Fluctuations, collectivity and correlations in high-energy nuclear collisions

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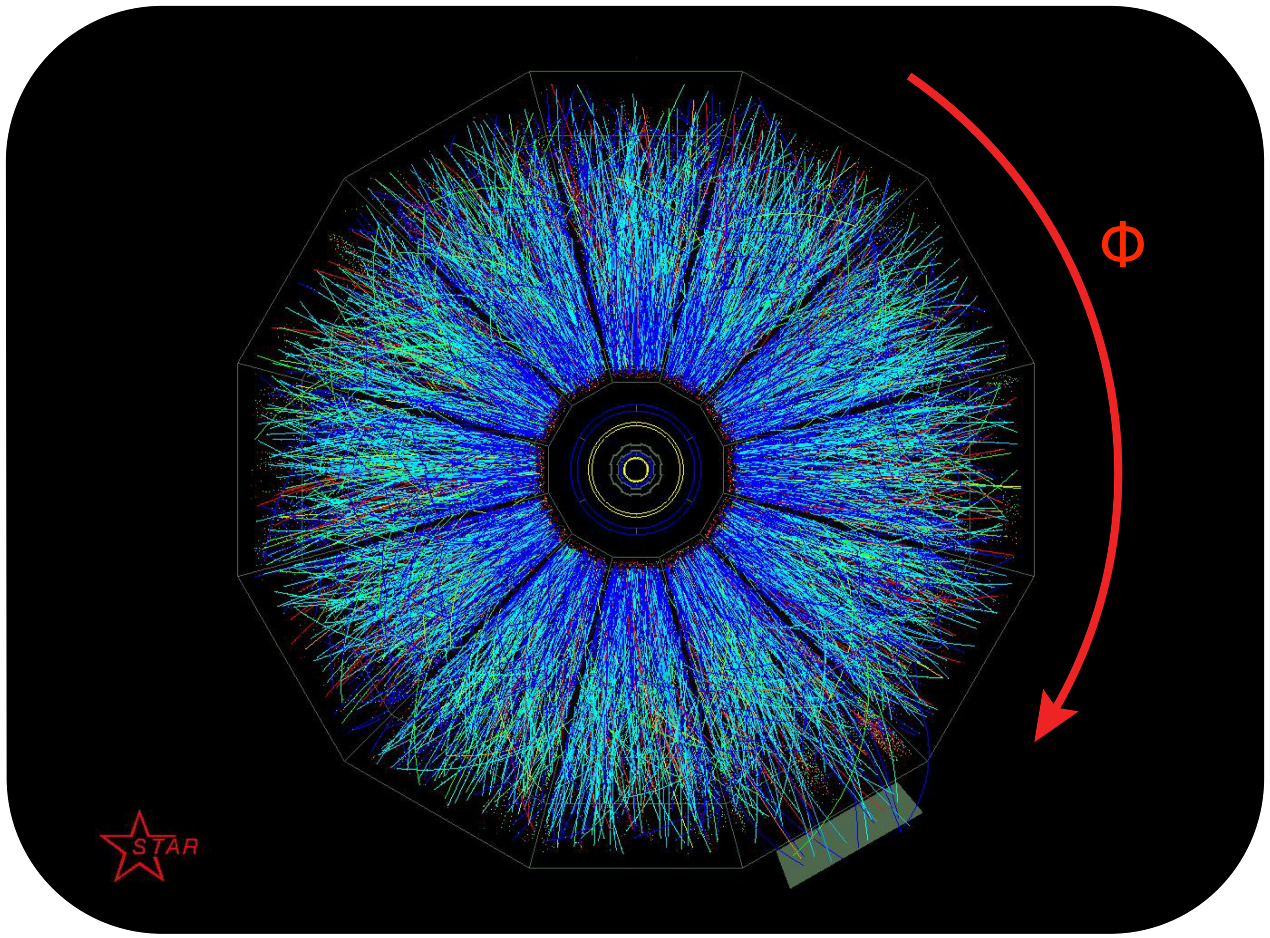
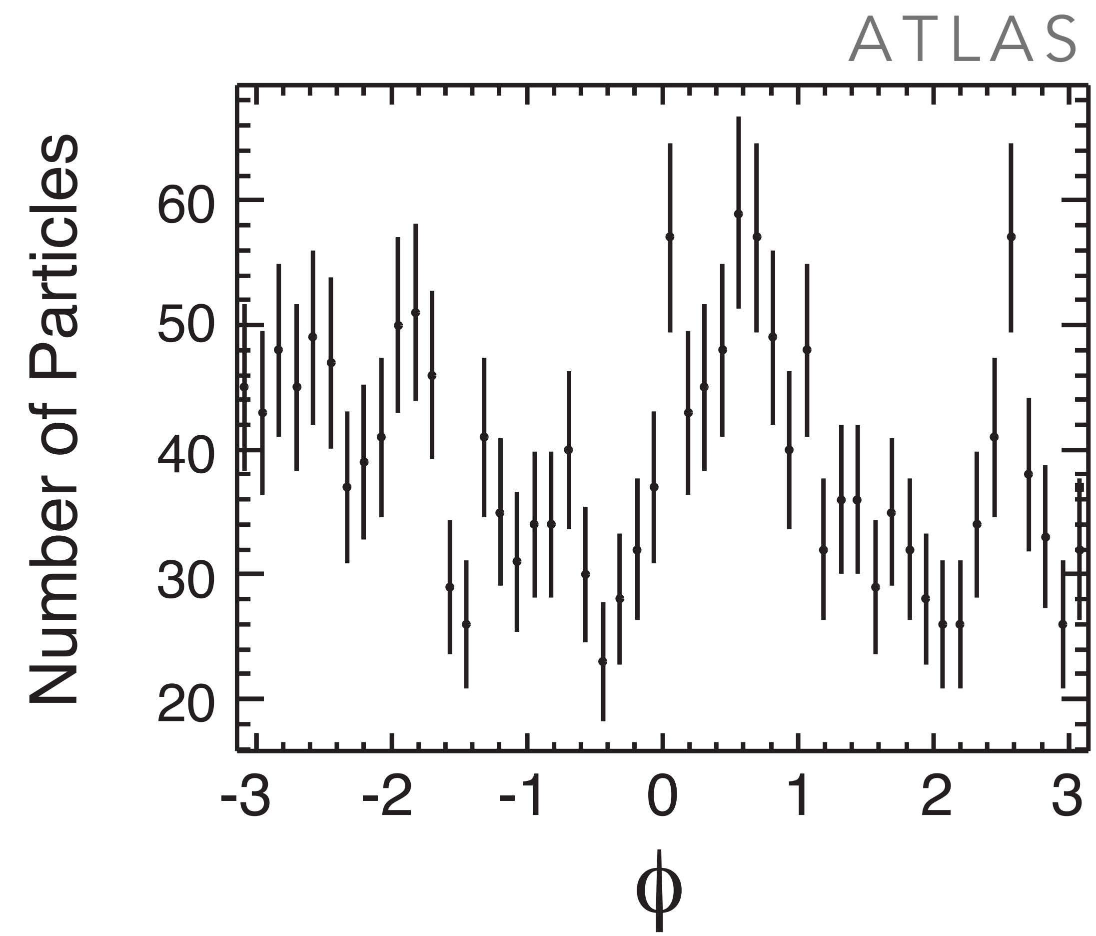
Fluid nature of nuclear matter in heavy-ion collisions

- 2005: Quark Gluon Plasma (QGP) created in Heavy Ion Collisions at RHIC behaves like a fluid
- This fluid is almost perfect
- 2007: 2+1D viscous fluid dynamics
- 2010: Fluctuations are important
- 2011: 3+1D viscous fluid dynamics + fluctuating initial conditions

How do we know we created an almost perfect fluid?

Measure the anisotropy in the transverse particle spectra





Quantify anisotropy using Fourier expansion:

$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left(1 + \sum_n 2v_n \cos(n\phi)\right)$$

How do we know we created an almost perfect fluid?

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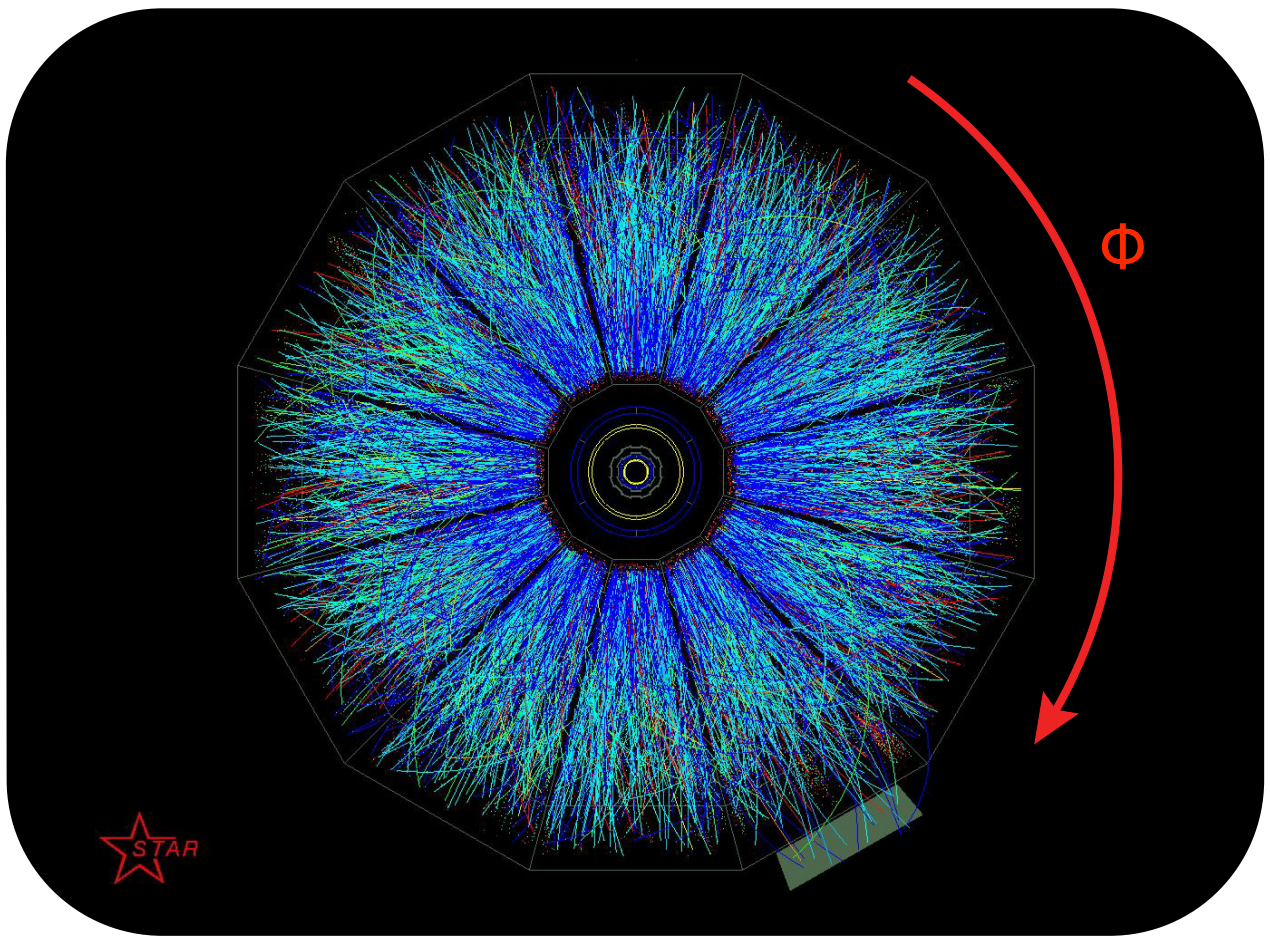
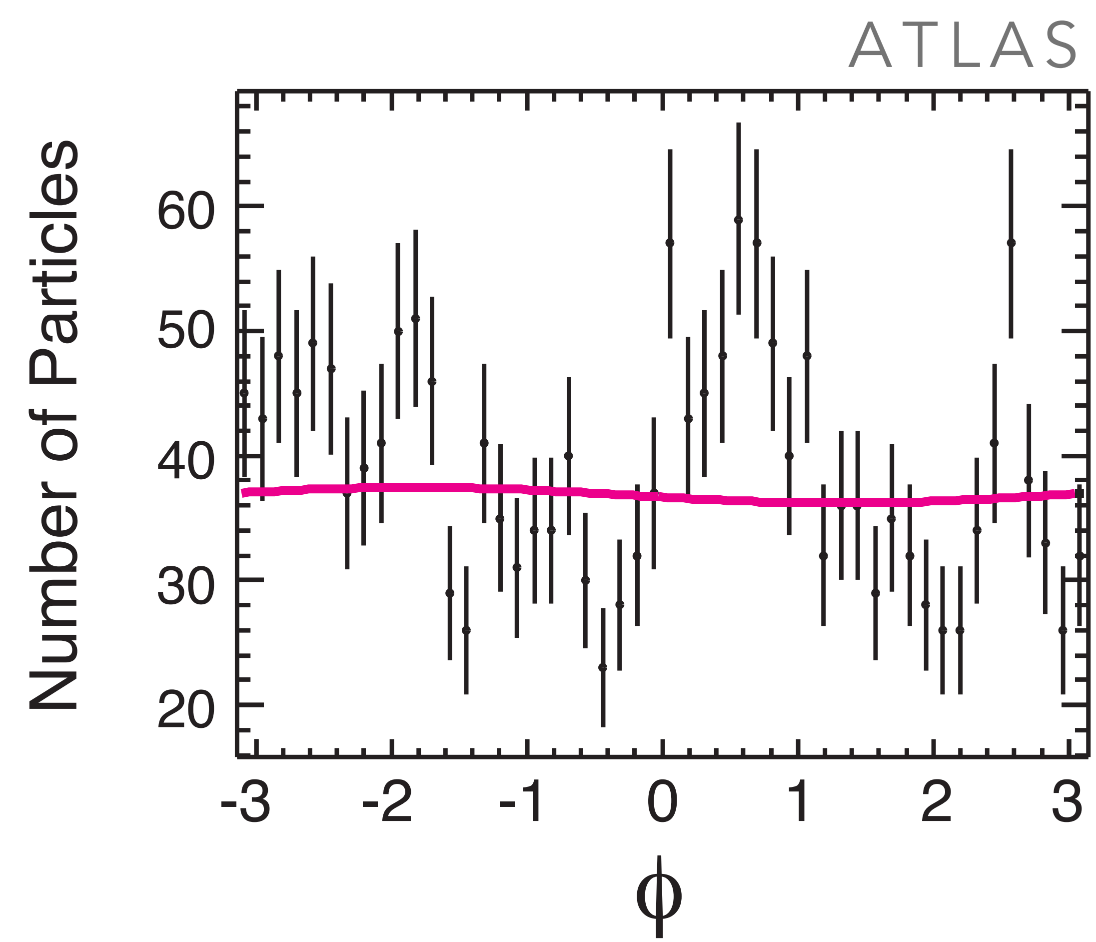


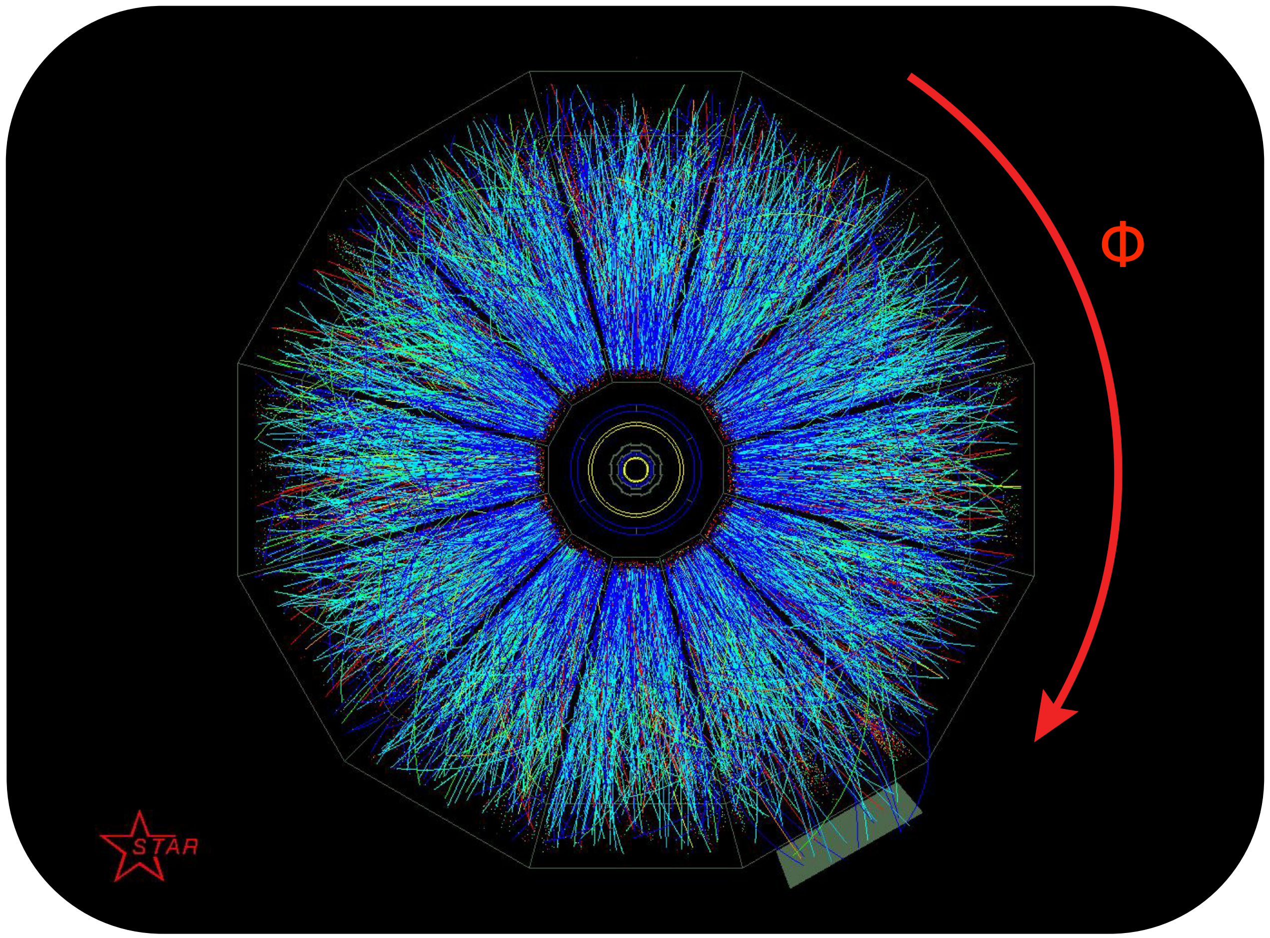


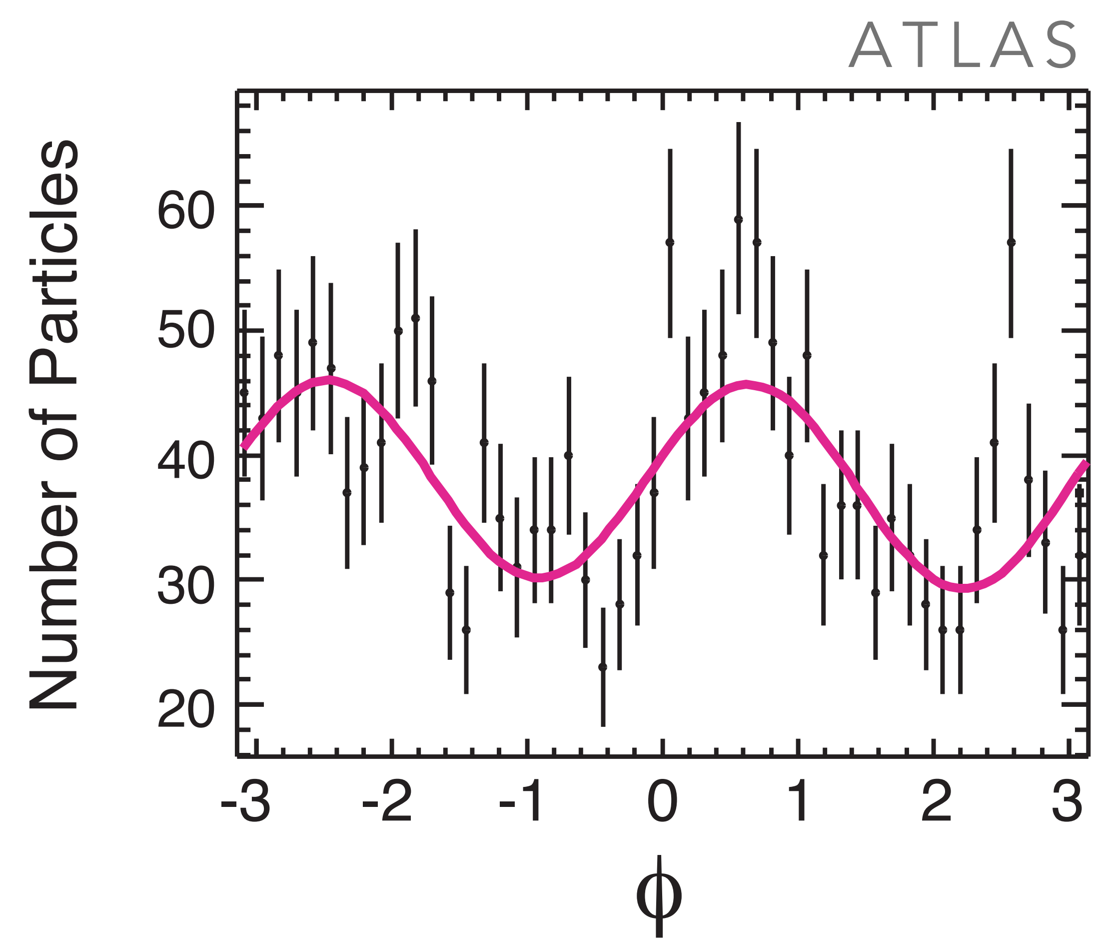
Quantify anisotropy using Fourier expansion:

$$\frac{dN}{d\phi} = \frac{N}{2\pi}\Big(1 + 2(v_1 \cos(\phi))\Big)$$

How do we know we created an almost perfect fluid?

Measure the anisotropy in the transverse particle spectra



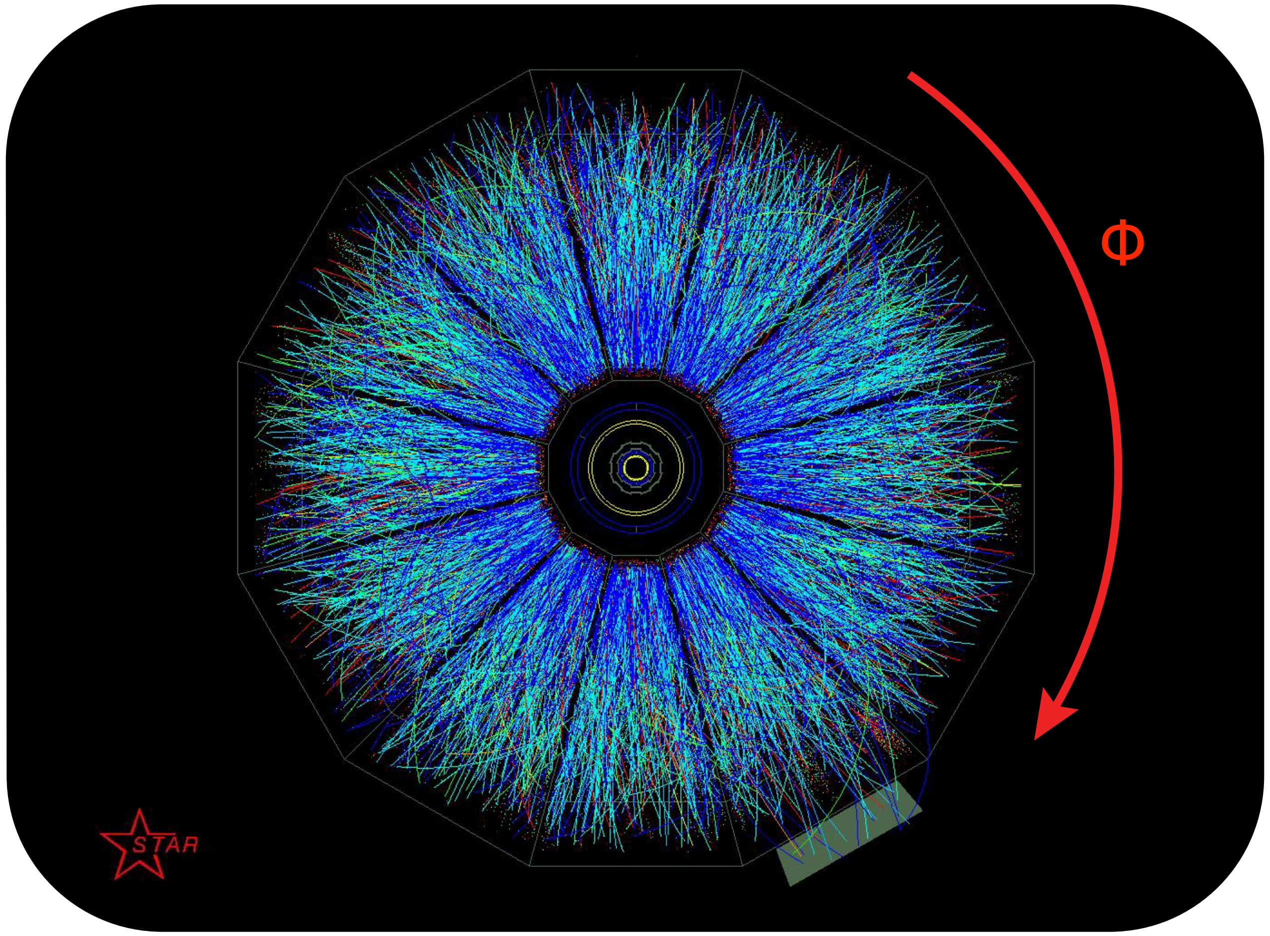


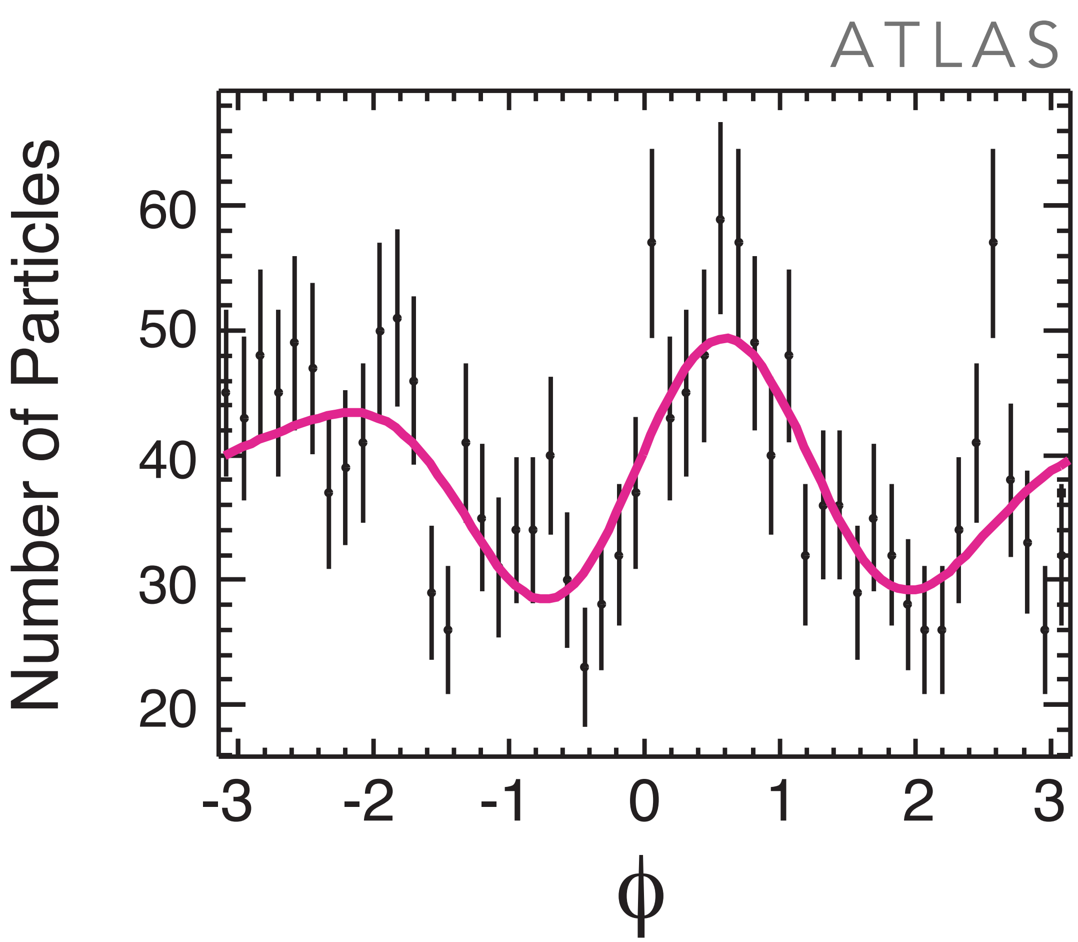
Quantify anisotropy using Fourier expansion:

$$\frac{dN}{d\phi} = \frac{N}{2\pi}\Big(1 + 2(v_1 \cos(\phi) + v_2 \cos(2\phi))\Big)$$

How do we know we created an almost perfect fluid?

Measure the anisotropy in the transverse particle spectra



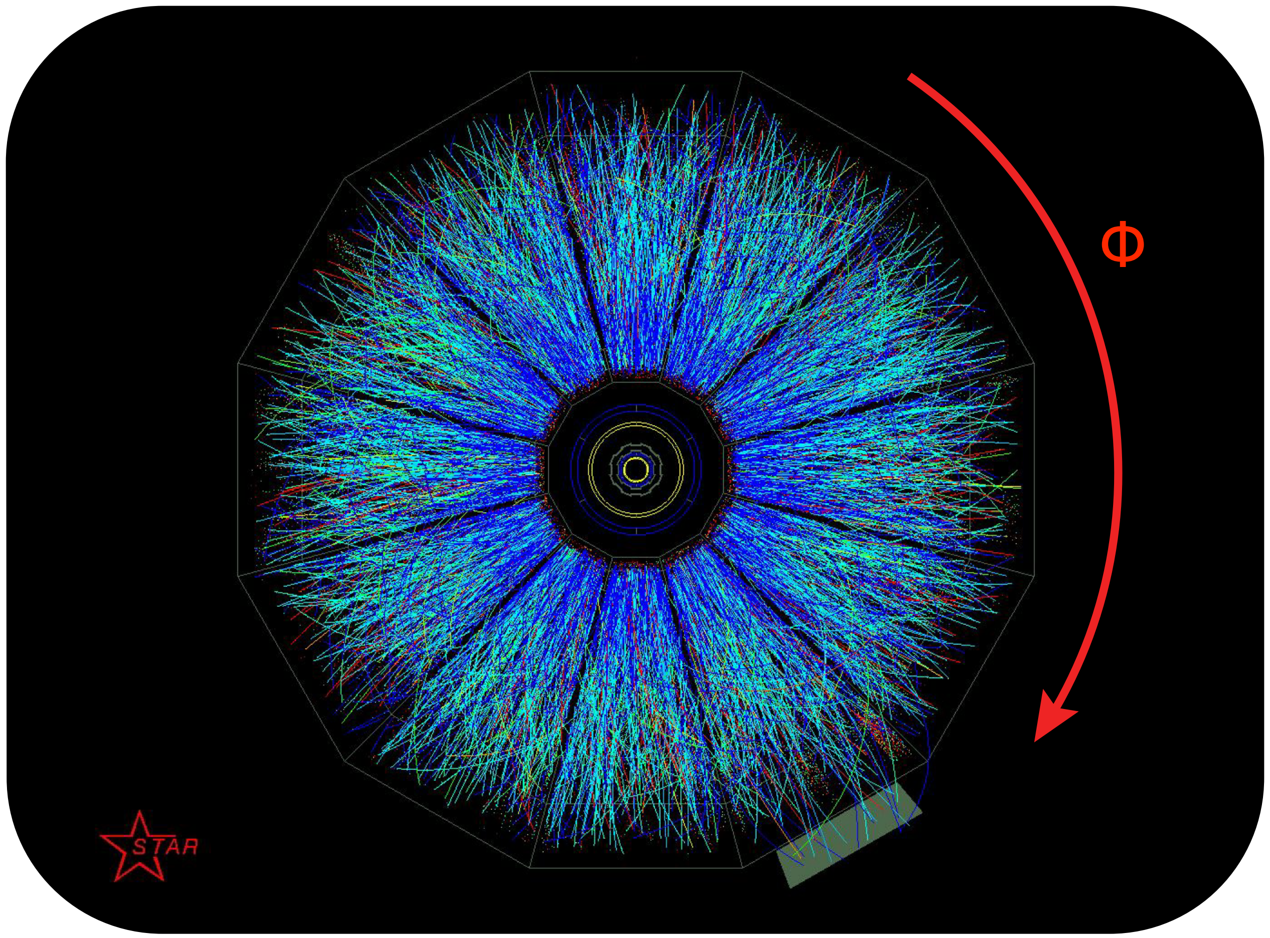


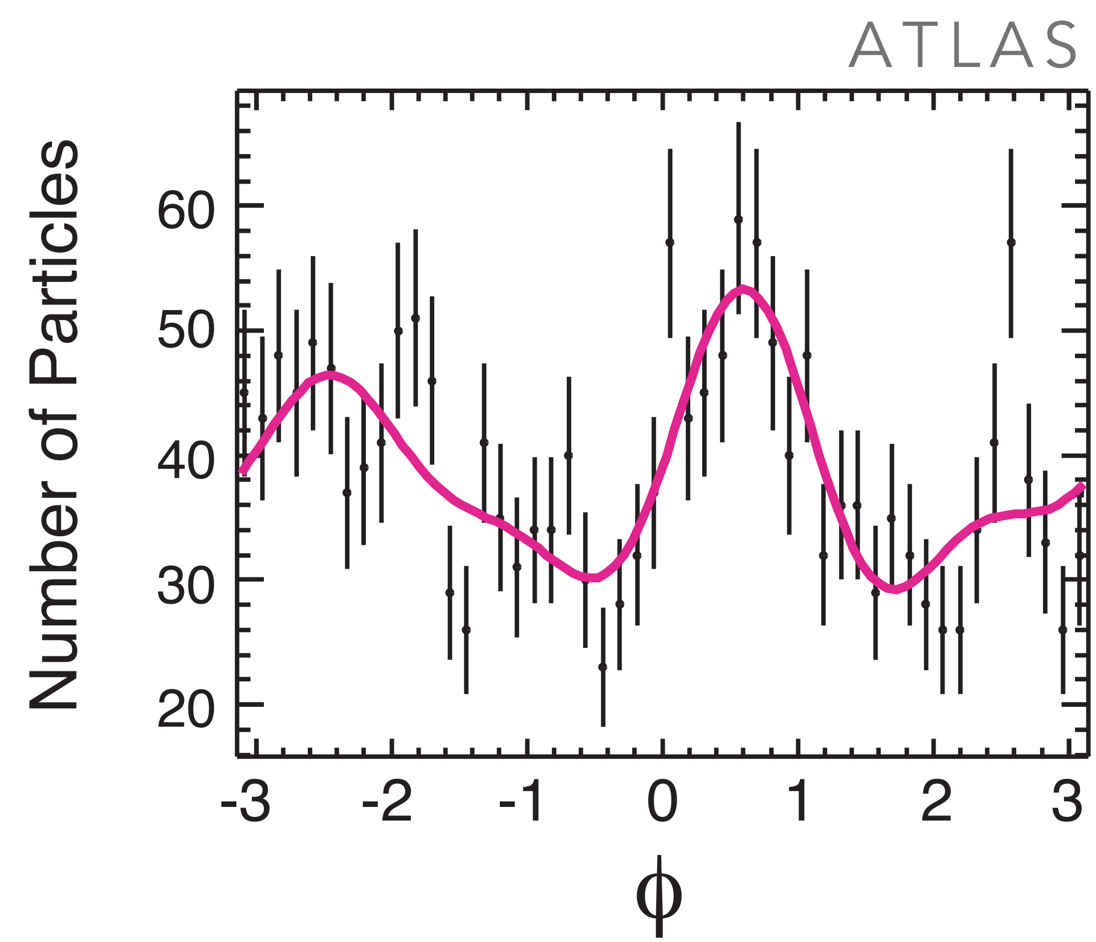
Quantify anisotropy using Fourier expansion:

$$\frac{dN}{d\phi} = \frac{N}{2\pi}\Big(1 + 2(v_1 \cos(\phi) + v_2 \cos(2\phi) + v_3 \cos(3\phi))\Big)$$

How do we know we created an almost perfect fluid?

Measure the anisotropy in the transverse particle spectra



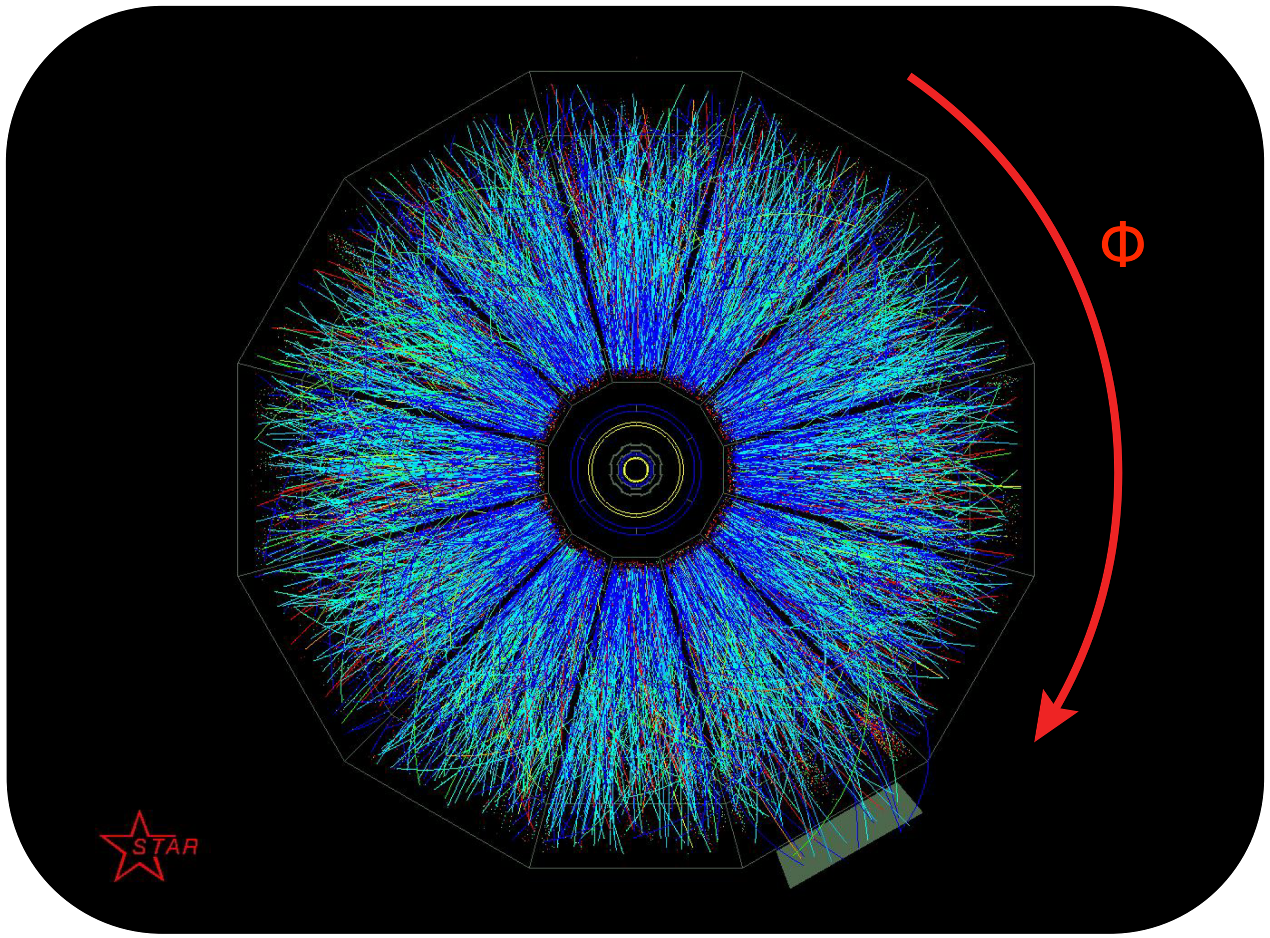


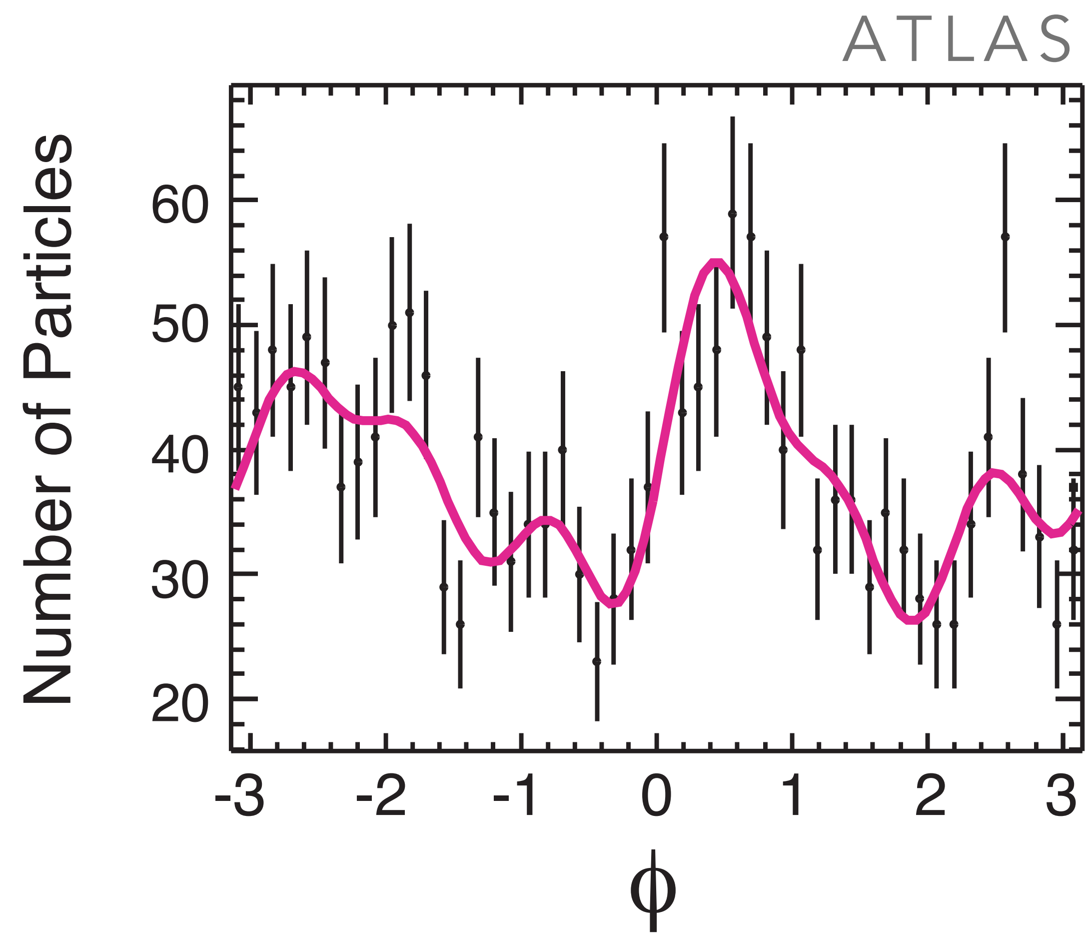
Quantify anisotropy using Fourier expansion:

$$\frac{dN}{d\phi} = \frac{N}{2\pi}\Big(1 + 2(v_1 \cos(\phi) + v_2 \cos(2\phi) + v_3 \cos(3\phi) + v_4 \cos(4\phi))\Big)$$

How do we know we created an almost perfect fluid?

Measure the anisotropy in the transverse particle spectra



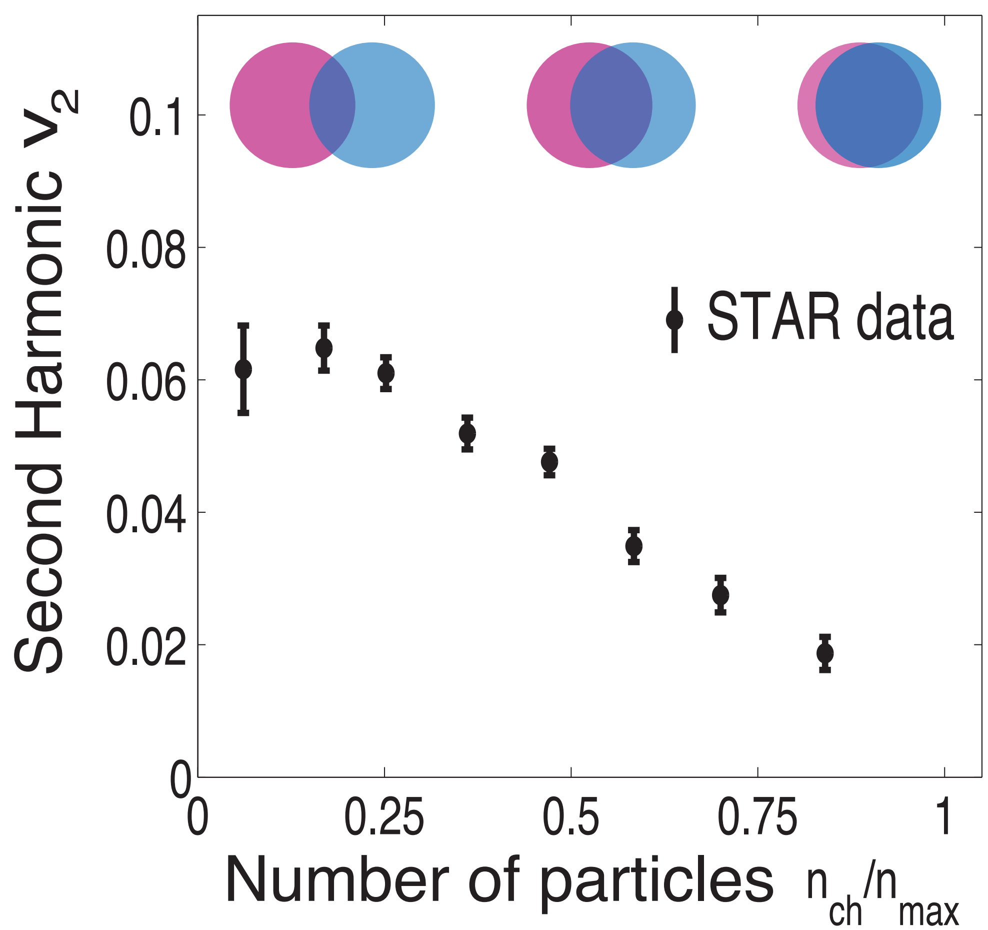


Quantify anisotropy using Fourier expansion:

$$\frac{dN}{d\phi} = \frac{N}{2\pi}\Big(1 + 2(v_1 \cos(\phi) + v_2 \cos(2\phi) + v_3 \cos(3\phi) + v_4 \cos(4\phi) + \ldots)\Big)$$

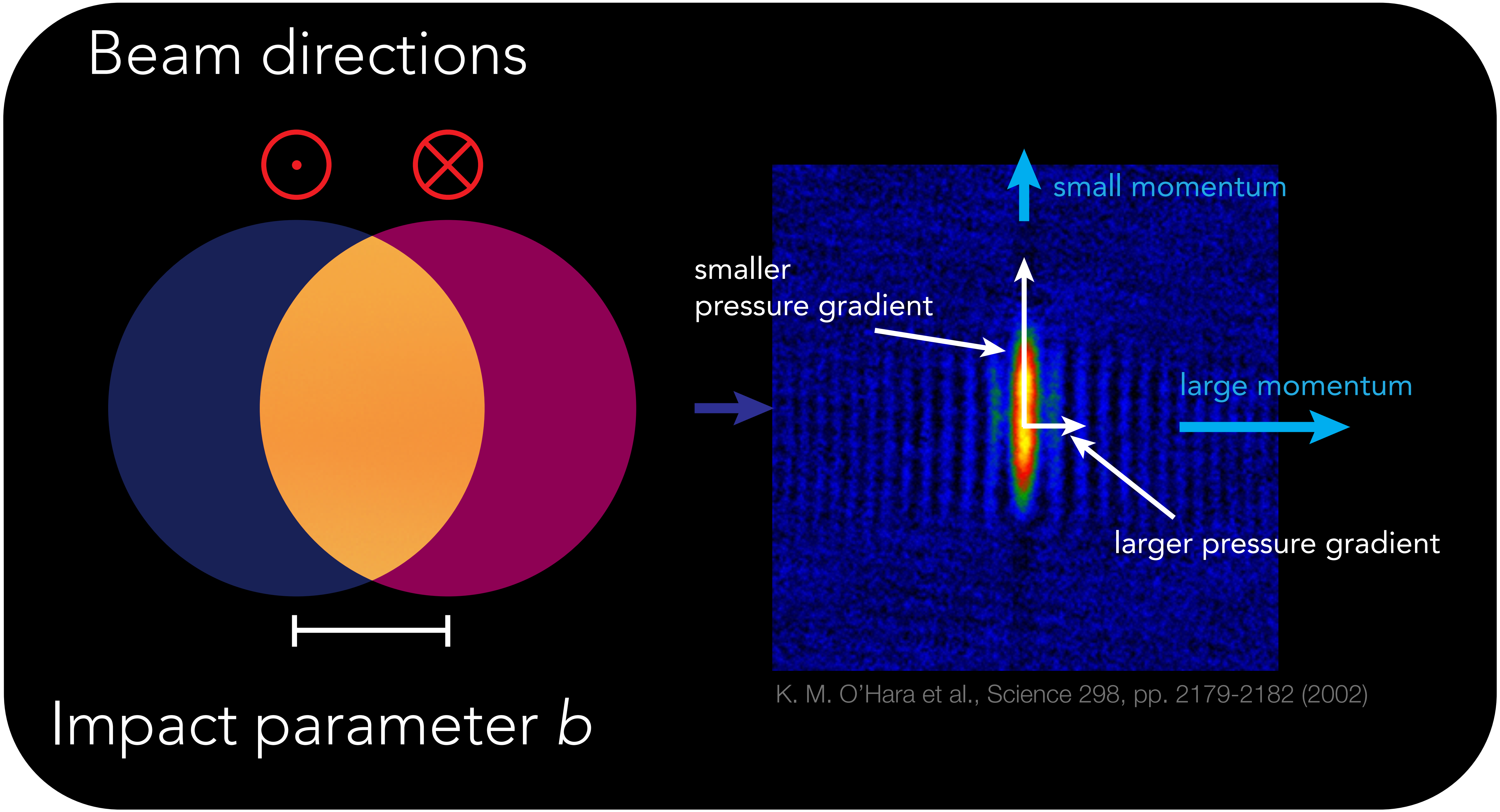
How do we know we created an almost perfect fluid?

- v_n coefficients of charged hadrons are large - in particular v_2
- value of v_2 is (anti-)correlated with the total number of particles via the collision geometry



- large v_2 means it is almost as large as it can be when generated by the response of the system to the initial geometry:
  Ideal fluid dynamics reproduces data quite well

Fluid dynamic expansion of the medium



Cheating of course: Animation is an ultra cold quantum gas

Relativistic viscous fluid dynamics (Israel-Stewart - IS)

- 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 $\Pi^{\mu\nu}$ (shear viscosity η only)

$$\Delta^\mu_\alpha \Delta^\nu_\beta (u \cdot \partial) \Pi^{\alpha\beta} = -\frac{1}{\tau_\pi}(\Pi^{\mu\nu} - S^{\mu\nu}) - \frac{4}{3}(\partial \cdot u)\Pi^{\mu\nu}$$

with $S^{\mu\nu} = \eta\left(\nabla^\mu u^\nu + \nabla^\nu u^\mu - \frac{2}{3}\Delta^{\mu\nu}(\partial \cdot u)\right)$

$\Delta^{\mu\nu} = g^{\mu\nu} - u^\mu u^\nu$ and $\nabla^\mu = \Delta^{\mu\nu}\partial_\nu$ $\qquad$ τ_π: relaxation time

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

Derivation from the Boltzmann equation (DNMR)

- Identifying the microscopic time scales of the Boltzmann equation, consider only the slowest
- Truncate EoMs for dissipative quantities according to power-counting in Knudsen and inverse Reynolds #
- Includes bulk viscous pressure, shear-stress tensor, and all couplings

$$\dot{\Pi} + \frac{\Pi}{\tau_\Pi} = -\beta_\Pi \theta - \delta_{\Pi\Pi}\Pi\theta + \varphi_1 \Pi^2 + \lambda_{\Pi\pi}\pi^{\mu\nu}\sigma_{\mu\nu} + \varphi_3 \pi^{\mu\nu}\pi_{\mu\nu} \ ,$$

$$\dot{\pi}^{\langle\mu\nu\rangle} + \frac{\pi^{\mu\nu}}{\tau_\pi} = 2\beta_\pi \sigma^{\mu\nu} + 2\pi_\alpha^{\langle\mu}\omega^{\nu\rangle\alpha} - \delta_{\pi\pi}\pi^{\mu\nu}\theta + \varphi_7 \pi_\alpha^{\langle\mu}\pi^{\nu\rangle\alpha} - \tau_{\pi\pi}\pi_\alpha^{\langle\mu}\sigma^{\nu\rangle\alpha} + \lambda_{\pi\Pi}\Pi\sigma^{\mu\nu} + \varphi_6 \Pi\pi^{\mu\nu} .$$

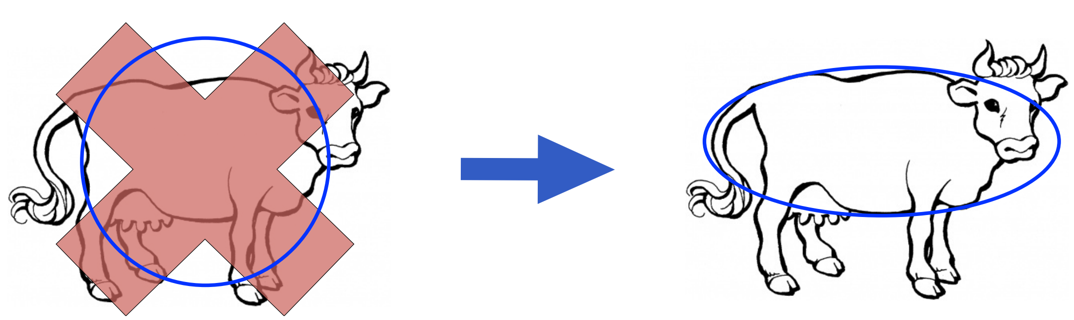
Denicol, Niemi, Molnar, Rischke, Phys.Rev. D85 (2012) 114047

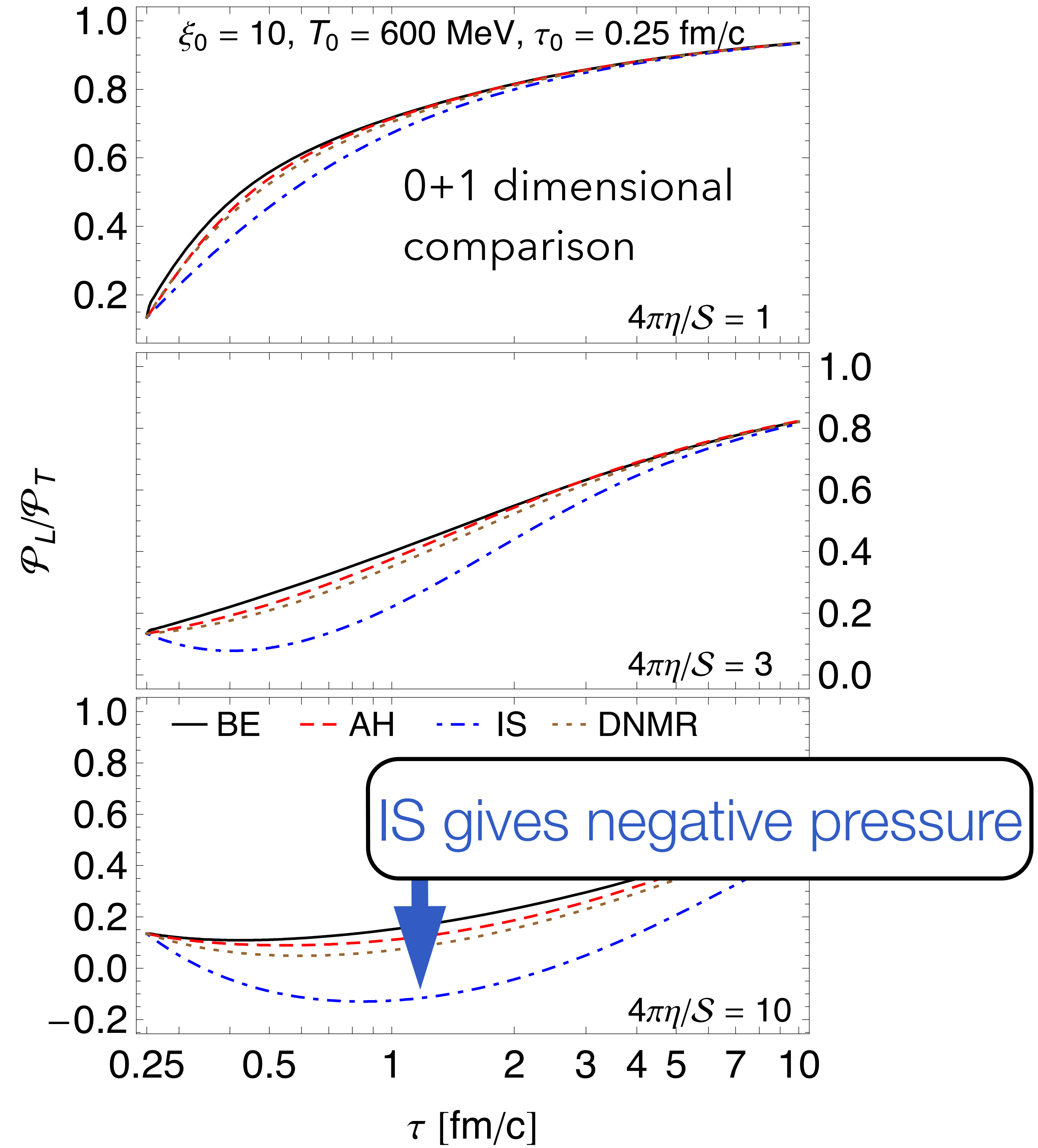
Anisotropic hydrodynamics (AH)

- At early times the system in heavy ion collisions can be very anisotropic because of the longitudinal expansion

- Expansion not around the local thermal distribution but around an anisotropic distribution

$$f(\tau, x, p) = f_{aniso}(p, \underbrace{\Lambda(\tau, x)}_{T_T}, \underbrace{\xi(\tau, x)}_{\text{anisotropy}}) + \delta\tilde{f}$$





Florkowski, Ryblewski, Strickland, Nuclear Physics A 916, 249 (2013)

Comparing with exact radially expanding solutions

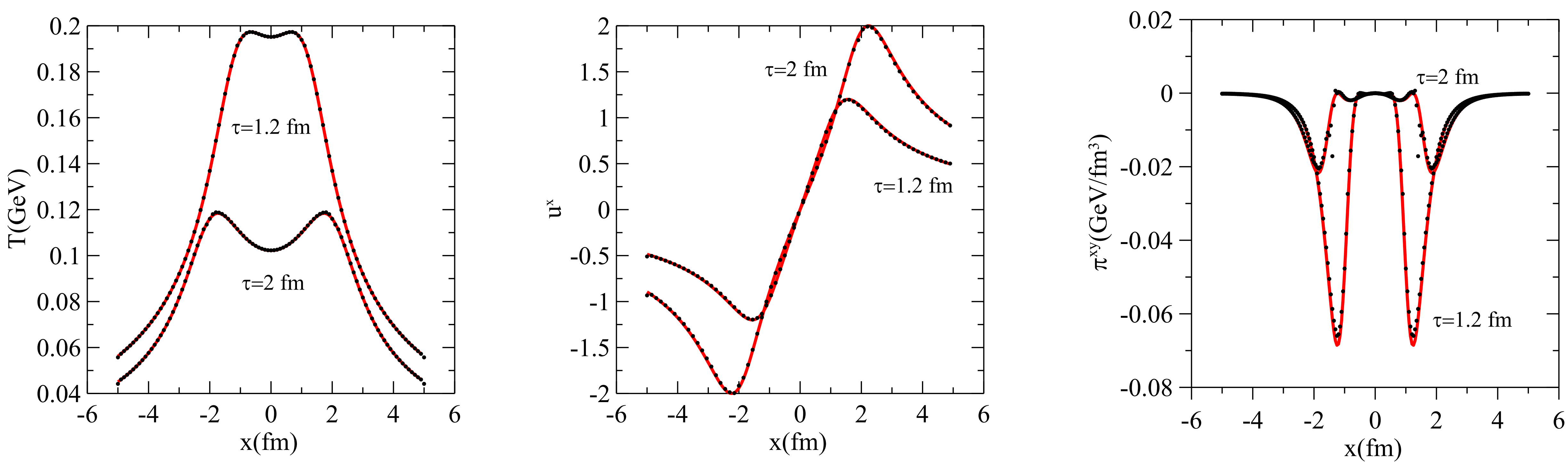
Marrochio, Noronha, Denicol, Luzum, Jeon, Gale, arXiv:1307.6130

- Use radially-expanding explicit solutions of the Israel-Stewart formulation of hydrodynamics by Gubser

  S. S. Gubser, Phys. Rev. D 82, 085027 (2010); S. S. Gubser and A. Yarom, Nucl. Phys. B 846, 469 (2011)

  Extension of Bjorken solution with radial expansion

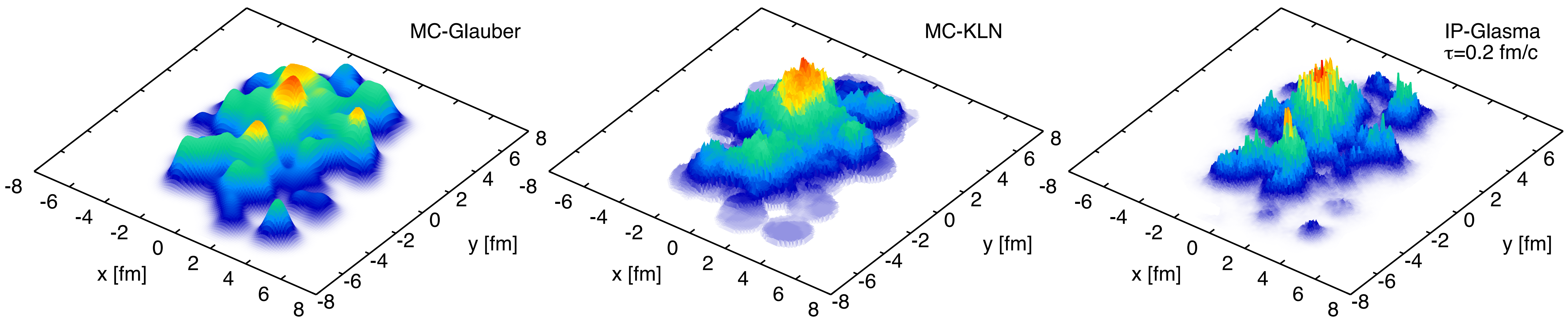
  Flow velocity is determined by symmetry constraints



Red lines: MUSIC (IS-FORMULATION) Black dots: semi-analytic

Initial conditions

- Models need to provide input for fluid dynamic simulations: initial energy density, flow velocities, shear stress tensor
- Initial conditions fluctuate from event to event
- Main source of fluctuations: nucleon positions
- Different models give different *energy density distributions*



C. Gale, S. Jeon, B. Schenke, Int.J.Mod.Phys. A28 (2013) 1340011

MC-Glauber model

SEE MILLER, REYGERS, SANDERS, STEINBERG, ANN. REV. NUCL. PART. SCI. 57, 205 (2007)

- Sample nucleon positions - e.g. from Woods-Saxon distribution - possibly including NN correlations
- Determine wounded nucleons using NN cross section (either black disk or with Gaussian probability)
- Assign energy density or entropy density to wounded nucleons and/or binary collisions
- To describe multiplicity distributions negative binomial fluctuations need to be included
- Model has problems describing v_n-distributions

RENK AND NIEMI, PHYS.REV. C89 (2014) 064907

MC-KLN model

H. J. DRESCHER AND Y. NARA, PHYS. REV. C75, 034905 (2007); PHYS.REV. C76, 041903 (2007)

- k_T-factorization
- $$\frac{dN}{d^2 r_T dy} \sim \int \frac{d^2 p_T}{p_T^2} \int d^2 k_T P_A P_B \phi(T_A/P_A)\phi(T_B/P_B)$$

  P_A : probability to find at least one nucleon at a given transverse coordinate in nucleus A
  T_A : nuclear thickness function
  ϕ : unintegrated gluon distribution

- fKLN: ϕ_A does not depend on properties of B as in KLN also has the right limit at the edge: ϕ of one nucleon

MC-KLN model

H. J. DRESCHER AND Y. NARA, PHYS. REV. C75, 034905 (2007); PHYS.REV. C76, 041903 (2007)

- valid only for $p_T \gtrsim Q_s$ because multiple scatterings are omitted
- is a better approximation in p+A than in A+A
- as in MC-Glauber, there are no negative binomial multiplicity fluctuations
  they were added in DUMITRU, NARA, PHYS.REV. C85 (2012) 034907
- does not describe v_2 and v_3 simultaneously
  QIU, SHEN, HEINZ, PHYS.LETT. B707 (2012) 151-155

IP-Glasma model

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

- IP-Sat model parametrizes $Q_s(x, \mathbf{b})$
  simple way to include impact parameter dependence
  KOWALSKI, TEANEY, PHYS.REV. D68 (2003) 114005
- Fit parameters to HERA diffractive data
  REZAEIAN, SIDDIKOV, VAN DE KLUNDERT, VENUGOPALAN, PHYS.REV. D87 (2013) 3, 034002
- One could do full JIMWLK evolution
  - pros: will include correlations + flucts. in rapidity
    cons: many uncertainties (running coupling, lattice effects, infrared problems …)

IP-Glasma model

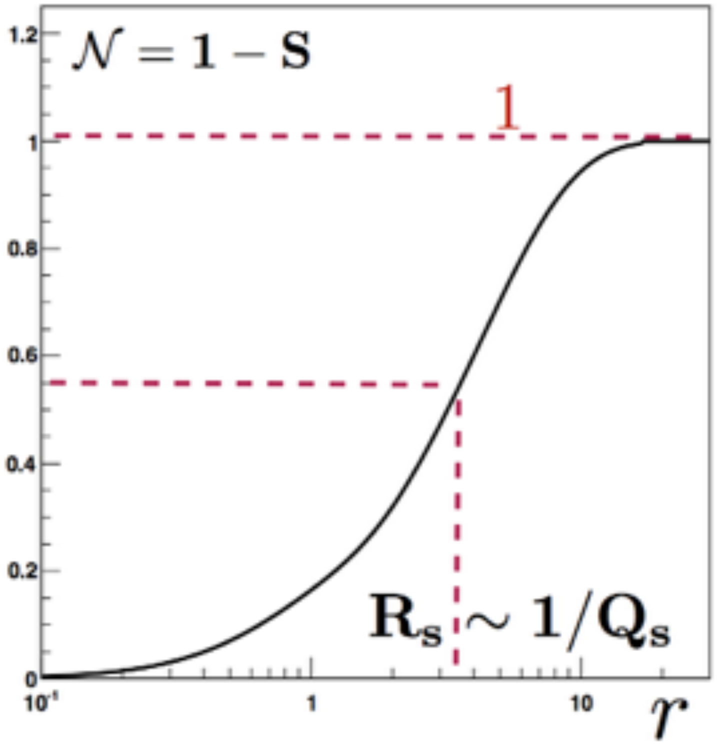
B.SCHENKE, P.TRIBEDY, R.VENUGOPALAN, PRL108, 252301 (2012), PRC86, 034908 (2012)

- Sample nucleon positions from Woods-Saxon distribution
- Add all (Gaussian) thickness functions

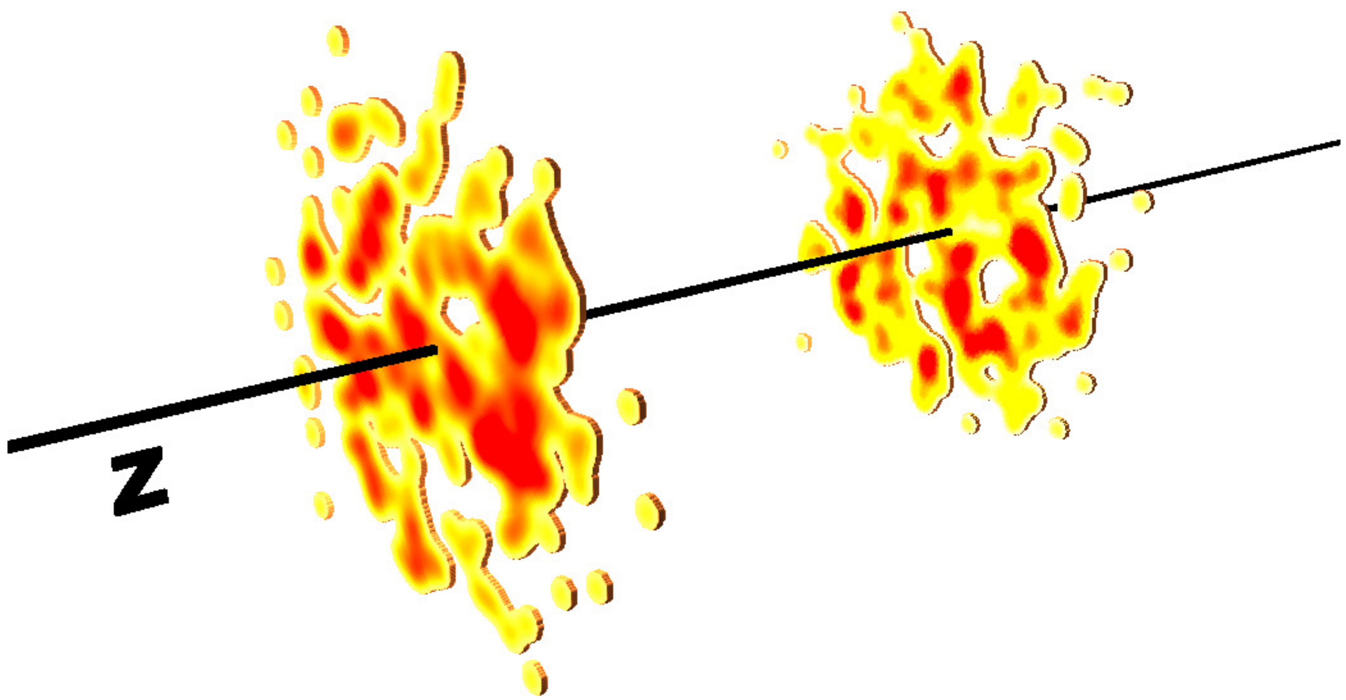
IP-SAT MODEL

$$\frac{d\sigma^p_{\rm dip}}{d^2\mathbf{x}_T}(\mathbf{r}_T, x, \mathbf{x}_T) = 2\mathcal{N}(\mathbf{r}_T, x, \mathbf{x}_T) = 2\left[1 - \exp\left(-\frac{\pi^2}{2N_c}\mathbf{r}_T^2\alpha_s(Q^2)xg(x,Q^2)\sum_{i=1}^{A} T_p(\mathbf{x}_T - \mathbf{x}_T^i)\right)\right]$$

- Extract $Q_s(x, \mathbf{x}_T)$



- Obtain color charge density distributions $g^2\mu \propto Q_s$

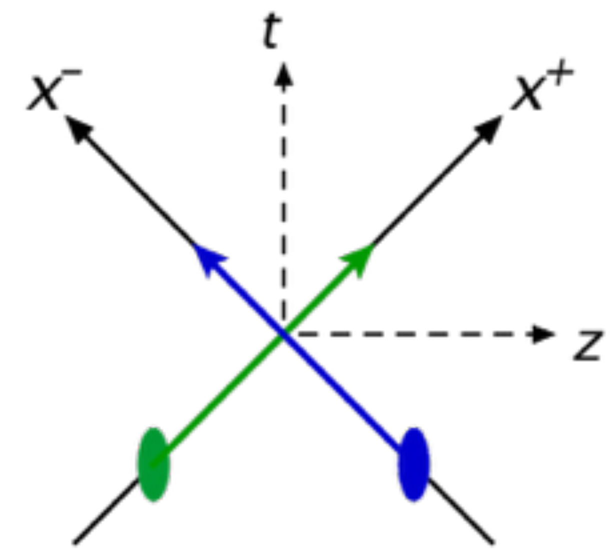


Classical gluon fields before the collision

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

Sample color charges $\rho_{(1,2)}(x^{\pm}, \mathbf{x}_T)$ from Gaussian dist.

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



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

Solution in covariant gauge:

$$A^{+}_{(1,2)\mathrm{cov}}(x^-, \mathbf{x}_T) = -\frac{g\rho_{(1,2)}(x^-, \mathbf{x}_T)}{\boldsymbol{\nabla}_T^2 + m^2}$$

$m \sim \Lambda_{\mathrm{QCD}}$

Solution in lightcone gauge:

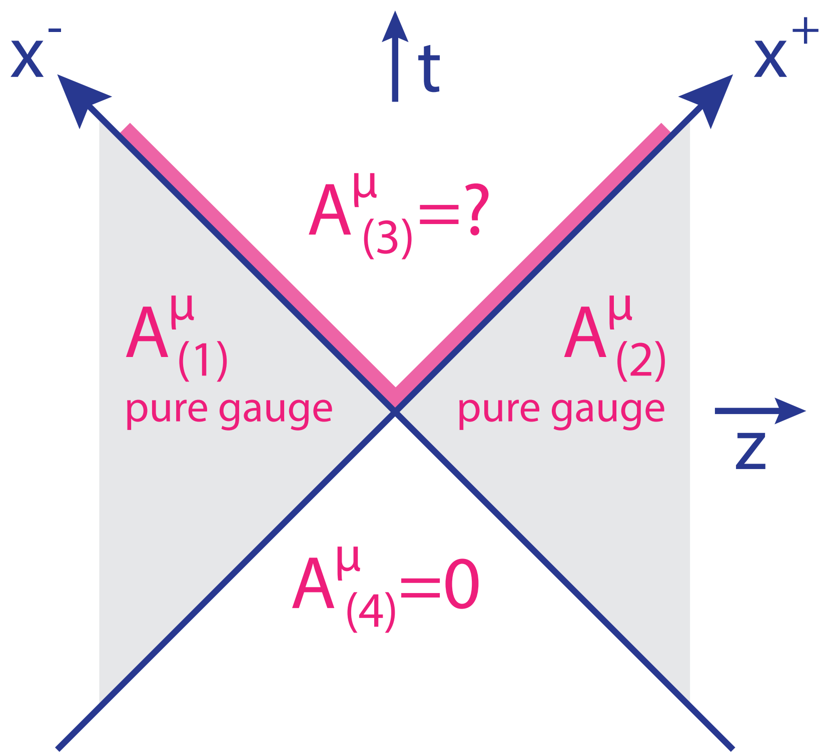
$$A^{+}_{(1,2)}(\mathbf{x}_T) = A^{-}_{(1,2)}(\mathbf{x}_T) = 0$$

$$A^{i}_{(1,2)}(\mathbf{x}_T) = \frac{i}{g} V_{(1,2)}(\mathbf{x}_T)\partial_i V^{\dagger}_{(1,2)}(\mathbf{x}_T)$$

V : Wilson line

Gauge fields after the collision

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



CONFIGURATION IN SCHWINGER GAUGE

Solution:

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

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

We solve for the gauge fields numerically

KRASNITZ, VENUGOPALAN, NUCL.PHYS. B557 (1999) 237

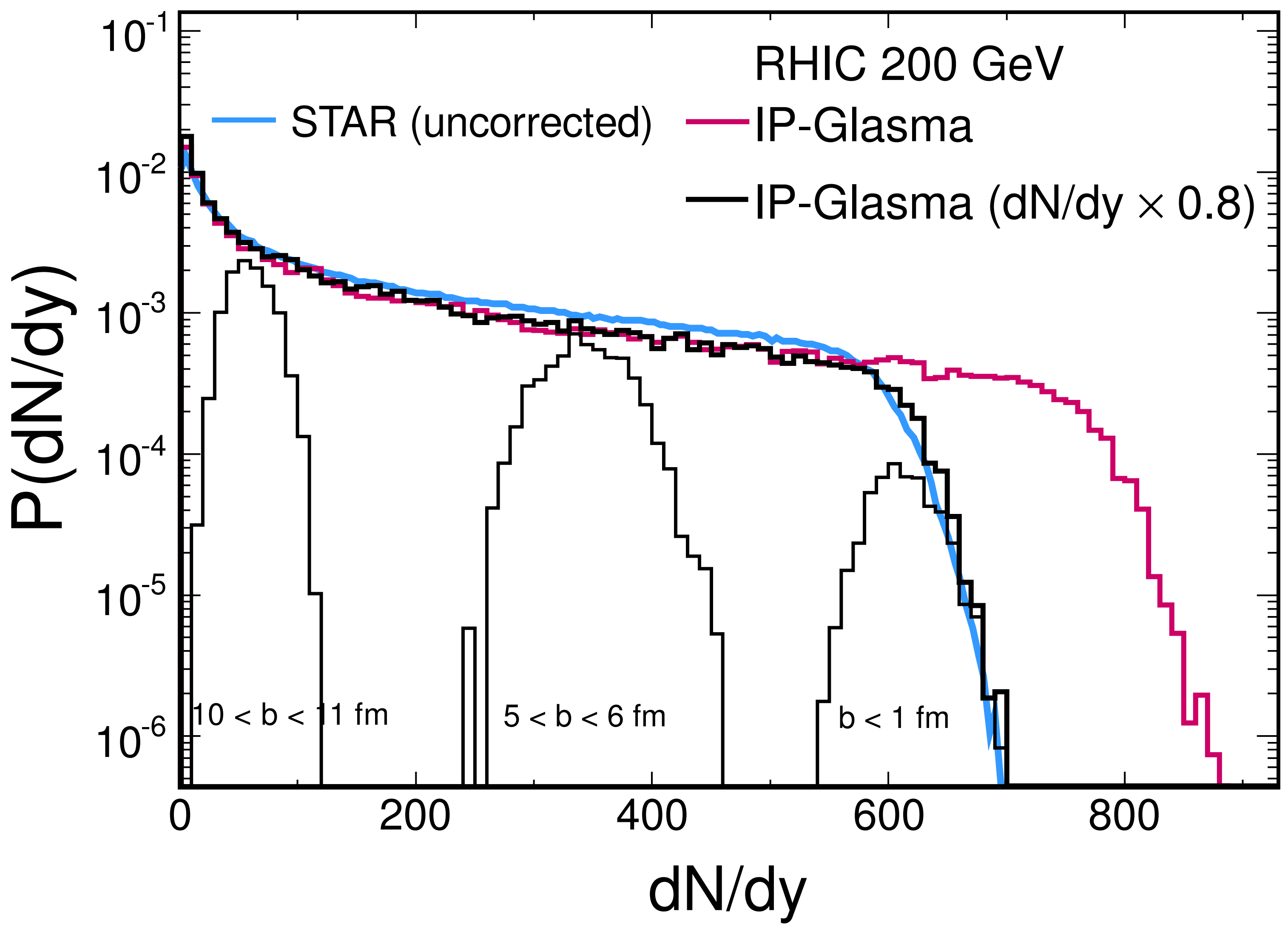
Leeds to boost-invariant solution

Time evolution follows free Yang-Mills equations

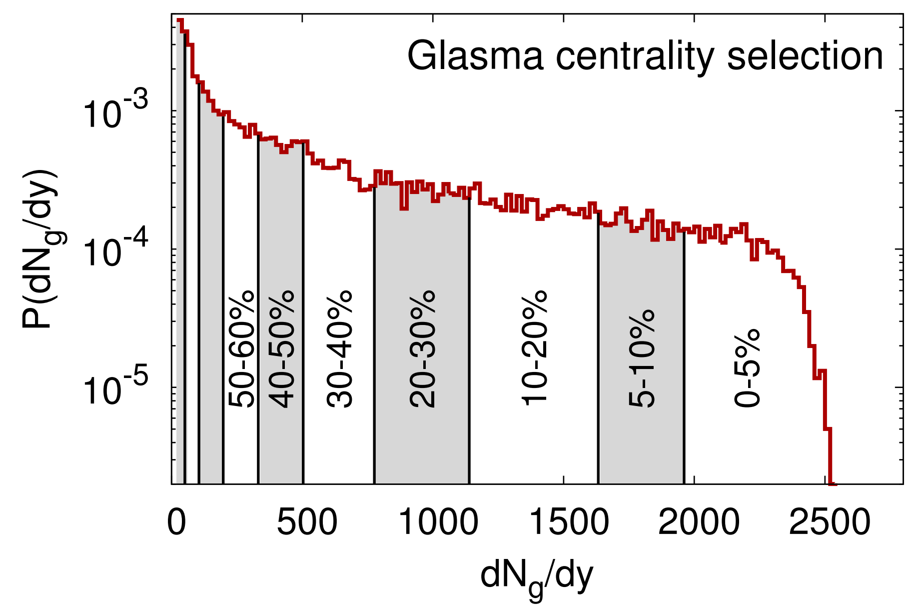
Multiplicity distributions

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

Experimental data: STAR, Phys. Rev. C79, 034909 (2009)



use this for centrality selection



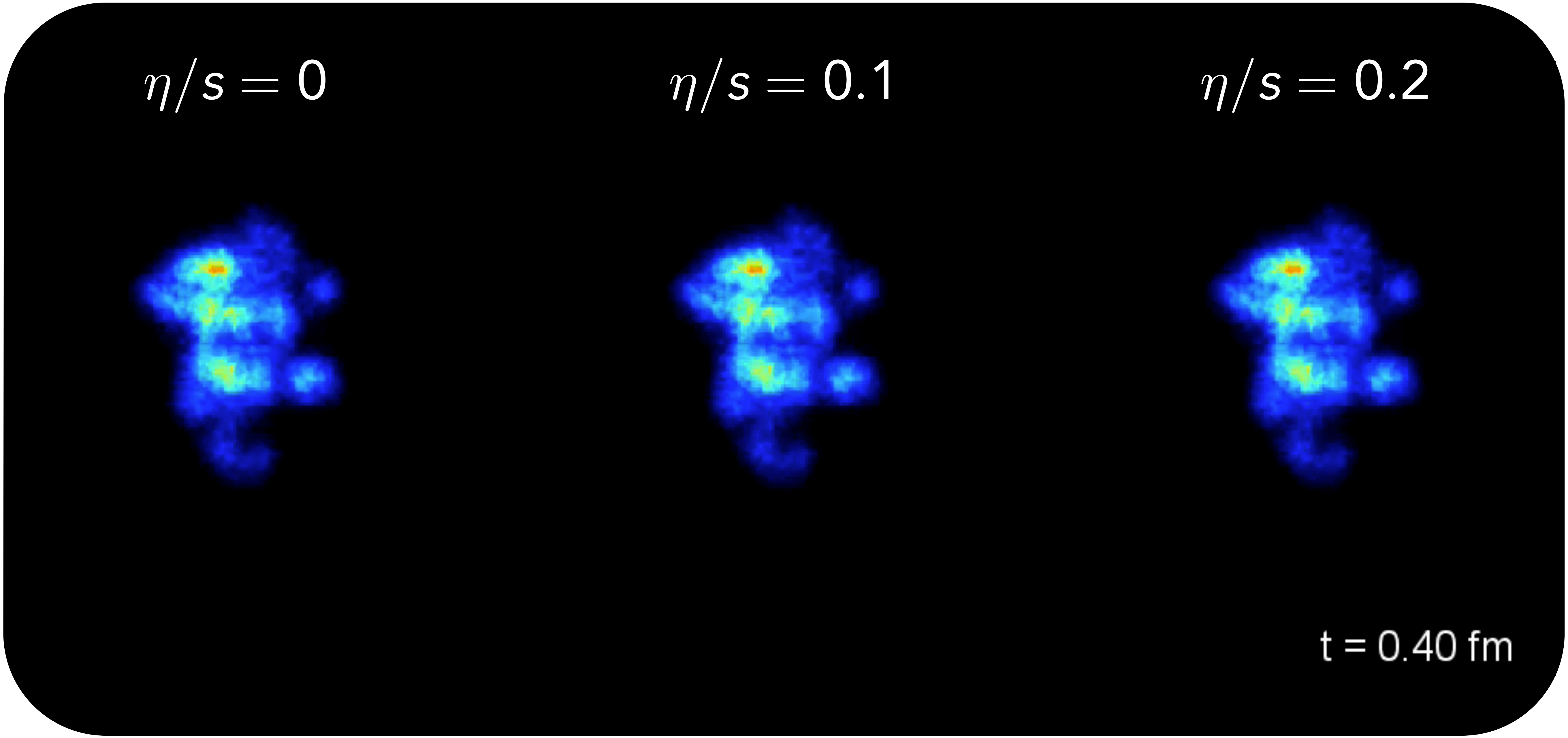
IP-Glasma model gives a convolution of negative binomial distributions

Input to fluid dynamics

C.GALE, S.JEON, B.SCHENKE, P.TRIBEDY, R.VENUGOPALAN, PHYS.REV.LETT. 110, 012302 (2013)

- Compute energy-momentum tensor $T^{\mu\nu}$ of the gluon fields at fixed time **τ**
- Extract energy density and flow vector via $u_\mu T^{\mu\nu} = \varepsilon u^\nu$ (solve eigen-system of $T^{\mu\nu}$)
- At the moment set initial $\Pi^{\mu\nu} = 0$
- $\Pi^{\mu\nu}$ can also be extracted, but $P_L = 0$
- Would need large bulk and shear to match

Fluid dynamic evolution with IP-Glasma initial condition



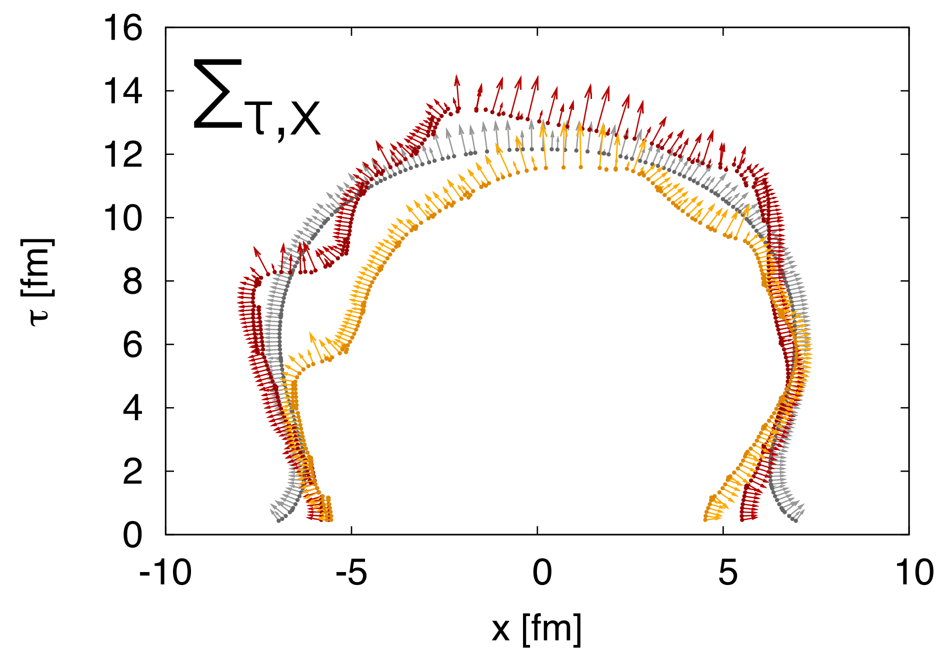
Effect of viscosity in a single event

Late stage and freeze-out

- System expands, becomes dilute, stops interacting strongly

- Convert fluid into particles using the Cooper-Frye formula

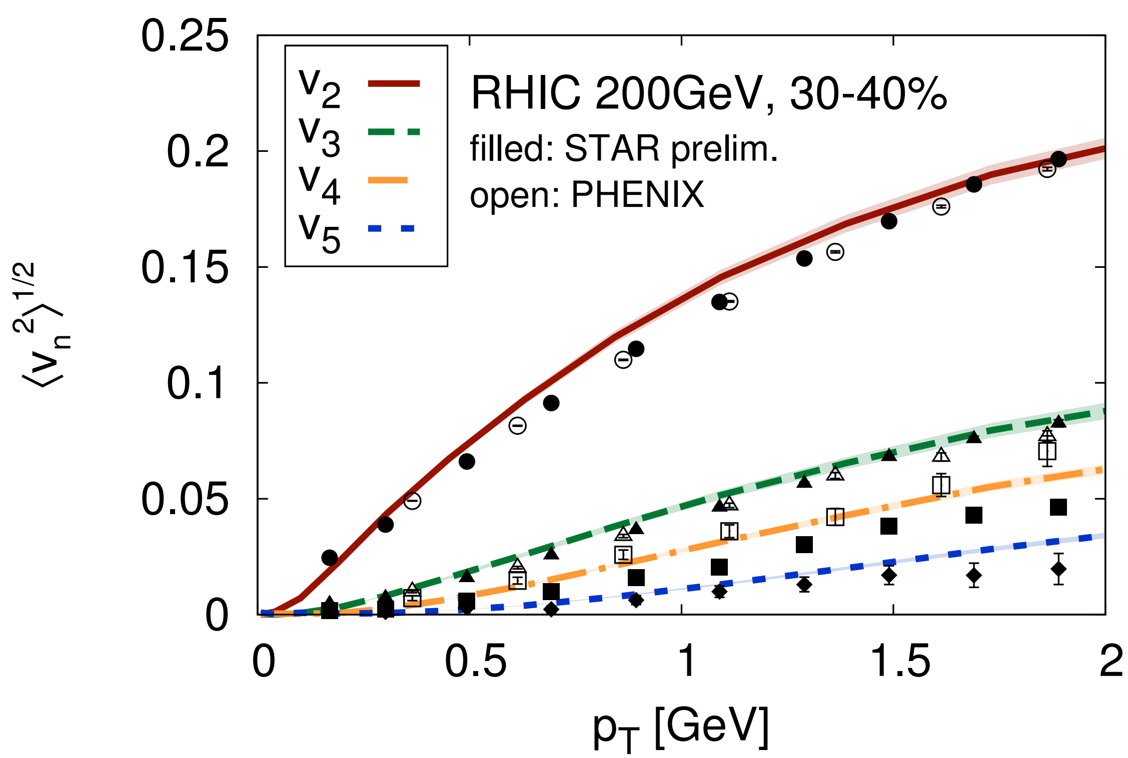
$$E\frac{dN}{d^3p} = \int_\Sigma d\Sigma_\mu p^\mu f(x, p_\mu u^\mu)$$

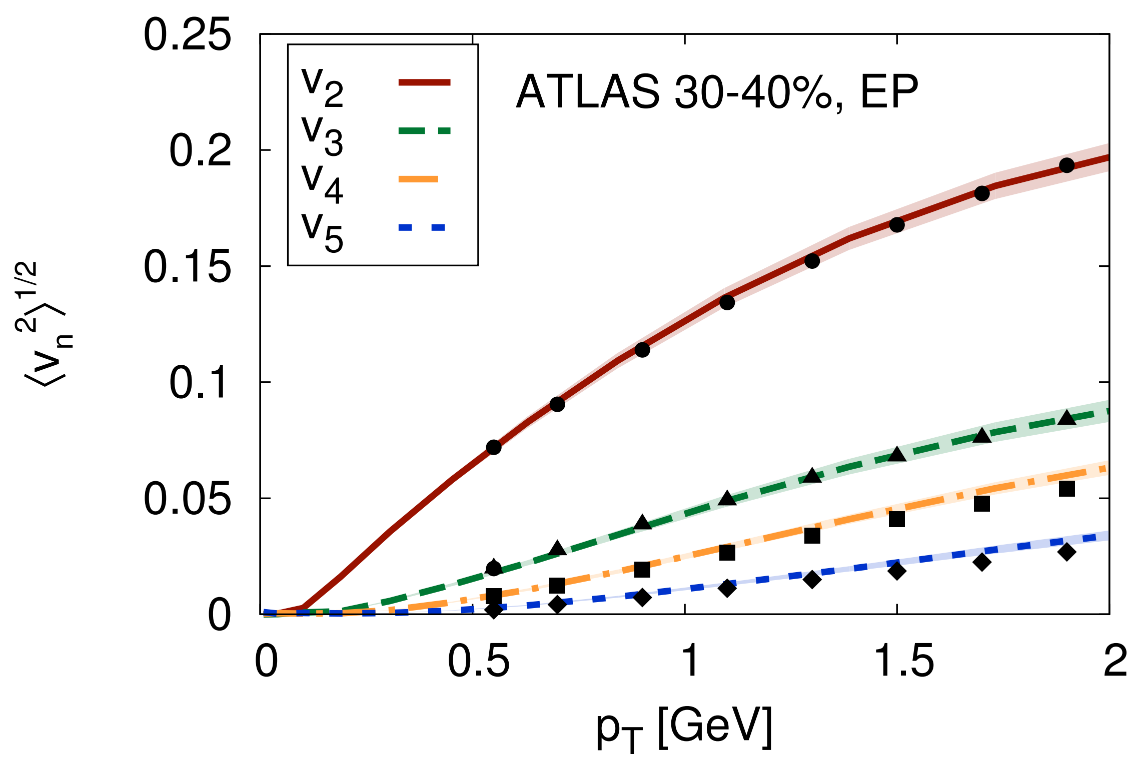


- Then either feed particles into hadronic cascade like UrQMD or just assume free streaming and let the unstable resonances decay (we do the latter)

IP-Glasma fluctuating initial state

Include more QCD dynamics and reduce free parameters
Consistently describes all flow harmonics for a given η/s



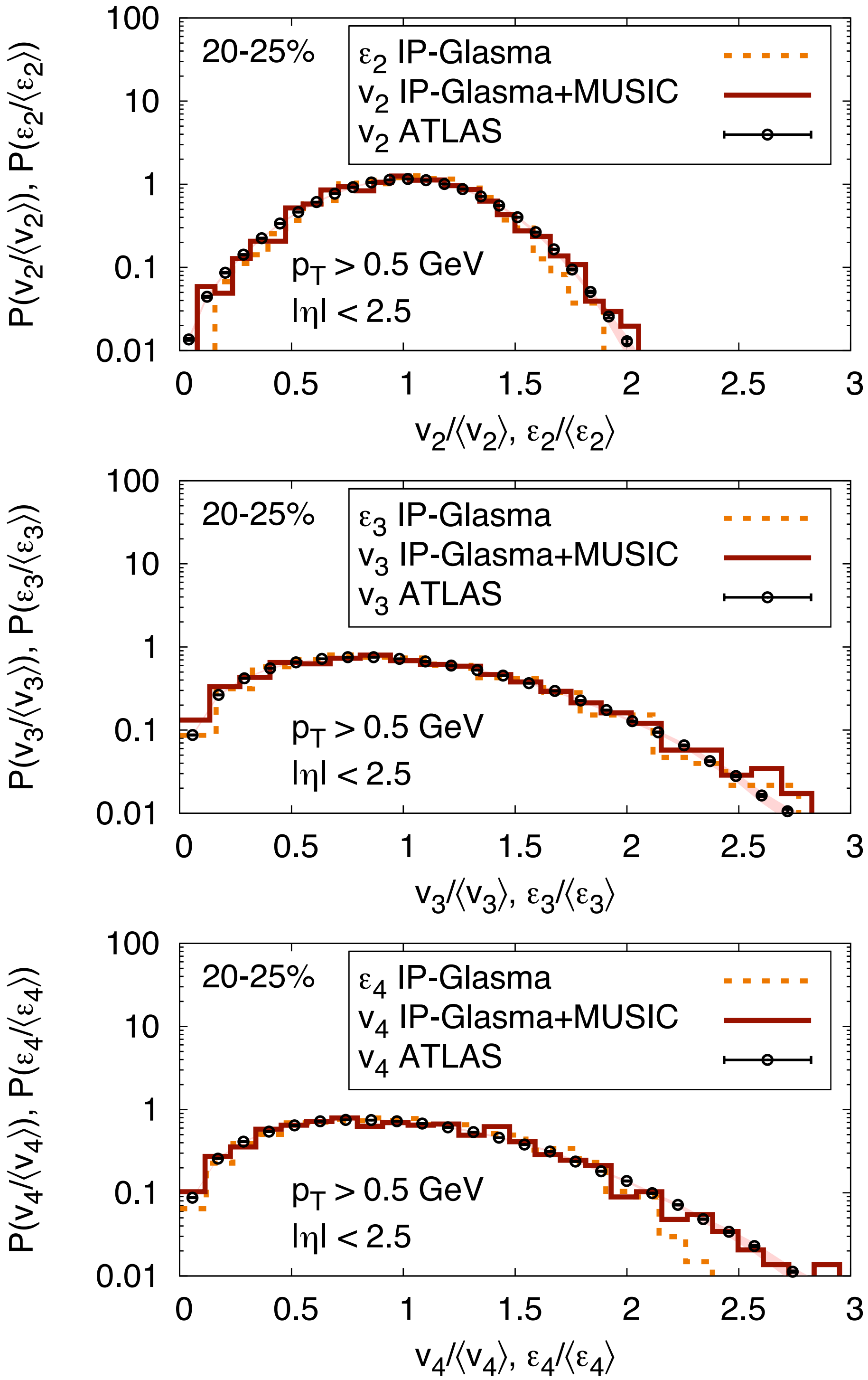


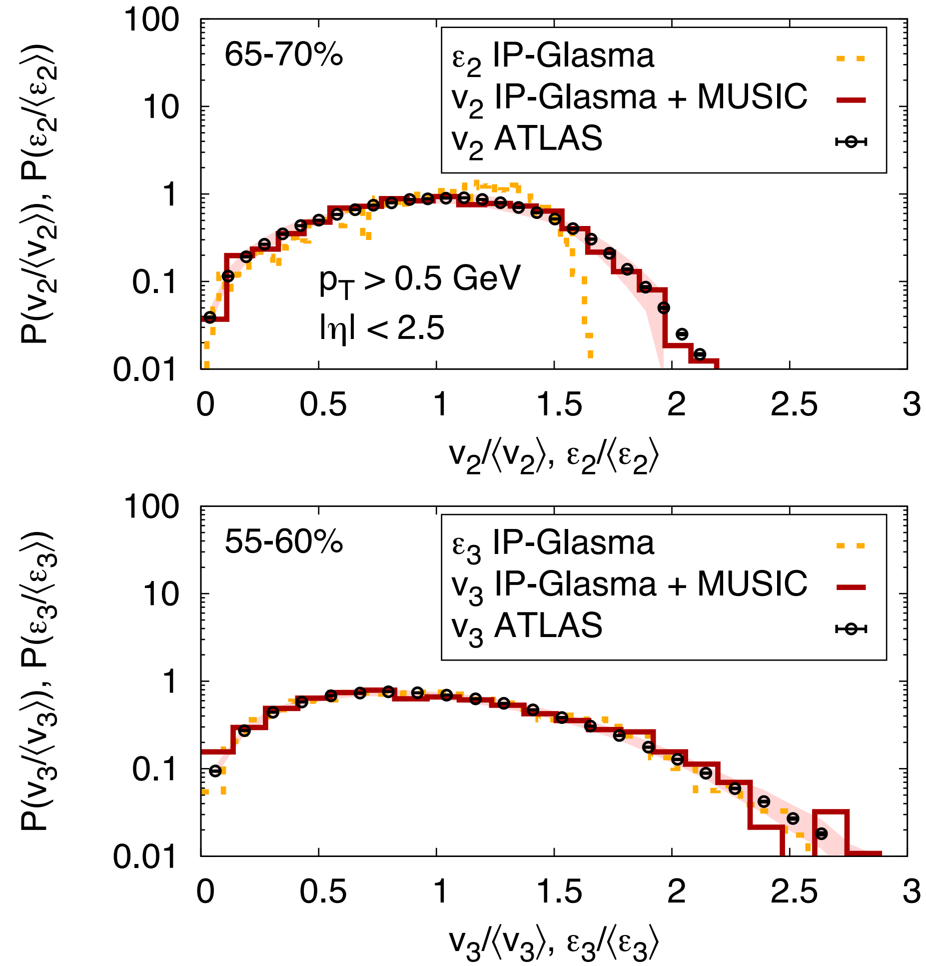
$\eta/s \approx 0.12$ at $\sqrt{s} = 0.2$ TeV $\eta/s \approx 0.2$ at $\sqrt{s} = 2.76$ TeV

C. Gale, S. Jeon, B. Schenke, P. Tribedy, R. Venugopalan, Phys. Rev. Lett. 110, 012302 (2013)
Experimental data:
A. Adare et al. (PHENIX Collaboration), Phys.Rev.Lett. 107, 252301 (2011)
Y. Pandit [for the STAR collaboration], Quark Matter 2012; Phys. Rev. C 88, 14904 (2013)
G. Aad et al. (ATLAS Collaboration), Phys.Rev. C86, 014907 (2012).

Event-by-event fluctuations of flow coefficients

C. Gale, S. Jeon, B. Schenke, P. Tribedy, R. Venugopalan, Phys. Rev. Lett. 110, 012302 (2013)
Experimental Data: ATLAS Collaboration, JHEP 1311, 183 (2013)

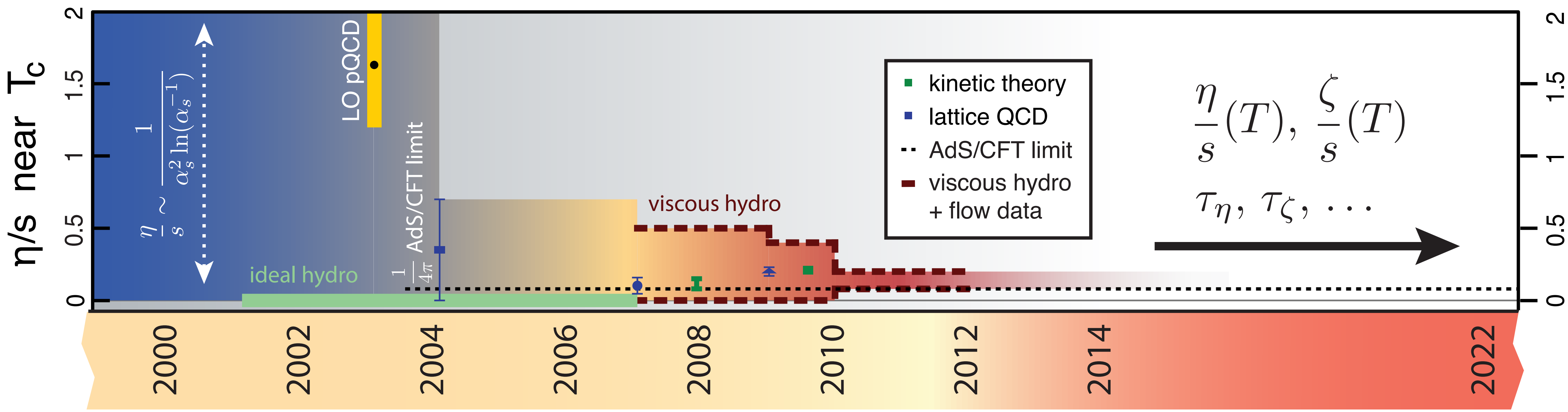




- Flow fluctuations reflect initial state fluctuations
- Support collectivity interpretation

Achieving quantitative understanding

Example: Shear viscosity to entropy density ratio η/s
Broad theoretical efforts and experimental advances lead to increasingly precise determination of η/s



LO pQCD: P. Arnold, G. D. Moore, L. G. Yaffe, JHEP 0305 (2003) 051
AdS/CFT: P. Kovtun, D. T. Son, A. O. Starinets, Phys.Rev.Lett. 94 (2005) 111601
Lattice QCD: A. Nakamura, S. Sakai, Phys.Rev.Lett. 94 (2005) 072305
H. B. Meyer, Phys.Rev. D76 (2007) 101701; Nucl.Phys. A830 (2009) 641C-648C
Ideal hydro: P. F. Kolb, J. Sollfrank, U. W. Heinz, Phys.Rev. C62 (2000) 054909
P. F. Kolb, P. Huovinen, U. W. Heinz, H. Heiselberg, Phys.Lett. B500 (2001) 232-240
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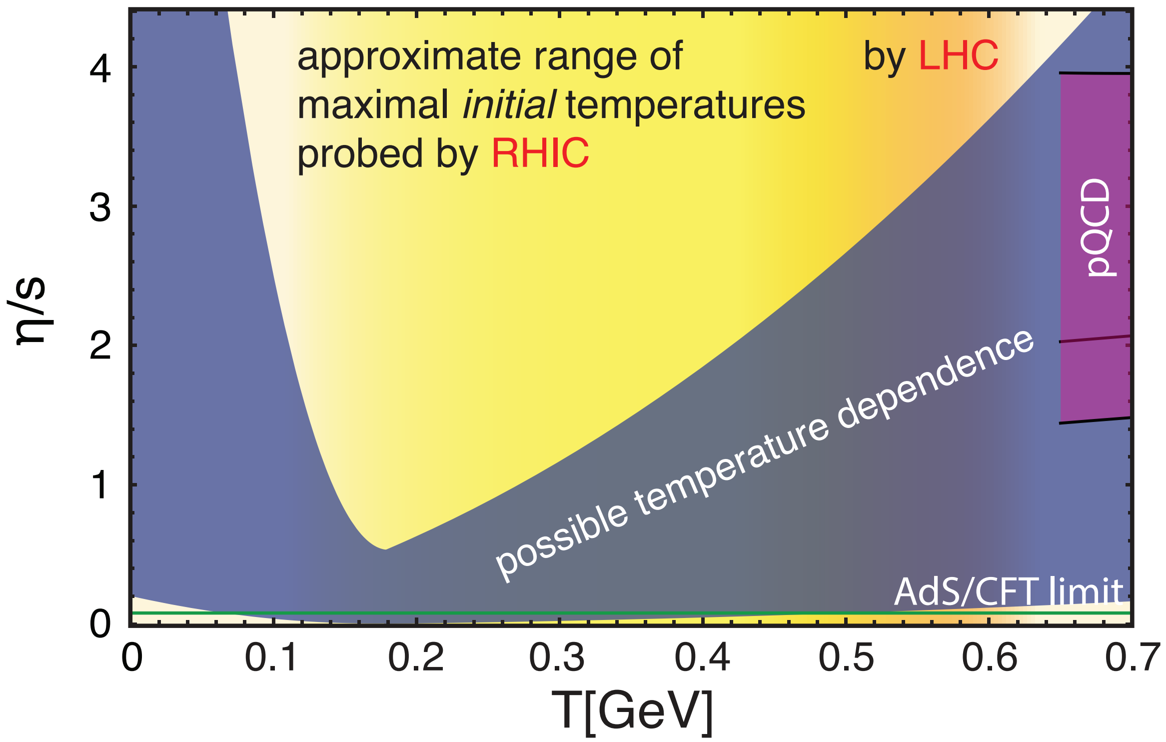
J.-W. Chen, H. Dong, K. Ohnishi, Q. Wang, Phys.Lett. B685 (2010) 277-282
Viscous hydro: P. Romatschke, U. Romatschke, Phys.Rev.Lett. 99 (2007) 172301
M. Luzum, P. Romatschke, Phys.Rev. C78 (2008) 034915
H. Song, U. W. Heinz, J.Phys. G36 (2009) 064033
H. Song, S. A. Bass, U. Heinz, T. Hirano, C. Shen, Phys.Rev.Lett. 106 (2011) 192301

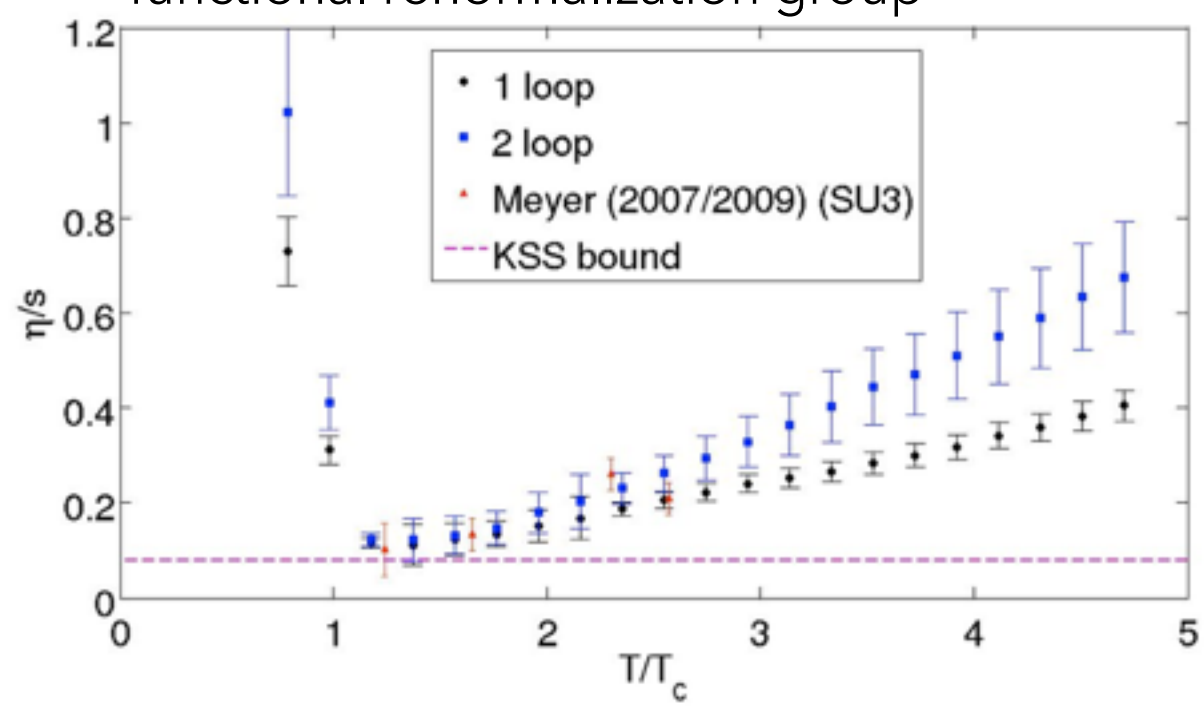
Temperature dependent transport parameters

Extract information on $(\eta/s)(T)$ from experimental data



- Need to vary collision energy over wide range

Maximum entropy method and functional renormalization group



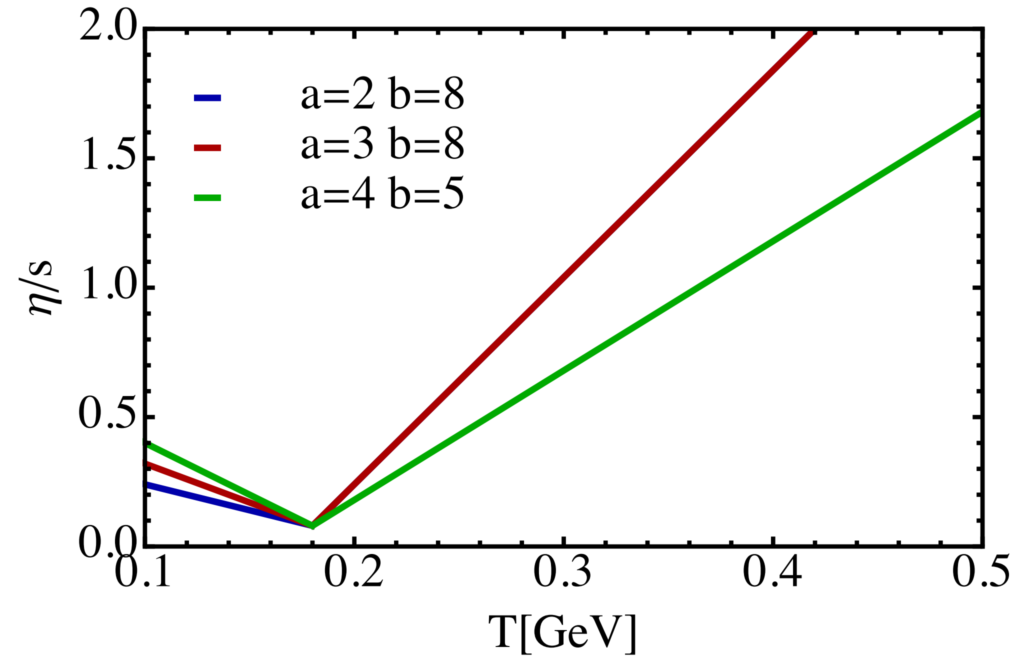
J. Pawlowski at Quark Matter 2014
(Christiansen, Haas, Pawlowski, Strodthoff)

- Compare to non-perturbative QCD approaches (Lattice, FRG)

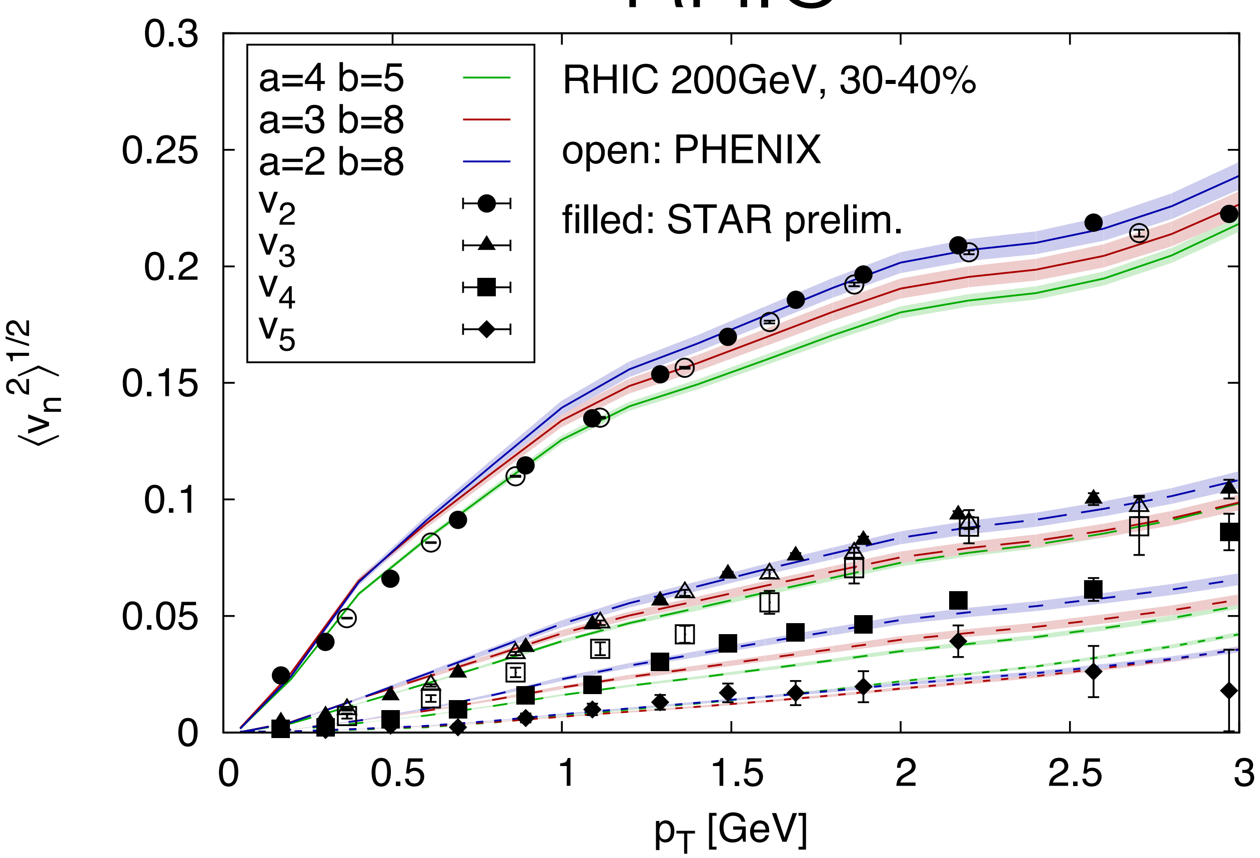
- Detailed simulations needed

Temperature dependent transport parameters

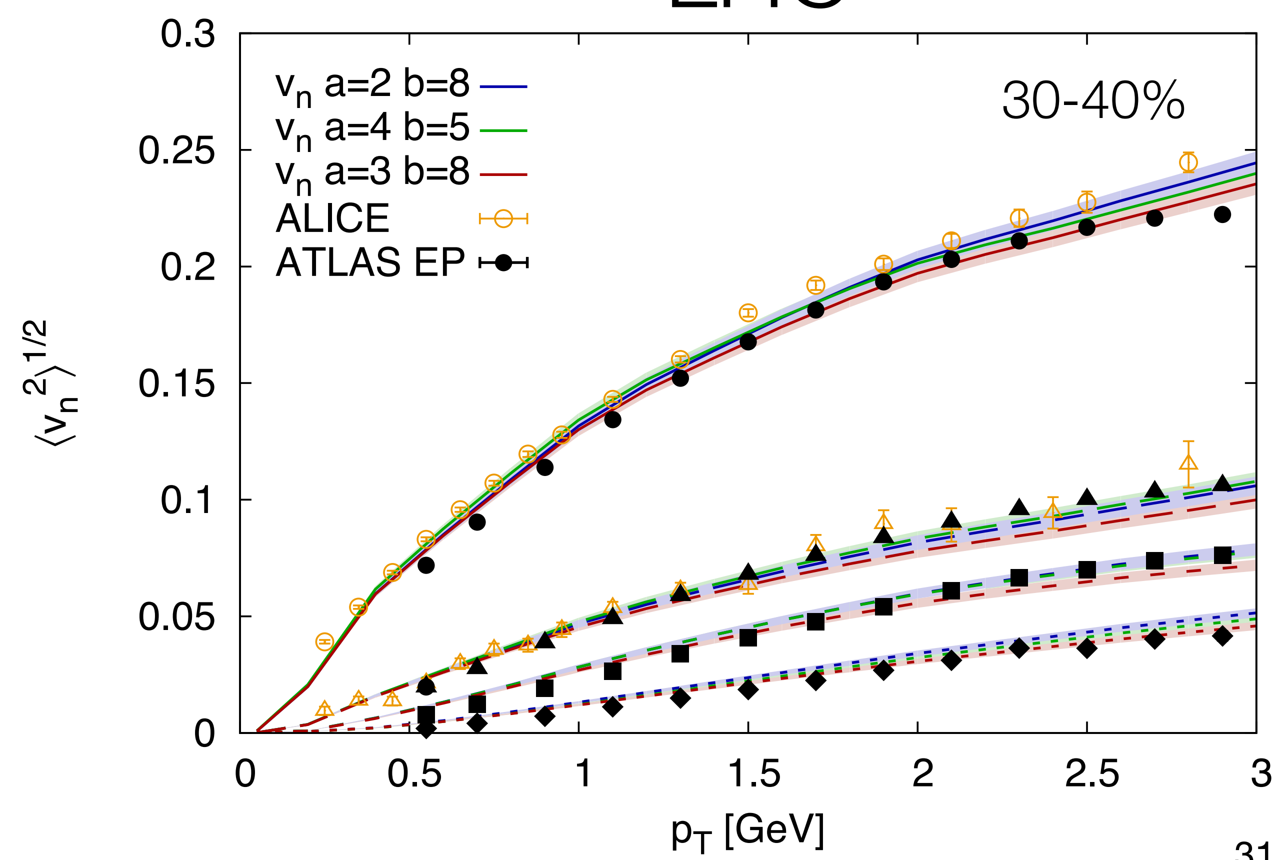
$$(\eta/s)(T) = \theta(T_{\min} - T)[(\eta/s)_{\min} + a(T_{\min} - T)] + \theta(T - T_{\min})[(\eta/s)_{\min} + b(T - T_{\min})]$$



RHIC



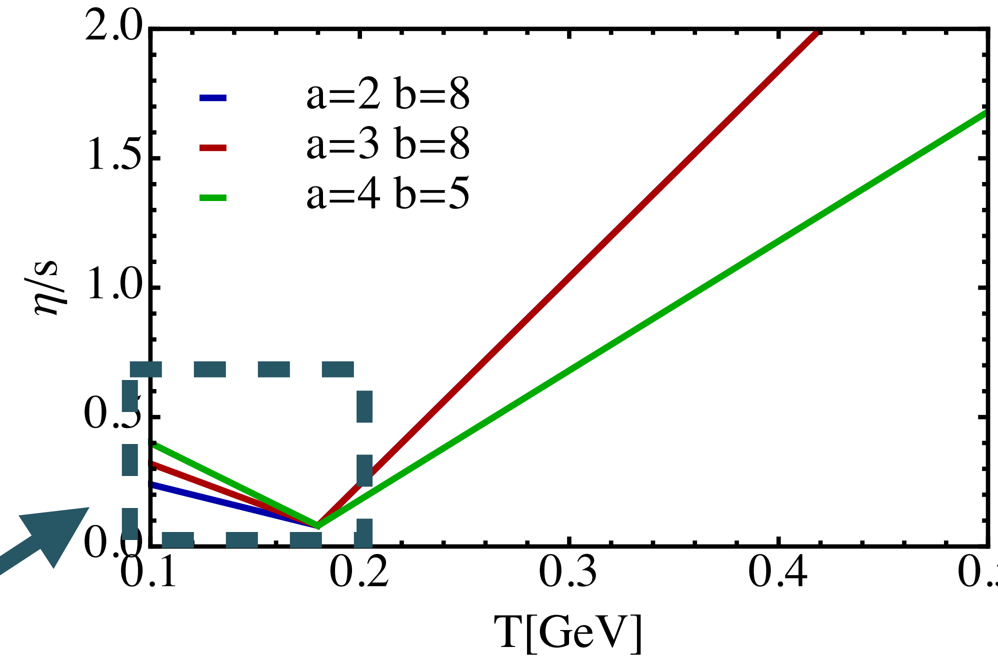
LHC



also see Niemi, Denicol, Huovinen, Molnar, Rischke, Phys.Rev. C86 (2012) 014909

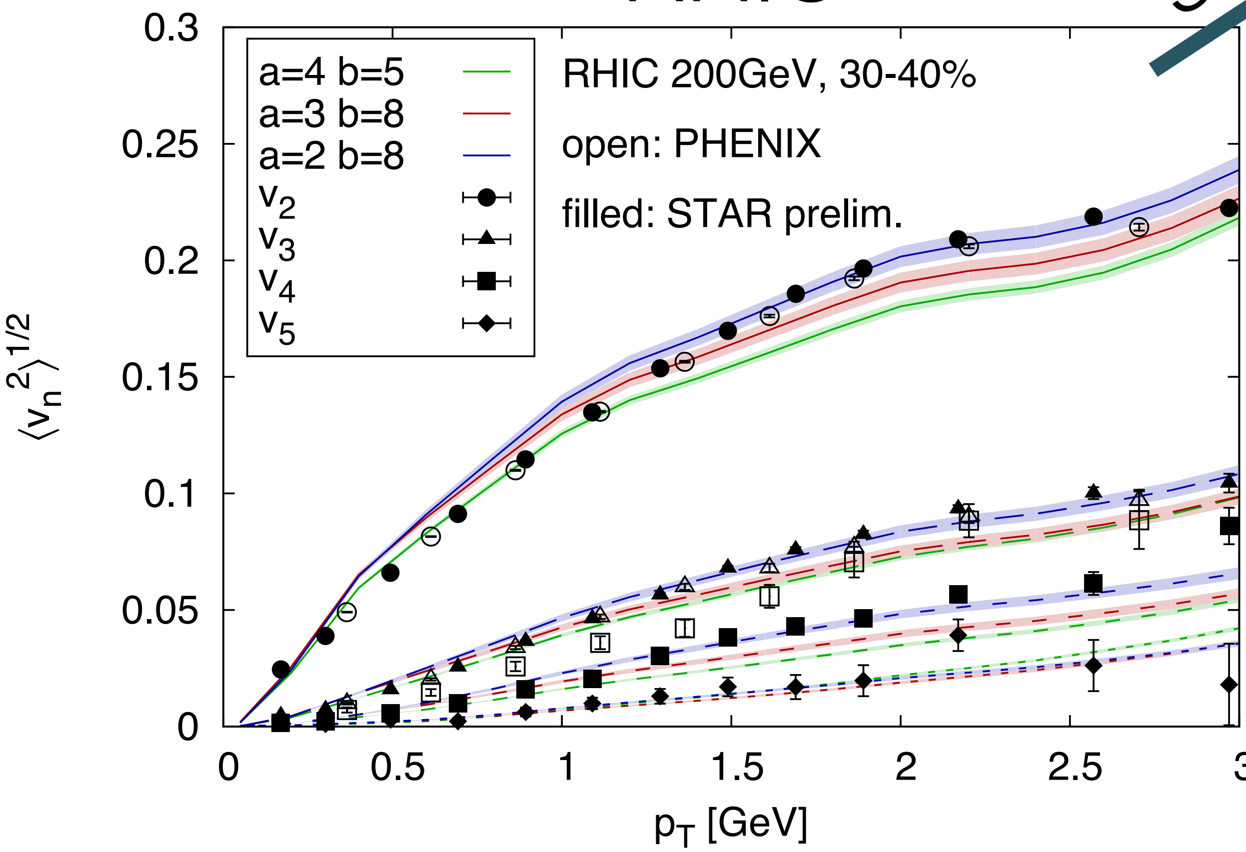
Temperature dependent transport parameters

$$(\eta/s)(T) = \theta(T_{\rm min} - T)[(\eta/s)_{\rm min} + a(T_{\rm min} - T)] + \theta(T - T_{\rm min})[(\eta/s)_{\rm min} + b(T - T_{\rm min})]$$

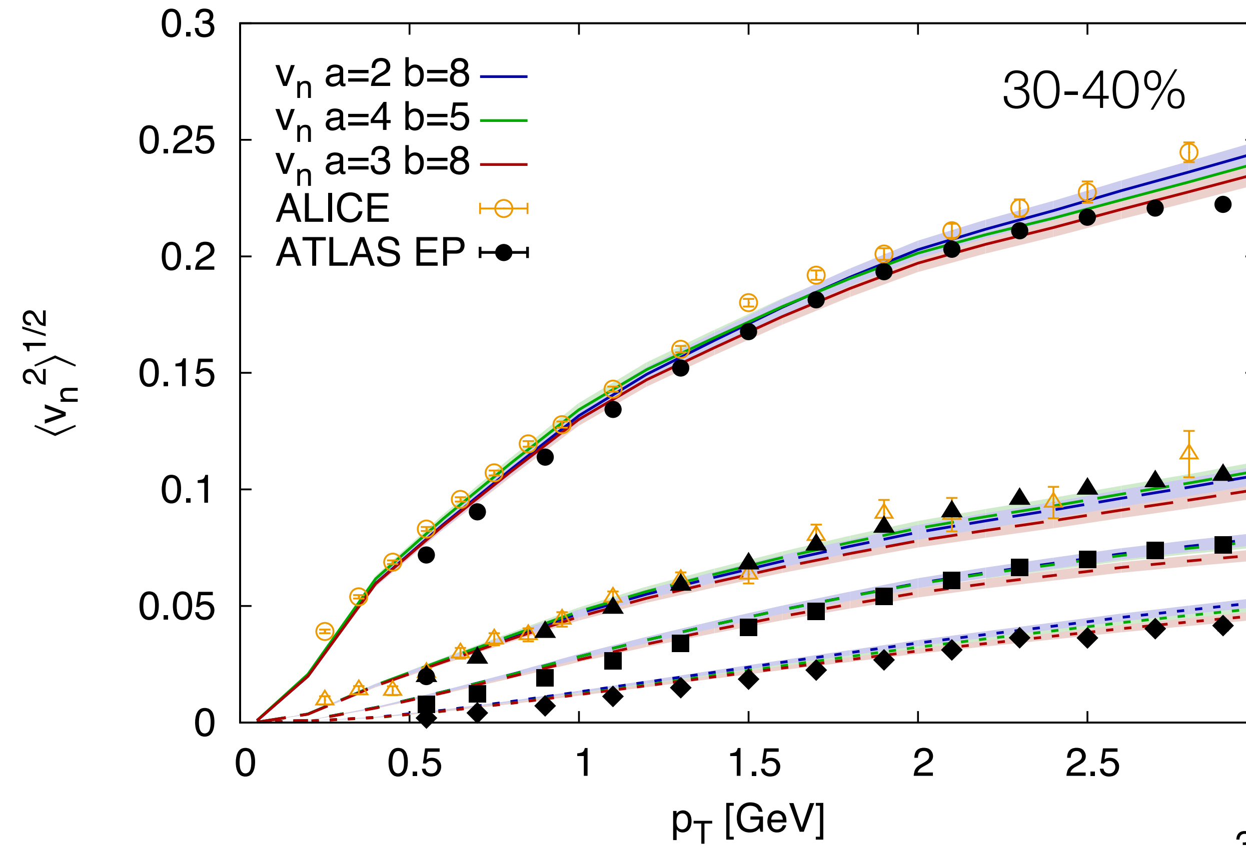


sensitive to

RHIC



LHC



also see Niemi, Denicol, Huovinen, Molnar, Rischke, Phys.Rev. C86 (2012) 014909

Effect of bulk viscosity

Include bulk viscosity

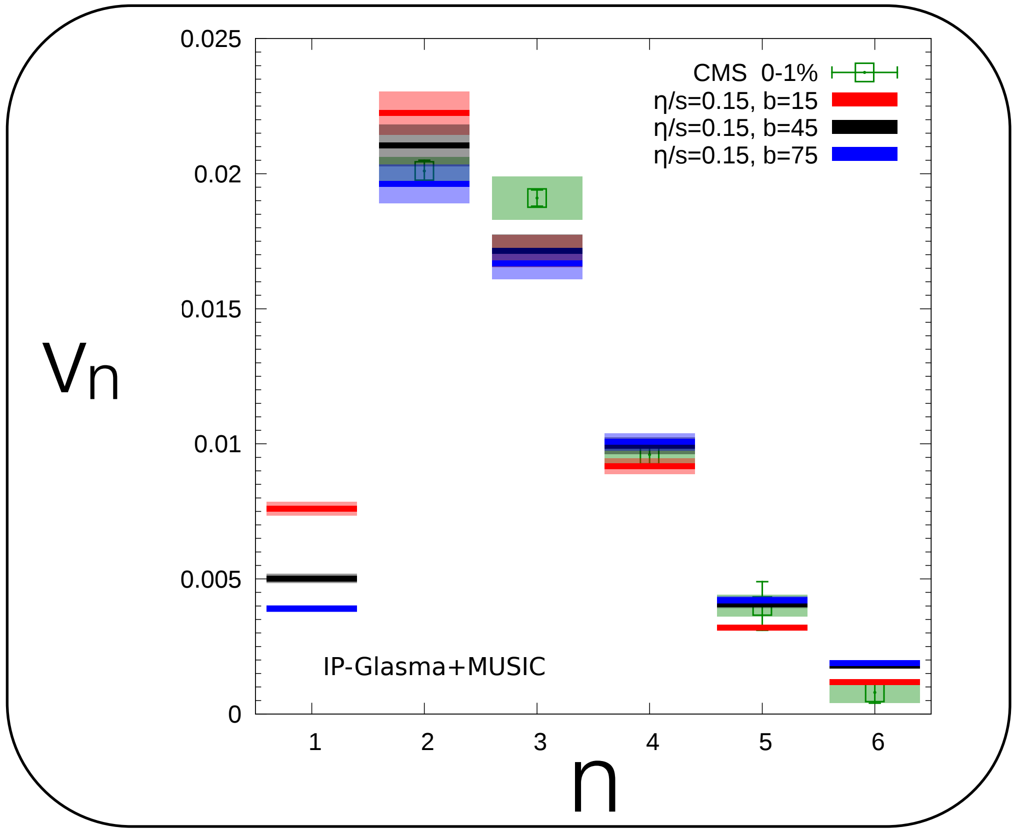
G.S.Denicol, H.Niemi, E.Molnar and D.H.Rischke,Phys. Rev. D85, 114047 (2012)
G.S.Denicol,S.Jeon and C.Gale, PRC, arXiv:1403.0962[nucl-th].

In addition to $\partial_\mu T^{\mu\nu} = 0$ solve the following equations

$$\tau_\Pi \dot{\Pi} + \Pi = -\zeta\theta - \delta_{\Pi\Pi}\Pi\theta + \lambda_{\Pi\pi}\pi^{\mu\nu}\sigma_{\mu\nu} \,,$$

$$\tau_\pi \dot{\pi}^{\langle\mu\nu\rangle} + \pi^{\mu\nu} = 2\eta\sigma^{\mu\nu} + 2\tau_\pi \pi_\alpha^{\langle\mu}\omega^{\nu\rangle\alpha} - \delta_{\pi\pi}\pi^{\mu\nu}\theta + \varphi_7 \pi_\alpha^{\langle\mu}\pi^{\nu\rangle\alpha} - \tau_{\pi\pi}\pi_\alpha^{\langle\mu}\sigma^{\nu\rangle\alpha} + \lambda_{\pi\Pi}\Pi\sigma^{\mu\nu}$$

Bulk viscosity is parametrized as $\zeta = b\eta\left(\frac{1}{3} - c_s^2\right)^2$



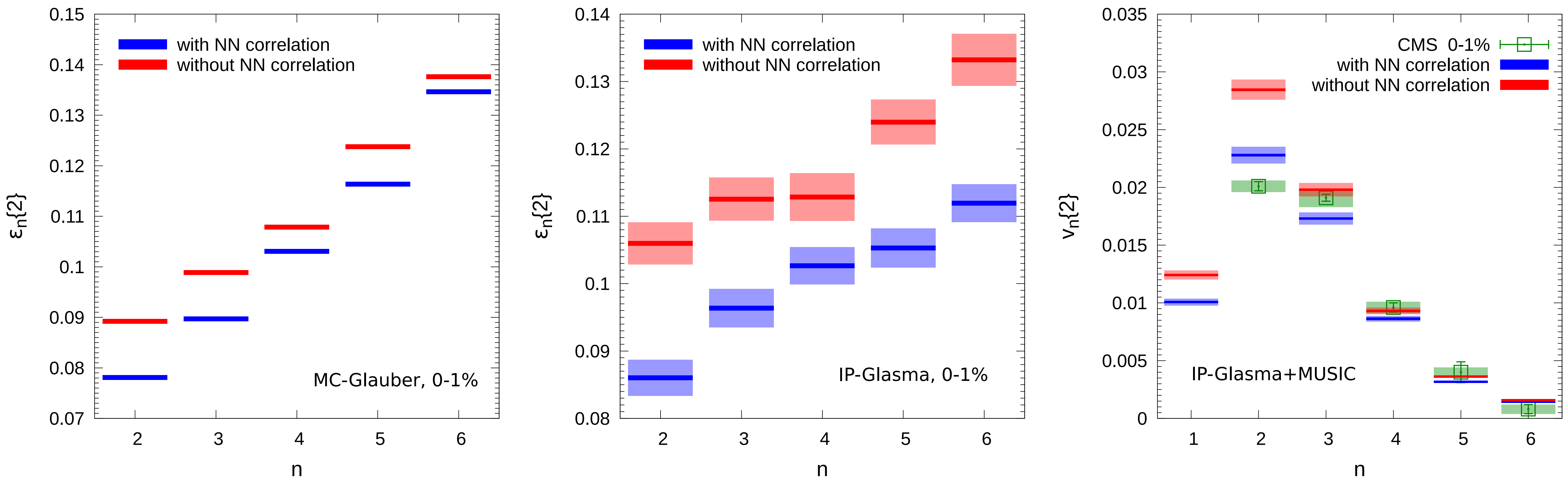
Effect in ultra-central collisions

J.-B. Rose, J.-F. Paquet, G. S. Denicol, M. Luzum,
B. Schenke, S. Jeon, C. Gale, arXiv:1408.0024
Data: S.Chatrchyanetal [CMS Collaboration], JHEP1402, 088 (2014)

Nucleon-Nuncleon correlations

G. S. DENICOL, C. GALE, S. JEON, J.-F. PAQUET, B. SCHENKE, ARXIV:1406.7792

Nucleon correlations matter in ultra-central collisions



using effective central correlations

M. ALVIOLI, H. -J. DRESCHER AND M. STRIKMAN, PHYS. LETT. B 680, 225 (2009)

Improves agreement with experimental data

DATA: S.CHATRCHYANETAL [CMS COLLABORATION], JHEP1402, 088 (2014)

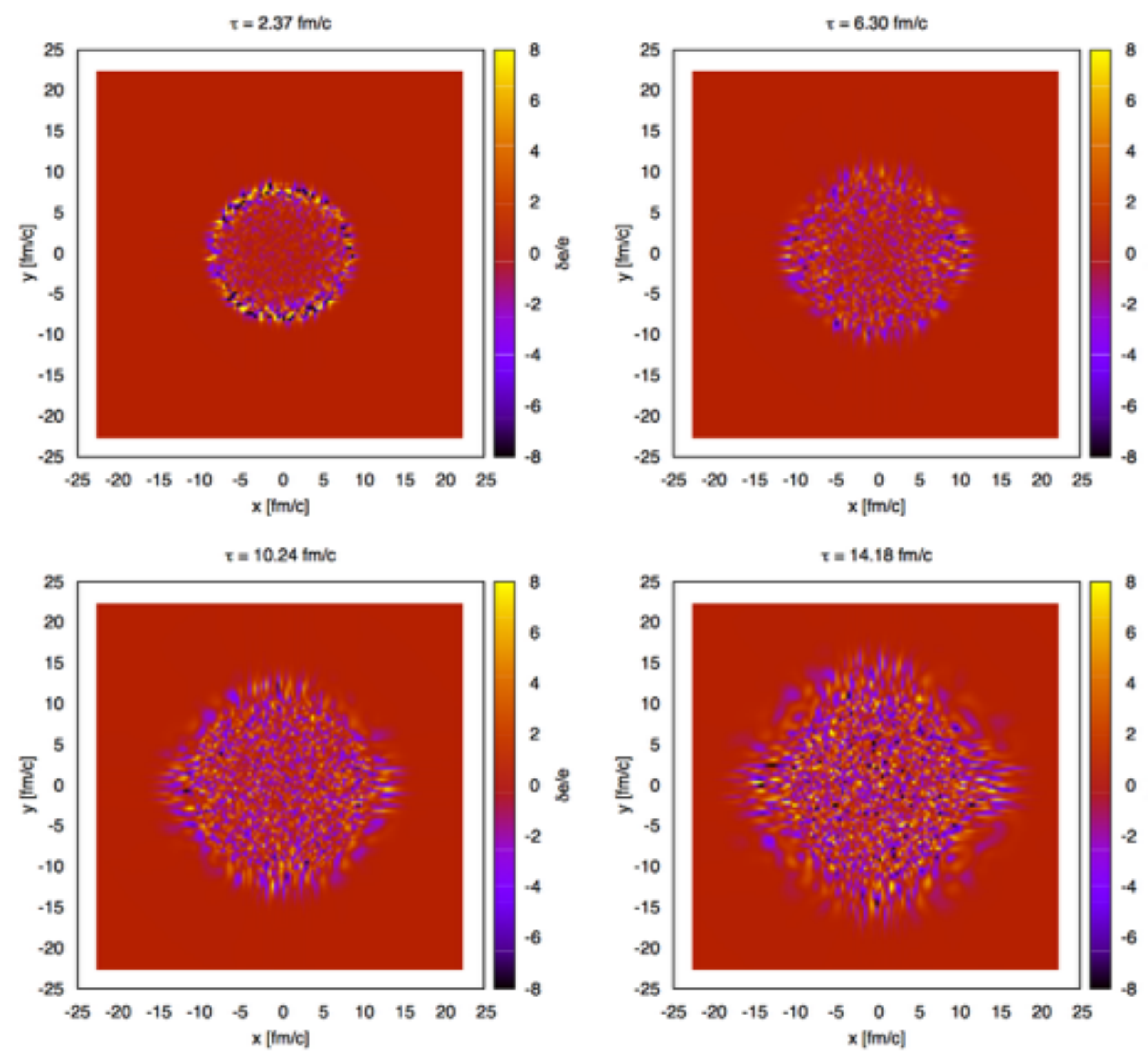
Hydrodynamic fluctuations

C. Young, J.I. Kapusta, C. Gale, S. Jeon, B. Schenke, arXiv:1407.1077

$$T^{\mu\nu}_{\rm tot} = T^{\mu\nu}_0 + \delta T^{\mu\nu}_{\rm id} + \delta W^{\mu\nu} + \Xi^{\mu\nu} \longleftarrow \text{noise}$$

In linear response one can derive coupled equations for the evolution of the fluctuating parts of $T^{\mu\nu}$

They are separate from the evolution of the average quantities



Hydrodynamic fluctuations

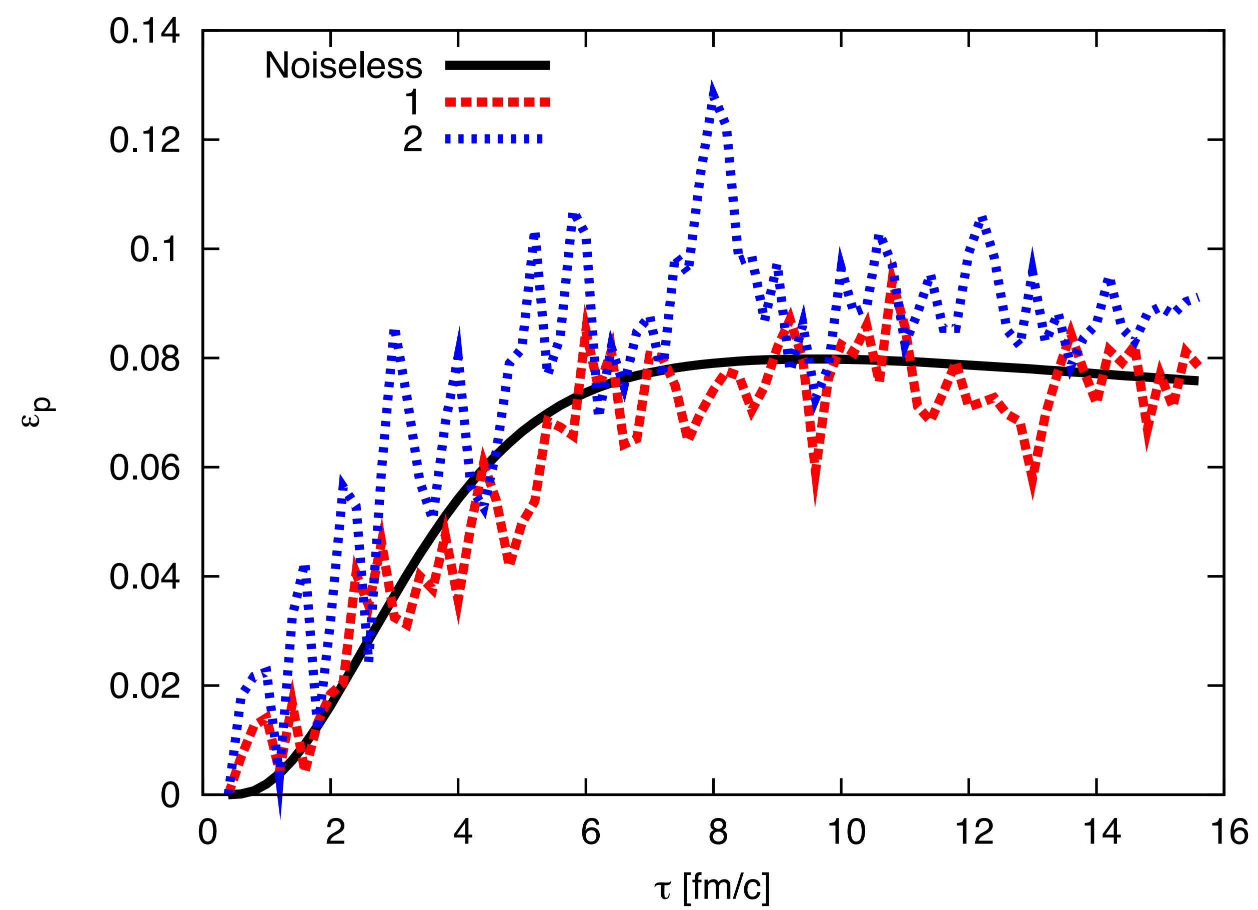
C. Young, J.I. Kapusta, C. Gale, S. Jeon, B. Schenke, arXiv:1407.1077

$$T^{\mu\nu}_{\text{tot}} = T^{\mu\nu}_0 + \delta T^{\mu\nu}_{\text{id}} + \delta W^{\mu\nu} + \Xi^{\mu\nu}$$ ← noise

Comparing the momentum anisotropy

$$\varepsilon_p = \sqrt{\frac{\langle T^{xx} - T^{yy}\rangle^2 + \langle 2T^{xy}\rangle^2}{\langle T^{xx} + T^{yy}\rangle^2}}$$

in two different fluctuating events to the average value

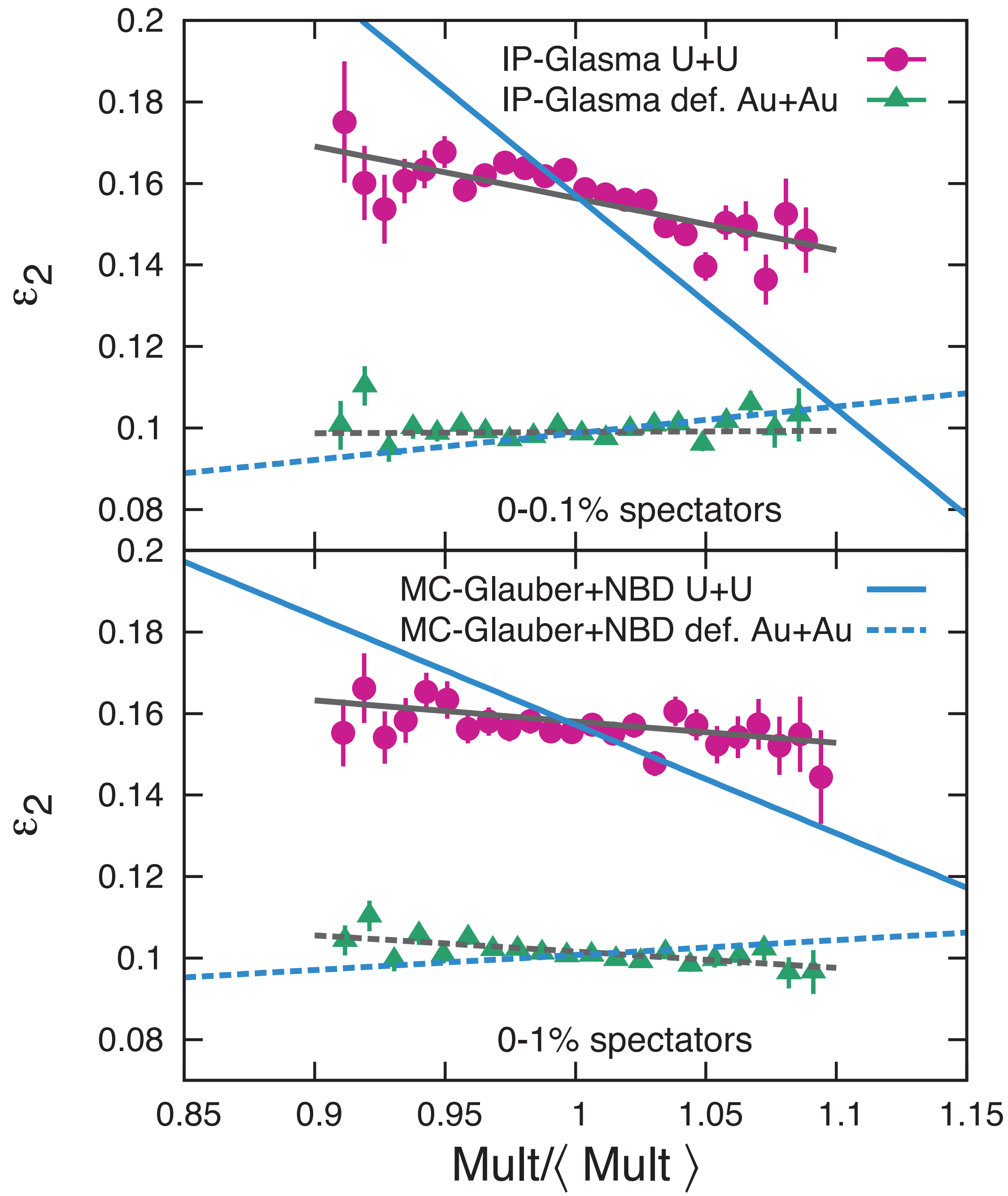


Deformed Nuclei

B. SCHENKE, P. TRIBEDY, R. VENUGOPALAN
PHYS. REV. C89, 064908 (2014)

- Select ultra-central events based on neutrons in the ZDC
- Study correlation between and multiplicity
- MC-Glauber gets (anti-)correlation because of N_{coll} in

$$\frac{dN}{d\eta} = n_{\text{pp}}\left(xN_{\text{coll}} + (1-x)\frac{N_{\text{part}}}{2}\right)$$

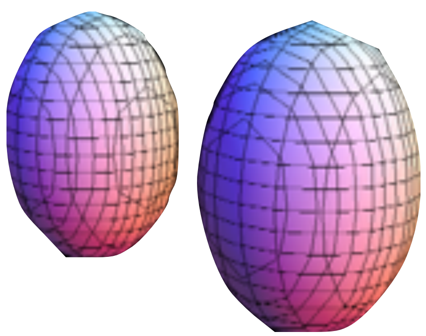


- IP-Glasma finds weaker anti-correlation

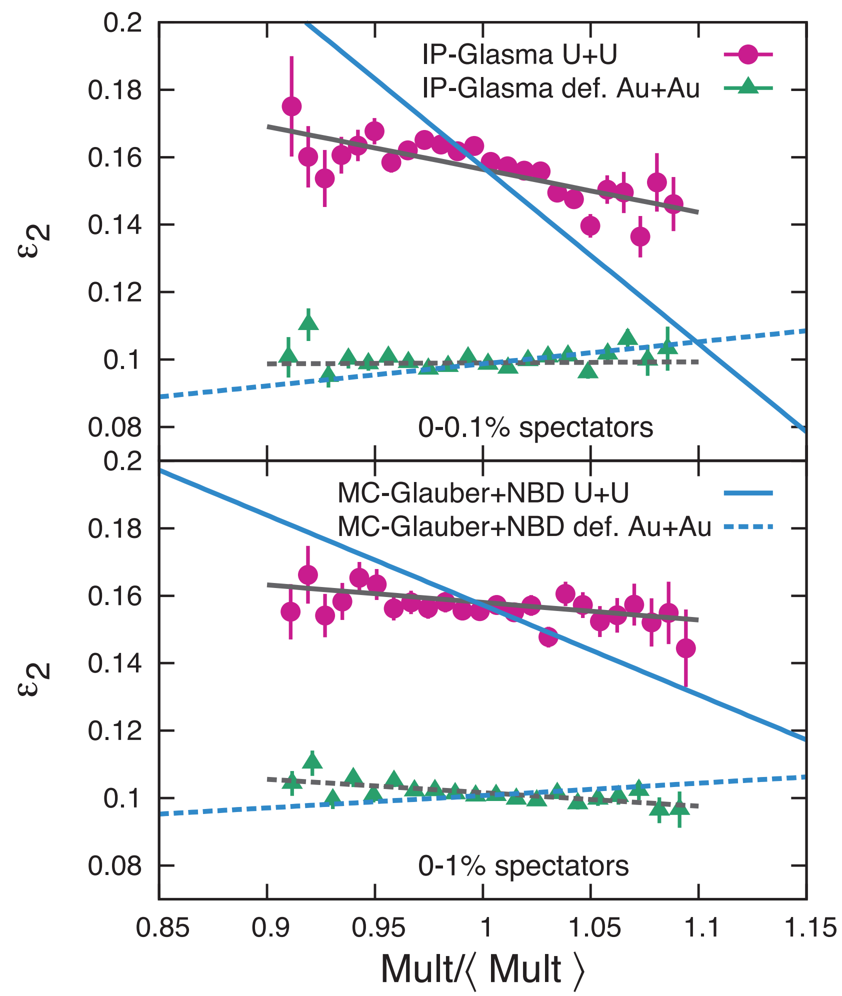
Deformed Nuclei

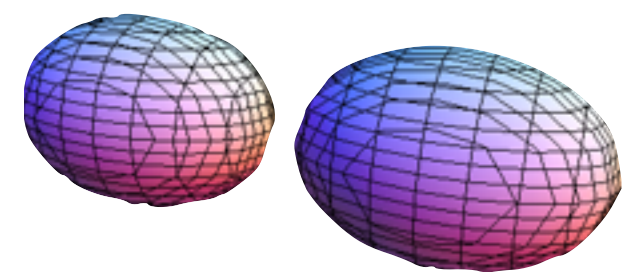
B. SCHENKE, P. TRIBEDY, R. VENUGOPALAN
PHYS. REV. C89, 064908 (2014)

- Uranium: prolate
- Gold: oblate

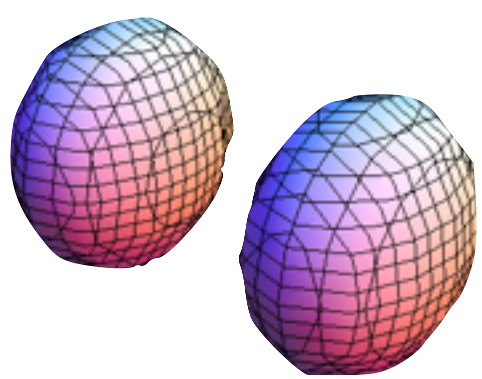


U+U, side-side

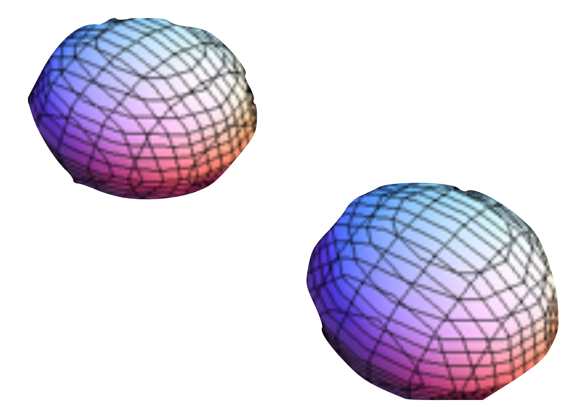




U+U, tip-tip



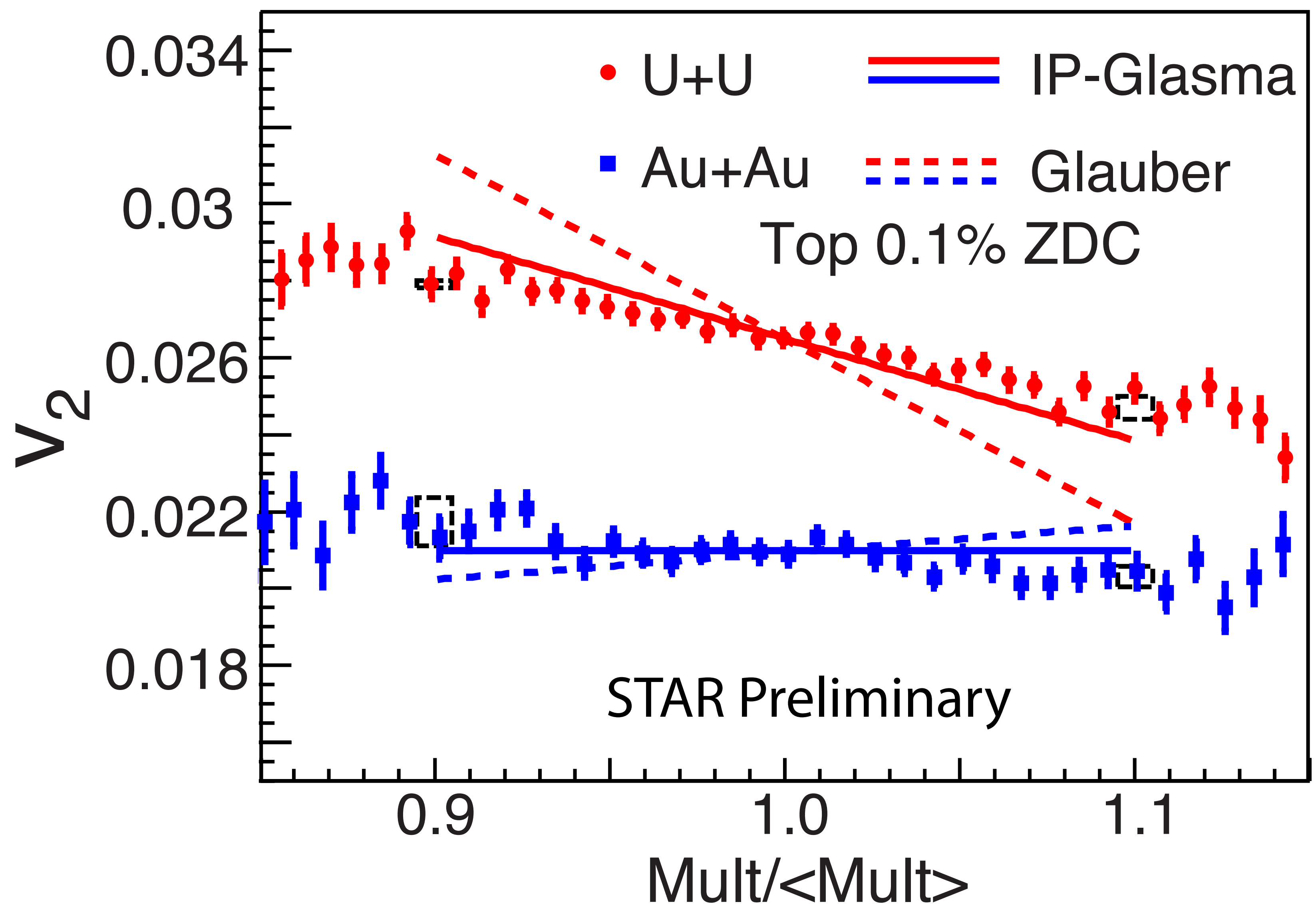
Au+Au, side-side



Au+Au, "tip-tip"

Testing the initial state model in U+U collisions

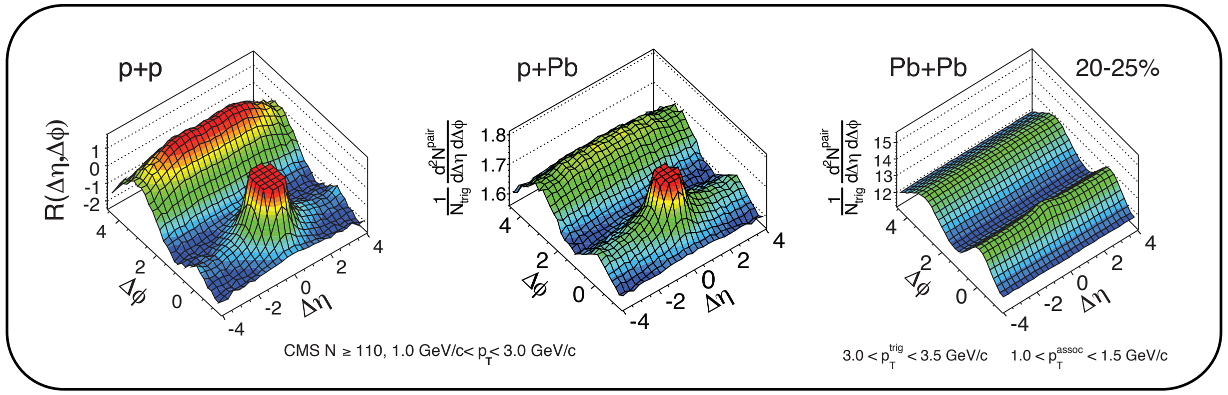
B. Schenke, P. Tribedy, R. Venugopalan, Phys. Rev. C89, 064908 (2014)
Experimental Data: STAR Collaboration, H. Wang, Nucl. Phys. A (in press, 10.1016/j.nuclphysa.2014.08.086)



Ultra-central collisions of deformed nuclei distinguish between different models of particle production - IP-Glasma preferred

Small systems: New questions, new opportunities

- 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

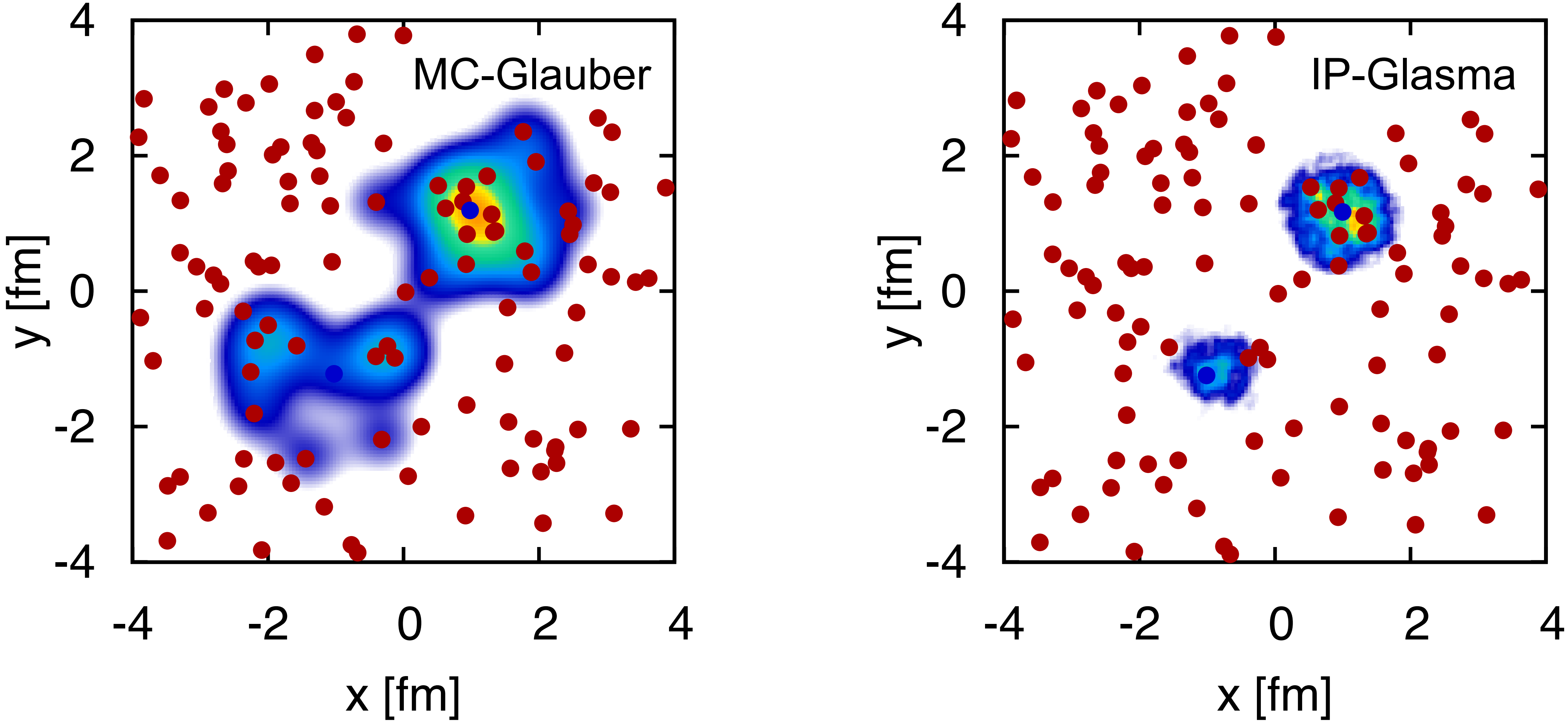


- Interpretation not yet clear:
  - Initial correlations? Theory on this is developing: new insights
  - Initial geometry + collective effects? Even fluid dynamics?
- Versatility of RHIC helps to address these questions for example by running ^{3}He+Au collisions (different geometry)

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

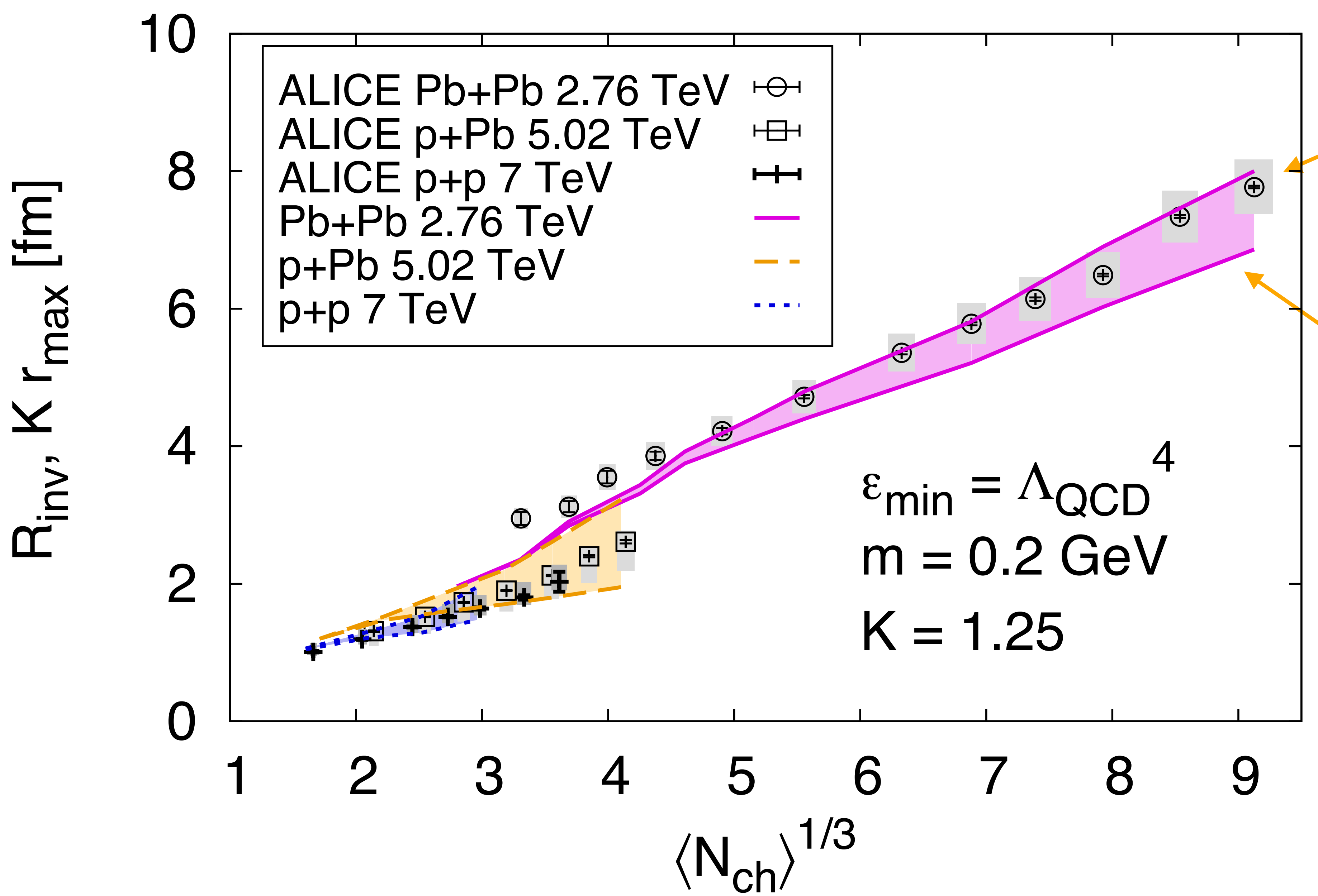
Small systems: Sensitive to initial state model

A. BZDAK, B. SCHENKE, P. TRIBEDY, R. VENUGOPALAN, PRC87, 064906 (2013)



System Size

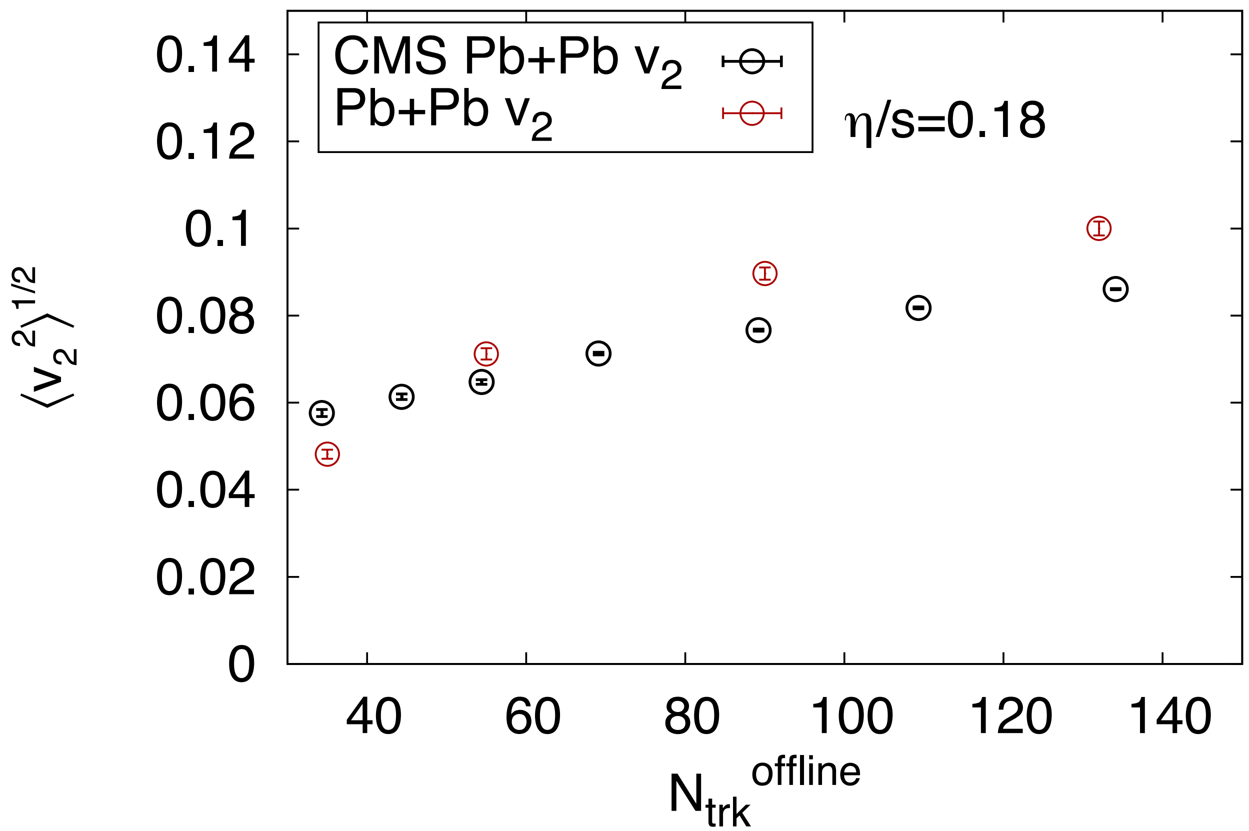
A. BZDAK, B. SCHENKE, P. TRIBEDY, R. VENUGOPALAN, PRC87, 064906 (2013)

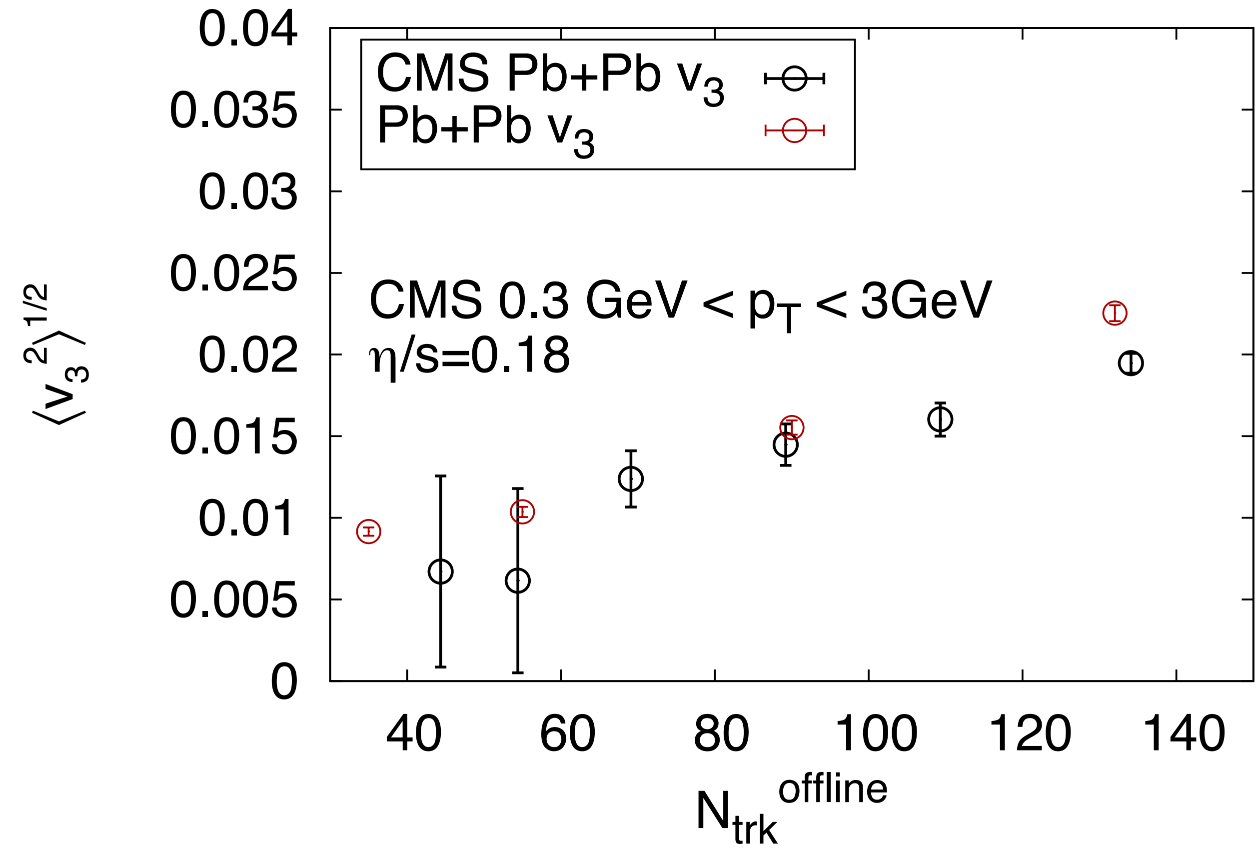


NOTE: Only a qualitative comparison to HBT data!

Fourier Harmonics in peripheral Pb+Pb

CMS COLLABORATION, PHYS.LETT. B724 (2013) 213-240

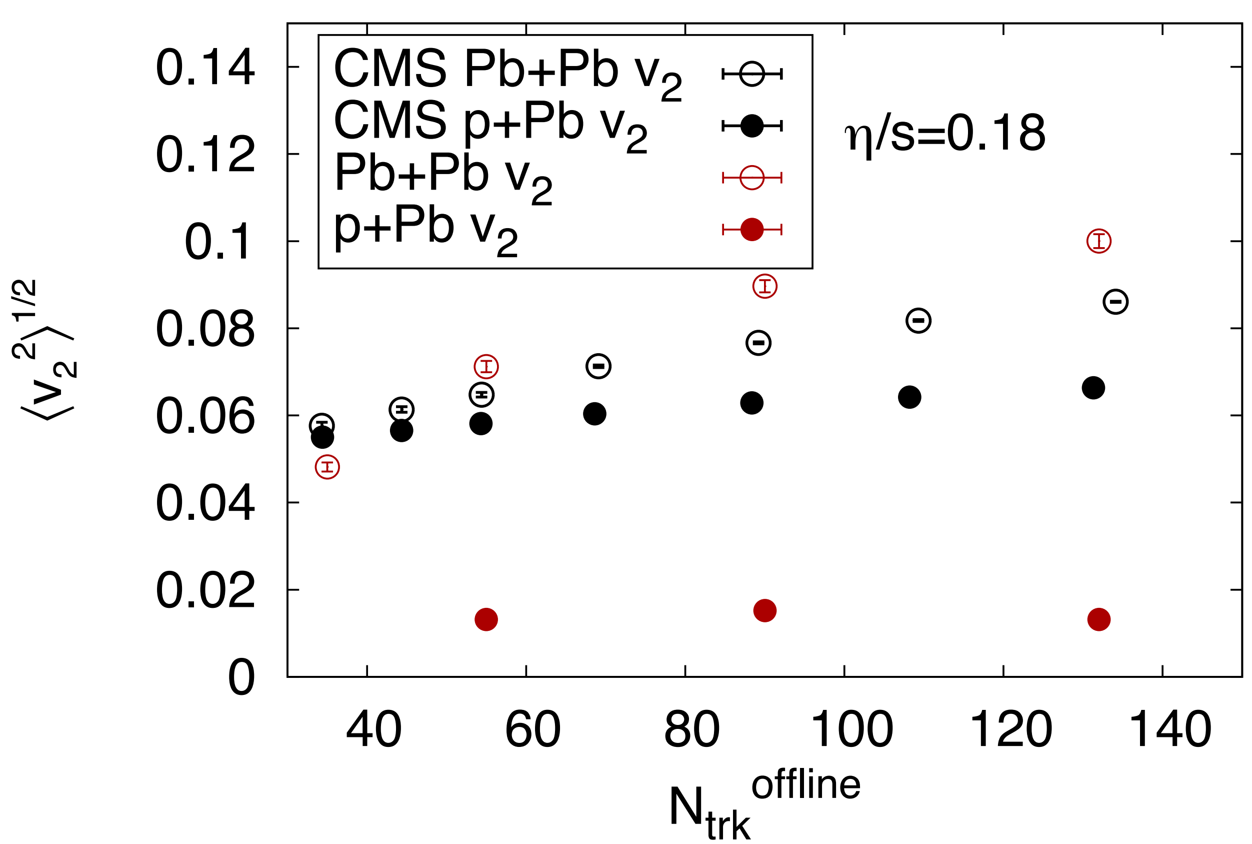


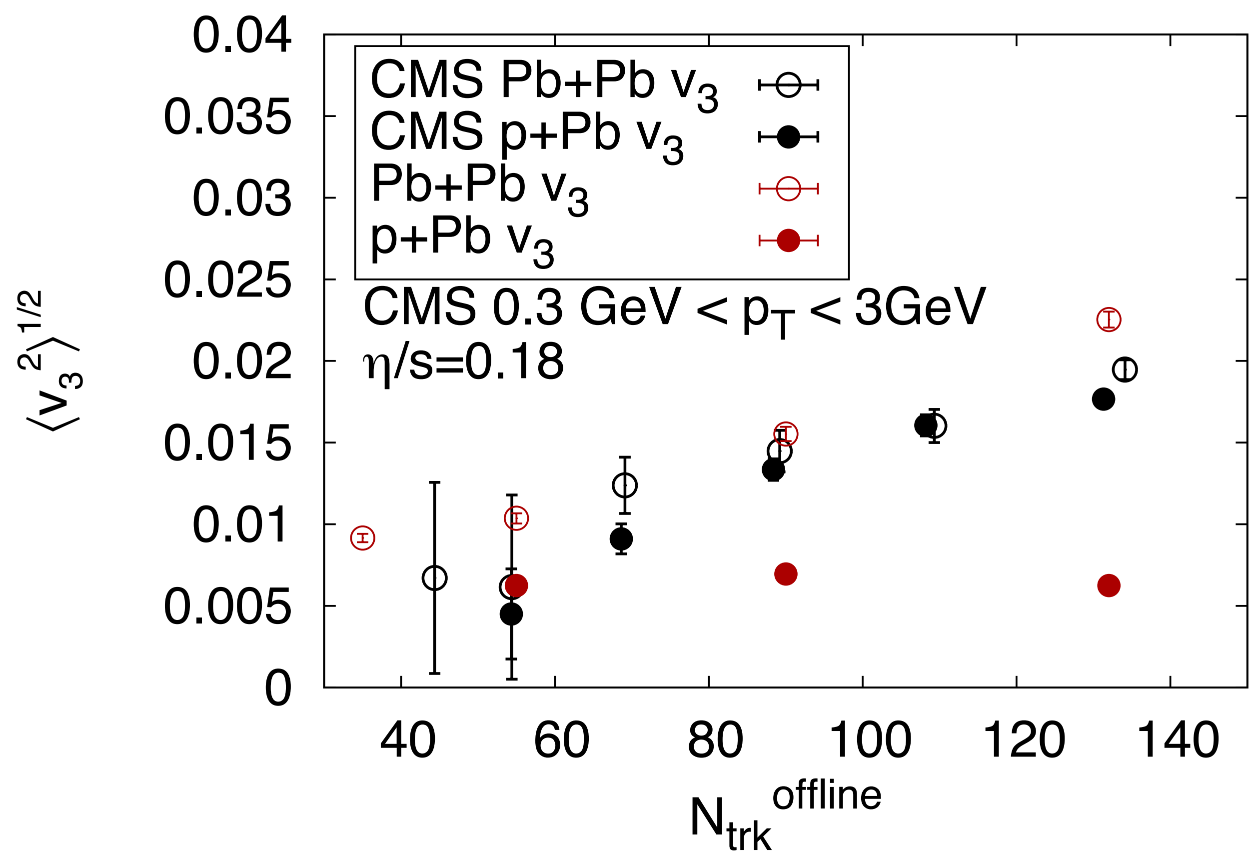


Red points: IP-Glasma + MUSIC

Fourier Harmonics in Pb+Pb and p+Pb

CMS COLLABORATION, PHYS.LETT. B724 (2013) 213-240

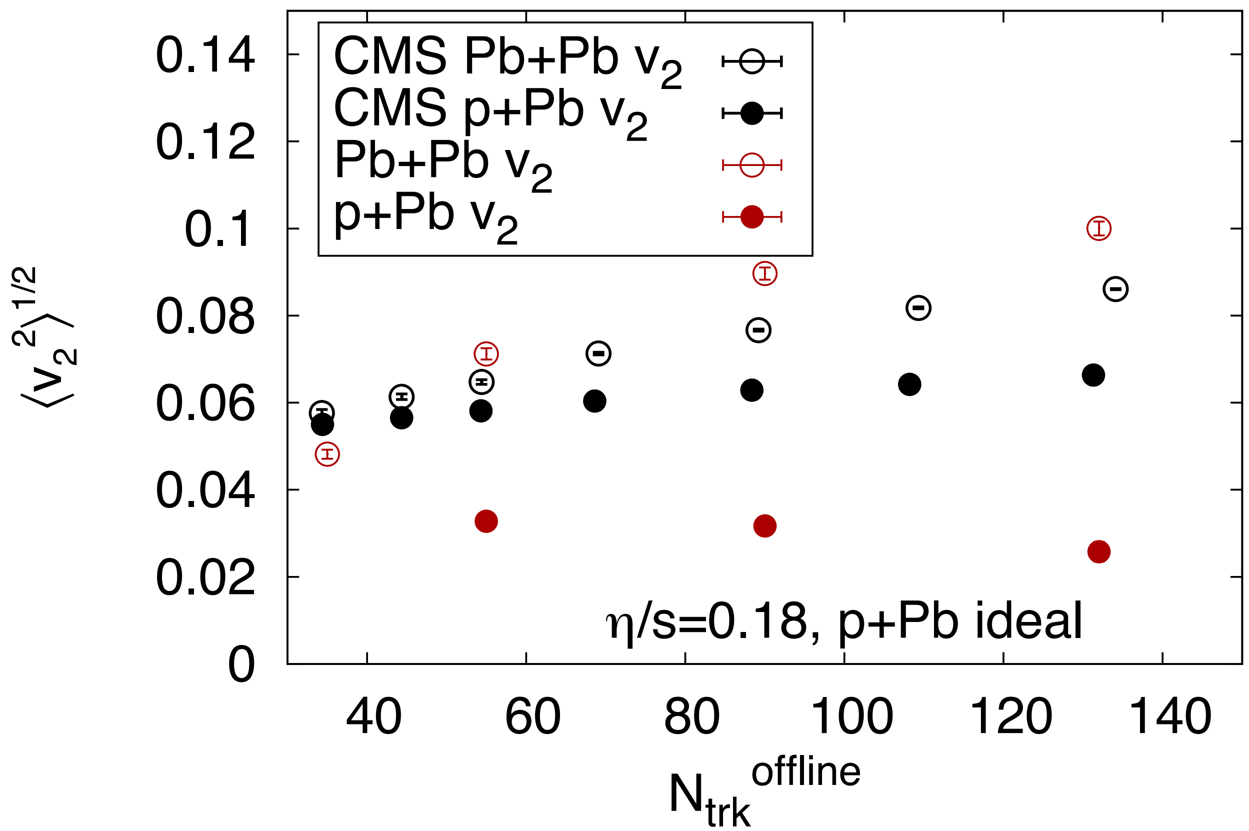


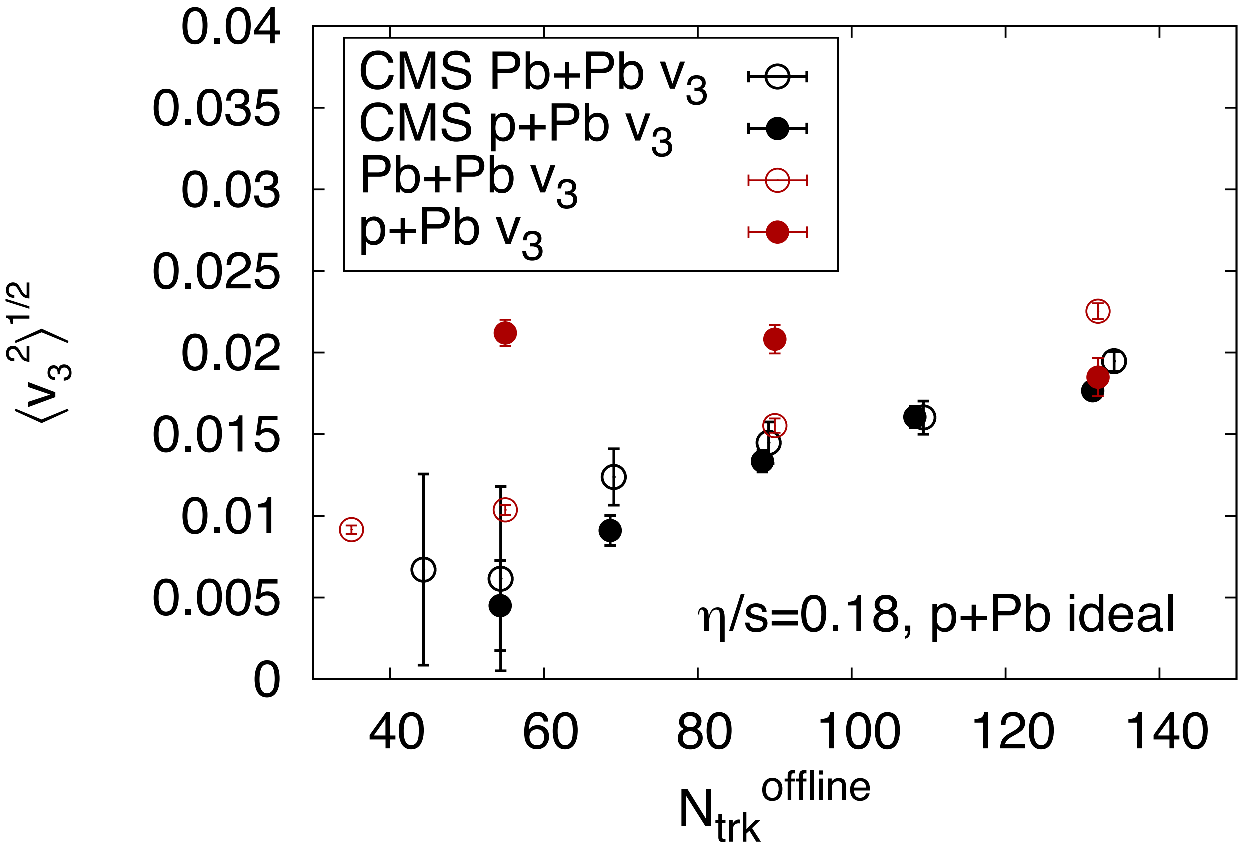


Red points: IP-Glasma + MUSIC

Fourier Harmonics in Pb+Pb and p+Pb

CMS COLLABORATION, PHYS.LETT. B724 (2013) 213-240



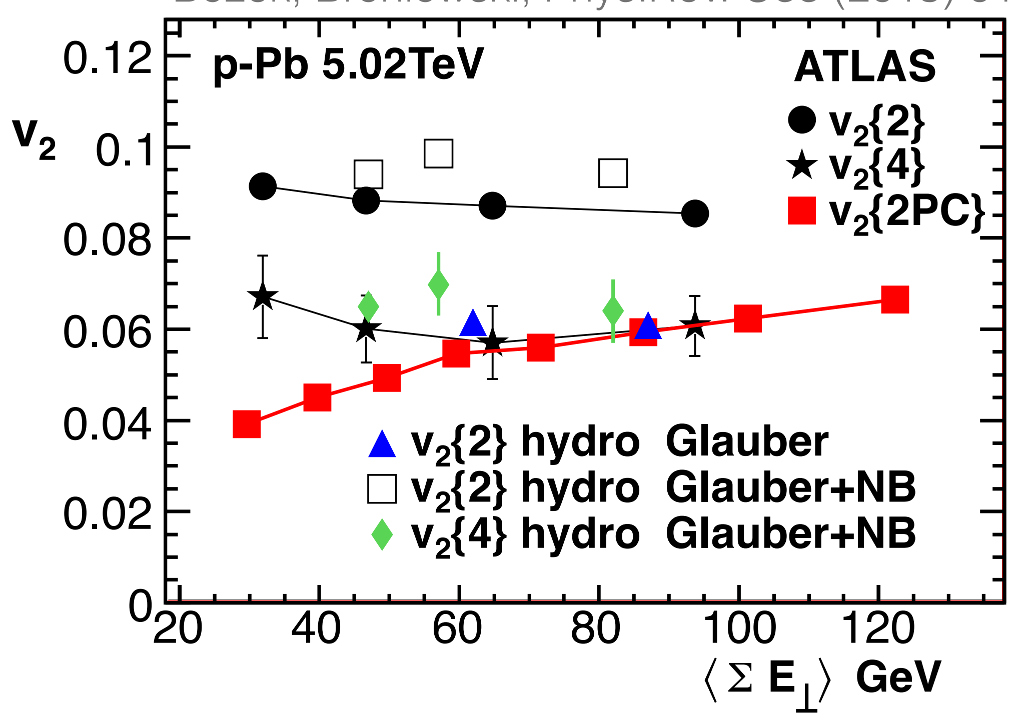


Red points: IP-Glasma + MUSIC

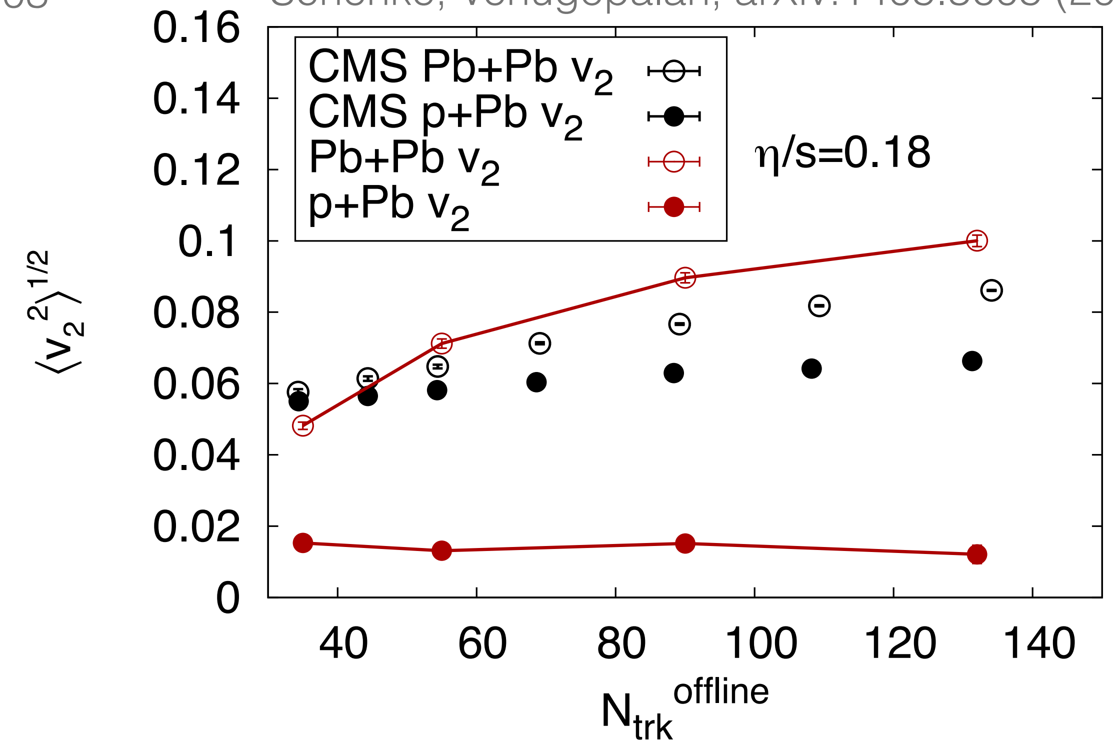
Small systems: New questions, new opportunities

- Can fluid dynamics work in such small systems? Viscous corrections become very large
- Initial state strongly depends on model
- Some models work, some don't. Not yet settled…

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



Schenke, Venugopalan, arXiv:1405.3605 (2014)

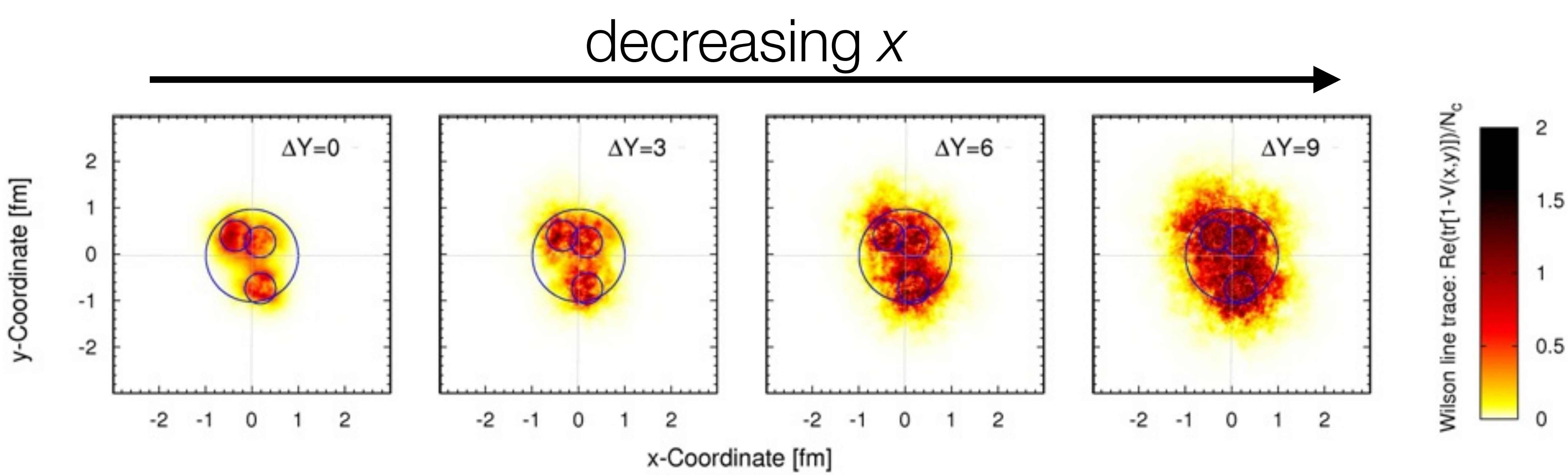


Are we sensitive to the shape of the proton?

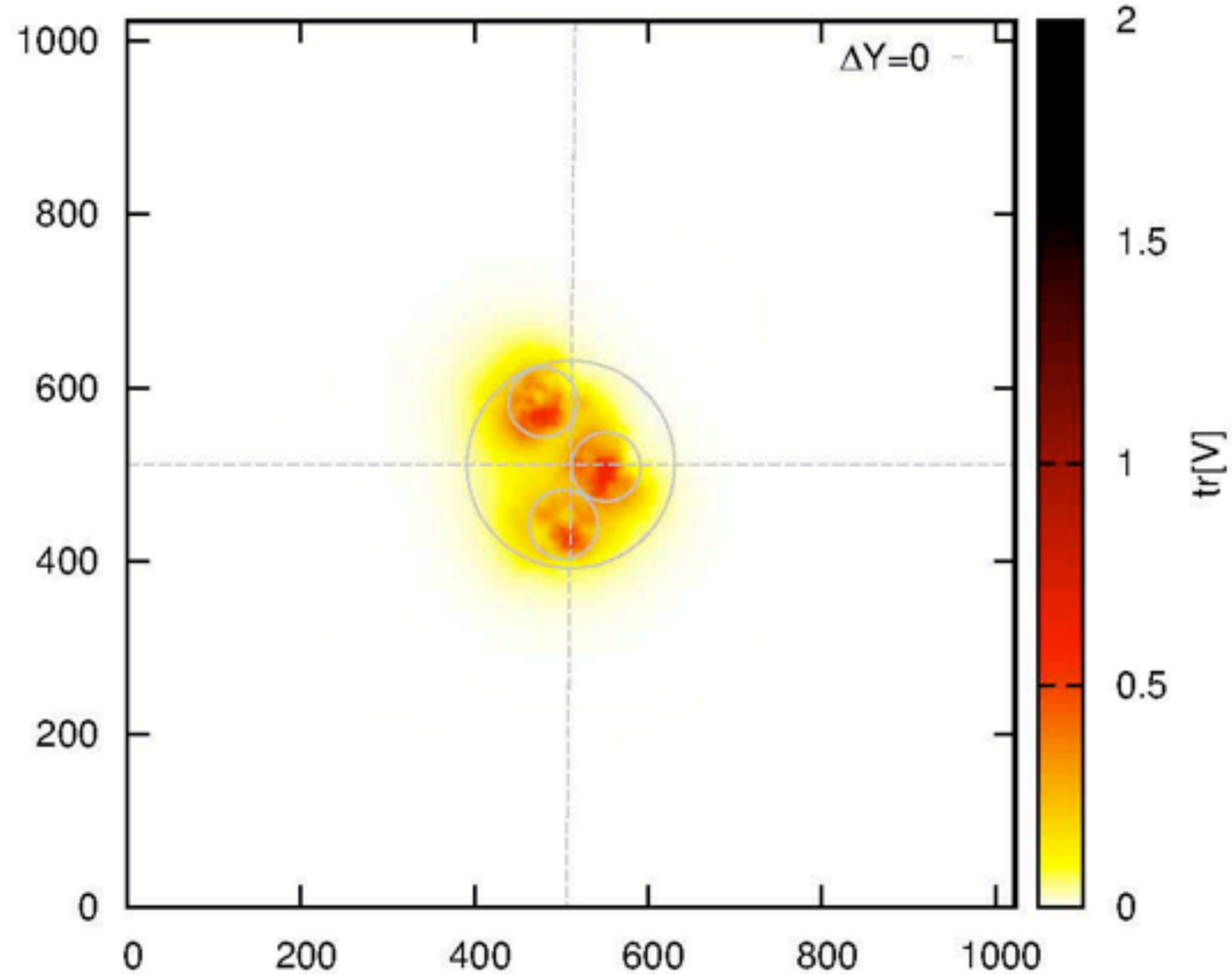
S. SCHLICHTING, B. SCHENKE, ARXIV:1407.8458

- Three "Constituent quarks" at large *x*

- JIMWLK evolution with infrared regulator to get gluon distribution at smaller *x*



Are we sensitive to the shape of the proton?



FIXED COUPLING JIMWLK EVOLUTION
OF TRACE OF THE WILSON LINE

Is viscous fluid dynamics even valid?

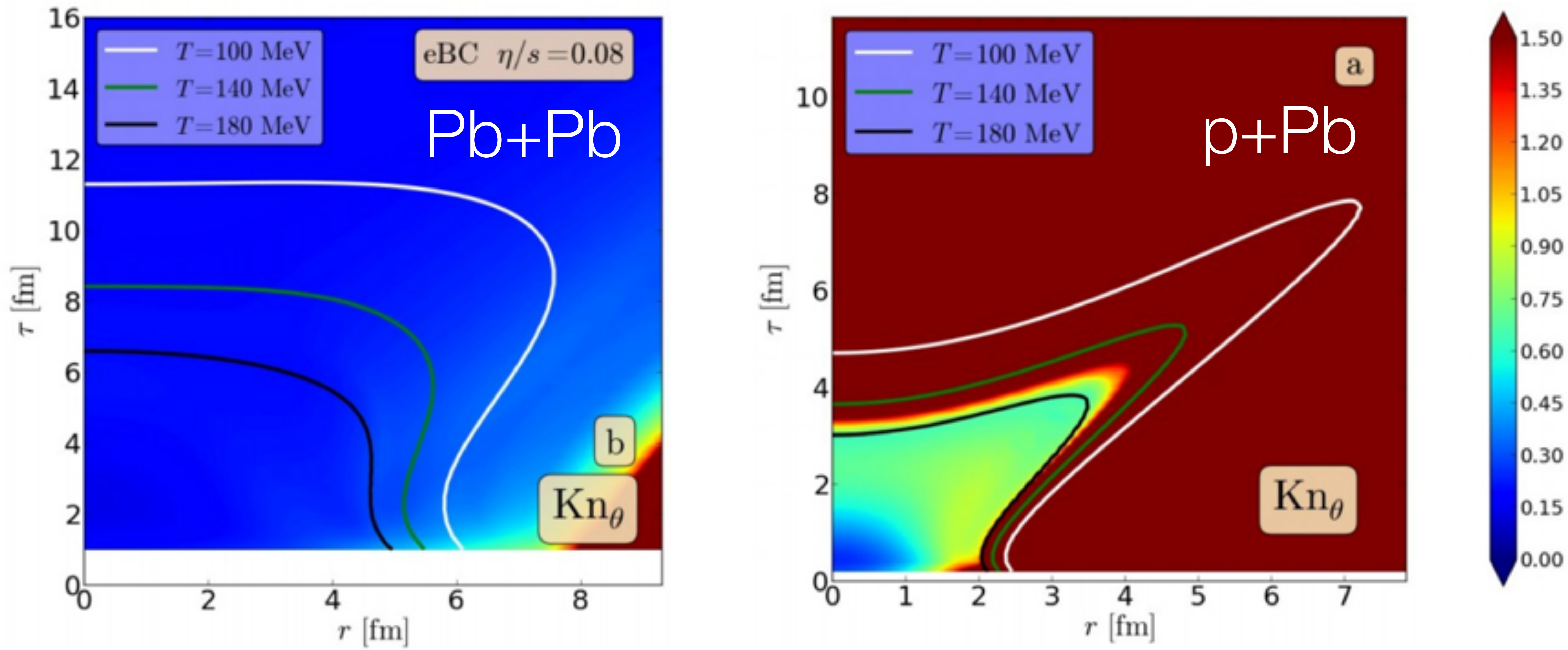
H. Niemi, G.S. Denicol, e-Print: arXiv:1404.7327

- Use the Knudsen number as a measure

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

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

- Small Knudsen number means fluid dynamics is valid



Is viscous fluid dynamics even valid?

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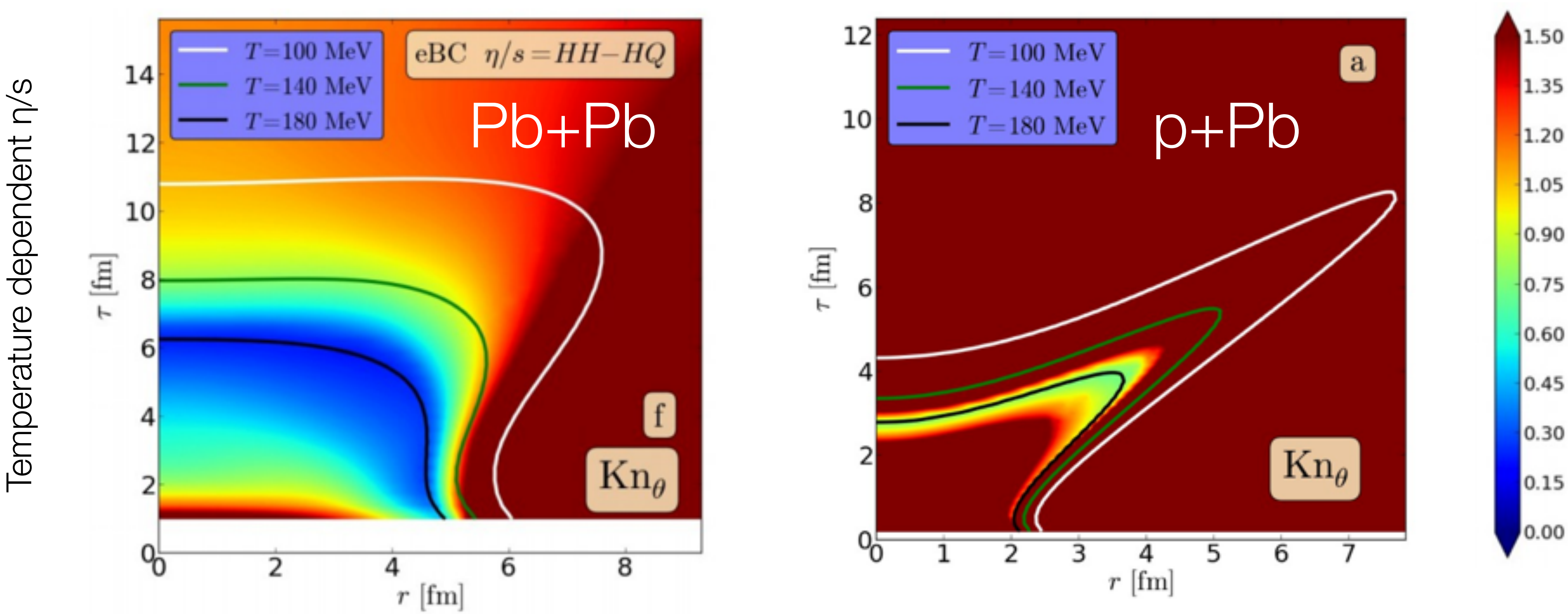
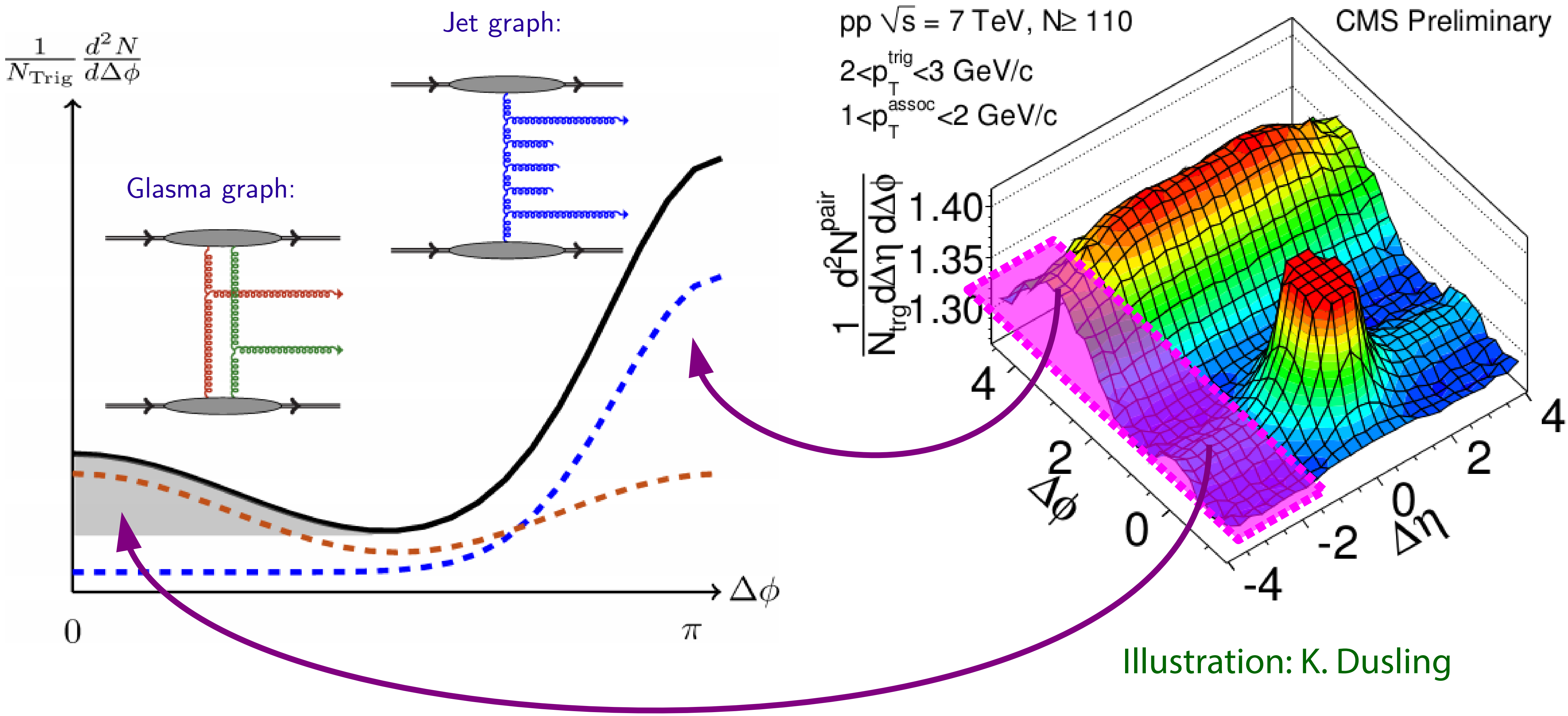


The ridge in high multiplicity p+p and p+A collisions

CGC produces angular correlations
that are long range in rapidity (think of flux tubes)



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

The ridge in high multiplicity p+p and p+A collisions

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

Correlation function: **p** and **q** momenta of produced gluons

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

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

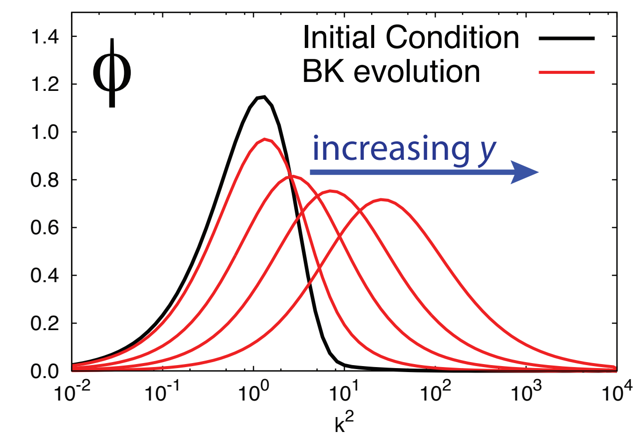
$$\Big\{ \phi_{A_1}^2(y_p,\mathbf{k}_\perp)\phi_{A_2}(y_p,\mathbf{p}_\perp-\mathbf{k}_\perp)[\phi_{A_2}(y_q,\mathbf{q}_\perp+\mathbf{k}_\perp)+\phi_{A_2}(y_q,\mathbf{q}_\perp-\mathbf{k}_\perp)]$$

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

Φ: unintegrated gluon distributions

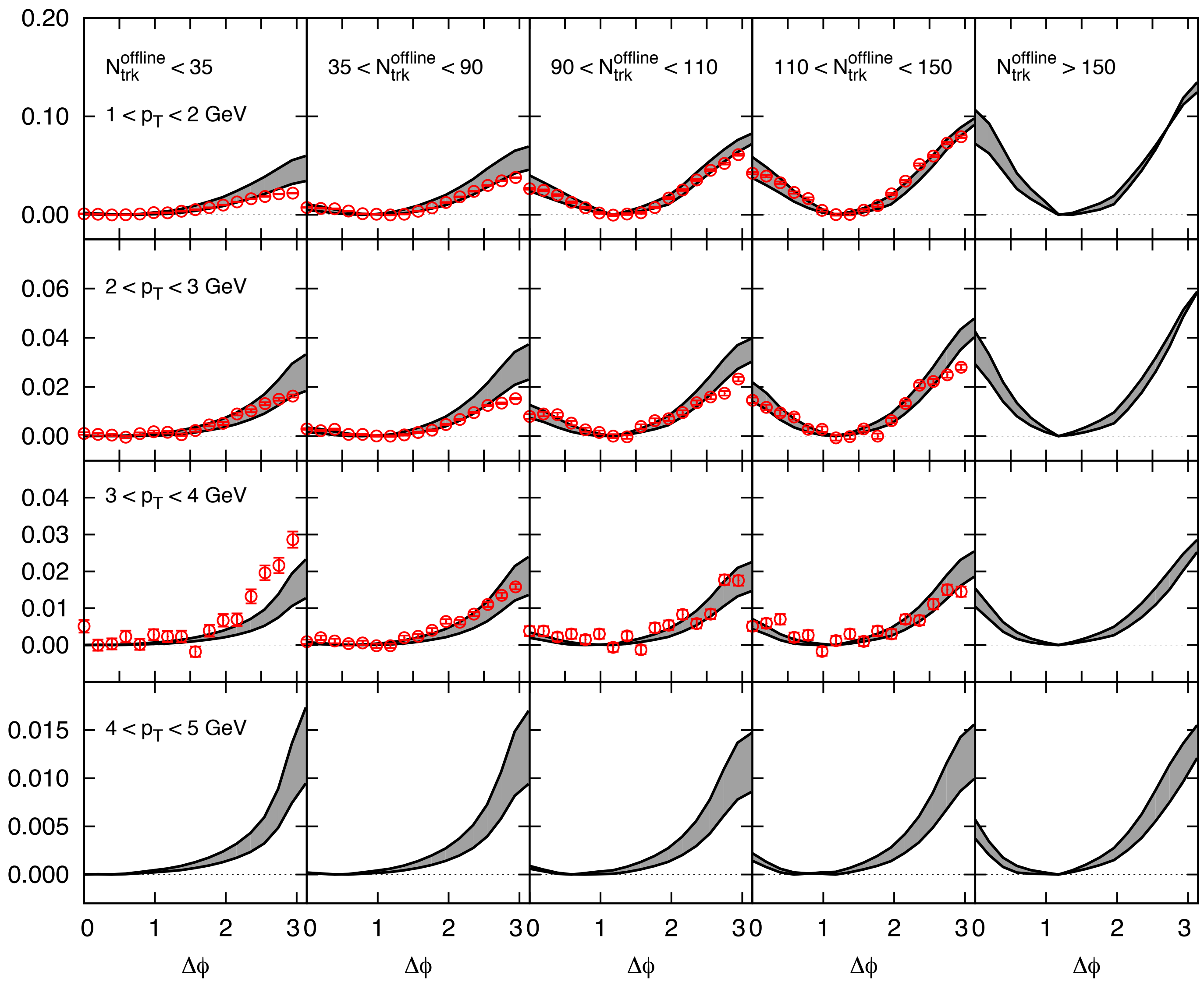
Their overlap determines the strength of the correlation

Arguments are vectors → angular dependence!



The ridge in high multiplicity p+p and p+A collisions

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

Is this maybe all there is? No flow in small systems?

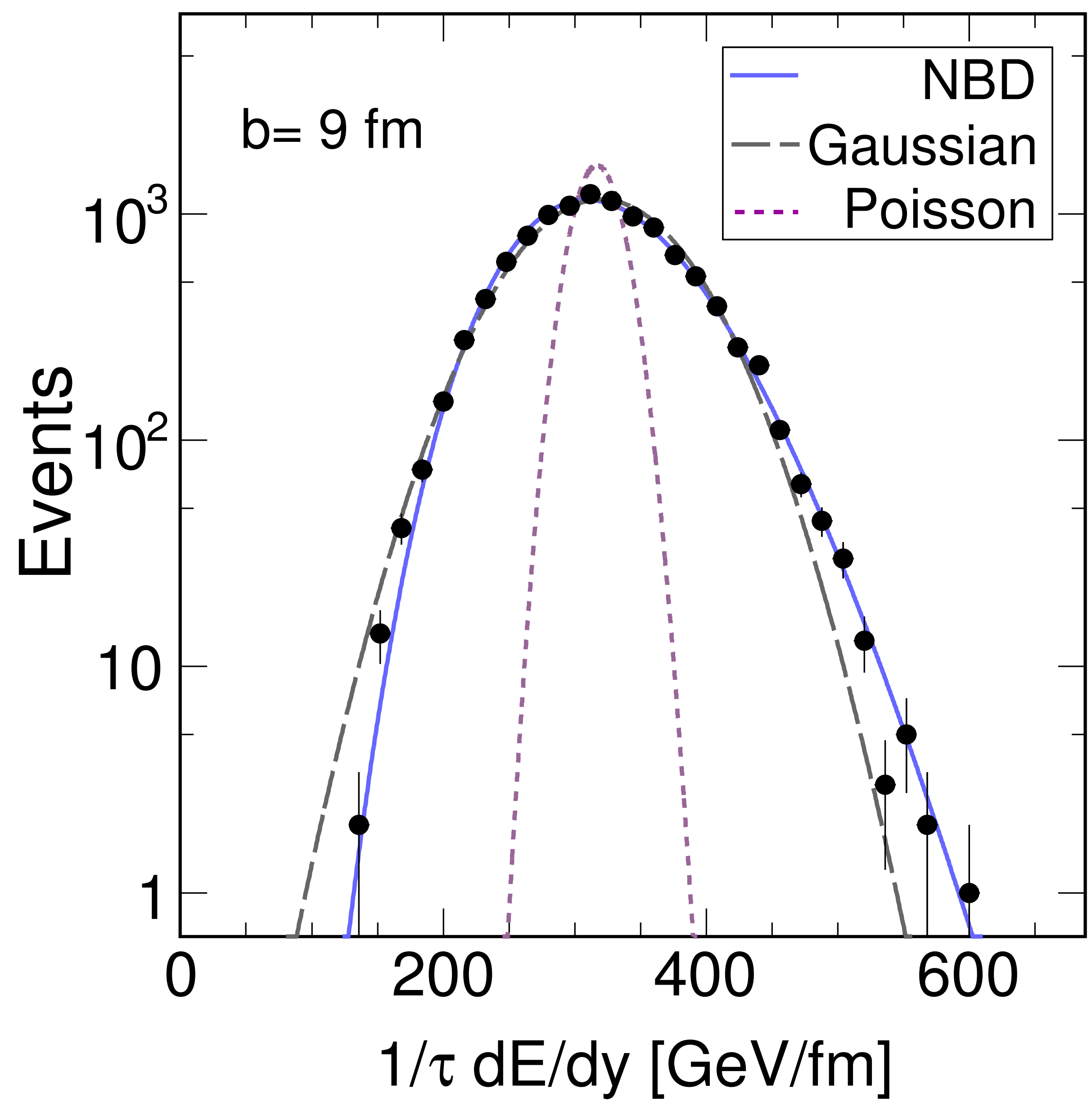
Conclusions

- Relativistic fluid dynamics has been very successful in describing the bulk properties of high energy heavy ion collisions
- Fluctuating initial conditions seem well under control at high energies - they allow the prediction of all flow harmonics
- Many recent advances: bulk viscosity, temperature dependence of transport parameters, hydro fluctuations, small systems
- We are now able to extract important quantitative information on the properties of hot and dense QCD matter from experimental data
- Small systems still a puzzle - how important are intrinsic correlations vs collective effects?

BACKUP

Negative binomial distributions

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



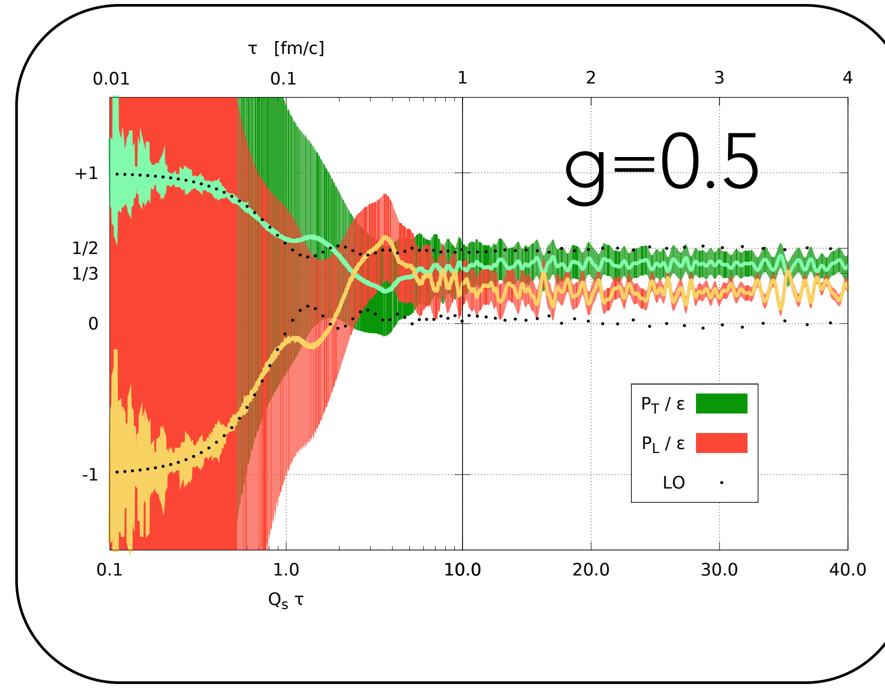
Best fit obtained with NBD

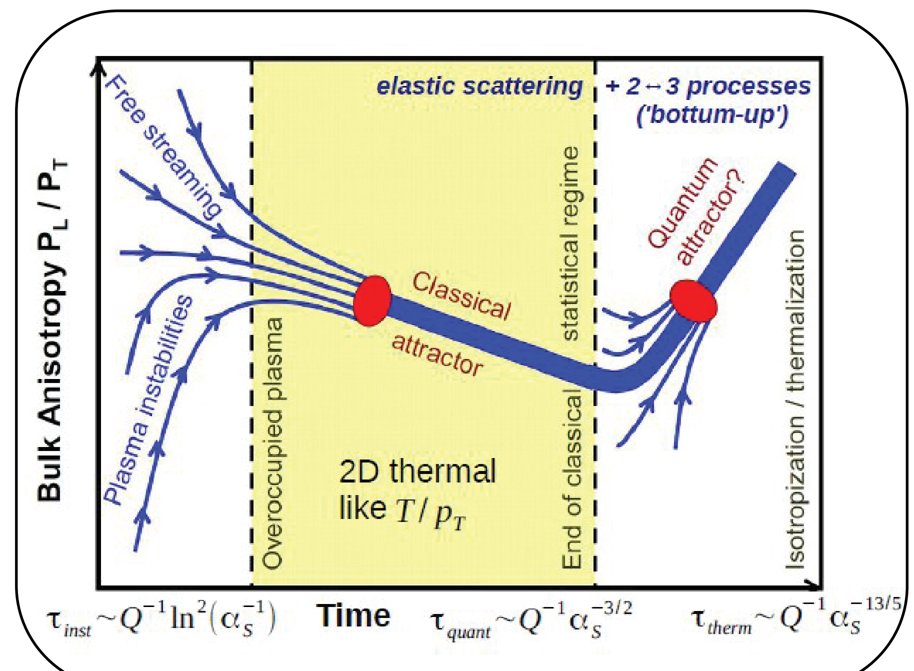
Pre-equilibrium dynamics - thermalization?

More sophisticated first principles computations of non-equilibrium early time dynamics

- Addressing the still open issue of rapid isotropization and thermalization

- Field has advanced significantly but issue is still under debate



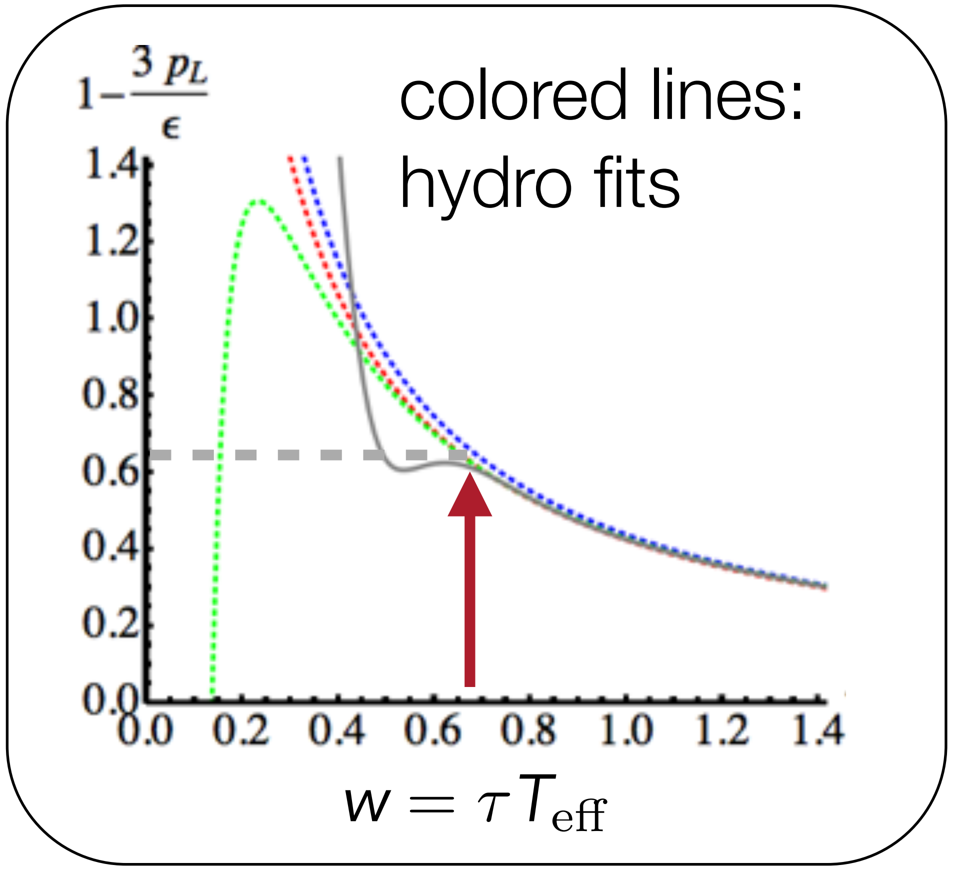


T. Epelbaum, F. Gelis, Phys.Rev.Lett. 111 (2013) 232301
J. Berges, K. Boguslavski, S. Schlichting, R. Venugopalan Phys.Rev. D89 (2014) 074011
M. Attems, A. Rebhan, M. Strickland, Phys.Rev. D87 (2013) 025010

Pre-equilibrium dynamics - thermalization?

Strong coupling limit:

AdS/CFT calculation shows "hydrodynamization" but no pressure isotropization at early times τ≈0.25 fm/c

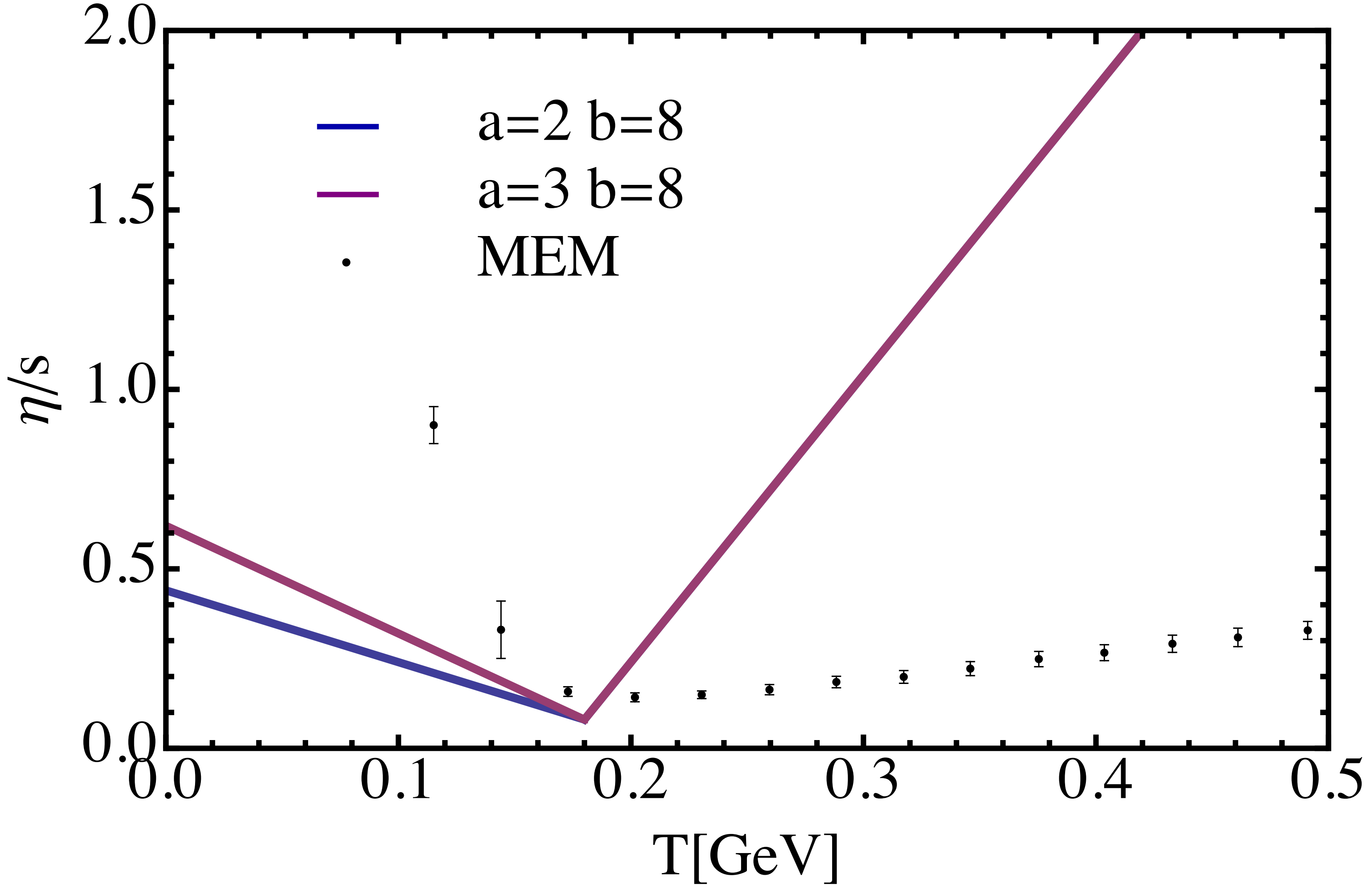


The pressure anisotropy is completely explained by dissipative hydrodynamics for τ≳0.25 fm/c

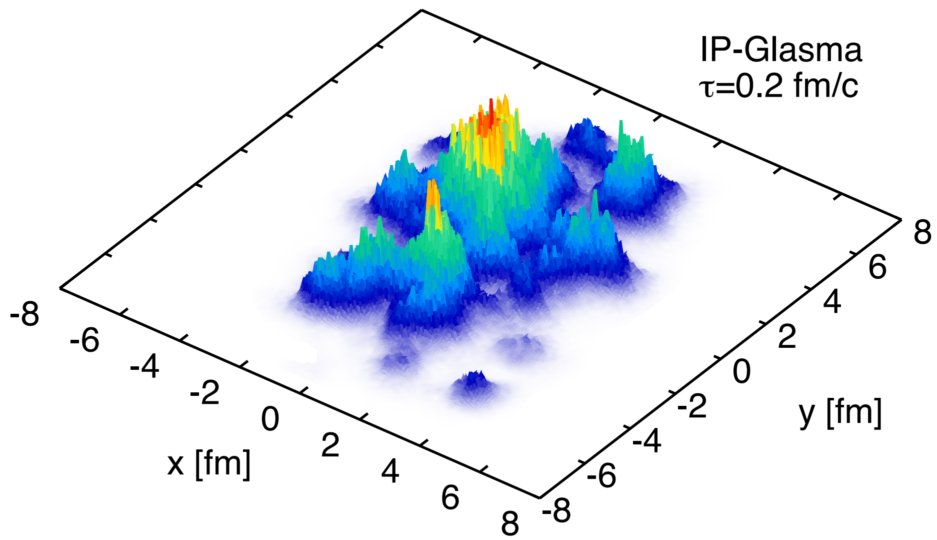
Before that non-equilibrium effects are important

M. P. Heller, R. Janik, P. Witaszczyk, Phys.Rev.Lett. 108 (2012) 201602

Temperature dependent η/s



Simple modeling of IP-Glasma?



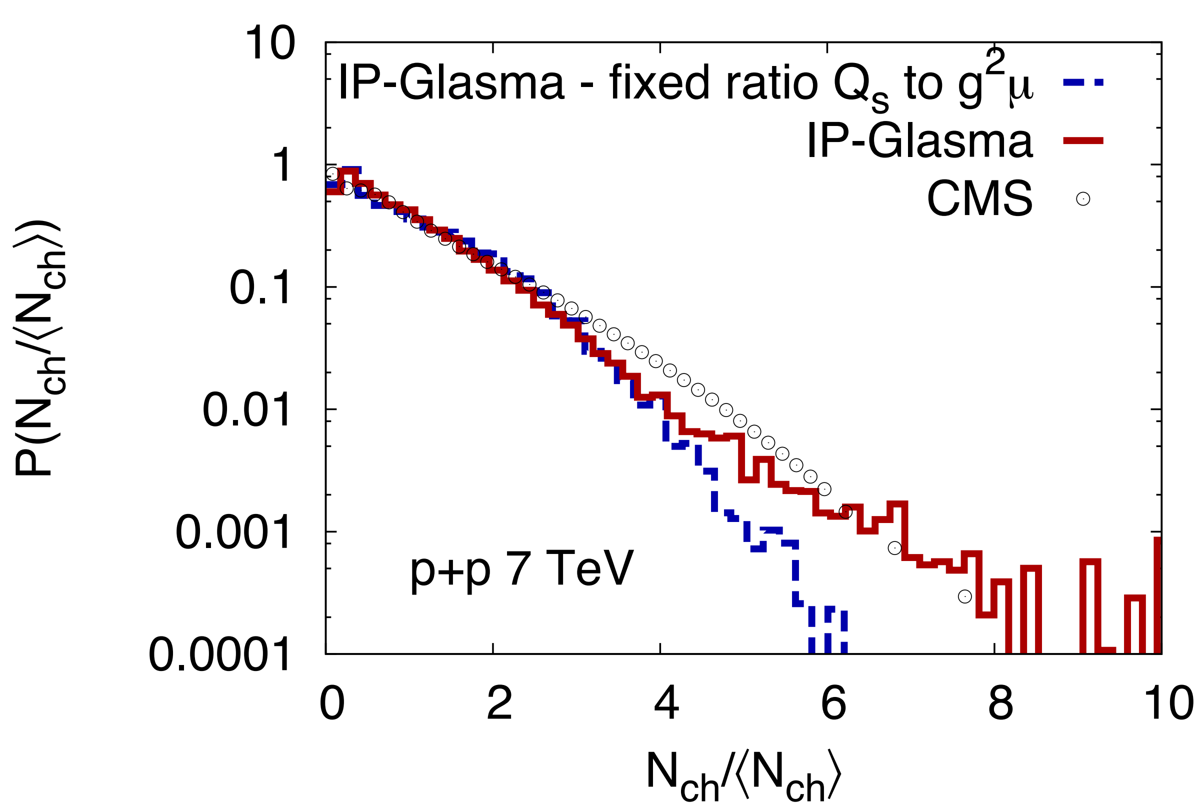
IP-Glasma includes sub-nucleonic fluctuations and correlation lengths related to the local Q_s

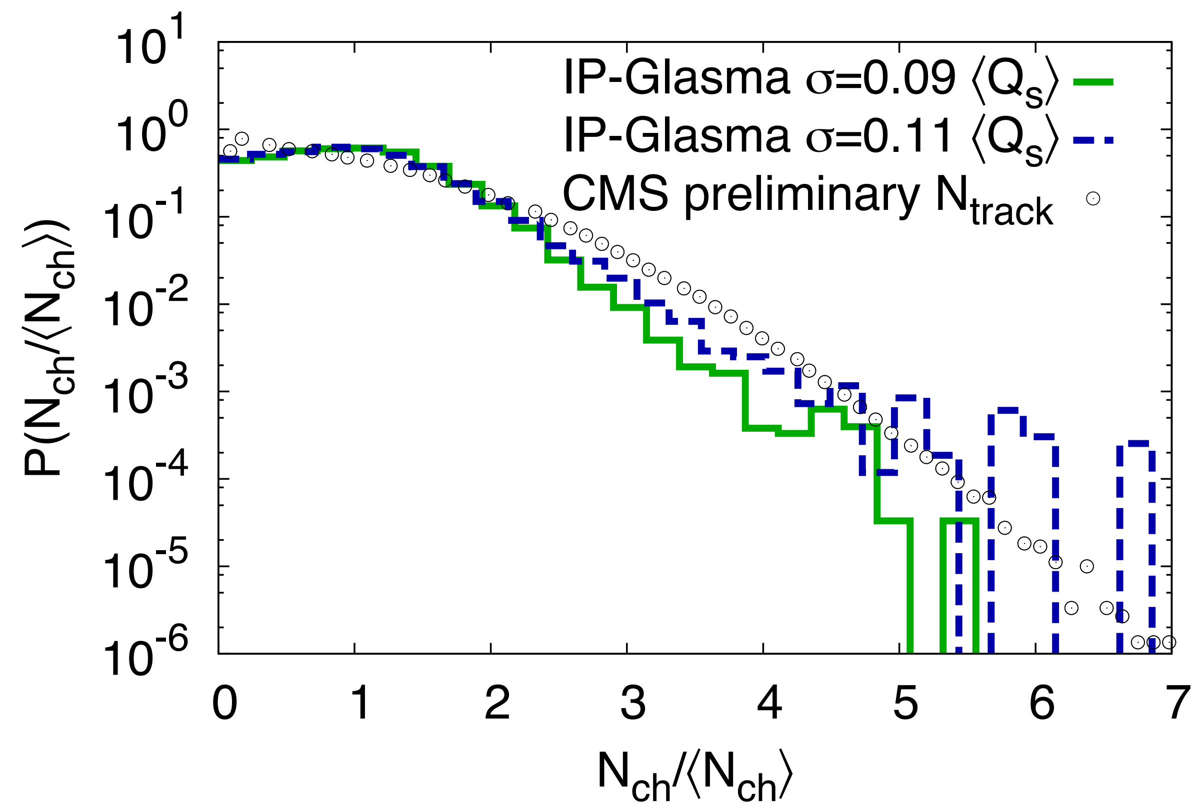
It should be possible to model this using an extension of an MC-Glauber model (faster)

Modeling the produced early time flow may be more difficult - but less important

Multiplicity distributions

B. SCHENKE, P. TRIBEDY, R. VENUGOPALAN, PHYS. REV. C89, 024901 (2014)
CMS COLLABORATION, JHEP 1101, 079 (2011)





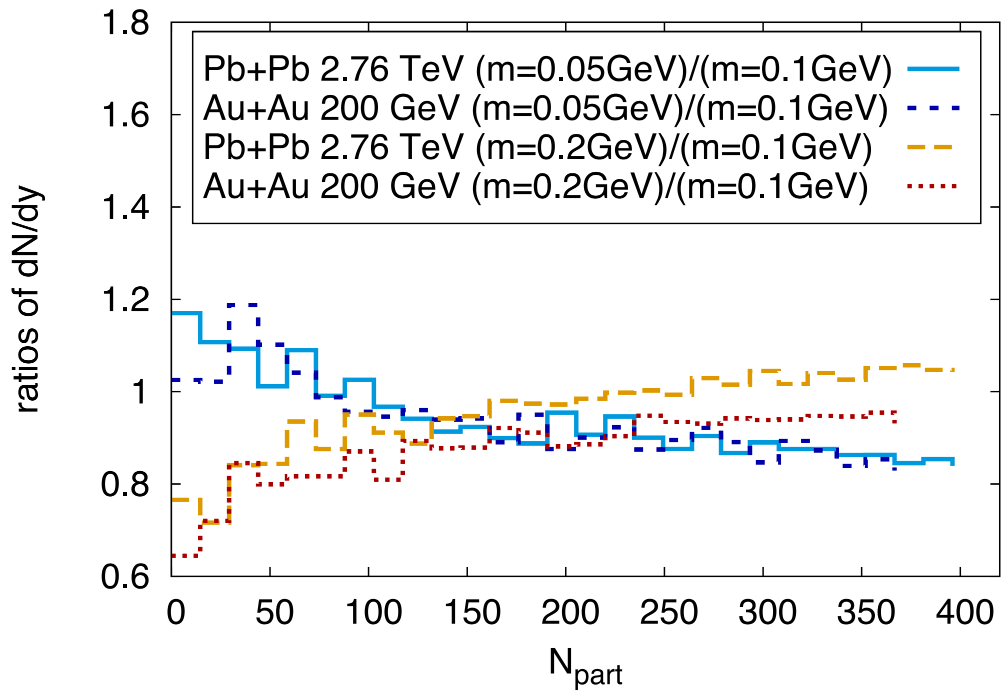
Multiplicity distributions in p+p and p+Pb collisions are not as wide as the experimental data

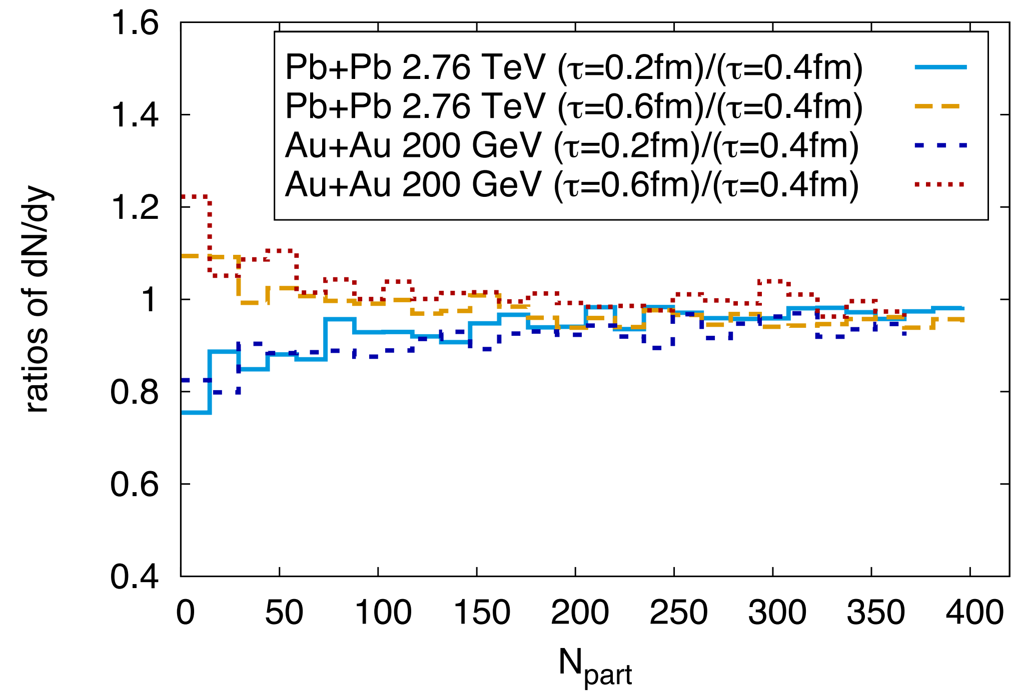
Introduce fluctuation of color charge density

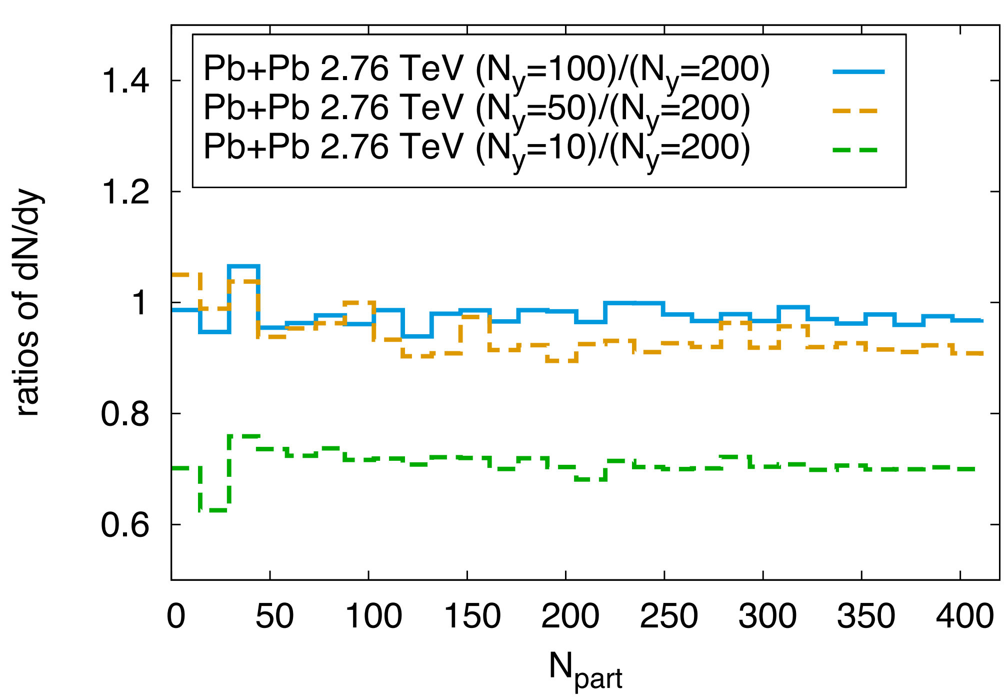
Hadronization can also widen the distribution

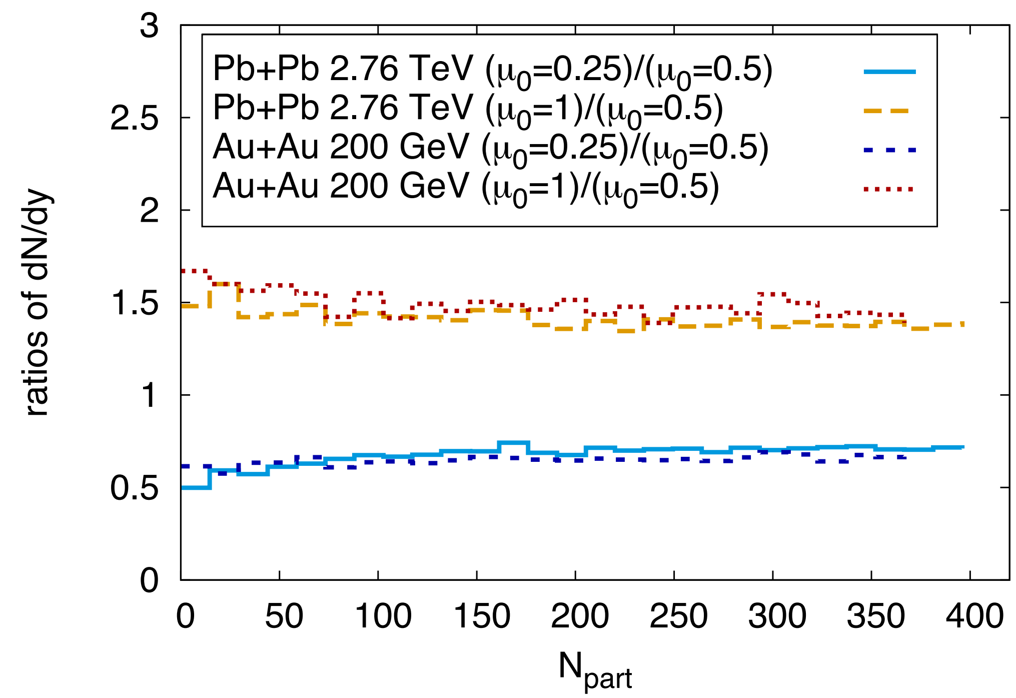
Parameter dependencies

B. SCHENKE, P. TRIBEDY, R. VENUGOPALAN, PHYS. REV. C89, 024901 (2014)









Parameter dependencies

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