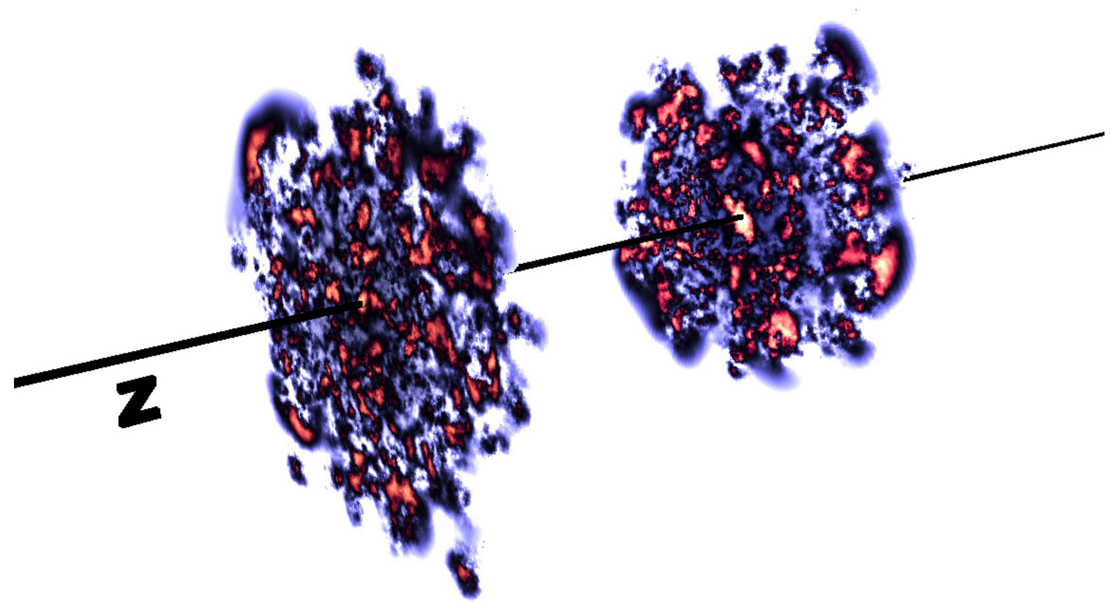
$$[D_\mu, F^{\mu\nu}] = J_1^\nu$$




$$J_2^\mu = \delta^{\mu -} \rho_2(x^+, \mathbf{x}_T)$$

$$[D_\mu, F^{\mu\nu}] = J_2^\nu$$

Solve Yang-Mills equations for the gauge fields in the incoming nuclei



# Initial state: IP-Glasma model

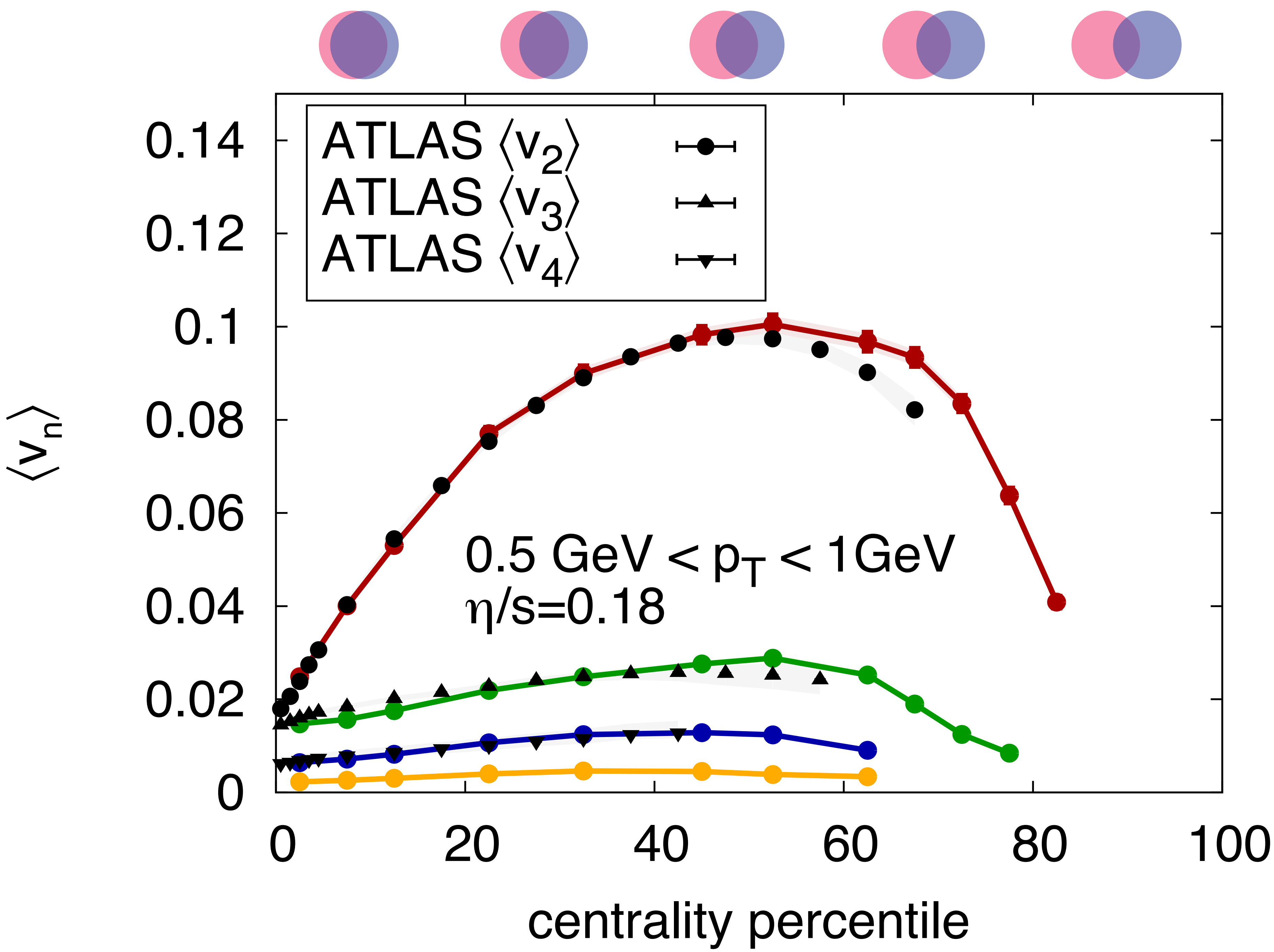
B.Schenke, P.Tribedy, R.Venugopalan, PRL108, 252301 (2012), PRC86, 034908 (2012)

- Yang-Mills equations determine:
  - Initial gluon fields after the collision
    KRASNITZ, VENUGOPALAN, NUCL.PHYS. B557 (1999) 237
  - Early non-equilibrium time evolution
- Then match fields' $T^{\mu\nu}$ to hydrodynamics by extracting $\varepsilon$ and $u^{\mu}$ - Then run viscous hydro

Final state picture
works well for heavy ion collisions

# Results in Pb+Pb collisions: Average $v_n$

EXPERIMENTAL DATA: ATLAS COLLABORATION, JHEP 1311 (2013) 183
B.SCHENKE, R.VENUGOPALAN, PHYS. REV. LETT. 113 (2014) 102301



# Results in Pb+Pb collisions: Event-by-event $v_n$

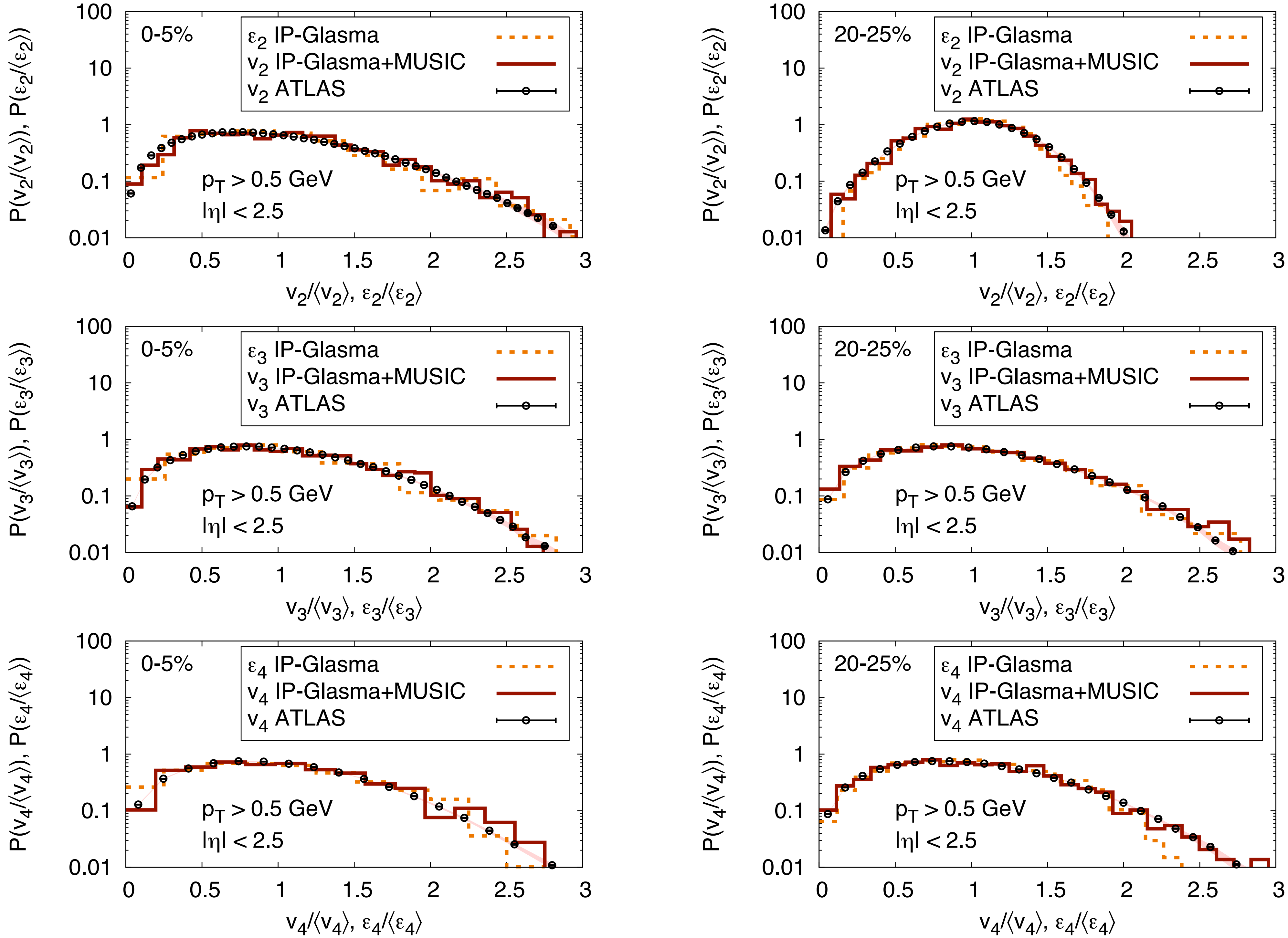
ATLAS COLLABORATION, JHEP 1311 (2013) 183
C. GALE, S. JEON, B.SCHENKE, P.TRIBEDY, R.VENUGOPALAN, PRL110, 012302 (2013)

0-5% | 20-25%

$v_2$

$v_3$

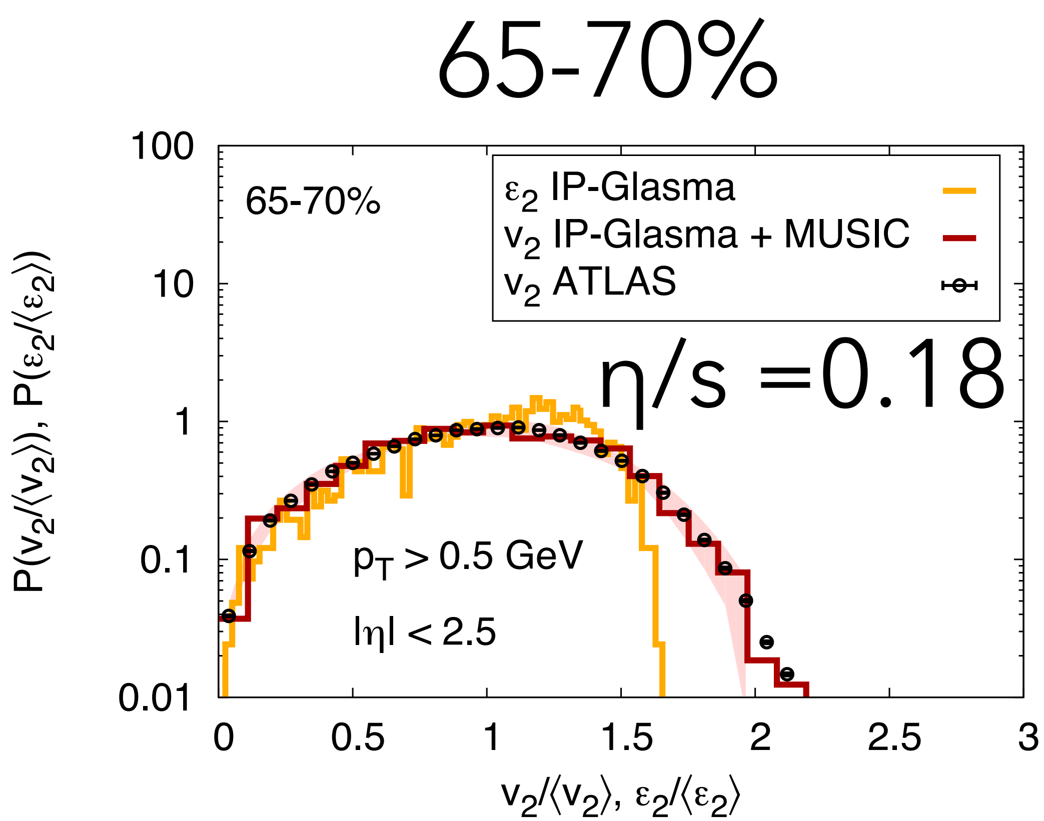
$v_4$

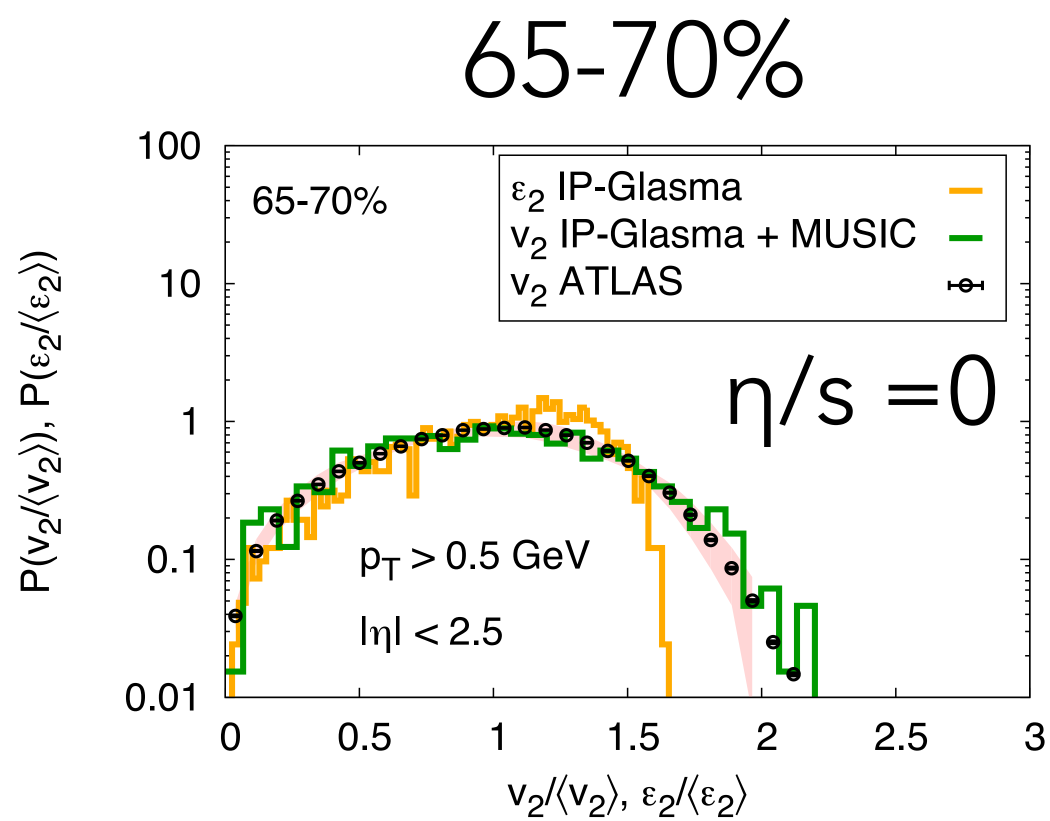


# Results in Pb+Pb collisions: Event-by-event $v_n$

ATLAS COLLABORATION, JHEP 1311 (2013) 183
B.SCHENKE, R.VENUGOPALAN, PHYS. REV. LETT. 113 (2014) 102301

$v_2$



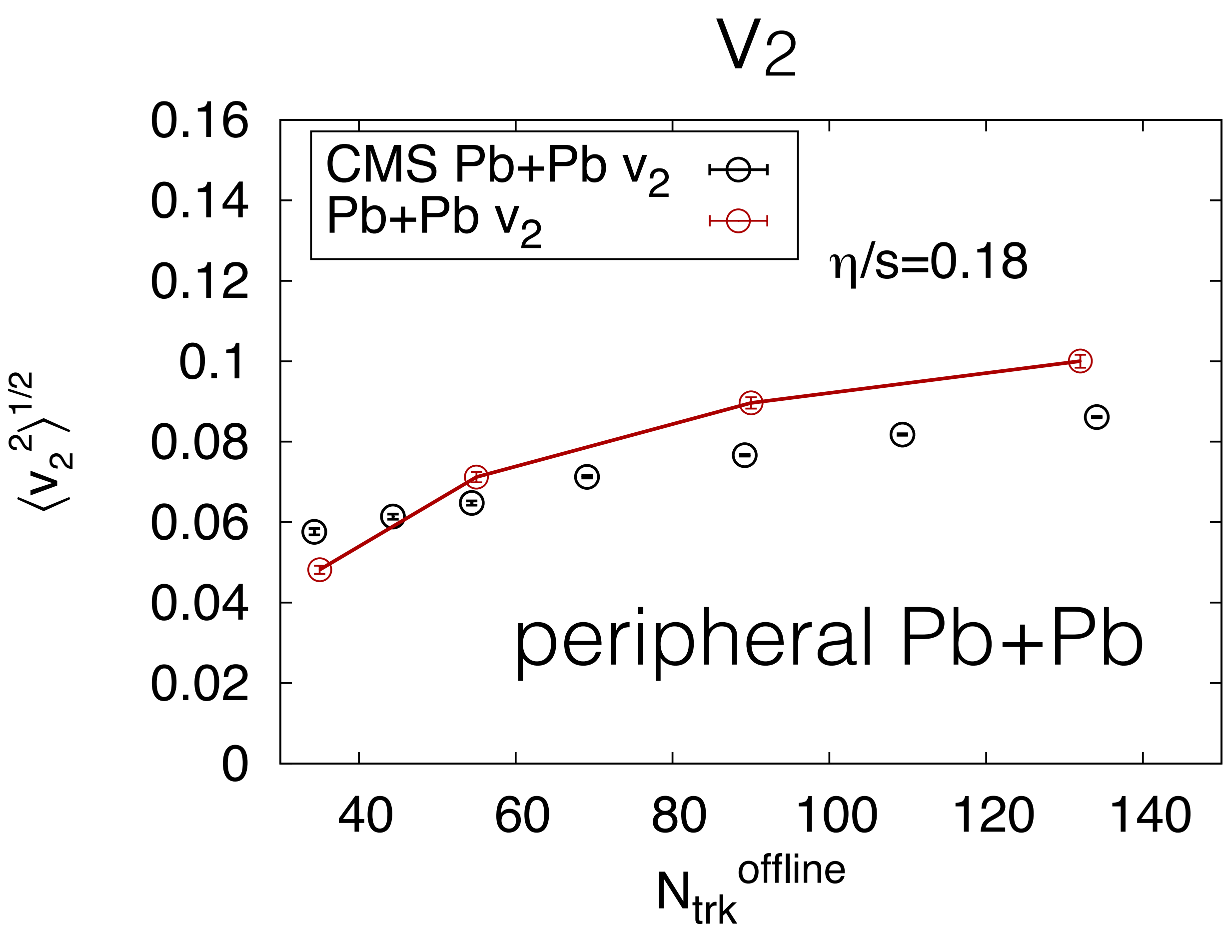

Detailed transport properties are not important

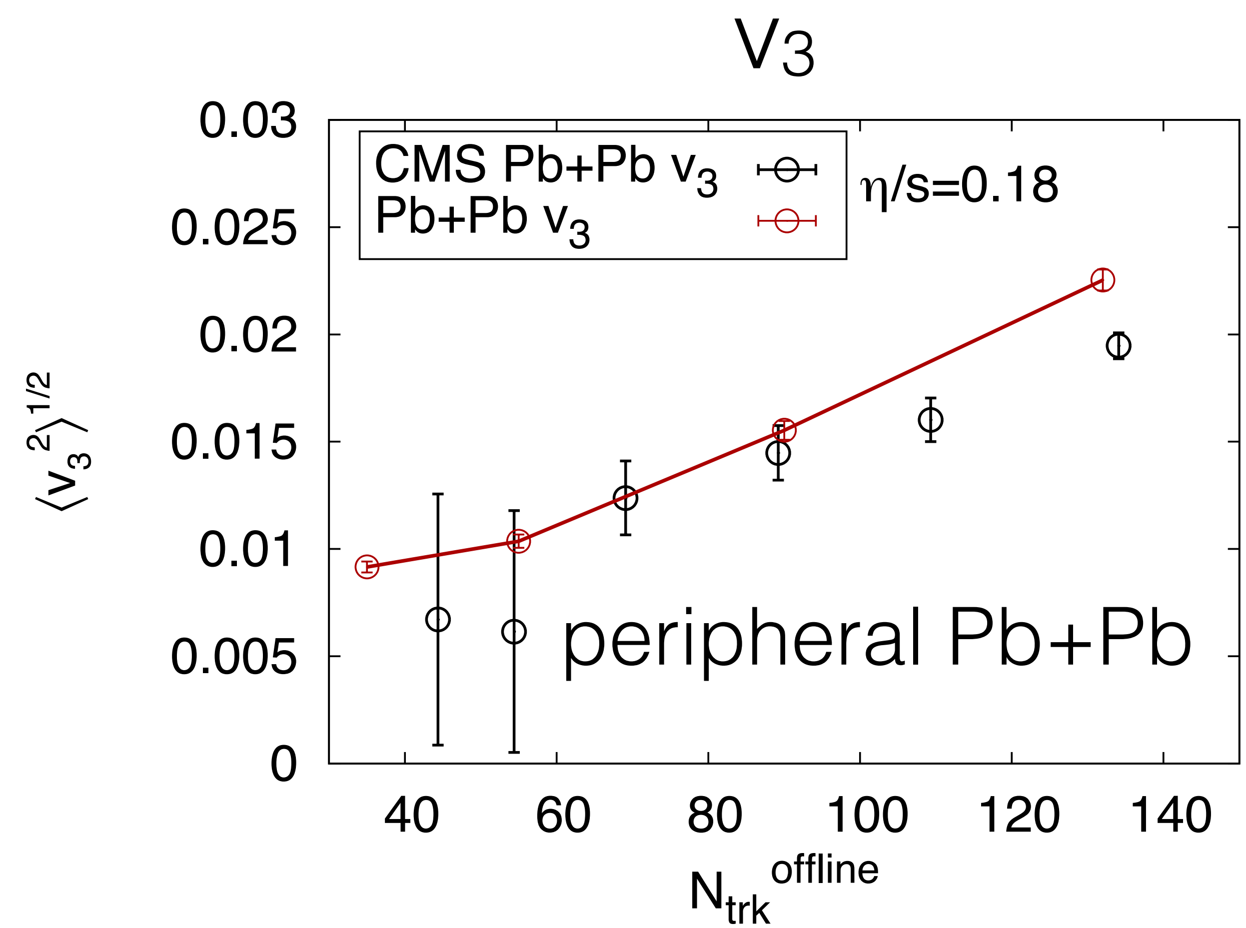
Good description out to very peripheral events

How about small systems?

# Fourier Harmonics in p+Pb (and Pb+Pb)

CMS COLLABORATION, PHYS.LETT. B724 (2013) 213-240
B.SCHENKE, R.VENUGOPALAN, PHYS. REV. LETT. 113 (2014) 102301




Open symbols: Pb+Pb

Red: IP-Glasma + MUSIC

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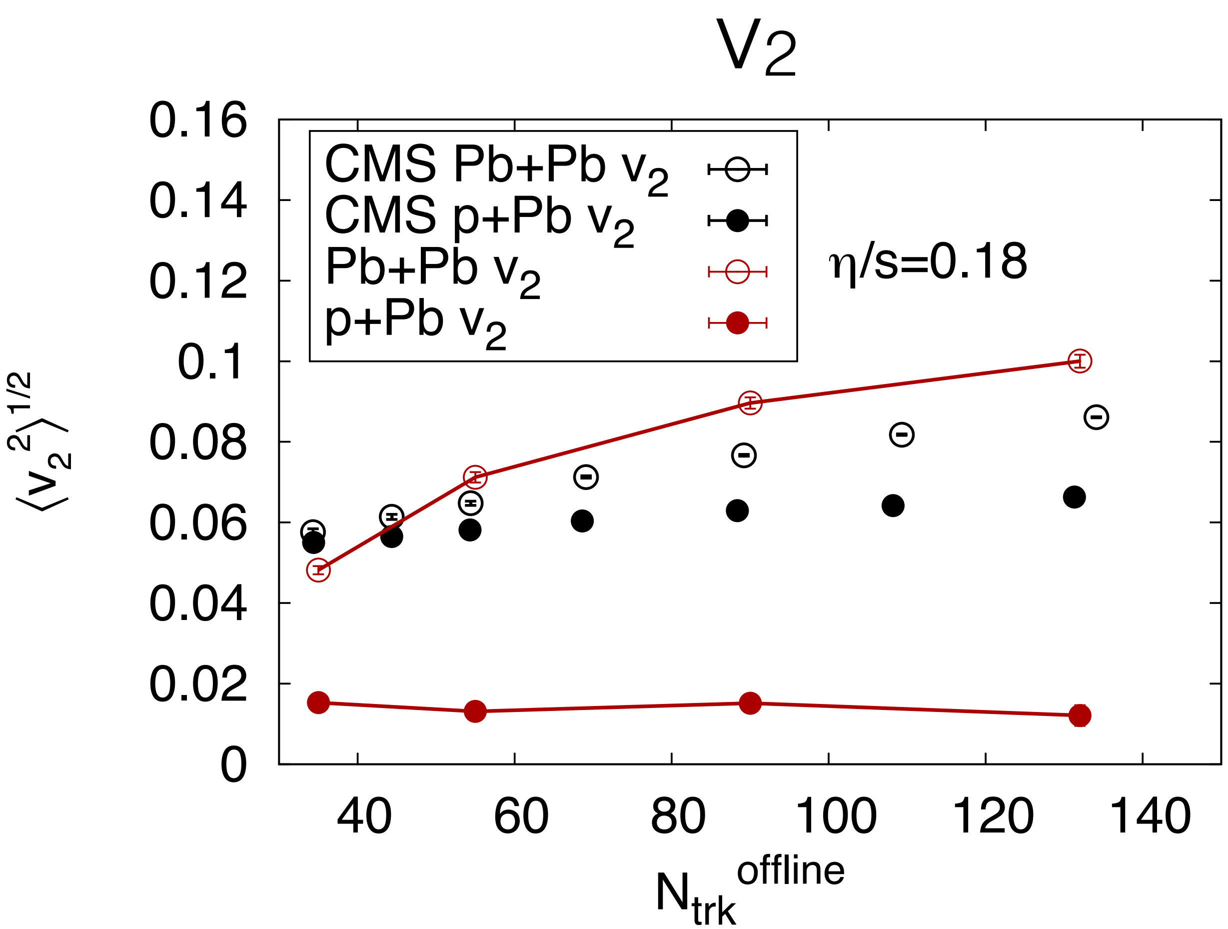
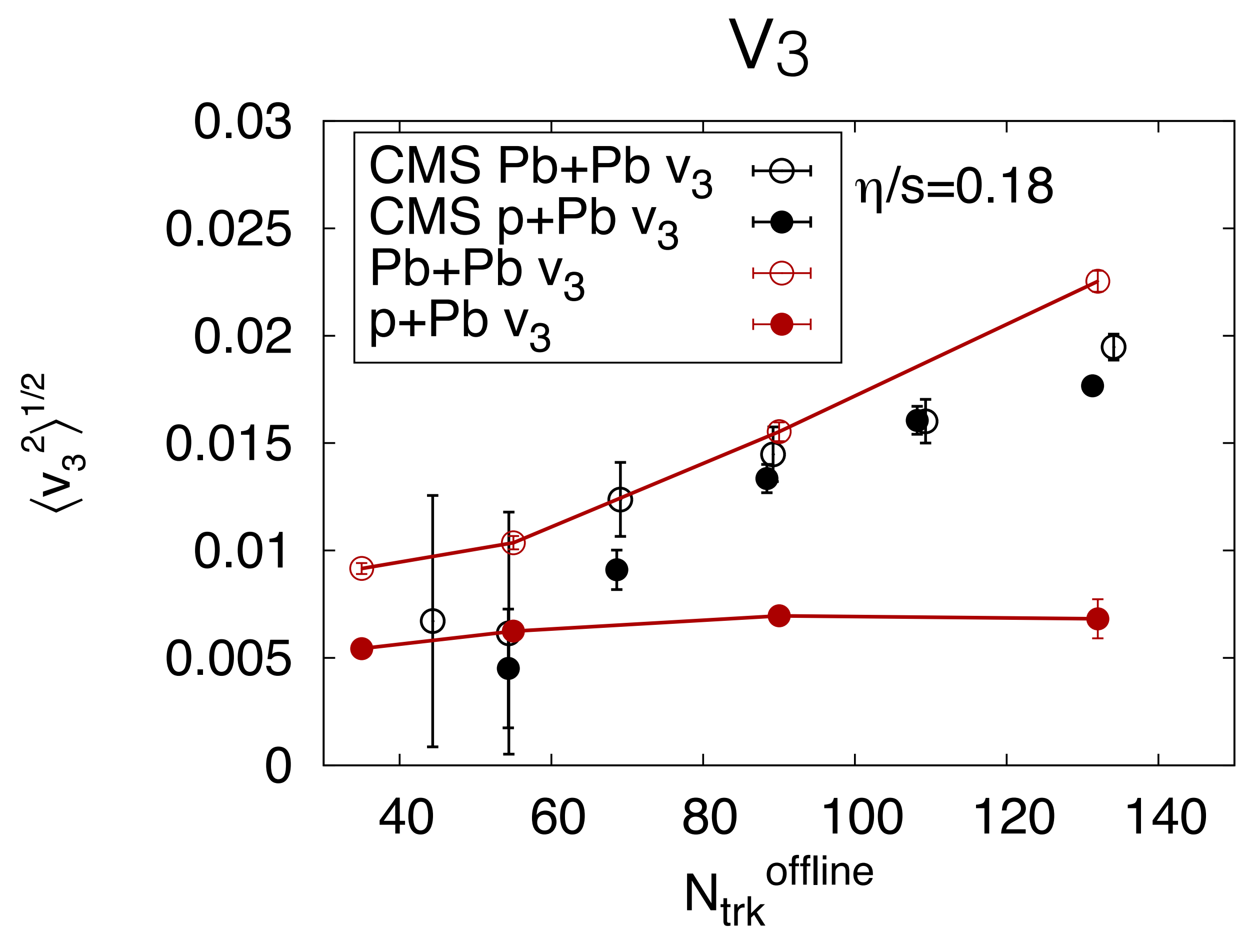


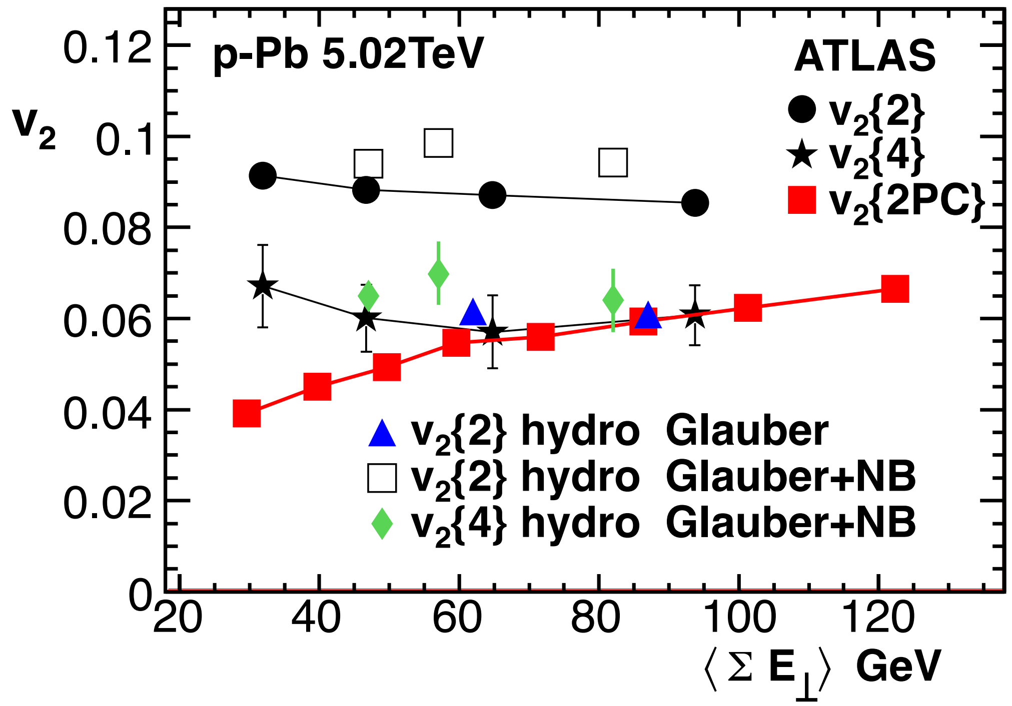




Open symbols: Pb+Pb
Filled symbols: p+Pb

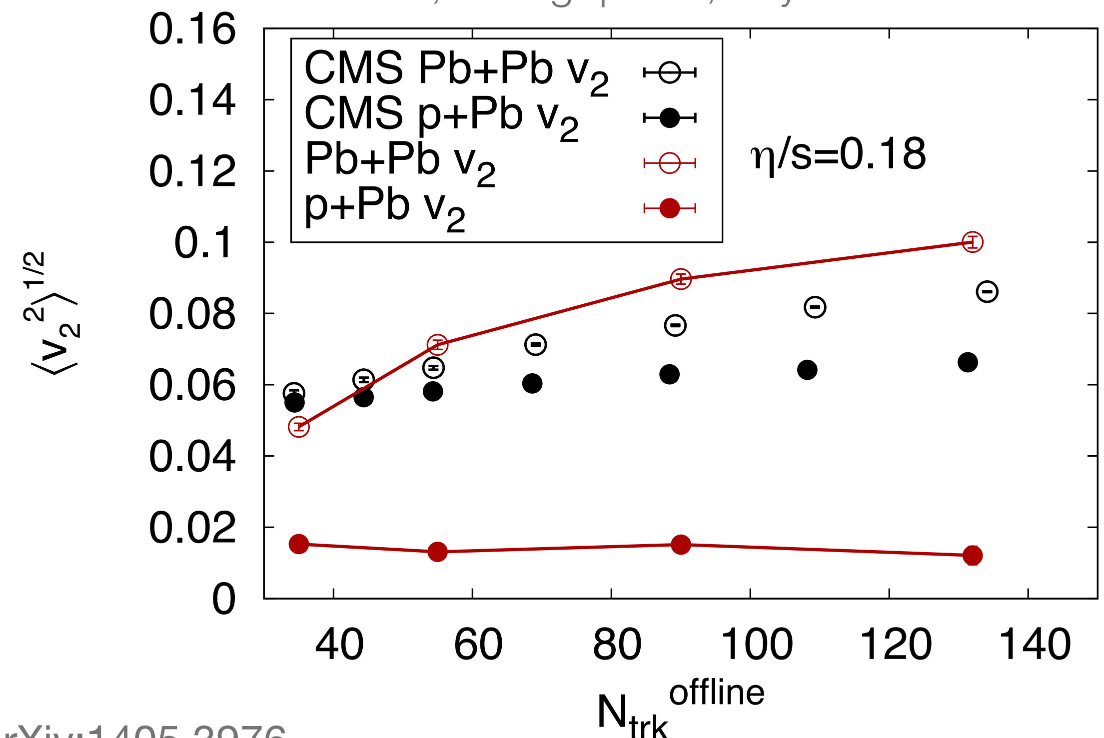
Red: IP-Glasma + MUSIC

# Difference to other hydro calculations: Initial state

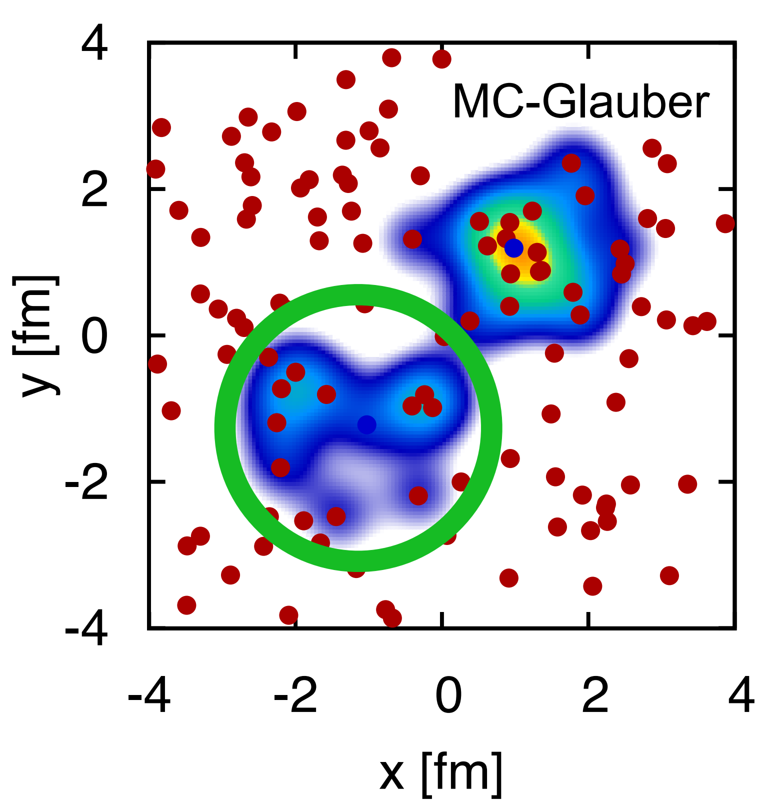
Bozek, Broniowski, Phys.Rev. C88 (2013) 014903

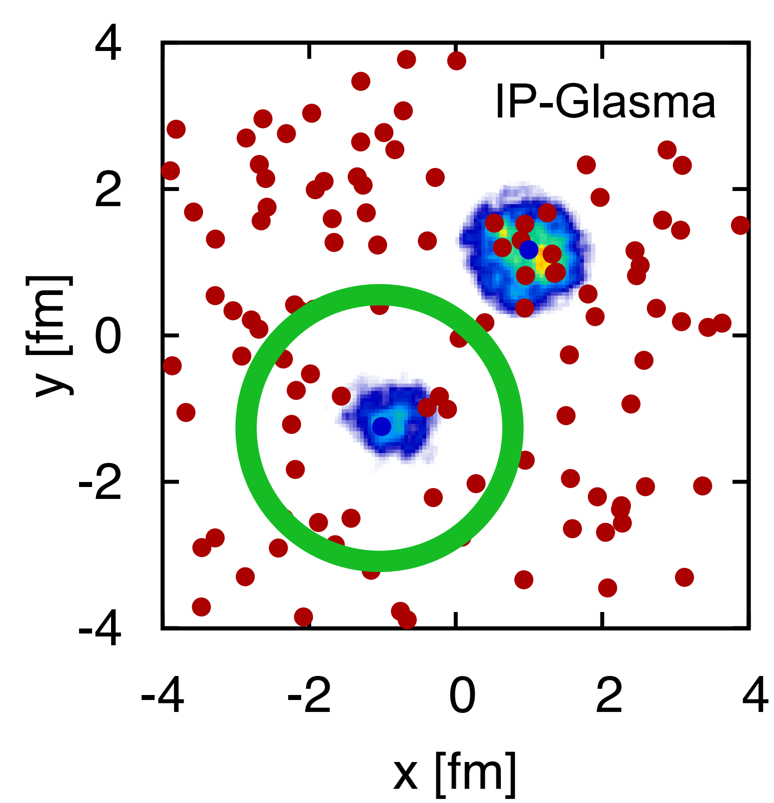



Schenke, Venugopalan, Phys. Rev. Lett. 113 (2014) 102301




see also: Kozlov, Luzum, Denicol, Jeon, Gale, arXiv:1405.3976

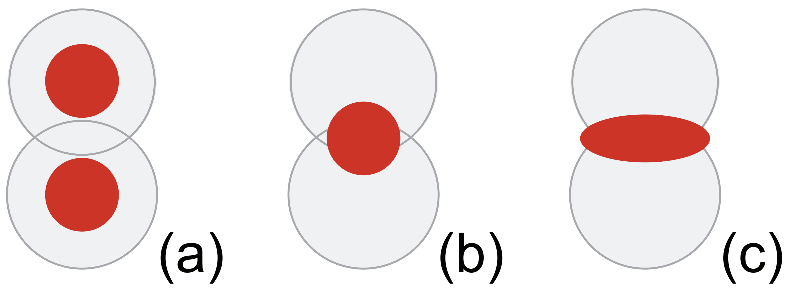



d+Au

# Issues in small systems (p+p, p+A)

- MC-Glauber does not constrain energy density dist.




Where do we put the energy?

What shape does it have?

- IP-Glasma constrains energy density deposition

  However, it does not describe $v_n$ in p+Pb

- Proton substructure should matter

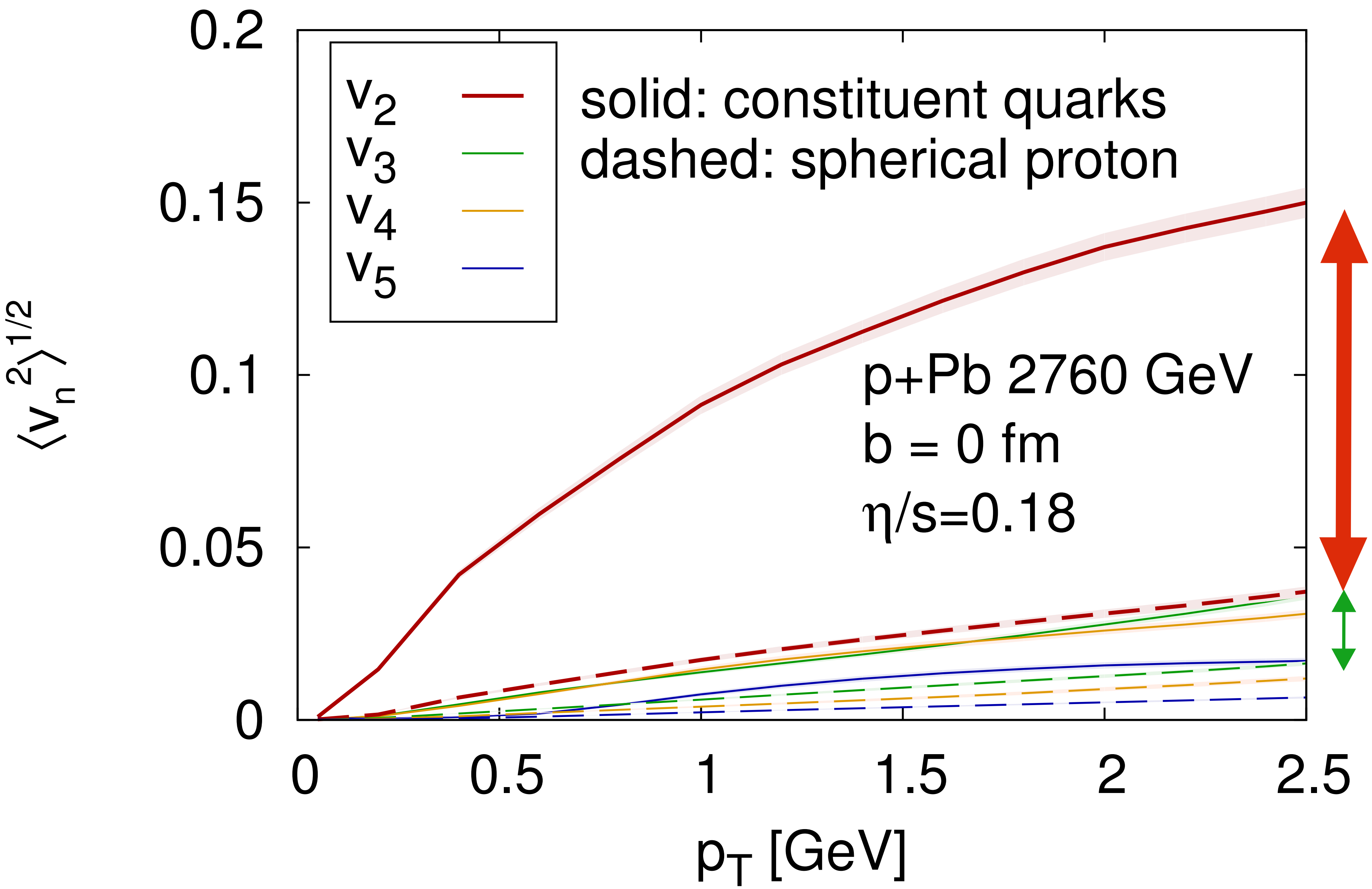
  (if main effect is of collective origin or not)

- Introduce proton substructure using

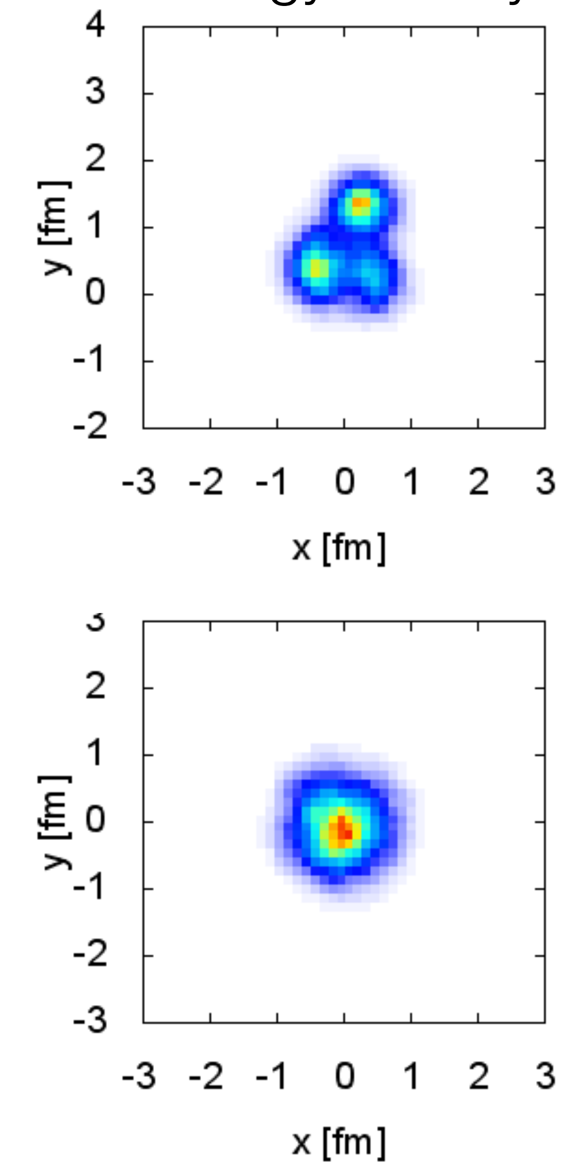
  constituent quarks to test this

# Round vs. structured proton: IP-Glasma + MUSIC

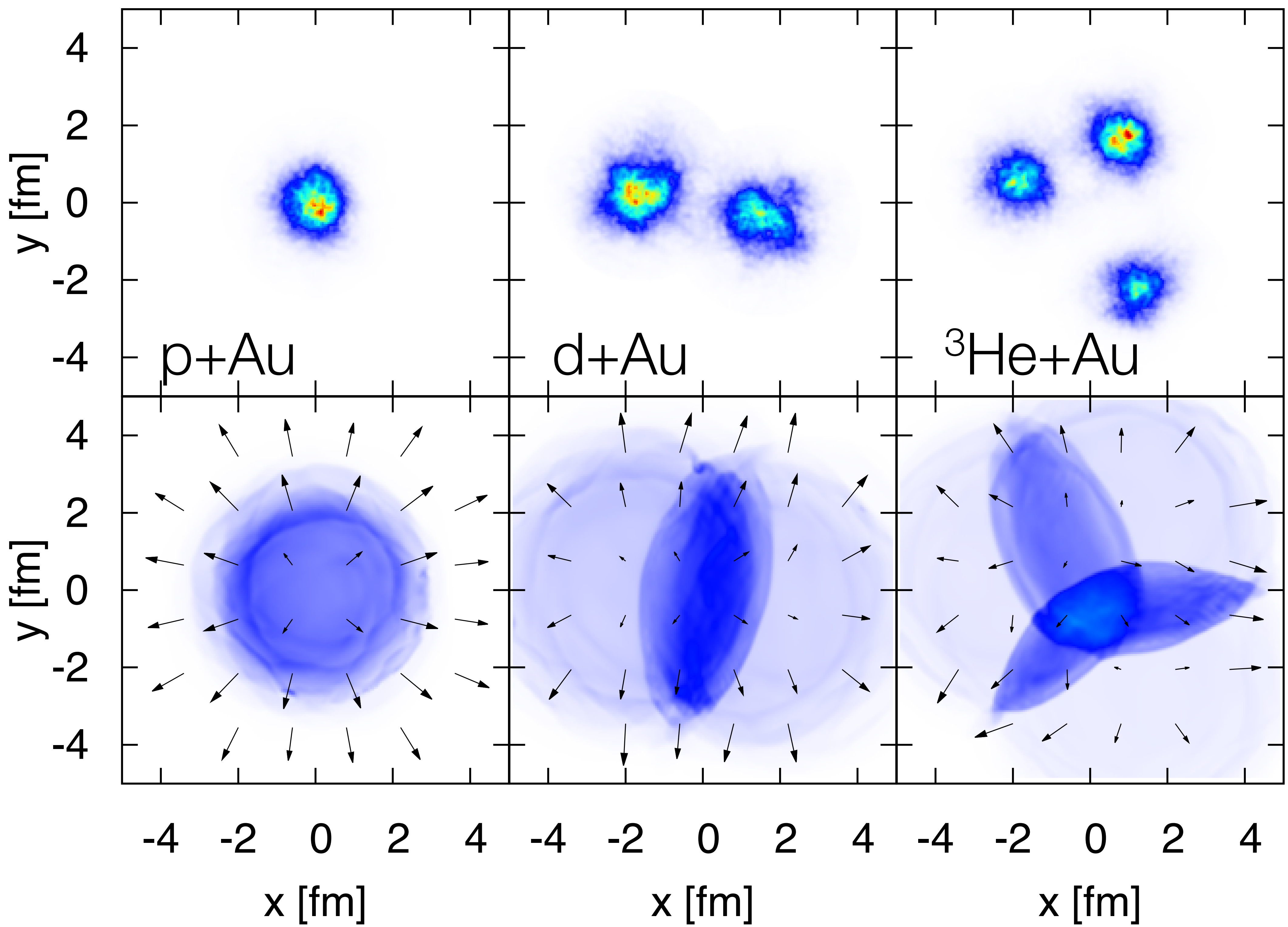
## **It makes a huge difference!**




initial
energy density



# Various small collision systems: IP-Glasma + MUSIC

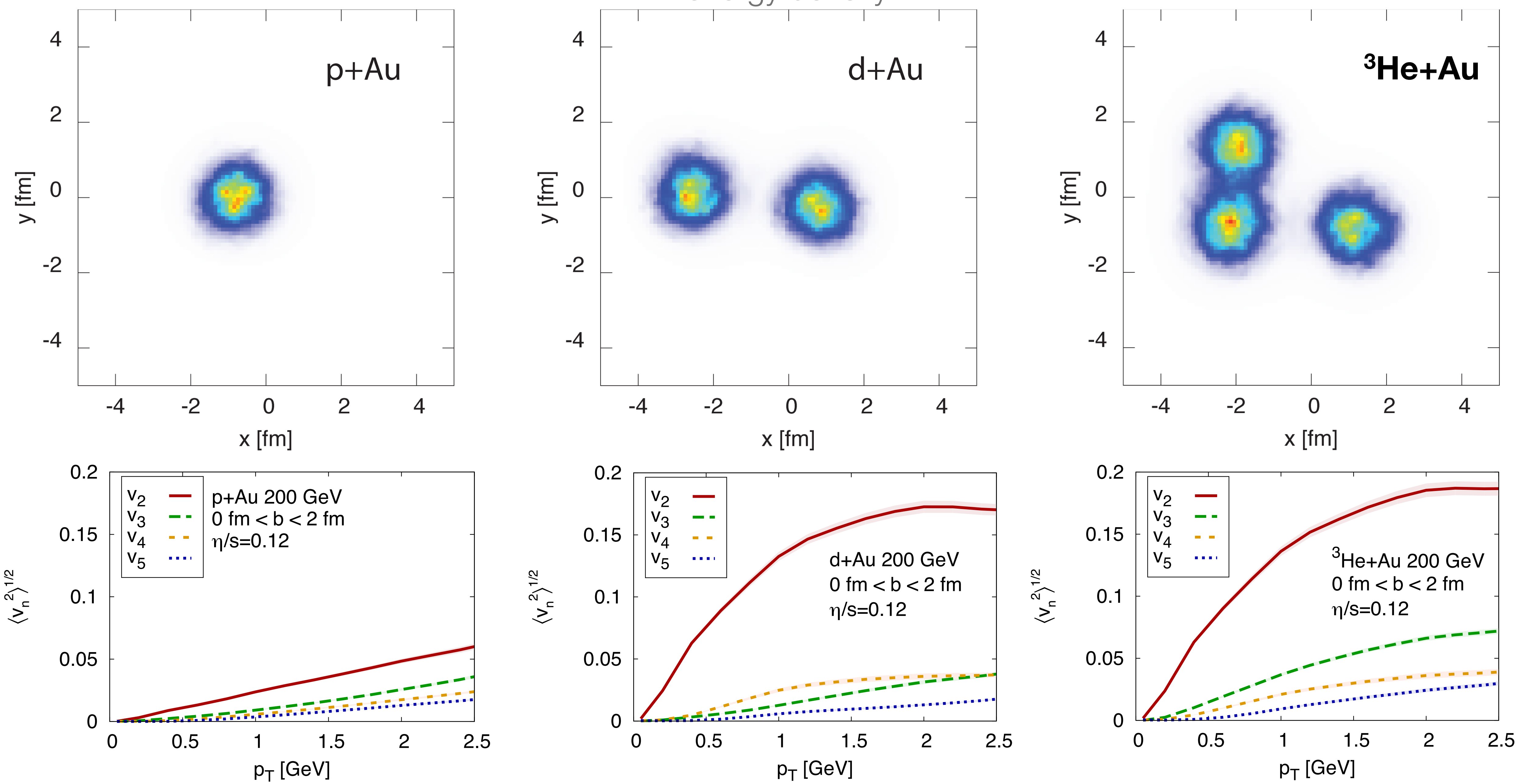


# $^{3}$He+Au results from IP-Glasma + MUSIC

B. SCHENKE, R. VENUGOPALAN, NUCL.PHYS. A931 (2014) 1039-1044

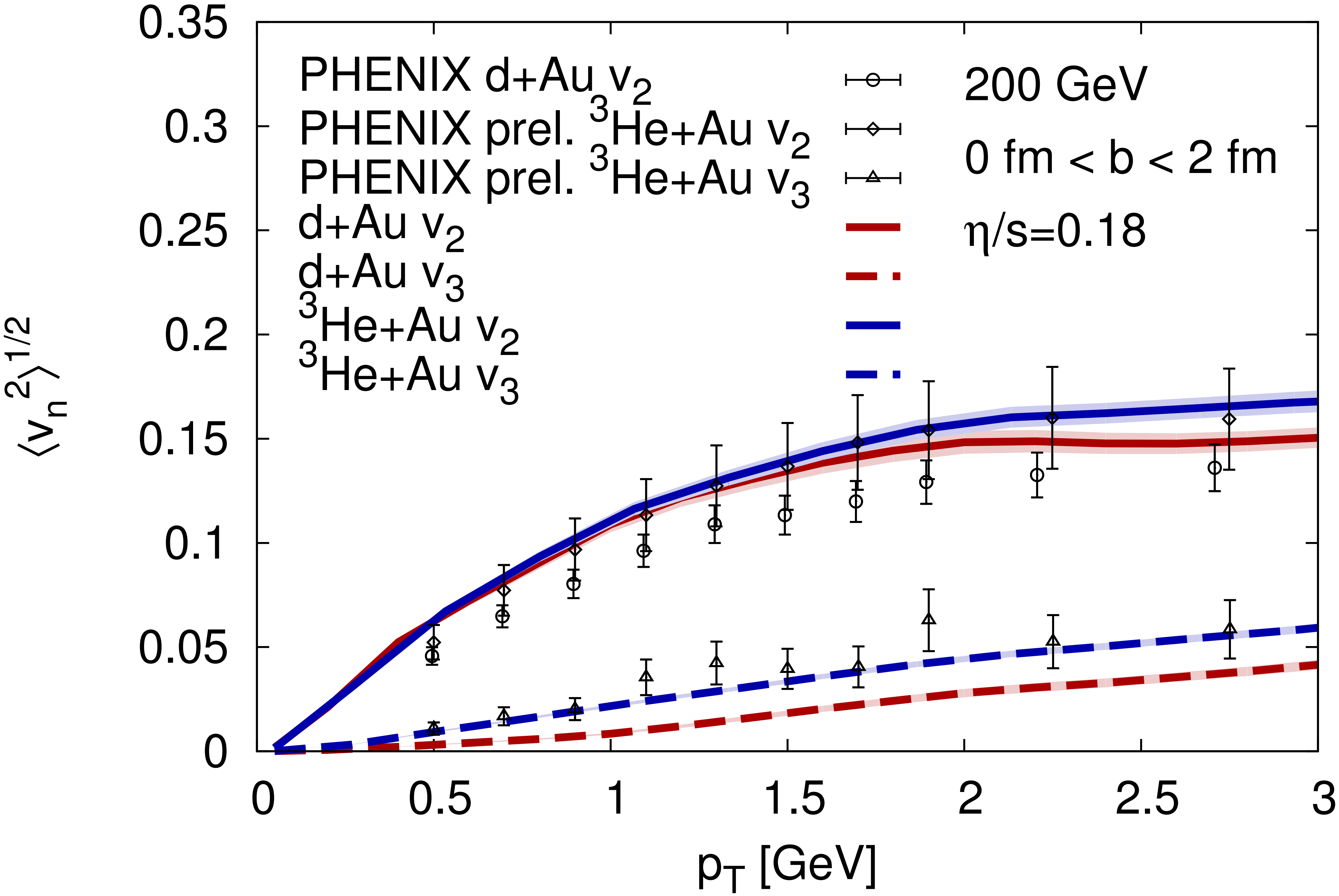
## Predictions for η/s = 0.12:

energy density



# $^3$He+Au results from IP-Glasma + MUSIC

Adjust parameter: $\eta/s$ = 0.18 - compare d+Au and $^3$He+Au




Note: No realistic centrality selection

Hydrodynamics can work very well in small systems

But results depend strongly on the initial geometry

# Is viscous fluid dynamics even valid?

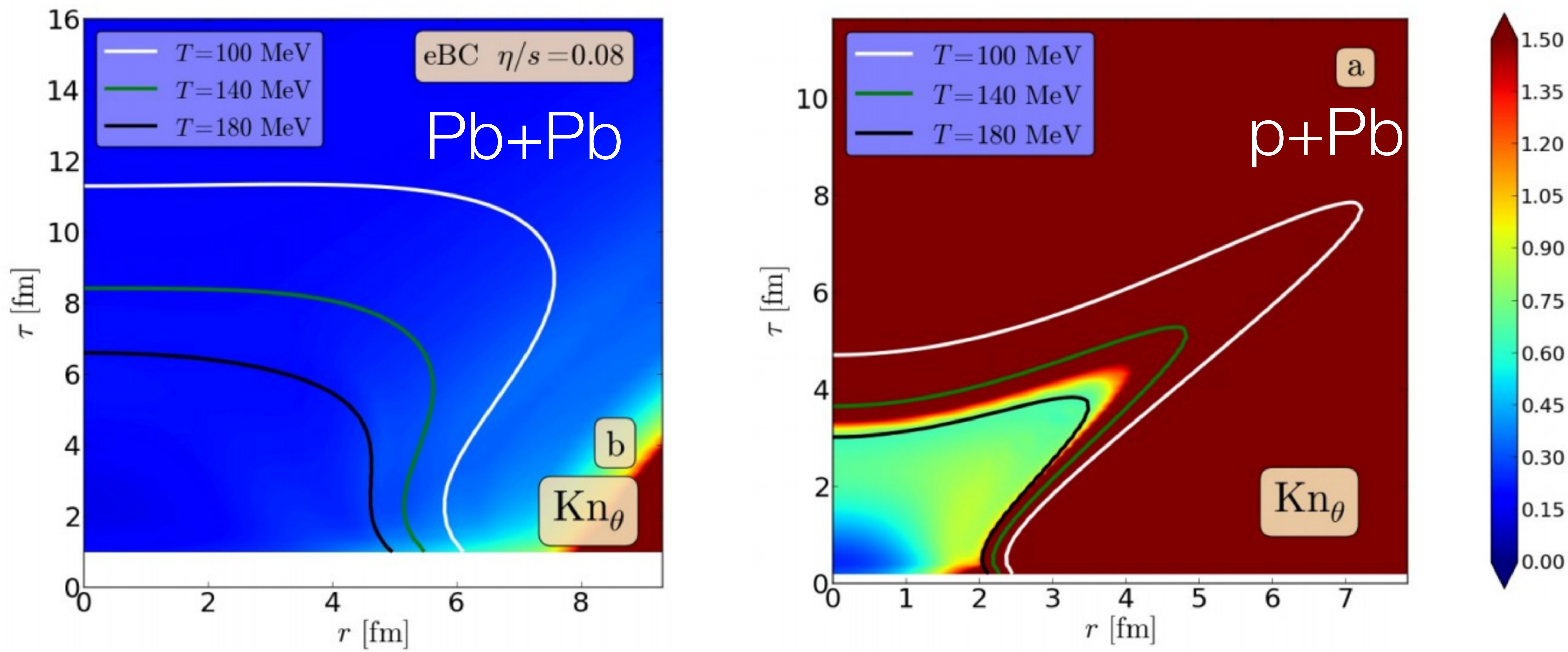
H. Niemi, G.S. Denicol, e-Print: arXiv:1404.7327

- Use the Knudsen number as a measure

$$Kn_\theta = l_{\mathrm{micro}}/L^{\theta}_{\mathrm{macro}} = \tau_\pi/\theta \quad \text{(this is one specific choice)}$$

where $\tau_\pi$ is the shear relaxation time and $\theta = \partial_\mu u^\mu$

- Small Knudsen number means fluid dynamics is valid



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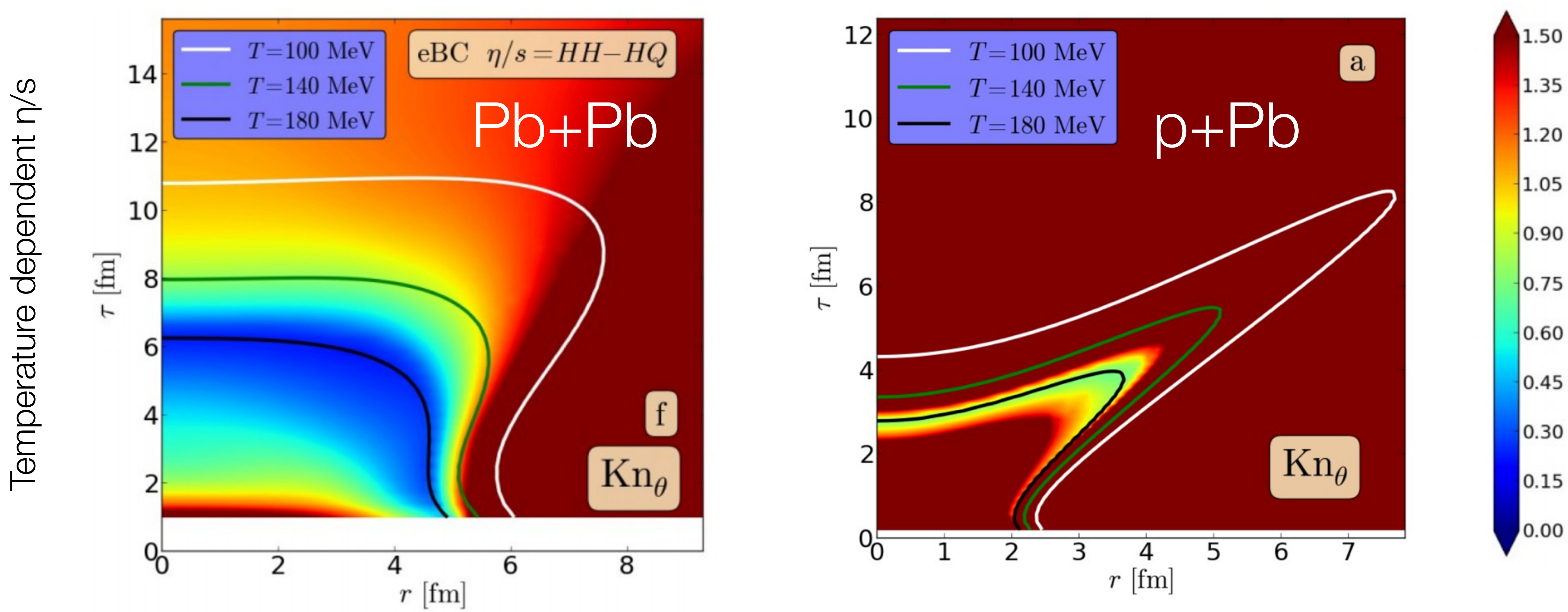
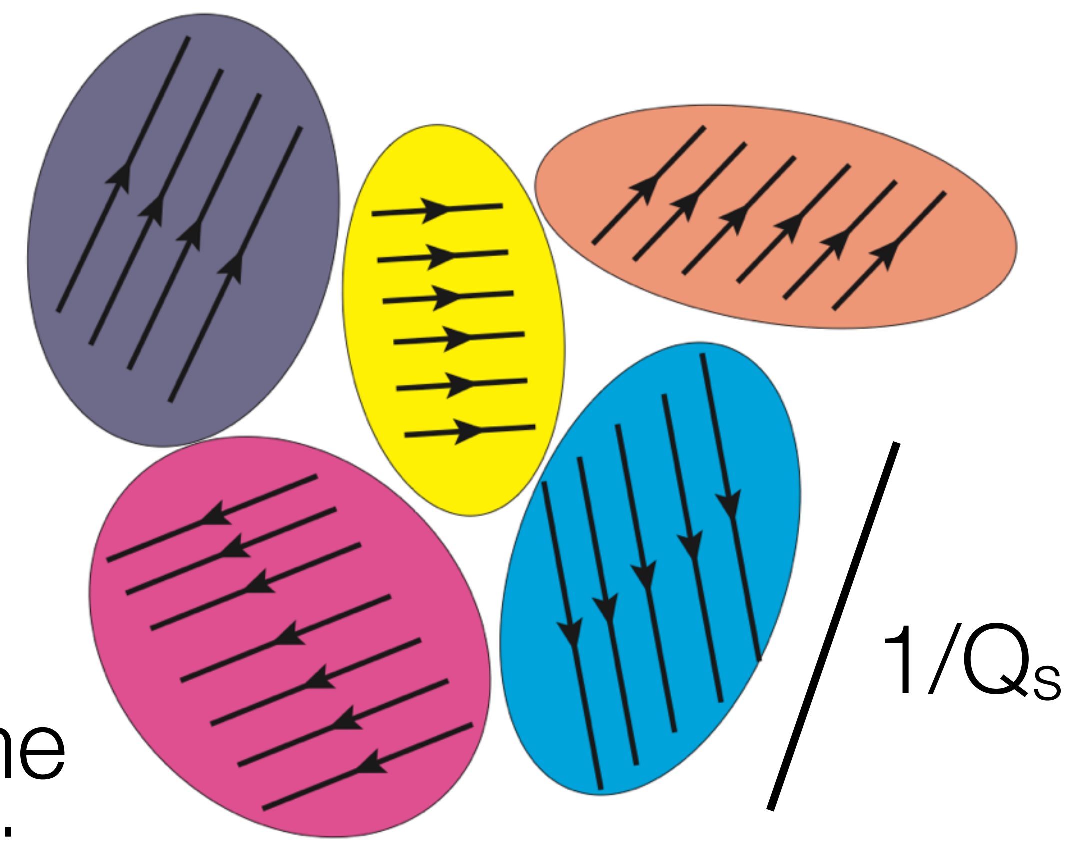


Option 2:
The initial state contribution

# Correlations from the initial state

**Intuitive picture:**

Quarks (or gluons) scatter off (are produced) from color field domains




Particles that come from the same domain get similar kicks: correlation

Effect is suppressed by the number of colors and the number of domains (it is small for heavy ions)

Figure: T. Lappi, B. Schenke, S. Schlichting, R. Venugopalan, JHEP 1601 (2016) 061
see also: A. Dumitru, A.V. Giannini, Nucl.Phys.A933 (2014) 212; A. Dumitru, V. Skokov, Phys.Rev.D91 (2015) 074006; A. Dumitru, L. McLerran, V. Skokov, Phys.Lett.B743 (2015), 134; V. Skokov. Phys.Rev.D91 (2015) 054014

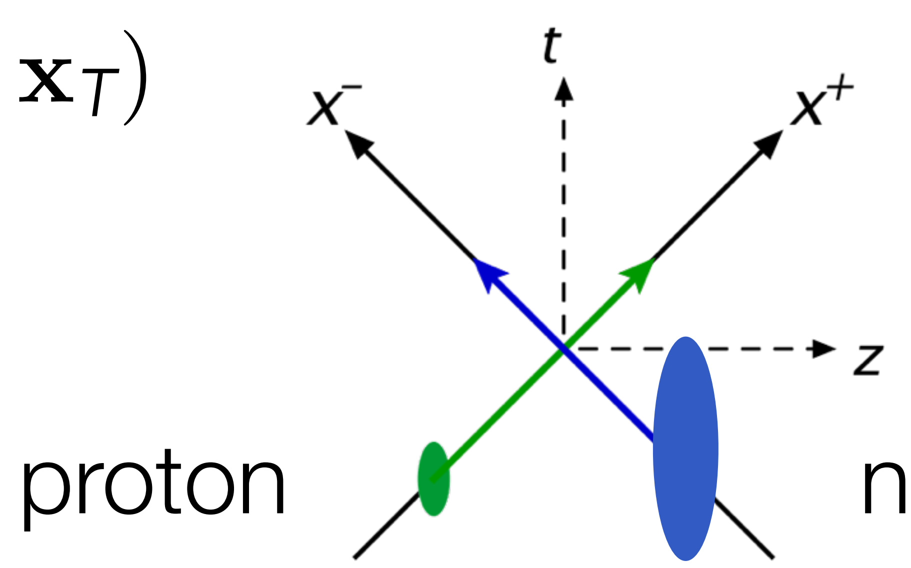
# Correlations from the initial state

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

p+A collisions in the Color Glass Condensate framework:

For high multiplicity events, both target and projectile are best described as dense objects - like in the IP-Glasma framework

$$J_1^\mu = \delta^{\mu +}\rho_1(x^-, \mathbf{x}_T)$$
$$[D_\mu, F^{\mu\nu}] = J_1^\nu$$




$$J_2^\mu = \delta^{\mu -}\rho_2(x^+, \mathbf{x}_T)$$
$$[D_\mu, F^{\mu\nu}] = J_2^\nu$$

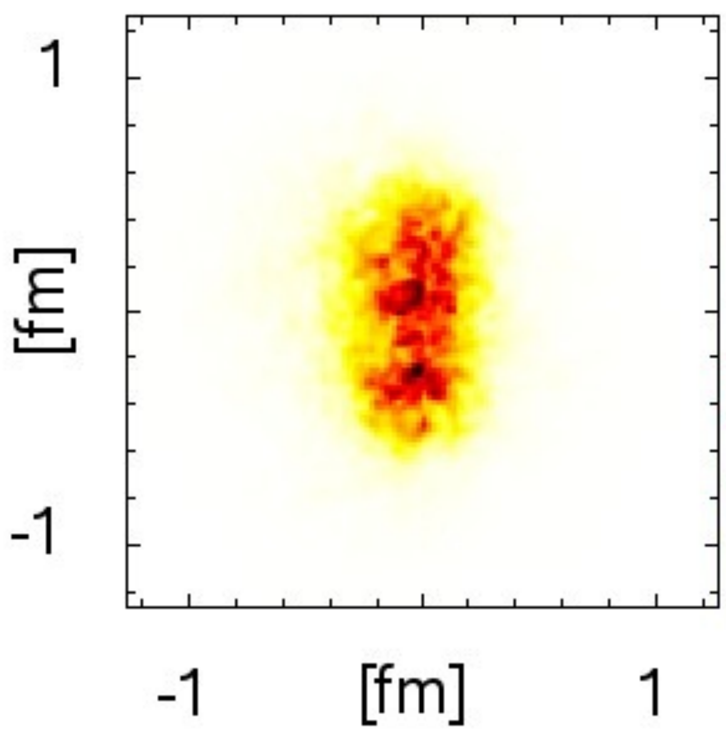
Compute the gluon momentum distribution from the initial fields after the collision - Then analyze its anisotropy

# Initial state properties immediately after the collision

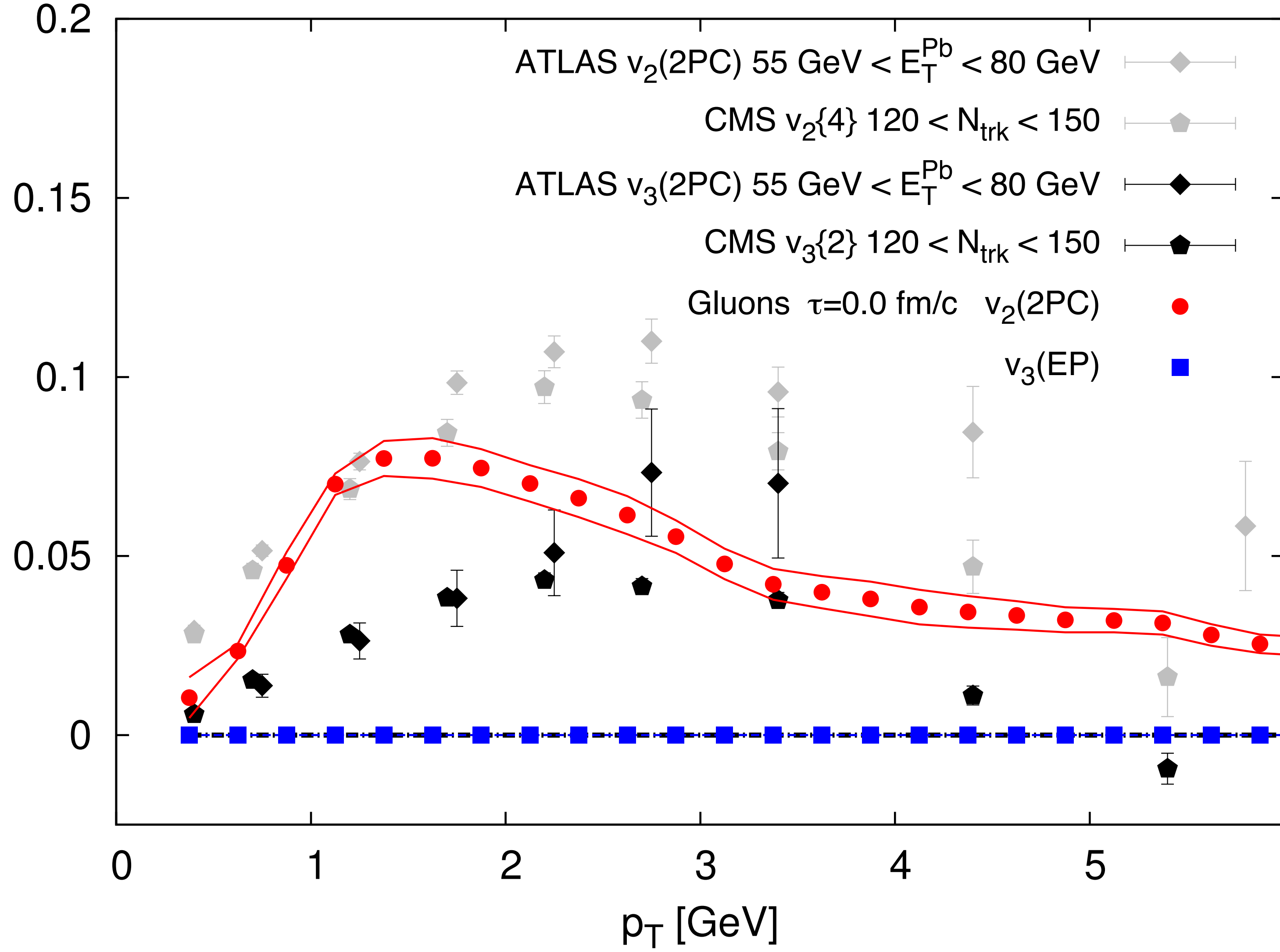
Schenke, Schlichting, Venugopalan, Phys. Lett. B747, 76-82 (2015)

τ=0.0 fm/c

Energy density profile
*(single event)*




Fourier harmonics *(event average)*



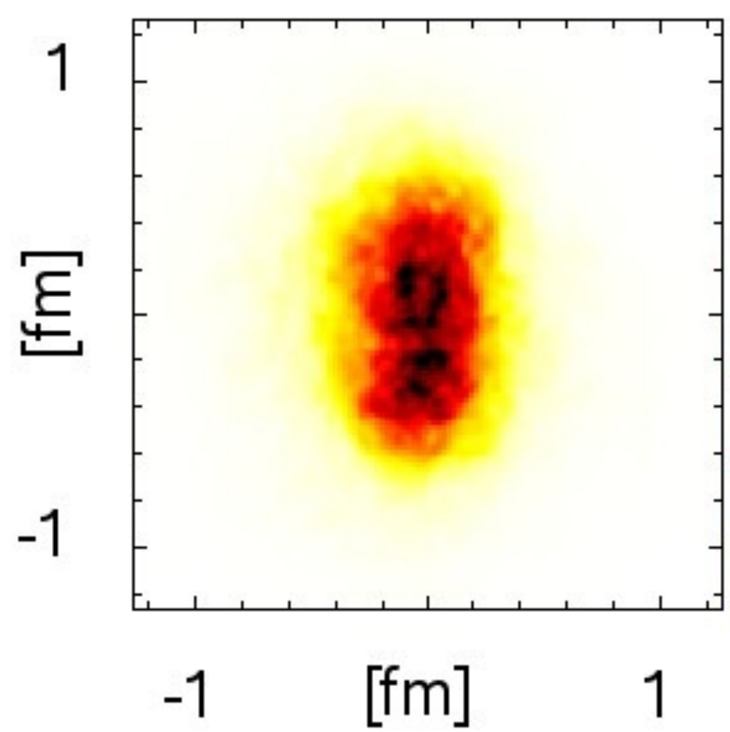

Significant $v_2$ at time $0^+$ which cannot be produced by flow
No odd harmonics for gluons without final state interactions

# Initial state properties immediately after the collision

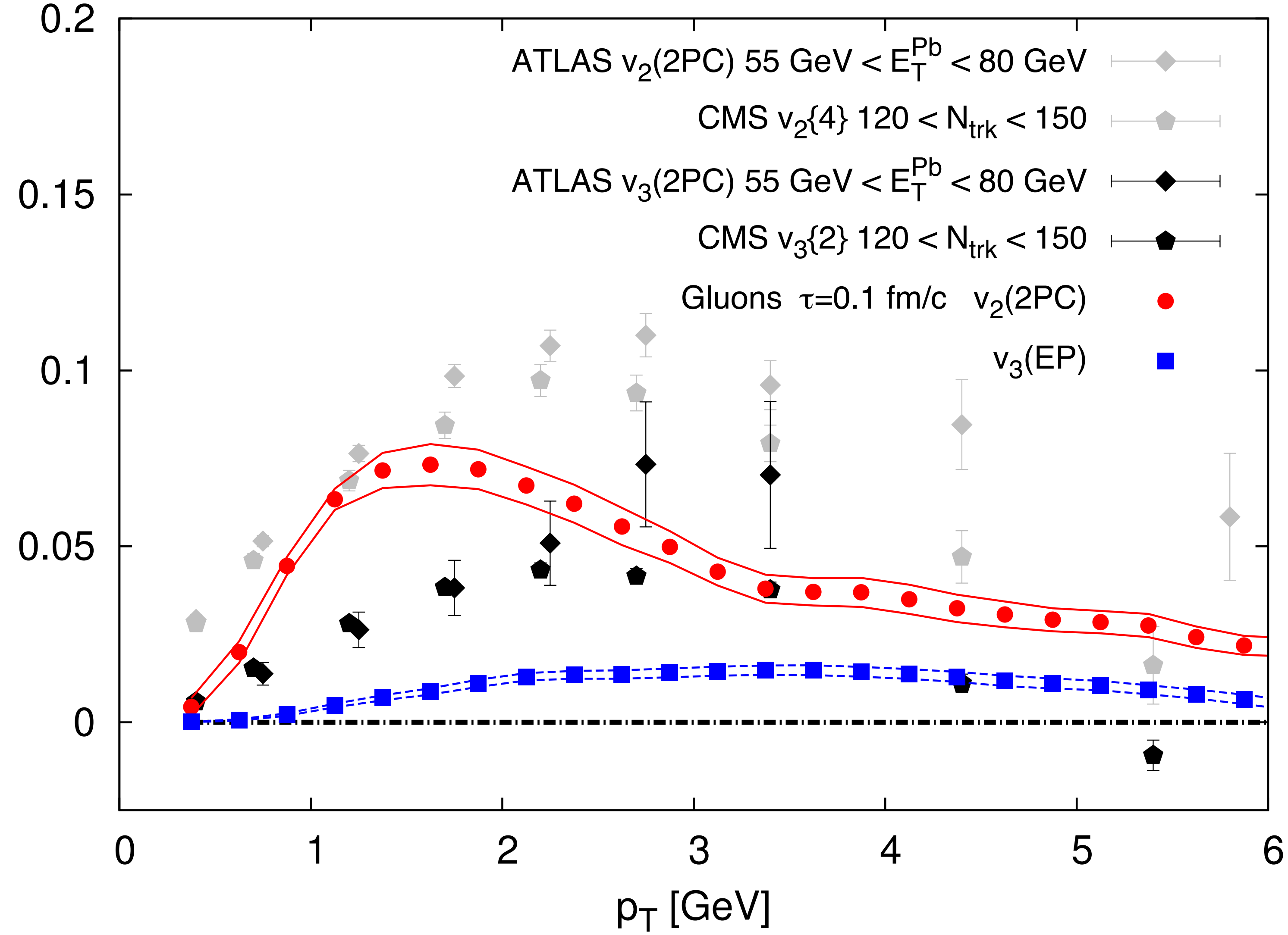
Schenke, Schlichting, Venugopalan, Phys. Lett. B747, 76-82 (2015)

## $\tau$=0.1 fm/c

Energy density profile
*(single event)*




## Fourier harmonics *(event average)*

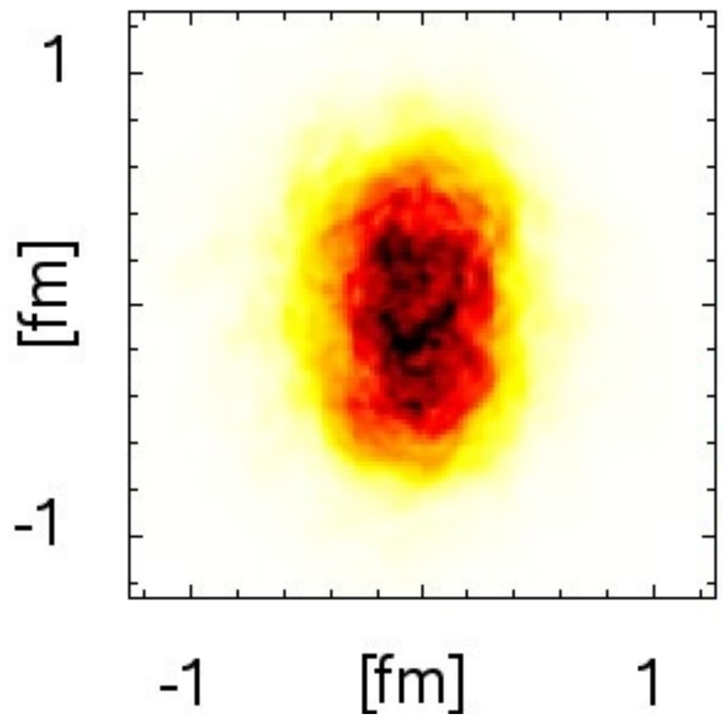


# Initial state properties immediately after the collision

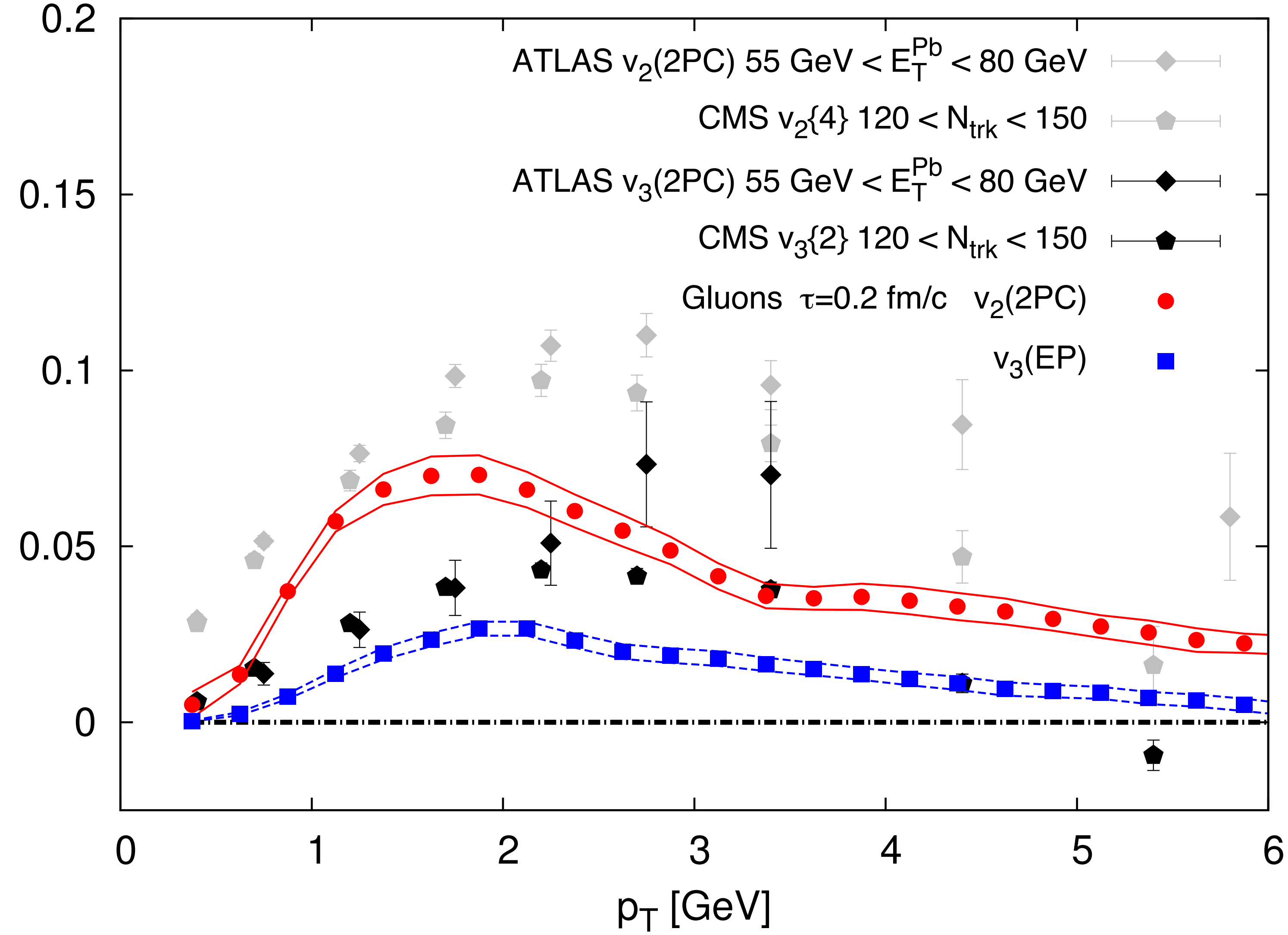
Schenke, Schlichting, Venugopalan, Phys. Lett. B747, 76-82 (2015)

$\tau$=0.2 fm/c

Energy density profile
*(single event)*




Fourier harmonics *(event average)*

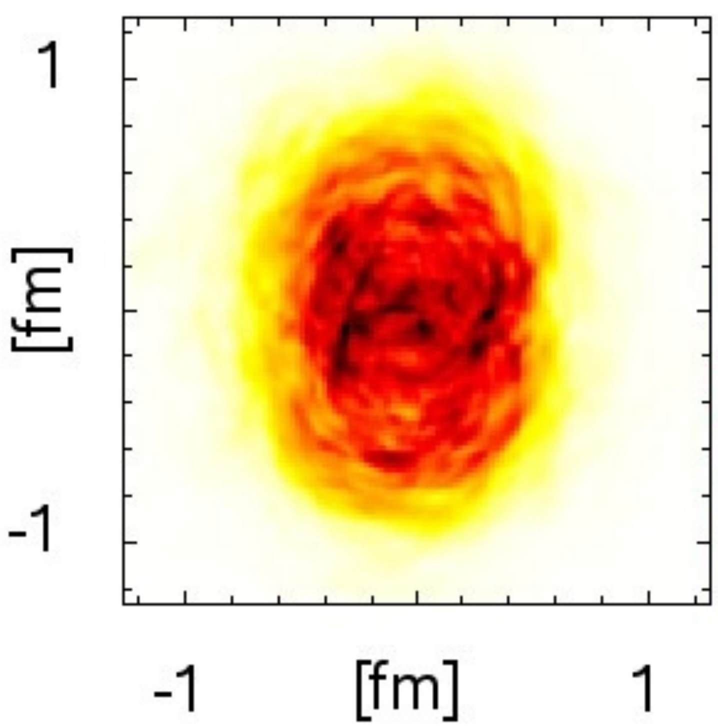


# Initial state properties immediately after the collision

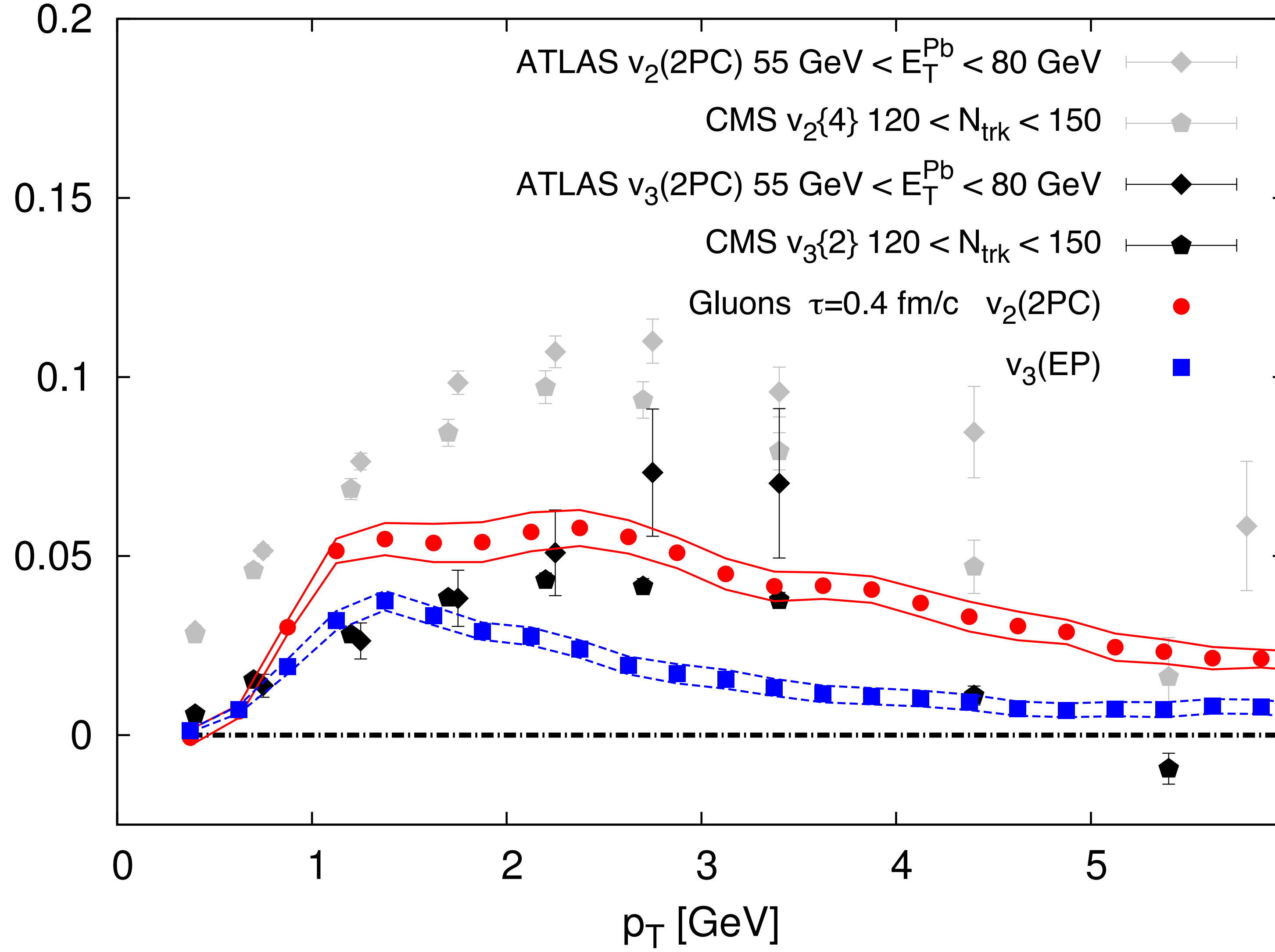
Schenke, Schlichting, Venugopalan, Phys. Lett. B747, 76-82 (2015)

τ=0.4 fm/c

Energy density profile
*(single event)*




Fourier harmonics *(event average)*




Odd harmonics generated by pre-equilibrium dynamics.
However, no correlation with global triangularity!

# Glasma graph approximation

Dusling, Venugopalan, Phys.Rev. D87 054014 (2013)

More approximate scheme but data comparison done: Glasma graphs. Do not include multi-gluon interactions

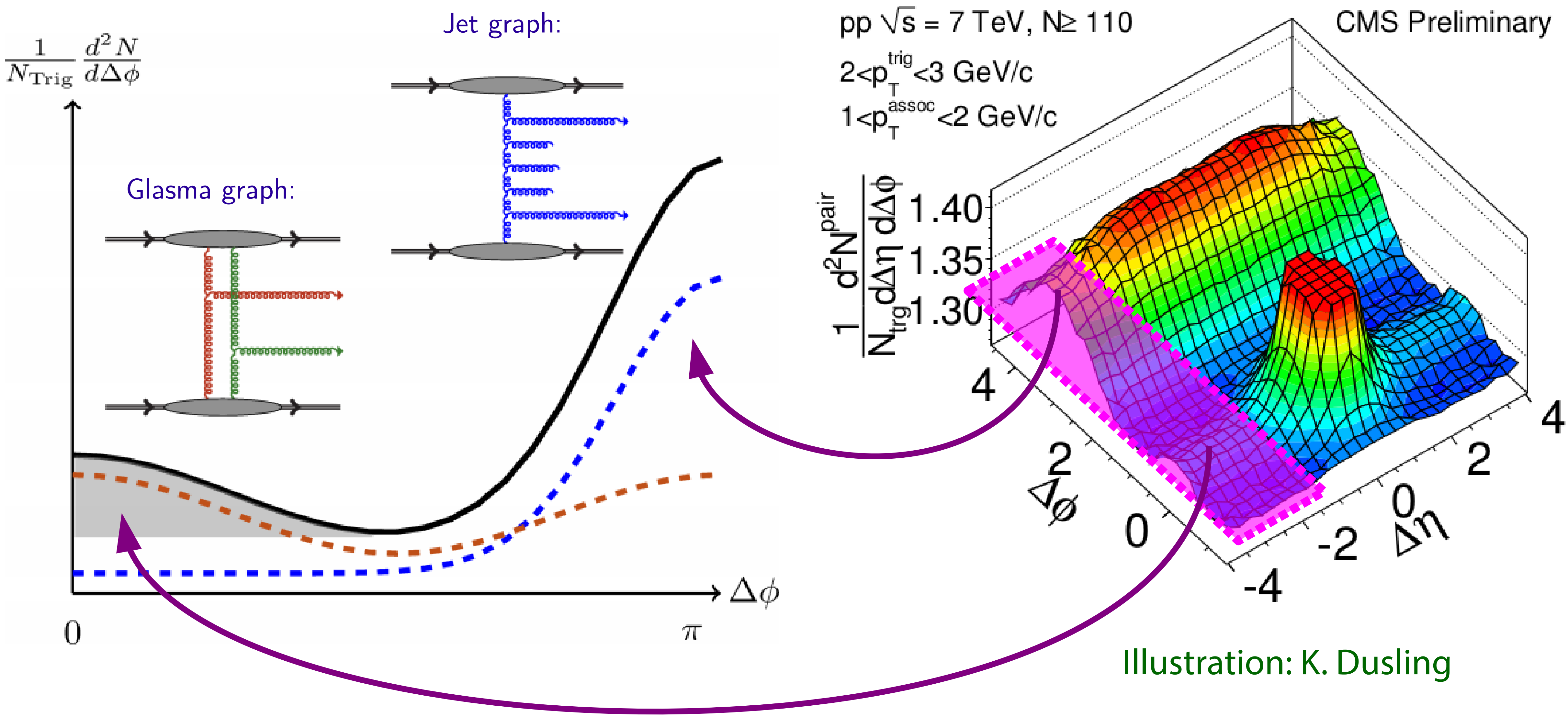
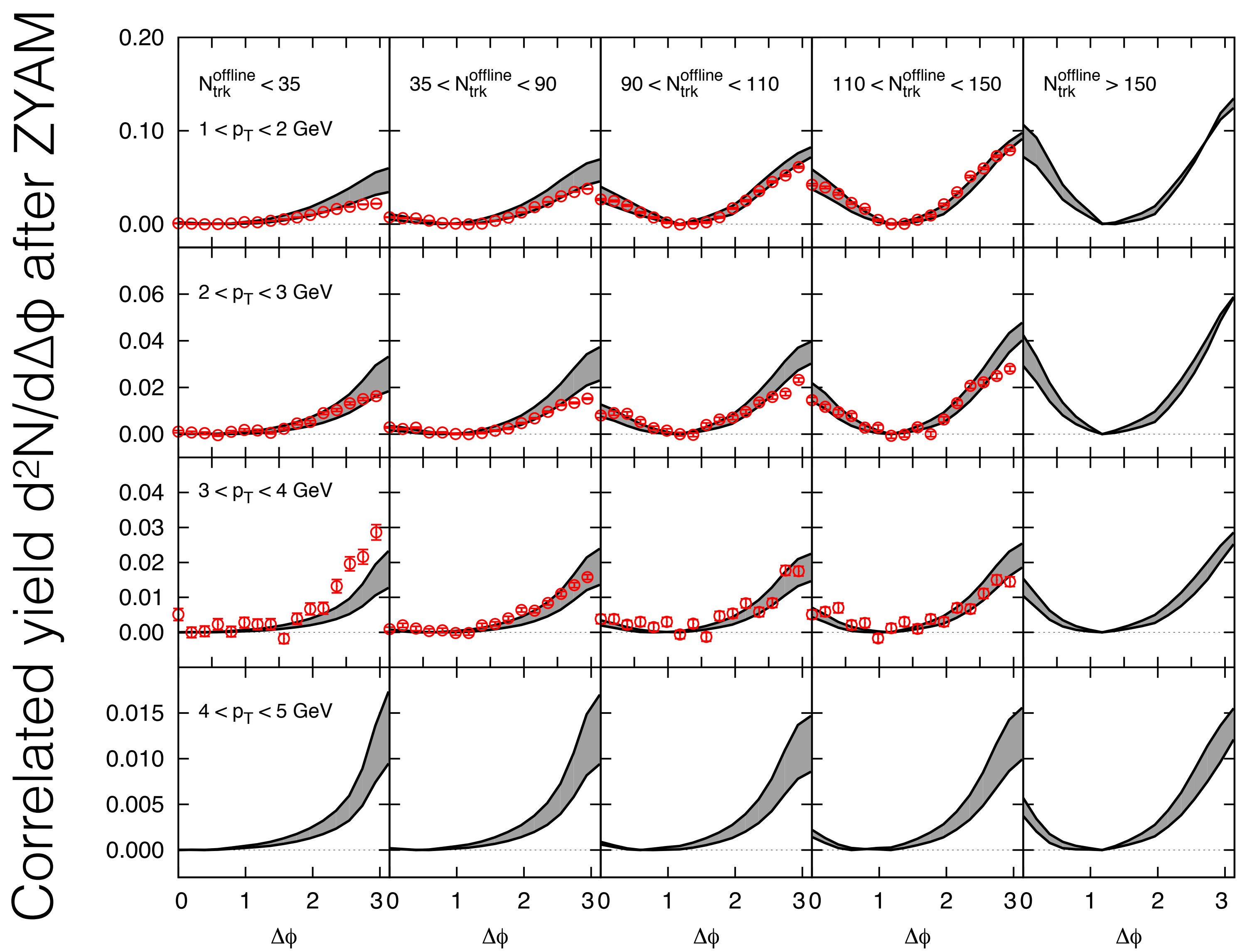



Illustration: K. Dusling

# Correlated yield vs. angular difference

Dusling, Venugopalan, Phys.Rev. D87 054014 (2013), Exp: CMS collaboration, Phys. Lett. B 718 795 (2013)




Systematics well described

Ridge larger in p+A than in p+p because of larger saturation scale

# Comparing various initial state calculations

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, 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”

# Comparing various initial state calculations

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

Dilute-dense limit:

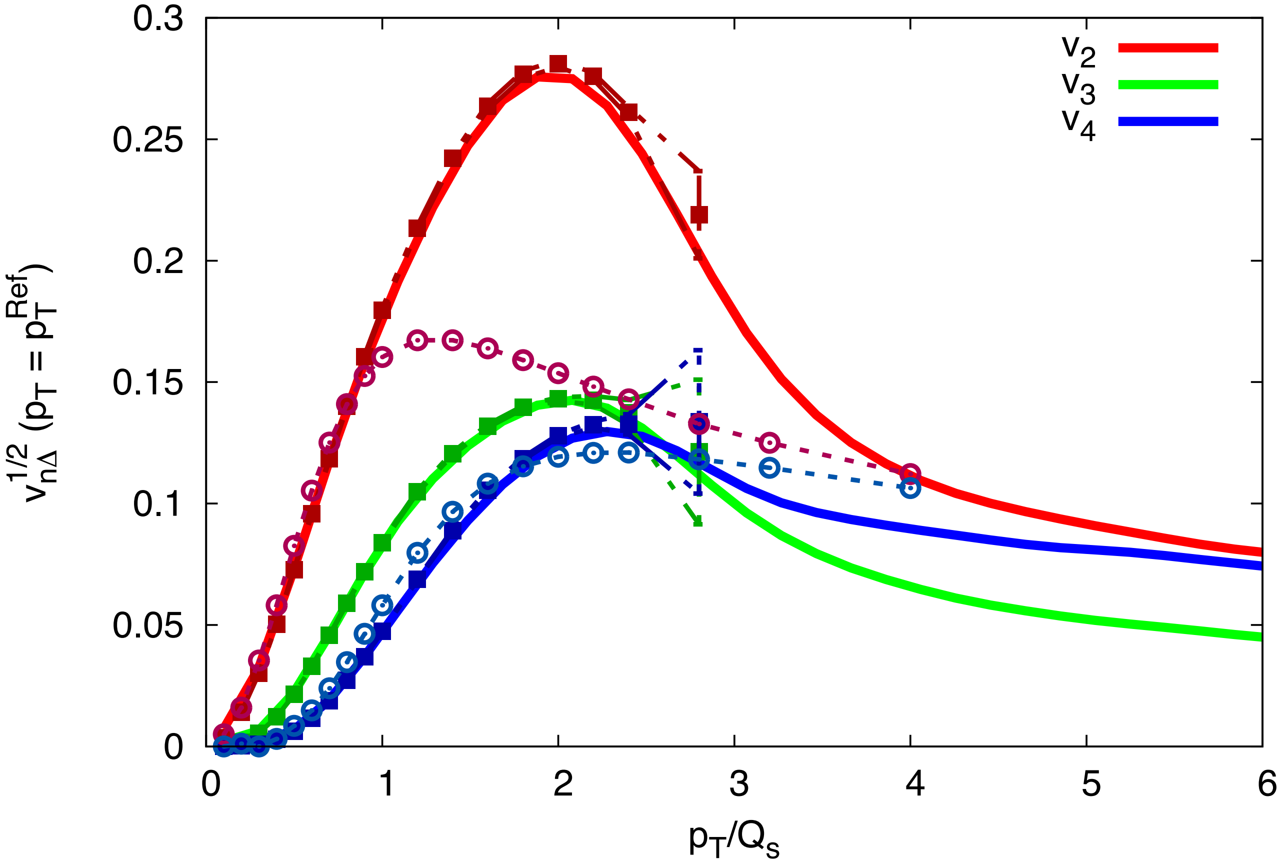
- Study simple situation of parton scattering off color fields of a large nucleus
- Two-particle correlations encoded in dipole-dipole correlator
- Different approximations for that correlator ordered in increasing amount of approximations:
  - Numerical evaluation of Wilson lines using JIMWLK
    exact given a certain initial condition for the *x*-evolution
  - Non-linear Gaussian approximation
    neglects non-Gaussianities
  - Glasma graph approximation
    neglects non-Gaussianities and more than two-gluon exchanges

# Dilute-dense limit: approximation schemes

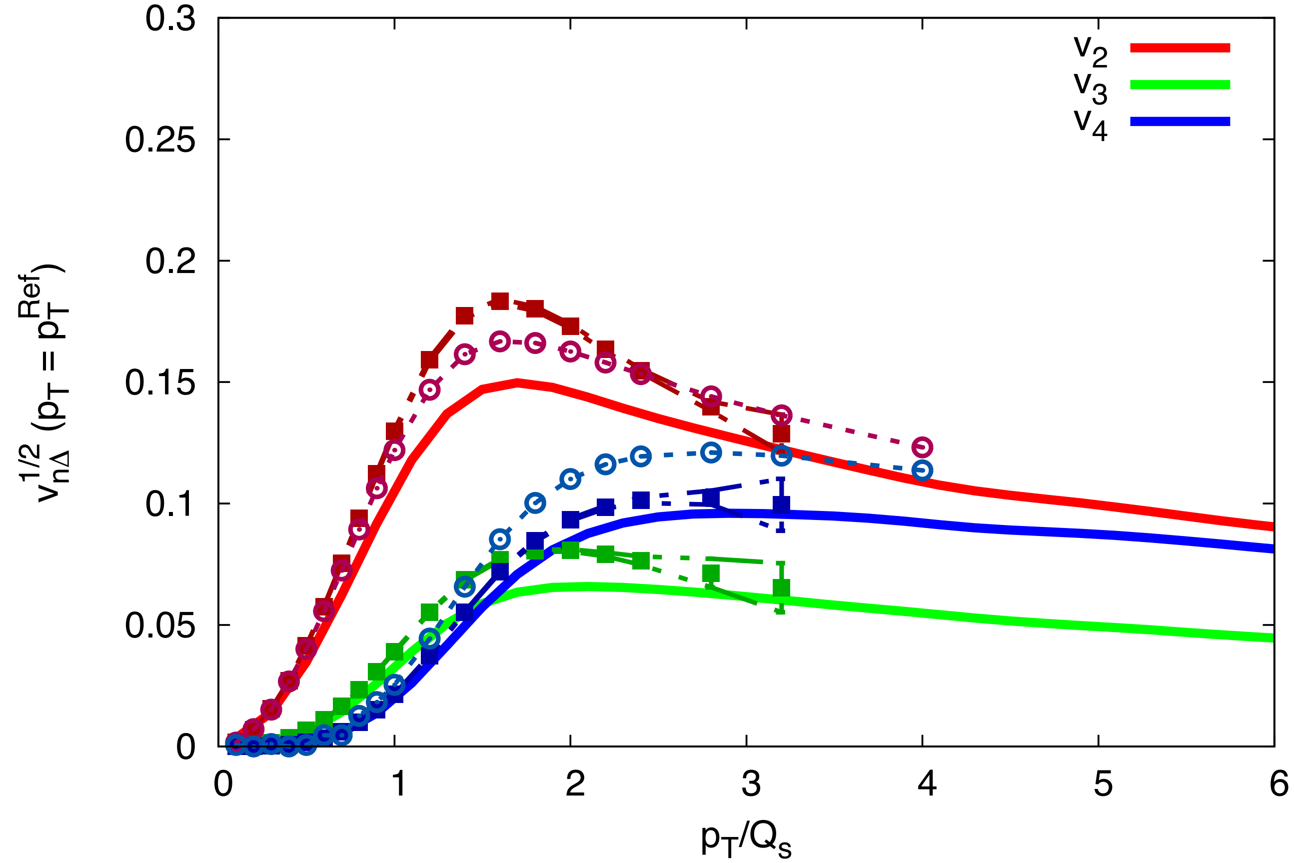
T. Lappi, B. Schenke, S. Schlichting, R. Venugopalan, JHEP 1601 (2016) 061

Scattering of two independent quarks off a large nucleus

MV model




after JIMWLK evolution




solid:numerical JIMWLK
dash-dotted (squares): non-linear Gaussian
dotted (circles): glasma graph

The two approximate schemes use the dipole operator extracted from the numerical JIMWLK evolution

# Dilute-dense limit: approximation schemes

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

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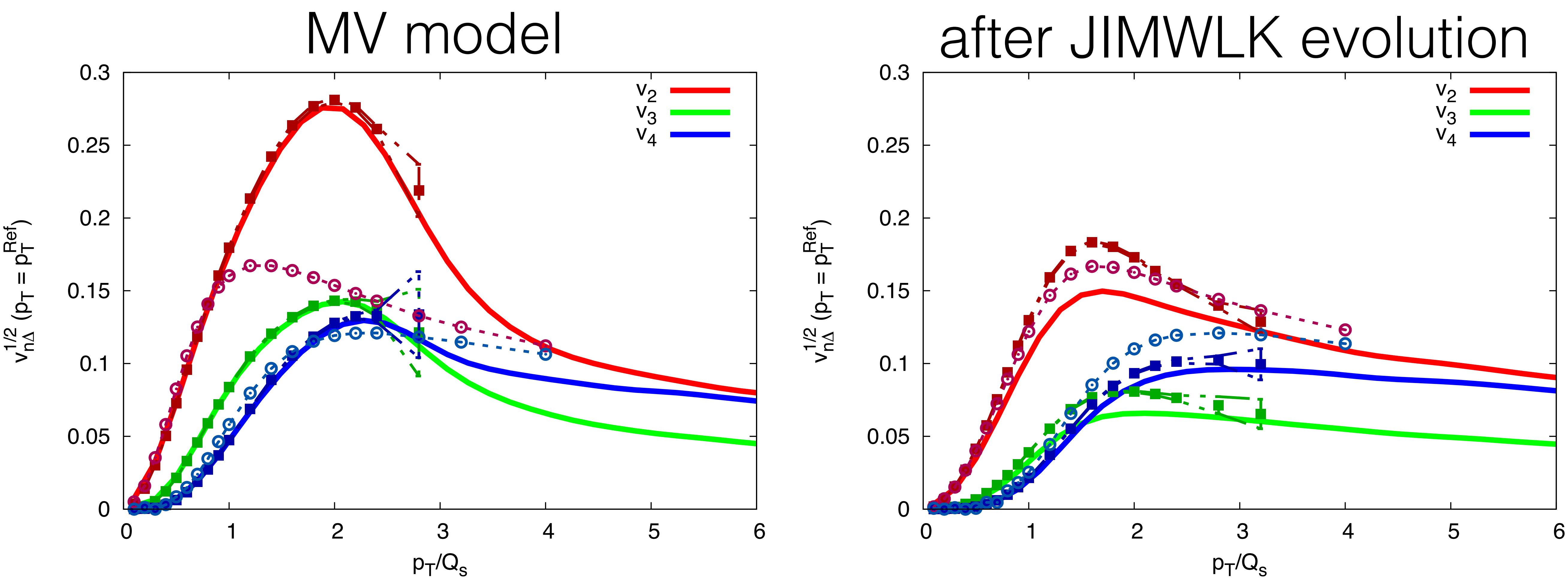
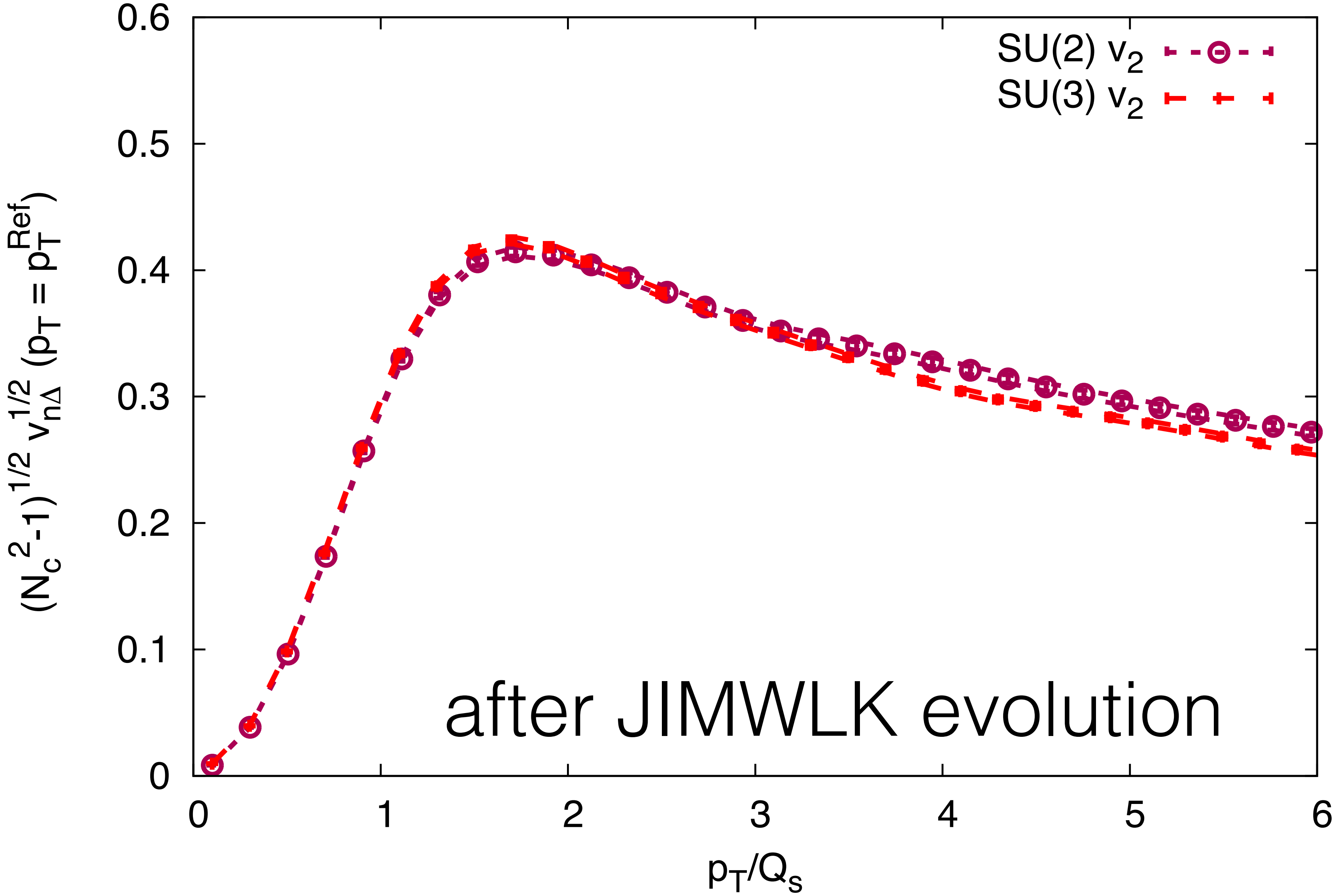



- No odd $v_n$ in glasma graph approximation by symmetry
- Perfect agreement between non-linear Gaussian approximation and numerical result in MV (must be)

# Correlations are suppressed by the number of colors

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

## Scattering of two independent quarks off a large nucleus




$v_n$ scales as $(N_c^2 - 1)^{-\frac{1}{2}}$

azimuthal correlations in the double inclusive spectrum $\sim (N_c^2 - 1)^{-1}$

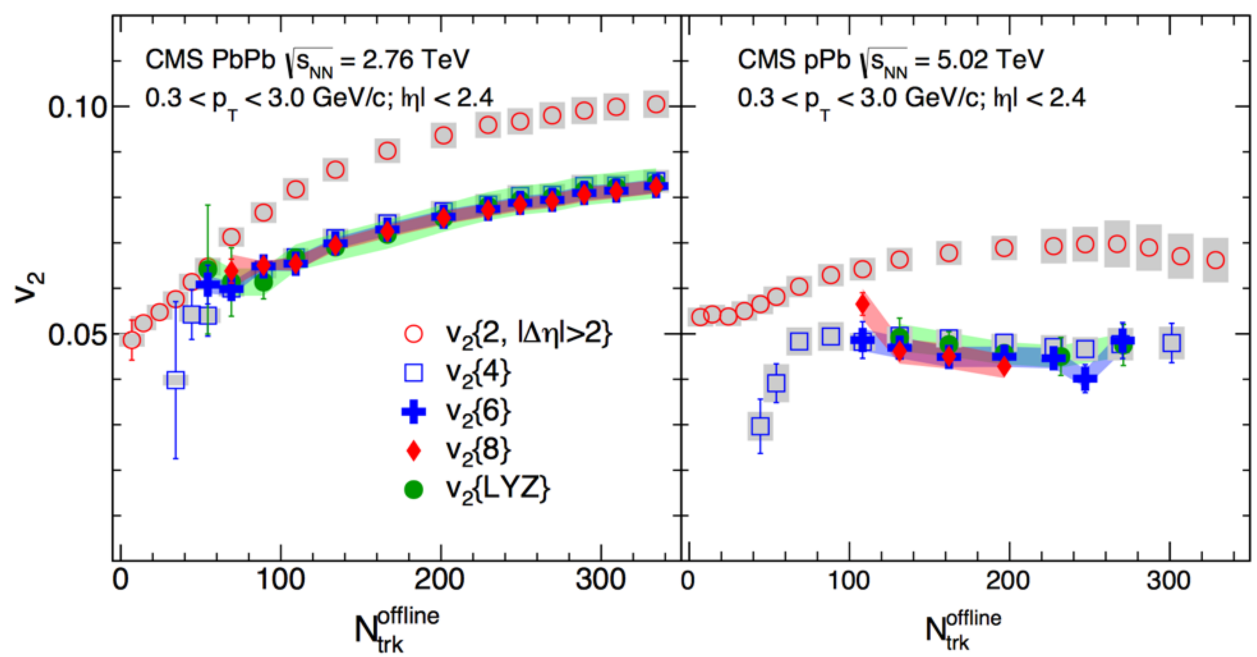
Any way to distinguish initial and final state effects?

# How to distinguish a "flow" and an "initial state" scenario

- **$c_2\{4\}$ turning positive** as multiplicity increases
  could mean collectivity sets in but also alternative explanations
  Dumitru, McLerran, Skokov, Phys.Lett. B743 (2015) 134-137

- Higher order cumulants:
  Data shows that
  **$v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$ …**
  Natural in hydrodynamics
  But initial state could
  also get that

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




- **Mass splitting of mean $p_T$ and $v_n$**:
  Natural in any situation where particles are produced from a common boosted source: e.g. fluid cell, strings
  So just hadronization via strings could do it…

# How to distinguish a “flow” and an “initial state” scenario

- **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, Phys. Lett. B 739 (2014) 139-151

  But even within hydro models different initial states can lead to different results
  P. Bozek, W. Broniowski, Phys.Lett. B720 (2013) 250-253
  B. Schenke, R. Venugopalan, Phys.Rev.Lett. 113 (2014) 102301

- So unfortunately, we do not have the final answer yet
- Also see the review e-Print: arXiv:1509.07939
  K. Dusling, W. Li, B. Schenke

# Summary and conclusions

- Azimuthal anisotropies in small collision systems are similar to those in heavy ion collisions

- Final state effect or initial state correlations?

- Hydrodynamics could work but:
  - results depend strongly on initial state
  - one might be on the edge of its validity
- Initial state correlations are there but:
  - can they survive strong final state effects?
  - do they reproduce details of data after hadronization?

- Possibly we have a mixture of both - need to determine what effect dominates in which system/multiplicity

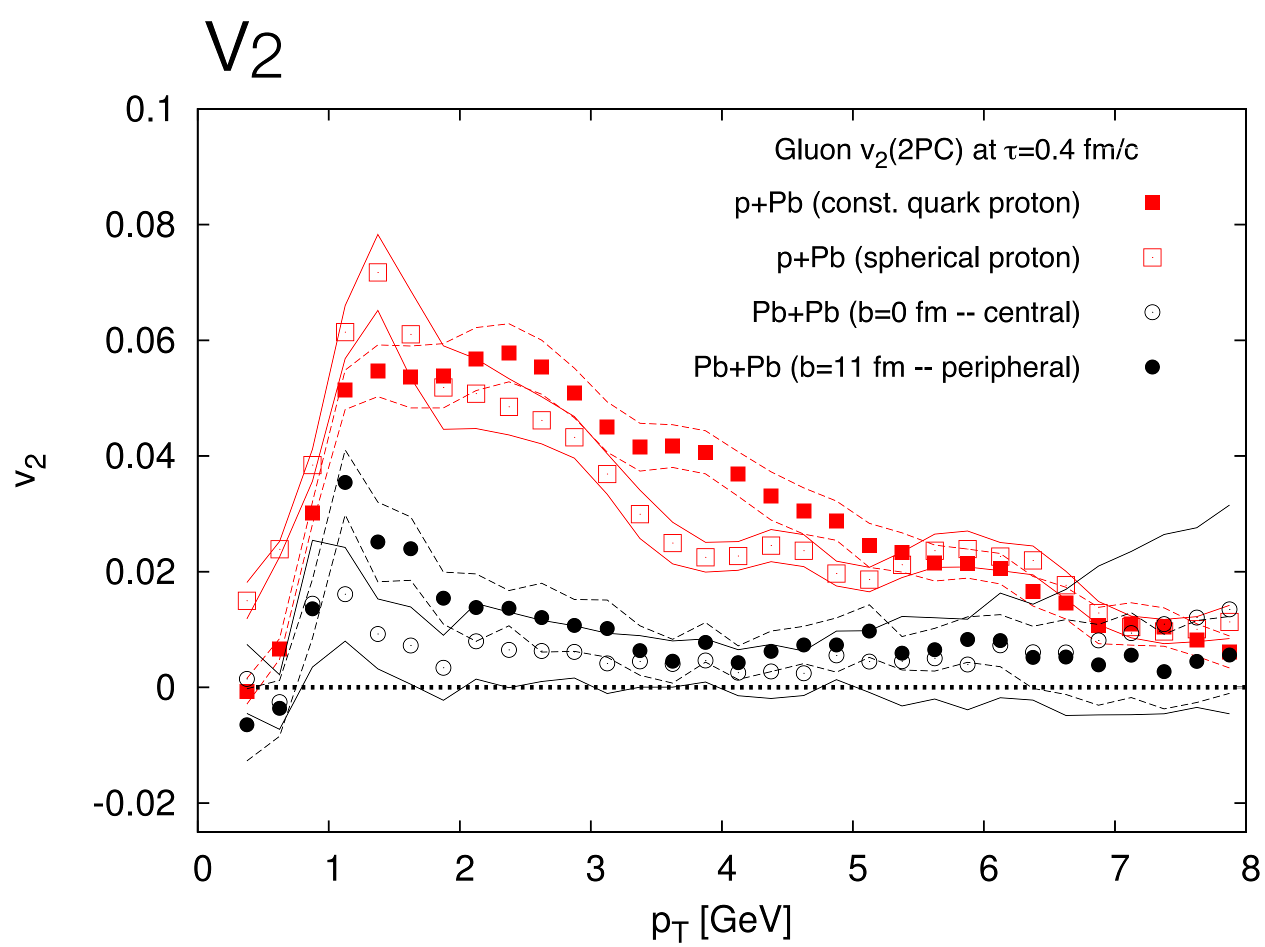
Thank you

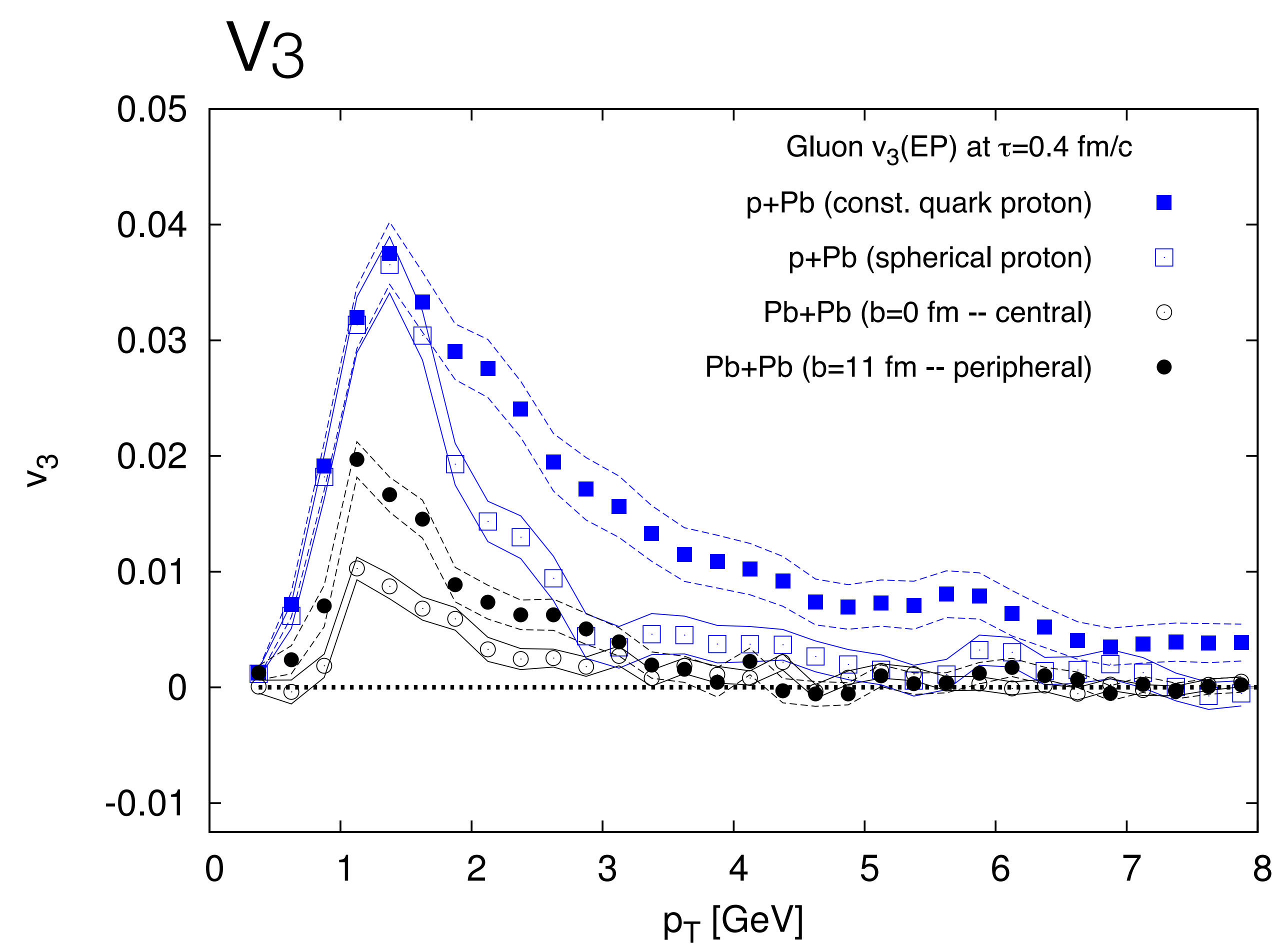
# Backup

# BACKUP

# Sensitivity to system size

Schenke, Schlichting, Venugopalan, arXiv:1502.01331




Black points: open: central Pb+Pb, solid: peripheral Pb+Pb

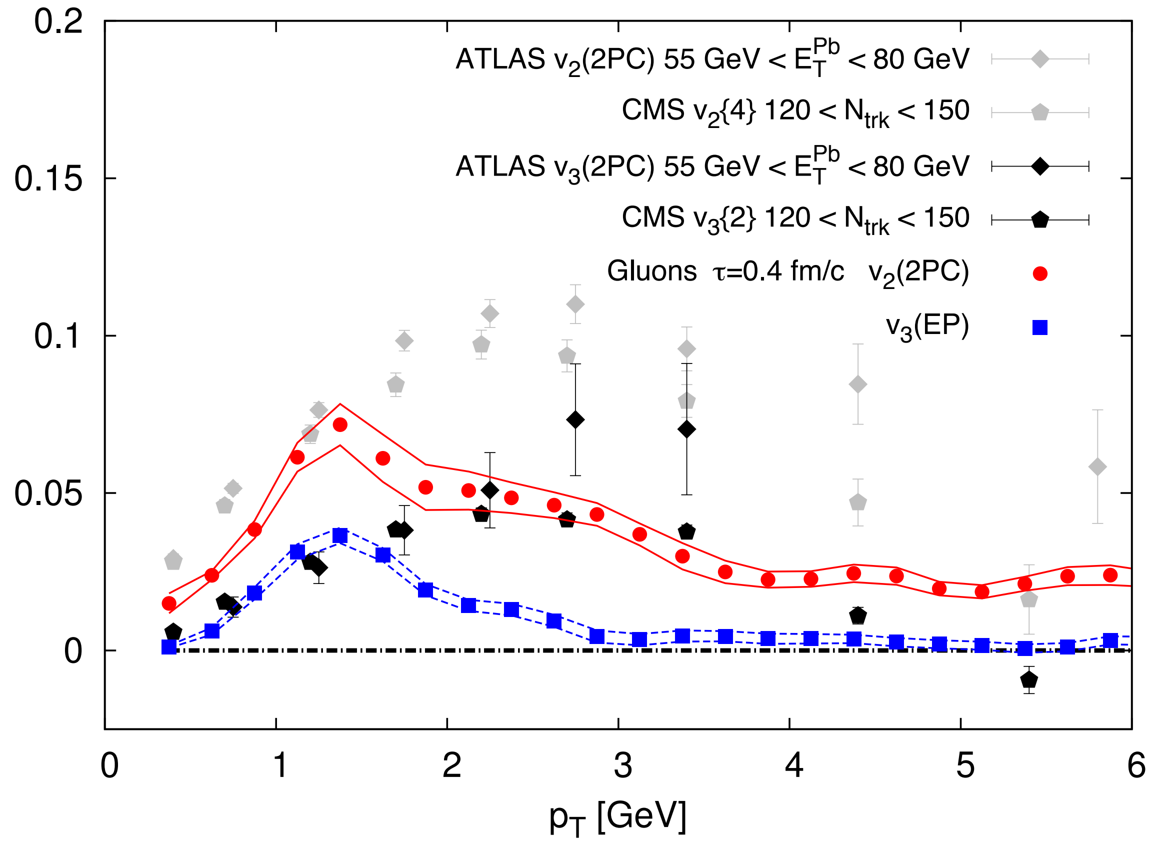
Small effect in Pb+Pb! Reason:

Gluons produced from many uncorrelated color field domains

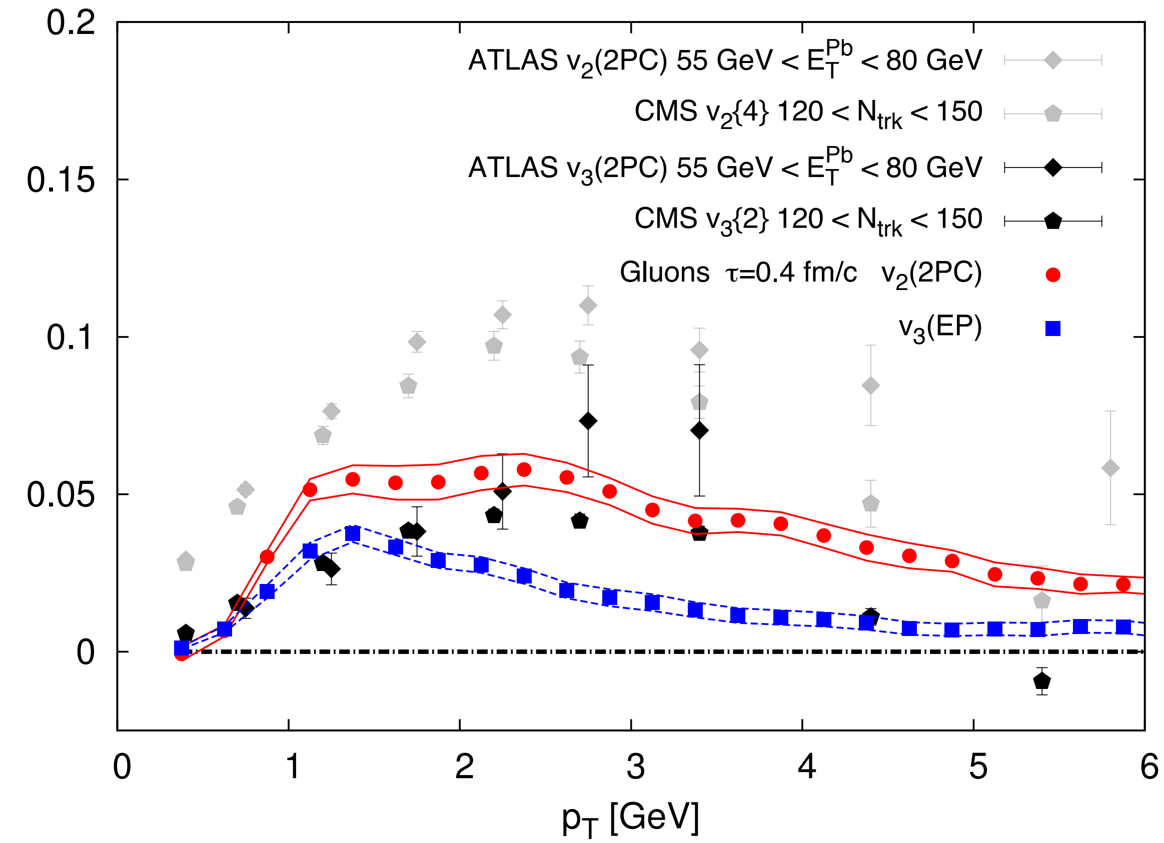
# Sensitivity to proton shape

Schenke, Schlichting, Venugopalan, arXiv:1502.01331

## Spherical proton



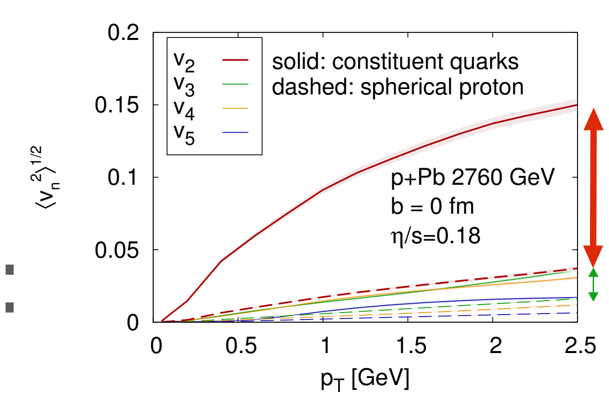

## "Eccentric proton"




Small sensitivity to structure on the scale of the proton size

Very different from hydrodynamics

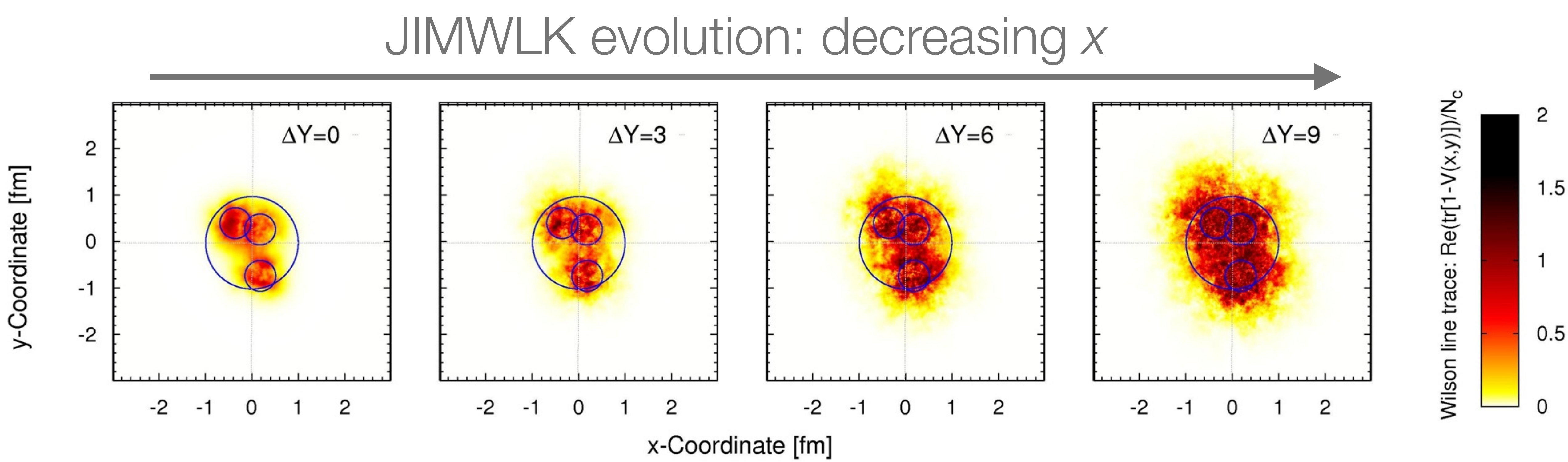
Remember hydro result:



# Are we sensitive to the shape of the proton?

S. SCHLICHTING, B. SCHENKE, PHYS. LETT. B739, 313-319 (2014)

- Three "Constituent quarks" at large x
- JIMWLK evolution with infrared regulator to get gluon distribution at smaller x




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

# Glasma graph approximation

Correlation function: $\mathbf{p}$ and $\mathbf{q}$ momenta of produced gluons

$$C(\mathbf{p},\mathbf{q}) = \left\langle \frac{dN_2}{dy_p d^2\mathbf{p}_\perp dy_q d^2\mathbf{q}_\perp} \right\rangle - \left\langle \frac{dN}{dy_p d^2\mathbf{p}_\perp} \right\rangle \left\langle \frac{dN}{dy_q d^2\mathbf{q}_\perp} \right\rangle$$

$$= \frac{\alpha_s^2}{16\pi^{10}} \frac{N_c^2 S_\perp}{(N_c^2-1)^3 \mathbf{p}_\perp^2 \mathbf{q}_\perp^2} \int d^2\mathbf{k}_\perp \times$$

$$\Big\{ \phi_{A_1}^2(y_p,\mathbf{k}_\perp)\phi_{A_2}(y_p,\mathbf{p}_\perp-\mathbf{k}_\perp)[\phi_{A_2}(y_q,\mathbf{q}_\perp+\mathbf{k}_\perp)+\phi_{A_2}(y_q,\mathbf{q}_\perp-\mathbf{k}_\perp)]$$

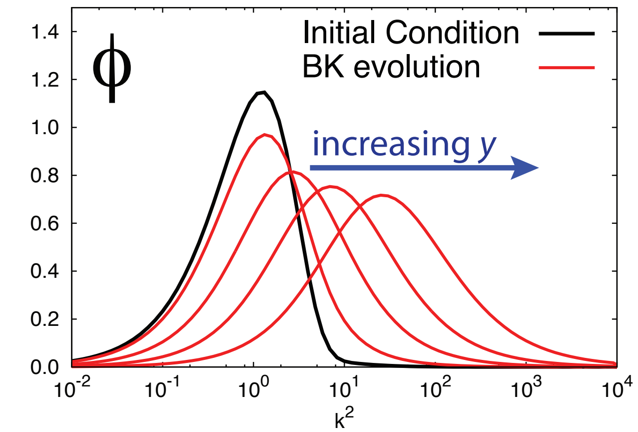
$$\phi_{A_2}^2(y_q,\mathbf{k}_\perp)\phi_{A_1}(y_p,\mathbf{p}_\perp-\mathbf{k}_\perp)[\phi_{A_1}(y_q,\mathbf{q}_\perp+\mathbf{k}_\perp)+\phi_{A_1}(y_q,\mathbf{q}_\perp-\mathbf{k}_\perp)] \Big\}$$

$\Phi$: unintegrated gluon distributions

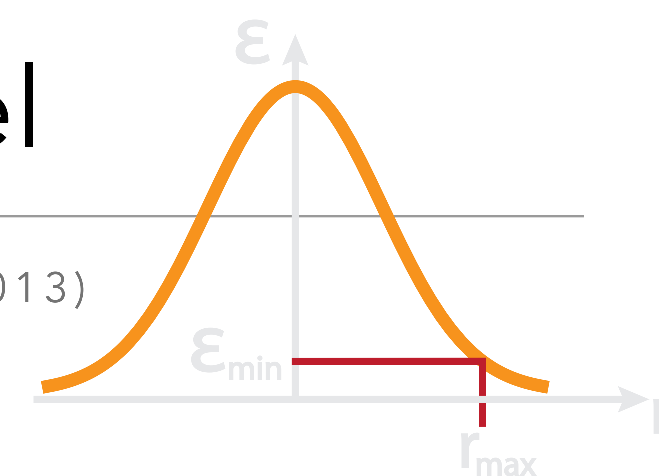
Their overlap determines the strength of the correlation

Arguments are vectors → angular dependence!

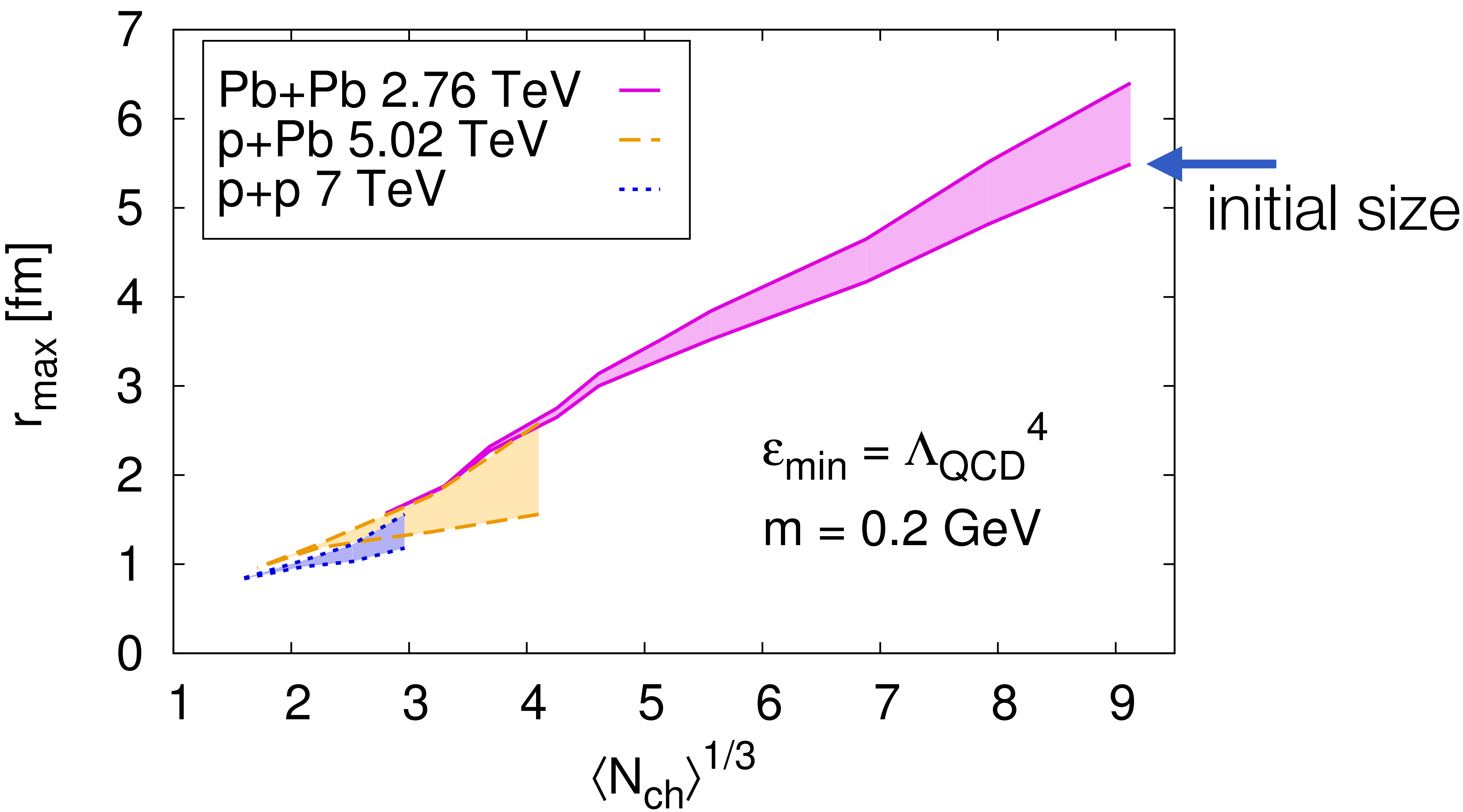
Dependence on shape of $\Phi$ at different $x$



# System Size from the IP-Glasma model



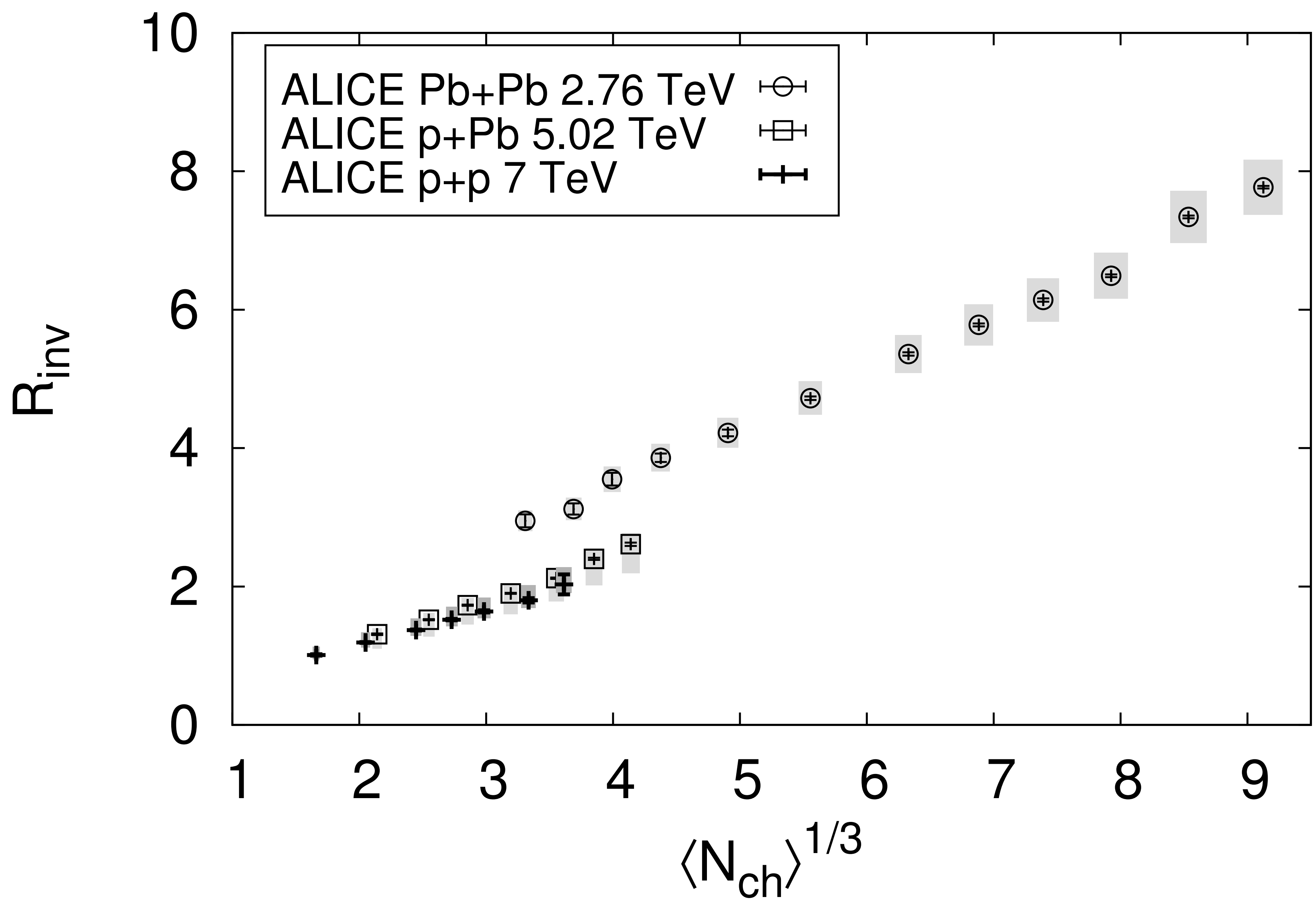

A. BZDAK, B. SCHENKE, P. TRIBEDY, R. VENUGOPALAN, PRC87, 064906 (2013)
B. SCHENKE, R. VENUGOPALAN, PHYS. REV. LETT. 113 (2014) 102301




Initial size in p+Pb closer to that in p+p than p+Pb

# System Size: Same trend seen in data

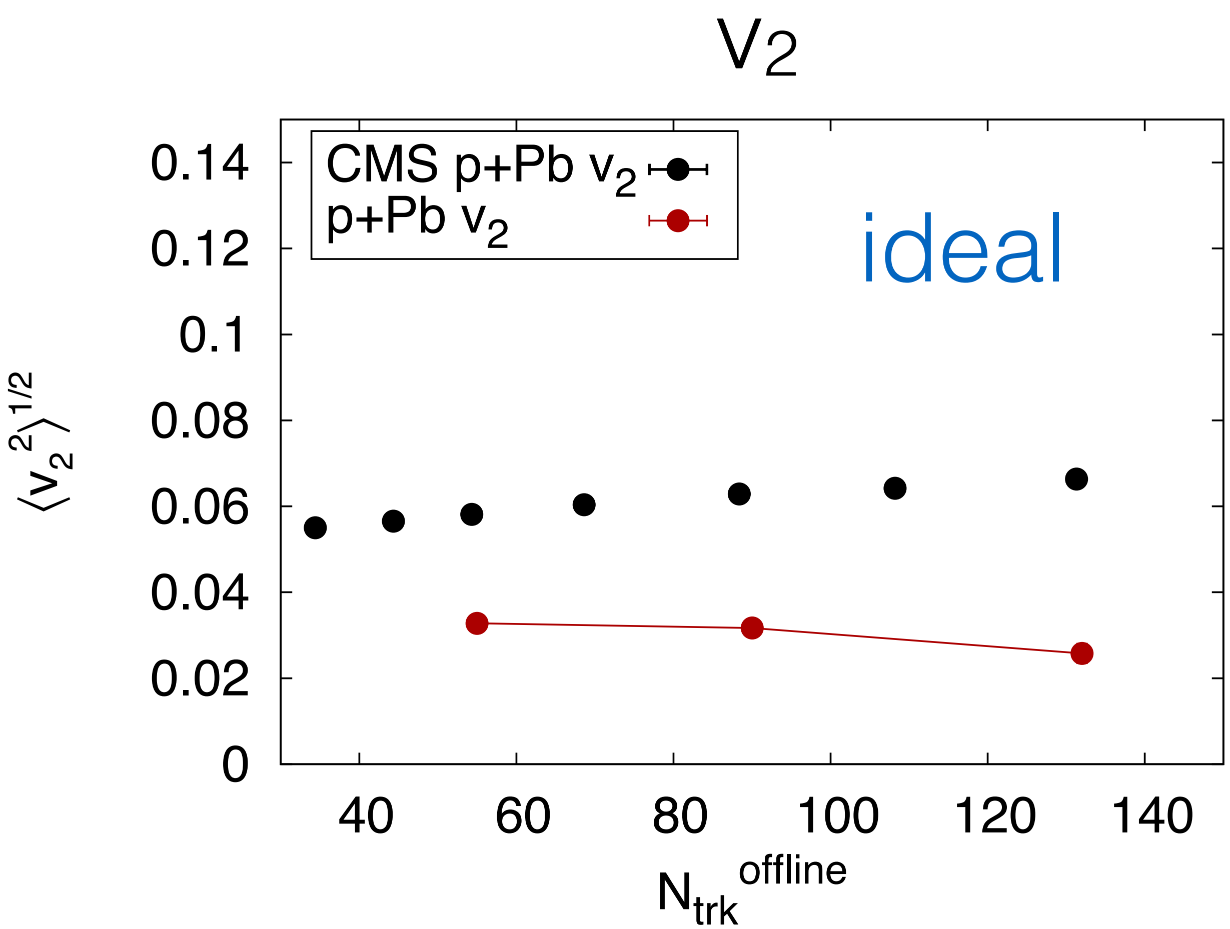
HBT DATA: ALICE COLLABORATION, PHYS.LETT. B739 (2014) 139-151

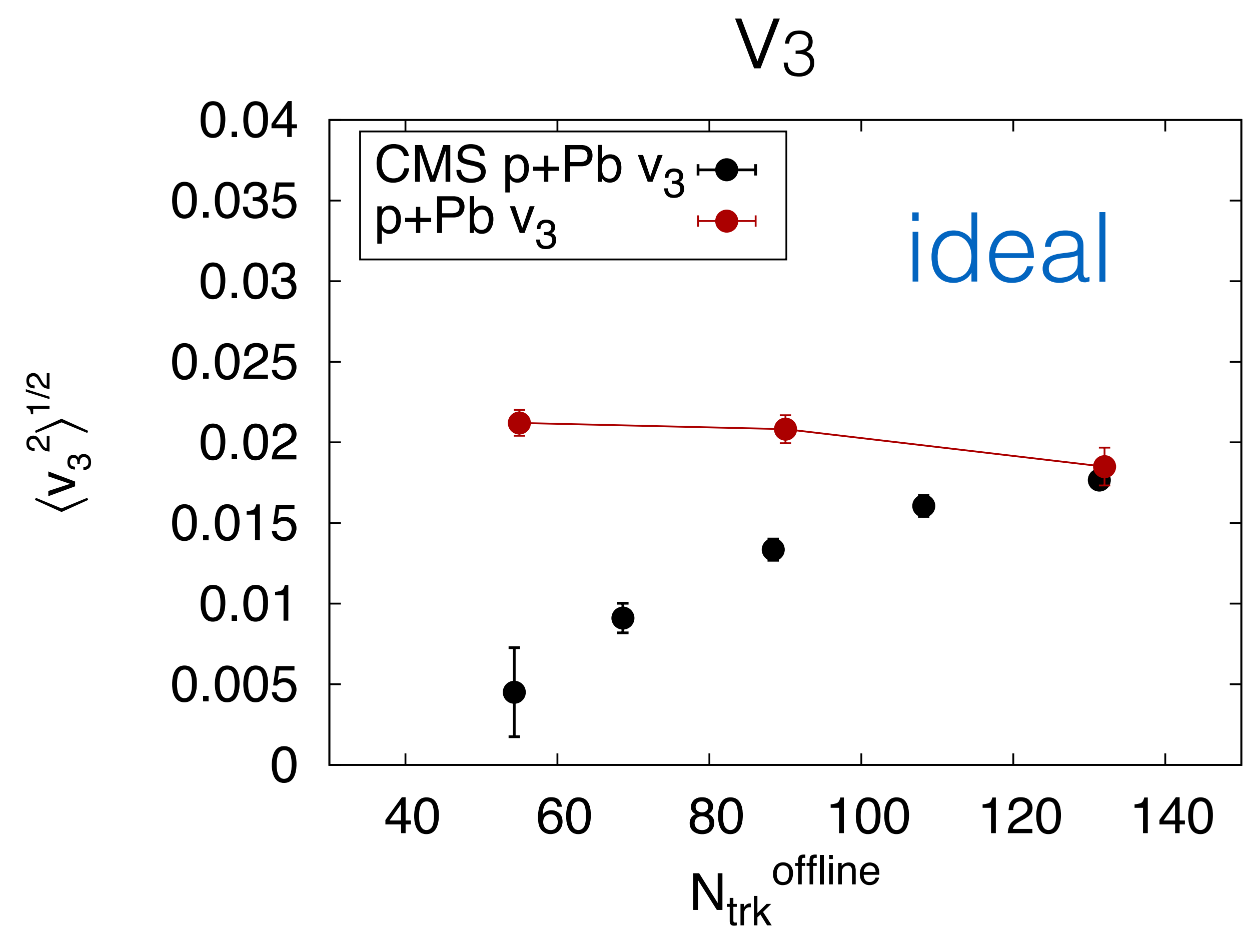



$R_{inv}$ in p+Pb closer to that in p+p than p+Pb

# Fourier Harmonics in p+Pb

CMS COLLABORATION, PHYS.LETT. B724 (2013) 213-240
B.SCHENKE, R.VENUGOPALAN, PHYS. REV. LETT. 113 (2014) 102301




Filled symbols: p+Pb

Red: IP-Glasma + MUSIC

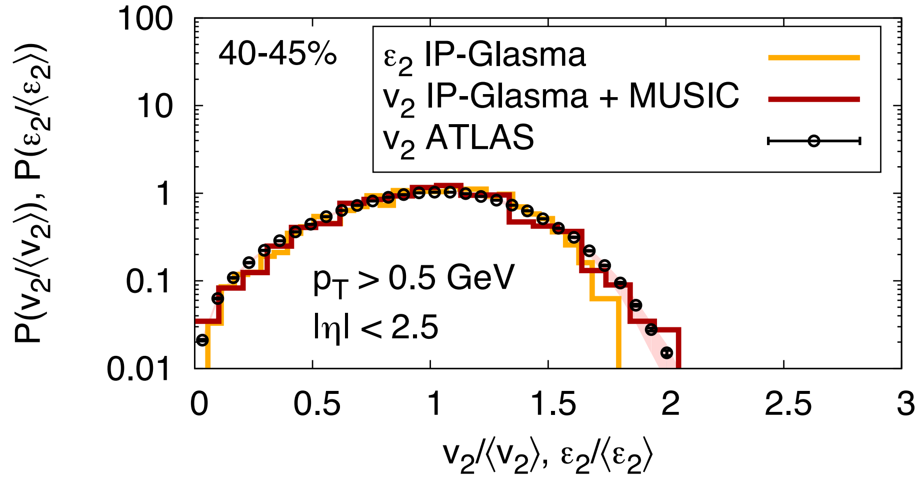
IP-Glasma + hydro does not work at all for p+Pb collisions

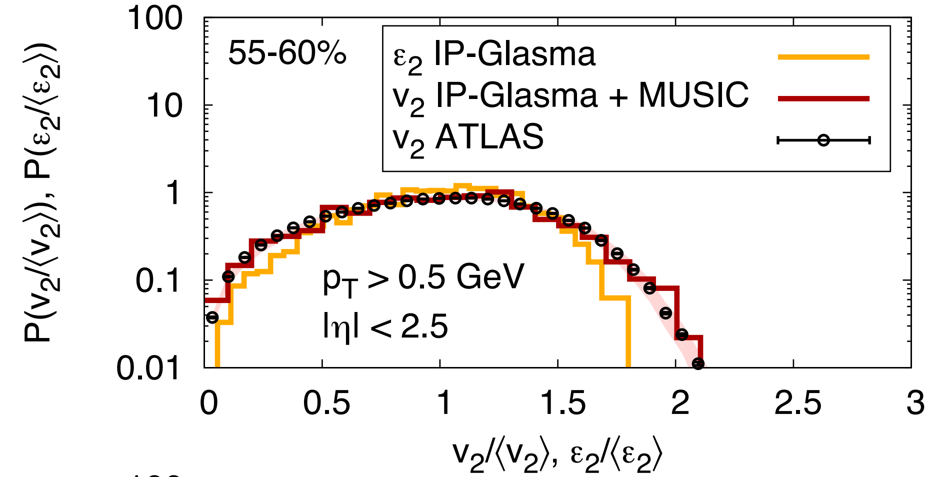
# Results in Pb+Pb collisions: Event-by-event $v_n$

ATLAS COLLABORATION, JHEP 1311 (2013) 183
B.SCHENKE, R.VENUGOPALAN, PHYS. REV. LETT. 113 (2014) 102301

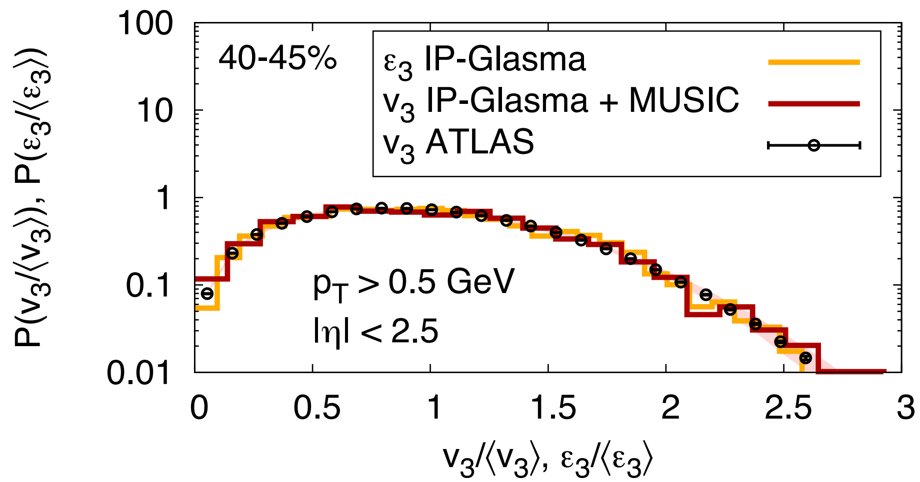
40-45% | 55-60%

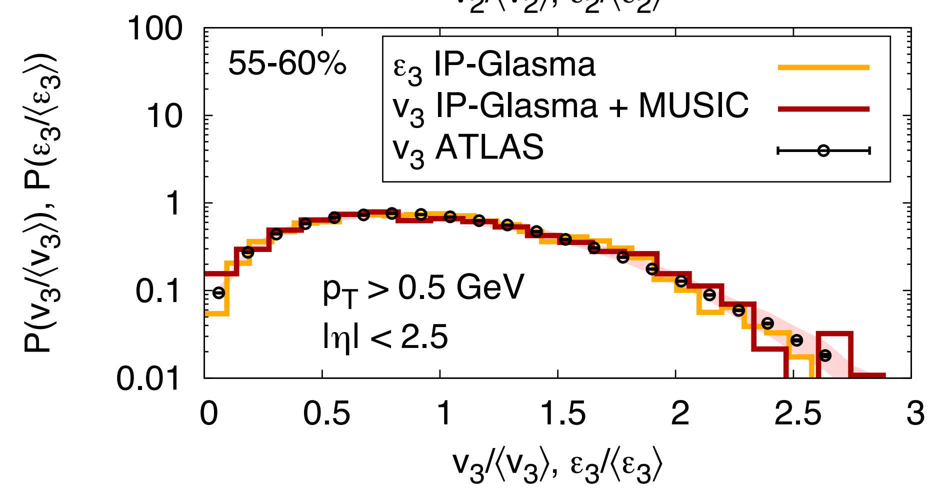
$v_2$




$v_3$




$v_4$