Hydrodynamic flow in p+p and p+Pb collisions

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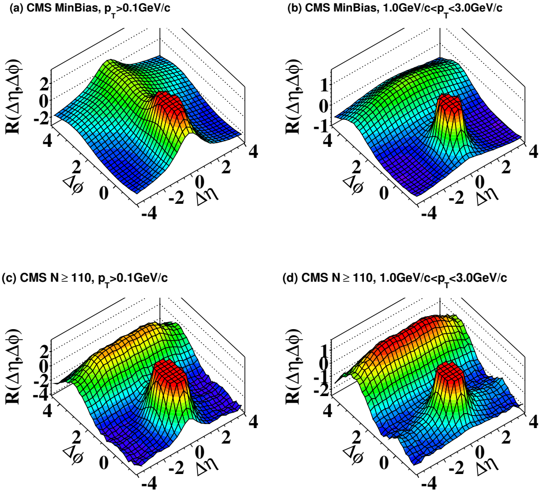
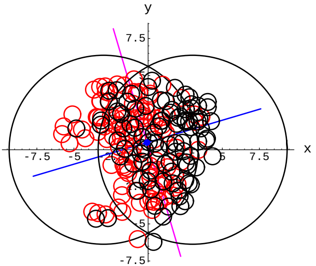
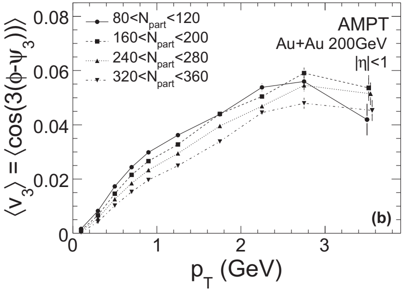


intriguing ridge seen in p-p

Initial profile



fluctuating initial density
→ larger eccentricity
→ fluctuating eccentricity
→ triangular deformation ϵ_3

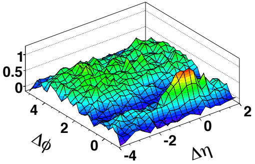


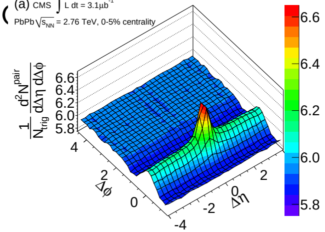
B. Alver, G. Roland

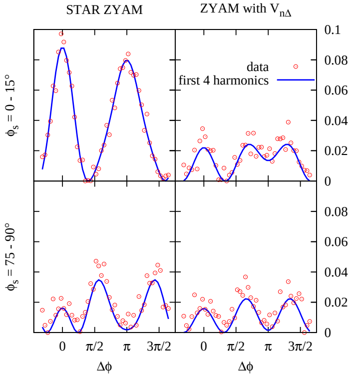
azimuthal asymmetry $\frac{dN}{d\phi} \propto 1 + 2v_2 \cos(\phi - \Psi_2) + \dots$

two-particle correlation $\frac{dN}{d\Delta\phi} \propto 1 + 2v_2^2 \cos(\phi_1 - \phi_2) + \dots$

Flow in A-A

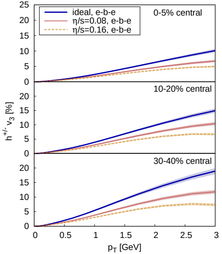




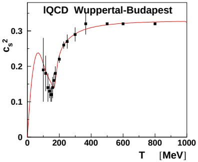


Luzum arXiv: 1011.5773 - flow harmonics

3 + 1-D viscous hydrodynamics



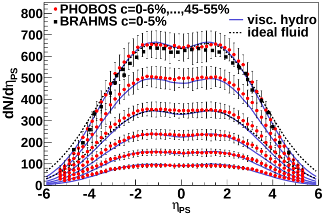
first 3+1D visc. : B.Schenke et al.

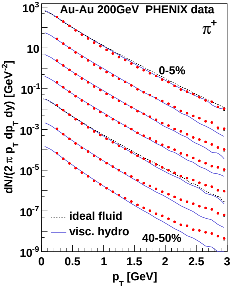


lQCD + Hadron Gas

$\eta/s = 0.08(0.16)$

Au-Au 200GeV

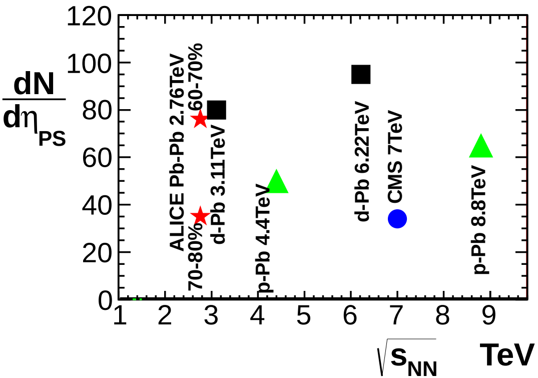




Collective elliptic flow in p-Pb?

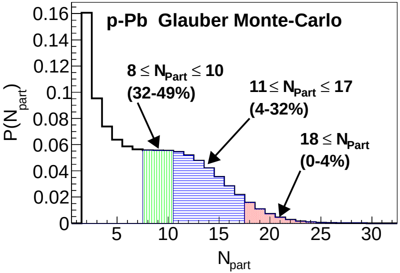
- Large enough density? yes
- Large enough eccentricity? yes?
- Large enough size? (?) but should and can be tested in pA
- Small enough gradients? no - beyond viscous hydro

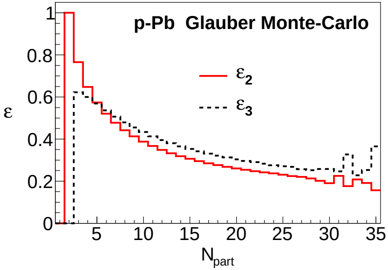
p-Pb, d-Pb @ LHC



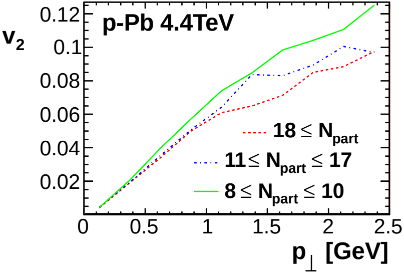
large multiplicity - large fireball - collective expansion?

Fireball in p-Pb

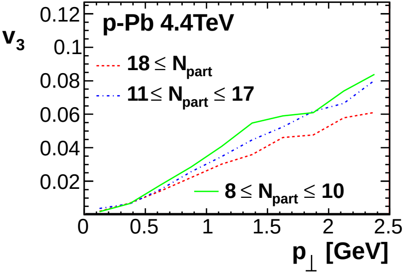




Measurable flow in p-Pb

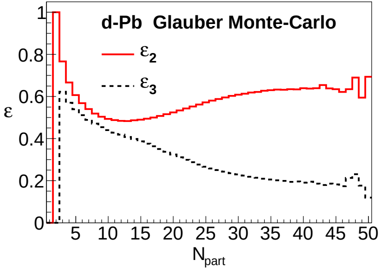


elliptic flow in p-Pb

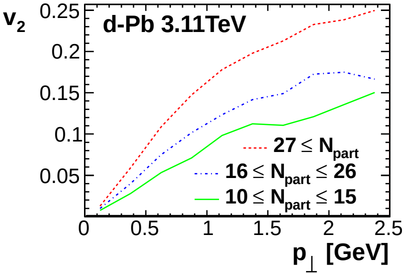


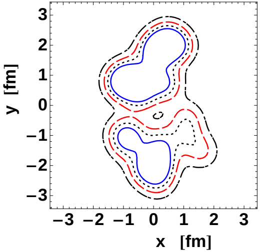
triangular flow

d-Pb

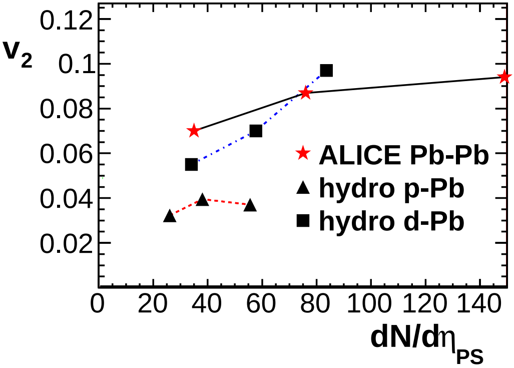


large elliptic flow



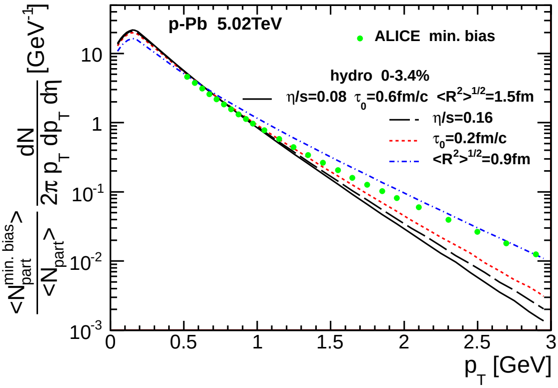


prediction 11.2011



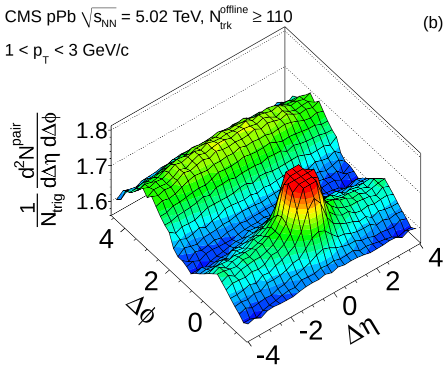
- collective flow effects $\simeq$ peripheral Pb-Pb
- can be observed
- p-Pb (d-Pb) is not p-p superposition
- only p-p as baseline

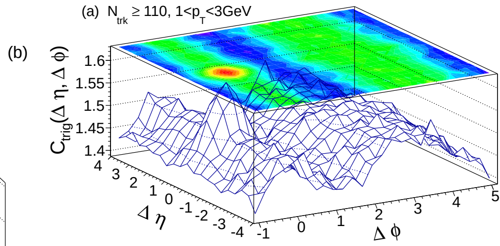
First results on pPb@5.02TeV - ALICE, CMS, ATLAS



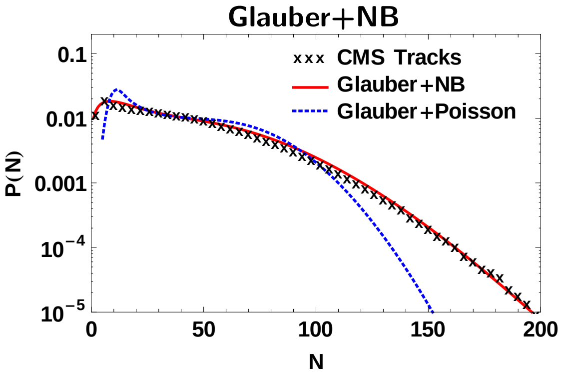
- statistical for $p_{\perp} < 1.5$-2Gev
- early flow, viscosity, density profile?

Ridge in p-Pb





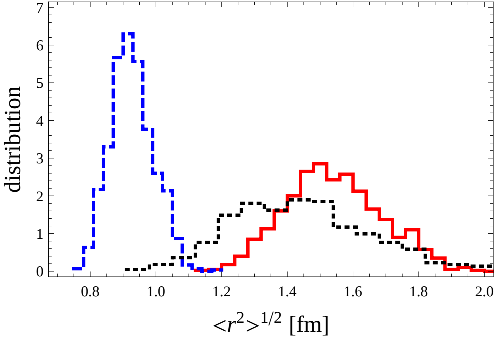
PB, W.Broniowski, 2012



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

Additional fluctuations of density (compared to Glauber)

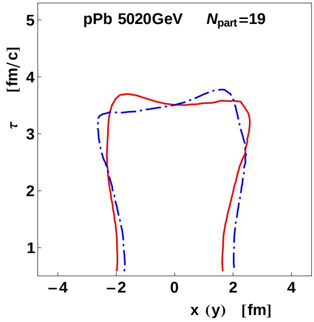
Very different fireball size



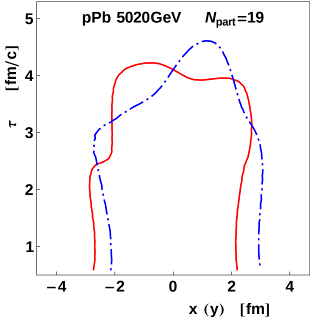
Compact (0.9fm), Glauber+NB (1.4fm), Standard (1.5fm)

Expansion of the fireball

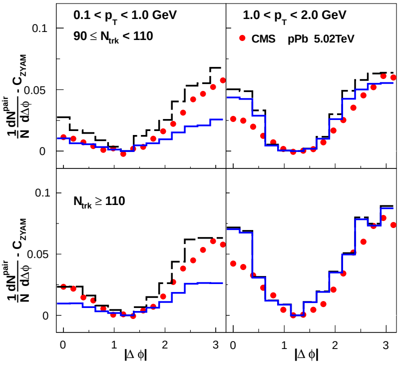
Compact source



Standard (large) source

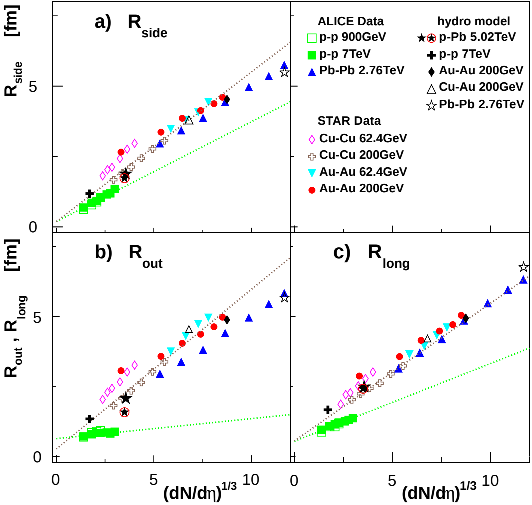


Azimuthal correlations



- collective flow

HBT systematics

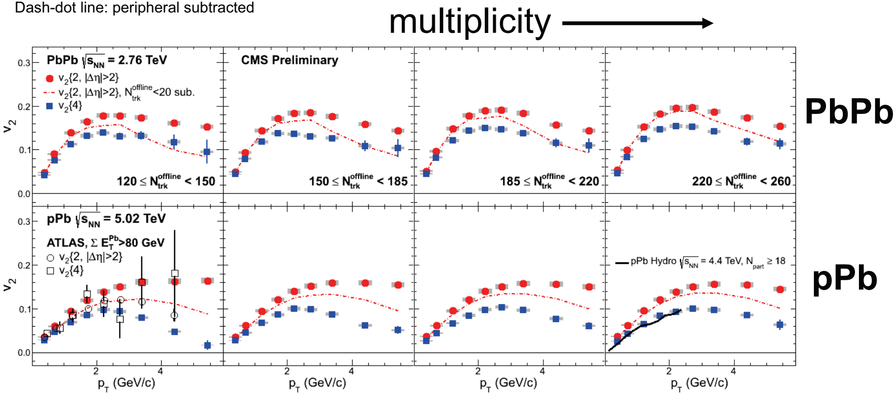


PB, W.Broniowski, 2013

small system corrections! - Sinyukov, Shapoval

v_2 in pPb and PbPb

Dash-dot line: peripheral subtracted



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

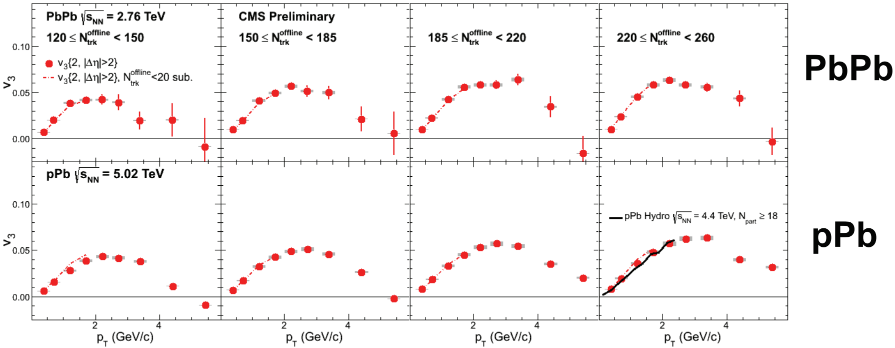
$v_2\{4\}$ is only 20% smaller than $v_2\{2\}$ below 2 GeV/c

"Peripheral subtraction" has small effect at high multiplicity

v_3 in pPb and PbPb

Dash-dot line: peripheral subtracted

multiplicity →



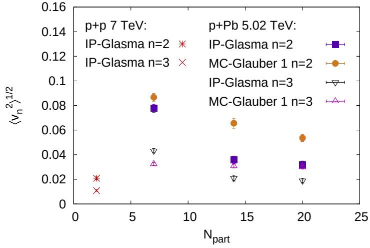
v_3 has similar shape in pPb and PbPb; magnitude comparable

"Peripheral subtraction" makes essentially no difference

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

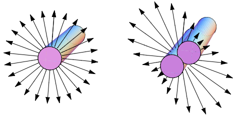
Hydrodynamic flow in p-p?

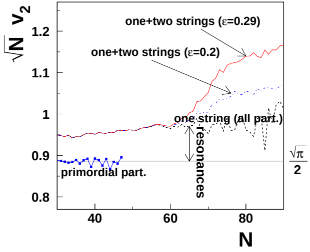
- Humanic - nucl-th/0612098 (pythia, cascade)
- Romatschke, Luzum - arXiv: 0901.4588 (overlap)
- Prasad, Roy, Chattopadhyay, Chaudhuri - arXiv: 0910.4844 (overlap)
- Bozek - arXiv: 0911.2392 (flux-tubes)
- Yan, Dong, Zhou, Li, Ma, Sa - arXiv: 0912.3342 (transport)
- Werner, Karpenko, Pierog - arXiv: 1011.0375 (EPOS)
- Deng, Xu, Greiner - arXiv: 1112.0470 (hot-spot, transport model)
- Shuryak, Zahed - arXiv: 1301.4470 (symmetric)
- Bzdak, Schenke, Tribedy, Venugopalan - arXiv: 1304.3403 (IP-Glasma)



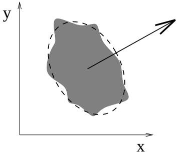
- Is hydrodynamics valid?
- What is the initial eccentricity ?

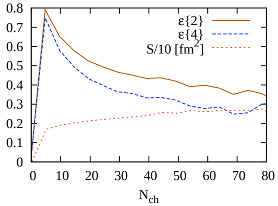
Fireball shape in pp





PB, 0911.2397

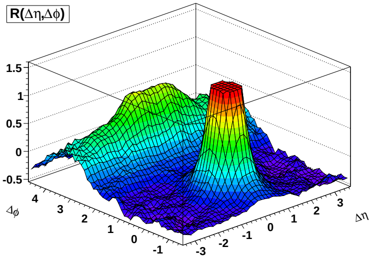




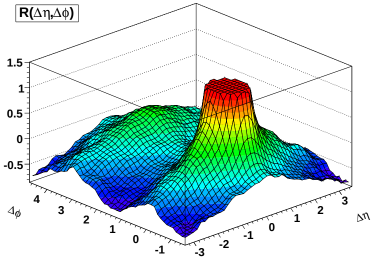
E.Asar et al., 1009.5643

EbE v_2 deconvolution? (ATLAS, Jia, Mohapatra)

Hydro ridge in p-p



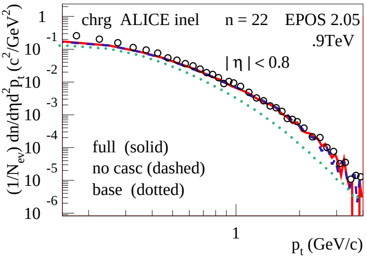
No collectivity

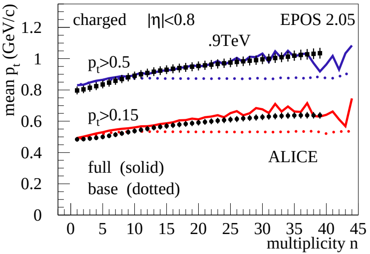


EPOS+hydro

Werner, Karpenko, Pierog arXiv: 1011.0375

Spectra in p-p

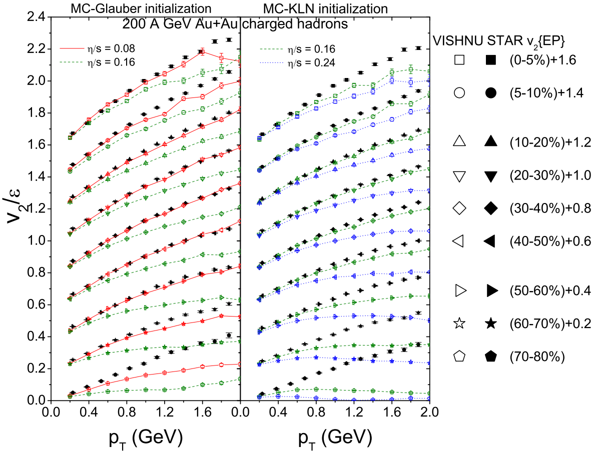




Werner, Karpenko, Pierog, Bleicher, Mikhailov arXiv: 1010.0400

Can we reduce the uncertainties

go back to very peripheral A-A



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

Strong corrections to longitudinal pressure

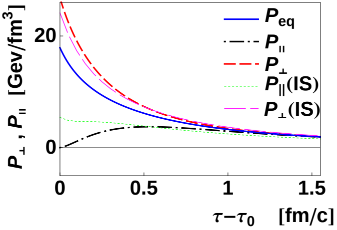
Non-equilibrium and/or viscosity
Early stage

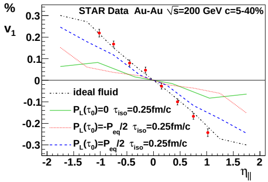
$$T^{\mu\nu} = \begin{pmatrix} \epsilon & 0 & 0 & 0 \\ 0 & p + \pi/2 & 0 & 0 \\ 0 & 0 & p + \pi/2 & 0 \\ 0 & 0 & 0 & p - \pi \end{pmatrix}$$

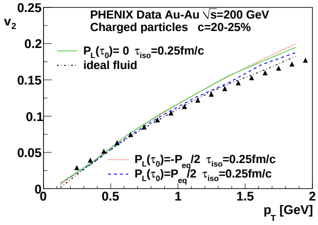
$$\pi = \frac{4}{3}\frac{\eta}{\tau} \quad \text{Navier-Stokes}$$

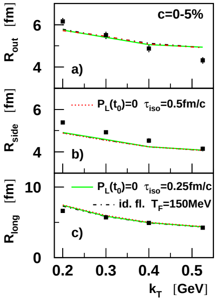
more general π possible - (initial value, dynamics, far off-equilibrium)

Pressure anisotropy









PB, I.Wyskiel, 2010

early pressure anisotropy irrelevant - Vredevoogd, Pratt, 2009

other higher gradients could be important ?

Summary

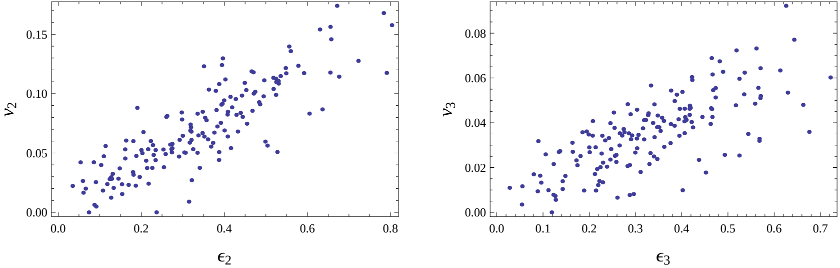
- Ev-by-ev hydro for pA
- Collectivity (FSI) in pPb@LHC , explains observed ridge and v_2
- HBT radii in p-Pb ?
- Is it collective flow ? - In many aspects consistent
- Other sources of correlations !
- Limits of hydro!

- Why hydrodynamics would work?

- Prospects: **Experiment**

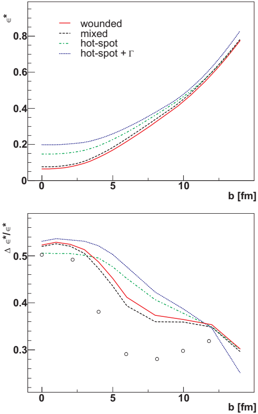
... and initial state, peripheral A-A, p-p??, core-corona, disentangling: collectivity, CGC, jets ...

Fireball anisotropy - flow asymmetry



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

Eccentricity fluctuations, central collisions



$$\frac{\Delta\epsilon}{\epsilon} = \sqrt{\frac{4}{\pi} - 1}$$

Broniowski, Bozek, Rybczynski arXiv: 0706.4266

central A-A, Gaussian limit $\longrightarrow$ $v_2\{4\} \simeq 0$

central p-A (Glauber+NB) $\frac{\Delta\epsilon}{\epsilon} < \sqrt{\frac{4}{\pi} - 1}$ and $v_2\{4\} > 0$

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

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

- nonequilibrium initial $T^{\mu\nu}$