

Correlations in hydrodynamics

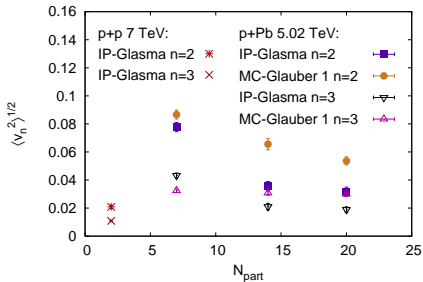
Piotr Bożek

Institute of Nuclear Physics and AGH, Kraków
with Wojciech Broniowski and Giorgio Torrieri



Hydrodynamic flow in p-p?

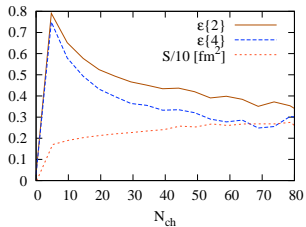
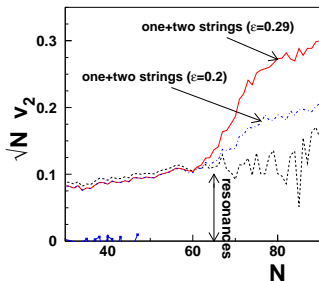
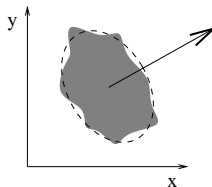
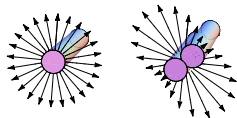
- ▶ Humanic-nucl-th/0612098 (pythia, cascade)
- ▶ Romatschke, Luzum-arXiv:0901.4588 (overlap)
- ▶ Prasad, Roy, Chattopadhyay, Chaudhuri -arXiv: 0910.4844 (overlap)
- ▶ Bozek-arXiv: 0911.2393 (flux-tubes)
- ▶ Yan, Dong, Zhou, Li, Ma, Sa- arXiv: 0912.3342 (transport)
- ▶ Werner, Karpenko, Pierog, Bleicher, 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?

Fireball shape in pp



Bozek, 0911.2397

E.Asar et al., 1009.5643

Casalderrey-Solana, Wiedemann, 0911.4400

Collective elliptic flow in **p-Pb**?

- ▶ Large enough density? **yes**
- ▶ Large enough eccentricity **yes?**
- ▶ Large enough size? **(?)**
but should and can be tested
- ▶ Small enough gradients? **no**
- beyond viscous hydro

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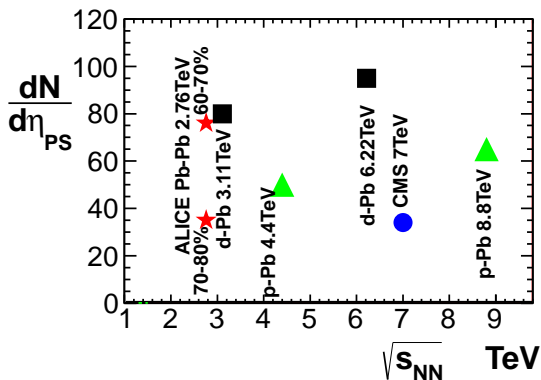
in **p-p**?

yes (high mult.)

(?)

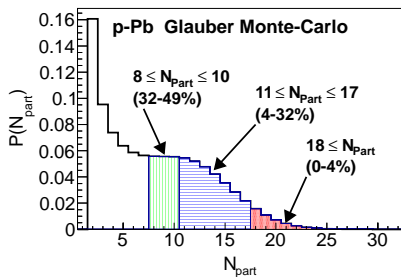
(???)

no!

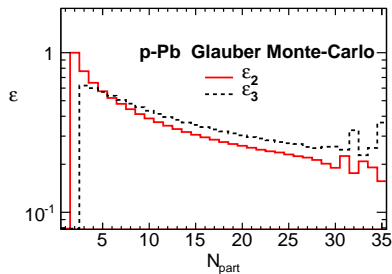


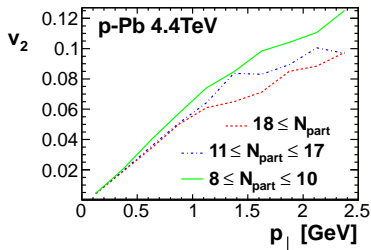
large multiplicity - large fireball - collective expansion?

Fireball in p-Pb

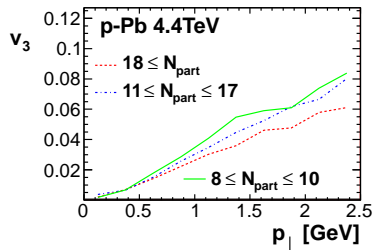


PB, arXiv:1112.0912



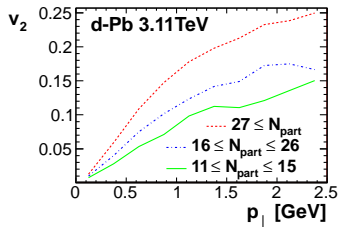
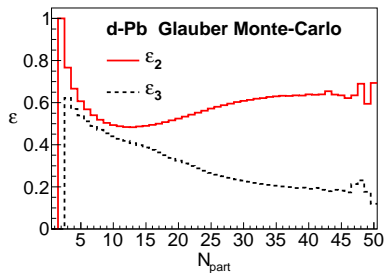


elliptic flow in p-Pb



triangular flow

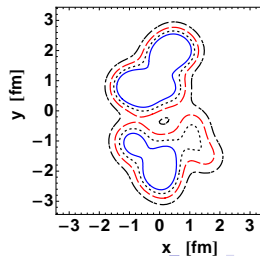
PB, arXiv:1112.0912

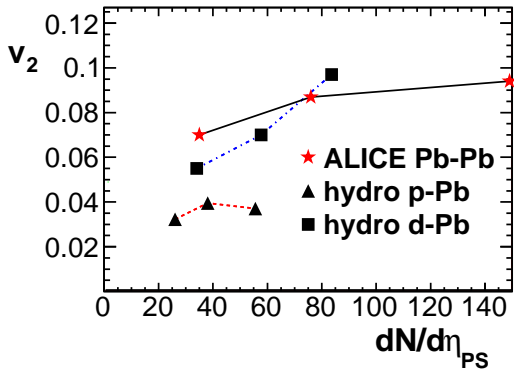


large elliptic flow

PB, arXiv:1112.0912

can it be seen at RHIC?



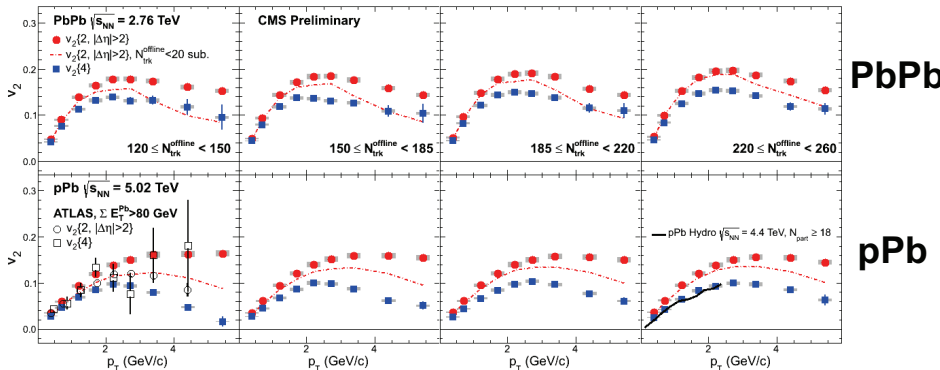


- ▶ collective flow effects \simeq peripheral Pb-Pb
- ▶ can be observed
- ▶ p-Pb (d-Pb) is not p-p superposition
- ▶ only p-p as baseline

v_2 in pPb and PbPb

Dash-dot line: peripheral subtracted

multiplicity \longrightarrow



v_2 shows similar shape in pPb and PbPb, but is smaller in pPb

$v_2\{4\}$ is only 20% smaller than $v_2\{2\}$ below 2 GeV/c

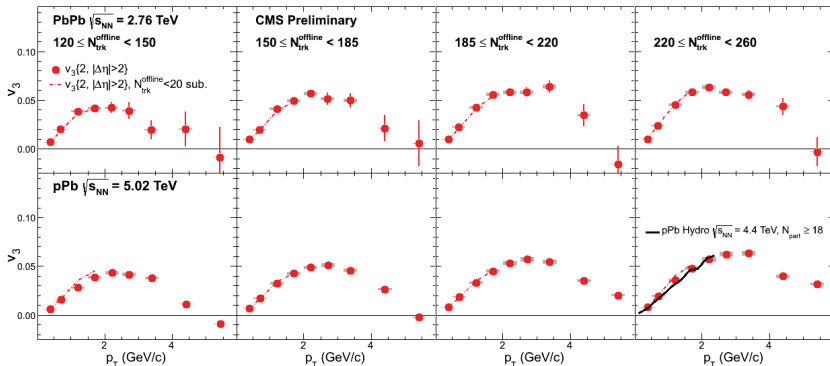
“Peripheral subtraction” has small effect at high multiplicity



v_3 in pPb and PbPb

Dash-dot line: peripheral subtracted

multiplicity \longrightarrow



PbPb

pPb

v_3 has similar shape in pPb and PbPb; magnitude comparable

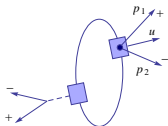
“Peripheral subtraction” makes essentially no difference

Hydro prediction: Bozek, $v_3\{PP\}$, not including fluctuations

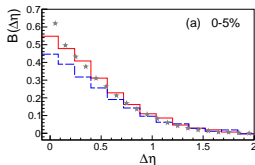


Charge balancing

local charge conservation



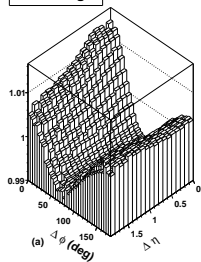
charge balance function



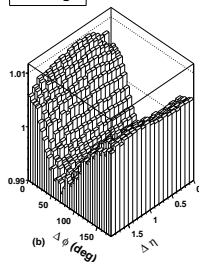
PB, W.Broniowski, arXiv: 1204.3580

STAR data

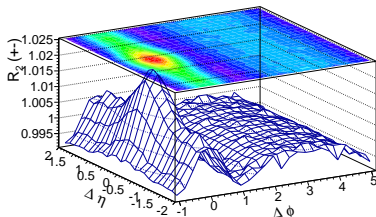
Unlike-sign



Like-sign



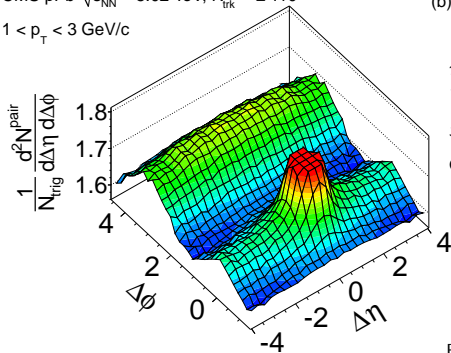
0-5%



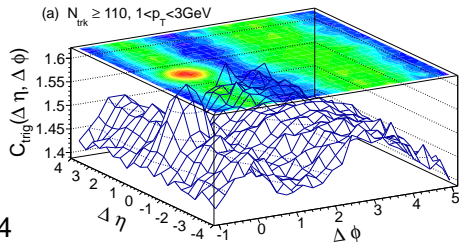
Ridge in p-Pb

CMS pPb $\sqrt{s_{NN}} = 5.02$ TeV, $N_{trk}^{offline} \geq 110$

$1 < p_T < 3$ GeV/c



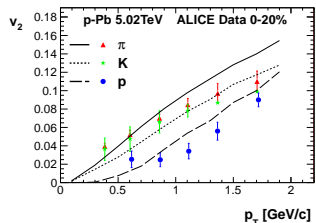
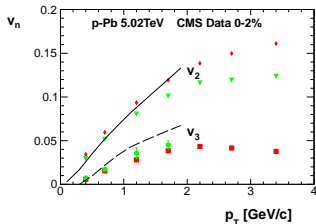
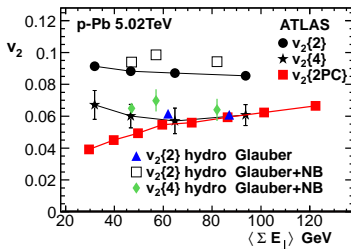
(b)



PB, W.Broniowski, arXiv:1211.0845

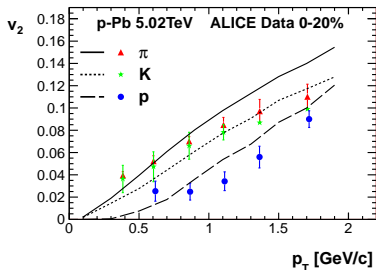
symmetric ridge also from CGC, K.Dusling, R. Venugopalan, arXiv:1210.3890, 1211.3701, 1302.7018

Elliptic and triangular flow



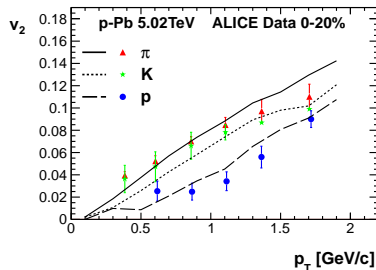
PB, W.Broniowski, G. Torrieri arXiv:1306.5442

v_2 from late stage



$$T_f = 150\text{MeV}$$

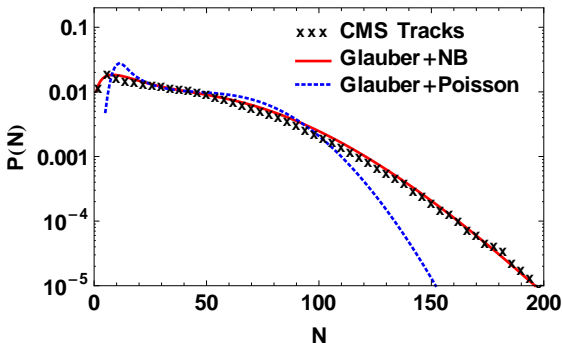
- pions : 0.75 collisions after emission



$$T_f = 140\text{MeV}$$

- pions : 0.65 collisions after emission

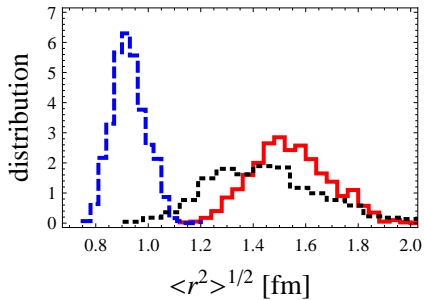
Glauber+NB



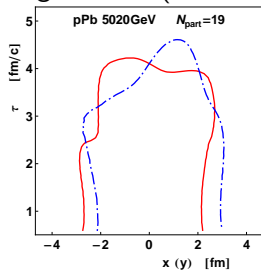
$$P(n) = \sum_i P_{part}(i) N p \lambda_i, \kappa i(n)$$

Additional fluctuations of density (compared to Glauber)

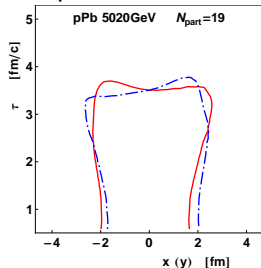
very different source sizes



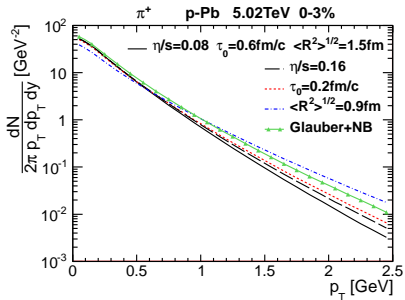
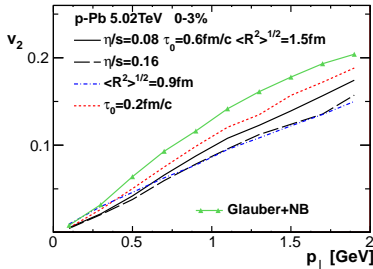
large source (standard)



compact source

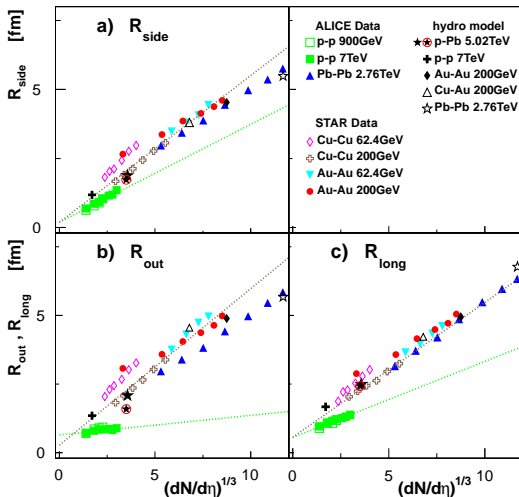


dependence on model details



- response strength depends on details, initial eccentricity

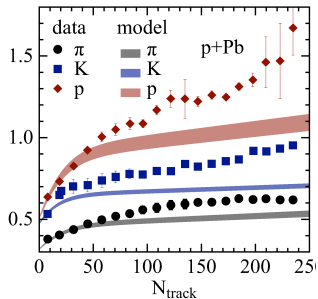
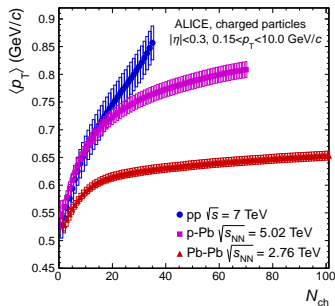
HBT systematics



PB, W.Broniowski, arXiv:1301.3314

small system corrections!- Sinyukov, Shapoval - arXiv:1209.1747

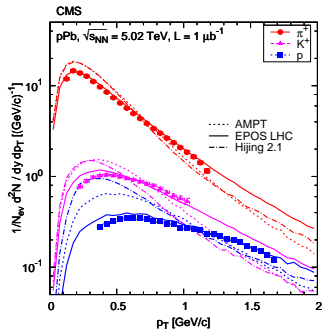
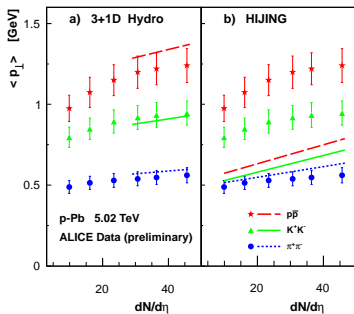
Spectra - $\langle p_{\perp} \rangle$



larger $\langle p_{\perp} \rangle$ in smaller systems

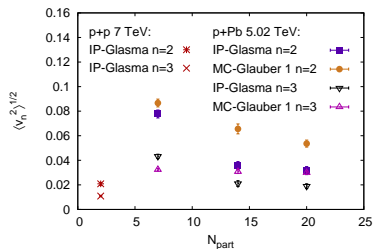
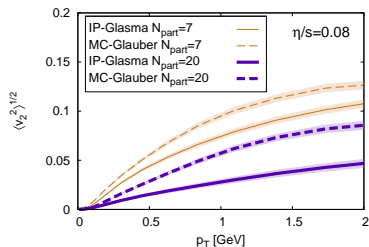
Bzdak, Skokov, arXiv:1306.5442

Spectra - $\langle p_{\perp} \rangle$



PB, W.Broniowski, G. Torrieri arXiv:1306.5442

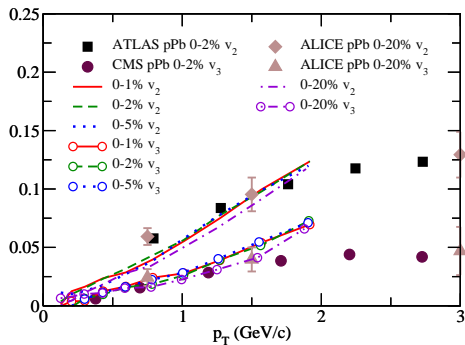
3+1D visc. hydro



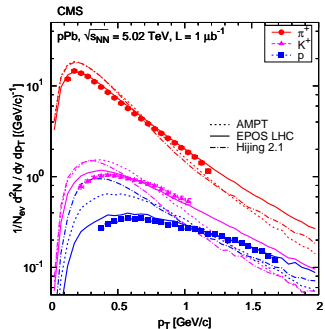
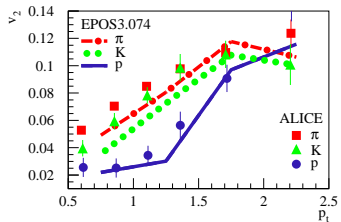
dependence on initial model, v_n small for IP-Glasma i.c.

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

3+1D hydro



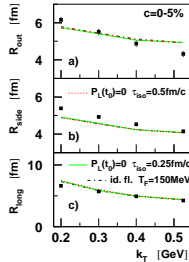
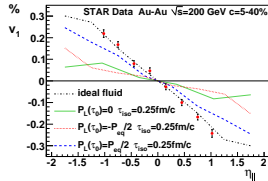
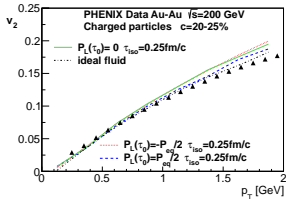
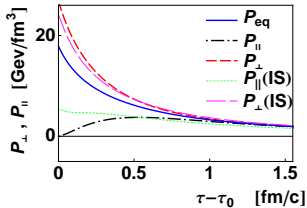
G-Y.Qin, B. Müller arXiv: 1306.3439



excellent description of spectra

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

pressure anisotropy

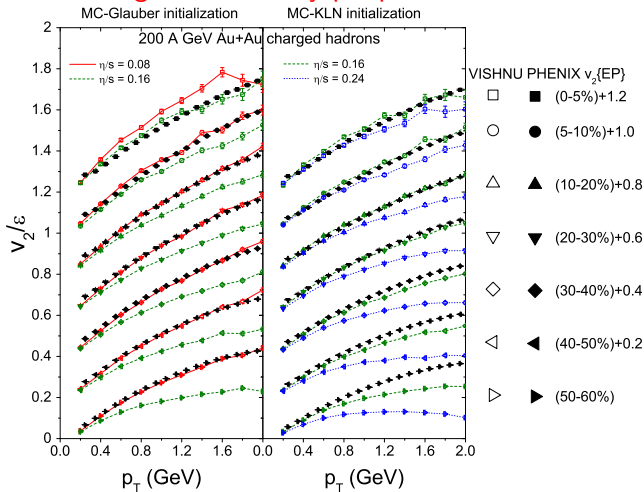


PB, I. Wyskiel - arXiv:1009.0701

- early pressure anisotropy irrelevant!

Can we reduce uncertainties?

go back to very peripheral A-A



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

Summary

- ▶ Ev-by-Ev hydro for pPb
- ▶ Collectivity in pPb@LHC explains v_2 , ridge, $\langle p_{\perp} \rangle$
 - ▶ triangular flow
 - ▶ identified particle v_2
 - ▶ mass dependence of $\langle p_{\perp} \rangle$
- ▶ Observations consistent with collective flow
many exp. results; several calculations
- ▶ HBT radii in p-Pb?
- ▶ Limits of hydro!
- ▶ Why hydrodynamics would work?

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

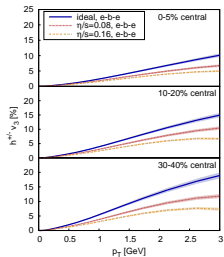
$$\Delta^{\mu\alpha} \Delta^{\nu\beta} u^\gamma \partial_\gamma \pi_{\alpha\beta} = \frac{2\eta\sigma^{\mu\nu} - \pi^{\mu\nu}}{\tau_\pi} - \frac{1}{2}\pi^{\mu\nu} \frac{\eta T}{\tau_\pi} \partial_\alpha \left(\frac{\tau_\pi u^\alpha}{\eta T} \right)$$

- ▶ bulk viscosity

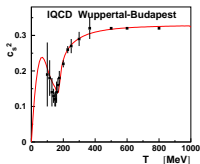
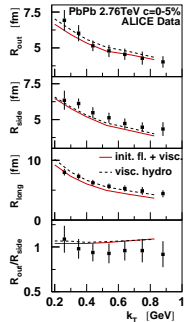
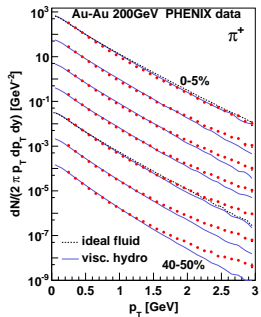
$$u^\gamma \partial_\gamma \Pi = \frac{-\zeta \partial_\gamma u^\gamma - \Pi}{\tau_\Pi} - \frac{1}{2}\Pi \frac{\zeta T}{\tau_\Pi} \partial_\alpha \left(\frac{\tau_\Pi u^\alpha}{\zeta T} \right)$$

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

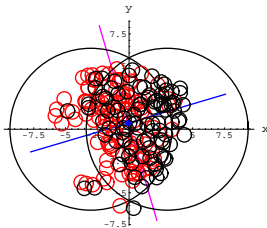
3+1D hydrodynamics



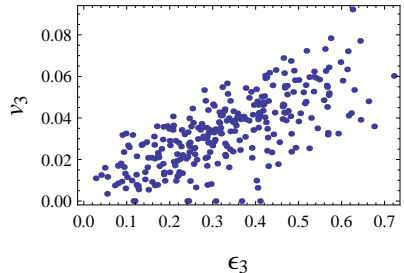
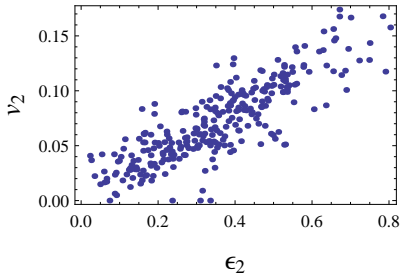
3+1D visc. : B.Schenke et al.



IQCD + Hadron Gas



fireball asymmetry - flow asymmetry



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