Geometry and Collective Behavior in Small Systems from PHENIX

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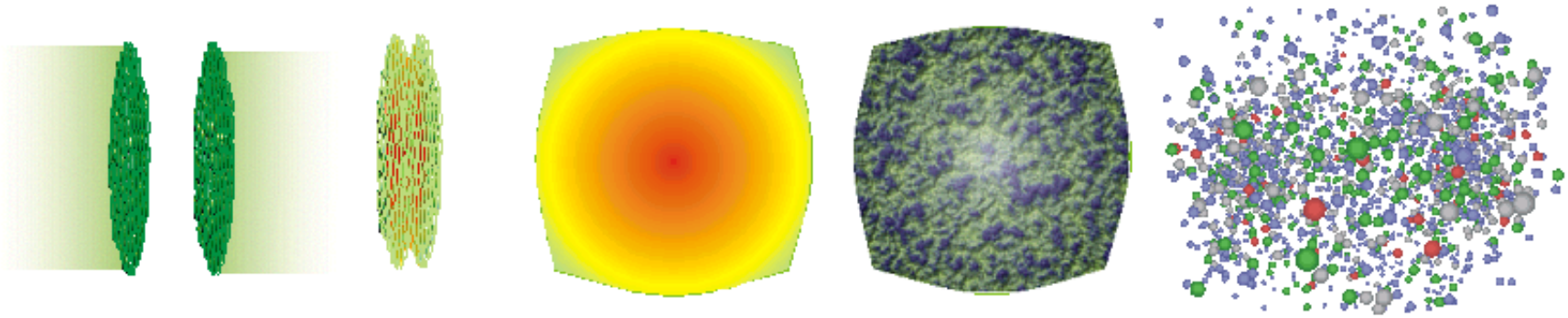
for the PHENIX Collaboration

Moriond QCD, March 27th, 2015

Collective flow in heavy ion collisions

Pre-equillibrium

Hadronization



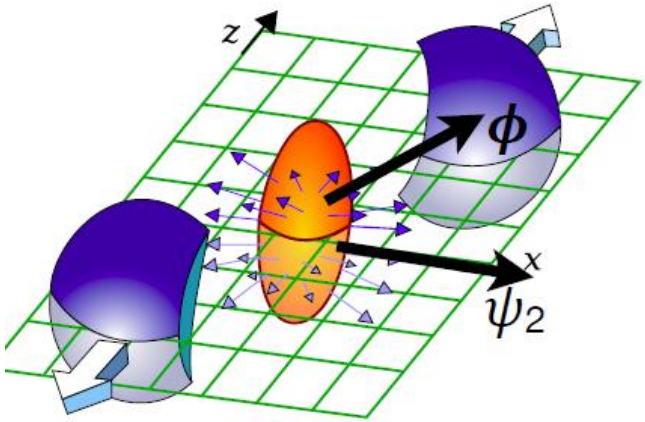
Initial state

Quark Gluon Plasma
thermally equilibrated
Hydrodynamic collective flow

Hadronic phase
and freezeout

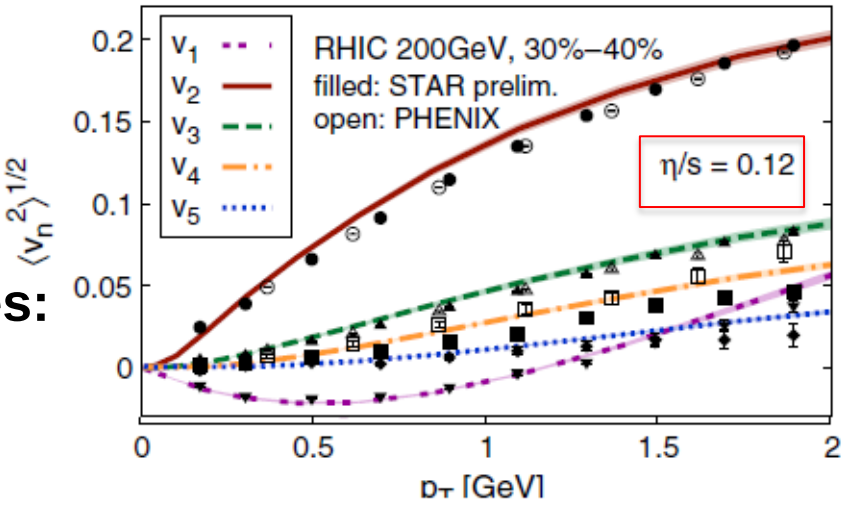
Modeling of all stages is important !

$$dN/d\phi = 1 + \sum_n 2v_n \cos(n(\phi - \Psi_n))$$

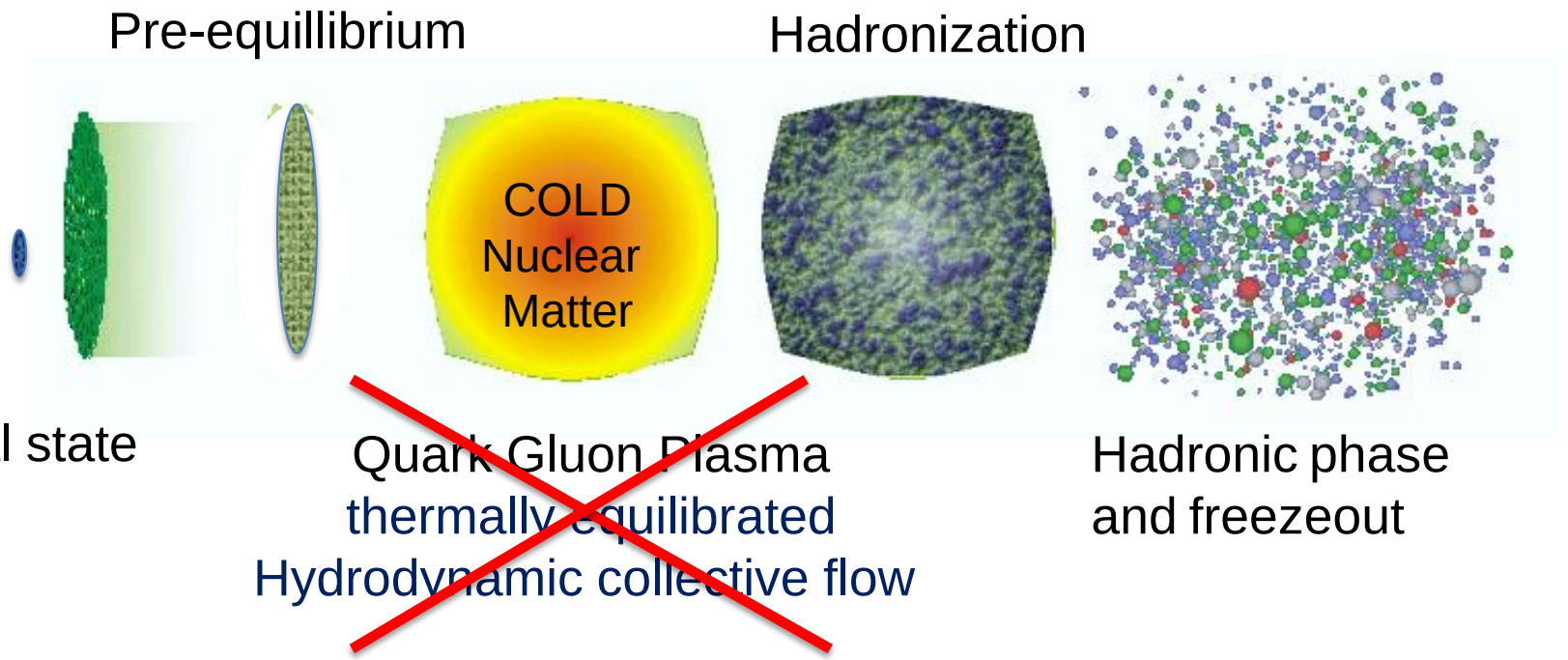


Measure v_n
Compare to theory
Extract QGP properties:

- **specific viscosity**
- **equation of state**
- **initial state**



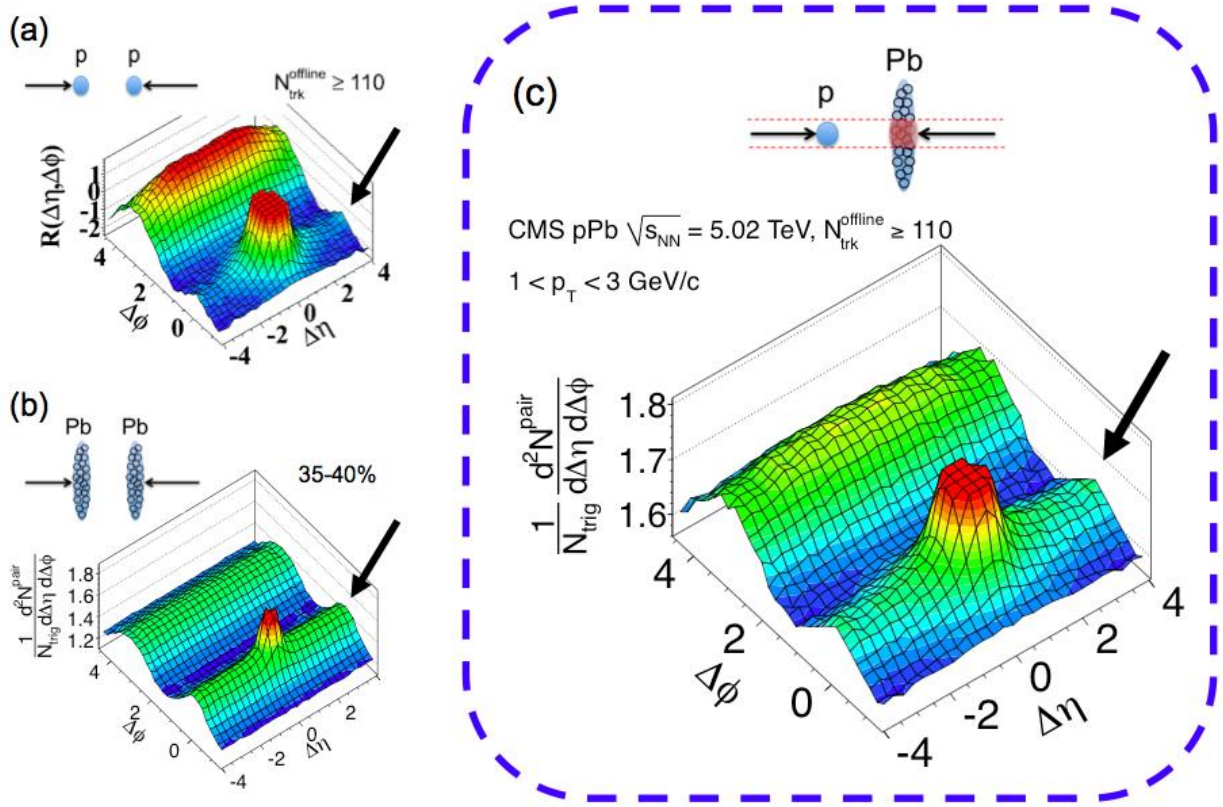
Small systems paradigm



- Not enough particles to achieve equilibration
- No QGP
- pp collisions serve as a reference baseline
- pA or dA: reference for cold nuclear matter effects

Motivation: at LHC ridges are everywhere !

2010: Discovery ridge in pp **high multiplicity** events: JHEP 1009 (2010) 091
2012 pilot run: Discovery of ridge in pPb **high multiplicity** events PLB 718 (2013) 795

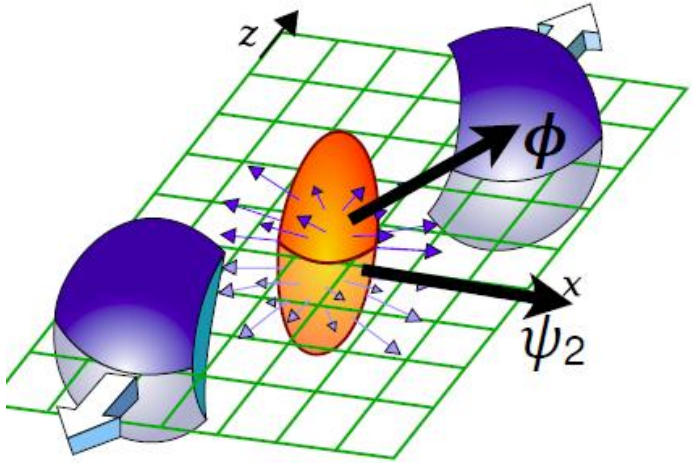


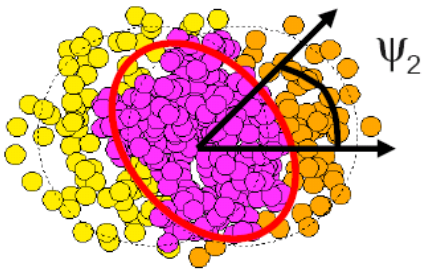
- Are these correlations also present at RHIC ?
- In 2013 PHENIX revisits data from d+Au from 2008
- 2014: ^{3}He+Au; 2015 : p+Al, p+Au, and pp

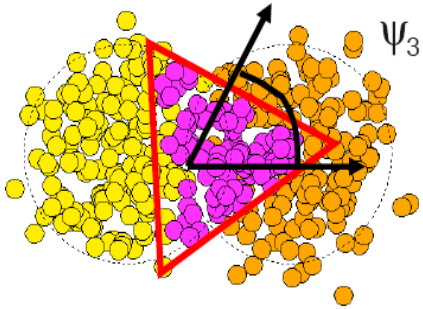
Experimental methods in PHENIX

Event plane: determined at large pseudorapidity
Particles: tracked and identified at midrapidity

$$dN/d\phi = 1 + \sum_n 2v_n \cos(n(\phi - \Psi_n))$$





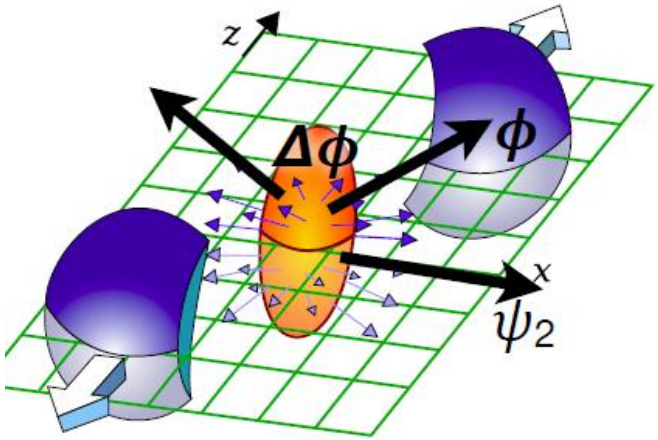


Or

- particle at midrapidity + energy cluster at forward rapidity (no p_T available)
- 2-particle correlations at midrapidity

pair amplitude modulation

$$c_n = v_n^a \times v_n^b$$

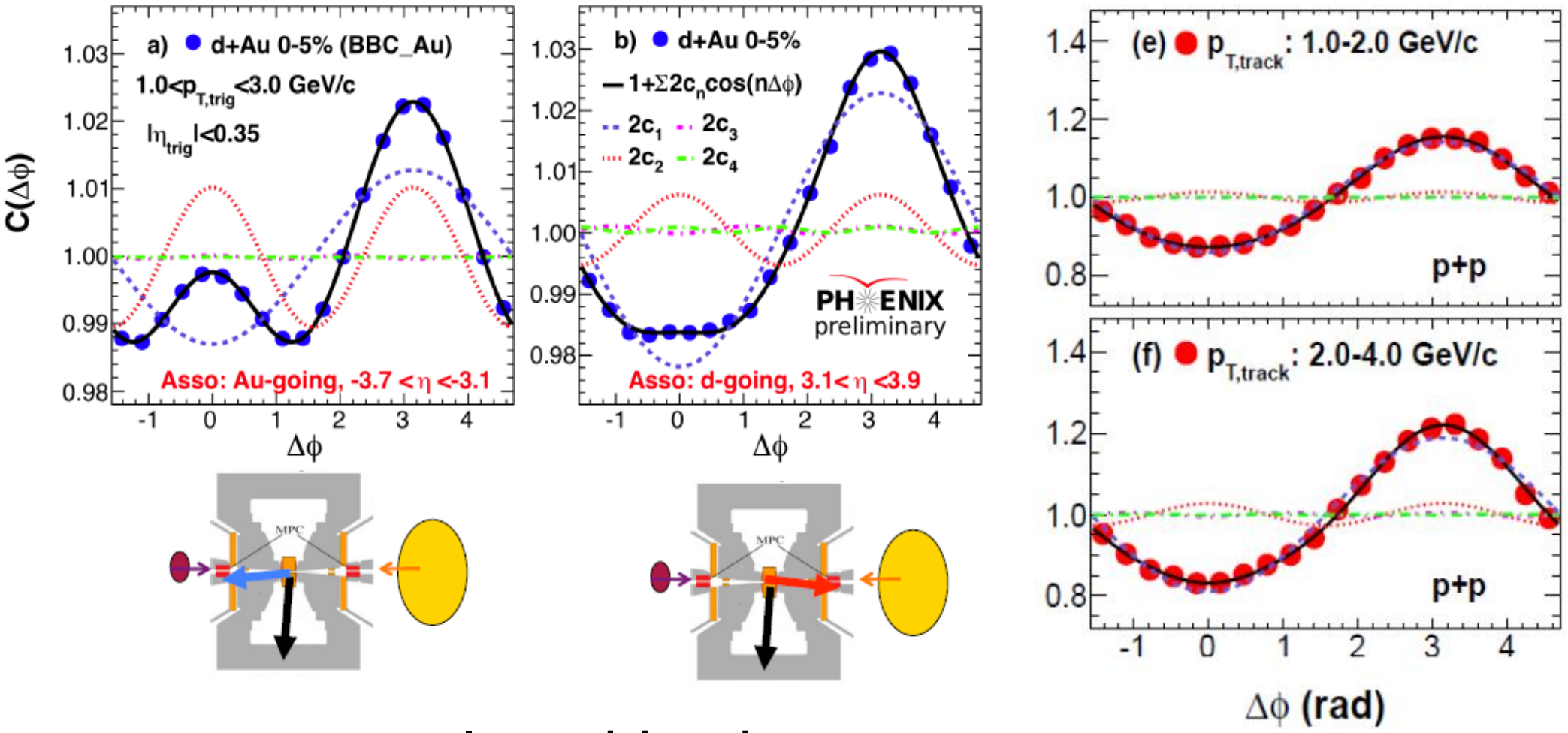


Long range correlations in d+Au

Central d+Au

arXiv:1404.7461

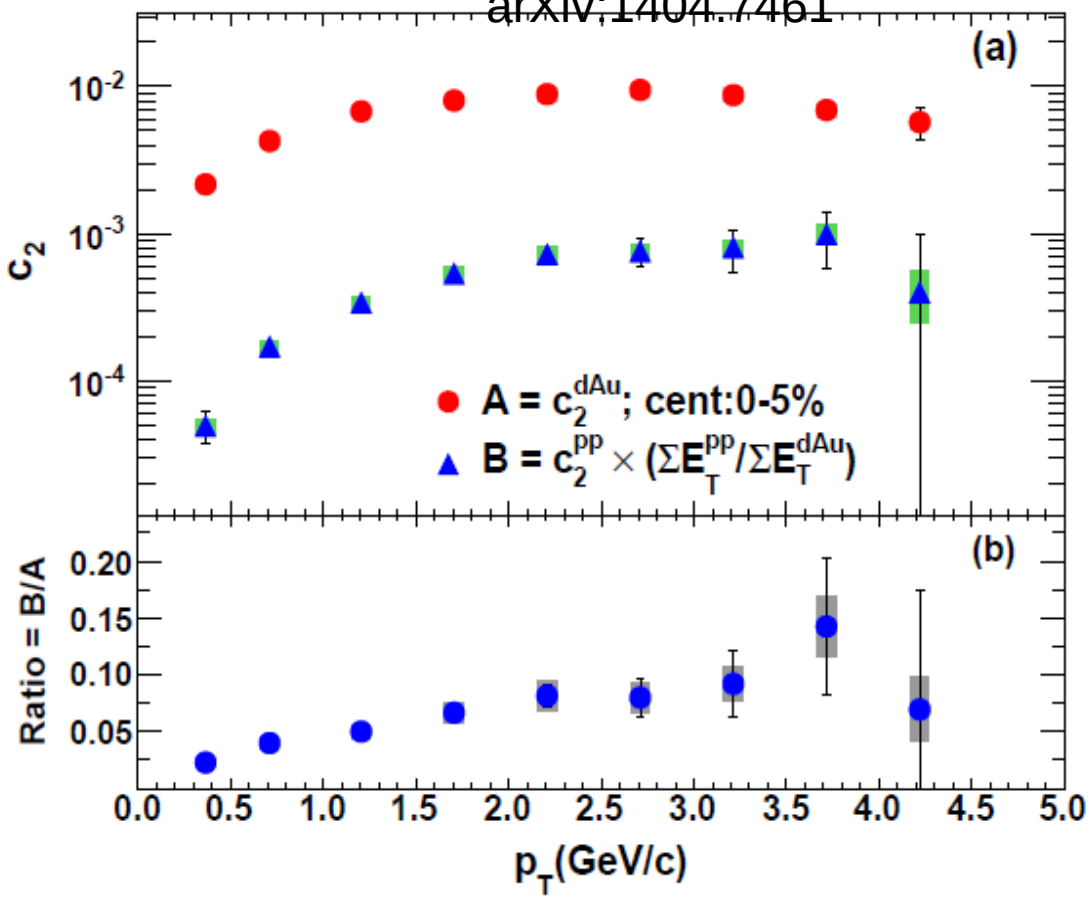
Min bias p+p



- **|Δη|>2.75 :** a clear ridge is seen on the Au-going side
- Collective effect ? Residual jet correlations ?

Jet contributions to c_2 in 0-5% d+Au collisions

arXiv:1404.7461

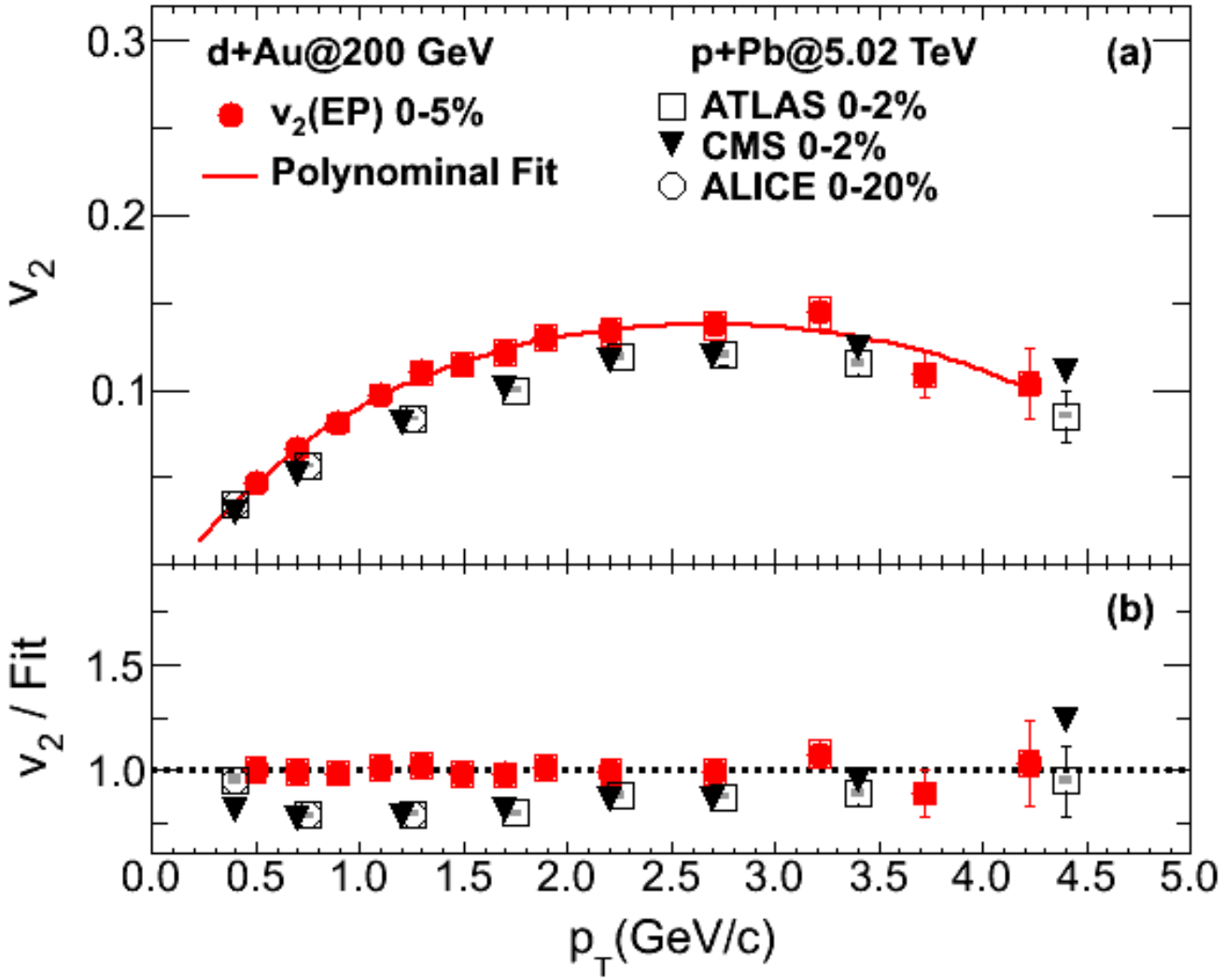


$$c_2^{dAu}(p_T) = c_2^{\text{Non-elem.}}(p_T) + c_2^{\text{Elem.}}(p_T)$$
$$\approx c_2^{\text{Non-elem.}}(p_T) + c_2^{pp}(p_T)\frac{\Sigma E_T^{pp}}{\Sigma E_T^{dAu}}$$

- With $|\Delta\eta|>2.75$ jet contribution (estimated from pp) is small
- Next: use EP method with $|\Delta\eta|>2.75$

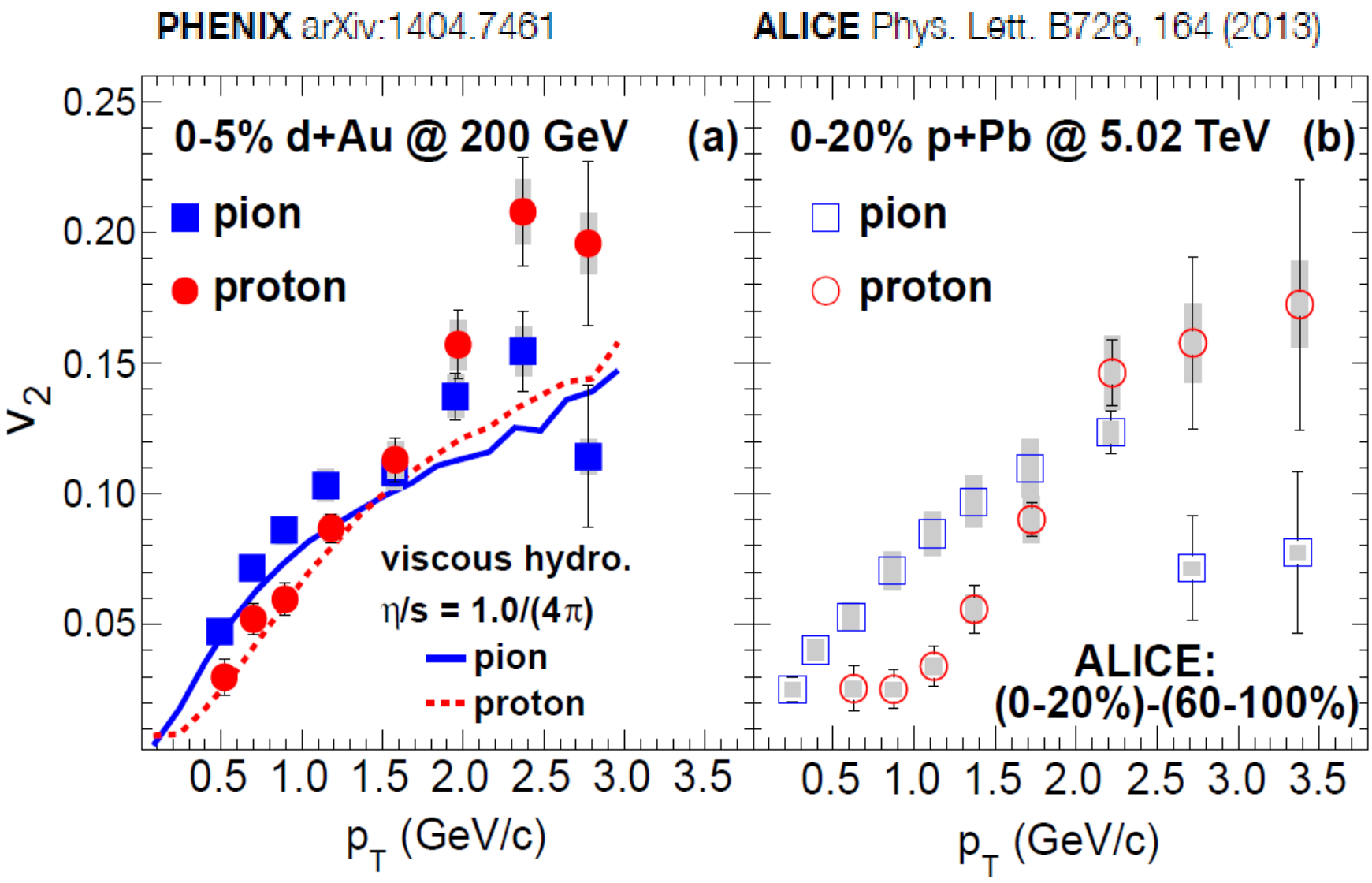
Charged particles: RHIC dAu and LHC pPb

arXiv:1404.7461



- PHENIX dAu and LHC pPb results - similar v_2

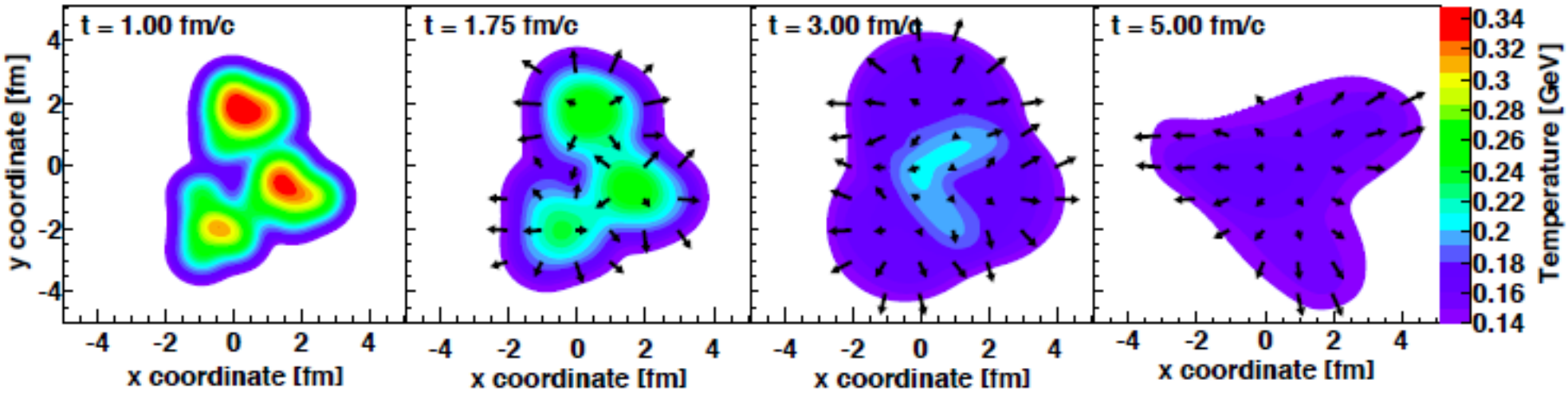
Identified hadrons: v_2 of π and p in d+Au



Mass ordering for identified hadrons in both d+Au and p+Pb
- consistent with hydrodynamic flow (common velocity field)

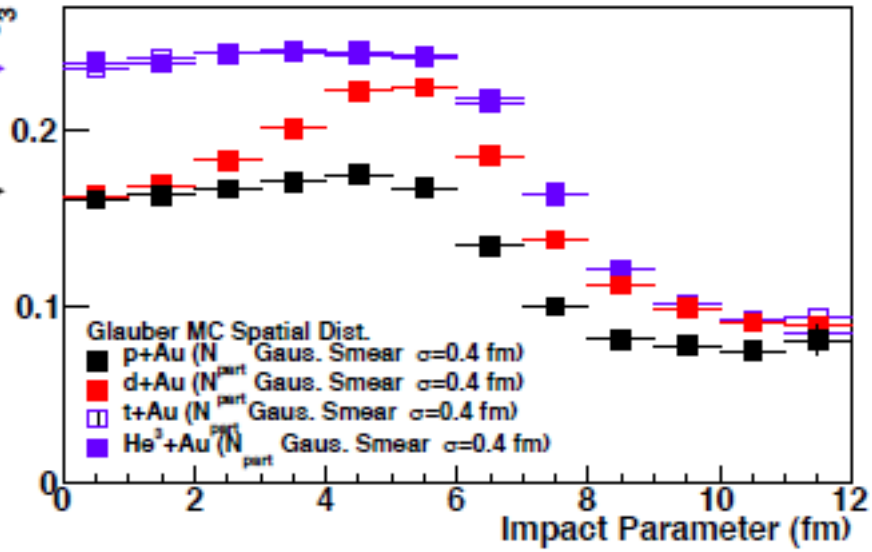
Geometry engineering:

J.Nagle et al, Phys. Rev. Lett. 113, 112301 (2014)



He^3+Au →

d+Au and p+Au →

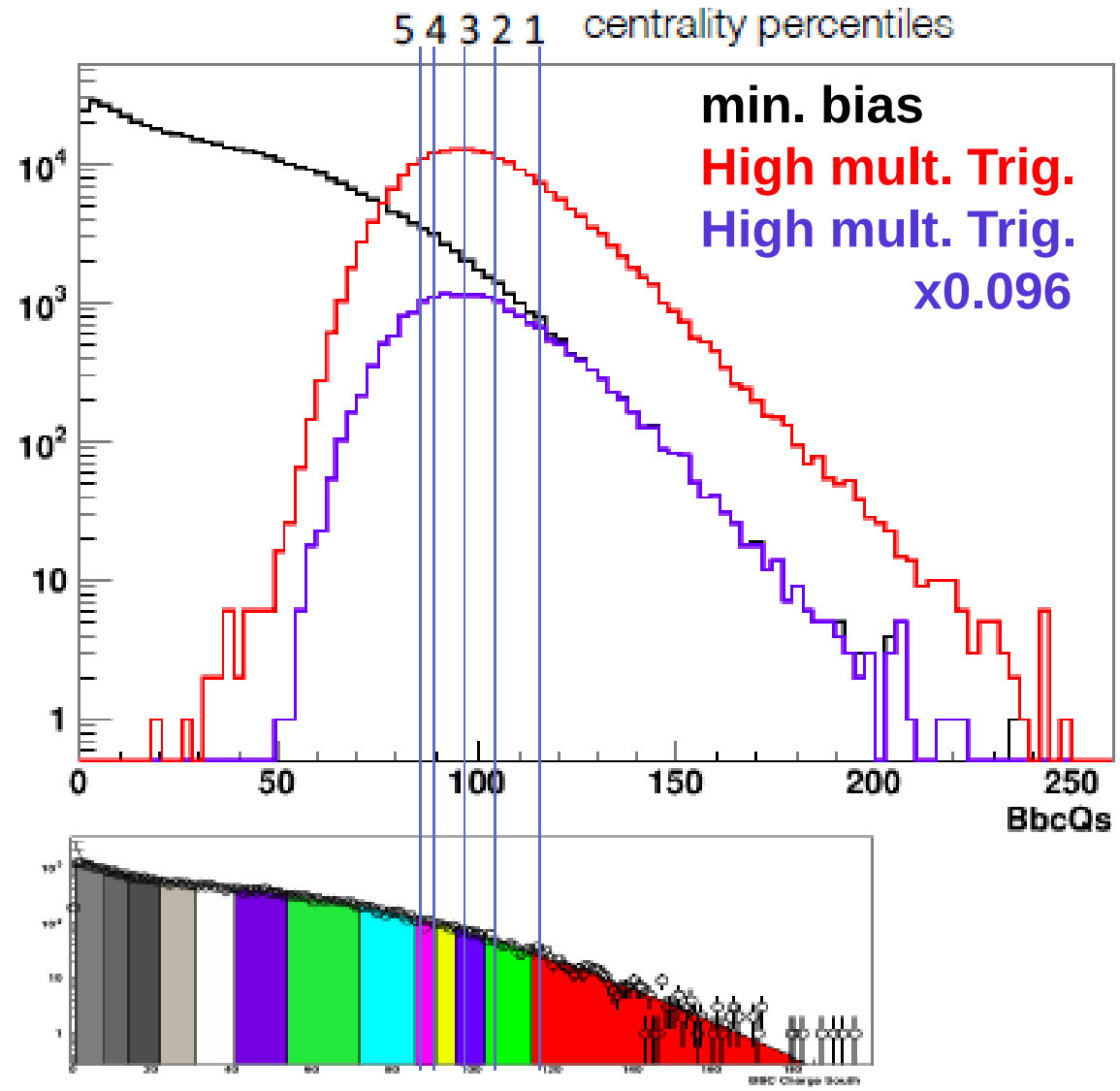


^{3}He+Au (0-5%) N_{part}=25.0
ε_2=0.504 ε_3=0.283

d+Au (0-5%) N_{part}=17.8
ε_2=0.540 ε_3=0.190

From idea to reality: ^{3}He+Au

PHENIX proposal May 2013 → **theory predictions Dec 2013** → **data taking June 2014** → **results Dec 2014**



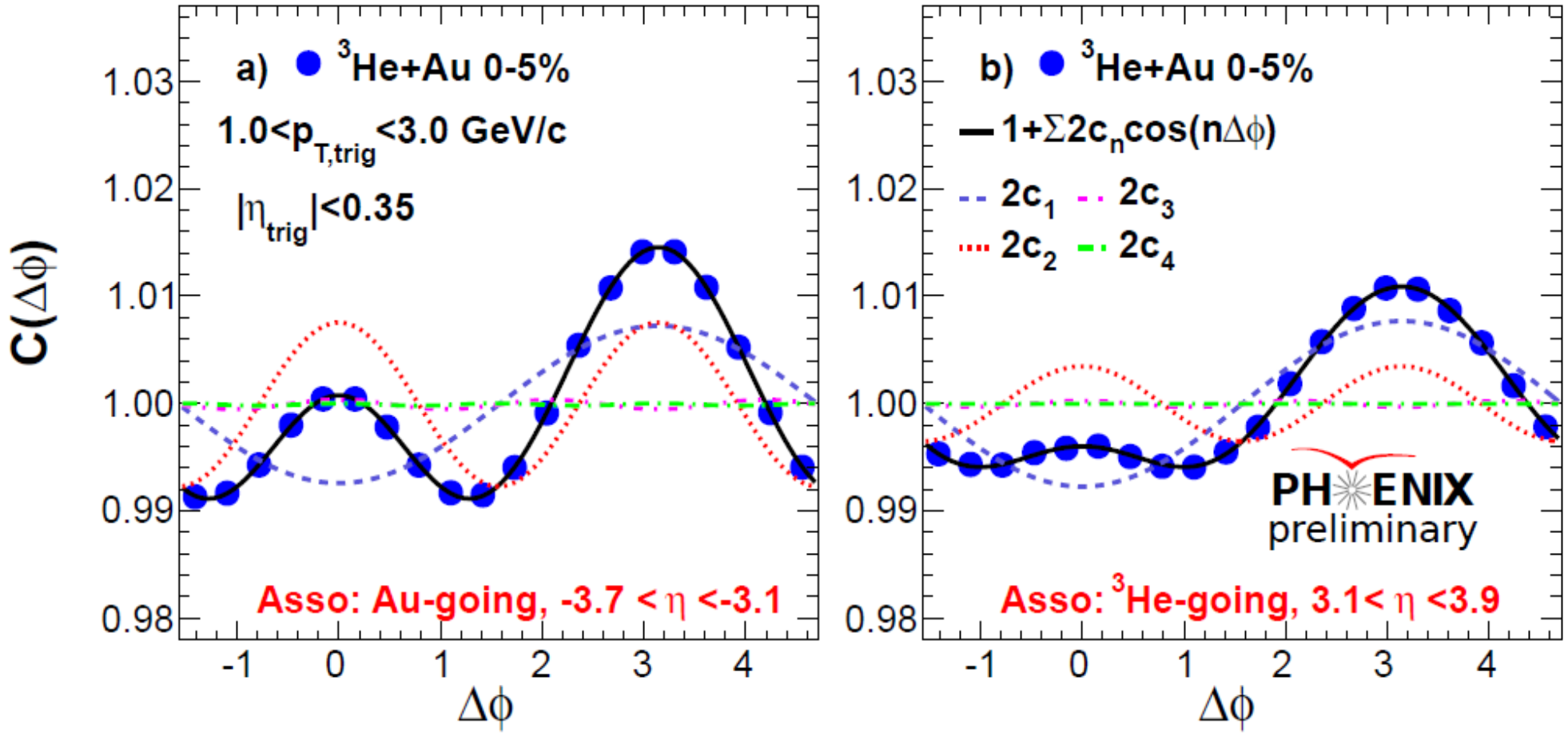
new centrality trigger based on beam-beam counter in Au-going direction

Two weeks **^{3}He+Au@200 GeV** in the end of Run 14

PHENIX recorded:
2.2 billion min. bias events
0.8 billion central events

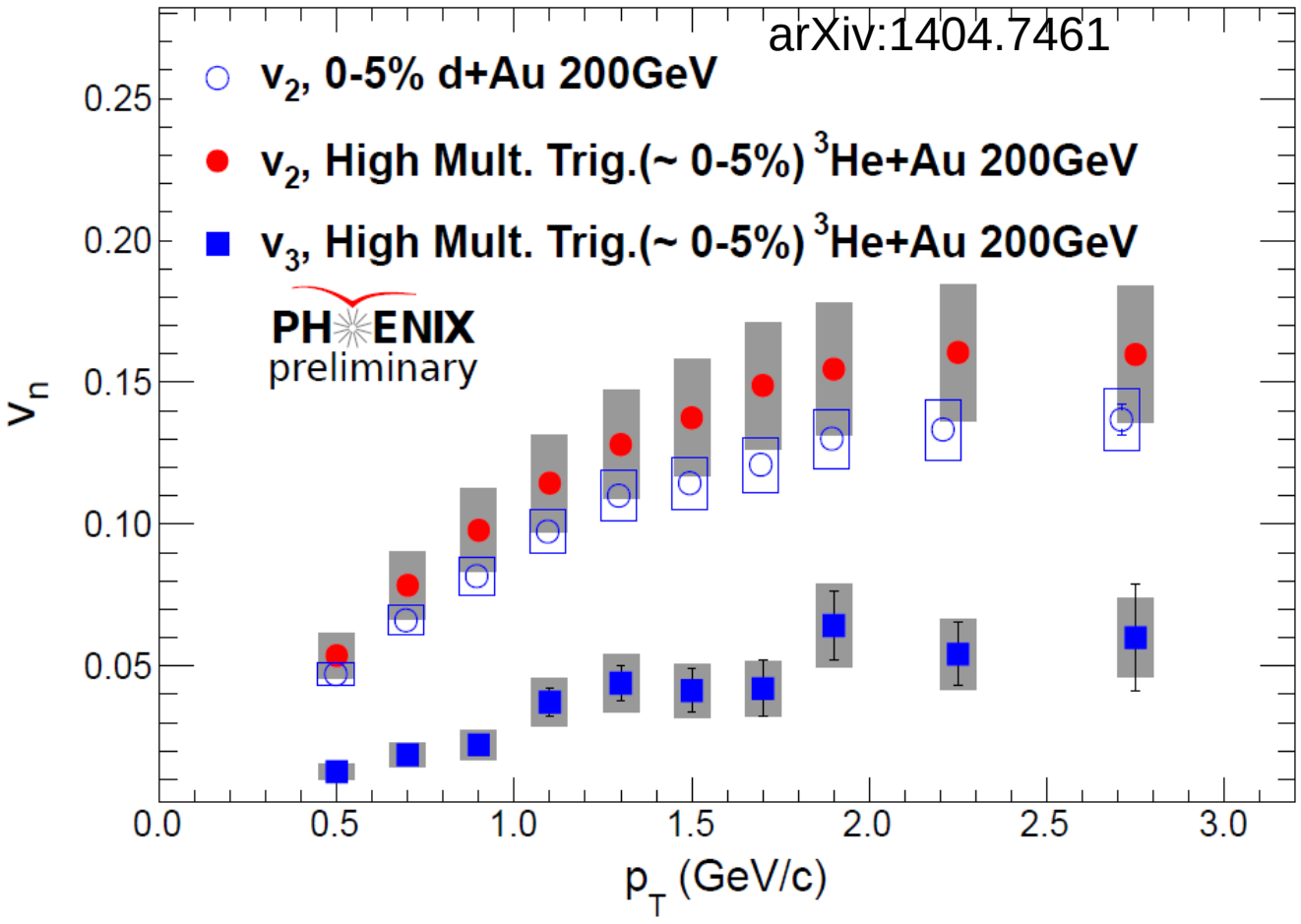
Long range correlations in ^{3}He+Au

"Au-going" vs "^{3}He-going"



Ridges are seen on both Au-going and ^{3}He-going sides

System comparison
v_2 and v_3 in ^{3}He+Au, v_2 in d+Au



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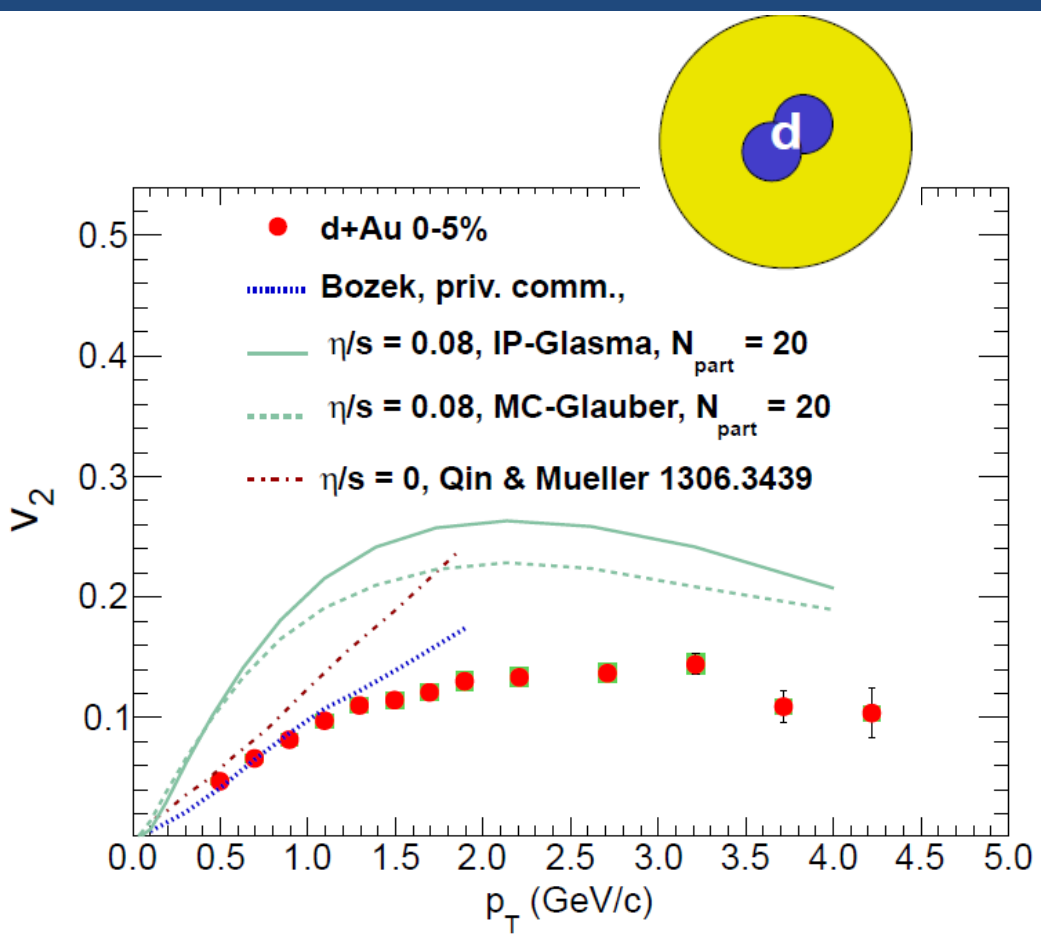
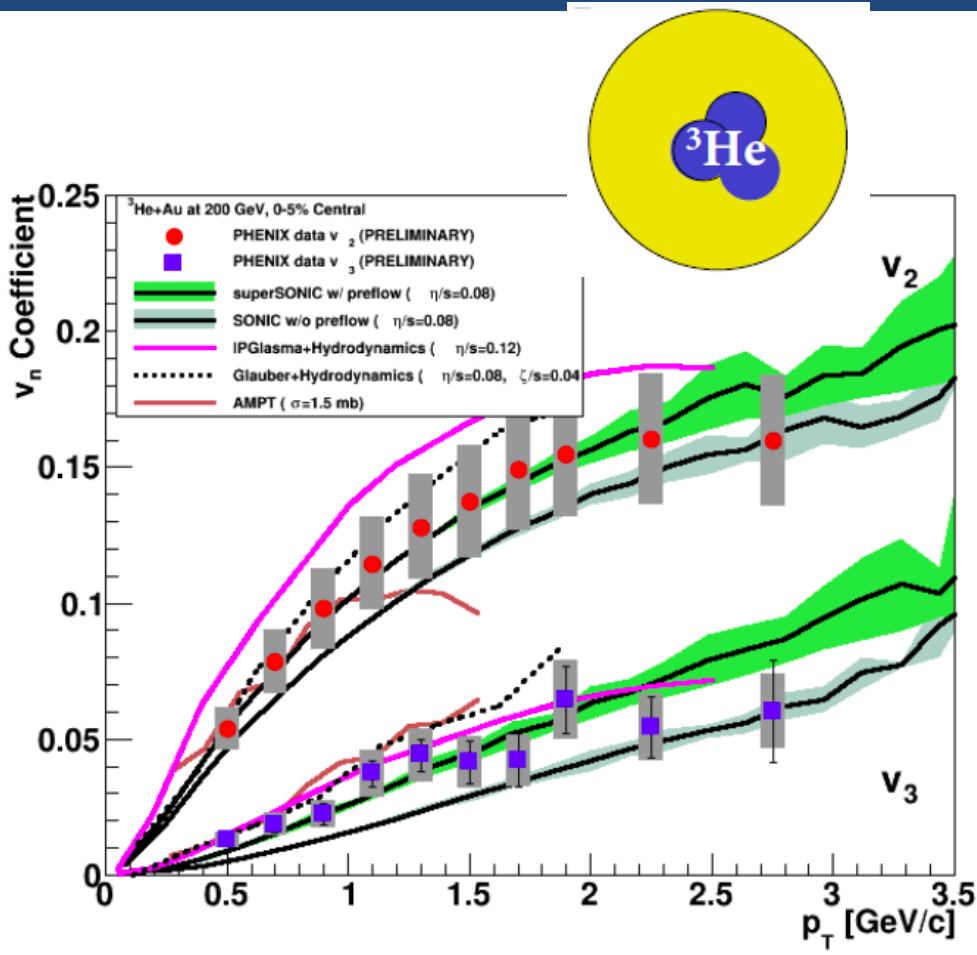
Similar v_2 in **^{3}He+Au** and **d+Au**

clear **v_3** in **^{3}He+Au**

- Geometry engineering seems to work!
- Need to test more systems

Theorists are hard at work !



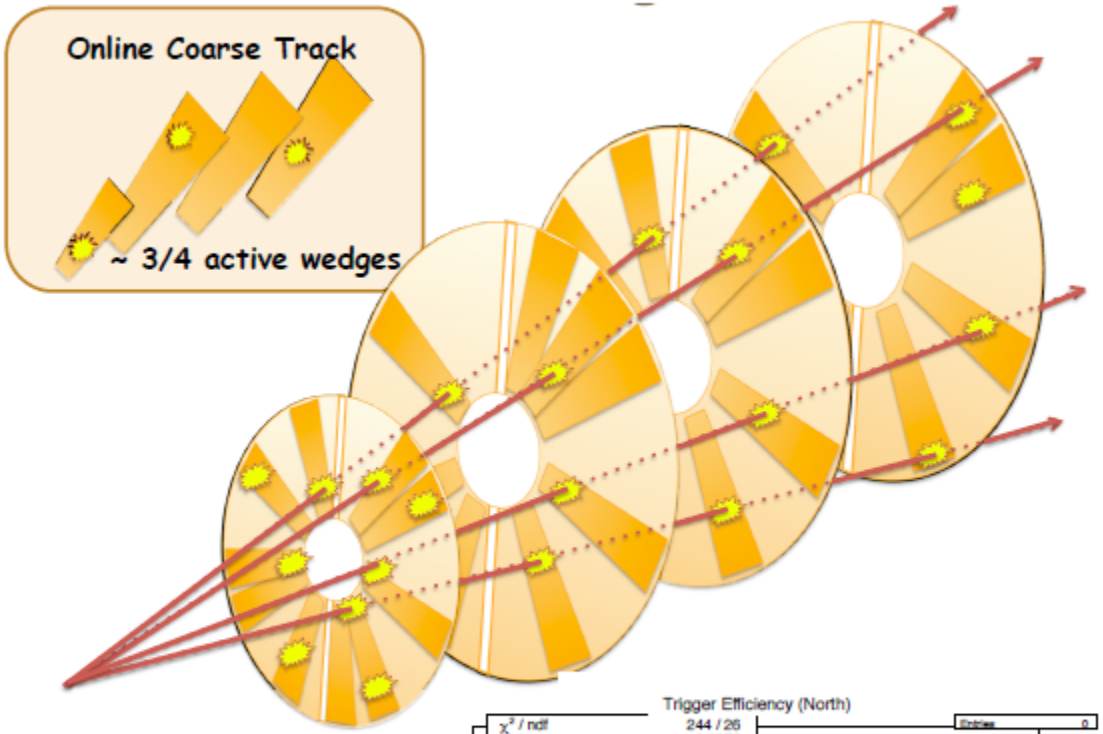


- Several hydro calculations with different initial conditions, η/s, pre-equilibrium flow, hadronic stage
- Modeling of ALL stages is important!
- **^{3}He+Au** also described by AMPT string melting, σ=1.5 mb

Ongoing Run 15: pp @ 200 GeV
New high multiplicity trigger deployed!

PHENIX forward silicon vertex (FVTX)

N_{trk}^{FVTX} $(1.2 < |\eta| < 2.2) \geq 12$

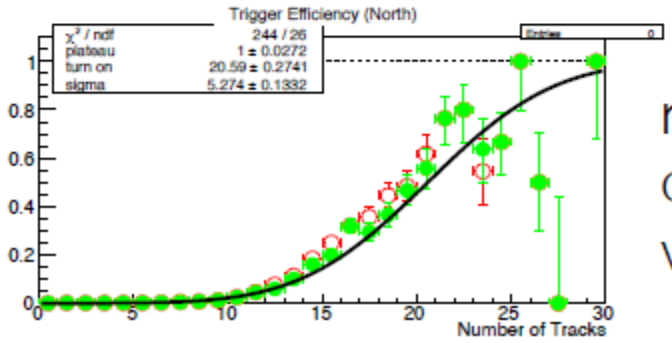


Run15 pp

100 Hz bandwidth for FVTX HighMulti Trigger

9 weeks of pp running assuming 30% uptime

300 Mevents to be accumulated
(~ x4 of Run8 dAu central)



rejection power of ~1500 in combination with a ±10 cm primary vertex trigger (based on BBC)

Ongoing Run 15: pp @ 200 GeV
New high multiplicity trigger deployed!

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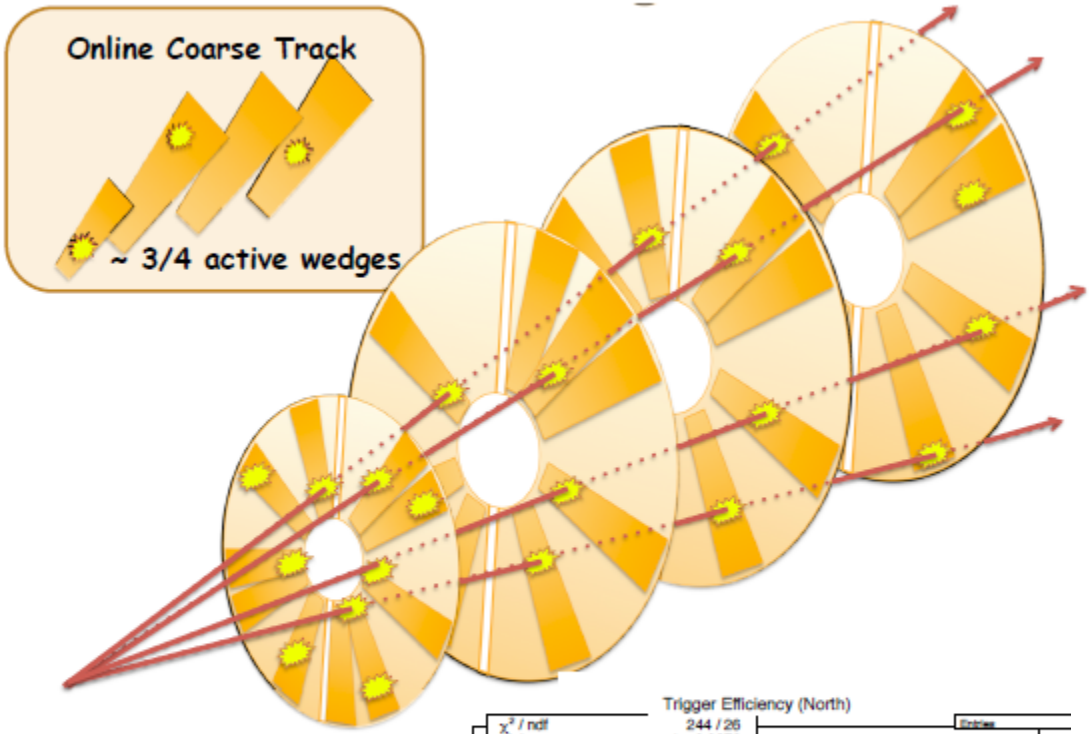
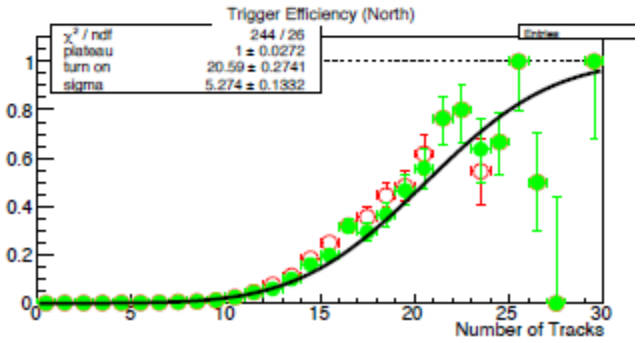
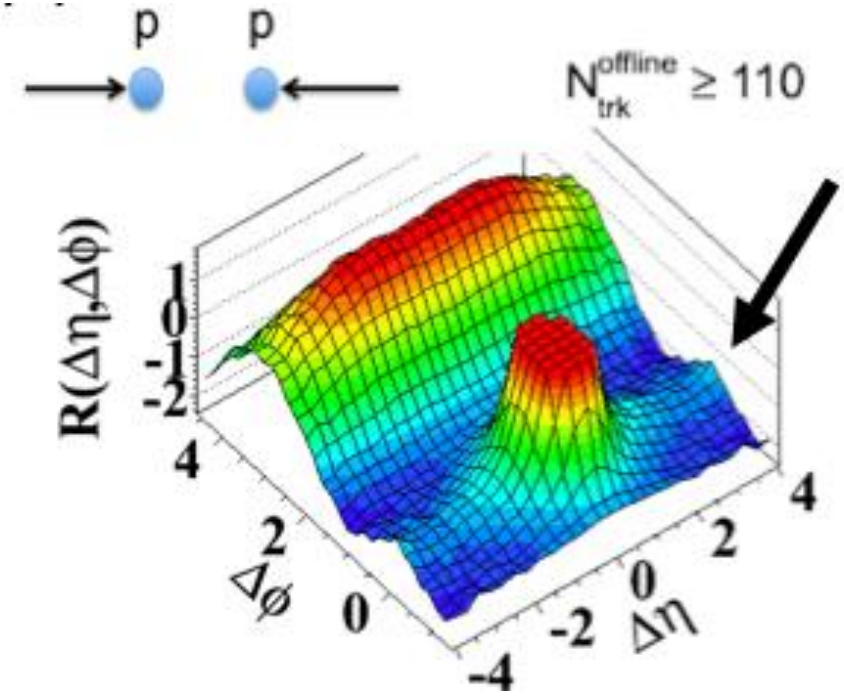
N_{trk}^{FVTX} $(1.2 < |\eta| < 2.2) \geq 12$

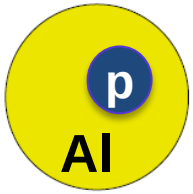


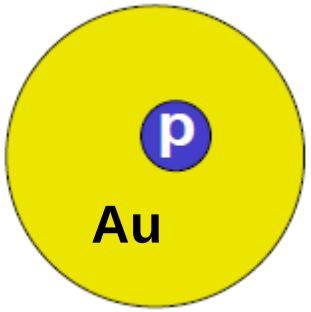


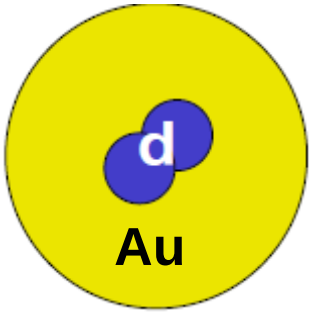


Can we see a ridge in high multiplicity pp at RHIC ?

Do size and eccentricity matter ?







Presently running pp at $\sqrt{s_{NN}}$ = 200 GeV

Still to come in Run 15

2 weeks of p+Al at $\sqrt{s_{NN}}$ = 200 GeV

5 weeks of p+Au at $\sqrt{s_{NN}}$ = 200 GeV

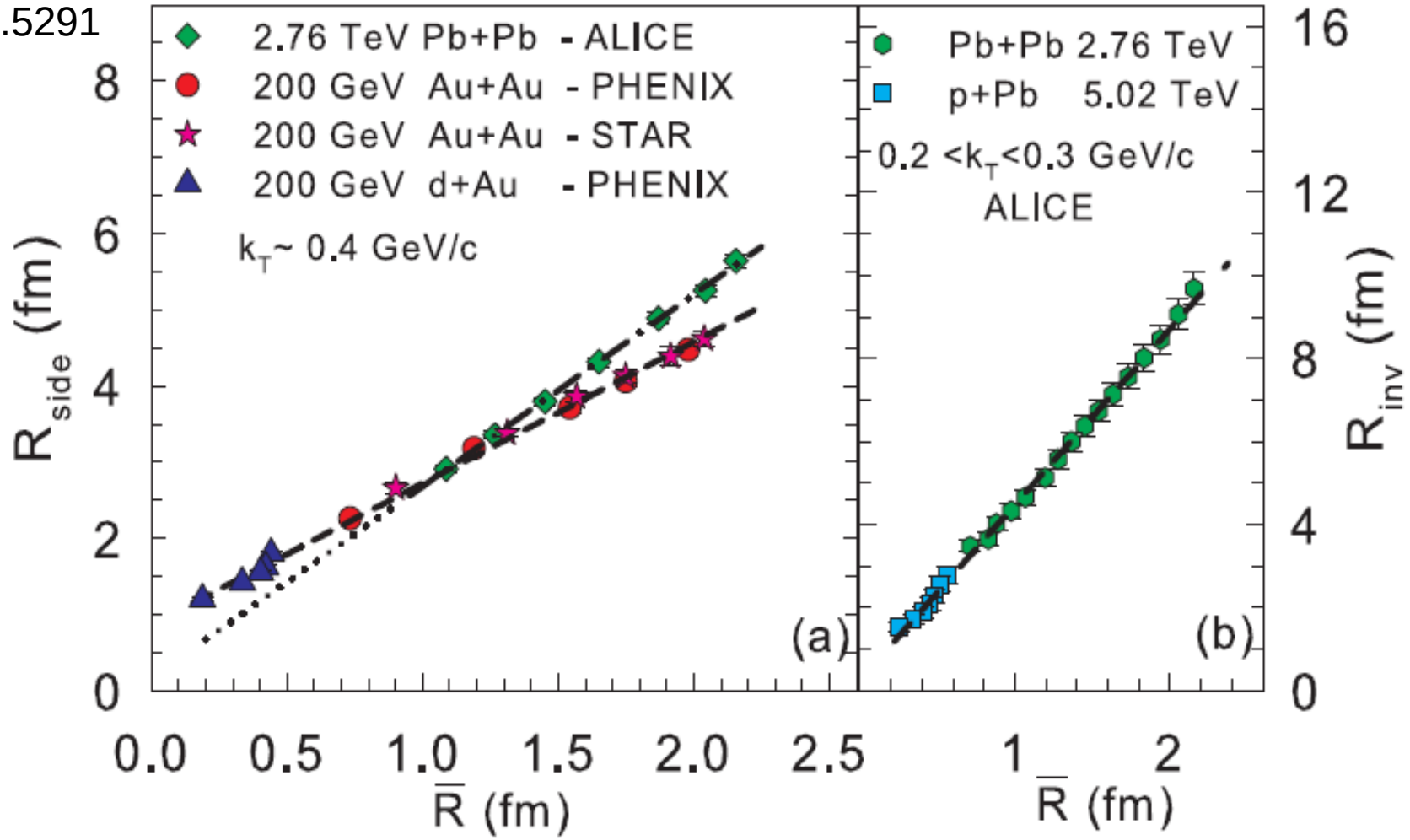
- A full set of geometries to explore collective behavior in small systems
- Can we turn the QGP off ?

Summary

- Paradigm shift in understanding small systems
- Strong collective effects observed in central d+Au and ^{3}He+Au collisions at RHIC at 200 GeV
- Elliptic anisotropy coefficient v_2 of similar magnitude in d+Au, ^{3}He+Au at 200 GeV and in p+Pb at 5 TeV
- Mass ordering of $v_2(p_T)$ consistent with hydrodynamics
- Sizable triangular flow observed in ^{3}He+Au reflecting the intrinsic triangularity in the initial geometry
- Hydro models in qualitative agreement with the data
- More data to enable test of initial geometry underway in Run 15 of RHIC

The HBT radii d+Au, Au+Au, Pb+Pb,p+Pb

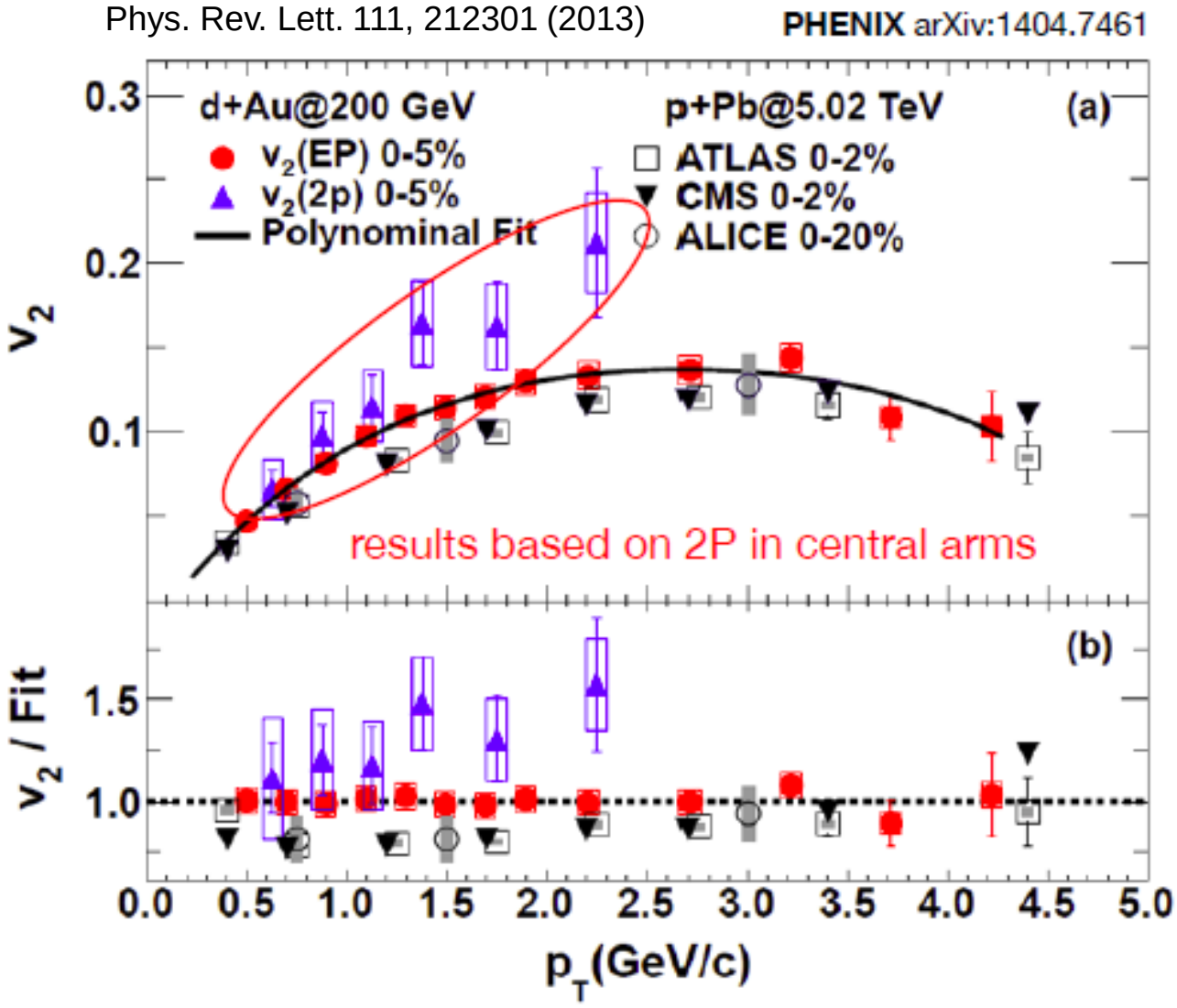
arXiv:1410.5291



Rbar(initial transverse size): $1/Rbar=sqrt(1/\sigma_x^2+ 1/\sigma_y^2)$

- Linear dependence and good scaling from small (p/d+A) to bigger(A+A) collision systems, implying radial expansion in p/d+A collisions
- The different slopes between RHIC and LHC imply different expansion rates

Charged particles: RHIC dAu and LHC pPb



- PHENIX dAu and LHC pPb results - similar v_2
- Some non-flow in central arm 2P correlations