Collective flow in *small* systems

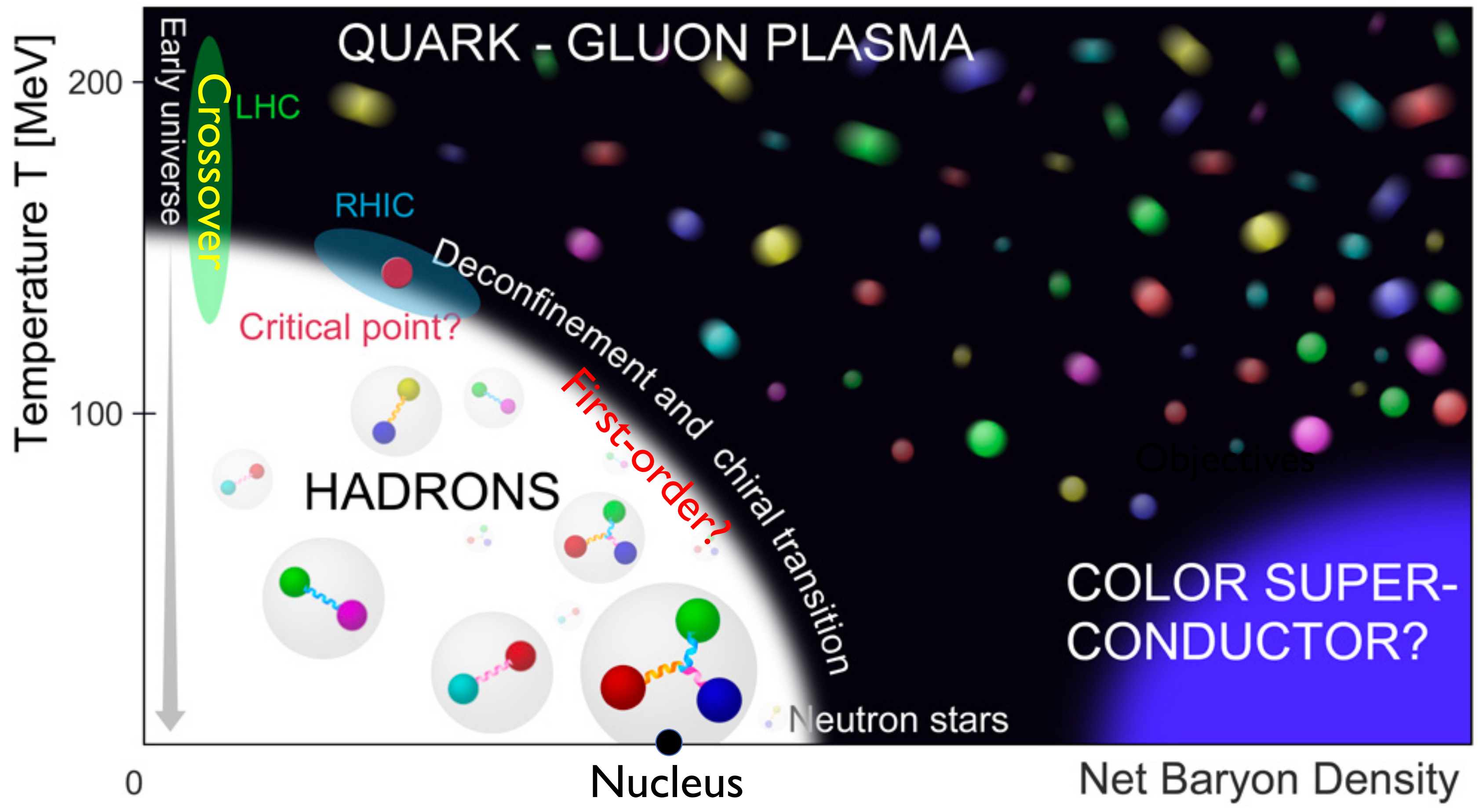
– *lessons*, *puzzles* and *opportunities*

Wei Li
Rice University

RHIC-BES seminar series
November 10, 2020

How large is large? How small is small?

Physics of QCD many-body systems



Key objectives:

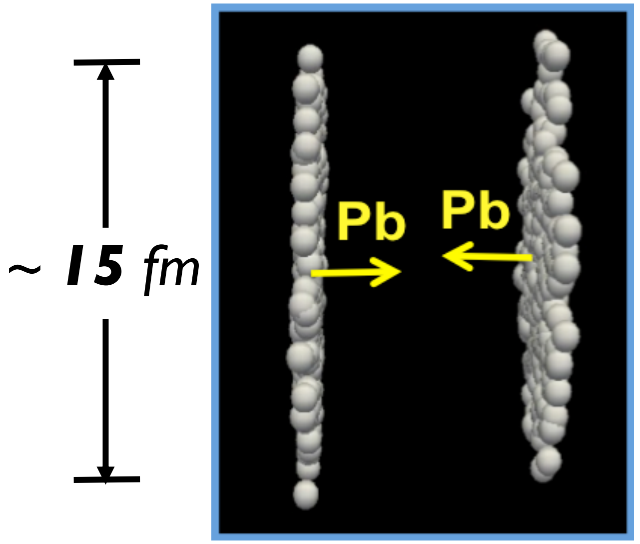
- Search for and study deconfined quark-gluon matter
- Understand nature of QCD phase transitions

Recreating "Little Bangs" in the lab

Nuclear Physics

Colliding large *nuclei*

T.D. Lee, RMP 47, 267(1975)



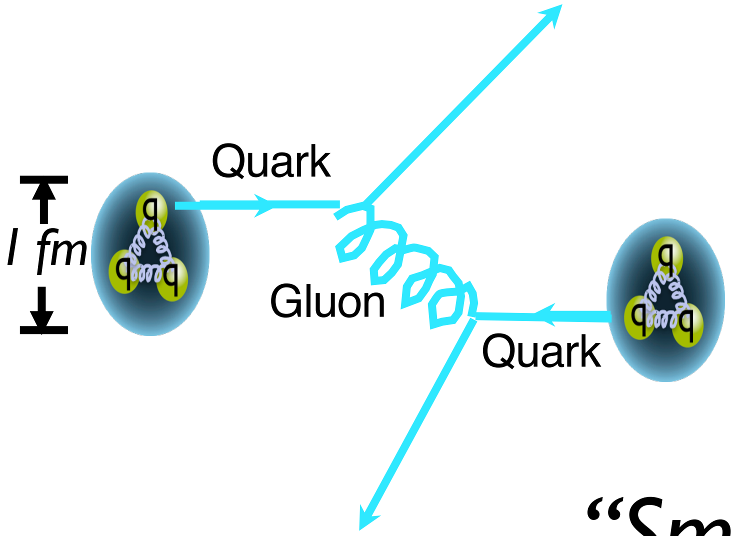
"Large"

Large volume to form a medium and interact with hard probes (jets)

vs.

High Energy Physics

Proton-proton

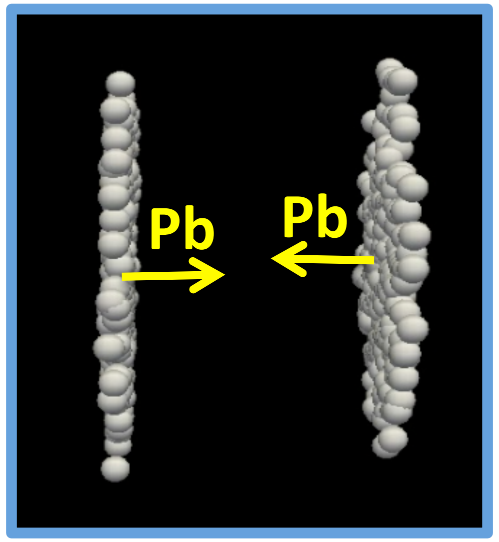


"Small"

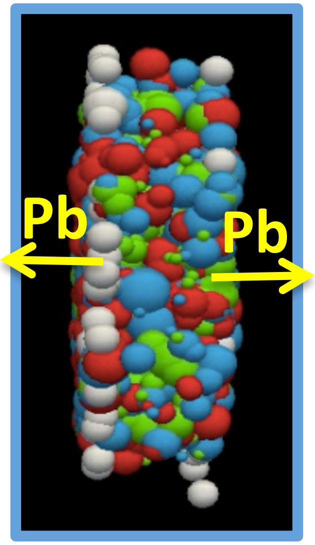
Point-like, too small for partonic rescatterings!

Standard paradigm of heavy ion collisions

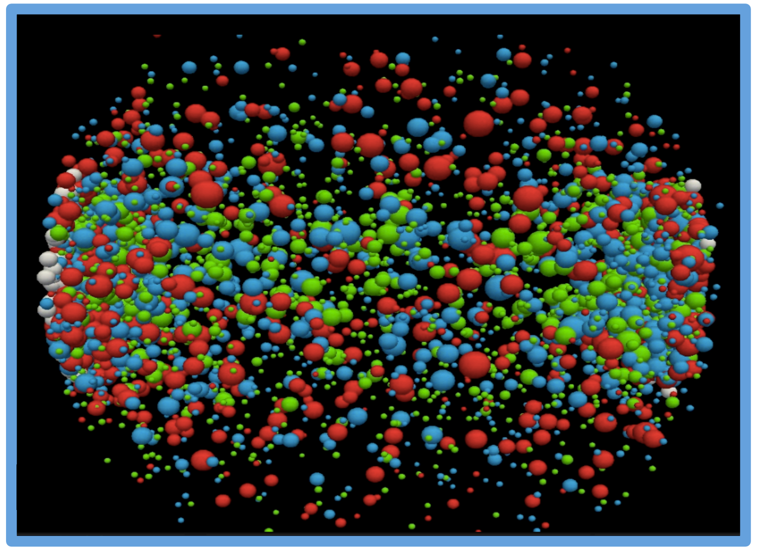
Pre-reaction



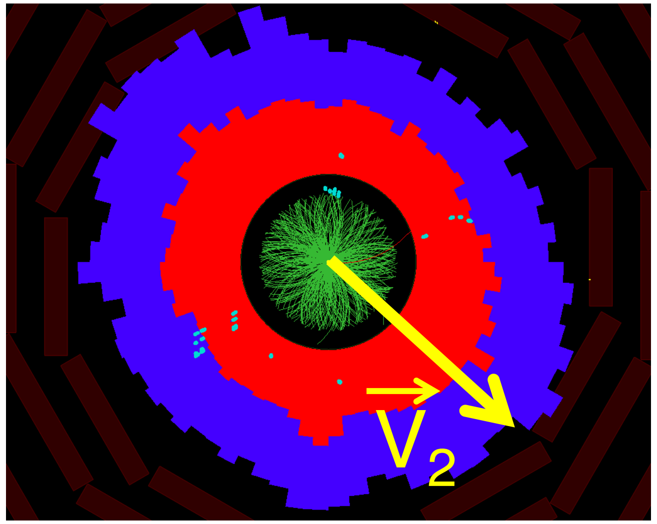
QGP



Hadronization



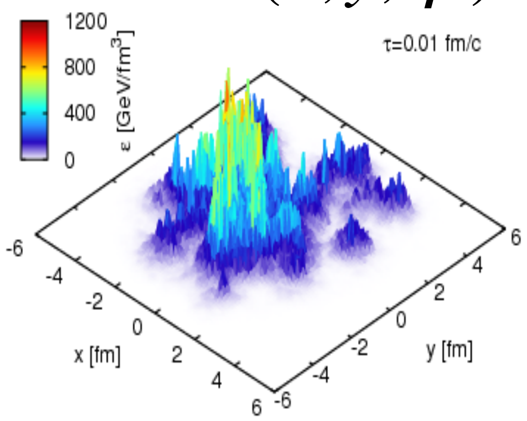
Detection



time $f(p_T,\eta,\phi)$

Initial state:

$\varepsilon(x,y,\eta^s)$



Pre-equilibrium

Hydrodynamics

$\partial_\mu T^{\mu\nu} = 0 + (\eta, \zeta, \ldots)$

Freeze-out;
Hadronic transport

Final-state collective flow:

$$f(p_T,\eta,\phi) = N(p_T,\eta)\sum_{n=-\infty}^{+\infty}\vec{V}_n(p_T,\eta)e^{-in\phi}$$

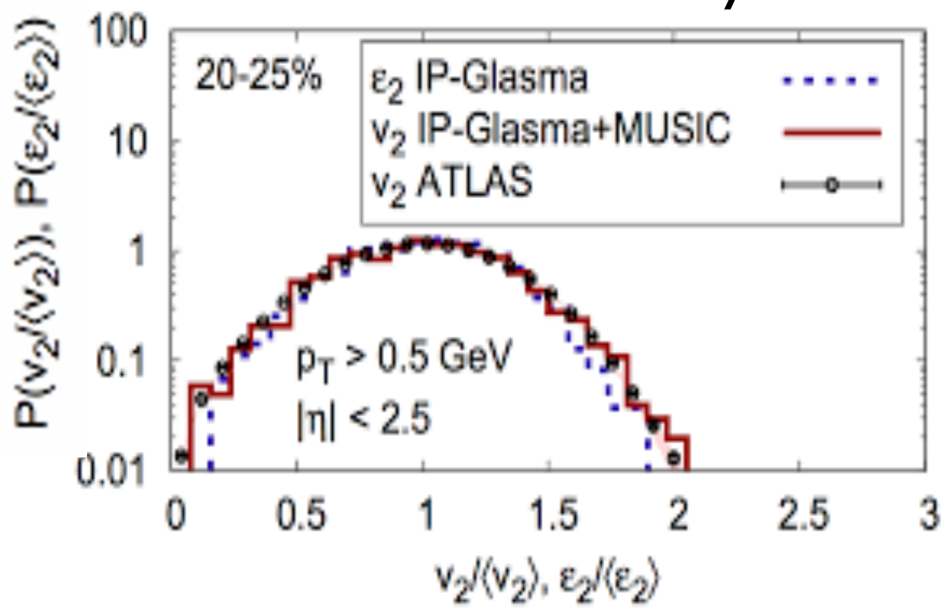
Radial flow

Anisotropy flow

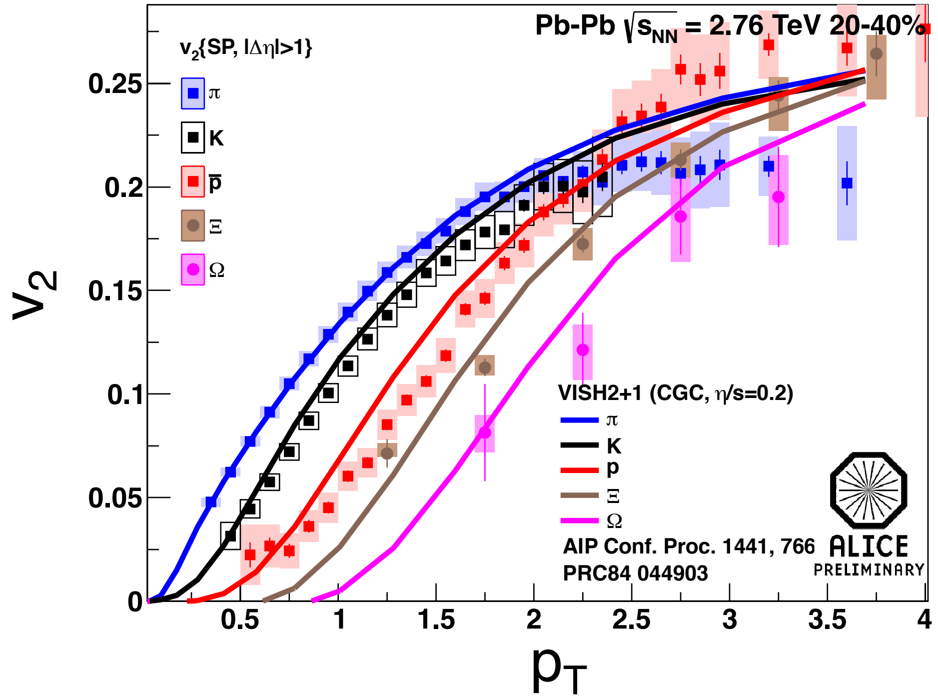
$\vec{V}_n = v_n e^{in\Psi_n}$

Collective flow in large systems

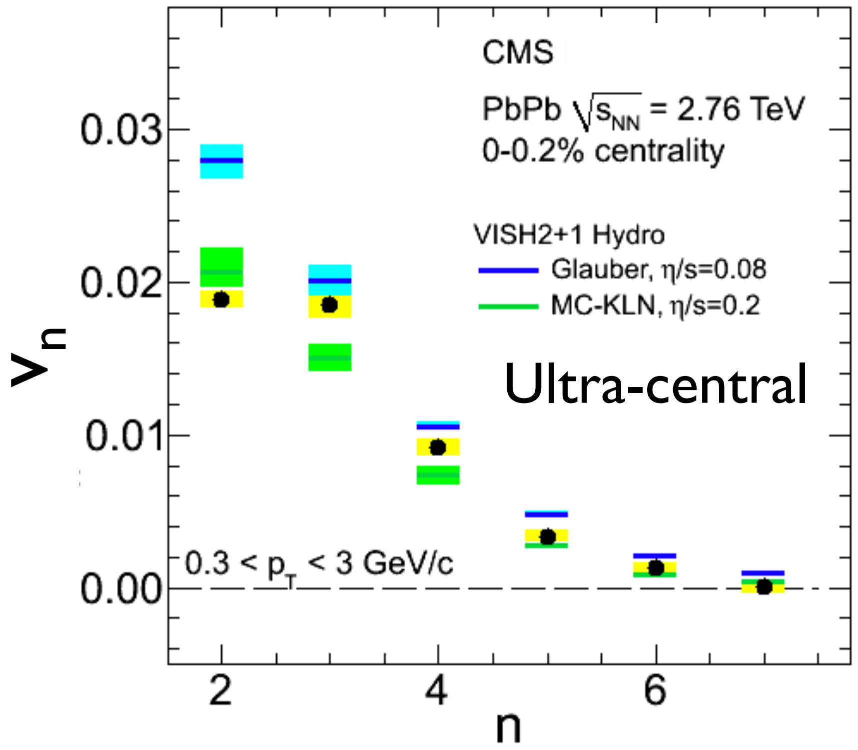
"Geometry" at work
event-by-event



"Mass ordering"



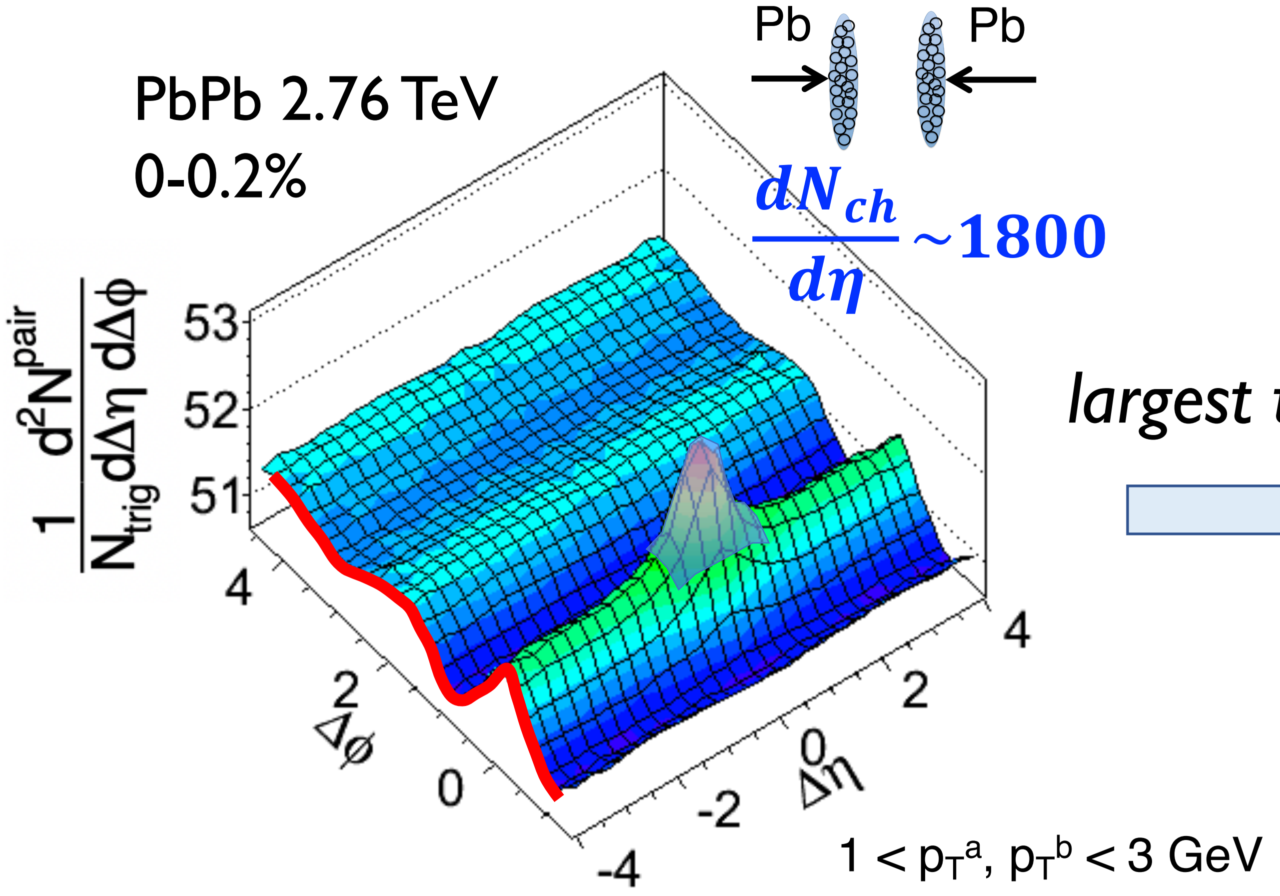
"Fine imprints" of QGP



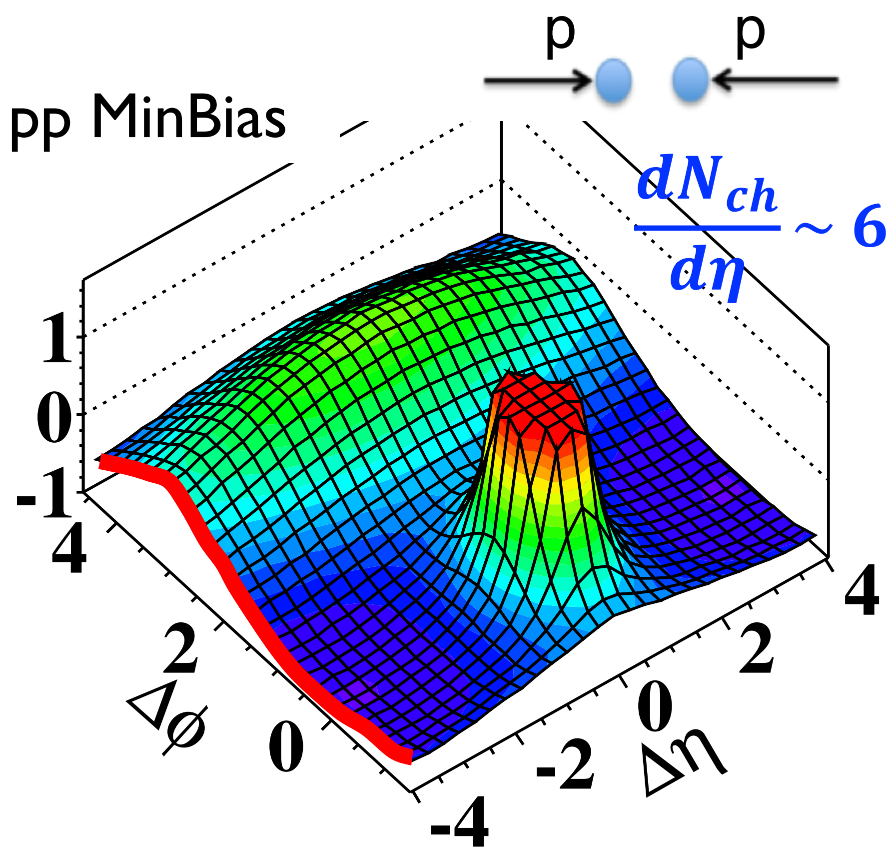
Some tension between v_2 vs v_3

- ✓ Described by nearly ideal (η/s ~ 0.08-0.2) hydro. – "perfect liquid"
- ✓ Initial "geometry" driven: $v_{2,3} = \kappa\varepsilon_{2,3}$

Collective flow in large systems

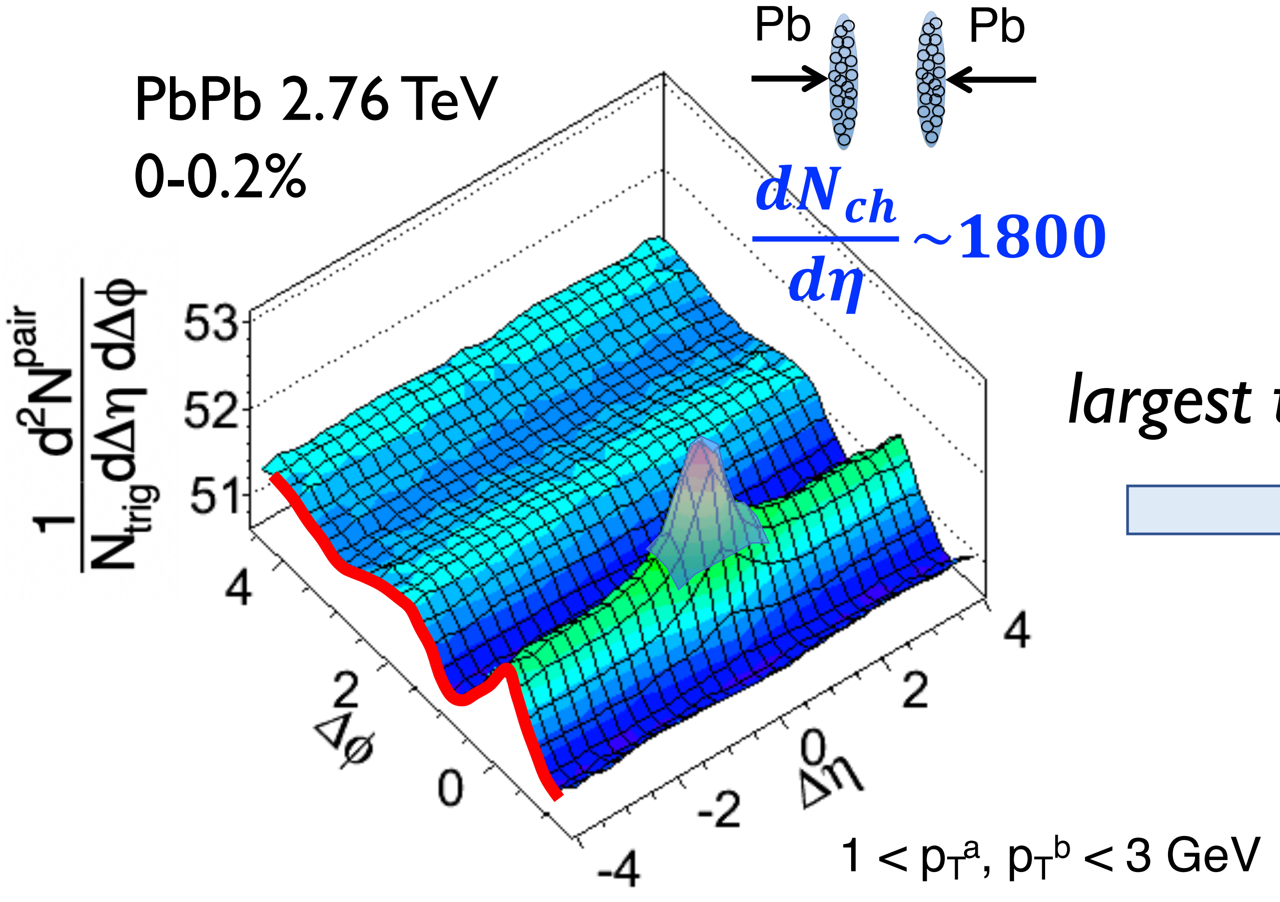


largest to smallest



Flow appears to disappear in pp

Collective flow in large systems



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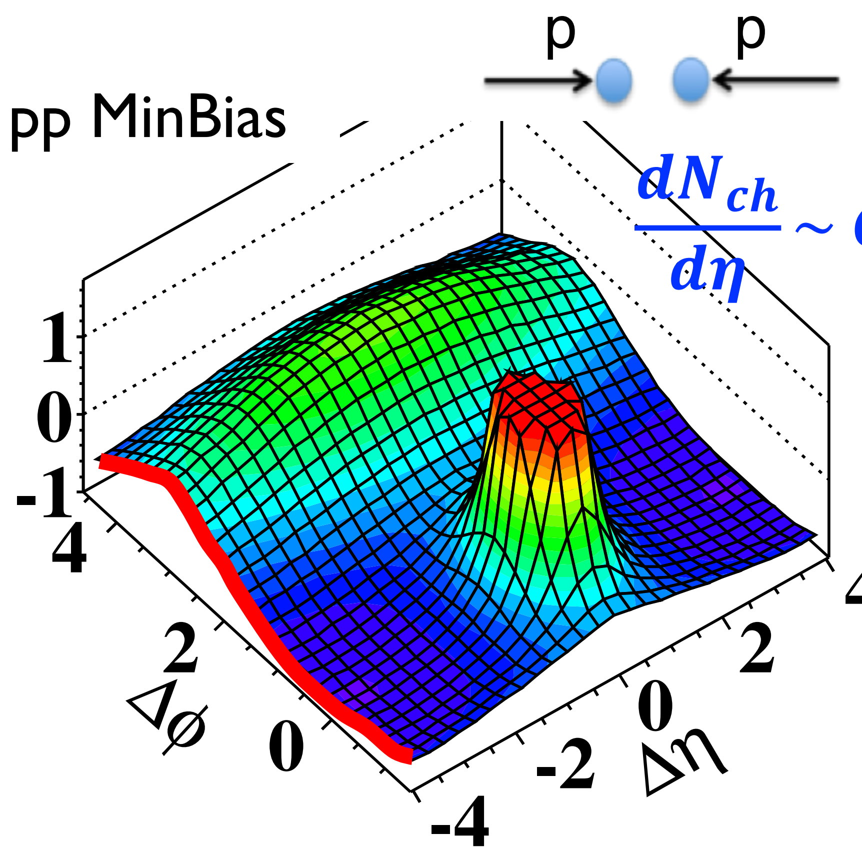
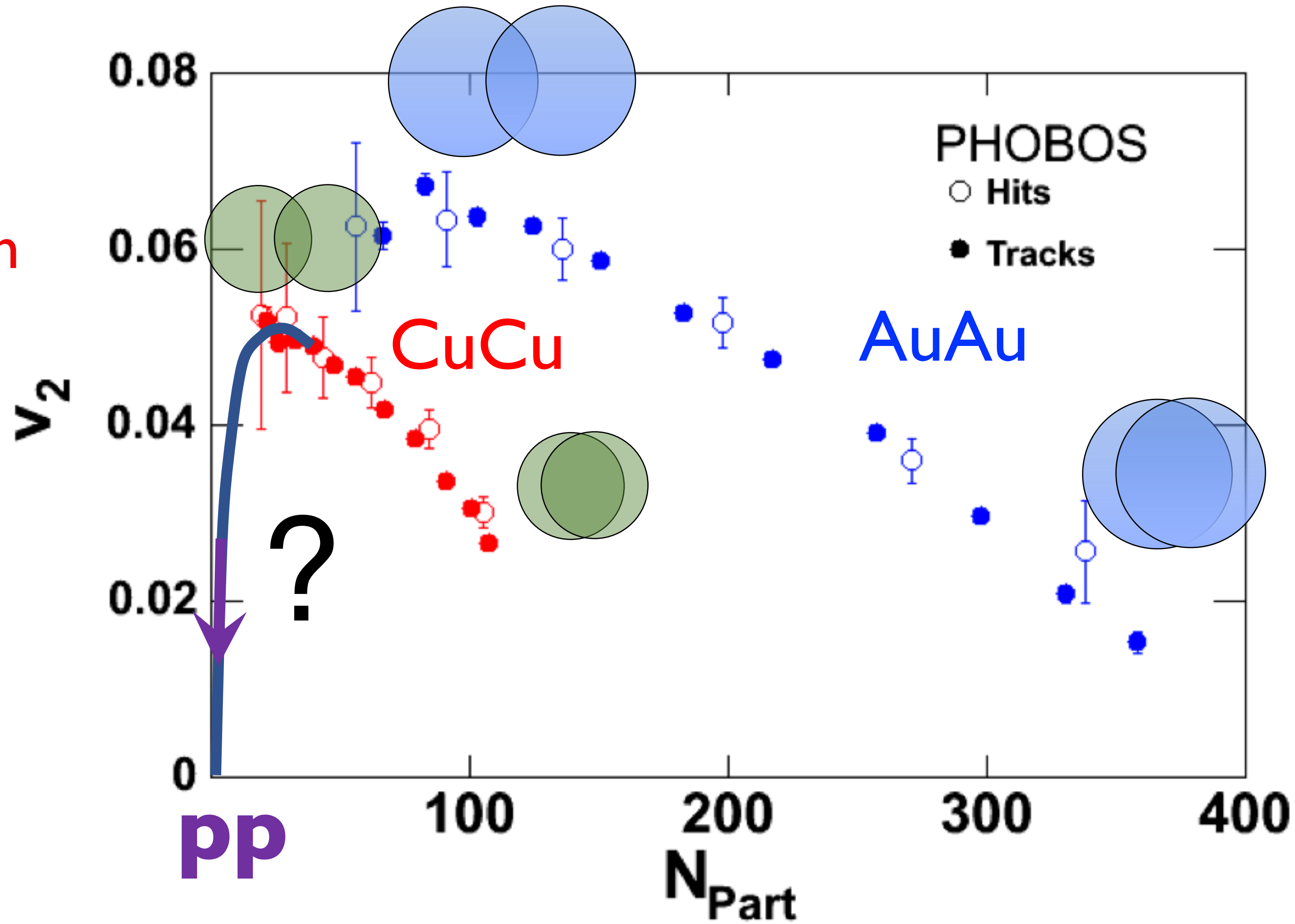


Flow appears to disappear in pp

- When and how does it turn off as system size decreases (or if at all)?
- Is "QGP" always a "perfect liquid" no matter how small it is?
  (QCD is intrinsically nonperturbative, as opposed to QED)

How small a "QGP fluid" can be?

Smaller CuCu system at RHIC (2005)



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Fermi (1950): statistical approach in pp

241.

HIGH ENERGY NUCLEAR EVENTS

« Progr. Theor. Theoret. Phys. », 5, 570–583 (1950).

ABSTRACT

A statistical method for computing high energy collisions of protons with multiple production of particles is discussed. The method consists in assuming that as a result of fairly strong interactions between nucleons and mesons the probabilities of formation of the various possibile numbers of particles are determined essentially by the statistical weights of the various possibilities.

1. INTRODUCTION.

The meson theory has been a dominant factor in the development of physics since it was announced fifteen years ago by Yukawa. One of its outstanding achievements has been the prediction that mesons should be produced in high energy nuclear collisions. At relatively low energies only one meson can be emitted. At higher energies multiple emission becomes possible.

In this paper an attempt will be made to develop a crude theoretical approach for calculating the outcome of nuclear collisions with very great energy. In particular, phenomena in which two colliding nucleons may give rise to several π–mesons, briefly called hereafter pions, and perhaps also to some anti-nucleons, will be discussed.

In treating this type of processes the conventional perturbation theory solution of the production and destruction of pions breaks down entirely. Indeed, the large value of the interaction constant leads quite commonly to situations in which higher approximations yield larger results than do lower approximations. For this reason it is proposed to explore the possibilities of a method that makes use of this fact. The general idea is the following:

When two nucleons collide with very great energy in their center of mass system this energy will be suddenly released in a small volume surrounding the two nucleons. We may think pictorially of the event as of a collision in which the nucleons with their surrounding retinue of pions hit against each other so that all the portion of space occupied by the nucleons and by their surrounding pion field will be suddenly loaded with a very great amount of energy. Since the interactions of the pion field are strong we may expect that rapidly this energy will be distributed among the various degrees of freedom present in this volume according to statistical laws. One can then compute statistically the probability that in this tiny volume a certain number of pions will be created with a given energy distribution. It is then assumed that the

Landau (1955): hydrodynamics in pp

88. A HYDRODYNAMIC THEORY OF MULTIPLE FORMATION OF PARTICLES

1. INTRODUCTION

Experiment shows that in collisions of very fast particles a large number of new particles are formed in multi-prong stars. The energy of the particles which produce such stars is of the order of 10^{12} eV or more. A characteristic feature is that such collisions occur not only between a nucleon and a nucleus but also between two nucleons. For example, the formation of two mesons in neutron–proton collisions has been observed at comparatively low energies, of the order of 10^9 eV, in cosmotron experiments[1].

Fermi[2,3] originated the ingenious idea of considering the collision process at very high energies by the use of thermodynamic methos. The main points of his theory are as follows.

(1) It is assumed that, when two nucleons of very high energy collide, energy is released in a very small volume V in their centre of mass system. Since the nuclear interaction is very strong and the volume is small, the distribution of energy will be determined by statistical laws. The collision of high-energy particles may therefore be treated without recourse to any specific theories of nuclear interaction.

(2) The volume V in which energy is released is determined by the dimensions of the meson cloud around the nucleons, whose radius is $\hbar/\mu c$, μ being the mass of the pion. But since the nucleons are moving at very high speeds, the meson cloud surrounding them will undergo a Lorentz contraction in the direction of motion. Thus the volume V will be, in order of magnitude,

$$V = \frac{4\pi}{3}\left(\frac{\hbar}{\mu c}\right)^3 \frac{2Mc^2}{E'}, \qquad (1.1)$$

where M is the mass of a nucleon and E' the nucleon energy in the centre of mass system.

(3) Fermi assumes that particles are formed, in accordance with the laws of statistical equilibrium, in the volume V at the instant of collision. The particles formed do not interact further with one another, but leave the volume in a "frozen" state.

С. З. Беленький и Л. Д. Ландау, Гидродинамическая теория множественного образования частиц, *Успехи Физических Наук*, 56, 309 (1955).
S. Z. Belenkij and L. D. Landau, Hydrodynamic theory of multiple production of particles, *Nuovo Cimento*, Supplement, 3, 15 (1956).

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Fermi National Accelerator Laboratory

FERMILAB-Conf-90/205-E
[E-735]

A Quark-Gluon Plasma Search in p̄–p at √s=1.8 TeV *

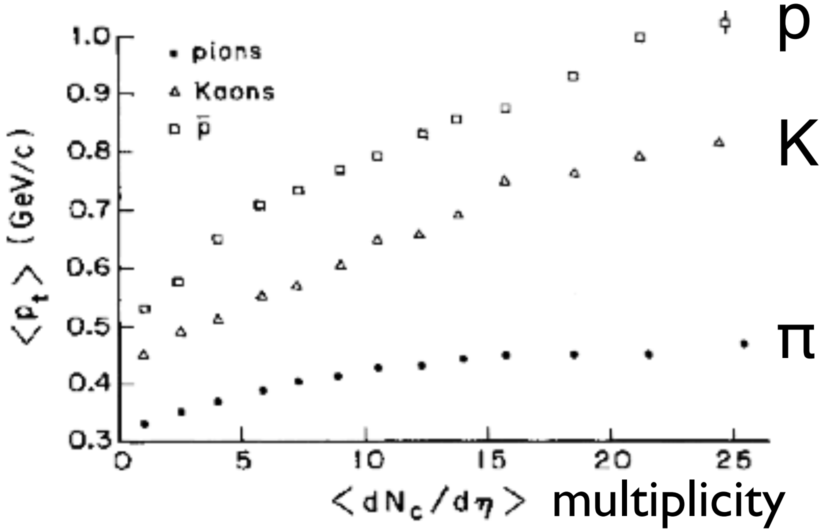
The E-735 Collaboration

presented by

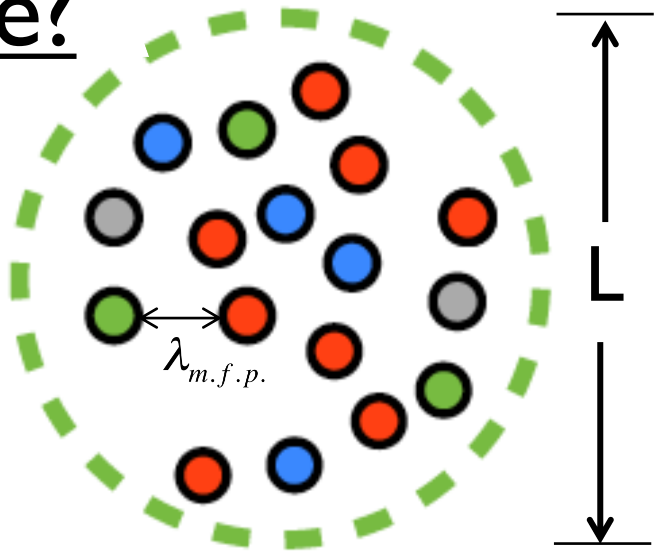
Frank Turkot
Fermi National Acceleraor Laboratory
P.O. Box 500
Batavia, Illinois 60510

October 8, 1990

PRD48, 984 (1993)



How small a "QGP fluid" can be?



Hydrodynamics applies when:

$$L >> \lambda_{m.f.p.}$$

where $\lambda_{m.f.p.} \sim \frac{1}{g^4 T}$

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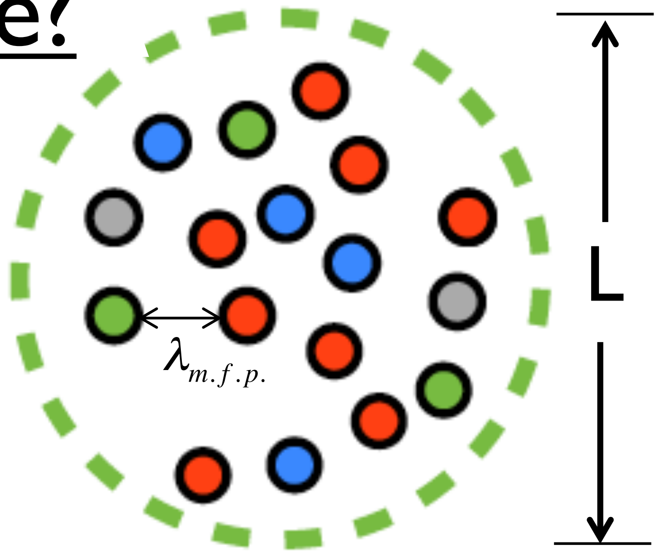


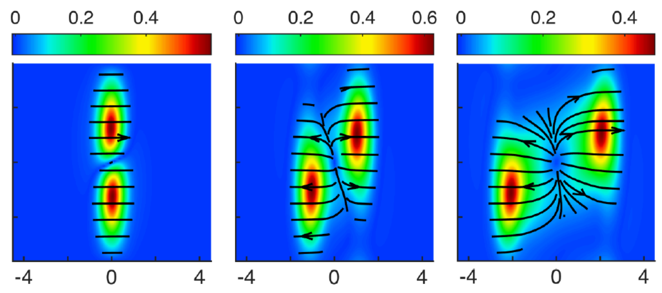
- For $g \sim 1$,

  ⇨ $LT >> 1$

OR

- In the limit of $g \to \infty$

  $LT \sim 1$



QGP fluid in pp

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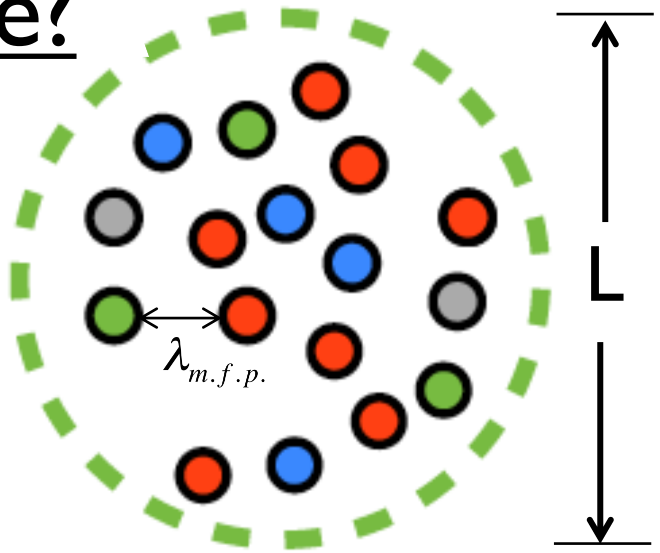

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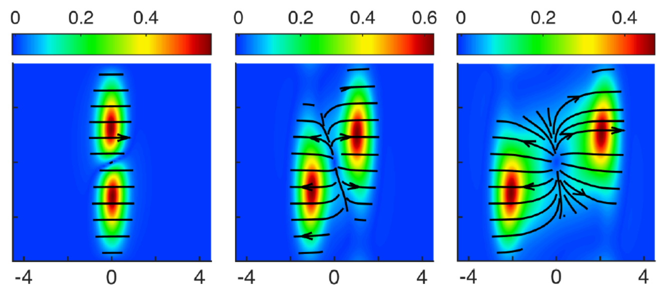

P. Chesler
QGP fluid in pp

Experimental handles:

$$N_{trk} \sim (LT)^3$$

$$\left(N_{trk}/L^3 \sim s \sim T^3\right)$$

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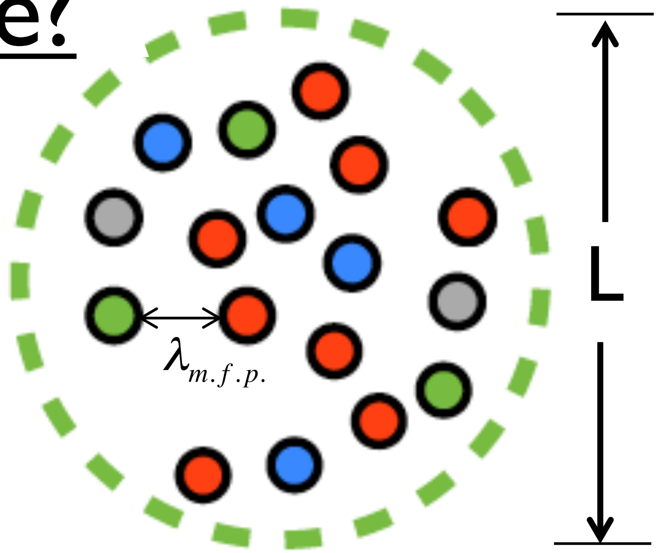

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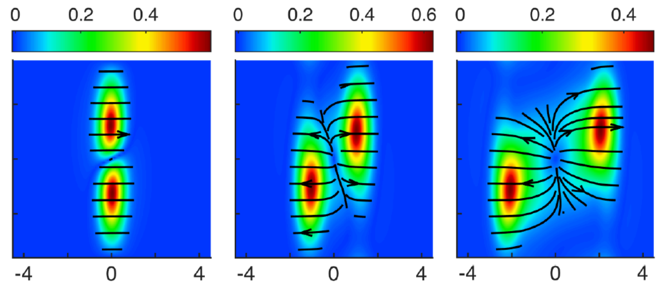

P. Chesler

QGP fluid in pp

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$$N_{trk} \sim (LT)^3$$

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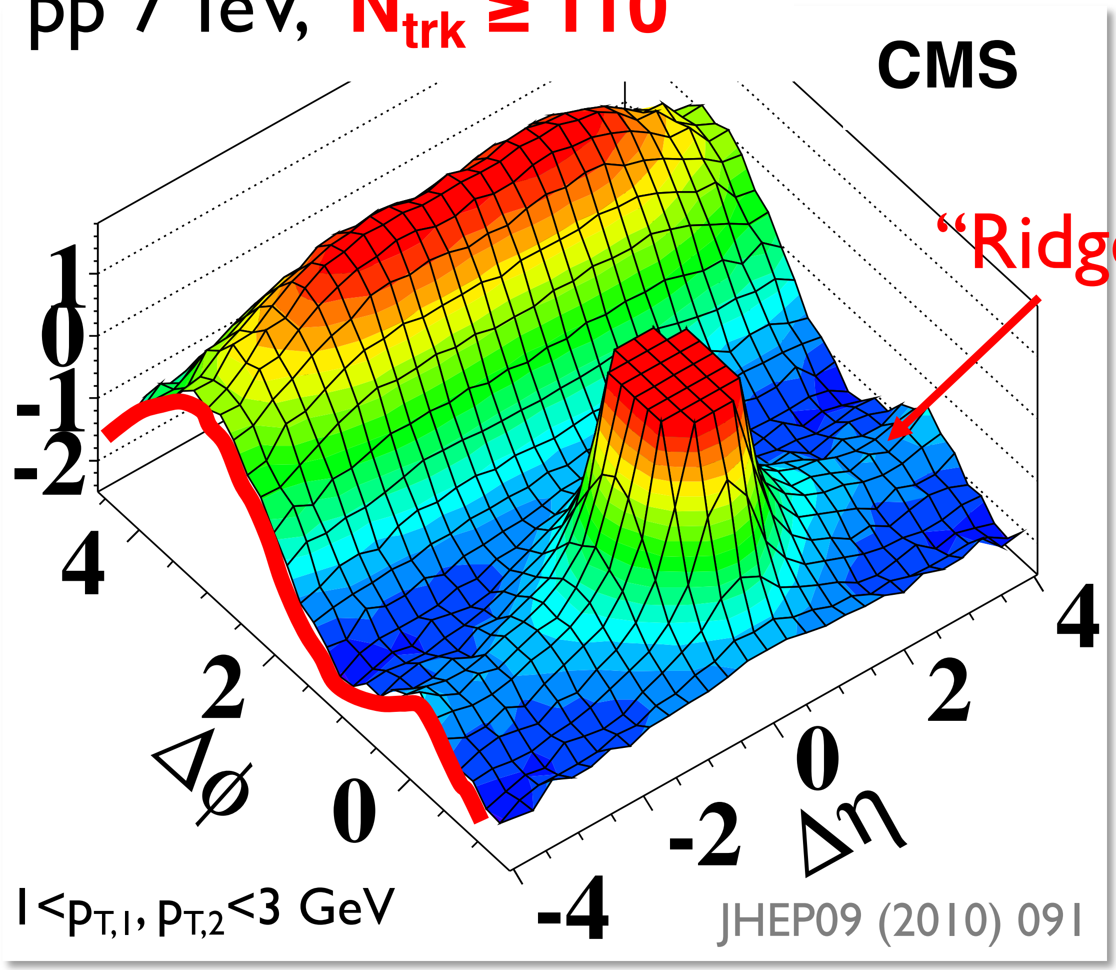
Pushing to extreme domains of applicability:

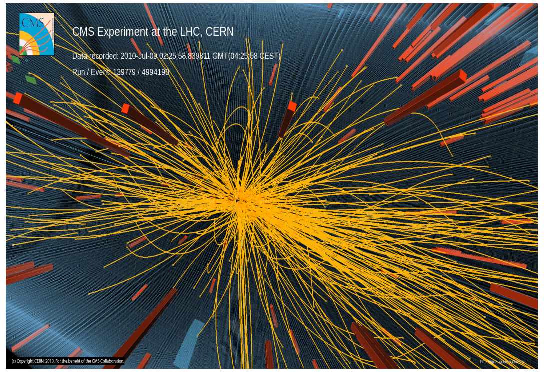
- ➢ *Small N_{trk}, L (and collision energy)?*
- ➢ *Different (hard) probes (to vary the coupling)*

Observation of “flow” in small systems

pp 7 TeV, **$N_{trk} \geq 110$**



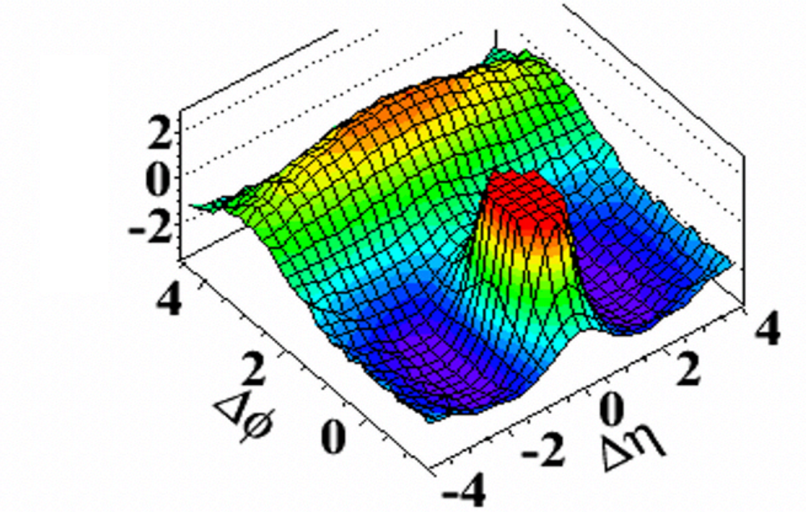
Rare, high multiplicity pp, N_{trk}>110



Small L, but large N_{trk}

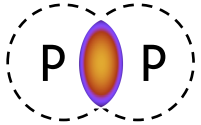
O(10^{-6}) most violent events

PYTHIA8, **$N_{trk} \geq 110$**



NO “ridge” in MC models

A QGP droplet at sub-fermi scales in pp?

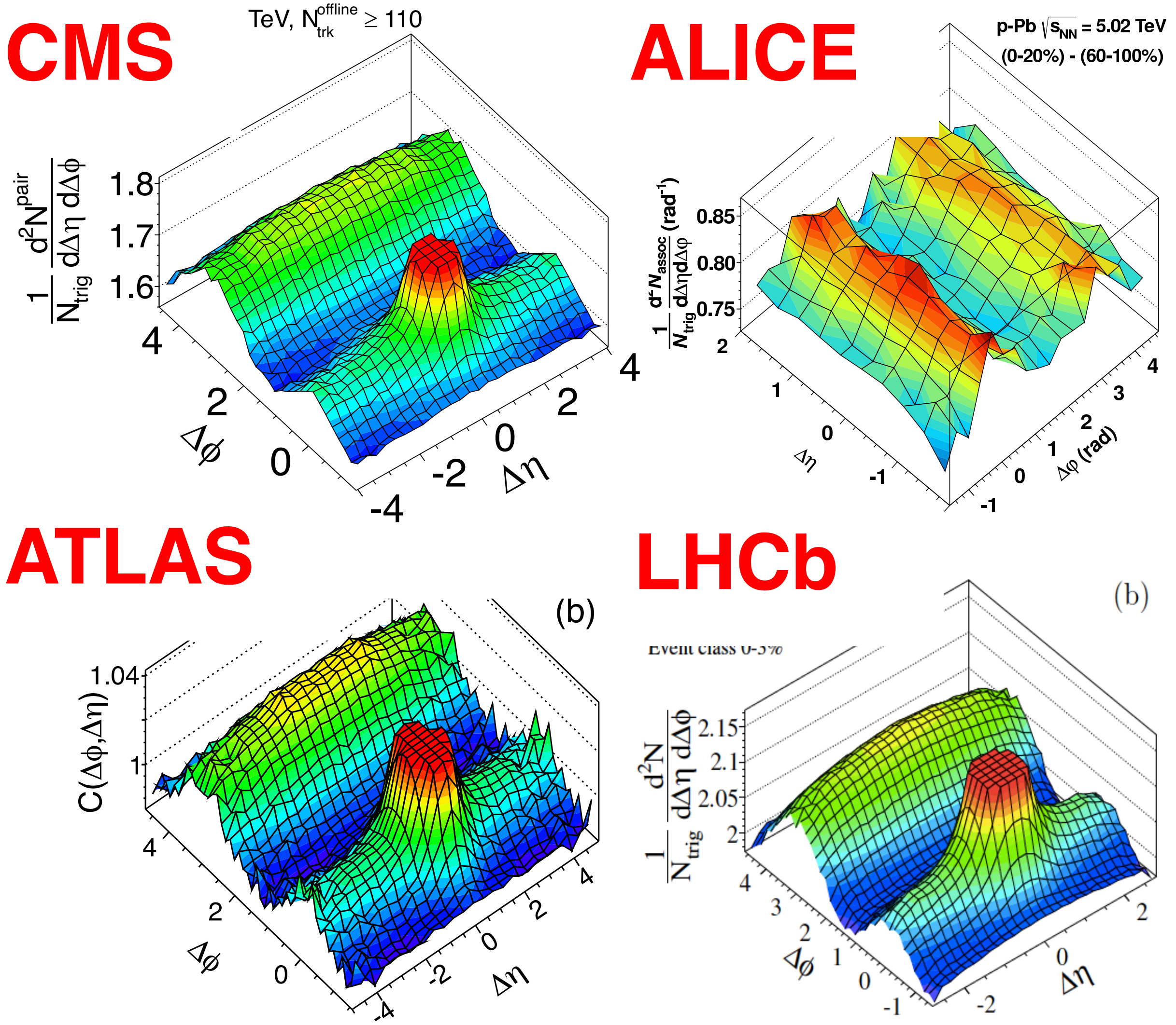


?

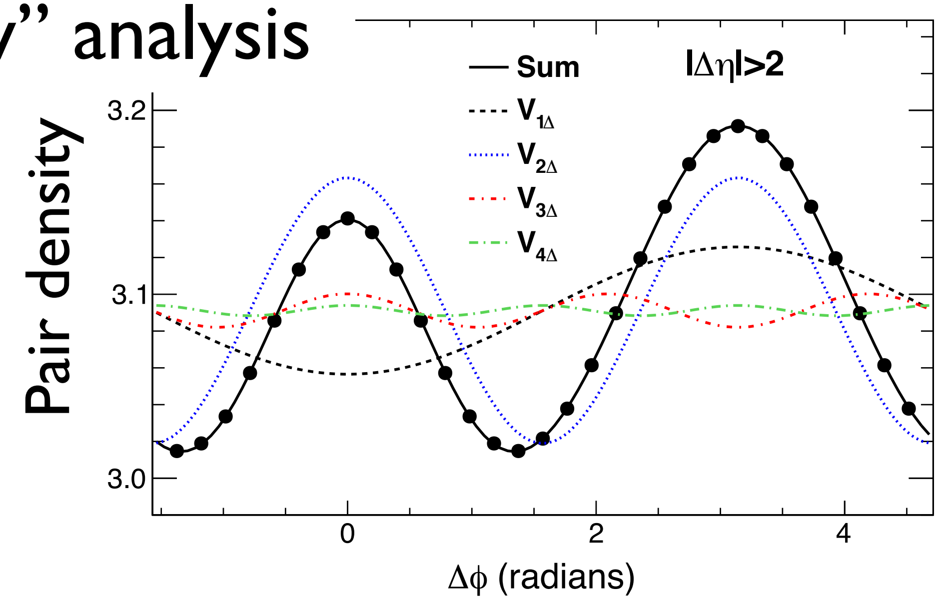
Or there is NO QGP anywhere?!

Observation of "flow" in small systems

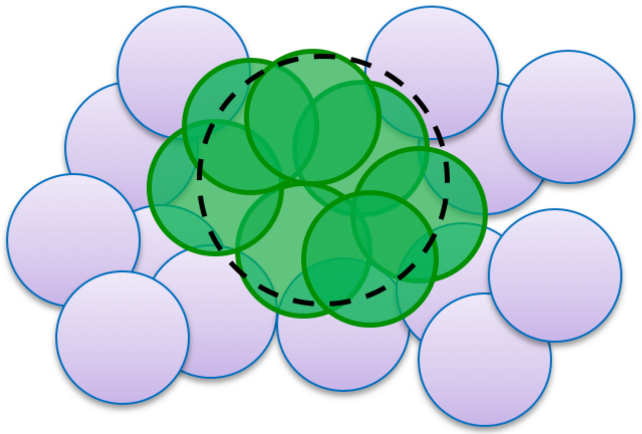
Ridge tsunami in pA at the LHC (>2012)



"Flow" analysis



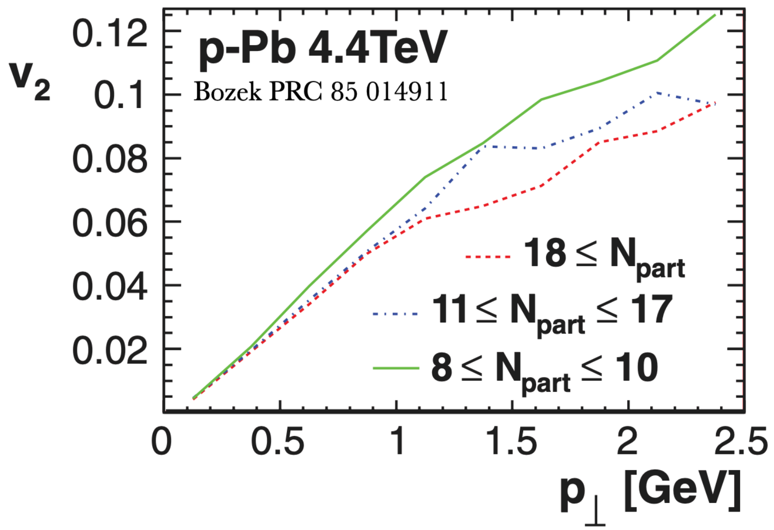
Geometry in pA



Proton projectile

Nucleus Participants

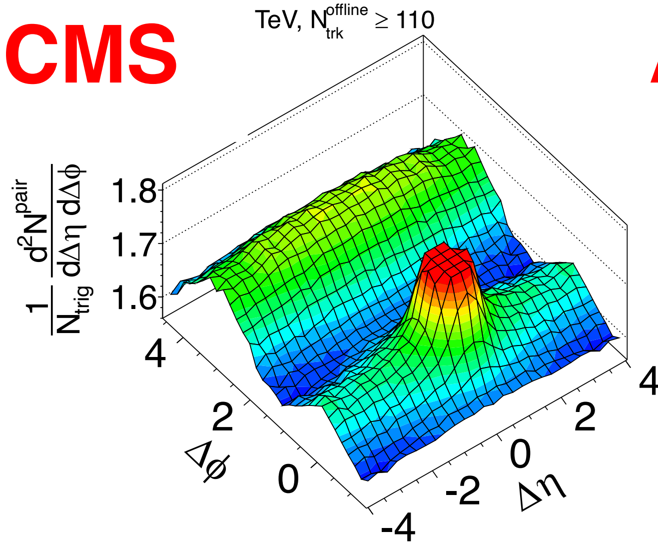
Hydro. prediction



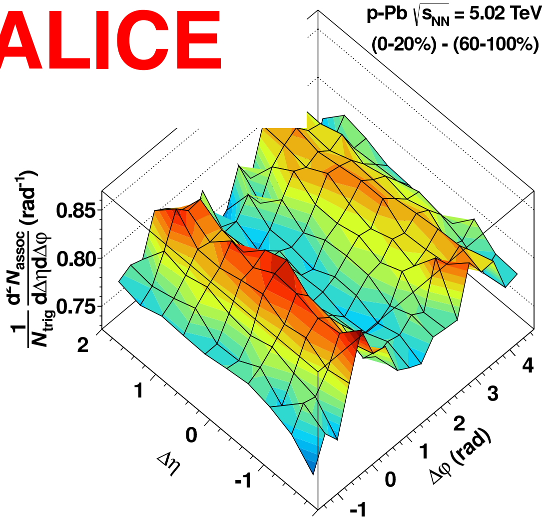
Observation of “flow” in small systems

Ridge tsunami in pA at the LHC (>2012)

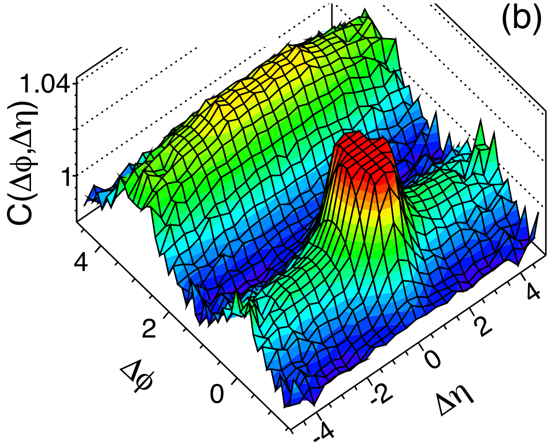
CMS



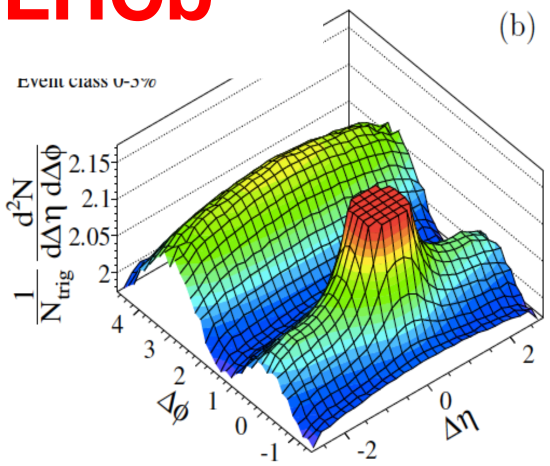
ALICE



ATLAS



LHCb



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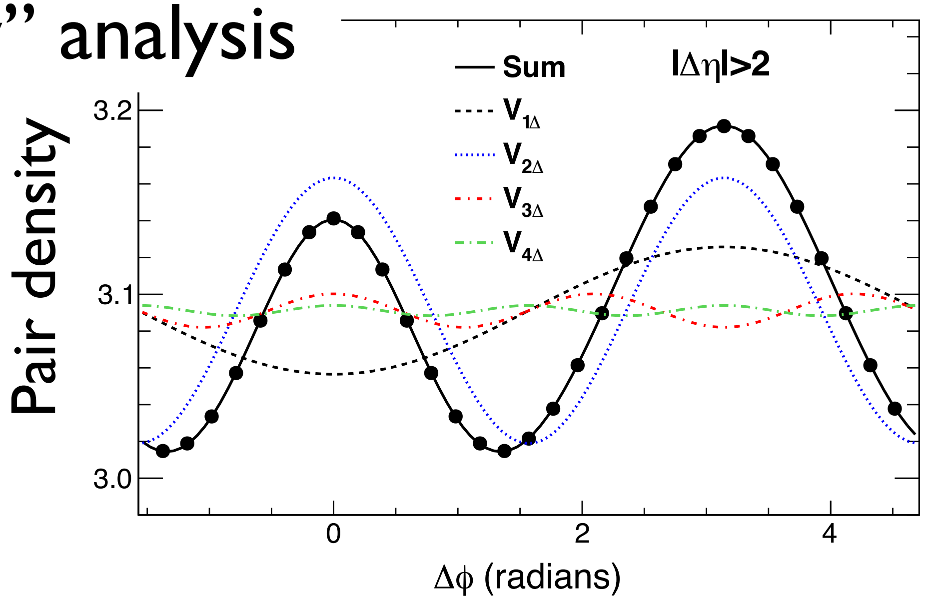

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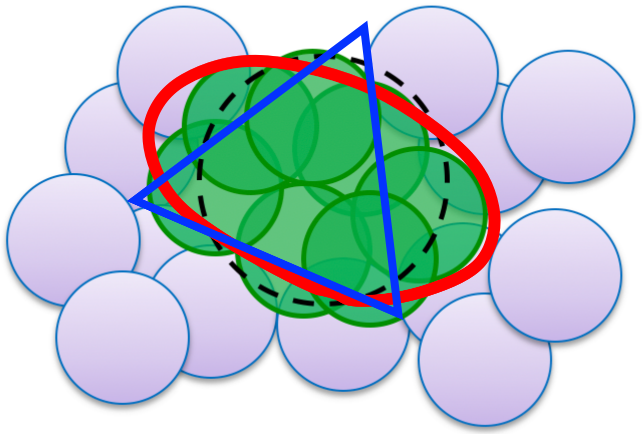

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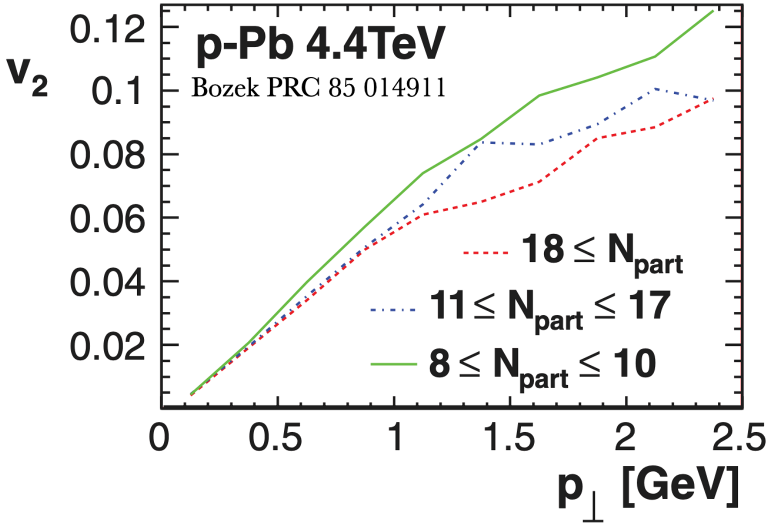
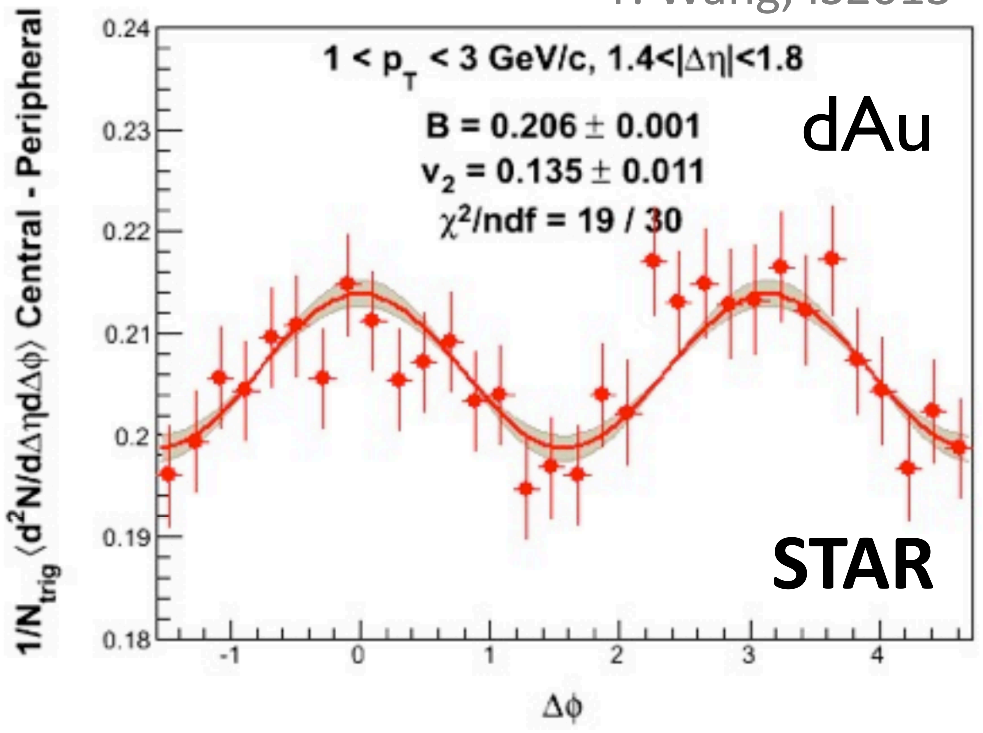


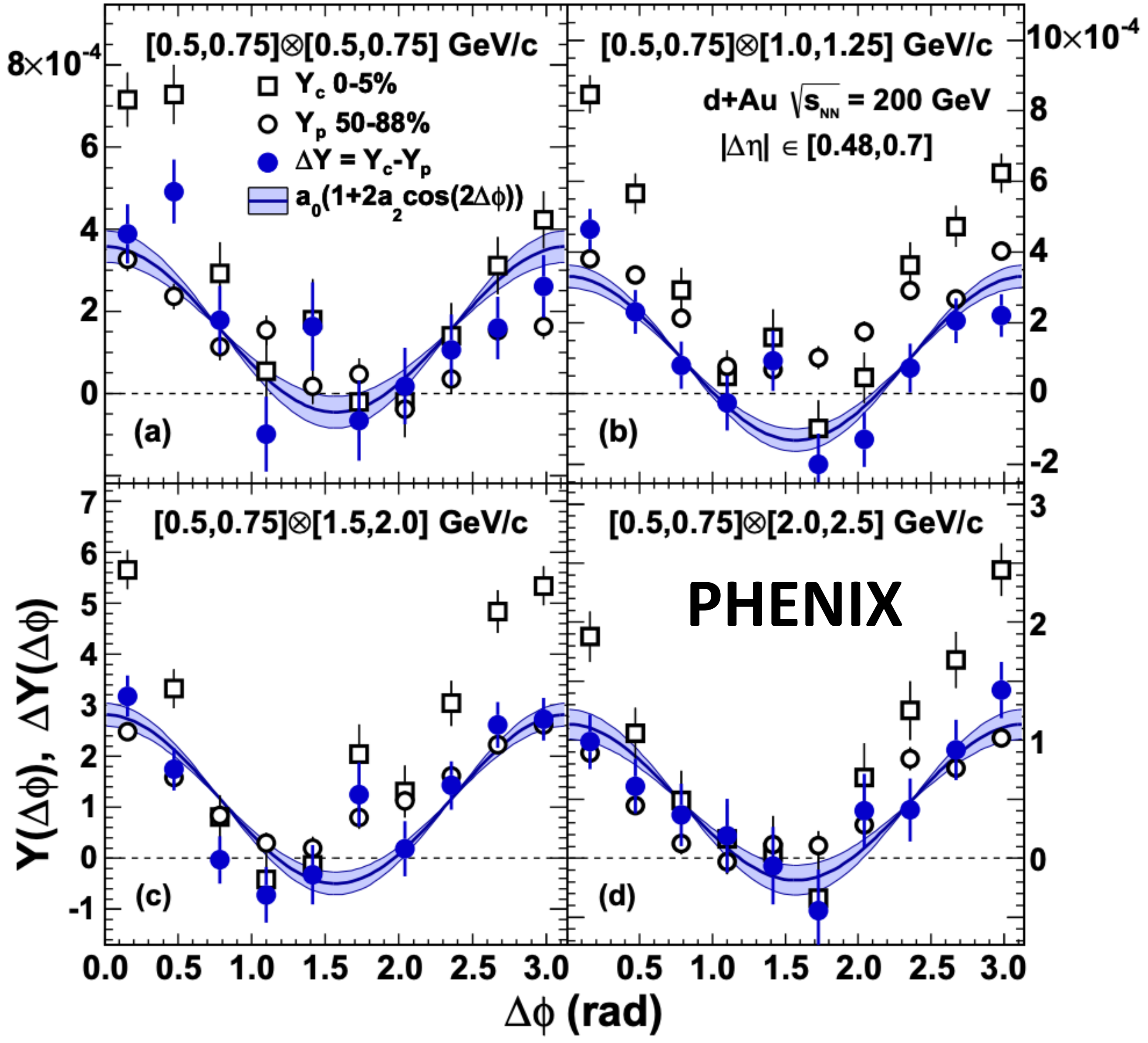
Observation of "flow" in small systems

Ridge in dAu at RHIC
(data taken in 2008)

F. Wang, IS2013



PHENIX, PRL 111, 212301 (2013)



Origin of the ridge in small systems?

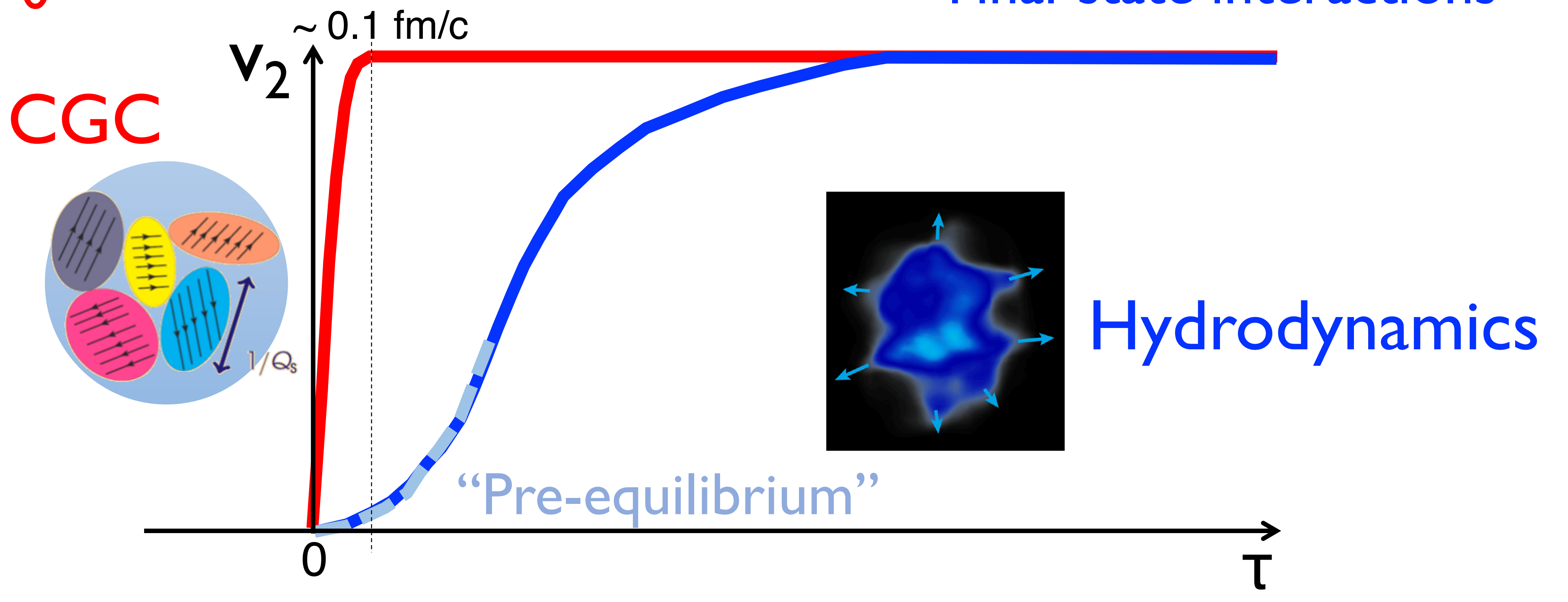
Initial-State Correlations (ISC)

- Momentum collectivity at t ~ 0

vs.

Final-State Correlations (FSC)

- Initial geometry driven
- Final-state interactions



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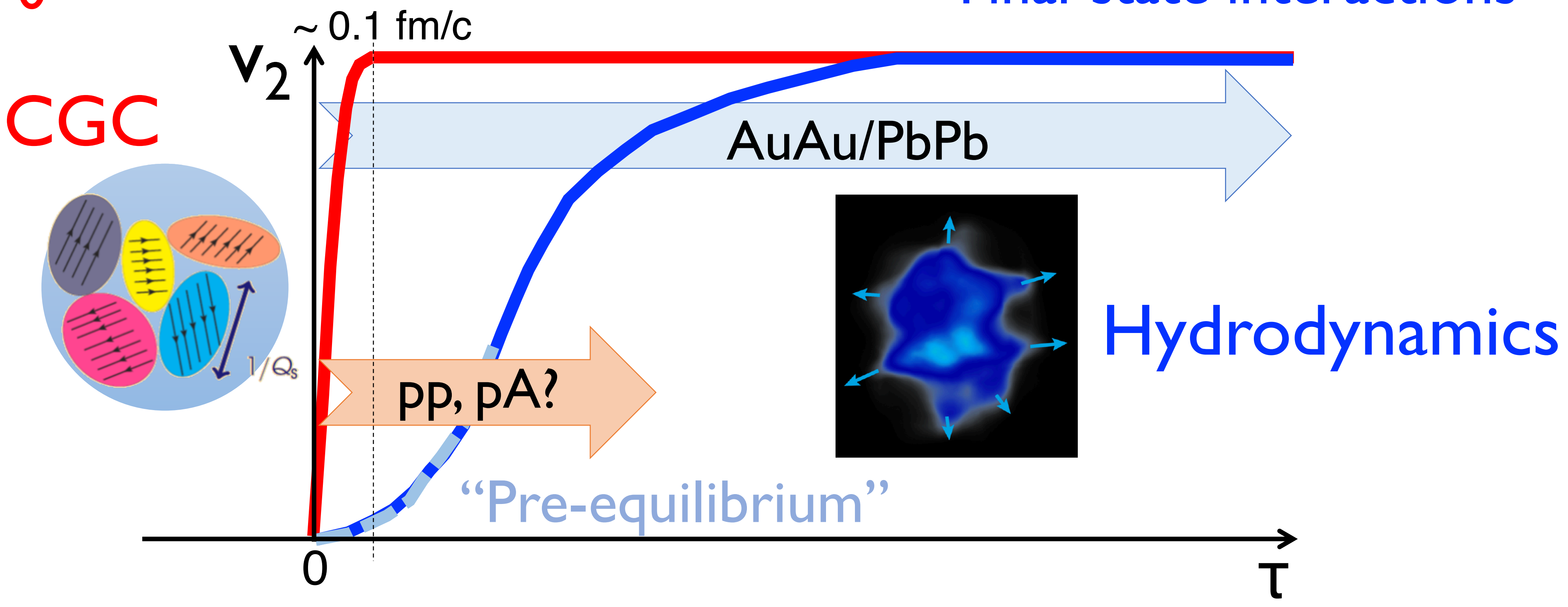

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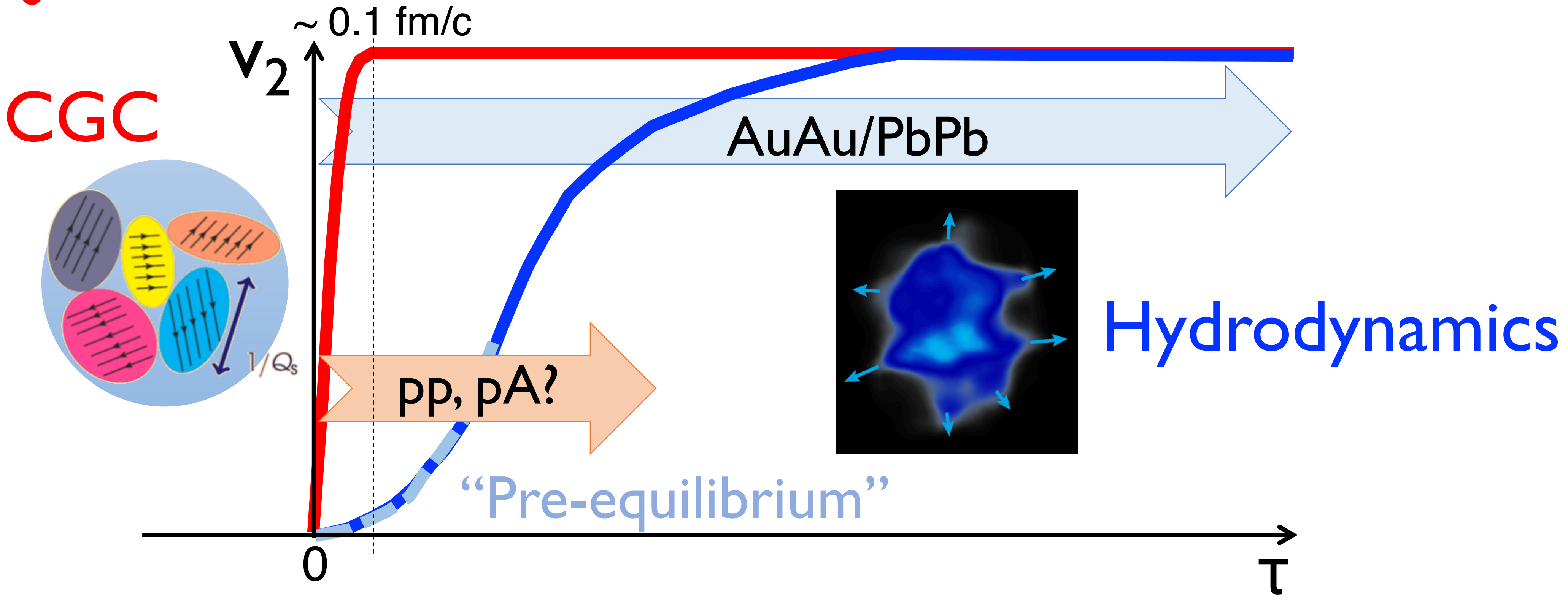
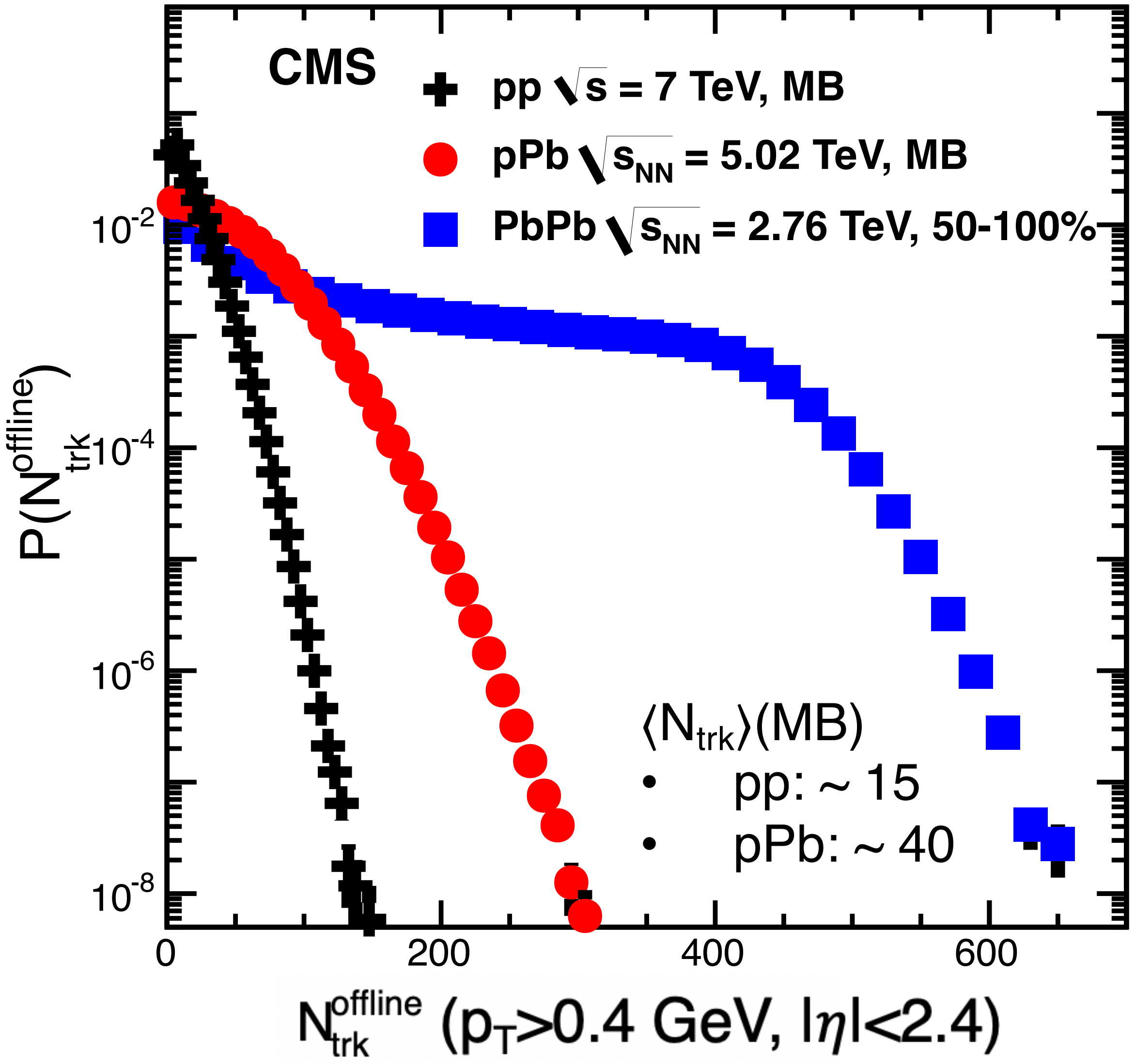


Pushing the boundaries of knowledge to extreme domains

➢ Is there evidence/need for "new" physics?

Centrality vs. Event Activity (N_{trk}) classification



Centrality in AA has a geometric meaning but NOT the case in small system (pp, pA)

- L and N_{trk} vary together in AA while L is more or less fixed in pp/pA

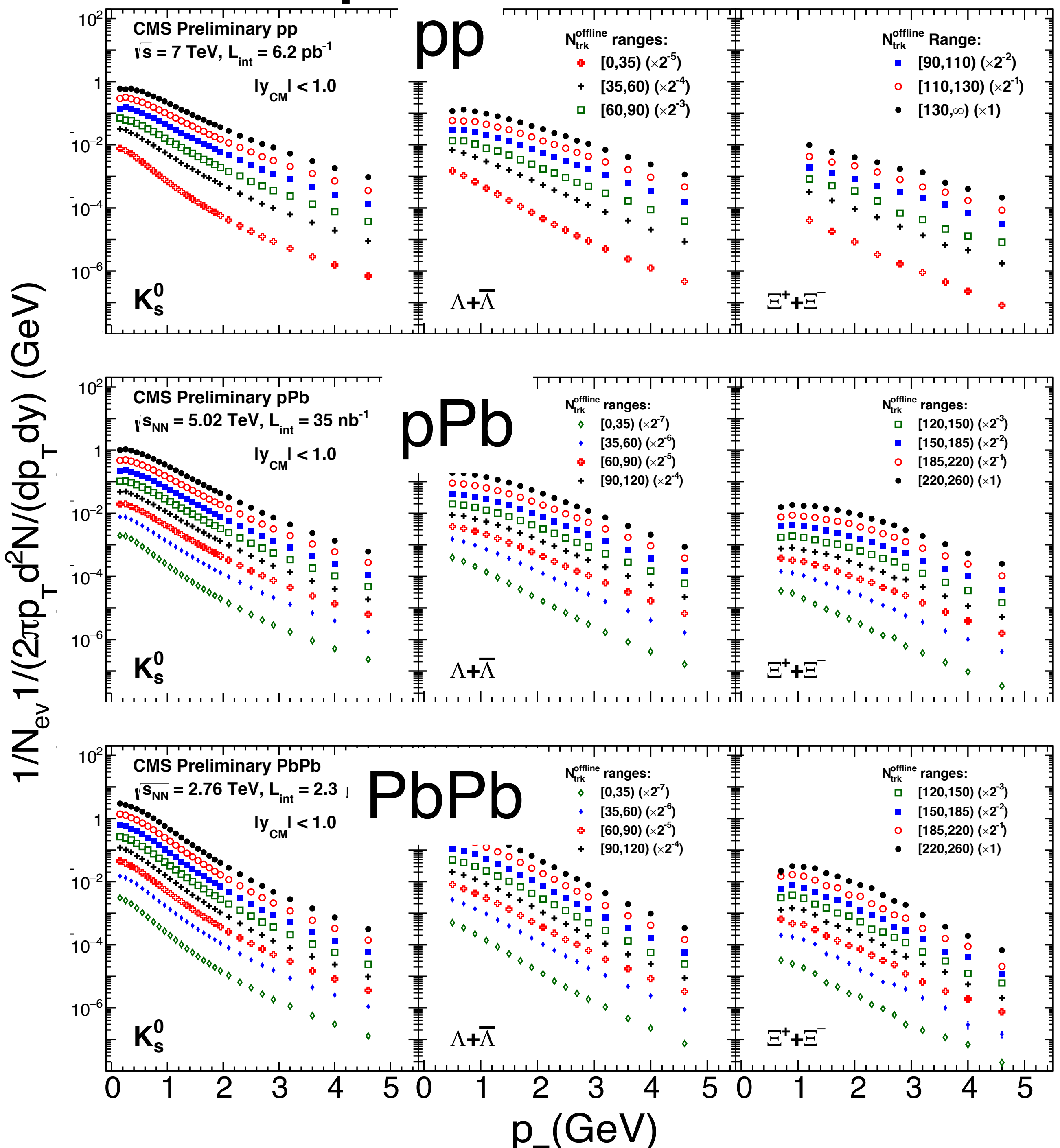
Event activity represents the "system size"

- drawbacks: experiment dependent

$N_{trk}^{offline}$	Fraction			$\langle N_{trk}^{offline} \rangle$			$\langle N_{trk}^{corrected} \rangle$		
	5 TeV	7 TeV	13 TeV	5 TeV	7 TeV	13 TeV	5 TeV	7 TeV	13 TeV
MB	1.0	1.0	1.0	13	15	16	16±1	17±1	19±1
[0, 10)	0.48	0.44	0.43	4.8	4.8	4.8	5.8±0.3	5.5±0.2	5.9±0.3
[10, 20)	0.29	0.28	0.26	14	14	14	17±1	16±1	17±1
[20, 30)	0.14	0.15	0.15	24	24	24	28±1	28±1	30±1
[30, 40)	0.06	0.08	0.08	34	34	34	41±2	40±2	42±2
[40, 60)	0.03	0.05	0.07	47	47	47	56±2	54±2	58±2
[60, 85)	3×10^{-3}	7×10^{-3}	0.02	66	67	68	80±3	78±3	83±3
[85, 95)	9×10^{-5}	3×10^{-4}	1×10^{-3}	88	89	89	106±4	103±4	109±4
[95, 105)	2×10^{-5}	9×10^{-5}	5×10^{-4}	98	99	99	118±5	114±4	121±5
[105, 115)	5×10^{-6}	2×10^{-5}	2×10^{-4}	108	109	109	130±5	126±5	133±5
[115, 125)	1×10^{-6}	8×10^{-6}	6×10^{-5}	118	118	119	142±6	137±5	145±6
[125, 135)	2×10^{-7}	2×10^{-6}	2×10^{-5}	126	128	129	153±6	149±6	157±6
[135, 150)	5×10^{-8}	4×10^{-7}	8×10^{-6}	139	140	140	167±7	162±6	171±7
[150, ∞)	5×10^{-9}	8×10^{-8}	2×10^{-6}	155	156	158	186±8	181±7	193±8

Provide full information if possible

Spectra and "radial flow" in small systems

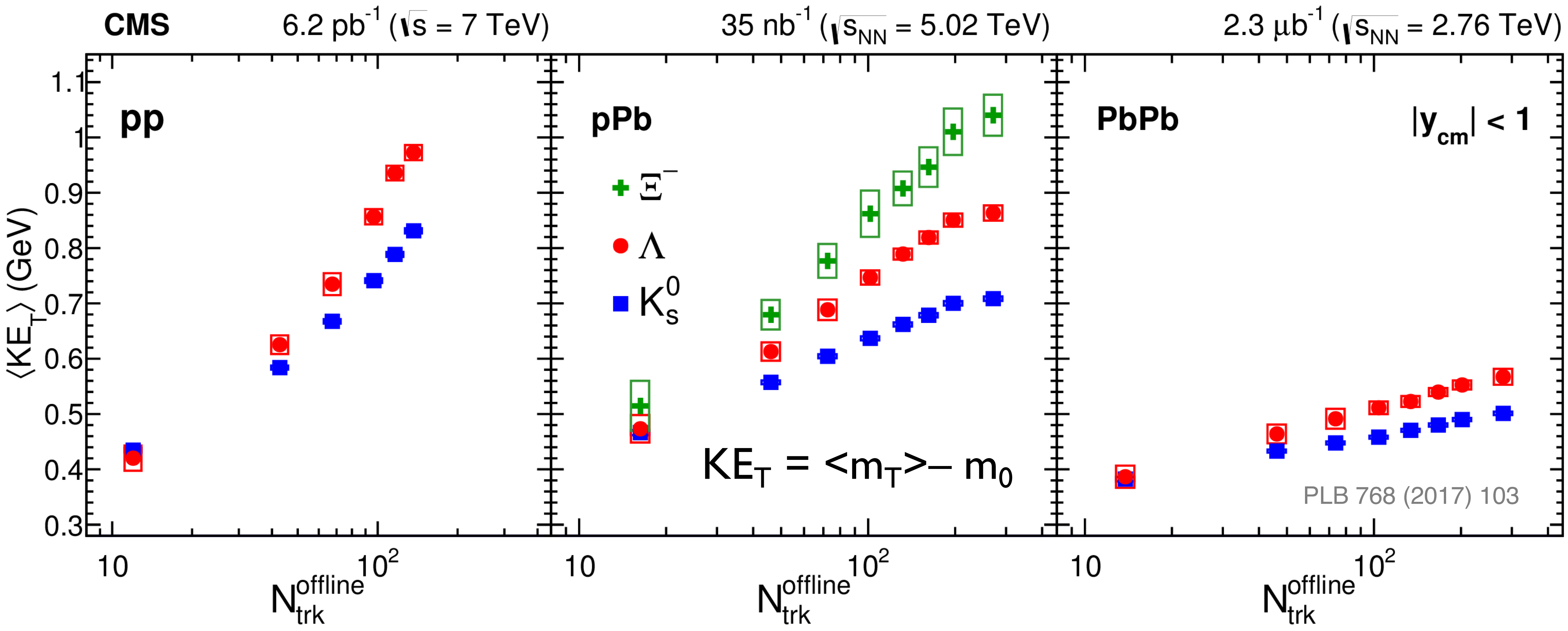


$|y_{cm}|<1$

How does spectra shape evolves with

- particle species
- N_{trk}
- system size
- particle rapidity

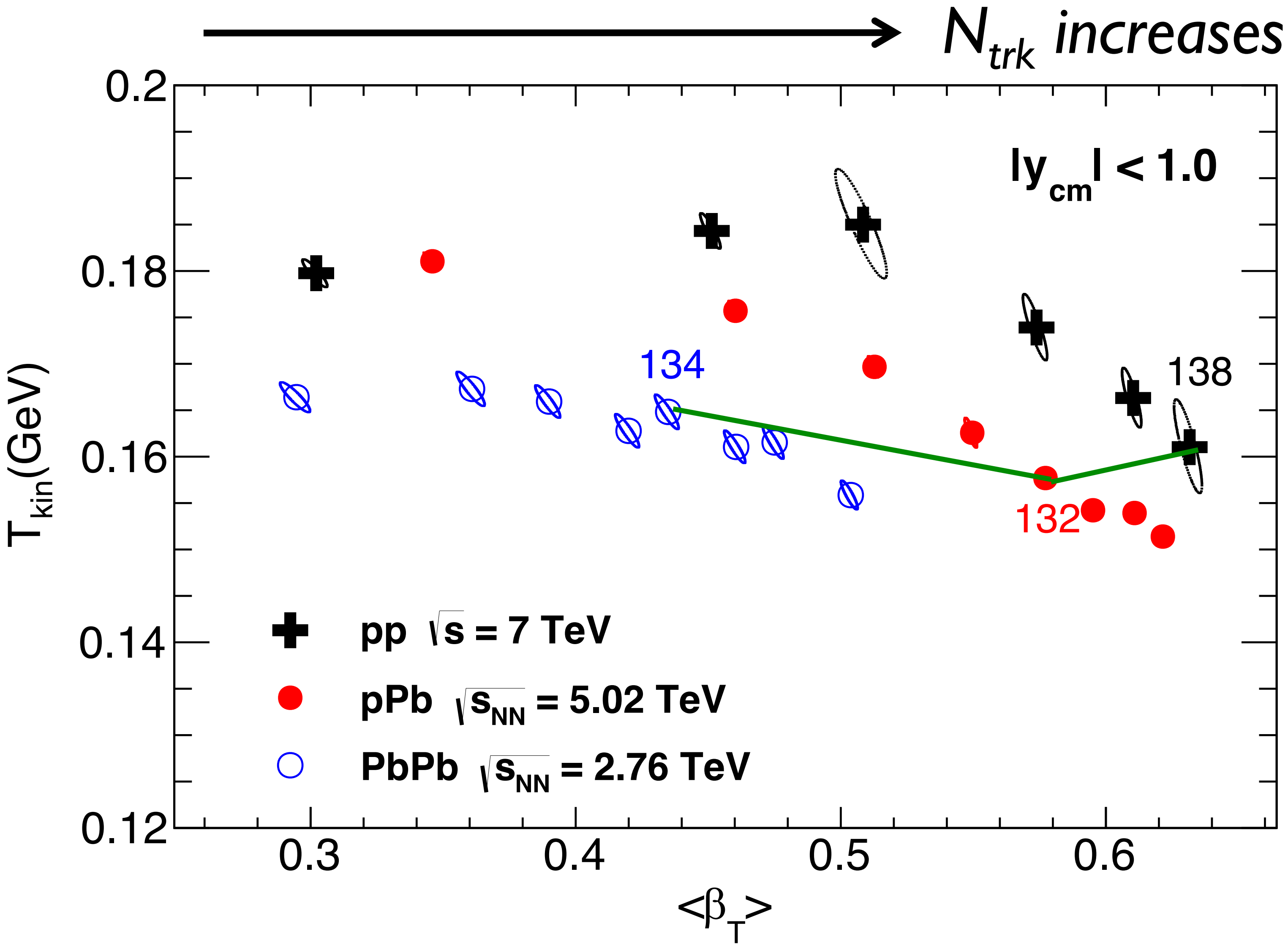
Spectra and "radial flow" in small systems



Mass-dependent splitting of KE_T as N_{trk} increases, faster in small systems

– common velocity field

Spectra and "radial flow" in small systems



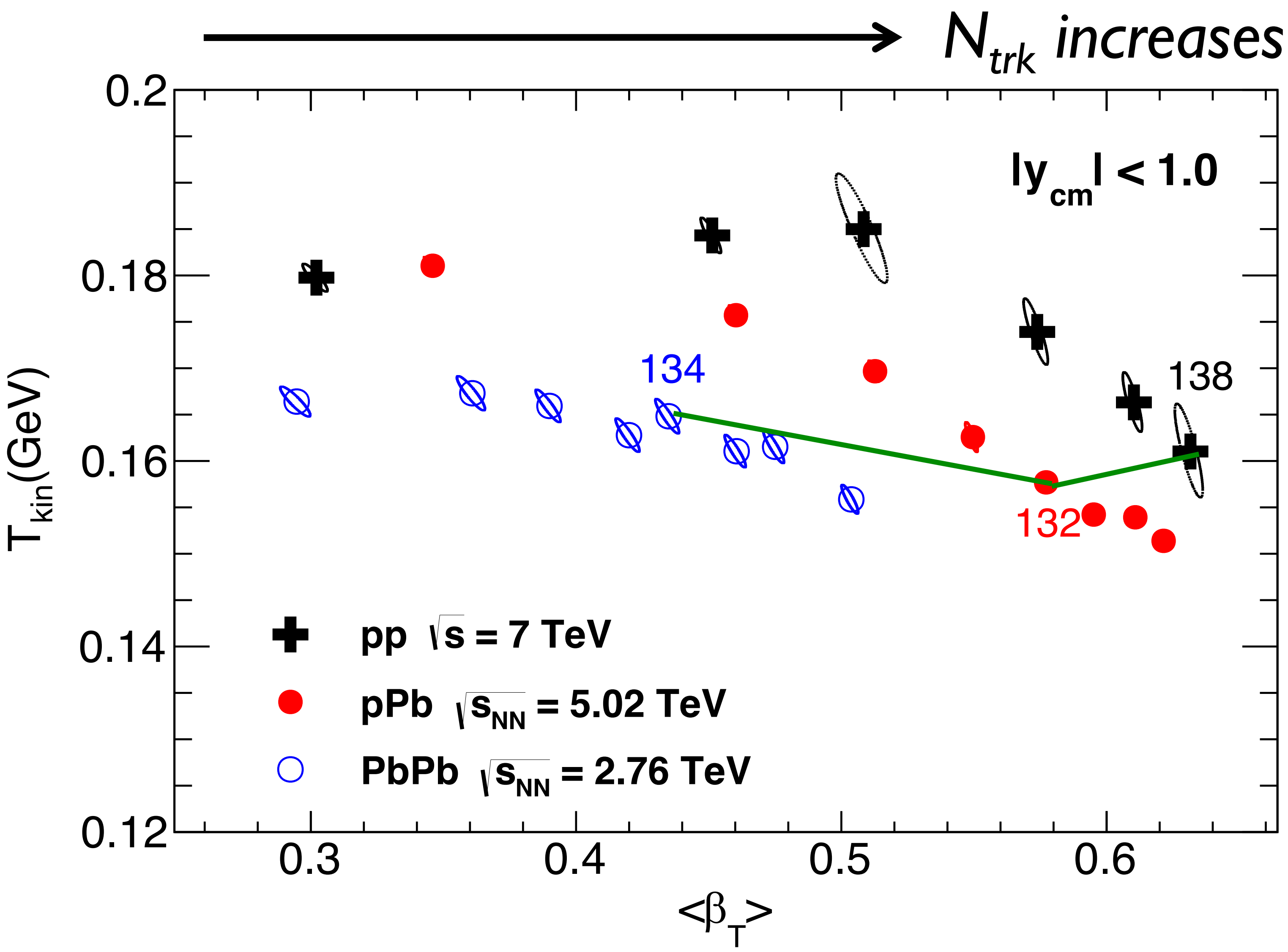
Simultaneous Blast-Wave fits:

$$\langle\beta_T\rangle_{pp} > \langle\beta_T\rangle_{pPb} > \langle\beta_T\rangle_{PbPb}$$

for similar N_{trk}

Some features reproduced by color reconnection model

Spectra and "radial flow" in small systems



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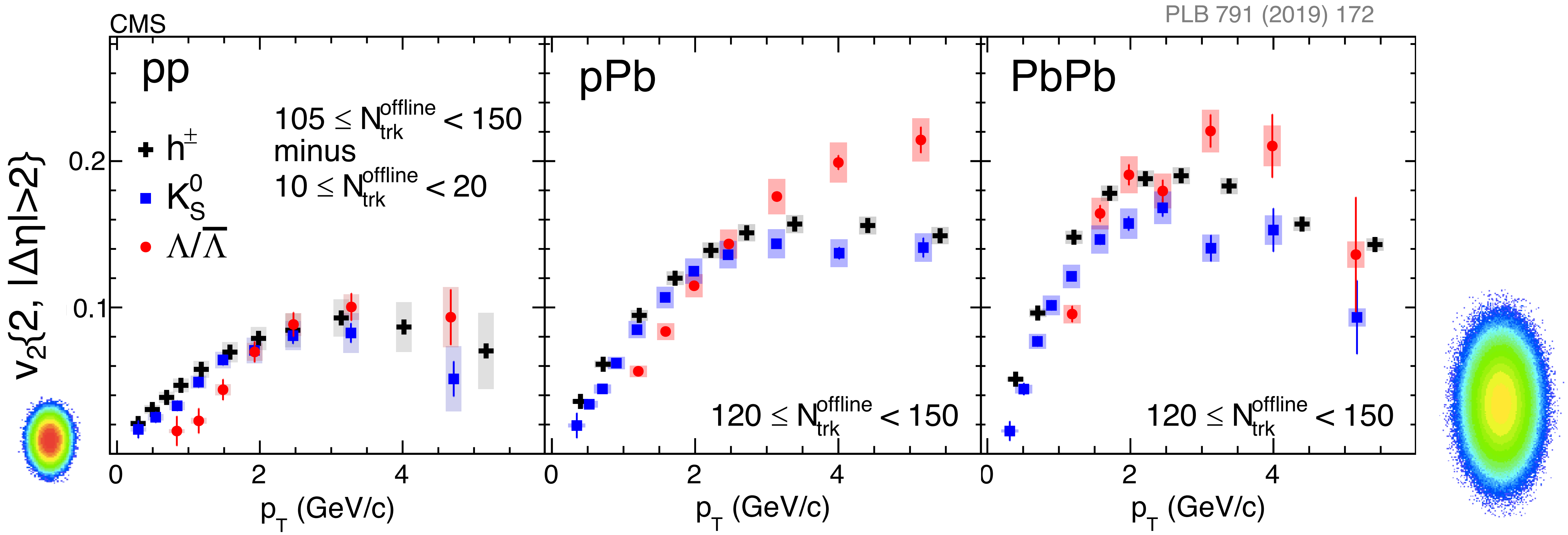
for similar N_{trk}

Smaller QGP more explosive?!

Some features reproduced by color reconnection model

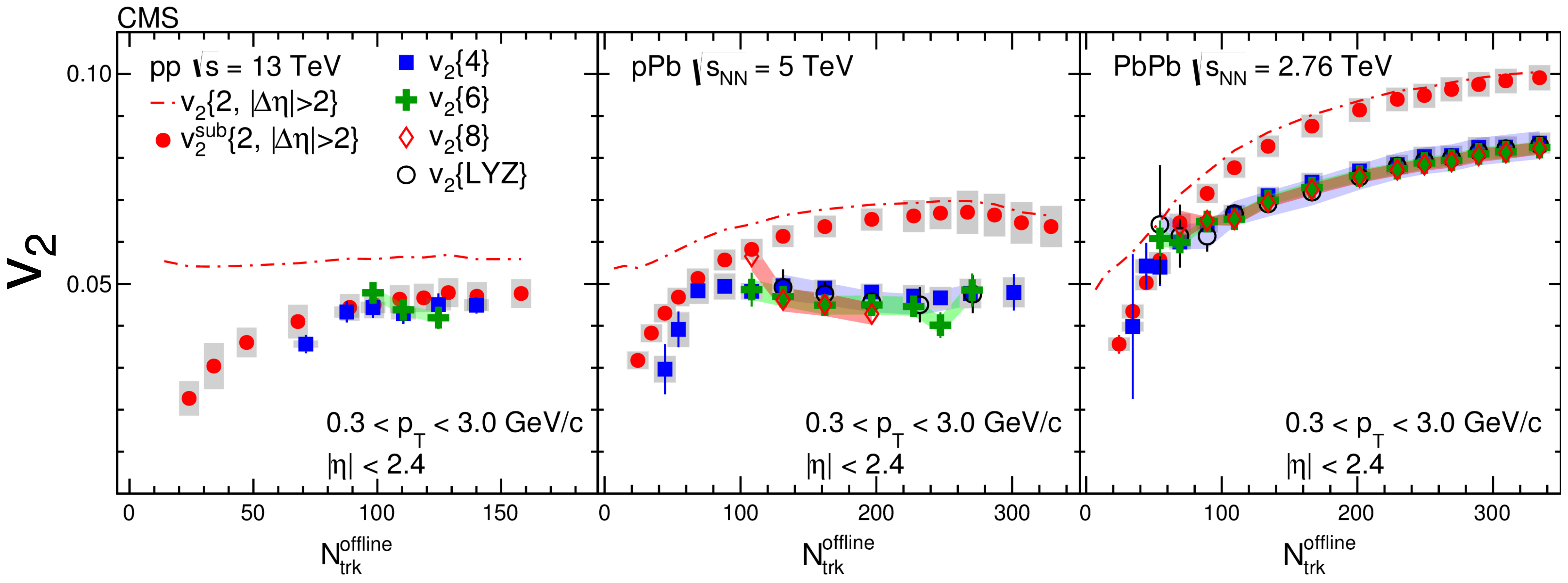
Anisotropy flow in small systems

Mass ordering of v_2



Smaller QGP more explosive?!

Everything flows ?!!

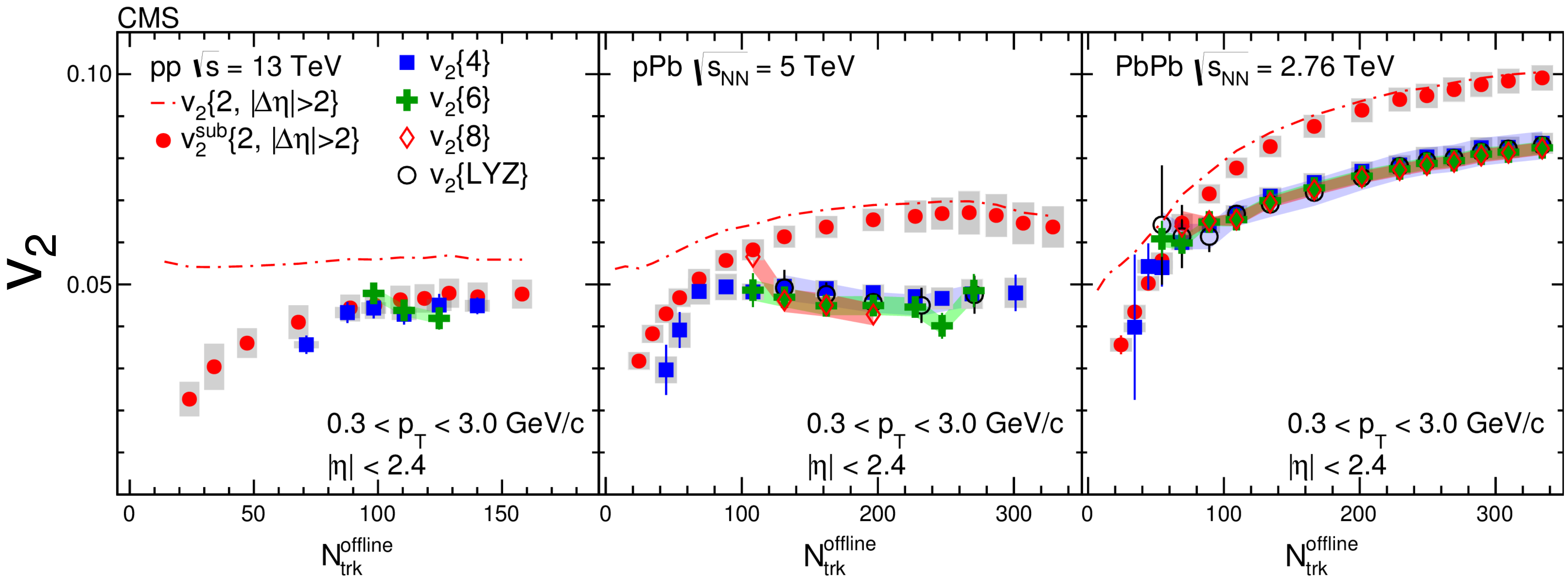


For N_{trk} > ~100,

Strong, direct evidence for long-range collectivity!

$v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$ ("nonflow" insignificant for low p_T)

Everything flows ?!!



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Strong, direct evidence for long-range collectivity!

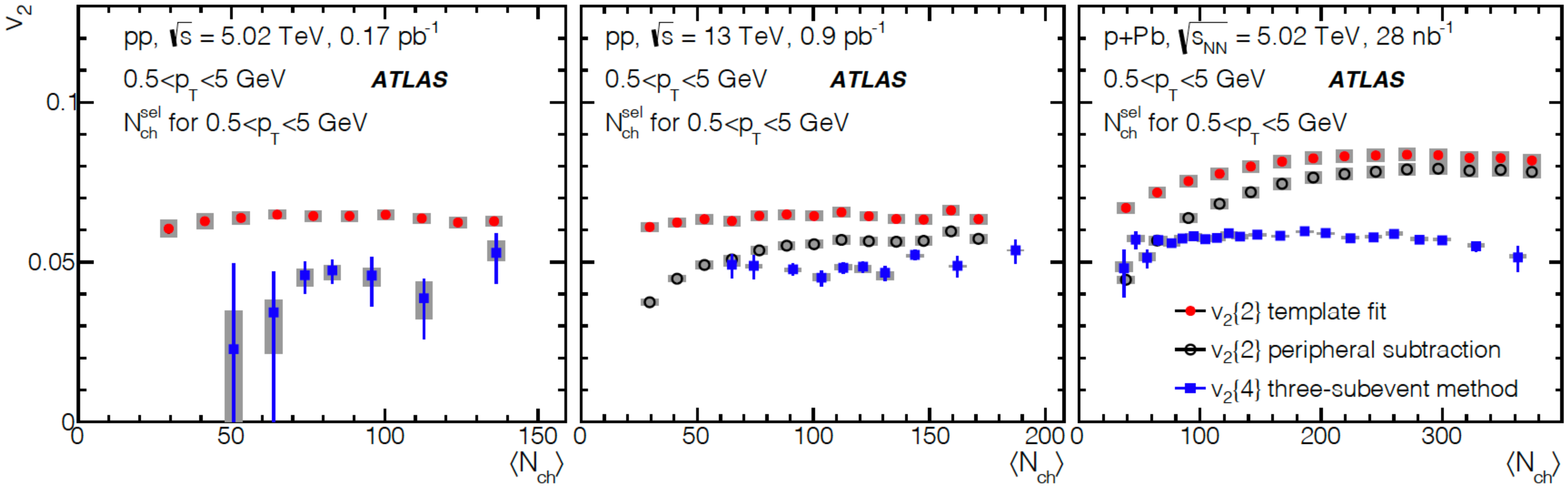
$v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$ ("nonflow" insignificant for low p_T)

Does collective flow eventually turn off at very low N_{trk}?

Everything flows ?!!

Subevent cumulants to suppress nonflow at low N_{trk}

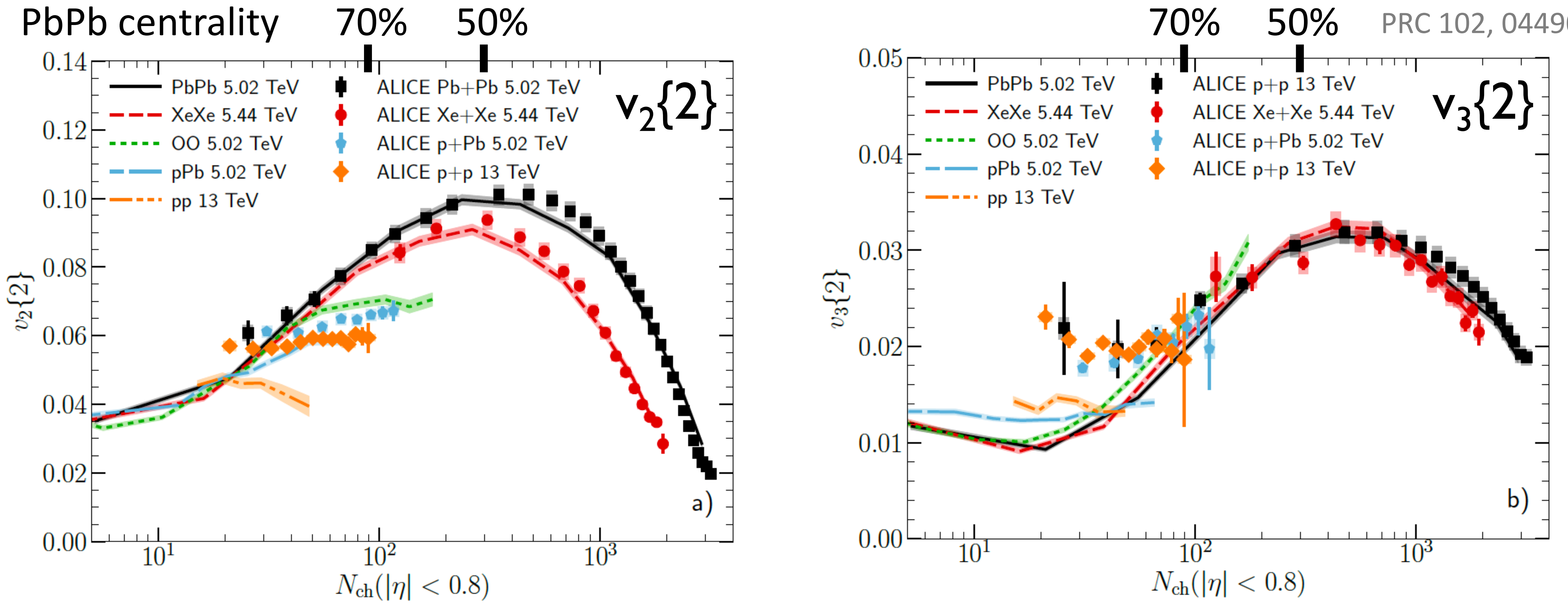
PRC 97, 024904 (2018)



Does collective flow eventually turn off at very low N_{trk}?

Origin of flow in small systems

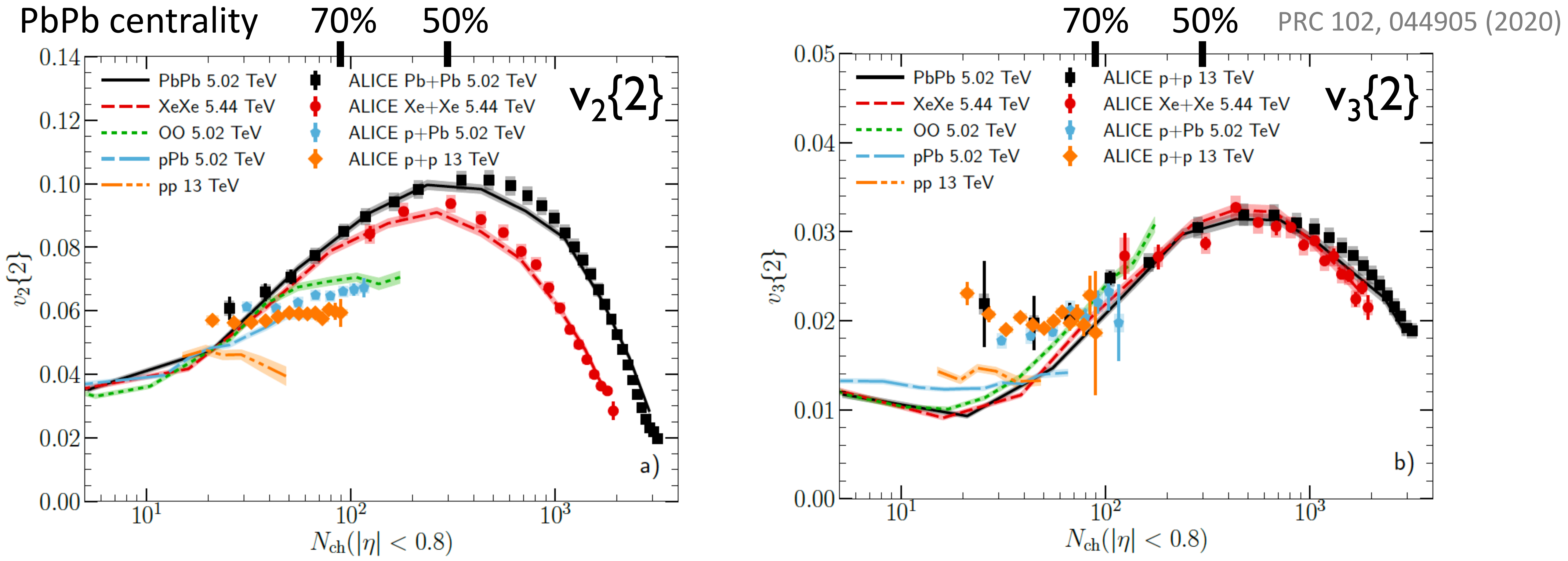
PRC 102, 044905 (2020)



IP-Glasma (w/ ISC)+MUSIC+UrQMD

- Good description of PbPb data but not the case for pp/pPb data

Origin of flow in small systems



IP-Glasma (w/ ISC)+MUSIC+UrQMD

- Good description of PbPb data but not the case for pp/pPb data

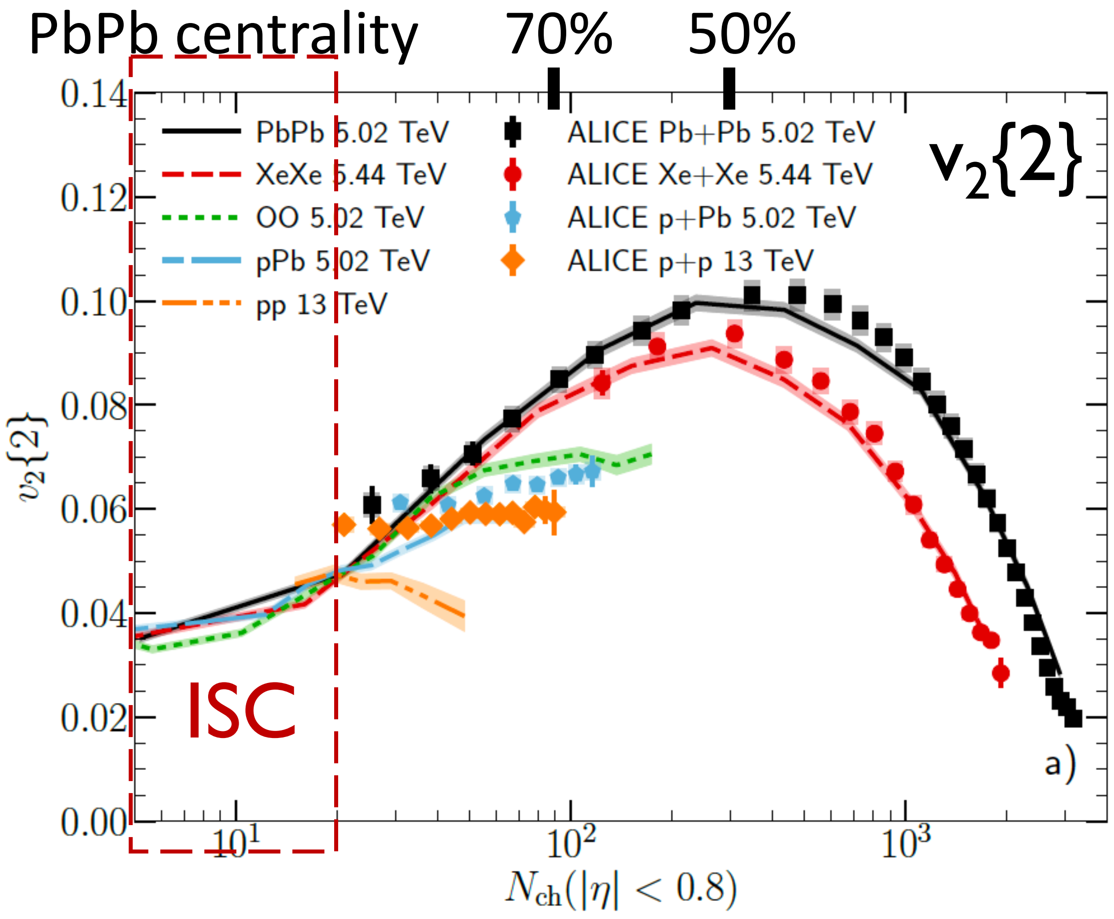
why? ⇒

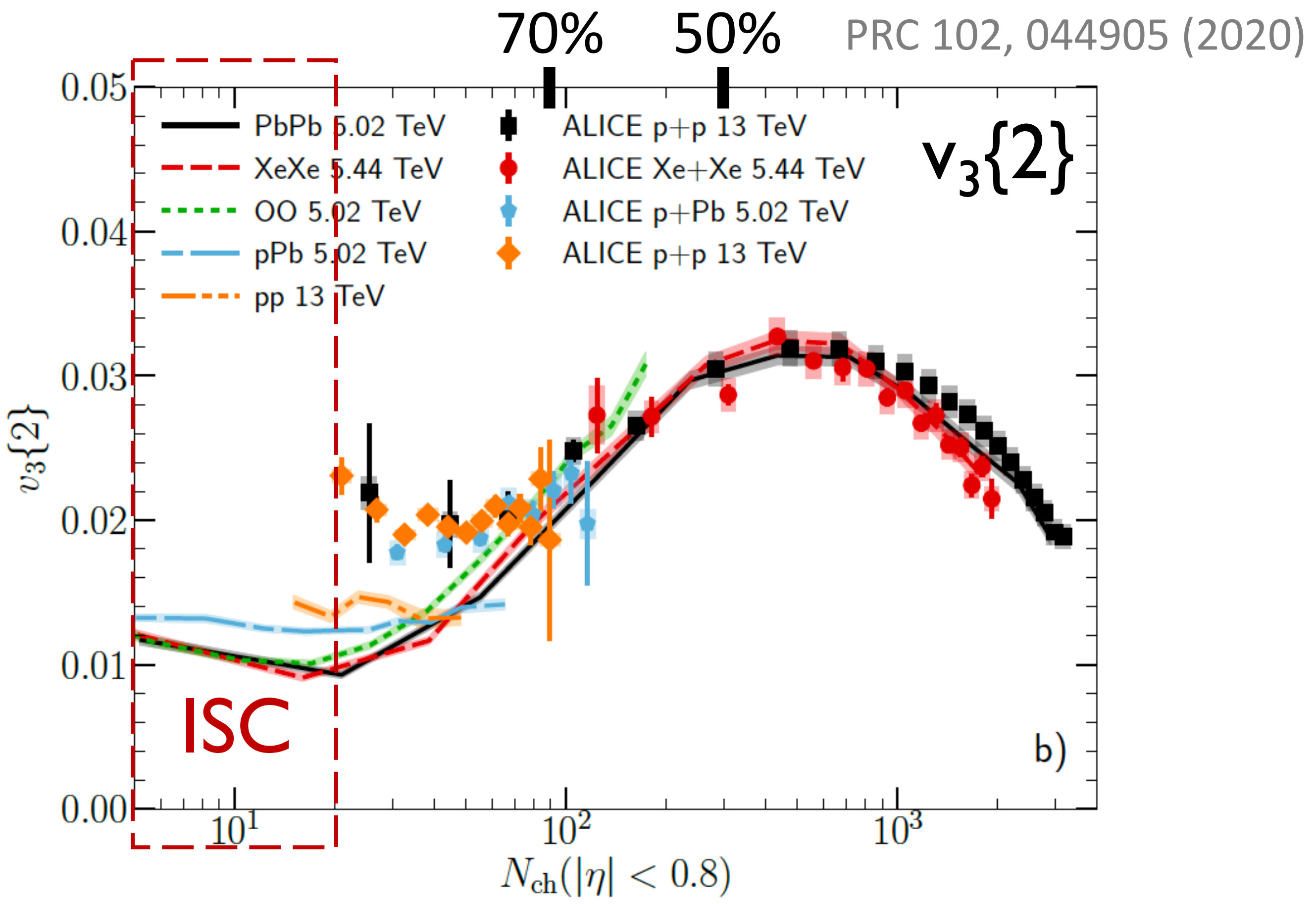
(1) Modeling of initial geometry? η/s? etc.

(2) Hydro. (grad. exp.) breakdown?

(3) Other sources of correlations (ISC)?

Origin of flow in small systems





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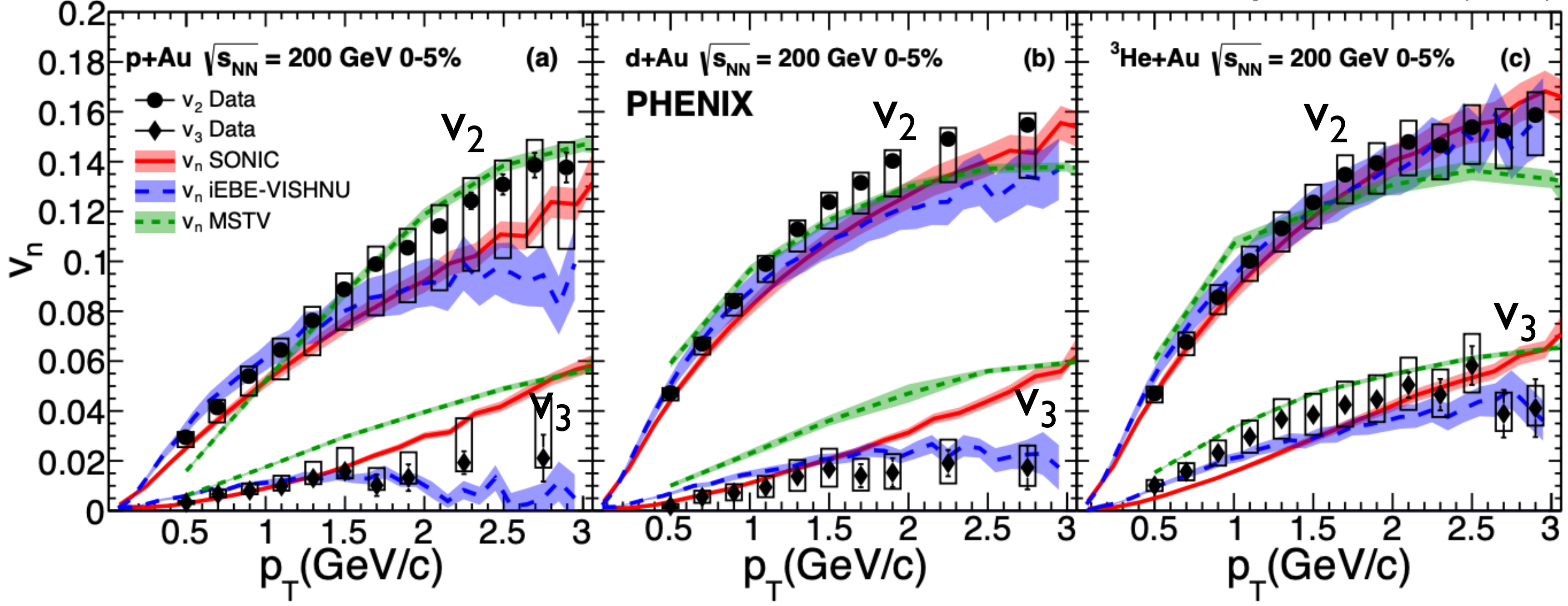
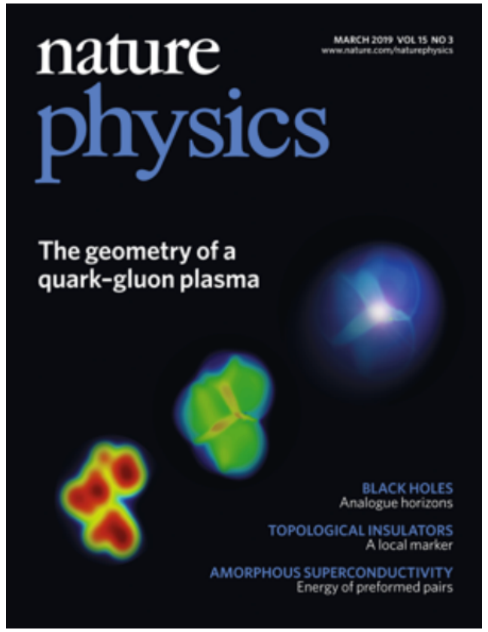
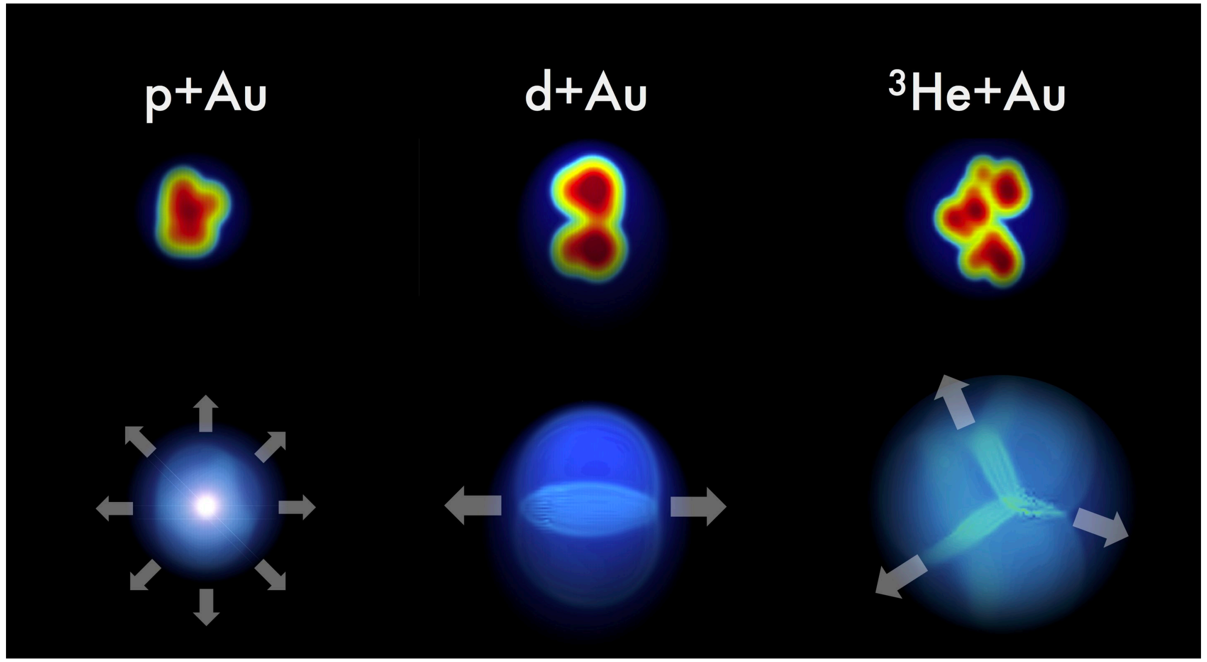
(1) Role of initial geometry in small system

Nature Physics 15, 214 (2019)





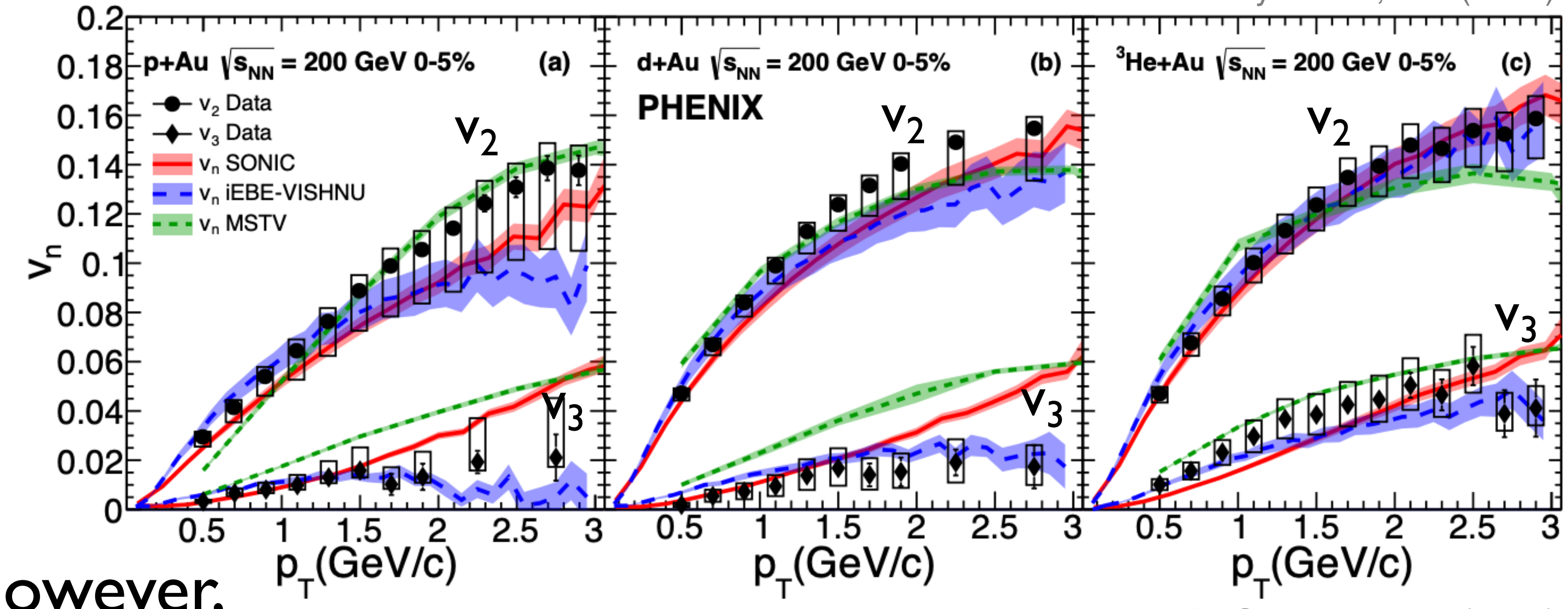


Expect from geometry:

- ➢ $\varepsilon_2^{pAu} < \varepsilon_2^{dAu} \approx \varepsilon_2^{^3HeAu}$
- ➢ $\varepsilon_3^{pAu} \approx \varepsilon_3^{dAu} < \varepsilon_3^{^3HeAu}$

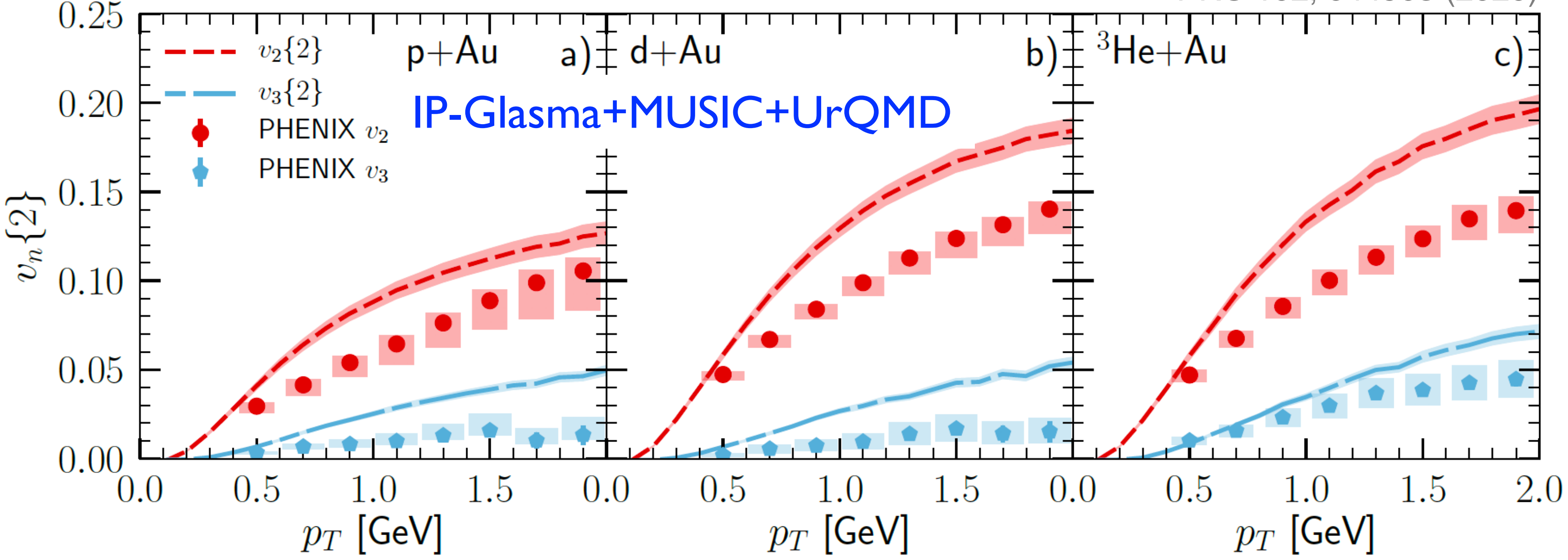
(1) Role of initial geometry in small system

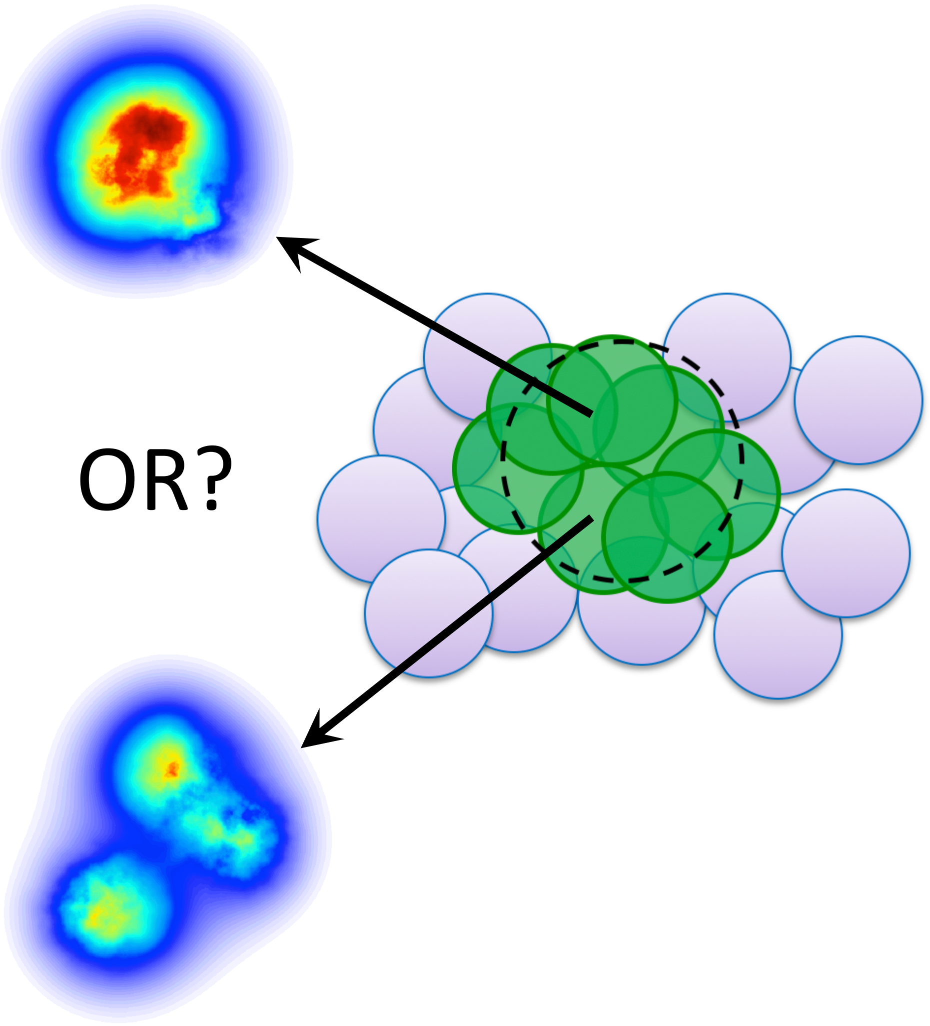
Nature Physics 15, 214 (2019)



However,

PRC 102, 044905 (2020)



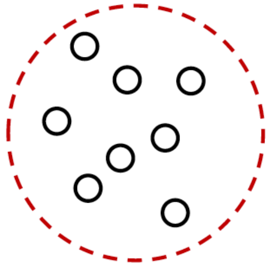


How to model proton ε_s?

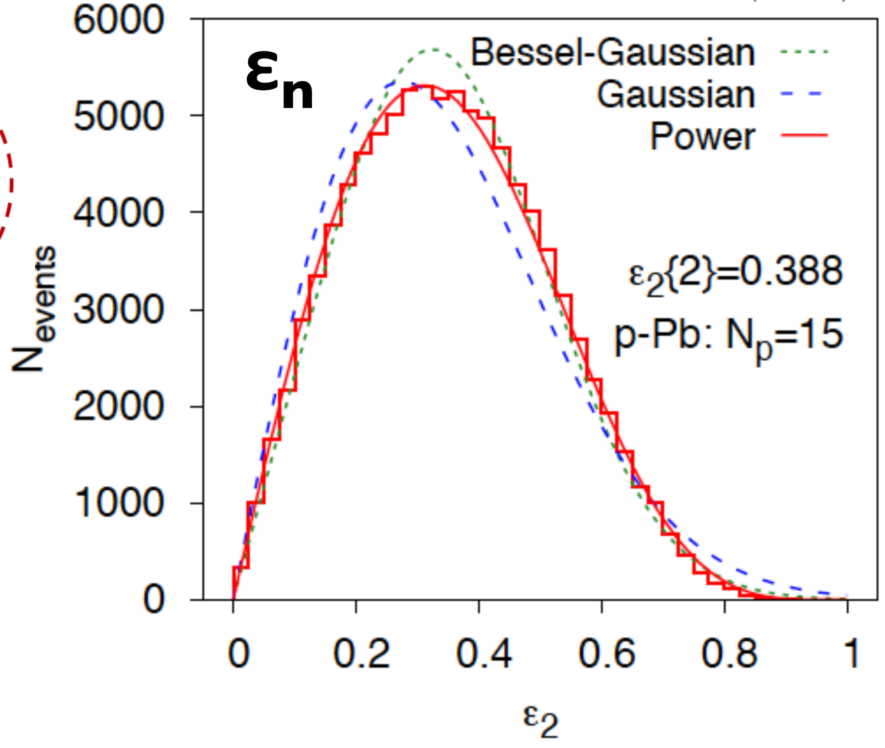
Can it be measured?

(1) Role of initial geometry in small system

Universal fluctuation-driven geometry



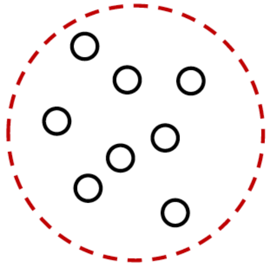
Yan, Ollitrault, PRL 112, 082301 (2014)

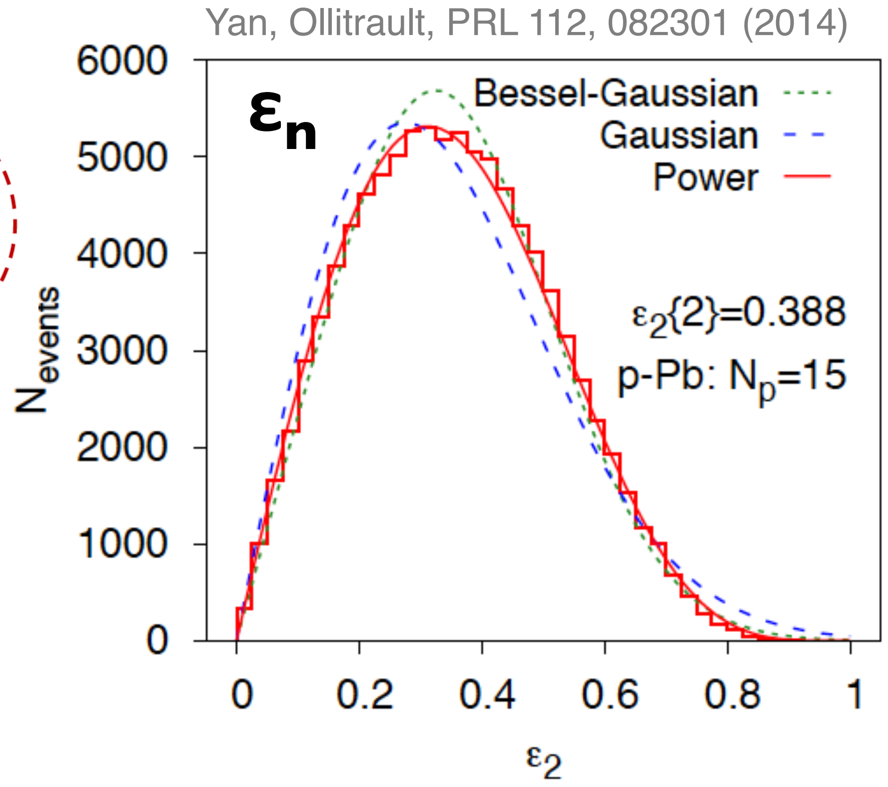


$$P(\varepsilon) = 2\alpha\varepsilon(1-\varepsilon^2)^{\alpha-1}$$

(1) Role of initial geometry in small system

Universal fluctuation-driven geometry





$$P(\varepsilon) = 2\alpha\varepsilon(1-\varepsilon^2)^{\alpha-1}$$

linear $\longrightarrow$ $\mathbf{v_{2,3}\{m\}}$

(m = 2, 4, 6, 8 …)

Predictions (nearly model indep.):

(1) Fine splitting of $v_2\{m\}$:

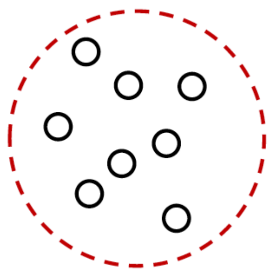
$v_2\{2\} : v_2\{4\} : v_2\{6\} : v_2\{8\}$

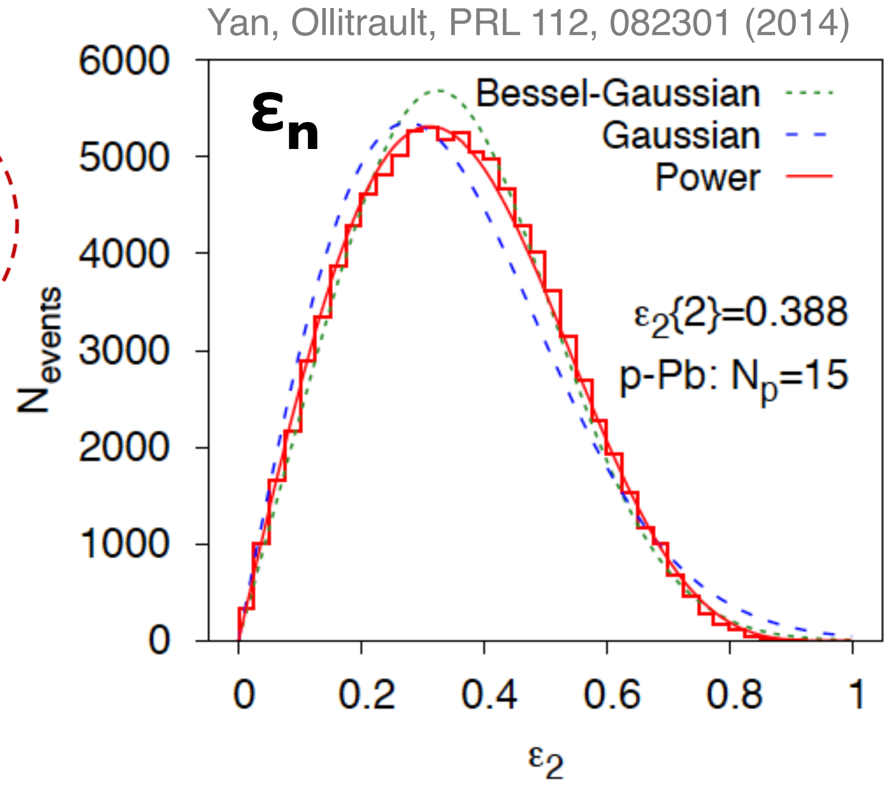
(depending on N_p)

(2) $$\frac{v_2\{4\}}{v_2\{2\}} \approx \frac{v_3\{4\}}{v_3\{2\}}$$

(1) Role of initial geometry in small system

Universal fluctuation-driven geometry



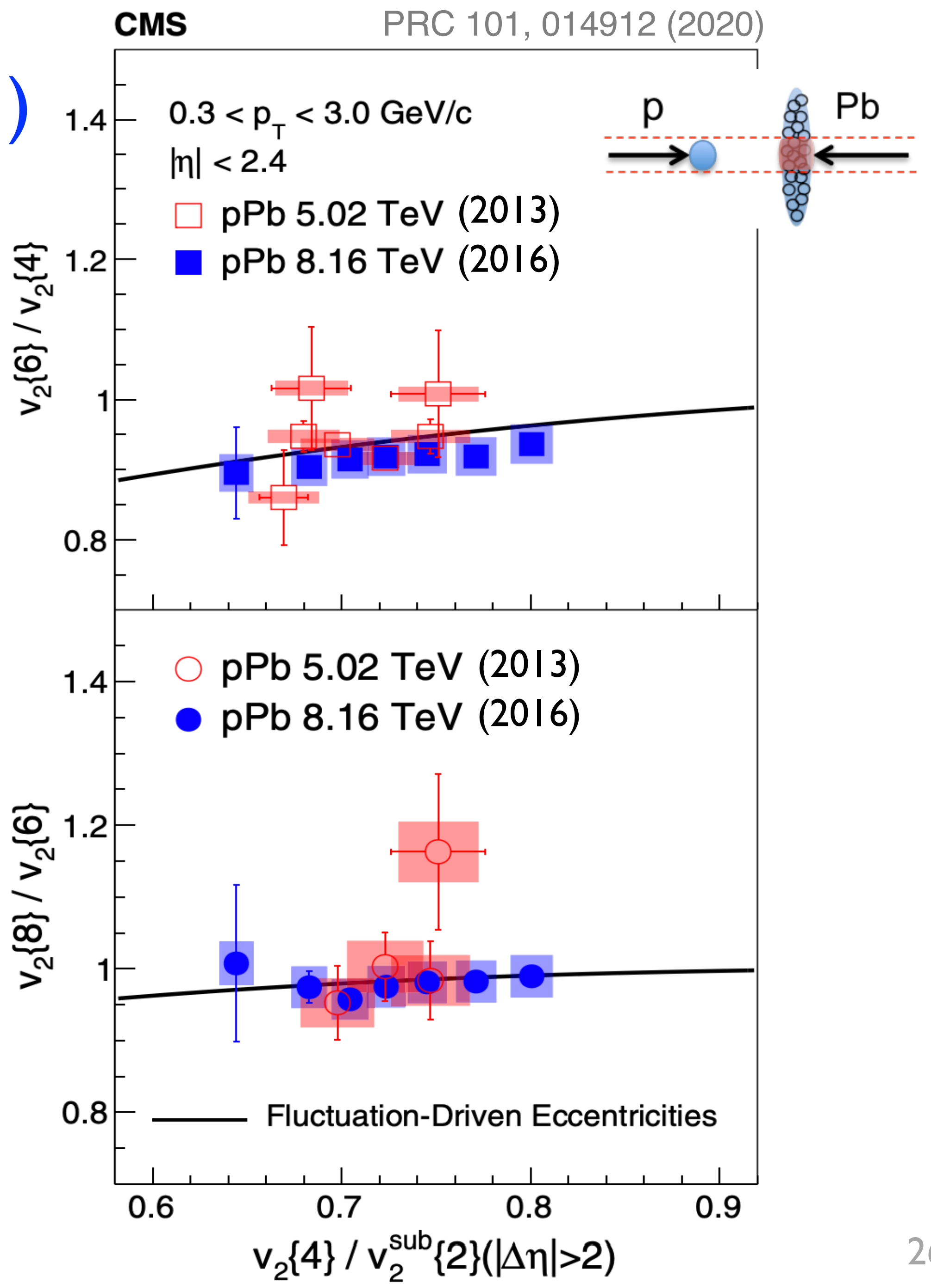


$$P(\varepsilon) = 2\alpha\varepsilon(1-\varepsilon^2)^{\alpha-1}$$

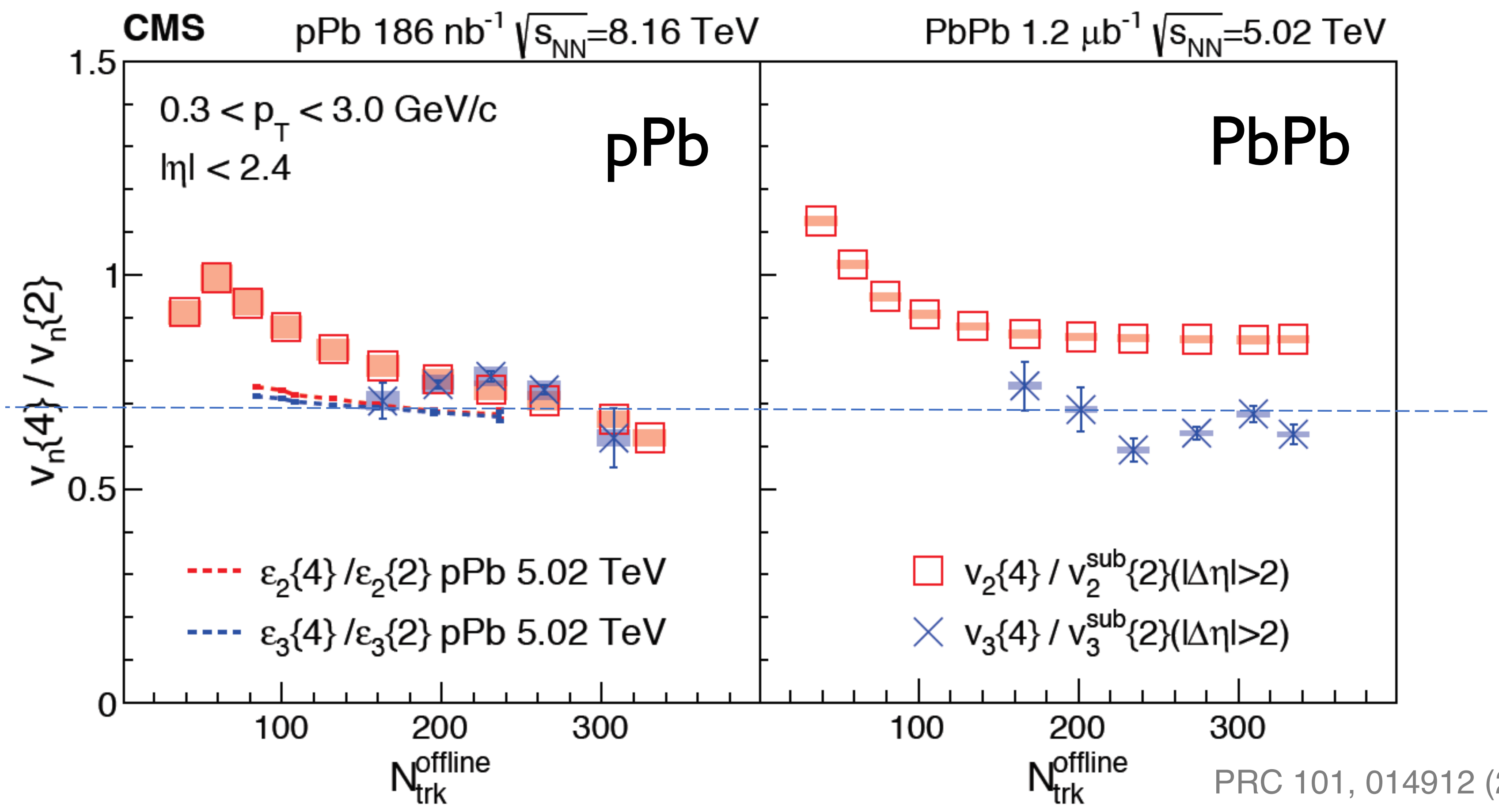
linear → $v_{2,3}\{m\}$

(m = 2, 4, 6, 8 …)

Prediction (1) confirmed



(1) Role of initial geometry in small system



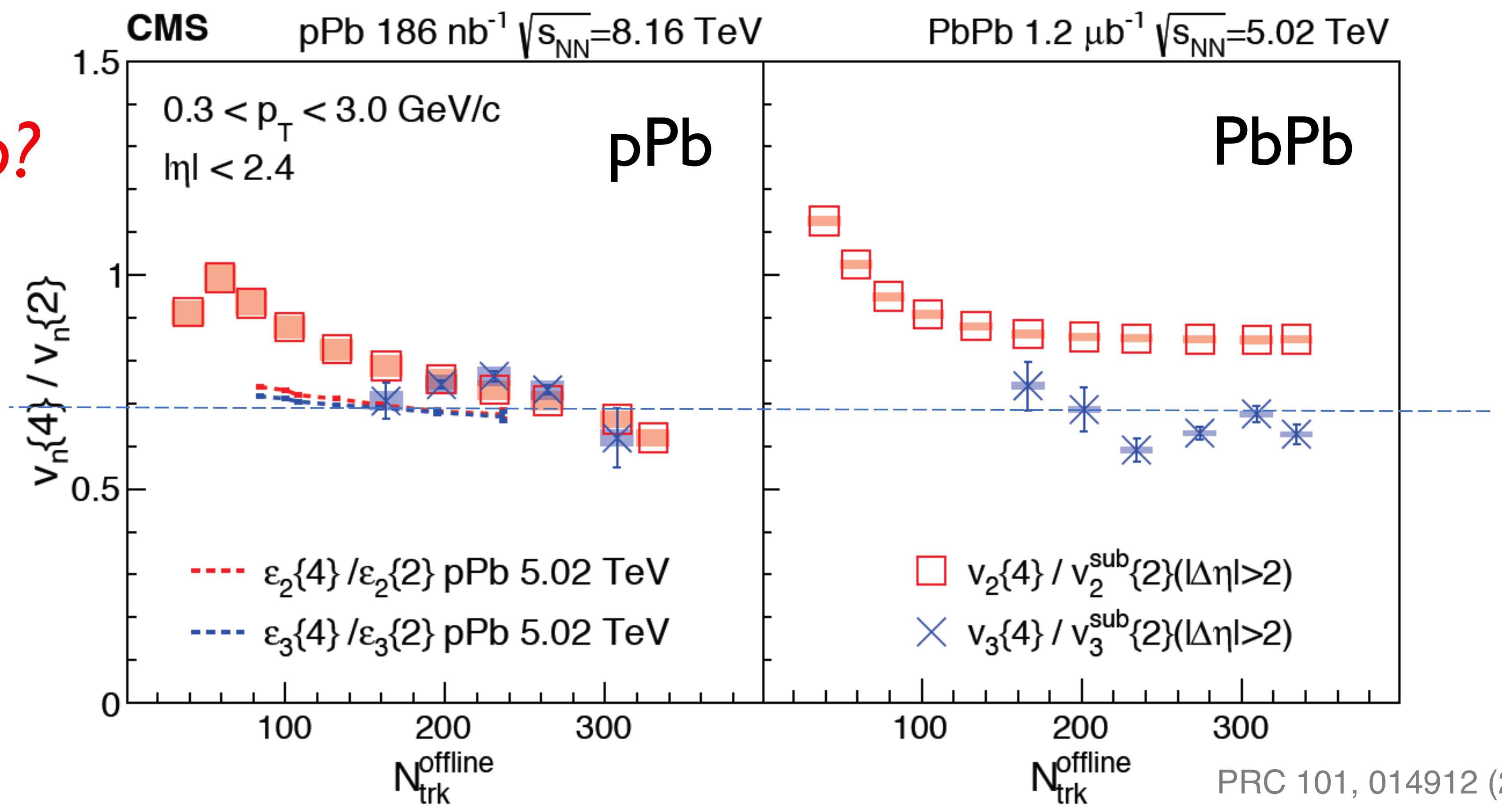
PRC 101, 014912 (2020)

Prediction (2) confirmed!

- $\frac{v_2\{4\}}{v_2\{2\}} \approx \frac{v_3\{4\}}{v_3\{2\}}$ in pPb
- $\frac{v_3\{4\}}{v_3\{2\}}$ similar in pPb and PbPb

(1) Role of initial geometry in small system

How about pp?



PRC 101, 014912 (2020)

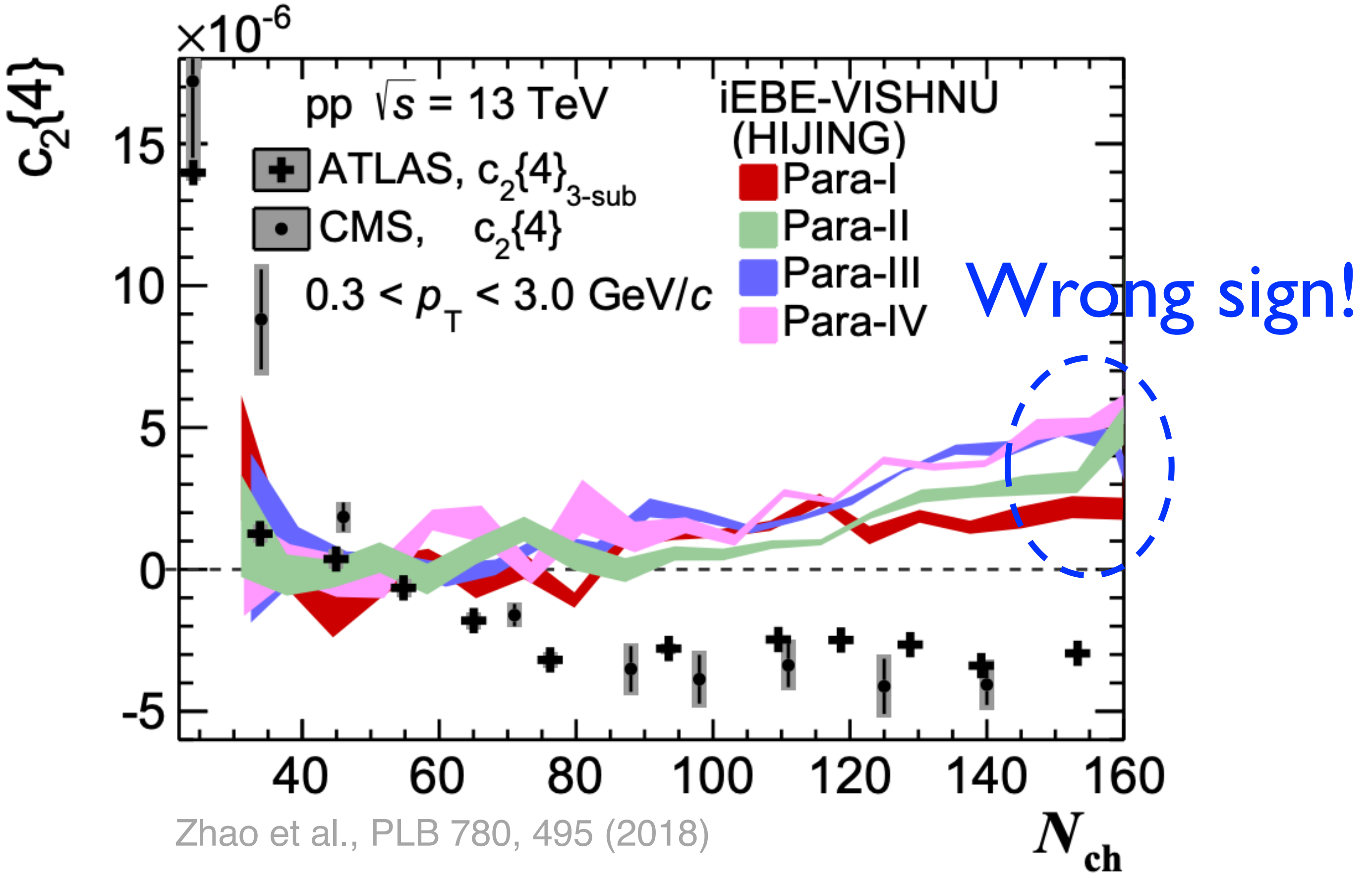
Prediction (2) confirmed!

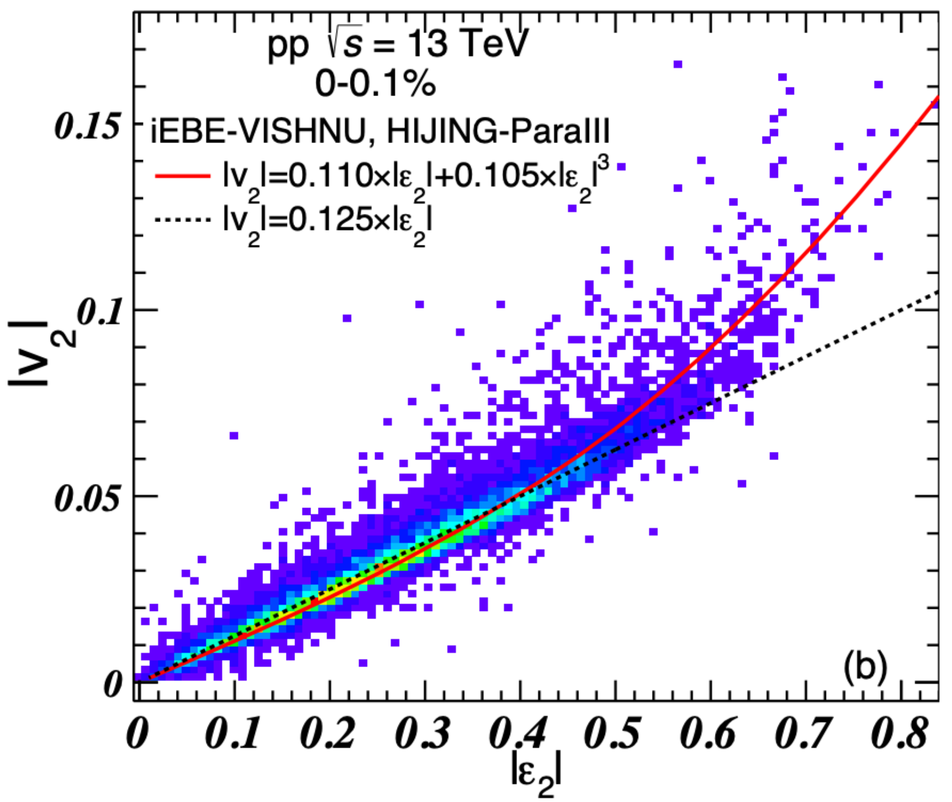
No room/need for "new physics"!

- $\frac{v_2\{4\}}{v_2\{2\}} \approx \frac{v_3\{4\}}{v_3\{2\}}$ in pPb
- $\frac{v_3\{4\}}{v_3\{2\}}$ similar in pPb and PbPb

(2) Does hydrodynamics break down?

– If so, how to observe it decisively?





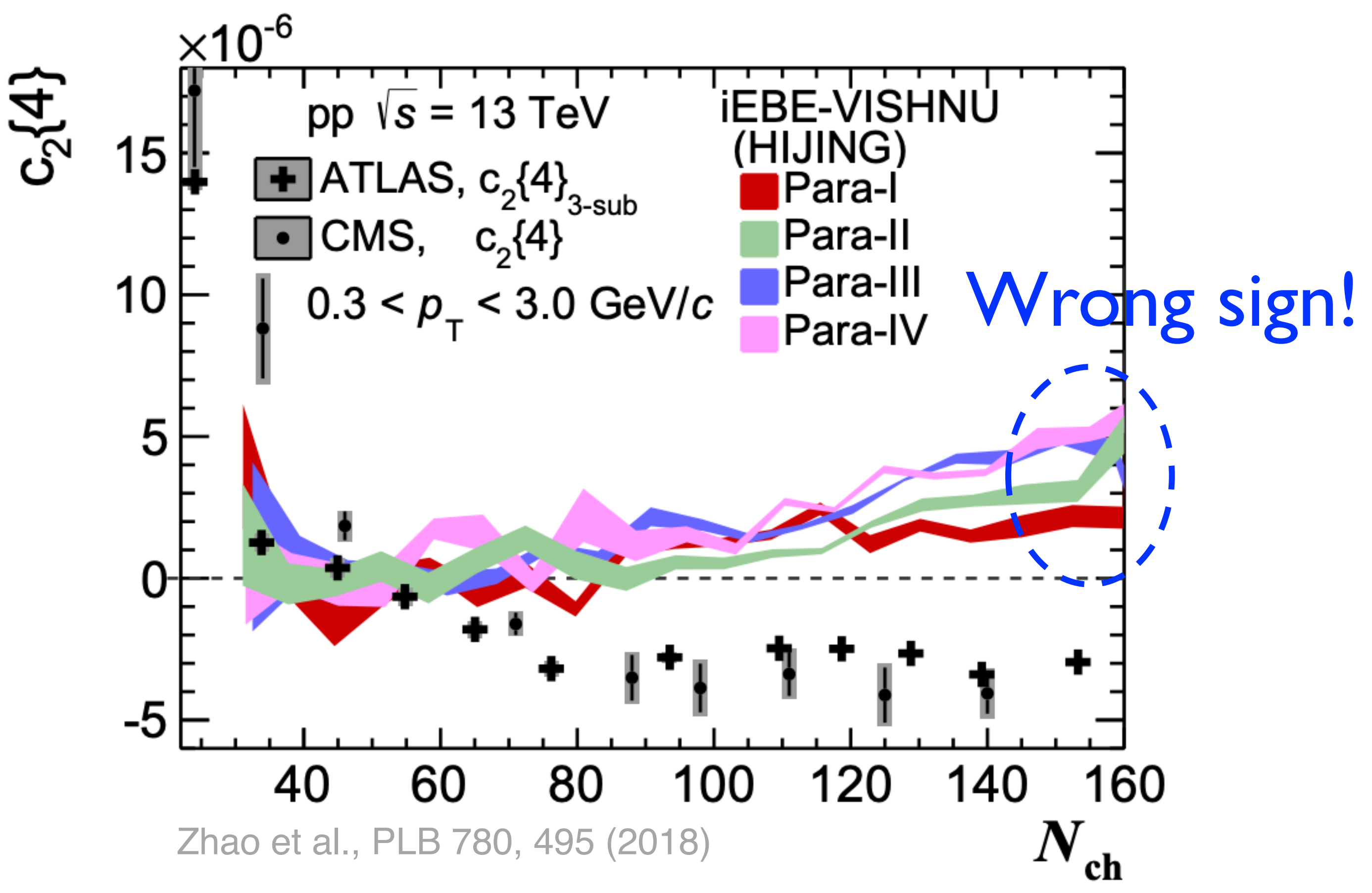
Hydro fails to describe $v_n\{4\}$ data in pp

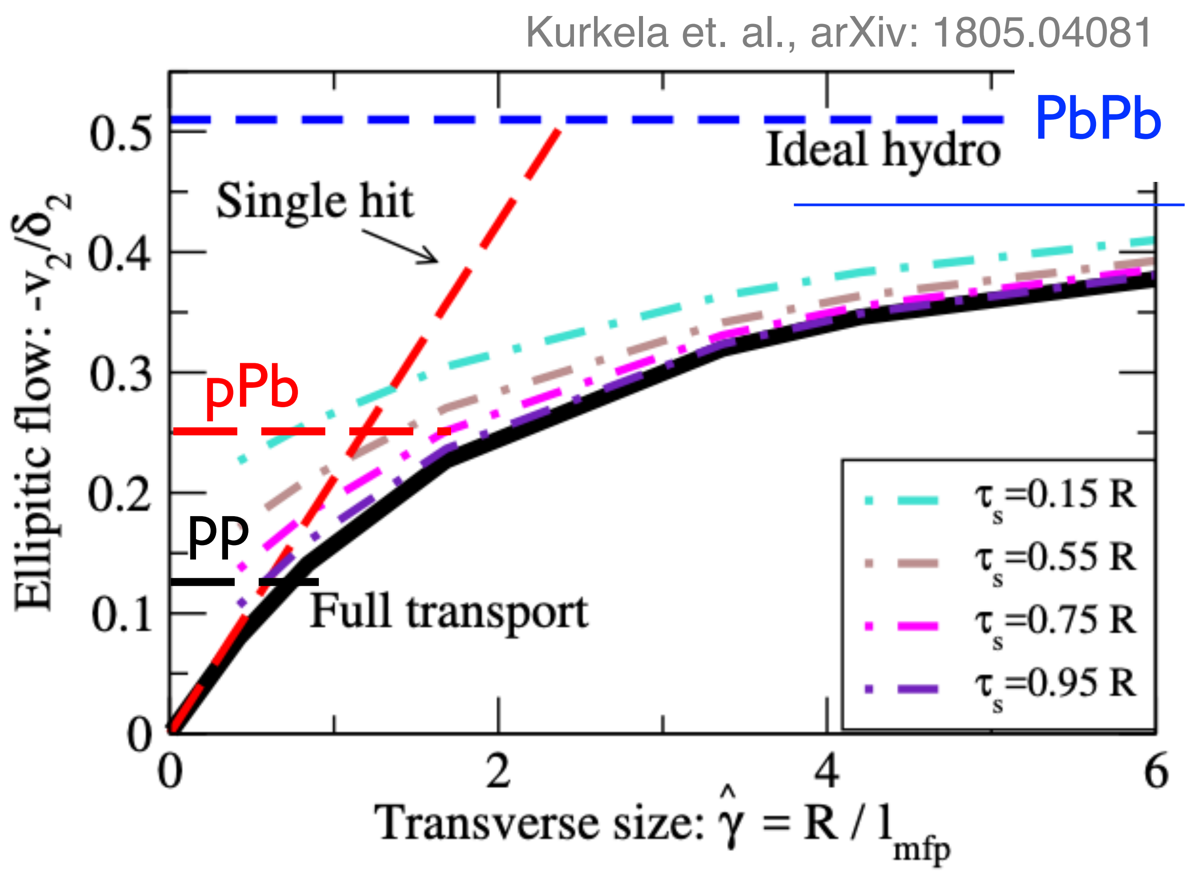
- Non-linear response: $v_2 \neq \kappa\varepsilon_2$
- κ is small (~0.1) ⇨ large smearing in v_2

➢ v_2 fluctuation does not follow that of ε_2 in pp hydro. model

(2) Does hydrodynamics break down?

– If so, how to observe it decisively?





Hydro fails to describe $v_n\{4\}$ data in pp

Transport approach more effective in retaining $v_2 = \kappa\varepsilon_2$? AMPT?

➢ *Dilute system* with a few scatterings in pp (pA), instead of a QGP droplet?

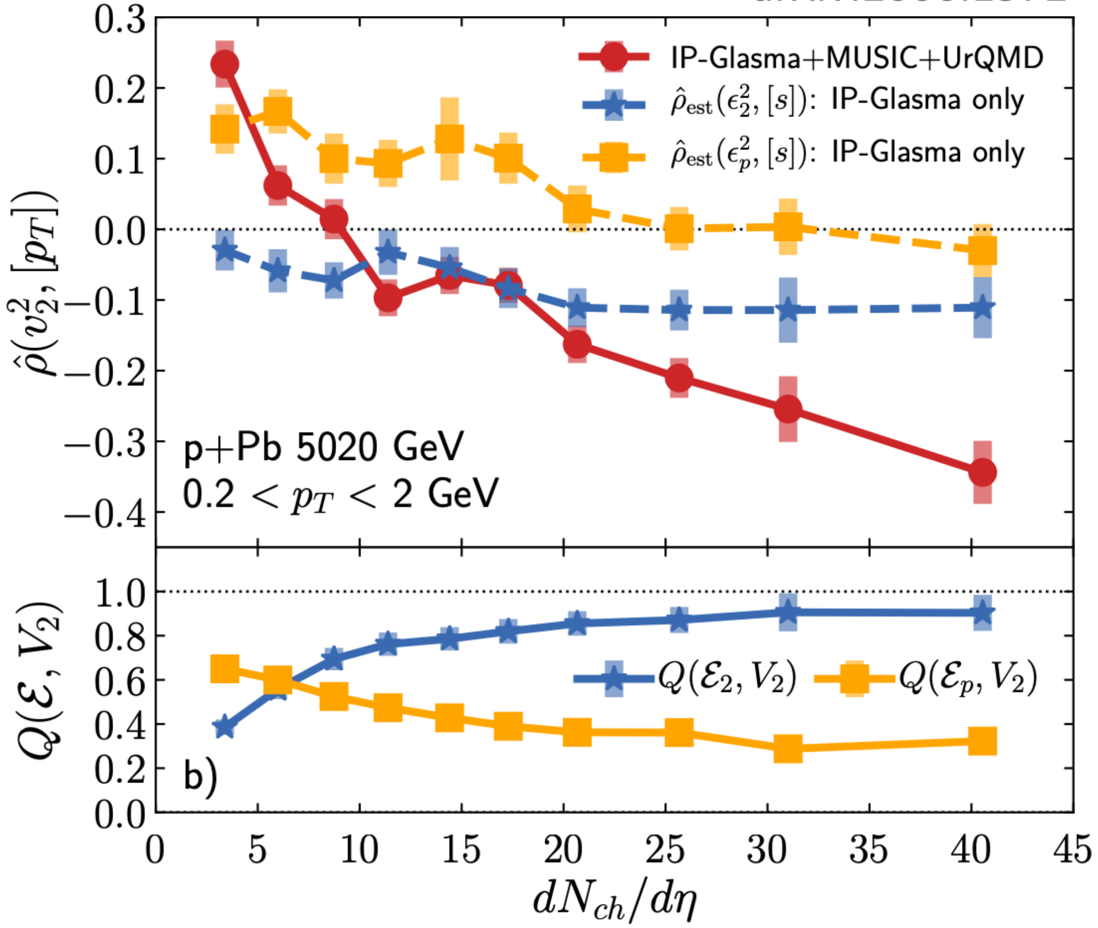
(3) Do initial-state correlations exist?

– If so, how to observe it decisively?

ISC is predicted to be prominent at very low N_{trk}

v_2-p_T correlations as a promising observable

arXiv:2006.1572



$\hat{\rho}(v_2^2, [p_T])$ >0 for ISC, <0 for FSC

Still need to check its performance with nonflow at low N_{trk}

(3) Do initial-state correlations exist?

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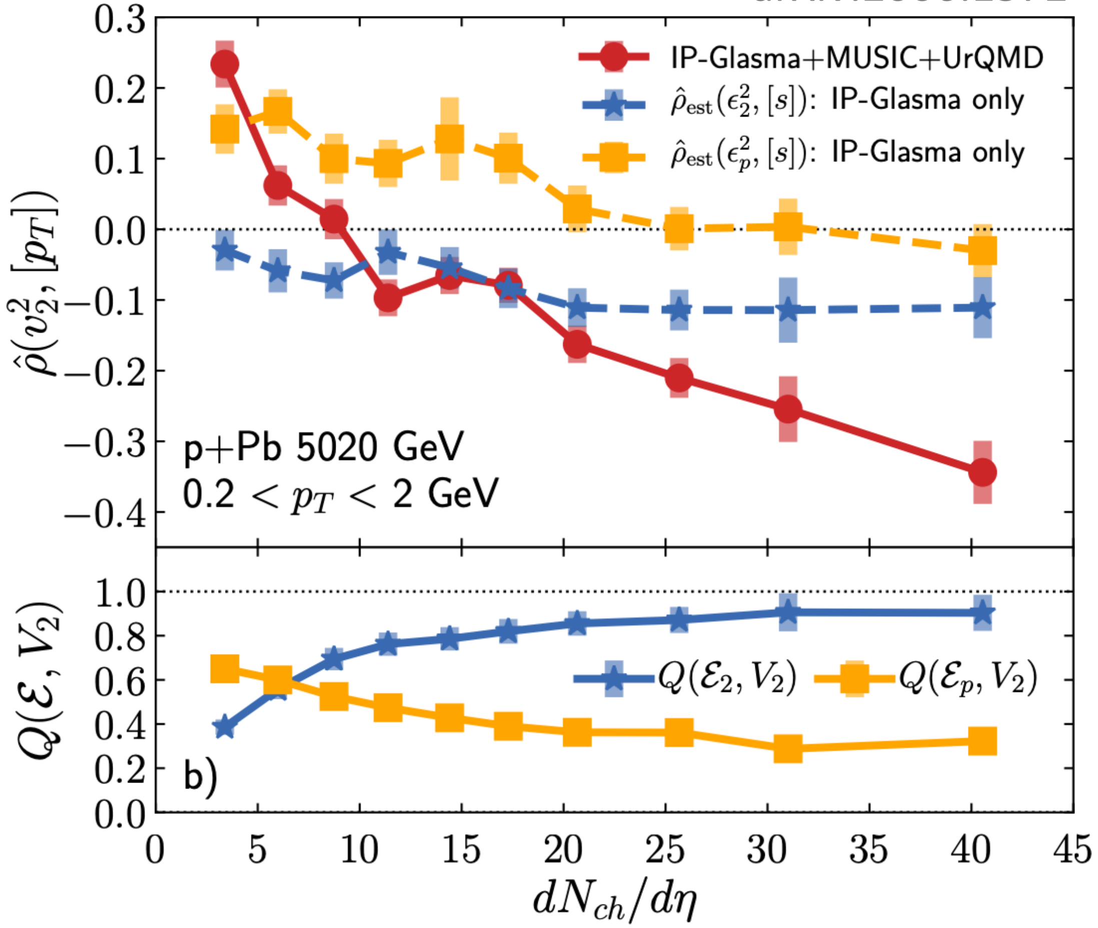
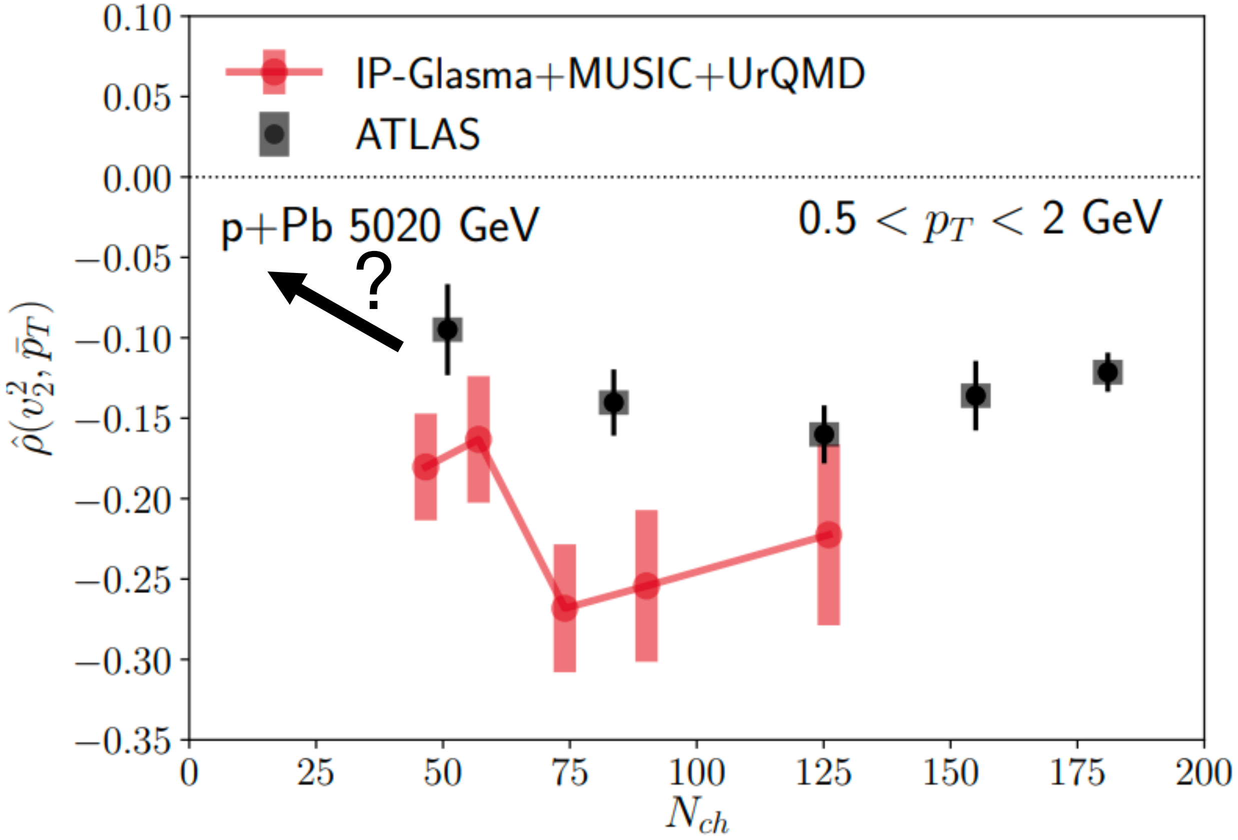
ISC is predicted to be prominent at very low N_{trk}

v_2-p_T correlations as a promising observable

arXiv:2006.1572



arXiv:1907.05176



Summary (Part I)

Lessons:

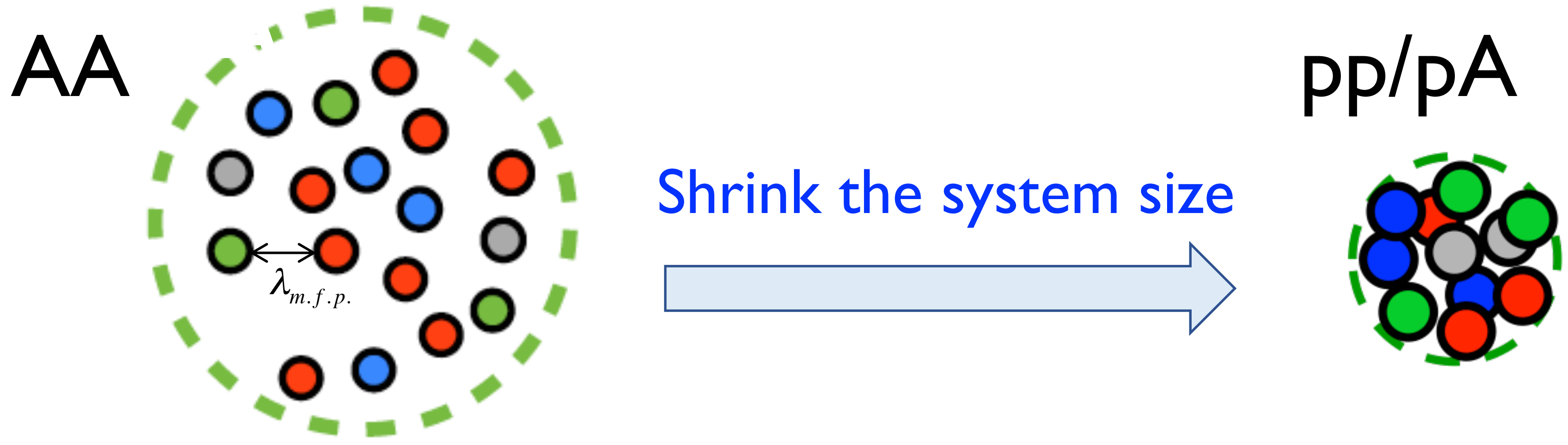
- Collective flow observed across all systems with high multiplicities
- Strong evidence for initial-geometry driven in pA and AA via high precision measurements

Puzzles/open issues:

- Low multiplicity region:
  - Does collectivity extend down to low N_{trk}?
  - Is ISC present and observable?
- pp remains a big challenge:
  - How to properly model proton eccentricity?
  - Is hydro. really applicable to pp? wrong sign for $v_2\{4\}$!

Keep pushing to extreme domains:

Heavy quark collectivity in small systems



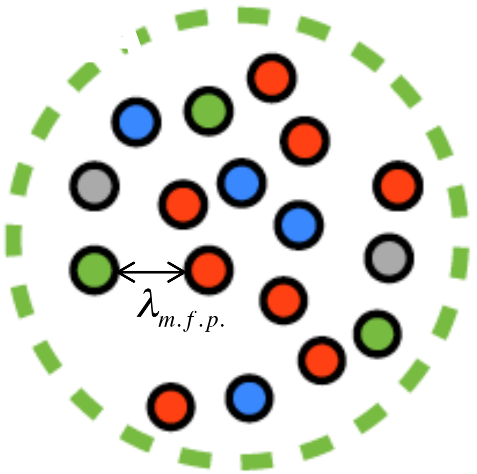
$$L >> \lambda_{m.f.p.}$$

$$\lambda_{m.f.p.} \sim \frac{1}{g^4 T}$$

Keep pushing to extreme domains:

Heavy quark collectivity in small systems

AA



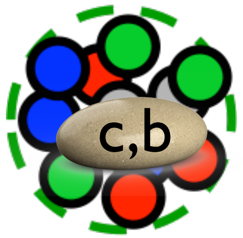
Shrink the system size

pp/pA

$$L >> \lambda_{m.f.p.}$$

$$\lambda_{m.f.p.} \sim \frac{1}{g^4 T}$$

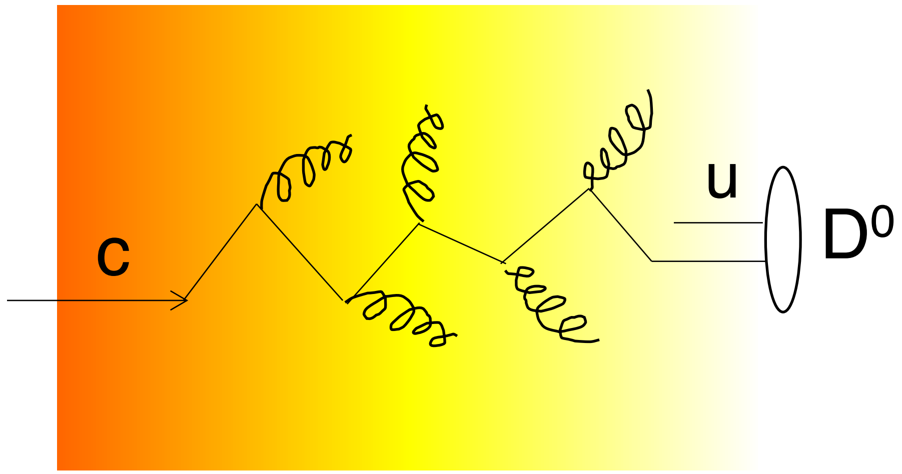
Increase $\lambda_{m.f.p.}$

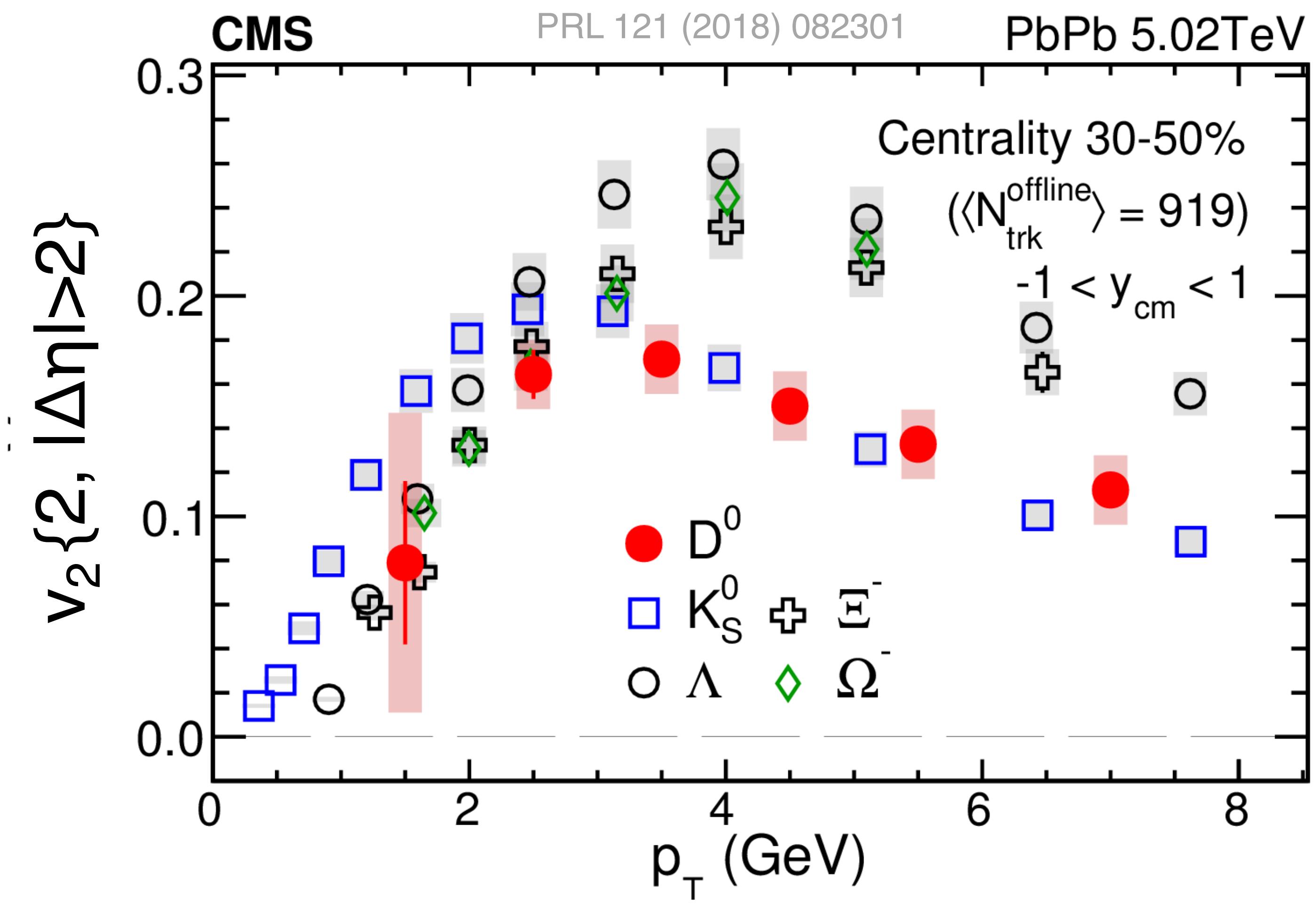


Heavy flavor hadrons (D, B, J/ψ, …)

- Perturbative scale
- Produced at early stages

Heavy quark collectivity in large AA systems



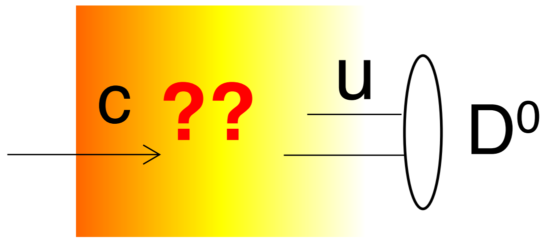


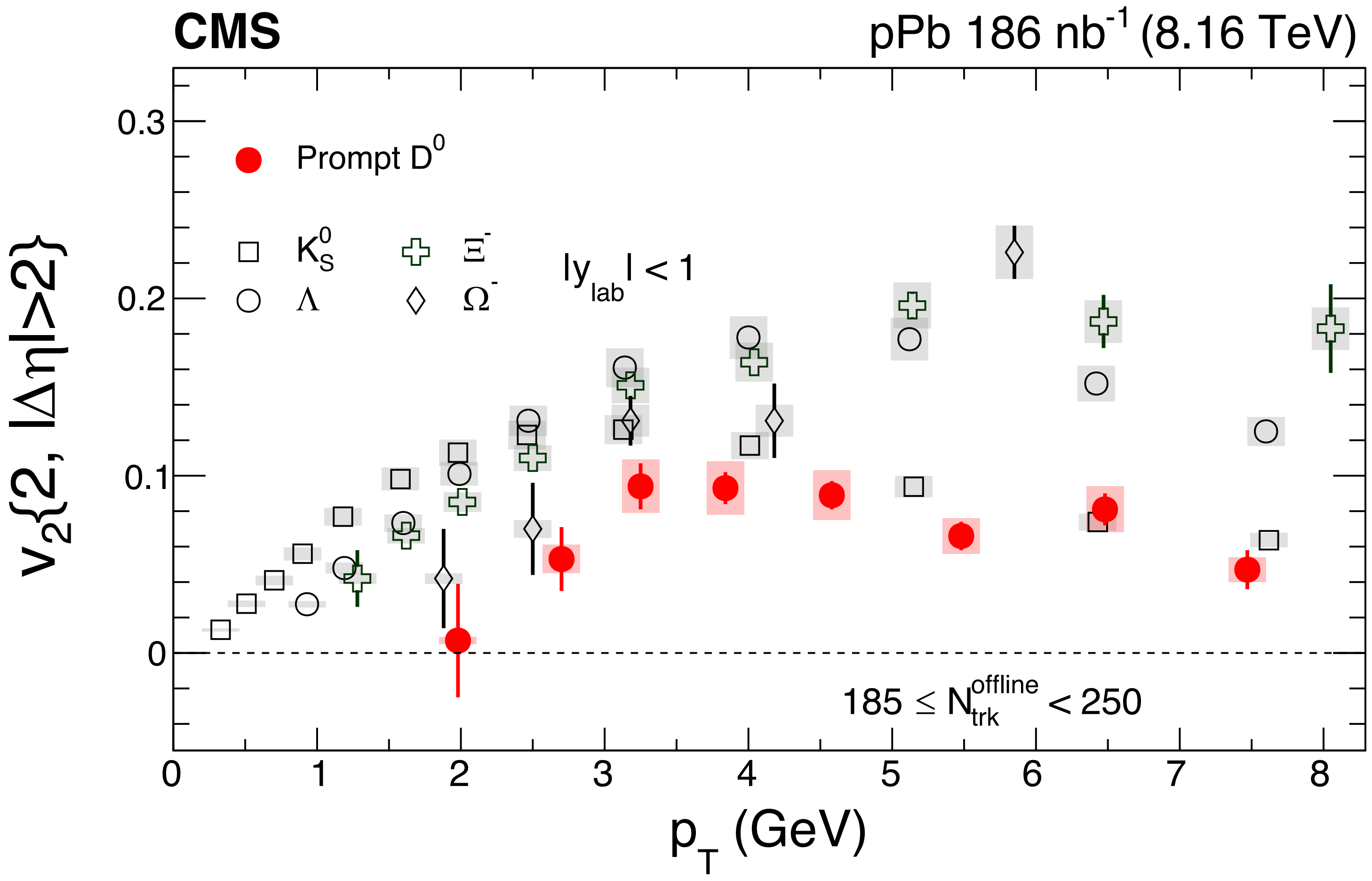
Strong charm flow similar to light flavor in AA at RHIC and the LHC

Heavy quark collectivity in small systems

Shrink the system size: N_{trk} ~ 900 ⟶ N_{trk} ~ 200

In small systems?



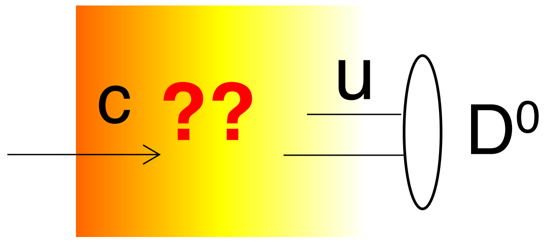


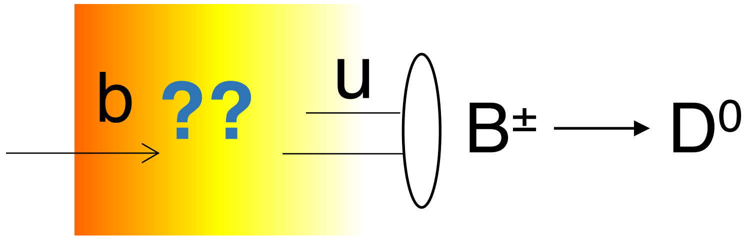
✓ Strong charm flow, maybe some indication < v_2(K)

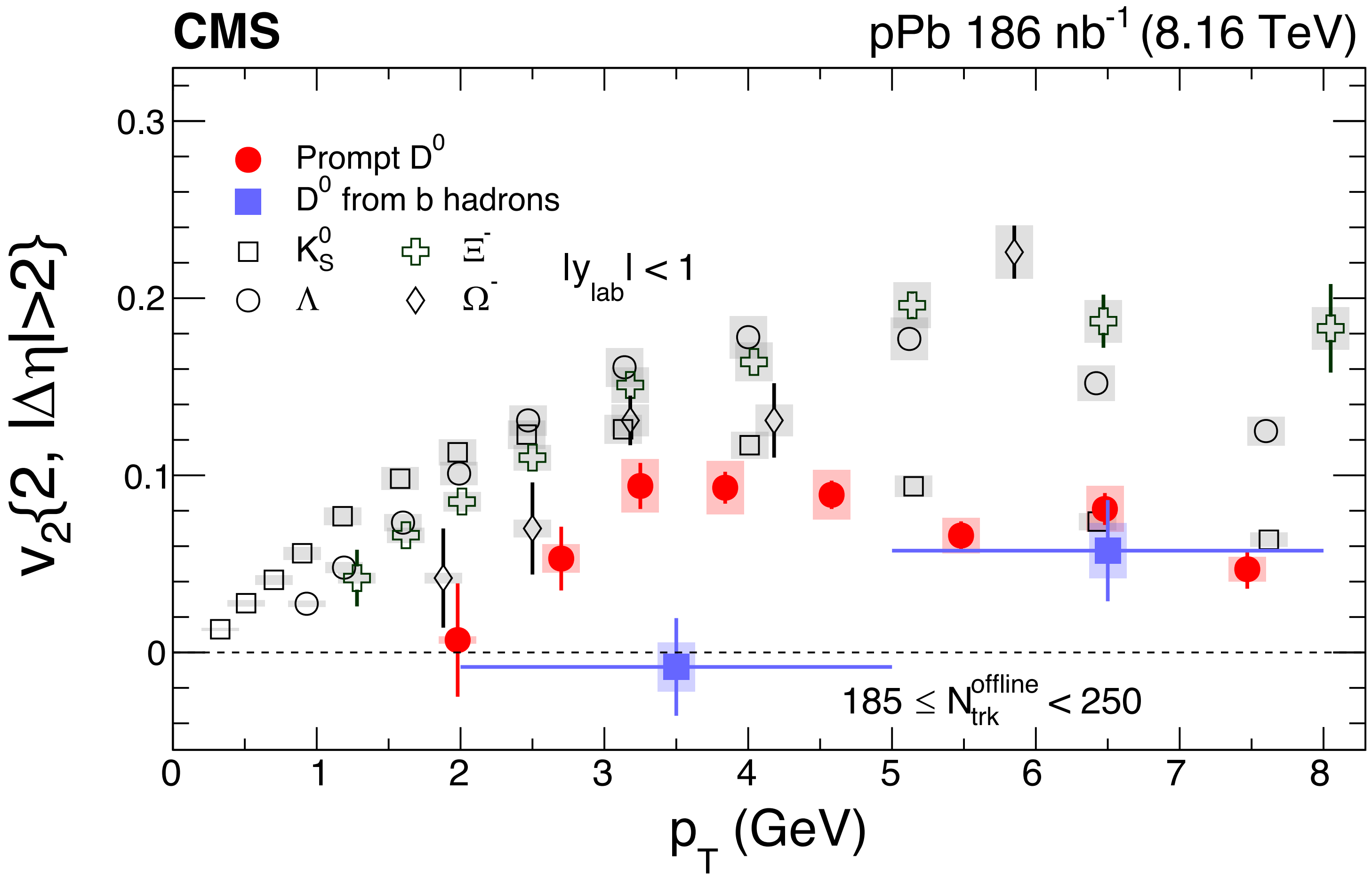
Heavy quark collectivity in small systems

Shrink the system size: $N_{trk} \sim 900 \longrightarrow N_{trk} \sim 200$

In small systems?







Charm *vs.* Beauty

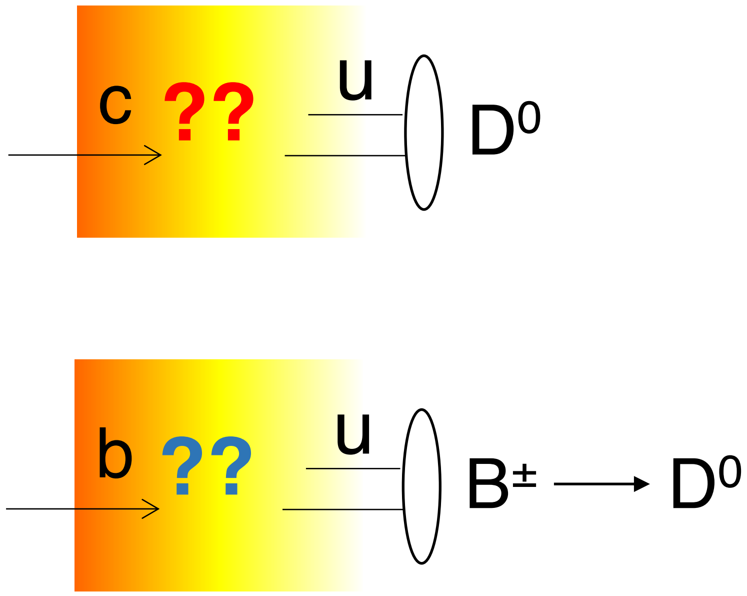
✓ Strong charm flow, maybe some indication < v_2(K)

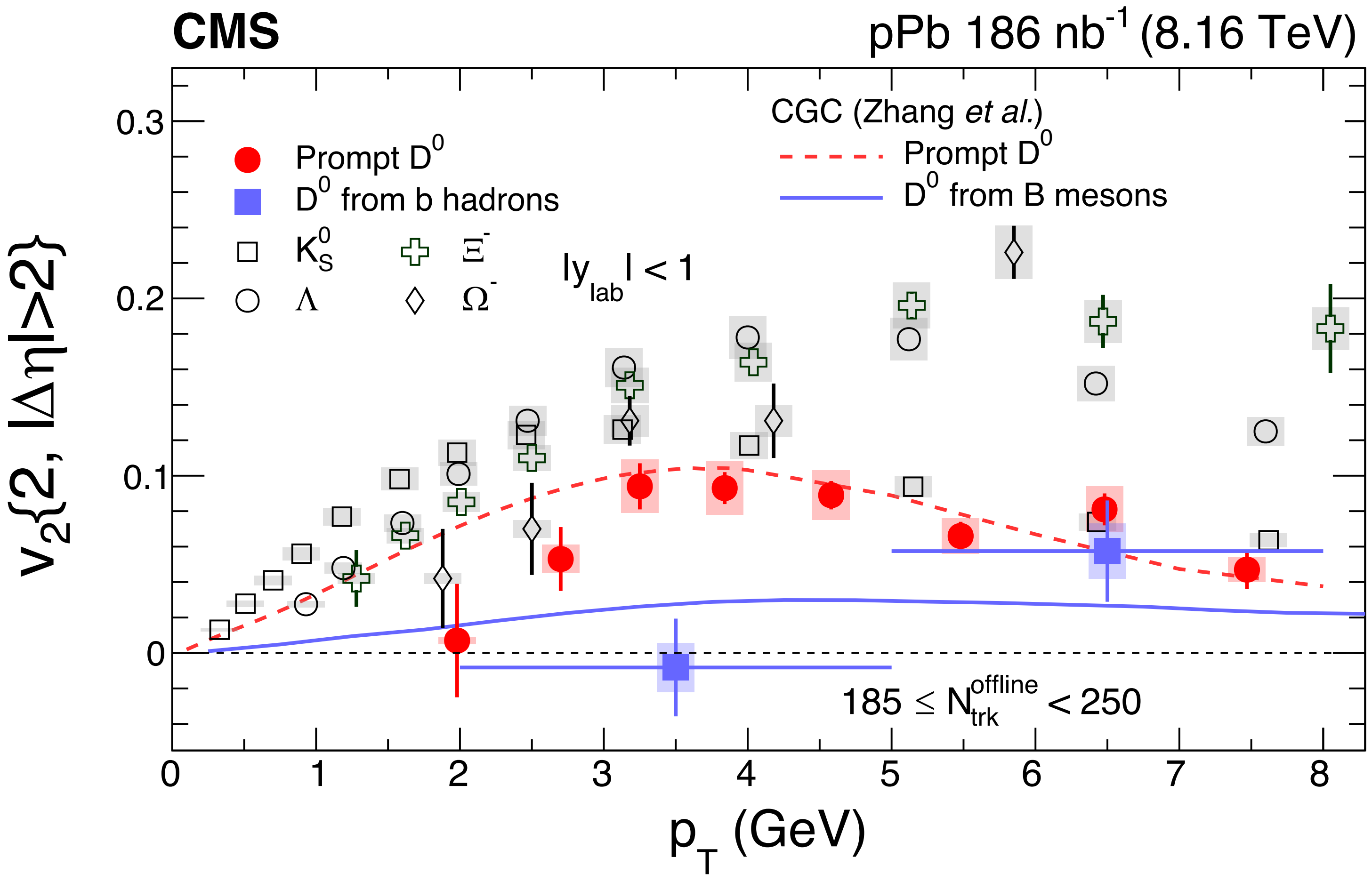
✓ Beauty flow < charm flow (flavor hierachy)?!

Heavy quark collectivity in small systems

Shrink the system size: $N_{trk} \sim 900 \longrightarrow N_{trk} \sim 200$

In small systems?





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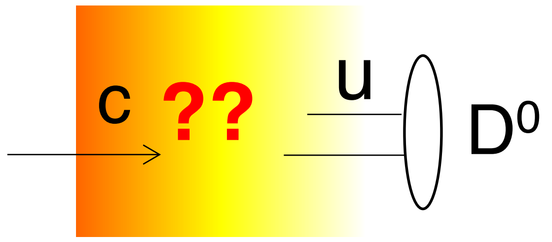
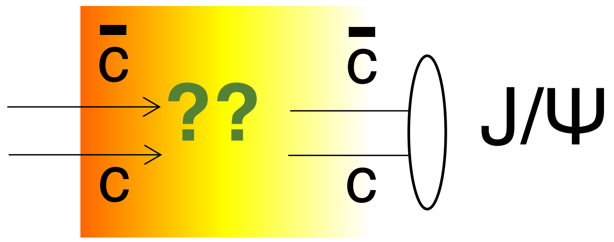
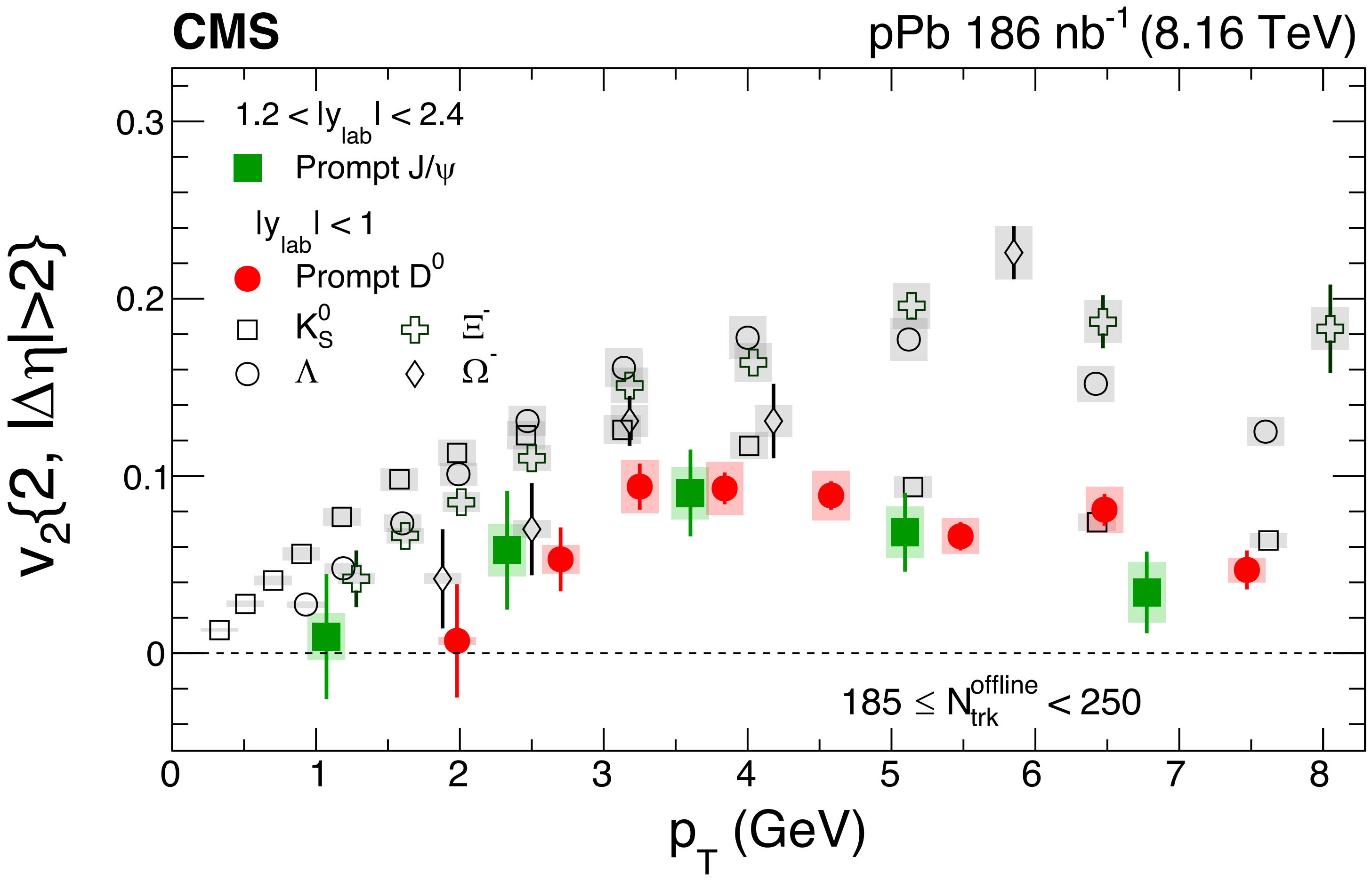
Shrink the system size: $N_{trk} \sim 900 \longrightarrow N_{trk} \sim 200$

In small systems?





Open *vs.* Hidden



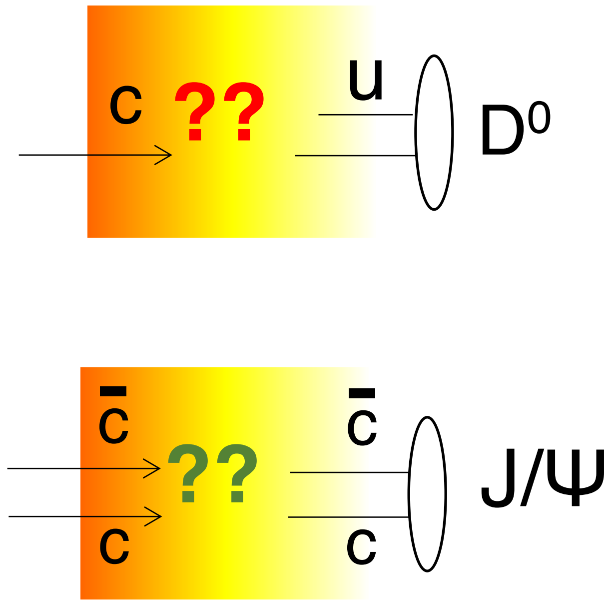
✓ Strong charm flow, maybe some indication < v_2(K)

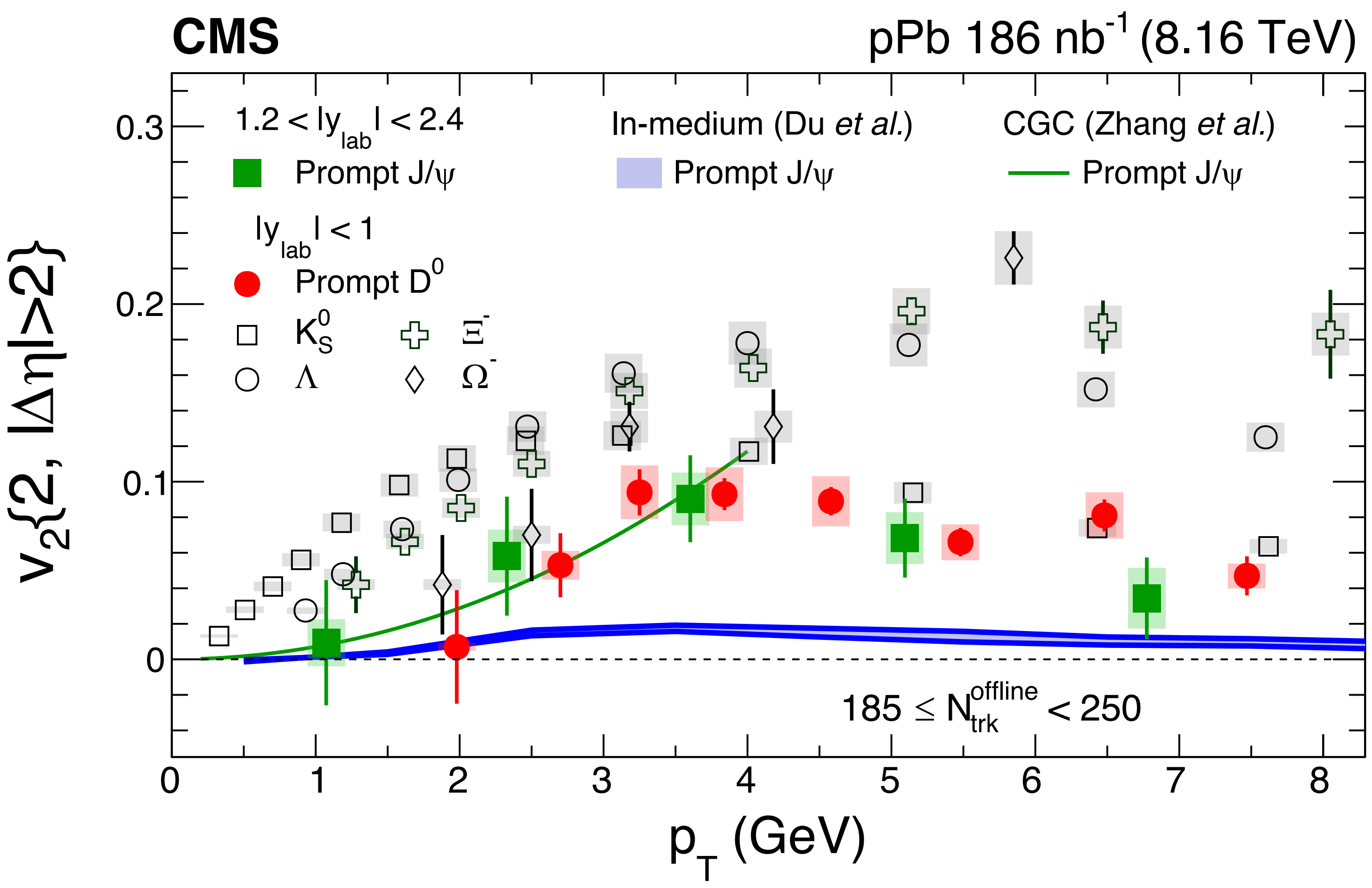
✓ (Surprisingly!?) large J/ψ v2 signal → ISC needed?

Heavy quark collectivity in small systems

Shrink the system size: N_{trk} ~ 900 ⟶ N_{trk} ~ 200

In small systems?





Open *vs.* Hidden

✓ Strong charm flow, maybe some indication < v_2(K)

✓ (Surprisingly!?) large J/ψ v2 signal → ISC needed?

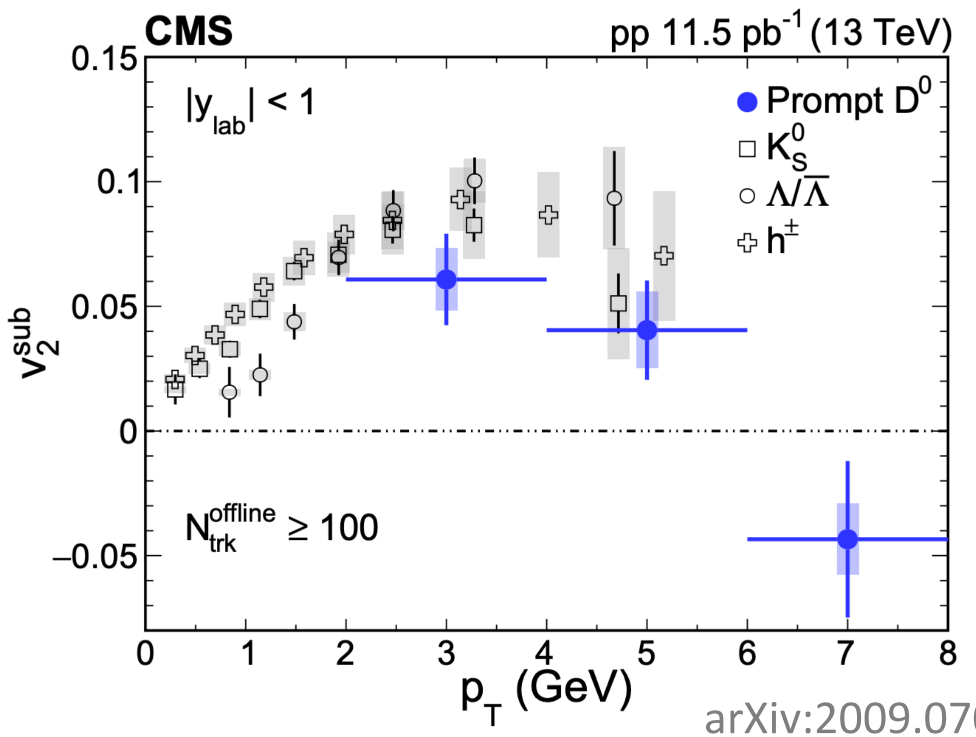
Heavy quark collectivity in small systems

Summary and outlook

	pp		pPb	
	v_2	yield	v_2	yield
Open Charm Meson	✓	✓	✓	✓
Open Beauty Meson	✓	✓	✓	✓
Open Charm Baryon	x	✓	x	✓
Open Beauty Baryon	x	x	x	x
Charmonia	x	✓	✓	✓
Bottomonia	x	✓	x	✓

Most ✓ to be improved with better precision

Prompt D^0 in HM pp



arXiv:2009.07065

Future opportunities for small systems

Proposed LHC run schedule

HI-LHC HI yellow report: arXiv: 1812.06772

	Year	Systems, $\sqrt{s_{NN}}$	Time	L_{int}
Run3	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)
Run4	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	

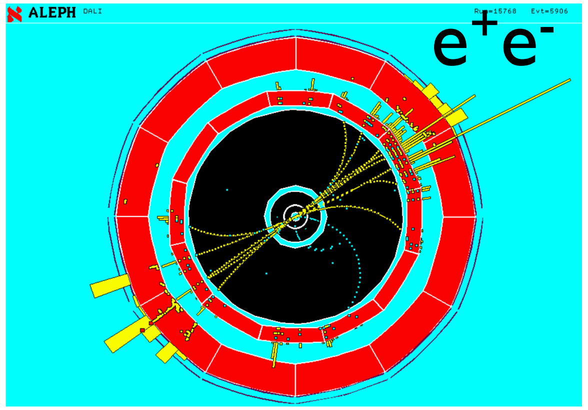
Detector upgrades

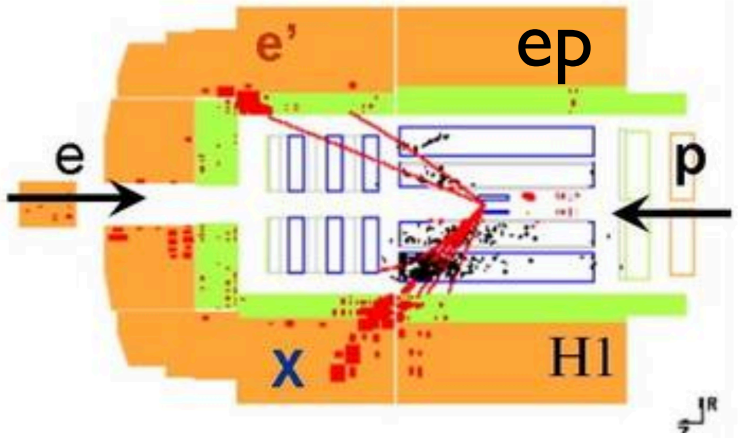
First OO 200 GeV likely at RHIC in 2021! Strong synergy with the LHC

➢ Smaller AA system with better controlled geometry

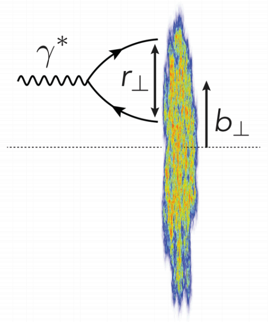
Where else to find "QGP"?

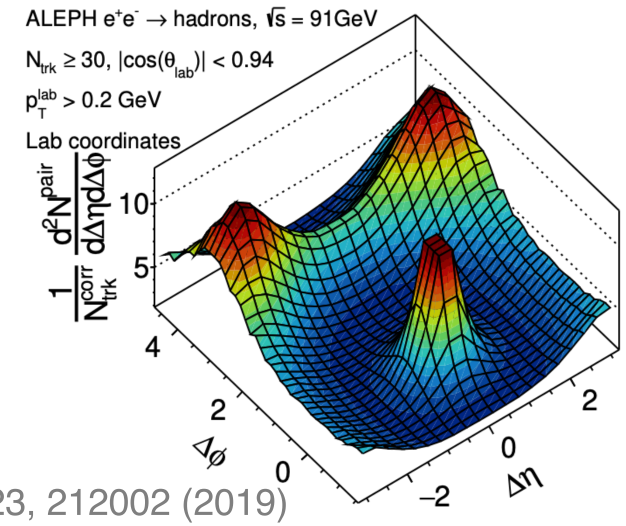
Keep pushing to extreme domains: smaller than pp?



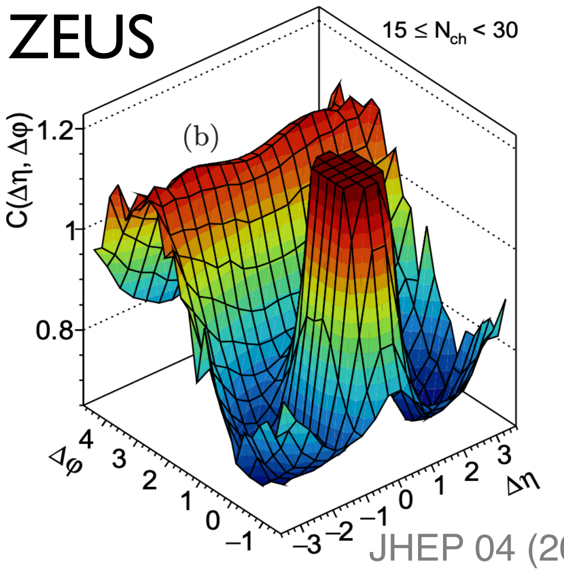


γA and γp

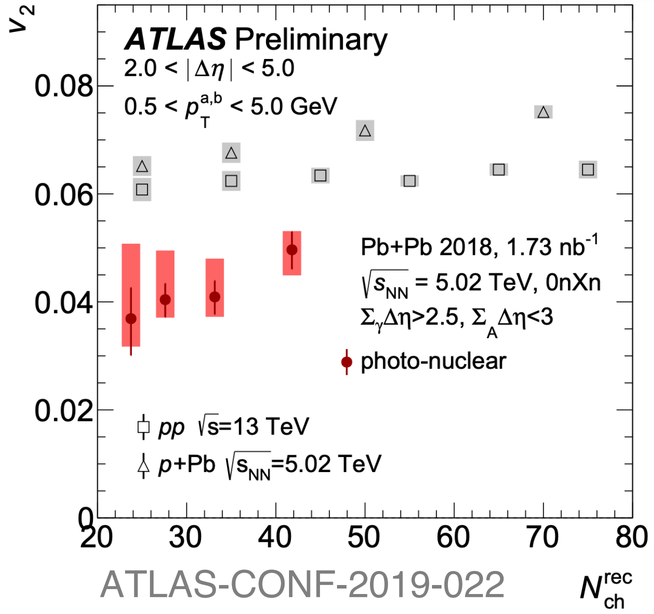




PRL 123, 212002 (2019)



JHEP 04 (2020) 070

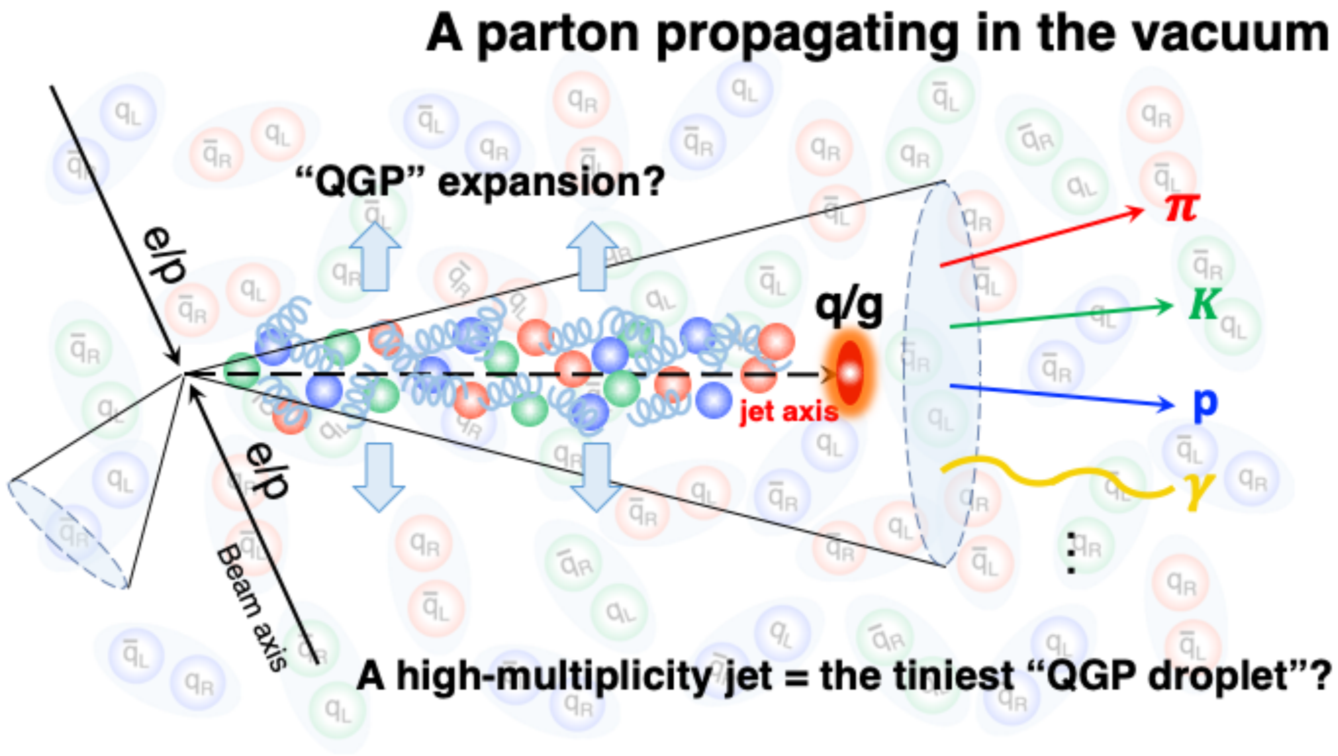


ATLAS-CONF-2019-022

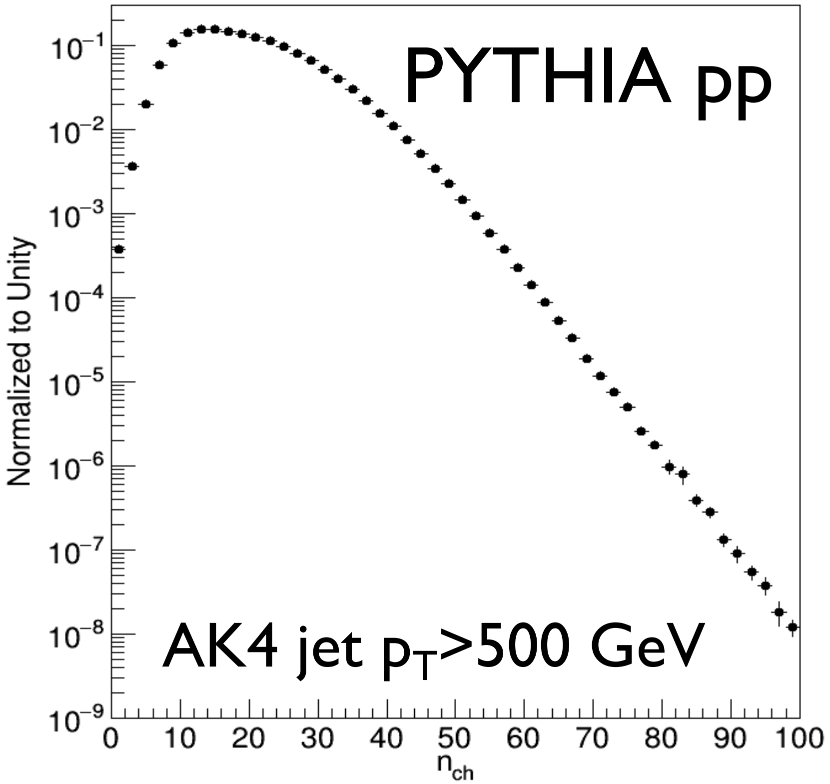
- No ridge seen so far, esp. hard to reach high multiplicities
- v_2 in γA: "flow" or "nonflow"? MC Models? Search at EIC?

Where else to find "QGP"?

Keep pushing to extreme domains: QGP from a single parton?



Charged multiplicity from a jet



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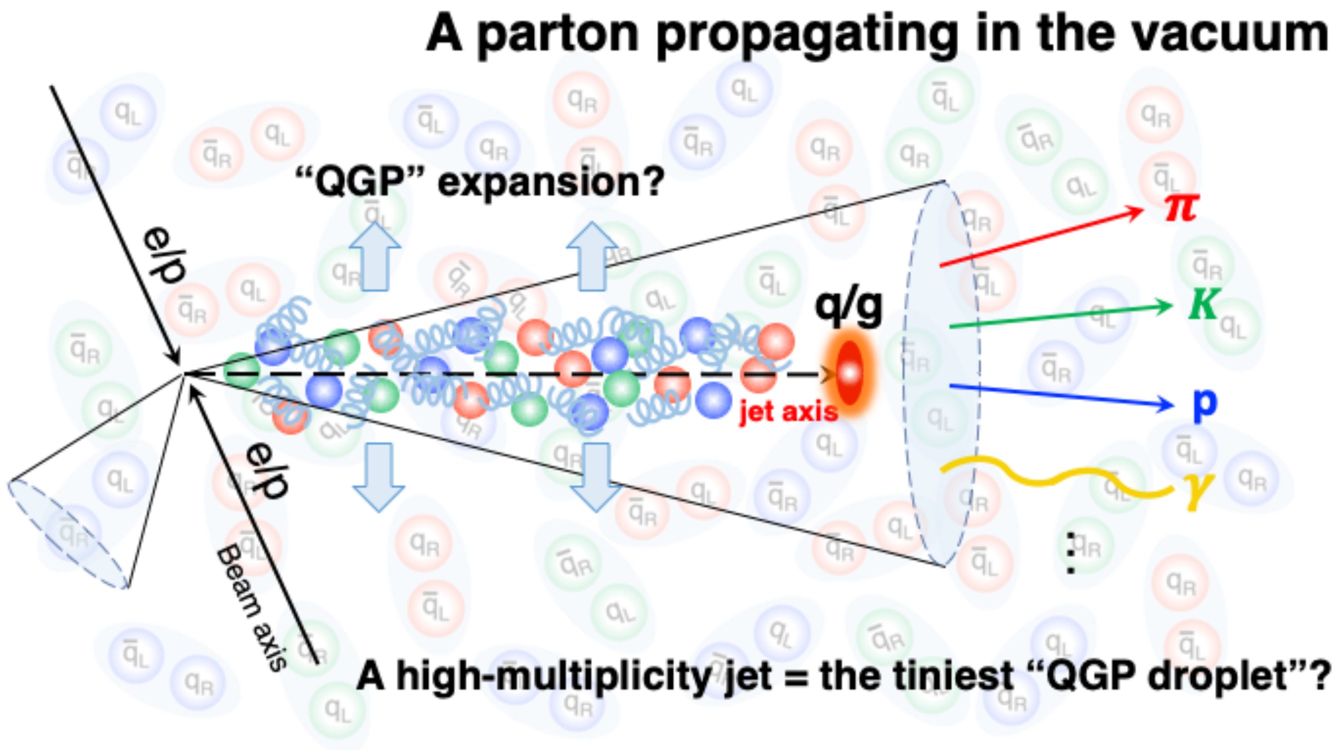
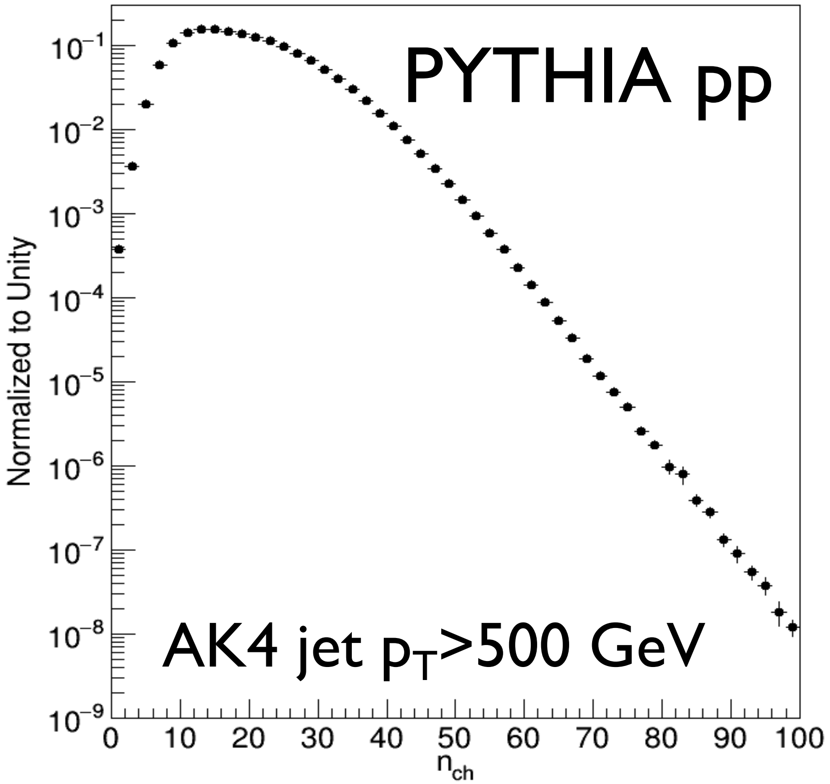


Charged multiplicity from a jet



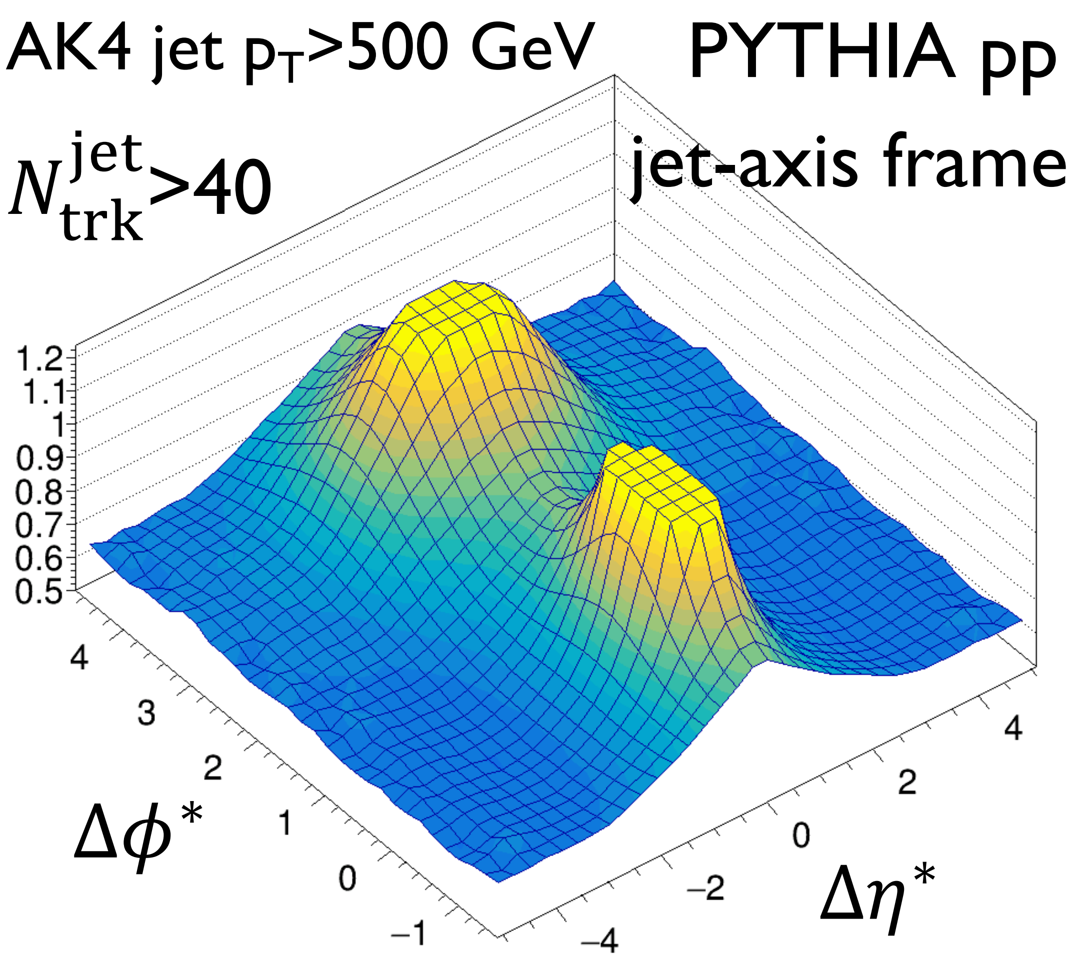
Is soft fragmentation process reminiscent of “QGP” expansion?

“Thermal” feature observed in e+e- related to a single-parton “QGP”?

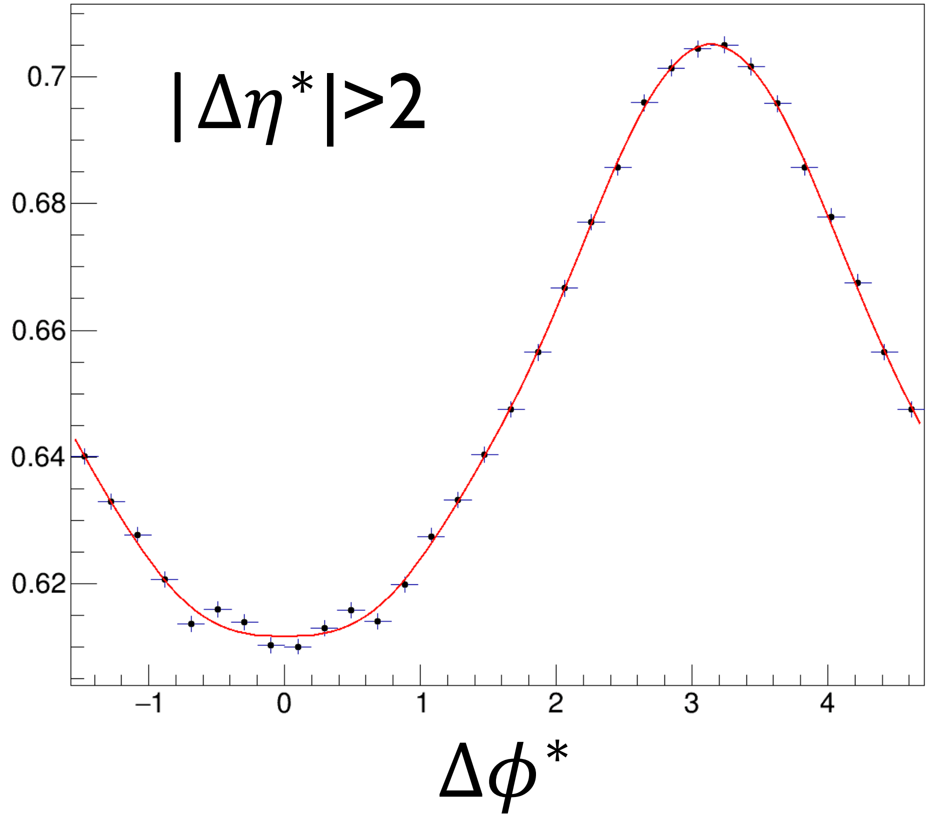
F. Becattini, Z. Phys. C69, 485 (1996)

Where else to find "QGP"?

Keep pushing to extreme domains: QGP from a single parton?



0.3<j_T<3 GeV



Not very different from beam axis

Summary

Very exciting past 10 years with small systems!

- Understood better the collectivity at where it is expected

  – *"Large systems"*

- Discovered the collectivity at where it was not expected and making rapid progress in understanding it

  – *"Small systems"*

Exciting opportunities ahead to look for collectivity elsewhere and learn about QCD in most extreme conditions

Acknowledgement

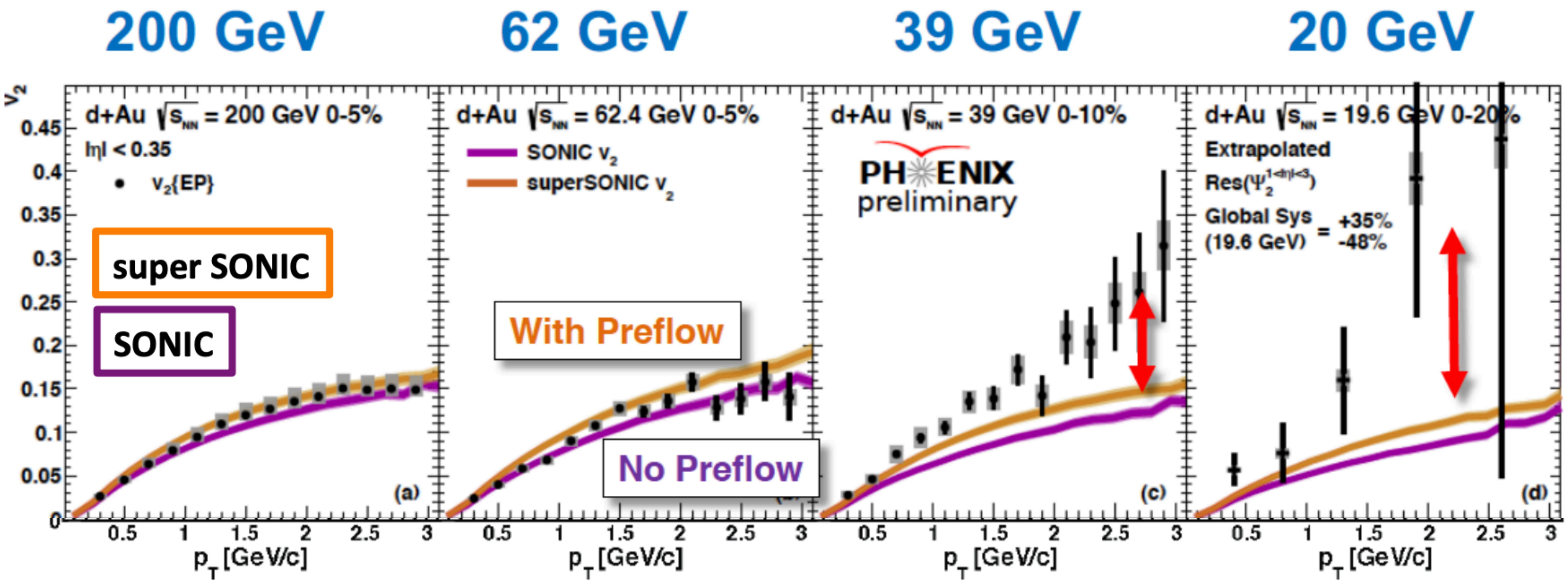
U.S. DEPARTMENT OF ENERGY

Office of Science

Alfred P. Sloan FOUNDATION

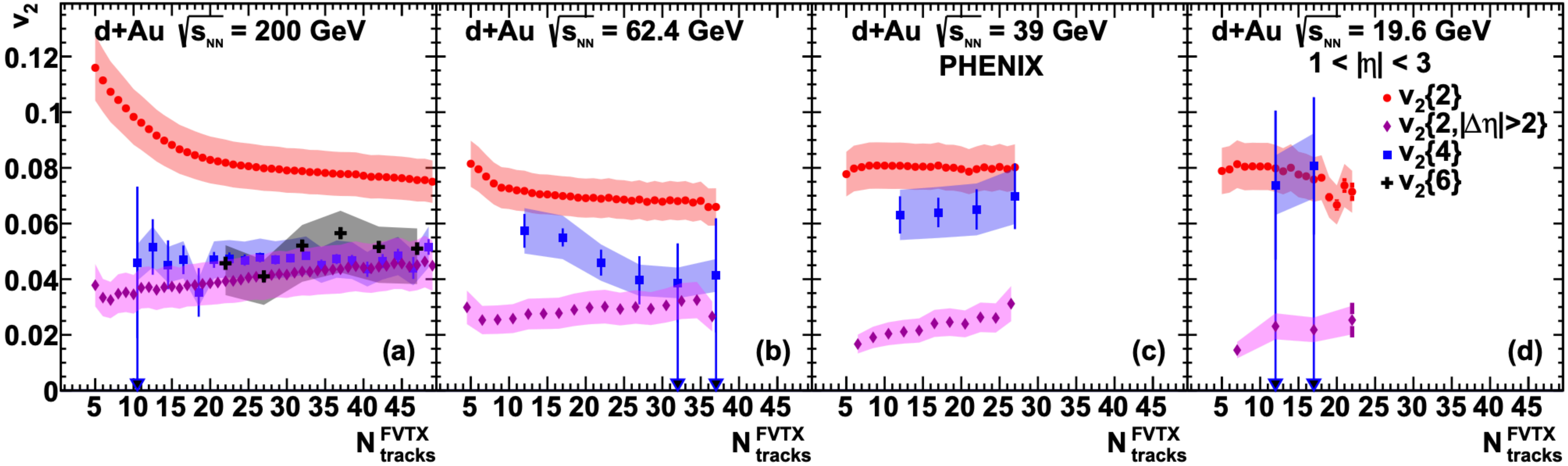
THE Welch FOUNDATION

Backups



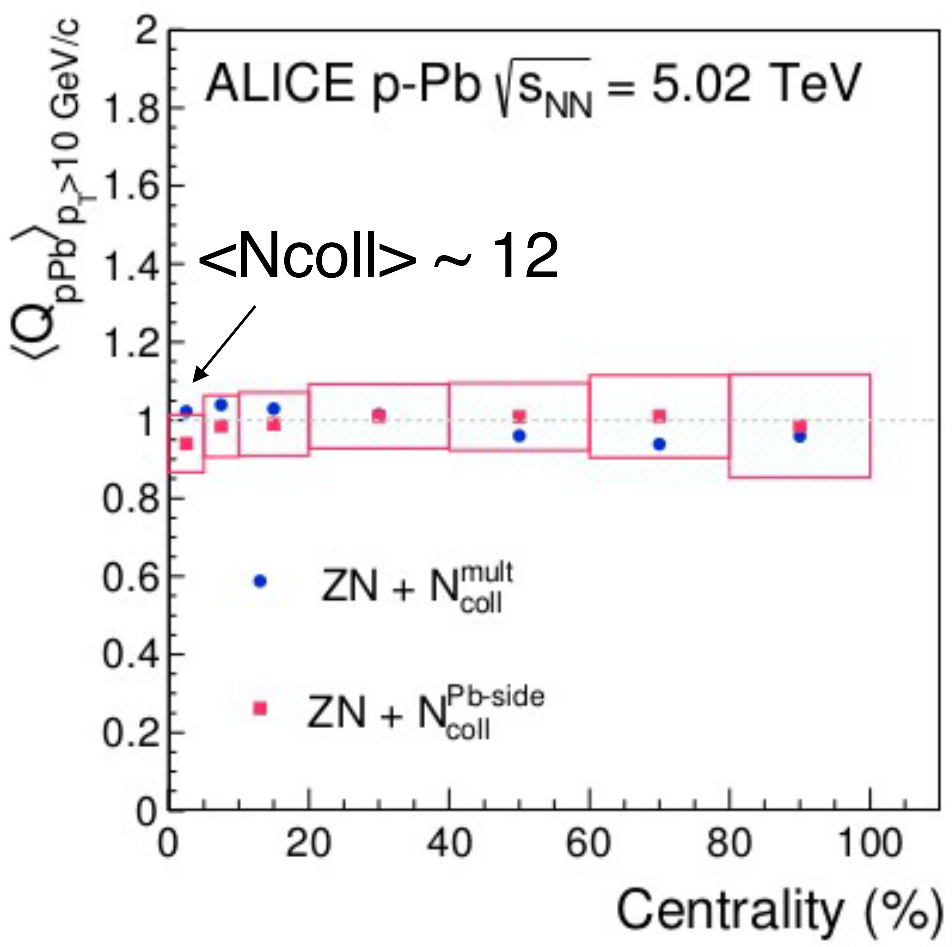
200 GeV
62 GeV
39 GeV
20 GeV
d+Au √s_NN = 200 GeV 0-5%
|η| < 0.35
v2{EP}
super SONIC
SONIC
d+Au √s_NN = 62.4 GeV 0-5%
SONIC v2
superSONIC v2
With Preflow
No Preflow
d+Au √s_NN = 39 GeV 0-10%
PHENIX preliminary
d+Au √s_NN = 19.6 GeV 0-20%
Extrapolated
Global Sys (19.6 GeV) = +35% -48%
v2
pT [GeV/c]
(a)
(c)
(d)

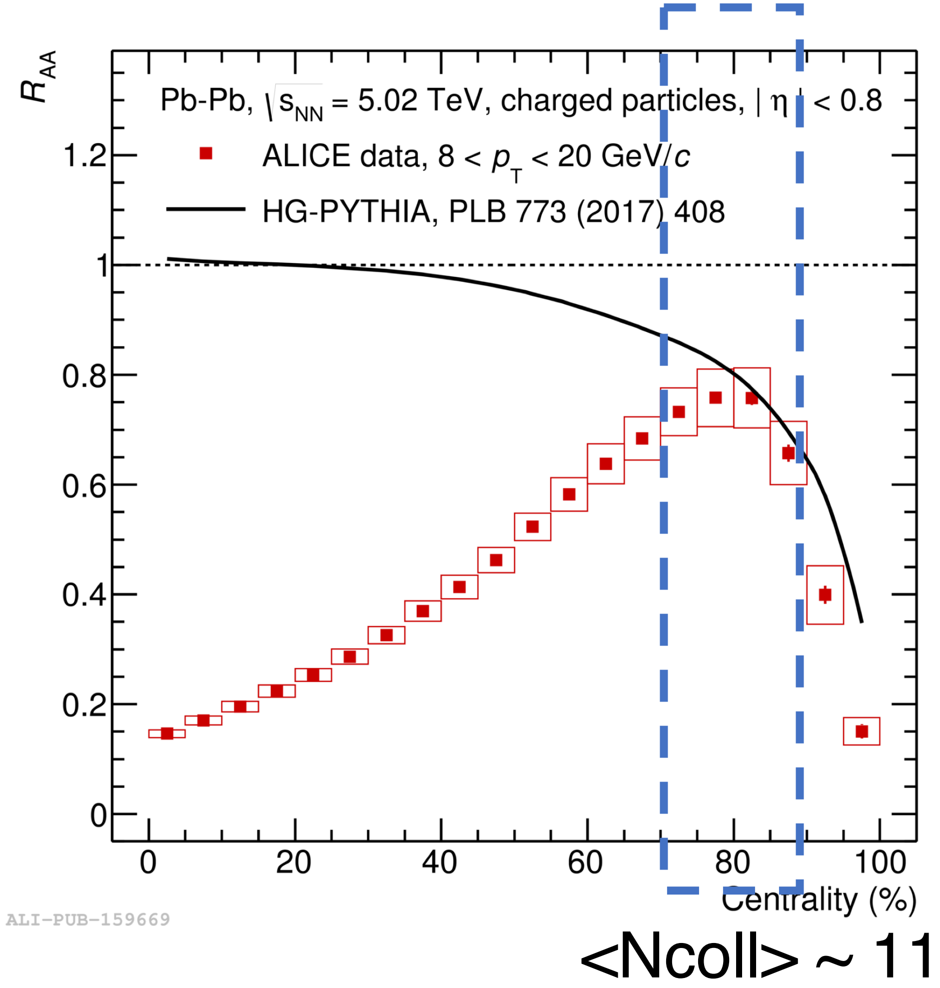
arXiv:1707.06108



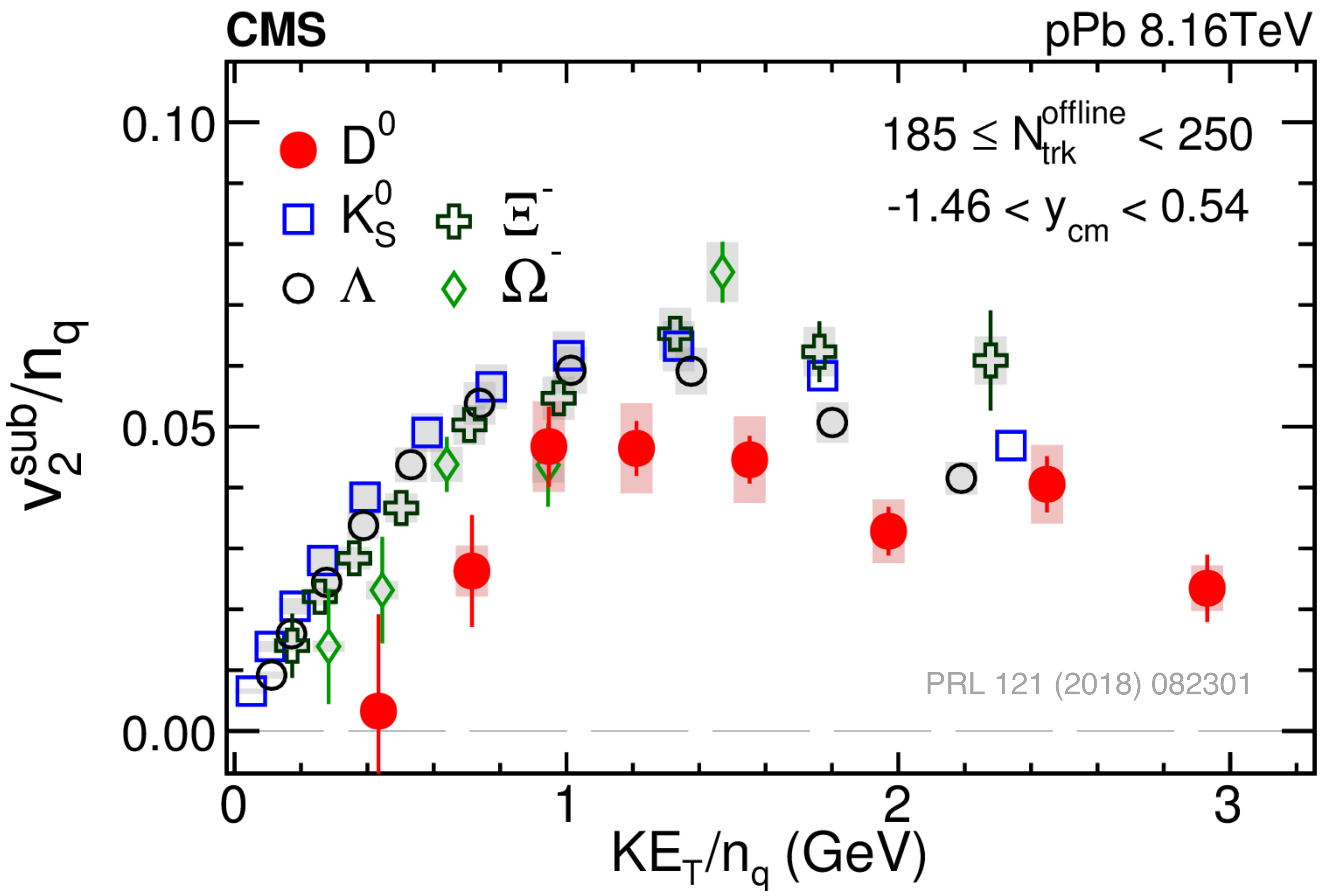
Evidence for later-time interactions?

Nuclear modification factors

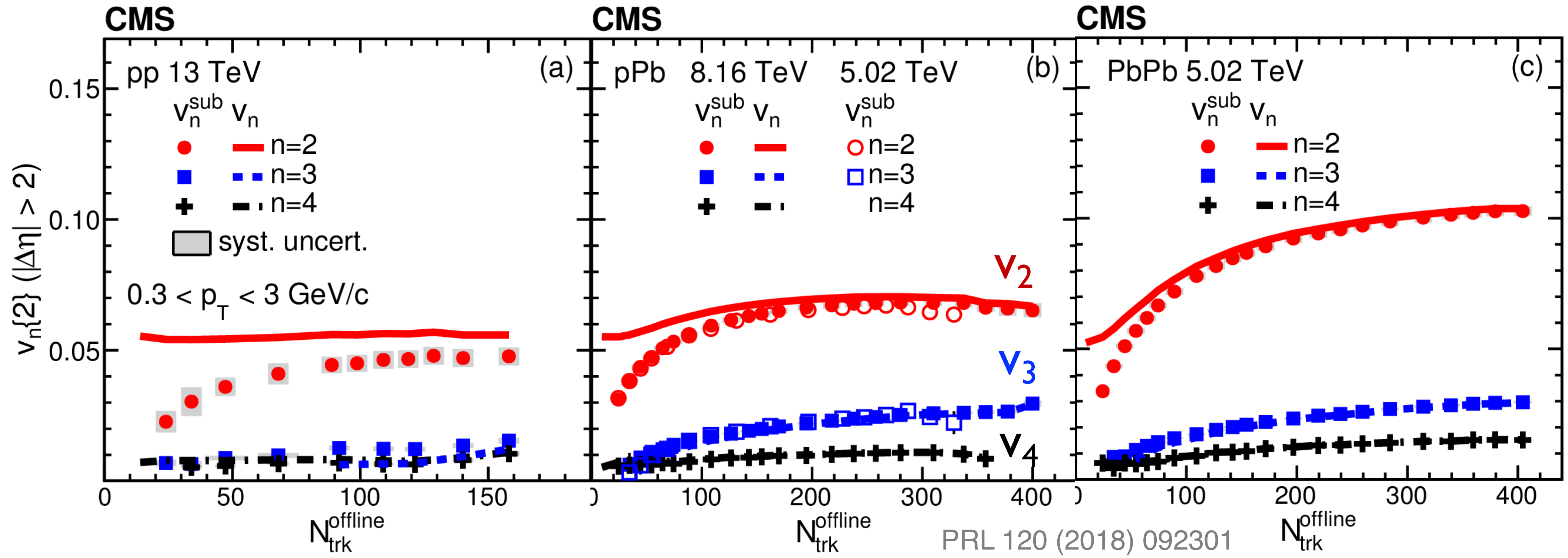




"Absence" of jet quenching consistent with expectation



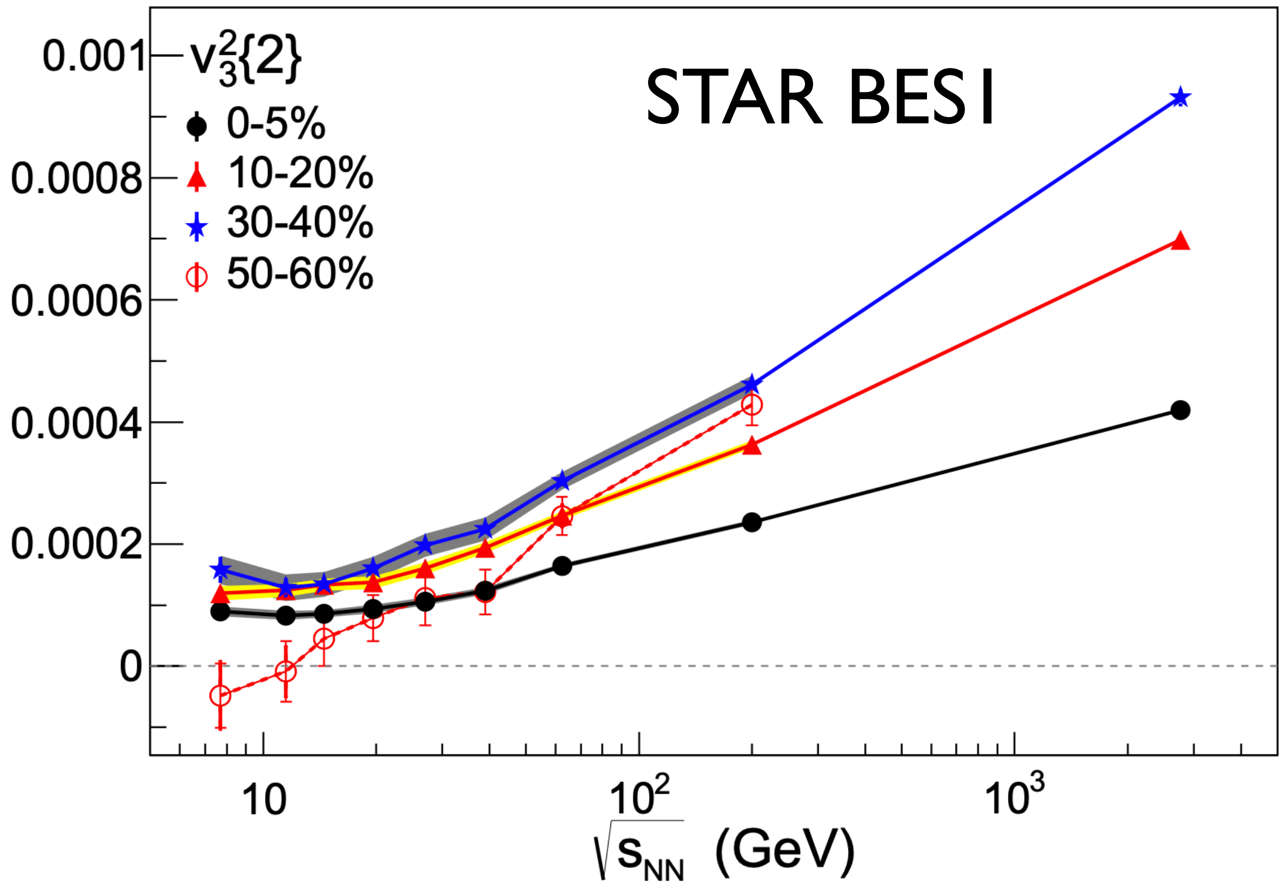
CMS
pPb 8.16TeV
D0
K0S
Ξ-
Λ
Ω-
185 ≤ N_trk^offline < 250
-1.46 < y_cm < 0.54
PRL 121 (2018) 082301
v2sub/nq
0.10
0.05
0.00
0
1
2
3
KET/nq (GeV)



PRL 120 (2018) 092301

Collective flow in AuAu at BES 2

Low energy AuAu are also effectively "small" $L >> \lambda_{m.f.p.}$ $\lambda_{m.f.p.} \sim \frac{1}{g^4 T}$



Collective flow in AuAu vs N_{trk} at BES2 highly interesting!