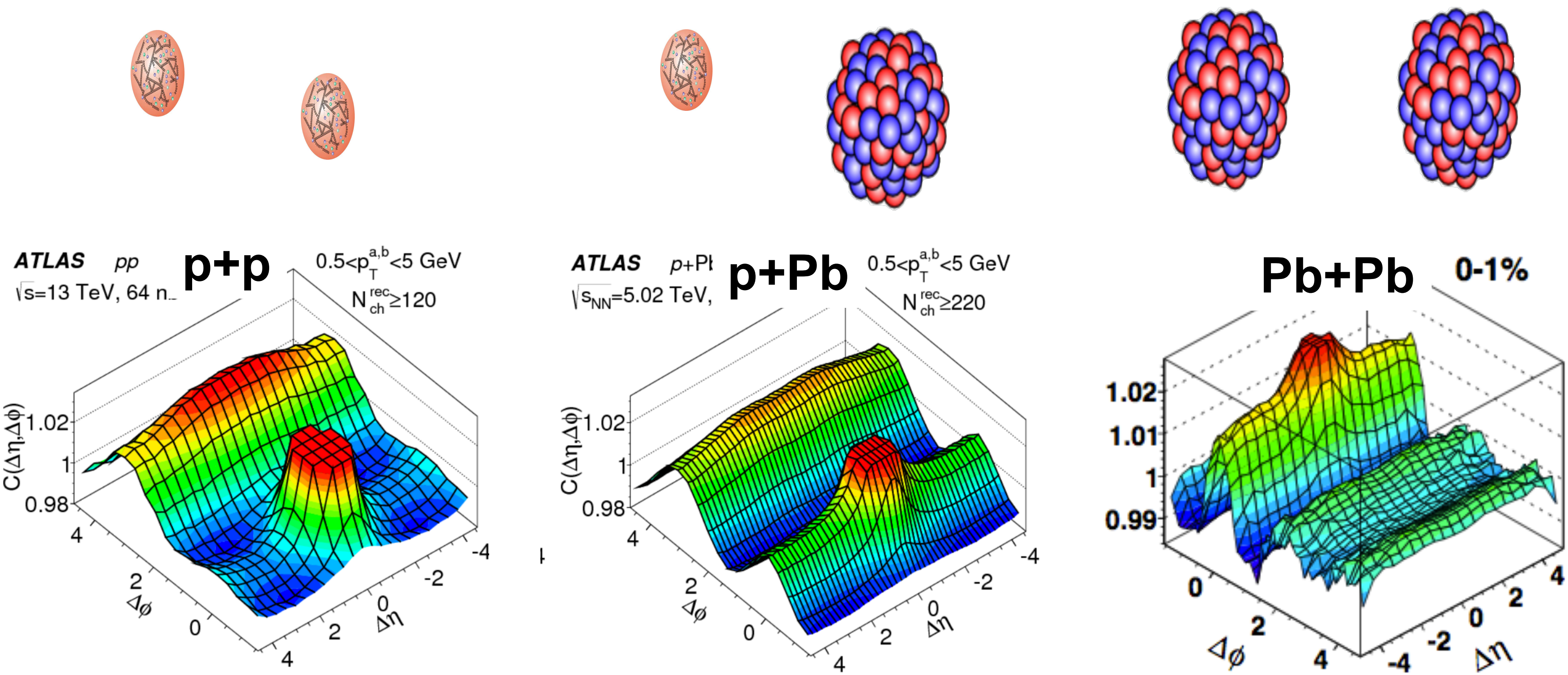
Stony Brook University | The State University of New York

Future opportunities for a small-system scan at RHIC

Jiangyong Jia

put together with Wei Li, with inputs from Zhenyu Chen, ShinIchi Esumi, Shengli Huang, Roy Lacey, Constantin Loizides, Li Yi, Aihong Tang, Prithwish Tribdey, Fuqiang Wang

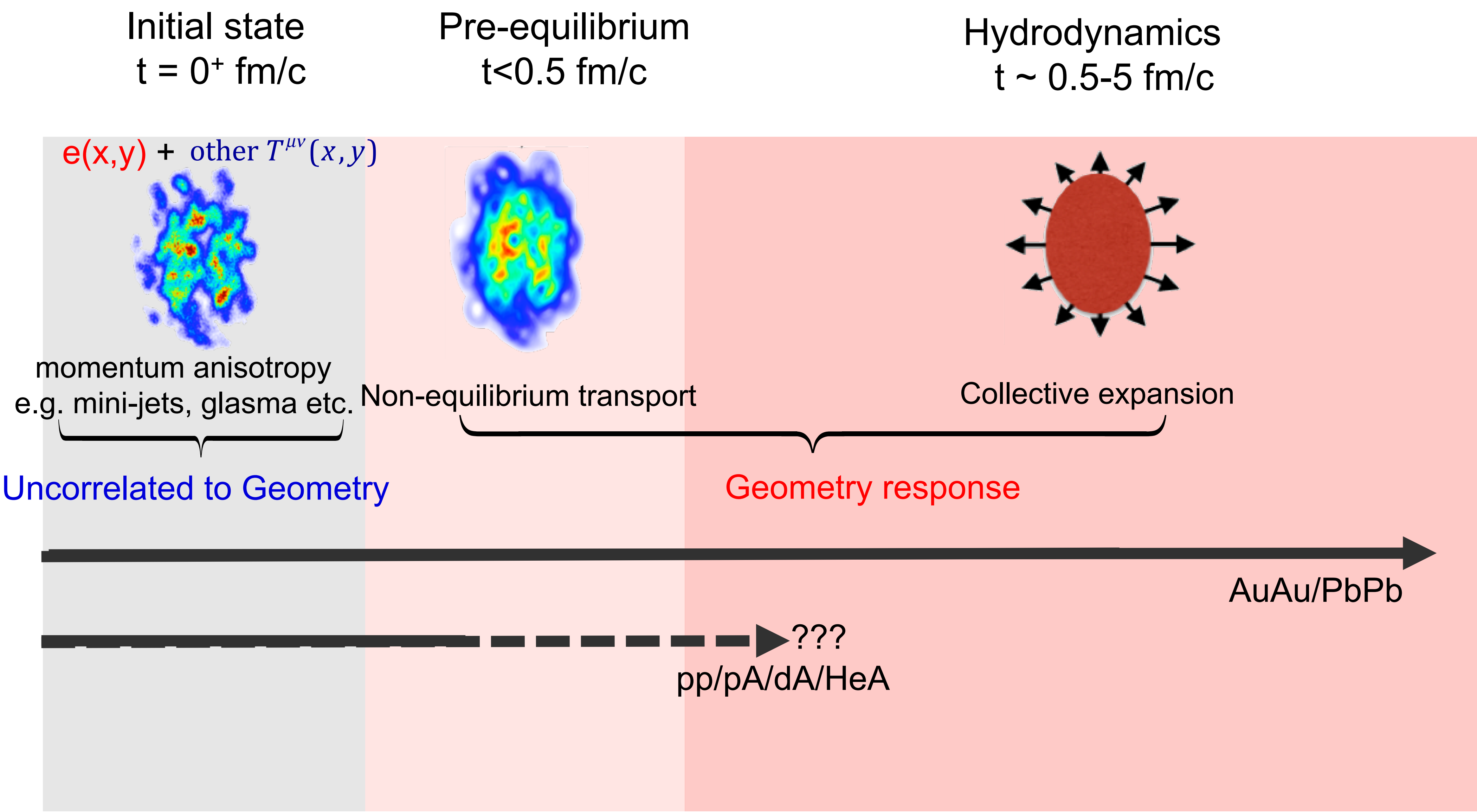
Long-range collectivity in different systems



- 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?

Time-scale for emergence of collectivity



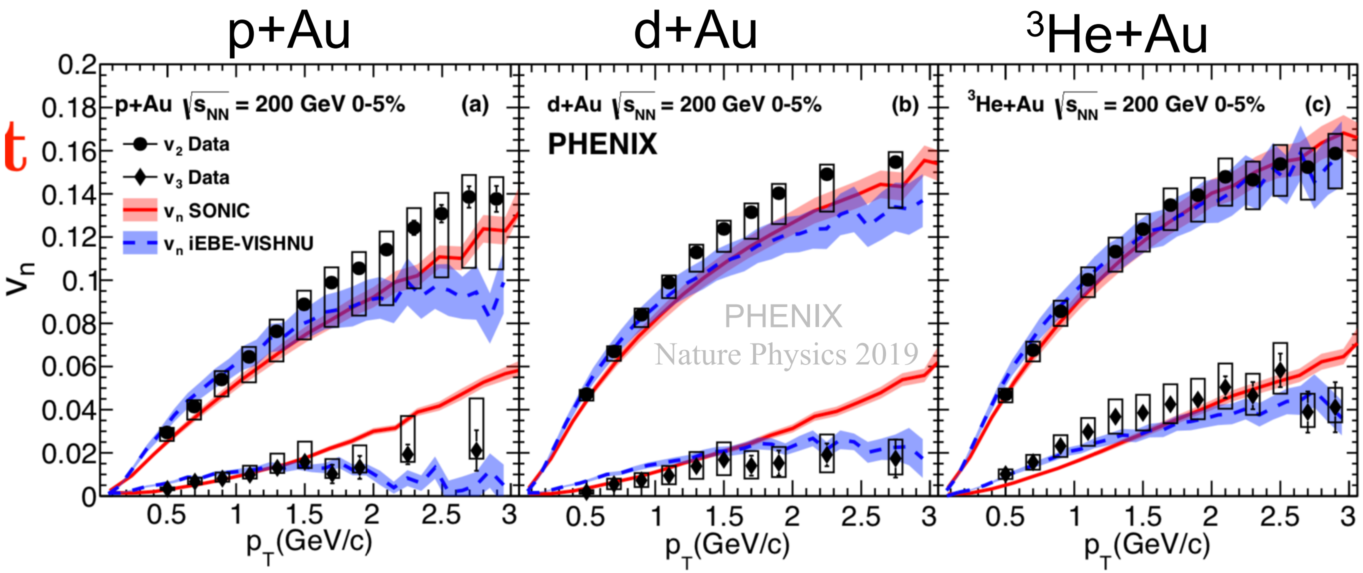
Can we disentangle these three scenarios?

P. Bozek, PRC, 85, 014911 (2012), J. Nagle PRL113, 112301 (2014)

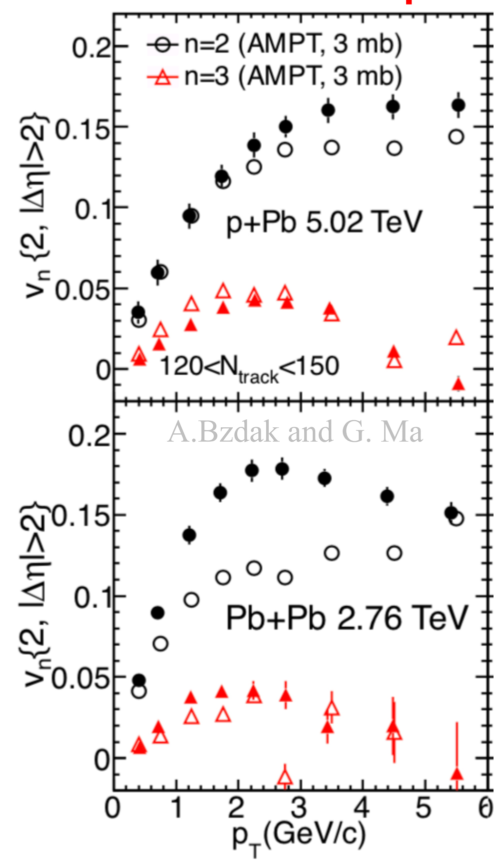
Interpretation of small system data

Geometry response models can describe the data

Hydrodynamics



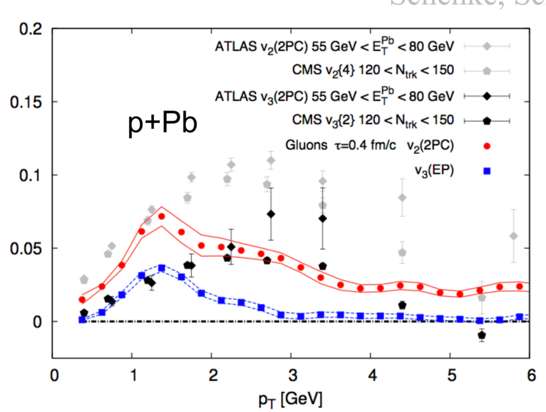
Non-equilibrium transport

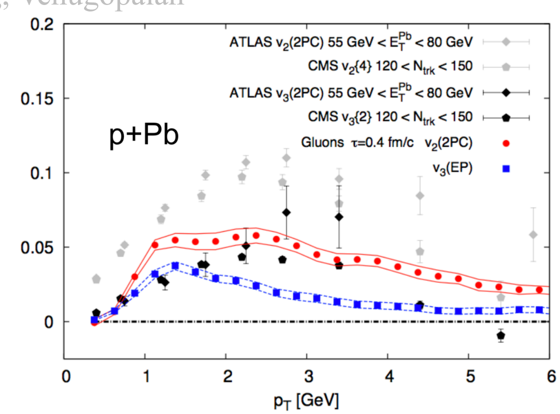


Initial momentum anisotropy contribution could be large

'Spherical' proton

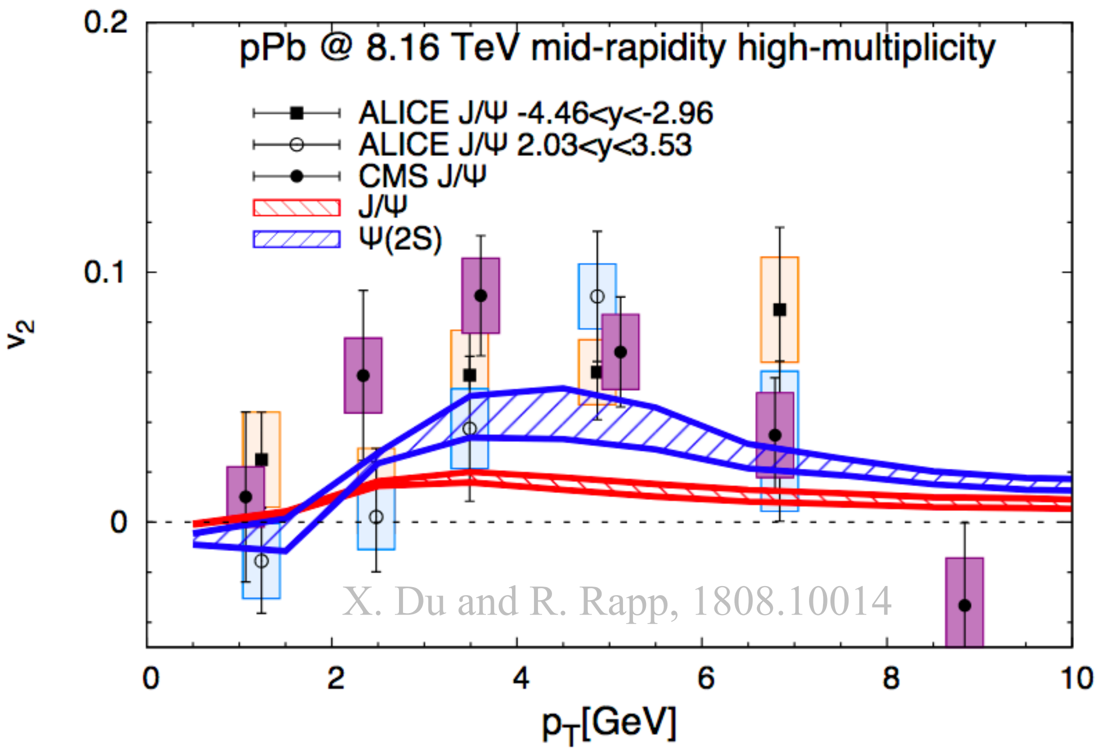
'Eccentric' proton



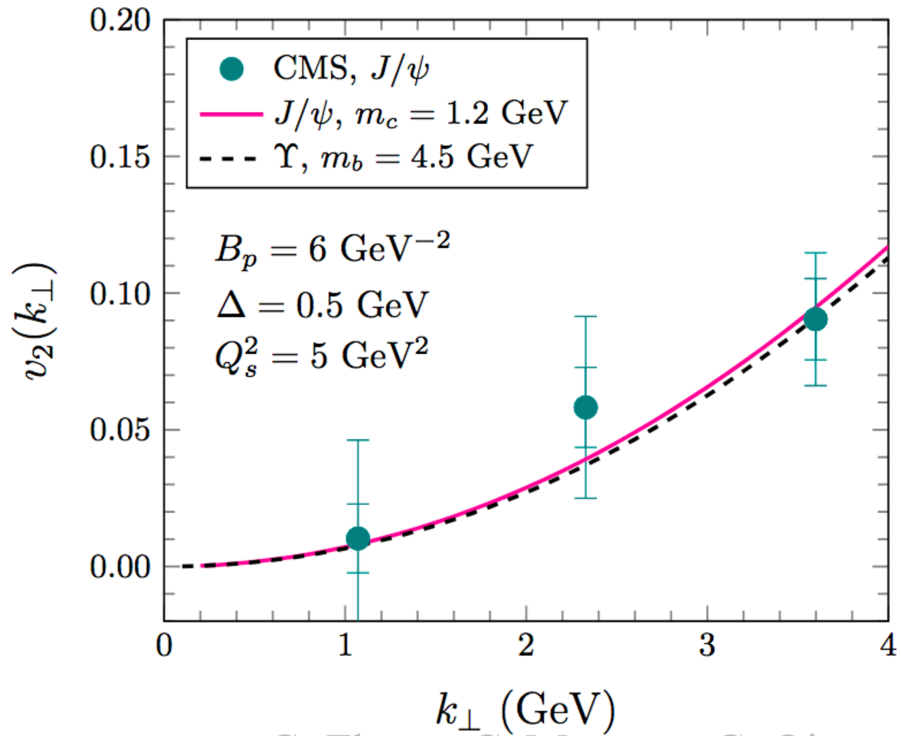


Interpretation of J/Ψ & heavy-flavor v_2 data

Geometry response models under-predicts the data



Initial momentum anisotropy models seem to work



C. Zhang, C. Marquet, G. Qin, S. Wei, B. Xiao 1901.10320

pPb J/Ψ data from ALICE 1709.06807, CMS 1810.01473, D^0 data from CMS 1804.09767

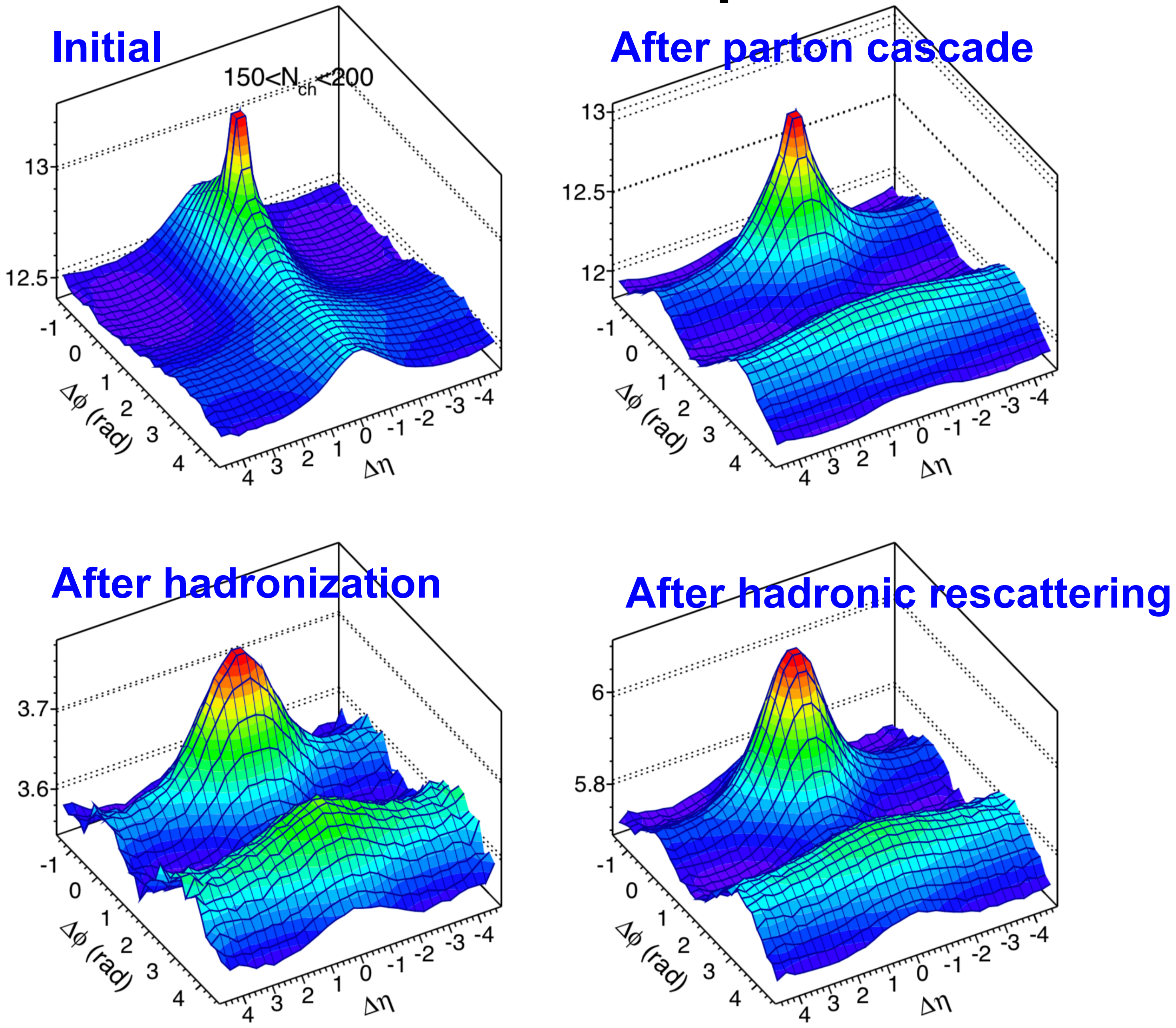
Initial P-anisotropy or final state?
non-eq. transport or hydro?

Go beyond a simple yes/no question

A test with transport model

AMPT transport model has four stages

p+Pb 5 TeV

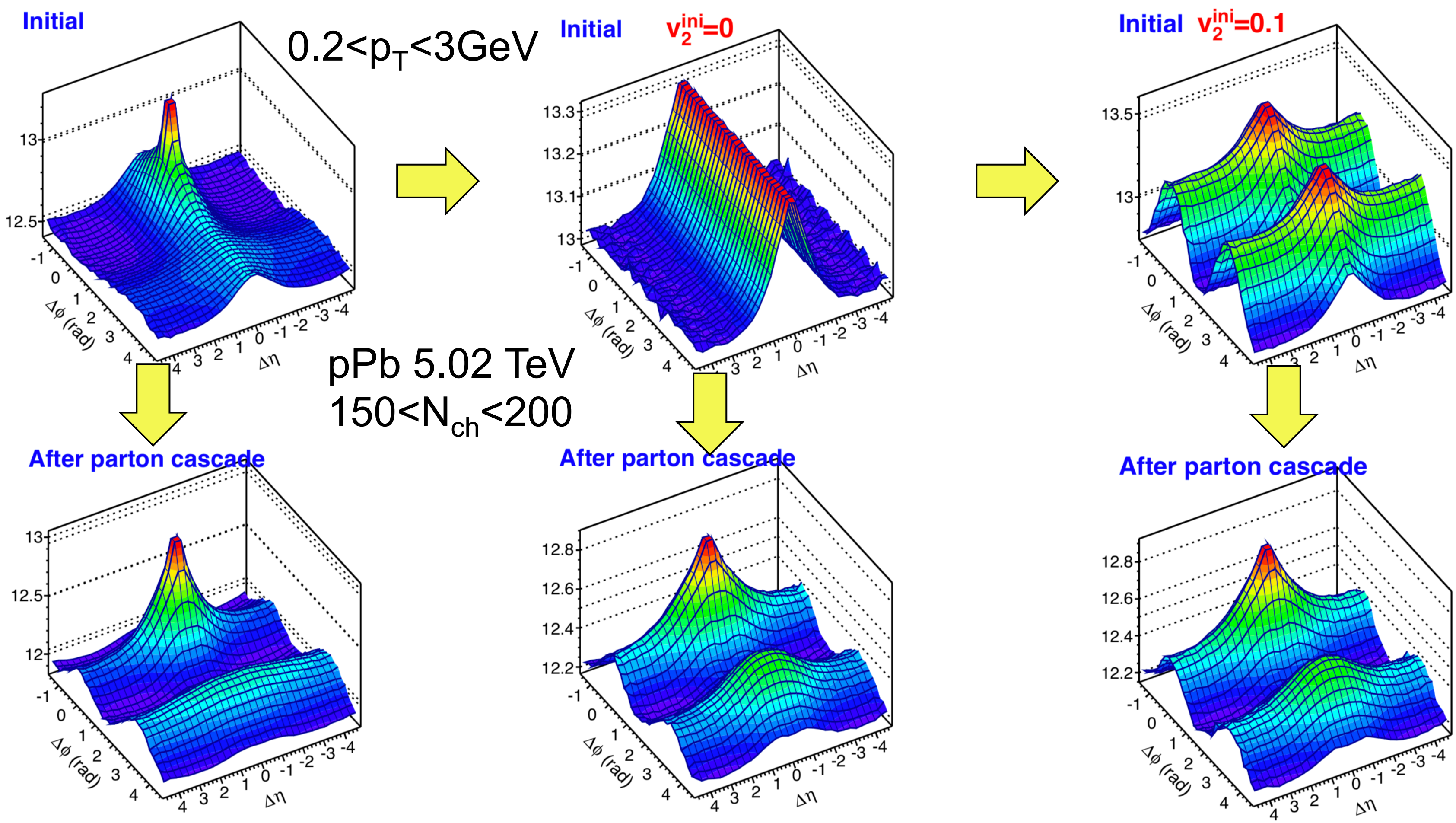


A test with transport model

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

With Maowu Nie, Yi Li, Guoliang Ma

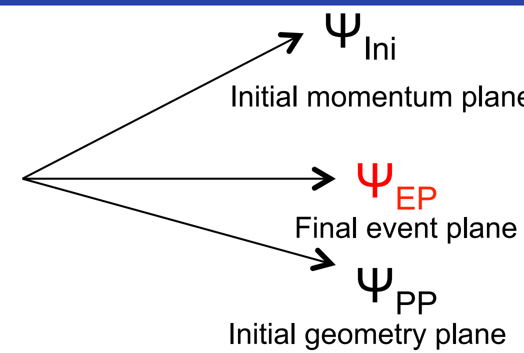
- Add initial-flow via flow-afterburner with a random phase.
  - This is event-wise anisotropy but uncorrelated with geometry.



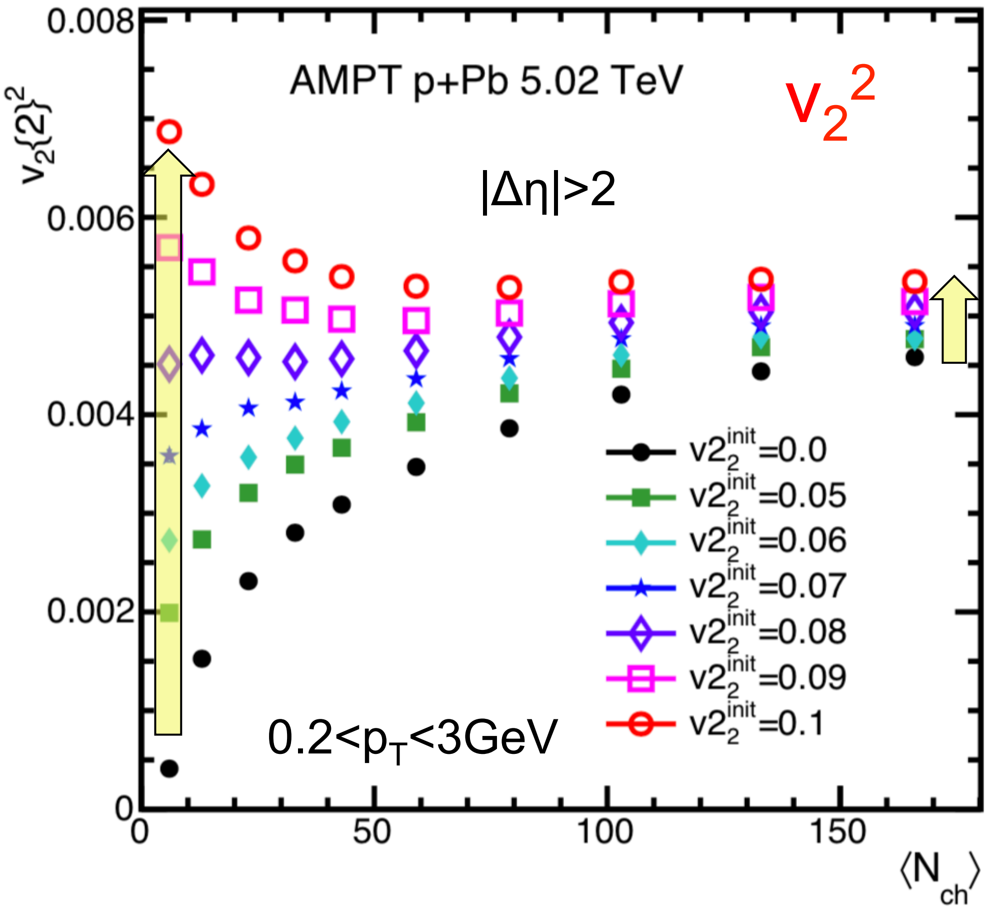
How initial momentum anisotropy survives to final stage?

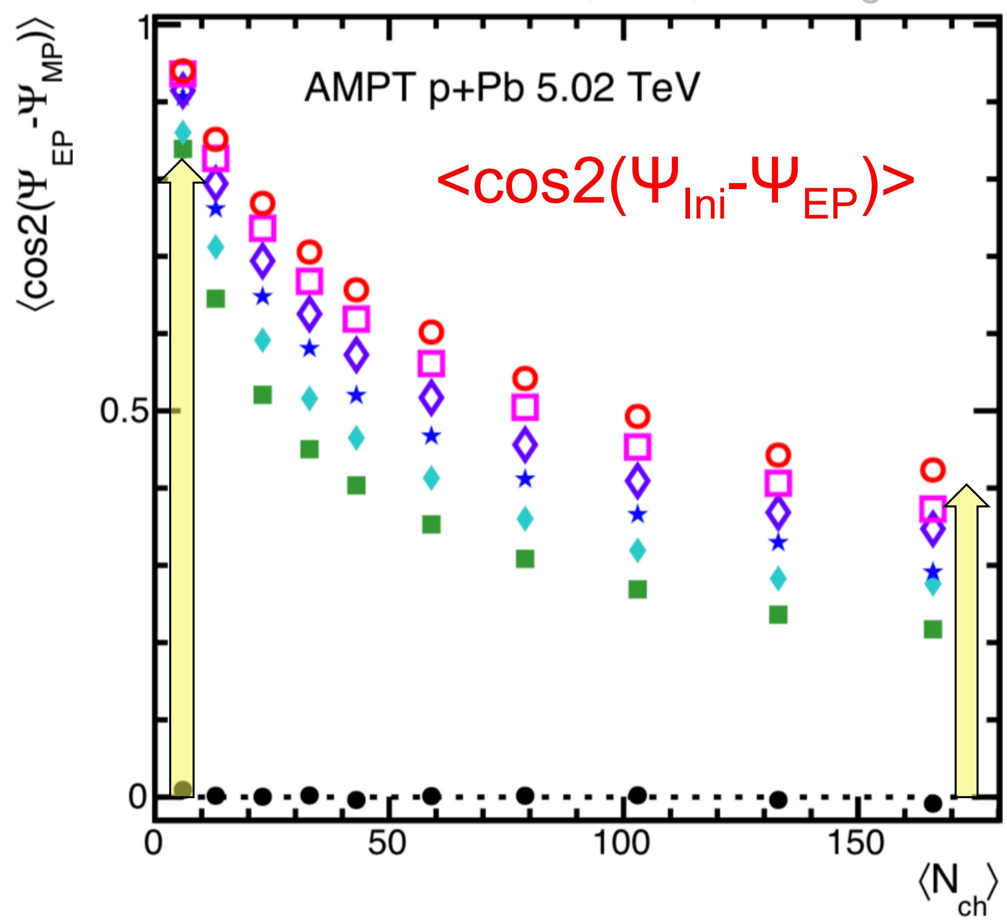
Influence of final flow by initial momentum anis.

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



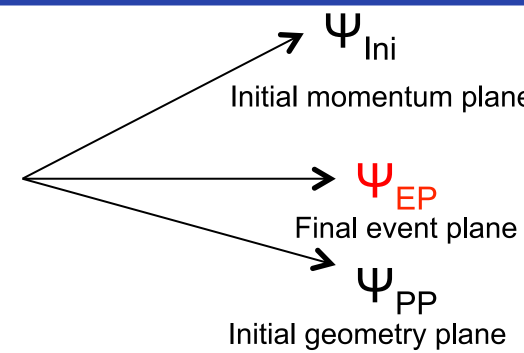
With Maowu Nie, Yi Li, Guoliang Ma





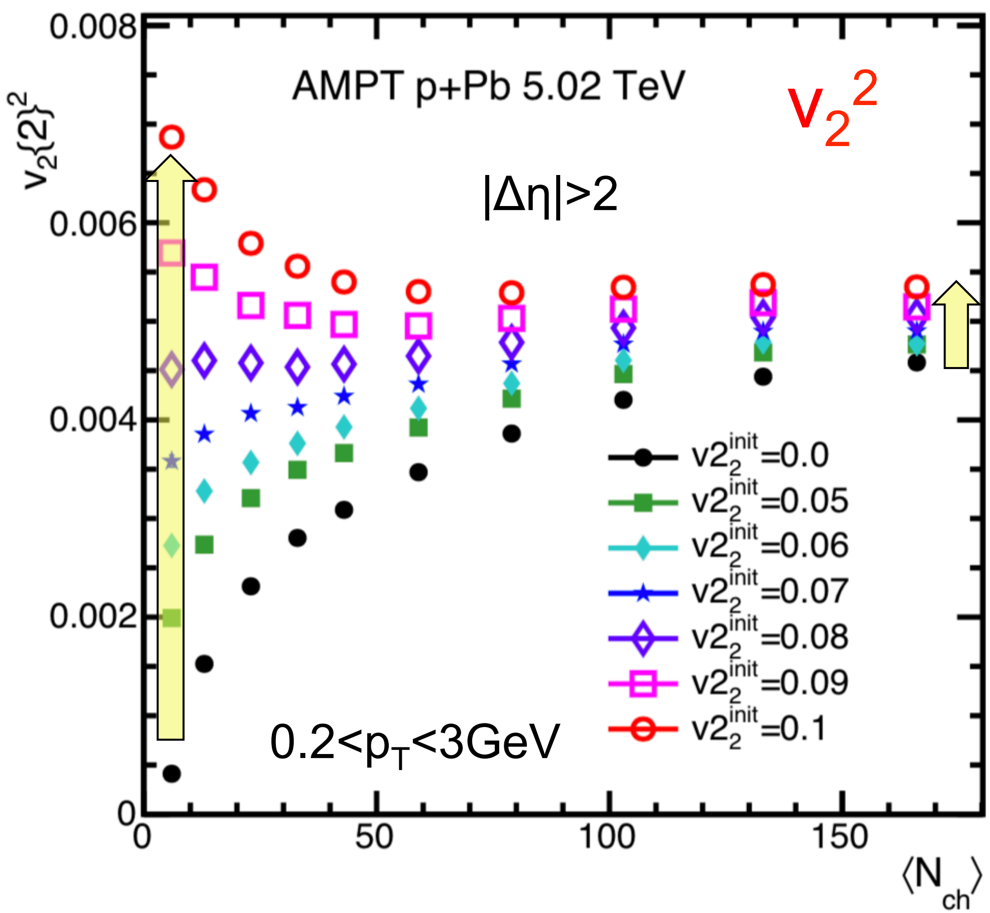
Influence of final flow by initial momentum anis.

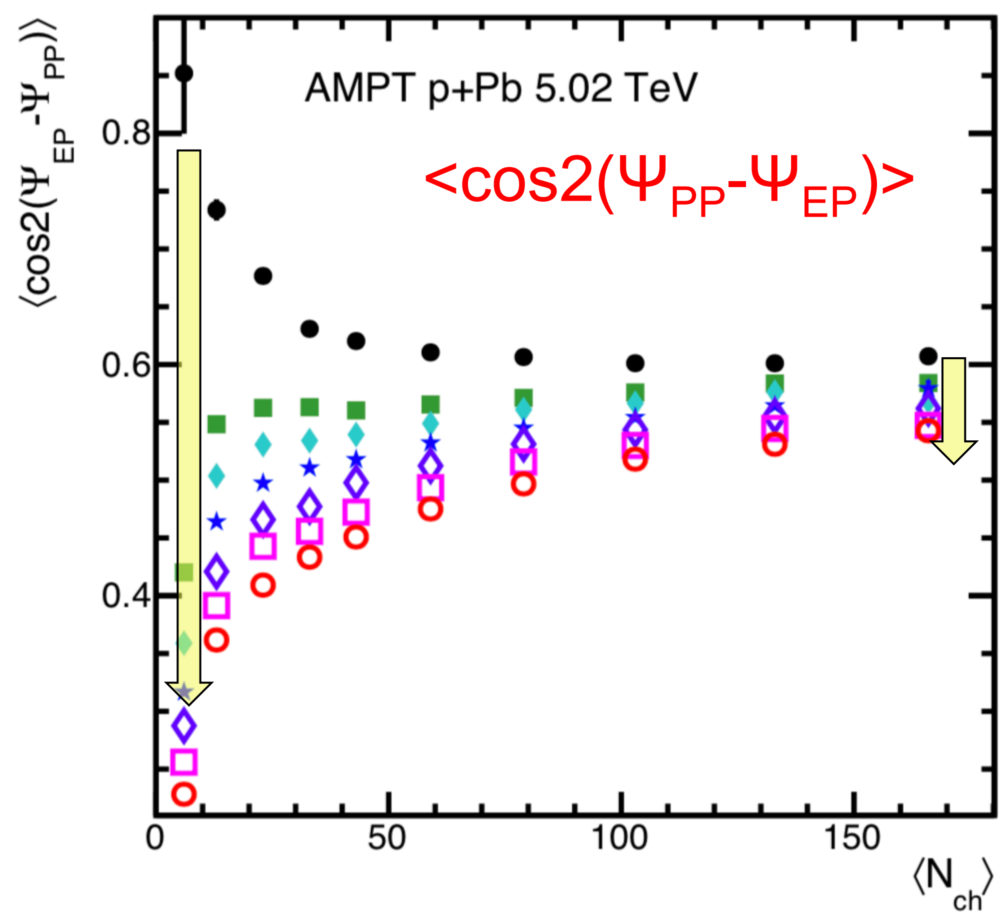
- Low N_{ch} : Final flow ≈ Initial flow expected for free streaming
- High N_{ch}: Final flow increase slowly with initial flow.
- Final flow is biased toward direction of initial momentum flow
- Weakening the correlation with initial geometry direction



Similar studies in M. Greif, C. Greiner, B. Schenke, S. Schlichting, Z. Xu1708.02076

Initial anisotropy survives and biases the geometry-driven flow!





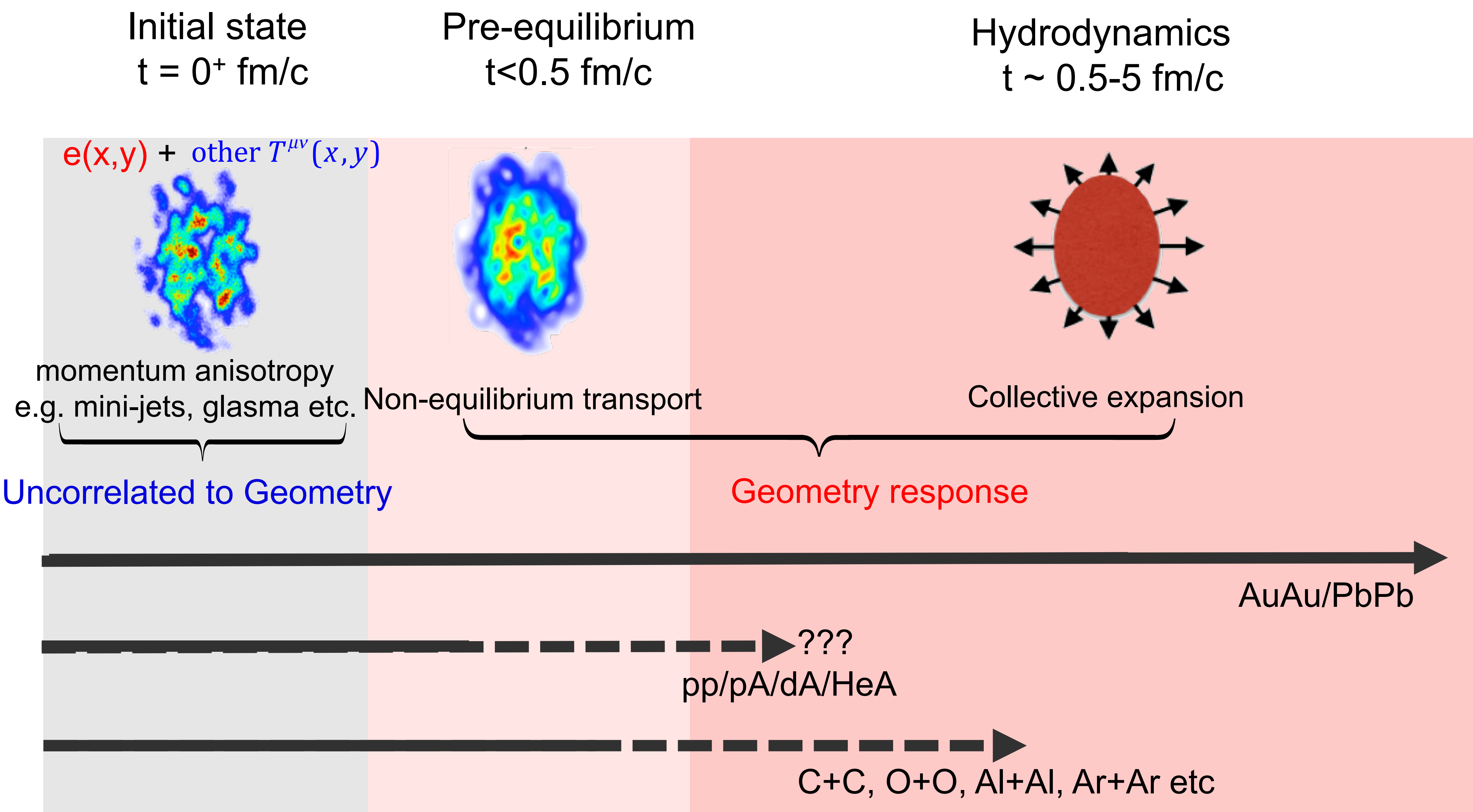
- The large body of correlation data from RHIC/LHC shows evidence for geometry response in small systems.

- But mere evidence for geometry response does not rule out possible large contributions from initial state in small systems.

- Disentangling these requires further detailed (A)-symmetric small system scan+detector capabilities. RHIC is ideal for this due to its flexibility.
    - Synergy with LHC's precision and large lever-arm in $\sqrt{s}$.

What questions addressed by further small system scan at RHIC?

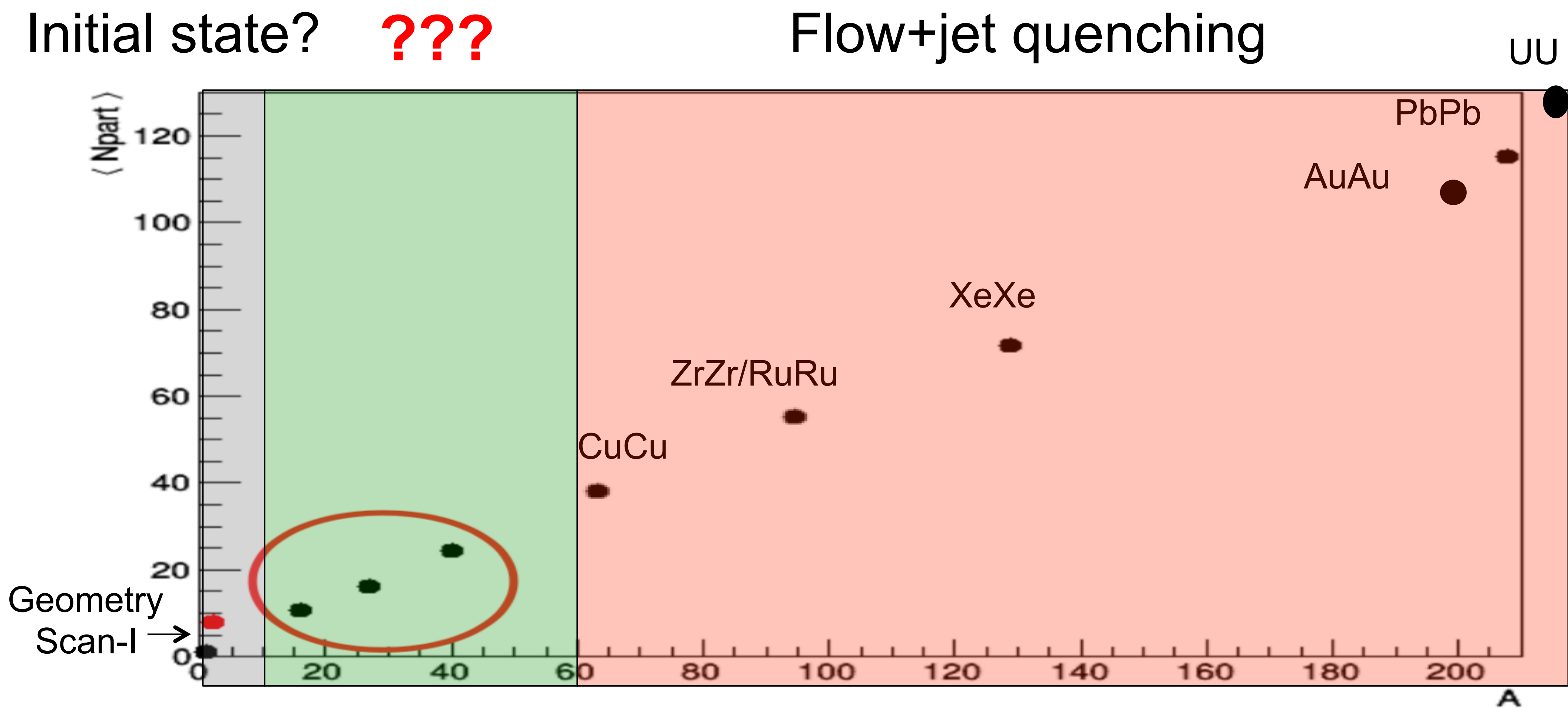
Time-scale for emergence of collectivity?



Extend the lever-arm to bridge the three stages+ detector capability: answer how much each contributes and where?

Jak Noronhahostier 1901.01319 Piotr Bozek, W. Broniowski PRC97 (2018) 034912

"On/off" behavior of IS and FS effects?

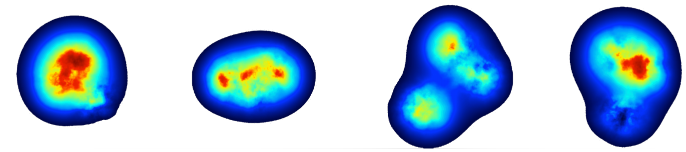


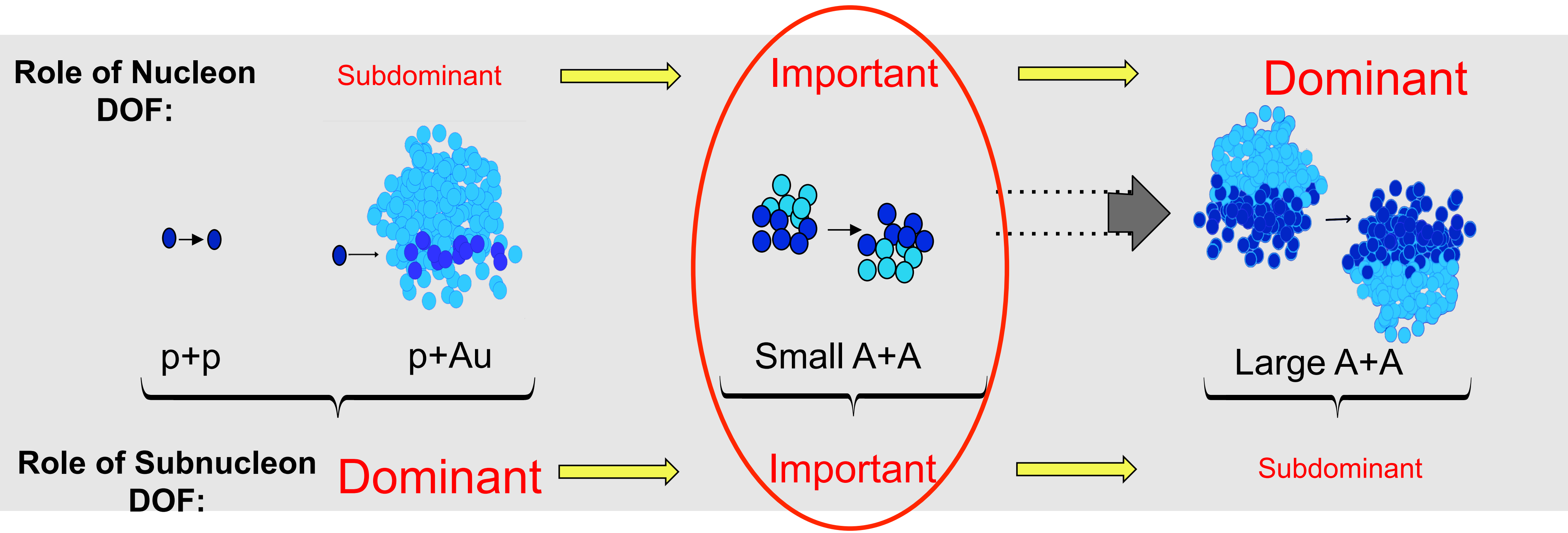
- Where initial momentum anisotropy becomes subdominant?
- What is the "turn-on" behavior for collectivity and jet quenching?
- What is the role of pre-equilibrium vs hydrodynamics?

Answer these with (A)symmetric system scan + improved detectors at RHIC

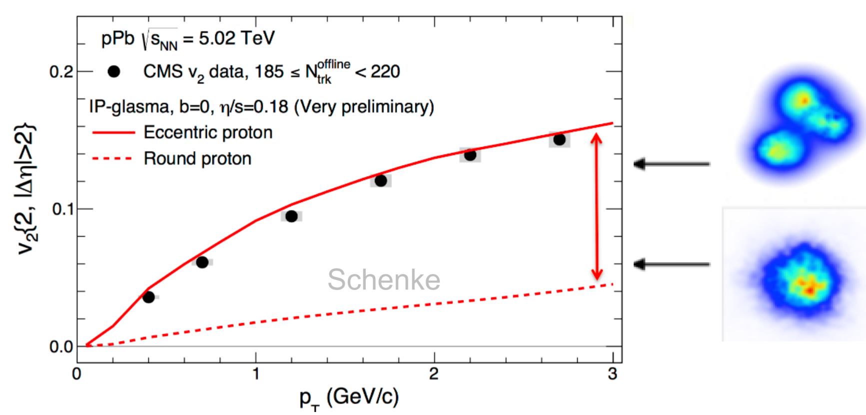
Nucleon vs Subnucleon fluctuations?

The fluctuating shape/structure of the proton:



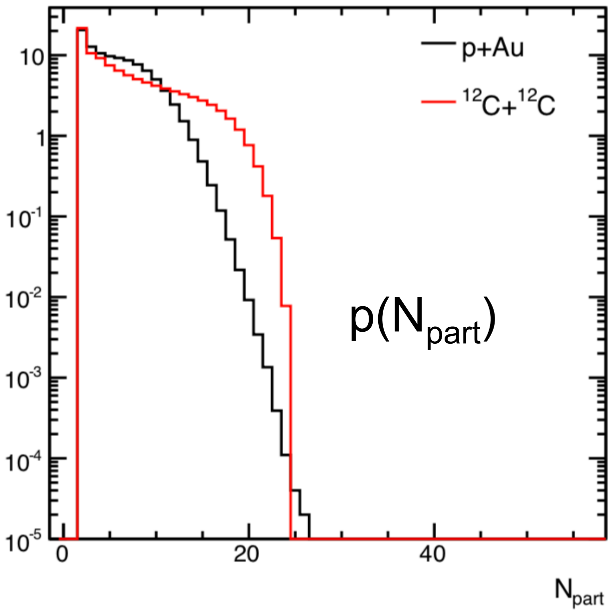


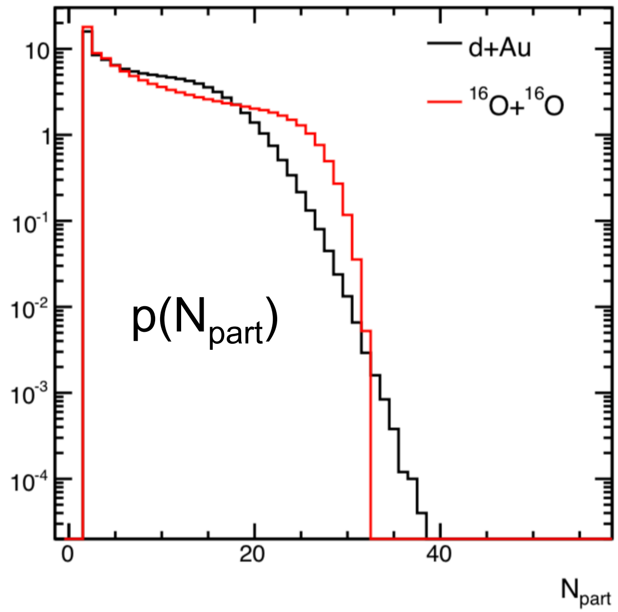
- Asymmetric+Symmetric small system scan:
  - Disentangle nucleon substructure from nuclear geometry.
  - Valuable information for cold-QCD and EIC

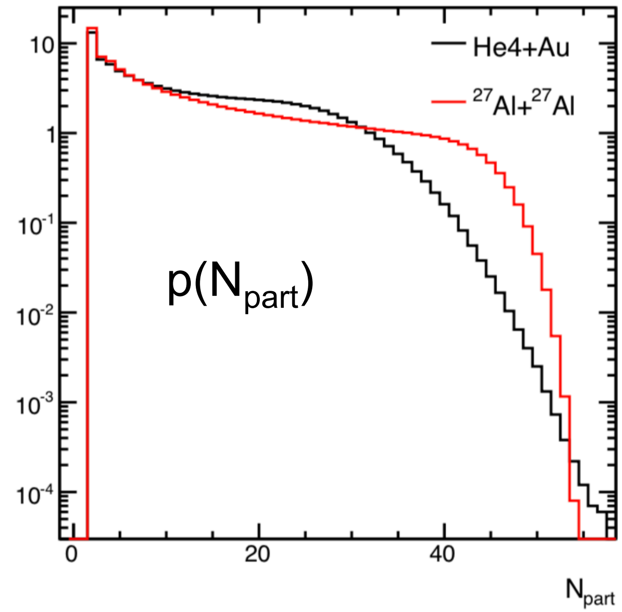


Symmetric vs Asymmetric

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





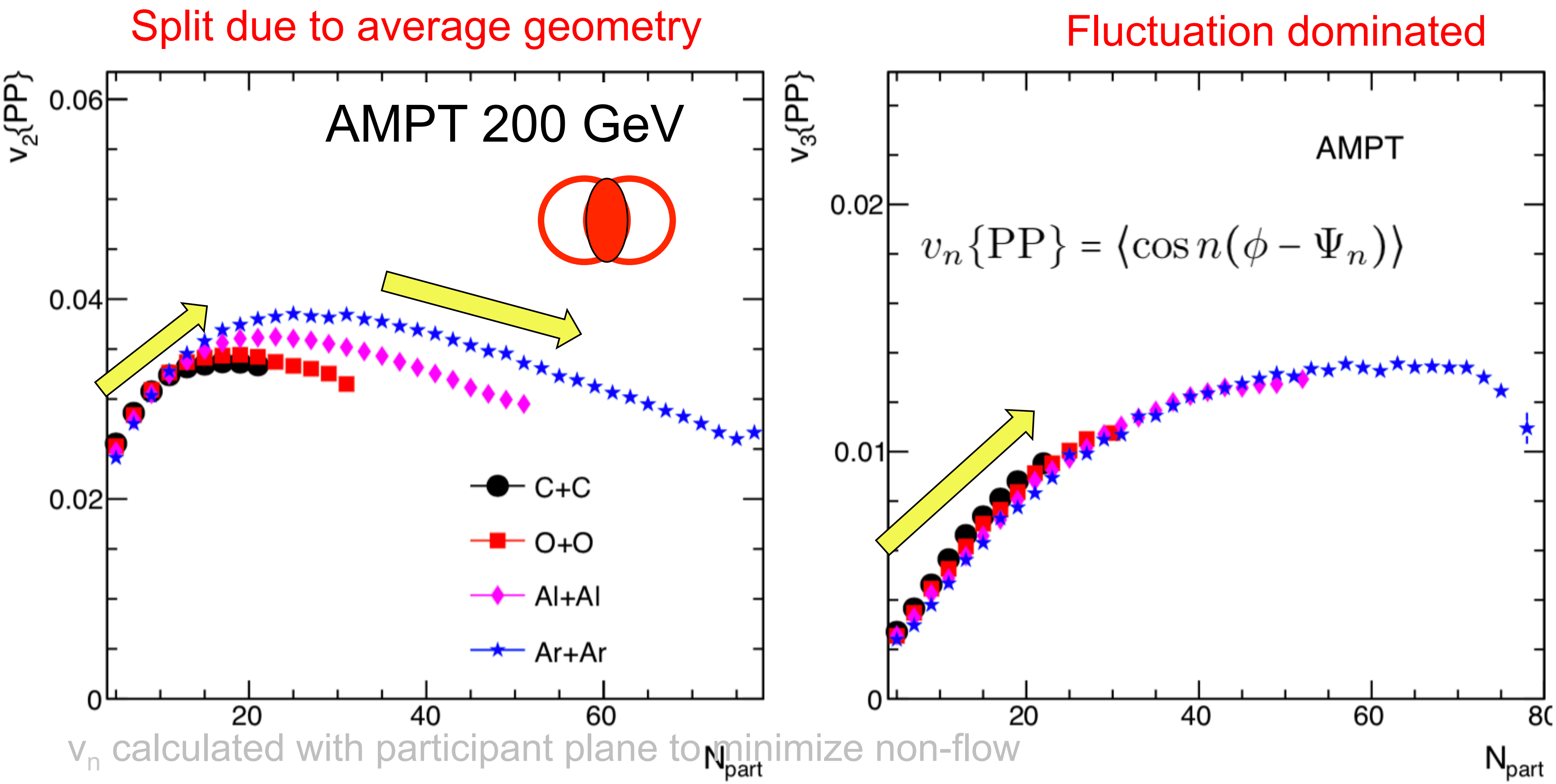


$$p(n_{ch}) = p(N_{part}) \otimes p(n_{ch} | N_{part})$$

- Asymmetric: subnucleon fluctuations more important.
- Symmetric: nucleon fluctuations more important.
  - Less centrality bias & better selection of geometry (N_{part}, ε_n & N_{coll})

Explore geometry responses in small A+A

See M.Sievert J. Noronha-Hostler 1901.01319 for a similar calculation at LHC



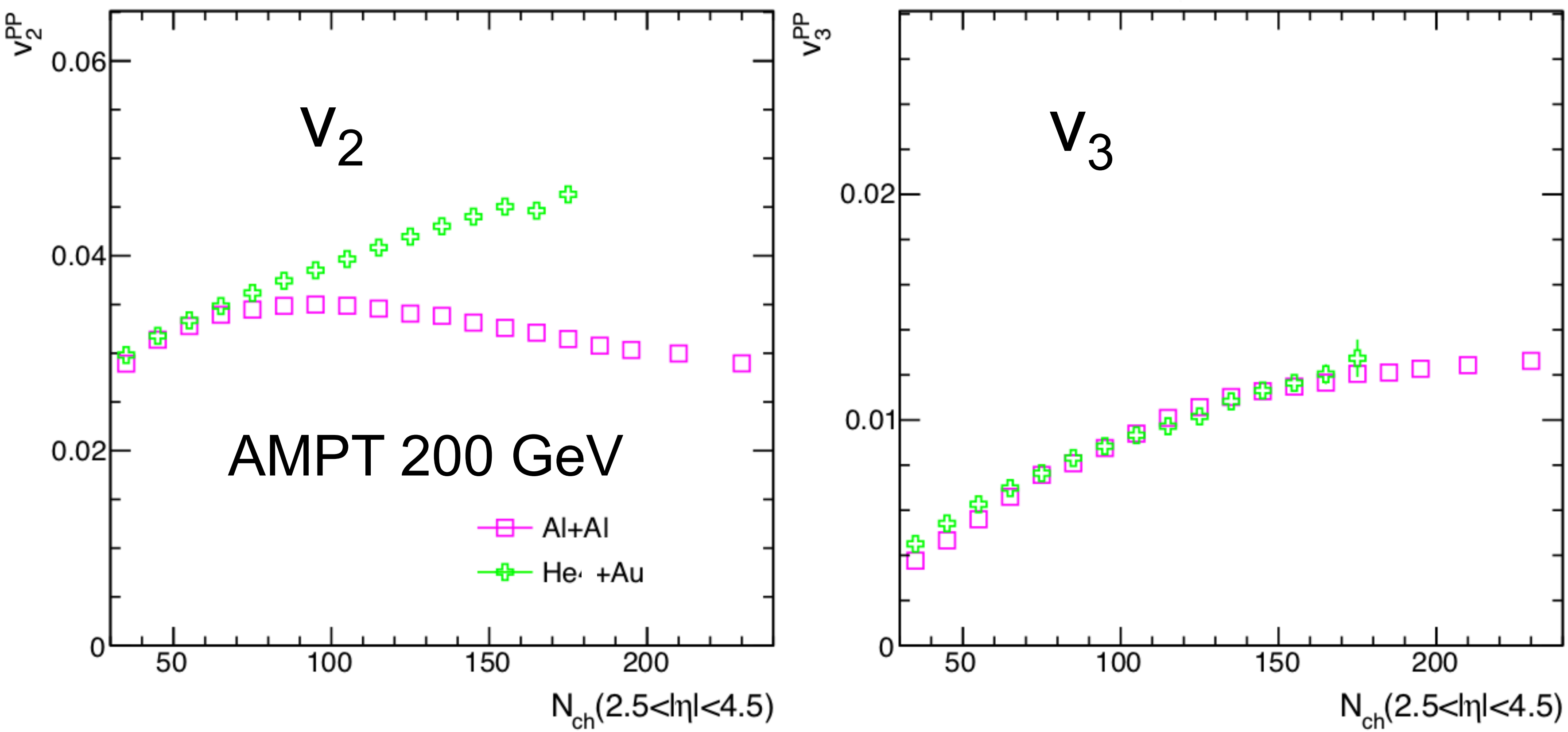
v_n calculated with participant plane to minimize non-flow

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

Such geometry response not expected for pure initial state picture
Would be good to compare transport with hydro prediction

Geometry responses: symmetric vs asymmetric

v_n calculated with participant plane to minimize non-flow

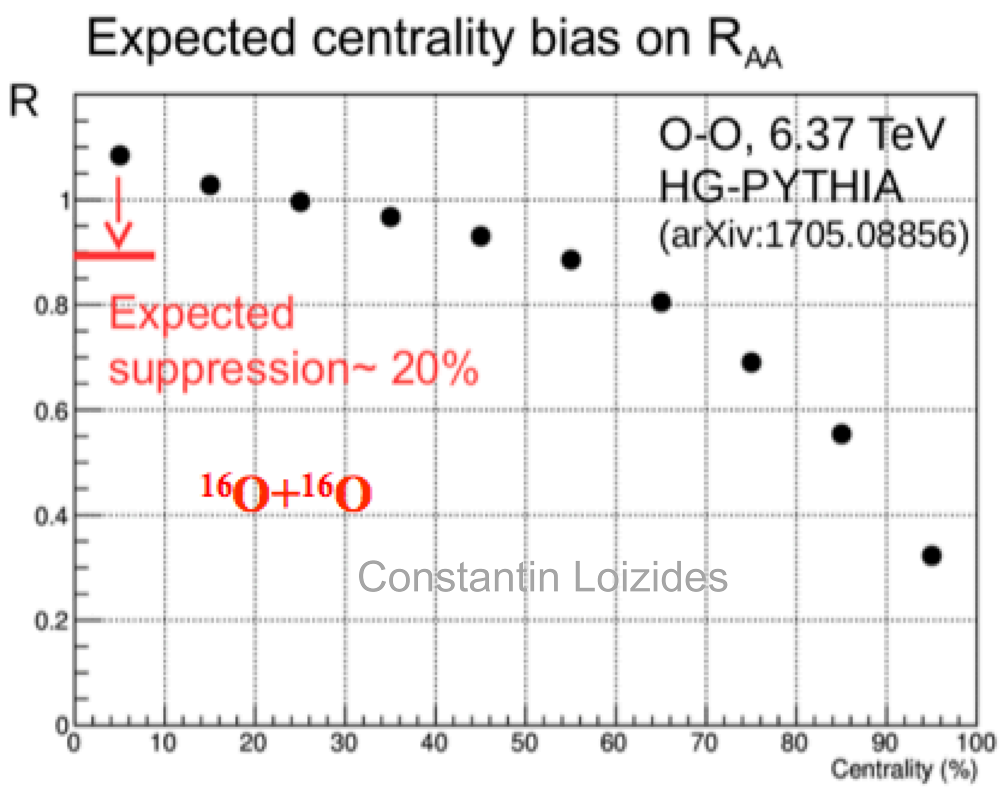


- Asymmetric system: v_2, v_3 increase with N_{ch}.
- Symmetric system: v_2 rise and fall with N_{ch}, v_3 increase with N_{ch}.

Different geometry response, interesting to compare also flow fluctuations: $c_n\{4,..\}$ etc.

Onset of jet quenching in small AA

- Better control of system size N_{part} and hard-scattering rate N_{coll}.
- Same parton spectral shape but changing geometry size.
  - Different from energy scan: same size but changing spectral shape.
- Different (less) initial-state effects from pA, e.g. nPDF, smaller Q_s



R_{AA}, I_{AA}, high-p_T v_2, PID spectra possible with short run

$\langle N_{part} \rangle$~=26 in 0-5% O+O

Synergy with LHC small system program

Proposed LHC run schedule HI-LHC HI yellow report: arXiv: 1812.06772

Year	Systems, $\sqrt{s_{NN}}$	Time	L_{int}
2021	Pb–Pb 5.5 TeV	3 weeks	2.3 nb^{-1}
	pp 5.5 TeV	1 week	3 pb^{-1} (ALICE), 300 pb^{-1} (ATLAS, CMS), 25 pb^{-1} (LHCb)
2022	Pb–Pb 5.5 TeV	5 weeks	3.9 nb^{-1}
	O–O, p–O	1 week	500 μb^{-1} and 200 μb^{-1}
2023	p–Pb 8.8 TeV	3 weeks	0.6 pb^{-1} (ATLAS, CMS), 0.3 pb^{-1} (ALICE, LHCb)
	pp 8.8 TeV	few days	1.5 pb^{-1} (ALICE), 100 pb^{-1} (ATLAS, CMS, LHCb)
2027	Pb–Pb 5.5 TeV	5 weeks	3.8 nb^{-1}
	pp 5.5 TeV	1 week	3 pb^{-1} (ALICE), 300 pb^{-1} (ATLAS, CMS), 25 pb^{-1} (LHCb)
2028	p–Pb 8.8 TeV	3 weeks	0.6 pb^{-1} (ATLAS, CMS), 0.3 pb^{-1} (ALICE, LHCb)
	pp 8.8 TeV	few days	1.5 pb^{-1} (ALICE), 100 pb^{-1} (ATLAS, CMS, LHCb)
2029	Pb–Pb 5.5 TeV	4 weeks	3 nb^{-1}
Run-5	Intermediate AA	11 weeks	e.g. Ar–Ar 3–9 pb^{-1} (optimal species to be defined)
	pp reference	1 week	

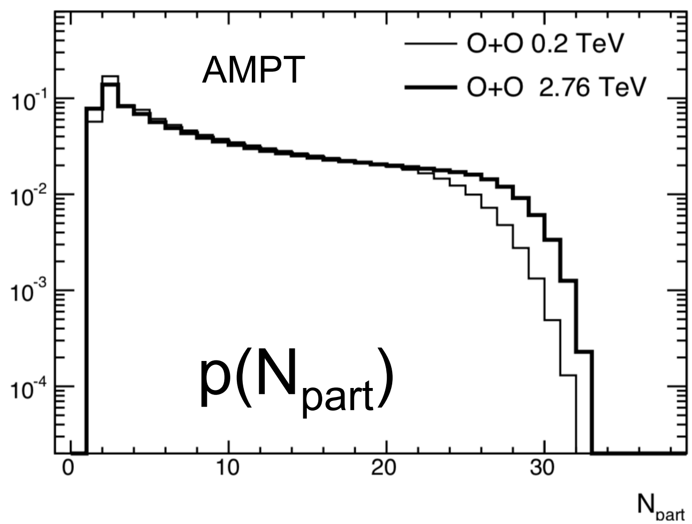
- A short $^{16}O+^{16}O$ run at RHIC after BESII would be very timely
  - First time comparison of same small system with ~identical Glauber geometry, but different initial subnucleonic fluctuations (Q_s).
  - Compare Flow and Jet quenching measurements at 0.2 TeV and 2-7 TeV

Allow better understanding of results at each energy

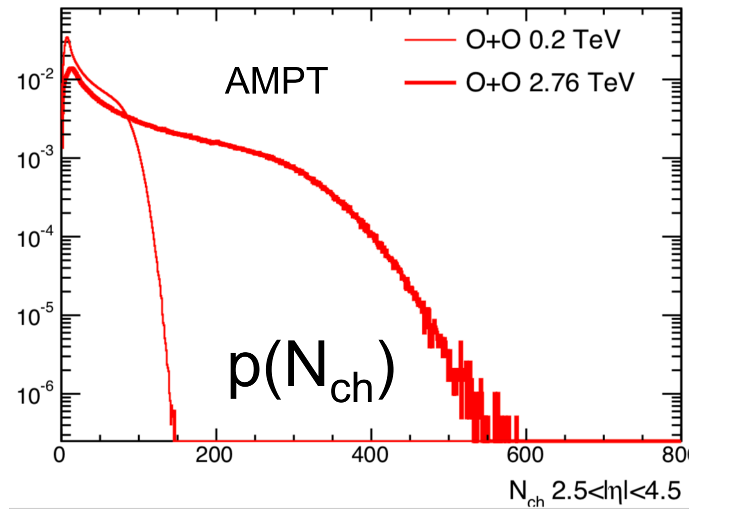
RHIC vs LHC energy-scan

- Similar Glauber geometry but different particle production

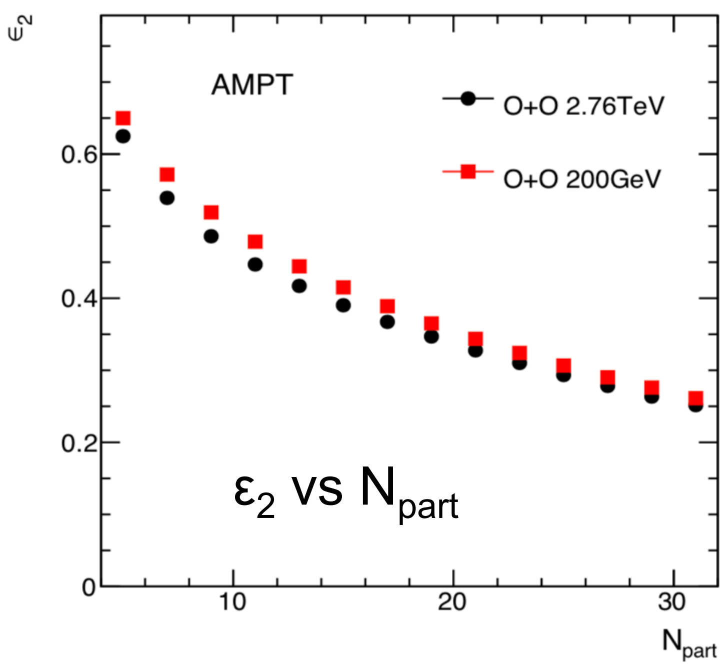
Glauber

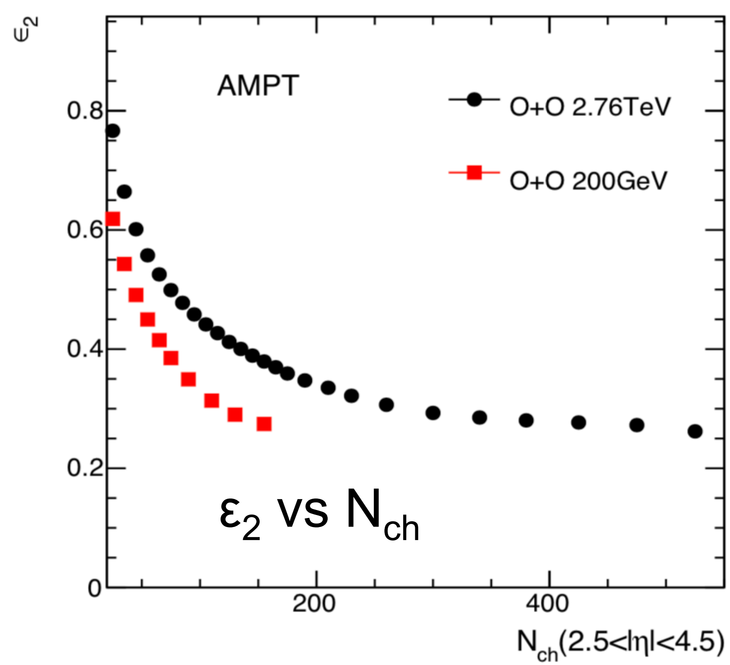


Glauber + fluctuations per nucleon



- Expect larger multiplicity/centrality smearing @LHC

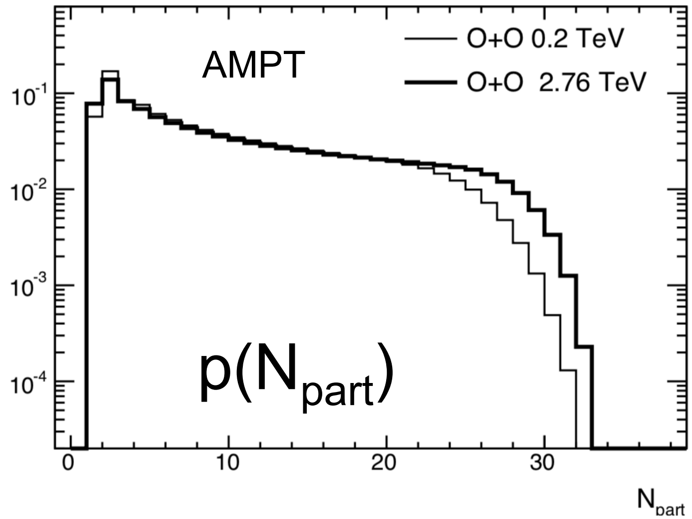




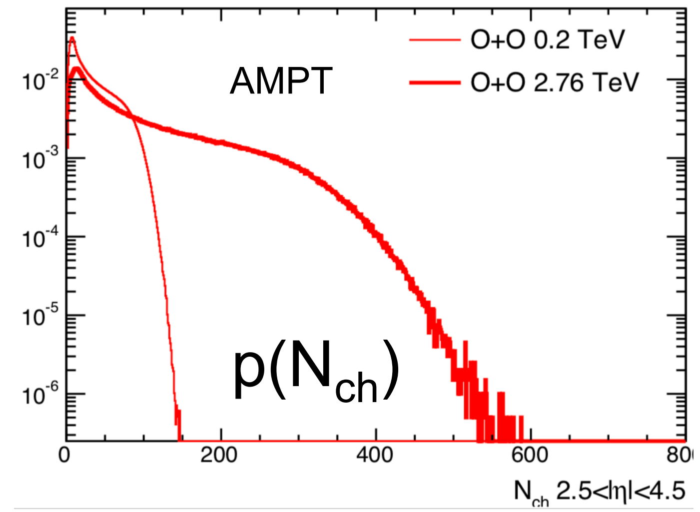
RHIC vs LHC energy-scan

- Similar Glauber geometry but different particle production

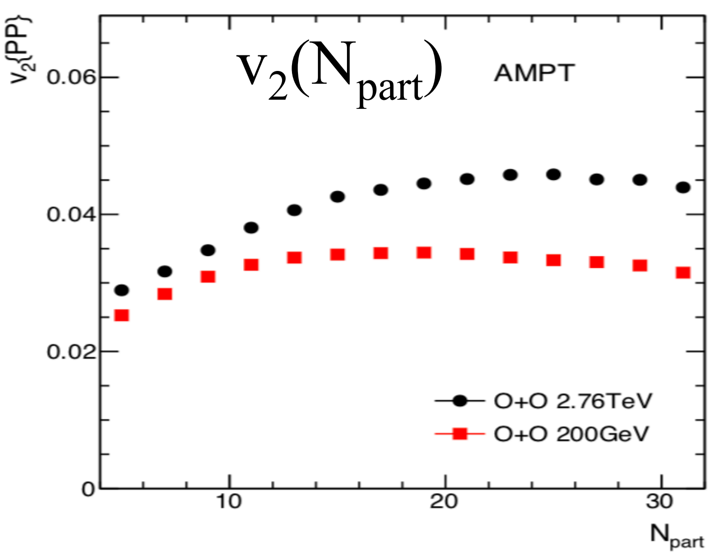
Glauber



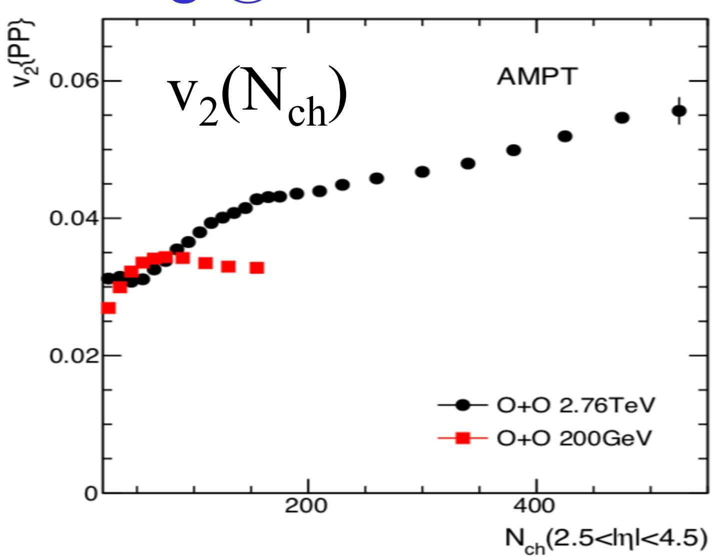
Glauber + fluctuations per nucleon



- Expect larger multiplicity/centrality smearing @LHC

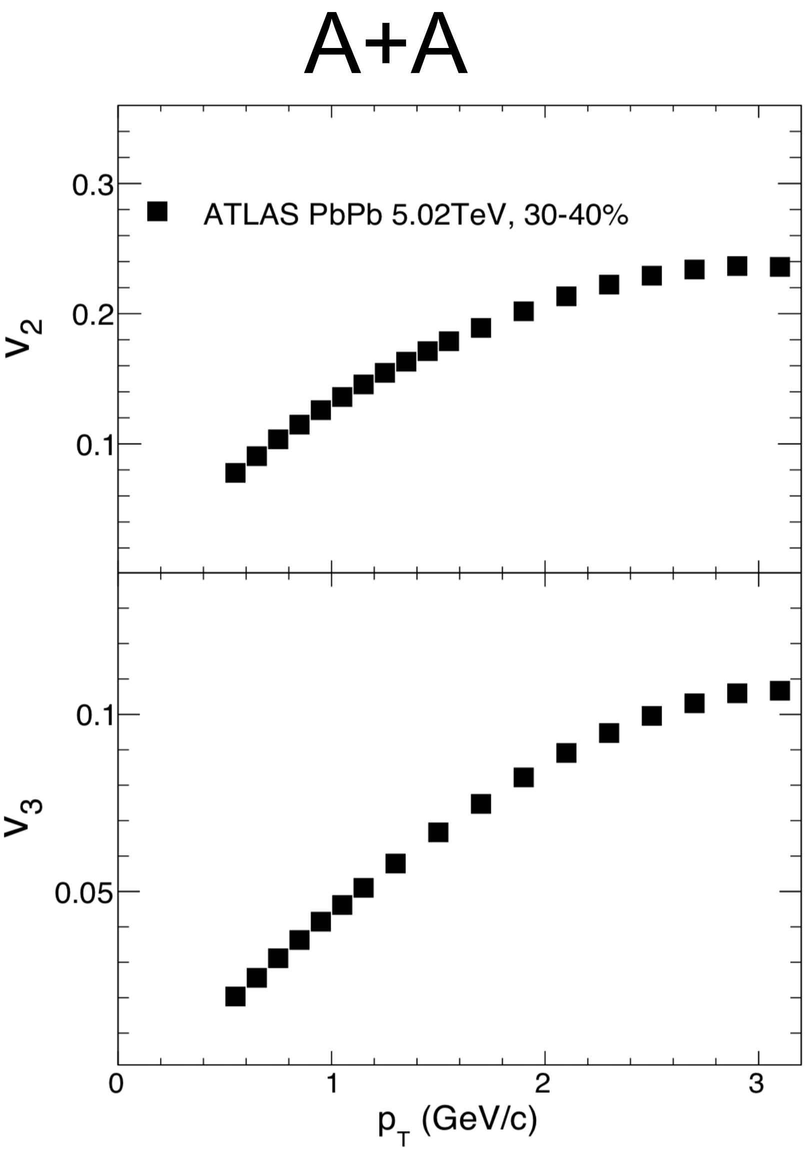


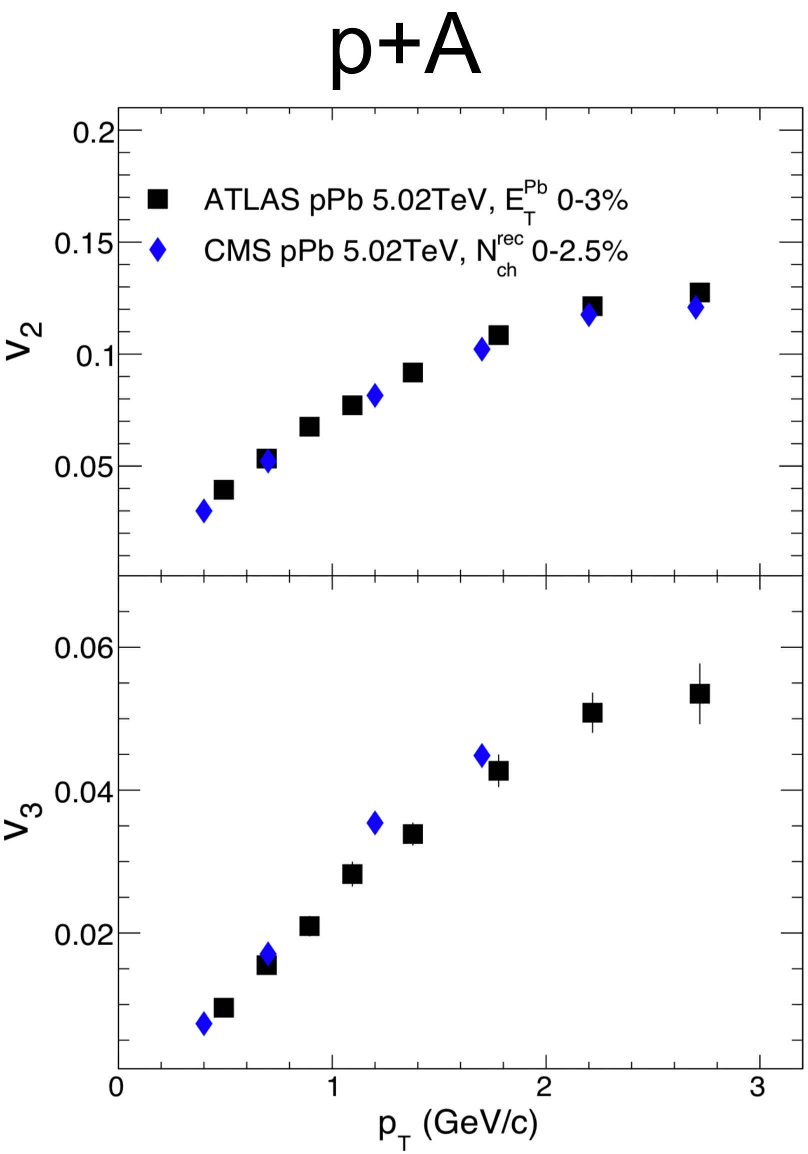
Largely geometry response



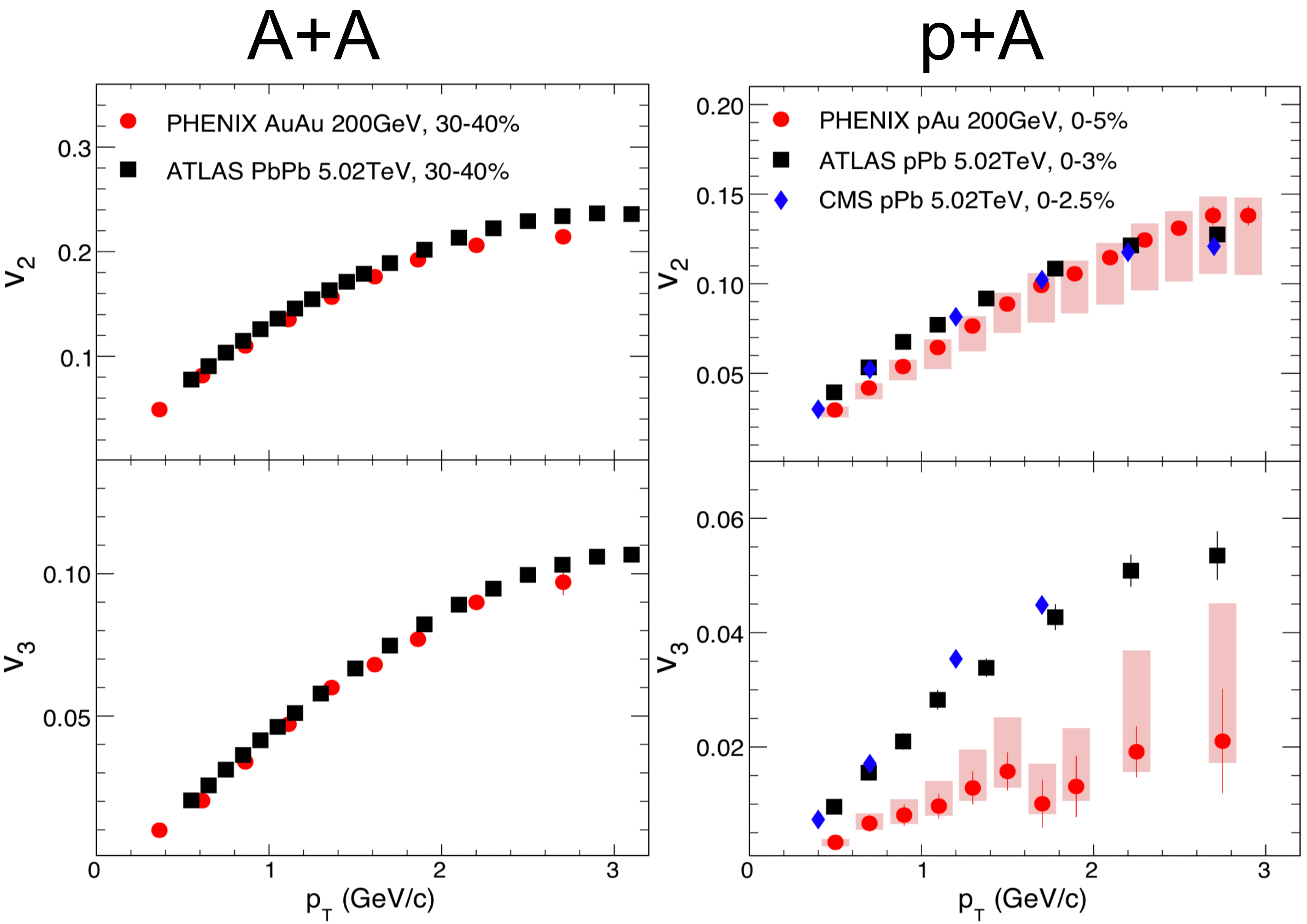
N_{ch} smeared by subnucleon/multiplicity fluctuation at larger $\sqrt{s}$

RHIC vs LHC energy-scan





RHIC vs LHC energy-scan



RHIC vs LHC energy-scan

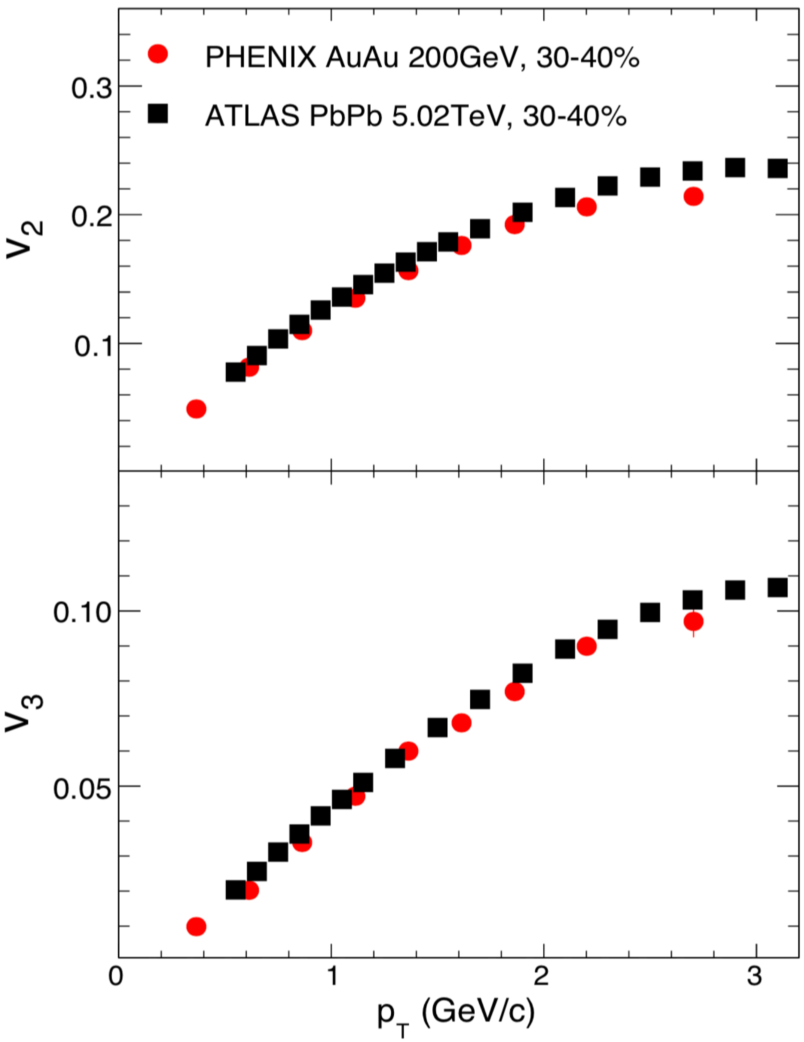
- $\sqrt{s}$-dependence of $v_3(p_T)$ in pA is different from large A+A !?

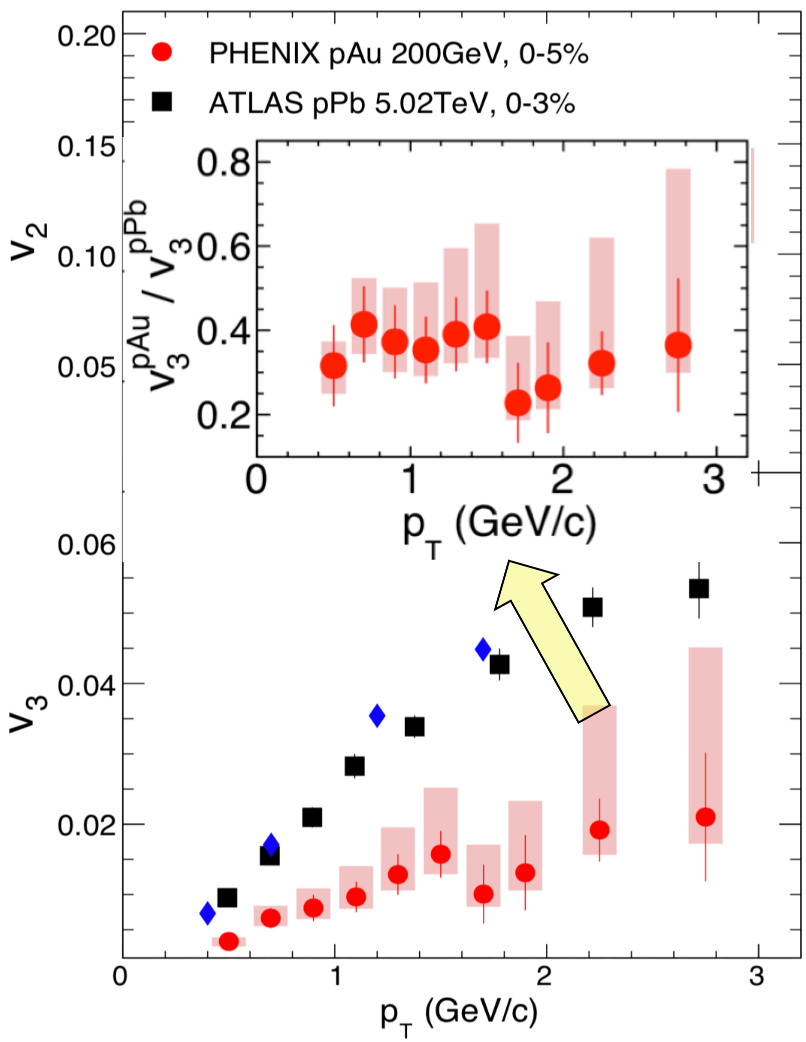
A+A

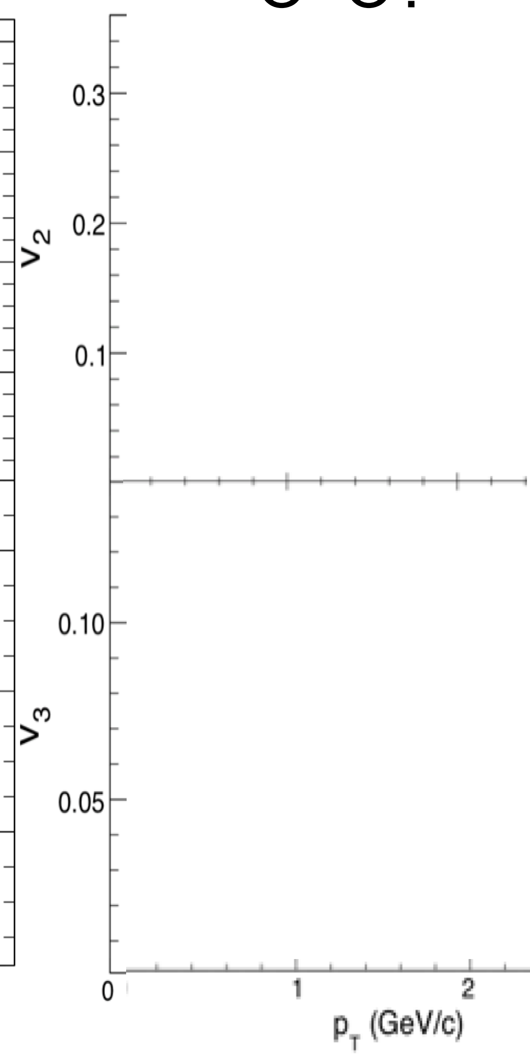
See 1904.10415

p+A

How about O+O?







Status of Geometry-Scan-I at RHIC

- Previous p/d/He+Au scan establish an active small-system program at RHIC at low $\sqrt{s}$, complementary to the LHC program at high $\sqrt{s}$.

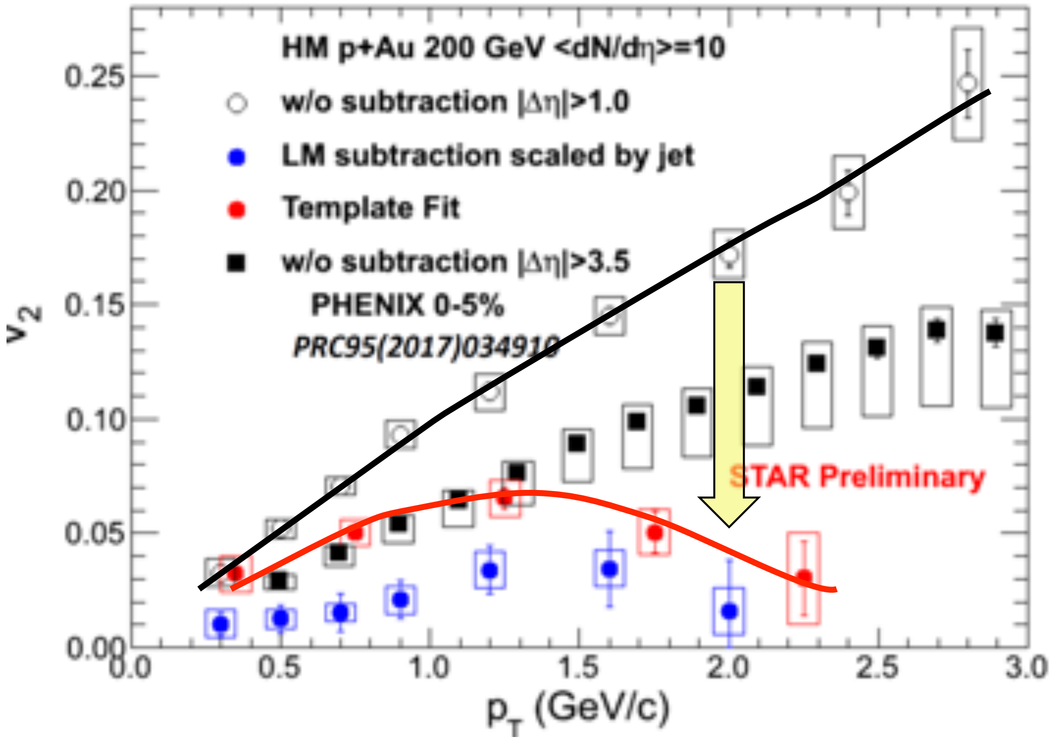
- But current PHENIX/STAR measurement limited by detector capability.
  - Mostly based on 2PC + non-flow subtraction
  - Longitudinal dynamics and how it affects existing measurements not understood
  - Large class of multi-particle observables not explored.

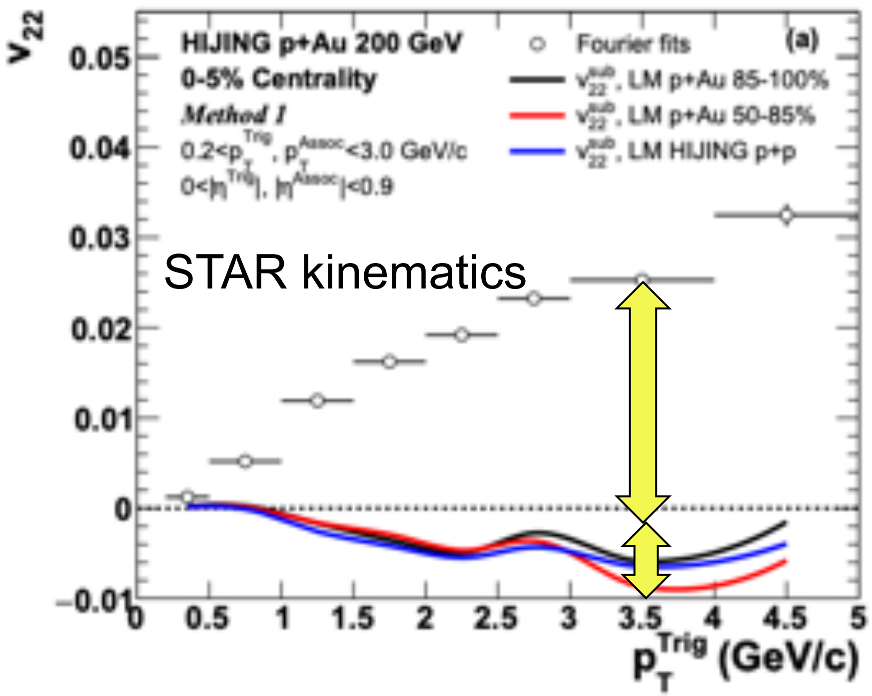
- Impossible to do apple-to-apple PHENIX/STAR comparison with existing data

Non-flow systematics

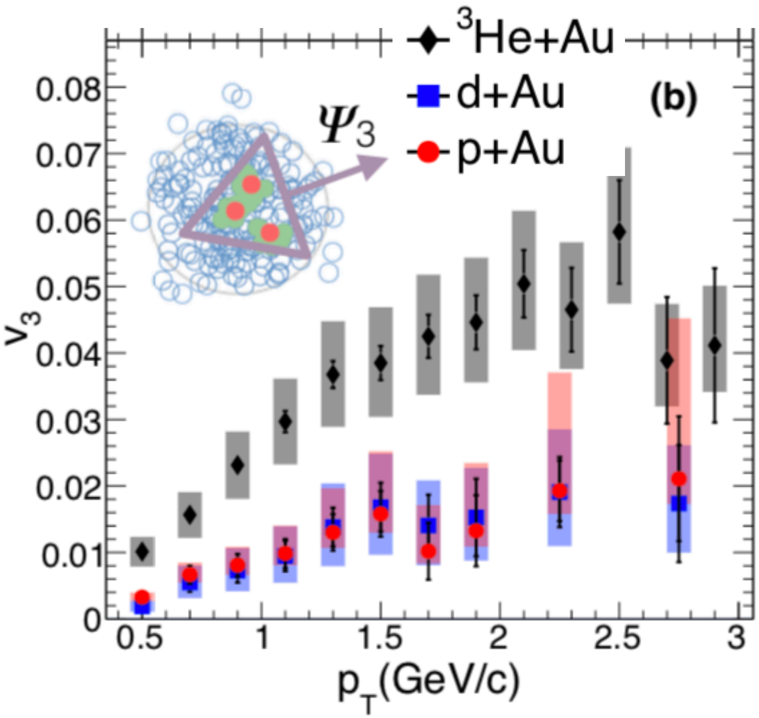
- STAR: Subtraction significantly reduces non-flow, but may lead to over-subtraction at high p_T (1902.11290)
- PHENIX: pAu non-flow could still be large.
  - Non-flow is smaller than STAR w/o subtraction, but not shown whether it is smaller than STAR w/ subtraction.
  - Closure test need to be done for PHENIX kinematics for a fair conclusion.

S. Lim, Q. Hu, R. Belmont, K.Hill, J.Nagle, D. Perepelitsa 1902.11290

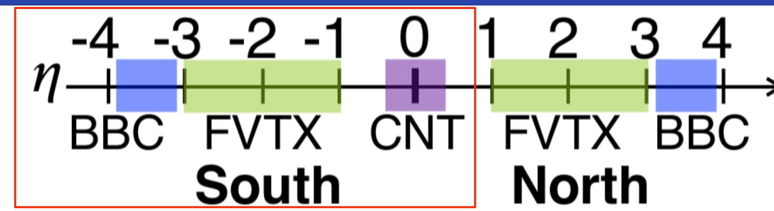




Longitudinal dynamics



1805.02973



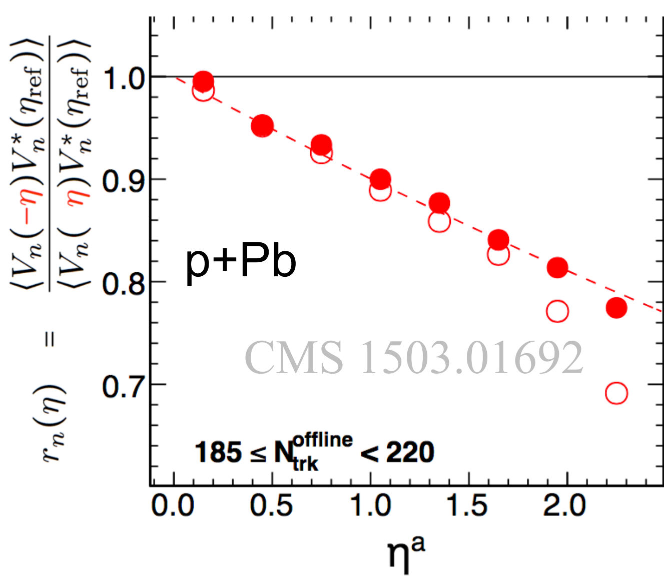
$$v_3 = \frac{\langle \cos(3(\phi - \psi_3)) \rangle}{R(\psi_3)}$$

$$R(\psi_3) = \sqrt{\frac{\langle \cos 3(\psi_3^{BBCS} - \psi_3^{FVTXS}) \rangle \langle \cos 3(\psi_3^{BBCS} - \psi_3^{CNT}) \rangle}{\langle \cos 3(\psi_3^{FVTXS} - \psi_3^{CNT}) \rangle}}$$

and central arms. The calculated resolutions are 6.7% and 5.7% in p+Au and d+Au collisions, respectively.

Why pAu reso is larger than dAu?

- Significant decorrelations effects not considered

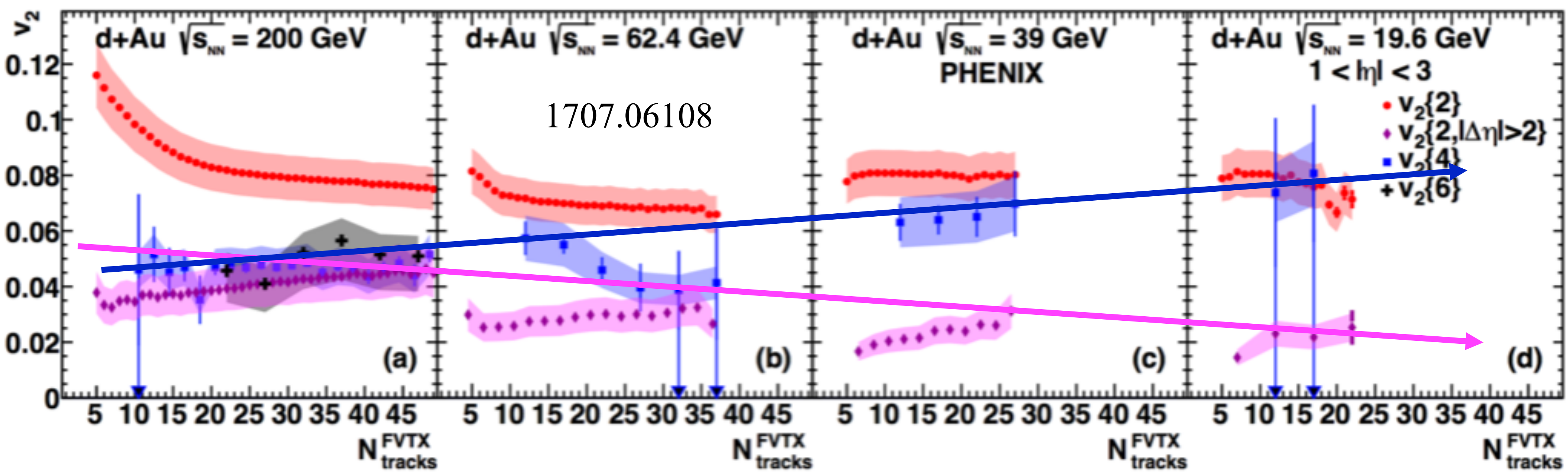


CMS 1503.01692

Could be 30% effects assuming scaling by beam rapidity

Status of multi-particle correlations

- Carry important information about EbyE fluctuations
- $v_2\{4\}$ and $v_2\{2\}$ change with beam energy in a non-trivial way.
  - Can hydro models compared with the 200 GeV $v_2\{2\}$ data describe these systematics? Personally don't know how to understand with either Hydro or initial state models)-:



No p_T information in these measurements

No multi-particle cumulants results in ^{3}HeAu and pAu collisions

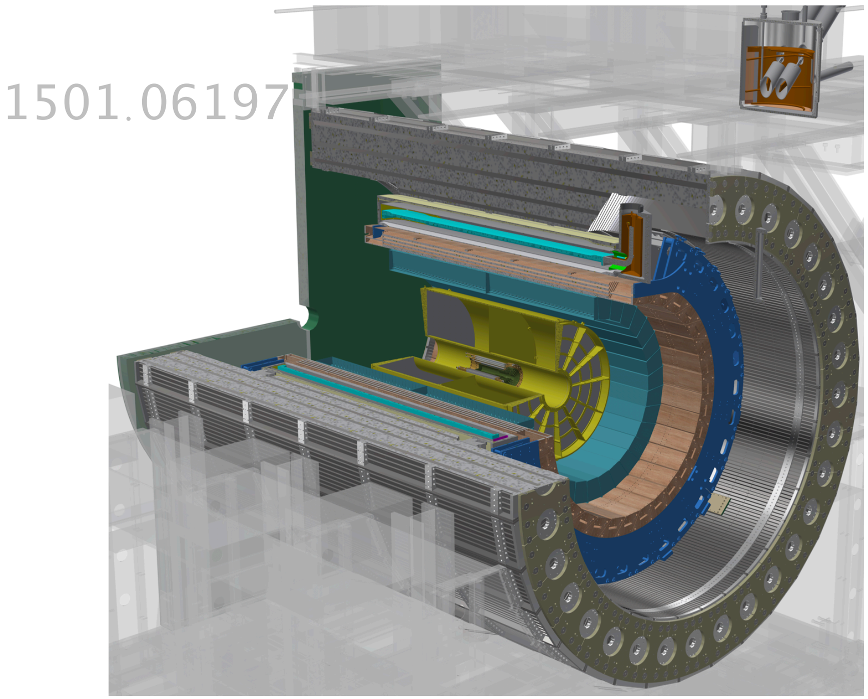
Further progress difficult w/o new data & large acceptance detector

What STAR/sPHENIX @ RHIC can offer in the future?

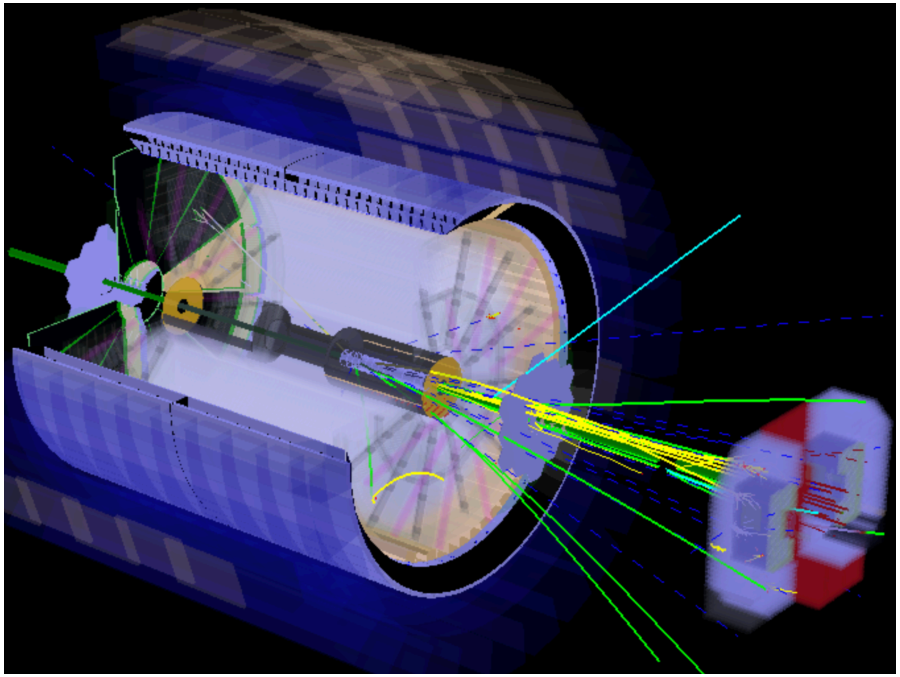
Prospect for future small system scan

- Opportunities with enhanced STAR acceptance/kinematics
  - New subsystems: iTPC ($|\eta|<1.5$, PID), EPD ($2.1<|\eta|<5$) and eTOF (2019+)
  - Forward upgrade with p_T, E_T, some ID (K_s,Λ,π^0) at $2.5<\eta<4$ (2021+)
- New sPHENIX detector (2023+)
- Complementarity between sPHENIX and STAR
  - sPHENIX:final-state effects via jet/heavy-probes+ collectivity, high rate.
  - STAR :bulk properties of collectivity + some hard-probes, large acceptance & PID.

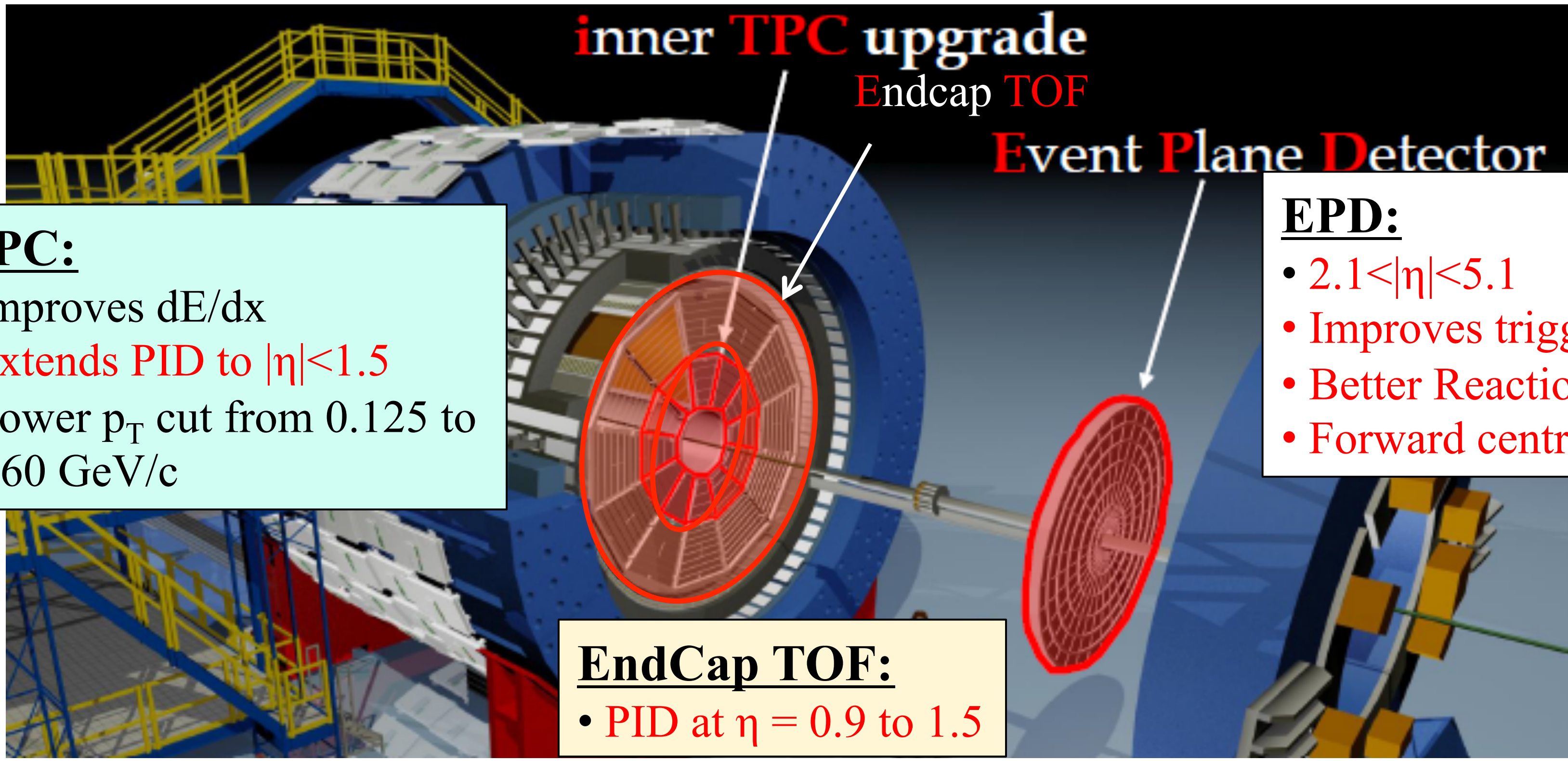
sPHEIX: HARD/Rare probes



STAR: Bulk sector



What present STAR detector can do



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

These three detectors haven't seen small system data

- Allow experimental definition of collectivity via two & multi-particle correlations
  - Explore all the observables and methods developed in A+A at RHIC/LHC

A dream scenario

50+ papers

Table 8: Summary of bulk observables or effects in Pb–Pb collisions, as well as in high multiplicity p–Pb and pp collisions at the LHC. References to ke measurements for the various observables and systems are given. See text for detail

HI-LHC HI yellow report: arXiv: 1812.06772

Observable or effect	Pb–Pb	p–Pb (high mult.)	pp (high mult.)	Refs.
Low p_T spectra ("radial flow")	yes	yes	yes	[47, 71, 317, 318, 654, 657, 663, 664, 667, 668]
Intermediate p_T ("recombination")	yes	yes	yes	[317, 657–663]
Particle ratios	GC level	GC level except Ω	GC level except Ω	[318, 638, 664, 665]
Statistical model	$\gamma_s^{GC} = 1$, 10–30%	$\gamma_s^{GC} \approx 1$, 20–40%	MB: $\gamma_s^{C} < 1$, 20–40%	[318, 638, 669]
HBT radii ($R(k_T)$, $R(\sqrt[3]{N_{ch}})$)	$R_{out}/R_{side} \approx 1$	$R_{out}/R_{side} \lesssim 1$	$R_{out}/R_{side} \lesssim 1$	[670–677]
Azimuthal anisotropy (v_n) (from two particle correlations)	v_1–v_7	v_1–v_5	v_2–v_4	[48, 312–314, 632, 633, 652, 678–688]
Characteristic mass dependence	v_2–v_5	v_2, v_3	v_2	[48, 315, 326, 683, 686, 689–691]
Directed flow (from spectators)	yes	no	no	[692]
Charge-dependent correlations	yes	yes	yes	[249, 253, 254, 693–696]
Higher-order cumulants (mainly $v_2\{n\}, n \geq 4$)	"$4 \approx 6 \approx 8 \approx$ LYZ" +higher harmonics	"$4 \approx 6 \approx 8 \approx$ LYZ" +higher harmonics	"$4 \approx 6$"	[316, 683, 688, 697–708]
Symmetric cumulants	up to SC(5, 3)	only SC(4, 2), SC(3, 2)	only SC(4, 2), SC(3, 2)	[227, 687, 709–712]
Non-linear flow modes	up to v_6	not measured	not measured	[713]
Weak η dependence	yes	yes	not measured	[685, 707, 714–719]
Factorization breaking	yes ($n = 2, 3$)	yes ($n = 2, 3$)	not measured	[682, 684, 720–722]
Event-by-event v_n distributions	$n = 2$–4	not measured	not measured	[723–725]
Direct photons at low p_T	yes	not measured	not observed	[544, 726]
Jet quenching through dijet asymmetry	yes	not observed	not observed	[348, 360, 374, 727–729]
Jet quenching through R_{AA}	yes	not observed	not observed	[323, 344, 346, 347, 352, 730–737]
Jet quenching through correlations	yes (Z–jet, γ–jet, h–jet)	not observed (h–jet)	not measured	[354, 357, 375, 376, 380, 388, 733, 738–740]
Heavy flavor anisotropy	yes	yes	not measured	[262, 326, 460–464, 497, 741–745]
Quarkonia production	suppressed†	suppressed	not measured	[262, 454, 456, 459, 478, 479, 491, 492, 494, 495, 497, 579, 746–755]

A small system program in place until 2028+

Do this in parallel with LHC but with more flexibility in species!

The full proposal (under discussion)

- A short run of $^{16}O+^{16}O$ before or concurrent with LHC.
  - Comparison with LHC: same geometry but different initial flow
  - Motivate & strengthen case for future small system scan at RHIC.
  - Own virtue: detailed study via updated STAR detector the IS & FS effects.

also HBT, alpha cluster etc

P. Bozek, W. Broniowski PRL 112 (2014) 112501, PRC 97, 034912 (2018)
Zhiwan Xu et al, Nucl.Sci.Tech. 29 (2018) 186

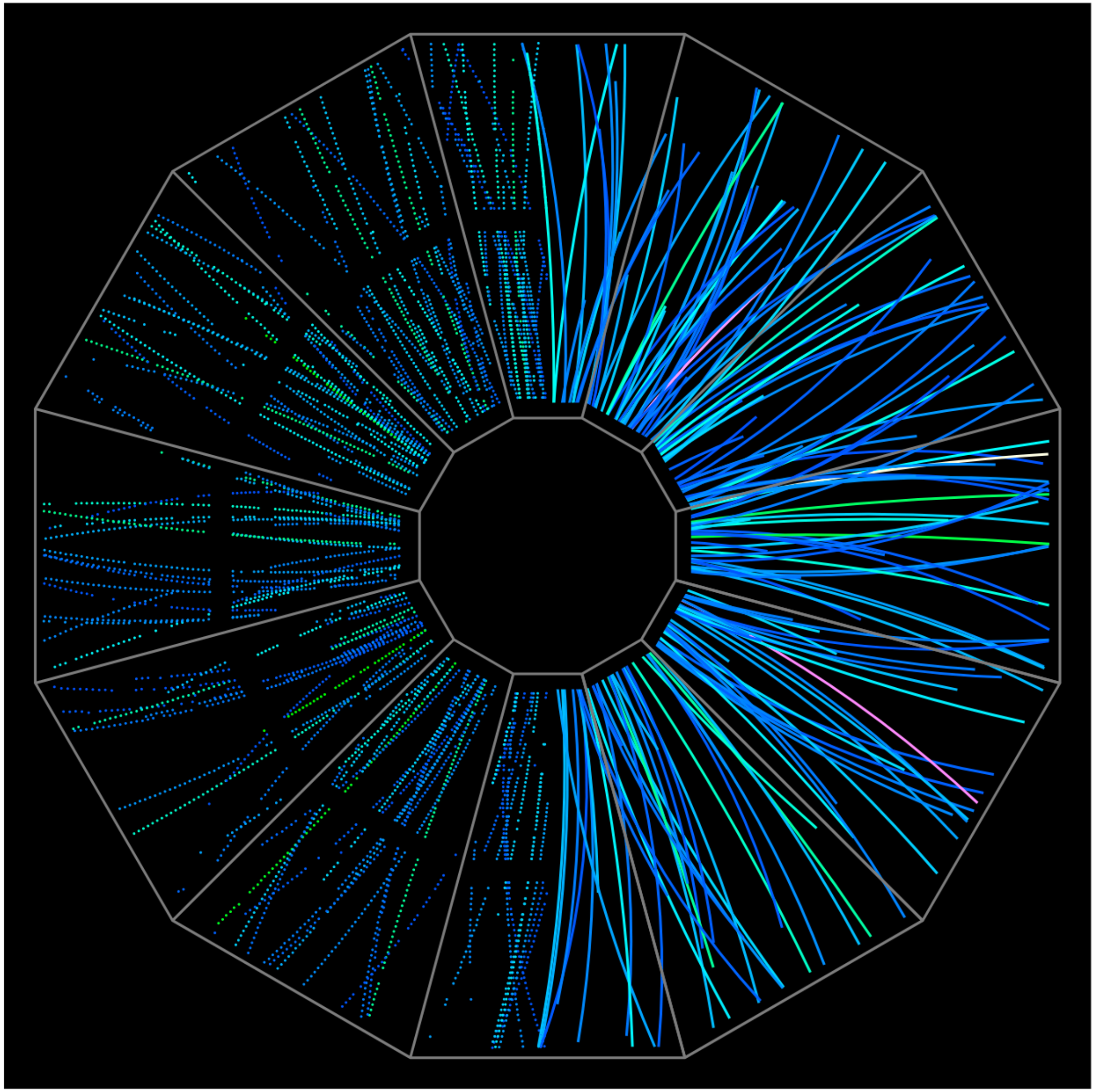
- If possible, commission trigger strategy in cold QCD (pp500GeV)
  - Minbias and High-multiplicity triggers with low-pileup.
  - Interesting physics with limited dataset: ridge in 500 GeV pp?

- Possible scan of asymmetric & small symmetric systems (2023+).
  - Fully benefit from the STAR Forward upgrade (occupancy not an issue)
  - Complementary to sPHENIX:
    - sPHENIX : Final-state effects via jet/heavy-probes + collectivity, high rate.
    - STAR: bulk properties of collectivity + some hard-probes, large acceptance & PID.

A STAR proposal for O+O in 2020/2021

The STAR Beam Use Request for Run-20 and Run-21

The STAR Collaboration



May 15, 2019

A STAR proposal for O+O in 2020/2021

Table 2: Proposed Run-20 assuming 28 cryo-weeks, including five weeks of LEReC commissioning, an initial one week of cool-down and a one week set-up time for each collider energy.

2020

Single-Beam Energy (GeV/n)	$\sqrt{s_{NN}}$ (GeV)	Run Time	Species	Events (MinBias)	Priority	Sequence
5.75	11.5	9.5 weeks	Au+Au	230M	1	1
4.55	9.1	9.5 weeks	Au+Au	160M	1	3
19.5	6.2 (FXT)	2 days	Au+Au	100M	2	5
13.5	5.2 (FXT)	2 days	Au+Au	100M	2	6
5.75	3.5 (FXT)	2 days	Au+Au	100M	2	2
4.55	3.2 (FXT)	2 days	Au+Au	100M	2	4
3.85	3.0 (FXT)	2 days	Au+Au	100M	2	7
100	200	1 week[2]	O+O	400M 200M (central)	3	8

Table 4: Proposed Run-21 assuming 20 cryo-weeks, including an initial one week of cool-down and a one week set-up time for each collider energy.

2021

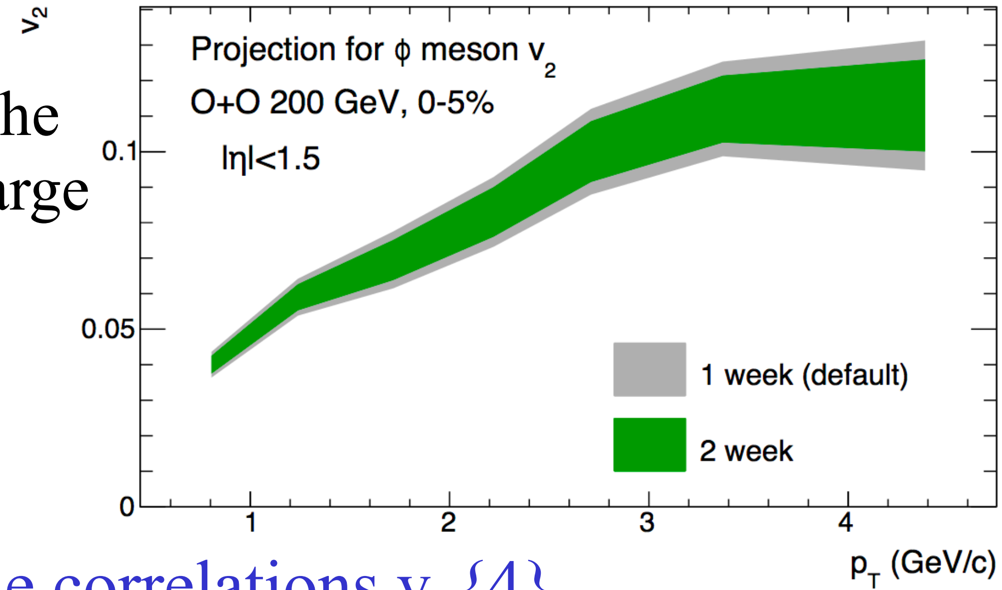
Single-Beam Energy (GeV/n)	$\sqrt{s_{NN}}$ (GeV)	Run Time	Species	Events (MinBias)	Priority	Sequence
3.85	7.7	12 weeks	Au+Au	100M	1	1
8.35	16.7	5 weeks	Au+Au	250M	2	2
100	200	1 week[4]	O+O	400M 200M (central)	2	3

Assume one week low pileup, 20kHz constant collision rate
12hour/day,2kHz data rate, 2/3 for minbias 1/3 for 0-5% central.
Central triggers based on TPC (|η|<1.5) or EPD (2<|η|<5)

Physics potential

- PID (pi,k, p, ϕ) v_2 and v_3 vs N_{ch} and p_T.

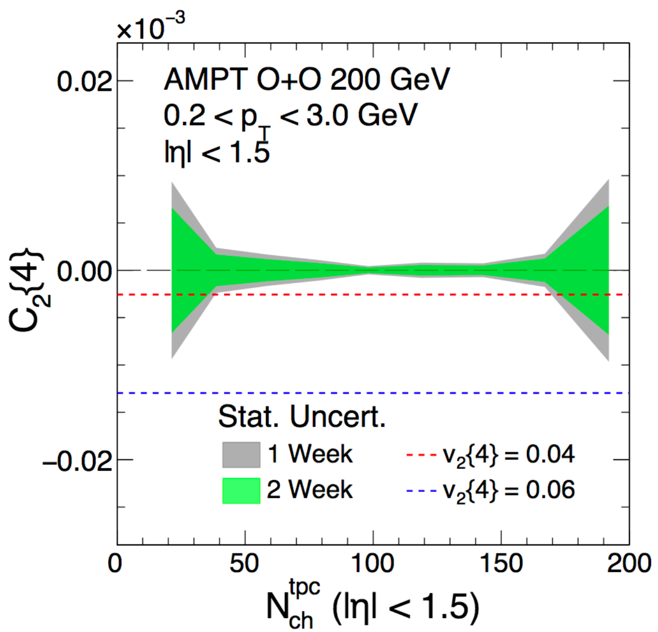
Assume $v_{2,\varphi}$ same as $v_{2,h}$ in pAu. Scales the φ $v_2(p_T)$ in peripheral AuAu to match charge v_2 in pAu, accounting for differences in ⟨Npart⟩, EP- reso., and N_{events}

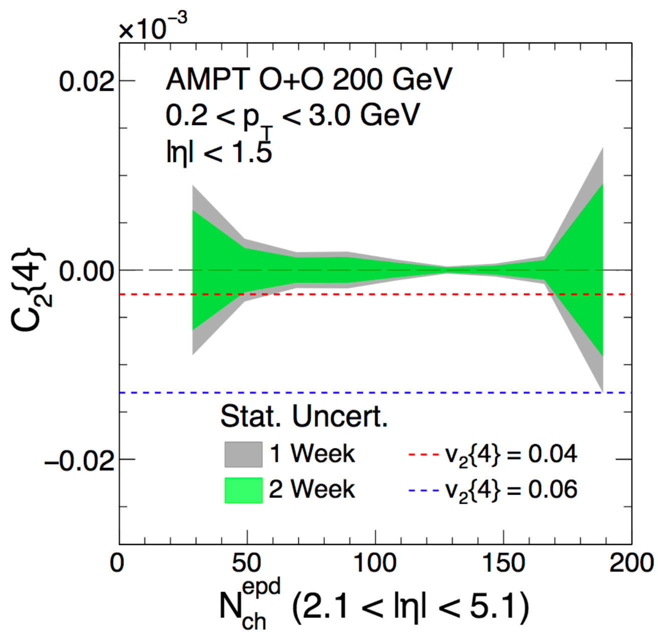


- Decent measurement of four-particle correlations $v_2\{4\}$

Assume $v_2\{4\}$ in similar to dAu, which is 4-6%

1707.06108





Latest news from LHC Program Committee

15

Next Steps for Oxygen Run

- No show stoppers found for having Oxygen in LHC
  - Will require significant preparations and beam time in injectors, so would need to make request for preparations to start
- Possible bunch intensities seem more than sufficient to satisfy original luminosity requests for O-O and p-O
  - Potential for order of magnitude more at little cost (TBC)
- Possible, very rough, LHC beam time estimate:
  - 2-3 days for setup including validation
  - 1 day O-O running
  - 1 day p-O running
  - 2 day contingency

i.e. would be usual <1 week special run

- Injectors would strongly prefer run in 2023 and not 2022
  - They might need to continue commissioning Pb slip-stacking in 2022

LHCb and LHCf have expressed strongest interest in pO, while ALICE/ATLAS/CMS more interested in O-O

Experiments still prefers 2022

https://indico.cern.ch/event/820221/

Summary

- Further understanding origin of collectivity require disentangling contributions from different stages
  - Initial state, non-equilibrium transport, and fluid dynamics.
- A scan of small (A)symmetric systems at RHIC + new detector capabilities could disentangle the three contributions.
  - Study shape, size, density dependence of collectivity.
  - EbyE fluctuations are different: multi-particle correlations.
  - Property of medium via jet quenching and other final state effects.
- Complementarity and synergy with the LHC small system program.
  - Further constrain three scenarios, also nucleon vs subnucleon fluctuations

- STAR propose a short O+O run in 2020/2021.
  - Motivate & strengthen case for future possible small system scan 2021+

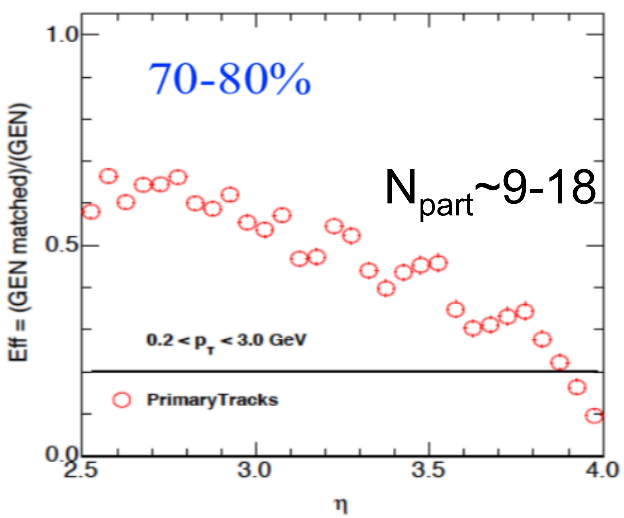
Backup

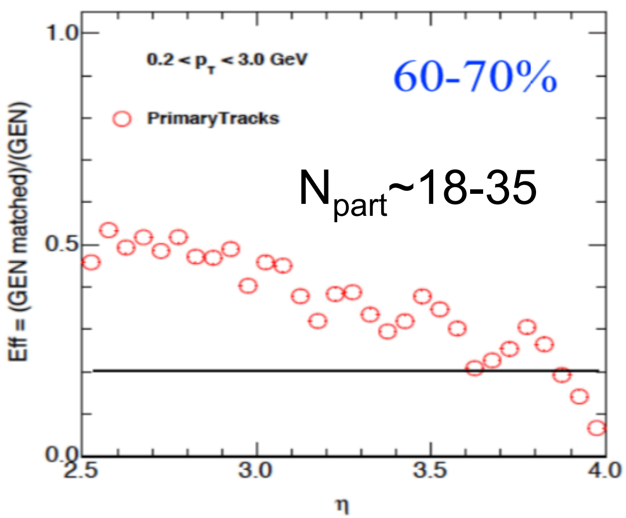
How STAR forward upgrade perform in small system

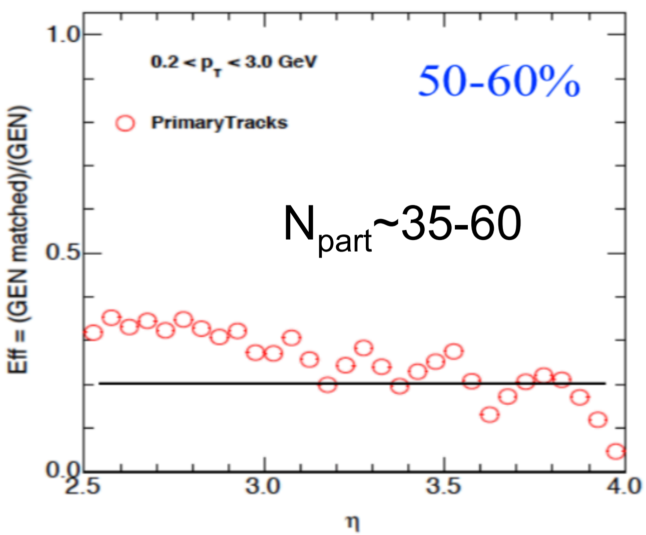
- Provide p_T and E_T differential info on particles, PID ($\Lambda/K_s/\pi^0$) possible
  - Properties of small systems at lower T: proxy for √s scan.
  - Detailed exploration of longitudinal dynamics (stronger in small system)

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 $^{32}S+^{32}S$







Performance can be further improved