Collective effects in small systems from geometry and energy scan at RHIC

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VANDERBILT UNIVERSITY

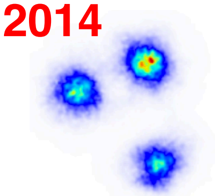
PHENIX

Two experimental handles on collectivity in small systems

Geometry Engineering

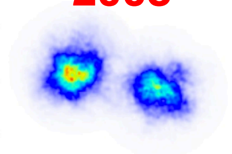
^{3}He+Au

2014



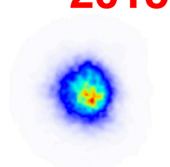
d+Au

2008



p+Au, p+Al

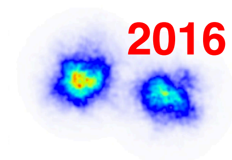
2015



Beam Energy Scan

d+Au

2016



20 GeV

39 GeV

62.4 GeV

200 GeV

Two experimental handles on collectivity in small systems

Geometry Engineering

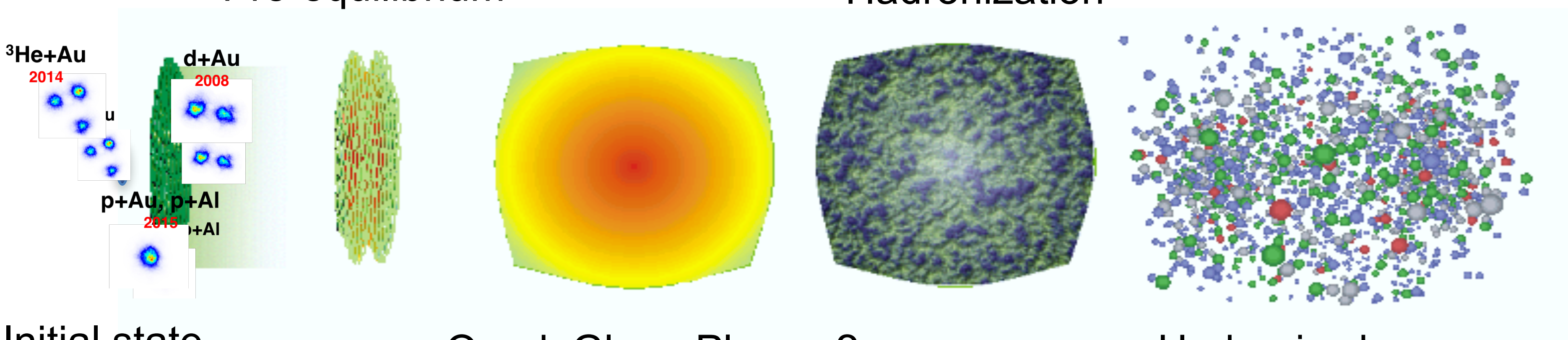
Beam Energy Scan

Test if the initial geometry is translated to final-state momentum anisotropy

vary the duration of each stage to assess their relative importance

Pre-equilibrium

Hadronization



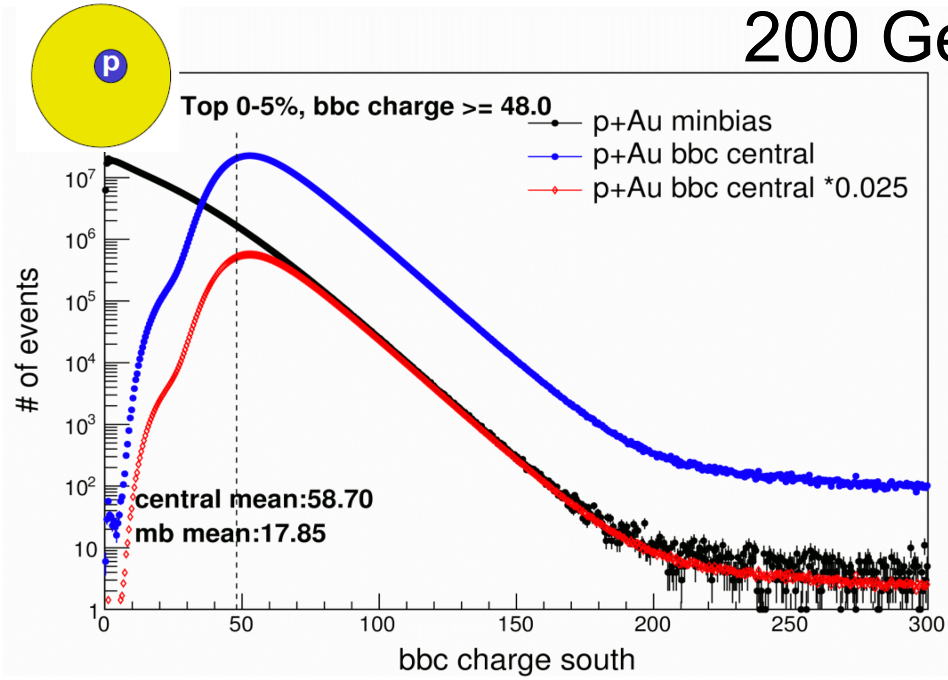
Initial state

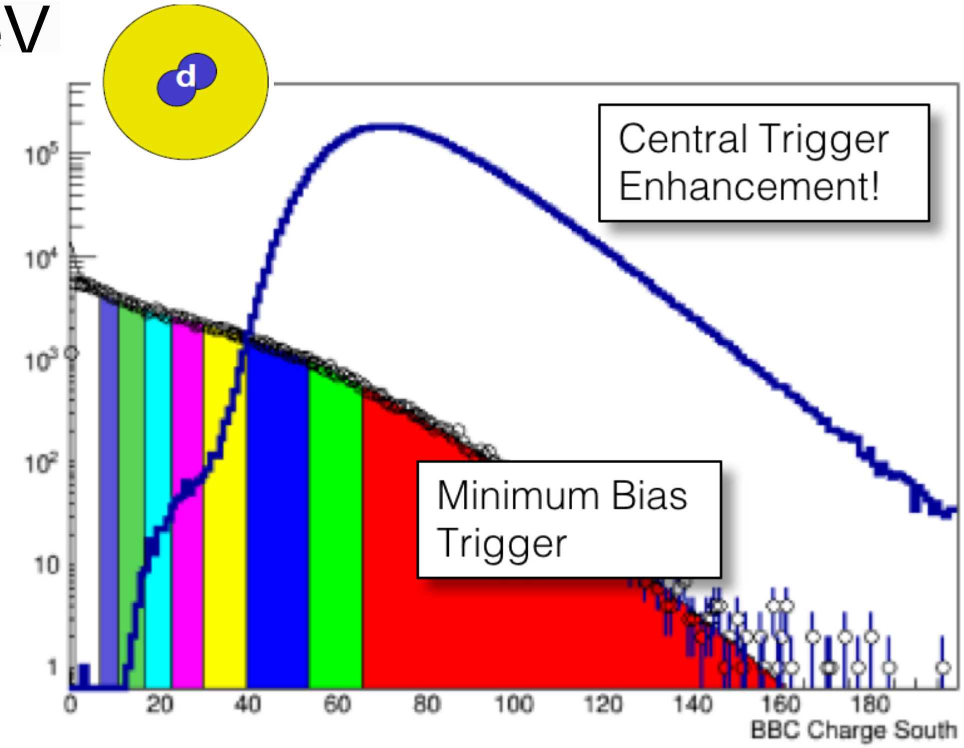
Quark Gluon Plasma?
thermally equilibrated ?

Hadronic phase
and freezeout

High-multiplicity triggered event samples

200 GeV





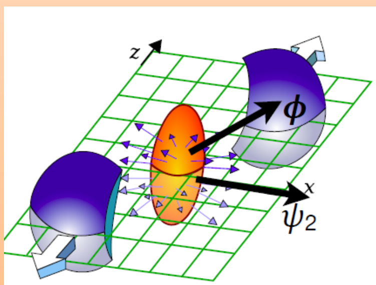
collision system (200 GeV)	increase in central events
p+Au *PRC 95 (2017) 034910*	**x40**
d+Au *preliminary*	**x15**
^{3}He+Au *PRL115, 142301 (2015)*	**x10**

2016 d+Au $\sqrt{s_{NN}}$ (GeV)	Number of Central Events Recorded
20	15 Million
39	137 Million
62.4	131 Million
200	636 Million

Experimental methods in PHENIX

Event plane: determined at large backward pseudorapidity
Particles: tracked over a large pseudorapidity range

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

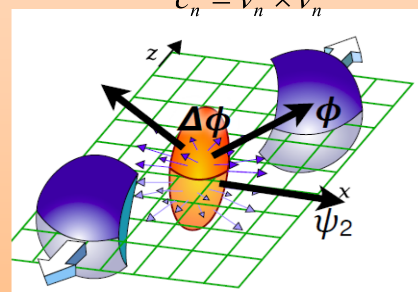


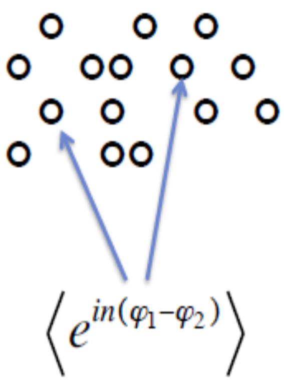
2-particle correlations comprised of:

1) particle at midrapidity
2) energy cluster in BBC
3) tracks in FVTX

pair amplitude modulation

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



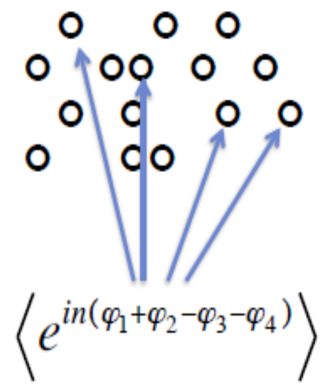


Calculation of cumulants

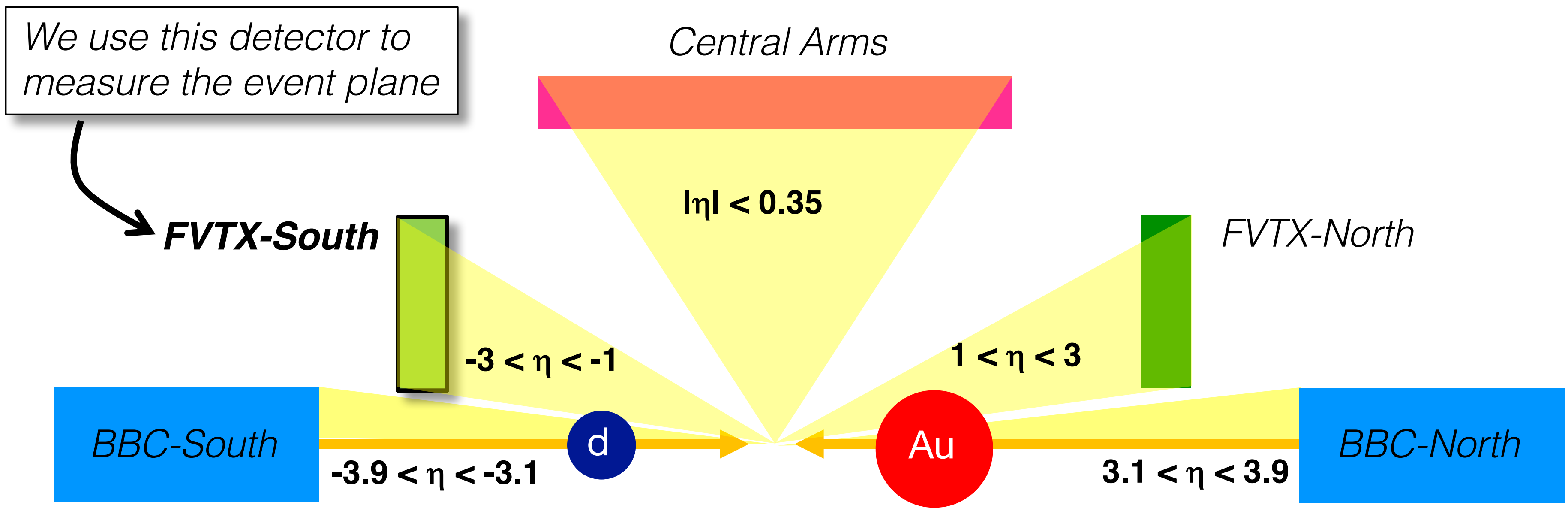
$$c_n\{2\} = \langle\langle 2 \rangle\rangle$$
$$c_n\{4\} = \langle\langle 4 \rangle\rangle - 2\langle\langle 2 \rangle\rangle^2$$

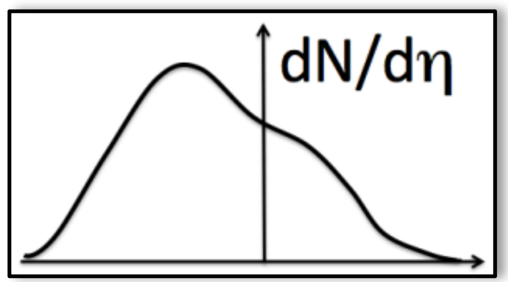
Determination of harmonic coefficients

$$v_n\{2\} = \sqrt{c_n\{2\}}$$
$$v_n\{4\} = \sqrt[4]{-c_n\{4\}}$$



EP: Measurements of $v_n(p_T)$ at mid rapidity



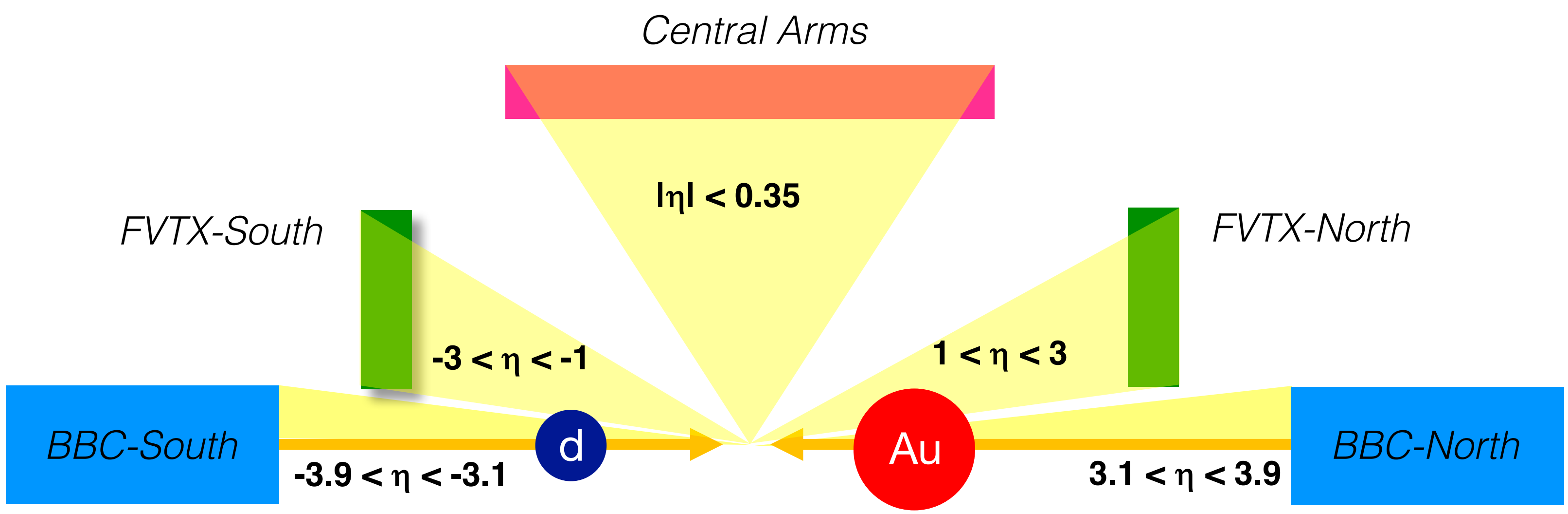


$$v_2 = \frac{\langle \cos 2(\phi - \Psi_2) \rangle}{\text{Res}(\Psi_2)}$$

To optimize Resolution, we use:

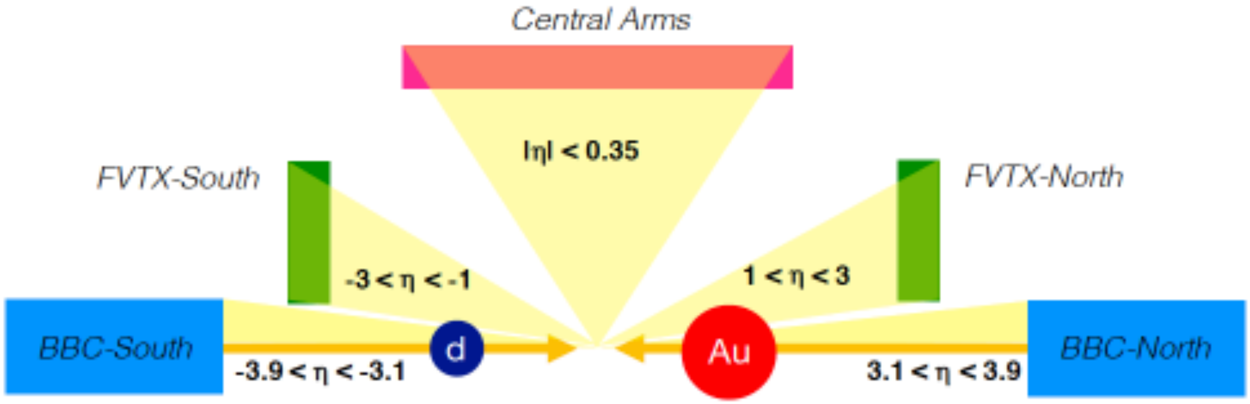
- Central Arms
- FVTX-South
- BBC-South

2-particle correlations

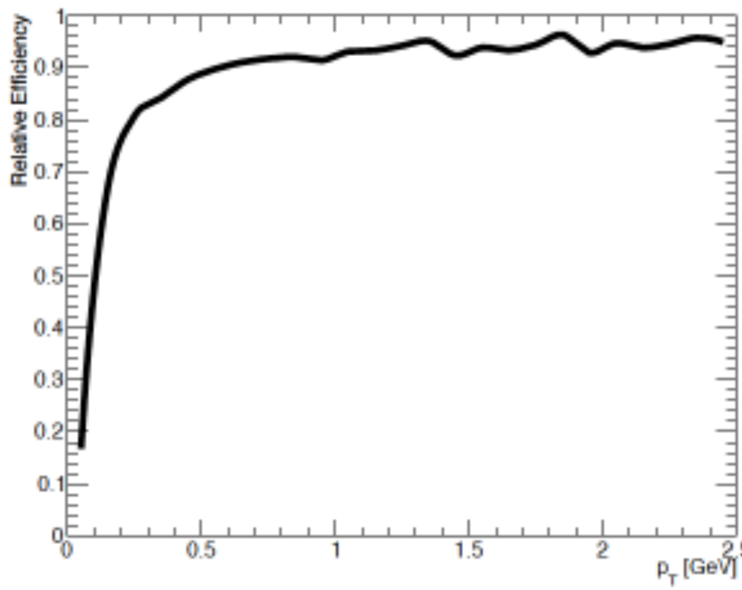


- various detector combinations are used
- 2-particle correlations used for:
  - estimate nonflow (in conjunction with min bias pp data)
  - look for the ridge
  - in some cases -> to confirm the EP measurements

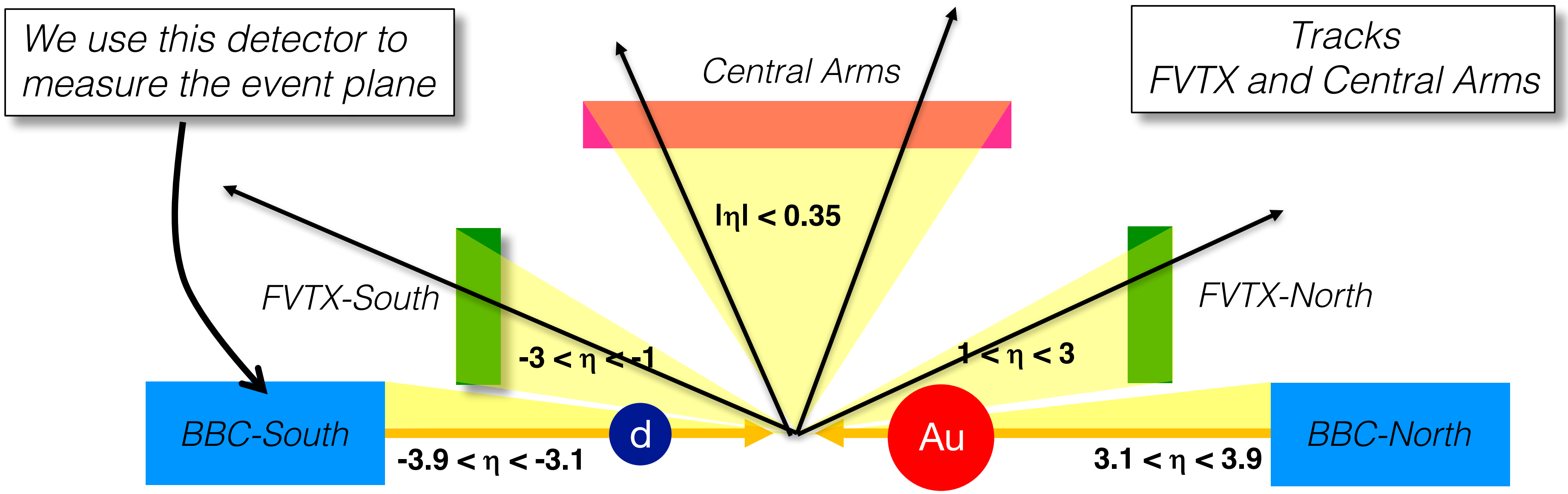
Cumulants: measure integrated v_2 from tracks in FVTX as a function of N_{trk}



- FVTX: forward vertex detector —silicon strip technology
- Very precise vertex/DCA determination
- No momentum determination, p_T dependent efficiency — measured v_2 roughly 18% higher than true



v_2 vs η: analysis method



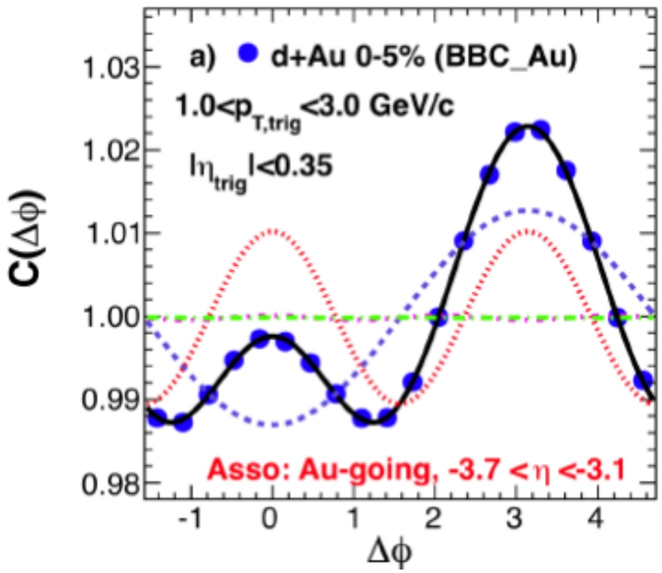
- We want to measure integrated v_2 ($0<p_T<\infty$)
- No p_T information available from FVTX
- Devise a correction based on AMPT

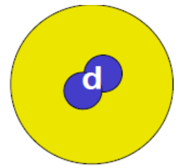
RESULTS

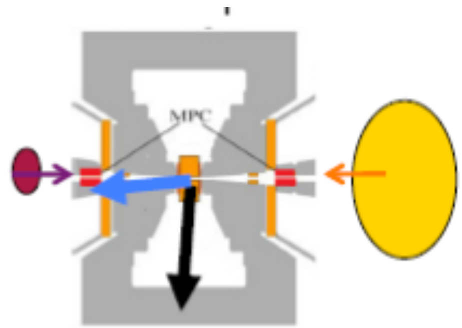
1. Ridge in different systems
2. Geometry scan: flow of inclusive and identified particles
3. Energy scan with dAu

Ridge (d/^{3}He+Au), and no clear ridge pA

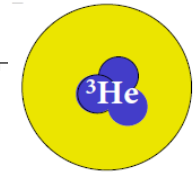
Phys. Rev. Lett. 114, 192301, 2015

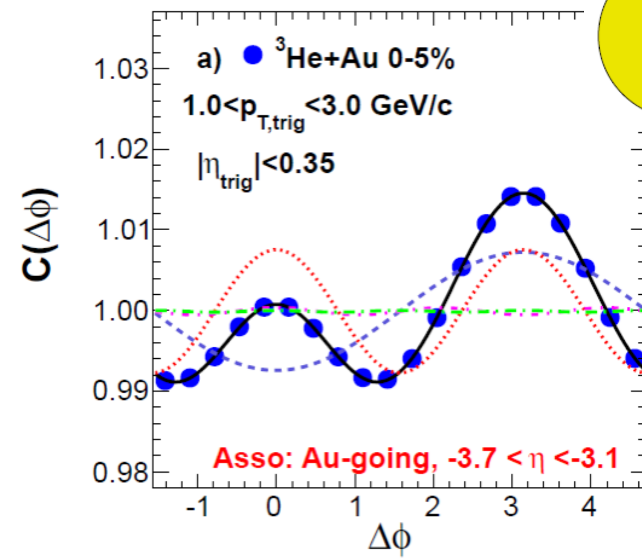


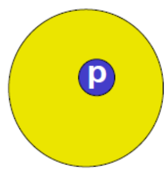




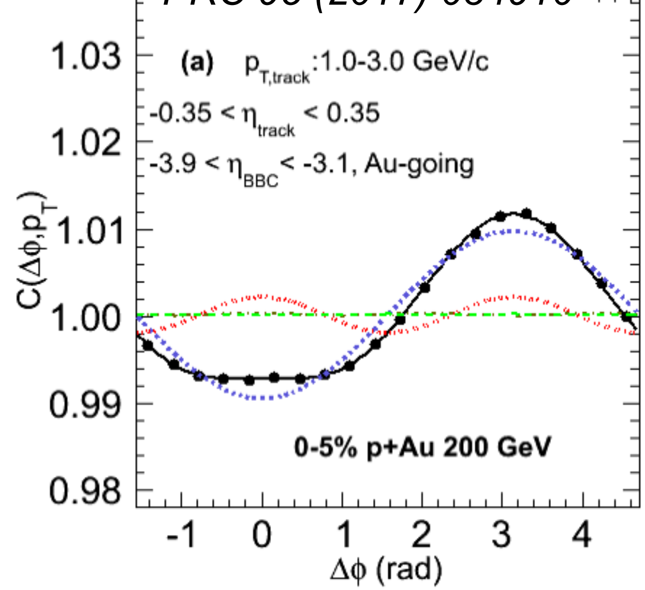
Phys. Rev. Lett. 115, 142301 , 2015



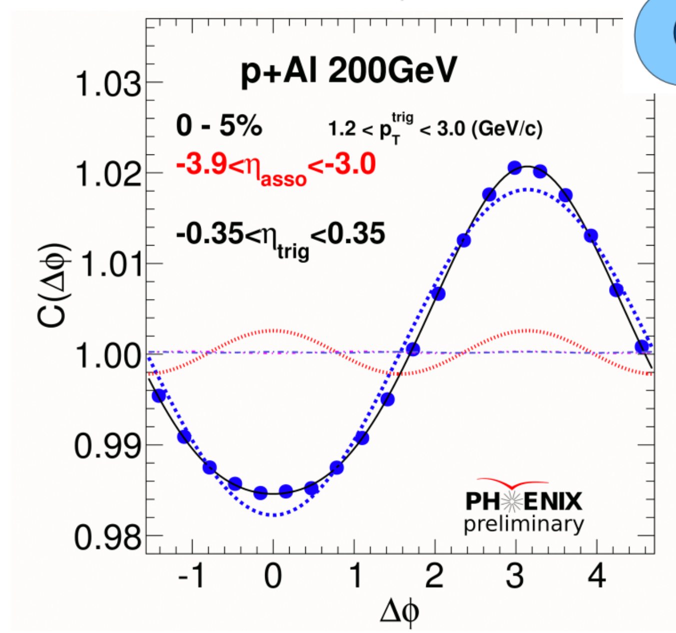




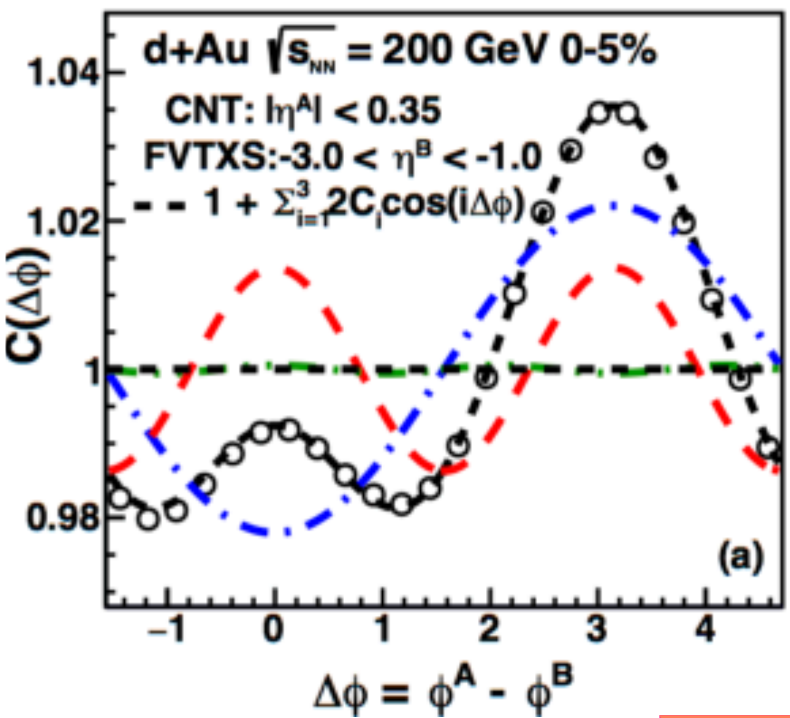
PRC 95 (2017) 034910

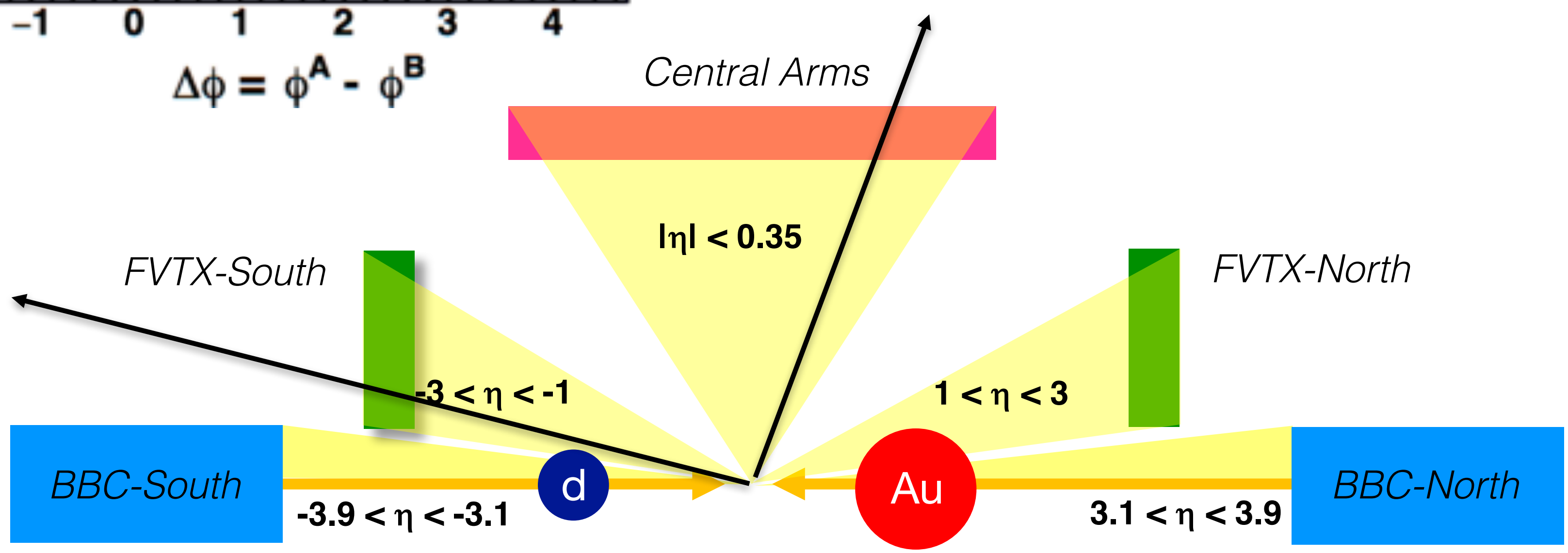


$|\Delta\eta|>2.75$



d+Au at 200 GeV: ridge evolution with Δη





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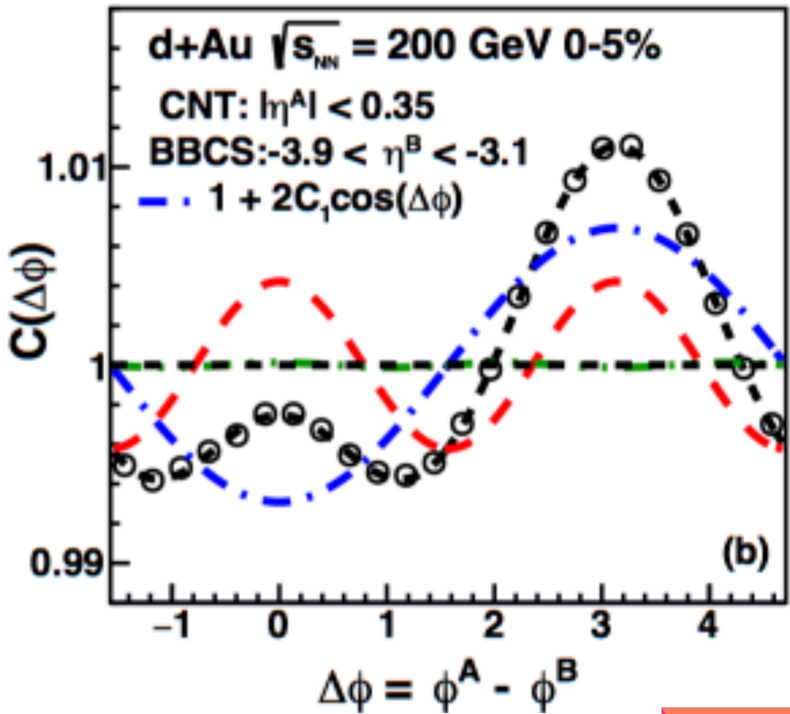
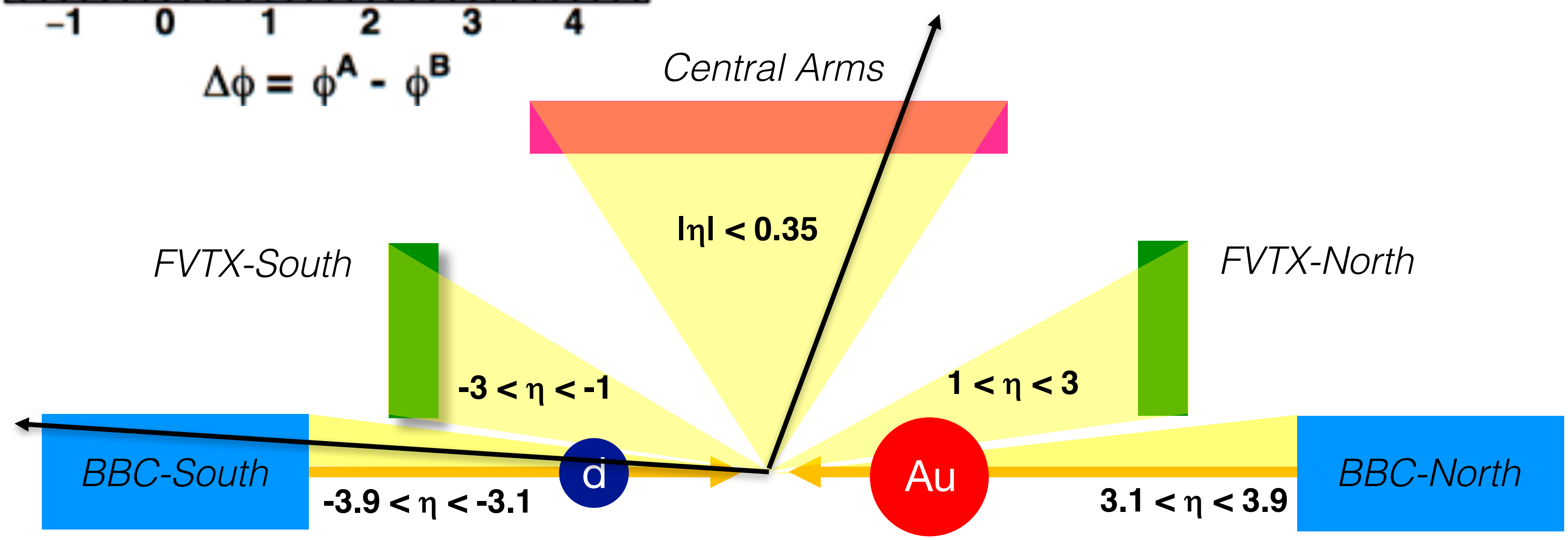
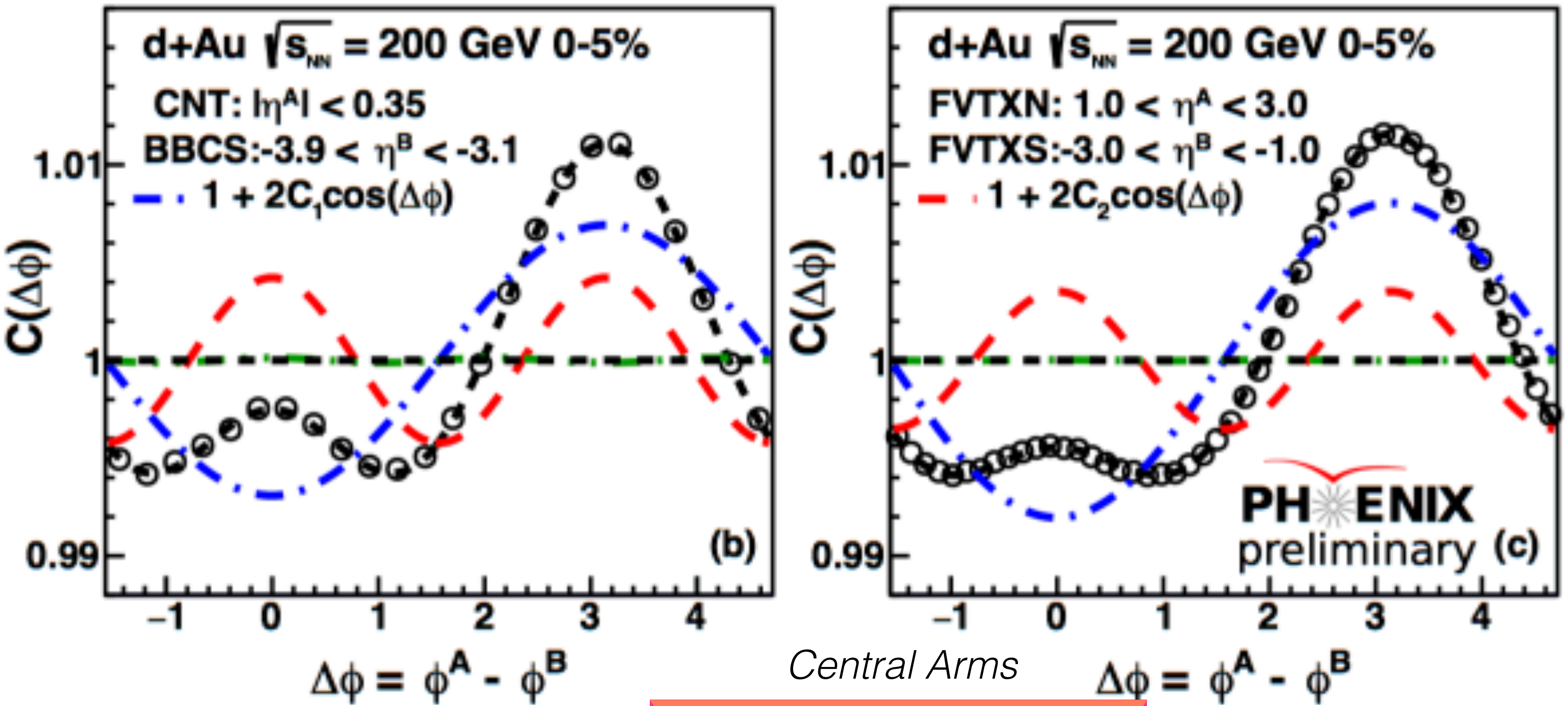
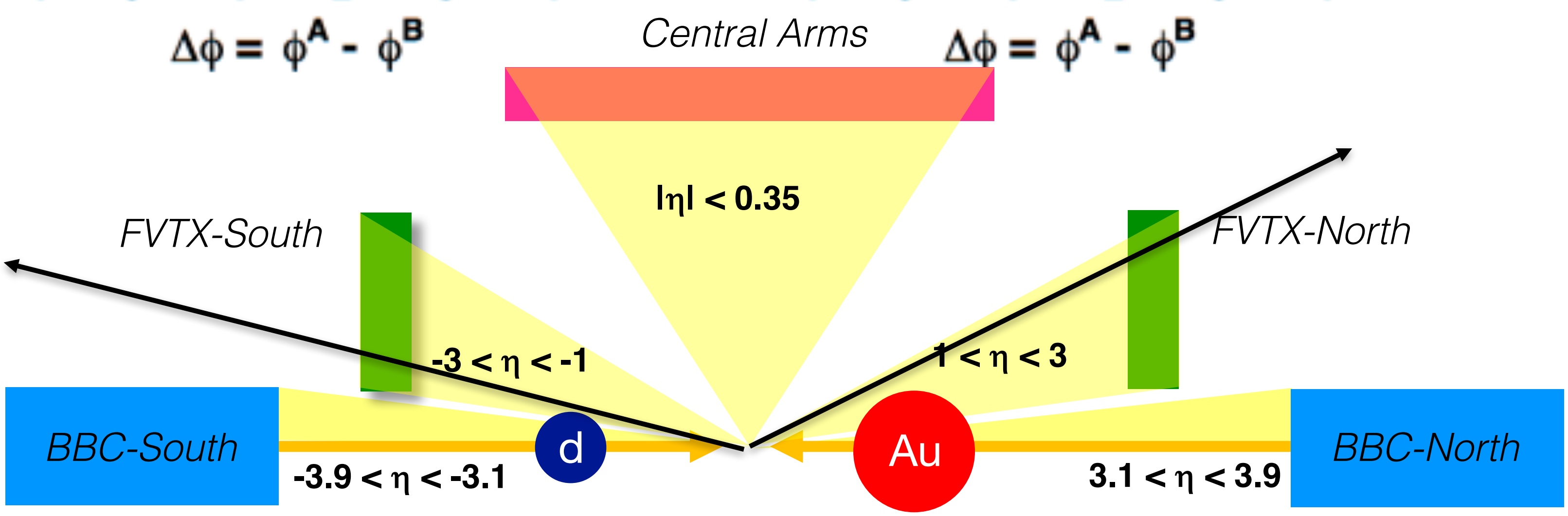
d+Au at 200 GeV: ridge evolution with Δη



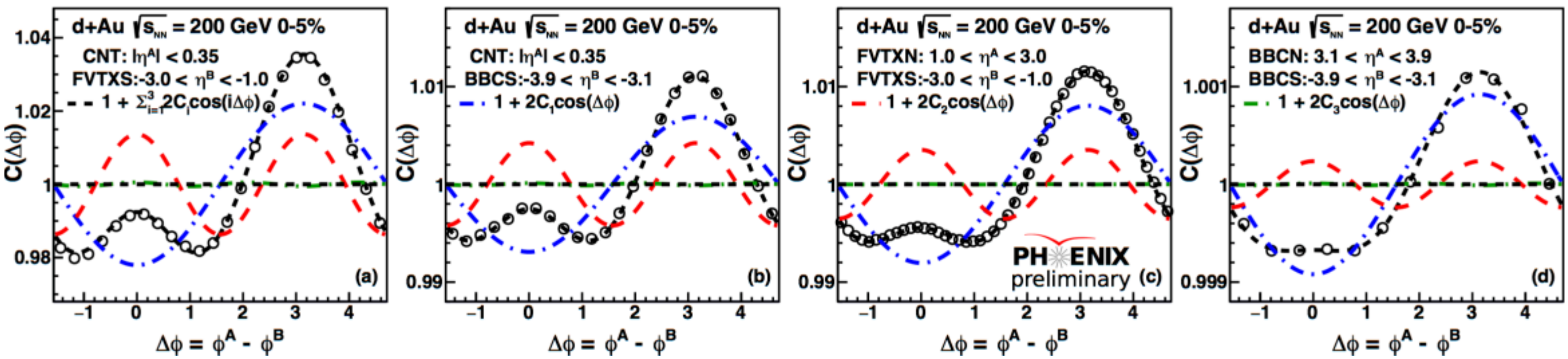


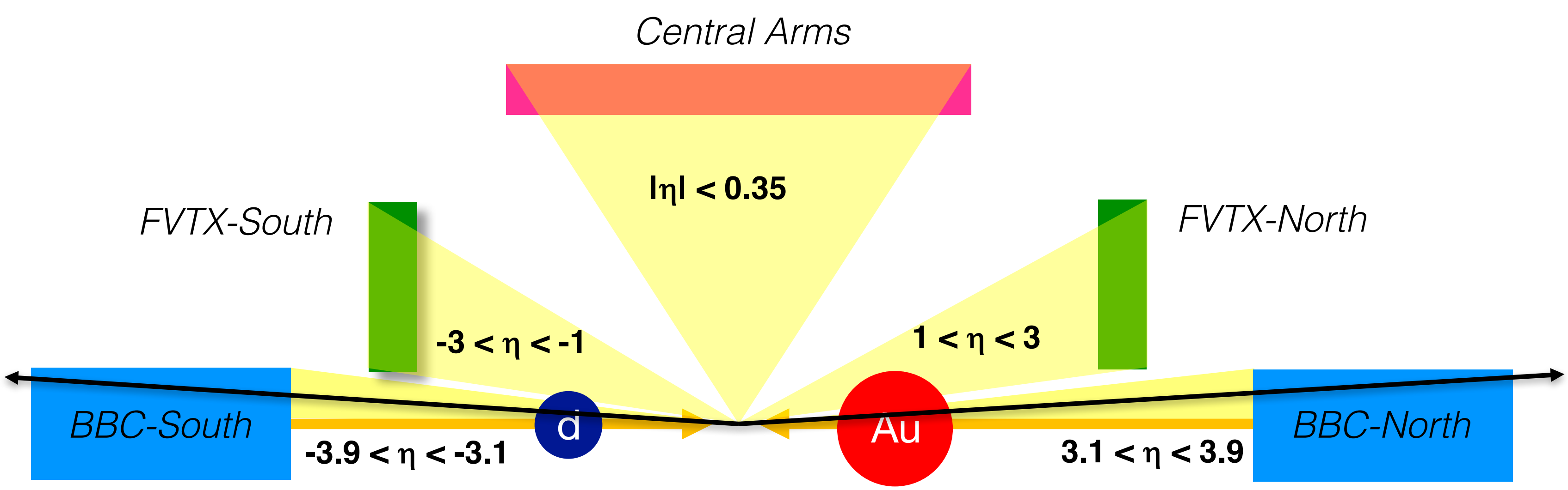
d+Au at 200 GeV: ridge evolution with Δη





d+Au at 200 GeV: ridge evolution with $\Delta\eta$





A clear ridge is seen with all detector combinations, even for $\Delta\eta > 6.2$

RESULTS

1. Ridge in different systems at 200 GeV
   - Pronounced ridge in d/^{3}He+Au, but not in pAl
   - In d+Au, the ridge extends over $\Delta\eta > 6.2$
2. **Geometry scan: flow harmonics of inclusive and identified particles**

3. Energy scan with dAu

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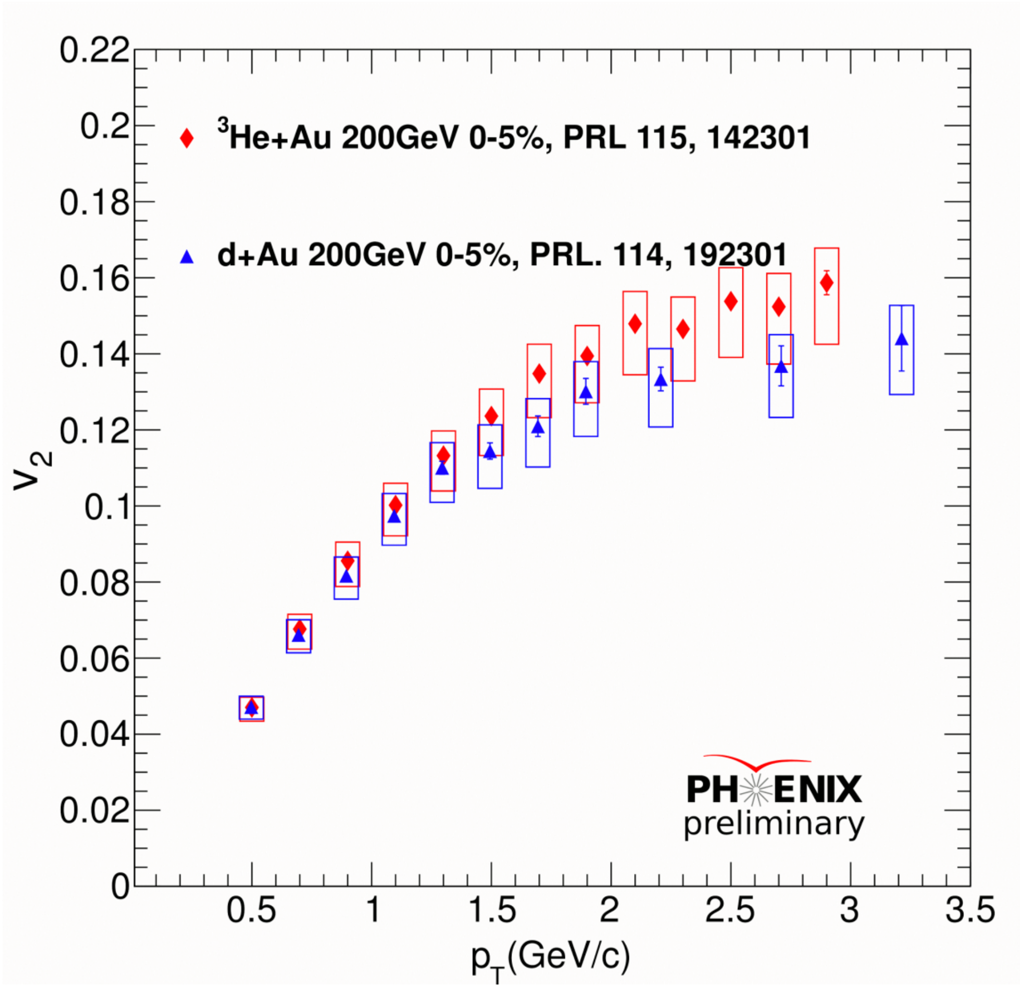
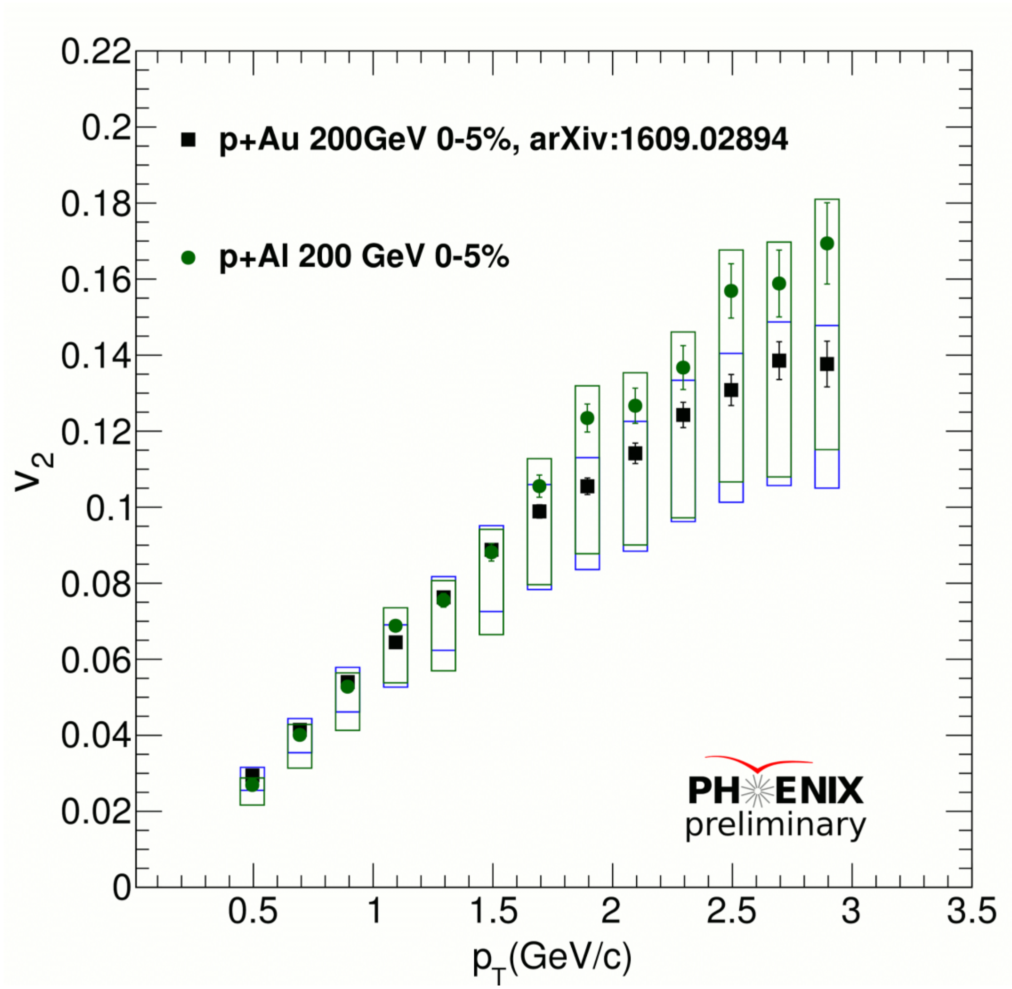
Charged hadron v_2: d/^{3}He+Au



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

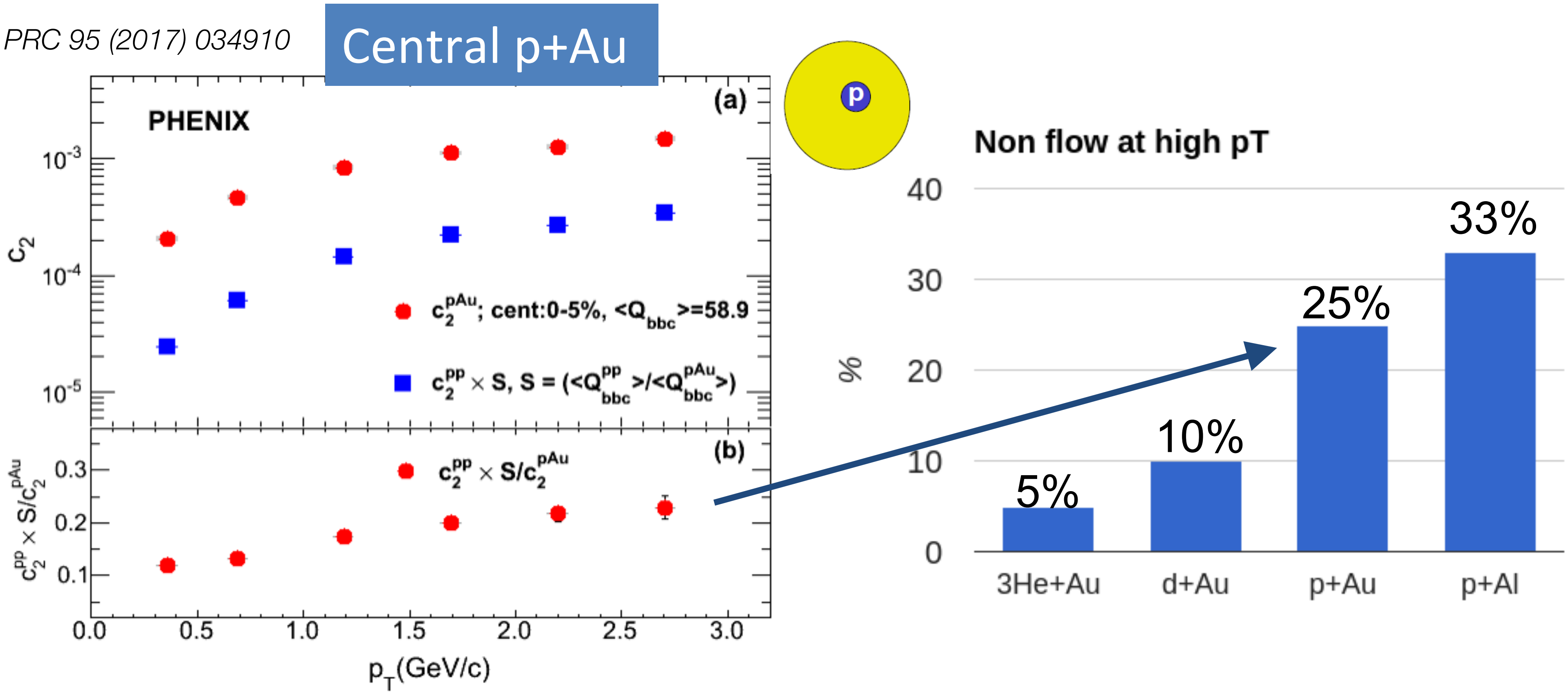
Charged hadron v_2: p+Au, p+Al



(growing) asymmetric systematics from nonflow

- $v_2(pAu) \sim v_2(pAl)$
- $\varepsilon_2(pAu) = 0.23$, $\varepsilon_2(pAl) = 0.30$

Nonflow estimation based on pp data



- Correlations in pp minbias data scaled by multiplicity
- Not subtracted - cited as a systematic uncertainty

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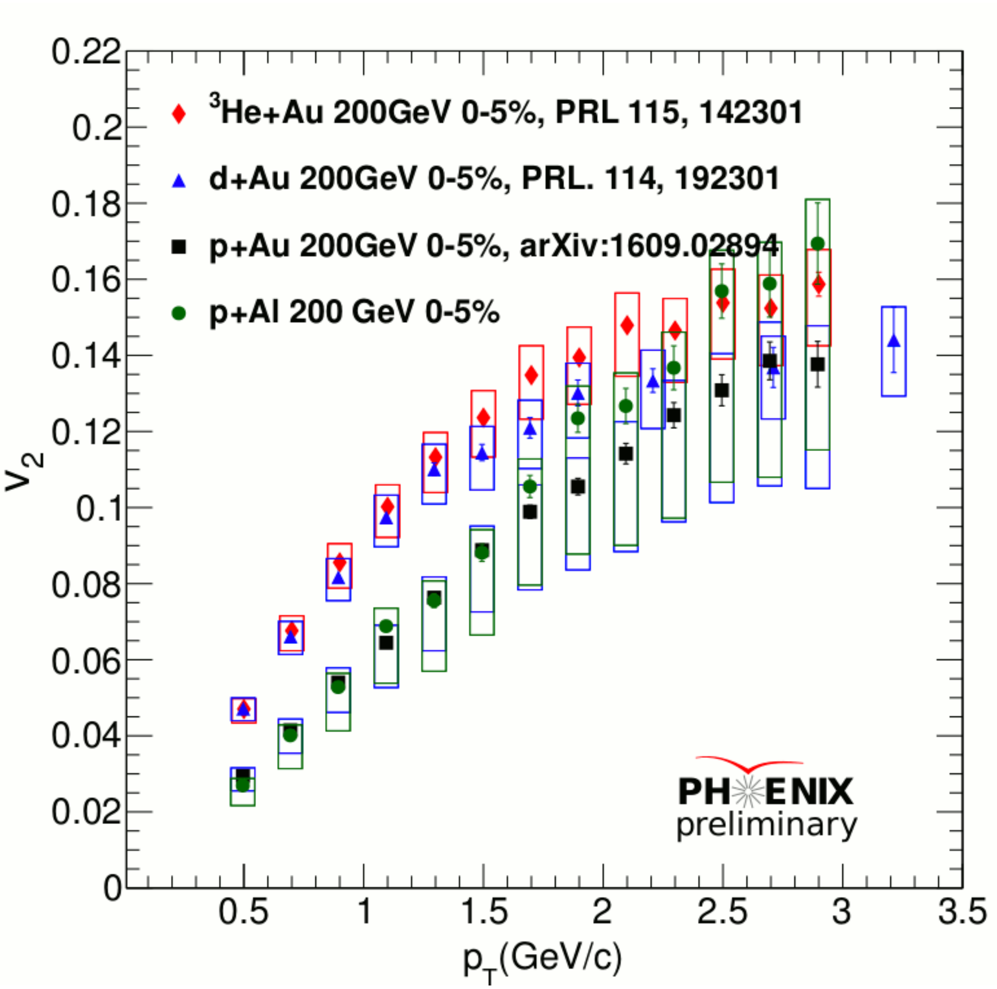
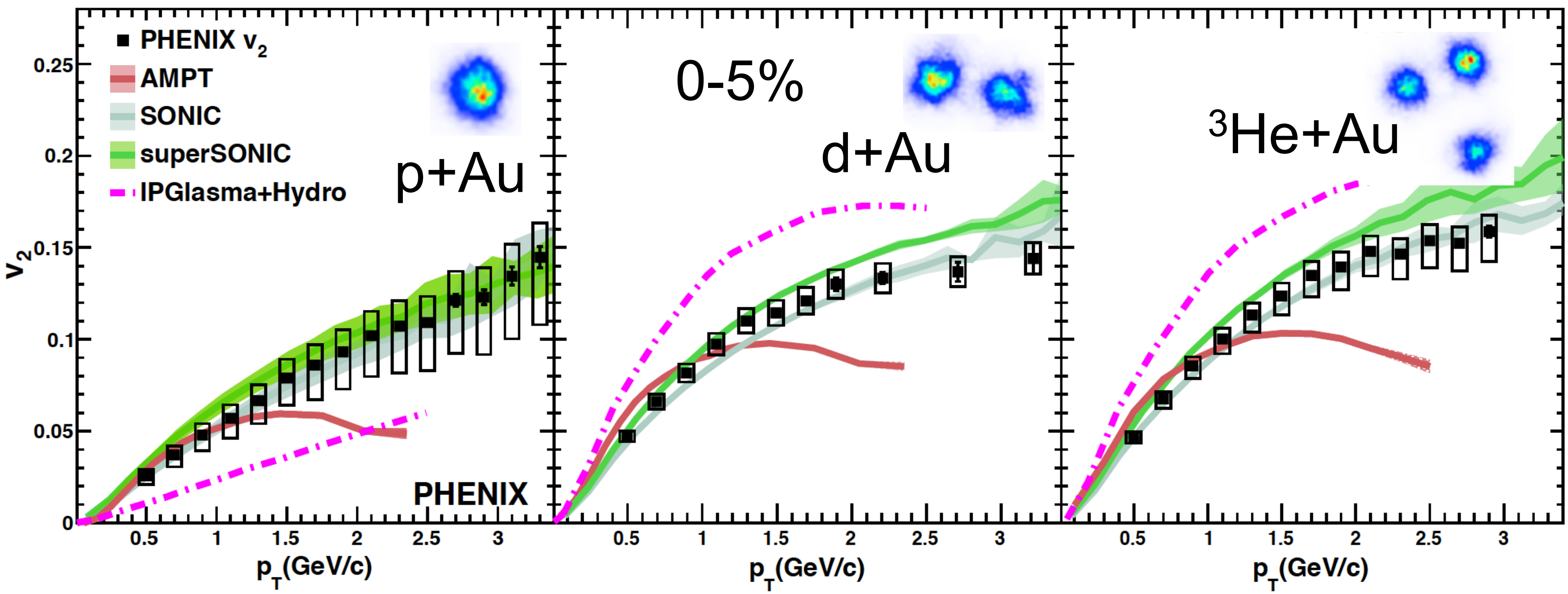
Charged hadron v_2: systems group by ε



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

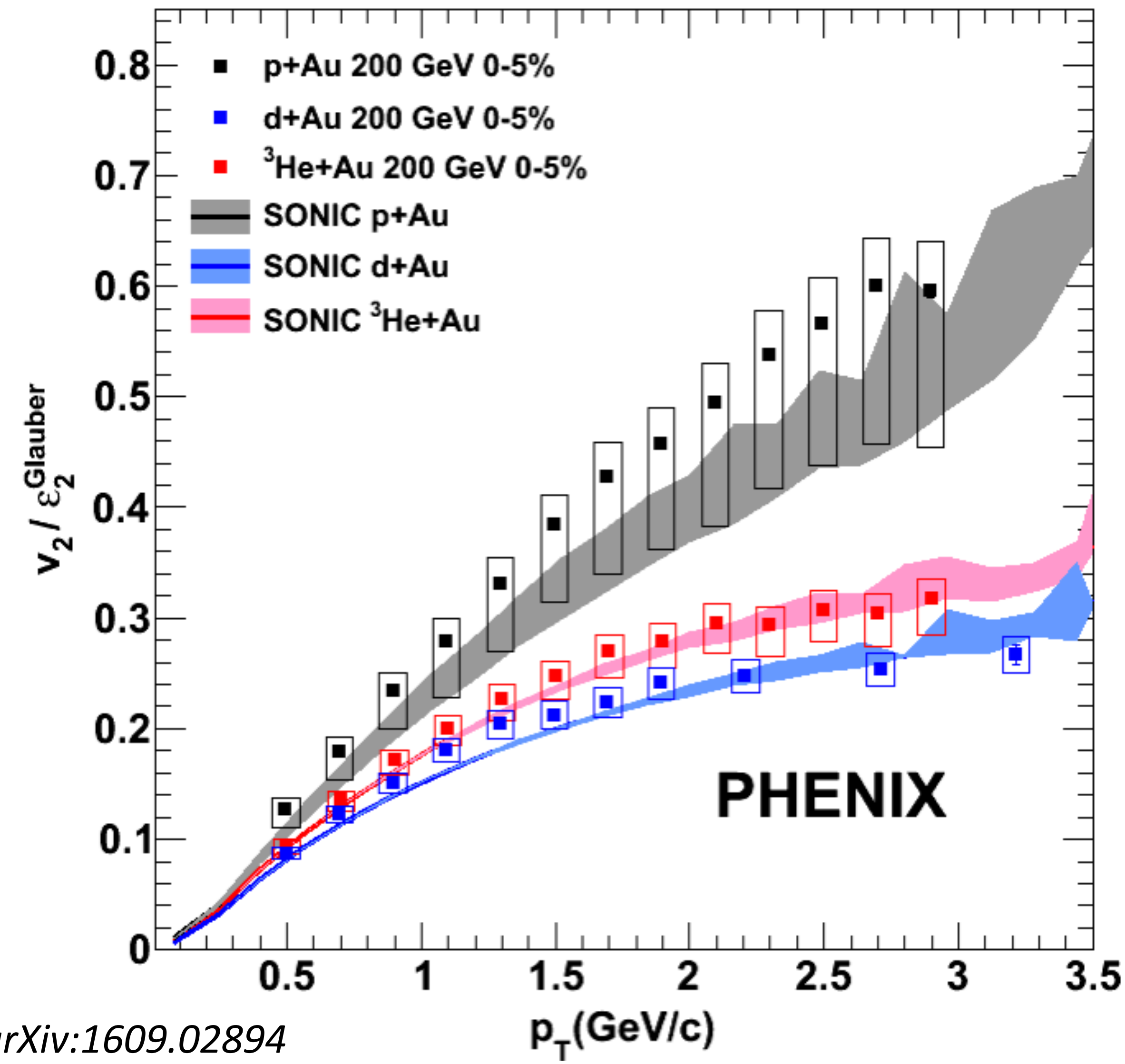
Geometry engineering, v_2 (p_T), and models

PRC 95 (2017) 034910 *PRL 114, 192301, (2015)* *PRL 115, 142301, (2015)*



- Hydrodynamics with small η/s works!
- AMPT: weakly coupled partonic cascade+quark coallescence+hadronic cascade also works at low p_T.
- Other obesrvables ?

v_2/ε_2 in systems with different geometry



arXiv:1609.02894

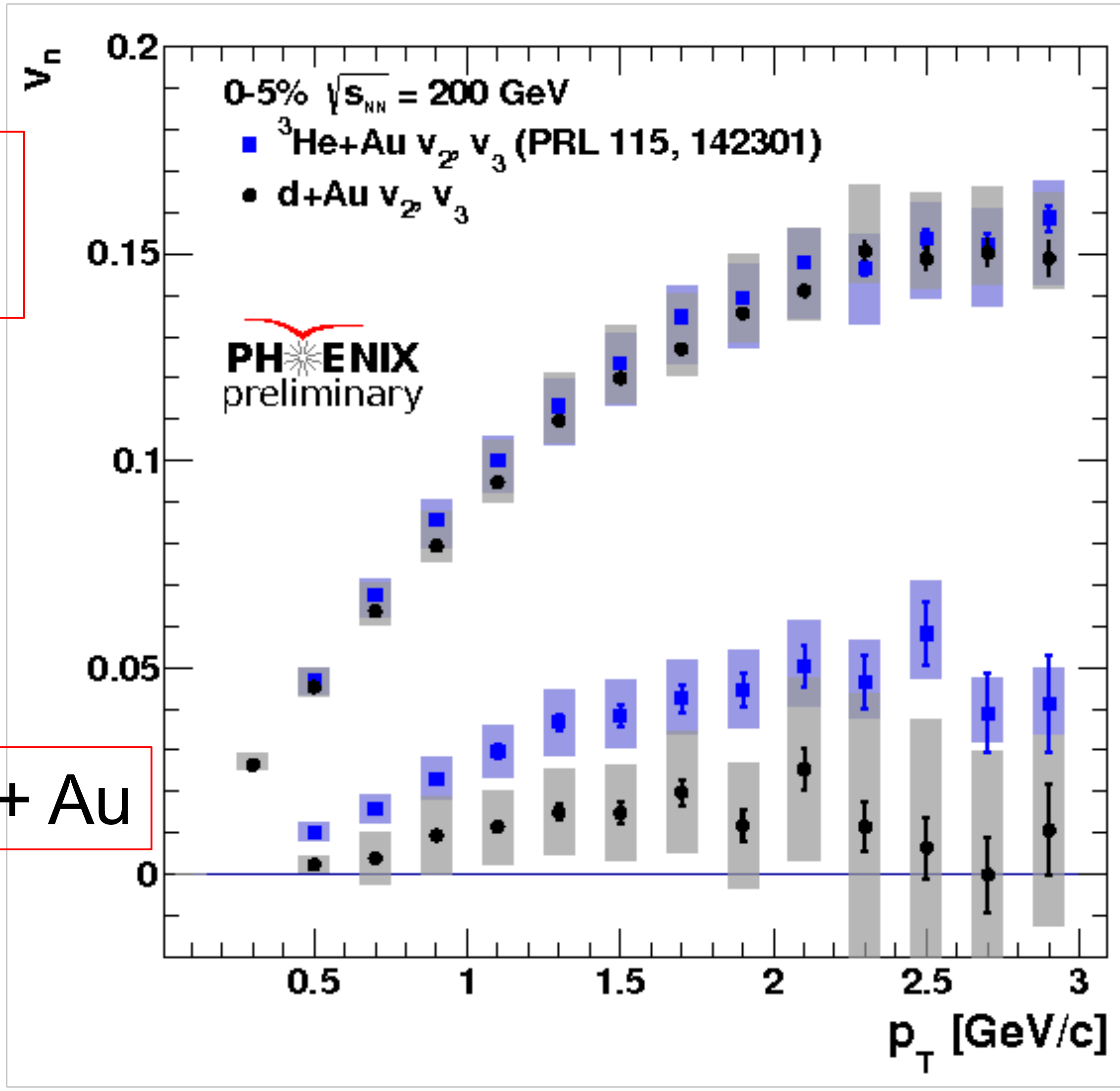
The v_2/ε_2 in p+Au is higher than that of d+Au and ^{3}He+Au collisions

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

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

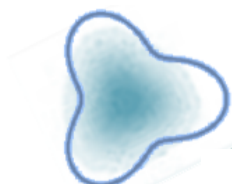
Triangular flow at 200 GeV in different systems: insights about the role of preflow

v_2 in d/^{3}He+ Au
Nearly identical



v_2

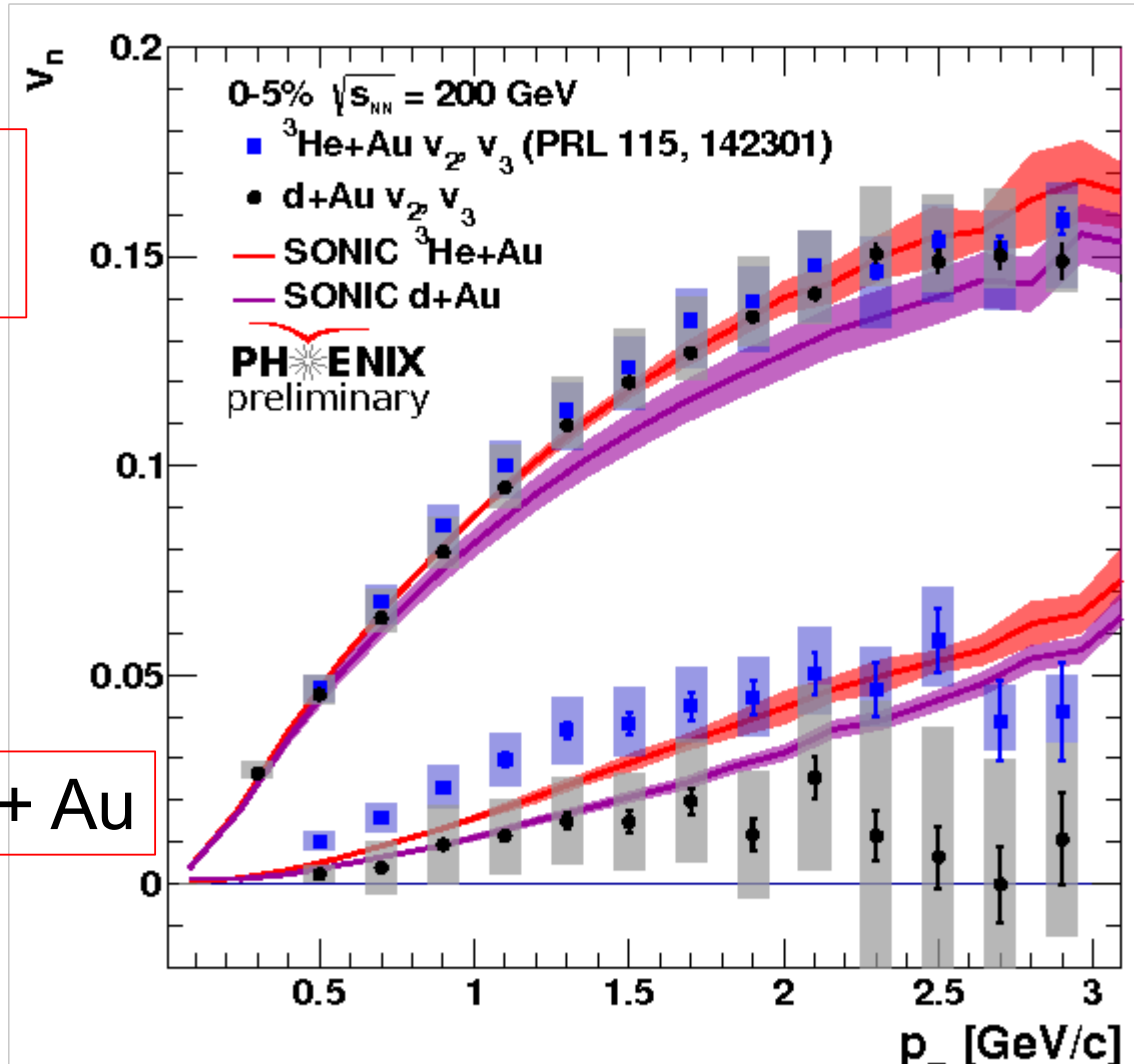
v_3



v_3 smaller in d+ Au

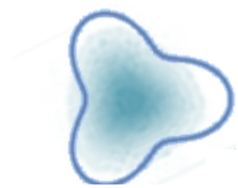
Triangular flow at 200 GeV in different systems: insights about the role of preflow

v_2 in d/^{3}He+ Au
Nearly identical



v_2

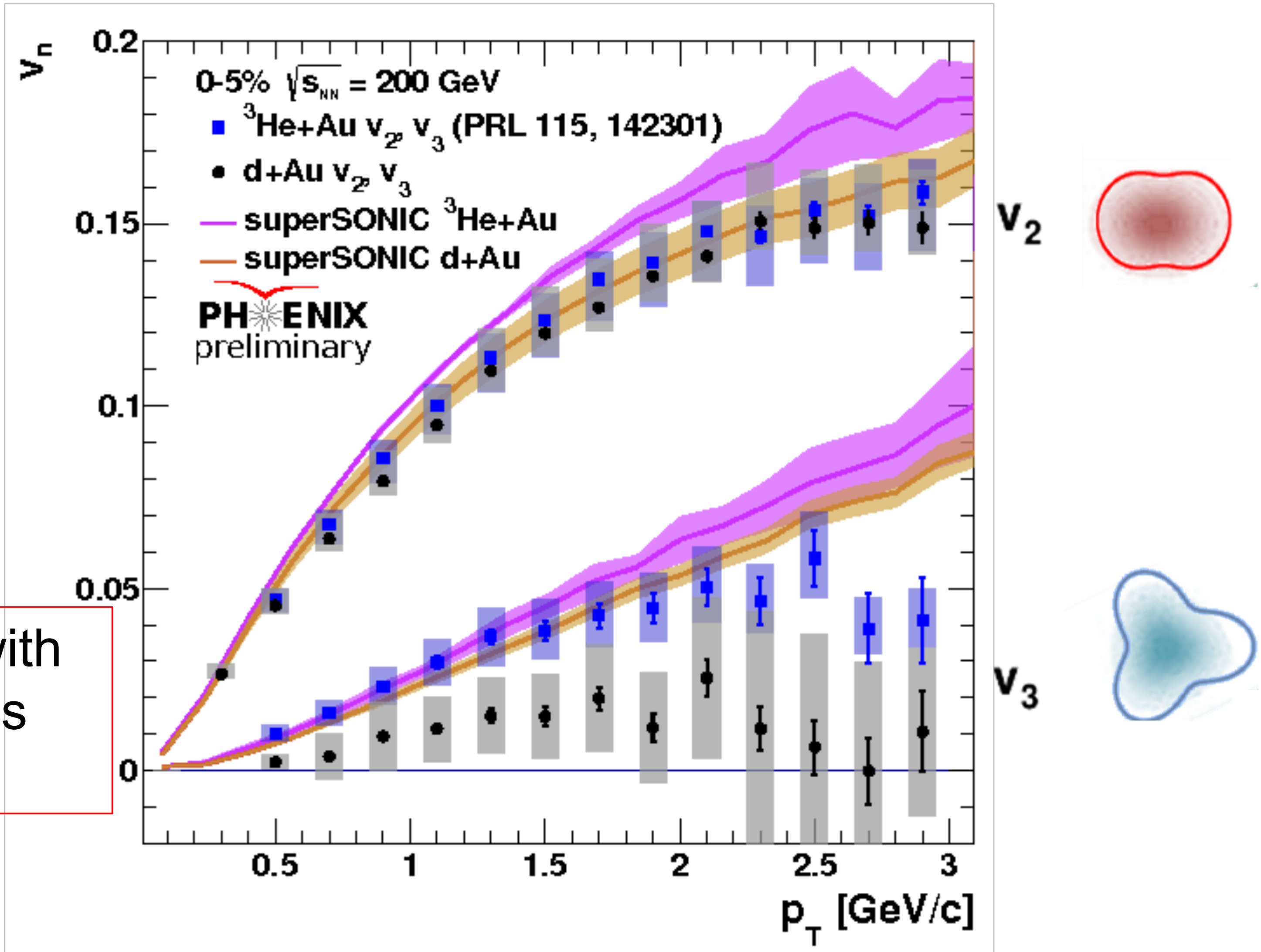
v_3



v_3 smaller in d+ Au

- Trends well described with hydro without preflow

Include pre-equilibrium flow



worse agreement with data when preflow is included

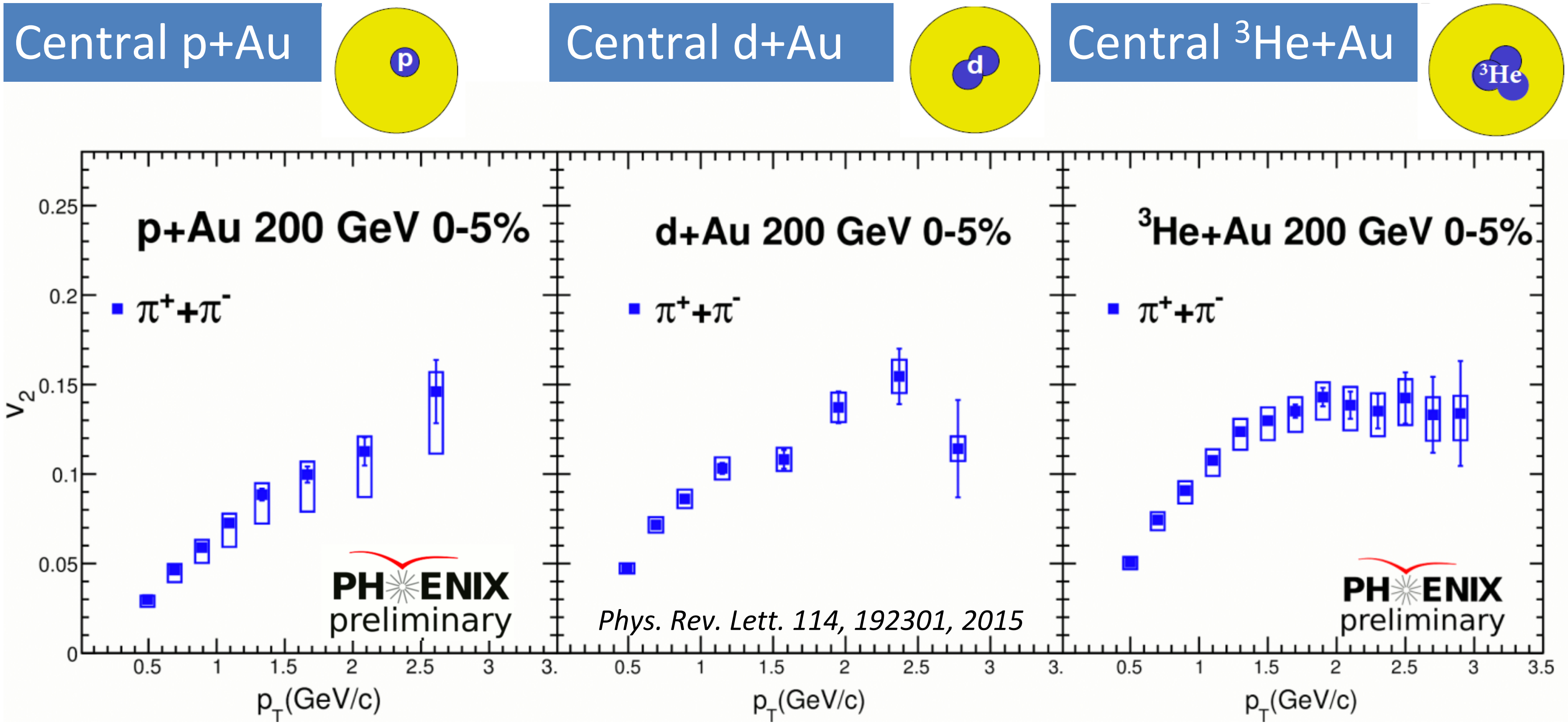
Relative contributions from pre-equilibrium and QGP need retuning ?

Identified particle v_2 in different systems

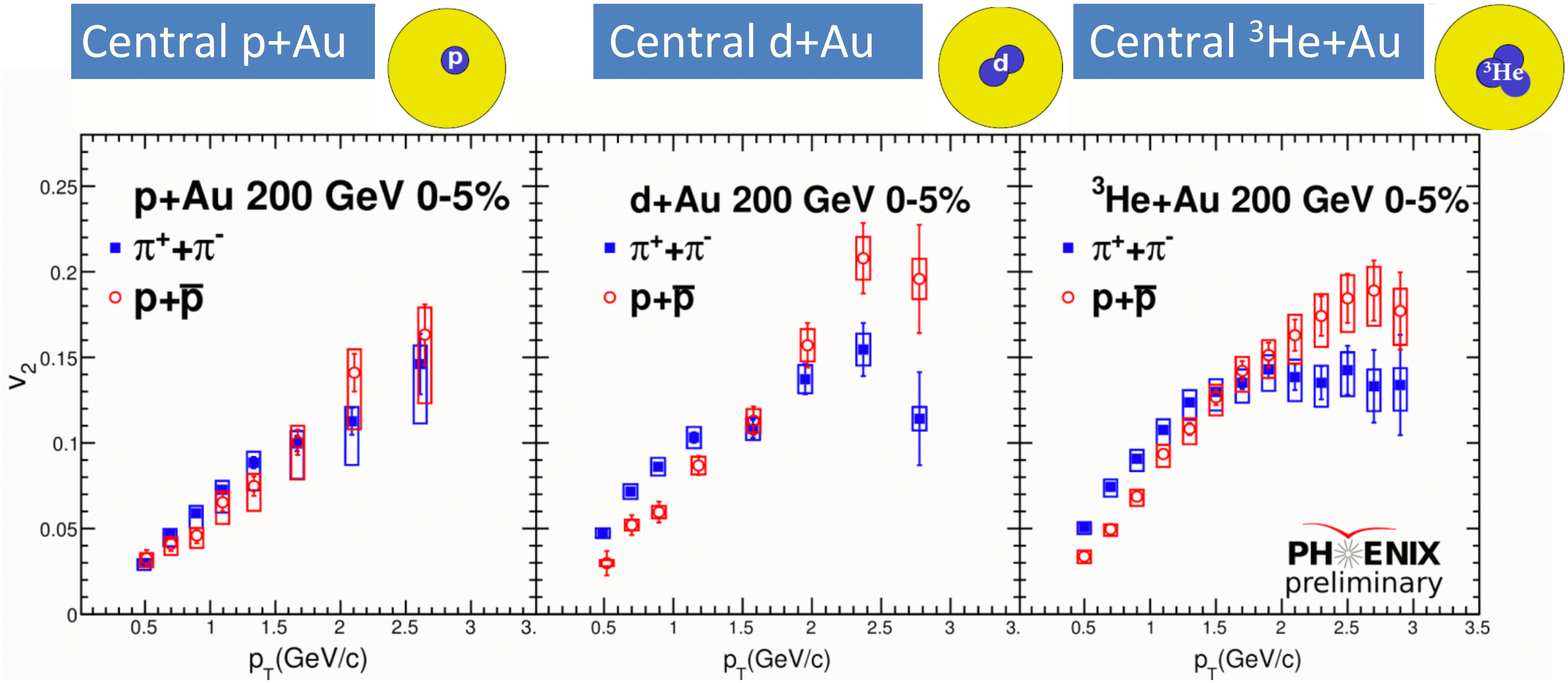
Central p+Au

Central d+Au

Central ^{3}He+Au



Identified particle v_2 in different systems



- Mass-ordering in all three systems
- Less pronounced in p+Au than in d+Au and ^{3}He+Au
- Need to compare to models

RESULTS

1. Ridge in different systems at 200 GeV
   - Pronounced ridge in d/^{3}He+Au, but not in pAl
   - In d+Au, the ridge extends over $\Delta\eta > 6.2$
2. Geometry scan: flow of inclusive and identified particles
   - $v_2(p_T)$ and $v_3(p_T)$ follow initial geometry
   - hydro and AMPT describe the data up to p_T ~ 3 or 1 GeV
   - v_3 in dAu and ^{3}HeAu discriminate against preflow/flow
   - identified particle $v_2(p_T)$ shows mass ordering → data/theory comparisons needed
3. **Energy scan with dAu**
   - $v_2(p_T)$ at midrapidity
   - $v_2(\eta)$
   - $v_2\{2\}$ and $v_2\{4\}$ vs multiplicity

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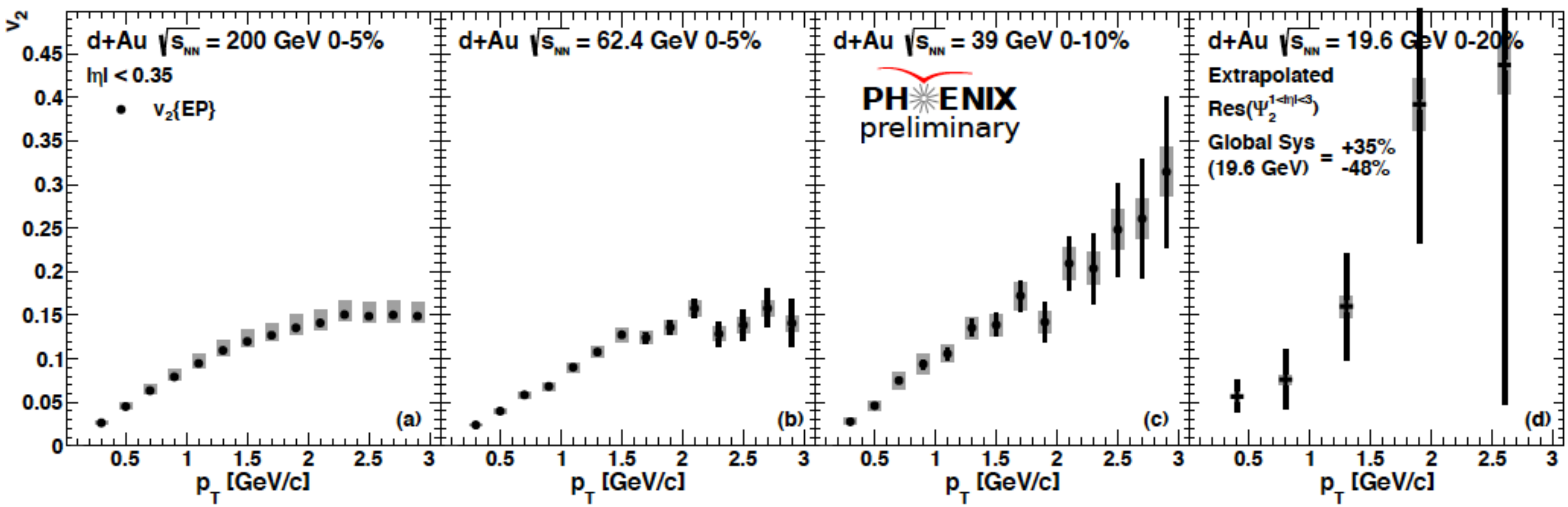
dAu BES: Event plane measurements of v_2

200 GeV **62 GeV** **39 GeV** **20 GeV**

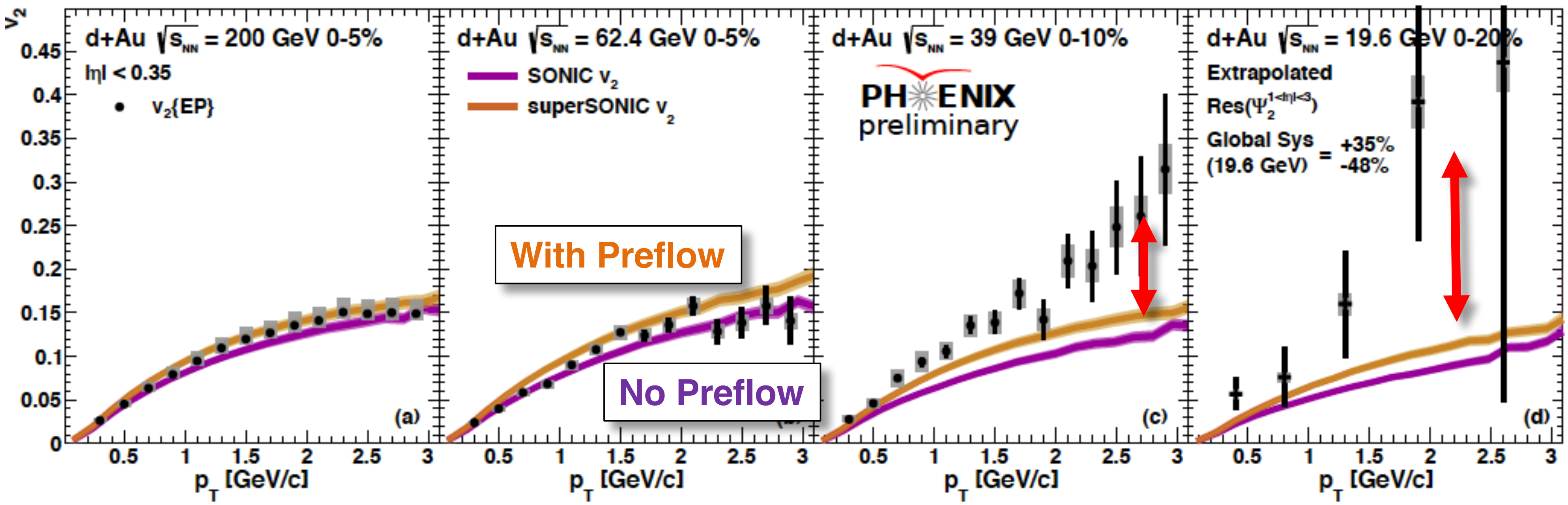


Nearly identical

Increase at high p_T ?

dAu BES: $v_2(p_T)$ and hydro models

200 GeV **62 GeV** **39 GeV** **20 GeV**

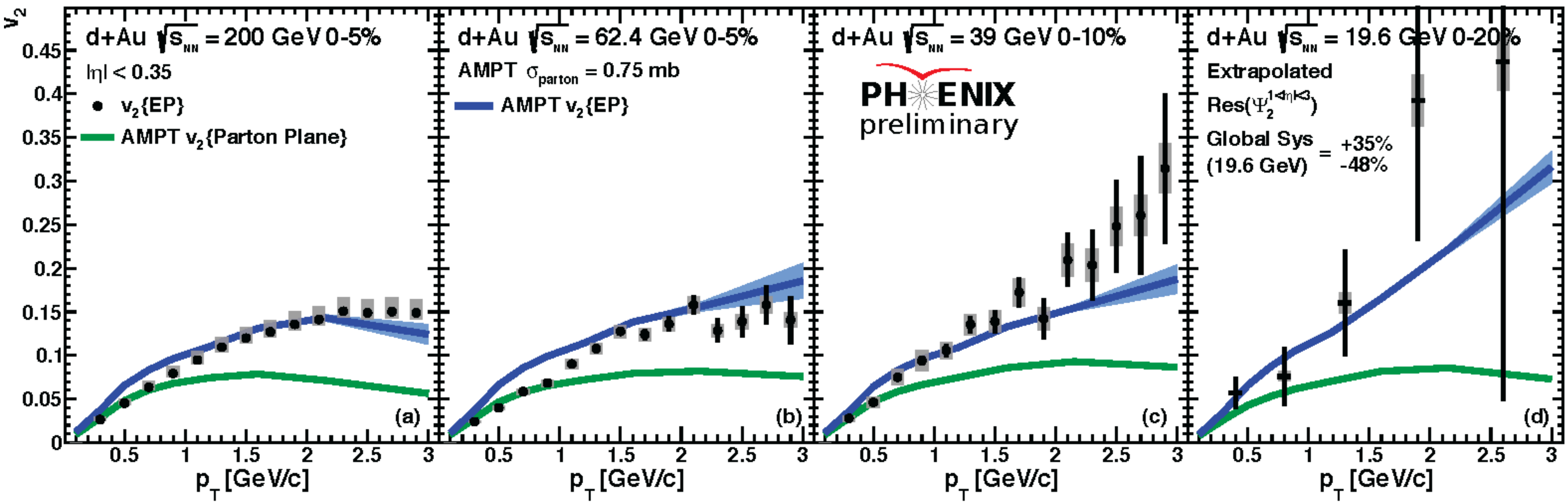


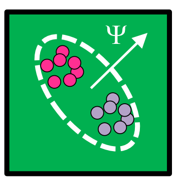
Nearly identical
Well described by hydro
No clear trend with preflow

Increase at high p_T ?
Nonflow ?

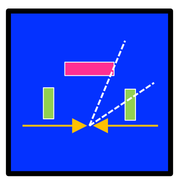
Nonflow correlations: insights from AMPT

200 GeV **62 GeV** **39 GeV** **20 GeV**





Pure Flow

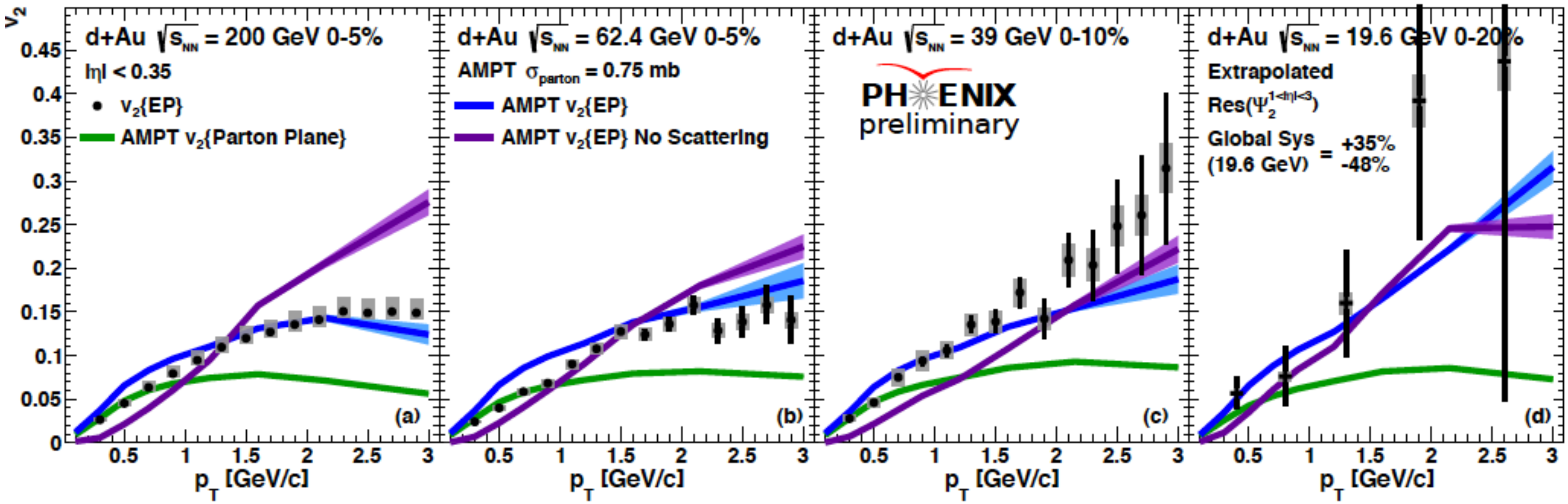


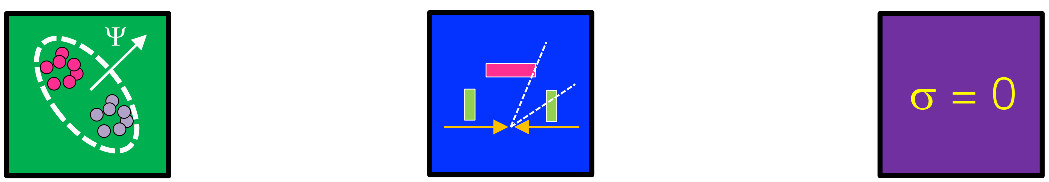
With Non-Flow

- Evidence for collective effects down to 39 GeV
- Nonflow correlations at 20 GeV require further studies

Nonflow correlations: insights from AMPT

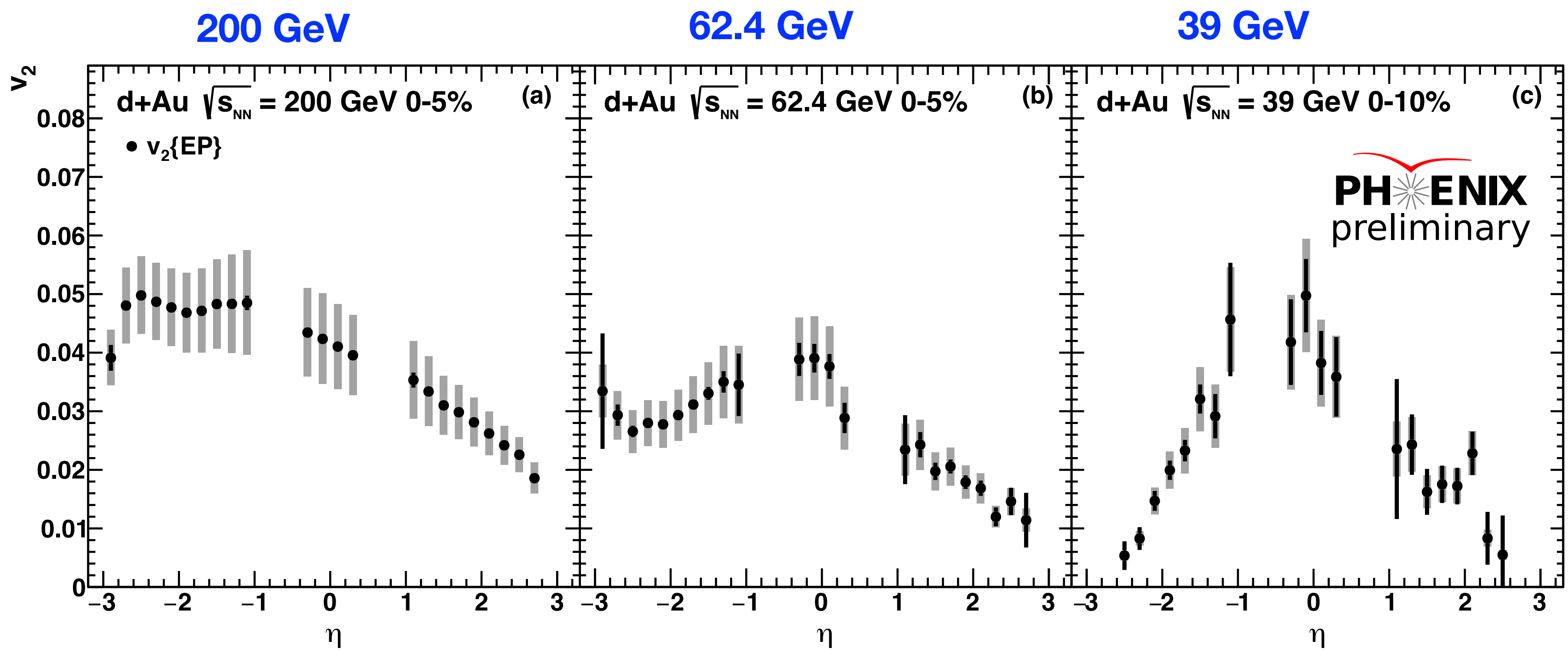
200 GeV **62 GeV** **39 GeV** **20 GeV**



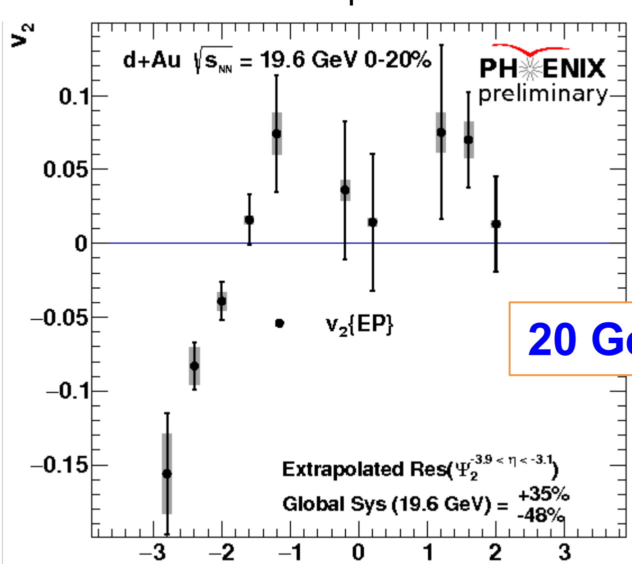


Pure Flow **With Non-Flow** **All Non-Flow**

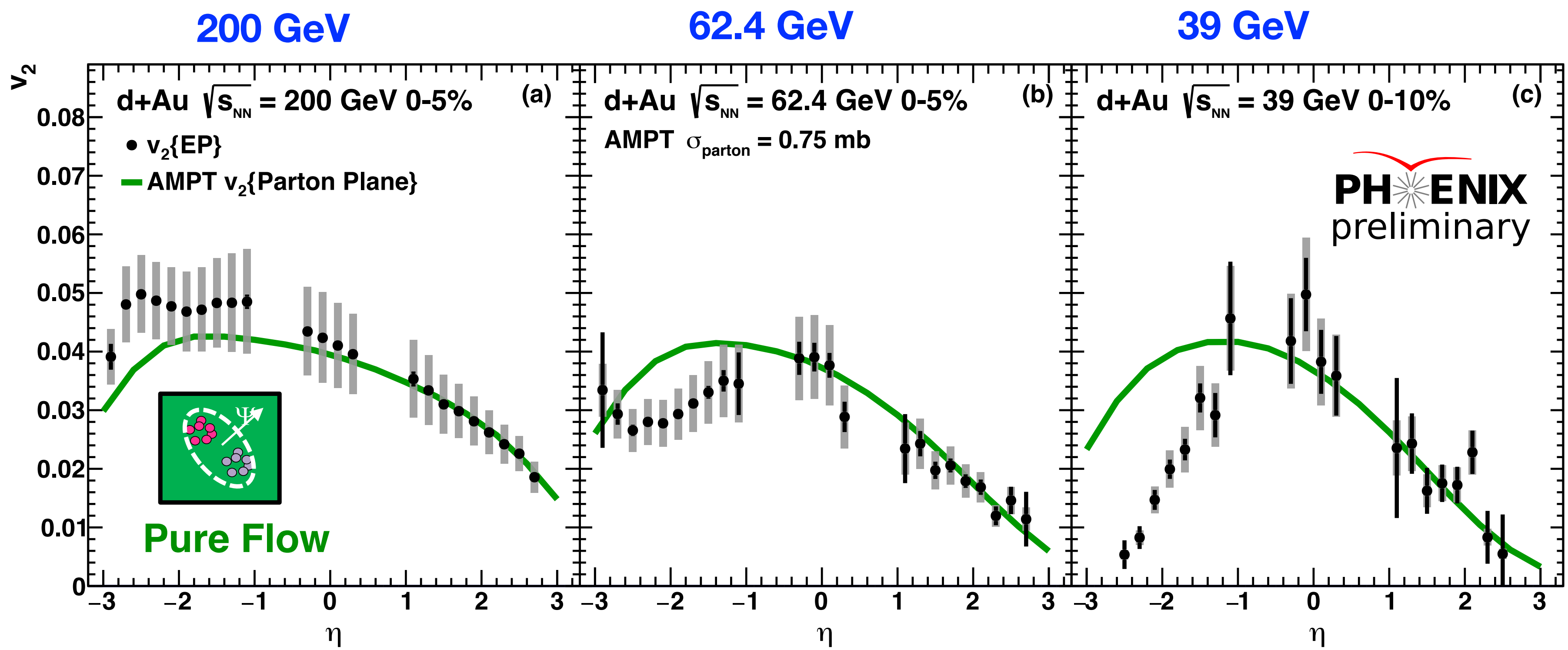
v_2 vs η



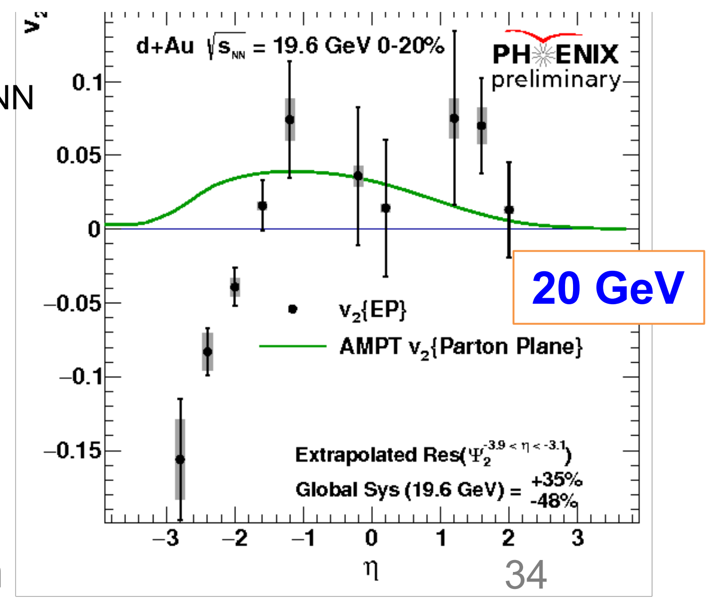
- Forward: similar values at all $\sqrt{s_{NN}}$
- Backward: decrease with $\sqrt{s_{NN}}$



Insights from AMPT

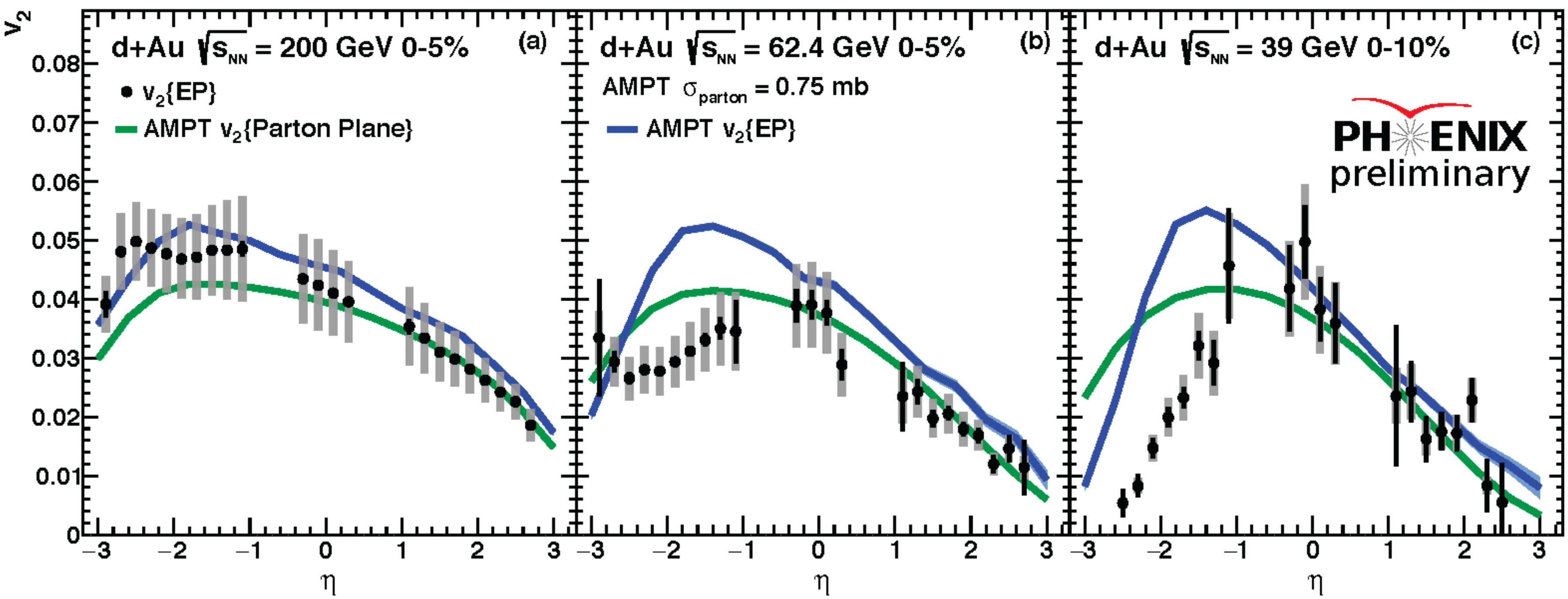


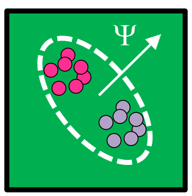
- Forward: well described at all $\sqrt{s_{NN}}$
- Backward: AMPT deviates from data at low energy



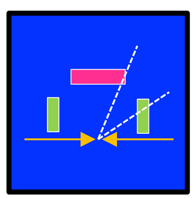
Insights from AMPT

200 GeV | 62.4 GeV | 39 GeV

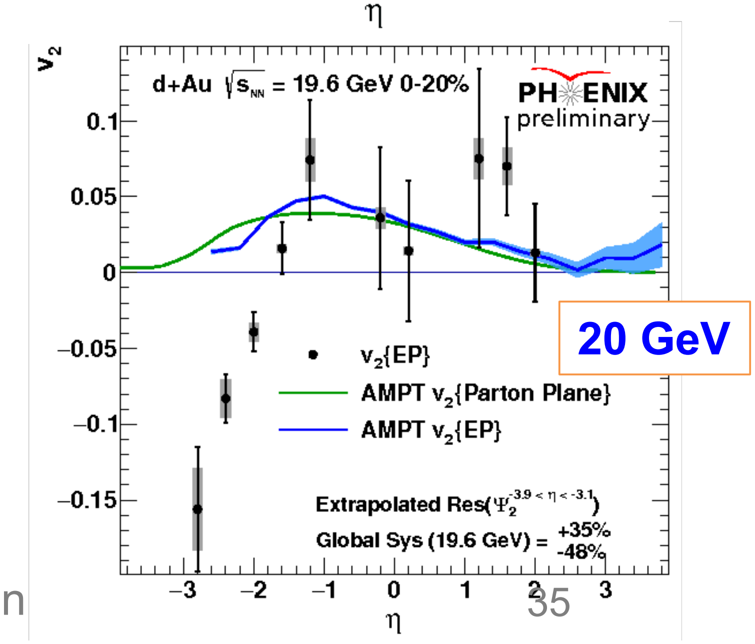




Pure Flow



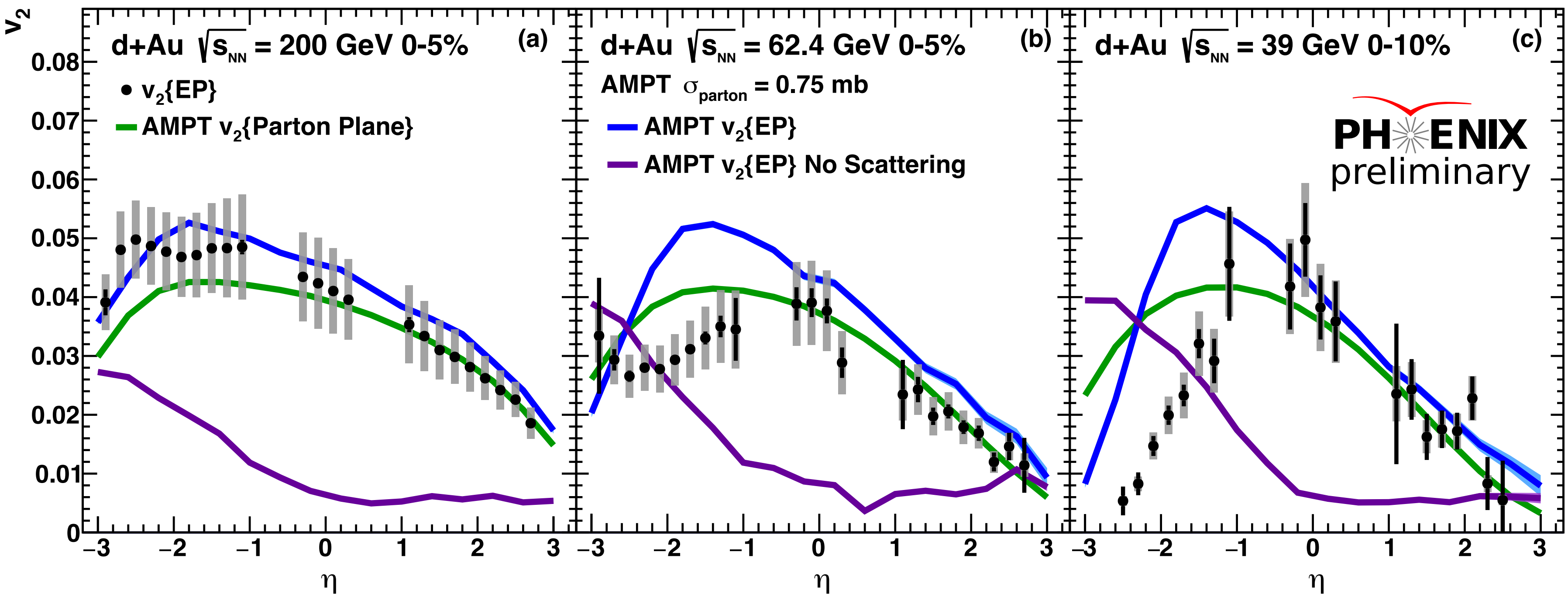
With Non-Flow

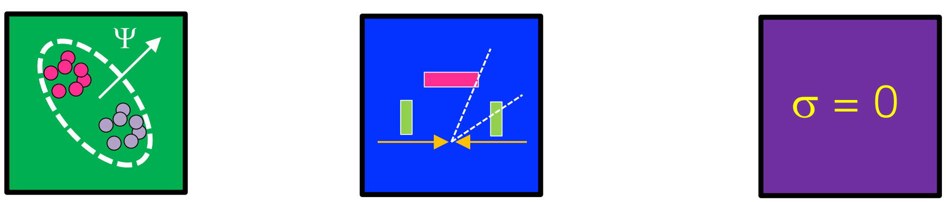


- Flow dominates at forward and middle pseudorapidity

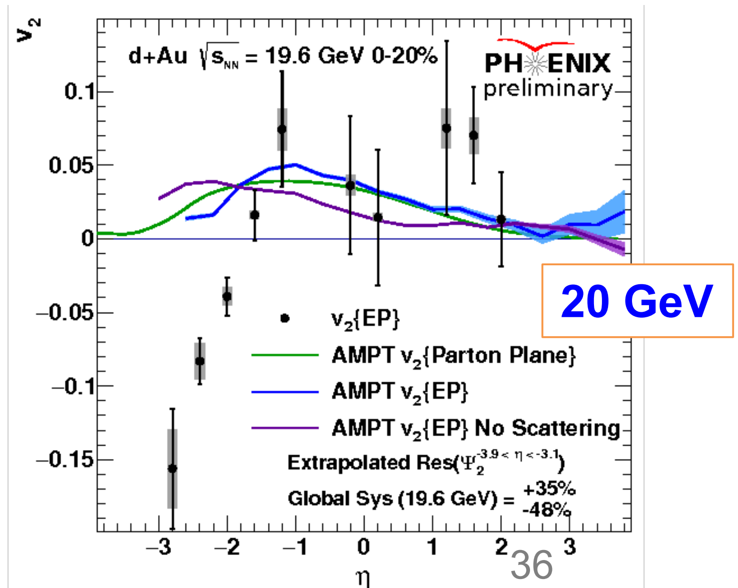
Insights from AMPT

200 GeV **62.4 GeV** **39 GeV**



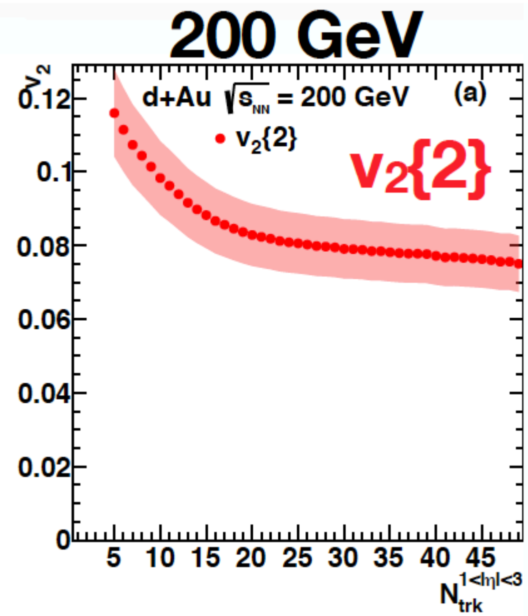


Pure Flow **With Non-Flow** **All Non-Flow**



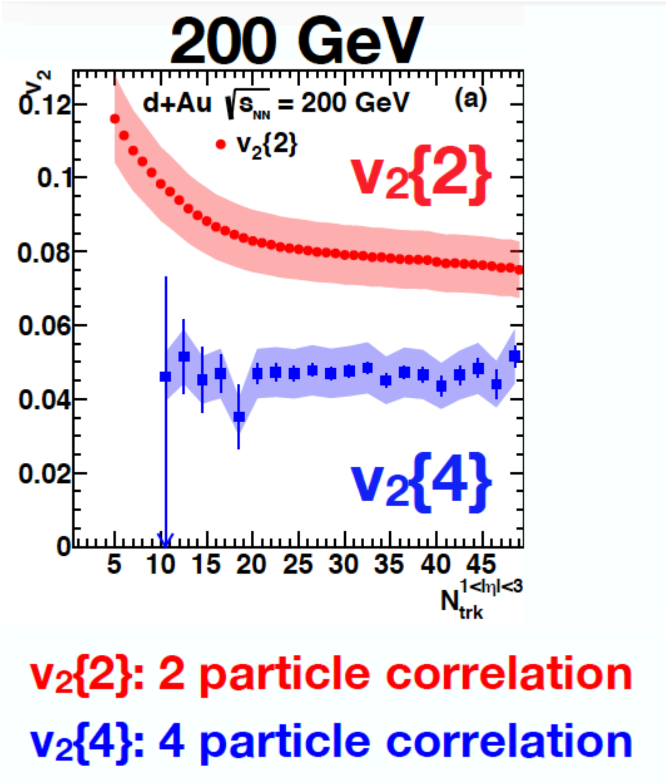
- Flow dominates at forward η

dAu BES: v_2 vs multiplicity from cumulants



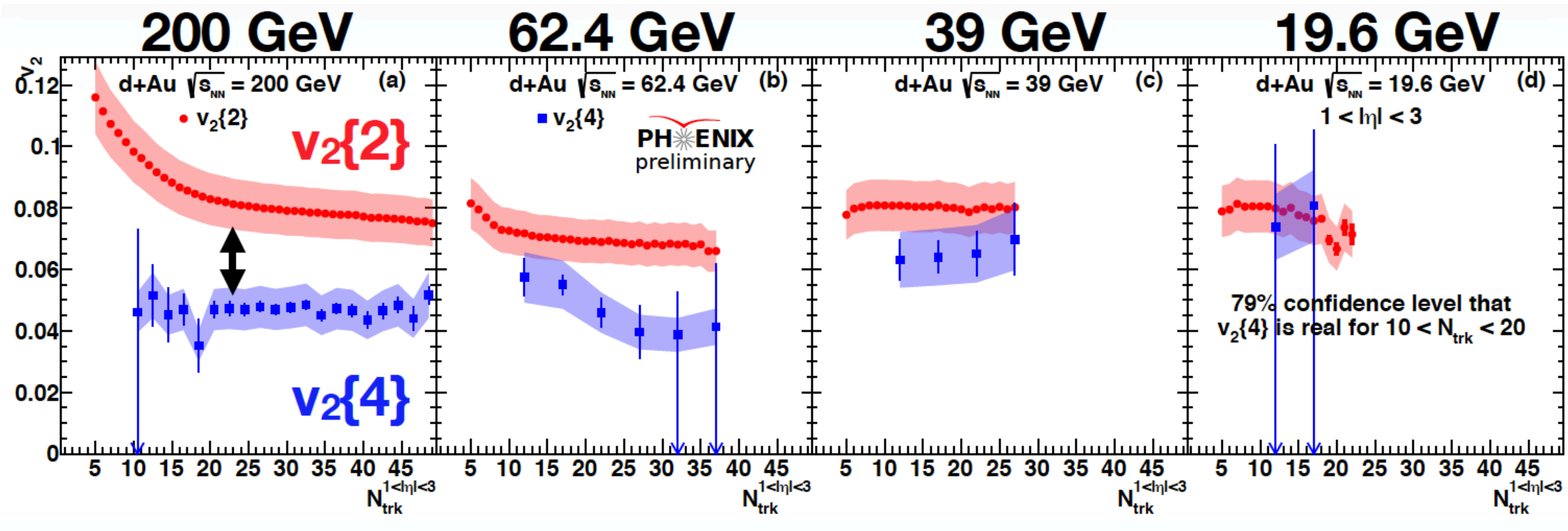
$v_2\{2\}$: 2 particle correlation

dAu BES: v_2 vs multiplicity from cumulants



the difference can be attributed to nonflow + fluctuations

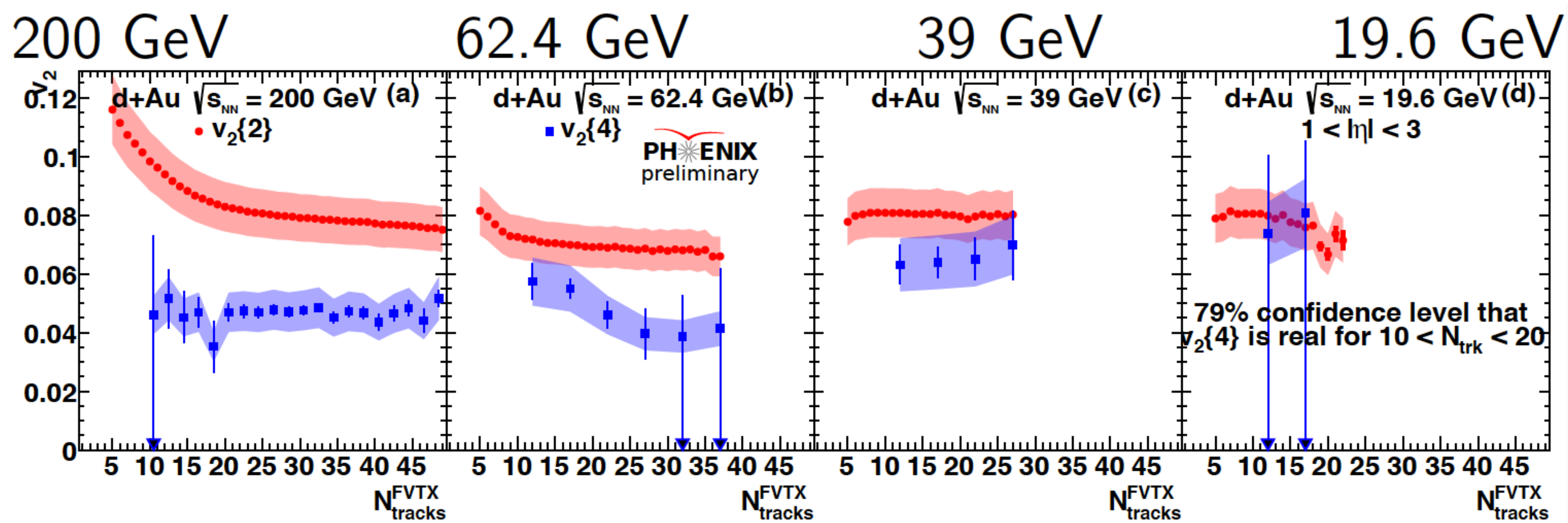
dAu BES: v_2 vs multiplicity from cumulants

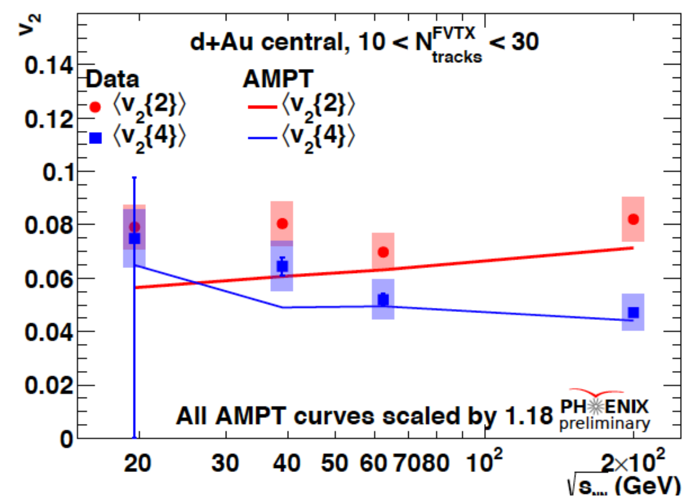


Real v2{4} at all 4 energies!

Evidence of collectivity down to 19.6 GeV

dAu BES: v_2 vs multiplicity from cumulants





- Select $10 < N^{FVTX}_{tracks} < 30$, integrate
- Trend of $v_2\{2\}$ and $v_2\{4\}$ merging as $\sqrt{s_{NN}}$ is lowered
- AMPT sees the same trend

Interesting correlation at low multiplicities needs to be understood further !

RESULTS AND CONCLUSIONS

1. Ridge in different systems at 200 GeV
   - Pronounced ridge in d/^{3}He+Au, but not in pAl
   - In d+Au, the ridge seen for $\Delta\eta > 6.2$–> **truly long-range**
2. Geometry scan: flow of inclusive and identified particles
   - $v_2(p_T)$ and $v_3(p_T)$ follow initial geometry
   - hydro and AMPT describe the data up to $p_T \sim 3$ or 1 GeV
   - v_3 in dAu and ^{3}HeAu discriminate against preflow/flow
   - identified particle $v_2(p_T)$ shows mass ordering → data/theory comparisons needed
3. Energy scan with dAu
   - $v_2(p_T)$ at midrapidity – nonzero v_2 at all energies
   - $v_2(\eta)$ – flow dominated at forward η; additional correlations at backward η
   - $v_2\{2\}$ and $v_2\{4\}$ vs multiplicity: evidence for collectivity down to 20 GeV !

PHENIX

BACKUP

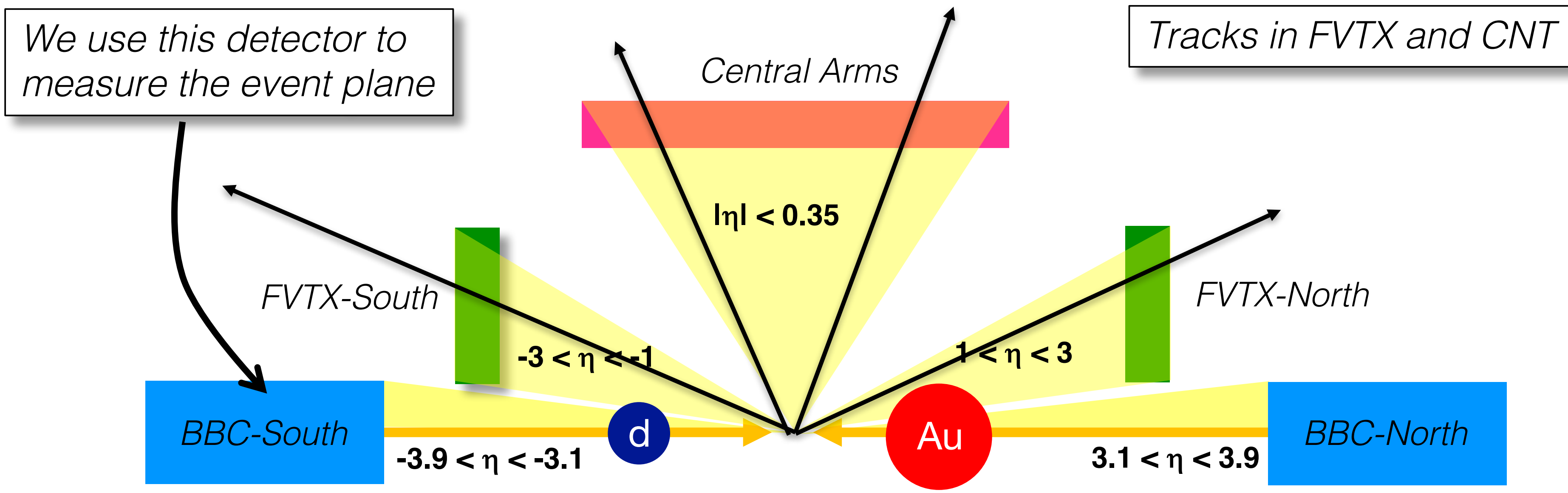
Table 6: Summary of the systematic uncertainties on the v_2 vs p_T measurements at 200, 62.4, and 39 GeV.

Sys	200	62.4	39
Double interactions	$+9.4\%$	$< 1\%$	$< 1\%$
Event Plane	4.5%	4.5%	4.5%
East vs West	1.6%	3.6%	5.9%
PC3 Match	1%	1%	1%
ϕ shift	1%	1%	10% $p_T < 1$ and 5% $p_T > 1$
Total	$^{+10.6\%}_{-4.9\%}$	$\pm5.8\%$	$\pm7.5\%$

Table 8: A summary of the systematic uncertainties applied to the measurement of v_2 vs η in 200, 62.4, and 39 GeV d+Au collisions.

Sys	Type	200	62	39
Double Interactions	B	$+2\%$	$< 1\%$	$< 1\%$
Event Plane	B	4.8%	4.8%	4.8%
Fake Tracks	B	3.3%	3.3%	3.3%
E vs W	B	1.6%	3.6%	5.9%
AMPT correction	B	$\sim 0-3\%$	$\sim 0-3\%$	$\sim 0-3\%$
Total (approx.)	B	$^{+8\%}_{-7\%}$	$\pm8\%$	$\pm9\%$

v_2 vs η: analysis method



1. d+Au collisions generated with AMPT

- Determine parton-plane angle ,"true" ψ_2
- Use all final-state charged particles to determine "true" $v_2(\eta)$

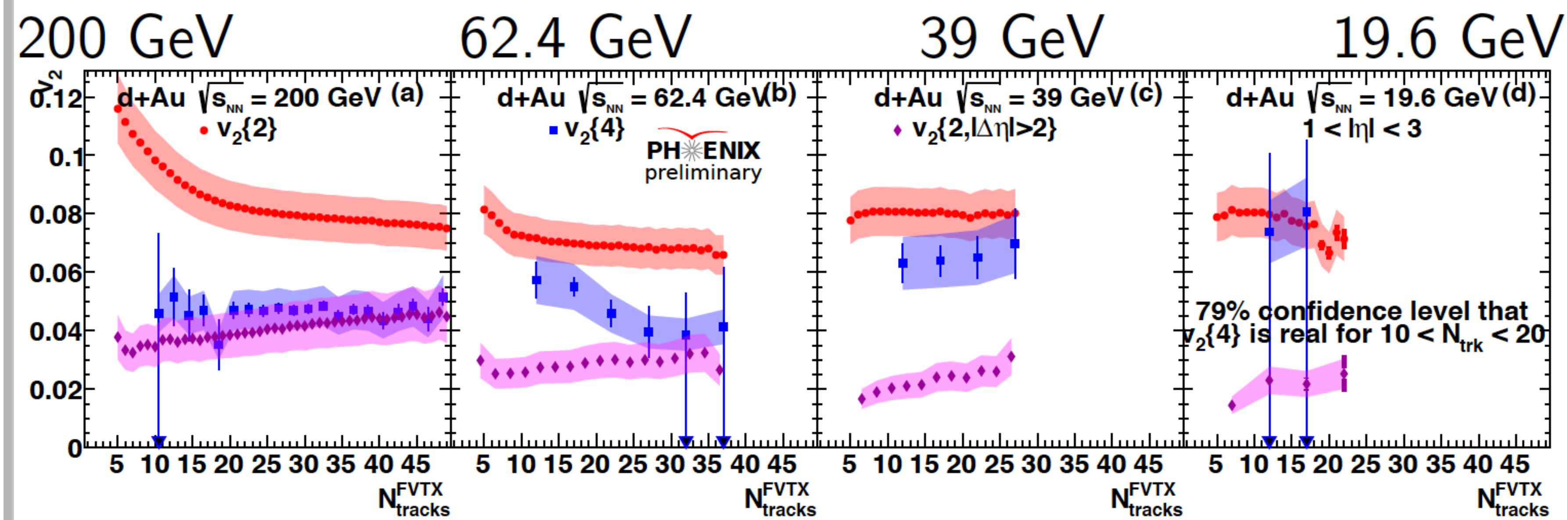
2. reconstruct events with full GEANT simulation in PHENIX

- Analyze using final-state particles in the PHENIX acceptance to get $v_2(\eta)$

Correction factor = v_2 from step (2)/ (1)

- Apply correction to data $v_2(\eta)$
- Change the AMPT input parton cross section (and resulting v_2)→ repeat
- Change the input p_T spectra → repeat

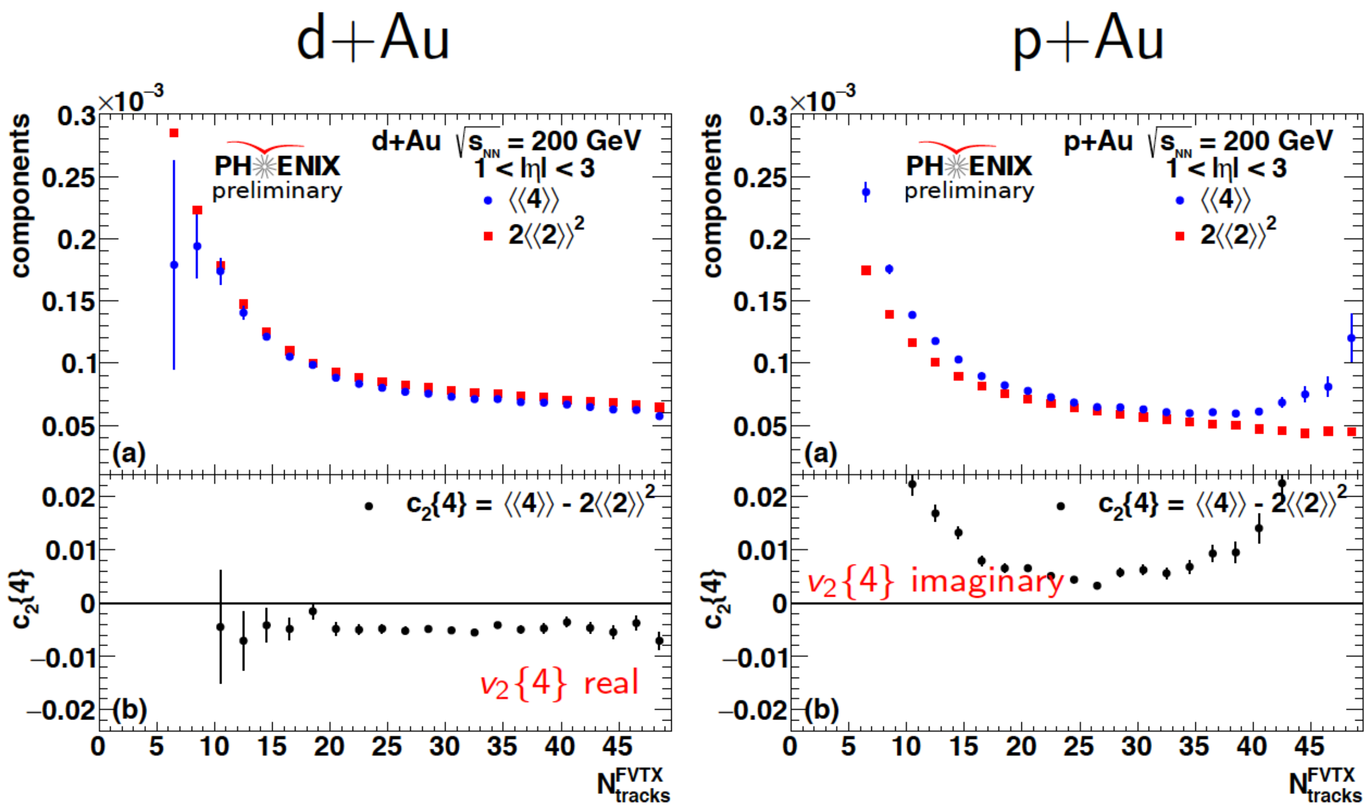
Understanding $v_2\{2\}$, $v_2\{4\}$, and $v_2\{2, |\Delta\eta| > 2\}$



- $v_2\{2\}$ and $v_2\{4\}$ vs N_{tracks}^{FVTX}—weighted average of v_2^B and v_2^F
- $v_2\{2, |\Delta\eta| > 2\}$ vs N_{tracks}^{FVTX}—fixed, equal weighting $\sqrt{v_2^B v_2^F}$
- $dN_{ch}/d\eta$ and v_2 vs η alone may explain these results

Ron Belmont QM17

Components and cumulants in p+Au and d+Au at 200 GeV



- Real $v_2\{4\}$ in d+Au, imaginary $v_2\{4\}$ in p+Au
- Fluctuations could dominate in the p+Au ($v_2\{4\} = \sqrt{v_2^2 - \sigma^2}$)