COLLECTIVE BEHAVIOR IN SMALL COLLISION SYSTEMS

Matthew Luzum

I. Kozlov, ML, G. Denicol, S. Jeon, C. Gale; arXiv:1405.3976

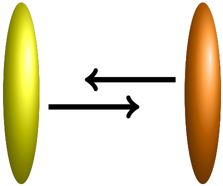
Universidade de Santiago de Compostela

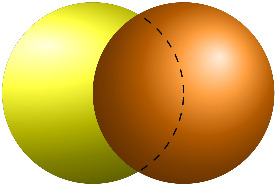
July 15, 2015

Outline

1. Introduction
   - Perfect fluidity in nucleus-nucleus collisions
   - Similar observation in proton-nucleus collisions
2. Hydrodynamic calculations
   - Comparison to existing data
3. Proposal for new measurement r_n
   - Transverse momentum structure of pair correlation
   - Predictions
   - Comparison to subsequent measurements

WHAT WE SEE IN A-A COLLISIONS: PAIR CORRELATION





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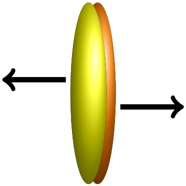

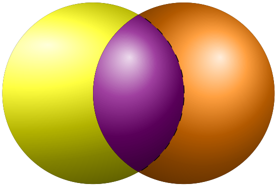

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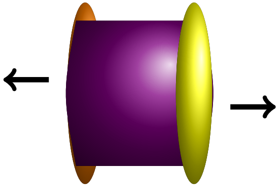

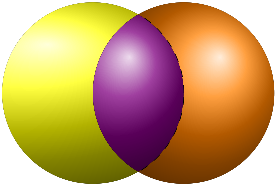

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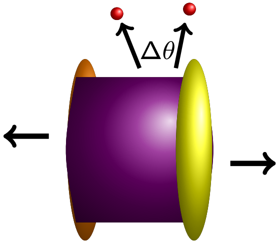

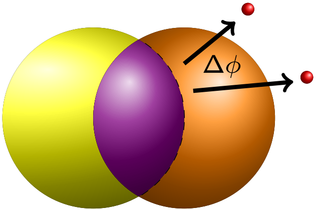

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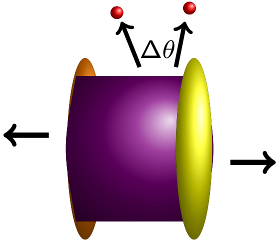
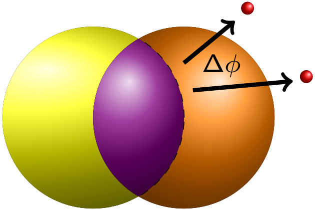
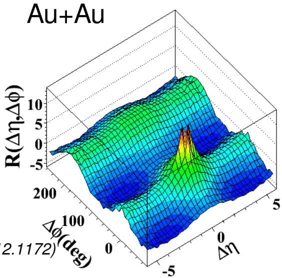




$$\sim \frac{dN_{pairs}}{d\Delta\eta d\Delta\phi}$$



(PHOBOS, arXiv:0812.1172)

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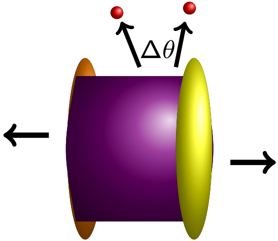

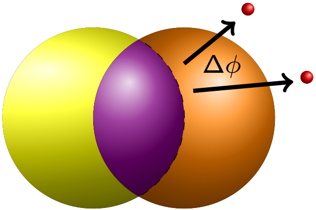

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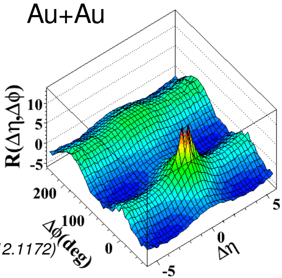

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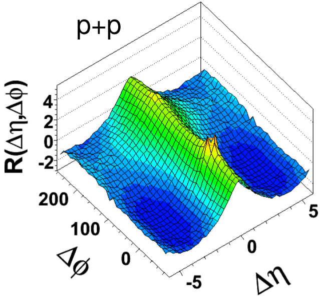

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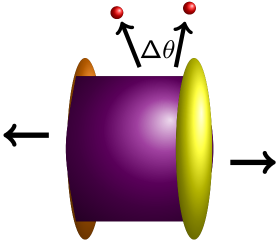

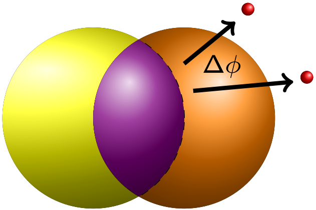

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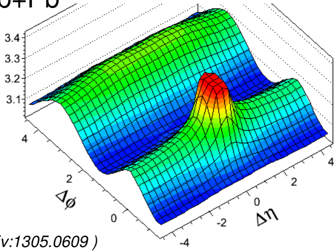
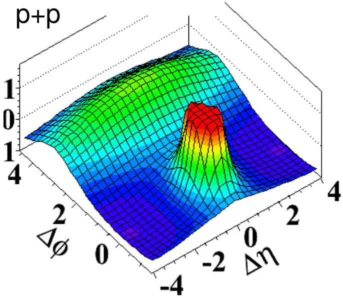
Pb+Pb



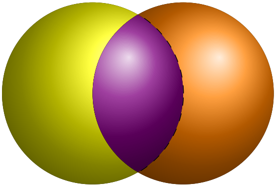
(CMS, arXiv:1305.0609)

p+p



INTERPRETATION: FLOW

- Hydro picture: system thermalizes and expands as fluid
- Particles emitted independently at end of evolution



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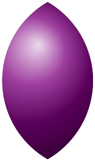

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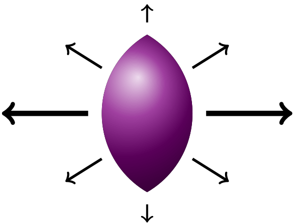

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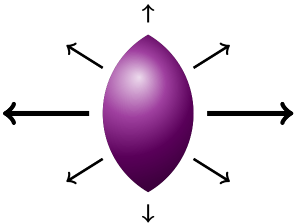

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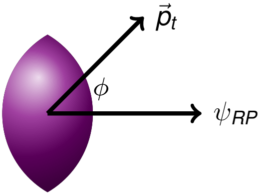
$$\frac{2\pi}{N}\frac{dN}{d\phi} \simeq 1 + 2v_2 \cos 2\phi$$



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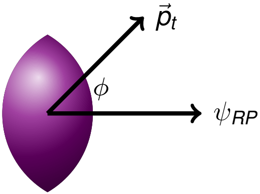
$$\frac{2\pi}{N}\frac{dN}{d\phi} \simeq 1 + 2v_2 \cos 2\phi$$

- $\Longrightarrow$ pair distribution is product of single-particle distributions

$$\frac{dN_{\text{pairs}}}{d^3p^a d^3p^b} = \frac{dN}{d^3p^a} \times \frac{dN}{d^3p^b}$$



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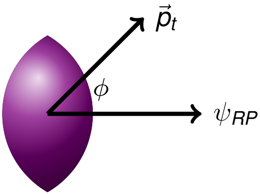
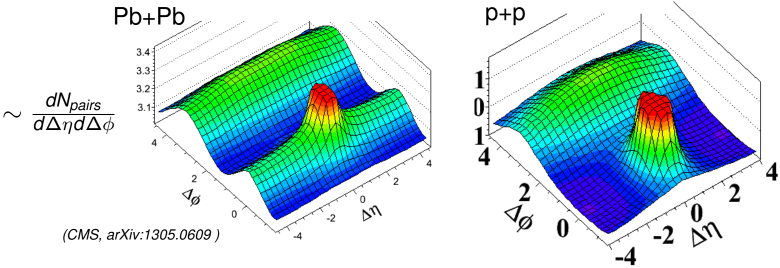
$$\frac{dN_{\text{pairs}}}{d\Delta\phi} \overset{\text{(flow)}}{\propto} 1 + 2{v_2}^2 \cos 2(\Delta\phi)$$



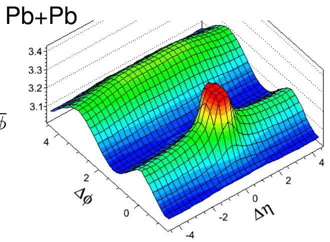
FLOW-LIKE CORRELATIONS IN P-A COLLISIONS

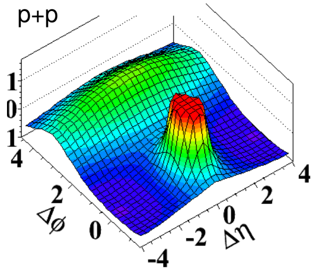


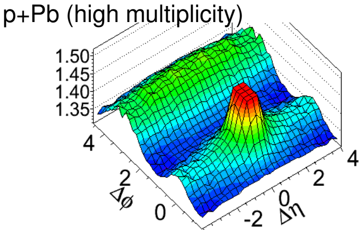
(CMS, arXiv:1305.0609)

FLOW-LIKE CORRELATIONS IN P-A COLLISIONS

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







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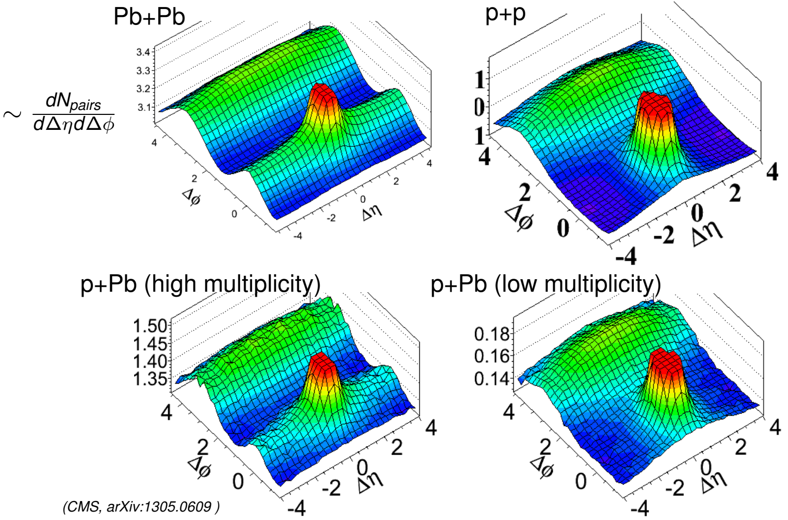

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FLOW IN HEAVY-ION COLLISIONS

- Validity of hydrodynamics requires separation of scales
- $\Longrightarrow$ should break down when system size becomes too small

QUESTIONS

- Do the observed pA correlations indicate collective behavior?
- Can proton-nucleus collision behave as a fluid?

Flow in heavy-ion collisions

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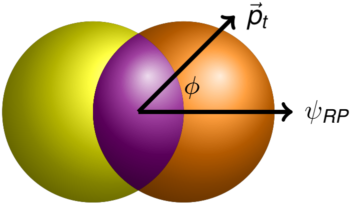
MEASURING v_n

$$\frac{2\pi}{N}\frac{dN}{d\phi} \simeq 1 + 2v_2 \cos 2\phi$$



MEASURING v_n

Fluctuations are important!

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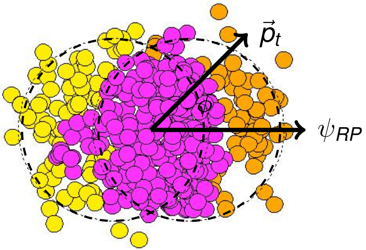

Measuring v_n

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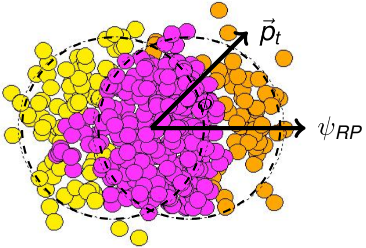
$$\frac{2\pi}{N}\frac{dN}{d\phi} = 1 + \sum_{n=1}^{\infty} 2 v_n \cos n(\phi - \psi_n)$$



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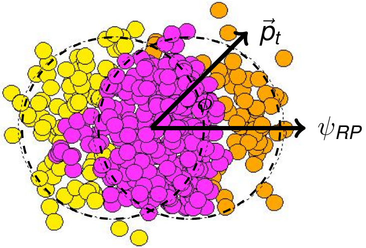

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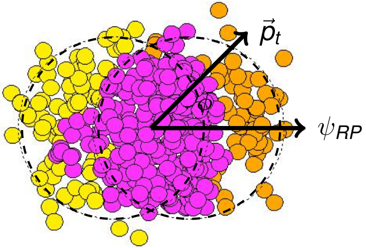

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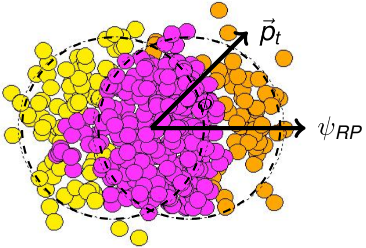
$$\left\langle \langle e^{in(\phi_1+\phi_2-\phi_3-\phi_4)} \rangle_{\text{quad.}} \right\rangle \overset{\text{(flow)}}{=} \left\langle v_n^4 \right\rangle$$



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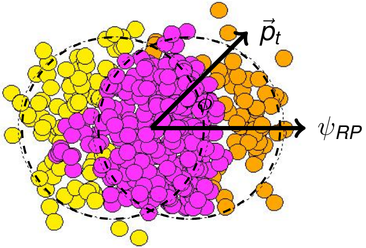
$$\left\langle \langle e^{in(\phi_1+\phi_2-\phi_3-\phi_4)} \rangle_{\text{quad.}} \right\rangle - 2 v_n\{2\}^2 = -v_n\{4\}^4 \overset{\text{(flow)}}{=} \left\langle v_n^4 \right\rangle - 2 \left\langle v_n^2 \right\rangle^2$$

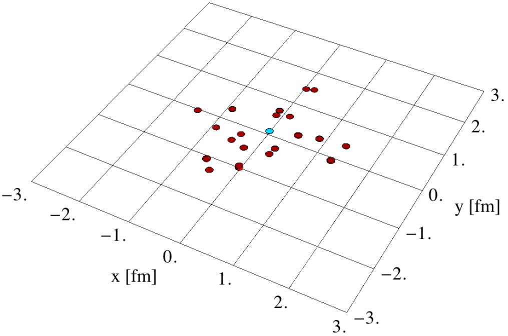


STRATEGY

1. Explore plausibility:
    - Perform hydrodynamic calculations of p-Pb collisions
    - Look for generic trends
    - Is it possible to naturally describe (simultaneously) existing data with a reasonable model?
2. Look for “smoking gun”:
    - Try to find more rigorous test of collectivity
    - Can we kill flow as a possible explanation for data?
    - Make predictions (and compare to subsequent measurements)

DETAILS OF HYDRODYNAMIC CALCULATIONS

Start with traditional Glauber participant model:

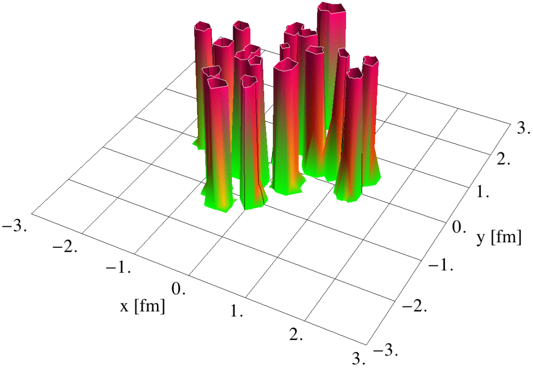


(Animation from Igor Kozlov)

DETAILS OF HYDRODYNAMIC CALCULATIONS

Start with traditional Glauber participant model:
Each 'participant' contributes entropy as transverse Gaussian

$$\sigma = 0.05 \text{ fm}$$

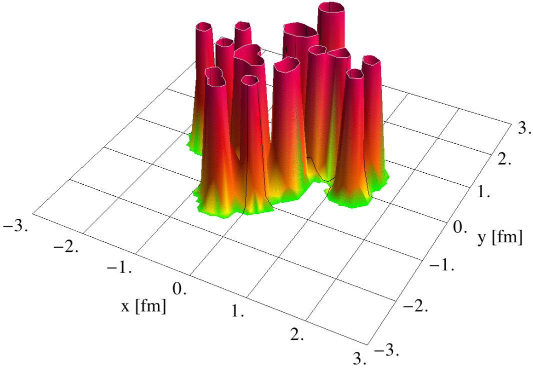


(Animation from Igor Kozlov)

DETAILS OF HYDRODYNAMIC CALCULATIONS

Start with traditional Glauber participant model:
Each 'participant' contributes entropy as transverse Gaussian

$$\sigma = 0.10 \text{ fm}$$

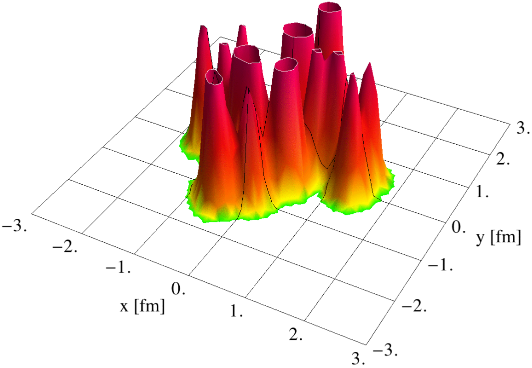


(Animation from Igor Kozlov)

DETAILS OF HYDRODYNAMIC CALCULATIONS

Start with traditional Glauber participant model:
Each 'participant' contributes entropy as transverse Gaussian

$$\sigma = 0.15 \text{ fm}$$

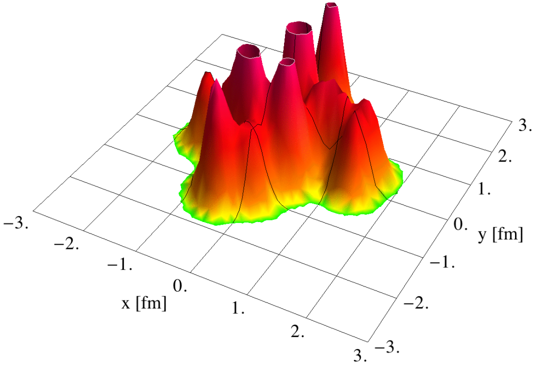


(Animation from Igor Kozlov)

DETAILS OF HYDRODYNAMIC CALCULATIONS

Start with traditional Glauber participant model:
Each 'participant' contributes entropy as transverse Gaussian

$$\sigma = 0.20 \text{ fm}$$

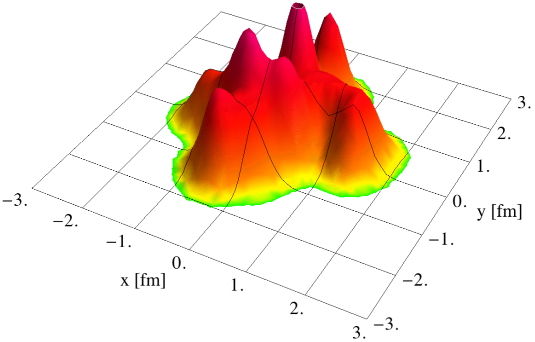


(Animation from Igor Kozlov)

DETAILS OF HYDRODYNAMIC CALCULATIONS

Start with traditional Glauber participant model:
Each ‘participant’ contributes entropy as transverse Gaussian

$$\sigma = 0.25 \text{ fm}$$

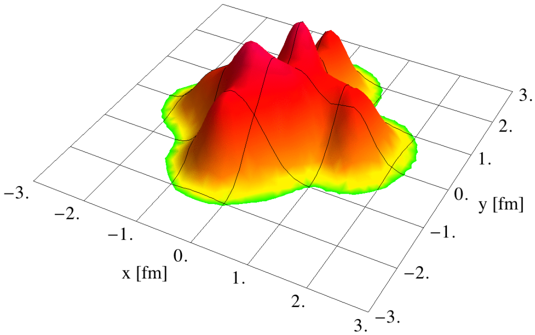


(Animation from Igor Kozlov)

DETAILS OF HYDRODYNAMIC CALCULATIONS

Start with traditional Glauber participant model:
Each 'participant' contributes entropy as transverse Gaussian

$$\sigma = 0.30 \text{ fm}$$

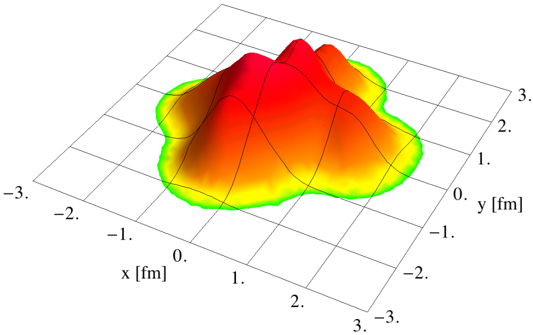


(Animation from Igor Kozlov)

DETAILS OF HYDRODYNAMIC CALCULATIONS

Start with traditional Glauber participant model:
Each 'participant' contributes entropy as transverse Gaussian

$$\sigma = 0.35 \text{ fm}$$

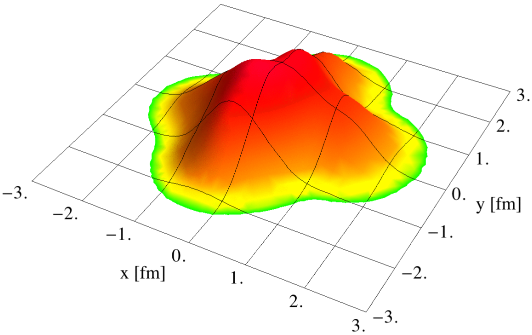


(Animation from Igor Kozlov)

DETAILS OF HYDRODYNAMIC CALCULATIONS

Start with traditional Glauber participant model:
Each 'participant' contributes entropy as transverse Gaussian

$$\sigma = 0.40 \text{ fm}$$

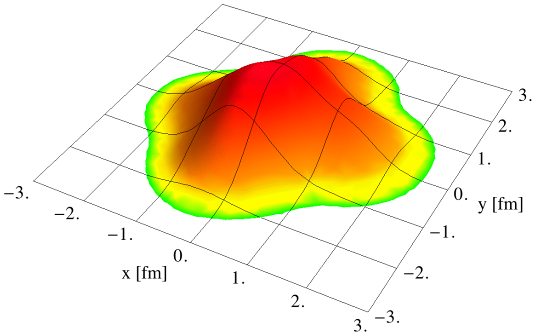


(Animation from Igor Kozlov)

DETAILS OF HYDRODYNAMIC CALCULATIONS

Start with traditional Glauber participant model:
Each 'participant' contributes entropy as transverse Gaussian

$$\sigma = 0.45 \text{ fm}$$

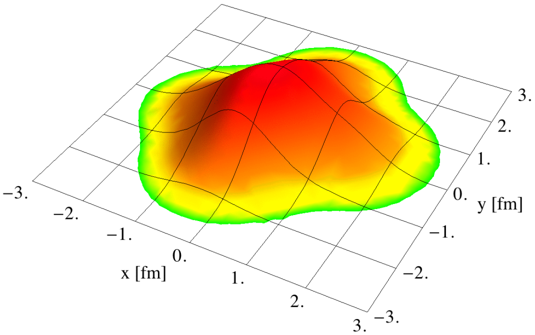


(Animation from Igor Kozlov)

DETAILS OF HYDRODYNAMIC CALCULATIONS

Start with traditional Glauber participant model:
Each 'participant' contributes entropy as transverse Gaussian

$$\sigma = 0.50 \text{ fm}$$



(Animation from Igor Kozlov)

DETAILS OF HYDRODYNAMIC CALCULATIONS

Start with traditional Glauber participant model:
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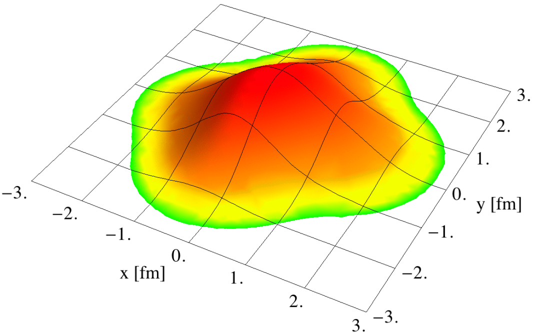
$$\sigma = 0.55 \text{ fm}$$



(Animation from Igor Kozlov)

DETAILS OF HYDRODYNAMIC CALCULATIONS

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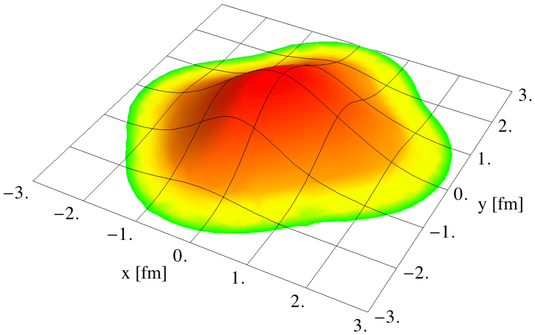

(Animation from Igor Kozlov)

DETAILS OF HYDRODYNAMIC CALCULATIONS

Start with traditional Glauber participant model:
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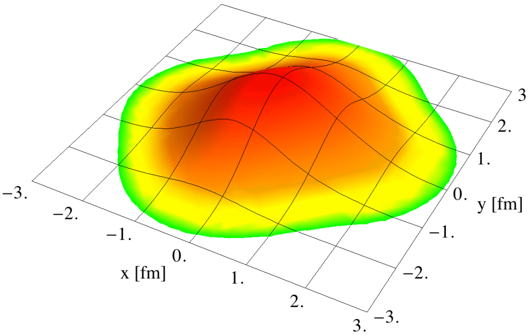
$$\sigma = 0.65 \text{ fm}$$

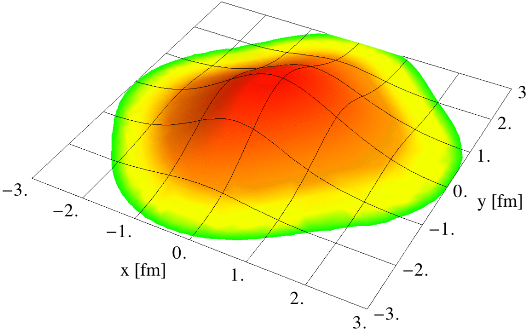


(Animation from Igor Kozlov)

DETAILS OF HYDRODYNAMIC CALCULATIONS

Start with traditional Glauber participant model:
Each ‘participant’ contributes entropy as transverse Gaussian

$$\sigma = 0.70 \text{ fm}$$



(Animation from Igor Kozlov)

Details of hydrodynamic calculations

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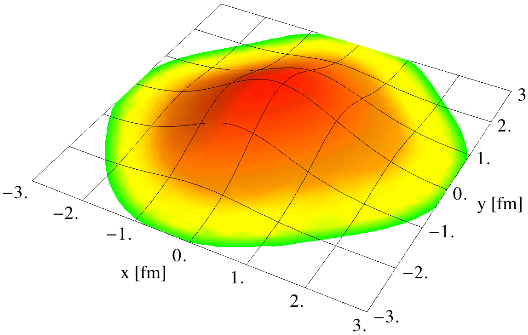
$$\sigma = 0.75 \text{ fm}$$



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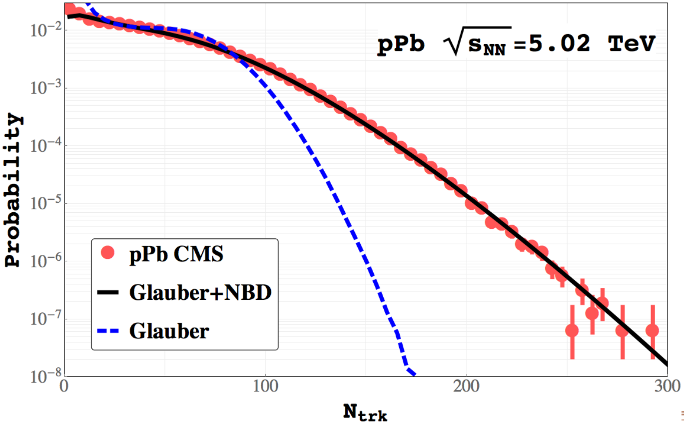
DETAILS OF HYDRODYNAMIC CALCULATIONS

GLAUBER + NBD

Entropy contribution of each participant chosen according to Negative Binomial Distribution



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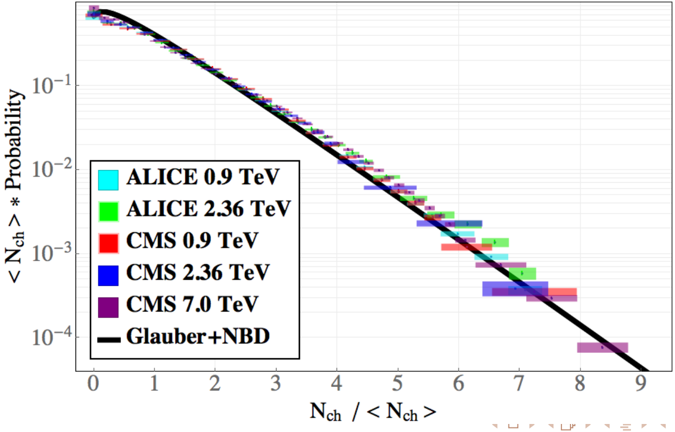
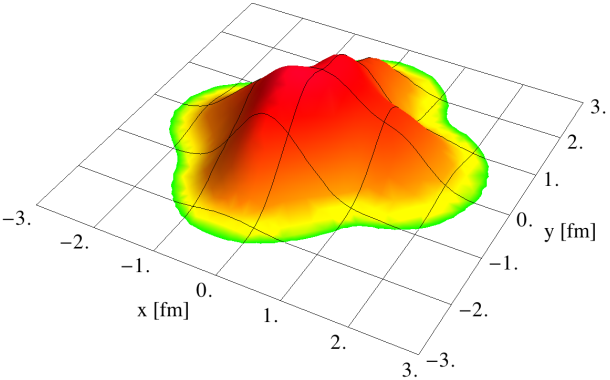


DETAILS OF HYDRODYNAMIC CALCULATIONS

Without NBD:

$$\sigma = 0.40 \text{ fm}$$



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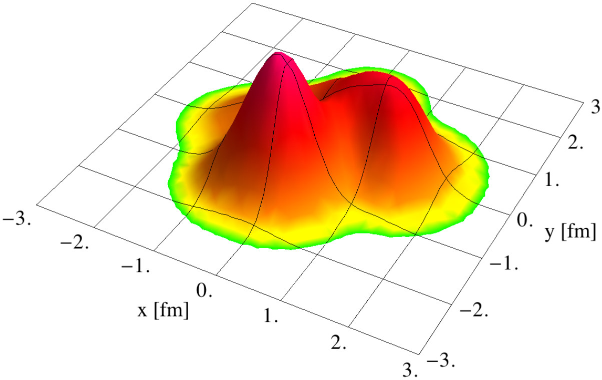
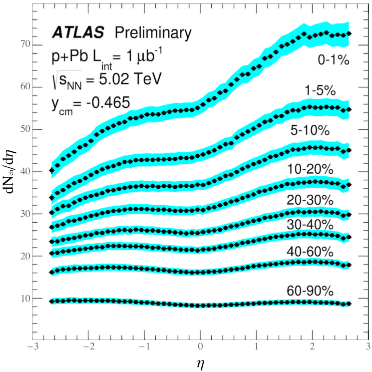
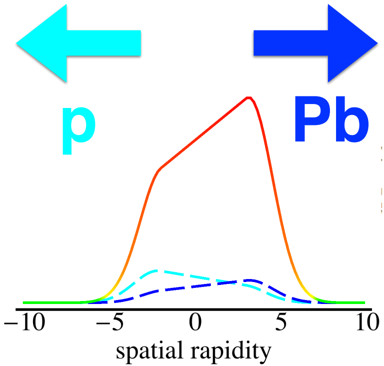


DETAILS OF HYDRODYNAMIC CALCULATIONS

GLAUBER + RAPIDITY DEPENDENCE

Choose asymmetric contribution from each participant





(ATLAS arXiv:1403.5738)

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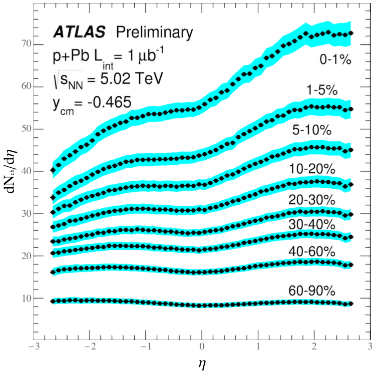

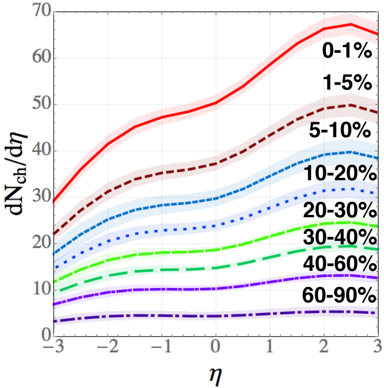

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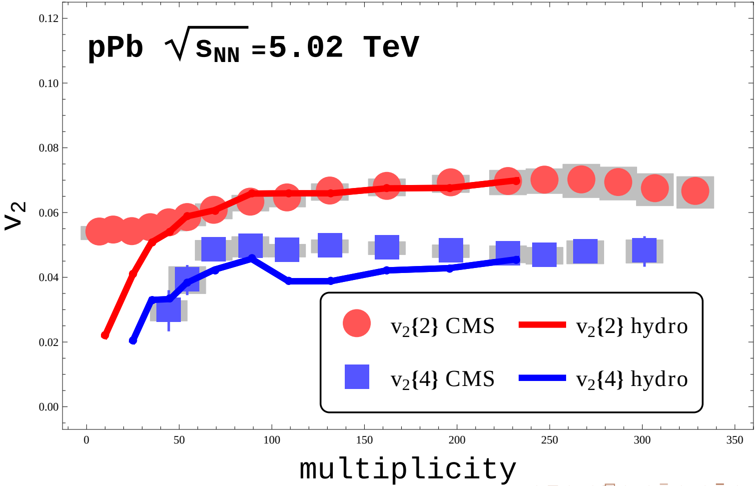
Results: v_2

$\sigma = 0.4$ fm, $\eta/s = 0.08$



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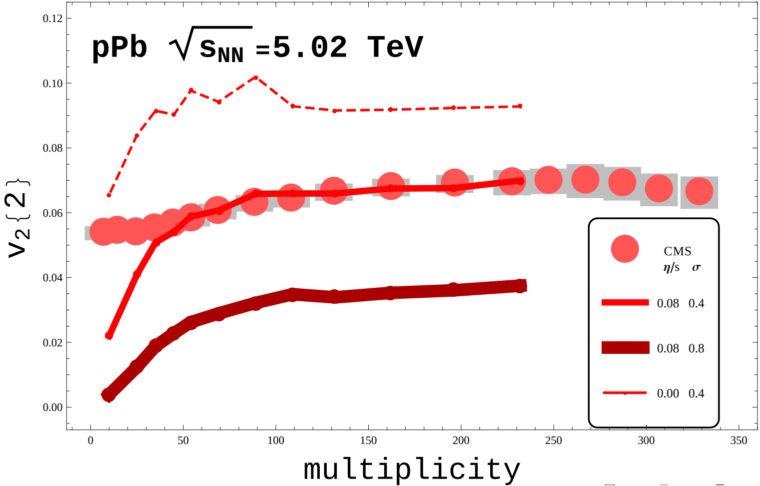
σ = 0.4–0.8 fm, η/s = 0.0–0.08



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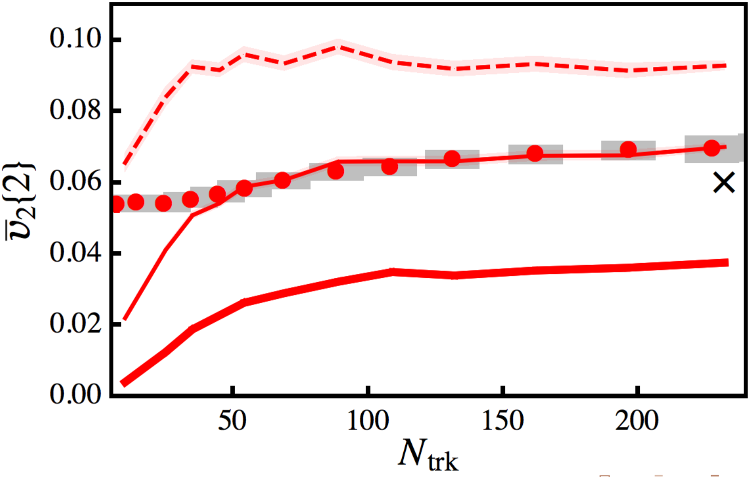

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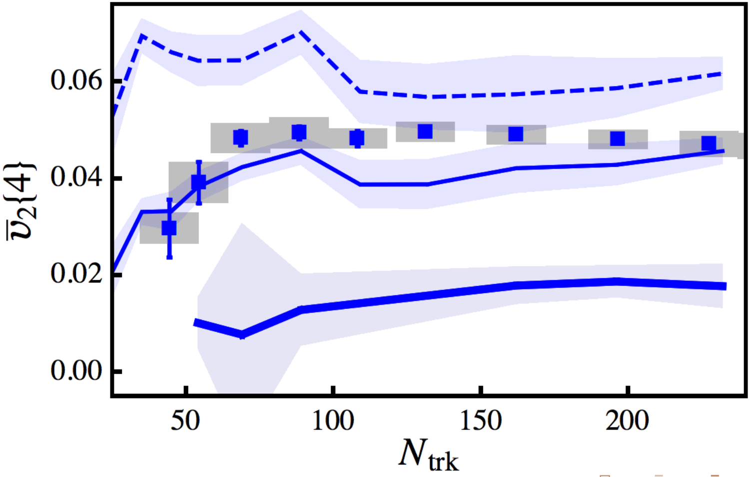

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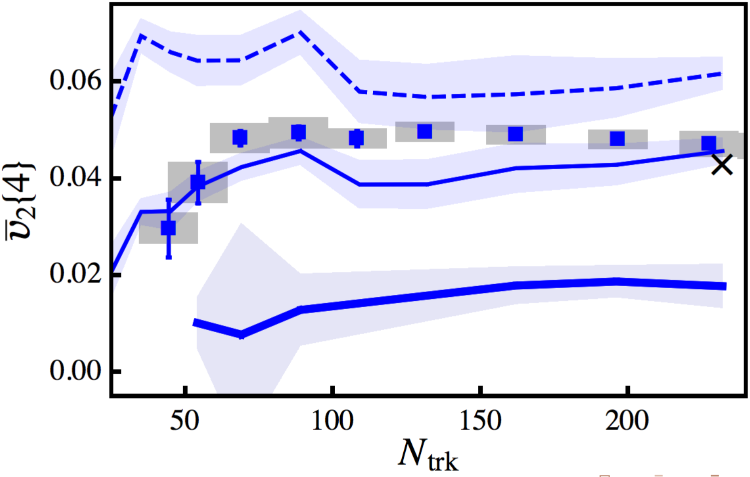

Results: $v_2\{2\}(p_T)$

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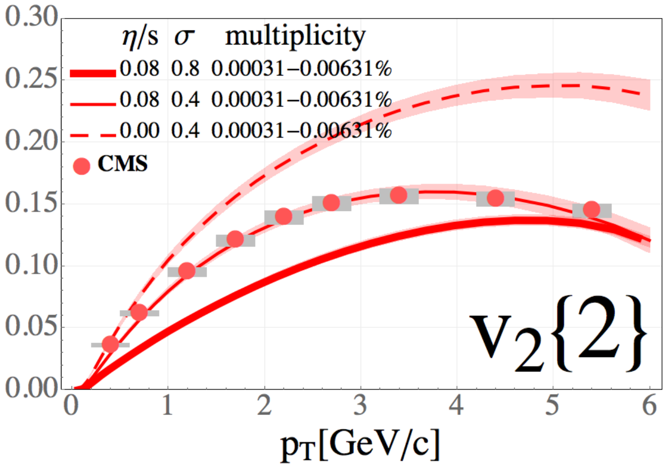

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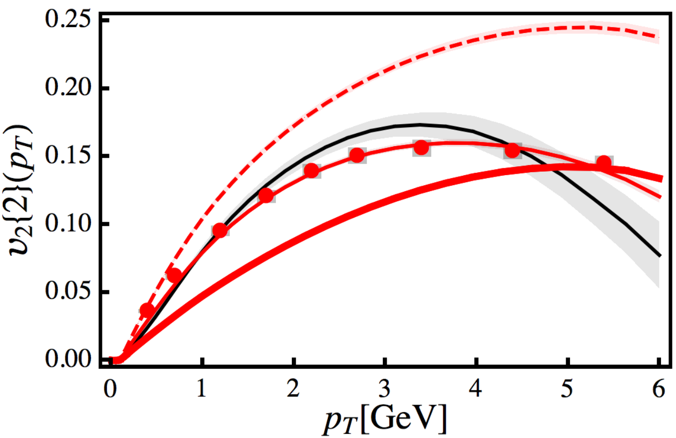

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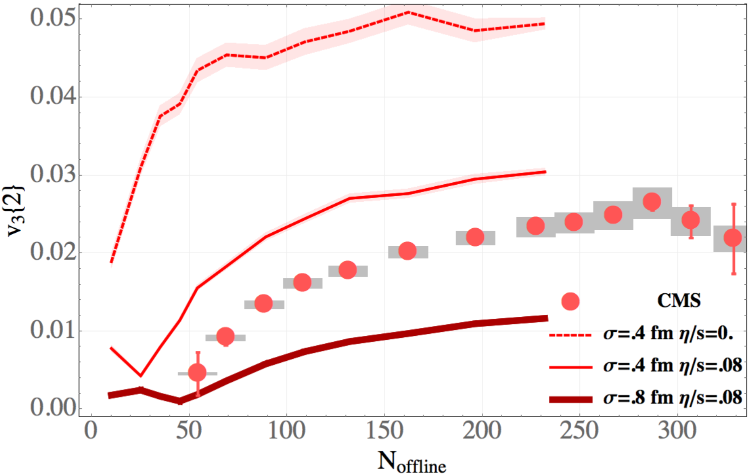

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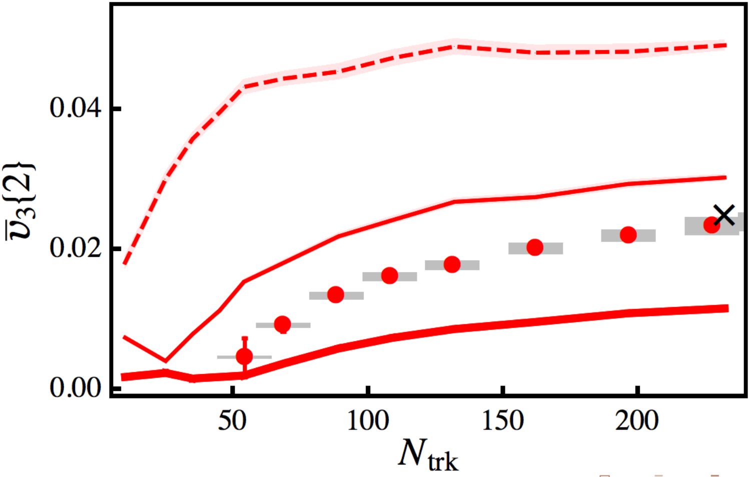

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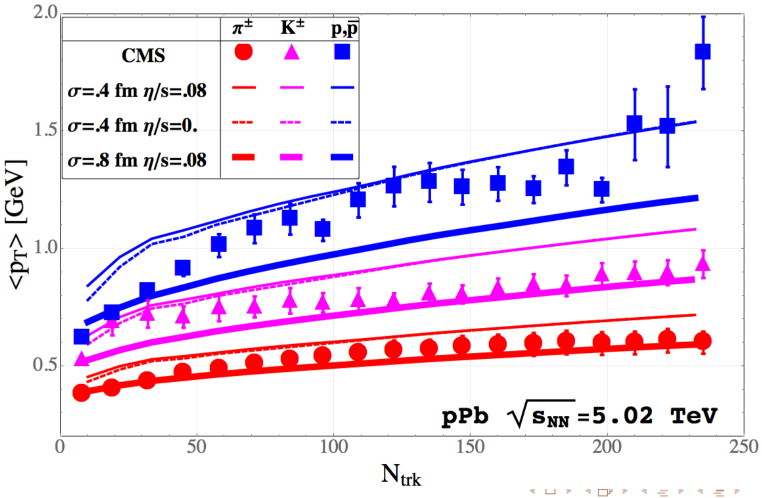
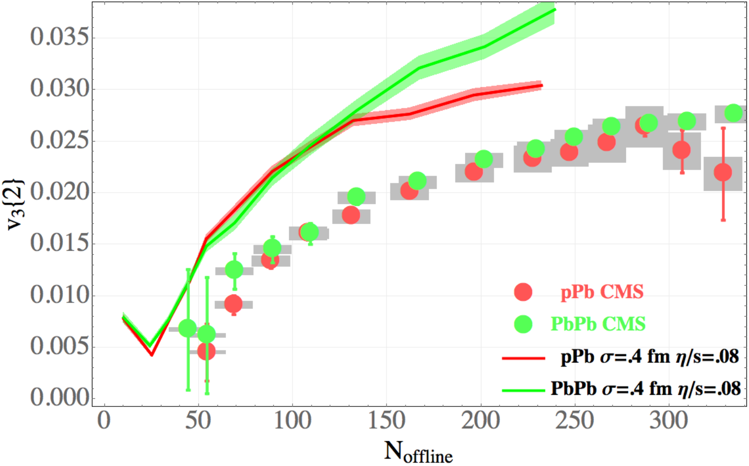


RESULTS: $v_3\{2\}$

$v_3\{2\}$ the same in p-Pb and Pb-Pb:



HOW DO WE UNDERSTAND v_3 IN PA VS. AA?

We compare collisions with the same multiplicity.
A naive expectation:

- $dN/d\eta \propto N_{part} \implies$ equal N_{part}
- $\varepsilon_3 \propto 1/\sqrt{N_{part}} \implies$ equal ε_3

How do we understand v_3 in pA vs. AA?

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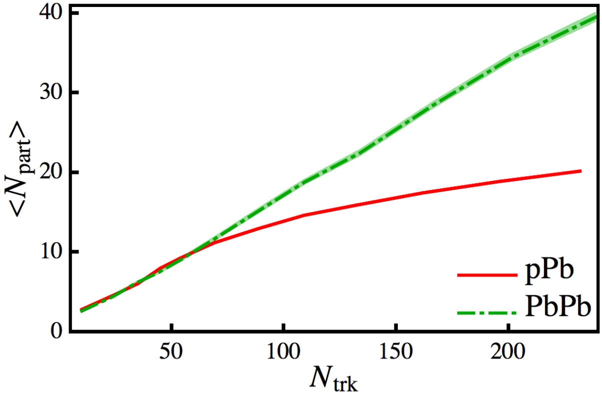

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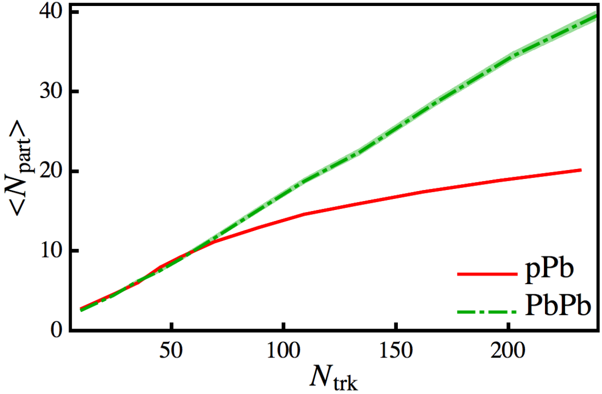

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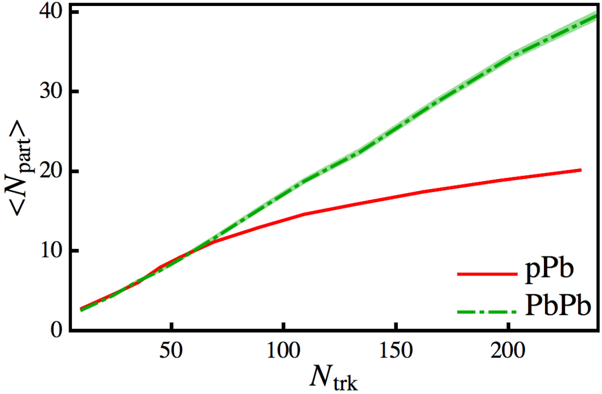

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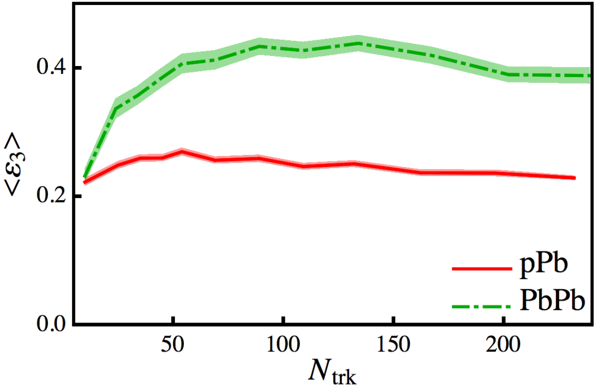

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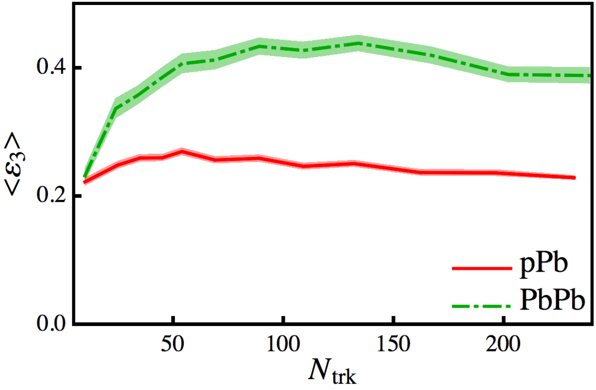

INTERIM CONCLUSIONS

- Hydrodynamic calculations can reasonably describe many observables in high multiplicity p-Pb collisions
- Collective flow remains as a plausible explanation

QUESTION

Can we come up with a new measurement that will act as a more strict test of collectivity?

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Two-particle correlation is a multidimensional matrix:

$$\left\langle \cos n(\phi^a - \phi^b) \right\rangle = f(p_T^a, \eta^a, p_T^b, \eta^b)$$

- Most "flow" measurements v_n probe momentum of at most one particle of the pair
- $\Longrightarrow$ There is more information available!
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FLOW

- In the flow picture, particles are emitted according to an underlying probability (which differs from event to event):

$$\frac{2\pi}{N}\frac{dN}{d\phi} = \sum_{n=-\infty}^{\infty} V_n e^{-in\phi}$$

$$V_n = \{e^{-in\phi}\} = v_n e^{in\Psi_n}$$

$$\frac{dN_{pairs}}{d^3p^a d^3p^b} = \frac{dN}{d^3p^a} \times \frac{dN}{d^3p^b} + C(p^a, p^b)$$

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$$\implies \langle \cos n(\phi^a-\phi^b)\rangle \overset{\text{(flow)}}{=} \left\langle v_n(p_T^a) v_n(p_T^b) \cos n\left(\Psi_n(p_T^a) - \Psi_n(p_T^b)\right)\right\rangle$$

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This expression directly implies a set of inequalities:

$$V_{n\Delta}(p_T^a, p_T^b) \equiv \left\langle V_n^a V_n^{b*} \right\rangle = \left\langle v_n^a v_n^b \cos n(\Psi_n^a - \Psi_n^b) \right\rangle$$

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- If inequalities broken $\implies$ unmistakable signal of non-flow
- If first inequality is satisfied, we can define the ratio

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

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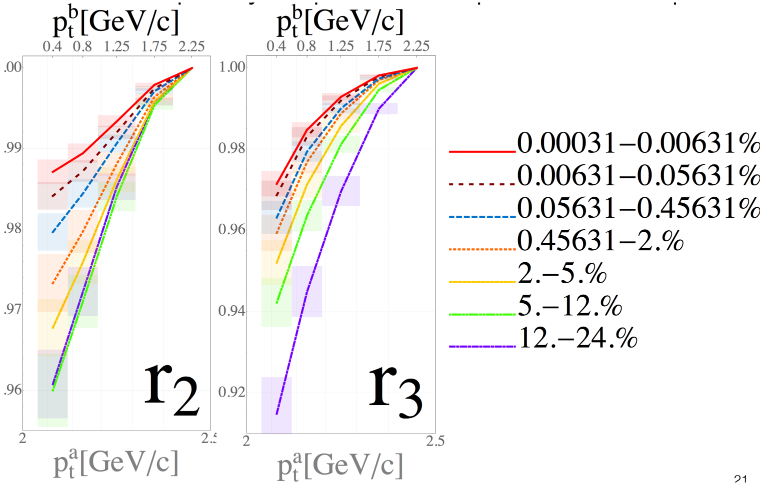
PREDICTIONS: CENTRALITY DEPENDENCE

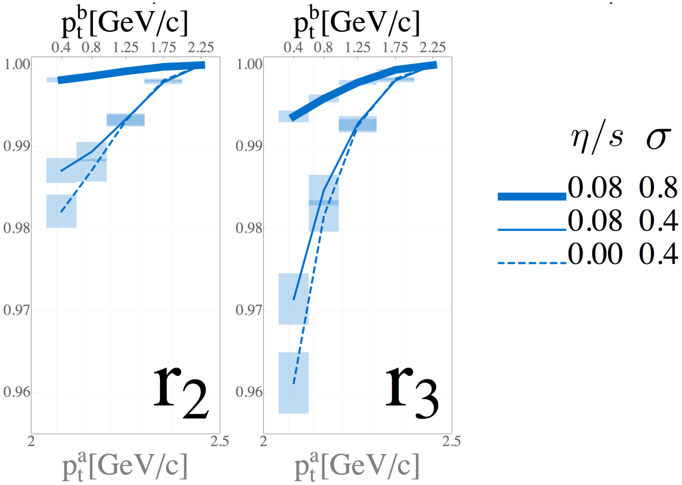
r_n close to 1, closer with increasing multiplicity



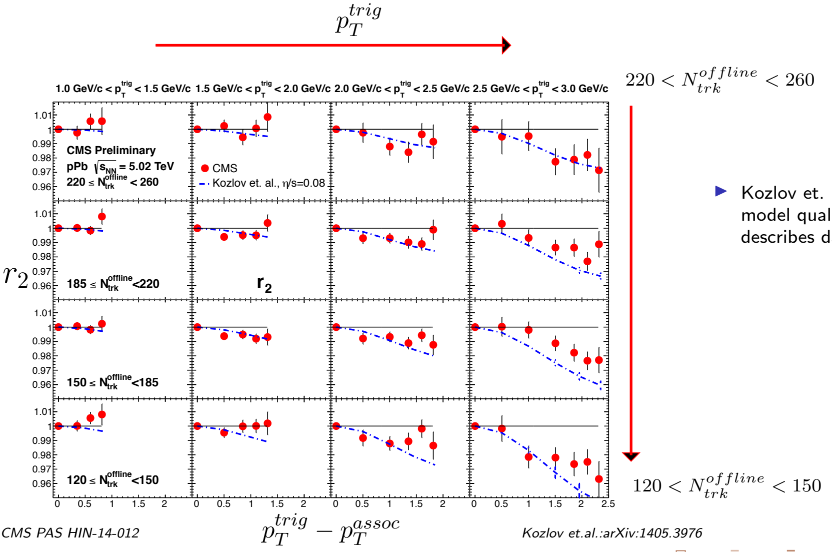
21

Predictions: centrality dependence

r_n insensitive to viscosity, sensitive to granularity



PRELIMINARY DATA: D. DEVETAK, QM14

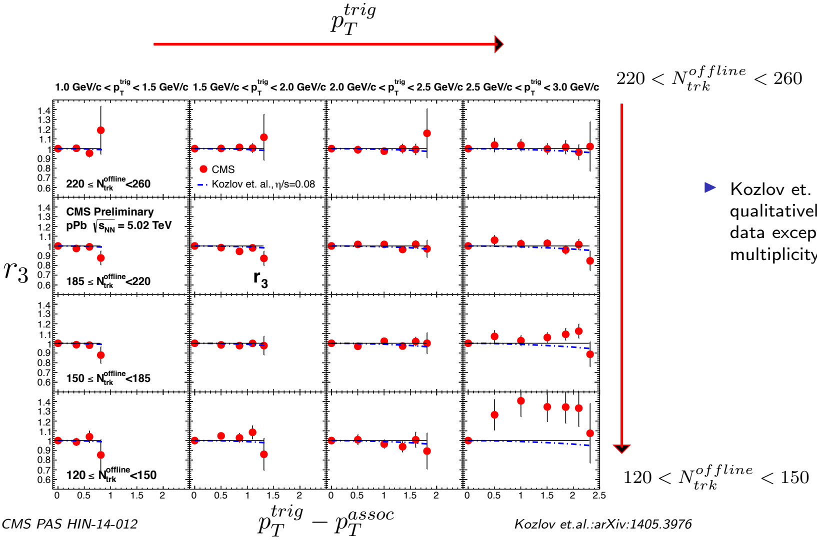


- Kozlov et. al. hydro model qualitatively describes data

CMS PAS HIN-14-012

Kozlov et.al.:arXiv:1405.3976

Preliminary data: D. Devetak, QM14



- Kozlov et. al. model qualitatively describes data except in lower multiplicity bins

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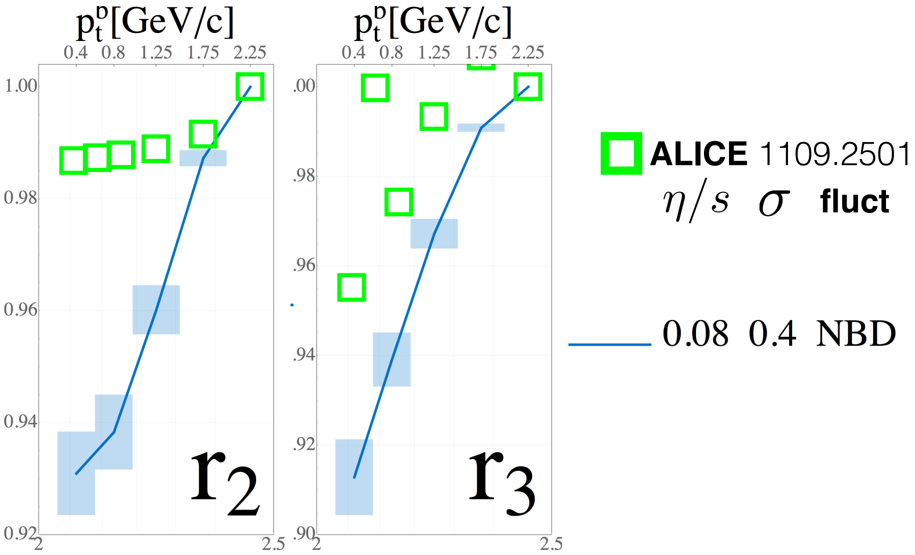
Kozlov et.al.:arXiv:1405.3976

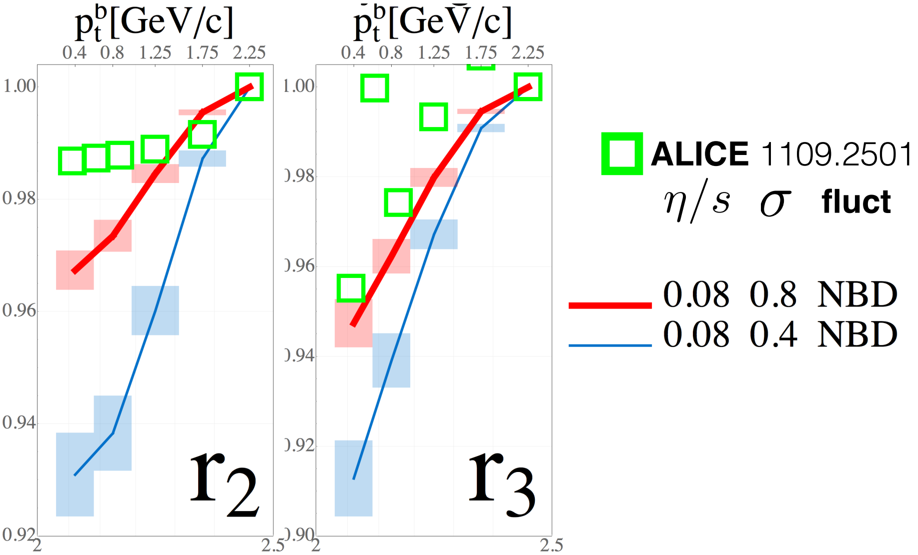
Interim conclusions

- Experimental data for r_n agree with hydrodynamic predictions
- r_n indicates the breakdown of flow dominance ($p_T > 2.5$ GeV + $N_{ch} < 150$)

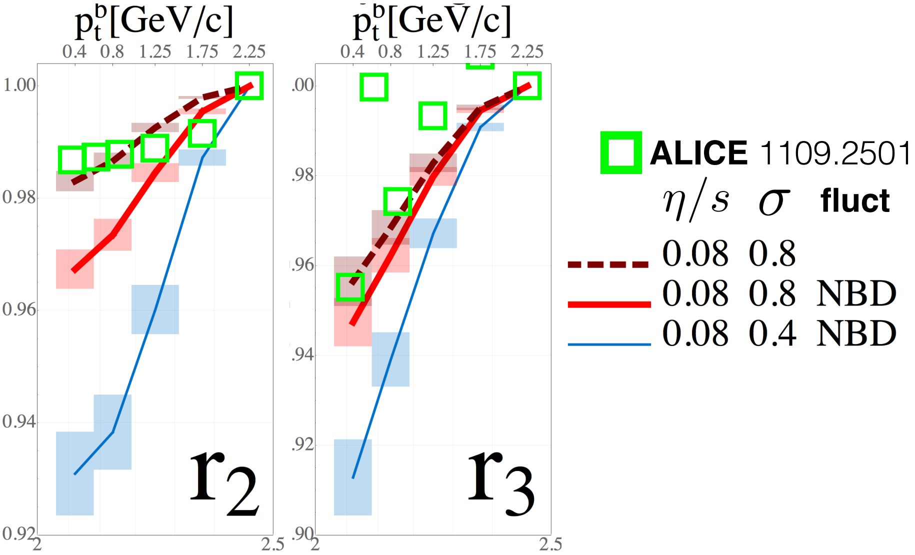
REVISITING NUCLEUS-NUCLEUS COLLISIONS



REVISITING NUCLEUS-NUCLEUS COLLISIONS



Revisiting nucleus-nucleus collisions



Revisiting nucleus-nucleus collisions

Puzzle

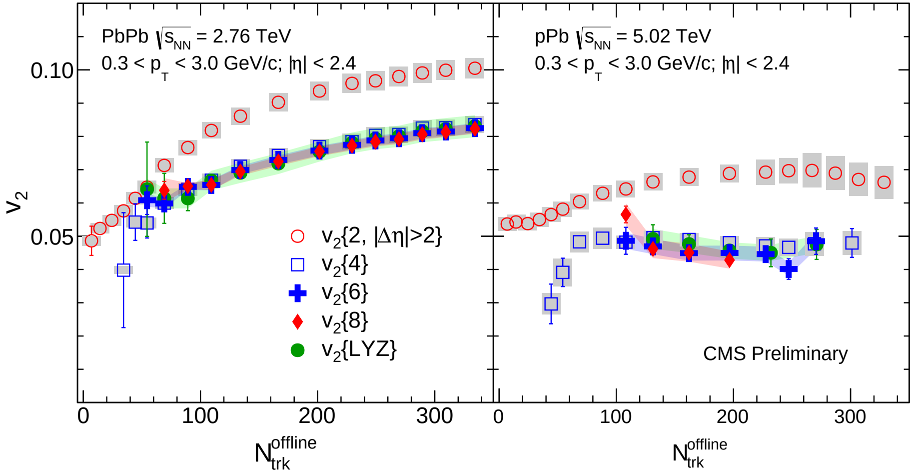
Including r_n adds tension to simultaneous description of p-Pb and Pb-Pb

CONCLUSIONS

- Hydrodynamic calculations can describe many observables in high multiplicity p-Pb collisions
- Preliminary data for r_n agree with hydrodynamic predictions
- r_n observable provides a useful new handle on physics. E.g.,
    - to indicate where hydrodynamic description breaks down
    - to probe aspects of initial condition not probed by other observables (granularity)

Extra Slides

Higher cumulants



Results: p-Pb vs Pb-Pb