Theory of pp/pA/small systems

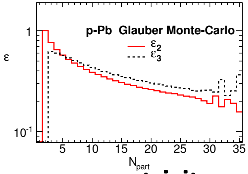
Piotr Bożek

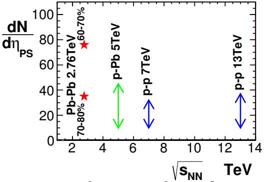
AGH University of Science and Technology, Kraków

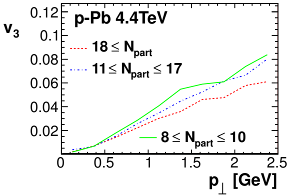
Flow in p-Pb is expected

- multiplicity as in peripheral A-A $\rightarrow$ large energy density
- sQGP observed in A-A
- $\eta/s = 0.08 \leftrightarrow$ mean free path $\simeq 0.2 - 0.3$fm $\ll$ size of the system
- size at freeze-out $\gg$ confinement scale
- collectivity *also* from preequilibrium flow
- large eccentricity

smoking gun for collectivity



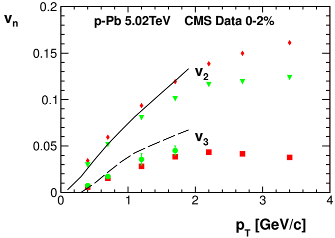




eccentricity + **large density** $\longrightarrow$ v_2, v_3

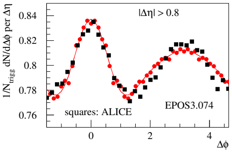
Elliptic and triangular flow observed in p-Pb

- Glauber MC initial cond. - agreement with data



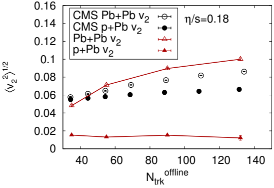
PB, W.Broniowski, G. Torrieri arXiv:1306.5442; G.Y. Qin, B. Müller 1306.3439; I. Kozlov et al. 1405.3976; A. Bzdak et al. 1304.34003, K. Kawaguchi et al. Poster 206

- EPOS3 - agreement with data



K. Werner et al. 1307.4379

- IP-Glasma initial cond. - small v_2, v_3 !



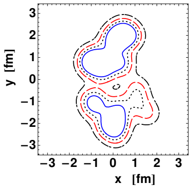
B. Schenke, R. Venugopalan 1405.3605

- v_2, v_3 consistent with hydro (Glauber MC, EPOS3)
- sensitive probe of init. cond.

$v_{2,3}$ - hydro response to initial deformation !

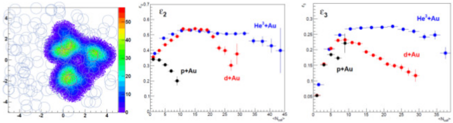
Small system with large deformation

- deuteron projectile
  intrinsic deformation dominates over fluctuations → large v_2



PB 1112.0915

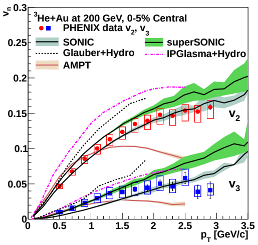
- ^{3}He projectile
  larger triangular flow



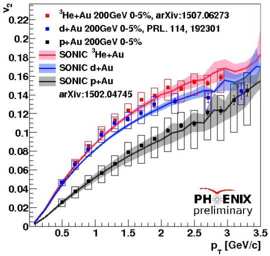
Nagle et al. arXiv:1312.4565

central collisions - deformed fireball, **control of initial geometry**

Elliptic and triangular flow in d-Au, ^{3}He-Au and p-Au



PHENIX, arXiv:1507.06273



PHENIX

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

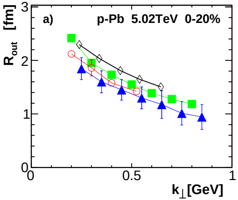
hydrodynamic calculations reproduce the data

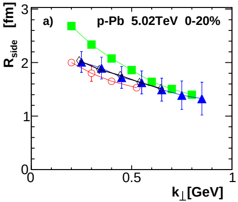
sensitivity to details, limits of applicability of hydro - systematic model uncertainty

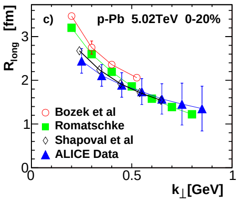
large eccentricity - large flow component

collective response to geometry

Interferometry radii





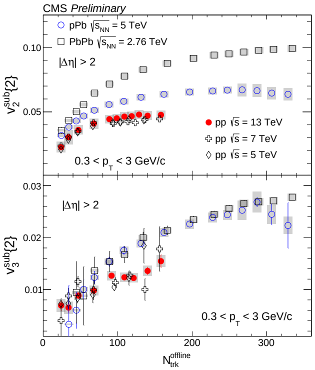


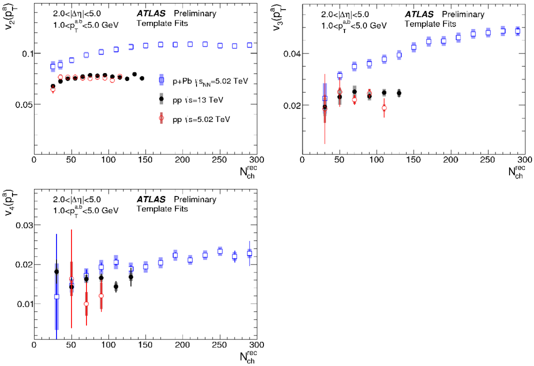
- $k_\perp$ dependence of $R_{o,l,s}$
R_{side}, R_{out} consistent with hydro
- similar results for d-Au

right magnitude and $k_\perp$ dependence of HBT radii support collective scenario

Requires small intial fireball size

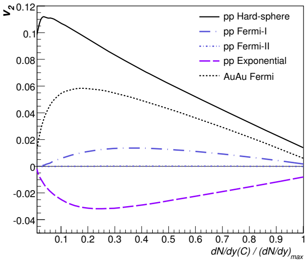
Collective flow in pp?



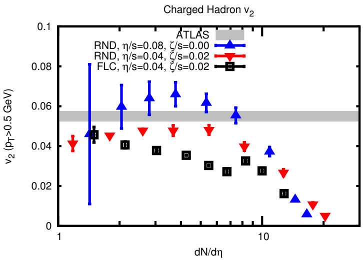


Collective like correlations observed in pp

V_n in optical Glauber + hydro(response)



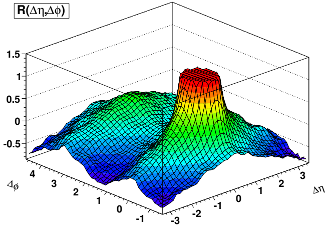
D'Enterria et al, 0910.3029



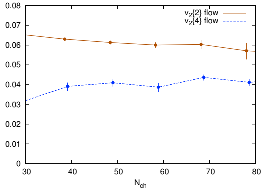
Habich et al. 1512.05354

- 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

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



Werner, Karpenko, Pierog, 1011.0375

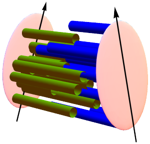


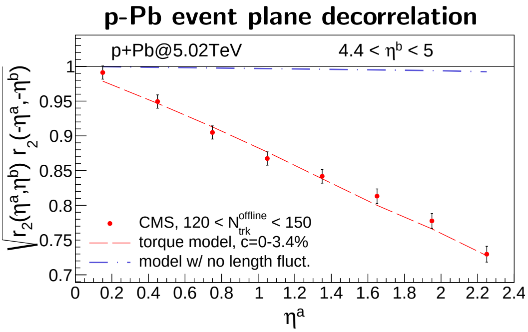
Avsar, Flensburg, Hatta, Ollitrault, Ueda, 1009.5643

- 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

flow in small systems - what can we learn
mapping of space time distribution by flow - rapidity



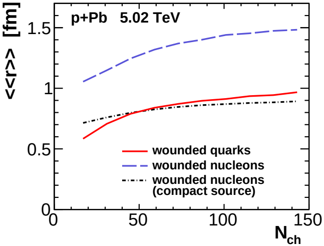


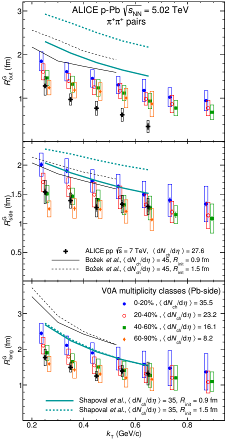
PB, W. Broniowski 1506.04362

sensitivity to fluctuations in energy deposition
event-plane decorrelation in p-Pb indicates the presence of longitudinal fluctuations - random flux tubes

flow in small systems - what can we learn
mapping of space time distribution by flow - transverse plane

Fireball size in p-Pb





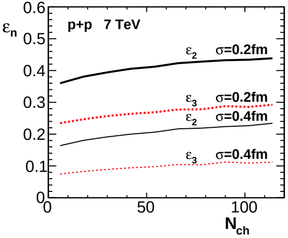
PB, Broniowski, Rybczynski 1604.07697

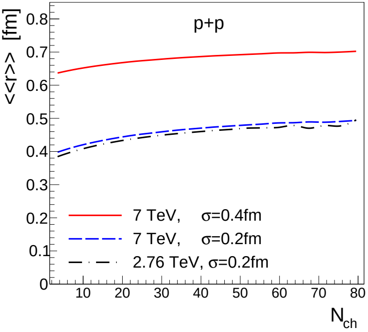
- wounded quark model gives small fireball size

- *compact source* consistent with p-Pb data

(HBT, $< p_\perp >$)

p-p collisions (quark Glauber model)

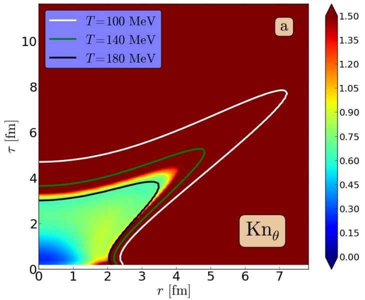




- significant eccentricities in p-p
- small size of the interaction region 0.4fm

Hydrodynamics in small systems?

Hydrodynamics $K < 1$



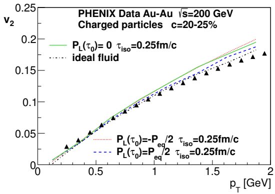
H. Niemi, G. Denicol 1404.7327

large gradients in the evolution

higher order corrections,

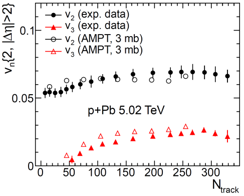
effective viscosity reduced

1. Early stage, pressure asymmetry $P_L \ll P_\perp$



PB, I. Wyskiel-Piekarska 1011.6210; J. Vredevoogt, S. Pratt 0810.4325
early pressure asymmetry - irrelevant

2. Late stage, decoupling at freeze-out



A.Bzdak, G.L. Ma 1404.4129; L. He et al. 1502.05572
hydrodynamics similar to AMPT cascade

SIGNS OF COLLECTIVITY IN SMALL SYSTEMS

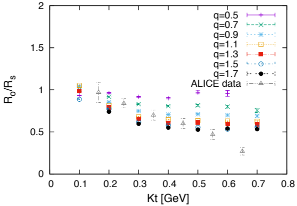
1. **Elliptic and triangular flow**
2. **Hierarchy of v_2 and v_3 in p-A, d-A, He-A**
   collective response to geometry (final state effect)
3. **HBT radii**

$+\dots$

- **Density driven collective expansion**
- **Hydrodynamics describes data for $p_\perp < 1.5$GeV**
- **Collectivity $\neq$ QGP ??**

Stronger flow in p-p ?

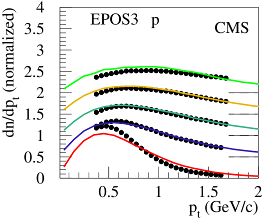
Interferometry



Y. Hirono, E. Shuryak 1412.0063

stronger transverse flow in p-p !

Spectra



K. Werner et al 1312.1233,

T. Kalaydzhyan, E. Shuryak 1503.05213

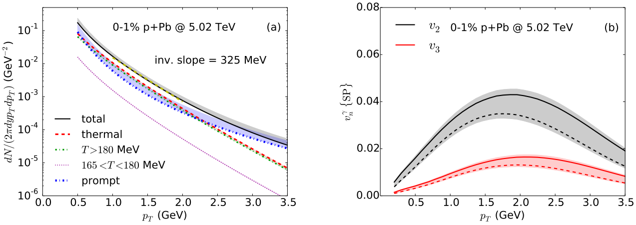
Hardening of spectra for high multiplicity events

but: quantitative predictions for flow asymmetry
less robust in p-p, no smoking gun

flow in small systems - what can we learn

3. what flows?

medium probes in small systems: photons, jets, heavy flavors, balance functions

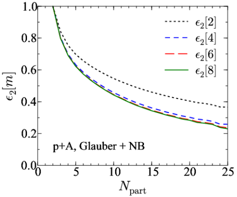


direct photons: S. Shen et al. 1504.07989

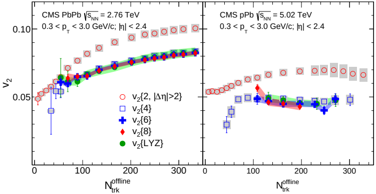
2) Flow from higher cumulants

- 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



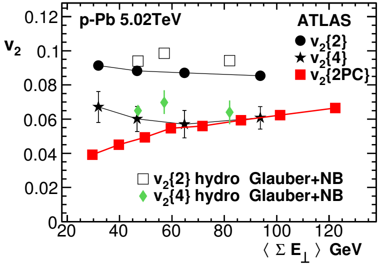
CMS 1502.05382

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

universal prediction for differences $v_2\{4\} \neq v_2\{6\} \neq v_2\{8\}$ L. Yan, J.Y. Ollitrault 1312.6555

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

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



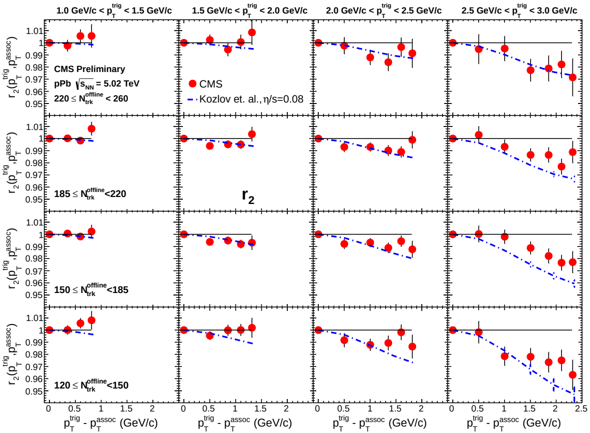
PB, W. Broniowski 1304.3044

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

4) Factorization at intermediate $p_\perp$

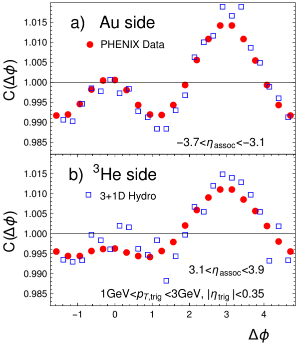


- factorization holds for v_2 and v_3 up to 2.5 GeV
- **small** deviations explained by hydro+Glauber Kozlov, Luzum, Denicol, Jeon, Gale, 1405.3976

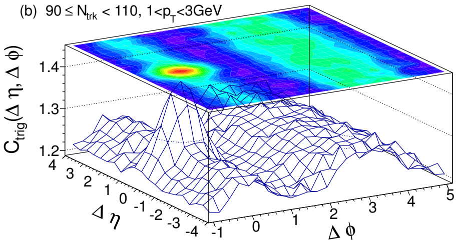
geometry driven origin of correlations at small **and** intermediate $p_\perp$

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

^{3}He-Au



p-Pb



PB, Broniowski 1211.0845

geometry driven origin of correlations at forward and backward rapidities