

# Collective dynamics in small systems

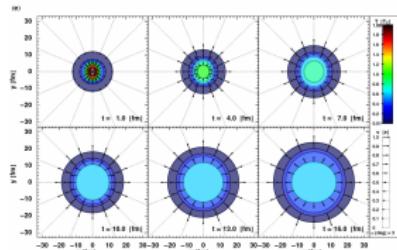
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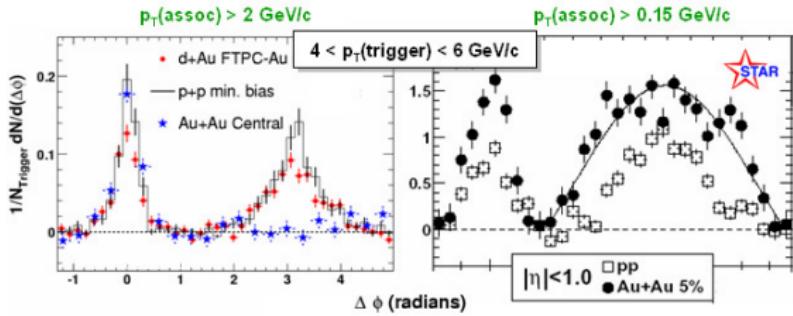
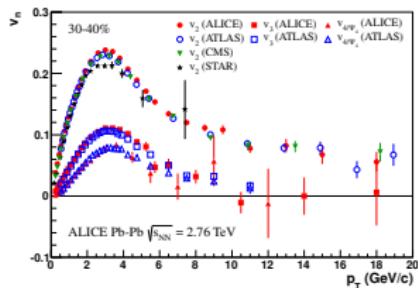


# QGP formed in A-A collisions - sQGP

## elliptic and triangular flow



## Jet quenching



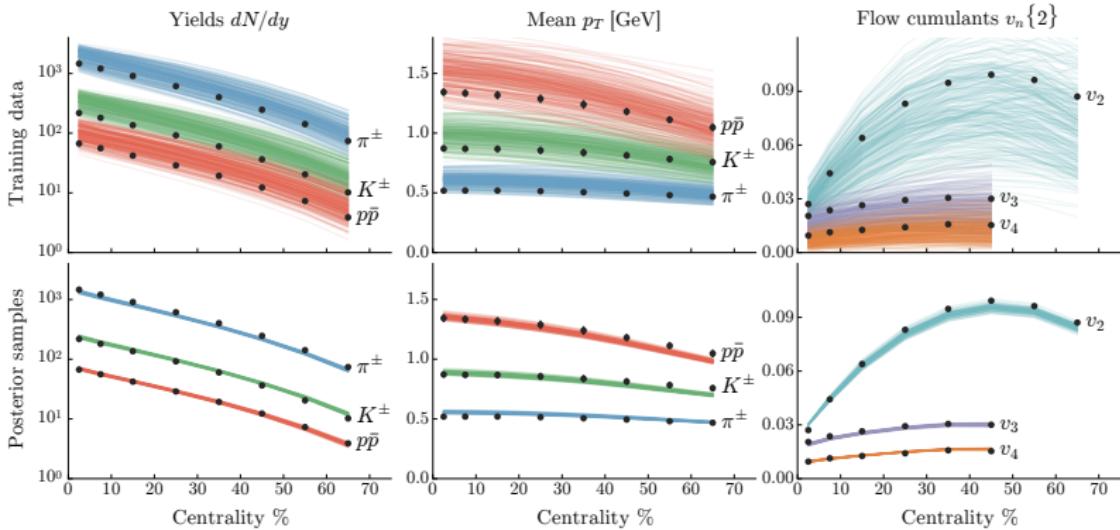
$$\frac{dN}{d\phi} \propto 1 + 2v_2 \cos(2(\phi - \Psi_2)) + 2v_3 \cos(3(\phi - \Psi_3)) + \dots$$

p-p and p-A as reference systems!

# Bayesian parameter estimation

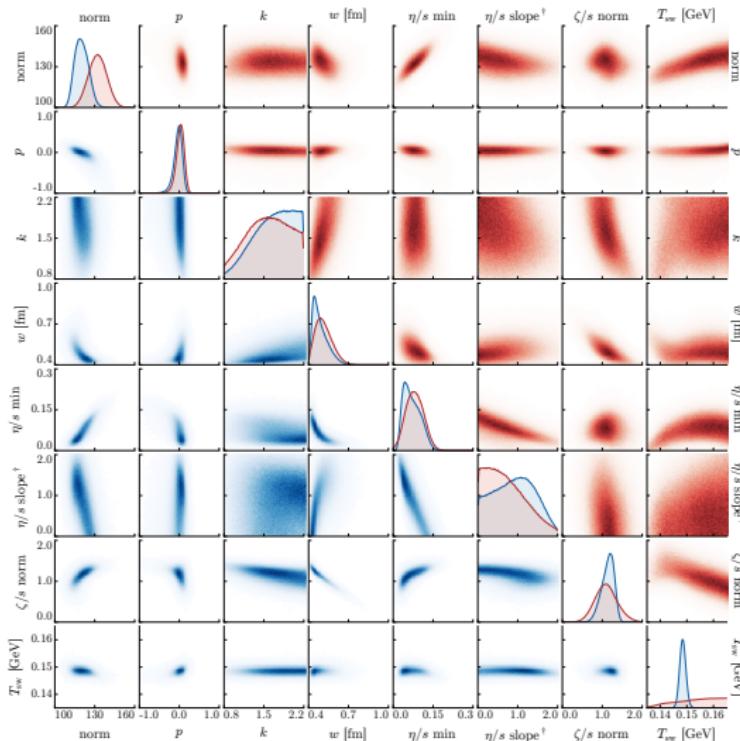
## fitting initial densities AND medium parameters

### 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

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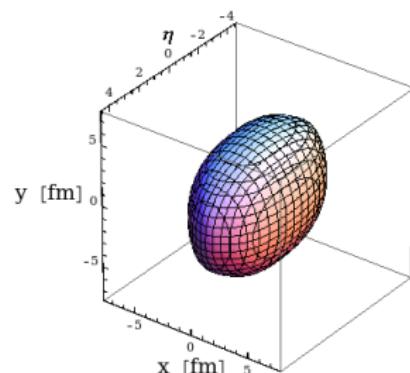
## Abstract

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.

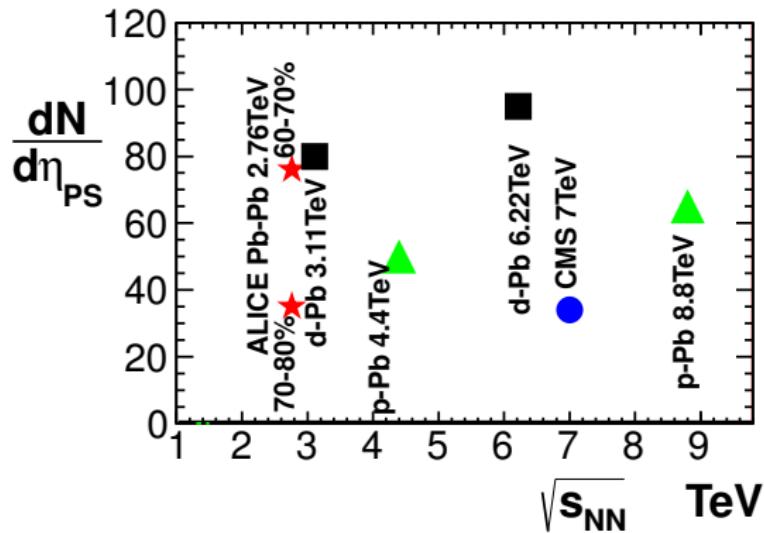
# hydrodynamic model

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

**can hydrodynamics work in small systems?**

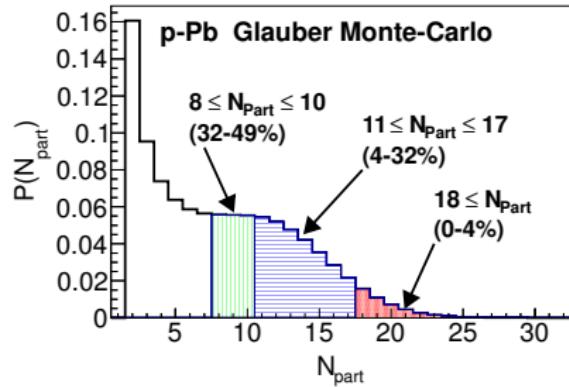


# p-Pb, d-Pb @ LHC

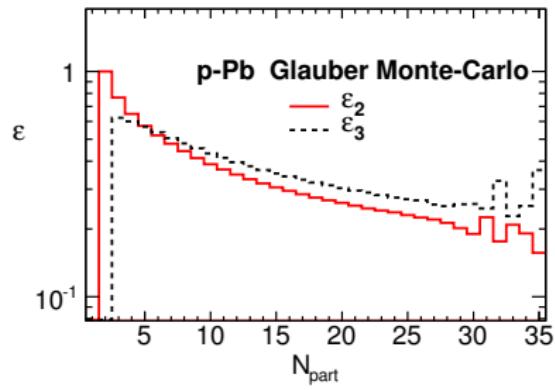


large multiplicity - large fireball - collective expansion?

# 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?

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but should and can be tested
- ▶ Small enough gradients? no?  
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in p-p?

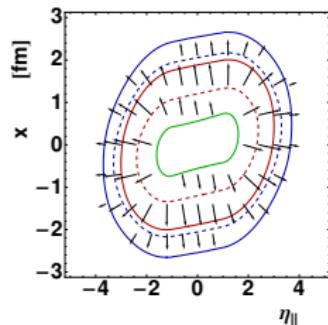
yes (high mult.)

(?)

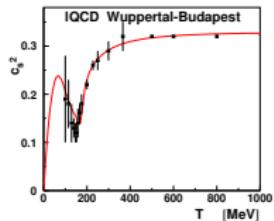
(???)

no!

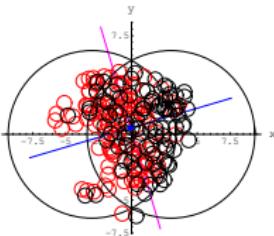
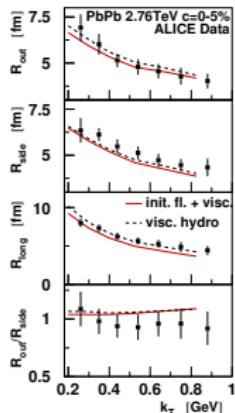
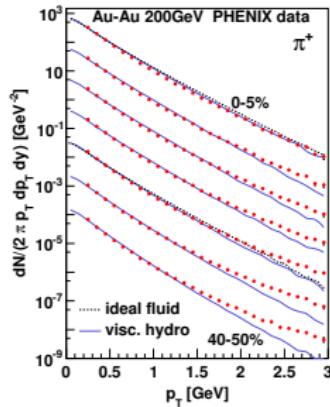
# 3+1D hydrodynamics



3+1D visc. hydro

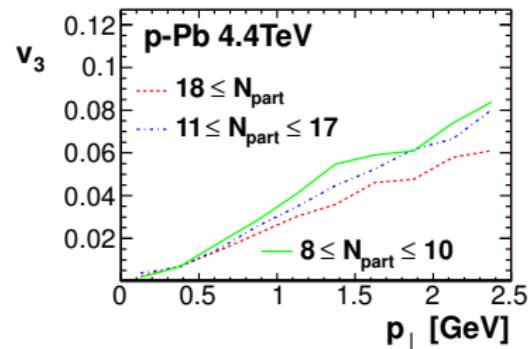
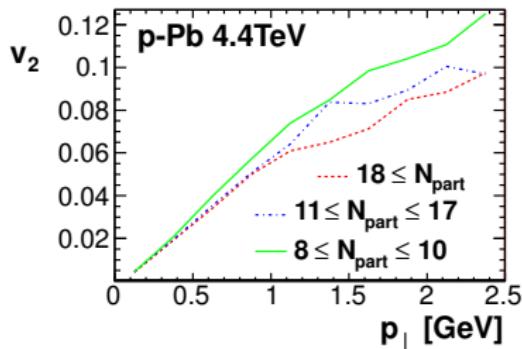


IQCD + Hadron Gas



- ▶ 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



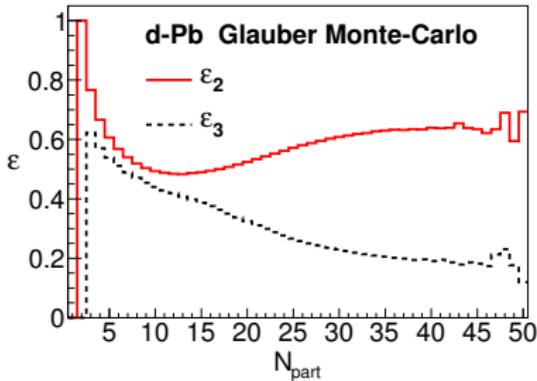
elliptic flow in p-Pb

triangular flow

PB, arXiv:1112.0912

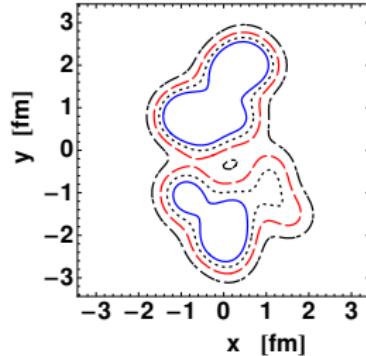
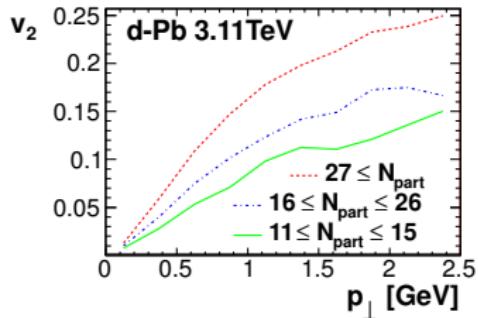
# d-Pb

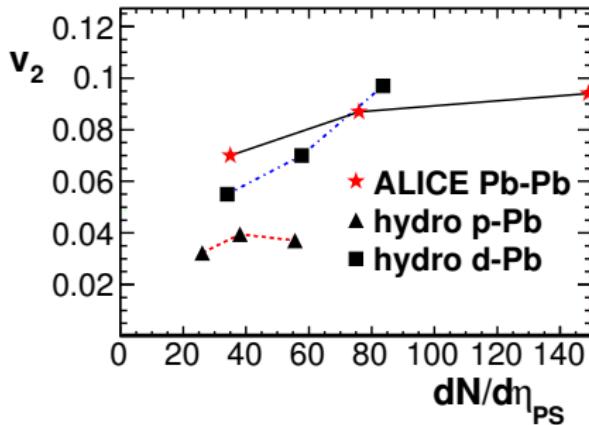
- ▶ small deformed projectile
- ▶ well defined initial deformation
- ▶ multiplicity controls eccentricity



large elliptic flow

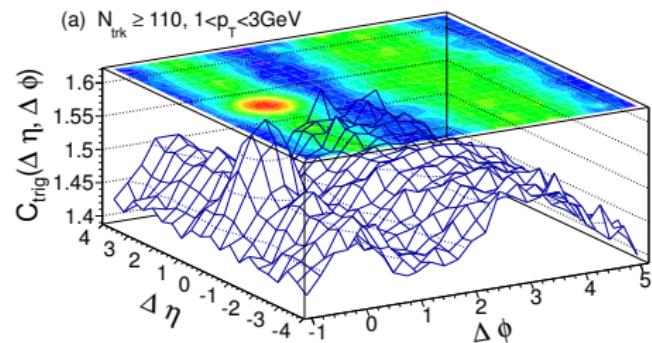
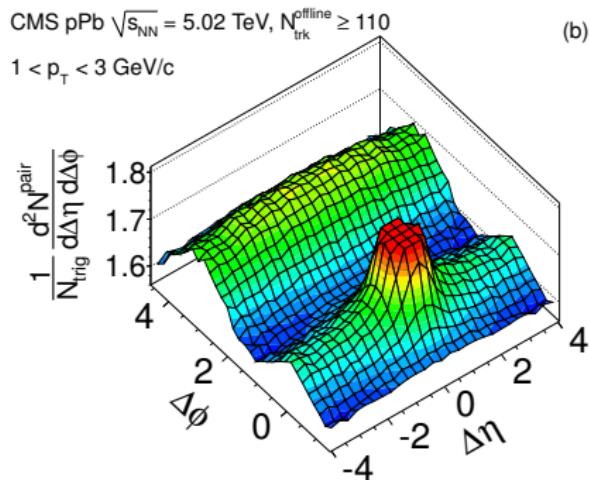
PB, arXiv:1112.0912





- ▶ 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



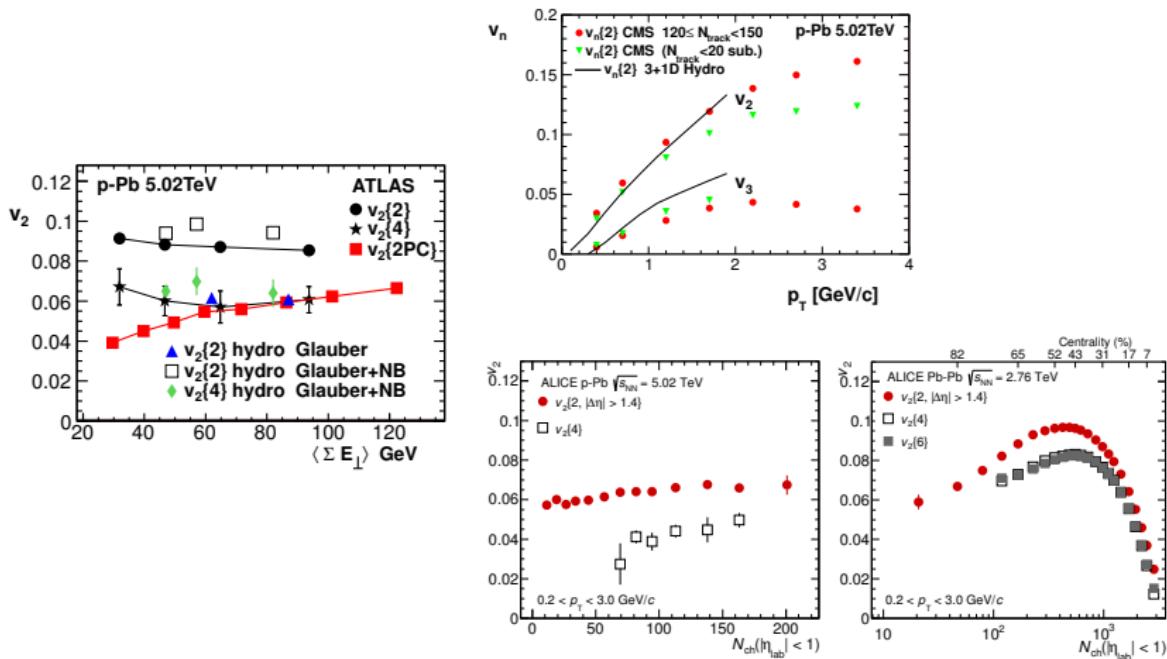
PB, W.Broniowski, arXiv:1211.0845

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

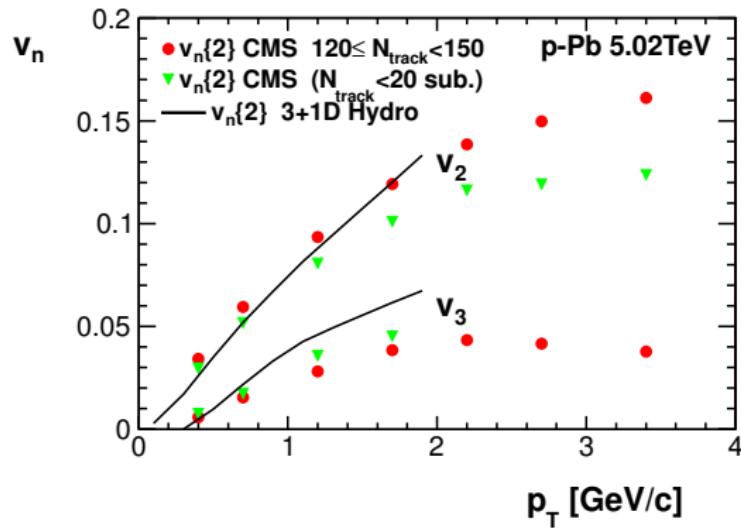
## Indications of collective flow in p-A, d-A, He-A

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  $\eta$ , correlated to geometry
6. **Mass splitting of  $v_2$**
7. Mass hierarchy of spectra ( $\langle p_\perp \rangle$ )

# 1) Elliptic and triangular flow observed in p-Pb



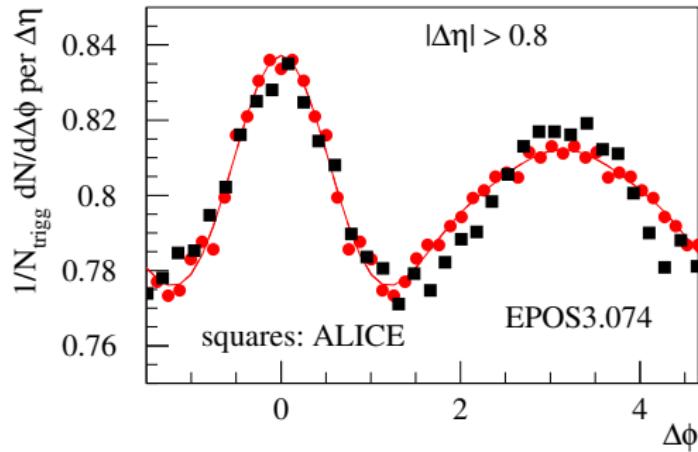
- Glauber MC initial cond. - agreement with data



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



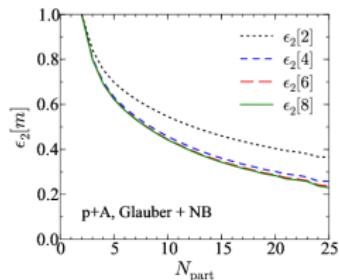
Double ridge from EPOS simulation

K. Werner et al. 1307.4379

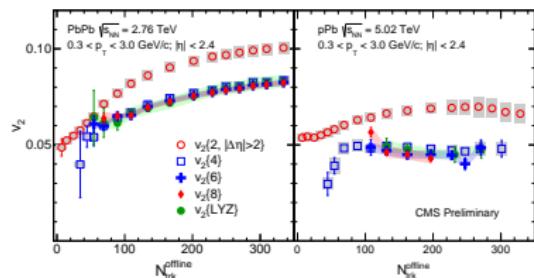
## 2) Flow from higher cumulants

- hierarchy of cumulants

$$\epsilon_2\{4\} \simeq \epsilon_2\{6\} \simeq \epsilon_2\{8\} < \epsilon_2\{2\} \rightarrow \text{hydro response} \rightarrow v_2\{4\} \simeq v_2\{6\} \simeq v_2\{8\} < v_2\{2\}$$



A. Bzdak, PB, L. McLerran, 1311.7325

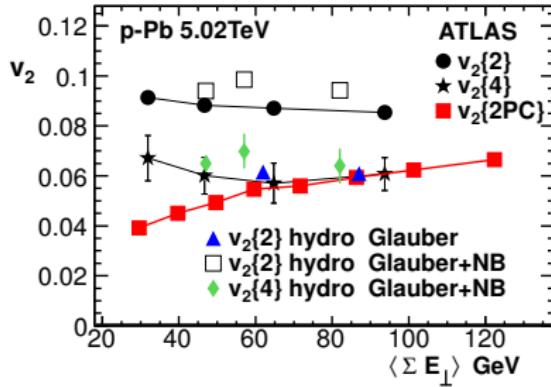


CMS 1502.05382

- 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



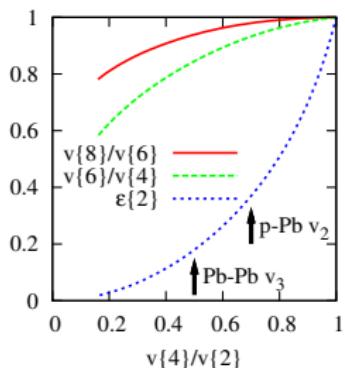
PB, W. Broniowski 1304.3044

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

also: I. Kozlov et al. 1412.3147

**Note:**  $\epsilon_n + \text{hydro response} \rightarrow$  correct centrality dependence of  $v_n$

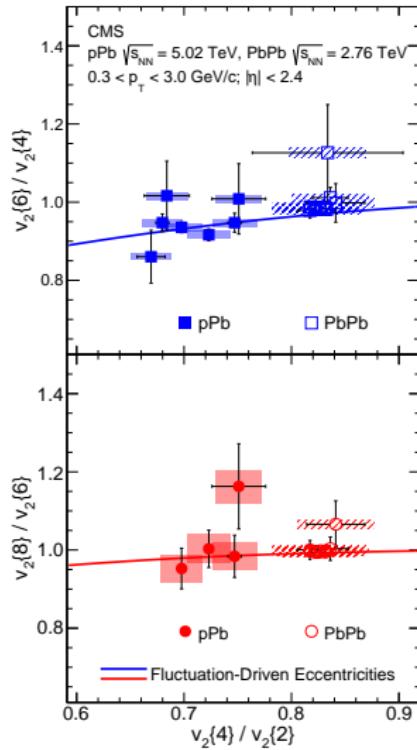
# Detailed hierarchy of cumulants



L. Yan, J.Y. Ollitrault 1312.6555

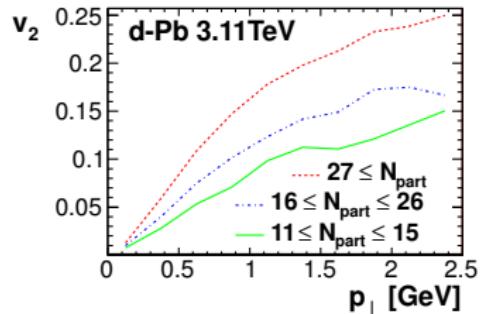
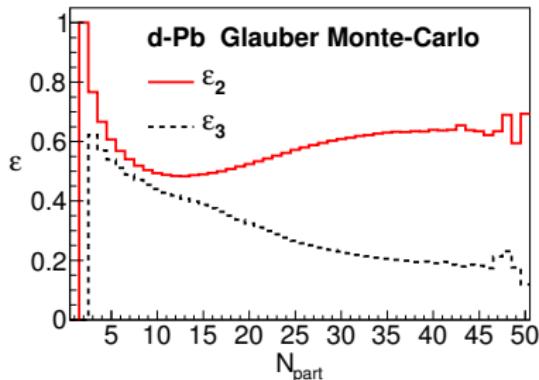
universal prediction for differences  
 $v_2\{4\} \neq v_2\{6\} \neq v_2\{8\}$   
 power-ellipticity distributions

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

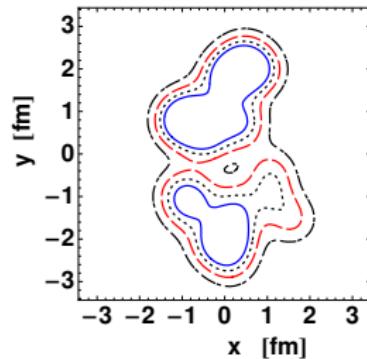


CMS 1502.05382

## small system with large deformation d-Pb



large elliptic flow

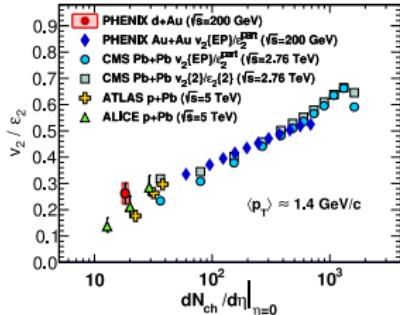
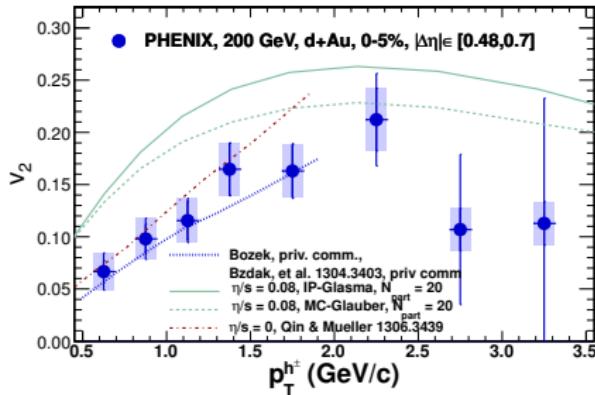


PB, arXiv:1112.0912

control of initial geometry,

central collisions - deformed fireball

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

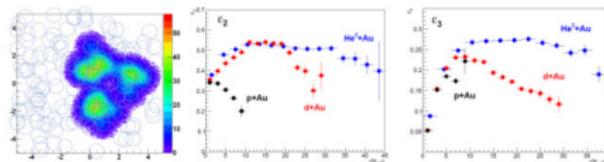


PHENIX, arXiv:1303.1794

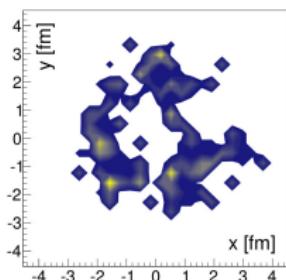
large eccentricity - large elliptic flow

# small on big collisions

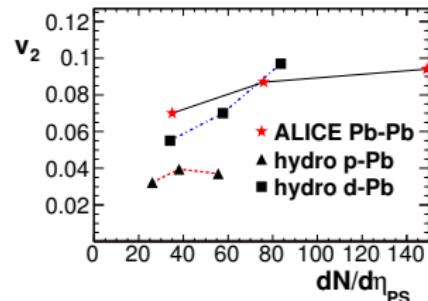
## $^3\text{He}-\text{Au}$ collisions



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



$\alpha$  clusters in  $^{12}\text{C}$  Broniowski, Arriola arXiv:1312.0289



PB, arXiv:1112.0912

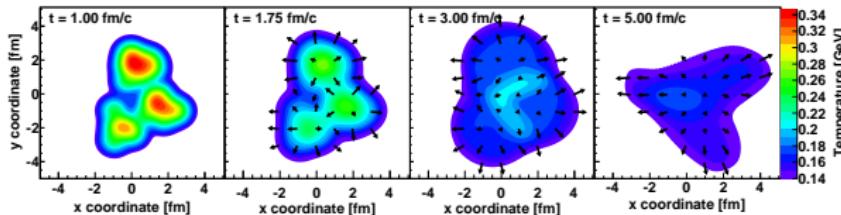
strong effect for d-A

intrinsic deformation dominates over fluctuations

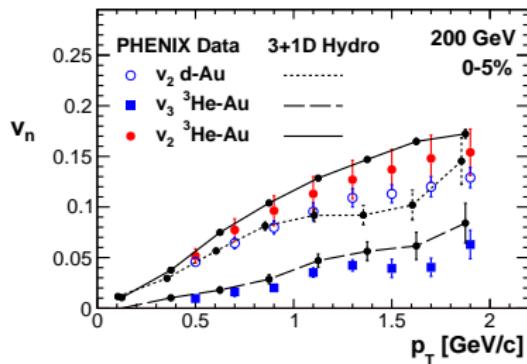
effect for  $v_3$  in  $^3\text{He}-A$ ,

Nagle et al. arXiv:1312.4565

### 3b) Triangular flow in $^3\text{He-Au}$



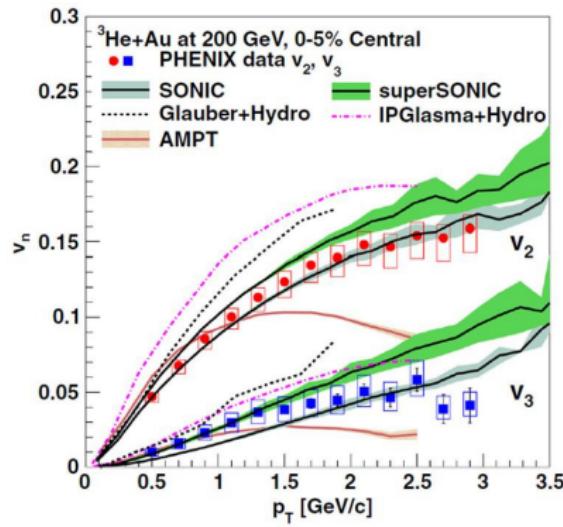
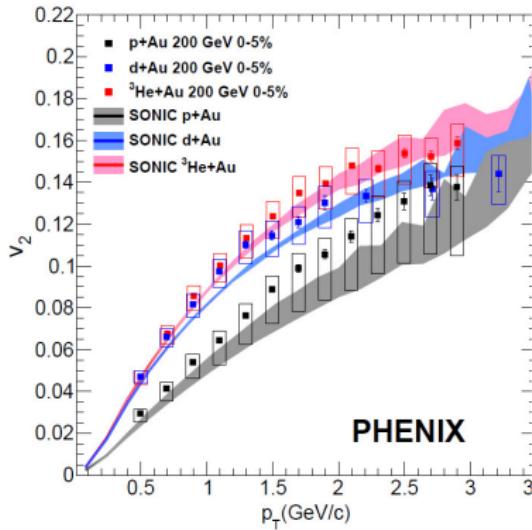
Nagle et al. 1312.4565



- ▶ observed  $v_3 \rightarrow$  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**  $^3\text{He}-\text{Au}$
- small  $v_2$  in p-Au
- strong  $v_3$  in  $^3\text{He}-\text{Au}$

**Collective response to initial 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

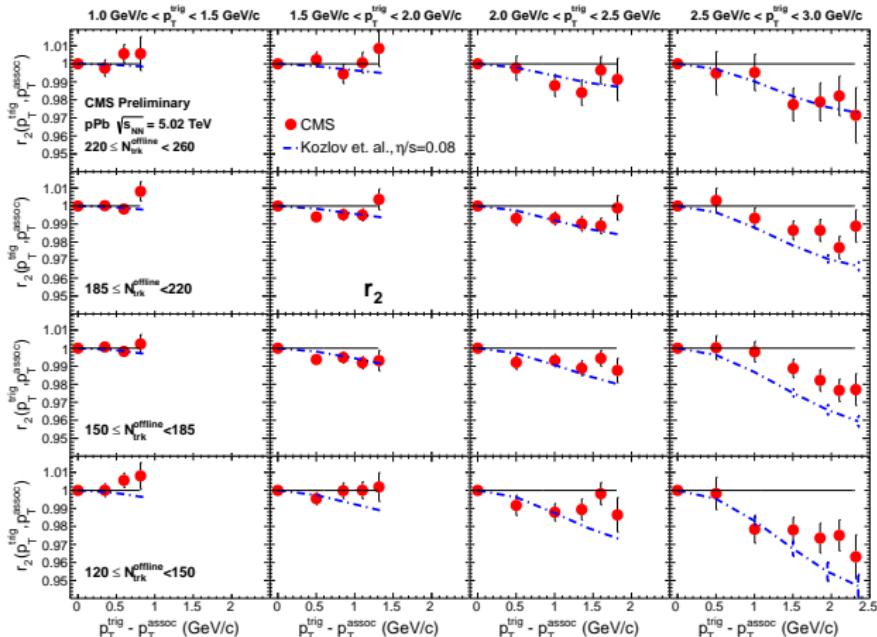
$$\begin{aligned} C(\Delta\phi, p_1, p_2) &= 1 + 2V_2(p_1, p_2)\cos(2\Delta\phi) = \\ (\text{if flow}) &\simeq 1 + 2v_2(p_1)v_2(p_2)\cos(2\Delta\phi) \end{aligned}$$

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

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

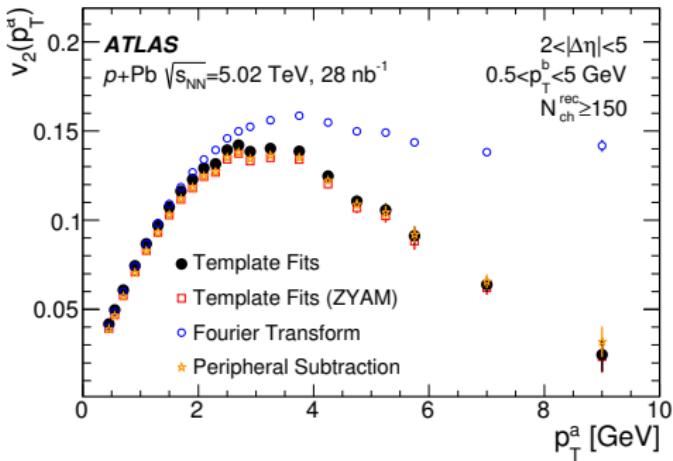
Slightly different event planes expected for particles at different  $p_\perp$   
(or rapidity Bozek et al. 1011.3354) due to fluctuations

## 4a) Factorization at intermediate $p_{\perp}$



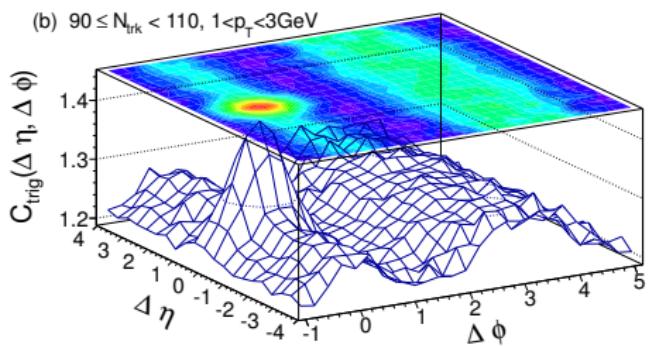
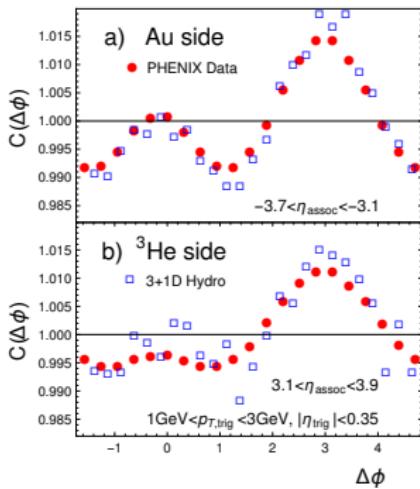
- factorization holds for  $v_2$  and  $v_3$  up to 3 GeV
- small deviations explained by hydro+Glauber Kozlov, Luzum, Denicol, Jeon, Gale, 1405.3976
- geometry driven origin of correlations at small **and** intermediate  $p_{\perp}$

## Correlations between soft and hard particles



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

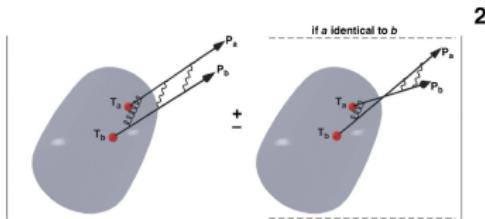
## 4c) Correlations at large $\Delta\eta$ (Ridge)



PB, Broniowski 1211.0845

- correlations between particles at different  $\eta$
- 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

# Hanbury Brown-Twiss correlations(HBT)



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

2

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

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

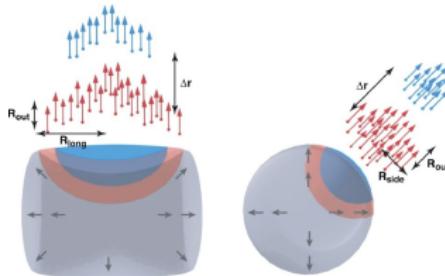
- ▶ experimentally we reconstruct

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

using *mixed event pairs* in the denominator

- ▶ 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 Coulomb interactions)

## Bertsch-Pratt parameterization



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

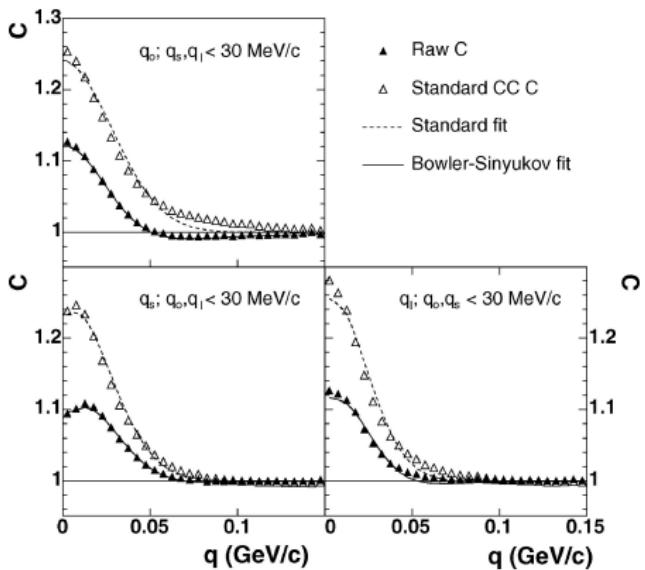
- ▶ correlations for a fixed average pair momentum  $k = (p_1 + p_2)/2$
- ▶ we go to the *local comoving system* LCMS with  $k_z = 0$  (pair momentum along the beam axis), which gives  $k = (k_\perp, 0)$
- ▶ the relative momentum vector is split into 3 component  $q_{long} = q_z$ ,  $q_{out}$  (parallel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

## HBT radii

the correlations function after subtracting final state interaction effects

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

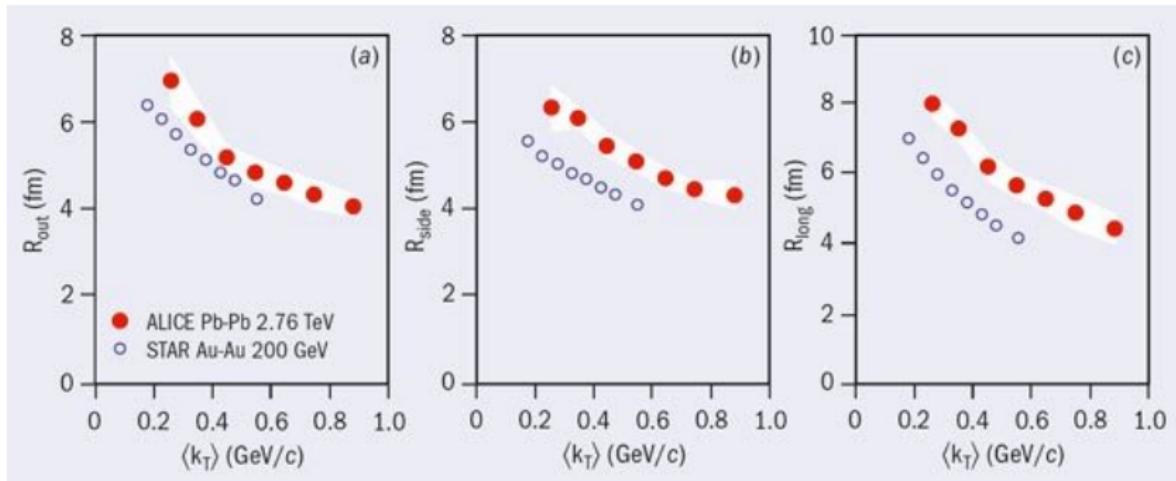
The parameters  $R$  measure the size of the emission region  
*interferometry, femtoscopy, HBT*



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

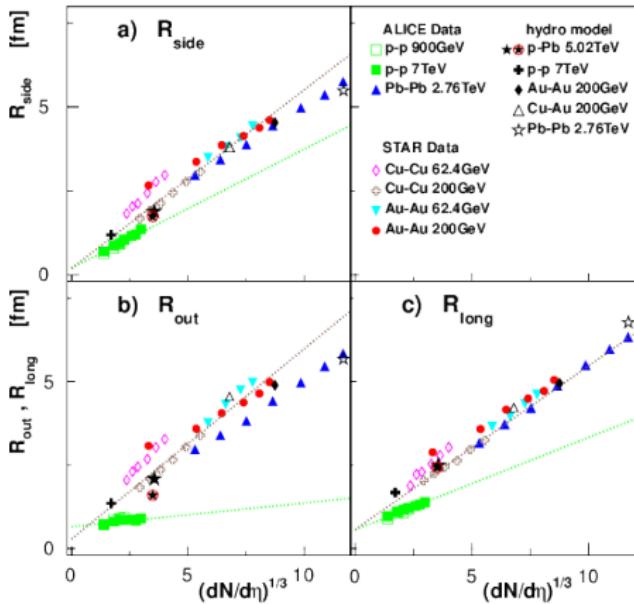
# Dependence on pair momentum

- ▶ particle pairs with similar momenta are emitted from the same fluid region (with flow velocity along along the pair momentum)
- ▶ the larger the average pair momentum the more collimated are the momenta of the two particles which means they must be emitted from a smaller region
- ▶ the emission region is called *homogeneity region* and its size the *homogeneity length*
- ▶ for a finite average pair momentum we measure the size of only a small part of the total fireball
- ▶ HBT radii get smaller with increasing  $k_{\perp}$

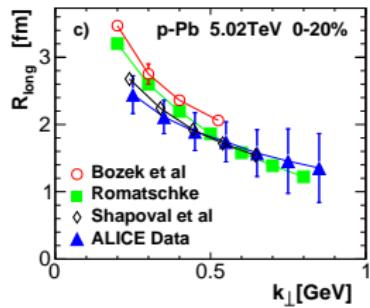
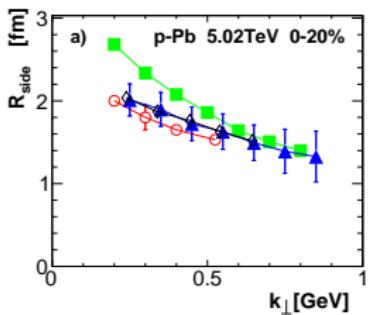
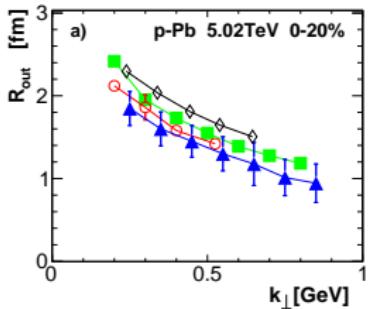


# Dependence of multiplicity and size

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

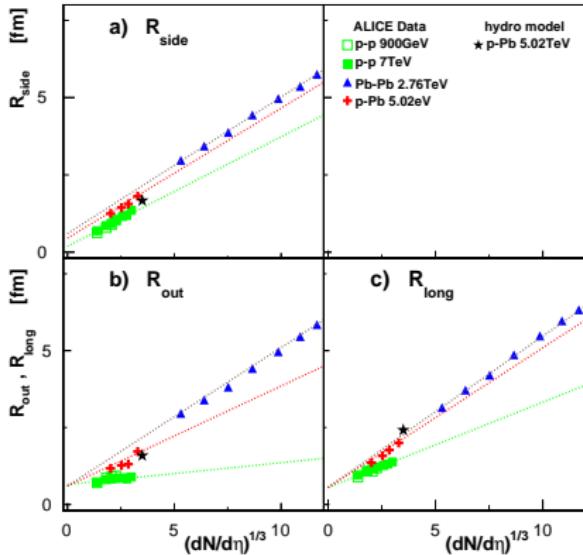


## 5) Interferometry radii



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

# Interferometry radii - pp, pA, AA

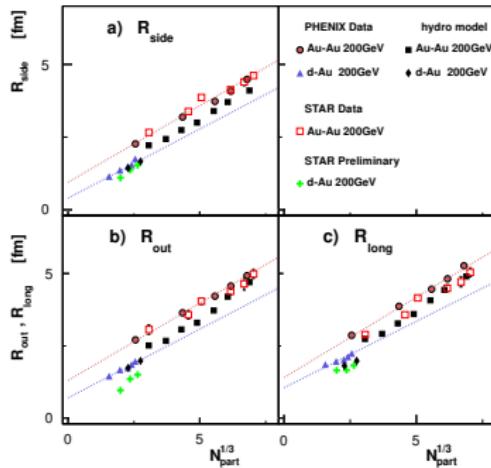


- pA system size in between pp and AA  
(differences in flow strength, initial size, flow profile)

- HBT in pA consistent with hydrodynamics

# Interferometry radii (d-Au, He-Au)

d-Au (PHENIX data)

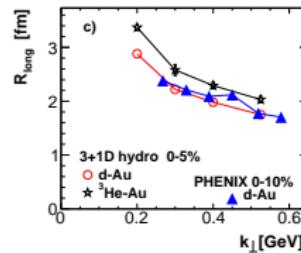
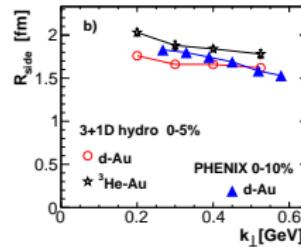
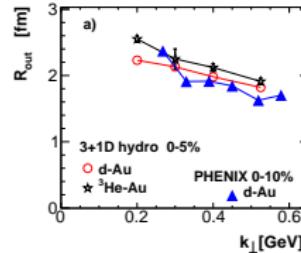


$k_{\perp}$  dependence of  $R_{o,l,s}$

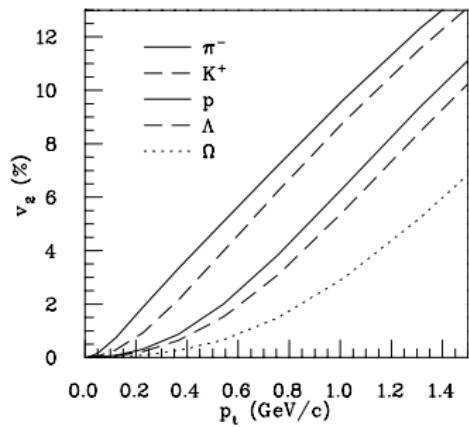
$R_{\text{side}}$  consistent with hydro

PB, 1408.1264

Romatschke 1502.04745

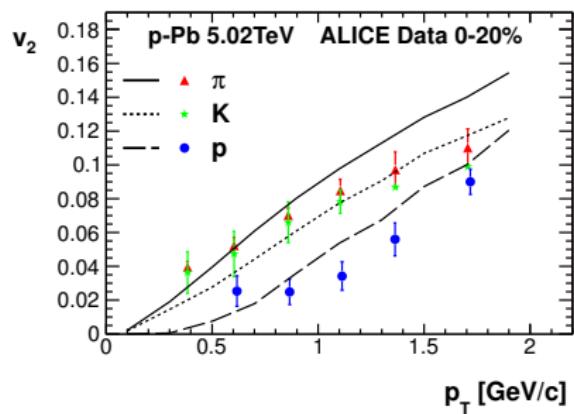


## Mass splitting of $\nu_2$



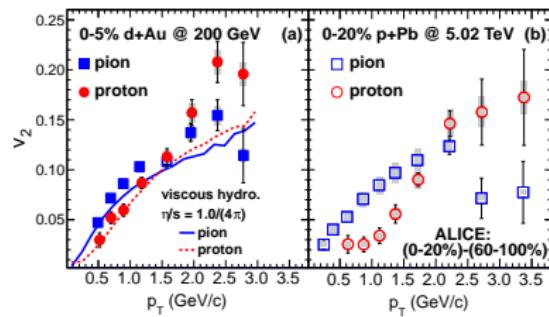
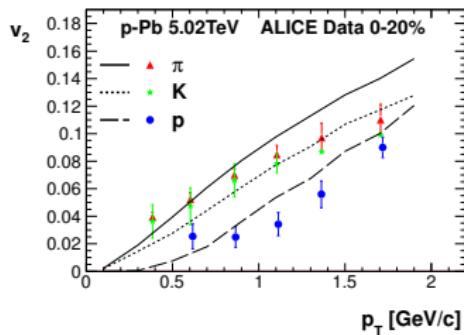
mass splitting of  $\nu_2$  in hydro models

Huovinen et al. 2001



Observed in  $p\text{-Pb}$

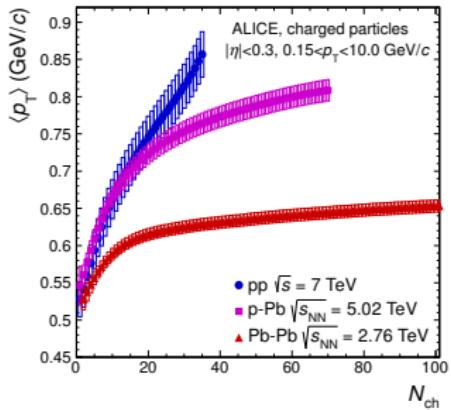
## 6) Mass splitting of $v_2$



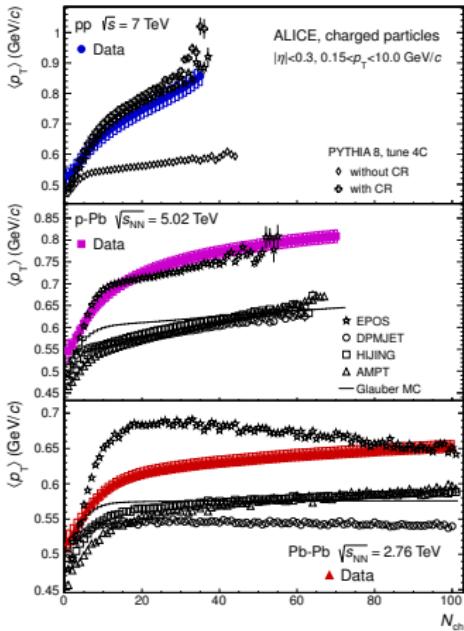
PB, Broniowski, Torrieri, 1307.5060

-mass splitting of  $v_2$  as expected from hydrodynamics

## 7a) Large $\langle p_{\perp} \rangle$

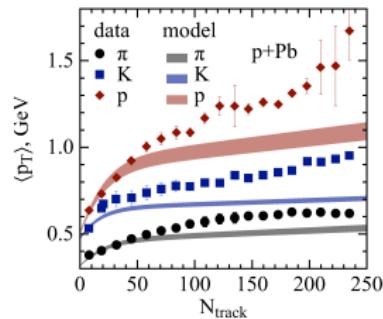
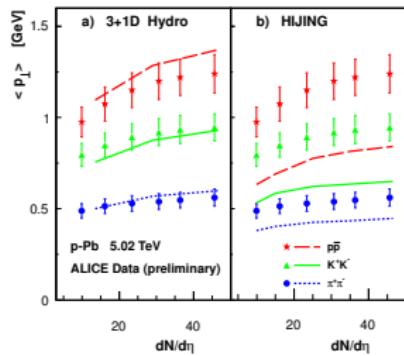


larger  $\langle p_{\perp} \rangle$  in smaller systems



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



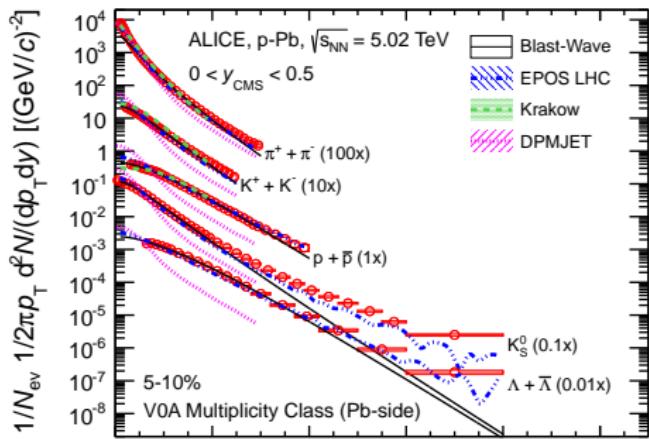
PB, W.Broniowski, G. Torrieri arXiv:1306.5442

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

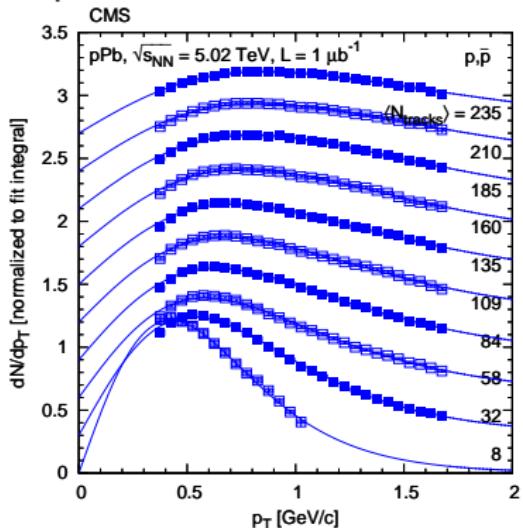
Bzdak, Skokov, arXiv:1306.5442

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  $\eta$ , correlated to geometry
6. Mass splitting of  $v_2$
7. Mass hierarchy of spectra ( $\langle p_{\perp} \rangle$ )

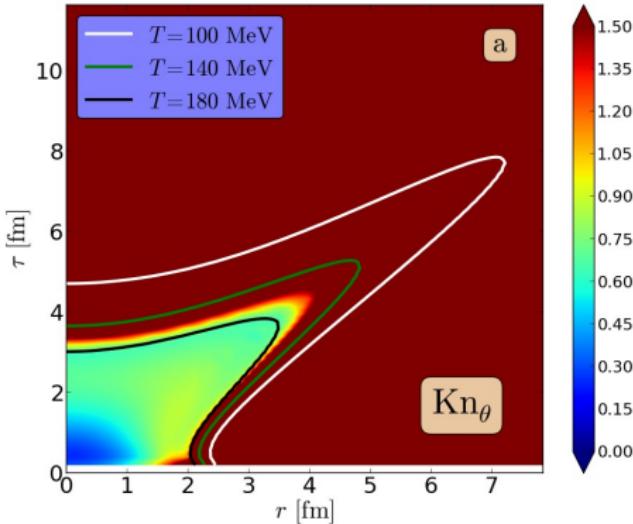
these effects can be described by hydrodynamics

**what does it mean?**

**can hydrodynamics be applied to small systems?**

# Hydrodynamics in small systems?

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

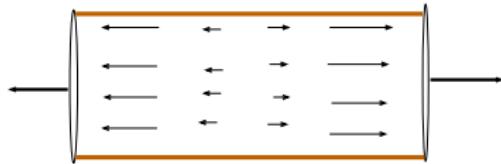


H. Niemi, G. Denicol 1404.7327

large gradients in the evolution  
higher order corrections,

effective viscosity reduced

## early times - longitudinal expansion - pressure asymmetry

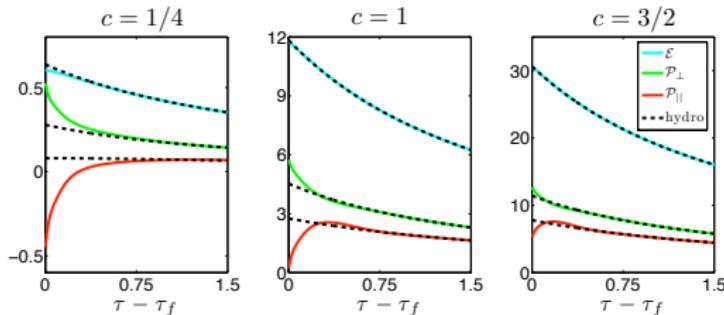


$$T^{\mu\nu} = \begin{pmatrix} \epsilon + p & 0 & 0 & 0 \\ 0 & p + \frac{2\eta}{3\tau} & 0 & 0 \\ 0 & 0 & p + \frac{2\eta}{3\tau} & 0 \\ 0 & 0 & 0 & p - \frac{4\eta}{3\tau} \end{pmatrix}$$

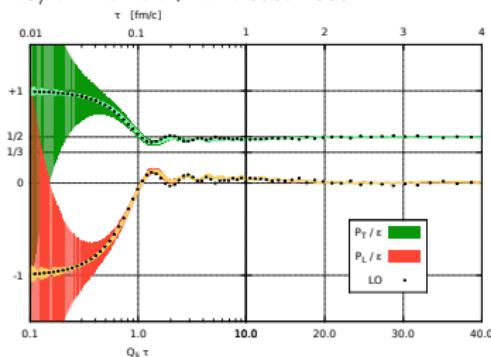
deviations from local equilibrium in early times  
asymmetry between longitudinal and transverse pressure  
intensively studied in kinetic theory and *asymmetric* hydrodynamics

Florkowski, Martinez, Ryblewski, Strickland, ...

# Pressure asymmetry - generic feature



AdS/CFT Chesler, Yaffe 0907.4503

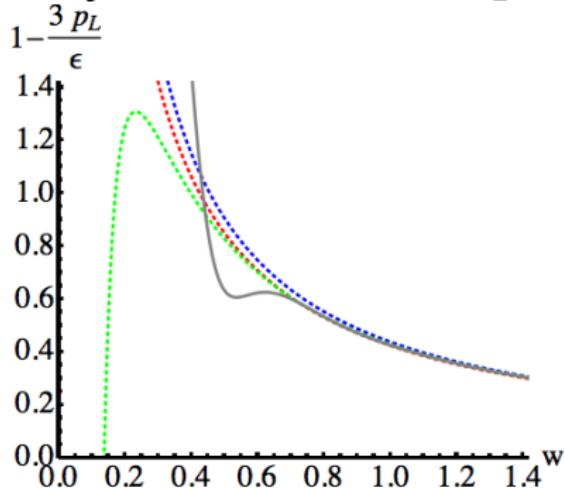


weak coupling Epelbaum, Gelis 1307.2214

# Why hydrodynamic works I

Hydrodynamics works even for large pressure asymmetry

Hydrodynamics works with  $P_L \ll P_\perp$

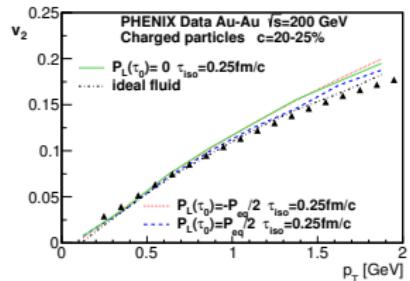
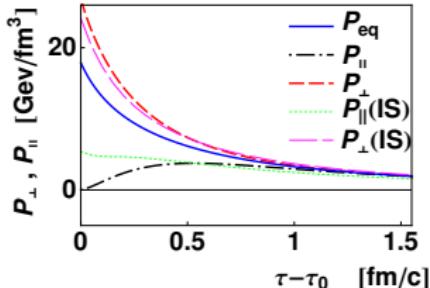


Heller, Janik, Witaszczyk 1103.3452

full solution converges to hydro

# Why hydrodynamic works II

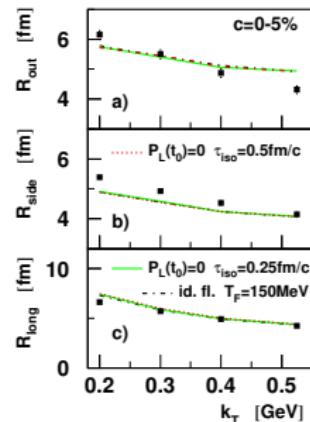
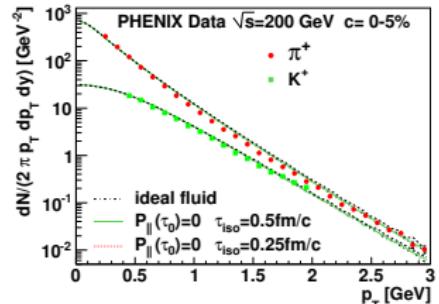
## pressure anisotropy irrelevant for flow



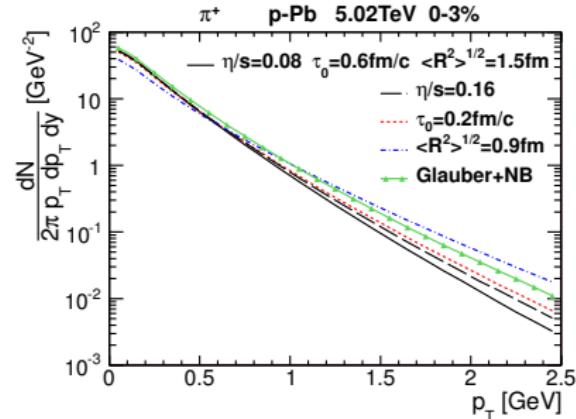
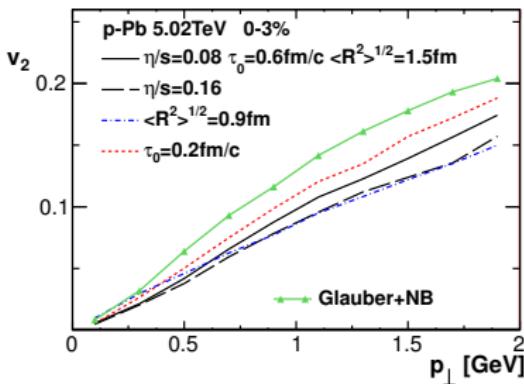
PB, I. Wyskiel - arXiv:1009.0701

- early pressure anisotropy irrelevant!

Vredevoogd, Pratt, 0810.4325



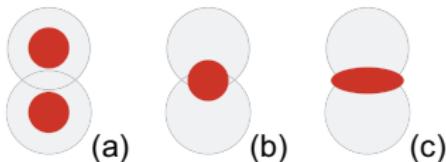
## dependence on model details



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

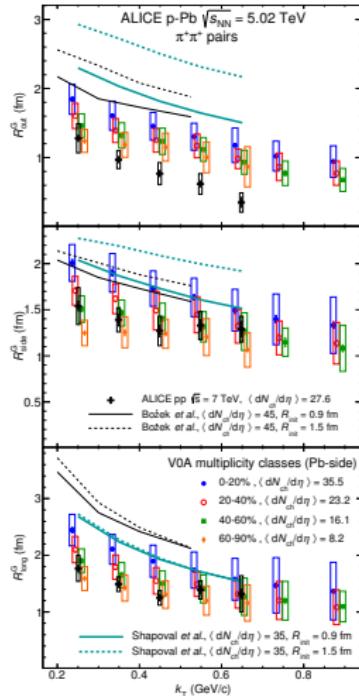
- ▶ initial eccentricity
- ▶ initial size 'compact' vs 'standard'
- ▶ viscosity
- ▶ initial time for expansion

# compact source



Bzdak et al. 1304.3403

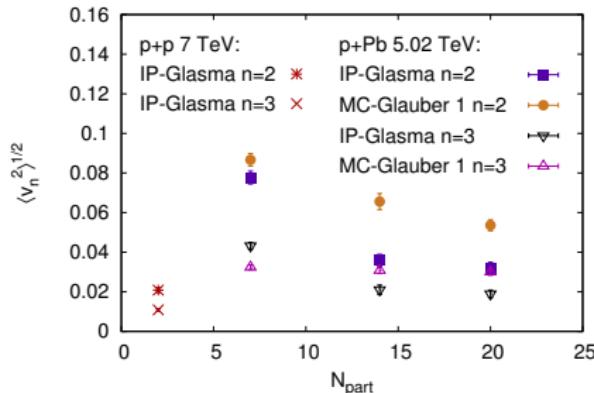
compact source 0.9fm  
standard source 1.5fm



HBT → initial size of the fireball in pA small

# Hydrodynamic flow in p-p?

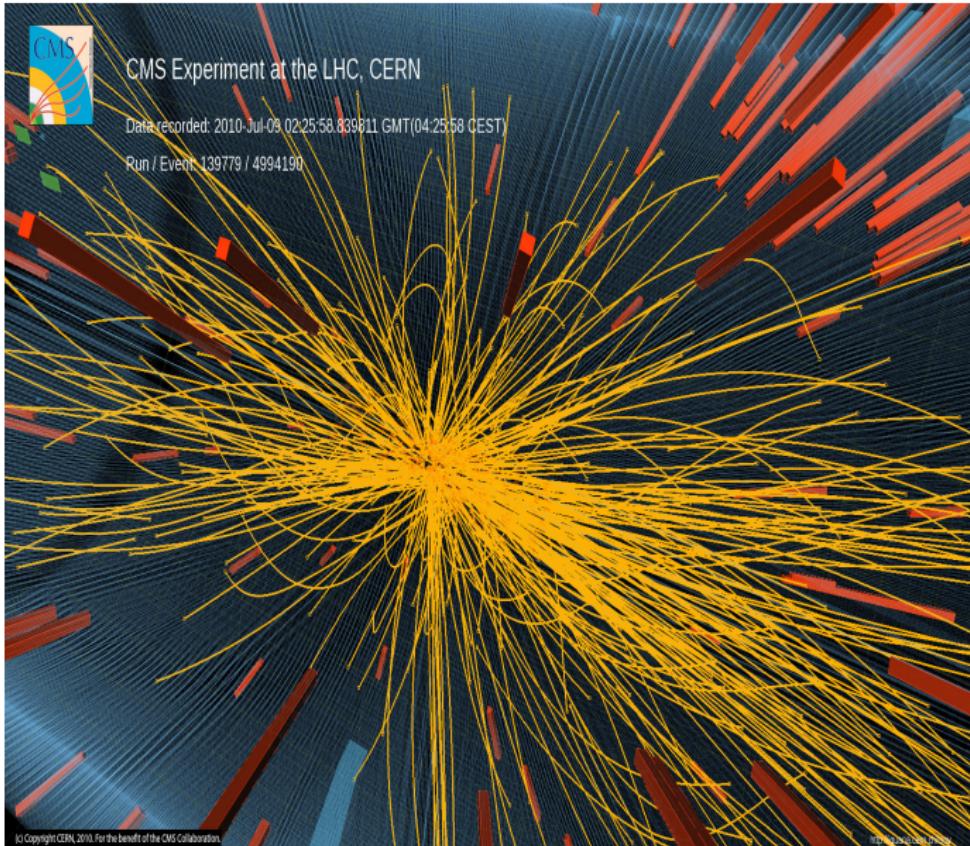
- ▶ Humanic-nucl-th/0612098 (pythia, cascade)
- ▶ Romatschke, Luzum-arXiv:0901.4588 (overlap)
- ▶ Prasad, Roy, Chattopadhyay, Chaudhuri -arXiv: 0910.4844 (overlap)
- ▶ Bozek-arXiv: 0911.2393 (flux-tubes)
- ▶ Yan, Dong, Zhou, Li, Ma, Sa- arXiv: 0912.3342 (transport)
- ▶ **CMS ridge in pp** arxiv: 10094122
- ▶ 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?

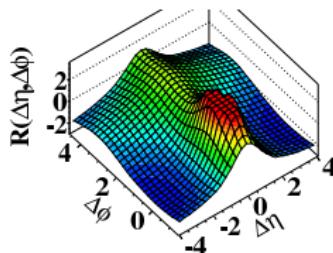
# High multiplicity events in pp



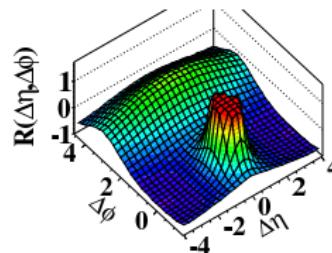
# Ridge in p-p

first observation or “flow-like” correlations in small systems

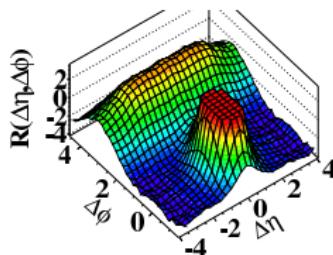
(a) CMS MinBias,  $p_T > 0.1 \text{ GeV}/c$



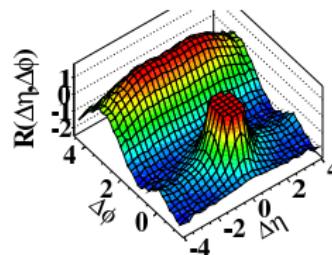
(b) CMS MinBias,  $1.0 \text{ GeV}/c < p_T < 3.0 \text{ GeV}/c$



(c) CMS  $N \geq 110$ ,  $p_T > 0.1 \text{ GeV}/c$

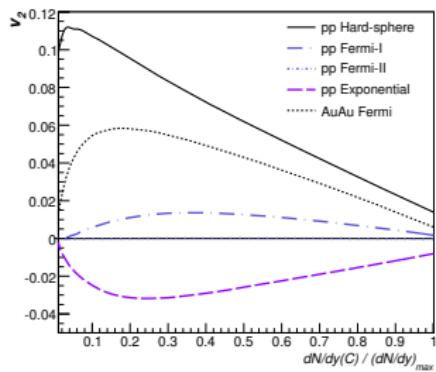


(d) CMS  $N \geq 110$ ,  $1.0 \text{ GeV}/c < p_T < 3.0 \text{ GeV}/c$

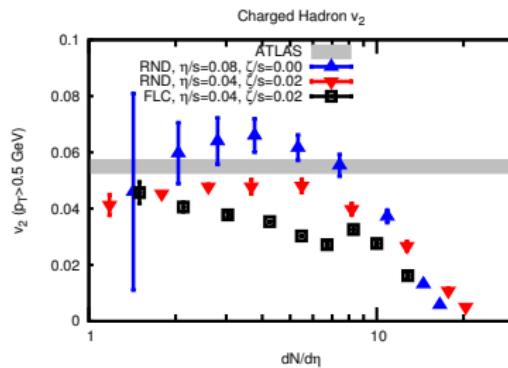


can we measure (or calculate)  $v_2$  in p-p

## pp collisions $V_n$ in optical Glauber + hydro(response)



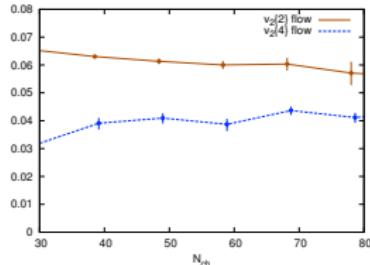
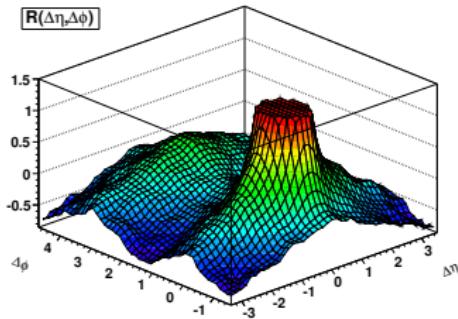
D'Enterria et al, 0910.3029



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)(...)



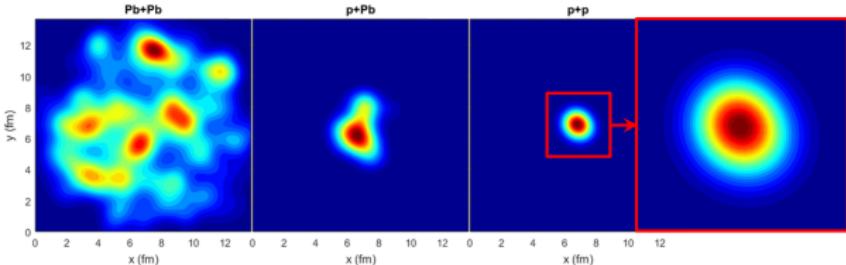
Avsar, Flensburg, Hatta, Ollitrault, Ueda, 1009.5643

Werner, Karpenko, Pierog, 1011.0375

- ▶ 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**

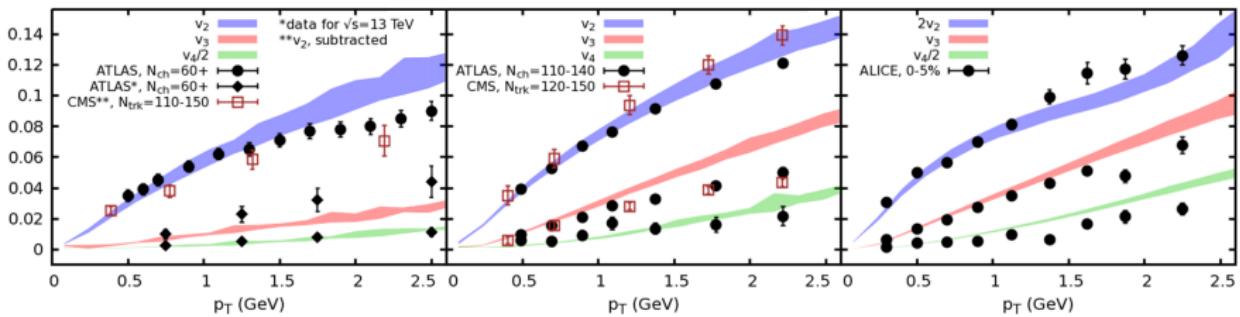
# "Same" hydrodynamics in p-p p-Pb Pb-Pb



superSONIC for p+p,  $\sqrt{s}=5.02$  TeV, 0-1%

superSONIC for p+Pb,  $\sqrt{s}=5.02$  TeV, 0-5%

superSONIC for Pb+Pb,  $\sqrt{s}=5.02$  TeV, 0-5%

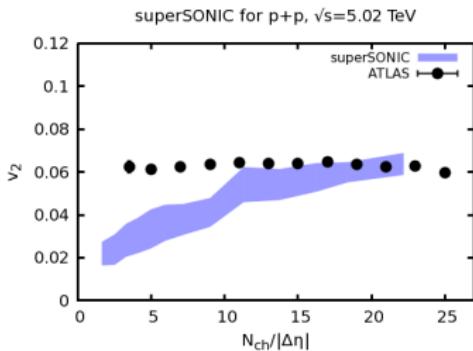


Weller, Romatschke, 1701.07145

same fluid from p-p to Pb-Pb

# Problems with hydrodynamics in p-p

## Multiplicity dependence

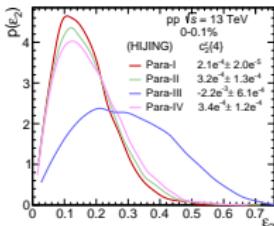


Weller, Romatschke, 1701.07145

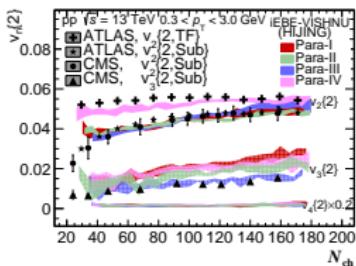
**Contribution from initial state correlations?**

# Problems with hydrodynamics in p-p

## wrong sign of $c_2\{4\}$



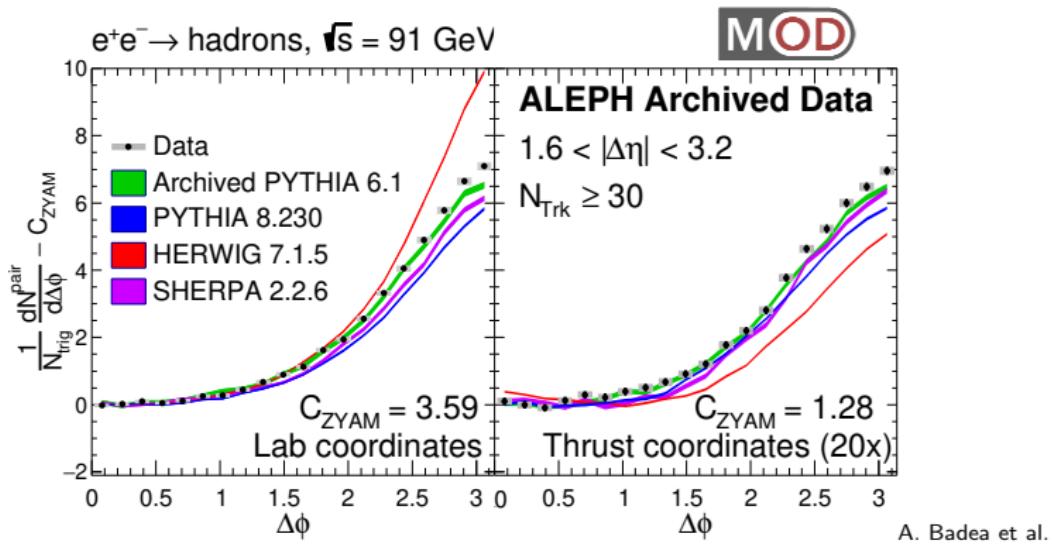
correct  $v_2\{2\}$



W. Zhao et al. 1801.00271

No hydrodynamic calculation with correct  $v_2\{4\}$   
 nonlinear hydrodynamic response  
 can we find the correct initial conditions for p-p?

## No sign of collectivity in $e^+ - e^-$



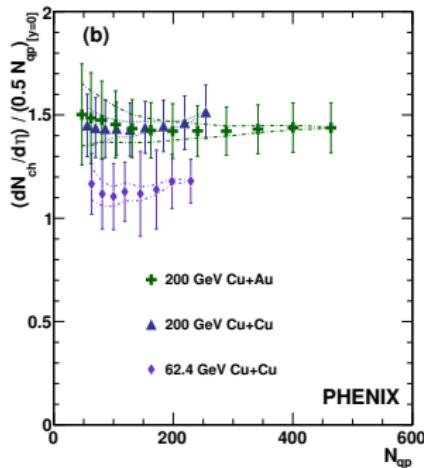
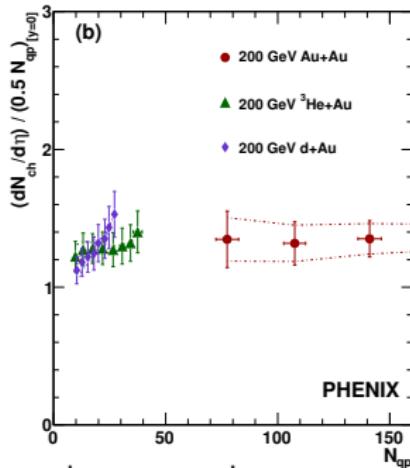
1906.00489

Observed angular correlations consistent with models without flow

- ▶ **Collective flow observed in p-A,d-A,He-A**
  - ▶ soft particles well described by hydrodynamics
  - ▶ some tension for high  $p_T$  and heavy flavor
- ▶ Dominance of final state interactions vs initial state correlation unclear in p-p
- ▶ No sign of collectivity in  $e^+ - e^-$  experiments

# Constituent quark model - PHENIX

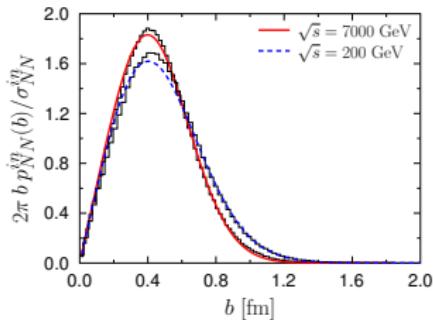
PHENIX 2015



- 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

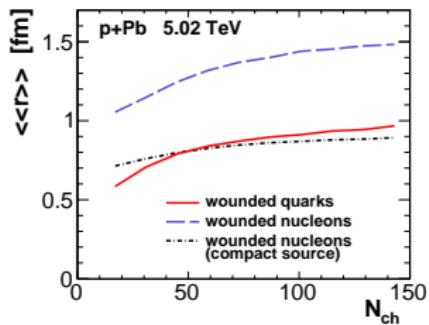
- three quarks distributed in each nucleon  $\rho(r) \simeq e^{-r/b}$
- recentering
- Gaussian Q-Q wounding profile
- parameters fitted to reproduce N-N scattering



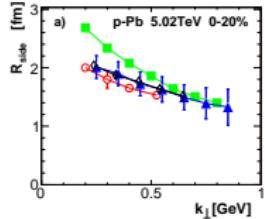
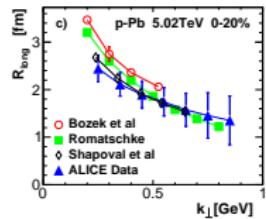
(200GeV,  $\sigma_{QQ} = 7\text{mb}$ ,  $r_{QQ} = 0.29\text{fm}$ )    (7000GeV,  $\sigma_{QQ} = 14.3\text{mb}$ ,  $r_{QQ} = 0.30\text{fm}$ )

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

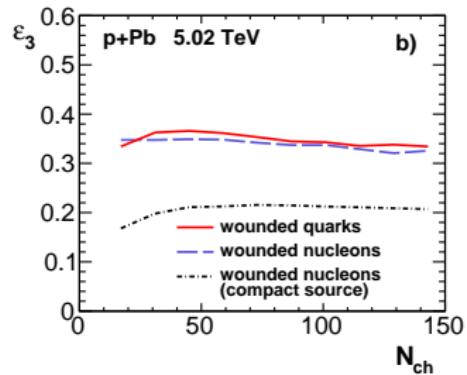
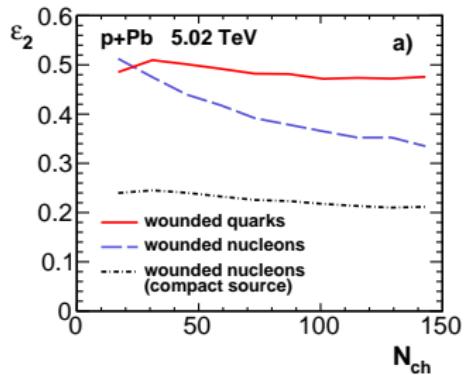
# Fireball size in p-Pb



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

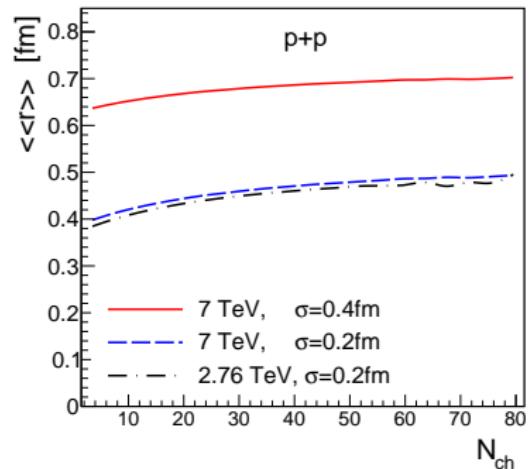
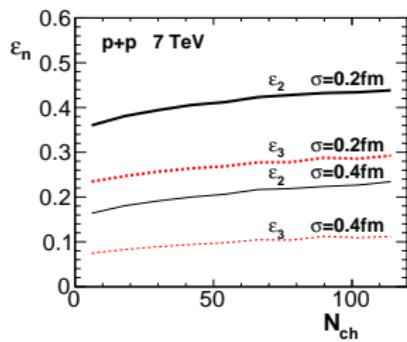


## Fireball eccentricities in p-Pb



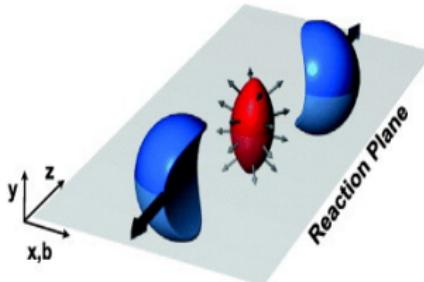
- significant eccentricities in p-Pb
- consistent experimental observation of  $v_2$  and  $v_3$  in p-Pb

## 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

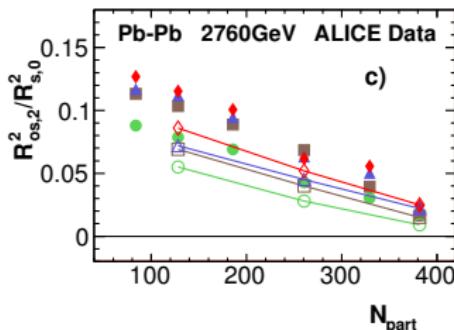
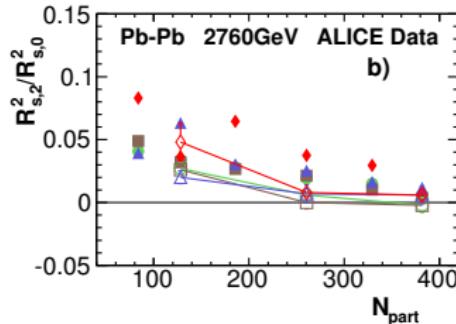
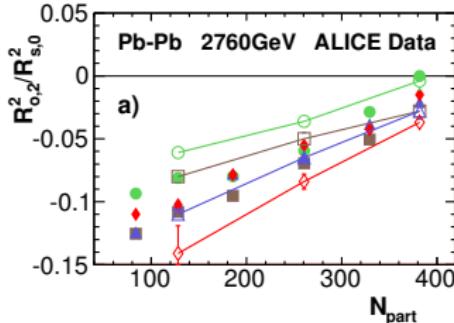
$$C(k_{\perp}, \phi, q) = 1 + \lambda e^{-R_o^2 q_o^2 - R_s^2 q_s^2 - R_i^2 q_i^2 - R_{os}^2 q_o q_s}$$

- dependence on  $\phi$

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

- new radius parameter  $R_{os}$

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



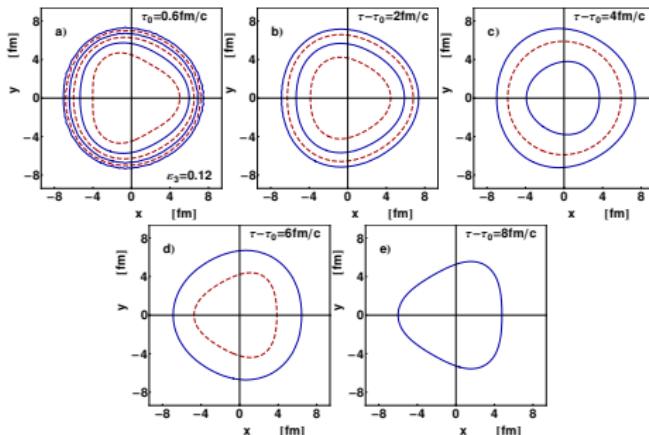
- ▶ eccentricity and elliptic flow give azimuthal angle dependence
- ▶ fair agreement with data

- Further confirmation of elliptic flow and deformation

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

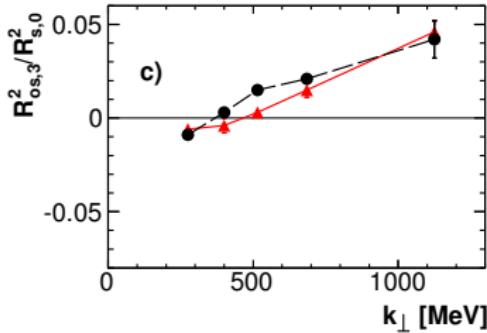
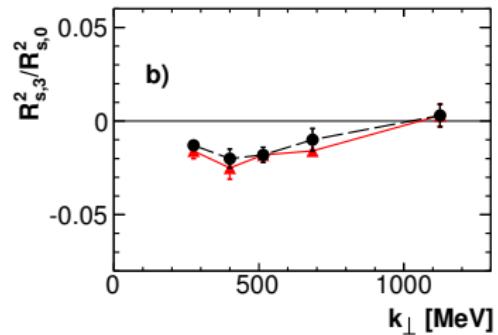
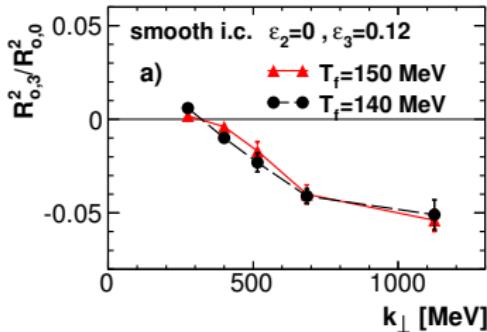
what is the origin of the  $\cos(3\Phi)$  angular dependence (Plumberg, Shen, Heinz, 2013)

- ▶ deformed geometry + radial flow
- ▶ triangular flow



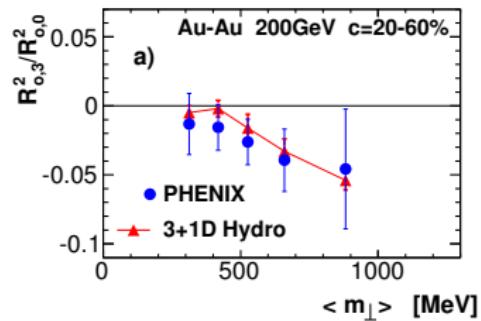
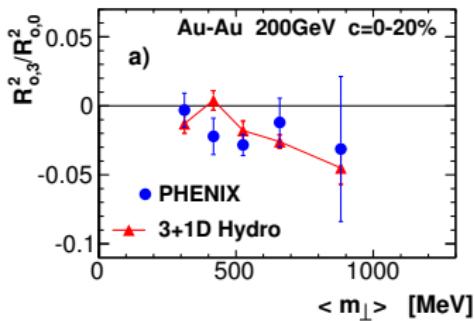
- ▶ OR both flow and geometry
- ▶ OR both flow and inverted geometry (example)

# HBT third order reaction plane, smooth density (example)



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

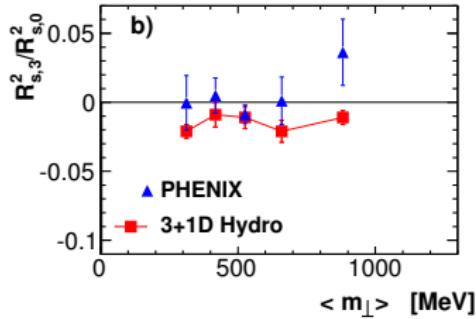
## HBT third order reaction plane $R_{O,3}^2$



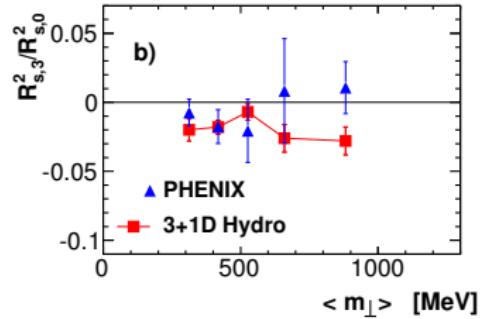
fair agreement with PHENIX

## HBT third order reaction plane $R_{s,3}^2$

0-20%

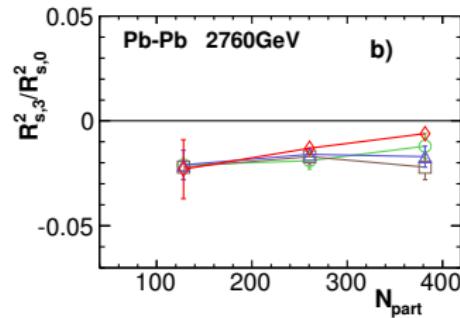
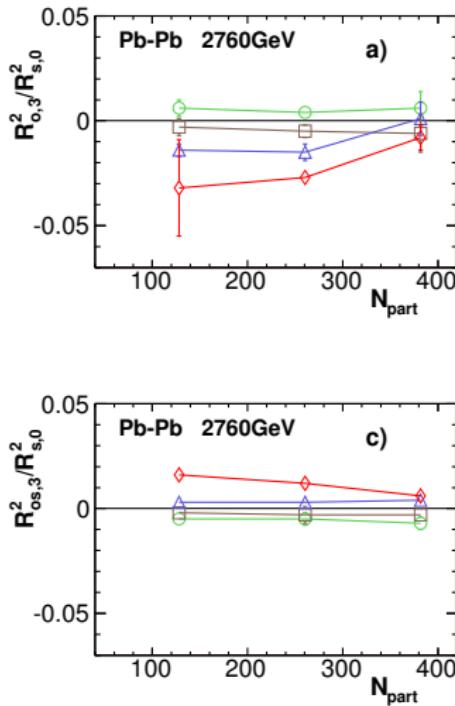


20-60%



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

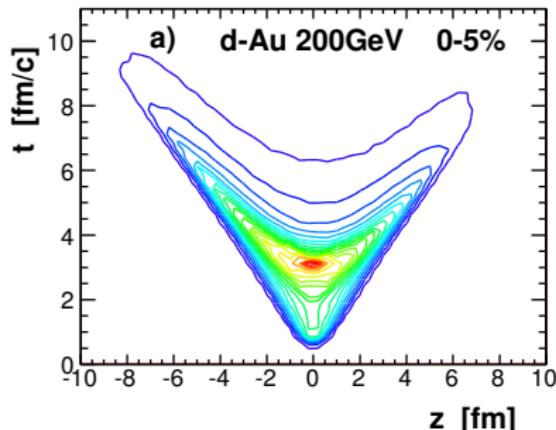
# azHBT in Pb-Pb at 2.76TeV (third order reaction plane)



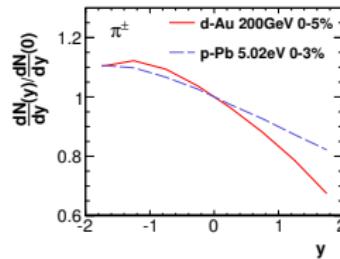
- ▶ similar as Au-Au at RHIC
- ▶ small negative  $R_{s,3}^2$
- ▶ negative,  $k_\perp$  depend.  $R_{o,3}^2$

# Asymmetric collisions p-Pb, d-Au

different emission times in forward-backward hemispheres

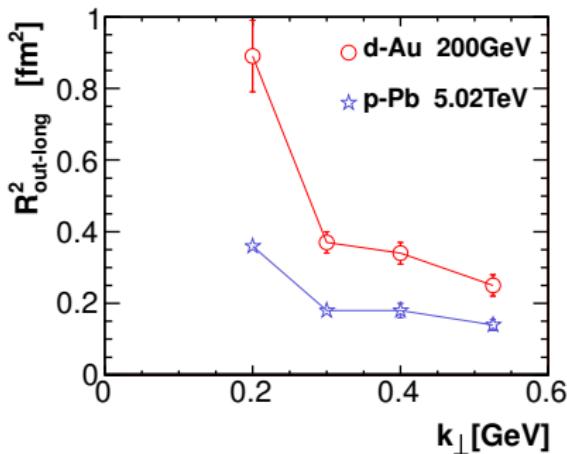


FB asymmetry



lcms of the pion

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

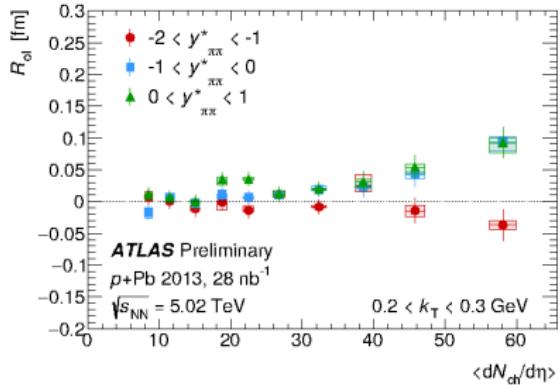
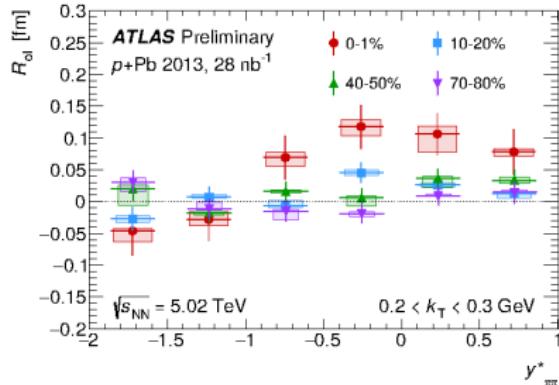


$$C(q, k_\perp) = 1 + \lambda e^{-R_o^2 q_o^2 - R_s^2 q_s^2 - R_l^2 q_l^2 - 2R_{ol}^2 q_o q_l}$$

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

$$\langle zx \cos(\Phi) \rangle, \langle zy \sin(\Phi) \rangle, \langle zt \rangle$$

## $R_{\text{ol}}$ cross term

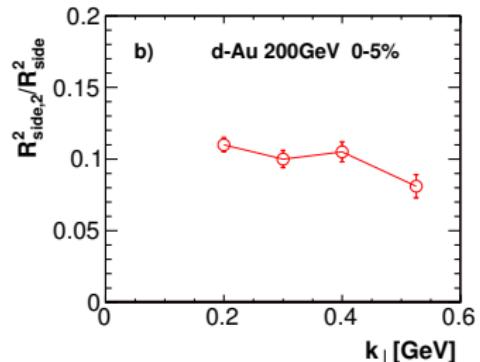
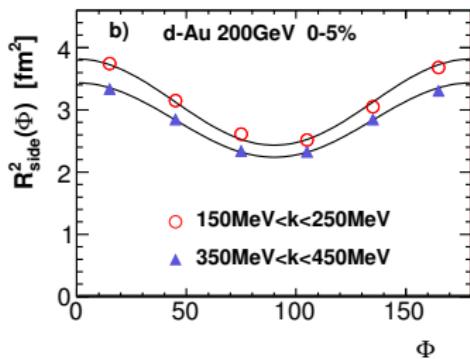


In *central events* on the *forward* side, there is strong evidence of a positive  $R_{\text{ol}}$  ( $4.8\sigma$  combined significance in 0–1% centrality)

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

## azimuthally sensitive HBT in d-Au

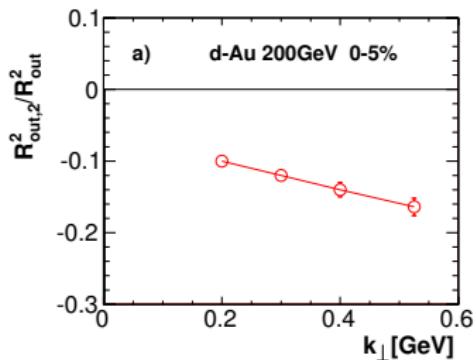
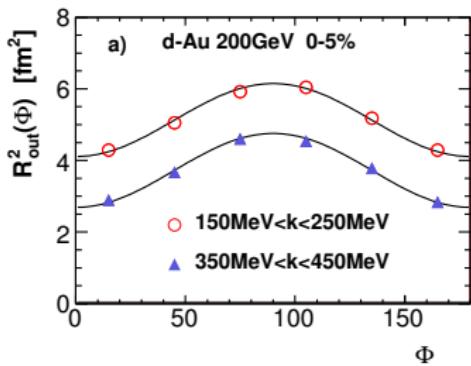
$$R_s^2(\Phi) = R_{s,0}^2 + 2R_{s,2}^2 \cos(2\Phi)$$



$R_{side}$  larger in-plane

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

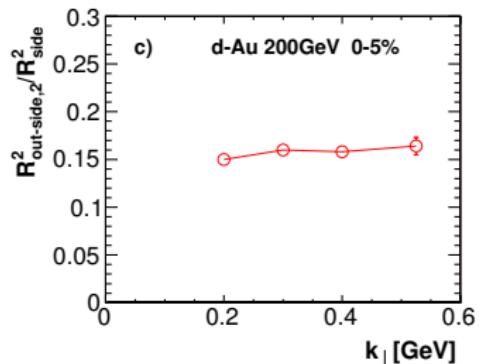
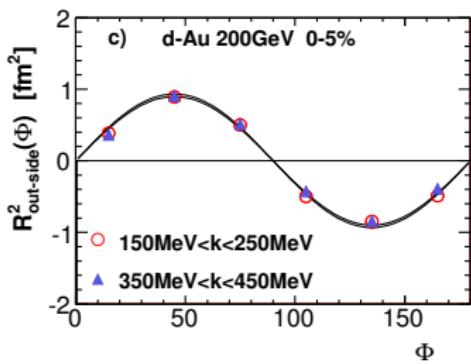
$$R_o^2(\Phi) = R_{o,0}^2 + 2R_{o,2}^2 \cos(2\Phi)$$



$R_{out}$  smaller in-plane

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

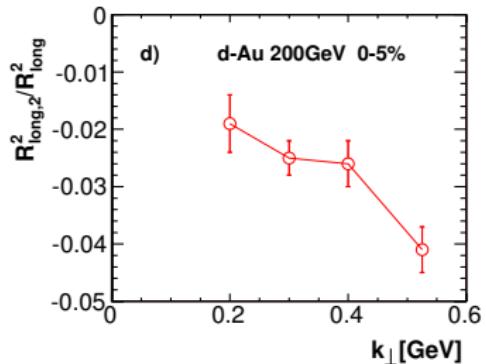
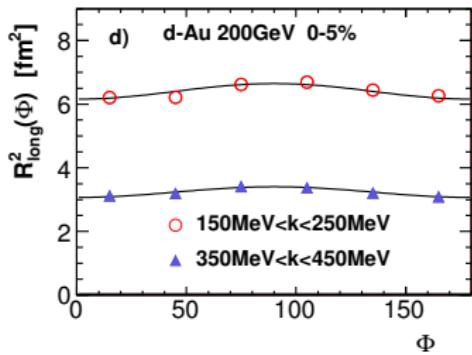
$$R_{os}^2(\Phi) = 2R_{os,2}^2 \sin(2\Phi)$$



$$R_{out-side} \neq 0$$

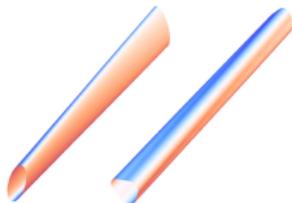
## azimuthally sensitive HBT in d-Au - $R_{long}$

$$R_I^2(\Phi) = R_{I,0}^2 + 2R_{I,2}^2 \cos(2\Phi)$$

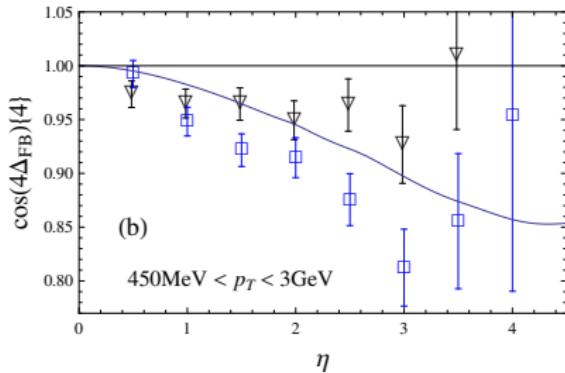


$$R_{long,2} \neq 0$$

event by event twist of the reaction plane



Fluctuating RP twist  
can be measured



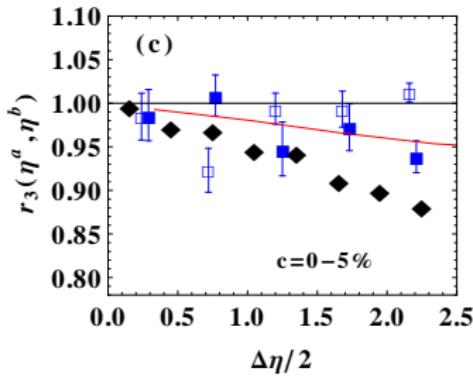
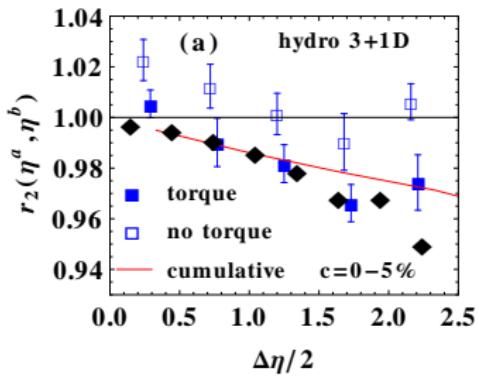
PB, Broniowski, Moreira, Phys. Rev. C83, 034911 (2011)

$$\begin{aligned}\cos(2k\Delta_{FB})\{4\} &\equiv \frac{\langle e^{ik[(\phi_{F,1}+\phi_{F,2})-(\phi_{B,1}+\phi_{B,2})]} \rangle}{\langle e^{ik[(\phi_{F,1}-\phi_{F,2})-(\phi_{B,1}-\phi_{B,2})]} \rangle} = \\ &\langle \cos(2k\Delta_{FB}) \rangle_{\text{events}} + \text{nonflow}\end{aligned}$$

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

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

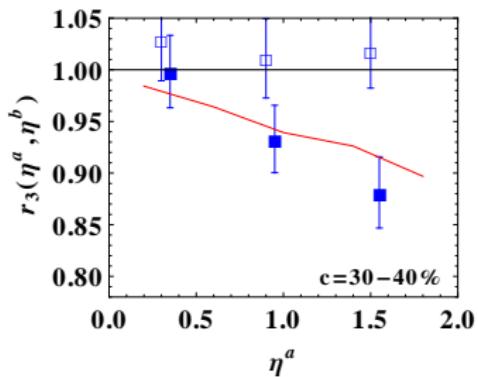
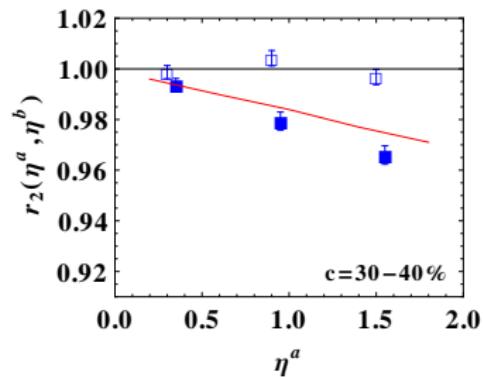
only pairs with large rapidity gap  $\eta_a - \eta_b$



- nonflow under control
- torque effect seen in the CMS data
- semiquantitative agreement, but need more fluctuations
- other calculation (hybrid hydro, AMPT) reproduce the data

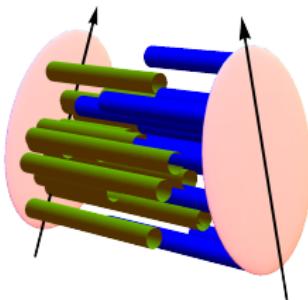
# $r_n(\eta_a, \eta_b)$ Au-Au at 200GeV

predictions ( $3 < \eta_b < 4.5$ )



- larger twist angle at RHIC energies

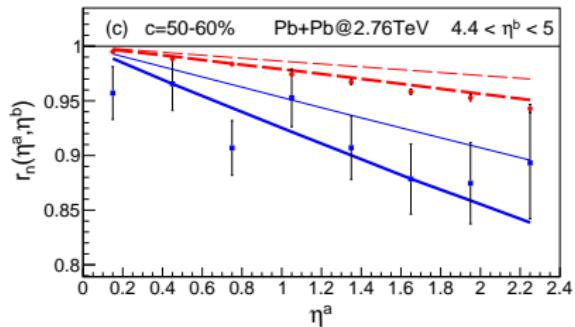
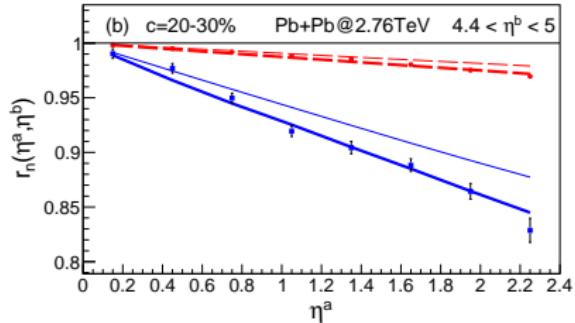
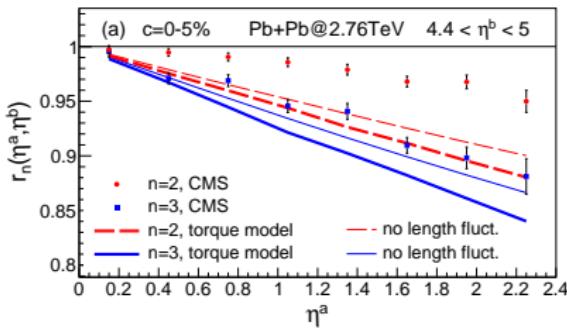
## Fluctuations in energy deposition from each source



- the position (in rapidity) of string ends is random
- long range fluctuations
- each source fluctuates differently → 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  $\eta$ )

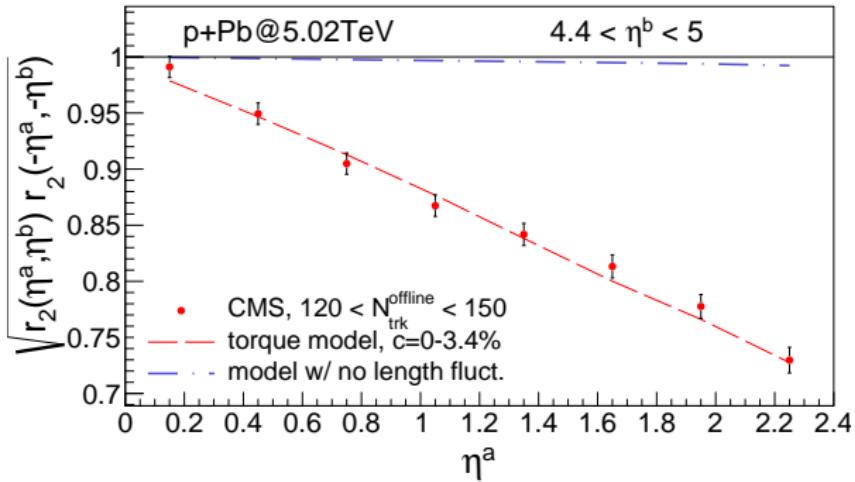
PB, Broniowski 1503.03655; Monnai, Schenke 1509.04362

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



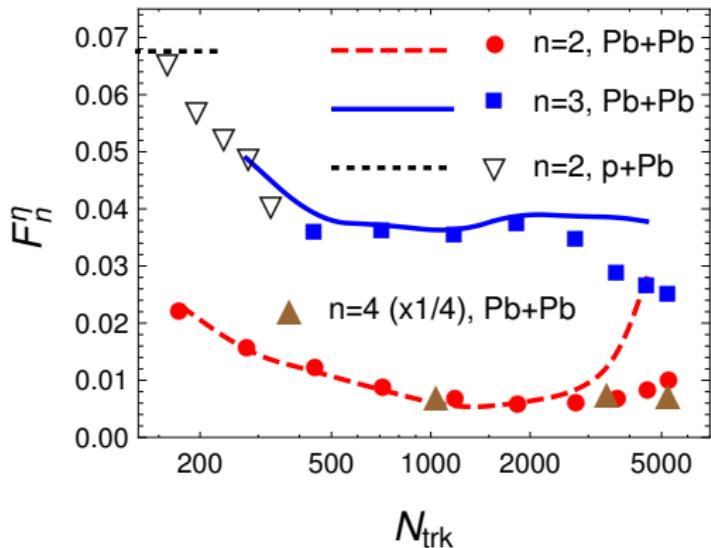
fluctuations improve description of  $r_2$   
in Pb-Pb  
except for  $r_2$  in central collisions

# 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  $\eta/s = 0.08$

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

## 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  $R > 0.5 fm$

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

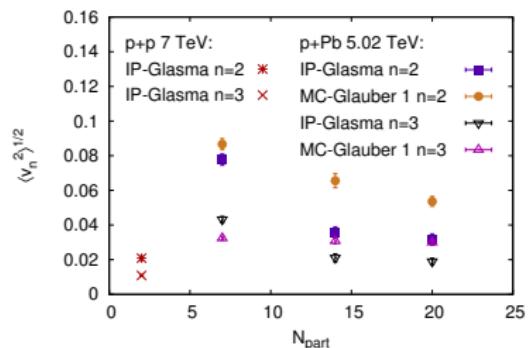
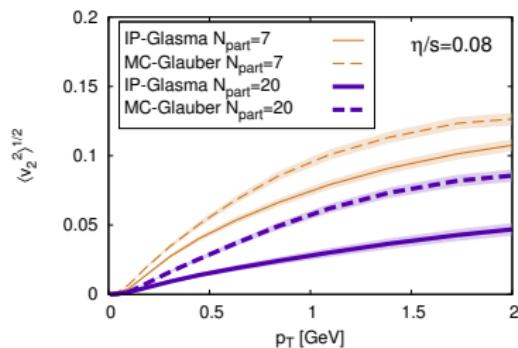
Success of hydrodynamics not accidental!

# 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 → many further studies possible: HBT, mapping of production mechanism via correlations, jets, check for chiral magnetic effect, ...

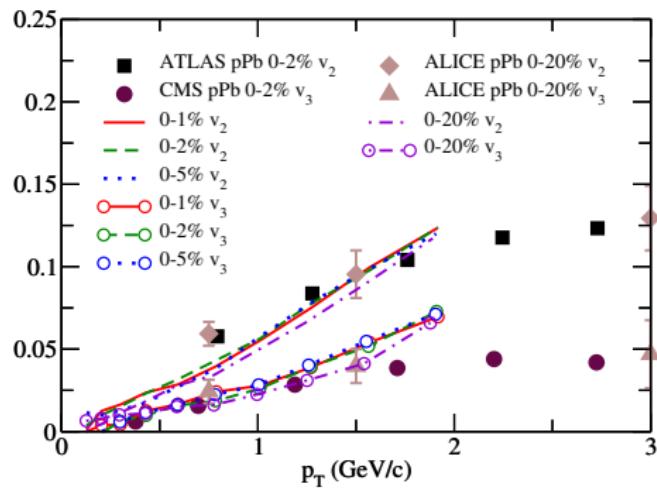
# 3+1D visc. hydro



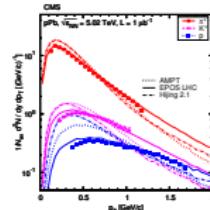
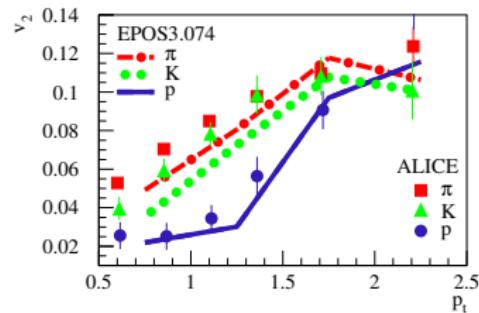
dependence on initial model,  $v_n$  small for IP-Glasma i.c.

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

# 3+1D hydro



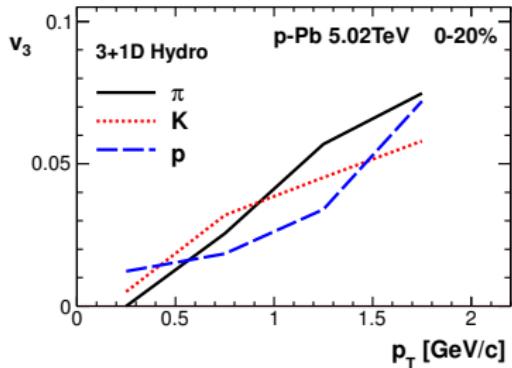
G-Y.Qin, B. Müller arXiv: 1306.3439



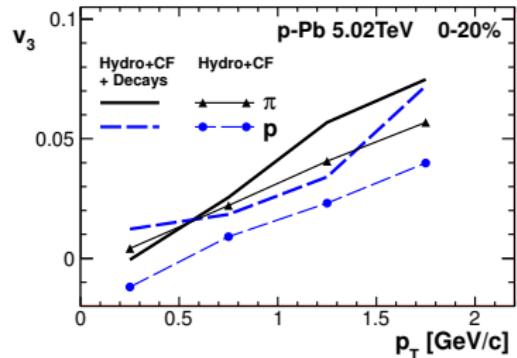
excellent description of spectra

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

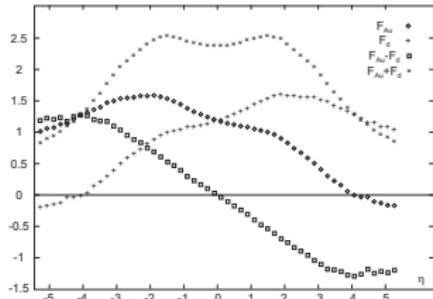
## $v_3$ - small mass splitting



limited mass splitting

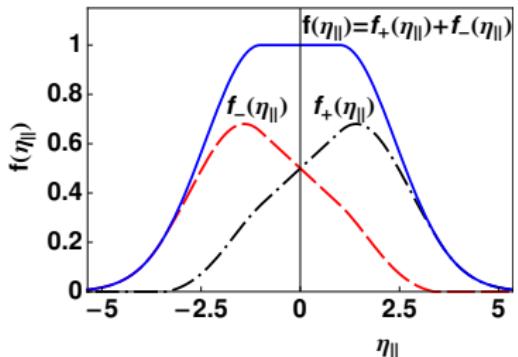


resonance decays spoil mass ordering

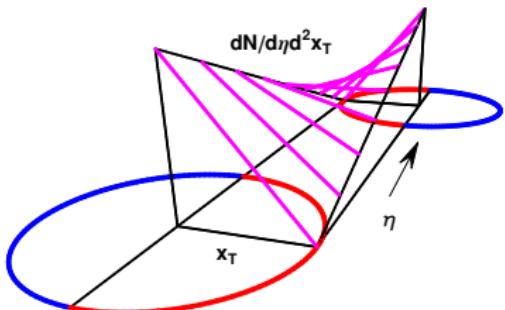


## Asymmetric emission

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

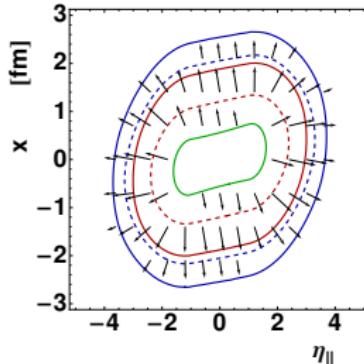
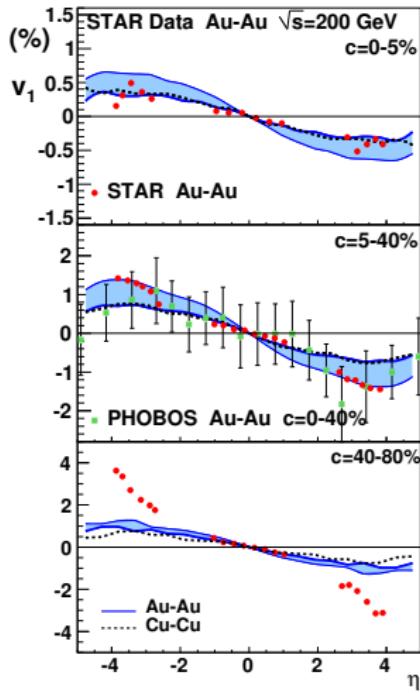


$$\begin{aligned}\rho(\eta, x, y) \propto & f_+(\eta) N_+(x, y) \\ & + f_-(\eta) N_-(x, y)\end{aligned}$$



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

# Directed flow- tilted source



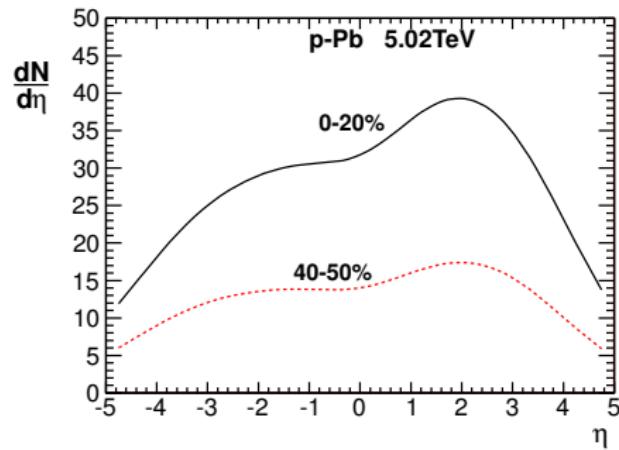
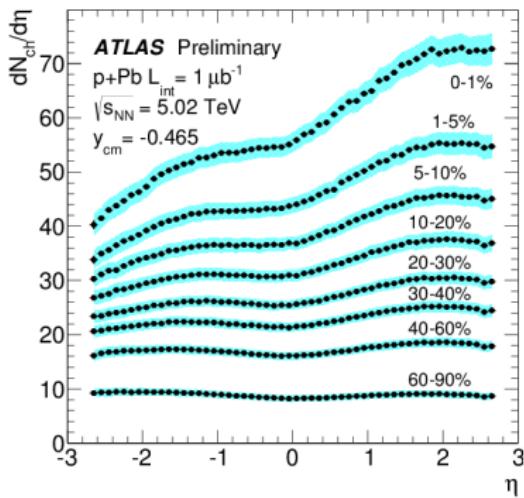
Bozek, Wyskiel, Phys. Rev. C81, 054902 (2010)

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

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

tilted source  $\rightarrow$  transverse pressure + longitudinal pressure  
Glauber model

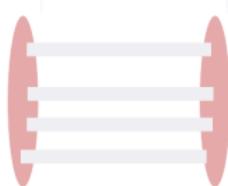
## Asymmetric distributions



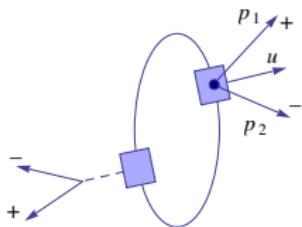
# FSI scenarios

## fields+thermalization

color fields

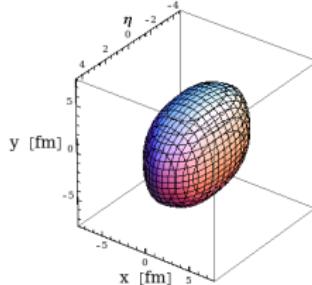


local thermalization  $\rightarrow$  hadronization

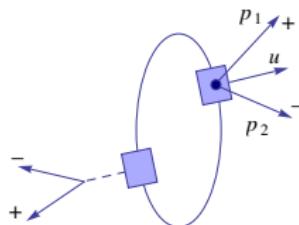


## hydrodynamics

hydrodynamic expansion

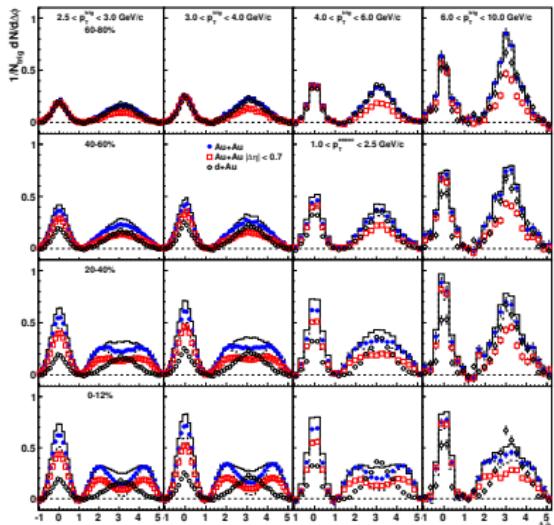


hadronization, statistical emission

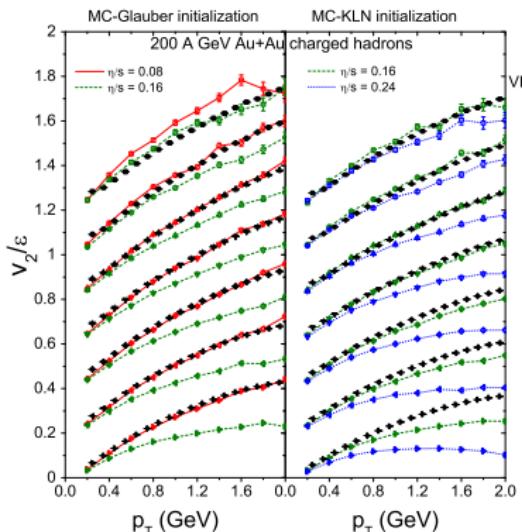


Give similar flow

# Can we reduce uncertainties? go back to very peripheral A-A



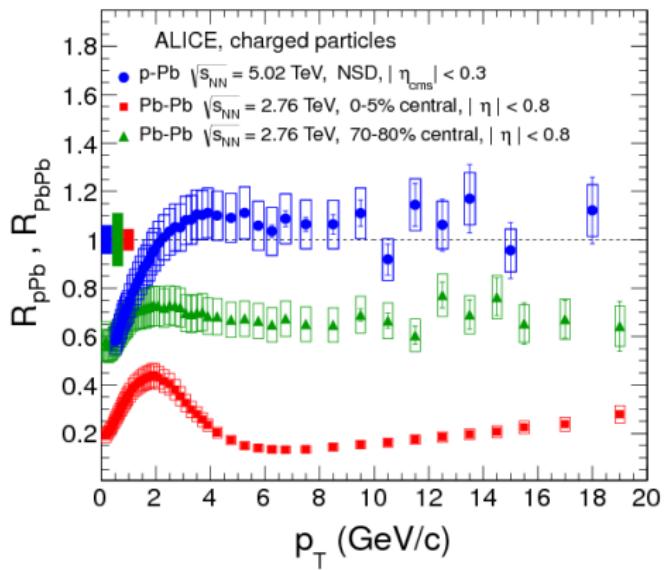
STAR-arXiv:1004.2377



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

also jet modification, dijet asymmetry, PID flow, HBT

# Flow without jet quenching?



## 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

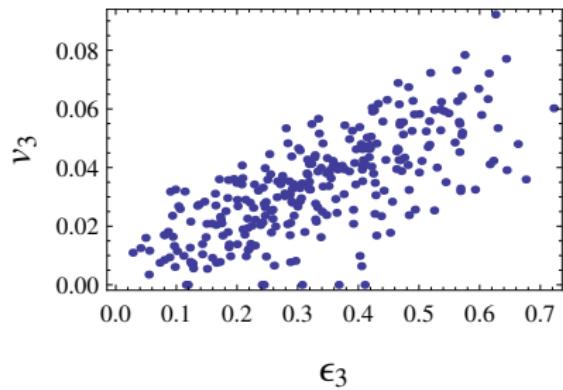
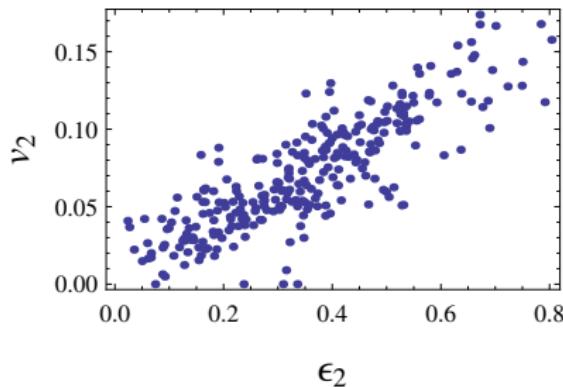
$$\Delta^{\mu\alpha} \Delta^{\nu\beta} u^\gamma \partial_\gamma \pi_{\alpha\beta} = \frac{2\eta \sigma^{\mu\nu} - \pi^{\mu\nu}}{\tau_\pi} - \frac{1}{2} \pi^{\mu\nu} \frac{\eta T}{\tau_\pi} \partial_\alpha \left( \frac{\tau_\pi u^\alpha}{\eta T} \right)$$

- ▶ 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

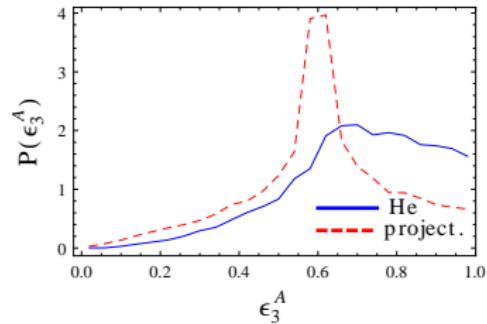
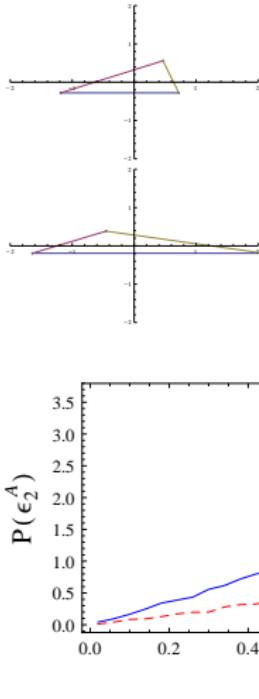
## fireball asymmetry - flow asymmetry



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

# $^3\text{He}$ configurations

elongated He configurations



- large  $\epsilon_2$
- even larger after projection
- broad distribution of  $\epsilon_3$
- after projection  $\epsilon_3 \simeq 0.6$

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

## Interferometry correlations

Hanbury Brown Twiss (1956) - measure of star diameter

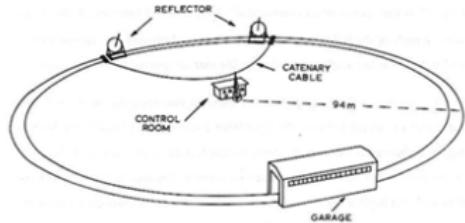
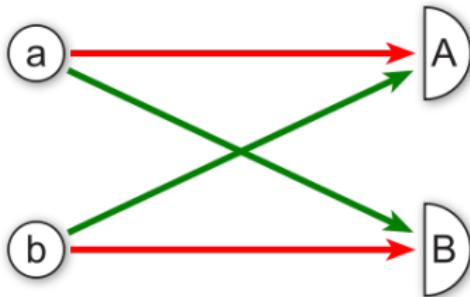


Figure 1. Aerial photo and illustration of the original HBT apparatus. They have been extracted from Ref.[1].

Intensity correlations in two detectors



$$\langle I_A I_B \rangle = \langle I_A \rangle \langle I_B \rangle (1 + C(r_{AB}))$$

## 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  $q\text{-}k_\perp$  bin

- ▶ generate mixed pairs for denominator

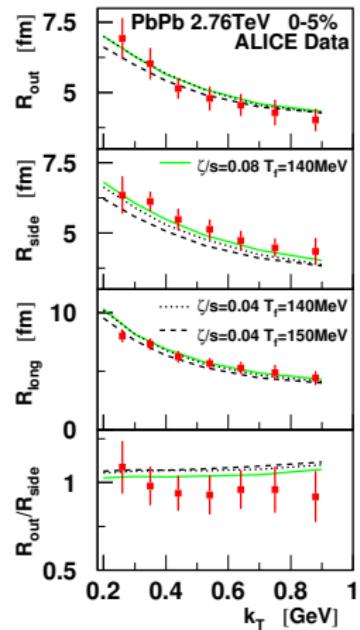
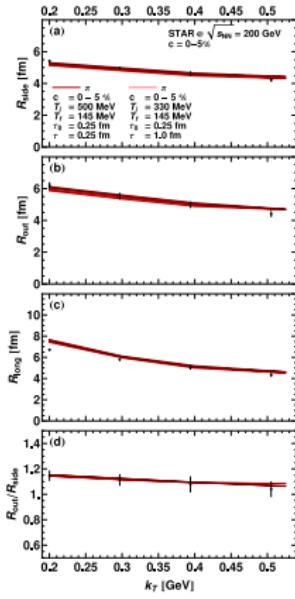
$$B = \frac{1}{N_{mixed\ pairs}} \sum_{pairs} \delta_{bin}$$

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

- ▶

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

# Hanbury Brown-Twiss (HBT) correlations in AA

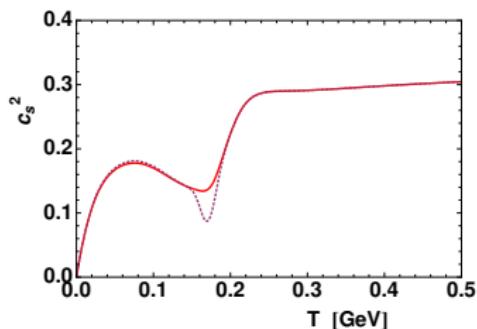


Broniowski, Chojnacki, Florkowski, Kisiel 2008,

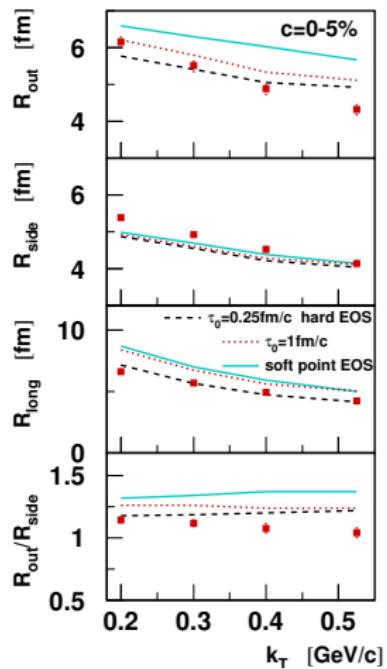
Pratt, 2009

PB, Wyskiel 1203.6513

## HBT - hard equation of state



soft EOS - wrong HBT



Heavy-ion experiments consistent with lattice QCD

HBT indicates explosive expansion : hard EOS, preequilibrium flow, viscosity

## correlations in event by event hydrodynamics

- ▶ combine several (many) events

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

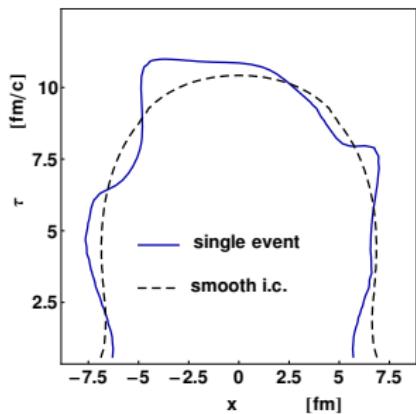
numerator - sum over different hydro events

denominator - sum over different hydro event pairs

increases the effective number of pairs (d-Au 5000×)

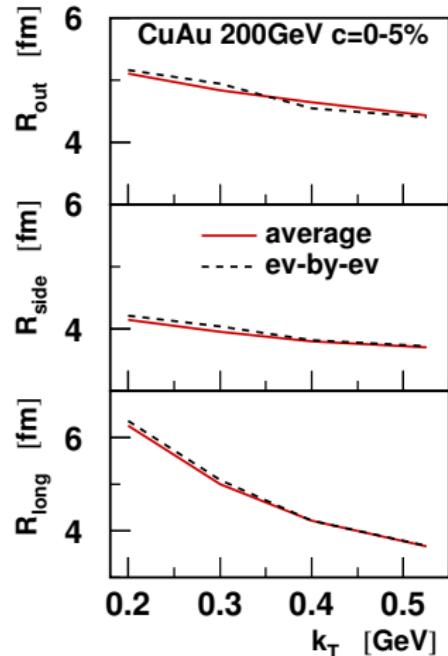
- ▶ azimuthally sensitive HBT possible with reasonable cost
- ▶ perfect event plane resolution

## HBT of fluctuating fireballs



can the lumpy surface be observed?

**NO**



## HBT of fluctuating fireballs II

- ▶ event by event emission function

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

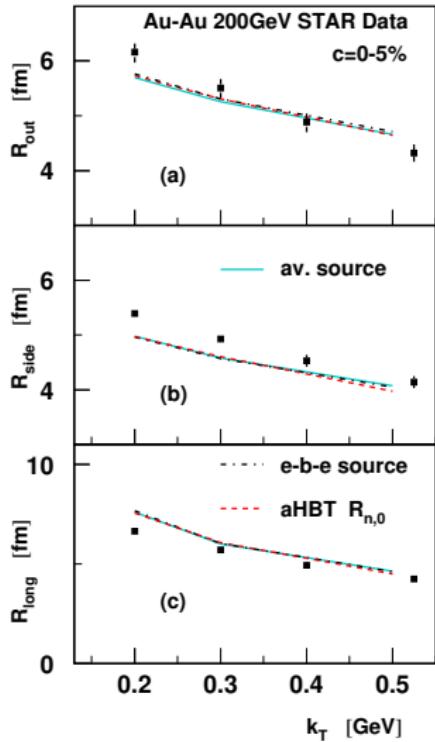
- ▶ average emission function

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

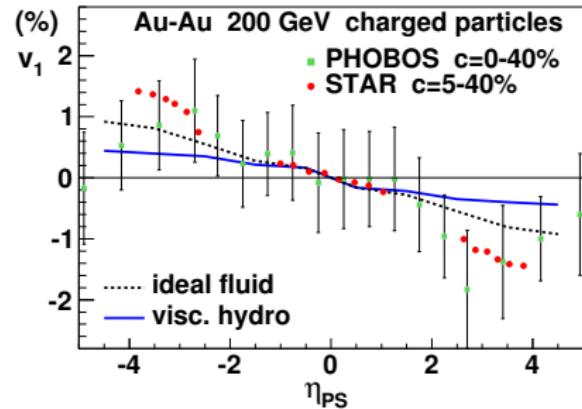
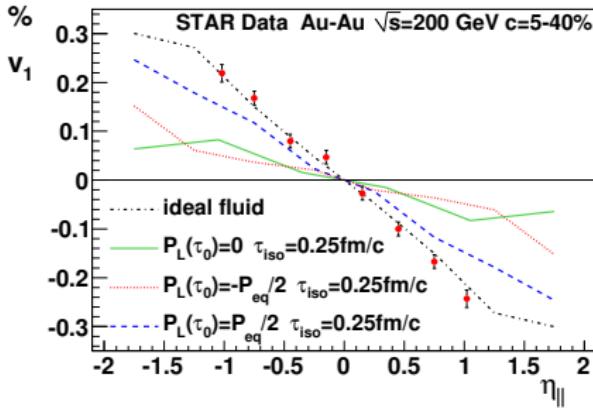
- ▶ emission function fluctuations

## 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



# Pressure anisotropy - directed flow



PB, I. Wyskiel - arXiv:1009.0701

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