Hydrodynamic flow in small systems

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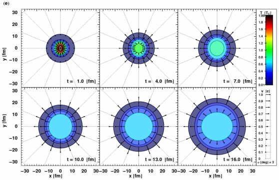
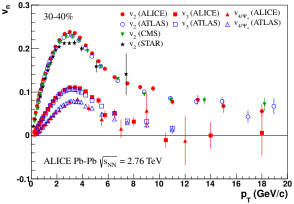
QGP formed in A-A collisions - sQGP

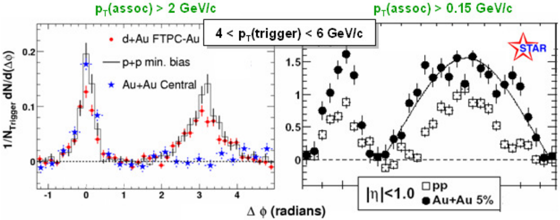
elliptic and triangular flow





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

Jet quenching

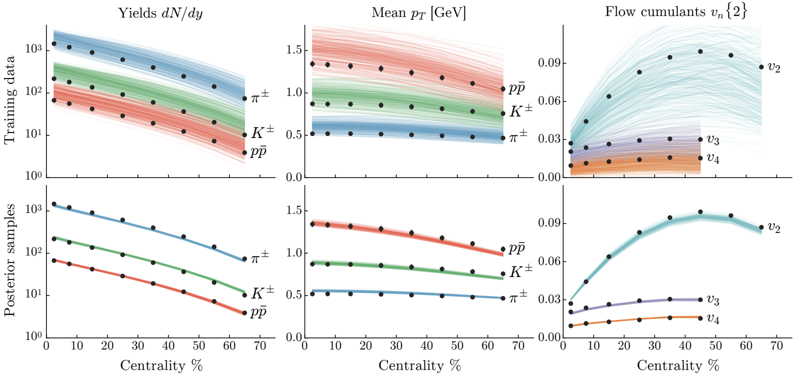


p-p and p-A as reference systems!

Bayesian parameter estimation

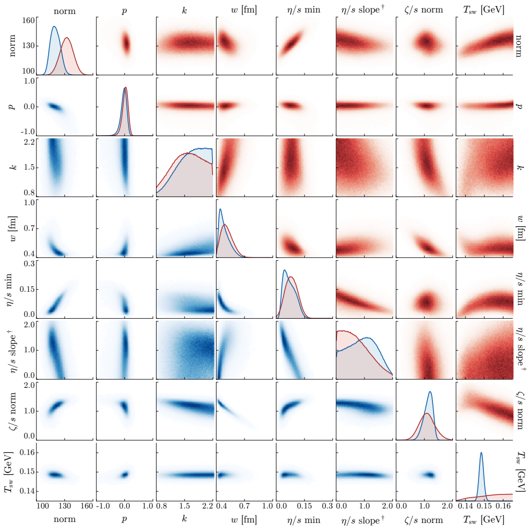
fitting initial densities AND medium parameters

hydrodynamic simulations compared to data



Bernhard et al. 1605.03954

Bayesian parameter estimation - results



involved analysis, many parameters, necessary to extract physical parameters

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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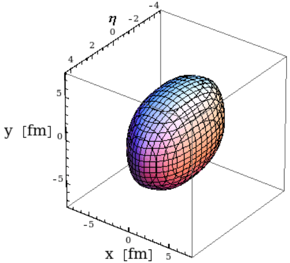
Contents

hydrodynamic model

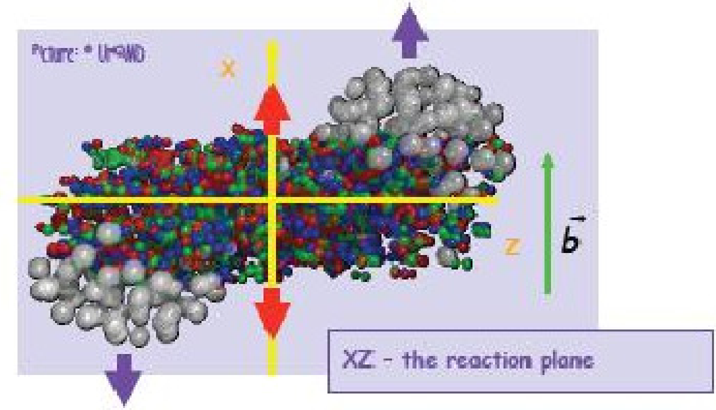
- expansion of dense matter
- close to local equilibrium
- initial conditions
- equation of state
- flow + thermal emission + decays + rescattering



can hydrodynamics work in small systems?

Large fireball in AA collisons

hydrodynamic model sensible

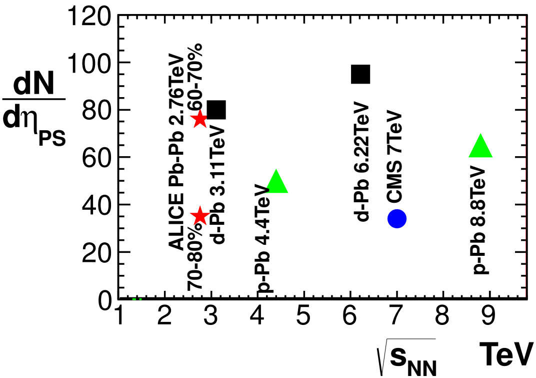


pA collision

p-Pb at 5.02TeV

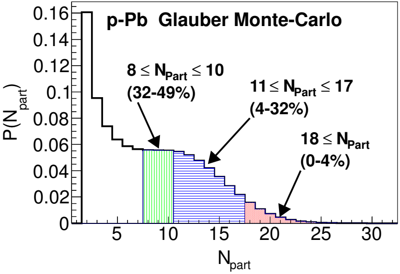
small dense fireball formed ?

p-Pb, d-Pb @ LHC

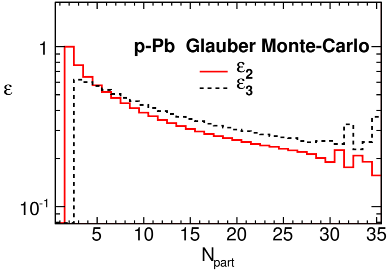


large multiplicity - large fireball - collective expansion?

Fireball in p-Pb



PB, arXiv:1112.0912



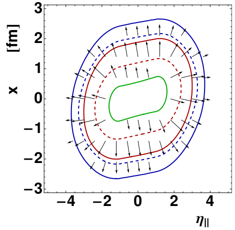
Collective elliptic flow in p-Pb?

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

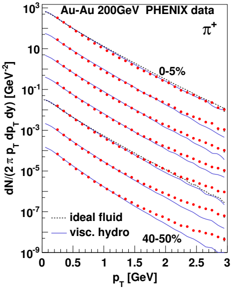
Collective elliptic flow in p-Pb? **in p-p?**

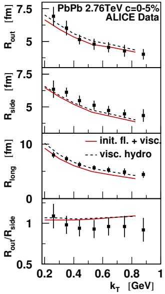
	p-Pb	p-p
Large enough density?	yes	yes (high mult.)
Large enough eccentricity	yes?	(?)
Large enough size?	yes??? but should and can be tested	(???)
Small enough gradients?	no? - beyond viscous hydro	no!

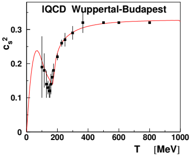
3+1D hydrodynamics



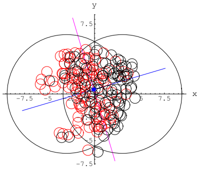
3+1D visc. hydro





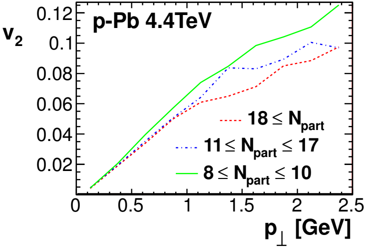


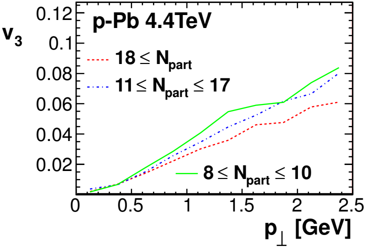
lQCD + Hadron Gas



- Glauber Initial state - M. Rybczynski, G. Stefanek, W. Broniowski, PB -1310.5475
- Statistical emission - M. Chojnacki, A. Kisiel, W. Florkowski, W. Broniowski - 1102.0273

collective flow in p-Pb 2011 prediction





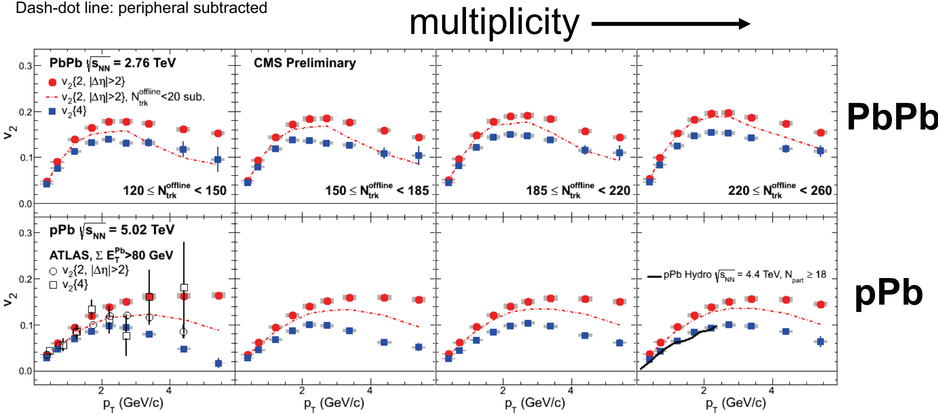
elliptic flow in p-Pb

triangular flow

PB, arXiv:1112.0912

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

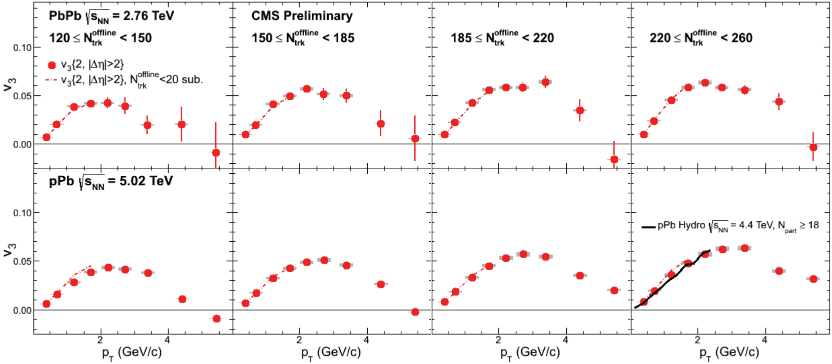
$v_2\{4\}$ is only 20% smaller than $v_2\{2\}$ below 2 GeV/c

"Peripheral subtraction" has small effect at high multiplicity

v_3 in pPb and PbPb

Dash-dot line: peripheral subtracted

multiplicity →



PbPb

pPb

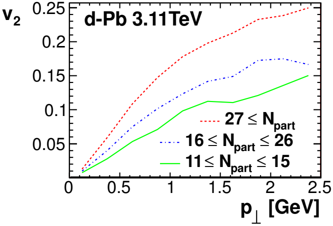
v_3 has similar shape in pPb and PbPb; magnitude comparable

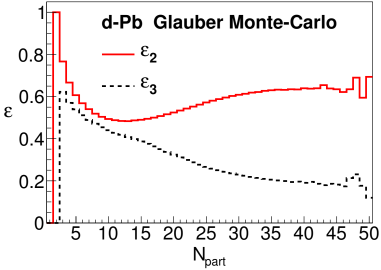
“Peripheral subtraction” makes essentially no difference

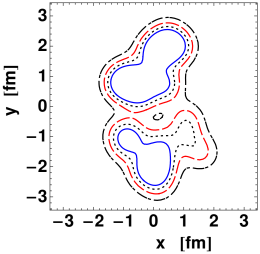
Hydro prediction: Bozek, $v_3\{PP\}$, not including fluctuations

d-Pb

- small deformed projectile
- well defined initial deformation
- multiplicity controls eccentricity



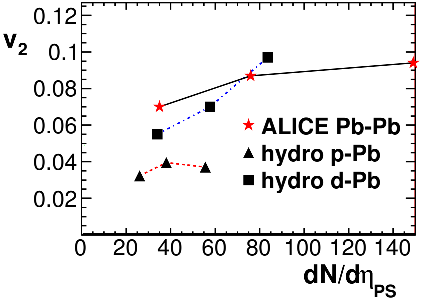




large elliptic flow

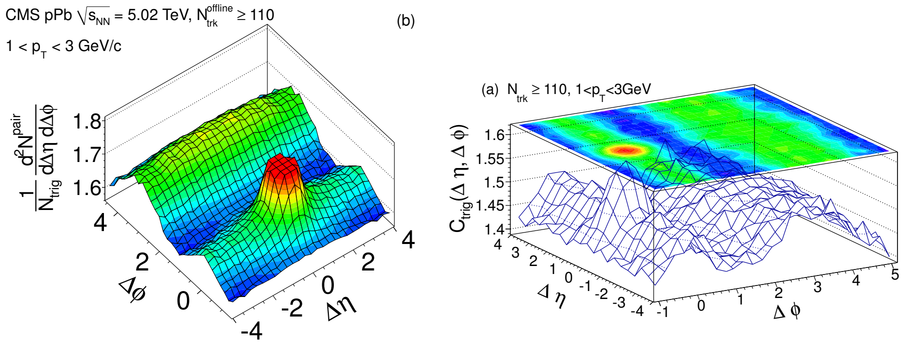
PB, arXiv:1112.0912

prediction 12.2011



- collective flow effects $\simeq$ peripheral Pb-Pb
- can be observed
- p-Pb is not p-p superposition
- d-Pb small deformed projectile
  - control of the initial shape!
- only p-p as baseline
  - or is it really a reference w/o FSI??

Ridge in p-Pb



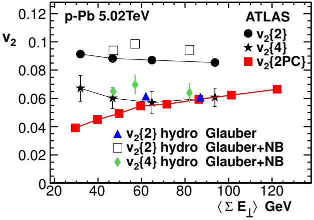
PB, W.Broniowski, arXiv:1211.0845

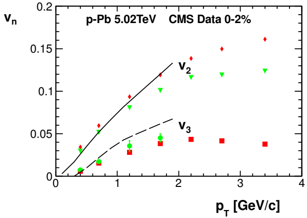
symmetric ridge also from CGC, K.Dusling, R. Venugopalan, arXiv:1210.3890, 1211.3701, 1302.7018

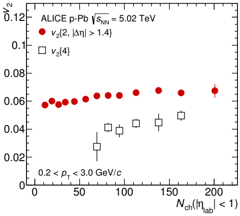
Indications of collective flow in p-A, d-A, He-A

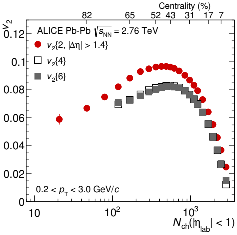
1. **Elliptic and triangular flow**
2. **Hierarchy of v_2 and v_3 in p-A, d-A, He-A**
   collective response to geometry (final state effect)
3. **Flow from higher cumulants**
4. **Interferometry radii**
5. **Factorization at intermediate $p_\perp$ and large $\Delta\eta$**
   particles at intermediate $p_\perp$, large η, correlated to geometry
6. **Mass splitting of v_2**
7. Mass hierarchy of spectra $(< p_\perp >)$

1) Elliptic and triangular flow observed in p-Pb

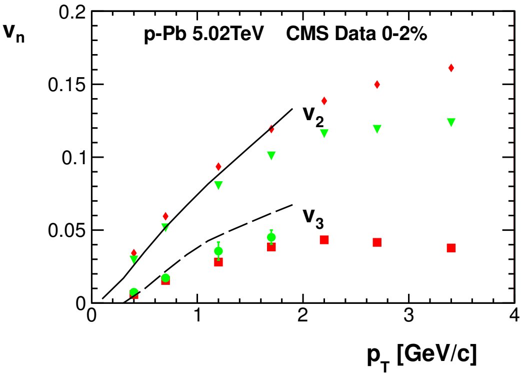








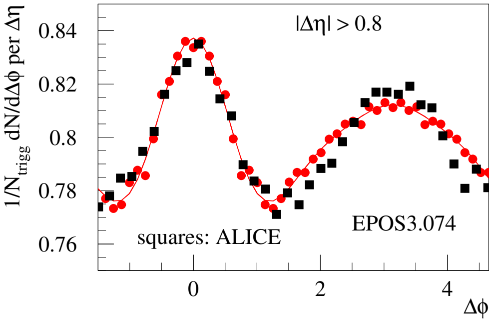
- Glauber MC initial cond. - agreement with data



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)
- sensitive probe of init. cond.

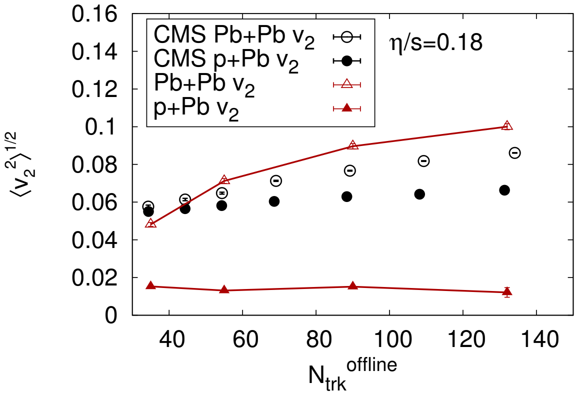
- EPOS3 - agreement with data



Double ridge from EPOS simulation

K. Werner et al. 1307.4379

- IP-Glasma initial cond. - small v_2 !

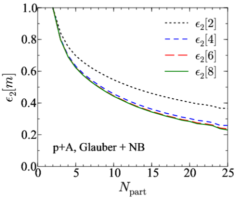


B. Schenke, R. Venugopalan 1405.3605

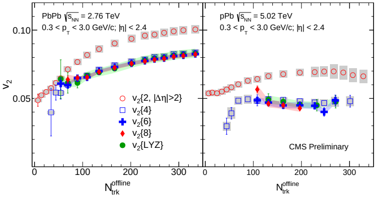
2) Flow from higher cumulants

- hierarchy of cumulants

$\epsilon_2\{4\} \simeq \epsilon_2\{6\} \simeq \epsilon_2\{8\} < \epsilon_2\{2\} \longrightarrow$ *hydro response* $\longrightarrow v_2\{4\} \simeq v_2\{6\} \simeq v_2\{8\} < v_2\{2\}$



A. Bzdak,PB, L. McLerran, 1311.7325

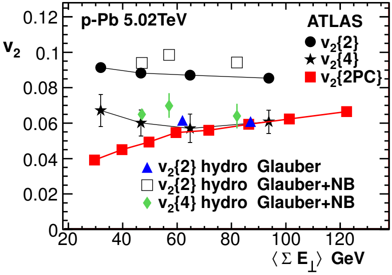


CMS 1502.05382

- **detailed** hierarchy of cumulants - consistent with data

$v_2\{n\}$ - hydro response to fluctuations of initial shape !

$v_2\{4\}$ and $v_2\{2\}$ - hydro calculation



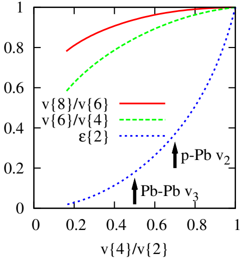
PB, W. Broniowski 1304.3044

hierarchy $v_2\{2\} > v_2\{4\} > 0$ confirmed in full hydro calculation

also: I. Kozlov et al. 1412.3147

Note: ϵ_n + *hydro response* $\rightarrow$ correct centrality dependence of v_n

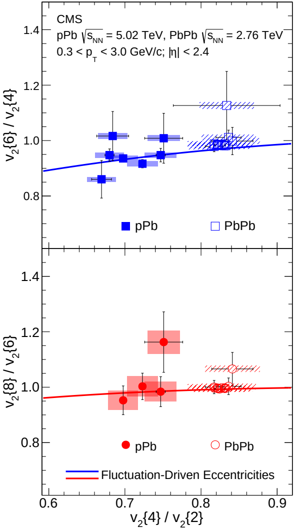
Detailed hierarchy of cumulants



L. Yan, J.Y. Ollitrault 1312.6555

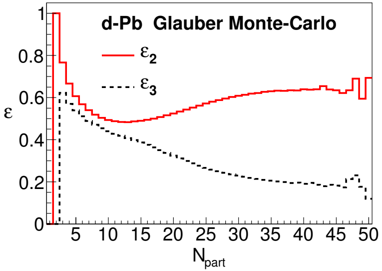
universal prediction for differences
$v_2\{4\} \neq v_2\{6\} \neq v_2\{8\}$
power-elliptic eccentricity distributions

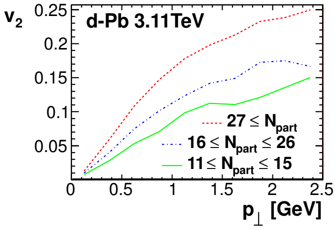
$$\epsilon\{4\} = \epsilon\{2\}^{3/2}\left(\frac{2}{1+\epsilon\{2\}^2}\right)$$



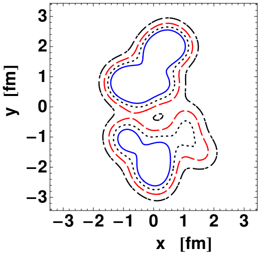
CMS 1502.05382

small system with large deformation d-Pb





large elliptic flow

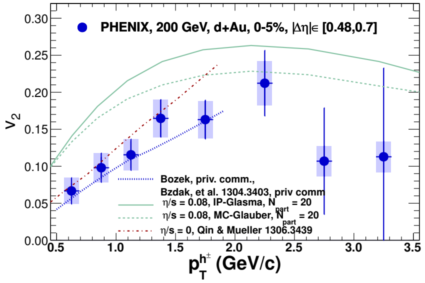


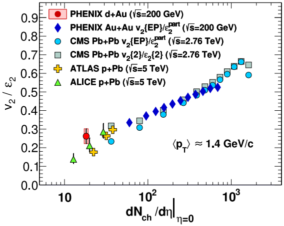
PB, arXiv:1112.0912

control of initial geometry,

central collisions - deformed fireball

3a) Elliptic flow observed in d-Au at 200GeV



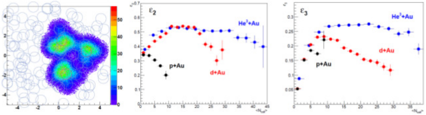


PHENIX, arXiv:1303.1794

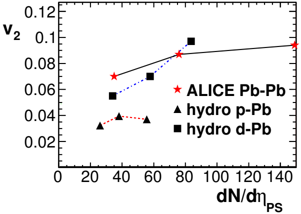
large eccentricity - large elliptic flow

small on big collisions

^{3}He-Au collisions



PHENIX proposal $\longrightarrow$ v_3, Sickles et al. arXiv:1401.2432

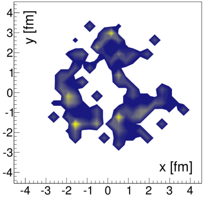


PB, arXiv:1112.0912

strong effect for d-A

intrinsic deformation dominates

over fluctuations



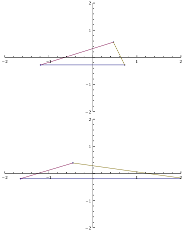
α clusters in ^{12}C Broniowski, Arriola arXiv:1312.0289

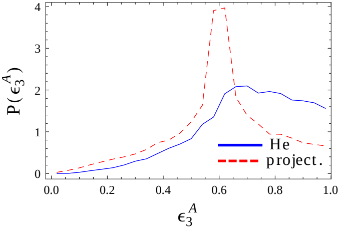
effect for v_3 in ^3He-A,

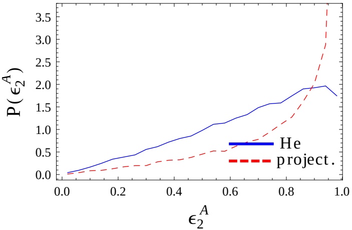
Nagle et al. arXiv:1312.4565

^{3}He configurations

elongated He configurations



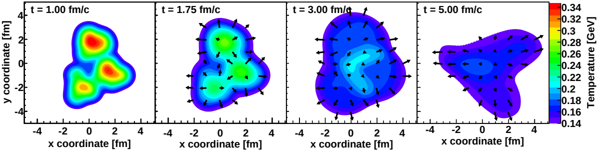




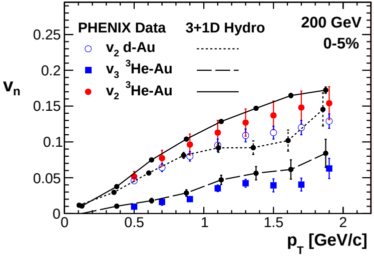
- large ϵ_2
- even larger after projection
- broad distribution of ϵ_3
- after projection $\epsilon_3 \simeq 0.6$

Expect large v_2 and smaller v_3 in ^{3}He-Au

3b) Triangular flow in ^{3}He-Au



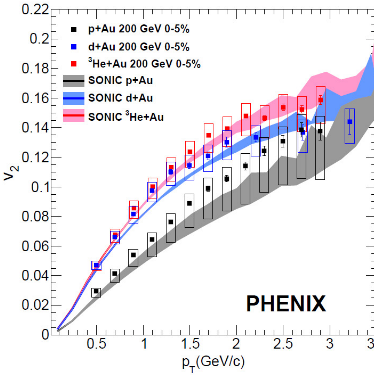
Nagle et al. 1312.4565

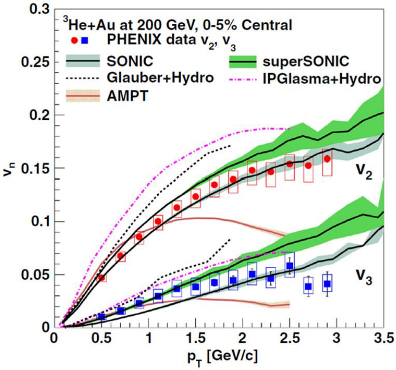


- observed $v_3 \longrightarrow$ collectivity
- hierarchy of v_2 and v_3 consistent with collective response on fireball geometry
- large v_2 in He-Au

Consistent with hydrodynamics

Comparing p-Au, d-Au, He-Au – PHENIX





-strong v_2 in d-Au **and** ^{3}He-Au

-small v_2 in p-Au

-strong v_3 in ^{3}He-Au

Collective response to inital geometry !

Factorizaton breaking

Flow yields two-particle correlations in angle

$$C(\Delta\phi) = 1 + 2v_2^2 cos(2\Delta\phi)$$

For two particles with different momenta -
Factorization if correlation due to flow) Gardim et al. 1211.0989

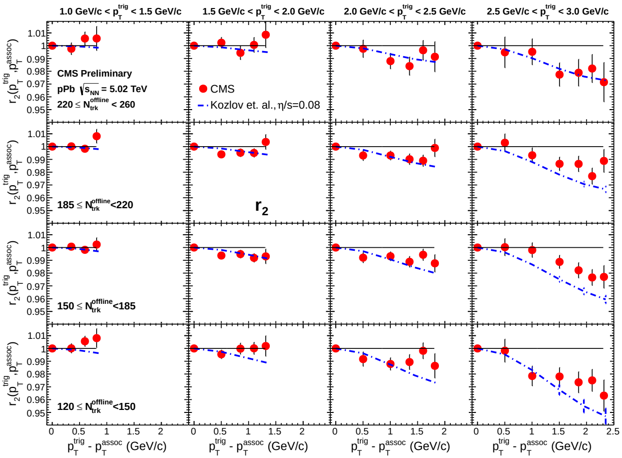
$$\begin{aligned} C(\Delta\phi, p_1, p_2) &= 1 + 2V_2(p_1, p_2)cos(2\Delta\phi) = \\ (\text{if flow}) & \simeq 1 + 2v_2(p_1)v_2(p_2)cos(2\Delta\phi) \end{aligned}$$

in flow scenario **small factorization breaking** expected
(event plane decorrelation)

$$r = \frac{V_2(p_1, p_2)}{v_2(p_1)v_2(p_2)} \simeq cos(\Psi_{p_1} - \Psi_{p_2}) < 1$$

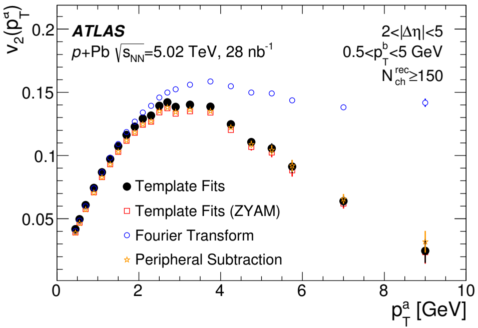
Slightly different event planes expected for particles at different $p_\perp$
(or rapidity Bozek et al. 1011.3354) due to fluctuations

4a) Factorization at intermediate $p_\perp$



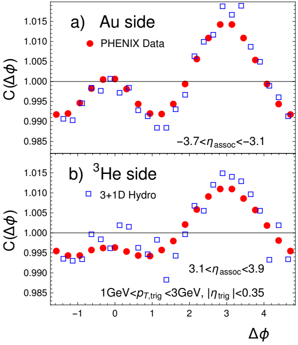
- factorization holds for v_2 and v_3 up to 3 GeV
- **small** deviations explained by hydro+Glauber Kozlov, Luzum, Denicol, Jeon, Gale, 1405.3976
- geometry driven origin of correlations at small **and** intermediate $p_\perp$

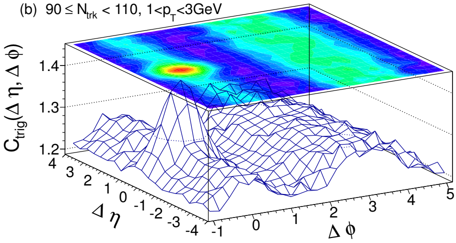
Correlations between soft and hard partices



- correlations between soft (bulk) particles and intermediate $p_\perp$ particles
- soft particles flow driven by geometry $\Longrightarrow$ high $p_\perp$ particles geometry driven (at least partly)
- possibly some final state interaction other than hydrodynamics

4c) Correlations at large $\Delta\eta$ (Ridge)





PB, Broniowski 1211.0845

- correlations between particles at differnt η
- flow driven by geometry at $\eta \simeq 0 \implies$ flow driven by geometry at forward rapidities
- well described by hydrodynamics

- similar mechanism in AMPT: Ma, Bzdak-arXiv: 1404.4129, Koop, Adare, Nagle-arXiv: 1501.06880

Interferometry correlations

Hanburry Brown Twiss (1956) - measure of star diameter

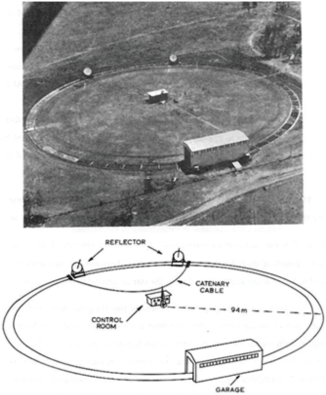
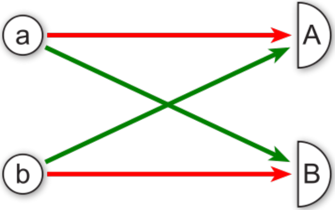


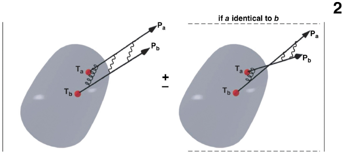
Figure 1. Aerial photo and illustration of the original HBT apparatus. They have been extracted from Ref.[1].

Intensity correlations in two detectors



$$< I_A I_B >=< I_A >< I_B > (1+C(r_{AB}))$$

Hanbury Brown-Twiss correlations(HBT)



Lisa MA, et al. 2005.
Annu. Rev. Nucl. Part. Sci. 55:357–402

- quantum correlation for (anti)symmetrization of production amplitudes
- we observe pairs of idenstical particles , $\pi^+ - \pi^+$

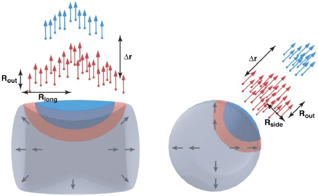
$$C(p_1, p_2) = \frac{\int d^4x_1 d^4x_2 S(x_1, p_1) S(x_2, p_2) |e^{i(x_1p_1 + x_2p_2)} + e^{i(x_2p_1 + x_1p_2)}|^2}{\int d^4x_1 S(x_1, p_1) \int d^4x_2 S(x_1, p_2)}$$

- experimetally we reconstruct

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

  using *mixed event pairs* in the denoominator
- pair correlations in relative momentum ($q = p_1 - p_2$) are measured for different average pair momenta $\mathbf{k} = \frac{p_1+p_2}{2}$
- in most general case we have 6 momentum variables
- in the pair wave function final-state interactions can be taken into account (like Columb interactions)

Bertsch-Pratt parameterization



Lisa MA, et al. 2005.
Annu. Rev. Nucl. Part. Sci. 55:357–402

- correlations for a fixed average pair momentum $k = (p_1 + p_2)/2$
- we go to the *local comoving system* LCMS with $k_z = 0$ (pair momentum along the beam axis), which gives $k = (k_\perp, 0)$
- the relative momentum vector is split into 3 component $q_{long} = q_z$, q_{out} (parralel to $k_\perp$) i q_{side} perpendicular to long and out directions

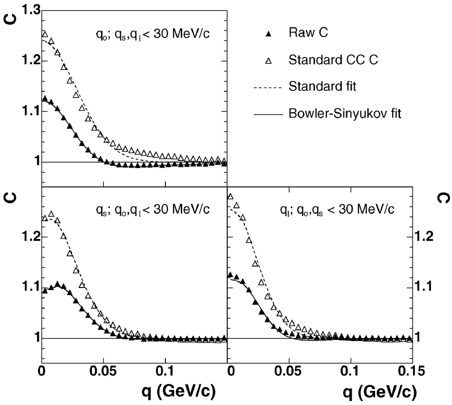
HBT radii

the correlations function after substracting final state interaction effects

$$C(q) = 1 + \lambda e^{-R_{out}^2 q_{out}^2 - R_{side}^2 q_{side}^2 - R_{long}^2 q_{long}^2}$$

The parameters R measure the size of the emission region

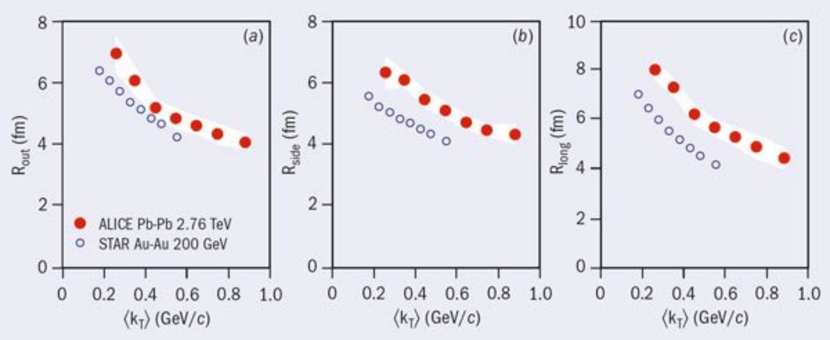
interferometry, femtoscopy, HBT



Lisa MA, et al. 2005.
Annu. Rev. Nucl. Part. Sci. 55:357–402

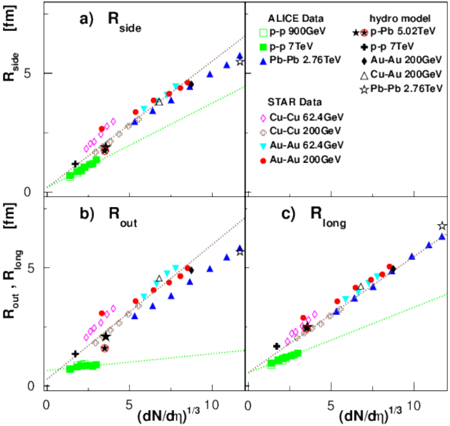
Dependence on pair momentum

- particle pairs with similar mamenta are emitted from the same fluid ragion (with flow velocity along along the pair mamentum)
- the larger the average pair momentu the more colimated are the momenta of the two particles which means they must be emitted from a smaller region
- the emission region is called *homgeneity region* and its size the *homgeneity length*
- for a finite average pair momentum we measure the size of only a small part of the totasl fireball
- HBT radii get smaller with increasinf $k_\perp$



Dependence of mulitplicity and size

- HBT radii get larger with mutiplicity $R \propto (dn/d\eta)^{1/3}$
- emission form a larger region of similar freze-out density
- $+$ some dependence on the amount of transverse flow



Calculating HBT correlations in models

- list of generated particles with momenta p_i and positions of last scattering r_i
- generate symmetrized pairs for all pairs of identical particles $\{(x_k, p_k), (x_l, p_l)\}$

$$A_{bin} = \frac{1}{N_{pairs}} \sum_{pairs} \Psi(q, x_k - x_l)\delta_{bin}$$

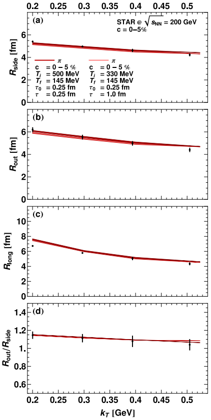
  for all pairs that fall into a given q-$k_\perp$ bin
- generate mixed pairs for denominator

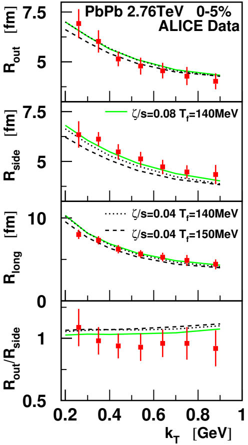
$$B = \frac{1}{N_{mixed\ \ pairs}} \sum_{pairs} \delta_{bin}$$

  for all pairs that fall into a given q-$k_\perp$ bin using particles from different events
-

$$C_{bin} = \frac{A_{bin}}{B_{bin}}$$

Hanbury Brown-Twiss (HBT) correlations in AA



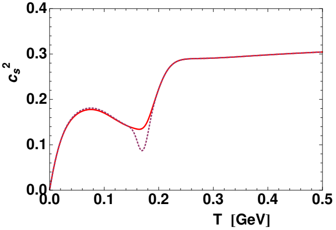


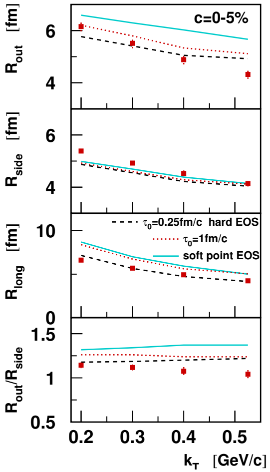
Broniowski, Chojnacki, Florkowski, Kisiel 2008,

Pratt, 2009

PB, Wyskiel 1203.6513

HBT - hard equation of state





soft EOS - wrong HBT

Heavy-ion experiments consistent with lattice QCD

HBT indicates explosive expasnion : hard EOS, prequilibrium flow, viscosity

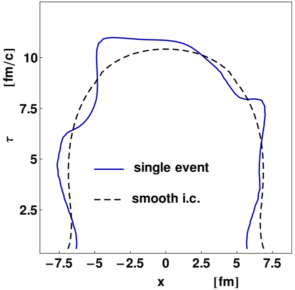
correlations in event by event hydrodynamics

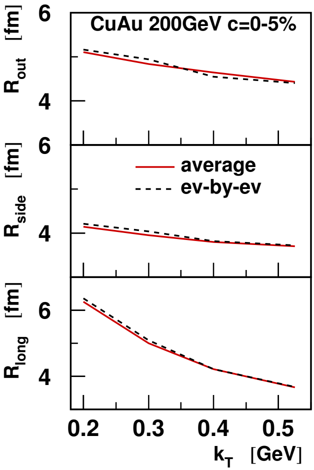
- combine several (many) events

$$C(q_a, k_b) = \frac{\frac{1}{N_{pairs,num}} \sum_{j=1}^{N_h} \sum_{m,l=1}^{N_e} \sum_{s=1}^{M_l} \sum_{f=1}^{M_m} \delta_{q_a} \delta_{k_b} \Psi(q, x_1 - x_2)}{\frac{1}{N_{pairs,den}} \sum_{i \neq j=1}^{N_h} \sum_{l,m=1}^{N_e} \sum_{s=1}^{M_l} \sum_{f=1}^{M_m} \delta_{q_a} \delta_{k_b}}$$

  numerator - sum over different hydro events
  denominator - sum over different hydro event pairs
  increases the effective number of pairs (d-Au 5000×)
- azimuthally sensitive HBT possible with reasonable cost
- perfect event plane resolution

HBT of fluctuating fireballs





can the lumpy surface be observed?

NO

HBT of fluctuating fireballs II

- event by event emission function

$$C(q,k) = \frac{\int d^4x_1 d^4x_2 \langle S(x_1,p_1)S(x_2,p_2)\rangle |\Psi(k,(x_1-x_2))|^2}{\int d^4x_1 \langle S(x_1,p_1)\rangle \int d^4x_2 \langle S(x_2,p_2)\rangle}$$

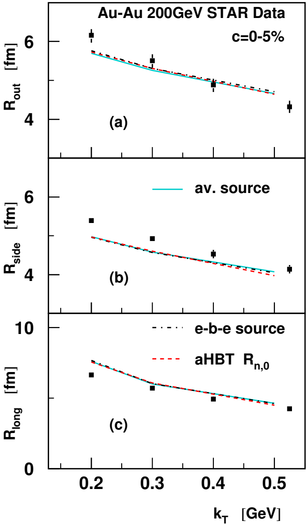
- average emission function

$$C_{av}(q,k) = \frac{\int d^4x_1 d^4x_2 \langle S(x_1,p_1)\rangle\langle S(x_2,p_2)\rangle |\Psi(k,(x_1-x_2))|^2}{\int d^4x_1 \langle S(x_1,p_1)\rangle \int d^4x_2 \langle S(x_2,p_2)\rangle}$$

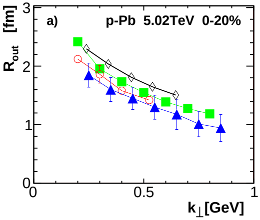
- emission function fluctuations

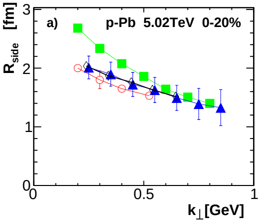
HBT of fluctuating fireballs II

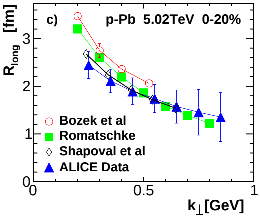
- event by event emission function similar to average emission function
- small source fluctuations
- spectra do not fluctuate event by event much



5) Interferometry radii

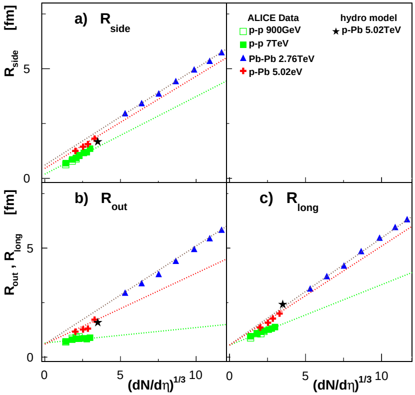






$k_\perp$ dependence of $R_{o,l,s}$
R_{side}, R_{out} consistent with hydro

Interferometry radii - pp, pA, AA

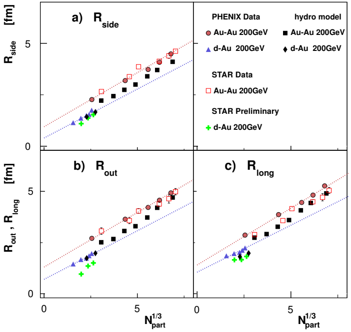


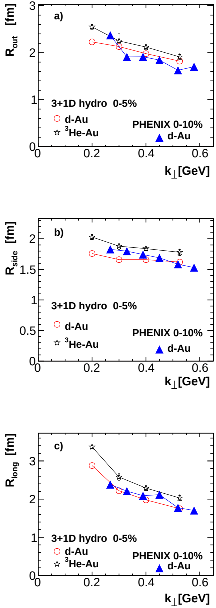
- pA system size in between pp and AA
(differences in flow strength, initial size, flow profile)

- HBT in pA consistent with hydrodynamics

Interferometry radii (d-Au, He-Au)

d-Au (PHENIX data)





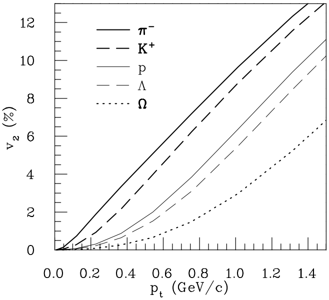
$k_\perp$ dependence of $R_{o,l,s}$

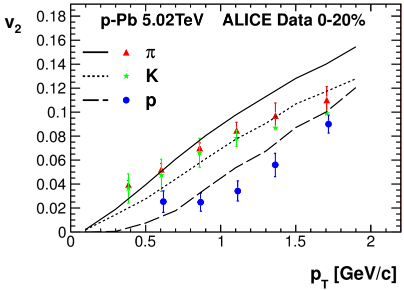
R_{side} consistent with hydro

PB, 1408.1264

Romatschke 1502.04745

Mass splitting of v_2



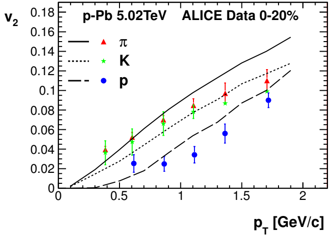


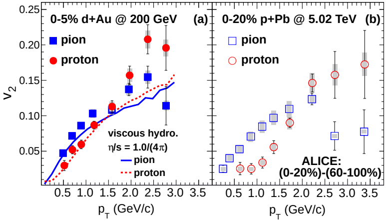
mass splititng of v_2 in hydro models

Huovinen et al. 2001

Observed in p-Pb

6) Mass splitting of v_2

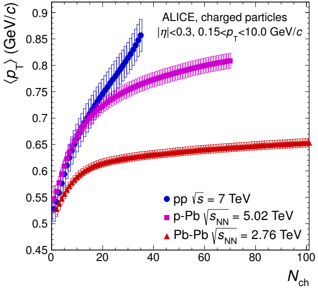


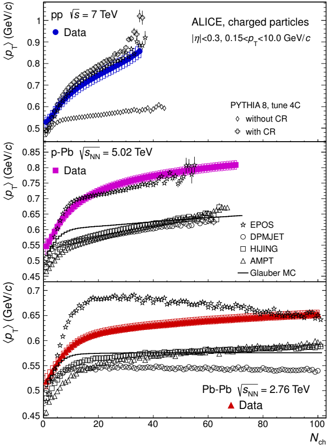


PB, Broniowski, Torrieri, 1307.5060

-mass splitting of v_2 as expected from hydrodynamics

7a) Large $< p_\perp >$

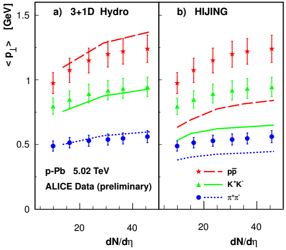


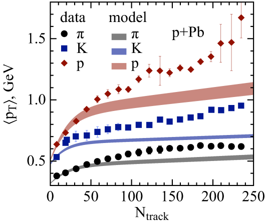


larger $< p_\perp >$ in smaller systems

- additional stronger transverse push in p-Pb and Pb-Pb
- in pp increase of $p_\perp$ can be explained by color reconnection

7b) Mass hierarchy of $< p_\perp >$





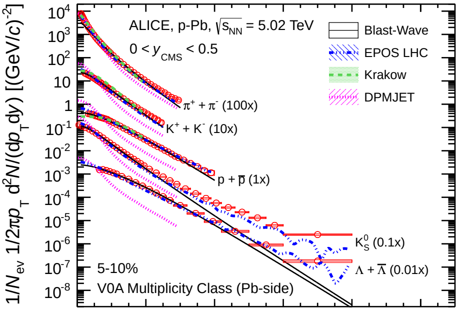
PB, W.Broniowski, G. Torrieri arXiv:1306.5442

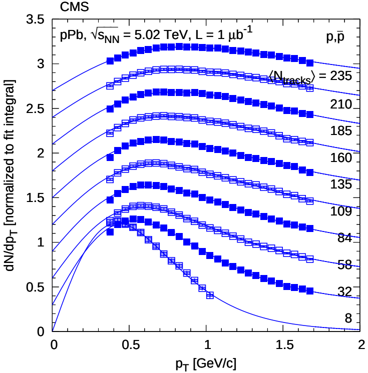
larger $< p_\perp >$ in smaller systems

Bzdak, Skokov, arXiv:1306.5442

additional transverse push stronger for heavy particles

transverse flow in $p_\perp$ spectra





$p_\perp$ spectra well described by hydrodynamic models

- spectra become harder with multiplicity
- hardening strongest for heavy particles
- consistent with strong collective transverse flow increasing for central events

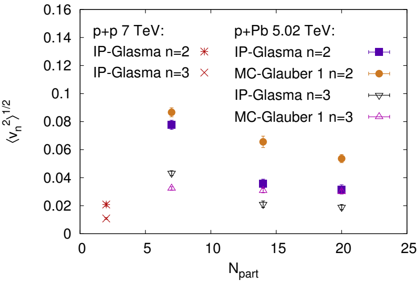
Experiments indicate a collective response to initial geometry

1. **Elliptic and triangular flow**
2. **Hierarchy of v_2 and v_3 in p-A, d-A, He-A**
   collective response to geometry (final state effect)
3. **Flow from higher cumulants**
4. **Interferometry radii**
5. **Factorization at intermediate $p_\perp$ and large $\Delta\eta$**
   particles at intermediate $p_\perp$, large η, correlated to geometry
6. **Mass splitting of v_2**
7. Mass hierarchy of spectra $(< p_\perp >)$

these effects can be described by hydrodynamics
what does it mean?
can hydrodynamics be applied to small systems?

Hydrodynamic flow in p-p?

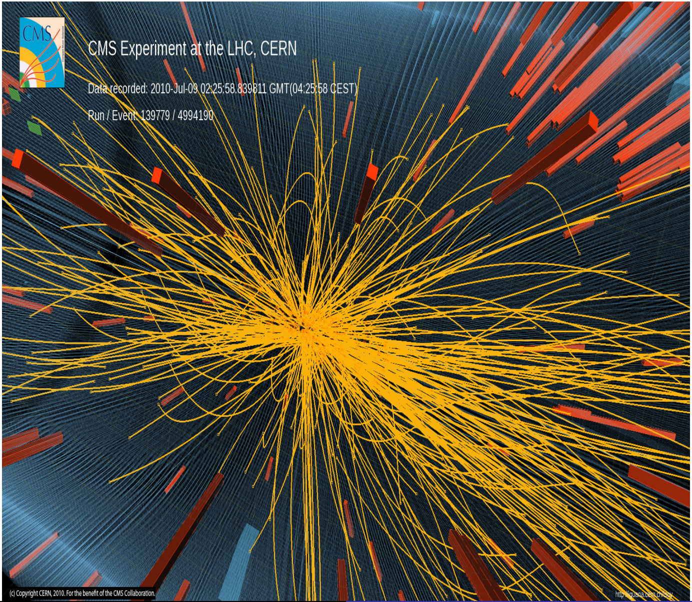
- Humanic-nucl-th/0612098 (pythia, cascade)
- Romatschke, Luzum-arXiv:0901.4588 (overlap)
- Prasad, Roy, Chattopadhyay, Chaudhuri -arXiv: 0910.4844 (overlap)
- Bozek-arXiv: 0911.2393 (flux-tubes)
- Yan, Dong, Zhou, Li, Ma, Sa- arXiv: 0912.3342 (transport)
- **CMS ridge in pp** arxiv: 10094122
- Werner, 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)
- **many other** estimates without full dynamics



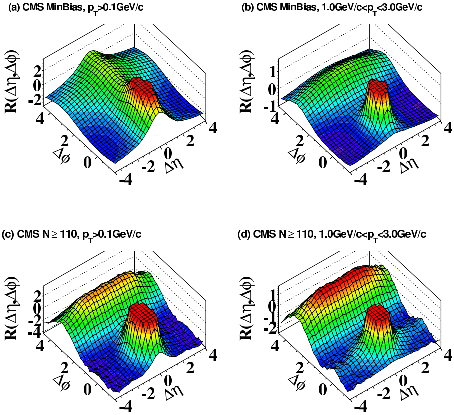
Bzdak et al. arXiv: 1304.3403

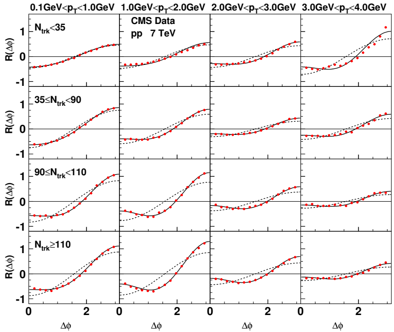
-Is hydrodynamics valid?
-What is the initial eccentricity?

High multiplicity events in pp



Ridge in pp

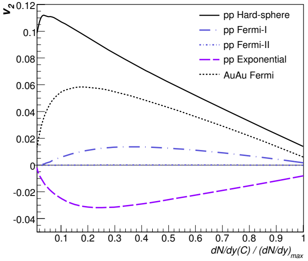




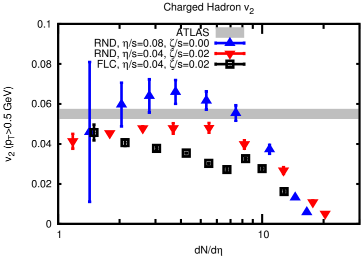
PB arXiv:1010.0405

can we measure (or calculate) v_2 in p-p

pp collisions V_n in optical Glauber + hydro(response)



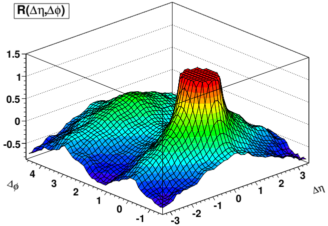
D'Enterria et al, 0910.3029



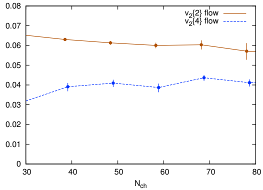
Habich et al. 1512.05354

- D'Enterria et al., 2009 ; hydro response, $v_2 \simeq 1\%$, wrong centrality dependence
- Luzumu, Romatschke, 2010 ; viscous hydro, $v_2 < 2\%$ wrong centrality dependence
- Habich et al. 2015, ; viscous hydro, $v_2 \simeq 3 - 4\%$, wrong centrality dependence

pp collisions v_n in fluctuating source + hydro(response)(...)



Werner, Karpenko, Pierog, 1011.0375



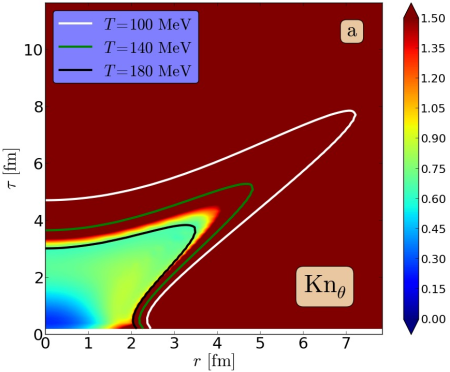
Avsar, Flensburg, Hatta, Ollitrault, Ueda, 1009.5643

- Casalderrey-Solana, Wiedemann, 2010, Avsar et al. 2010, hot-spots (DIPSY) + hydro response, $v_2 \simeq 6\%$, **correct centrality dependence**
- Werner et al., 2010, EPOS + hydro , ridge
- Deng et al. 2011, hot spots + parton cascade (BAMPS), large $v_2 \geq 5\%$, $v_3 \geq 1\%$
- Bzdak et al. 2013, IP-Glasma+Hydro $v_2 \simeq 2\%$
- Ma, Bzdak, 2014, AMPT, ridge (semi-quantitative)

Observed v_n in pp are not in opposition to collective scenario or CGC

Hydrodynamics in small systems?

Hydrodynamics $K = \frac{l_{micro}}{L_{macro}} < 1$

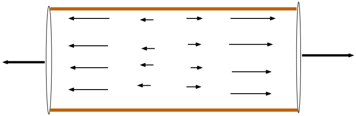


H. Niemi, G. Denicol 1404.7327

large gradients in the evolution
higher order corrections,

effective viscosity reduced

early times - longitudinal expansion - pressure asymmetry

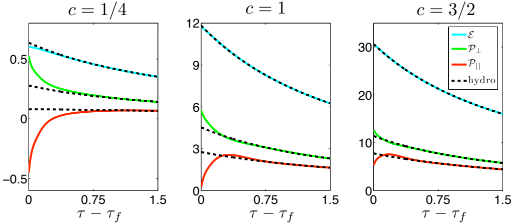


$$T^{\mu\nu} = \begin{pmatrix} \epsilon + p & 0 & 0 & 0 \\ 0 & p + \frac{2}{3}\frac{\eta}{\tau} & 0 & 0 \\ 0 & 0 & p + \frac{2}{3}\frac{\eta}{\tau} & 0 \\ 0 & 0 & 0 & p - \frac{4}{3}\frac{\eta}{\tau} \end{pmatrix}$$

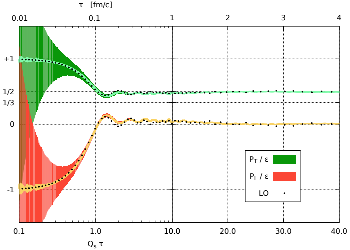
deviations from local equilibrium in early times
asymmetry between longitudinal and transverse pressure
intensivly studied in kinetic theory and *asymmetric* hydrodynamics

Florkowski, Martinez, Ryblewski, Strickland, ...

Pressure asymmetry - generic feature



AdS/CFT Chesler, Yaffe 0907.4503

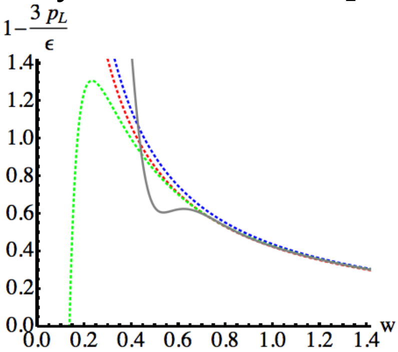


weak coupling Epelbaum, Gelis 1307.2214

Why hydrodynamic works I

Hydrodynamics works even for large pressure asymmetry

Hydrodynamics works with $P_L \ll P_\perp$

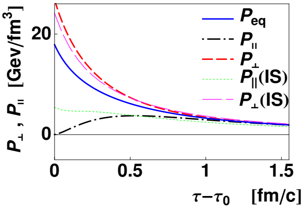


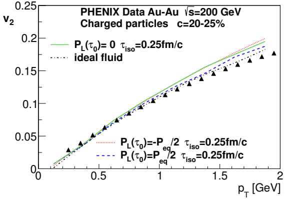
Heller, Janik, Witaszczyk 1103.3452

full solution converges to hydro

Why hydrodynamic works II

pressure anisotropy irrelevant for flow

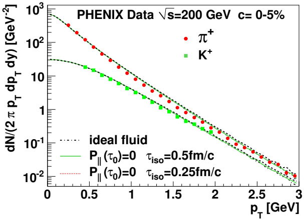


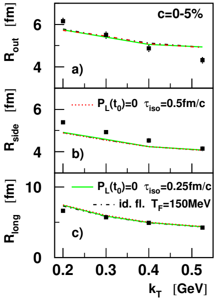


PB, I. Wyskiel - arXiv:1009.0701

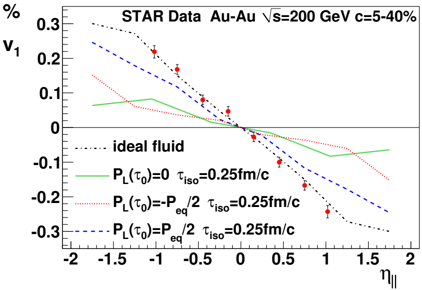
- early pressure anisotropy irrelevant!

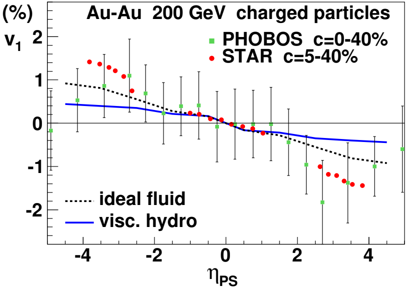
Vredevoogd, Pratt, 0810.4325





Pressure anisotropy - directed flow

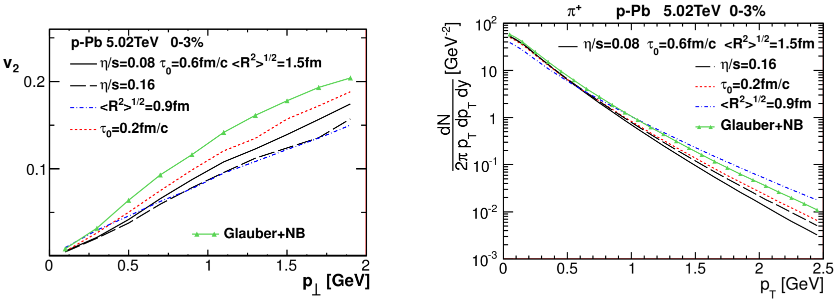




PB, I. Wyskiel - arXiv:1009.0701

- v_1 could be used to estimate isotropization time
- large model uncertainities
- same for bottomonia, dileptons
- asymmetry from viscosity compatible v_1 data in AA

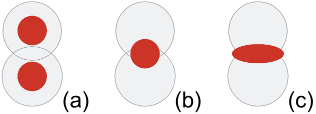
dependence on model details



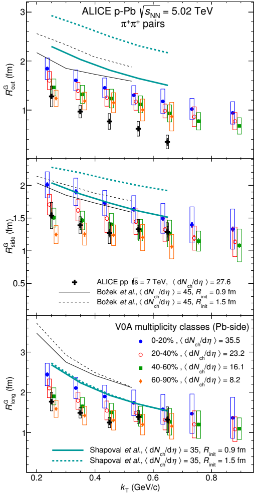
response strength depends on details (more than in AA!)

- initial eccentricity
- initial size 'compact' vs 'standard'
- viscosity
- initial time for expasnion

compact source



Bzdak et al. 1304.3403

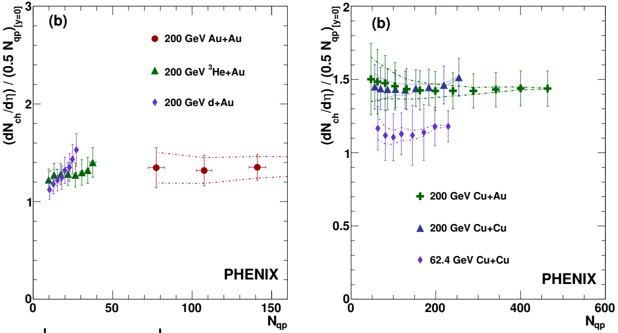


compact soure 0.9fm
standard source 1.5fm

HBT $\longrightarrow$ initial size of the fireball in pA small

Constituent quark model - PHENIX

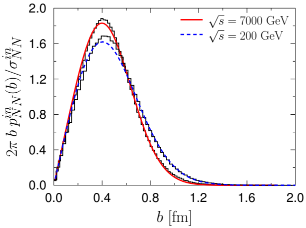
PHENIX 2015



- three quarks per nucleon
- Q distribution in N from electron-proton
- hard-sphere Q-Q scattering (8.17mb at 200GeV)
- fairly good scaling with N_Q, problem with p-p point
- recent (2016) calculations : Lacey et al., Zheng et al. , Loizides, Mitchell et al.

Wounded quark model - pp scattering

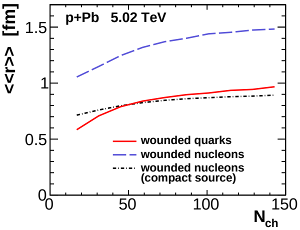
- three quarks distributed in each nucleon $\rho(r) \simeq e^{-r/b}$
- recentering
- Gaussian Q-Q wounding profile
- parameters fitted to reproduce N-N scattering

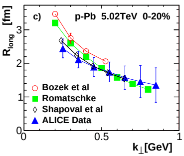


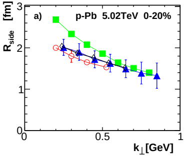
(200GeV, $\sigma_{QQ} = 7$mb, $r_{QQ} = 0.29$fm) (7000GeV, $\sigma_{QQ} = 14.3$mb, $r_{QQ} = 0.30$fm)

- small change of nucleon size with $\sqrt{s}$
- increase of σ_{QQ} with $\sqrt{s}$

Fireball size in p-Pb

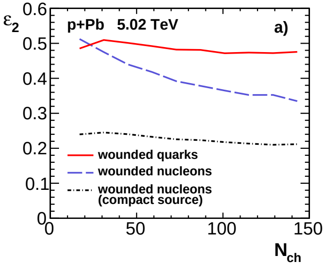


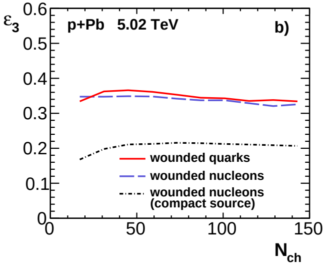




- wounded quark model gives small fireball size
- *compact source* consistent with p-Pb data (HBT, $< p_\perp >$)

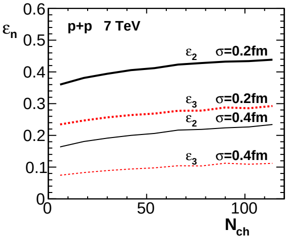
Fireball eccentricities in p-Pb

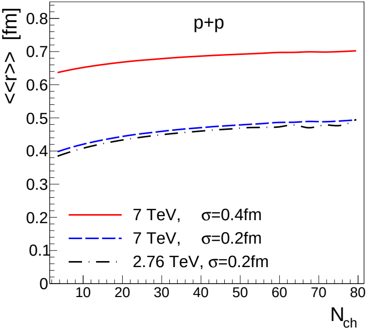




- significant eccentricities in p-Pb
- consistent experimental observation of v_2 and v_3 in p-Pb

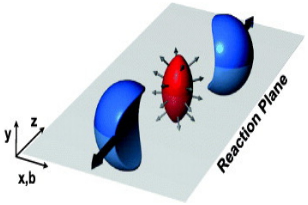
p-p scattering





- significant eccentricities in p-p
- small size of the interaction region 0.4fm

azimuthally-sensitive HBT



correlation measured at fixed angle w.r. to the event plane

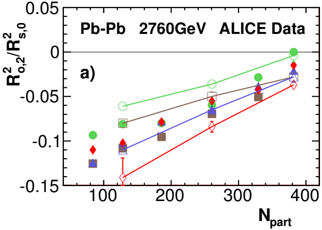
$$C(k_\perp, \phi, q) = 1 + \lambda e^{-R_o^2 q_o^2 - R_s^2 q_s^2 - R_l^2 q_l^2 - R_{os}^2 q_o q_s}$$

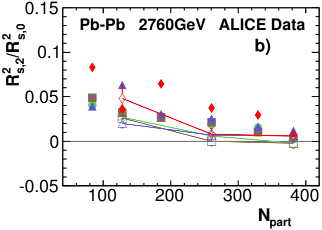
- dependence on ϕ

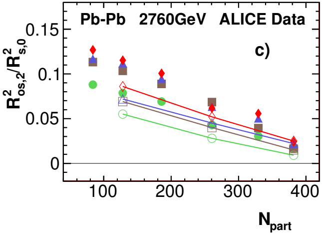
$$R_i(\phi)^2 = R_{i,0}^2 + 2cos(2\phi) R_{i,2}^2$$

- new radius parameter R_{os}

azHBT in Pb-Pb at 2.76TeV (second order reaction plane)







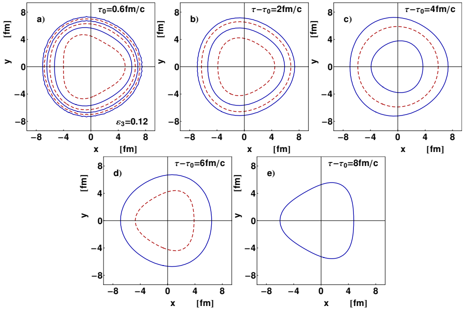
- eccentricity and elliptic flow give azimuthal angle dependence
- fair agreement with data

- Further confirmation of elliptic flow and deformation

azHBT in Au-Au at 200GeV (third order event plane)

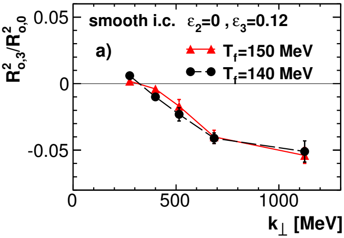
what is the origin of the $cos(3\Phi)$ angular dependence (Plumberg, Shen, Heinz, 2013)

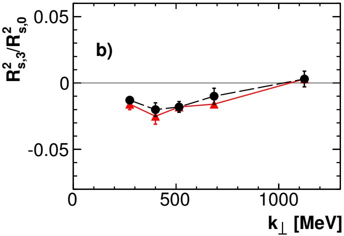
- deformed geometry + radial flow
- triangular flow

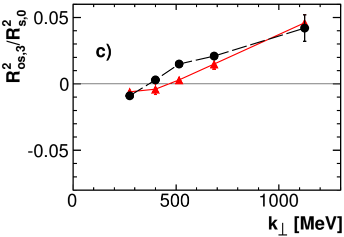


- OR both flow and geometry
- OR both flow and inverted geometry (example)

HBT third order reaction plane, smooth density (example)

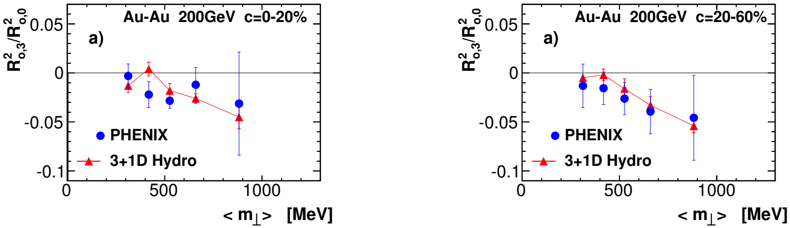






- negative, $k_\perp$ depend. $R^2_{o,3}$
- positive, $k_\perp$ depend. $R^2_{os,3}$
- small, negative $R^2_{s,3}$

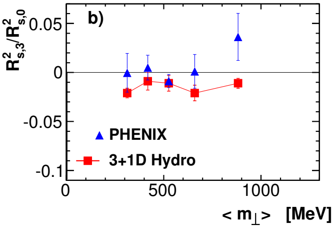
HBT third order reaction plane $R^2_{O,3}$



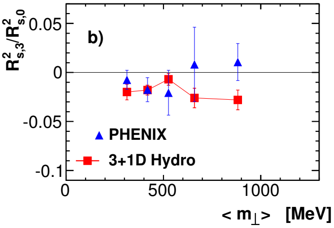
fair agreement with PHENIX

HBT third order reaction plane $R^2_{s,3}$

0-20%

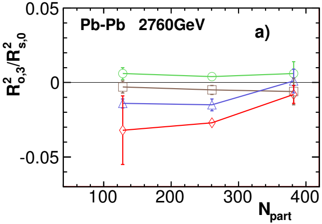


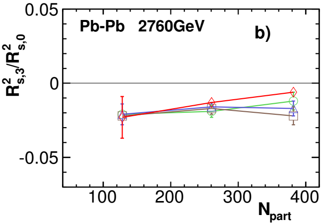
20-60%

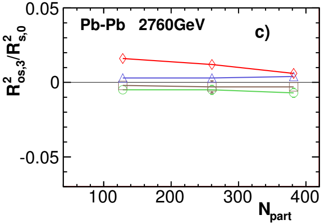


compatible with PHENIX data for 20-60%, tension for 0-20%

azHBT in Pb-Pb at 2.76TeV (third order reaction plane)



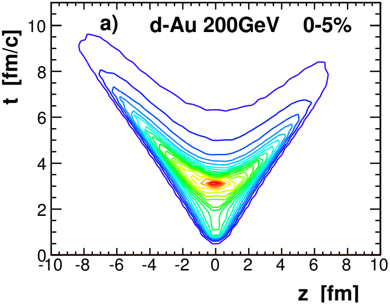




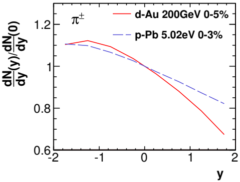
- similar as Au-Au at RHIC
- small negative $R^2_{s,3}$
- negative, $k_\perp$ depend. $R^2_{o,3}$

Asymmetric collisions p-Pb, d-Au

different emission times in forward-backward hemispheres

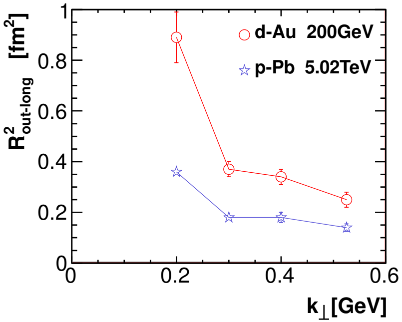


FB asymmetry



lcms of the pion

$R_{out-long} \neq 0$ in asymmetric collisions



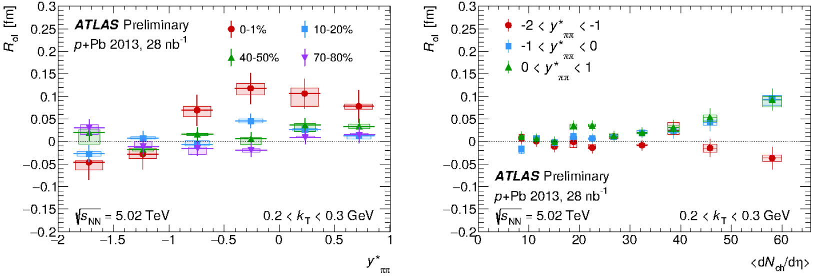
$$C(q, k_\perp) = 1 + \lambda e^{-R_o^2 q_o^2 - R_s^2 q_s^2 - R_l^2 q_l^2 - 2R_{ol}^2 q_o q_l}$$

$$R_{ol}^2 = H_1 + I_1 - G_0\beta_\perp + (I_1 + \dots)\cos(2\Phi)$$

$$< zxcos(\Phi) >, < zysin(\Phi) >, < zt >$$

R_{ol} observed - ATLAS preliminary

R_{ol} cross term



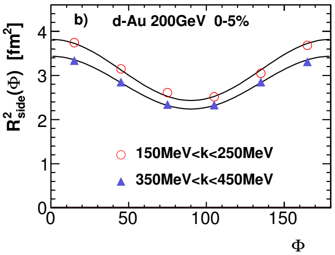
In *central events* on the *forward* side, there is strong evidence of a positive R_{ol} (4.8σ combined significance in 0–1% centrality)

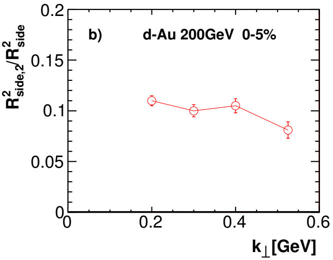
- demonstrates breaking of boost invariance: z-asymmetry is manifest in proton-going side.
- requires both longitudinal and transverse expansion in hydrodynamic models

ATLAS-CONF-2016-027

azimuthally sensitive HBT in d-Au

$$R_s^2(\Phi) = R_{s,0}^2 + 2R_{s,2}^2\cos(2\Phi)$$

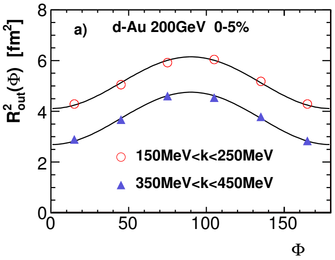


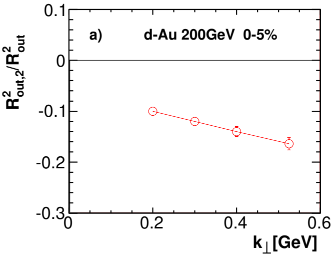


R_{side} **larger in-plane**

azimuthally sensitive HBT in d-Au - R_{out}

$$R_o^2(\Phi) = R_{o,0}^2 + 2R_{o,2}^2 \cos(2\Phi)$$

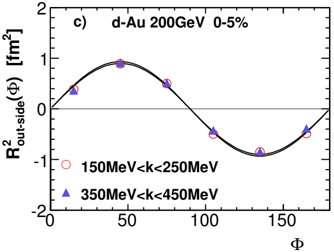


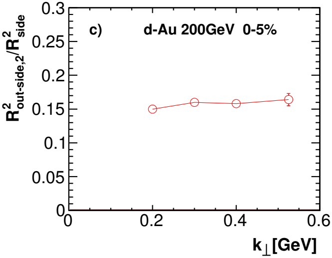


R_{out} **smaller in-plane**

azimuthally sensitive HBT in d-Au - $R_{out-side}$

$$R^2_{os}(\Phi) = 2R^2_{os,2}\sin(2\Phi)$$

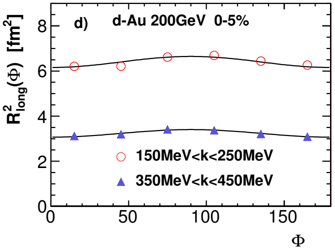


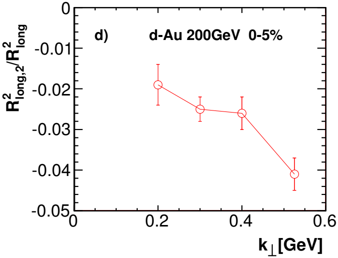


$R_{out-side} \neq 0$

azimuthally sensitive HBT in d-Au - R_{long}

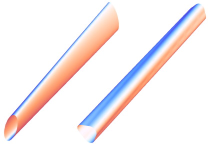
$$R_l^2(\Phi) = R_{l,0}^2 + 2R_{l,2}^2 \cos(2\Phi)$$



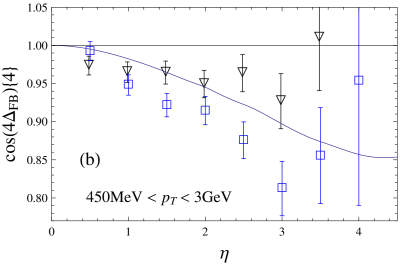


$R_{long,2} \neq 0$

event by event twist of the reaction plane



Fluctuating RP twist
can be measured



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

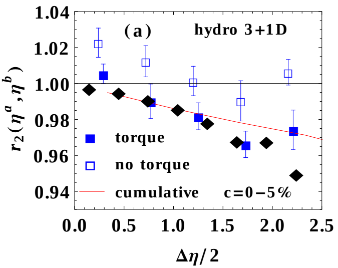
$$\cos(2k\Delta_{FB})\{4\} \equiv \frac{\langle e^{ik[(\phi_{F,1}+\phi_{F,2})-(\phi_{B,1}+\phi_{B,2})]}\rangle}{\langle e^{ik[(\phi_{F,1}-\phi_{F,2})-(\phi_{B,1}-\phi_{B,2})]}\rangle} =$$

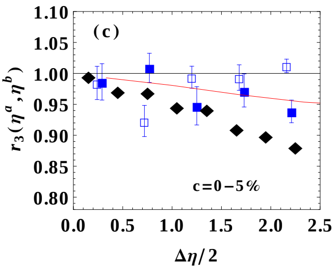
$$\langle \cos(2k\Delta_{FB})\rangle_{\mathrm{events}} + \mathrm{nonflow}$$

3-bin measure of event-plane decorrelation (CMS)

$$r_2(\eta_a, \eta_b) = \frac{<< cos[n(\phi_i(-\eta_a) - \phi_j(\eta_b))] >>}{<< cos[n(\phi_i(\eta_a) - \phi_j(\eta_b))] >>} \simeq \frac{cos[n(\Psi(-\eta_a) - \Psi(\eta_b)]}{cos[n(\Psi(\eta_a) - \Psi(\eta_b)]}$$

only pairs with large rapidity gap $\eta_a - \eta_b$



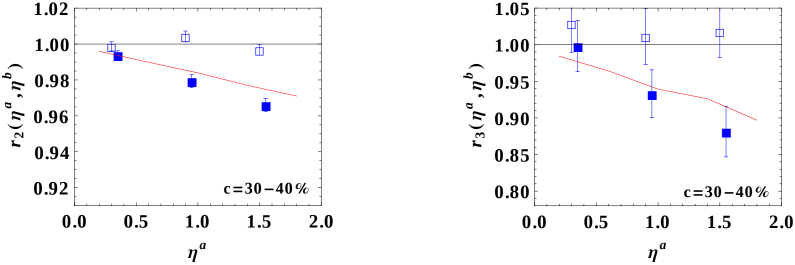


- nonflow under control
- torque effect seen in the CMS data
- semiquantitative agreement, but need more fluctuations

- **other calculation (hybrid hydro, AMPT) reproduce the data**

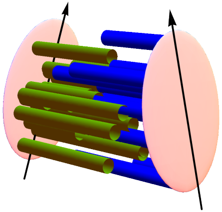
$r_n(\eta_a, \eta_b)$ **Au-Au at 200GeV**

predictions ($3 < \eta_b < 4.5$)



- larger twist angle at RHIC energies

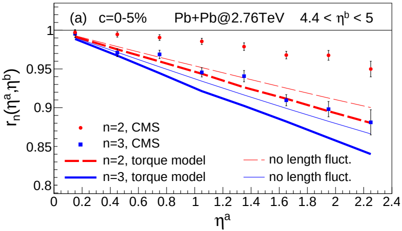
Fluctuations in energy deposition from each source

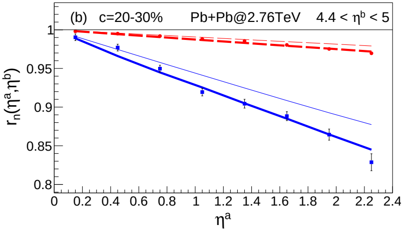


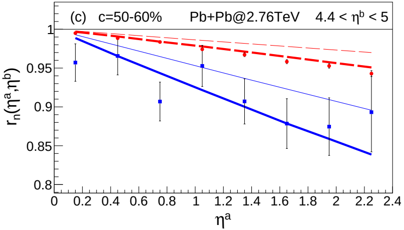
- the position (in rapidity) of string ends is random
- long range fluctuations
- each source fluctuates differently $\longrightarrow$ event-plan decorrelation in p-Pb
- short range fluctuations possible, but irrelevant for the CMS r_2
- average deposition same as in old model (linear in η)

PB, Broniowski 1503.03655; Monnai, Schenke 1509.04362

Fluctuating strings $r_n(\eta_a, \eta_b)$ (initial state only)



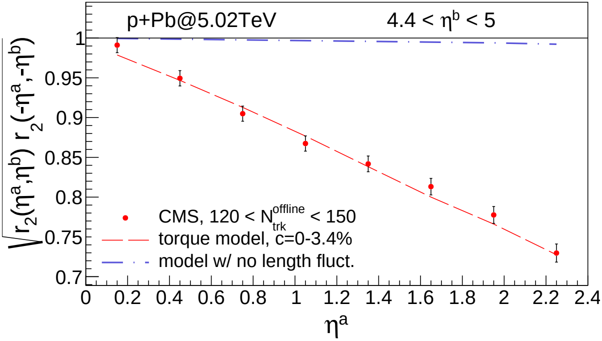




fluctuations improve description of r_2 in Pb-Pb

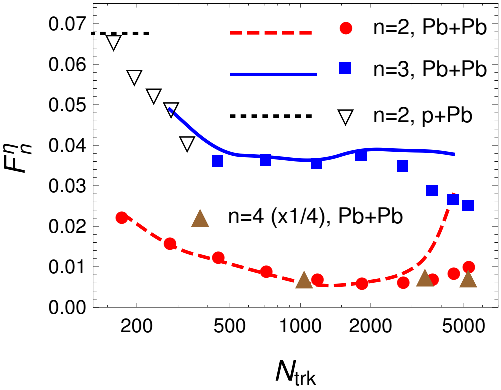
except for r_2 in central collisions

Fluctuating strings p-Pb



- fluctuations essential to describe event-plane decorrelation in p-Pb

F slope



- fair description of mid-central collisions
- overestimates decorrelation in central collisions
- $F_4 \simeq 4F_2$

Can hydrodynamic work in small systems

1. **Mean free path**
   - for $\eta/s = 0.08$

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

2. **Quantitative hydrodynamic model requires dominance of hydrodynamic modes**
   - estimate of minimal size R (Spalinski 1607.06381)

   $$RT > 2\pi\sqrt{2T\tau_\pi\ \eta/s} \simeq 1 - 3$$

3. **AdS/CFT**
   - in numerical AdS/CFT: $RT > 1$, (Chesler 1601.01583)
   - **minimal size** $R > 0.5fm$

Hydrodynamics works down to $N_{ch} = 10 - 30$ (ATLAS, CMS)

Success of hydrodynamics not accidental!

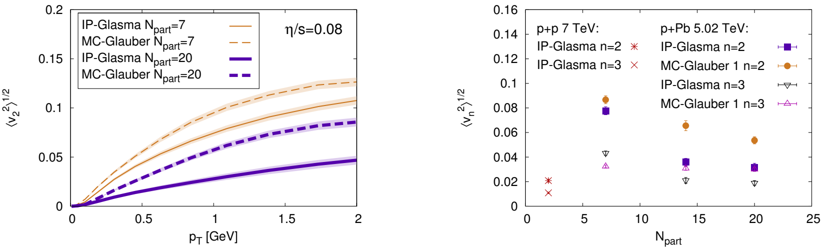
Break down of hydrodynamics difficult to observe (non-flow, jets . . .)

Summary

Relativistic viscous hydrodynamics describes the evolution of the fireball in small systems

1. Collective response to geometry
2. Hydrodynamic model describes the data
3. Using hydrodynamics in small systems "not absurd"
4. Small systems with collectivity $\longrightarrow$ many further studies possible: HBT, mapping of production mechanism via correlations, jets, check for chiral magnetic effect, ...

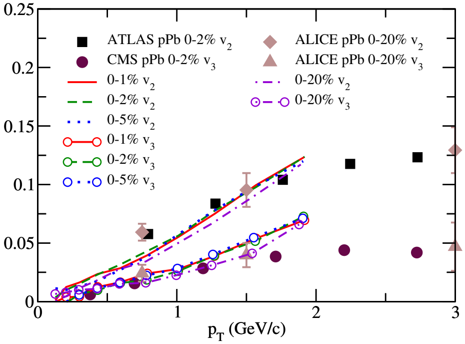
3+1D visc. hydro



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

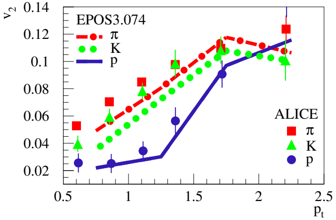
A.Bzdak, B.Schenke, P.Tribedy, R.Venugopalan - arXiv: 1304.3403

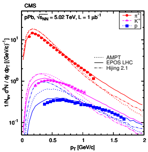
3+1D hydro



G-Y.Qin, B. Müller arXiv: 1306.3439

EPOS

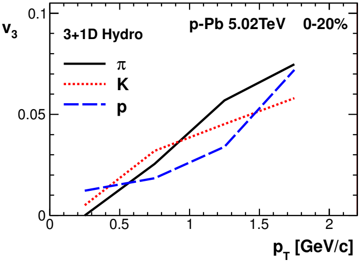


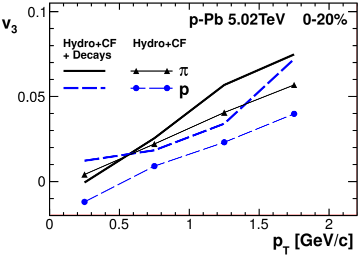


excellent description of spectra

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

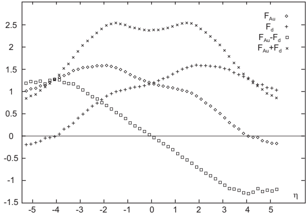
v_3 - small mass splitting





limited mass splitting

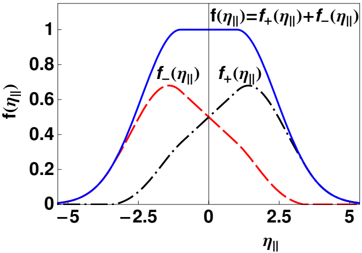
resonance decays spoil mass ordering

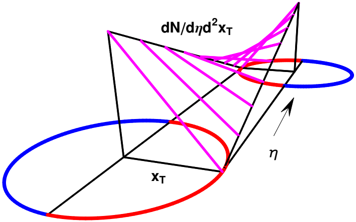


Asymmetric emission

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

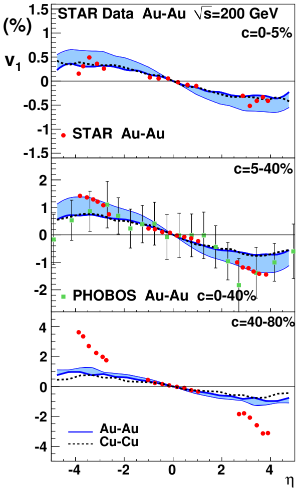
$$\rho(\eta, x, y) \quad \propto \quad f_+(\eta) N_+(x, y) + f_-(\eta) N_-(x, y)$$

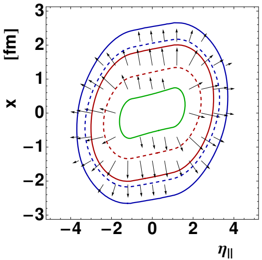




bremsstrahlung (Adil Gyulassy, Phys. Rev. C72, 034907 (2005))

Directed flow- tilted source





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

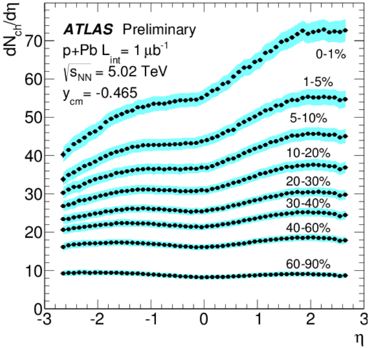
$$\partial_\tau u_x = -\frac{\partial_x p_\perp}{p+\epsilon}$$

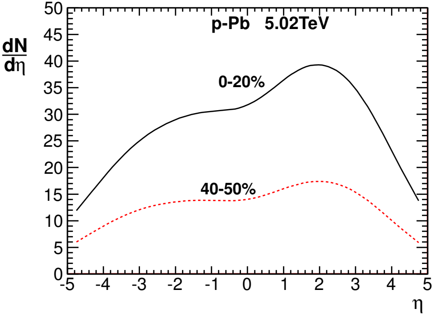
$$\partial_\tau Y = -\frac{\partial_\eta p_{||}}{\tau(p+\epsilon)}$$

tilted source $\rightarrow$ transverse pressure + longitudinal pressure

Glauber model

Asymmetric distributions

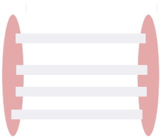




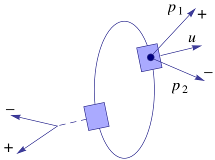
FSI scenarios

fields+thermalization

color fields

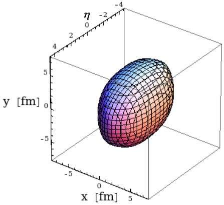


local thermalization → hadronization

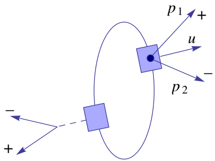


hydrodynamics

hydrodynamic expansion



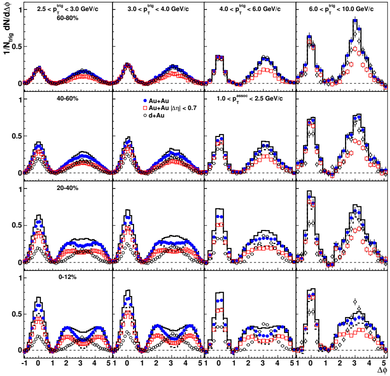
hadronization, statistical emission



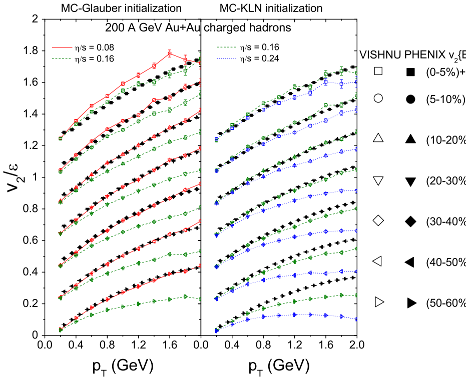
Give similar flow

Can we reduce uncertainties?

go back to very peripheral A-A



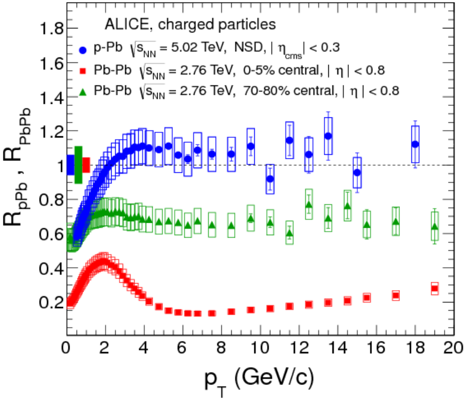
STAR-arXiv:1004.2377



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

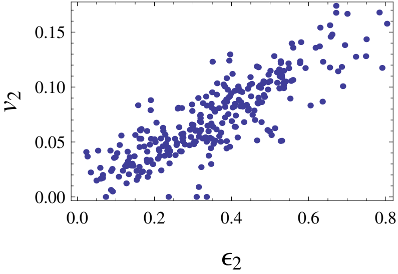
$$\Delta^{\mu\alpha}\Delta^{\nu\beta}u^\gamma\partial_\gamma\pi_{\alpha\beta} = \frac{2\eta\sigma^{\mu\nu} - \pi^{\mu\nu}}{\tau_\pi} - \frac{1}{2}\pi^{\mu\nu}\frac{\eta T}{\tau_\pi}\partial_\alpha\left(\frac{\tau_\pi u^\alpha}{\eta T}\right)$$

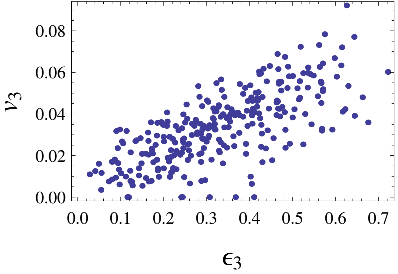
- bulk viscosity

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

- 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