Flow: small and large systems

Experimental overview

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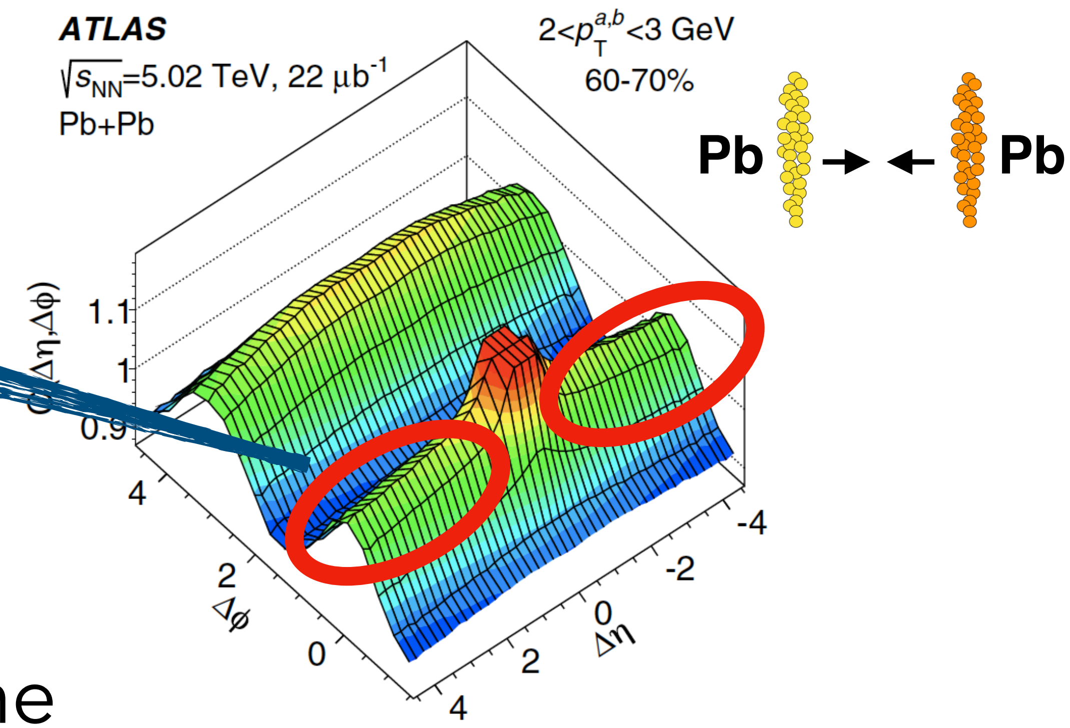
Beginnings of collectivity in small systems

ATLAS, EPJC, 78:997 (2018)

Large systems -> hydrodynamic flow

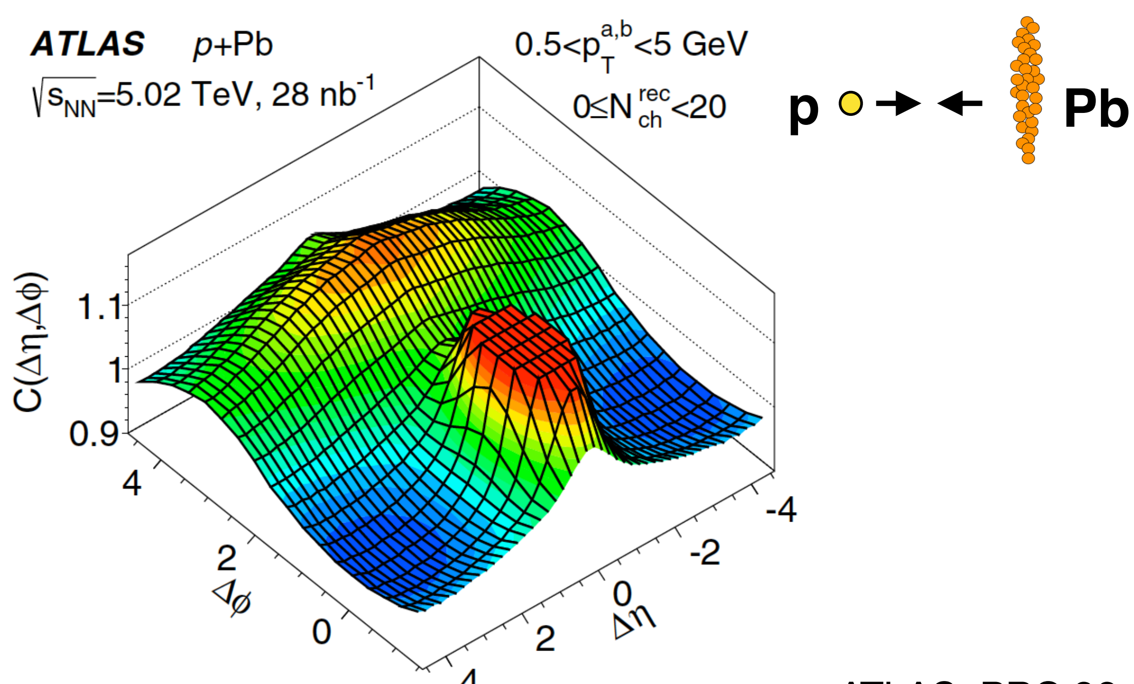
- Near-side ridge at $\Delta\Phi \approx 0$

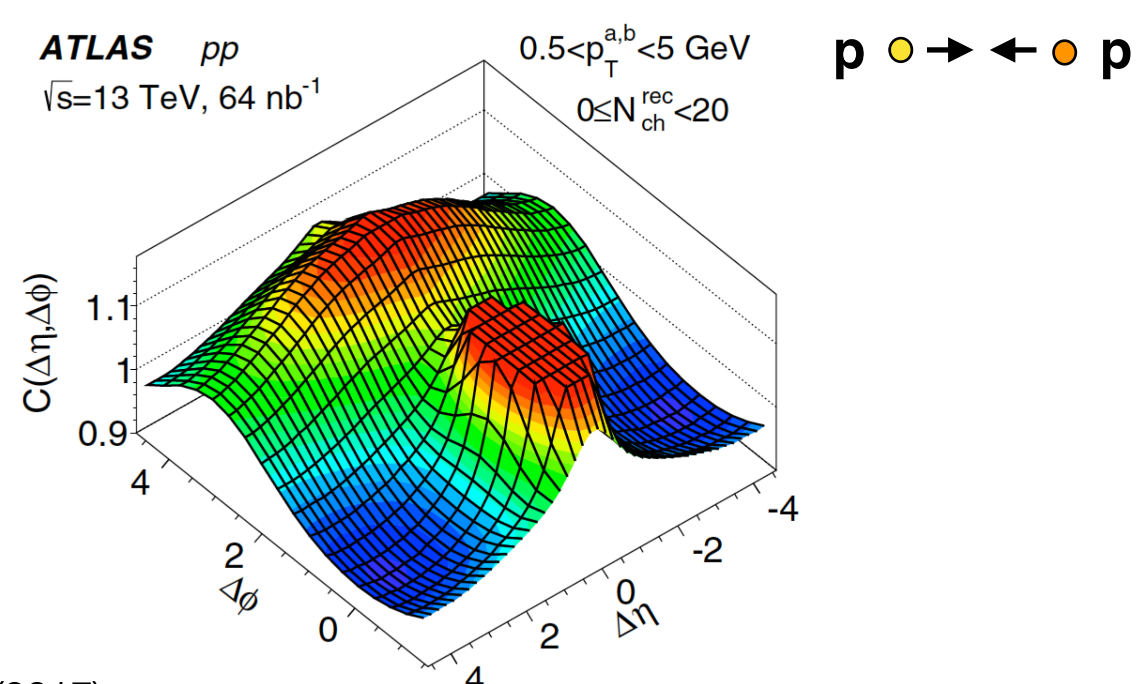
➡ Long-range correlations in η



Small systems -> no flow … just a baseline

- No near-side ridge





ATLAS, PRC **96**, 024908 (2017)

Beginnings of collectivity in small systems

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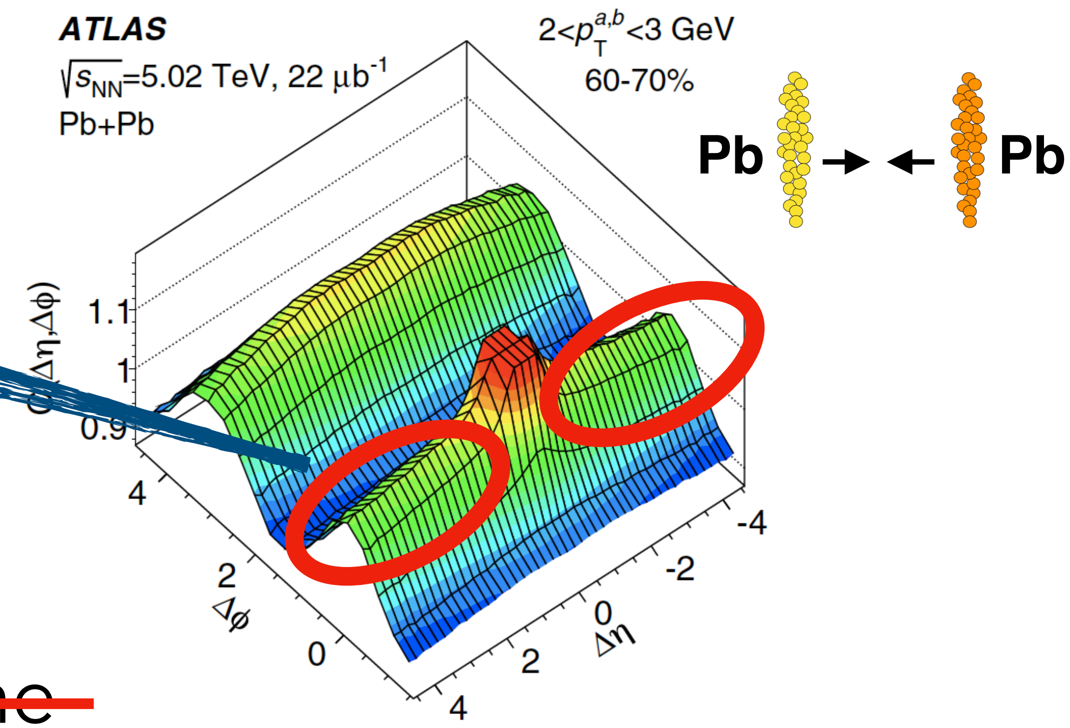


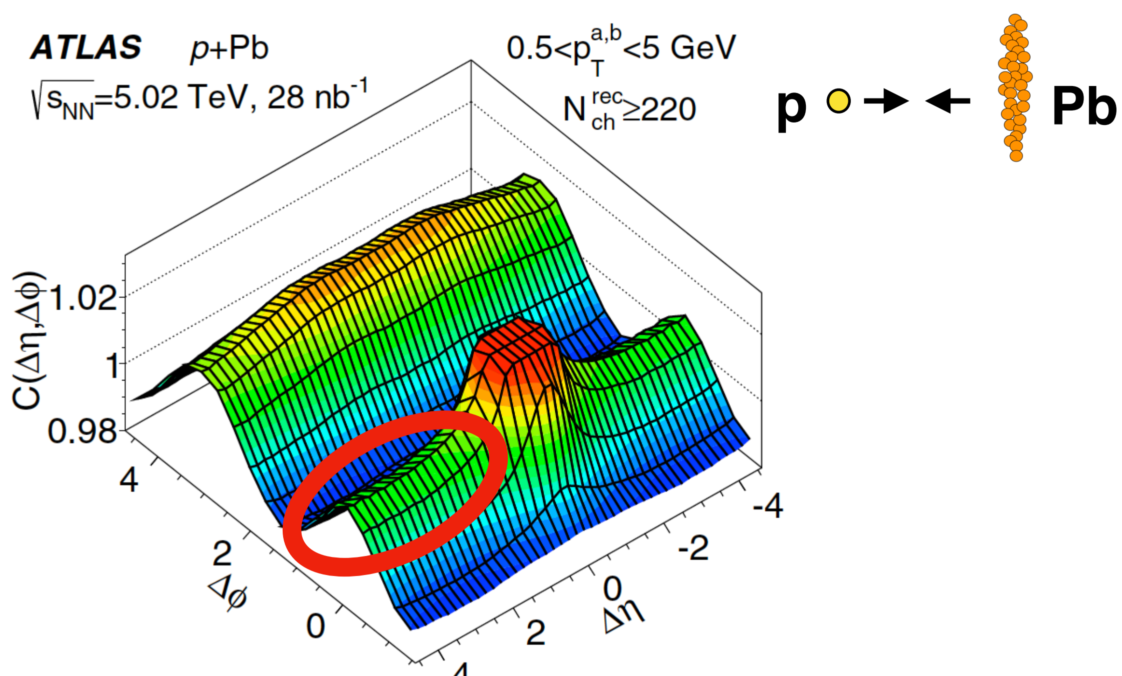
Large systems -> hydrodynamic flow

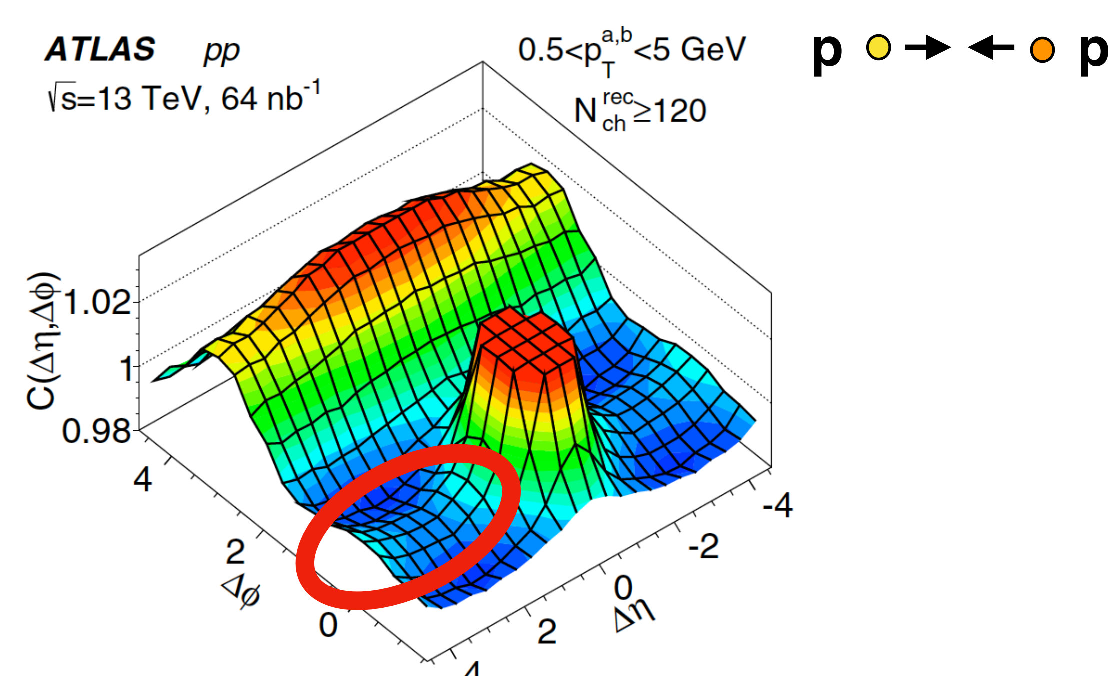
- Near-side ridge at ΔΦ ≈ 0

➡ Long-range correlations in η

High multiplicity
Small systems -> ~~no flow … just a baseline~~

- ~~No near-side ridge~~ -> ridge observed in both p-Pb and pp collisions

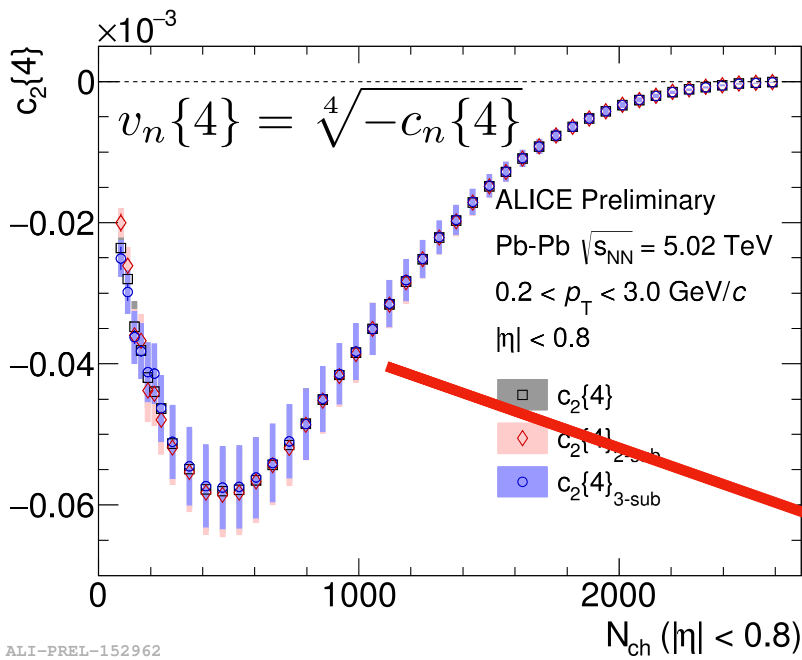


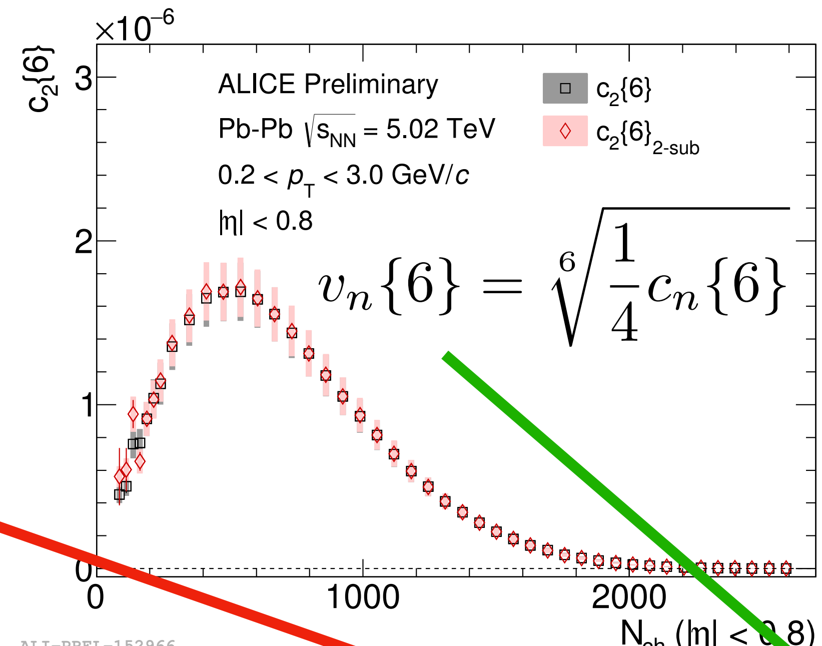


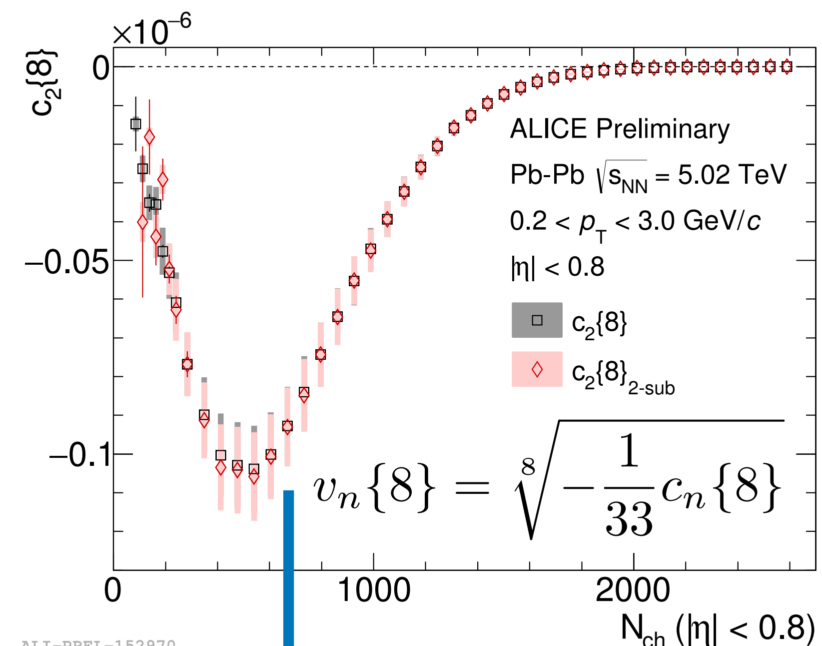
ATLAS, PRC **96**, 024908 (2017)

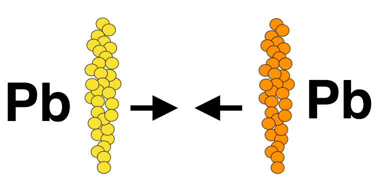
Investigation of collectivity: what to search for?

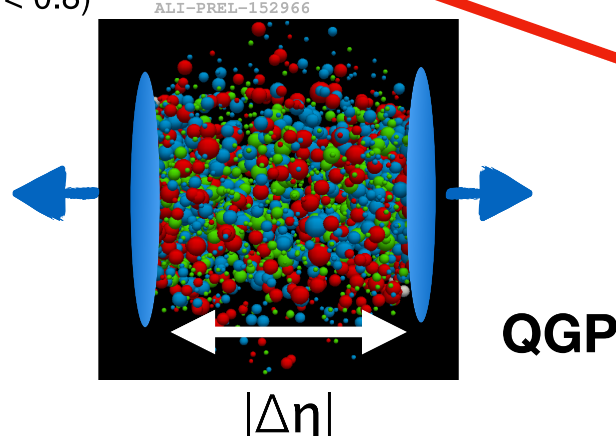
- Heavy-ion collisions are collective
  - Correlation of many particles w.r.t. a common symmetry plane spanning long range in η

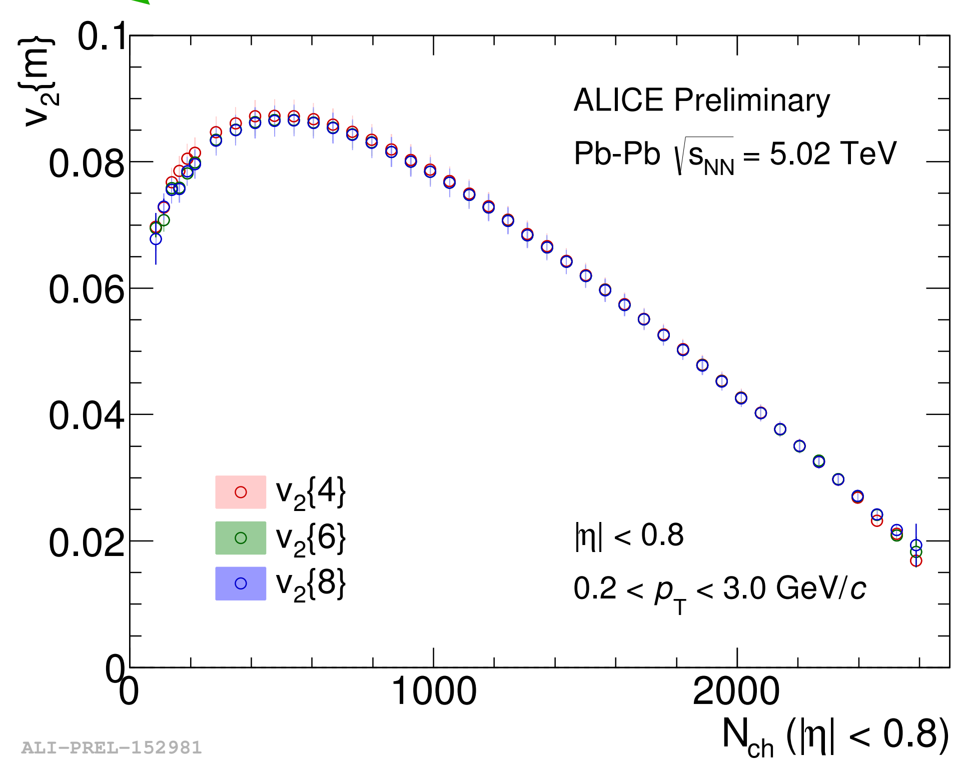






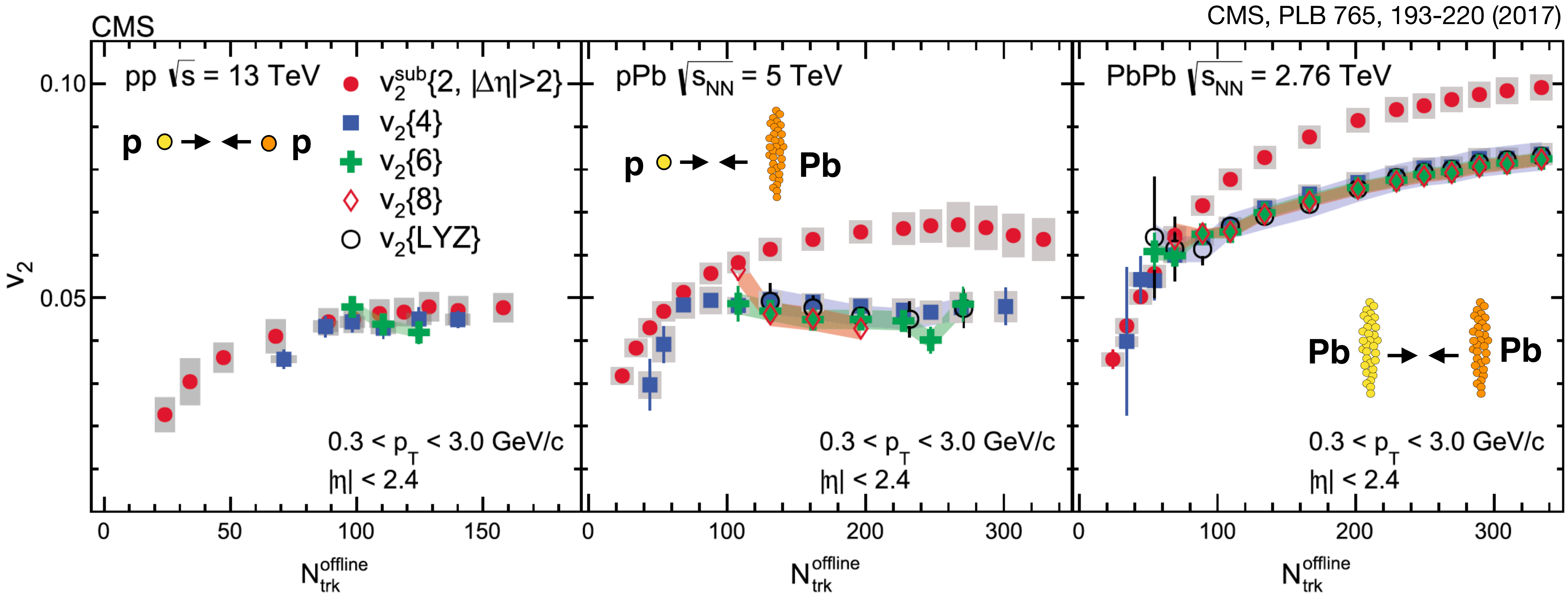






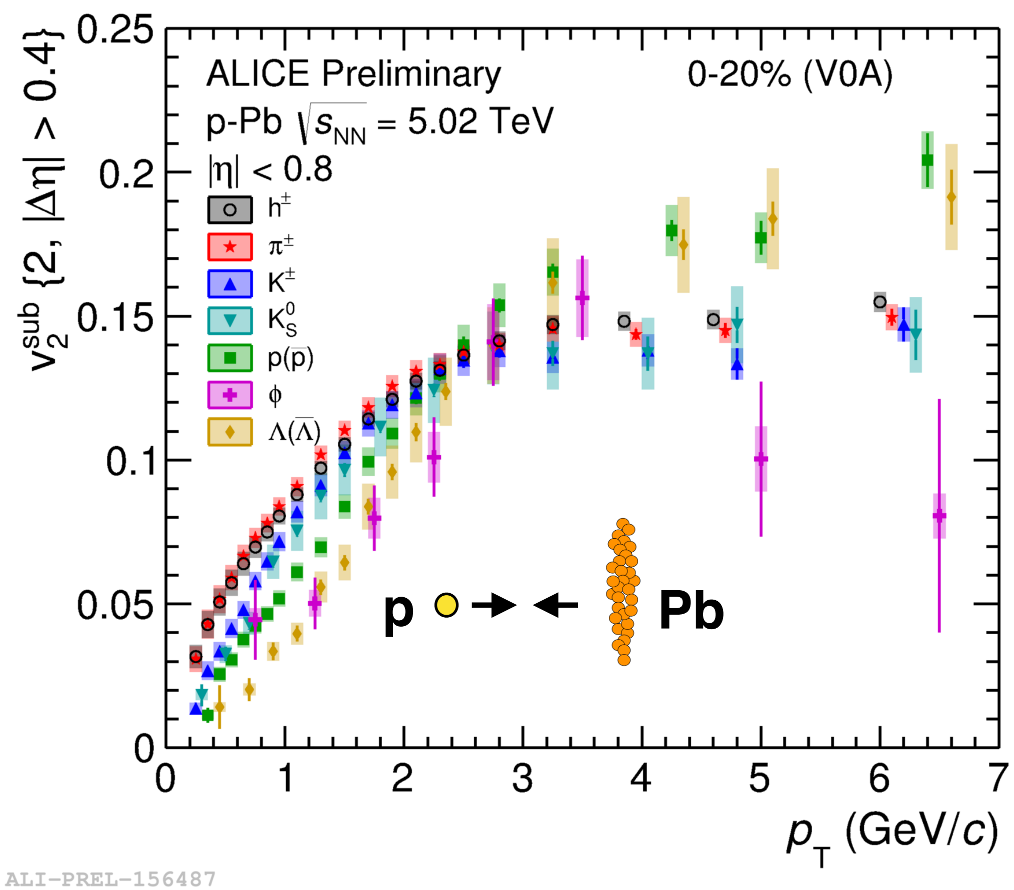
- Long-range multi-particle correlations
  - $v_n\{m\} \approx v_n\{m\}_{subevent}$
  - $v_n\{4\} \approx v_n\{6\} \approx v_n\{8\}$

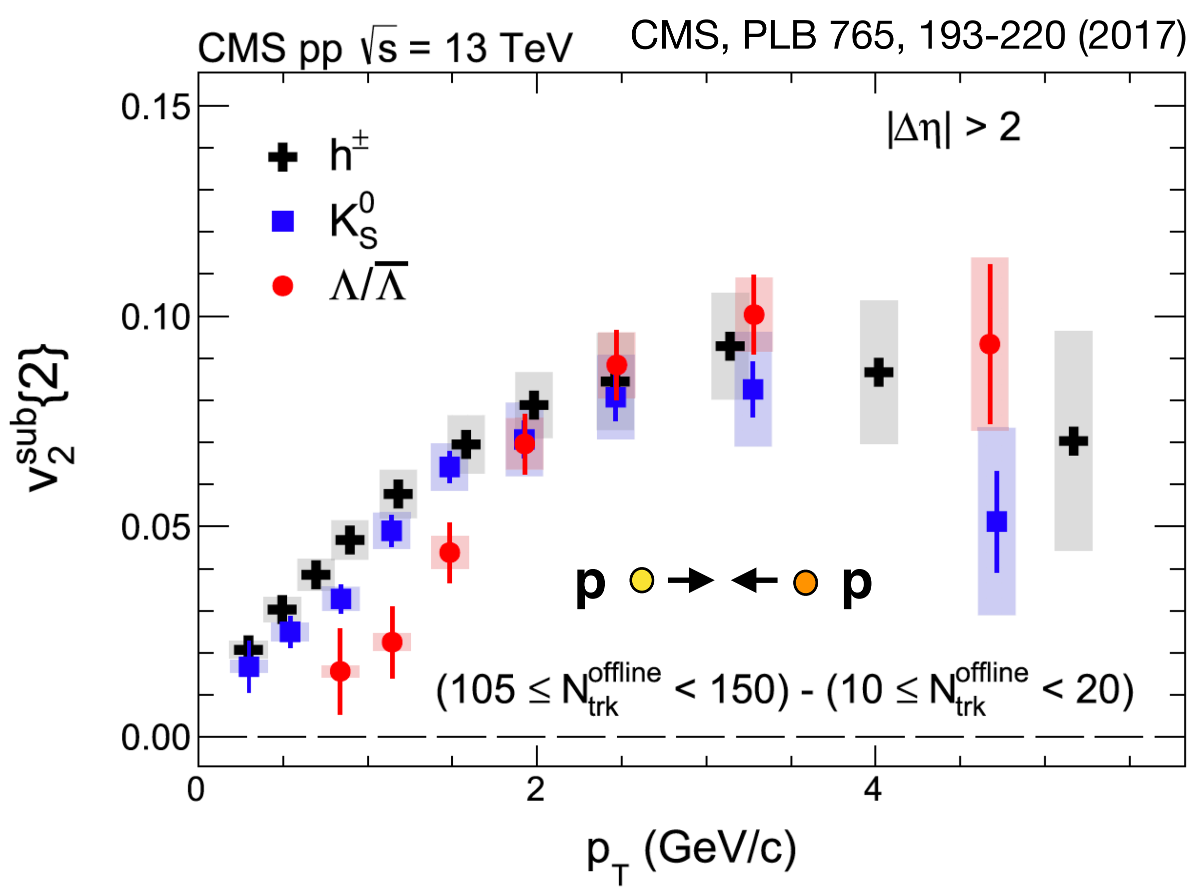
Collectivity down to pp collisions



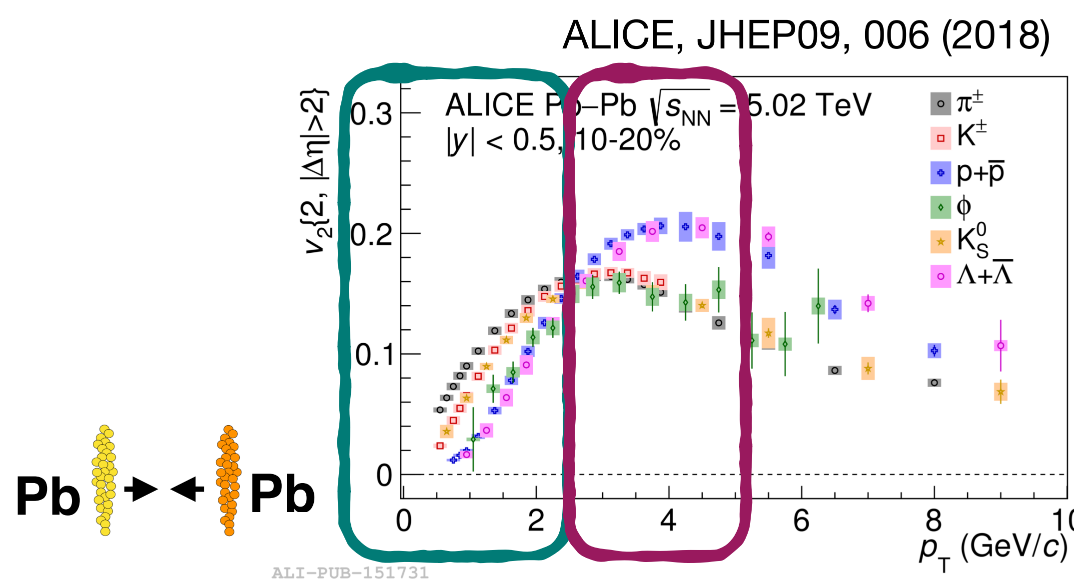
- Analogous observations to large collision systems
- Flow coefficients v_2 measured in small systems with multi-particle correlations are similar (**$v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$**)

Identified particle v_n





- Mass ordering at low p_T
  - Hydrodynamic flow
- Baryon-meson grouping at intermediate p_T
  - Partonic collectivity, coalescence
- Results from pPb and pp collisions **similar to large systems**



What is the origin of collectivity ?

Initial State (IS)

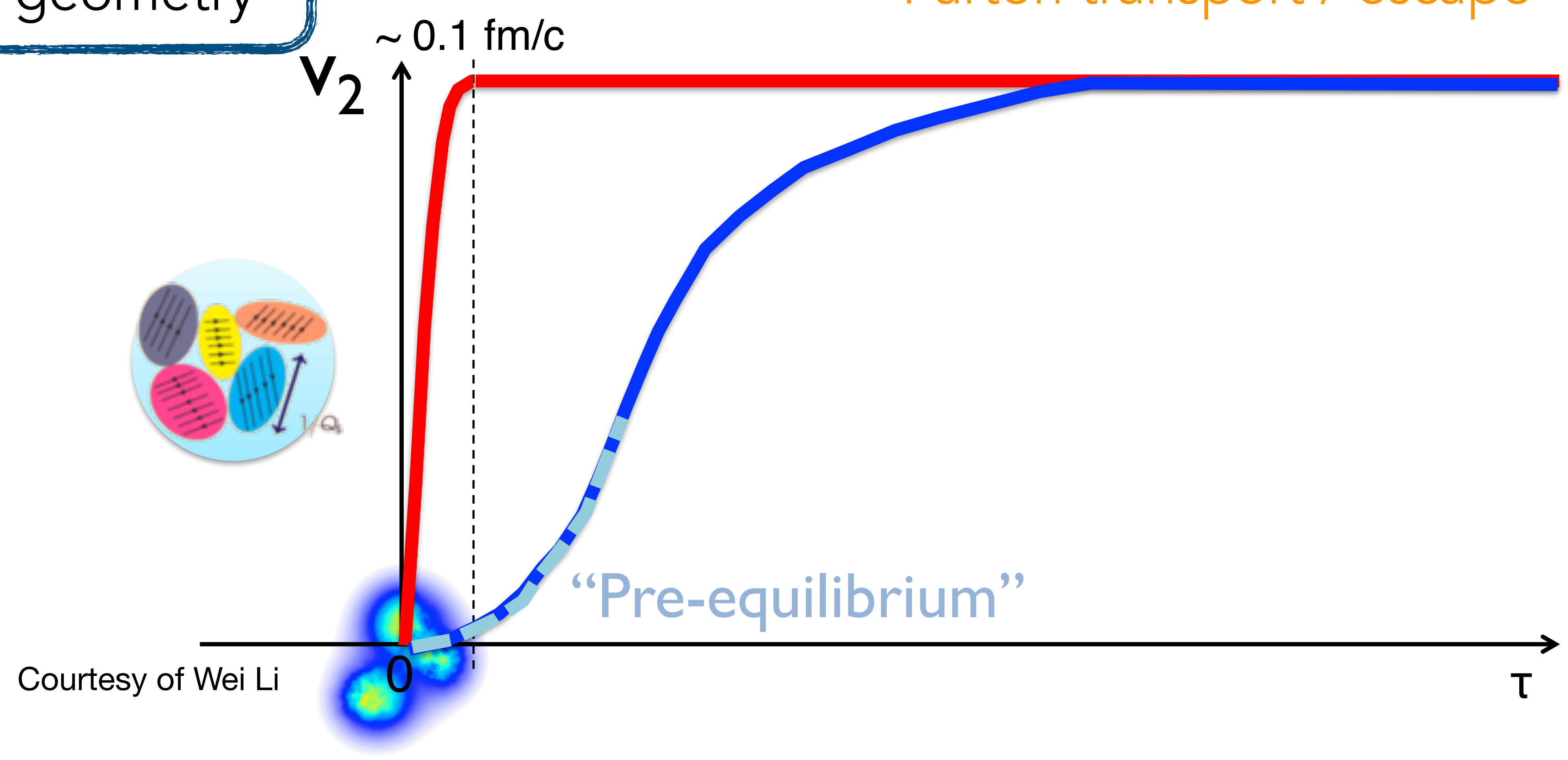
- Initial momentum correlations
- CGC

Not correlated to initial geometry

Final State (FS)

- Initial spatial anisotropy + interactions in the final state
- Hydrodynamics
- Parton transport / escape

Correlated to initial geometry



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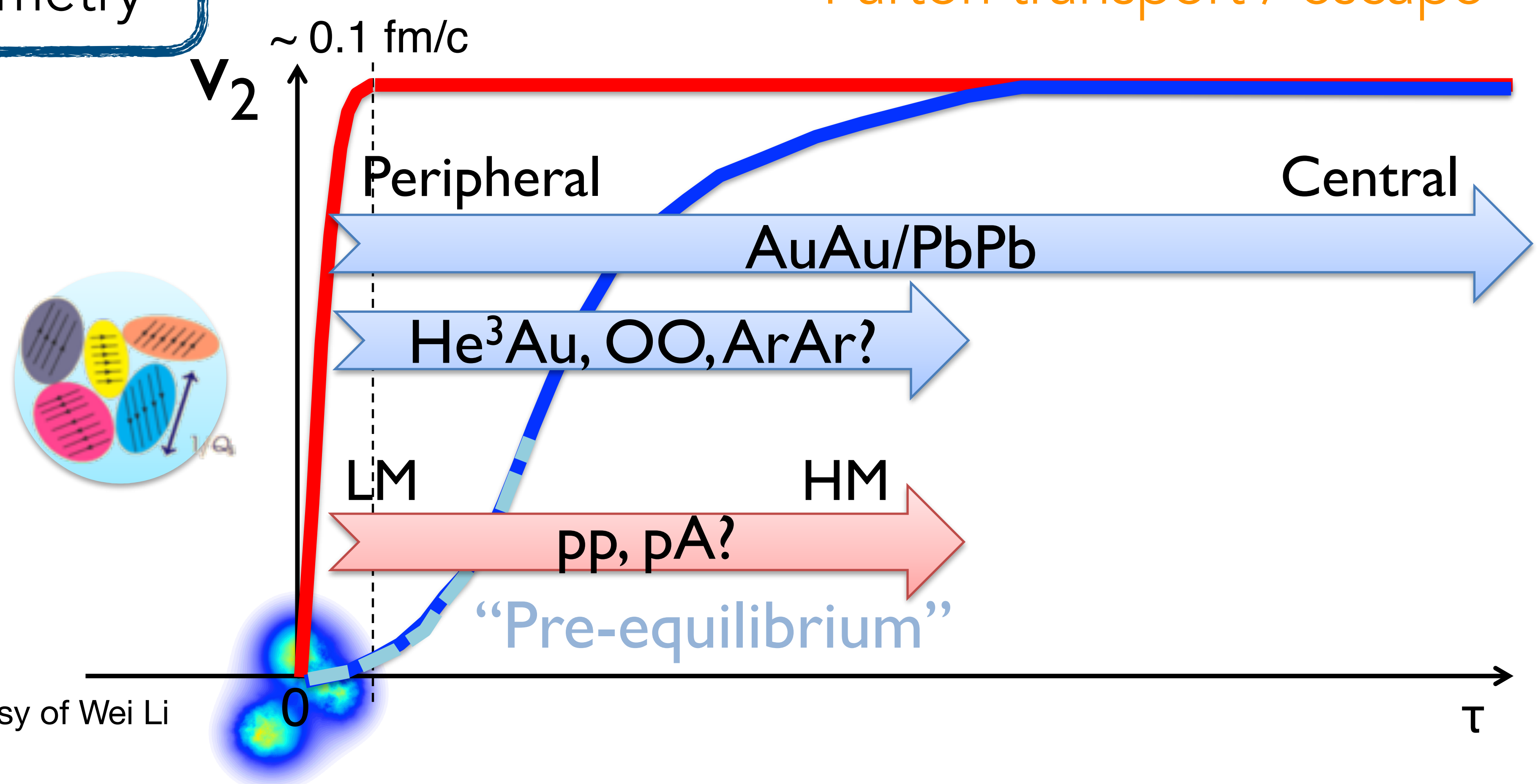
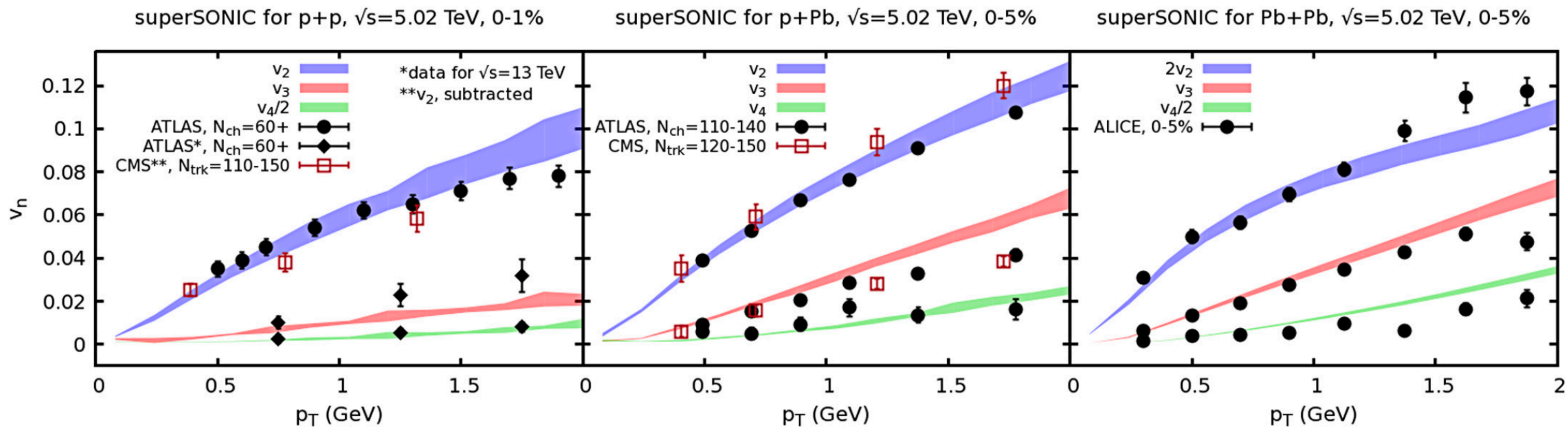


Courtesy of Wei Li

Need to investigate with experimental data and comparison to models.

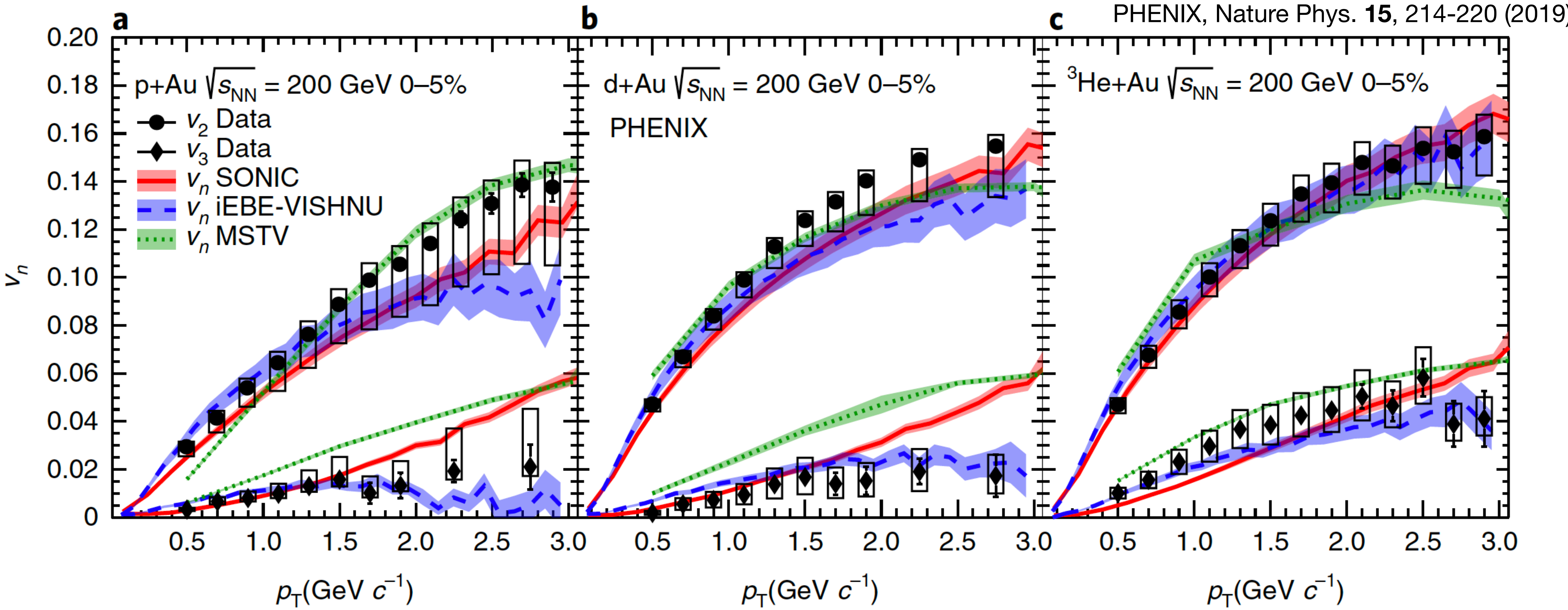
"One fluid to rule them all"

Weller, Romatschke, PLB 774 (2017) 351



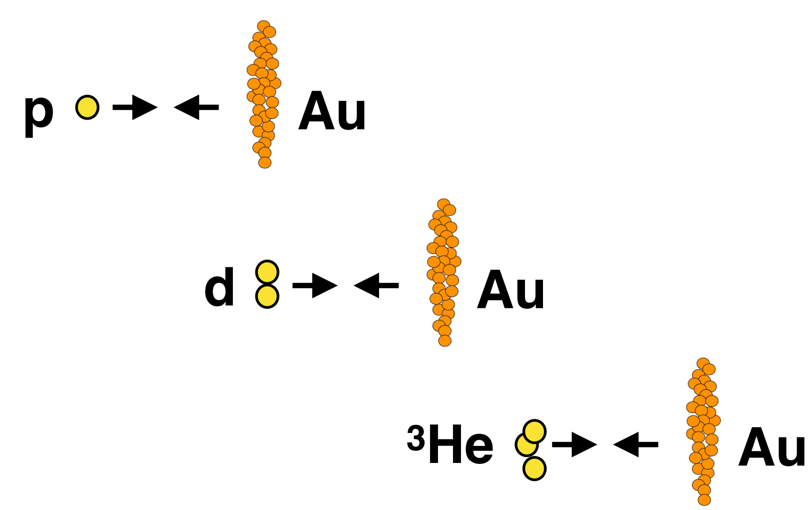
- **Continuous description** of collision systems of different sizes by one model with the same parametrization

Geometry driven anisotropy



v_2 (p+Au) < v_2 (d+Au) ~ v_2 (^{3}He+Au)

v_3 (p+Au) ~ v_3 (d+Au) < v_2 (^{3}He+Au)



- Within a hydrodynamic picture: $v_n \sim k_n \varepsilon_n$
- PHENIX: data **consistent with hydrodynamics**

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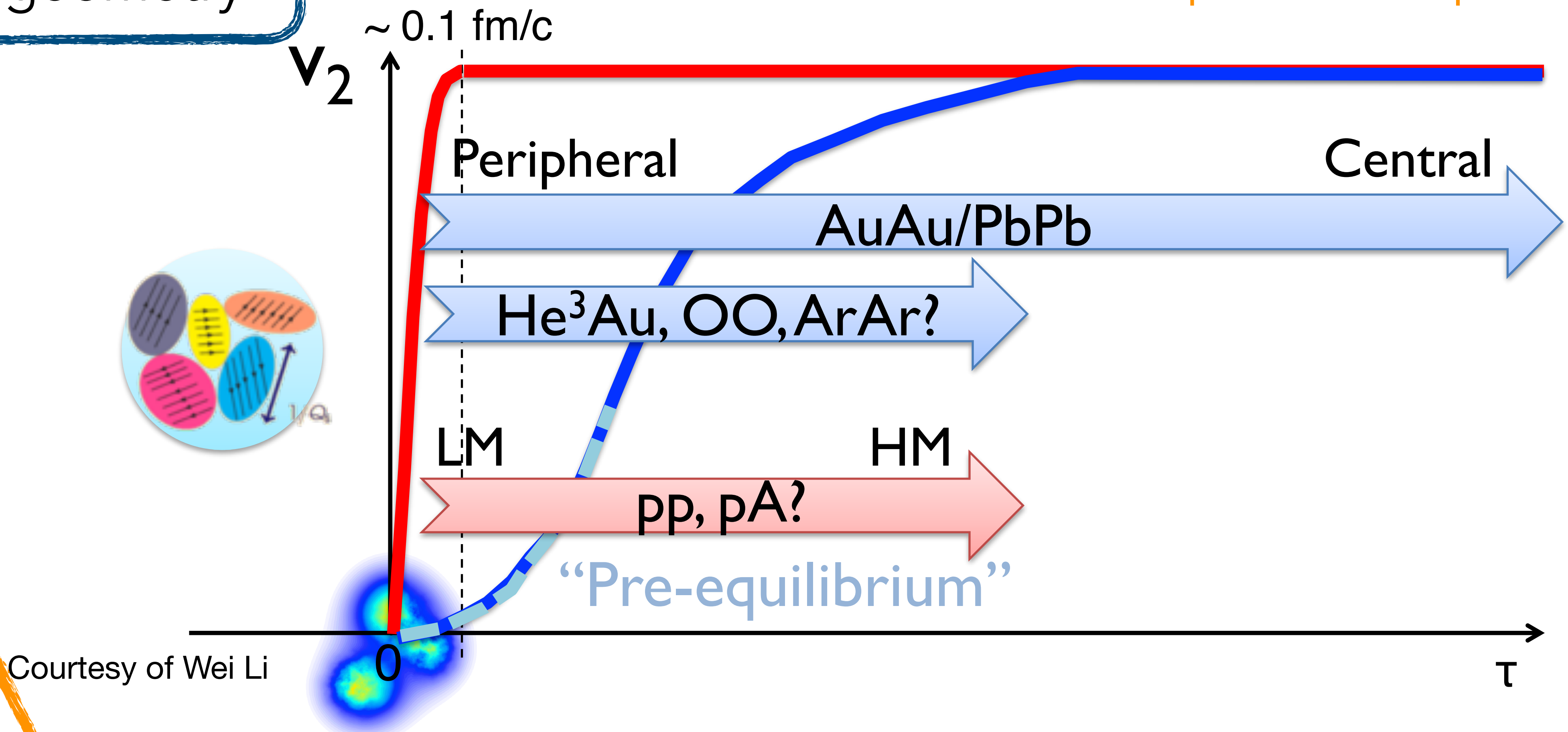
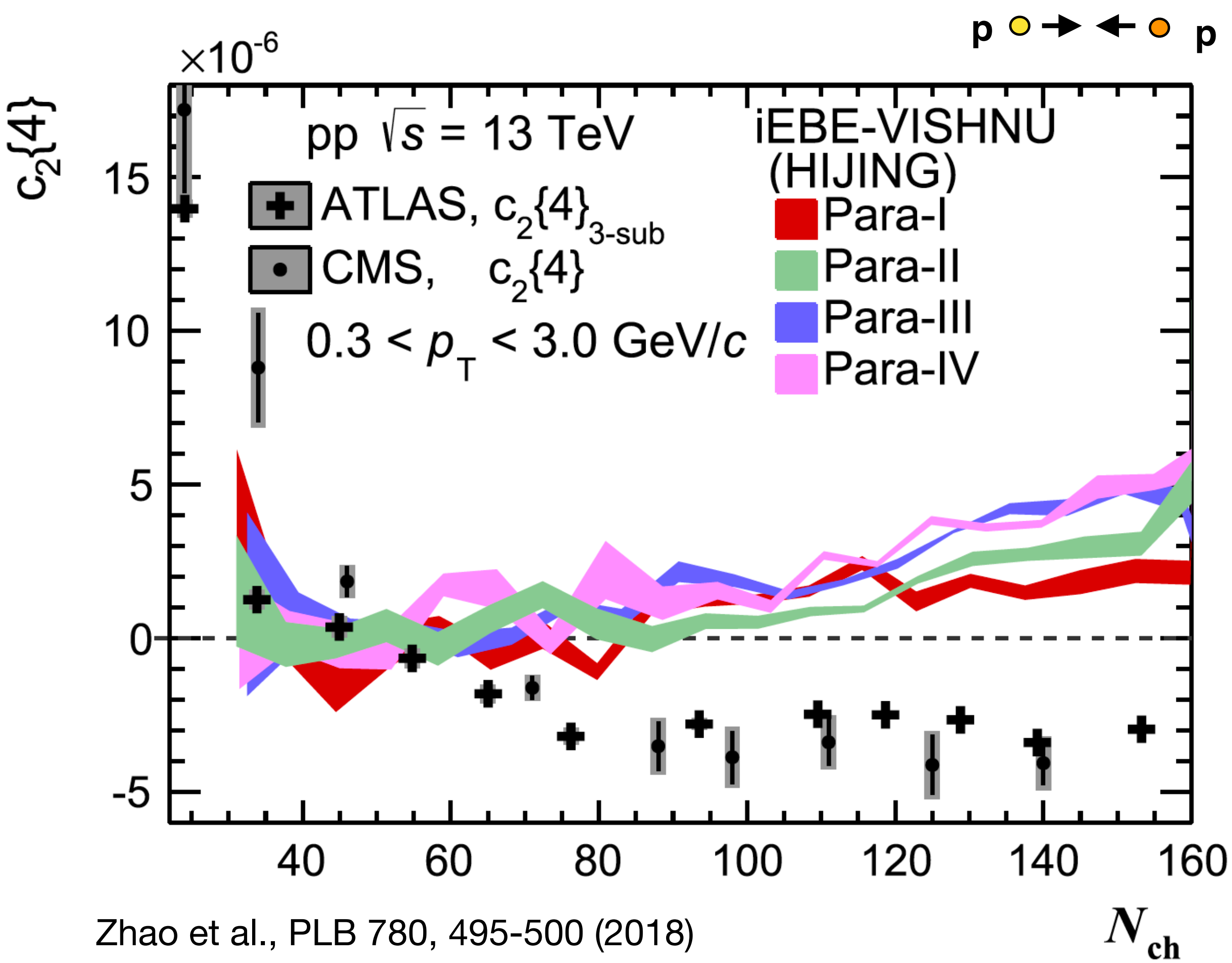


Obvious(?) Data seem to favour final state description.

Beware of gaps in the FS description

Reminder: **Collectivity** = long-range **multi-particle** correlations

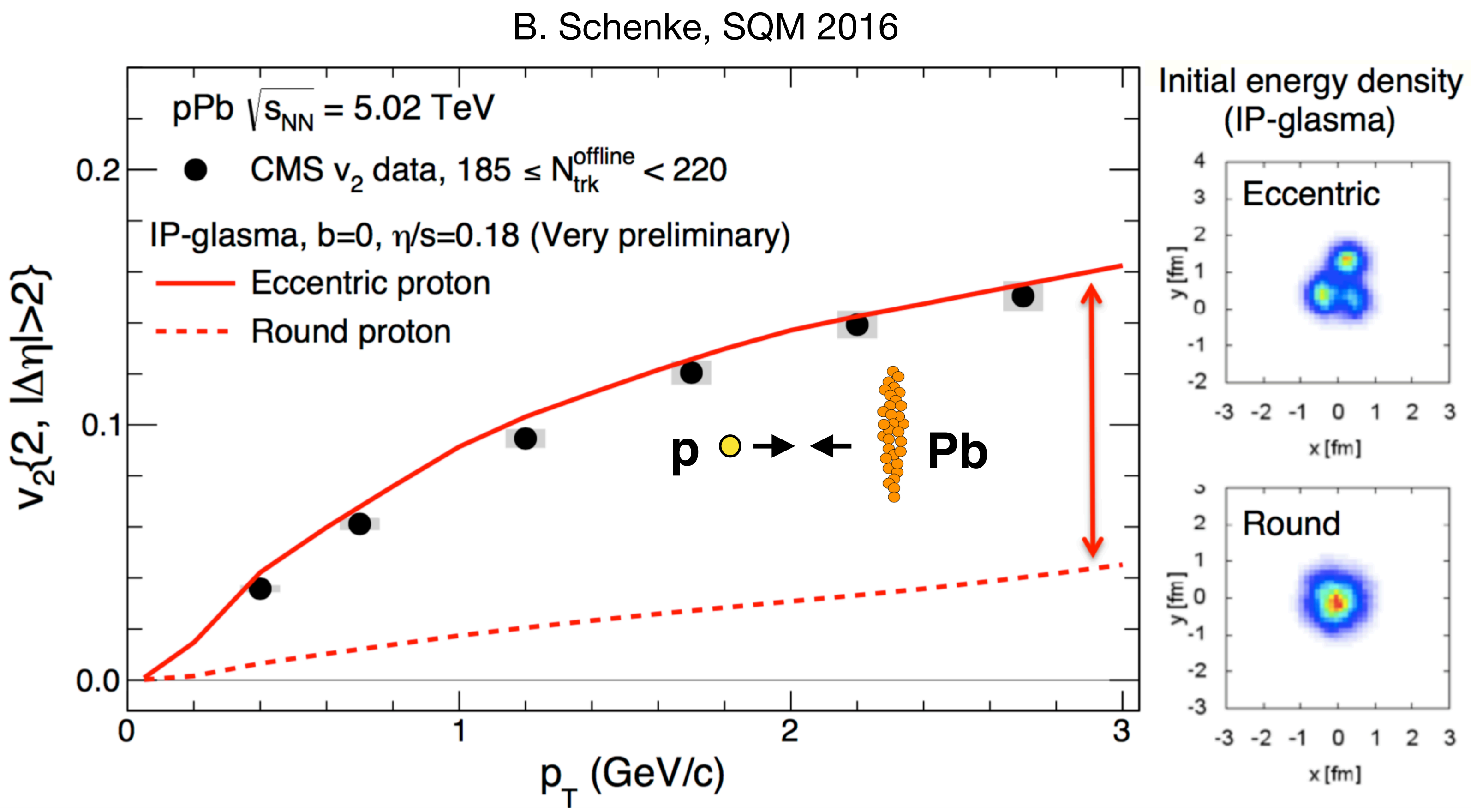
- Just one hydrodynamic description of multi-particle cumulants in pp collisions
  - Fails to describe the $c_2\{4\}$ -> Further **understanding of initial conditions is necessary**



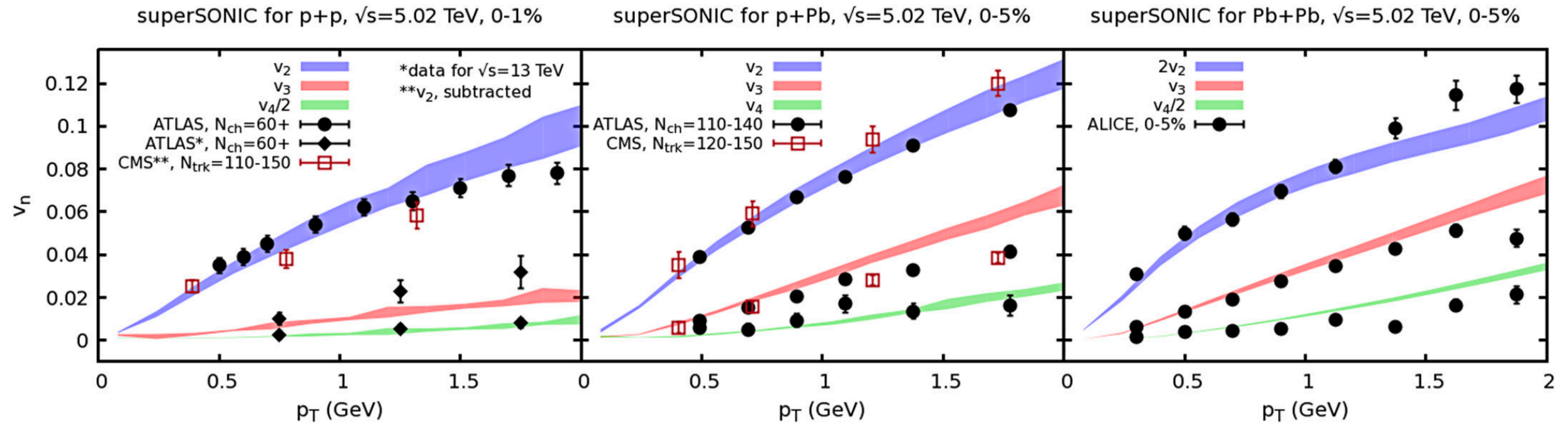
Zhao et al., PLB 780, 495-500 (2018)

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

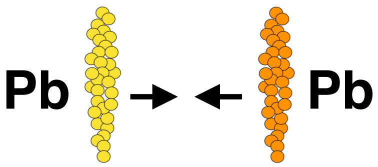
Important to investigate IS



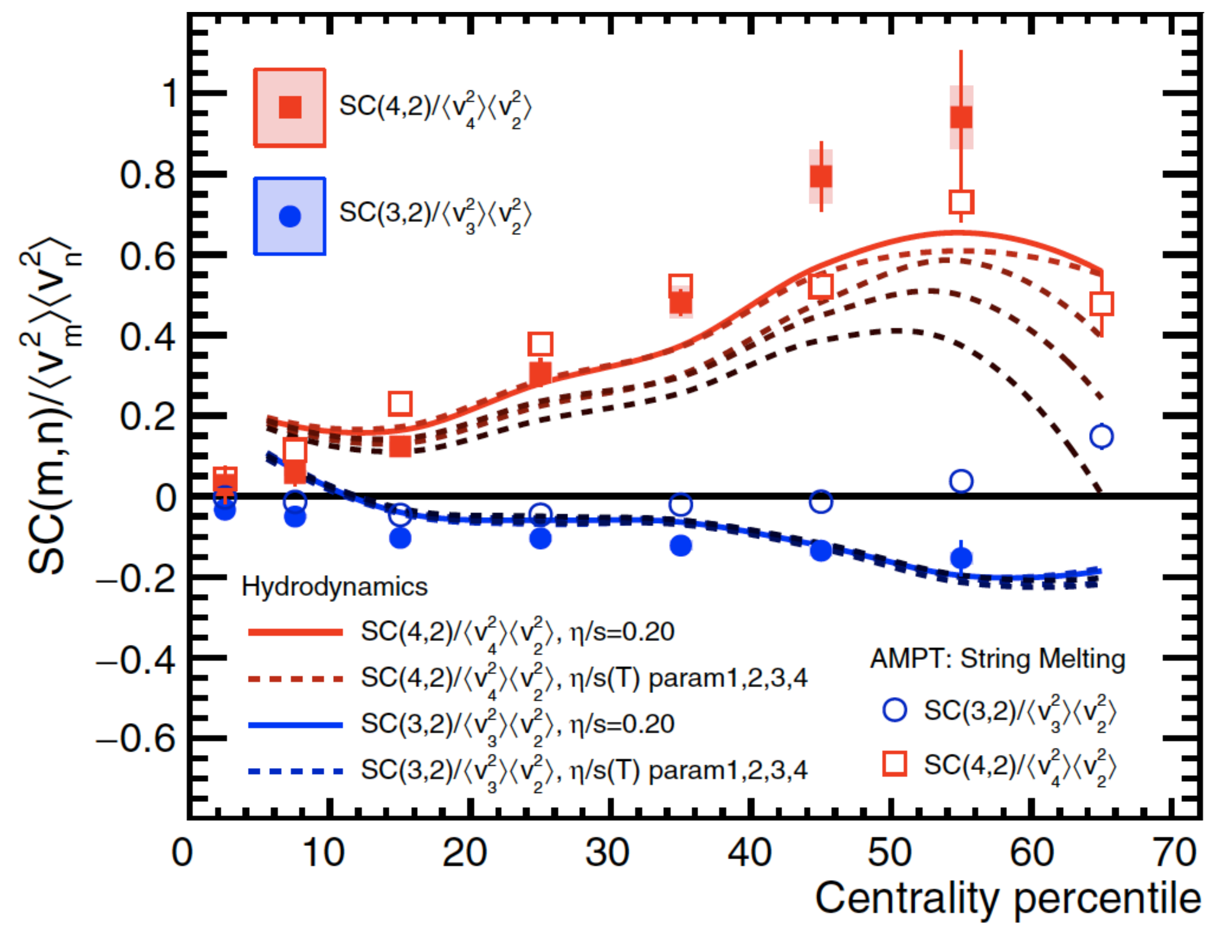
- **Proton substructure** becomes crucial to achieve correct data description
  - All the successful descriptions of measurements in small systems include proton substructure



How to experimentally constrain initial state



ALICE, PRL **117**, 182301 (2016)



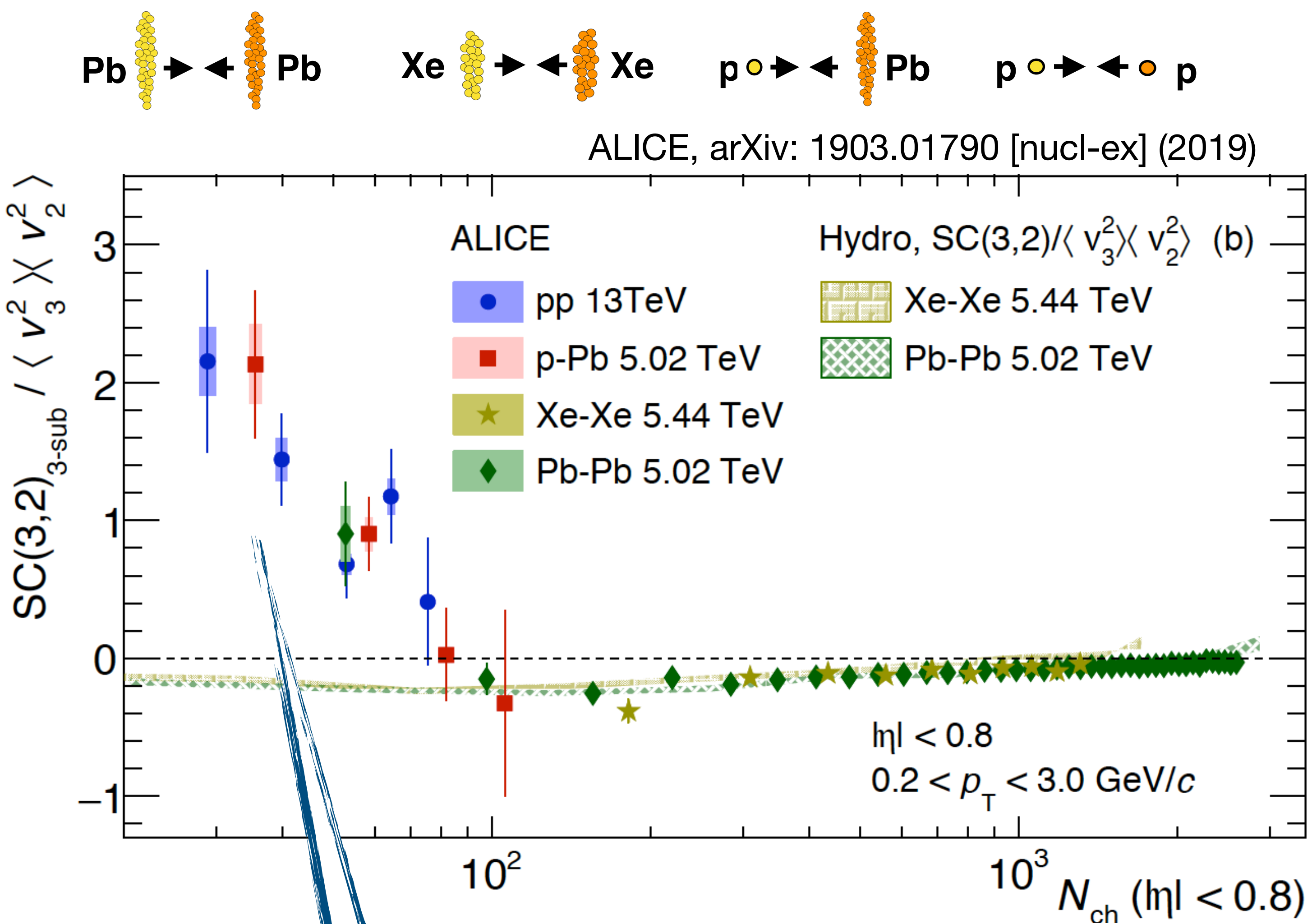
Symmetric Cumulants:

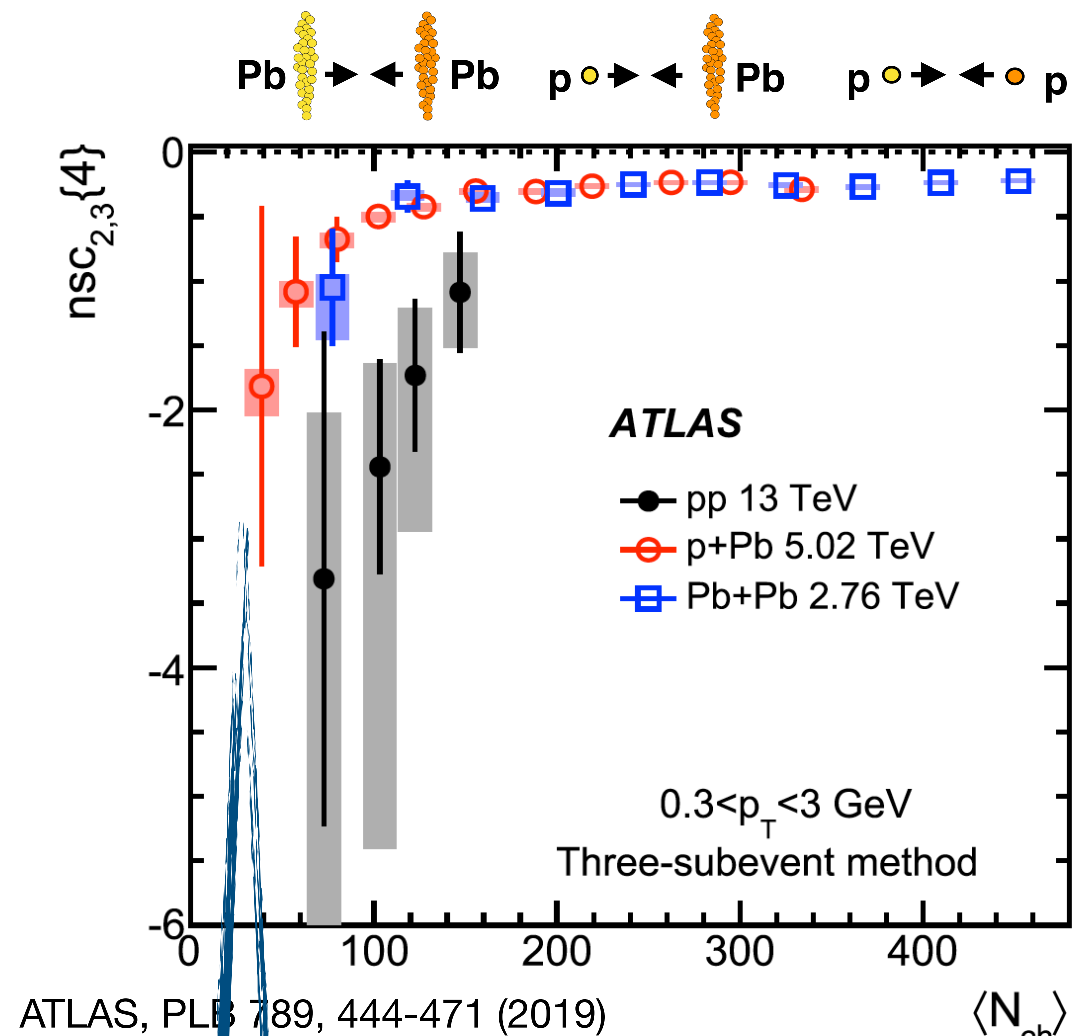
$$SC(m,n) = \langle v_m^2 v_n^2 \rangle - \langle v_m^2 \rangle \langle v_n^2 \rangle$$

Normalised SC: $$\frac{SC(m,n)}{\langle v_m^2 \rangle \langle v_n^2 \rangle}$$

- Correlations between different order harmonics put constraints on initial state and η/s(T) of the created system in heavy-ion collisions
  - SC(3,2): sensitive to initial conditions
- In small systems SC(m,n) can probe proton substructure
  - Albacete, Petersen, Soto-Otoso, PLB 778, 128-136 (2018)

Symmetric Cumulants in small systems





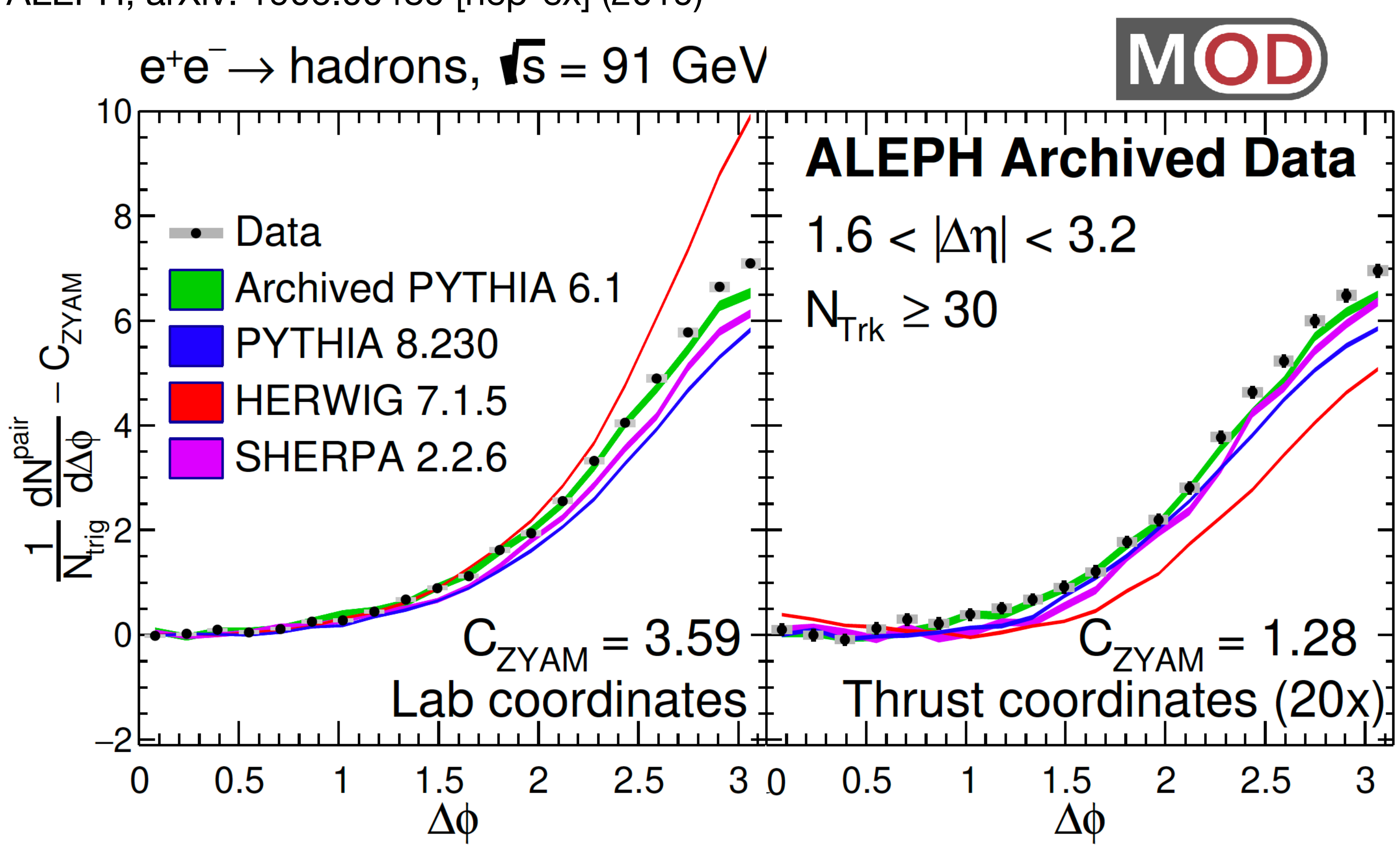
CMS, arXiv: 1905.09935

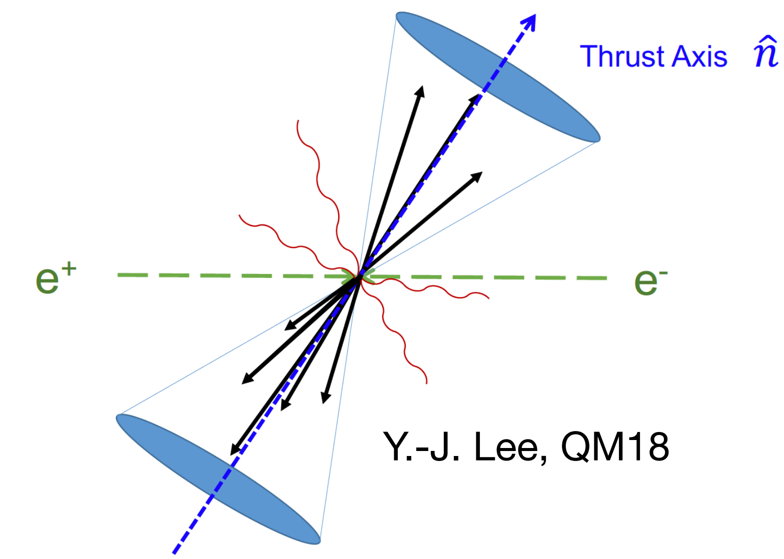
Caveat: results at low multiplicities are different when using different η acceptance

- **Similar pattern as in large systems**
- No model comparison with small systems available yet

Collisions of e+e-

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





- Advantage: well-defined initial state
- **No observation of near-side ridge**
  - Data consistent with models that do not contain any final state interactions

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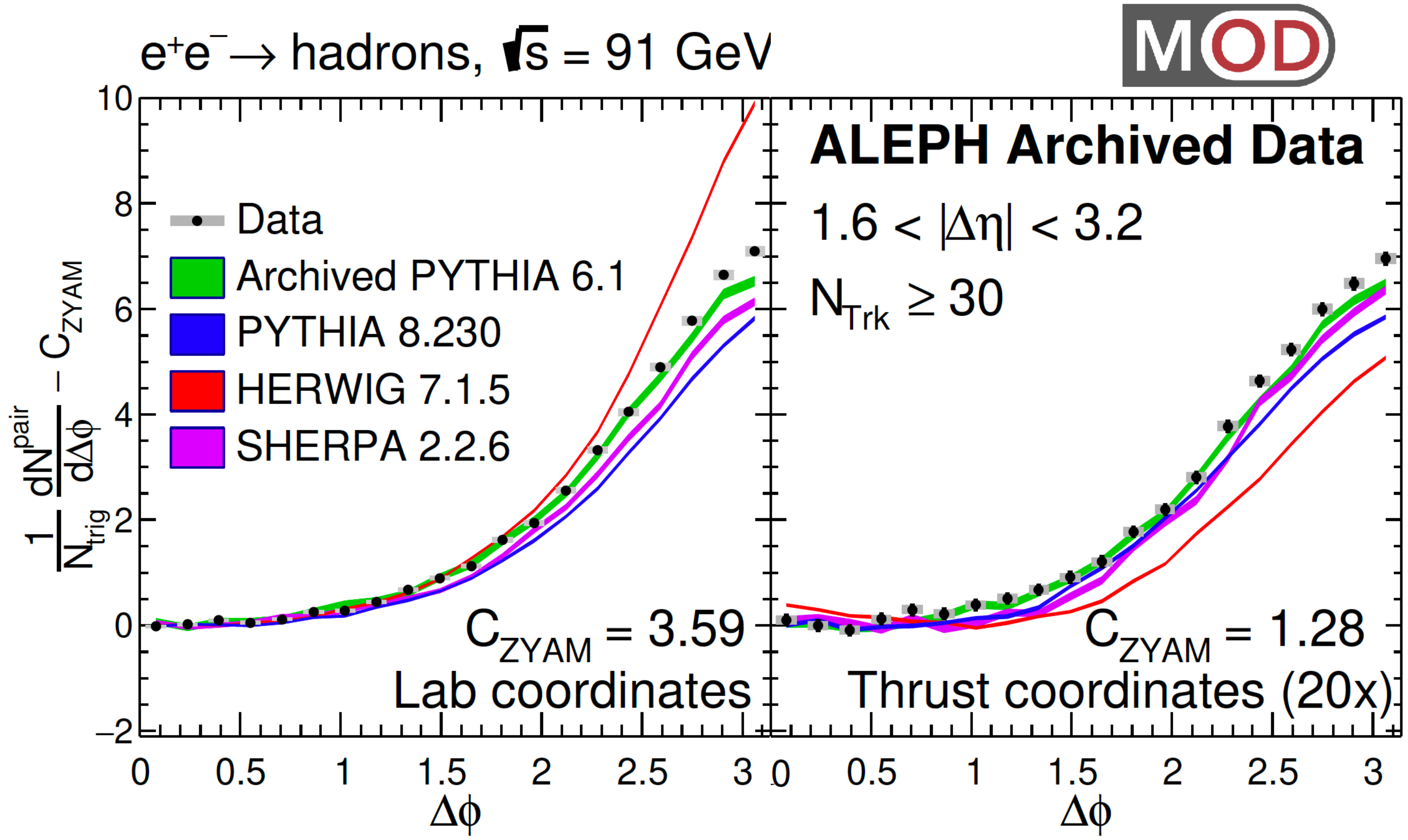

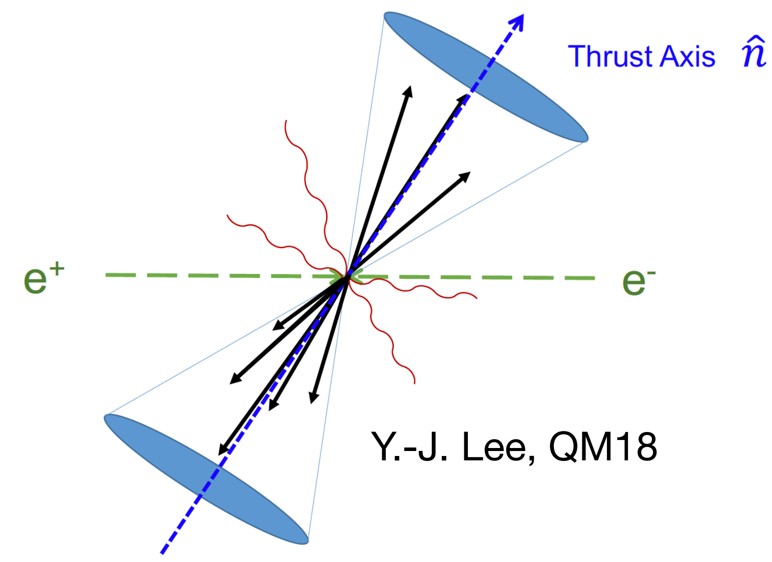

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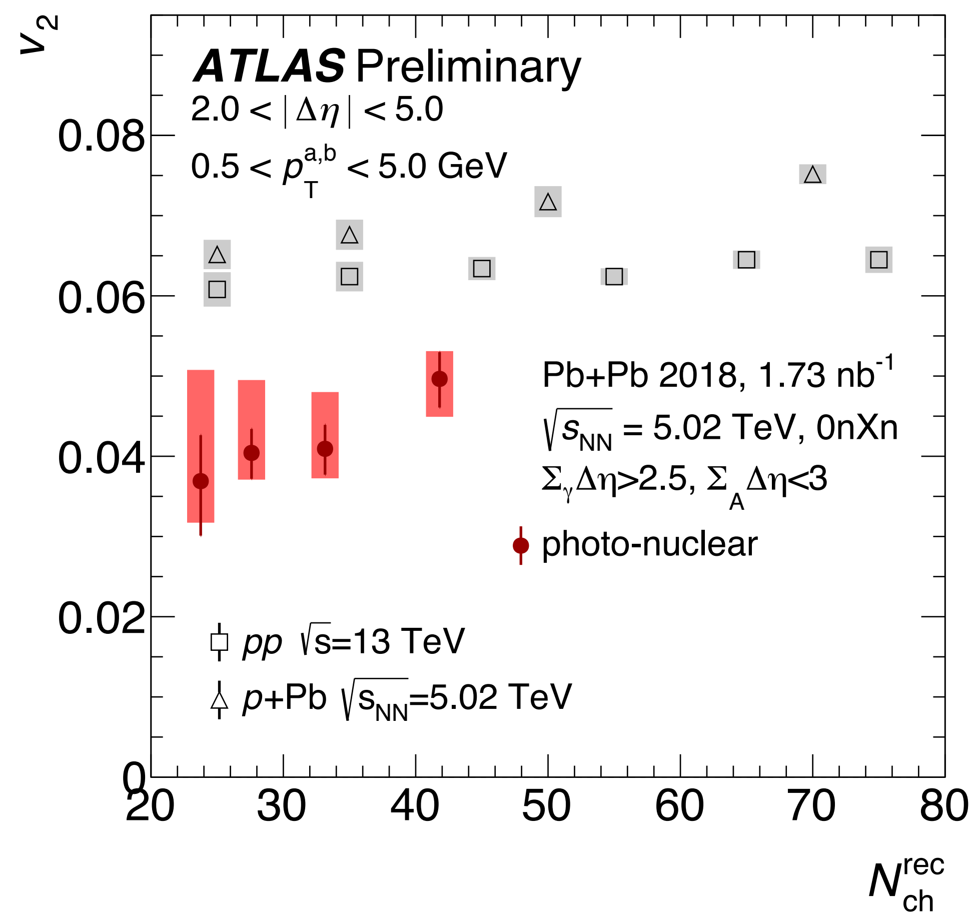

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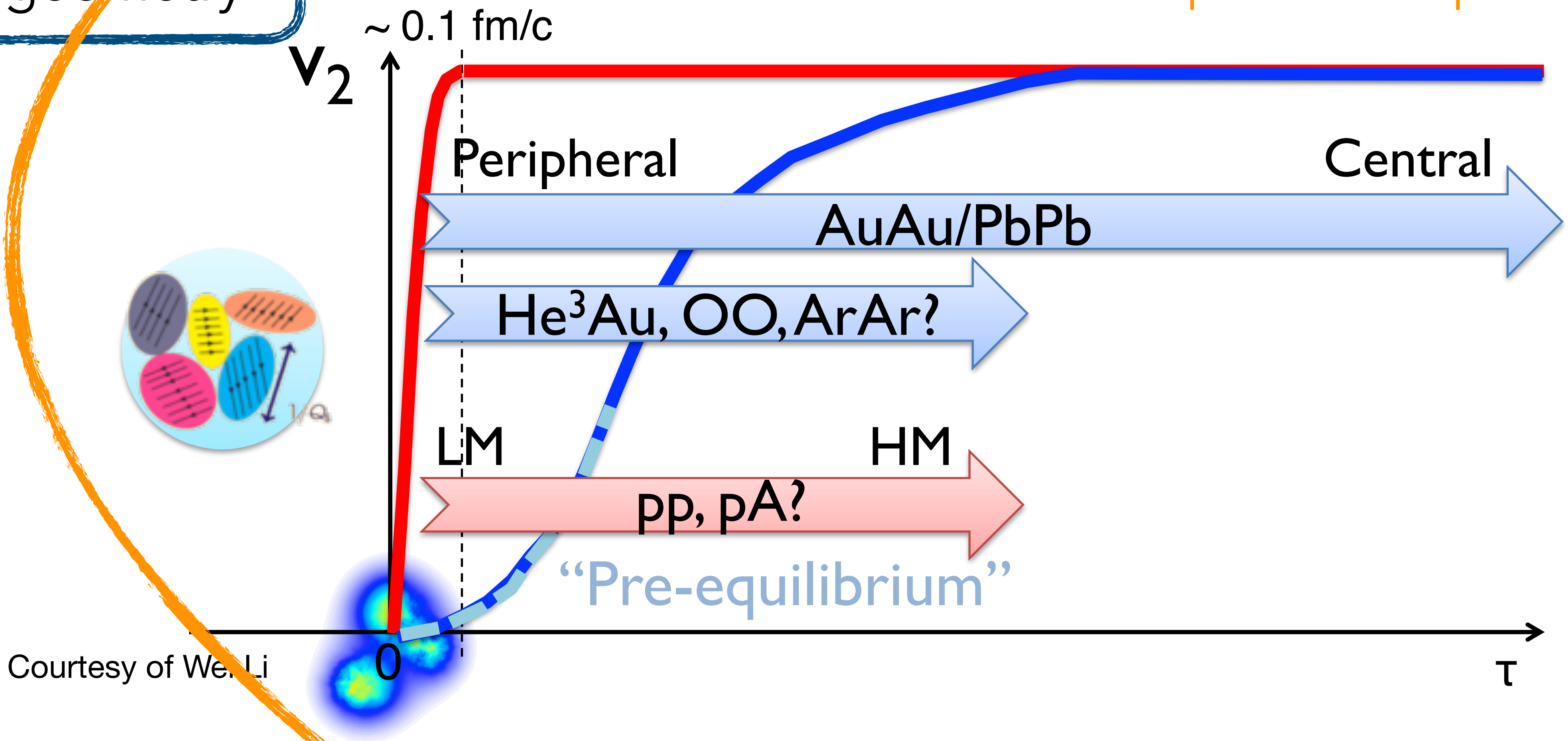


Need more measurements.

Backup

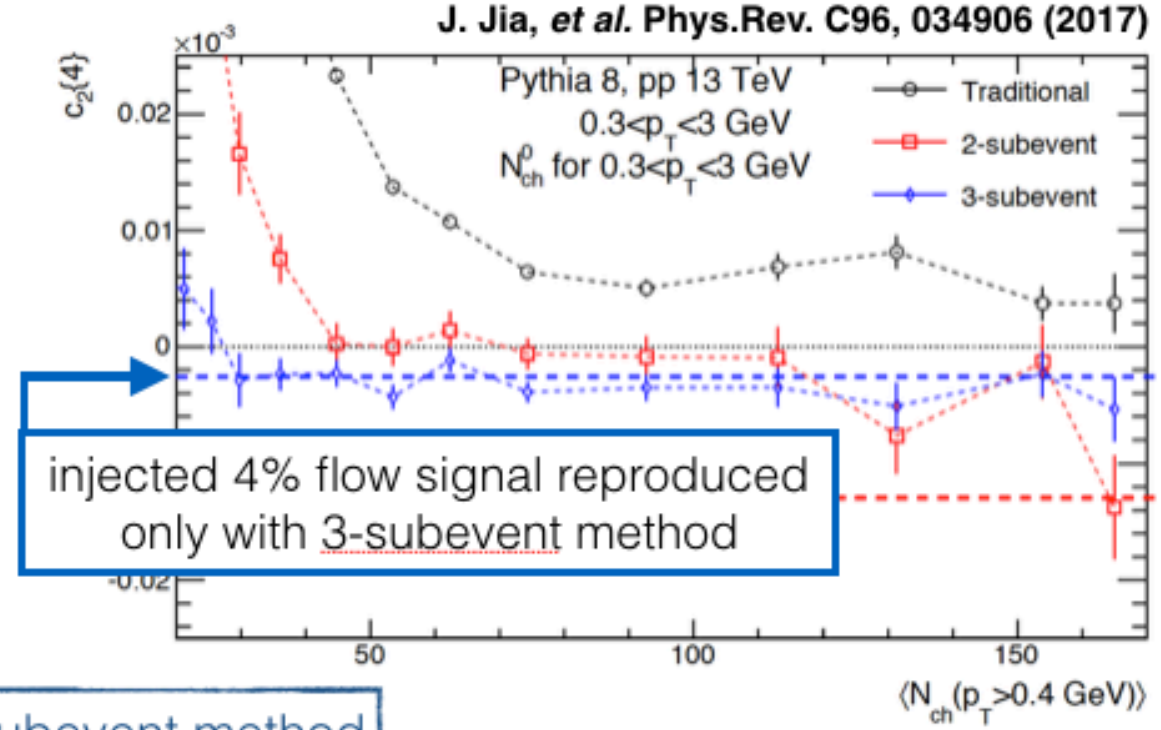
Non-flow effects - challenge in small collision systems

- **Non-flow**: correlations not associated with the common symmetry plane
  - Jets, resonance decays, …
- **Subevent method**: suppresses non-flow effects in multi-particle correlations
- Tested with PYTHIA simulations

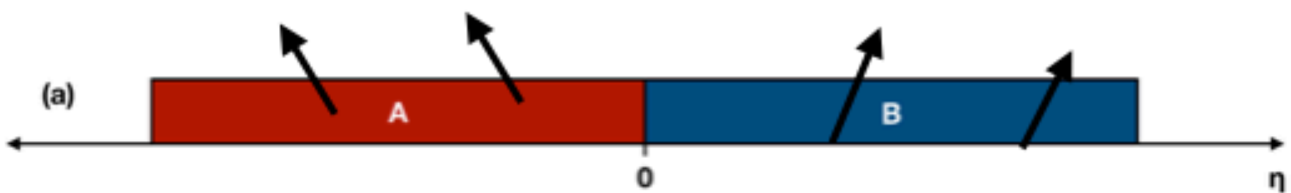
PRC 96, 034906 (2017), NPA 967, 437 (2017), NPA 967, 472 (2017)

K. Gajdosova, M. Zhou, QM17 (2017)

J. Jia, *et al.* Phys.Rev. C96, 034906 (2017)



2-subevent method

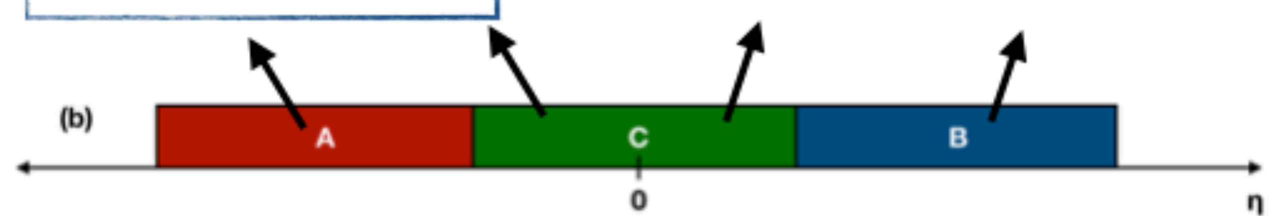


$$\langle\langle 2\rangle\rangle_{2-\mathrm{sub}} = \langle\langle \cos n(\varphi_1 - \varphi_2)\rangle\rangle$$

$$\langle\langle 4\rangle\rangle_{2-\mathrm{sub}} = \langle\langle \cos n(\varphi_1 + \varphi_2 - \varphi_3 - \varphi_4)\rangle\rangle$$

- Suppresses resonance decays, correlations within a jet cone

3-subevent method



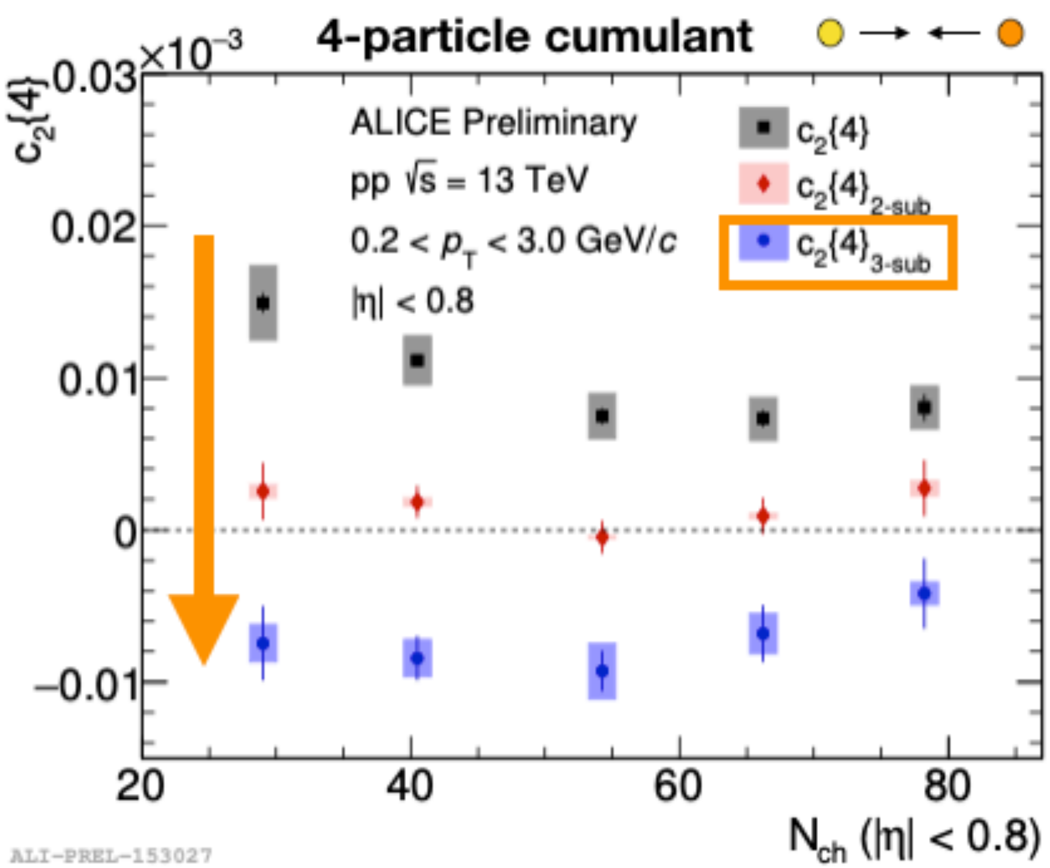
$$\langle\langle 4\rangle\rangle_{3-\mathrm{sub}} = \langle\langle \cos n(\varphi_1 + \varphi_2 - \varphi_3 - \varphi_4)\rangle\rangle$$

- Suppresses resonance decays, correlations within a jet cone, correlations between jet cones

Subevent method in measurements

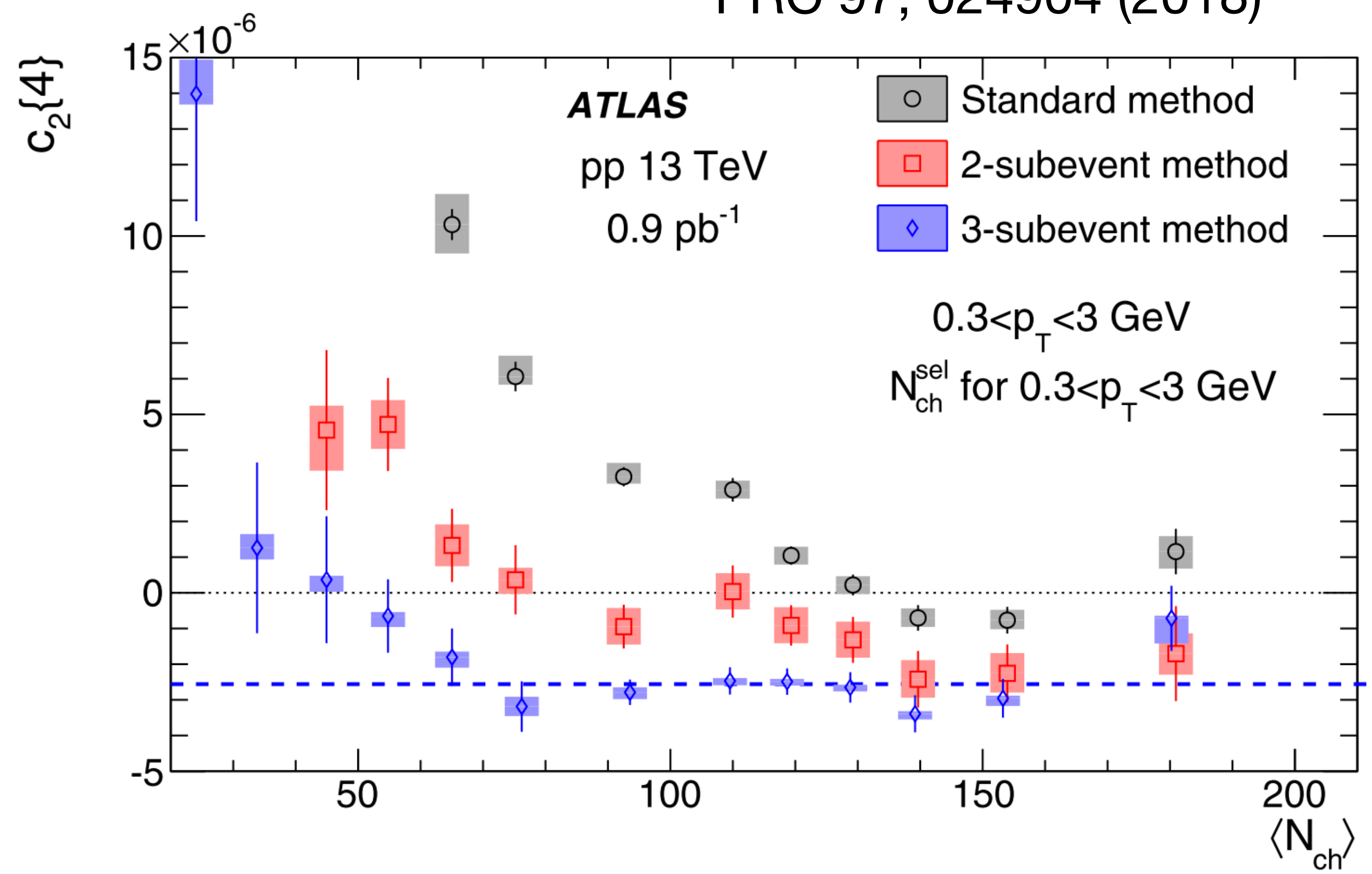
multi-particle correlation

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



- Significant decrease of $c_2\{4\}$ with subevent method
- Only with the 3-subevent method we are able to obtain a negative $c_2\{4\}$ in pp collisions
  - First such observation in ALICE *

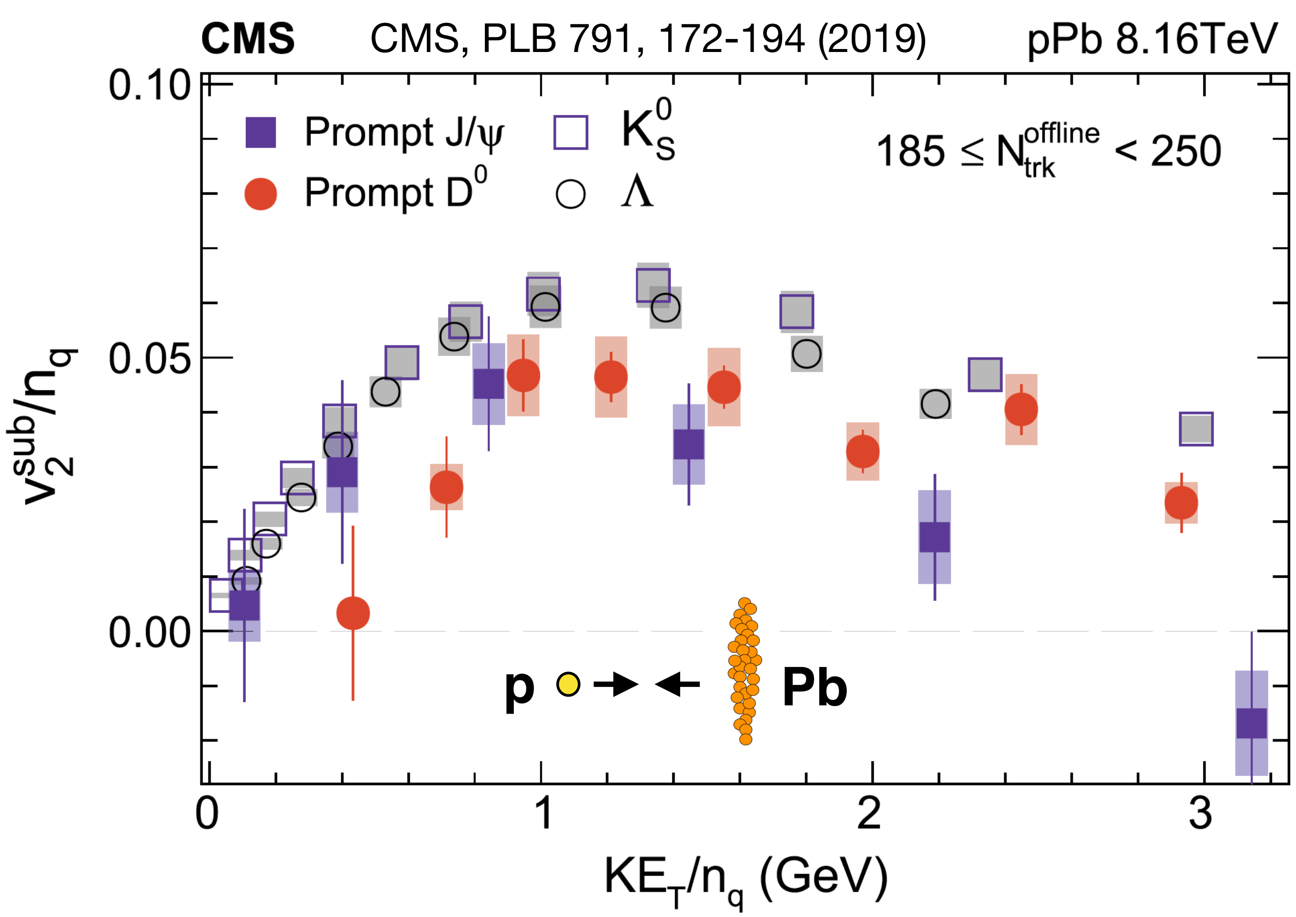
PRC 97, 024904 (2018)



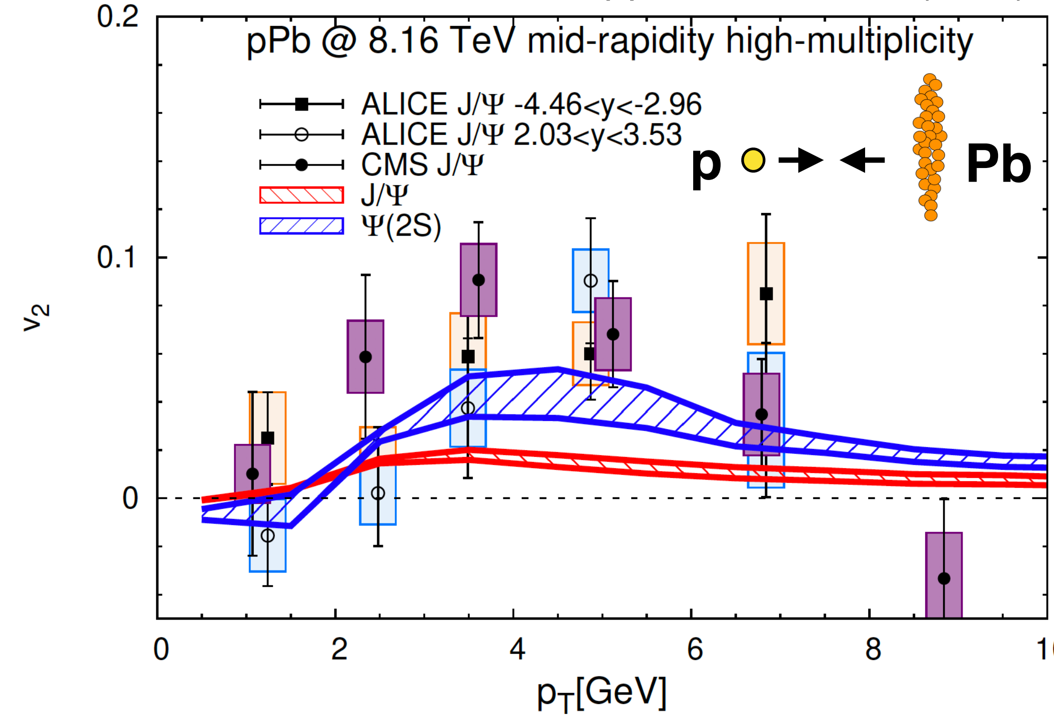
* Negative $c_2\{4\}$ also observed:
CMS: PLB 765, 193 (2017)
ATLAS: PRC 97, 024904 (2018)

Heavy flavor flow in small systems

IS model: Ch. Zhang, et al., PRL **122**, 172302 (2019)



X. Du, R. Rapp, JHEP03, 015 (2019)



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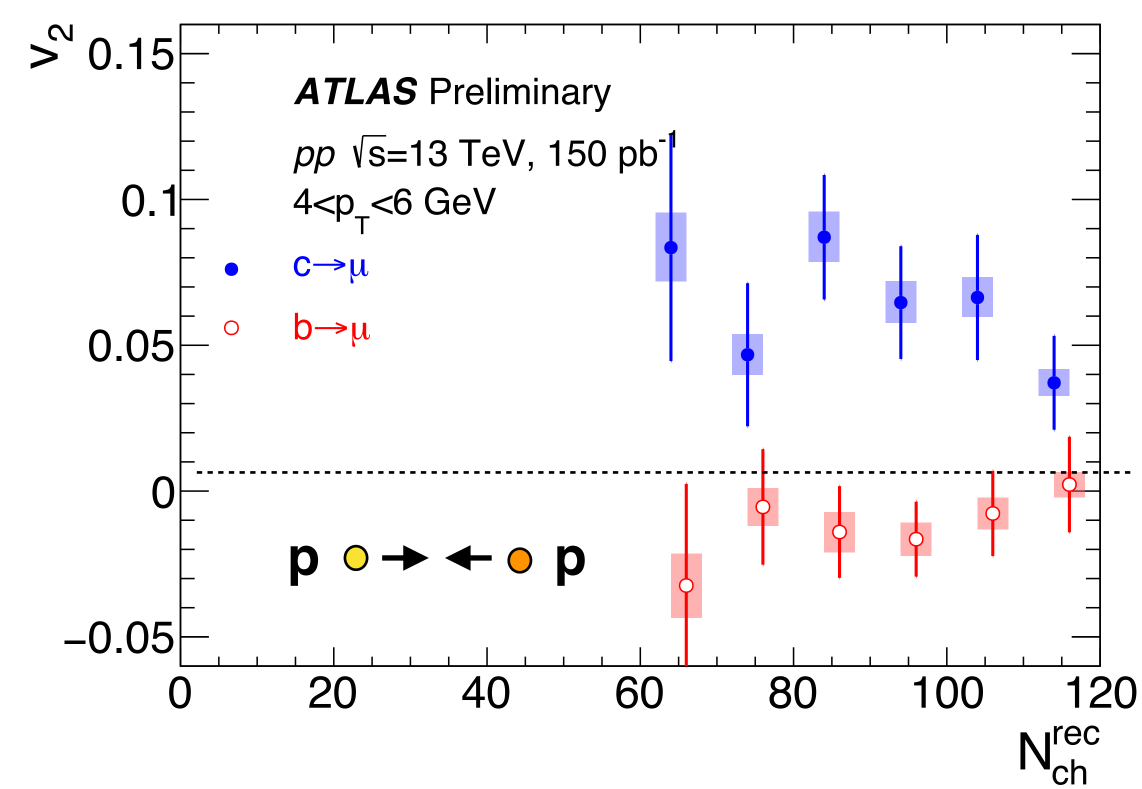


- Large v_2 of D and J/Ψ meson in p-Pb collisions

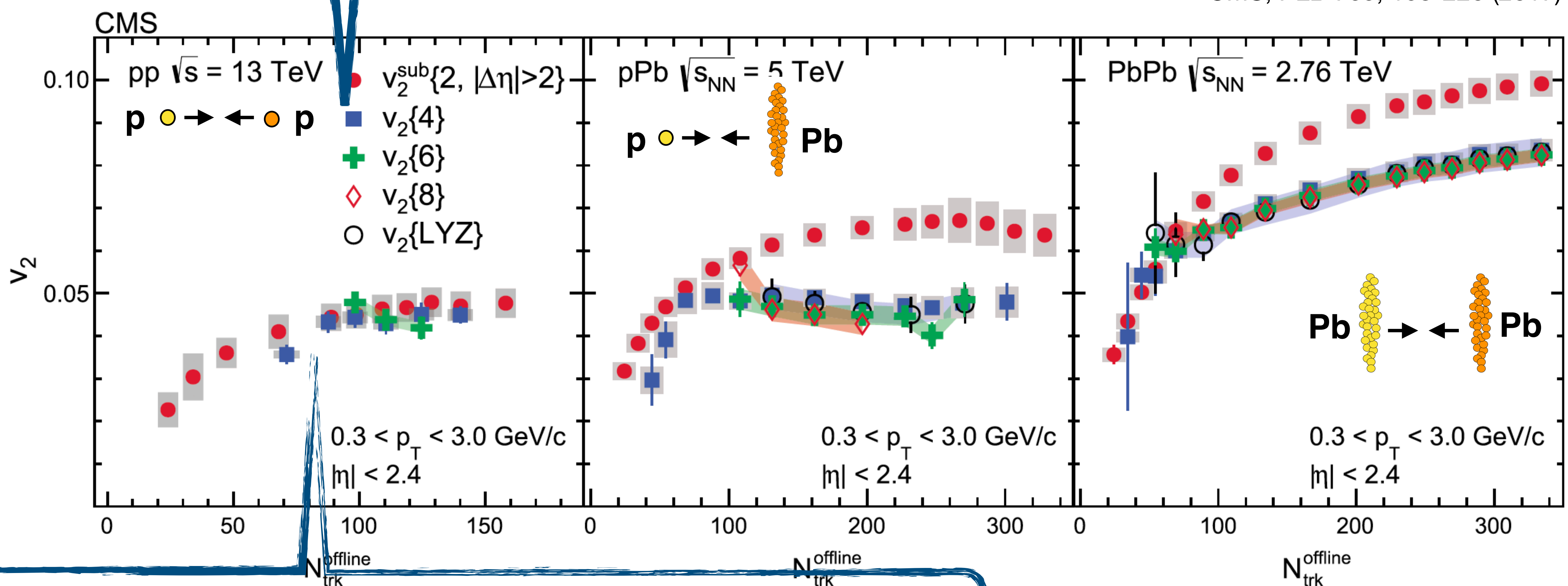
➡ **Cannot be explained only by final state interactions**

- **New**: charm still flows in pp collisions, but bottom doesn't (v_2 consisent with 0)

Collectivity down to pp collisions

Caveat: ATLAS & ALICE get “real” $v_2\{4\}$ in pp collisions only with the subevent method

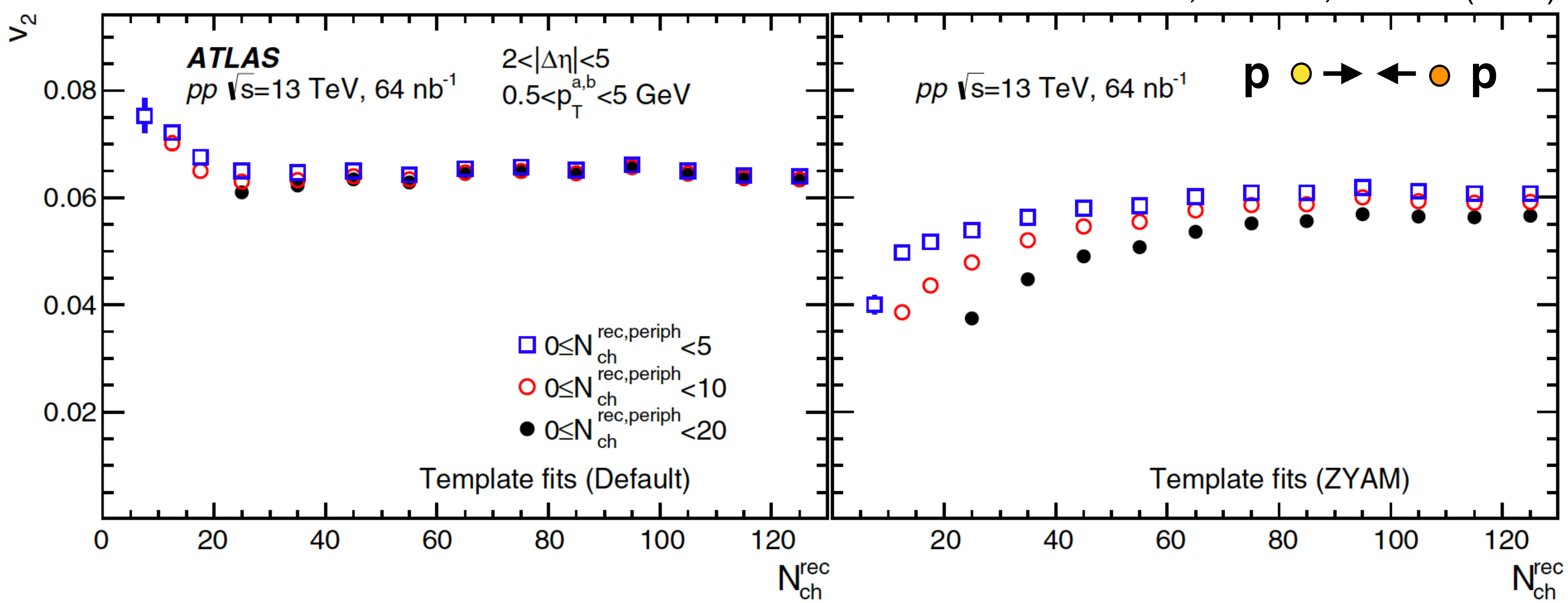
CMS, PLB 765, 193-220 (2017)



Caveat: How to understand $v_2\{2\} \approx v_2\{m\}$ in pp collisions?

Onset of collectivity ?

ATLAS, PRC **96**, 024908 (2017)

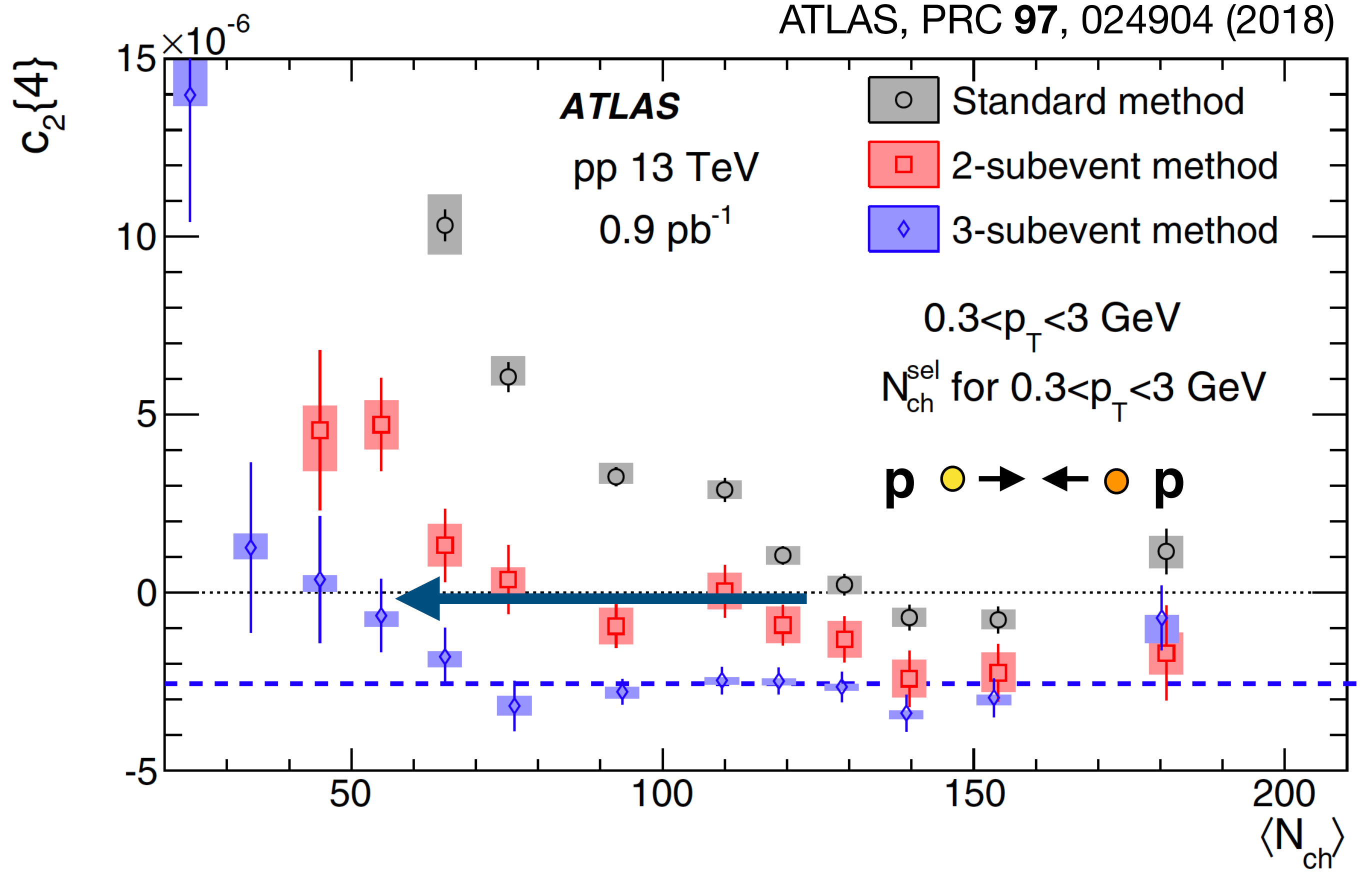


How low in multiplicity can we observe correlations?

(Onset of collectivity)

- Two-particle correlation down to N_{ch} (|η|<2.4) < 10 in pp collisions
- **Four-particle cumulant positive at low multiplicity** (N_{ch} (|η|<2.4) < 40)
  - Is that the onset of collectivity, or is it just non-flow?
  - Transition from positive to negative sign moves to lower multiplicities with the subevent method

ATLAS, PRC **97**, 024904 (2018)



What else?

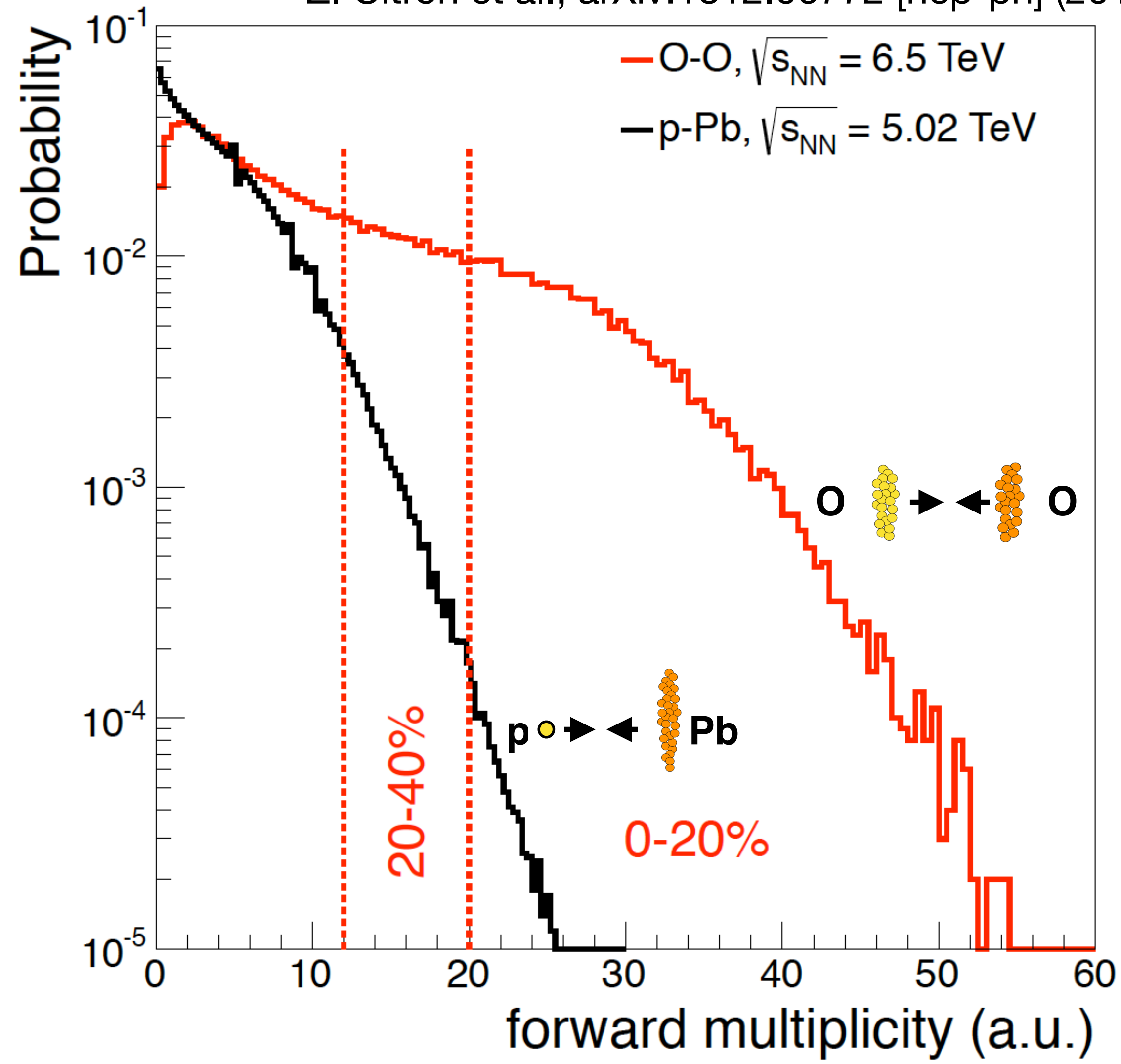
- **Scan of different collision systems?**
  - CuCu vs. AuAu @ RHIC
  - XeXe vs. PbPb @ LHC
  - Comparisons bring more information on the initial state

➡ Planned OO run @ LHC

- Similar multiplicities to p-Pb, but with well defined geometry
- Possible energy loss

➡ Need more such collisions to bridge the gap between small p(d)(^{3}He)-A and large AA collisions

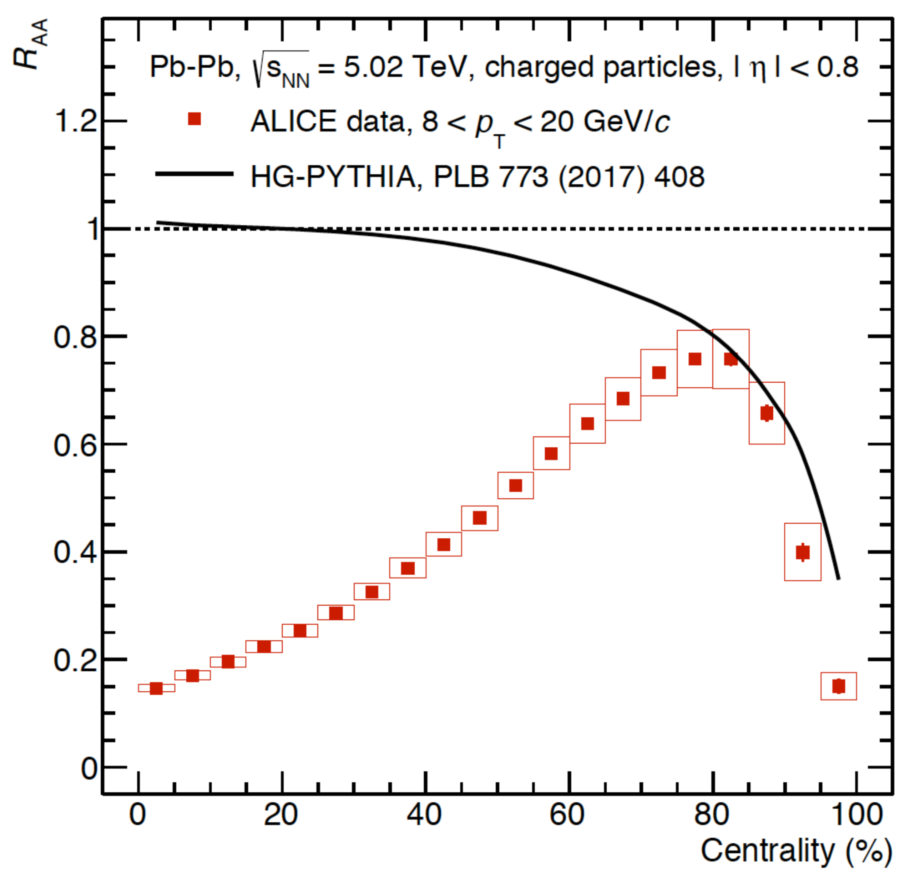
Z. Citron et al., arXiv:1812.06772 [hep-ph] (2018)



What else?

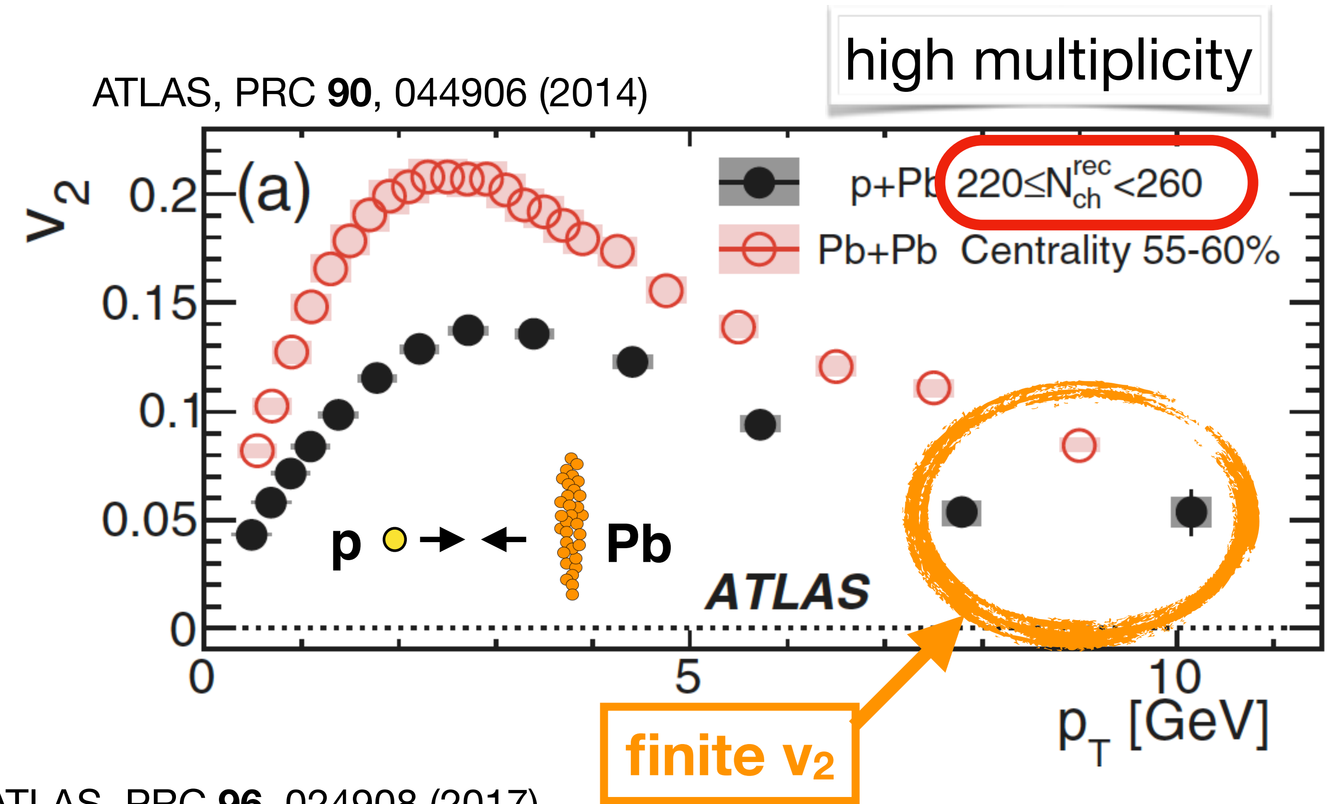
- **High-p_T flow**
  - Jet quenching not observed in pA collisions while it is seen in peripheral AA collisions
    - *Caveat*: selection bias

➡ Flow at high p_T not sensitive to such biases



ALICE, arXiv:1805.05212 [nucl-ex] (2018)

ATLAS, PRC **90**, 044906 (2014)



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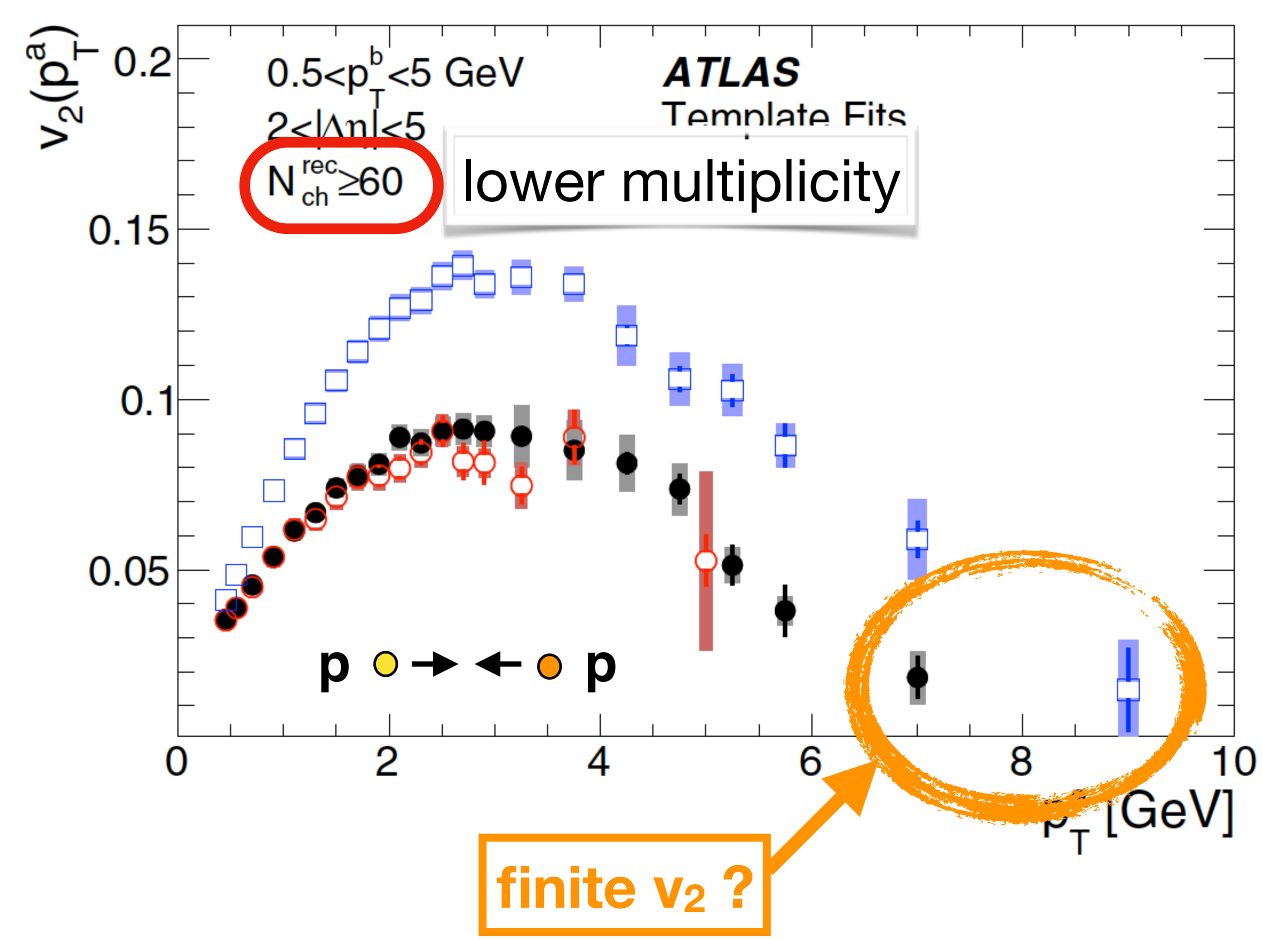
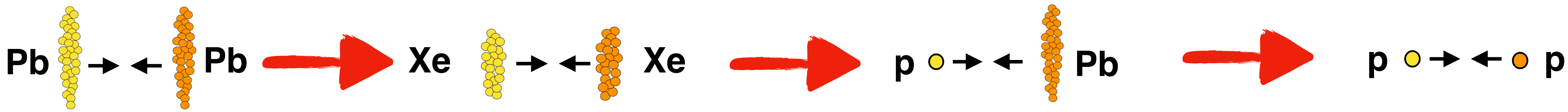
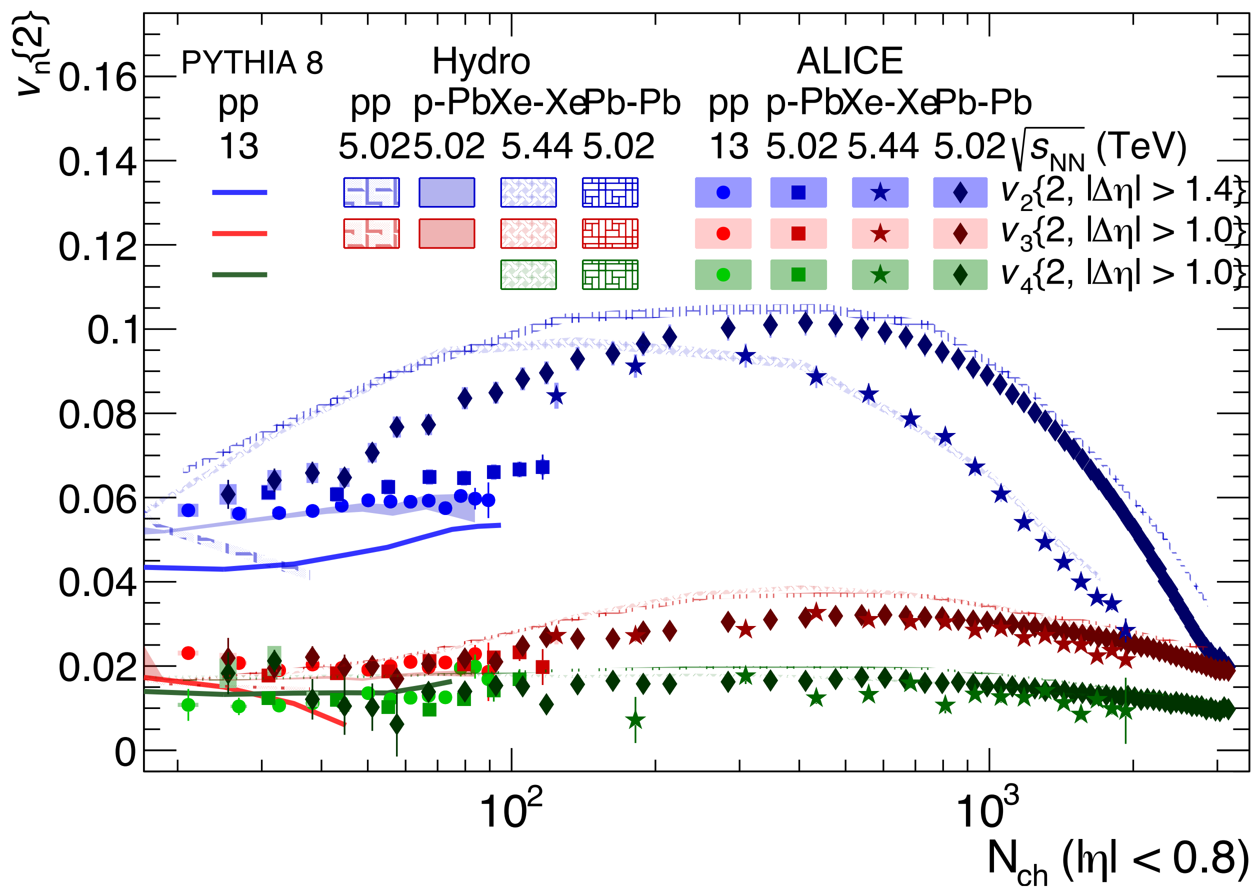
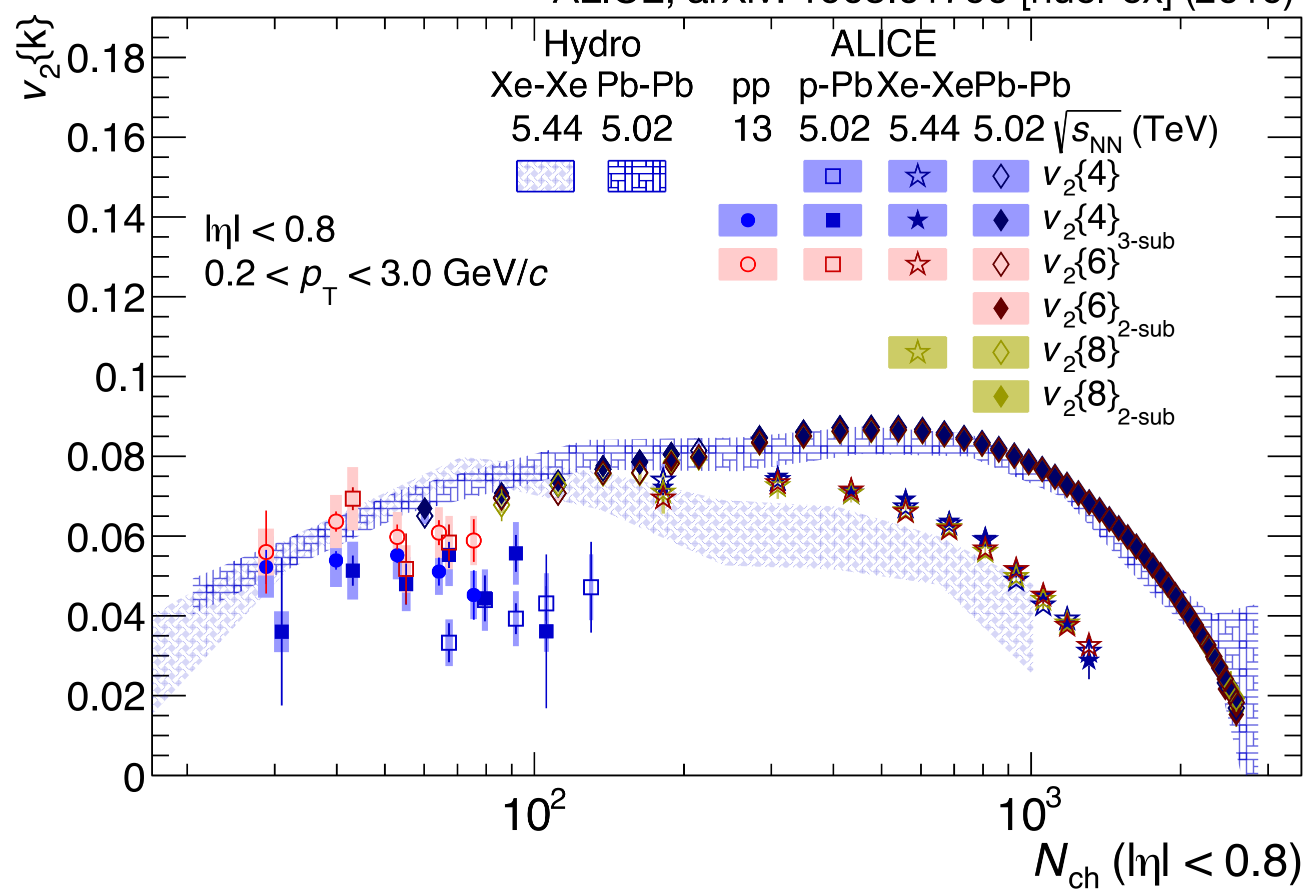


From large to low multiplicities & systems



ALICE, arXiv: 1903.01790 [nucl-ex] (2019)





small N_{ch} ← **large N_{ch}**　　**small N_{ch}** ← **large N_{ch}**

- Smooth transition from large to small multiplicity (large to small systems)