The 28th International Conference on Ultrarelativistic Nucleus-Nucleus Collisions
November 4-8, 2019, Wuhan, China

Probing QGP with flow
(including system size and energy dependence)

An experimental overview

Katarína Křížková Gajdošová
Czech Technical University in Prague

7th November 2019

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EVROPSKÁ UNIE
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MINISTERSTVO ŠKOLSTVÍ, MLÁDEŽE A TĚLOVÝCHOVY

This talk …

- … **is about** an overview of the latest results and developments in the field
- … **is not about** summary of Quark Matter 2019 parallel talks
  - Although we did see quite a lot of **new results and interesting implications**, which I cannot ignore
- … has only 25 minutes, so I apologise in advance if I **do not include** your work

Pointers to talks / posters:

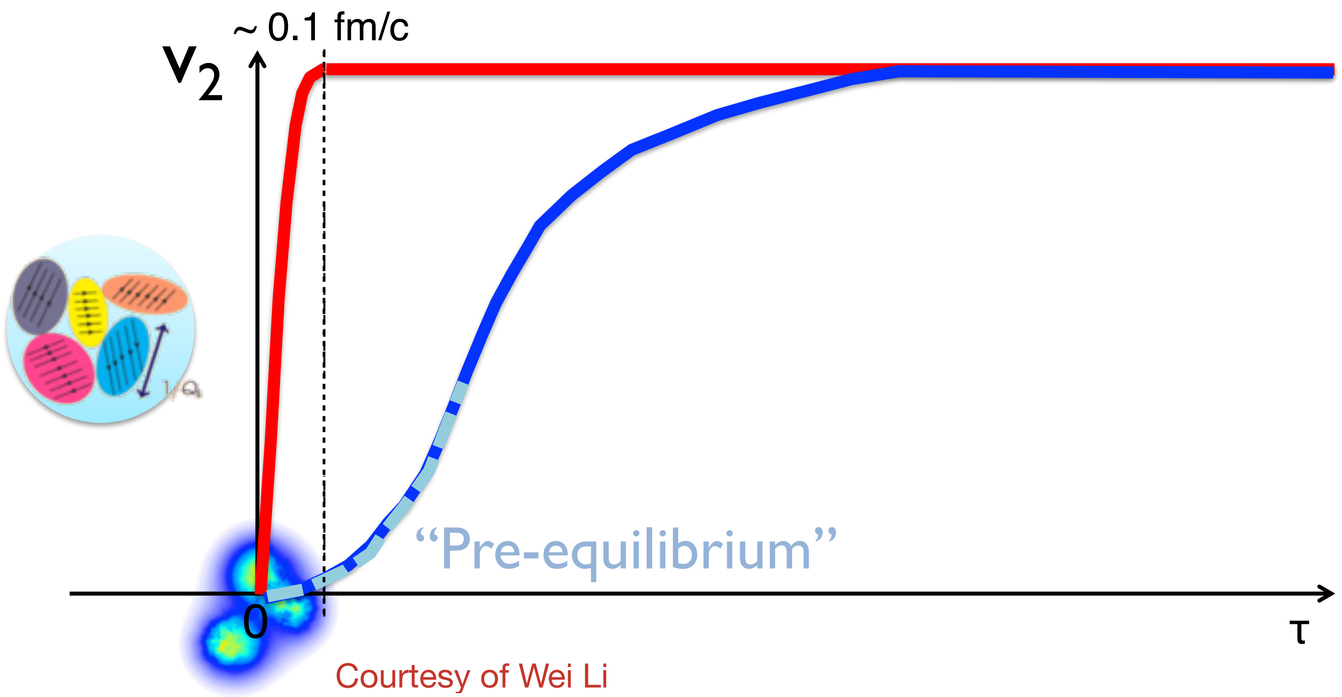
Speaker, day@time Results that are currently on the slide

Speaker, day@time Similar results that did not fit in

New at QM19 — New result from this Quark Matter

New — New result since last Quark Matter

What do we know: from AA down to pp



Courtesy of Wei Li

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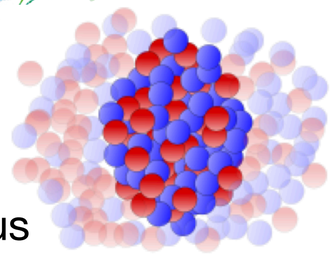
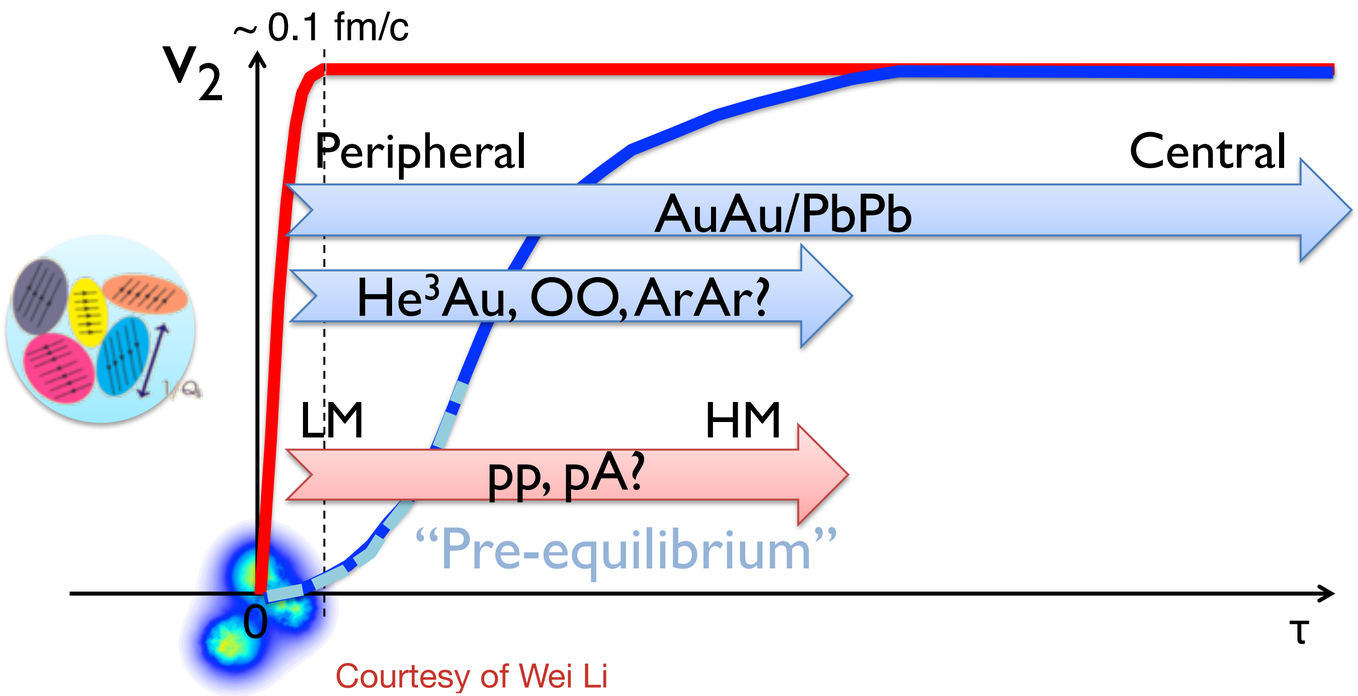


nucleus

Initial state geometry (overlapping nucleons) → In-medium interactions → Final momentum anisotropy



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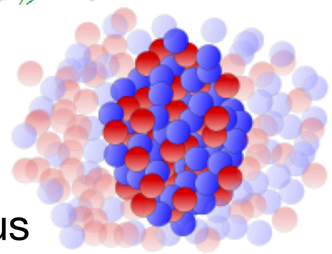

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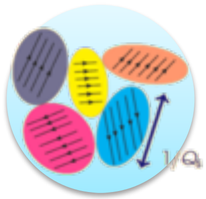

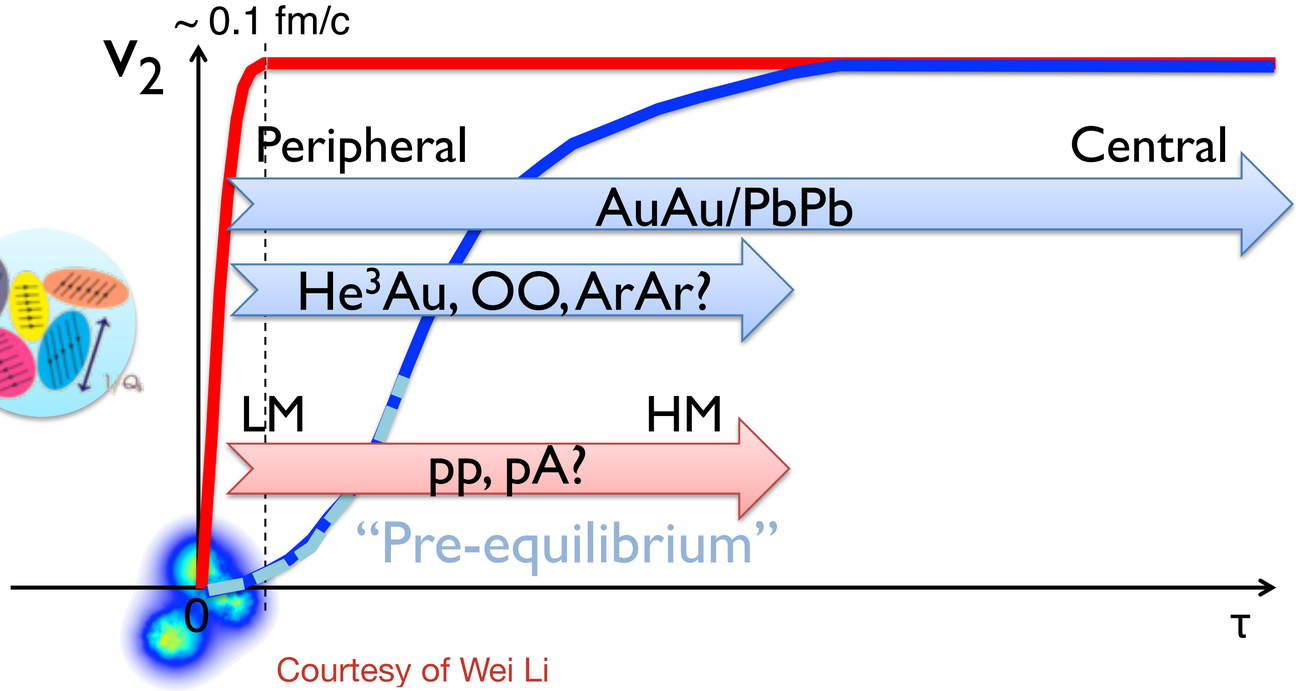

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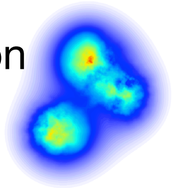
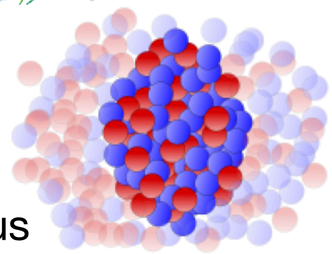


nucleon

Initial state geometry (sub-nucleon fluctuations) / gluon field momentum correlations → ? In-medium interactions → ? Final momentum anisotropy

What do we know: from AA down to pp



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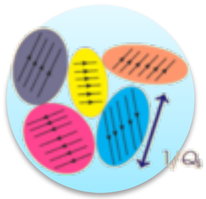
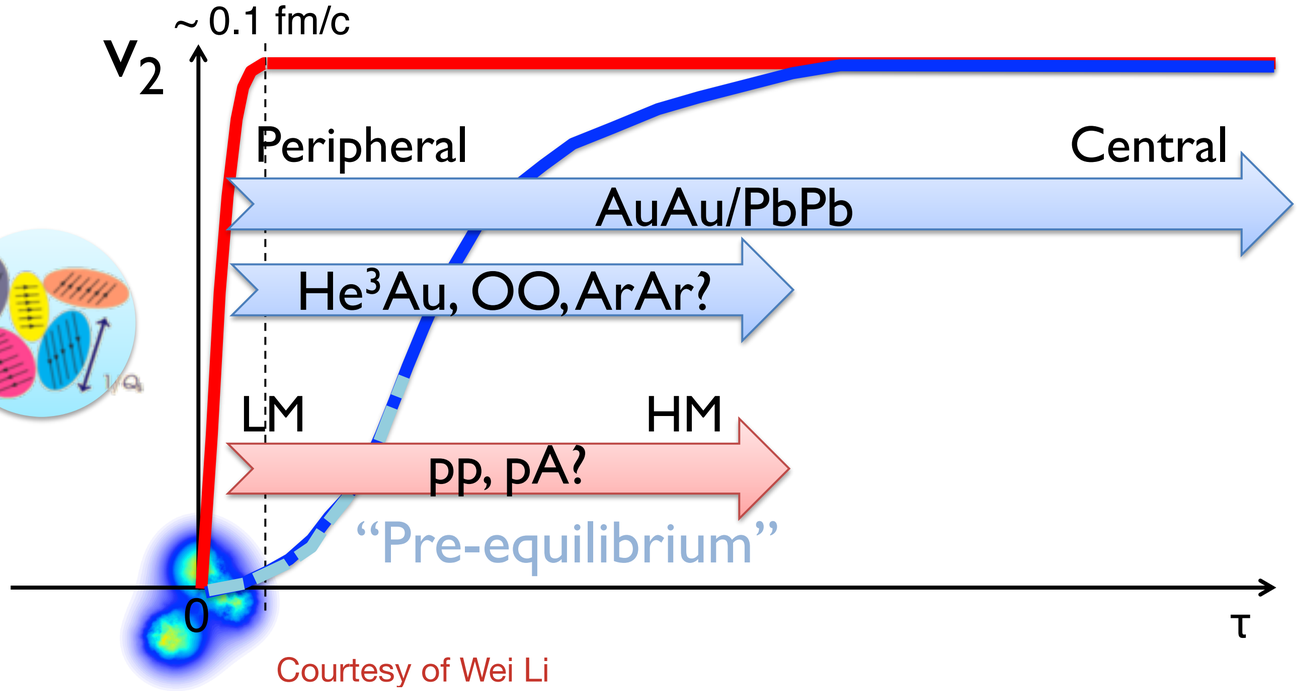
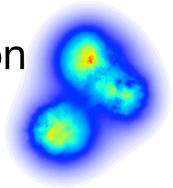




Courtesy of Wei Li

"Precision" measurements:
constraints on initial state,
transport coefficients (η/s, ζ/s, …)



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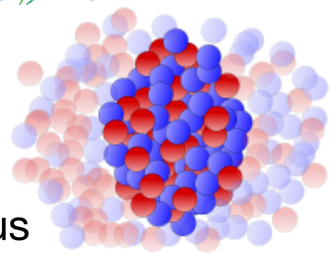

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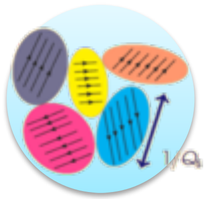
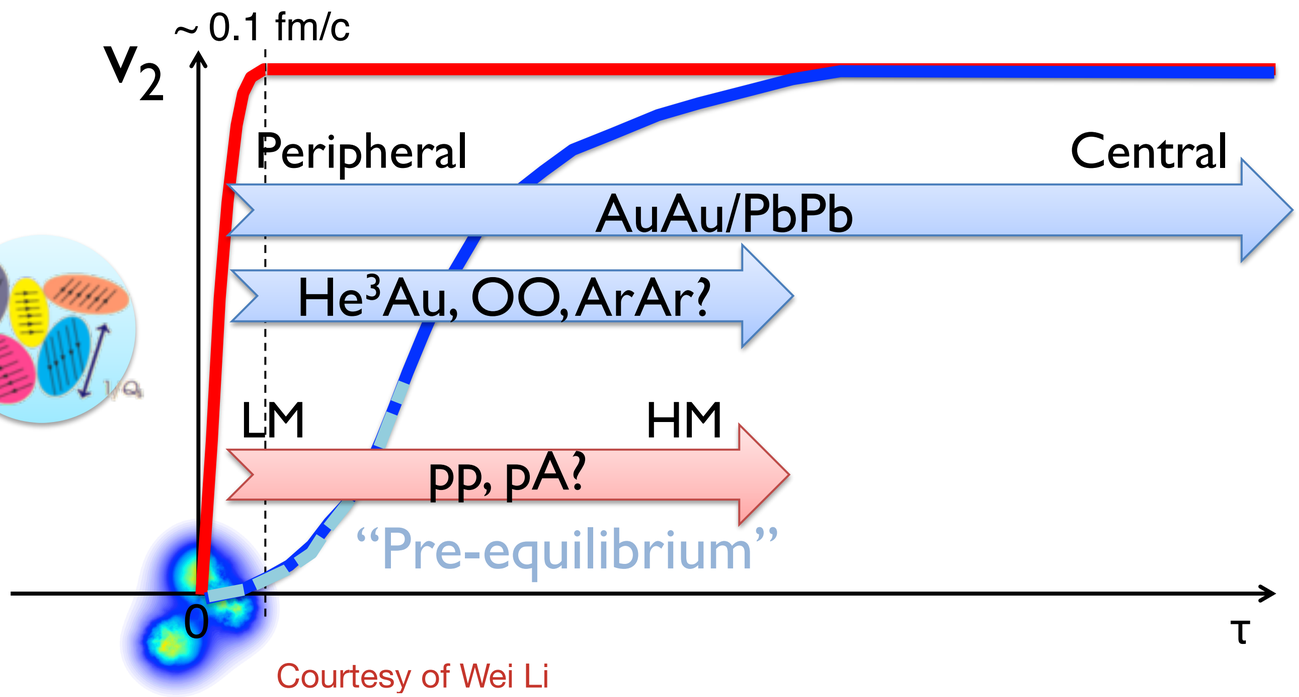
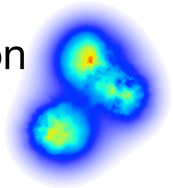




Courtesy of Wei Li

"Precision" measurements:
constraints on initial state,
transport coefficients (η/s, ζ/s, …)

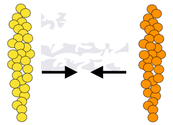
"Decision" measurements:
what is the origin of collectivity,
what kind of medium are we talking about
(if there is any)?

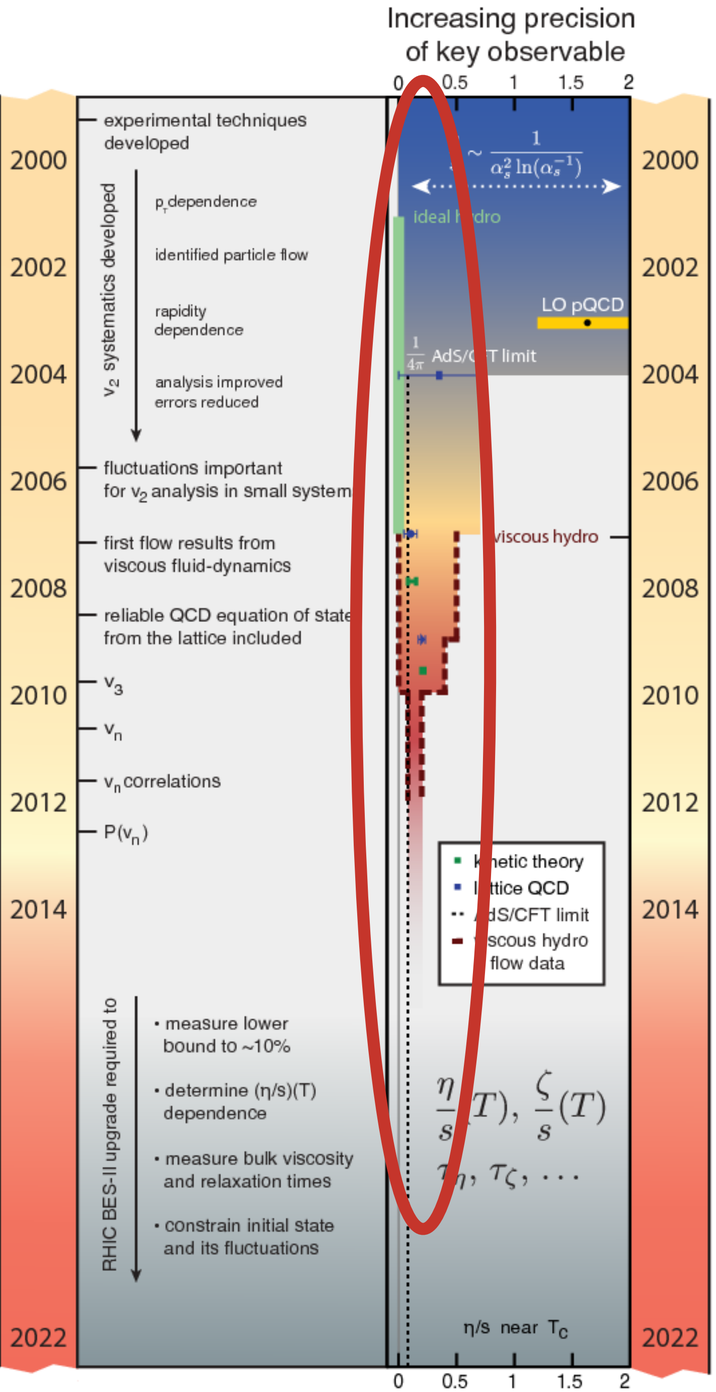


nucleon

Initial state geometry (sub-nucleon fluctuations) / gluon field momentum correlations → ? In-medium interactions → ? Final momentum anisotropy

Large collision systems

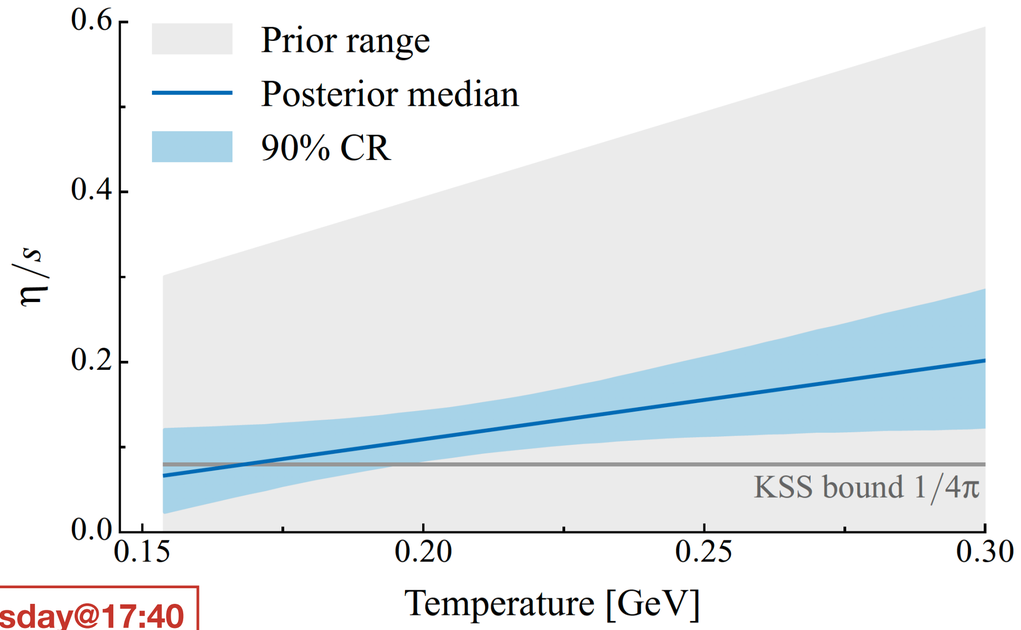




Gale et al., Int.J.Mod.Phys. A28 (2013) 1340011

- Significant improvements in our understanding of heavy-ion collisions
  - *Theory:* Ideal hydro -> viscous hydro with constant η/s -> viscous hydro with η/s (T)
  - *Experiment*: v_2 -> v_n -> identified hadron v_n -> fluctuations, …
- Large amount of data allows us to measure **more differential experimental measurements** -> precision era

J. Bernhard, et al., PRC 94, 024907 (2016)



J-F. Paquet, Tuesday@17:40

Large collision systems

$$P(\varphi) = \frac{1}{2\pi} \sum_{n=-\infty}^{\infty} V_n e^{(-in\varphi)} \qquad V_n = v_n e^{in\Psi_n}$$

Flow vector magnitude → *Flow coefficients (v_n)*

Flow vector fluctuations → *Flow de-correlations (p_T, η)*, *Flow fluctuations*, *Event shape engineering*

Flow vector correlations → *Symmetric cumulants*, *Non-linear flow modes*

Flow of identified hadrons → *Light flavor flow*, *Heavy flavor flow*

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Energy dependence
System dependence

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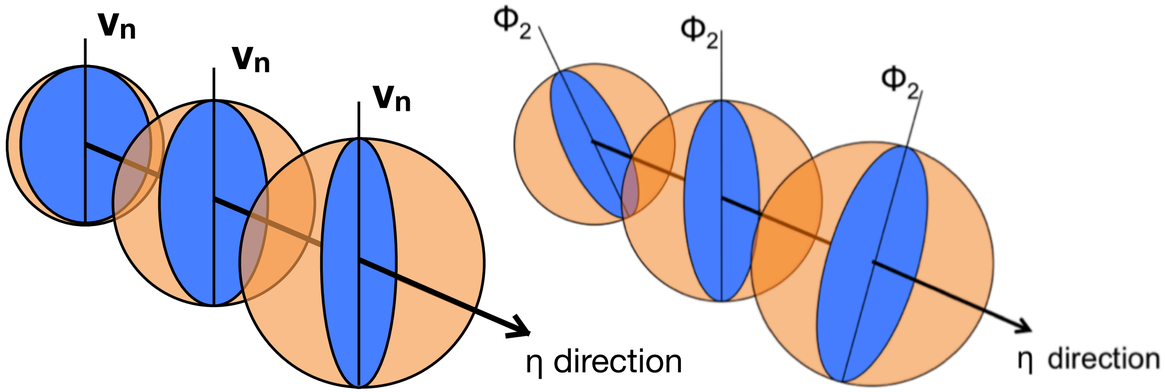
Energy dependence
System dependence

(Longitudinal) de-correlation of flow vector

J. Jia and P. Huo, PRC 90, 034905 (2014)

EbyE fluctuations in the initial state -> flow vector de-correlations



Constraints on fluctuation-driven longitudinal dynamics

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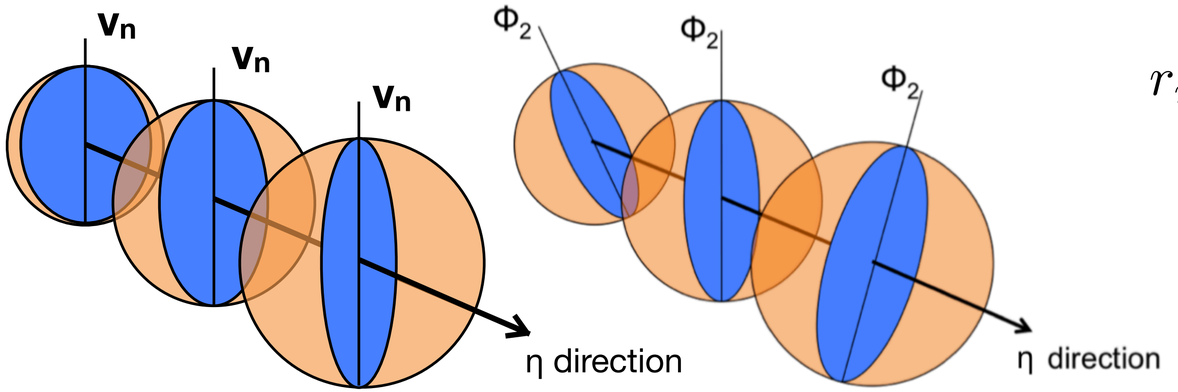
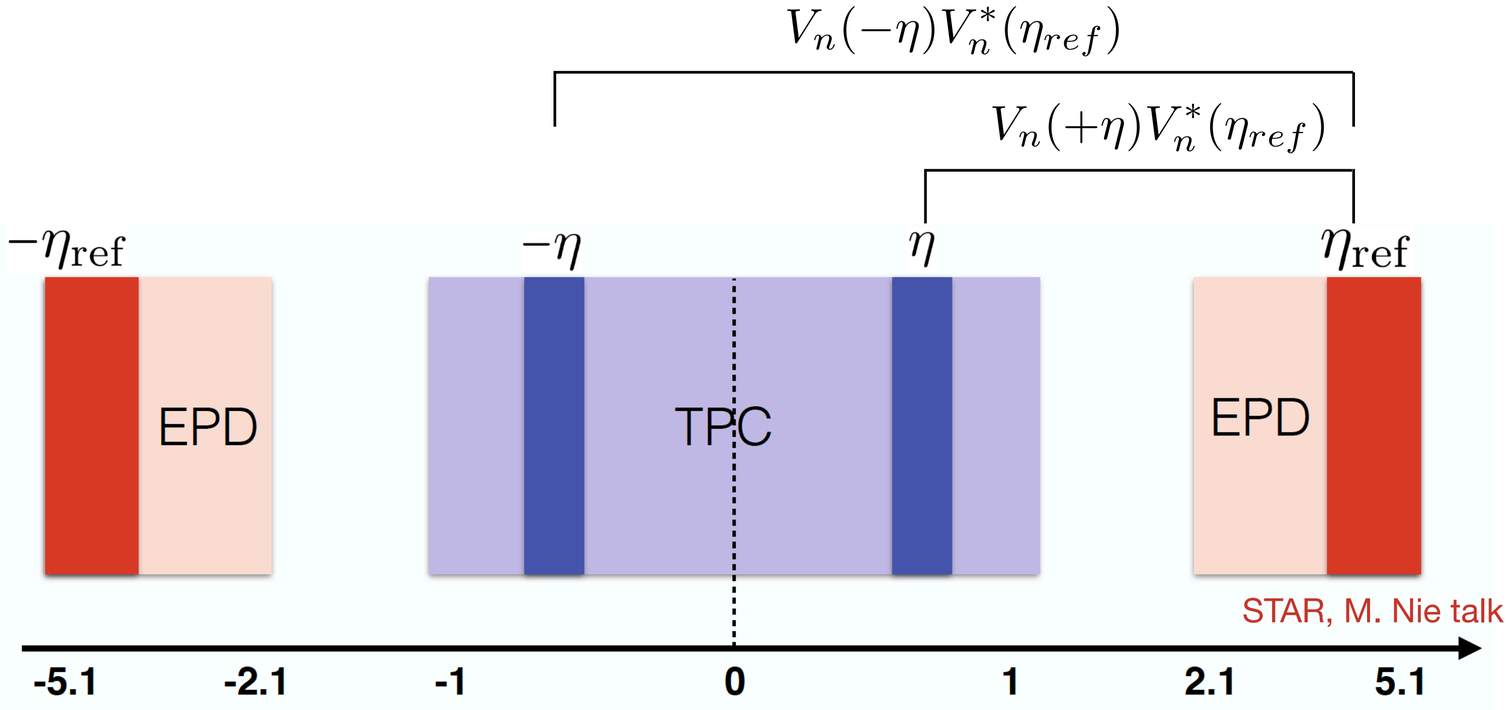


$$r_n(\eta) = \frac{\langle V_n(-\eta) V_n^*(\eta_{ref})\rangle}{\langle V_n(+\eta) V_n^*(\eta_{ref})\rangle}$$

$$= \frac{\langle v_n(-\eta) v_n(\eta_{ref}) \cos n(\Psi_n(-\eta) - \Psi_n(\eta_{ref}))\rangle}{\langle v_n(+\eta) v_n(\eta_{ref}) \cos n(\Psi_n(+\eta) - \Psi_n(\eta_{ref}))\rangle}$$

Constraints on fluctuation-driven longitudinal dynamics



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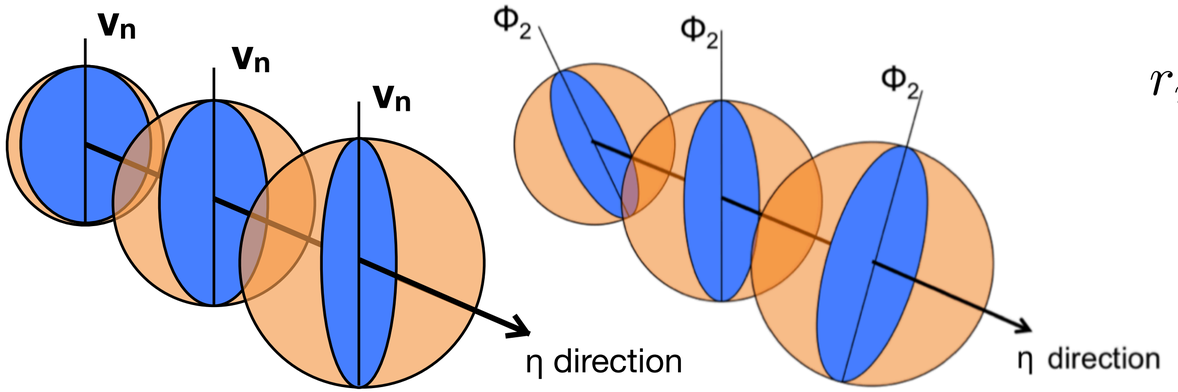

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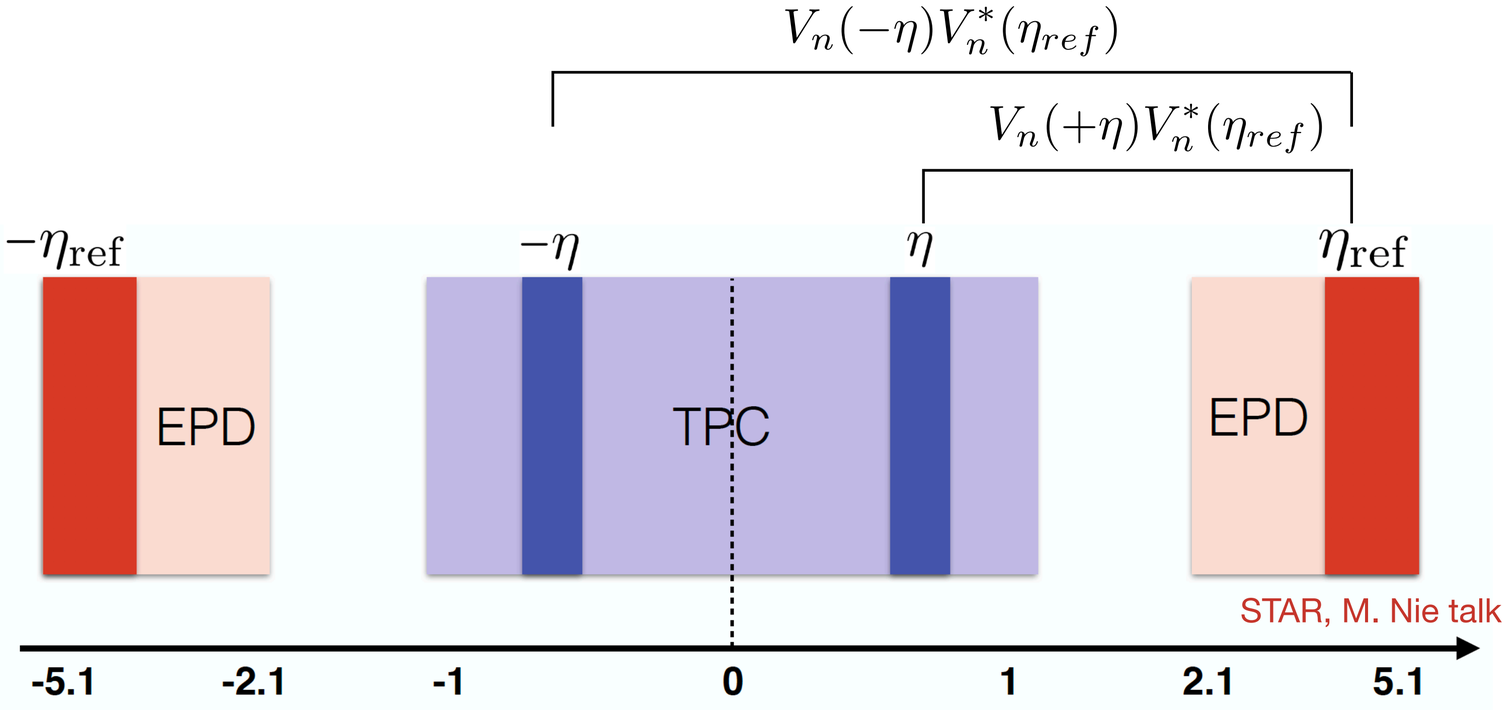
Constraints on fluctuation-driven longitudinal dynamics

No de-correlation: $r_n(\eta) = 1$

$$v_n(-\eta) = v_n(+\eta)$$
$$\Psi_n(-\eta) = \Psi_n(+\eta)$$

De-correlation: $r_n(\eta) < 1$

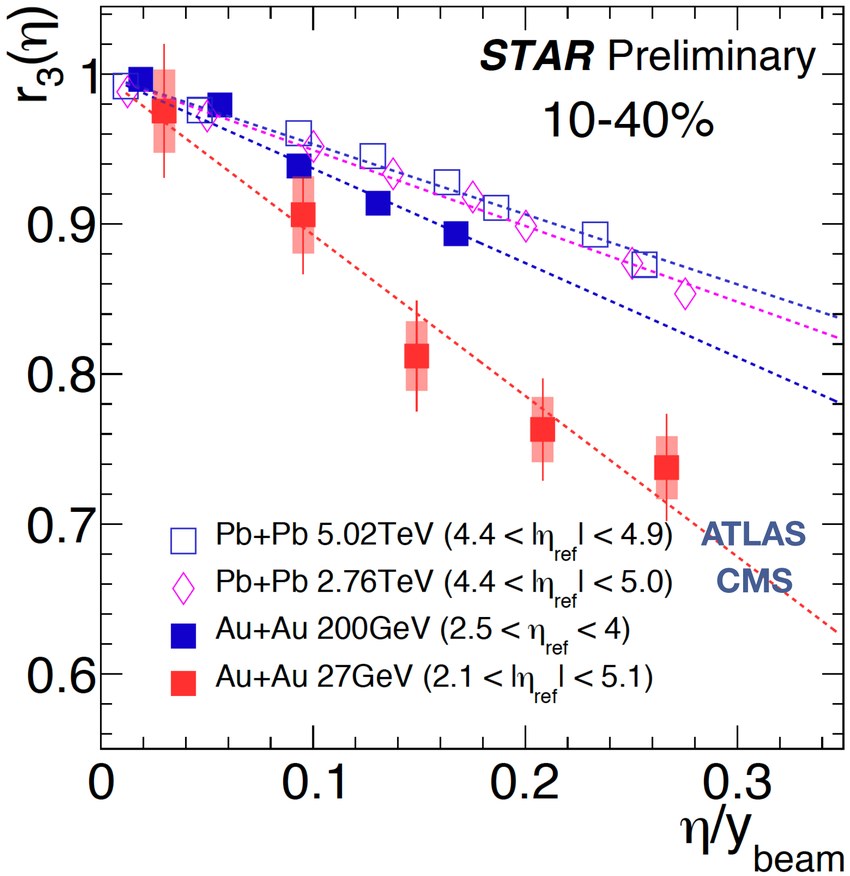


(Longitudinal) de-correlation of flow vector

New at QM19

Y. Sekiguchi, Wednesday@15:00 | S. Mohapatra, Tuesday@8:40 | M. Nie, Tuesday@9:00

[poster 148] A. Behera, Monday@16:30



- Strong energy dependence of $r_3(\eta)$

(Longitudinal) de-correlation of flow vector

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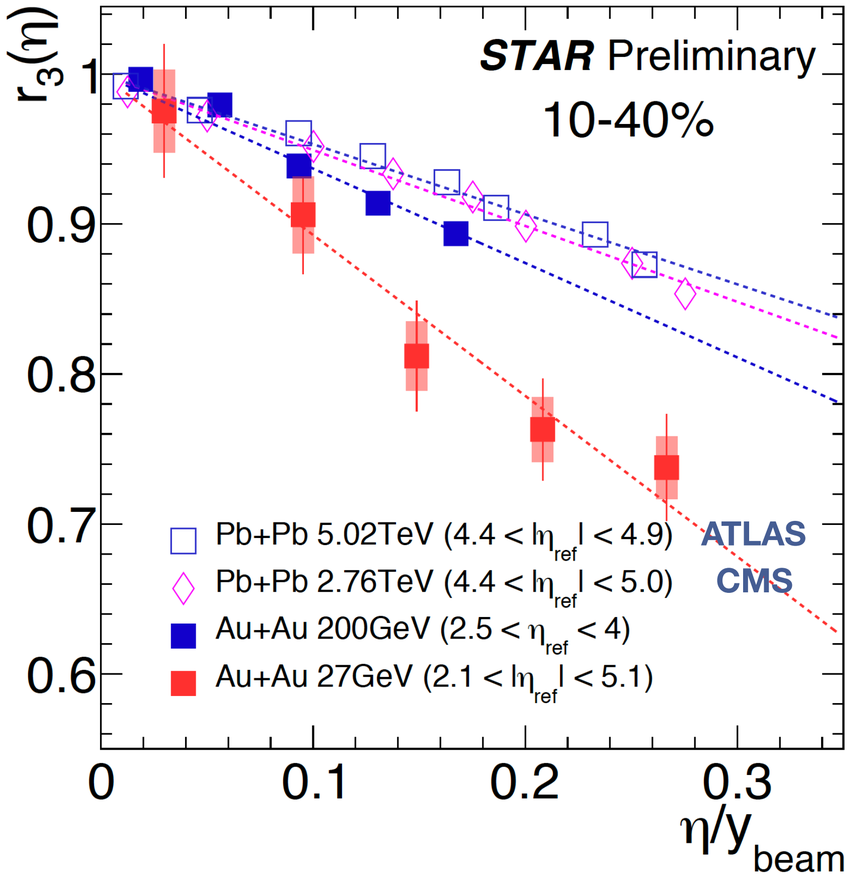
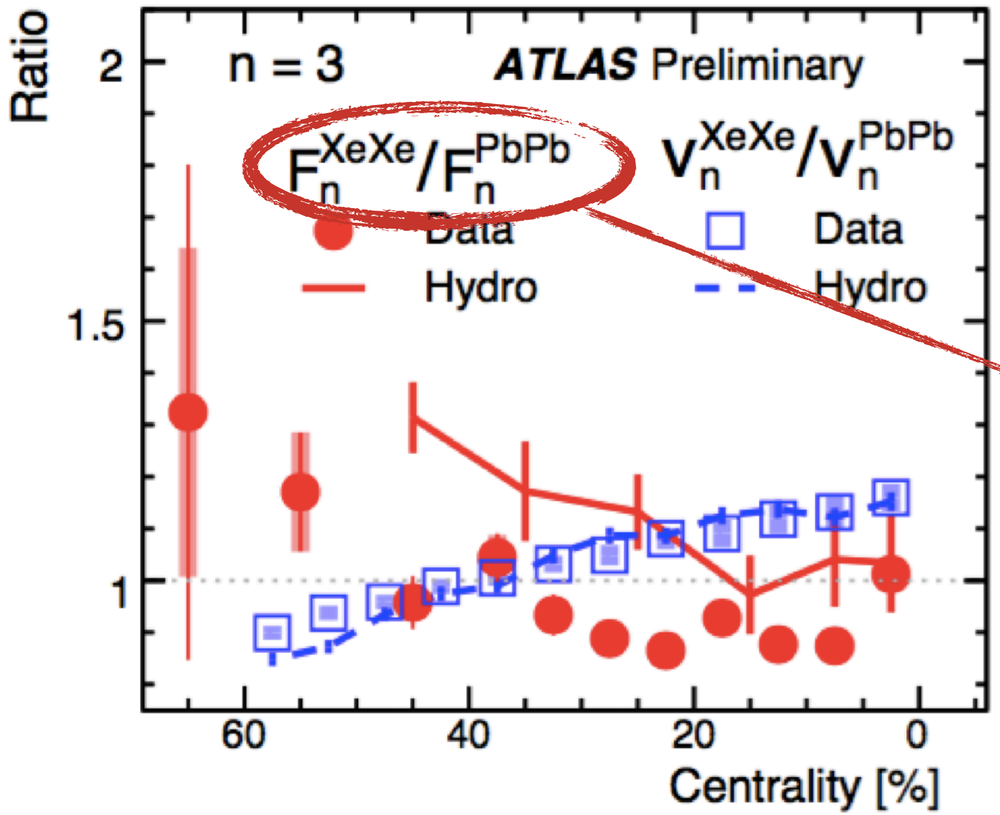




$$\propto \frac{r_n(\eta)^{XeXe}}{r_n(\eta)^{PbPb}}$$

- Strong energy dependence of $r_3(\eta)$
- XeXe vs. PbPb: sensitivity to initial geometry and viscous corrections

- Models tuned to describe v_n cannot reproduce this measurement

Flow fluctuations

Reminder:

$$\sqrt[4]{-c_n\{4\}} = v_n\{4\}$$

$$\sqrt[6]{\frac{1}{4}c_n\{6\}} = v_n\{6\}$$

$$\sqrt[8]{-\frac{1}{33}c_n\{8\}} = v_n\{8\}$$

Constraints on initial state fluctuations

Parametrisation of $P(v_n)$:

Bessel-Gaussian

$$v_n\{4\} = v_n\{6\} = v_n\{8\}$$

$$\frac{v_n\{m\}}{v_n\{k\}} = 1$$

not Bessel-Gaussian

$$v_n\{4\} \neq v_n\{6\} \neq v_n\{8\}$$

$$\frac{v_n\{m\}}{v_n\{k\}} < 1$$

$$m > k$$

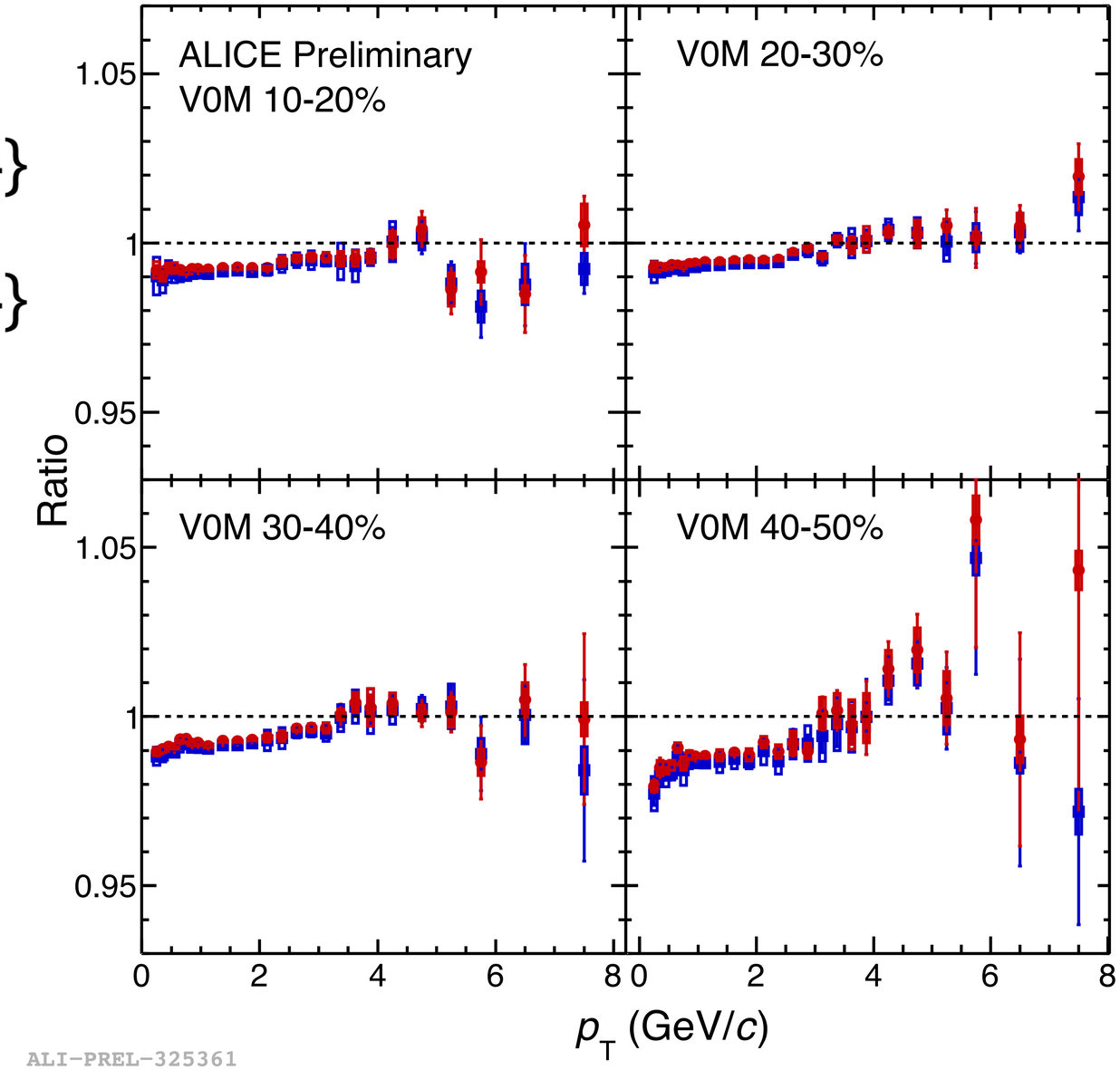
Flow fluctuations

New

Y. Zhu, Tuesday@10:00

- $v_2\{6\}/v_2\{4\}$
- $v_2\{8\}/v_2\{4\}$

Indication of a p_T dependence of flow fluctuations <- influence from the final state

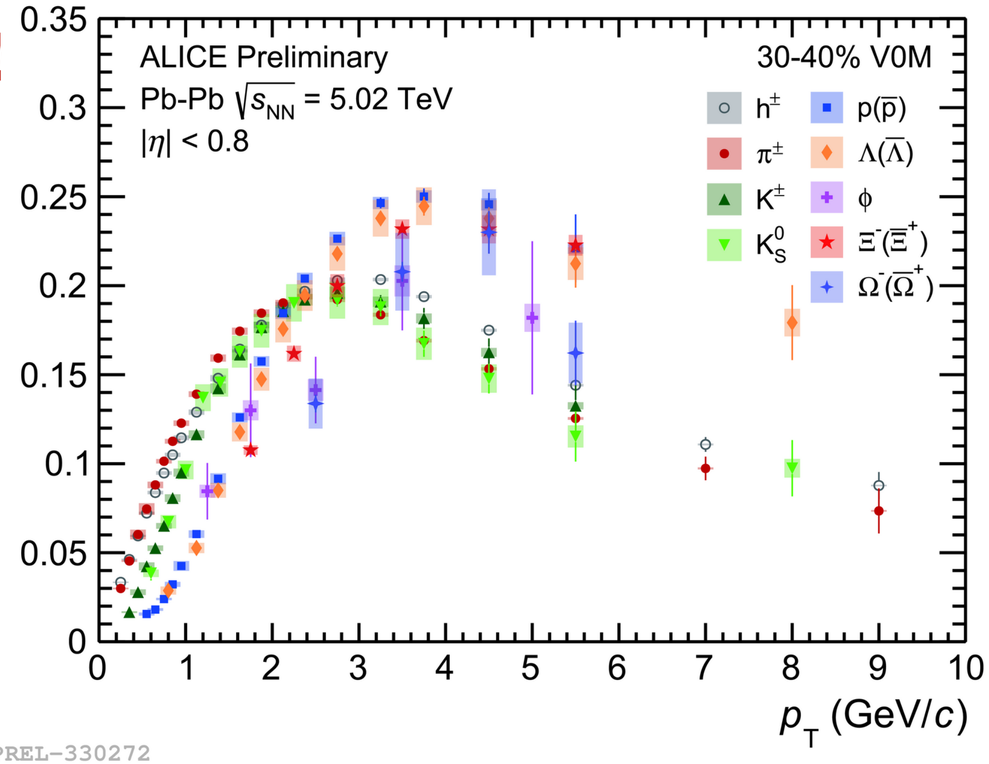


Flow fluctuations

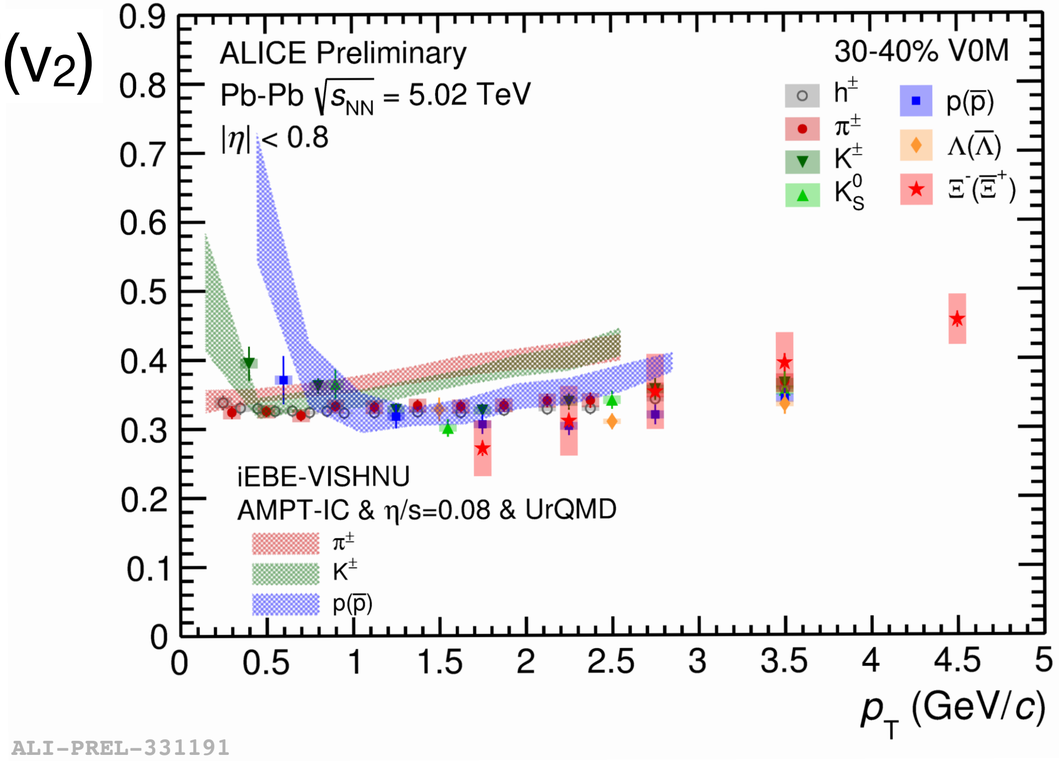
New at QM19

Y. Zhu, Tuesday@10:00

$v_2\{4\}$!



$F(v_2)$



$$\sigma_{v_n} \approx \sqrt{(v_n\{2\}^2 - v_n\{4\}^2)/2}$$

$$\langle v_n \rangle \approx \sqrt{(v_n\{2\}^2 + v_n\{4\}^2)/2}$$

$$\rightarrow F(v_n) = \frac{\sigma_{v_n}}{\langle v_n \rangle}$$

- Models: particle species dependence
- Data: **no particle species dependence observed**

Non-linear flow modes

New at QM19

$V_2 \propto \epsilon_2$

$V_3 \propto \epsilon_3$

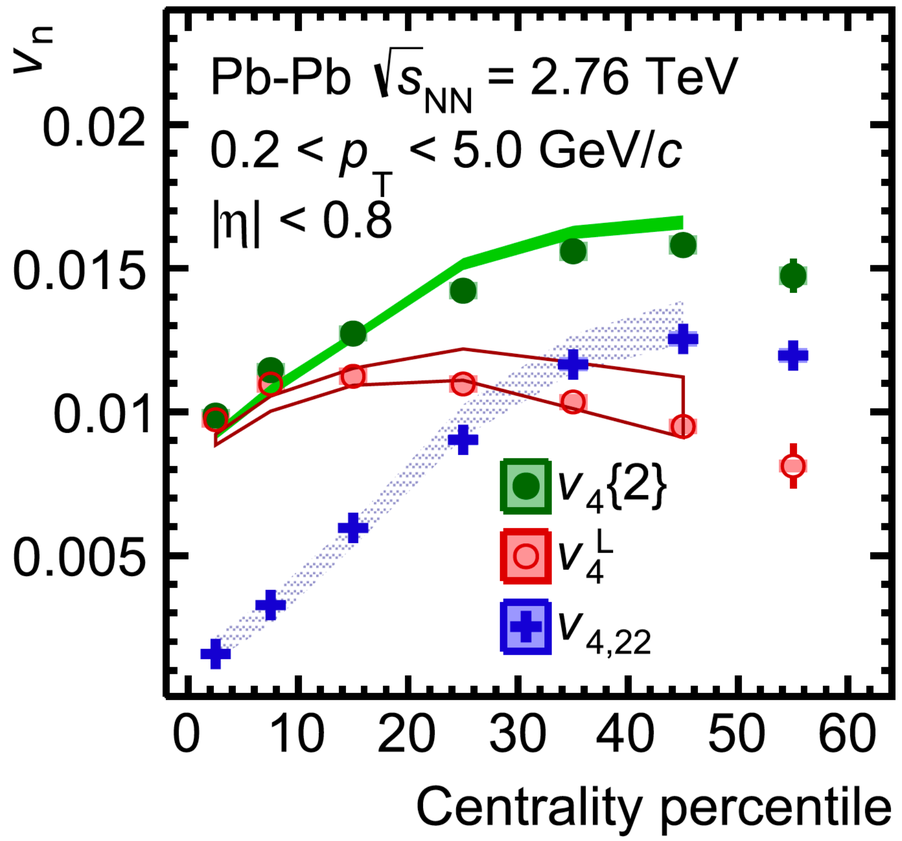
$$V_n = V_n^{NL} + V_n^L$$

e.g. $V_4 = \chi_{4,22}(V_2)^2 + V_4^L$

$\propto \epsilon_2^2$ $\quad$ $\propto \epsilon_4$

Sensitive to both initial conditions and transport coefficients

ALICE, PLB 773 (2017) 68-80



New at QM19

Non-linear flow modes

J. Parkkila, Wednesday@9:20

$V_2 \propto \epsilon_2$

$V_3 \propto \epsilon_3$

$V_n = V_n^{NL} + V_n^{L}$

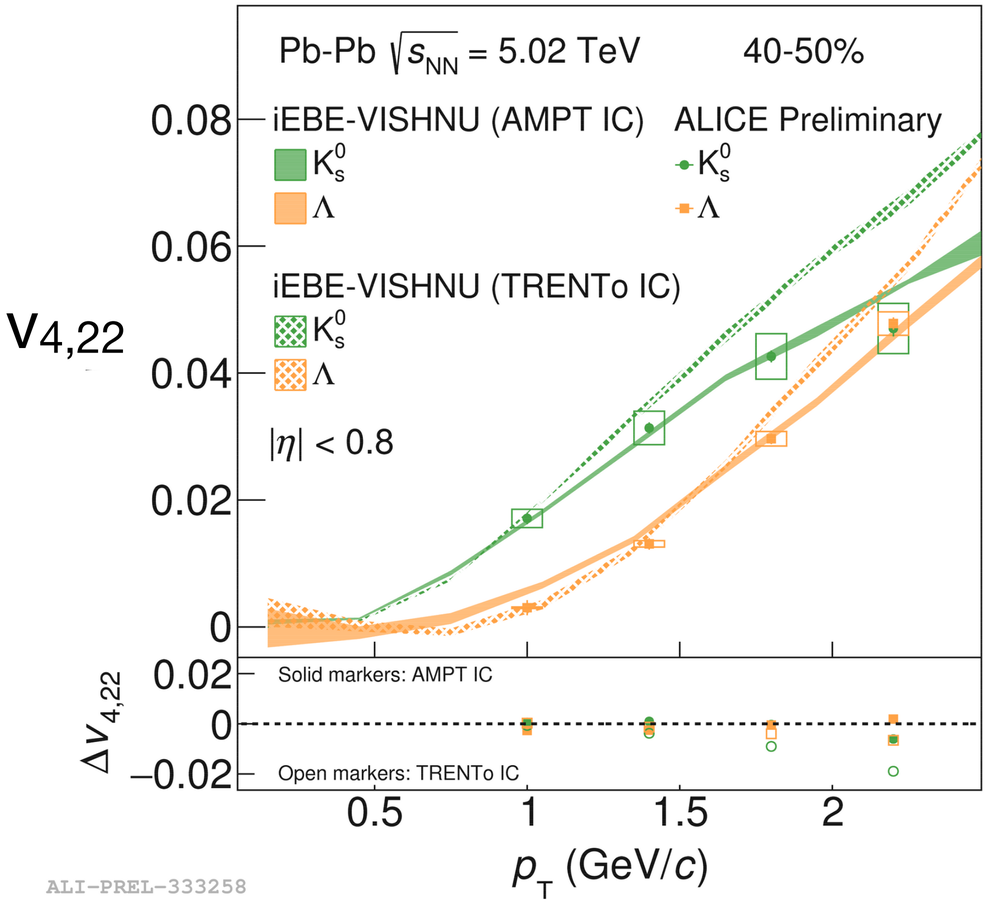
e.g. $V_4 = \chi_{4,22}(V_2)^2 + V_4^L$

$\propto \epsilon_2^2 \qquad \propto \epsilon_4$

Sensitive to both initial conditions and transport coefficients

Strong constraint on theory

- Measurements of identified particles



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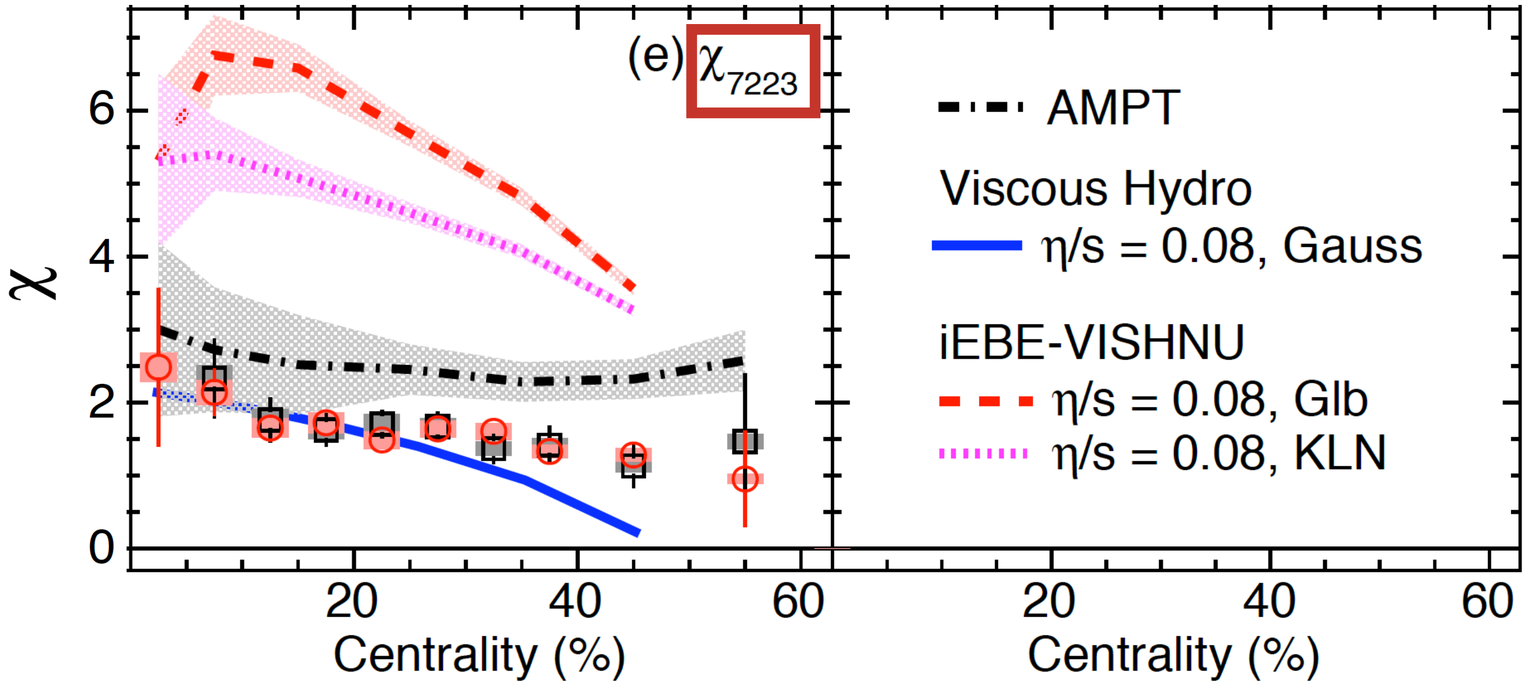
Sensitive to both initial conditions and transport coefficients

Strong constraint on theory

- Measurements of identified particles
- Measurements of high-order harmonics

CMS, arXiv: 1910.08789



New at QM19

Non-linear flow modes

N. Abdelrahman, Wednesday@9:40

$V_2 \propto \epsilon_2$

$V_3 \propto \epsilon_3$

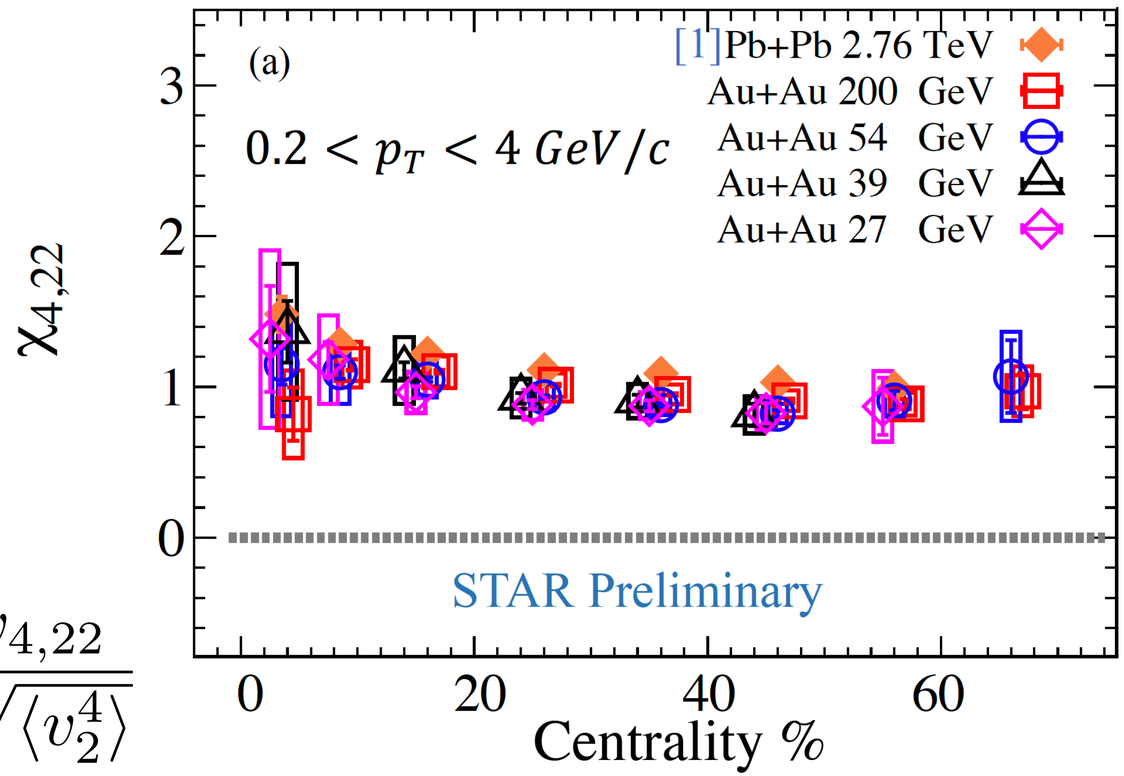
$$V_n = V_n^{NL} + V_n^L$$

e.g. $V_4 = \underbrace{\chi_{4,22}(V_2)^2}_{\propto \epsilon_2^2} + \underbrace{V_4^L}_{\propto \epsilon_4}$

Sensitive to both initial conditions and transport coefficients

Strong constraint on theory

- Measurements of identified particles
- Measurements of high-order harmonics
- Energy dependence vanishes for $\chi_{4,22}$
- Dependence on collision system size vanishes for $\chi_{4,22}$

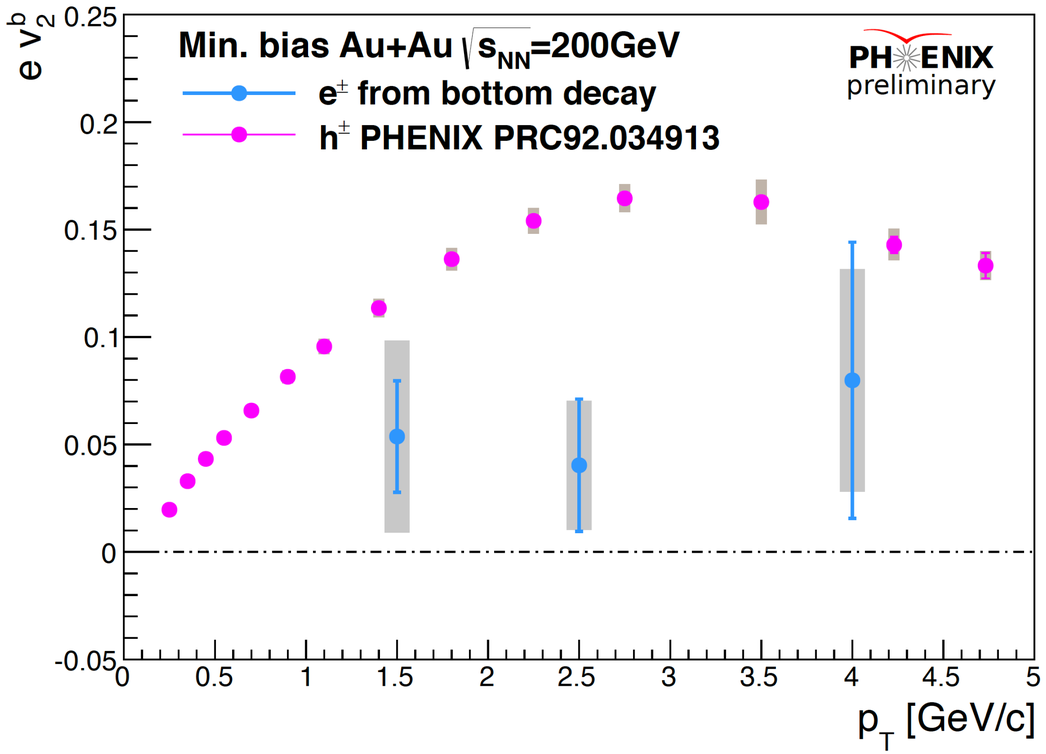


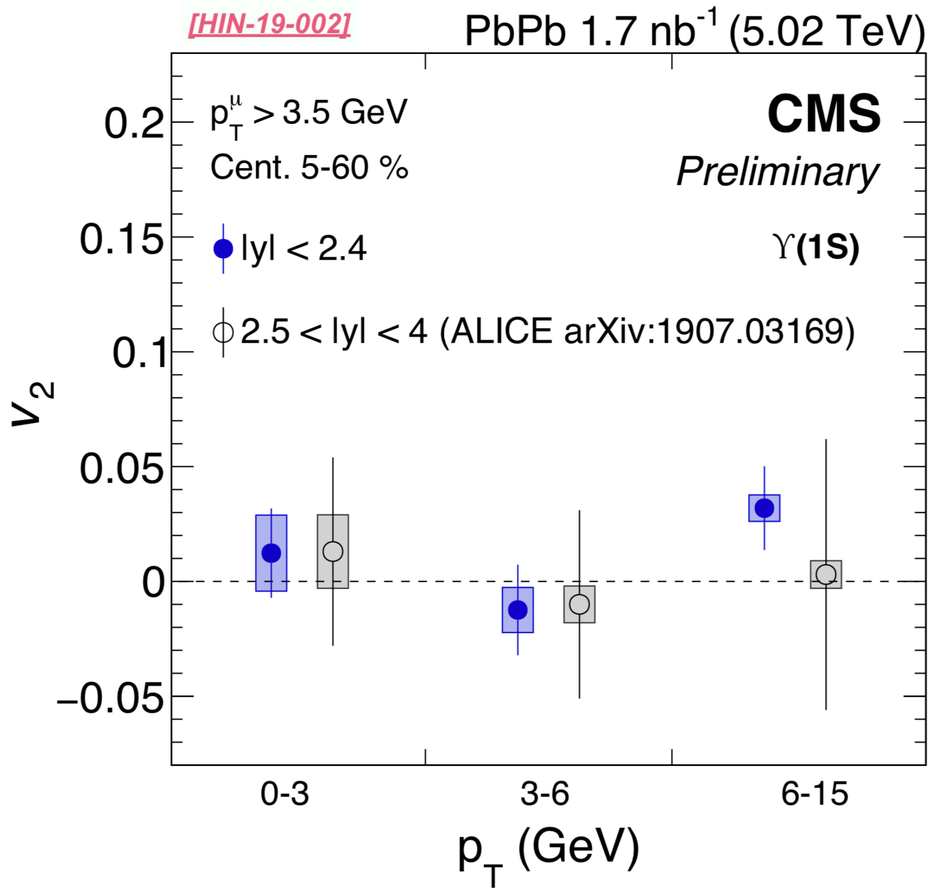
$$\chi_{4,22} = \frac{v_{4,22}}{\sqrt{\langle v_2^4 \rangle}}$$

Heavy (bottom) flavor flow

New at QM19

T. Todoroki, Tuesday@15:00 | S. Lim, Tuesday@9:00 | M. Kelsey, Tuesday@17:40 | S. Tang, Tuesday@16:40 | J. Park, Tuesday@16:20





- Heavy quark b->e(μ) flows (compatible with ALICE, ATLAS, STAR observations)
- Flow of charm > flow of beauty

- Flow of Upsilon compatible with 0

Quarkonia summary: Z. Tang, Friday@15:30 | **Heavy quarks summary: J. Wang, Friday@14:00**

Large collision systems

$$P(\varphi) = \frac{1}{2\pi} \sum_{n=-\infty}^{\infty} V_n e^{(-in\varphi)} \qquad V_n = v_n e^{in\Psi_n}$$

✔New constraints on theory

New at QM19

Flow vector magnitude → *Flow coefficients (v_n)* ✔

Flow vector fluctuations →
- *Flow de-correlations (p_T, η)* ✔
- *Flow fluctuations* ✔
- *Event shape engineering* ✔

Flow vector correlations →
- *Symmetric cumulants*
- *Non-linear flow modes* ✔

Flow of identified hadrons →
- *Light flavor flow* ✔
- *Heavy flavor flow* ✔

...

Energy dependence
System dependence

From large to small collision systems

- Is there collectivity in small systems?
- What is the origin of collectivity?

} We need “decision / discovery" measurements.

From large to small collision systems

- Is there collectivity in small systems?
- What is the origin of collectivity?

} We need “decision / discovery" measurements.

Decision:
Is there collectivity or not? → ***Long-range multi-particle correlations***

Decision:
Do we create similar medium as in large systems or not? →

- ***Flow of identified hadrons***
- ***Response to initial geometry?***
- ***Symmetric cumulants***
- ***Heavy flavor flow***
- ***High-pT flow: jet quenching?***
- ***Novel geometric configurations***

} Energy dependence
System dependence

From large to small collision systems

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- What is the origin of collectivity?

} We need “decision / discovery" measurements.

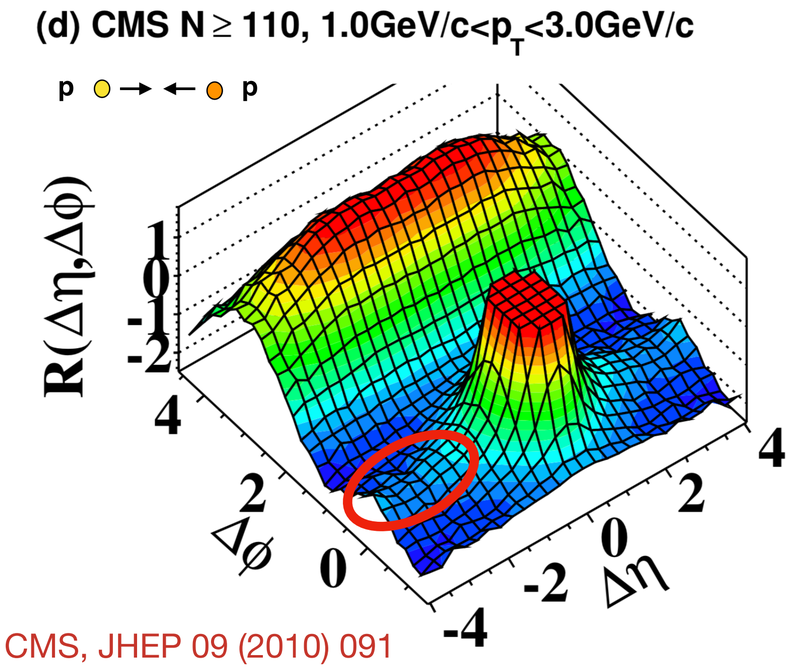
Decision:
Is there collectivity or not? → ***Long-range multi-particle correlations***

Decision:
Do we create similar medium as in large systems or not? →

- ***Flow of identified hadrons***
- ***Response to initial geometry?***
- ***Symmetric cumulants***
- ***Heavy flavor flow***
- ***High-pT flow: jet quenching?***
- ***Novel geometric configurations***

} Energy dependence
System dependence

Long-range correlations



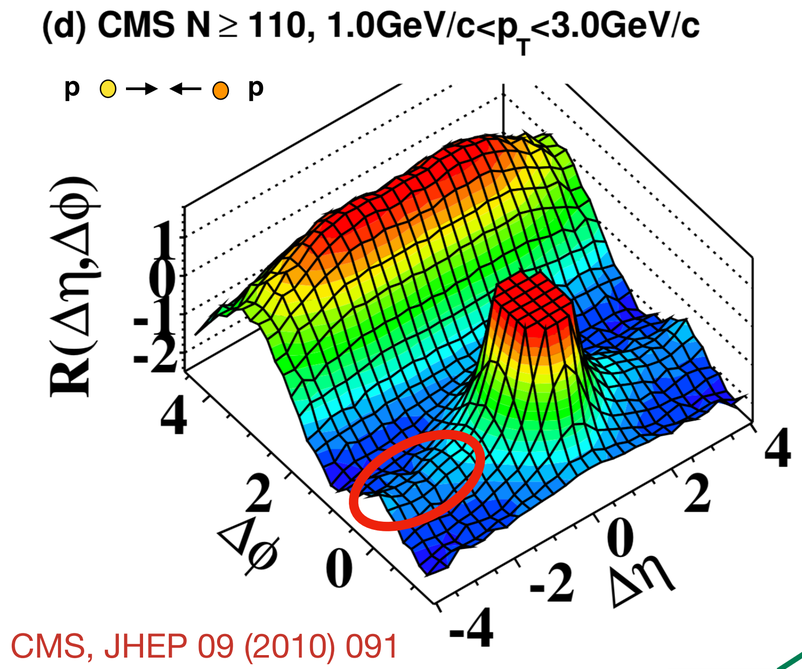
CMS, JHEP 09 (2010) 091

- Long-range correlations in pseudorapidity observed even at the smallest collision system

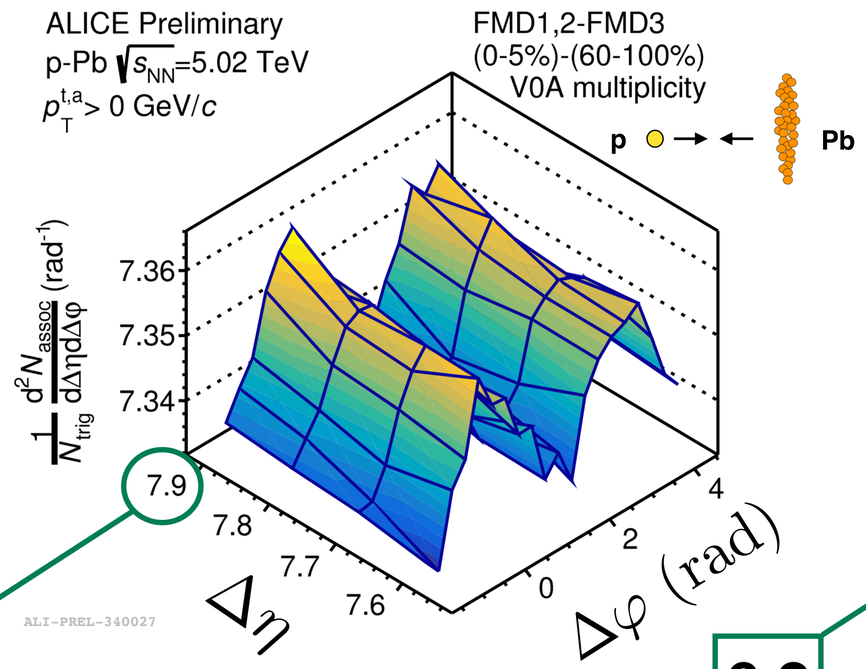
Long-range correlations

New at QM19

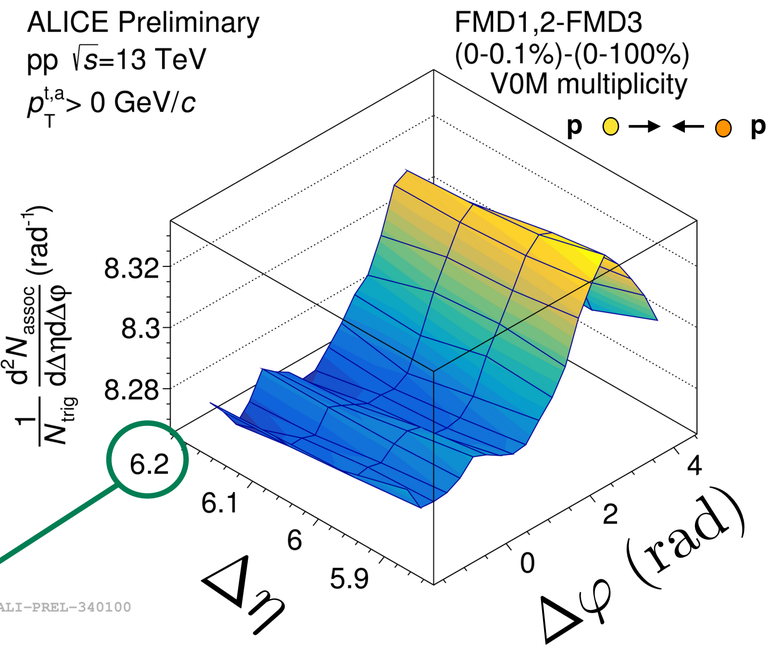
Y. Sekiguchi, Wednesday@15:00



CMS, JHEP 09 (2010) 091



7.9



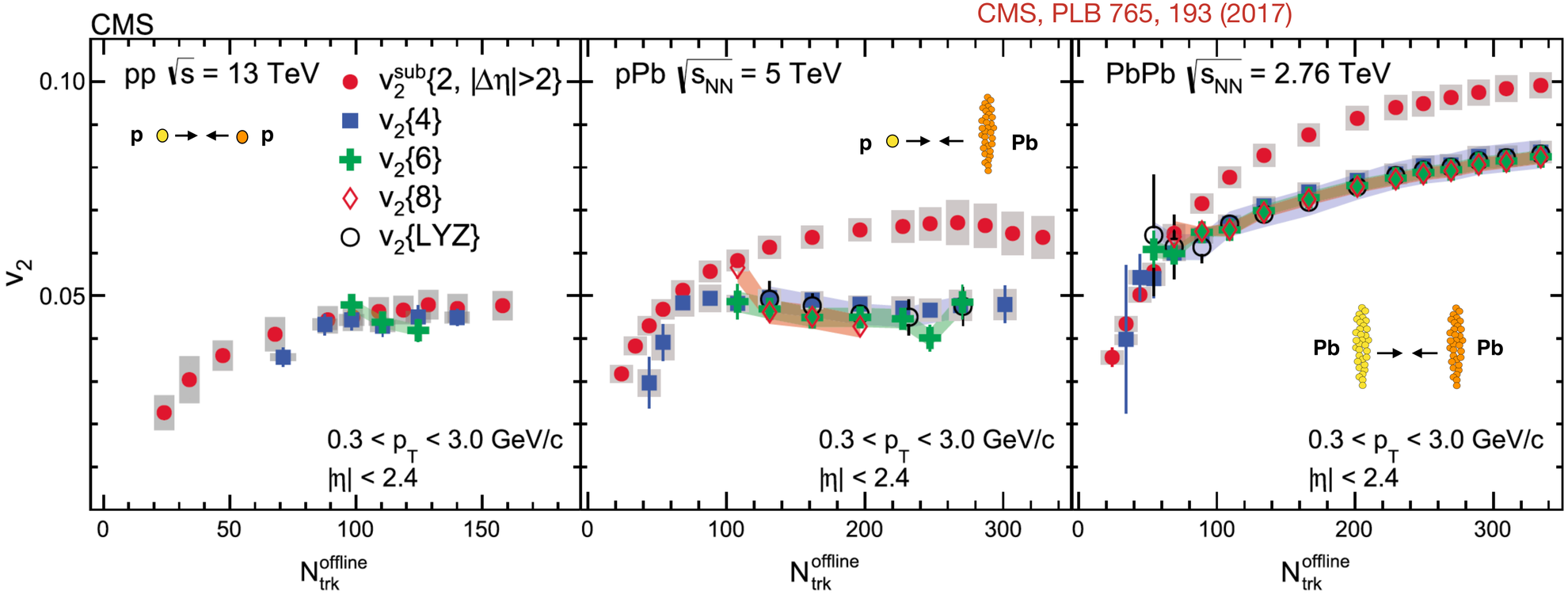
6.2

- Long-range correlations in pseudorapidity observed even at the smallest collision system
- Ridge persists up to very large Δη
  - **p-Pb: Δη~8**
  - **pp: Δη~6**

Collectivity down to pp collisions

Collectivity: long-range multi-particle correlations

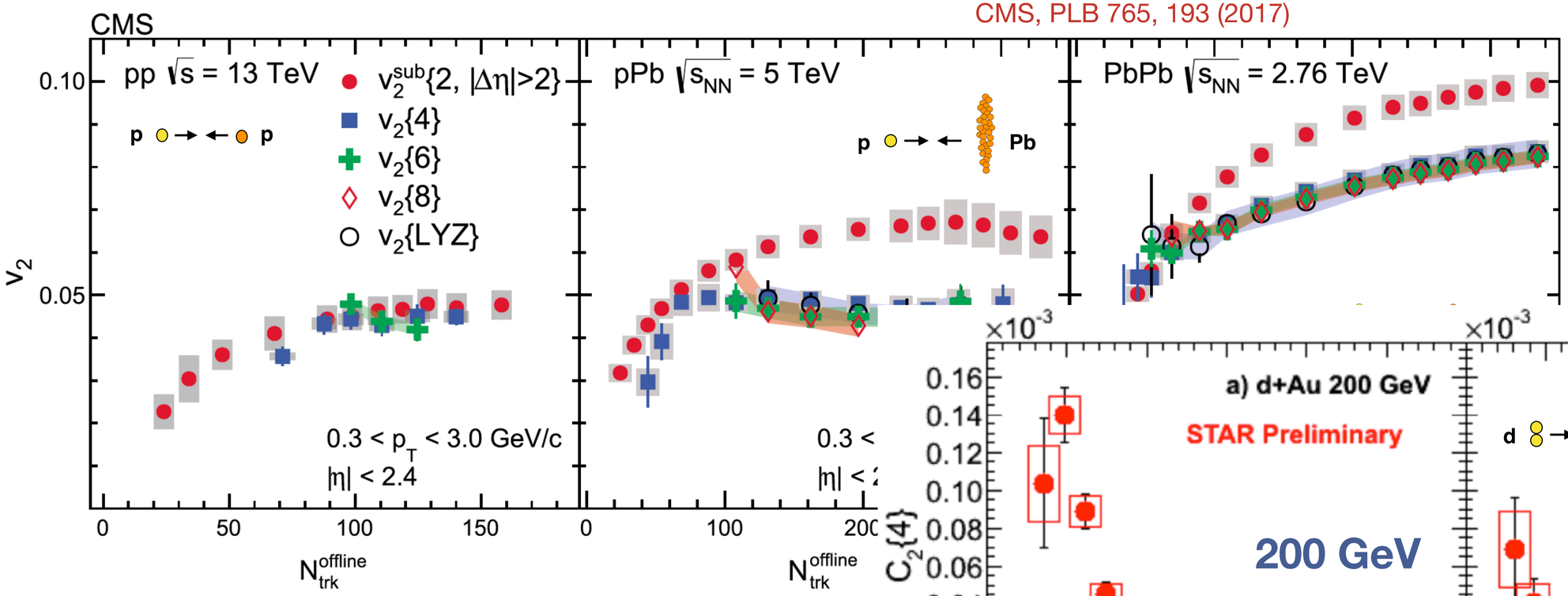
CMS, PLB 765, 193 (2017)



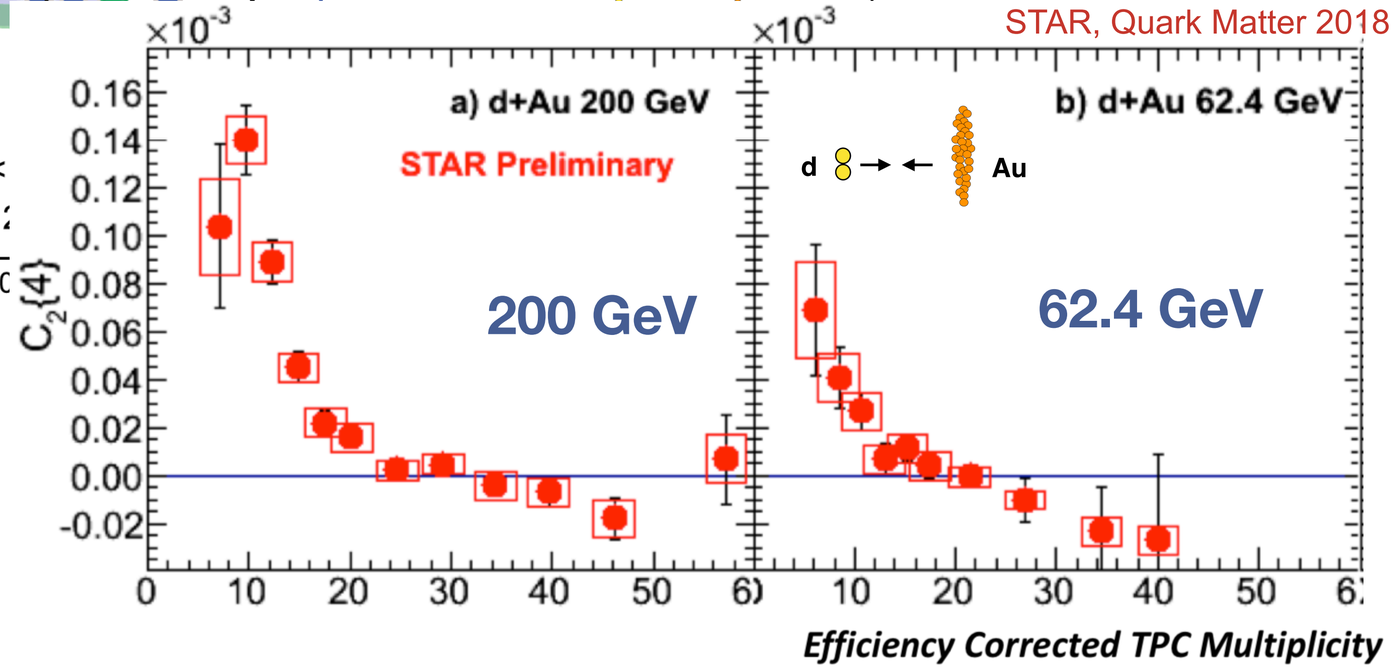
Collectivity down to low energies

Collectivity: long-range multi-particle correlations

CMS, PLB 765, 193 (2017)



STAR, Quark Matter 2018



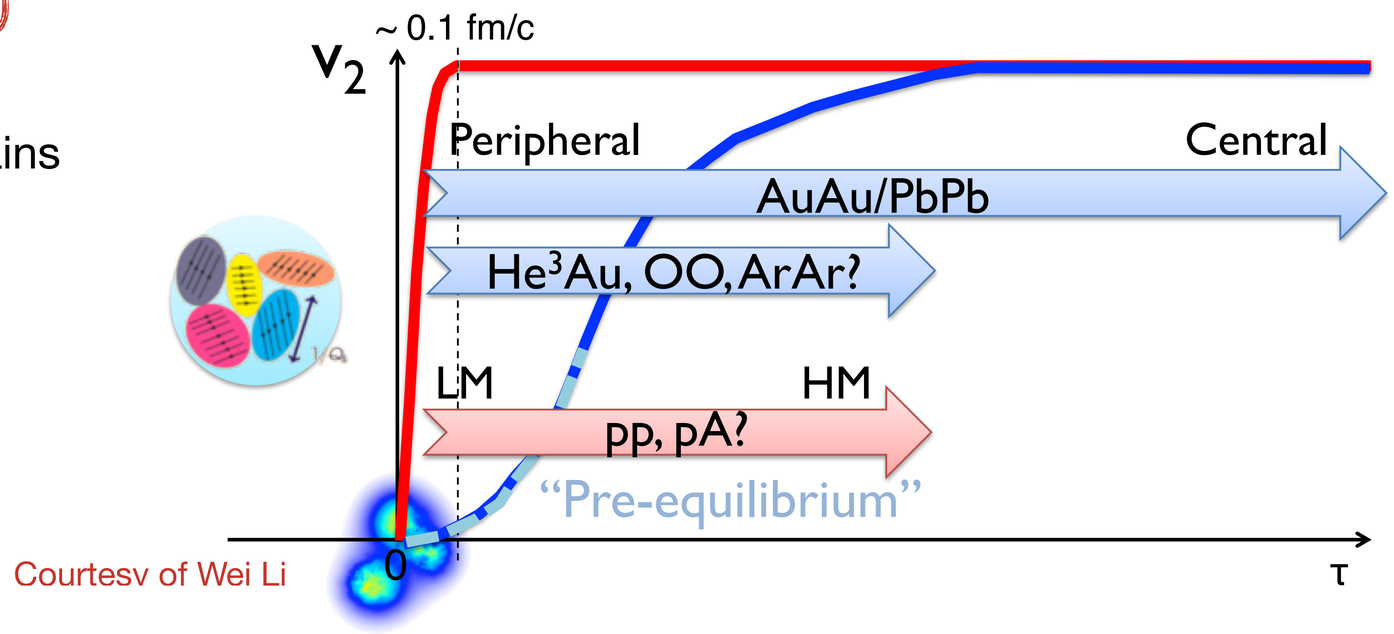
What is the origin of collectivity?

Initial State (IS)

- Initial momentum correlations
- CGC

Not correlated to initial geometry

Color correlations between gluon domains



Courtesv of Wei Li

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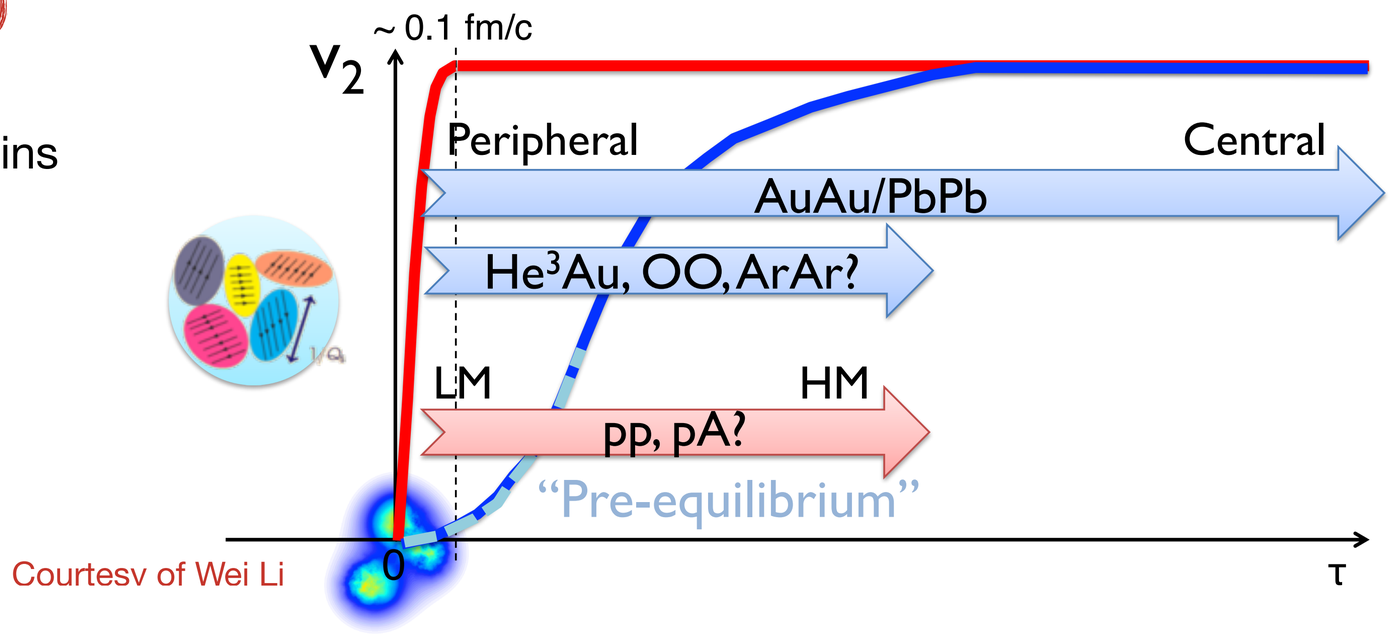
Sub-nucleon fluctuations



Courtesv of Wei Li

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$\lessapprox$

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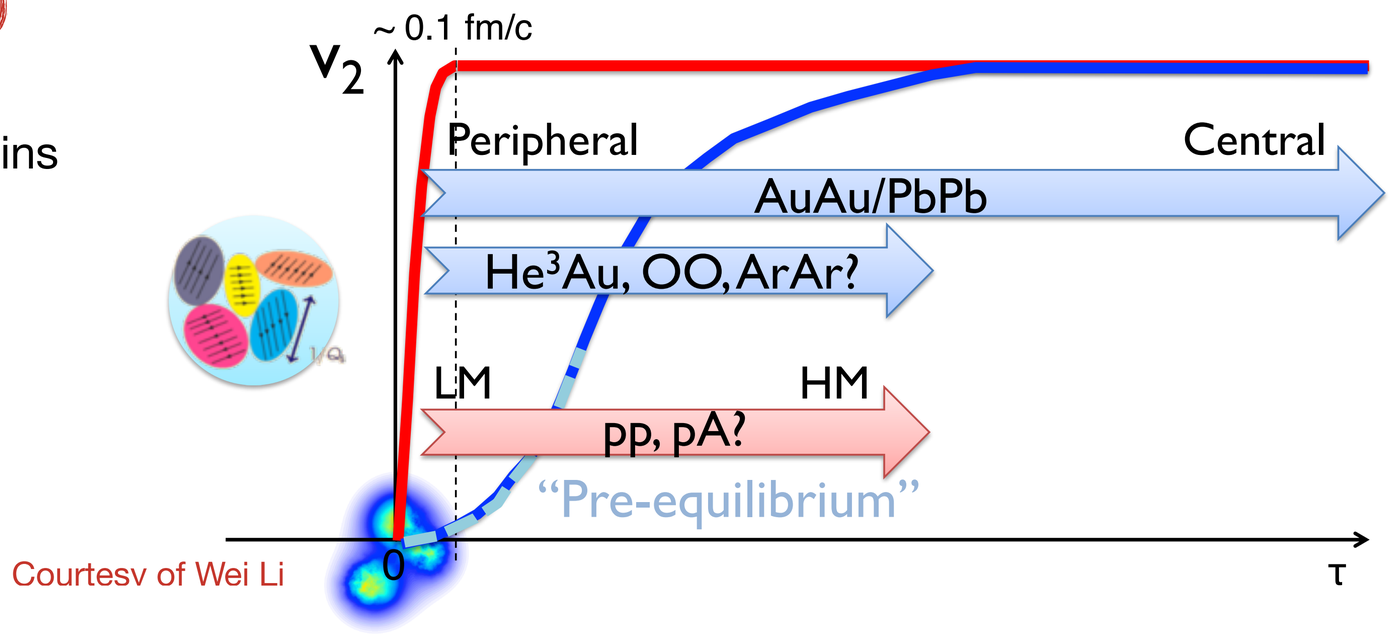


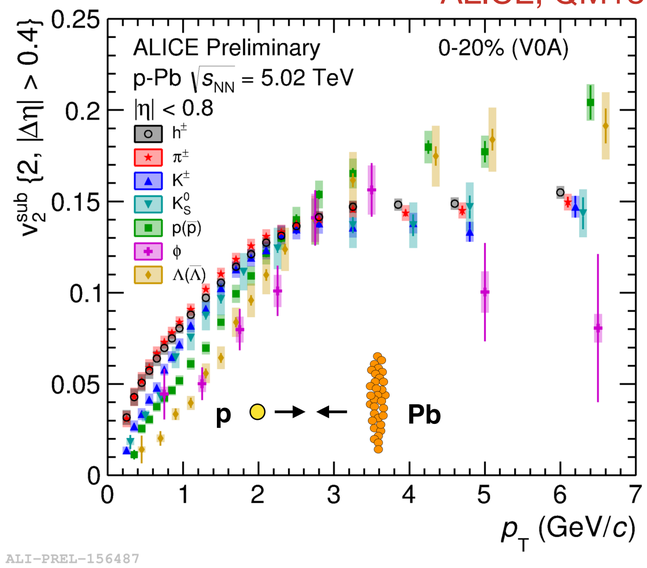
Courtesy of Wei Li

Need to investigate with more experimental data and comparison to models.

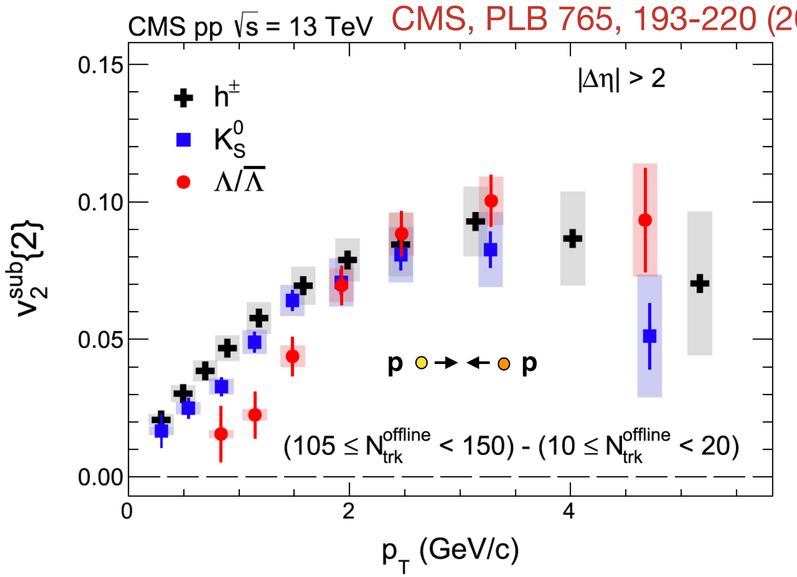
What do measurements tell us?

- ✓ Mass-ordering
- ✓ Particle-type grouping

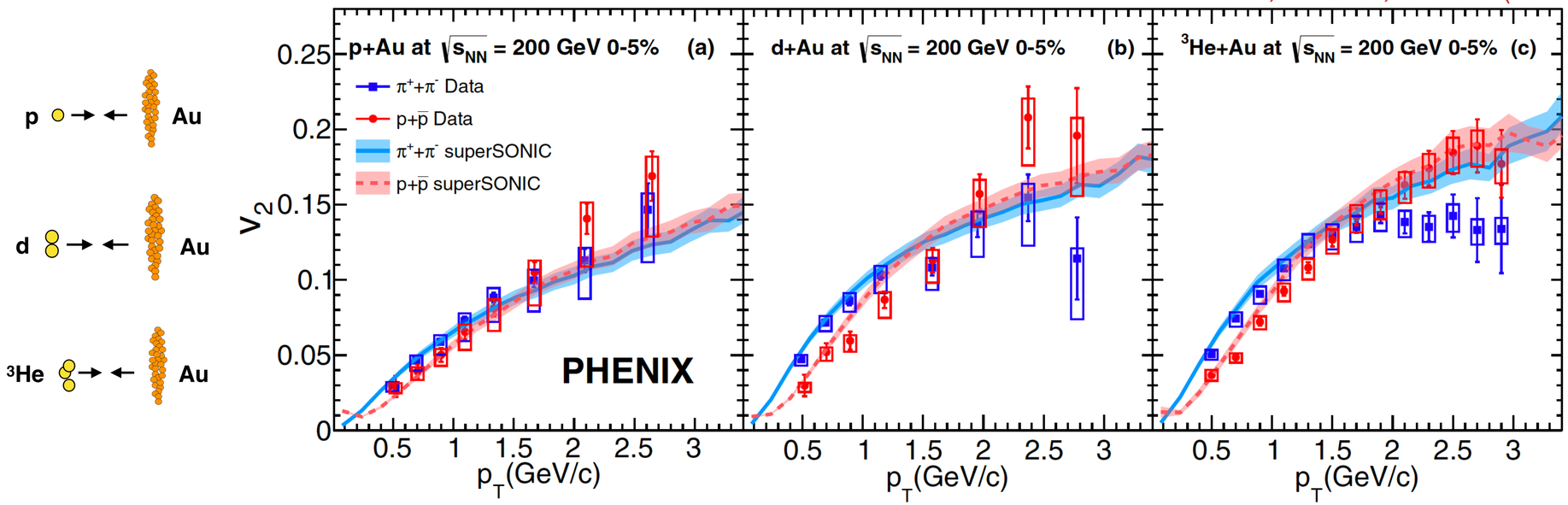
ALICE, QM18



CMS, PLB 765, 193-220 (2017)

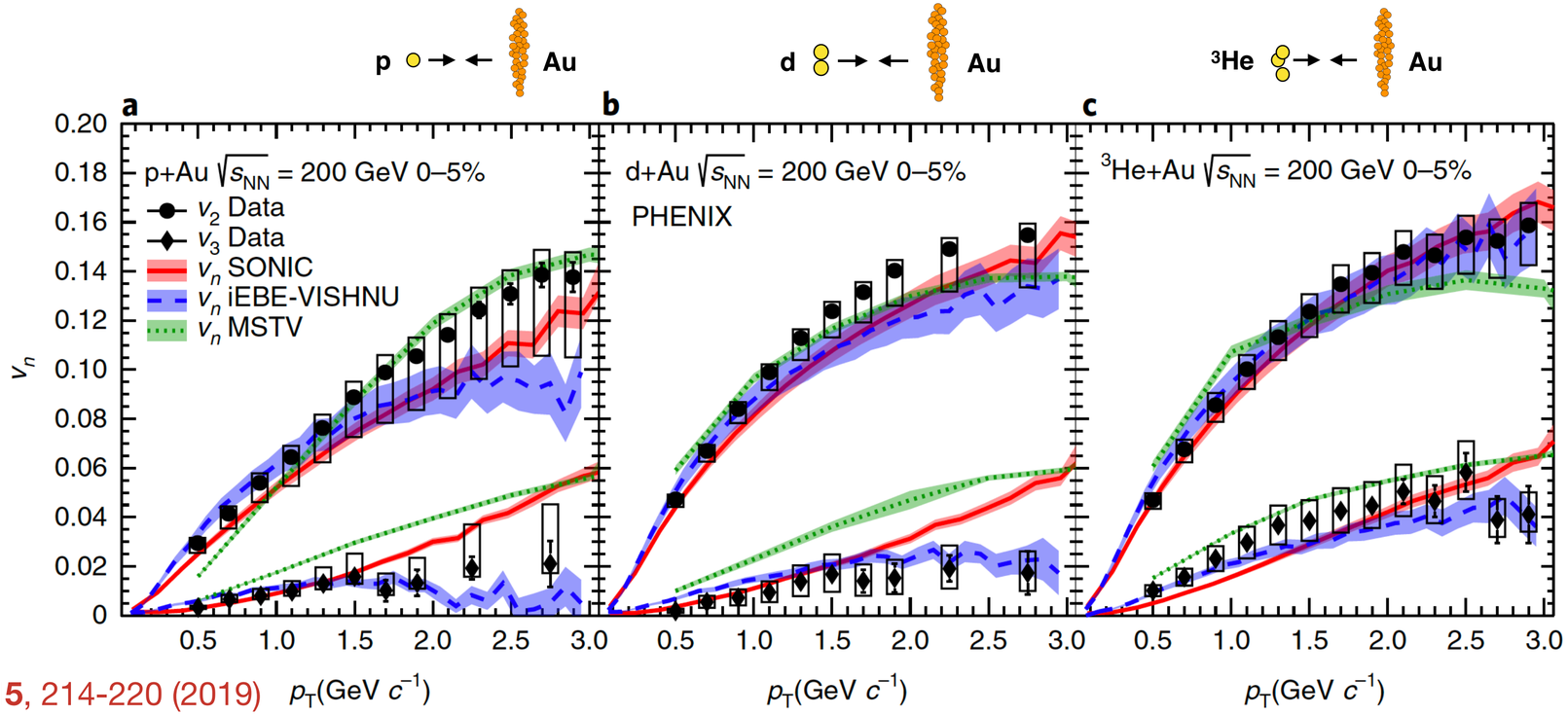


PHENIX, PRC 97, 064904 (2018)

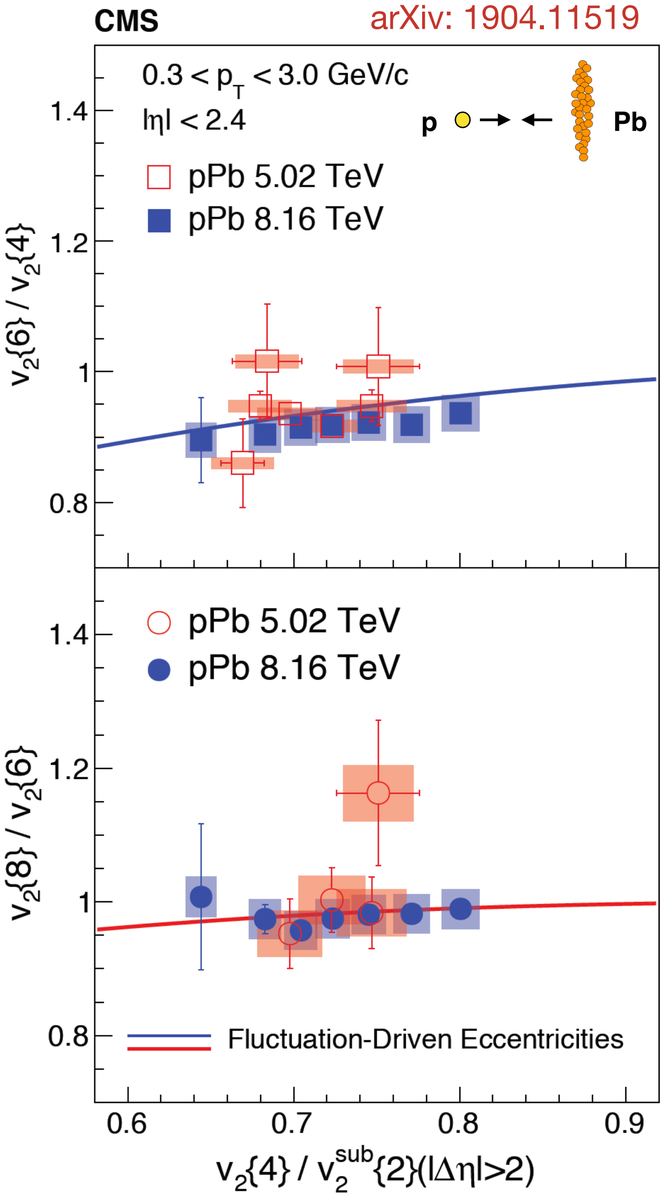


What do measurements tell us?

- ✓ Mass-ordering
- ✓ Particle-type grouping
- ✓ Geometry-driven

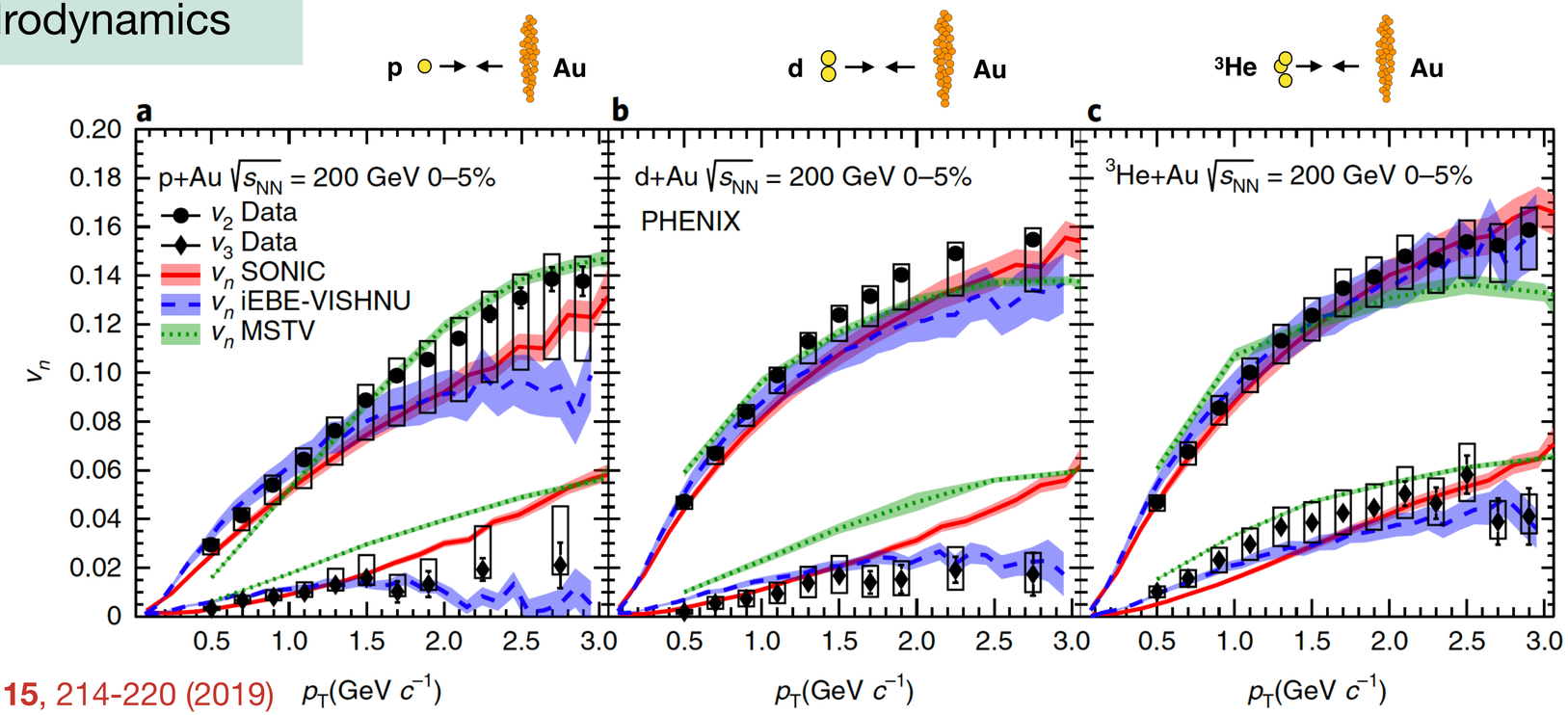


PHENIX,
Nature Phys. **15**, 214-220 (2019)

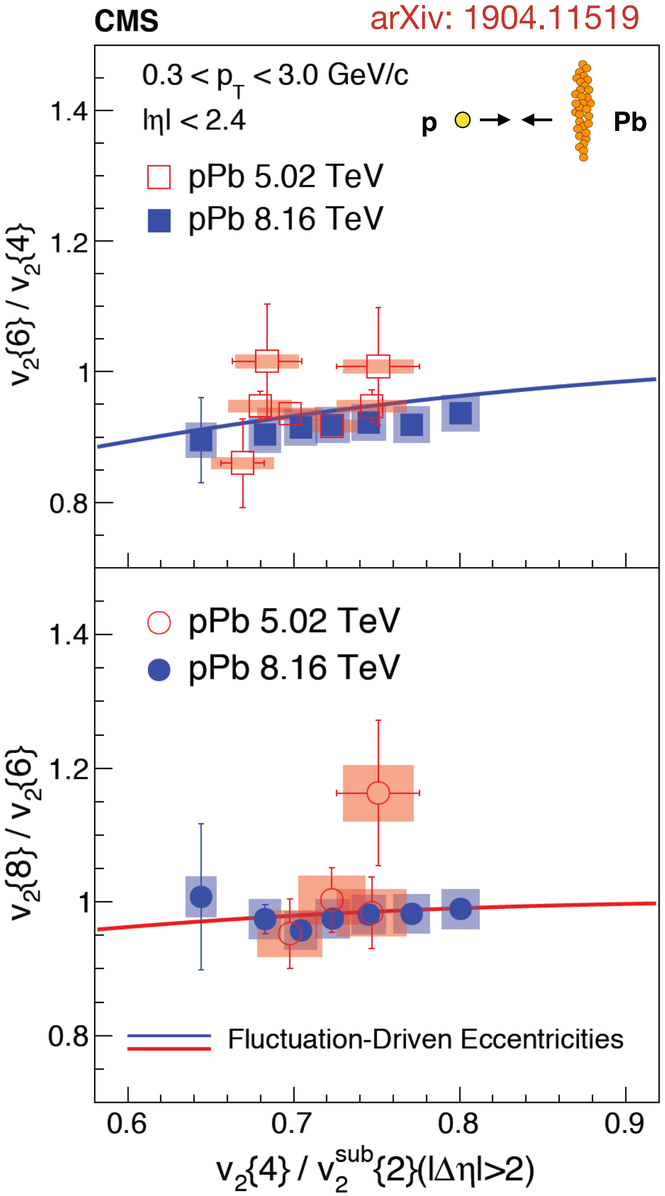


What do measurements tell us?

- ✓ Mass-ordering
- ✓ Particle-type grouping
- ✓ Geometry-driven
- ✓ Described by hydrodynamics



PHENIX,
Nature Phys. **15**, 214-220 (2019)



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$\approx$

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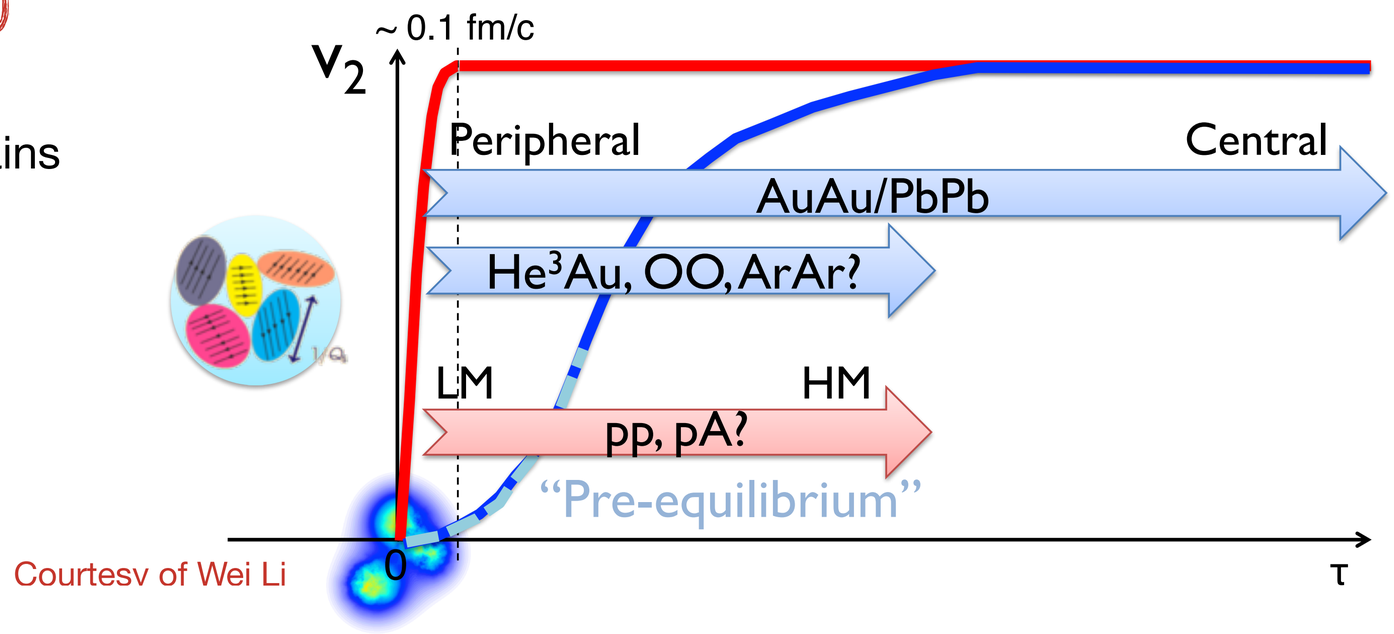


Courtesv of Wei Li

Correlated to initial geometry

Sub-nucleon fluctuations

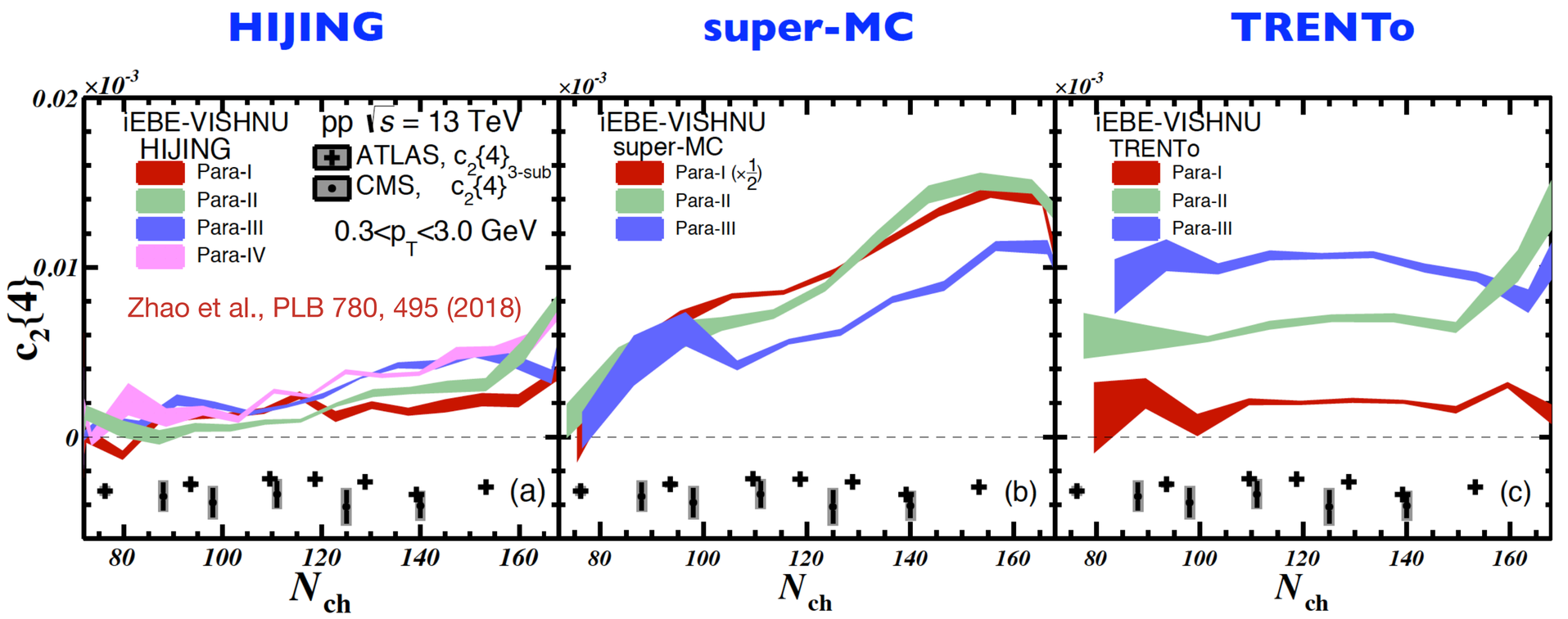
Data seem to favor the final state description (origin similar to large systems)

Beware of gaps in the FS description

New at QM19

Y. Zhou, Wednesday@15:40

Hydrodynamics fails to describe the negative $c_2\{4\}$ no matter what the $\varepsilon_2\{4\}$ is



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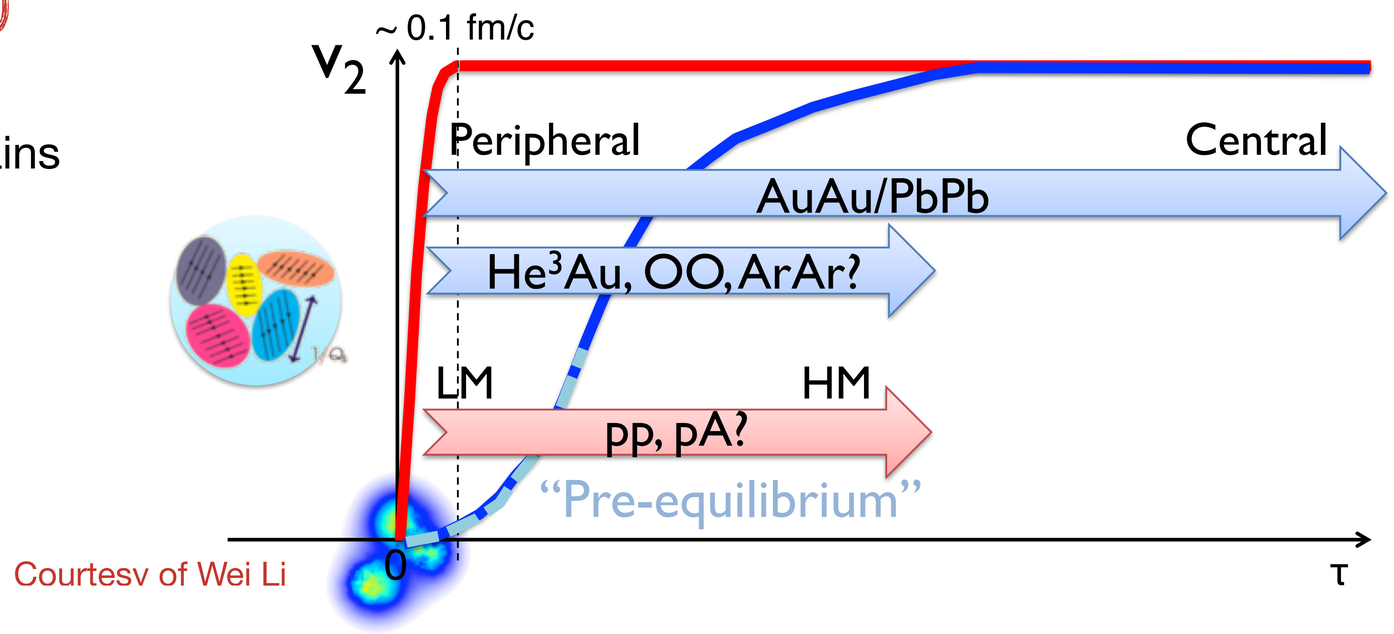


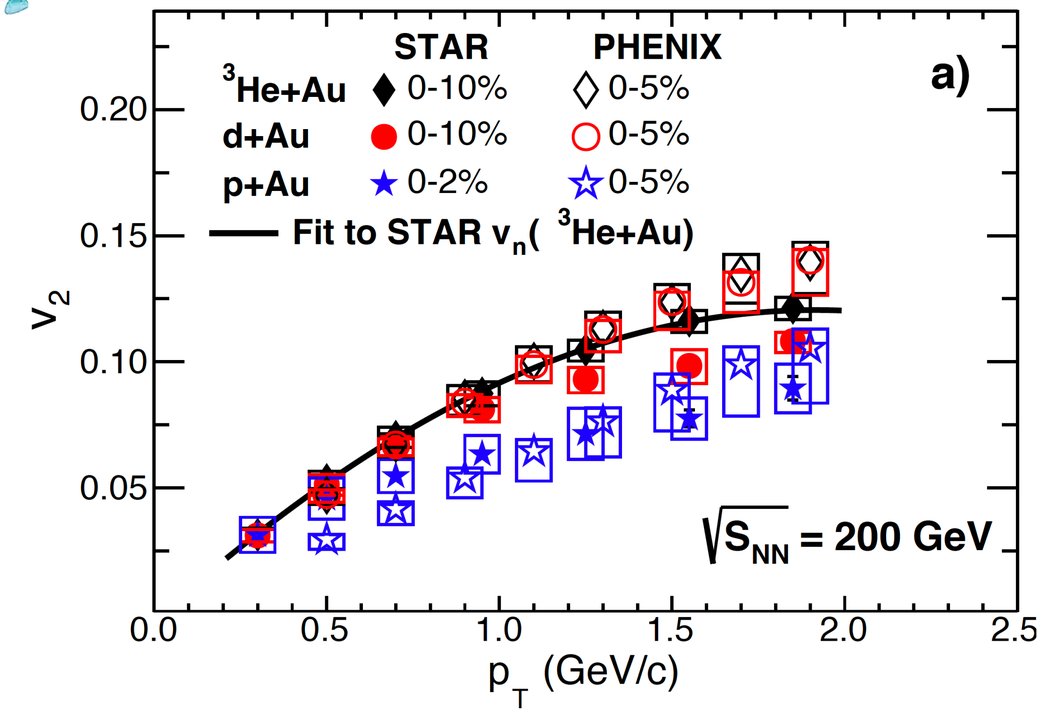
Courtesy of Wei Li

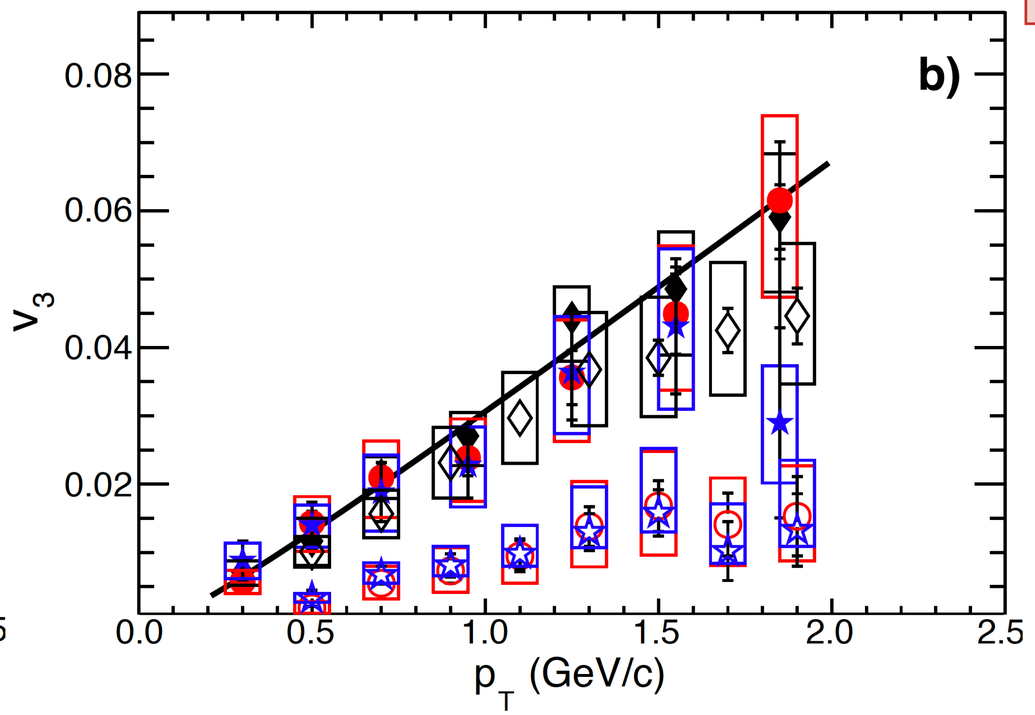
There is still a lot to understand. -> We need more measurements.

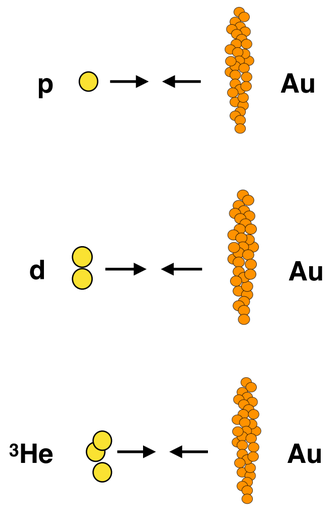
New at QM19

Small systems scan @ RHIC

R. Lacey, Tuesday@9:40







$$v_2(\mathrm{STAR}) \approx v_2(\mathrm{PHENIX})$$

$$v_3(\mathrm{STAR}) \neq v_3(\mathrm{PHENIX})$$

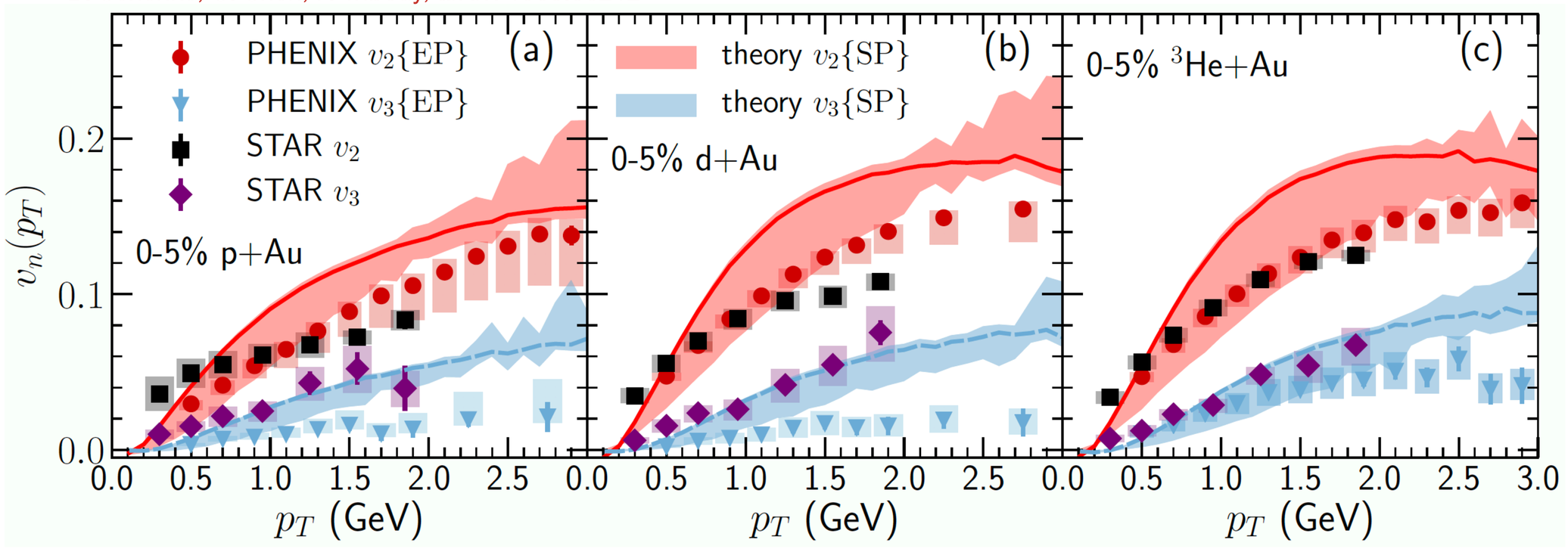
- STAR measurements of v_3 are system independent
  - Large difference between v_3 needs to be understood

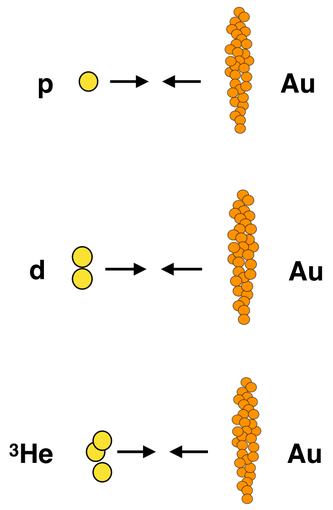
New at QM19

Small systems scan @ RHIC

B. Schenke, Wednesday@14:00

B. Schenke, C. Shen, P. Tribedy, arXiv: 1908.06212



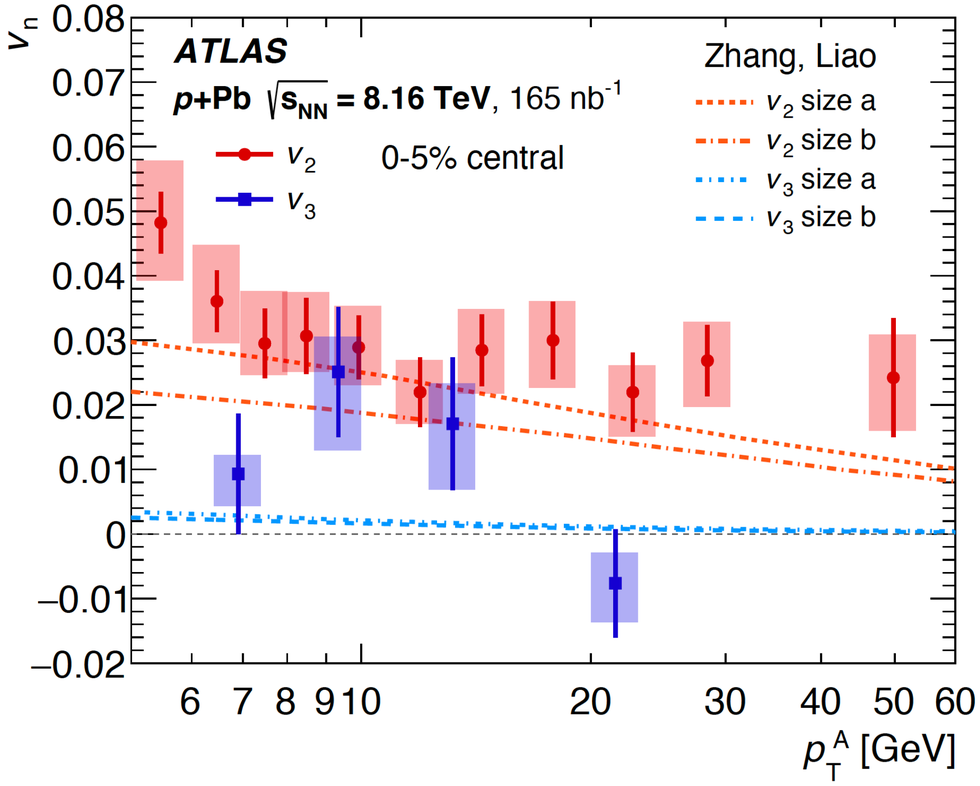


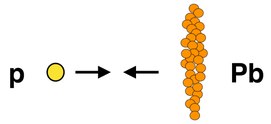
- STAR measurements of v_3 are system independent
  - Large difference between v_3 needs to be understood
- STAR measurements consistent with the important role of sub-nucleonic fluctuations

New at QM19

Jet quenching: is there, or is not there?

K. Keys Hill, Tuesday@11:20





EXPERIMENT	THEORY
$v_2(p_T) > 0$	$v_2(p_T) > 0$

New at QM19

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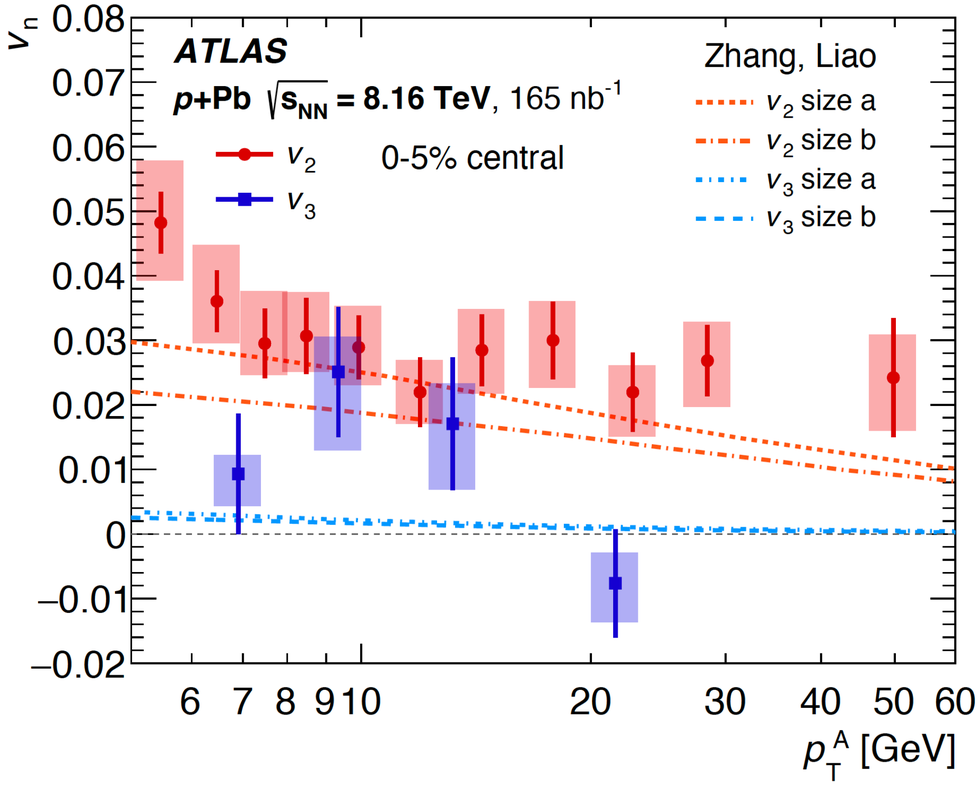
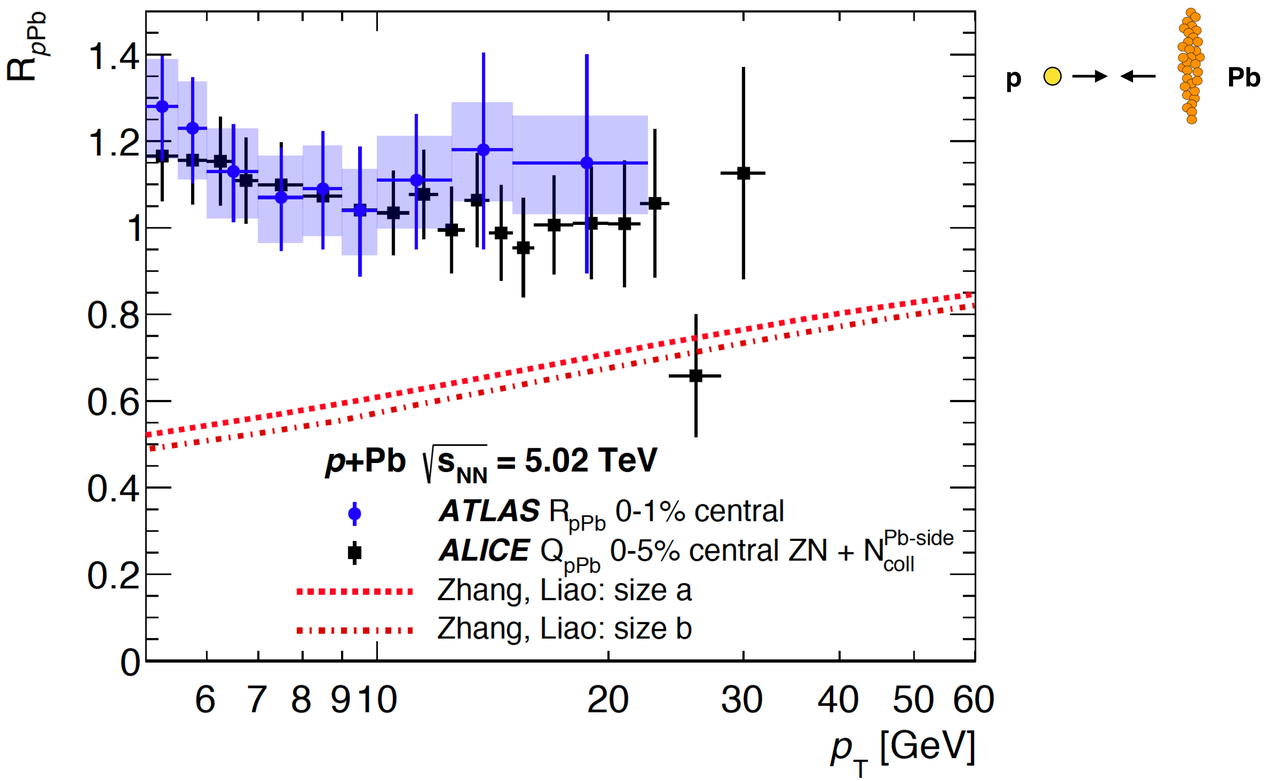
K. Keys Hill, Tuesday@11:20





EXPERIMENT	THEORY
$v_2(p_T) > 0$	$v_2(p_T) > 0$
$R_{pPb} \approx 1$	$R_{pPb} < 1$

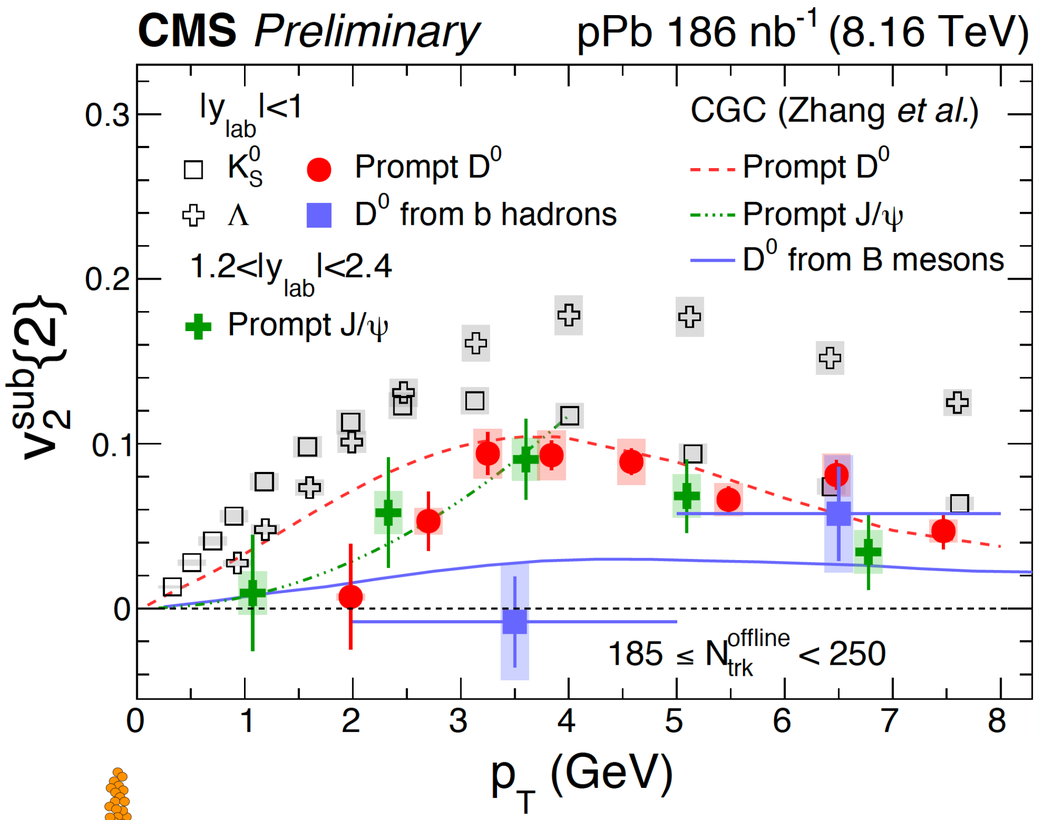
No evidence for jet quenching yet.

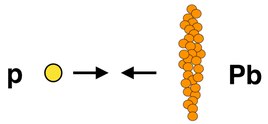
- Do we really observe no jet quenching in small systems?
  - Biases coming from event selection (ALICE, PLB 793 (2019) 420-432)

New at QM19

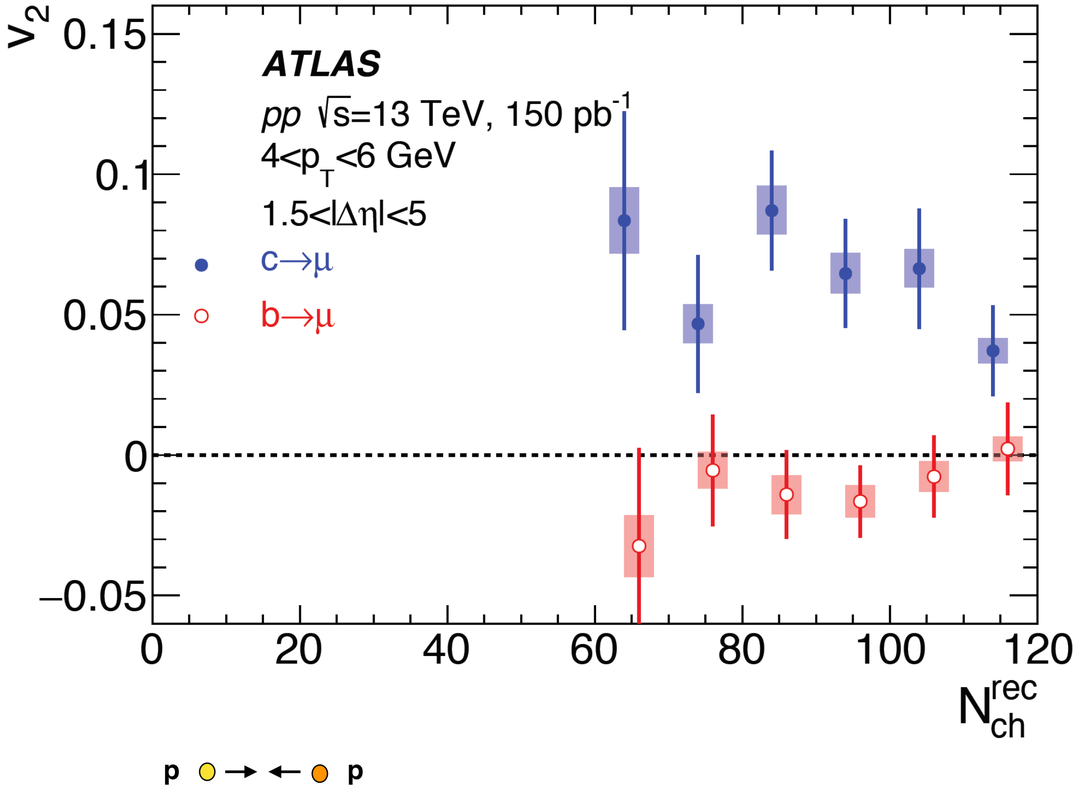
Flow of heavy flavor quarks

S. Lim, Tuesday@9:00 | A.A. Baty, Tuesday@8:40 | S. Tang, Tuesday@16:40





ATLAS, arXiv:1909.01650



- Bottom quark **doesn't flow** in small systems (Note: In large systems bottom quark flows)
  - While charm quark does

Heavy quarks summary: J. Wang, Friday@14:00

Summary

J. Nagle, Monday@14:30

Flow (theoretical) summary, Ch. Shen, Thursday@9:00

Large systems

- Exhaustive number of detailed measurements
- New constraints on theoretical calculations, new inputs for Bayesian analysis, …

Small systems

- Many new measurements available to challenge our understanding of small systems
- Final state seems to be important to describe data, but the influence from the initial state cannot be ignored (especially at low multiplicities)
- **What is the relative contribution of IS and FS?**
- Joined experimental (and theoretical) effort to …
  - … define observables that allow us to answer the above question
  - … define a precise event class selection common to all experiments and reproducible by theory
  - … properly deal with non-flow effects

Many thanks to: Y. Zhou, M. van Leeuwen, J. Jia, S. Esumi, W. Li, K. Safarik, B. Trzeciak, C. Loizides

Backup

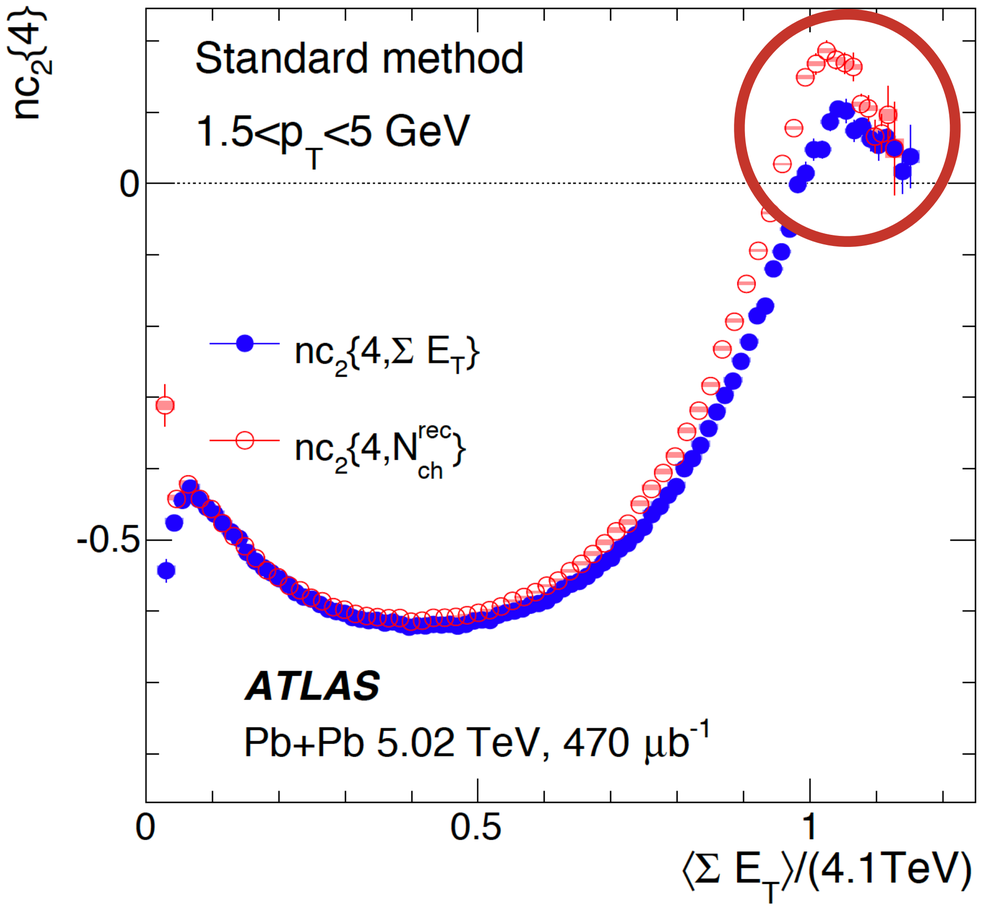
Flow fluctuations in ultracentral collisions

New

J. Jia, Tuesday@14:00

- Sign change of multi-particle cumulants -> **Influence from centrality fluctuations within a fixed centrality bin**, M. Zhou, J. Jia, PRC 98, 044903 (2018)
- "Wrong" sign of cumulants is not necessarily incorrect -> hint for new parametrisation of $P(v_n)$ in ultracentral collisions ?

ATLAS, arXiv:1904.04808

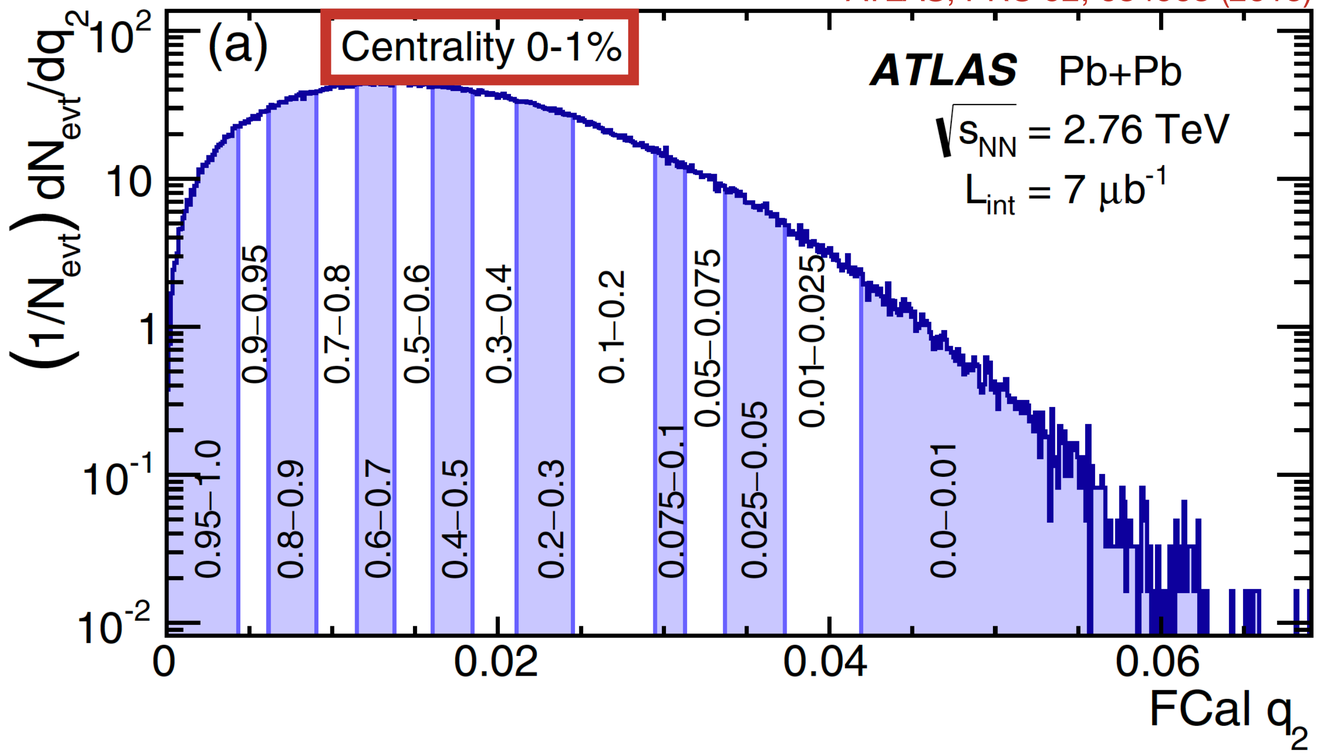


Normalized cumulant: $nc_2\{4\} = \frac{c_2\{4\}}{c_2\{2\}^2} = \frac{\langle v_2^4\rangle - 2\langle v_2^2\rangle^2}{\langle v_2^2\rangle^2}$

Reminder: $\sqrt[4]{-c_n\{4\}} = v_n\{4\}$ real-valued flow coefficient

Event-shape engineering

ATLAS, PRC 92, 034903 (2015)



Reduced flow vector: $$q_n = \frac{|Q_n|}{\sqrt{M}}$$

EbyE fluctuations in the initial state -> flow fluctuations within a fixed centrality

-> select events based on initial (geometrical) shape

-> further opportunity to constrain the initial conditions

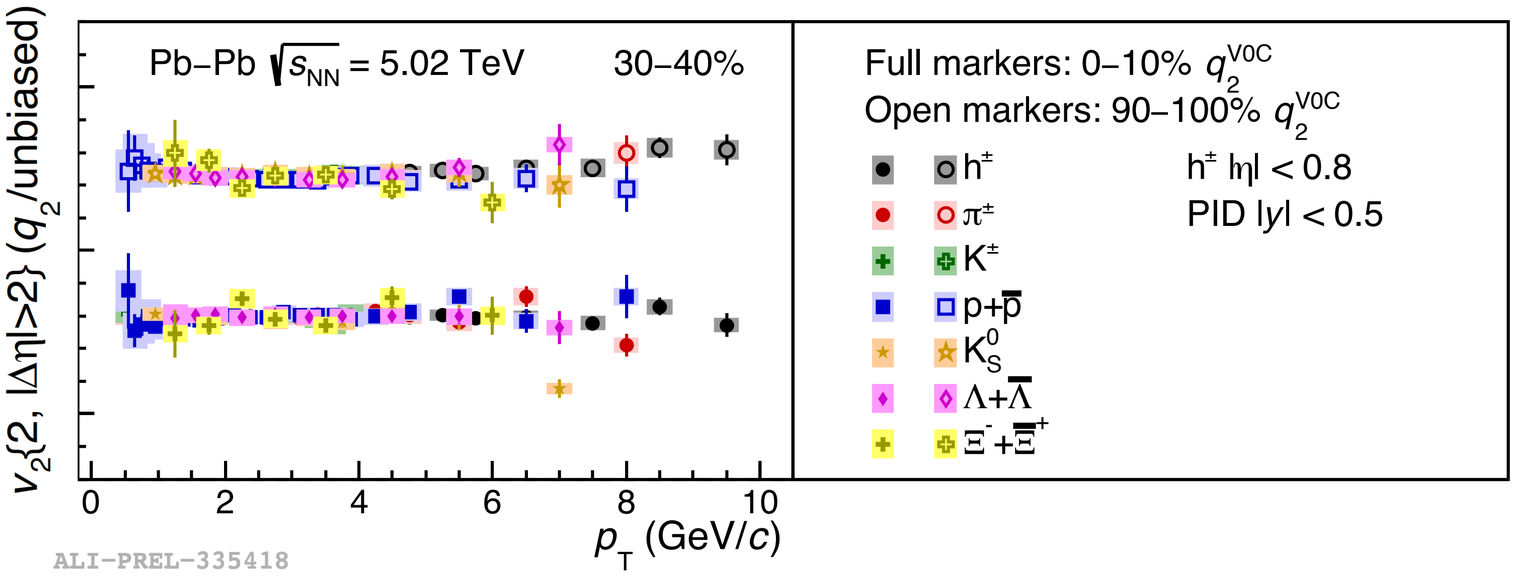
Event-shape engineering

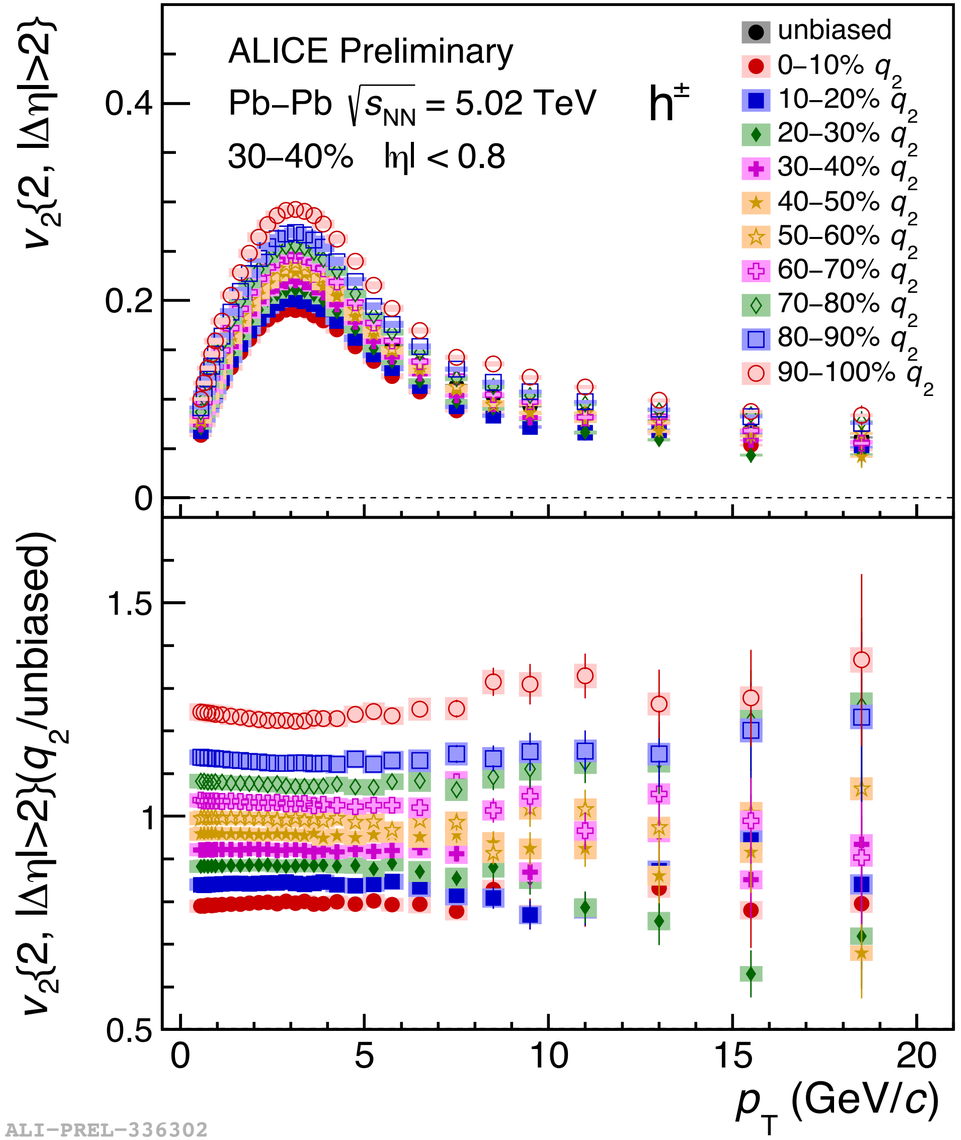
New at QM19

[poster 80] C. Ristea, Monday@16:30

M.G. Besoiu, Tuesday@16:20

Large q_2: 10% high Small q_2: 10% low



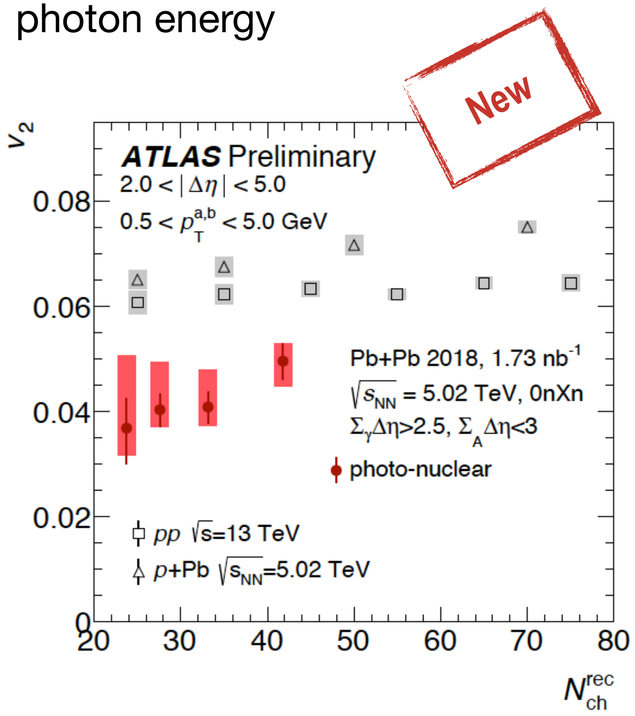


- No p_T dependence: same source of flow fluctuations (geometrical)
- No dependence on particle species found

Where do observations of collectivity stop?

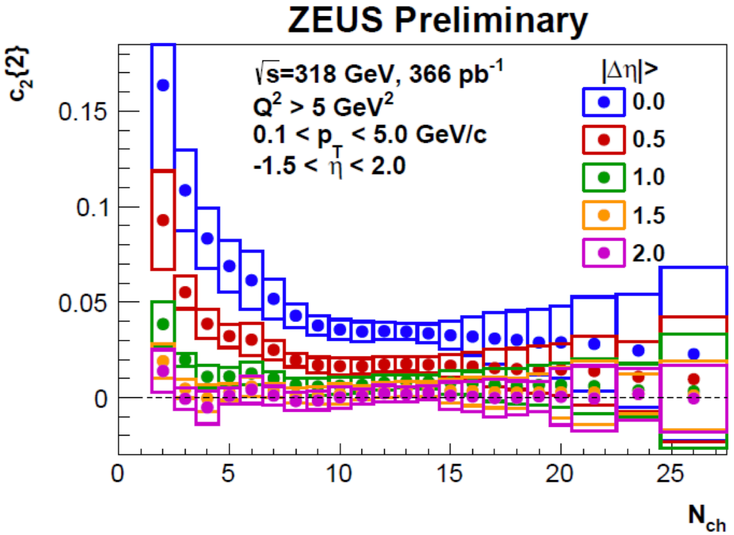
B. Cole, Wednesday@14:40

- **Photo-nuclear** (~meson-nuclear) **collisions**
  - Collision energy depends on the photon energy



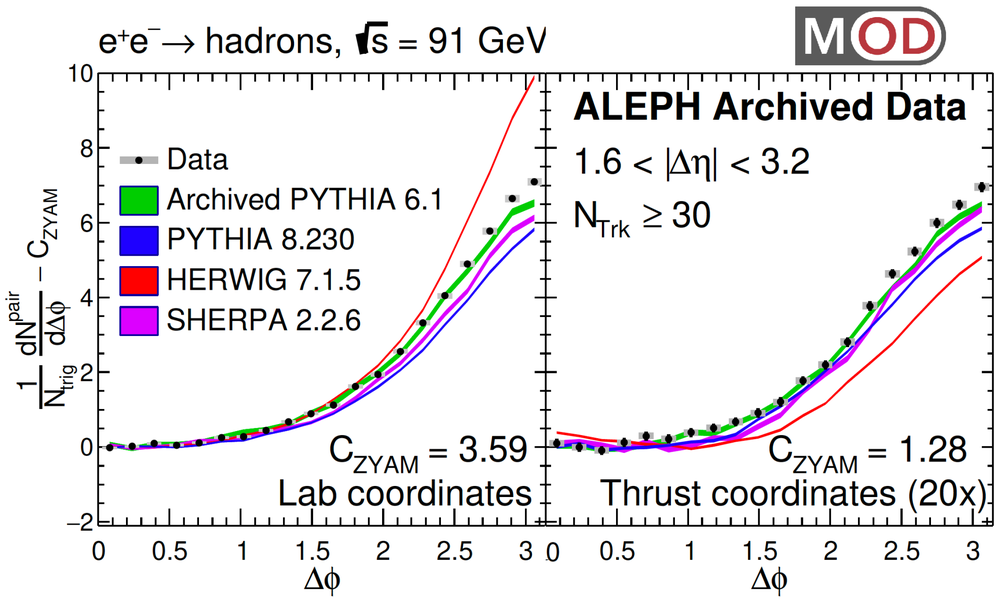
ATLAS-CONF-2019-022

- **ep collisions**
  - $c_2\{2, |\Delta\eta| > 2.0\} \sim 0$
  - Large statistical fluctuations, still room for small flow signal



ZEUS, Quark Matter 2018

- **e^+e^- collisions**
  - No ridge observed



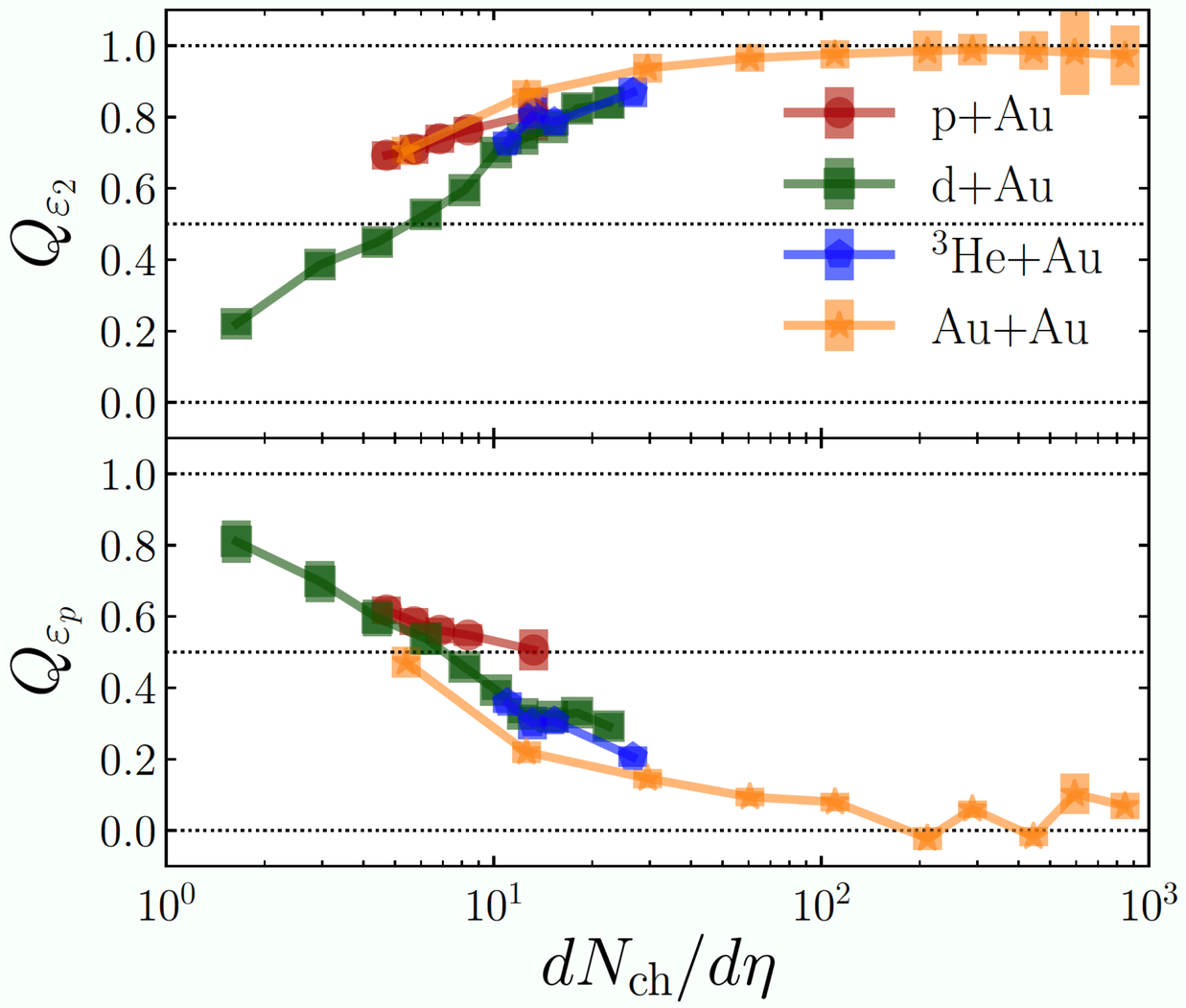
ALEPH, arXiv: 1906.00489 [hep-ex] (2019)

Relative contribution from IS and FS

B. Schenke, Wednesday@14:00

B. Schenke, C. Shen, P. Tribedy, arXiv: 1908.06212

- Correlation of v_n with geometry
  - Increases with multiplicity
- Correlation of v_n with initial momentum anisotropy
  - Decreases with multiplicity



Future

- Proposal for new collision systems: OO

@LHC

Year	Systems, $\sqrt{s_{\mathrm{NN}}}$	Time	L_{int}
2022	Pb–Pb 5.5 TeV	5 weeks	3.9 nb^{-1}
	O–O, p–O	1 week	500 $\mu\mathrm{b}^{-1}$ and 200 $\mu\mathrm{b}^{-1}$

@RHIC

Single-Beam Energy (GeV/n)	$\sqrt{s_{NN}}$ (GeV)	Run Time	Species	Events (MinBias)	Priority	Sequence
100	200	1 week[2]	O+O	400M 200M (central)	3	8

Z. Citron et al., arXiv:1812.06772