Hydrodynamic flow in p-Pb

Piotr Bożek

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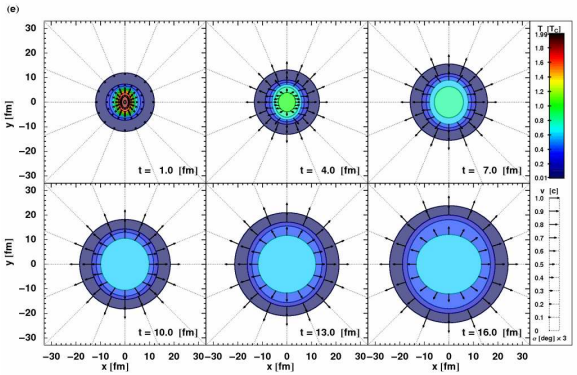
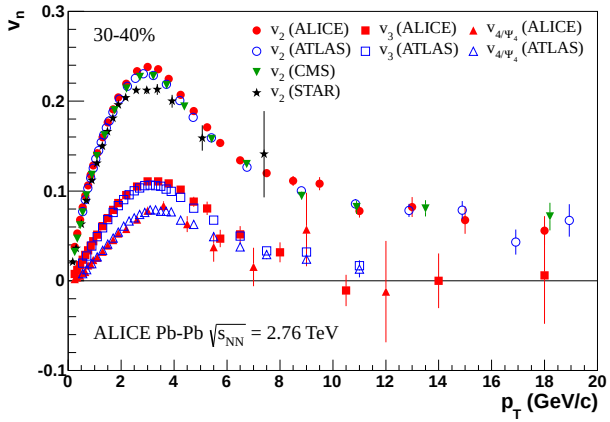
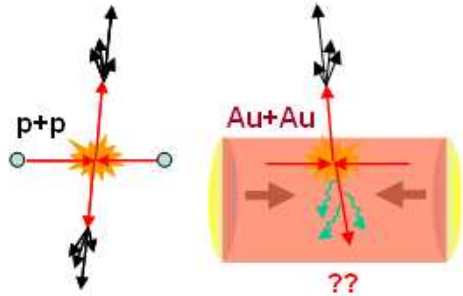
QGP formed in A-A collisions

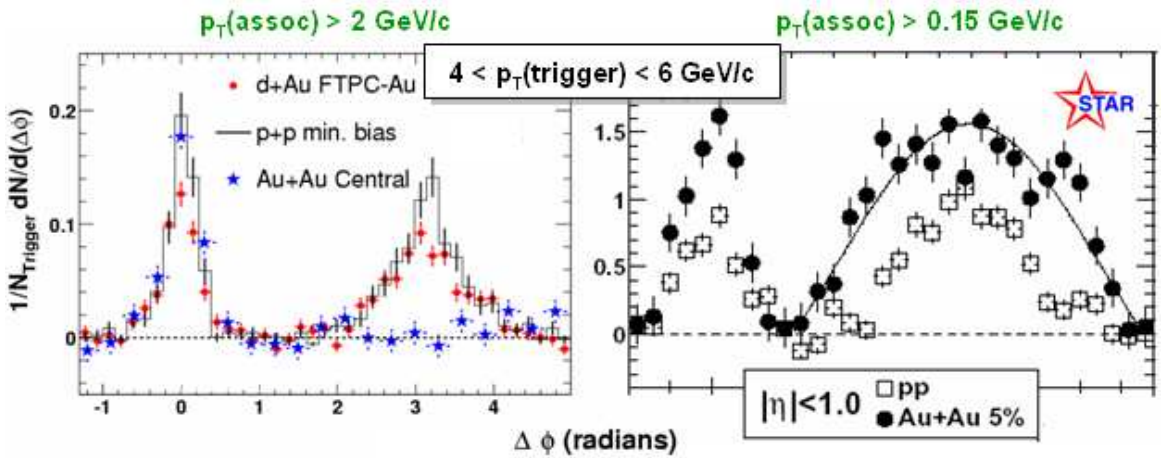
sQGP





Jet quenching

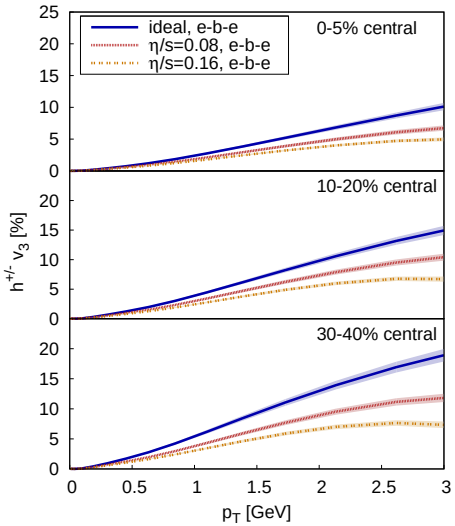




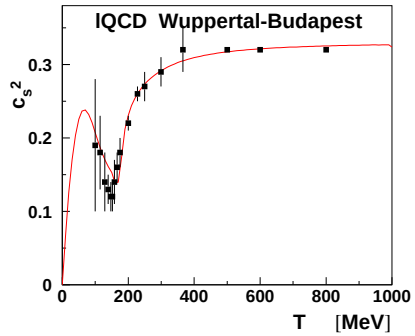
$$\frac{dN}{d\phi} \propto 1 + 2v_2 cos(2(\phi - \Psi_2))$$

$$+2v_3 cos(3(\phi - \Psi_3)) + \ldots$$

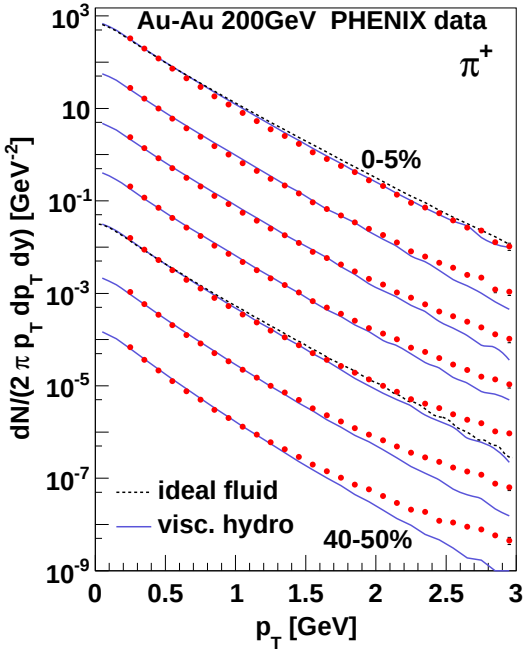
3+1D hydrodynamics

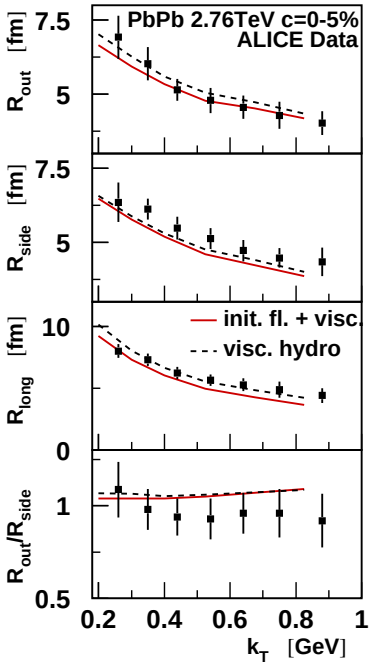


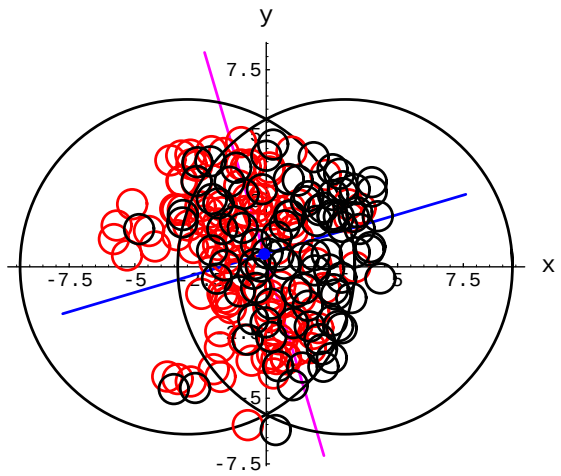
3+1D visc. : B.Schenke et al.



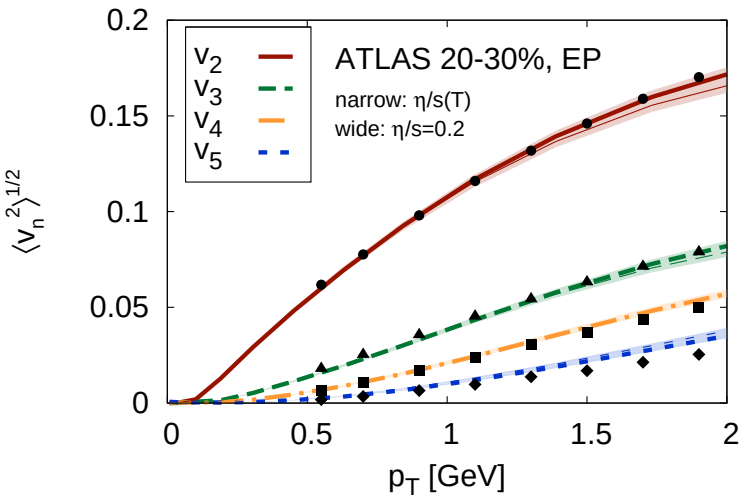
IQCD + Hadron Gas



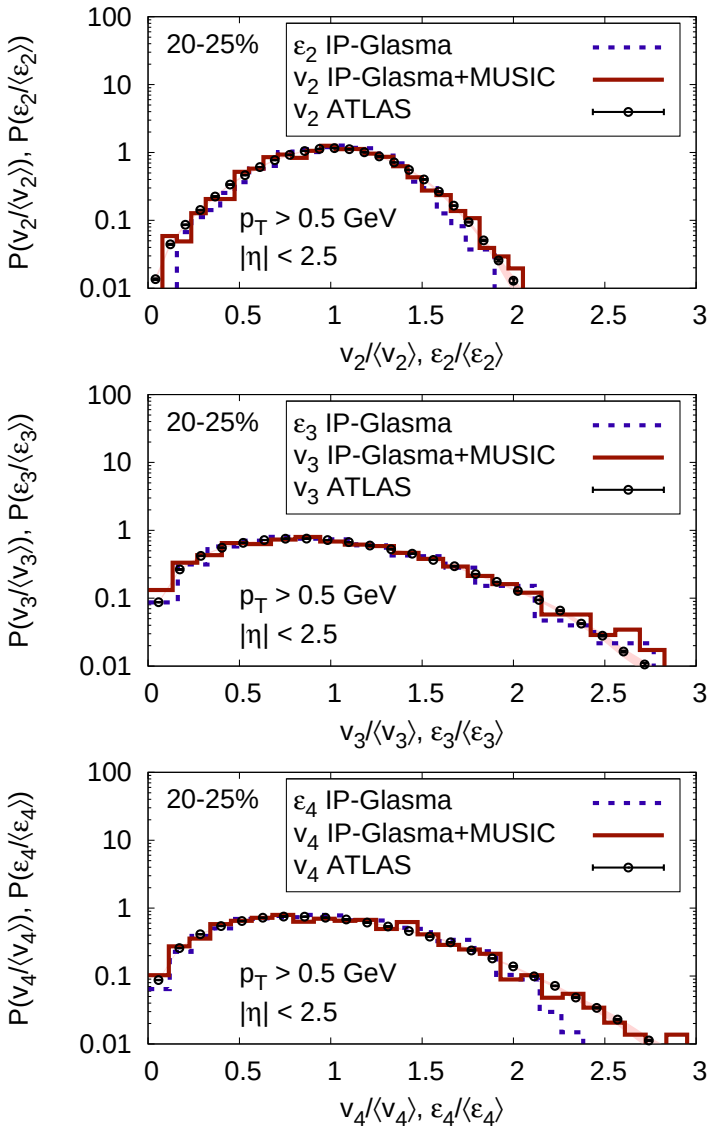




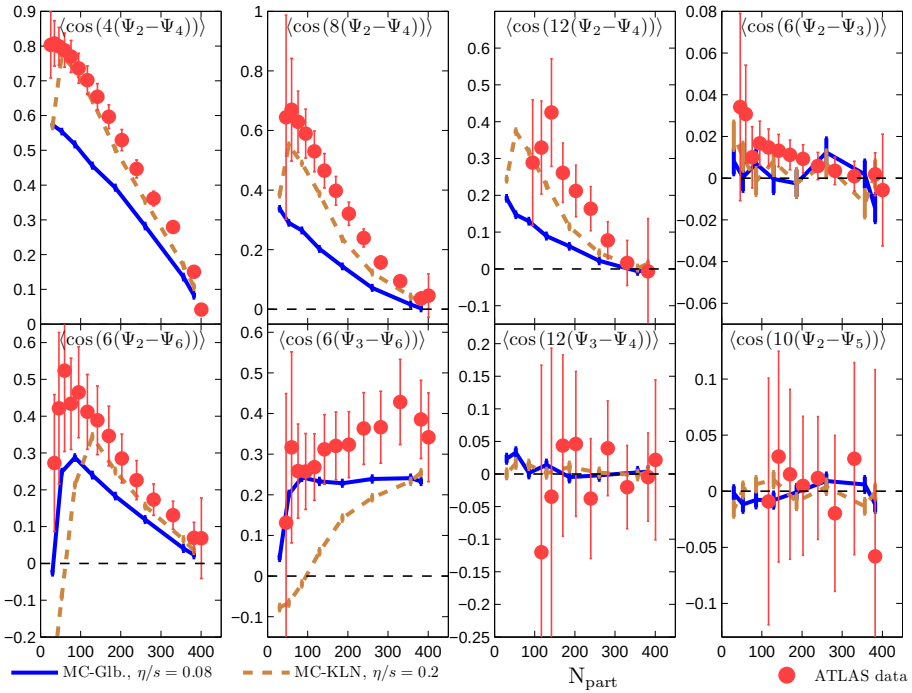
Event anisotropy



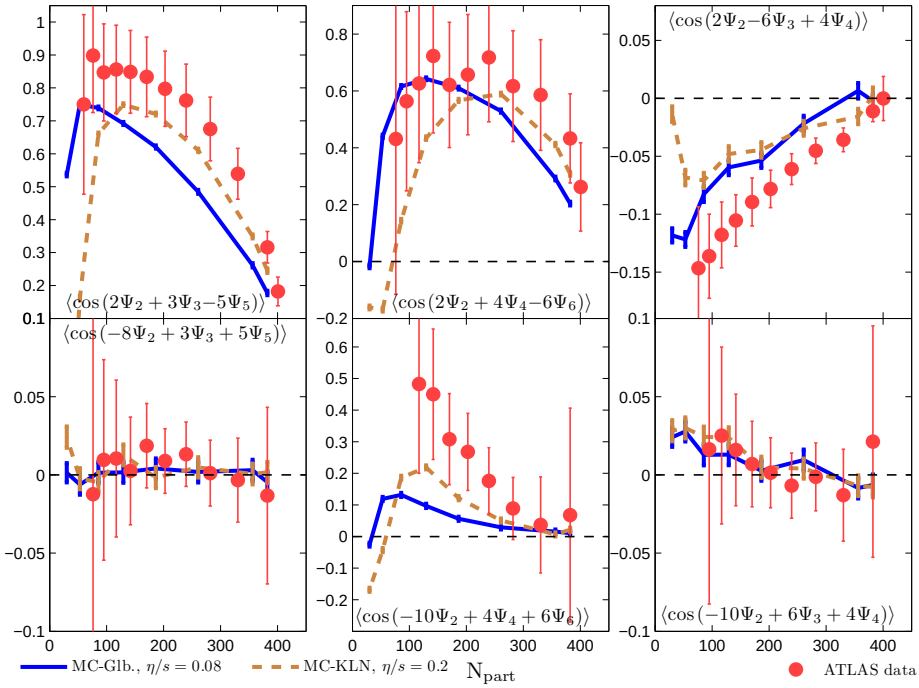
C.Gale et al. arXiv:1209.6330



Event planes correlations



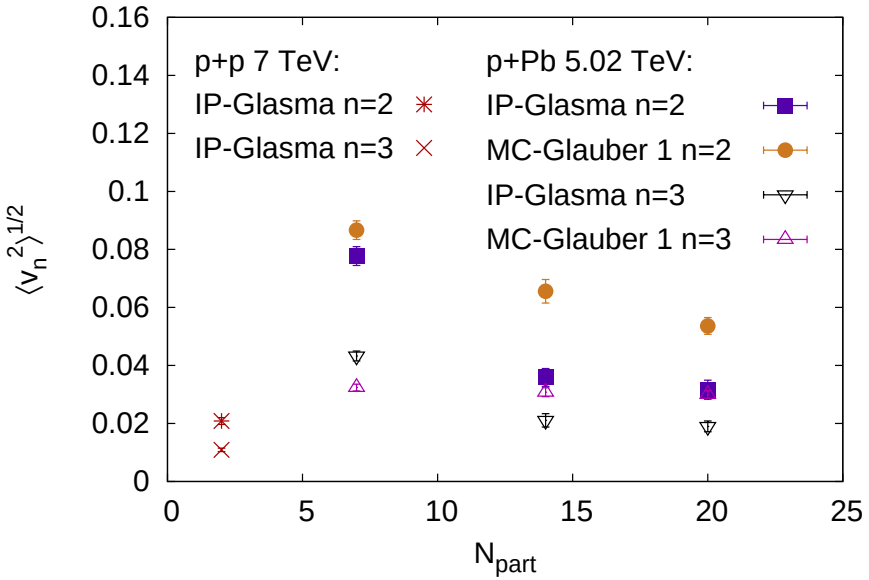
Z.Qiu, U.Heinz arXiv:1208.1200



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

Hydrodynamic flow in p-p?

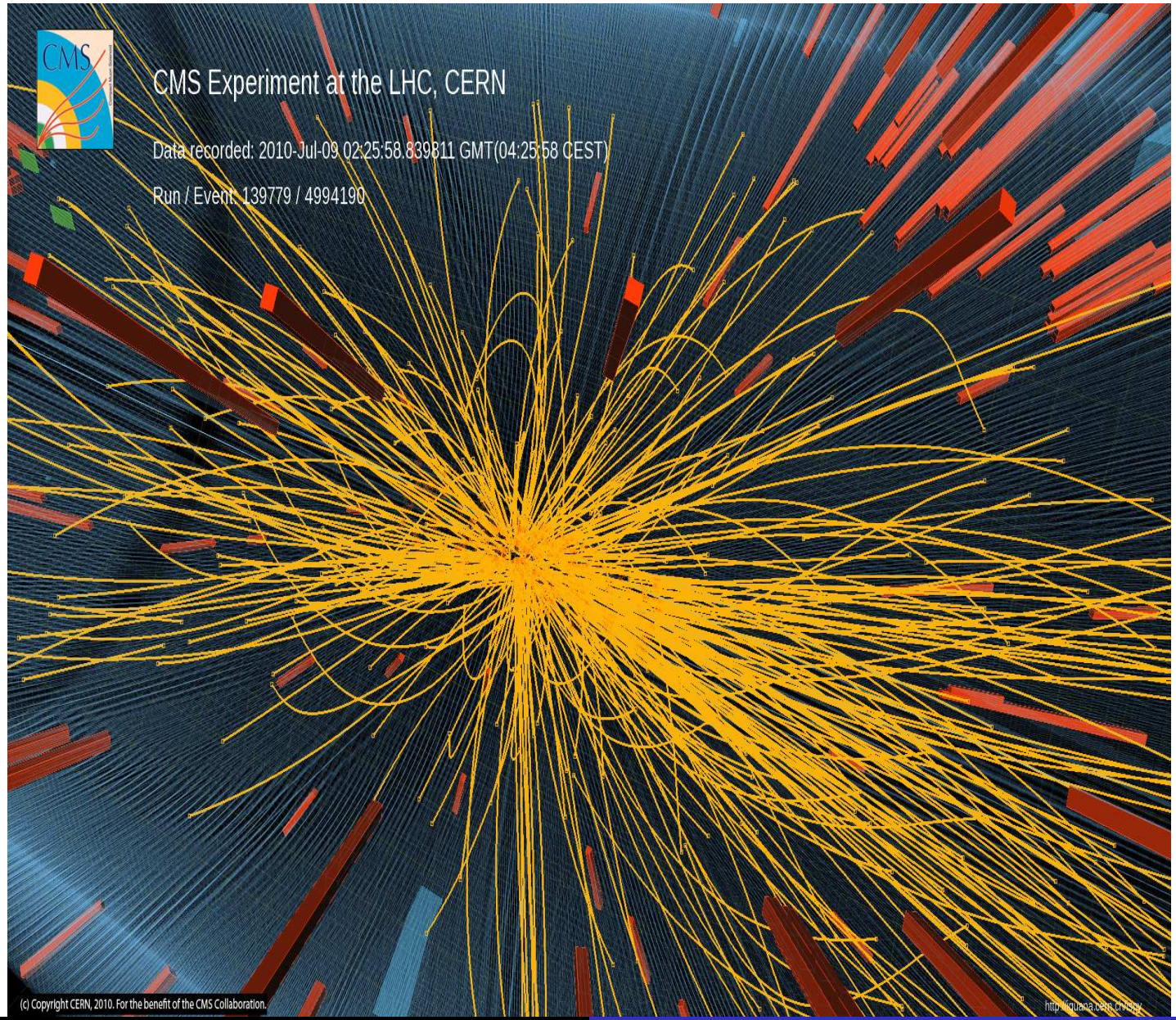
- Humanic-nucl-th/0612098 (pythia, cascade)
- Romatschke, Luzum-arXiv:0901.4588 (overlap)
- Prasad, Roy, Chattopadhyay, Chaudhuri -arXiv: 0910.4844 (overlap)
- Bozek-arXiv: 0911.2393 (flux-tubes)
- Yan, Dong, Zhou, Li, Ma, Sa- arXiv: 0912.3342 (transport)
- Werner, Karpenko, Pierog, Bleicher, Mikhailov-arXiv: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



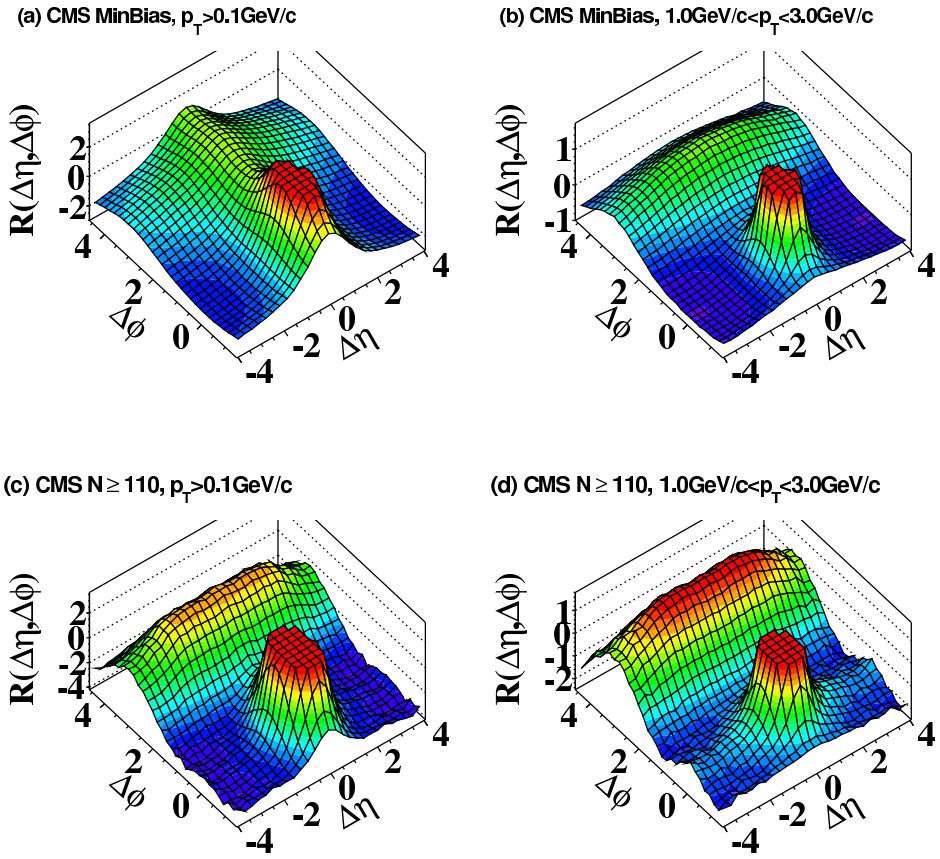
Bzdak et al. arXiv: 1304.3403

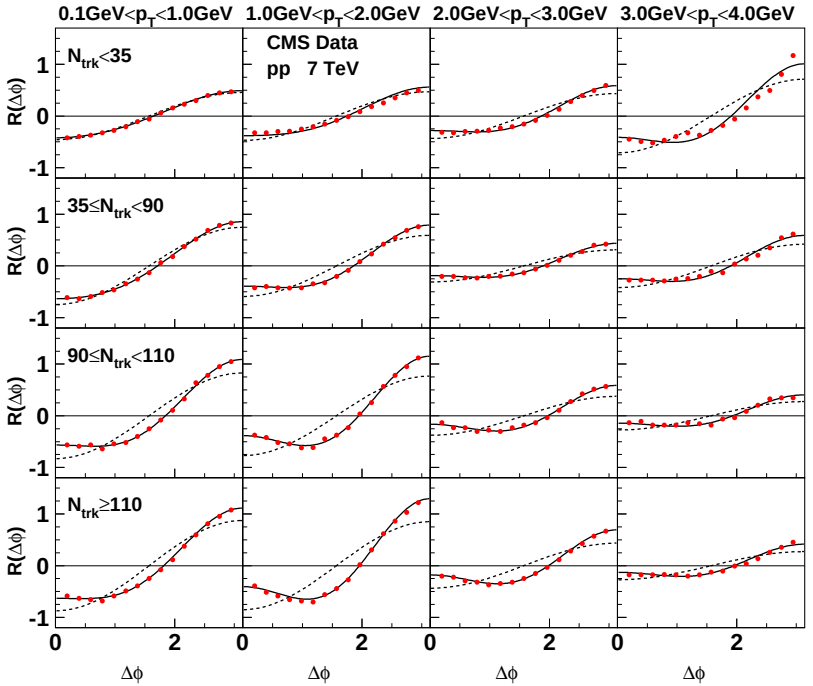
-Is hydrodynamics valid?
-What is the initial eccentricity?

High multiplicity events in pp



Ridge in pp

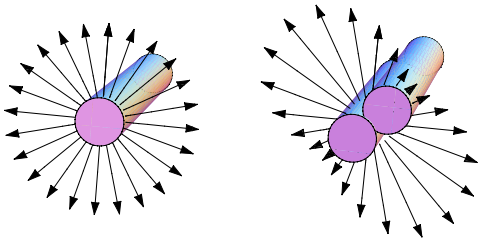


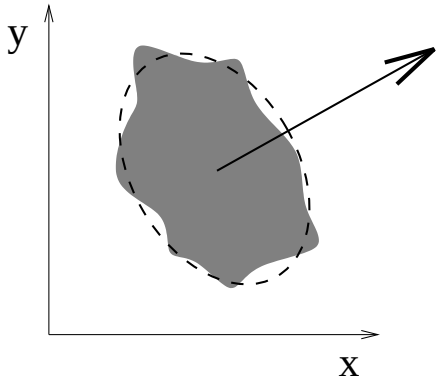


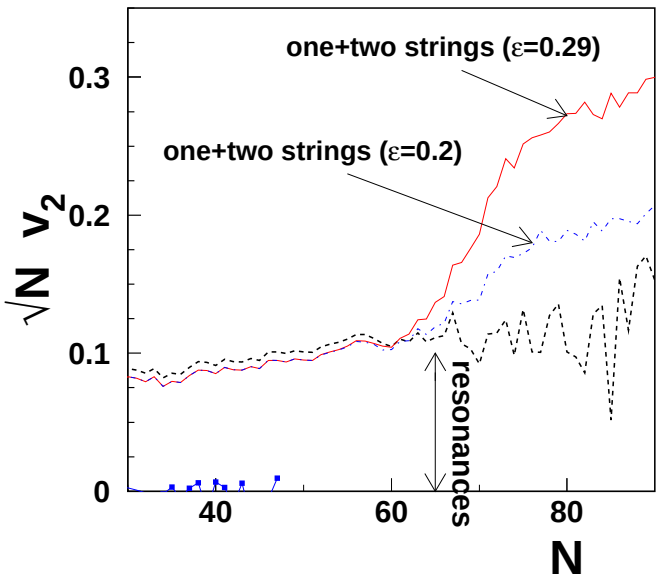
PB arXiv:1010.0405

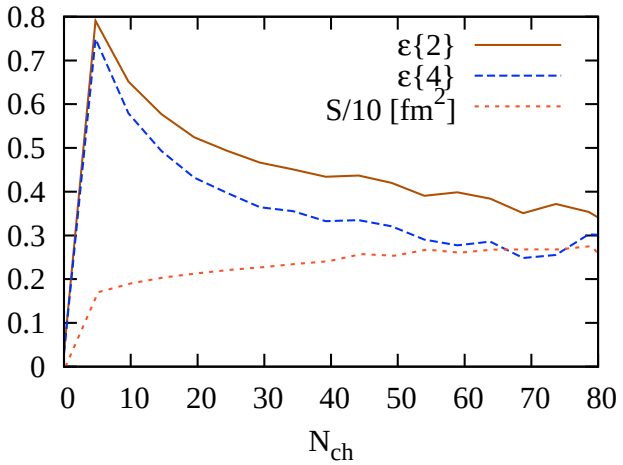
can we measure (calculate) v_2

Fireball shape in pp









Bozek, 0911.2397

E.Asar et al., 1009.5643

Casalderrey-Solana, Wiedemann, 0911.4400

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

Editor: *C. A. Salgado*[1]
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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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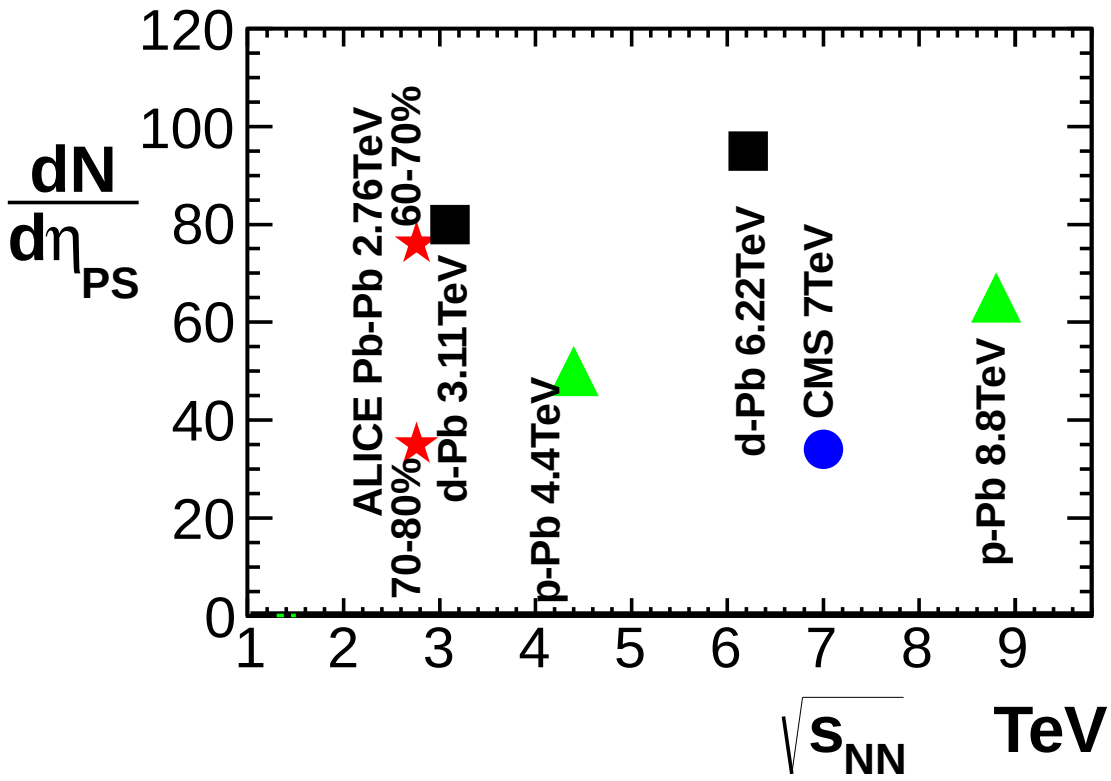
Contents

protonix-leadulus collision

p-Pb at 5.02TeV

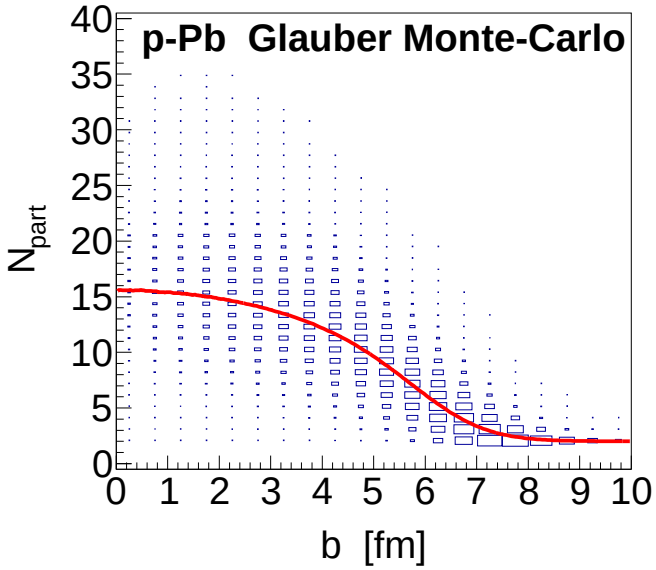
small dense fireball formed !

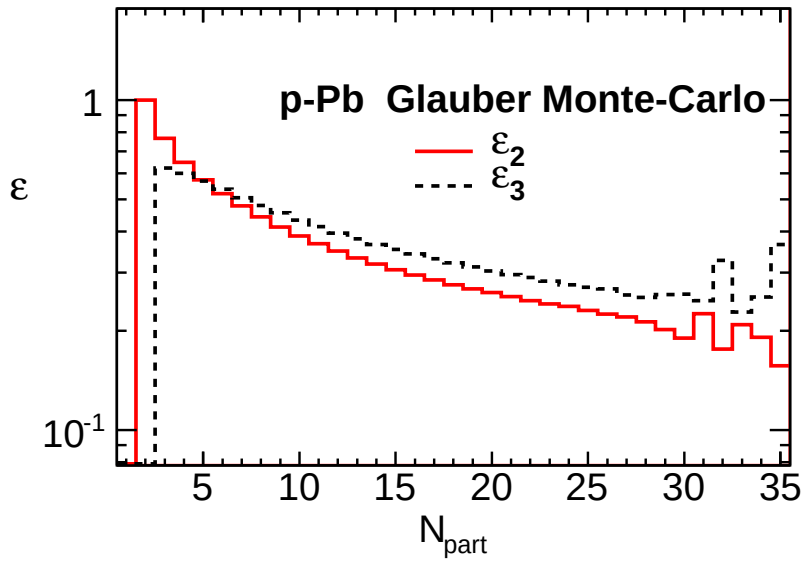
p-Pb, d-Pb @ LHC

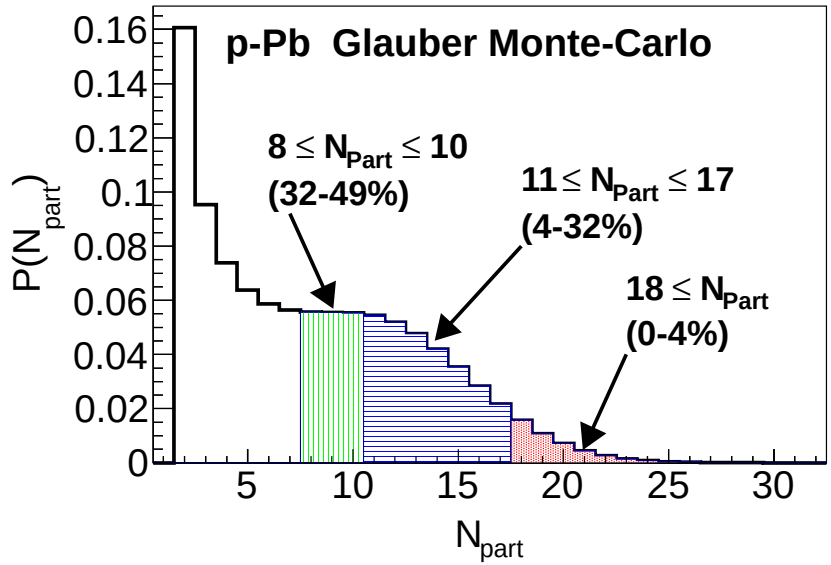


large multiplicity - large fireball - collective expansion?

Fireball in p-Pb



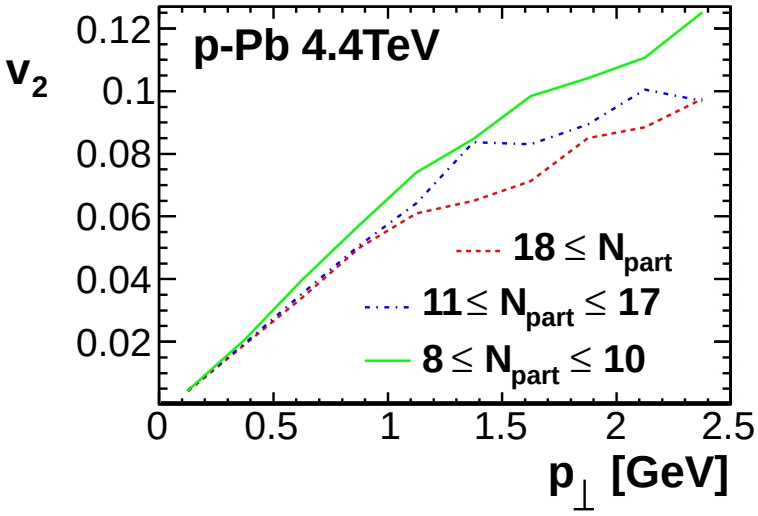




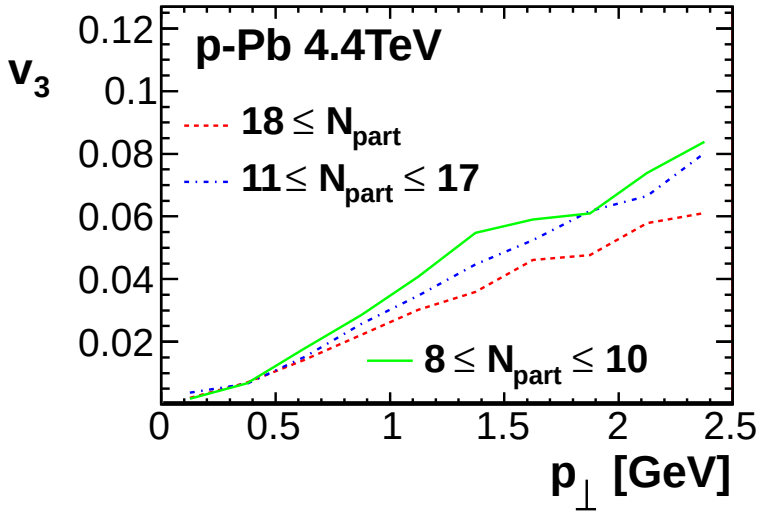
PB, arXiv:1112.0912

Collective elliptic flow in p-Pb? in 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? no — no!
  - beyond viscous hydro



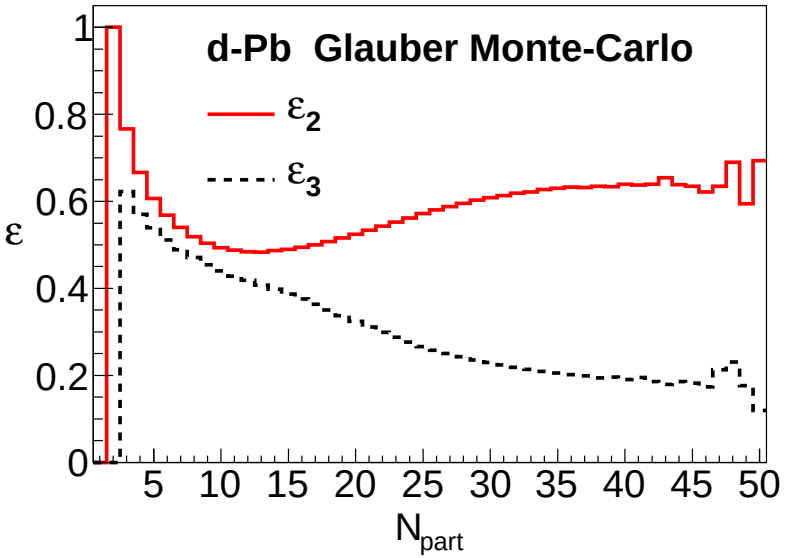
elliptic flow in p-Pb

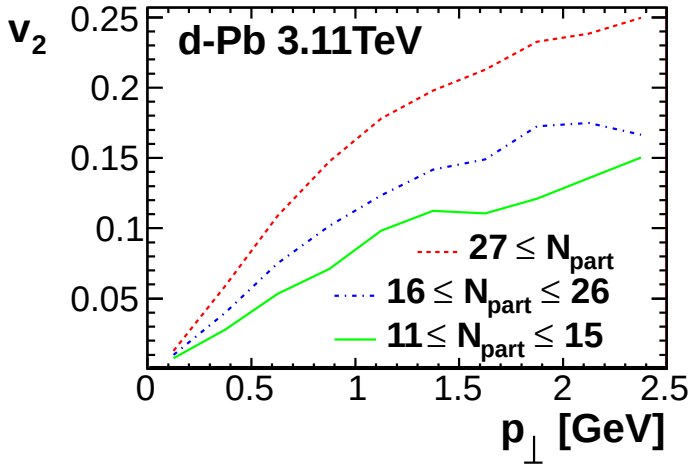


triangular flow

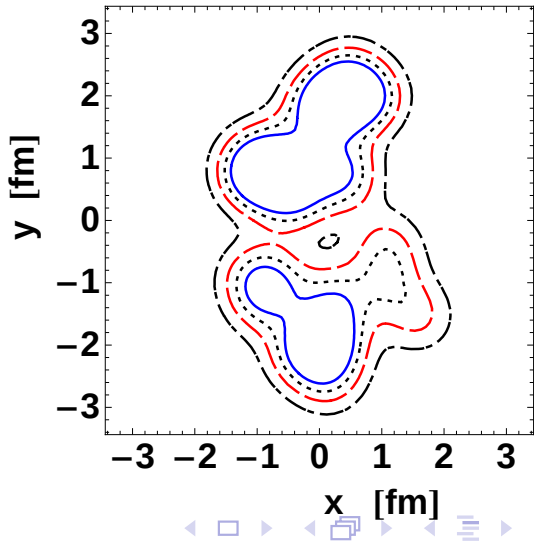
PB, arXiv:1112.0912

d-Pb





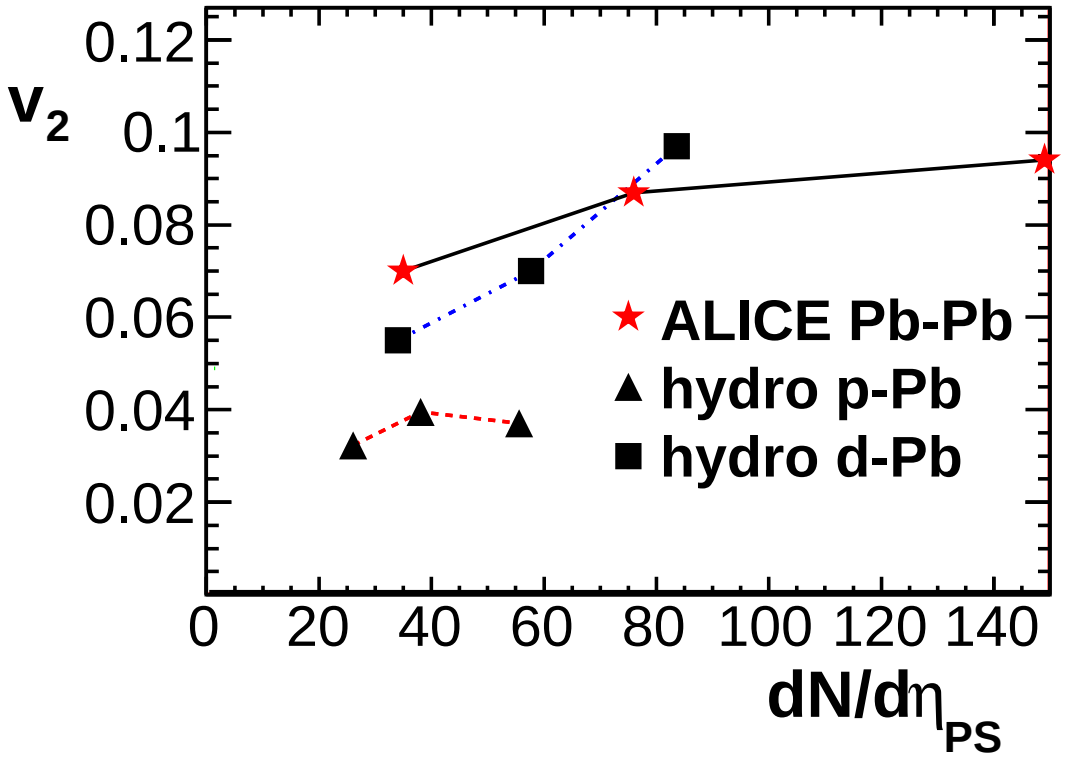
large elliptic flow



PB, arXiv:1112.0912

. . . it seems very interesting to look for collective effects in d-Au collisions at $\sqrt{s_N} = 200$GeV in RHIC experiments . . .

prediction 12.2011



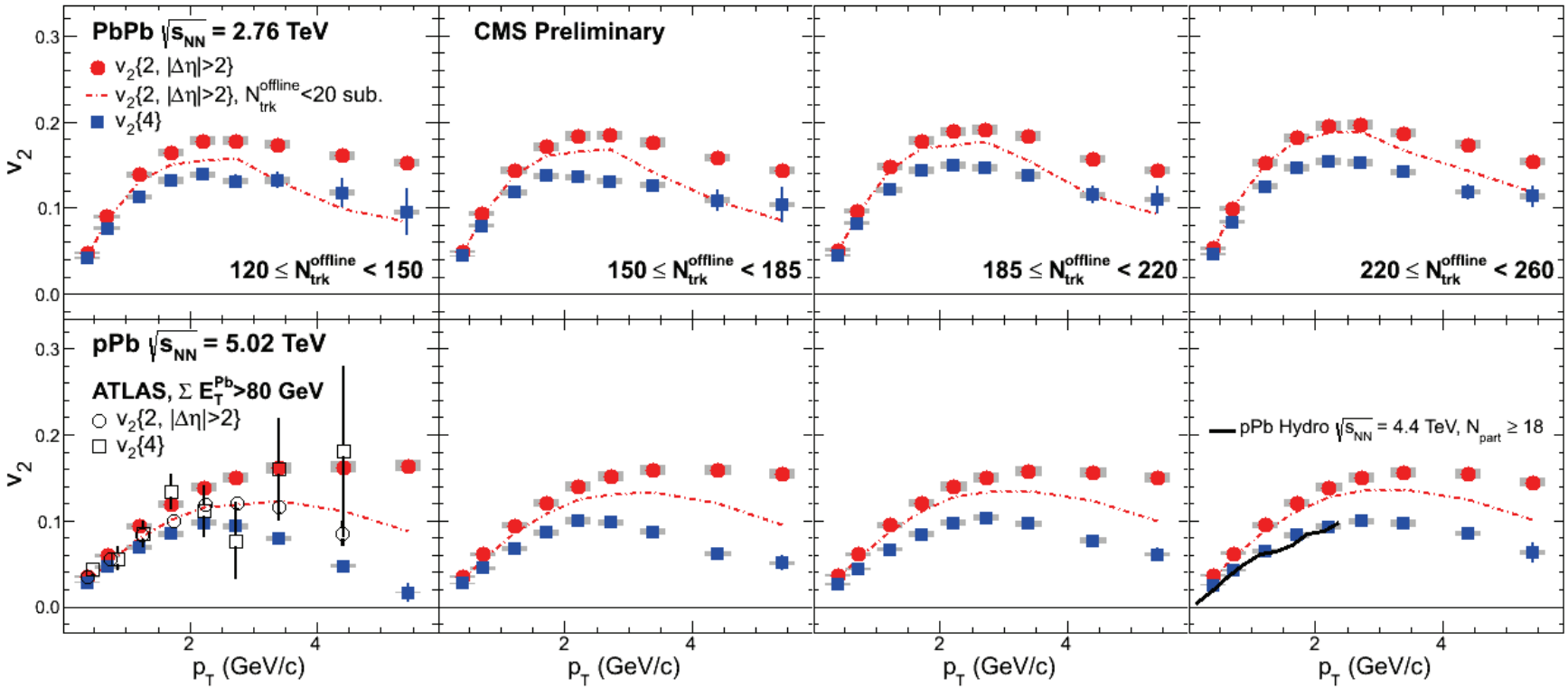
- collective flow effects $\simeq$ peripheral Pb-Pb
- can be observed
- p-Pb (d-Pb) is not p-p superposition
- only p-p as baseline

PB, arXiv:1112.0912

v_2 in pPb and PbPb

Dash-dot line: peripheral subtracted

multiplicity →



PbPb

pPb

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

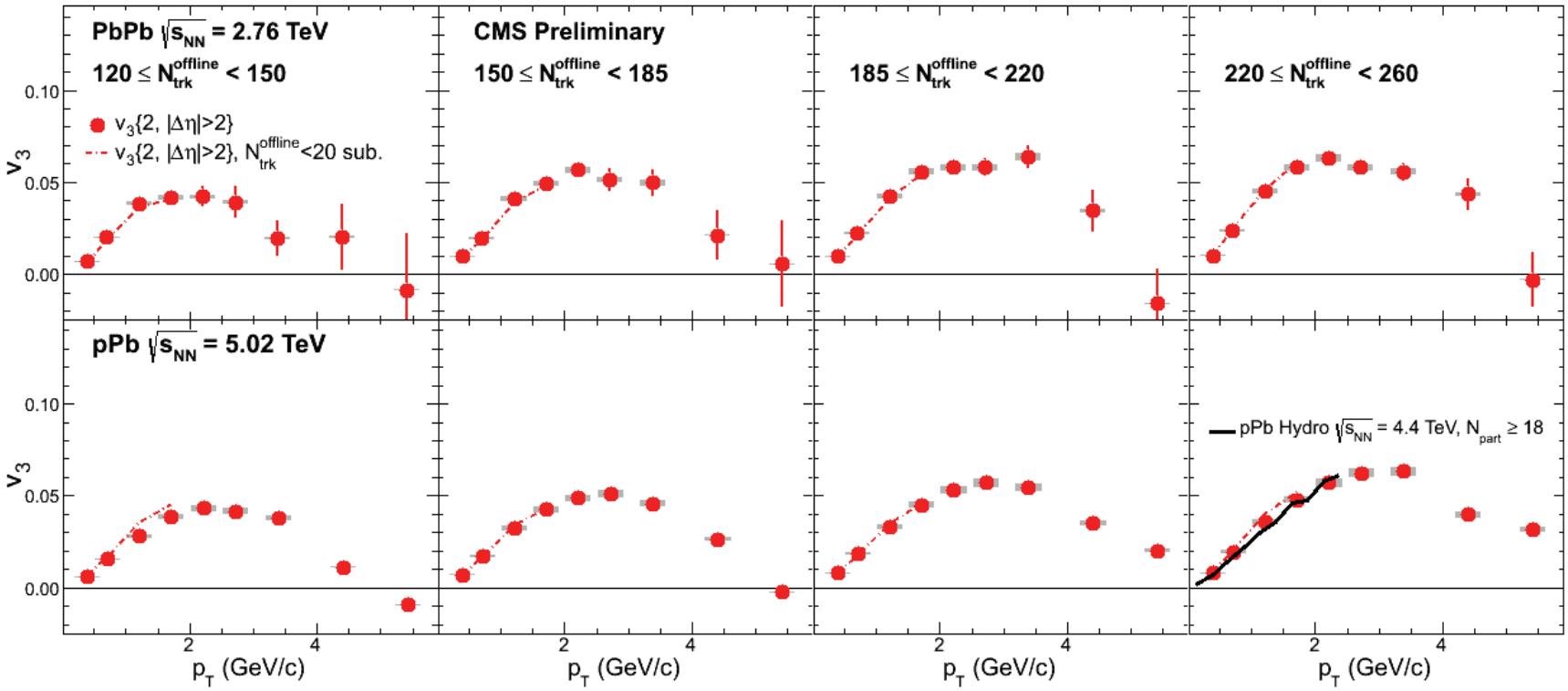
$v_2\{4\}$ is only 20% smaller than $v_2\{2\}$ below 2 GeV/c

"Peripheral subtraction" has small effect at high multiplicity

v_3 in pPb and PbPb

Dash-dot line: peripheral subtracted

multiplicity →



PbPb

pPb

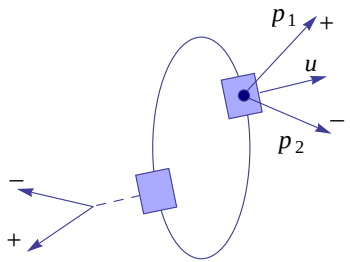
v_3 has similar shape in pPb and PbPb; magnitude comparable

"Peripheral subtraction" makes essentially no difference

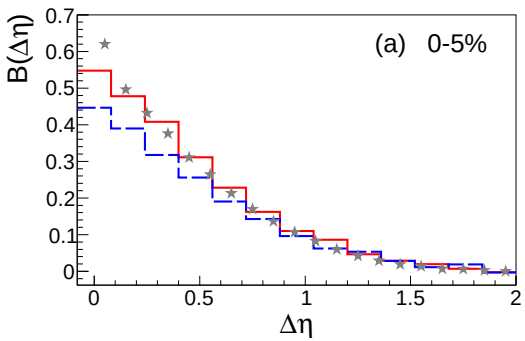
Hydro prediction: Bozek, v_3{PP}, not including fluctuations

Charge balancing

local charge conservation

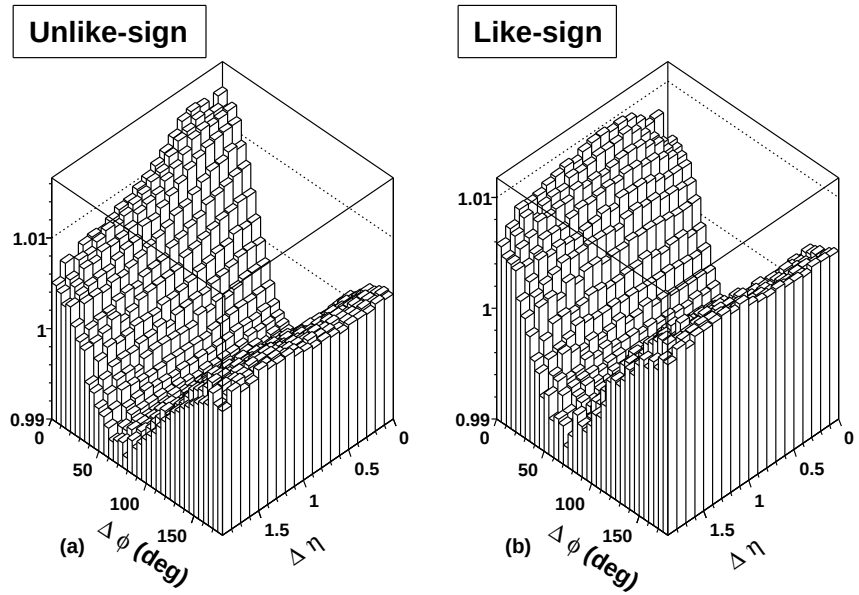


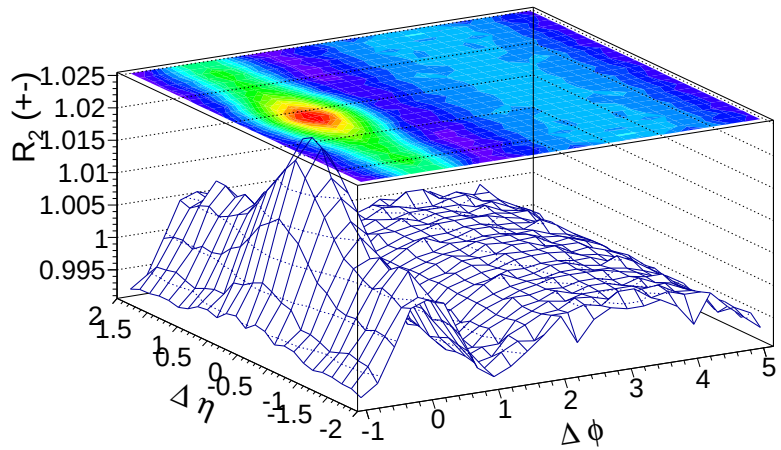
charge balance function



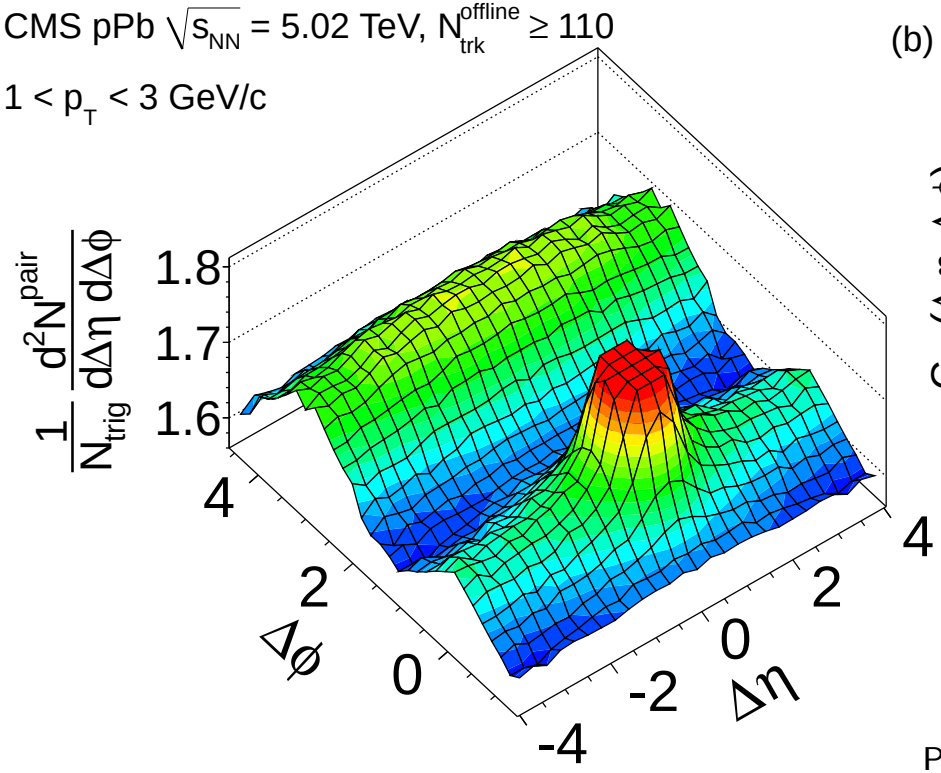
PB, W.Broniowski, arXiv: 1204.3580

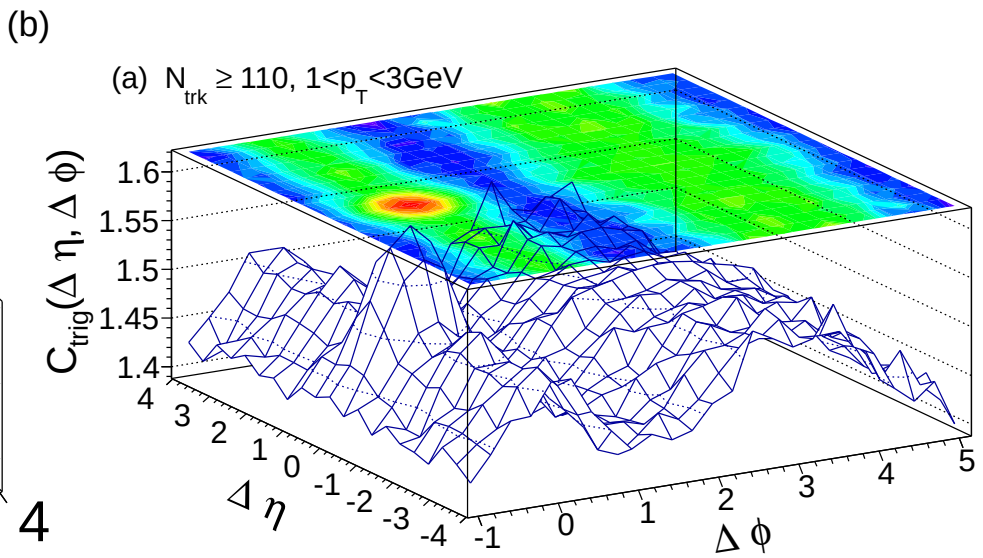
STAR data





Ridge in p-Pb

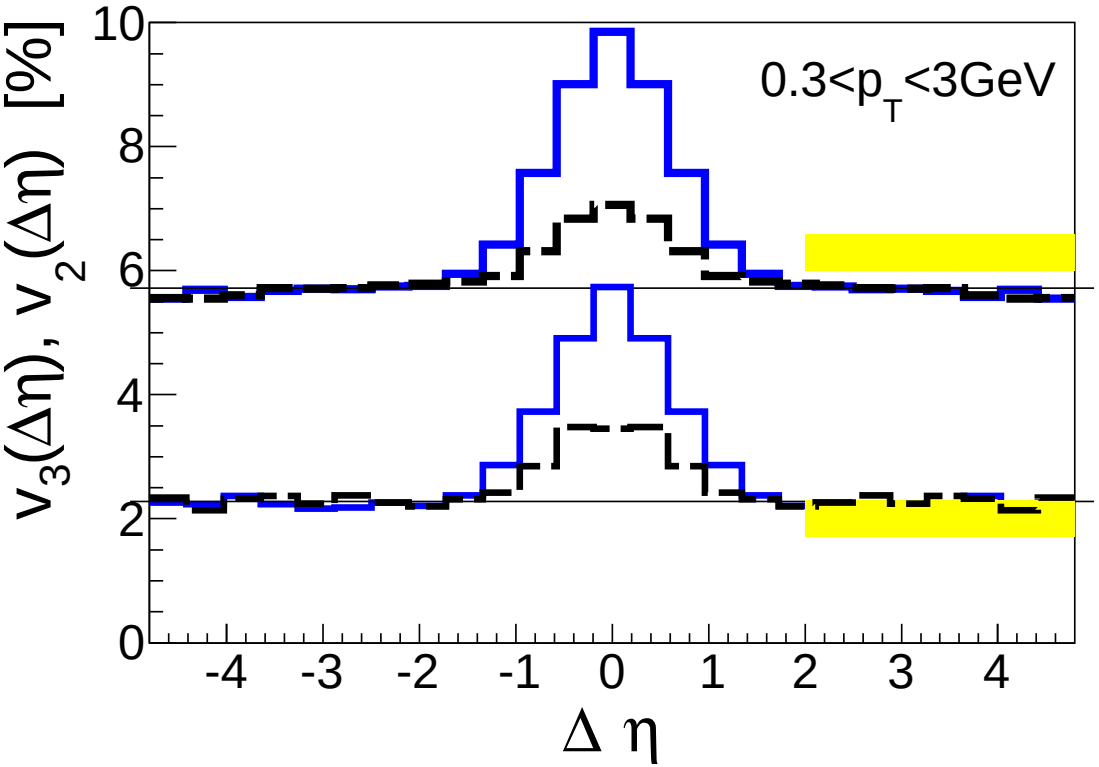




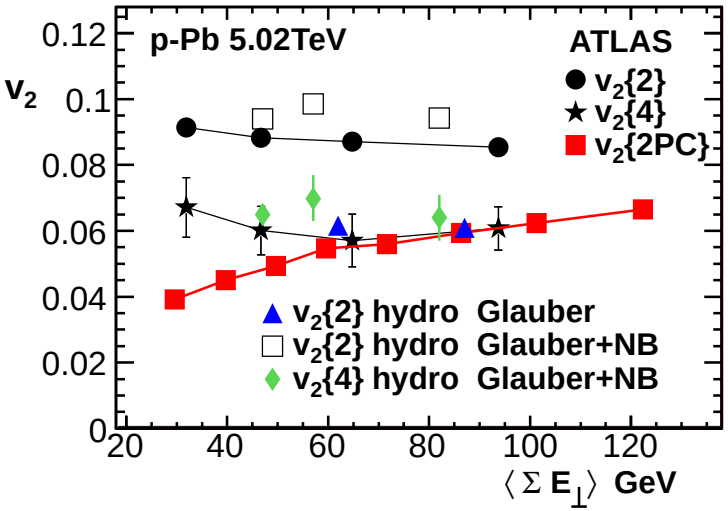
PB, W.Broniowski, arXiv:1211.0845

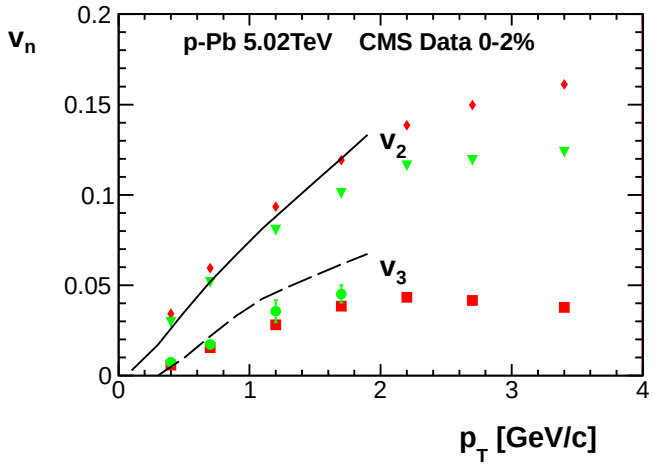
symmetric ridge also from CGC, K.Dusling, R. Venugopalan, arXiv:1210.3890, 1211.3701, 1302.7018

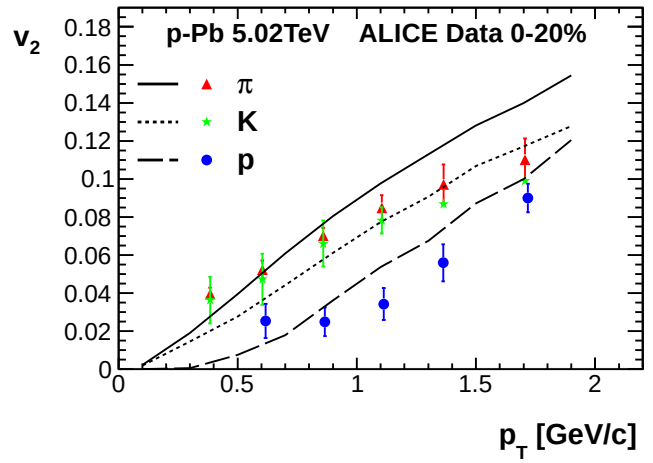
Extracting the flow correlations



Elliptic and triangular flow

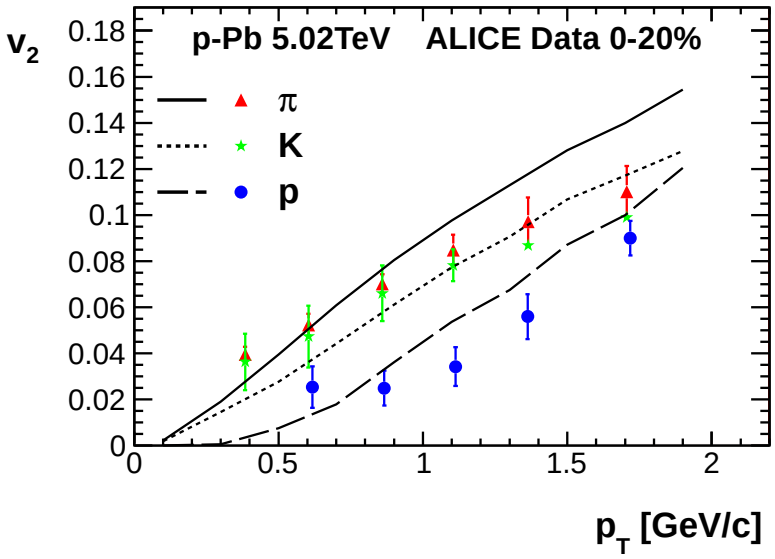


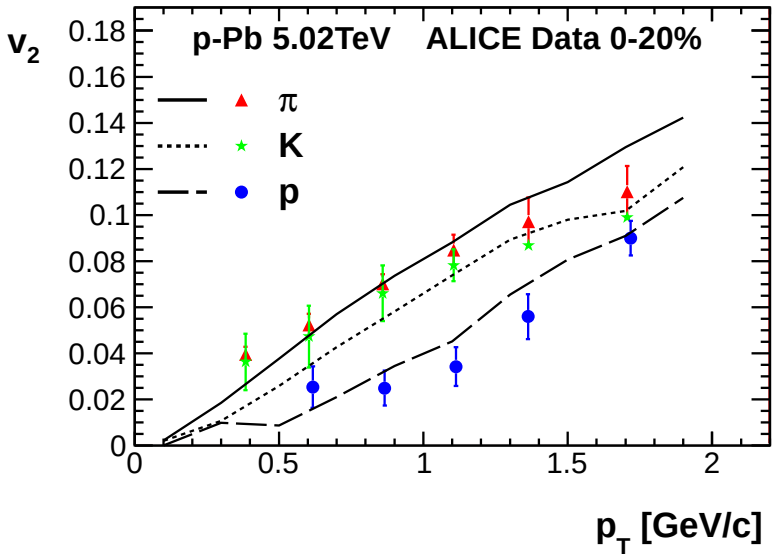




PB, W.Broniowski, G. Torrieri arXiv:1306.5442

v_2 from late stage





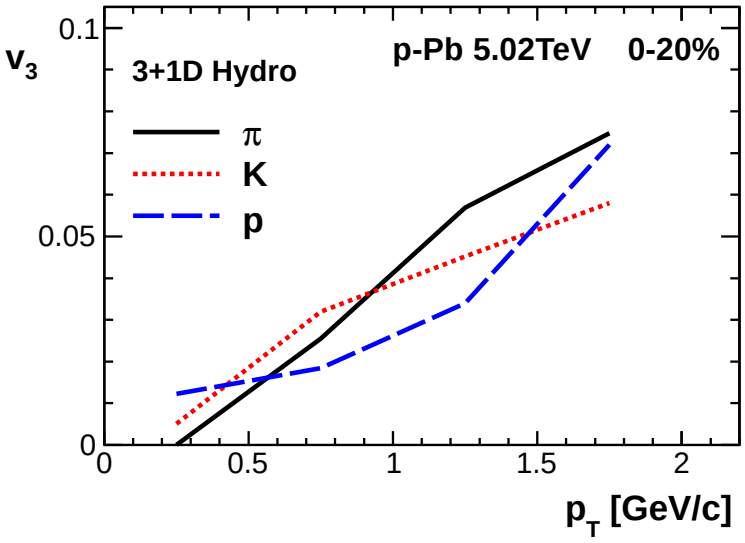
$T_f = 150$MeV

- pions : 0.75 collisions after emission

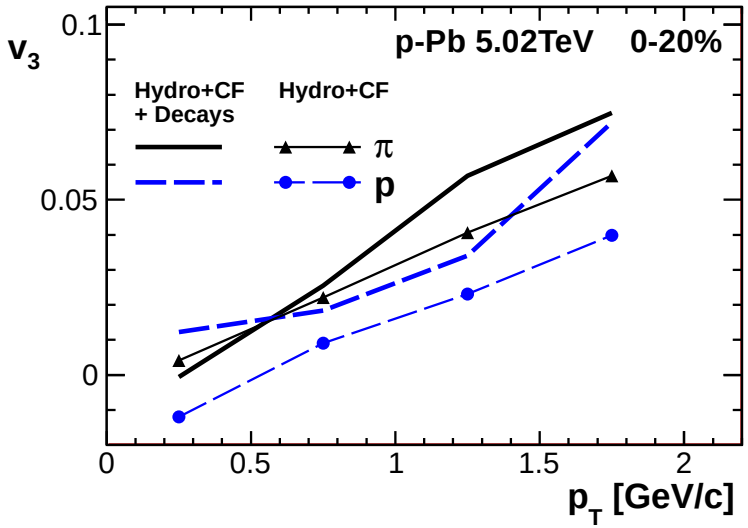
$T_f = 140$MeV

- pions : 0.65 collisions after emission

v_3 - small mass splitting



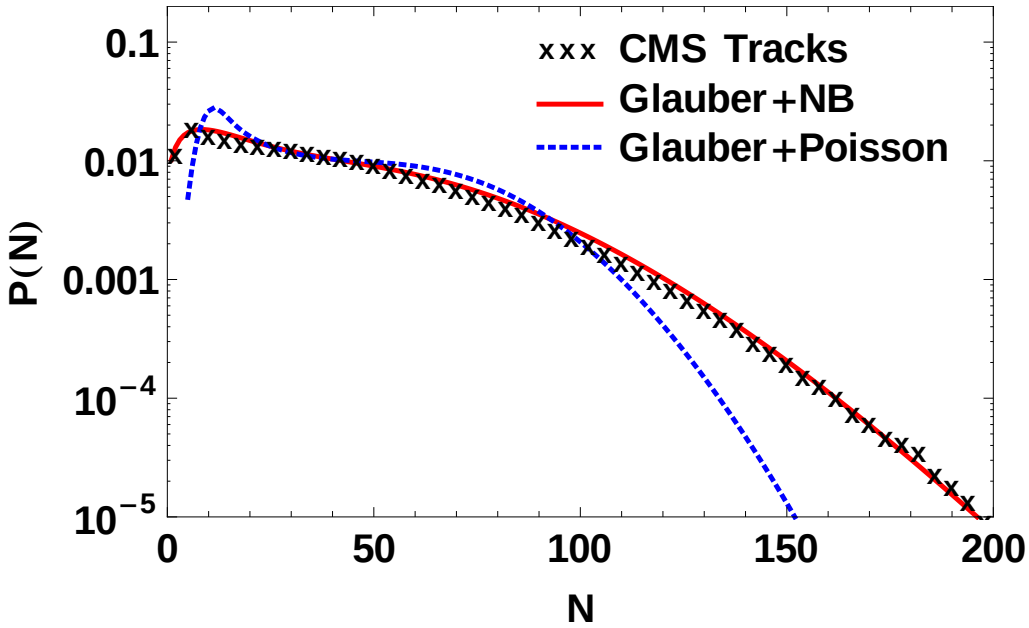
limited mass splitting



resonance decays spoil mass ordering

Glauber+NB

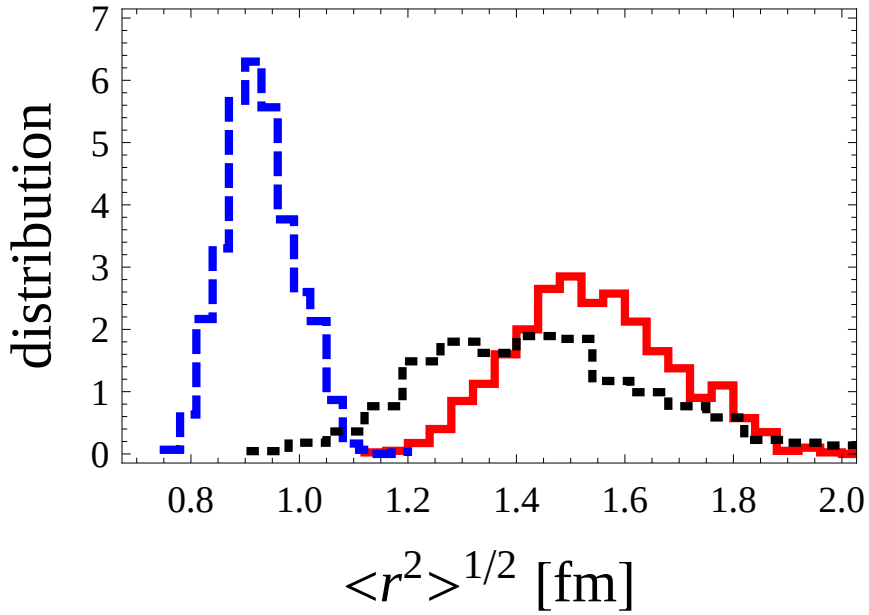
fluctuations from subnuclear dynamics



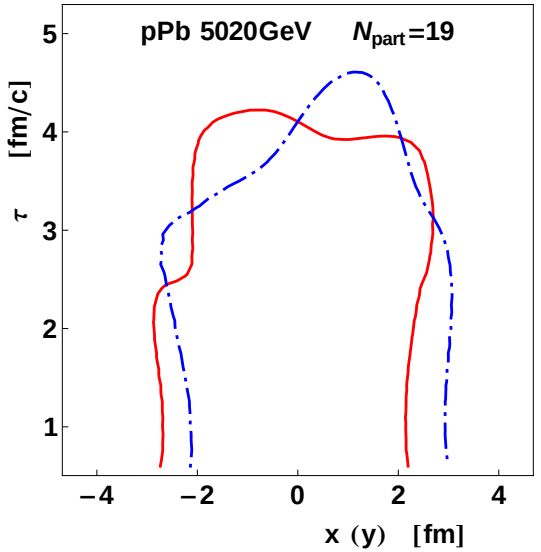
$$P(n) = \sum_i P_{part}(i) Np\lambda i, \kappa i(n)$$

Additional fluctuations of density (compared to Glauber)

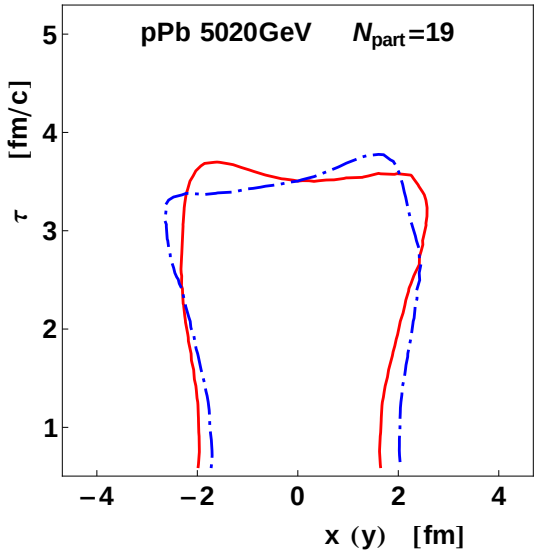
very different source sizes



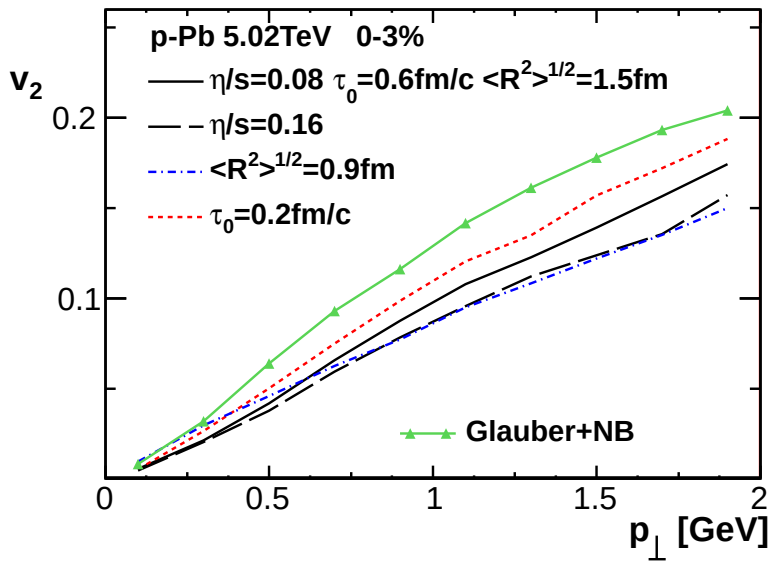
large source (standard)

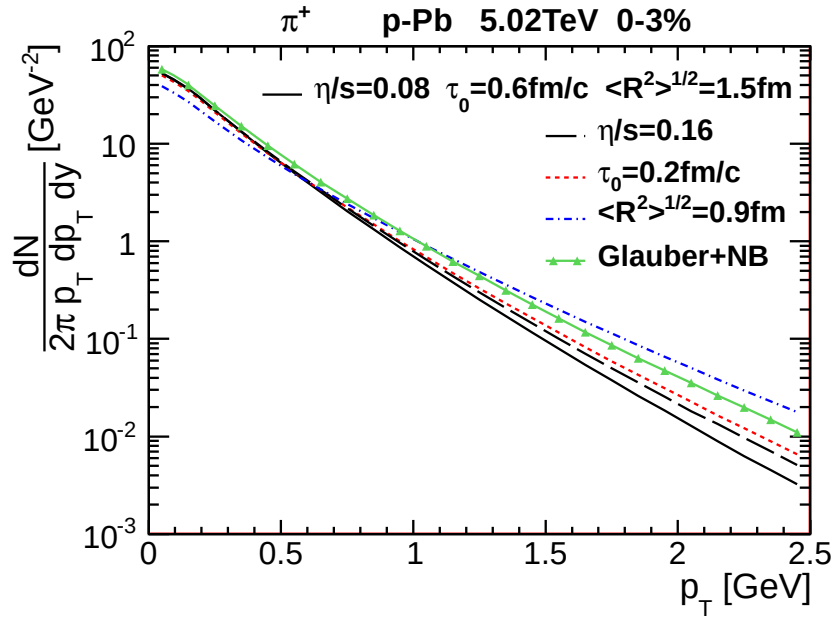


compact source



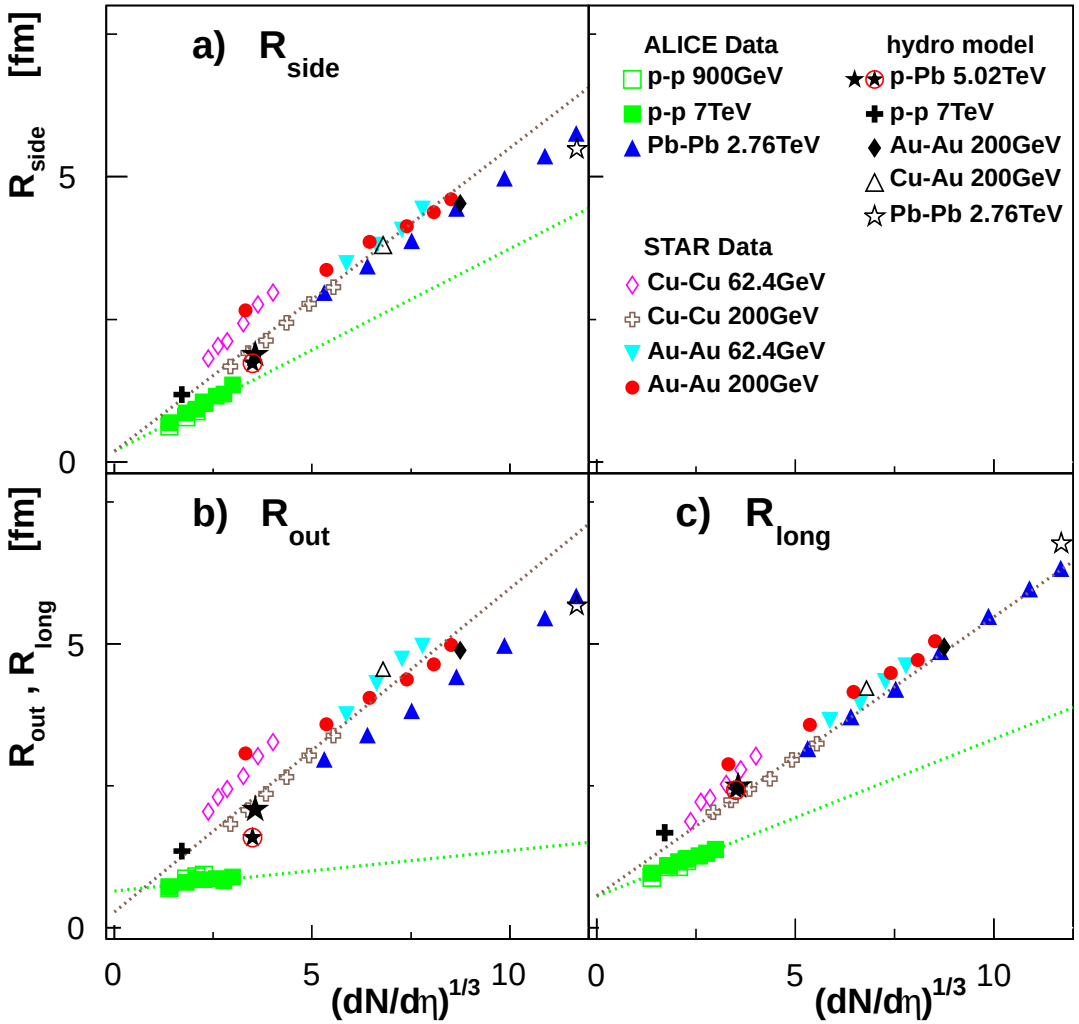
dependence on model details





- response strength depends on details, initial eccentricity

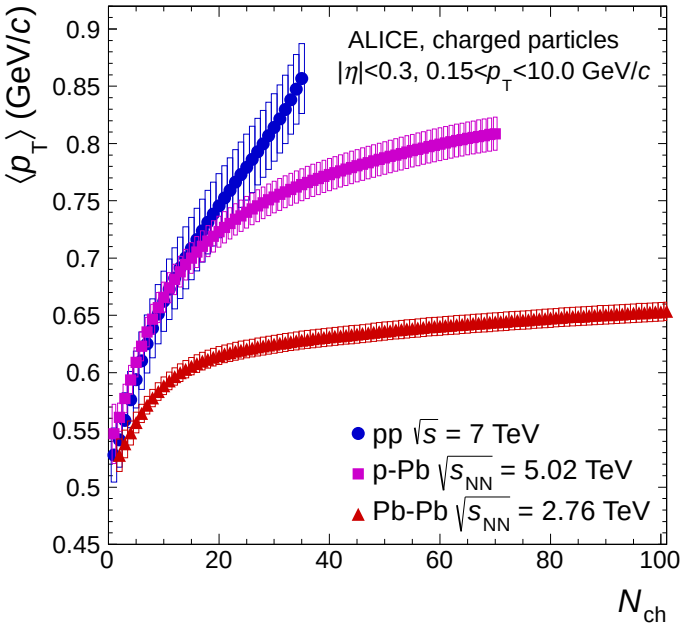
HBT systematics

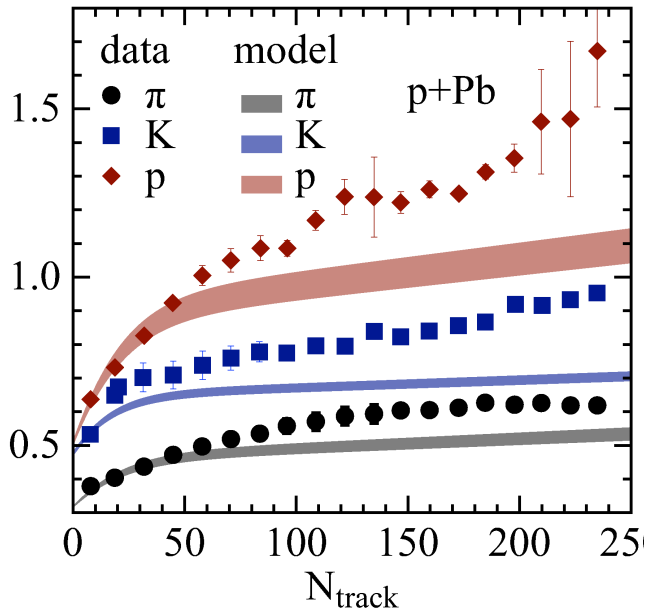


PB, W.Broniowski, arXiv:1301.3314

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

Spectra - $< p_\perp >$

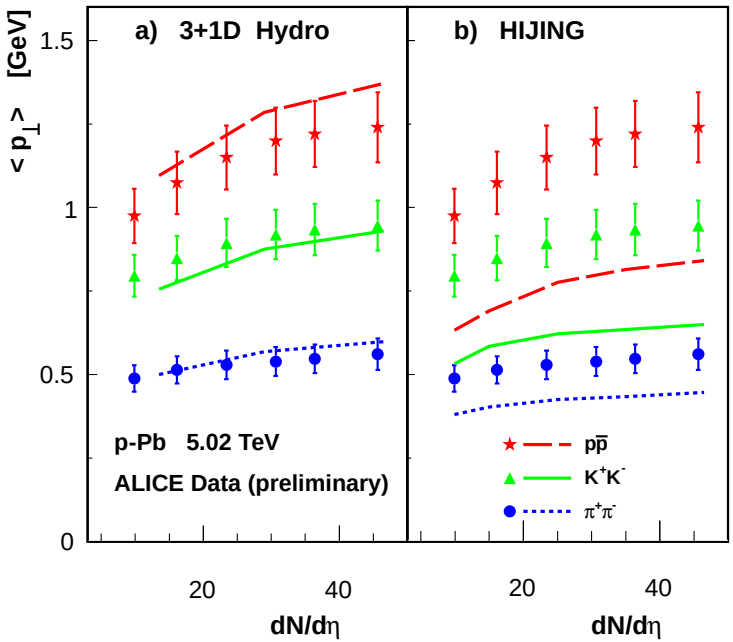


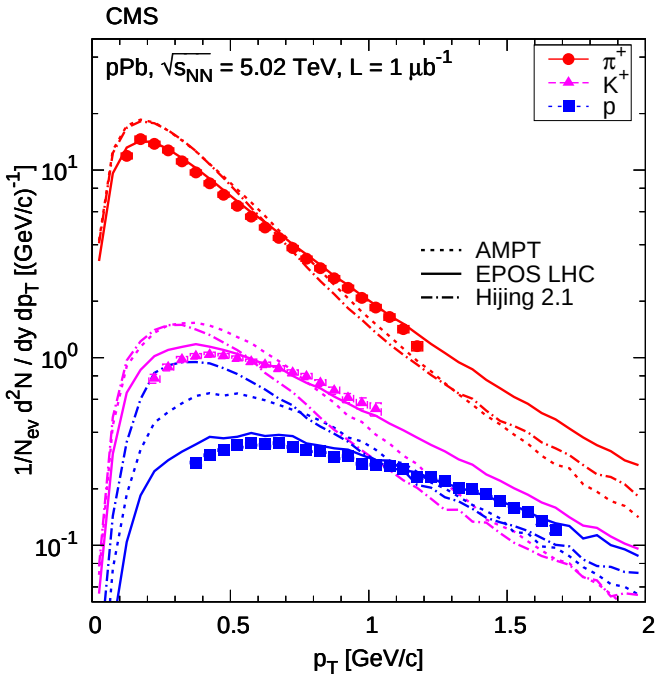


larger $< p_\perp >$ in smaller systems

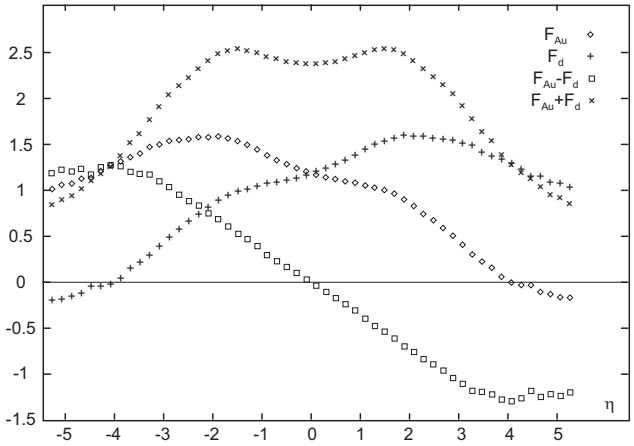
Bzdak, Skokov, arXiv:1306.5442

Spectra - $< p_\perp >$





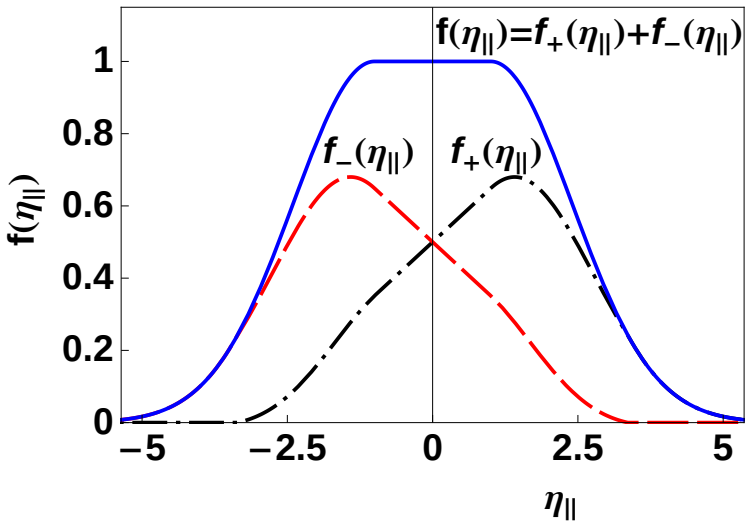
PB, W.Broniowski, G. Torrieri arXiv:1306.5442

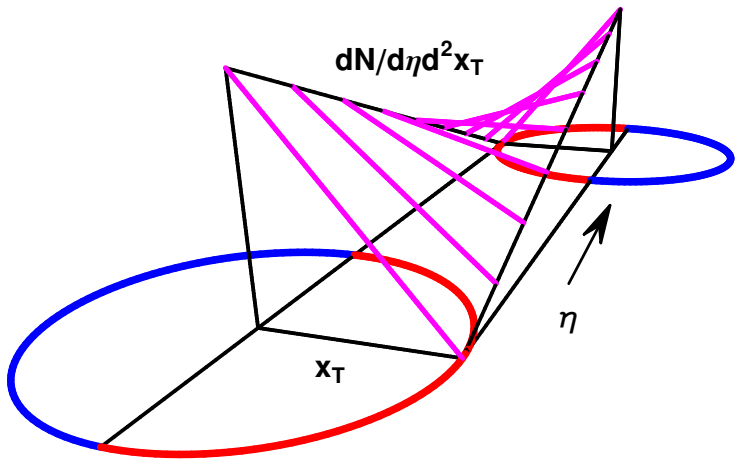


Asymmetric emission

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

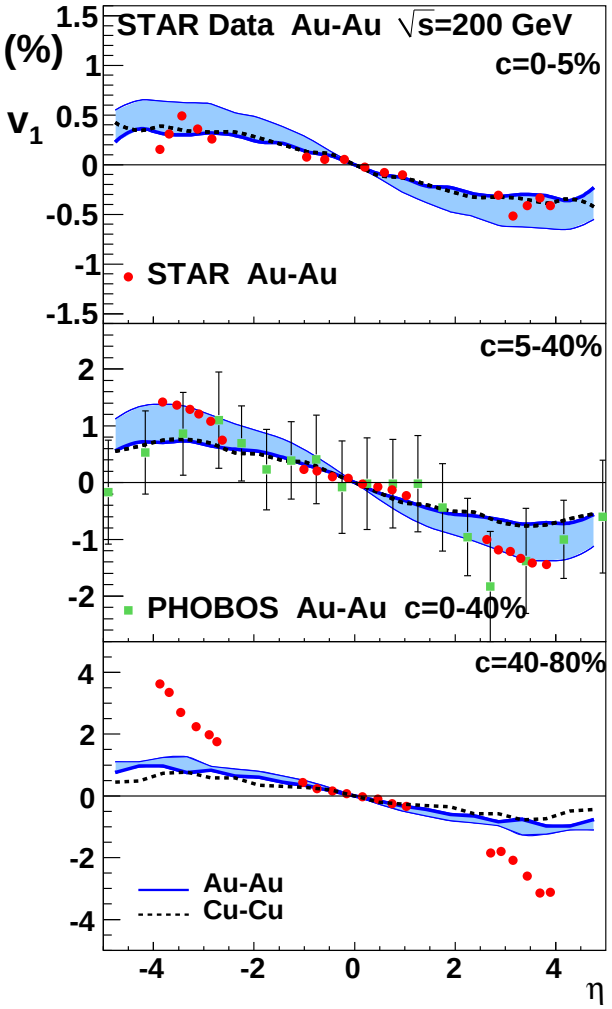
$$\rho(\eta, x, y) \propto f_+(\eta)N_+(x, y) + f_-(\eta)N_-(x, y)$$

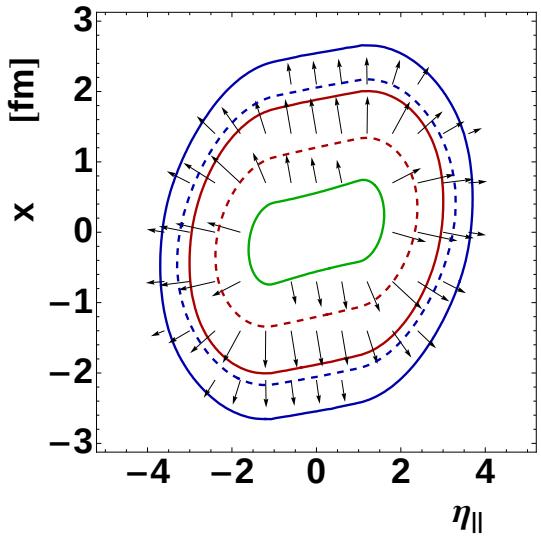




bremsstrahlung (Adil Gyulassy, Phys. Rev. C72, 034907 (2005)

Directed flow- tilted source





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

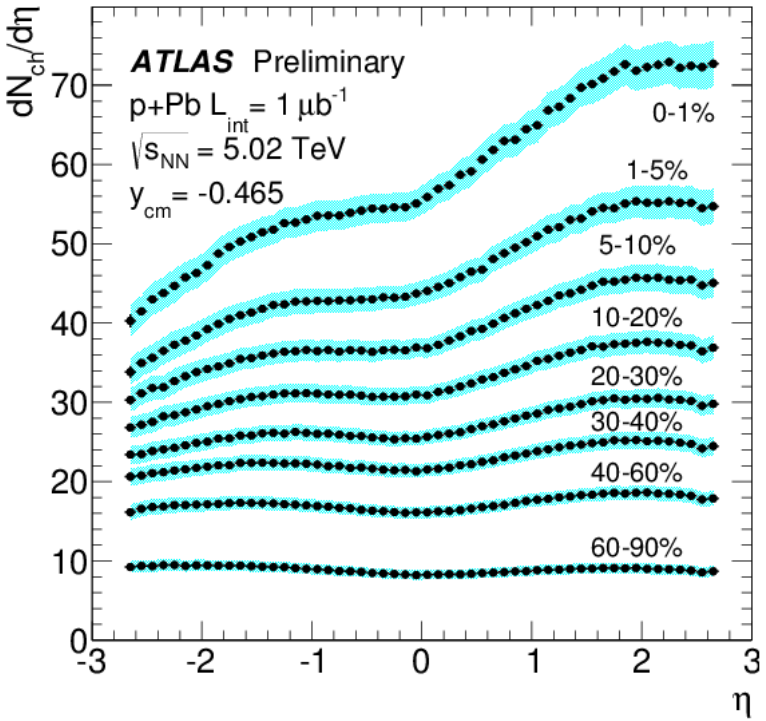
$$\partial_\tau u_x = -\frac{\partial_x p_\perp}{p+\epsilon}$$

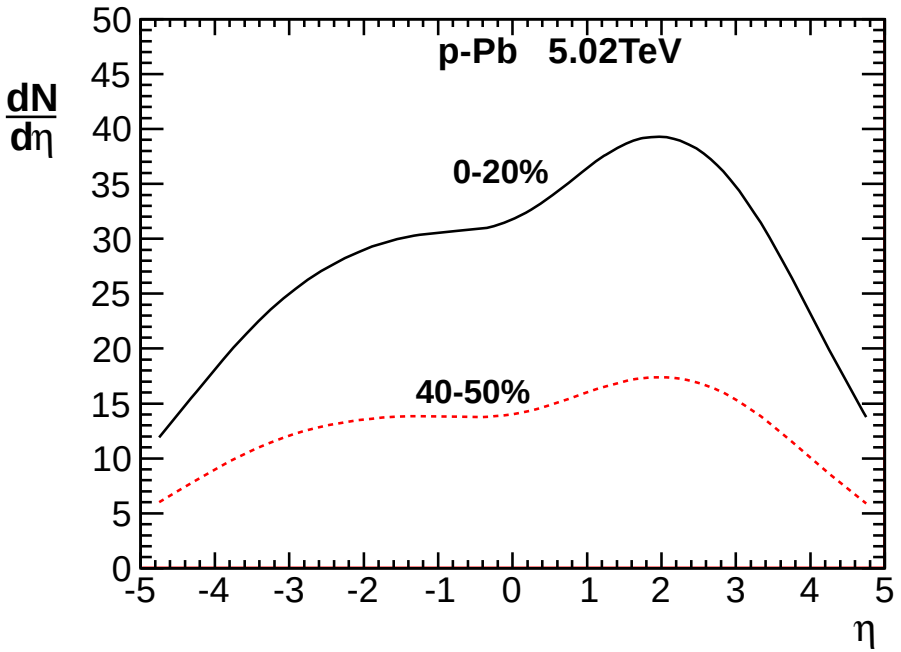
$$\partial_\tau Y = -\frac{\partial_\eta p_\parallel}{\tau(p+\epsilon)}$$

tilted source $\rightarrow$ transverse pressure + longitudinal pressure

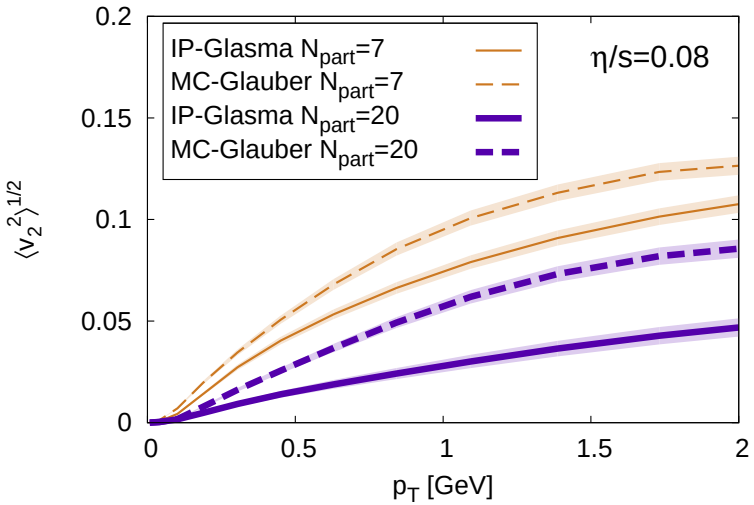
Glauber model

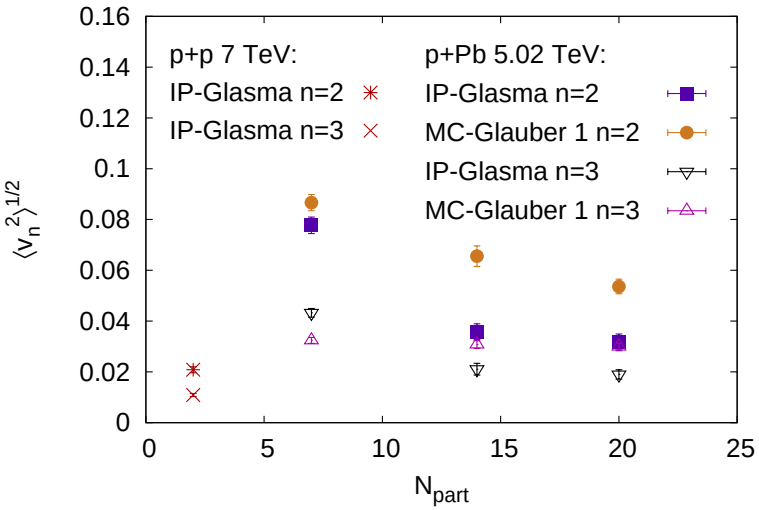
Asymmetric distributions





3+1D visc. hydro

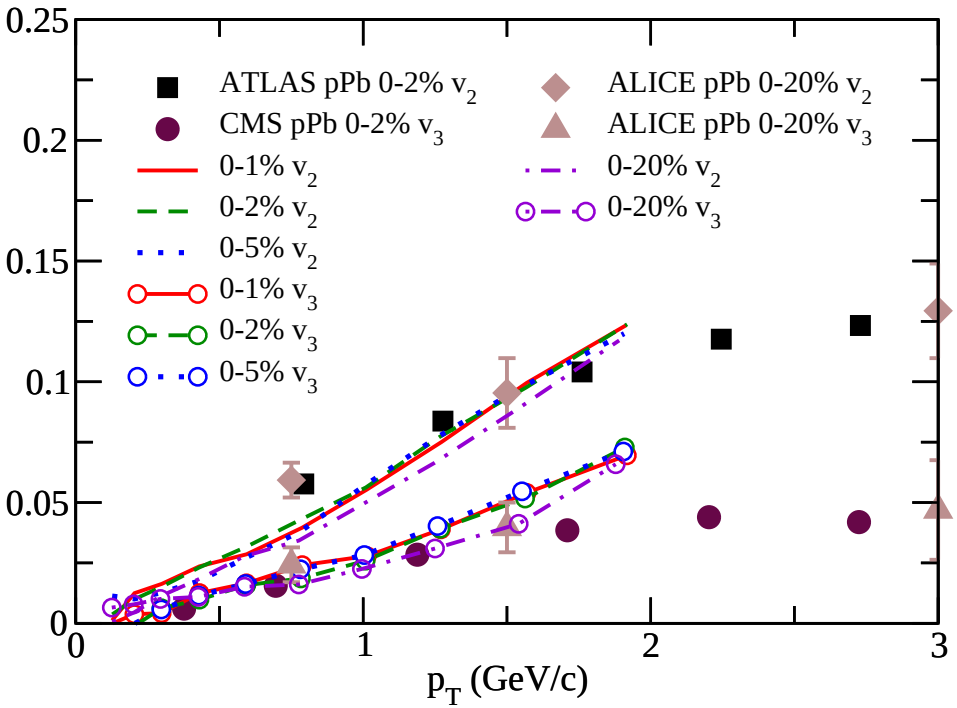




dependence on initial model, v_n small for IP-Glasma i.c.

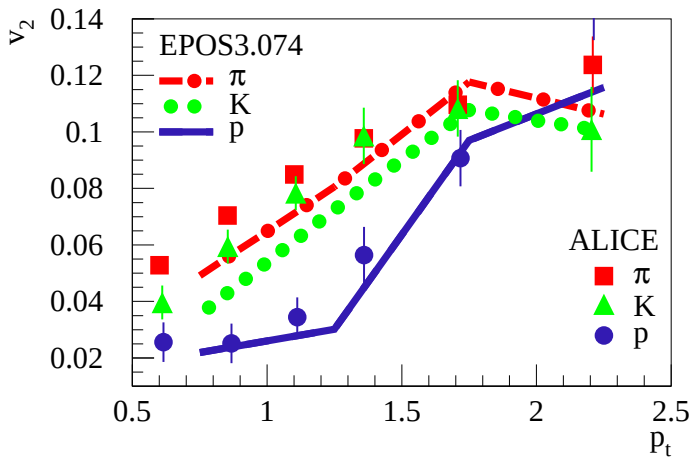
A.Bzdak, B.Schenke, P.Tribedy, R.Venugopalan - arXiv: 1304.3403

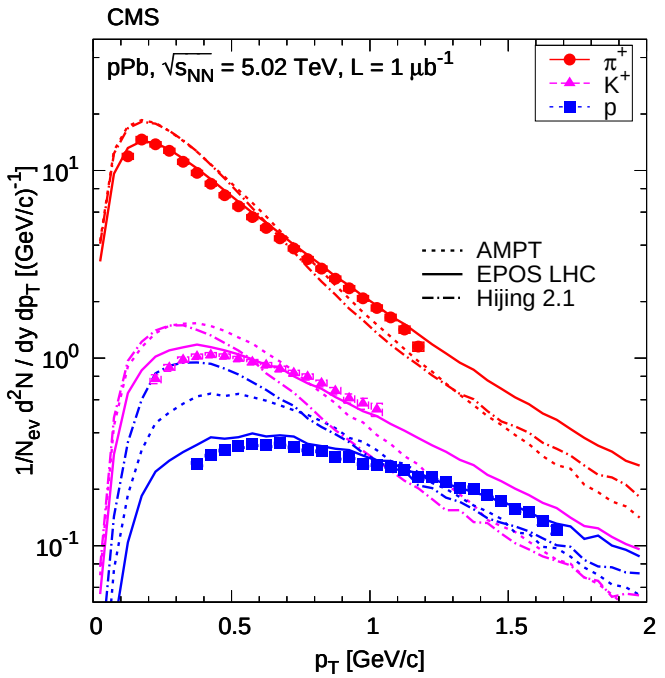
3+1D hydro



G-Y.Qin, B. Müller arXiv: 1306.3439

EPOS



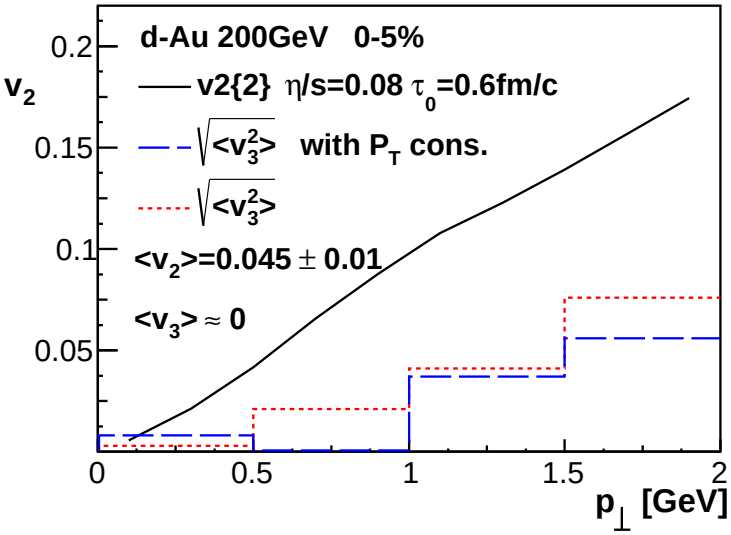


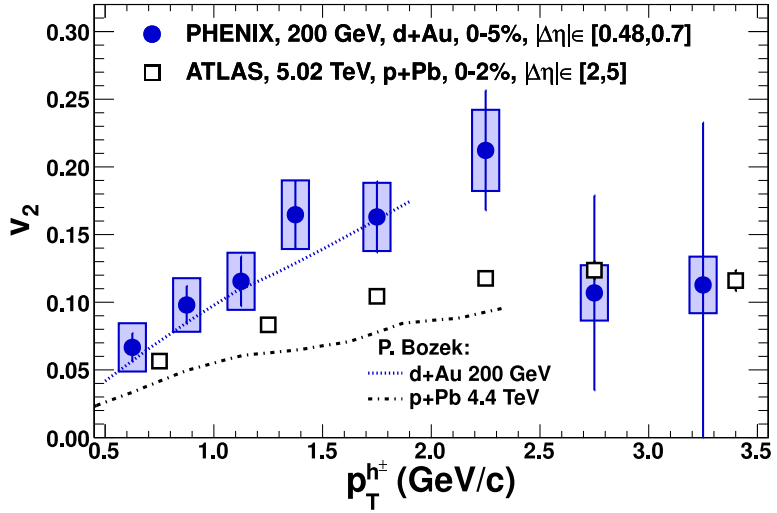
excellent description of spectra

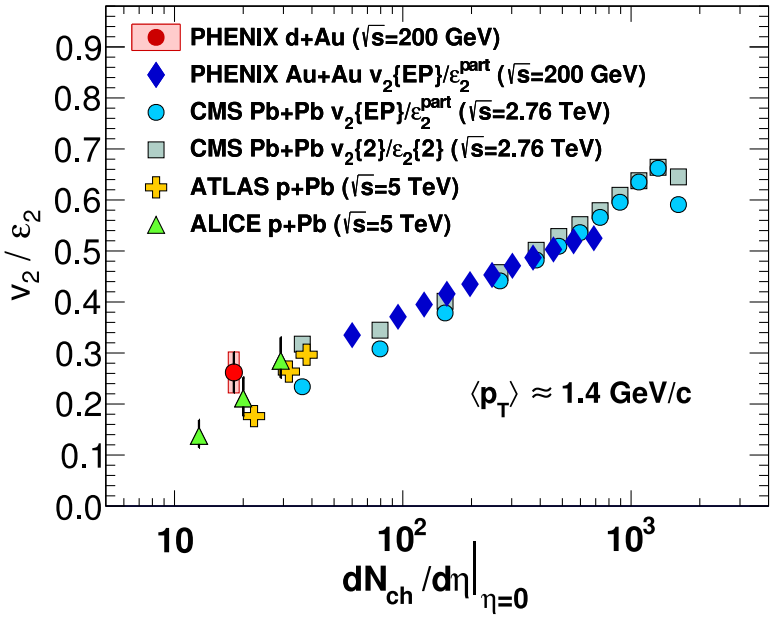
K. Werner, M. Bleicher, B. Guiot, Iu. Karpenko, T. Pierog - arXiv:1307.4379

d-Au 200GeV

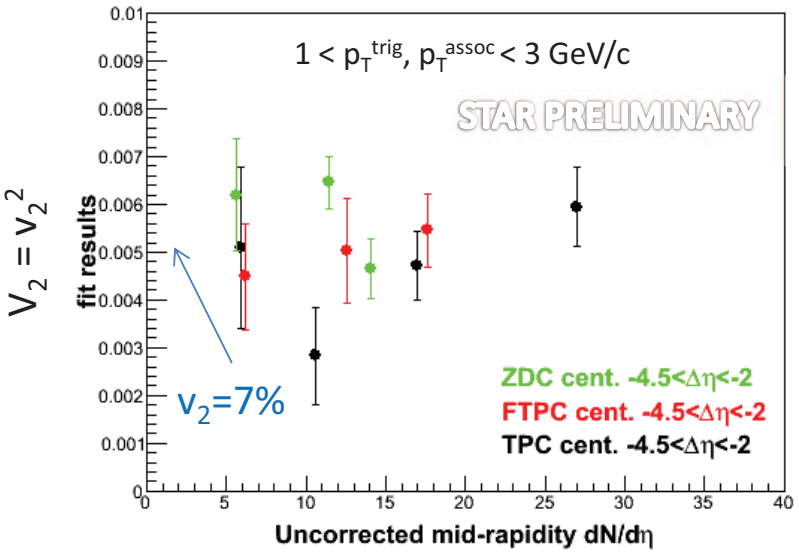
- large eccentricity
- large v_2
- small v_3

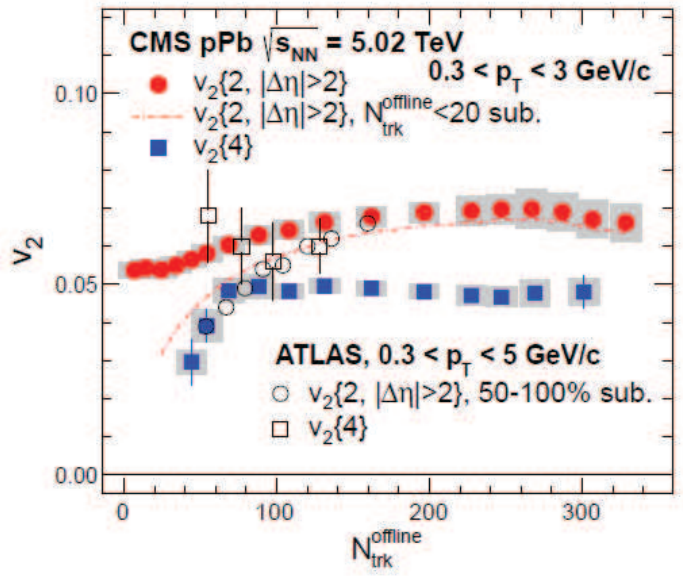






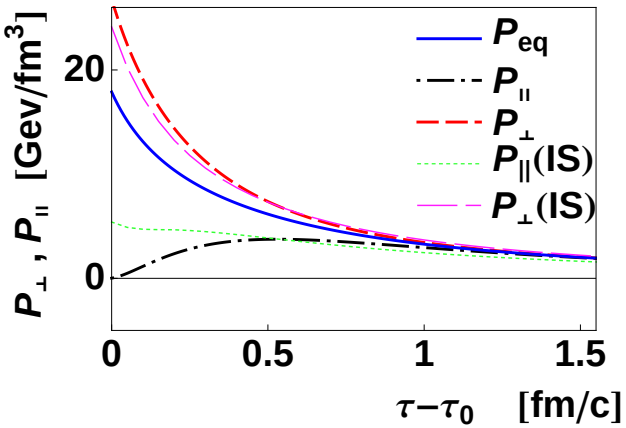
RHIC/LHC v_2 vs multiplicity

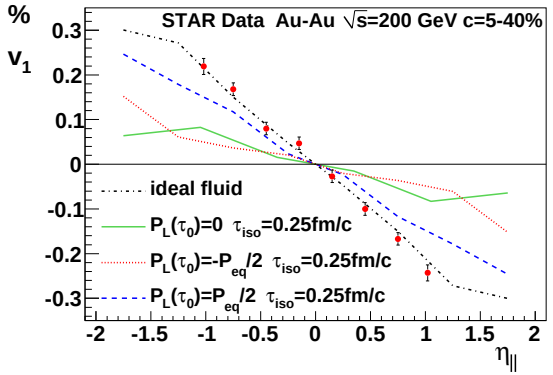


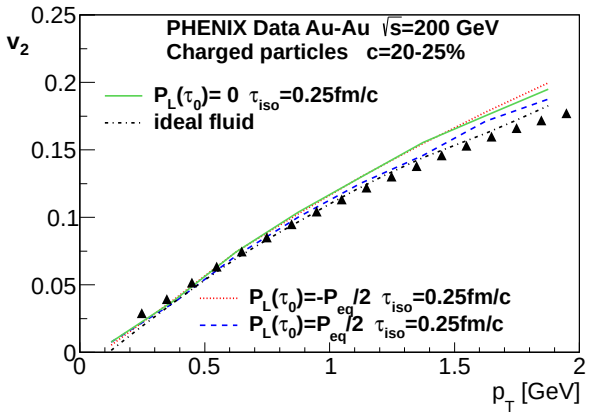


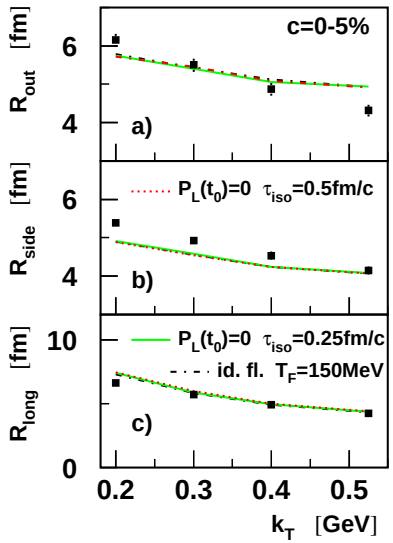
- LHC v_2{2} is also relatively insensitive to multiplicity.
- LHC v_2{4} is independent of multiplicity except peripheral. Nonflow or flow?
- **Hydrodynamic flow**: In peripheral? No increase with multiplicity?
- **CGC**: No increase with multiplicity?

pressure anisotropy









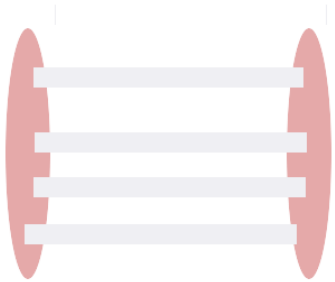
PB, I. Wyskiel - arXiv:1009.0701

- early pressure anisotropy irrelevant!

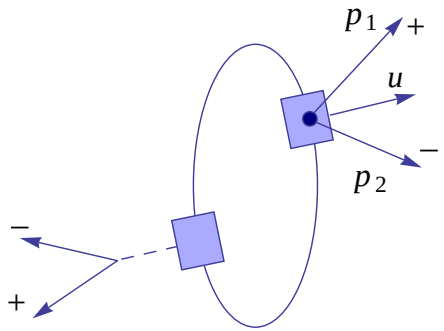
FSI scenarios

fields+thermalization

color fields

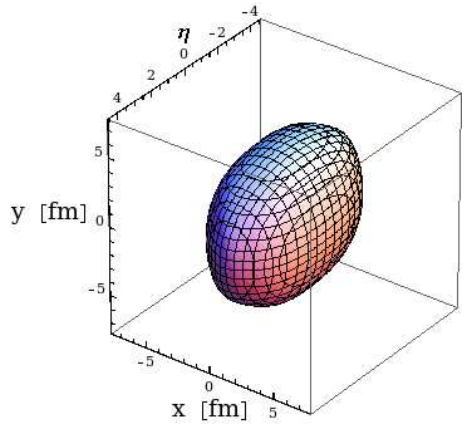


local thermalization $\longrightarrow$ hadronization

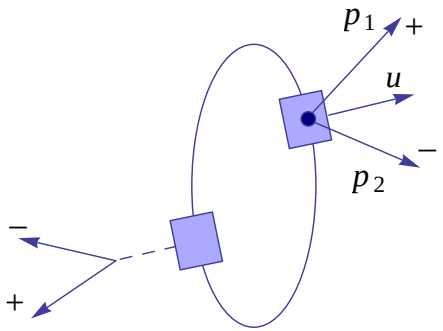


hydrodynamics

hydrodynamic expansion



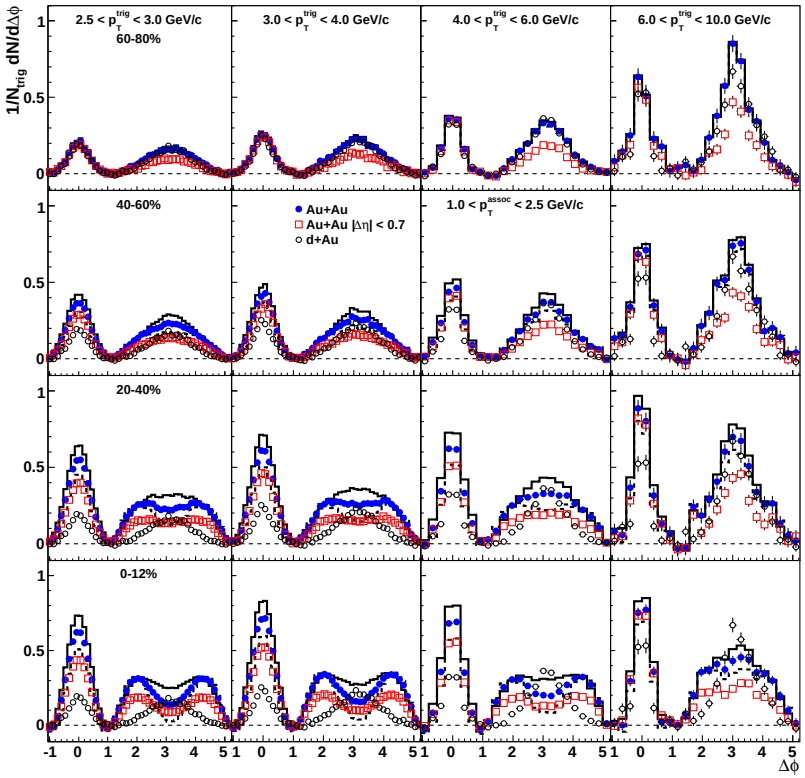
hadronization, statistical emission



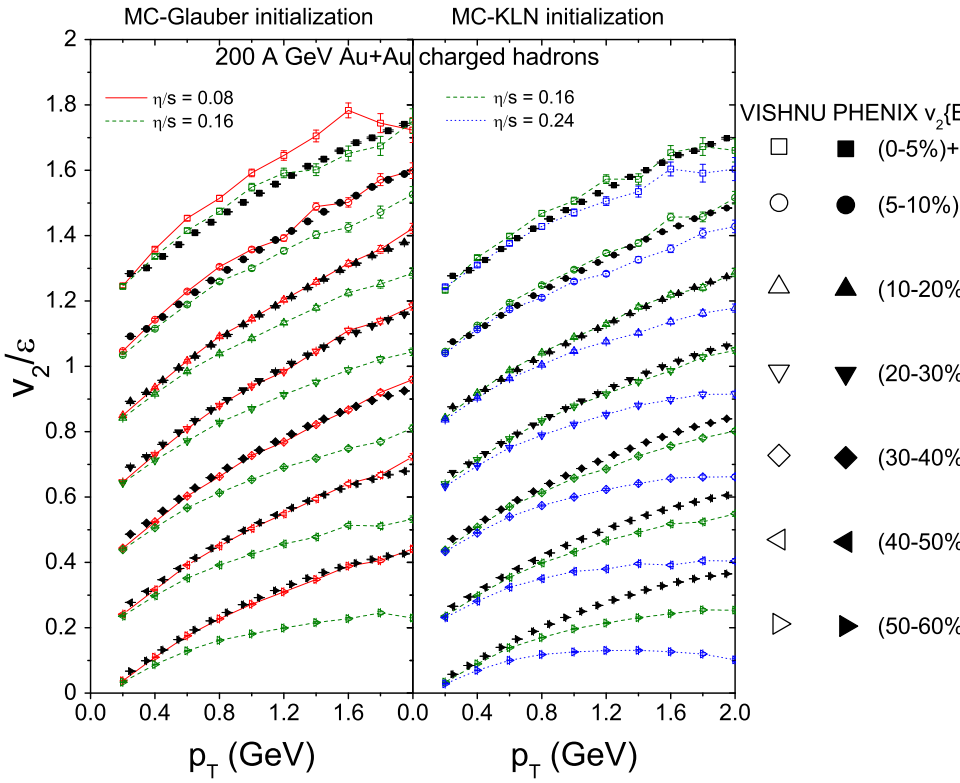
Give similar flow

Can we reduce uncertainties?

go back to very peripheral A-A



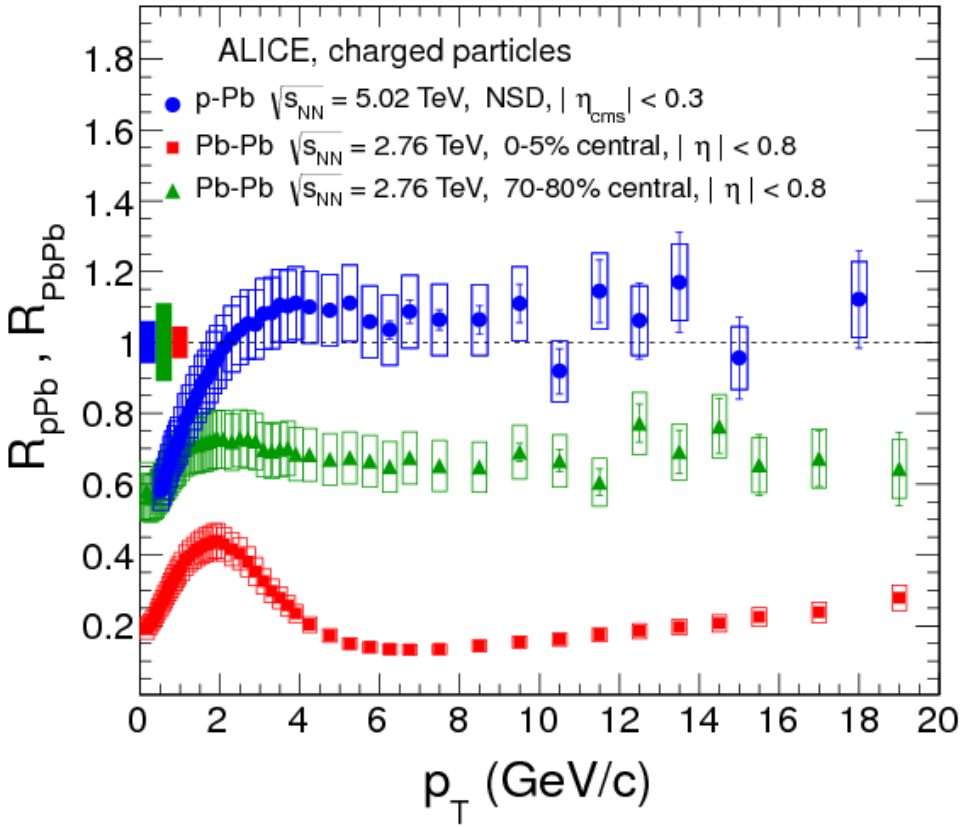
STAR-arXiv:1004.2377



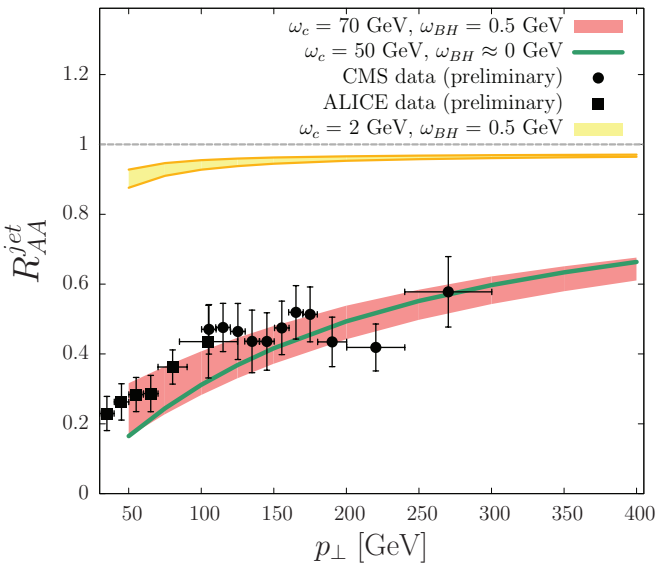
Song, Bass, Heinz, Hirano, Shen-arXiv:1101.4638

also jet modification, dijet asymmetry, PID flow, HBT

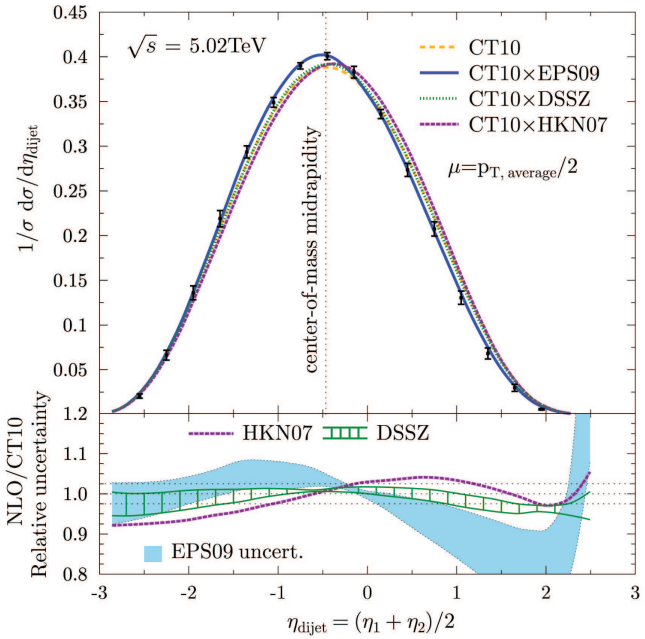
Flow without jet quenching?



No final-state effects



Eskola, Paukkunen, Salgado, arXiv:1308.6733



- Excellent situation to extract initial-state effects

also see H. Paukkunen's and J. Qiu's talks yesterday

Summary

- Ev-by-Ev hydro for pPb
- Collectivity in pPb@LHC explains v_2, v_3, ridge, $< p_\perp >$
- Observations consistent with collective flow
  many exp. results; several calculations
- HBT radii in p-Pb?
- Limits of hydro!

- Why hydrodynamics would work?
- **Effective theory for transverse expansion**
- We need observables for longitudinal pressure

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

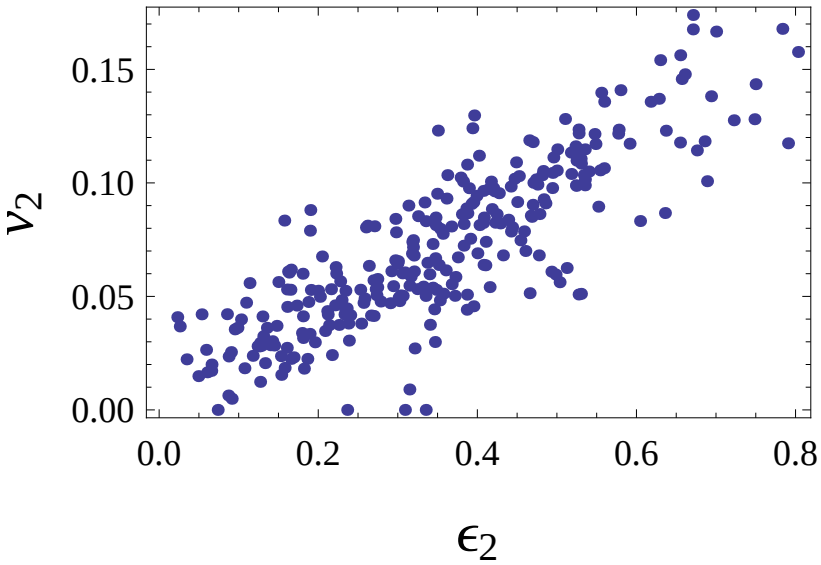
$$\Delta^{\mu\alpha}\Delta^{\nu\beta}u^{\gamma}\partial_{\gamma}\pi_{\alpha\beta} = \frac{2\eta\sigma^{\mu\nu} - \pi^{\mu\nu}}{\tau_{\pi}} - \frac{1}{2}\pi^{\mu\nu}\frac{\eta T}{\tau_{\pi}}\partial_{\alpha}\left(\frac{\tau_{\pi}u^{\alpha}}{\eta T}\right)$$

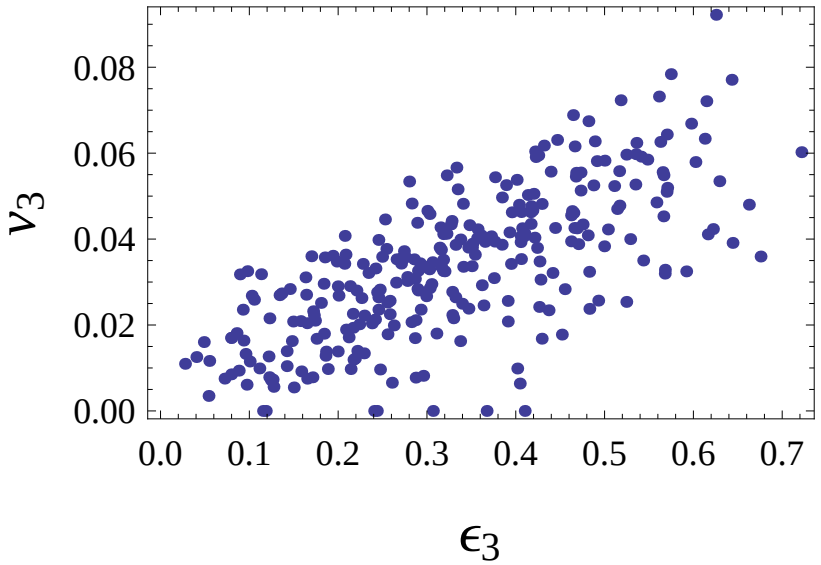
- bulk viscosity

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

- 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