Outlook — collectivity aspects

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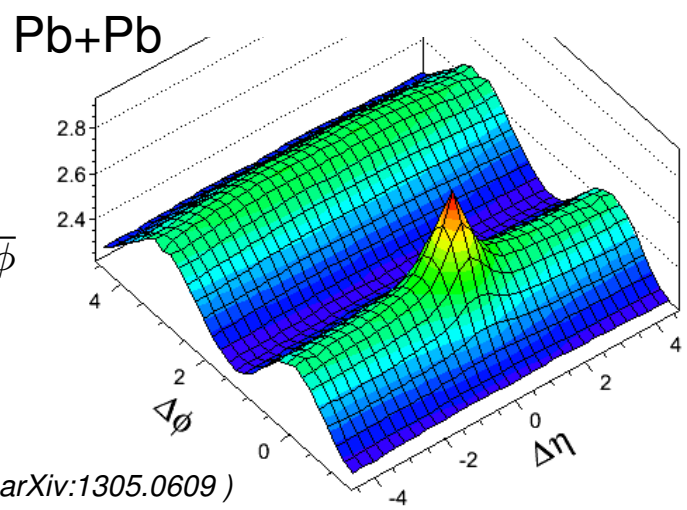
What is collectivity?

- My definition of collectivity: correlated motion between large numbers of particles
- Hydrodynamics $\implies$ collectivity
- Collectivity $\not\Longrightarrow$ hydrodynamics
- Either way, points to interesting physics

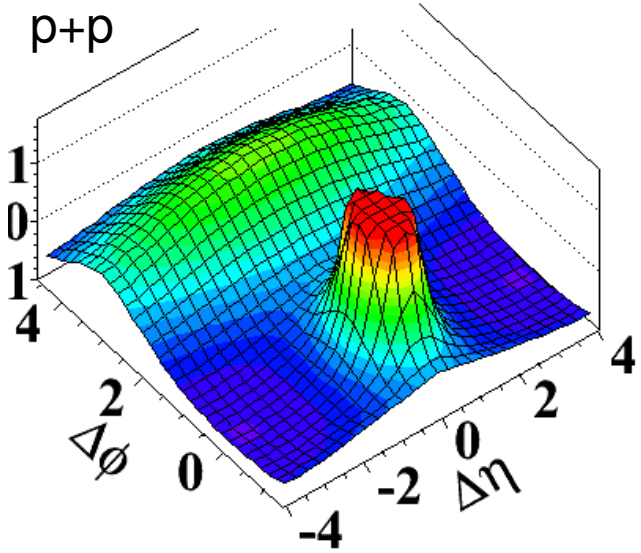
Part 1: Where do we see collectivity?

TWO-PARTICLE CORRELATIONS

$$\sim \frac{dN_{pairs}}{d\Delta\eta d\Delta\phi}$$



(CMS, arXiv:1305.0609)



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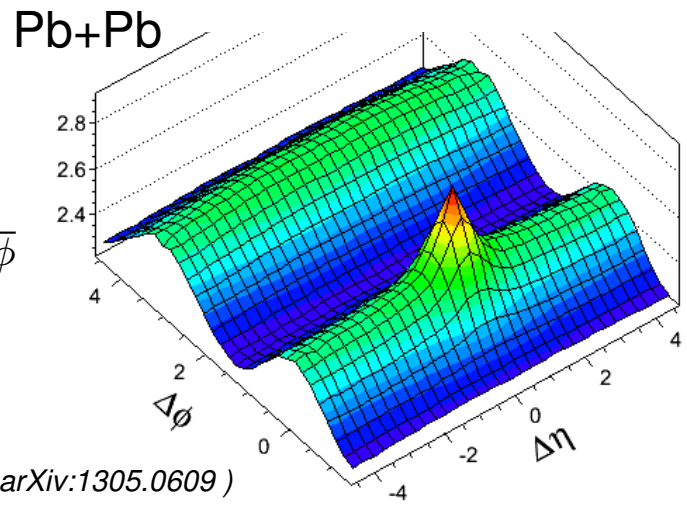

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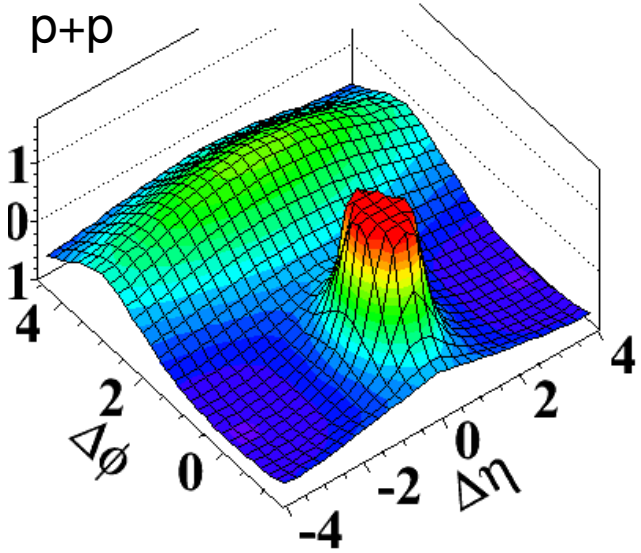
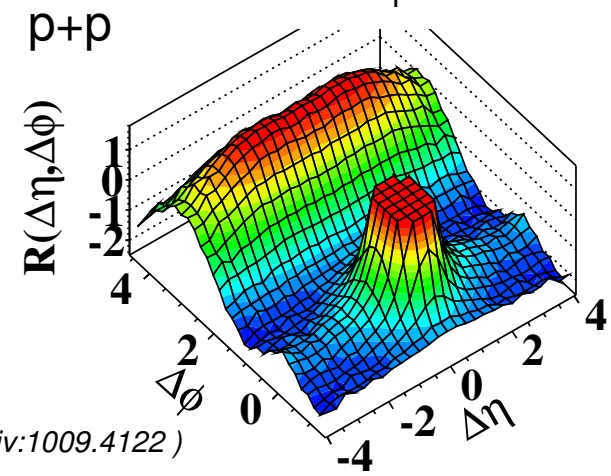


(d) CMS N ≥ 110, 1.0GeV/c<p_T<3.0GeV/c



(CMS, arXiv:1009.4122)

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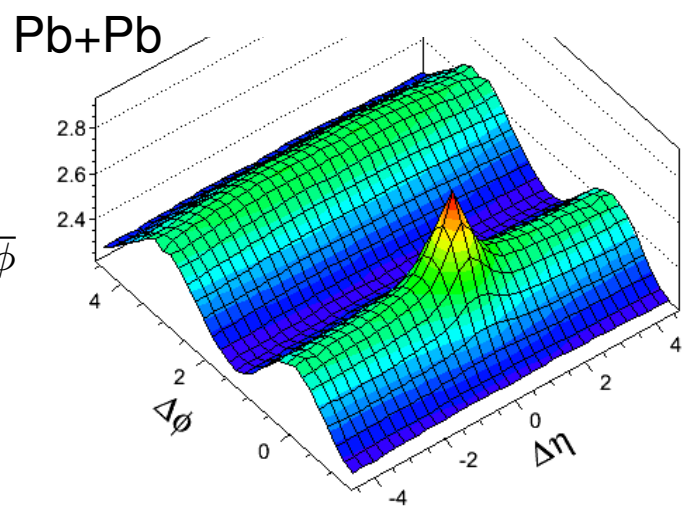

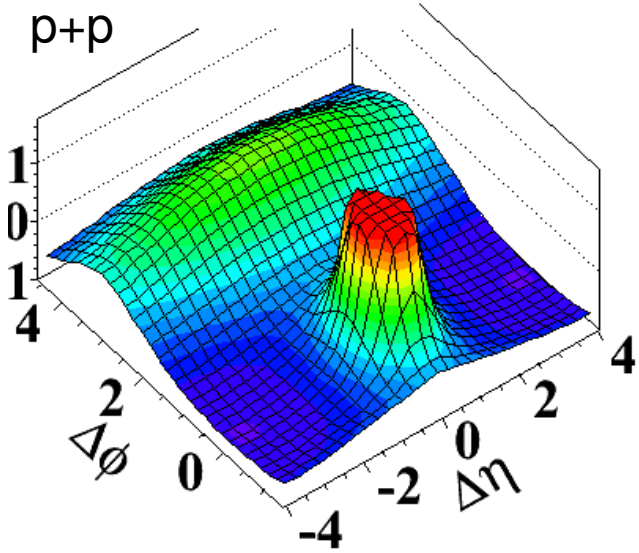

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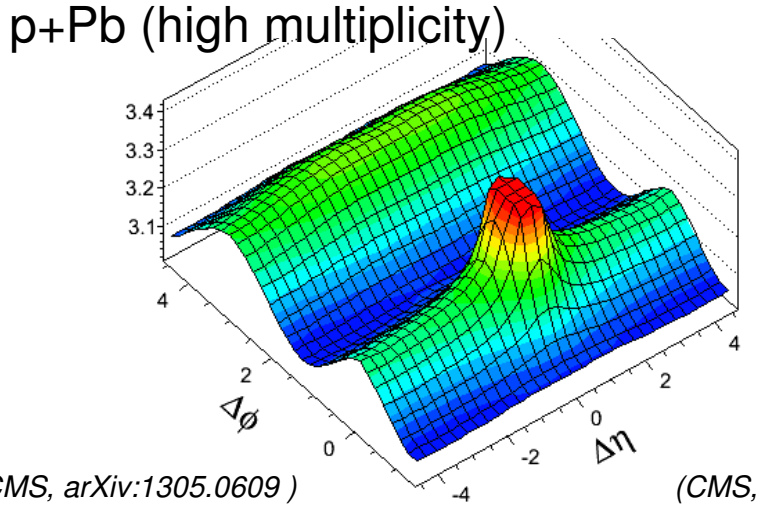

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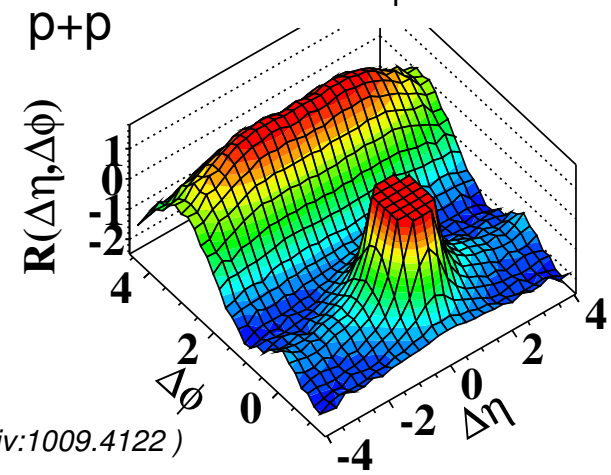

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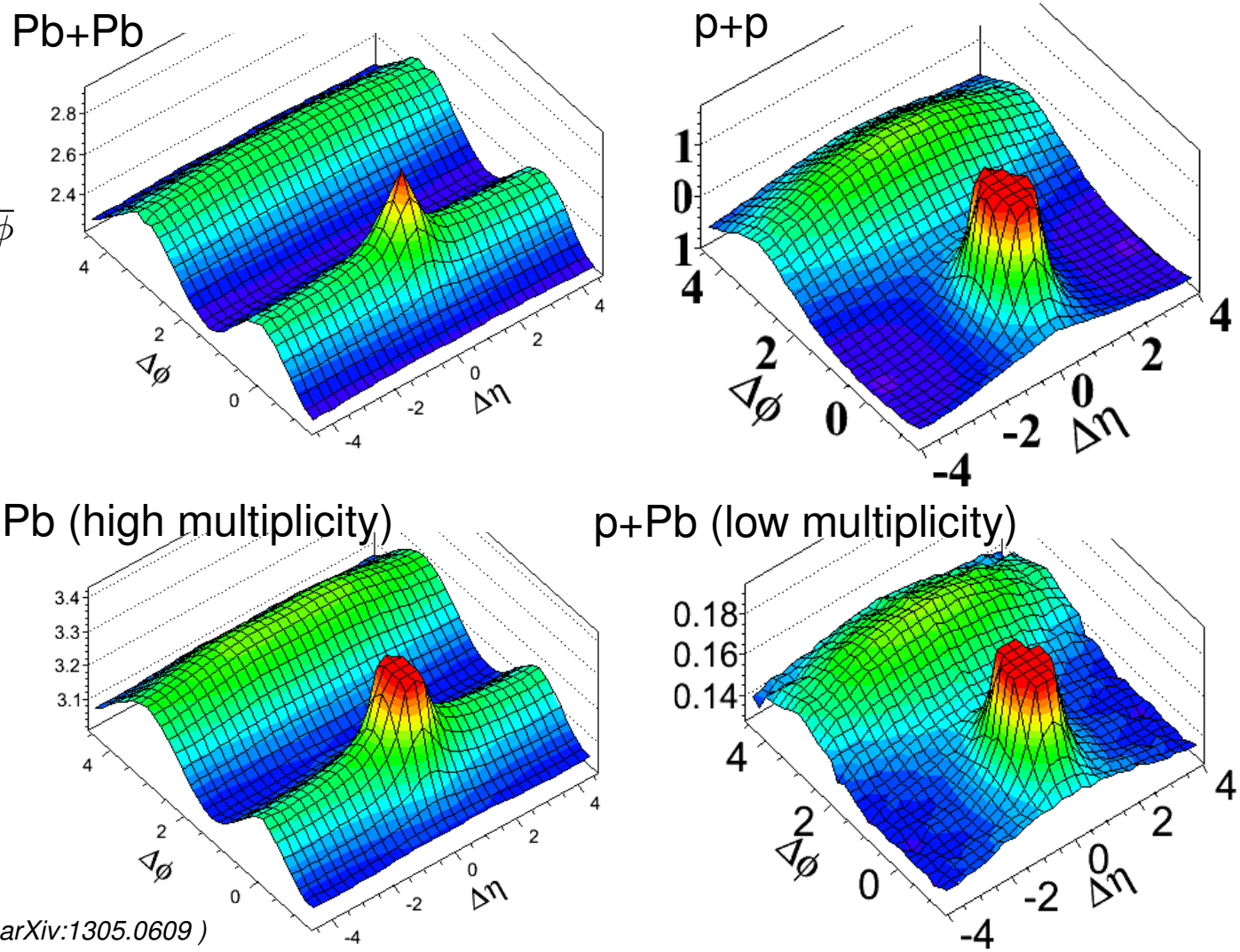

(CMS, arXiv:1305.0609)

- Striking long-range pair correlations are seen in small collisions systems
- Natural in a hydro picture
- Also explainable with intrinsic pair correlations from the initial state (without collectivity)
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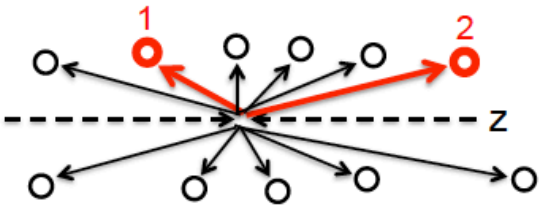
MULTIPARTICLE CORRELATIONS

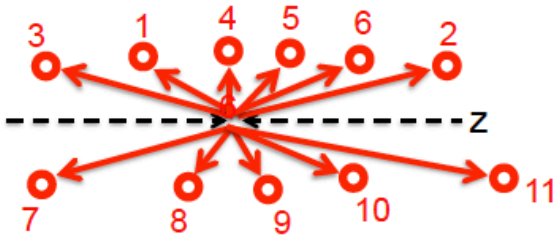
Collectivity?

Two-particle correlation



OR

Multi-particle correlation



Multi-particle (>2) cumulants:

$$\langle\langle 6\rangle\rangle = \left\langle\left\langle e^{in(\phi_1+\phi_2+\phi_3-\phi_4-\phi_5-\phi_6)}\right\rangle\right\rangle$$

$$c_n\{6\} = \langle\langle 6\rangle\rangle - 9\cdot\langle\langle 4\rangle\rangle\langle\langle 2\rangle\rangle + 12\cdot\langle\langle 2\rangle\rangle^3$$

$$v_n\{4\} = \sqrt[4]{-c_n\{4\}}$$

$$v_n\{6\} = \sqrt[4]{\frac{1}{4}c_n\{6\}}$$

$$v_n\{8\} = \sqrt[4]{-\frac{1}{33}c_n\{8\}}$$

Insensitive to non-flow effect

Q-cumulant, PRC 83 (2011) 044913

In hydrodynamics:

$$v_2\{2\} > v_2\{4\} \approx v_2\{6\} \approx v_2\{8\} \approx v_2\{\infty\}$$

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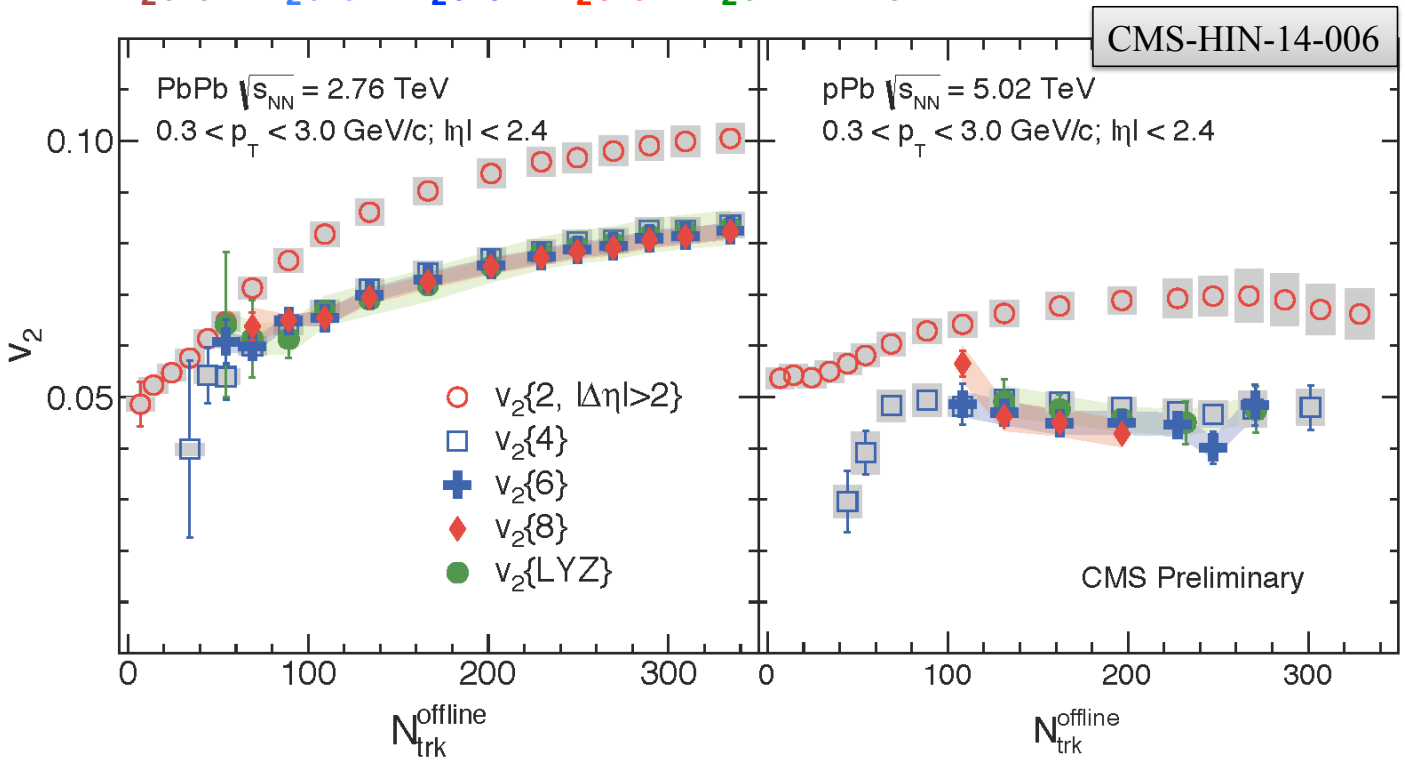
(Zenyu Chen, Wednesday)

MULTIPARTICLE CORRELATIONS

Collectivity!

$v_2\{2\} > v_2\{4\} \approx v_2\{6\} \approx v_2\{8\} \approx v_2\{LYZ, \infty\}$



Evidence of the collective nature of correlations in pPb!

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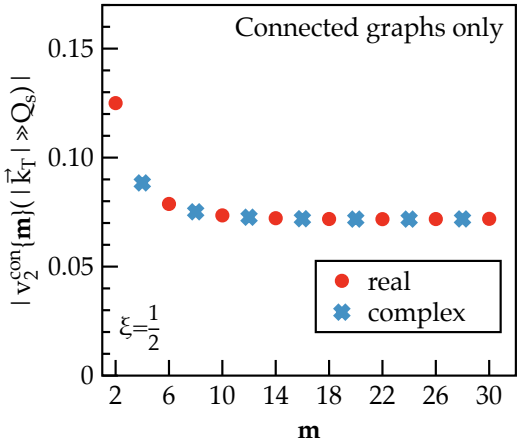
(Zenyu Chen, Wednesday)

MULTIPARTICLE CORRELATIONS

Cumulants imply true collectivity

$v_2\{m\}$ FROM CONNECTED DIAGRAMS: FINAL RESULT



A. Dumitru, L. McLerran, V. S. 1410.4844

V. S. in progress

- Hierarchy of $v_2\{m\}$.
- **Complex $v_2\{4k\}$, $k \in \mathcal{Z}$; including $v_2\{4\}$ and $v_2\{8\}$**
- Experiment: high multiplicity pA $c_2\{4\} < 0 \rightsquigarrow v_2\{4\} \in \mathcal{R}$
- **Theory: connected graph only** $c_2\{4\} > 0 \rightsquigarrow v_2\{4\} \in \mathcal{C}$
- In order to describe high $k_\perp$ with IS effects, one needs disconnected graphs with azimuthal anisotropy
- Similar conclusion is valid for dense-dense limit and "glasma" graph

(Vladimir Skokov, Thursday)

MULTIPARTICLE CORRELATIONS AND COLLECTIVITY

- Multiparticle cumulants strongly imply collectivity in pA, AA
- At least 8 particles at a time are correlated; likely more
- $\Longrightarrow$ shouldn't consider pair correlation in isolation

COLLECTIVITY FROM PAIR CORRELATION

Collectivity implies a momentum structure to the pair correlation.
If pair distribution is dominated by single particle distribution:

$$V_{n\Delta}(p_T^a, p_T^b) \equiv \left\langle V_n^a V_n^{b*} \right\rangle$$
$$\Longrightarrow \quad V_{n\Delta}(p_T^a, p_T^a) \geq 0$$
$$V_{n\Delta}(p_T^a, p_T^b)^2 \leq V_{n\Delta}(p_T^a, p_T^a) V_{n\Delta}(p_T^b, p_T^b)$$

- If inequalities broken $\Longrightarrow$ unmistakable signal of intrinsic pair correlation ("non-flow")
- If first inequality satisfied, can define ratio

$$r_n \equiv \frac{V_{n\Delta}(p_T^a, p_T^b)}{\sqrt{V_{n\Delta}(p_T^a, p_T^a) V_{n\Delta}(p_T^b, p_T^b)}}$$

2nd inequality ensures $-1 \leq r_n \leq 1$ when dominated by collectivity

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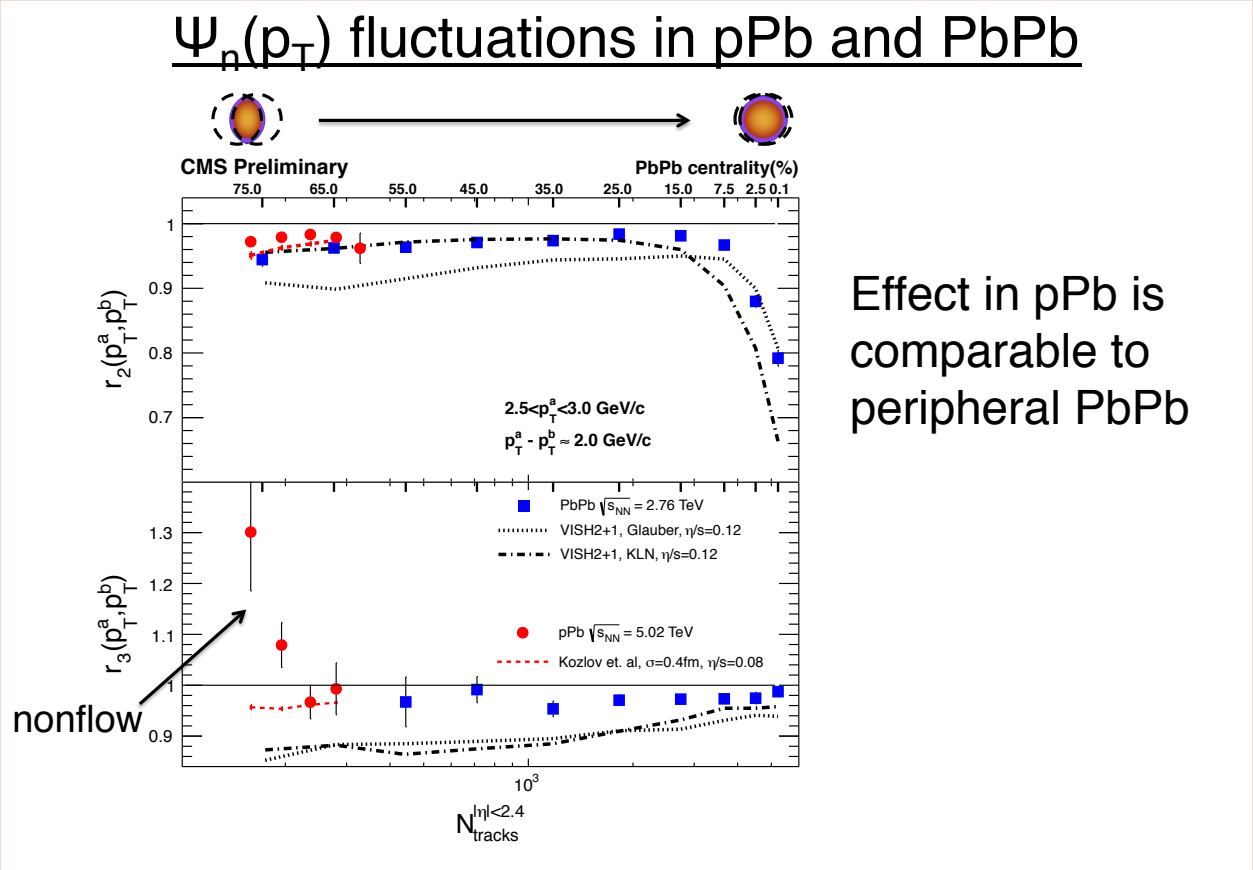
COLLECTIVITY FROM PAIR CORRELATION

r_n gives rigorous signal of pair correlation at low multiplicity, high p_T



Effect in pPb is comparable to peripheral PbPb

(Wei Li, Thursday)

Part 2: What generates collectivity?

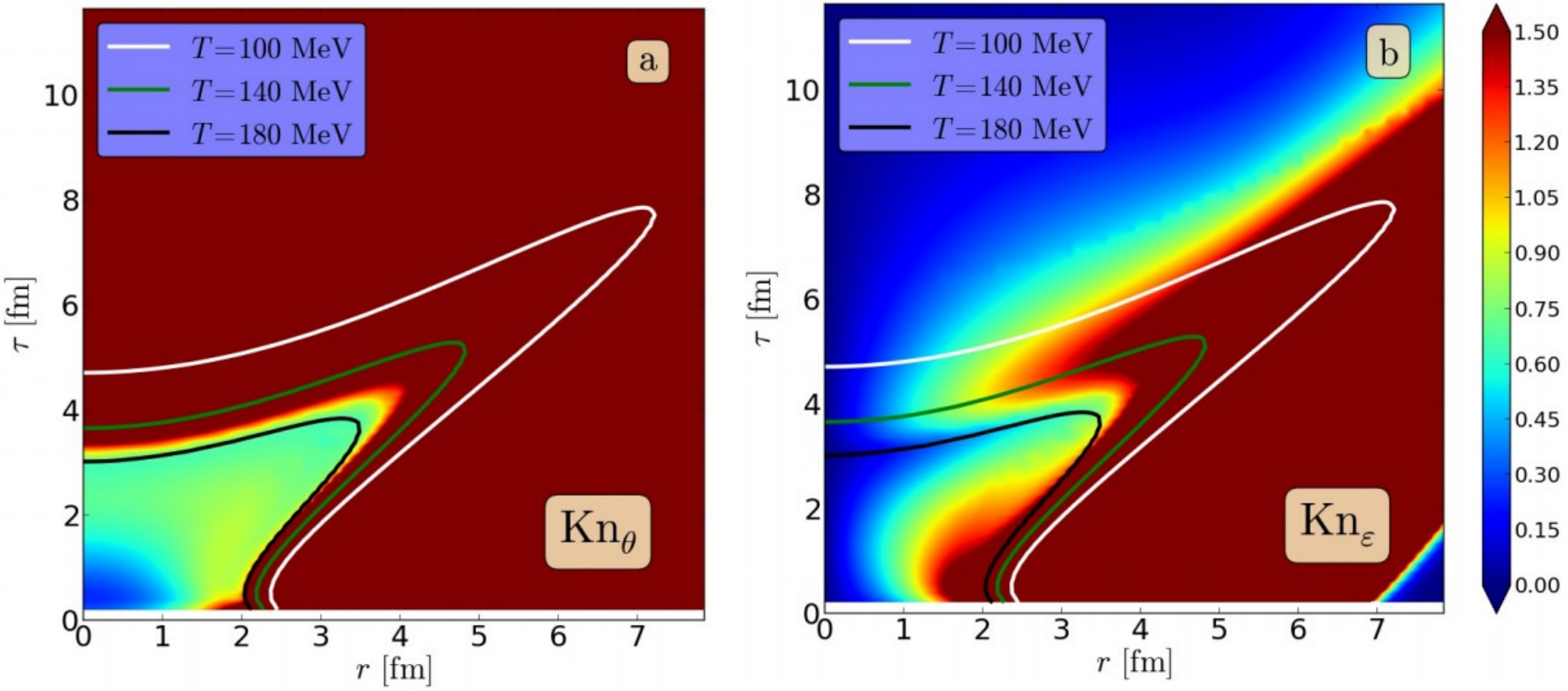
DO SMALL SYSTEMS BEHAVE HYDRODYNAMICALLY?

REMARK:

It's difficult to prove a theory is correct. The best one can do is try to disprove it, and failing that, look for other explanations that might be just as successful and more compelling.

KILLING HYDRO

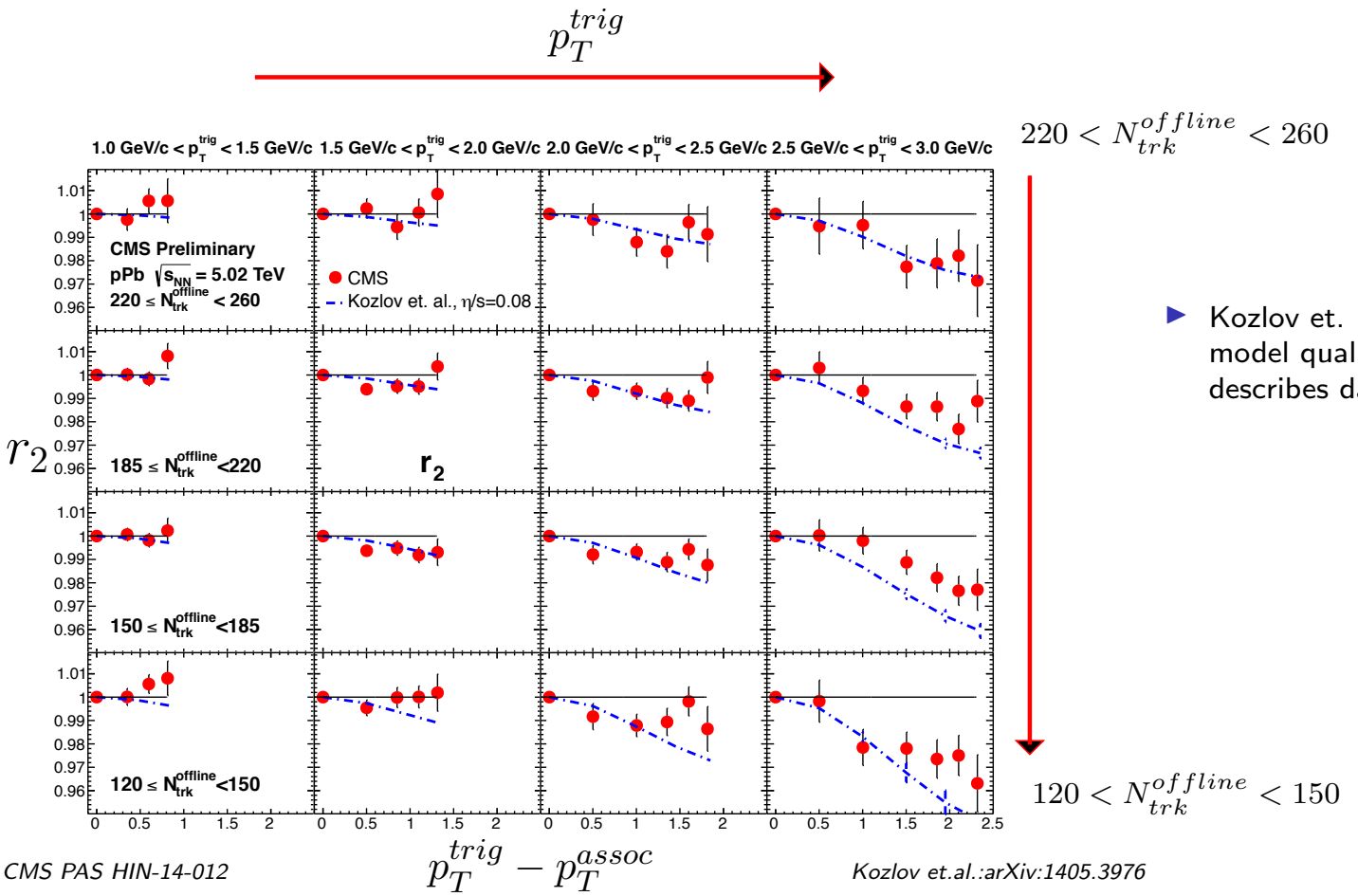
Is hydrodynamics valid in such small systems? Maybe.



(Niemi & Denicol, arXiv:1404.7327)

KILLING HYDRO

Pure hydro must have r_n<1; expect $r_n \sim 1$, increasing with multiplicity

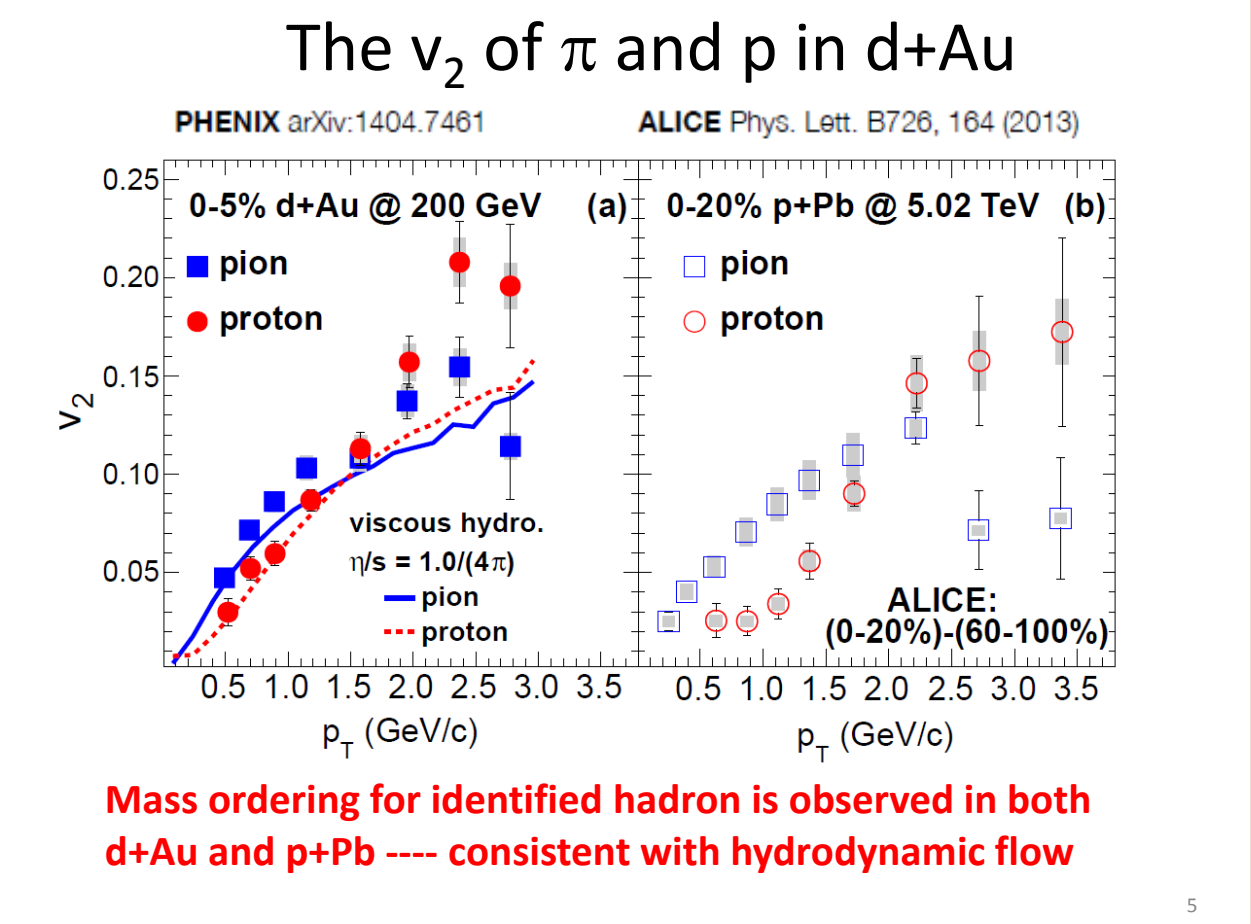


- Kozlov et. al. hydro model qualitatively describes data

(S. Devetak, QM2014)

GENERIC EXPECTATIONS

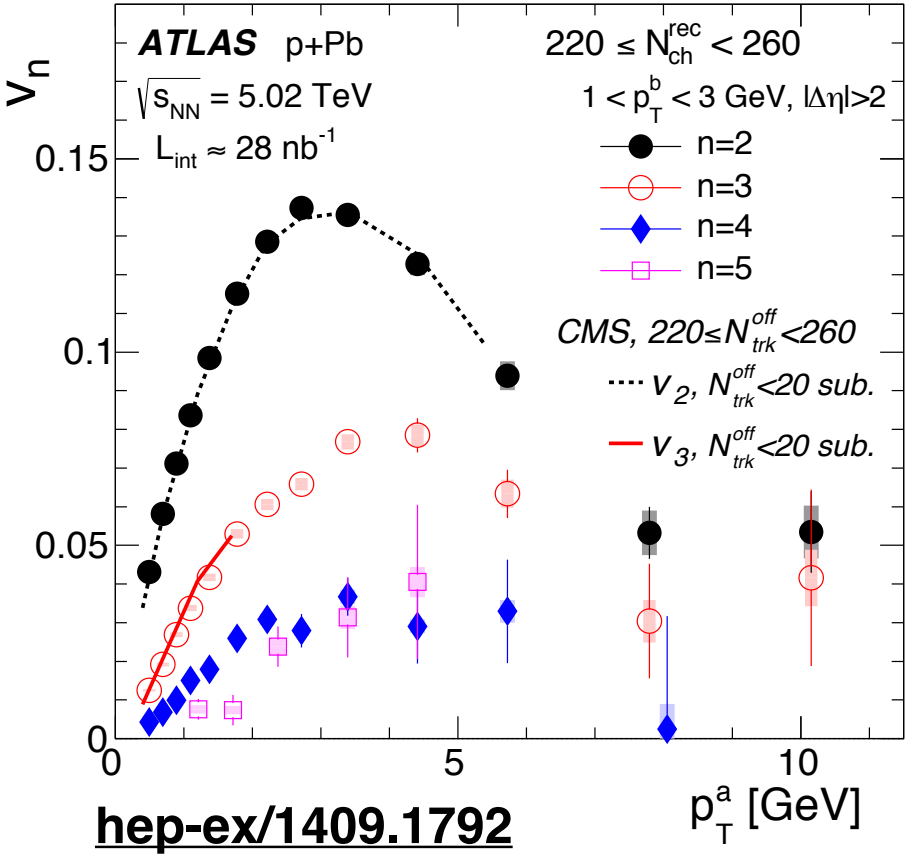
Mass ordering is also generic expectation from hydro



(Shengli Huang, Wednesday)

$v_n\{2\}$

Hadron pairs widely separated in p_T are correlated

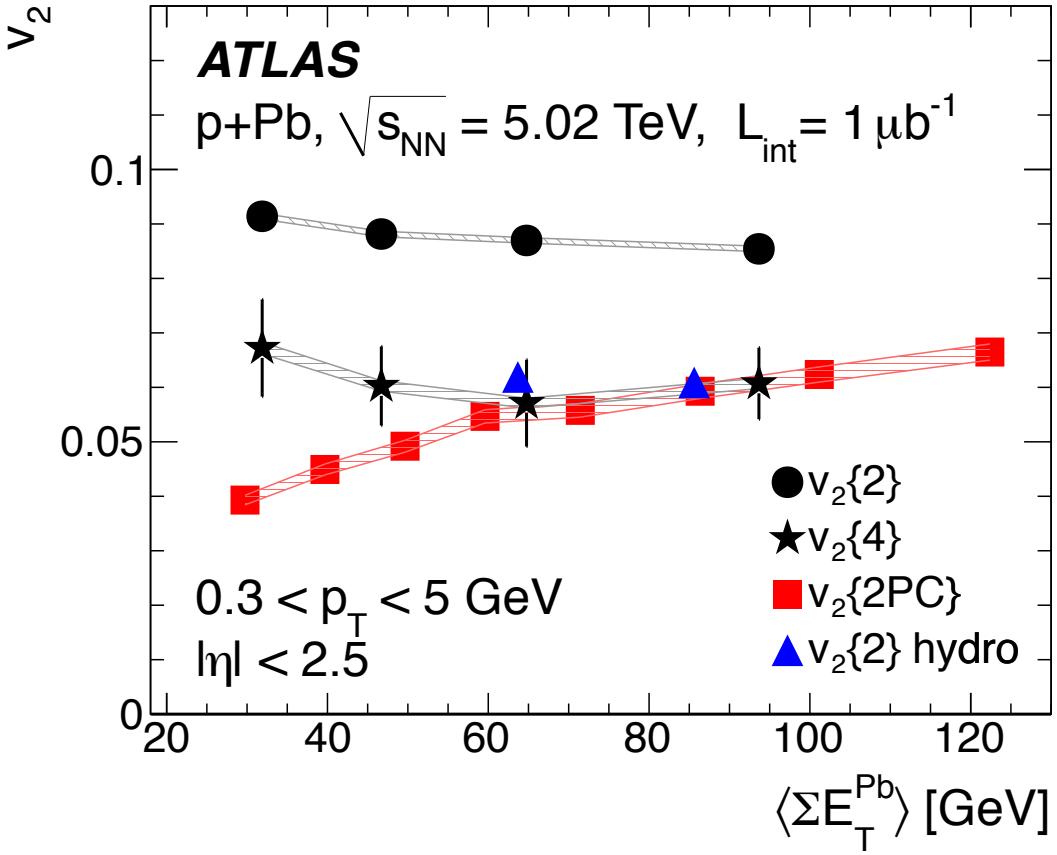


hep-ex/1409.1792

(Angerami, Wednesday)

HYDRO PREDICTIONS

Quantitative hydro predictions for p-Pb systems have been successful



(ATLAS, arXiv:1303.2084; prediction from Bozek & Broniowski, arXiv:1211.0845)

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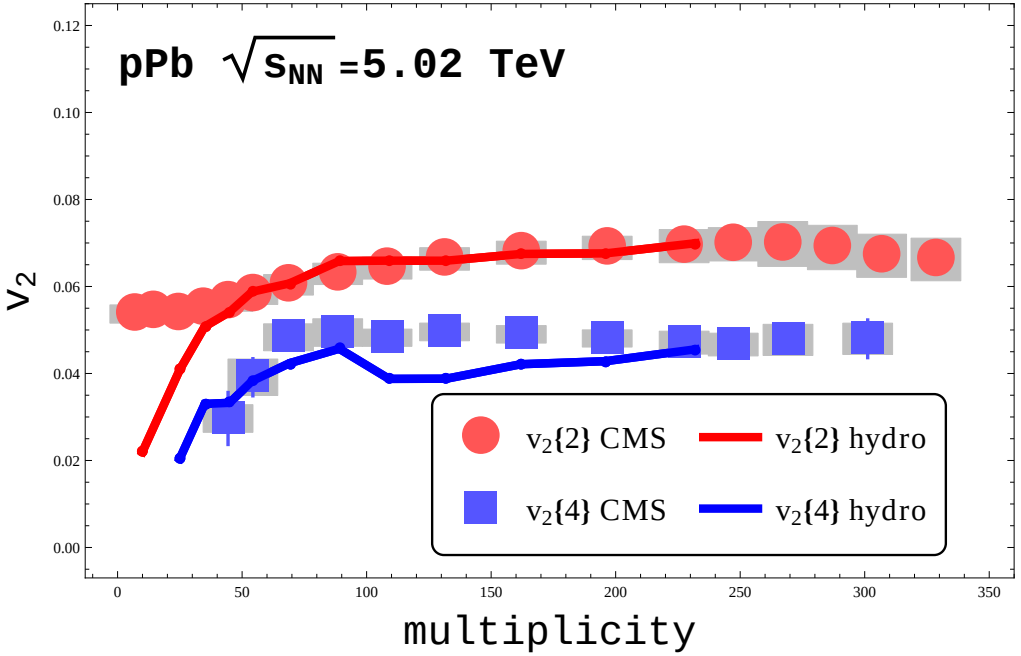
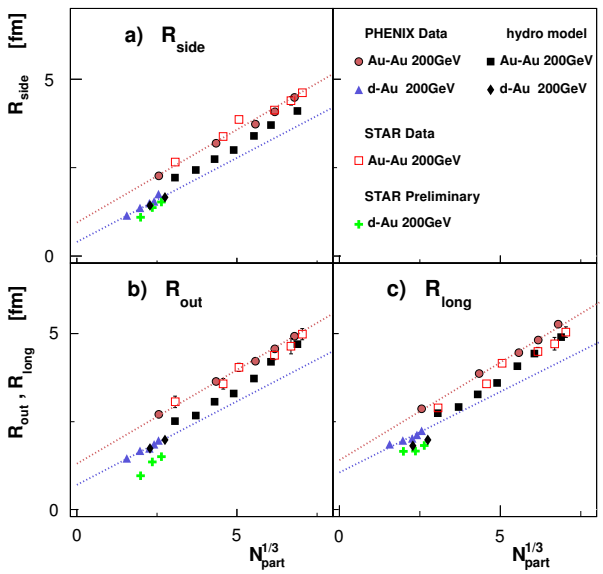


$$C(q, k_\perp) = 1 + \lambda e^{-R_o^2 q_o^2 - R_s^2 q_s^2 - R_l^2 q_l^2}$$



HBT in d-Au well described by hydro

(Kozlov, ML, Denicol, Jeon, Gale, arXiv:1405.3976) *(Bozek, Friday)*

Subsequently it has become clear that most (all?) relevant high-mult. p-Pb data can be described by hydrodynamic calculations

The correct interpretation is still an open question.
Interesting features that should be kept in mind when considering possible mechanisms for observed correlations:

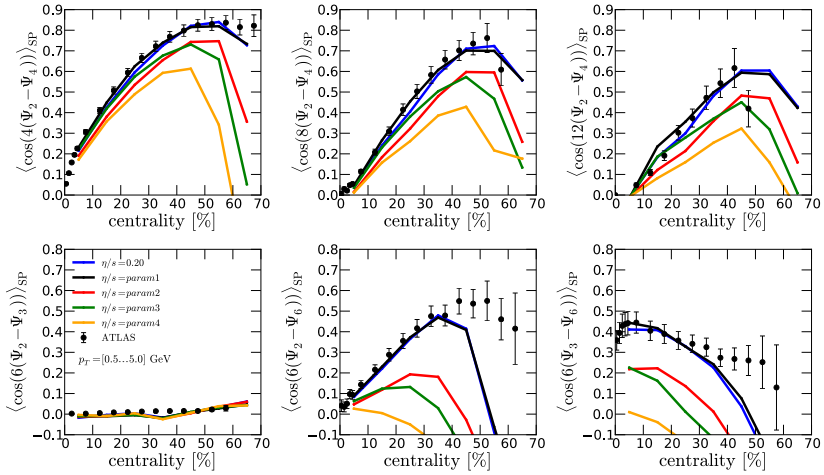
1. $v_n\{4\} \simeq v_n\{6\} \simeq v_n\{8\} \simeq v_n\{LYZ\} > 0$
2. Pair correlations almost factorized in p_T ($r_n \simeq 1$)
3. Dependence of correlations on multiplicity, system size
4. Correlation between particles of very different η, p_T

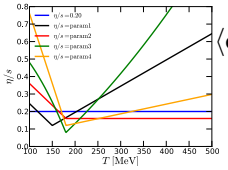
If all current data really admit multiple interpretations, more data may be needed.

Part 3: What can we learn from flow measurements?

QGP PROPERTIES

Event plane correlations at LHC

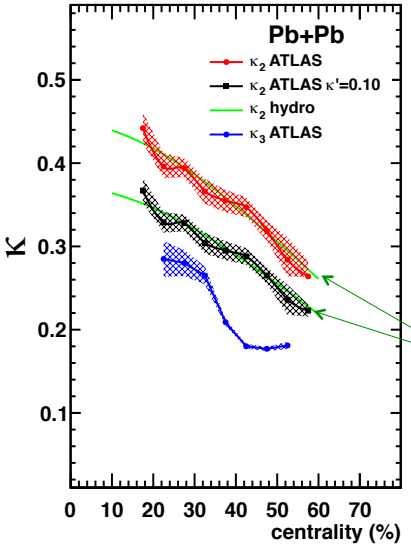




$$\langle \cos(k_1\Psi_1 + \ldots + nk_n\Psi_n)\rangle_{\rm SP} \equiv \frac{\langle v_1^{k_1}\ldots v_n^{k_n}\cos(k_1\Psi_1+\cdots+nk_n\Psi_n)\rangle_{\rm ev}}{\sqrt{\langle v_1^{2k_1}\rangle_{\rm ev}\ldots\langle v_n^{2k_n}\rangle_{\rm ev}}}$$

(Paatelainen, Wednesday)

κ Hydro Response Parameter



Assuming κ' does not vary with centrality

viscous hydro calc. of v/ε for η/s=0.19

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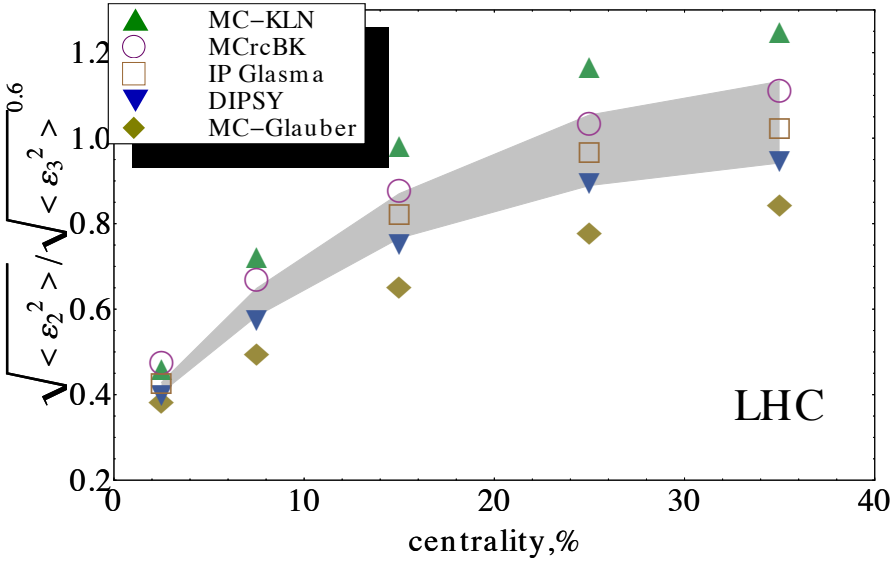
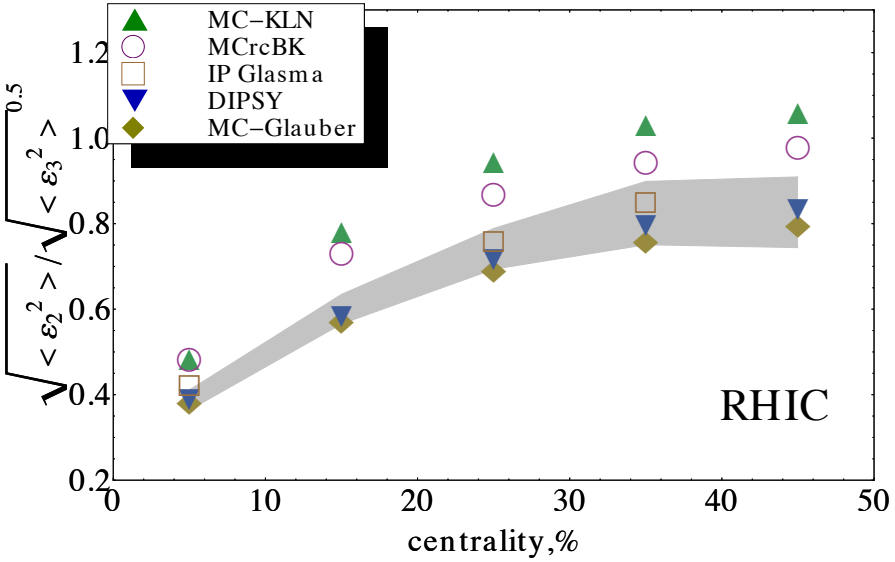
(Poskanzer, Thursday)

PROPERTIES OF INITIAL STATE FROM FLOW MEASUREMENTS



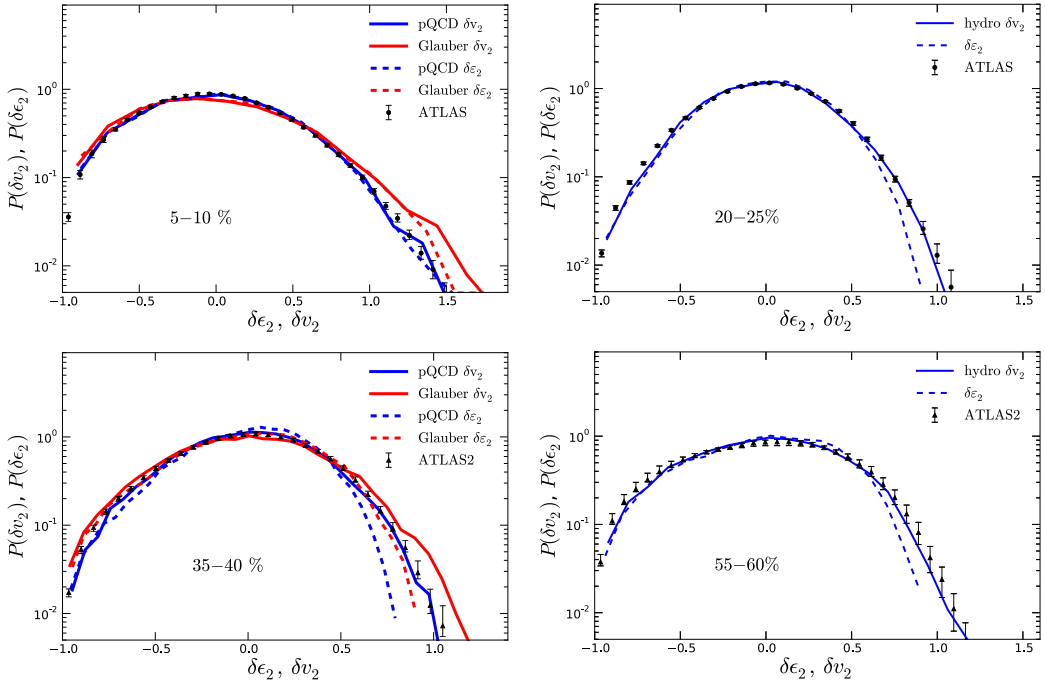


(Retinskaya, ML, Ollitrault, arXiv:1401.3241; IS2013 proceedings)

PROPERTIES OF INITIAL STATE FROM FLOW MEASUREMENTS

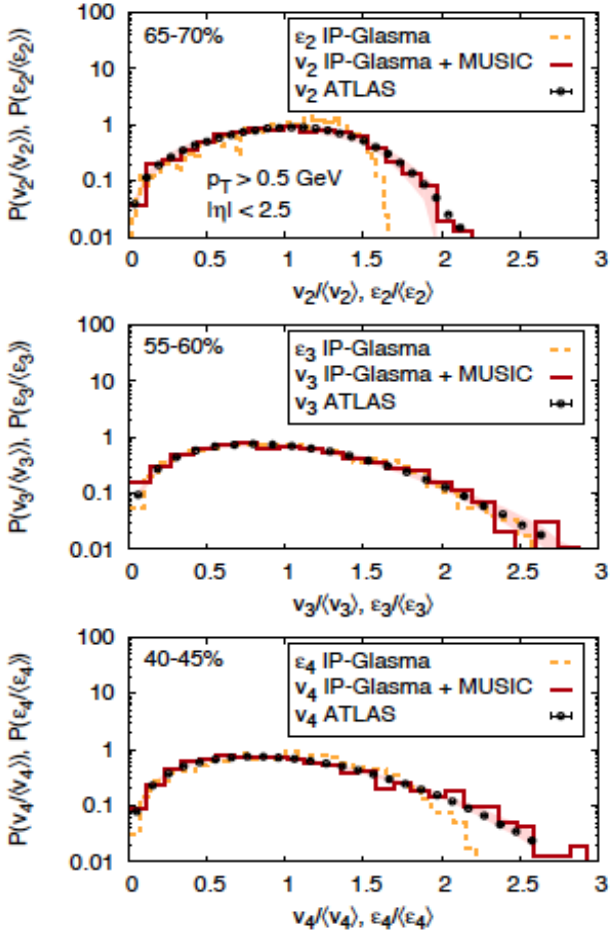
EbyE distributions of δv_2 and $\delta\epsilon_2$ at LHC

- constraint for initial state, not a viscous effect!



(Paatelainen, Wednesday)

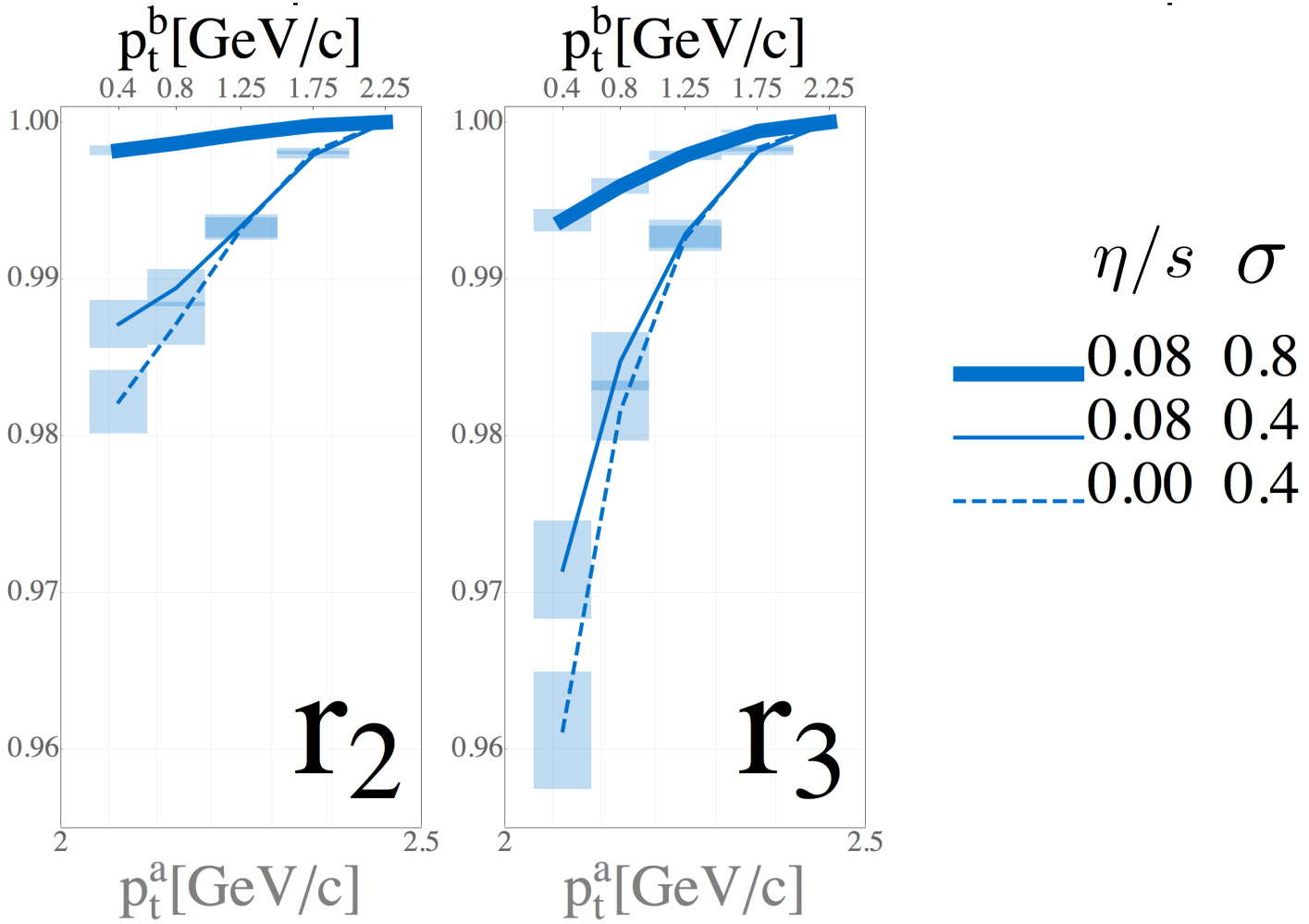
Schenke, Venugopalan, PRL 113 (2014) 102301



(Venugopalan, Wednesday)

INVESTIGATING THE LENGTH SCALE OF FLUCTUATIONS

r_n insensitive to viscosity, sensitive to granularity



(Kozlov, ML, Denicol, Jeon, Gale, arXiv:1405.3976)

CONCLUSIONS

- Strong evidence of collectivity seen in p-A collisions (slightly weaker in d-A, and much weaker in p-p)
- Source of collectivity still under investigation, but strong constraints exist in data.
- My opinion: hydro looks most promising at present for high-multiplicity p-Pb.
- When hydro is applicable — e.g. in A-A collisions — information can be obtained about initial state despite strong final state effects

Extra Slides