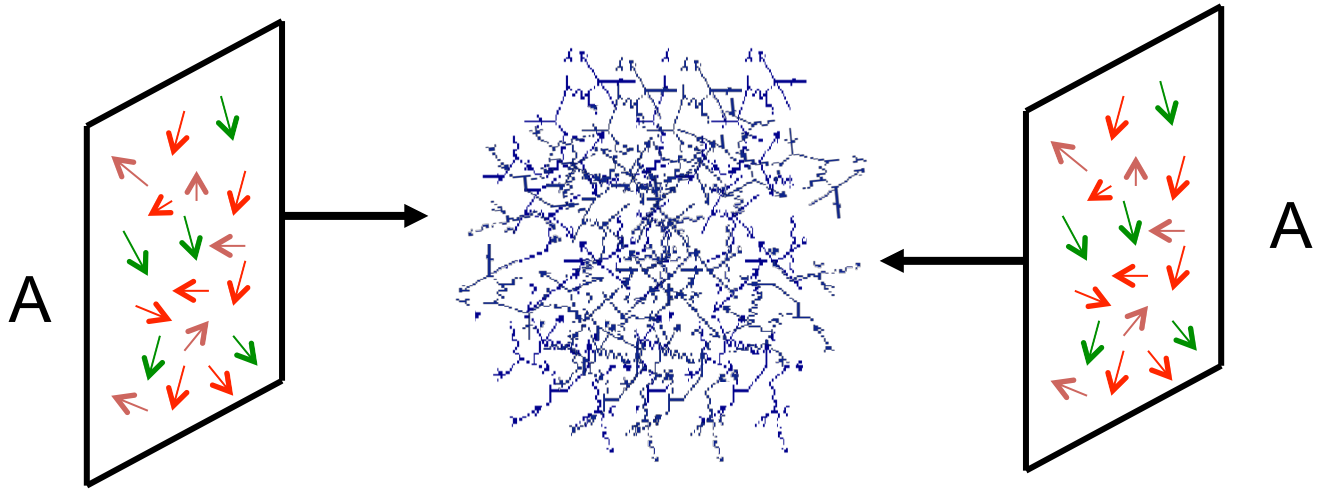
Flow and soft phenomena in heavy-ion collisions

Wei Li
Rice University

Latest results at Quark Matter 2014: http://qm2014.gsi.de

Emergent phenomena in QCD

Soft QCD is the least understood part of standard model



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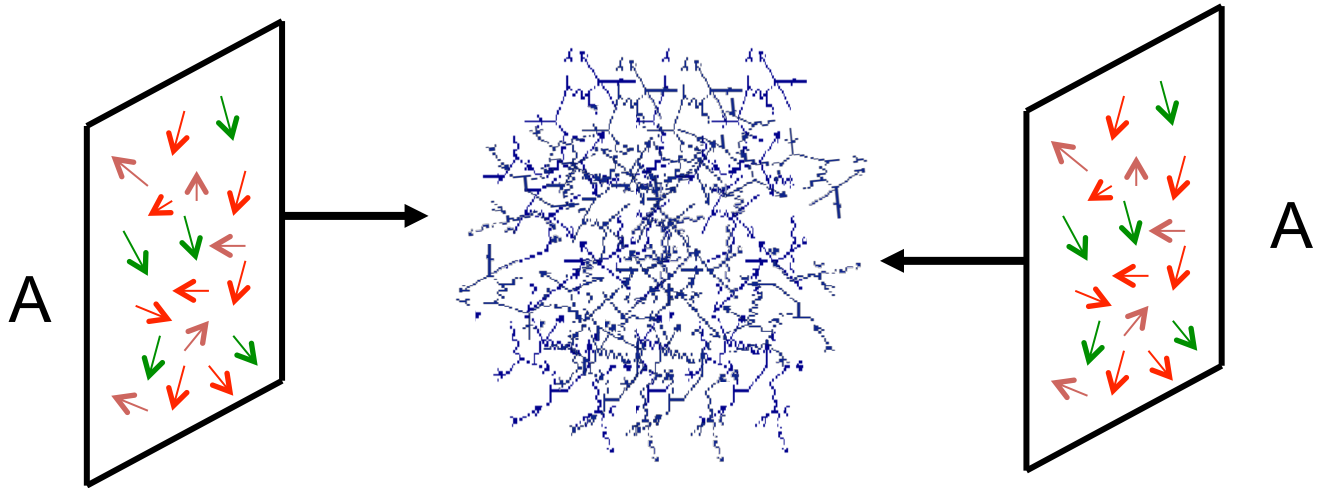
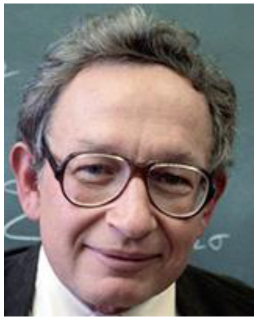


"More is different" – P. W. Anderson



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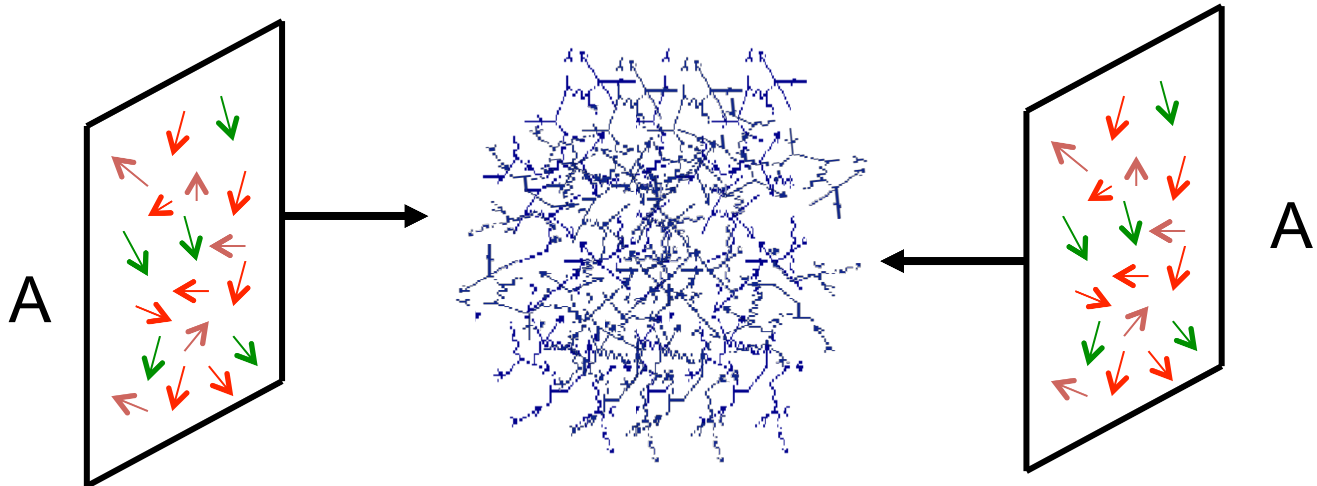

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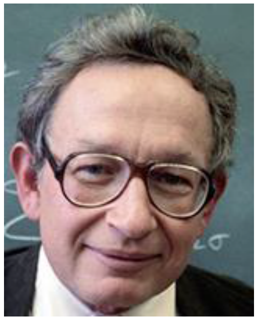
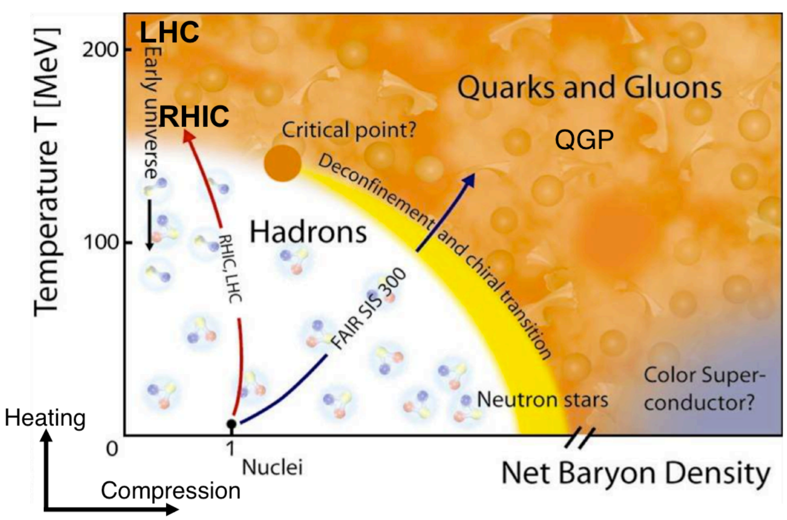
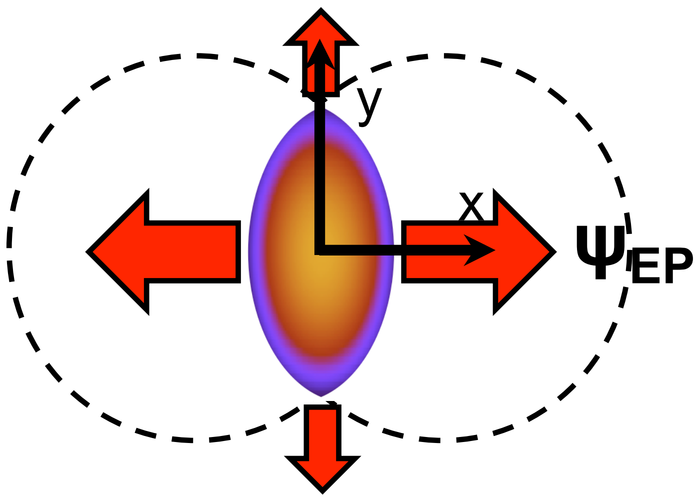


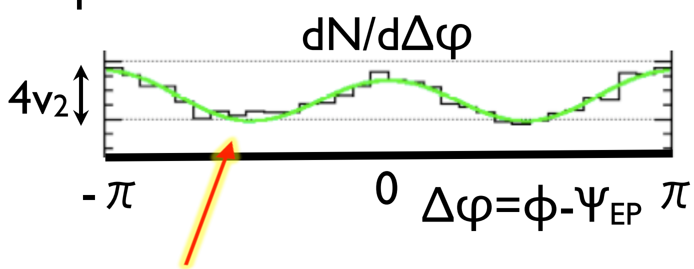


In heavy-ion collisions: **search for and study emergent phenomena in many-body QCD system**

Discovery of a "nearly perfect" liquid at RHIC



elliptic flow:



~ $1+ 2v_2\cos[2(\varphi-\Psi_{EP})]$

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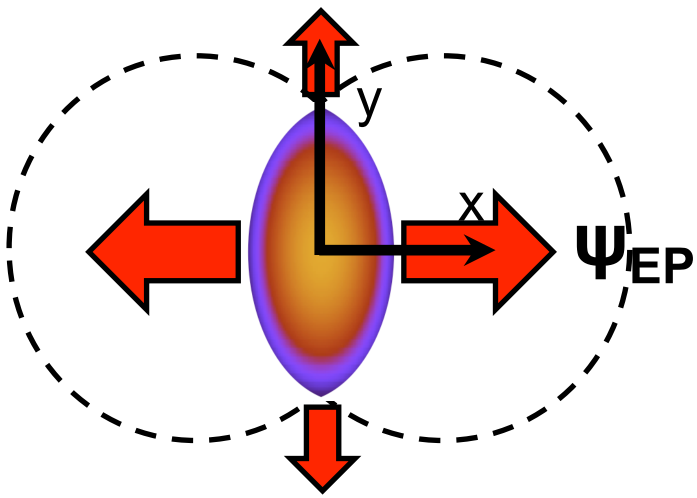

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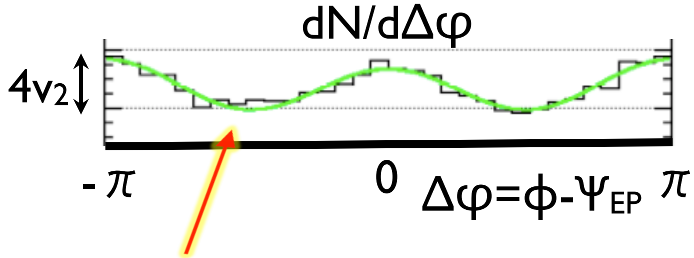
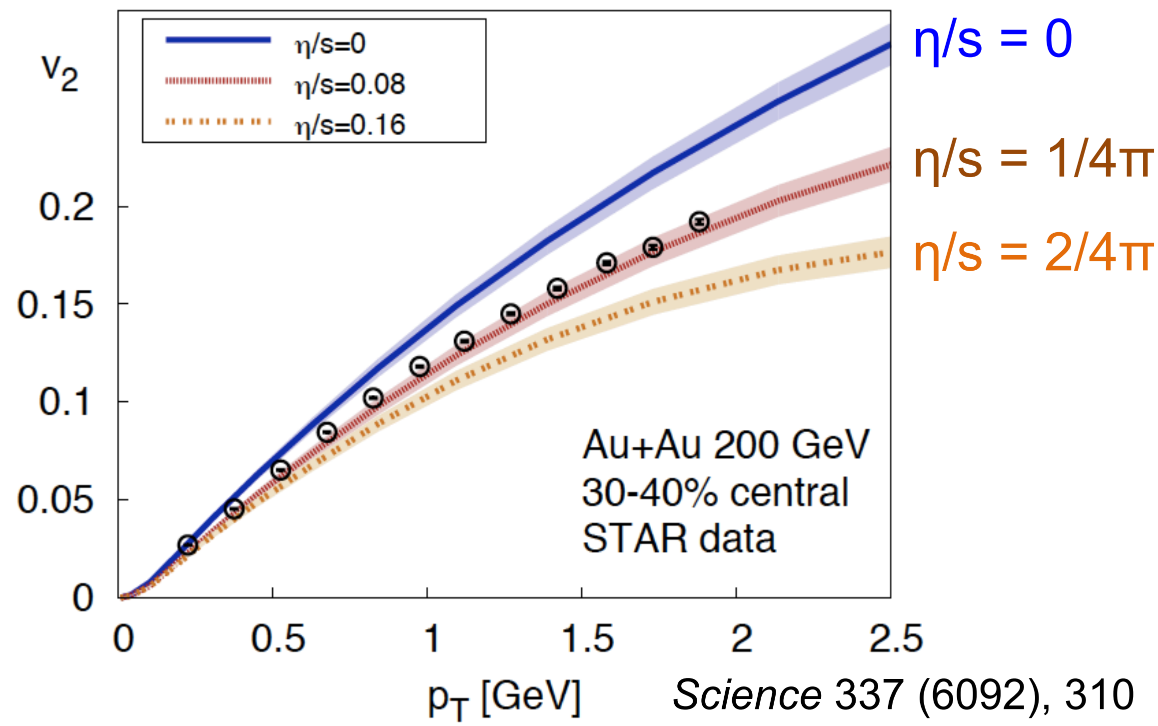


$\sim 1 + 2v_2\cos[2(\varphi - \Psi_{EP})]$

Hydrodynamics at work!



Science 337 (6092), 310

η/s of water: ~ 2

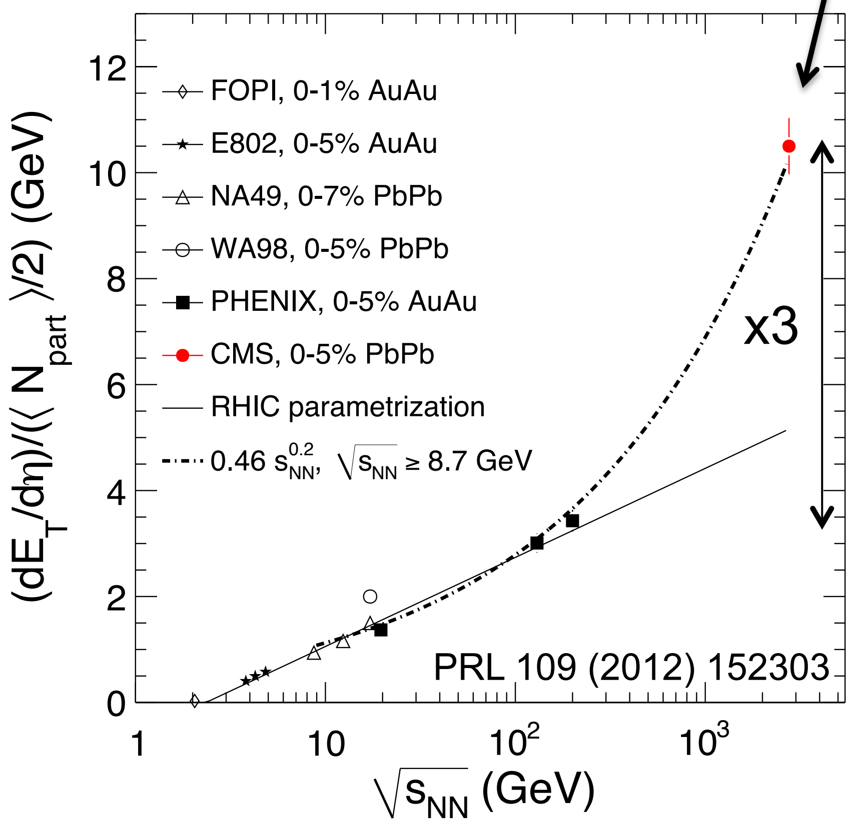
Strong collectivity of final-state particles discovered at RHIC

Behaving as a strongly coupled liquid with minimal frictional resistance (η/s)

QGP and flow at the LHC

2 TeV per unit η

Total transverse energy (E_T)



3-fold increase from RHIC to LHC

A hotter QGP!

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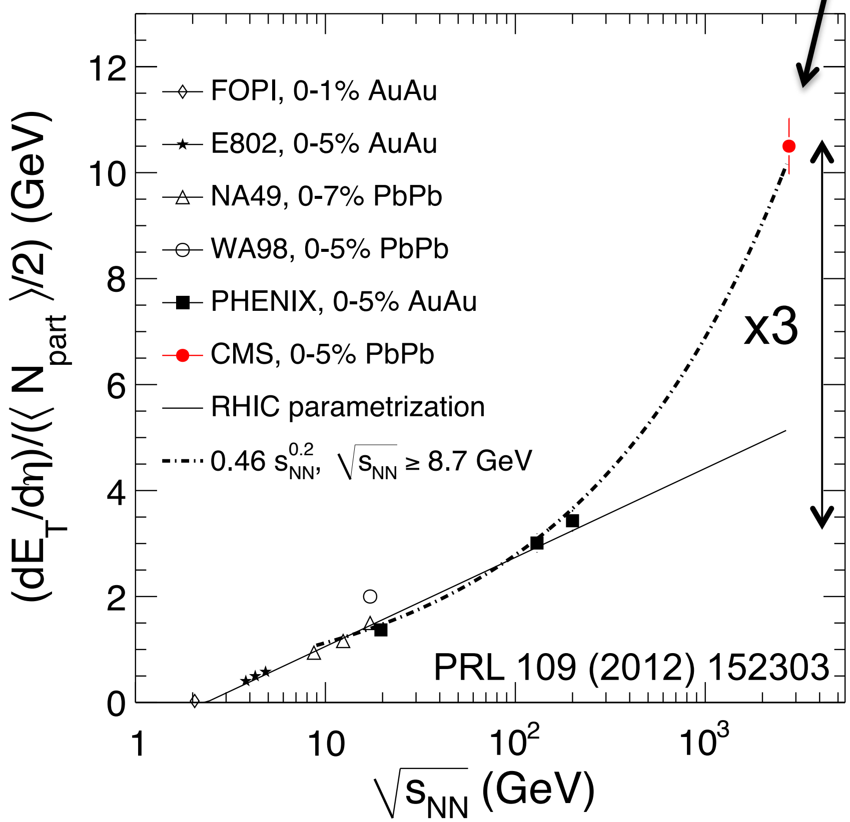
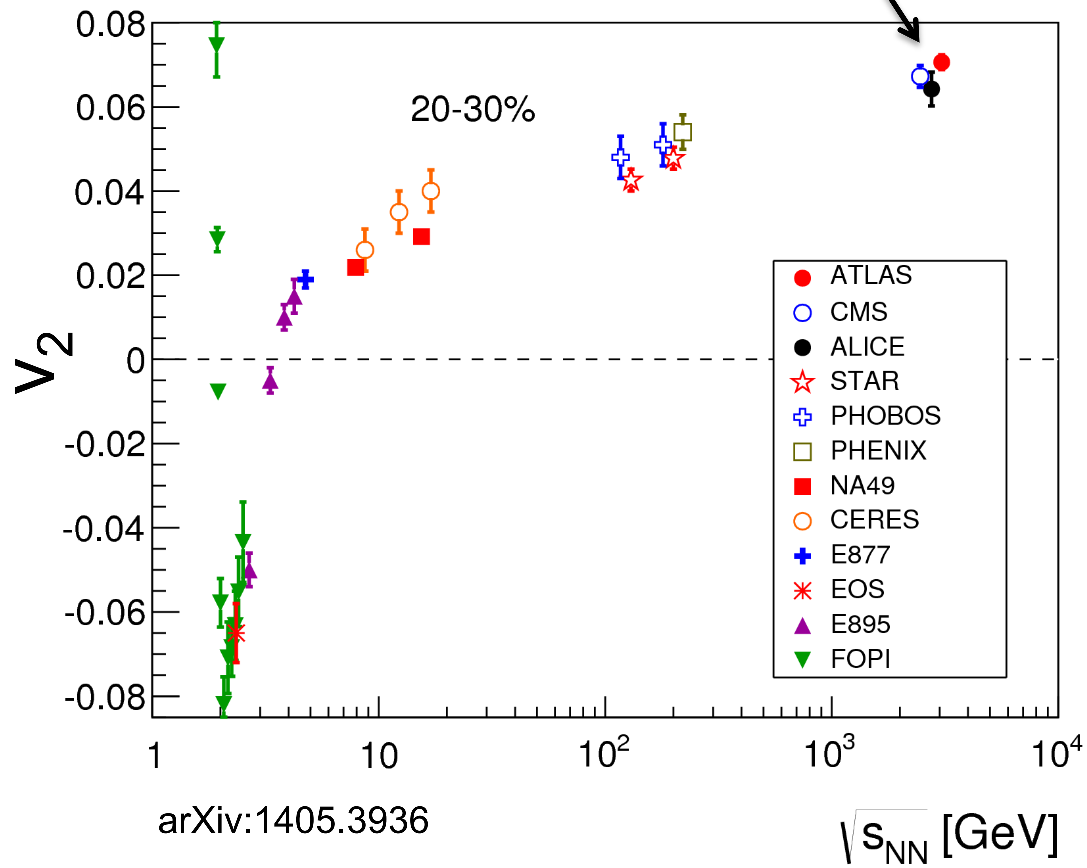


3-fold increase from RHIC to LHC

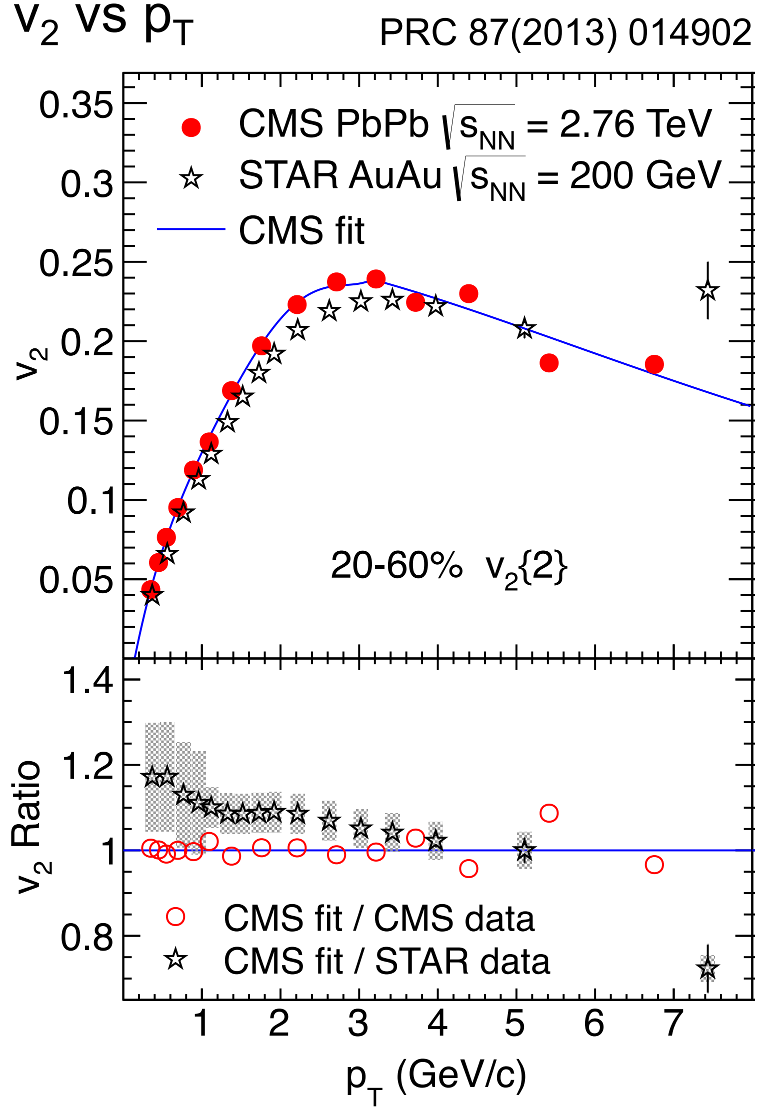
A hotter QGP!

Strong collective flow persists at the LHC



Elliptic flow at the LHC

v_2 vs p_T



Similar flow at RHIC and the LHC

Elliptic flow at the LHC

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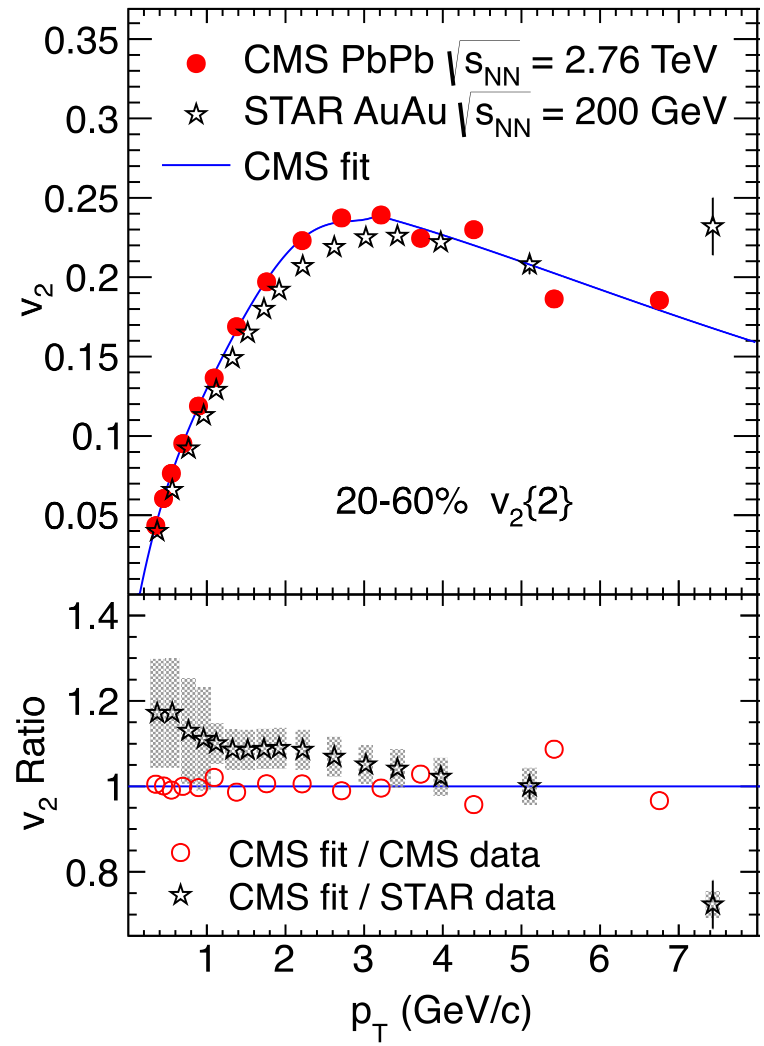
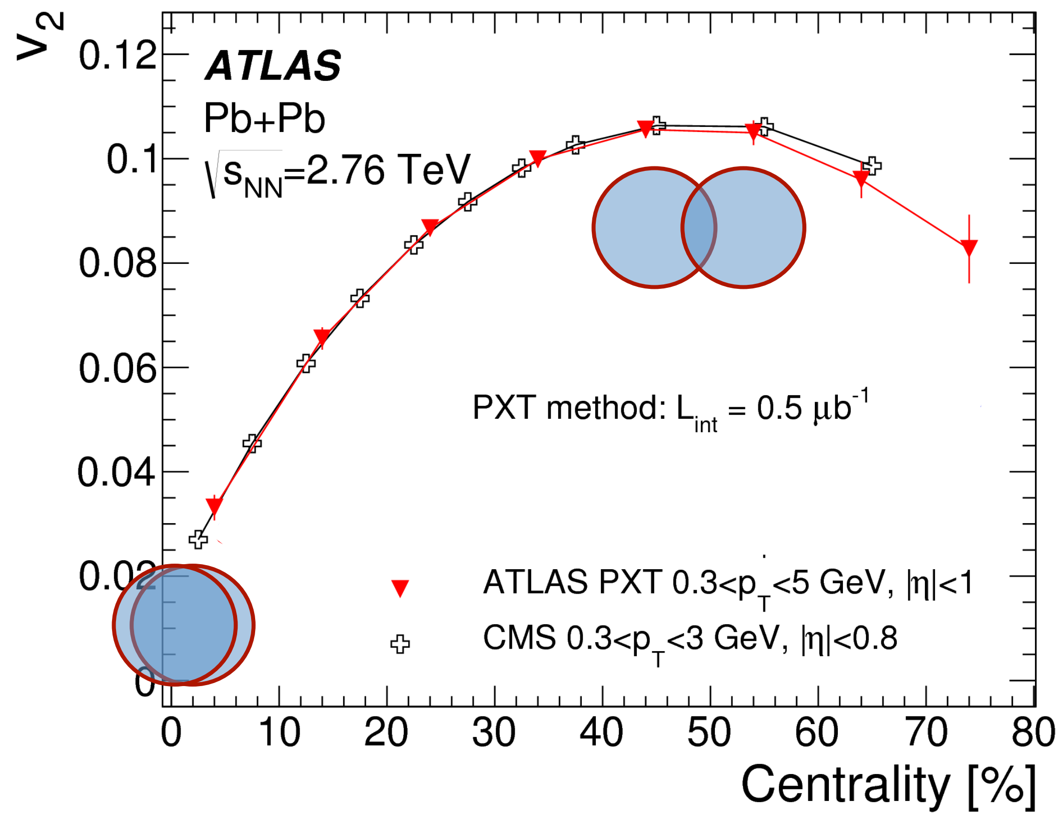
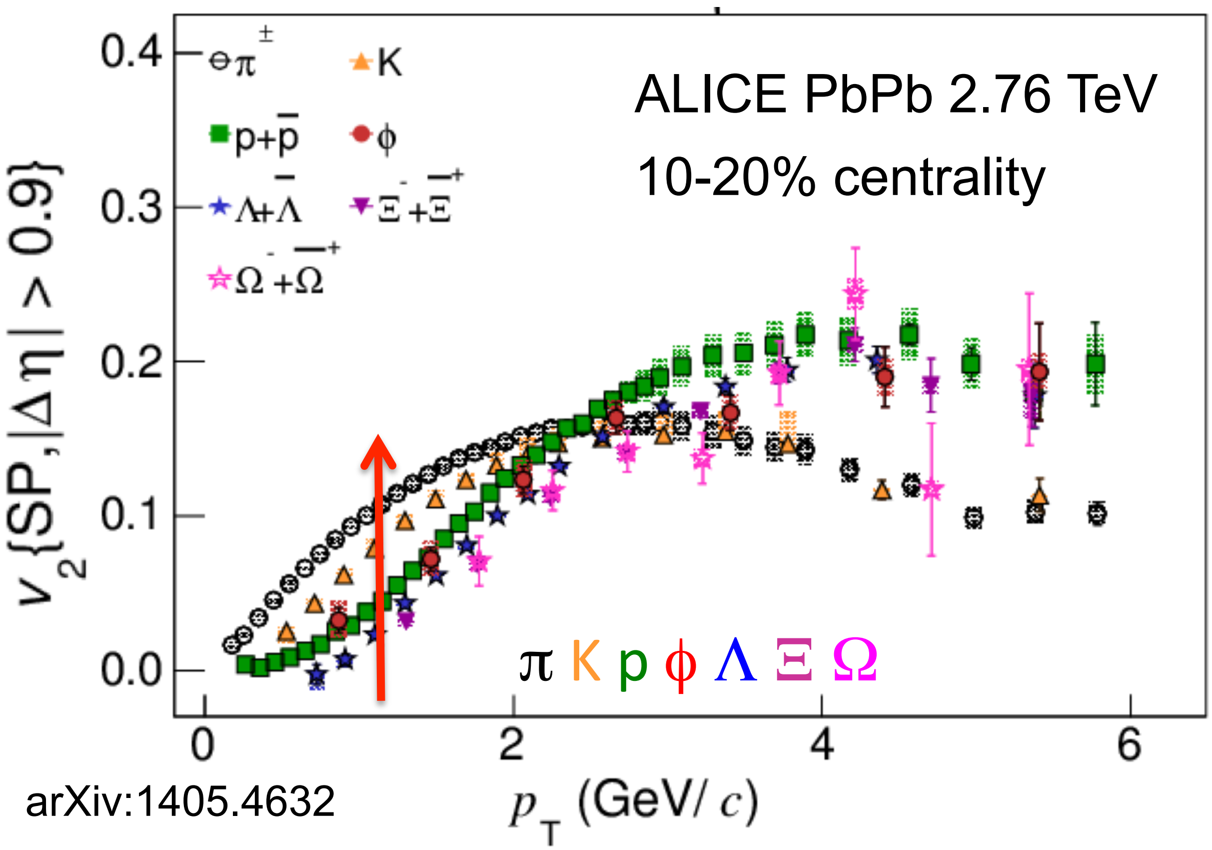




Flow is driven by initial-state geometry

Similar flow at RHIC and the LHC

Flow with identified particles



arXiv:1405.4632

- Mass ordering at low p_T: Smaller v_2 for heavier particles
- v_2(baryon) > v_2 (meson) at higher p_T

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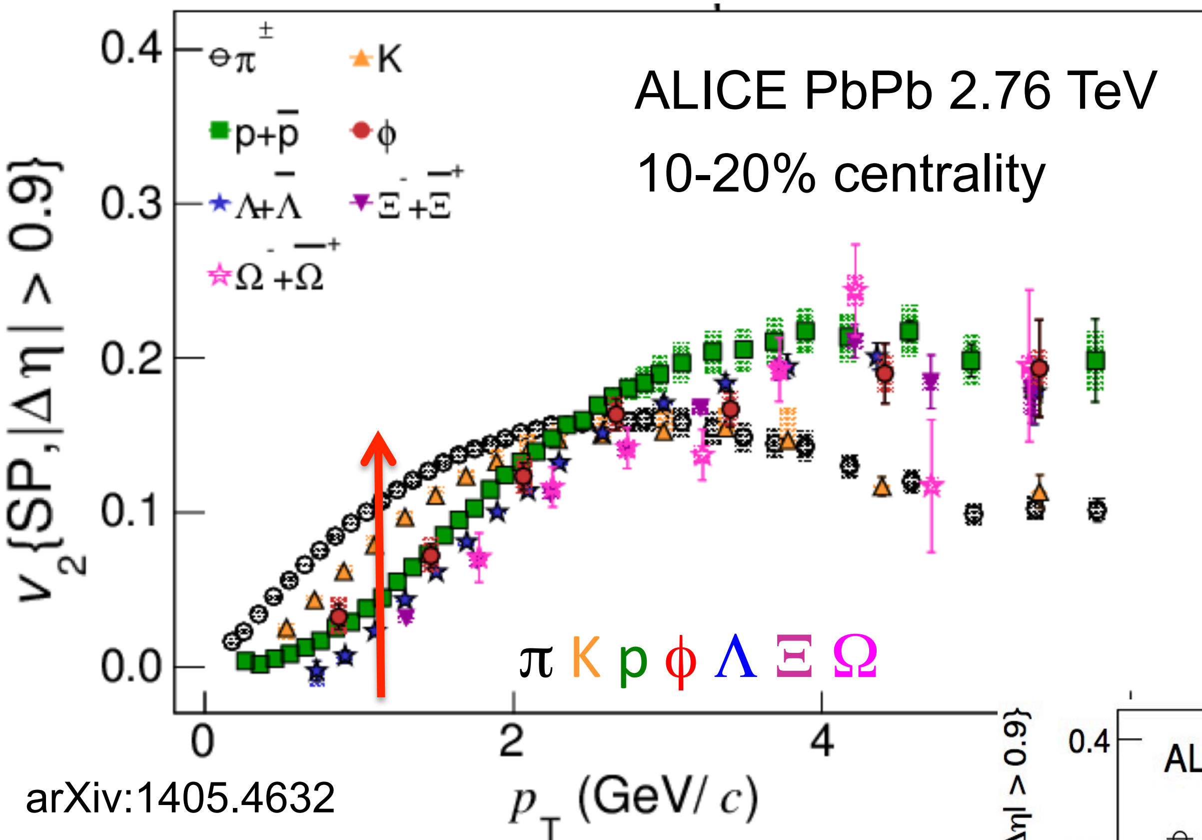

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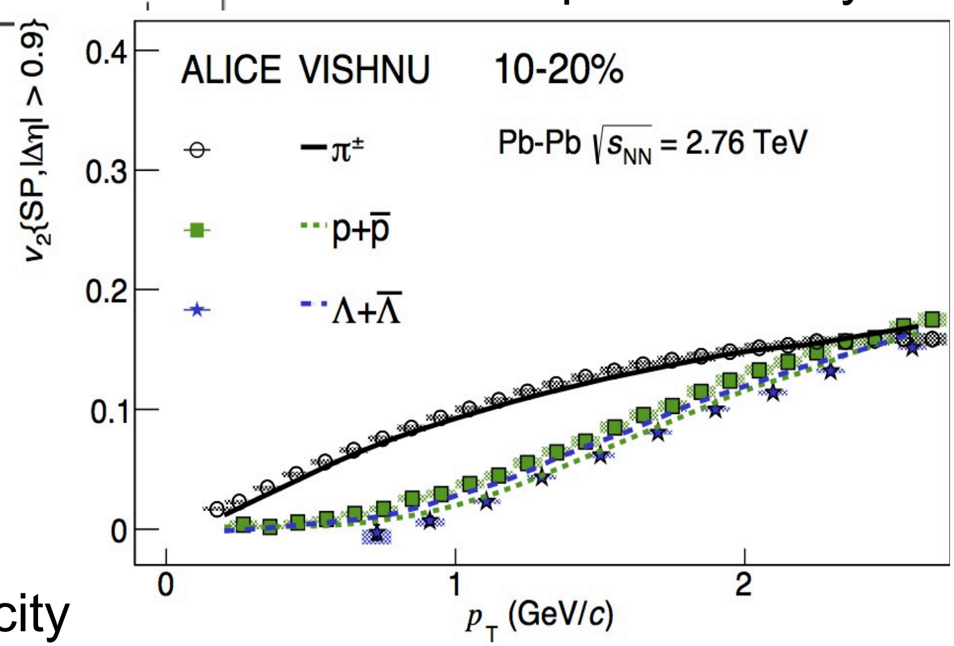
Comparison to hydro

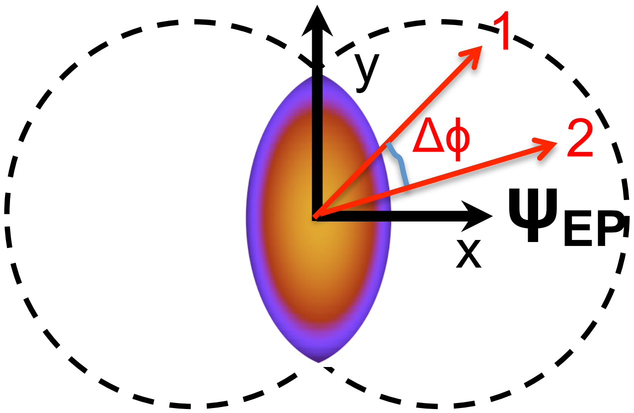


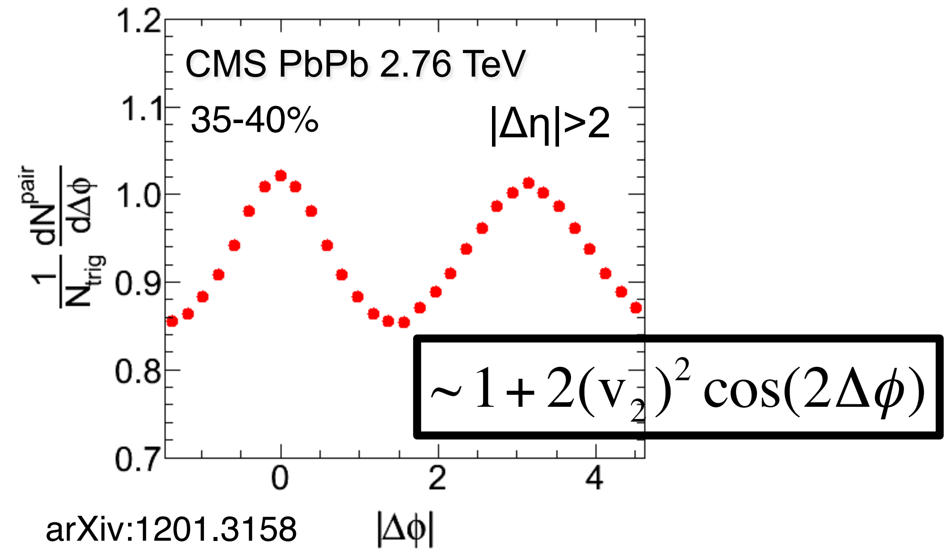
In hydro, radial flow boosts heavier particles to higher p_T

$$\Delta p_T \sim m\,\beta_T$$

radial flow velocity

Flow, two-particle correlations, ridge …





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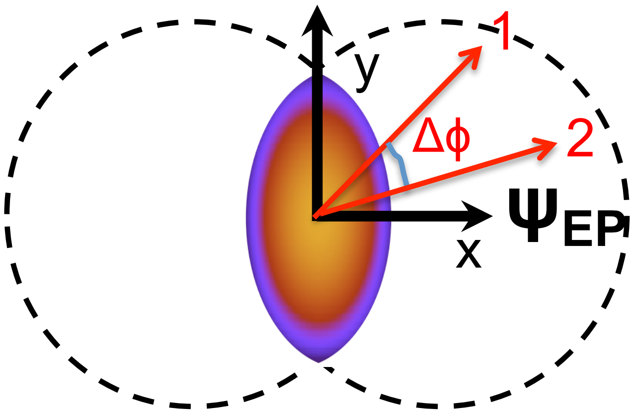
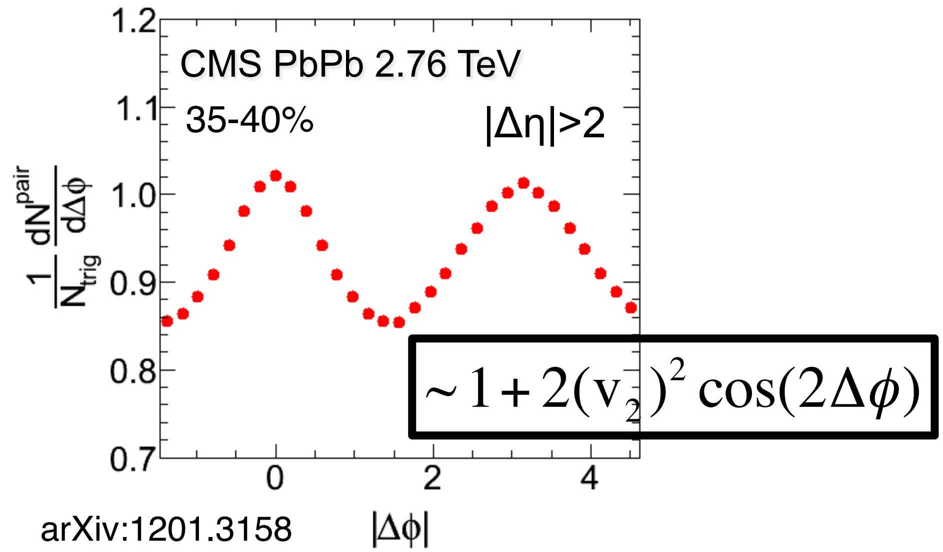
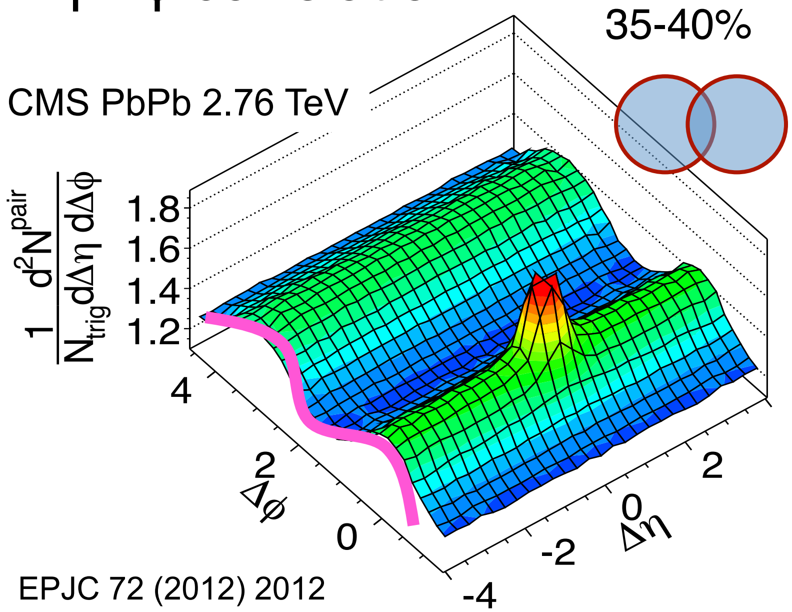




arXiv:1201.3158

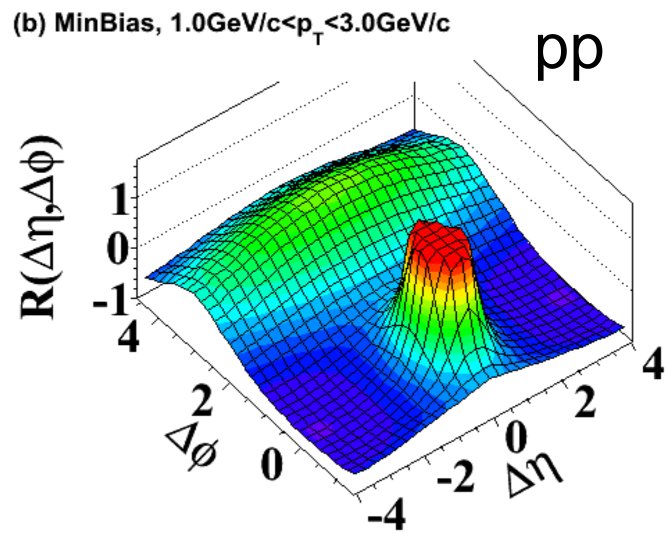
Elliptic flow is long-range in pseudorapidity (η)

Δη-Δϕ correlation:



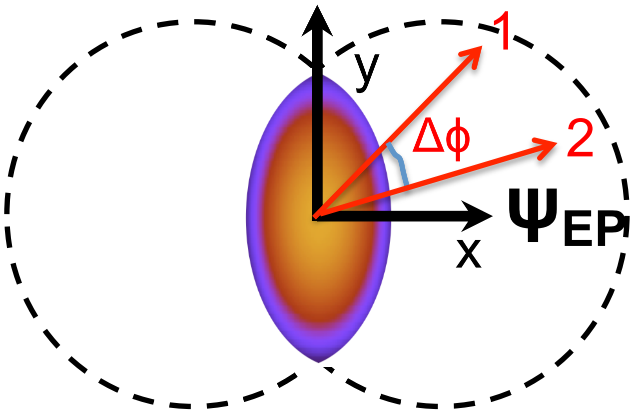
EPJC 72 (2012) 2012

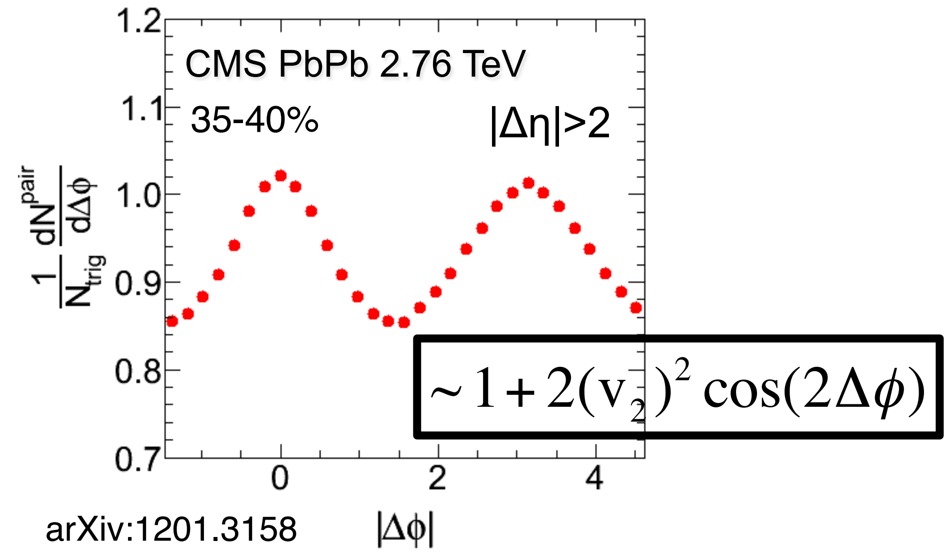
No near-side ridge in MB pp



Too small object to thermalize

Flow, two-particle correlations, ridge …





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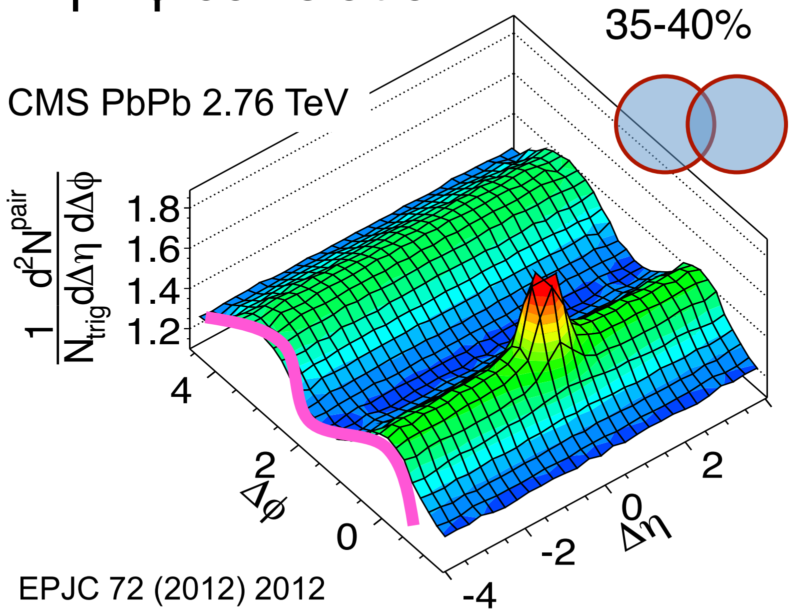
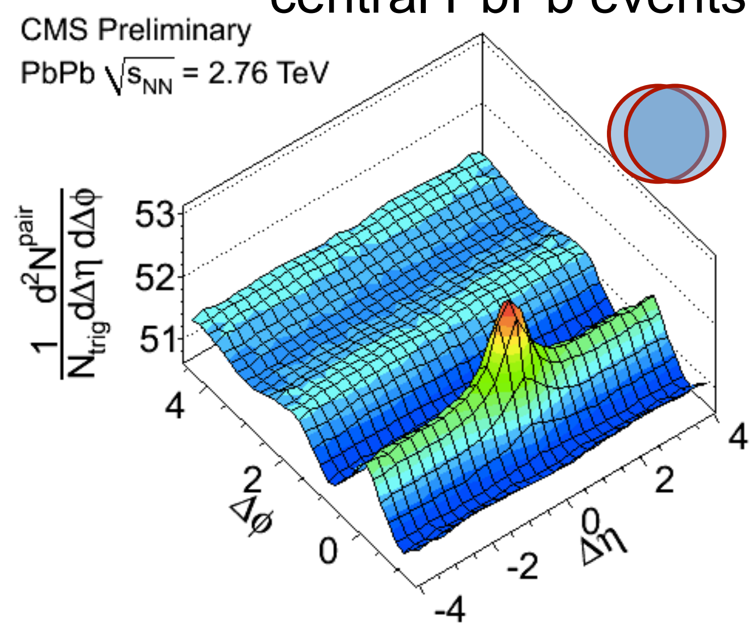
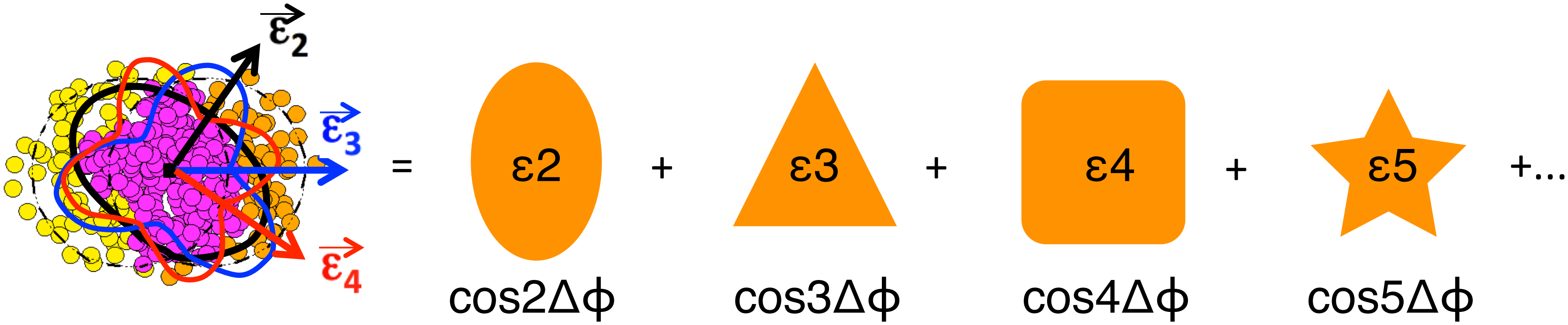


central PbPb events

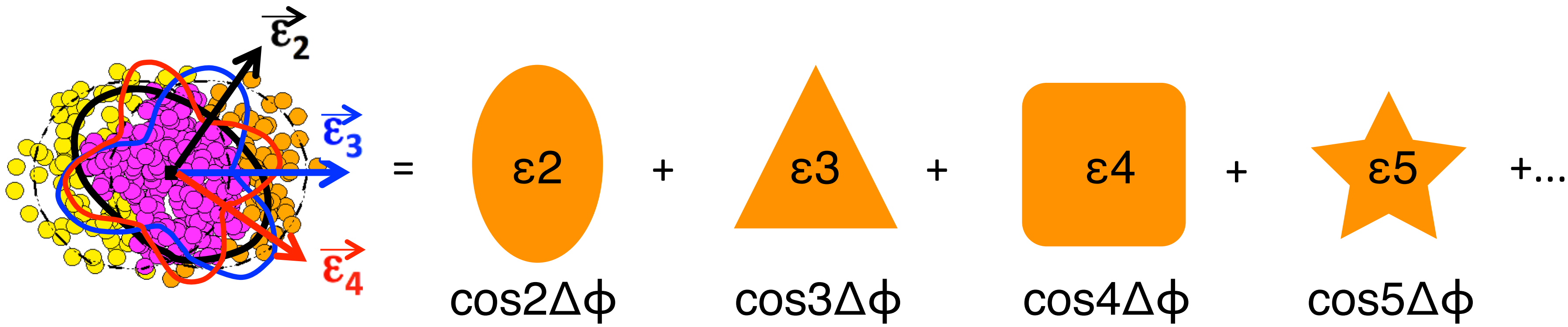


Higher-order deformation of initial state



Initial "QGP shape" includes higher multipole components

Higher-order deformation of initial state



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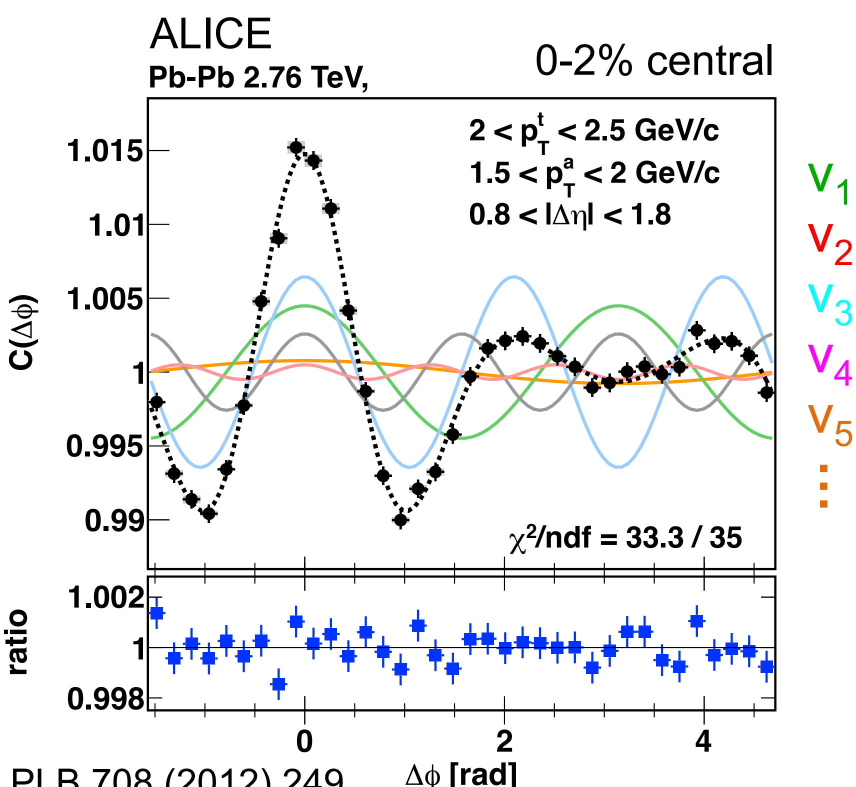

PLB 708 (2012) 249

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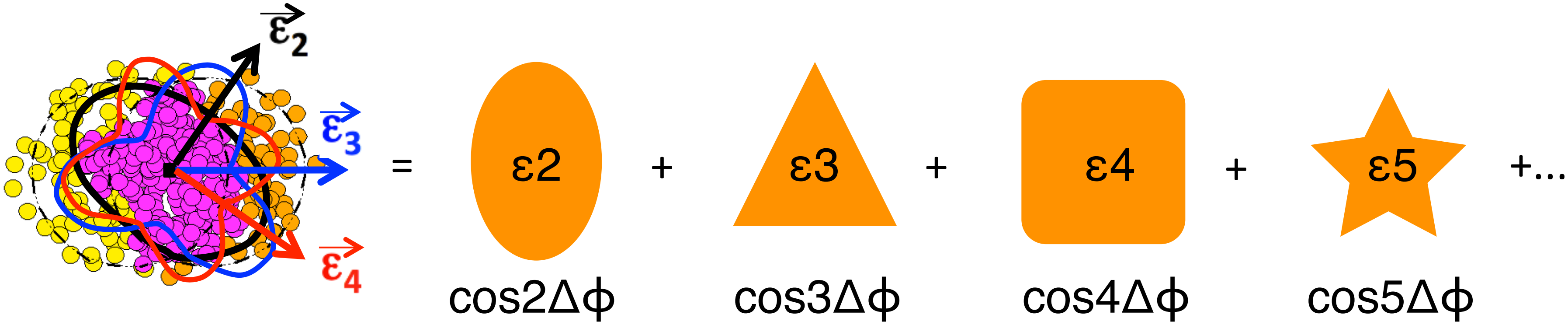

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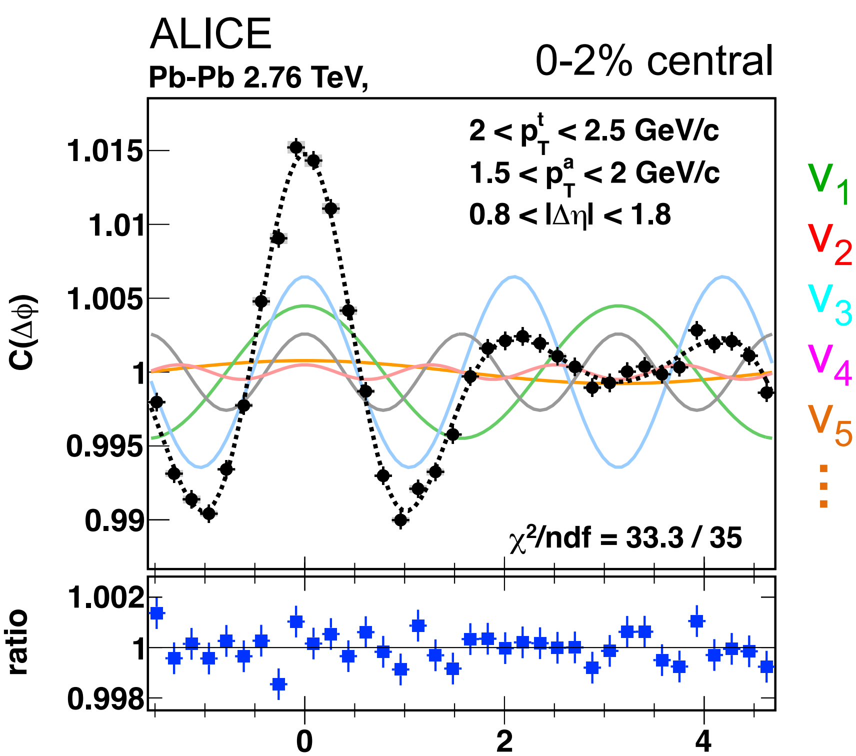

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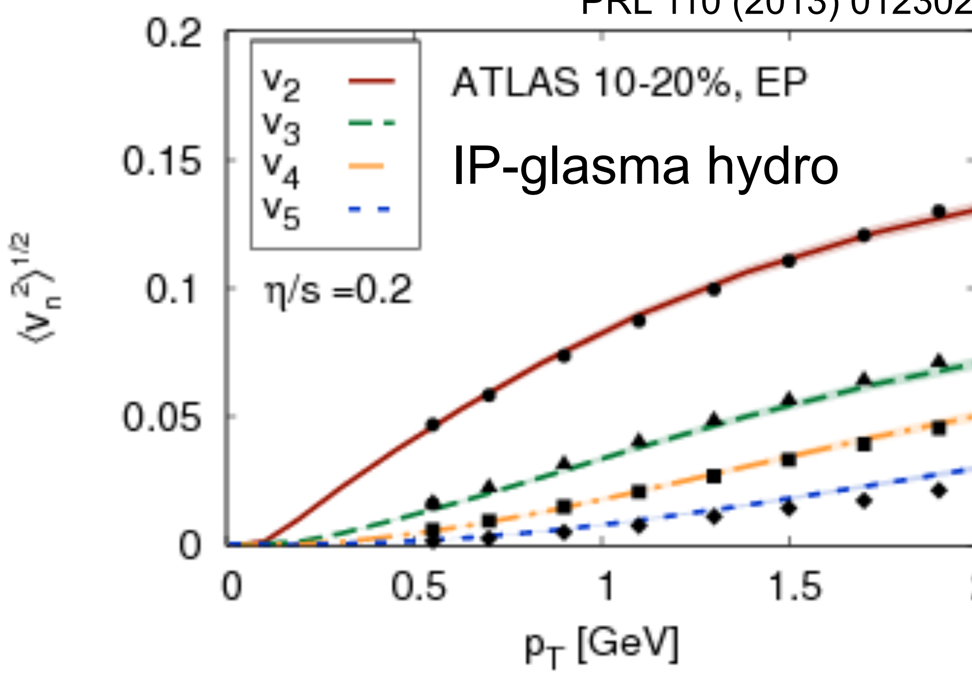
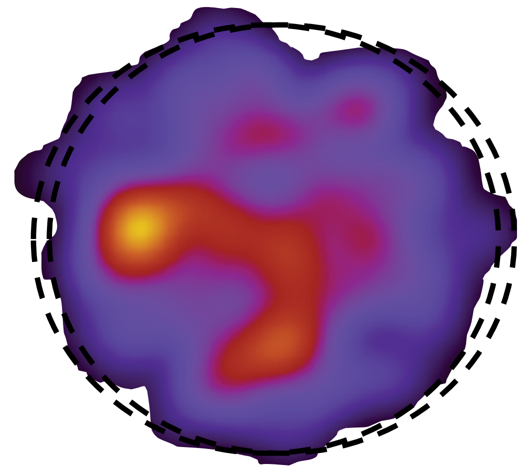


Hydro faithfully transposes the initial shape into final-state particle azimuthal distributions

Flow in ultra-central PbPb collisions

Initial-state geometry dominated by density perturbations

PbPb collisions with b ~ 0,
almost symmetric on average



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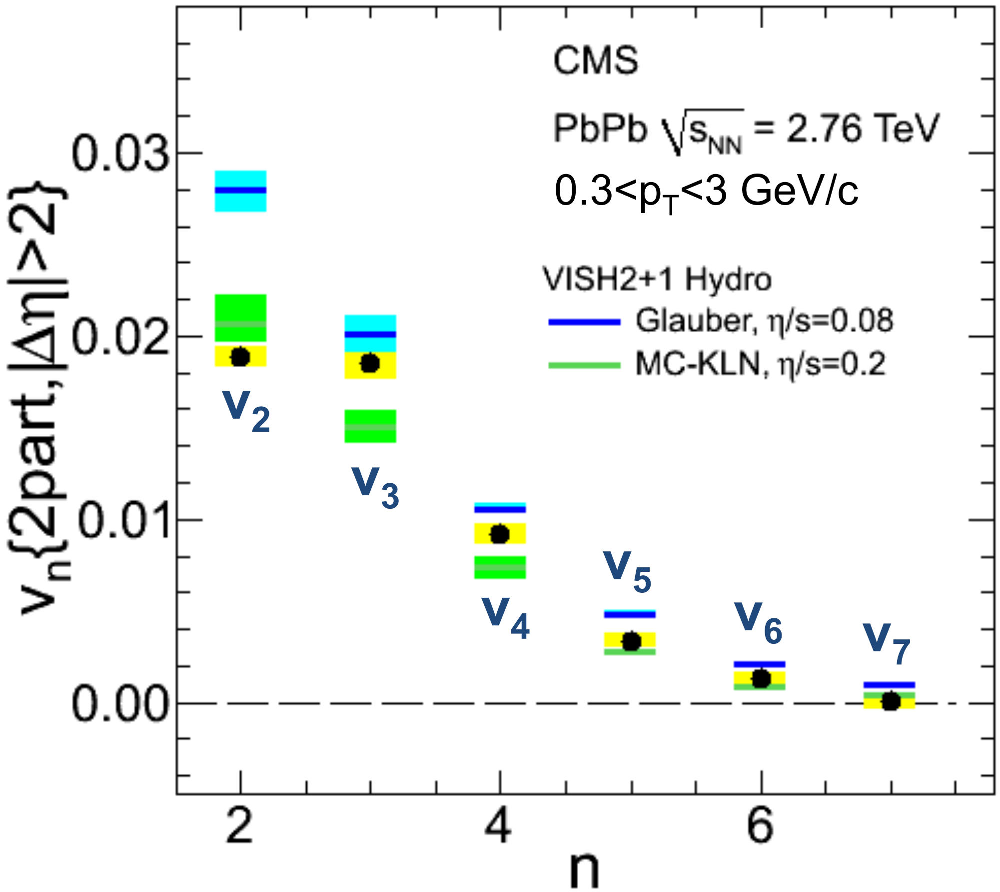
Top 0.2% central

JHEP 02 (2014) 088



Better agreement by including nucleon-nucleon correlations and bulk viscosity

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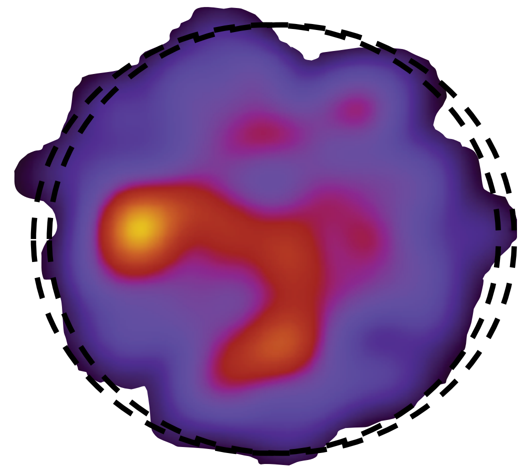

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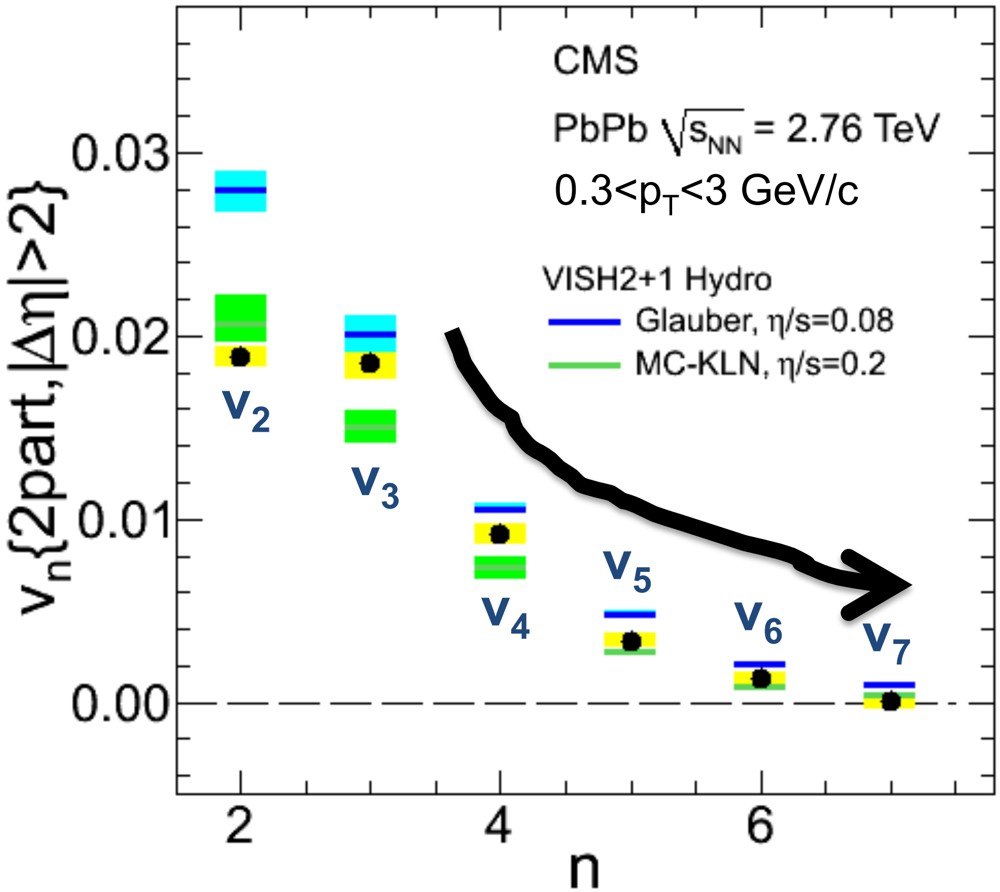

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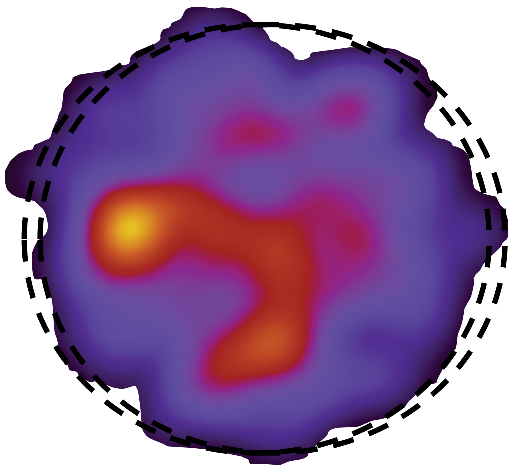

Damping of higher-order perturbations due to viscosity

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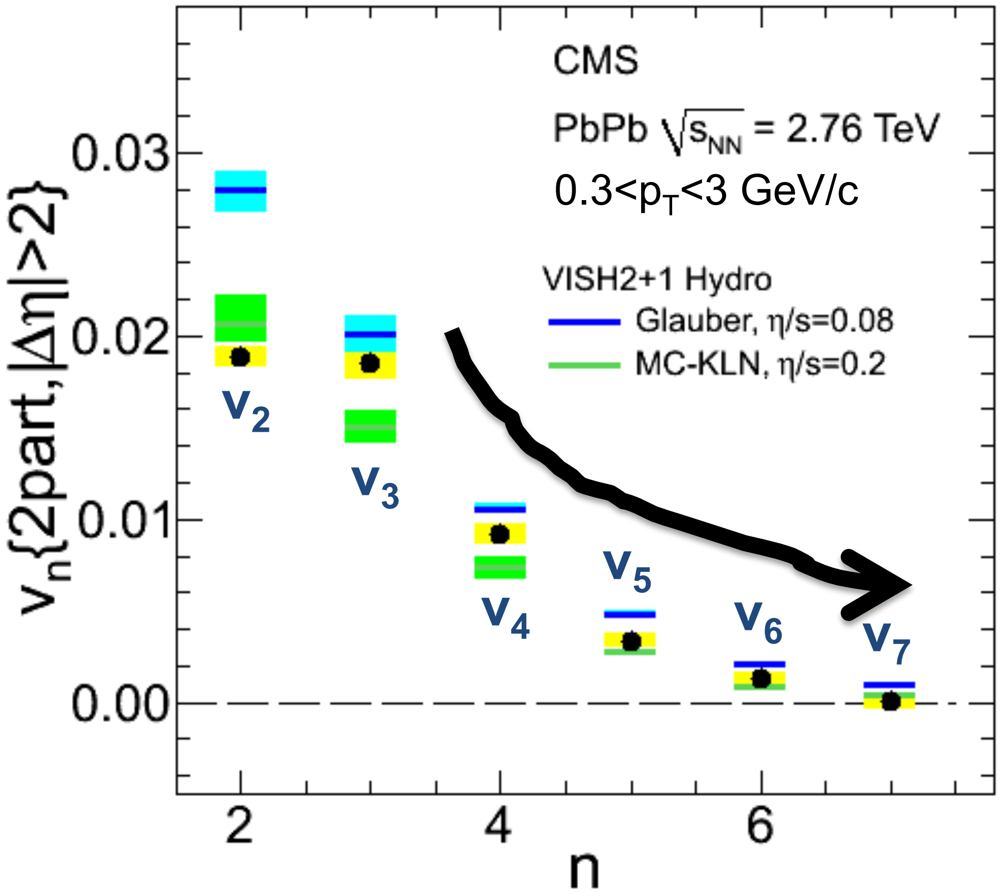

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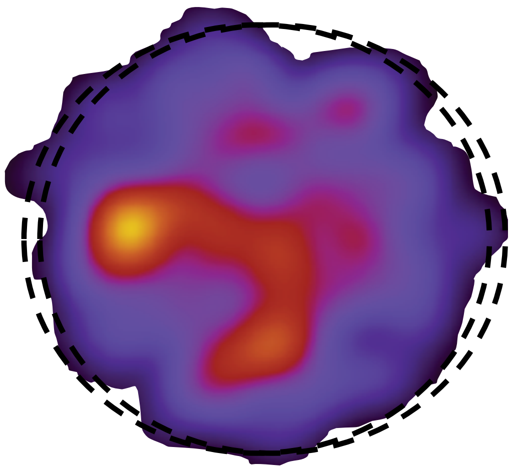

Damping of higher-order perturbations due to viscosity

η/s indeed very small: ~ 0.08 – 0.2

Better agreement by including nucleon-nucleon correlations and bulk viscosity

Flow in ultra-central PbPb collisions

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Top 0.2% central

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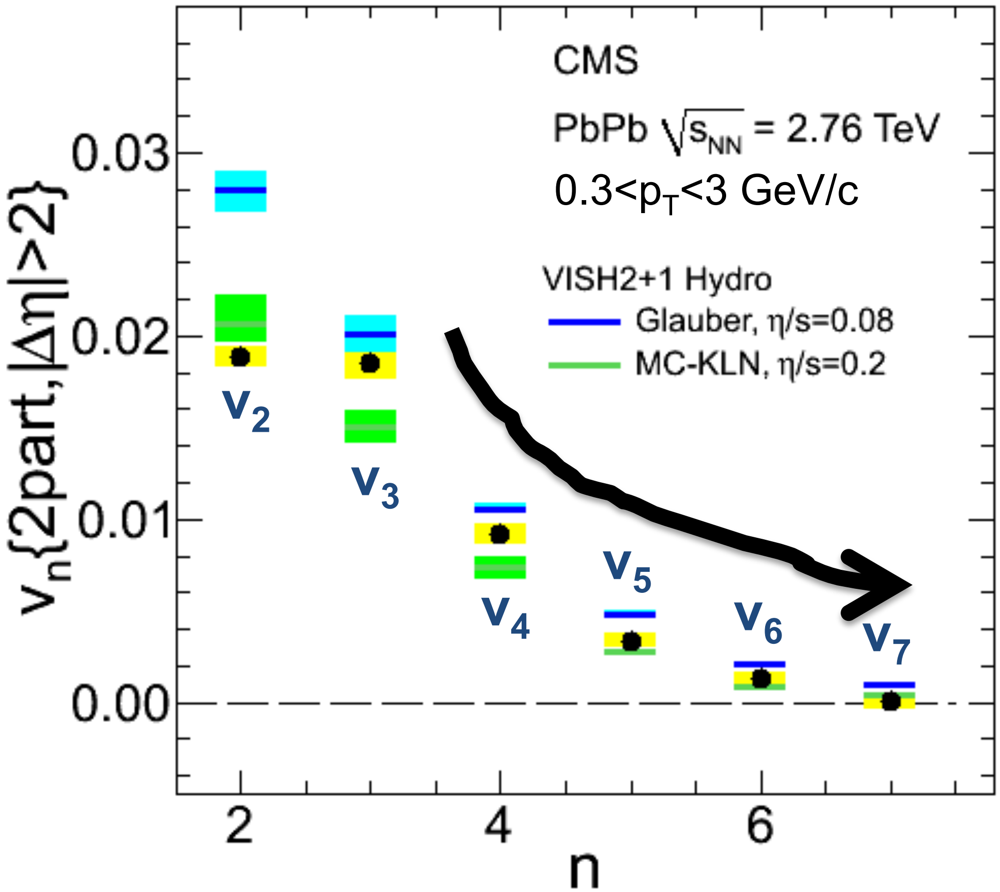
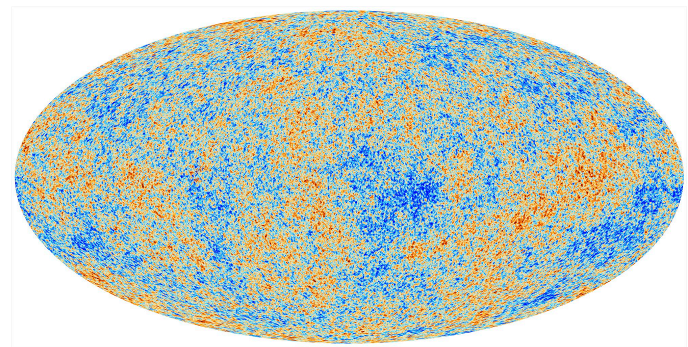
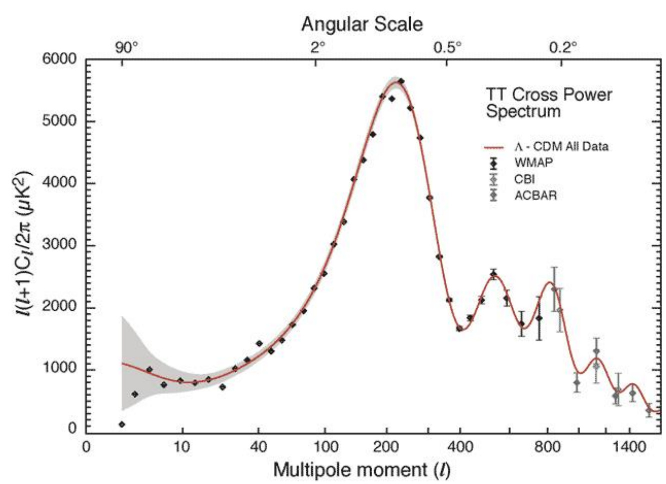


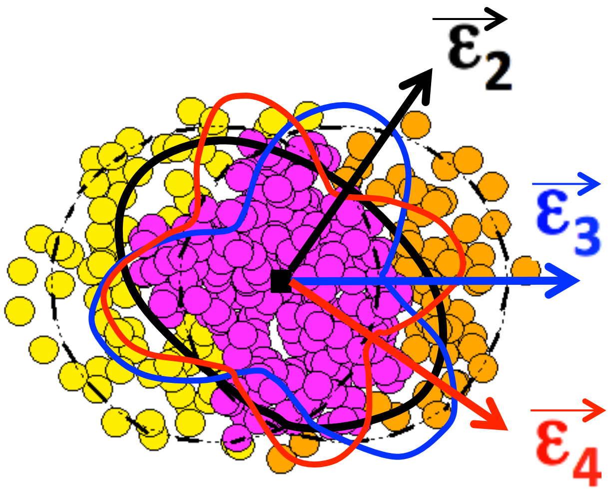
Better agreement by including nucleon-nucleon correlations and bulk viscosity

Mapping out propagation of initial perturbations as system evolves



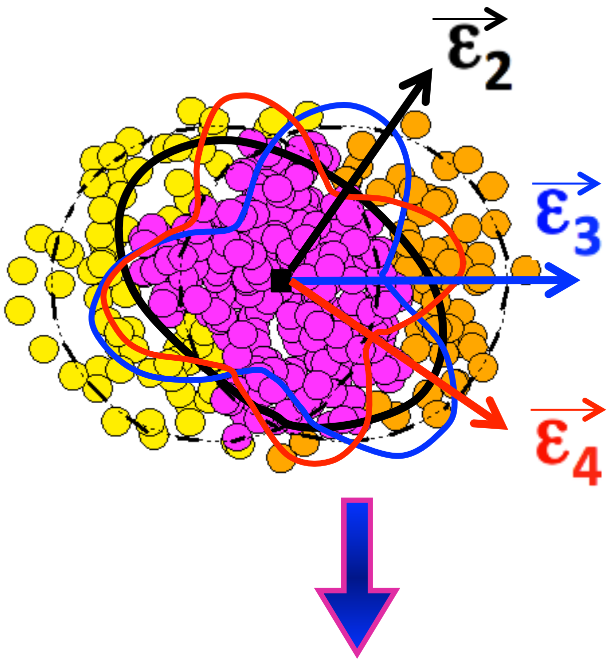


Event-by-event flow fluctuations



Initial-state geometry fluctuates on an ***event-by-event*** basis

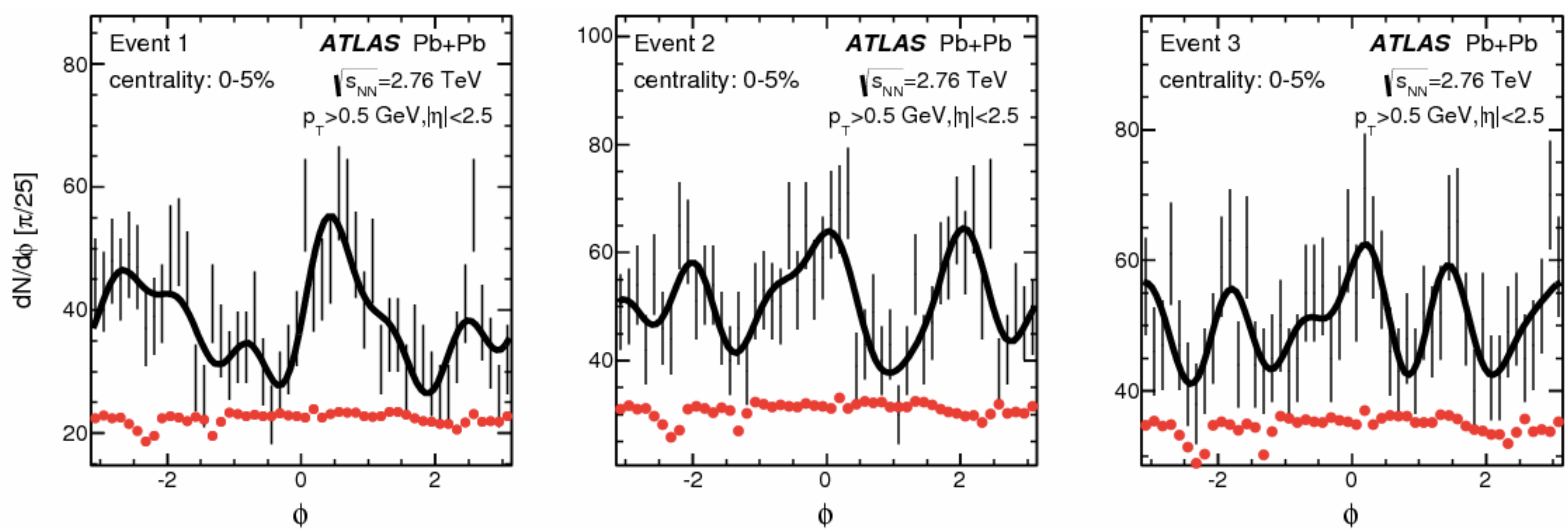
Event-by-event flow fluctuations



Initial-state geometry fluctuates on an ***event-by-event*** basis

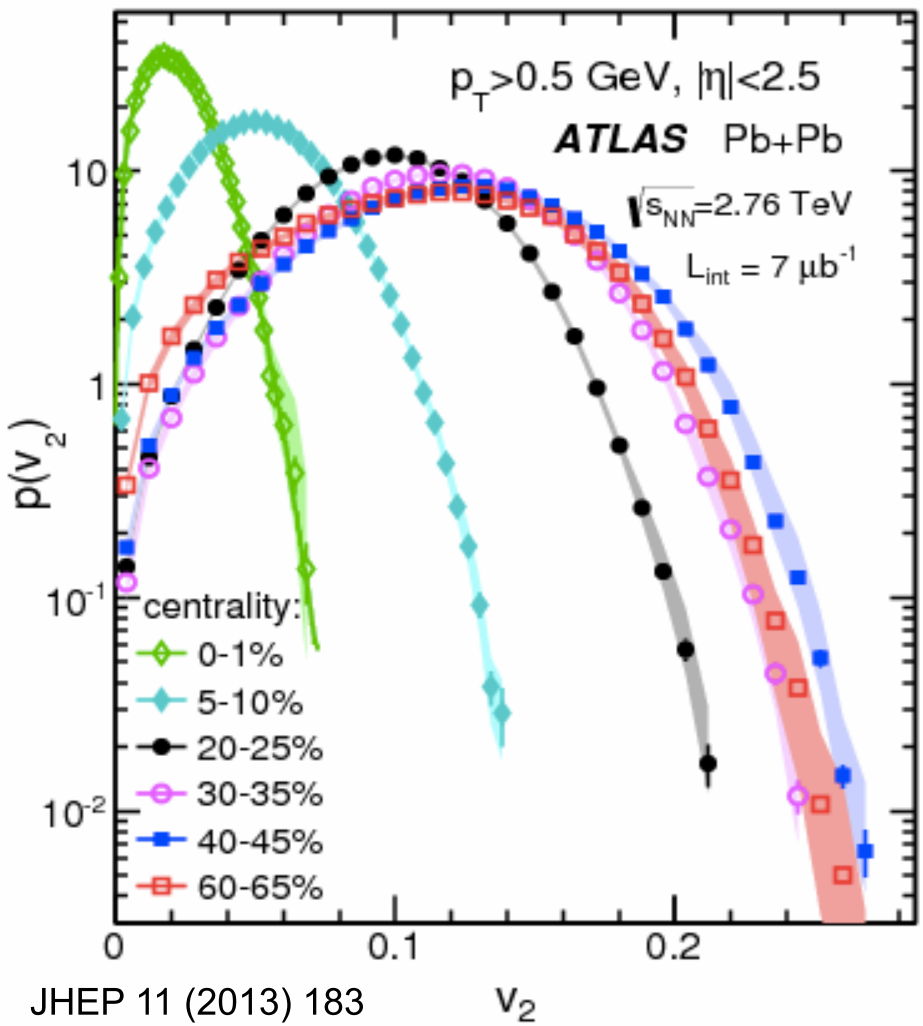
So does the response of final-state flow effect (v_n, Φ_n)?

$$\frac{dN}{d\phi} \propto 1 + 2\sum_n v_n \cos n(\phi - \Phi_n)$$



Event-by-event flow fluctuations

Full event-by-event v_2 distribution
(unfolded for finite resolution)



JHEP 11 (2013) 183

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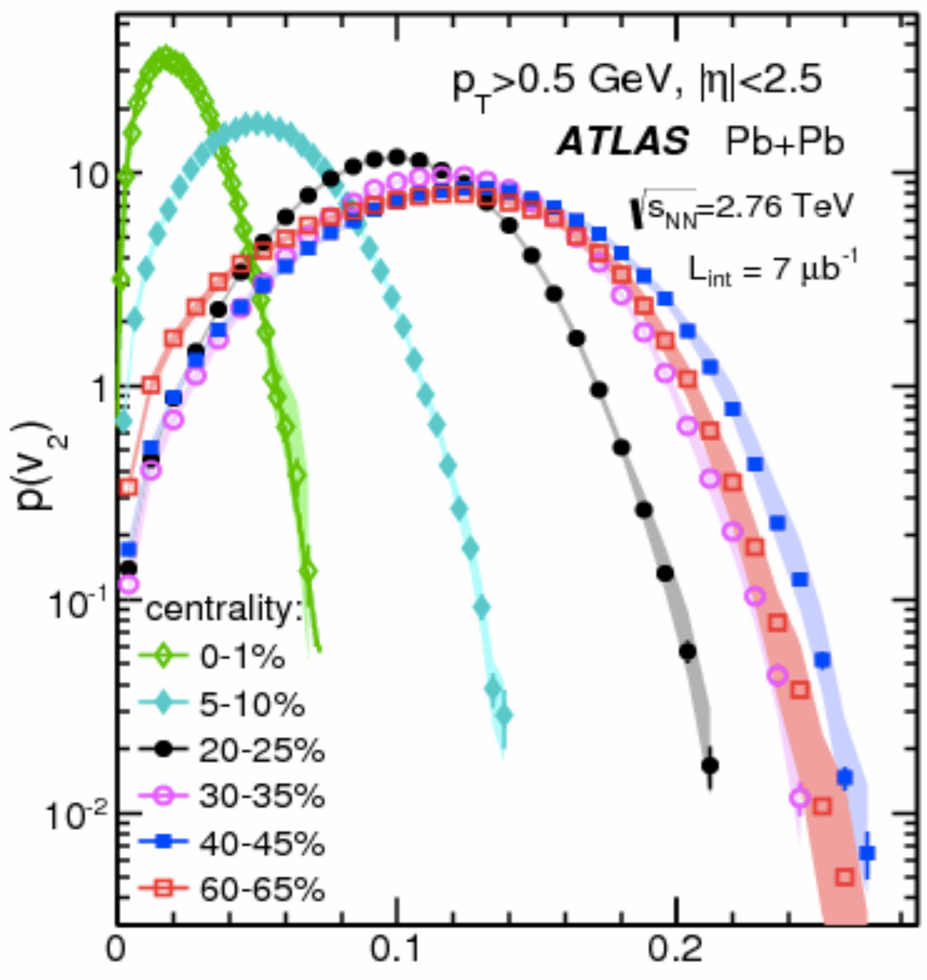
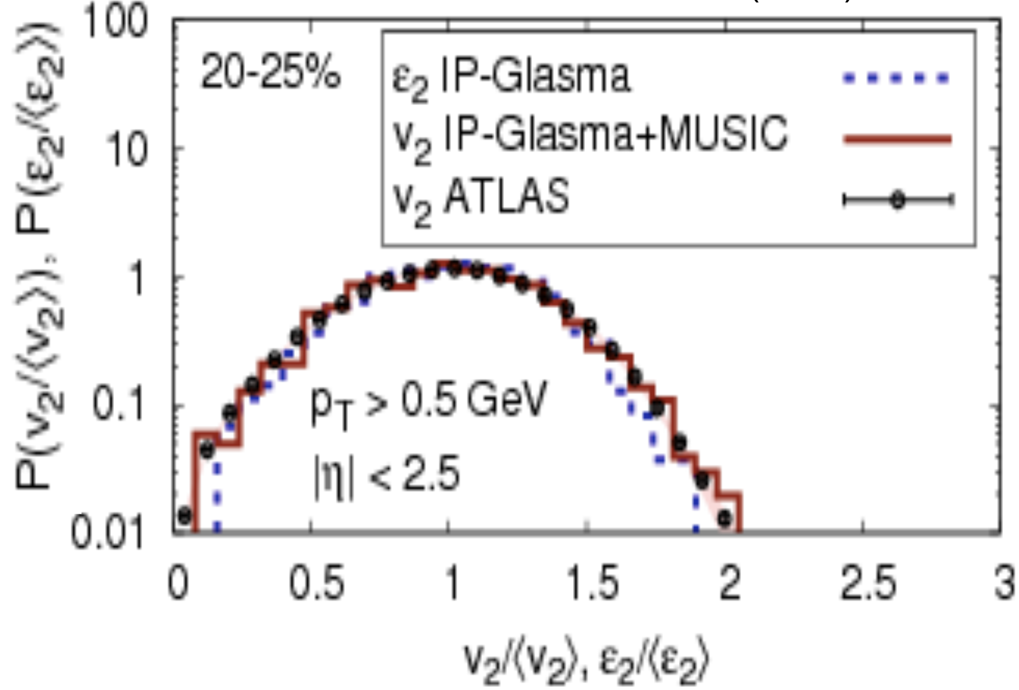


JHEP 11 (2013) 183

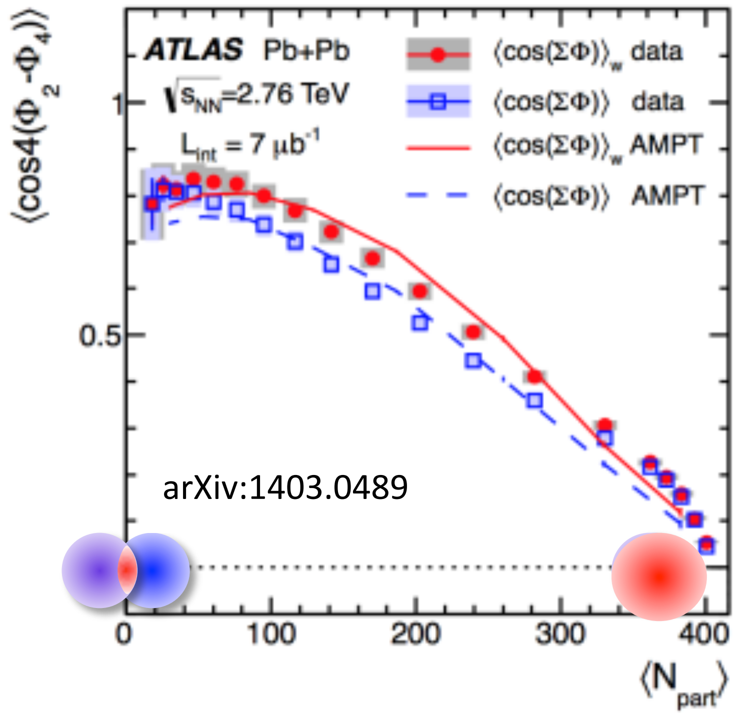
PRL 110 (2013) 012302



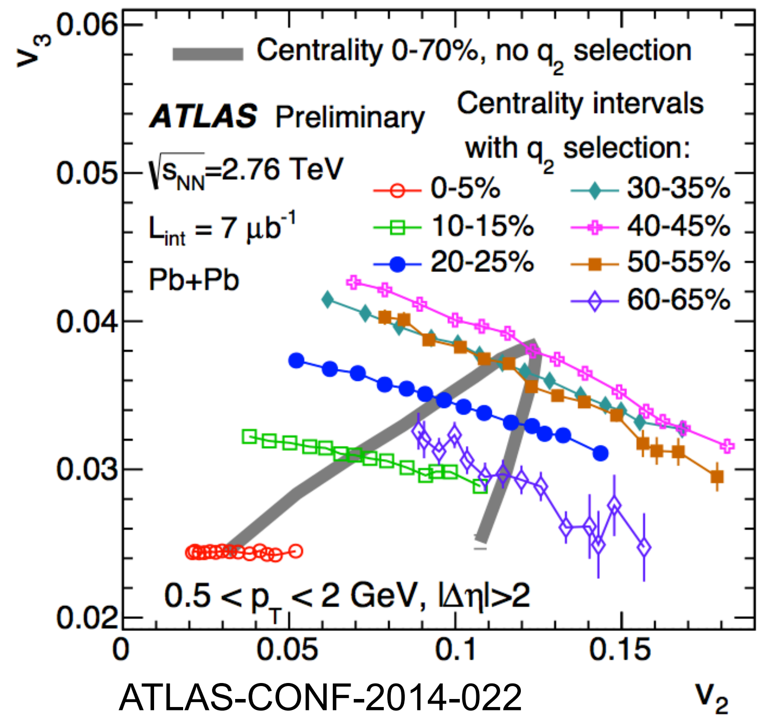
Successfully described by hydrodynamics, again

More on flow fluctuations …

Correlation between different Event plane angle (Φ_2 and Φ_4)



Anti-correlations between v_2 and v_3, expected from initial geometry



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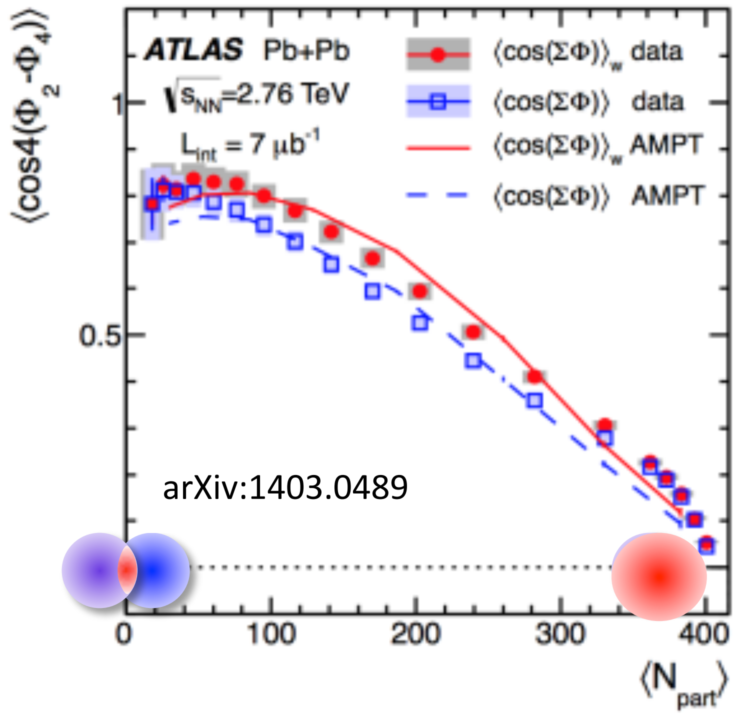

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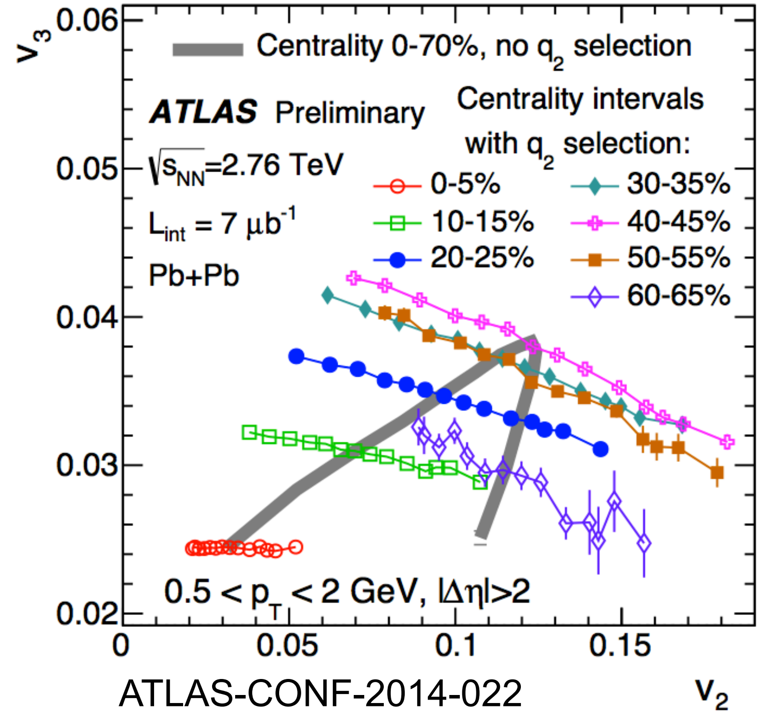


- **"Nearly perfect liquid" paradigm of heavy-ion collisions firmly established at RHIC and the LHC**
- **A phase of precision measurement, aiming to quantify the properties of QGP in detail**

A big strike in 2010 …

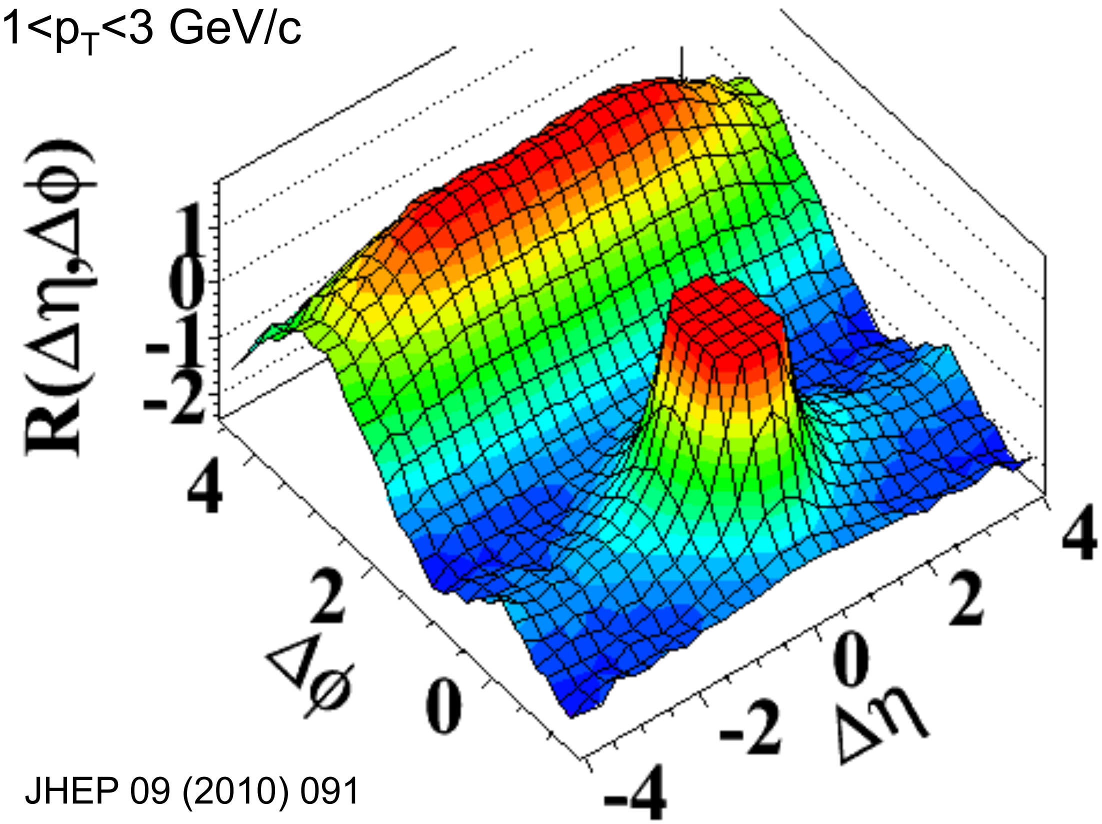
Breaking news In 2010:

A near-side ridge in pp at the LHC!

pp 7 TeV, N>=110

$1<p_T<3$ GeV/c

0-0.0007% central



JHEP 09 (2010) 091

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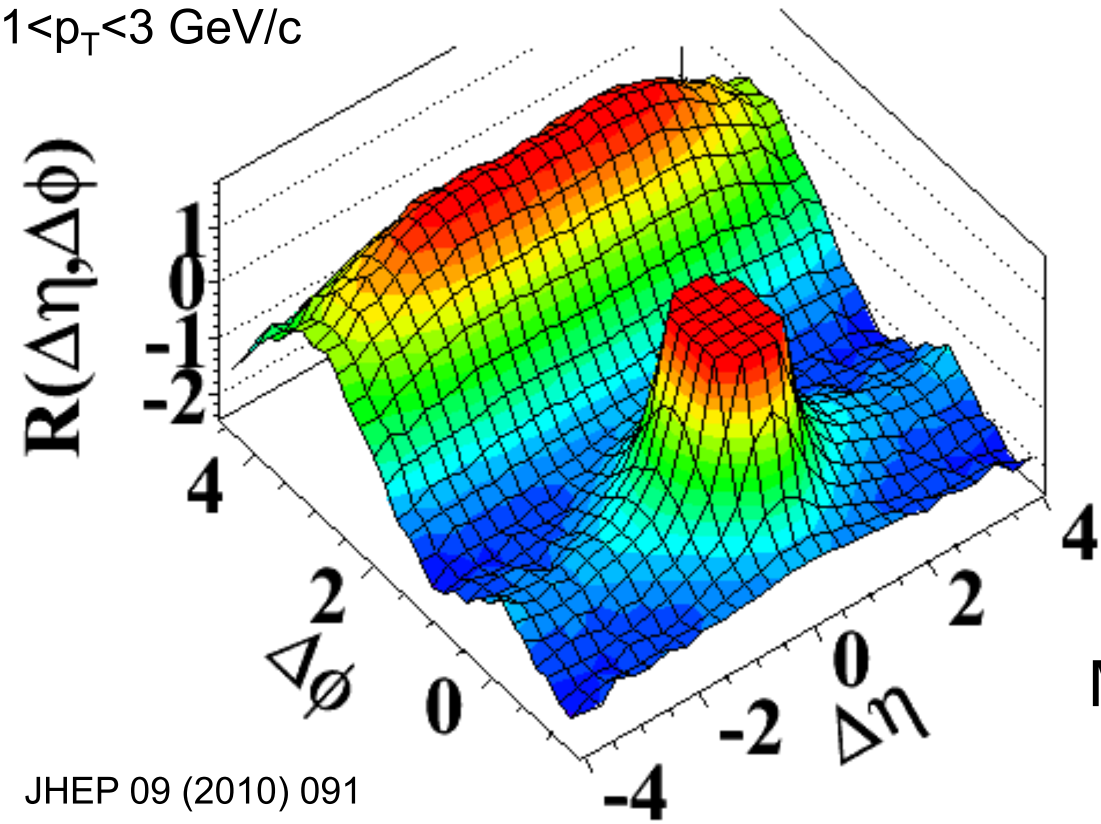
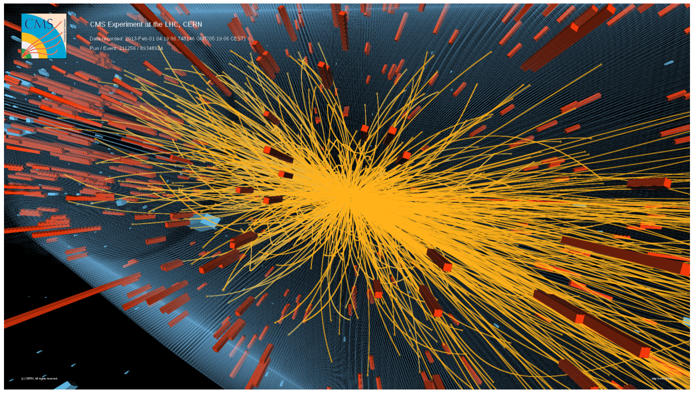


JHEP 09 (2010) 091

high-multiplicity pp event



Mini-QGP fluid (r ~ 1 fm) in pp?

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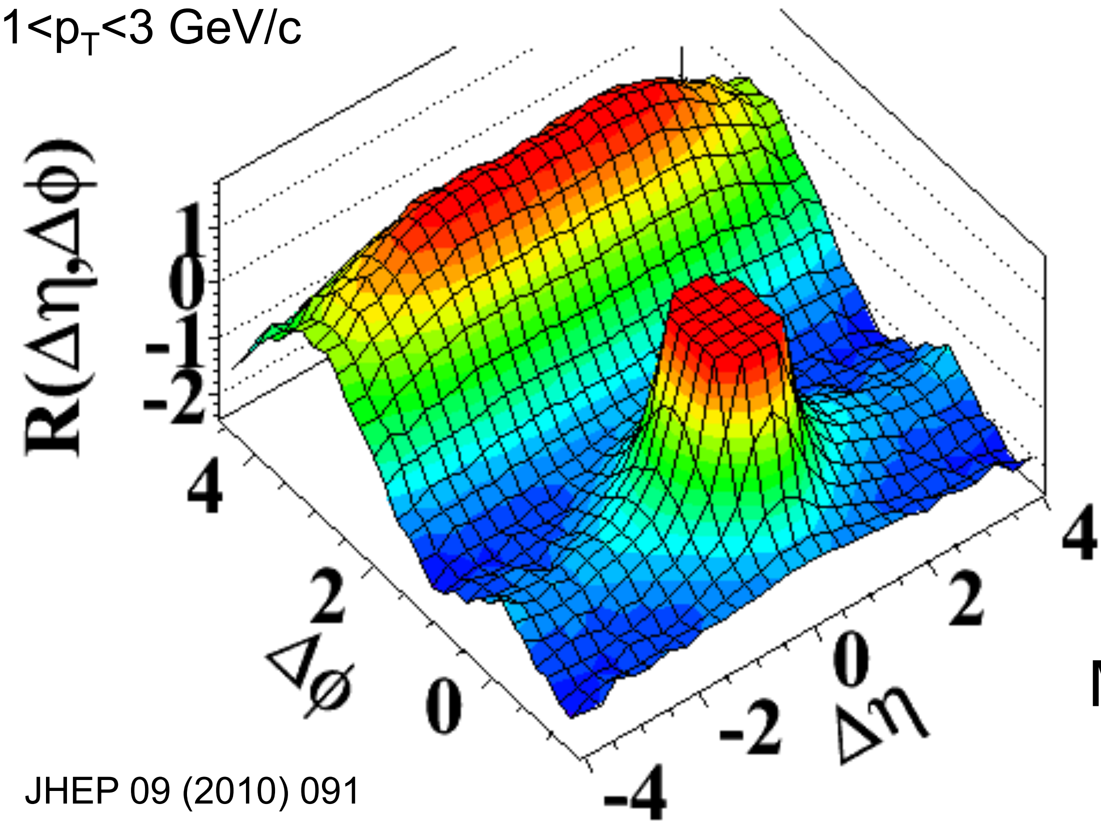

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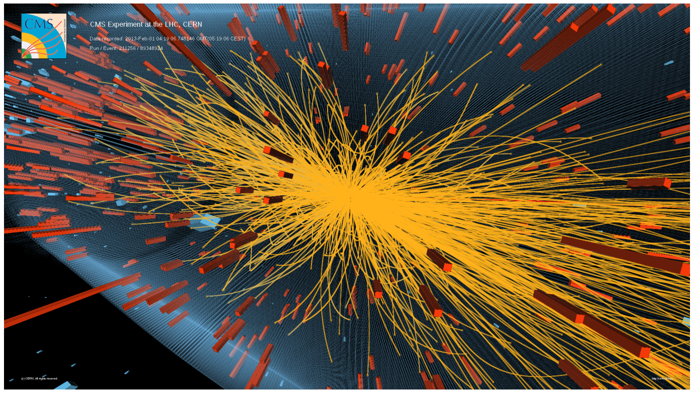
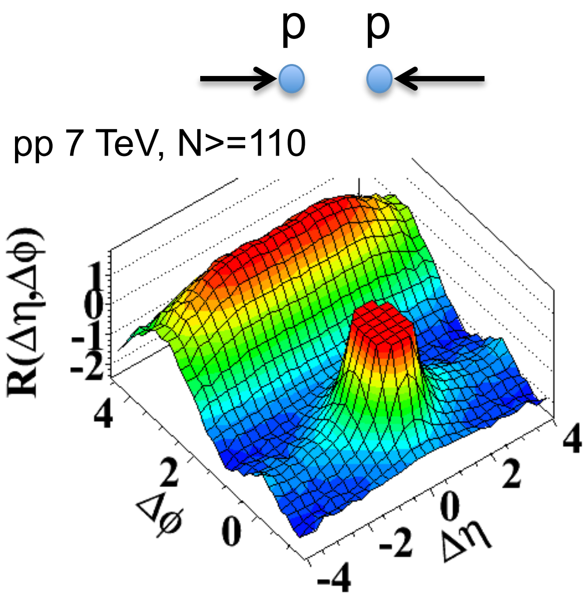
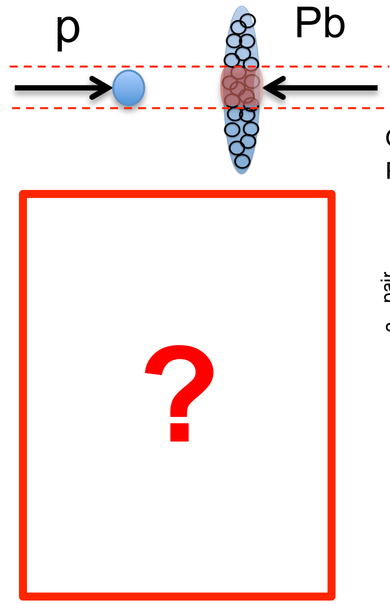


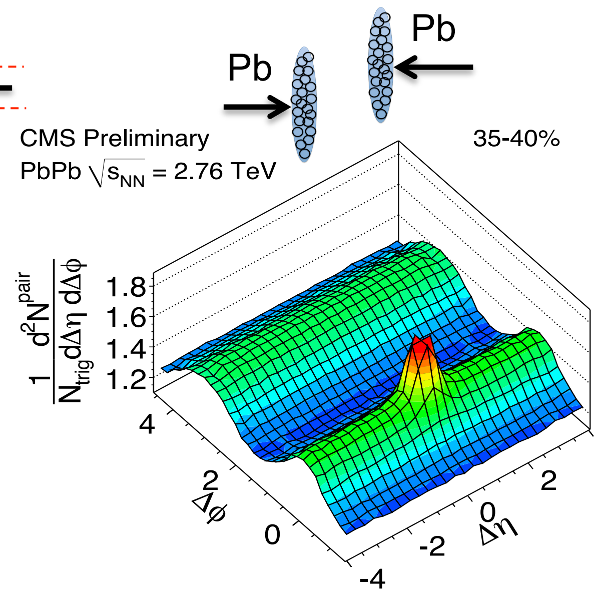
Mini-QGP fluid (r ~ 1 fm) in pp?

Beginning of a second "discovery" phase

The ridge is everywhere: pPb at the LHC

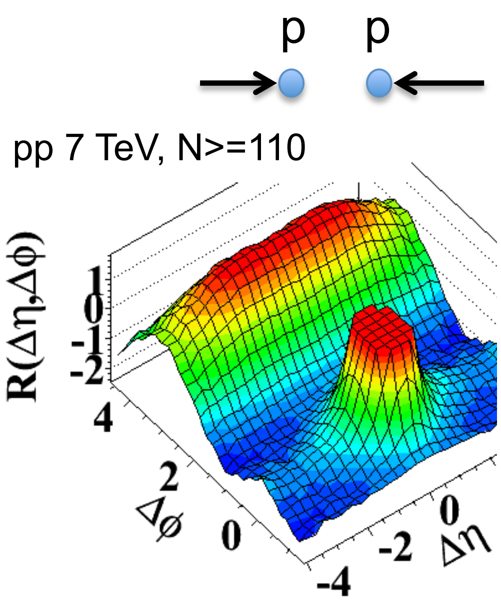


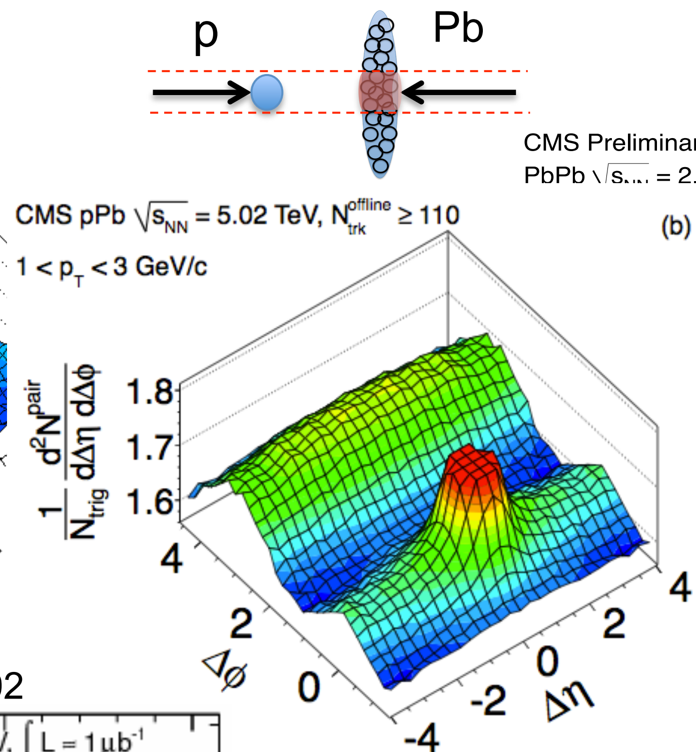


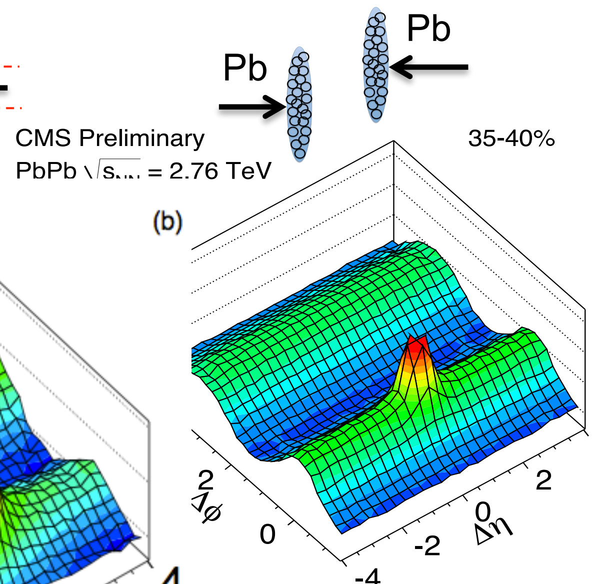


The ridge is everywhere: pPb at the LHC

pp 7 TeV, N>=110

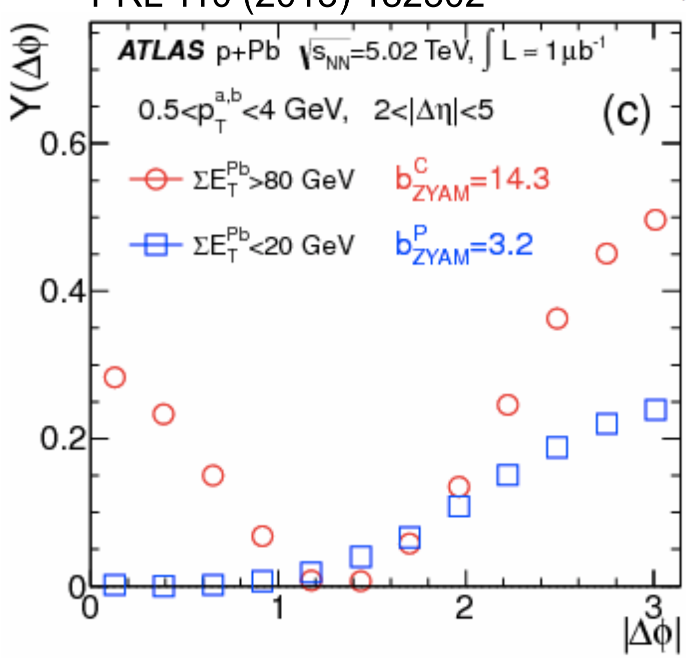






PLB 718 (2013) 795

PRL 110 (2013) 182302



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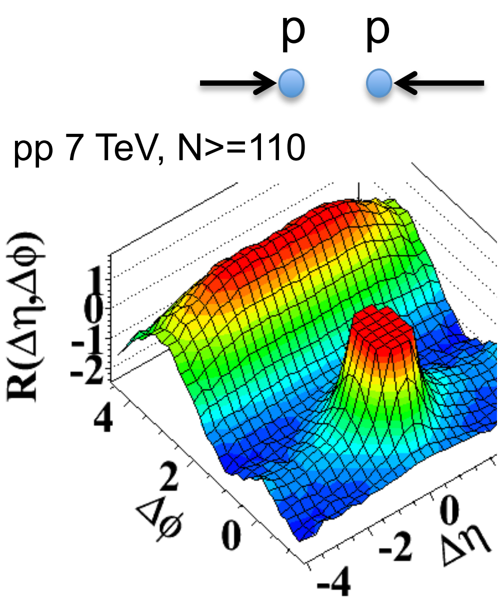

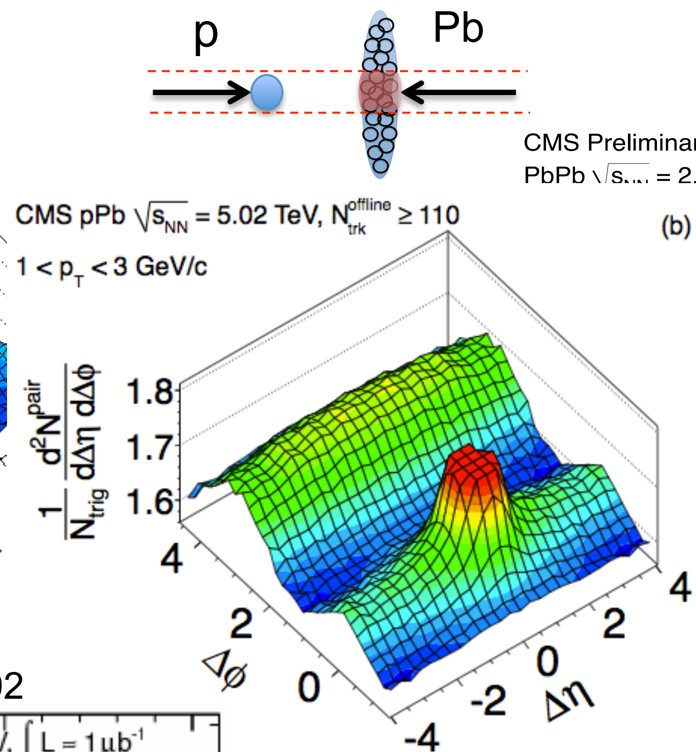

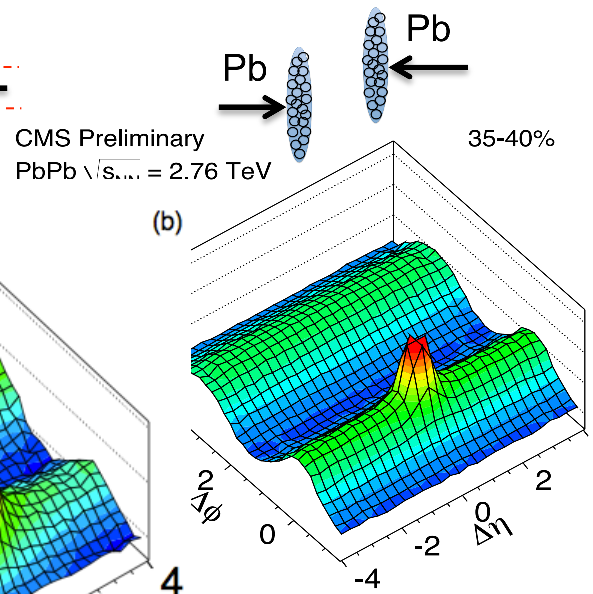

PLB 718 (2013) 795

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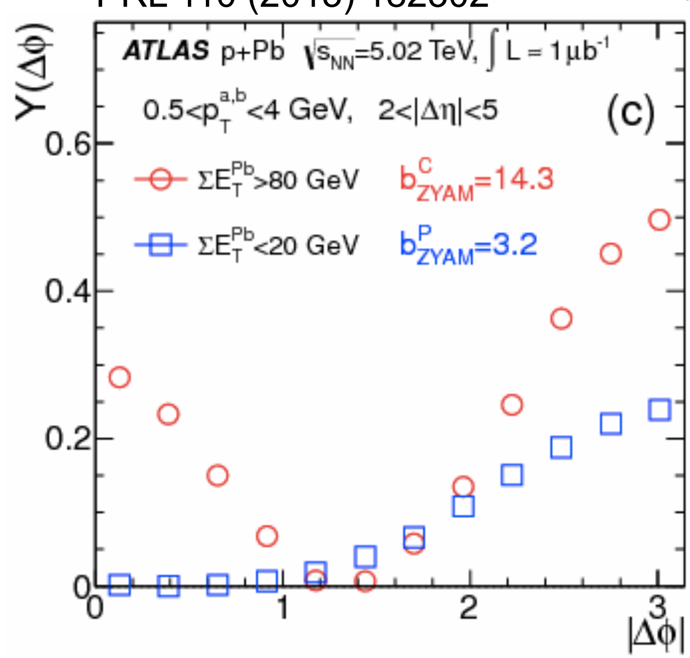
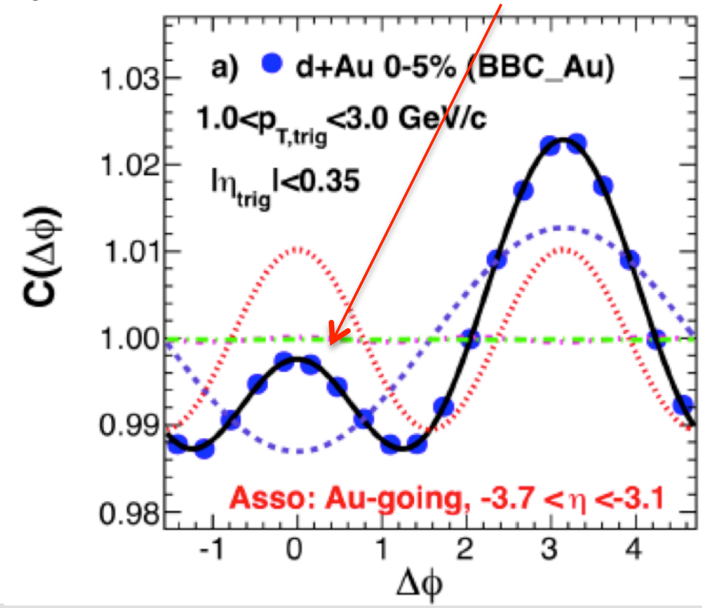
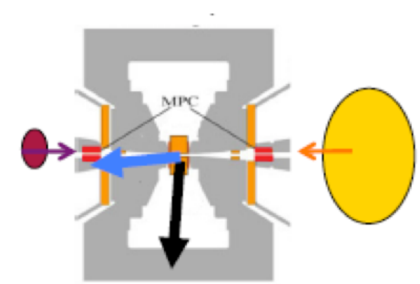


Ridge in dAu at RHIC!

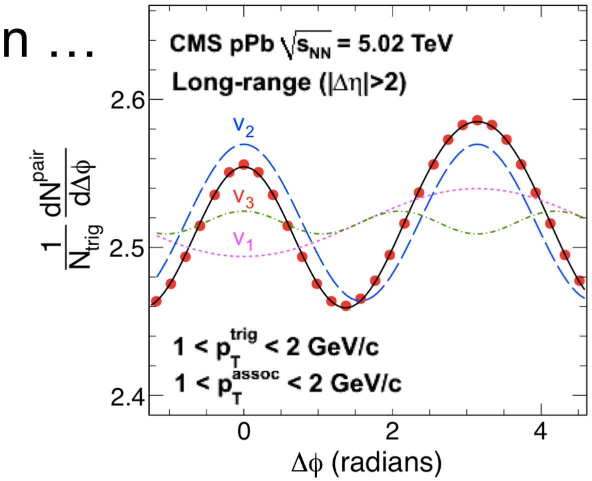


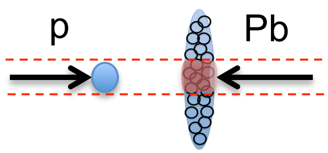


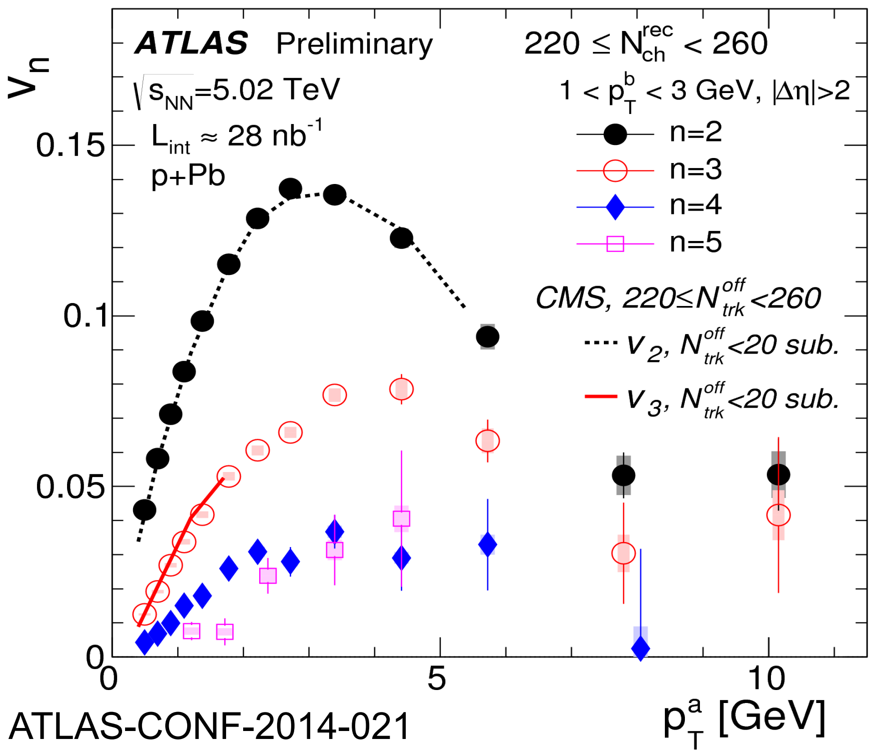
arXiv:1404.7461

Flow (v_n) in pPb

Fourier again …







ATLAS-CONF-2014-021

Flow (v_n) in pPb

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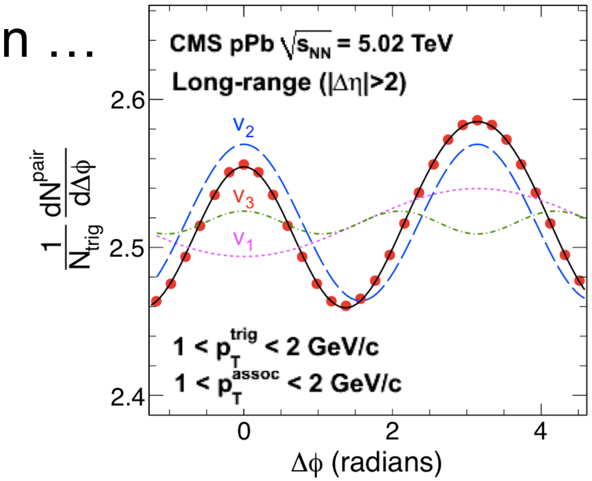
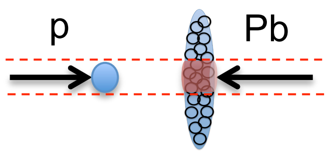
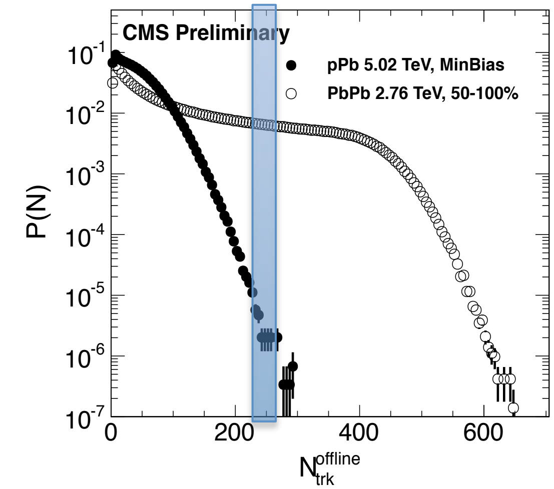
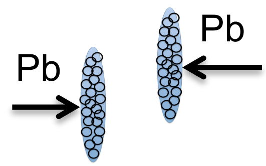
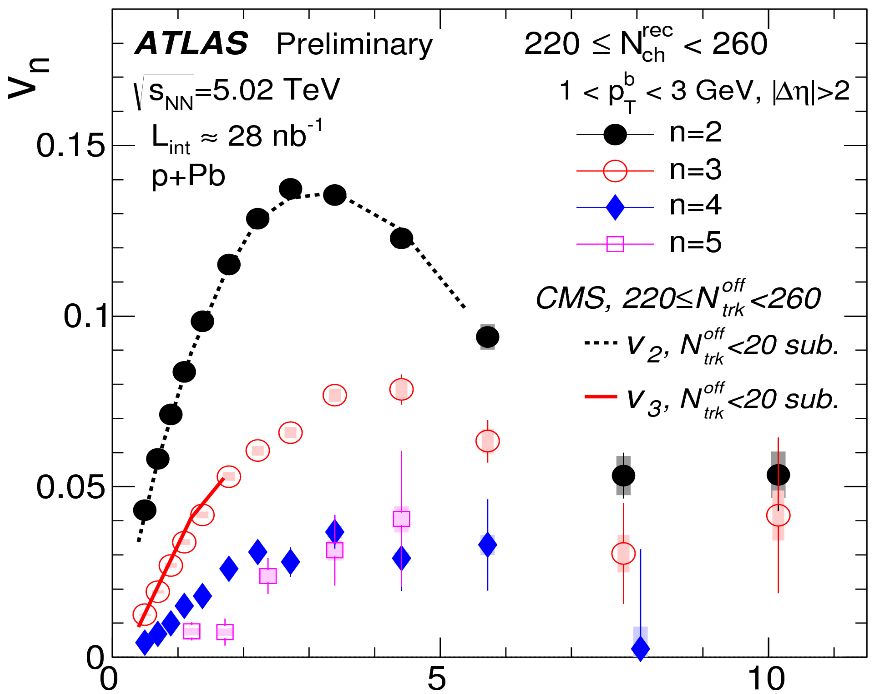




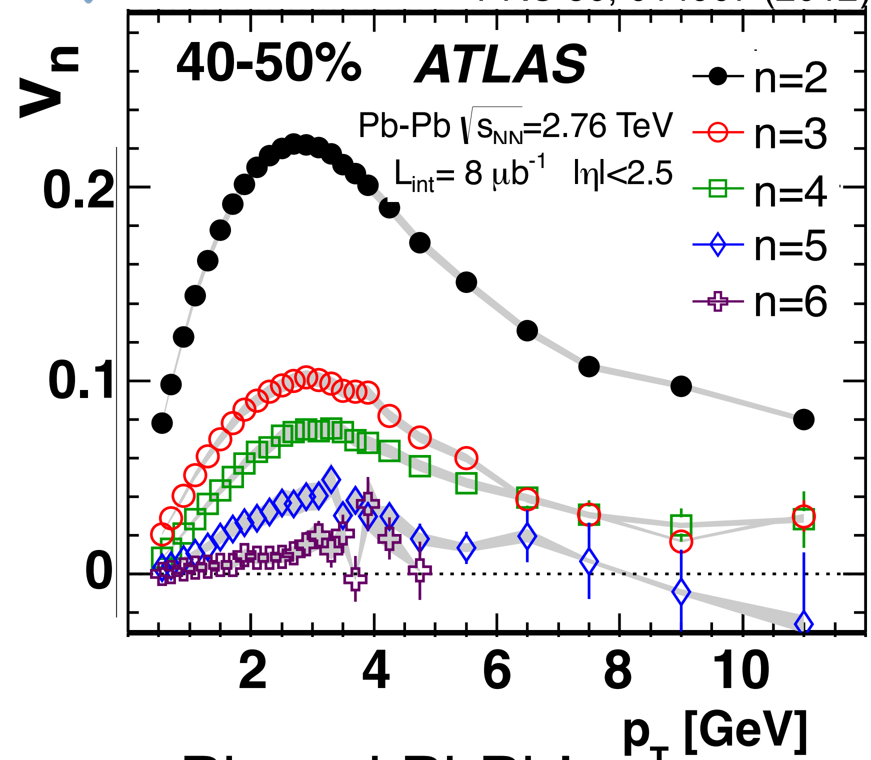




PRC 86, 014907 (2012)



ATLAS-CONF-2014-021

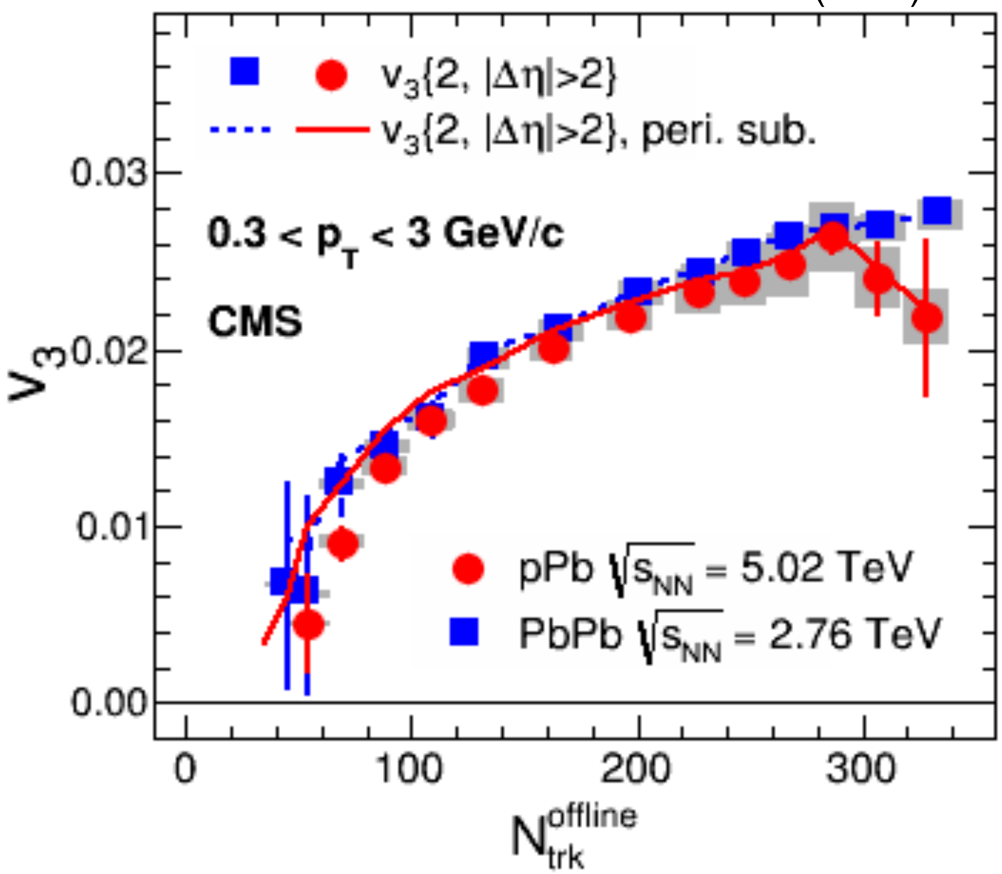


Intriguing similarity between pPb and PbPb!

Flow (v_n) in pPb

Triangular flow nearly identical in pPb and PbPb!

PLB 724 (2013) 213



Triangularity entirely from fluctuations, maybe system size does not matter?

Teaney, arXiv:1312.6770

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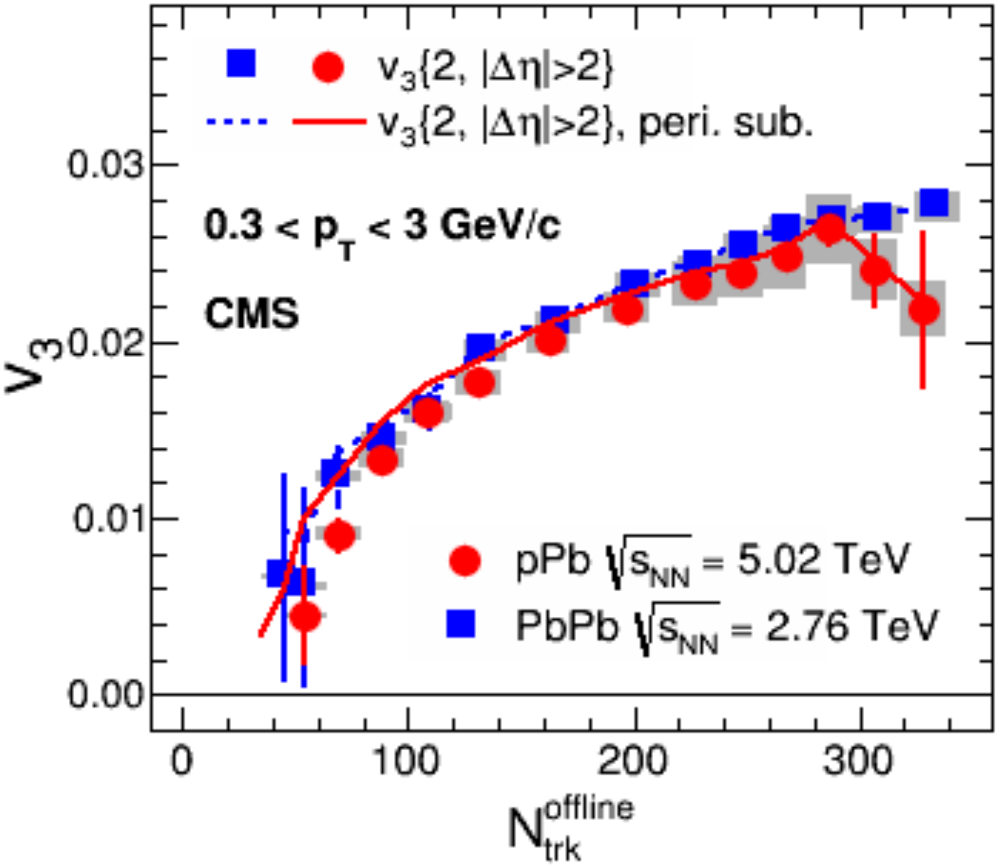
PLB 724 (2013) 213



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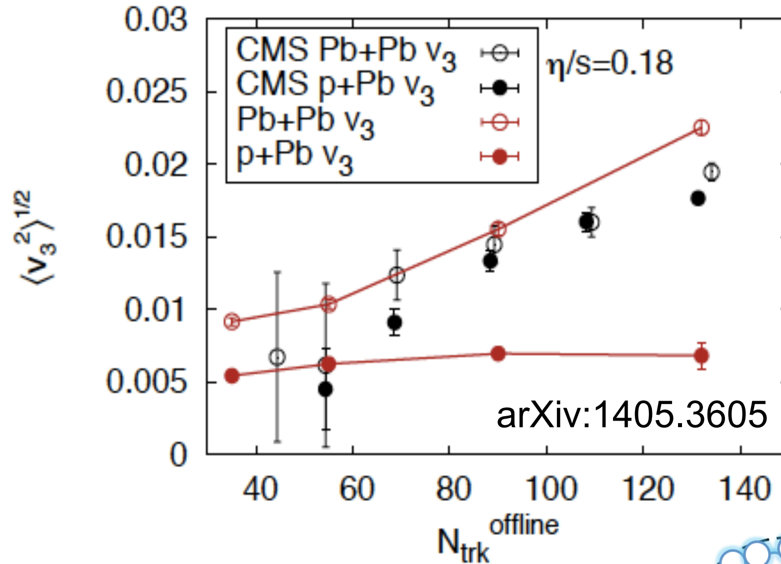
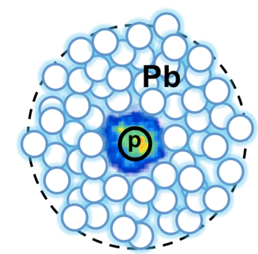
But, hydro. failed to describe the data



ε_3 driven by proton, which is too small since proton is spherical in the model



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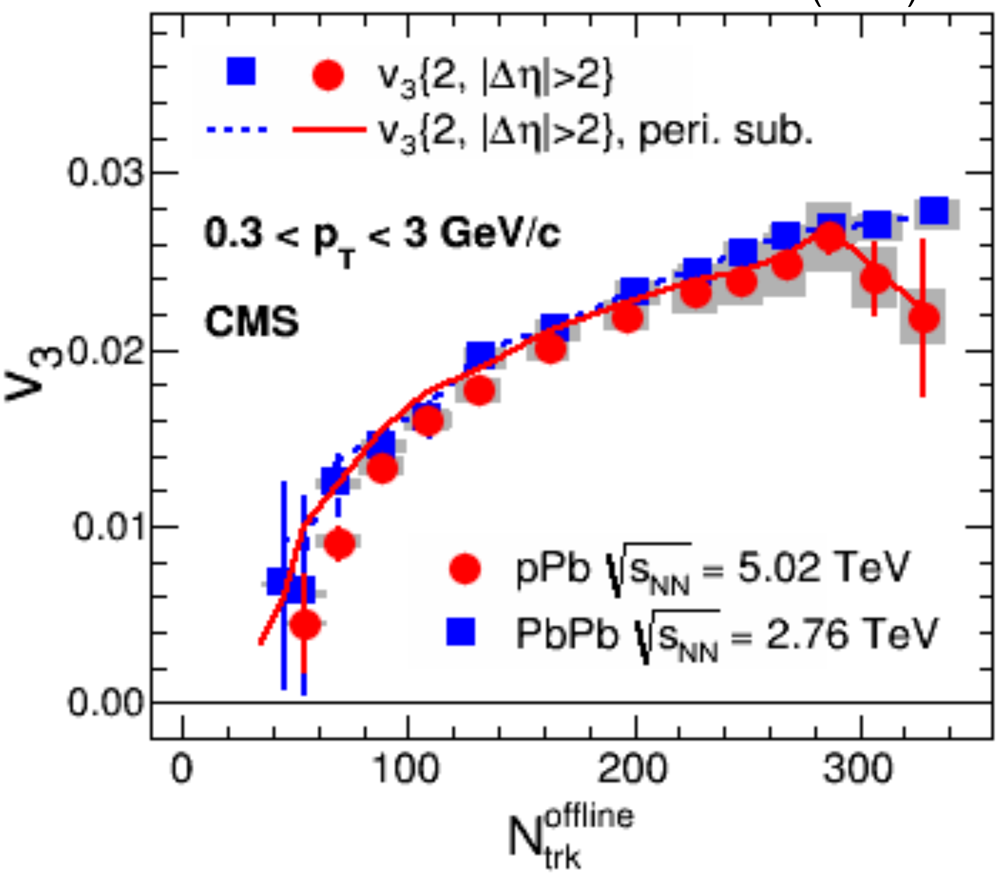
PLB 724 (2013) 213



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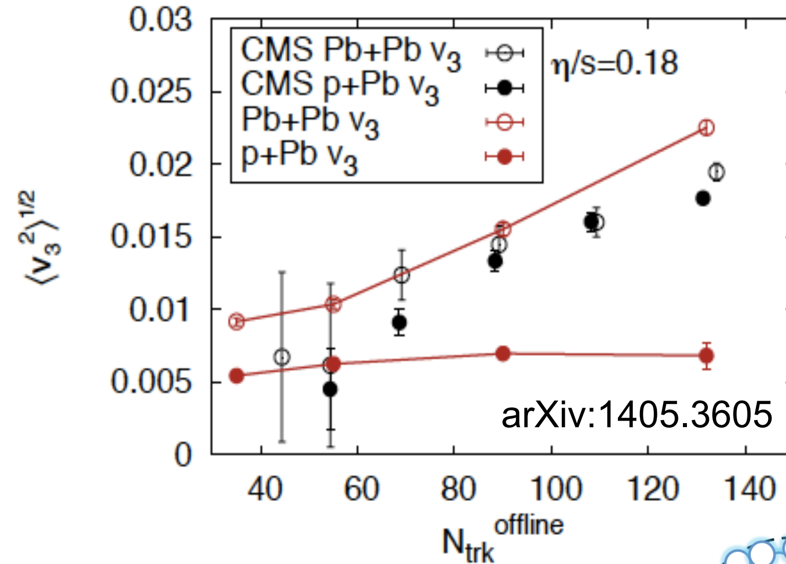

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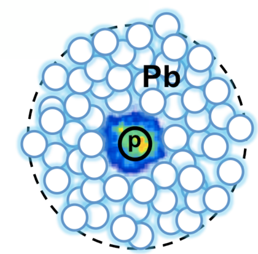
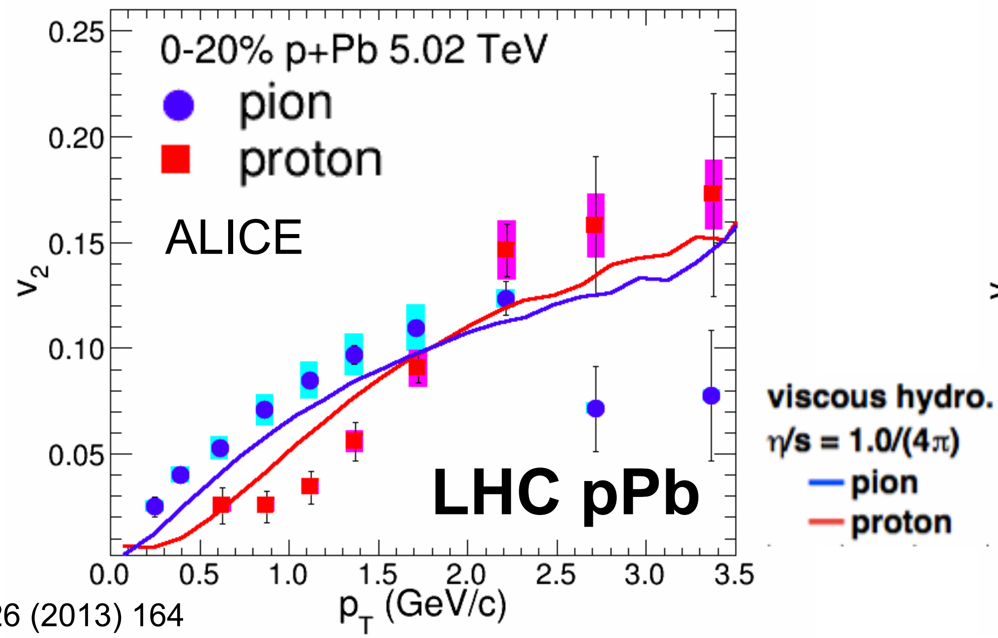


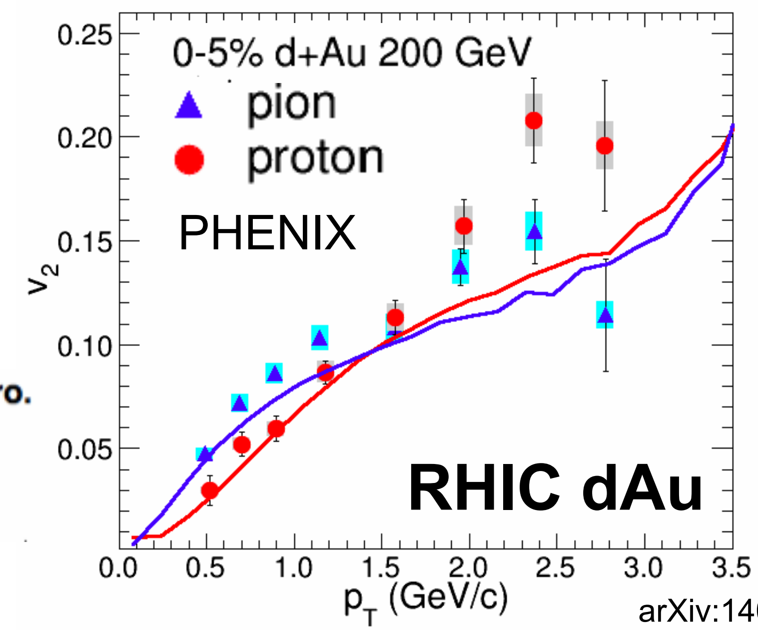
Stringy proton from quantum fluctuations caught by a nucleus?

PRD 89, 025019 (2014)

PID v_n in pPb



PLB 726 (2013) 164

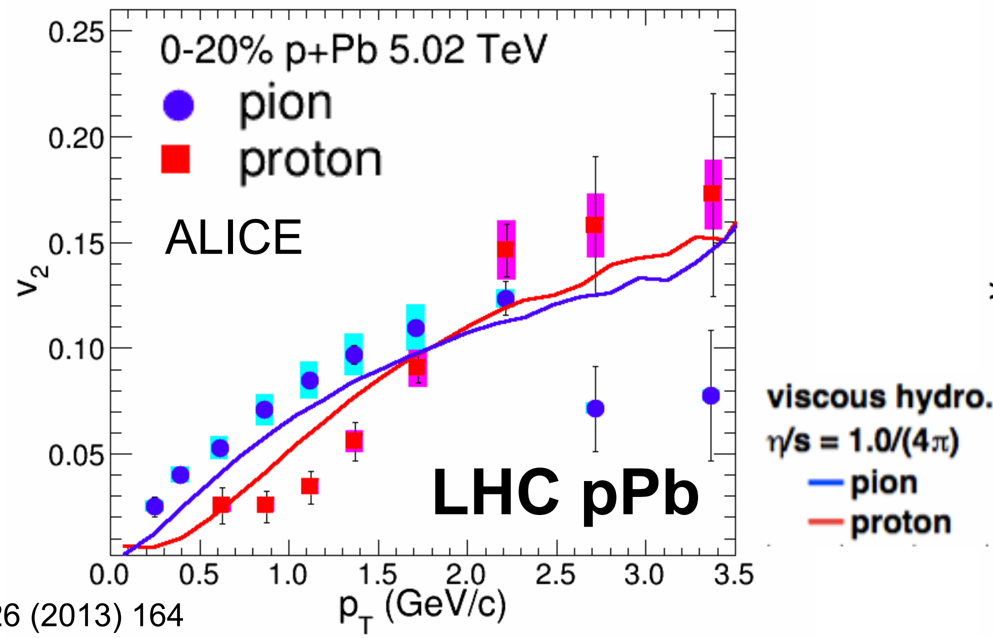


arXiv:1404.7461

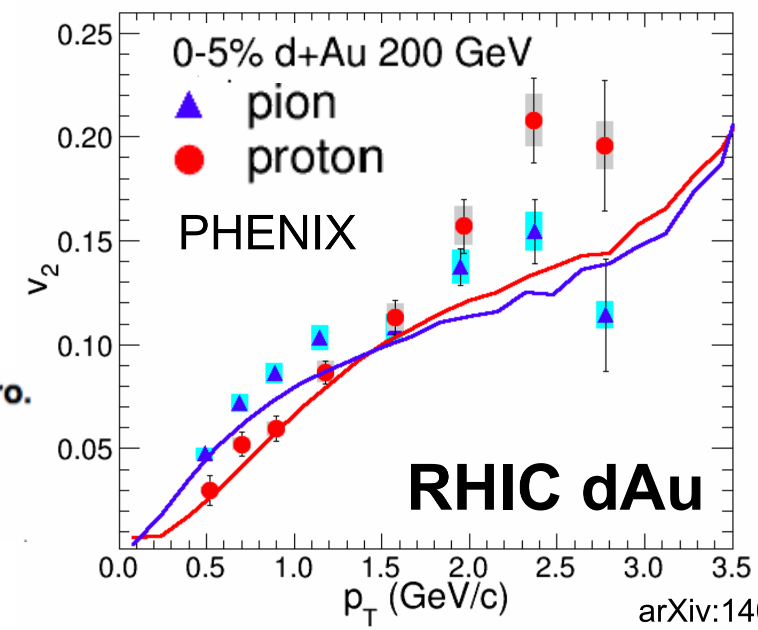
Mass splitting of v_2 in pPb:

- Smaller v_2 for heavier particles at low p_T
- Consistent with hydro.

PID v_n in pPb



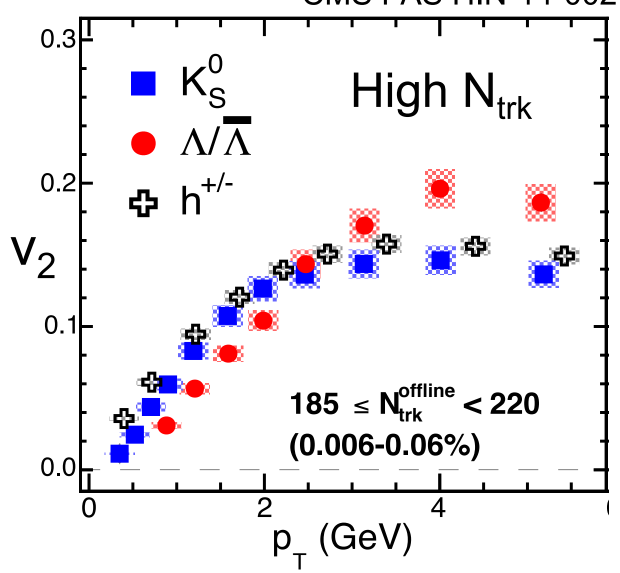
PLB 726 (2013) 164



arXiv:1404.7461

Strange hadrons: K^0_s and Λ

CMS PAS HIN-14-002



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Clear crossing at p_T ~ 2 GeV

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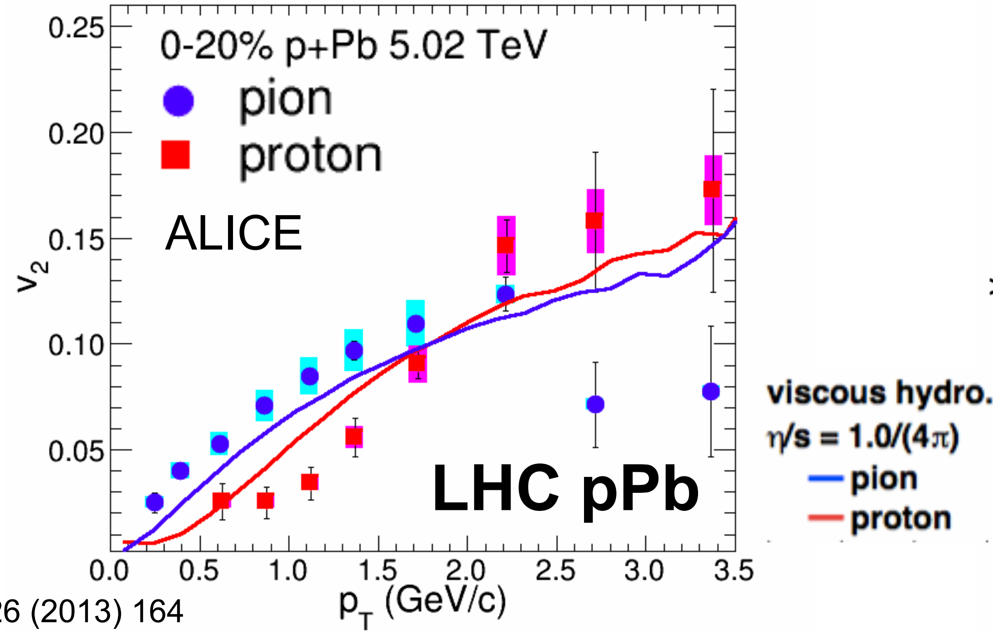
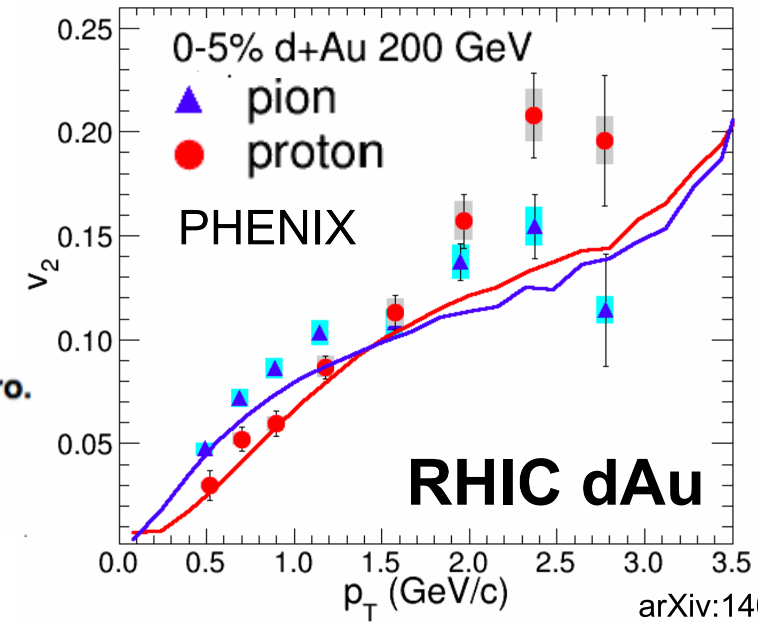


PLB 726 (2013) 164



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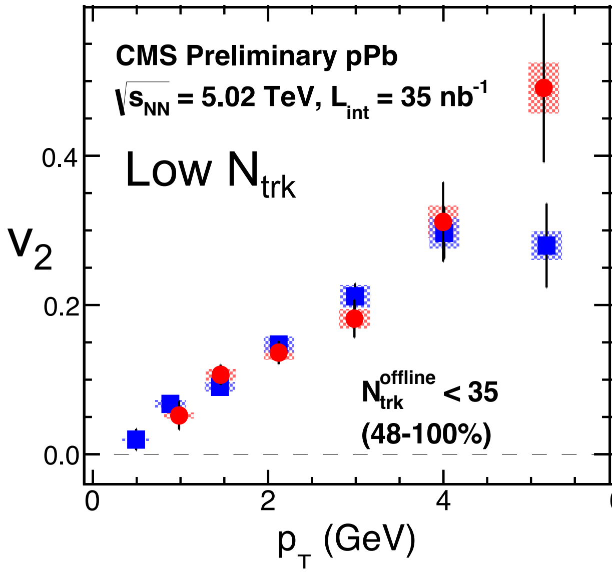

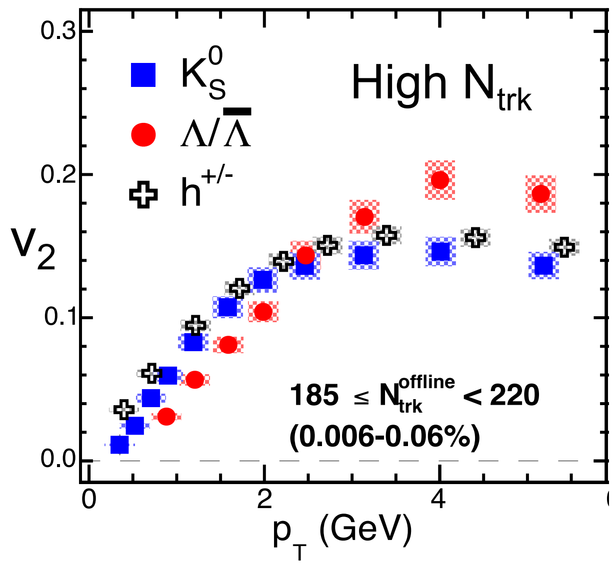

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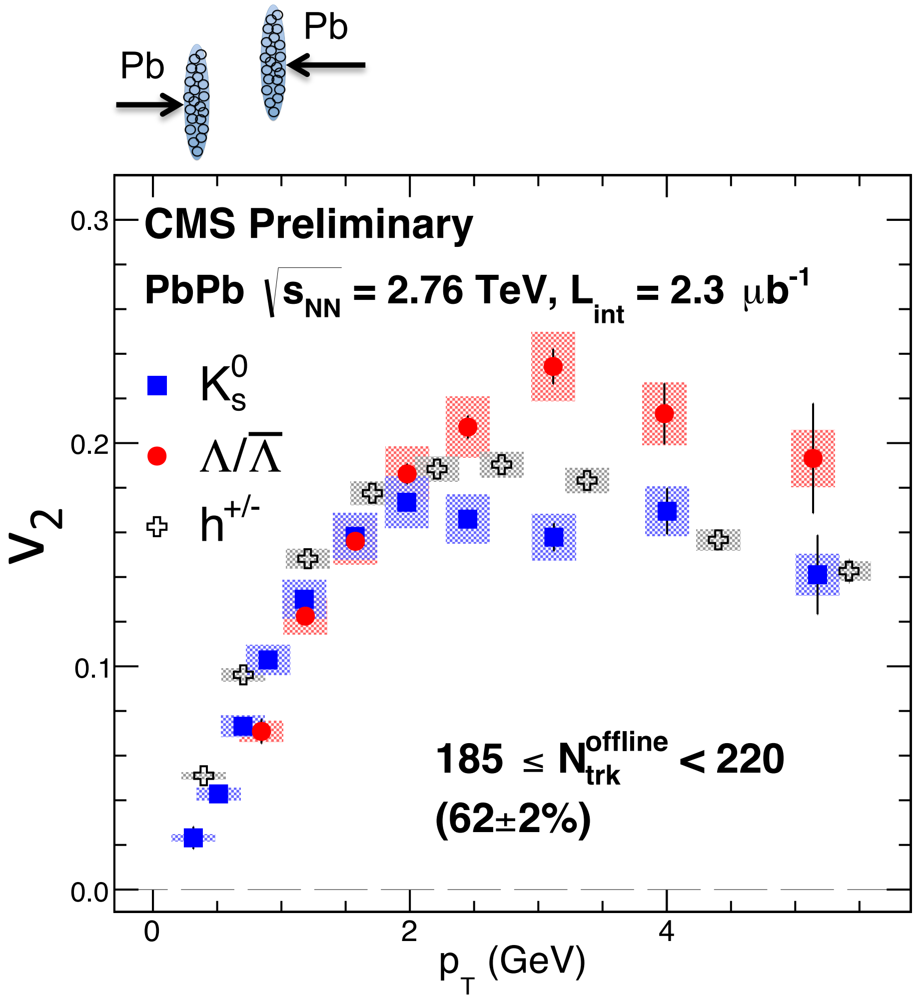
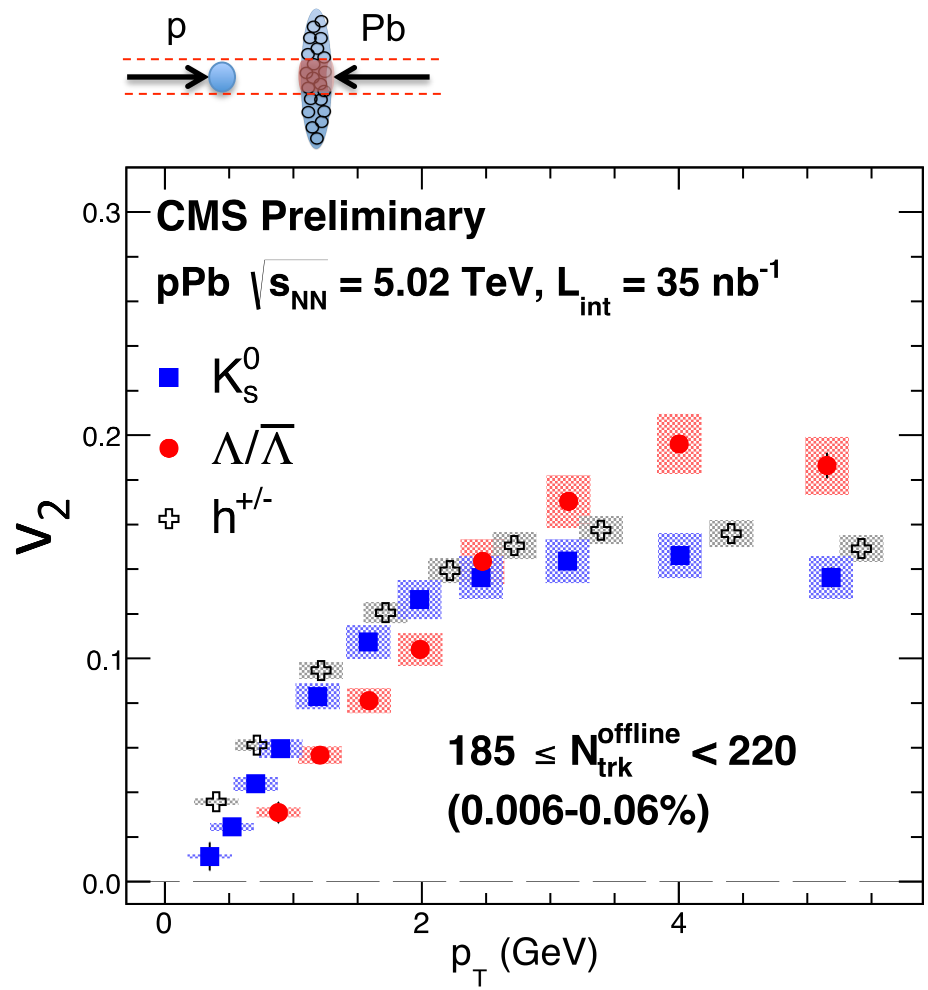
No mass dependence of Jet correlations at low N_{trk}

PID v_n in pPb





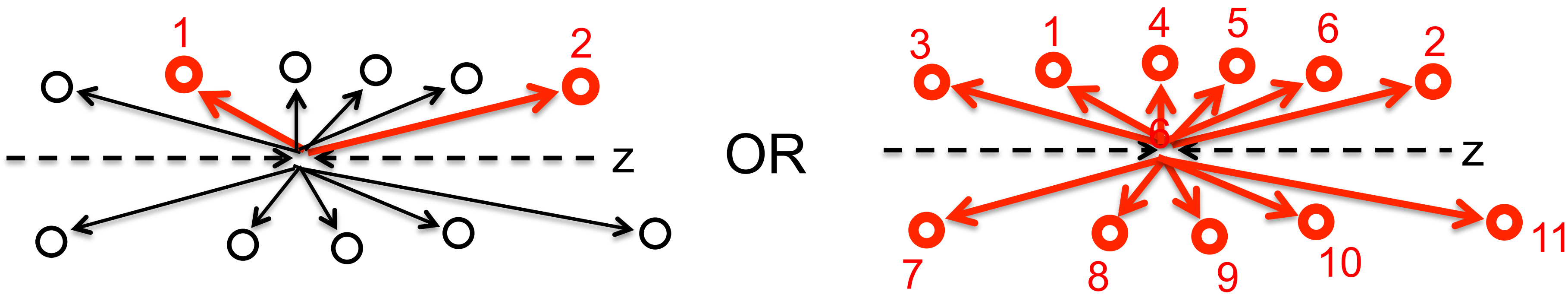
Larger mass splitting in pPb than in PbPb at similar multiplicity

→Stronger radial flow for smaller and denser system?

True collectivity in pPb?

The key question:

Does the ridge involve only two particles or more?



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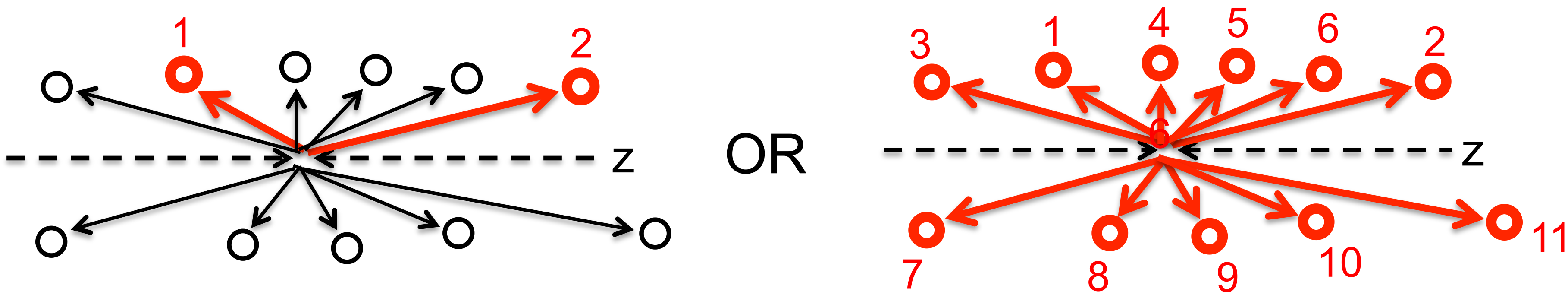

Or namely, is it a collective effect as hydro. describes?

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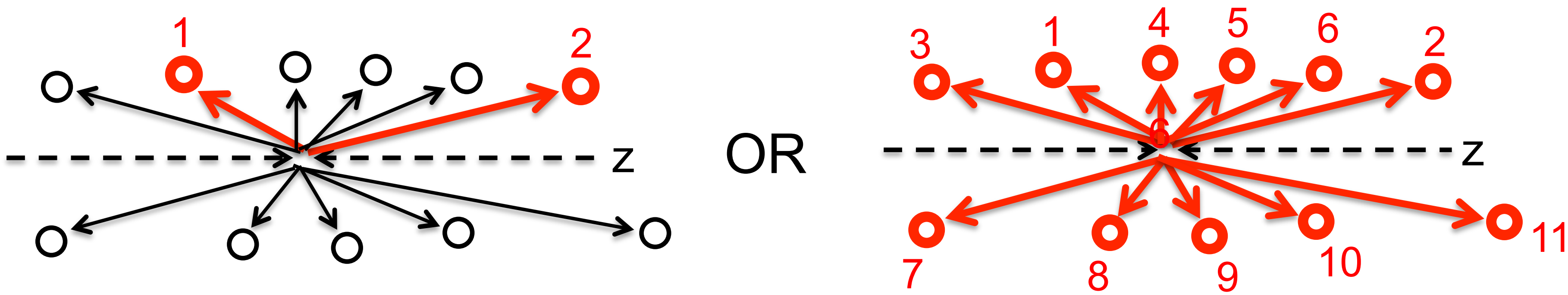


Or namely, is it a collective effect as hydro. describes?

Multi-particle (>2) correlations:

$$\langle \cos 2(\phi_1 - \phi_2) \rangle \sim (v_2)^2$$

$$\langle \cos 2(\phi_1 + \phi_2 - \phi_3 - \phi_4) \rangle \sim (v_2)^4$$

$$\langle \cos 2(\phi_1 + \phi_2 + \phi_3 - \phi_4 - \phi_5 - \phi_6) \rangle \sim (v_2)^6$$

$$\vdots$$

In hydrodynamics:

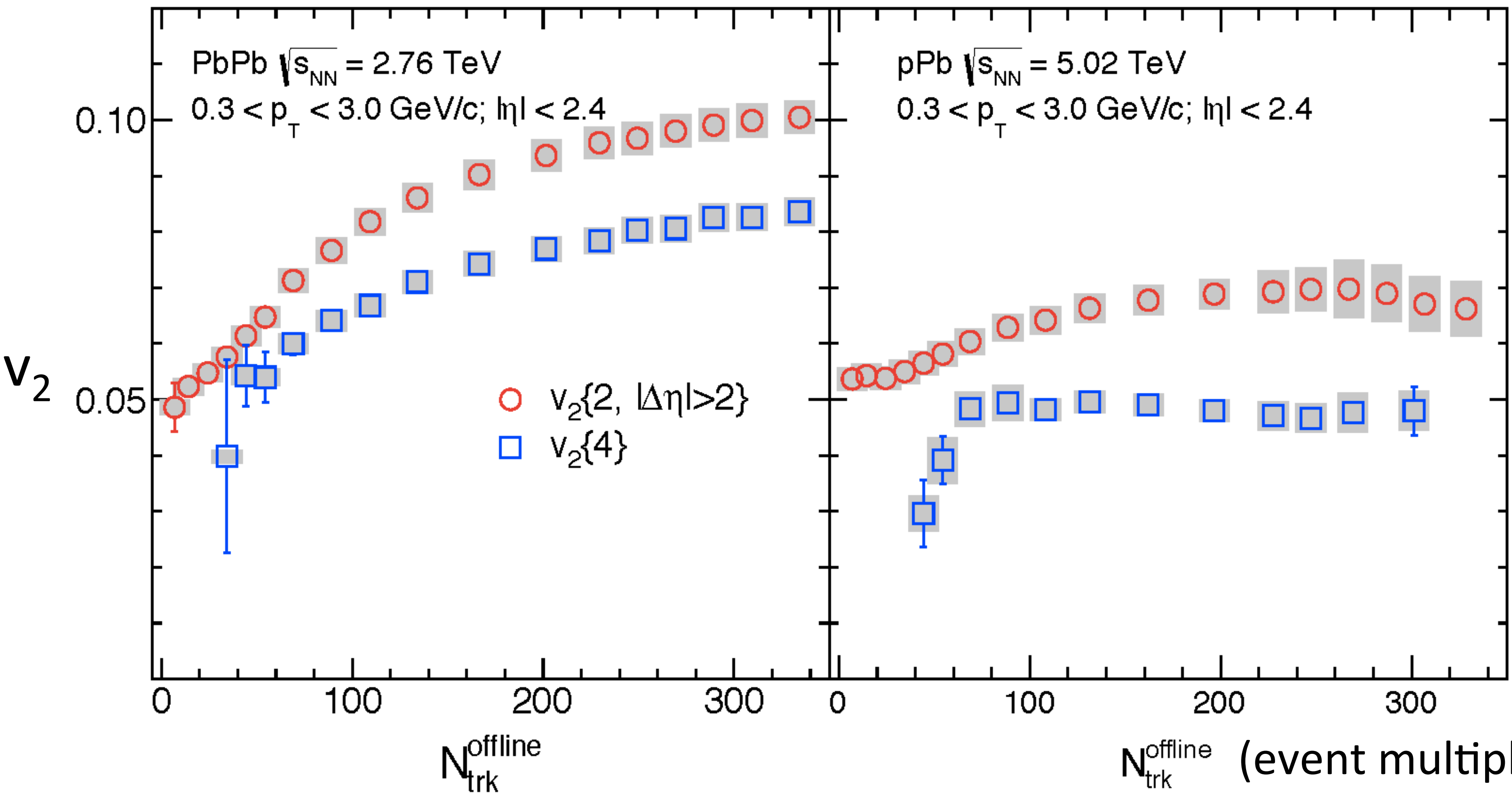
$$\mathbf{v_2\{2\} > v_2\{4\} \approx v_2\{6\} \approx v_2\{8\} \approx v_2\{\infty\}}$$

True collectivity in pPb?

$v_2\{2\} > v_2\{4\}$

(event-by-event fluctuations)

PLB724 (2013) 213



(event multiplicity)

True collectivity in pPb?

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

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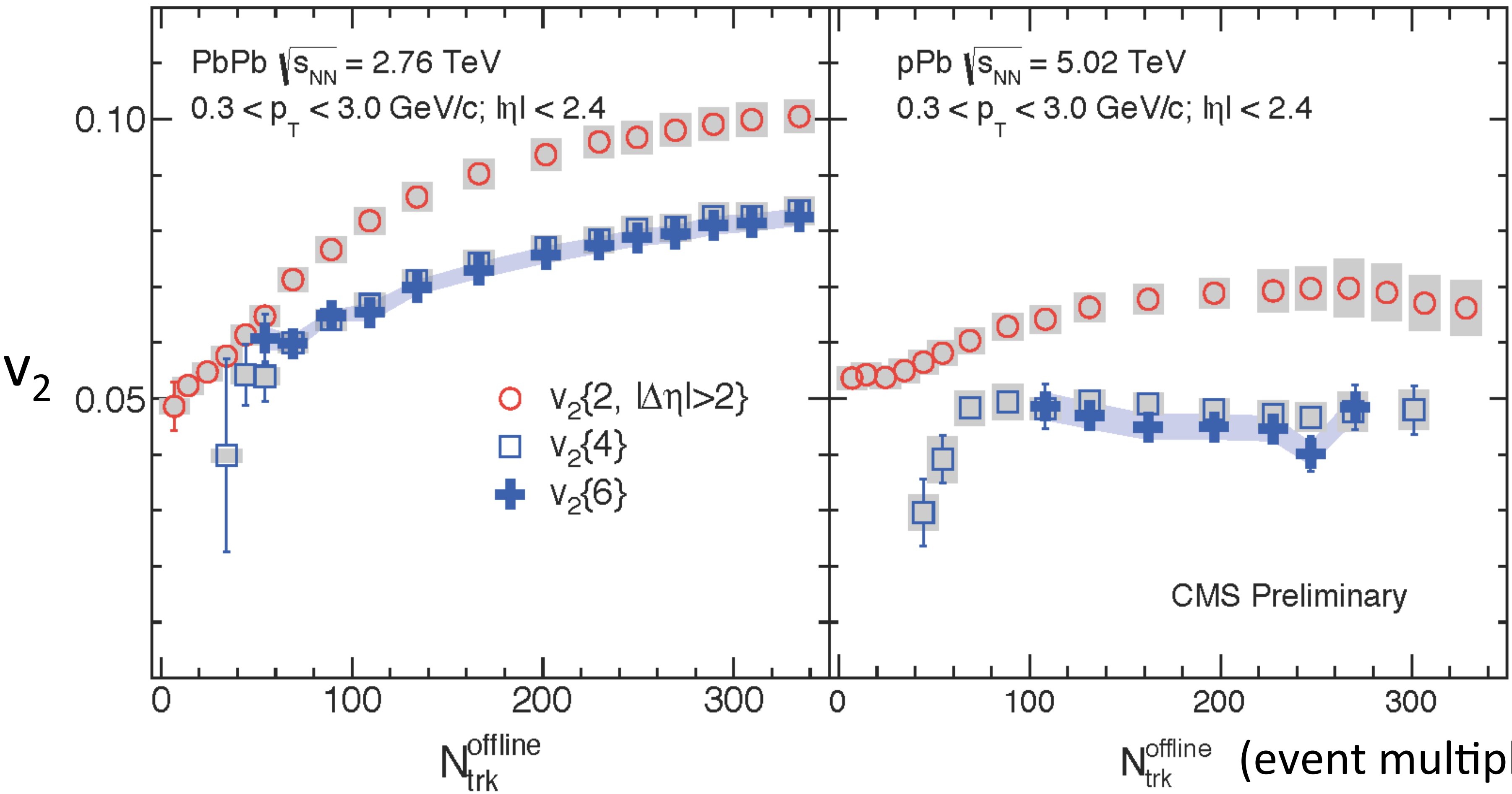
CMS PAS HIN-14-006



(event multiplicity)

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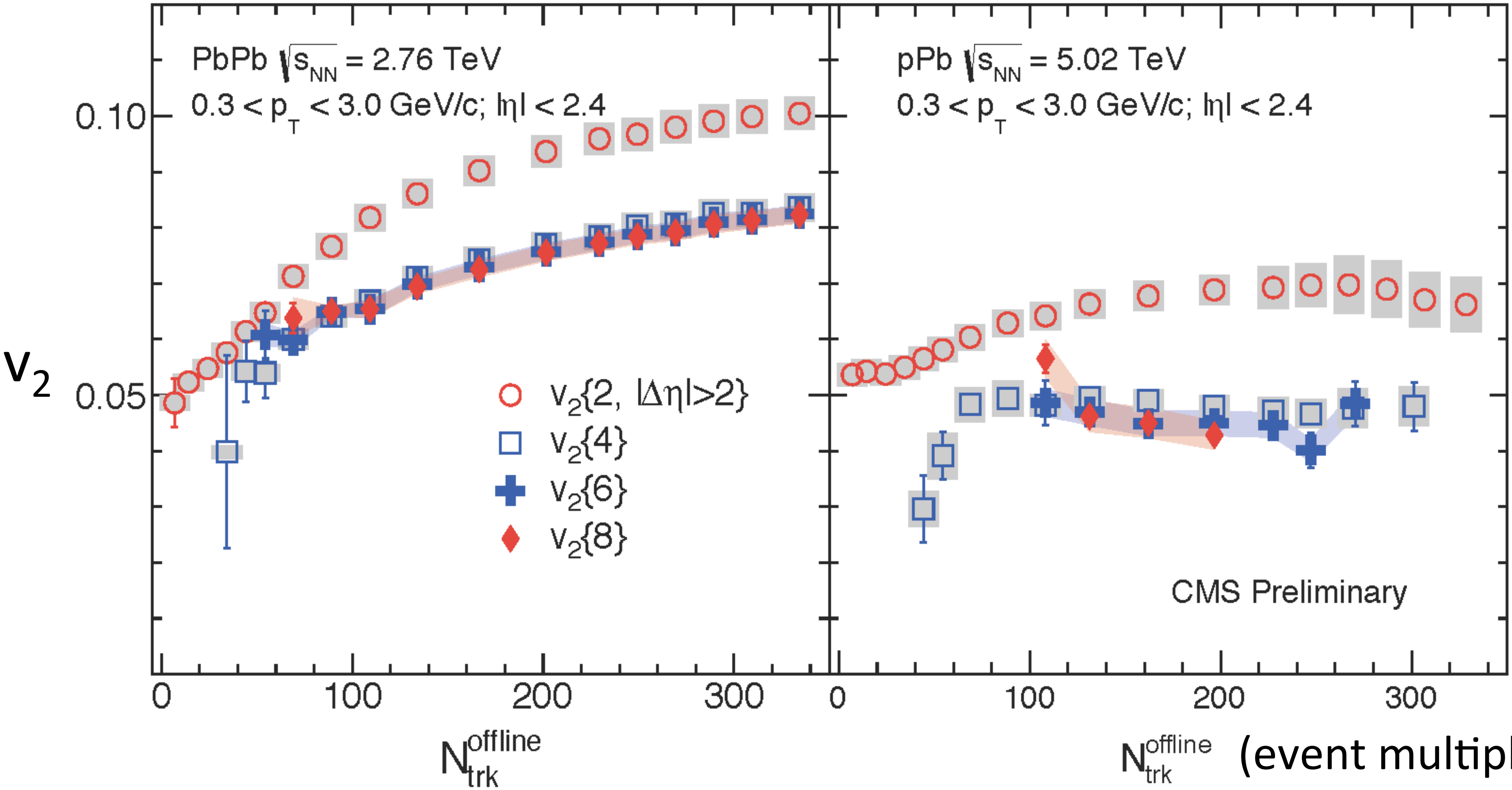
CMS PAS HIN-14-006



(event multiplicity)

True collectivity in pPb?

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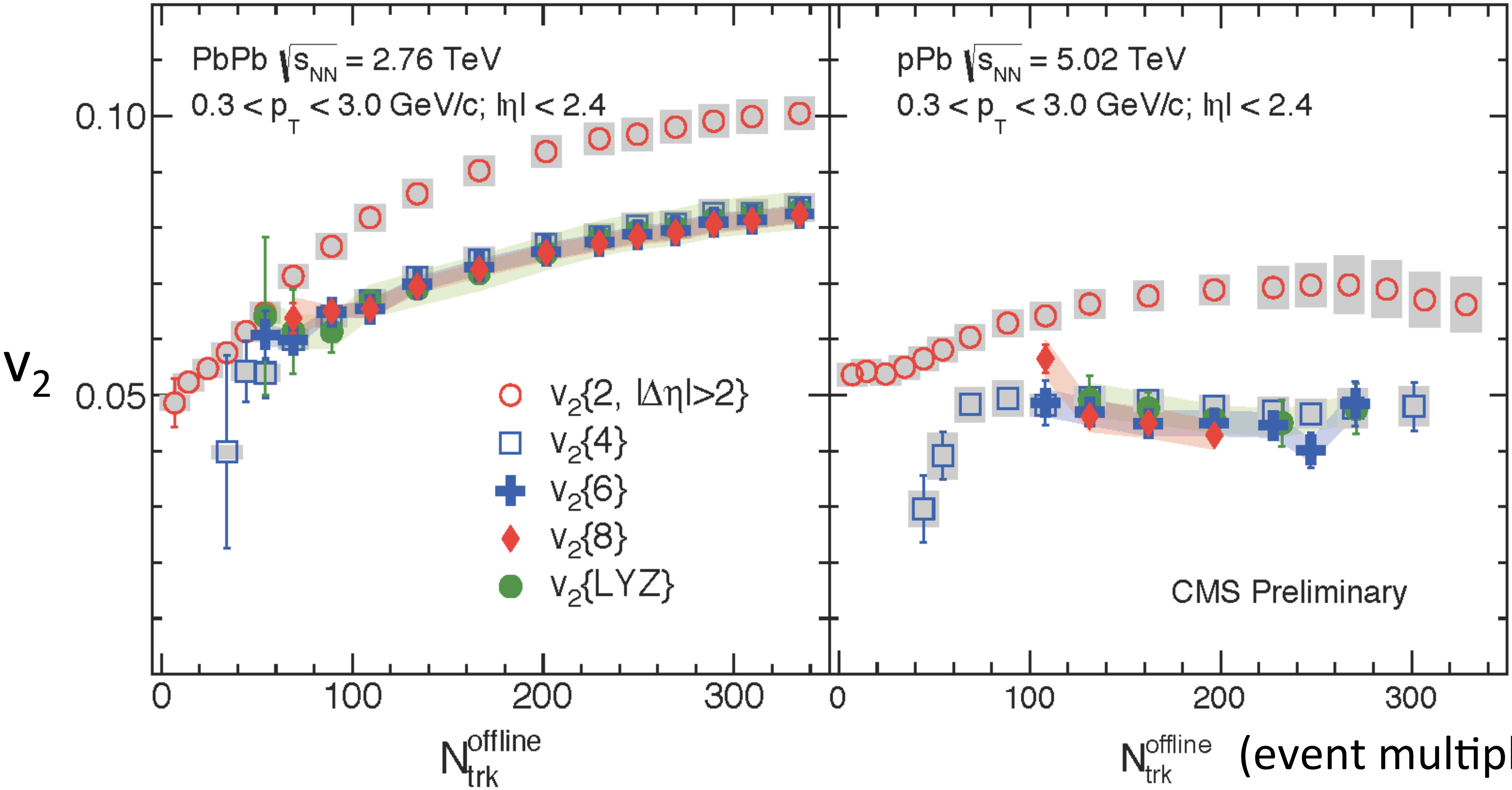
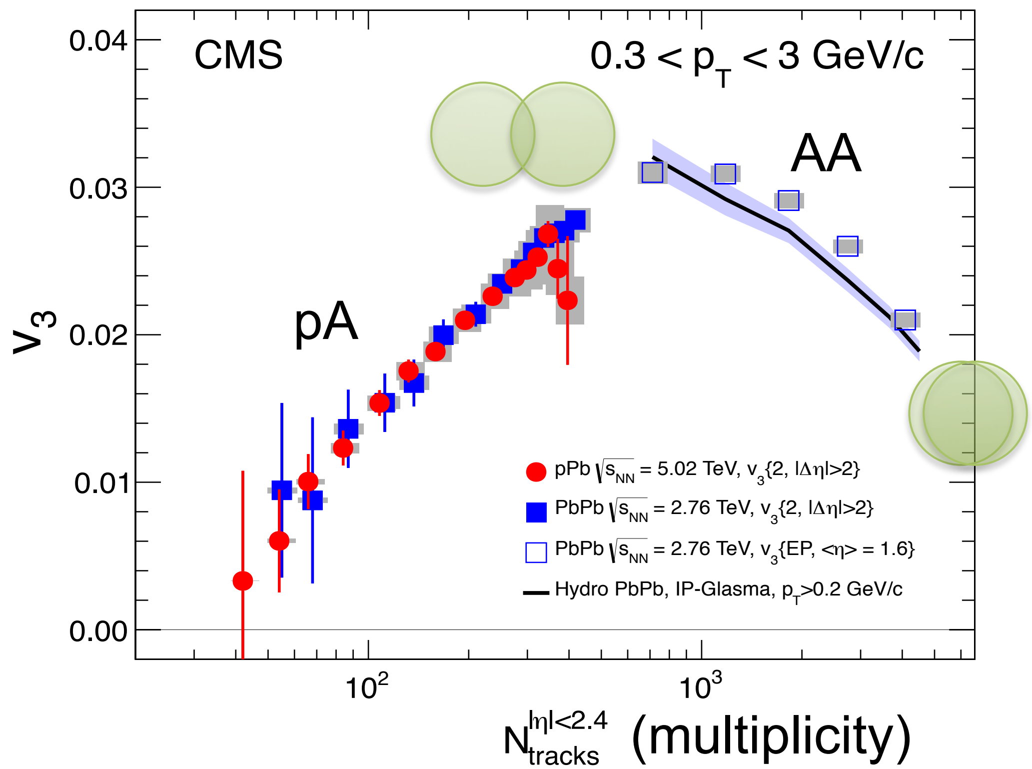
CMS PAS HIN-14-006



(event multiplicity)

Direct evidence of strong collectivity in pPb!

Toward a unified picture from pp, pA to AA



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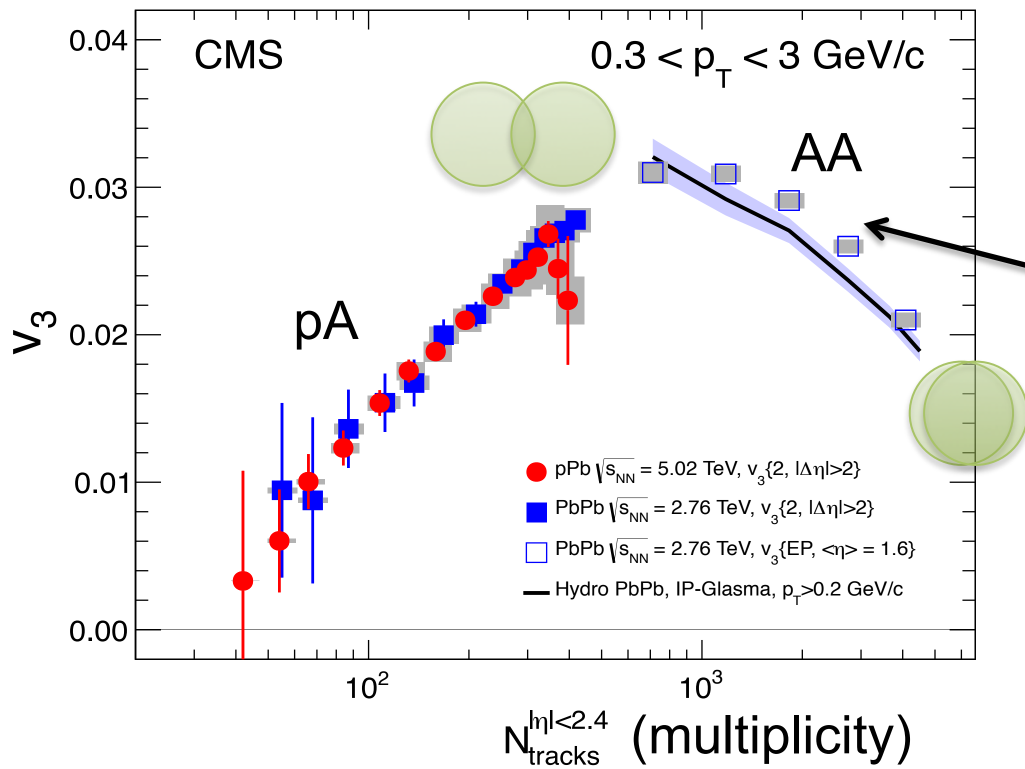
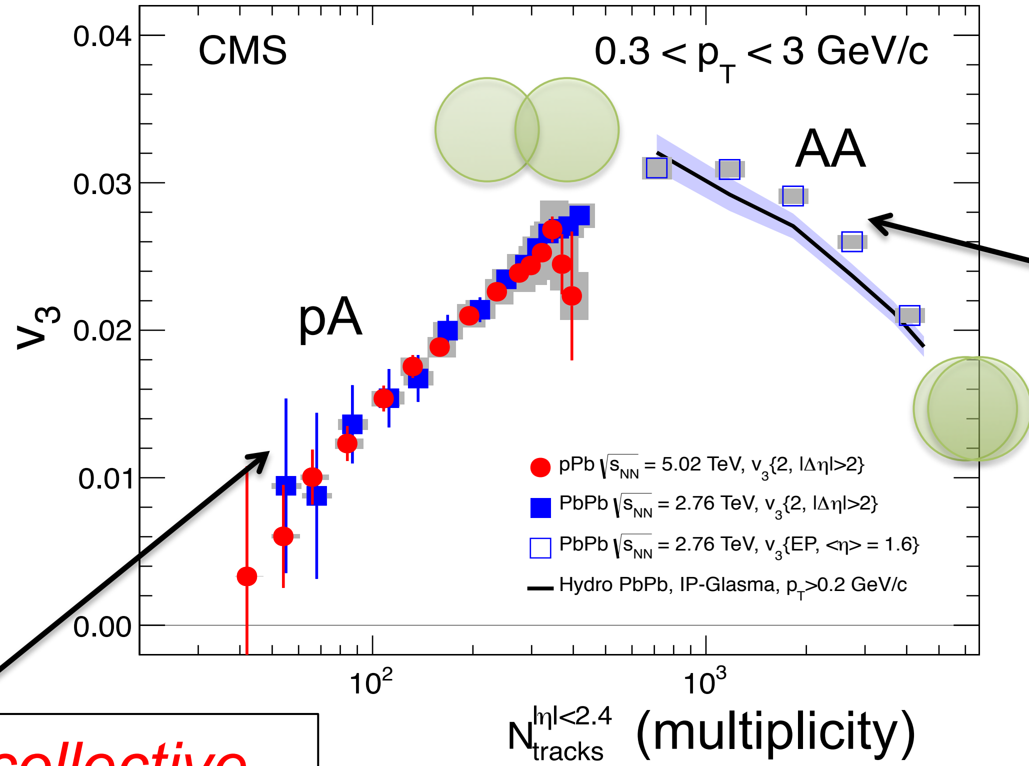


Hydrodynamics paradigm in AA

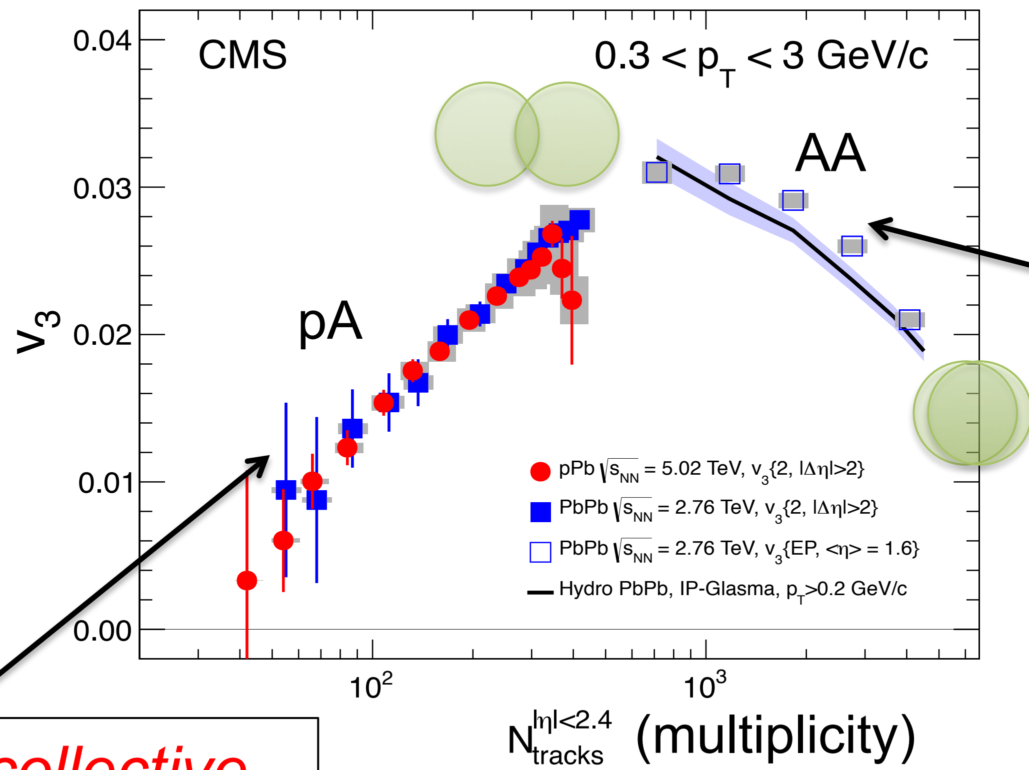
Toward a unified picture from pp, pA to AA



Hydrodynamics paradigm in AA

Discovery of *collective* "flow" phenomena in pA

Toward a unified picture from pp, pA to AA



Hydrodynamics paradigm in AA

Discovery of *collective* “flow” phenomena in pA

Other interpretations:

- Quantum entanglement of gluons:

PRD 87 (2013) 094034

- Non-abelian beam jet: arXiv:1405.7825

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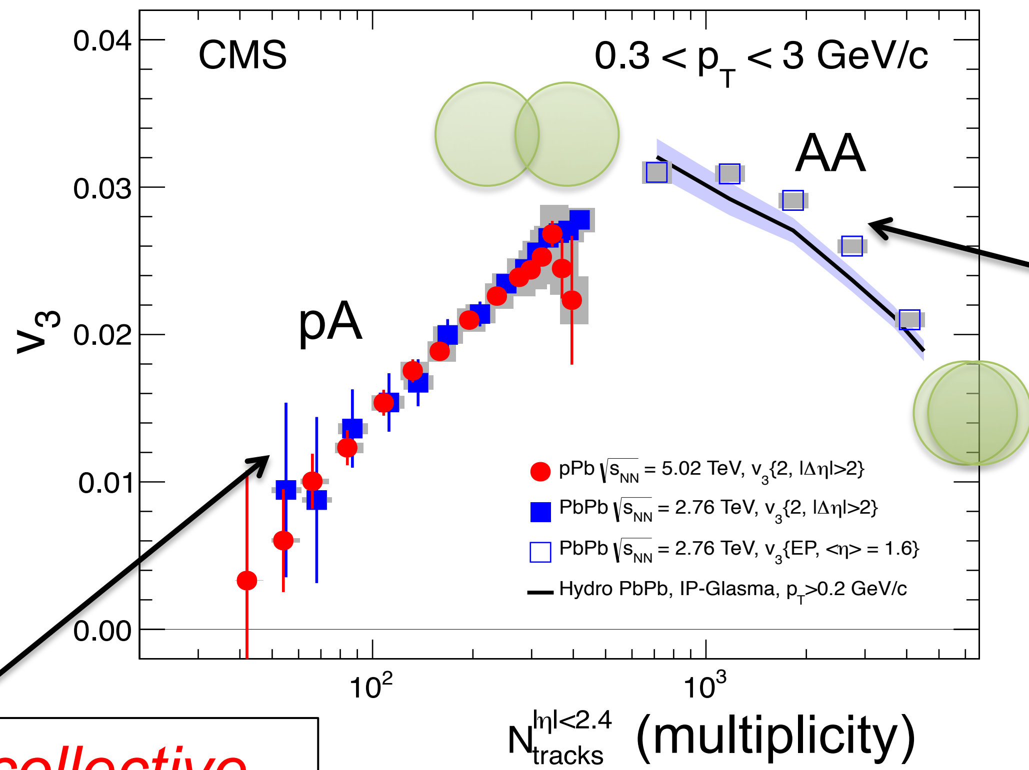

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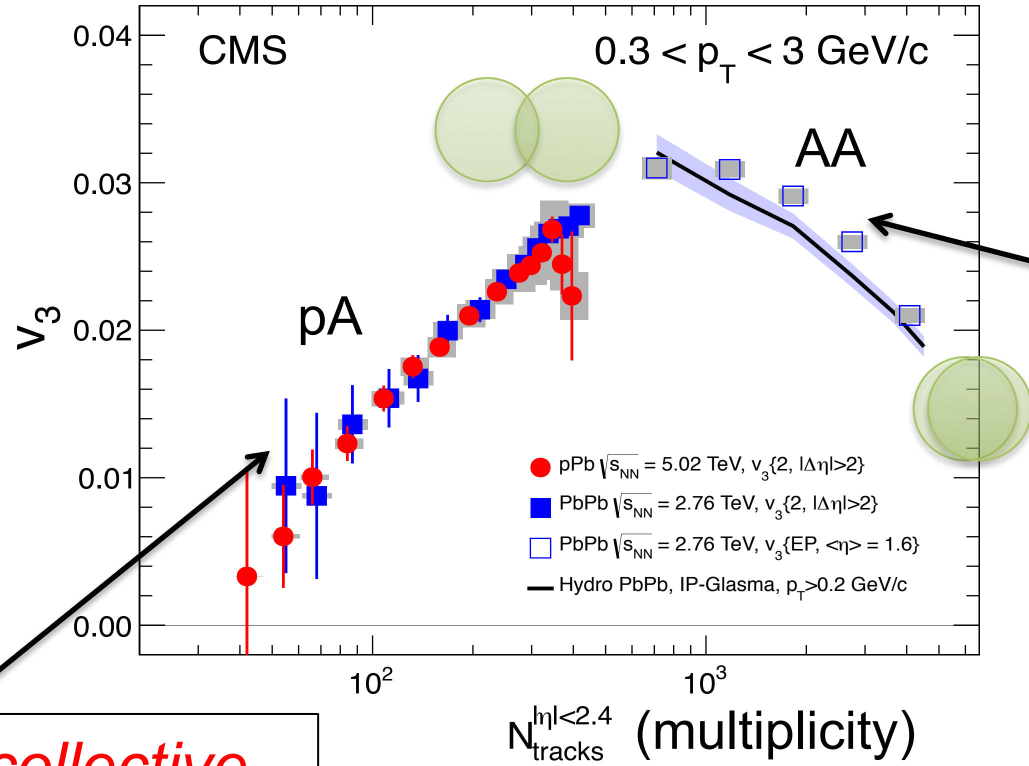
Toward a unified picture from pp, pA to AA



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Stay tuned for more excitements!

Backup