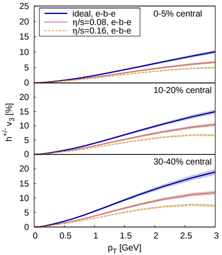
Particle production in viscous hydrodynamics

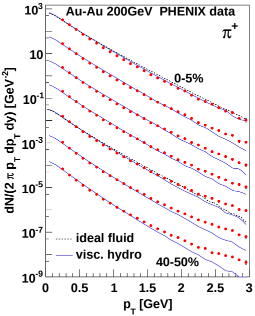
Piotr Bożek

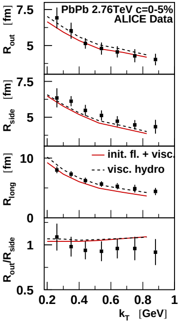
Institute of Nuclear Physics and AGH, Kraków

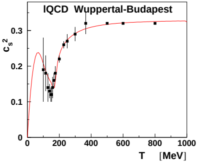
3 + 1-D viscous hydrodynamics



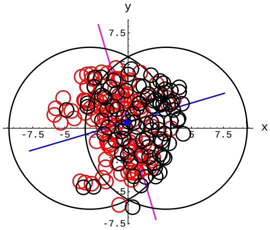
3+1D visc. : B.Schenke et al.



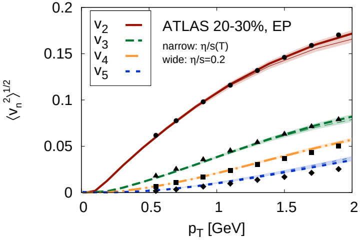




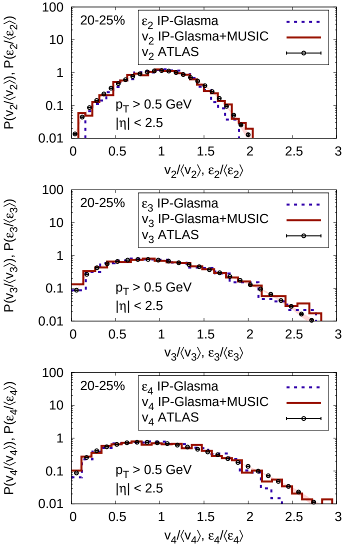
lQCD + Hadron Gas



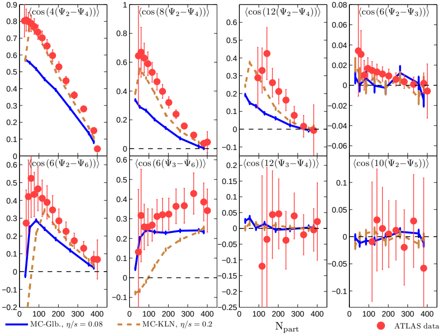
Event anisotropy

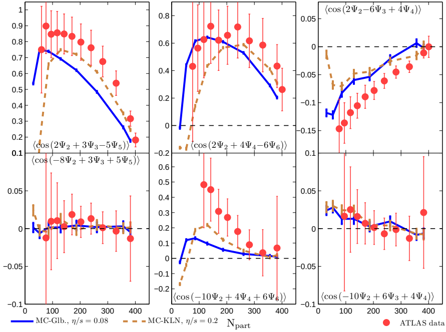


C.Gale et al. arXiv:1209.6330



Event planes correlations



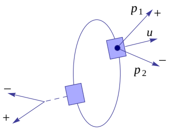


Z.Qiu, U.Heinz arXiv:1208.1200

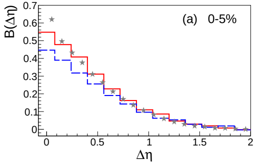
- correlations between EP $\langle \cos(nm(\Phi_n - \Phi_m)) \rangle$,
- initial correlations
- nonlinearities of viscous hydrodynamics

Charge balancing

local charge conservation

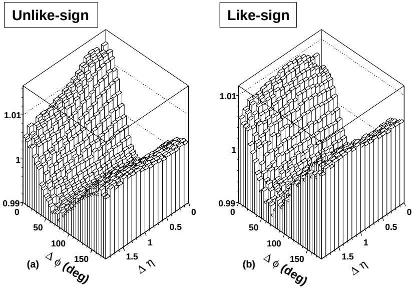


charge balance function

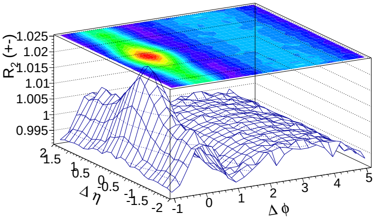


PB, W.Broniowski, arXiv: 1204.3580

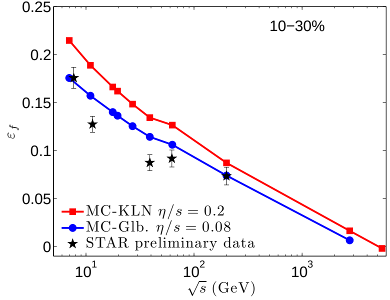
STAR data



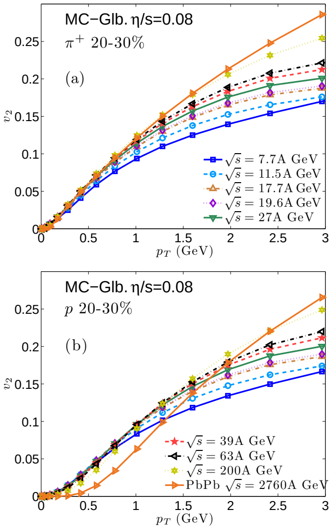
0-5%



Hydrodynamic beam energy scan



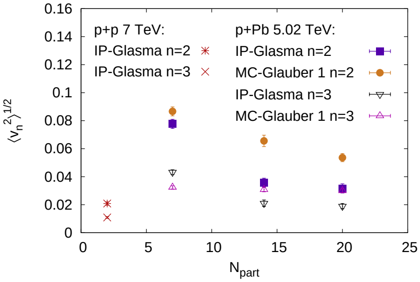
C.Shen, U.Heinz arXiv:1202.6602



talks I. Karpenko, hybrid model

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?

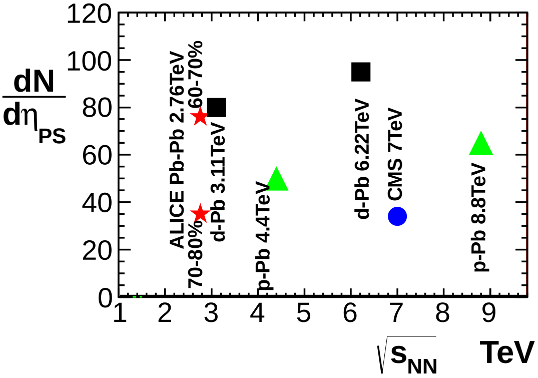
Collective elliptic flow in p-Pb?

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

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

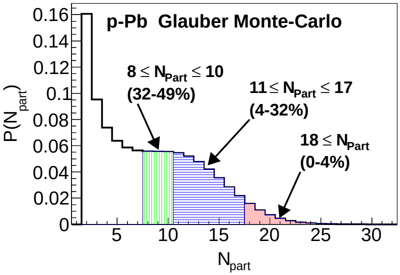
	p-Pb	p-p
Large enough density?	yes	yes (high mult.)
Large enough eccentricity	yes?	(?)
Large enough size? but should and can be tested	(?)	(???)
Small enough gradients? - beyond viscous hydro	no	no!

p-Pb, d-Pb @ LHC

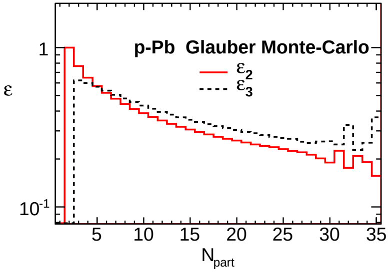


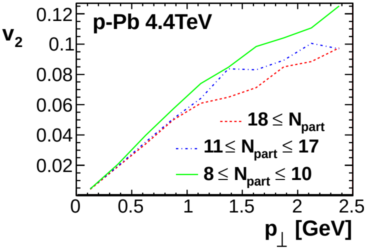
large multiplicity - large fireball - collective expansion?

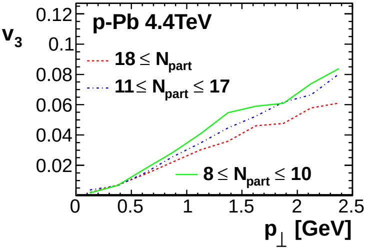
Fireball in p-Pb



PB, arXiv:1112.0912





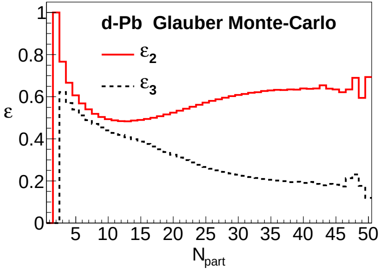


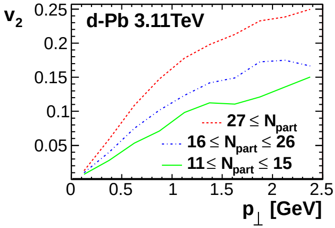
elliptic flow in p-Pb

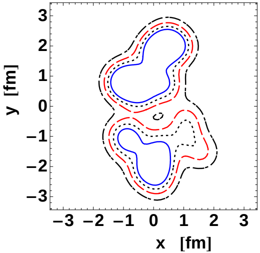
triangular flow

PB, arXiv:1112.0912

d-Pb



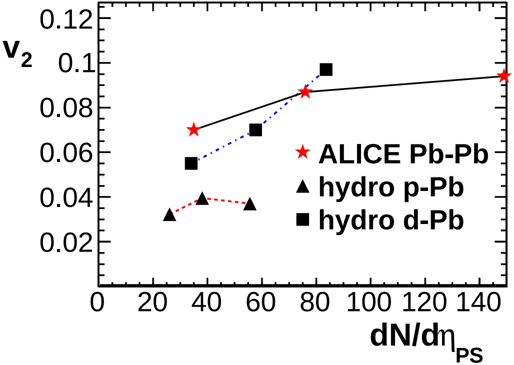




large elliptic flow

PB, arXiv:1112.0912

prediction 12.2011



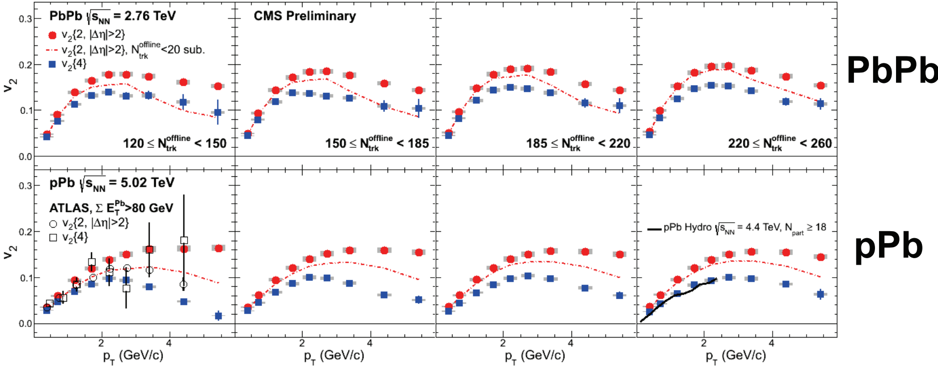
- collective flow effects $\simeq$ peripheral Pb-Pb
- can be observed
- p-Pb (d-Pb) is not p-p superposition
- only p-p as baseline

PB, arXiv:1112.0912

v_2 in pPb and PbPb

Dash-dot line: peripheral subtracted

multiplicity →



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

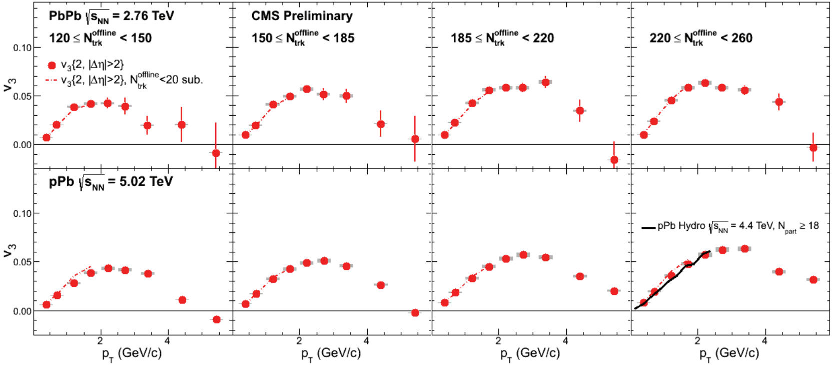
$v_2\{4\}$ is only 20% smaller than $v_2\{2\}$ below 2 GeV/c

"Peripheral subtraction" has small effect at high multiplicity

v_3 in pPb and PbPb

Dash-dot line: peripheral subtracted

multiplicity →

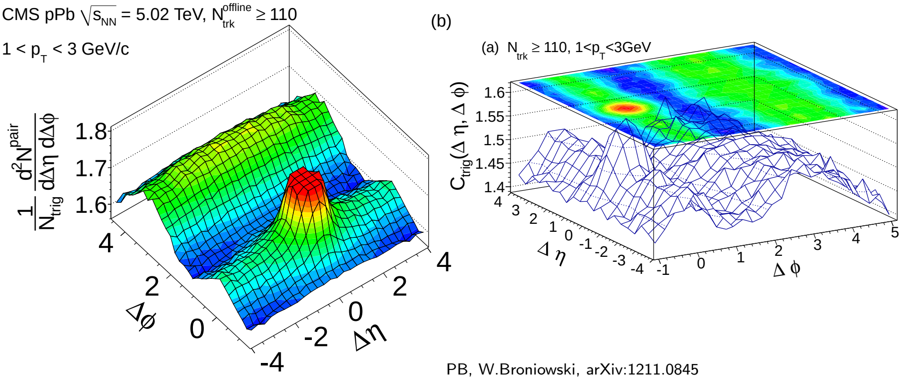


v_3 has similar shape in pPb and PbPb; magnitude comparable

"Peripheral subtraction" makes essentially no difference

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

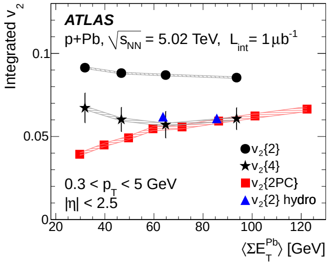
Ridge in p-Pb

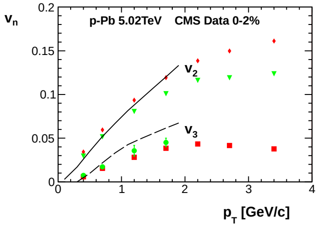


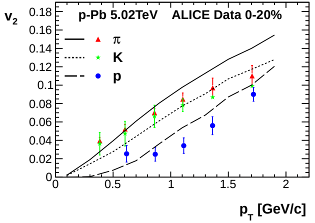
PB, W.Broniowski, arXiv:1211.0845

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

Elliptic and triangular flow

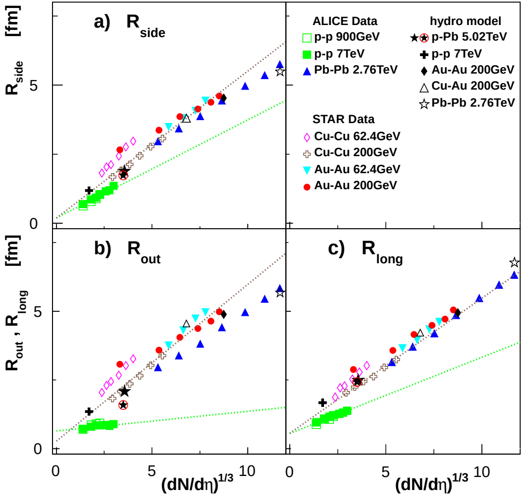






PB, W.Broniowski, G. Torrieri arXiv:1306.5442

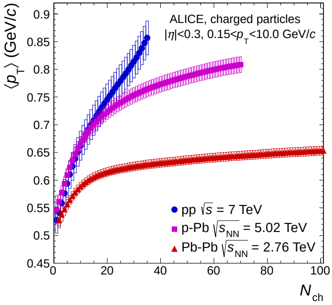
HBT systematics

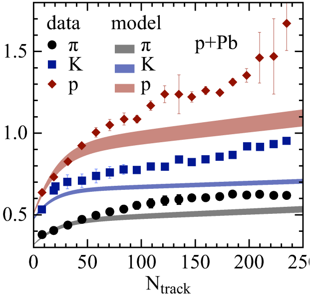


PB, W.Broniowski, arXiv:1301.3314

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

Spectra - $< p_\perp >$

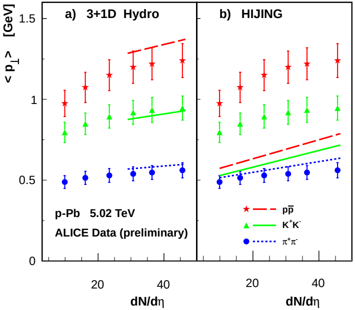


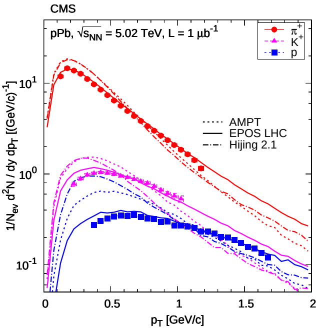


larger $< p_\perp >$ in smaller systems

Bzdak, Skokov, arXiv:1306.5442

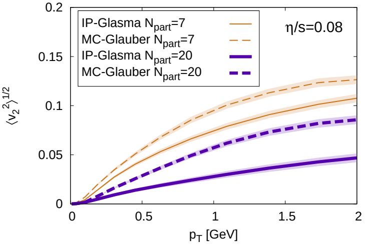
Spectra - $< p_\perp >$

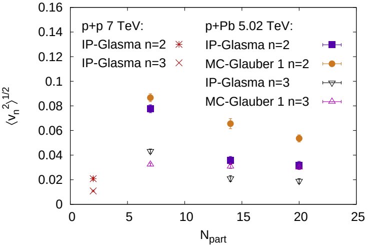




PB, W.Broniowski, G. Torrieri arXiv:1306.5442

3+1D visc. hydro

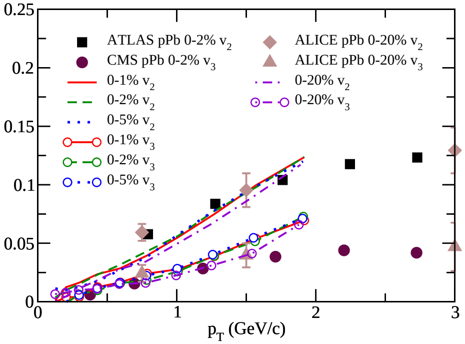




dependence on initial model, v_n small for IP-Glasma i.c.

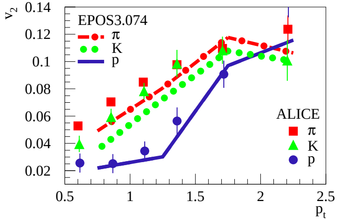
A.Bzdak, B.Schenke, P.Tribedy, R.Venugopalan - arXiv: 1304.3403

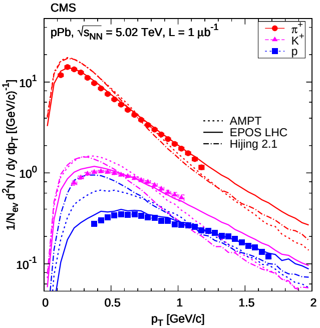
3+1D hydro



G-Y.Qin, B. Müller arXiv: 1306.3439

EPOS





excellent description of spectra

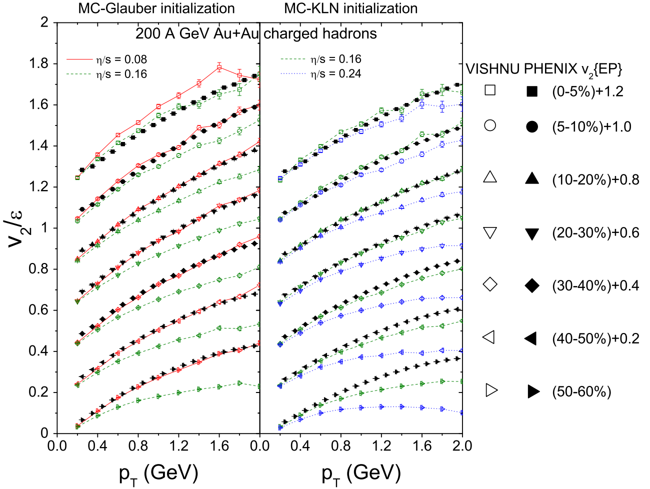
K. Werner, M. Bleicher, B. Guiot, Iu. Karpenko, T. Pierog - arXiv:1307.4379

Summary

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

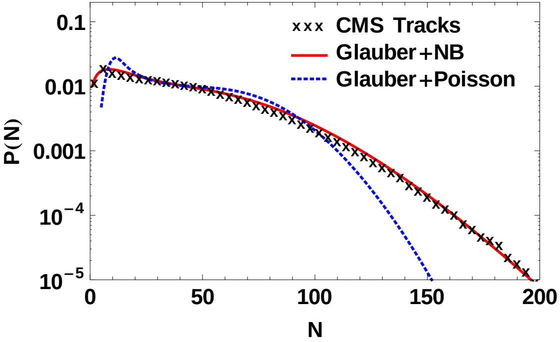
Can we reduce uncertainties?

go back to very peripheral A-A



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

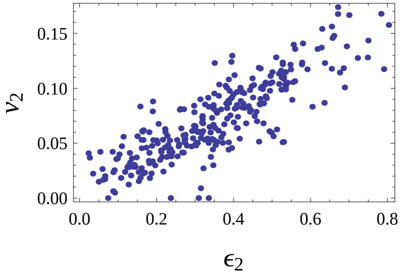
Glauber+NB

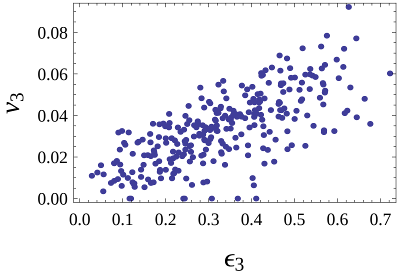


$$P(n) = \sum_i P_{part}(i) Np\lambda i, \kappa i(n)$$

Additional fluctuations of density (compared to Glauber)

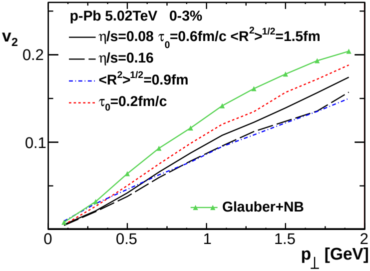
fireball asymmetry - flow asymmetry

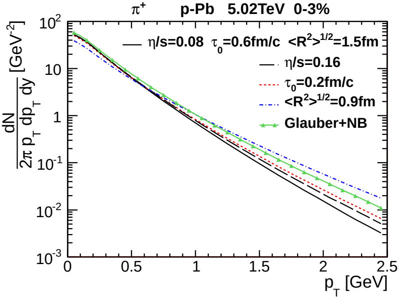




- Ev-by-Ev hydro response to geometry valid
- response strength depends on details

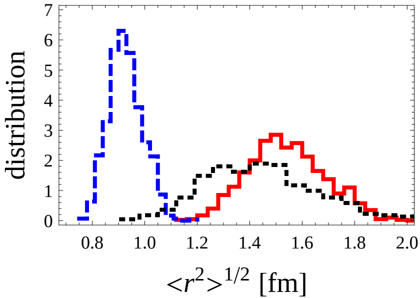
dependence on model details



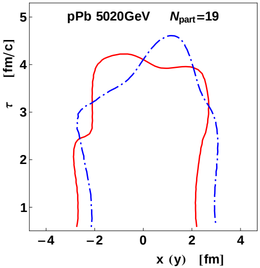


- response strength depends on details, initial eccentricity

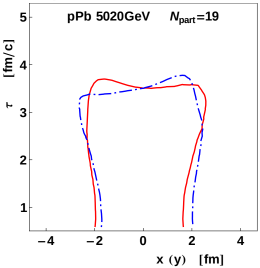
very different source sizes



large source (standard)



compact source



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

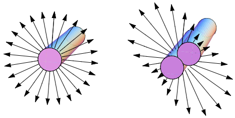
$$\Delta^{\mu\alpha}\Delta^{\nu\beta}u^\gamma\partial_\gamma\pi_{\alpha\beta} = \frac{2\eta\sigma^{\mu\nu} - \pi^{\mu\nu}}{\tau_\pi} - \frac{1}{2}\pi^{\mu\nu}\frac{\eta T}{\tau_\pi}\partial_\alpha\left(\frac{\tau_\pi u^\alpha}{\eta T}\right)$$

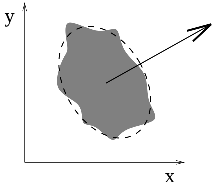
- bulk viscosity

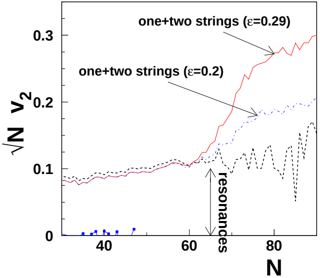
$$u^\gamma\partial_\gamma\Pi = \frac{-\zeta\partial_\gamma u^\gamma - \Pi}{\tau_\Pi} - \frac{1}{2}\Pi\frac{\zeta T}{\tau_\Pi}\partial_\alpha\left(\frac{\tau_\Pi u^\alpha}{\zeta T}\right)$$

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

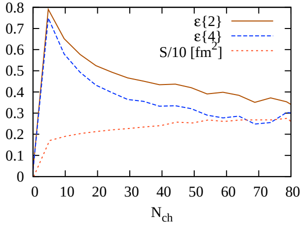
Fireball shape in pp







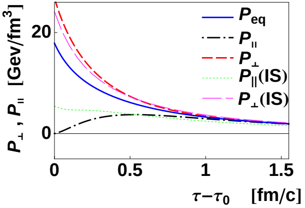
Bozek, 0911.2397

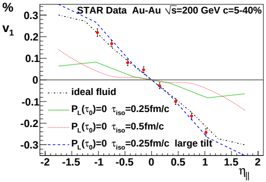


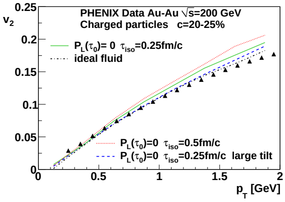
E.Asar et al., 1009.5643

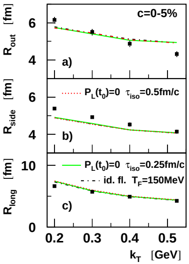
Casalderrey-Solana, Wiedemann, 0911.4400

pressure anisotropy





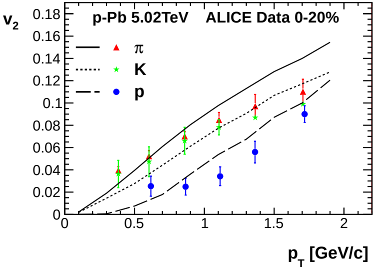


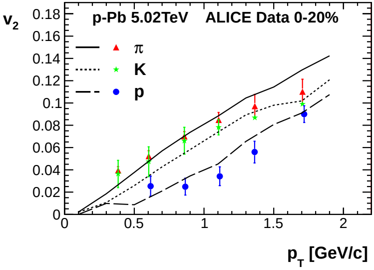


PB, I. Wyskiel - arrXiv:1009.0701

- early pressure anisotropy irrelevant!

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