PHENIX results on collectivity in high-multiplicity p + Au, d + Au and ^{3}He + Au collisions

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for the PHENIX Collaboration

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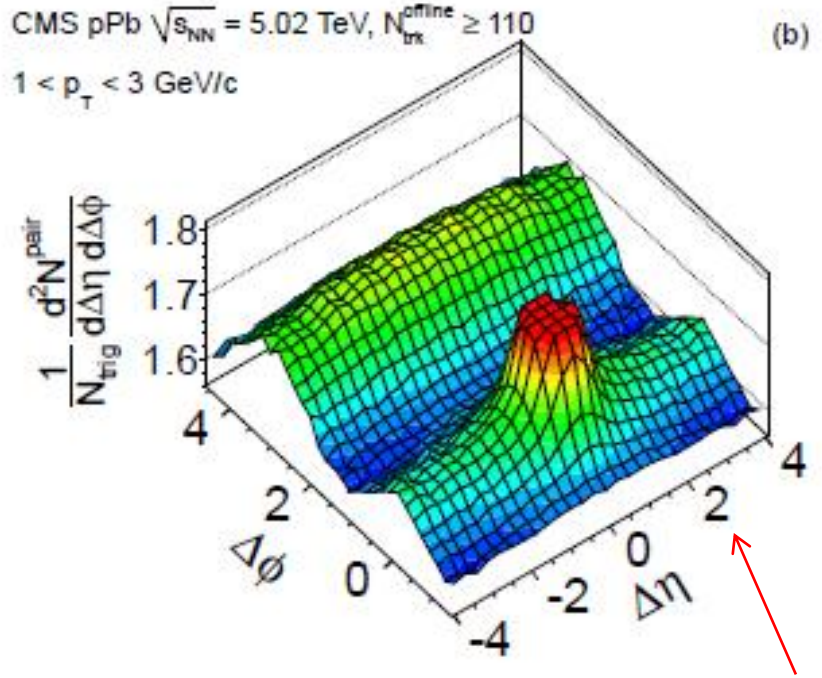
Outline

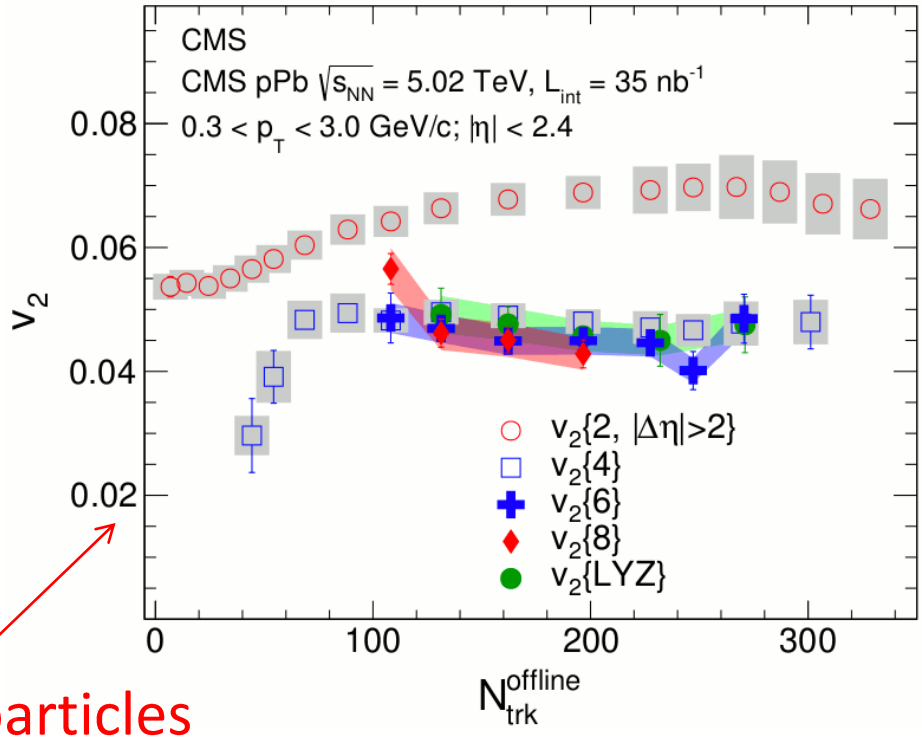
- Motivation
- Experimental details
- Results
  - Correlation functions in p/d/ ^{3}He+Au
  - Charged particle v_2 in p/d/ ^{3}He+Au; v_3 in ^{3}He+Au
  - Comparison to models
  - Identified particle v_2 in d+Au and ^{3}He+Au
  - Outlook for Run 16
- Summary and Conclusions

Motivation

CMS: Phys. Lett. B 7198(2013)



CMS: Phys. Rev. Lett. 115, 012301



Charged particles

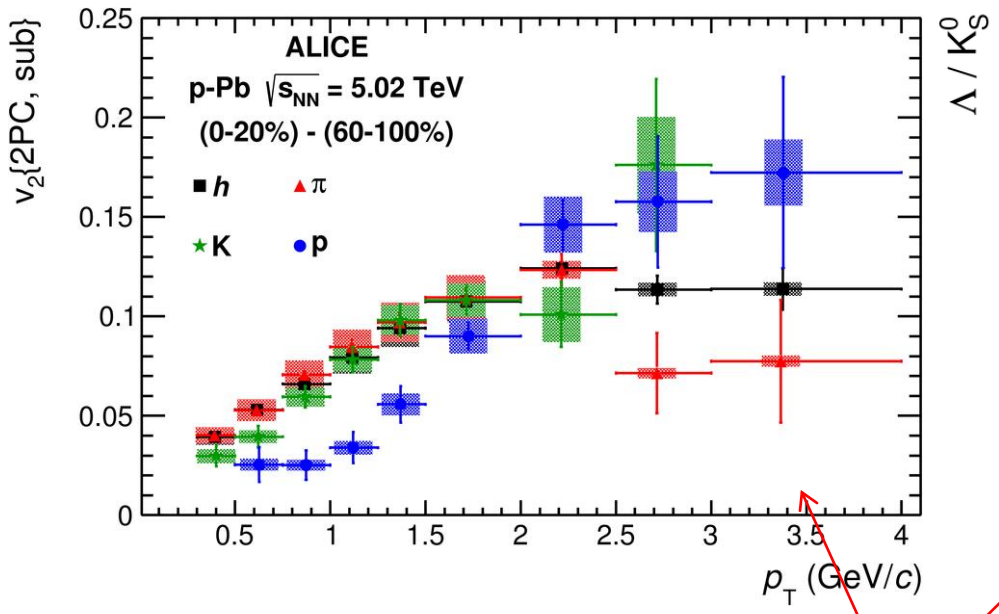
Near-side ridge in p-Pb

Multi-particle correlation in p-Pb

Is there collective behavior in small collision systems?

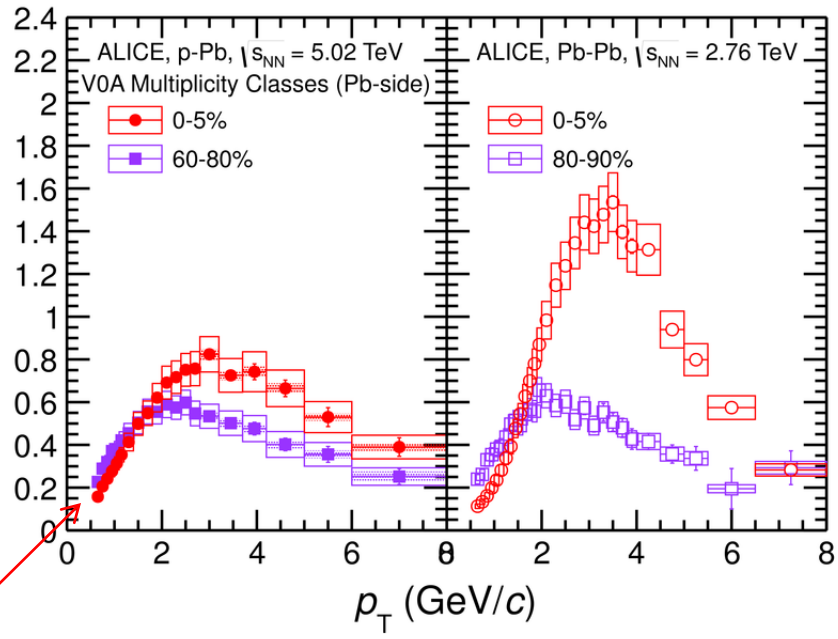
Motivation

Alice: Phys. Lett. B 726 (2013) 164–177



Pion/Kaon/Proton v_2 in p-Pb

Alice: Phys. Lett. B 728 (2014) 25-38



Sign of radial flow in p-Pb

Identified particles

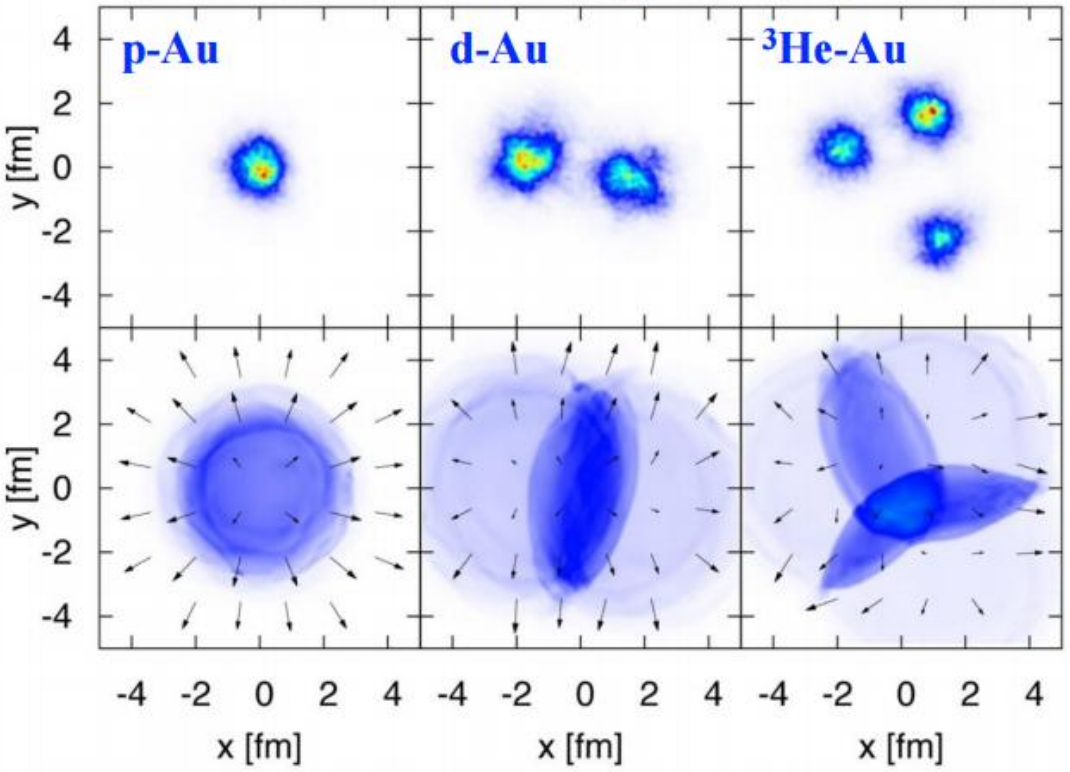
Is there collective behavior in small collision systems?

Motivation

- **Are these correlations also present at RHIC?**
- **Does initial geometry play a role?**

Run15 Run8 Run14

Phys. Rev. Lett. 113, 112301 (2014), figure courtesy of B. Schenke



Initial State Hot Spots
Glauber with nucleons

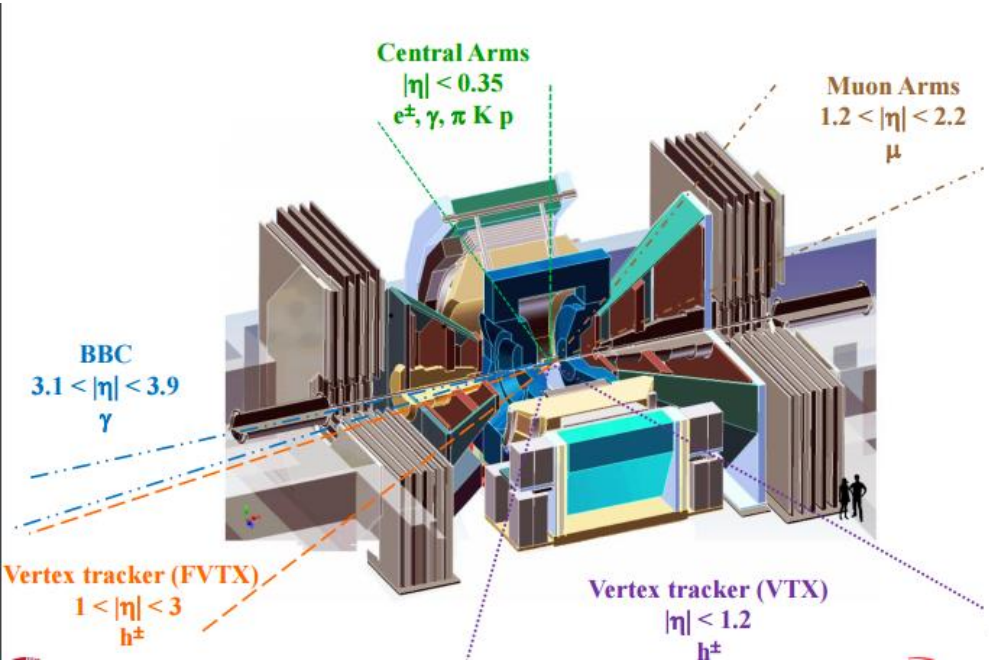
Hydrodynamics

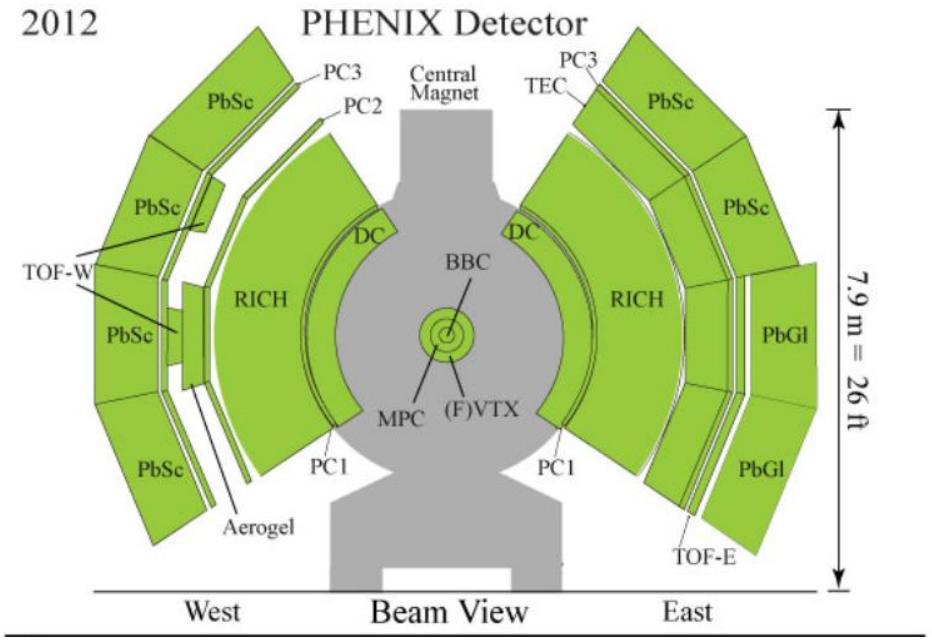
Collectivity in Final State

- $v_2(^3HeAu) \sim v_2(dAu) > v_2(pAu)$

2nd order harmonics 2nd order harmonics 2nd and 3rd order harmonics

Small system measurements in PHENIX



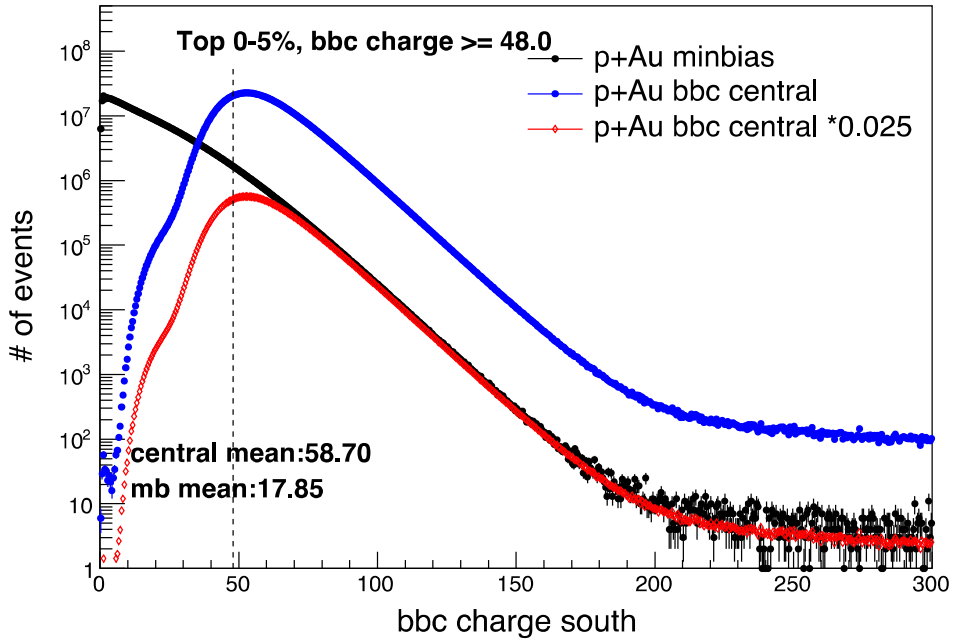


- The PHENIX extraordinary collection of heavy ion collisions:
  - p+Au, d+Au,^{3}He+Au, p+Al, Cu+Au, Cu+Cu, Au+Au, U+U
- **Geometry engineering at RHIC !**
- Midrapidity: DC, PC, TOF -> tracking and PID
- Forward: BBC, MPC, FVTX -> triggering, event selection, correlations with midrapidity particles, event plane determination

High-multiplicity triggering

- **High-multiplicity trigger in BBC**

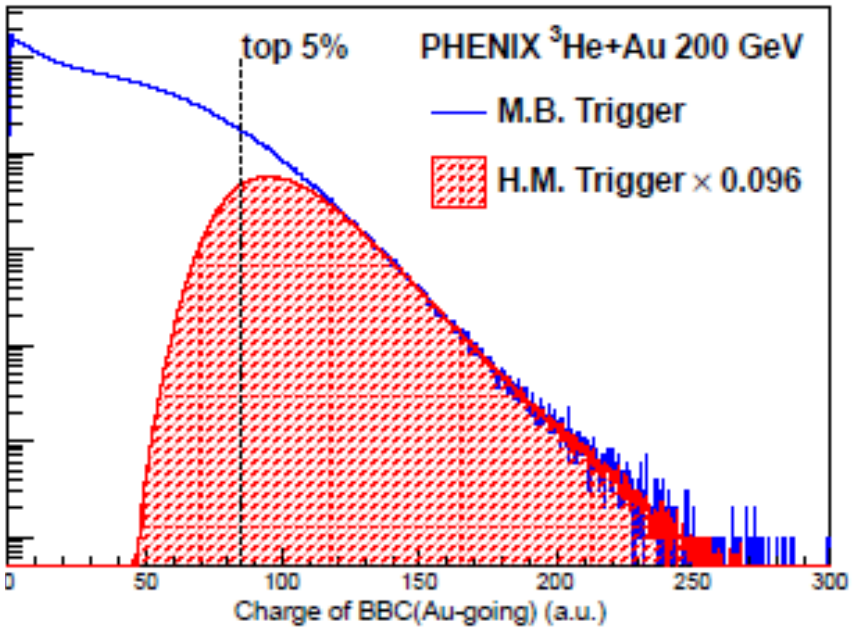
Phys. Rev. Lett. 115, 142301



More central collisions

p+Au: 3.1 billion min. bias events

1.2 billion central events



More central collisions

^{3}He+Au: 2.2 billion min. bias events

0.8 billion central events

- The trigger increase 0-5% most central events by 40 times in p+Au
- The trigger increase 0-5% most central events by 10 times in ^{3}He+Au

Analysis methods

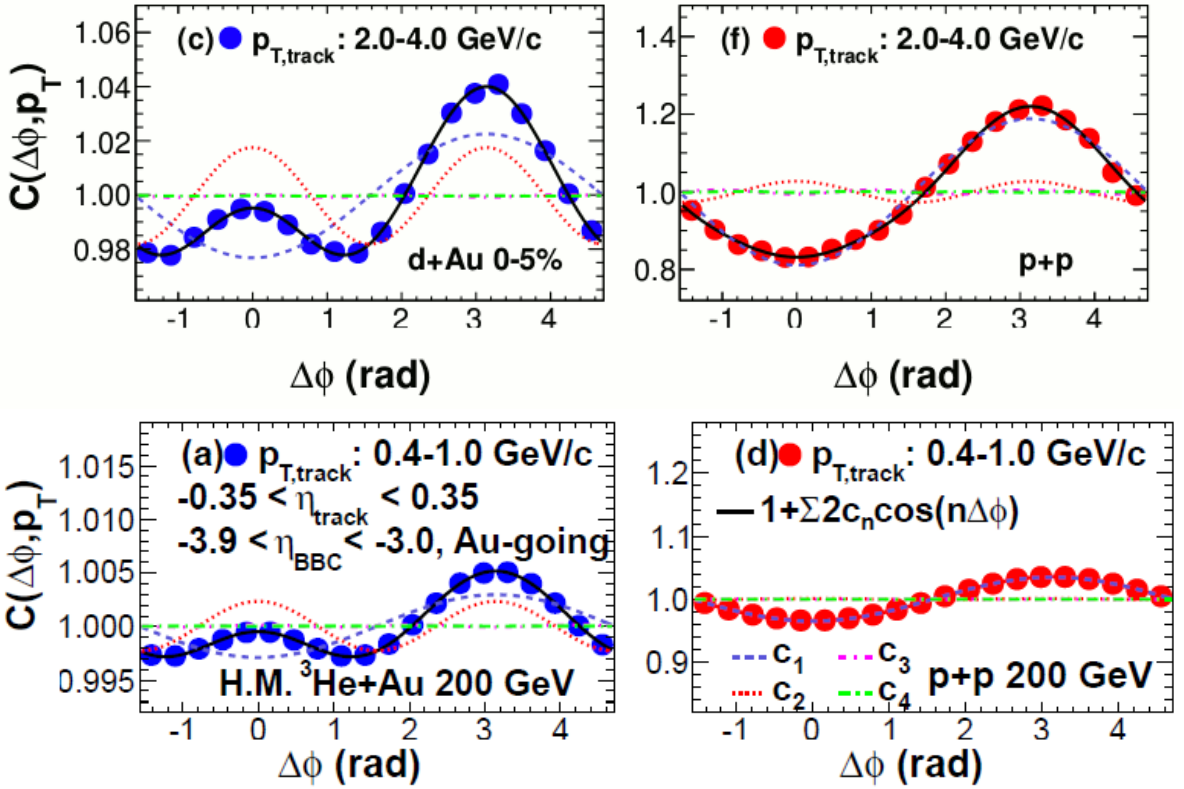
Two – particle correlation method

Pairs: $\frac{dN}{d\Delta\phi} \propto 1+\sum_n 2v_n^a v_n^b \cos(n\Delta\phi)$ **2PC method**

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

- Particles of interest: tracks in mid-rapidity($|\eta|<0.35$)
- Event plane determination:
  - Using detectors at larger pseudorapidity
  - Standard flattening and re-centering procedure applied
- Three sub-events method is used to evaluate the resolution.

Correlation function in d/^{3}He+Au



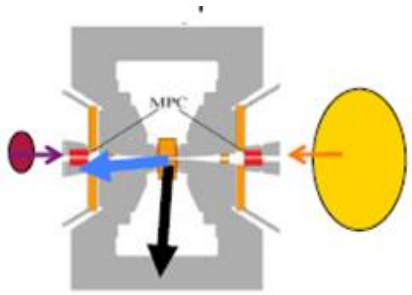
Central d+Au

Phys. Rev. Lett. 114, 192301

Both PRL highlights!

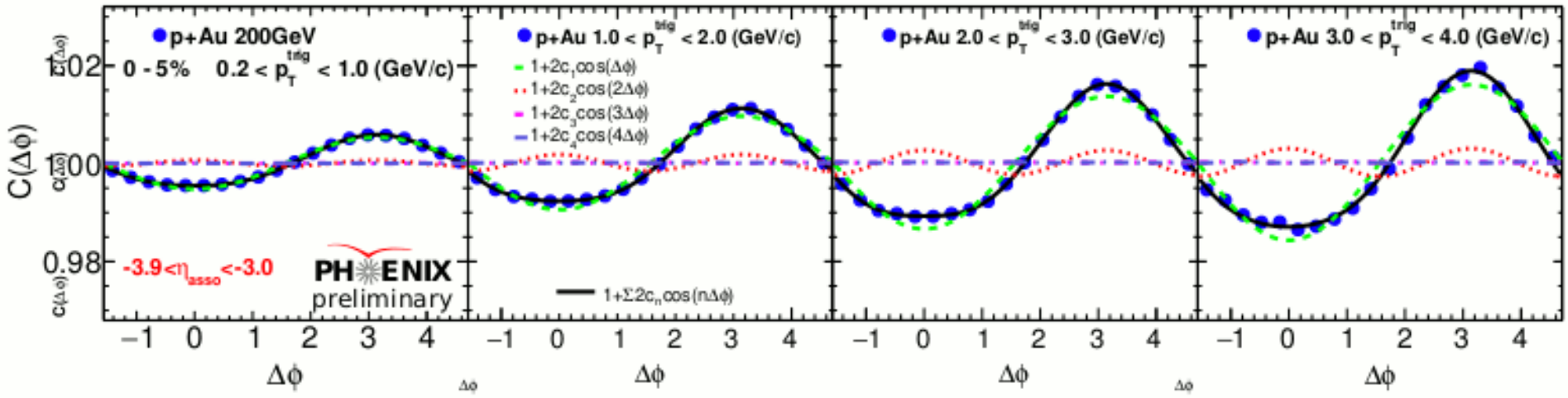
Phys. Rev. Lett. 115, 142301

Central ^{3}He+Au



- Clear near-side ridge
- Large pseudorapidity separation minimize the di-jet and resonance decay contribution
- In pp collision, dominated by momentum conservation and di-jet correlation

Correlation function in p+Au



- 2-particle correlation between mid-rapidity tracks and backward (Au-going) charge particles
- Separated by 2.75 units in pseudo-rapidity

$M(\Delta\phi, p_T)$: mixed event

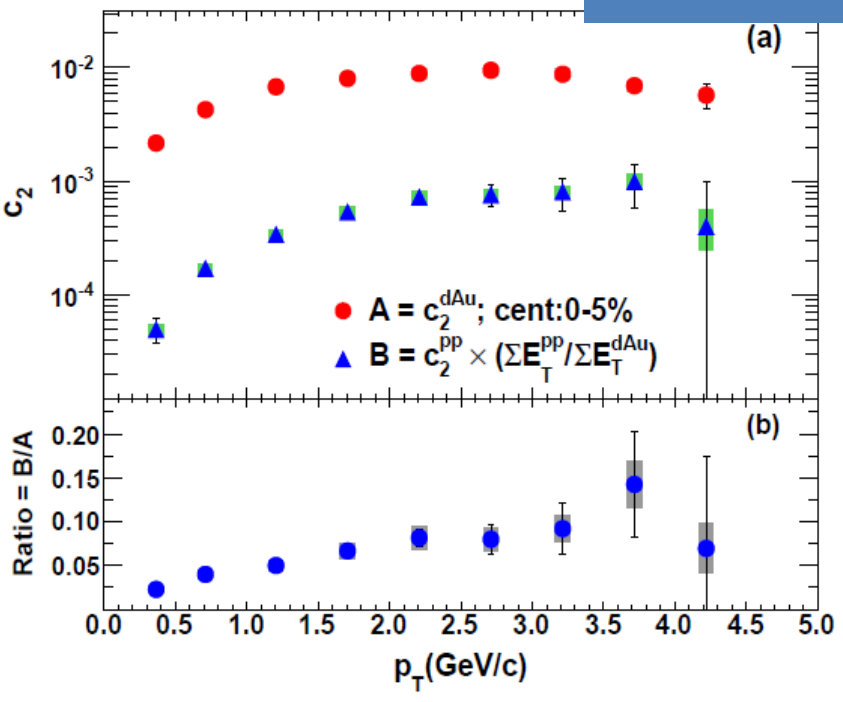
$$S(\Delta\phi, p_T) = \frac{d(w_{\mathrm{PMT}} N^{\mathrm{track}(p_T)\text{-}\mathrm{PMT}}_{\mathrm{Same\ event}})}{d\Delta\phi},$$

$$C(\Delta\phi, p_T) = \frac{S(\Delta\phi, p_T)}{M(\Delta\phi, p_T)} \frac{\int_0^{2\pi} M(\Delta\phi, p_T) d\Delta\phi}{\int_0^{2\pi} S(\Delta\phi, p_T) d\Delta\phi}$$

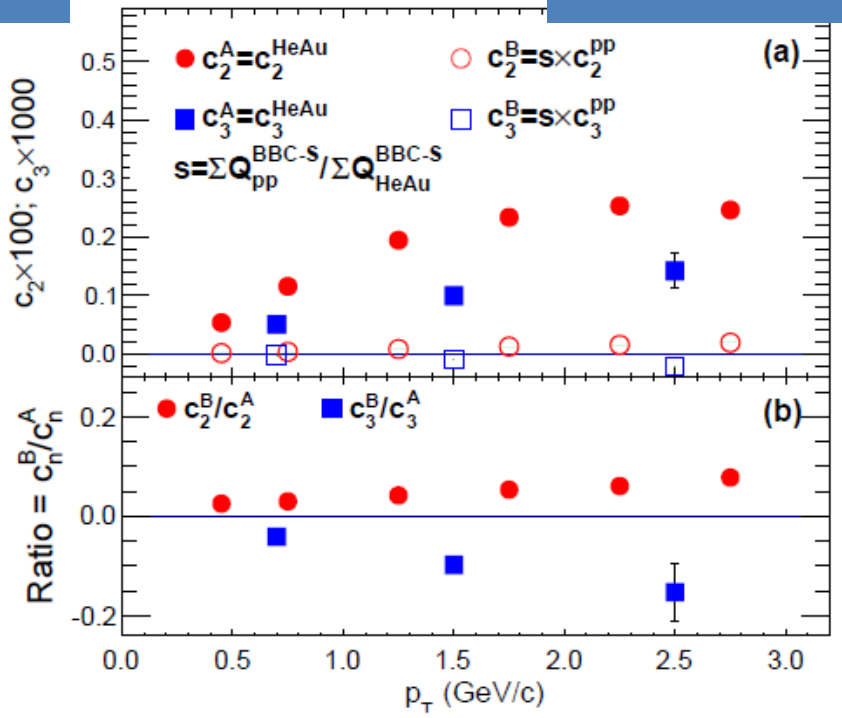
Nonflow estimation in d/^{3}He+Au

Phys. Rev. Lett. 114, 192301

Central d+Au



Central ^{3}He+Au

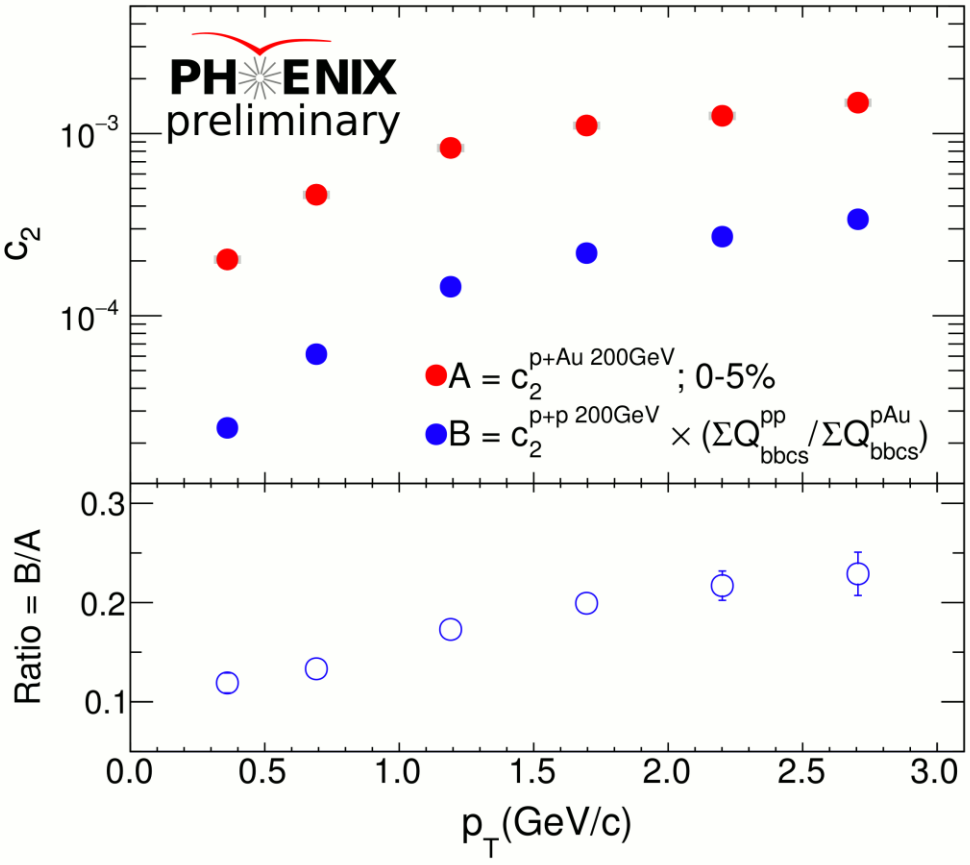


Phys. Rev. Lett. 115, 142301

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

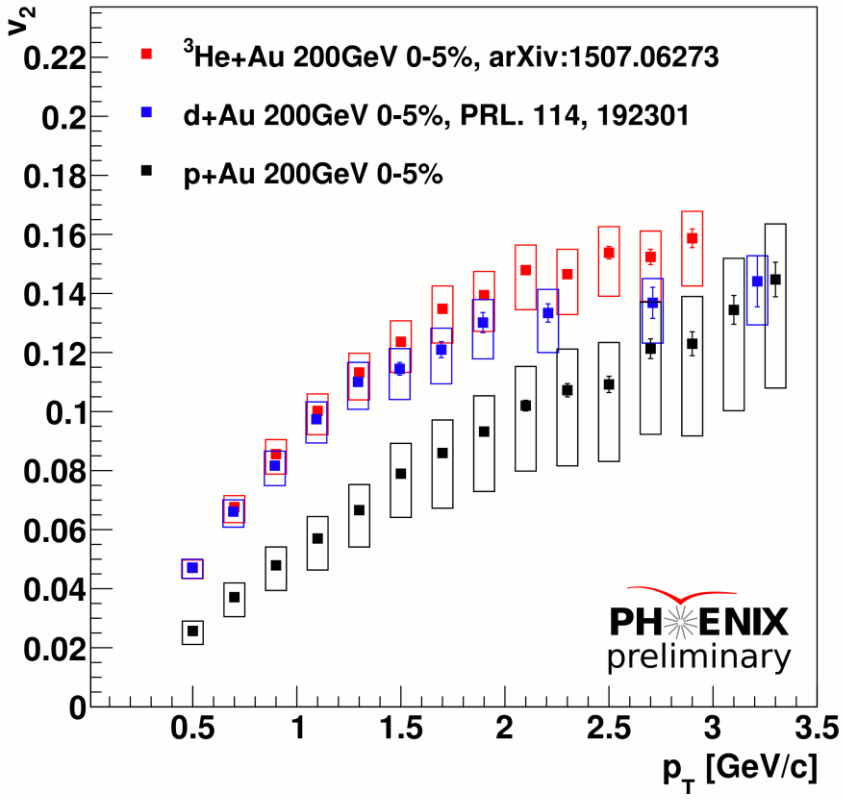
- Nonflow estimation in d/^{3}He+Au is small (<7% for v_2 , <15% for v_3)
- Cited as a systematic uncertainty

Nonflow estimation in p+Au



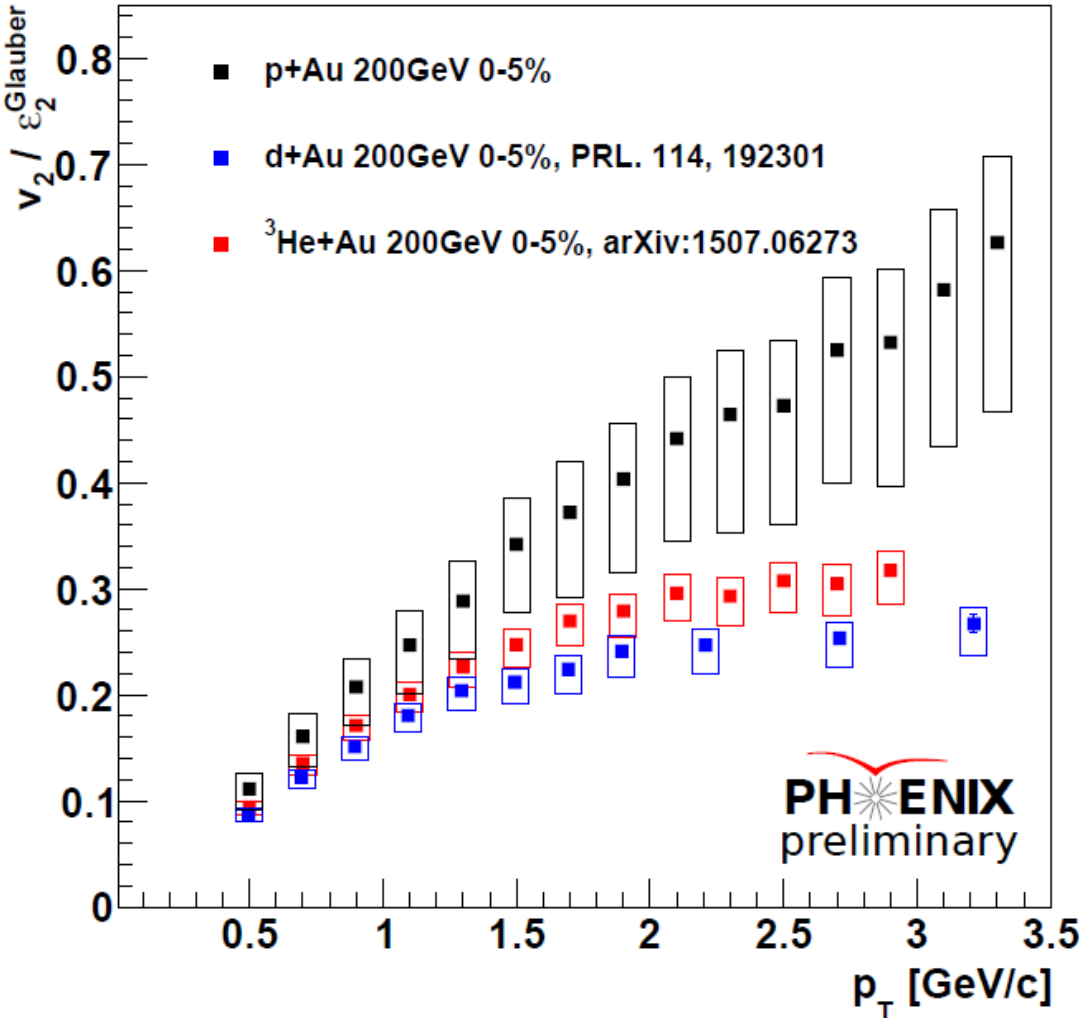
- Jet contribution (estimated from pp) rises with p_T and reaches 25%; Cited as a systematic uncertainty
- Working on evaluating different subtraction methods

Charged v_2 Comparison in three systems



- $v_2(^3\text{HeAu}) \sim v_2(\text{dAu}) > v_2(\text{pAu})$
- Geometry control works!

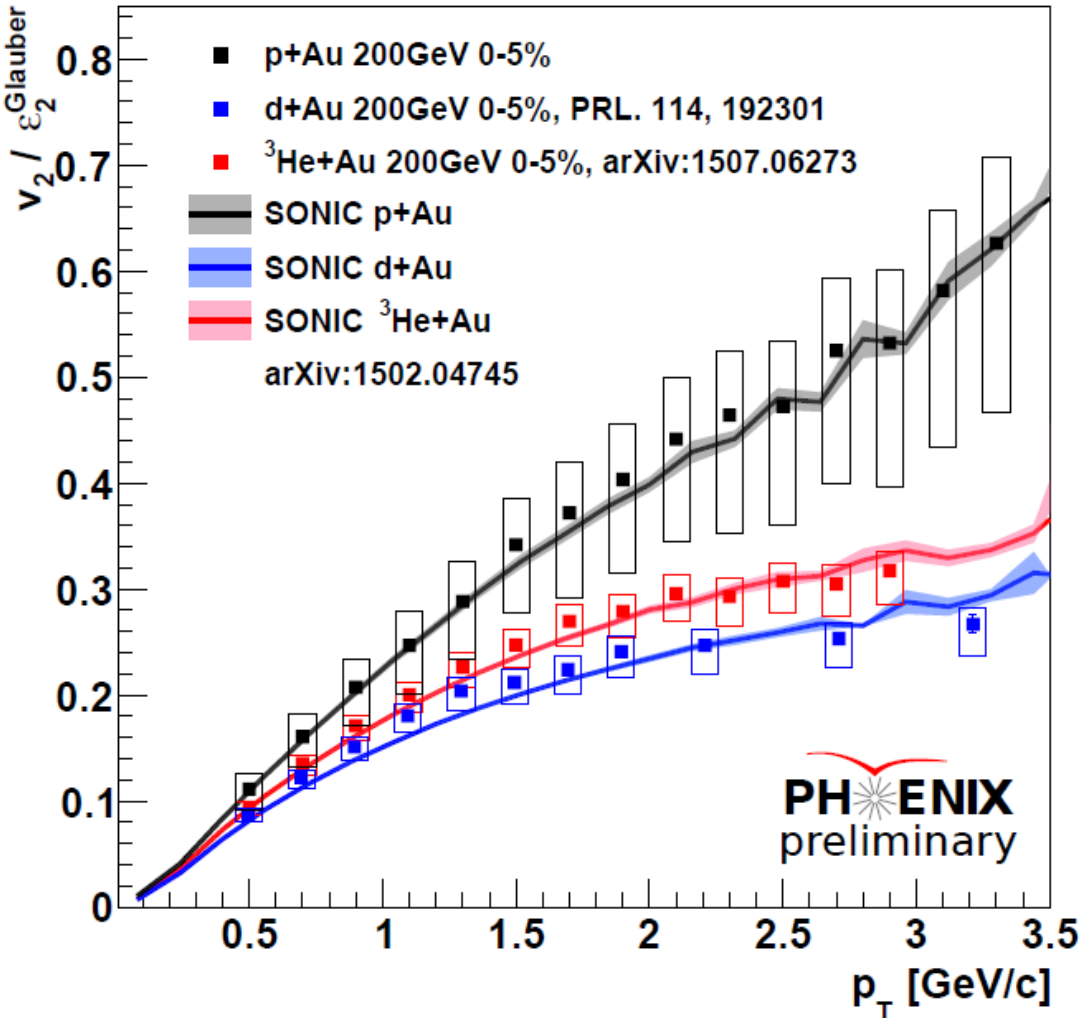
v_2/ε_2 in small collision systems



The v_2/ε_2 in p+Au is higher than that of d+Au and ^{3}He+Au collisions

May suggest substructure in proton

v_2/ε_2 in small collision systems

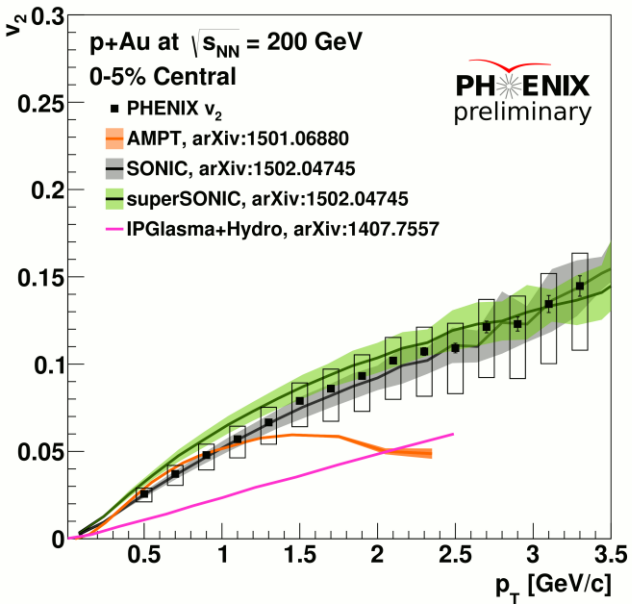


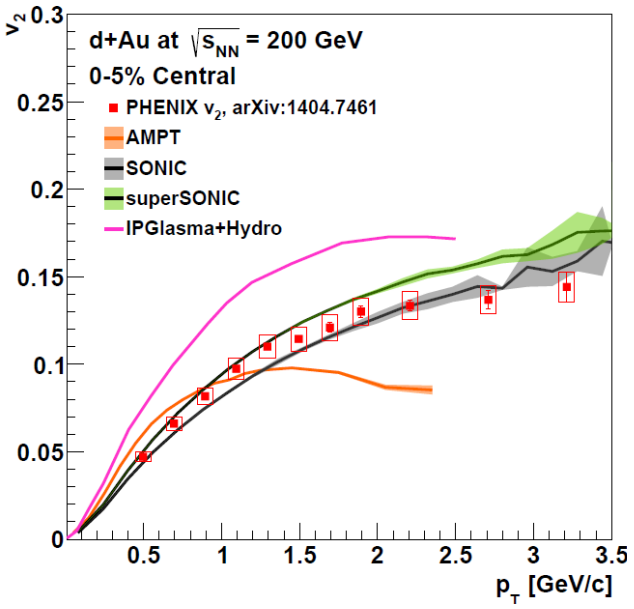
The v_2/ε_2 in p+Au is higher than that of d+Au and ^{3}He+Au collisions

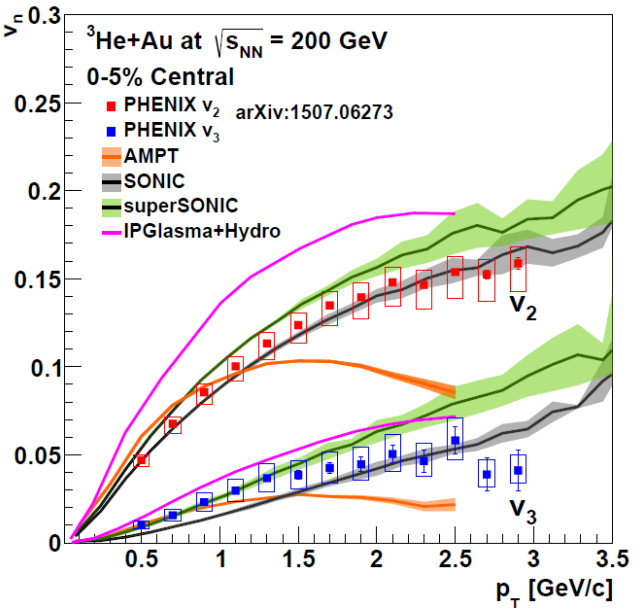
May suggest substructure in proton

This behavior is within the expectation of SONIC model, which includes Glauber initial geometry and viscous hydro evolution.

Charged v_2 and v_3 Compared to models







- Clear v_3 observed in central ^{3}He+Au events!
- SONIC model predicts the v2 values in all three systems
- AMPT model can predict the three systems up to 1.5GeV/c
- IPGlasma+Hydrodynamic model underpredict the p+Au results but overpredict the d/^{3}He+Au results

Identified particles v_2

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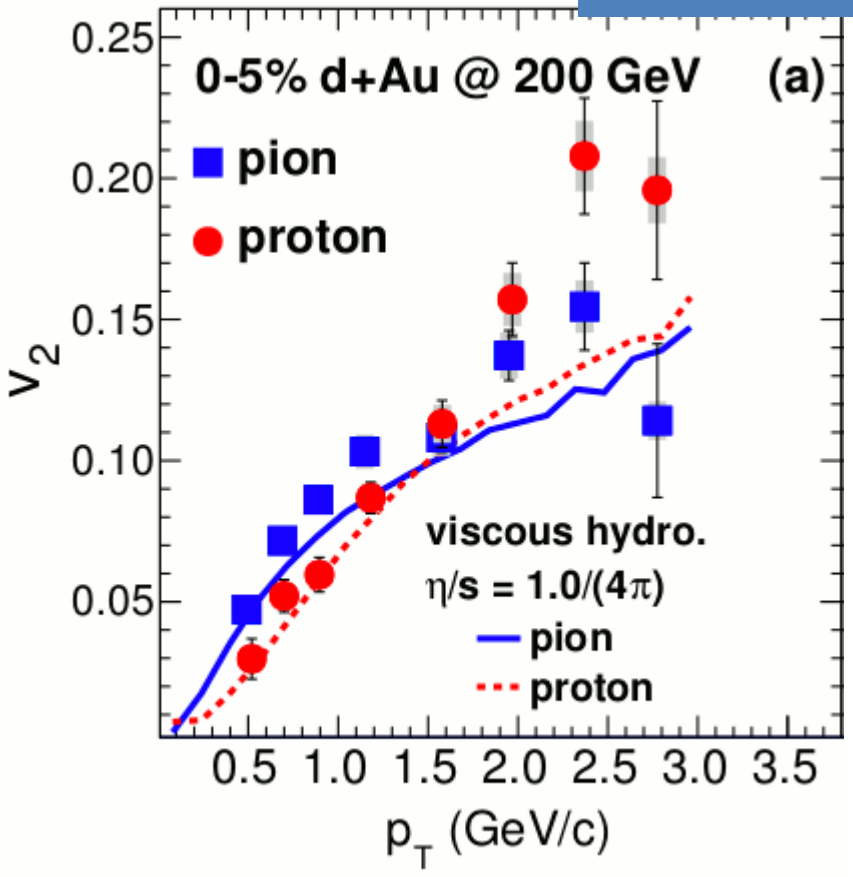
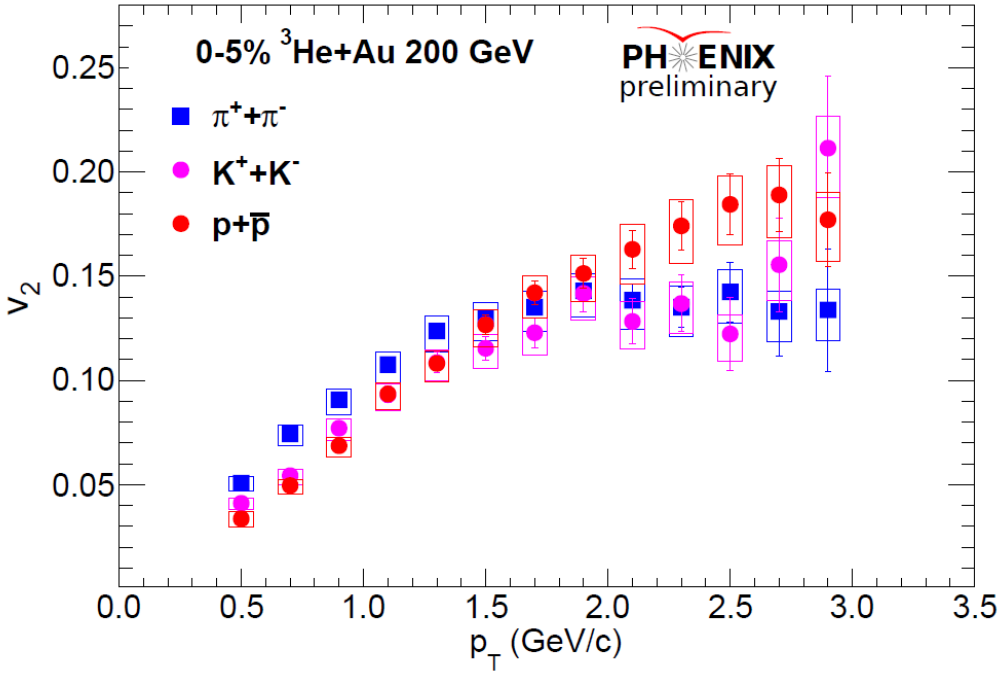
Central d+Au

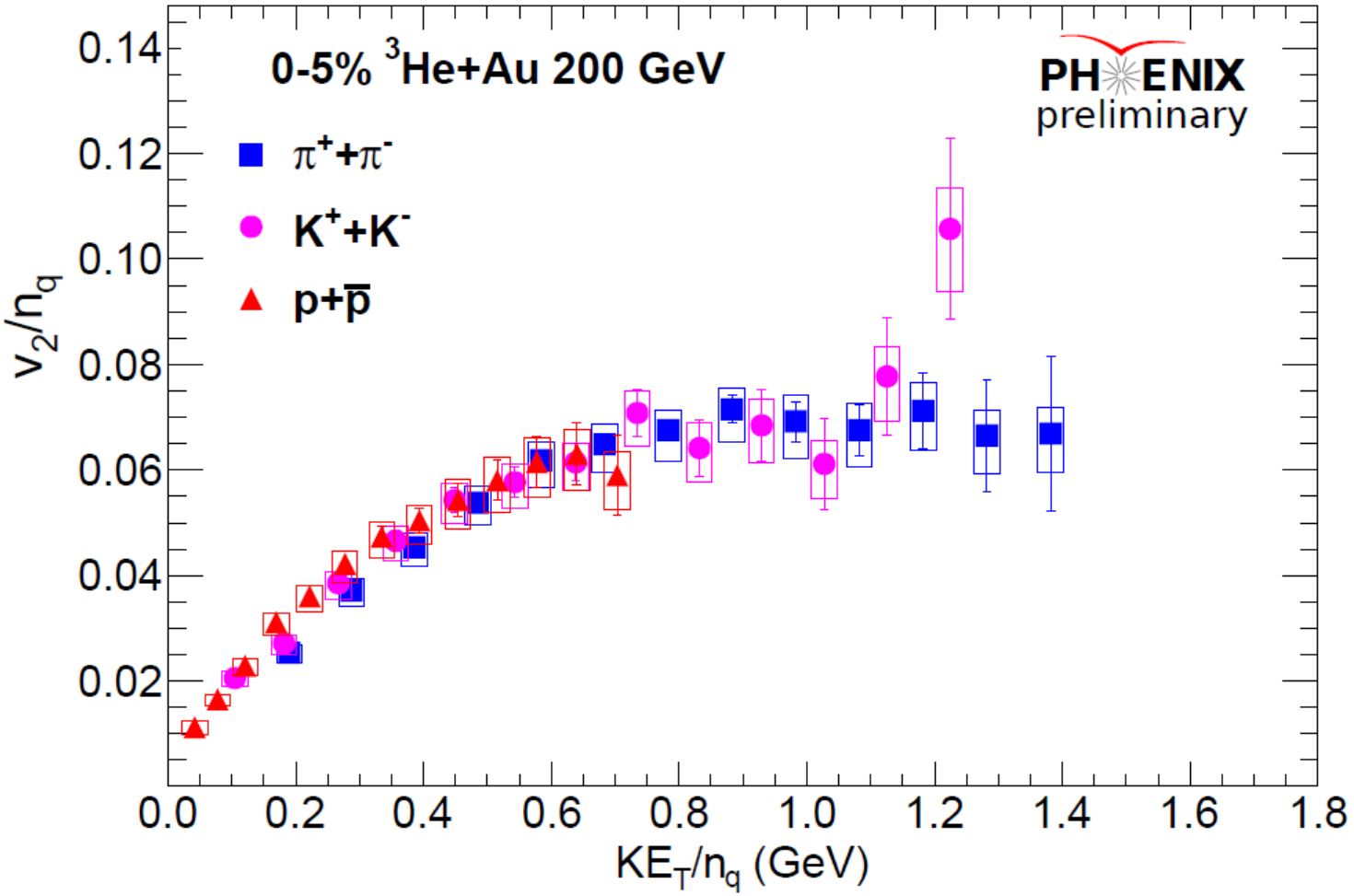


Central ^{3}He+Au



- Mass-ordering feature also observed in d/^{3}He+Au
- consistent with hydrodynamic flow (common velocity field)

Number of Quark Scaling in ^{3}He+Au

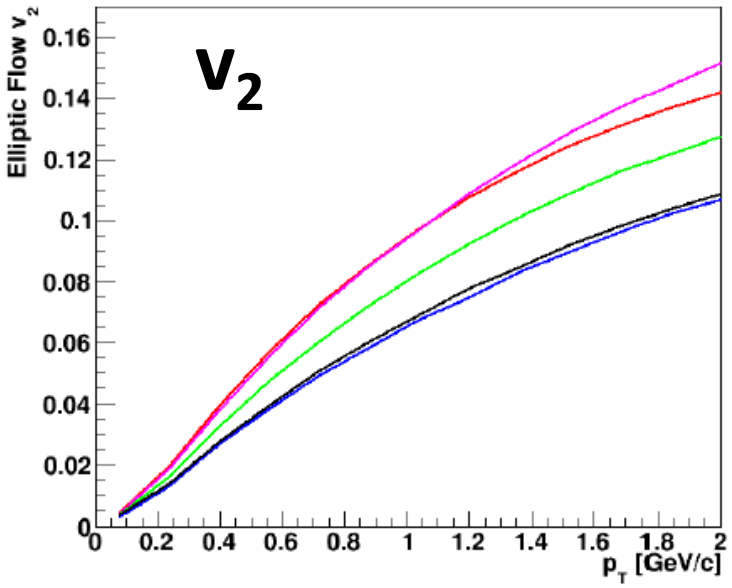


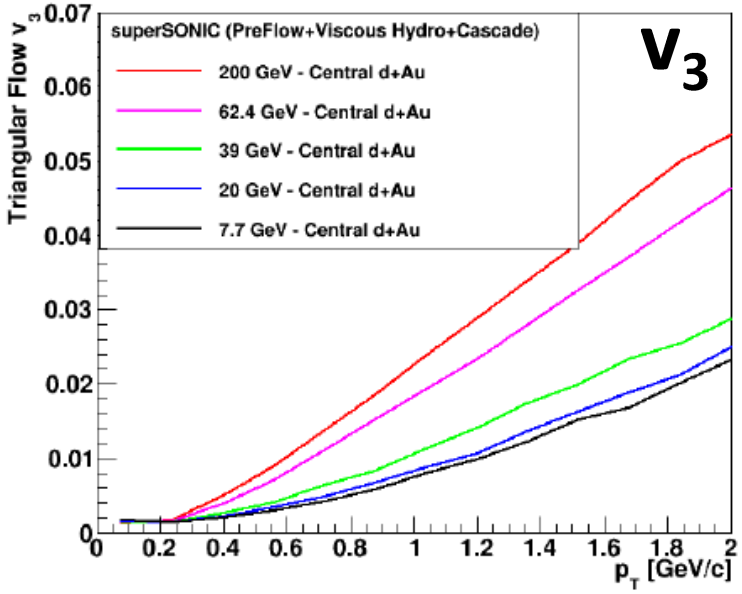
- The familiar behavior of number of quark scaling observed in Au+Au collisions is also seen in the small ^{3}He+Au system

Small systems and lower energy

- Does collective behavior persist to lower energy ?
  - "Yes", according to hydrodynamics

superSONIC predictions

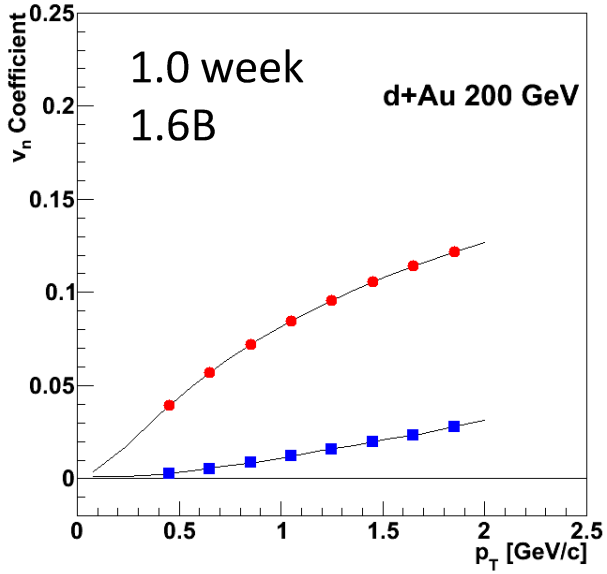


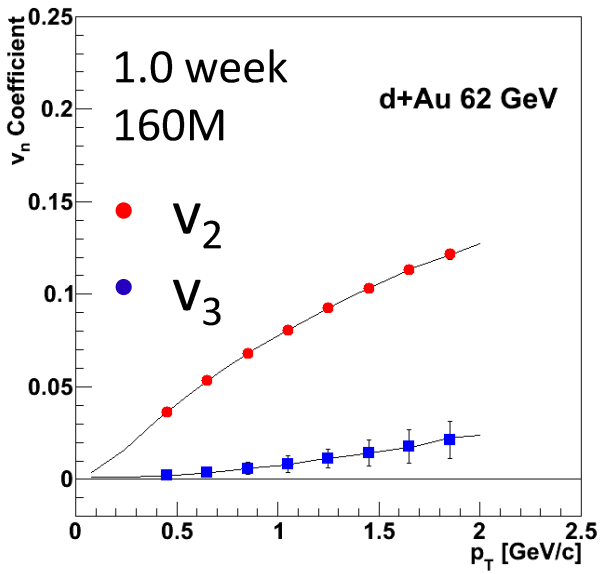


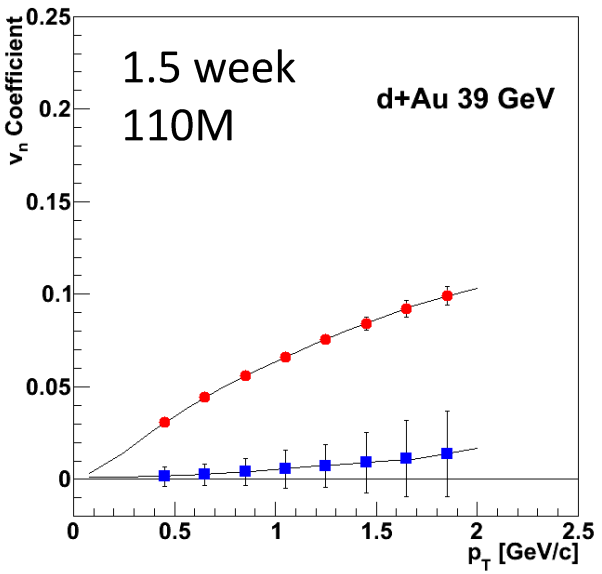
2016 RHIC d+Au energy scan!

5 weeks: 20, 39, 62, 200 GeV

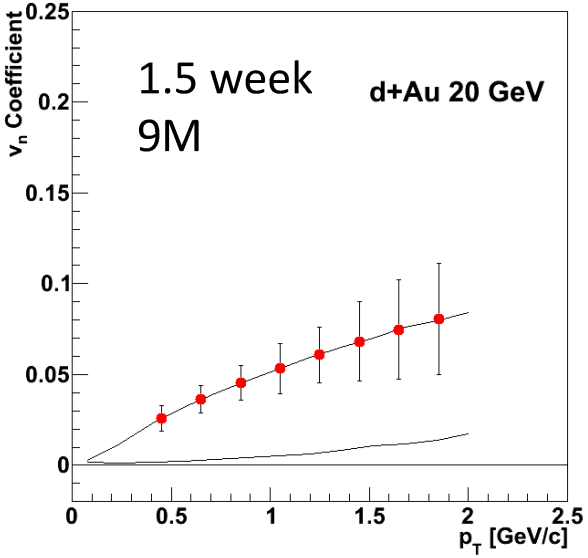
d+Au energy scan: projected uncertainties





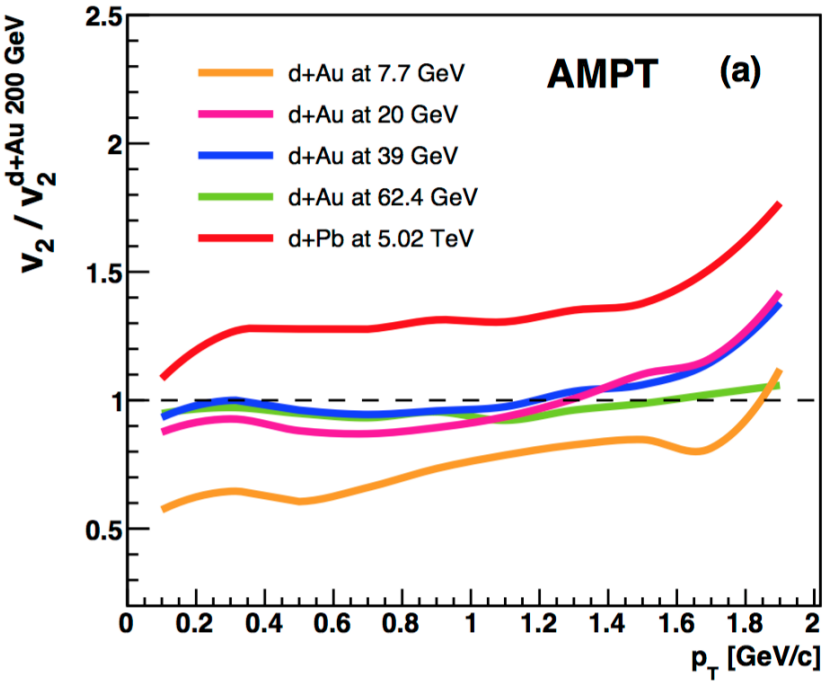


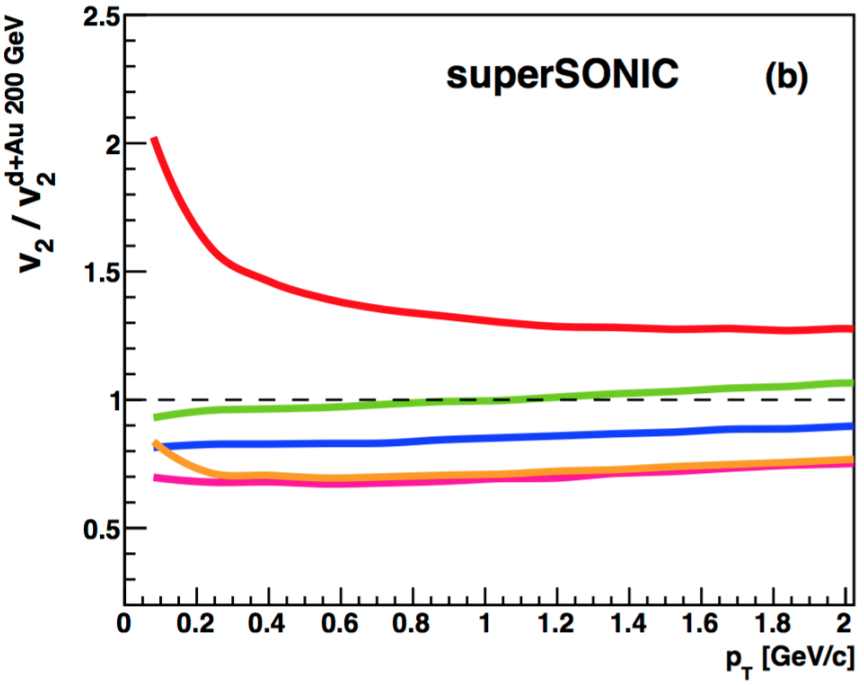
- Systematic study with the same detector in the same run: v_2 can be measured at all 4 energies
- Improved 200 GeV measurement with FVTX event plane (not available in 2008)
- v_3 may be accessible for the first time in d+Au
- Detailed test for hydro predictions



Can we discriminate between models?

arXiv:1512.06949





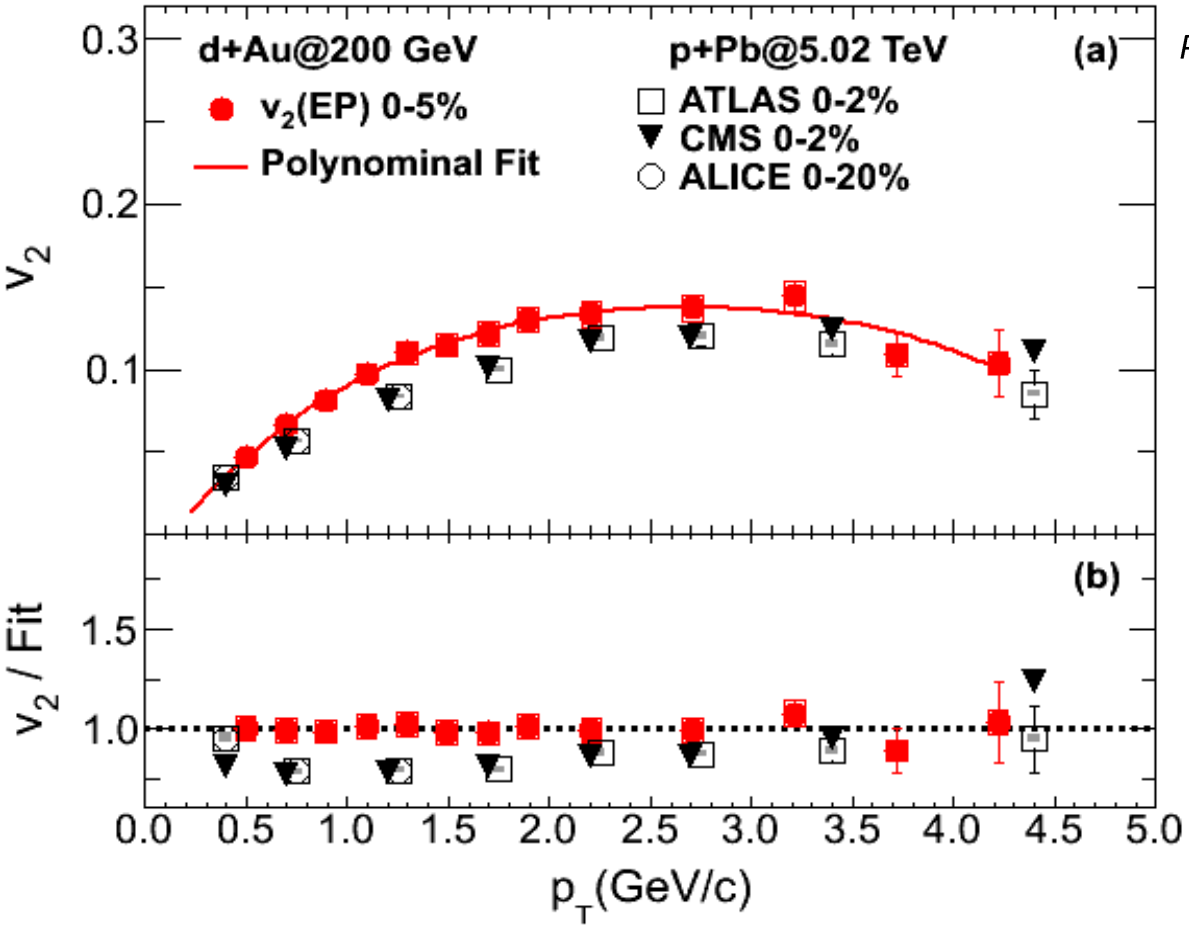
- AMPT has little energy dependence in the BES range
- superSONIC has energy dependence that we can test

Summary and Conclusions

- Ridge is seen in p/d/ ^{3}He+Au collisions
- Sizable v_2 is seen in p+Au, smaller than d/ ^{3}He+Au
- Sizable v_3 is seen in ^{3}He+Au
- Glauber + Hydrodynamics reproduces v_2
- Eccentricity scaling understood
- Quark number scaling works well
- Run16 – stay tuned!

Back Up

Charged particles: RHIC dAu and LHC pPb



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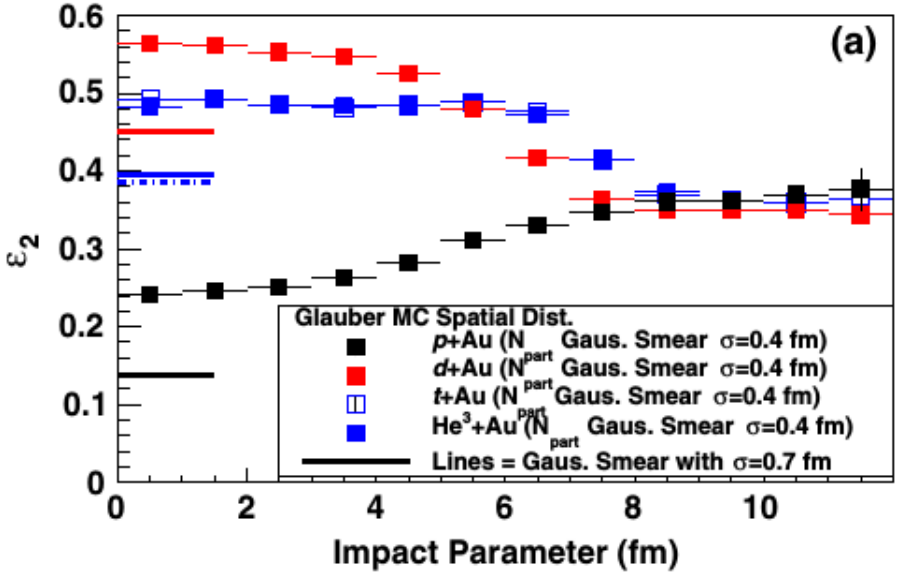
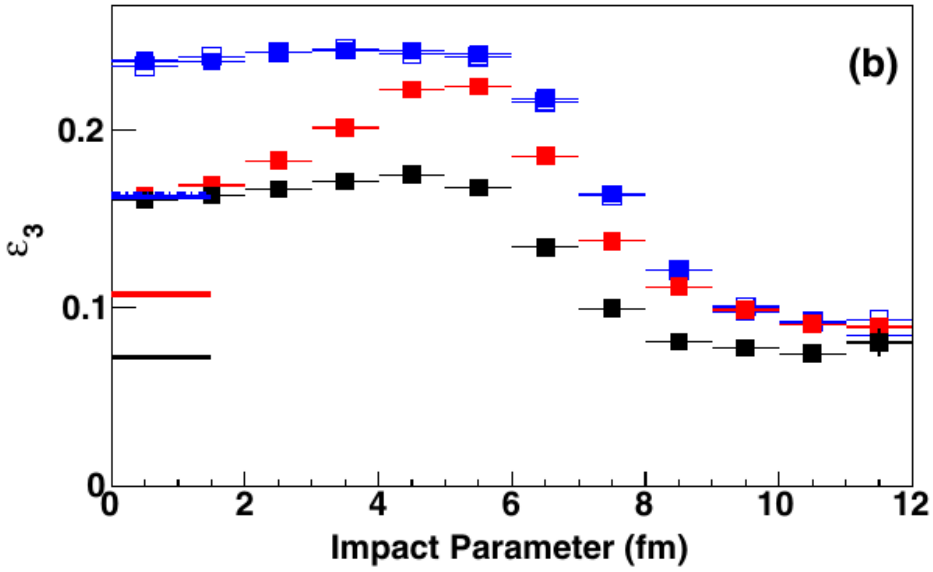
- PHENIX dAu and LHC pPb results - similar v_2

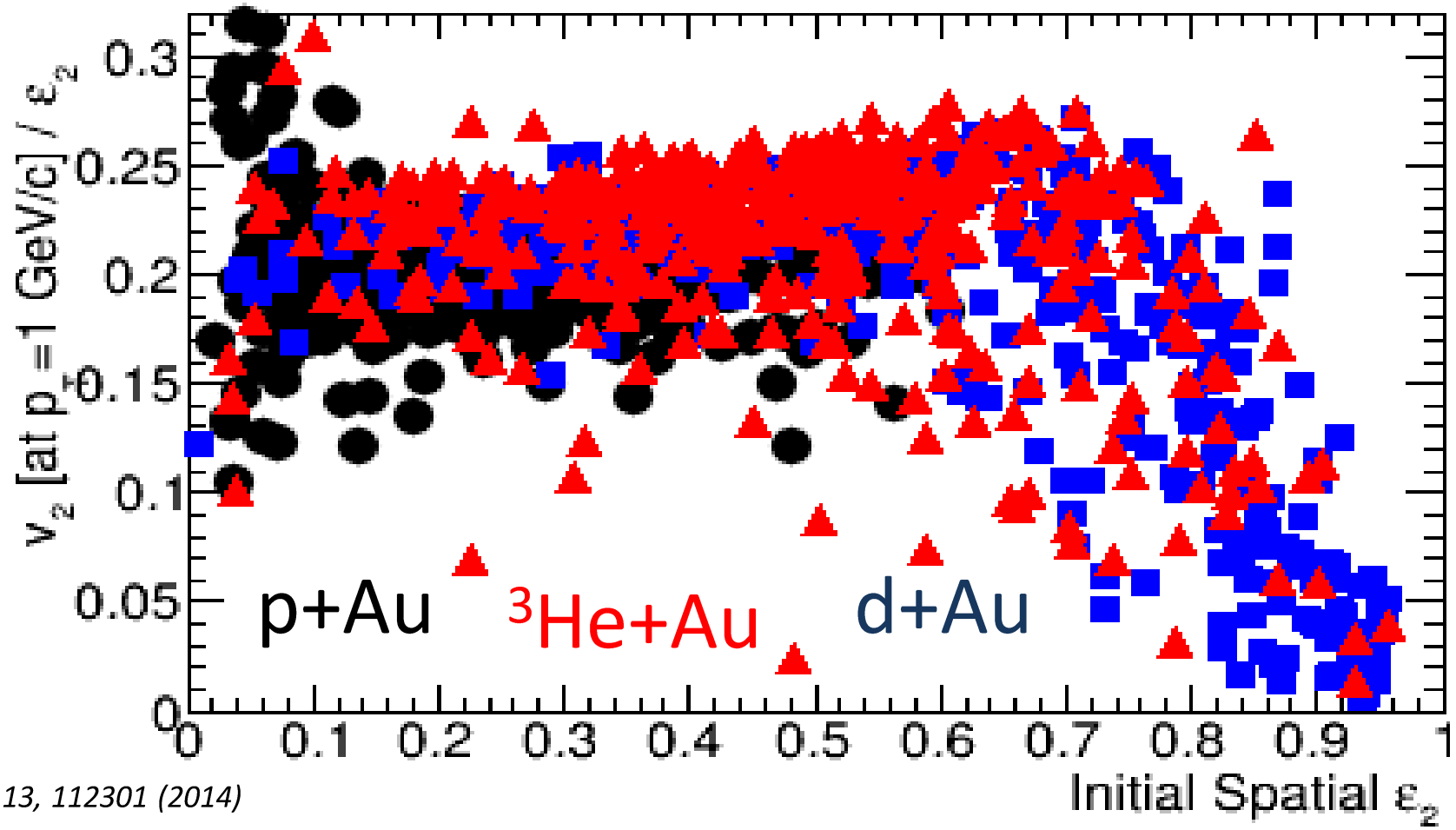
Initial eccentricity in Glauber models



PRL 113, 112301 (2014)



Eccentricity Scaling



PRL 113, 112301 (2014)

^{3}He/d+Au – some events hot spots never connect and so $\varepsilon_2 \rightarrow v_2$ translation incomplete