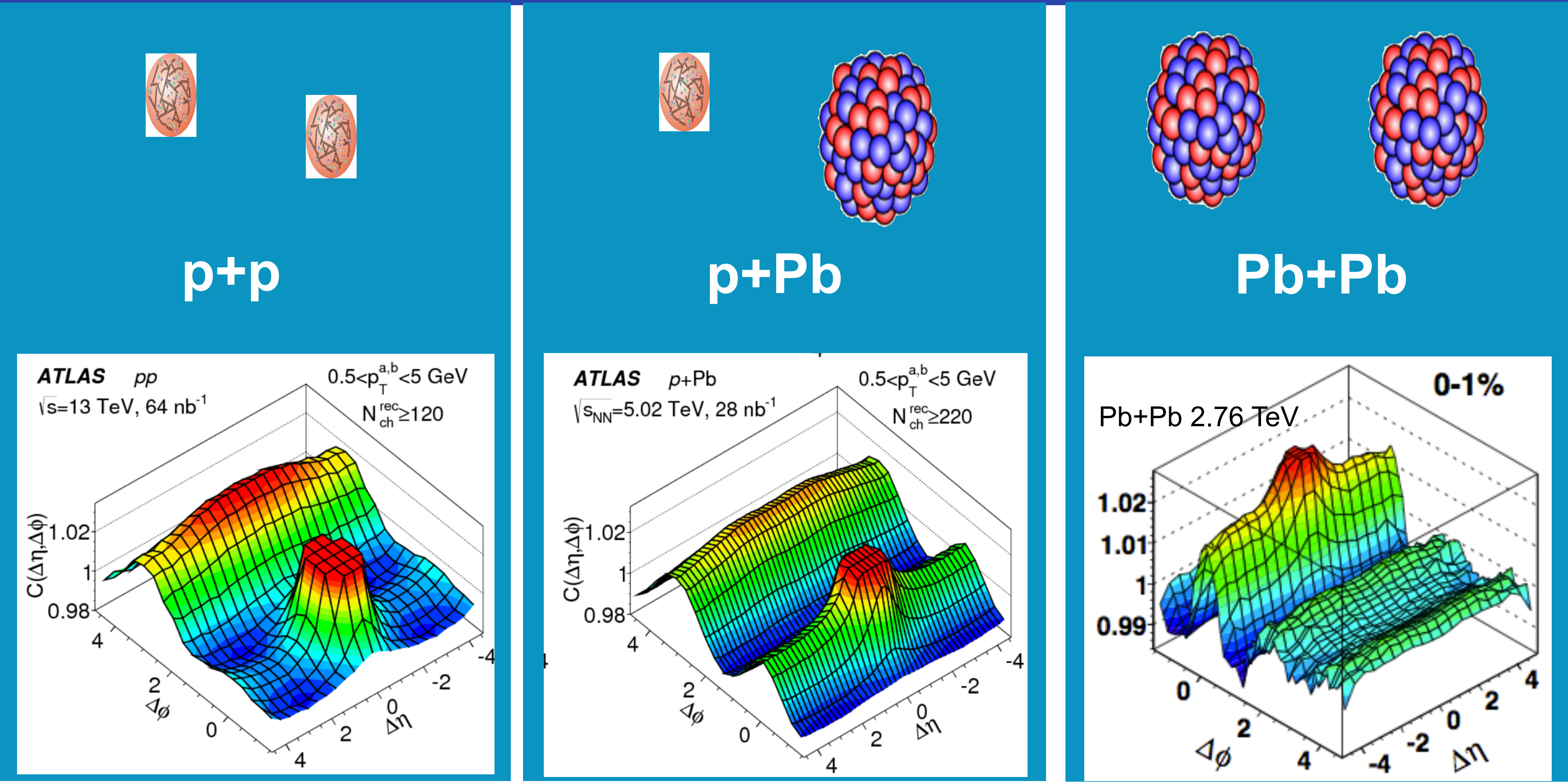
Stony Brook University | The State University of New York

"Long-range collectivity" in small systems

Jiangyong Jia, BNL and Stony Brook University

- What is collectivity?
- How to distinguish initial vs final state effects ?
- How are cumulants related to collectivity?

Long-range collectivity in different systems

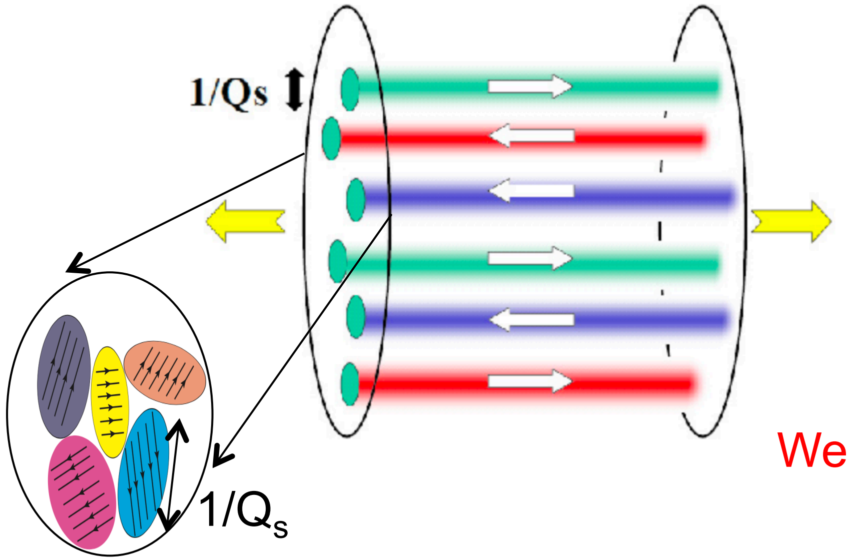


- Long-range correlation in momentum space comes
  - directly from early time t~0 (CGC)
  - or it is a final state response to spatial fluctuation at t=0 (hydro).

What is the timescale for emergence of collectivity?

Examples of initial vs final state scenarios

CGC



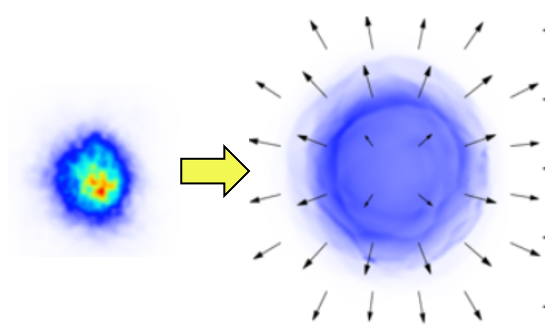
Domain of color fields of size $1/Q_s$, each produce multi-particles correlated across full η.

Uncorr. between domains, strong fluct. in Q_s

More domains, smaller v_n, more Q_s fluct, stronger v_n

Well motivated model framework, lack systematic treatment

Hydro



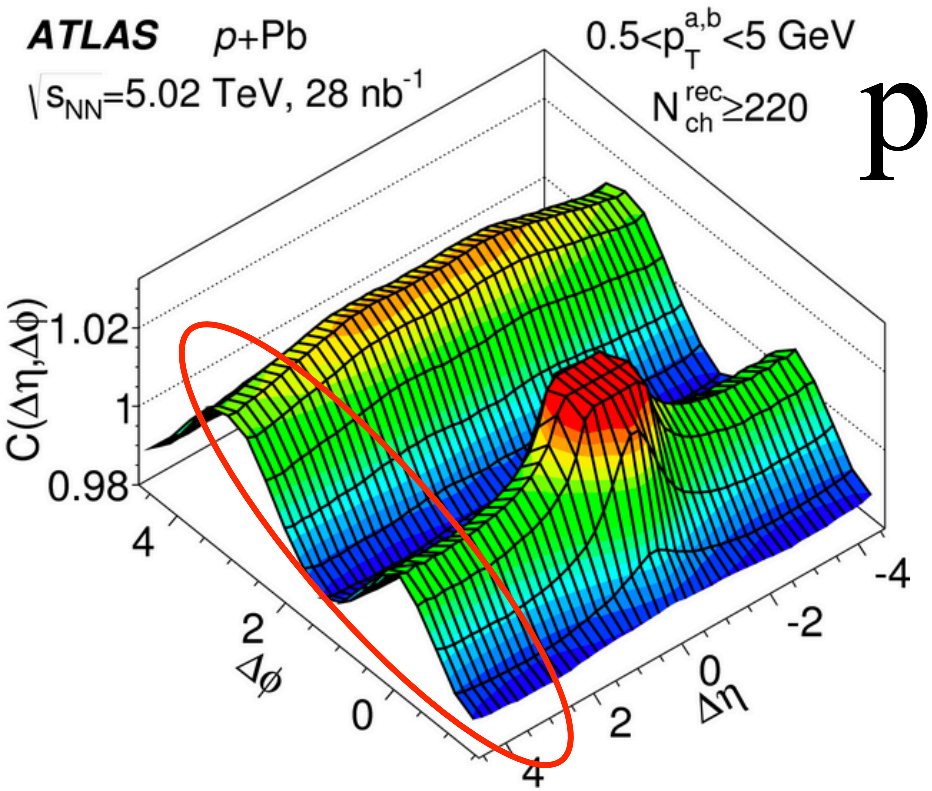
Hot spots (domains) in transverse plane e.g IP-plasma, boost-invariant geometry shape

Expansion and interaction of hot spots generate collectivity

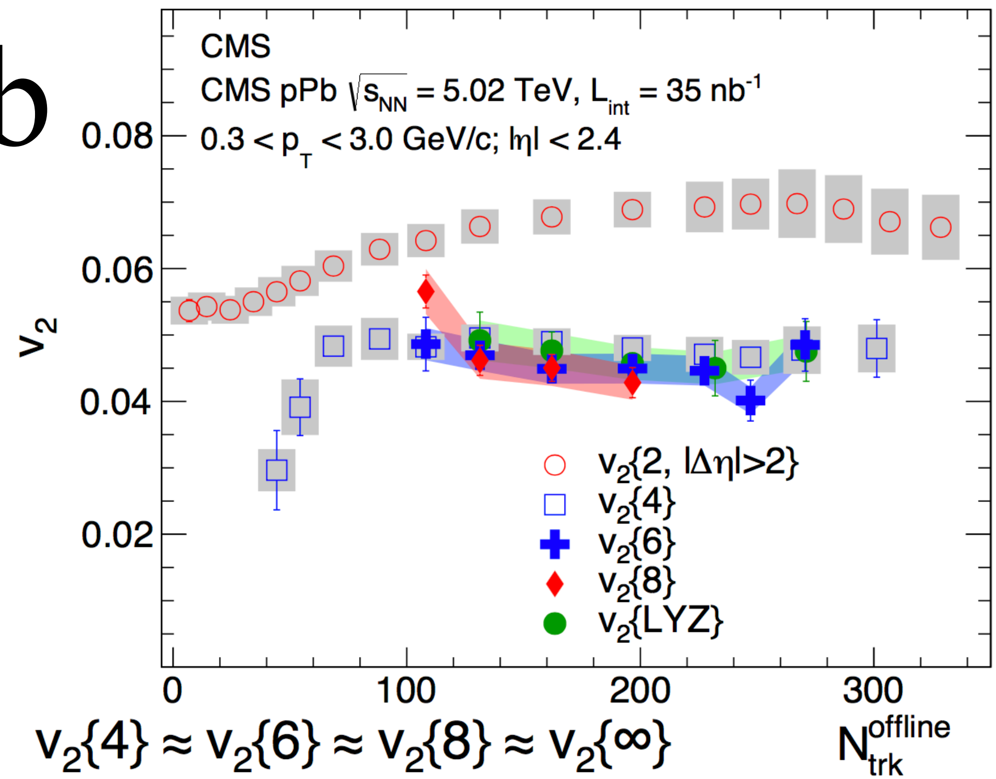
v_n depends on distribution of hot spots (ε_n) and transport properties.

Ongoing debate whether hydro is applicable in small systems

Features of collectivity in HM pPb



pPb

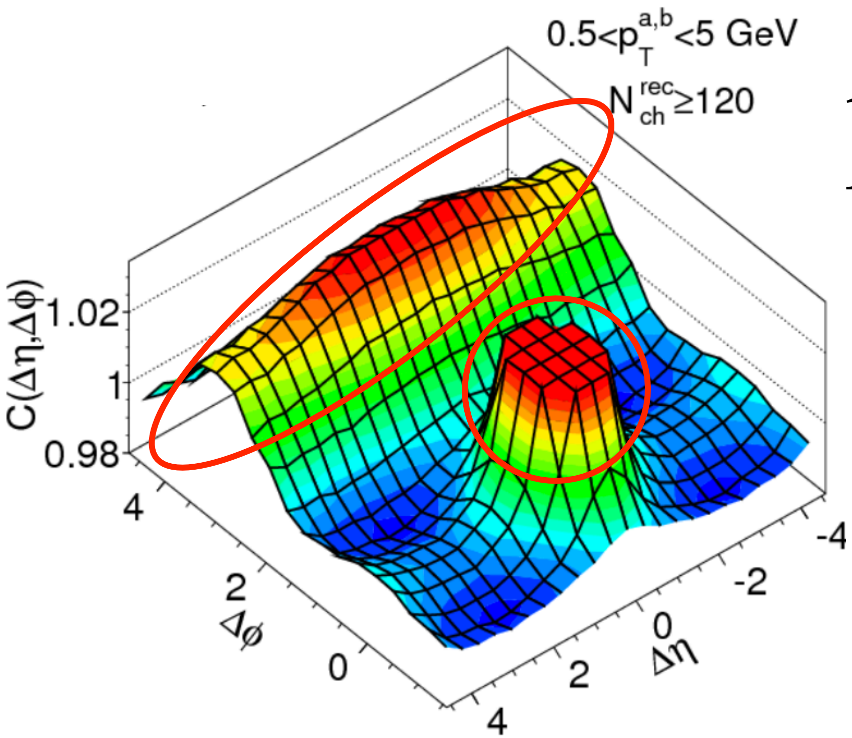


$v_2\{4\} \approx v_2\{6\} \approx v_2\{8\} \approx v_2\{\infty\}$

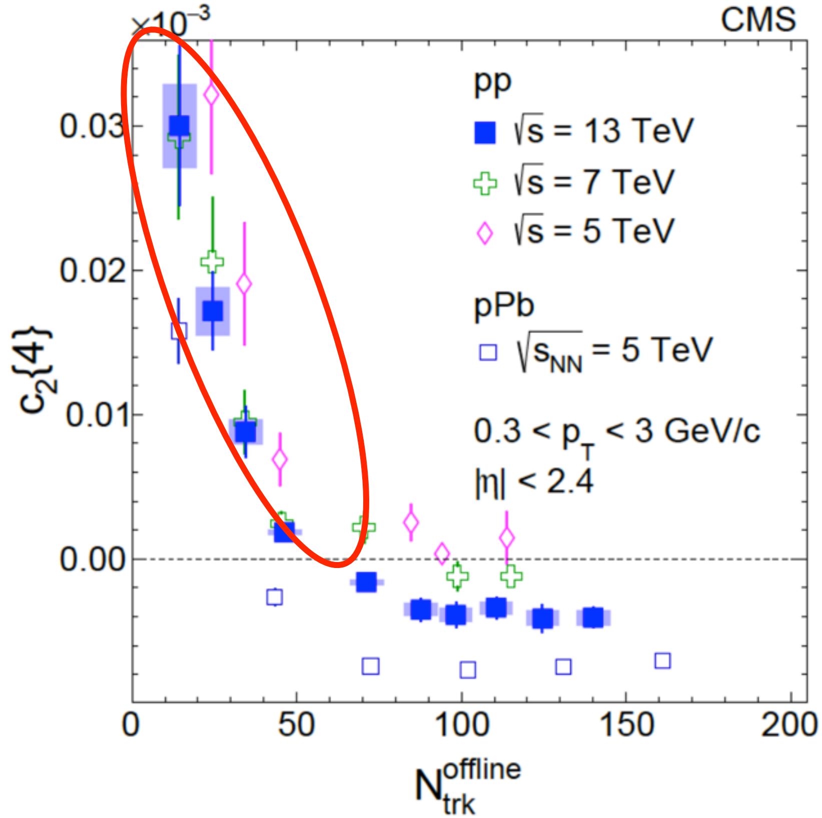
Long-range in η

Multi-particle signals

Features of collectivity in HM pp



pp



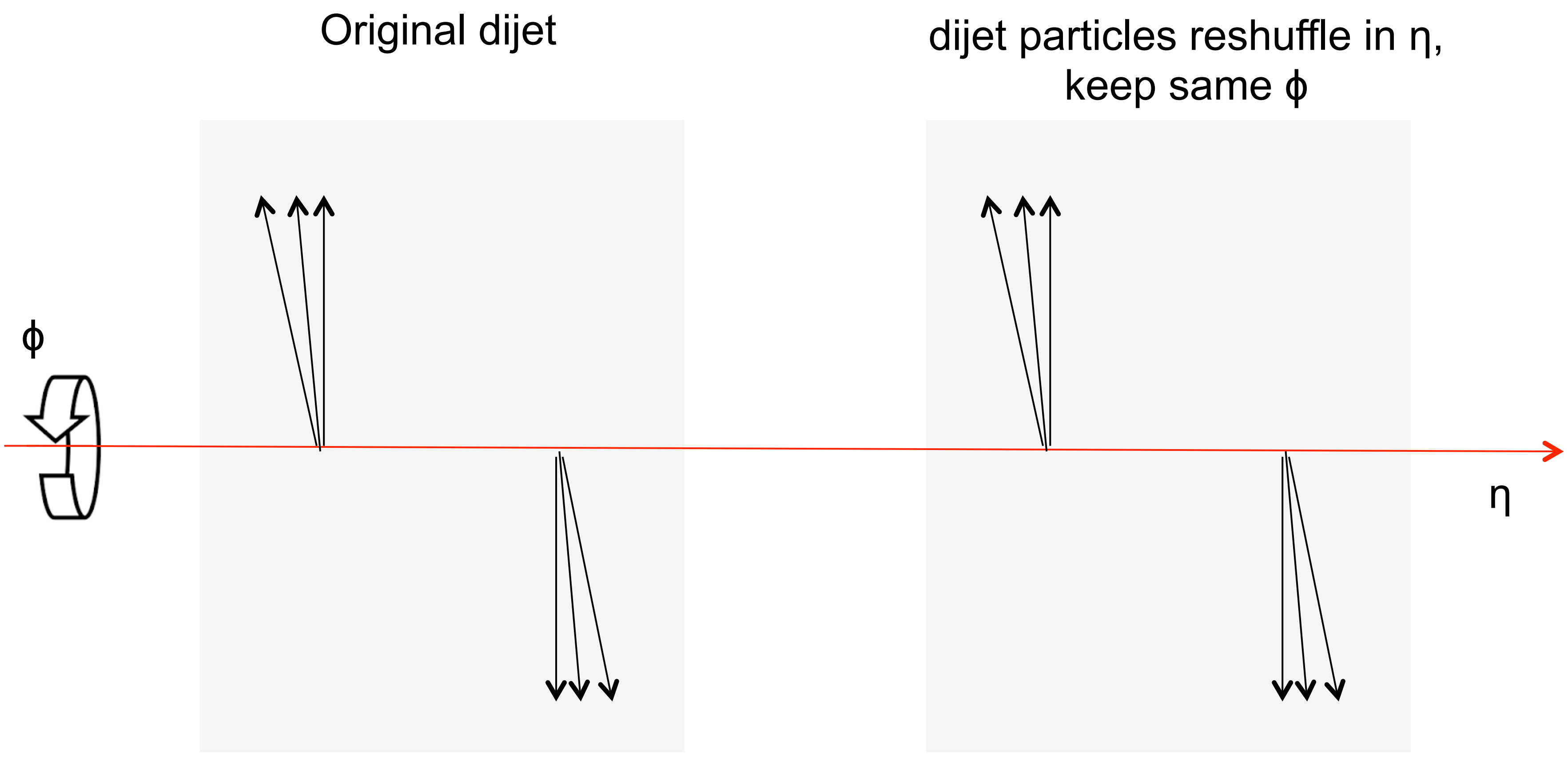
Long-range in η

Multi-particle signals

Non-flow can generate long-range (away-jet) or multi-particle correlation (fragmentation) but not both

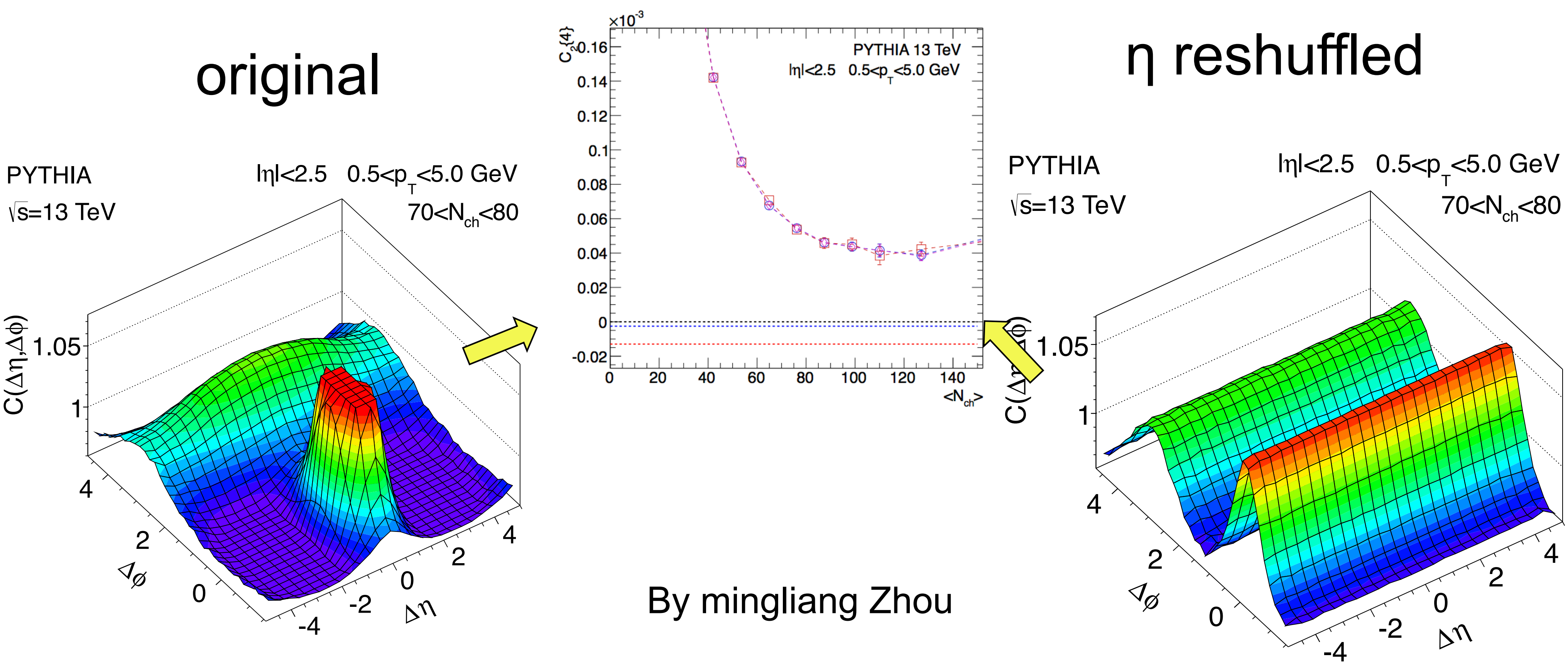
Collectivity must mean both

Azimuthal correlation from collectivity



They give the same flow coefficient $c_n\{4\}$ and $v_n\{4\}$, although clearly the first case is non-flow and the second case would be classified as flow

Azimuthal correlation from collectivity



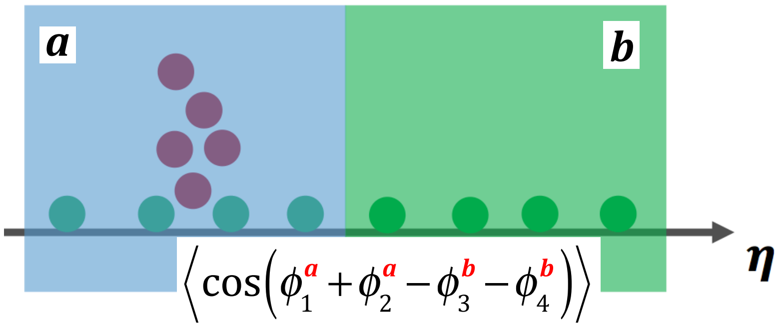
They give the same flow coefficient $c_n\{4\}$ and $v_n\{4\}$, although clearly the first case is non-flow and the second case would be classified as flow

Azumuthal corr. alone can’t distinguish flow & non-flow.

Long-range collectivity via subevent cumulants

arXiv:1701.03830

Event with jet

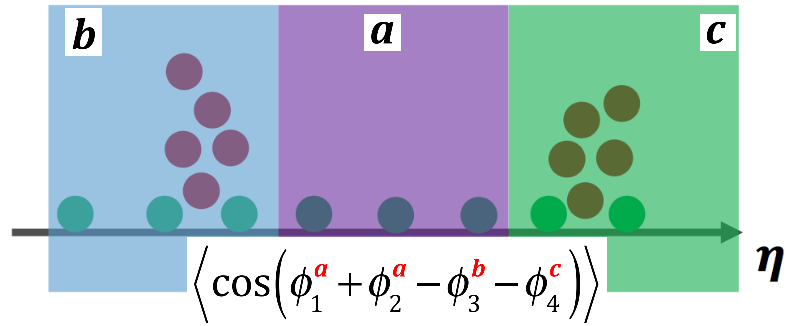


$$\left\langle \cos\left(\phi_1^a + \phi_2^a - \phi_3^b - \phi_4^b\right)\right\rangle$$

2 sub-event

removes intra-jet correlations

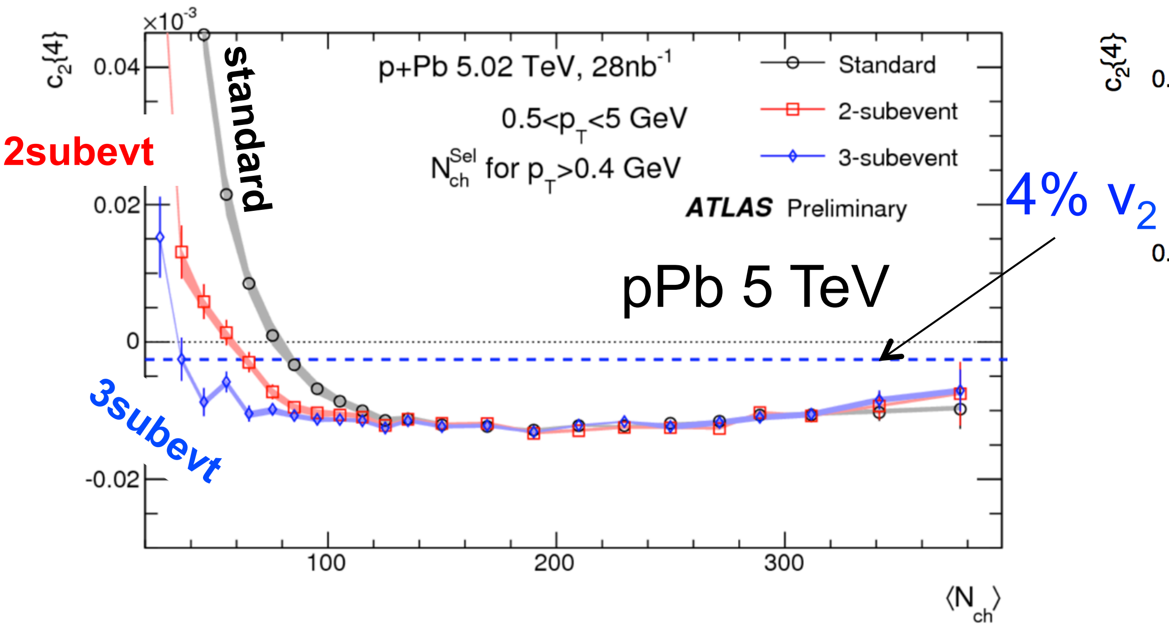
Event with dijet

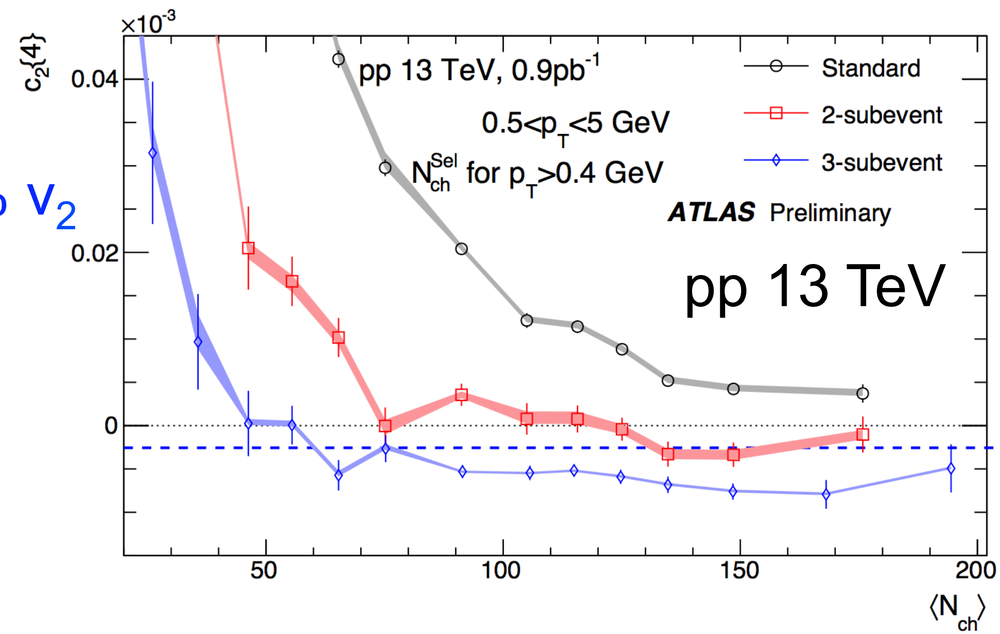


$$\left\langle \cos\left(\phi_1^a + \phi_2^a - \phi_3^b - \phi_4^c\right)\right\rangle$$

3 sub-event

removes inter-jet correlations





pPb: methods consistent for N_{ch}>100, but split below that

pp: Only subevent method gives reliable negative $c_2\{4\}$ in broad range of N_{ch}

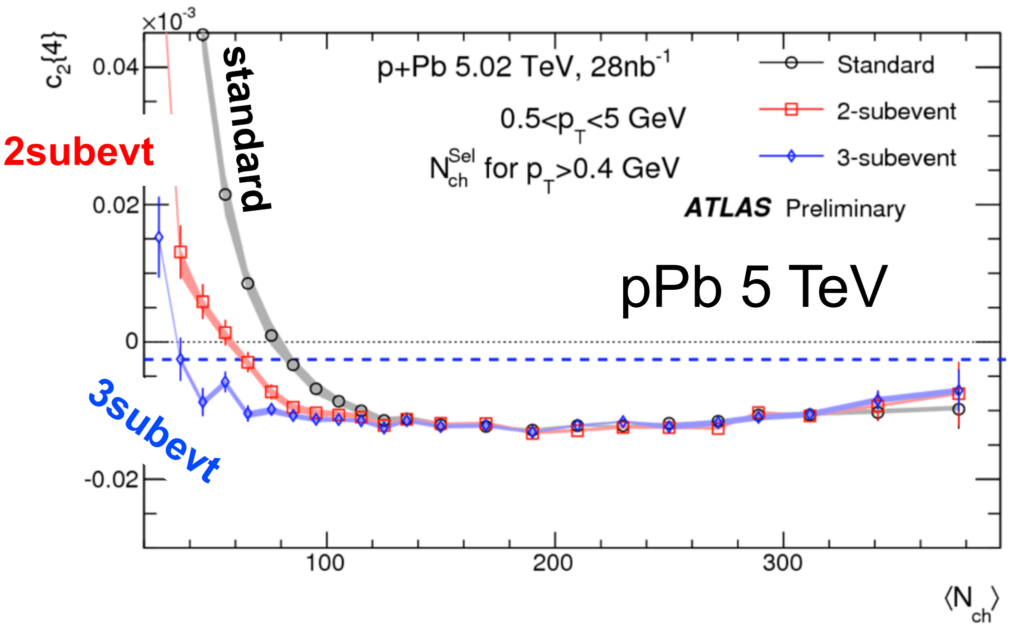
Sign-change of $c_2\{4\}$

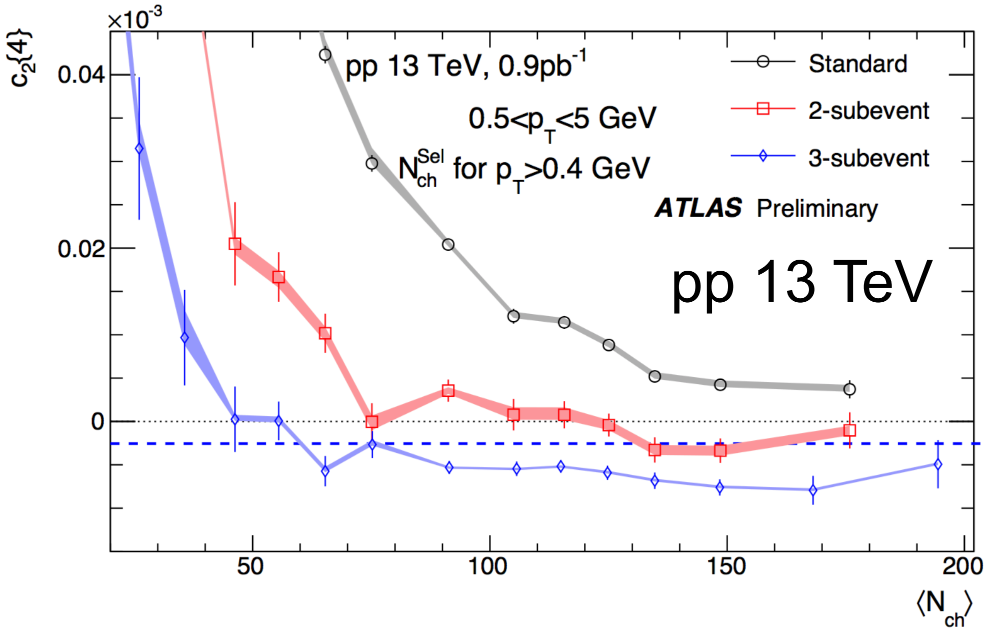
- Most positive $c_2\{4\}$ in standard cumulants are jets and dijets.
  - Remaining positive $c_2\{4\}$ in 3-subevent due to residual dijets.
- CGC expect sign-change at low N_{ch}

Dumitru,McLerran,Skokov

$$c_2\{4\} = \frac{1}{N_D^3}\left(\frac{1}{4(N_c^2-1)^3} - A^4\right)$$

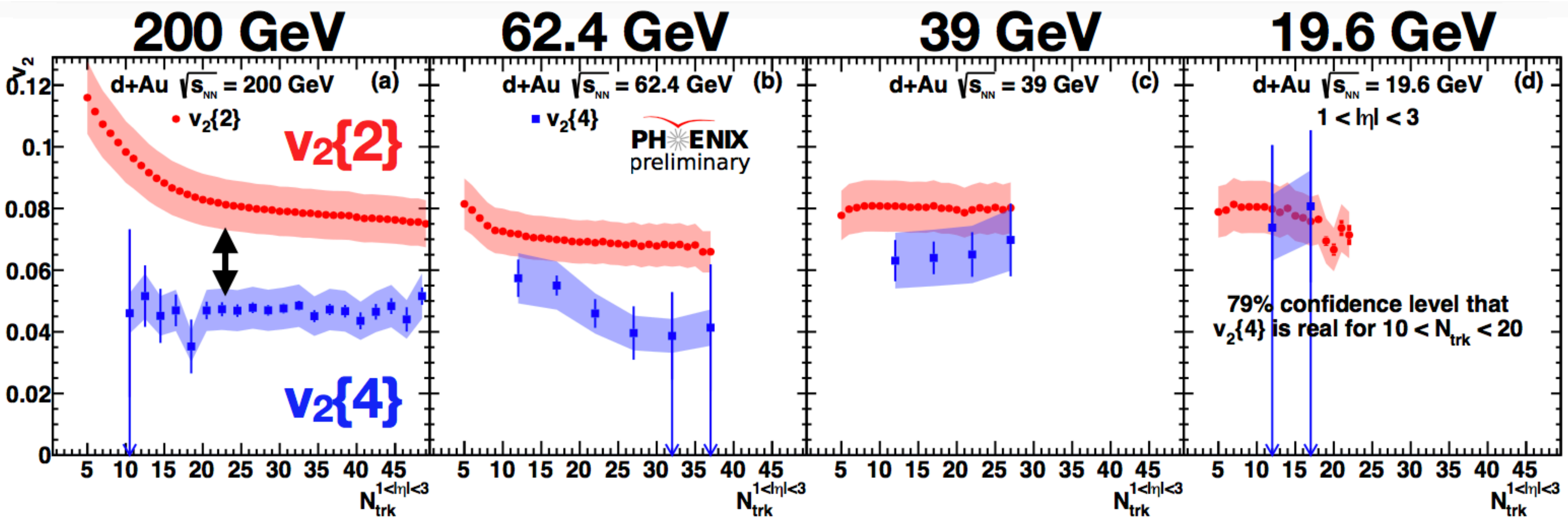
Glasma diagram — non-linear/non-Gaussian effects





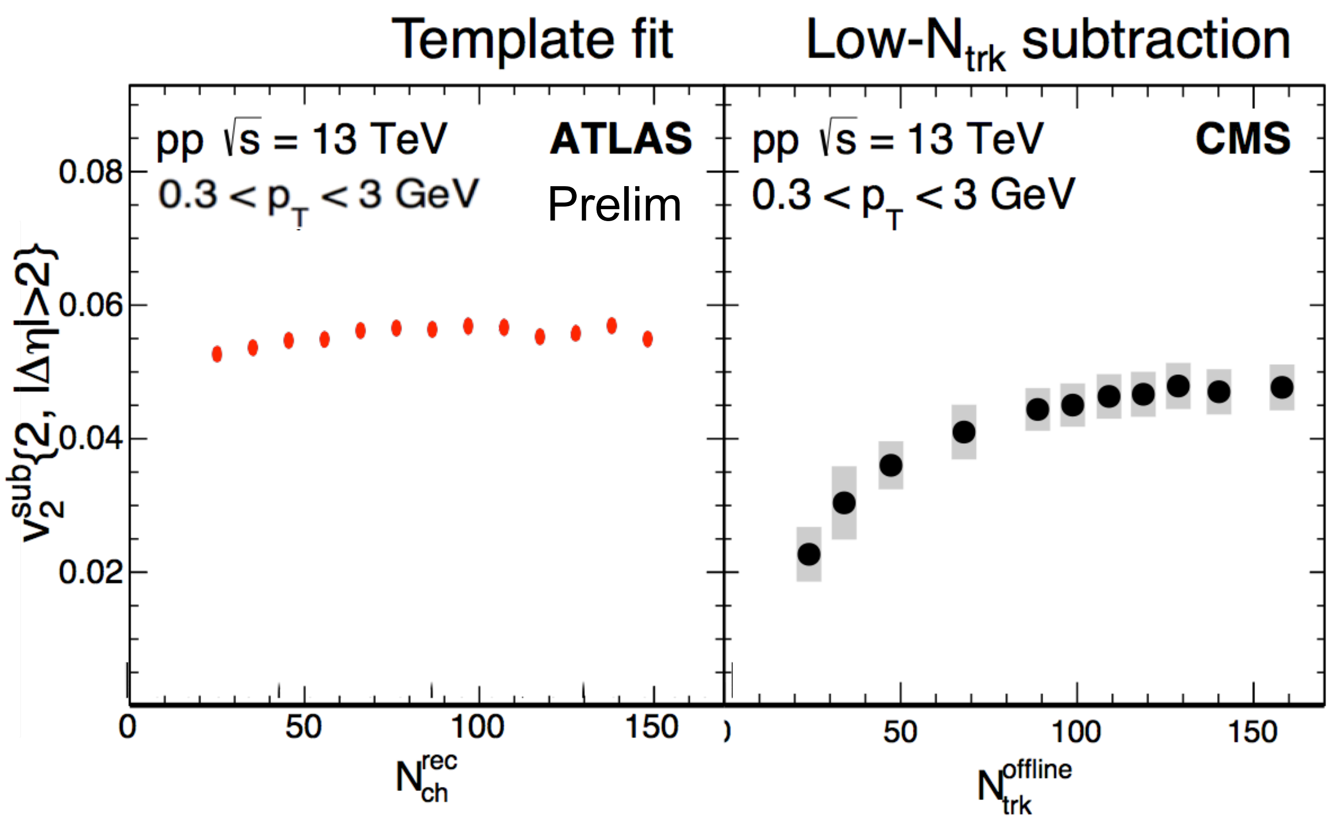
Glasma diagram contribution is small?

$\sqrt{s}$ dependence of $c_2\{4\}$ at RHIC



- Surprising features: $v_2\{4\}$ larger at lower $\sqrt{s}$, reaching $v_2\{2\}$.
- Difficult to describe in both CGC and hydro
- Important to understand non-flow in standard cumulant method

Does collectivity turn off at low N_{ch}?

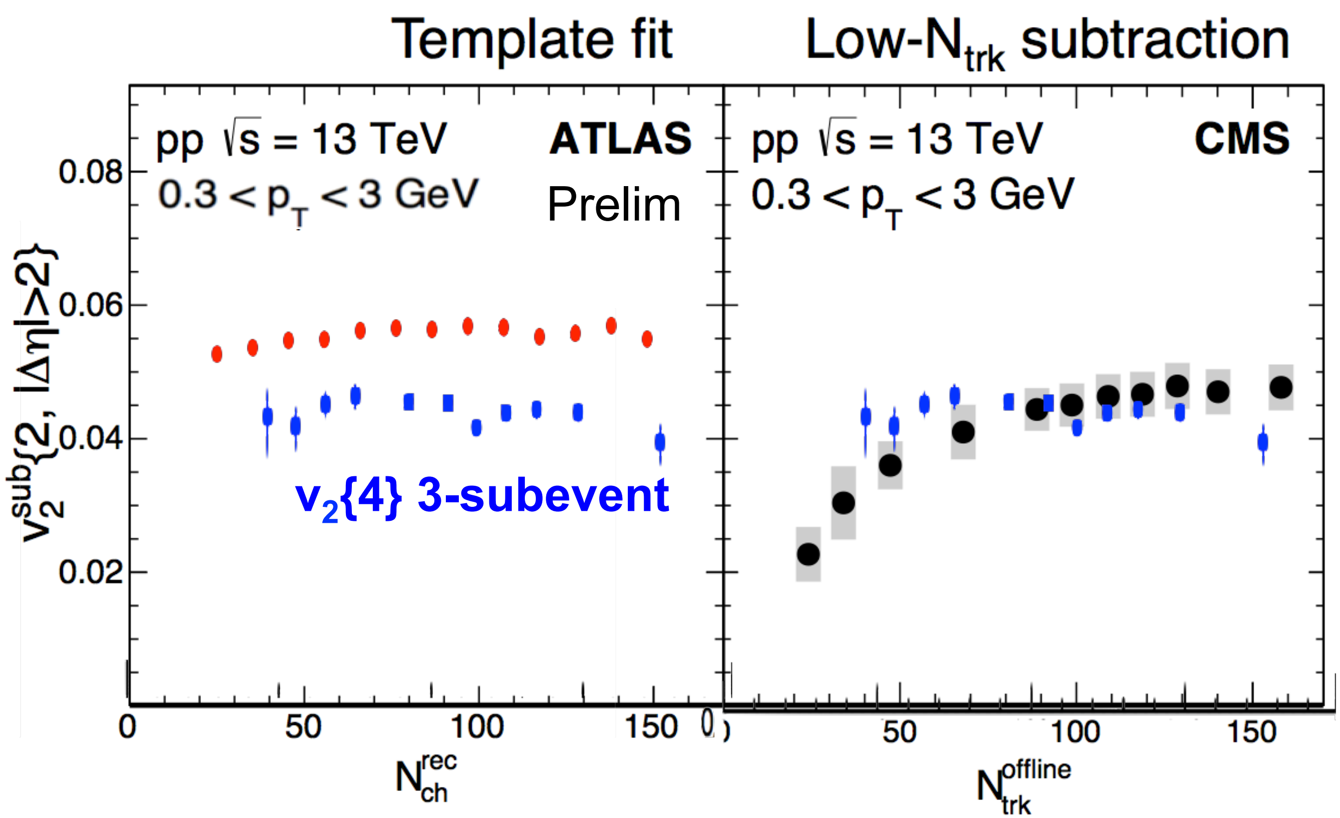


peripheral subtraction including peripheral pedestal (assuming the peripheral also has flow)
→so called template fit

peripheral subtraction not including peripheral pedestal (assuming the peripheral has no flow)
→ so call peripheral sub.

Mingliang Zhou's talk for more detail

Does collectivity turn off at low N_{ch}?



- $v_2\{4\}$ from 3-subevent show no dependence on N_{ch}.
- Why $v_2\{2\}_{\text{peri. sub}} \approx v_2\{4\}$ in pp? surprising because:

$$v_n\{2\}^4 - v_n\{4\}^4 = \langle v_n^4 \rangle - \langle v_n^2 \rangle^2 = \langle (v_n^2 - \langle v_n^2 \rangle)^2 \rangle \geq 0$$

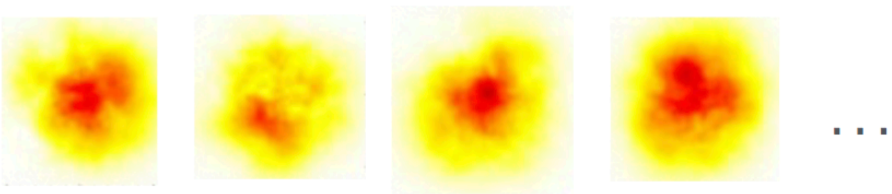
$v_2\{4\}$ also show No hint of collectivity turning-off at low N_{ch}!

Challenge both CGC and standard hydro?

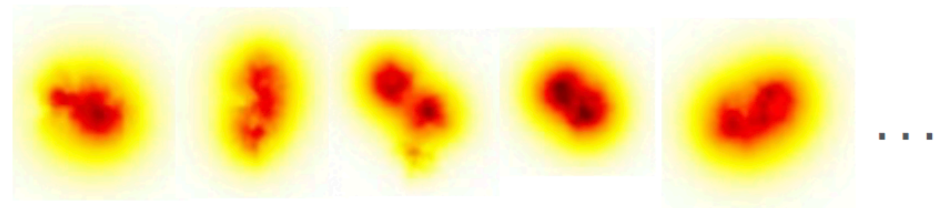
Role of initial geometry is very different

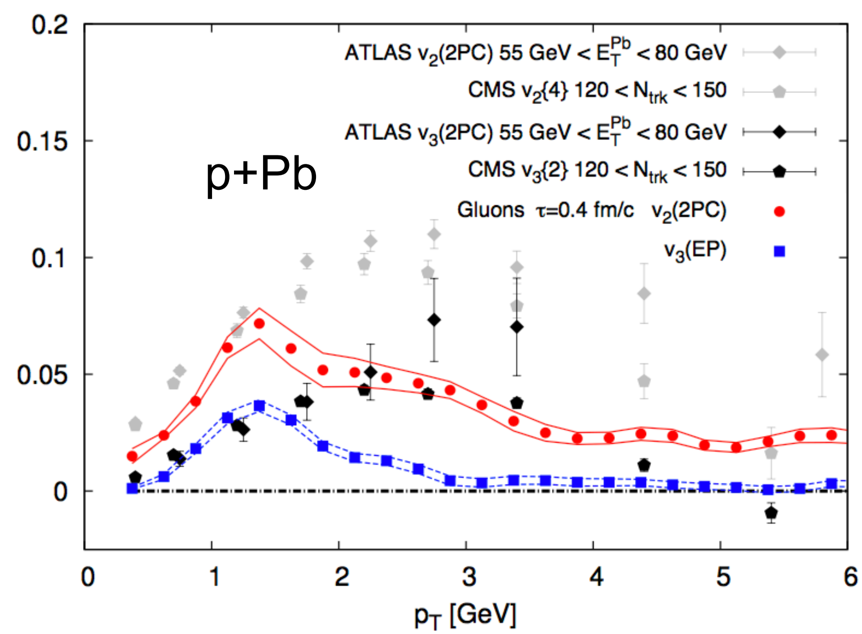
From Schenke, Schlichting, Venugopalan,

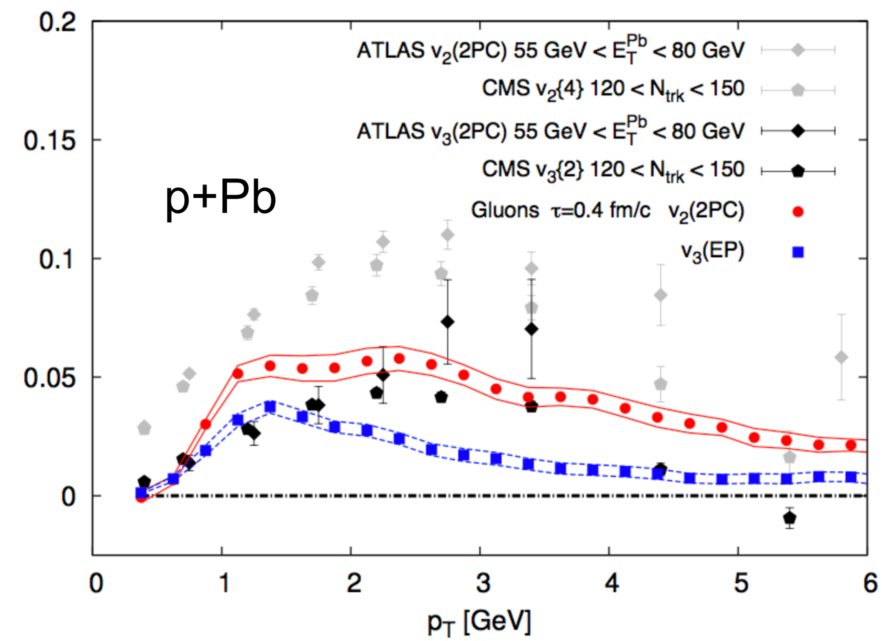
'Spherical' proton



'Eccentric' proton





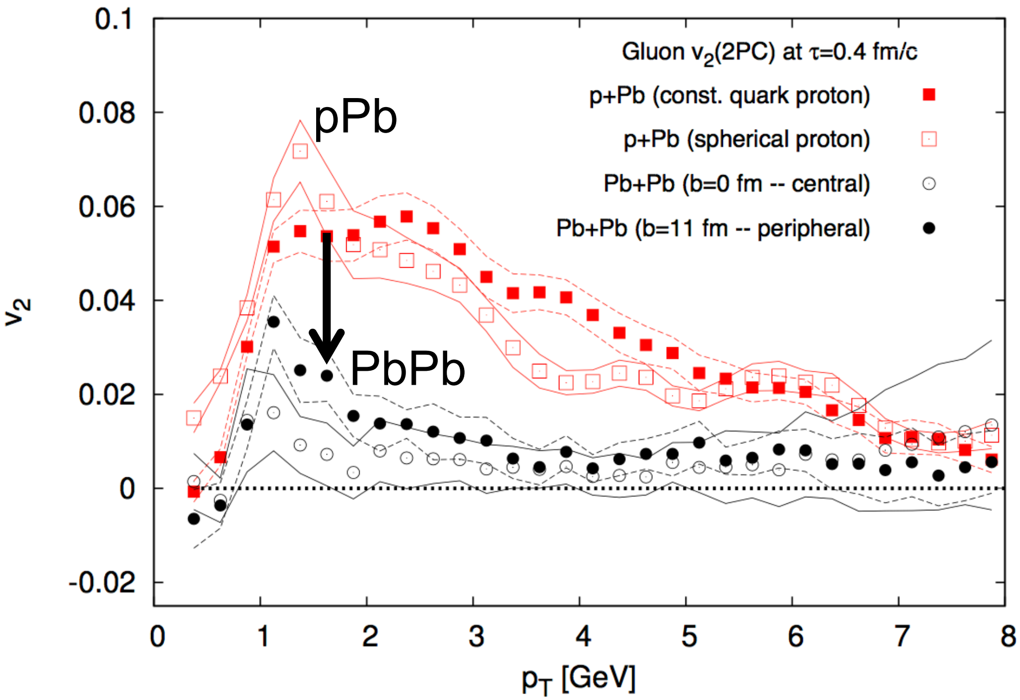


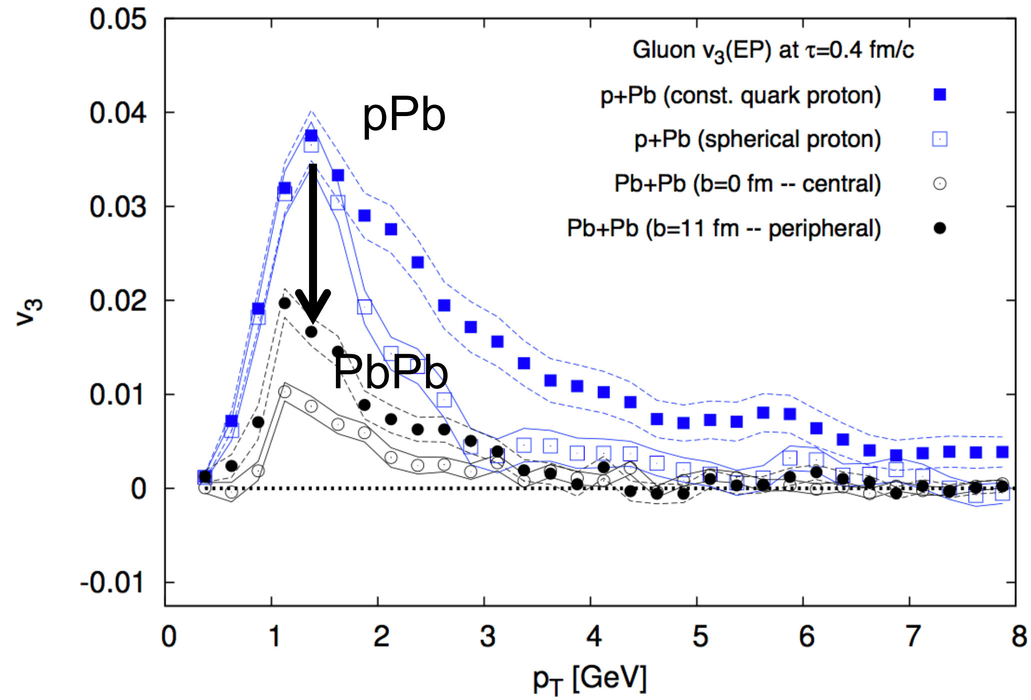
The orientation of collectivity is unrelated to initial eccentricity

→Very different from hydrodynamics

Role of initial geometry is very different

From Schenke, Schlichting, Venugopalan,





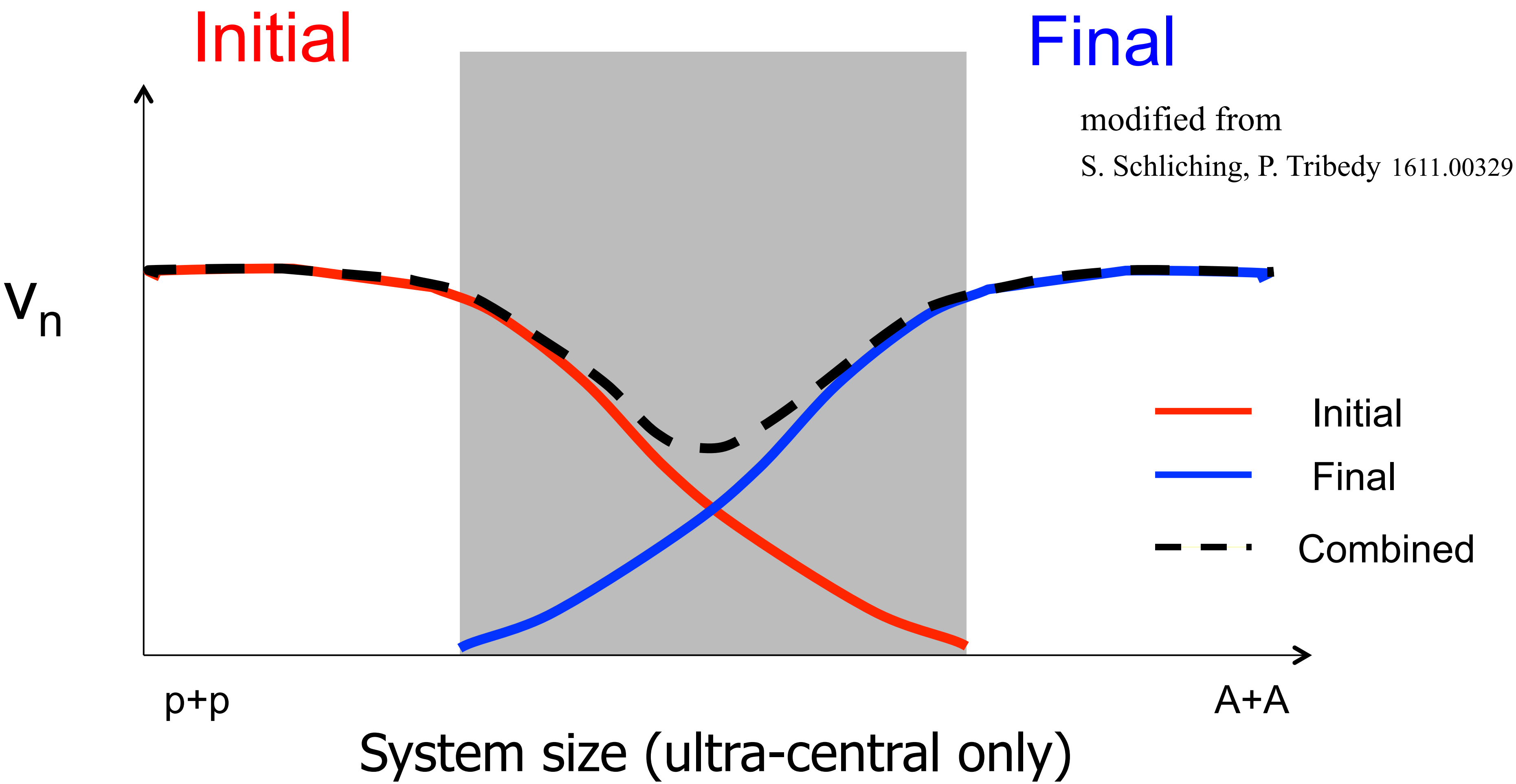
$$c_2\{4\} = \frac{1}{N_D^3}\left(\frac{1}{4(N_c^2-1)^3} - \mathcal{A}^4\right)$$

The orientation of collectivity is unrelated to initial eccentricity

→Very different from hydrodynamics

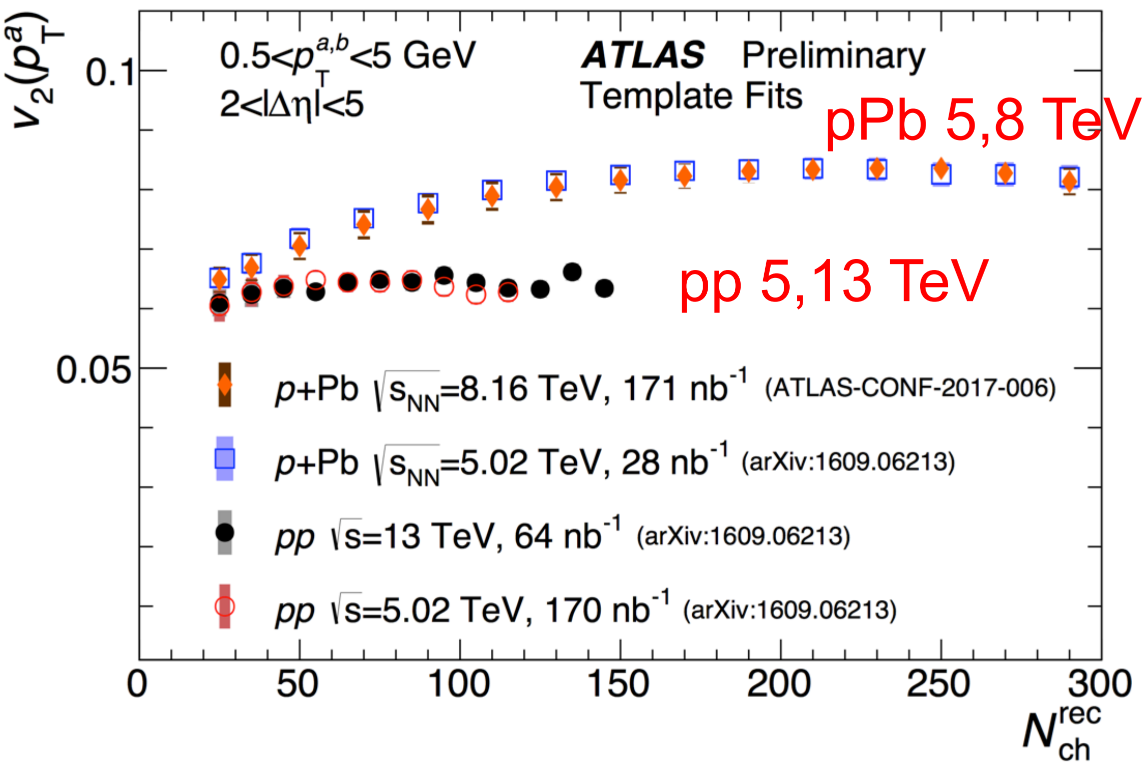
Expect contribution diminish as system size is increased

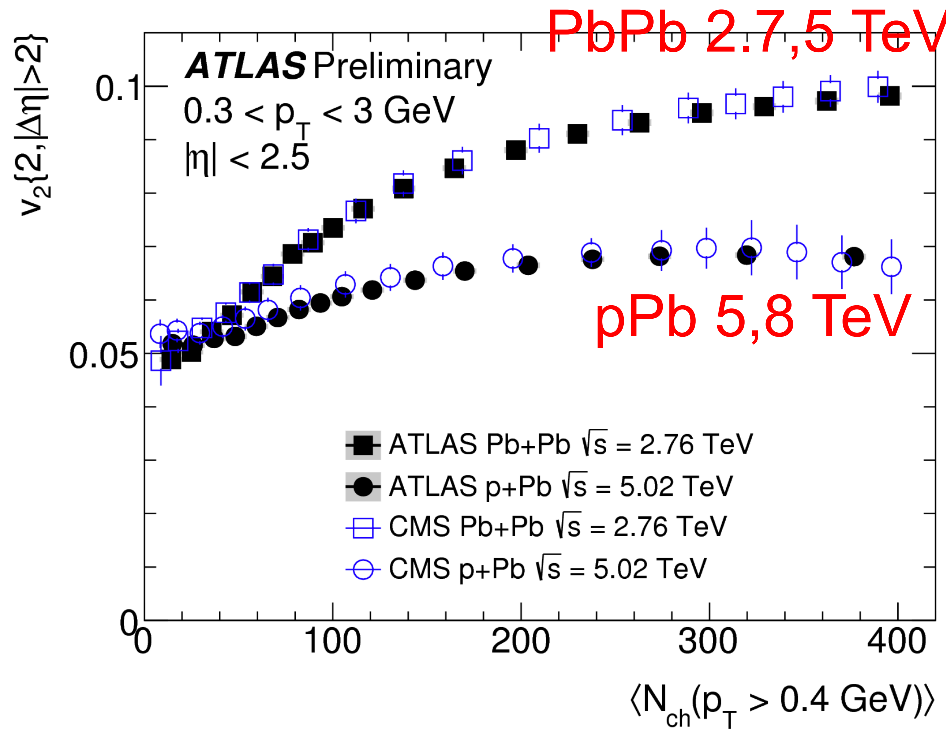
Presence of both initial and final state scenarios?



Phases of collectivity from CGC and hydro are unrelated
→ a minimum of total v_n at certain system size?

System size dependence





Clear dependence on collision systems but ~no dependence on √s

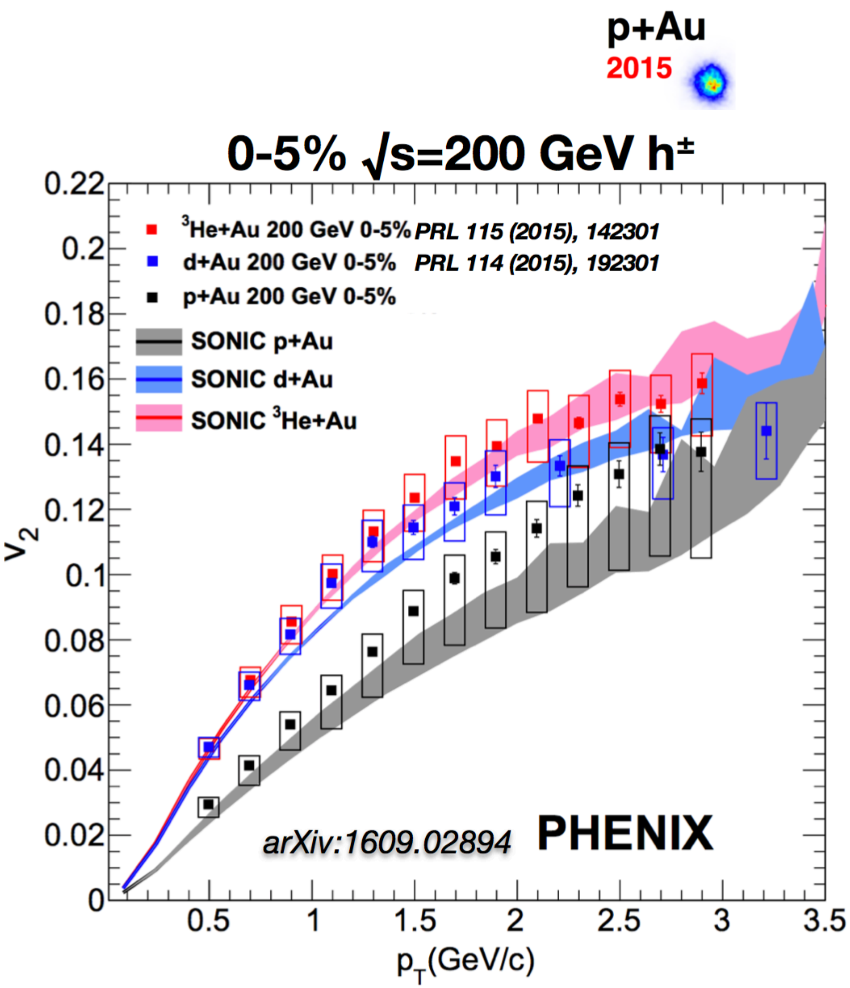
v_2^{pp} (high-mul)<v_2^{pPb}(low-mul)!

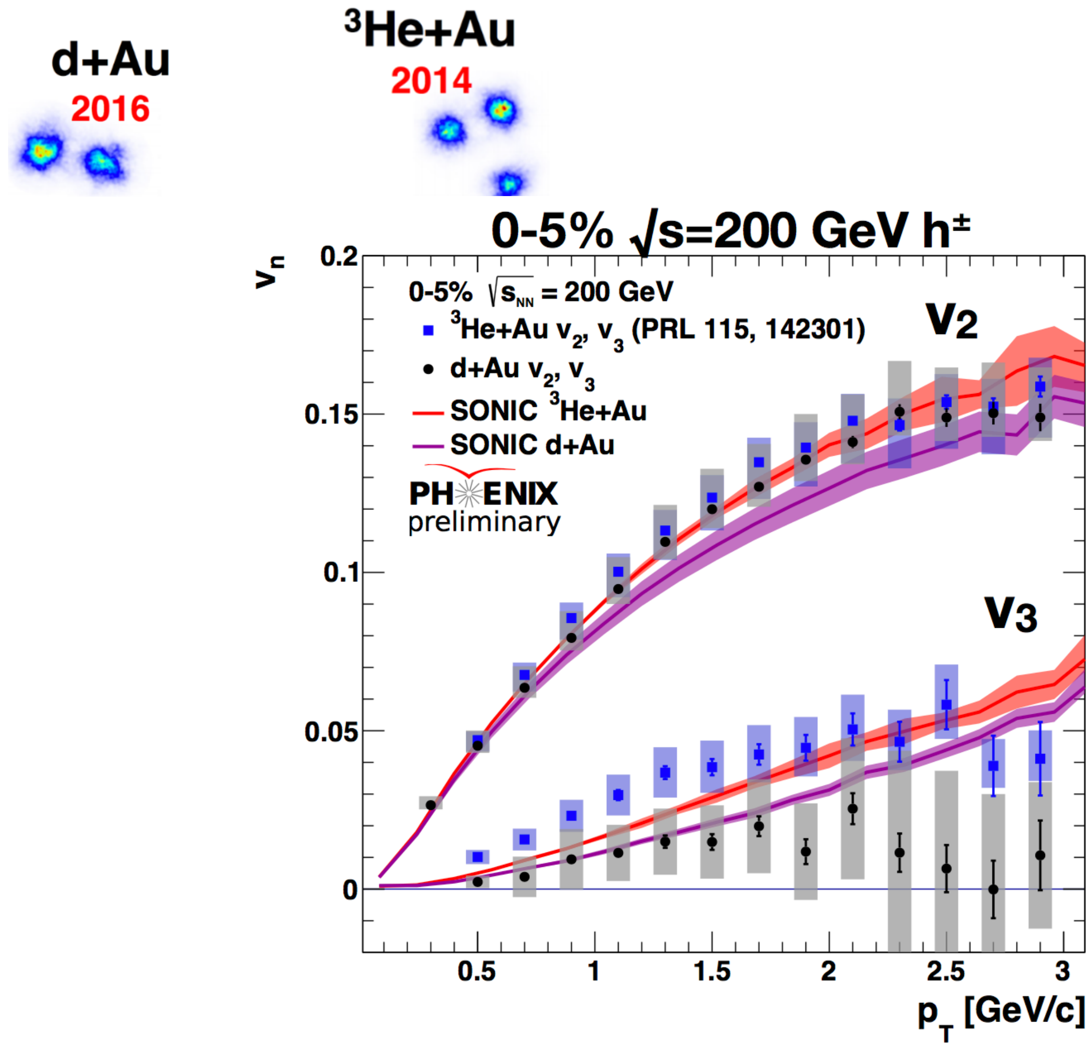
CGC Unclear if the pp/pPb hierarchy is expected.

Hydro Interplay between viscous damping and initial ε_n
pPb: may seen an average geometry effect
pp: geometry maybe poorly correlated with N_{ch}.

Kevin Welsh, Jordan Singer, and Ulrich Heinz 1605.09418

Geometry scan at RHIC





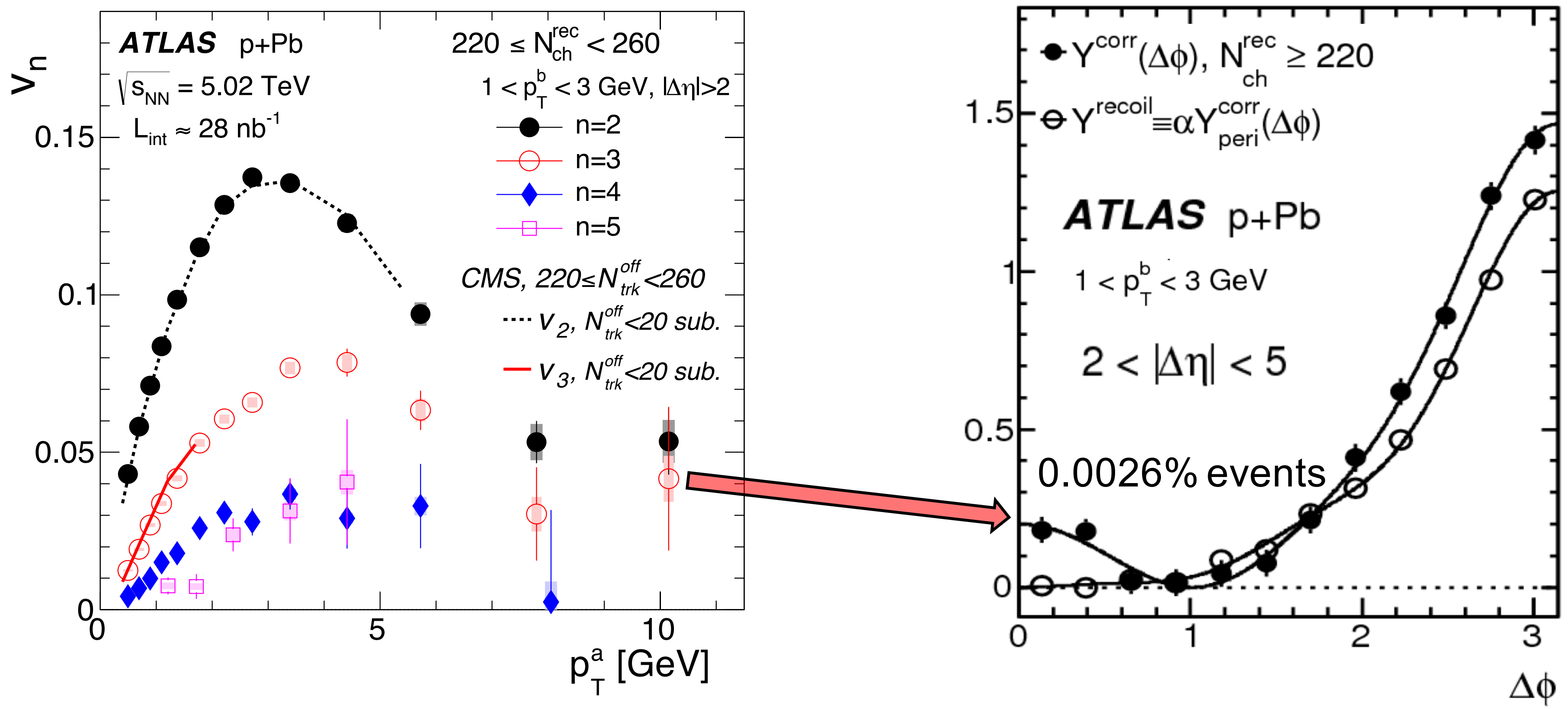
$v_2^{pAu} < v_2^{dAu} \leq v_2^{HeAu}$ $v_3^{dAu} < v_3^{HeAu}$

Hierarchy compatible with initial geometry + final state effects

Look forward to the CGC predictions

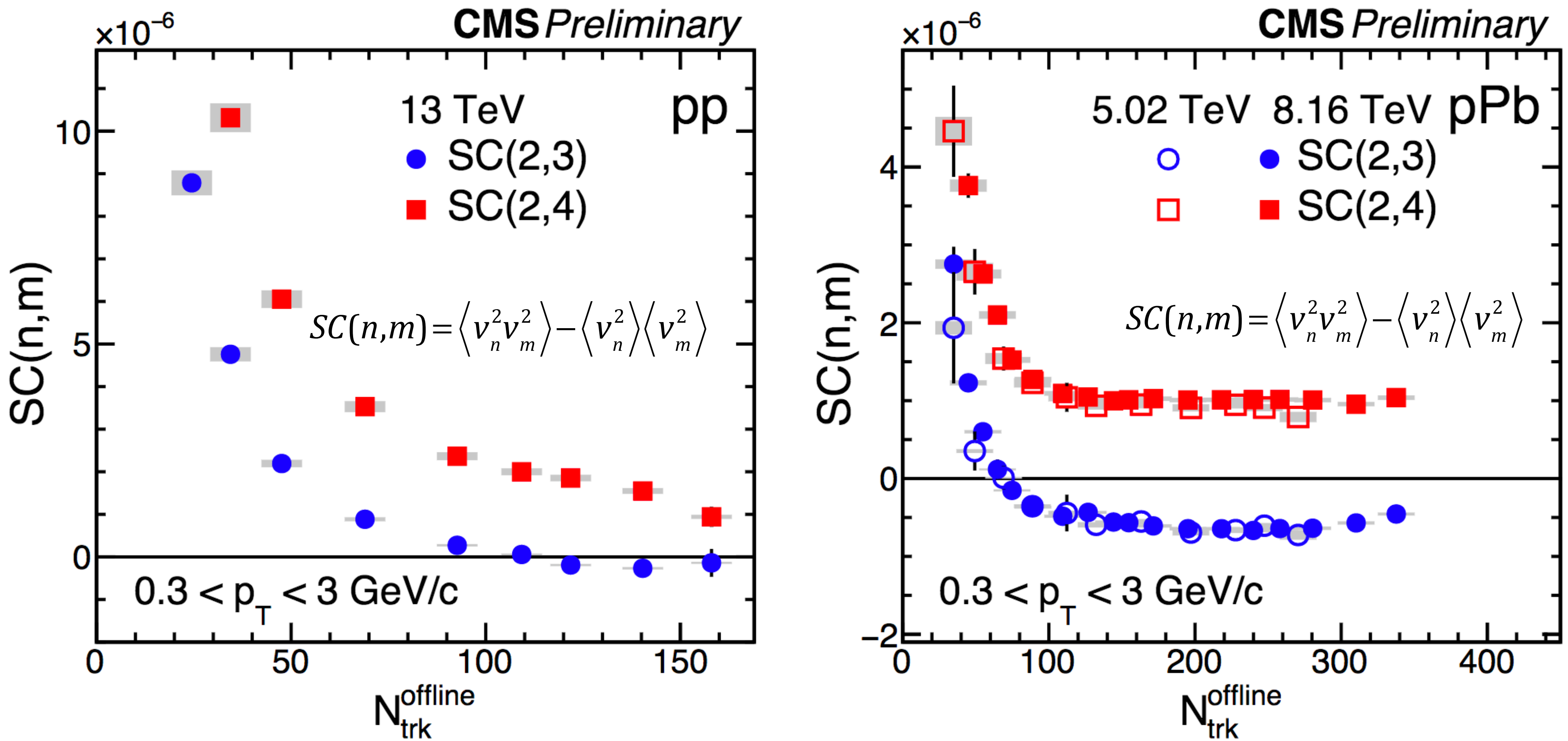
Original of high-p_T v_2?

- Ridge seen directly at 10 GeV or 5% v_2 in pPb
  - → final state effects, e.g. jet quenching (better observable than R_{AA})?
  - → initial state effects, rare Q_s fluctuation?



Outlook: more precision and higher p_T with 8 TeV pPb data

Symmetric cumulants



- Influence of non-flow need to be taken out, but see anti-correlation between v_2 v_3 and correlation between v_2 v_4.
- Naturally understood in hydrodynamics
  - v_2v_3 reflects $\varepsilon_2\varepsilon_3$ correlation, v_2v_4 correlation reflects mode-mixing effects
- In principle, some processes in CGC can also produce this 1705.00745

Summary of collectivity in small system

- Collectivity associated with ridge must involve many particles in multiple η ranges → subevent methods

Challenge for both initial & final state scenarios?

- LHC v_2 associated with ridge does not turn off at low N_{ch}.
- RHIC $v_2\{4\}$ increases and approaches $v_2\{2\}$ at lower $\sqrt{s}$

Challenge for initial state only scenarios?

- LHC $v_2^{pp} < v_2^{pPb}$ in all N_{ch} and all $\sqrt{s}$.
- LHC $c_2\{4\}$ <0 down to very low N_{ch} and more negative at higher p_T.
- RHIC geometry scan suggest ordering of v_n follows that of ε_n.
- LHC 5% v_2 at p_T~10 GeV.

…

Coexistence of initial state & final state scenarios?

Key issue: How to constrain timescales for emergence of collectivity? the role of CGC, preflow and hydro?

How are cumulants related to collectivity?

— the role of flow, non-flow and multiplicity fluctuation

1701.03830, 1412.4759

Role of flow & nonflow in multi-particle cumulant

- Flow vector for event with M particles: $\mathbf{q}_n \equiv \frac{\sum_i e^{in\phi_i}}{M} = q_n e^{in\Psi_n}$
- Contains contribution from flow and non-flow $\mathbf{q}_n = \mathbf{v}_n + \boldsymbol{s}_n$
- Cumulant is **additive** for convolution: (v and s are independent)

$$p(\mathbf{q}_n) = p(\mathbf{v}_n) \otimes p(\boldsymbol{s}_n) \Rightarrow c_n\{2k\} = c_n\{2k,\text{flow}\} + c_n\{2k,\text{non-flow}\}$$

- i.e. for four-particle cumulants:

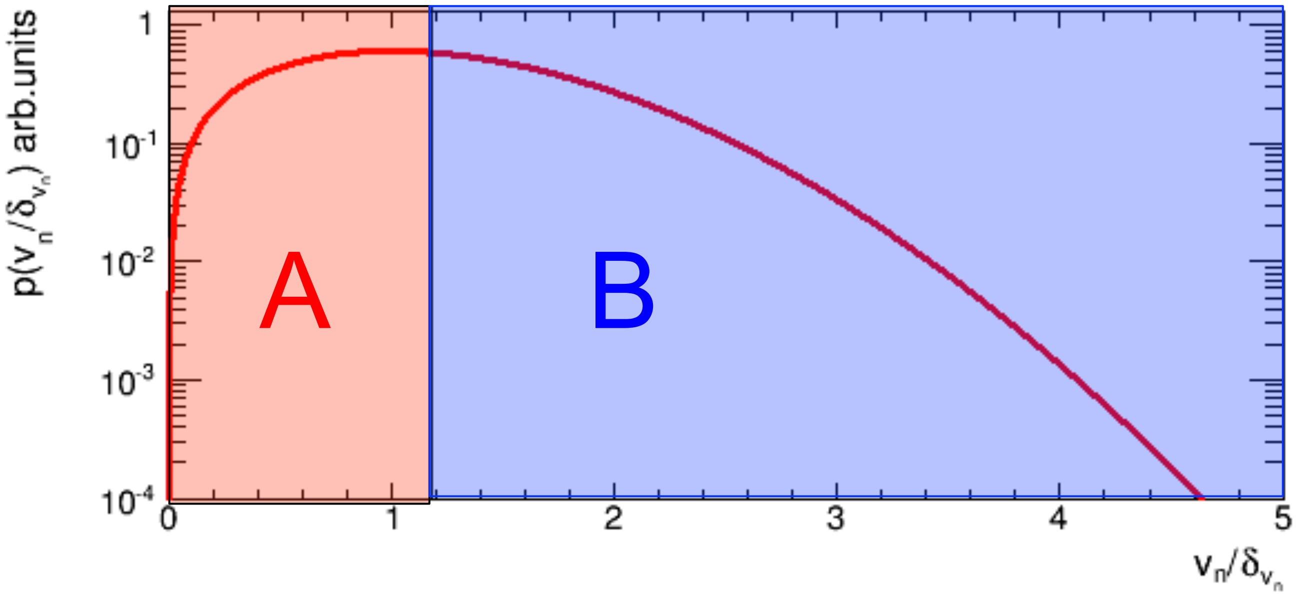
$$c_n\{4\} = \underbrace{\left\langle v_n^4 \right\rangle - 2\left\langle v_n^2 \right\rangle^2}_{c_n\{4,\text{flow}\}} + \underbrace{\left\langle s_n^4 \right\rangle - 2\left\langle s_n^2 \right\rangle^2}_{c_n\{4,\text{non-flow}\}}$$

The sign of $c_n\{2k\}$ depends on the nature of the p(flow) and p(non-flow)

Properties of flow cumulants

- Gaussian fluctuation without average geometry

$$p(v_n) = \frac{v_n}{\delta^2_{v_n}} e^{-v_n^2/(2\delta^2_{v_n})}$$



- Divide to 2 equal parts, and calculate cumulants separately.

	$v_n\{2\}$	$v_n\{4\}$	$v_n\{6\}$	$v_n\{8\}$	in units of δ
all	1.414	0	0	0	
A	0.783	0.685	0.671	0.667	
B	1.840	1.653	1.680	1.681	

- Not additive due to non-linear term: $c_n\{4\}_{\mathrm{ev1+ev2}} \neq \frac{c_n\{4\}_{\mathrm{ev1}} + c_n\{4\}_{\mathrm{ev2}}}{2}$

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

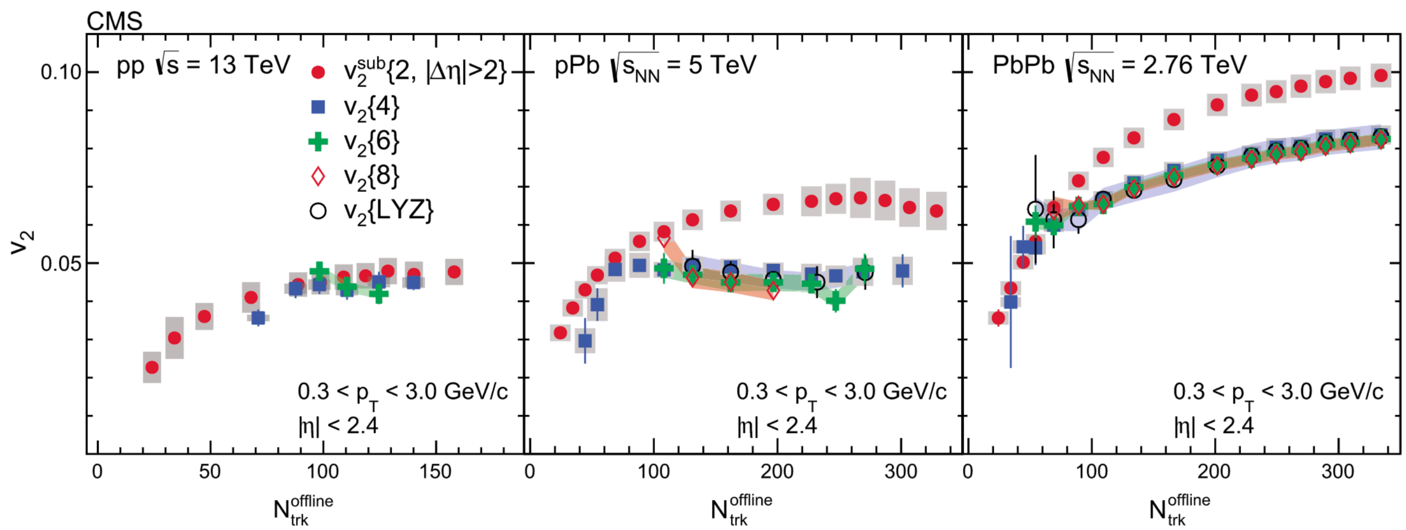
- Cumulants not very sensitive to $p(v_n)$ shape beyond 4^{th}-order!

Nature of collectivity fluctuations?

- Arguments based on initial eccentricity fluctuations
  - A+A system: Bessel-Gaussian, confirmed by $p(v_n)$ obtained from unfolding ✔
  - Small system: power distribution based on independent source model ?

$$p(v_n) = 2\frac{\alpha}{\kappa}\frac{v_n}{\kappa}\left(1-\left(\frac{v_n}{\kappa}\right)^2\right)^{\alpha-1} \qquad 2\alpha = N_s - 1$$

PRL112,082301(2014)



We can't know $p(v_n)$ given current precision of $v_2\{2k\}$!

Important to directly measure $p(v_n)$

“wrong” sign of $c_n\{2k\}$?

- In principle, $c_2\{2k\}$ with “correct” sign & $v_2\{4\}\approx v_2\{6\}\approx v_2\{8\}\approx v_2\{\infty\}$ neither necessary nor sufficient condition for collectivity.
- The sign & hierarchy controlled by shape of $p(v_n)$.
  - Mixing 1/3 events with flow and 2/3 with zero flow

$$p(v_n) = \frac{1}{3}\delta(v_n - v_0) + \frac{2}{3}\delta(v_n)$$

  - Cumulants have “wrong” sign, despite only flow is present

$$c_n\{4\} = \tfrac{1}{9}v_0^4,\ c_n\{6\} = -\tfrac{2}{9}v_0^6,\ c_n\{8\} = \tfrac{71}{9}v_0^8$$

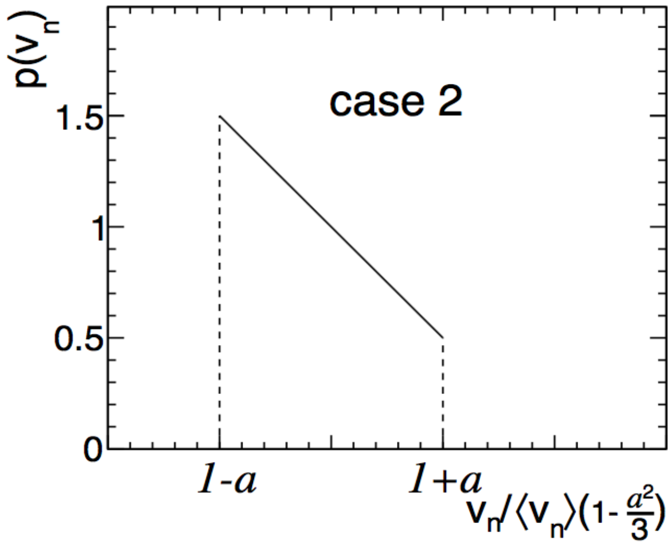
More examples given in 1412.4759

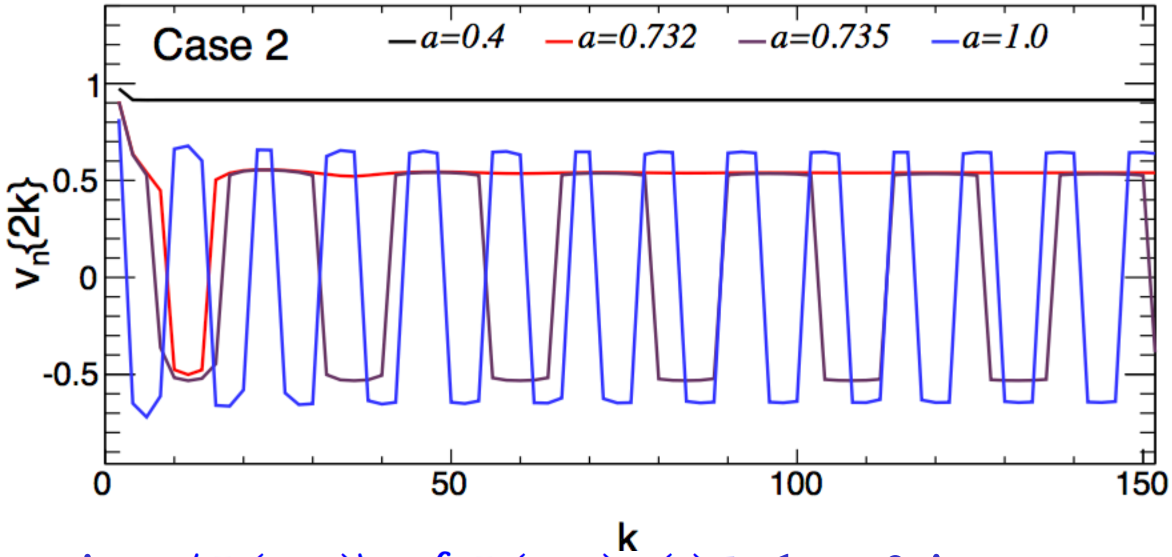
- Same discussion applies for non-flow as well: the sign of $c_n\{4\text{,non-flow}\}$ depends on EbyE fluctuation of non-flow $p(s_n)$

$$c_n\{4\} = \left\langle v_n^4\right\rangle - 2\left\langle v_n^2\right\rangle^2 + \boxed{\left\langle s_n^4\right\rangle - 2\left\langle s_n^2\right\rangle^2}$$

Understanding EbyE **non-flow fluctuation** is important for understanding flow fluctuation in small system

How cumulants depends on p(v)?





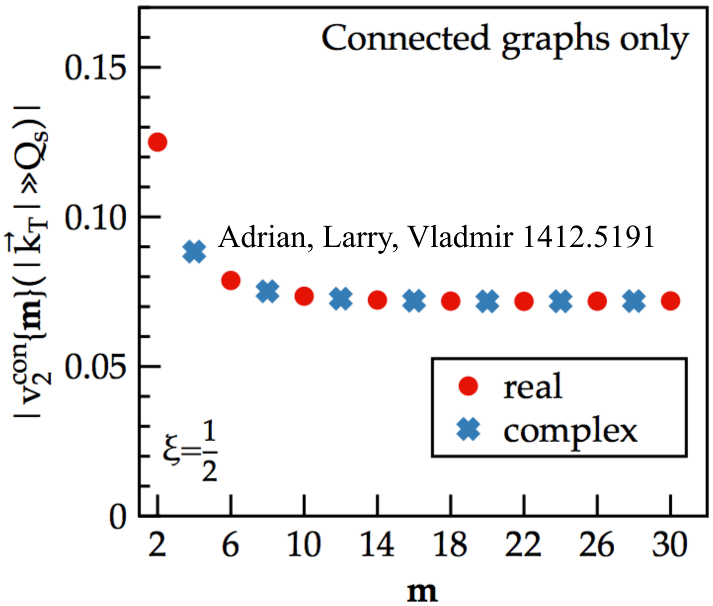
- Convergence of $\lim_{k\to\infty} v\{2k\}$ requires $\langle J_0(2vz)\rangle = \int J_0(2vz)p(v)dv$ has 0 in complex plane, i.e. LYZ method.
- p(v) from initial state color fluc is strongly non-Gaussian

$$c_2\{2\} = \frac{1}{N_D}\left(\mathcal{A}^2 + \frac{1}{4(N_c^2-1)}\right)$$

$$c_2\{4\} = -\frac{1}{N_D^3}\left(\mathcal{A}^4 - \frac{1}{4(N_c^2-1)^3}\right)$$

non-linear/non-Gaussian effects

Glasma diagram



Non-flow and multiplicity fluctuations

$$c_n\{4\} = \left\langle\left\langle e^{in(\phi_1+\phi_2-\phi_3-\phi_4)}\right\rangle\right\rangle_{\rm evt} - 2\left\langle\left\langle e^{in(\phi_1-\phi_2)}\right\rangle\right\rangle_{\rm evt}^2$$

calculated for selected particles average over an event class

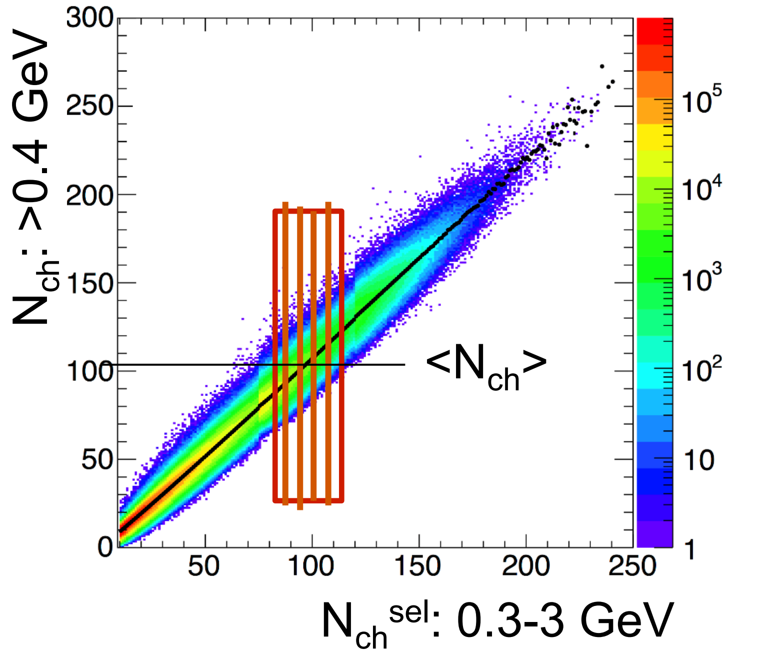
e.g. 0.5-5 GeV

N_{ch}^{Sel} : number of charge particles with e.g. 0.3-3, >0.2,>0.4,>0.6 GeV…

Map final results to a common centrality, e.g. $\langle N_{ch}\rangle$ for p_T>0.4 GeV

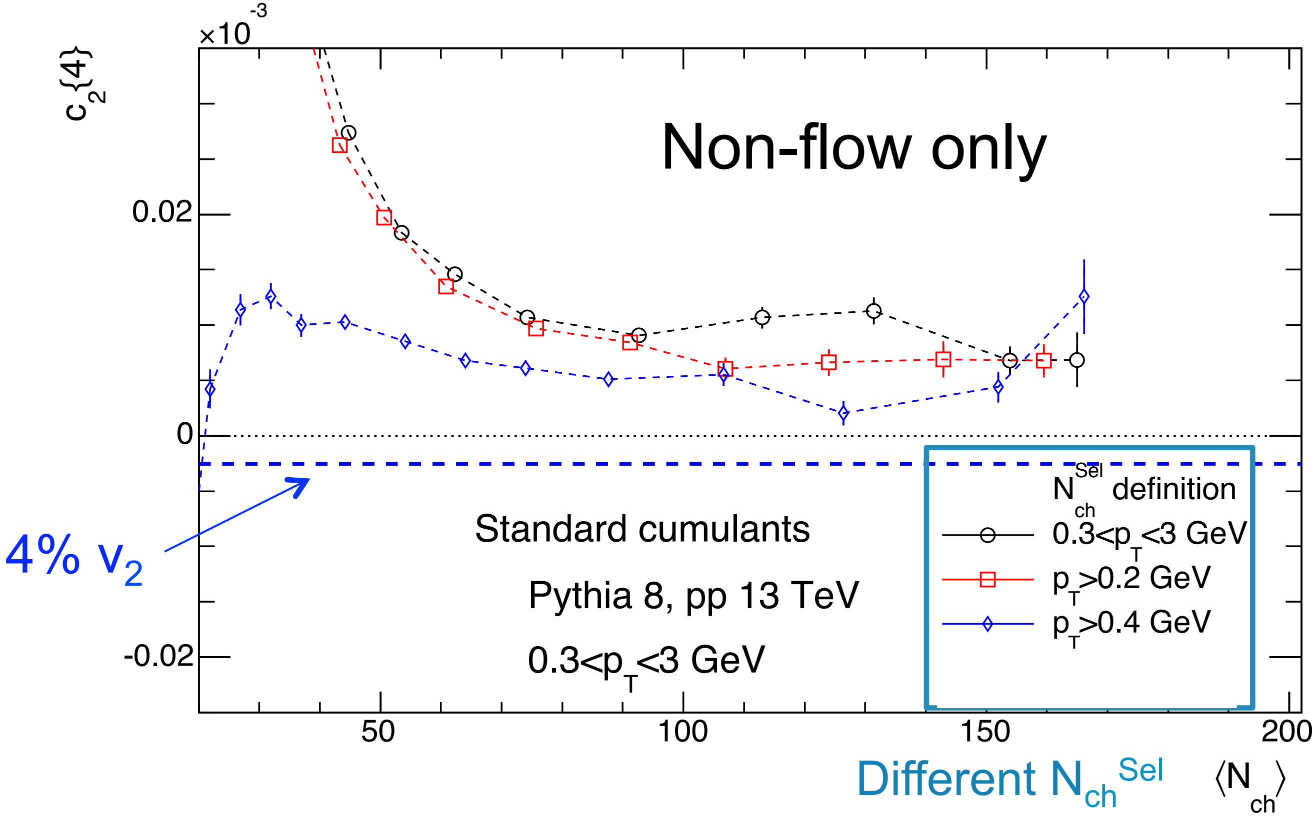
Because $c_n\{4\}$ is not additive:

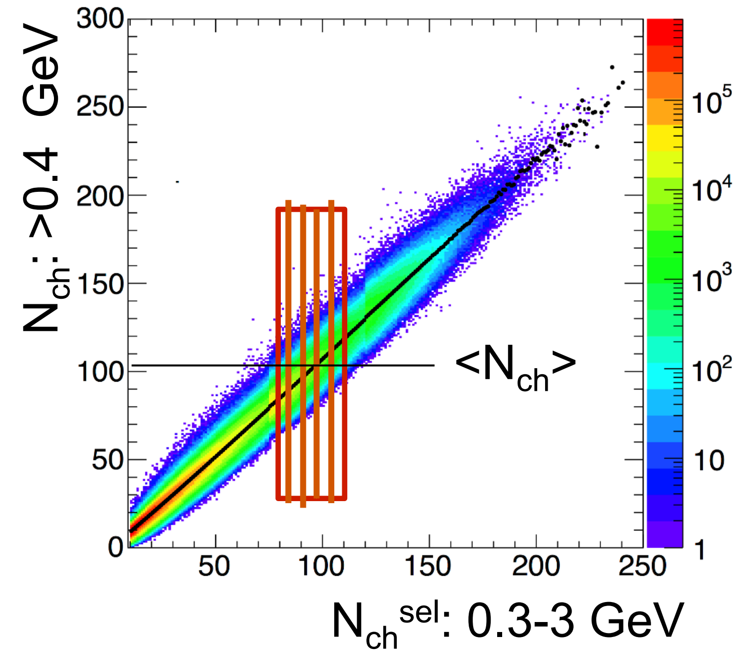
$$c_n\{4\}_{\rm ev1+ev2} \neq \frac{c_n\{4\}_{\rm ev1} + c_n\{4\}_{\rm ev2}}{2}$$



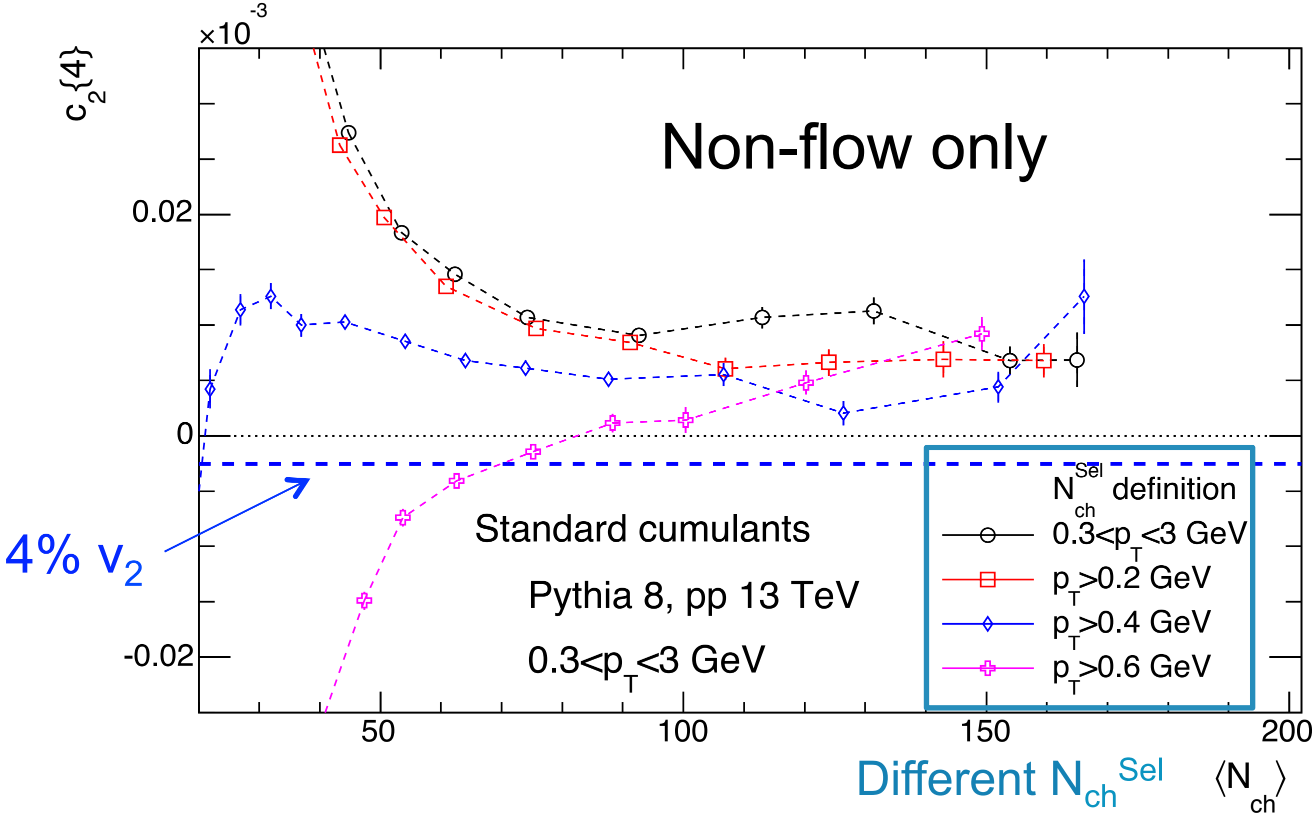
Results depend on the intermediate N_{ch}^{Sel} !
Mainly because p(non-flow) has strong dependence on N_{ch}

Dependence on N_{ch}^{Sel} in PYTHIA





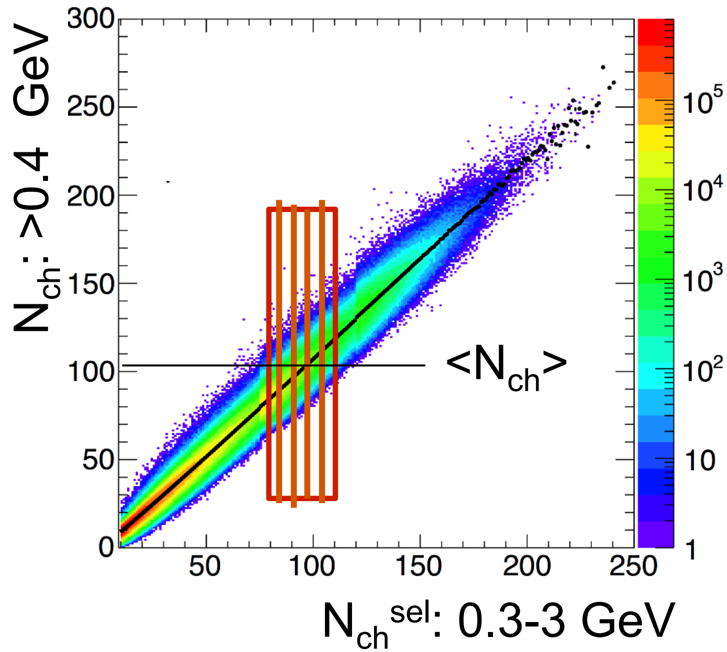
Dependence on N_{ch}^{Sel} in PYTHIA



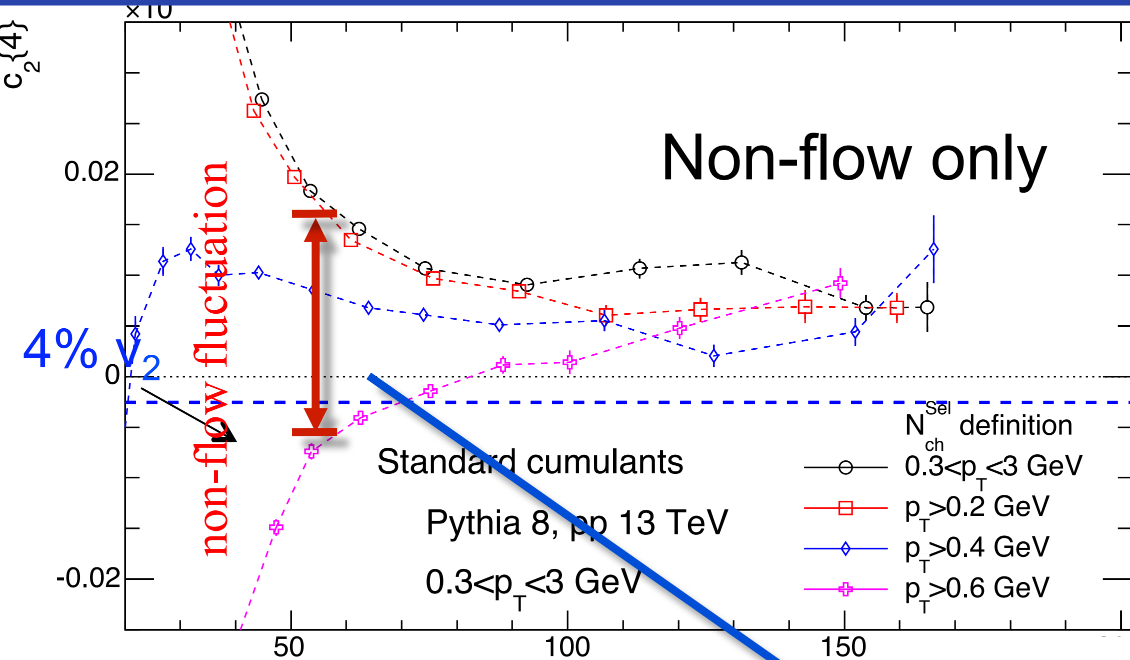
Different N_{ch}^{Sel}

Different non-flow fluctuations

Different $c_2\{4\text{,non-flow}\}$



Standard v.s. Subevent cumulants



Different N_{ch}^{Sel}

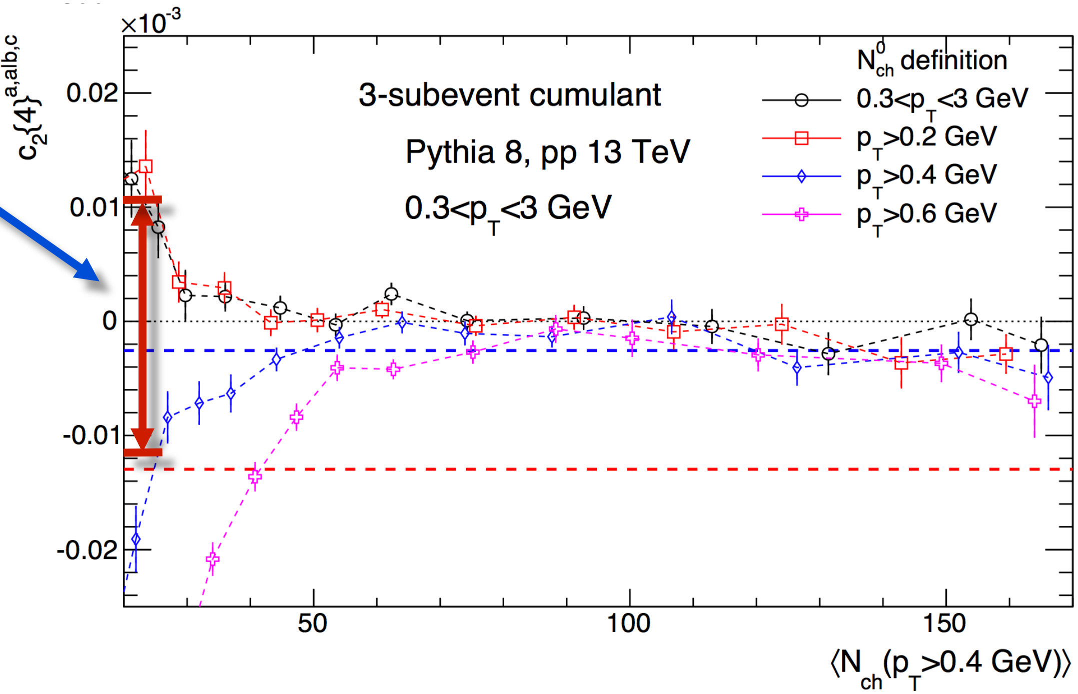
Different non-flow fluctuations

Different $c_2\{4\text{,non-flow}\}$

Less non-flow

Less non-flow fluctuations

Less dependence on N_{ch}^{Sel}



3 subevent cumulant is a more reliable method in small system

Summary of cumulants in small system

- Current precision of $c_n\{2k\}$ can't probe details of $p(v_n)$ shape, other than the mean and standard deviation.

- $c_n\{2k\}$ with "correct" sign & $v_n\{4\}\approx v_n\{6\}\approx v_n\{8\}\approx v_n\{\infty\}$ neither necessary nor sufficient condition for collectivity.

- In small systems, non-collective sources from dijet dominates the statistical properties of two- or multi-particle correlations
  - Reflected by strong sensitivity to multiplicity class definition and multiplicity bin-width.
- Cumulants based on subevents suppress such non-collective sources