Stony Brook University | The State University of New York

Future opportunities of collectivity in small systems at RHIC

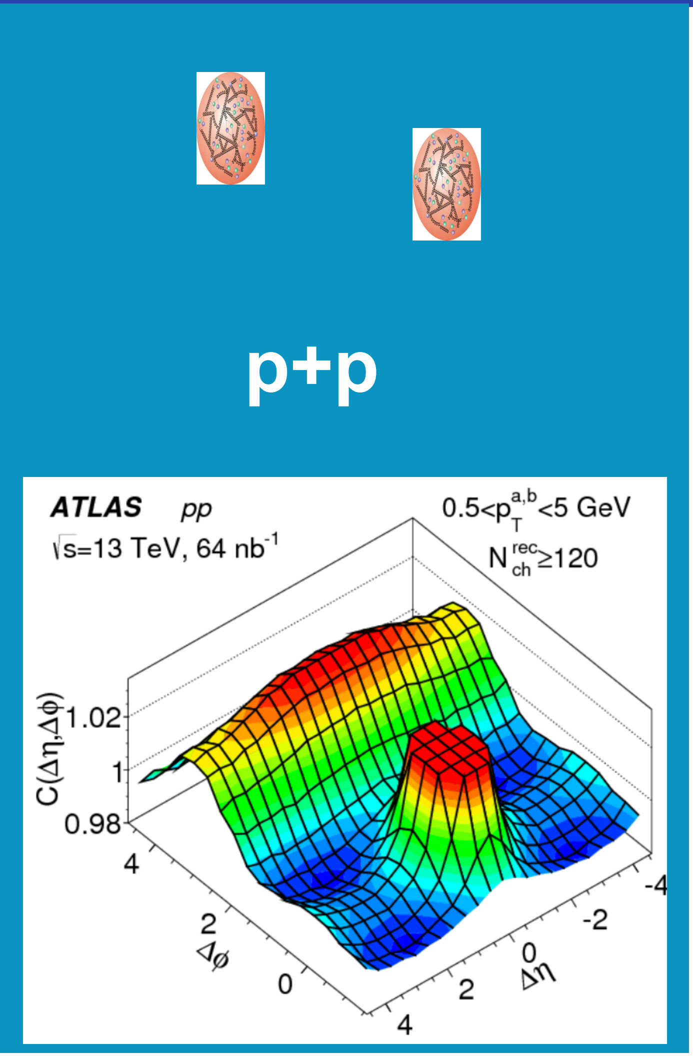
Jiangyong Jia

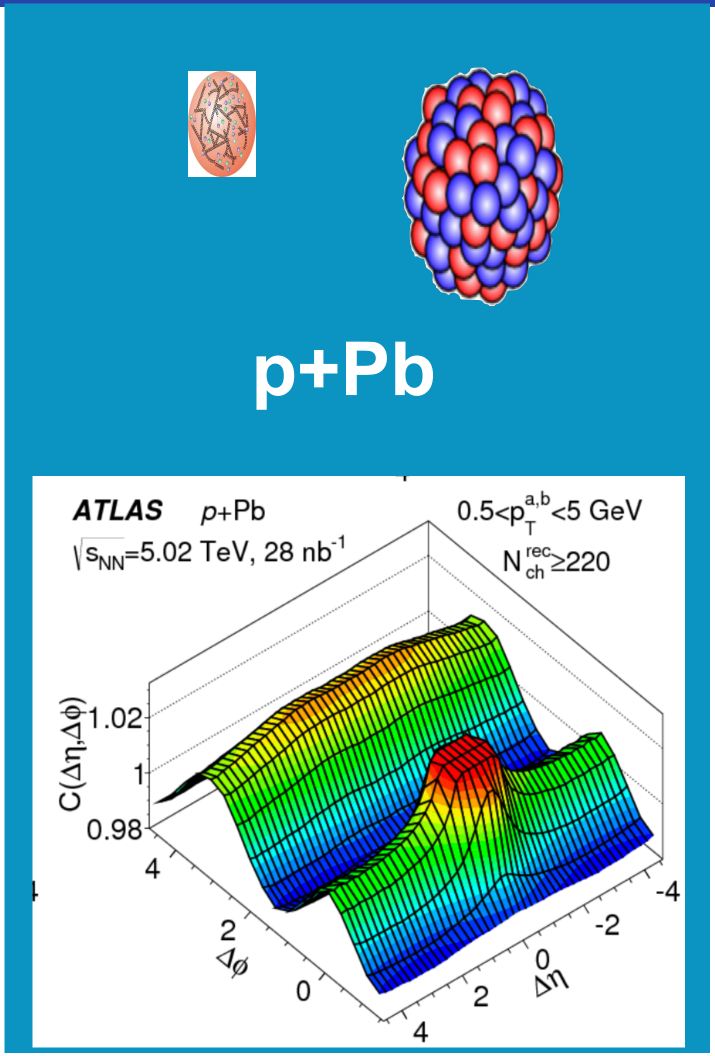
Stony Brook University and BNL

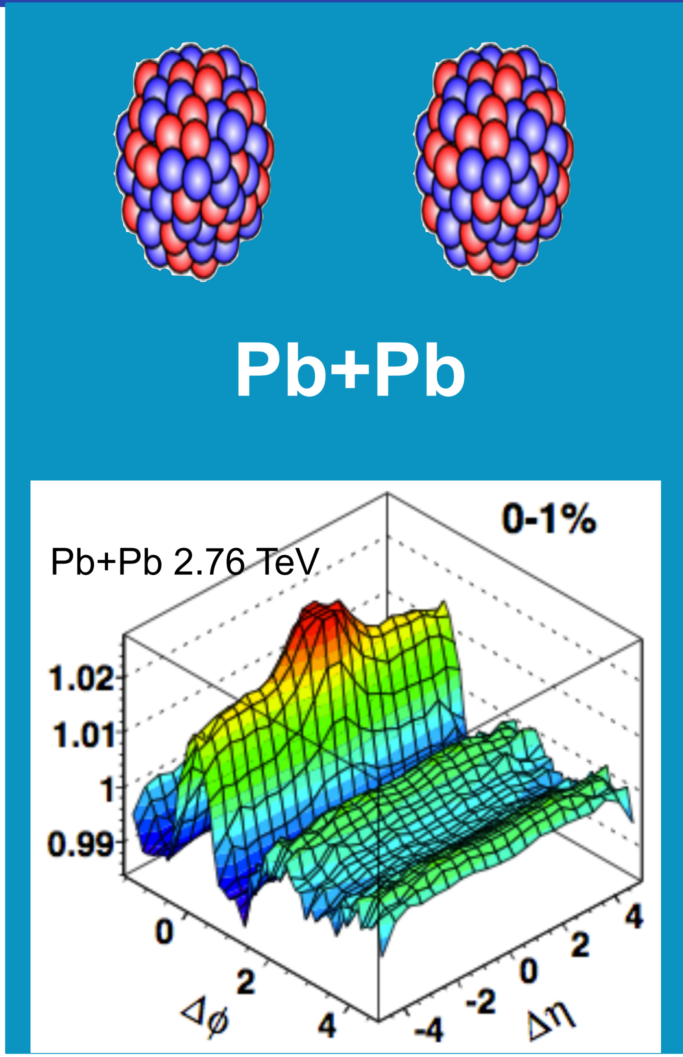
With help from Shengli Huang, Maowu Nie, Zhenyu Chen, Guoliang Ma….

Workshop on collectivity of small systems in high-energy collisions

Long-range collectivity in different systems





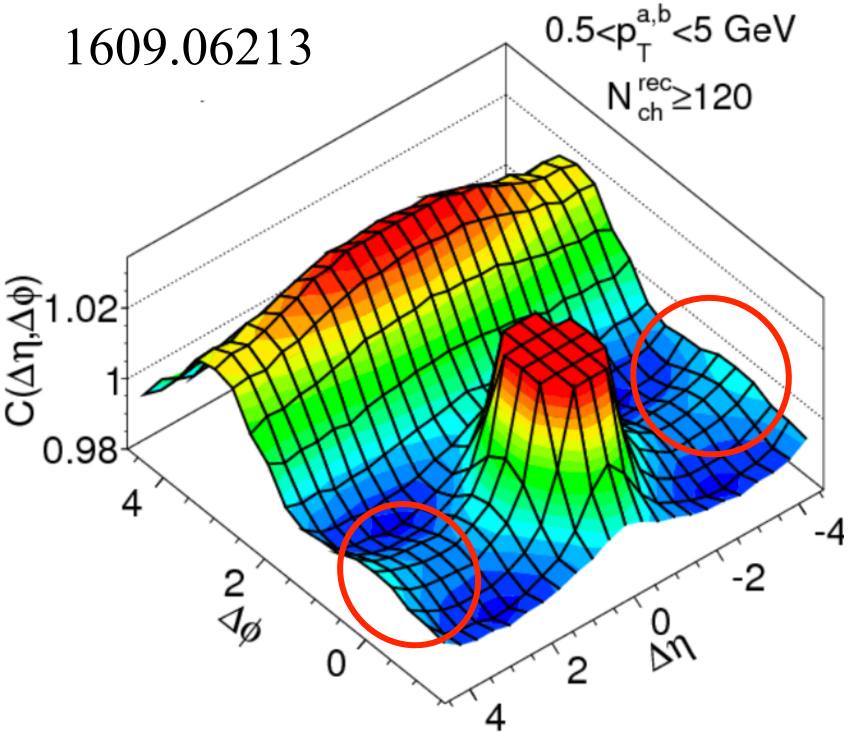


- Long-range correlation in momentum space comes
  - directly from early time t~0 (CGC)
  - or it is a final state response to spatial fluctuation at t=0 (hydro/transport).

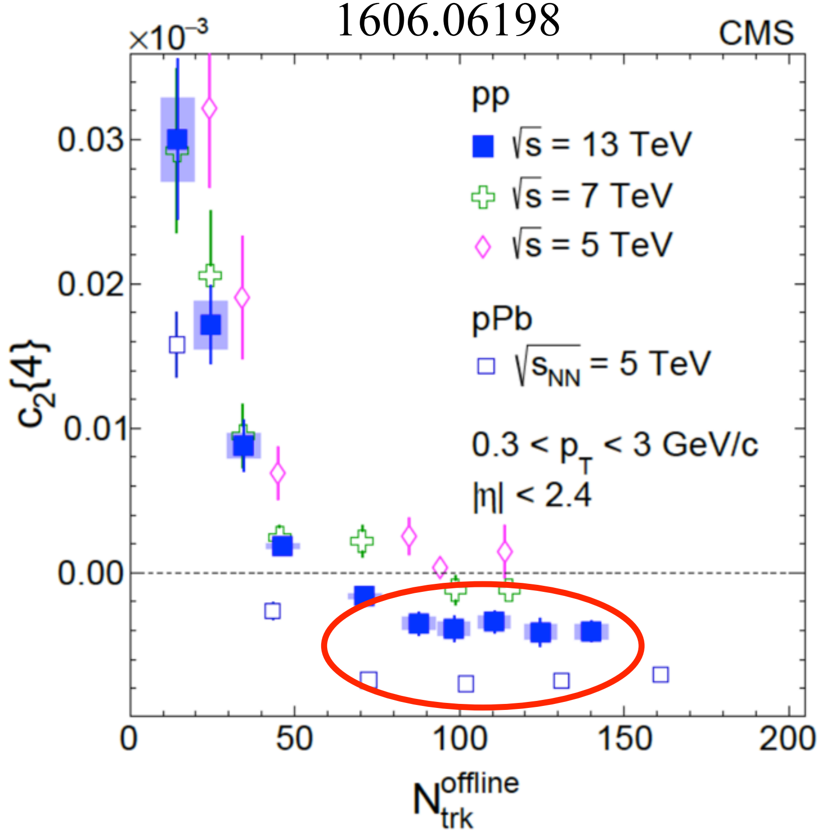
Timescale for collectivity and thermalization mechanism?

Features of collectivity in small system

1609.06213



1606.06198



Long-range in η

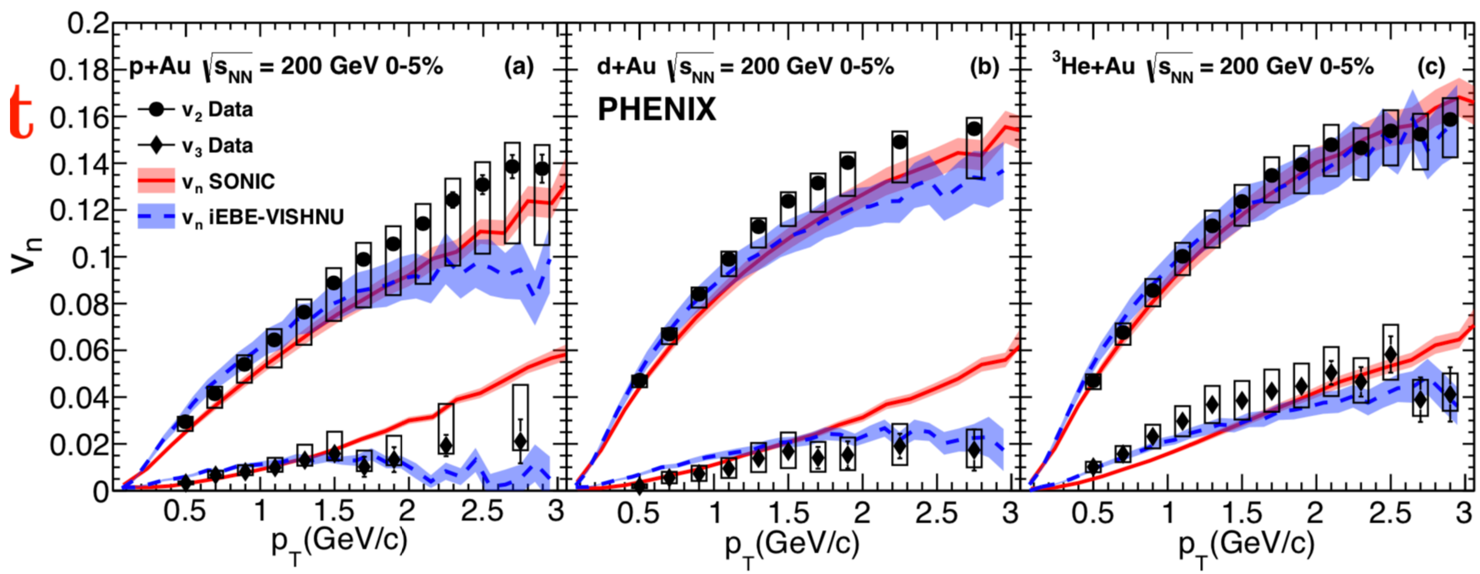
Multi-particle (3,4,5..) signal

Collectivity mean both

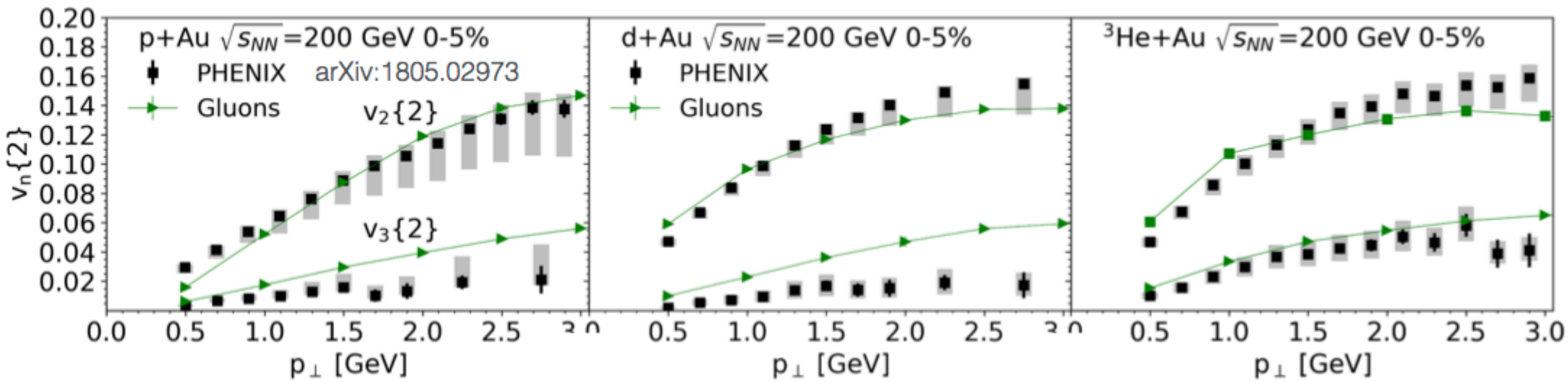
Initial-state vs final-state interpretation

Geometry response models naturally describe the data

p+Au d+Au ^{3}He+Au



One initial momentum anisotropy(pre-flow) picture seem also work



It is a quantitative question: how much each contribute and where?

Can one see collectivity in each event ?

- Yield difference in/out plane for single particle v_2 is $\frac{4v_2}{\pi} N \sim v_2 N$
- Random fluctuation gives $v_2 \sim \sqrt{\frac{1}{2N}}$, but no real correlation signal.
  - Such statistical non-flow averages out in correlation analysis

N_{ch}	20	100	1000
5% flow in/out plane diff v_2N	±1	±5	±50
Random noise in/out plane diff	±3	±7	±22

Difficult to see real v_2 on EbyE base, except in large system

Collectivity and non-flow in correlations

- Assume N particles from N/2 resonance. It gives real two-particle correlation with a strength of $v_{2\Delta} \sim \frac{1}{2N}, v_2 \sim \sqrt{\frac{1}{2N}}$

N_{ch}	20	100	1000
Correlated pairs	10	50	500
v_2^B	22%	10%	3%

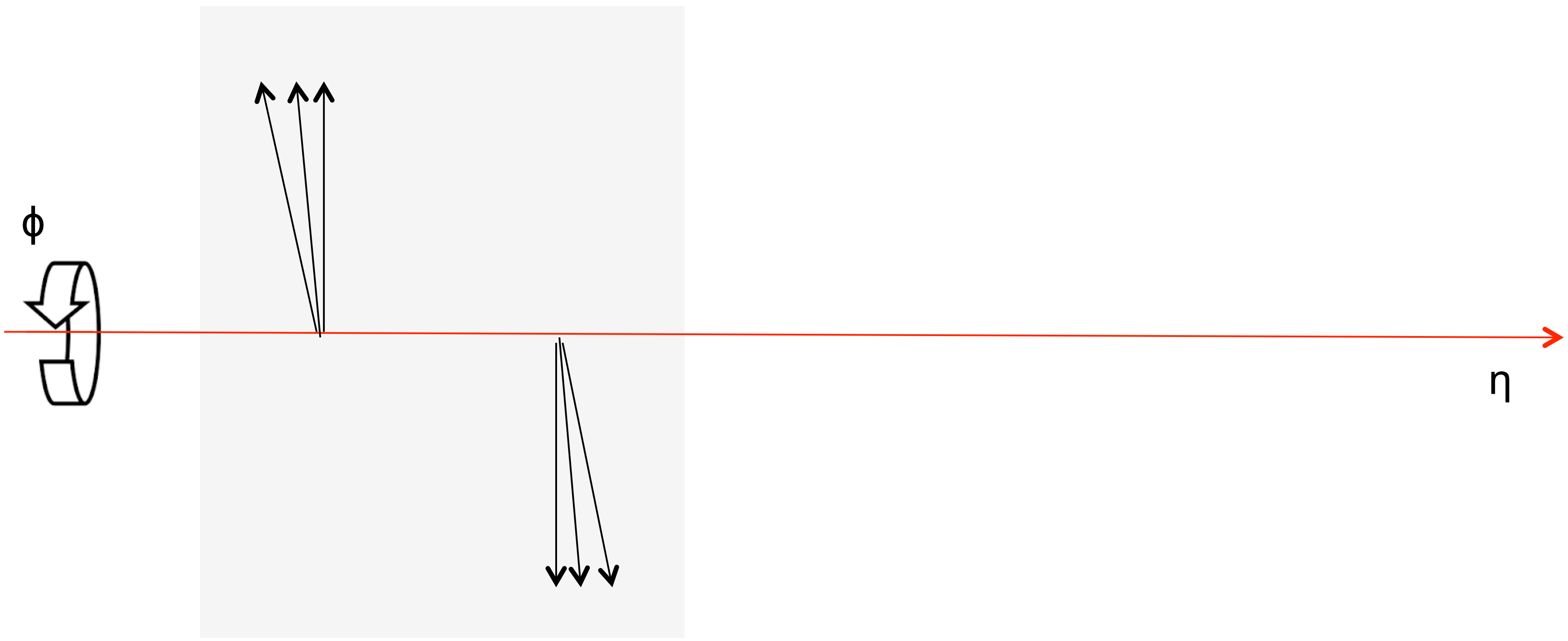
- Observation of $v_2 > v_2^B$ in 2PC requires collectivity involving more particles, this happens in PbPb system.

- Conversely, large raw 2PC v_2^{obs} in small systems do not necessary imply event-wise collectivity since real $v_2 < v_2^B$

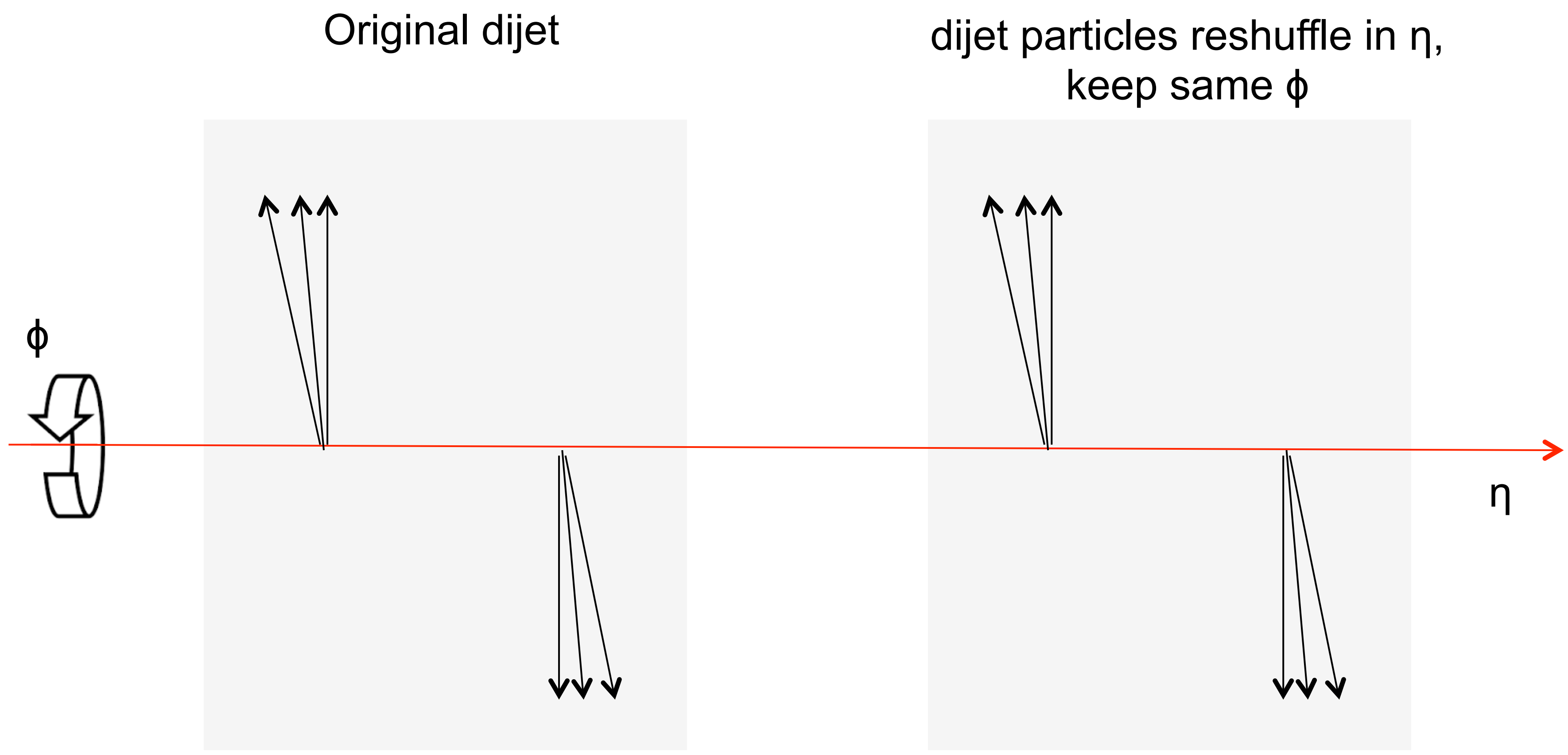
Multi-particle correlation is a must in small systems!

Collectivity w/o final state: A toy

Original dijet

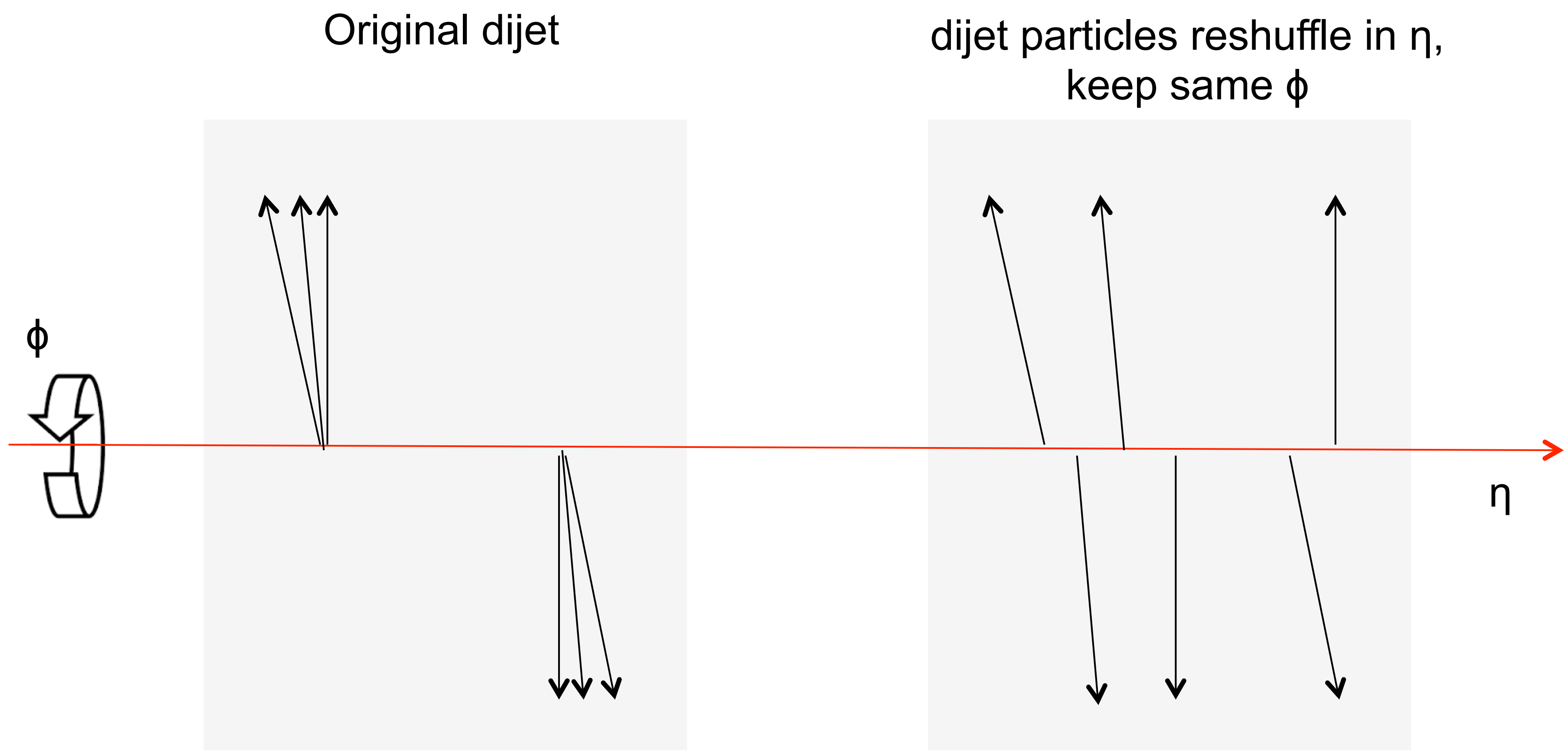


Collectivity w/o final state: A toy



Give the same non-zero flow coefficient $c_n\{2k\}$ and $v_n\{2k\}$, though clearly **NO event-wise collectivity**

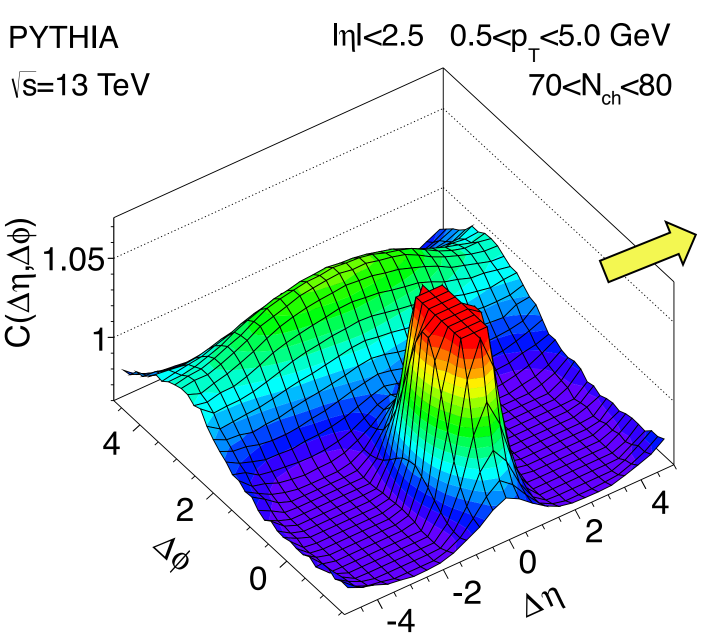
Collectivity w/o final state: A toy

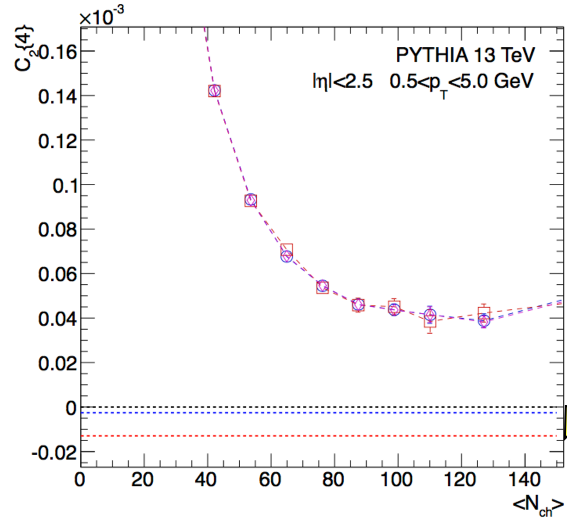


Give the same non-zero flow coefficient $c_n\{2k\}$ and $v_n\{2k\}$, though clearly **NO event-wise collectivity**

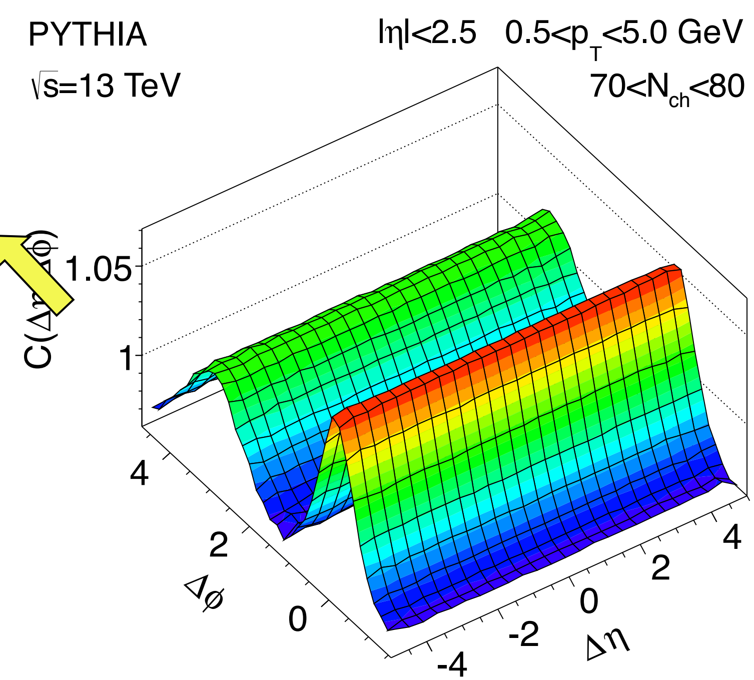
Collectivity w/o final state: A toy

original





η reshuffled



Give the same non-zero flow coefficient $c_n\{2k\}$ and $v_n\{2k\}$, though clearly **NO event-wise collectivity**

Seeing multi-part. corr. alone do not distinguish initial vs final

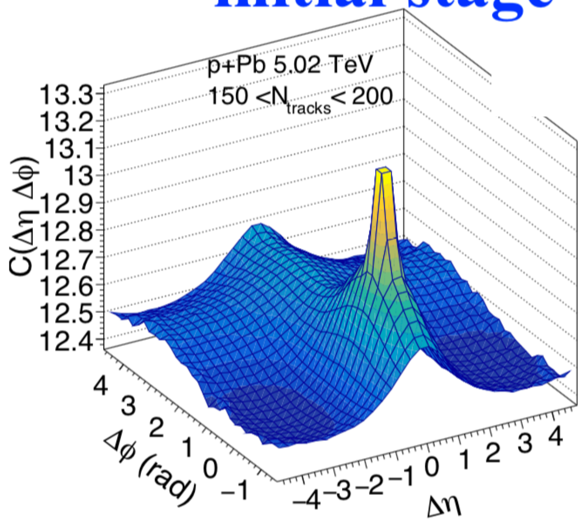
But: Final flow is geometrical response, while initial flow is not

Another test with AMPT model

A transport model with four stages

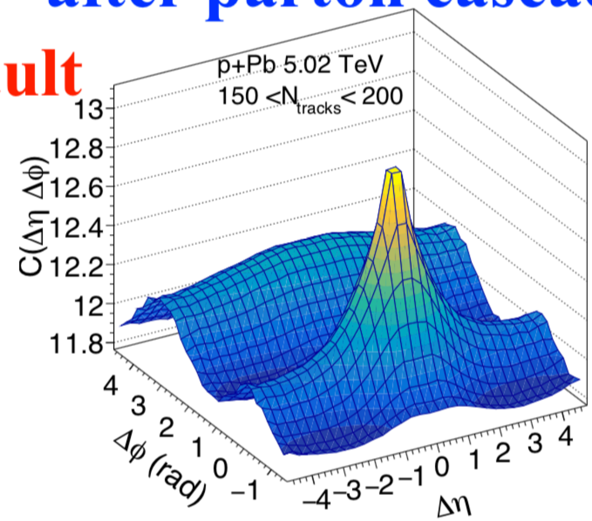
p+Pb 5 TeV

initial stage

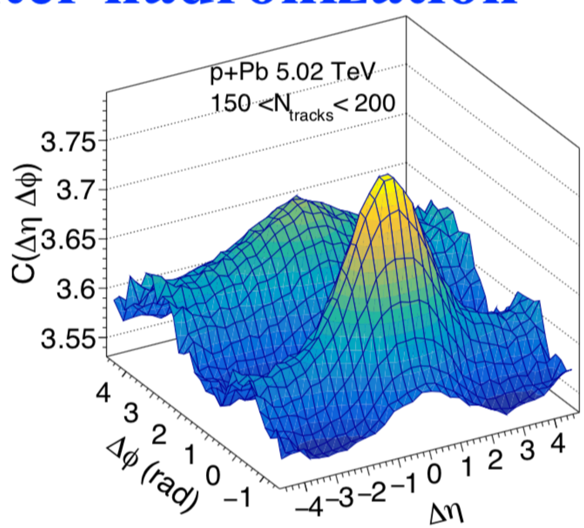


after parton cascade

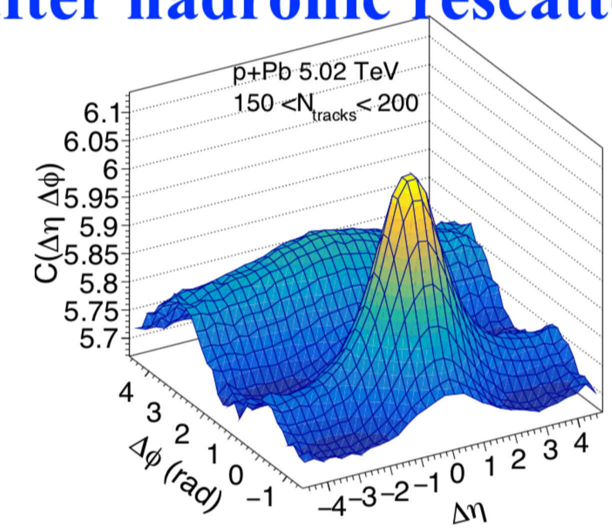
default



after hadronization



after hadronic rescattering

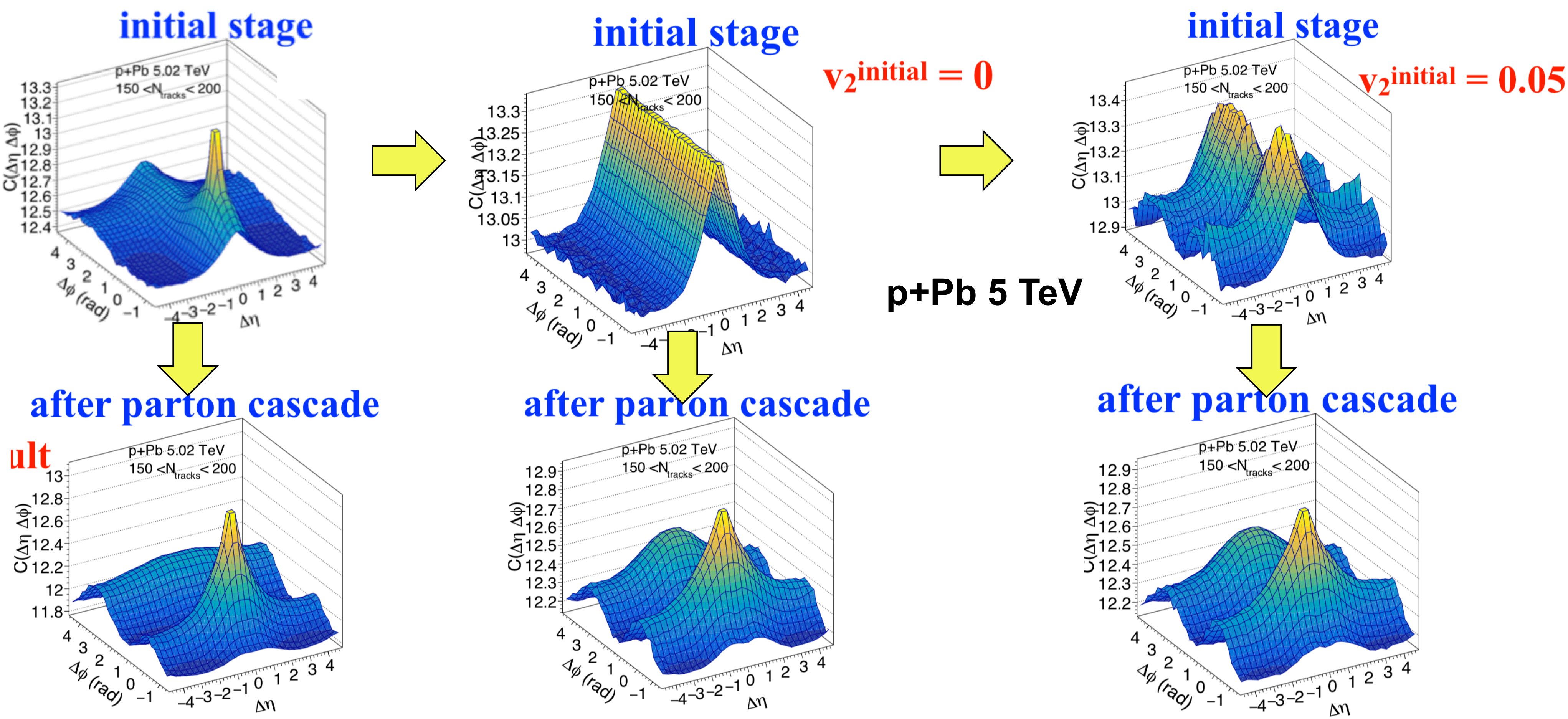


Another test with AMPT model

- Randomize azimuthal angle of the partons, but keep the p_T value.
  - Kill all initial flow..

with Maowu Nie, Guoliang Ma

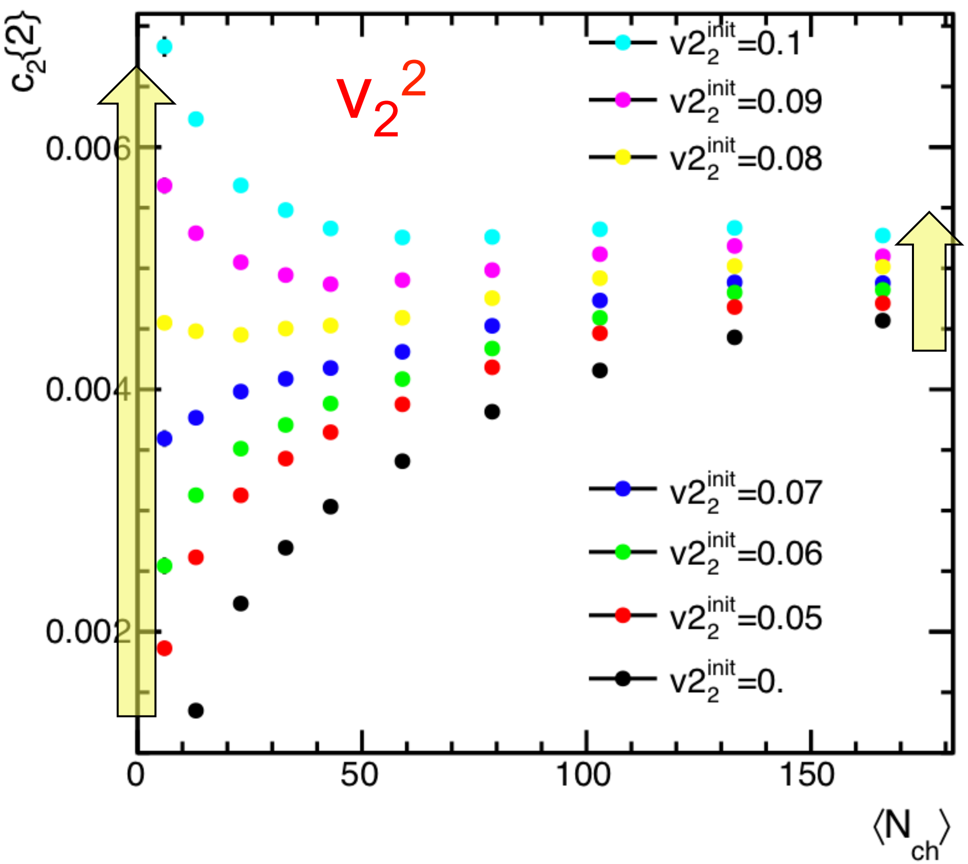
- Add initial flow via flow afterburner with a random phase.
  - This is event-wise flow but uncorrelated with PP.

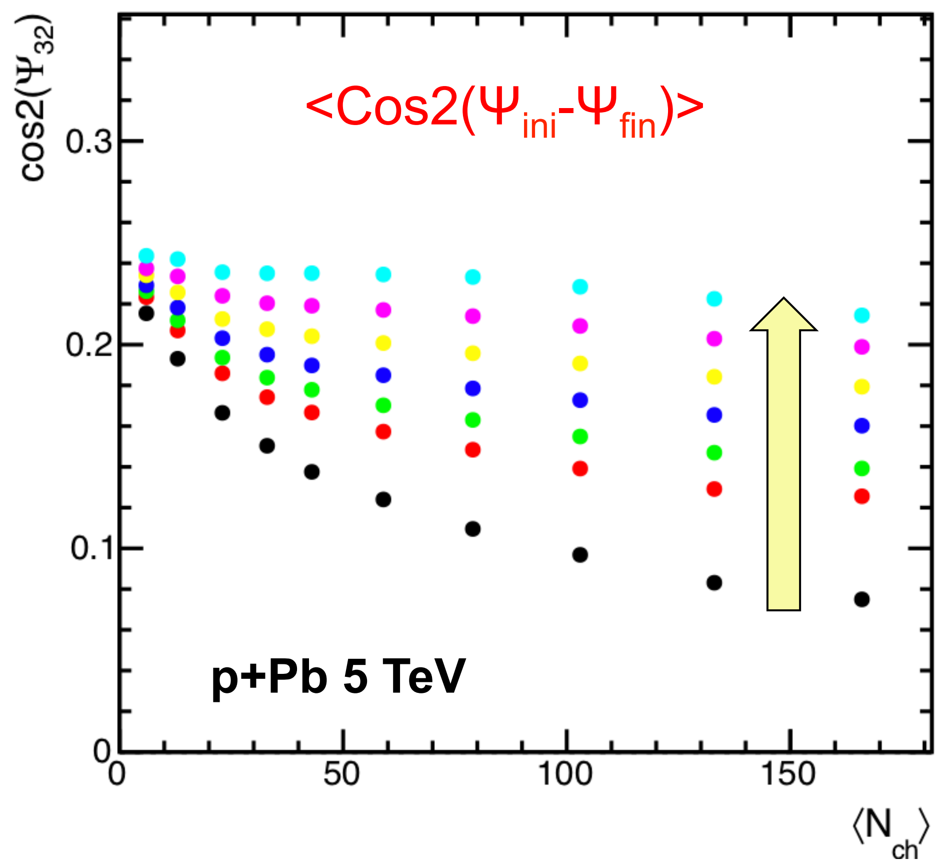


Initial momentum anisotropy does make a difference, but in a non-trivial way

Influence of final flow by initial flow

- Low N_{ch} : Final flow ≈< Initial flow expected for free streaming
- High N_{ch}: Final flow increase slowly with initial flow.
  - The final flow is biased toward the direction of the initial flow.

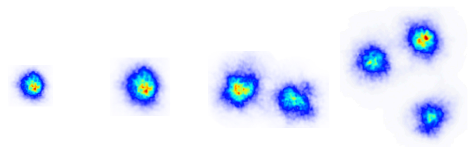




Initial flow could survive and bias the geometry-driven flow

What else can we do?

Initial state Geometry

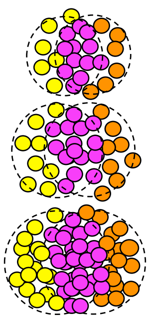


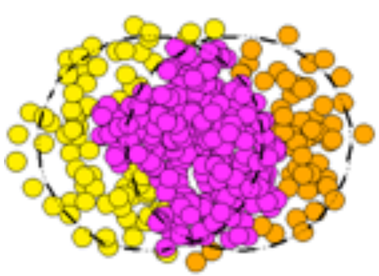
p+p p+A d+A ^{3}He+A

C+C

O+O

S+S



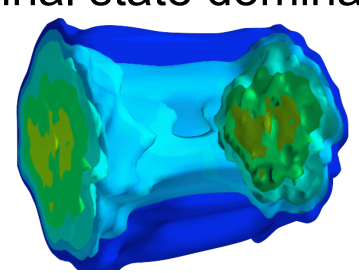


Pb+Pb, Au+Au, Cu+Cu

Space-time dynamics

Initial or final state?

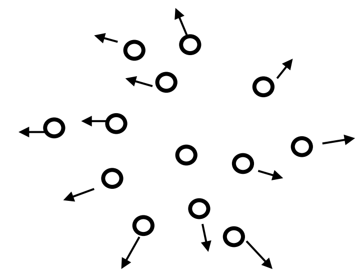
Final state dominate



$$\partial_\mu T^{\mu\nu} = 0$$

Hydrodynamics

Final state collectivity

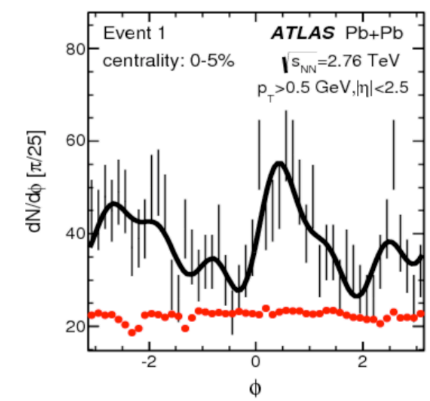


1) Better quantify collectivity:

- **Non-flow systematics**
- **New observables**

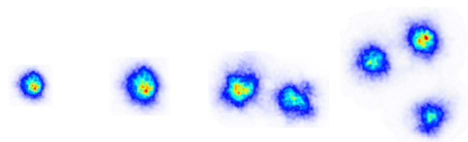
2) Other final state effects e.g. Jet quenching?

3) Where final-state dominates?



What else can we do?

Initial state Geometry

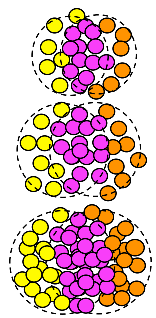


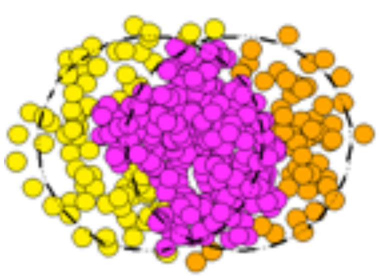
p+p p+A d+A ^{3}He+A

C+C

O+O

S+S



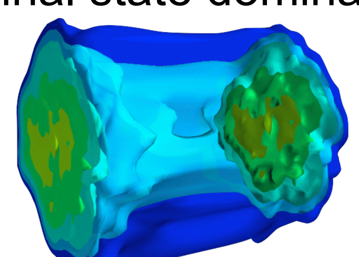


Pb+Pb, Au+Au, Cu+Cu

Space-time dynamics

Initial or final state?

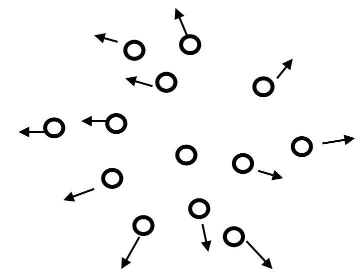
Final state dominate



$$\partial_\mu T^{\mu\nu} = 0$$

Hydrodynamics

Final state collectivity

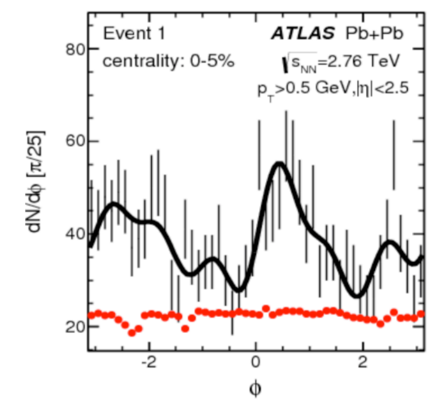


1) Better quantify collectivity:

- **Non-flow systematics**
- **New observables**

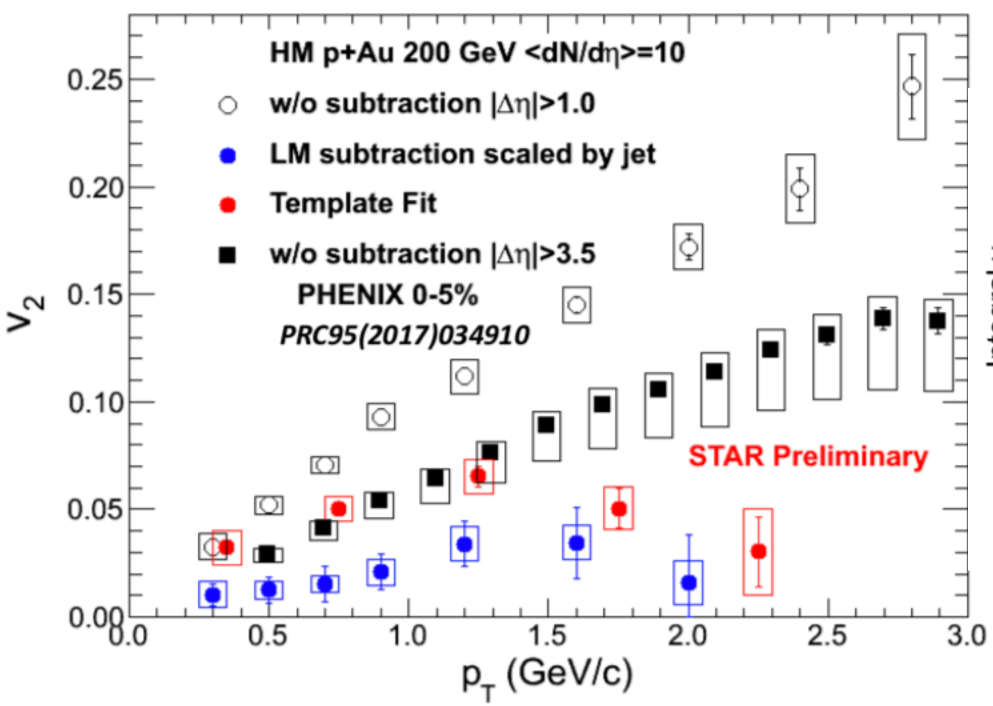
2) Other final state effects e.g. Jet quenching?

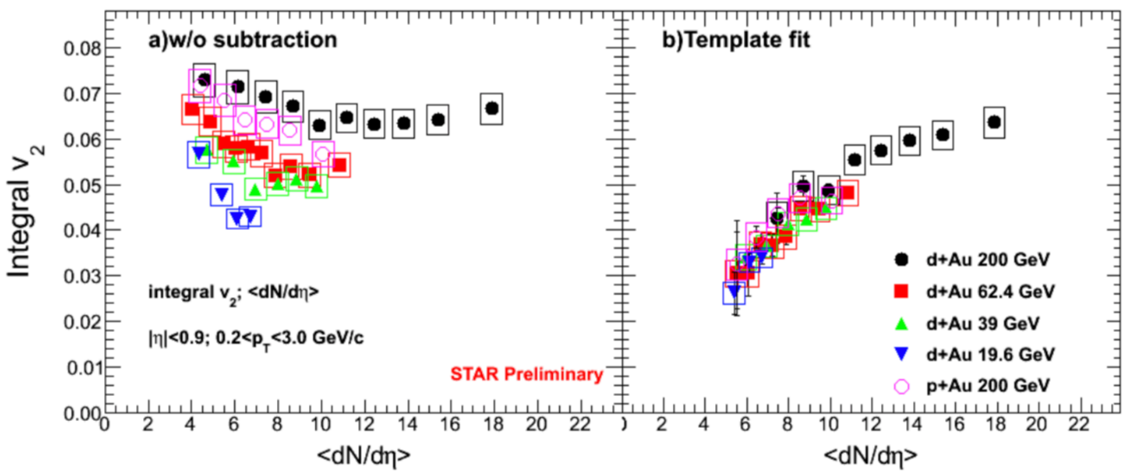
3) Where final-state dominates?



Better observables and methods

- Define more clearly the meaning of two or multi-particle collectivity.
  - Explore all the observables and methods developed in A+A system
- Two-particle correlations
  - Understand non-flow subtraction systematics.
  - Quantify behavior of collectivity at low N_{ch}.





Better observables and methods

- Define more clearly the meaning of two or multi-particle collectivity.
  - Explore all the observables and methods developed in A+A system
- Two-particle correlations
  - Understand non-flow subtraction systematics.
  - Quantify behavior of collectivity at low N_{ch}.
- Three- and four-particle correlations
  - Nature of the EbyE fluctuations $c_n\{4\}$
  - Correlation between different harmonics: symmetric & asymmetric cumulants
  - Subevent method to suppress non-flow.

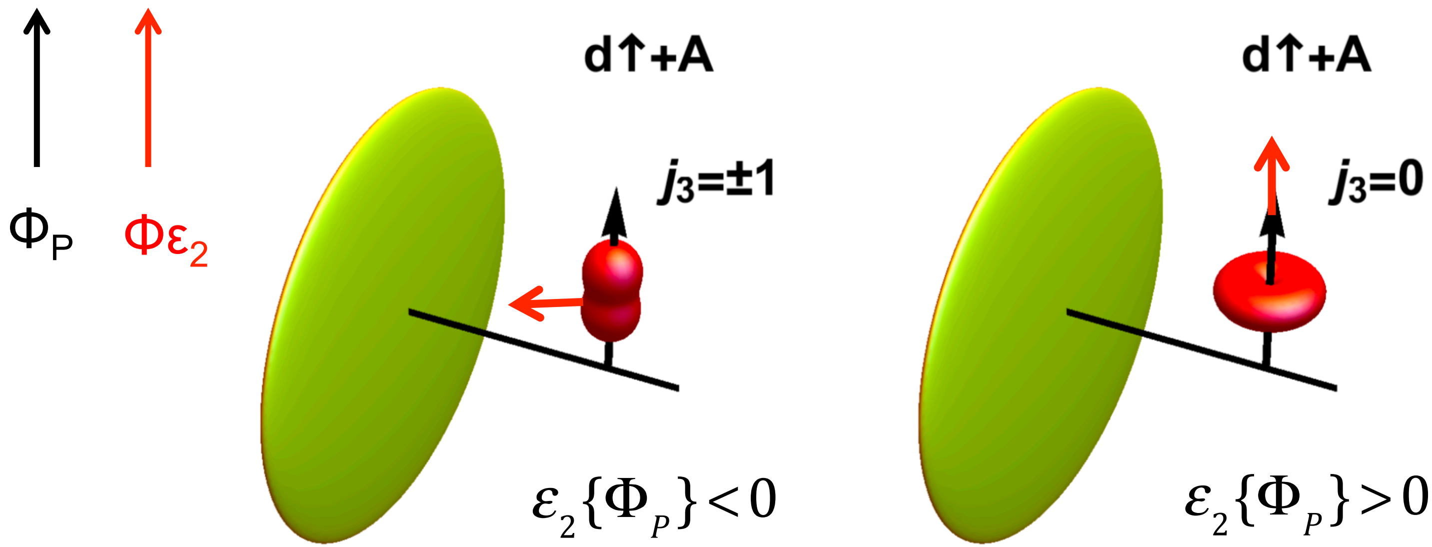
These have been explored at LHC, the situation may or may not be similar at RHIC (1902.11290).

Large acceptance detector with forward coverage is crucial for this.

Flow with polarized light-ion+A collisions

Deuterium: $J^P = 1^+$, 5%, $^3D_1$ wave, rest $^3S_1$ wave

W. Broniowski and P. Bozek
1808.09840



$\varepsilon_2\{\Phi_P\} < 0$
$v_2\{\Phi_P\} < 0$

$\varepsilon_2\{\Phi_P\} > 0$
$v_2\{\Phi_P\} > 0$

- Polarization direction serves as an absolute reference
  - uncorrelated with jets
  - Eccentricity projected to Φ_P has opposite sign
- The estimated signal is very small.

$$\frac{dN}{d\phi} \propto 1 + 2v_2 \cos\left[2(\phi - \Phi_P)\right] \quad v_2 \simeq k\epsilon_2, \quad k \sim 0.2$$

With 50% polarization: $-0.5\% \lesssim v_2\{\Phi_P\} \lesssim 1\%$

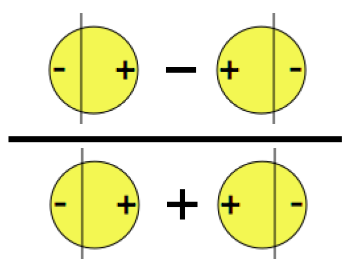
Flow with polarized light-ion+A collisions

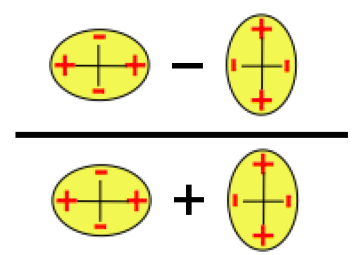
- Detector effects directly competes with Φ_P! Need to suppress them on EbyE level down to 1%.

- Minimize by flip polarization direction, commonly used in spin physics for asymmetry measurement.

$$\frac{d\sigma}{d\Omega}(\phi) = \left(\frac{d\sigma}{d\Omega}\right)_0 (1 + A_N \, P_y \, cos(\phi)) \qquad A_N = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

- Calculate flow relative to fixed polarization direction as:

$\langle \cos(\theta - \psi) \rangle =$ 

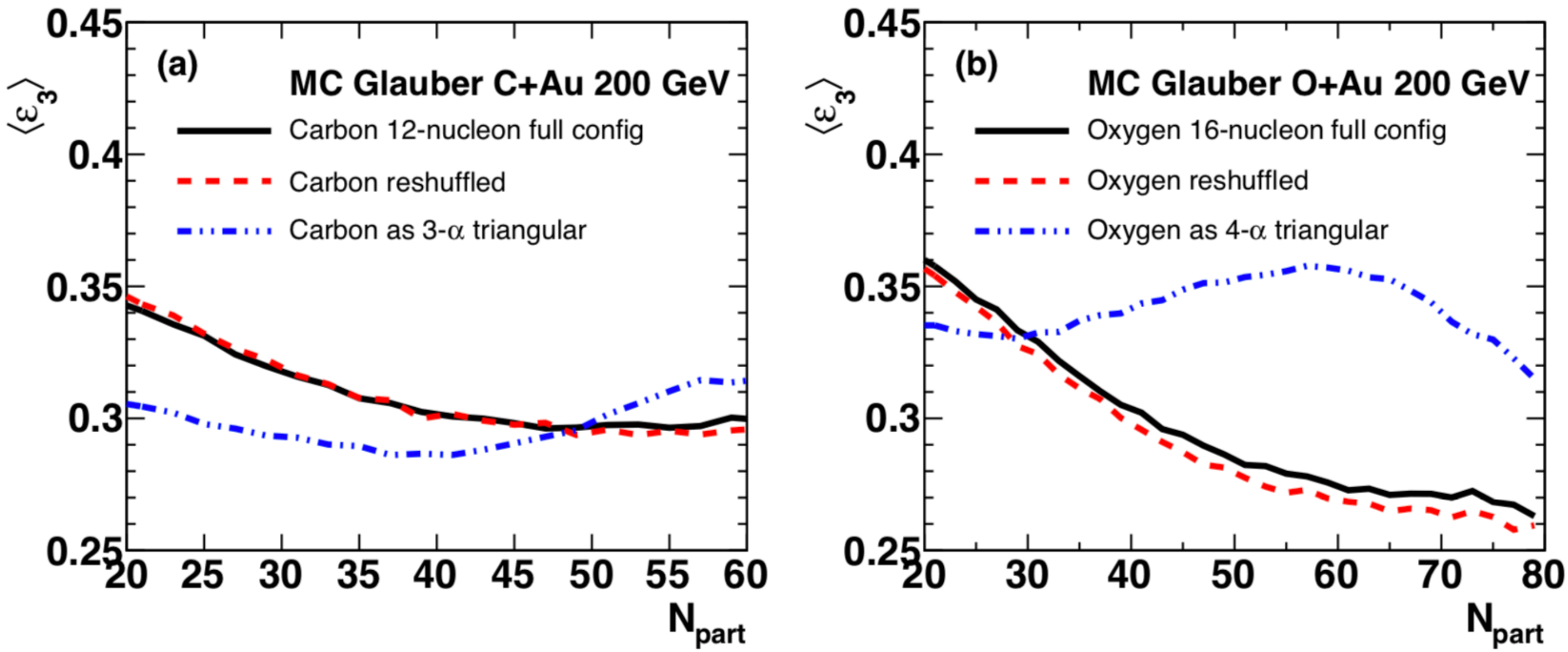
$\langle \cos 2(\theta - \psi) \rangle =$ 

  - Acceptance effects can be cancelled out with sqrt formula.
  - Need consider finite polarization & resolution of polarization direction.
  - Additional systematic control by having multiple polarization bunch-by-bunch, e.g. 0, π/2, π, 1.5π.

Search for evidence of Geometry response

Initial study of Geometry response

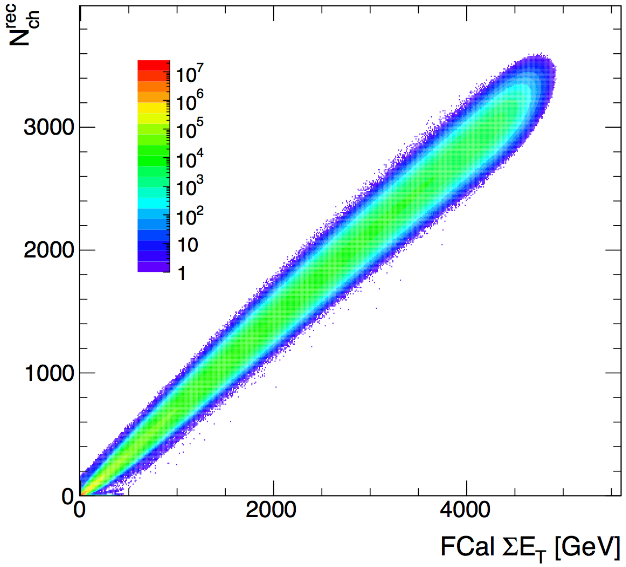
- Idea of original RHIC scan based on p+A, d+A, ^{3}He+A,
  - Change ε_2 and ε_3 and look for expected order of v_2 and v_3.
- Other asymmetric systems: ^{4}He+A, ^{7,9}Be+A, ^{16}O+A.. **1812.08096**
  - Need well controlled knowledge of nuclear structure
  - Geometry difference, in terms of ε_n and v_n, seems not dramatic.



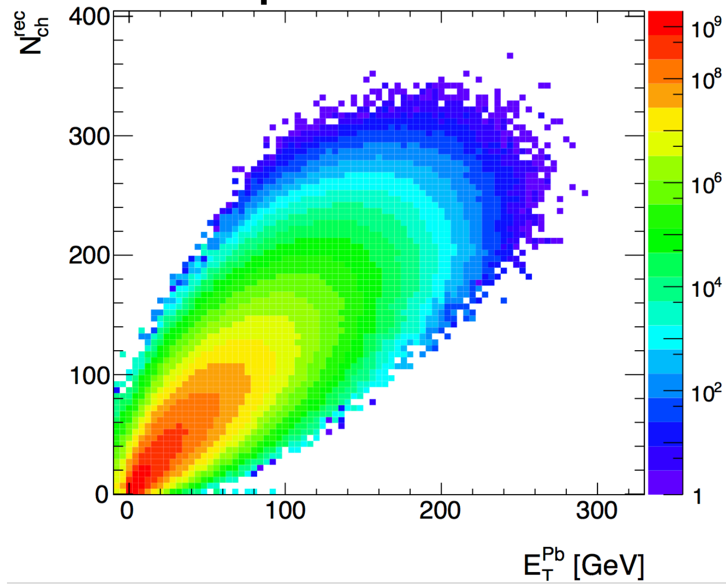
Sensitivity to alpha clustering not large

Issue : multiplicity/centrality fluctuations

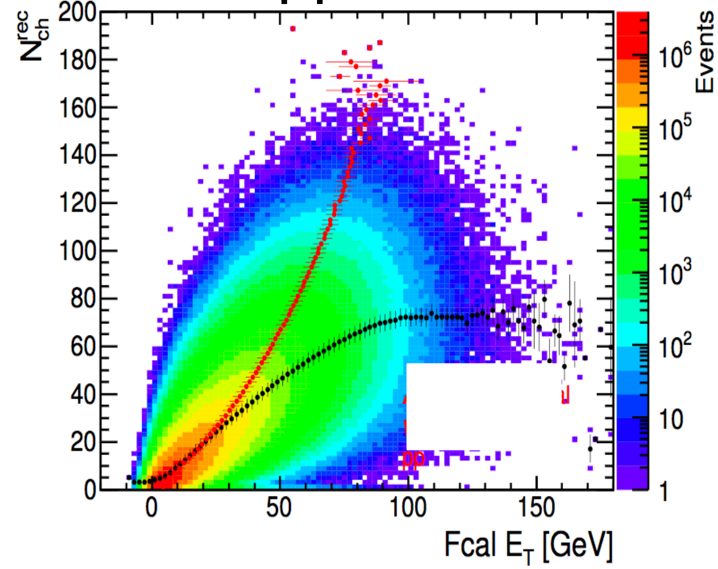
PbPb 5 TeV

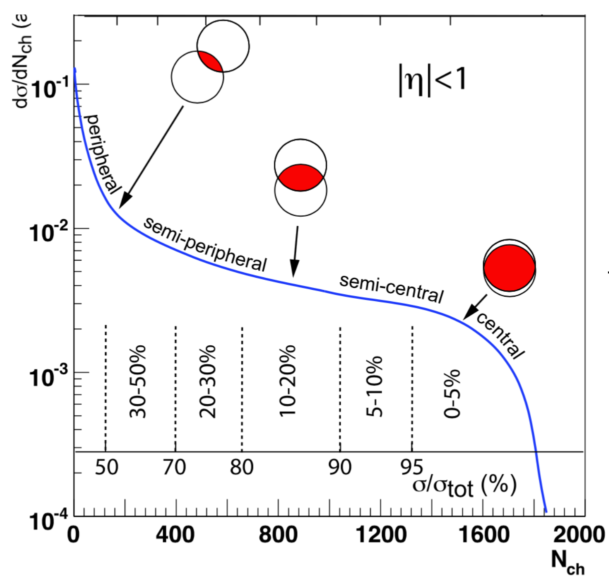


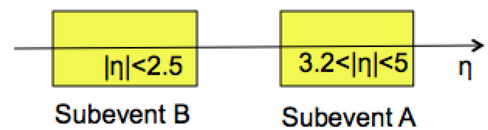
pPb 5 TeV



pp 13 TeV

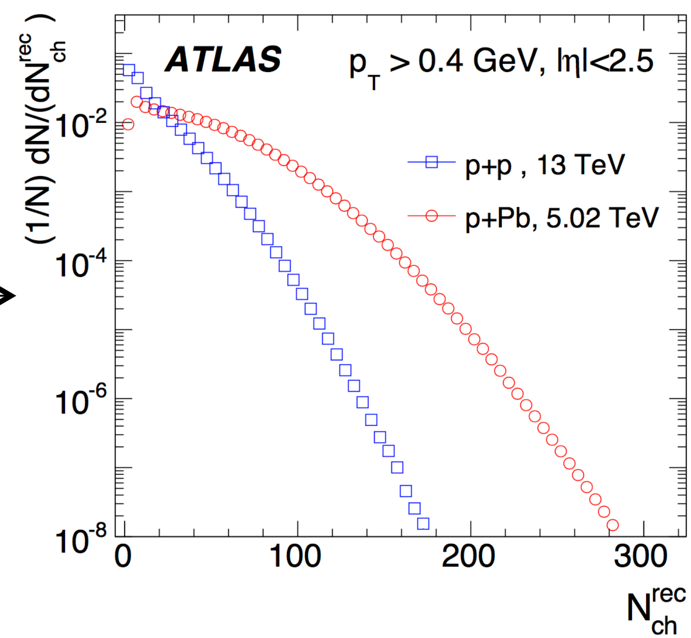






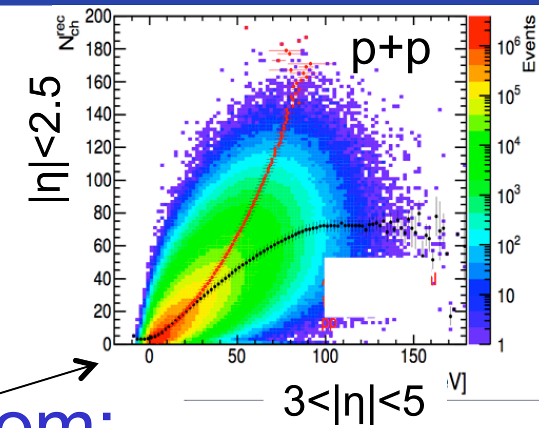
Centrality resolution worsen

In small systems

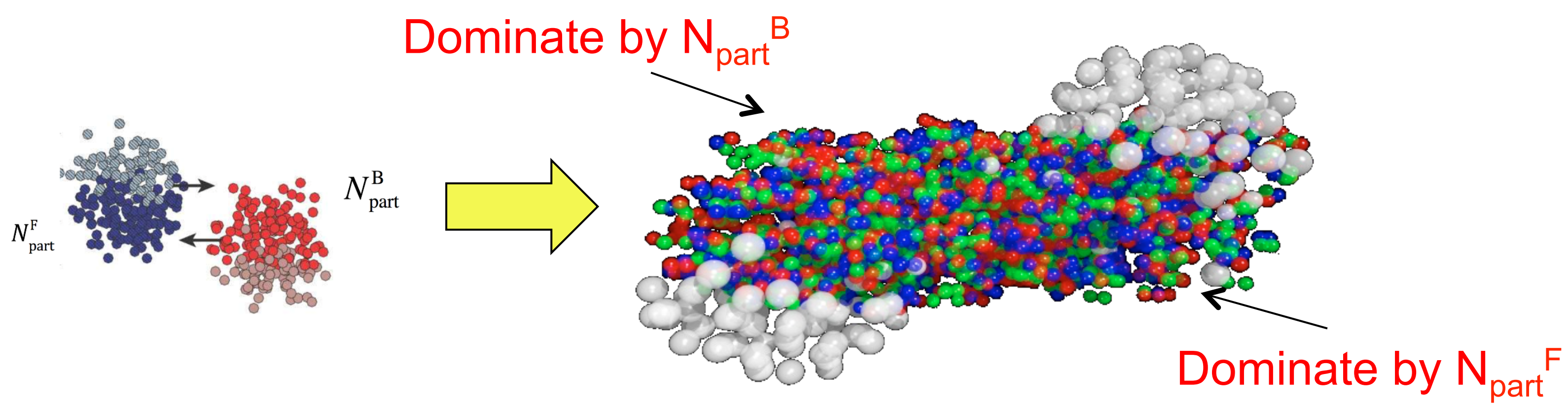


Issue : Longitudinal flow/centrality decorrelation

$$\frac{dN}{d\eta} = N(\eta)\left[1+2\sum_n \mathrm{v}_n(\eta)\cos n\left(\phi-\Phi_n(\eta)\right)\right]$$



- Centrality is 0th-order long-range correlations
- Must understand centrality resolution arise from:
  - Multiplicity fluctuations
  - Centrality decorrelation effects.

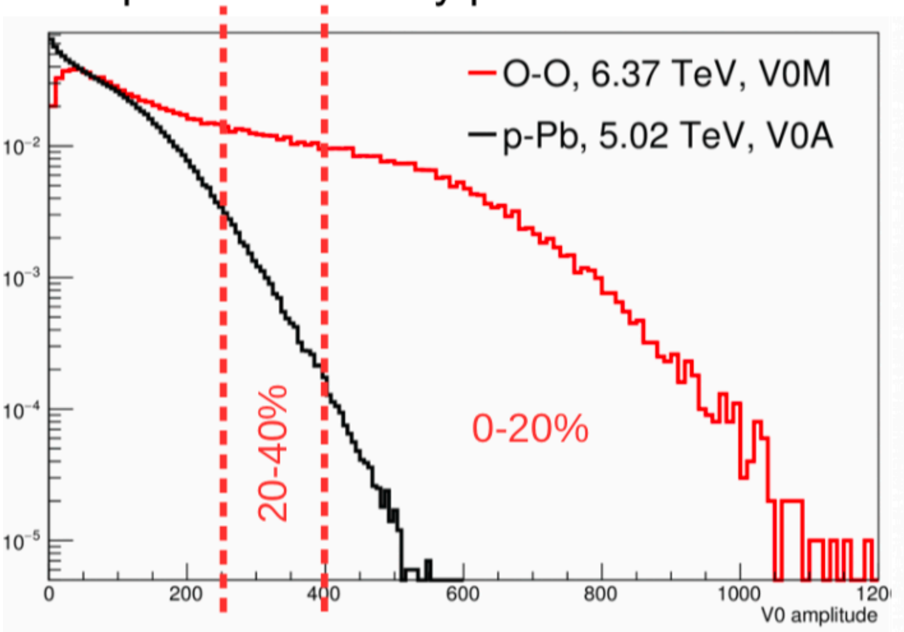


- Tools exist for studies of this and other longitudinal dynamics
  - Subevent multiplicity cumulants, sub-nucleon Glauber…

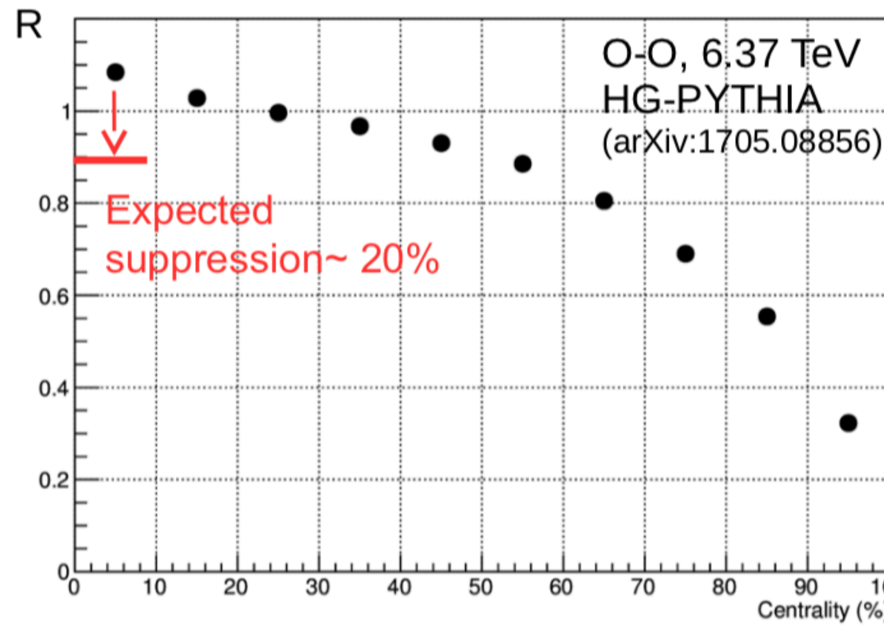
Forward acceptance is necessary for small system

Why small symmetric system like $^{16}O+^{16}O$?

Expected centrality plateau

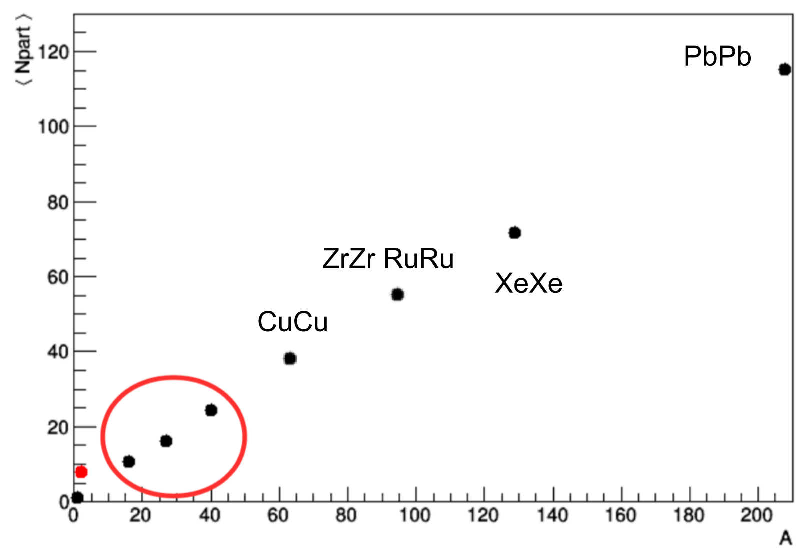


Expected centrality bias on R_{AA}



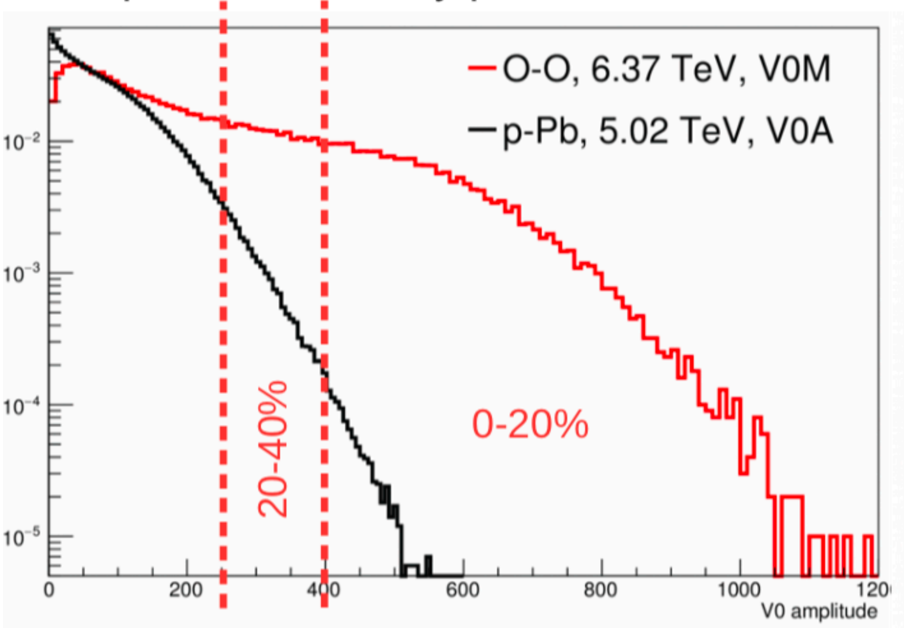
Also see CERN yellow report 1812.06772

- Centrality shoulder allowing selec of geometry (N_{coll} ε_2)
  - Clear advantage over asymmetric system (pA, or others)
- System maybe large enough for jet quenching (arguably should co-exist with hydro)
  - Maybe also in minbias events N_{part} = 10-30 range (Cu+Cu = 40)
- System scan ($^{12}C+^{12}C$, $^{16}O+^{16}O$, $^{32}S+^{32}S$, $^{40}Ar+^{40}Ar$)
  - Onset effects for both flow and jet quenching

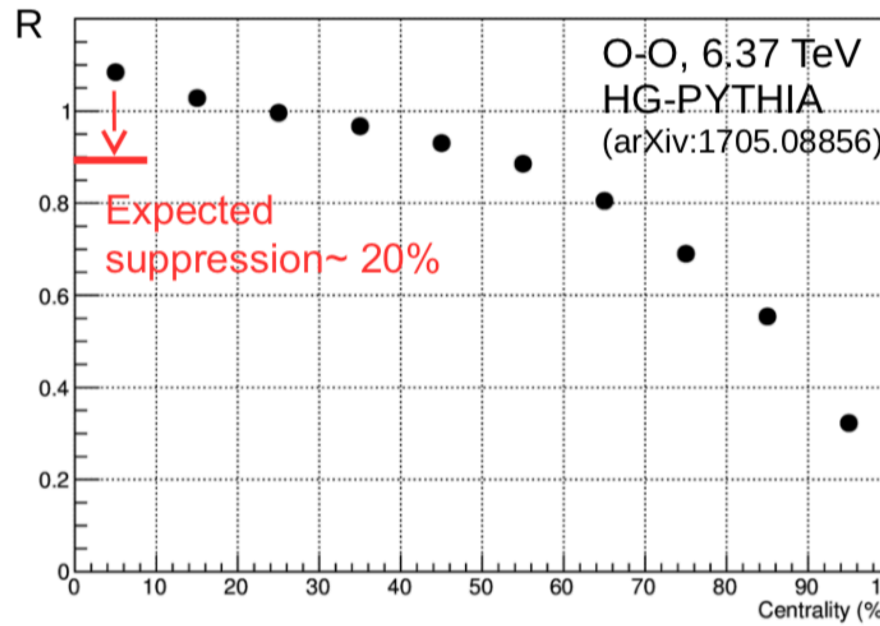


Why small symmetric system like $^{16}O+^{16}O$?

Expected centrality plateau



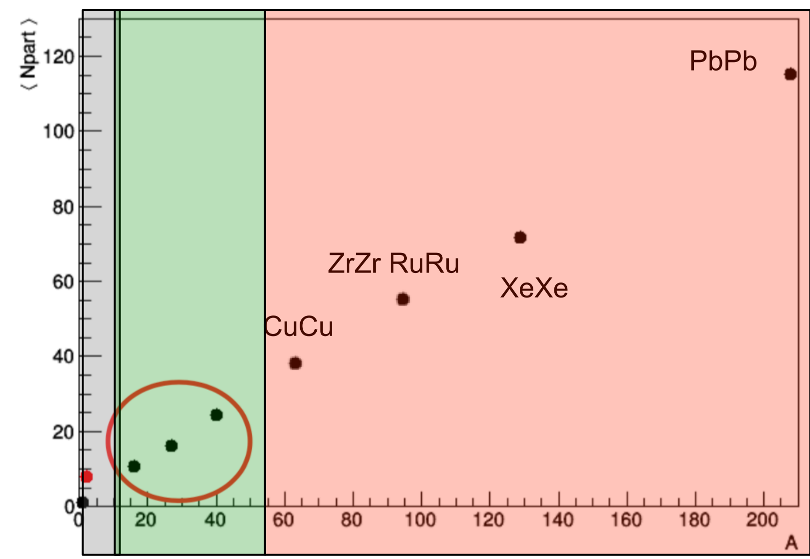
Expected centrality bias on R_{AA}



Also see CERN yellow report 1812.06772

Initial state ??

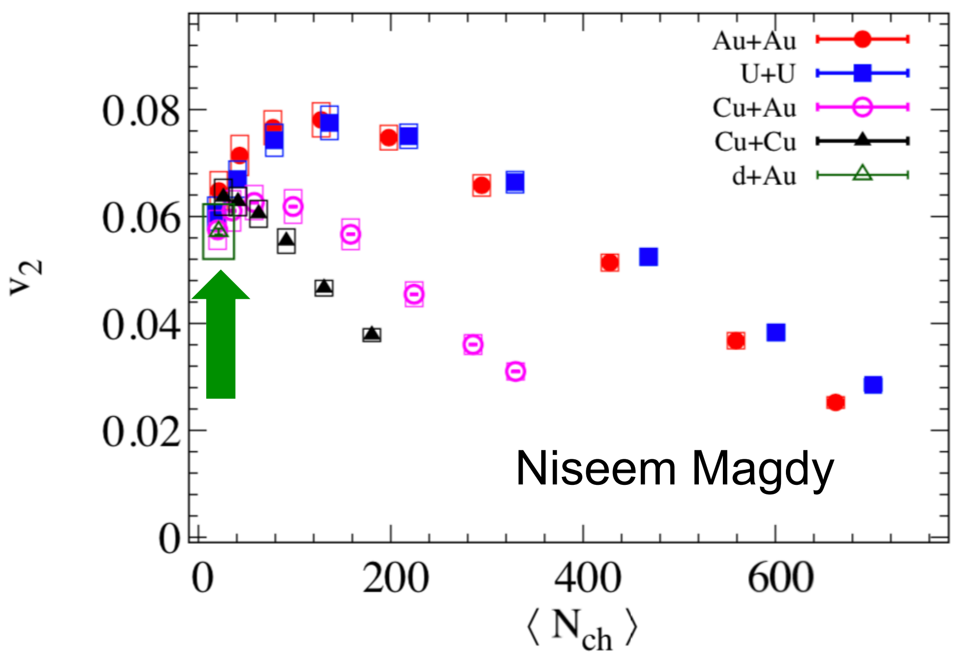
Flow+jet quenching

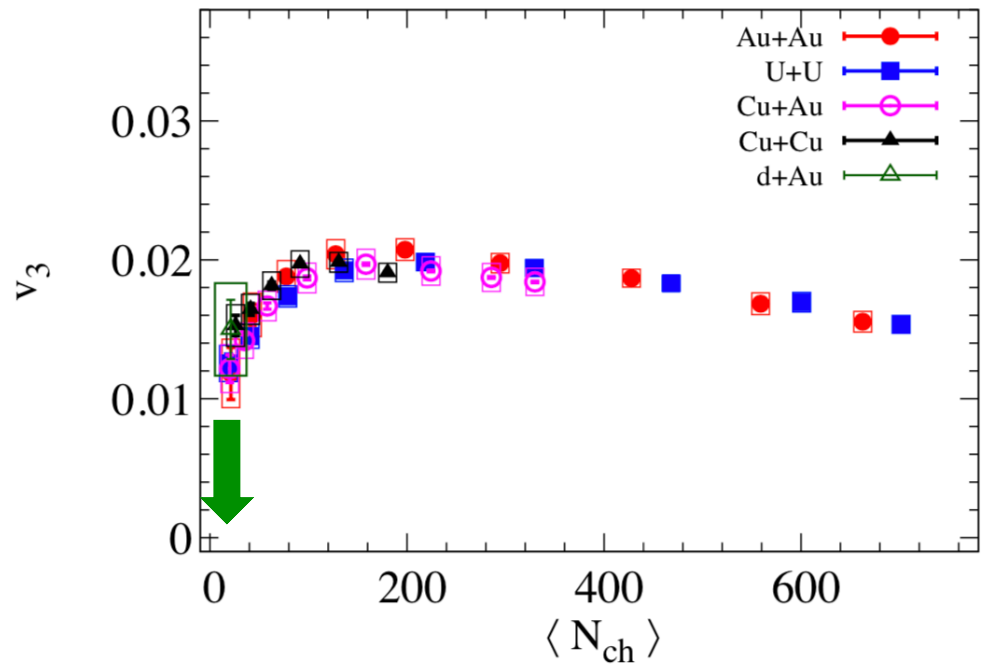


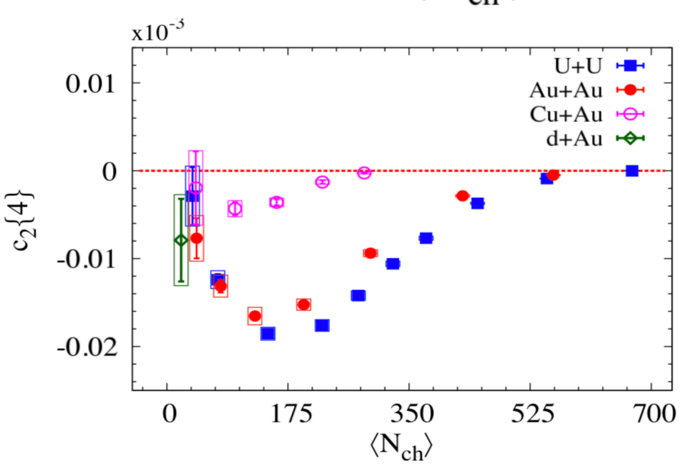
- Centrality shoulder allowing selec of geometry (N_{coll} ε_2)
  - Clear advantage over asymmetric system (pA, or others)
- System maybe large enough for jet quenching (arguably should co-exist with hydro)
  - Maybe also in minbias events N_{part} = 10-30 range (Cu+Cu = 40)
- System scan ($^{12}C+^{12}C$, $^{16}O+^{16}O$, $^{32}S+^{32}S$, $^{40}Ar+^{40}Ar$)
  - Onset effects for both flow and jet quenching

Another hallmark of geometry response

- Rise & fall of v_2 vs centrality: average geometry & viscous damping
- Different system size scaling behavior between v_2 and v_3
- Different flow fluctuations: $c_2\{4,6..\}>0$ vs $c_3\{4,6..\}\sim 0$





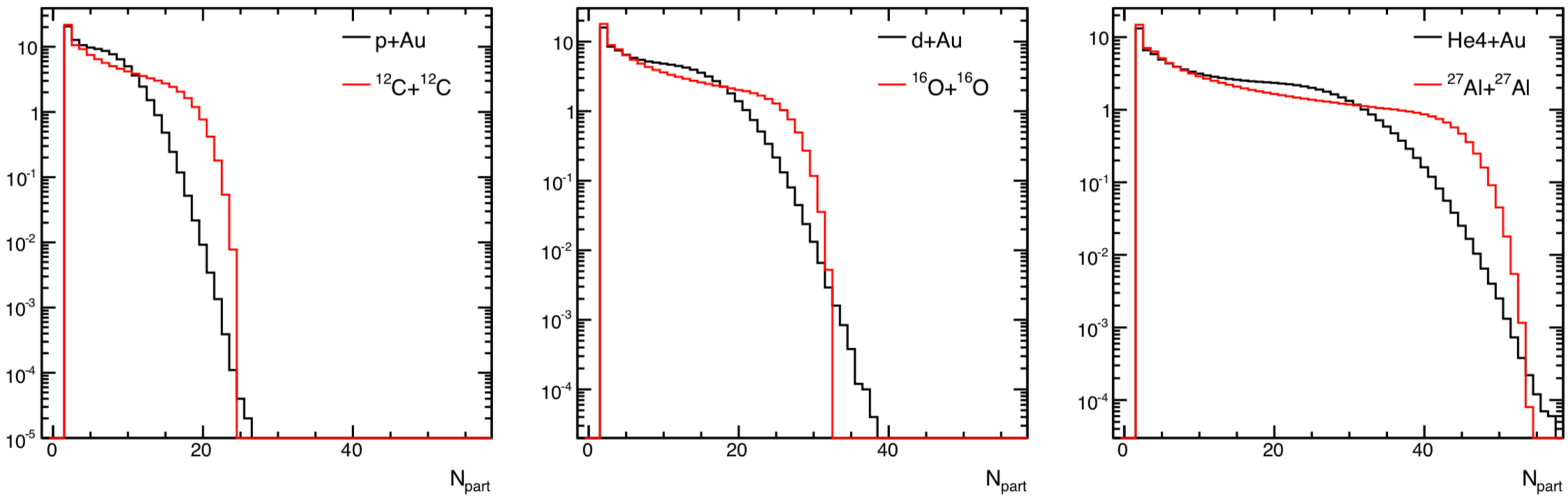


NB: Non-flow plays different role for v_2 & v_3.

For which system these patterns cease to exist?

Small (a)symmetric systems

Asymmetric system	pAu	dAu	He4Au	
$\langle N_{part} \rangle$	5.8	8.8	13.2	
Symmetric system	$^{12}C+^{12}C$	$^{16}O+^{16}O$	$^{27}Al+^{27}Al$	$^{32}S+^{32}S$
$\langle N_{part} \rangle$	7.2	9.5	14	18



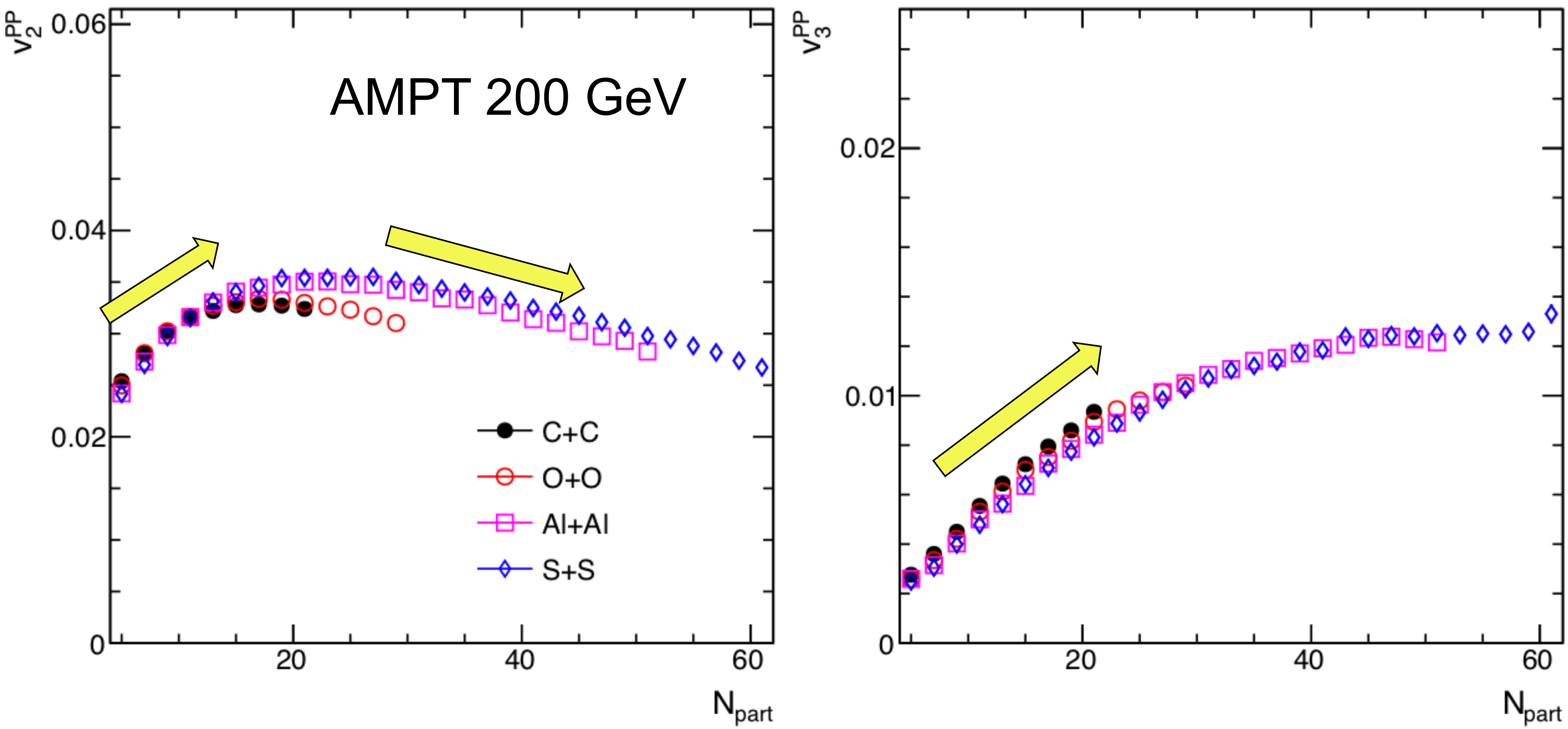
If IS effects are important in asymmetric system, maybe also in symmetric small system with similar N_{part}?

Seek guidance from AMPT model

Small symmetric-system scan

Shengli Huang

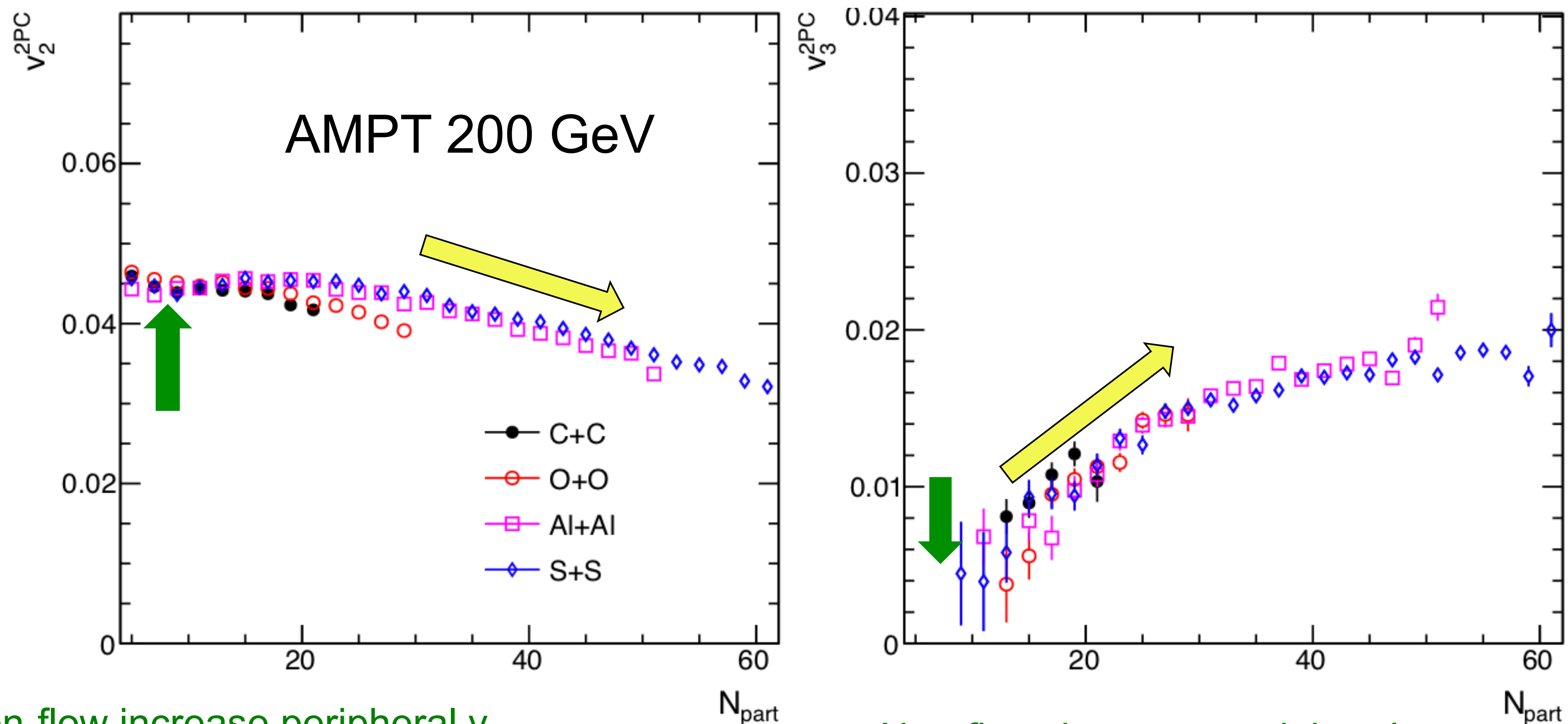
v_n calculated with participant plane to minimize non-flow



- Rise and fall of v_2 reflects average geometry
- v_3 increases with N_{part} reflects fluctuation-driven scenario

Small symmetric-system scan

v_n calculated with 2PC with $|\Delta\eta|>1$ gap



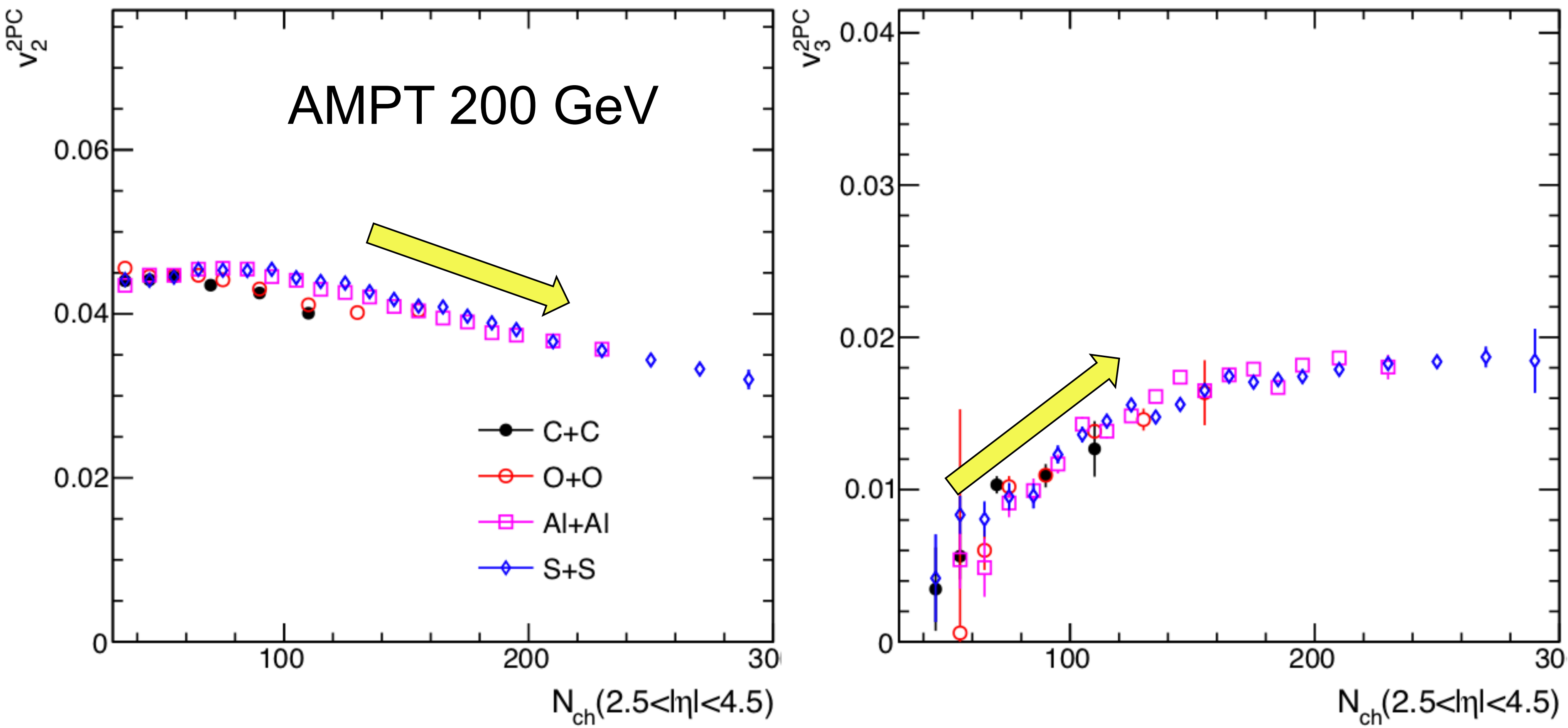
Non-flow increase peripheral v_2

Non-flow decrease peripheral v_3

- Rise and fall of v_2 reflects average geometry
- v_3 increases with N_{part} reflects fluctuation-driven scenario

Small symmetric-system scan

v_n calculated with 2PC with $|\Delta\eta|>1$ gap, using N_{ch} axis

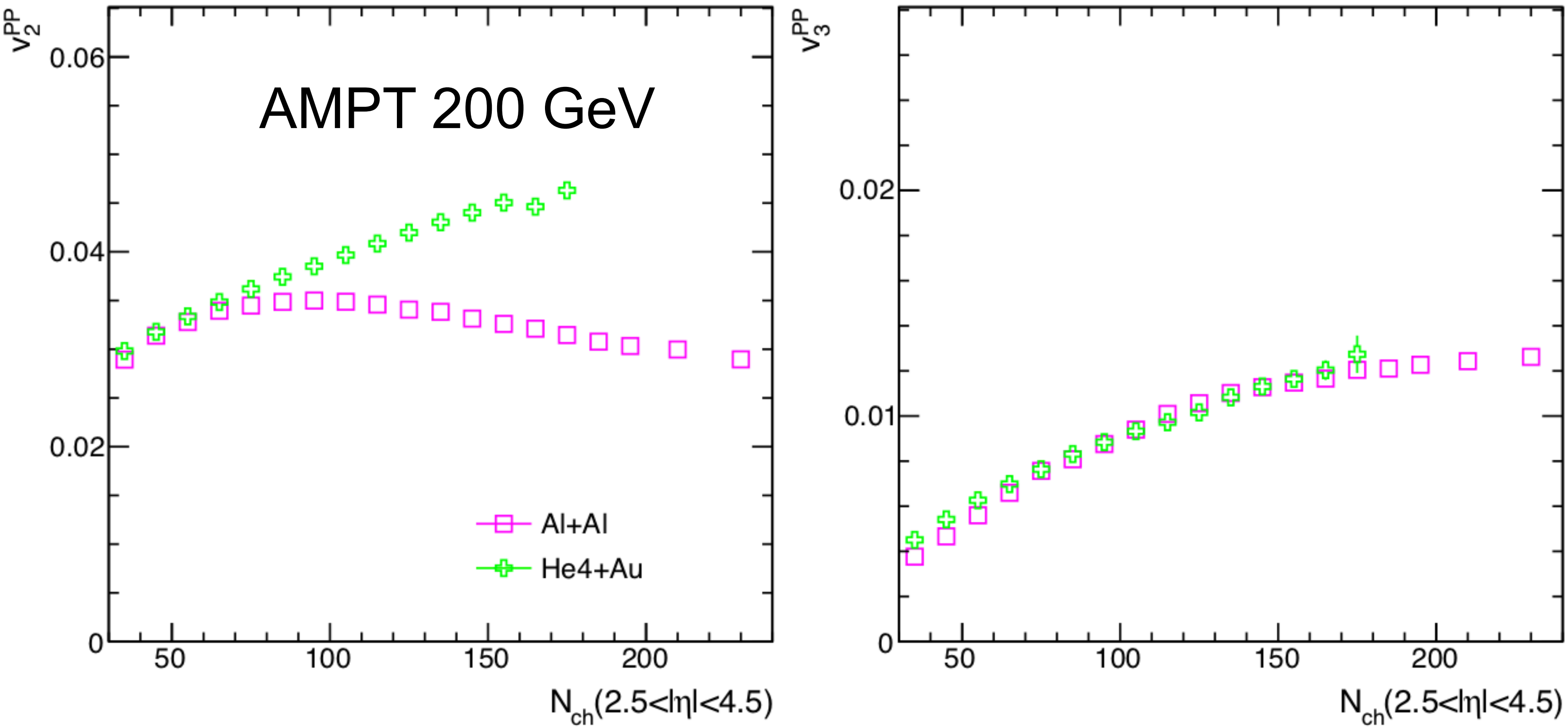


- Rise and fall of v_2 reflects average geometry
- v_3 increases with N_{part} reflects fluctuation-driven scenario

Such geometry response not expected for pure initial state picture

Asymmetric vs Symmetric

v_n calculated with participant plane to minimize non-flow



- Asymmetric system: v_2, v_3 increase with N_{ch}.
- Symmetric system: v_2 rise and fall with N_{ch}, v_3 increase with N_{ch}.

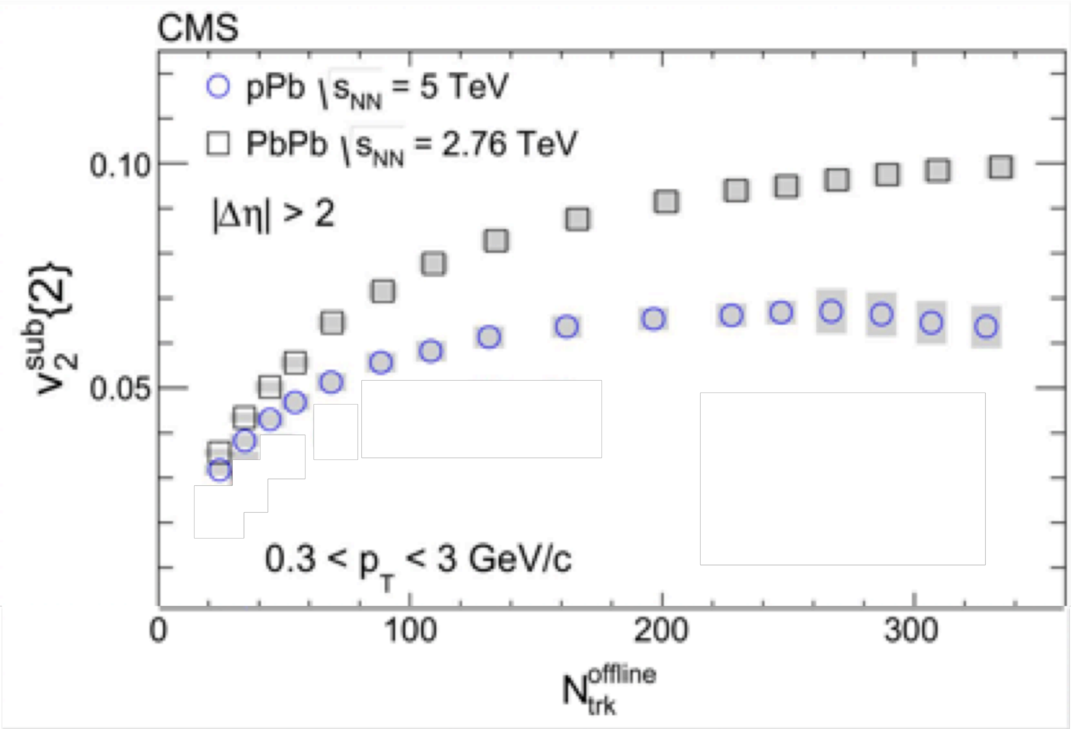
Expectation from pure initial effects: all increases with N_{ch}?

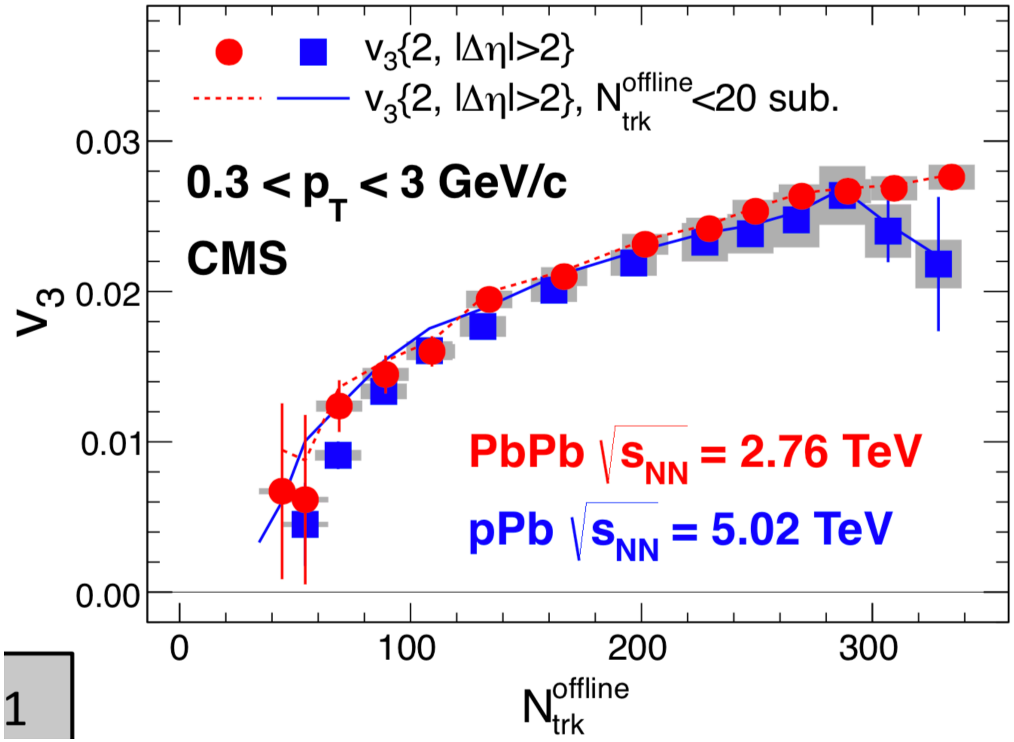
Ring a bell?

pPb vs PbPb at similar multiplicity at LHC

Geometry dominated

Fluctuation dominated





Synergy between RHIC and LHC

Proposed Run Schedule for Run 3 and 4

	Year	Systems, time, L_{int}	Total per Run (3 and 4)
RUN 3	2021 (4 weeks)	Pb-Pb 5.5 TeV, 3 weeks pp 5.5 TeV, 1 week	Pb-Pb: 6.2/nb ALICE/ATLAS/CMS, 1/nb LHCb p-Pb: 0.6/pb ATLAS/CMS, 0.3/pb ALICE/LHCb pp 5.5: 300/pb ATLAS/CMS, 25/pb LHCb, 3/pb ALICE pp 8.8: 100/pb ATLAS/CMS/LHCb, 1.5/pb ALICE O-O: 500/μb p-O: 200/μb
	2022 (6 weeks)	p-O + O-O 7 TeV, 1 week (after EYETS?) Pb-Pb 5.5 TeV, 5 weeks	
	2023 (4 weeks)	pp 8.8 TeV, few days p-Pb 8.8 TeV, 3.x weeks	
	LS3	ATLAS/CMS upgrades, ALICE: ITS3? FoCal?	
RUN 4	2027 (4 weeks)	Pb-Pb 5.5 TeV, 3 weeks pp 5.5 TeV, 1 week	Pb-Pb: 6.8/nb, ALICE/ATLAS/CMS, 1/nb LHCb p-Pb: 0.6/pb ATLAS/CMS, 0.3/pb ALICE/LHCb pp 5.5: 300/pb ATLAS/CMS, 25/pb LHCb, 3/pb ALICE pp 8.8: 100/pb ATLAS/CMS/LHCb, 1.5/pb ALICE
	2028 (6 weeks)	Pb-Pb 5.5 TeV, 2 weeks p-Pb 8.8 TeV, 3.x weeks pp 8.8 TeV, few days	
	2029 (4 weeks)	Pb-Pb 5.5 TeV, 4 weeks	

Run 5 will be discussed in the next talk

This is a proposal agreed in WG5 and reflects the physics discussed in the YR. The final run schedule is decided by the LHCC upon discussion with the experiments.

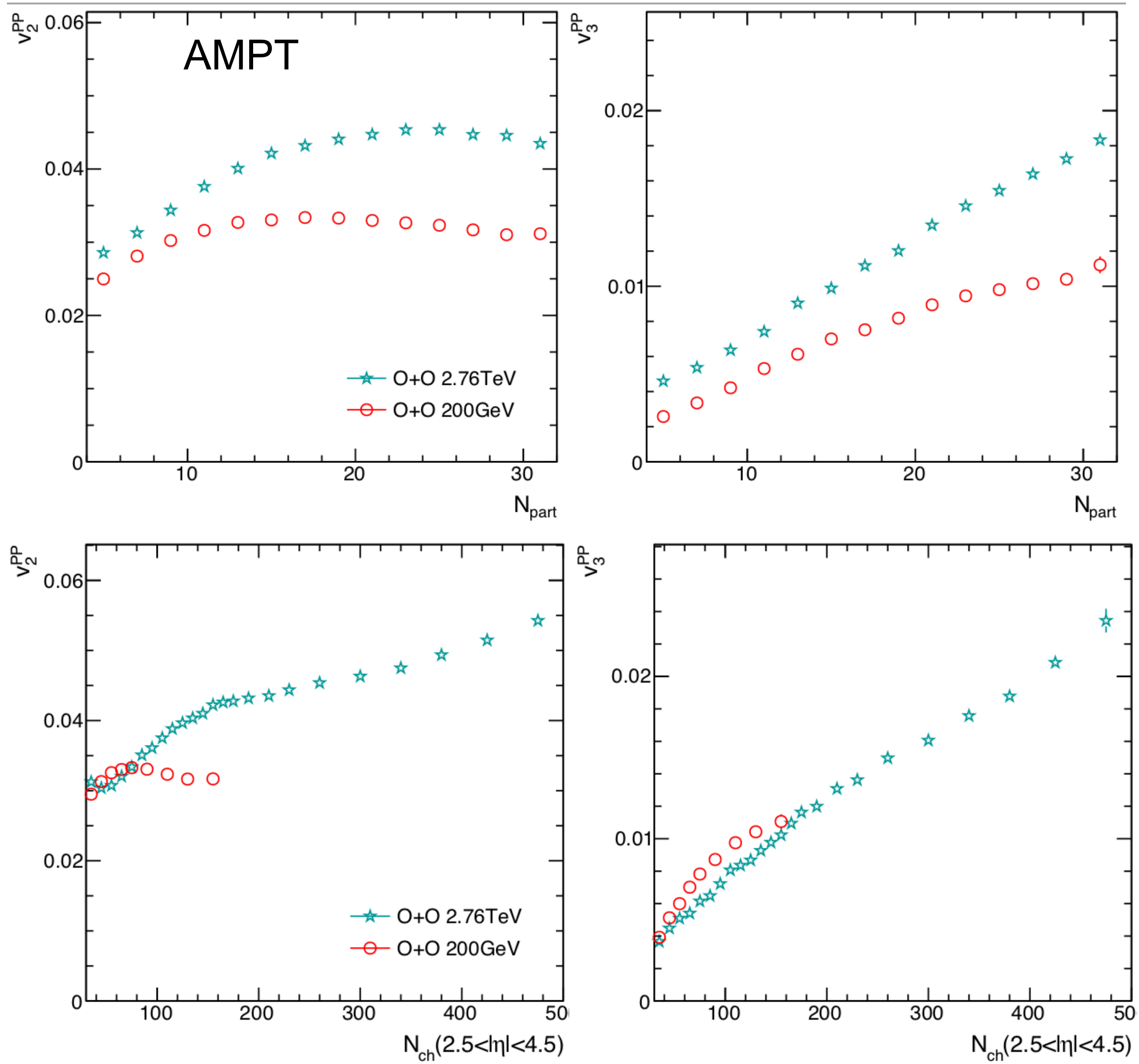
HL/HE-LHC Physics Workshop: final jamboree

Synergy between RHIC and LHC

v_n calculated with participant plane to minimize non-flow

Clear geometry response as a function of N_{part}

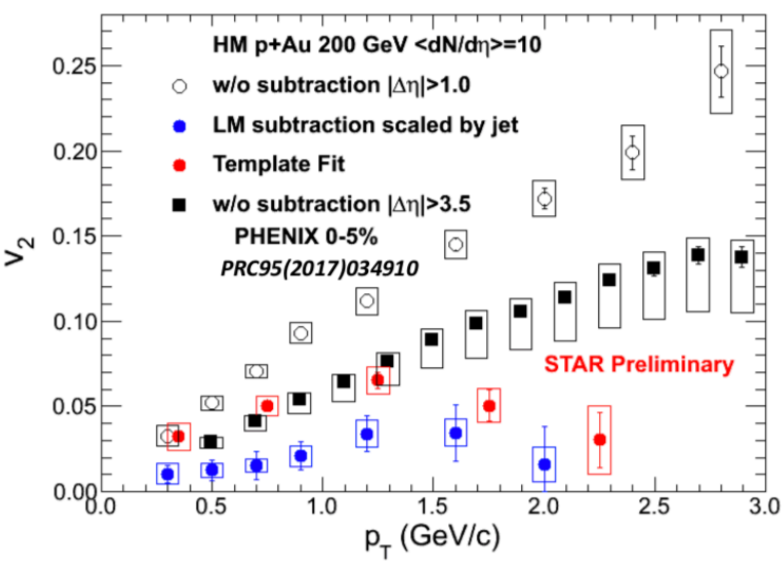
N_{ch}−axis: smear out by multiplicity fluctuations at larger $\sqrt{s}$

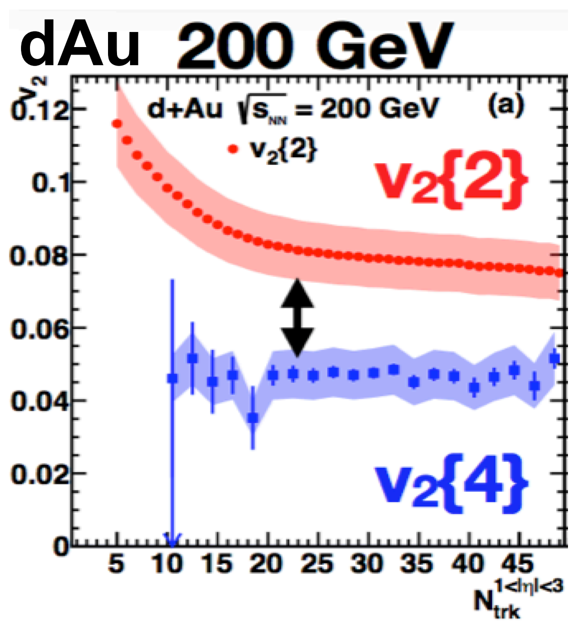


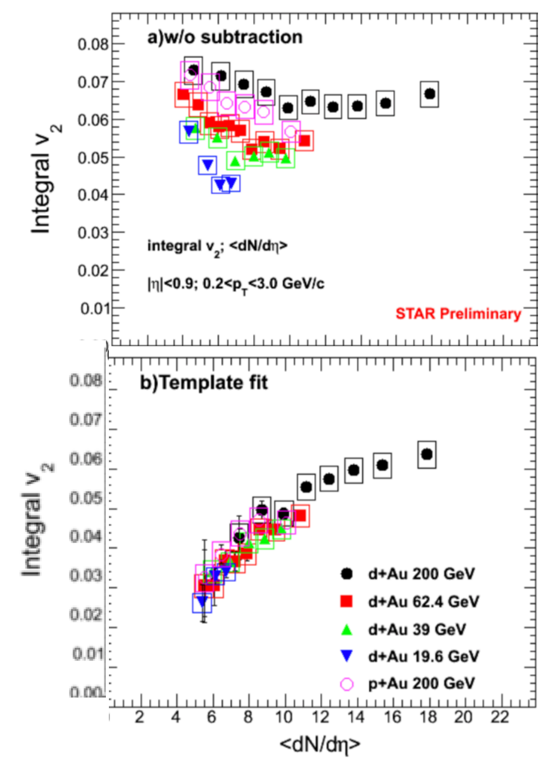
a short O+O run at RHIC after BESII would be interesting

Comment on RHIC measurements

- Large method systematics in data NOT settled
  - Due to Limited phase space (p_T,η, PID…)
  - Assume factorization, ignore longitudinal dynamics,
  - Limited multi-particle measurement, centrality systematics.
- STAR/PHENIX comparison
  - STAR: measurement |η|<1.5, poor forward N_{ch} resolution, poor triggers.
  - PHENIX: p_T |η|<0.35 + various EP/centrality detectors
    - No p_T information for $c_2\{4,6\}$







PHENIX/STAR meeting on 12/14/2018

Homework suggested by PHENIX:

1) Why not use a common LM reference from p+p
2) Can STAR be sure that non-flow is small for $|\Delta\eta|>1.0$
3) Can STAR do a (model-dependent) non-closure test of non-flow sub (see 1902.11290)

Homework suggested by STAR:

1) Can PHENIX tried different non-flow subtraction method: Scale by Nch, by c1, template fit method.

This will provide valuable data-driven information on the non-flow systematic.

The PYTHIA closure of these method hinted by Jame is useful.

2) Can PHENIX show the pT integral v2, see how it scales with dN/deta whether is consistent with STAR (slide 14 of Shengli QM talk)

since STAR template fit v2 agrees with PHENIX at low pT, I guess the pT integrated result would also agree.

3) Can PHENIX show results for low multiplicity region, here a non-flow subtraction would be necessary?

4) Can we identify a common analysis which allow an apple-to-apple comparison?

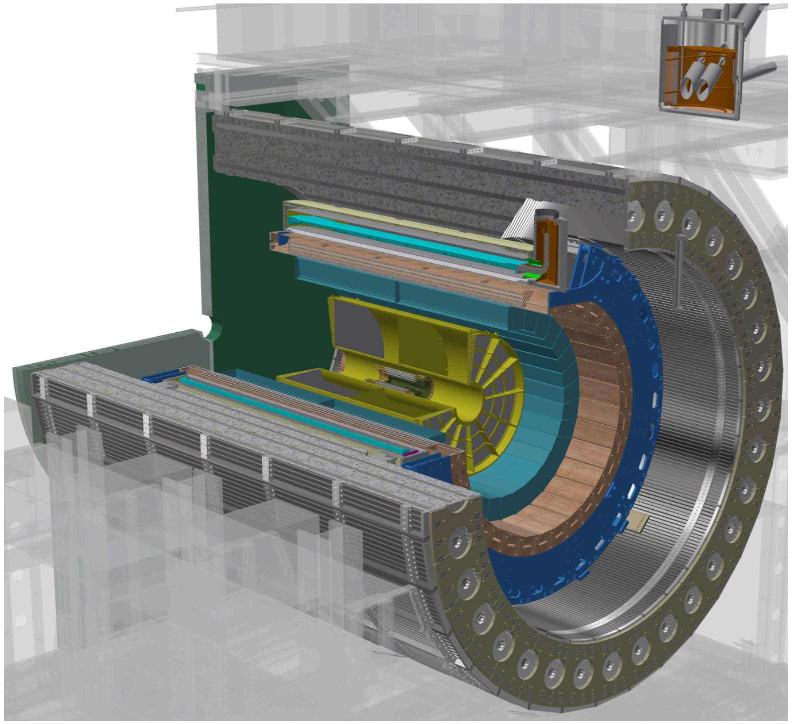
Conclusion: Very hard to do apple-to-apple comparison with existing data

Won't be settled w/o new data & large acceptance detector.

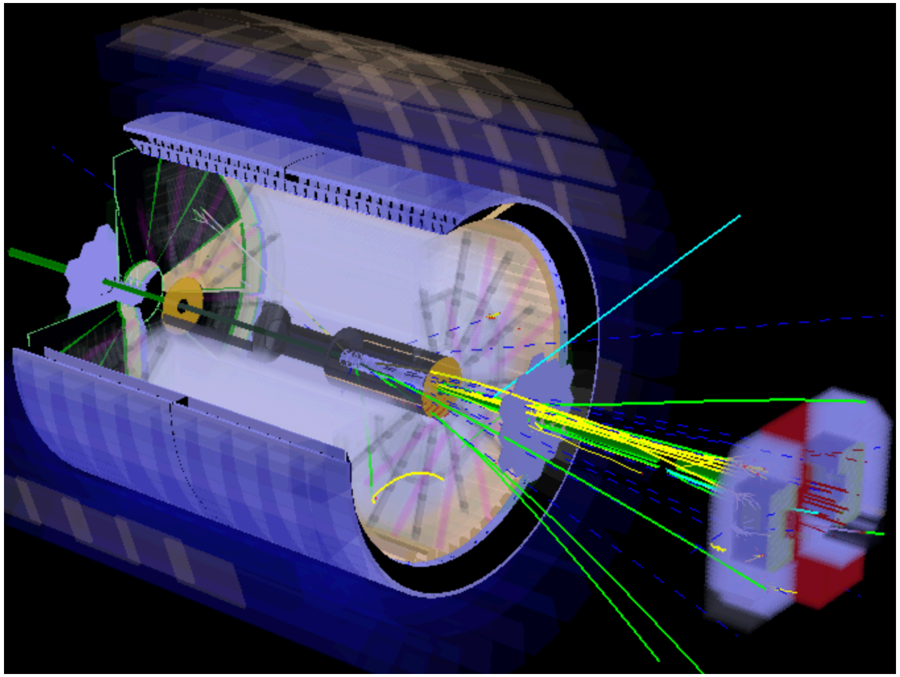
A future small system scan?

- Existing STAR small system data has poor quality
  - High pileup, High-multiplicity trigger not optimal, low-mult region has low efficiency
- New opportunity with STAR upgrade (iTPC, EPD, ETOF+ forward)
  - Control non-flow systematics and centrality bias; measure new multi-particle observables
- Complimentary with sPHENIX run 2023+
  - **sPHENIX focus: jet quenching & other modifications in small systems**
  - **STAR focus: bulk properties of collectivity**

sPHEIX: HARD/Rare probes



STAR: Bulk sector

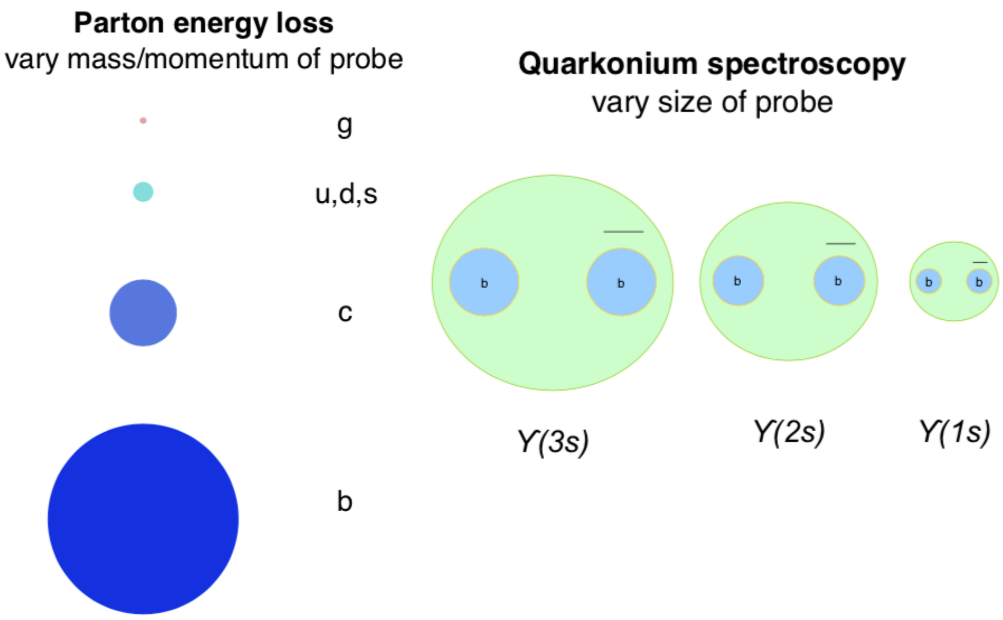


A future small system scan?

- Existing STAR small system data has poor quality
  - High pileup, High-multiplicity trigger not optimal, low-mult region has low efficiency
- New opportunity with STAR upgrade (iTPC, EPD, ETOF+ forward)
  - Control non-flow systematics and centrality bias; measure new multi-particle observables
- Complimentary with sPHENIX run 2023+
  - **sPHENIX focus: jet quenching & other modifications in small systems**
  - **STAR focus: bulk properties of collectivity**

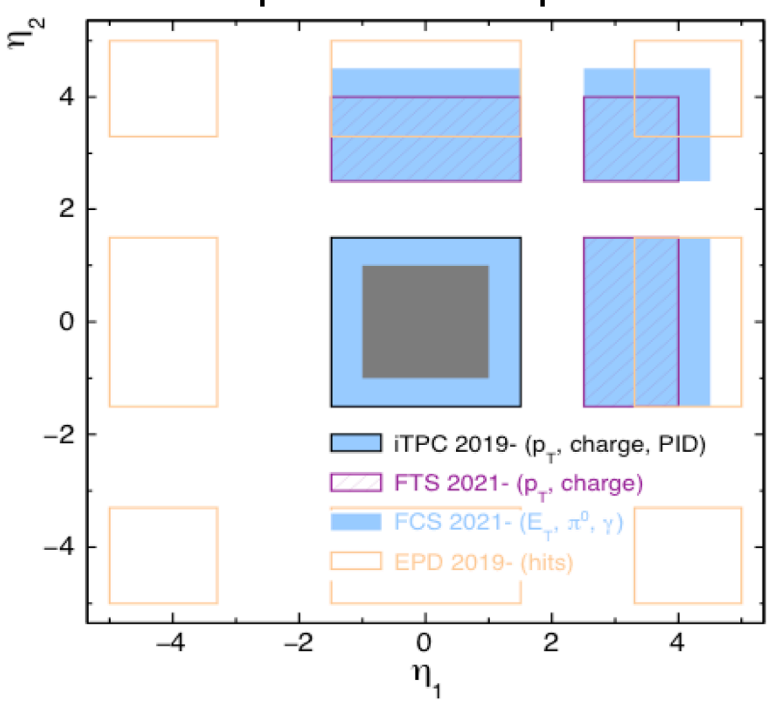
sPHEIX: HARD/Rare probes

Emphasize rates

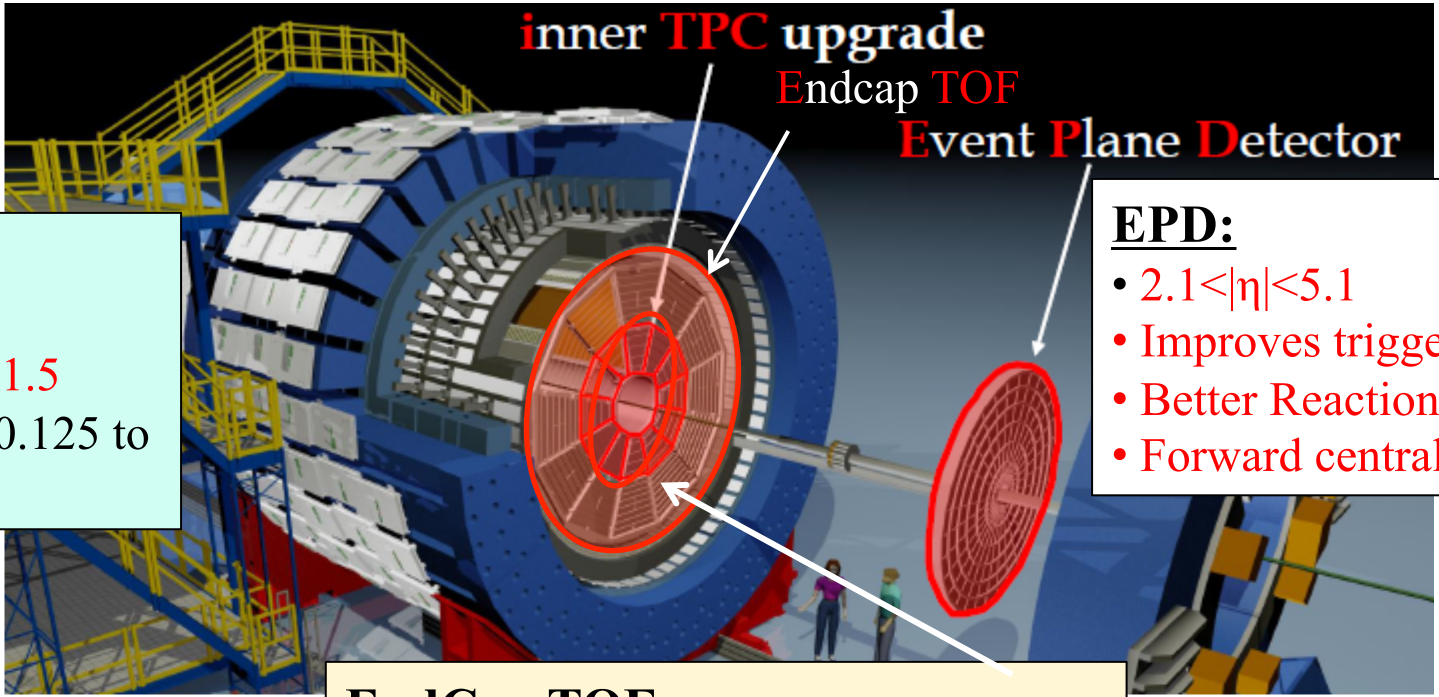


STAR: Bulk sector

Emphasize acceptance



STAR detector



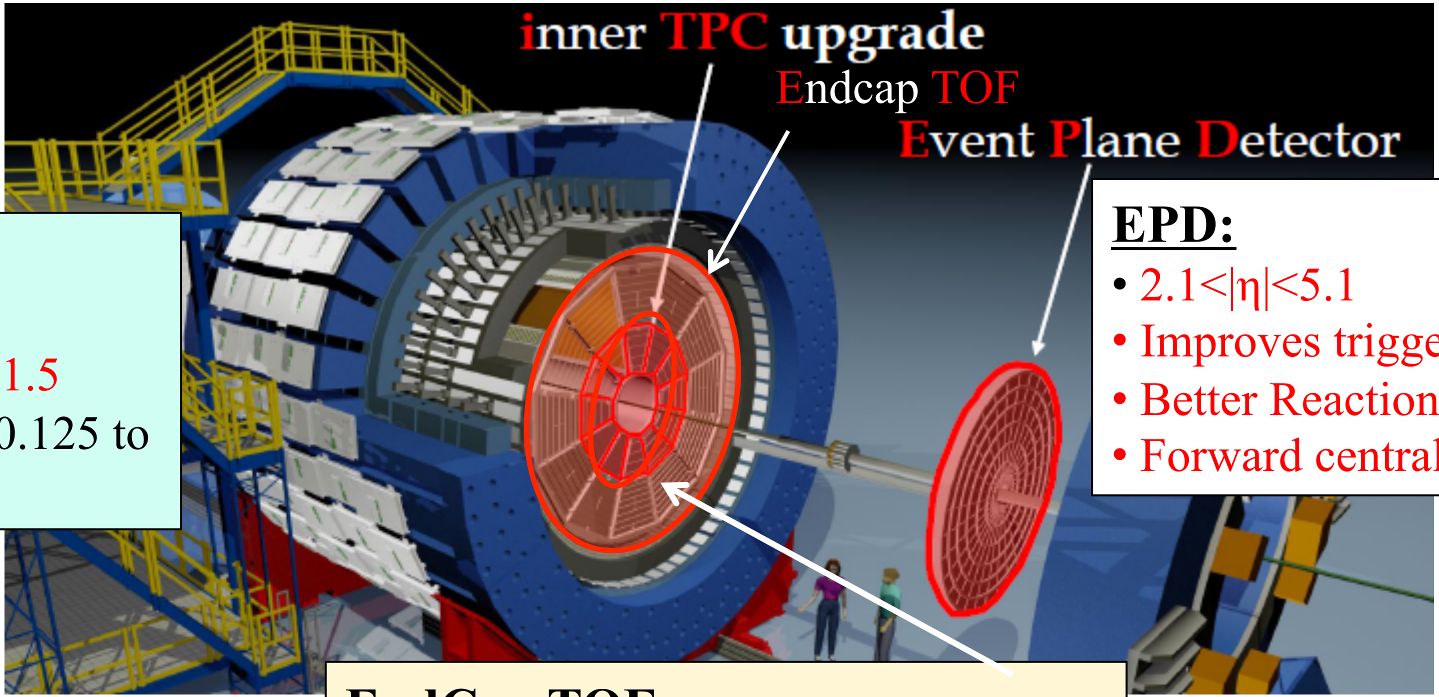
iTPC:
- Improves dE/dx
- Extends PID to $|\eta|<1.5$
- Lower p_T cut from 0.125 to 0.060 GeV/c

EPD:
- $2.1<|\eta|<5.1$
- Improves trigger
- Better Reaction Plane
- Forward centrality deter.

EndCap TOF:
- PID at η = 0.9 to 1.5

These three detectors haven't seen small system data

STAR detector



iTPC:
- Improves dE/dx
- Extends PID to |η|<1.5
- Lower p_T cut from 0.125 to 0.060 GeV/c

EPD:
- 2.1<|η|<5.1
- Improves trigger
- Better Reaction Plane
- Forward centrality deter.

EndCap TOF:
- PID at η = 0.9 to 1.5

STAR forward upgrade for cold+hot QCD program, aim for 2021+

2.5<η<4 Total DOE cost 5-6 M$

Forward Tracking System:

3 Silicon disks+4 sTGC disks

90, 140, 187, 270, 300, 330, 360 cm

US+China+Taiwan

Forward Calorimeter System

Ecal: reuse PHENIX PbSc

Hcal: sandwich iron-scint. sampling

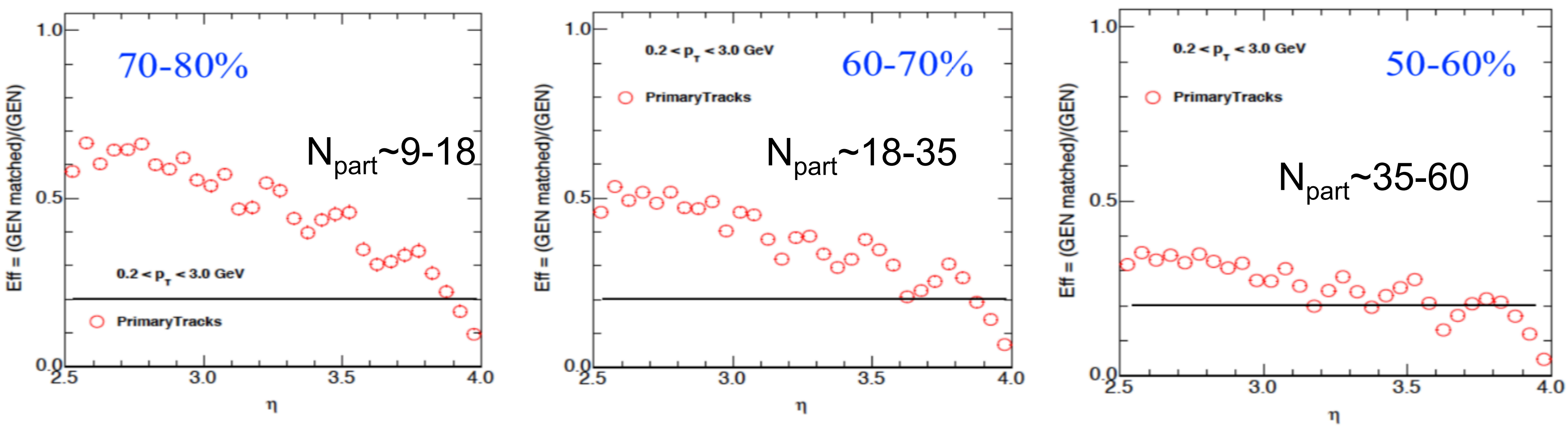
Positive report from BNL ALD review, Nov 2018

STAR Forward upgrade

- Provide p_T and E_T differential info on particles, PID ($\Lambda/K_s/\pi^0$)
  - Properties of small systems at lower T: proxy for √s scan.
  - Detailed exploration of longitudinal dynamics (stronger in small system)

Detector	pp and pA	AA
ECal	~10%/√E	~20%/√E
HCal	~50%/√E+10%	---
Tracking	charge separation photon suppression	$0.2<p_T<2$ GeV/c with 20-30% $1/p_T$

- Occupancy won't be a problem for small systems up to S+S



Summary

- Initial vs final debate should continue (beyond CGC vs Hydro)
  - Goal: time-scale for collectivity and thermalization mechanism

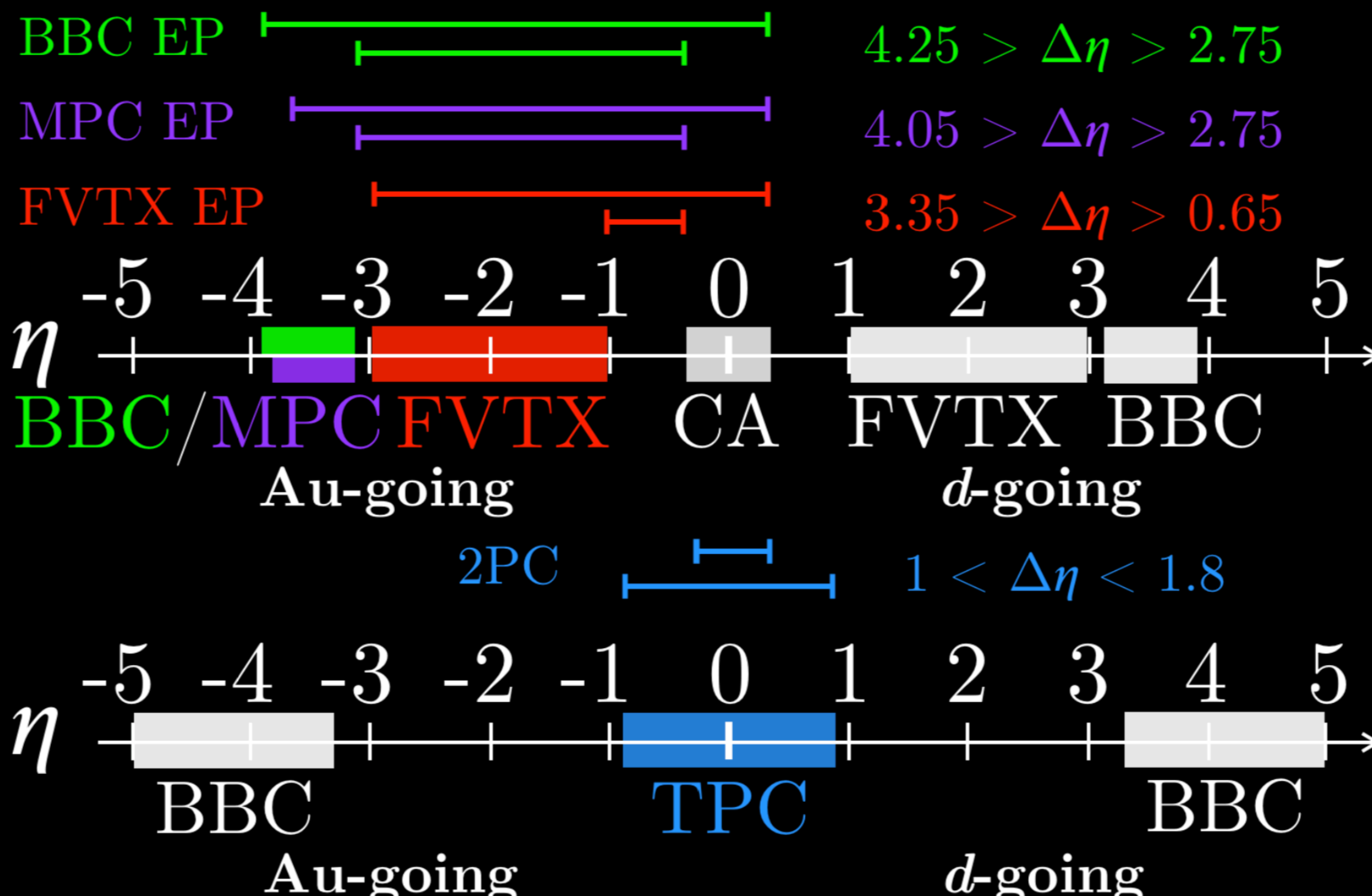
- Some possible directions forward
  - Detailed characterization of long-range collectivity
    - Multi-particle correlation, new observables etc.
  - Search for evidence of geometry responses
  - Longitudinal dynamics of long-range collectivity (not discussed)
  - Large acceptance detector with differential info needed!

- Future small system scan: asymmetric and symmetric.
  - Systematically map out where final state turns on.
  - Synergy and complementarity with the LHC small system program
  - Complementarity between sPHENIX (rates) vs STAR (acceptance)

Back up

From Julia

η separation: PHENIX and STAR



- $\Delta\eta$ range means STAR has a much larger issue with nonflow than PHENIX

Searching for jet quenching

- Cu+Cu shows jet quenching, maybe also in O+O and S+S?
  - Both in minbias and central collisions