From small to large systems: Paradigm change?

EMMI workshop: QGP Imprints
HD, April 16-17, 2015

Itzhak Tserruya

When and where were these two pictures taken?

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Outline

- Introduction
- "Collective" observables in small systems
  - Long range correlations
  - Flow: v_1, v_2, v_3 …

    mass ordering, quark scaling…
  - HBT radii
- Hard / penetrating probes in small systems
  - Energy loss?
  - HF and J/ψ R_{AB}
  - Photons, dileptons?
- Summary

How do we quantify small vs large

- Size of the colliding system:
  - pp < p,d+A << AuAu or PbPb
  - initial transverse size
  - N_{part}
  - N_{coll}
- Size of the medium formed:
  - $dN_{ch}/d\eta$
  - N_{ch}

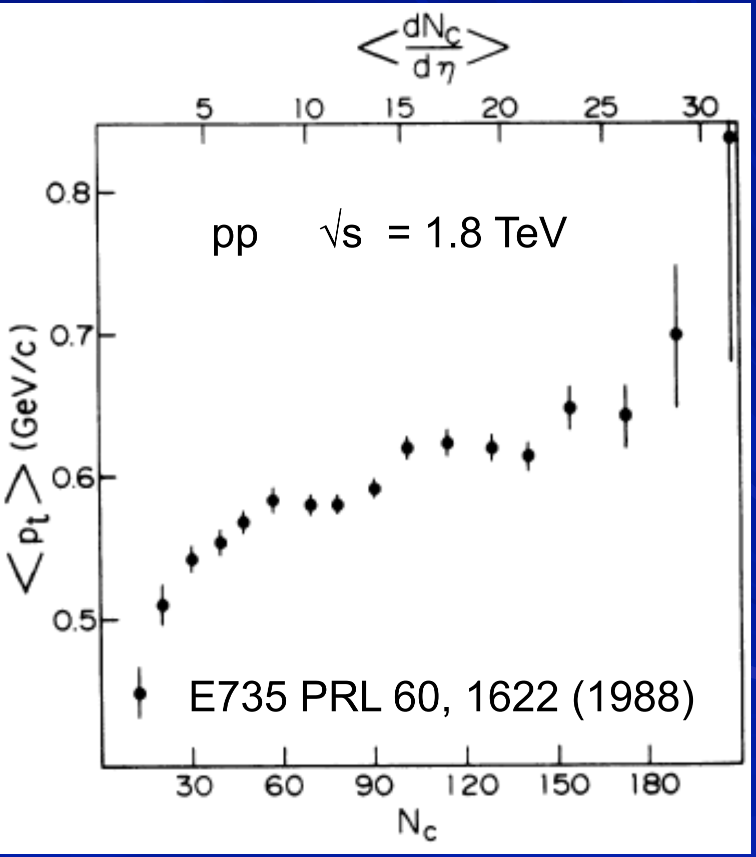
Small systems: paradigm change?

- p+p: reference baseline
- p,d+A:
  - System size too small for quark matter formation
  - Reference for cold nuclear matter effects
- Is that so? Many features seen in A+A collisions are also seen in high multiplicity p,d+A collisions:

Short historic regression

- The possibility that QGP matter is formed in high multiplicity pp events is not a new idea.

$<p_T>$ vs multiplicity



- Fermilab experiment E735 main goal was just that:

"… to search for evidence of a phase transition of hadronic matter to a deconfined quark-gluon state" in ppbar collisions."

- See also:

Friedlander and Weiner, PRL 43, 15 (1979) and PRL 57, 2119 (1986)

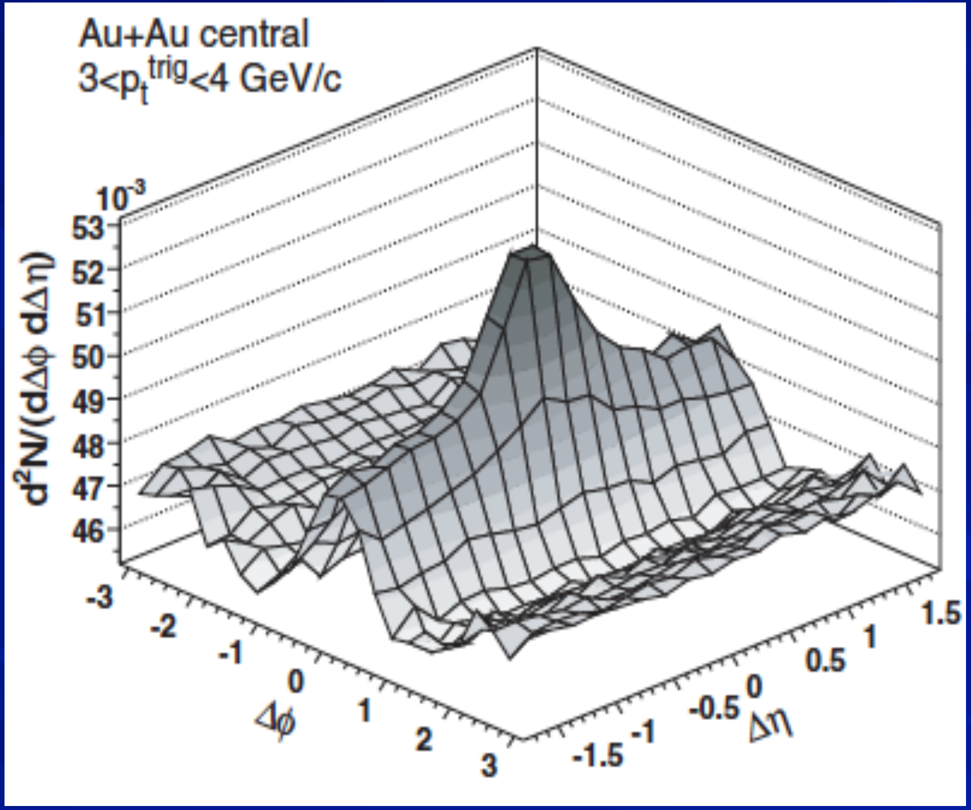
Small systems: paradigm change?

- p+p: reference baseline
- p,d+A:
  - System size too small for quark matter formation
  - Reference for cold nuclear matter effects
- Is that so? Many features seen in A+A collisions are also seen in high multiplicity p,d+A collisions:
    - Long range near-side correlations

Ridge discovered at RHIC

Ridge = Long-range near-side correlations

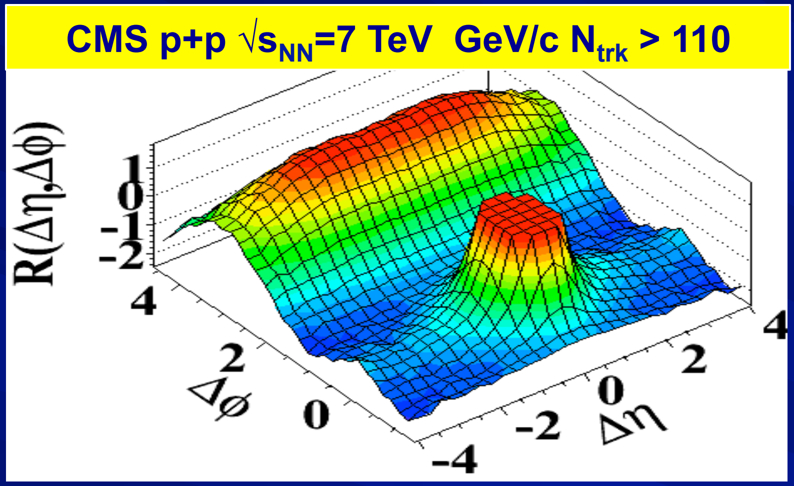
STAR Au+Au central $\sqrt{s_{NN}}$=200 GeV



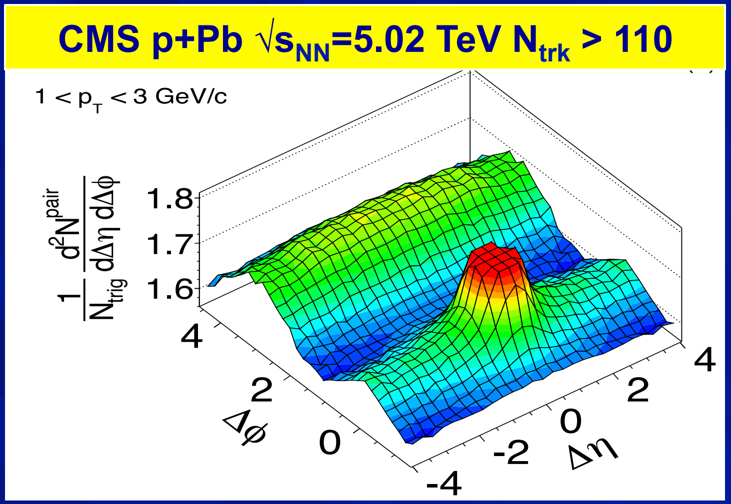
PRC 80, 064912 (2009)

Ridge in small systems at LHC

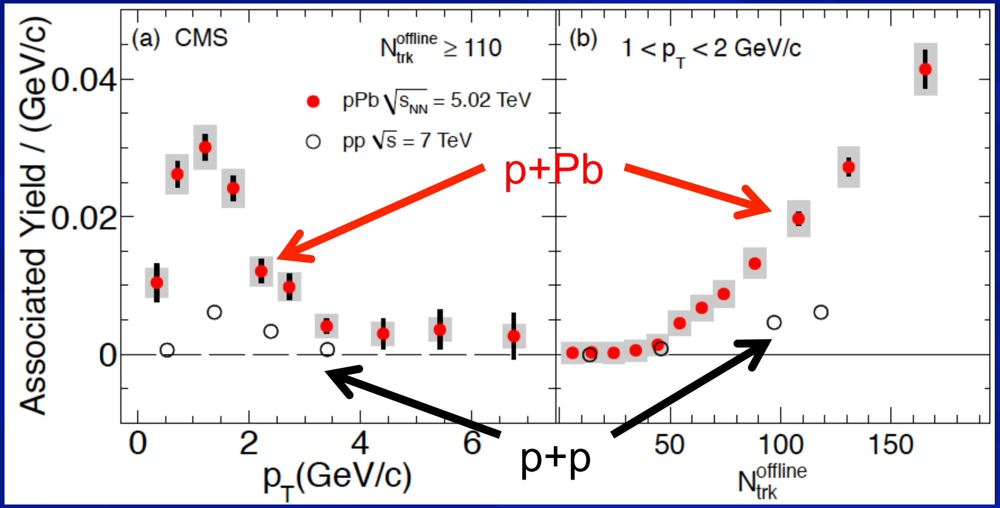
- Long-range near-side correlations first seen in high multiplicity p+p collisions and later also in high multiplicity p+Pb collisions at LHC



JHEP 09, 091 (2010)



PLB 718, 795 (2013)



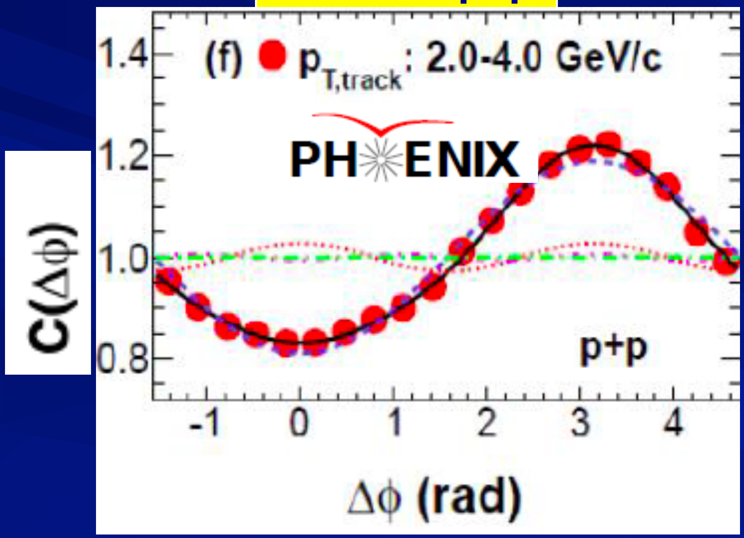
- Strength of correlation much smaller in p+p than in p+Pb

Ridge in small systems at RHIC

Two particle correlations measured over a large $|\Delta\eta| > 2.75$ gap

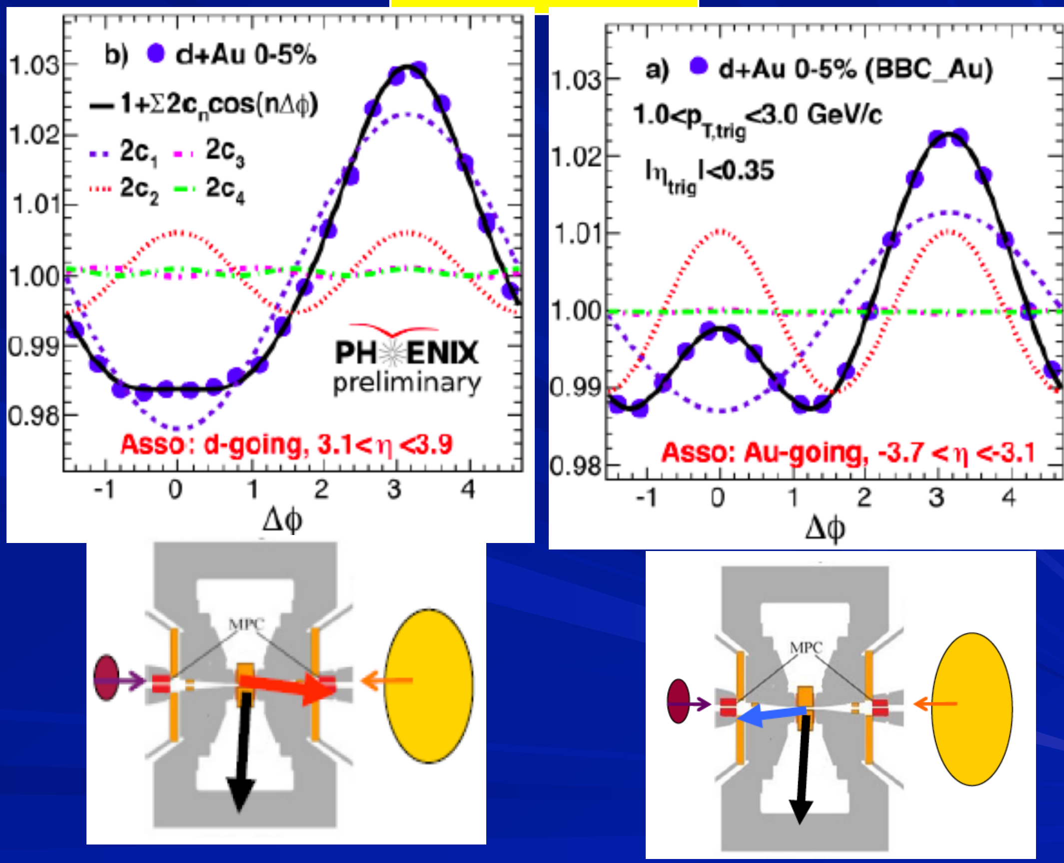
(charged track in central arm and tower hit in forward calorimeter)

Min bias p+p



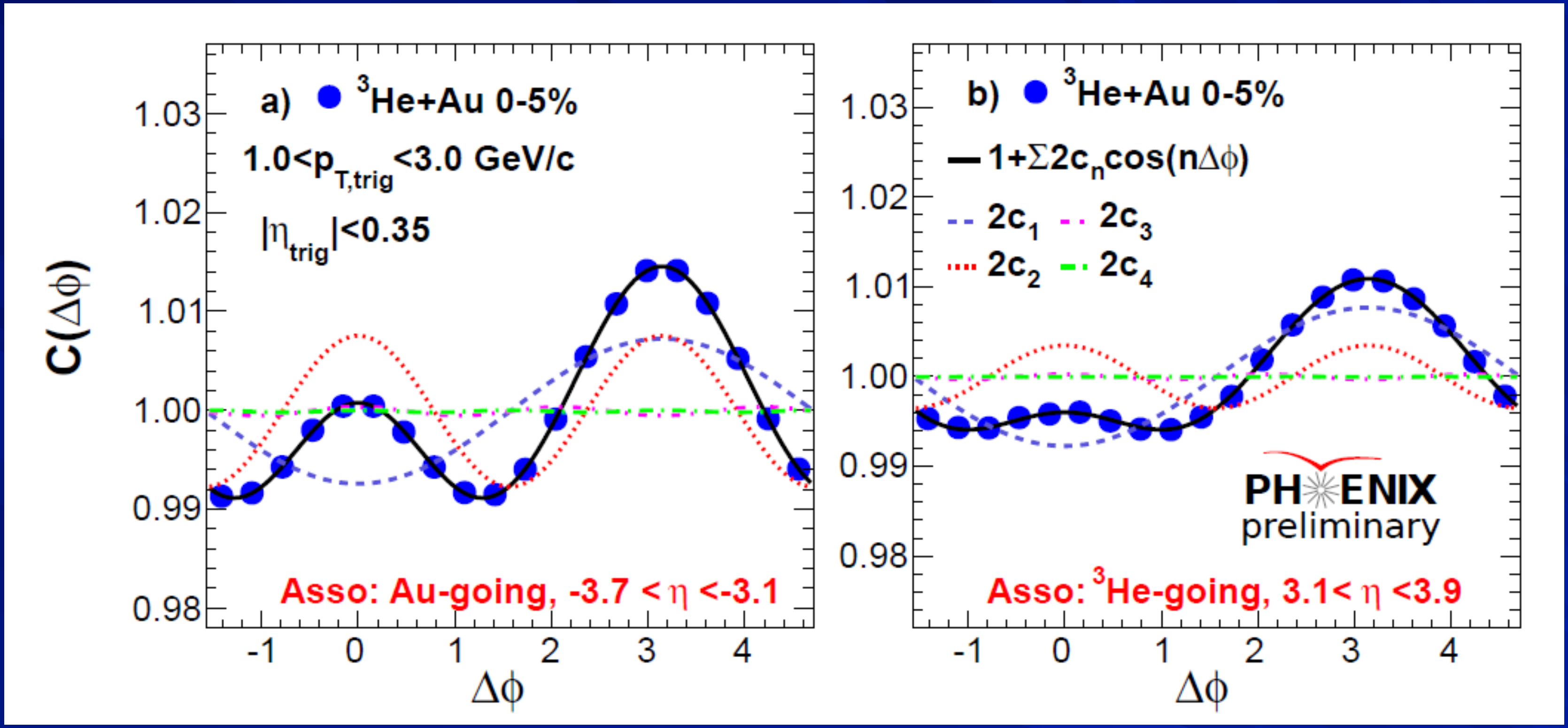
arXiv:1404.7461

Central d+Au



- Long-range near-side correlations in central d+Au collisions in the Au going direction
- Not present in minimum bias p+p collisions, in the d-going direction, in peripheral d+Au and

Shape engineering: ^{3}He+Au



- Long-range near-side correlations seen in both Au-going and ^{3}He-going directions

- **Hydro can explain and reproduce the ridge**
- **Initial state gluon saturation without final state interaction can also explain the ridge**

Small systems: paradigm change?

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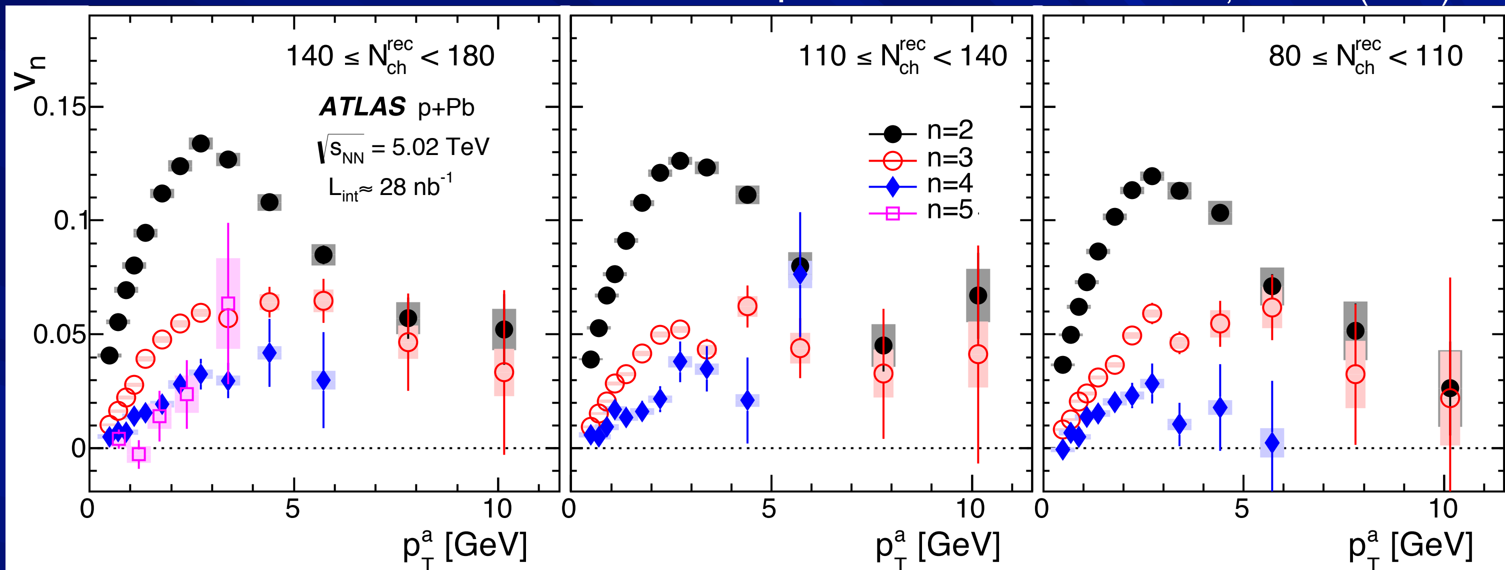
  - System size too small for quark matter formation
  - Reference for cold nuclear matter effects
- Is that so? Many features seen in A+A collisions are also seen in high multiplicity p,d+A collisions:
  - Long range near-side correlations
  - Flow

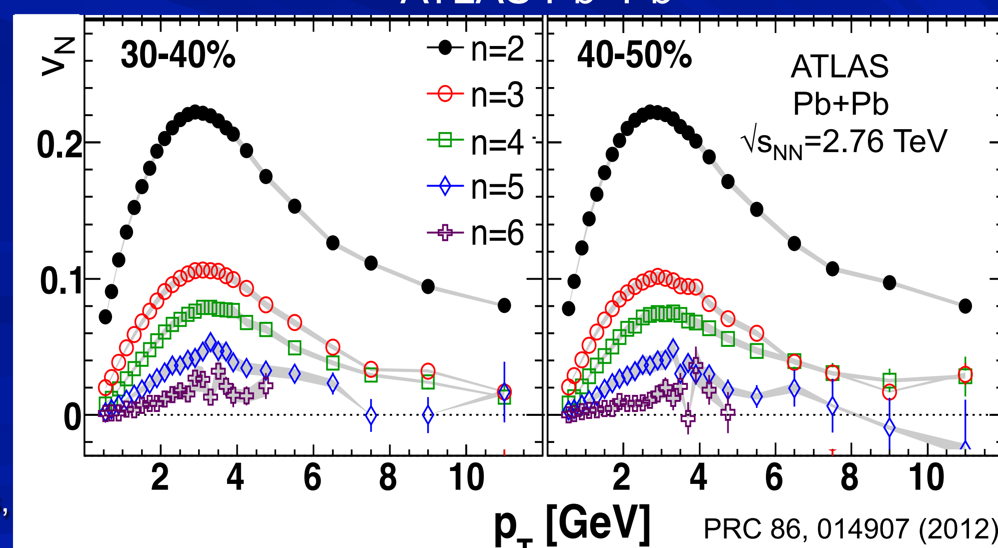
Flow in small systems: $v_n(p_T)$

ATLAS p+Pb

PRC 90, 044906 (2014)



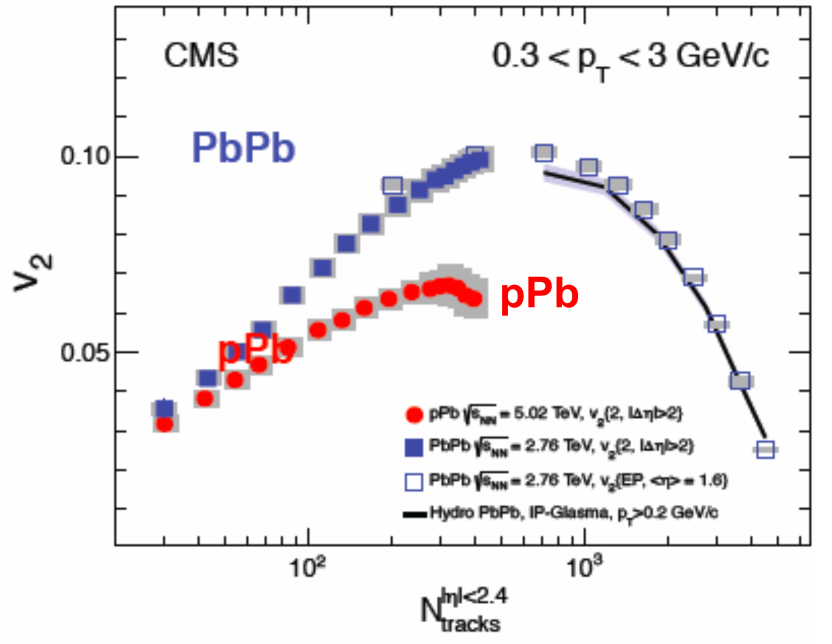
ATLAS Pb+Pb



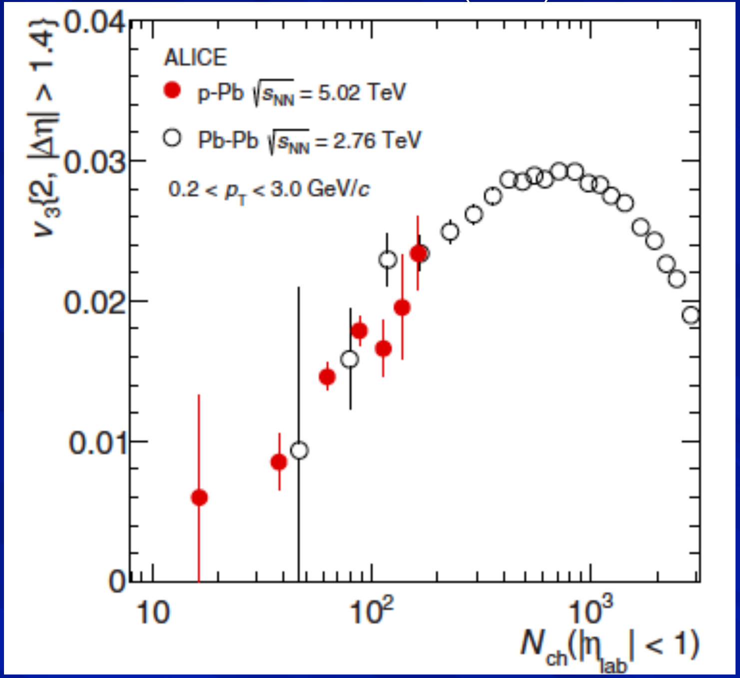
- Same qualitative features (v_n shapes and harmonic ordering) as in Pb+Pb
- Similar magnitude within a factor of two

Flow in small systems: multiplicity dependence

PLB 724, 213 (2013)



PRC 90, 054901 (2014)



$v_2(pPb) < v_2(PbPb)$

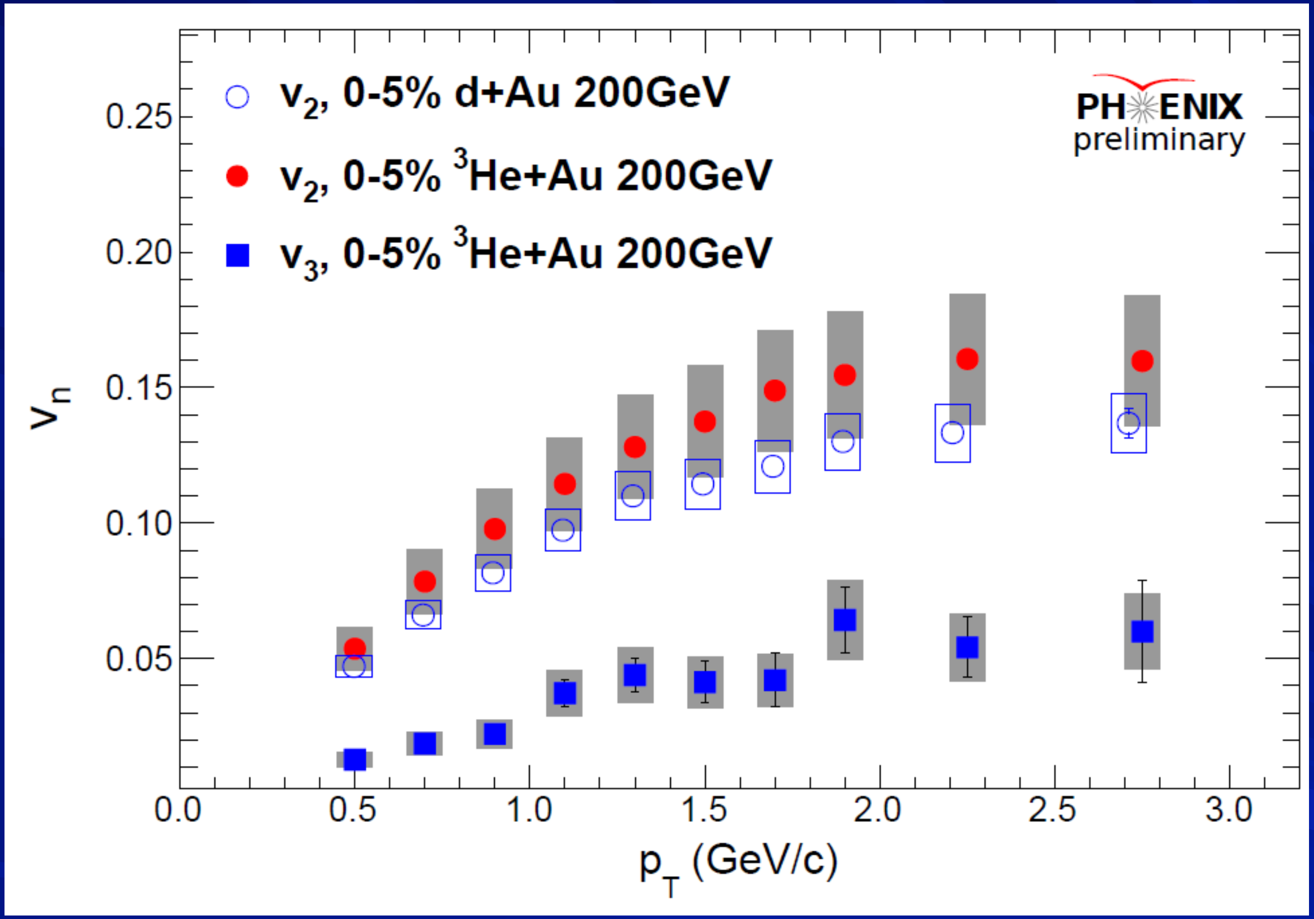
Expected

$v_3 < v_2$

$v_3(pPb) \approx v_3(PbPb)$

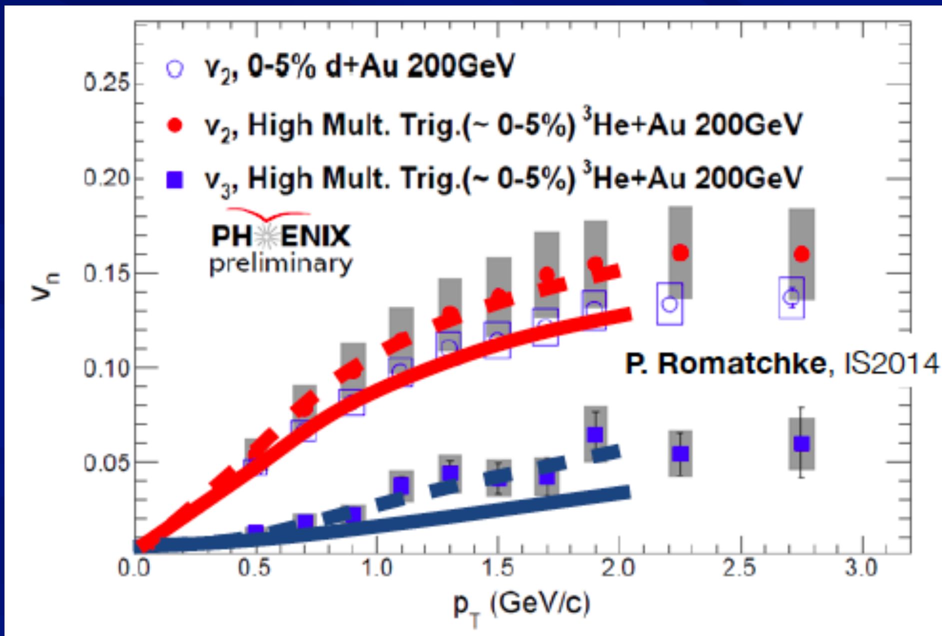
Similar triangular excentricity in pPb and PbPb

Shape engineering: d,^{3}He+Au



- v_2 of ^{3}He+Au similar to that of d+Au
- Clear v_3 signal in central ^{3}He+Au collisions

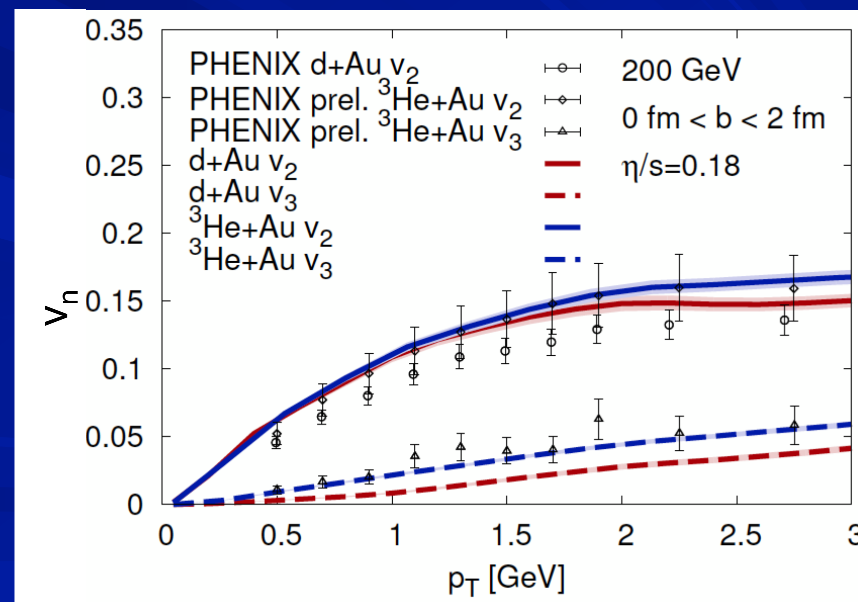
Flow in small systems: d,^{3}He+Au



Glauber+hydro+cascade

w preflow

w/o preflow

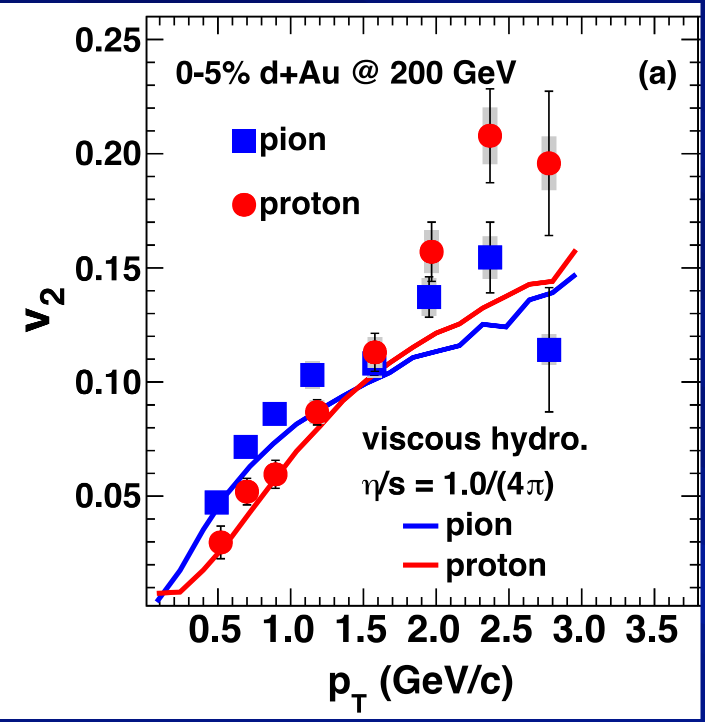


IP-Glasma (B. Schenke et al., PRL 108, 252301 (2012))

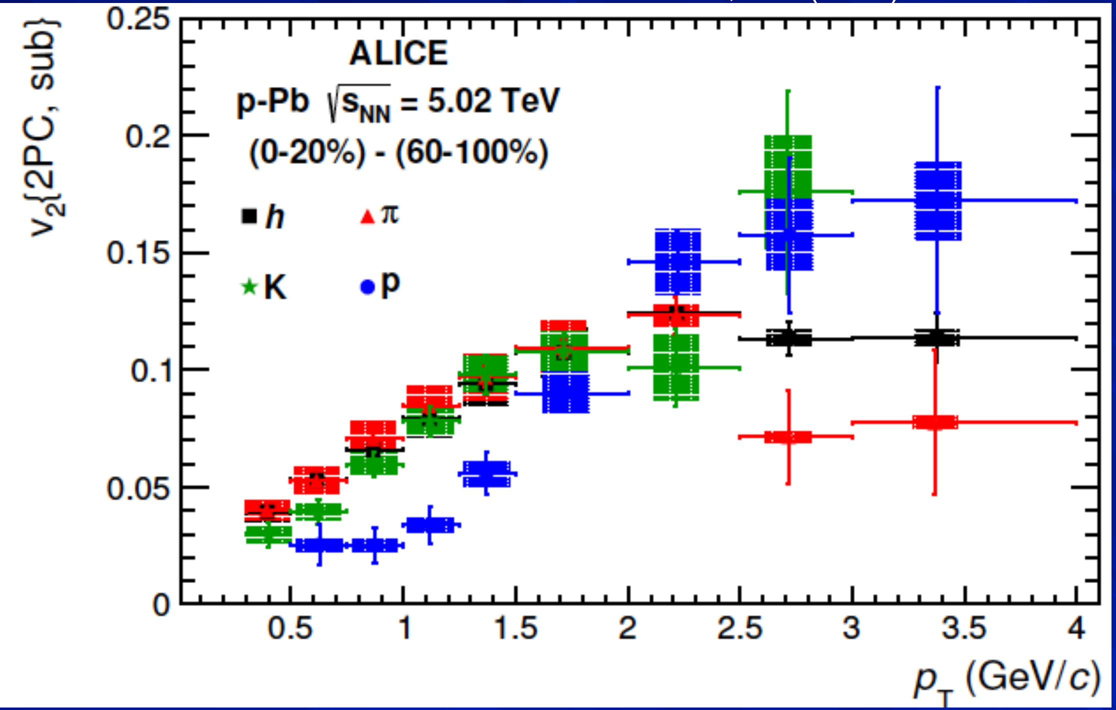
+MUSIC (B. Schenke et al., PRL 106, 042301 (2011))

Flow in small systems: mass ordering

PHENIX arXiv:1404.7461

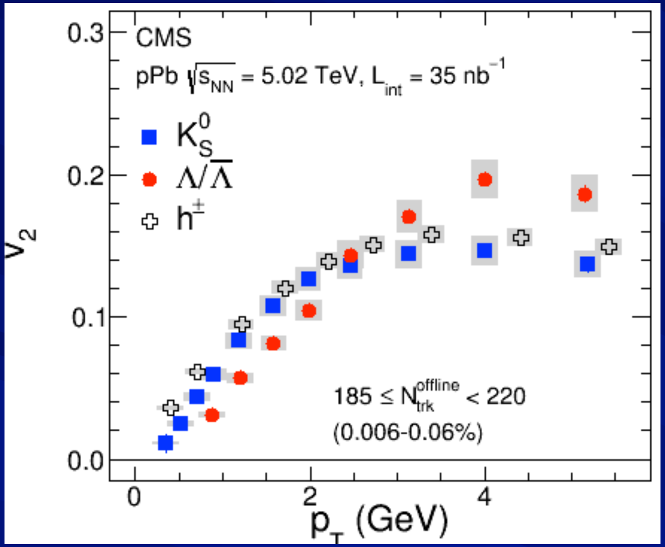


ALICE PLB 726, 164 (2013)



- Mass ordering in d+Au v_2 at RHIC
- PHENIX data consistent with viscous hydrodynamics (using $\eta/s = 1/4\pi$) at p_T<2 GeV/c
- Mass ordering in p+Pb at LHC, even more pronounced than in Pb+Pb at same multiplicity? Stronger radial flow in p+Pb?

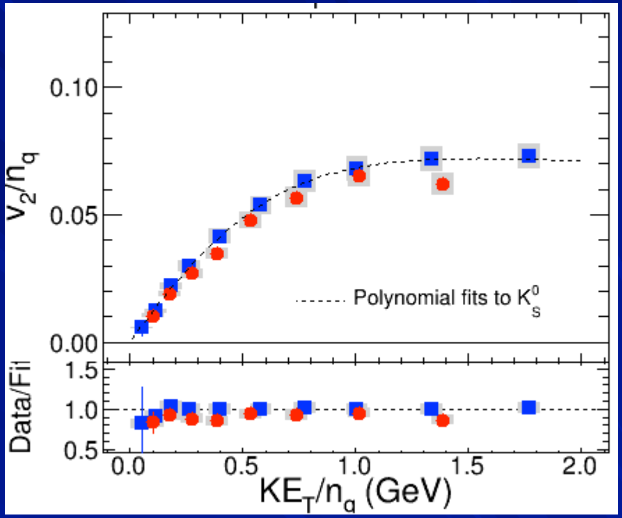
Flow: Quark scaling

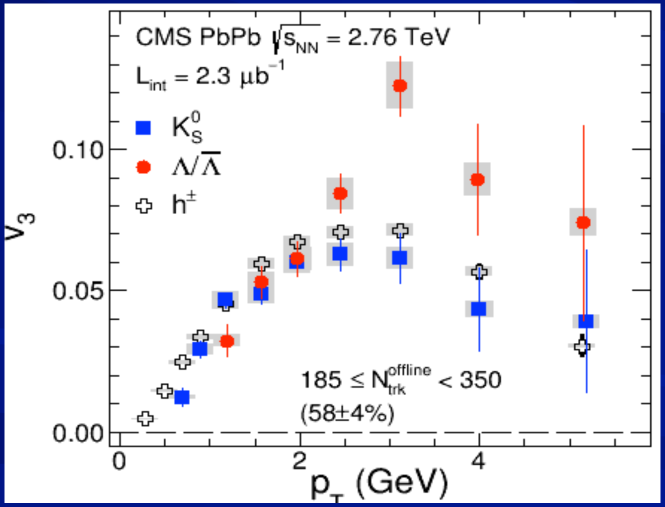


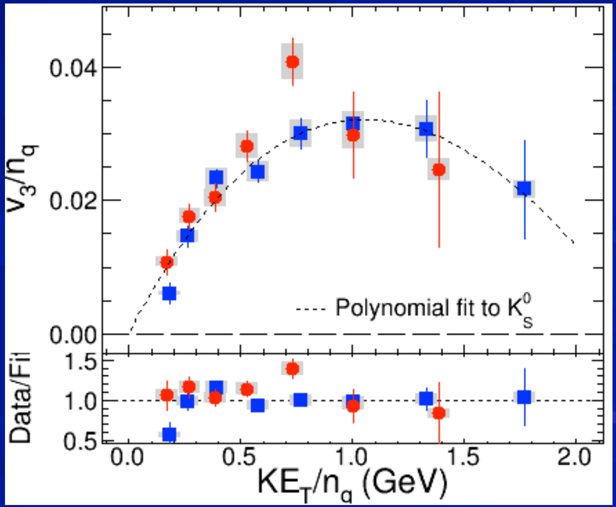
CMS PLB 742, 200 (2015)

Scale with nr of valence quarks

$p_T \rightarrow KE_T = \sqrt{(m^2 + p_T^2)} - m$



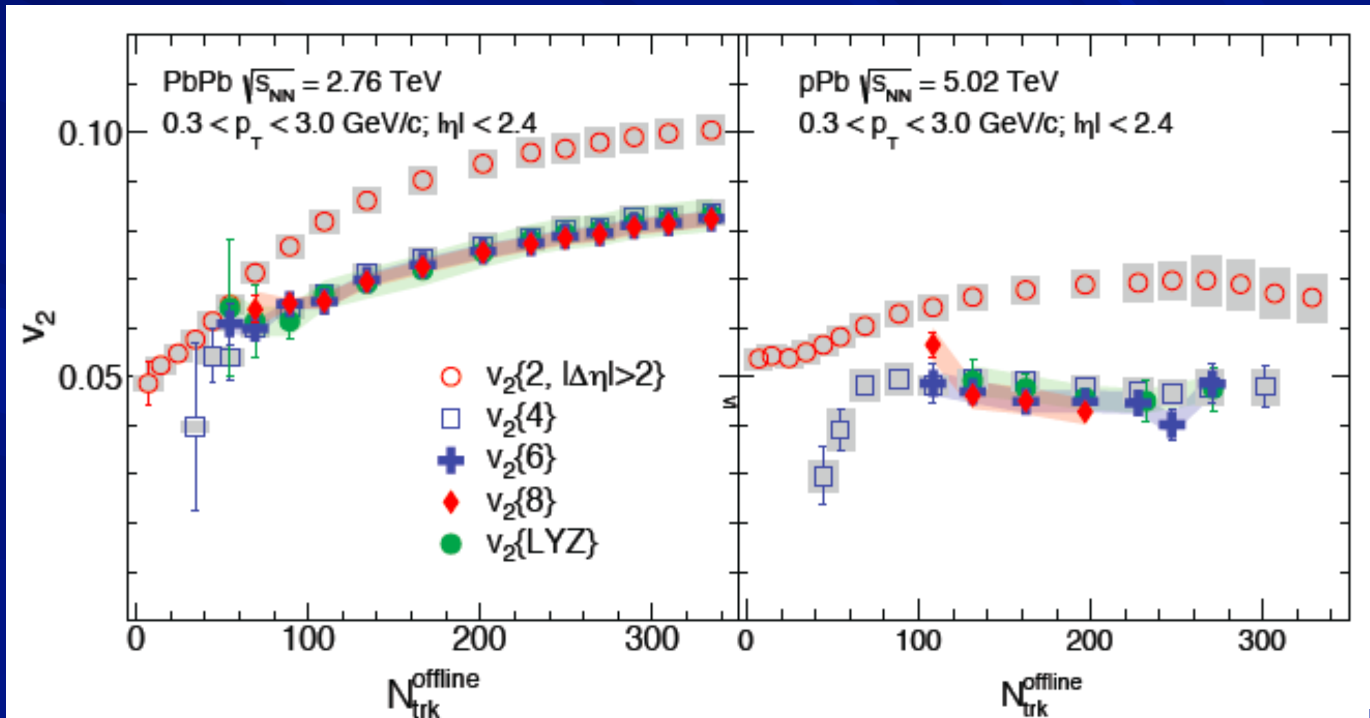




- Quark scaling works even better than in Pb+Pb
- Flow develops at partonic level?

Collectivity in pPb

CMS arXiv:1502.05382



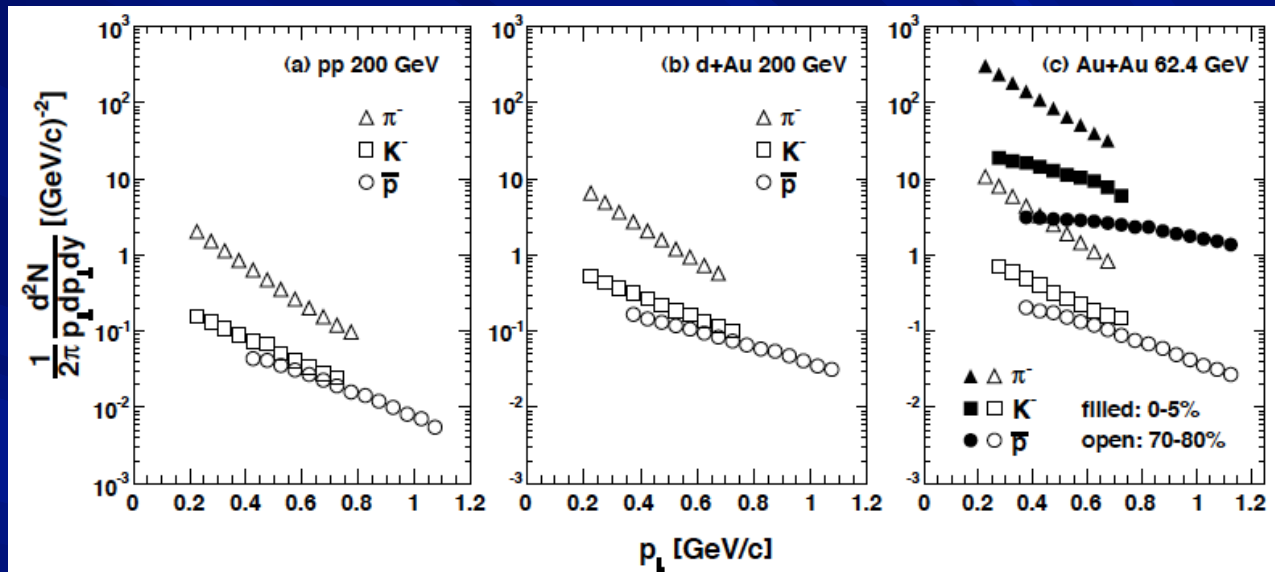
Flow analysis using the cumulant method in multiparticle azimuthal correlations

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

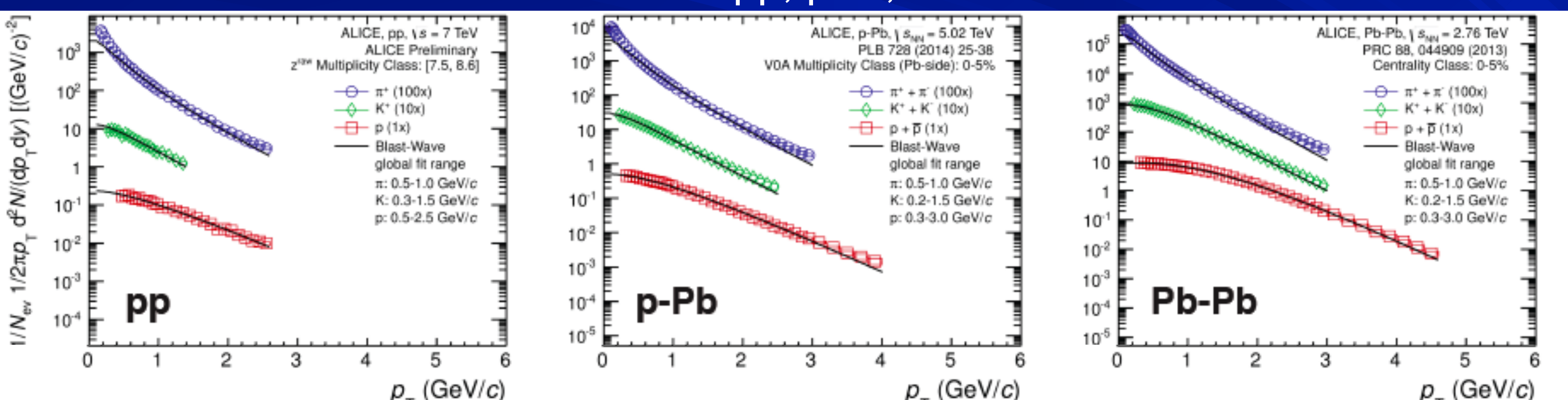
Radial flow

STAR pp, dAu, AuAu

PRC 79, 034909 (2009)



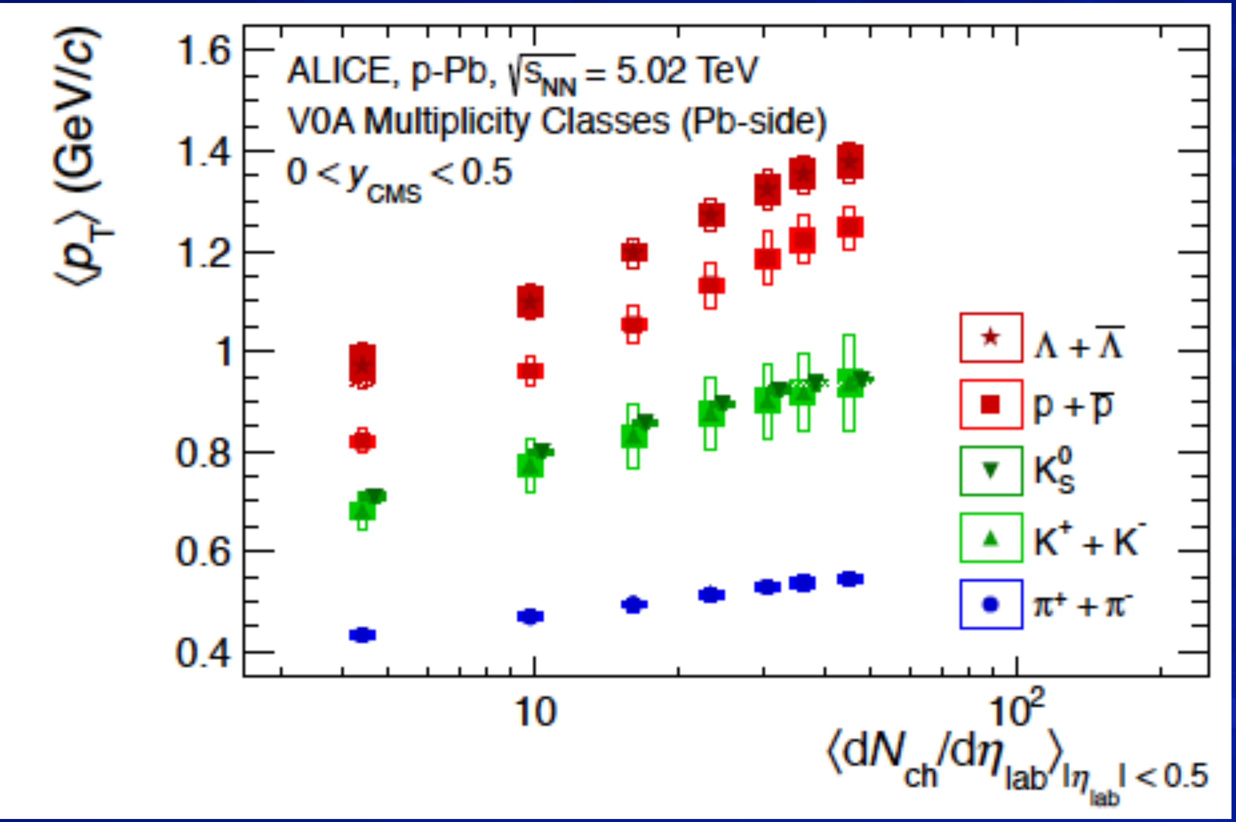
ALICE –pp, pPb, PbPb



BW fit quality comparably good in all three systems

Radial flow

ALICE PLB 728, 25 (2014),



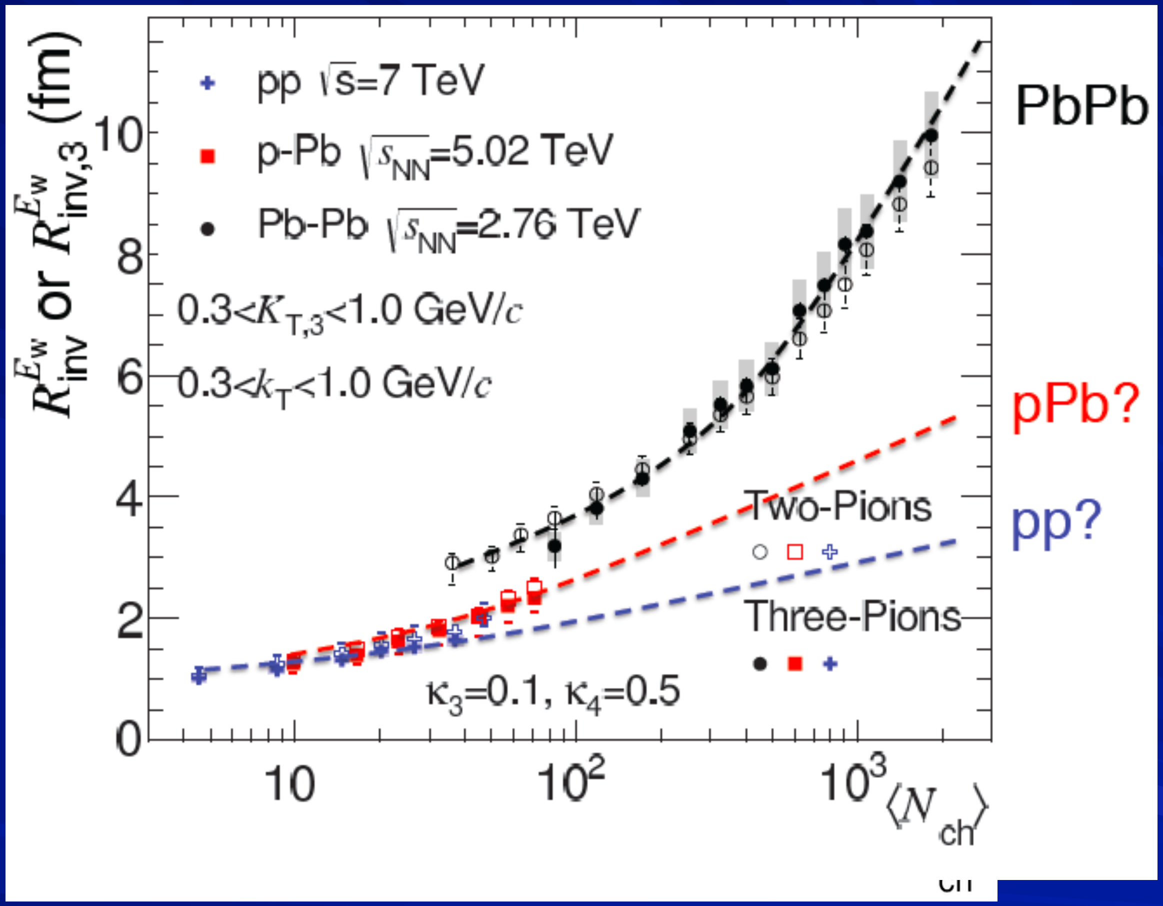
Mass ordering seen down to very low multiplicities

Natural explanation: collective radial expansion of the system

Small systems: paradigm change?

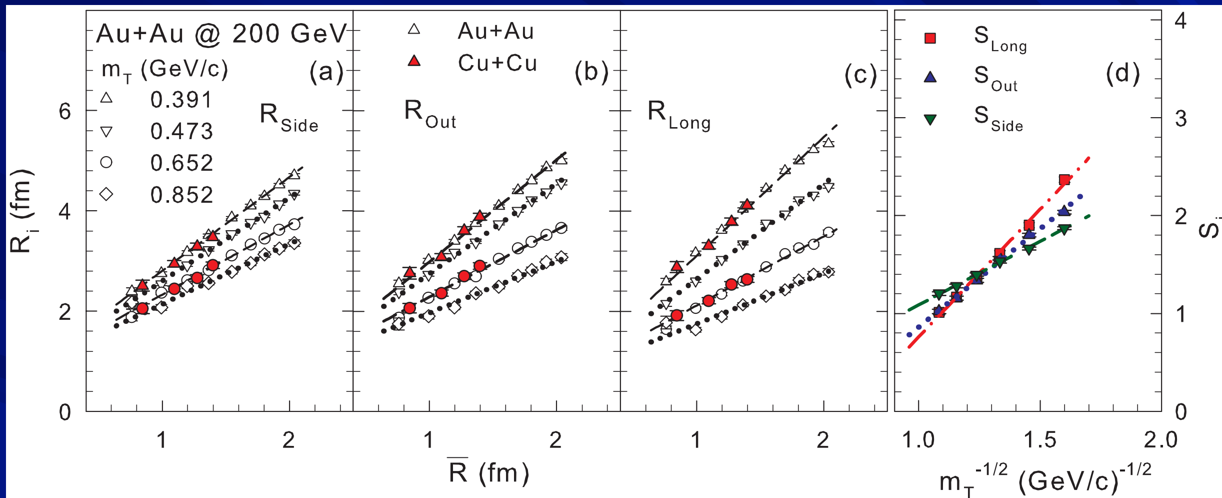
- p+p: reference baseline
- p,d+A:
  - System size too small for quark matter formation
  - Reference for cold nuclear matter effects
- Is that so? Many features seen in A+A collisions are also seen in high multiplicity p,d+A collisions:
  - Long range correlations in d,^{3}He+Au
  - Flow
  - HBT radii

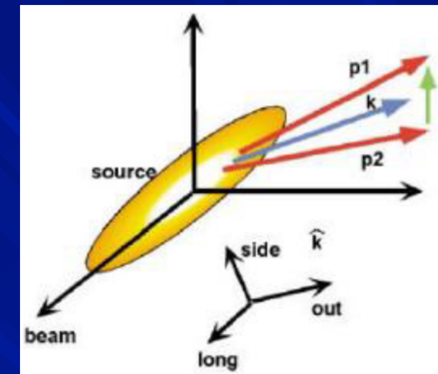
HBT radii and multiplicity



ALICE PLB 739, 139 (2014)

HBT radii scale with size

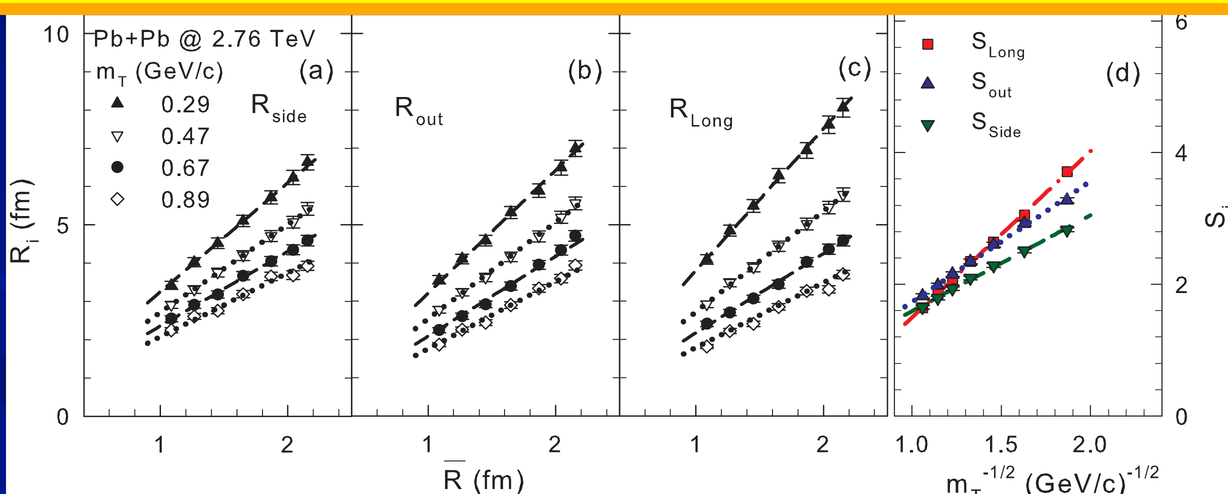




arXiv:1410.2559

- **PHENIX Au+Au and Cu+Cu: HBT radii scale linearly with initial transverse size**

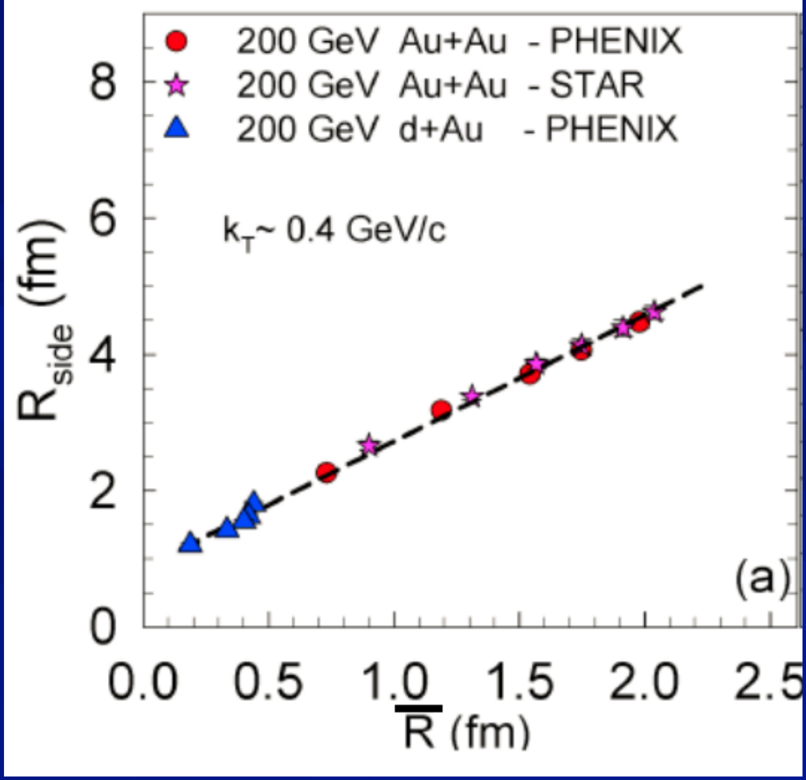
$$1/\overline{R} = \sqrt{(1/\sigma_x)^2 + (1/\sigma_y)^2}$$

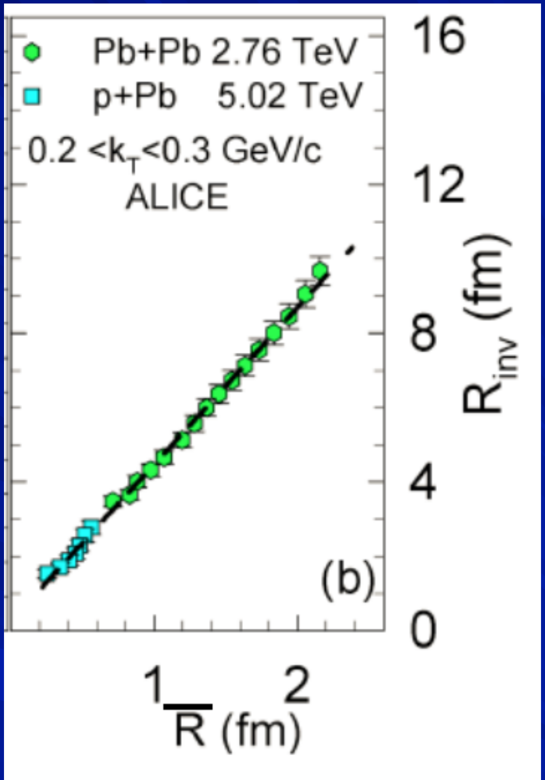


- **ALICE Pb+Pb : same behavior**

...also in small systems

arXiv:1404.5291





- HBT radii scale linearly with the initial transverse size
- Smooth behavior from small (d+Au, p+Pb) to large (Au+Au, Pb+Pb) systems at RHIC and LHC.
- Imply or consistent with radial expansion in small systems and fsi

Intermediate summary of experimental facts

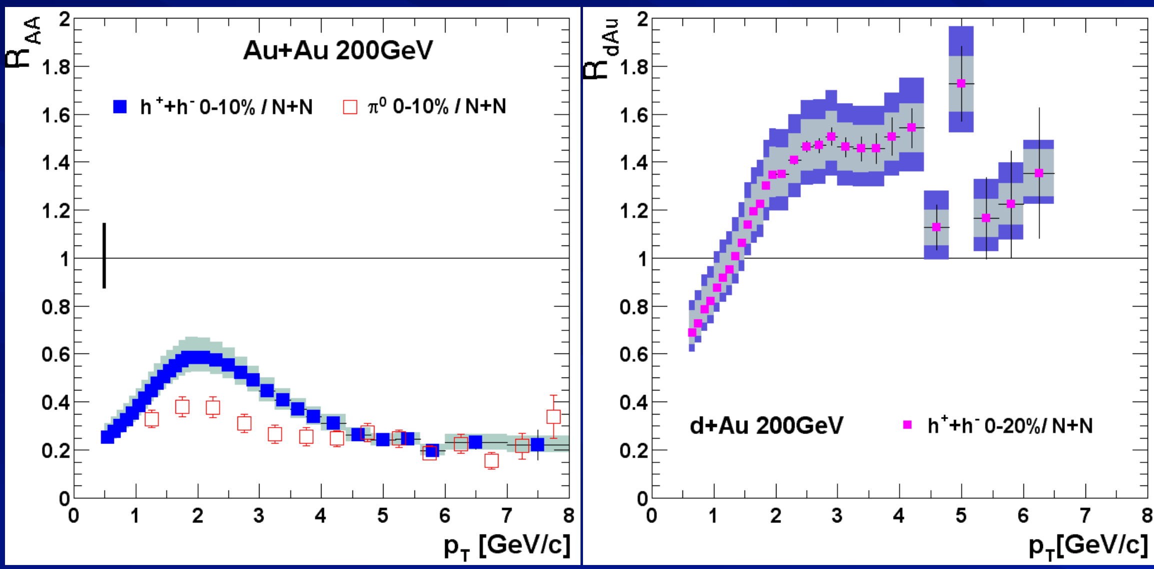
- Many features seen in A+A collisions are seen in p,d+A collisions and even in p+p collisions at high multiplicity:
  - Long range correlations
  - Flow:
    - $v_n(p_T)$ – similar shape
    - v_2 mass ordering
    - v_2 quark scaling
    - multiparticle correlations
    - strong radial flow
  - HBT radii scaling with initial transverse size
- Smooth evolution from small to large systems.
- Small systems exhibit collective behavior consistent with hydro.

and what about Hard / e.m Probes?

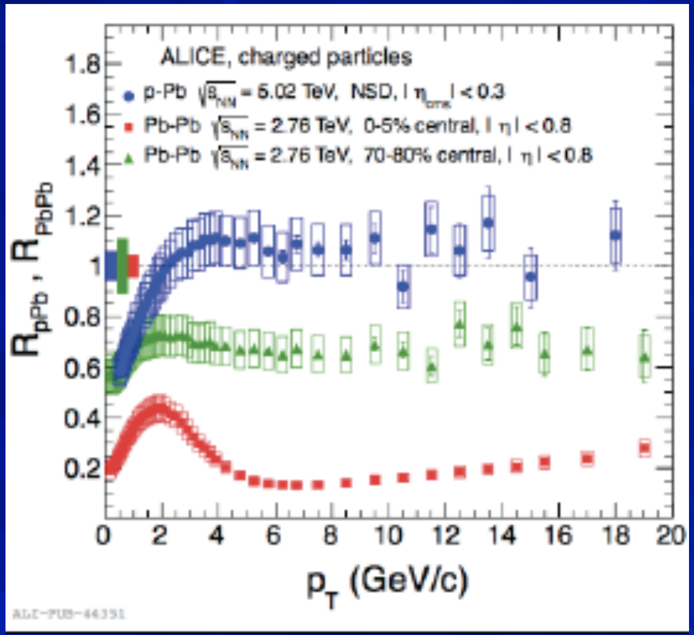
- If QGP is formed in small systems we should also see all the characteristic features of the medium:
  - high p_T suppression / jet quenching
  - J/ψ suppression
  - Photons and dileptons

Energy loss / quenching ?

PHENIX



ALICE

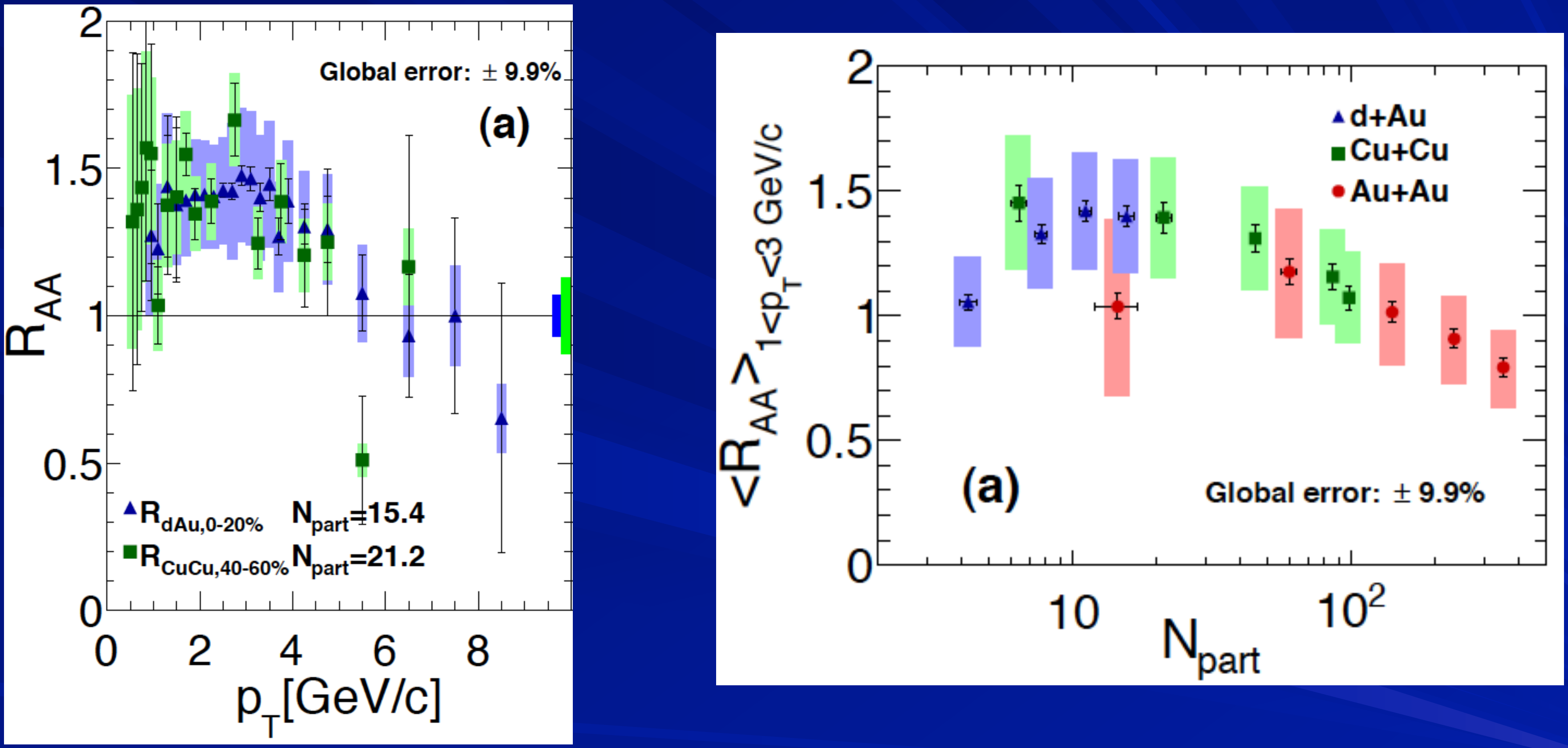


- ❑ No evidence of charged particle suppression in d+Au or in p+Pb
- ❑ Need trigger on much higher multiplicity events

Suppression clearly seen in Au+Au at 40-50% centrality → $dN_{ch}/d\eta \approx 100$

HF R_{AA} system-size dependence

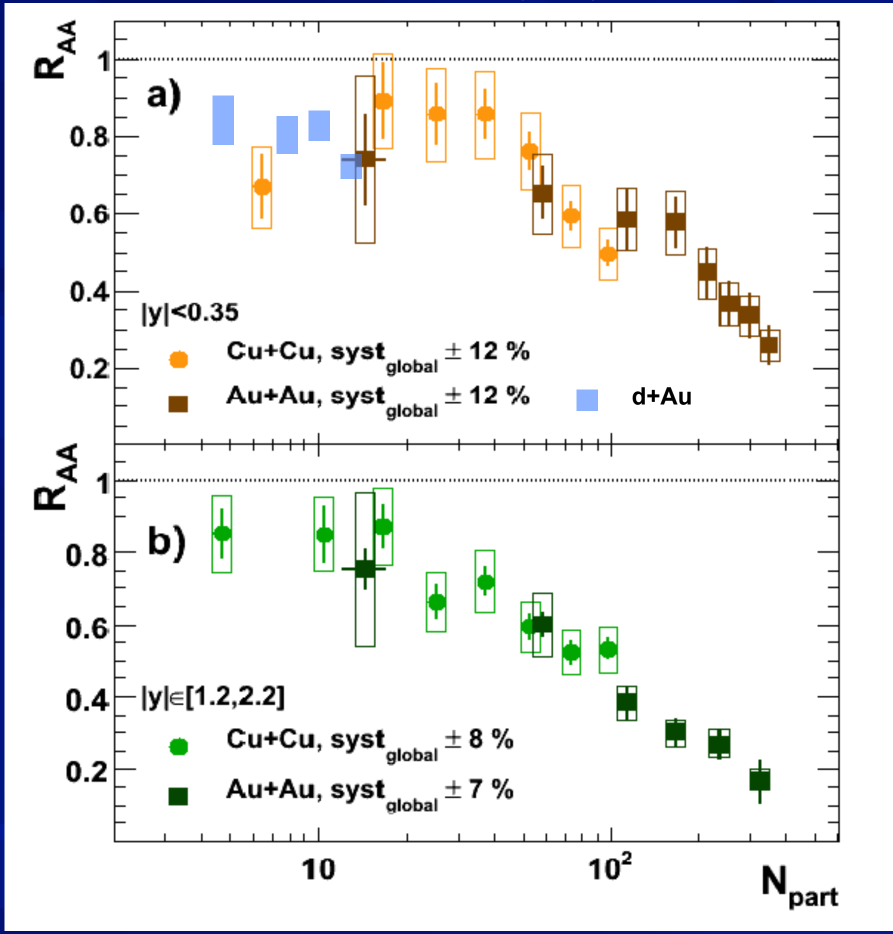
PRC 90, 034903 (2014)



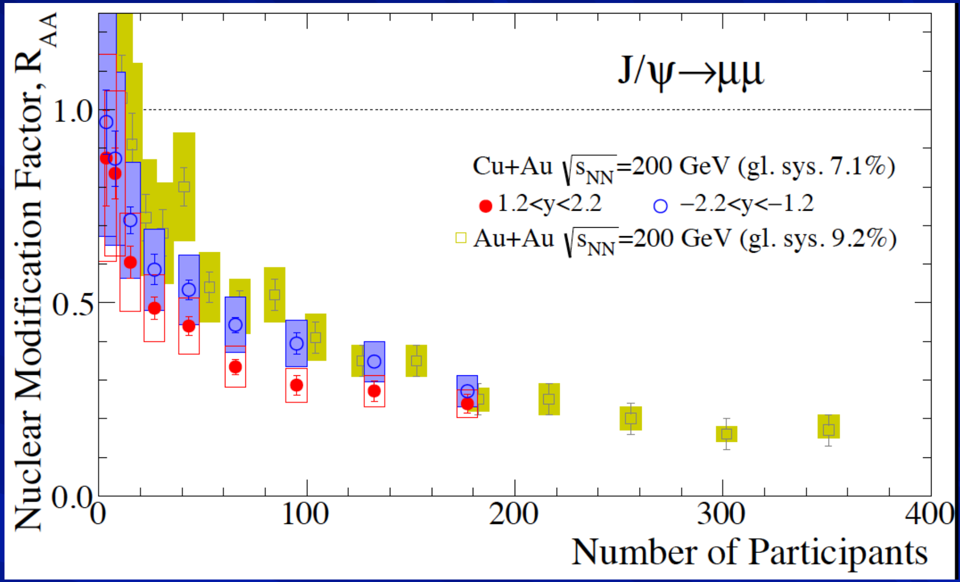
- Smooth evolution of HF R_{AA} from enhancement in small systems to suppression in large systems

J/ψ system-size dependence

PRL 101, 122301 (2008)



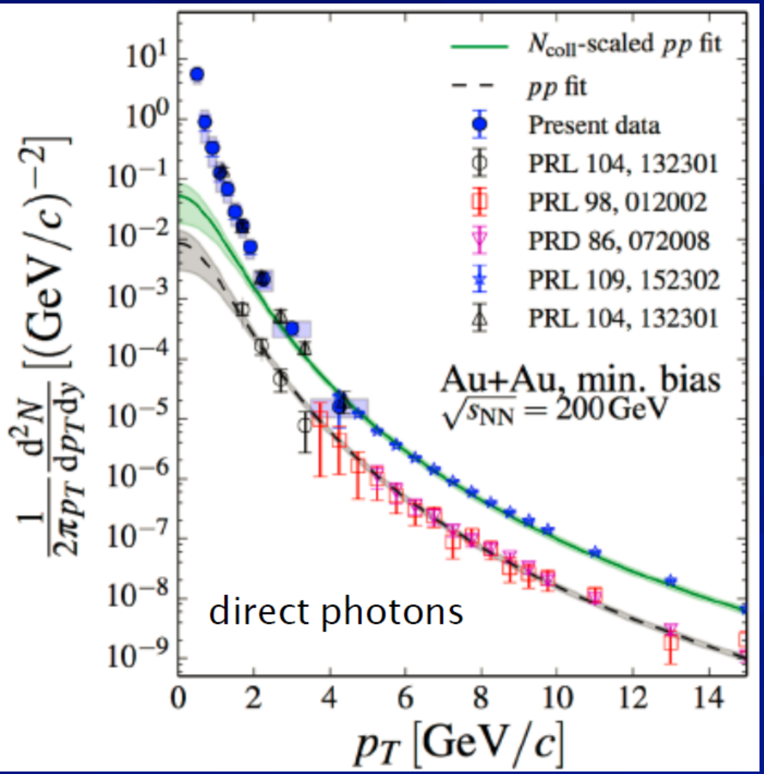
PRC 90, 064908 (2014)



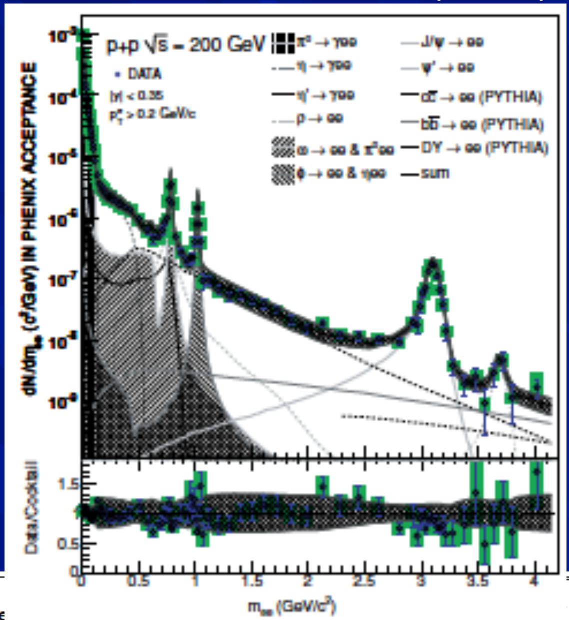
- Similar R_{AA} at similar N_{part} in dAu, CuCu and AuAu systems.
- Similar suppression in Cu+Au (Au-going direction) and Au+Au
- Stronger suppression in Cu+Au (Cu-going direction) – opposite of expected trend if suppression is prop to particle density

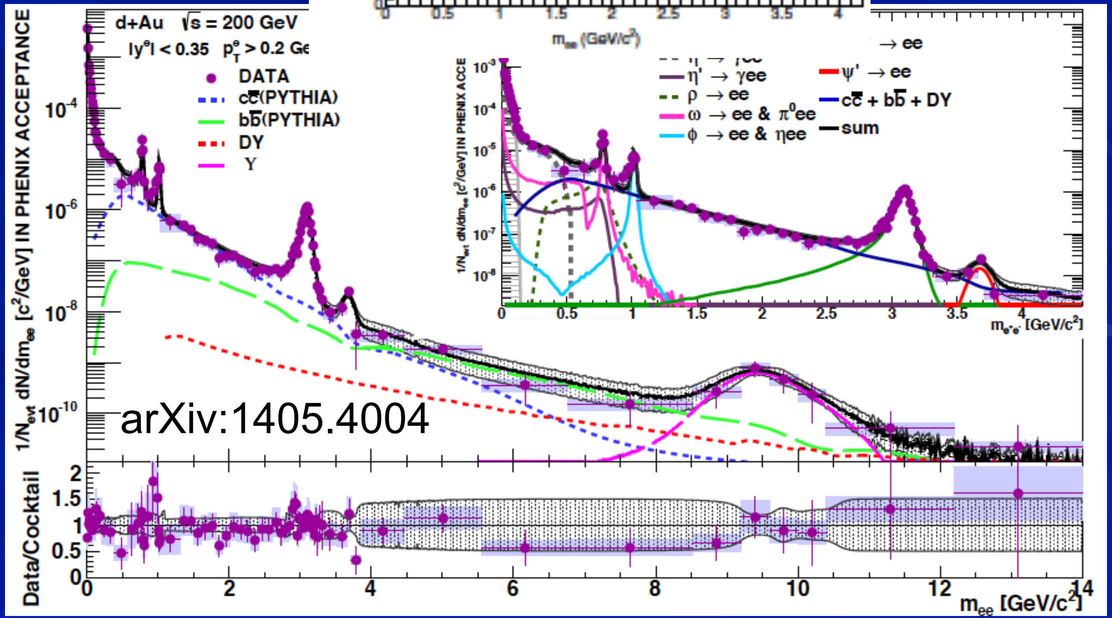
Photons and Dileptons

arXiv:1405.3940



PRC 81, 034911 (2010)





Probably no chance

Itzhak Tserruya

Summary

- Many features seen in A+A collisions are seen in p,d+A collisions and even in p+p collisions at high multiplicity:
  - long range correlations
  - Flow:
    - $v_n(p_T)$ – similar shape
    - v_2 mass ordering
    - v_2 quark scaling
    - multiparticle correlations
    - strong radial flow
  - HBT radii scaling with initial transverse size
- Smooth evolution from small to large systems.
- Small systems exhibit collective behavior consistent with hydro
- No evidence of energy loss or jet quenching in small systems
- Heavy flavor and J/ψ: smooth evolution from small to large systems.
- Need similar systematic approach on hard probes observables in small systems, triggering on very high multiplicity events.

Happy birthday Johanna !