Collective flow in relativistic nuclear collisions

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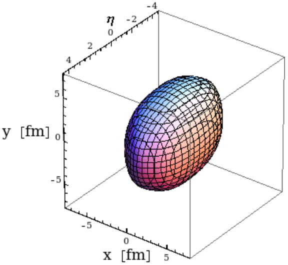
hydrodynamic model

- expansion of dense matter
- close to local equilibrium
- initial conditions
- equation of state
- flow + thermal emission + decays + rescattering



ideal hydrodynamics

- energy momentum tensor

$$T_{id}^{\mu\nu} = (\epsilon + p) g^{\mu\nu} - P u^{\mu} u^{\nu}$$

- ideal hydro (5 functions in 3+1D),
  energy density, pressure, flow velocity

$$\epsilon(x_\mu) \ , \ P(x_\mu) \ , \ \vec{v}(x_\mu)$$

- 4 hydrodynamic equations

$$\partial_\mu T^{\mu\nu} = 0$$

- equation of state (zero baryon density)

$$\epsilon = \epsilon(P)$$

massless gas $\epsilon = 3p$

hydro equations

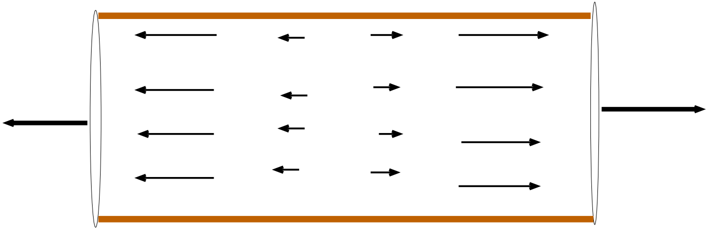
- using $\epsilon + P = Ts$, $d\epsilon = Tds$, $dP = sdT$
- we calculate $u_\nu \partial_\mu T^{\mu\nu}$

$$\partial_\mu (s u^\mu) = 0$$

  one equation = entropy conservation (ideal hydro)
- 3 other equations for flow velocity

$$s u_\mu \partial^\mu u^\nu = (g^{\mu\nu} - u^\mu u^\nu)\partial_\mu P$$

longitudinal expansion



Bjorken flow

- the density depends on the proper time $\tau = \sqrt{t^2 - z^2}$ only,
  flow velocity $u^\mu = (t/\tau, 0, 0, z/\tau)$
- one equation

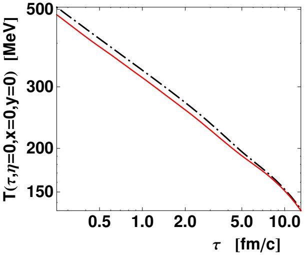
$$\frac{d\epsilon(\tau)}{d\tau} = -\frac{\epsilon(\tau) + P(\tau)}{\tau}$$

  cooling from longitudinal expansion
- if $\frac{1}{3}\epsilon \simeq P$

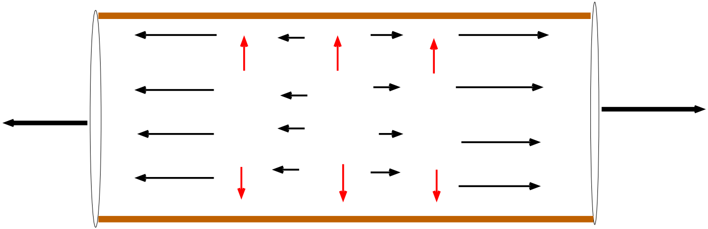
$$\epsilon(\tau) = \epsilon_0 \left(\frac{\tau_0}{\tau}\right)^{4/3}$$

- in 3+1D faster cooling when transverse expansion sets in

cooling in 2+1D and 3+1D



longitudinal+transverse expansion

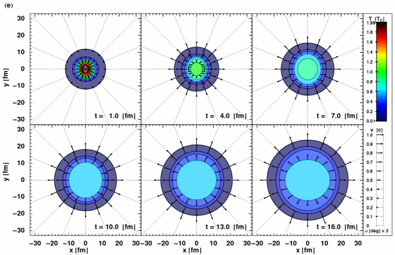


3+1D expansion

collective transverse expansion

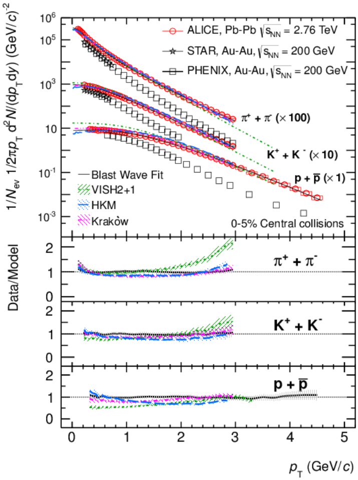
$$u^\mu \partial_\mu u_x = -\frac{1+u_x^2}{sT}\partial_x P - \frac{u_x u_y}{sT}\partial_y P + \dots$$
$$u^\mu \partial_\mu u_y = -\frac{1+u_y^2}{sT}\partial_y P - \frac{u_x u_y}{sT}\partial_x P + \dots$$

faster expansion in the direction of large pressure gradient



M. Chojnacki

OBSERVATION 1 - transverse flow

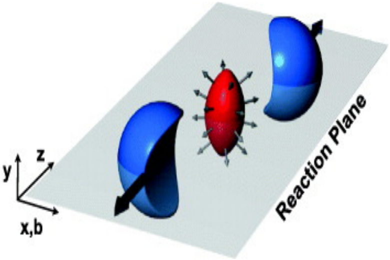


- spectra flatter due to flow
- stronger flow at the LHC
- stronger effect for heavy particles
- only soft spectra from hydro $p_\perp < 2$GeV
- chemical ratios - normalization
- excess of soft pions?

asymmetry in the transverse plane at finite impact parameter

Glauber model, KLN model, IP-Glasma

eccentricity - $\epsilon_2 = -\frac{\int dxdy(x^2-y^2)\rho(x,y)}{\int dxdy(x^2+y^2)\rho(x,y)}$



Snellings 2011

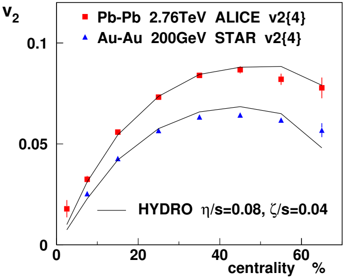
larger gradient and stronger flow in-plane - $v_2 > 0$ - **elliptic flow**

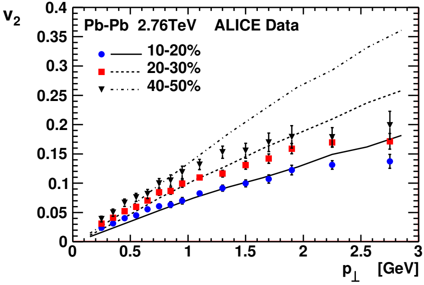
$$\frac{dN}{d\phi} \propto 1 + 2v_2 cos(2\phi)$$

$$\epsilon_2 + \text{HYDRO RESPONSE} \longrightarrow \text{v}_2$$

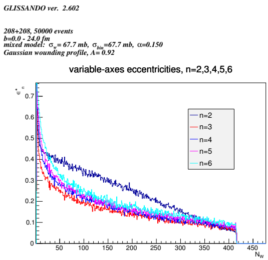
Event Plane (Reaction plane) must be reconstructed in each event

OBSERVATION 2 - Elliptic flow



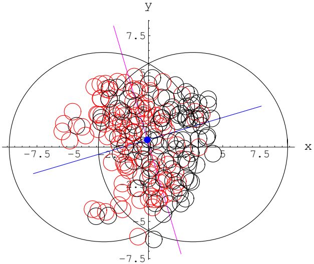


initial shape asymmetry transformed into flow asymmetry
strong indication of collective behavior



smoking gun for collectivity

fluctuating initial conditions



fluctuating initial density

$\rightarrow$ larger eccentricity

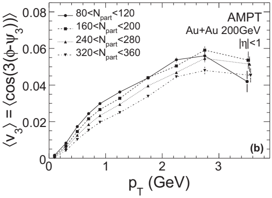
$\rightarrow$ fluctuating eccentricity

$\rightarrow$ triangular deformation ϵ_3

$\rightarrow$ dipolar (directed) flow v_1

$\rightarrow$ $< p_\perp >$ fluctuations

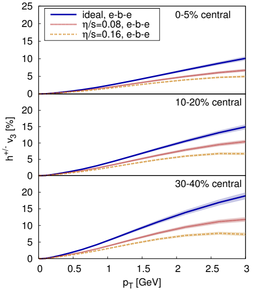
$\rightarrow$ RP orientation, torqued fireball



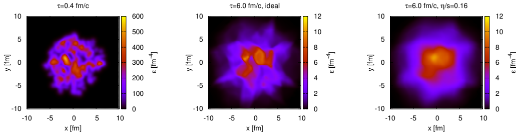
B. Alver, G. Roland

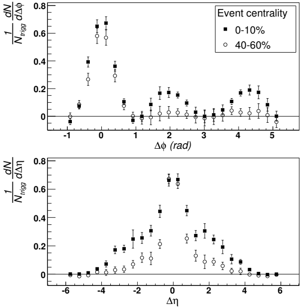
$$\frac{dN}{d\phi} \propto 1+2v_1\cos(\phi-\Psi_1)+2v_2\cos(2(\phi-\Psi_2))+2v_3\cos(3(\phi-\Psi_3))+\ldots$$

Event by event hydro



Schenke, Jeon, Gale, Phys. Rev. 106, 042301 (2011)



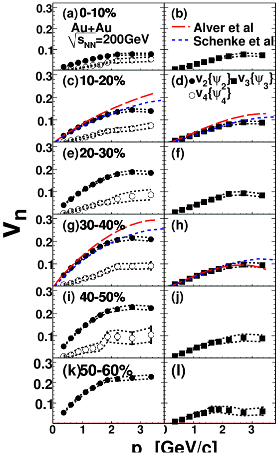


Takahashi et al., Phys. Rev. 103, 242301 (2009)

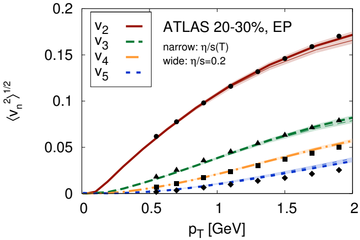
event by event ideal hydro - Andrade, Grassi, Hama, Kodama, Socolowski 2006

OBSERVATION 3 - triangular flow

odd harmonics generated by fluctuations in initial conditions



PHENIX

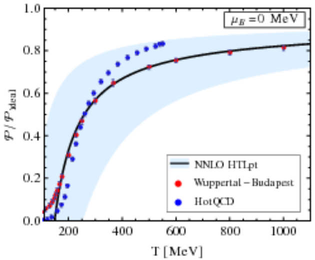


C.Gale et al. arXiv:1209.6330

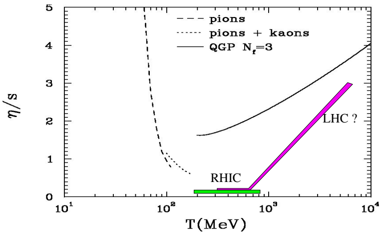
(viscous) event by event hydrodynamics

sQGP or wQGP ?

How to see the difference?



Haque, Andersen, Mustafa, Strickland, Su, 2013



Csernai, Kapusta, McLerran, 2006

small viscosity fluid

- strongly coupled theory $\frac{\eta}{s} = \frac{1}{4\pi} \simeq 0.08$
- short mean-free path, large cross section

$$\eta = \frac{1}{3} n p L_{mfp}$$

- for $\eta/s = 0.08$

$$L_{mfp} = \frac{3s}{4\pi n p} \simeq 0.15 - 0.3 fm$$

- mean-free path comparable to wavelength

$$L_{mfp} \simeq 0.9\lambda$$

- mean-free path comparable to inter-particle distance

$$L_{mfp} \simeq 0.5 n^{-1/3}$$

all of the above means no quasi-particles, no kinetic description energy-momentum tensor

$$T^{\mu\nu} = \begin{pmatrix} \epsilon & 0 & 0 & 0 \\ 0 & p + \Pi & 0 & 0 \\ 0 & 0 & p + \Pi & 0 \\ 0 & 0 & 0 & p + \Pi \end{pmatrix} + \pi^{\mu\nu}$$

- shear viscosity

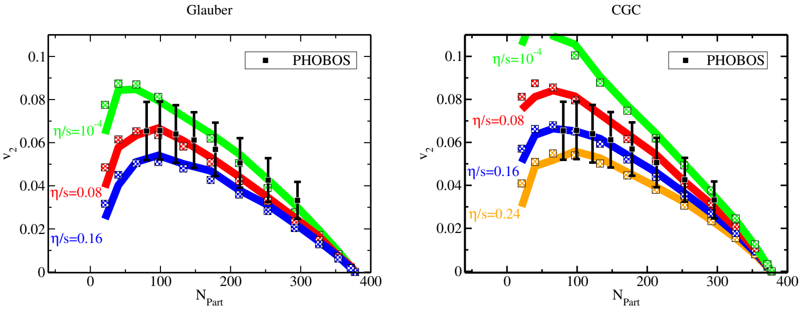
$$\Delta^{\mu\alpha}\Delta^{\nu\beta}u^\gamma\partial_\gamma\pi_{\alpha\beta} = \frac{2\eta\sigma^{\mu\nu} - \pi^{\mu\nu}}{\tau_\pi} - \frac{1}{2}\pi^{\mu\nu}\frac{\eta T}{\tau_\pi}\partial_\alpha\left(\frac{\tau_\pi u^\alpha}{\eta T}\right)$$

- bulk viscosity

$$u^\gamma\partial_\gamma\Pi = \frac{-\zeta\partial_\gamma u^\gamma - \Pi}{\tau_\Pi} - \frac{1}{2}\Pi\frac{\zeta T}{\tau_\Pi}\partial_\alpha\left(\frac{\tau_\Pi u^\alpha}{\zeta T}\right)$$

viscosity corrections from velocity gradients

OBSERVATION 4 - small viscosity



Luzum, Romatschke, Phys. Rev. C78, 034915 (2009)

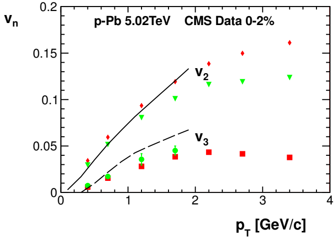
Model uncertainties

Small viscosity : $\eta/s = 0.08 - 0.2$ - sQGP

Strongly interacting fluid

OBSERVATION 5 - Elliptic and triangular flow observed in p-Pb

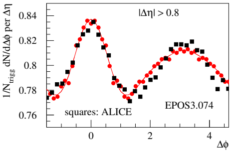
- Glauber MC initial cond. - agreement with data



PB, W.Broniowski, G. Torrieri arXiv:1306.5442; G.Y. Qin, B. Müller 1306.3439; I. Kozlov et al. 1405.3976; A. Bzdak et al. 1304.34003

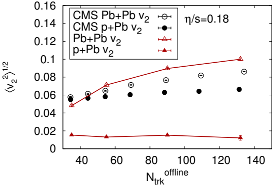
- v_2, v_3 consistent with hydro (Glauber MC, EPOS3)
- sensitive probe of init. cond.

- EPOS3 - agreement with data



K. Werner et al. 1307.4379

- IP-Glasma initial cond. - small v_2, v_3 !

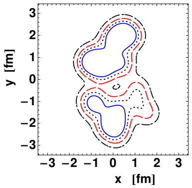


B. Schenke, R. Venugopalan 1405.3605

$v_{2,3}$ - hydro response to initial deformation !

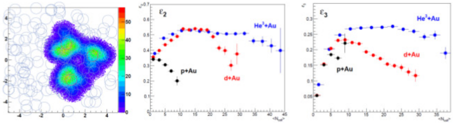
Small system with large deformation

- deuteron projectile
  intrinsic deformation dominates over fluctuations $\rightarrow$ large v_2



PB 1112.0915

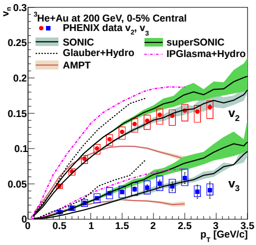
- ^{3}He projectile
  larger triangular flow



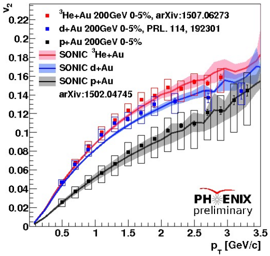
Nagle et al. arXiv:1312.4565

central collisions - deformed fireball, **control of initial geometry**

Elliptic and triangular flow in d-Au, ^{3}He-Au and p-Au



PHENIX, arXiv:1507.06273



PHENIX

- observed $v_3 \longrightarrow$ collectivity
- hierarchy of v_2 and v_3 consistent with collective response on fireball geometry

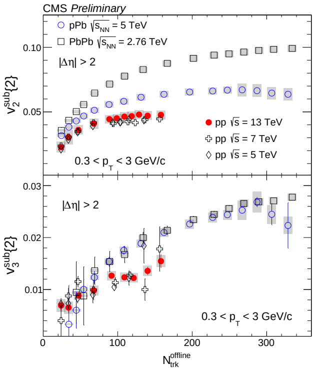
hydrodynamic calculations reproduce the data

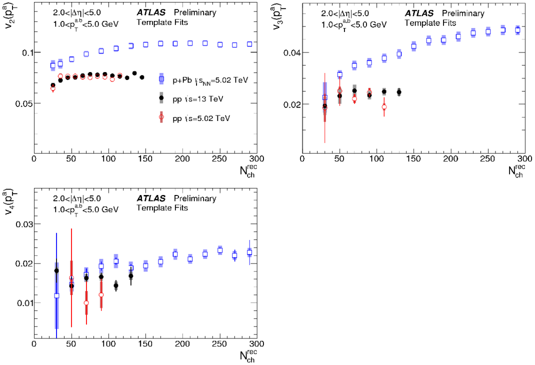
sensitivity to details, limits of applicability of hydro - systematic model uncertainty

large eccentricity - large flow component

collective response to geometry

Collective flow in pp?

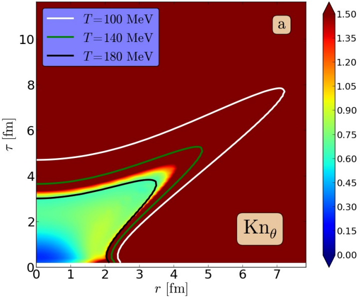




Collective like correlations observed in pp

Hydrodynamics in small systems?

Hydrodynamics $K < 1$



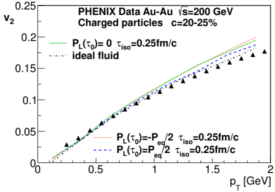
H. Niemi, G. Denicol 1404.7327

large gradients in the evolution

higher order corrections,

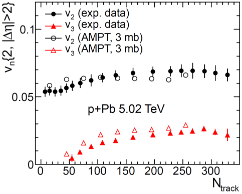
effective viscosity reduced

1. Early stage, pressure asymmetry $P_L \ll P_\perp$



PB, I. Wyskiel-Piekarska 1011.6210; J. Vredevoogt, S. Pratt 0810.4325
early pressure asymmetry - irrelevant

2. Late stage, decoupling at freeze-out



A.Bzdak, G.L. Ma 1404.4129; L. He et al. 1502.05572
hydrodynamics similar to AMPT cascade

Summary

nuclear collisions - hydrodynamic expansion

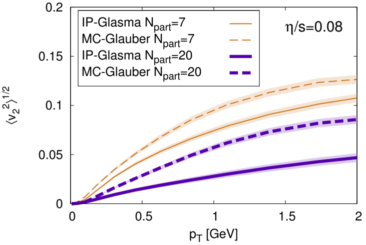
- significant transverse flow generated
- elliptic flow reflecting initial asymmetry
- triangular flow - fluctuating initial conditions - flow fluctuations
- small viscosity fluid - sQGP

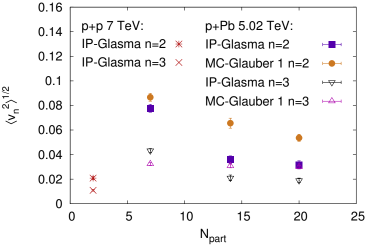
NEW: colectivity in small systems

- **flow in small systems observed** (p-A, . . .)
  - density driven collective expansion
  - collectivity $\neq$ QGP ??

Collective expansion more general than hydrodynamic expansion

3+1D visc. hydro

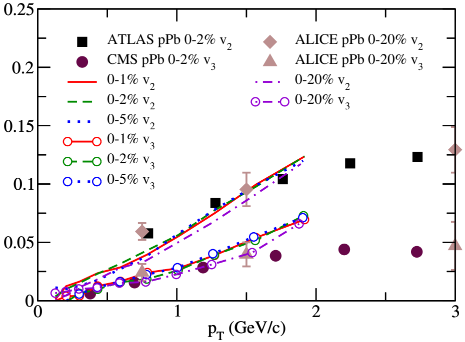




dependence on initial model, v_n small for IP-Glasma i.c.

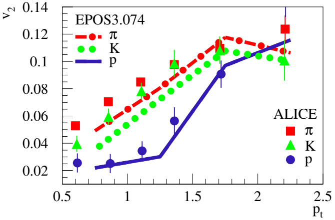
A.Bzdak, B.Schenke, P.Tribedy, R.Venugopalan - arXiv: 1304.3403

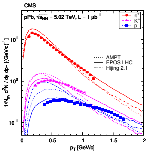
3+1D hydro



G-Y.Qin, B. Müller arXiv: 1306.3439

EPOS

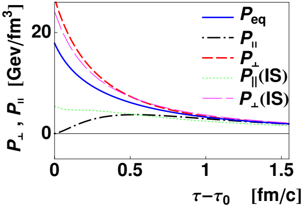


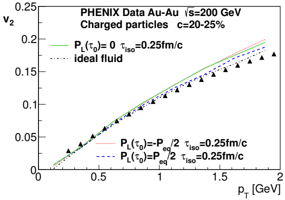


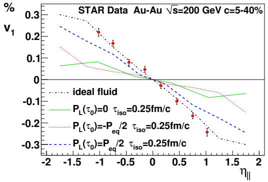
excellent description of spectra

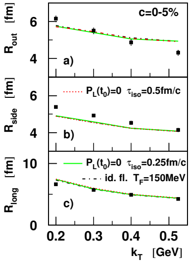
K. Werner, M. Bleicher, B. Guiot, Iu. Karpenko, T. Pierog - arXiv:1307.4379

pressure anisotropy



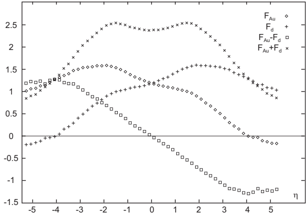






PB, I. Wyskiel - arXiv:1009.0701

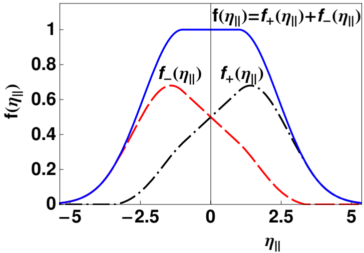
- early pressure anisotropy irrelevant!

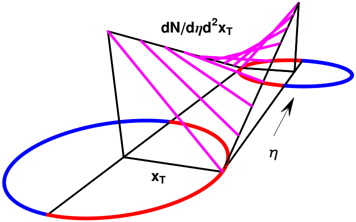


$$\rho(\eta,x,y) \propto f_+(\eta)N_+(x,y) + f_-(\eta)N_-(x,y)$$

Asymmetric emission

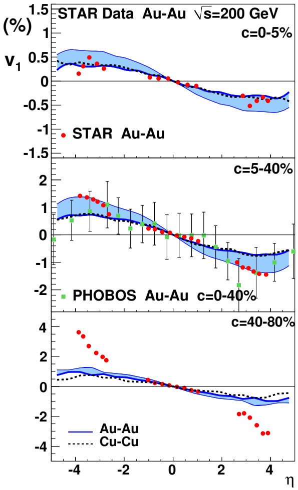
(Białas, Czyż, Acta Phys.Polon.B36, 905 (2005)

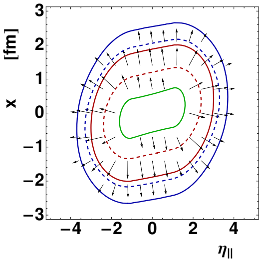




bremsstrahlung (Adil Gyulassy, Phys. Rev. C72, 034907 (2005)

Directed flow- tilted source





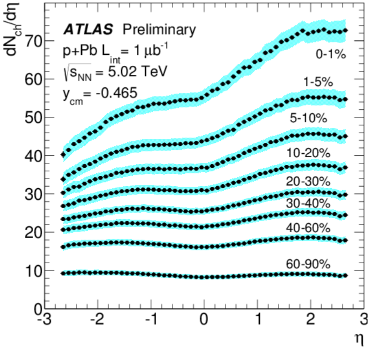
Bozek, Wyskiel, Phys. Rev. C81, 054902 (2010)

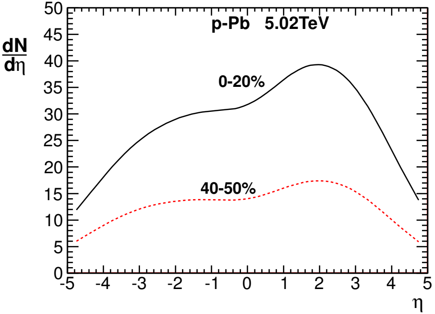
$$\partial_\tau u_x = -\frac{\partial_x p_\perp}{p+\epsilon}$$

$$\partial_\tau Y = -\frac{\partial_\eta p_\parallel}{\tau(p+\epsilon)}$$

tilted source $\rightarrow$ transverse pressure + longitudinal pressure
Glauber model

Asymmetric distributions

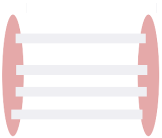




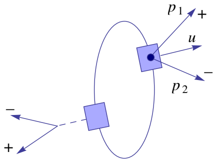
FSI scenarios

fields+thermalization

color fields

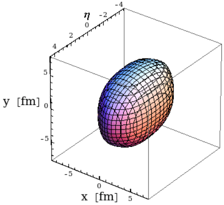


local thermalization $\rightarrow$ hadronization

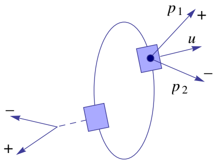


hydrodynamics

hydrodynamic expansion



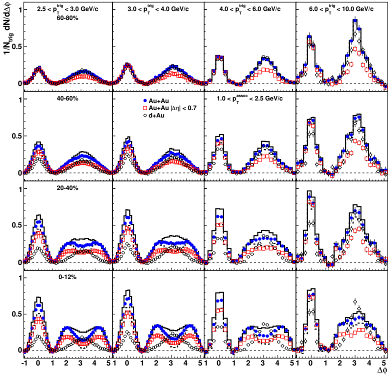
hadronization, statistical emission



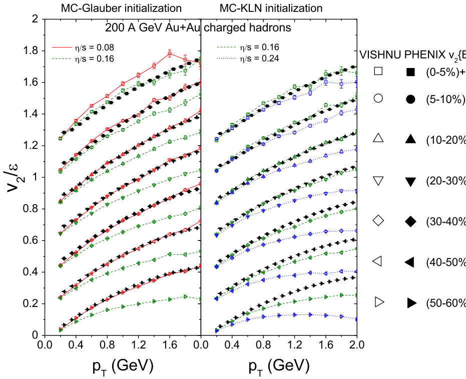
Give similar flow

Can we reduce uncertainties?

go back to very peripheral A-A



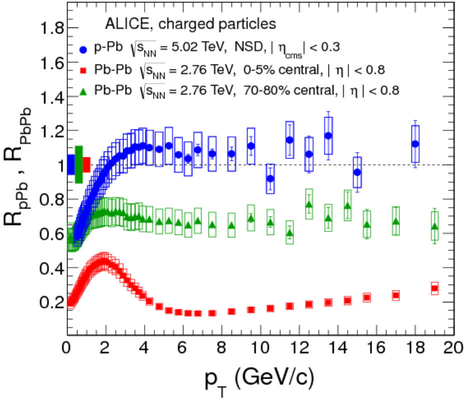
STAR-arXiv:1004.2377



Song, Bass, Heinz, Hirano, Shen-arXiv:1101.4638

also jet modification, dijet asymmetry, PID flow, HBT

Flow without jet quenchinq?



energy-momentum tensor

$$T^{\mu\nu} = \begin{pmatrix} \epsilon & 0 & 0 & 0 \\ 0 & p+\Pi & 0 & 0 \\ 0 & 0 & p+\Pi & 0 \\ 0 & 0 & 0 & p+\Pi \end{pmatrix} + \pi^{\mu\nu}$$

- shear viscosity

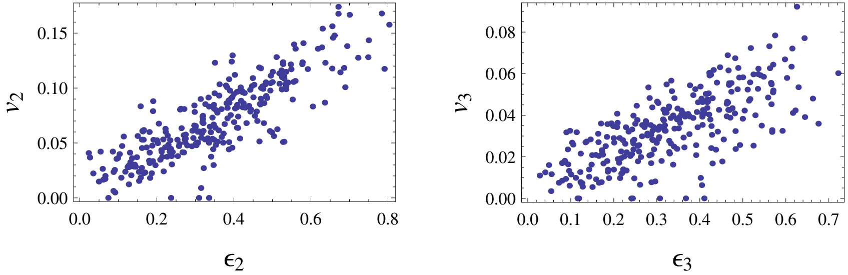
$$\Delta^{\mu\alpha}\Delta^{\nu\beta}u^\gamma\partial_\gamma\pi_{\alpha\beta} = \frac{2\eta\sigma^{\mu\nu} - \pi^{\mu\nu}}{\tau_\pi} - \frac{1}{2}\pi^{\mu\nu}\frac{\eta T}{\tau_\pi}\partial_\alpha\left(\frac{\tau_\pi u^\alpha}{\eta T}\right)$$

- bulk viscosity

$$u^\gamma\partial_\gamma\Pi = \frac{-\zeta\partial_\gamma u^\gamma - \Pi}{\tau_\Pi} - \frac{1}{2}\Pi\frac{\zeta T}{\tau_\Pi}\partial_\alpha\left(\frac{\tau_\Pi u^\alpha}{\zeta T}\right)$$

- viscosity corrections from velocity gradients
- **initial** stress tensor - pressure anisotropy
- equation of state

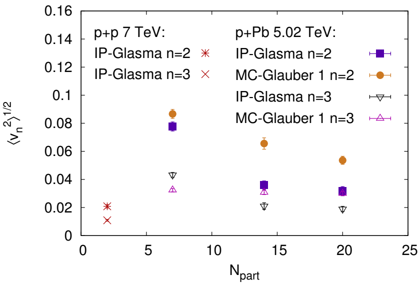
fireball asymmetry - flow asymmetry



- Ev-by-Ev hydro response to geometry valid
- response strength depends on details

Hydrodynamic flow in p-p?

- Humanic-nucl-th/0612098 (pythia, cascade)
- Romatschke, Luzum-arXiv:0901.4588 (overlap)
- Prasad, Roy, Chattopadhyay, Chaudhuri -arXiv: 0910.4844 (overlap)
- Bozek-arXiv: 0911.2393 (flux-tubes)
- Yan, Dong, Zhou, Li, Ma, Sa- arXiv: 0912.3342 (transport)
- Werner, Karpenko, Pierog, Bleicher, Mikhailov-arXiv: 1010.0400 (EPOS)
- Deng, Xu, Greiner-arXiv: 1112.0470 (hot-spots, transport model)
- Shuryak, Zahed-arXiv:1301.4470 (symmetric)
- Bzdak, Schenke, Tribedy, Venugopalan-arXiv: 1304.3403 (IP-Glasma)



Bzdak et al. arXiv: 1304.3403

-Is hydrodynamics valid?
-What is the initial eccentricity?

p-Pb reference system - No FSI expected

CERN-PH-TH/2011-119
LHC-Project-Report-1181

Proton-Nucleus Collisions at the LHC: Scientific Opportunities and Requirements

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Abstract
Proton-nucleus (p+A) collisions have long been recognized as a crucial component of the physics programme with nuclear beams at high energies, in particular for their reference role to interpret and understand nucleus-nucleus data as well as for their potential to elucidate the partonic structure of matter at low parton fractional momenta (small-x). Here, we summarize the main motivations that make a proton-nucleus run a decisive ingredient for a successful heavy-ion programme at the Large Hadron Collider (LHC) and we present unique scientific opportunities arising from these collisions. We also review the status of ongoing discussions about operation plans for the p+A mode at the LHC.

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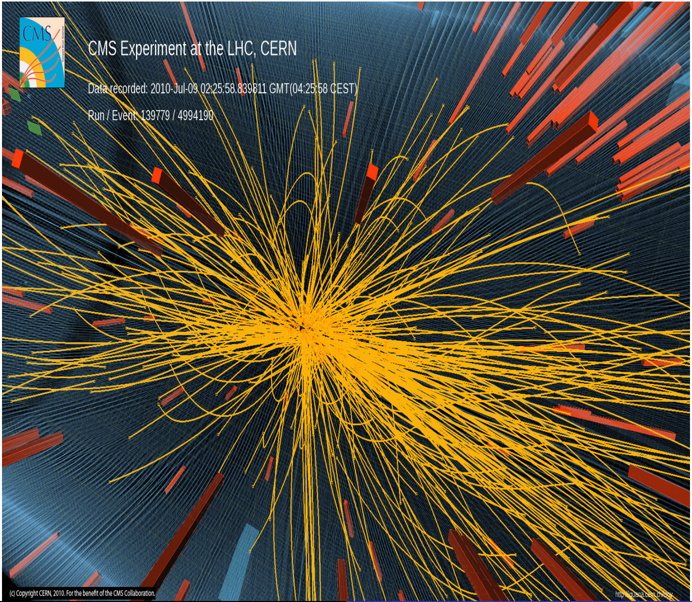
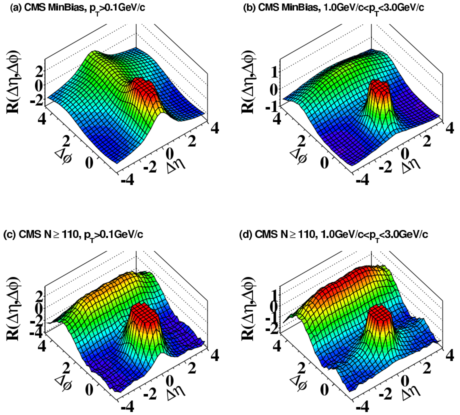
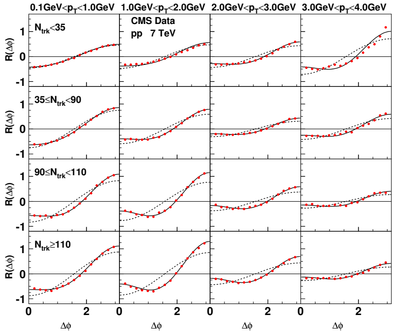
High multiplicity events in pp



Ridge in pp

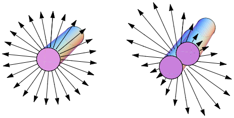


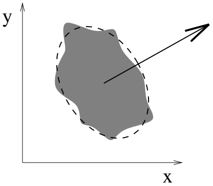


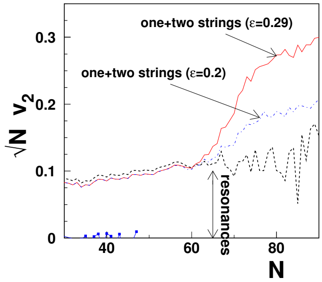
PB arXiv:1010.0405

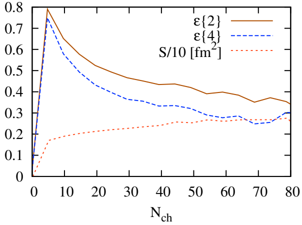
can we measure (calculate) v_2

Fireball shape in pp









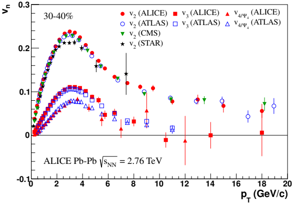
E.Asar et al., 1009.5643

Casalderrey-Solana, Wiedemann, 0911.4400

Bozek, 0911.2397

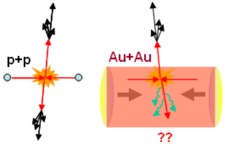
sQGP formed in A-A collisions

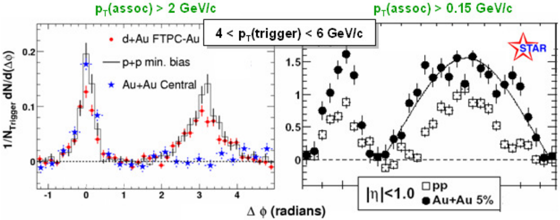
sQGP



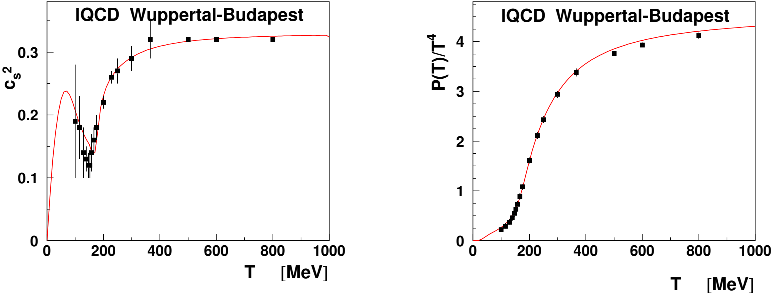
$$\frac{dN}{d\phi} \propto 1 + 2v_2 cos(2(\phi - \Psi_2)) + 2v_3 cos(3(\phi - \Psi_3)) + \ldots$$

Jet quenching





equation of state - input



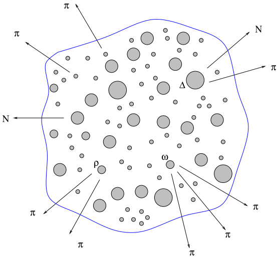
- lattice equation of state at high T
- hadron gas at low temperature (know resonances from PDG)
- matching at T_c Laine, Schroder 2006, Chojnacki, Florkowski 2007, Huovinen, Petreczky 2009
- crossover - not first order phase transition

freezeout

- density drops - hydrodynamic evolution stops
- usually surface of constant temperature
- particles emitted from fluid elements Cooper-Frye formula

$$E\frac{d^3N}{dp^3} = \int d\Sigma_\mu p^\mu f[p_\mu u^\mu(x)]$$

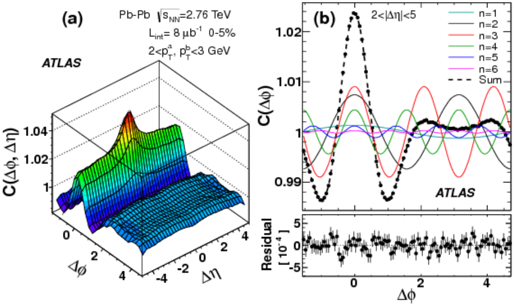
- fluid velocity + thermal momenta
- latter - resonance decays and/or rescattering



two-particle correlations in relative azimuthal angle

$$C(\Delta\phi) \propto \int d\phi_1 d\phi_2 \delta(\phi_1 + \Delta\phi - \phi_2) \frac{dN}{d\phi_1 d\phi_2}$$
$$\propto 1 + 2v_1^2 \cos(\Delta\phi) + 2v_2^2 \cos(2\Delta\phi) + 2v_3^2 \cos(3\Delta\phi) + \ldots$$

rms v_2 can be measured from two-particle correlations
$\sqrt{\langle v_2^2 \rangle} = \langle \frac{1}{N_{pair}} \sum_{ij} cos(\phi_i - \phi_j) \rangle$ **(cummulant method)**



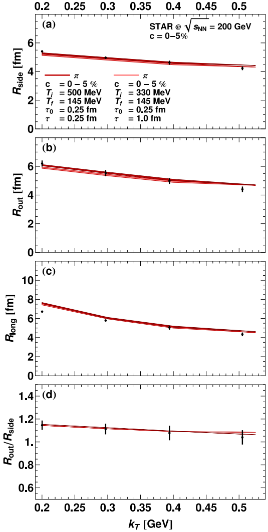
(v_1 - directed flow, v_3 - triangular flow) odd harmonics from fluctuations - see below

Hanbury Brown-Twiss (HBT) correlations

correlation between identical particles

$$C(P,q) = \frac{N(p_1,p_2)}{N(p_1)N(p_2)}$$

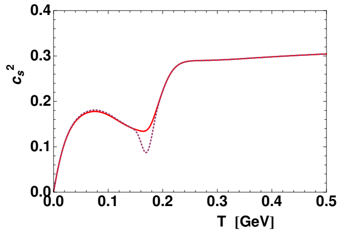
$$C(q) = 1 + \lambda exp[-q_S^2 R_s^2 - q_l^2 R_l^2 - q_o^2 R_o^2]$$



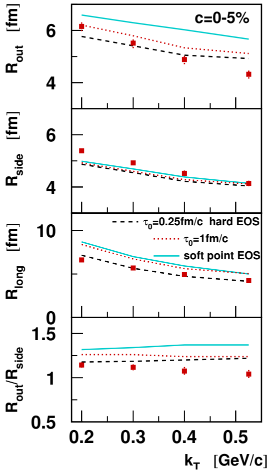
HBT requires hard equation of state

Broniowski, Chojnacki, Florkowski, Kisiel 2008, Pratt, 2009

OBSERVATION - hard equation of state

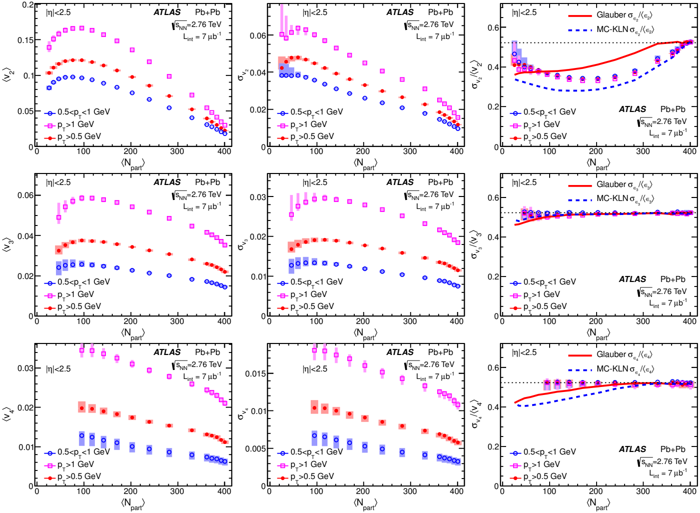


soft EOS - wrong HBT



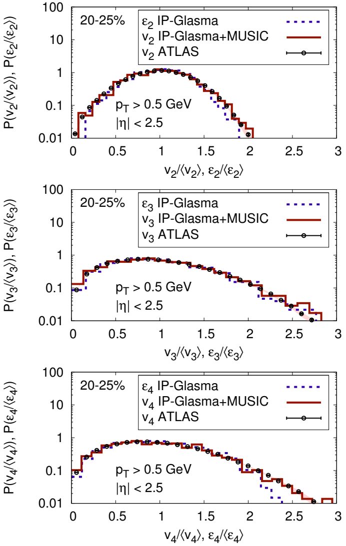
Heavy-ion experiments consistent with lattice QCD

OBSERVATION -flow fluctuations



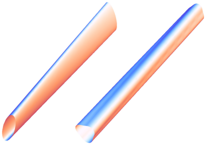
$< v_n >$, $< v_n^2 >$ and the whole distribution of v_n can be reconstructed.

good description of flow fluctuations with IP-glasma + hydro

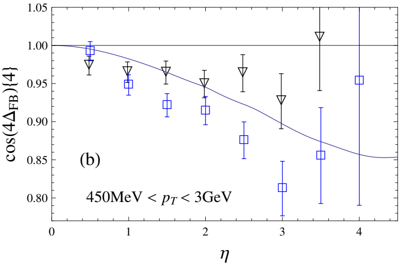


C.Gale et al. arXiv:1209.6330

event by event twist of the reaction plane



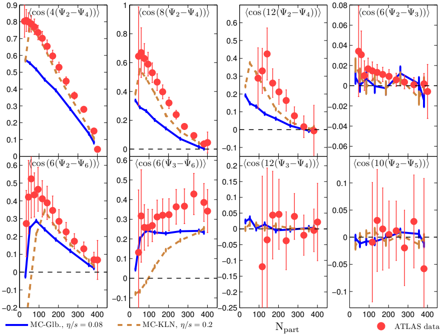
Fluctuating RP twist
can be measured



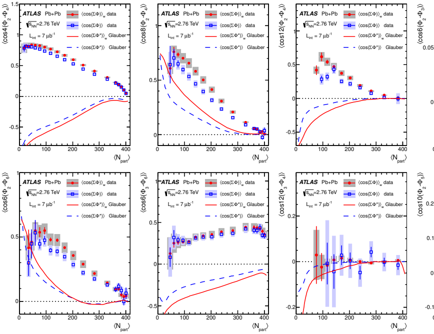
PB, Broniowski, Moreira, Phys. Rev. C83, 034911 (2011)

$$\cos(2k\Delta_{FB})\{4\} \equiv \frac{\langle e^{ik[(\phi_{F,1}+\phi_{F,2})-(\phi_{B,1}+\phi_{B,2})]}\rangle}{\langle e^{ik[(\phi_{F,1}-\phi_{F,2})-(\phi_{B,1}-\phi_{B,2})]}\rangle} = \langle\cos(2k\Delta_{FB})\rangle_{\text{events}} + \text{nonflow}$$

Event planes correlations

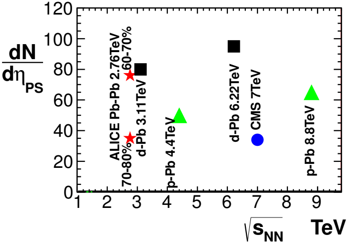


Bhalerao, Luzum, Ollitrault 2011, Qiu, Heinz 2012



- correlations between EP $\langle \cos(nm(\Phi_n - \Phi_m)) \rangle$,
- initial correlations
- nonlinearities of viscous hydrodynamics

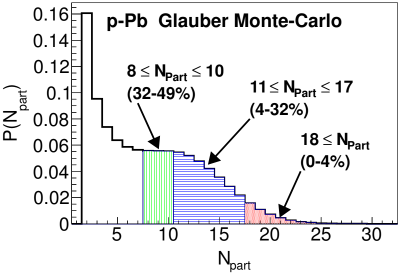
pA collision

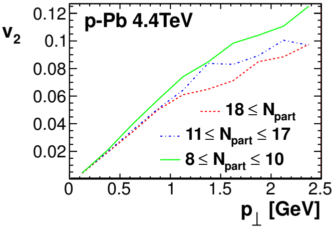


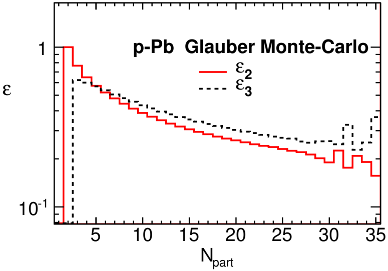
p-Pb at 5.02TeV

small dense fireball formed !

Fireball in p-Pb



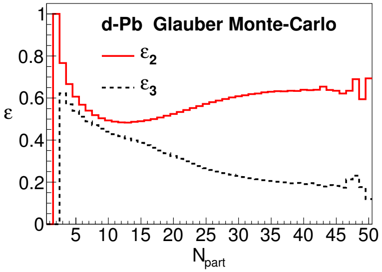


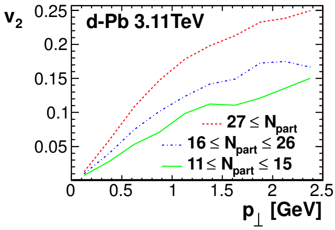


PB, arXiv:1112.0912

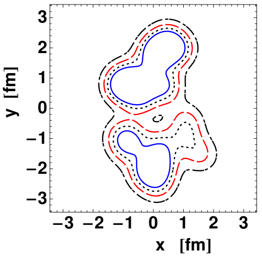
- collective flow effects $\simeq$ peripheral Pb-Pb
- can be observed
- p-A (d-A) is not p-p superposition

d-Pb





large elliptic flow

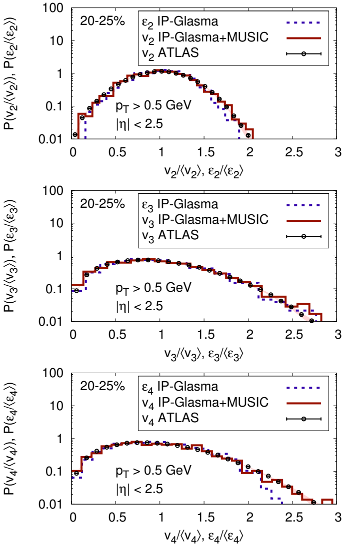


PB, arXiv:1112.0912

small-on-large system

with controled eccentricity

IP-glasma $\eta/s \simeq 0.2$



C.Gale et al. arXiv:1209.6330