Investigation of flow-like behavior in d+Au BES

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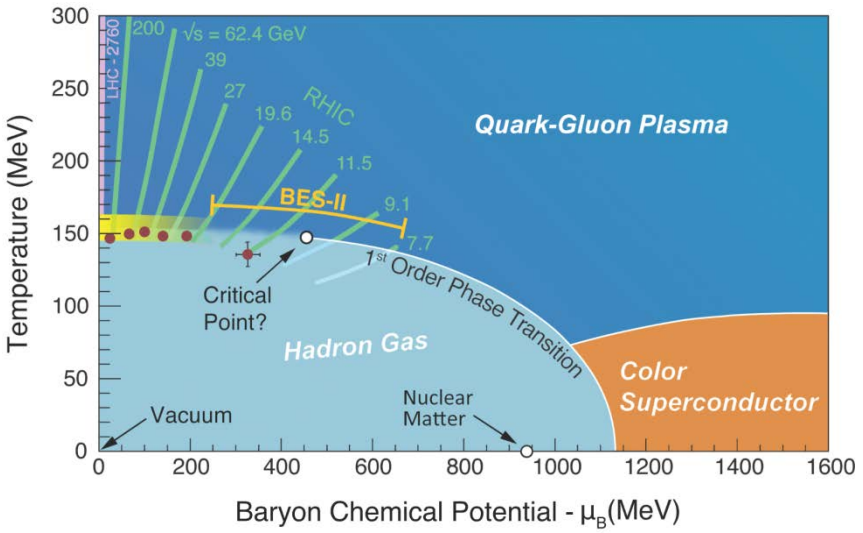
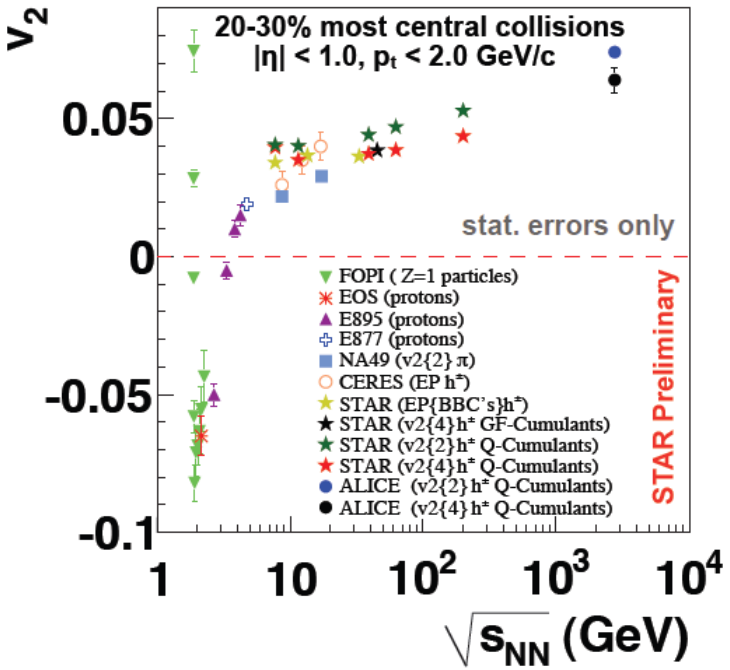
BES in large systems

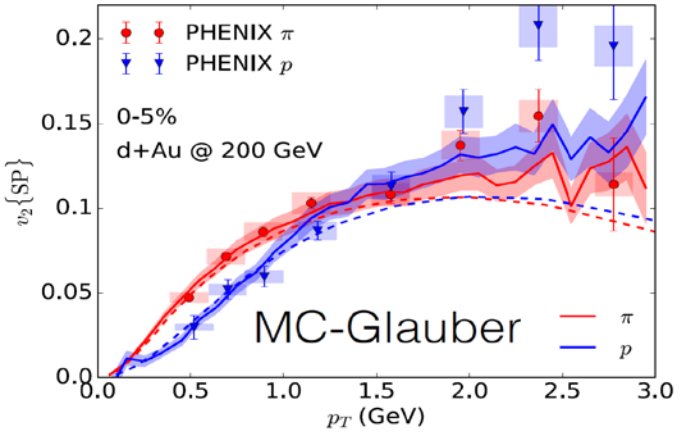
- We found QGP, but is it THE QGP?→ No! QGP world is broad.
- At RHIC: lower energy density, and higher baryon density QGP
  - Critical point should be on one of the paths.
  - Systematic study of various observables will help understand the systems
  - v_2 systematics is one of them
- At LHC: hotter (and more free gas like) and smaller QGP

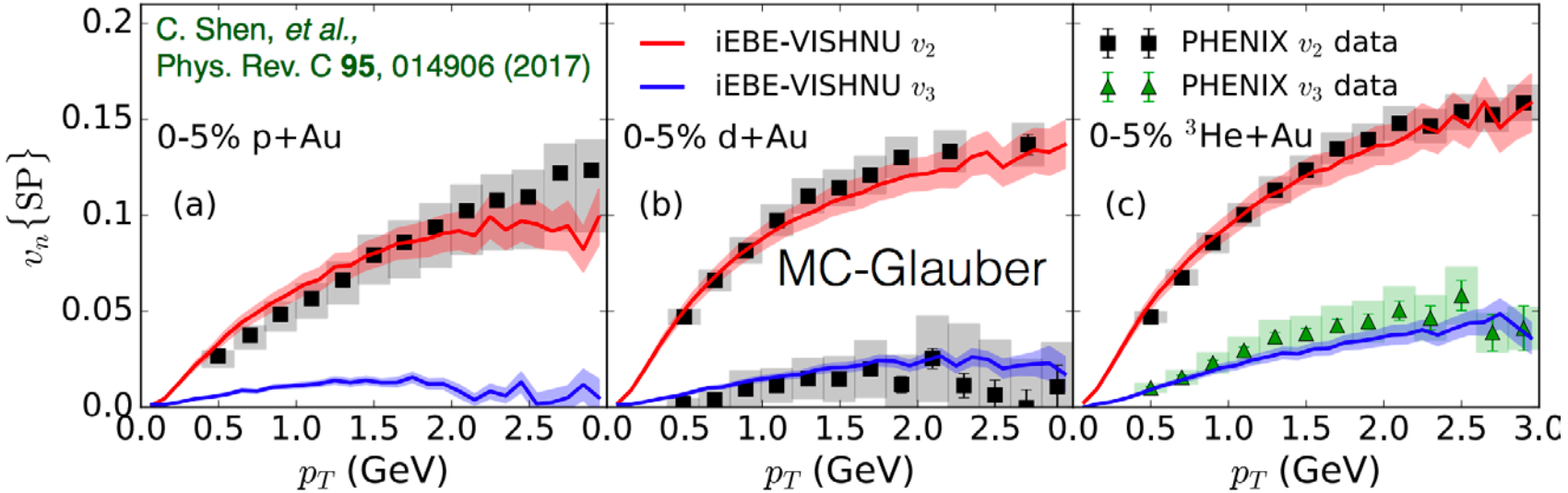




Hydrodynamics worked in small systems

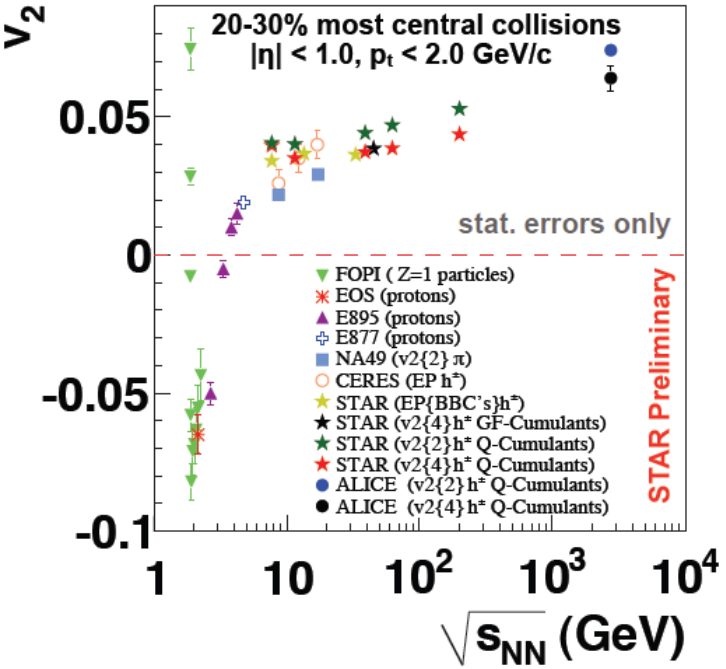
- Mass ordering was also observed in the data and well described by hydro in d+Au
- Hydro can describe the collision geometry dependence of the v_n at 200GeV
  - p+Au, d+Au, ^{3}He+Au

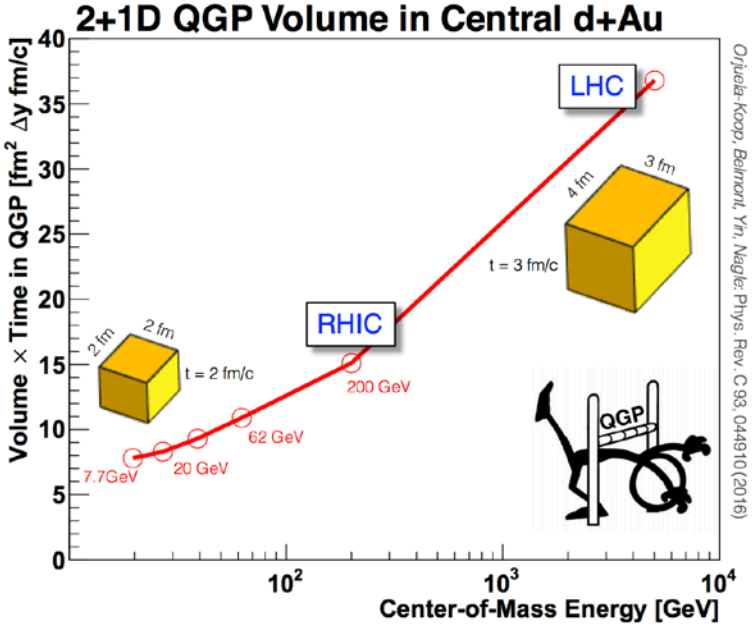




BES in small systems

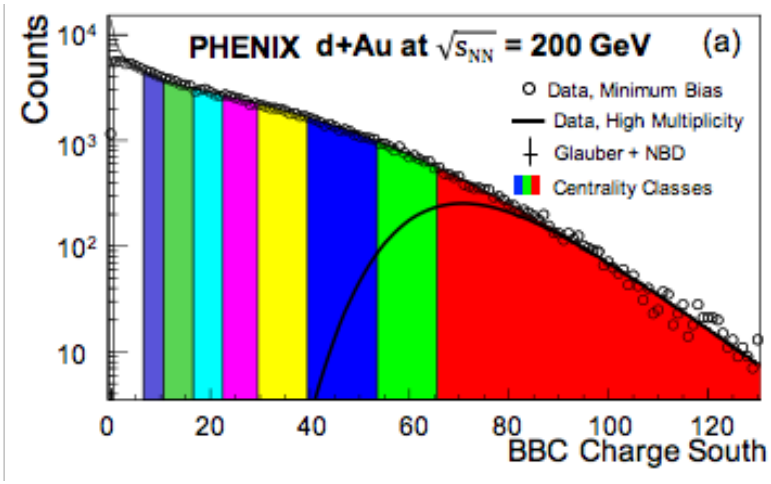
- We found QGP, but is it THE QGP?→ No! QGP world is broad.
- Smaller QGP is found not only at LHC, but also at RHIC?
  - Mass ordering of flow is seen
  - Good description of the data by Hydro
  - Similar systems?
- As like large systems, we should perform BES in small systems
  - Volume is smaller, but still expect energy density that may produce QGP phase.

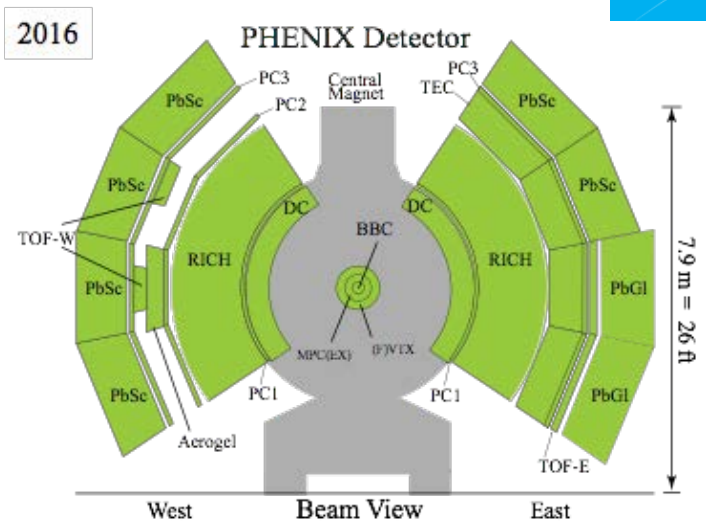


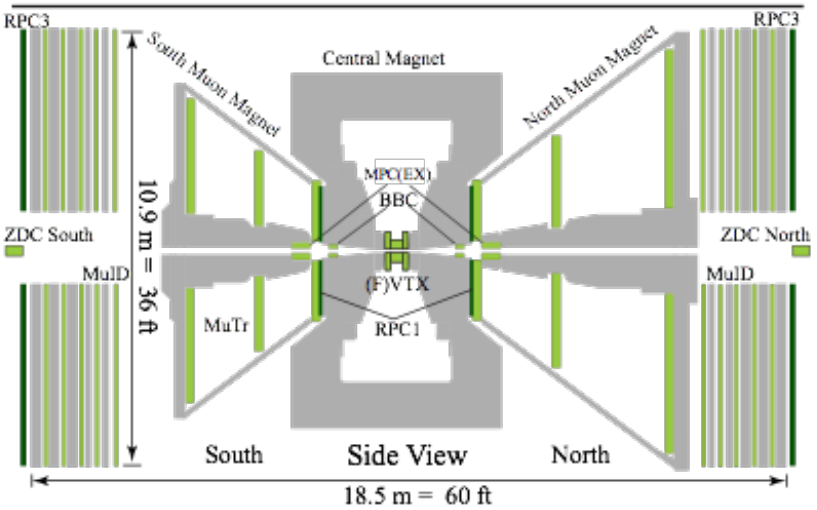


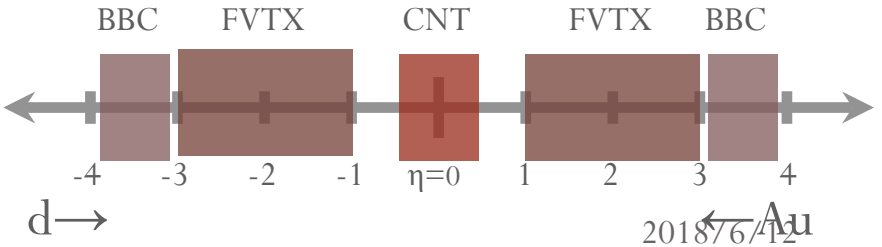
PHENIX detector

- CNT - Charged particle tracking
- FVTX - Unidentified particle tracking, Event Plane
- BBC- Centrality determination, Event Plane.

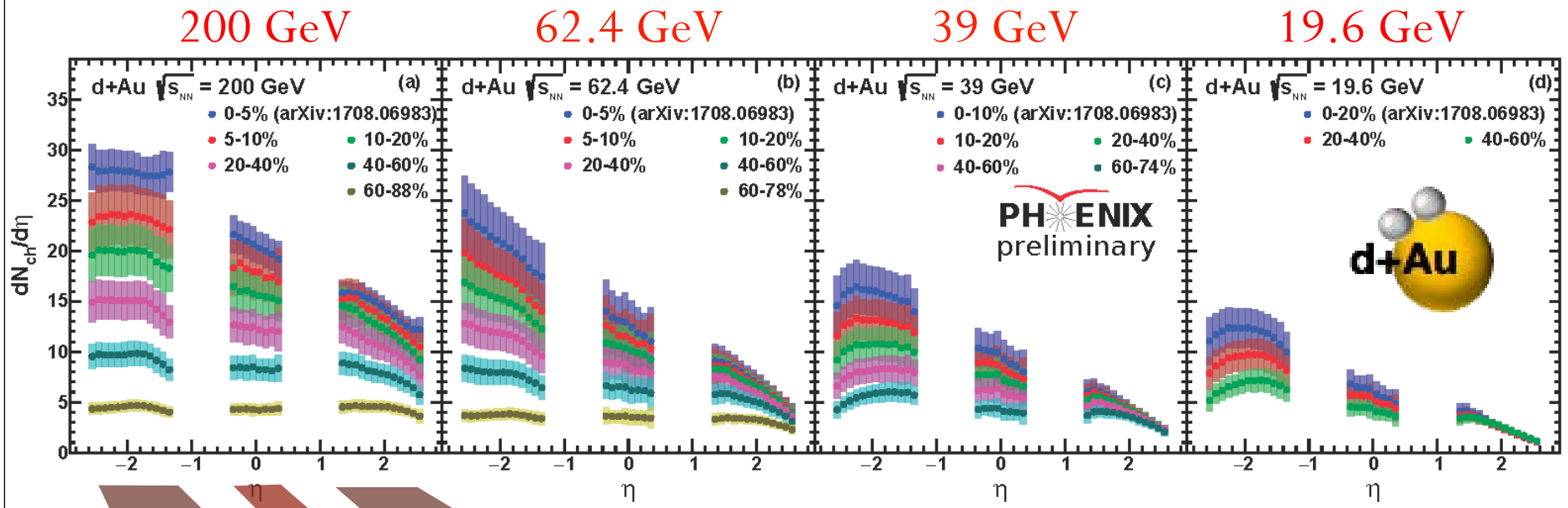


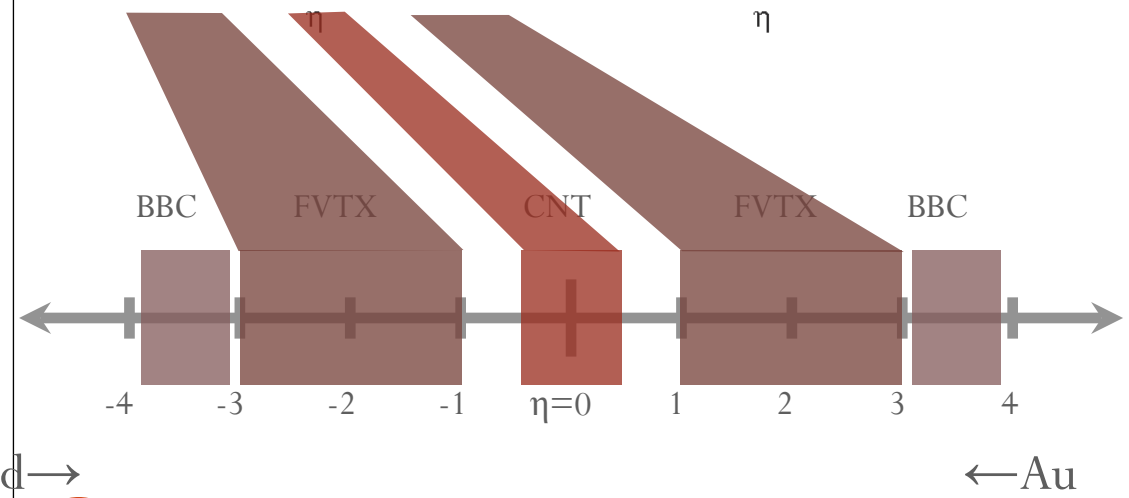






$dN_{ch}/d\eta$ in d+Au



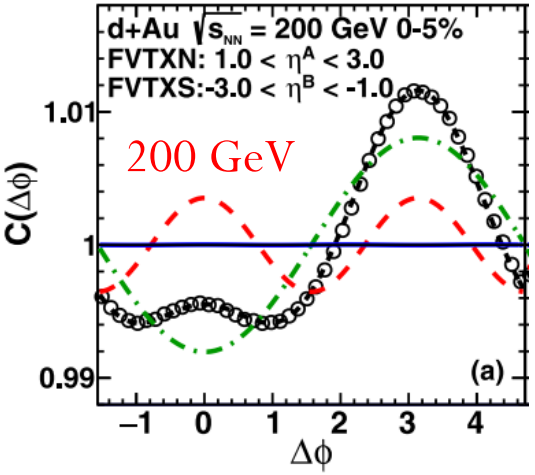


- Monotonic overall decrease of $dN_{ch}/d\eta$ from 200 to 20GeV
- Asymmetry is kept over the energy range

Correlated η-ranges

d+Au

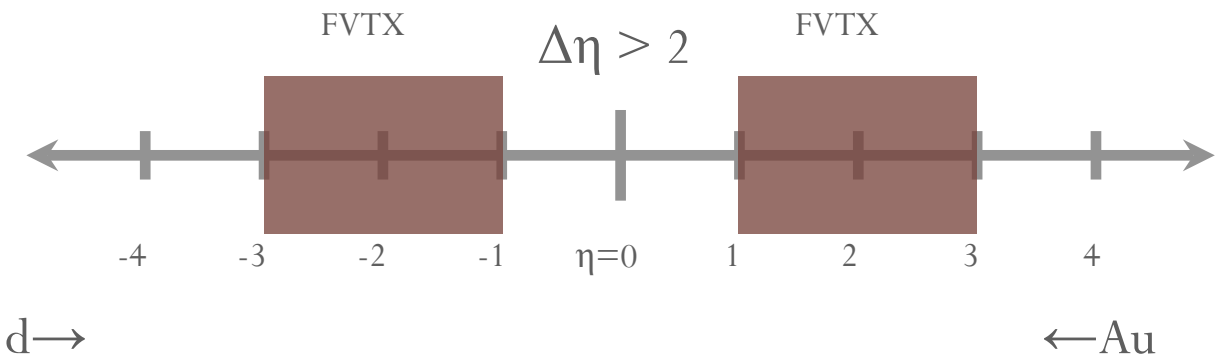
FVTXS — FVTXN



$2.00 < |\Delta\eta| < 6.00$

- $1 + \Sigma_{n=1}^{3} 2C_n \cos(n\Delta\phi)$
- $1 + 2C_1 \cos(\Delta\phi)$
- $1 + 2C_2 \cos(2\Delta\phi)$
- $1 + 2C_3 \cos(3\Delta\phi)$

Near-side correlation is clearly seen



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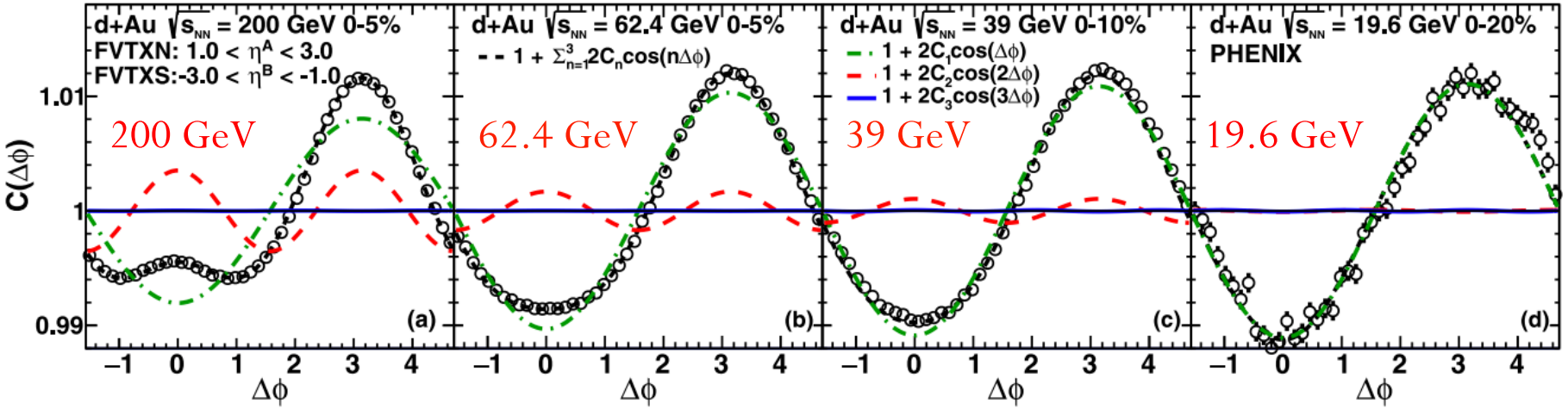
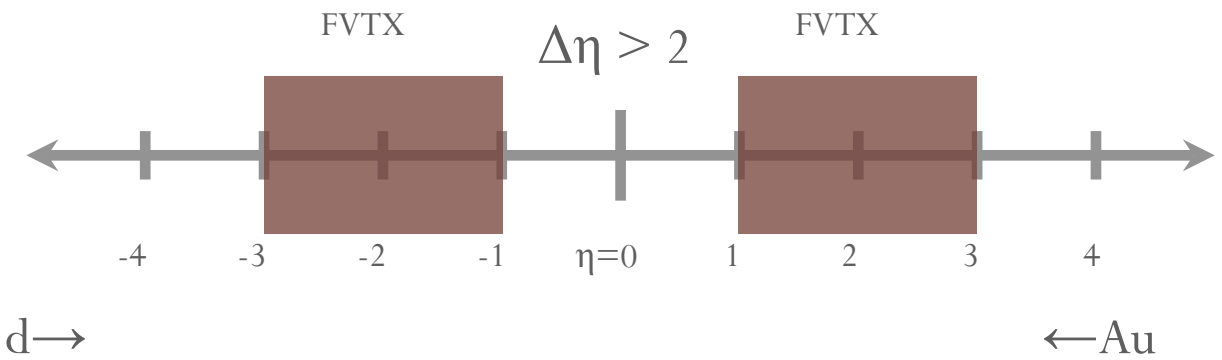
Correlated η-ranges become narrower

d+Au

FVTXS — FVTXN





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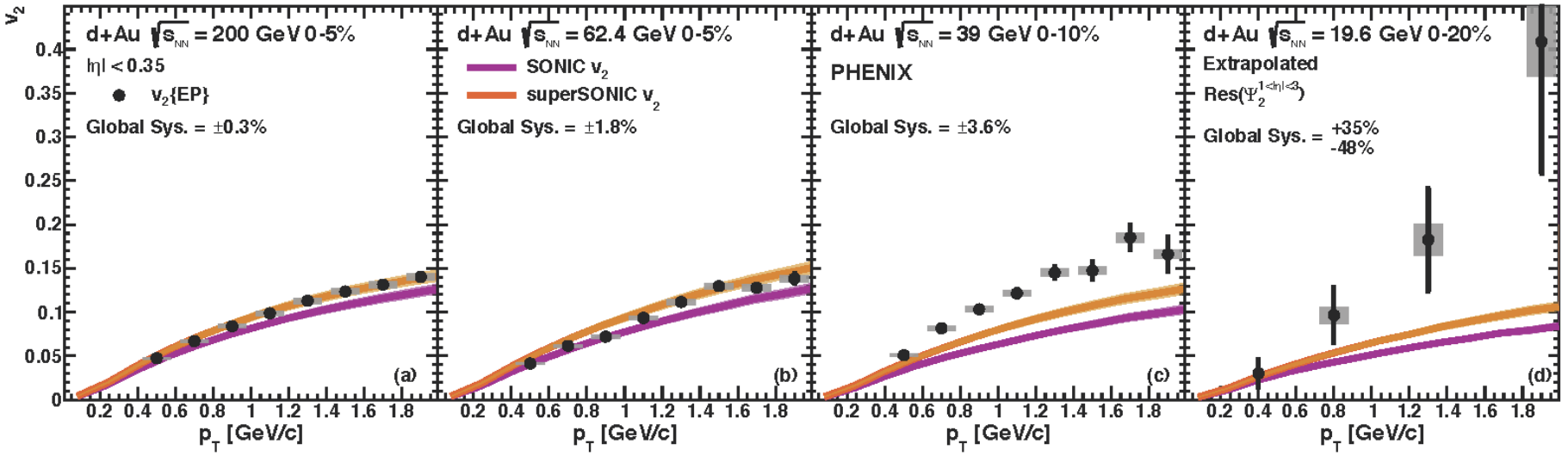
Energy dependence of v_2 in d+Au

- v_2 in d+Au as a function of collision energy
  - Significant v_2 signal is seen at all 4 energies.
  - Eventplane is determined at $\eta \sim 3$ (BBC)
- Comparison with (super)SONIC
  - It describes data very well at 200 & 62.4 GeV, but not at 39 & 19.6 GeV
- Model doesn't have non-flow component, however, measurement does.



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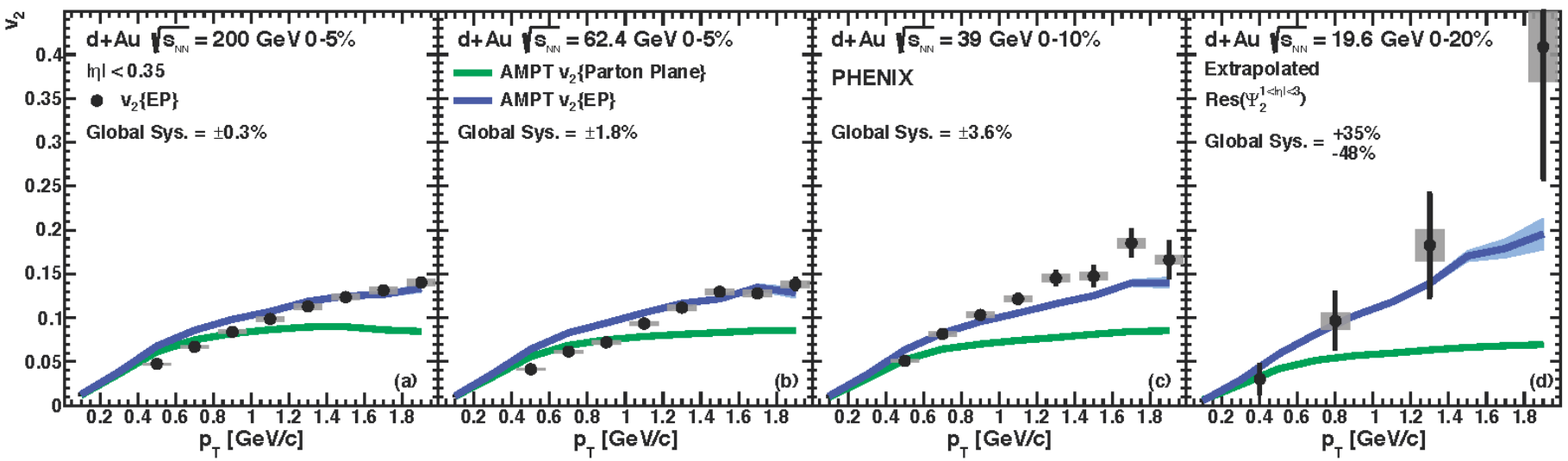
Studying with AMPT

- Using AMPT events, two v_2s are produced
- AMPT $v_2\{\text{Parton Plane}\}$: genuine v_2 that AMPT generates
- AMPT $v_2\{\text{EP}\}$: "real" analysis of AMPT events
  - Reconstruct eventplane, and measure flow.
  - Same as real data analysis. Non-flow effect is naturally involved.

- AMPT v2.26
- Black disk MC Glauber w/Hulthen wave func.
- String Melting
- partonic & hadronic scattering
- $\sigma_{parton} = 0.75$ mb
- Centrality defined by N_{ch} in $-3.9 < \eta < -3.1$

Non-flow dominant in 19.6GeV?



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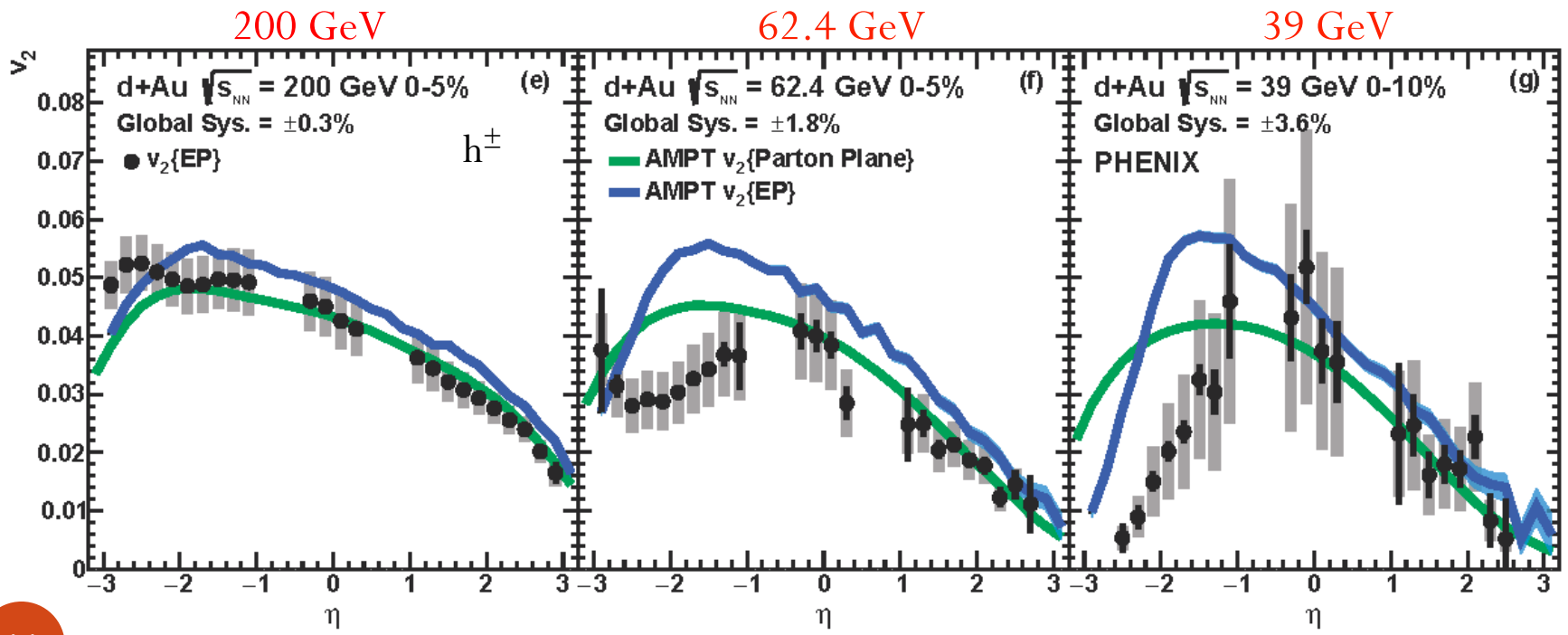
η-dependence v_2 comparing to AMPT

- Eventplane is determined at -3.9<η<-3.1 (BBCS)
- AMPT v_2 {Parton Plane} : genuine v_2 that AMPT generates
- AMPT v_2 {EP} : "real" analysis of AMPT events
  - Same as real data analysis. Non-flow effect is naturally involved.

Interesting behavior at backward rapidity and lower energies



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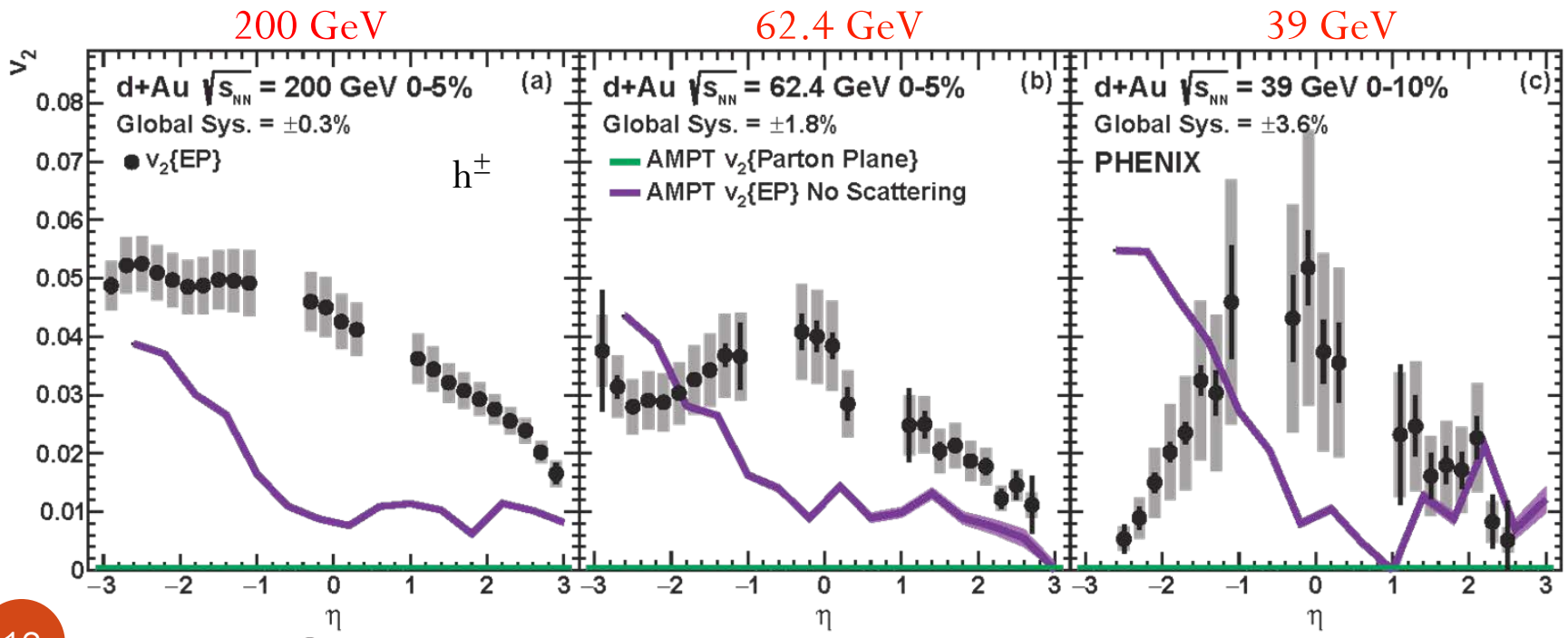
η-dependence v_2 comparing to AMPT

- AMPT v_2 {Parton Plane} : genuine v_2 that AMPT generates
- v_2 {EP} No Scattering: Turn off partonic and hadronic scattering (Nonflow only)
- ***Non-flow-only underestimates the measured v_2***



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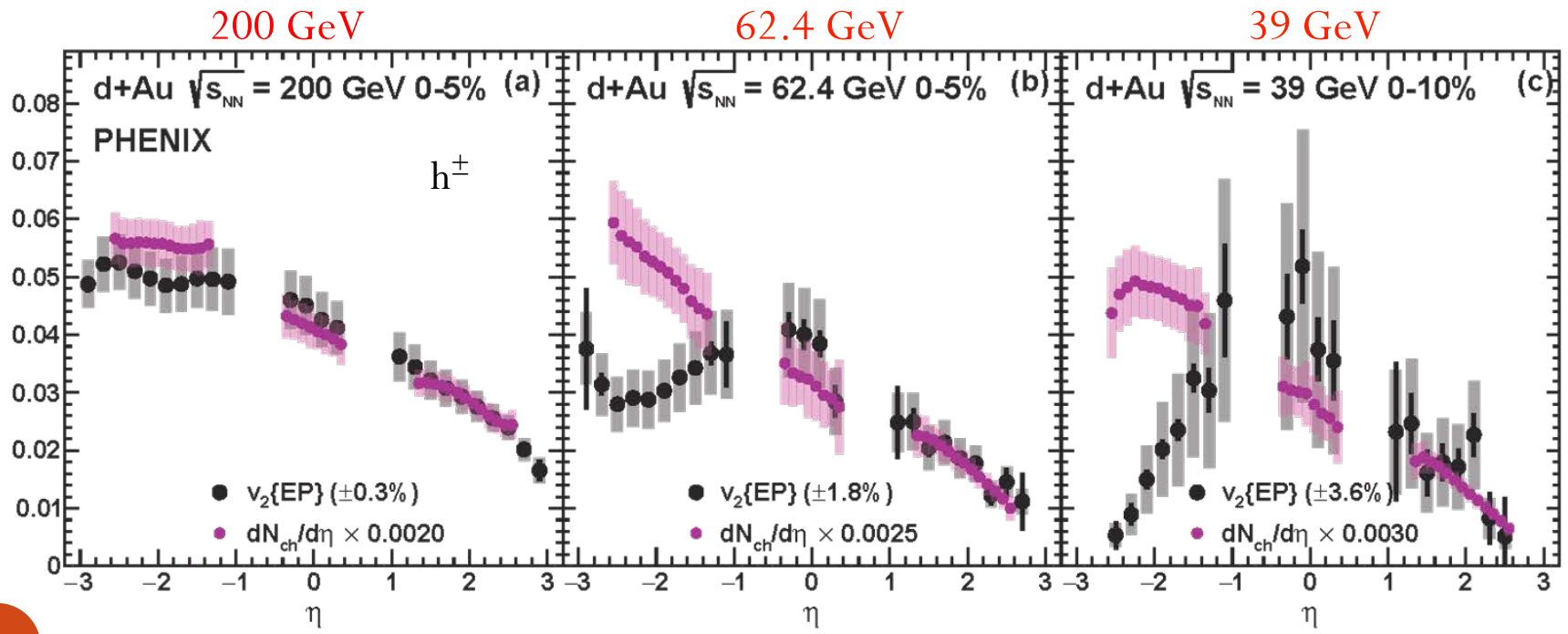
η-dependence v_2 comparing to $dN_{ch}/d\eta$

- $dN_{ch}/d\eta$ is scaled so that the values are consistent with v_2 at $1<\eta<3$
- Scaled $dN_{ch}/d\eta$ and v_2 are consistent at 200GeV, while not at 62 and 39GeV
  - A hint that 200GeV is the only system that has fully developed "QGP"?
- What about models?



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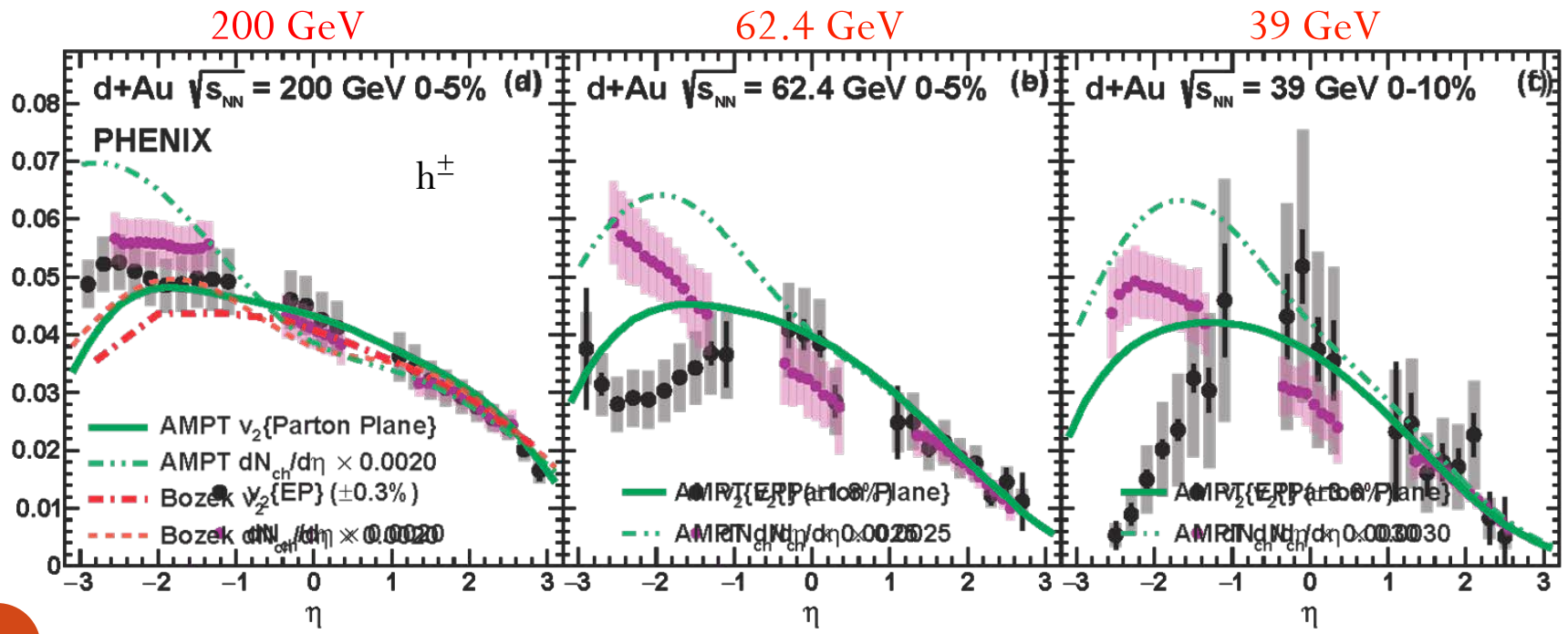
η-dependence v_2 comparing to $dN_{ch}/d\eta$

- $dN_{ch}/d\eta$ is scaled so that the values are consistent with v_2 at $1<\eta<3$
- Trend of v_2 and $dN_{ch}/d\eta$ in mid-forward region is well described by both AMPT and hydro.
  - AMPT: $dN_{ch}/d\eta$ is always higher than v_2 in backward region
  - Hydro (Bozek et al) shows v_2 follows $dN_{ch}/d\eta$ (200GeV only, unfortunately)



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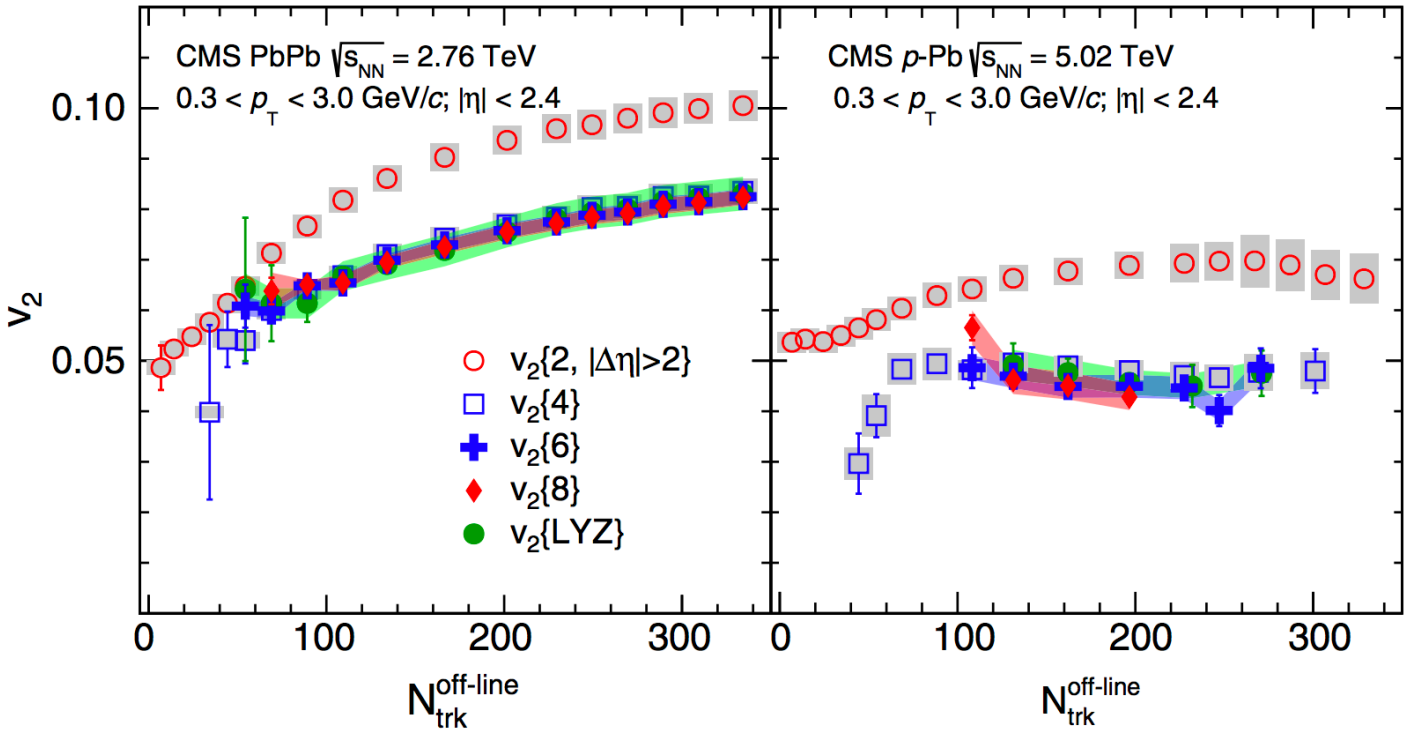
Cumulant method for flow "check"

- Cumulants have proven to be effective in both A+A and p+A at the LHC
- Involving more particles will "enhance" the genuine flow (flow correlated with a source), and "suppress" uncorrelated contribution (like jets).
- Can be applied to RHIC data.



Analysis procedure

- We use FVTX tracks for this analysis
- Make angular correlators by picking 2, 4 or 6 particles out of events

$$\langle 2 \rangle = \langle \cos(n(\phi_1 - \phi_2)) \rangle = \langle v_n^2 \rangle,$$

$$\langle 4 \rangle = \langle \cos(n(\phi_1 + \phi_2 - \phi_3 - \phi_4)) \rangle = \langle v_n^4 \rangle,$$

- Calculate cumulants as follows

$$c_n\{2\} = \langle\langle 2 \rangle\rangle,$$

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

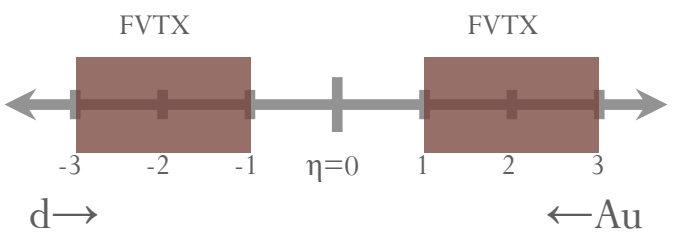
$$c_n\{6\} = \langle\langle 6 \rangle\rangle - 9\langle\langle 4 \rangle\rangle\langle\langle 2 \rangle\rangle + 12\langle\langle 2 \rangle\rangle^3,$$

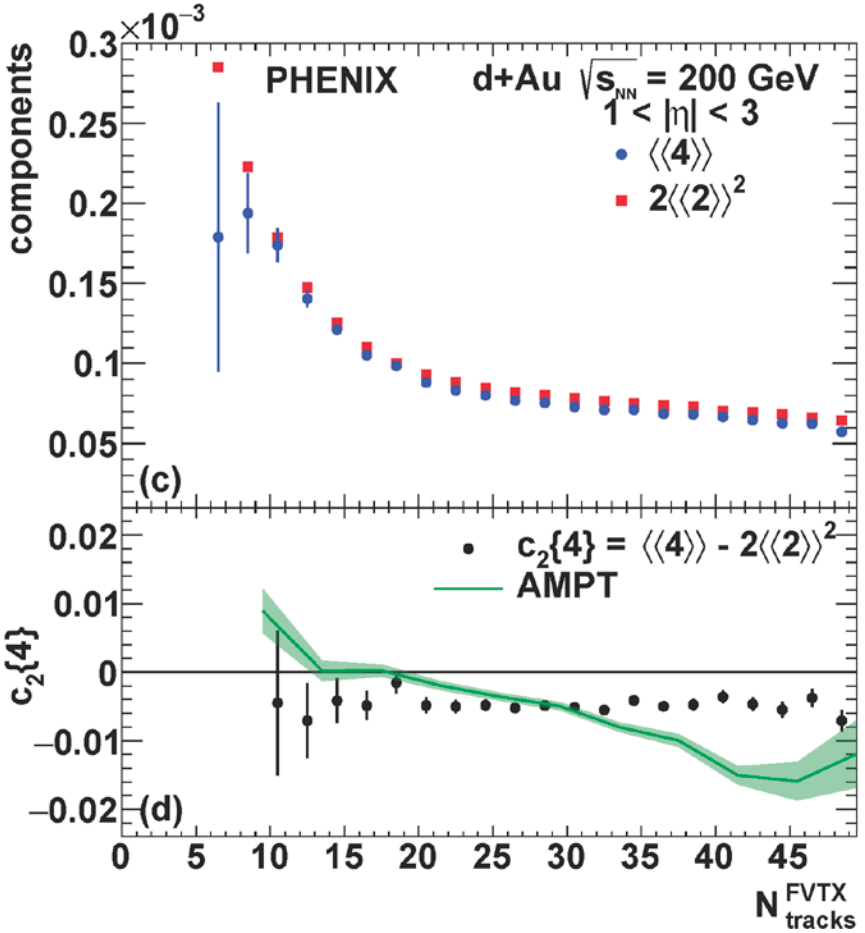
- v_n are then obtained as follows

$$v_n\{2\} = (c_n\{2\})^{1/2},$$

$$v_n\{4\} = (-c_n\{4\})^{1/4}, \quad \text{and}$$

$$v_n\{6\} = \left(\frac{1}{4} c_n\{6\}\right)^{1/6}.$$





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Cumulant results

- At 200GeV, $v_2\{4\}$ and $v_2\{6\}$ are consistent each other as well as $v_2\{2, |\Delta\eta|<2\}$.
  - They may reflect true flow component?

$$v_2\{2\} = \sqrt{v_2^2 + \sigma^2 + \delta^2}$$

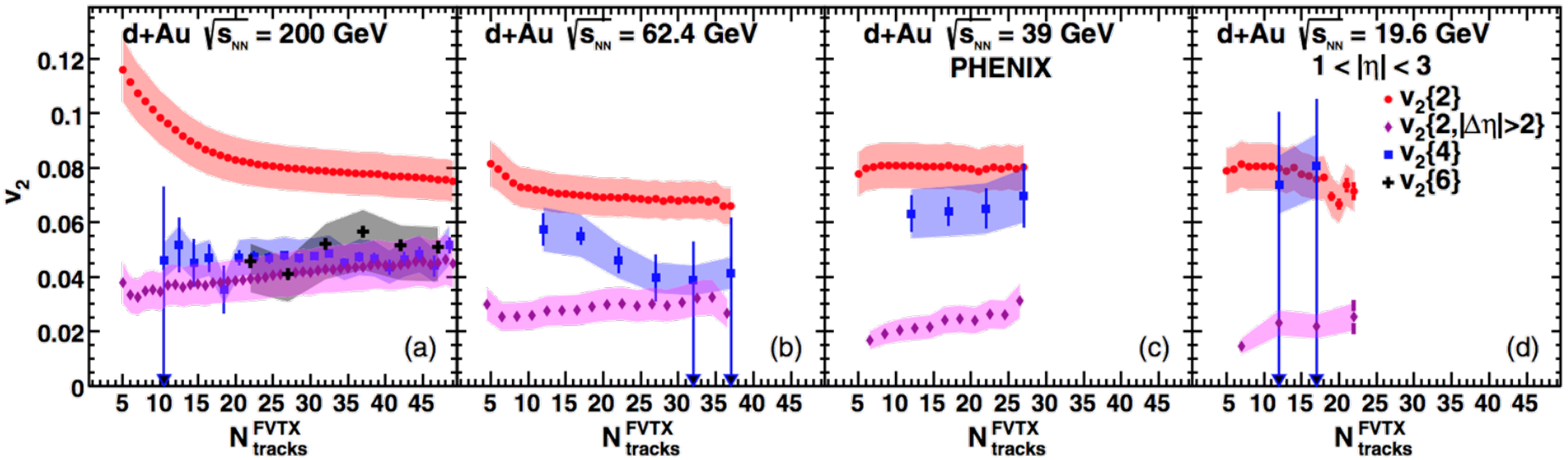
$$v_2\{4\} \approx v_2\{6\} = \sqrt{v_2^2 - \sigma^2}$$

σ: variation of dist.

δ: non-flow term

- At lower energies, $v_2\{4\}$ became more consistent with $v_2\{2\}$ and deviates from $v_2\{6\}$
  - Non-flow effect at the four-particle correlator level manifests at lower energies?

$v_2\{2, |\Delta\eta|<2\}$: two particles have $|\Delta\eta|<2$



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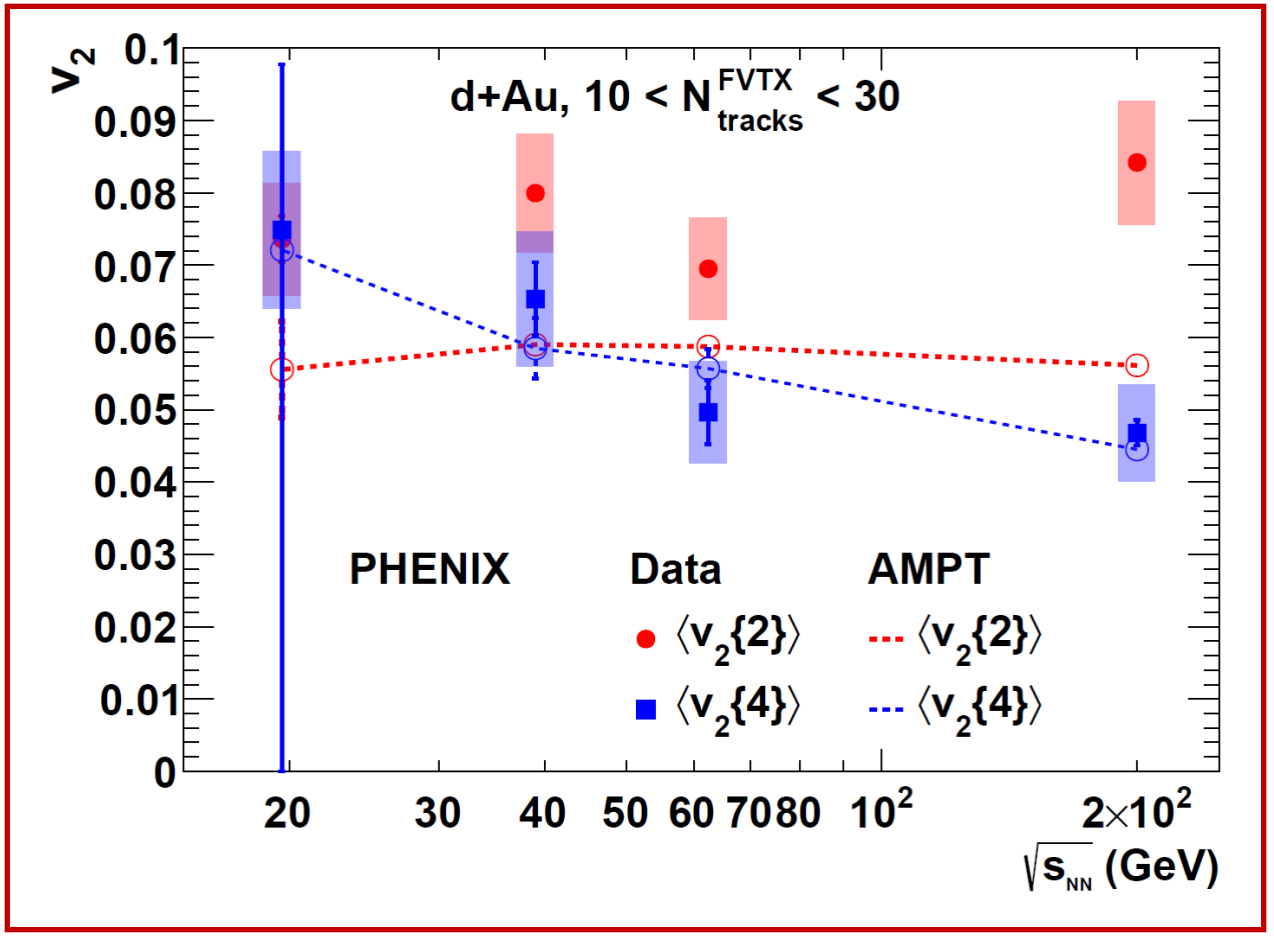
Comparison with AMPT

- General trend is reproduced by AMPT



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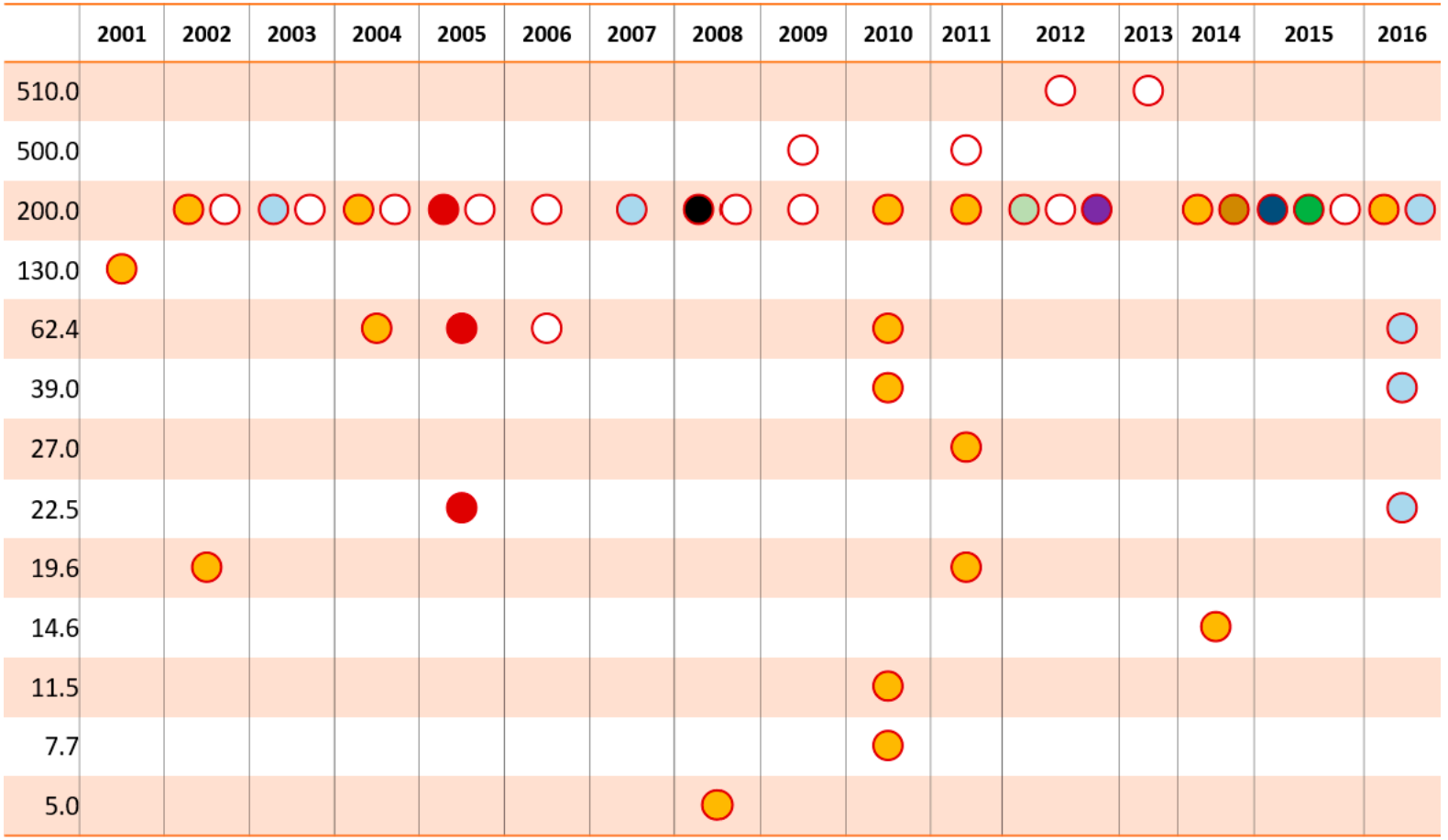
Summary

- v_2 in small systems are investigated over collision energies
  - Sizable v_2 is observed even at 19.6GeV
- η-dependent v_2 qualitatively follow the η-dependence of $dN_{ch}/d\eta$
- As going to lower energy, non-flow component starts dominating
  - However, AMPT with no partonic & hadronic scattering significantly under-describe the data over the energies down to 39GeV
  - There is no 1st order transition of flow turn on-off seen.
- Non-flow component is also quantified by cumulant method
  - At 200GeV, $v_2\{4\}$ and $v_2\{6\}$ are very consistent, meaning they may reflect true flow component
  - At lower energies, $v_2\{4\}$ became more consistent with $v_2\{2\}$ and deviates from $v_2\{6\}$, suggesting non-flow effect at the four-particle level manifests?

Backup

Dataset collected by PHENIX



○ p+p ● Au+Au ● d+Au ● Cu+Cu ● U+U ● Cu+Au ● He+Au ● p+Au ● p+Al

See details at http://www.rhichome.bnl.gov/RHIC/Runs/

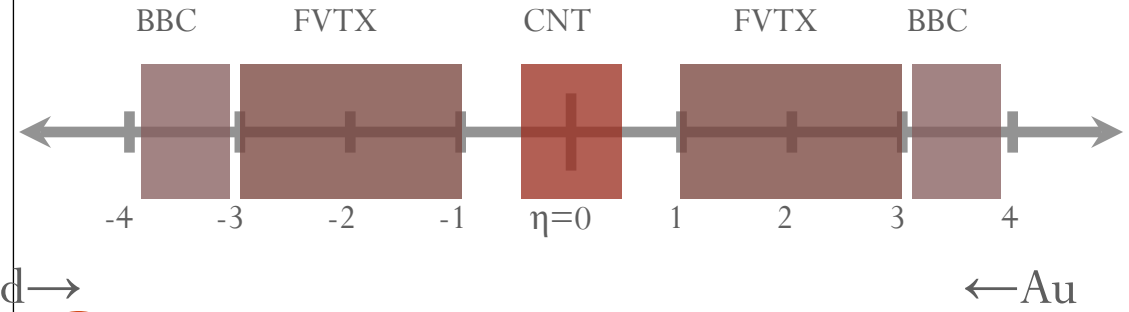
PHENIX centrality

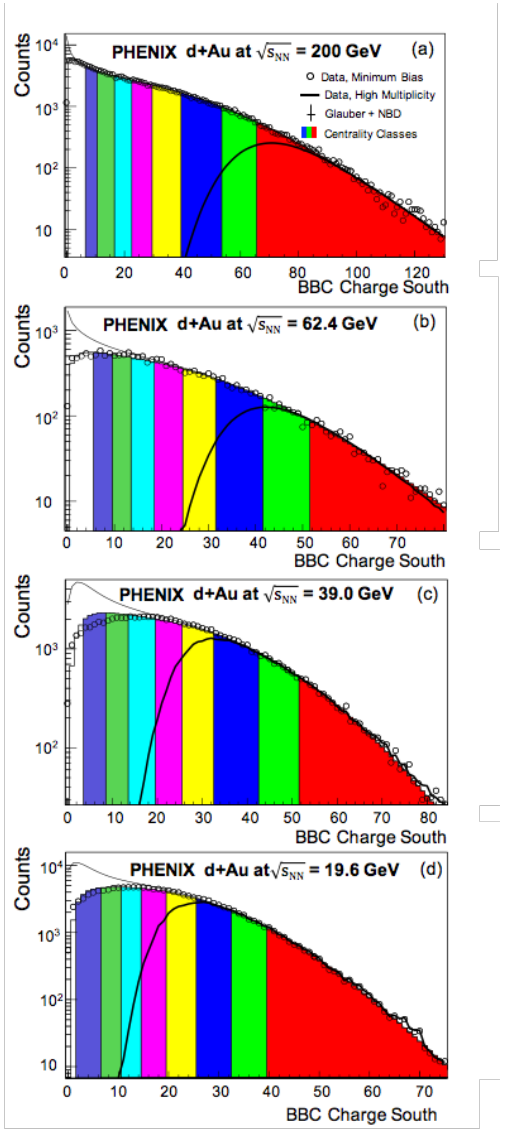
TABLE II. Summary of the mean number of participants, $\langle N_{part} \rangle$, and eccentricity, $\langle \varepsilon_2 \rangle$, for central $d + Au$ collisions at $\sqrt{s_{NN}} = 200$, 62.4, 39, and 19.6 GeV.

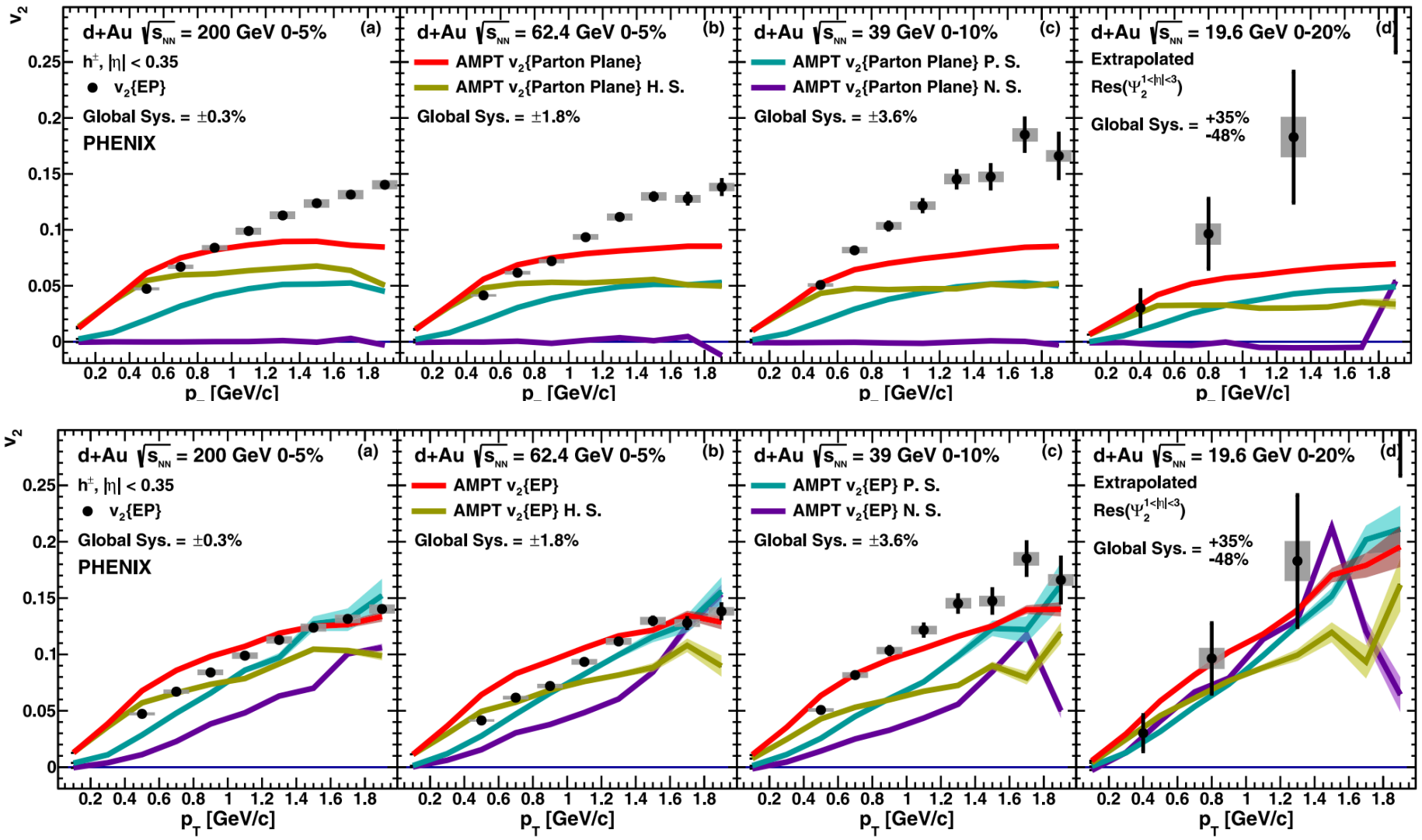
$\sqrt{s_{NN}}$ [GeV]	Centrality	$\langle N_{part} \rangle$	$\langle \varepsilon_2 \rangle$
200	0%–5%	17.8 ± 1.2	0.54 ± 0.04
62.4	0%–5%	16.3 ± 1.0	0.55 ± 0.05
39	0%–10%	15.9 ± 1.0	0.56 ± 0.06
19.6	0%–20%	13.6 ± 1.0	0.55 ± 0.05

MB Triggering using BBC and FVTX

Centrality characterization using BBCS






d+Au √sNN = 200 GeV 0-5% (a)
h±, |η| < 0.35
v2{EP}
Global Sys. = ±0.3%
PHENIX
d+Au √sNN = 62.4 GeV 0-5% (b)
AMPT v2{Parton Plane}
AMPT v2{Parton Plane} H. S.
Global Sys. = ±1.8%
d+Au √sNN = 39 GeV 0-10% (c)
AMPT v2{Parton Plane} P. S.
AMPT v2{Parton Plane} N. S.
Global Sys. = ±3.6%
d+Au √sNN = 19.6 GeV 0-20% (d)
Extrapolated
Global Sys. = +35% -48%
AMPT v2{EP}
AMPT v2{EP} H. S.
AMPT v2{EP} P. S.
AMPT v2{EP} N. S.
v2
pT [GeV/c]

v_2 vs centrality

low-p_T (0.6 — 0.8)

AMPT:

v_2 decreases towards peripheral

Nonflow subdominant

(~2% difference $v_2\{PP\}$ vs $v_2\{EP\}$)

Data:

v_2 flat or increasing toward peripheral

Increased nonflow?

high-p_T (2.0 — 2.5)

AMPT:

$v_2\{PP\}$ decreases towards peripheral

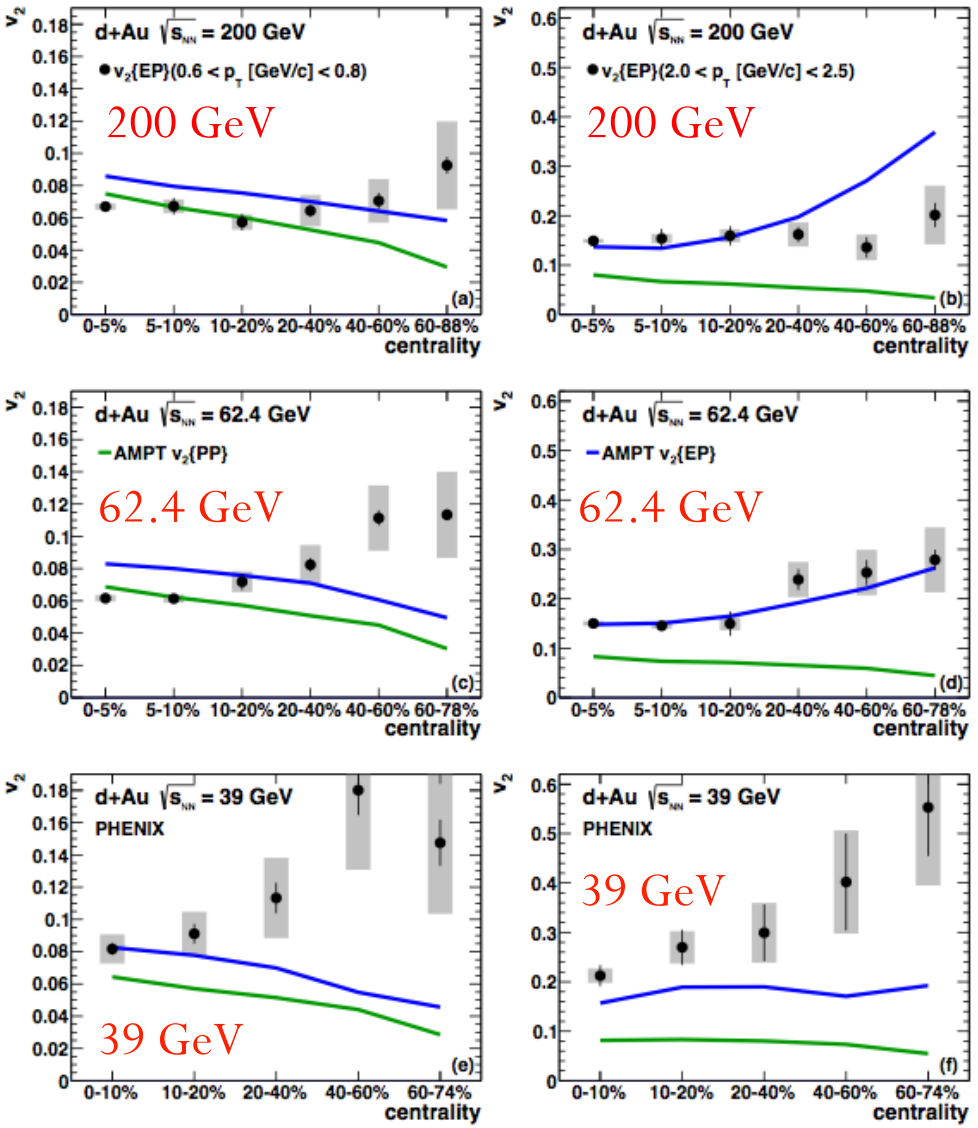
$v_2\{EP\}$ increases towards peripheral

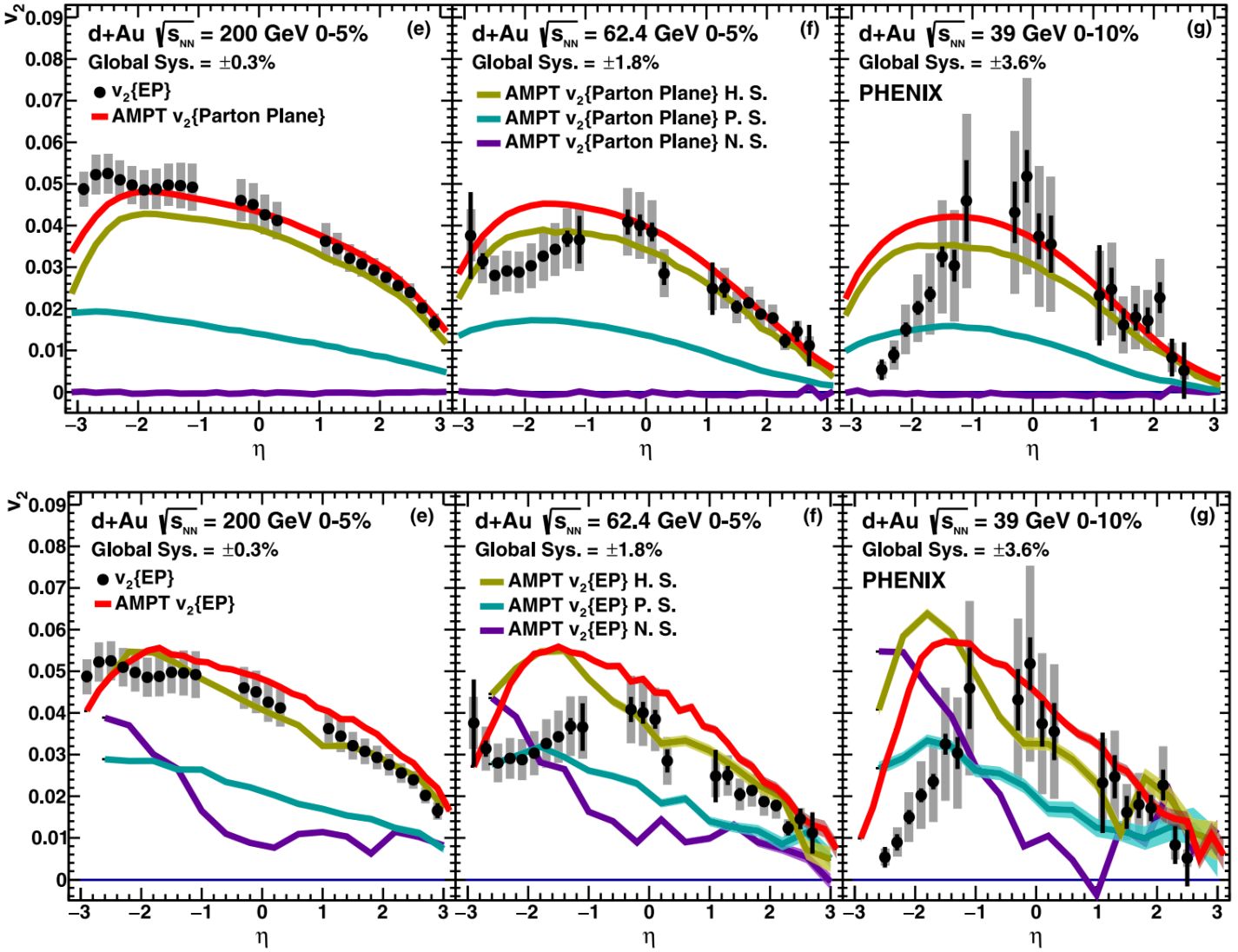
Nonflow dominant

Data:

v_2 increasing toward peripheral

arXiv:1708.06983

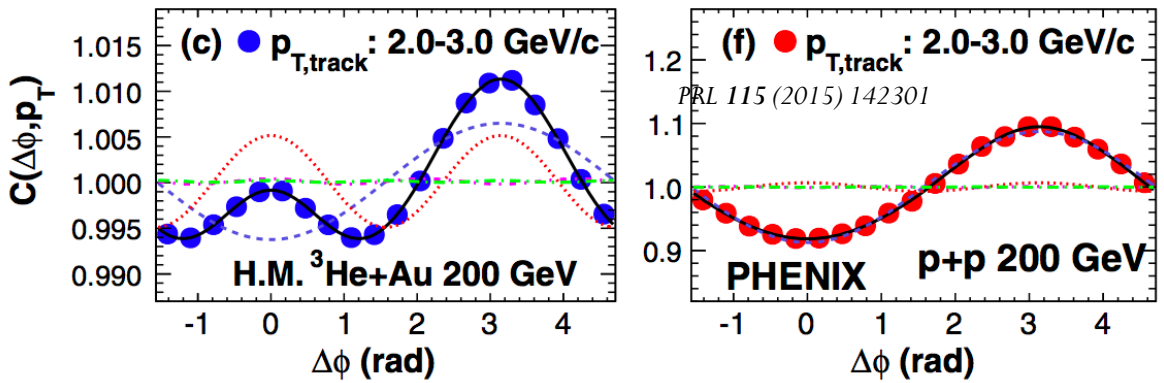


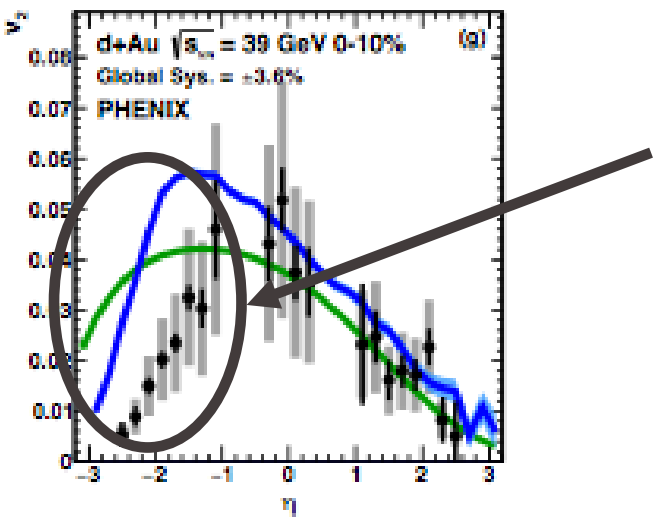

d+Au $\sqrt{s_{NN}}$ = 200 GeV 0-5%
(e)
Global Sys. = ±0.3%
v_2\{EP\}
AMPT v_2\{Parton Plane\}
d+Au $\sqrt{s_{NN}}$ = 62.4 GeV 0-5%
(f)
Global Sys. = ±1.8%
AMPT v_2\{Parton Plane\} H. S.
AMPT v_2\{Parton Plane\} P. S.
AMPT v_2\{Parton Plane\} N. S.
d+Au $\sqrt{s_{NN}}$ = 39 GeV 0-10%
(g)
Global Sys. = ±3.6%
PHENIX
v_2
η
d+Au $\sqrt{s_{NN}}$ = 200 GeV 0-5%
(e)
Global Sys. = ±0.3%
v_2\{EP\}
AMPT v_2\{EP\}
d+Au $\sqrt{s_{NN}}$ = 62.4 GeV 0-5%
(f)
Global Sys. = ±1.8%
AMPT v_2\{EP\} H. S.
AMPT v_2\{EP\} P. S.
AMPT v_2\{EP\} N. S.
d+Au $\sqrt{s_{NN}}$ = 39 GeV 0-10%
(g)
Global Sys. = ±3.6%
PHENIX
v_2
η

Why don't we subtract/estimate nonflow?

Most proposed methods utilize low multiplicity p+p collisions to estimate Non flow

We don't have measured p+p references at all 4 energies





Also … most proposed methods assume linear combination of Flow & Nonflow

AMPT results indicate that that may not be the case …

Most proposed methods we've tested don't pass a closure test in AMPT (d+Au @ RHIC)