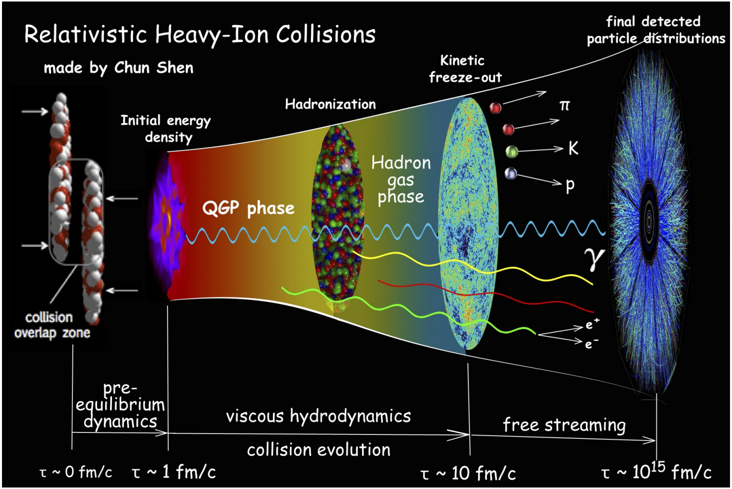
Standard Model of Little Bangs

Wojciech Broniowski

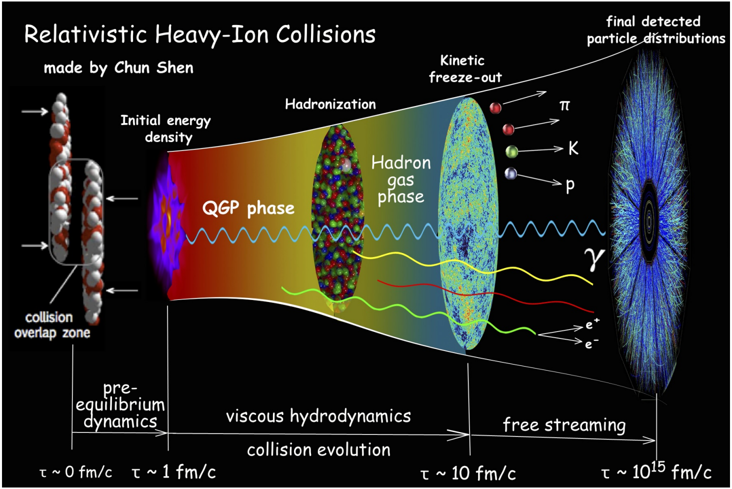
IFJ PAN & UJK

NCBJ, 27.03.17

Little Bangs



[U. Heinz 2000]: *analogous to . . . Big Bang . . . the Hubble expansion (which goes on until today), the cosmic microwave background of thermal photons (which decoupled when our universe was about 300,000 years old), and the measured abundances of light atomic nuclei . . .*



Analogy of fluctuations in Little Bangs to the Face of God – the CMB inhomogeneities, originating from primordial fluctuations during the inflation phase

3 stages of the "Standard Model"

time ⟶

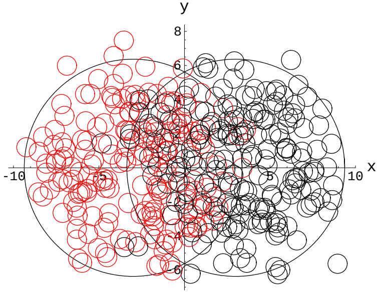
partons   hydrodynamization   quark-gluon plasma   freeze-out   hadrons

1. Initial pre-equilibrium dynamics: instabilities [Mrówczyński 1988], AdS/CFT [. . . Janik, Heller, Spaliński . . .], color glass condensate, wounded nucleon model [Białas, Błeszyński, Czyż 1976]
2. Collective evolution: hydrodynamics, large anisotropy [. . . Florkowski, Ryblewski . . .], viscous, event-by-event [. . . Bożek . . .]
3. Freeze-out and production of hadrons (hydrodynamics takes care of this by passing through the cross over, supported by the thermal model for hadron yields) [. . . Kraków, Wrocław . . .]

Collectivity

Initial geometry

Au+Au collision at RHIC
(view along the beam)



1. Participants determine the geometry of the overlap region
2. Initial entropy distribution in more microscopic approaches (IP Glasma) also follows the geometry of the overlap region
3. Strong radial flow
4. Initial eccentricity → anisotropic flow of hadrons [Ollitrault 1992]

Initial geometry

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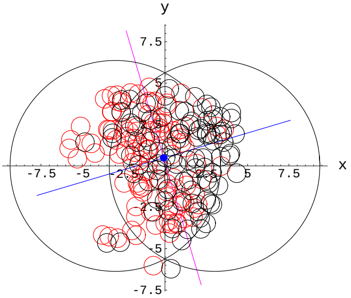

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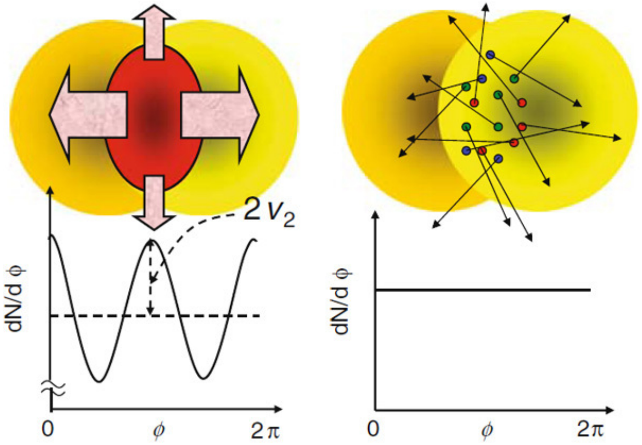
Rescattering/collectivity essential

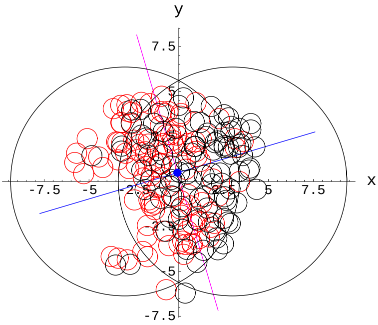


[ALICE]

$$dN/d\phi = A\left(1 + 2\sum_n v_n \cos[n(\phi - \Psi_n)]\right)$$

Fluctuations

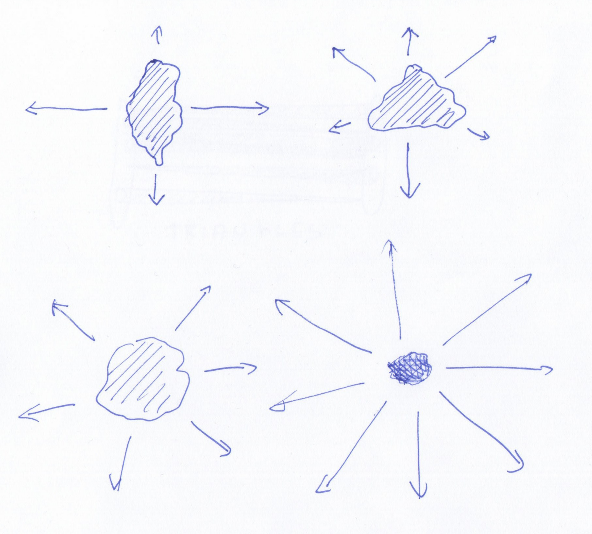
Collapse of the nuclear wave function → each Little Bang different



1. Higher Fourier components appear
2. Odd harmonics also show up, triangular flow
3. Fluctuations dominant for central A+A and for *small systems*, such as p+A

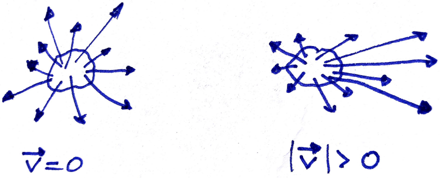
New thinking since [Miller and Snellings 2003]

Collectivity: shape/size – flow transmutation



Doppler effect

- Emission from a fast moving element of fluid
- Collimation of hadrons (increasing with mass)
- Thermal motion

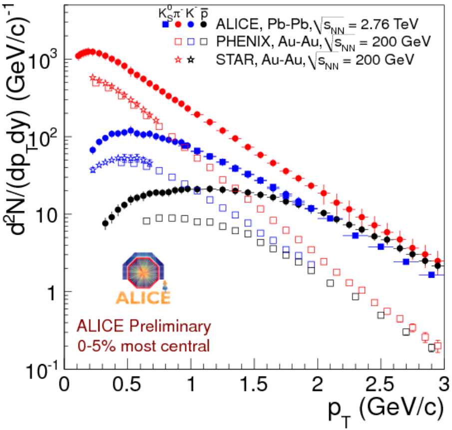


Multi-particle correlations in the azimuth are used in cumulant methods to extract flow coefficients without the non-flow contamination from jets or resonance decays

[Borghini, Ollitrault 2001]

Signatures of flow

1. Mass ordering in p_T spectra from radial flow
2. Mass ordering of harmonic flow coefficients v_n
3. Higher harmonics suppressed
4. Near-side ridge (discussed later on) - the real "proof" of harmonic flow



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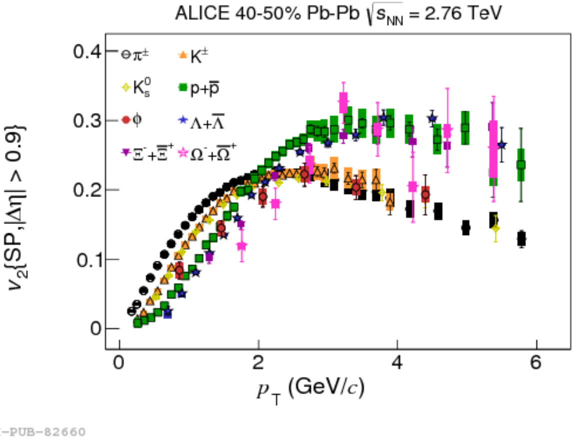

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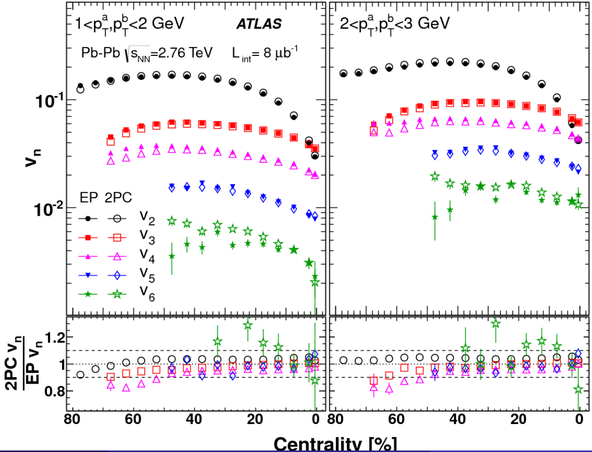
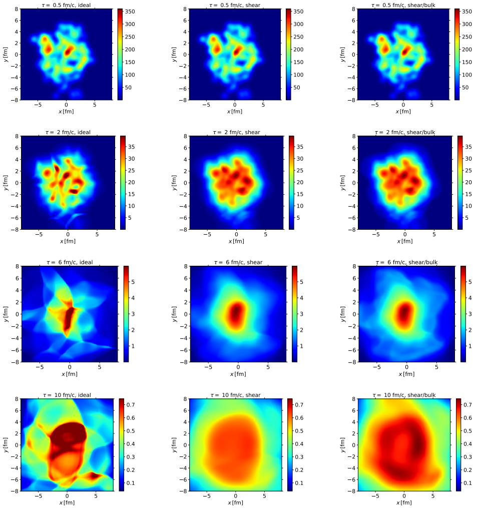


Role of viscosity

perfect | shear | shear+bulk

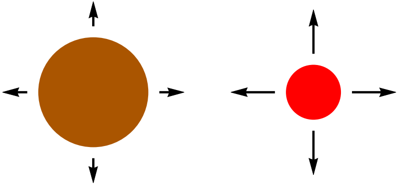


- Quenching of flow with viscosity
- Increasing with the Fourier rank
- Sets limits on viscosity, which is close to the KSS bound $\eta/s = 1/4\pi$
- ... but many other model parameters

Figure:
[Bazow, Heinz, Strickland 2016]

Event-by-event p_T fluctuations

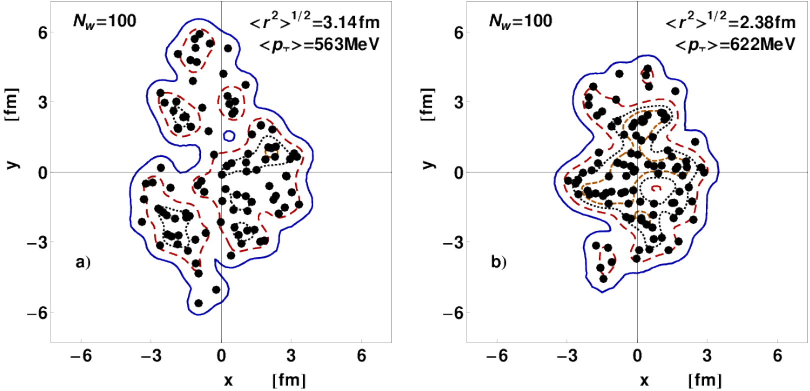
Size – radial flow transmutation



smaller size → stronger flow
larger size → weaker flow

[WB, Chojnacki, Obara 2009]

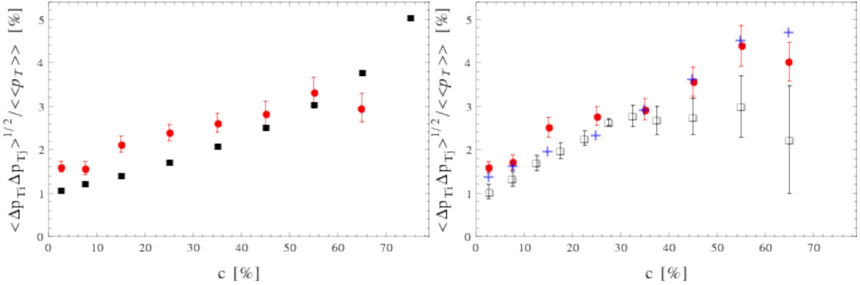
E-by-e size fluctuations



[Bożek, WB 2012]

- Same number of participants, $N_W = 100$
- Different size (and shape)

Transverse momentum fluctuations in Au+Au@200GeV

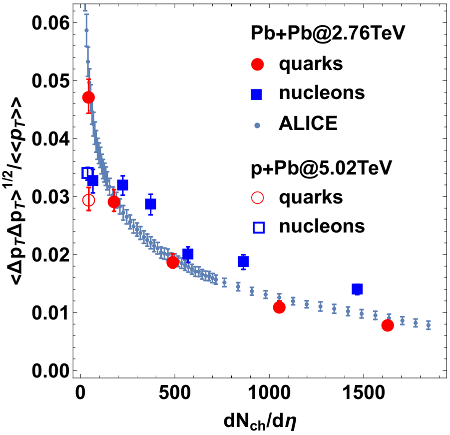


STAR PHENIX

red points – model

- Measure removes trivial fluctuations from finite sampling
- Model overshoots the data by about 50% for most central collisions
- Hydro response not modified by viscosity, freeze-out temperature, smearing, core-corona, total momentum conservation, centrality definition
  $\Delta\langle p_T\rangle/\langle\langle p_T\rangle\rangle \simeq 0.4\Delta\langle r\rangle/\langle\langle r\rangle\rangle$
- Need to decrease the fluctuations in the initial state

Wounded quark model as implemented in [Bożek, WB, Rybczyński 2016]:
more participants → less fluctuation



[Bożek, WB 2017]

Transverse momentum fluctuations with wounded quarks

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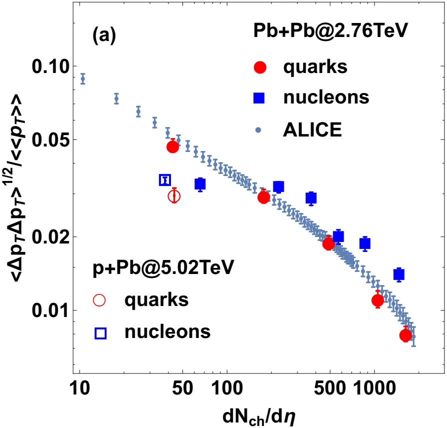
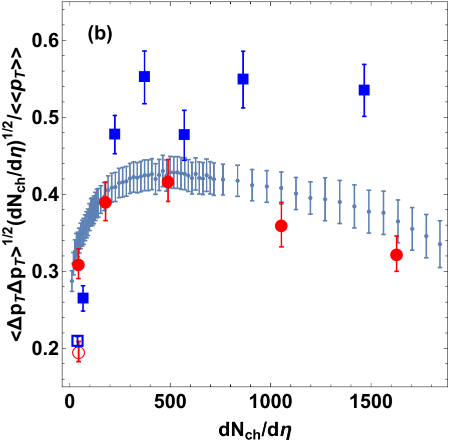


[Bożek, WB 2017]

Transverse momentum fluctuations with wounded quarks

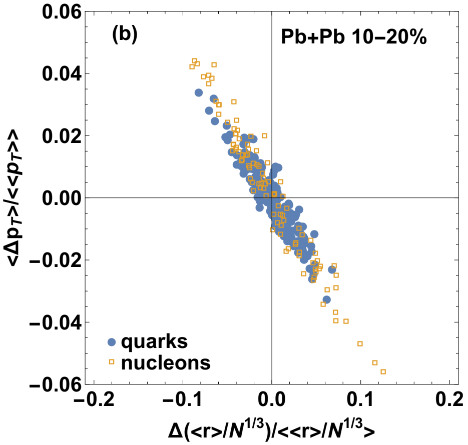
Nontrivial dependence on multiplicity



Excludes independent production from sources (would be flat)

Size – flow anti-correlation

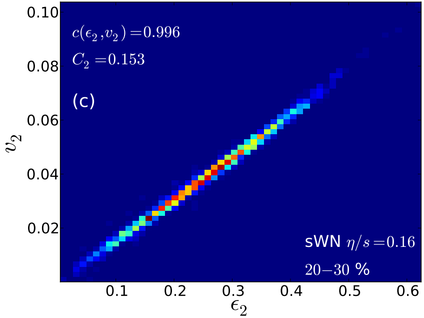
Very strong e-by-e anti-correlation of size and $\langle p_T \rangle$

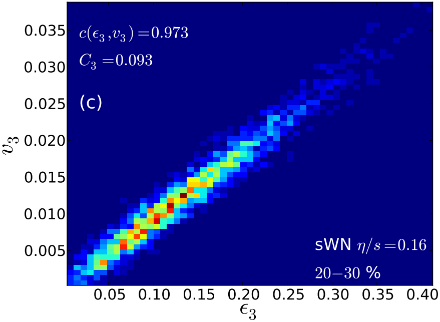


- This is the mechanism for p_T fluctuations!

Back to harmonic flow . . .

Proportionality of flow to eccentricity



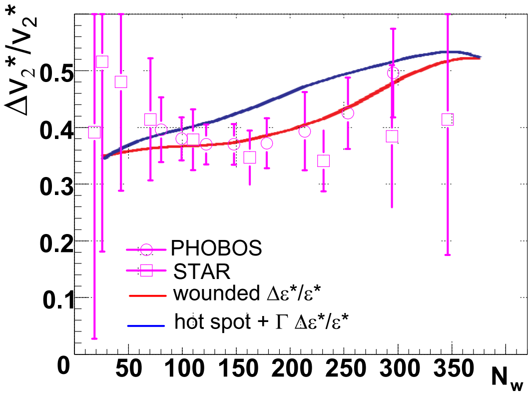


[Niemi, Denicol, Holopainen, Huovinen 2012]

$$v_n = \kappa_n \epsilon_n$$

- Allows us to build scale-less combinations independent of the response coefficient κ_n

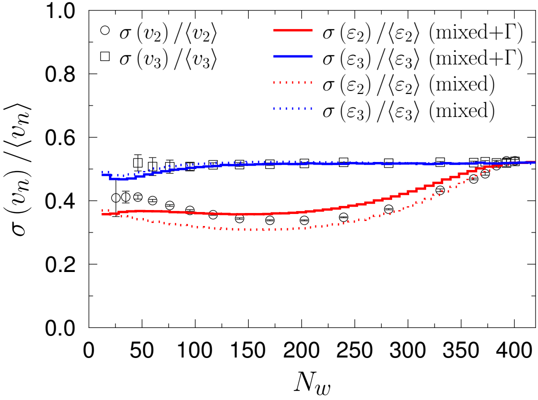
Flow fluctuations



$\leftarrow \quad \sqrt{4/\pi - 1}$

[WB 2007]

Flow fluctuations

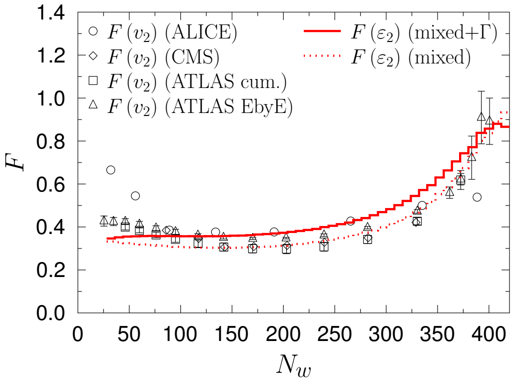


$\leftarrow \quad \sqrt{4/\pi - 1}$

[WB, Rybczyński 2016]

Flow fluctuations

$$F_n = \sqrt{\frac{\varepsilon_n\{2\}^2 - \varepsilon_n\{4\}^2}{\varepsilon_n\{2\}^2 + \varepsilon_n\{4\}^2}}$$



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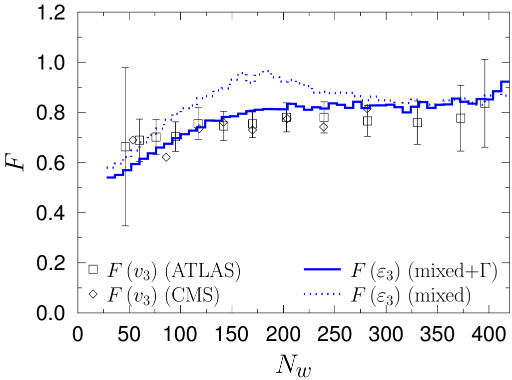


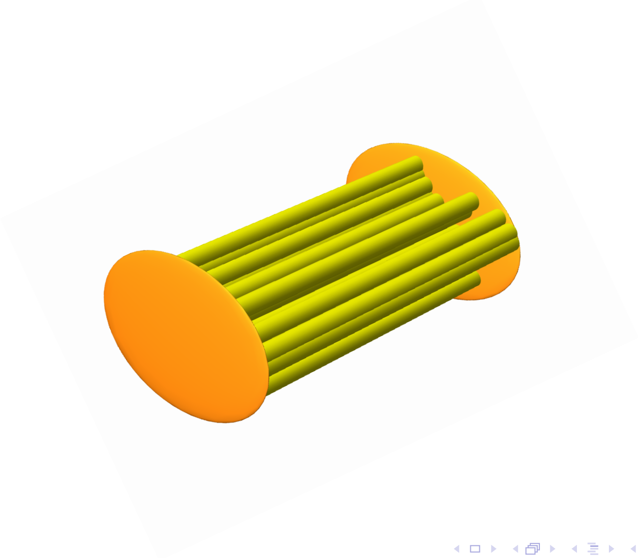
[WB, Rybczyński 2016]

Going longitudinal

Non-flow events

Factorization of the transverse and longitudinal distributions

left-moving participants strings right-moving participants



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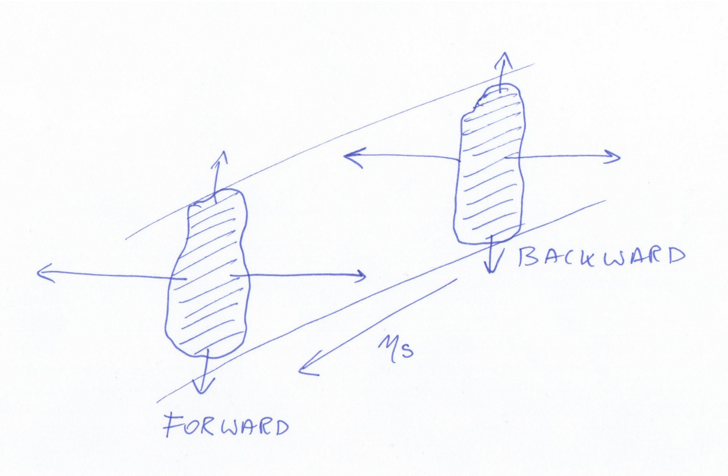
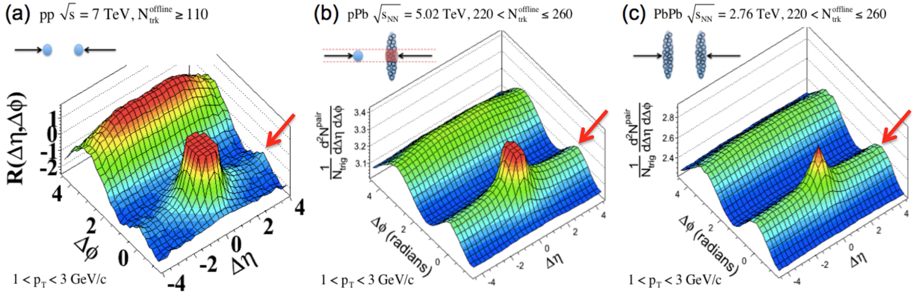


Approximate (up to fluctuations) alignment of F and B event planes

Collimation of flow at very distant longitudinal separations → ridges!

Surfers - the near-side ridge

Ridge

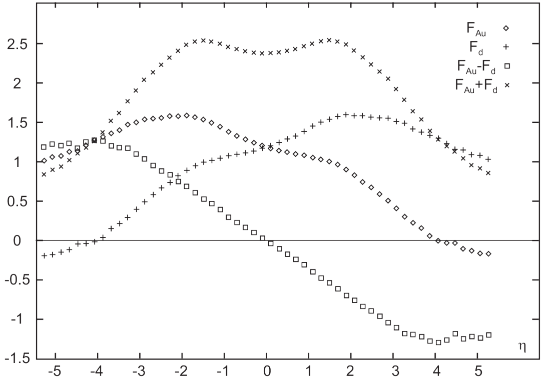


Near-side ridge indicates collectivity

Total surprise in p-p!

Triangles

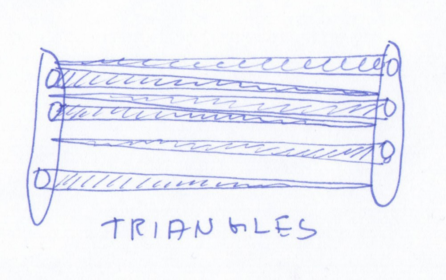
Extracted from the d-Au collisions at RHIC:

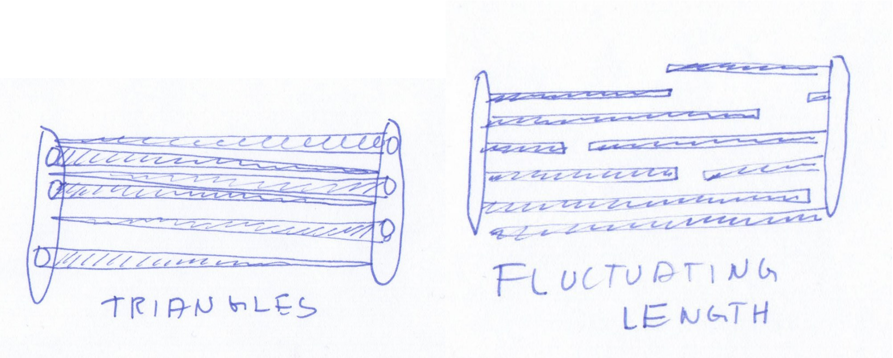


[Białas, Czyż 2004]

Source emits mostly in its own froward hemisphere

Triangles



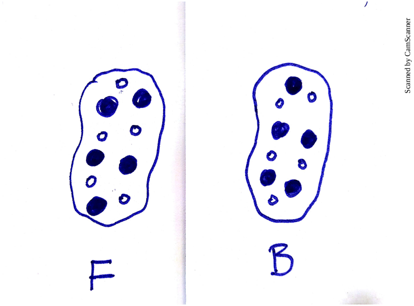


[. . . Bierlich, Gustafson, Lönnblad 2016, Monnai, Schenke 2015, Schenke, Schlichting 2016 . . . Brodsky, Gunion, Kuhn, 1977]

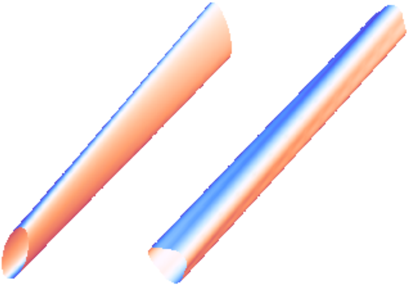
Torque

Torque effect (event-by-event)

Transverse sections with triangles



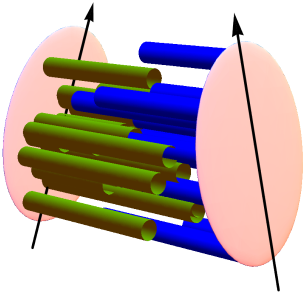
e-by-e longitudinal twist (a few degrees)



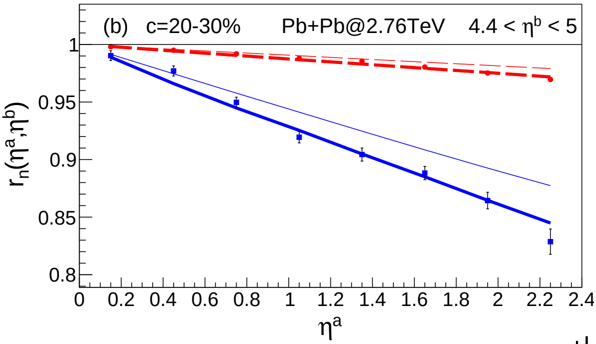
- Both e-by-e fluctuations and longitudinal asymmetry of the emission profile needed

[prediction in PB, WB, Moreira 2010 & PB, WB, Olszewski 2015, PB, WB 2016]

Fluctuating strings



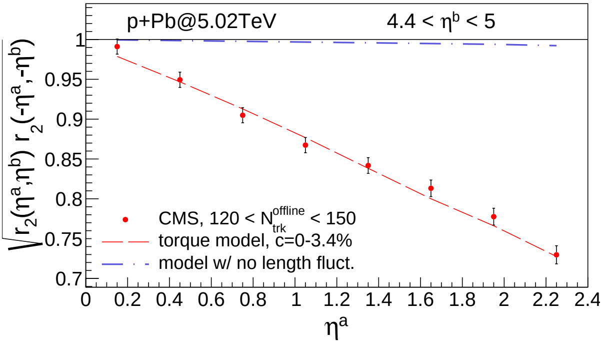
Torque in Pb+Pb



thin - triangles
thick - string breaking
v_2 and v_3

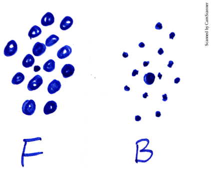
$$r_n(\eta_a,\eta_b) = \frac{\langle\langle\cos(n[\phi_i(-\eta_a) - \phi_j)\eta_b)])\rangle\rangle}{\langle\langle\cos(n[\phi_i(\eta_a) - \phi_j)\eta_b)])\rangle\rangle}$$

Torque in p-Pb

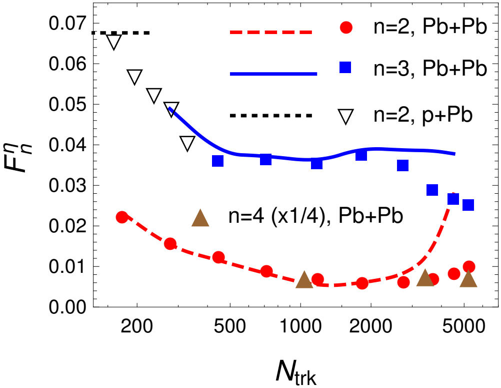


- String breaking essential to describe torque in p-Pb

With triangles:



Slope of r_n



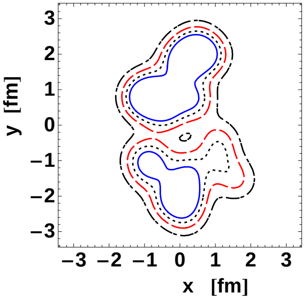
- Fair description of mid-central collisions
- Way too much decorrelation in central collisions
- $F_4 \simeq 4F_2$

Small systems

d-A

d has an intrinsic dumbbell shape with a large deformation: rms $\simeq 2$ fm

Initial entropy density in a d-Pb collision with $N_{\rm part} = 24$ [Bożek 2012]



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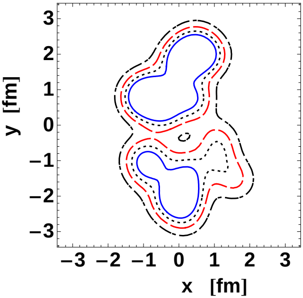
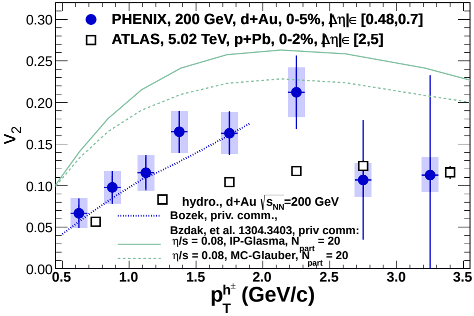
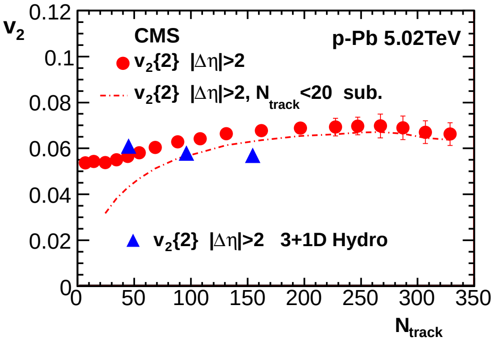




Resulting large elliptic flow confirmed with the later RHIC analysis (geometry + fluctuations)

Collectivity in p+A

Practically no geometry, only fluctuations



[Bożek, WB, Torrieri 2013]

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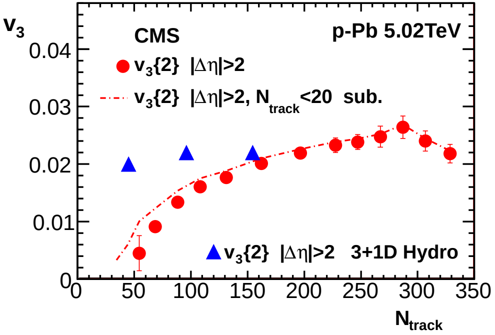
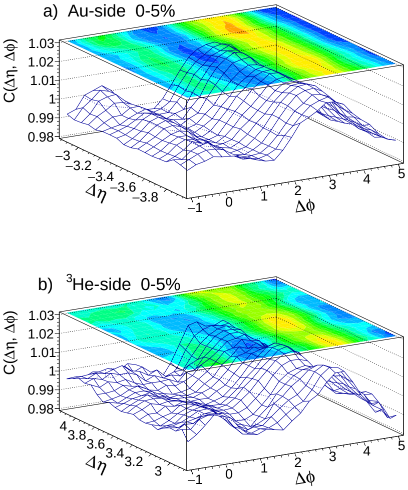
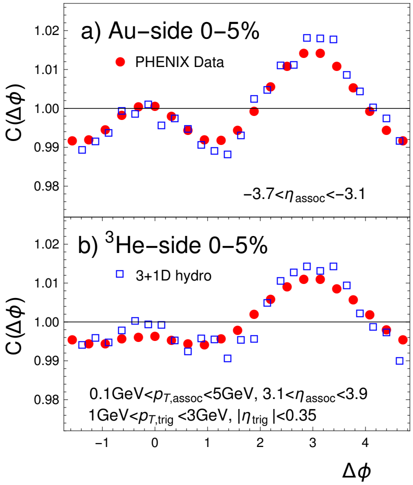


[Bożek, WB, Torrieri 2013]

^{3}He-Au at RHIC





(seen on both pseudorapidity sides)

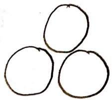
[Bożek, WB 2015]

^{12}C-Pb – role of α clusters

Nuclear structure from ultra-relativistic collisions!
Probe to what degree ^{12}C is made of three α's

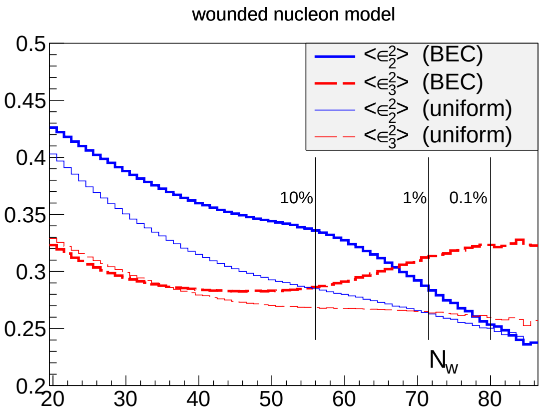
Specific features of the ^{12}C collisions with a "wall":

The cluster plane parallel or perpendicular to the transverse plane:

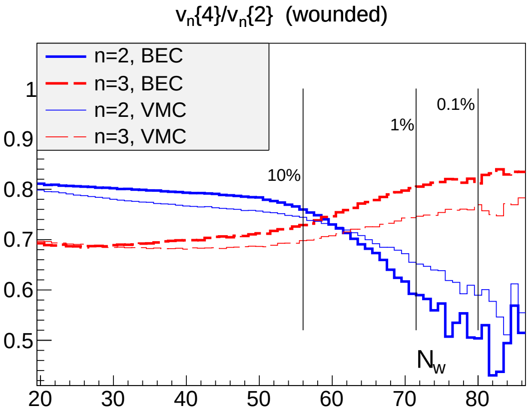


higher multiplicity	lower multiplicity
higher triangularity	lower triangularity
lower ellipticity	higher ellipticity

Ellipticity and triangularity vs multiplicity



Ellipticity and triangularity vs multiplicity



Conclusions

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Standard model (almost) works!

- Collectivity in A+A beyond doubt
- Explanation of the near-side ridge
- Cognitive role of e-by-e fluctuations
- Mechanism for p_T fluctuations (seem too much for central)
- Torque (event-plane angles decorrelation)
- Torque in p-Pb $\rightarrow$ longitudinal fluctuations (string breaking)
- . . .

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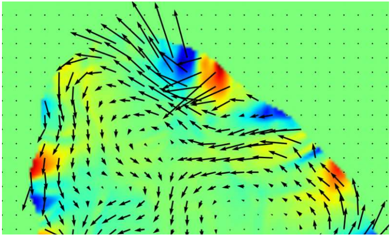
Not mentioned:

- Jet quenching by the medium
- Early probes
- Femtoscopy
- Chiral magnetic effect
- Vorticity and Λ polarization
- ...



[RHIC simulation, Pang et al. 2016]

Thank you!