PHENIX results on collective behavior in small systems from geometry-controlled experiments at $\sqrt{s_{NN}} = 200$ GeV

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for the PHENIX Collaboration

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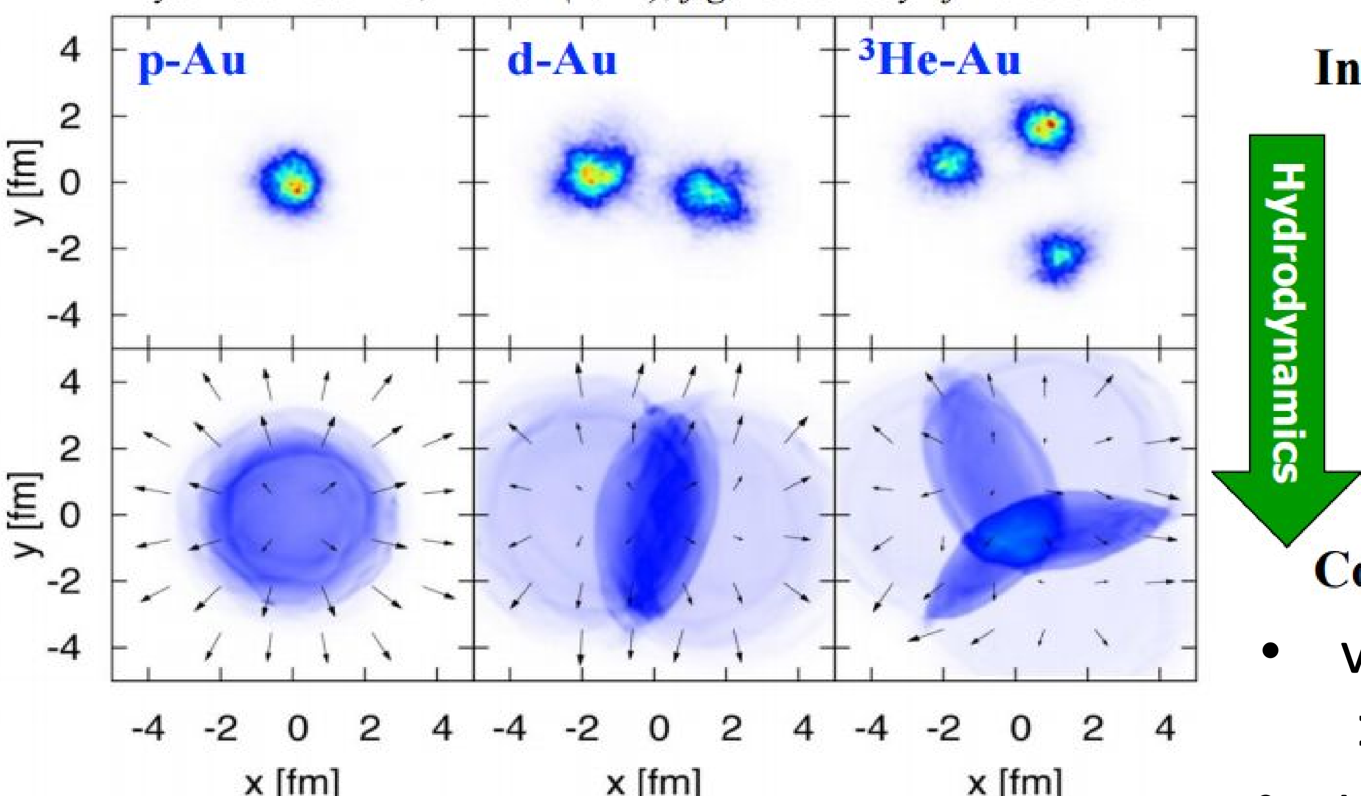
Motivation

- **Does initial geometry play a role?**

RHIC geometry control experiments:change projectile/target

Run15 Run16/Run8 Run14

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



Initial State Hot Spots

Collectivity in Final State

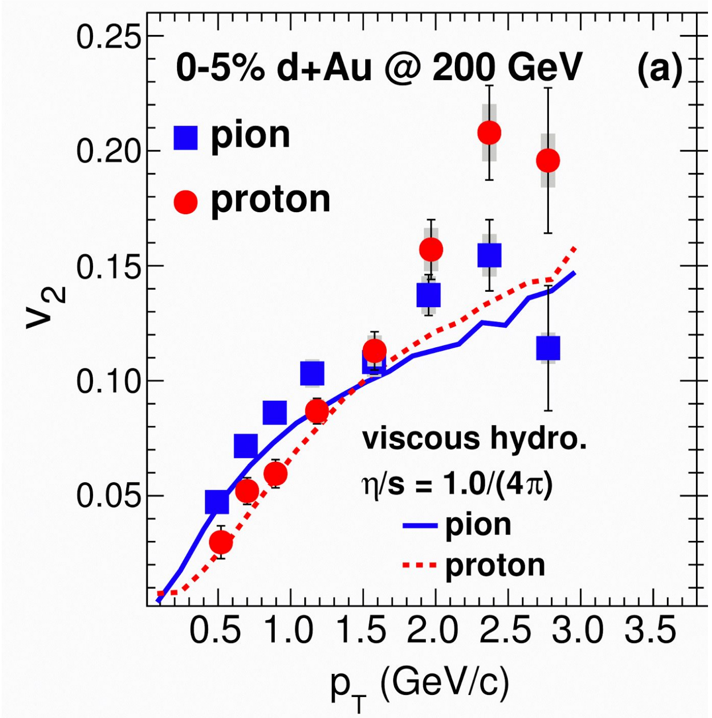
- $v_2(^3HeAu) \sim v_2(dAu) > v_2(pAu) \sim v_2(pAl)$
- $v_3(^3HeAu) > v_3(dAu)$

2^{nd} order harmonics 2^{nd} and 3^{rd} order harmonics 2^{nd} and 3^{rd} order harmonics

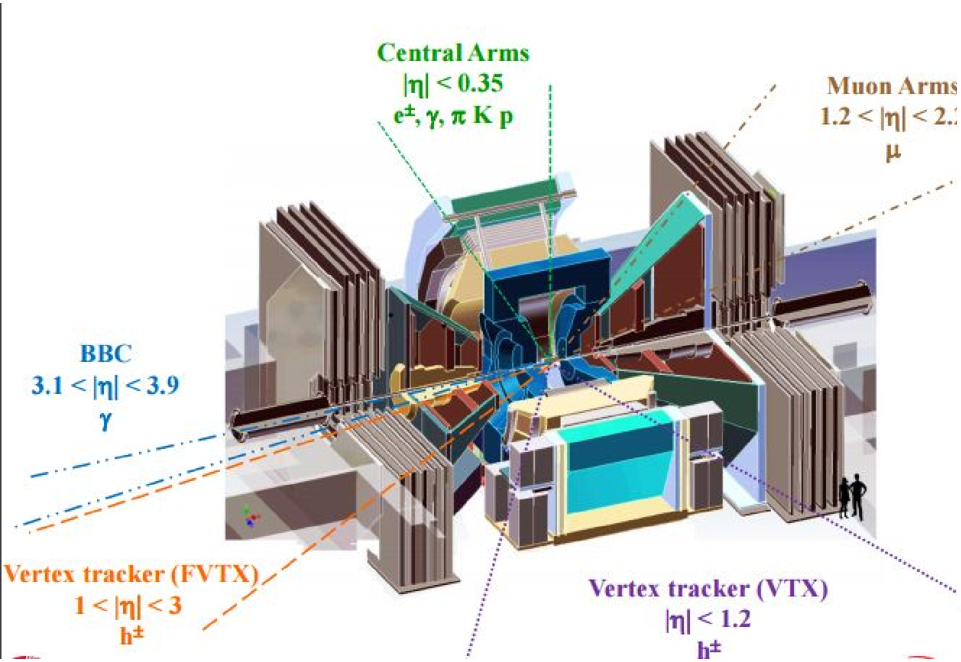
Motivation & Outline

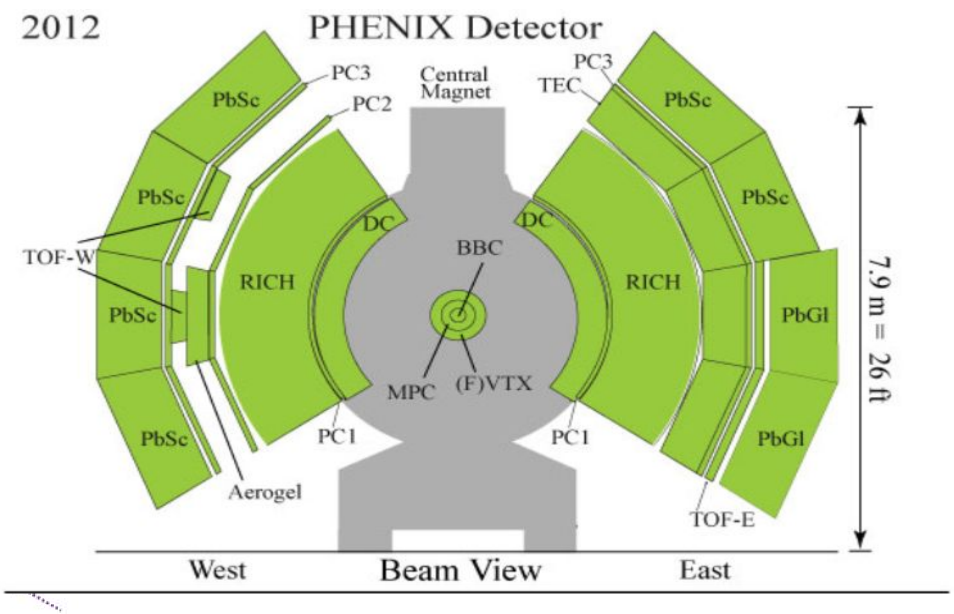
Hydrodynamics predicts:

- initial state eccentricity -> final state azimuthal correlation
  - Correlation functions in p+Al, p/d/^{3}He+Au
  - v_2 in p+Al, p/d/^{3}He+Au
  - v_3 in d/^{3}He+Au
- common flow velocity
  - d+Au identified particle flow result shows mass ordering
  - identified particle flow in p/^{3}He+Au



Small system measurements in PHENIX



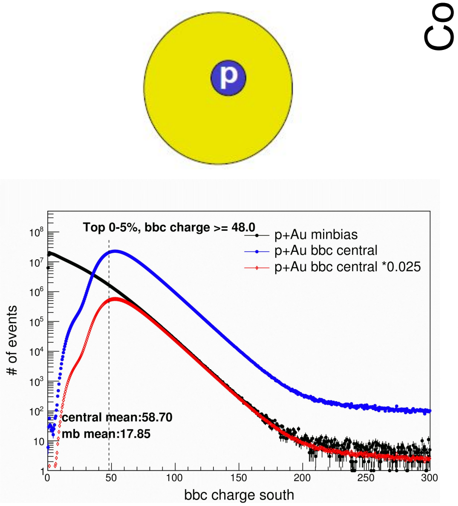


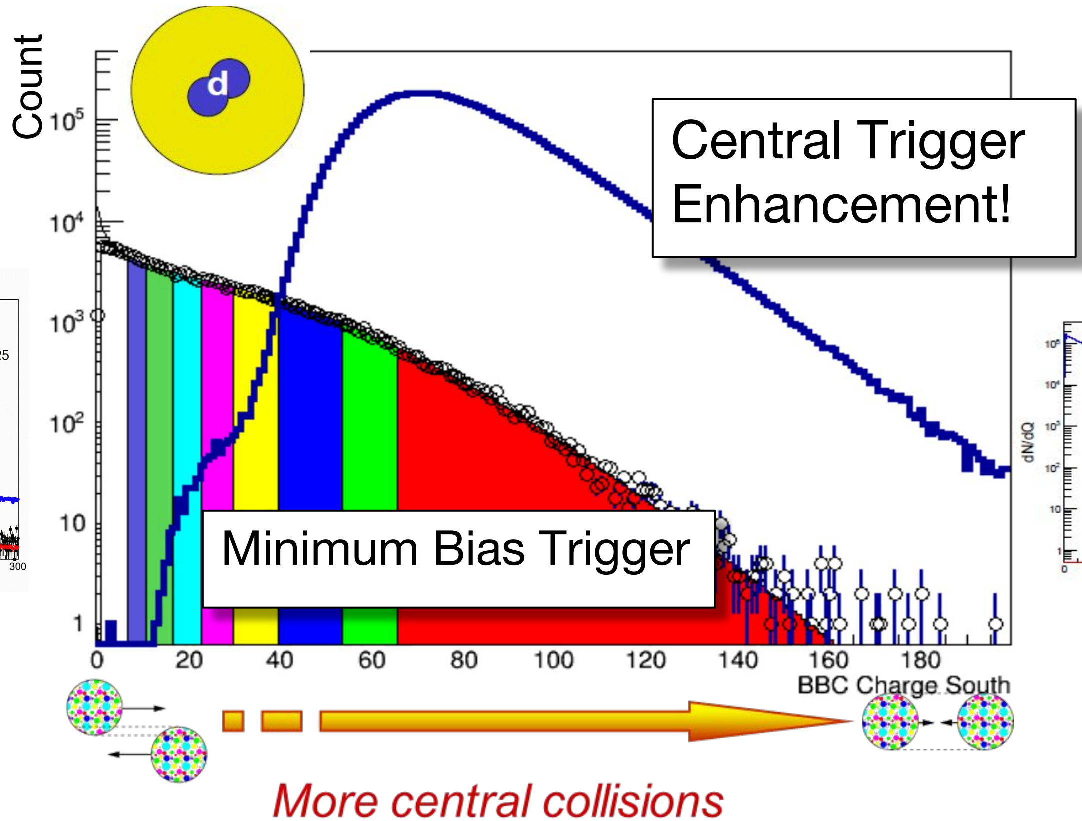
- The RHIC extraordinary collection of heavy ion collisions:
  - p+Al, p+Au, d+Au, ^{3}He+Au, Cu+Au, Cu+Cu, Au+Au, U+U
- **Geometry engineering at RHIC !**
- Midrapidity: DC, PC, TOF -> tracking and PID
- Forward: BBC, MPC, FVTX -> triggering, event selection, correlations with midrapidity particles,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

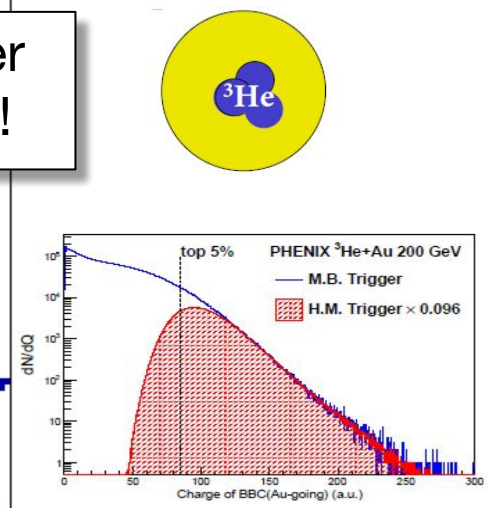
High-multiplicity triggering

- **High-multiplicity trigger in Beam Beam Counter**

Phys. Rev. Lett. 115, 142301 (2015)







- The trigger increases 0-5% most central events by 40 times in p+Au
  - by 15 times in d+Au
  - by 10 times in ^{3}He+Au

Analysis methods

Two – particle correlation method

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

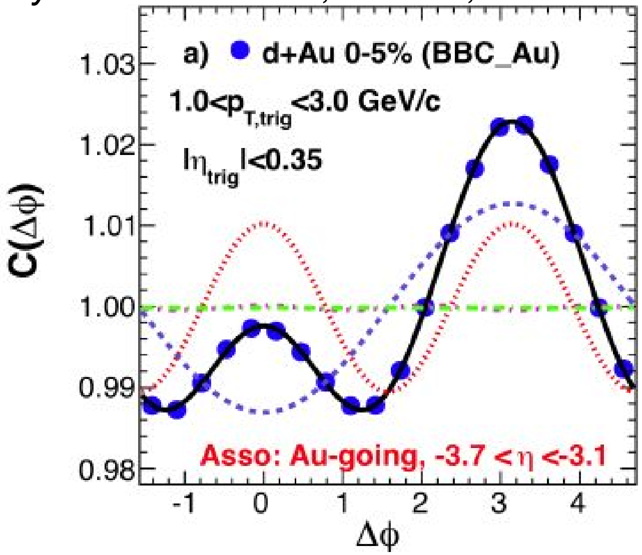
Event plane method: $$dN/d\phi = 1+\sum_n 2v_n \cos(n(\phi-\Psi_n))$$

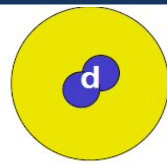
- Particles of interest: tracks in mid-rapidity(|η|<0.35)
- Event plane determination:
  - Using detectors at larger pseudorapidity
  - Standard flattening and re-centering procedure applied
- Three sub-events method is used to evaluate the resolution.

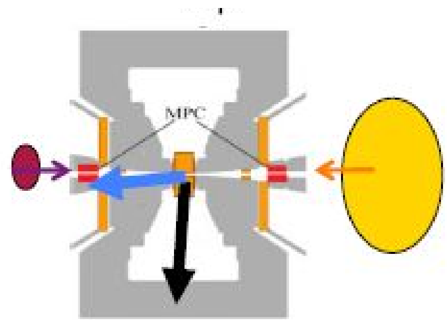
Inclusive Hadrons

Correlation function in small systems

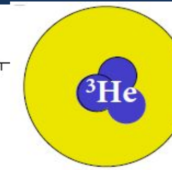
Phys. Rev. Lett. 114, 192301, 2015

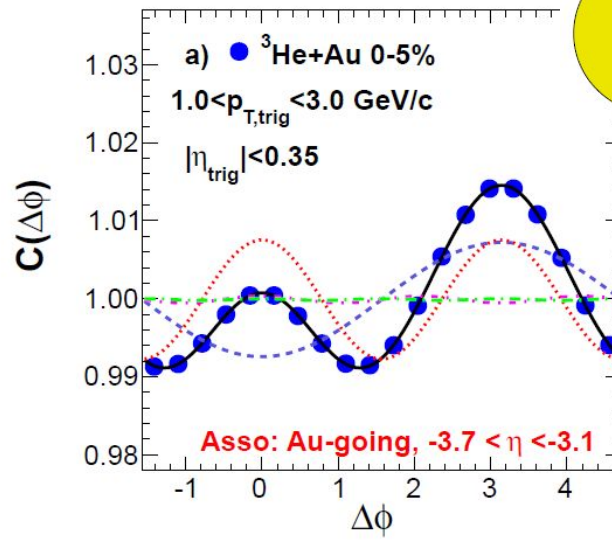


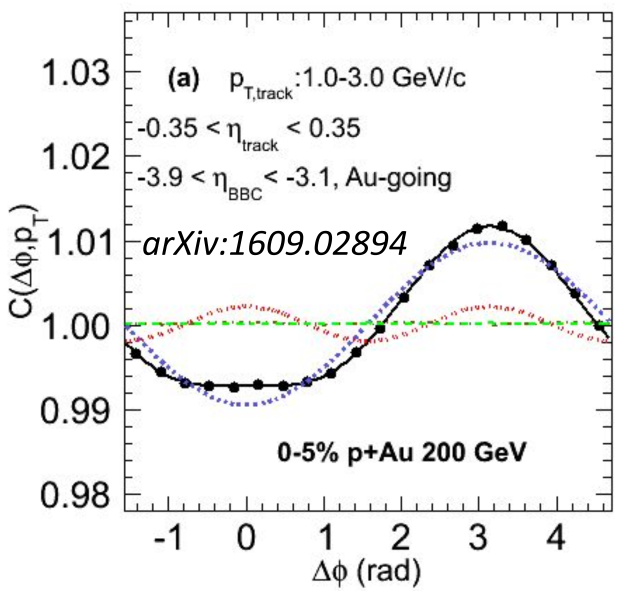


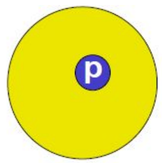


Phys. Rev. Lett. 115, 142301 , 2015

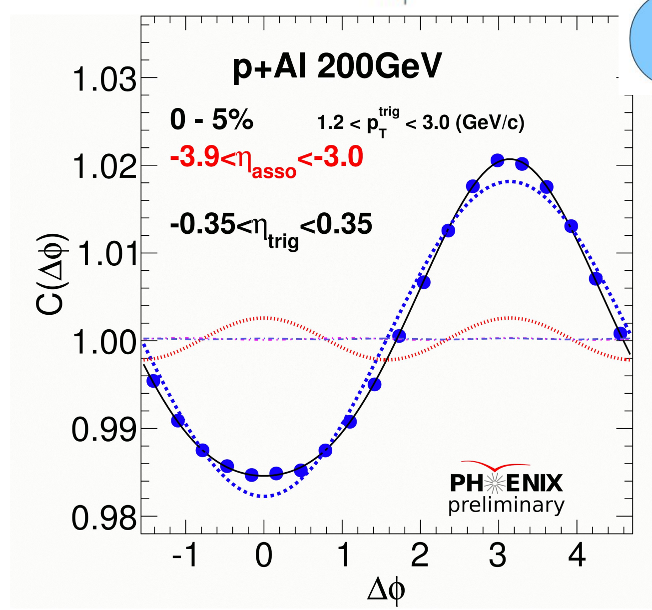








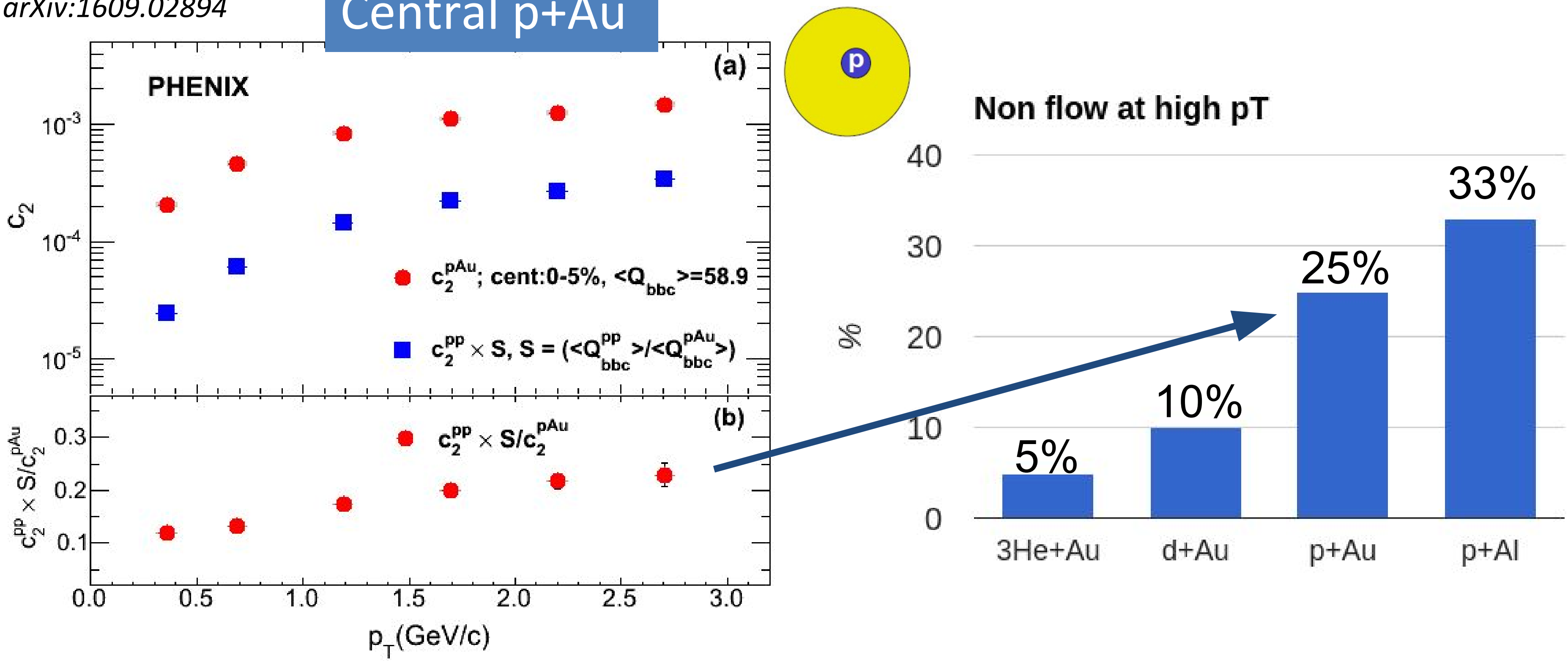
$|\Delta\eta|>2.75$



Nonflow estimation in small systems

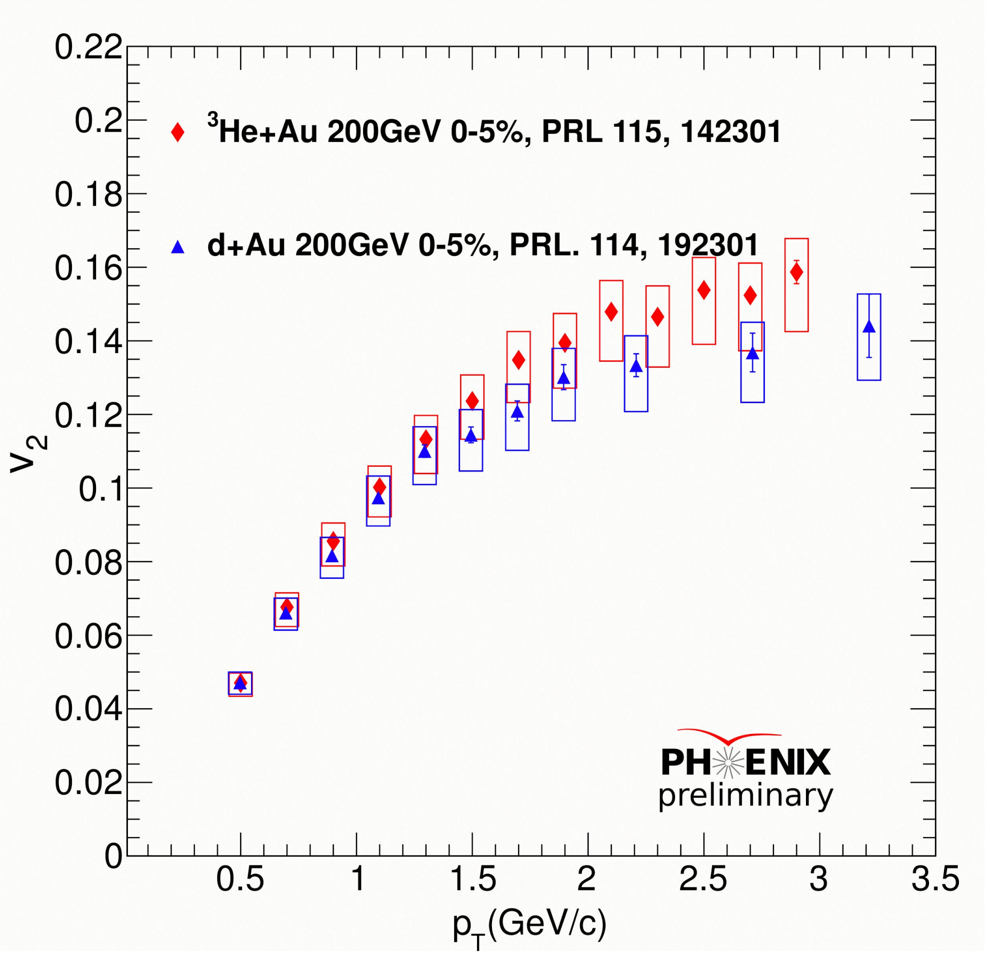
arXiv:1609.02894

Central p+Au



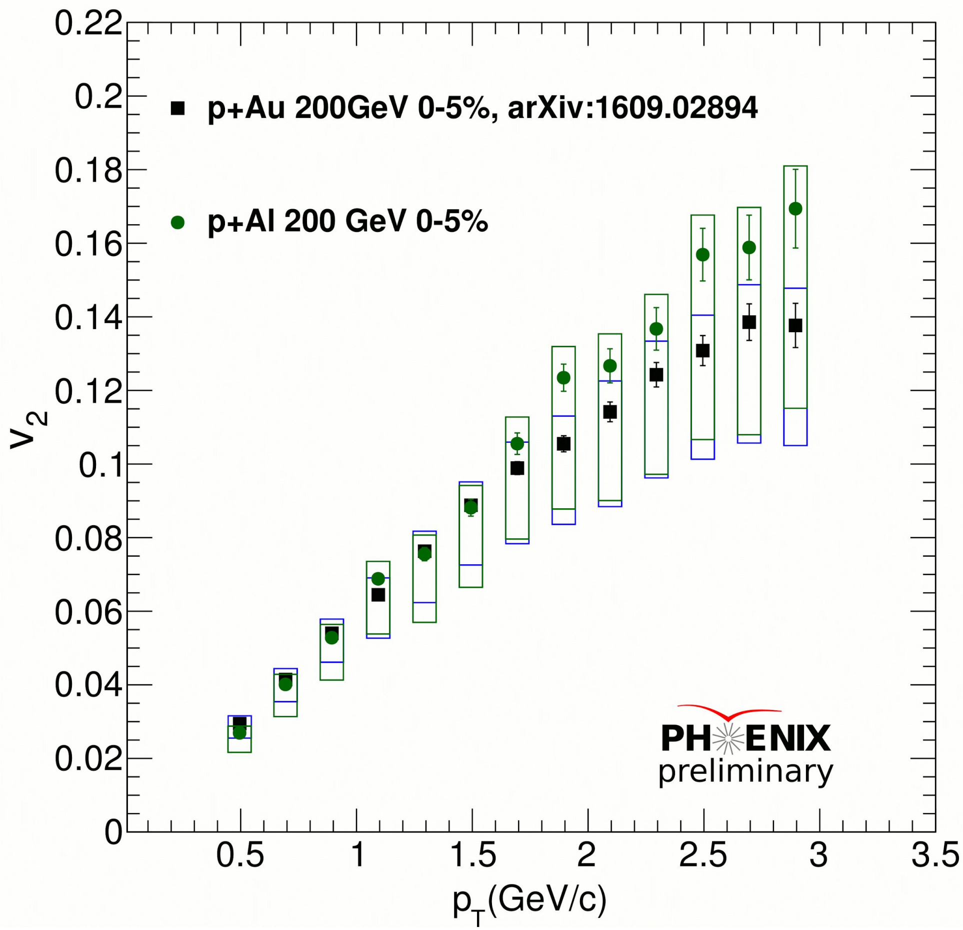
- Nonflow contribution is estimated by p+p minbias data scaled by its multiplicity
- Cited as a systematic uncertainty instead of being subtracted

Charged v_2 Comparison between systems



- $v_2(^3\text{HeAu}) \sim v_2(\text{dAu})$
- $\varepsilon_2(^3\text{HeAu}) = 0.50$, $\varepsilon_2(\text{dAu}) = 0.54$

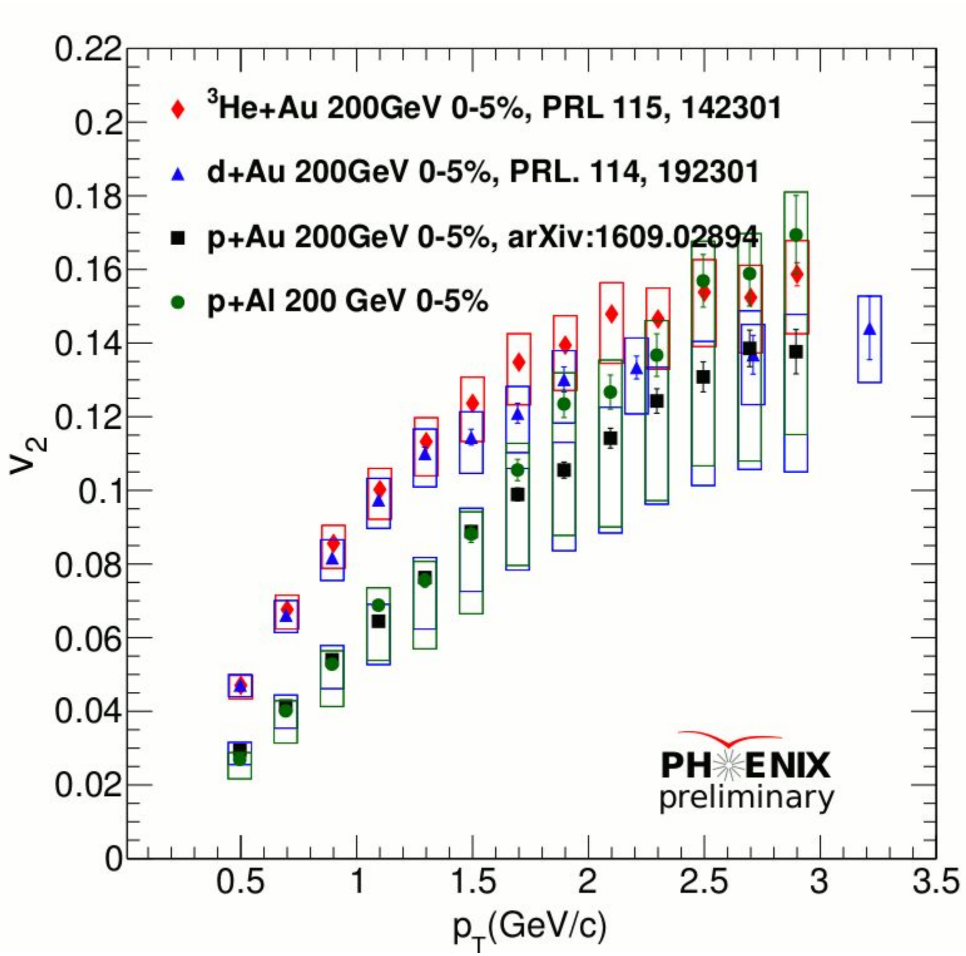
Charged v_2 Comparison between systems



Asymmetry systematics comes from nonflow effect

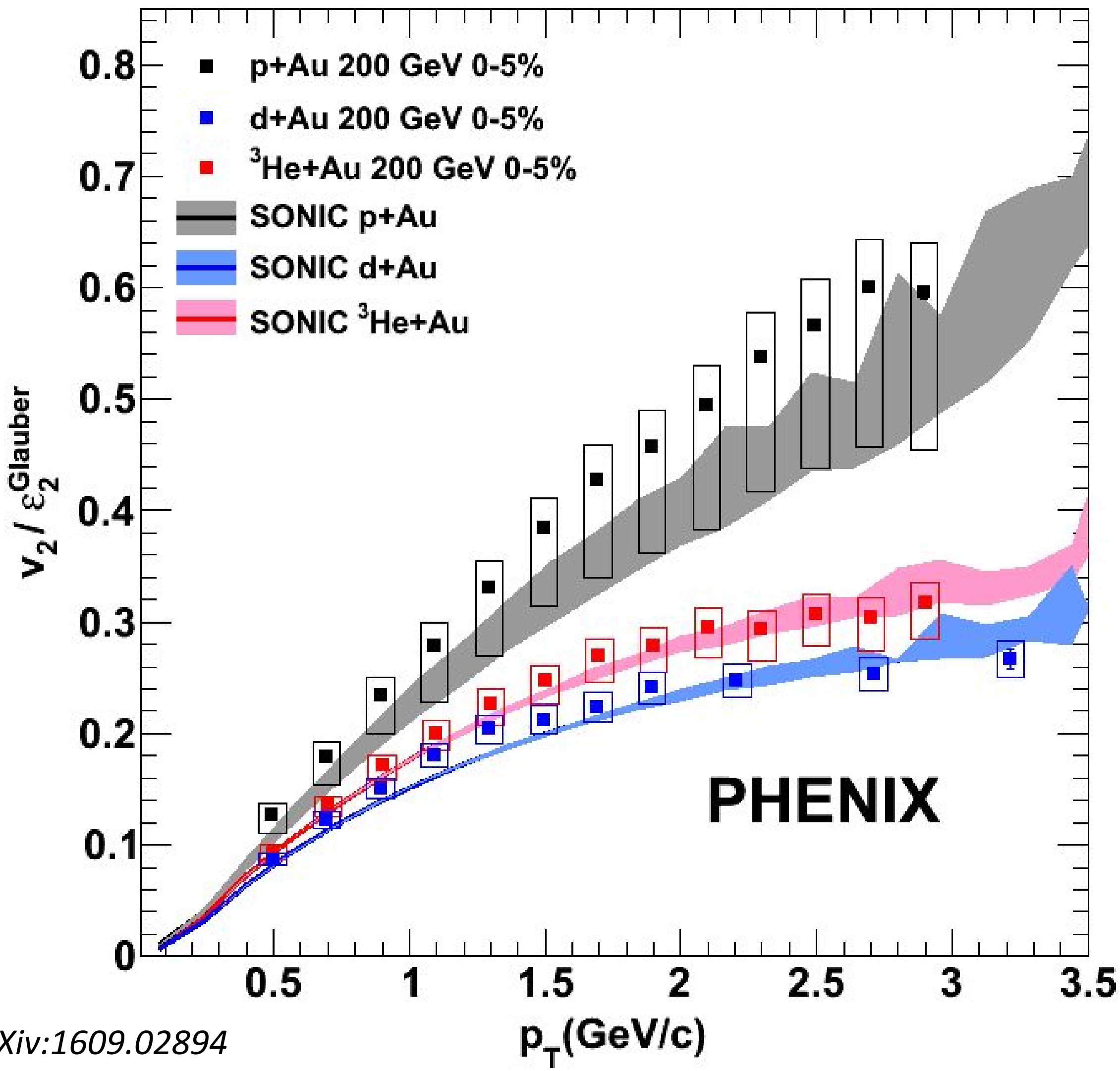
- v_2(pAu) ~ v_2(pAl)
- ε_2(pAu) = 0.23, ε_2(pAl) = 0.30

Charged v_2 Comparison between systems



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

v_2/ε_2 in small collision systems



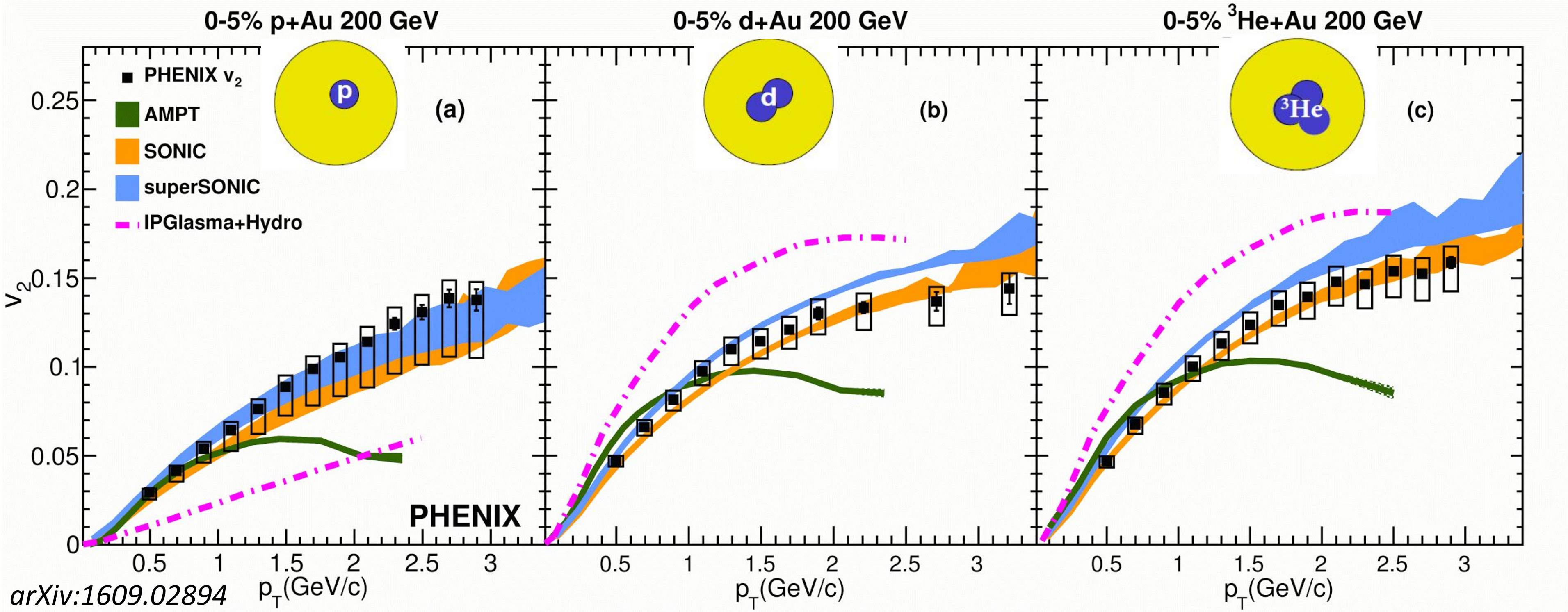
arXiv:1609.02894

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

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

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

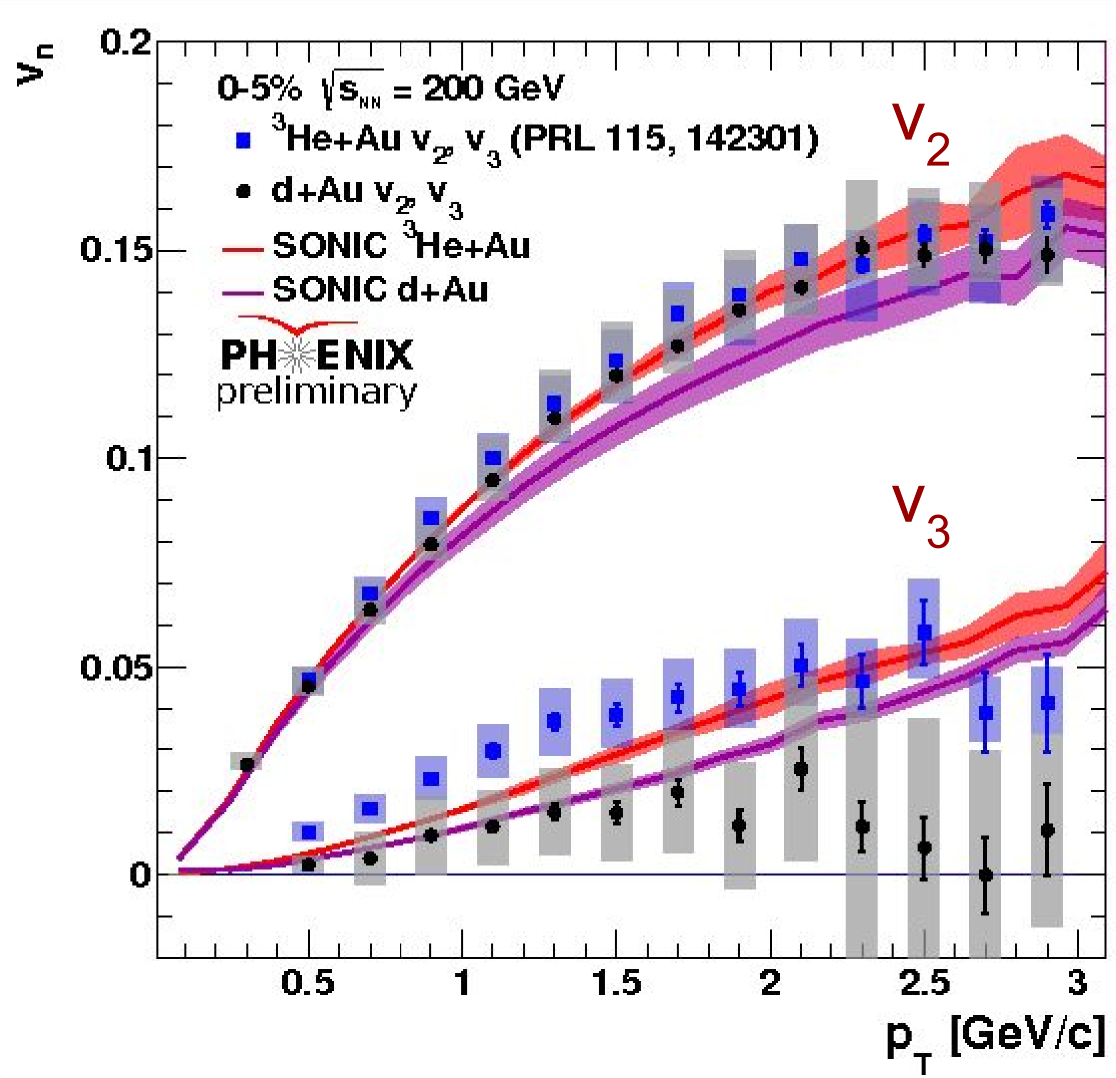
Charged v_2 Compared to models



arXiv:1609.02894

- SONIC model predicts the v_2 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

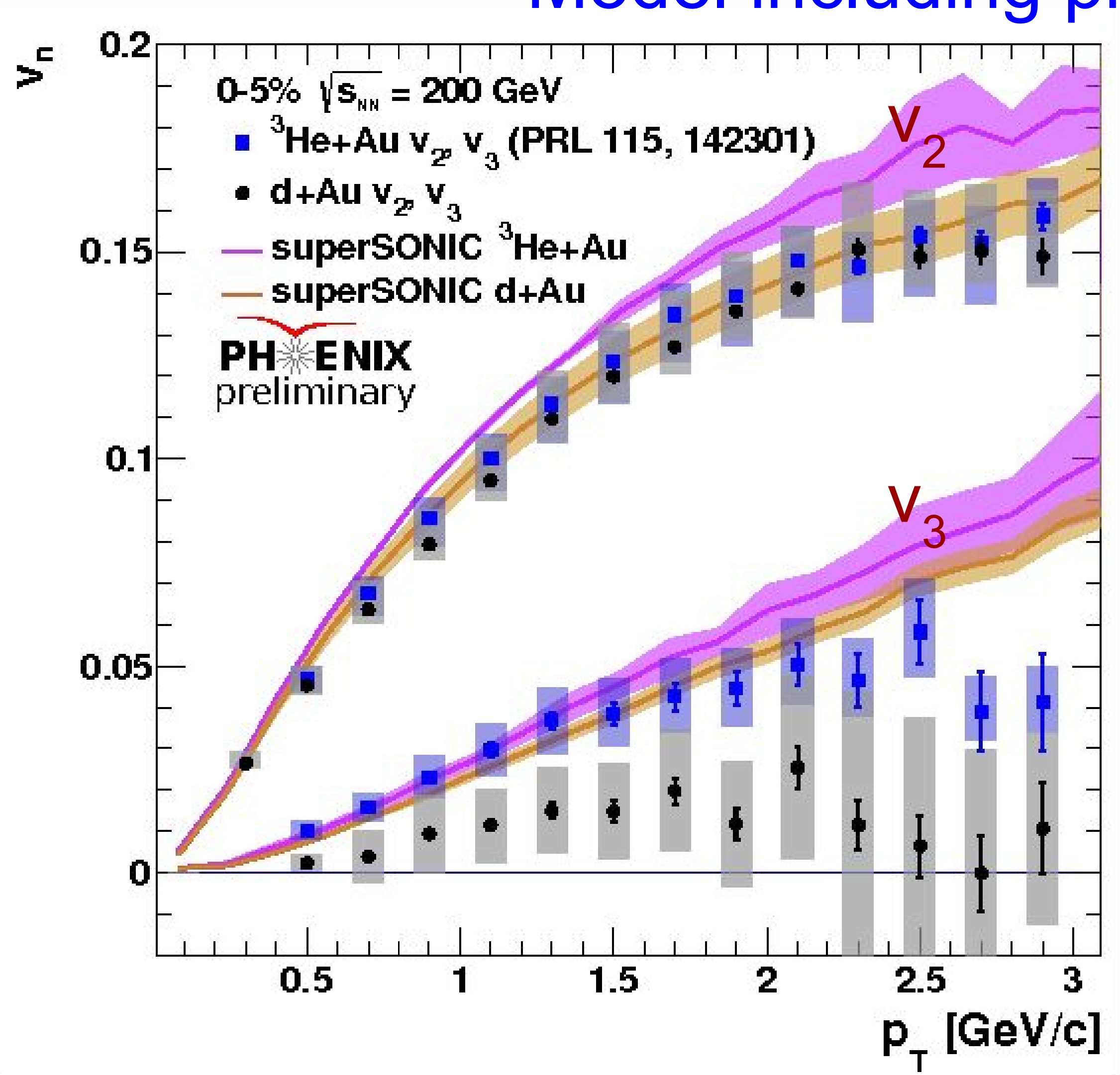
v_2 and v_3 in d/^{3}He+Au collisions



- v_3 in d+Au is systematically smaller than in ^{3}He+Au
- SONIC prediction agrees with data qualitatively

v_2 and v_3 in d/^{3}He+Au collisions

Model including pre-flow

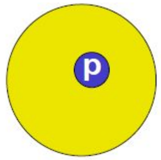


- pre-flow makes the v_2 & v_3 larger
- Imply that pre-flow may not be so important at 200 GeV energy

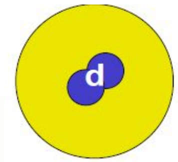
Identified Particles

Identified particles v_2 in p/d/^{3}He+Au

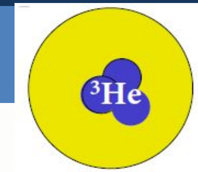
Central p+Au

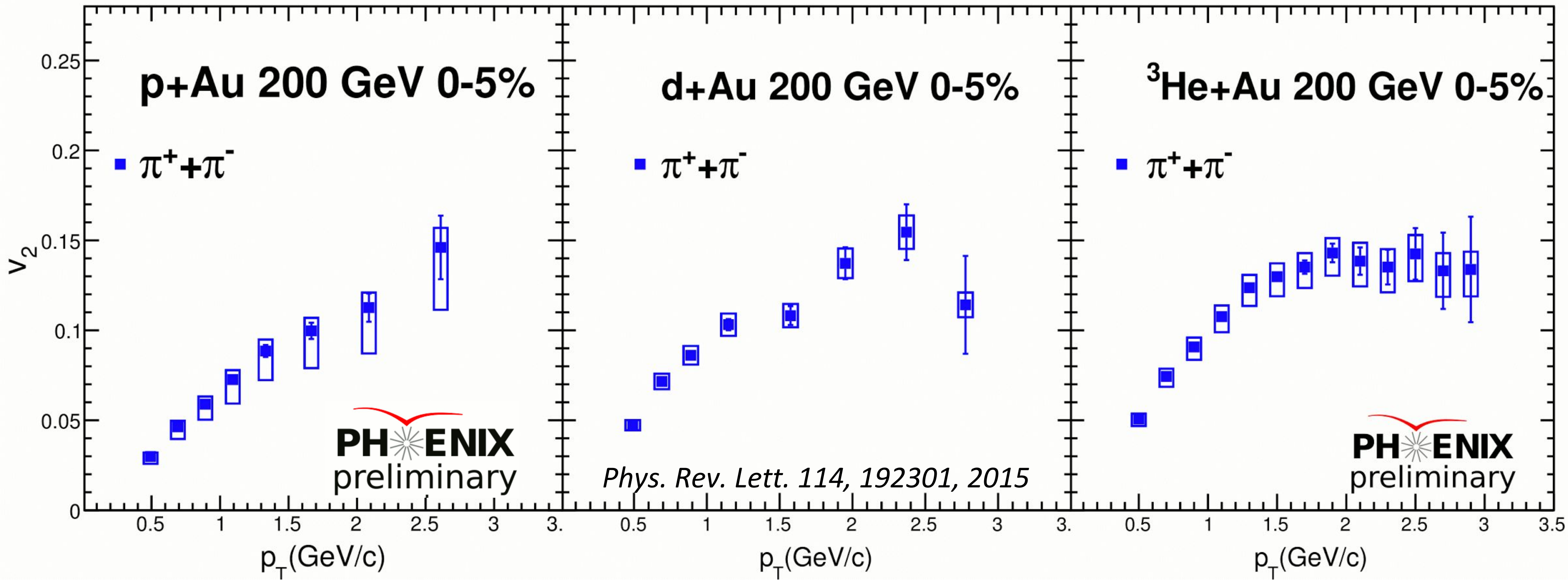


Central d+Au

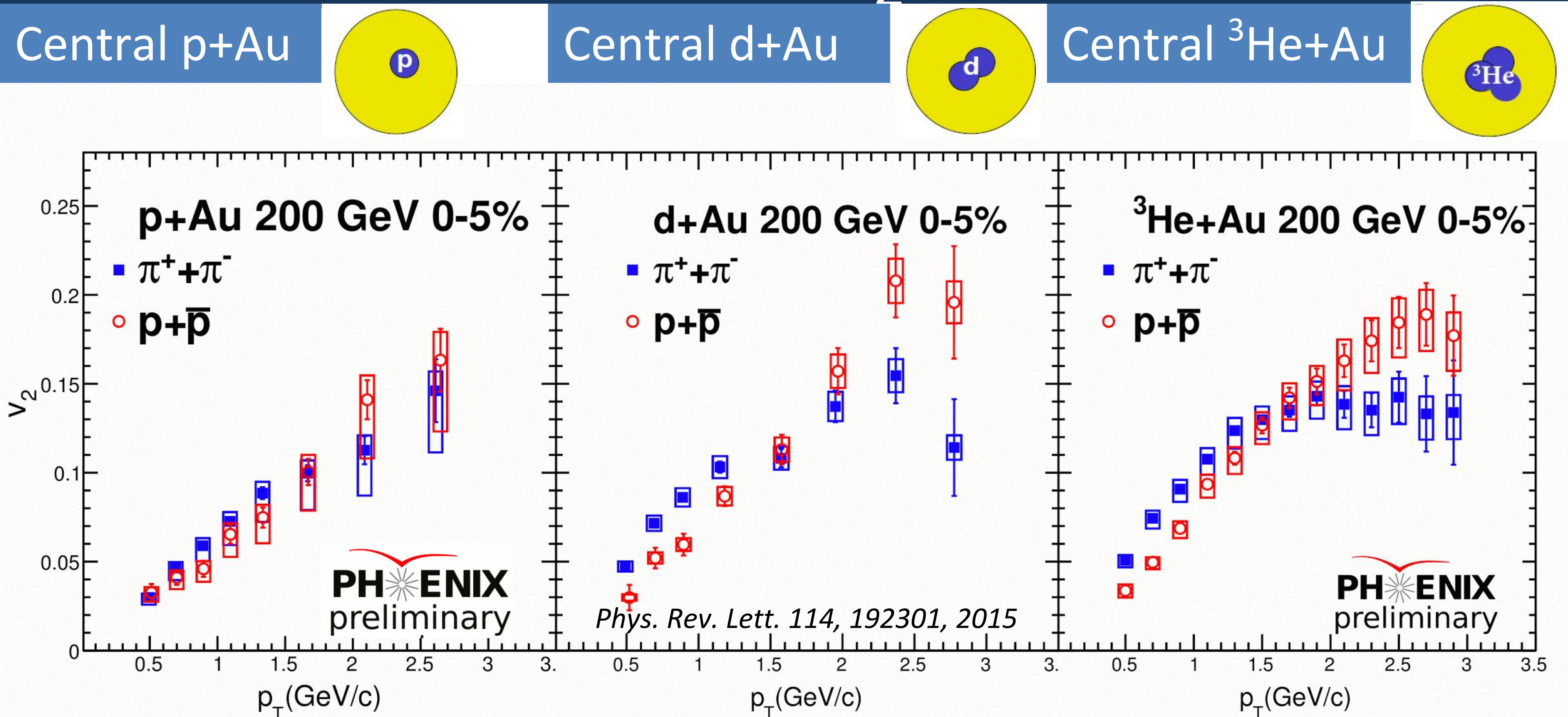


Central ^{3}He+Au





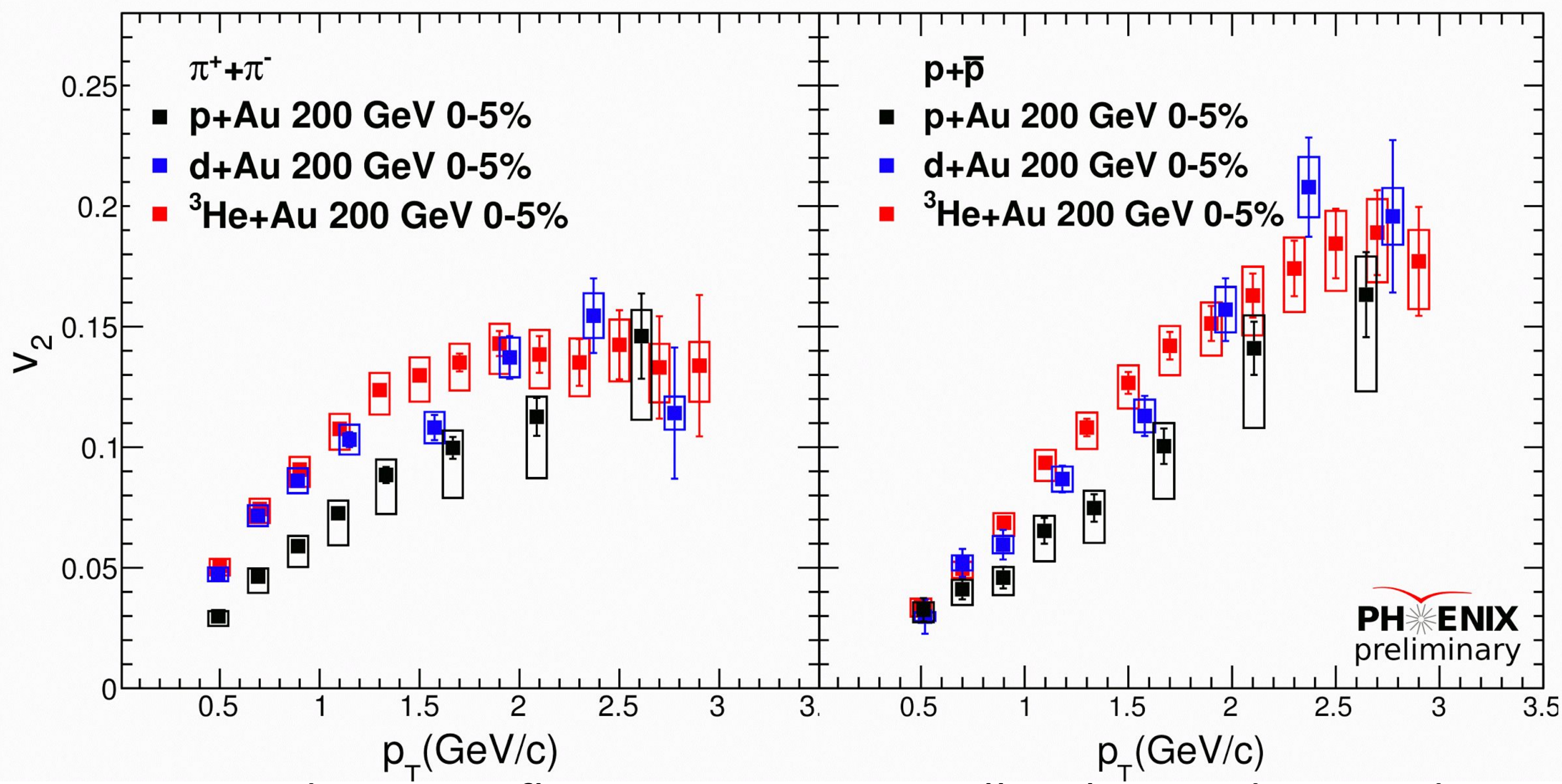
Identified particles v_2 in p/d/^{3}He+Au



Details see Poster J17
by Weizhuang Peng

- Mass-ordering feature is observed in p+Au
- Less pronounced in p+Au than in d+Au and ^{3}He+Au
- consistent with hydrodynamic flow (common velocity field)

Identified particles v_2 between systems



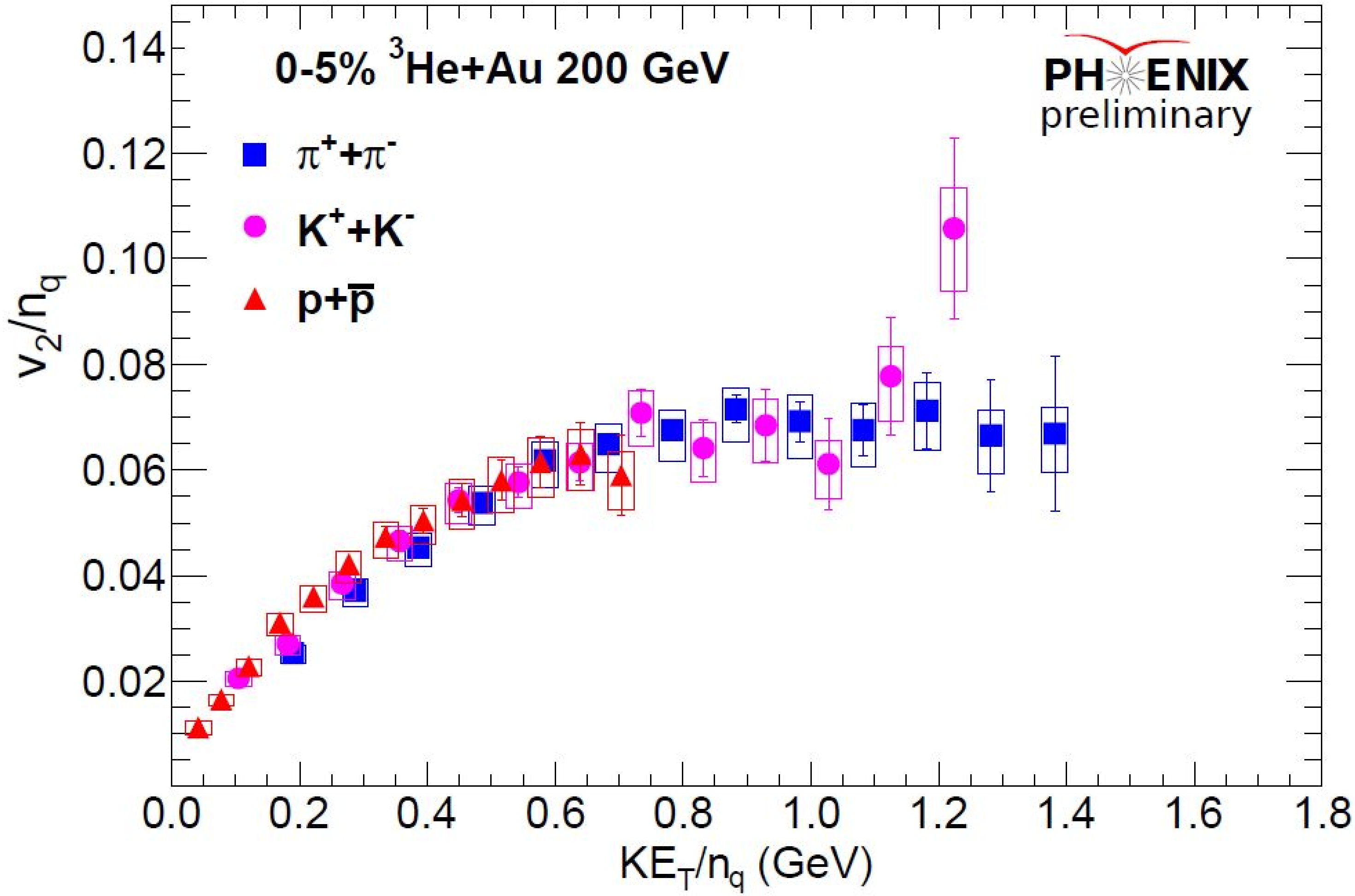
- Pions and protons flow in p+Au are smaller than in d+Au and ^{3}He+Au

Summary

- Ridge is seen in p+Al, p/d/ ^{3}He+Au collisions
- Sizable v_2 is seen in p+Al/Au, smaller than d/ ^{3}He+Au
- Non-zero v_3 is seen in d+Au, smaller than in ^{3}He+Au
- Glauber + Hydrodynamics reproduces v_2 & v_3
- Eccentricity scaling understood
    - eccentricity transferred to anisotropy incomplete
- Mass ordering observed in p+Au, less obvious than in d/^{3}He+Au

Back Up

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

Details of the methods

Non flow estimation method:

$$
\begin{aligned}
c_2^{dAu}(p_T) &= c_2^{\mathrm{Non-elem.}}(p_T) + c_2^{\mathrm{Elem.}}(p_T) \\
&\approx c_2^{\mathrm{Non-elem.}}(p_T) + c_2^{pp}(p_T)\frac{\Sigma E_T^{pp}}{\Sigma E_T^{dAu}}
\end{aligned}
$$

Two particle correlation Method:

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

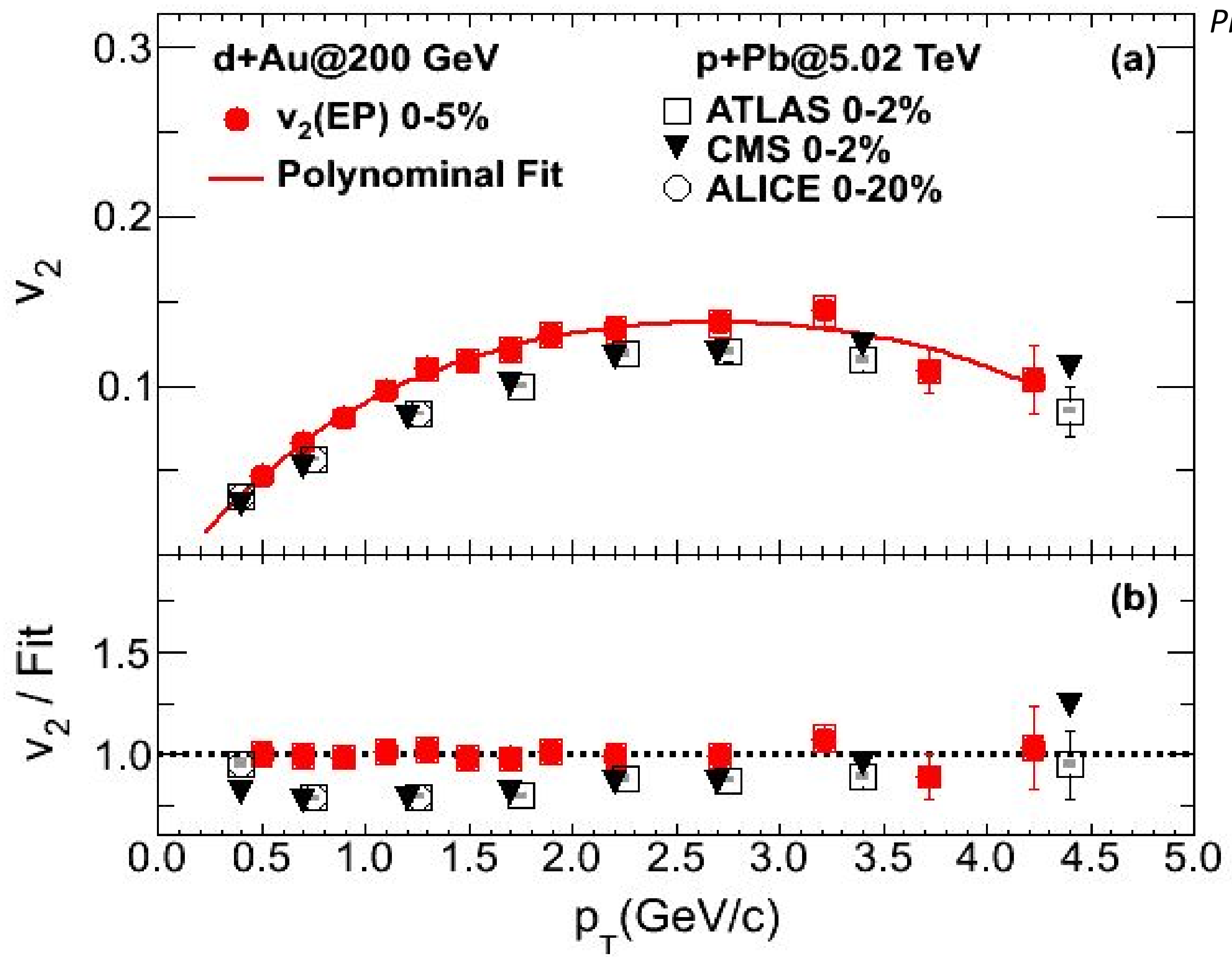
$M(\Delta\phi, p_T)$: mixed event

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

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

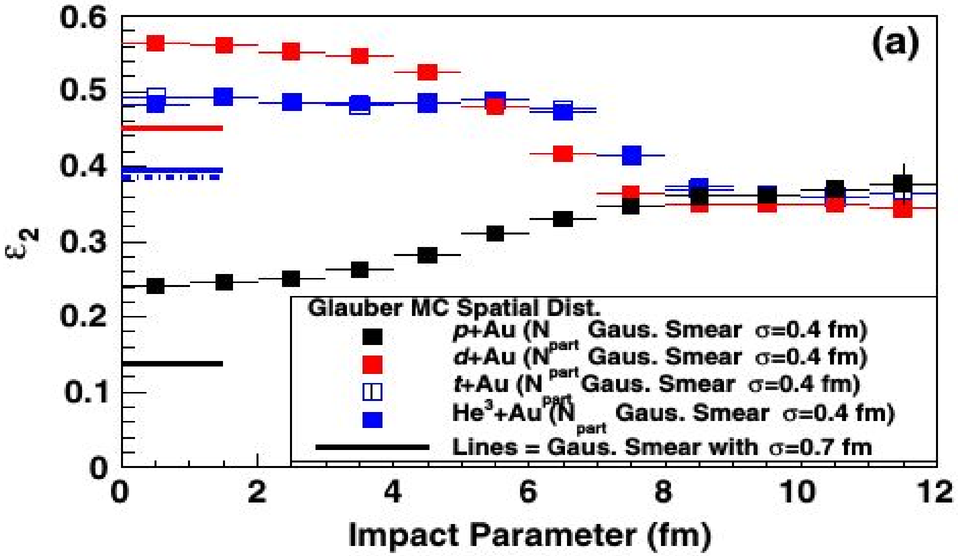
Charged particles: RHIC dAu and LHC pPb

Phys. Rev. Lett. 114, 192301

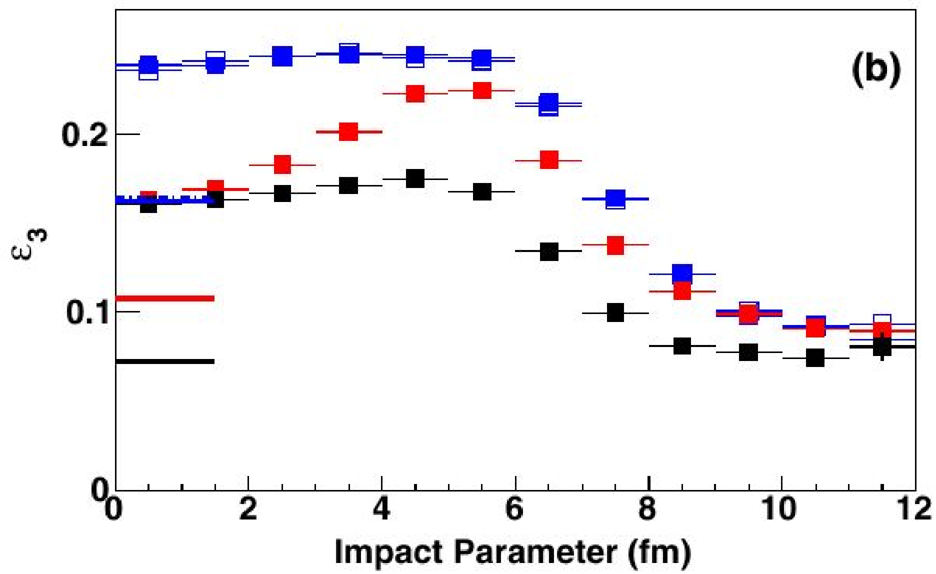


- PHENIX dAu and LHC pPb results - similar v_2

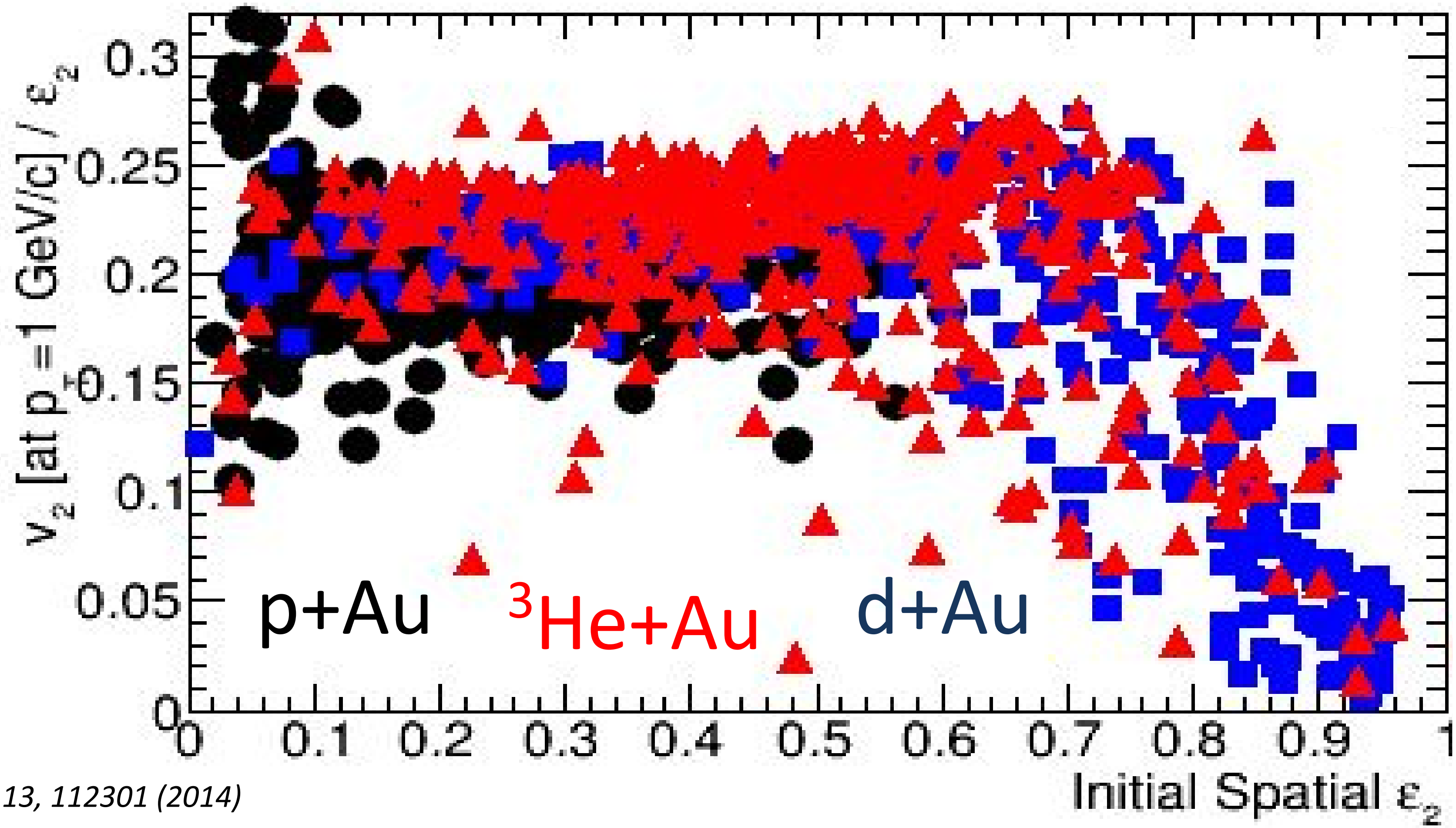
Initial eccentricity in Glauber models



PRL 113, 112301 (2014)



Eccentricity Scaling



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