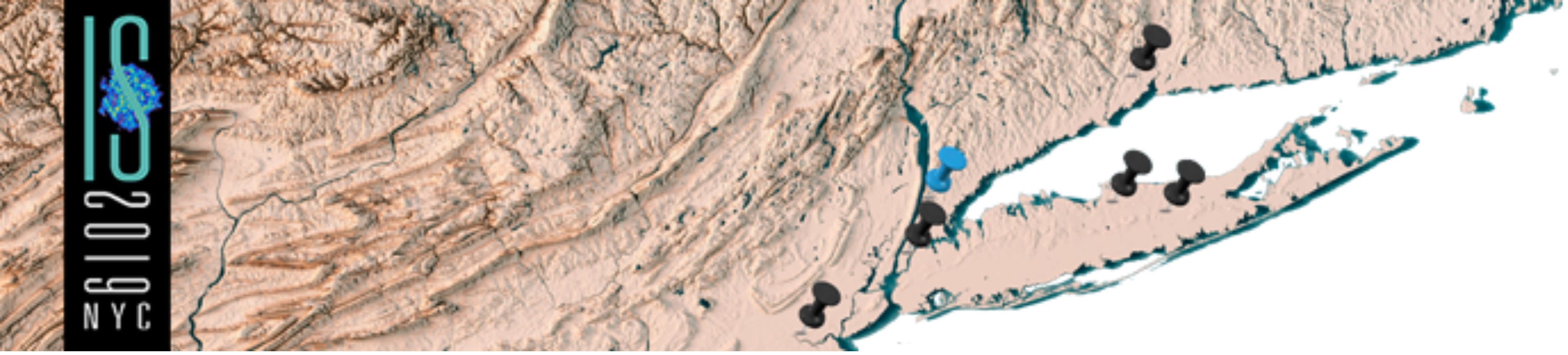



# Flow: small and large systems

## Experimental overview

Katarína Křížková Gajdošová
Czech Technical University in Prague
Faculty of Nuclear Sciences and Physical Engineering

Initial Stages, New York, USA
26.06.2019

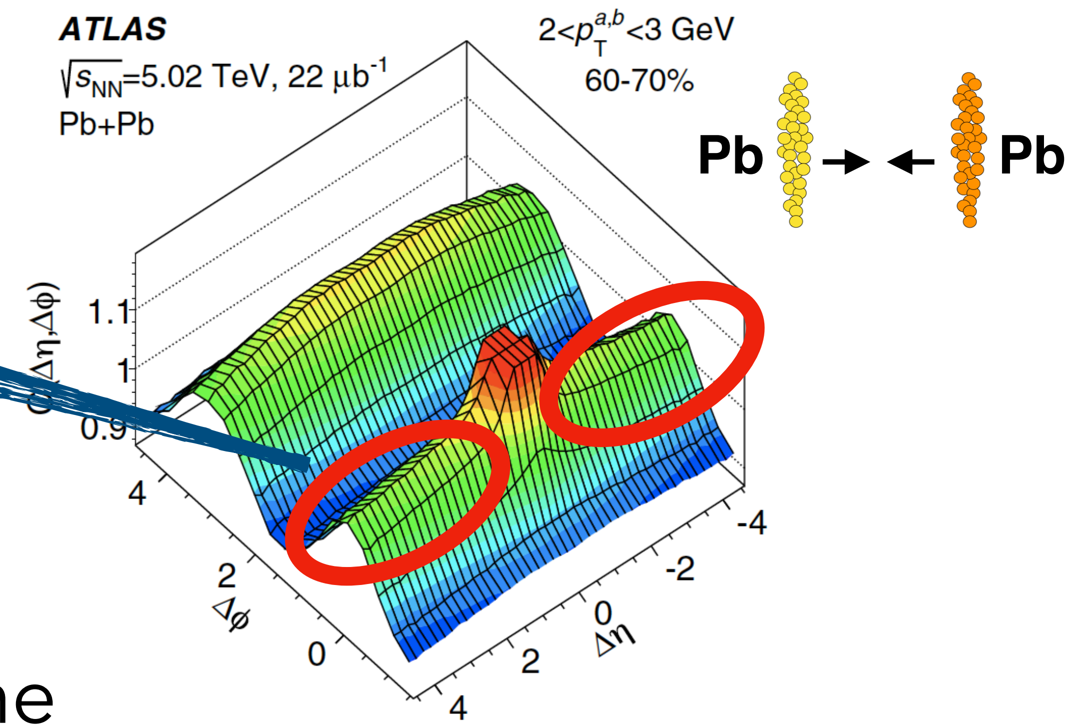
# Beginnings of collectivity in small systems

ATLAS, EPJC, 78:997 (2018)

## Large systems -> hydrodynamic flow

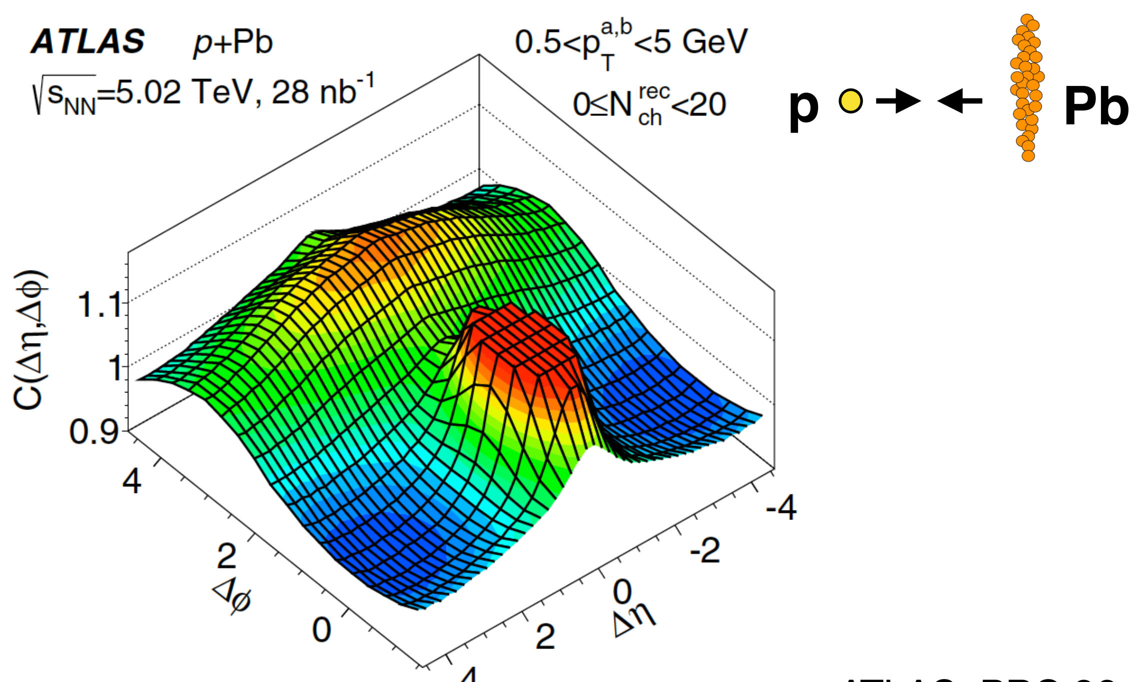
- Near-side ridge at $\Delta\Phi \approx 0$

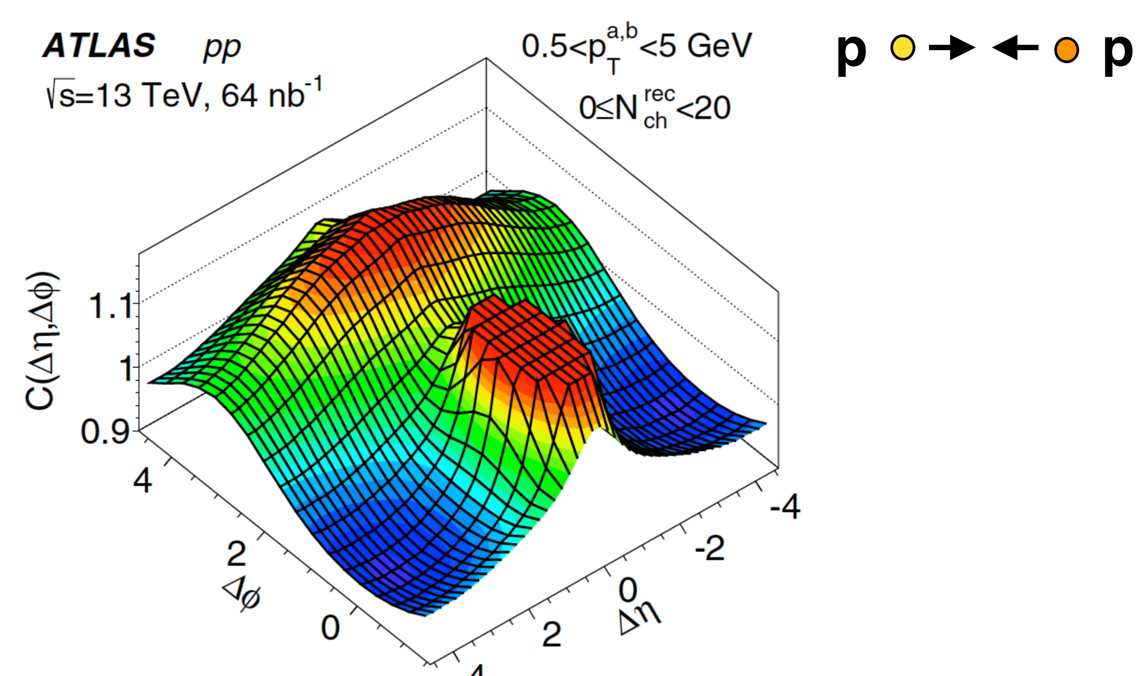
➡ Long-range correlations in η




## Small systems -> no flow … just a baseline

- No near-side ridge




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

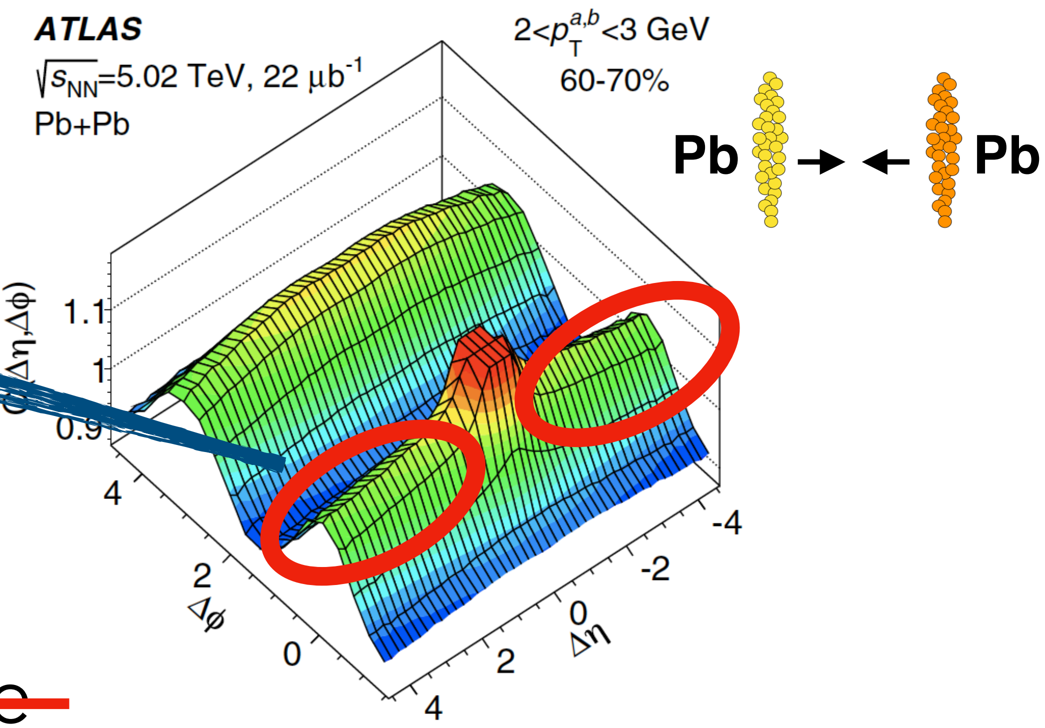
# Beginnings of collectivity in small systems

ATLAS, EPJC, 78:997 (2018)

**Large systems -> hydrodynamic flow**

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

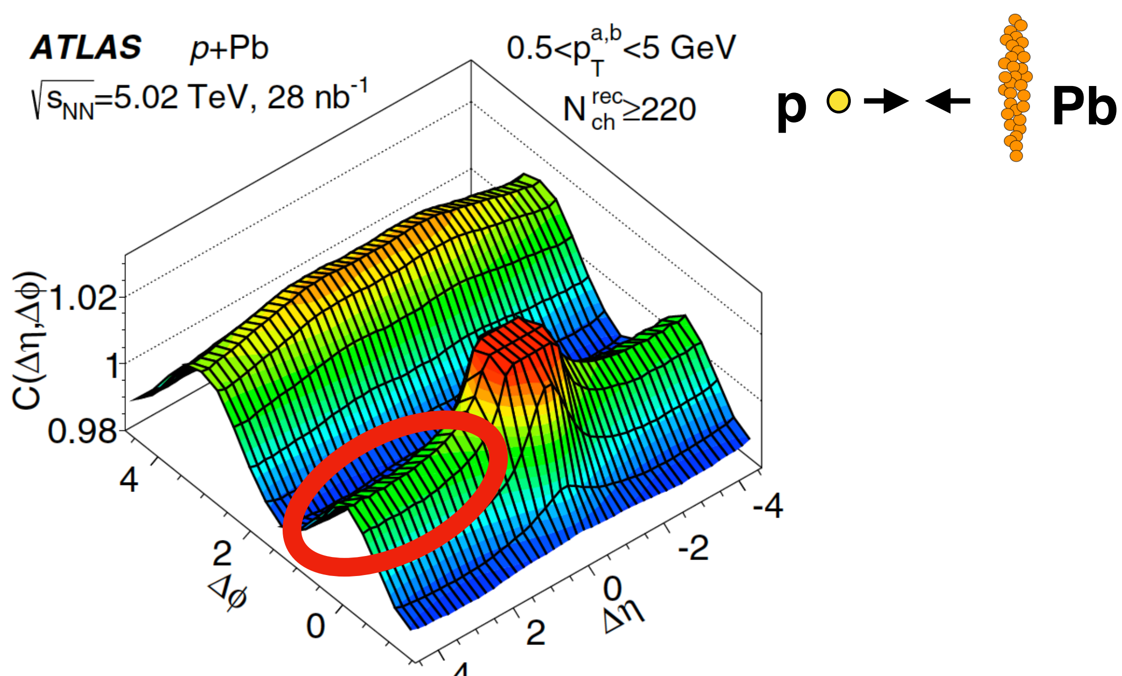
➡ Long-range correlations in $\eta$

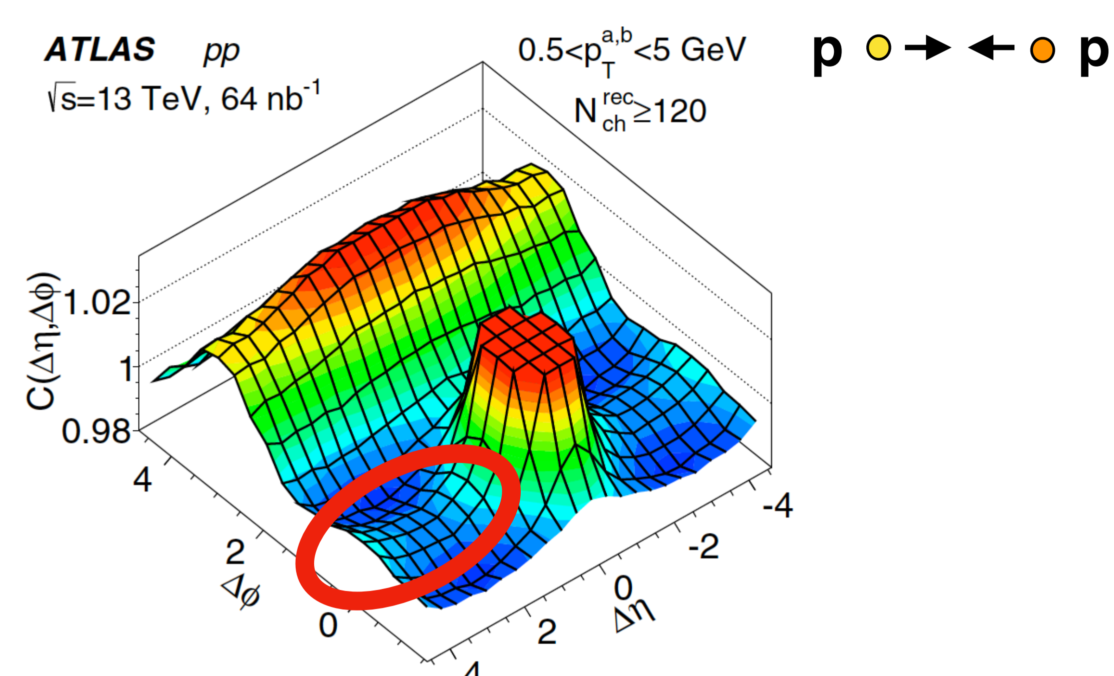



**High multiplicity**

**Small systems -> ~~no flow … just a baseline~~**

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

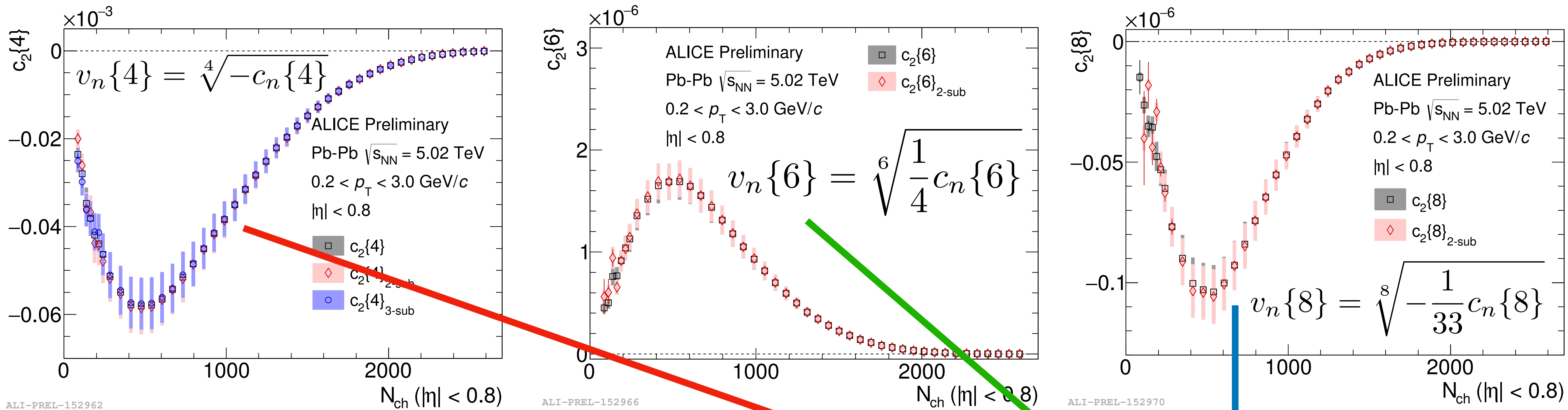


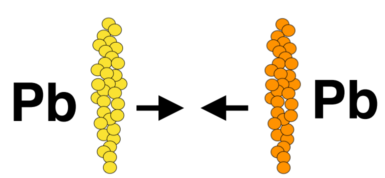



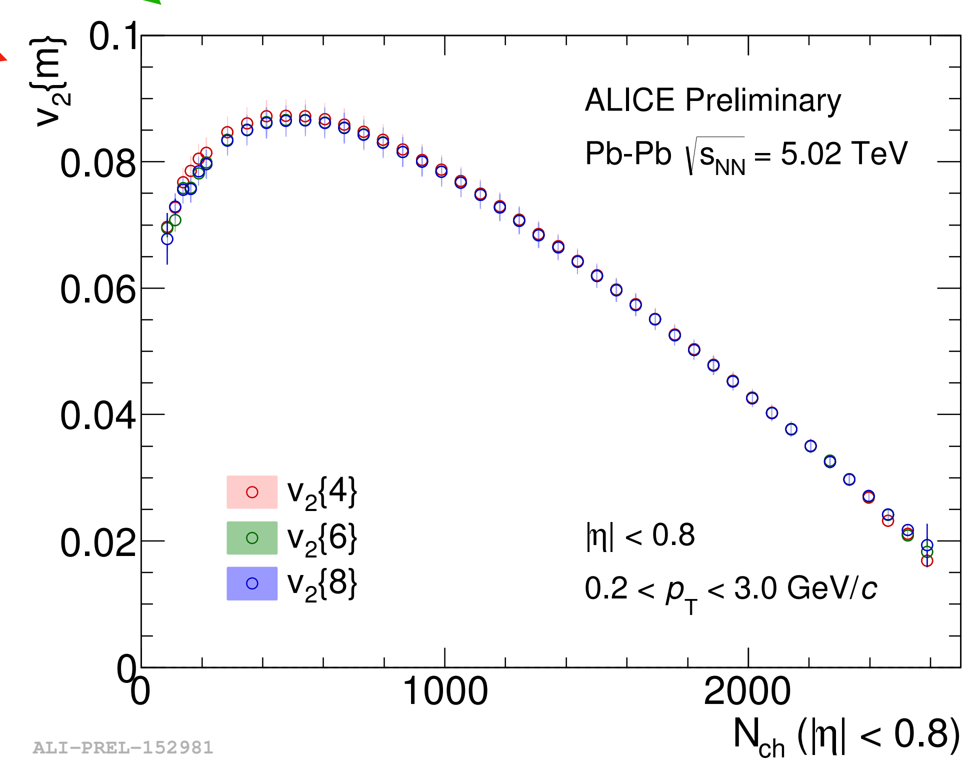

ATLAS, PRC **96**, 024908 (2017)

# 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



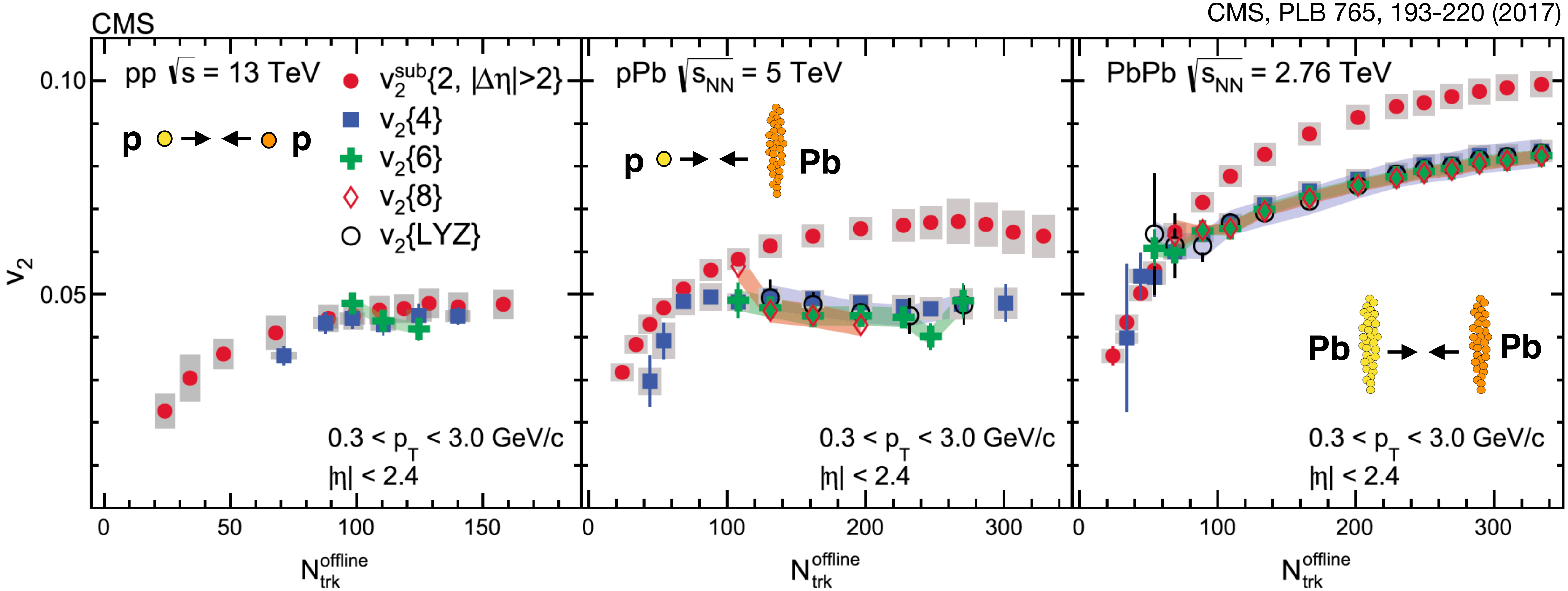




- Long-range multi-particle correlations
  - $v_n\{m\} \approx v_n\{m\}_{subevent}$
  - $v_n\{4\} \approx v_n\{6\} \approx v_n\{8\}$

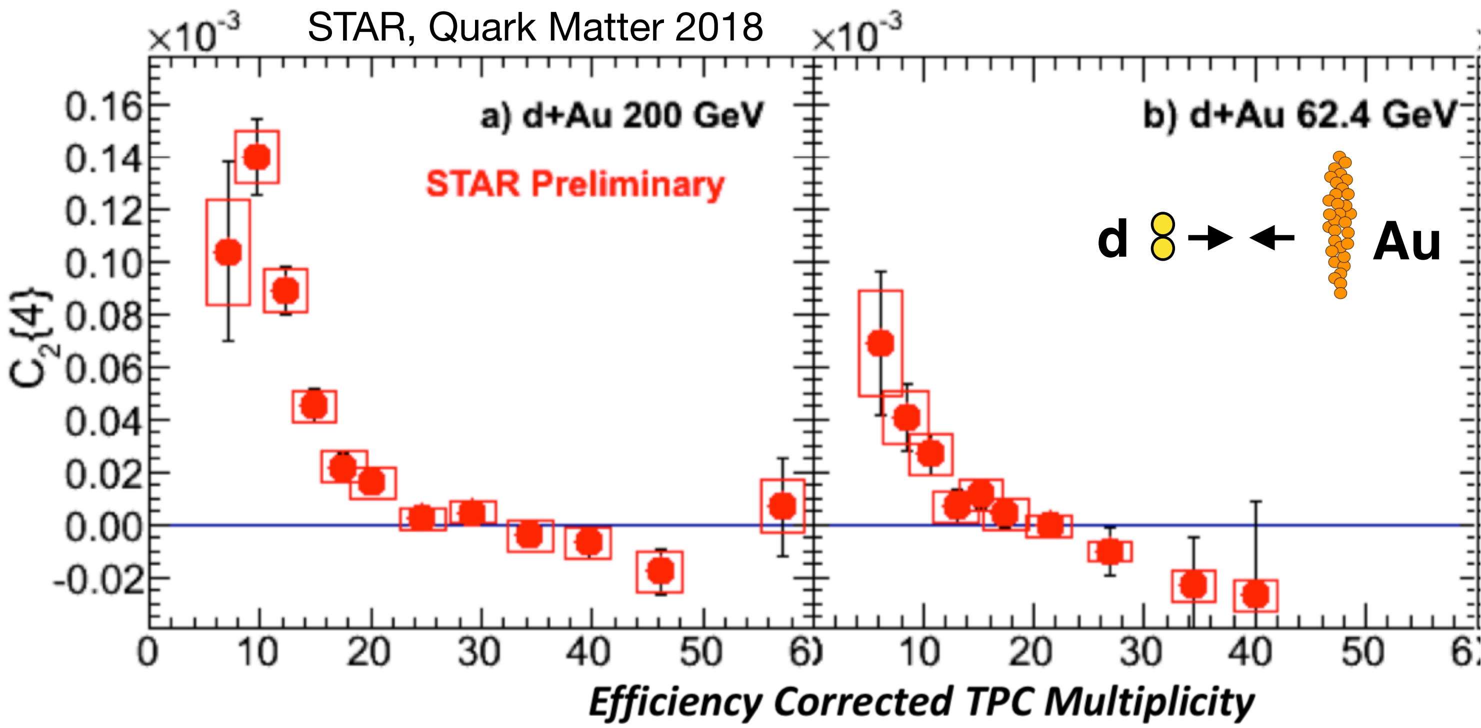
# Collectivity down to pp collisions

CMS, PLB 765, 193-220 (2017)




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

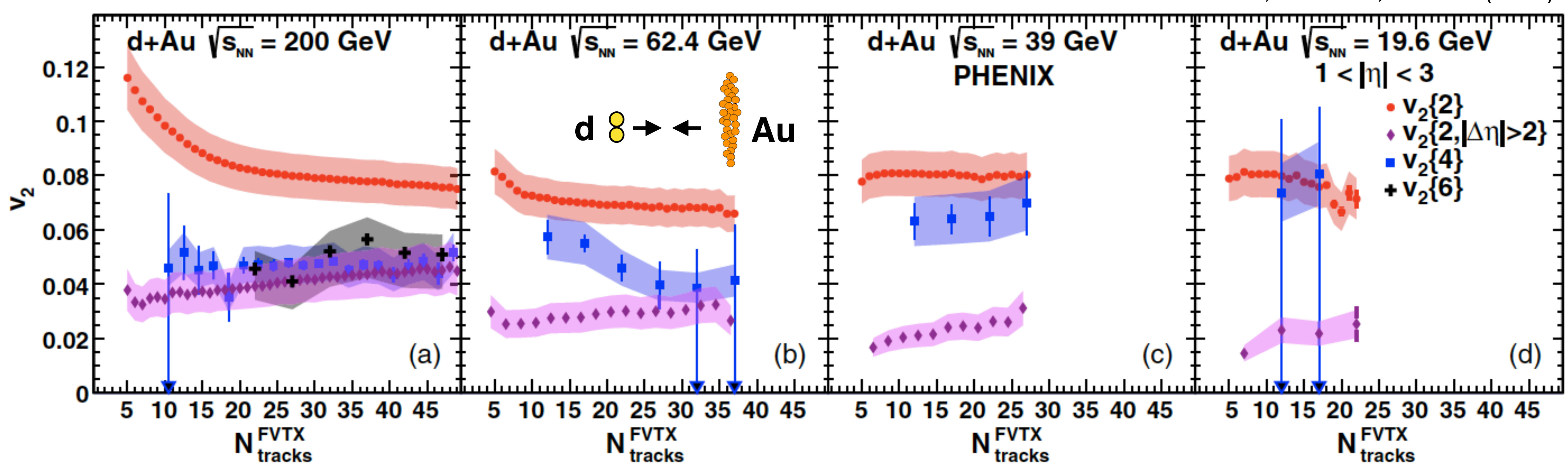
# From large to small energies




**Collectivity observed at RHIC**

- STAR: $c_2\{4\}$ negative in d-Au at 200 GeV and 62.4 GeV

PHENIX, PRL 120, 062302 (2018)




- PHENIX: $v_2\{4\}$ observed in d-Au down to energy 19.6 GeV

Wednesday @16:50, Qiao Xu (PHENIX)

# What is the origin of collectivity ?

## Initial State (IS)

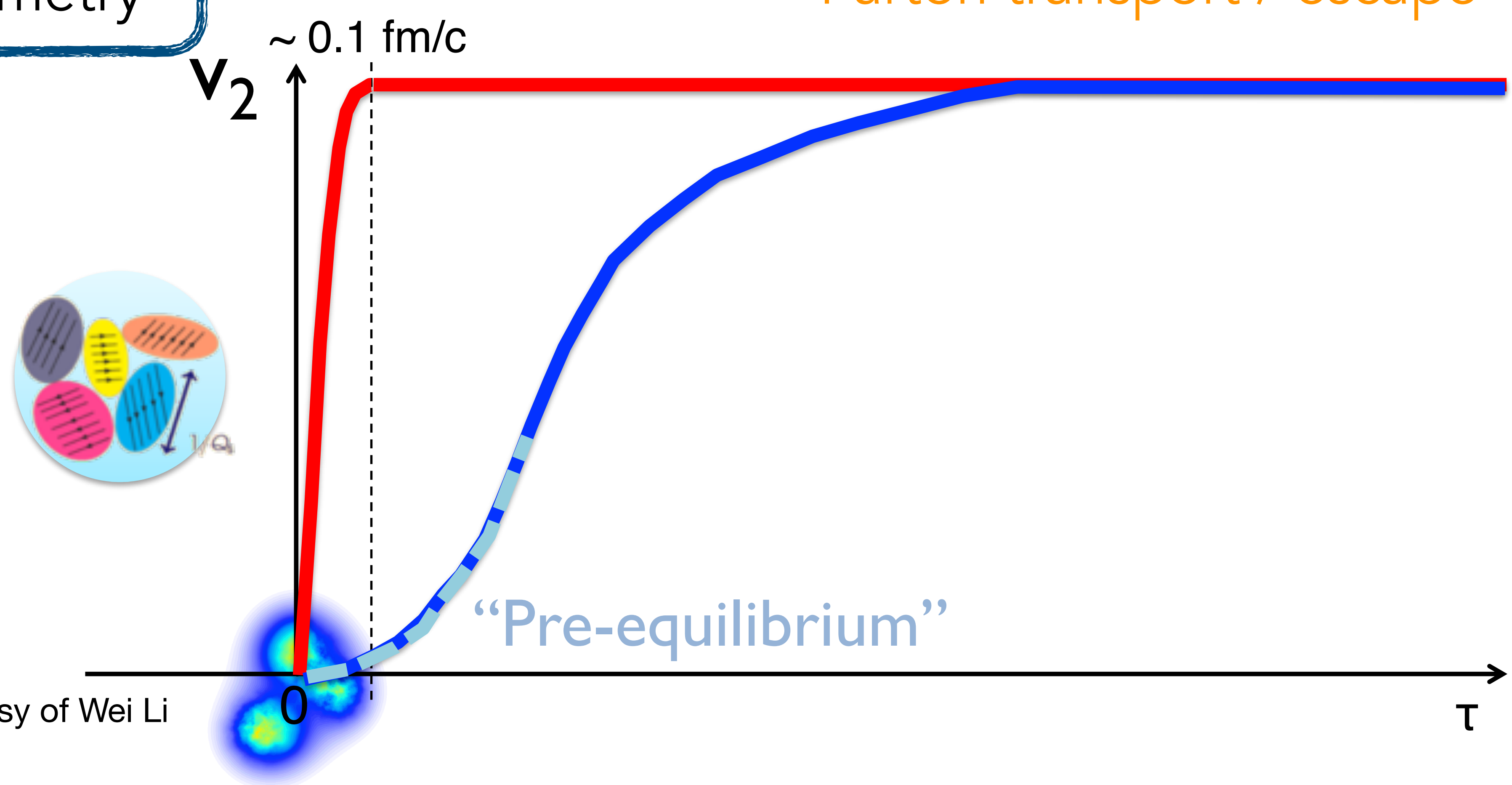
- Initial momentum correlations
- CGC

Not correlated to initial geometry

## Final State (FS)

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

Correlated to initial geometry




Courtesy of Wei Li

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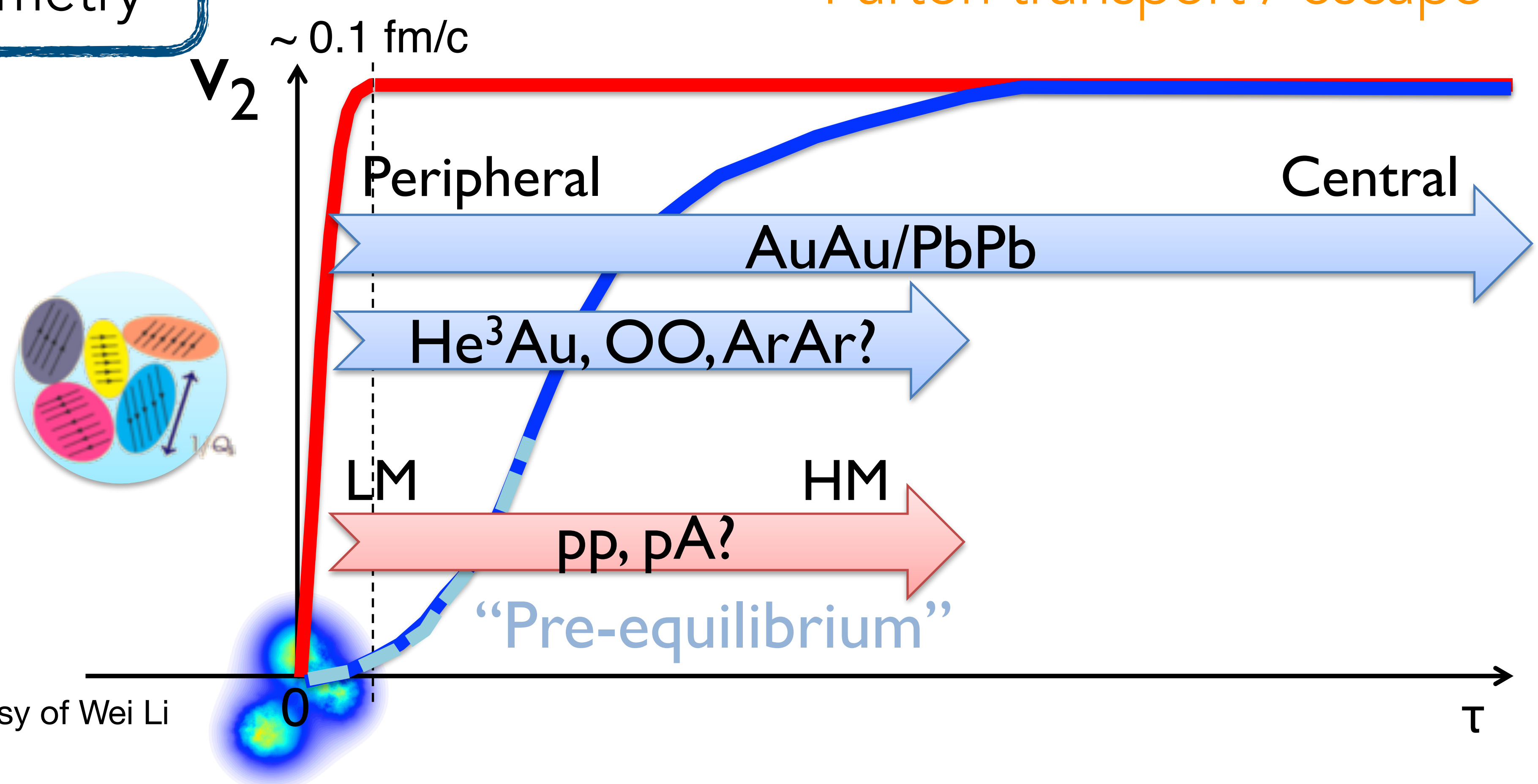
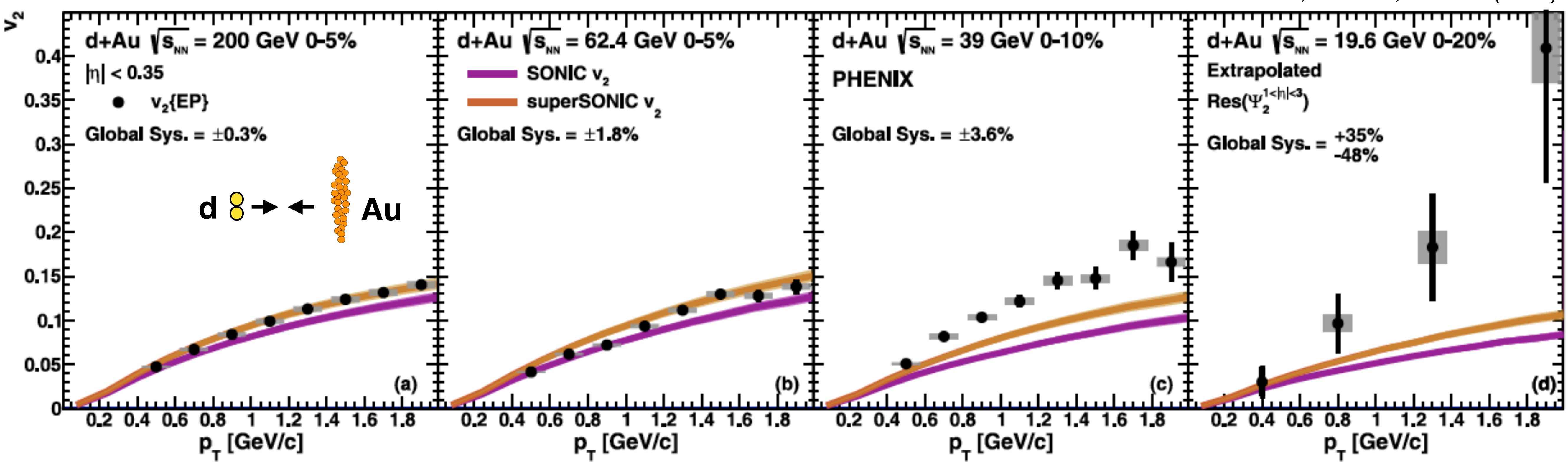



Courtesy of Wei Li

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

# Energy scan of small systems

PHENIX, PRC 96, 064905 (2017)

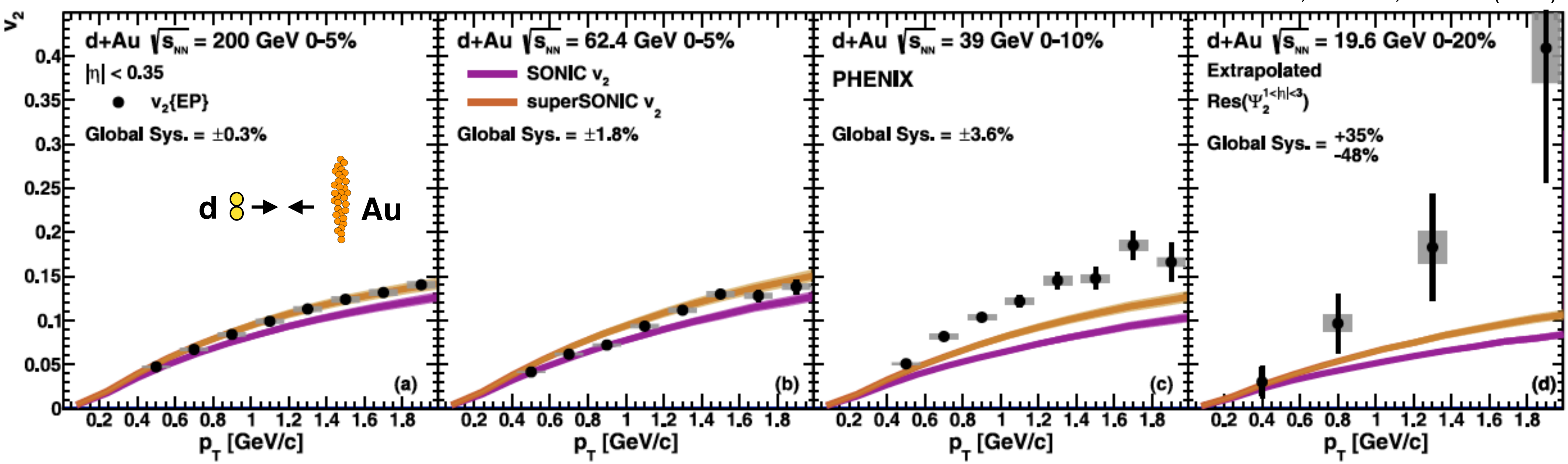



- Results of $v_2$ in d+Au collisions **reproduced by hydrodynamics** at energies 200 GeV and 62.4 GeV

# Energy scan of small systems

0 IS : FS 1

PHENIX, PRC 96, 064905 (2017)

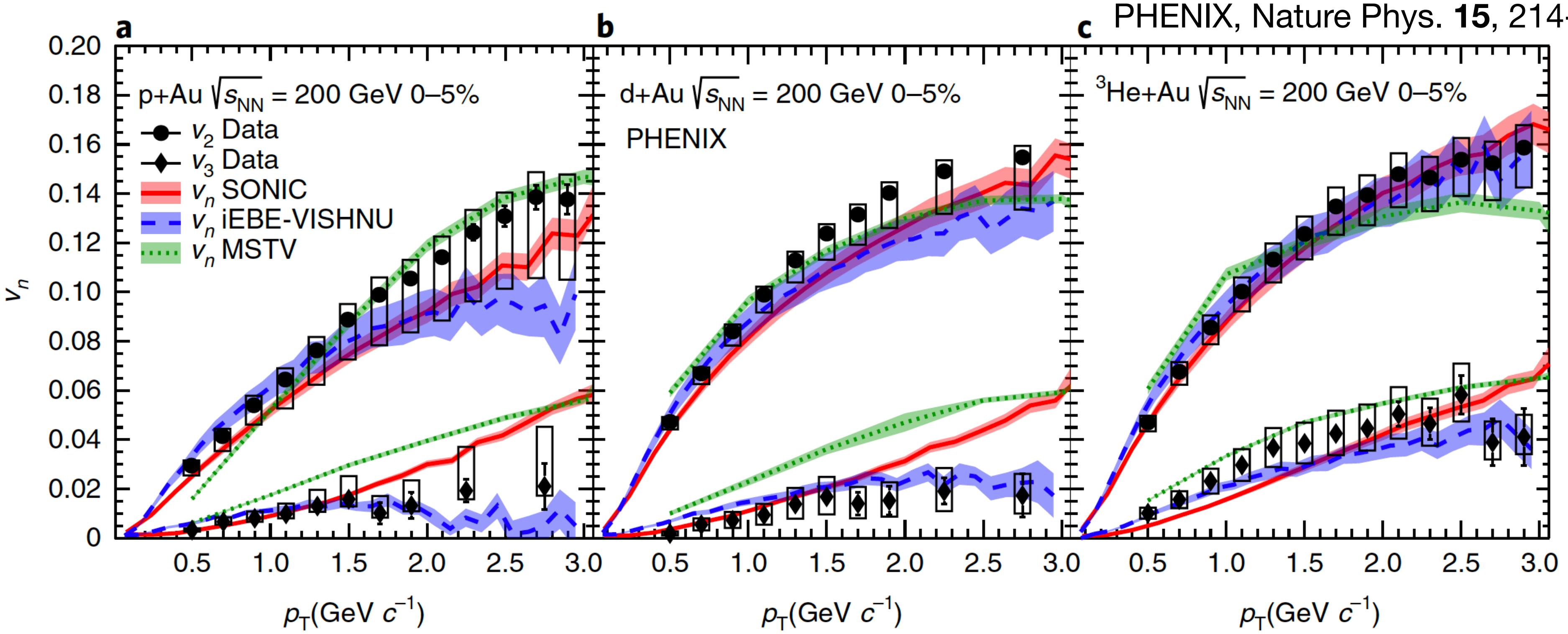


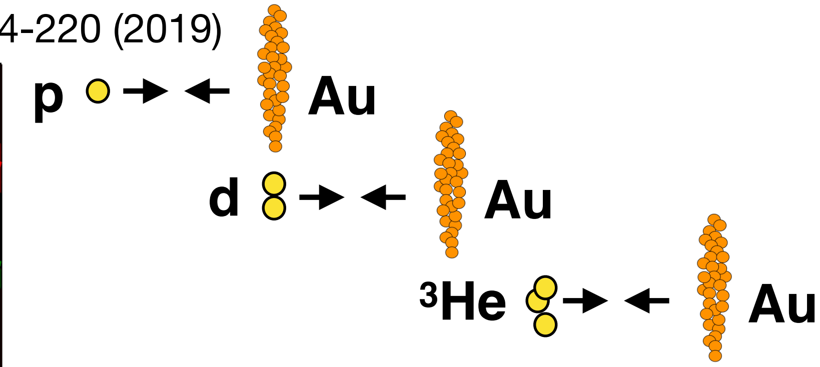

- Results of $v_2$ in d+Au collisions **reproduced by hydrodynamics** at energies 200 GeV and 62.4 GeV

# Geometry driven anisotropy

**0 IS : FS 2**

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




**$v_2$ (p+Au) < $v_2$ (d+Au) ~ $v_2$ ($^3$He+Au)**

**$v_3$ (p+Au) ~ $v_3$ (d+Au) < $v_2$ ($^3$He+Au)**

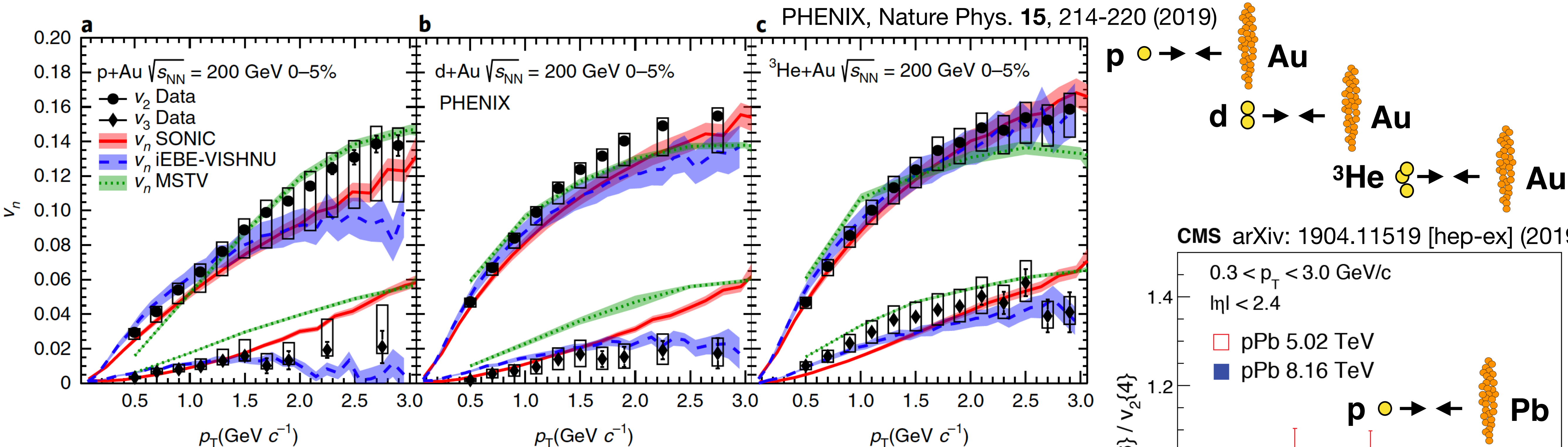
- Within a hydrodynamic picture: $v_n \sim k_n \varepsilon_n$
- PHENIX: data **consistent with hydrodynamics**

**Wednesday @16:50, Qiao Xu (PHENIX)**

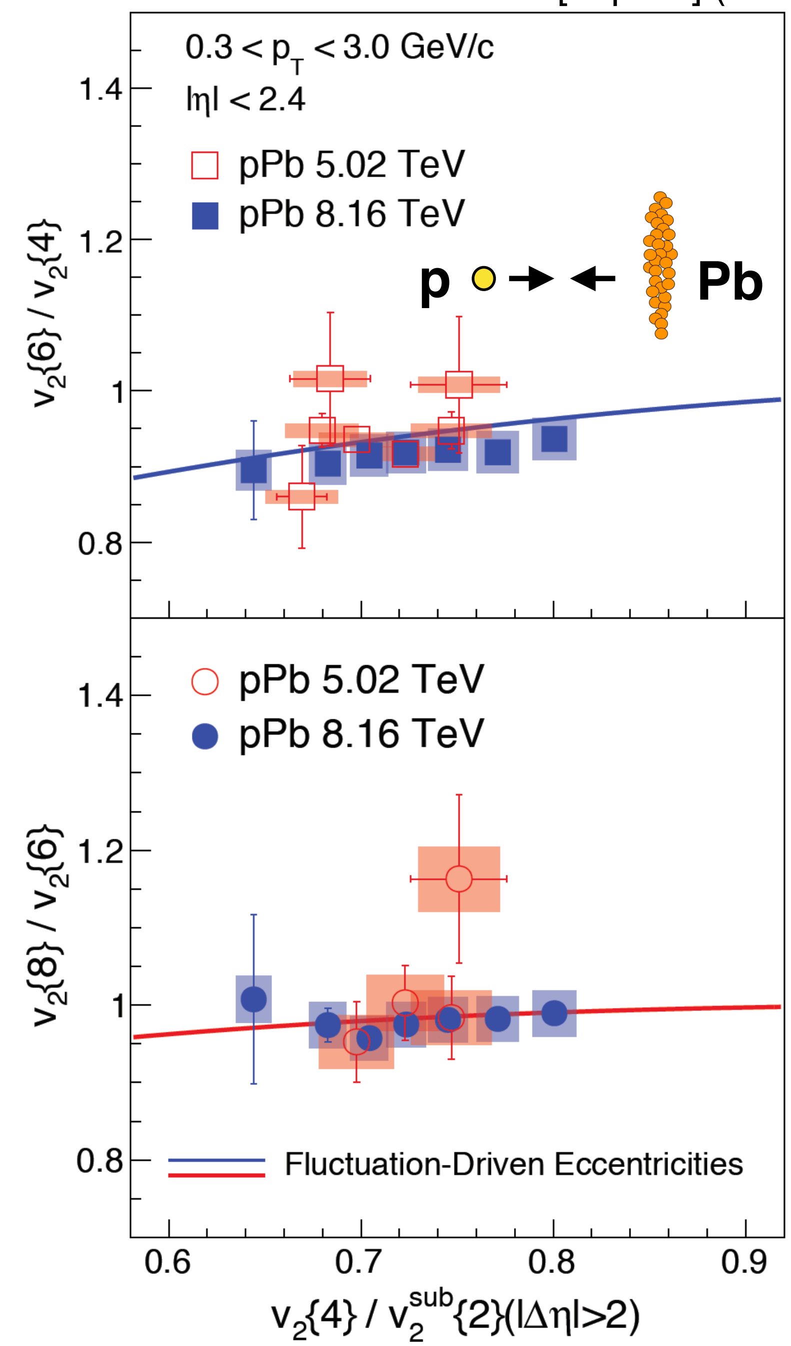
# Geometry driven anisotropy

**0 IS : FS 3**

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




CMS arXiv: 1904.11519 [hep-ex] (2019)




**$v_2$ (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**
- CMS: ratios of multi-particle cumulants are **consistent with geometry driven assumption**

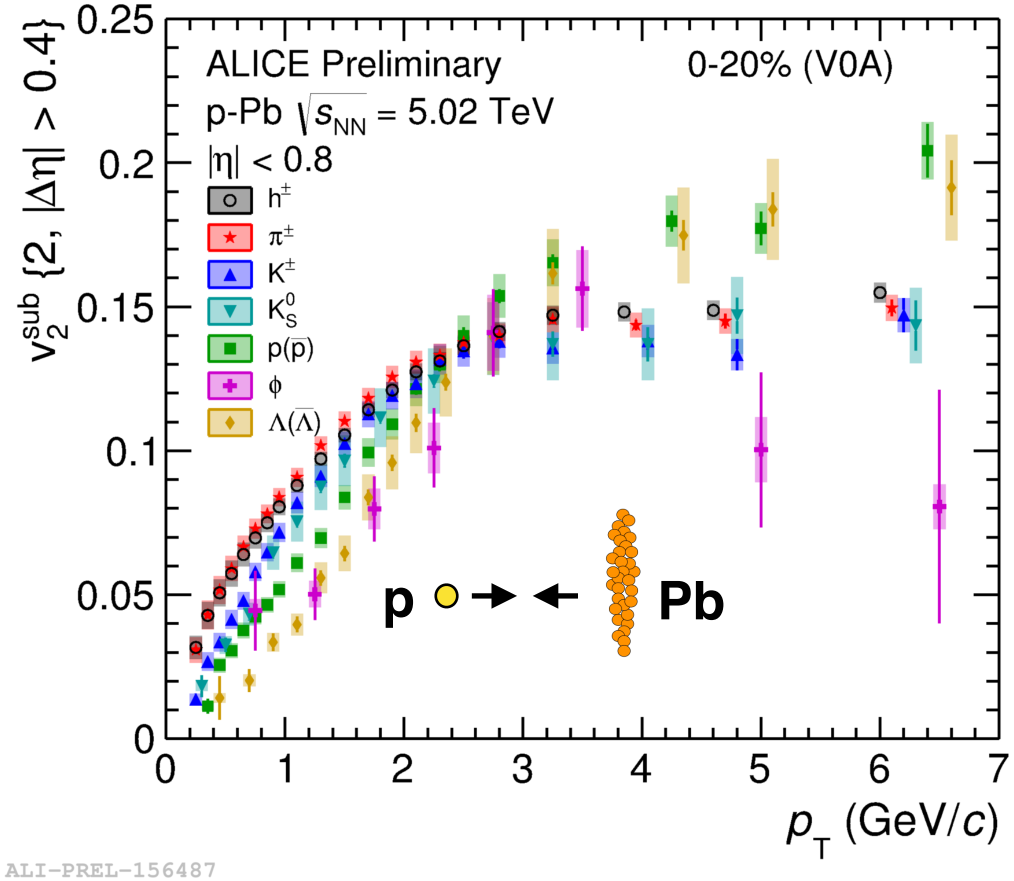
**Wednesday @16:50, Qiao Xu (PHENIX)**

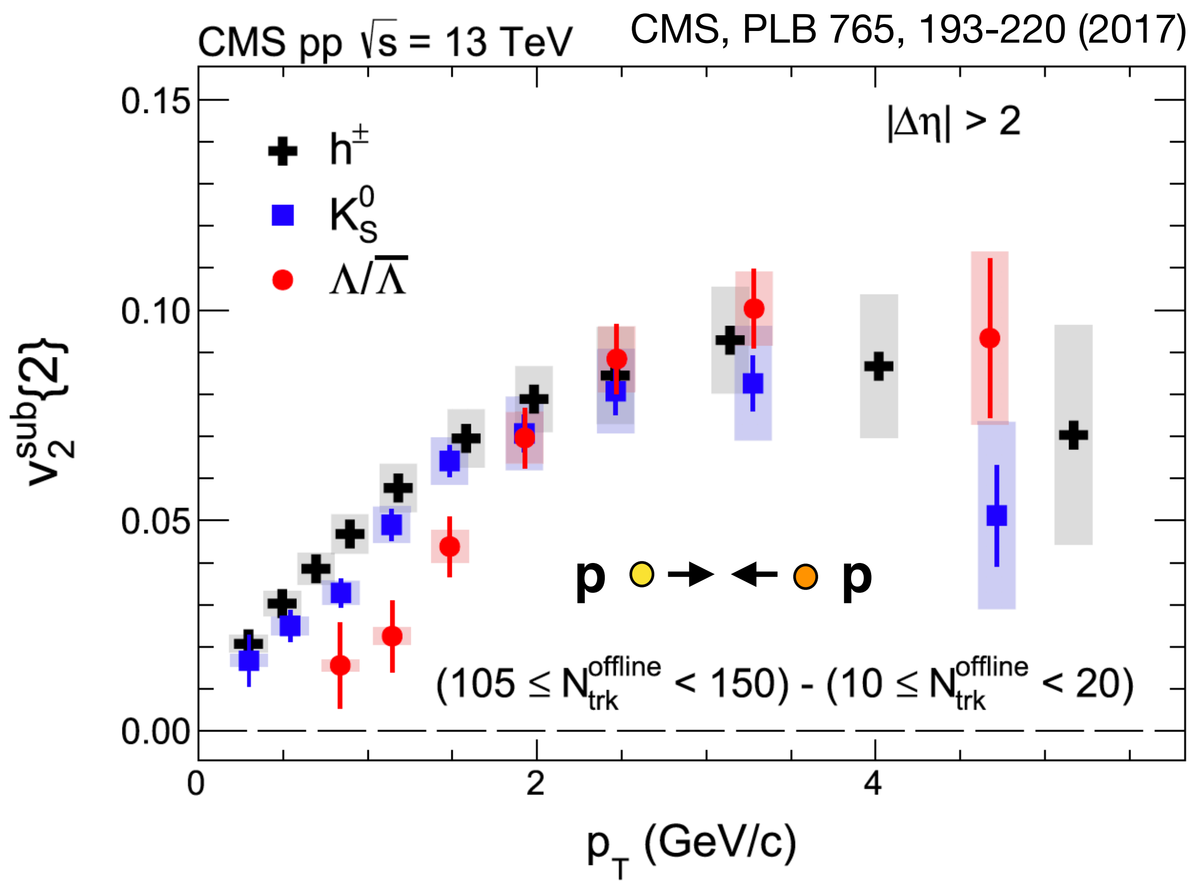
**Wednesday @16:30, Shengquan Tuo (CMS)**

# Identified particle $v_n$ @ LHC

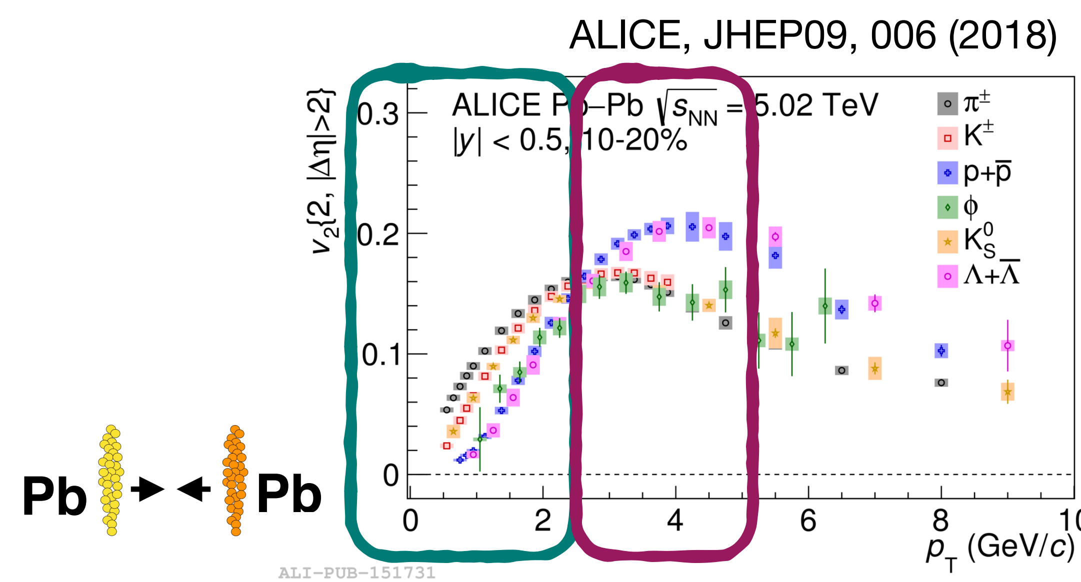
0 IS : FS 4

Wednesday @15:20, Vojtech Pacik (ALICE)



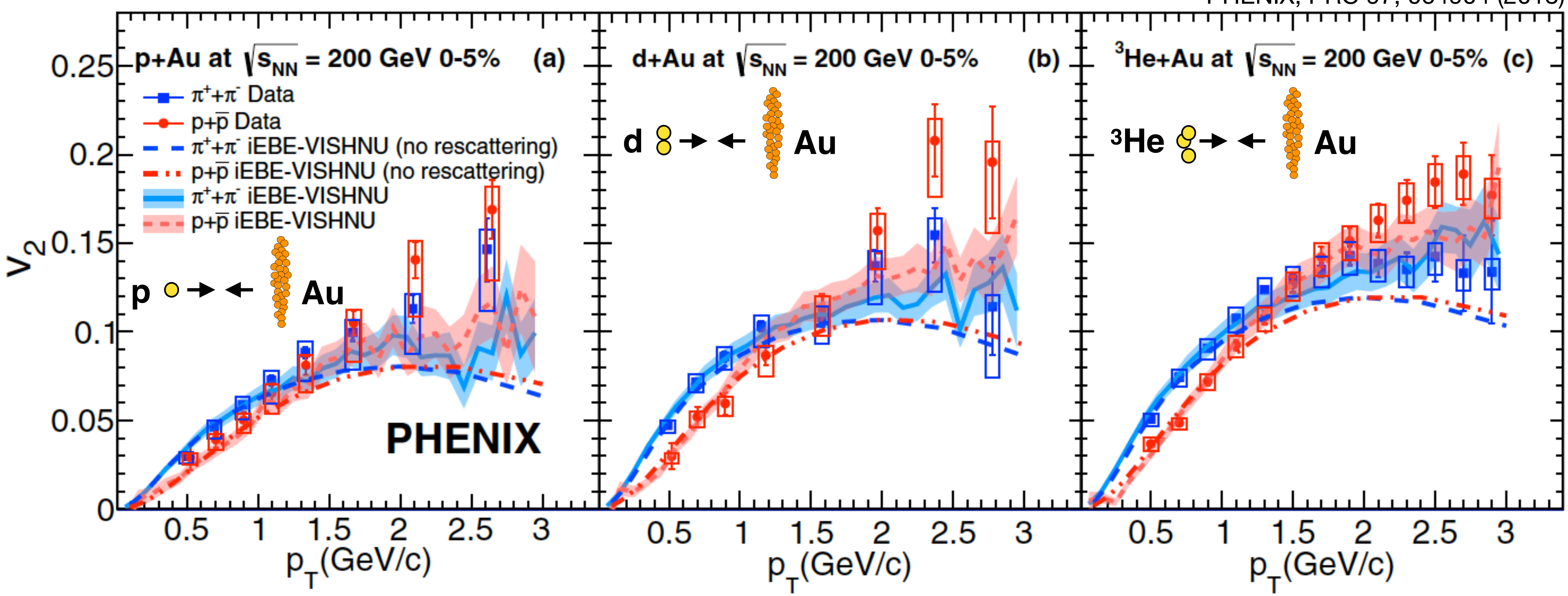

- Mass ordering at low $p_T$
  - Hydrodynamic flow
- Baryon-meson grouping at intermediate $p_T$
  - Partonic collectivity, coalescence
- Results from pPb and pp collisions **similar to large systems**



# Identified particle $v_n$ @ RHIC

0 IS : FS 5

PHENIX, PRC 97, 064904 (2018)




- Mass ordering at low $p_T$ in d+Au and $^3$He+Au, a hint in p+Au
- **Described by hydrodynamics**

# What is the origin of collectivity ?

## Initial State (IS)

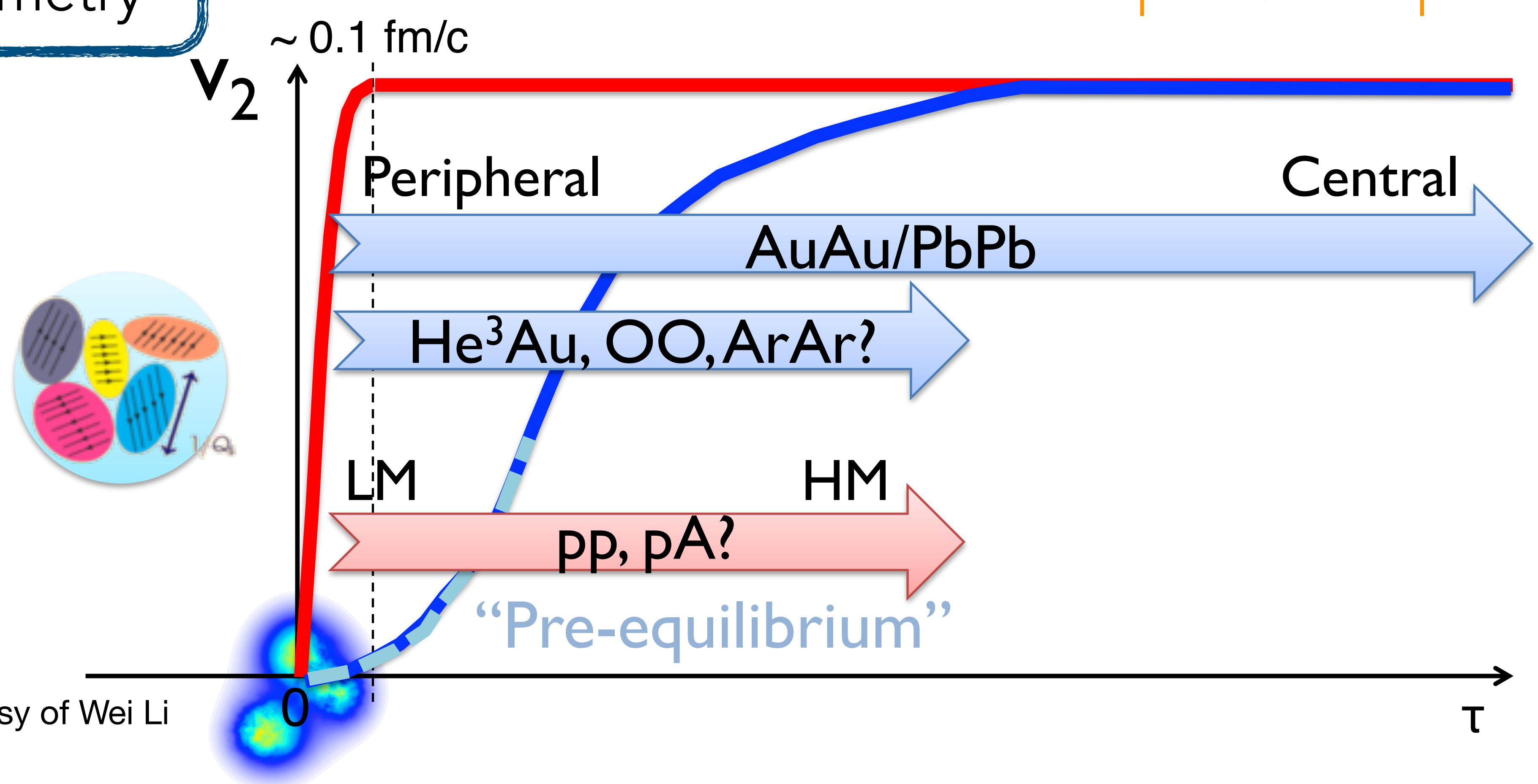
- Initial momentum correlations
- CGC

Not correlated to initial geometry

## Final State (FS)

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

Correlated to initial geometry



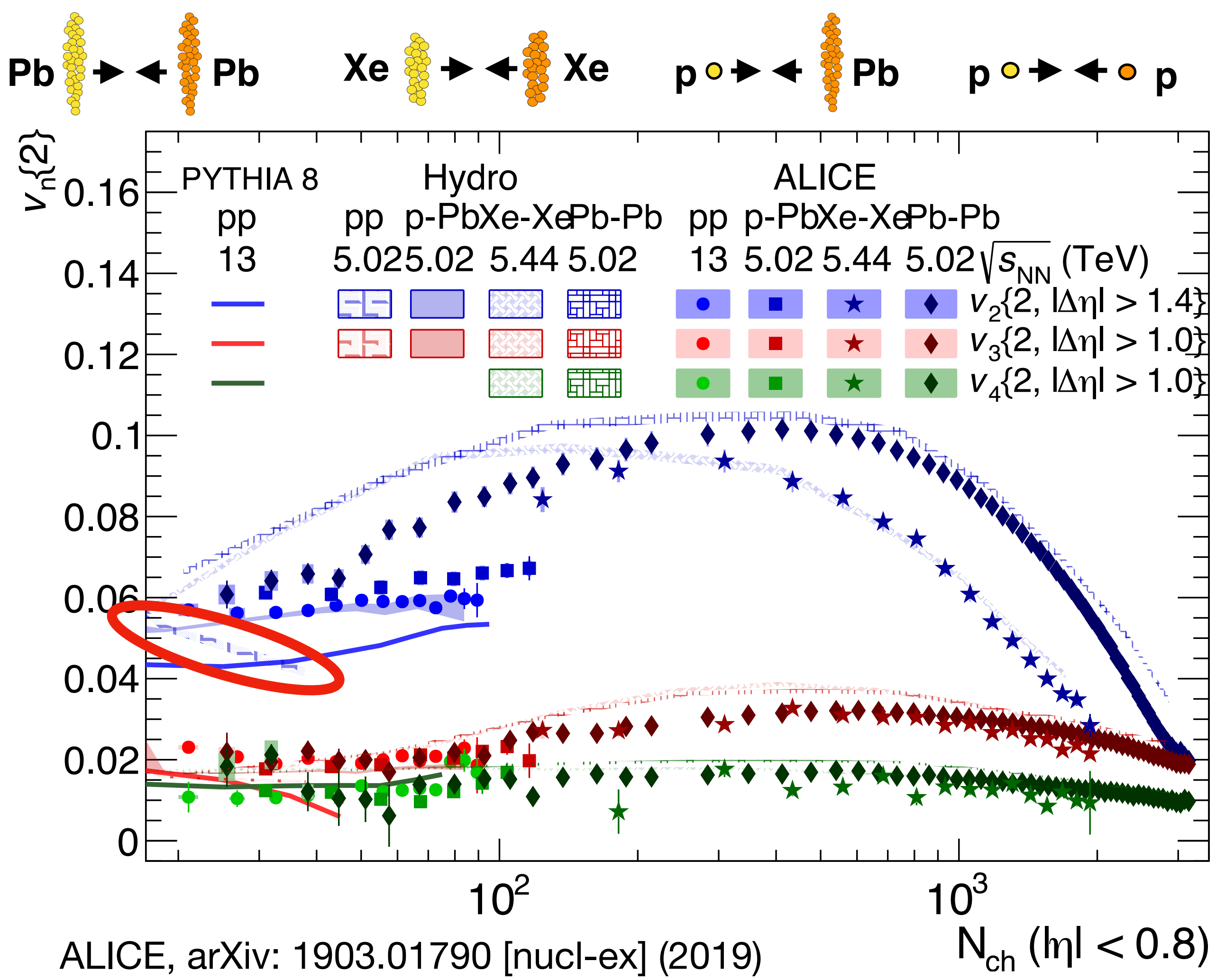

Courtesy of Wei Li

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

# Beware of gaps in the FS description

**1 IS : FS 5**

- Multiplicity dependence of $v_2\{2\}$ in pp collisions is not described by hydrodynamic model (IP-Glasma + MUSIC + UrQMD)
  - **Influence from the initial state**



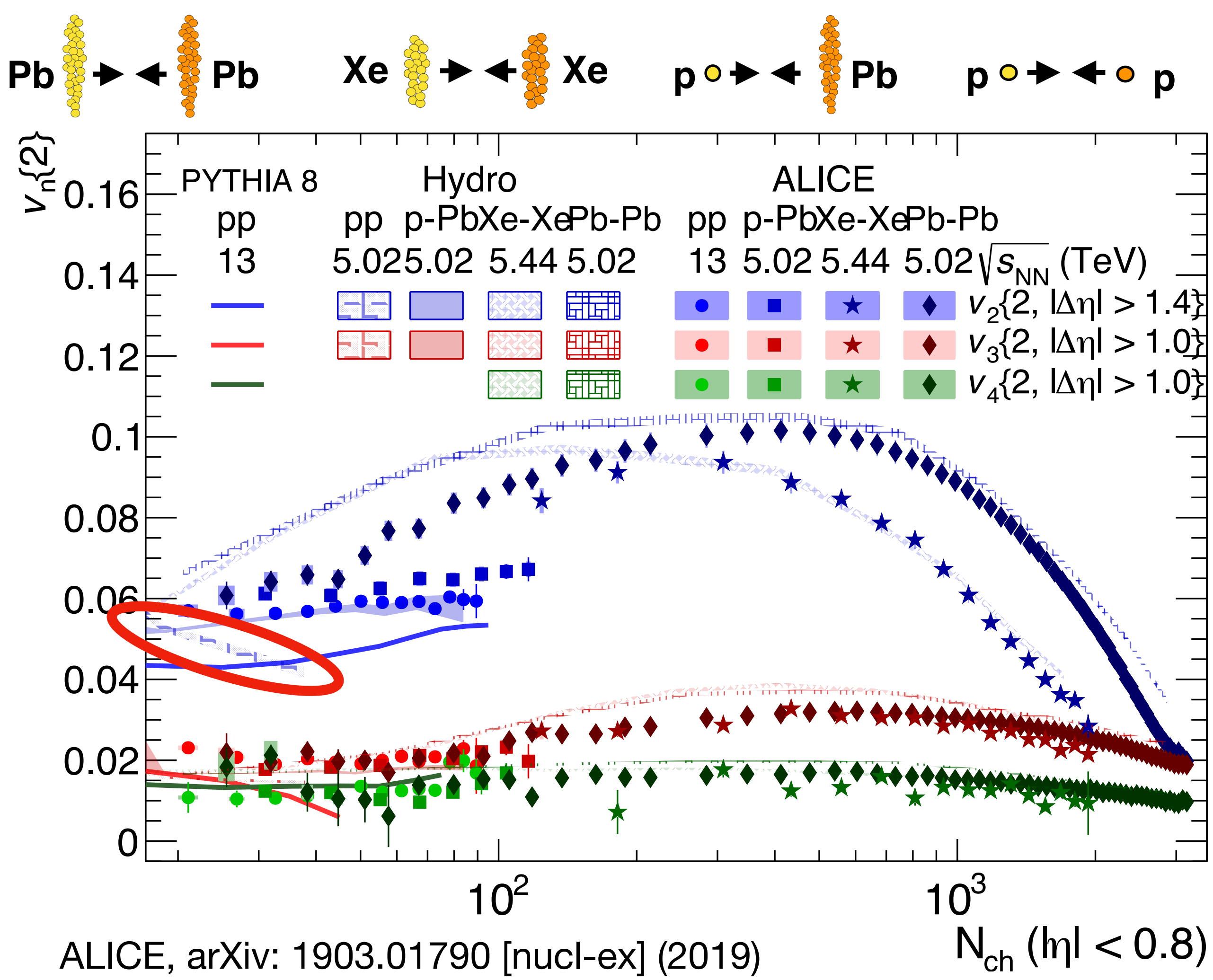

ALICE, arXiv: 1903.01790 [nucl-ex] (2019)

Wednesday @15:20, Vojtech Pacik (ALICE)

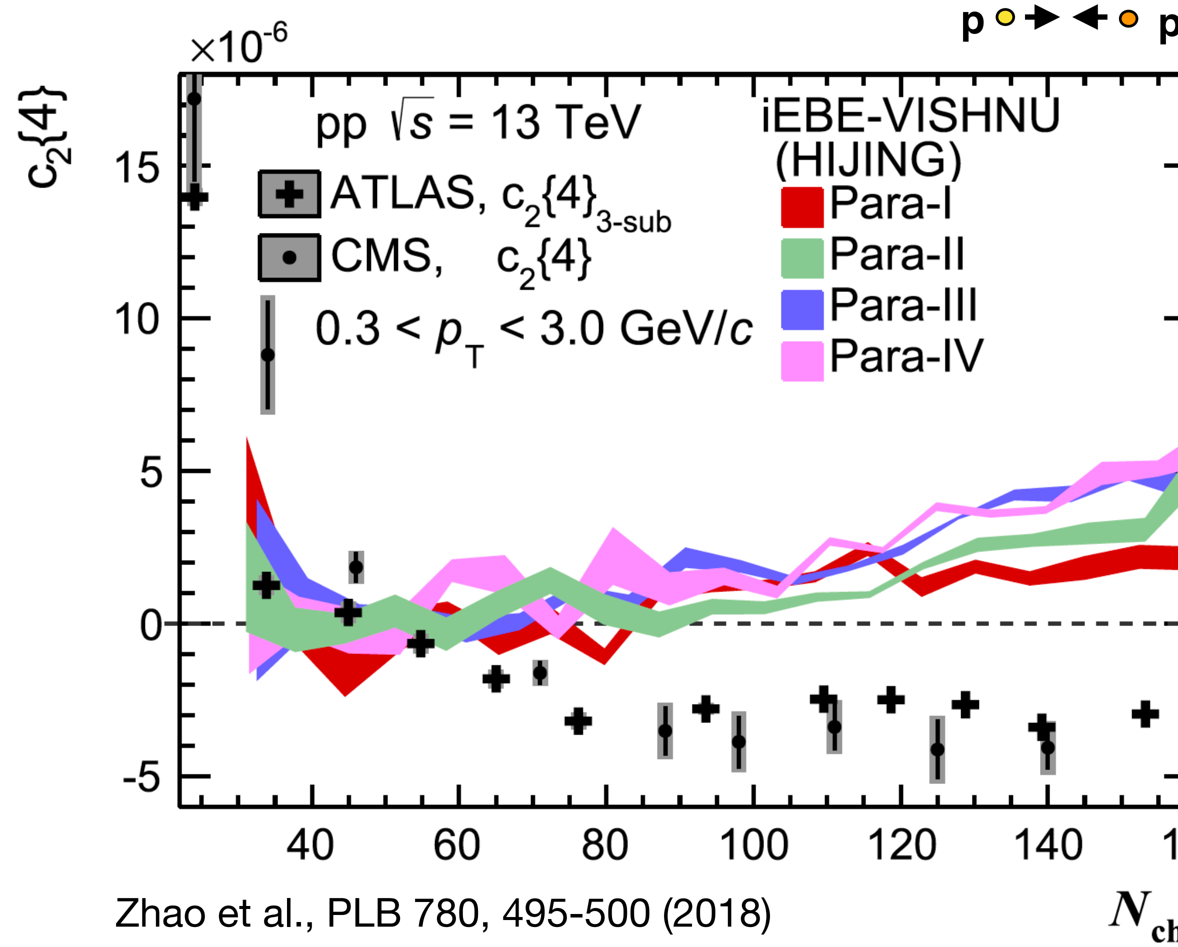
# Beware of gaps in the FS description

**2 IS : FS 5**

- Multiplicity dependence of $v_2\{2\}$ in pp collisions is not described by hydrodynamic model (IP-Glasma + MUSIC + UrQMD)
  - **Influence from the initial state**
- 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**




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



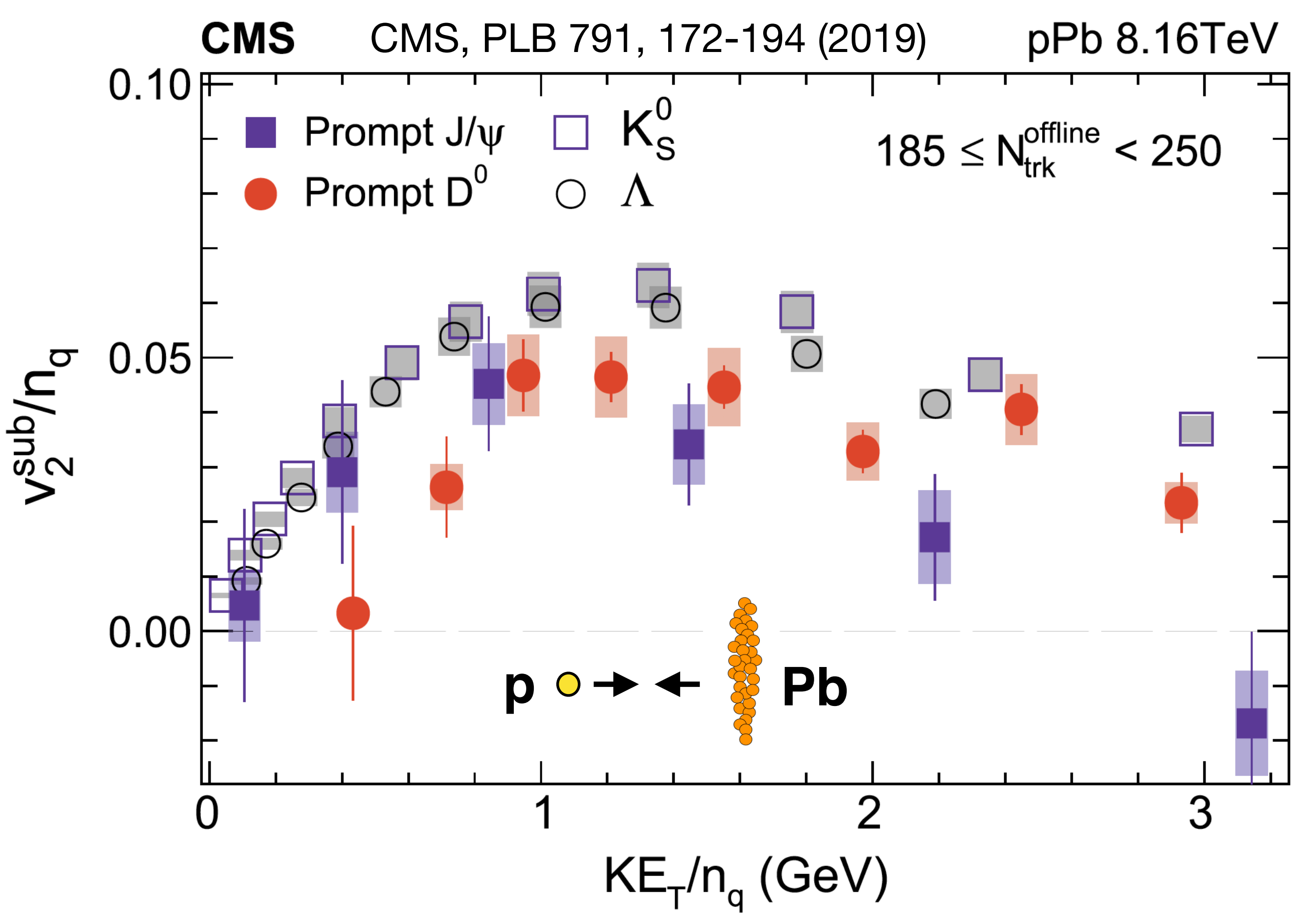

Zhao et al., PLB 780, 495-500 (2018)

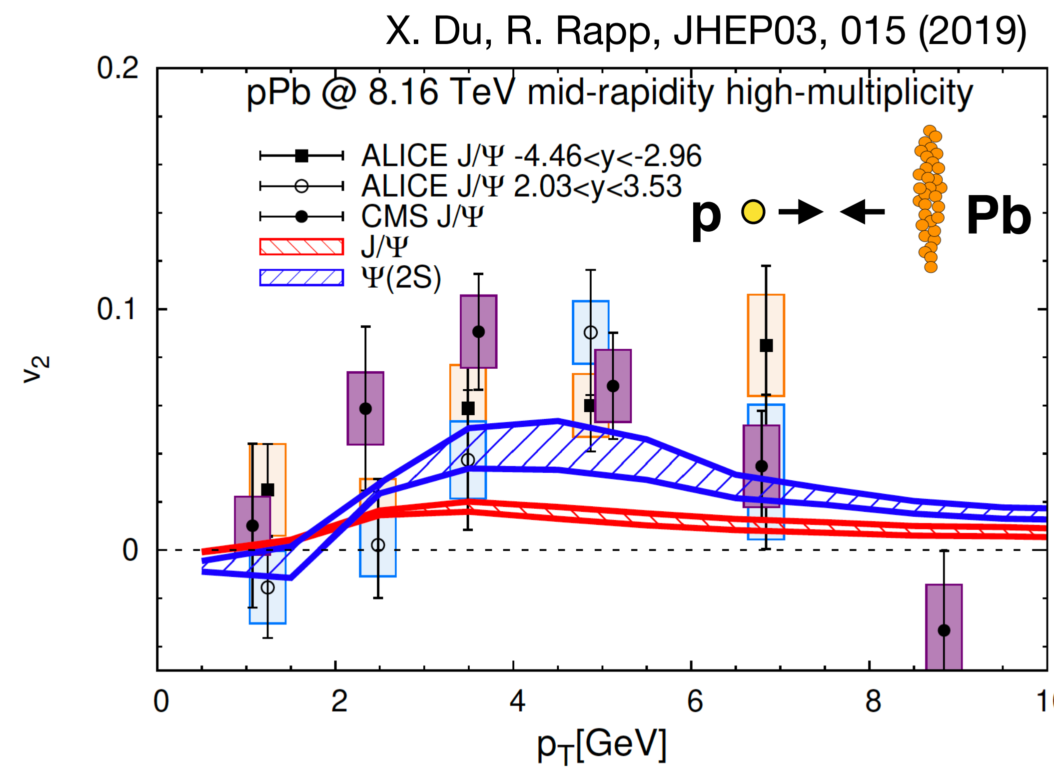
Wednesday @15:20, Vojtech Pacik (ALICE)

# Beware of gaps in the FS description

3 IS : FS 5

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



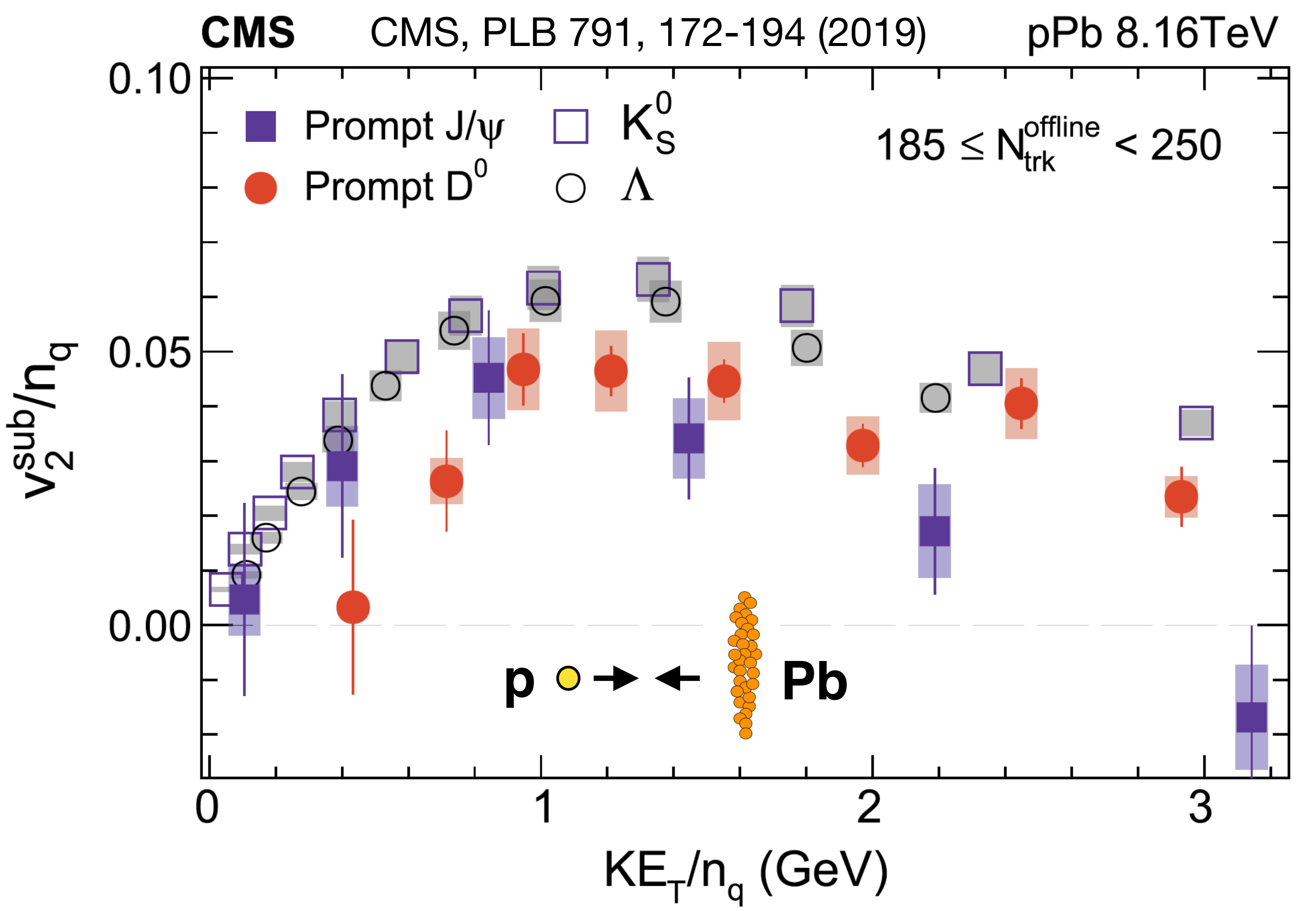




- Large $v_2$ of D and J/Ψ meson in p-Pb collisions

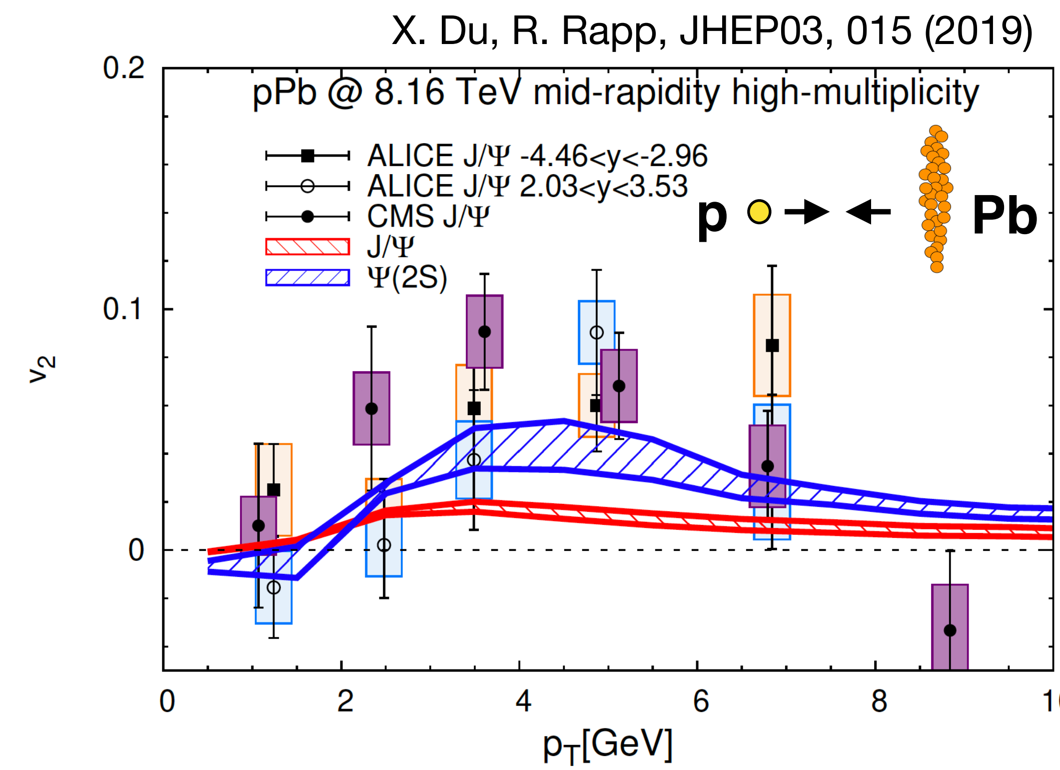
➡ **Cannot be explained only by final state interactions**

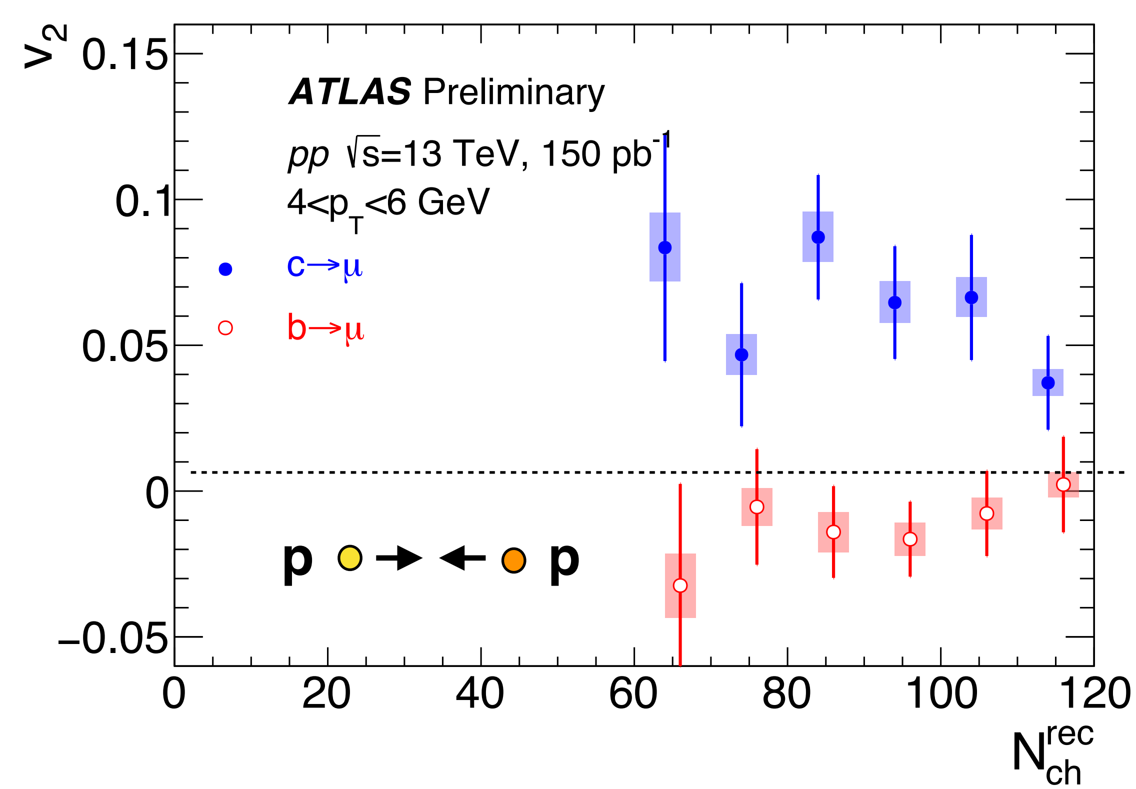
# Beware of gaps in the FS description

**3 IS : FS 5**




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




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

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

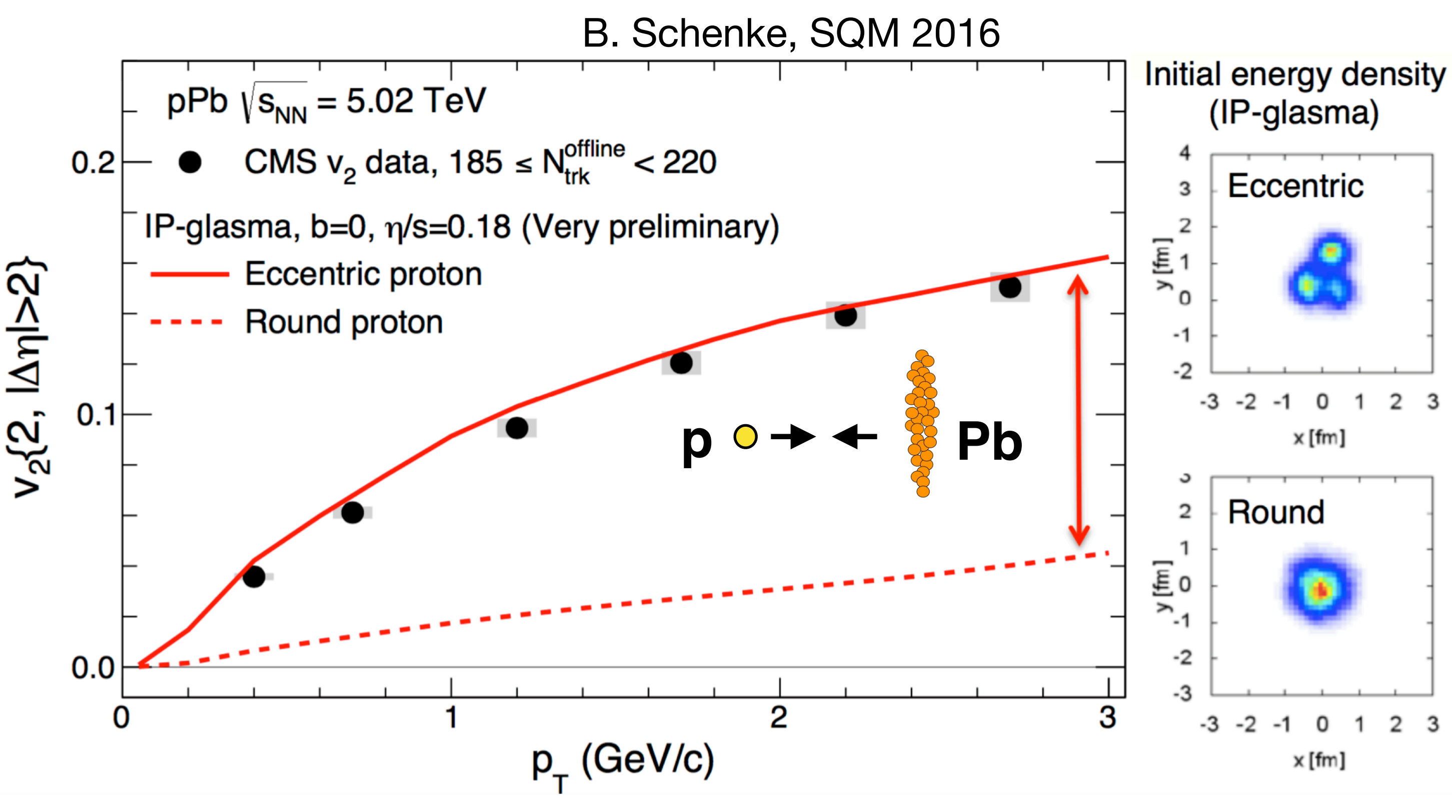
- **New**: charm still flows in pp collisions, but bottom doesn't ($v_2$ consisent with 0 )

**Wednesday @14:20, Kurt Hill (ATLAS)**

**Wednesday @15:20, Fabio Colamaria (ALICE)**

# Important to investigate IS

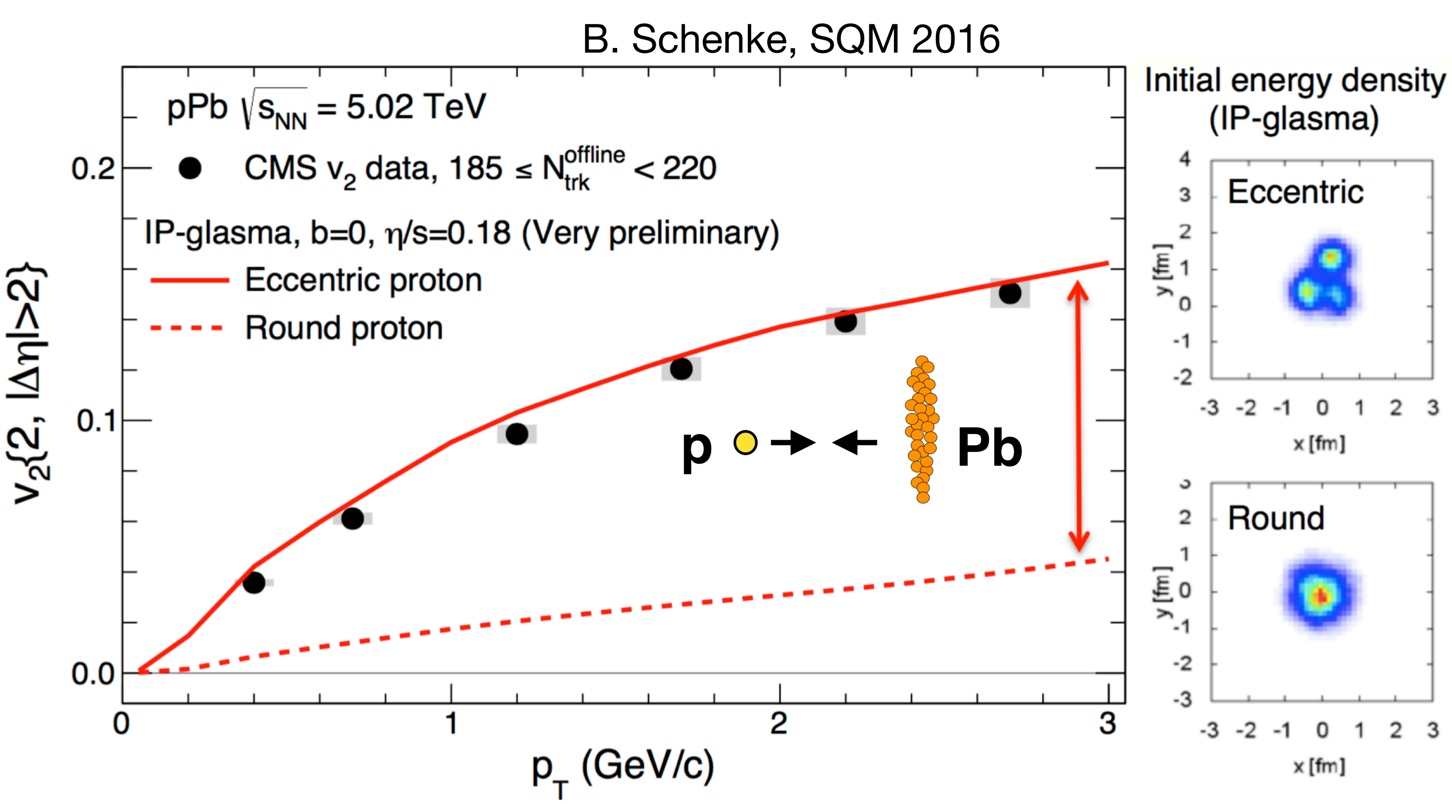
4 IS : FS 5

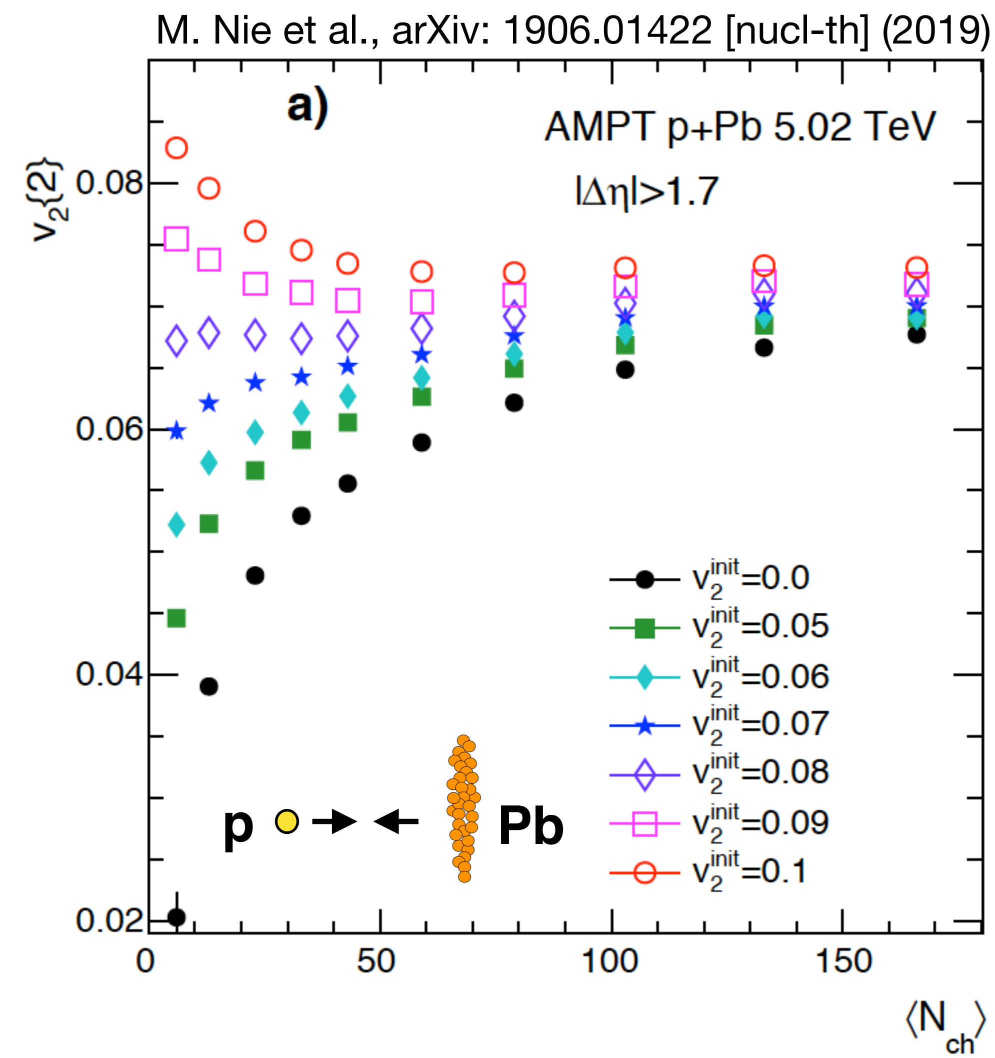



- **Proton substructure** becomes crucial to achieve correct data description

# Important to investigate IS

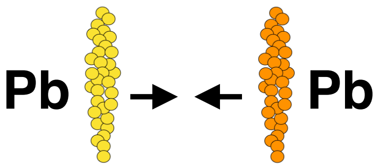
5 IS : FS 5




- **Proton substructure** becomes crucial to achieve correct data description
- Evidence for geometry driven flow does not mean that influence of the initial state is not important
  - Large impact of IS at low multiplicities
  - IS also influences final flow at high multiplicities

# How to experimentally constrain initial state

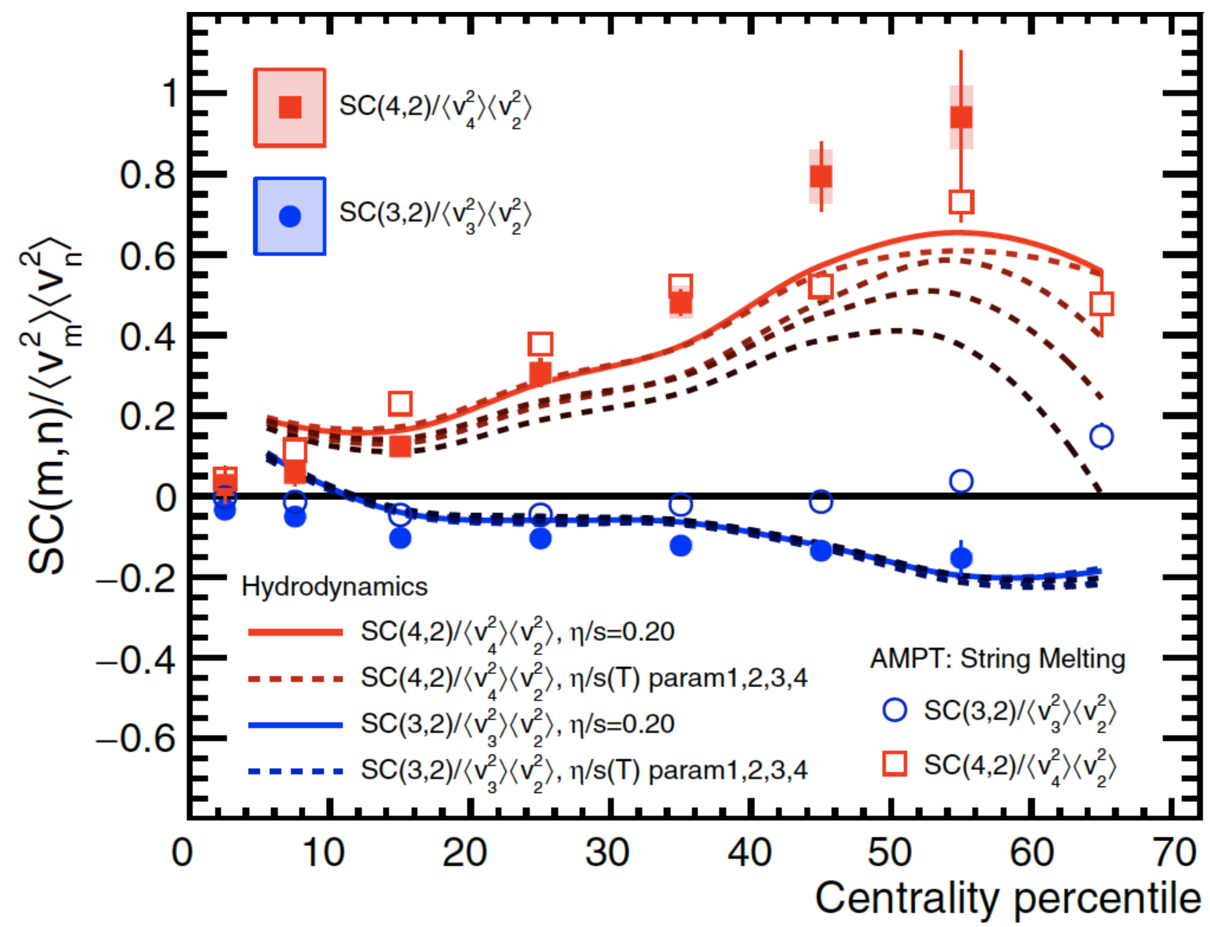



**Symmetric Cumulants:**

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

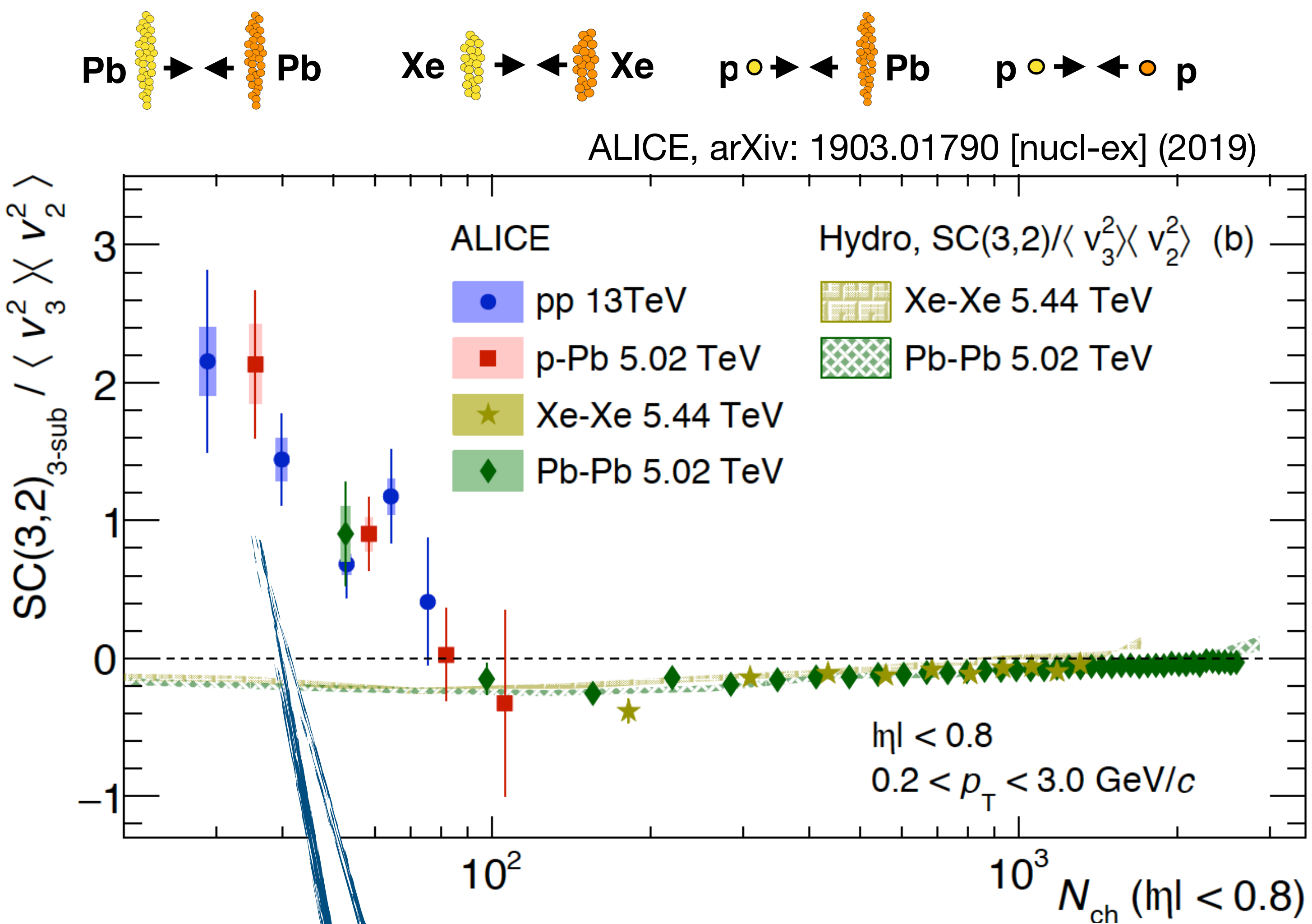
**Normalised SC:** $$\frac{SC(m,n)}{\langle v_m^2 \rangle \langle v_n^2 \rangle}$$

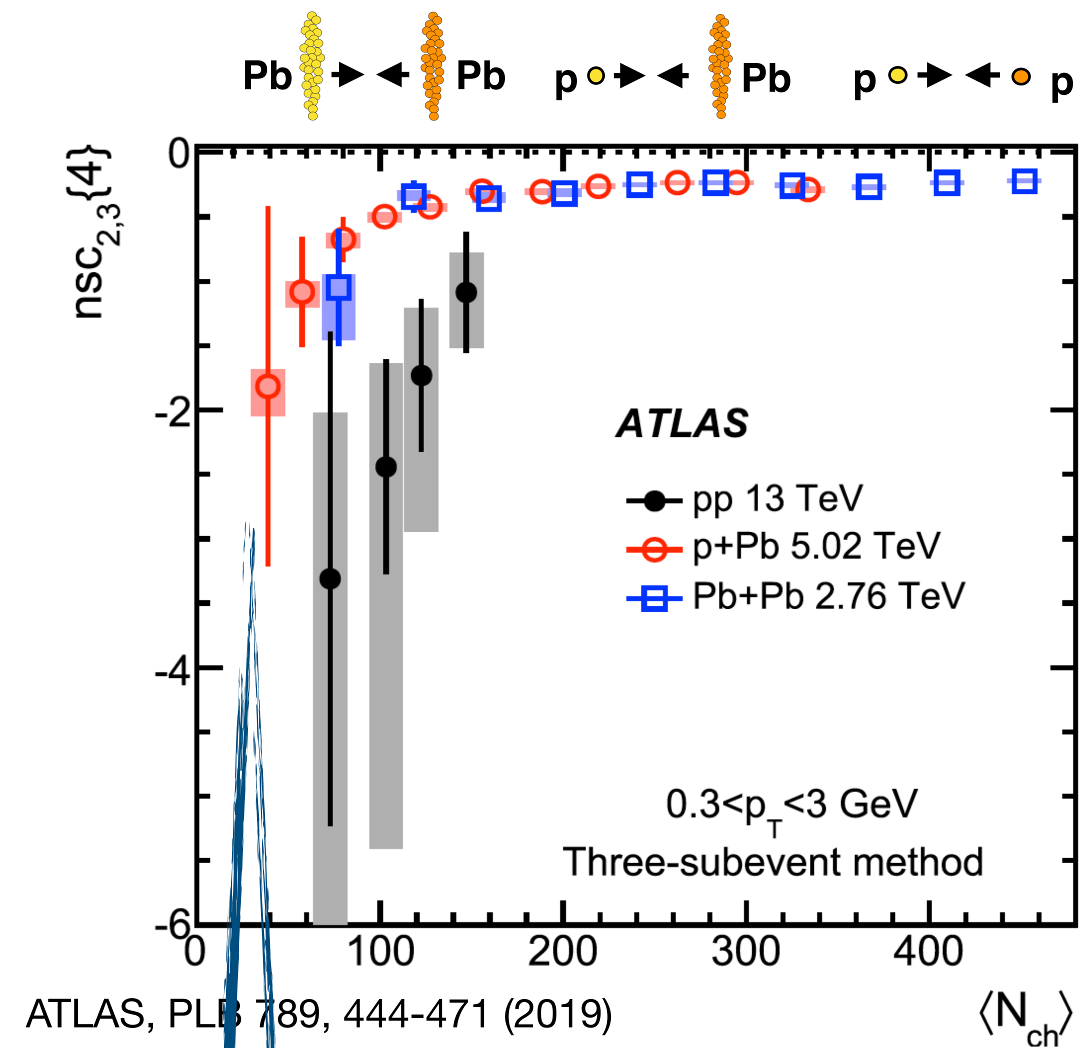
ALICE, PRL **117**, 182301 (2016)




- 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

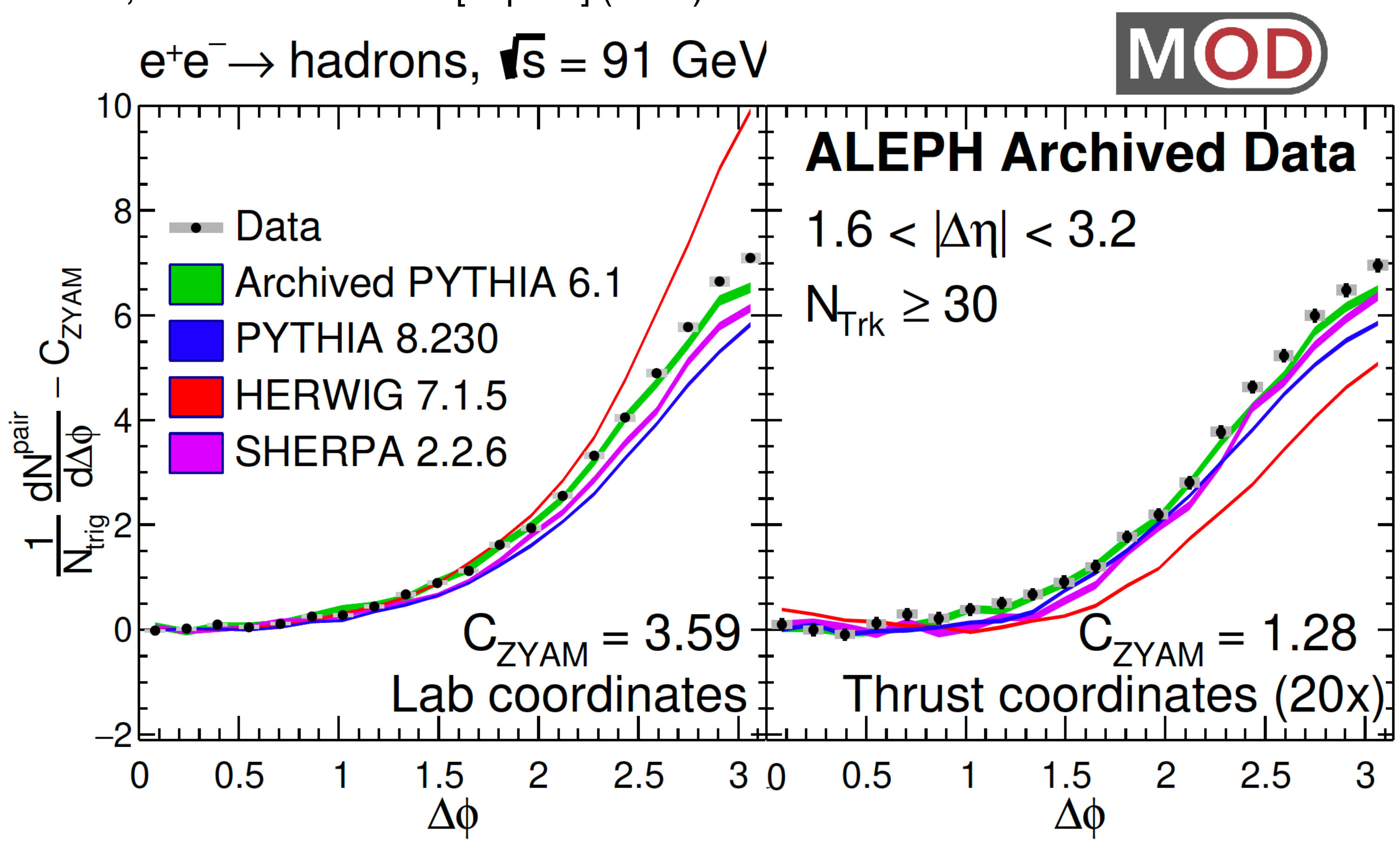
*Caveat*: results at low multiplicities are different when using different η acceptance

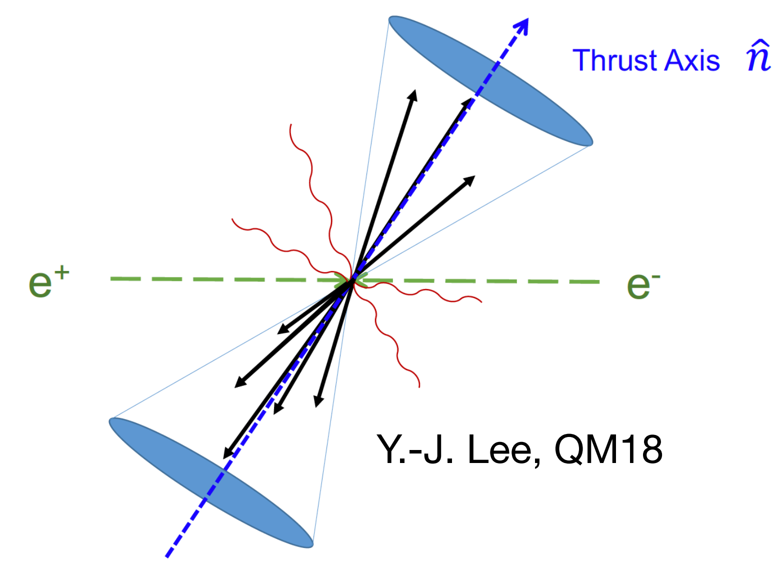
- **Similar pattern as in large systems**
- No model comparison with small systems available yet

**Wednesday @15:20, Vojtech Pacik (ALICE)**

# Collisions of e+e-

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

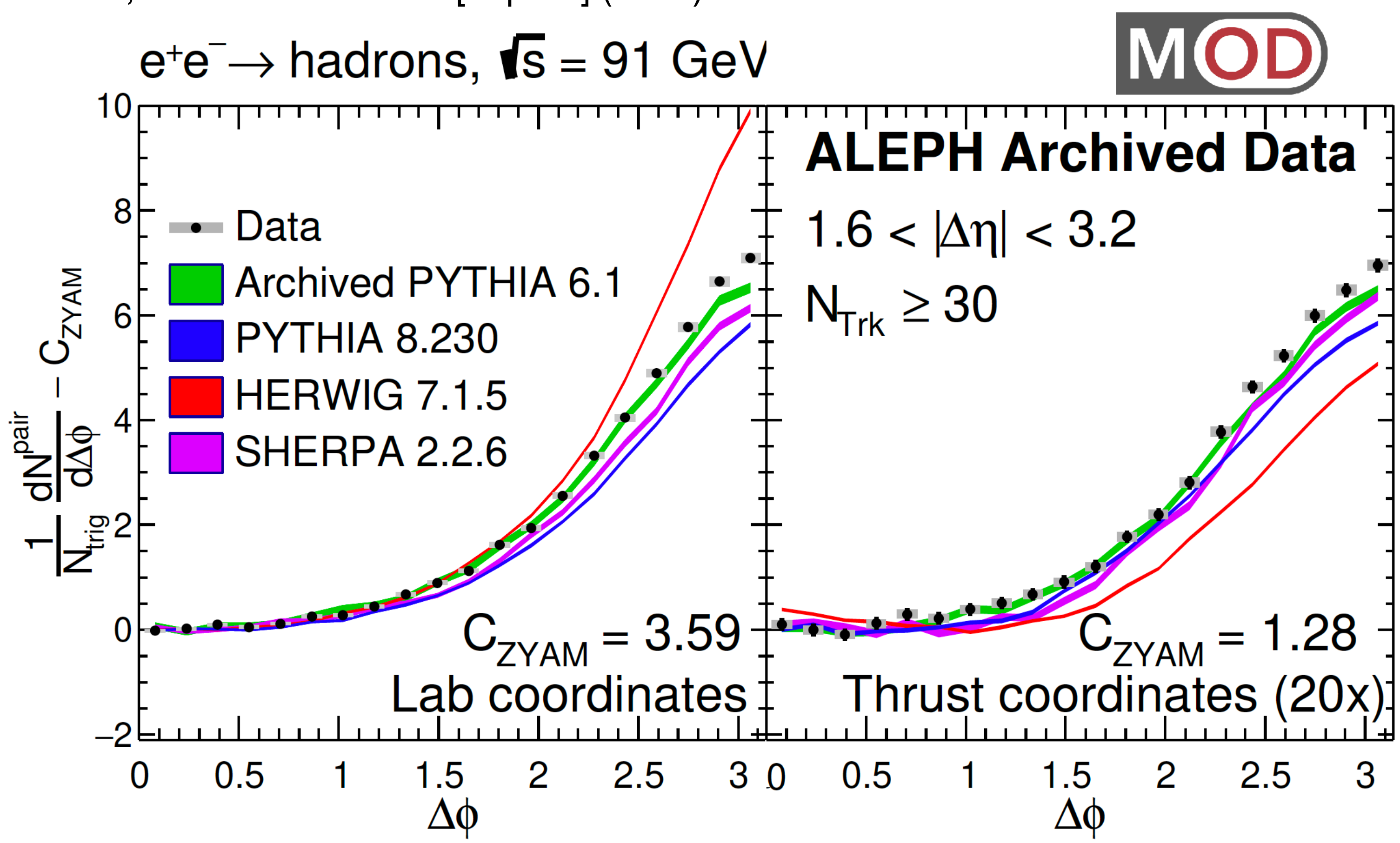


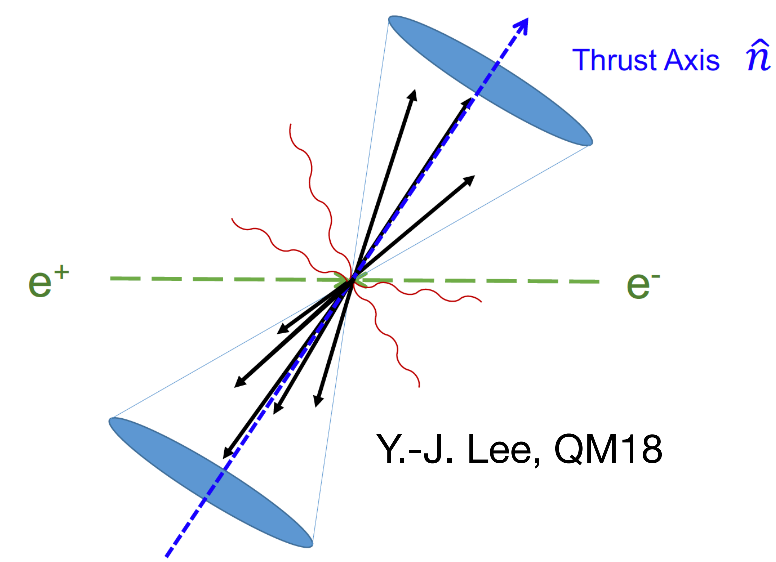




- Advantage: well-defined initial state
- **No observation of near-side ridge**
  - Data consistent with models that do not contain any final state interactions

# Collisions of e+e-

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

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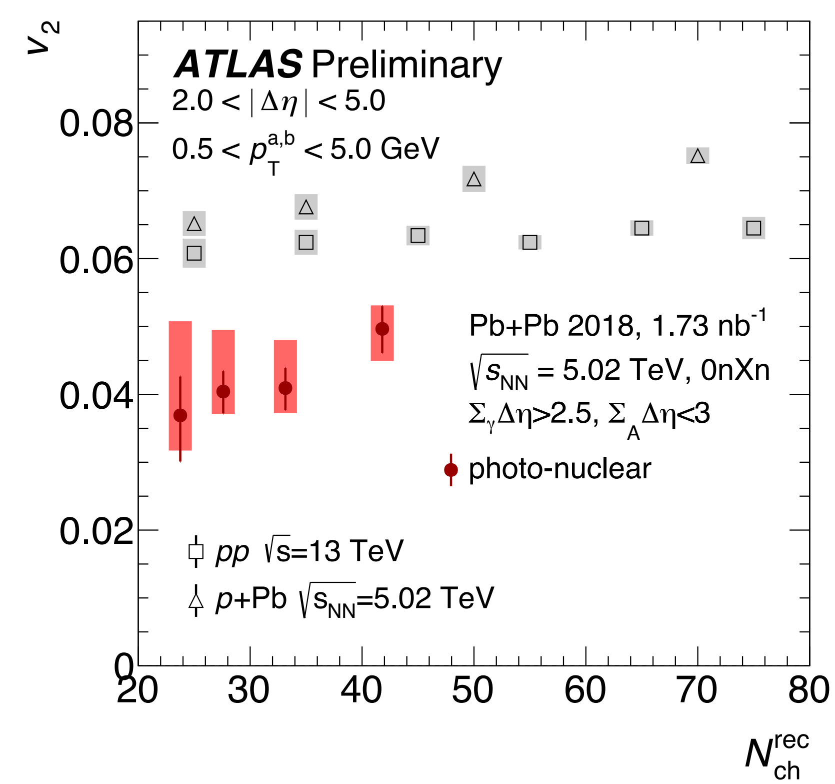


**Wednesday @15:00, Blair Seidlitz (ATLAS)**

# What is the origin of collectivity ?

## Initial State (IS) ≈/≠ ??? Final State (FS)

- Initial momentum correlations
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Not correlated to initial geometry

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- Hydrodynamics
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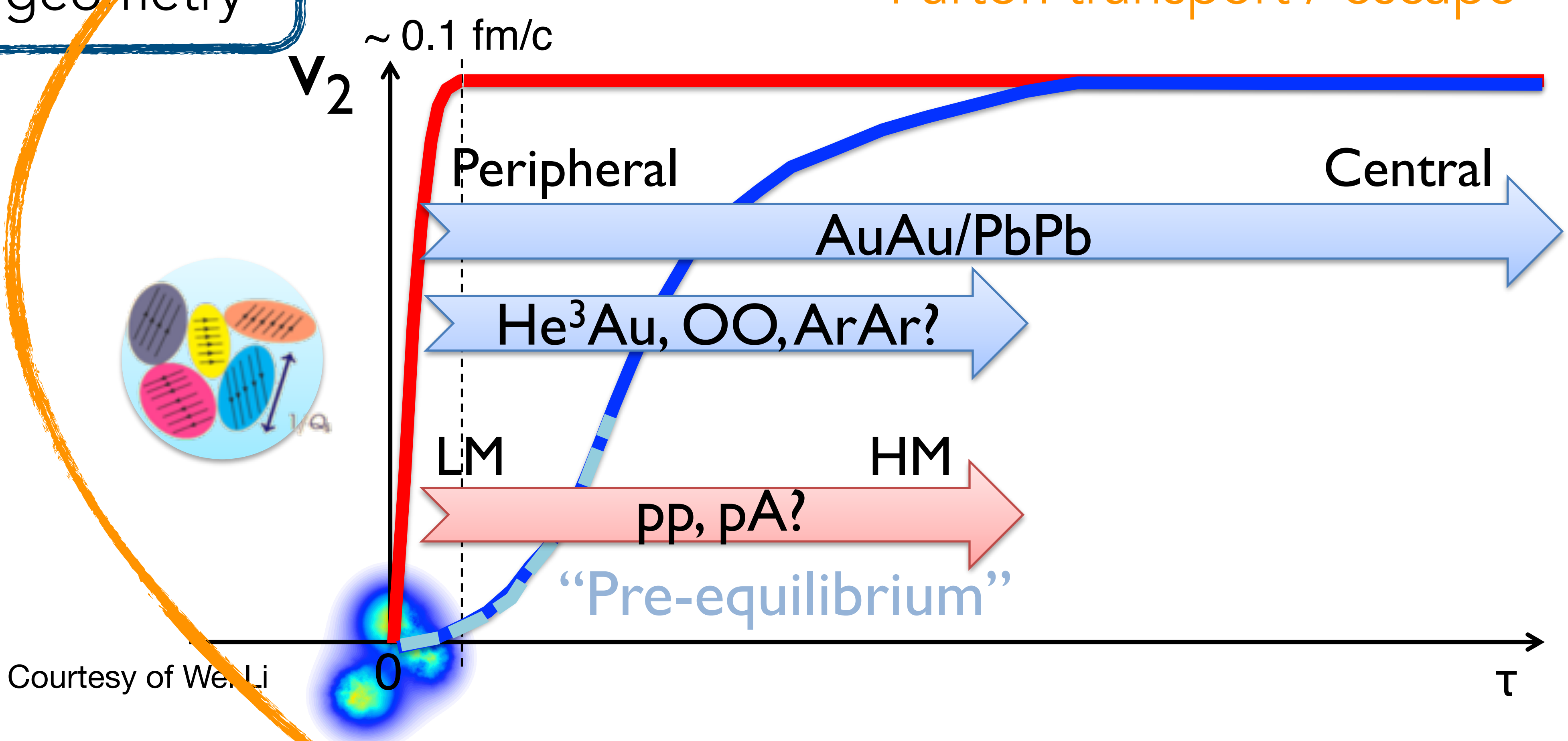
Correlated to initial geometry

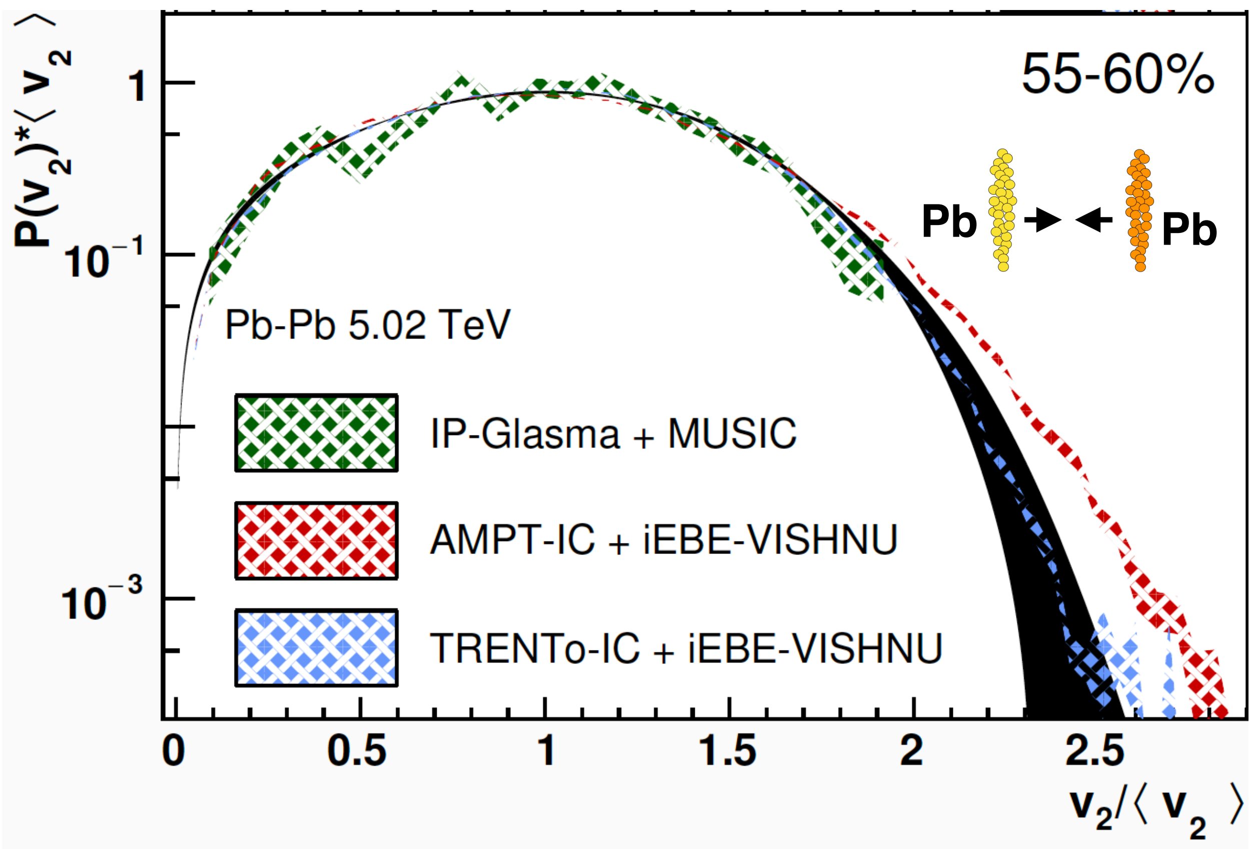



**Need more measurements.**

# What else?

- Probability distribution $P(v_n)$
  - Sensitive to initial conditions and final state dynamics in heavy-ion collisions
  - Not measured in pp and pA collisions so far

ALICE, JHEP 1807, 103 (2018)



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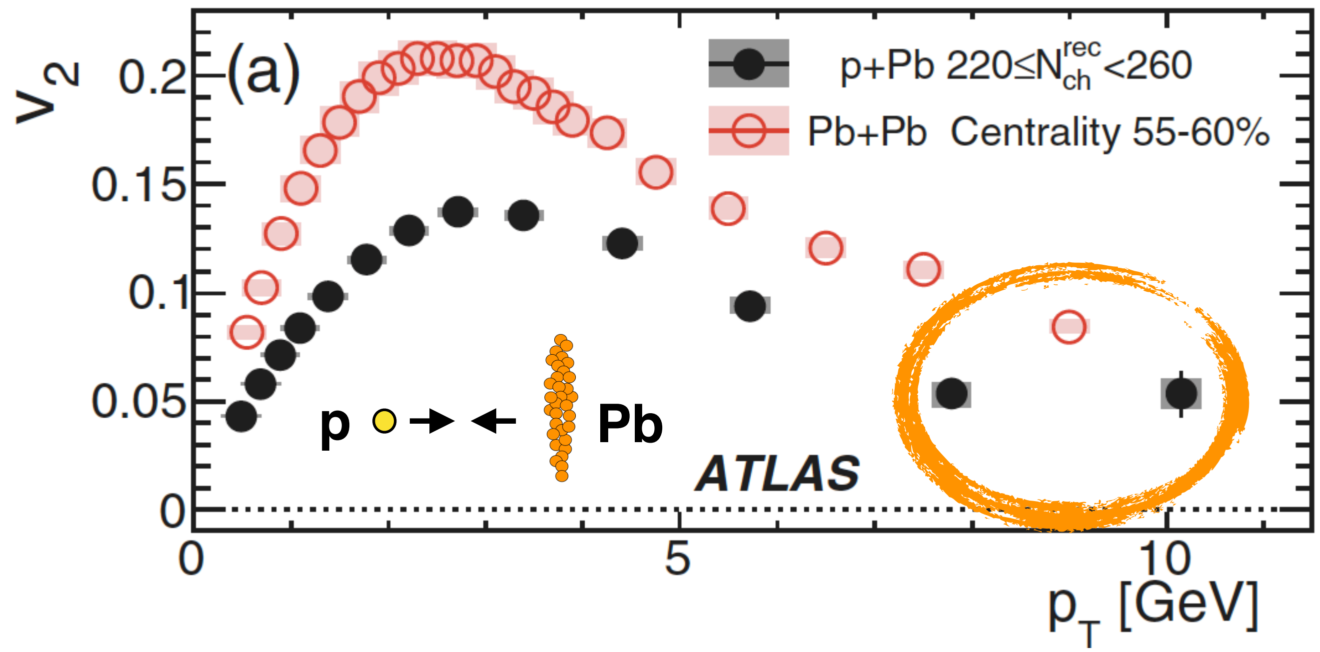
- Probability distribution $P(v_n)$
  - Sensitive to initial conditions and final state dynamics in heavy-ion collisions
  - Not measured in pp and pA collisions so far

- High-$p_T$ flow
  - Study of jet quenching without selection bias

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



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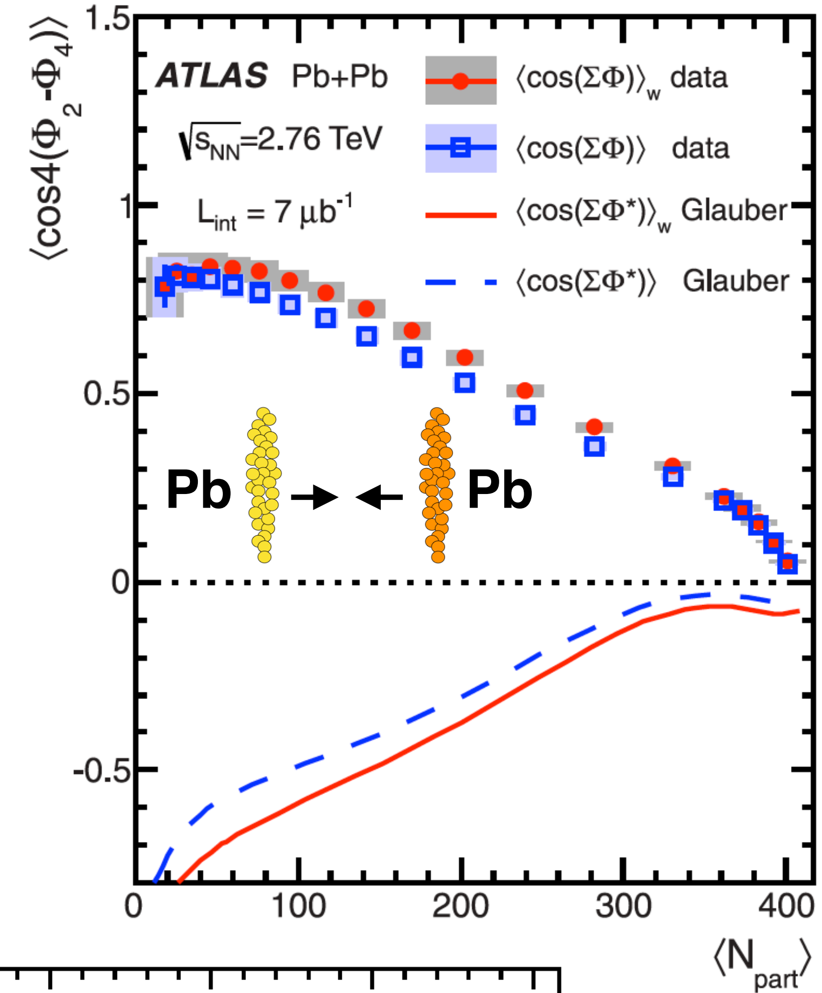
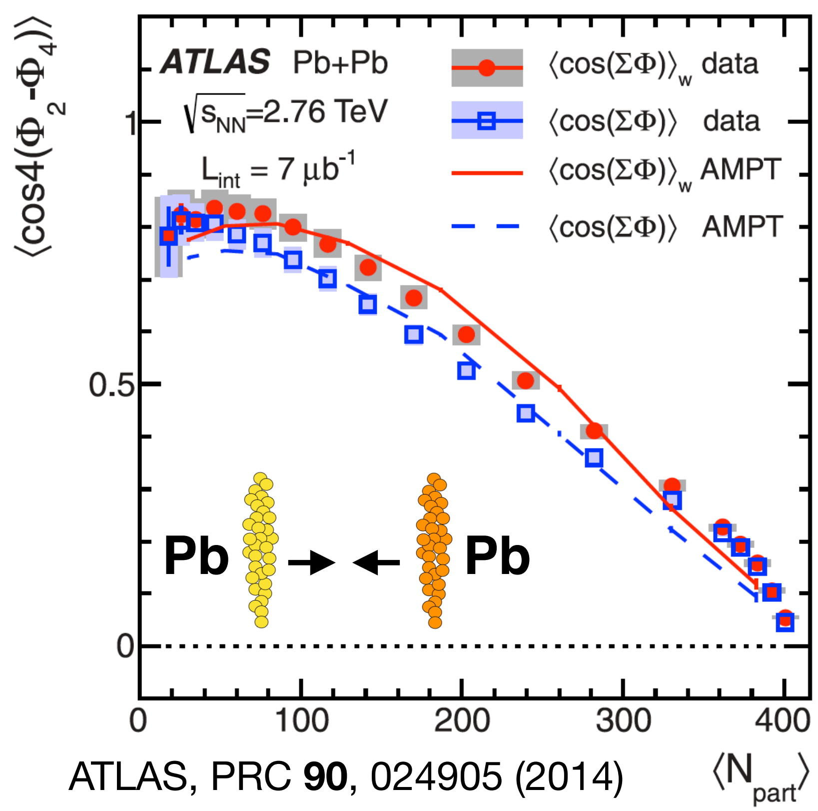
- High-$p_T$ flow
  - Study of jet quenching without selection bias

- Nonlinear (hydrodynamic) response to IS fluctuations
  - Correlations between event plane angles $\Psi_n$ / non-linear modes of higher order flow $v_n$ (n>4)
  - *"Experimentum crucis in support of hydrodynamic paradigm"*

U. Heinz, R. Snellings, Annu. Rev. Nucl. Part. Sci. **63**, 123-151 (2013)




ATLAS, PRC **90**, 024905 (2014)

# Summary

- **Wealth of experimental measurements in small systems**
  - Many of them couldn't fit into this talk, but stay tuned for the parallel sessions!

| | Constraints on IS | p(d)($^3$He)-A | FS description | pp | FS description |
|---|---|---|---|---|---|
| Two-particle correlations | | ✔ | ✔ | ✔ | ✔ (orange) |
| Multi-particle cumulants | | ✔ | **missing** | ✔ | ✘ |
| Symmetric Cumulants | ✔ | ✔ | **missing** | ✔ | **missing** |
| Flow of identified hadrons | | ✔ | ✔ | ✔ (orange) | **missing** |
| Heavy flavor flow | ✔ (orange) | ✔ | ✘ | ✔ | **missing** |
| High $p_T$ flow | | ✔ (orange) | **missing** | ✔ (orange) | **missing** |
| $P(v_n)$ | ✔ | **missing** | **missing** | **missing** | **missing** |
| Non-linear response | ✔ | **missing** | **missing** | **missing** | **missing** |
| ... | **???** | **???** | **???** | **???** | **???** |

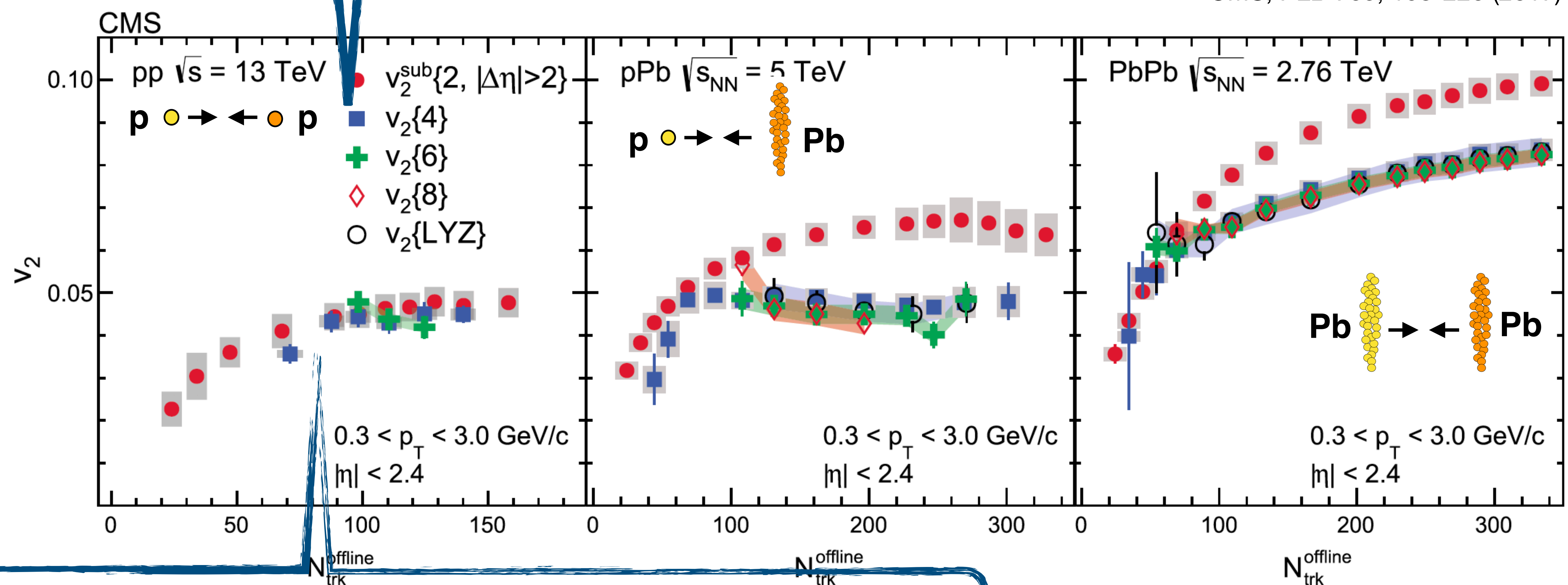
- Need for understanding the influence of the initial state correlations
- More ideas on the measurements that can clearly disentangle contributions from different stages?

# Backup

# Collectivity down to pp collisions

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

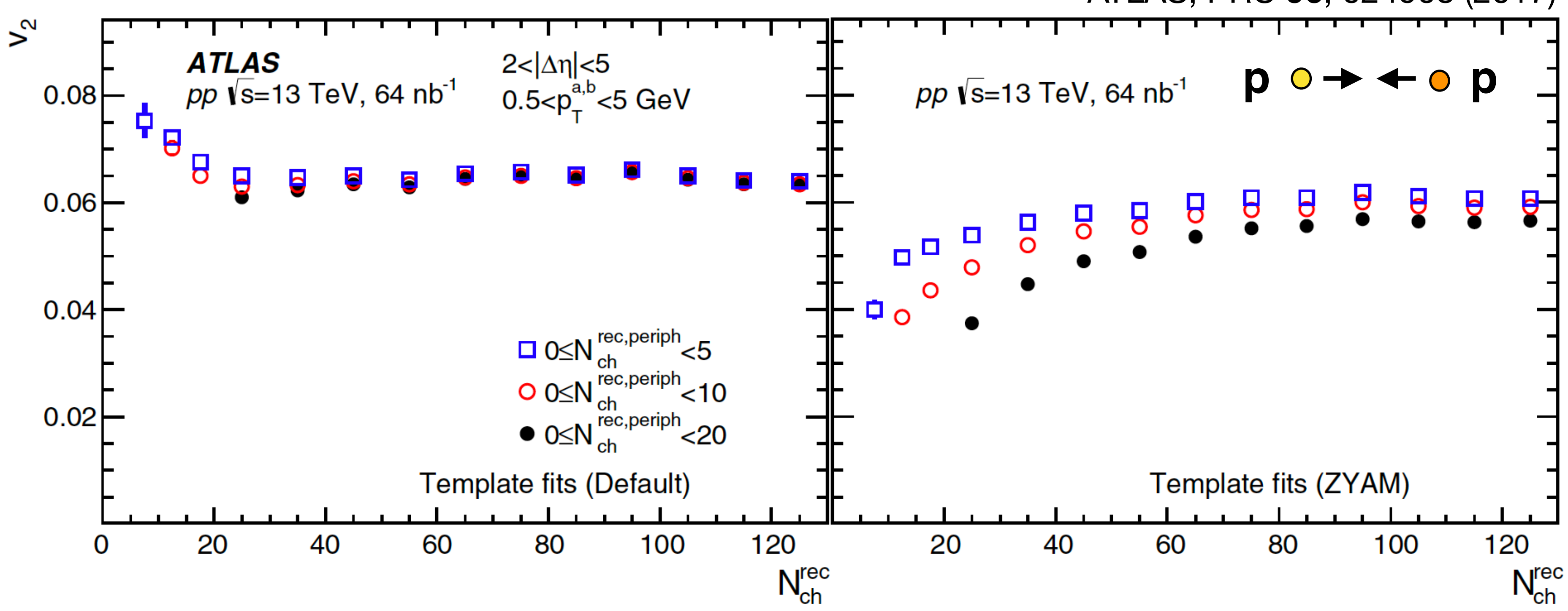
CMS, PLB 765, 193-220 (2017)




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

# Onset of collectivity ?

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

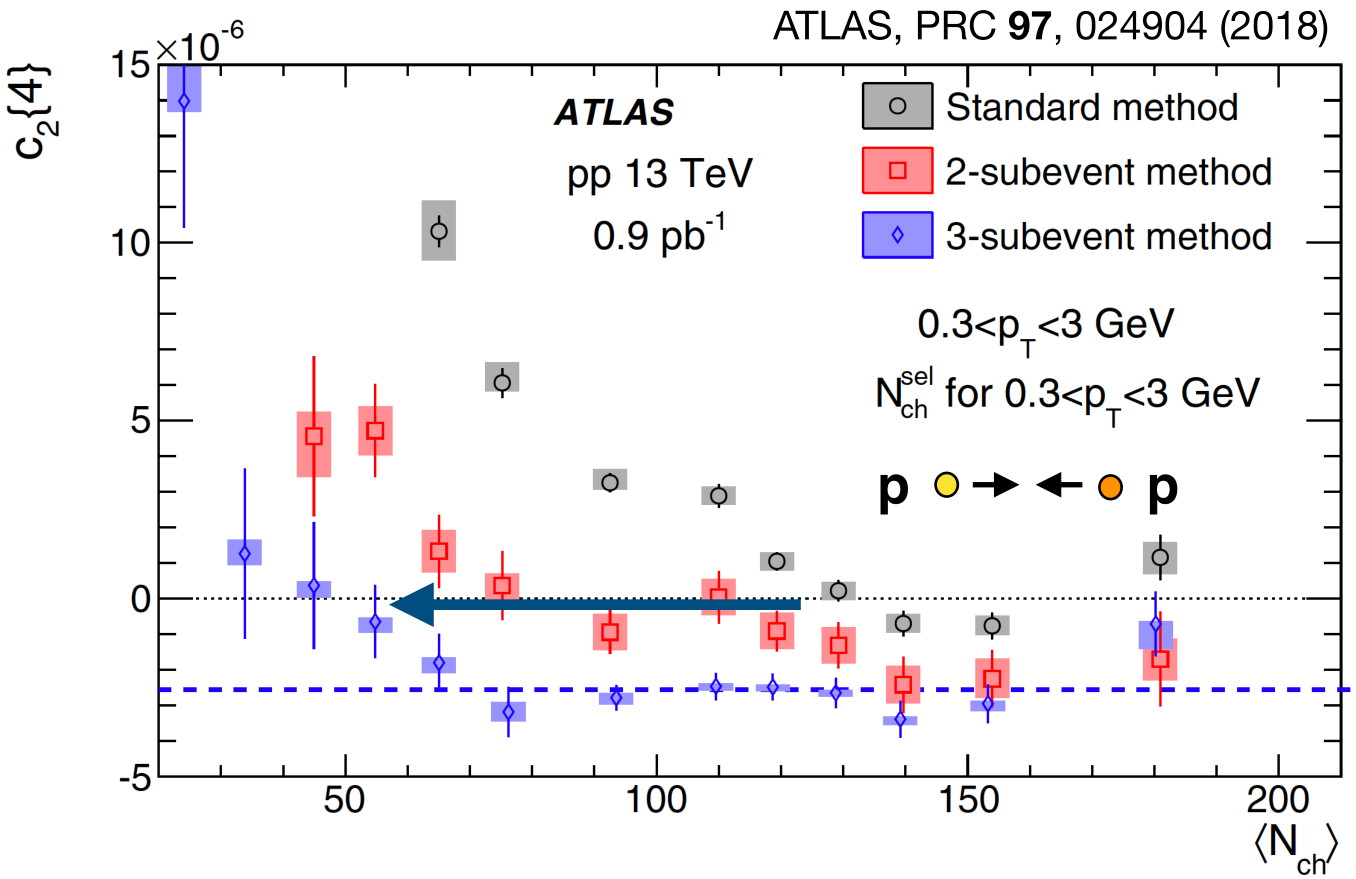



**How low in multiplicity can we observe correlations?**

**(Onset of collectivity)**

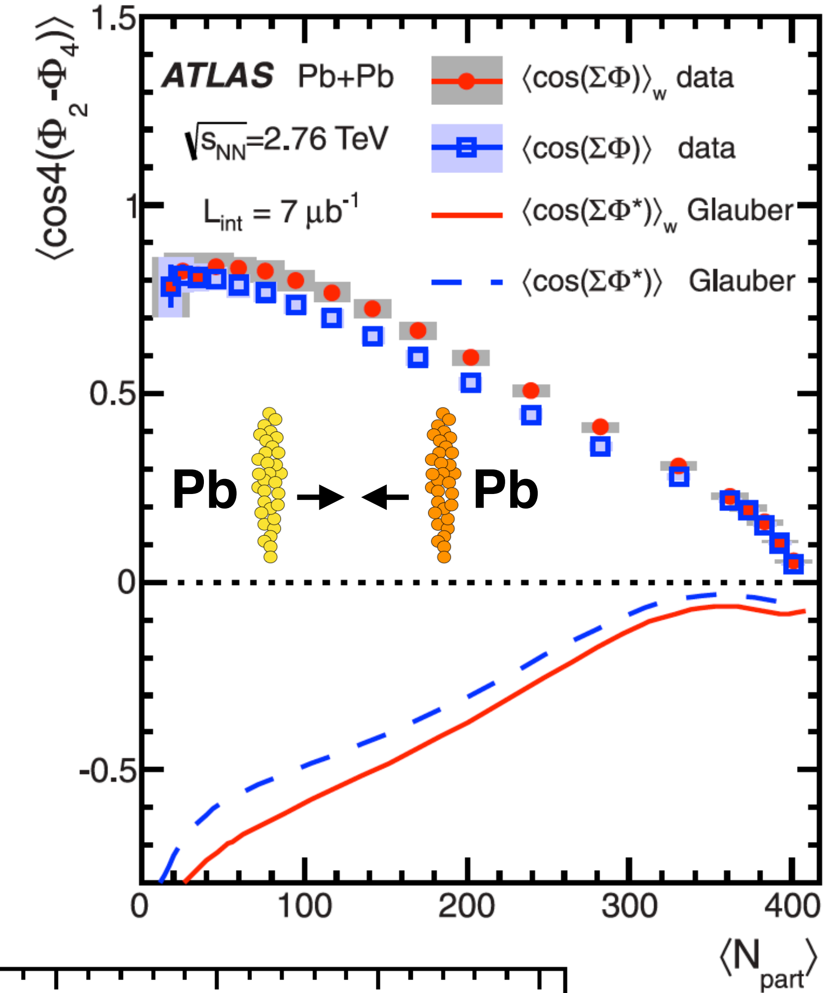
- Two-particle correlation down to $N_{ch}$ ($|\eta|<2.4$) < 10 in pp collisions
- **Four-particle cumulant positive at low multiplicity** ($N_{ch}$ ($|\eta|<2.4$) < 40)
  - Is that the onset of collectivity, or is it just non-flow?
  - Transition from positive to negative sign moves to lower multiplicities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

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

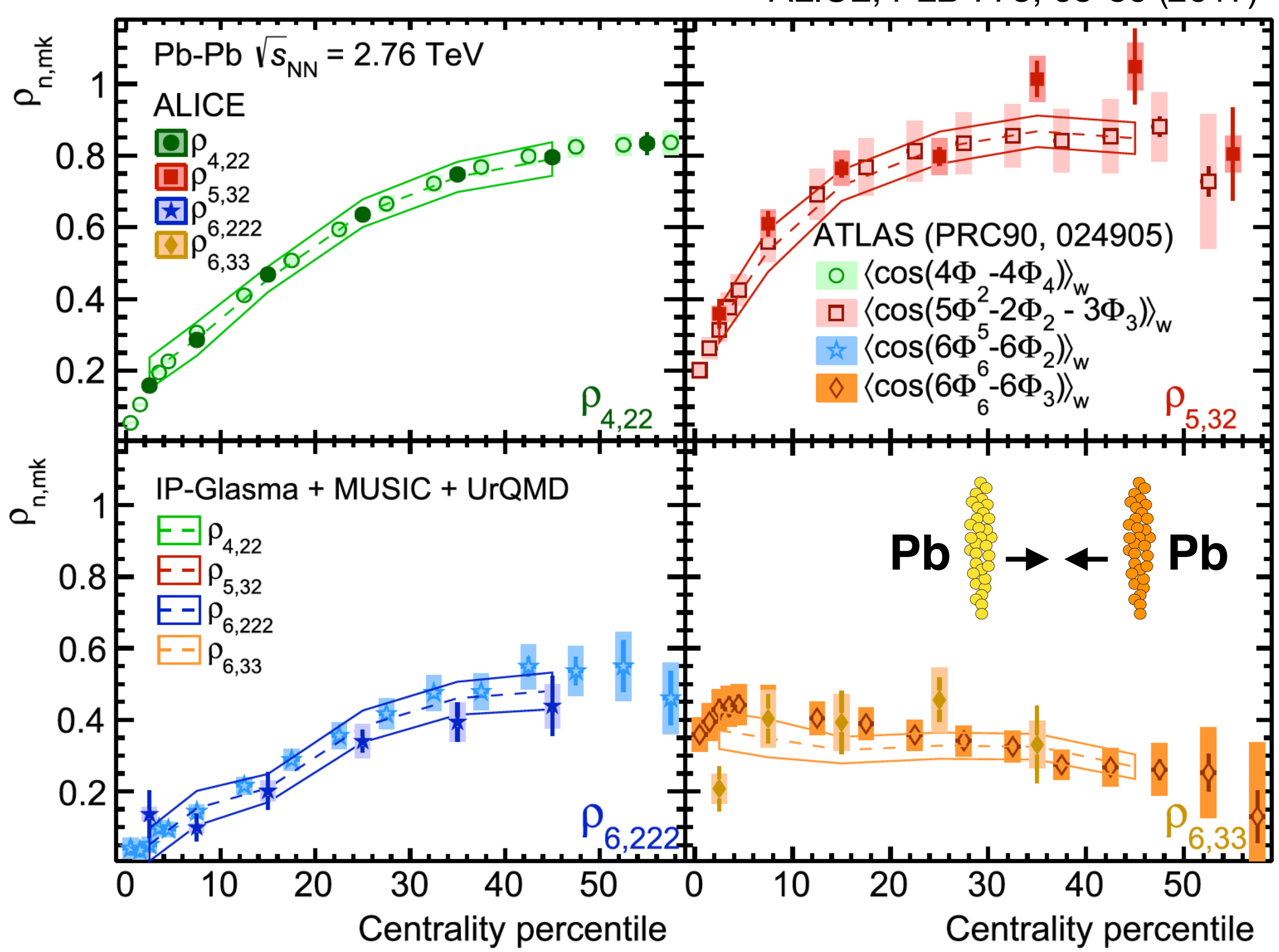


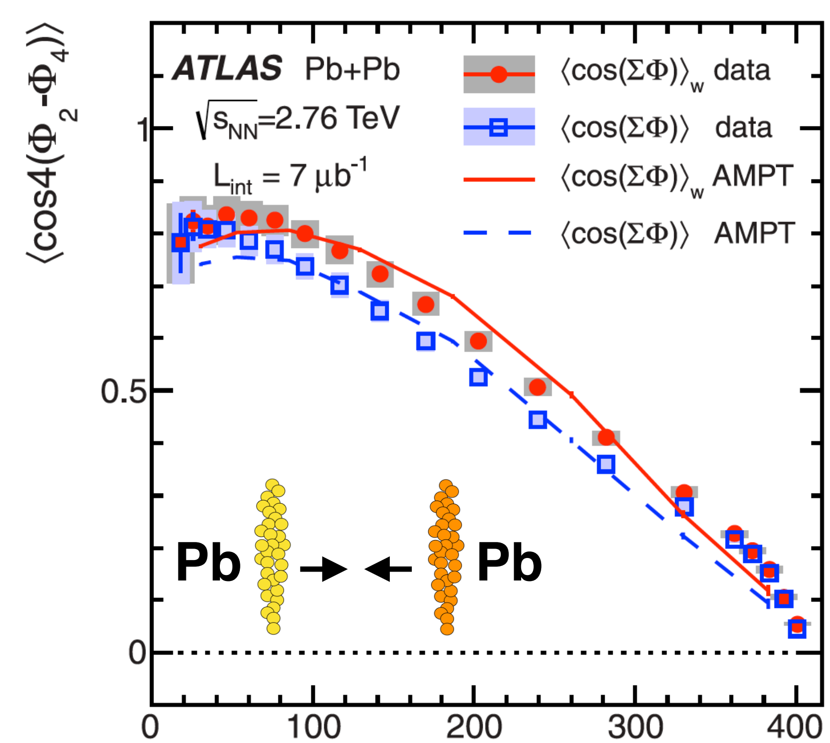
# What else?

- **Nonlinear** (hydrodynamic) **response** to IS fluctuations
  - Correlations between event plane angles $\Psi_n$ / non-linear modes of higher order flow $v_n$ (n>4)
  - Data described only when nonlinear response is included




ALICE, PLB 773, 68-80 (2017)




ATLAS, PRC **90**, 024905 (2014) $\langle N_{part}\rangle$

# What else?

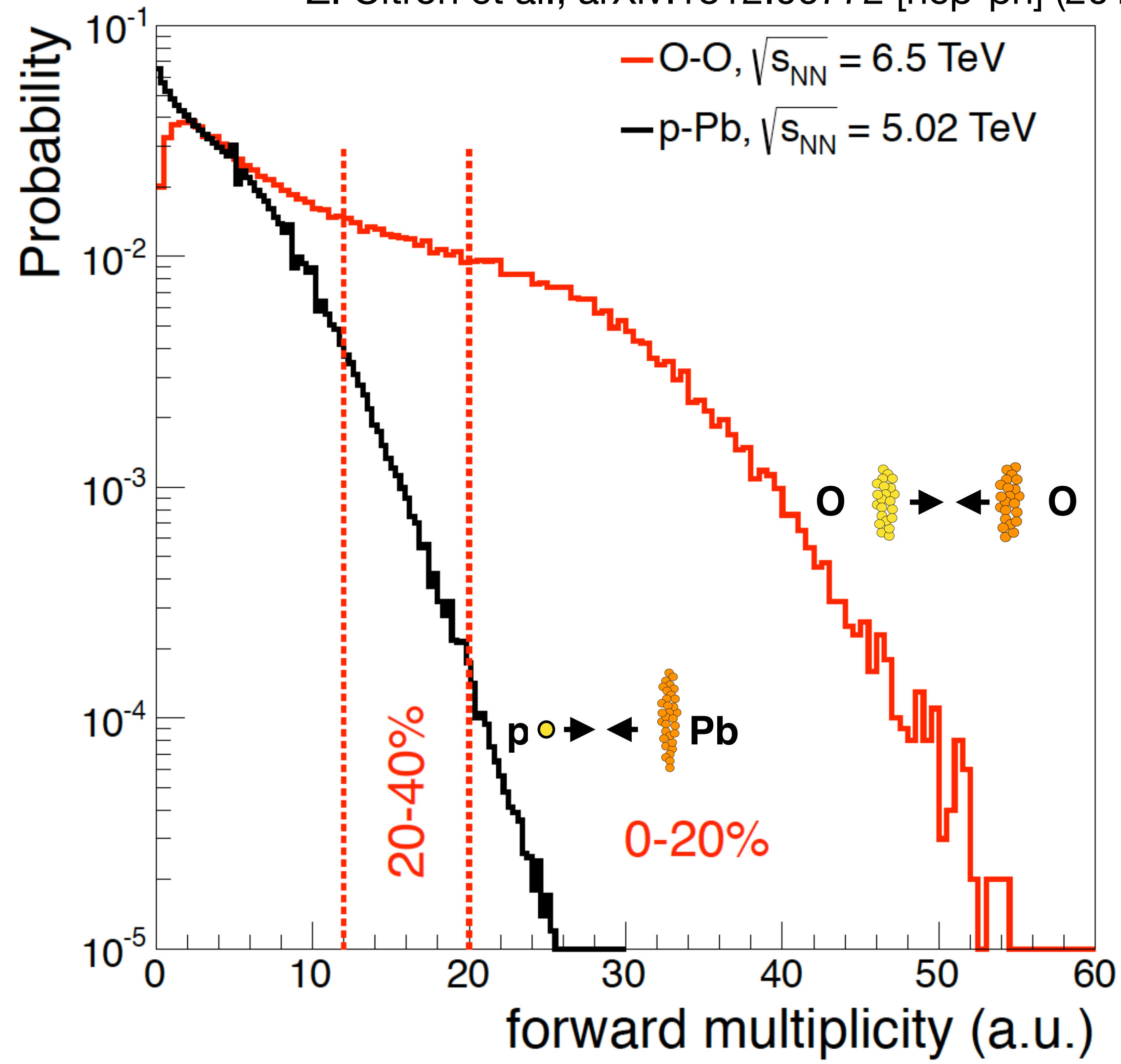
- **Scan of different collision systems?**
  - CuCu vs. AuAu @ RHIC
  - XeXe vs. PbPb @ LHC
  - Comparisons bring more information on the initial state

➡ 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

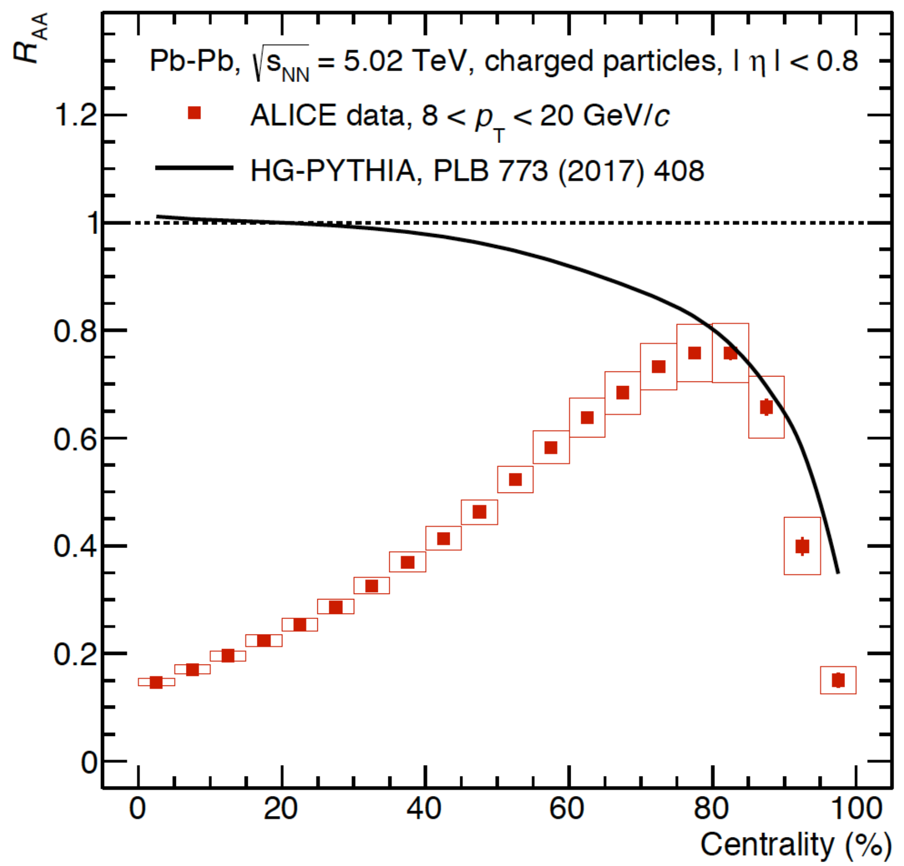
Z. Citron et al., arXiv:1812.06772 [hep-ph] (2018)



# What else?

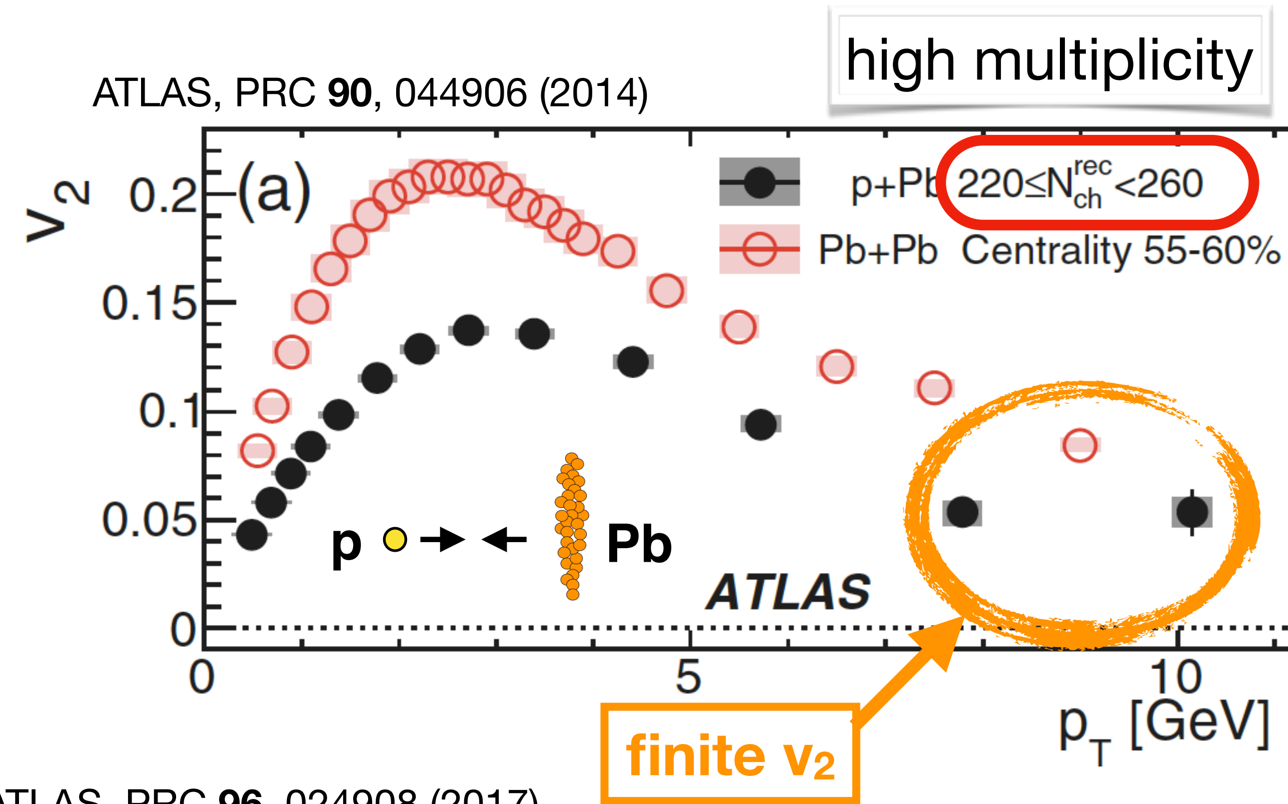
- **High-$p_T$ flow**
  - Jet quenching not observed in pA collisions while it is seen in peripheral AA collisions
    - *Caveat*: selection bias

➡ Flow at high $p_T$ not sensitive to such biases

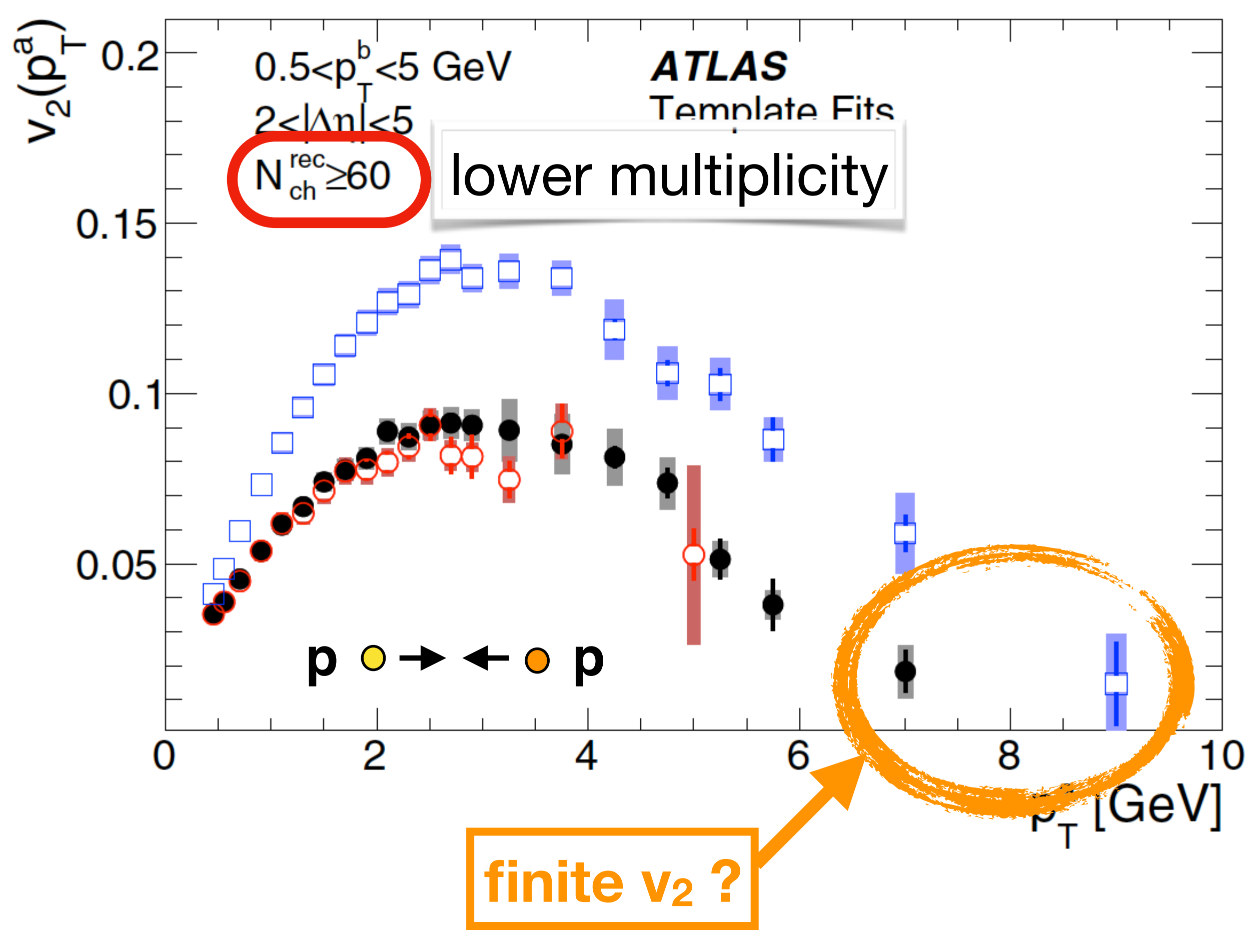



ALICE, arXiv:1805.05212 [nucl-ex] (2018)

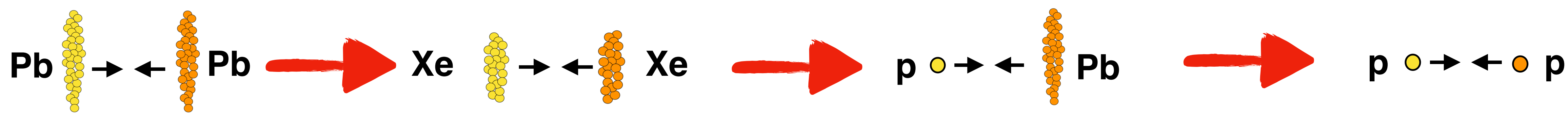
ATLAS, PRC **90**, 044906 (2014)

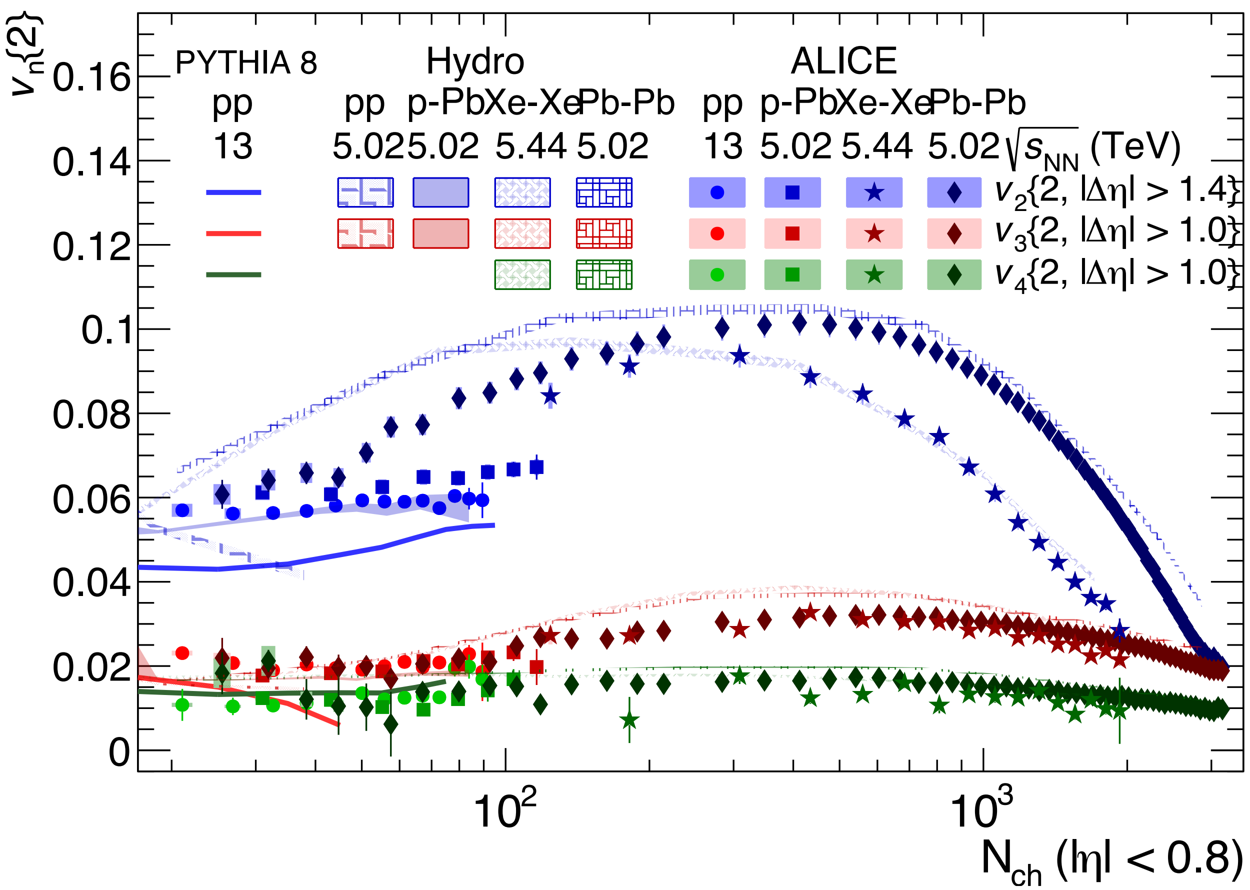


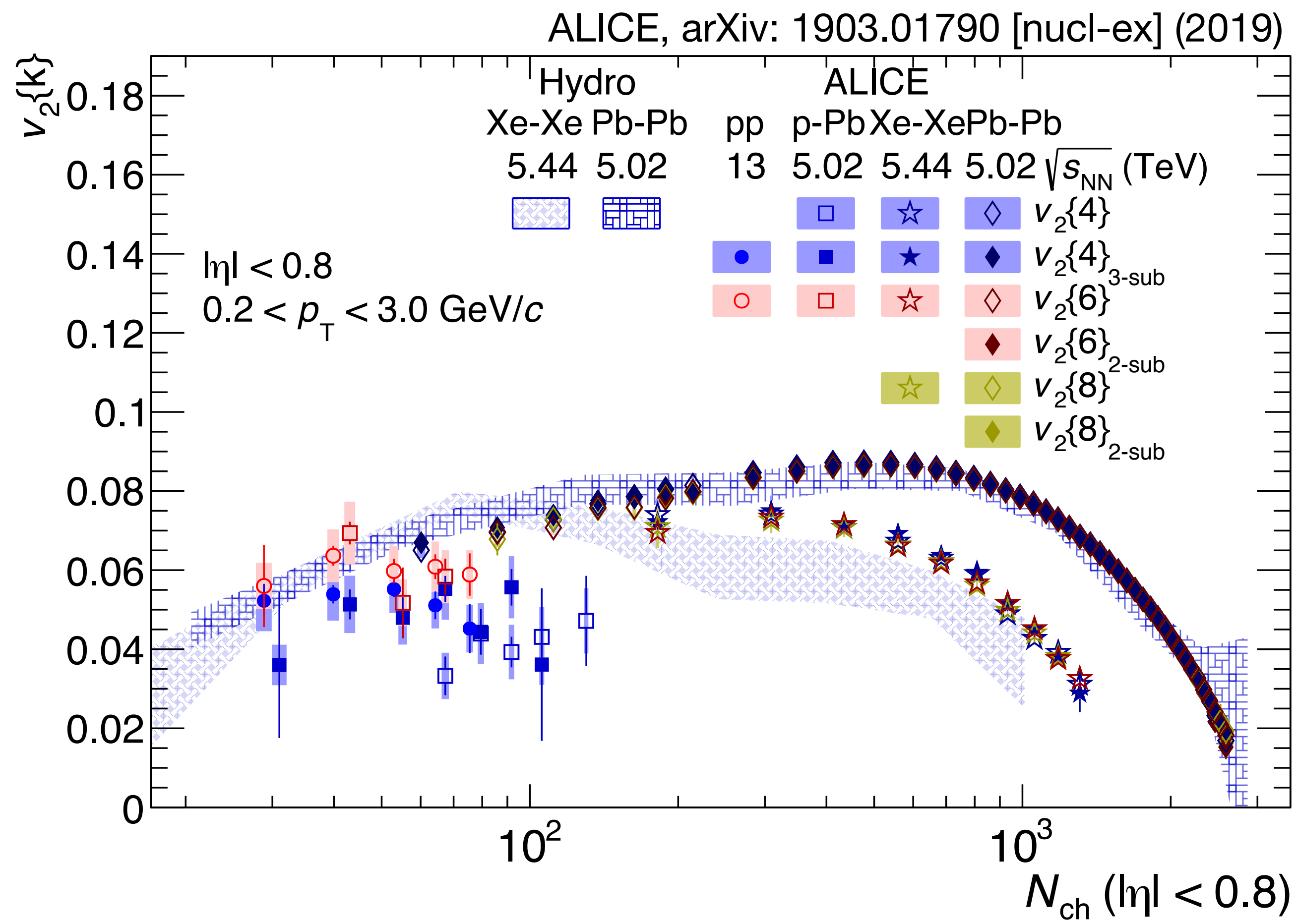

ATLAS, PRC **96**, 024908 (2017)



# From large to low multiplicities & systems




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

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

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