The Collective Behavior at the Small Collision Systems Measured by the PHENIX Experiment at RHIC

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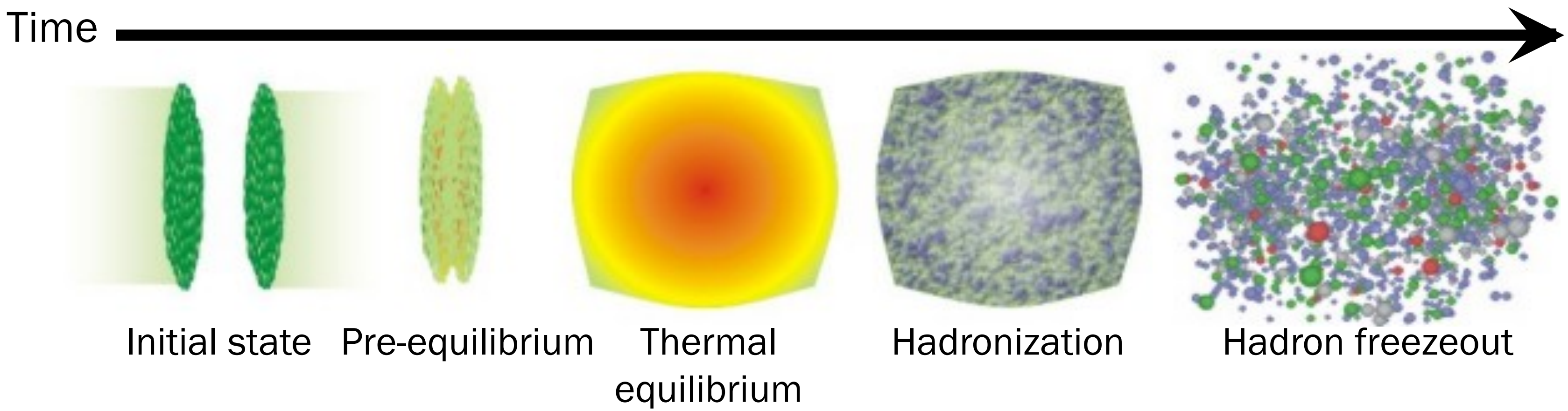
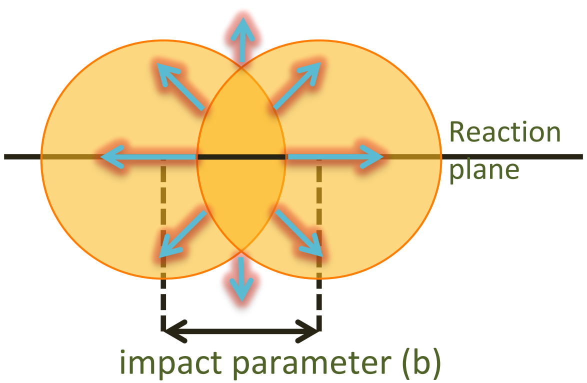
Collective behavior in heavy ion collision





- Common understanding of A+A collisions
- Nearly ideal fluid with low viscosity created – sQGP.
- Multi-particle correlations among rapidities which originated from a common source.
- In dihadron correlations, Fourier harmonics v_n are commonly attributed to hydrodynamic flow.
- **Nonflow** : Non-collective originated correlation also exists; jet, particle decays, EP decorrelations, HBT etc.

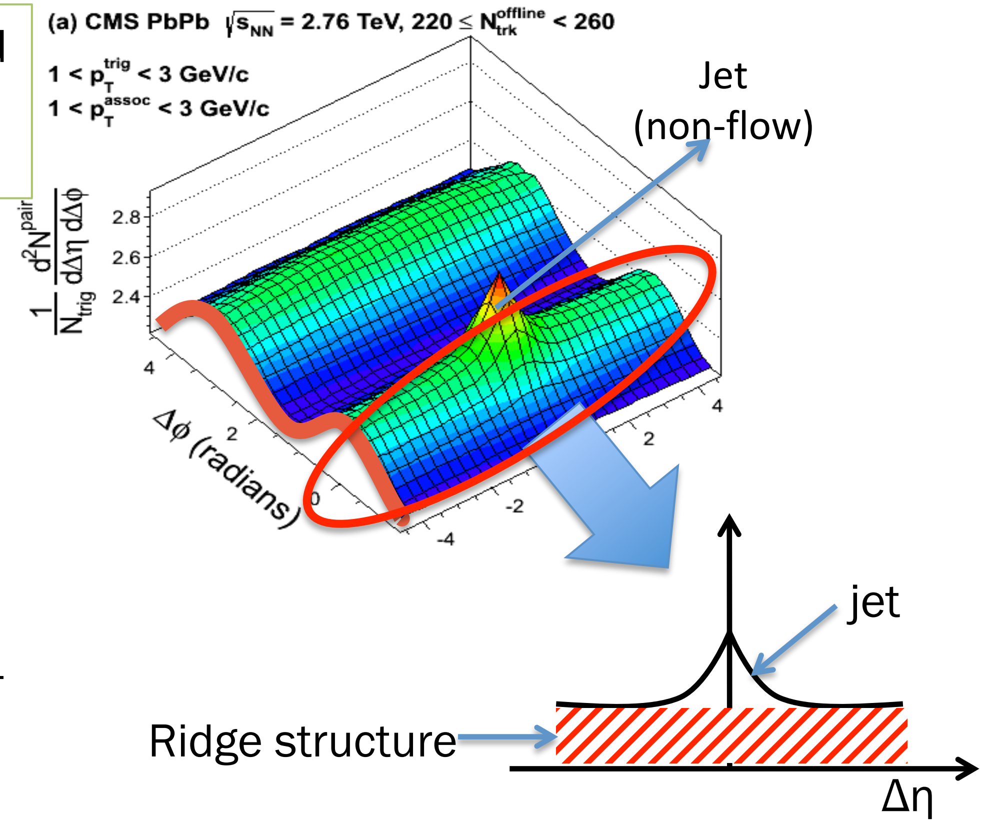
Near-side long-range ridge structure

From the two-particle correlation, multiplied value shown at the near-side ridge:

$v_2(p_T^A)\, v_2(p_T^B) = c_2^{AB}$

$$\frac{1}{N_{trig}}\frac{dN^{pair}}{d\Delta\phi} \sim 1 + 2(v_2)^2\cos(2\Delta\phi)$$

Non-zero!



"Elliptic flow"

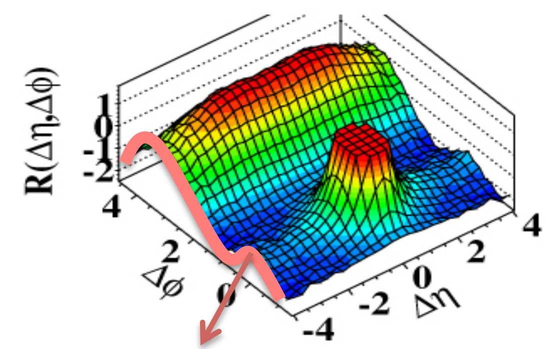
The non-zero v_2 explains the near-side long-range ridge structure which corresponds to the elliptical shape of the generated medium.

Collective dynamics of the small systems

- What is the smallest system size that can create a QGP?
- What is the role of the initial geometry?
- How important are the contributions from the initial state and the hadronization process?
- How do we quantify the long range ridge structure?
- What is the physics behind?

JHEP09(2010)091

CMS $N \geq 110$, $1.0\text{GeV/c} < p_T < 3.0\text{GeV/c}$



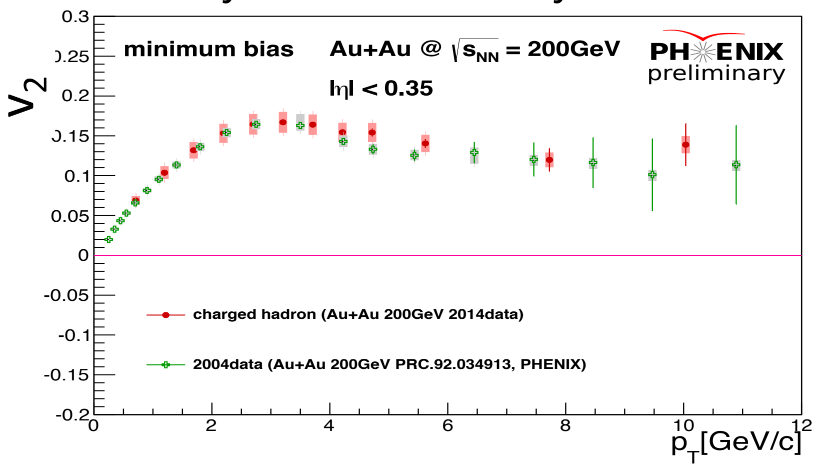
QGP-originated elliptic flow?

Considerable size of near-side long-range ridge structure measured at p+p 7TeV(CMS) at the very high multiplicity events.

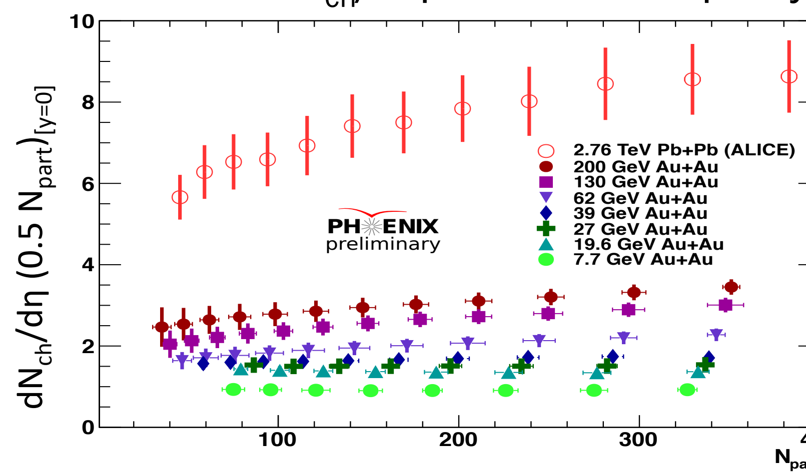
PHENIX datasets

$\sqrt{s_{NN}}$ [GeV]	U+U	Au+Au	Cu+Au	Cu+Cu	^{3}He+Au	d+Au	p+Au	p+p
510								✔
200	✔	✔	✔	✔	✔	✔	✔	✔
62.4		✔		✔		✔		✔
39		✔				✔		
19.6		✔		✔		✔		

Collective dynamics of Heavy ion collisions



Measured $dN_{ch}/d\eta$ at the mid-rapidity



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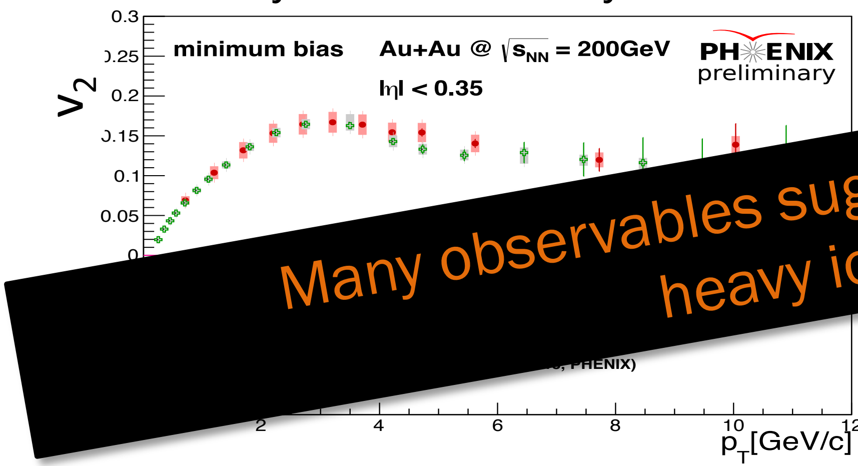

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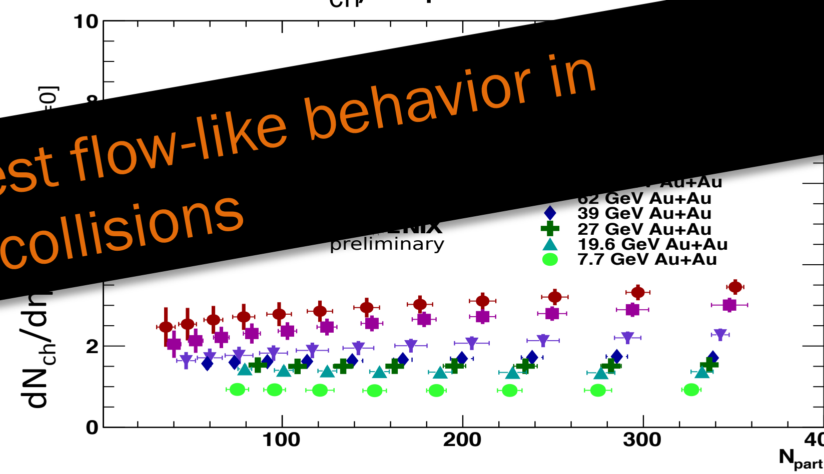

Many observables suggest flow-like behavior in heavy ion collisions

PHENIX datasets

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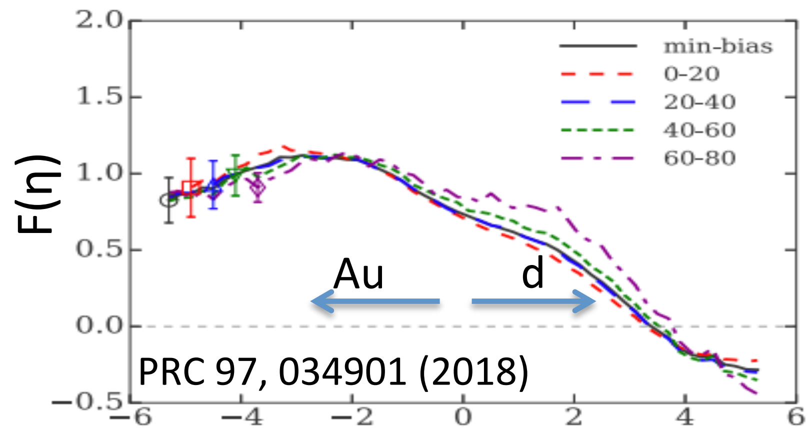
Nature Physics **15**, 214-220 (2019)

PRL **120**, 062302 (2018)
PRC **96**, 064905 (2017)

- In small collision systems, can we find some similar features of the heavy ion collisions case?
- Do these features indicate QGP formation?
- How can we interpret them based on our present understanding of the QGP?



small systems F(η) of wounded quark model using PHOBOS d+Au 200GeV

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PRL **120**, 062302 (2018)
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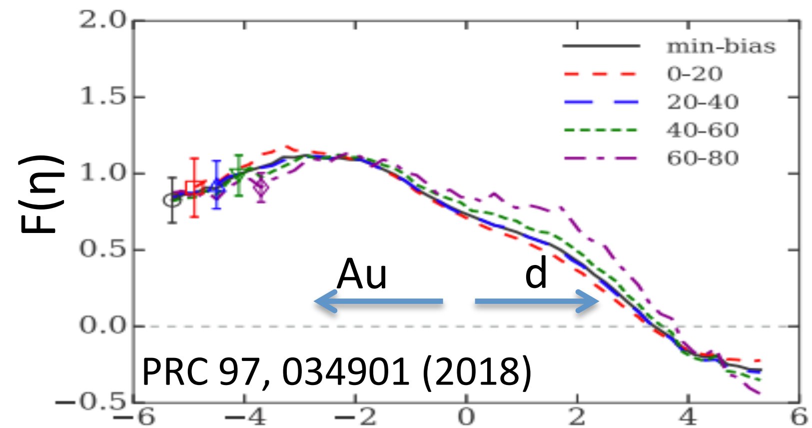
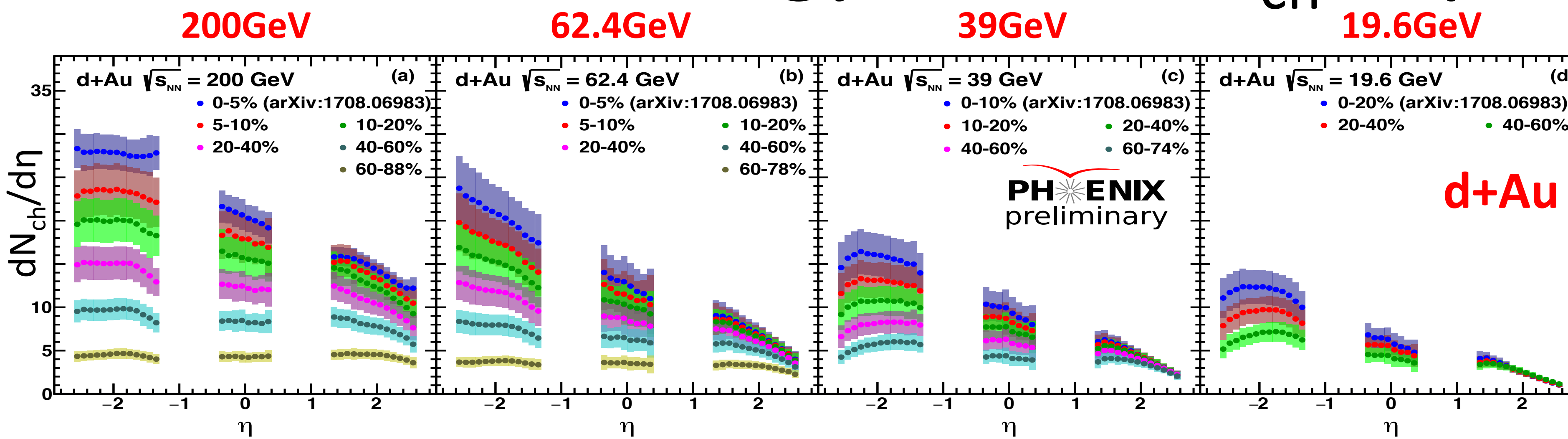
What about small systems?

- Beam-energy scan data of d+Au



small systems F(η) of wounded quark model using PHOBOS d+Au 200GeV

d+Au Beam Energy Scan : $dN_{ch}/d\eta$

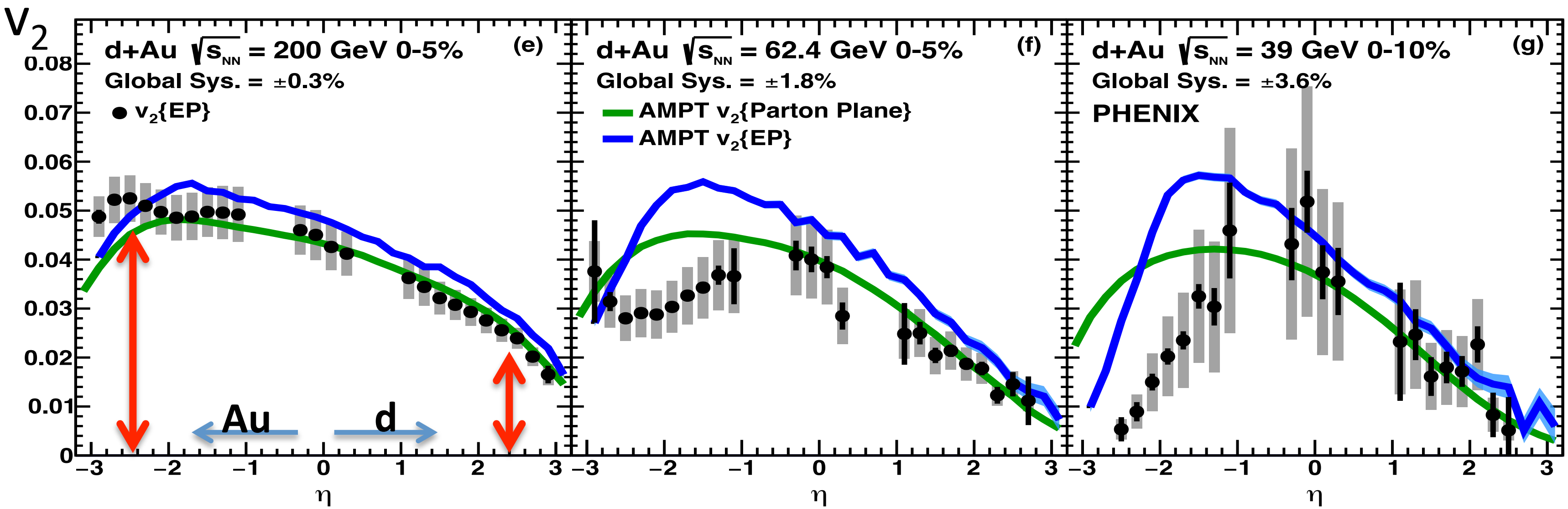


Collision energy gets to be smaller by
a factor of about ~10

$dN_{ch}/d\eta$ decreases by a factor of ~3

PRC 96, 064905 (2017)

d+Au Beam Energy Scan : v_2 vs η



Larger v_2 in Au-going direction, but this asymmetry becomes smaller in lower energies.

d-going, η>0

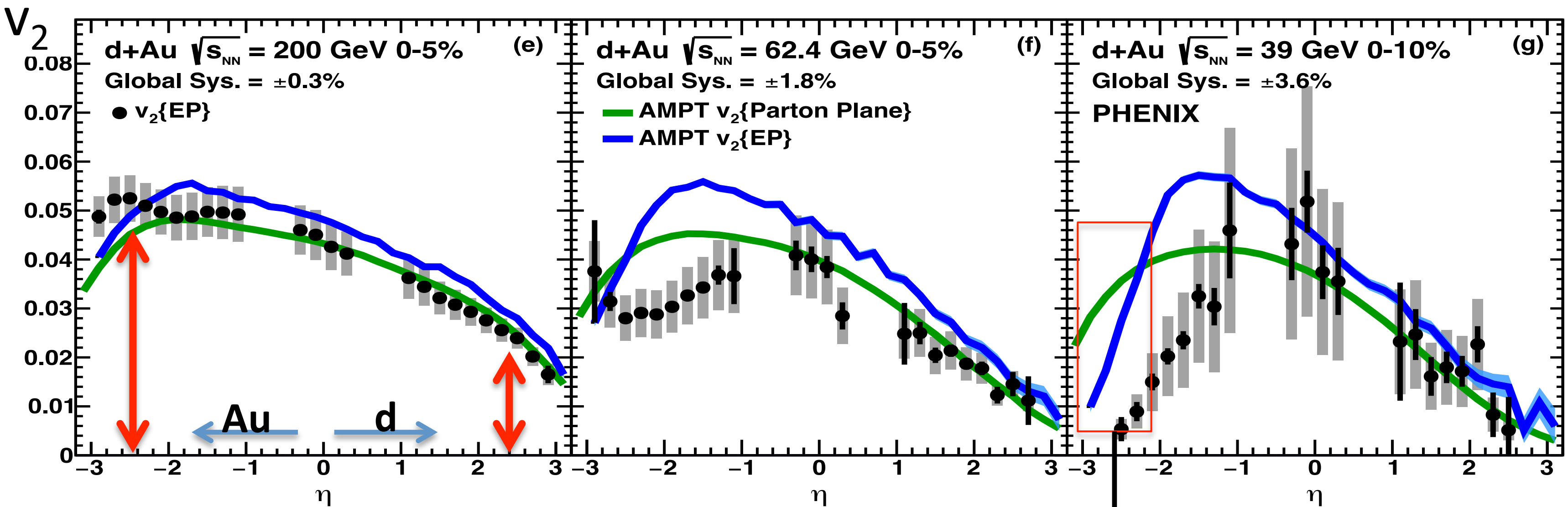
- 3 energies have similar size of v_2
- AMPT $v_2^{\{EP\}}$ describes the data quite well in all three collision energies with small non-flow contribution.

Au-going, η<0

- v_2 decreasing at the lower energy
- AMPT $v_2^{\{EP\}}$ described data points well, but tends to overshoot in lower energies.

PRC 96, 064905 (2017)

d+Au Beam Energy Scan : v_2 vs η



Larger v_2 in Au-going direction, but this asymmetry becomes smaller in lower energies.

Nonflow is not additive!

d-going, η>0

- 3 energies have similar size of v_2
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Au-going, η<0

- v_2 decreasing at the lower energy
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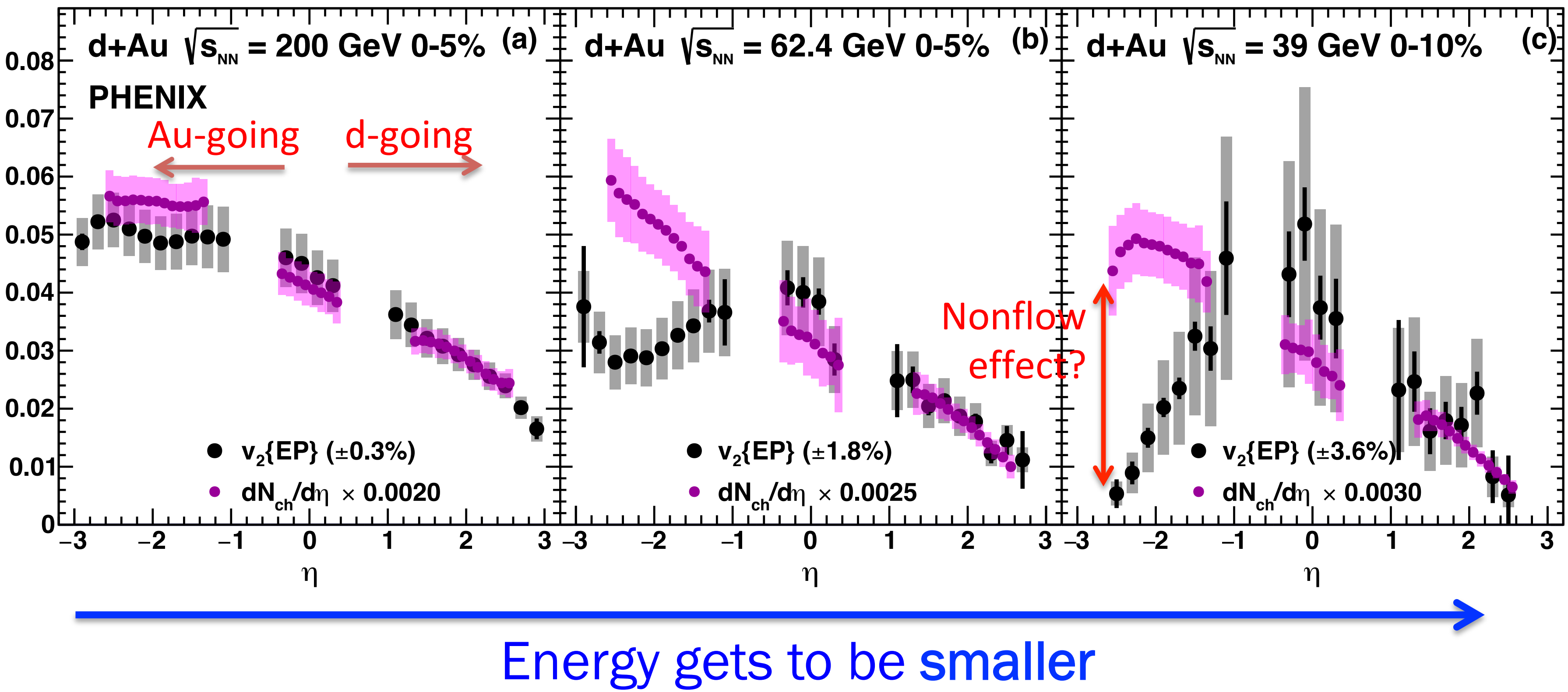
PRC 96, 064905 (2017)

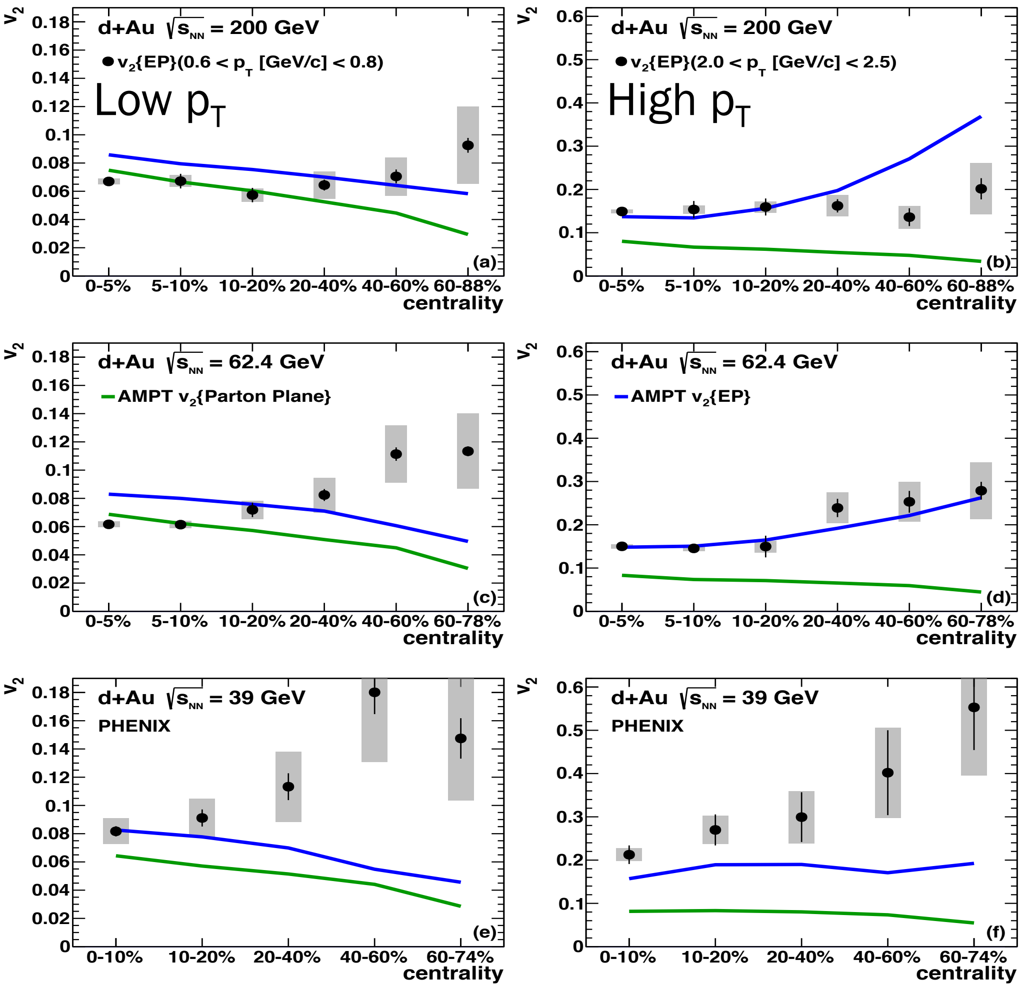
d+Au v_2 and the scaling $dN_{ch}/d\eta$



- One interesting feature of v_2 and the $dN_{ch}/d\eta$

PRC 96, 064905 (2017)

v_2 vs. centrality



v_2 increases: low multiplicity

-As the collisions become more peripheral.

-As the collision energy decreases.

AMPT predicts

-$v_2^{PartonP}$ decrease as centrality

-At lower p_T, two curves more in agreement.

-At high p_T, v_2^{EP} is significantly larger than v_2^{ParonP} where non-flow effects may dominant.

There would be additional nonflow effect which are not included.

PHENIX datasets

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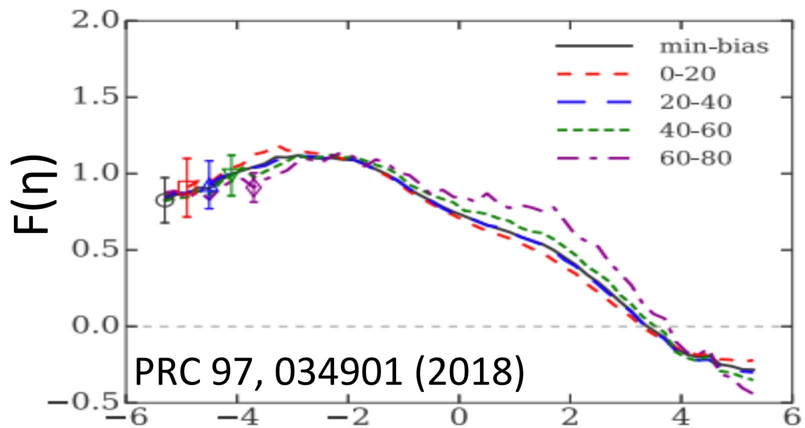
Nature Physics **15**, 214-220 (2019)

What about small systems?

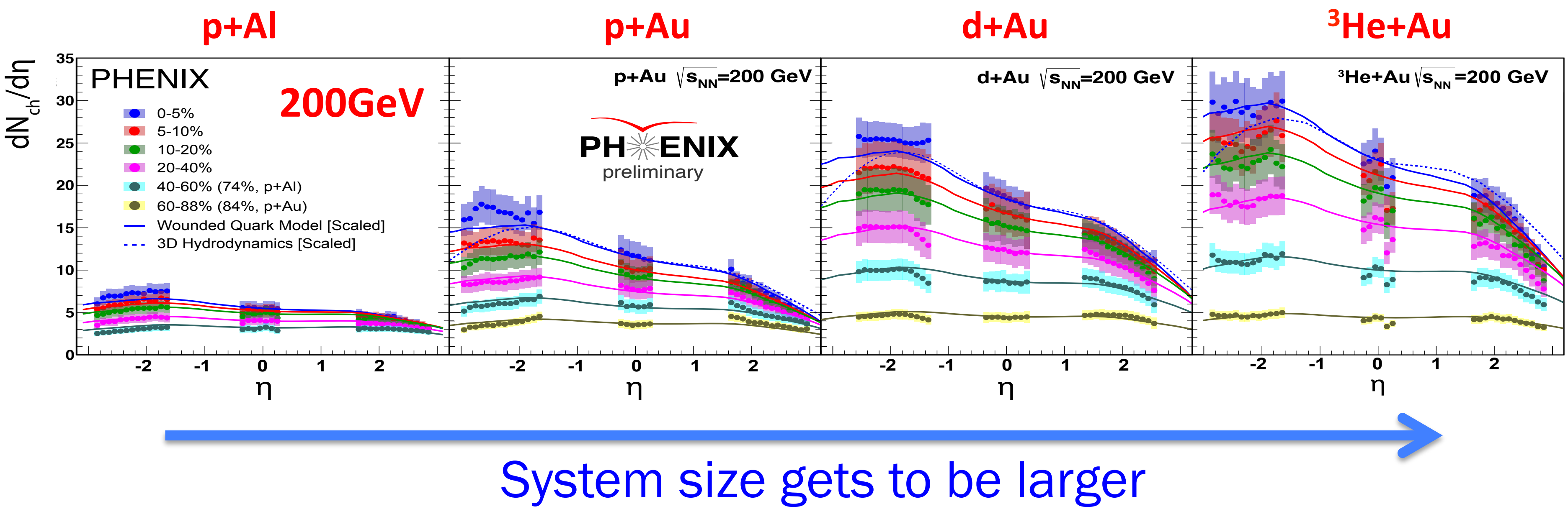
- System-size, and initial geometry dependence for small systems



small systems F(η) of wounded quark model using PHOBOS d+Au 200GeV

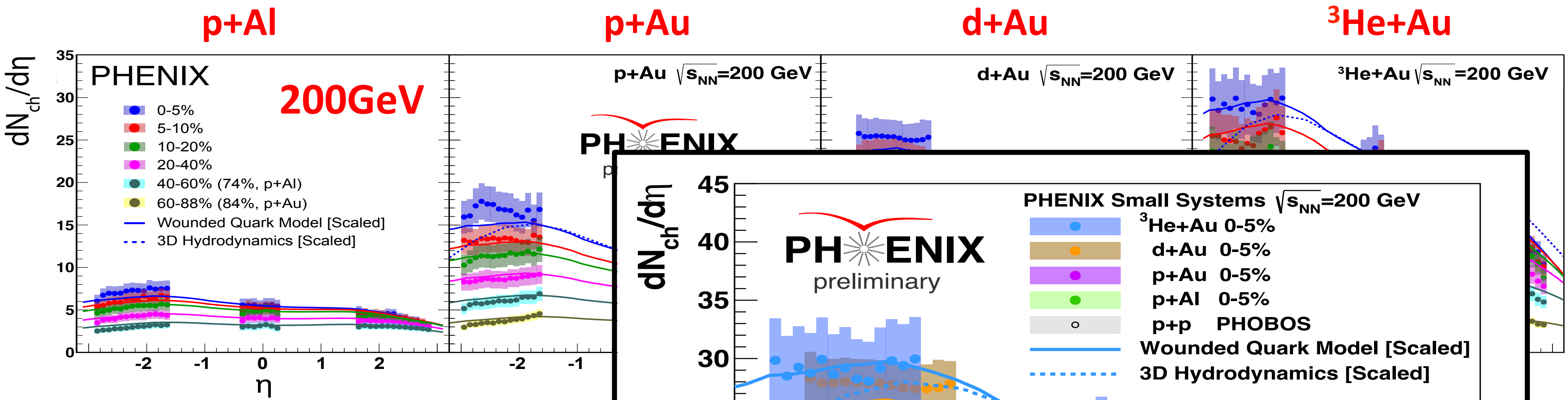
PRL 212, 22301 (2018)

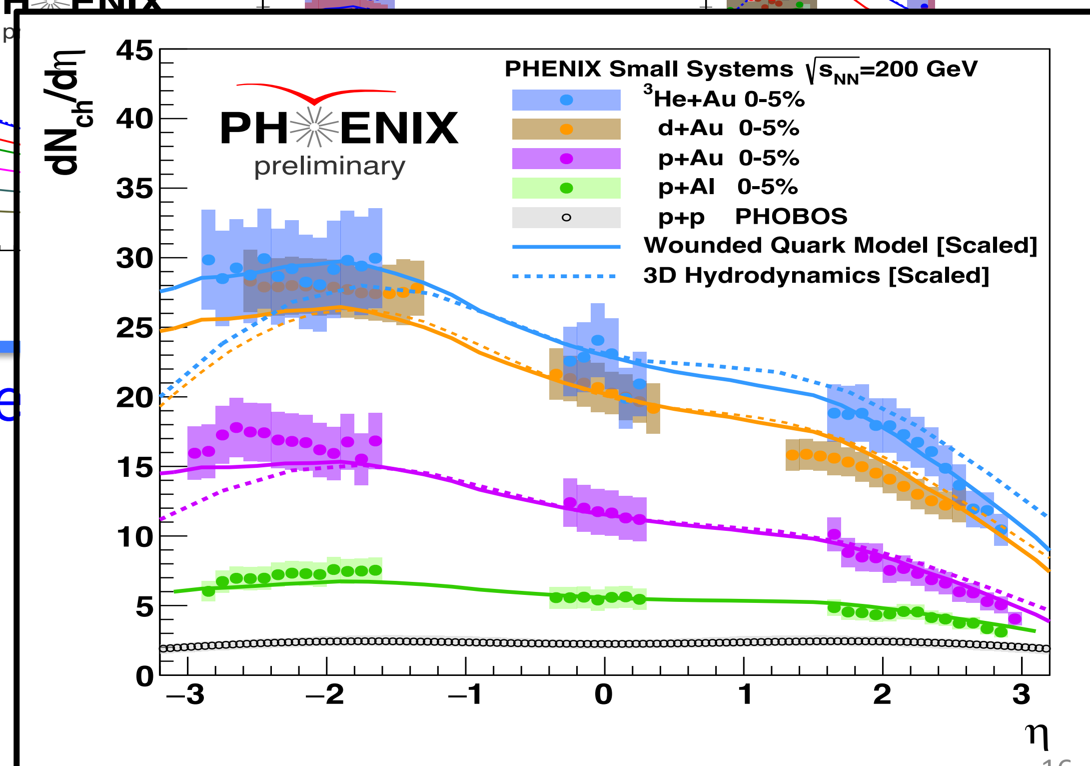
Collision system size dependence



PRL 212, 22301 (2018)

Collision system size dependence





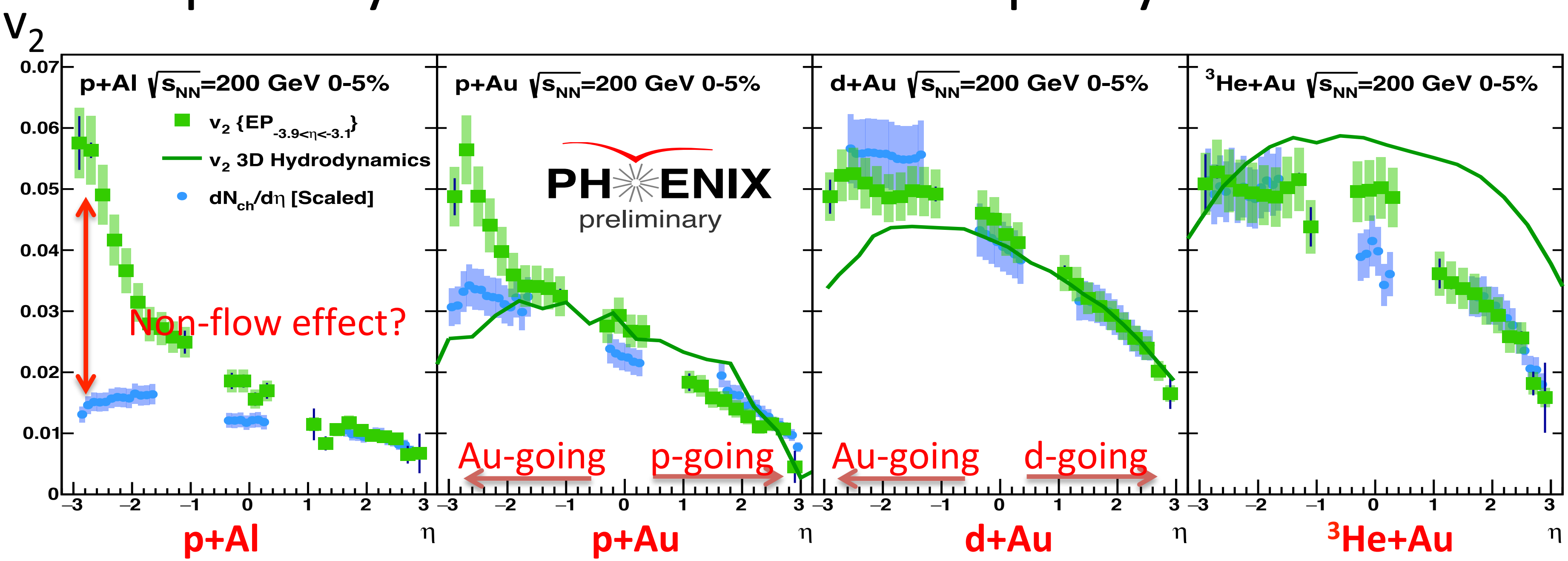
Syste

$dN_{ch}/d\eta$ reasonably well-described by wounded quark model

PRL 121, 222301 (2018)

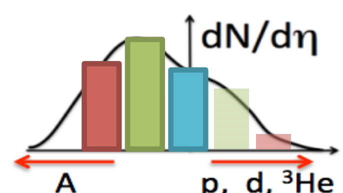
v_2 and the scaling $dN_{ch}/d\eta$

- Different systems are also shown similar shape especially at the mid-forward rapidity



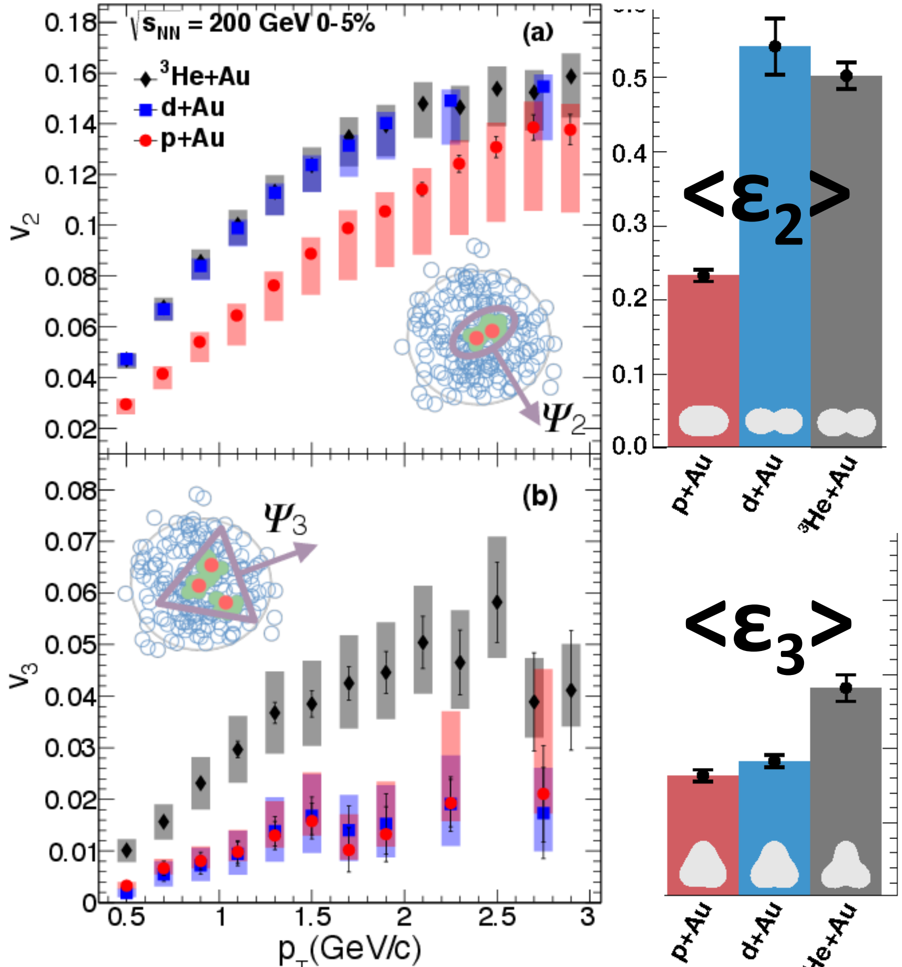
3D hydrodynamics gives

- reasonably describe the rapidity dependence of v_2
- larger differences at the Au(Al)-going side.



Nature Phys. 15, 214 (2019)

Initial geometry and the v_n



v_2[p+Au] < v_2[d+Au] ≈ v_2[^{3}He+Au]

ε_2[p+Au] < ε_2[d+Au] ≈ ε_2[^{3}He+Au]

v_3[p+Au] ≈ v_3[d+Au] < v_3[^{3}He+Au]

ε_3[p+Au] ≈ ε_3[d+Au] < ε_3[^{3}He+Au]

Initial geometry dependence of v_2 is studied using different collision systems.

The hierarchy of v_2 and v_3 consistent with that of ε_n.

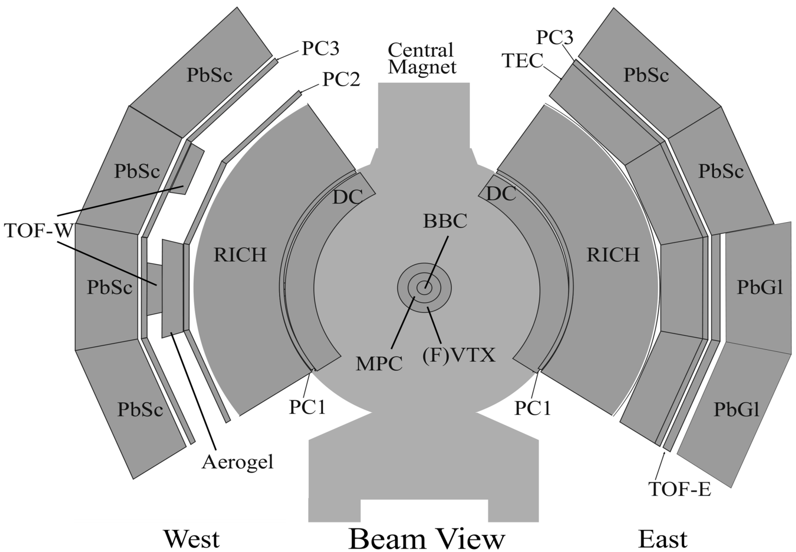
Summary

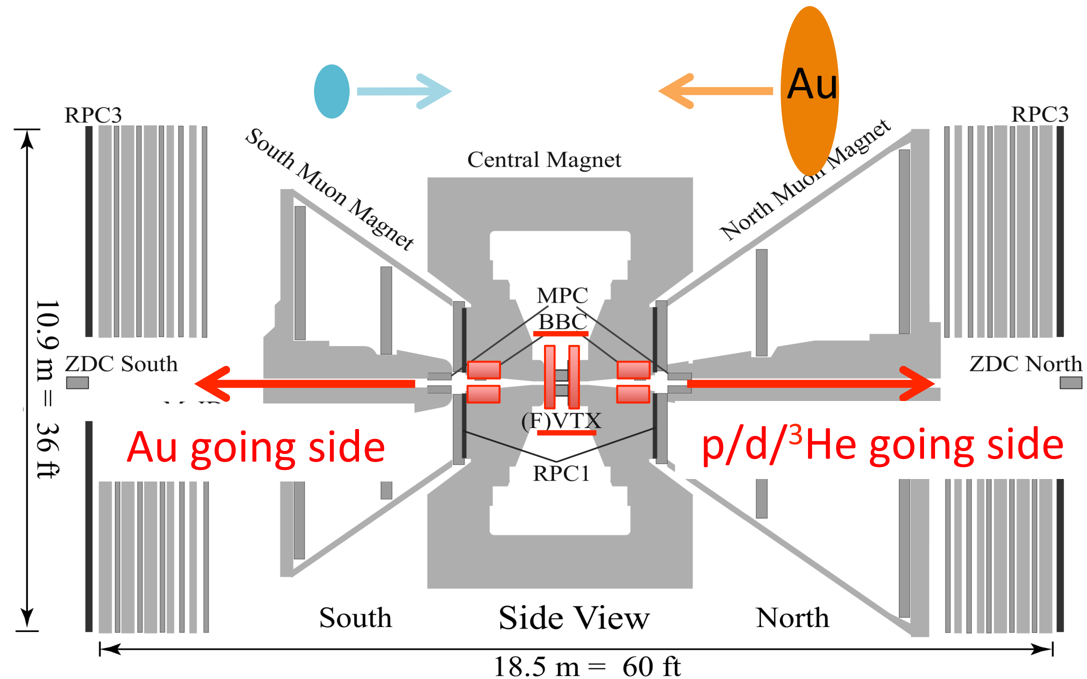
- Collective-like behavior was observed in small systems by the PHENIX experiment.
  - Measured v_n are well described by viscous hydro model.
  - $dN_{ch}/d\eta$ is described by the wounded quark model.
  - Confirmed initial geometry effect in the medium formed in small systems (p/d/^{3}He + Au)
  - 3D hydrodynamics reasonably well describe the rapidity(η) dependence of the v_2.
  - Measured centrality dependence but it is not described by AMPT.
- Nonflow contribution needs to be studied for the better understanding of small collision systems.

THANK YOU

BACKUP

PHENIX detectors



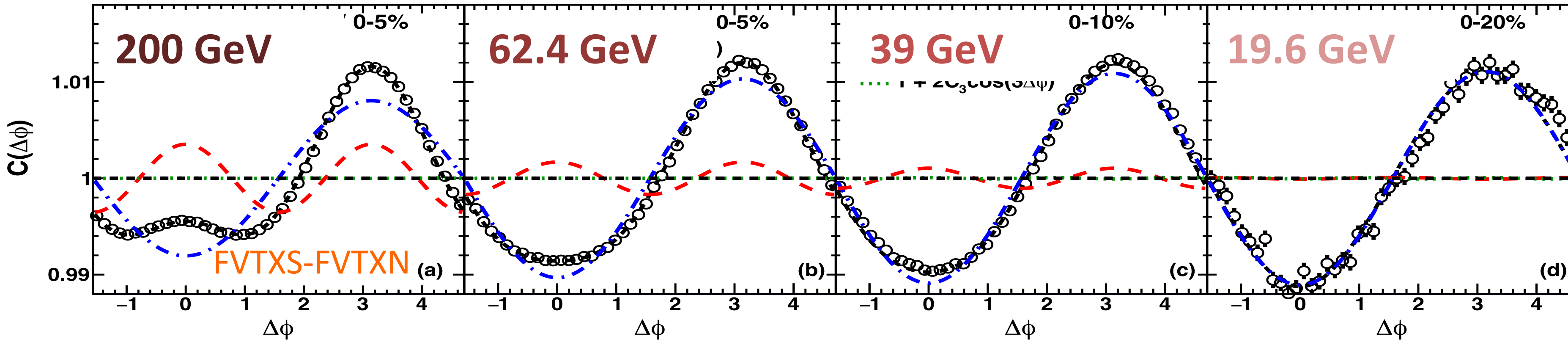


Central arm :
charged particle measurement, particle identification

Forward-backward arm :
charged particle measurement, triggering, event-plane determination

PRC 96, 064905 (2017)

d+Au Beam Energy Scan : v_2 vs. p_T



PRC 96, 064905 (2017)

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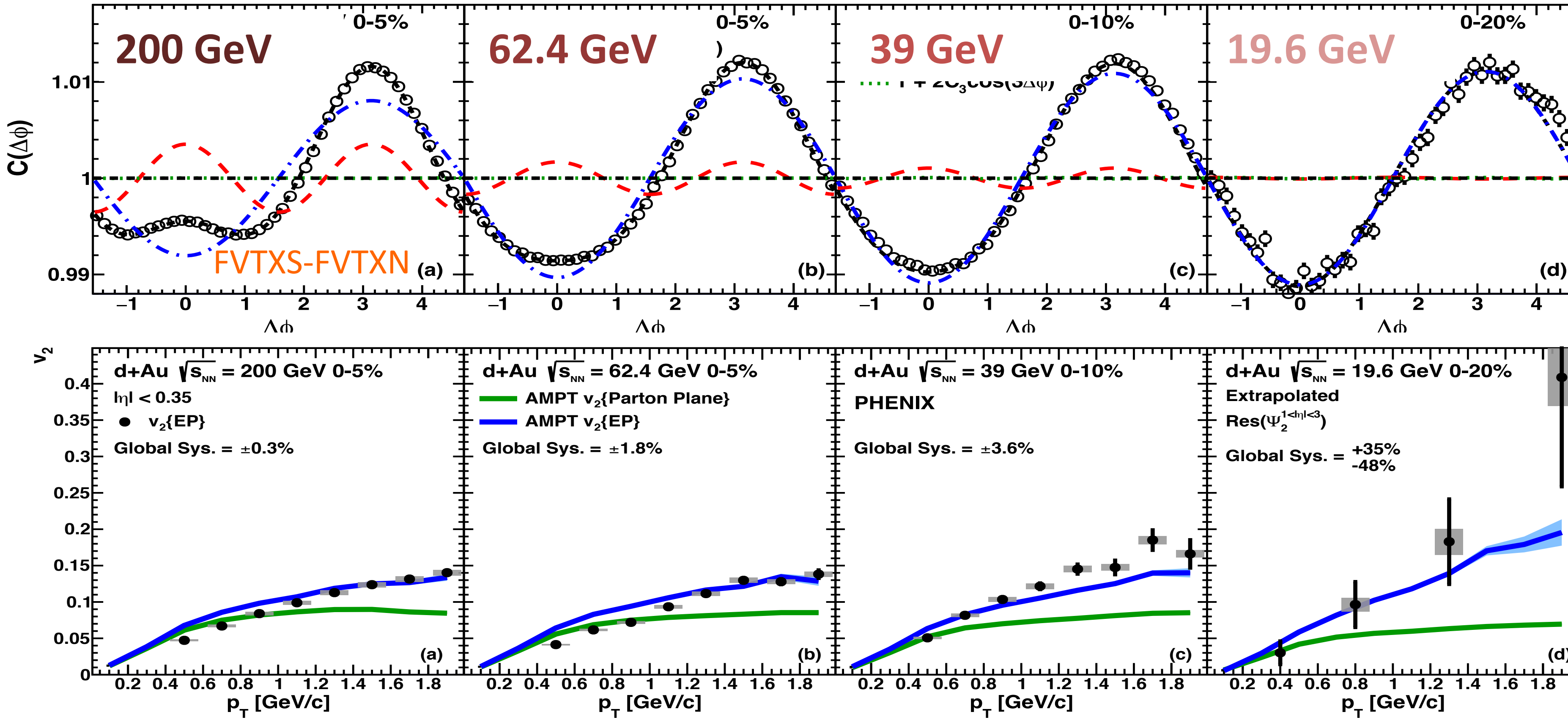
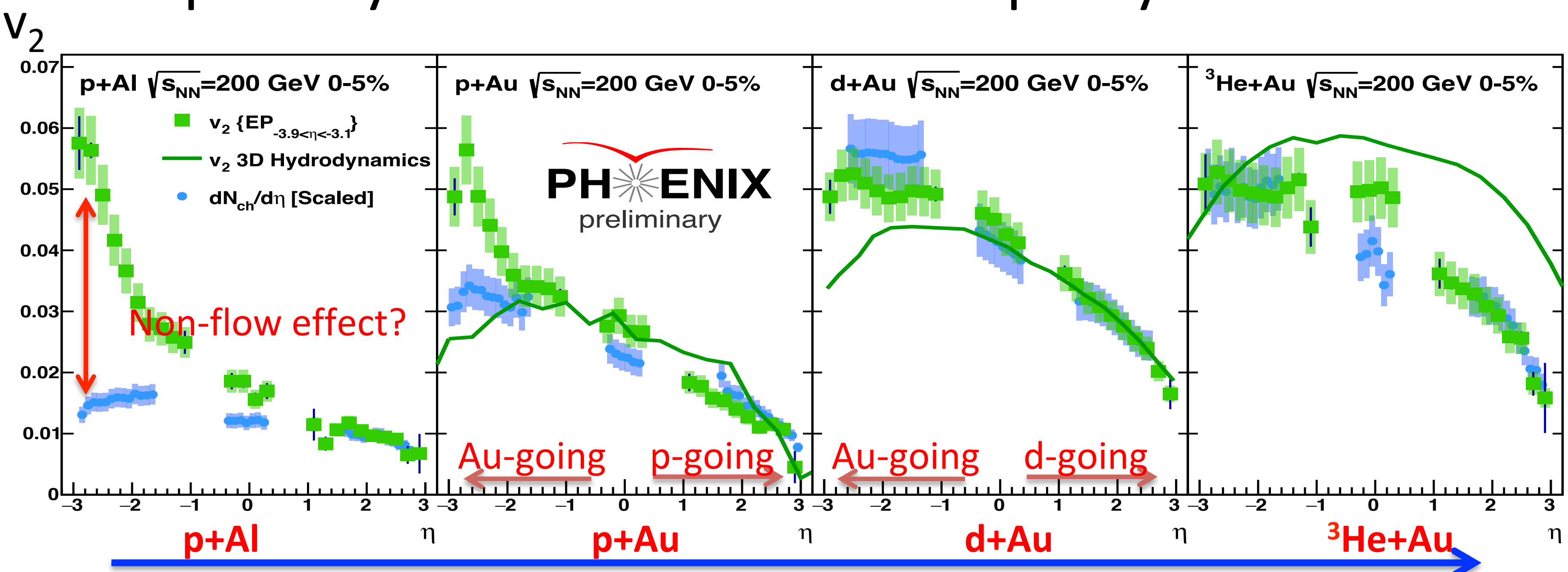


Non-zero v_2 measured at all energies and AMPT reproduces event plane result reasonably well. Discrepancies between $v_2^{\{EP\}}$ and $v_2^{\{Parton\ Plane\}}$ in AMPT became larger in lower energy and it implies measured v_2 might be more and more dominated by non-collectivity effects.

PRL 121, 222301 (2018)

v_2 and the scaling $dN_{ch}/d\eta$

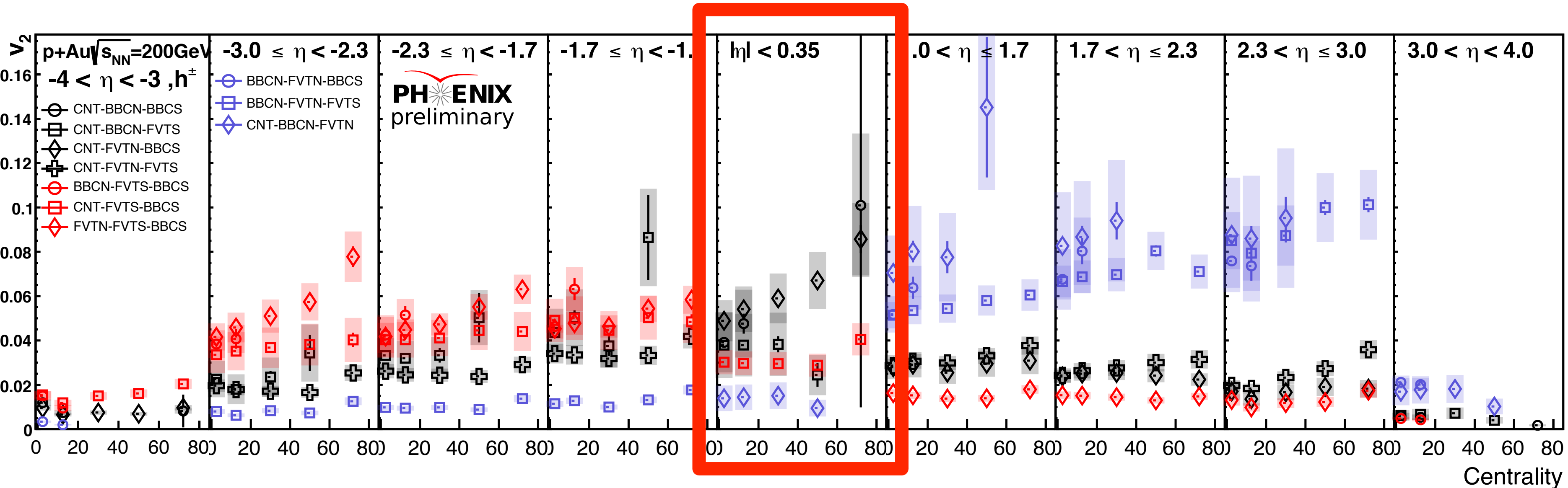
- Different systems are also shown similar shape especially at the mid-forward rapidity

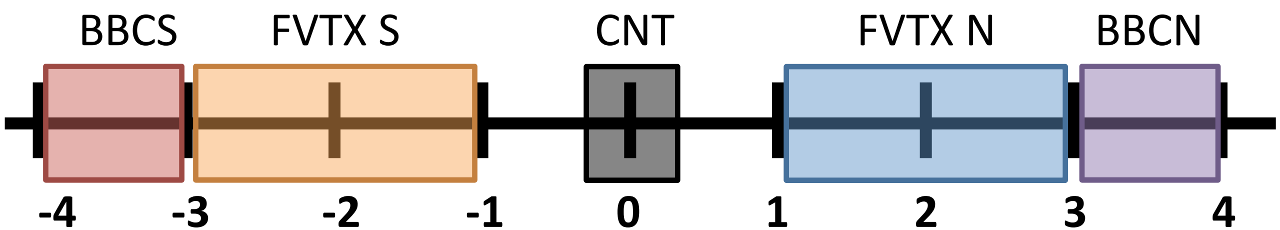


System size gets to be larger

3D hydrodynamics estimates only the flow effect.

p+Au v_2 vs. centrality





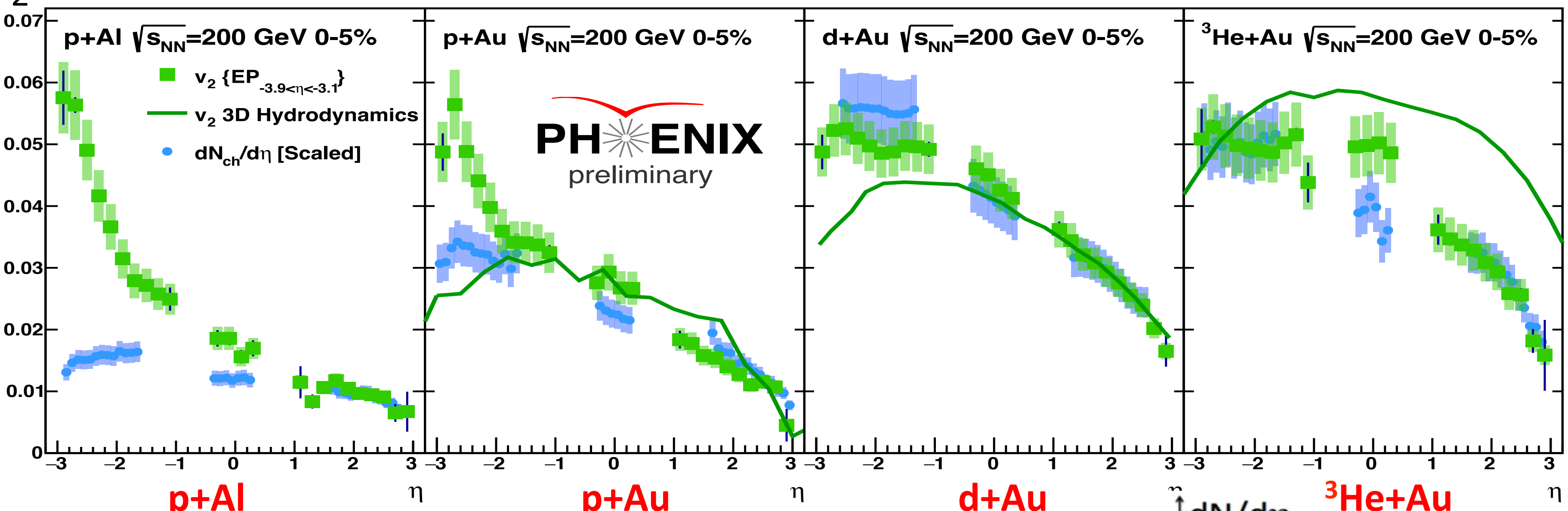
Two North = Blue

Two South = Red

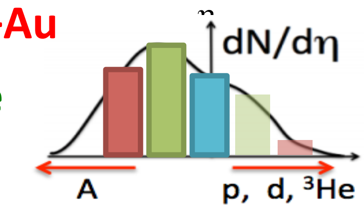
One North, One South = Black

v_2 scaling

- One interesting feature of v_2 and the $dN_{ch}/d\eta$
  - Shapes are similar each other!



3D hydrodynamics gives larger differences at the Au(Al)-going side on these results.



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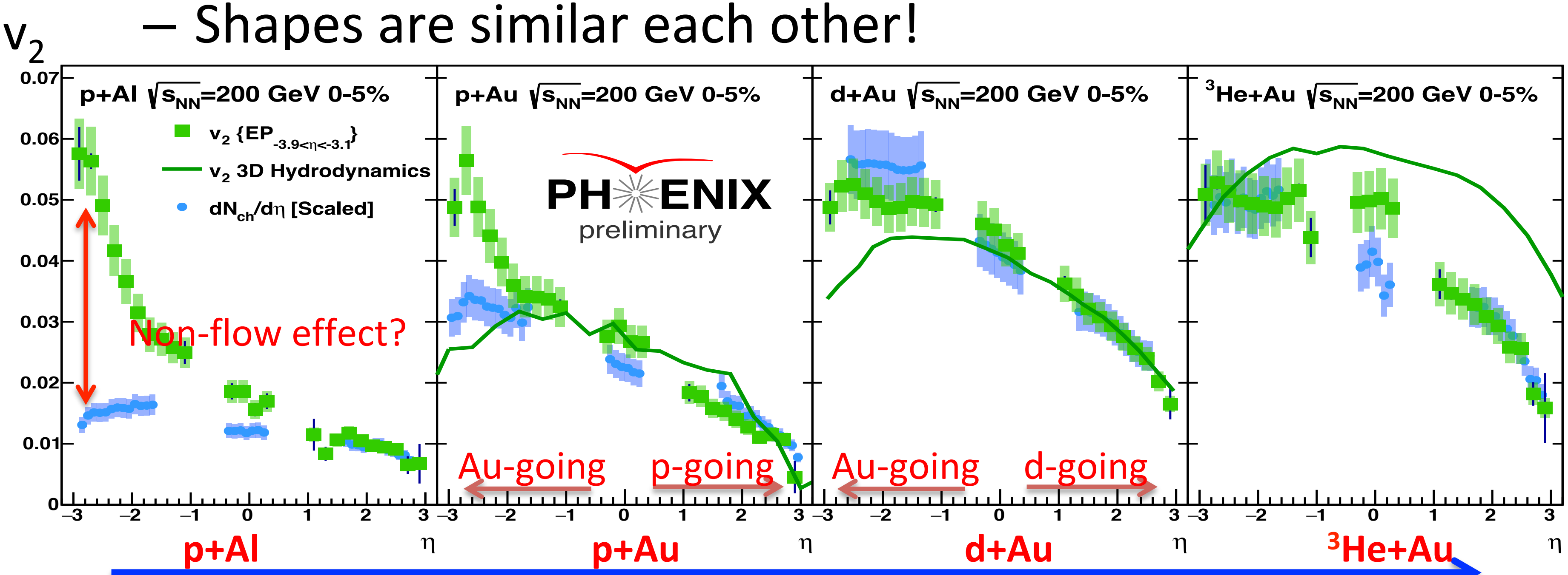

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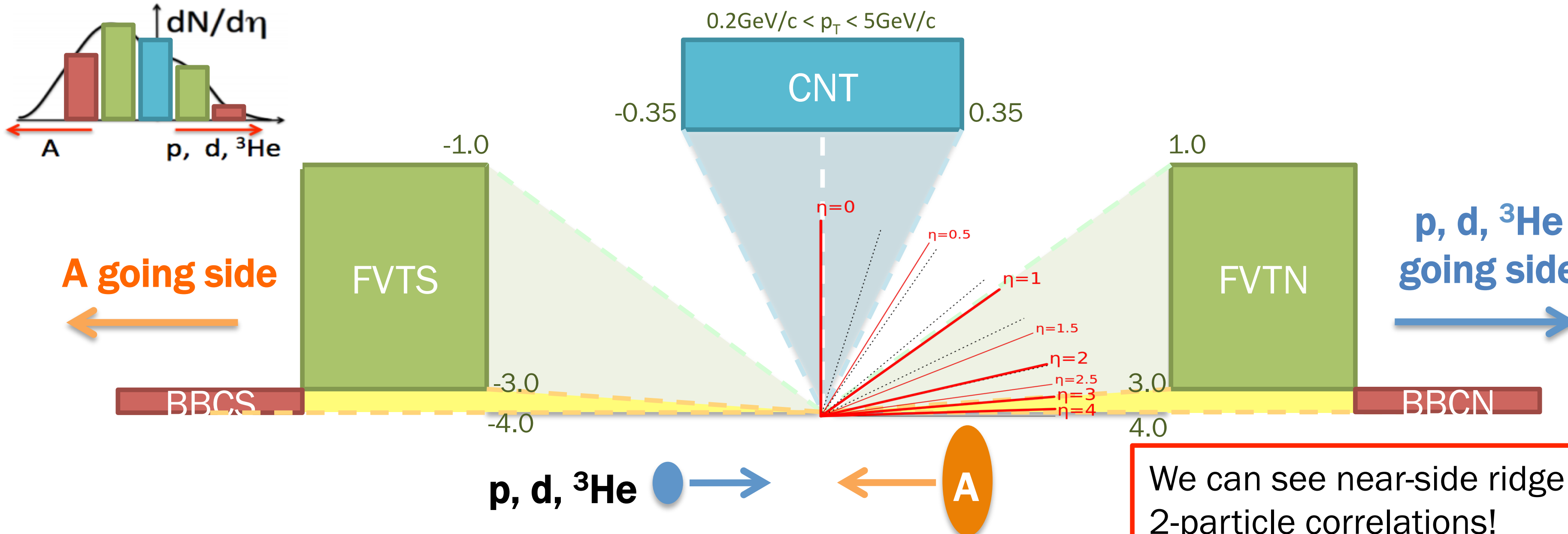
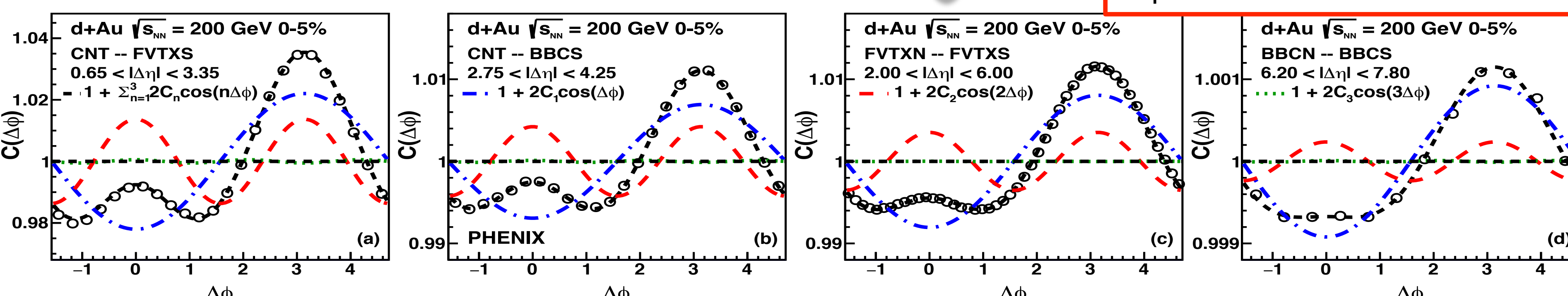
PHENIX detectors

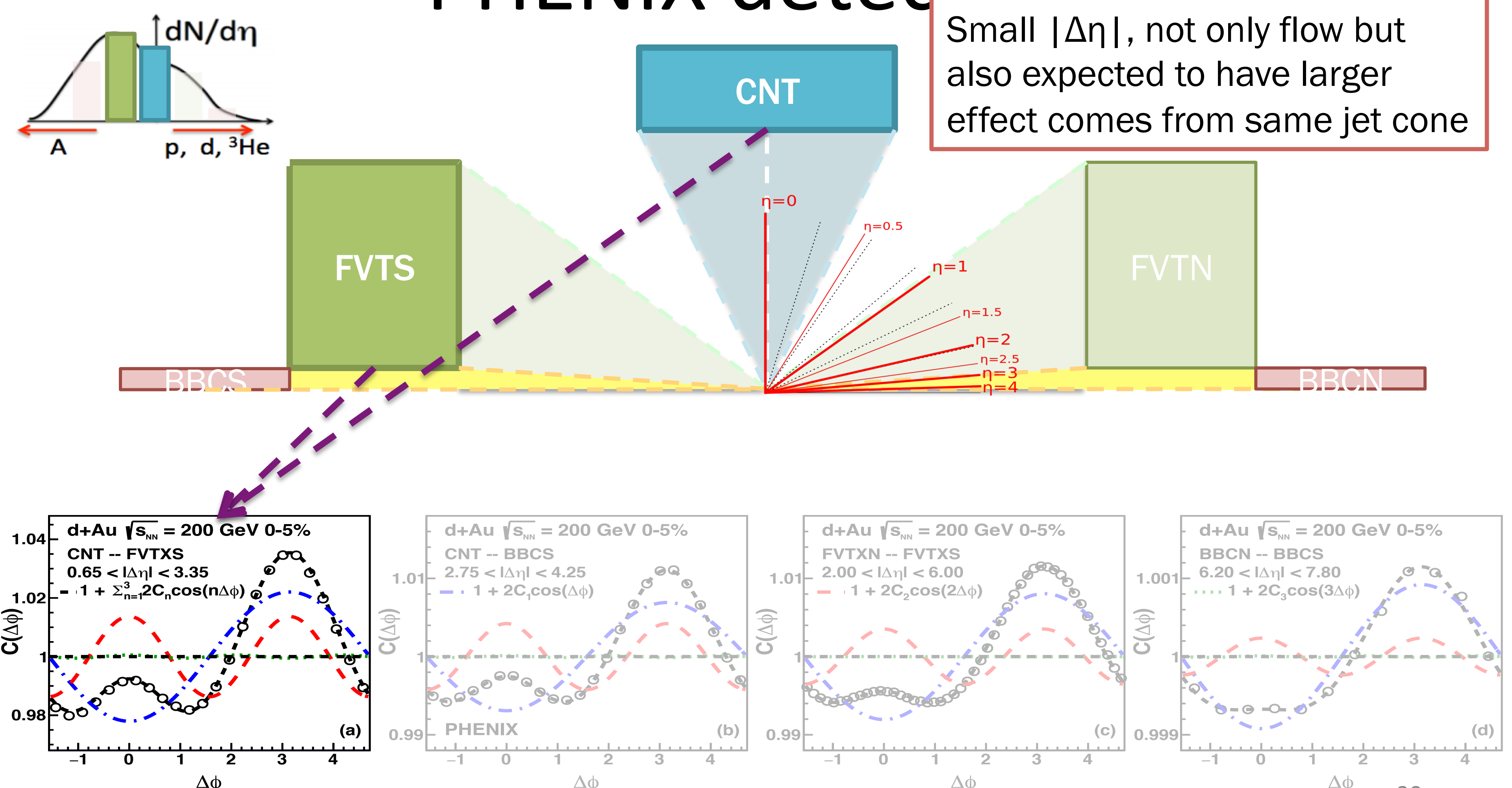


We can see near-side ridge in 2-particle correlations!

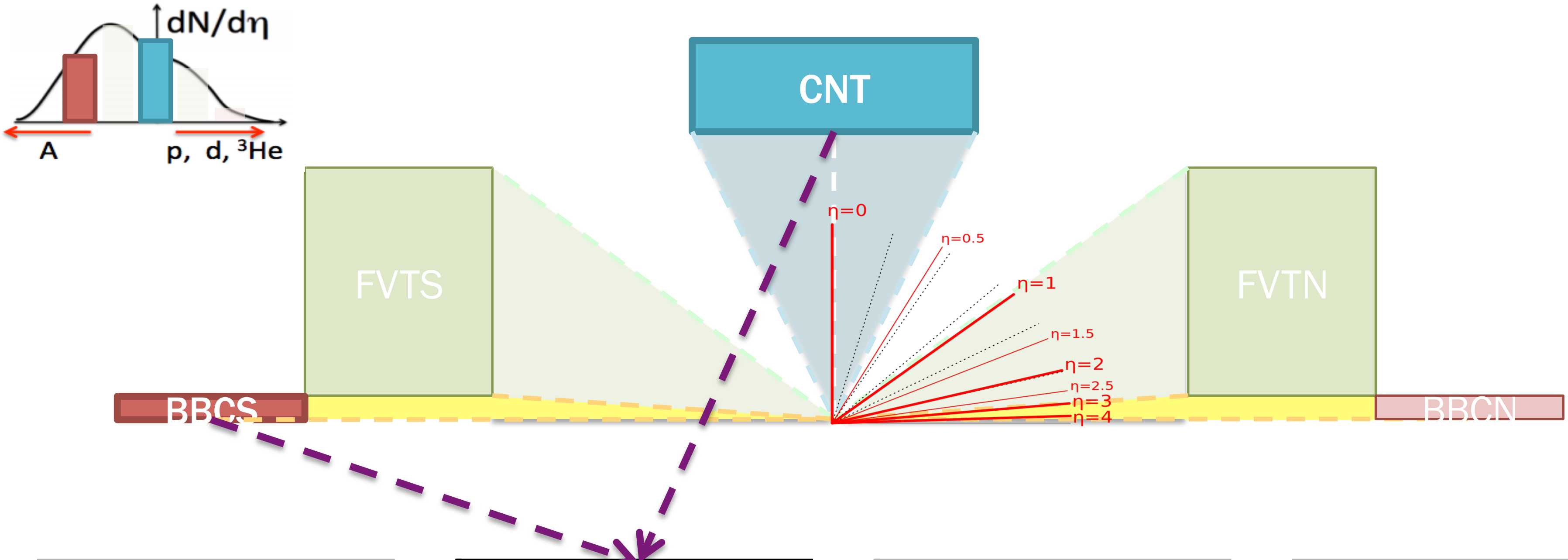


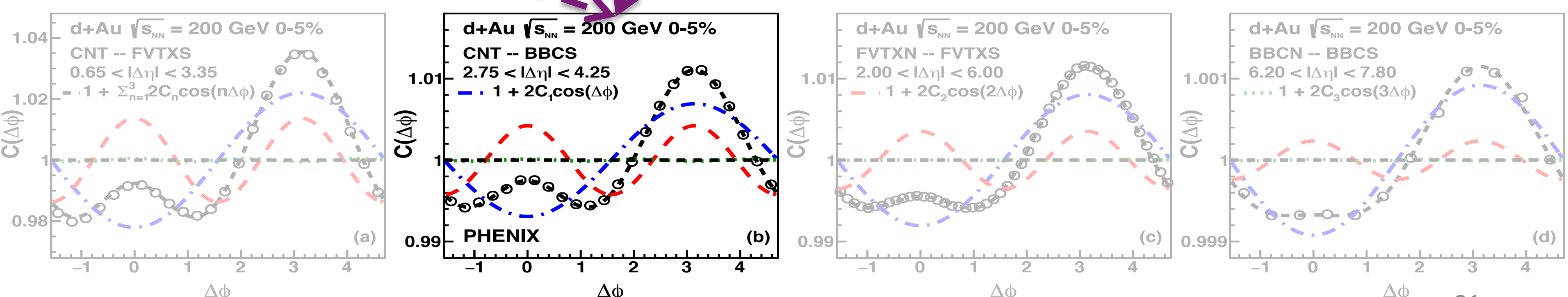
PHENIX detectors

Small |Δη|, not only flow but also expected to have larger effect comes from same jet cone



PHENIX detectors





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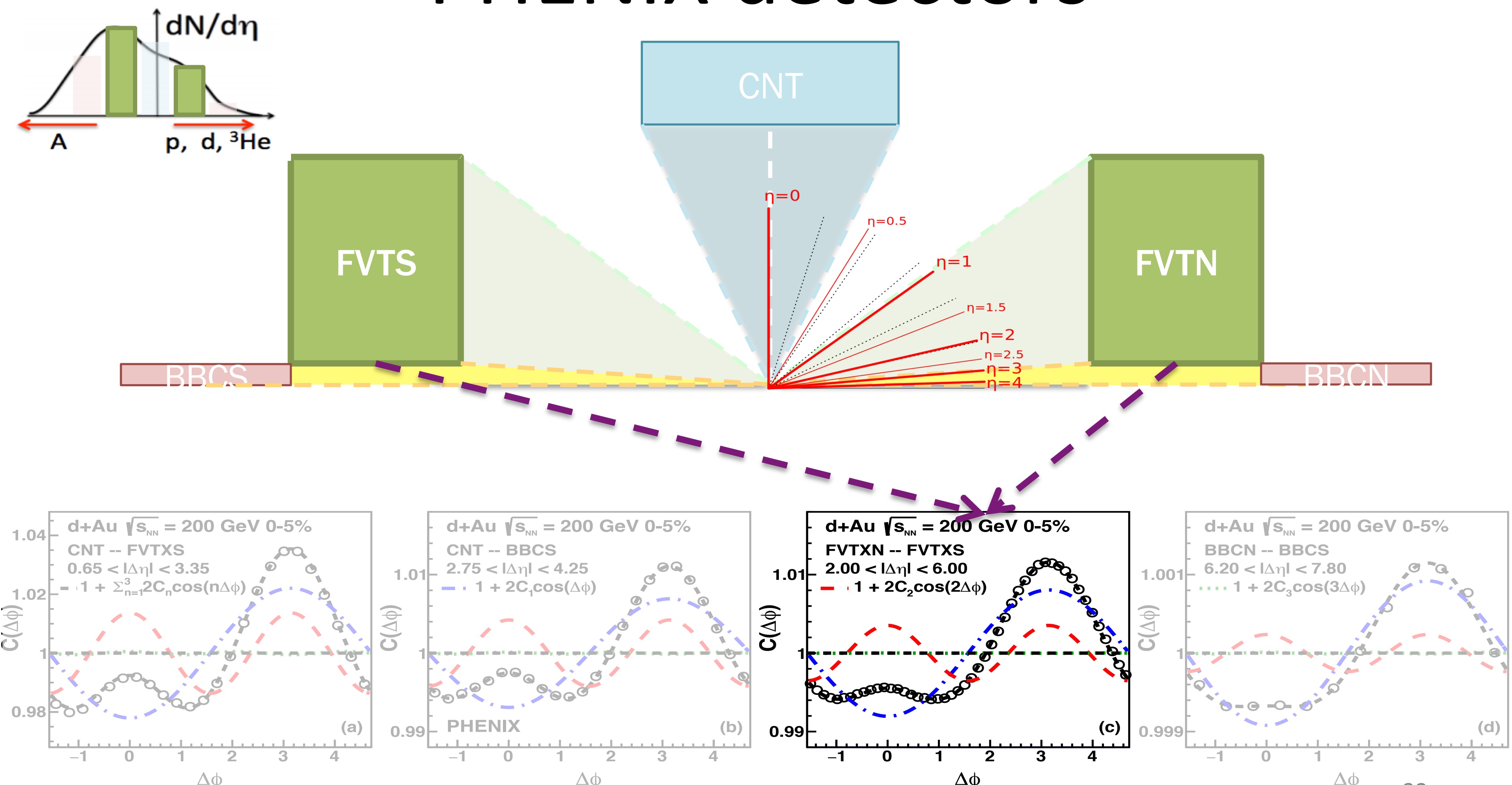

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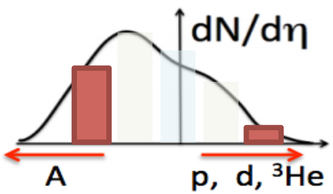
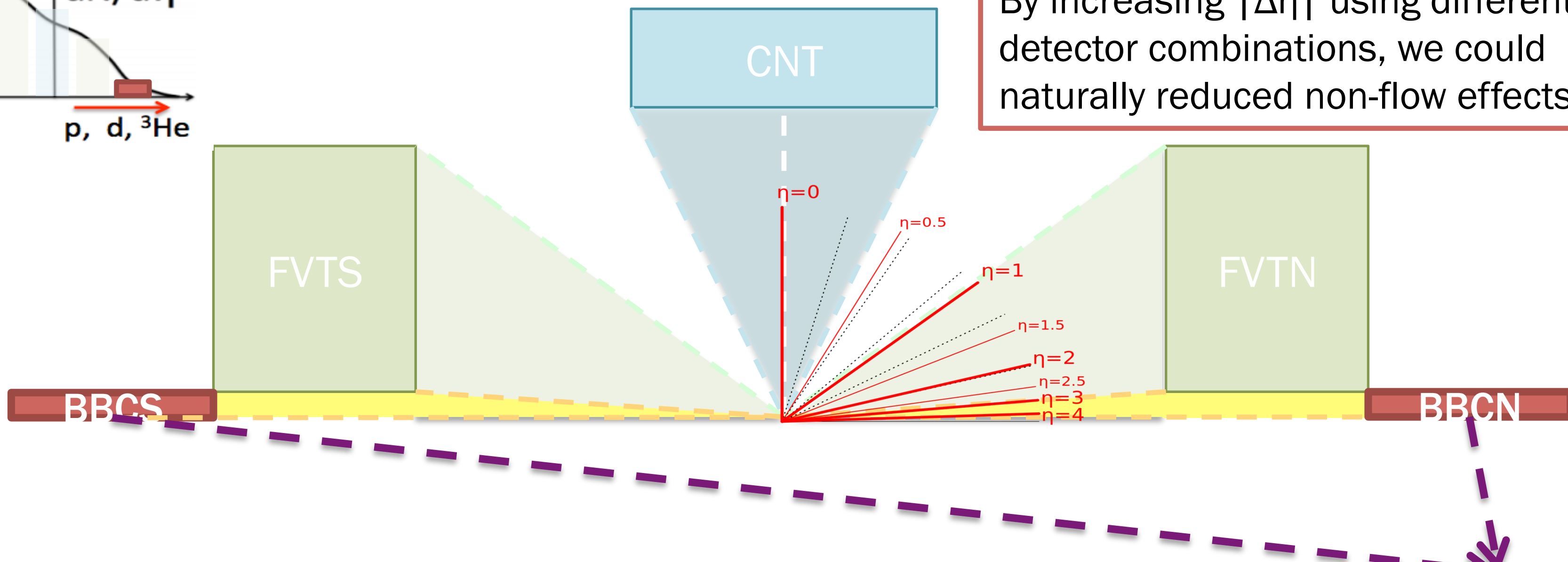
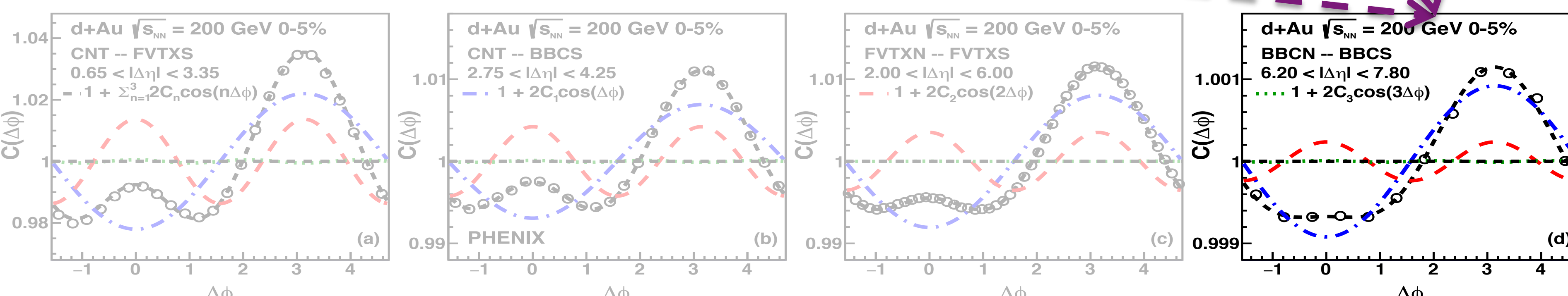


By increasing |Δη| using different detector combinations, we could naturally reduced non-flow effects.





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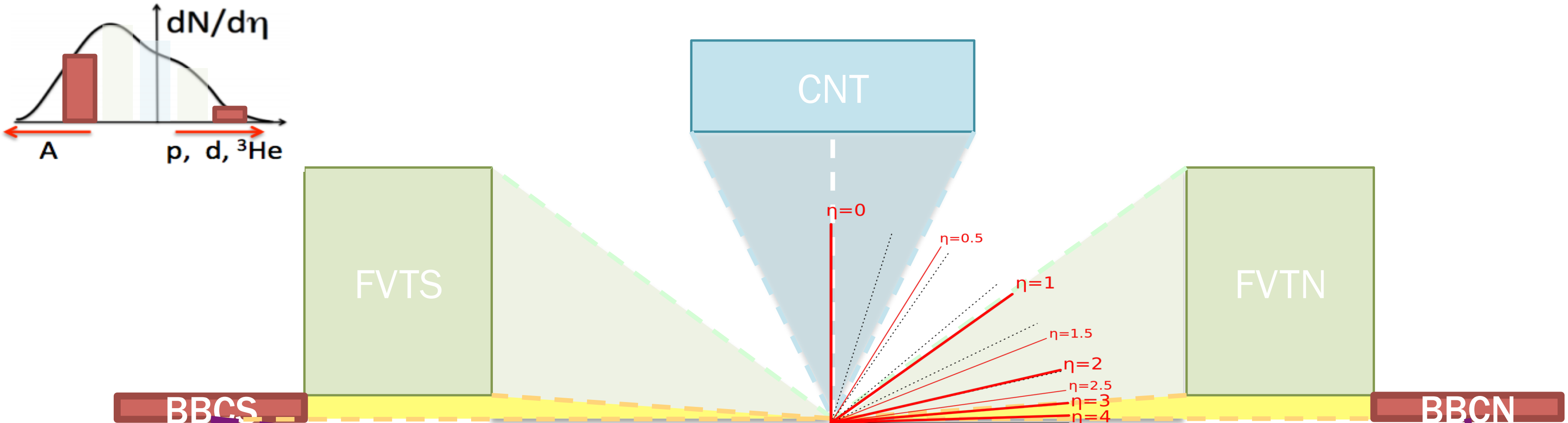
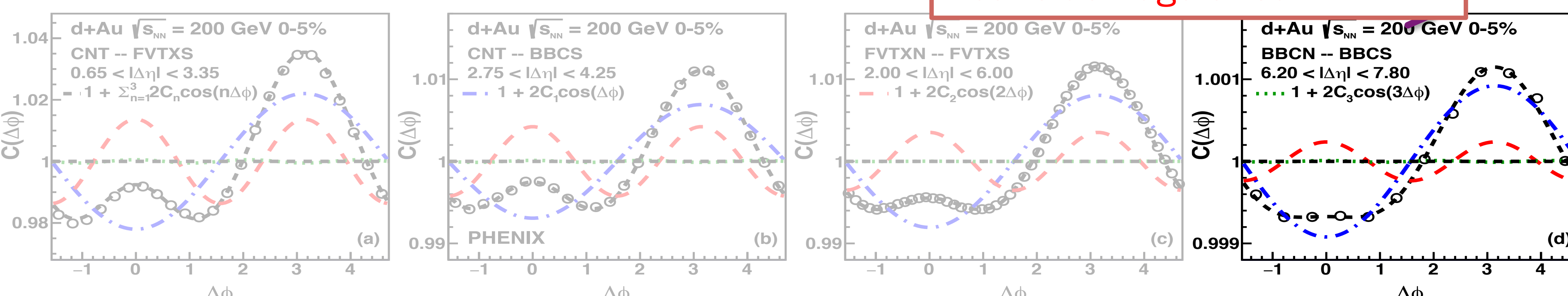


Largest |Δη| but still non-zero near-side ridge exist



Wounded model

Another candidate of QGP evidence!

Quark / Nucleon

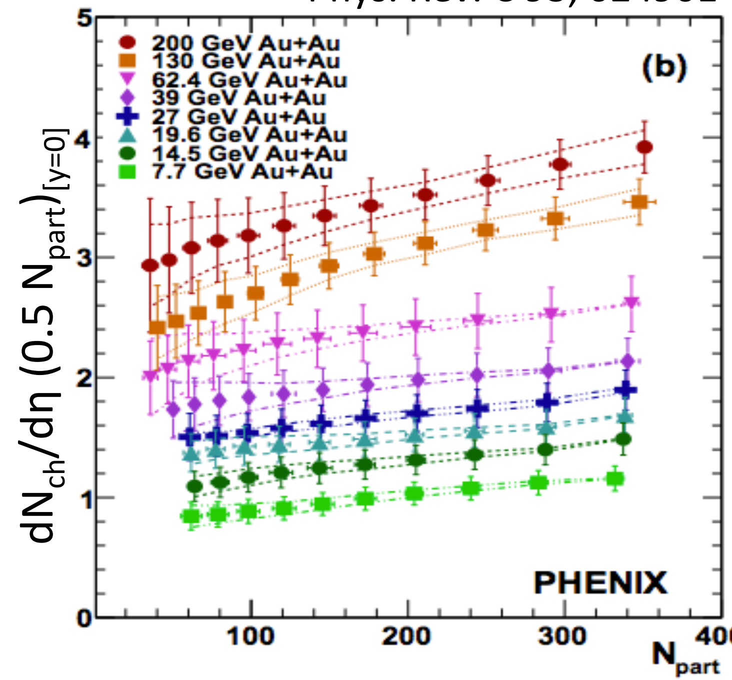
- Inelastic collision: What is actually crashed?

$$\frac{dN_{ch}}{d\eta} = \omega_L F(\eta) + \omega_R F(-\eta)$$

F(η) = Wounded source emission function
ω = average number of wounded particles

- Asymmetric collision is the perfect circumstance to study the wounded model
- Scaling behaviors of small/ large collision systems can be observed

Phys. Rev. C 93, 024901



PHENIX measurements of Au+Au $dN_{ch}/d\eta$ at the mid-rapidity

Wounded model

Another candidate of QGP evidence! Quark / Nucleon

- Inelastic collision: What is actually crashed?

$$F(\eta) = \frac{1}{2}\left(\frac{N(\eta)+N(-\eta)}{\omega_L+\omega_R} + \frac{N(\eta)-N(-\eta)}{\omega_L-\omega_R}\right)$$

F(η) = Wounded source emission function
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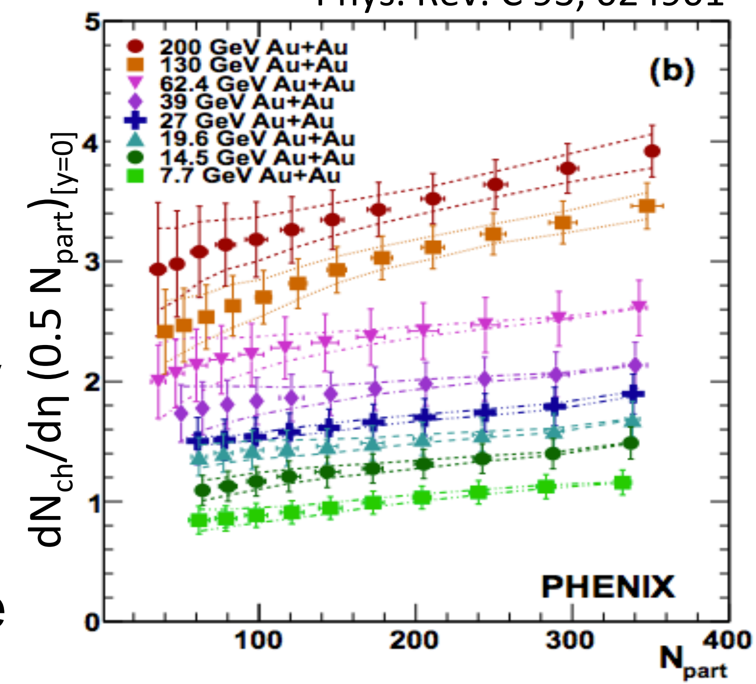


PHENIX measurements of Au+Au $dN_{ch}/d\eta$ at the mid-rapidity

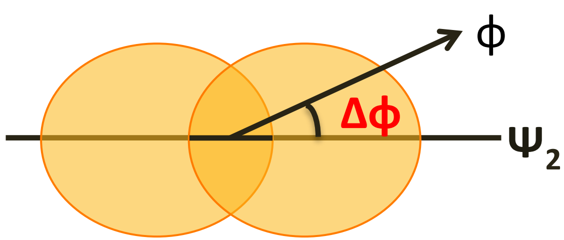
PSEUDO-RAPIDITY DEPENDENCE OF HADRON PRODUCTION

Analysis method

Event-plane method

- Define event-plane using FVTX-S clusters(hits)
- Calculate resolution of event-plane(Ψ_2) with 3 detectors; CNT,FVTS,BBCS

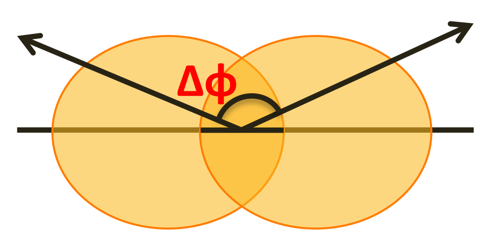
$$v_2^{CNT} = \frac{\langle \cos 2(\phi^{CNT} - \Psi_2) \rangle}{Res(\Psi_2)}$$



2-particle correlation

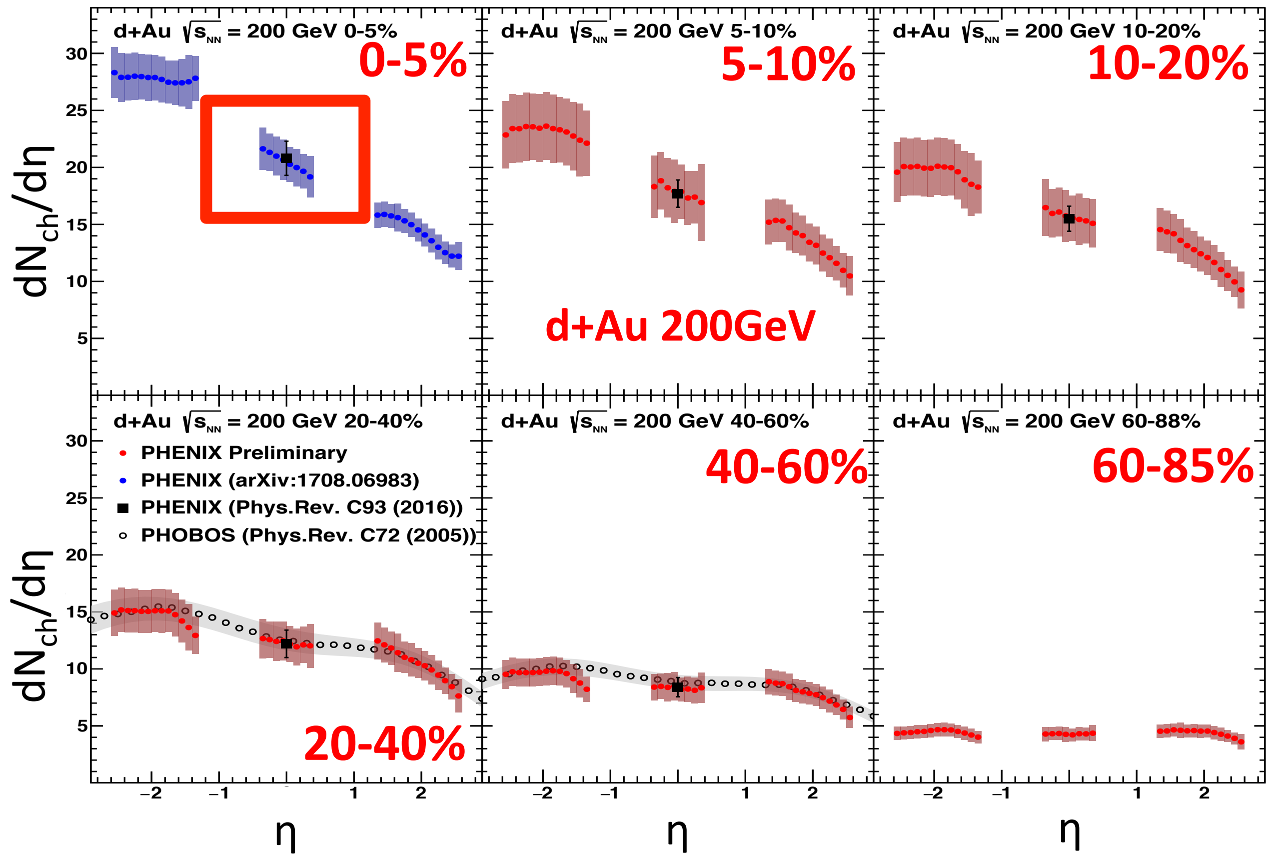
- Calculate correlation of two tracks Δϕ in two different detectors
- Normalize with background correlations
- Fourier expansion fitting and coefficient of cos 2ϕ modulation c_2,

$$v_2^{CNT} = \sqrt{\frac{c_2^{CNT-BBCS} * c_2^{CNT-FVTS}}{c_2^{BBCS-FVTS}}}$$

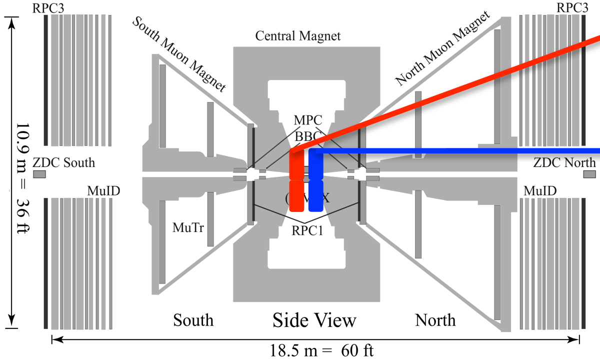


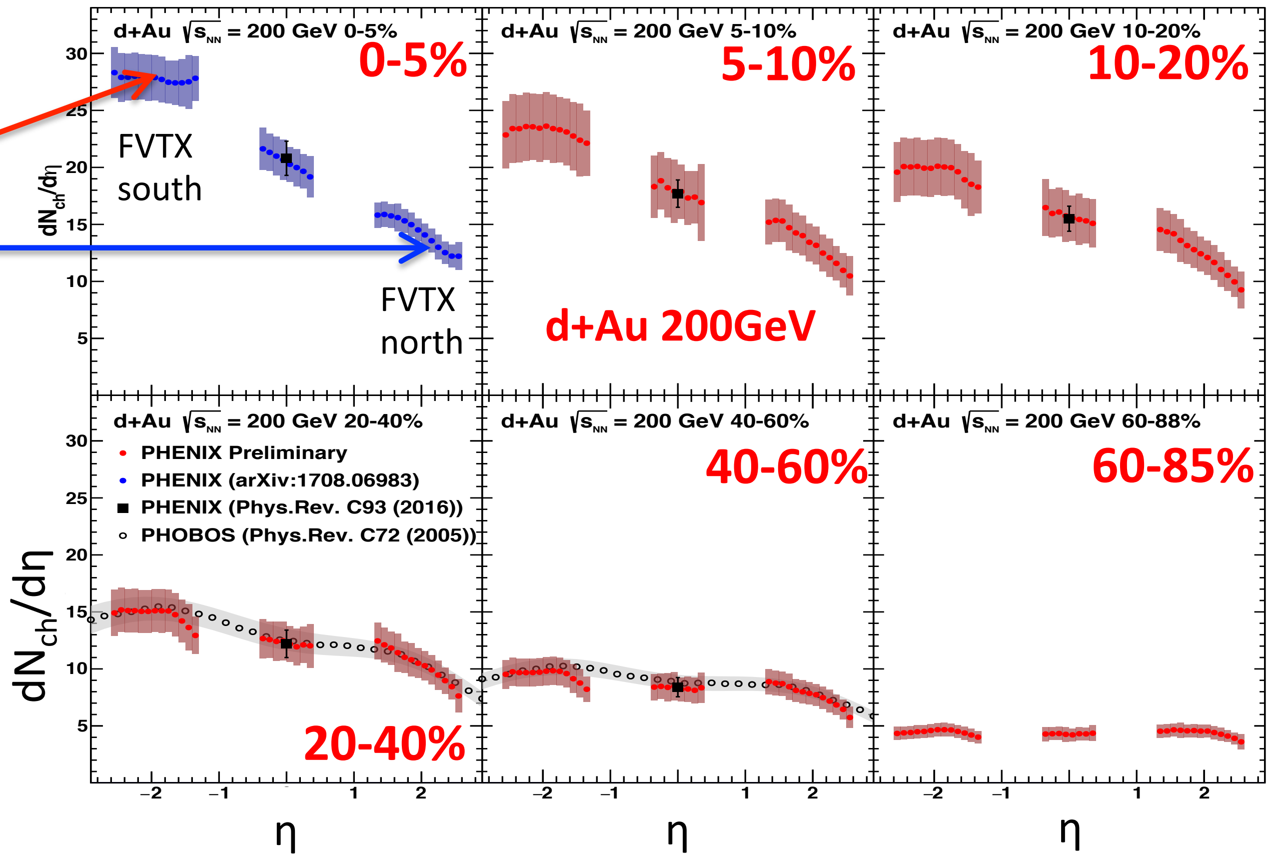
Expanded pseudo-rapidity

The new PHENIX results are in **good agreement** with the previous PHENIX results (Run 8) at the mid-rapidity.



Expanded pseudo-rapidity

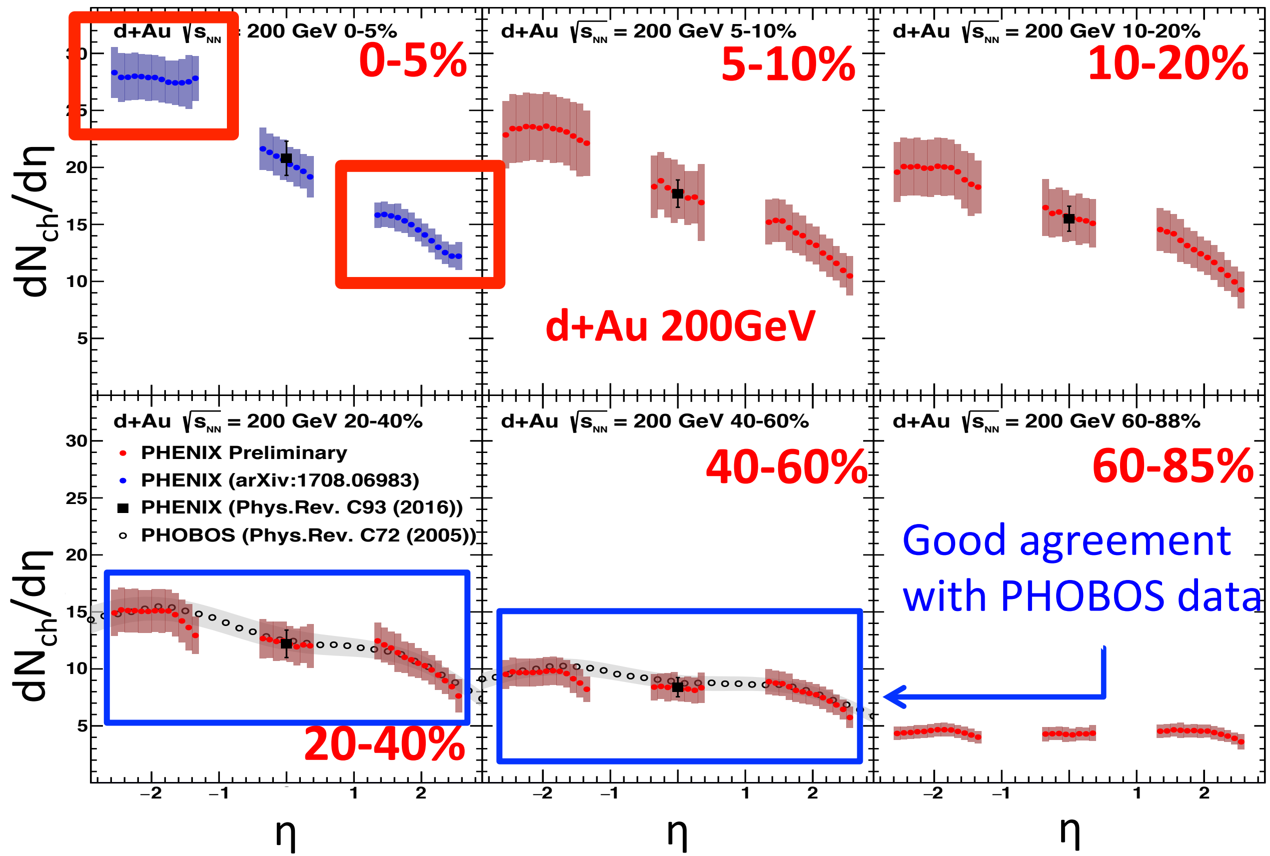




Expanded pseudo-rapidity

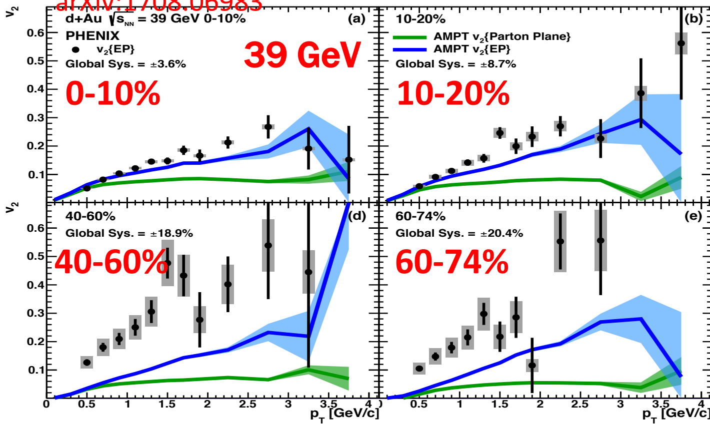
The new PHENIX results are in **good agreement** with the previous PHENIX results (Run 8) at the mid-rapidity.

Also the $dN_{ch}/d\eta$ measured at the wider range of rapidity by using the FVTX.



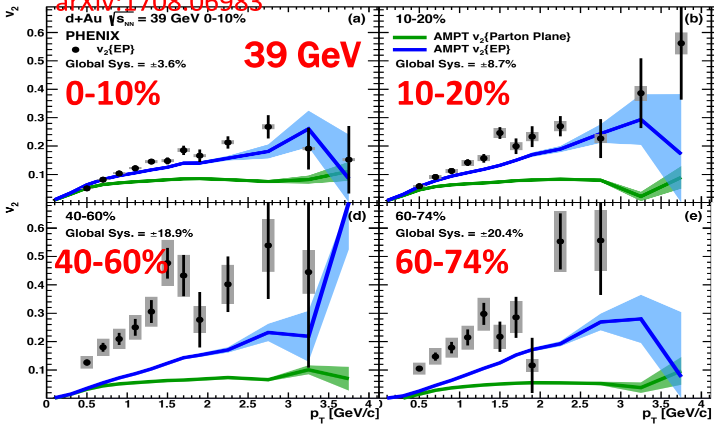
d+Au Beam Energy Scan : v_2 vs. p_T

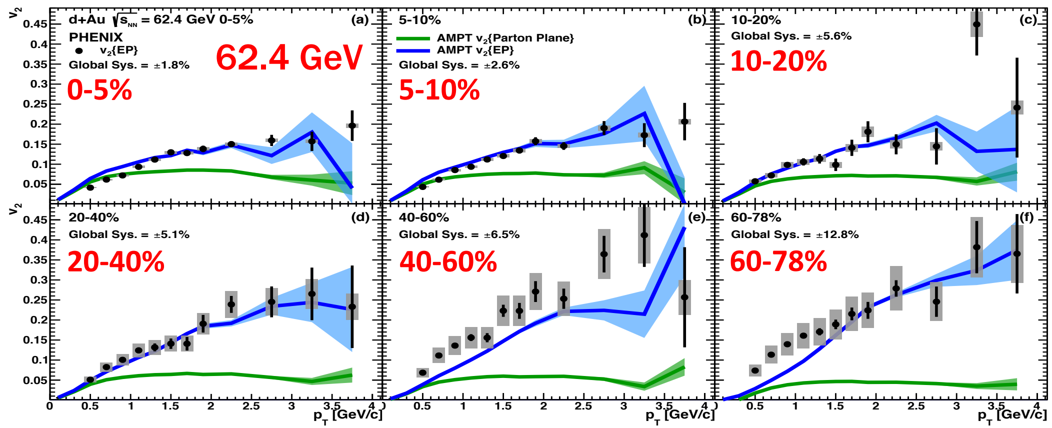
arXiv:1708.06983



d+Au Beam Energy Scan : v_2 vs. p_T

arXiv:1708.06983





d+Au Beam Energy Scan : v_2 vs. p_T

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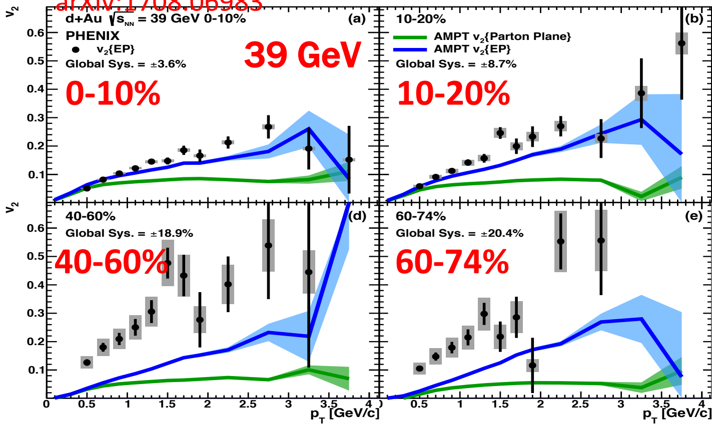

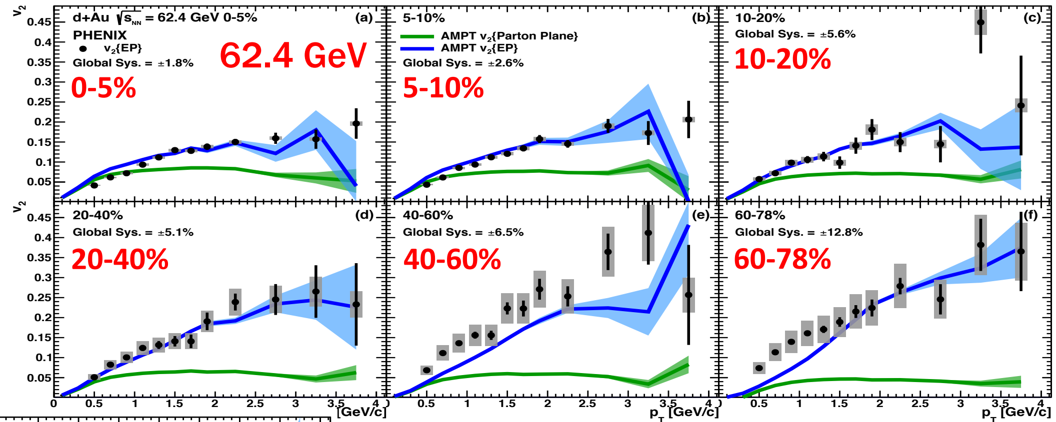

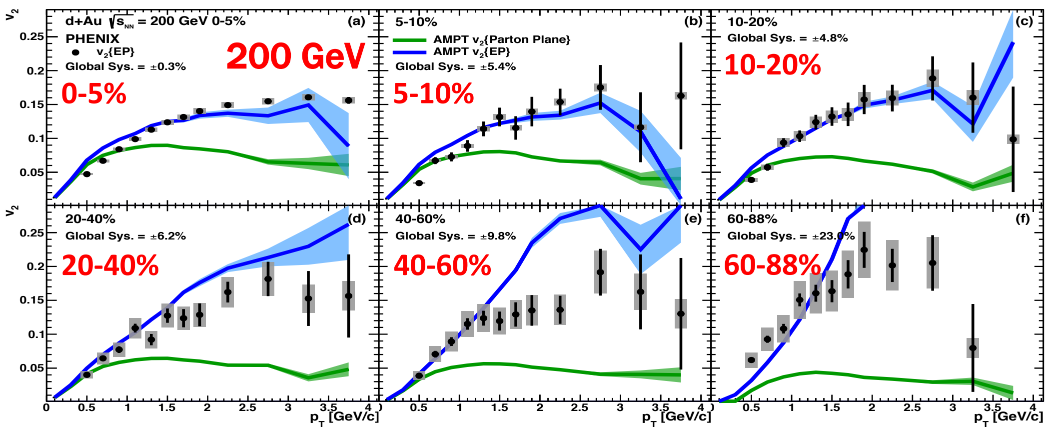

d+Au Beam Energy Scan : v_2 vs. p_T

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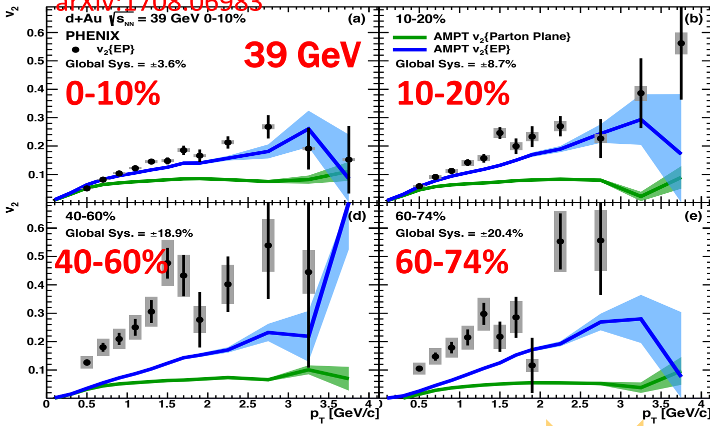
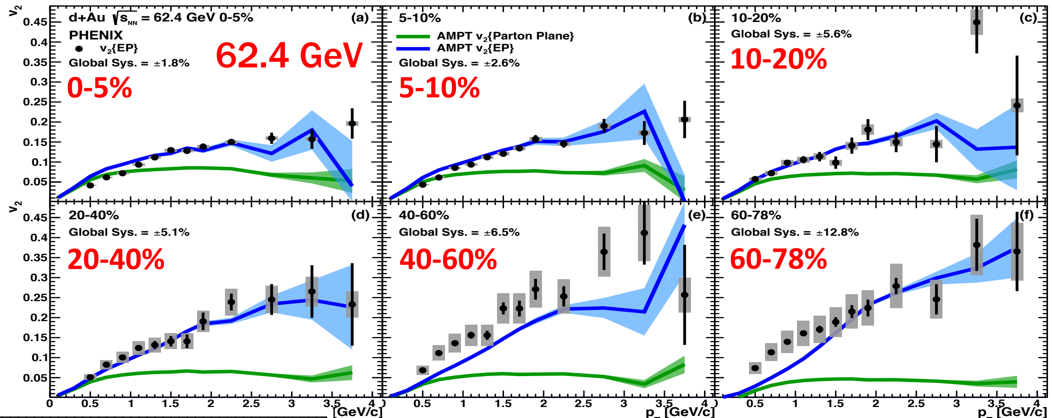
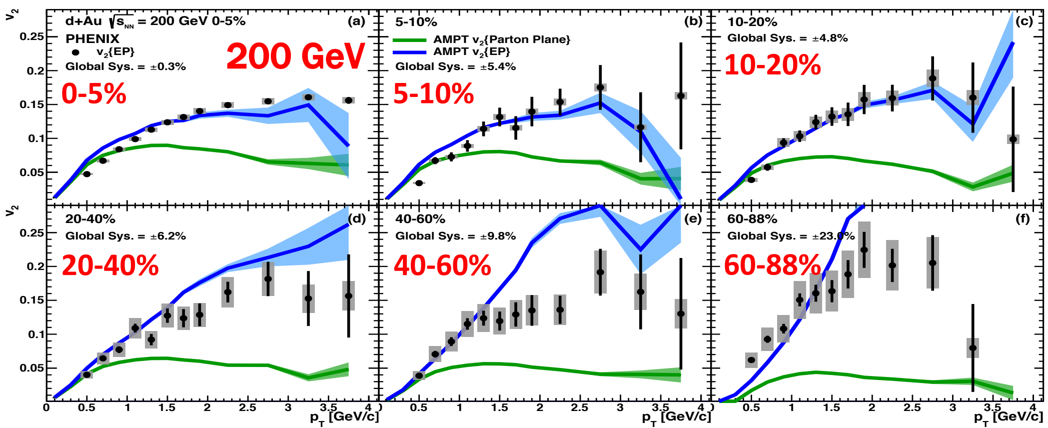


Energy higher





In all 3 different energies,

AMPT $v_2^{\{EP\}}$ reproduces general shape of data.

Non-flow contribution becomes significant in peripheral collisions or high p_T.

In lower collision energy,

AMPT $v_2^{\{EP\}}$ starts to underestimate v_2 especially at high p_T or peripheral