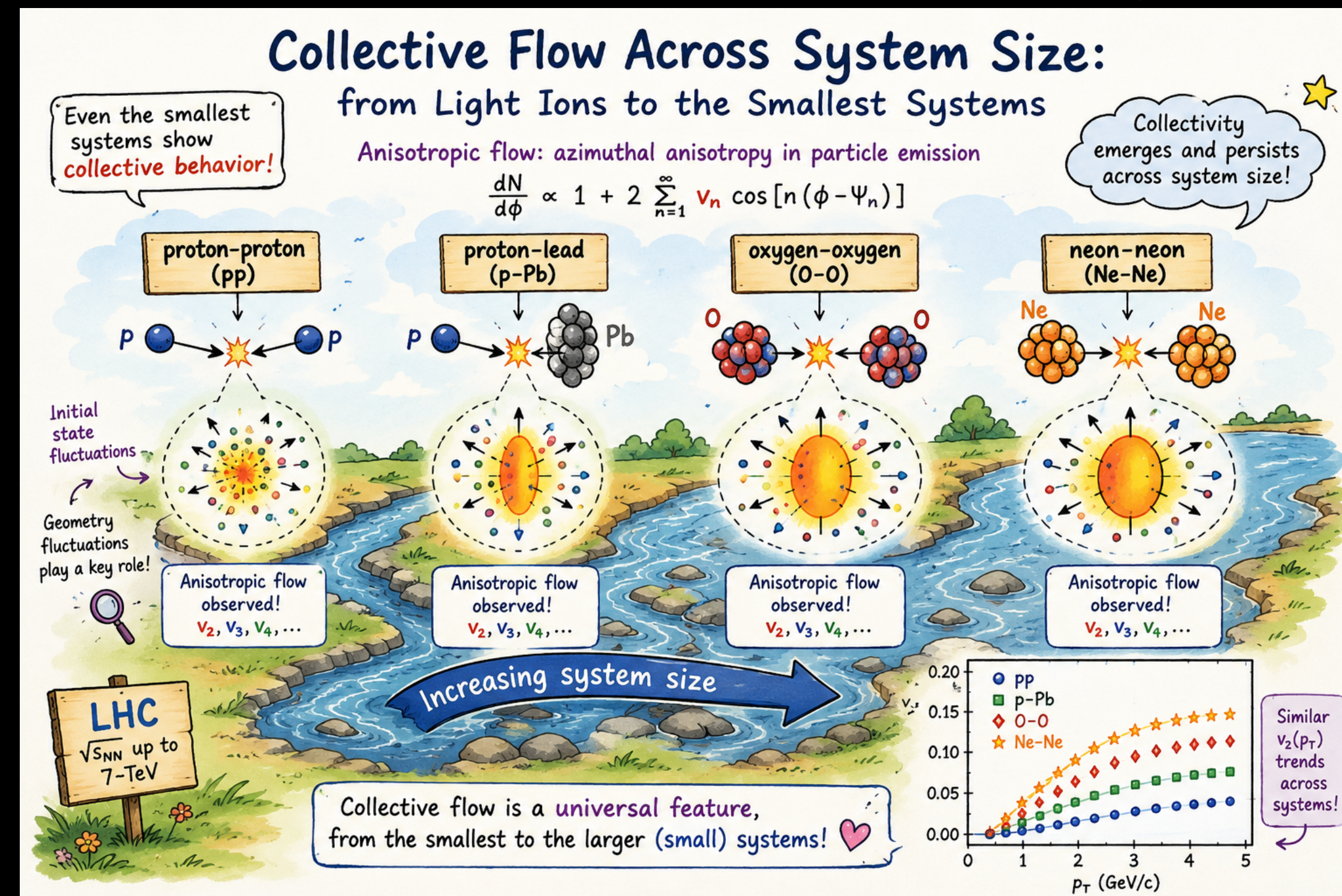


# Collective Flow Across System Size:

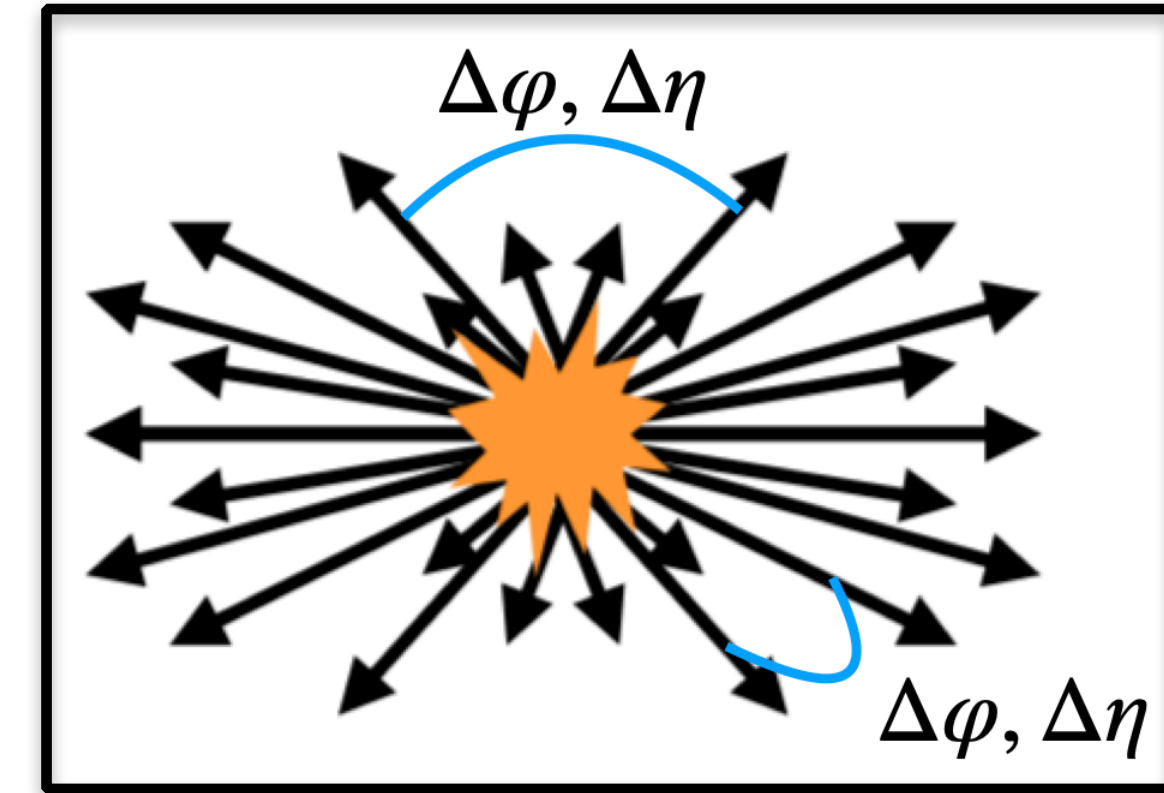
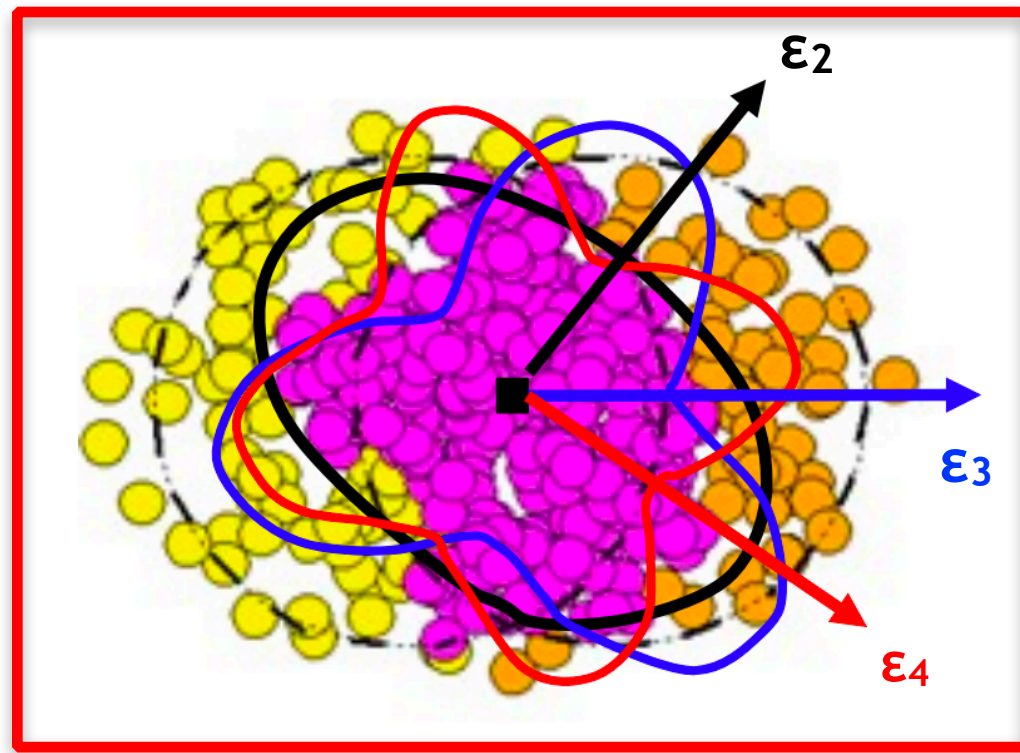
## Experimental overview on the most recent results

(Credit/mistakes by ChatGPT)





# What is collective flow



Jean-Yves Ollitrault,  
PRD 46, 229 (1992)

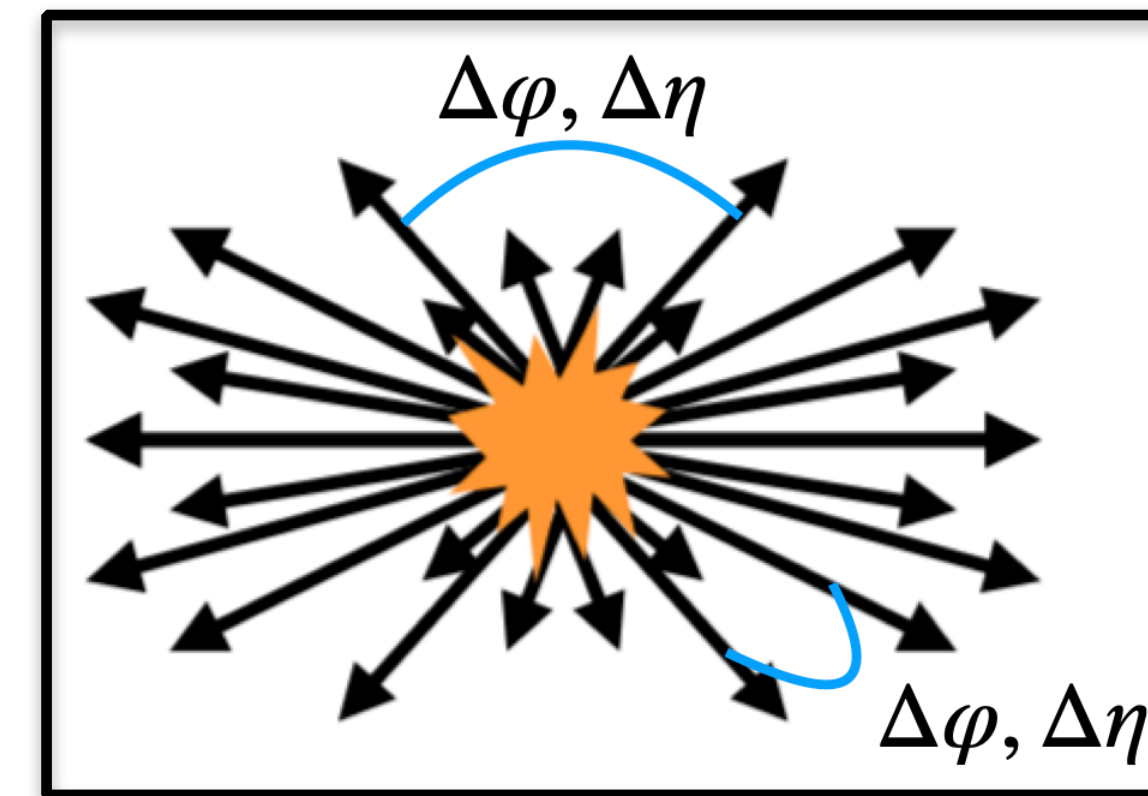
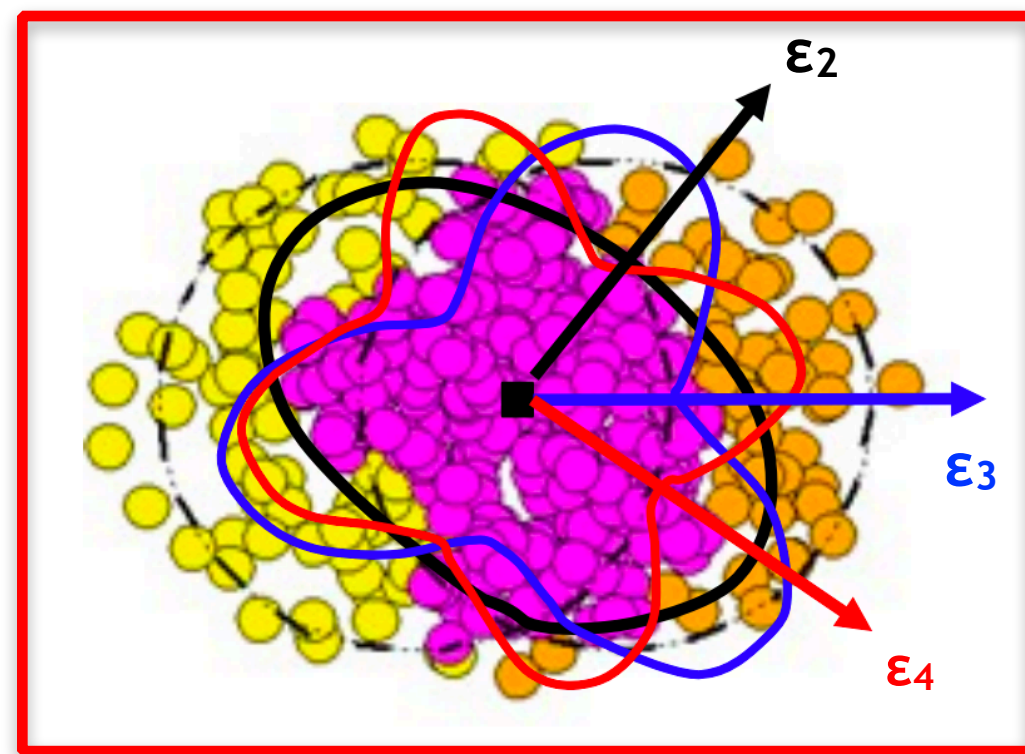
$$P(\epsilon_m, \epsilon_n, \epsilon_k, \dots, \Phi_m, \Phi_n, \Phi_k, \dots)$$



$$P(v_m, v_n, v_k, \dots, \Psi_m, \Psi_n, \Psi_k, \dots)$$



# What is collective flow



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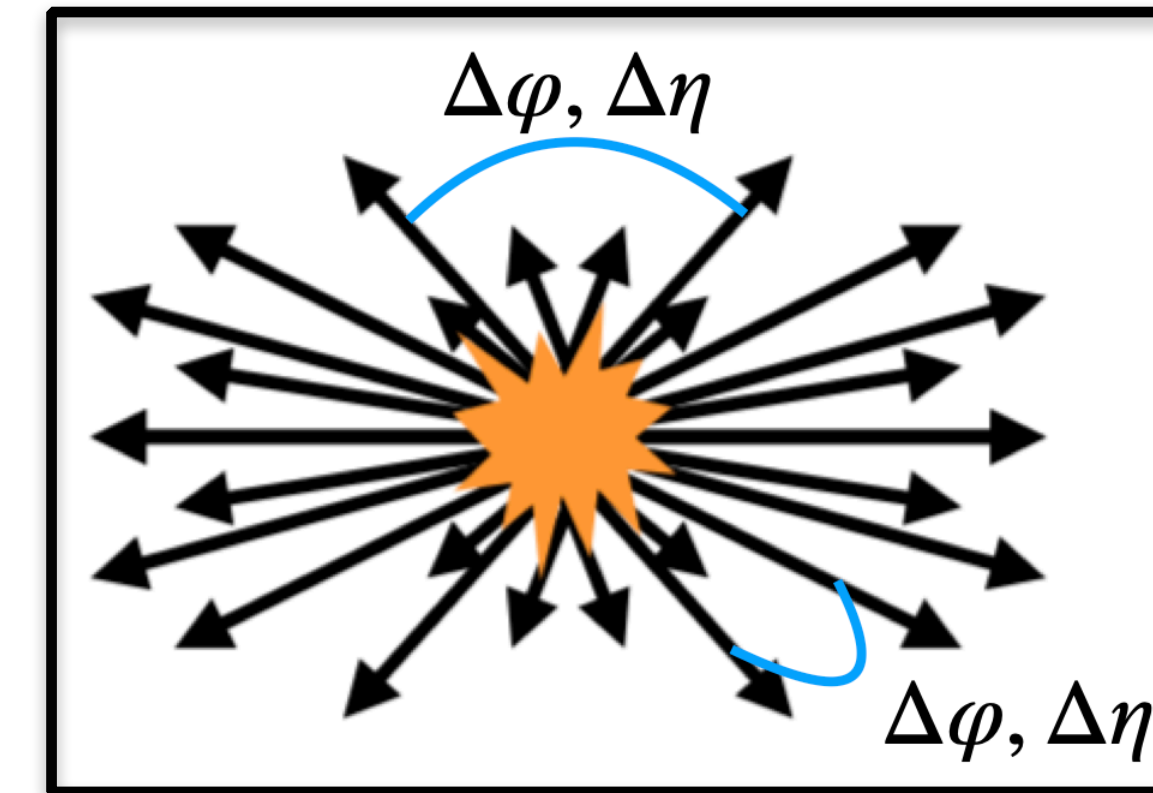
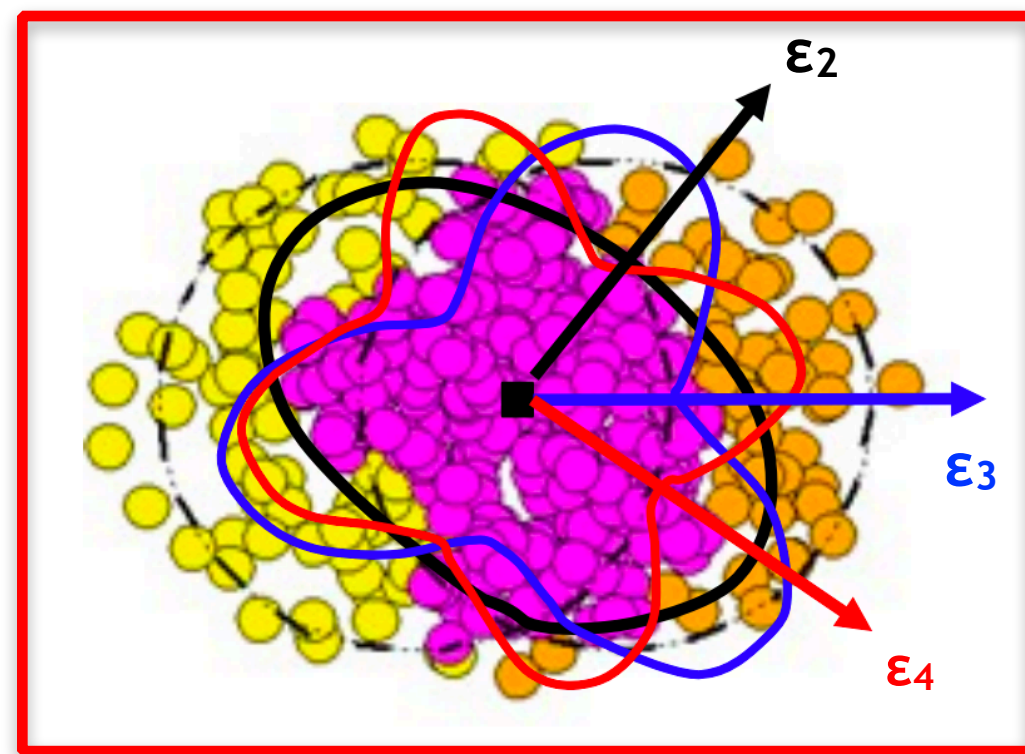
How does  $v_n$   
fluctuate

$$P(v_n)$$

ALICE, arXiv:2509.06428, accepted by PRL  
ALICE, Phys. Lett. B 850 (2024) 138477  
ALICE, JHEP 05 (2023) 243  
ALICE, Phys. Lett. B 777 (2018) 201  
ALICE, JHEP07(2018)103  
ALICE, Phys. Rev. Lett 116, 132302 (2016)  
ALICE, JHEP 06 (2015) 190  
ALICE, Phys. Rev. Lett 107, 032301 (2011)



# What is collective flow



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How does  $\psi_n$   
fluctuate

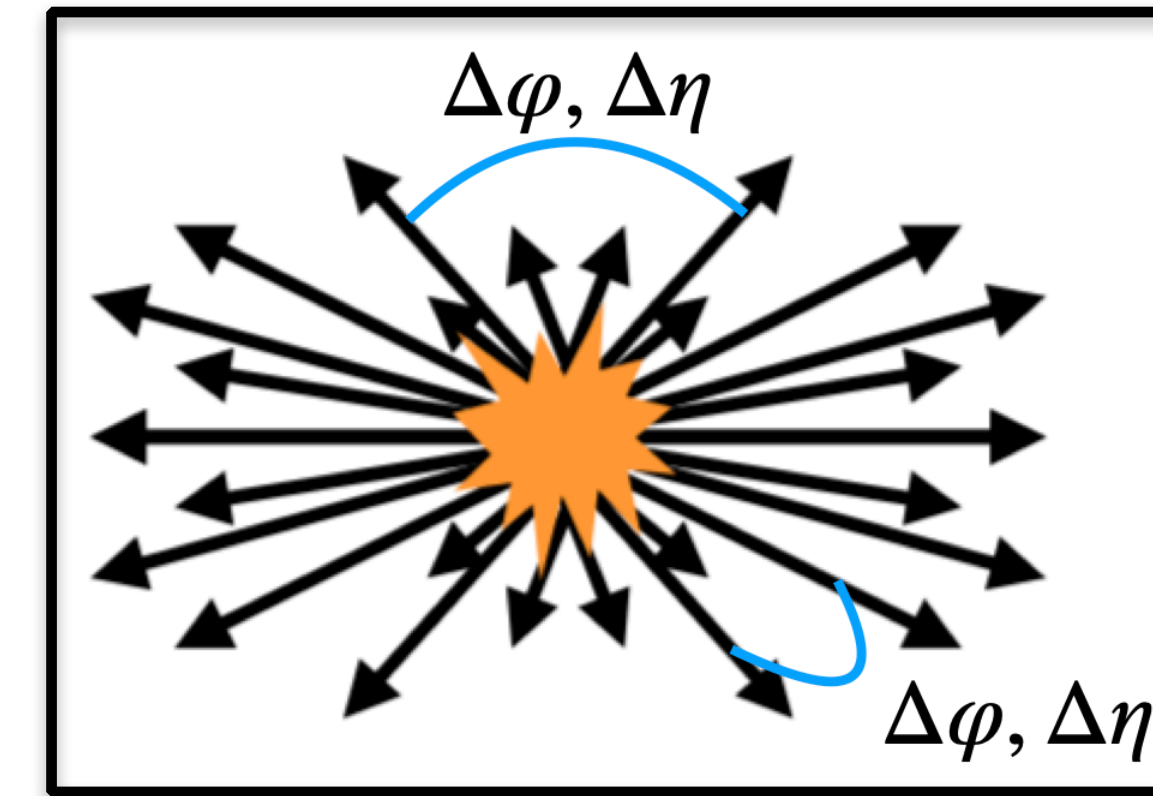
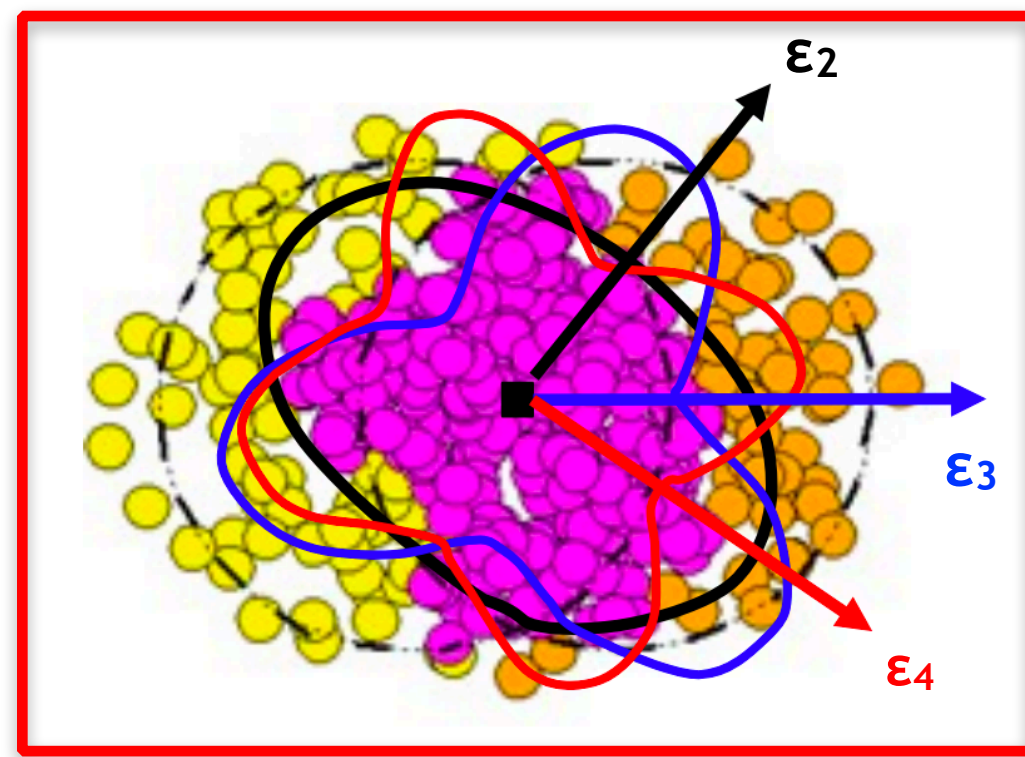
$$P(\Psi_n)$$

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ALICE, JHEP 09 (2017) 032



# What is collective flow



Jean-Yves Ollitrault,  
PRD 46, 229 (1992)

$$P(\varepsilon_m, \varepsilon_n, \varepsilon_k, \dots, \Phi_m, \Phi_n, \Phi_k, \dots)$$

$$P(v_m, v_n, v_k, \dots, \Psi_m, \Psi_n, \Psi_k, \dots)$$

How does  $v_n$   
fluctuate

$$P(v_n)$$

How does  $\psi_n$   
fluctuate

$$P(\Psi_n)$$

How do  $v_n$  and  $v_m$   
correlate

$$P(v_m, v_n, v_k, \dots)$$

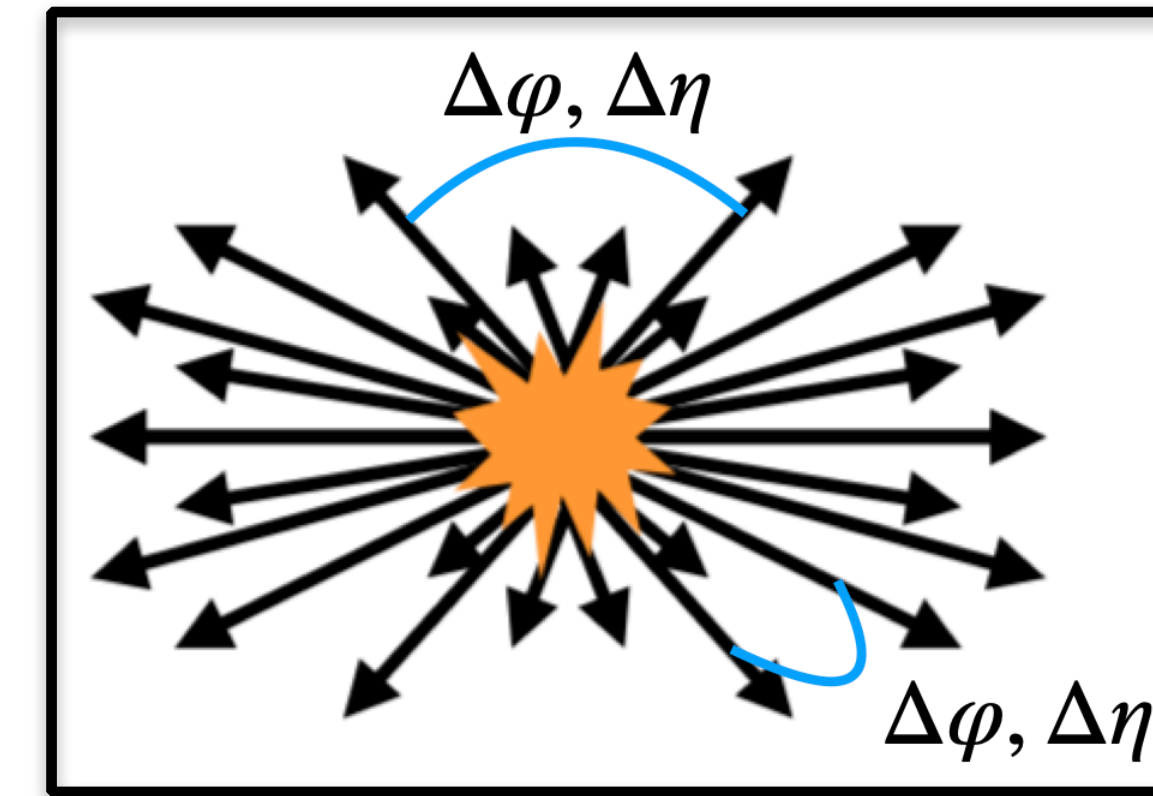
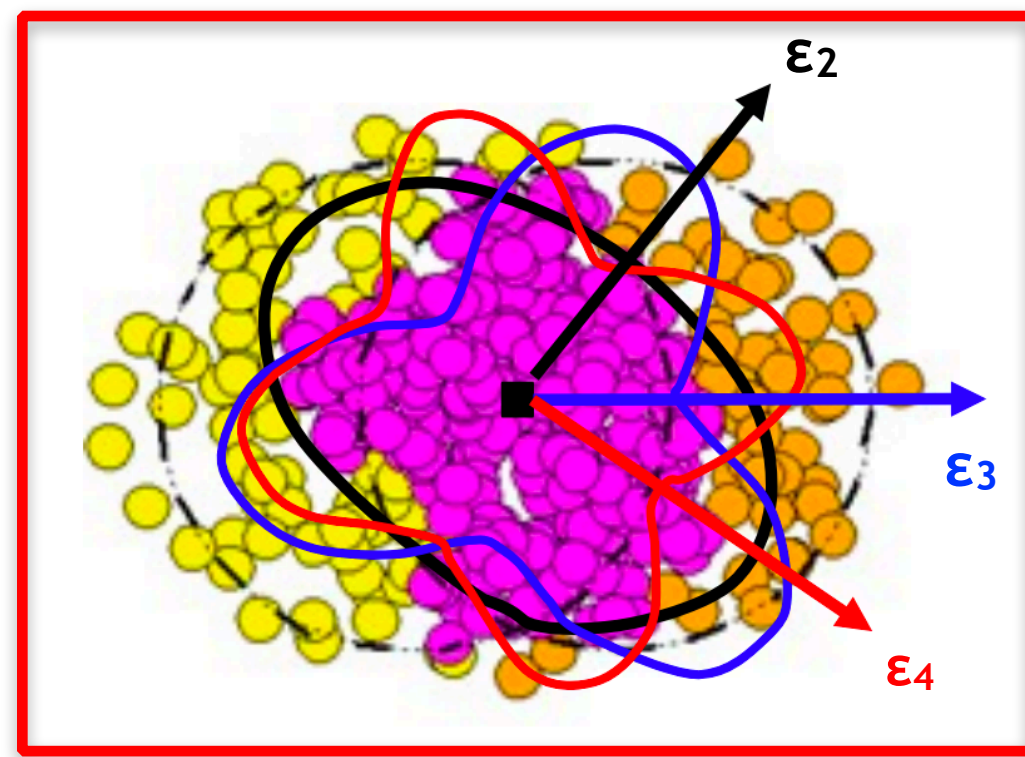
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ALICE, Phys. Lett. B 818 (2021) 136354  
ALICE, Phys. Rev. C 97, 024906 (2018)  
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# What is collective flow



Jean-Yves Ollitrault,  
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ALICE, Phys. Rev. C 107 (2023) L051901  
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ALICE, JHEP 09 (2017) 032

How do  $v_n$  and  $v_m$   
correlate

$$P(v_m, v_n, v_k, \dots)$$

ALICE, Phys. Lett. B 869 (2025) 139855  
ALICE, Phys. Lett. B 818 (2021) 136354  
ALICE, Phys. Rev. C 97, 024906 (2018)  
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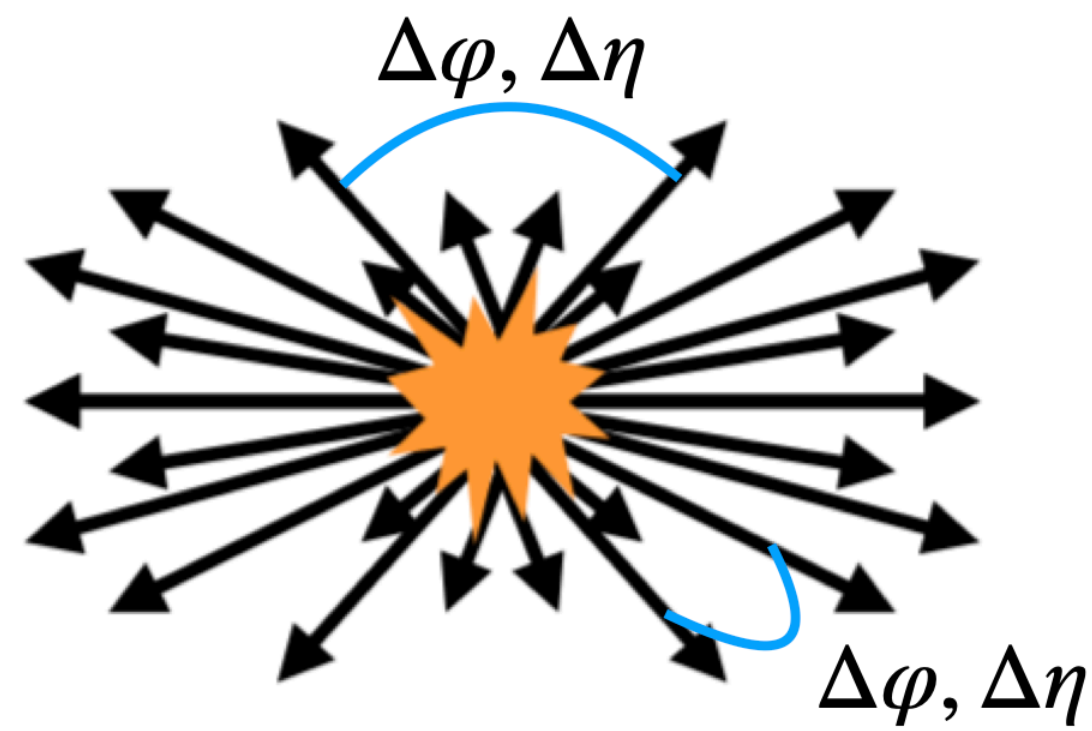
How do  $\psi_n$  and  
 $\psi_m$  correlate

$$P(\Psi_m, \Psi_n, \Psi_k, \dots)$$

ALICE, Phys. Lett. B 869 (2025) 139855  
ALICE, JHEP05 (2020) 085  
ALICE, JHEP06 (2020) 147  
ALICE, Phys. Lett. B 773 (2017) 68

# flow vs nonflow

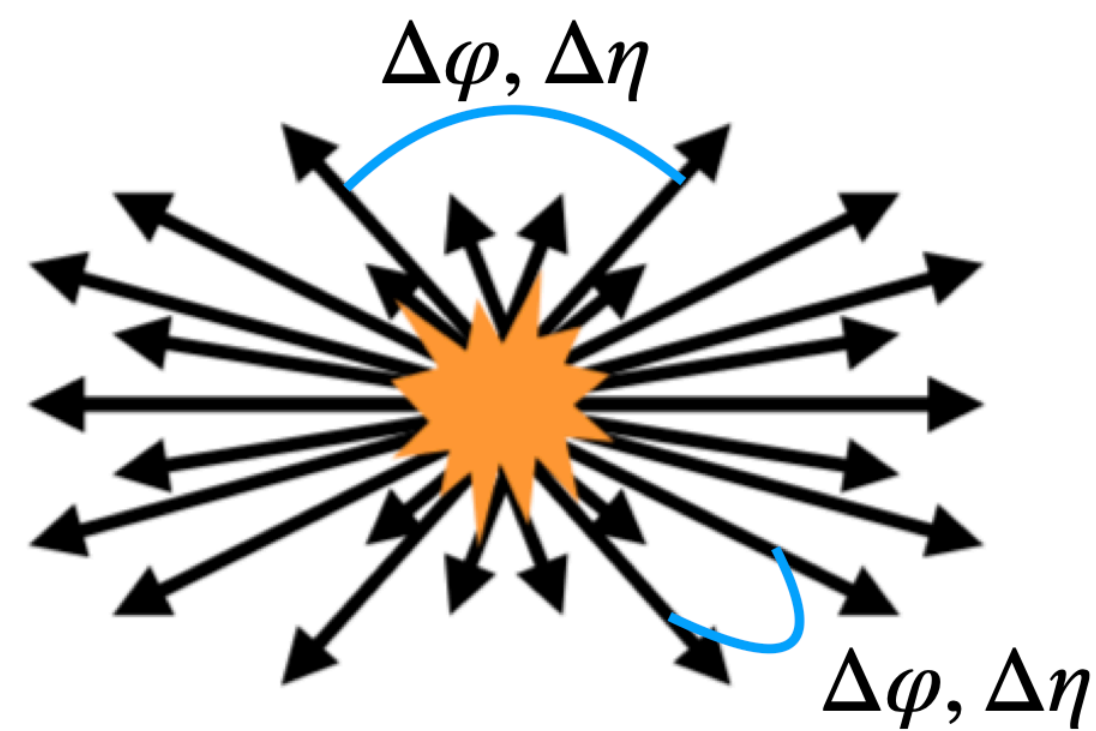
Flow





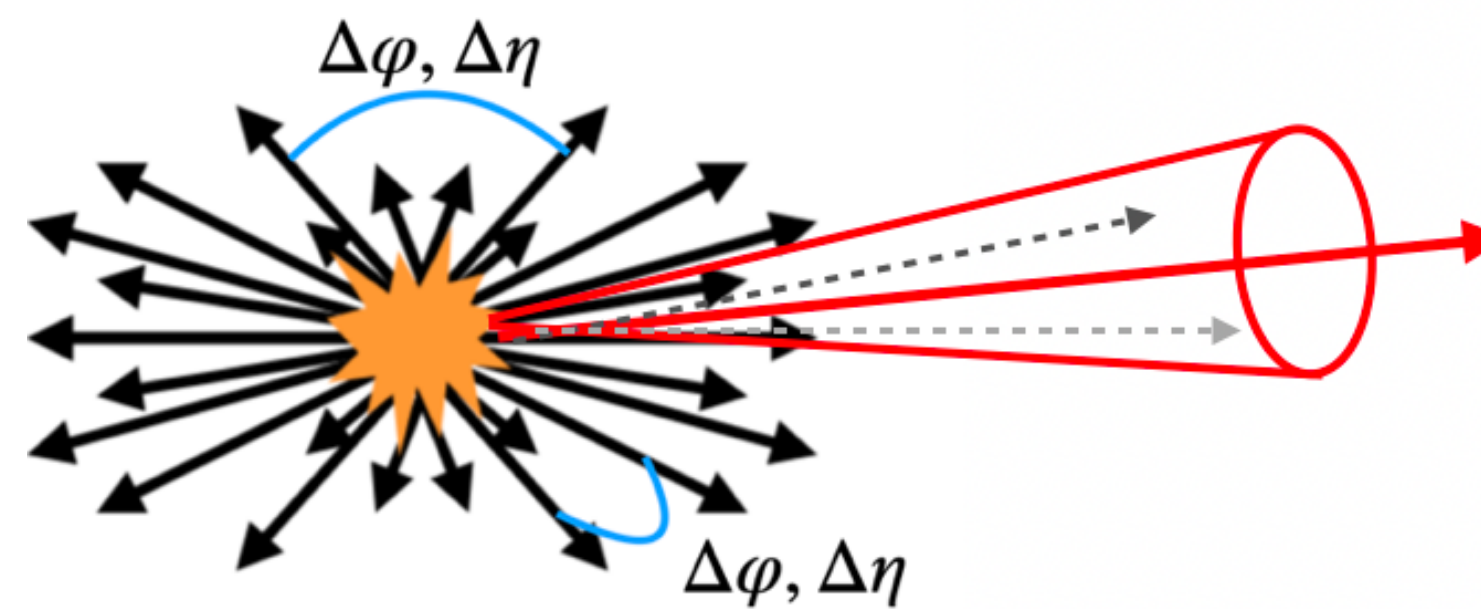
# flow vs nonflow

Flow

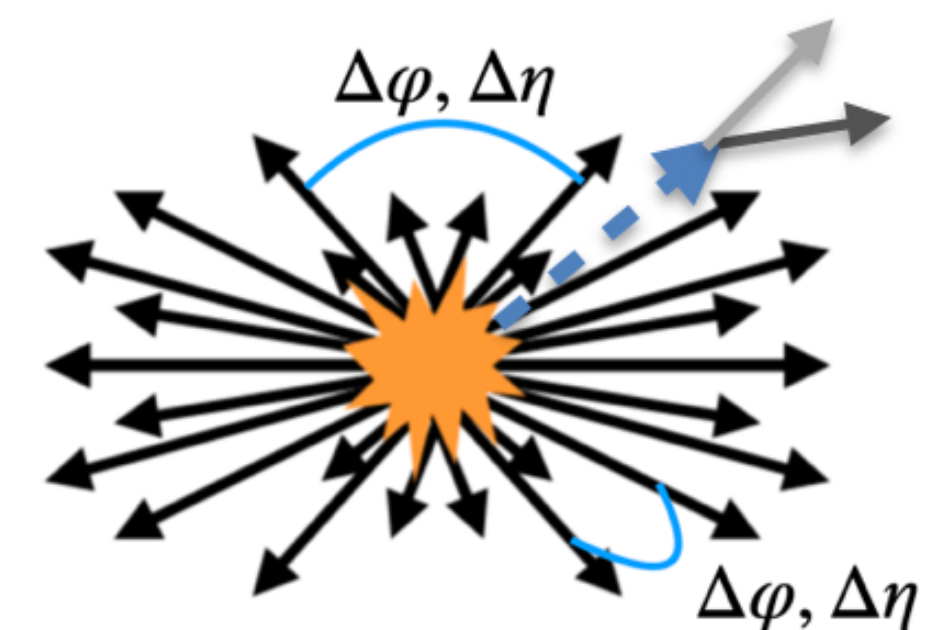


Nonflow

Jets



Resonances decay



# Flow vs nonflow

2017

Workshop on Collectivity in Small Collision Systems

May 9 – 11, 2017  
Niels Bohr Institute  
Europe/Copenhagen timezone

Enter your search term

Overview

Call for Abstracts

Timetable

Contribution List

Author List

My Conference

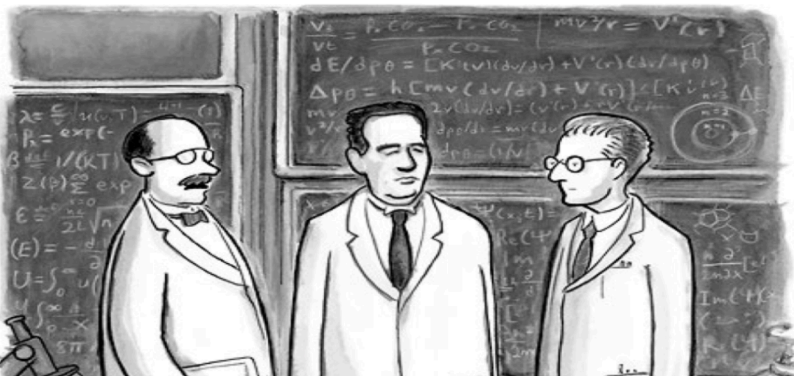
My Contributions

Registration

Accommodation

Participant List

Practical information



Is there collectivity in small systems? Copenhagen interpretation @  
**Workshop on Collectivity in Small Collision Systems**

2018

Second international workshop on Collectivity in Small Collision Systems (CSCS2018)

13–15 Jun 2018  
Wuhan, China  
Asia/Shanghai timezone

Enter your search term

Overview

Call for Abstracts

Timetable

Contribution List

Registration

CSCS2018 is the second edition of workshop on Collectivity in Small Collision Systems, following the recent event in [Copenhagen \(2017\)](#). It brings together physicists from around the world to discuss new developments in collectivity in small collision system. It aims at building a consensus on how to measure flow and interpret the results for small collision systems.

The workshop will take place at [Central China Normal University \(CCNU\)](#) in Wuhan, China.

2019

Workshop on collectivity of small systems in high-energy collisions

14–16 Mar 2019  
Rice University  
US/Central timezone

Enter your search term

Overview

Scientific Programme

Timetable

There has been long ongoing debate about the question whether the data on anisotropic particle emission in small systems are unambiguous evidence of collective flow from a hydrodynamic, expanding QGP medium, or whether they can also be explained in models describing the data as effects caused by the initial-state parton structure of the colliding nuclei.

2024

The 4th International Workshop on QCD Collectivity at the Smallest Scales

24–28 Jun 2024  
Qingdao Haitian Financial Center Hotel, Qingdao, China  
Asia/Shanghai timezone

Enter your search term

Overview

Program Committee

Call for Abstracts

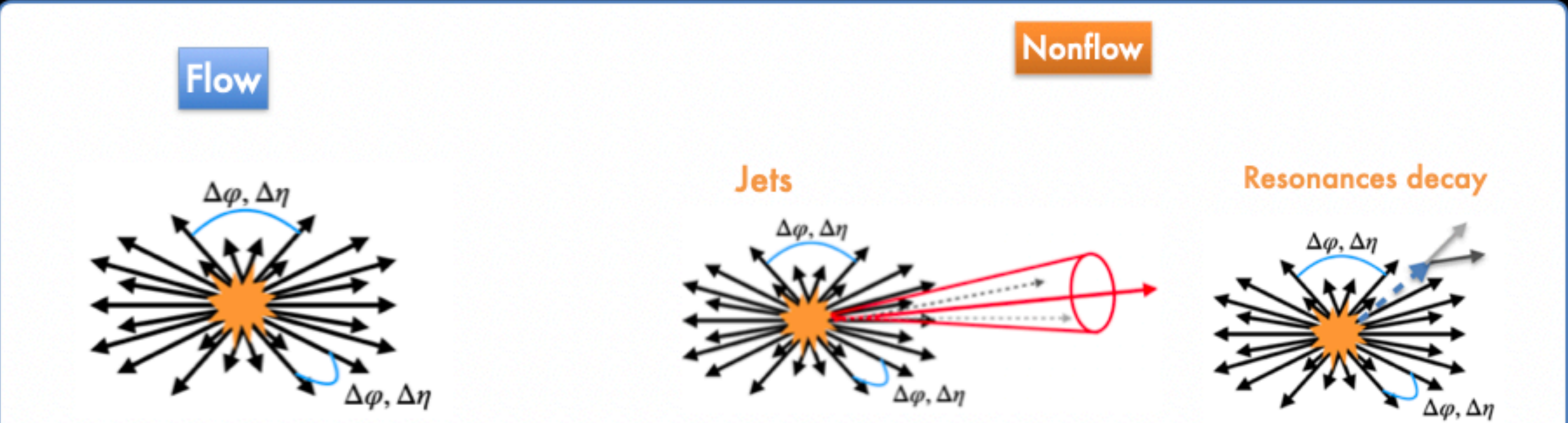
Timetable

The 4th edition of the International Workshop on QCD Collectivity at the Smallest Scales will be held June 24-28, 2024 in Qingdao. The workshop is organized by the institute of frontier and interdisciplinary science, Shandong University. It is dedicated to bring together experimentalist and theorist to discuss the recent experimental results and theoretical developments, to improve our understanding of collectivity in small systems, and to explore the future opportunities.

flow vs nonflow

Flow

Nonflow



❖ **Conceptually** flow is the global anisotropic particle expansion that described by a unified p.d.f.

❖ **Working definition:** Long-Range Multi-particle correlations

- Short-range correlation -> nonflow
- Few particle correlations-> nonflow

Small system workshops:  
NBI/Copenhagen (2017),  
CCNU/Wuhan (2018),  
Rice/Houston (2019),  
SDU/Qingdao (2024)

UNIVERSITY OF COPENHAGEN

You Zhou (NBI) @ Qingdao, China

June 24<sup>th</sup>, 2024

4

You Zhou (NBI) @ Small system Workshop, Paris

June 29<sup>th</sup>, 2026

4



UNIVERSITY OF COPENHAGEN



# Working definition

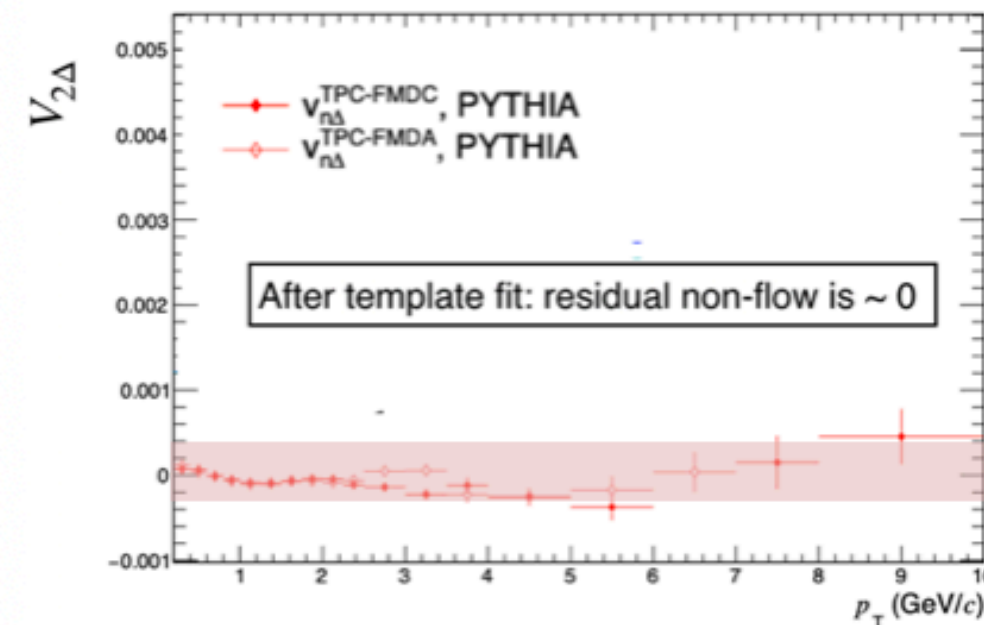
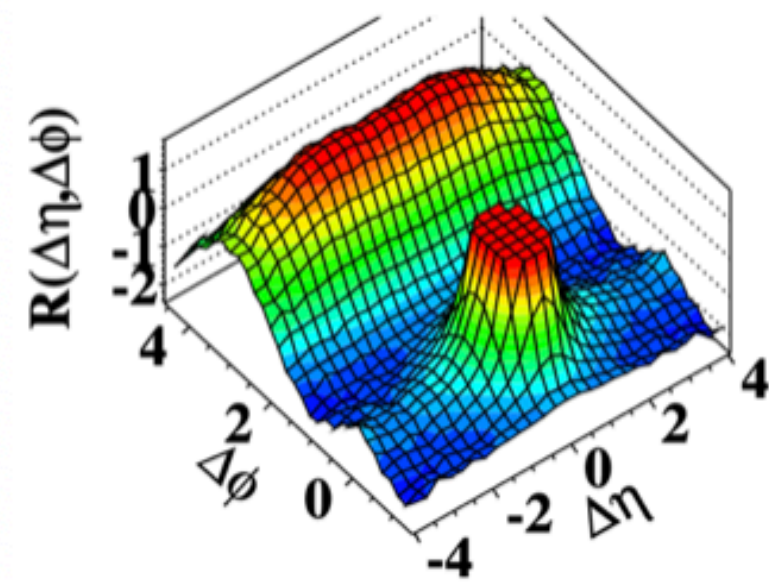
## Two-particle correlations

### Working definition for small systems

❖ How about 2-particle (di-hadron) correlations?

CMS, JHEP 09 (2010) 091

(d) CMS  $N \geq 110$ ,  $1.0 \text{ GeV}/c < p_T < 3.0 \text{ GeV}/c$



- The 2-particle correlations in the **nonflow** model, after subtraction, are compatible with zero (necessary conditions)

### Non-flow subtraction in di-hadron correlation

- Peripheral subtraction
- Template fit
- Improved template fit



# Working definition

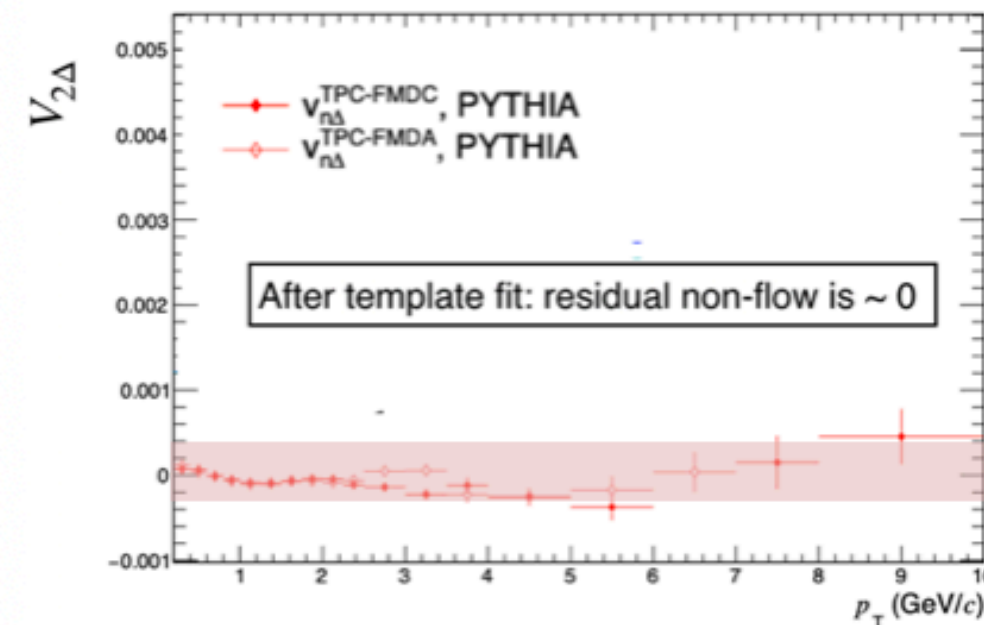
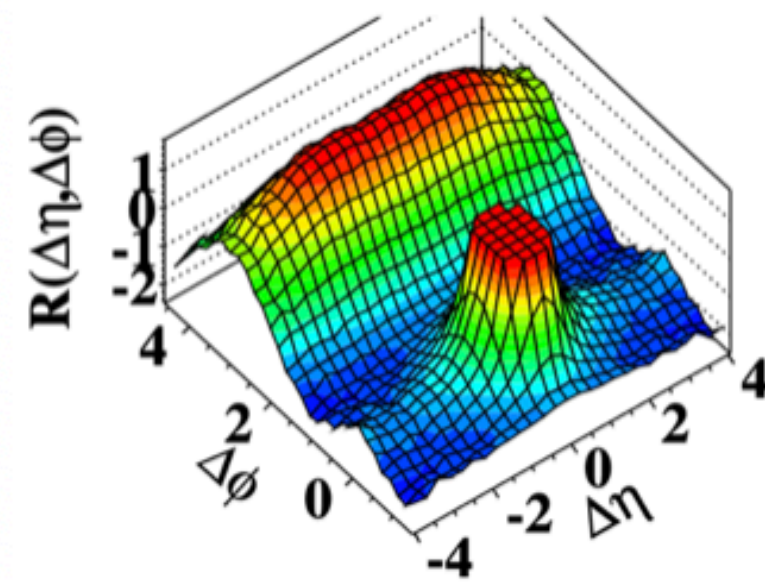
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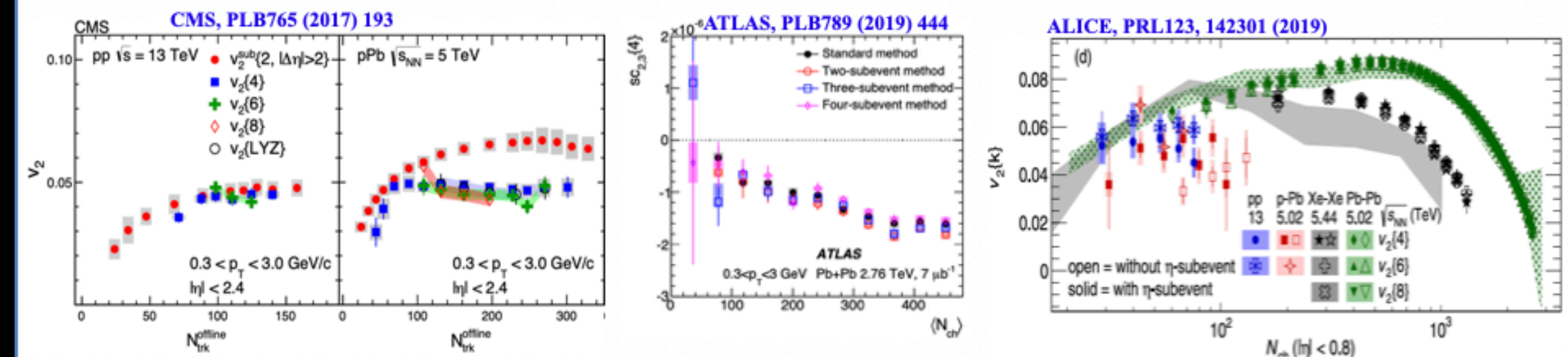


- The 2-particle correlations in the **nonflow** model, after subtraction, are compatible with zero (necessary conditions)

## Multi-particle correlations

### Working definition for small systems

❖ **Working definition:** Long-Range Multi-particle correlations



- $v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$
- Compatible results of multi-particle cumulants with two-sub, three-sub and four-subevent methods
- Evidence of flow in small collision systems at the LHC

### Non-flow subtraction in di-hadron correlation

- Peripheral subtraction
- Template fit
- Improved template fit

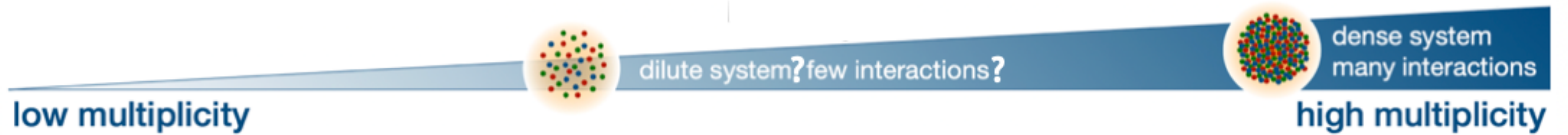
### Sub-event method:

- J. Jia etc., PRC 96 (2017) 3, 034906
- P. Huo etc., PLB 777 (2018) 201

For nonflow subtraction in multi-particle correlations, see:  
Z. Wang etc., arXiv:2606.10258



# Status before July 2025



# Status before July 2025



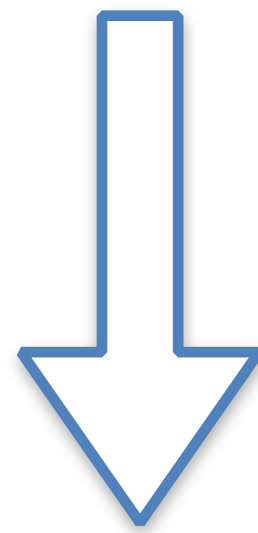
- ❖ Observation of flow
- ❖ Signature of QGP
- ❖ Nicely described by theory



# Status before July 2025

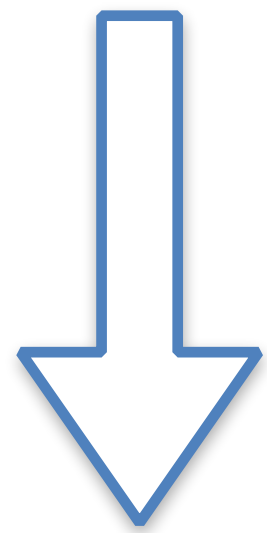


HM  $pp/p\text{-Pb}$



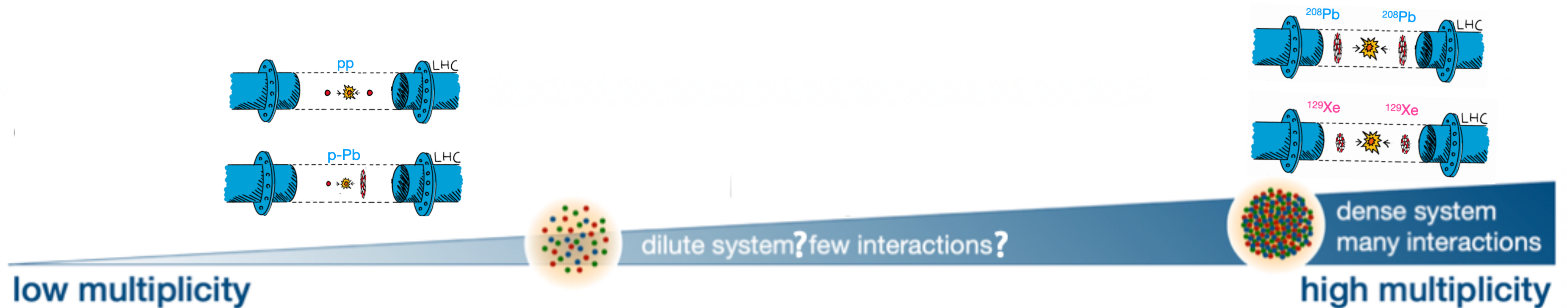
- ❖ Observation of flow
- ❖ Signature of QGP
- ❖ Not described by theory

Heavy-ion



- ❖ Observation of flow
- ❖ Signature of QGP
- ❖ Nicely described by theory

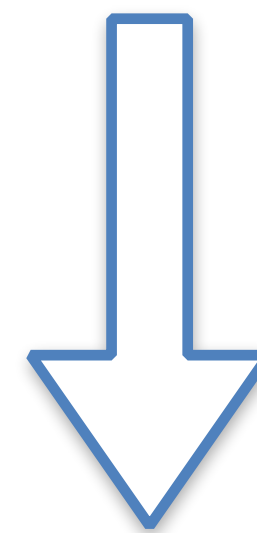
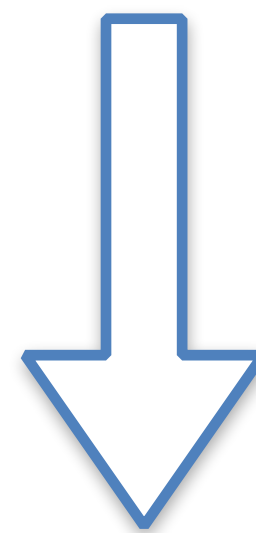
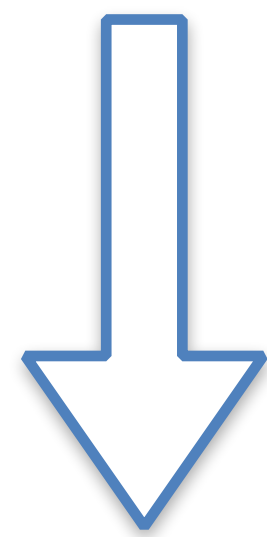
# Status before July 2025



M.B. pp/p-Pb

HM pp/p-Pb

Heavy-ion



- ❖ Observation of flow
- ❖ No signature of QGP
- ❖ Not described by any theory

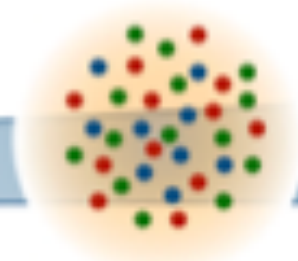
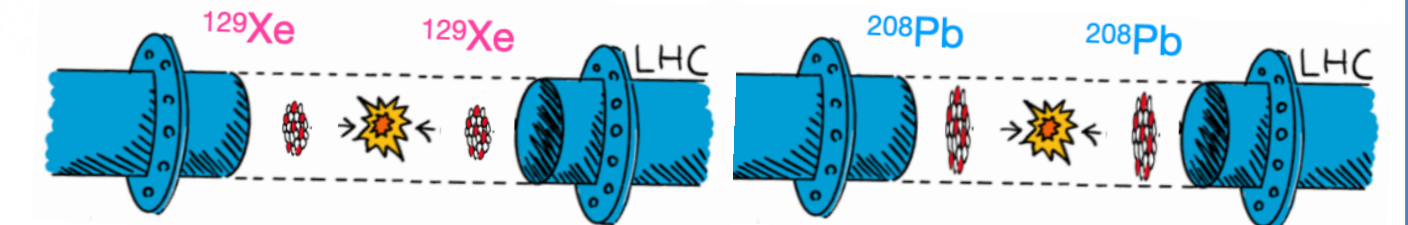
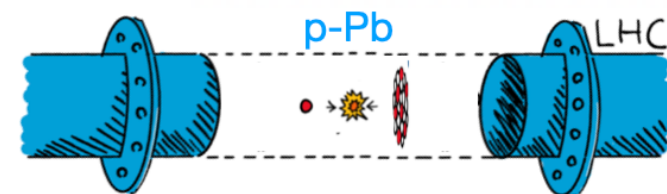
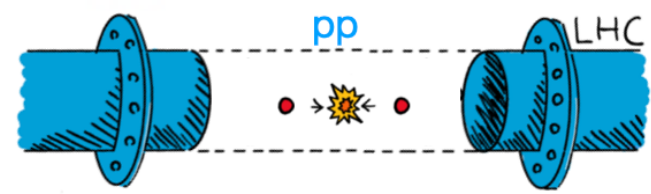
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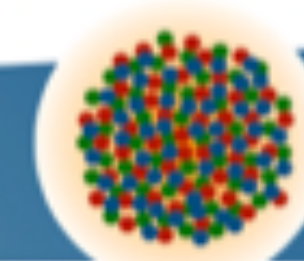


# Bridges the gap with light-ion collisions

Run 3



dilute system? few interactions?

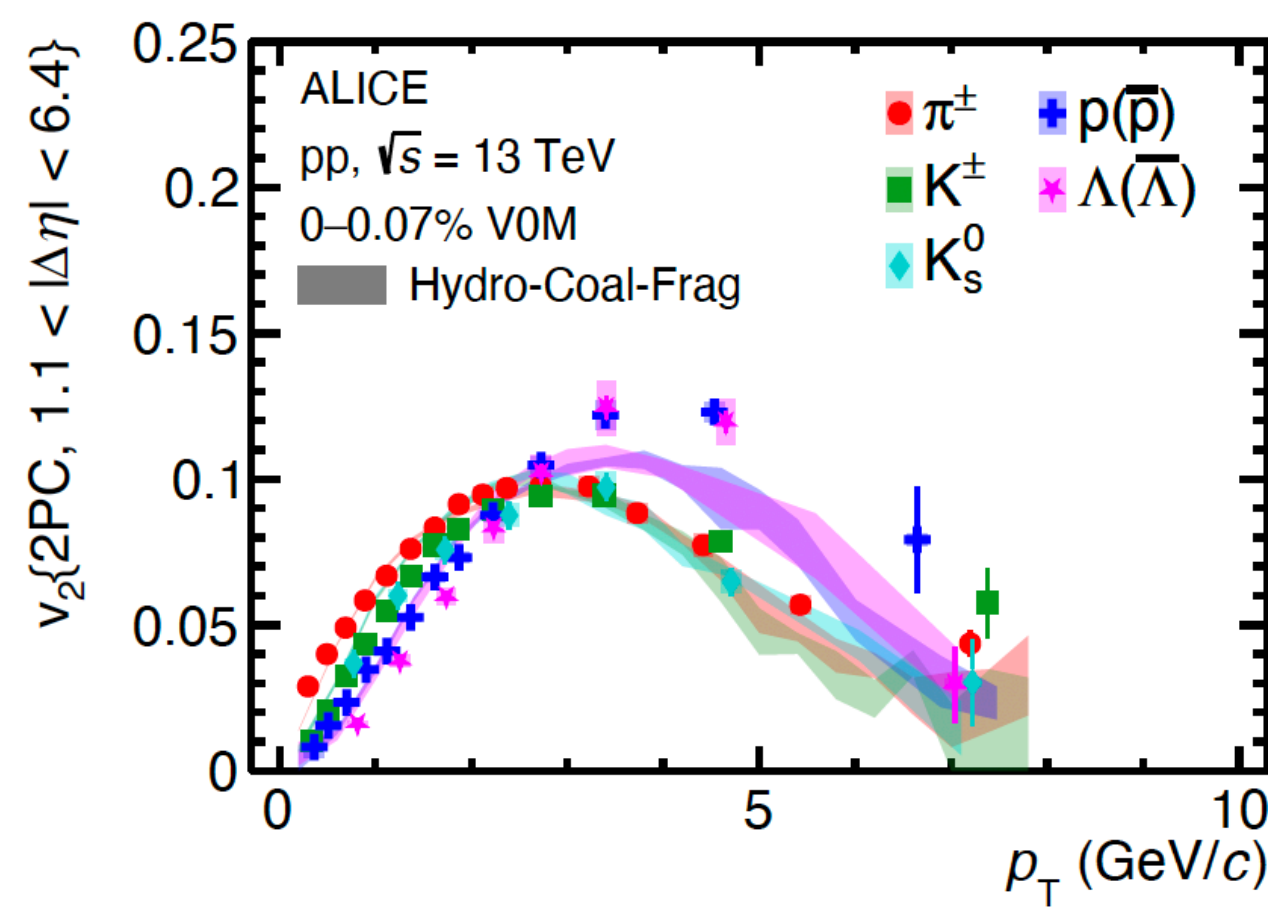


dense system  
many interactions

low multiplicity

high multiplicity

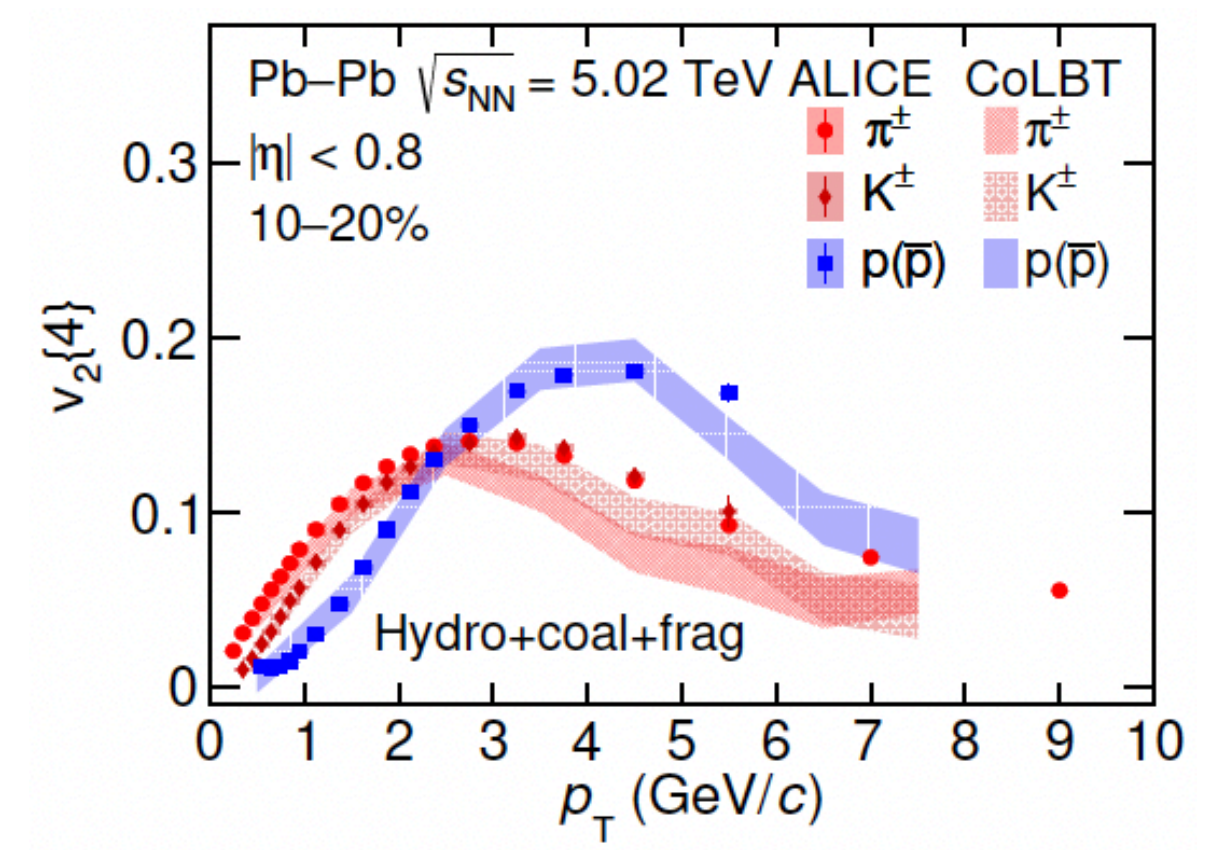
**pp and p-Pb**



Geometry fluctuation-driven flow

→ Very challenging to model

**Pb-Pb**



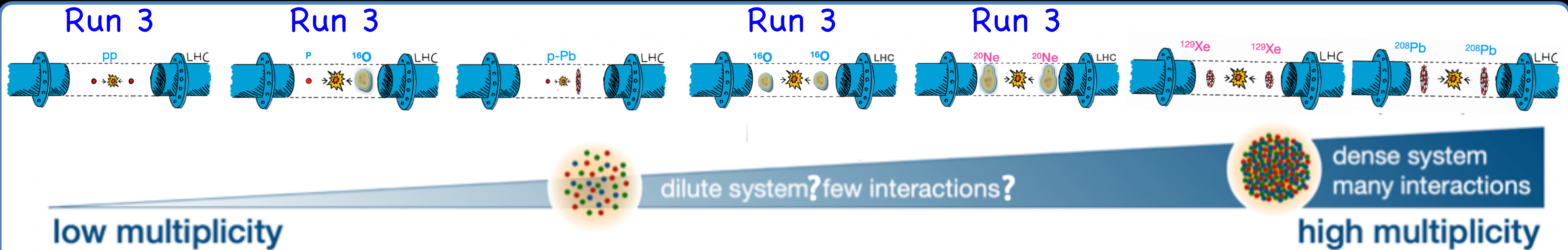
Geometry-driven flow

→ Precise model description

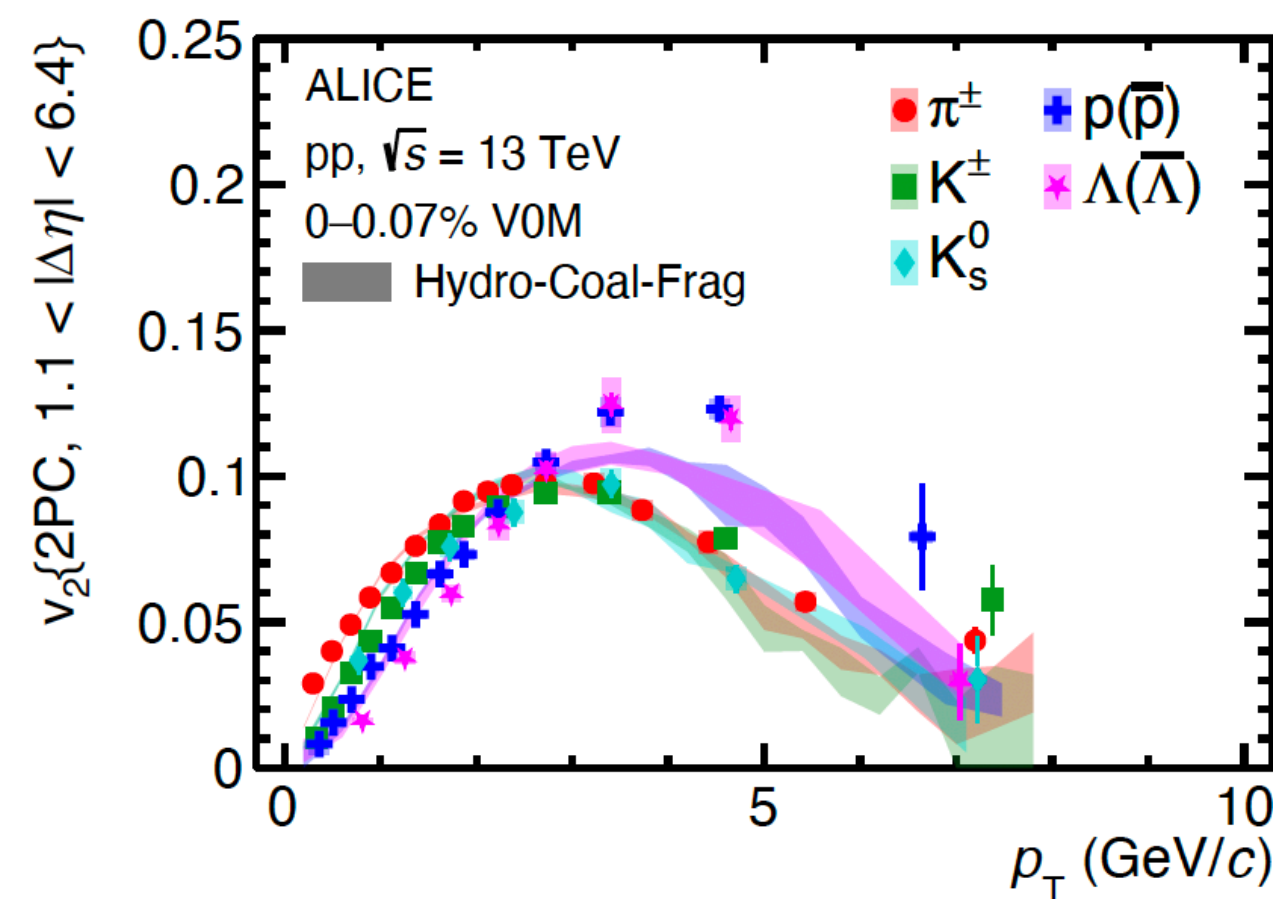




# Bridges the gap with light-ion collisions



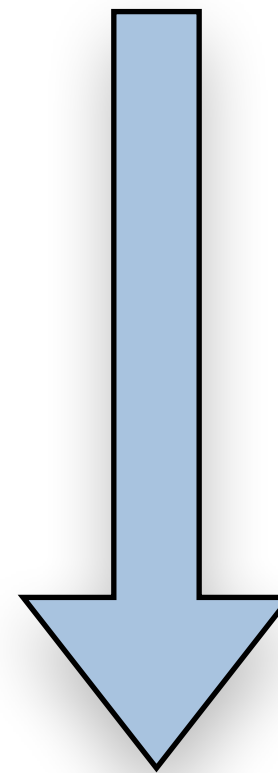
***pp and p-Pb***



# Geometry fluctuation-driven flow

➔ Very challenging to model

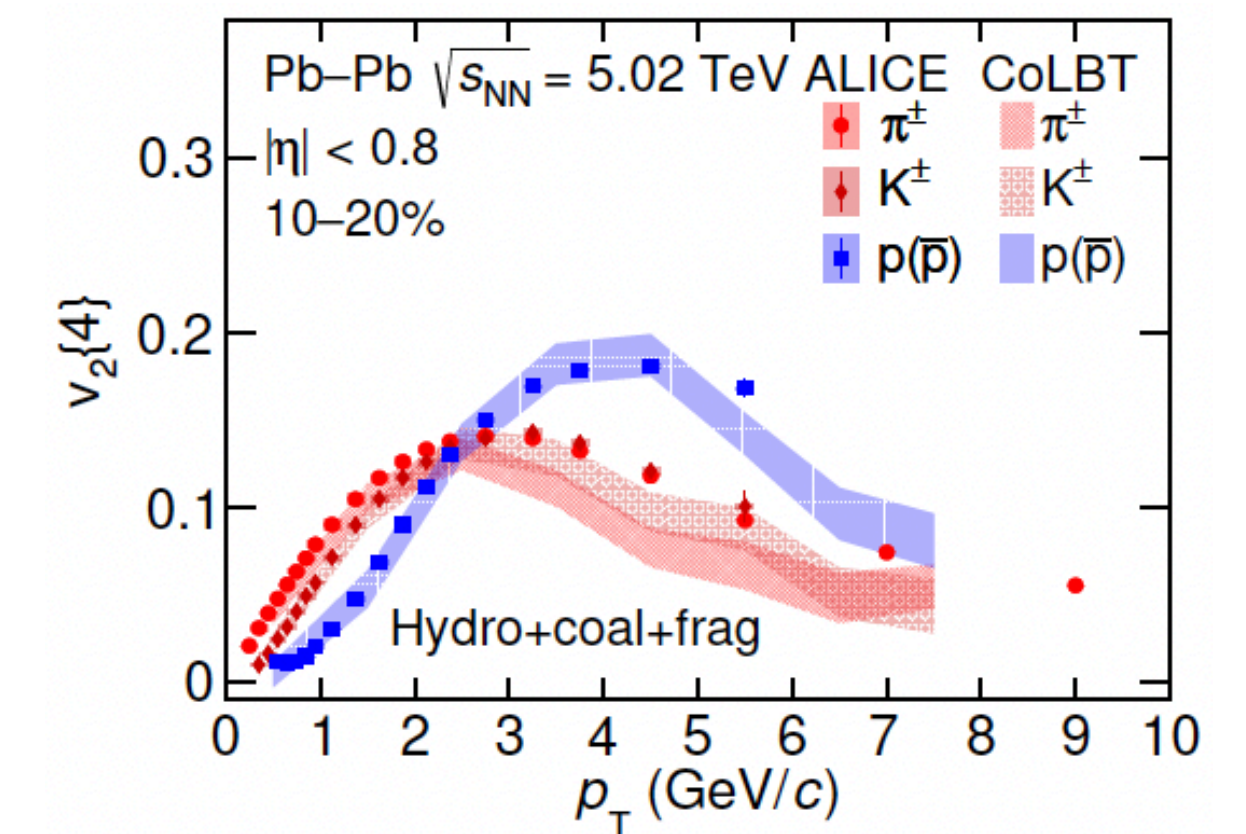
## July 2025, OO and Ne-Ne



## Emergence of geometry-driven flow

→ Well known Nuclear Structure as input

***Pb—Pb***



# Geometry-driven flow

➔ Precise model description



# Summary in the CERN Yellow Report



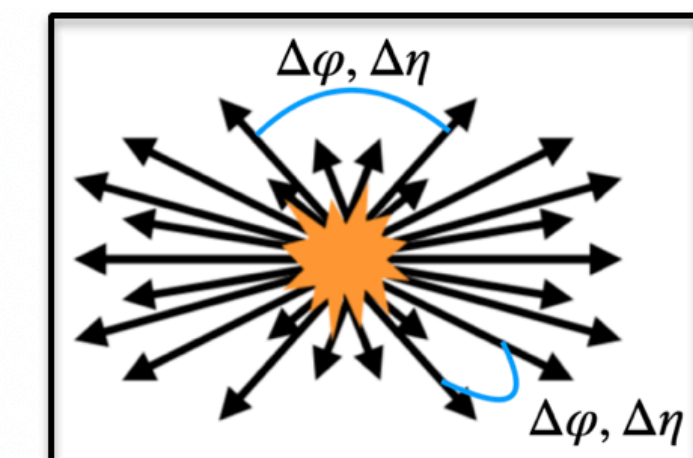
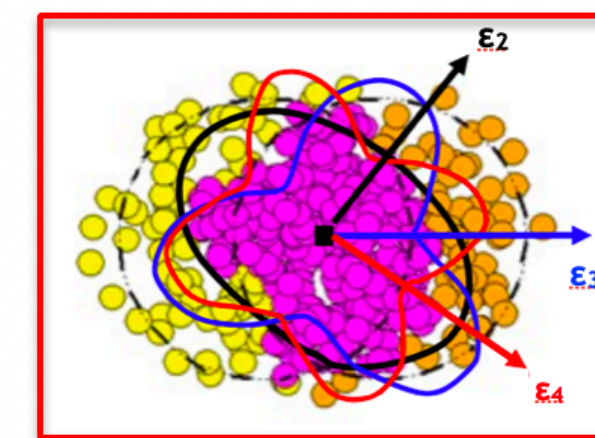
CERN-LPCC-2018-07  
February 26, 2019

## Future physics opportunities for high-density QCD at the LHC with heavy-ion and proton beams

Report from Working Group 5 on the Physics of the HL-LHC, and Perspectives at the HE-LHC

### 9 Emergence of hot and dense QCD matter in small systems

| Observable or effect                                            | Pb-Pb                                                             | p-Pb (high mult.)                                                 | pp (high mult.)         |
|-----------------------------------------------------------------|-------------------------------------------------------------------|-------------------------------------------------------------------|-------------------------|
| Azimuthal anisotropy ( $v_n$ ) (from two particle correlations) | $v_1-v_7$                                                         | $v_1-v_5$                                                         | $v_2-v_4$               |
| Characteristic mass dependence                                  | $v_2-v_5$                                                         | $v_2, v_3$                                                        | $v_2$                   |
| Directed flow (from spectators)                                 | yes                                                               | no                                                                | no                      |
| Charge-dependent correlations                                   | yes                                                               | yes                                                               | yes                     |
| Higher-order cumulants (mainly $v_2\{n\}, n \geq 4$ )           | " $4 \approx 6 \approx 8 \approx \text{LYZ}$ " + higher harmonics | " $4 \approx 6 \approx 8 \approx \text{LYZ}$ " + higher harmonics | " $4 \approx 6$ "       |
| Symmetric cumulants                                             | up to SC(5, 3)                                                    | only SC(4, 2), SC(3, 2)                                           | only SC(4, 2), SC(3, 2) |
| Non-linear flow modes                                           | up to $v_6$                                                       | not measured                                                      | not measured            |
| Weak $\eta$ dependence                                          | yes                                                               | yes                                                               | not measured            |
| Factorization breaking                                          | yes ( $n = 2, 3$ )                                                | yes ( $n = 2, 3$ )                                                | not measured            |
| Event-by-event $v_n$ distributions                              | $n = 2-4$                                                         | not measured                                                      | not measured            |



Jean-Yves Ollitrault,  
PRD 46, 229 (1992)

$$P(\varepsilon_m, \varepsilon_n, \varepsilon_k, \dots, \Phi_m, \Phi_n, \Phi_k, \dots)$$

$$P(v_m, v_n, v_k, \dots, \Psi_m, \Psi_n, \Psi_k, \dots)$$

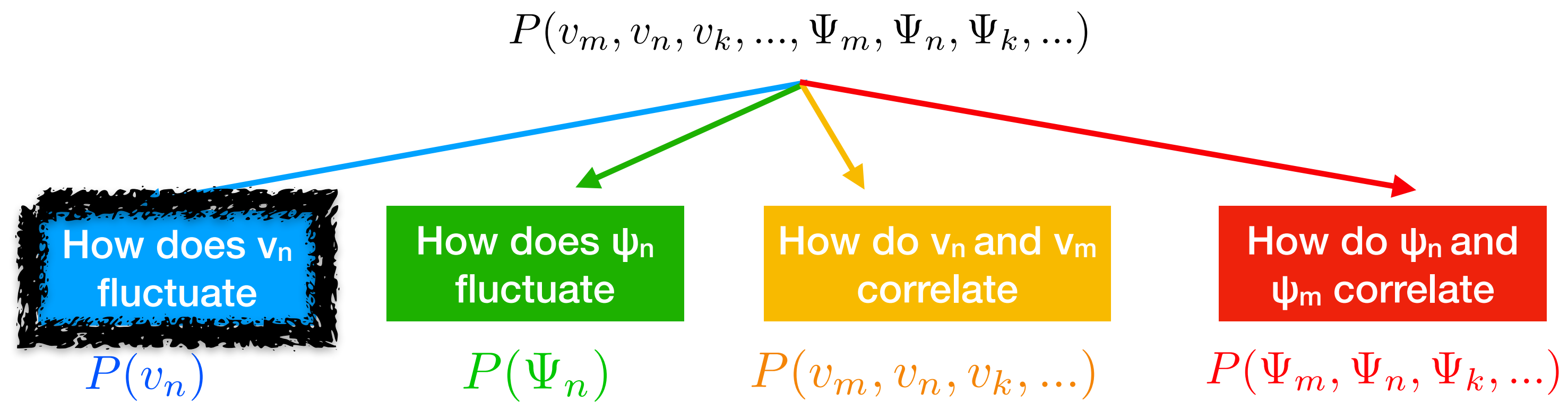
How does  $v_n$  fluctuate  
 $P(v_n)$

How does  $\psi_n$  fluctuate  
 $P(\Psi_n)$

How do  $v_n$  and  $v_m$  correlate  
 $P(v_m, v_n, v_k, \dots)$

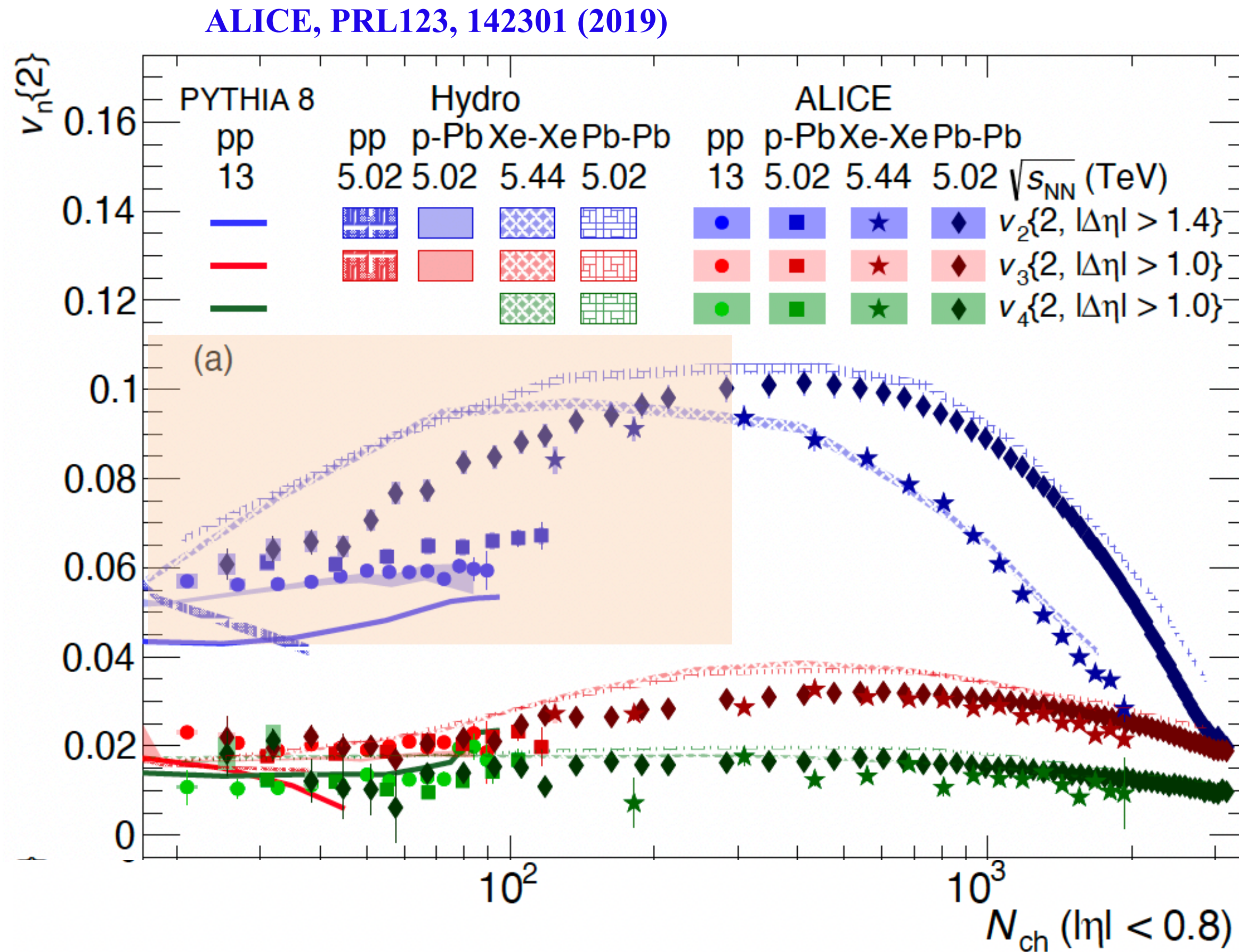
How do  $\psi_n$  and  $\psi_m$  correlate  
 $P(\Psi_m, \Psi_n, \Psi_k, \dots)$







# Origin(s): geometry driven @ LHC System Scan



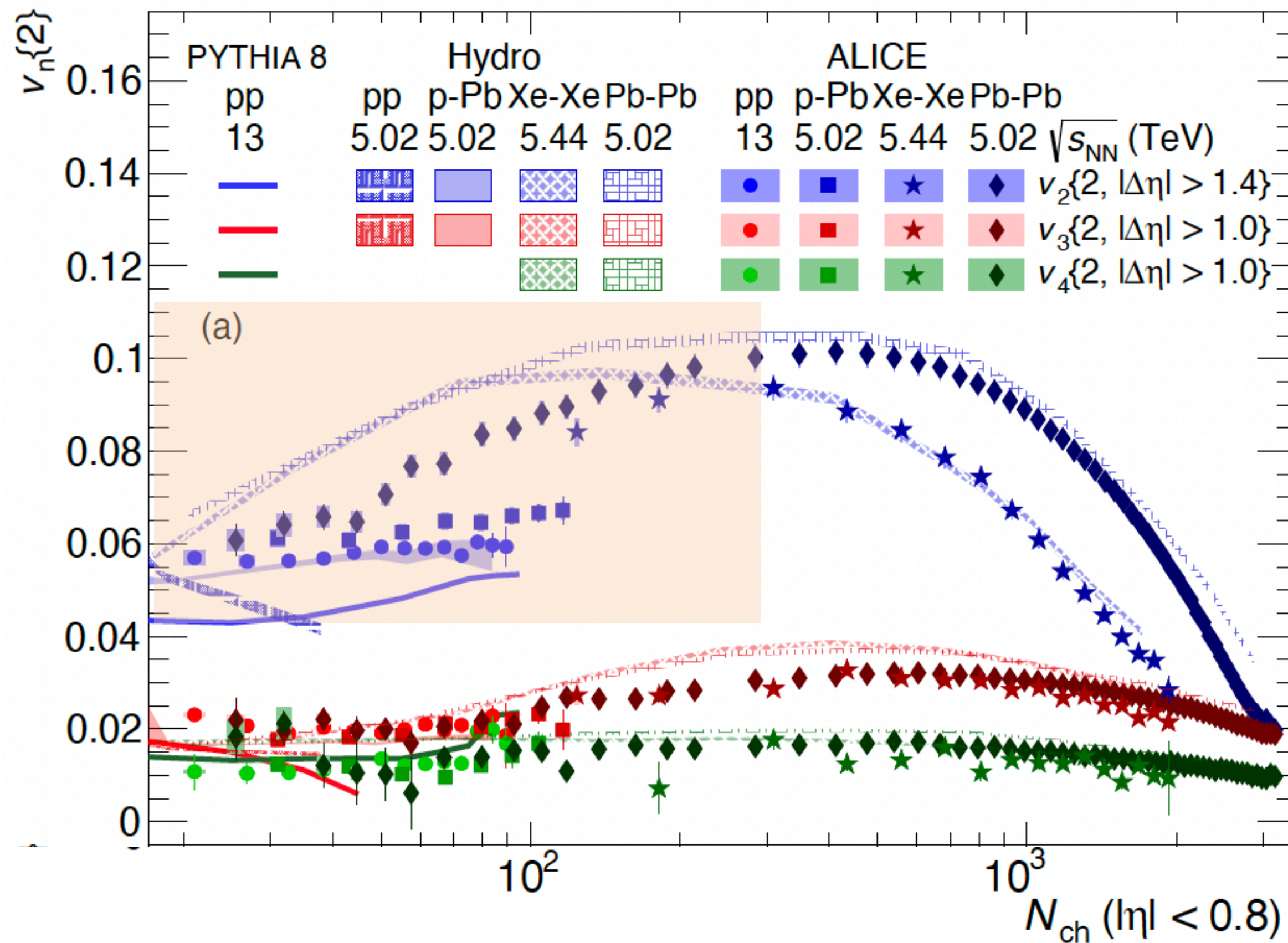
$$v_2 \text{ pp} < v_2 \text{ pPb} < v_2 \text{ XeXe} < v_2 \text{ PbPb}$$

$$v_3 \text{ pp} \approx v_3 \text{ pPb} \approx v_3 \text{ XeXe} \approx v_3 \text{ PbPb}$$



# Origin(s): geometry driven @ LHC System Scan

ALICE, PRL123, 142301 (2019)



$$v_2 \text{ pp} < v_2 \text{ pPb} < v_2 \text{ XeXe} < v_2 \text{ PbPb}$$

$$v_3 \text{ pp} \approx v_3 \text{ pPb} \approx v_3 \text{ XeXe} \approx v_3 \text{ PbPb}$$

- Flow in small systems is driven by the *fluctuating initial geometry* through the *final state effects (FSE)*

## What FSE?

- Hydro?
- Parton escape?
- String shoving?
- Others?

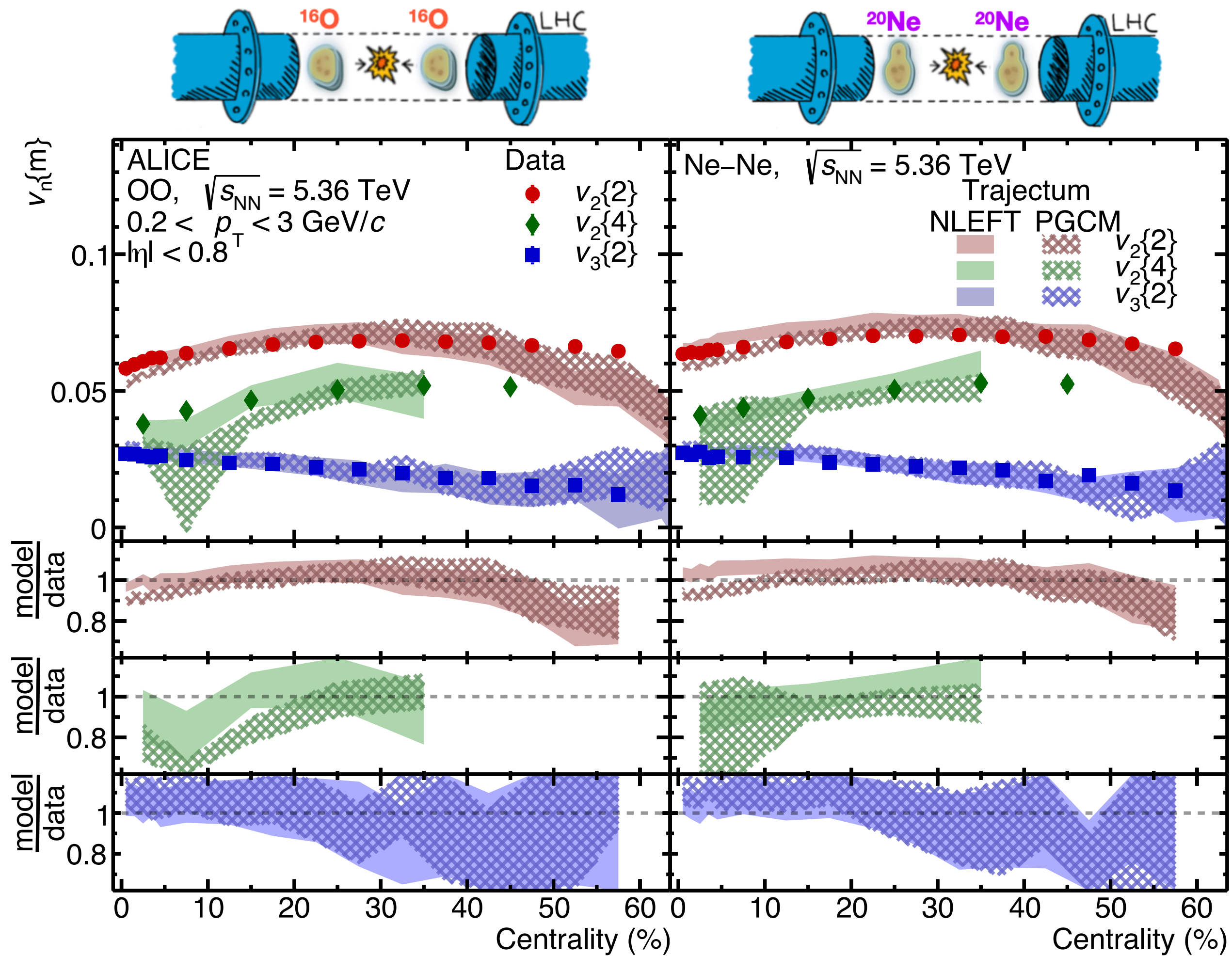
- Both hydro and AMPT have been updated since 2019, details see:
  - Hydro: Wenbin Zhao @ Thursday
  - AMPT: Ziwei Lin @ Tuesday





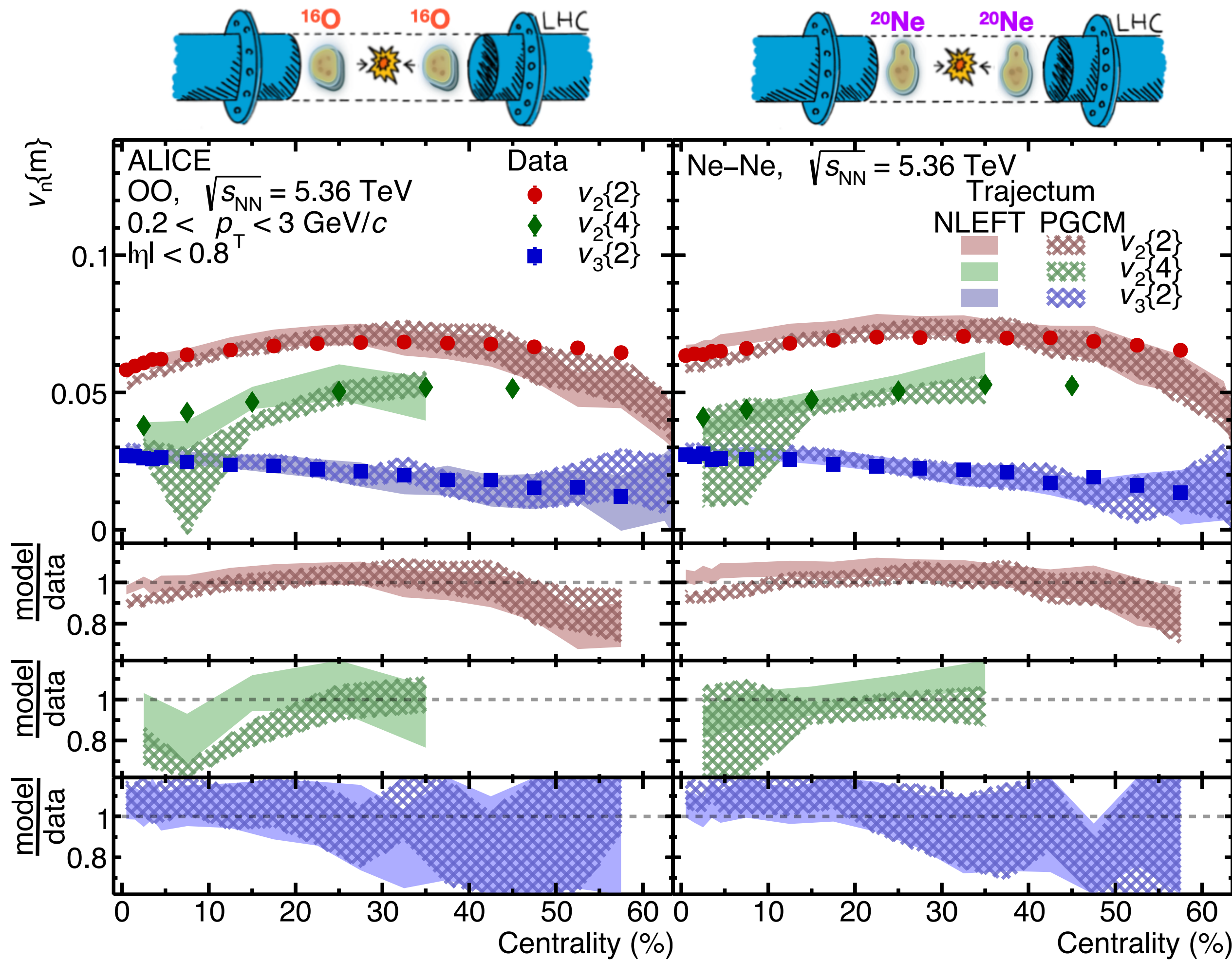
# Geometry-driven hydrodynamic flow in OO and Ne-Ne

ALICE, arXiv:2509.06428, accepted by Phys. Rev. Lett.



# Geometry-driven hydrodynamic flow in OO and Ne-Ne

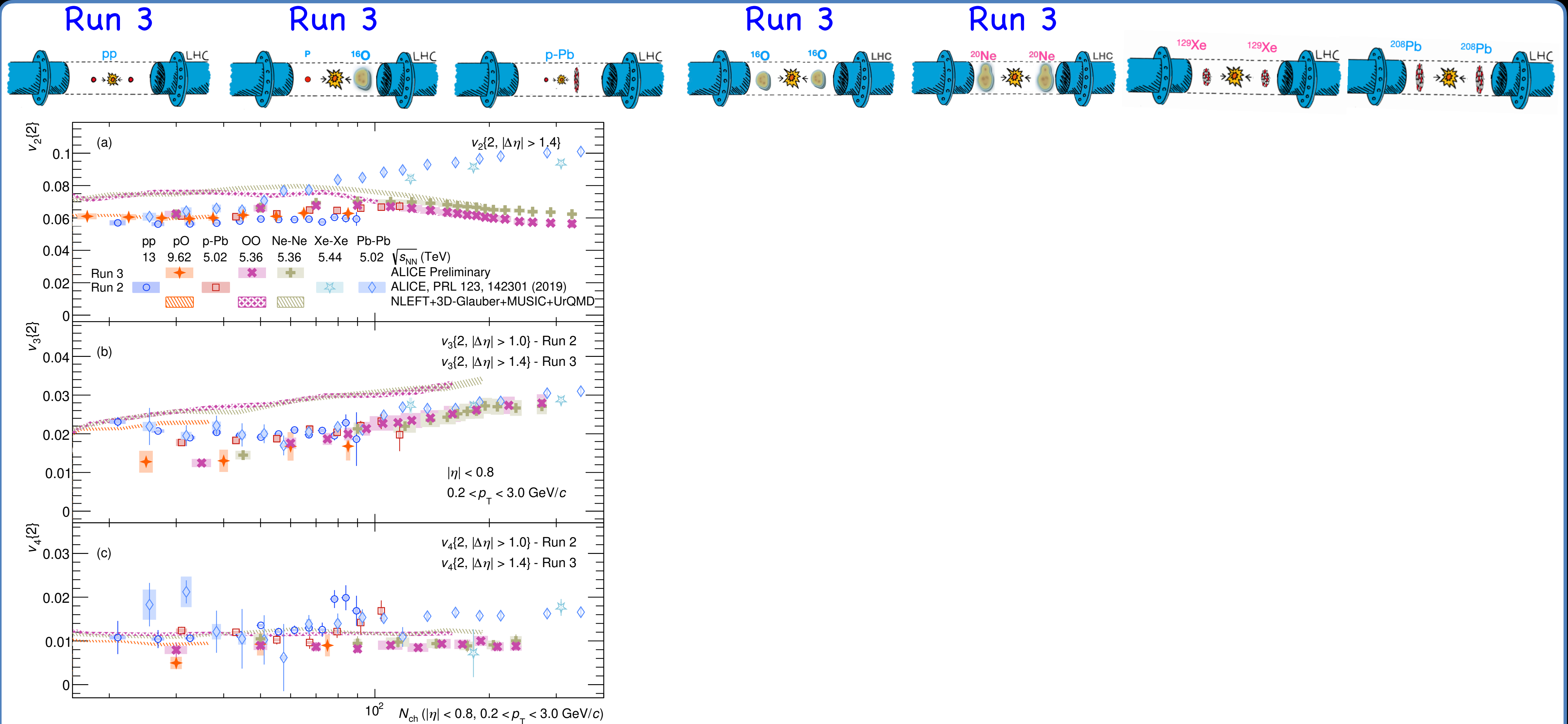
ALICE, arXiv:2509.06428, accepted by Phys. Rev. Lett.



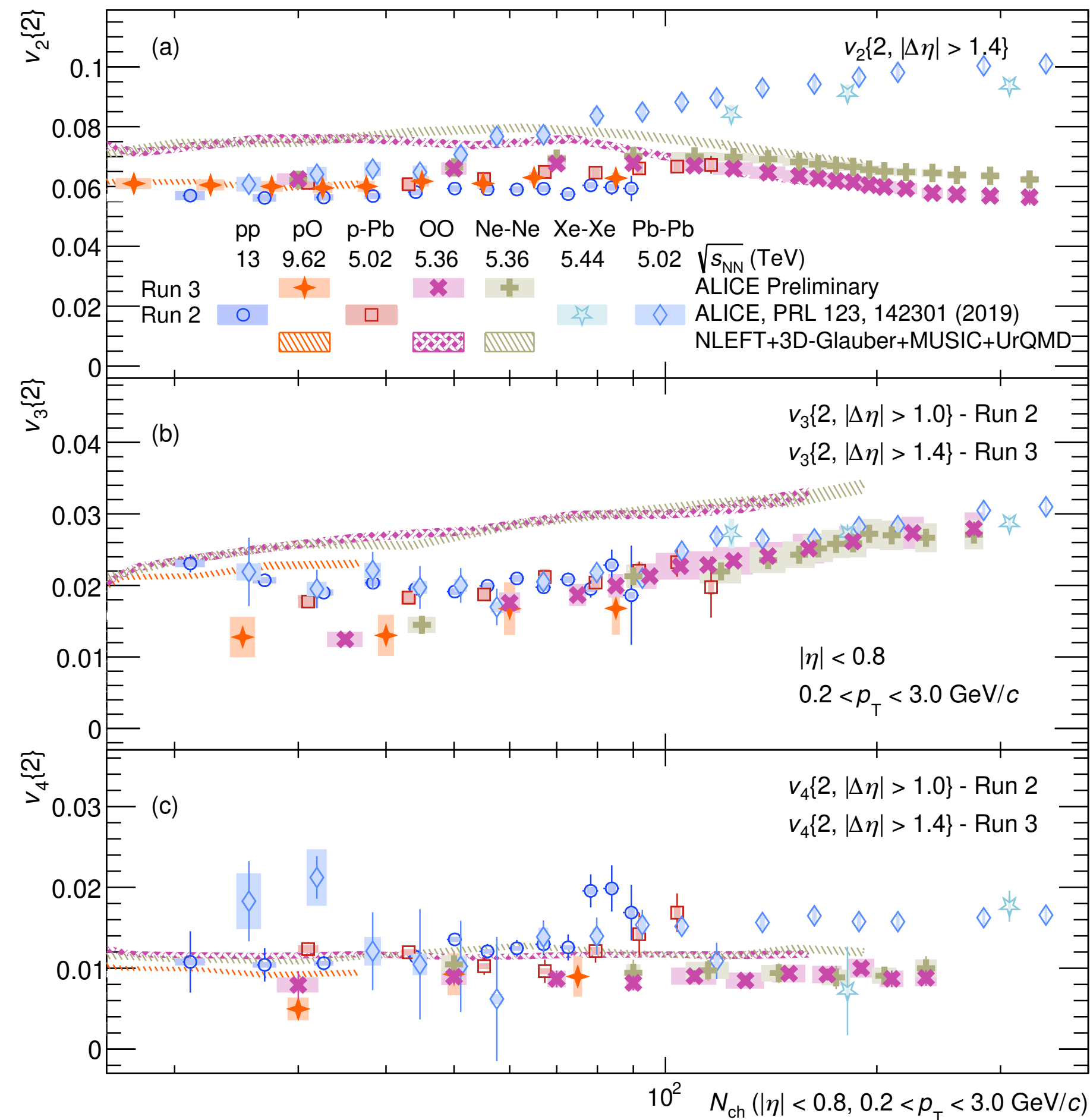
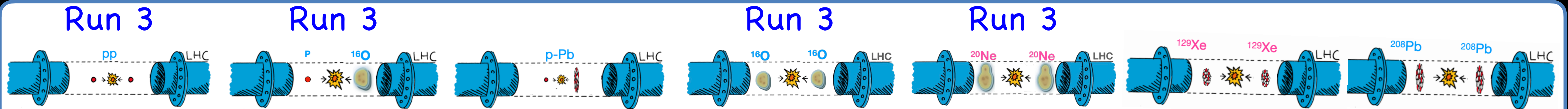
- ❖ Nicely described by predictions from Trajectum(NS+hydro)
  - Nuclear geometry driven hydrodynamic flow observed in light ion collisions
  - *For the first time reasonable agreement (equivalent if not better than Pb-Pb) between hydro predictions and data in small systems*



# Comprehensive flow patterns across systems



# Comprehensive flow patterns across systems

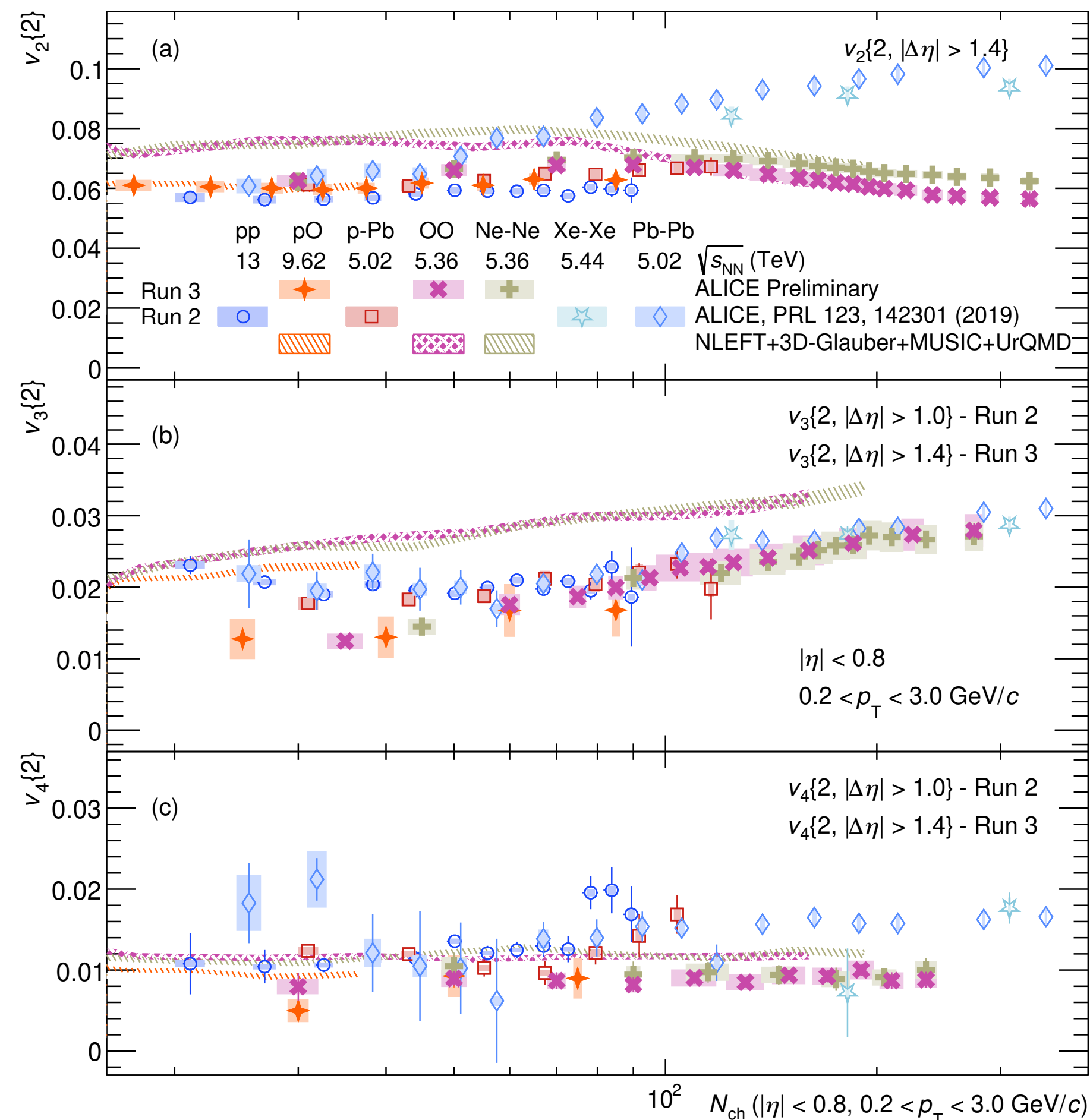
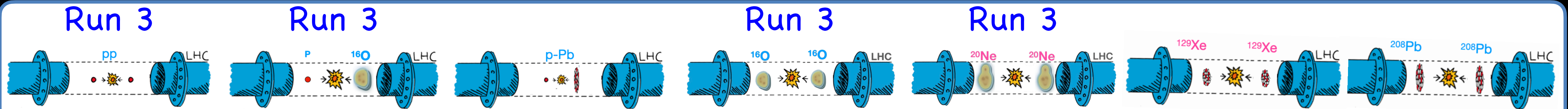


## ❖ Characteristic flow patterns in ALICE data

- $v_2(\text{Pb-Pb}) > v_2(\text{Xe-Xe}) > v_2(\text{Ne-Ne}) > v_2(\text{OO})$   
 $> v_2(\text{p-Pb}) > v_2(\text{pO}) > v_2(\text{pp})$
- The differences in  $v_3$  and  $v_4$  might be due to different  $|\Delta\eta|$  gaps.



# Comprehensive flow patterns across systems



## ❖ Characteristic flow patterns in ALICE data

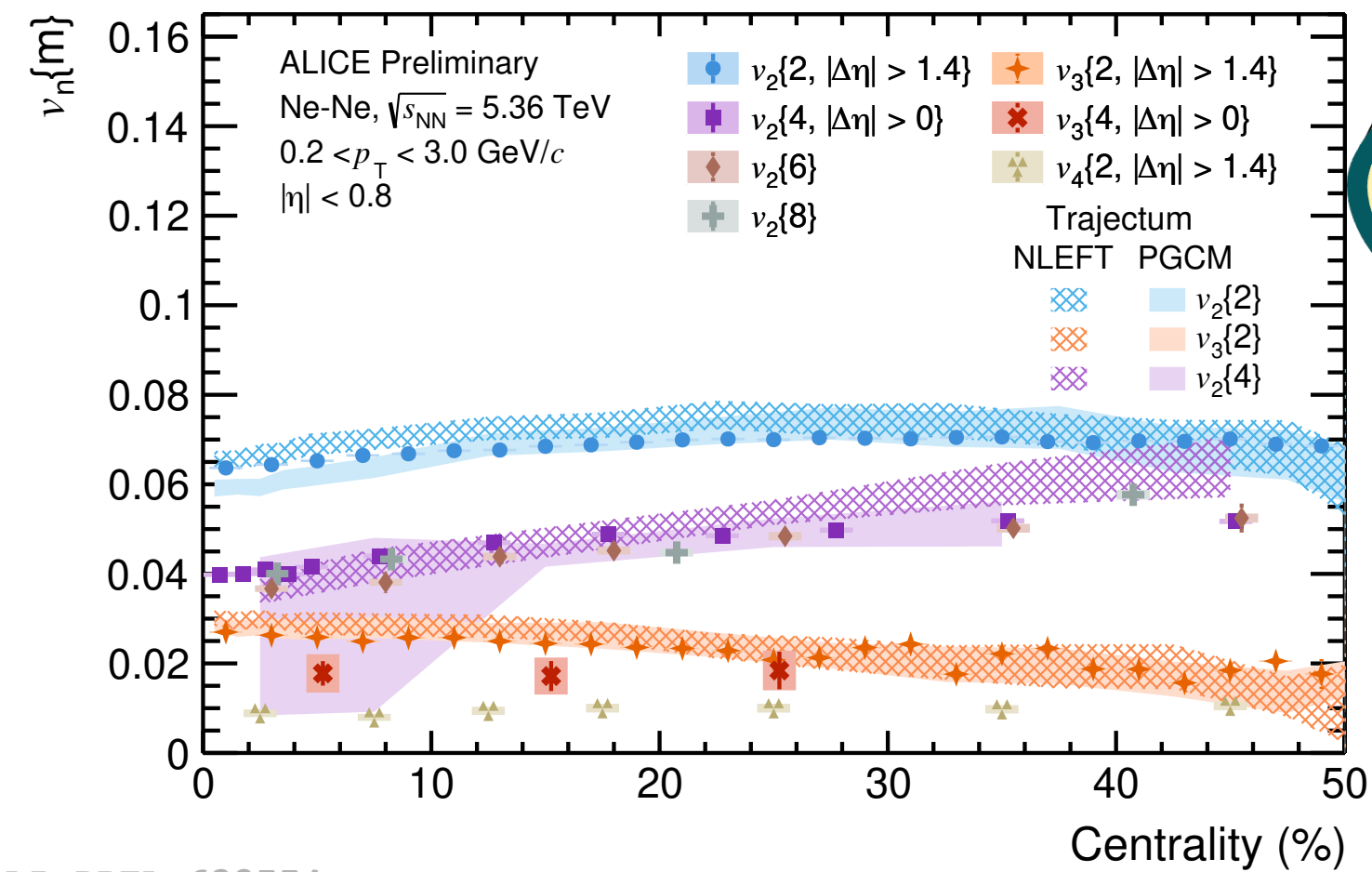
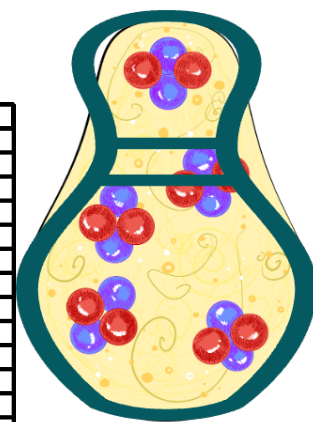
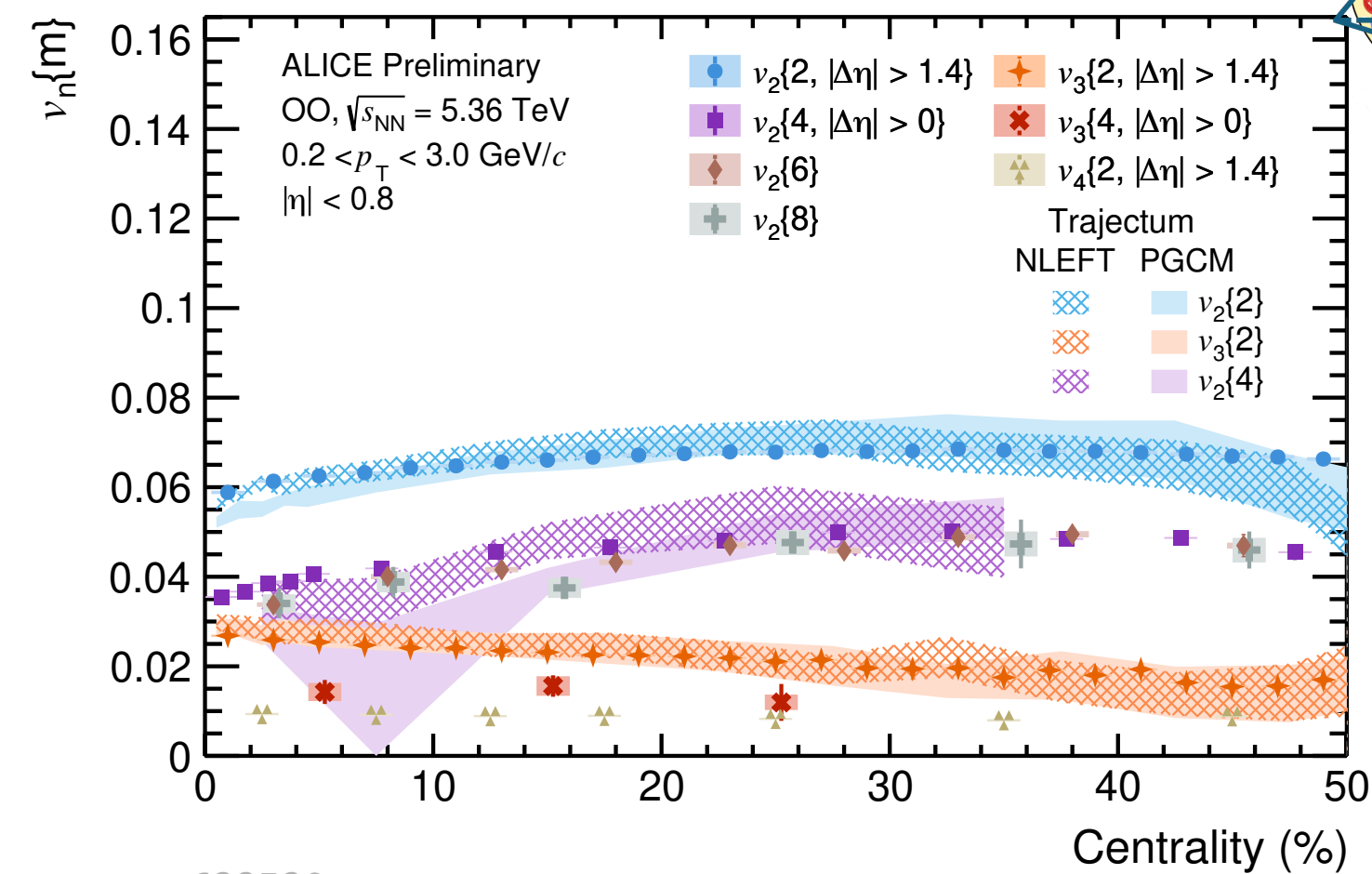
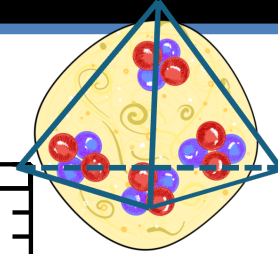
- $v_2(\text{Pb-Pb}) > v_2(\text{Xe-Xe}) > v_2(\text{Ne-Ne}) > v_2(\text{OO})$   
 $> v_2(\text{p-Pb}) > v_2(\text{pO}) > v_2(\text{pp})$
- The differences in  $v_3$  and  $v_4$  might be due to different  $|\Delta\eta|$  gaps.

## ❖ NLEFT+3D-Glauber+MUSIC+UrQMD

- Quantitatively describe  $v_2$  in Ne-Ne and OO for the high multiplicity, overestimates the  $v_2$  at low multiplicity ( $N_{ch} < 100$ )
- quantitatively describes  $v_2$  in pO
- The model overestimates the  $v_3$  and  $v_4$  in Ne-Ne, OO and pO collisions

# Multi-particle cumulant and $P(v_2)$

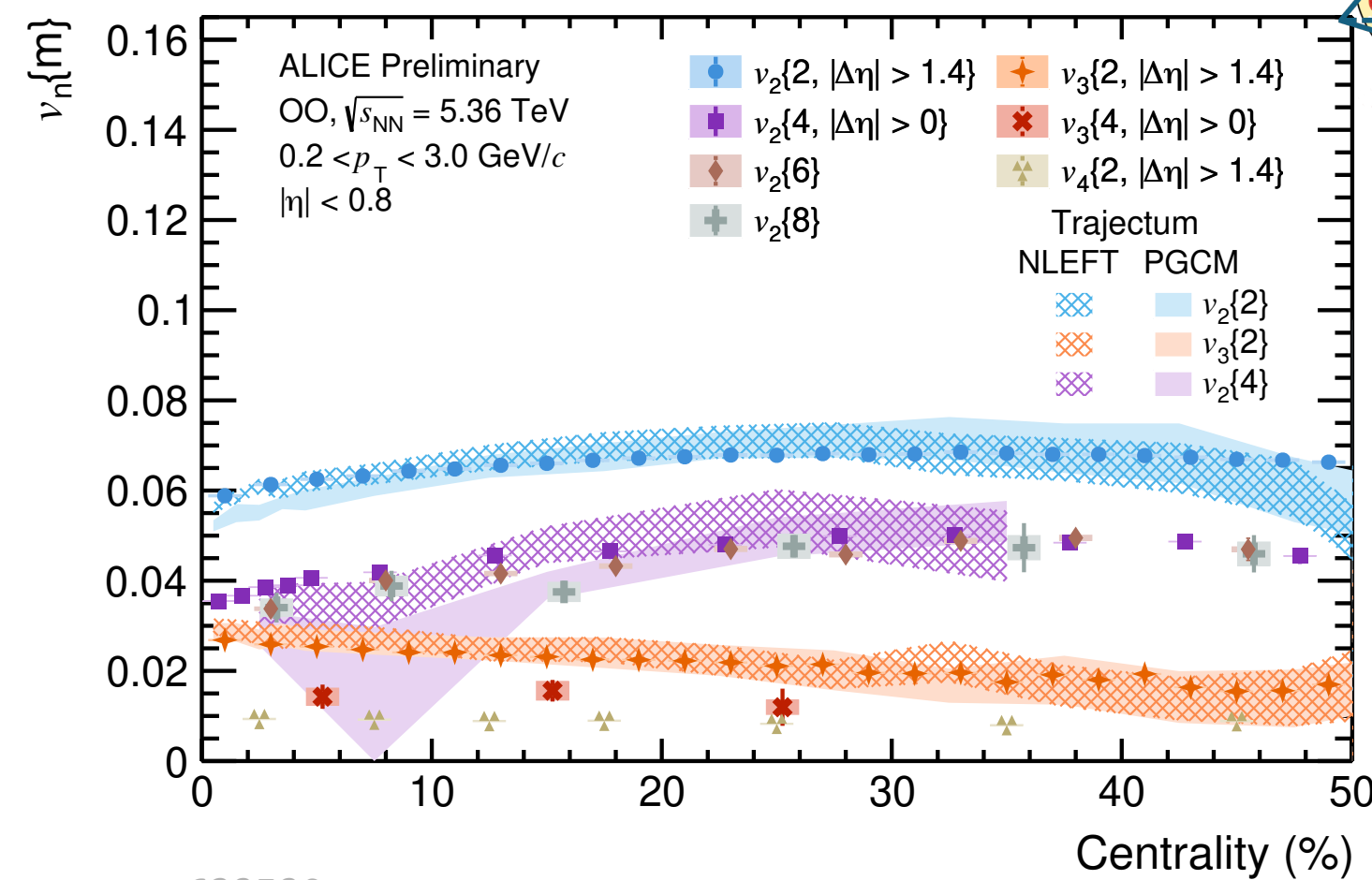
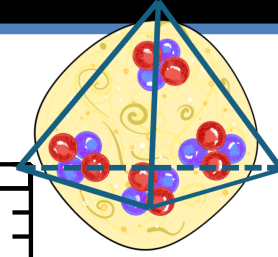
Vojtech Machacek (NBI), SQM2026



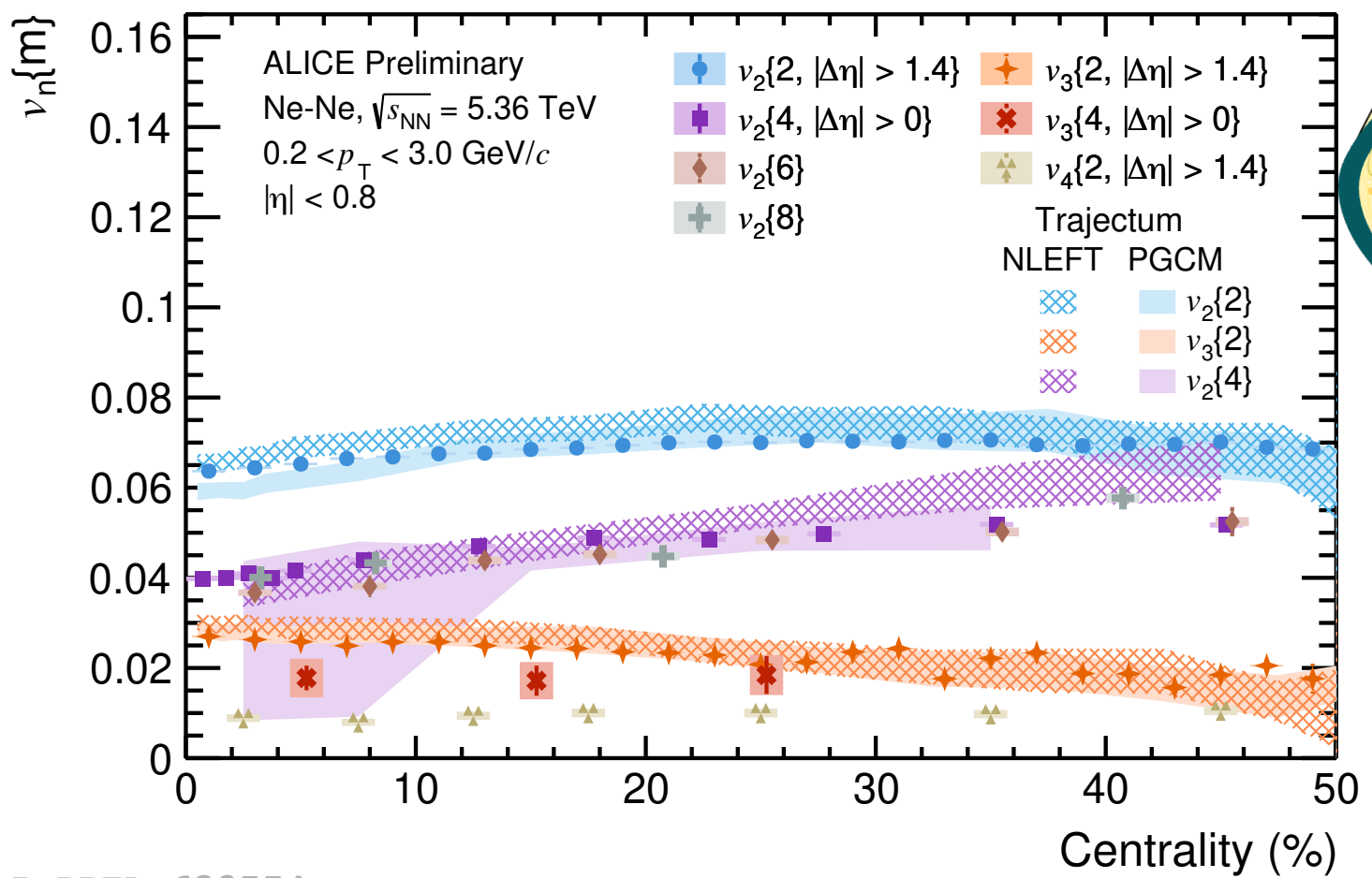


# Multi-particle cumulant and $P(v_2)$

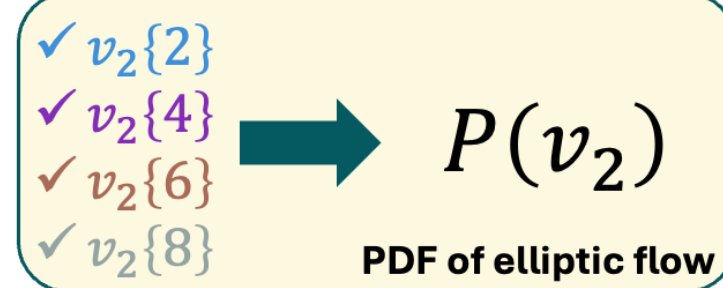
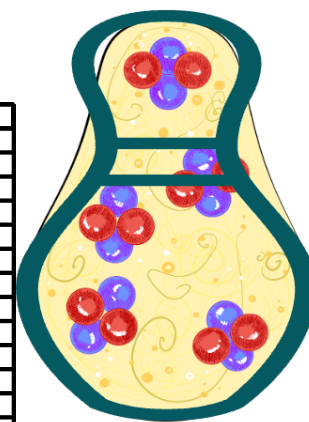
Vojtech Machacek (NBI), SQM2026



ALI-PREL-623530



ALI-PREL-623554



$$P(v_2) = \frac{2\alpha v_2}{k_2^2} \left(1 - \frac{v_2^2}{k_2^2}\right)^{\alpha-1} \left(1 - \frac{v_2 \varepsilon_0}{k_2}\right)^{-1-2\alpha} (1 - \varepsilon_0^2)^{\alpha+\frac{1}{2}} {}_2F_1\left(\frac{1}{2}, 1+2\alpha; 1, \frac{2v_2 \varepsilon_0}{v_2 \varepsilon_0 - k_2}\right)$$

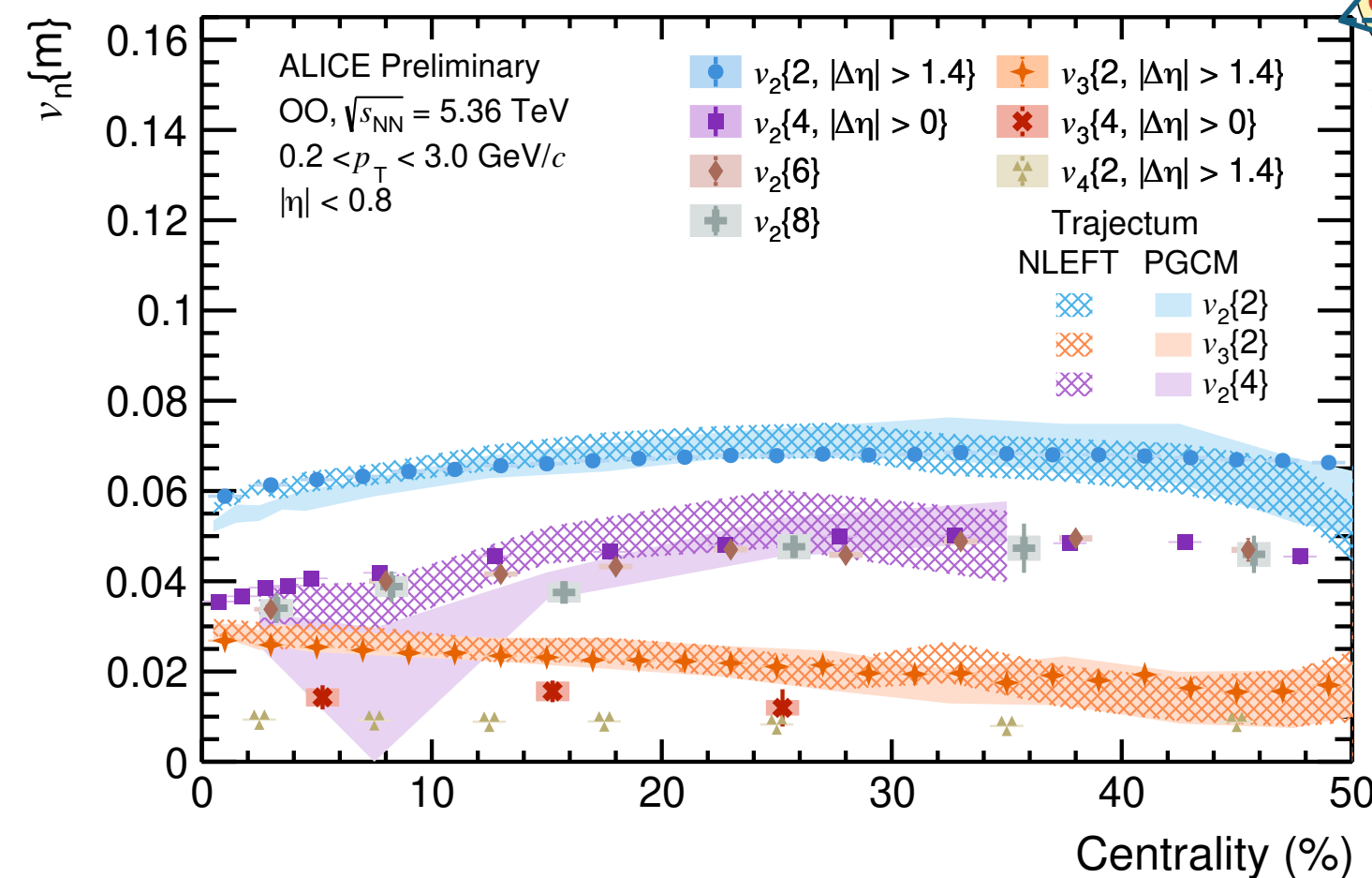
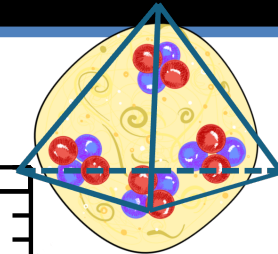
Elliptic-Power function:

L. Yan etc., PRC 90, 024903 (2014)

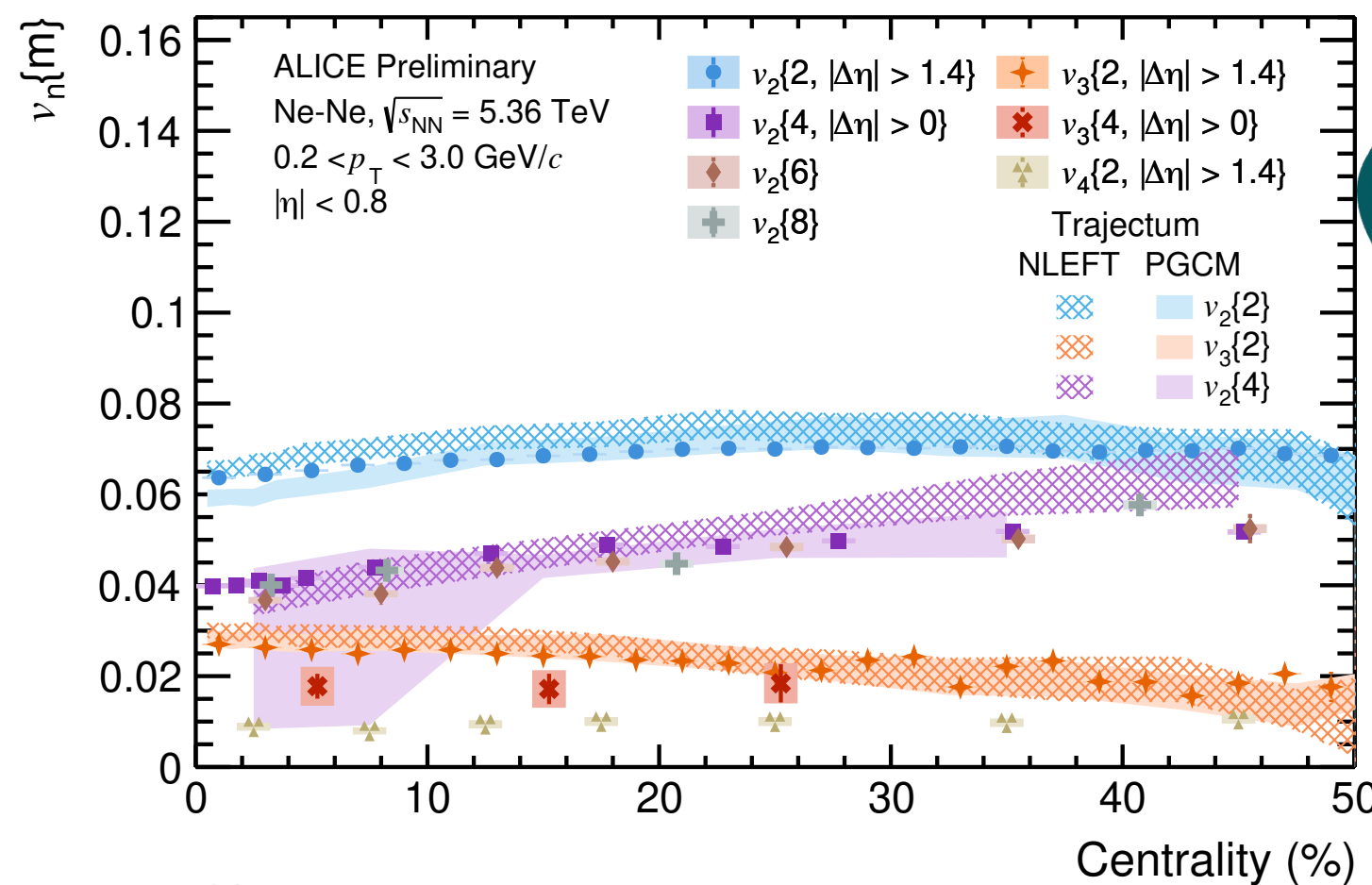
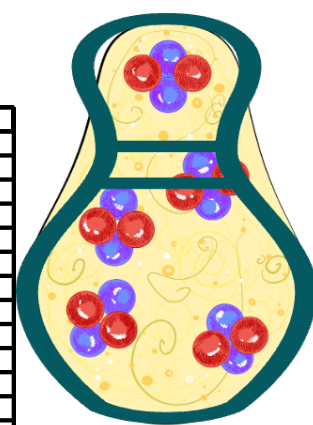
L. Yan etc., PRL 112 (2014) 082301

# Multi-particle cumulant and $P(v_2)$

Vojtech Machacek (NBI), SQM2026



ALI-PREL-623530



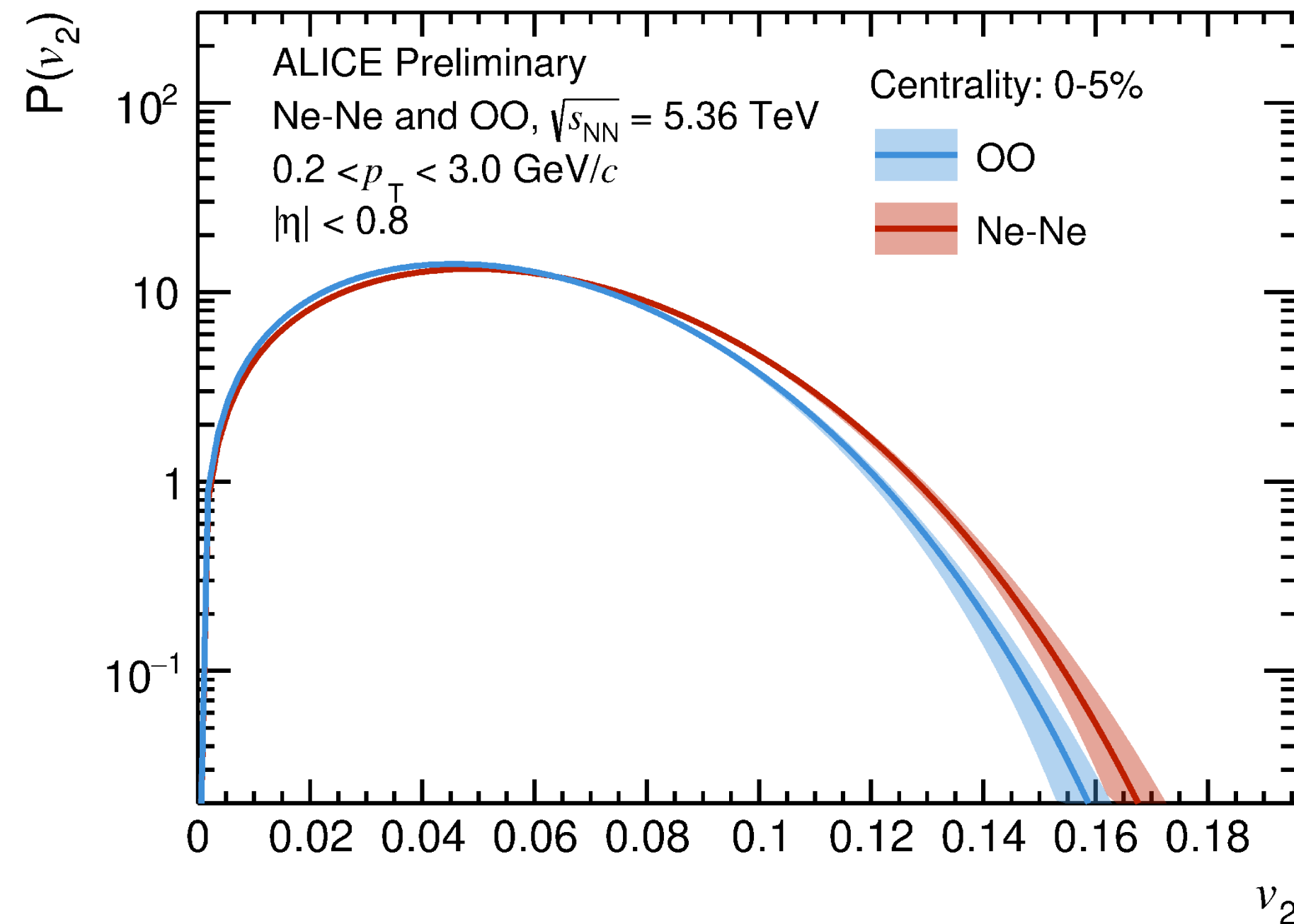
ALI-PREL-623554

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

$\rightarrow P(v_2)$

PDF of elliptic flow

$$P(v_2) = \frac{2\alpha v_2}{k_2^2} \left(1 - \frac{v_2^2}{k_2^2}\right)^{\alpha-1} \left(1 - \frac{v_2 \varepsilon_0}{k_2}\right)^{-1-2\alpha} (1 - \varepsilon_0^2)^{\alpha+\frac{1}{2}} {}_2F_1\left(\frac{1}{2}, 1+2\alpha; 1, \frac{2v_2 \varepsilon_0}{v_2 \varepsilon_0 - k_2}\right)$$



ALI-PREL-623559

**Elliptic-Power function:**  
 L. Yan etc., PRC 90, 024903 (2014)  
 L. Yan etc., PRL 112 (2014) 082301

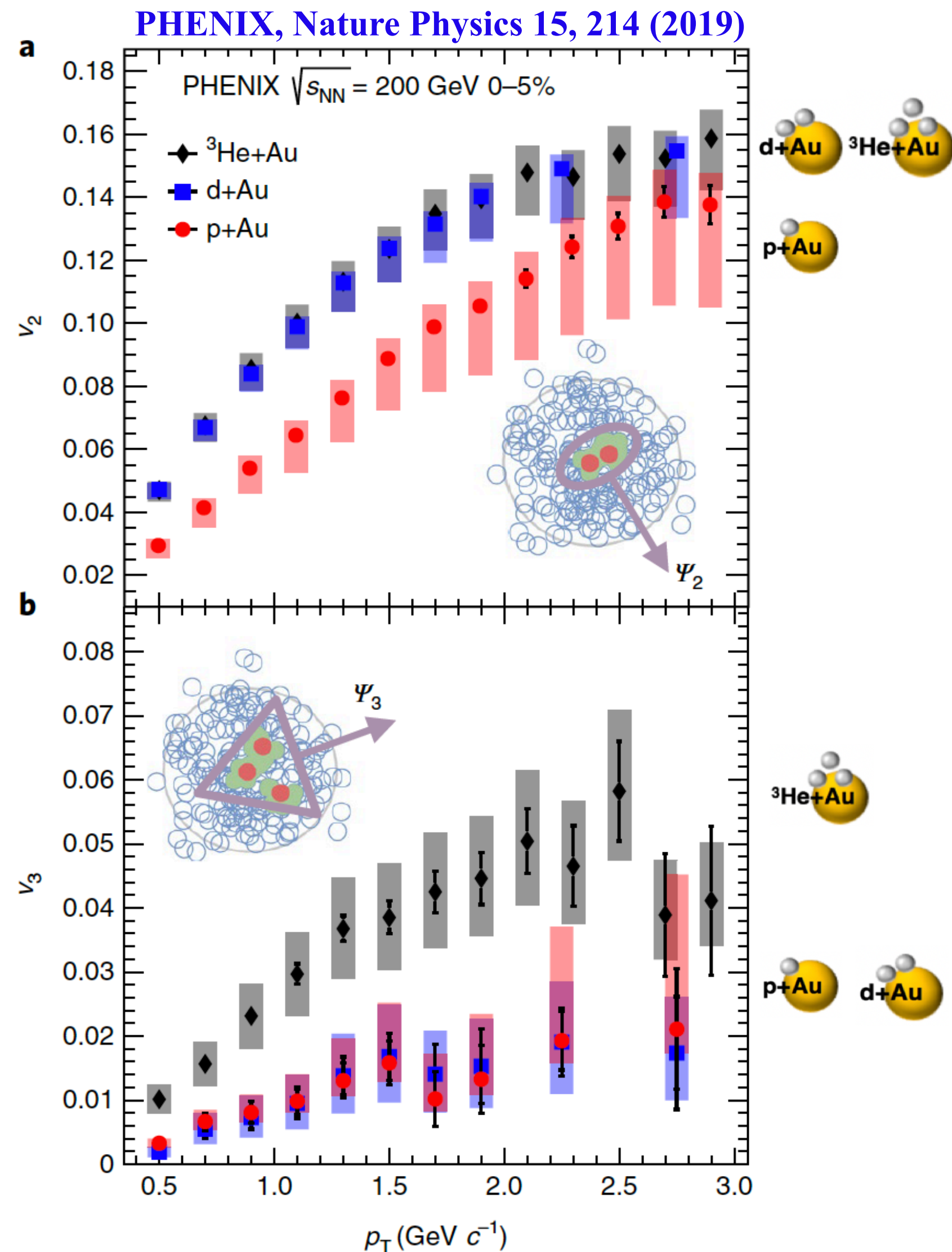
First-ever reconstruction of  $P(v_2)$  distribution in small systems

- Direct access to all moments of distribution
- Larger  $\langle v_2 \rangle$  in Ne-Ne than in OO over a wide range of centralities due to bowling-pin like structure of  $^{20}\text{Ne}$

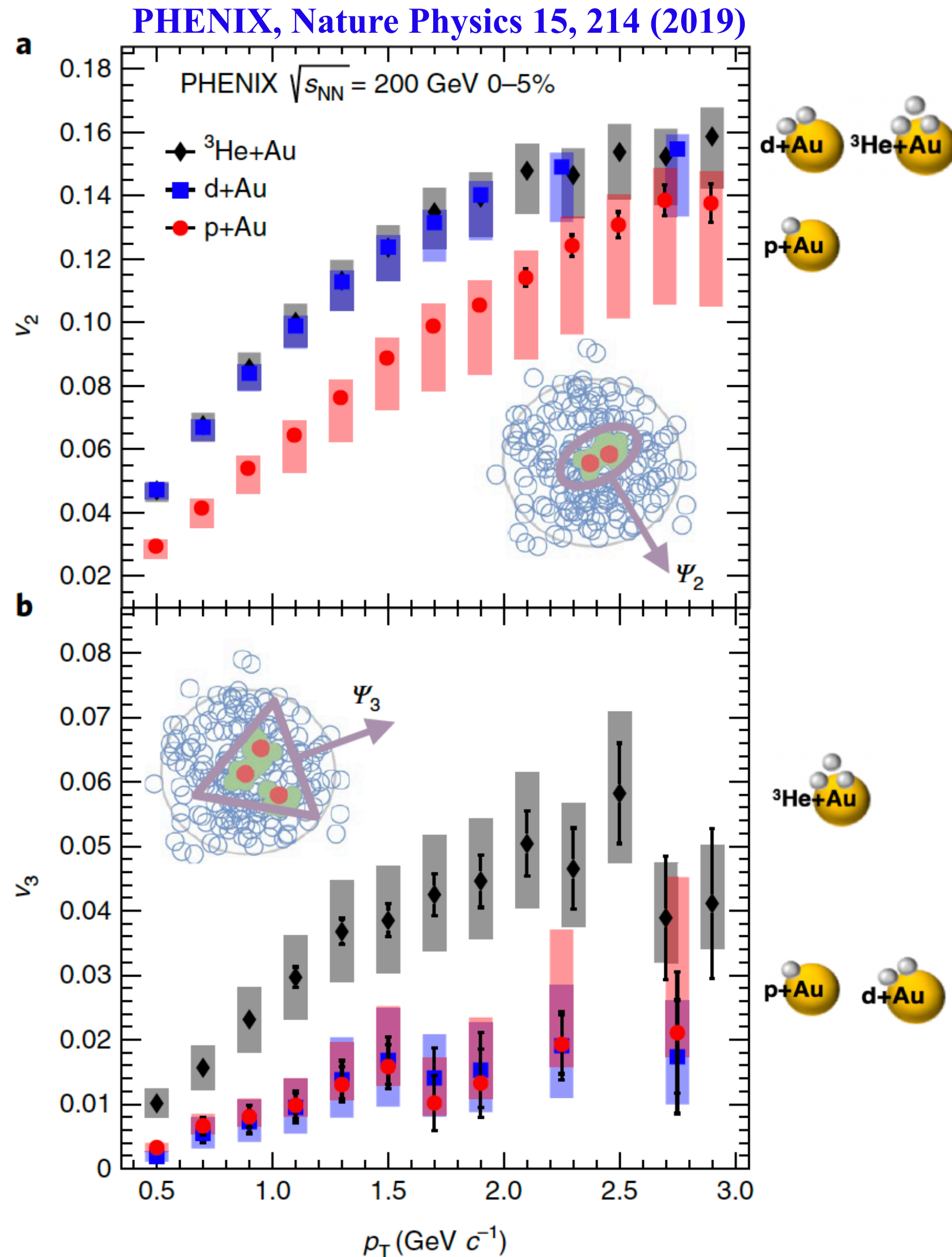




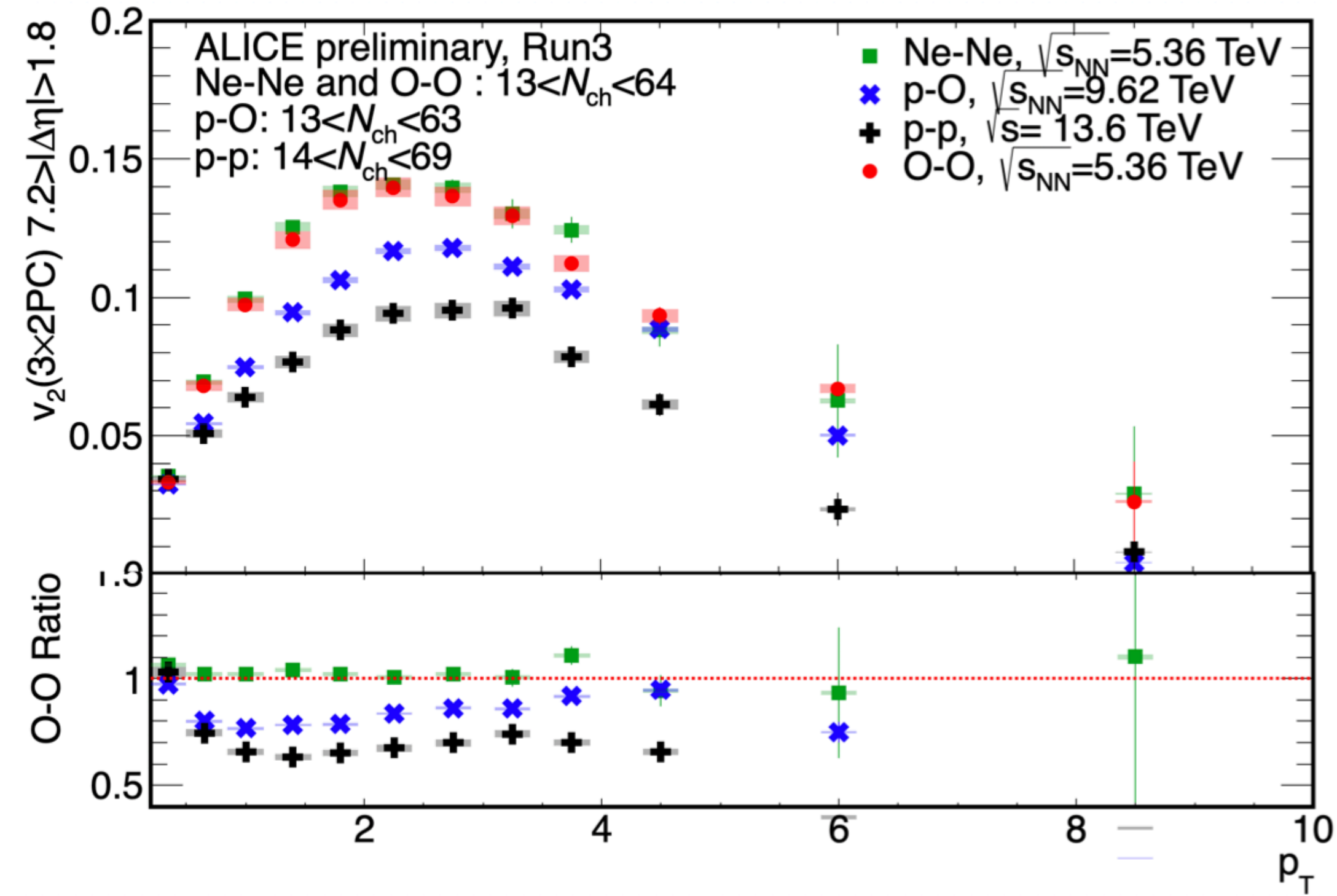
# Geometry scan at the LHC



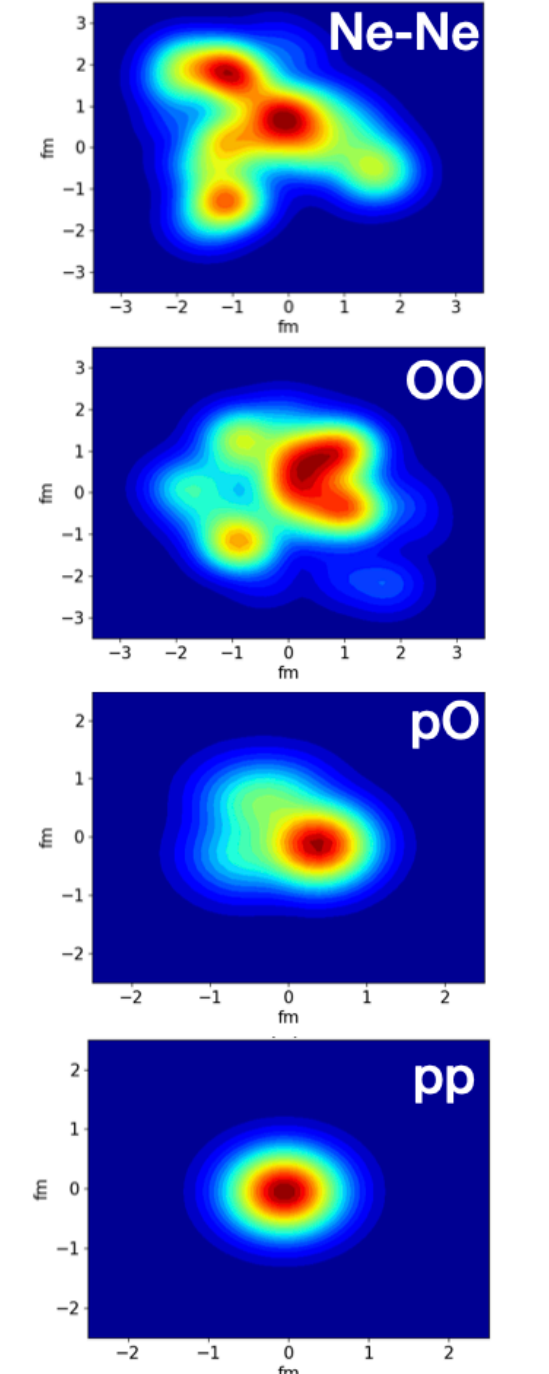
# Geometry scan at the LHC



Thor K. Jensen (NBI), New since HP2026



LHC Geometry Scan



First geometry scan of  $v_2(p_T)$  in small systems at the LHC

- Follow naive expectations of  $v_2(pp) < v_2(pO) < v_2(OO) \leq v_2(Ne-Ne)$
- Careful initial eccentricity calculations in various systems and fixed  $N_{ch}$  ranges are necessary

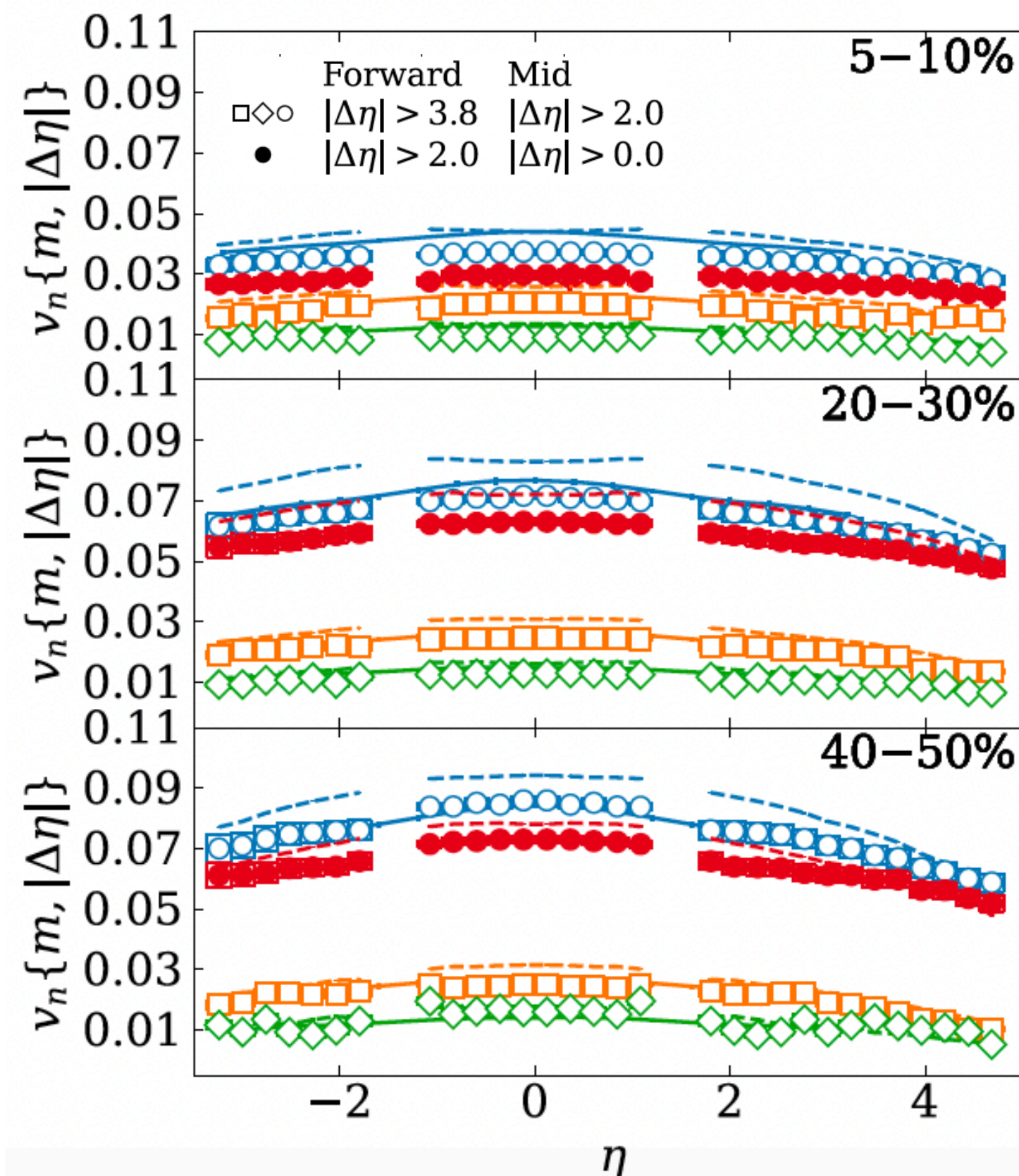


# Ultra-long-range correlation in small systems

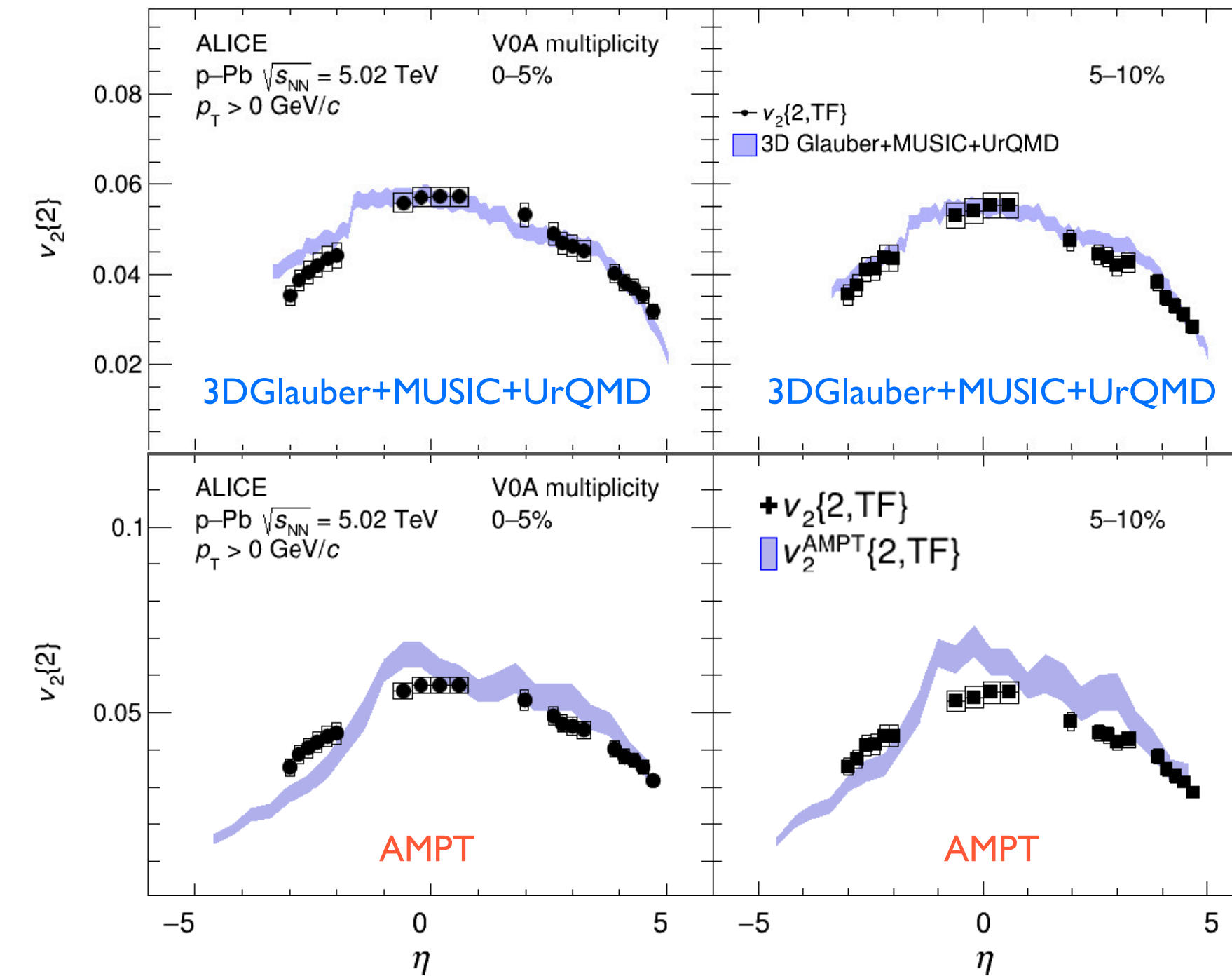
ALICE, PLB850 (2024) 138477

ALICE Pb–Pb  $\sqrt{s_{NN}} = 5.02$  TeV

$\circ$   $n = 2, m = 2$      $\square$   $n = 3, m = 2$   
 $\bullet$   $n = 2, m = 4$      $\diamond$   $n = 4, m = 2$   
 ----- AMPT    — CLVisc

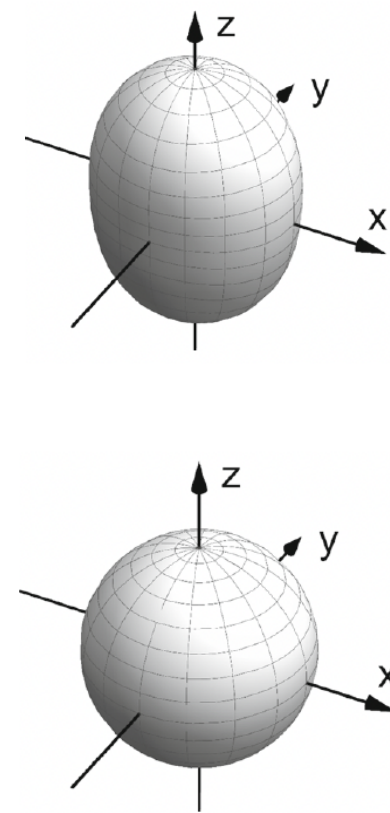
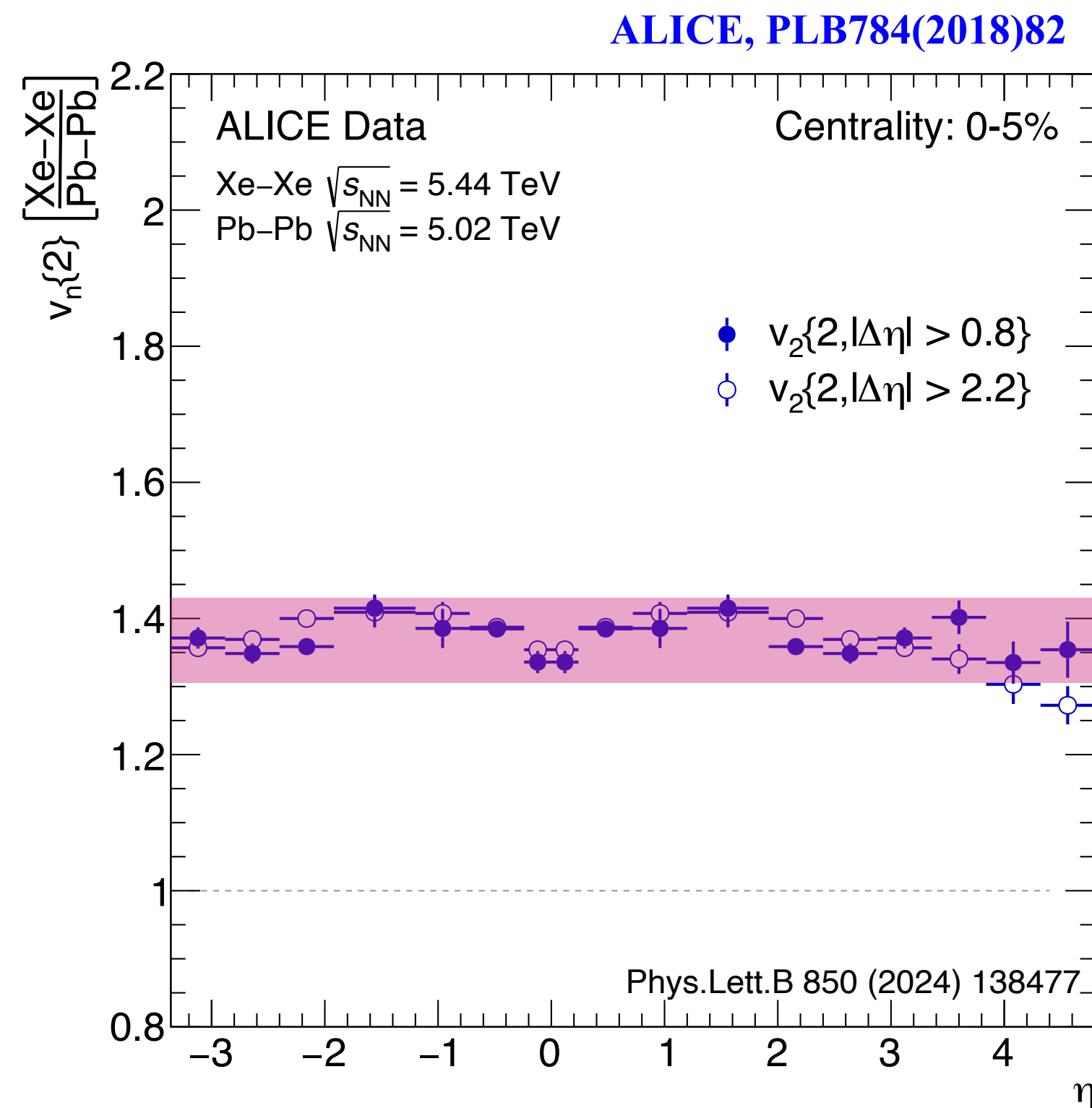


ALICE, JHEP01(2024)199



- ❖ Anisotropic flow over a very wide pseudorapidity coverage ( $-3.5 < \eta < 5.0$ ) is observed in both Pb-Pb and p-Pb collisions
- ❖ The results in p-Pb can be reproduced by **3D Glauber+MUSIC+UrQMD** model and **AMPT** model
  - Indication of partonic/hydrodynamic flow in p-Pb collisions?

# $v_2(\eta)$ in light-ion collision

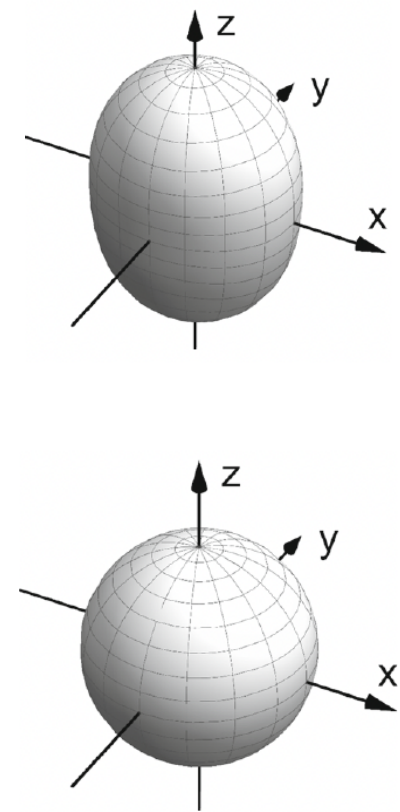
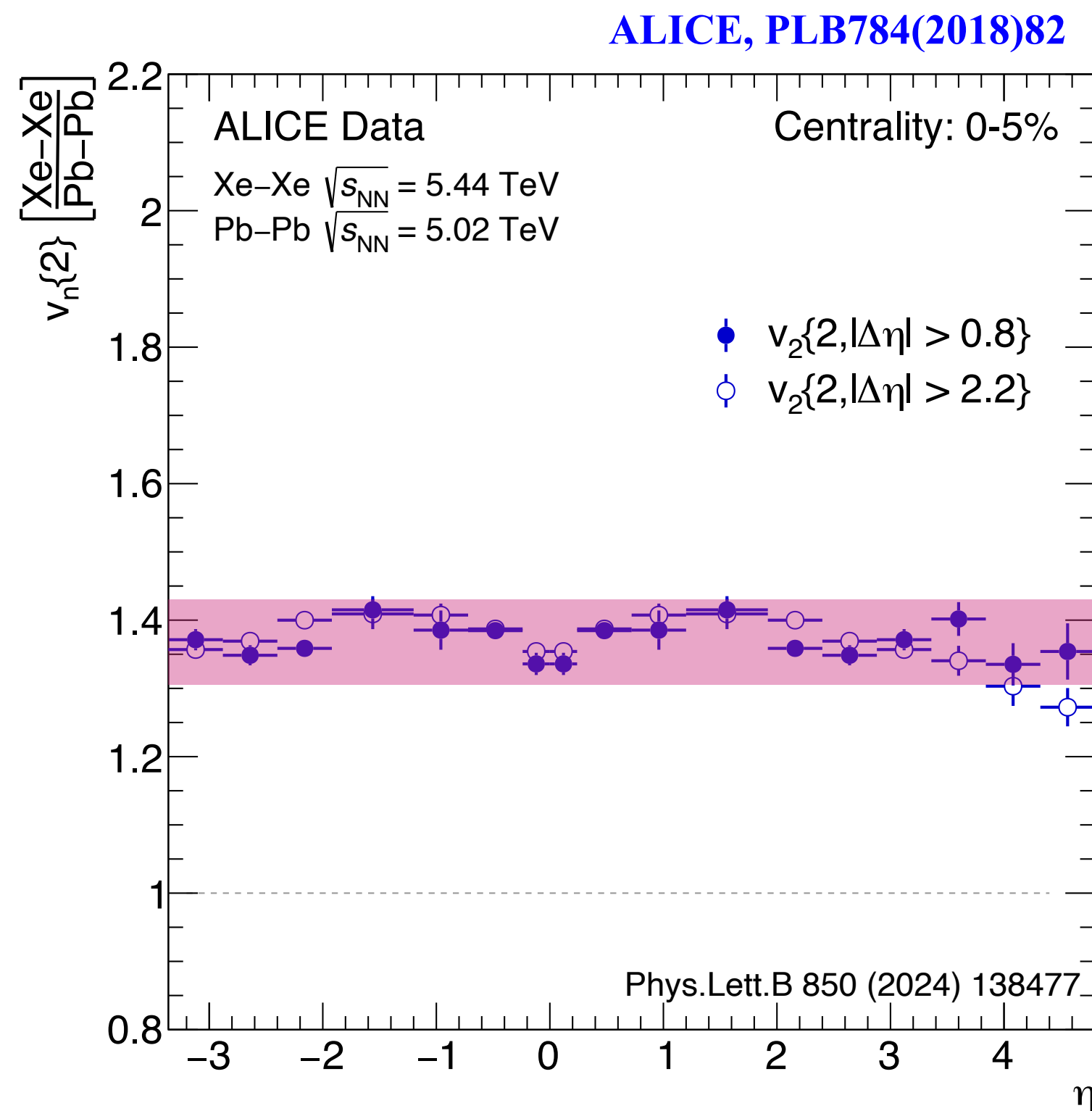


For illustration, real ALICE data available in a few days

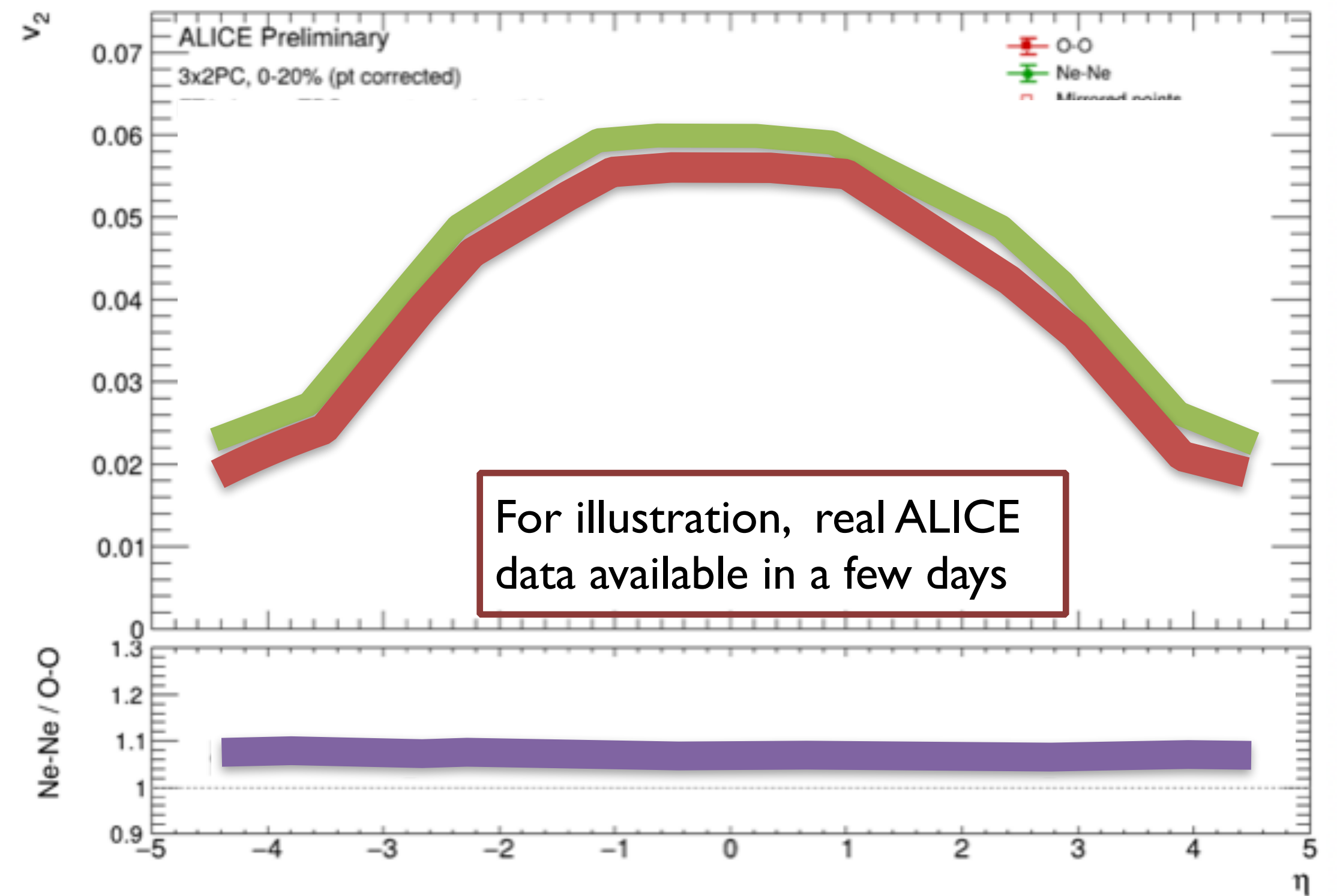
- ❖ The impact of NS persists over a very wide pseudorapidity range ( $-5 < \eta < 5$ )
  - Geometry driven flow
  - New input for the low-x physics (any impact from CGC, which yields short-range correlations)



# $v_2(\eta)$ in light-ion collision

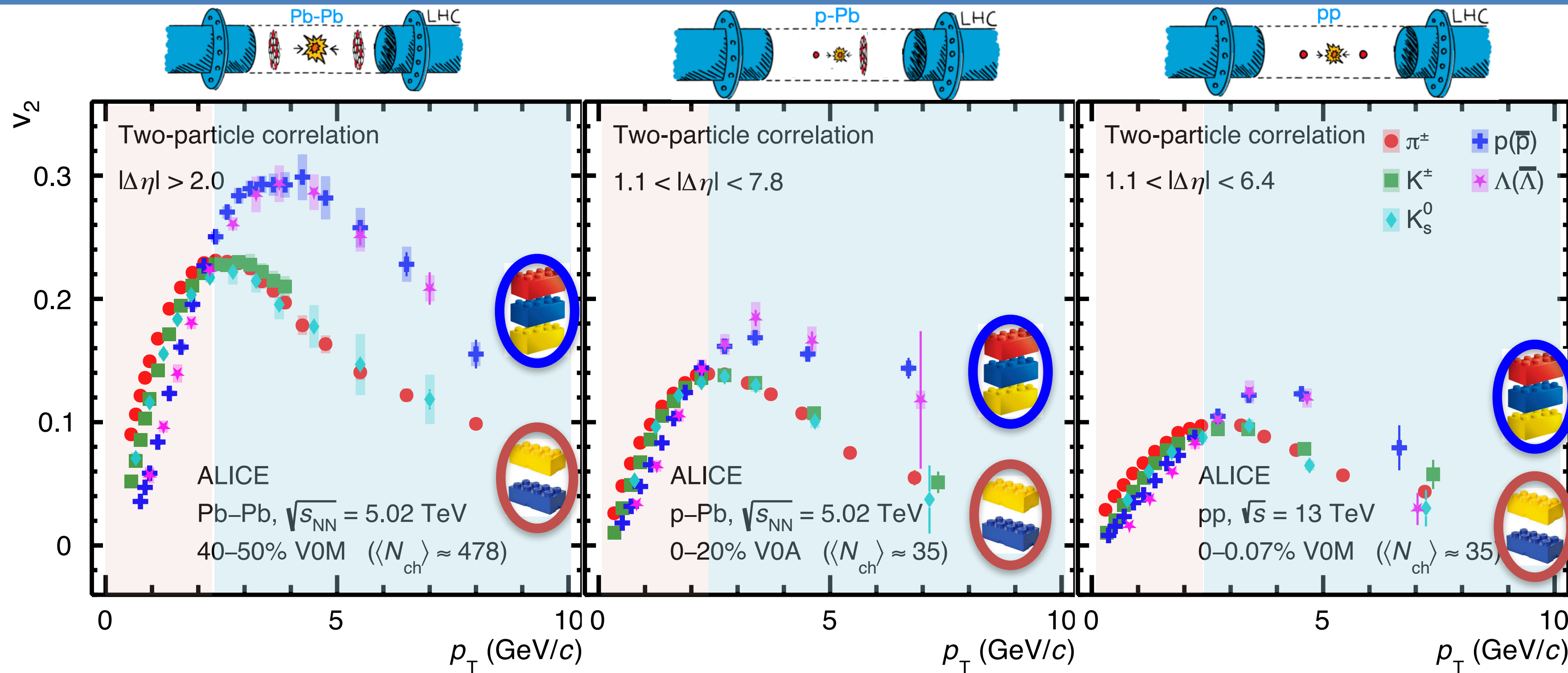


Martijn Laarhoven (NBI), HP2026 Approval



- ❖ The impact of NS persists over a very wide pseudorapidity range ( $-5 < \eta < 5$ )
  - Geometry driven flow
  - New input for the low-x physics (any impact from CGC, which yields short-range correlations)

# Partonic flow in high multiplicity p-Pb and pp



ALICE, Nature Communications  
17, 2585 (2026)

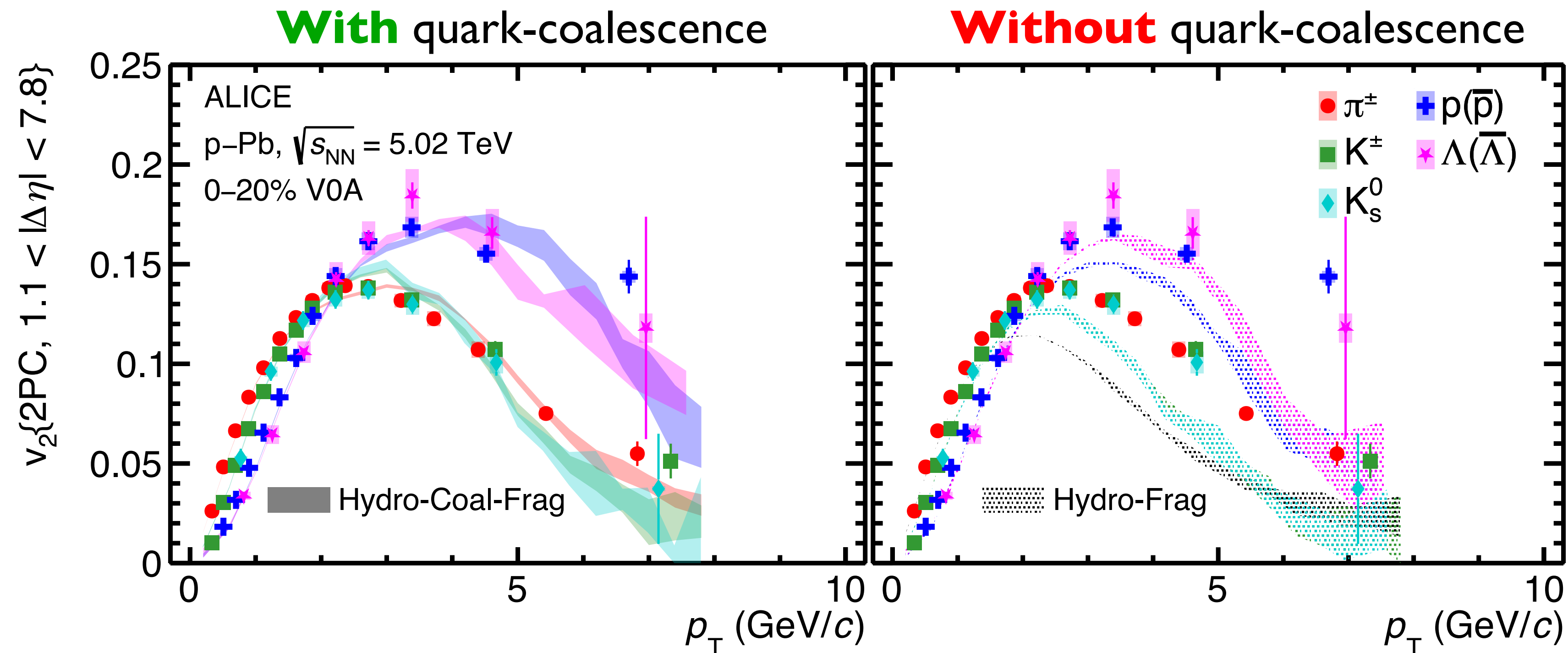


❖ **Similar observations** in Pb-Pb, high multiplicity p-Pb and pp collisions!

- **low  $p_T$  ( $p_T < 3$  GeV/c)** - Mass ordering.
- **Intermediate  $p_T$  ( $3 < p_T < 6$  GeV/c)**
  - Baryon-meson grouping ( $\sim 1\sigma$  confidence)
  - Splitting between baryons and mesons  $v_2$  ( $> 5\sigma$  confidence)



# Importance of quark-coalescence in small systems



ALICE, Nature Communications  
17, 2585 (2026)



PKU model:

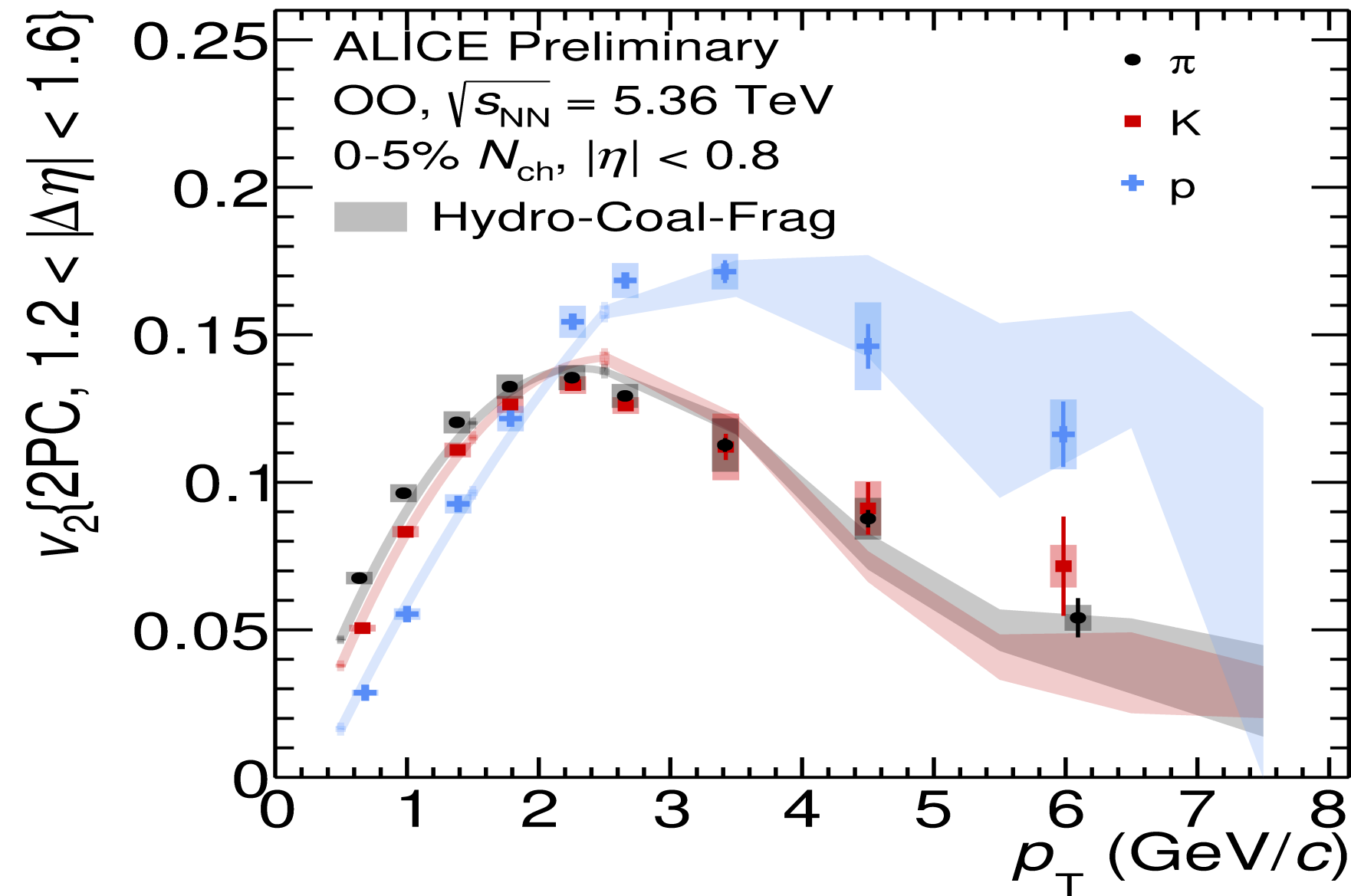
W. Zhao etc., PRL125 (2020), 072301

Y. Wang etc, arXiv:2401.00913

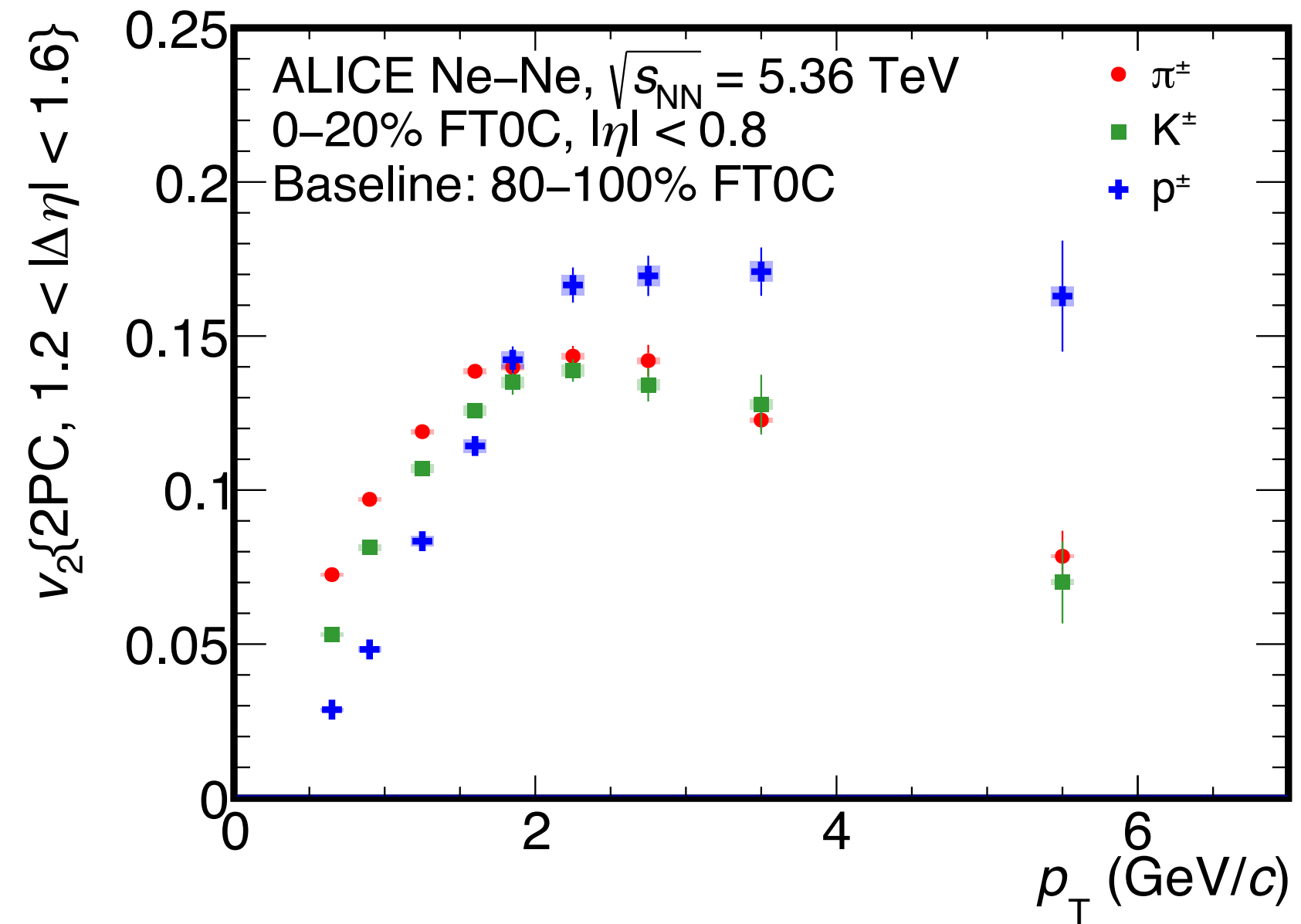
- ❖ Low  $p_T$  ( $p_T < 3$  GeV/c)
  - Mass ordering, reproduced by both models (hydro dominant)
- ❖ Intermediate  $p_T$  ( $3 < p_T < 6$  GeV/c)
  - **With** quark-coalescence: **successfully reproduces** baryon/meson grouping and splitting
  - **Without** quark-coalescence: mass dependence, **fails** to reproduce grouping and splitting effects

# New PID $v_2$ in the light-ion collisions

Preet B. Pati (NBI), SQM2026



Preet B. Pati (NBI), Quark Confinement 2026



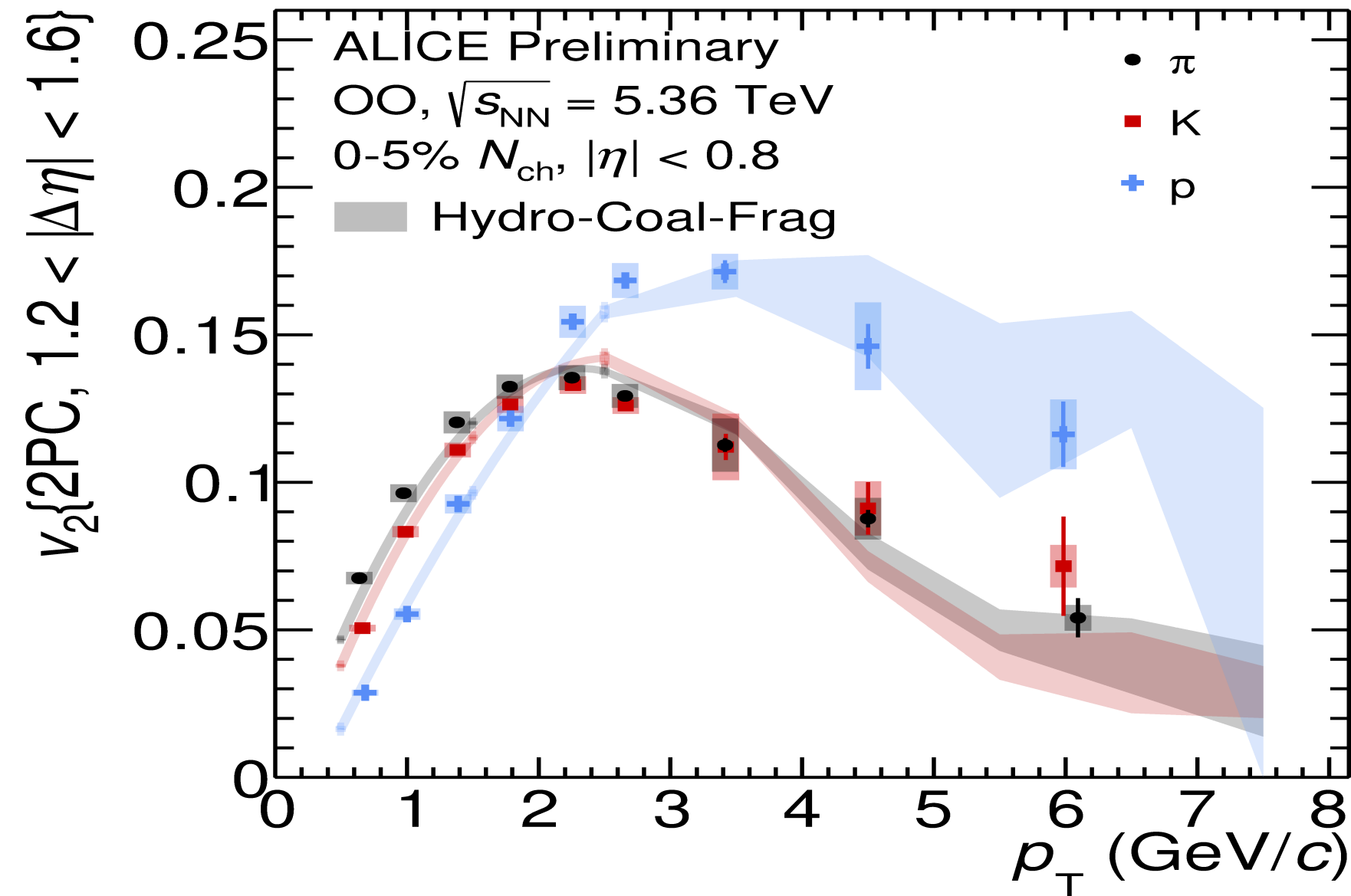
❖ PID  $v_2$  in OO and Ne-Ne are similar to that in Pb-Pb

- low  $p_T$  ( $p_T < 3$  GeV/c) - Mass ordering.
- Intermediate  $p_T$  ( $3 < p_T < 6$  GeV/c)
  - $v_2(\pi) \approx v_2(K^\pm)$  (with 1  $\sigma$  confidence)
  - Splitting between baryons and mesons  $v_2$  (with 5  $\sigma$  confidence)

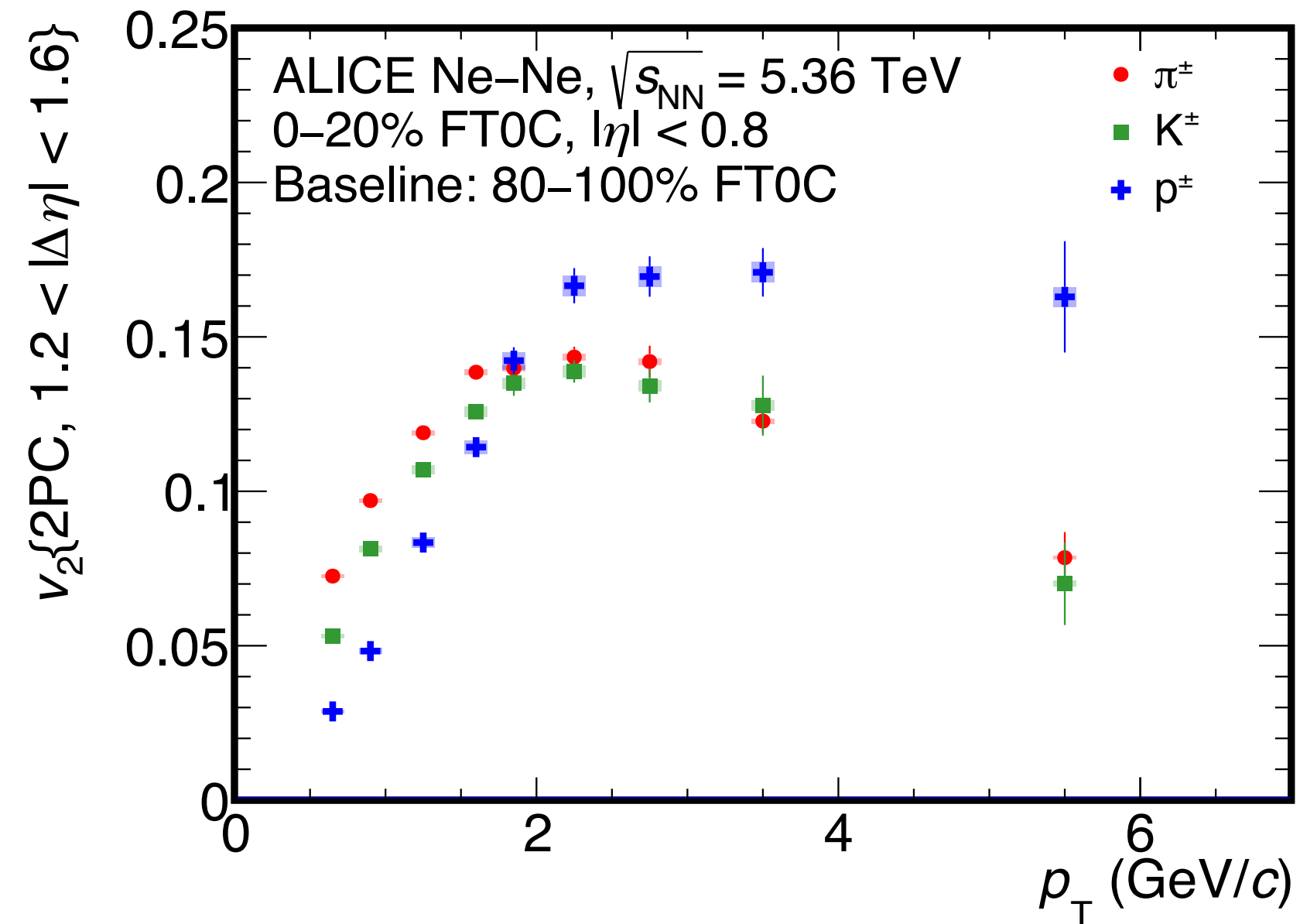


# New PID $v_2$ in the light-ion collisions

Preet B. Pati (NBI), SQM2026



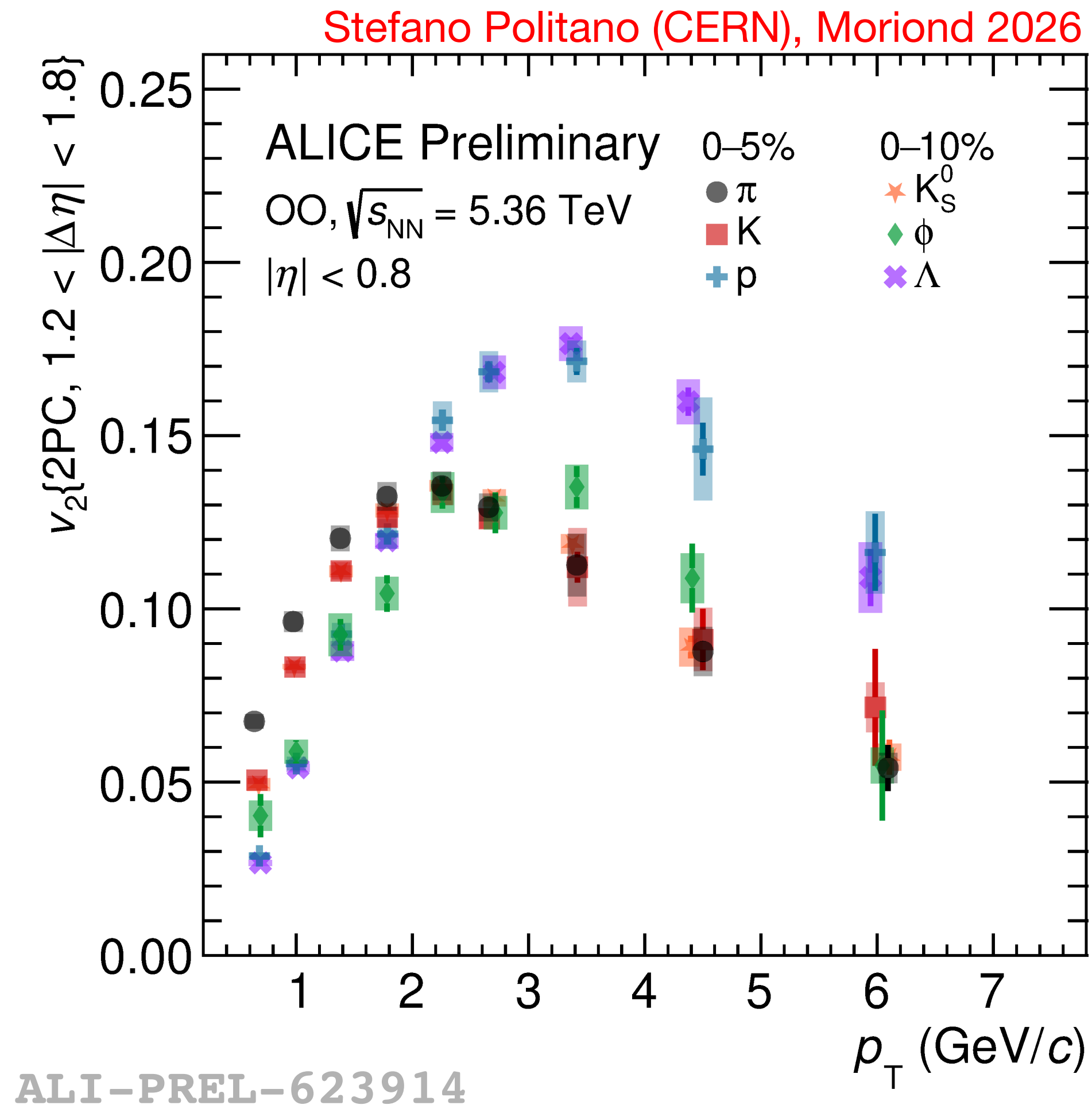
Preet B. Pati (NBI), Quark Confinement 2026



❖ PID  $v_2$  in OO and Ne-Ne are similar to that in Pb-Pb

- low  $p_T$  ( $p_T < 3$  GeV/c) - Mass ordering.
- Intermediate  $p_T$  ( $3 < p_T < 6$  GeV/c)
  - $v_2(\pi) \approx v_2(K^\pm)$  (with 1  $\sigma$  confidence)
  - Splitting between baryons and mesons  $v_2$  (with 5  $\sigma$  confidence)
  - **No surprise in the measurement, a nice agreement with predictions will be.**

# Potential issue in the existing results and future publication

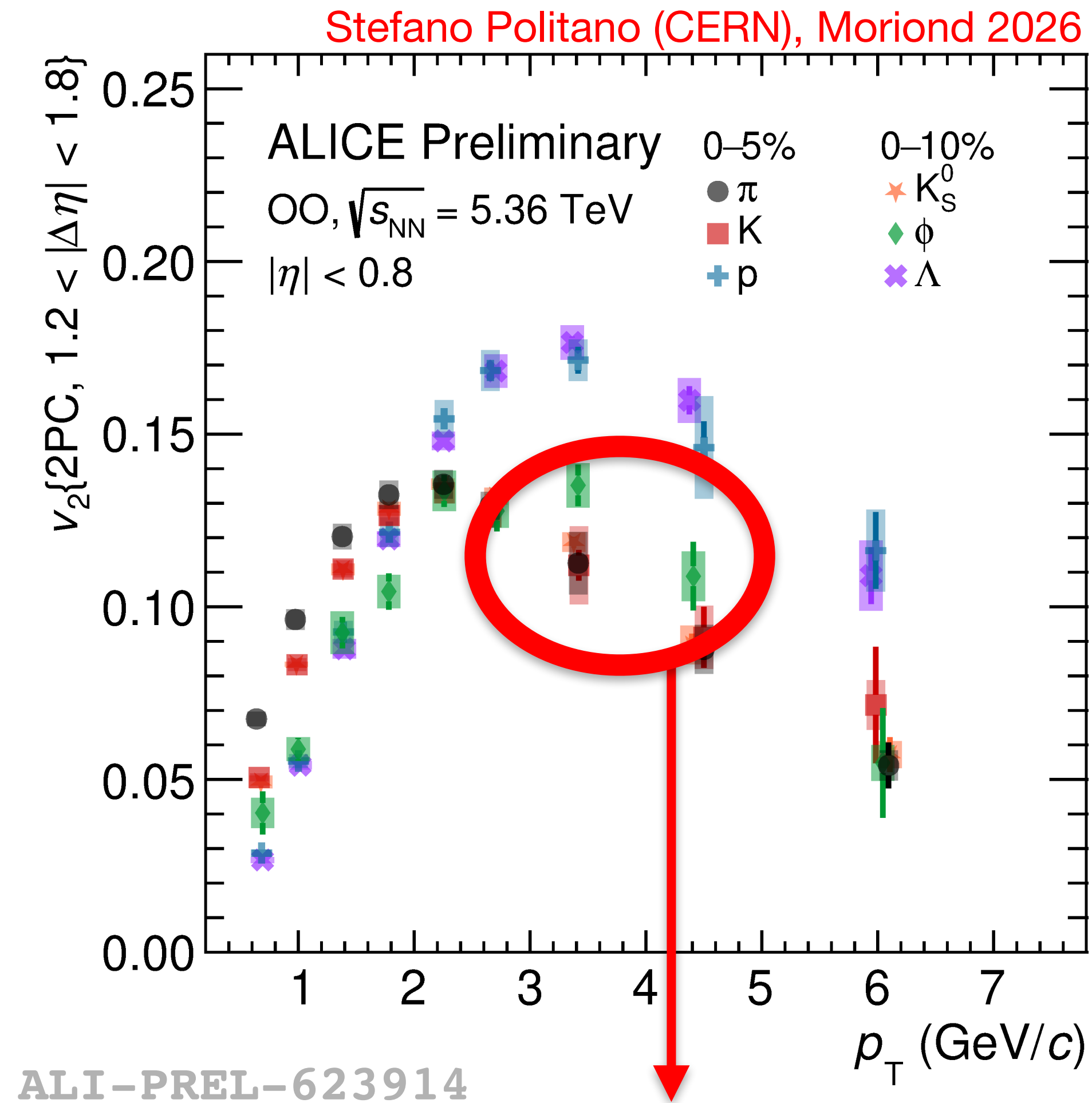


## ❖ PID $v_2$ in OO and Ne-Ne are similar

- When putting the results together with  $K_S^0$ ,  $\Lambda$  and  $\Phi$   $v_2$ , there is an indication that  $\Phi$   $v_2$  is slightly larger
- This could be explained by the event selection bias (i.e., when asking for a  $\Phi$  meson at 4-5 GeV/c, the selected events are no longer regular events but “ $\Phi$ -targeted” events with larger  $[p_T]$ )
- **Caution:** it might be the same for  $J/\Psi$ , D etc.
- ALICE must revisit the  $\Phi$   $v_2$  results the publication!



# Potential issue in the existing results and future publication

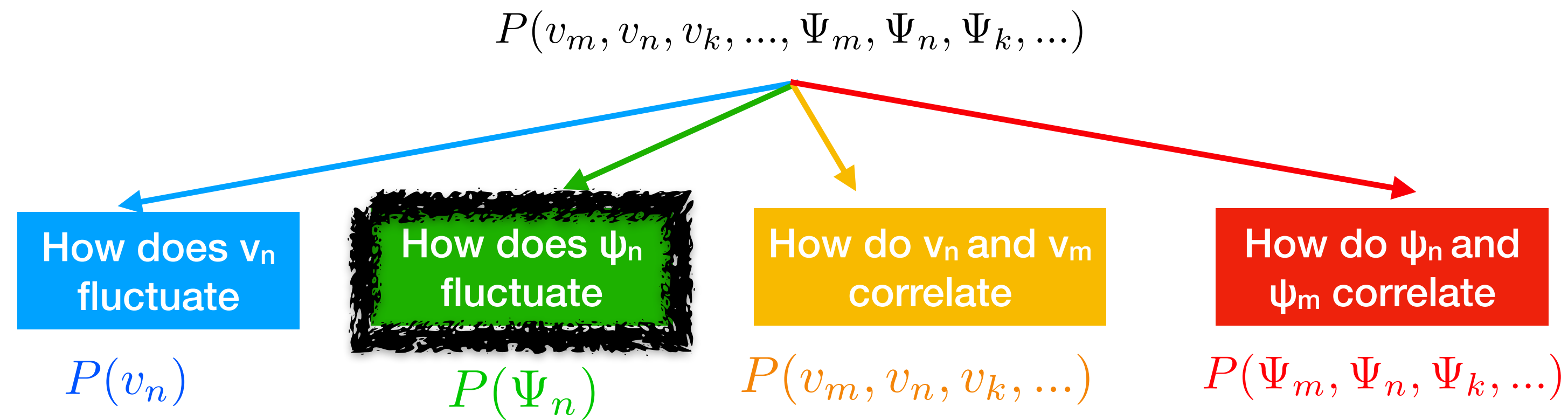


$\phi$   $v_2$  is a bit larger?  
Why? Selection bias?

## ❖ PID $v_2$ in OO and Ne-Ne are similar

- When putting the results together with  $K_S^0$ ,  $\Lambda$  and  $\Phi$   $v_2$ , there is an indication that  $\Phi$   $v_2$  is slightly larger
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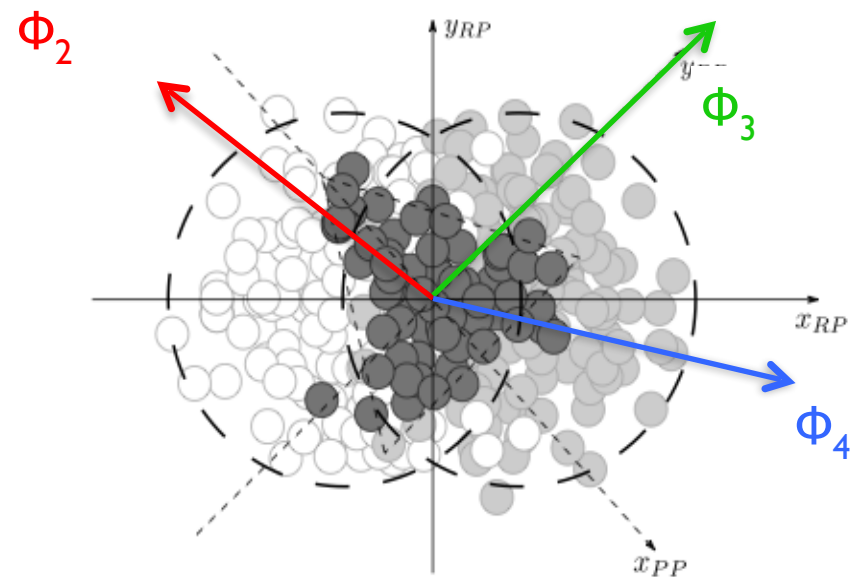
# Flow vector decorrelations



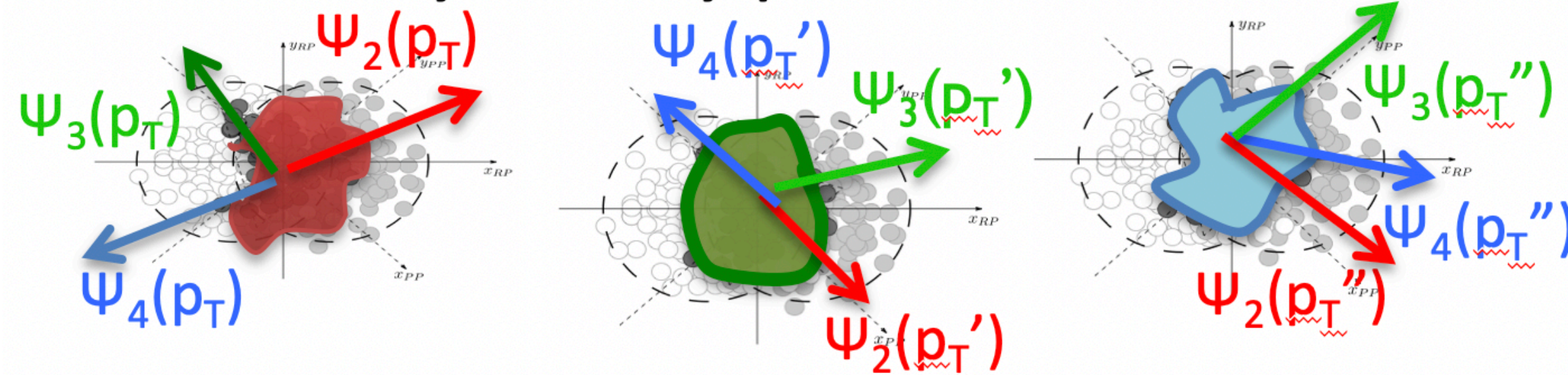


# Flow vector decorrelations

Initial symmetry planes



Final symmetry planes ??



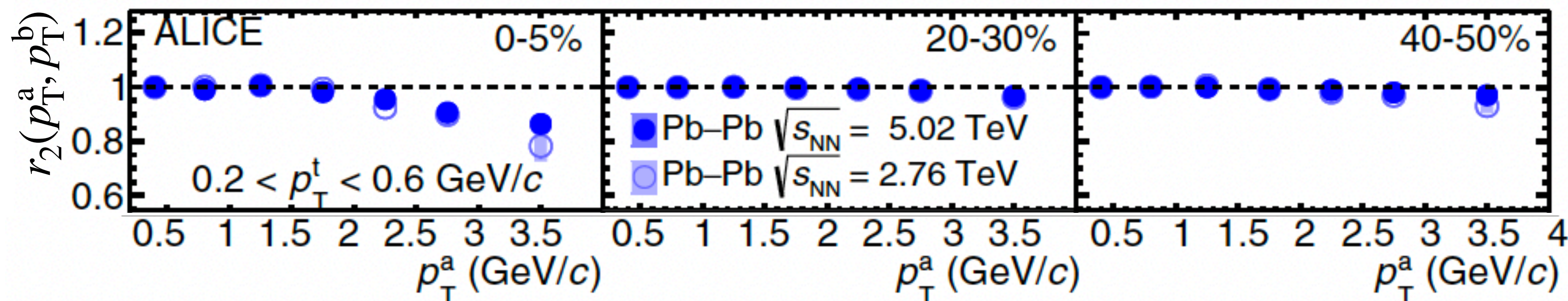
Initial proposal:

U. Heinz etc., PRC87, 034913 (2013)

F. G. Gardim etc., PRC 87, 031901(R) (2013).

$$r_2(p_T^a, p_T^b) = \frac{V_{2\Delta}(p_T^a, p_T^b)}{\sqrt{V_{2\Delta}(p_T^a, p_T^a)V_{2\Delta}(p_T^b, p_T^b)}} = \frac{\langle v_n(p_T^a) v_n(p_T^b) \cos n[\Psi_n(p_T^a) - \Psi_n(p_T^b)] \rangle}{\sqrt{\langle v_n(p_T^a)^2 \rangle} \sqrt{\langle v_n(p_T^b)^2 \rangle}}$$

→ Flow angle fluctuations  
→ Flow magnitude fluctuations

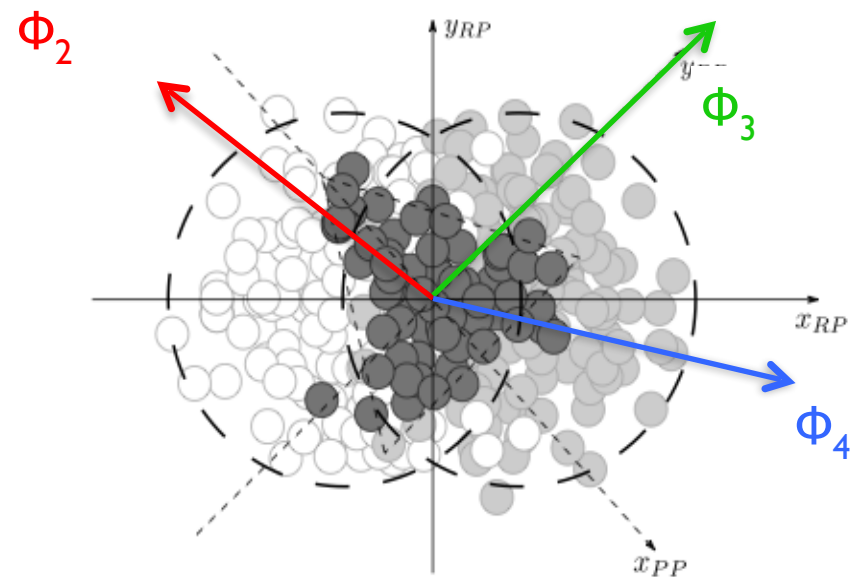


E.G. Nielsen, YZ, EPJC 83 (2023) 6, 545

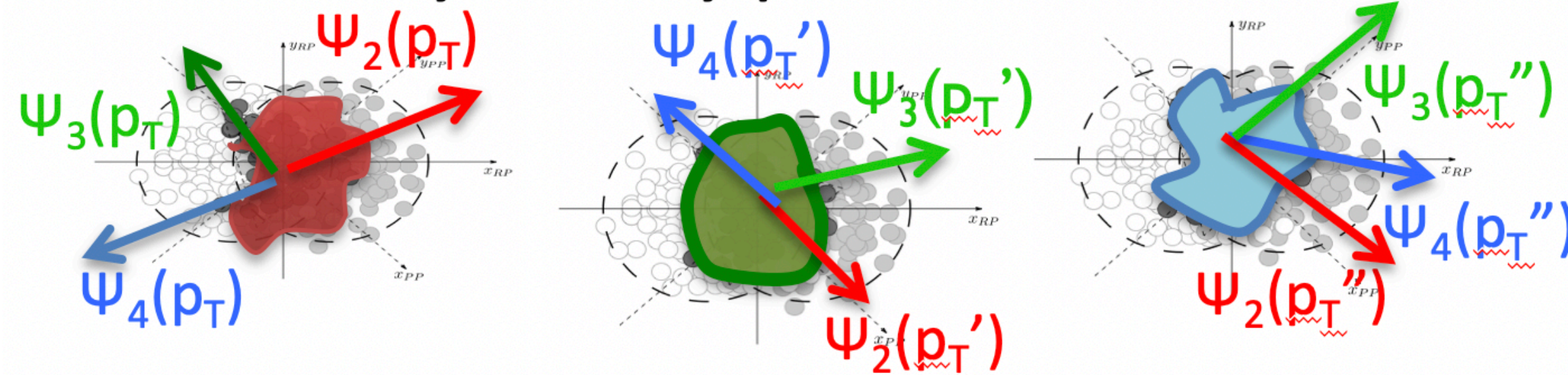


# Flow vector decorrelations

Initial symmetry planes



Final symmetry planes ??



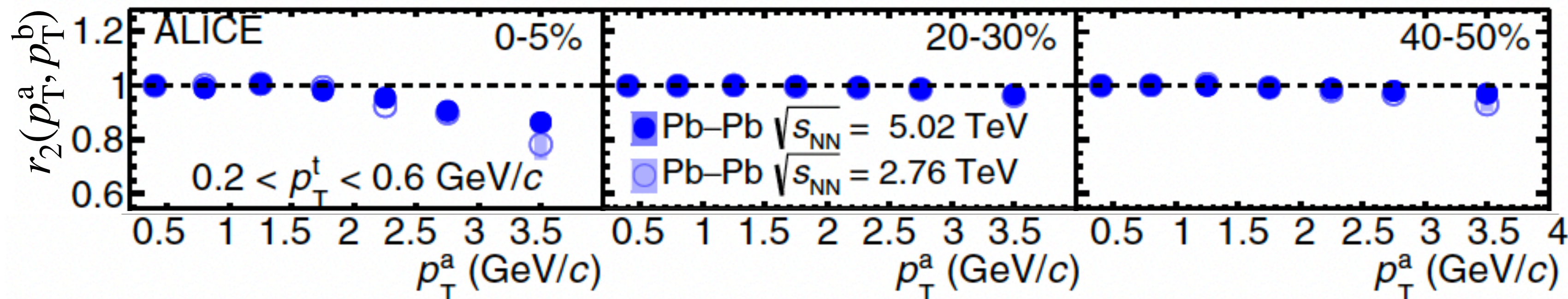
Initial proposal:

U. Heinz etc., PRC87, 034913 (2013)

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$$r_2(p_T^a, p_T^b) = \frac{V_{2\Delta}(p_T^a, p_T^b)}{\sqrt{V_{2\Delta}(p_T^a, p_T^a)V_{2\Delta}(p_T^b, p_T^b)}} = \frac{\langle v_n(p_T^a) v_n(p_T^b) \cos n[\Psi_n(p_T^a) - \Psi_n(p_T^b)] \rangle}{\sqrt{\langle v_n(p_T^a)^2 \rangle} \sqrt{\langle v_n(p_T^b)^2 \rangle}}$$

→ Flow angle fluctuations  
→ Flow magnitude fluctuations



ALICE, JHEP 09 (2017) 032

ALICE, PRC107 (2023) L051901

ALICE, PRC109 (2024) 065202

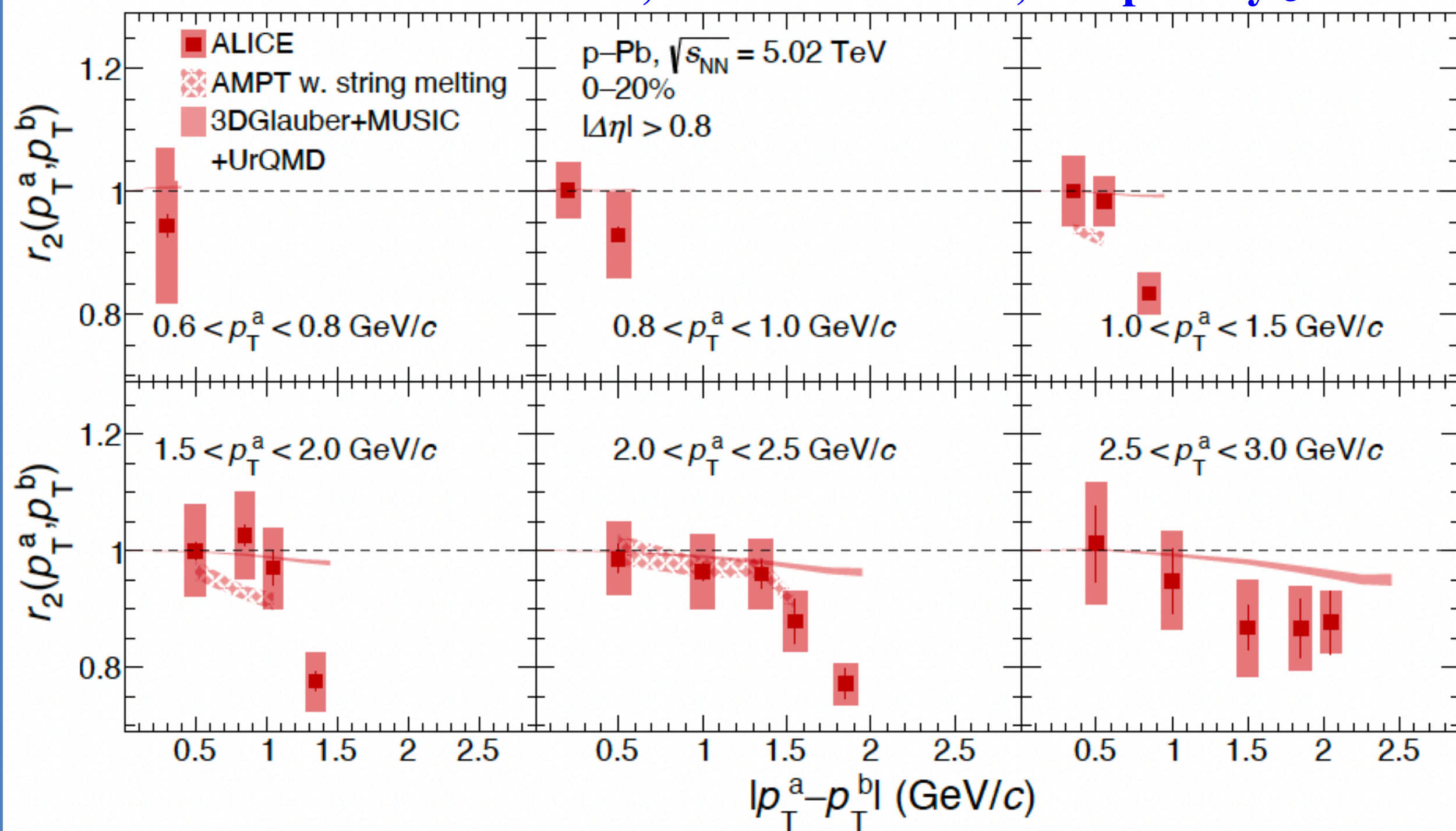
- ❖  $r_2(p_T^a, p_T^b)$  deviates from unity, observation of flow-vector fluctuations in Pb-Pb collisions
  - Driven by the initial geometrical fluctuations E.G. Nielsen, YZ, EPJC 83 (2023) 6, 545



# Flow vector decorrelations in $p_T$

$$r_2(p_T^a, p_T^b) = \frac{\langle v_n(p_T^a) v_n(p_T^b) \cos n[\Psi_n(p_T^a) - \Psi_n(p_T^b)] \rangle}{\sqrt{\langle v_n(p_T^a)^2 \rangle} \sqrt{\langle v_n(p_T^b)^2 \rangle}}$$

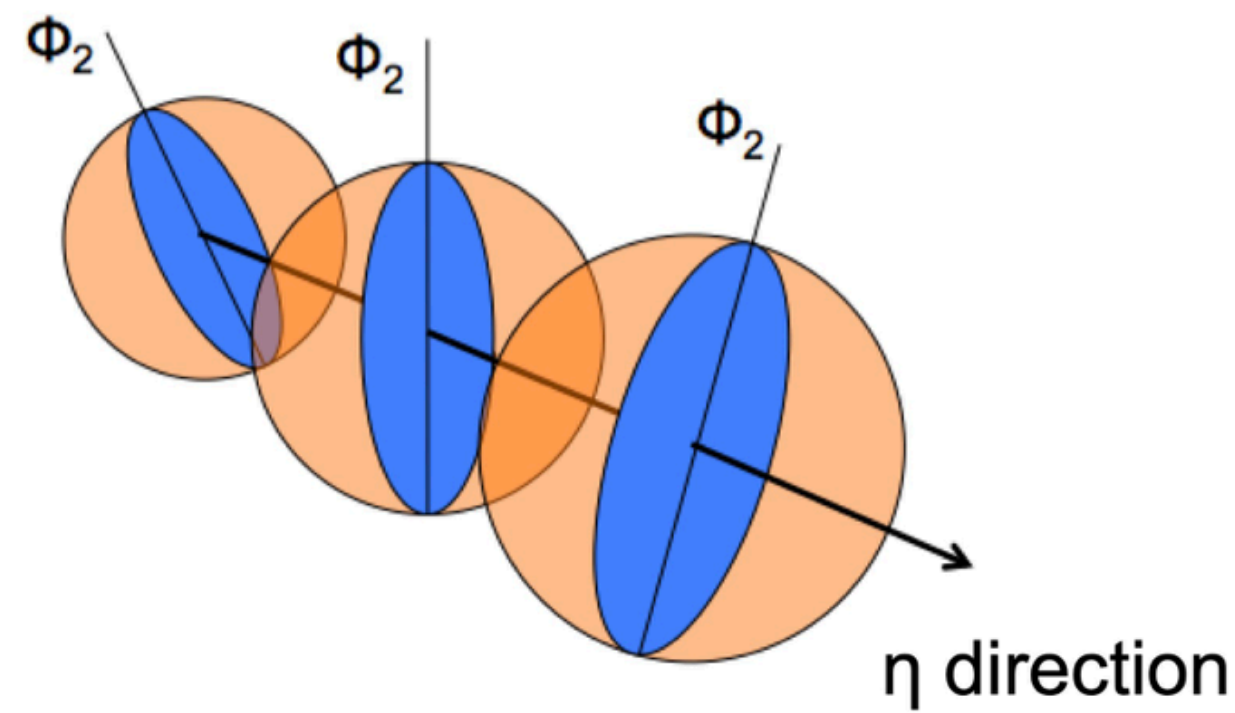
ALICE, arXiv:2602.10645, accepted by JHEP



- ❖  $r_2$  decrease with increasing  $|p_T^a - p_T^b|$ , deviation from unity is observed
  - Results can not be explained by nonflow
  - Evidence of flow vector decorrelations in  $p_T$  in p-Pb collisions
- ❖ AMPT model can reproduce the data, hydrodynamic model underestimates the decorrelation effect.
- ❖ Constraining initial conditions in **transverse direction**

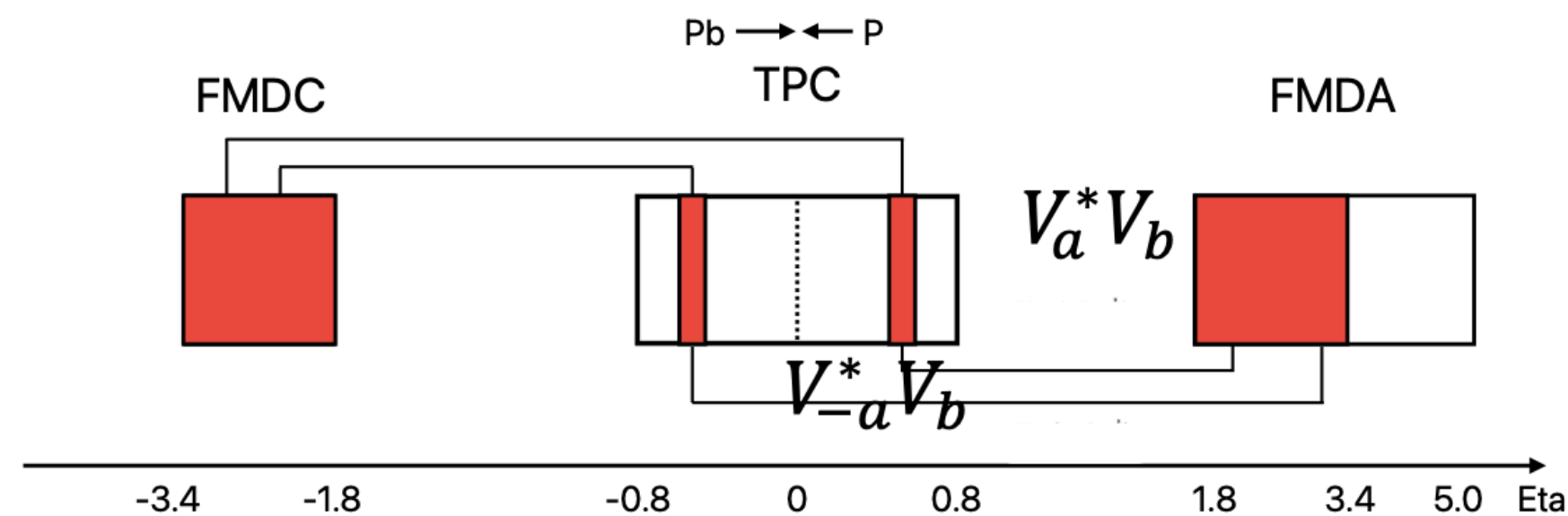


# Flow vector decorrelations in $\eta$ in p-Pb



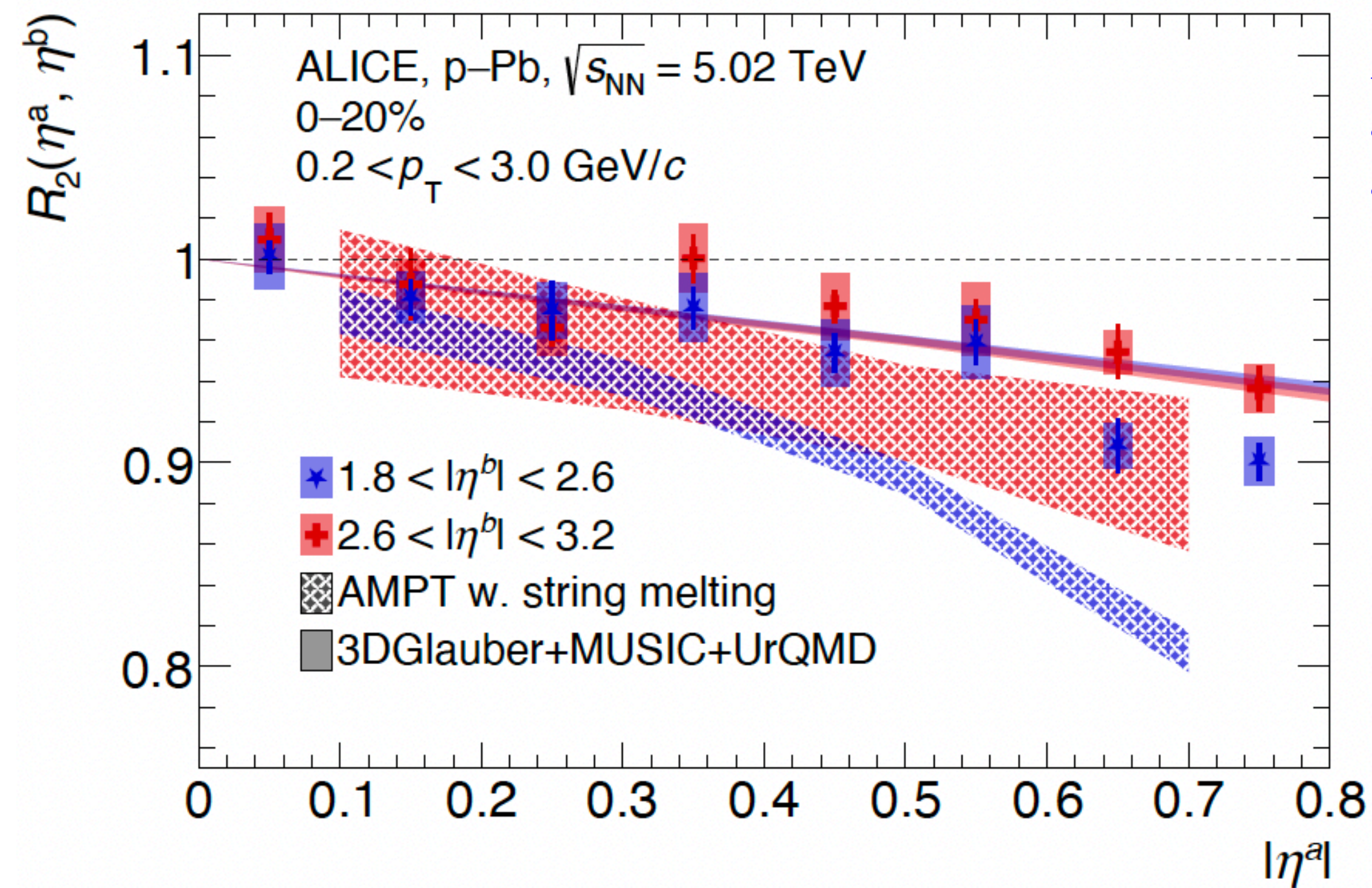
$$V_n(\eta_1) \neq V_n(\eta_2)$$

$$\langle V_a^* V_b \rangle \neq \sqrt{\langle V_a^* V_a \rangle \langle V_b^* V_b \rangle}$$



$$\sqrt{r_2(\eta^a, \eta^b) r_2(-\eta^a, -\eta^b)} = \sqrt{\frac{V_{2\Delta}(-\eta^a, -\eta^b)}{V_{2\Delta}(\eta^a, -\eta^b)} \frac{V_{2\Delta}(\eta^a, \eta^b)}{V_{2\Delta}(-\eta^a, \eta^b)}}$$

$$= \sqrt{\frac{\langle v_n(\eta^a) v_n(-\eta^b) \cos(n(\psi_n^{-a} - \psi_n^b)) \rangle}{\langle v_n(-\eta^a) v_n(-\eta^b) \cos(n(\psi_n^a - \psi_n^b)) \rangle} \frac{\langle v_n(-\eta^a) v_n(\eta^b) \cos(n(\psi_n^a - \psi_n^{-b})) \rangle}{\langle v_n(\eta^a) v_n(\eta^b) \cos(n(\psi_n^{-a} - \psi_n^{-b})) \rangle}}$$

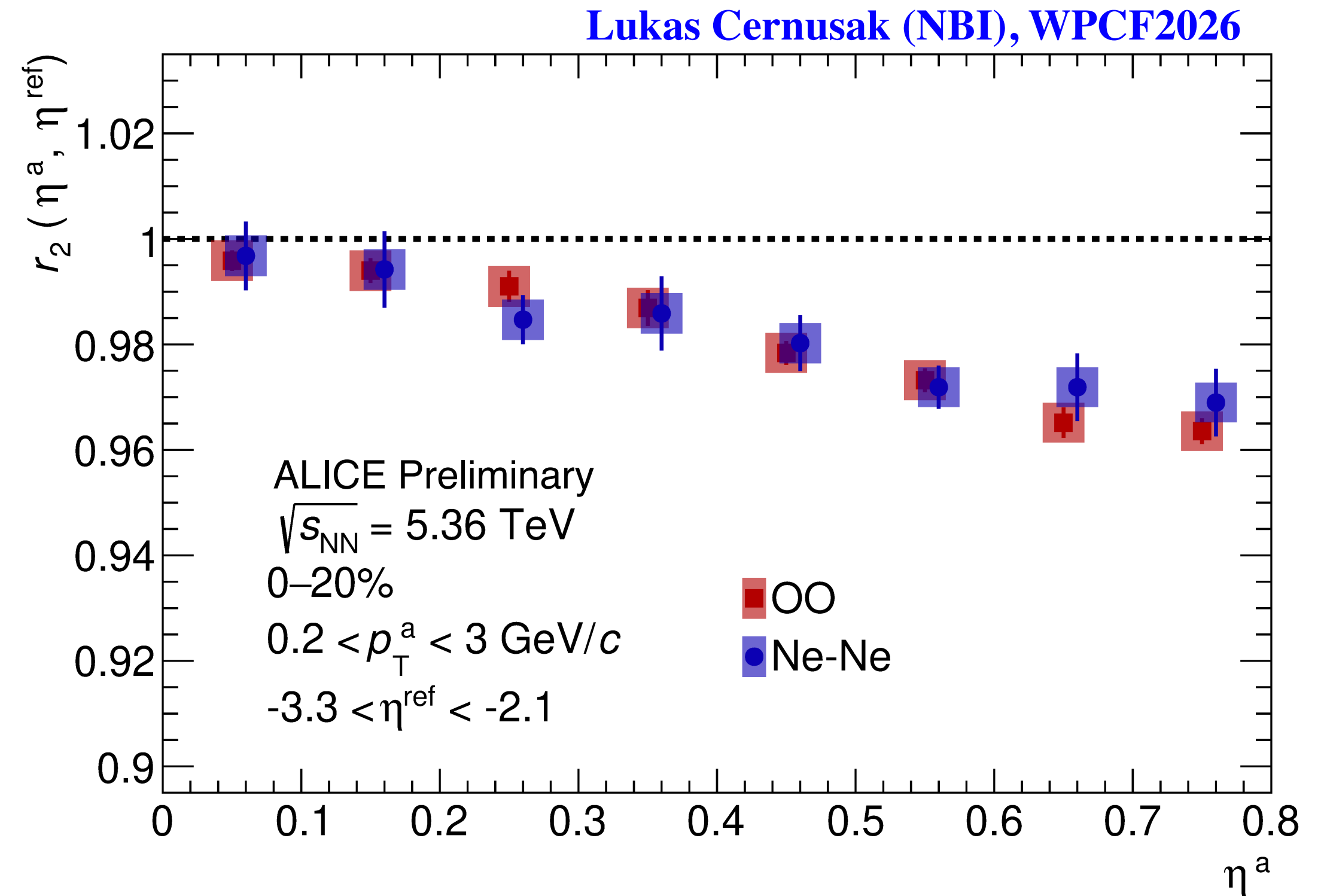
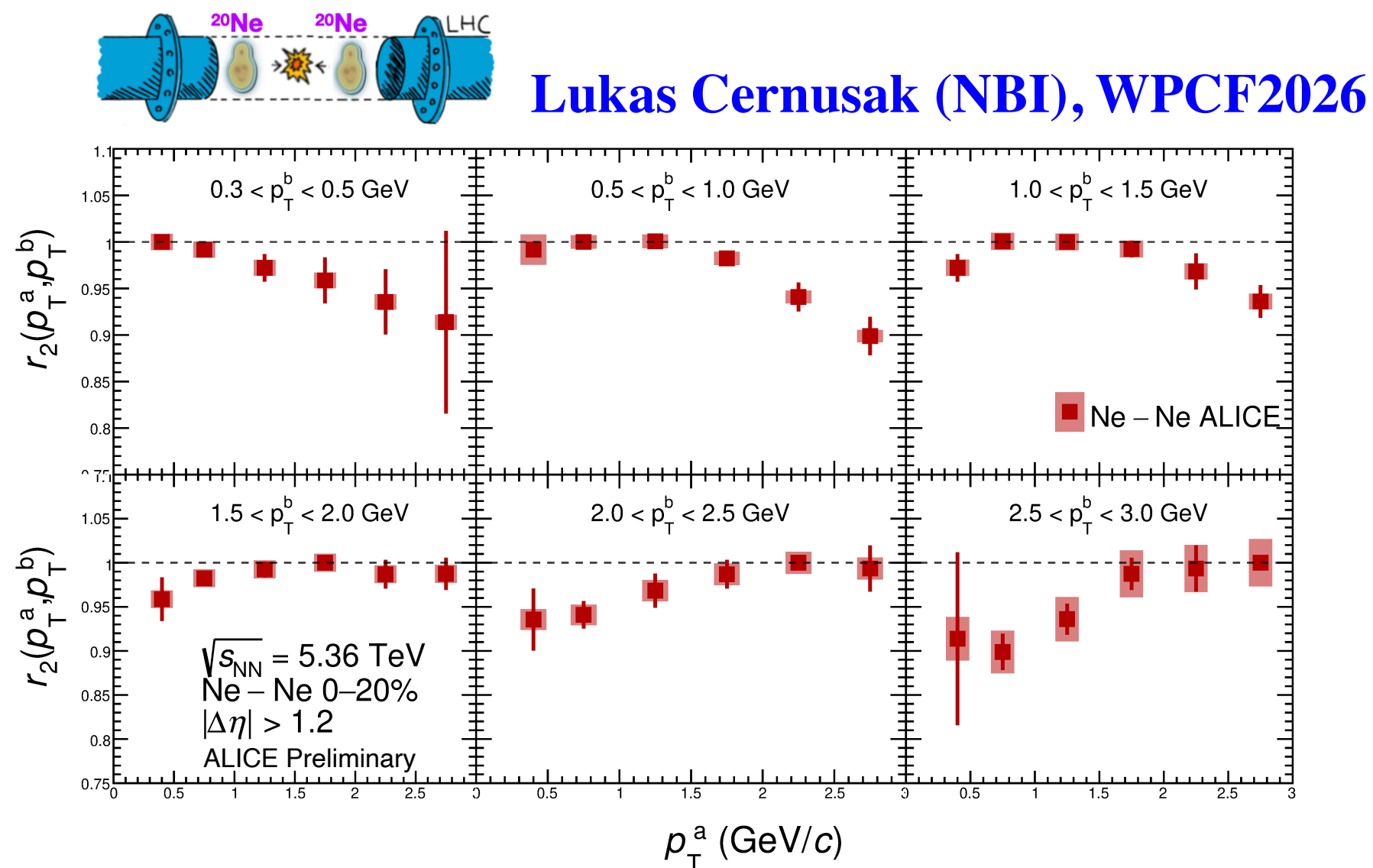
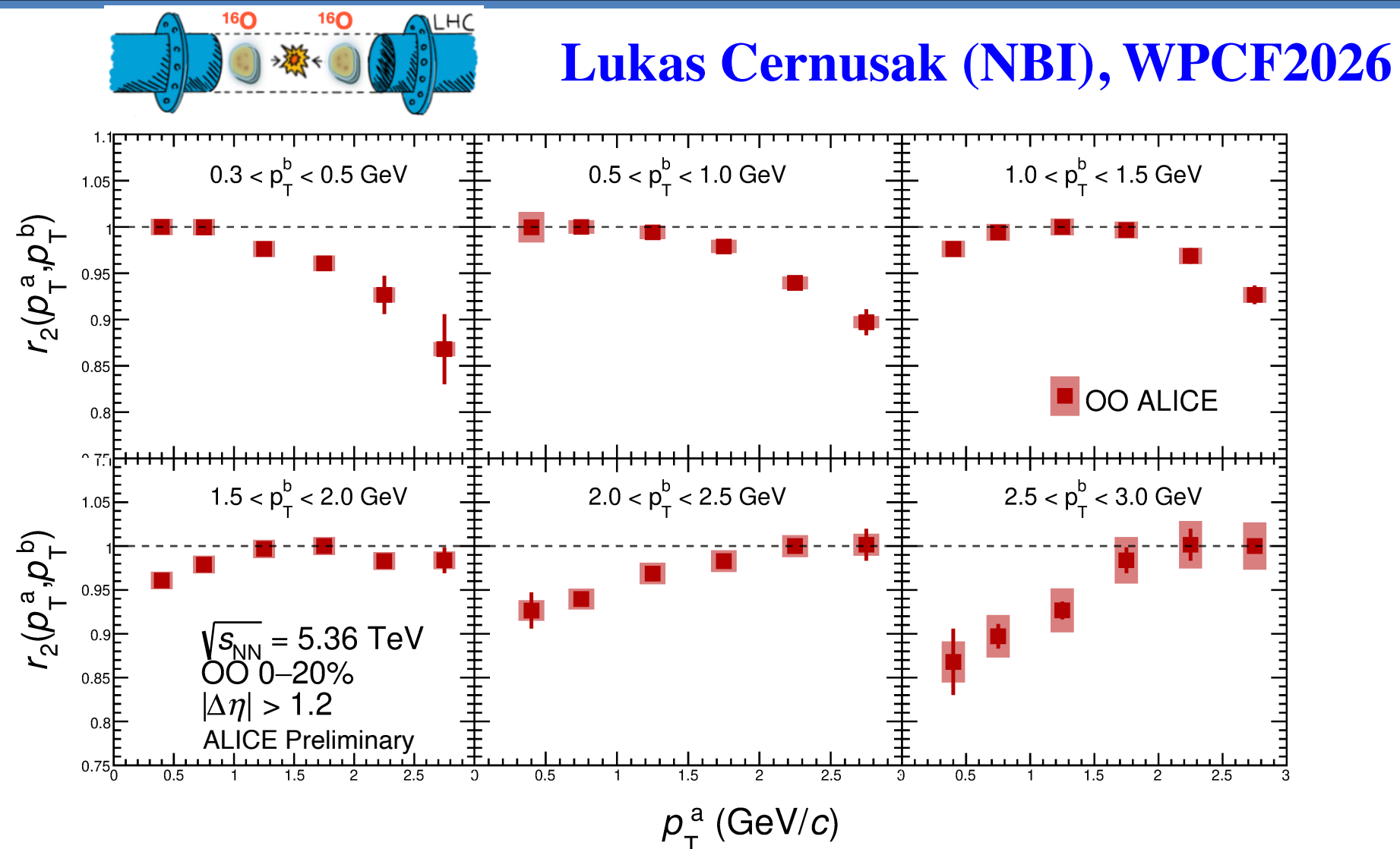


ALICE,  
arXiv:2602.10645,  
accepted by JHEP

❖ Constraining initial conditions in longitudinal direction

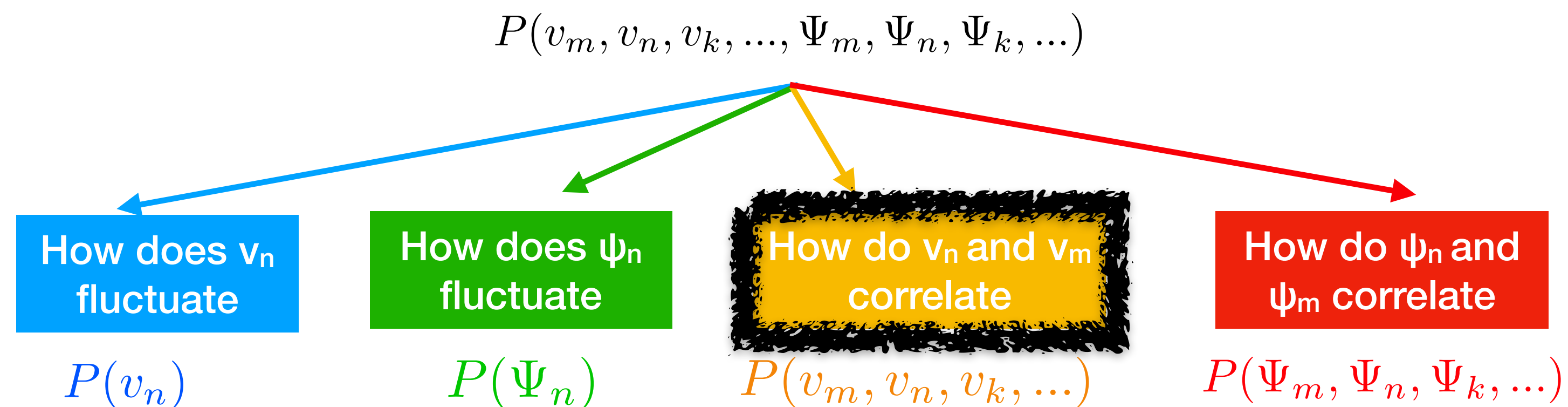


# Flow vector decorrelations in $\eta$ in OO and Ne-Ne



- ❖ Evidence of both  $p_T$ - and  $\eta$ -dependent flow-vector fluctuations in both OO and Ne-Ne
- ❖ fluctuations become stronger with  $|p_T^a - p_T^b|$  or  $|\eta^a - \eta^{\text{ref}}|$
- ❖ Results in OO and Ne-Ne are compatible with uncertainties, no significant impact from nuclear structure found yet

# Correlations between $v_m$ and $v_n$





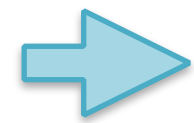
# Correlations between $v_m$ and $v_n$

## Symmetric cumulants:

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

(Suggested by Jean-Yves in QM15 to look at normalised SC)

$$\begin{aligned} v_2 &\propto \varepsilon_2 \\ v_3 &\propto \varepsilon_3 \end{aligned}$$



$$\frac{\langle v_2^2 v_3^2 \rangle - \langle v_2^2 \rangle \langle v_3^2 \rangle}{\langle v_2^2 \rangle \langle v_3^2 \rangle} = \frac{\langle \varepsilon_2^2 \varepsilon_3^2 \rangle - \langle \varepsilon_2^2 \rangle \langle \varepsilon_3^2 \rangle}{\langle \varepsilon_2^2 \rangle \langle \varepsilon_3^2 \rangle}$$

$$\text{Or: } NSC^v(3, 2) = NSC^\varepsilon(3, 2)$$

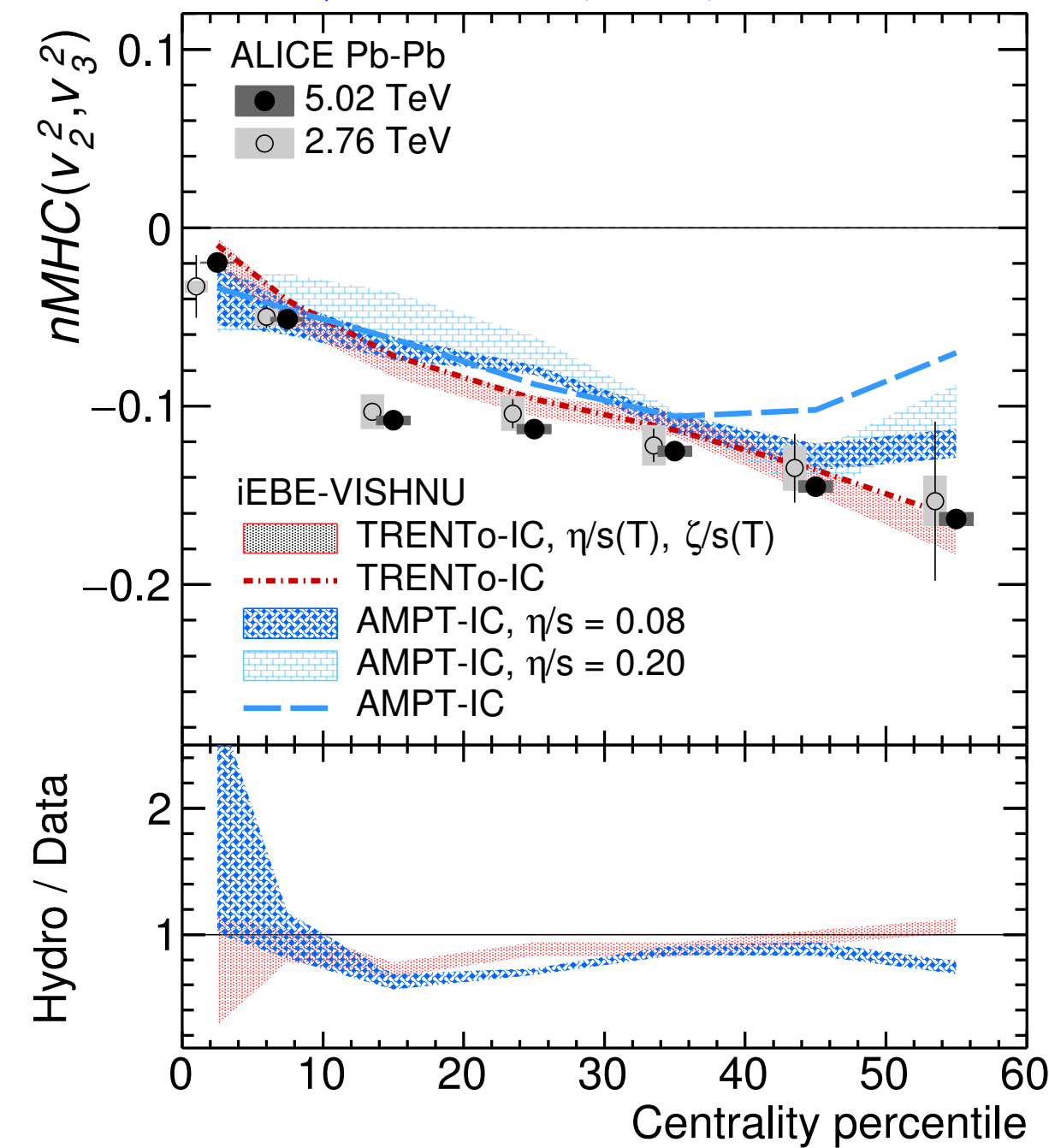
YZ, K. Xiao, F. Zhao, F. Liu, R. Snellings, PRC93, 034909 (2016)

X. Zhu, YZ, H. Xu, and H. Song, PRC95, 044902 (2017)

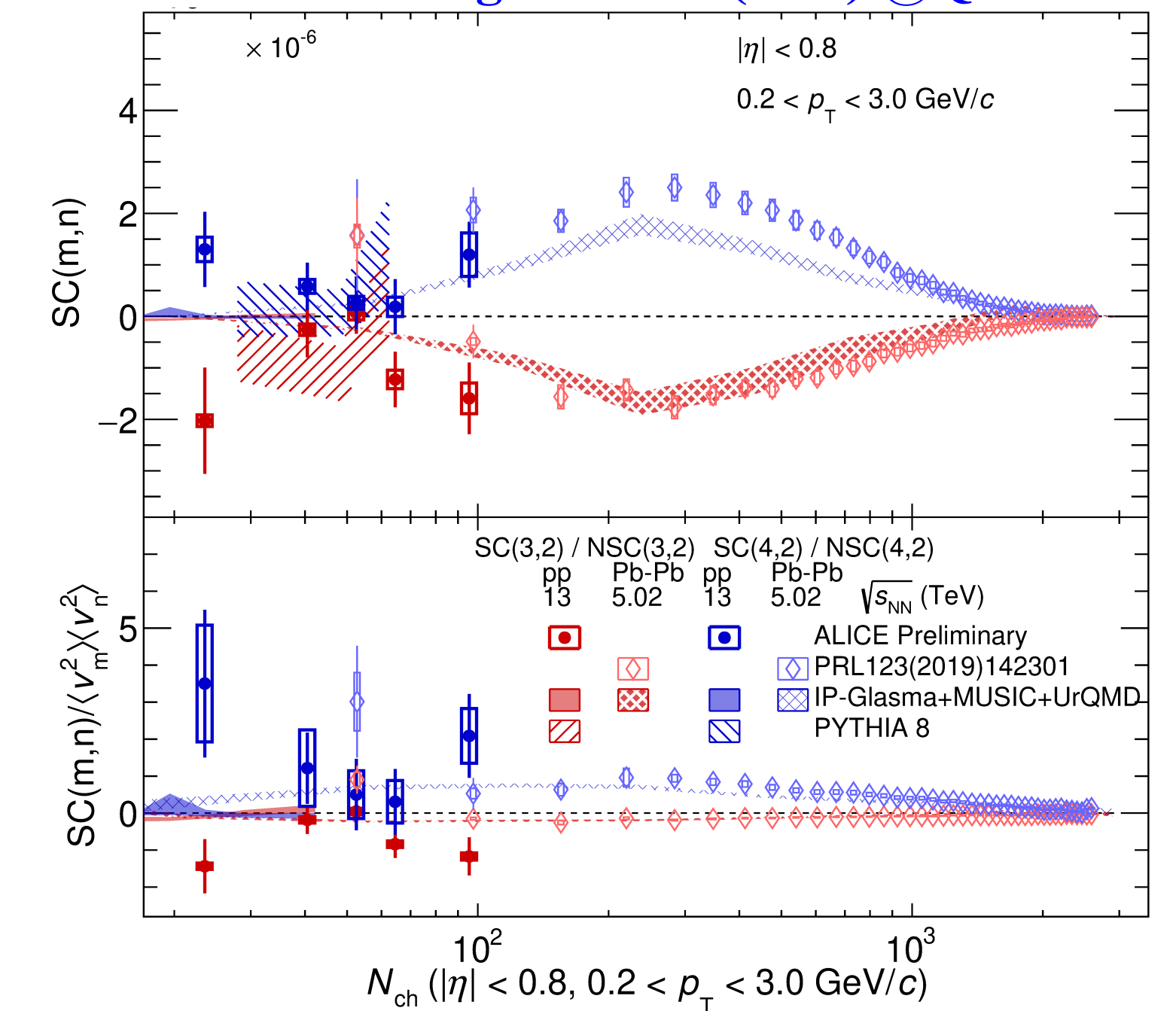
Z. Moravcova, K. Gulbrandsen, YZ, PRC103, 024913 (2021)

M. Li, YZ, ...H. Song, PRC104.024903(2021)

ALICE, PLB818 (2021) 136354

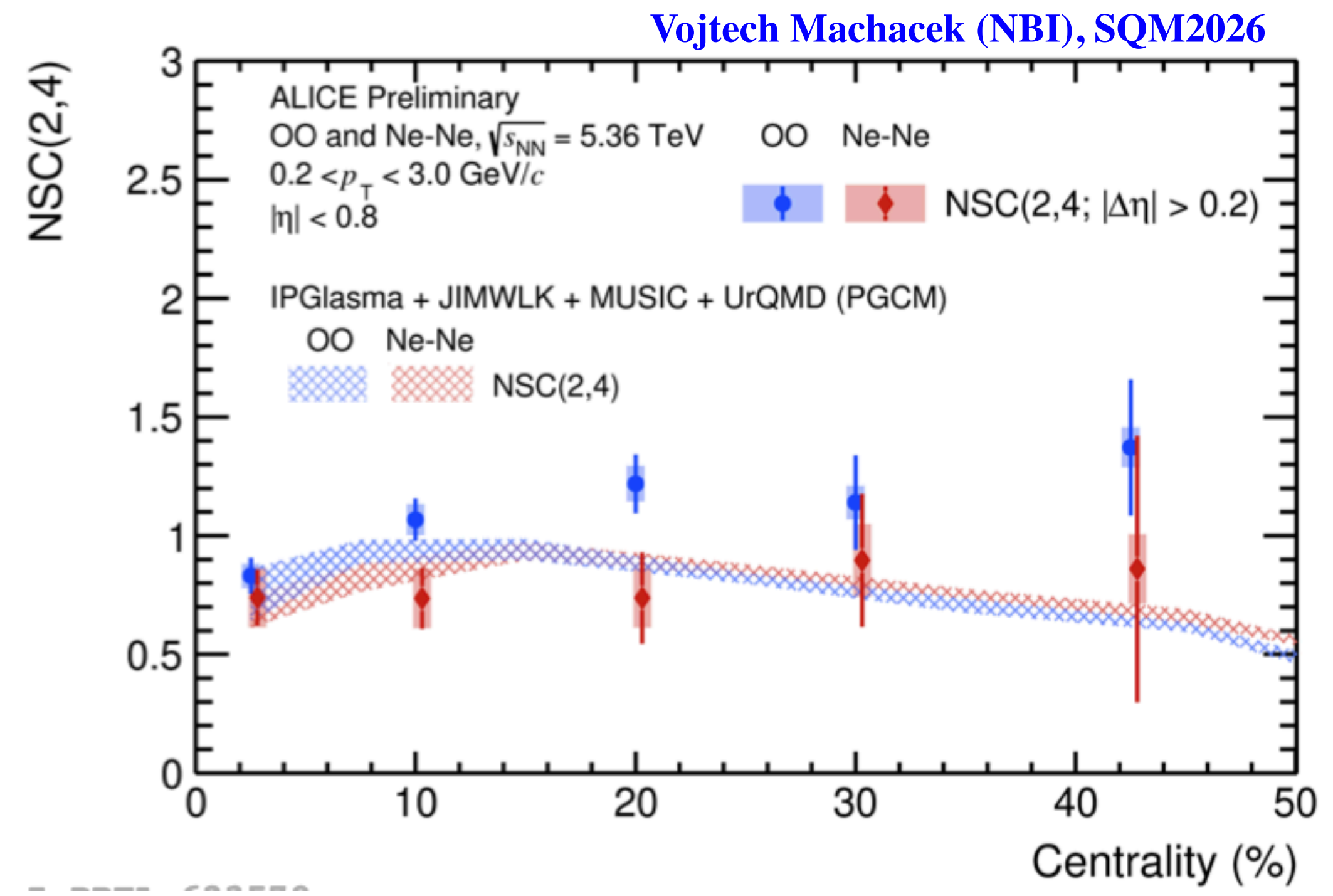
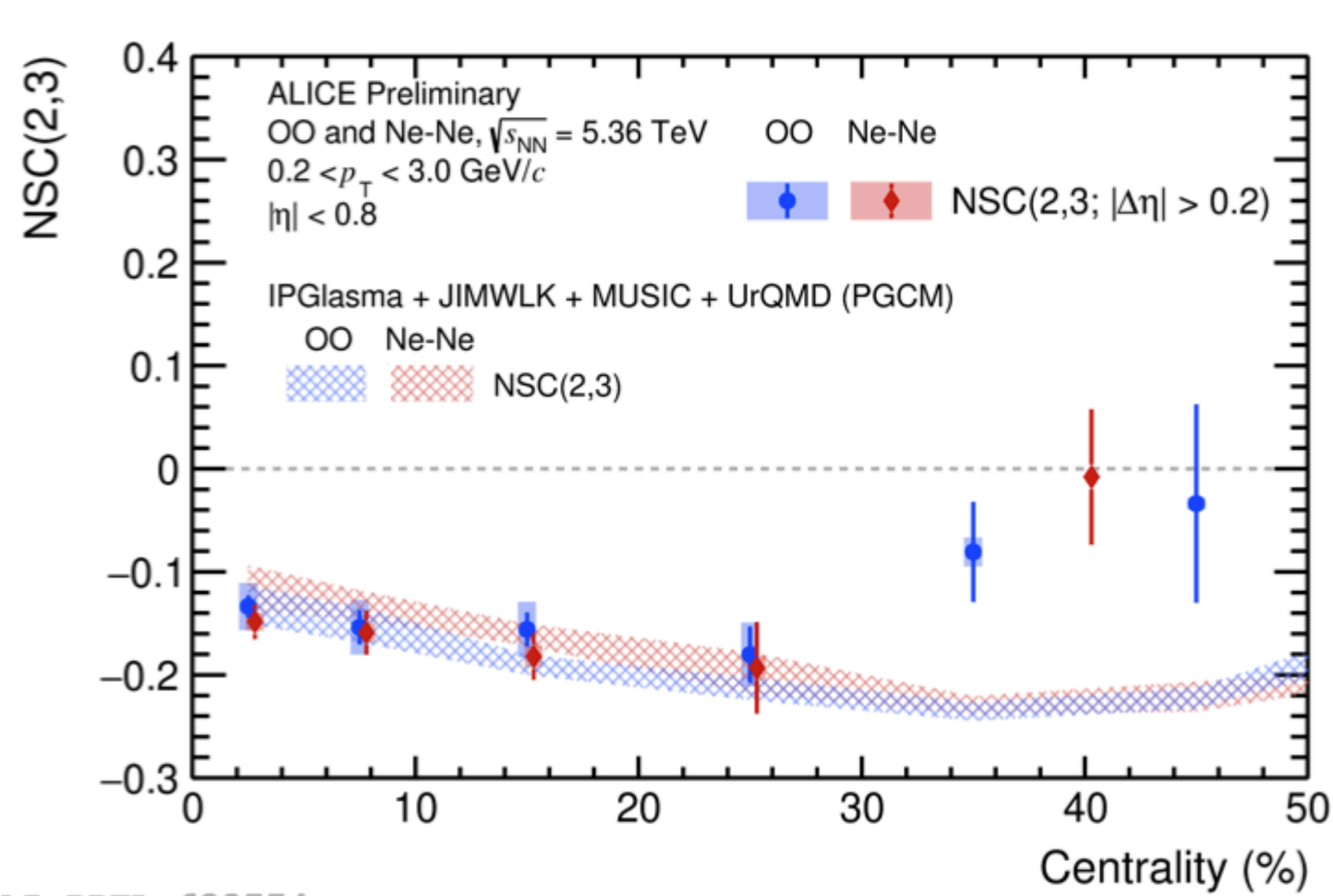


Mingrui Zhao (NBI) @QM2023



ALI-PREL-507164

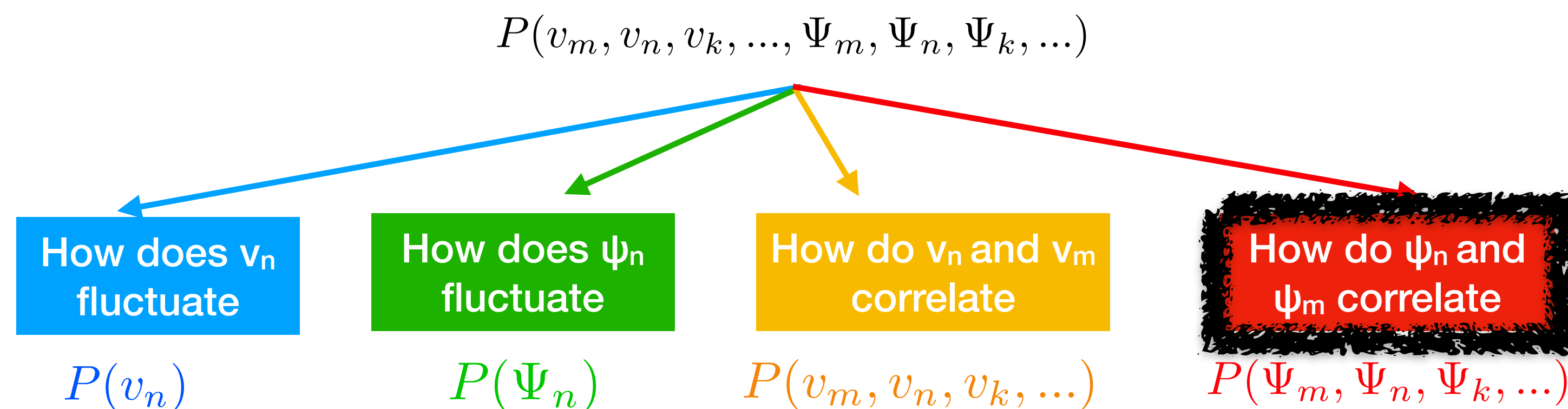
# Correlations between $v_m$ and $v_n$ in Ne-Ne and OO



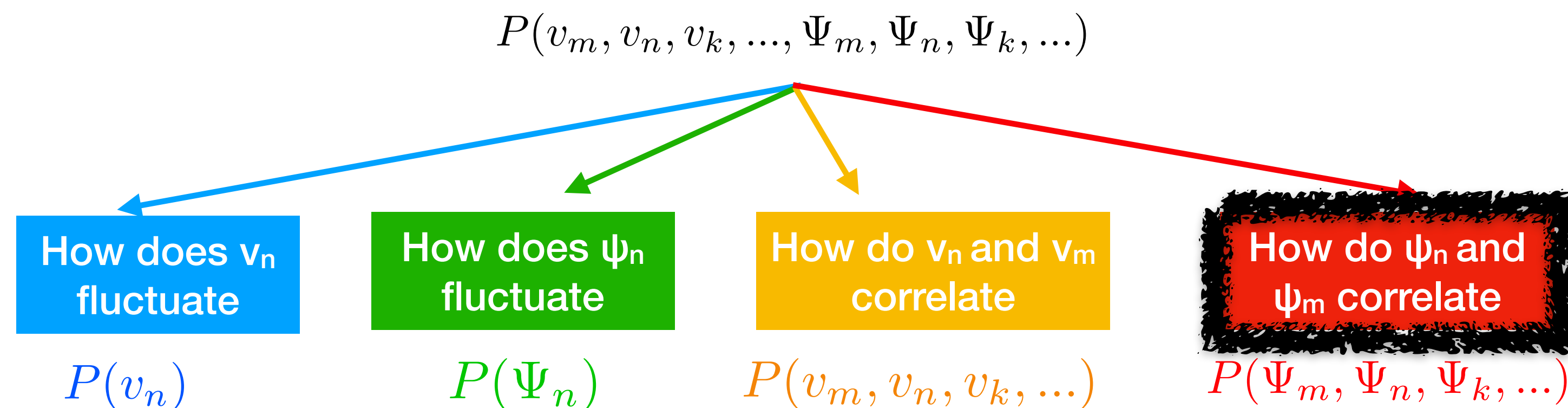
- ❖ For central and semi-central collisions:
  - Negative NSC(2,3), positive NSC(2,4)
    - Qualitatively described by hydrodynamic predictions incorporating nuclear structure
    - Similar to non-peripheral heavy-ion collisions
- ❖ For more peripheral collisions
  - Discrepancy w.r.t. hydro, similar to peripheral heavy-ion collisions



# Correlations between $v_m$ and $v_n$



# Correlations between $v_m$ and $v_n$





# Take home message



- Flow-like behavior observed in small system
  - Flow from Pb-Pb down to M.B. pp



# Take home message



- Flow-like behavior observed in small system
  - Flow from Pb-Pb down to M.B. pp



# Take home message



- Flow-like behavior observed in small system
  - Flow from Pb-Pb down to M.B. pp
- Smoking gun evidence of partonic flow, established in AA, discovered in small system.



# Take home message



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  - Flow from Pb-Pb down to M.B. pp
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Please cite ALICE, Nature Commun. 17 (2026) 1, 2585



# Take home message



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Please cite ALICE, Nature Commun. 17 (2026) 1, 2585

- To confirm existence of QGP in small systems, after hydrodynamic flow and jet quenching, what's else missing?
  - ➔ When can we start to say QGP in the light ion collisions?



# Take home message



- Flow-like behavior observed in small system
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Please cite ALICE, Nature Commun. 17 (2026) 1, 2585

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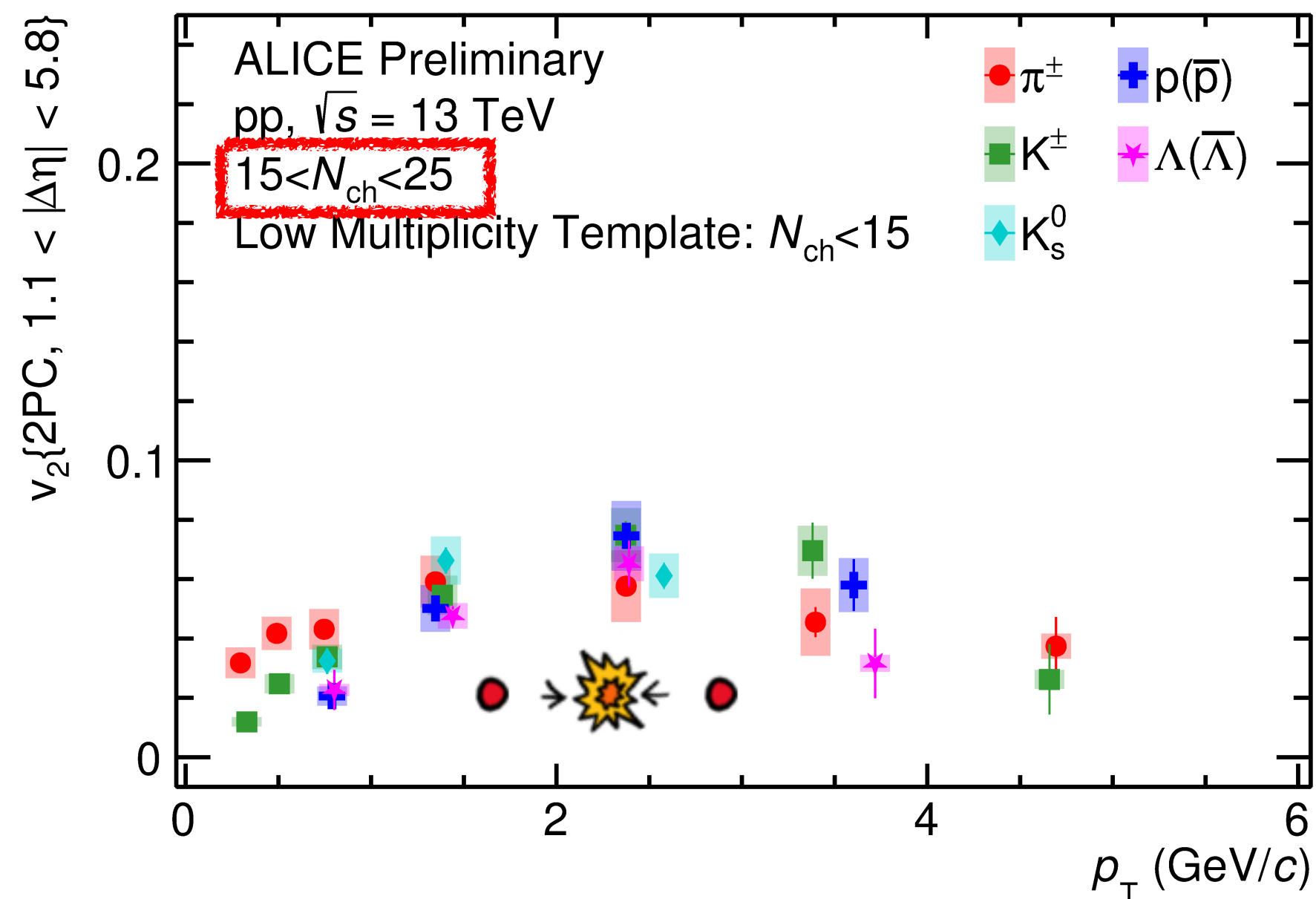
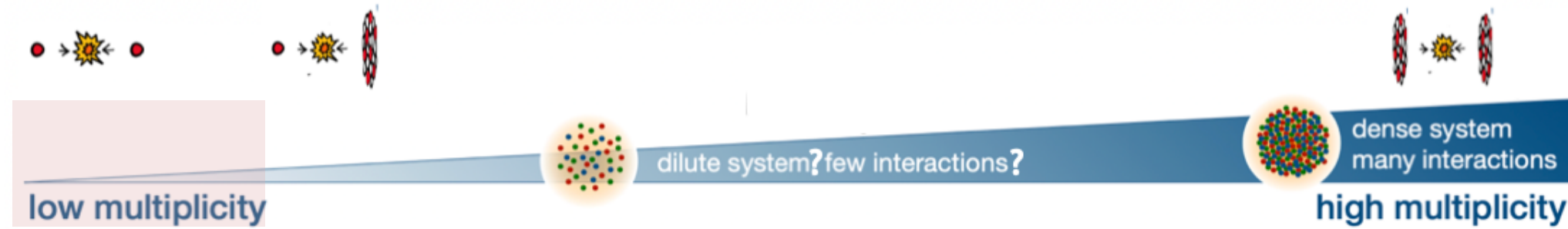




# Backup

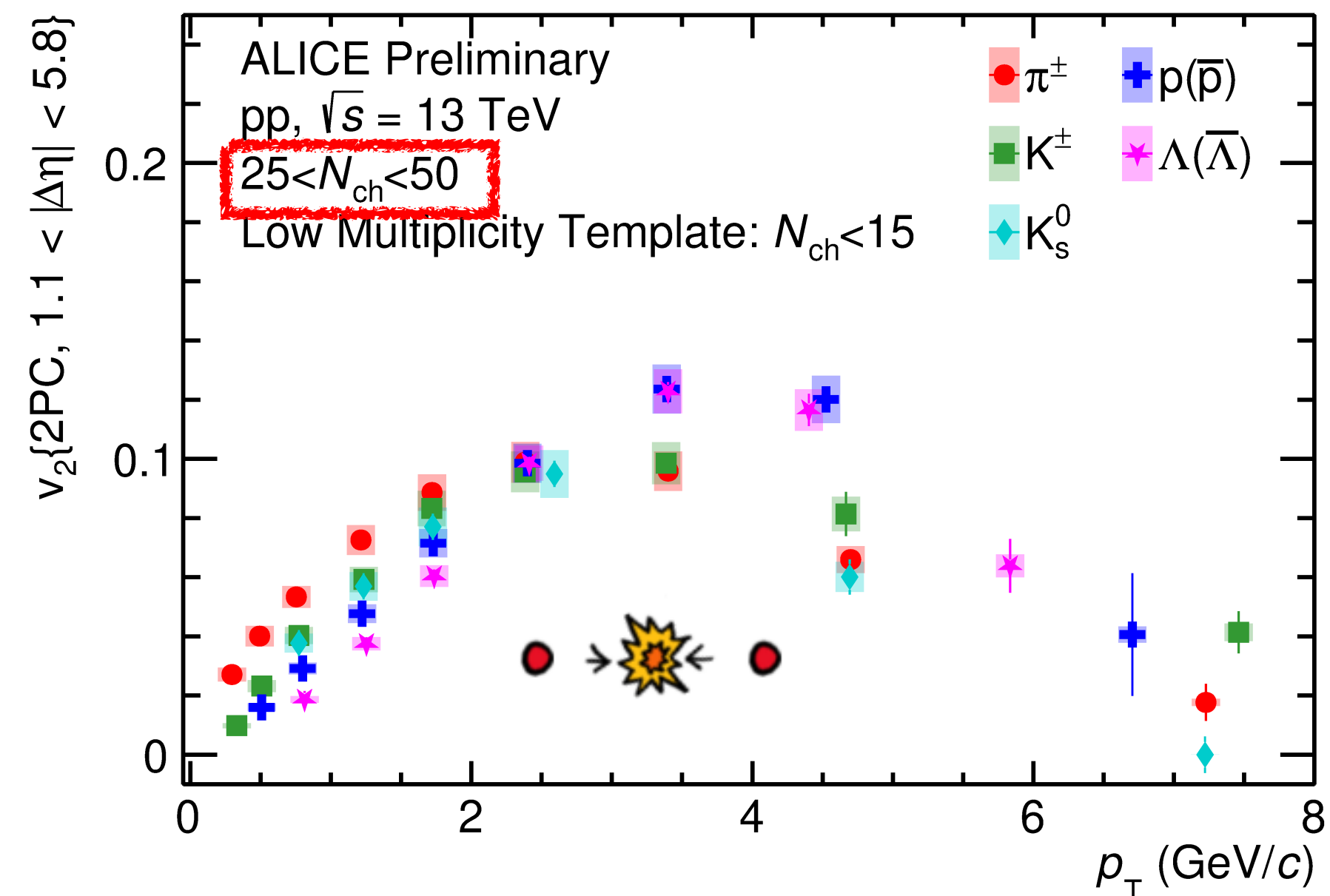


# PID $v_2$ for low $N_{ch}$ **pp** collisions



ALI-PREL-573045

ALICE, in preparation for PLB (post CR1)



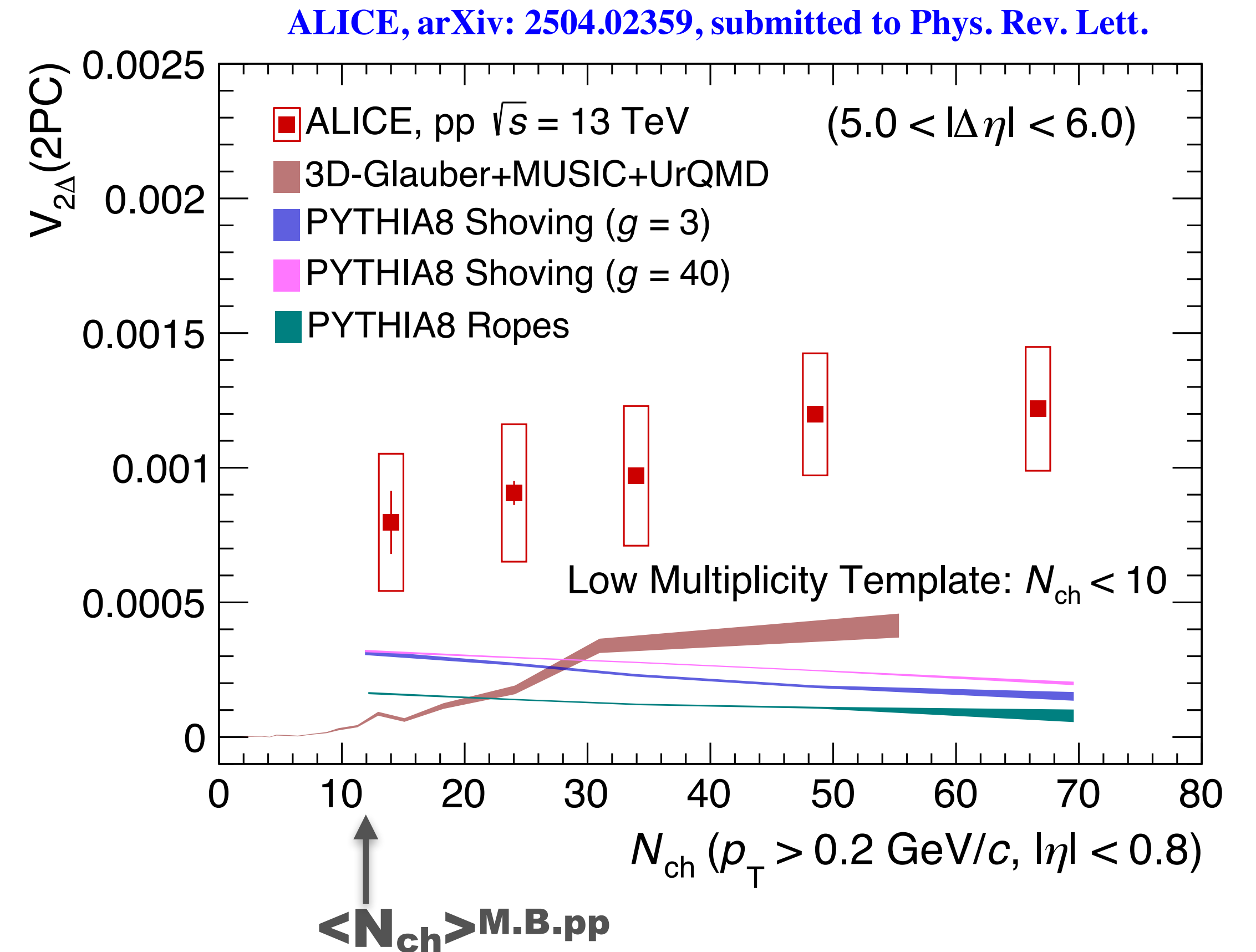
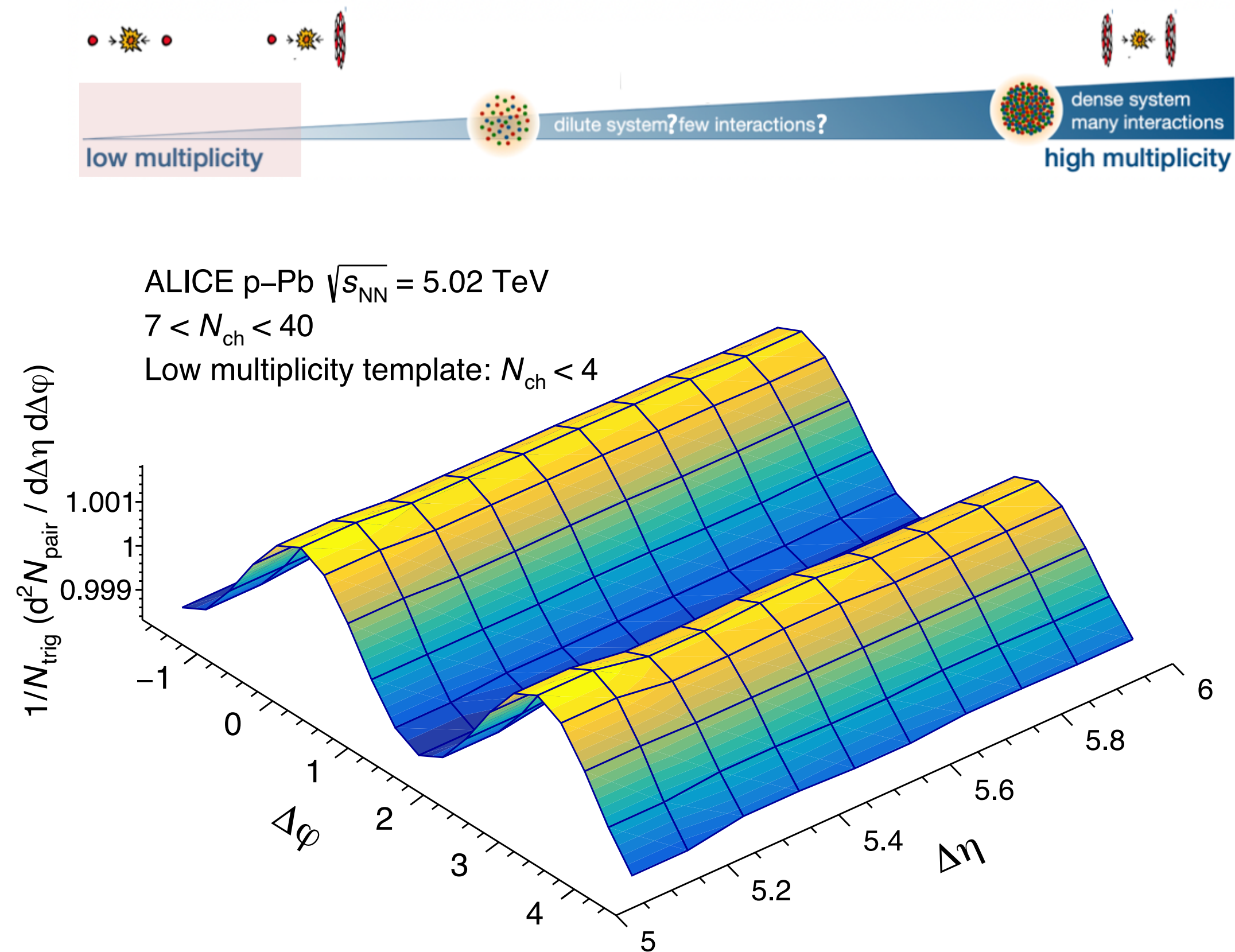
ALI-PREL-573050

## ❖ For **pp collisions**: non-zero PID $v_2$ :

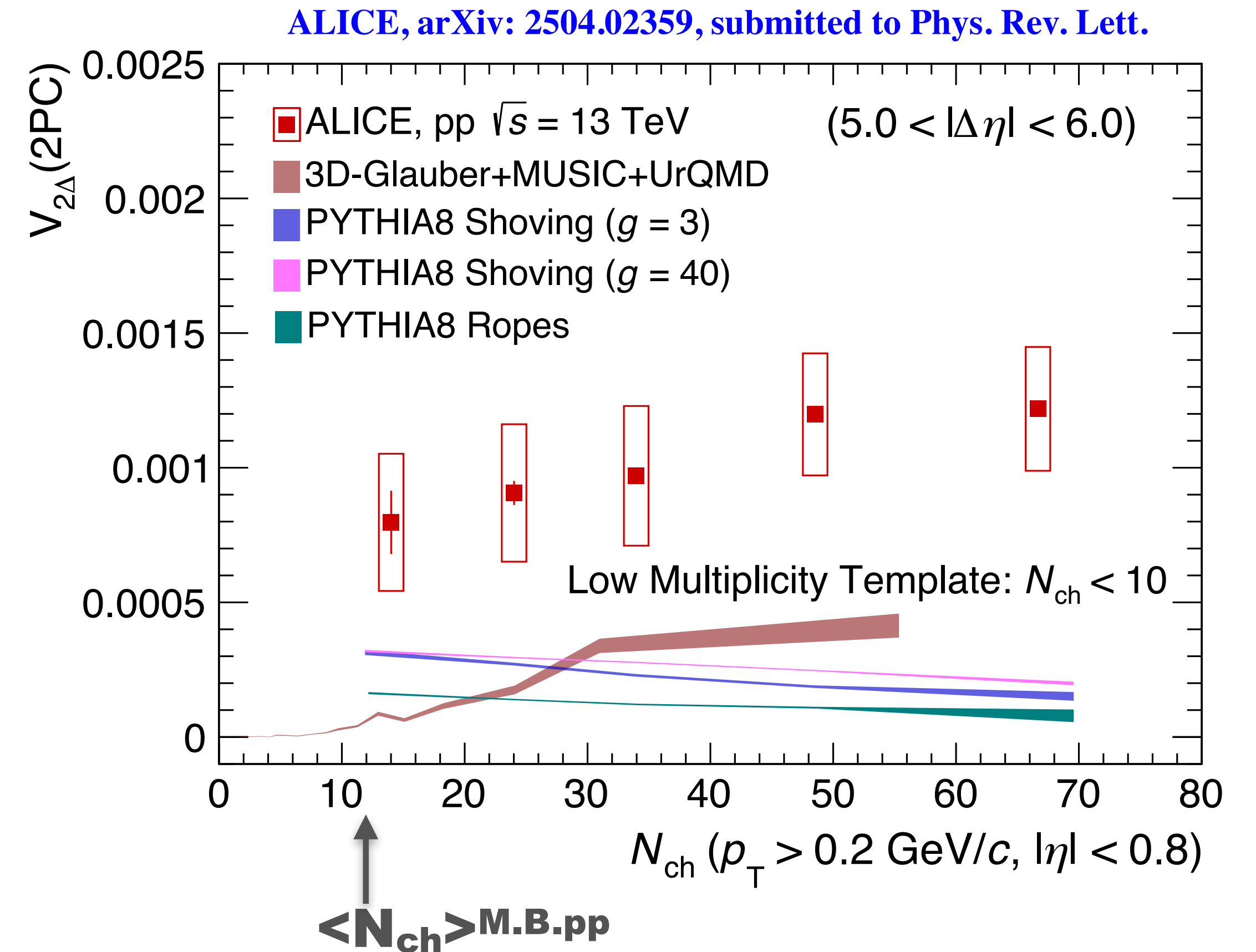
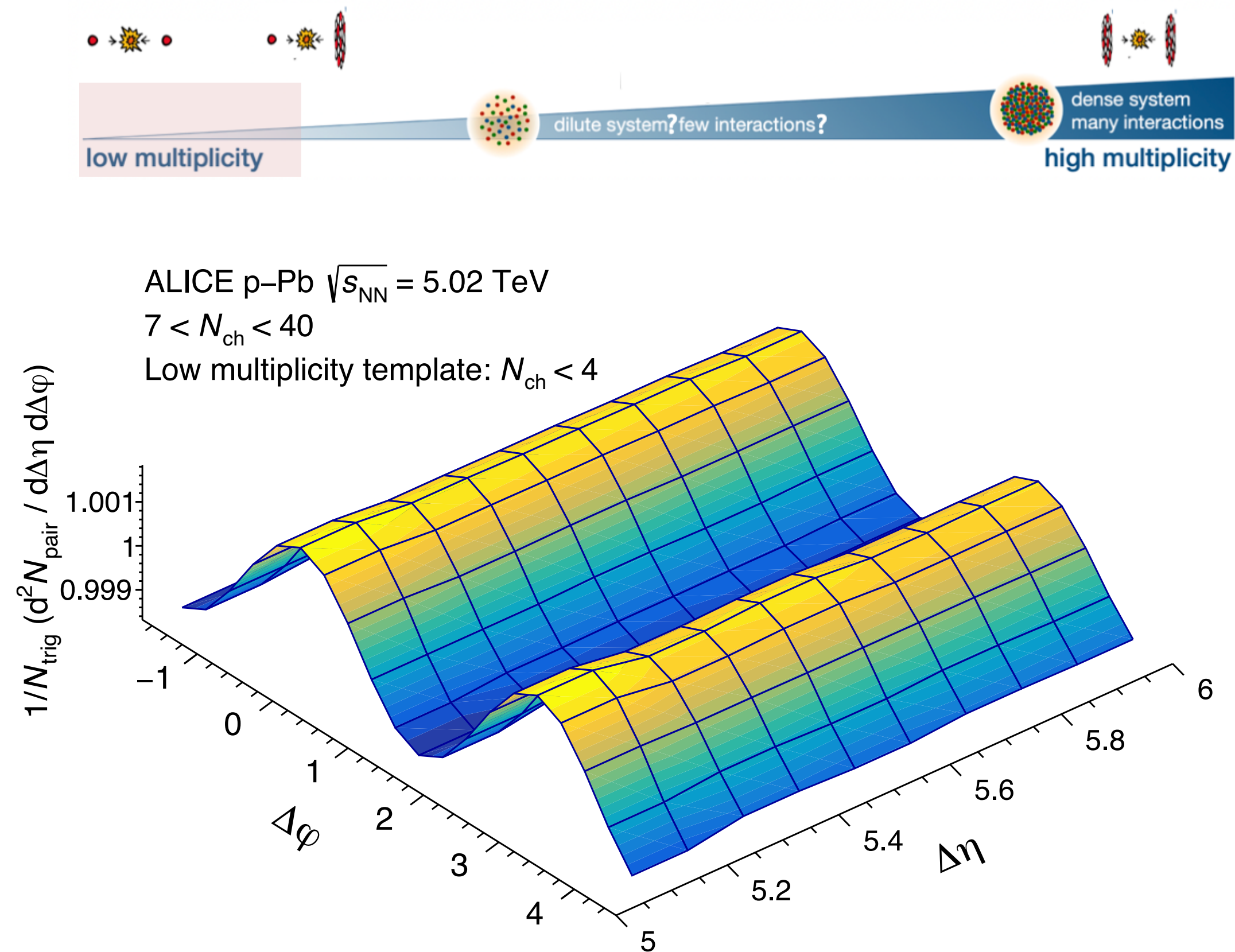
- $N_{ch} > 25$  : Baryon-meson grouping ( $\sim 1\sigma$  confidence) and splitting ( $5\sigma$  confidence) of  $v_2$  at intermediate  $p_T$
- $15 < N_{ch} < 25$ : grouping and splitting (within  $1\sigma$  confidence) diminished!
- Results could be improved by using the entire Run 3 pp data



# Observation of ultra-long-range correlation



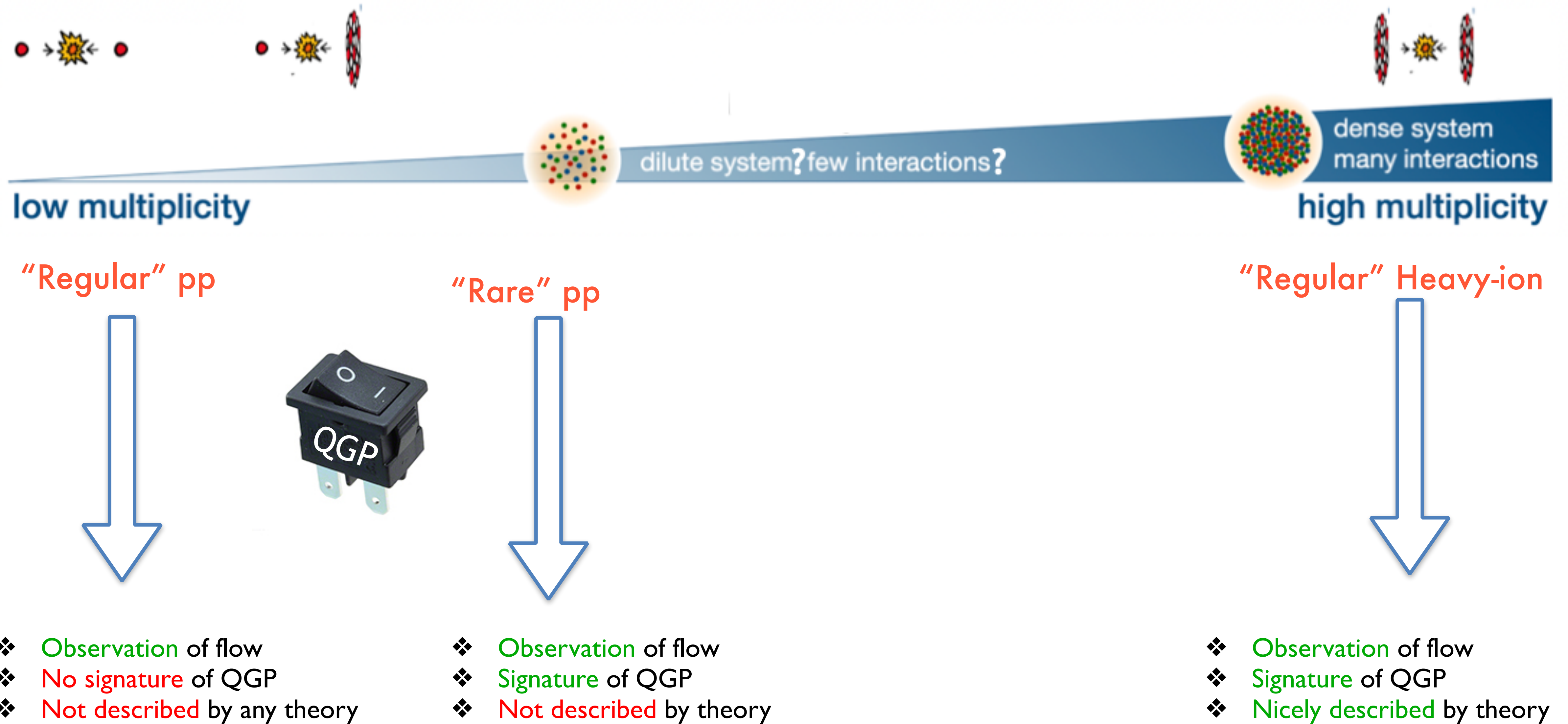
# Observation of ultra-long-range correlation



- ❖ Observation of **ultra-long-range correlation** in **low multiplicity** region
- ❖ Currently huge discrepancies between data and model calculations



# Status by June 2025





# OO and Ne-Ne collisions at the LHC

- Nov 2024, Light ion workshop

Light ion collisions at the LHC

Location: 4/3-006, CERN  
Website: [cern.ch/lightions](https://cern.ch/lightions)

Date: Nov. 11-15, 2024

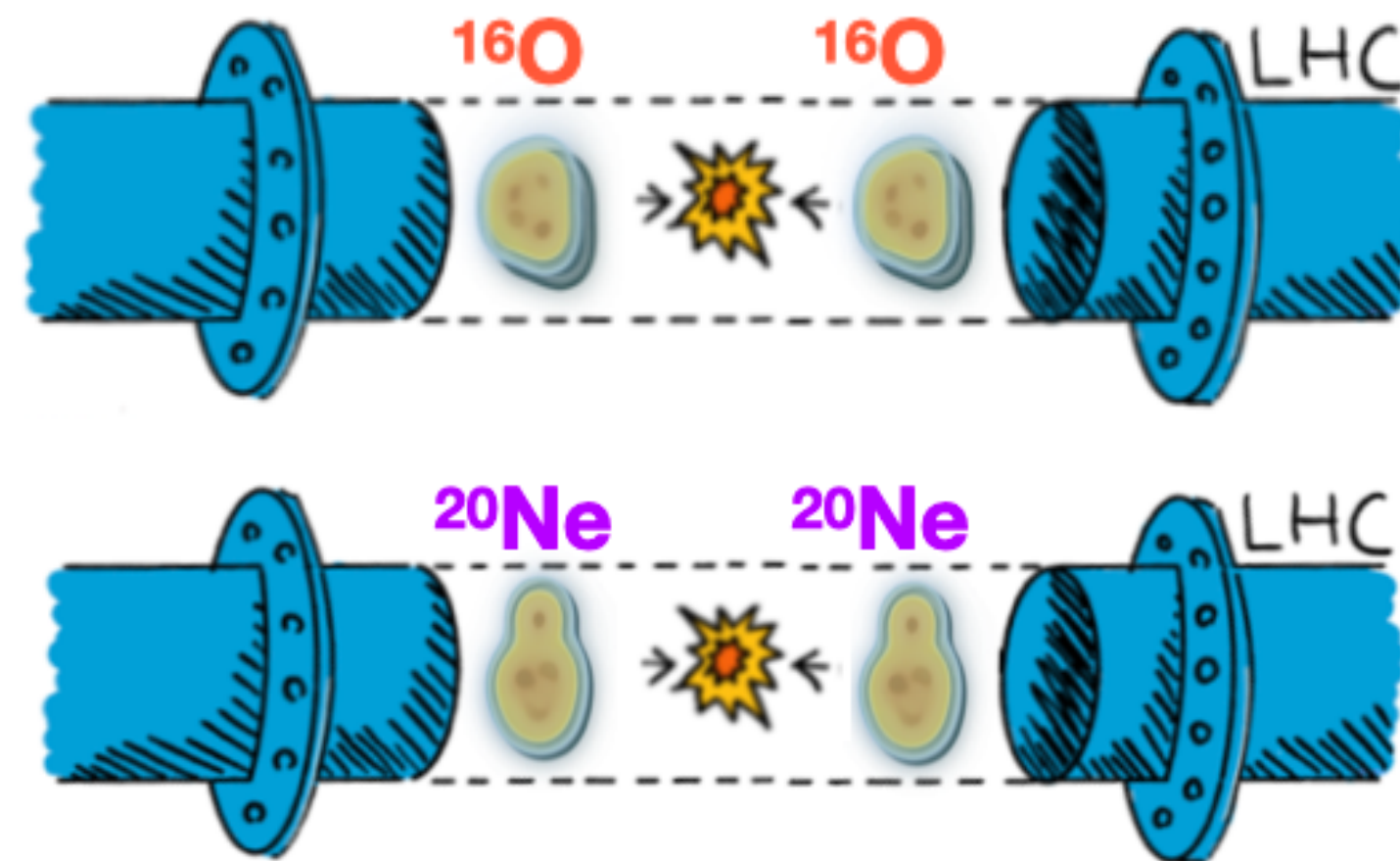
QR code

Topics covered in relation to small systems:

- Experimental highlights and projections
- Heavy flavour
- Hydrodynamics
- Initial conditions
- Jets
- Ultraperipheral collisions
- Nuclear parton distribution functions
- Nuclear structure
- LHC accelerator opportunities

Organisers:

- Reyes Alemany Fernandez
- Giuliano Giacalone
- Qipeng Hu
- Govert Hugo Nijss
- Saverio Mariani
- Wilke van der Schee
- Huichao Song
- Jing Wang
- Urs Wiedemann
- You Zhou



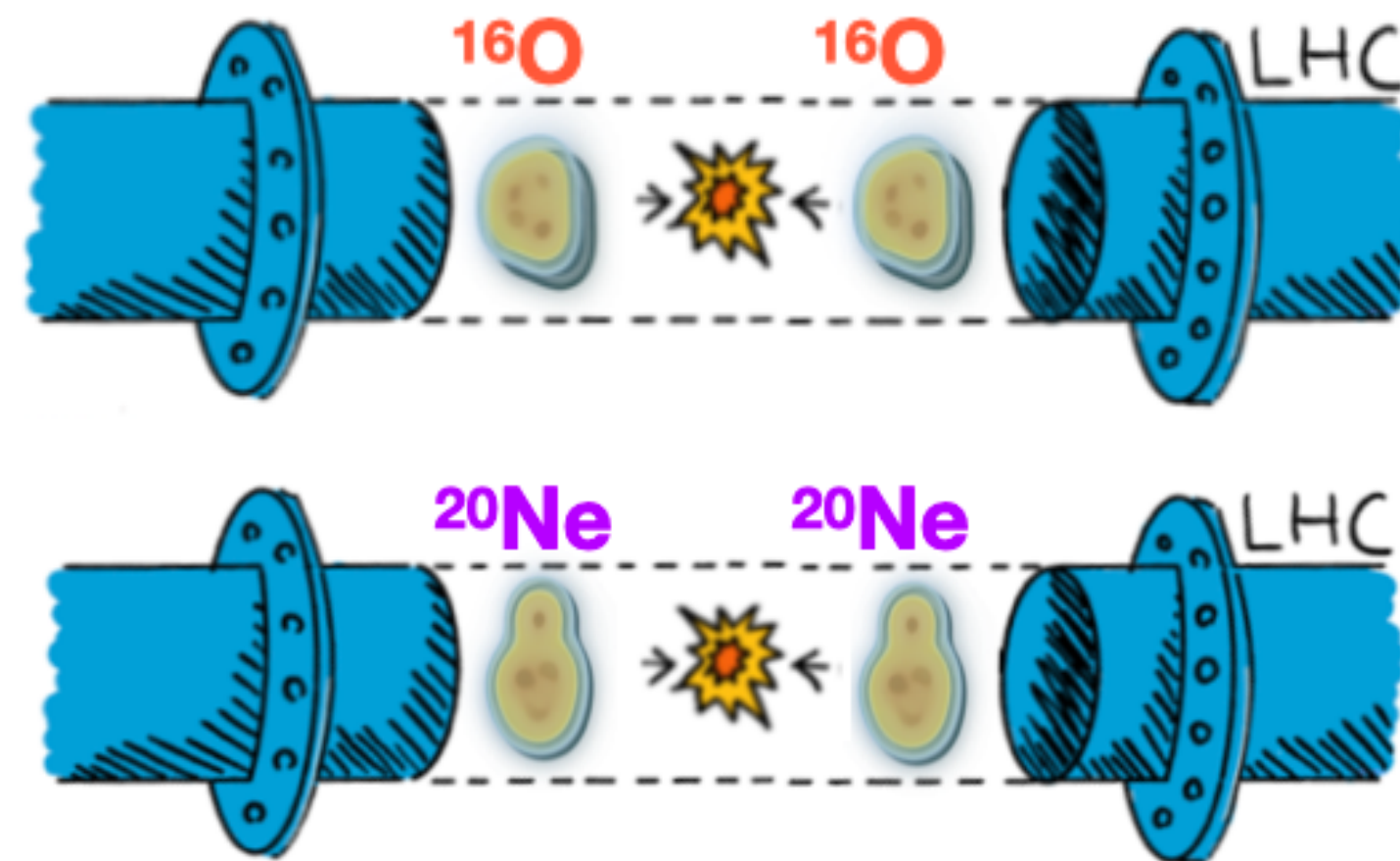
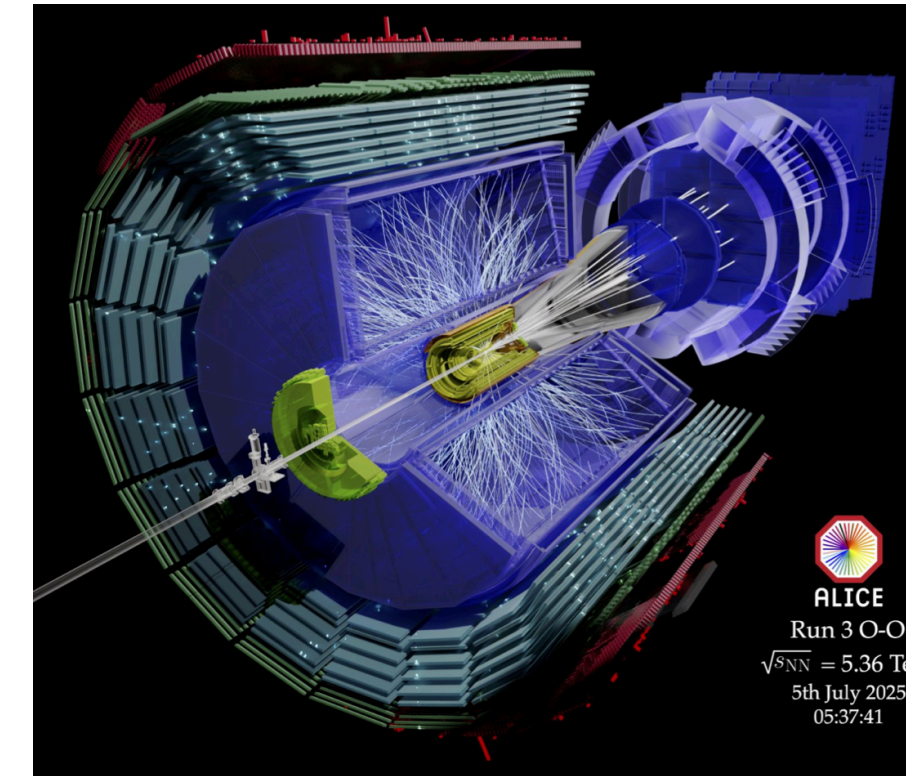


# OO and Ne-Ne collisions at the LHC

- Nov 2024, Light ion workshop



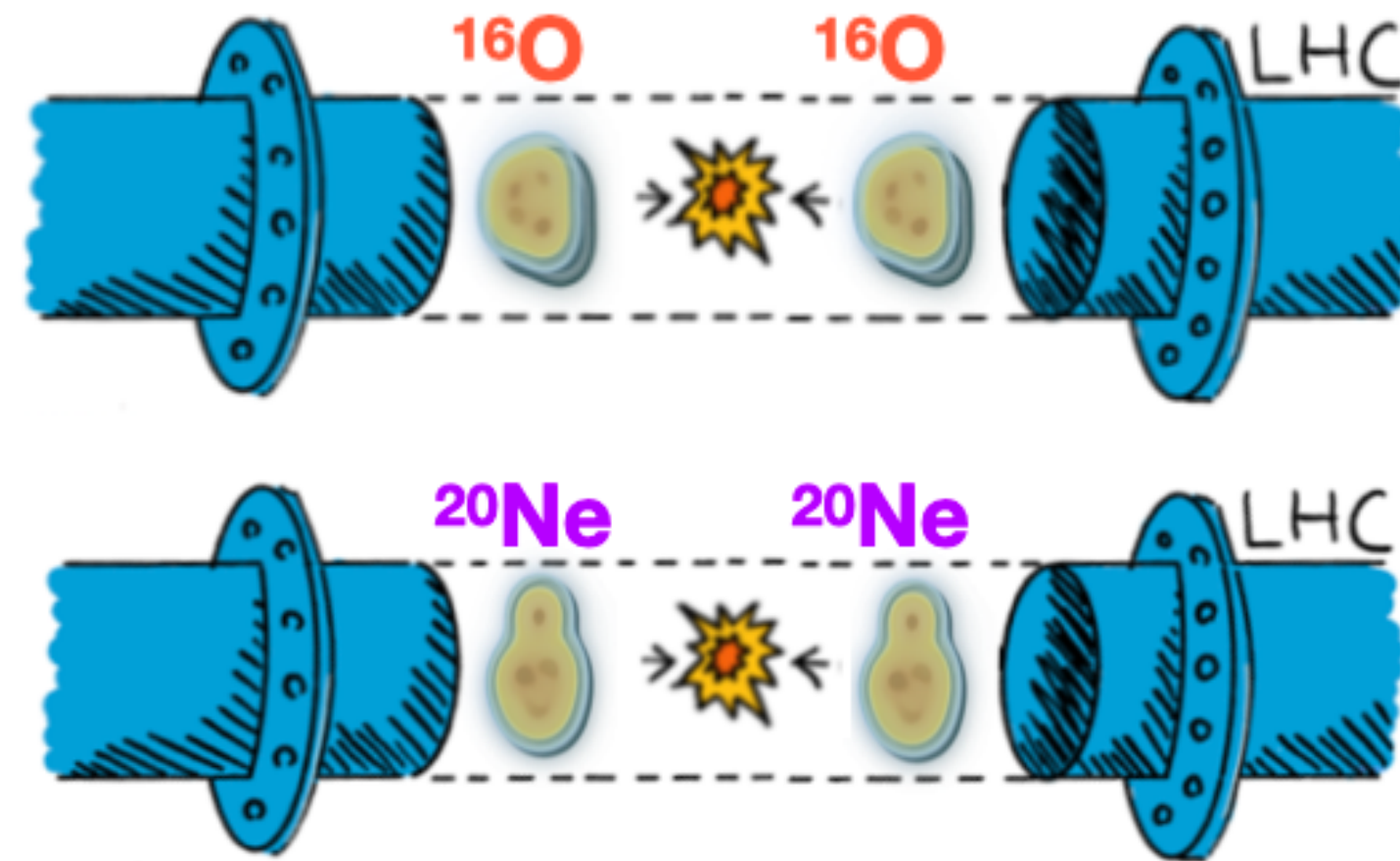
- July 2025, OO and Ne-Ne collisions at the LHC



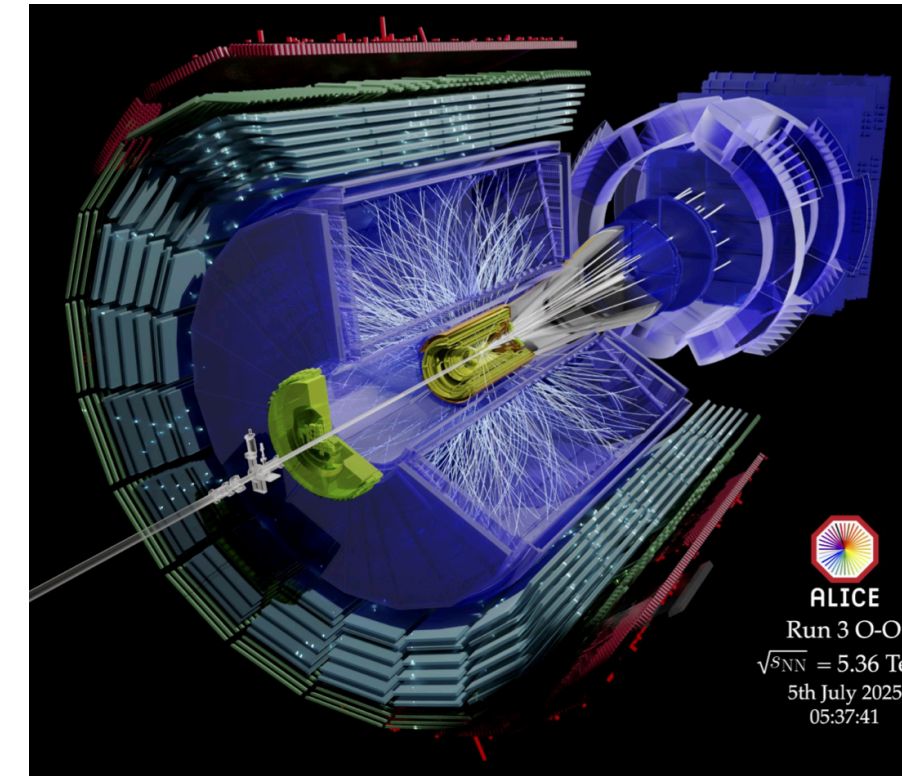


# OO and Ne-Ne collisions at the LHC

- Nov 2024, Light ion workshop



- July 2025, OO and Ne-Ne collisions at the LHC



- September 2025, Flow measurements in OO and Ne-Ne

arXiv > nucl-ex > arXiv:2509.06428

Nuclear Experiment

[Submitted on 8 Sep 2025]

**Evidence of nuclear geometry-driven anisotropic flow in OO and Ne-Ne collisions at  $\sqrt{s_{NN}} = 5.36 \text{ TeV}$**

ALICE Collaboration

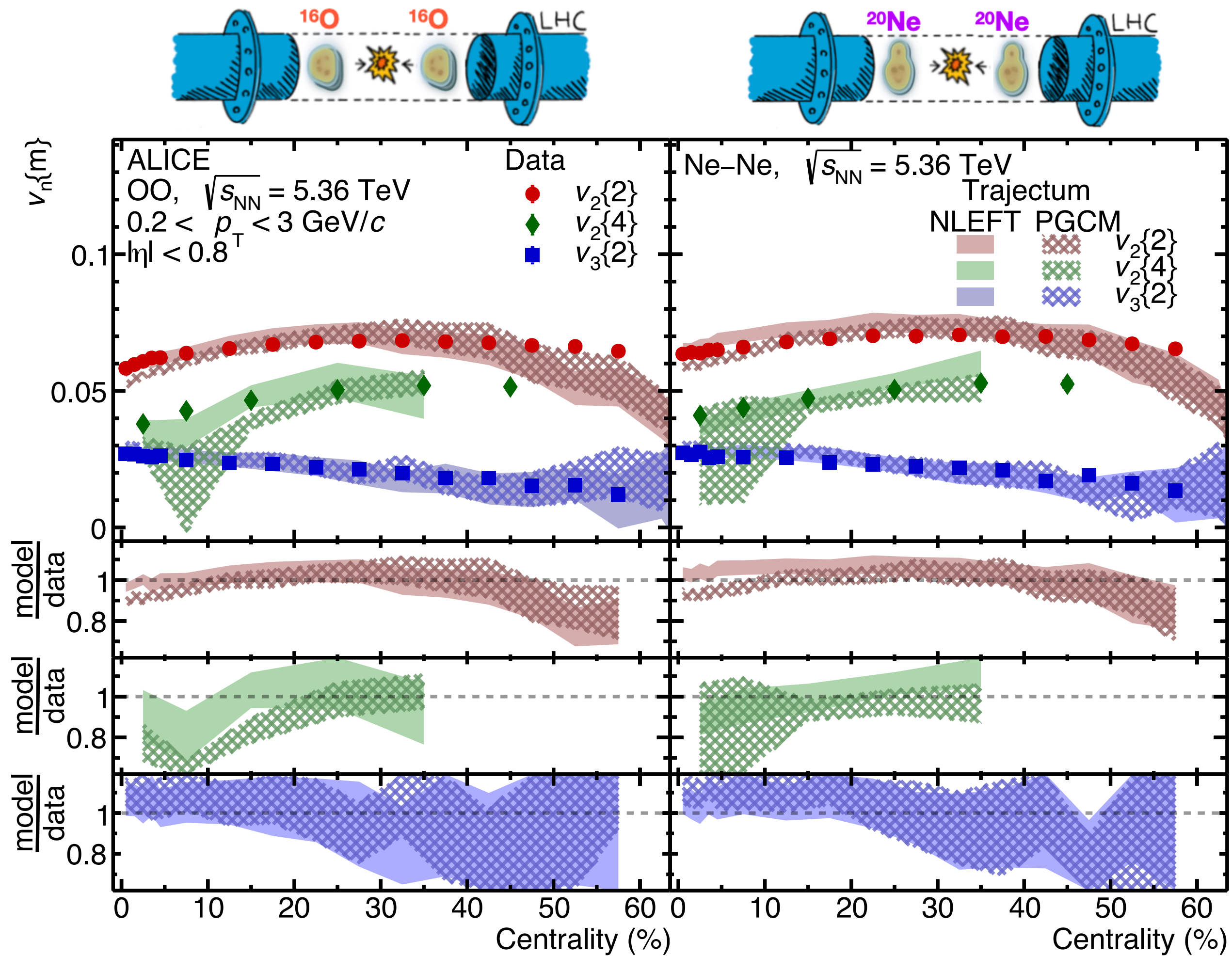
A central question in strong-interaction physics, governed by quantum chromodynamics (QCD), is whether femto-scale droplets of quark-gluon plasma (QGP) form in small collision systems involving projectiles significantly smaller than heavy ions. Collisions of light ions such as  $^{16}\text{O}$  and  $^{20}\text{Ne}$  offer a unique opportunity to probe the emergence of collective behavior in QCD matter. This Letter presents the first measurements of elliptic ( $v_2$ ) and triangular ( $v_3$ ) flow of charged particles in  $^{16}\text{O}-^{16}\text{O}$  and  $^{20}\text{Ne}-^{20}\text{Ne}$  collisions at a center-of-mass energy per nucleon pair of  $\sqrt{s_{NN}} = 5.36 \text{ TeV}$  with the ALICE detector. The hydrodynamic model predictions, explicitly incorporating the nuclear structures of  $^{16}\text{O}$  and  $^{20}\text{Ne}$ , exhibit a good agreement with the flow measurements presented. The observed increase of  $v_2$  in central Ne-Ne collisions relative to OO collisions, driven by the nuclear geometries, highlights the importance of utilizing light nuclei with well-defined geometric shapes to constrain the initial conditions. These findings support the presence of nuclear geometry-driven hydrodynamic flow in light-ion collisions at the LHC.

ALICE, arXiv:2509.06428, accepted by PRL.



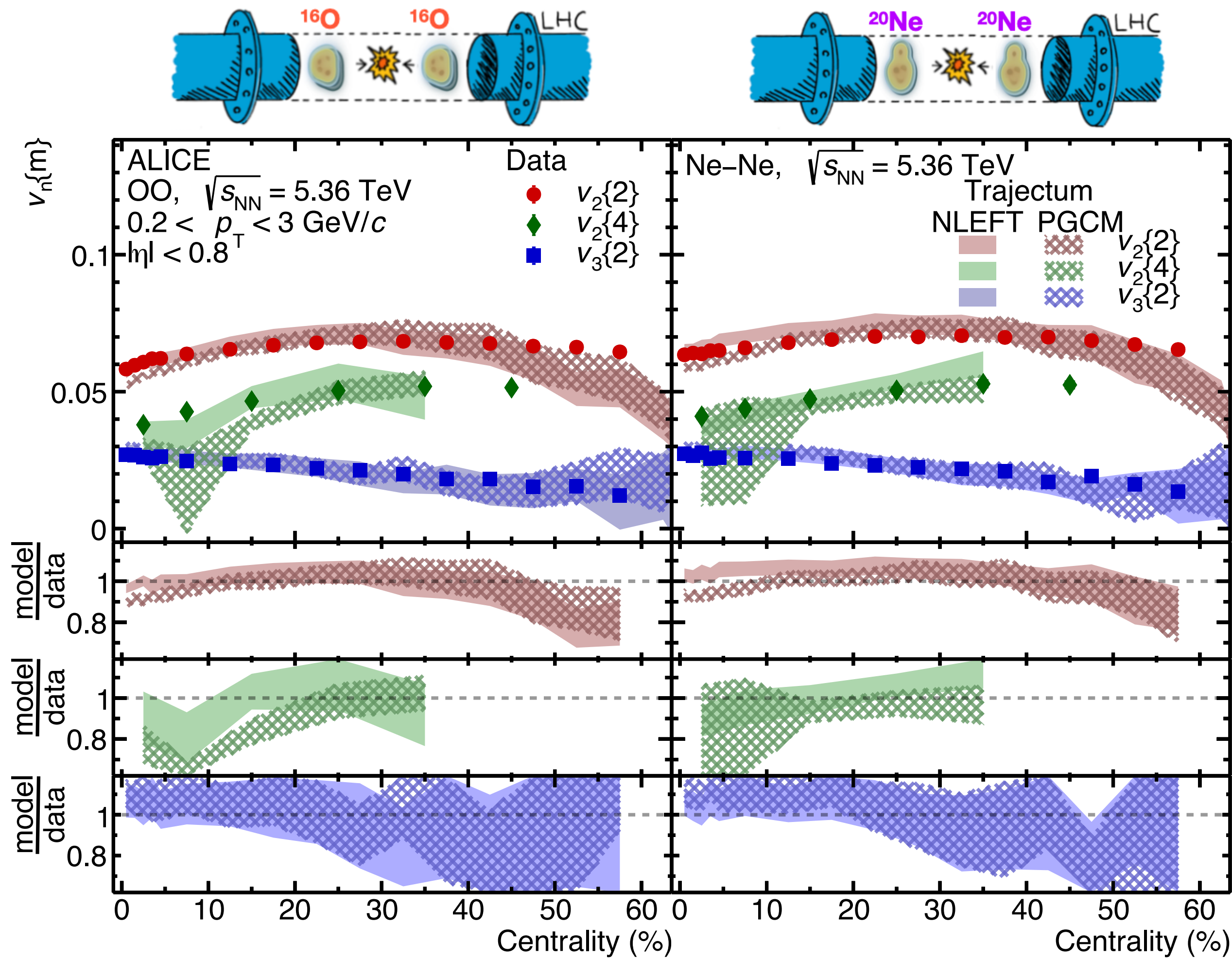
# Geometry-driven hydrodynamic flow in OO and Ne-Ne

ALICE, arXiv:2509.06428, accepted by Phys. Rev. Lett.



# Geometry-driven hydrodynamic flow in OO and Ne-Ne

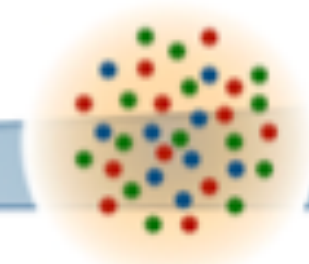
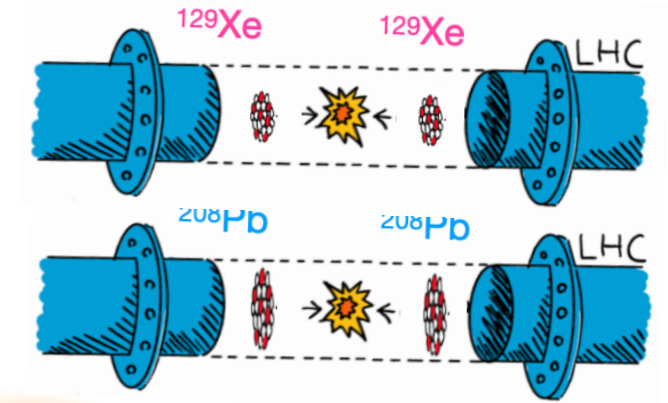
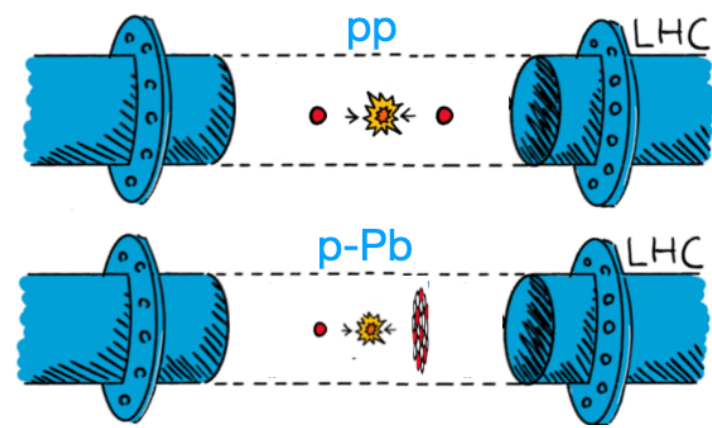
ALICE, arXiv:2509.06428, accepted by Phys. Rev. Lett.



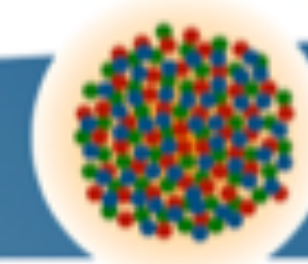
- ❖ Nicely described by predictions from Trajectum(NS+hydro)
  - Nuclear geometry driven hydrodynamic flow observed in light ion collisions
  - *For the first time reasonable agreement (equivalent if not better than Pb-Pb) between hydro predictions and data in small systems*



# Bridges the gap with light-ion collisions



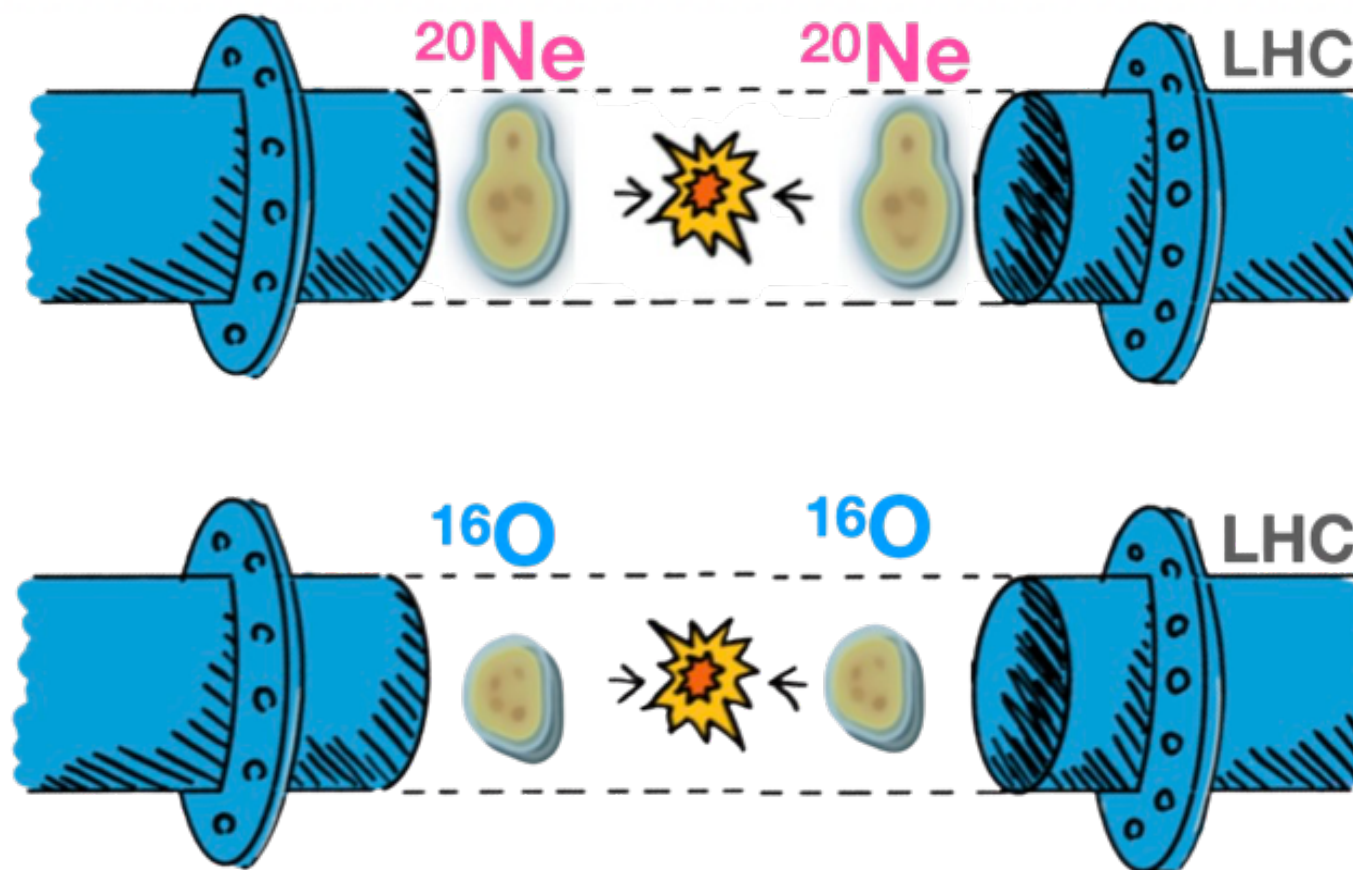
dilute system? few interactions?



dense system  
many interactions

low multiplicity

high multiplicity



- ❖ Observation of flow
- ❖ Signature of QGP creation
- ❖ Not described by any theory

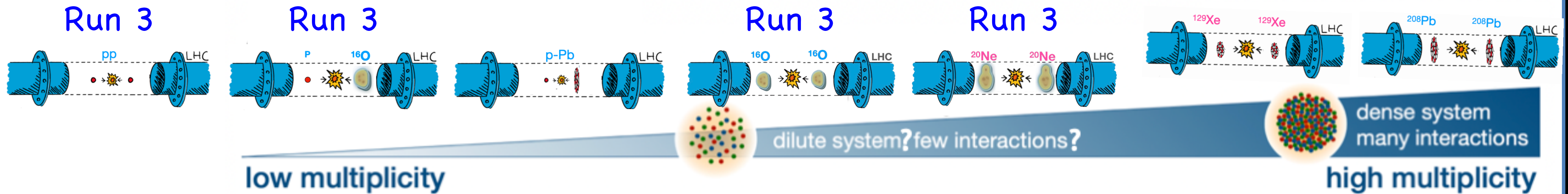
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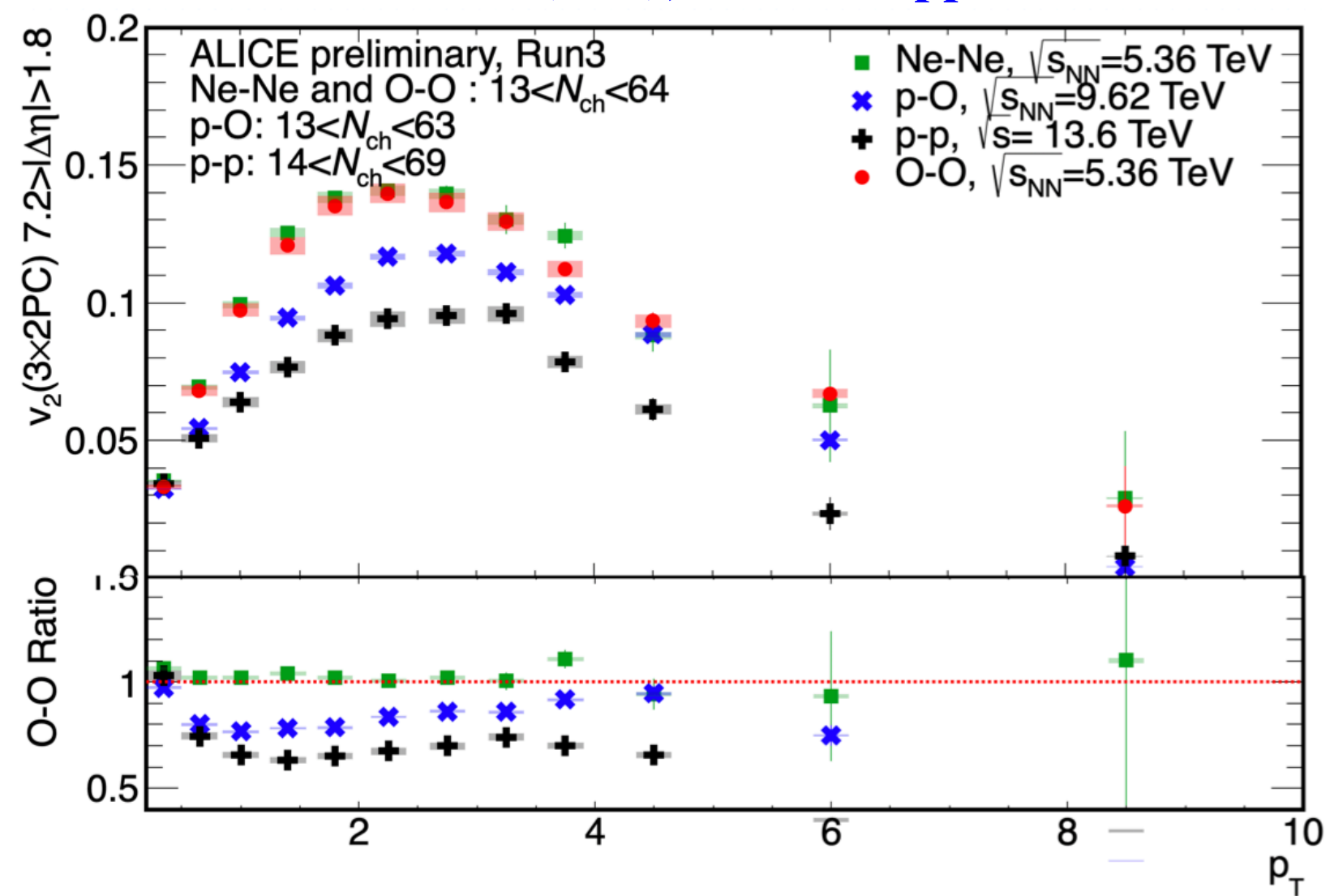




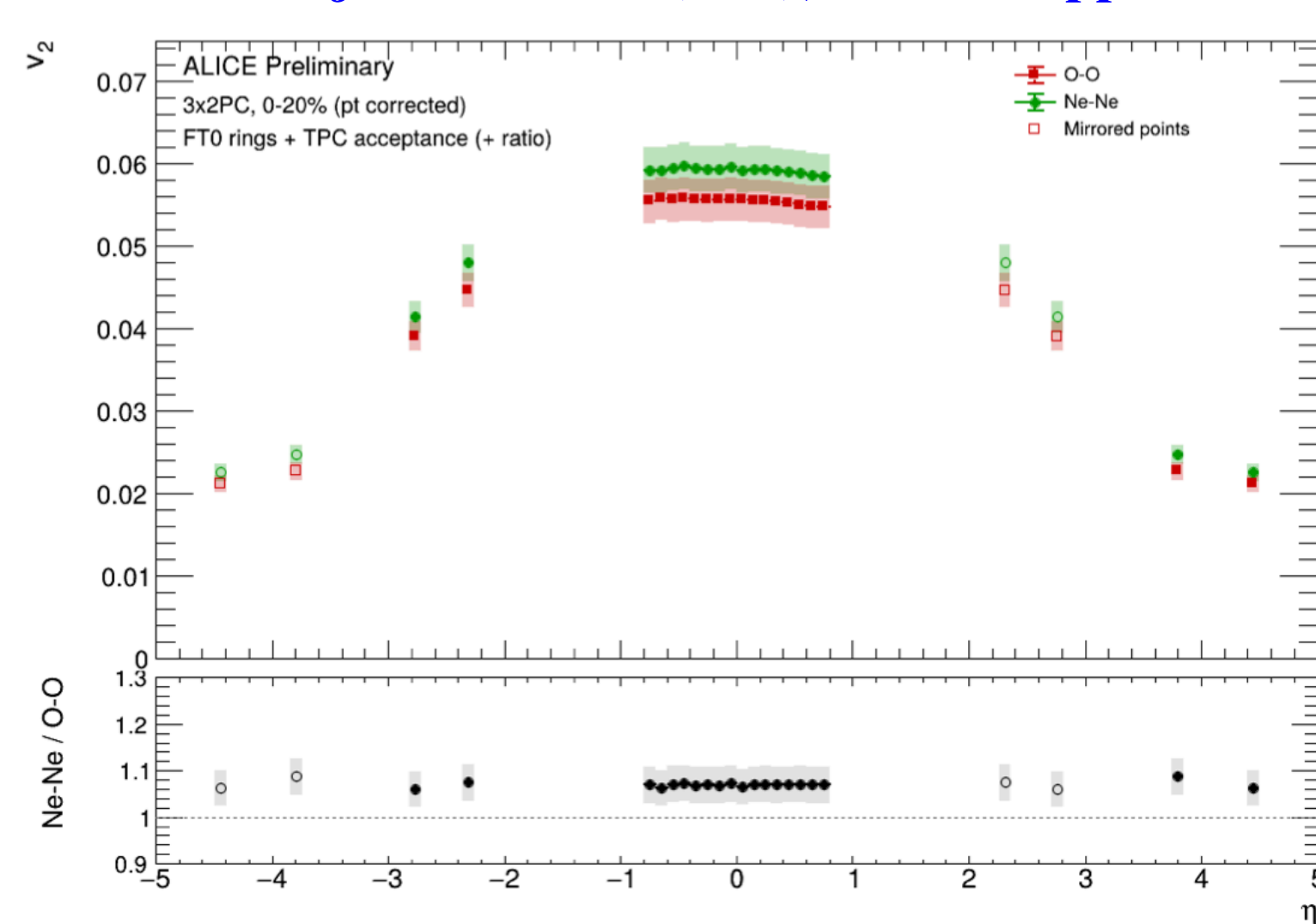
# Many new flow results approved last week



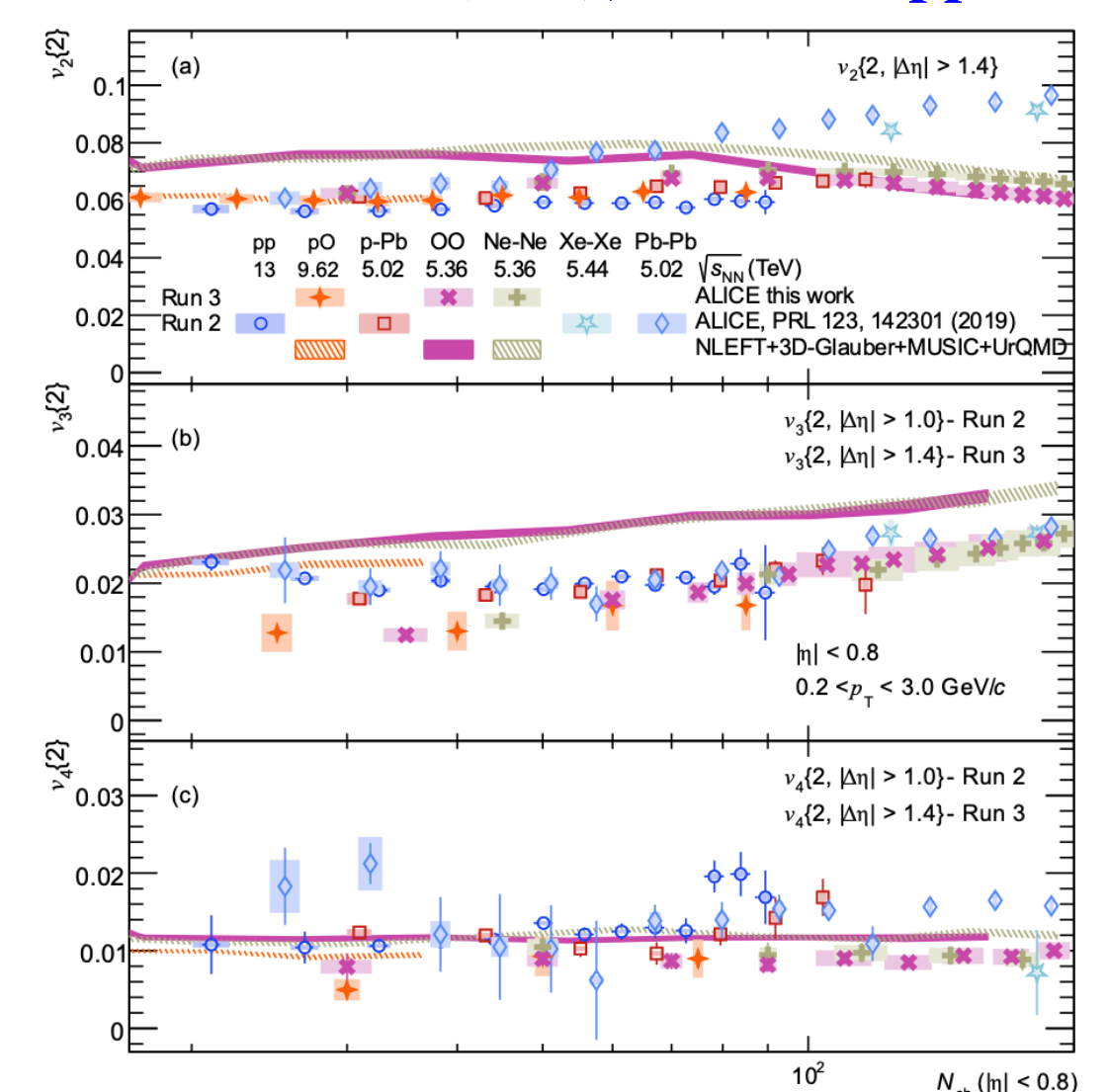
**Thor K. Jensen (NBI), HP2026 Approval**



**Martijn Laarhoven (NBI), HP2026 Approval**

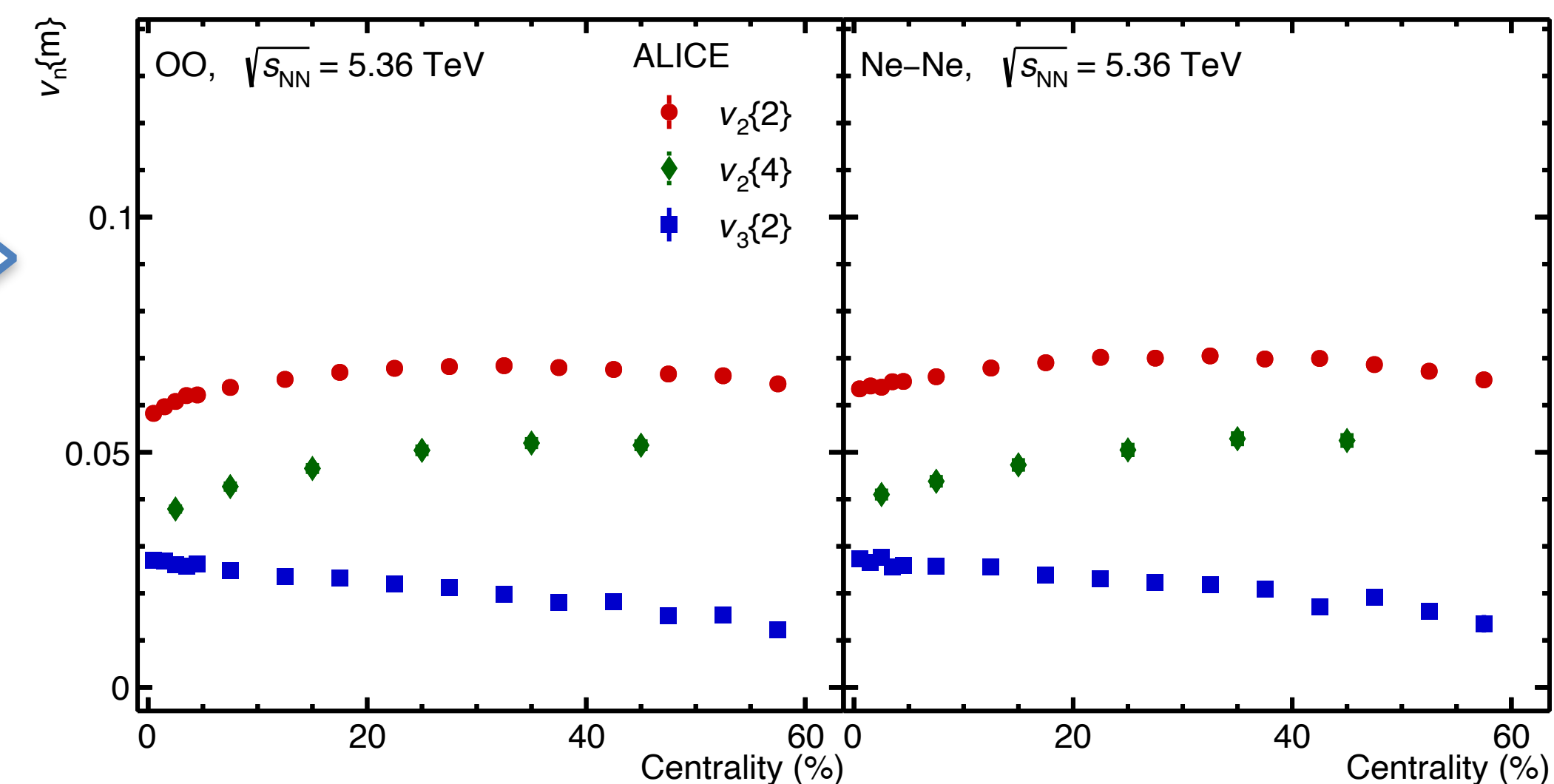
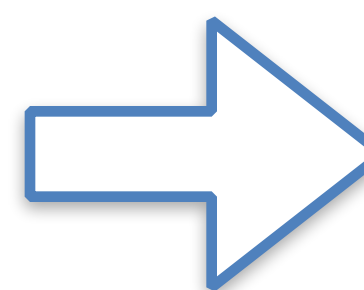


**Dina Dervisevic (NBI), HP2026 Approval**





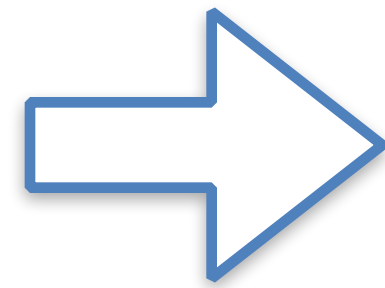
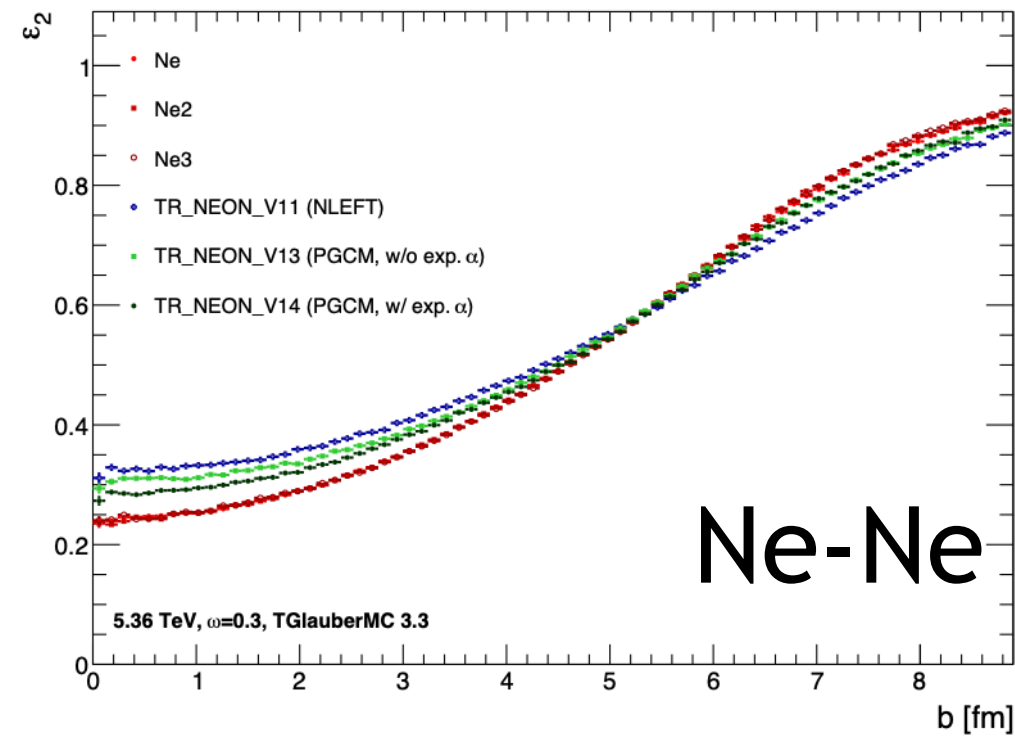
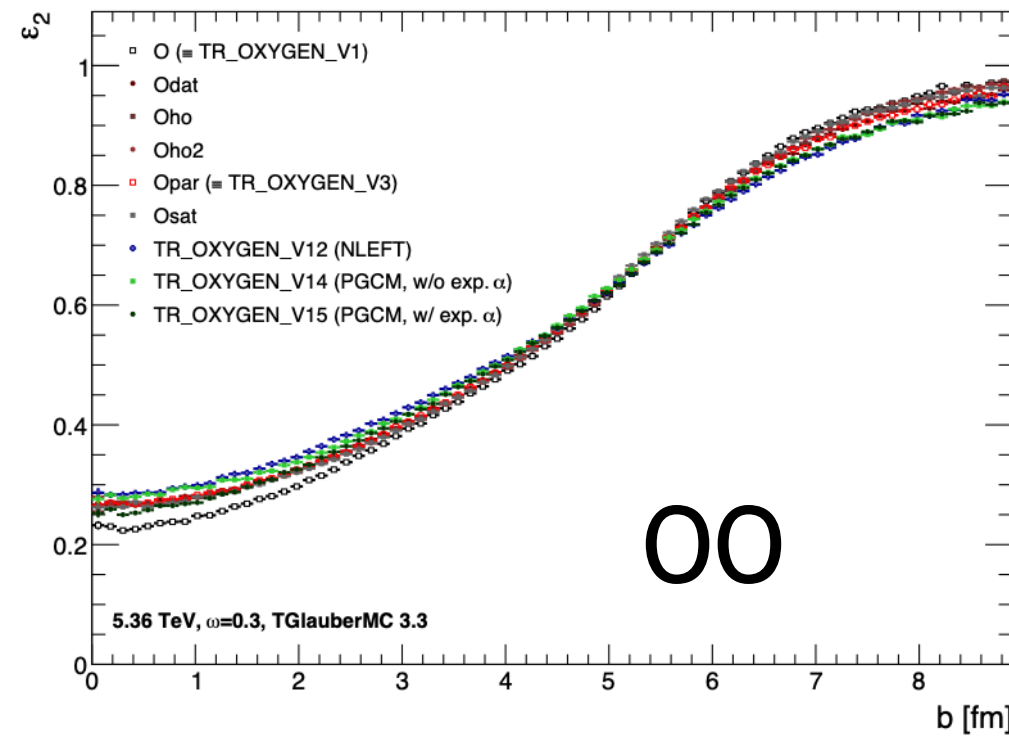
# Significant non-linear dynamic response



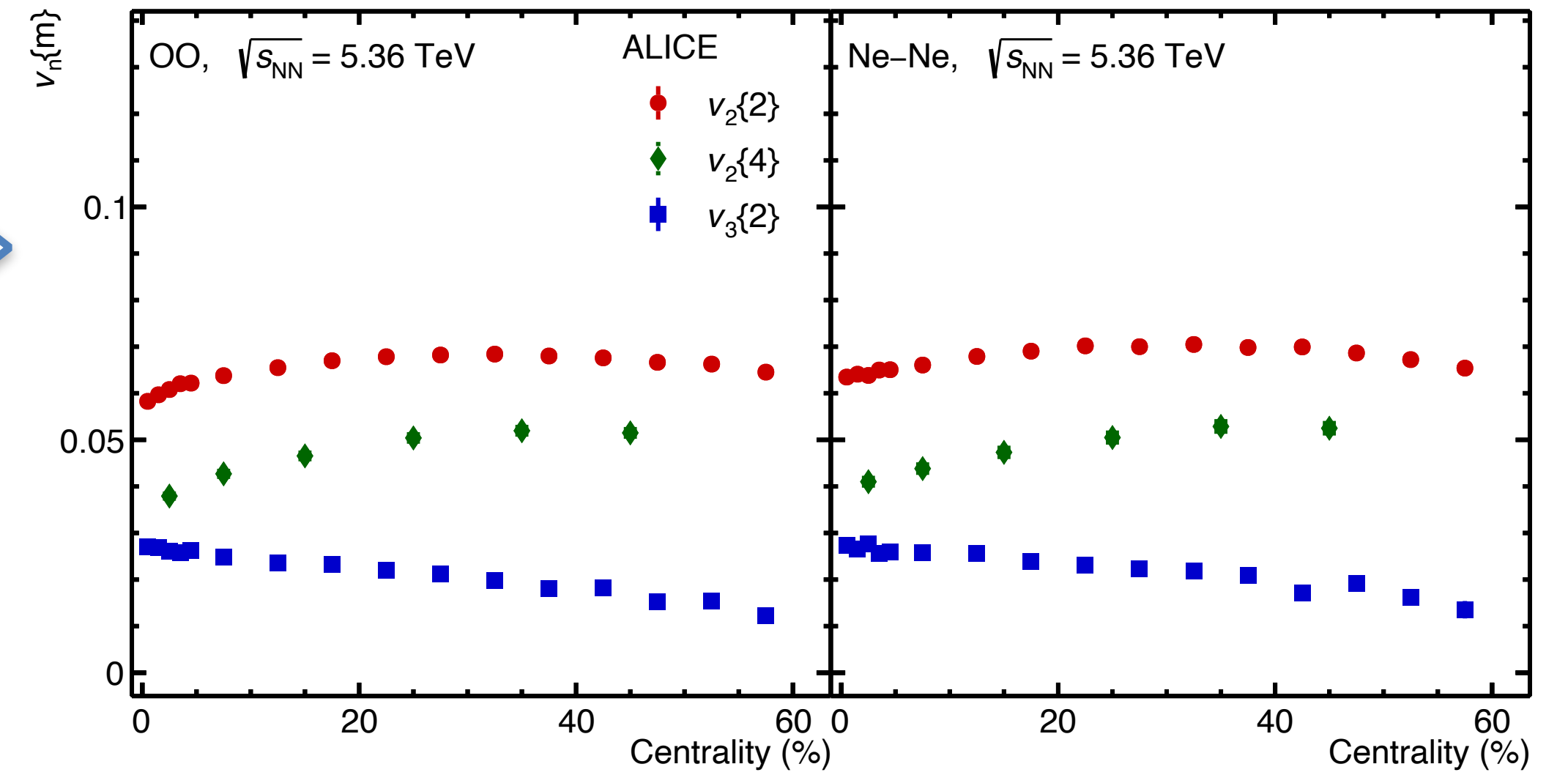
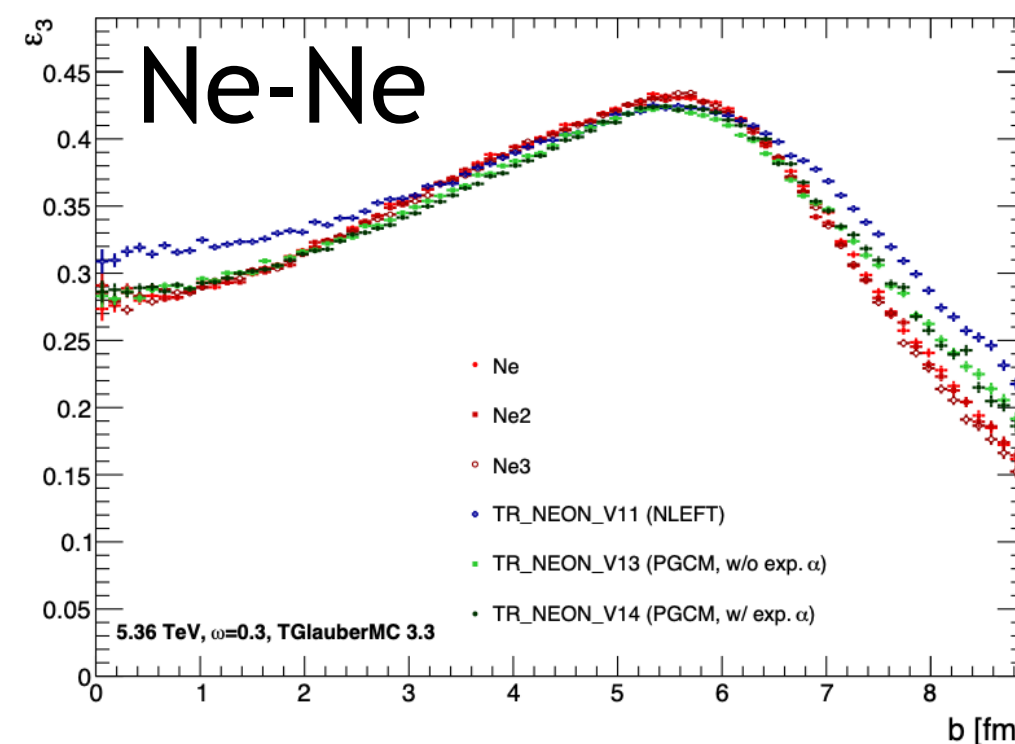
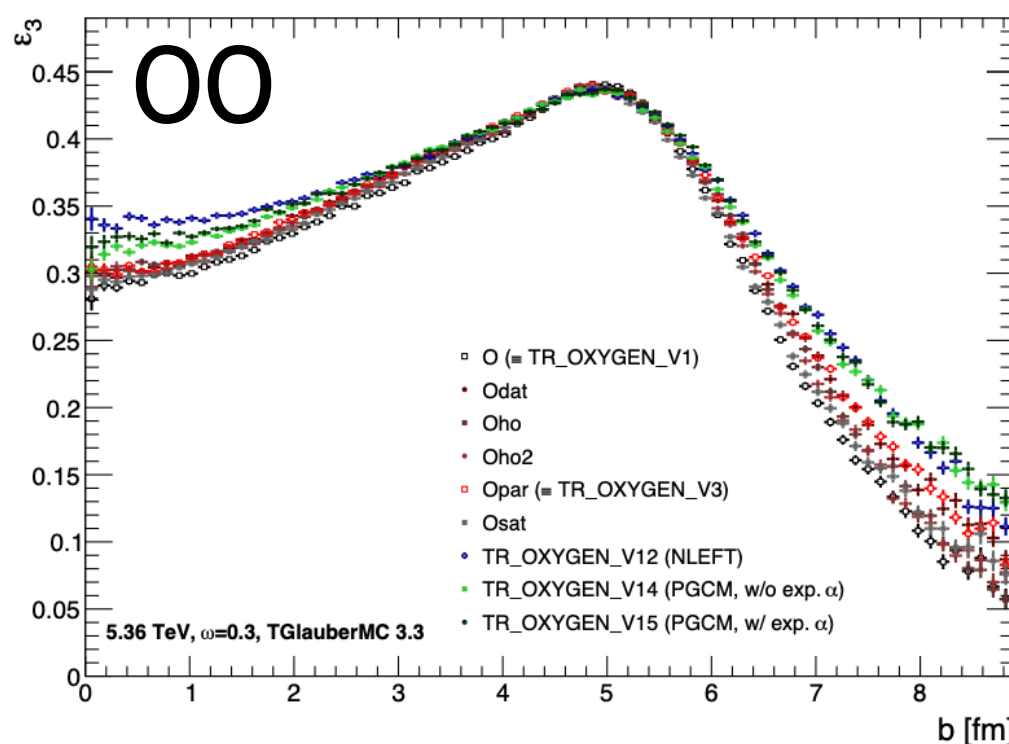
ALICE, arXiv:2509.06428, submitted to Phys. Rev. Lett.

# Significant non-linear dynamic response

$\epsilon_2$



$\epsilon_3$

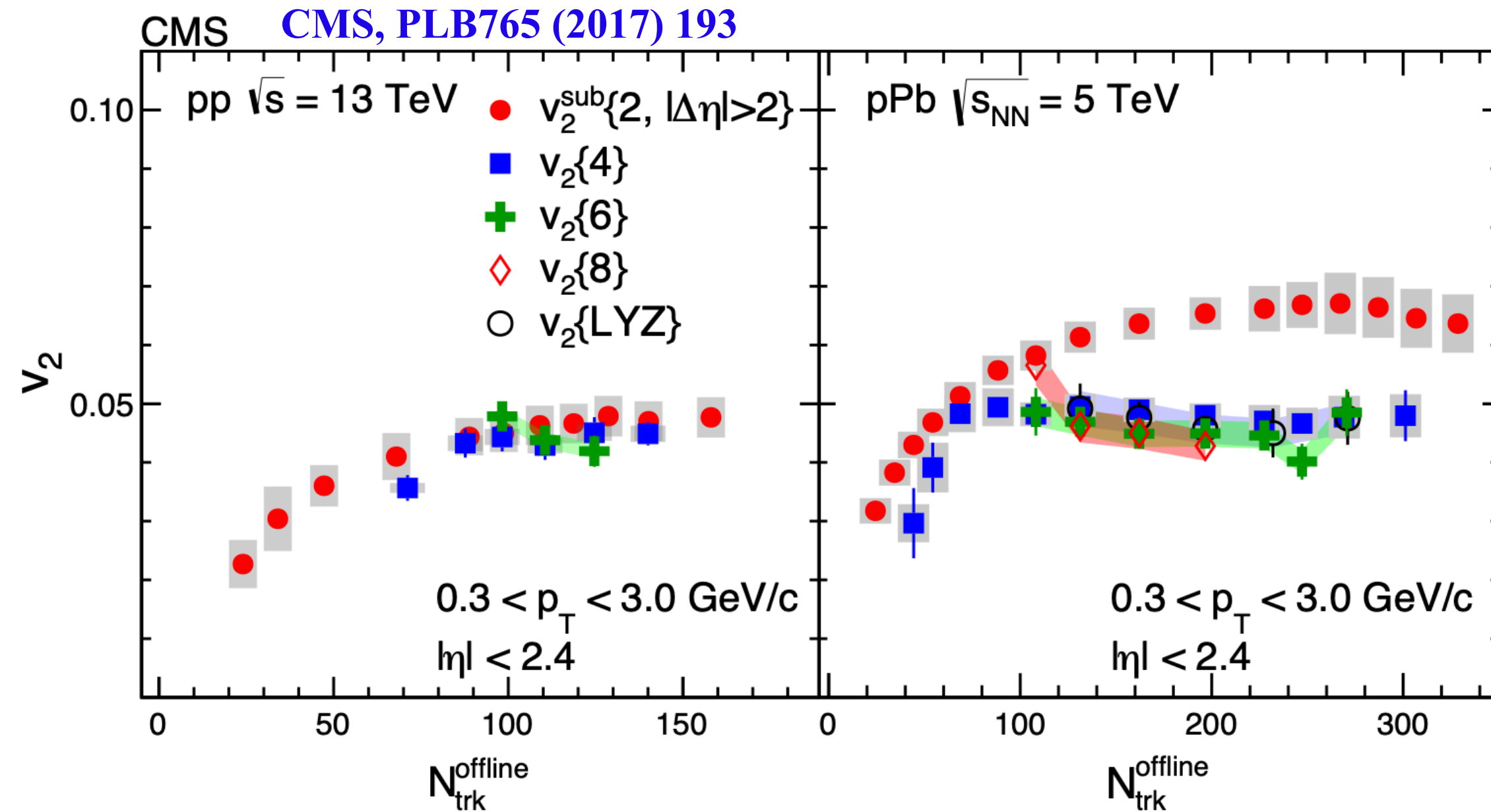


C. Loizides, arXiv:2507.05853

ALICE, arXiv:2509.06428, submitted to Phys. Rev. Lett.



# Multi-particle cumulants: theoretical challenges

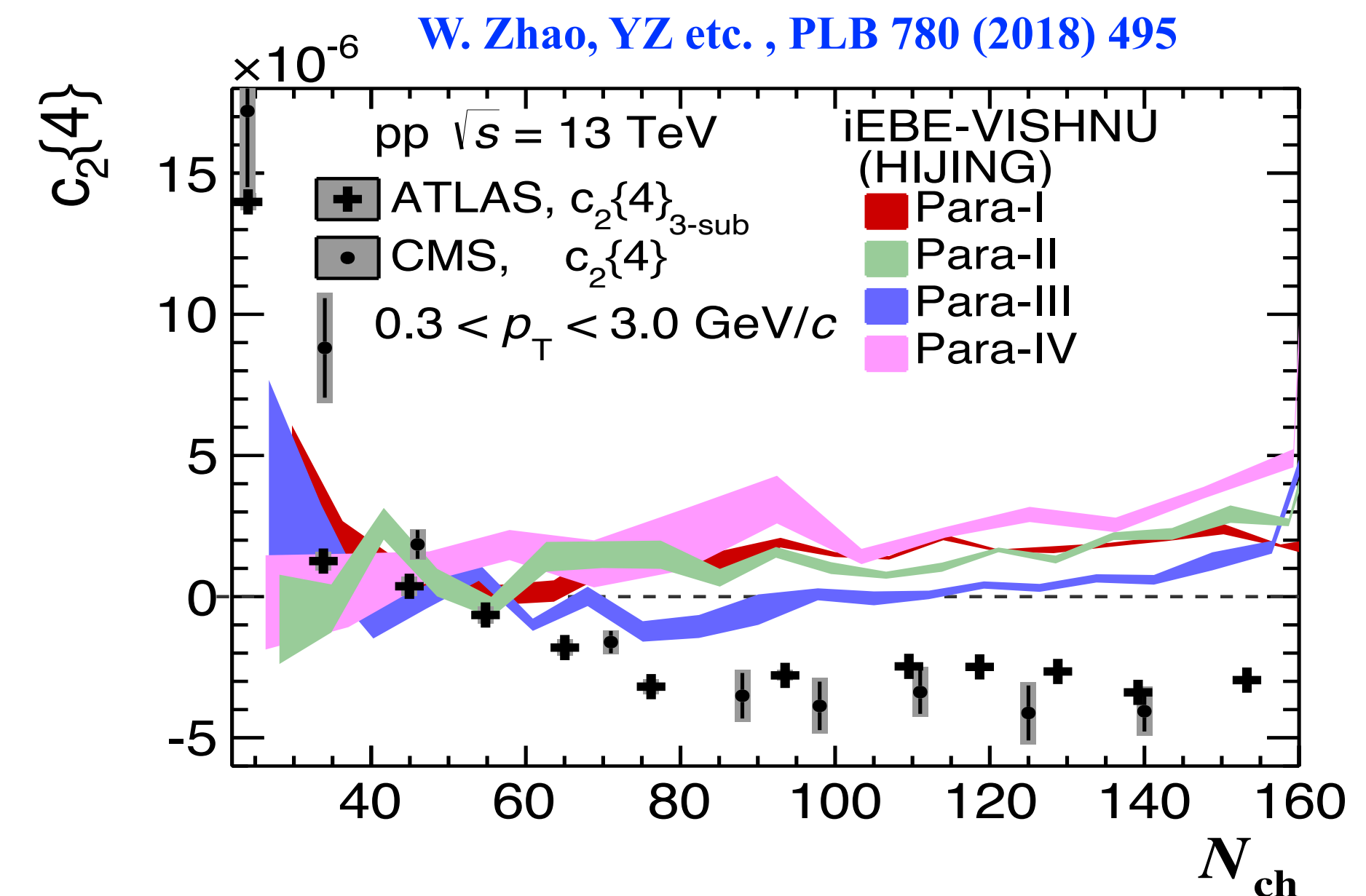
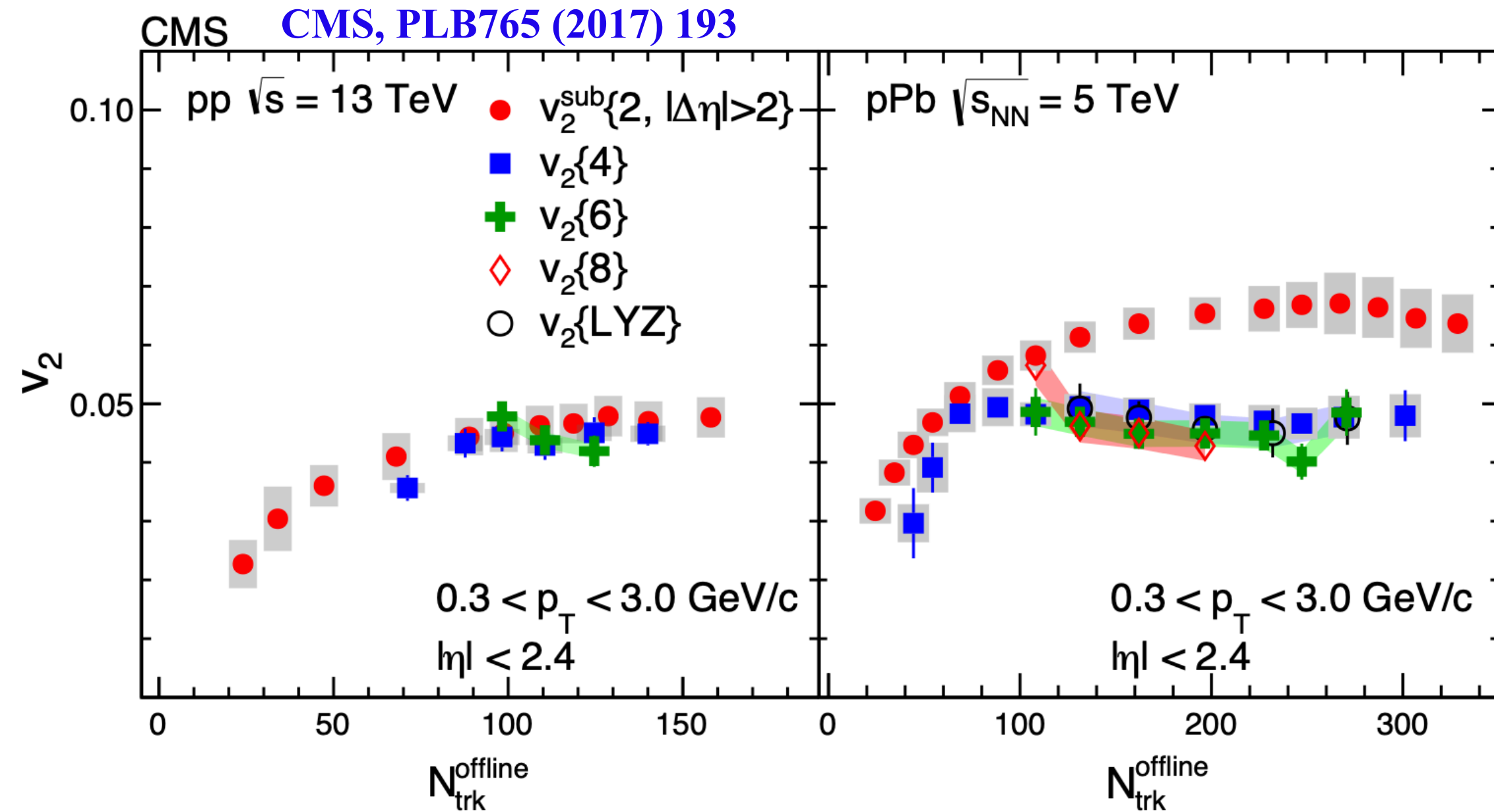


## [EXP]

❖  $v_2\{4\} = v_2\{6\} = v_2\{8\}$ ?

- Observed also by ATLAS and ALICE
- Confirm collective flow of multi-particles

# Multi-particle cumulants: theoretical challenges



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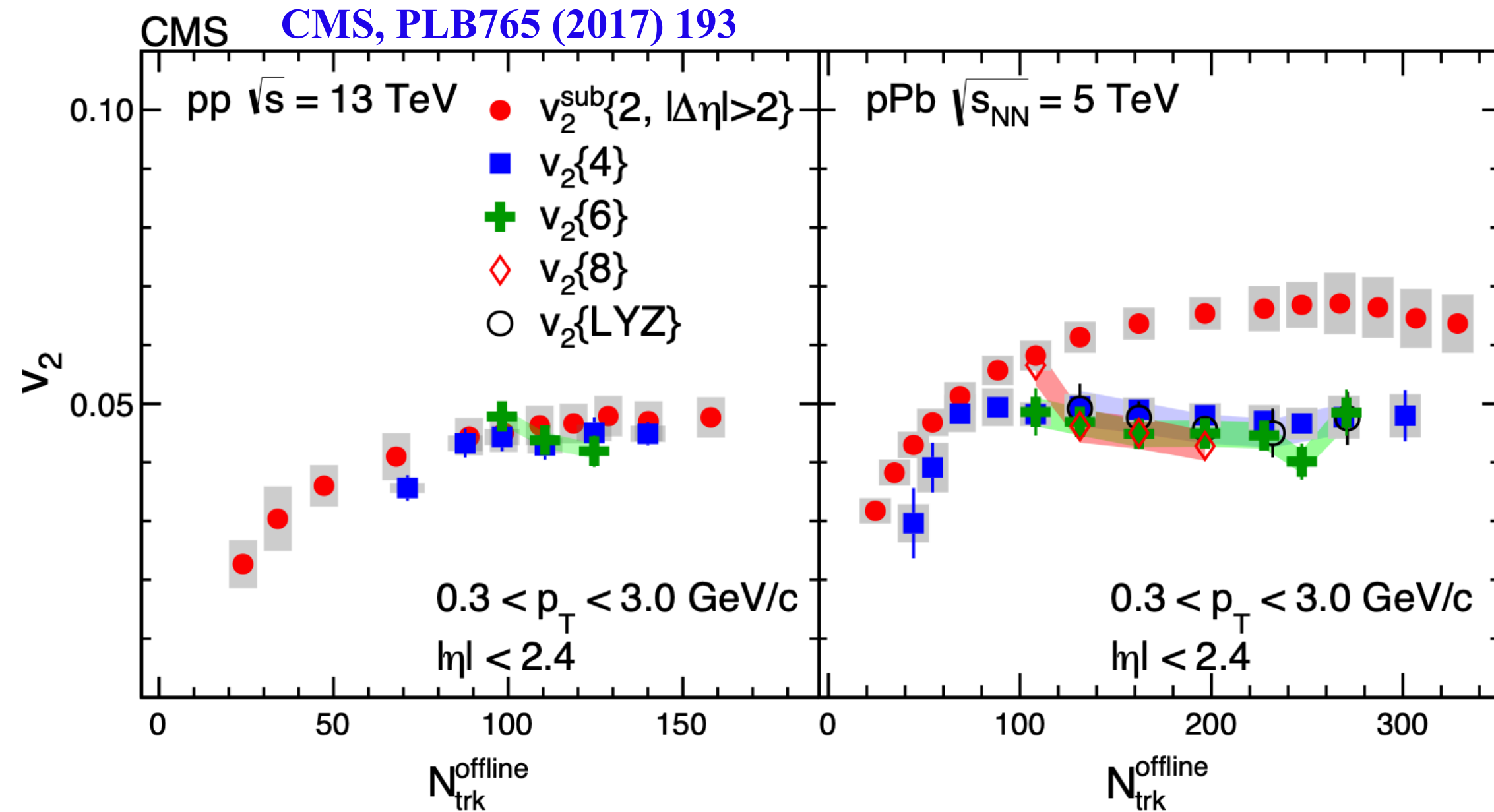
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## [TH]

- ❖ Long-standing difficulty to reproduce negative  $c_2\{4\}$  with **hydro** in pp collisions

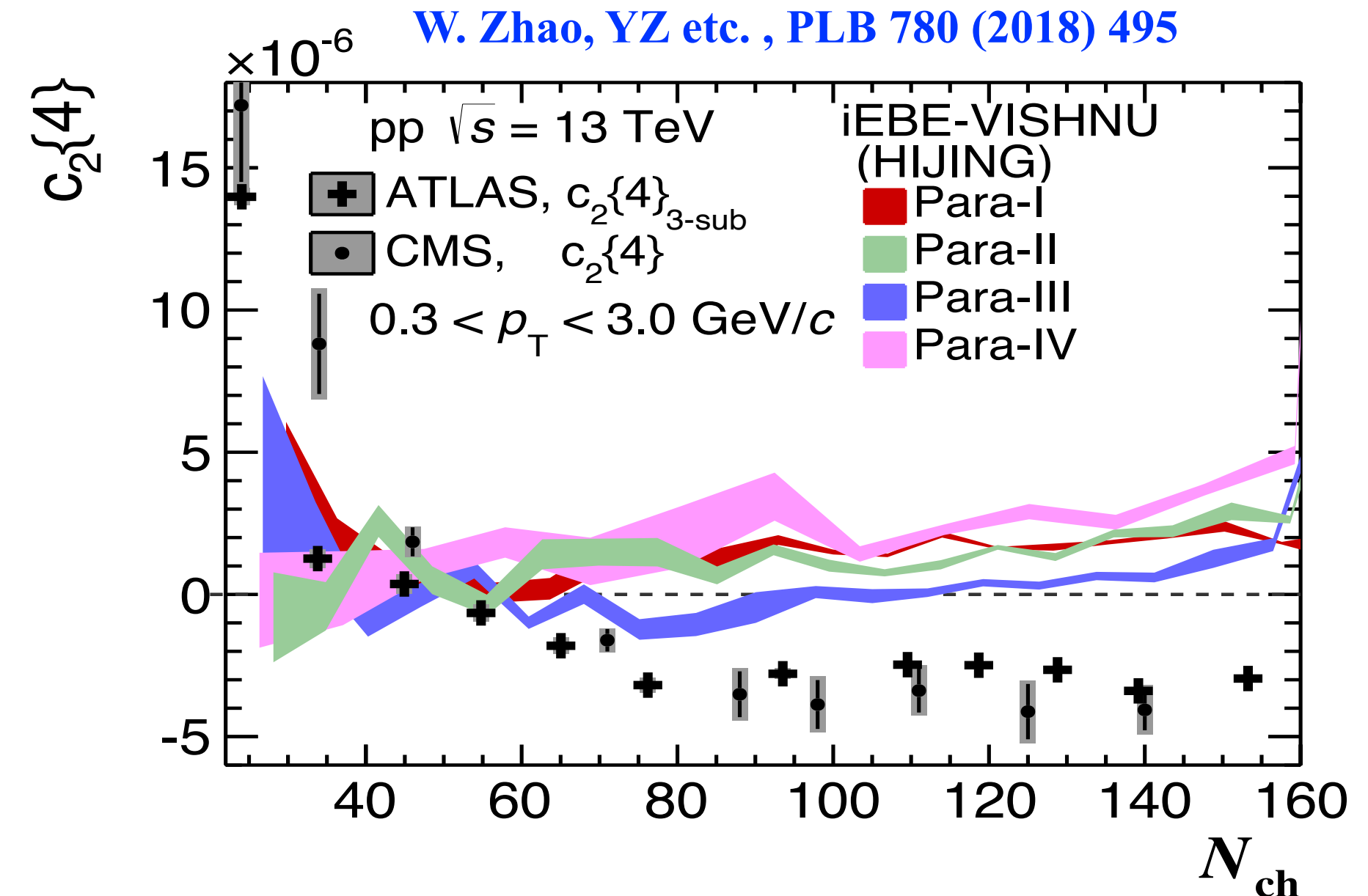


# Multi-particle cumulants: theoretical challenges



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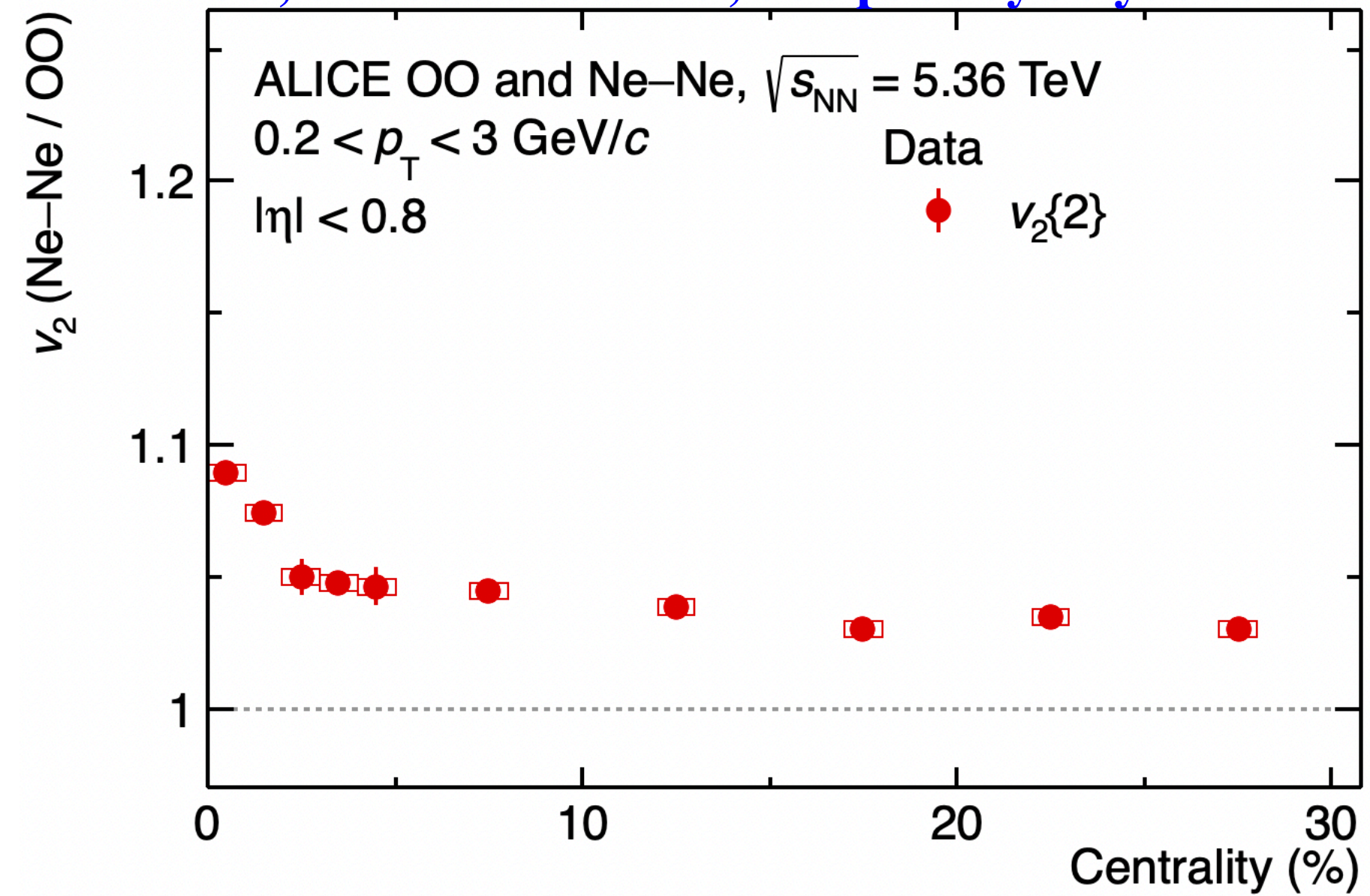


## [TH]

- ❖ Long-standing difficulty to reproduce negative  $c_2\{4\}$  with **hydro** in pp collisions
- ❖ What is the problem:
  - Inprecise initial conditions?
  - Significant improvements in hydro needed?

# Flow ratios (Ne-Ne / OO)

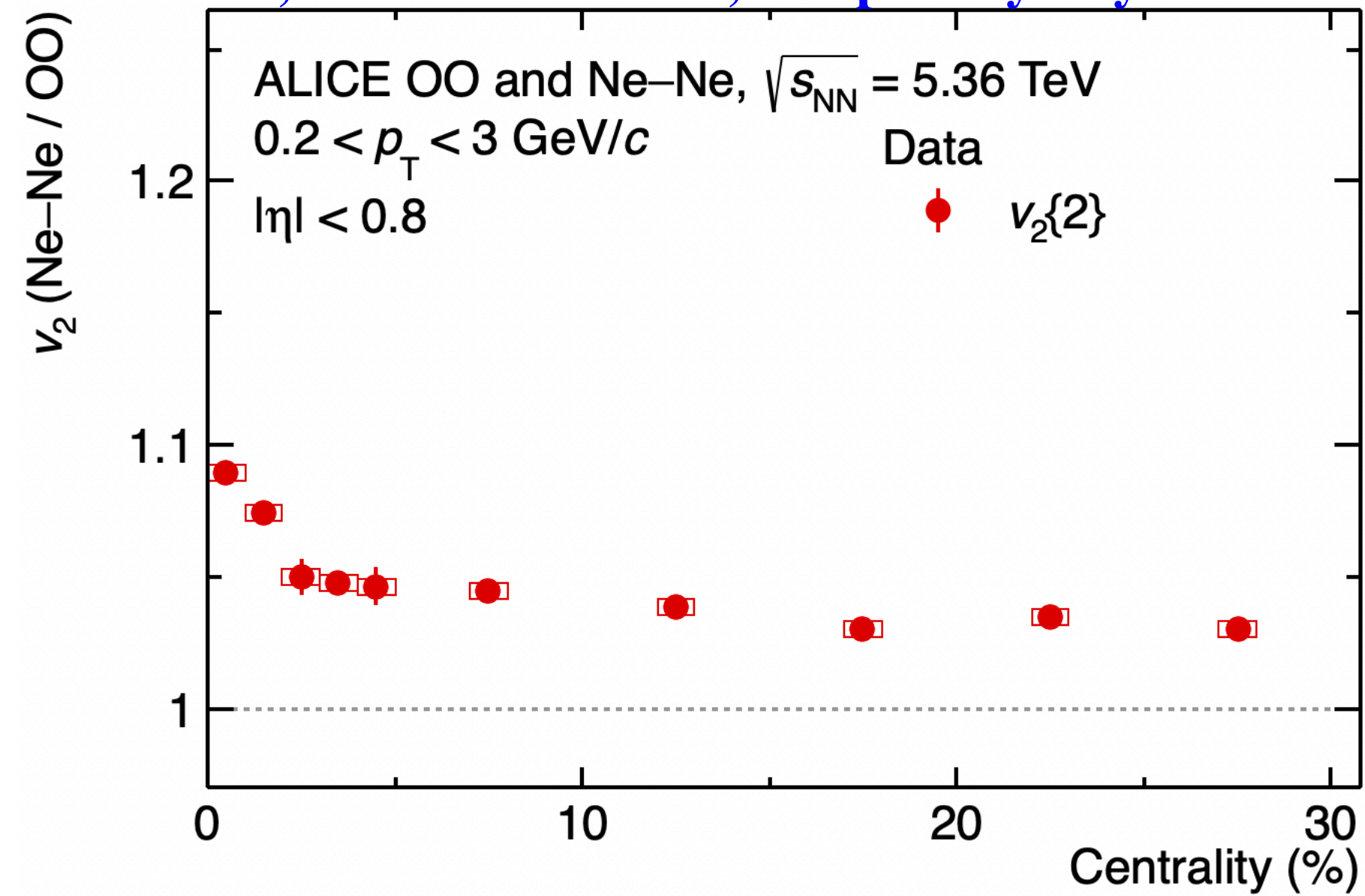
ALICE, arXiv:2509.06428, accepted by Phys. Rev. Lett.





# Flow ratios (Ne-Ne / OO)

ALICE, arXiv:2509.06428, accepted by Phys. Rev. Lett.

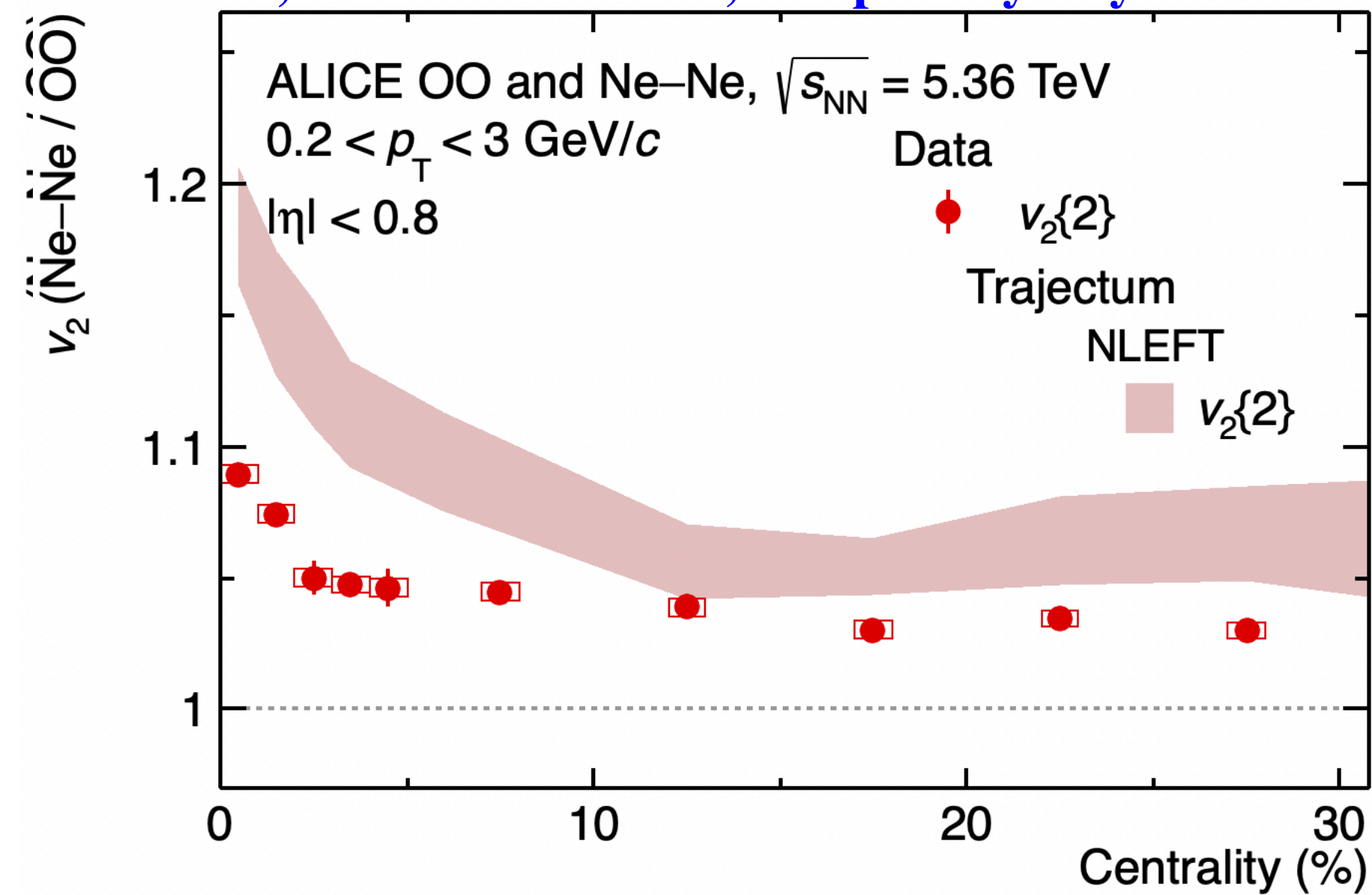


## ❖ Enhanced $v_2$ in Ne-Ne than OO

- Driven by nuclear geometrical shape of  $^{20}\text{Ne}$  (larger deformation compared to  $^{16}\text{O}$ )

# Flow ratios (Ne-Ne / OO)

ALICE, arXiv:2509.06428, accepted by Phys. Rev. Lett.



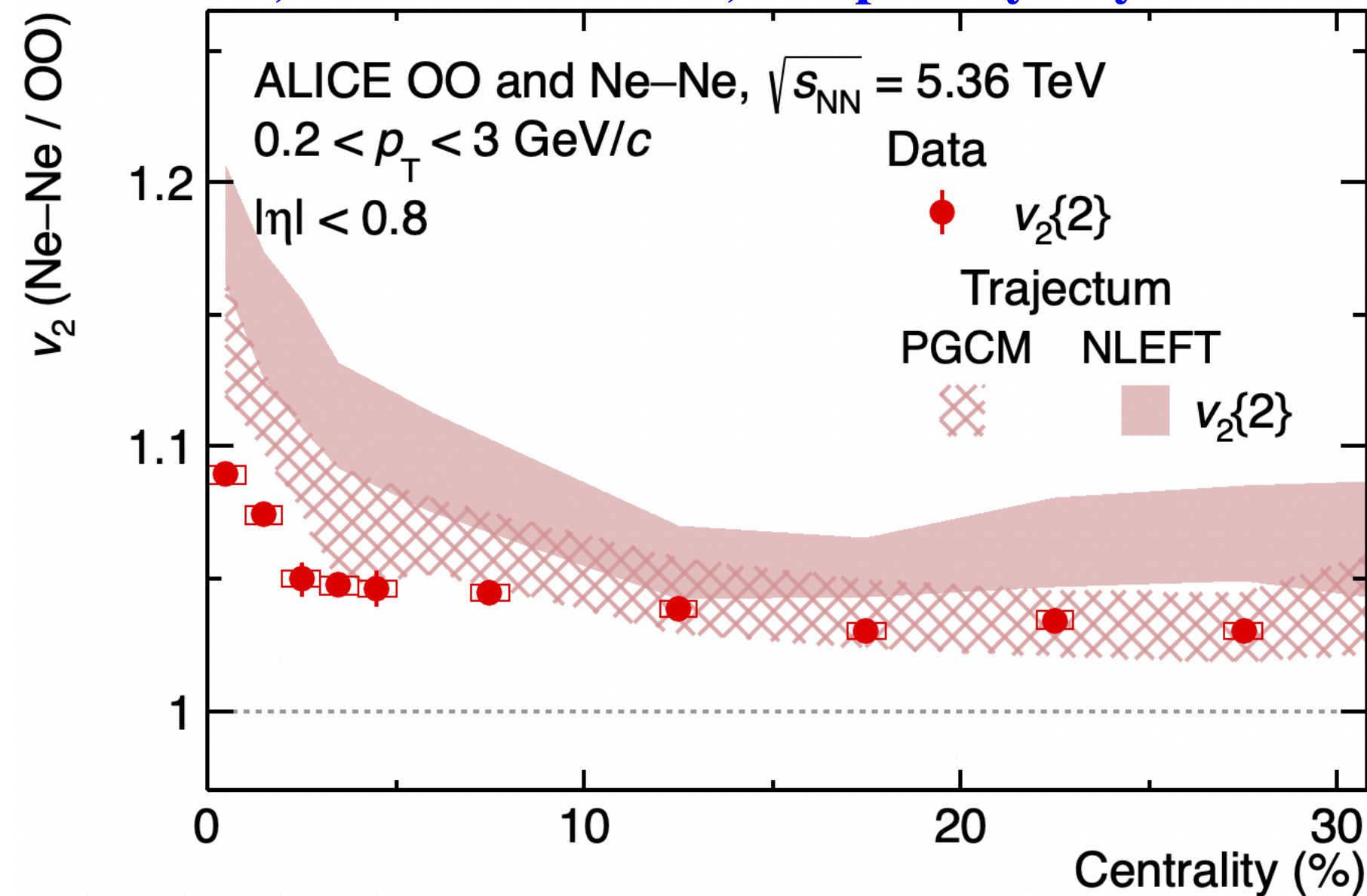
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# Flow ratios (Ne-Ne / OO)

ALICE, arXiv:2509.06428, accepted by Phys. Rev. Lett.

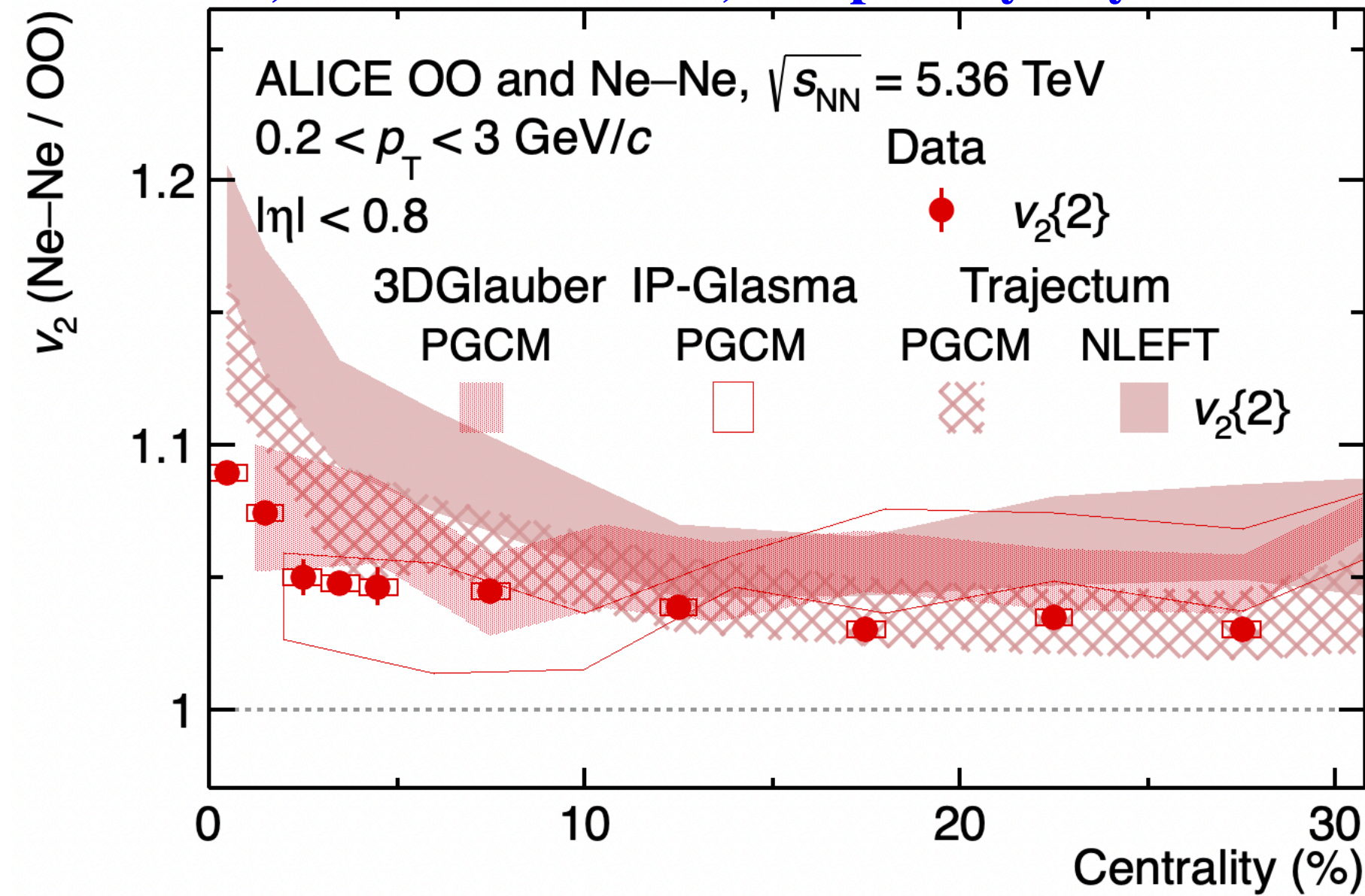


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- Trajectum prediction using PGCM-NS agrees better although still overestimates the ratio

# Flow ratios (Ne-Ne / OO)

ALICE, arXiv:2509.06428, accepted by Phys. Rev. Lett.



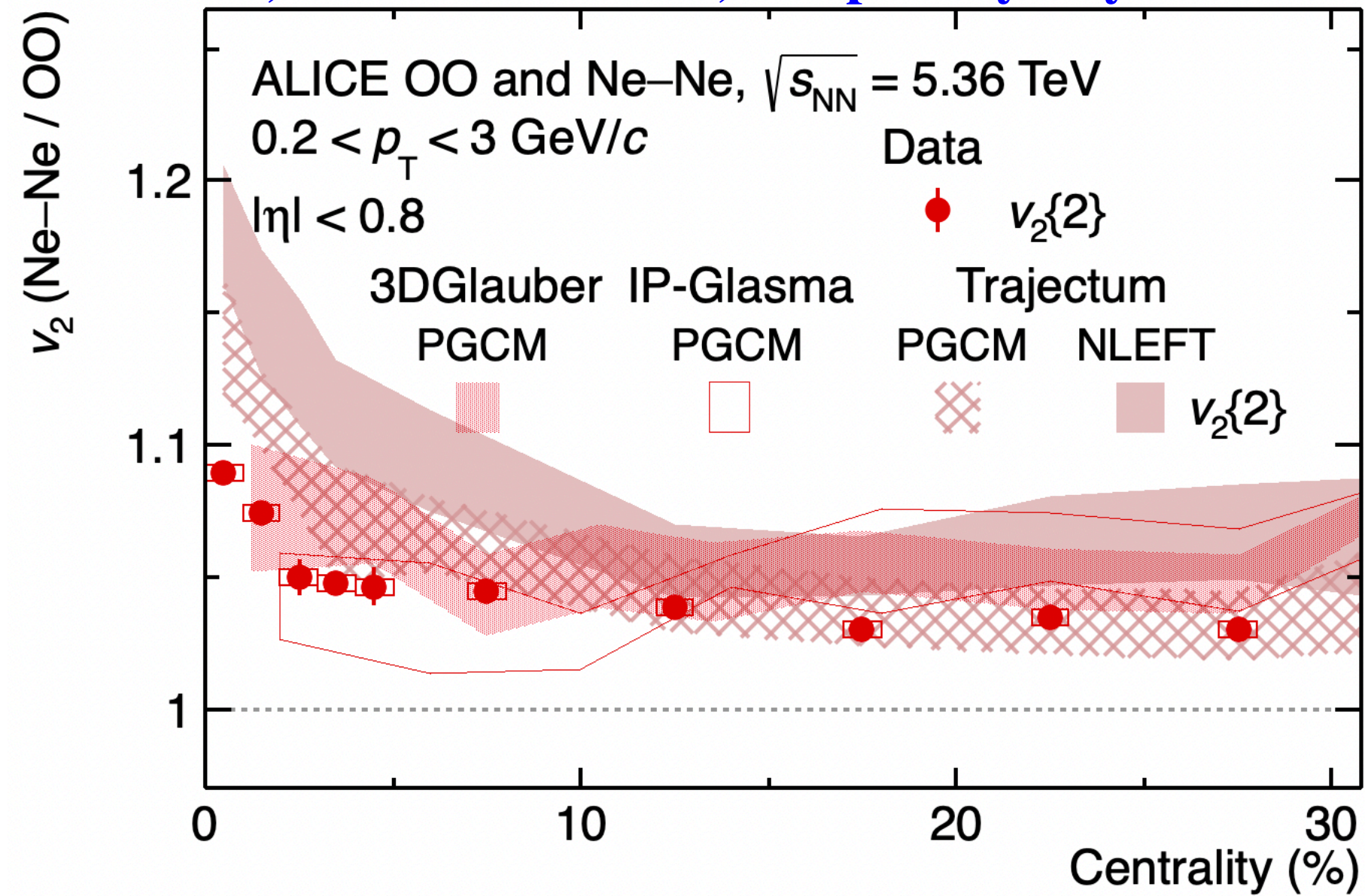
## ❖ Enhanced $v_2$ in Ne-Ne than OO

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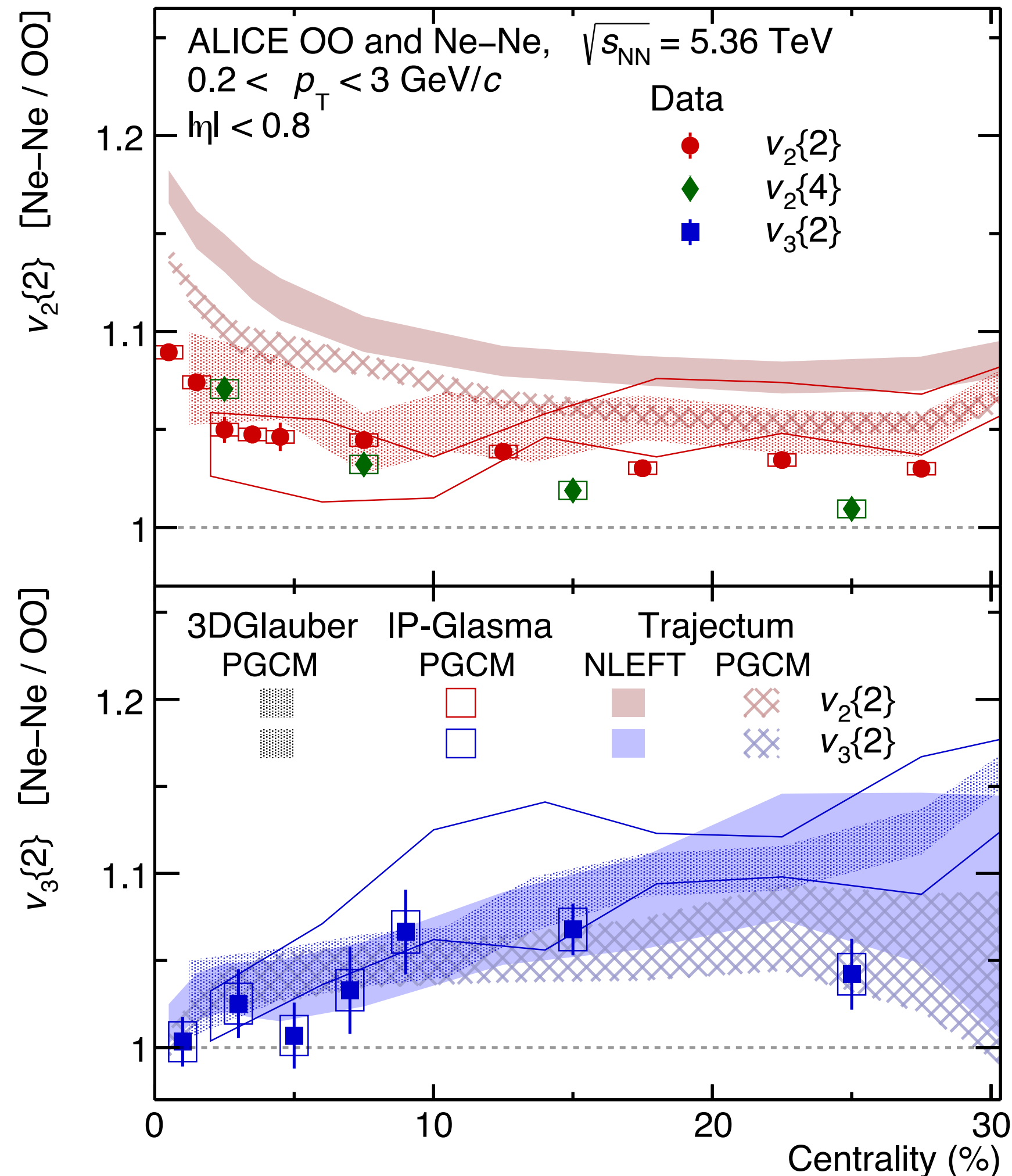


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- Data better described by the models using a smaller sub-nucleon ( $\sim 0.1$  fm)

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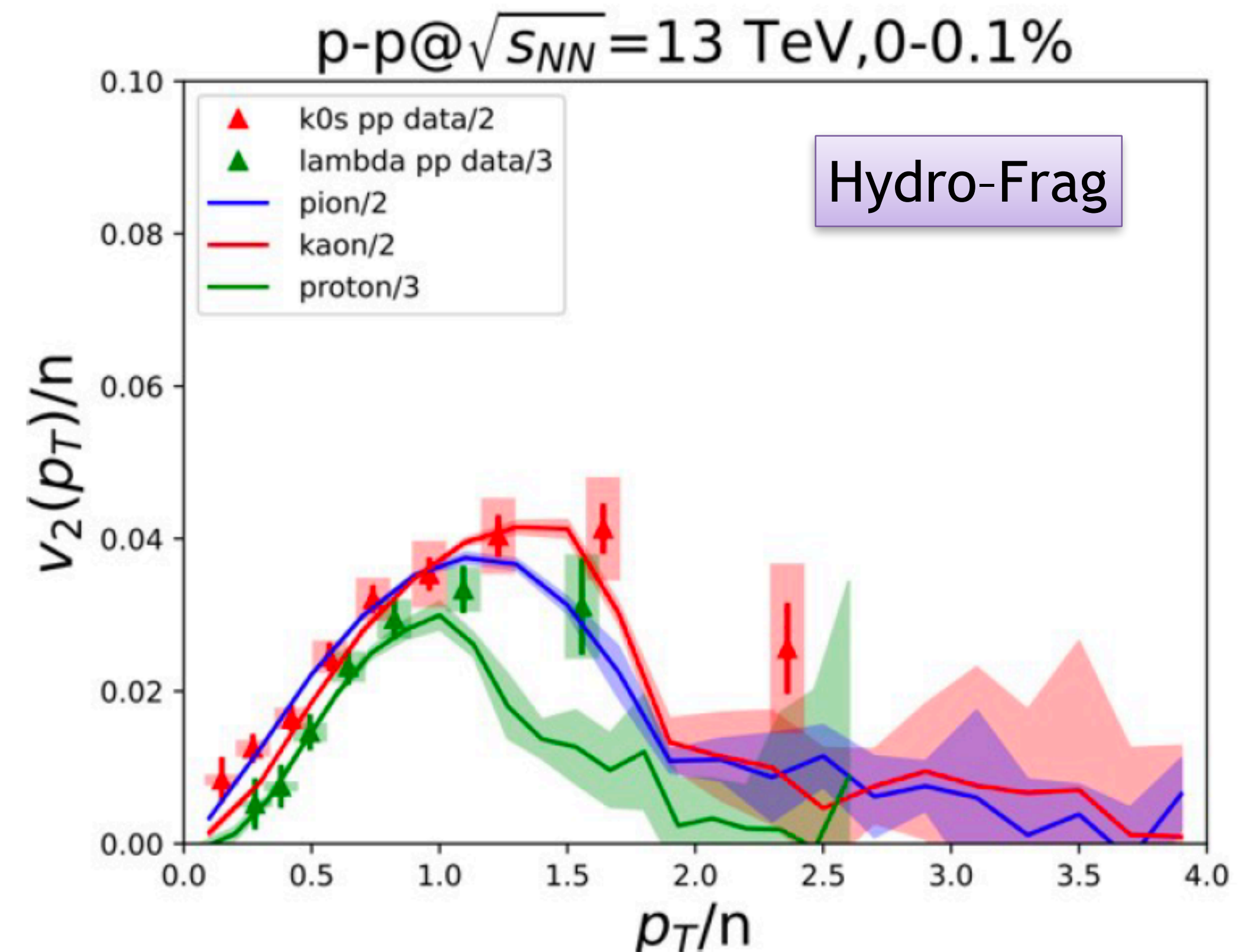
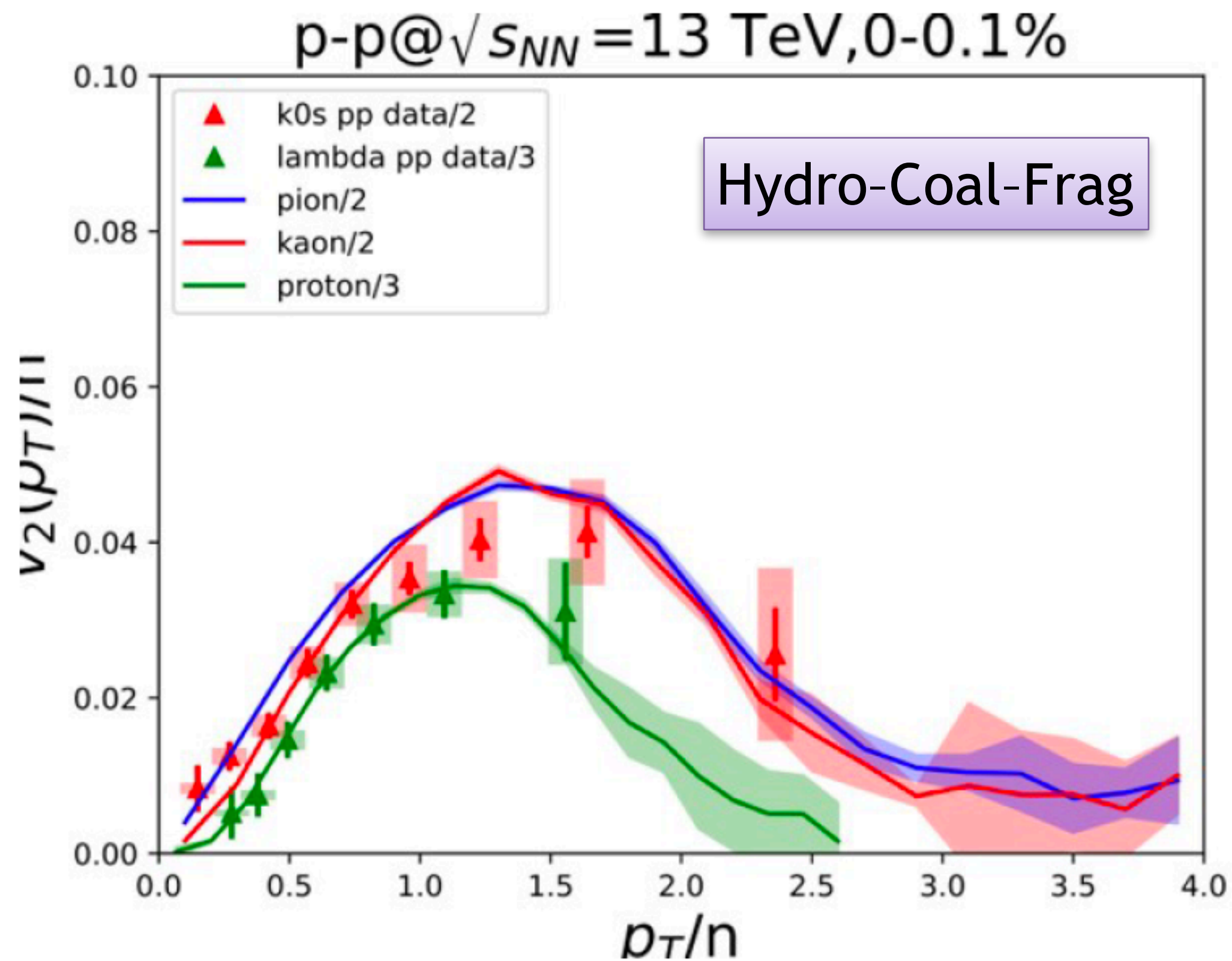
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## ❖ $v_3$ ratio is close to unity in the central collisions due to large $\beta_3$ from tetrahedral shape of $^{16}\text{O}$ , then increases toward peripheral collisions



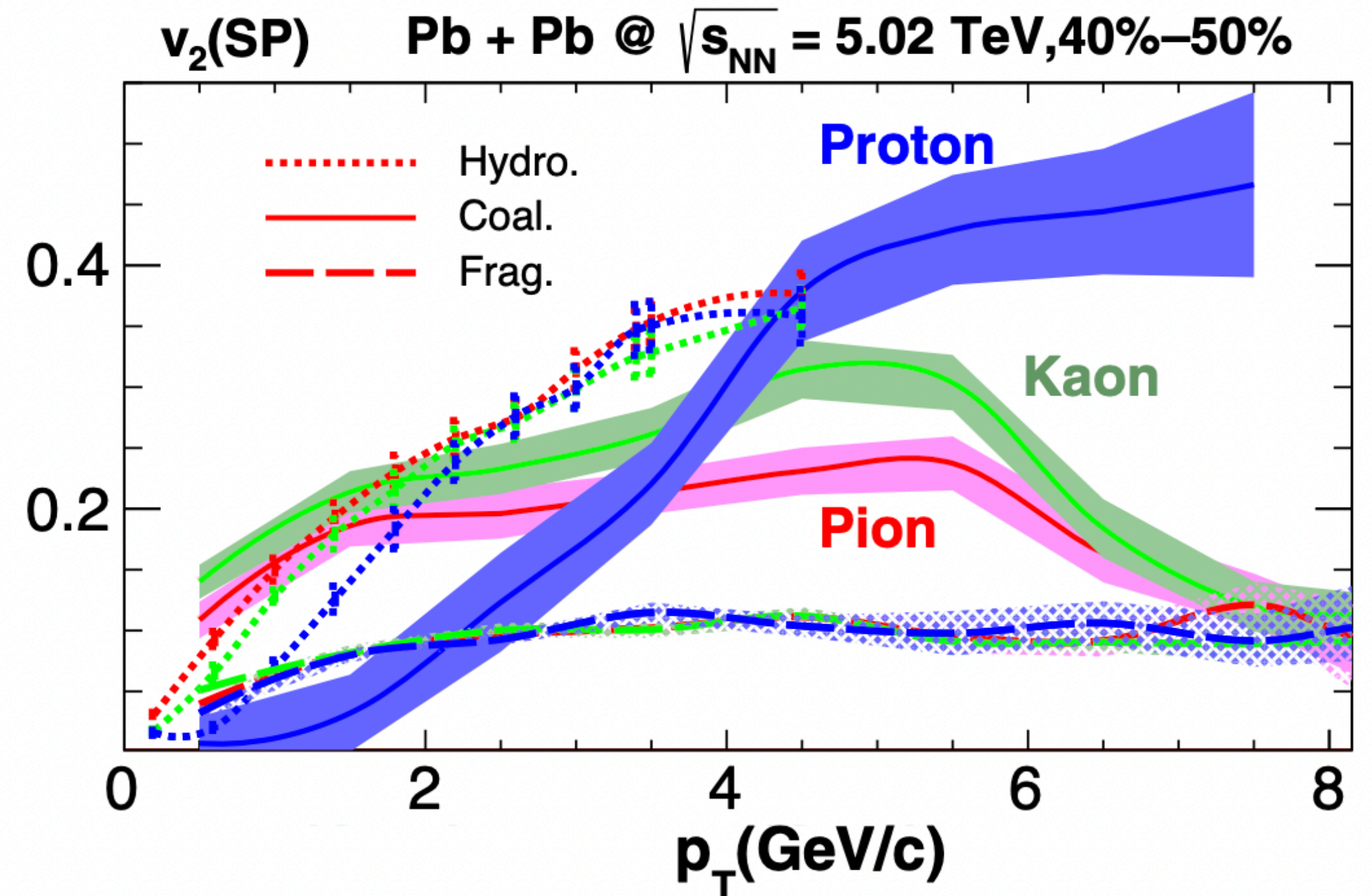
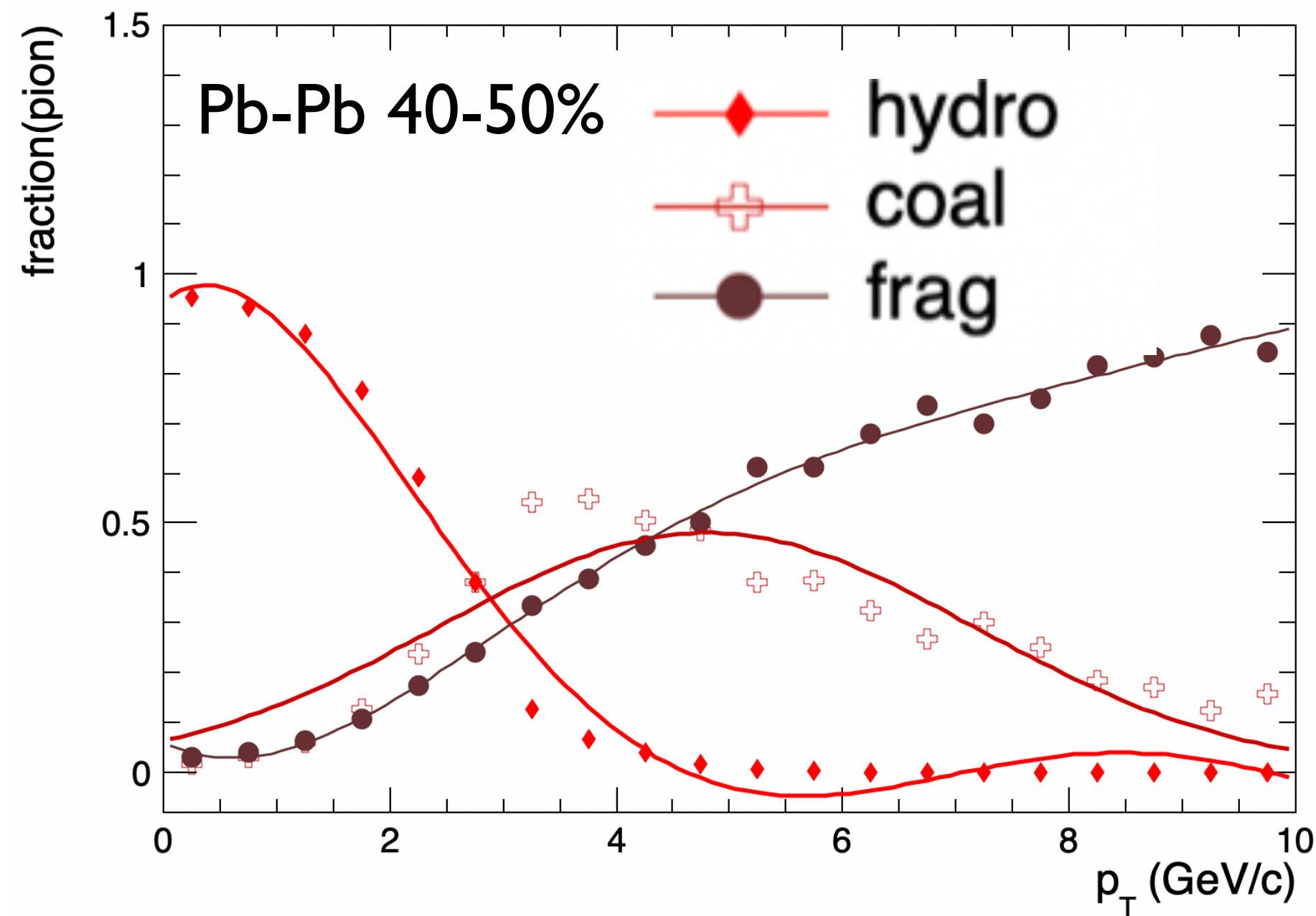
# Behavior of NCQ scaling is predictable



Without quark-coal, the values of  $v_2$  are smaller, in particular for baryons.



# NCQ scaling is NOT an ideal tool



## ❖ What do we learn:

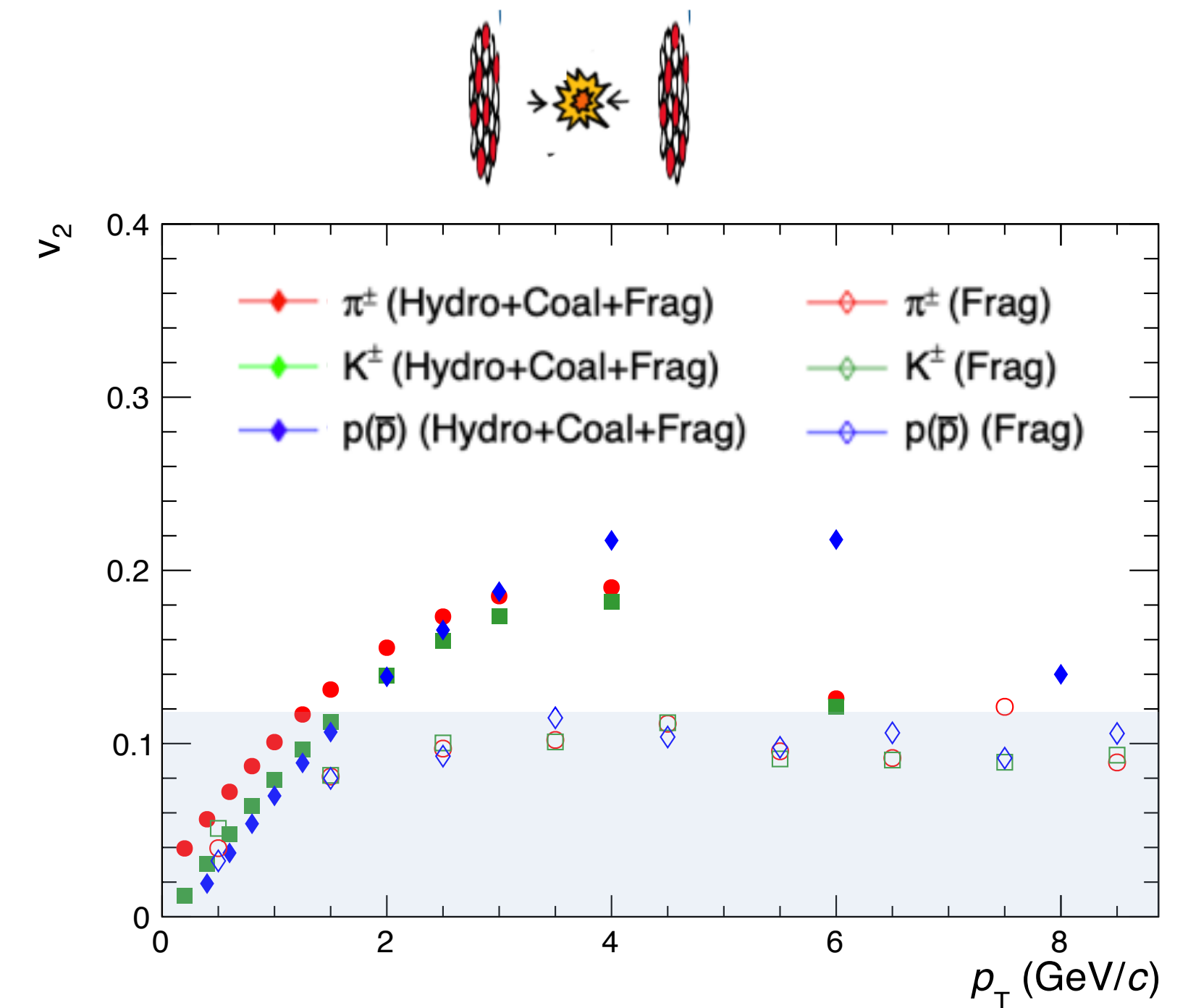
- hydro:  $v_2(\pi) > v_2(K) > v_2(p)$   $\longrightarrow$  No scaling
- quark-coal:  $v_2(p) > v_2(K) \sim v_2(\pi)$   $\longrightarrow$  scaling
- Jet-frag:  $v_2(p) \sim v_2(K) \sim v_2(\pi)$ .  $\longrightarrow$  No scaling
- **Contributions from hydro & frag will break the NCQ scaling, as observed in Pb-Pb collisions and small systems**

Model: W. Zhao etc., PRL128 (2022), 022302  
W. Zhao etc., PRL125 (2020), 072301

Very detailed discussions:  
ALICE, JHEP 05 (2023) 243



# Large $v_2$ but no parton energy loss: Puzzle (?)

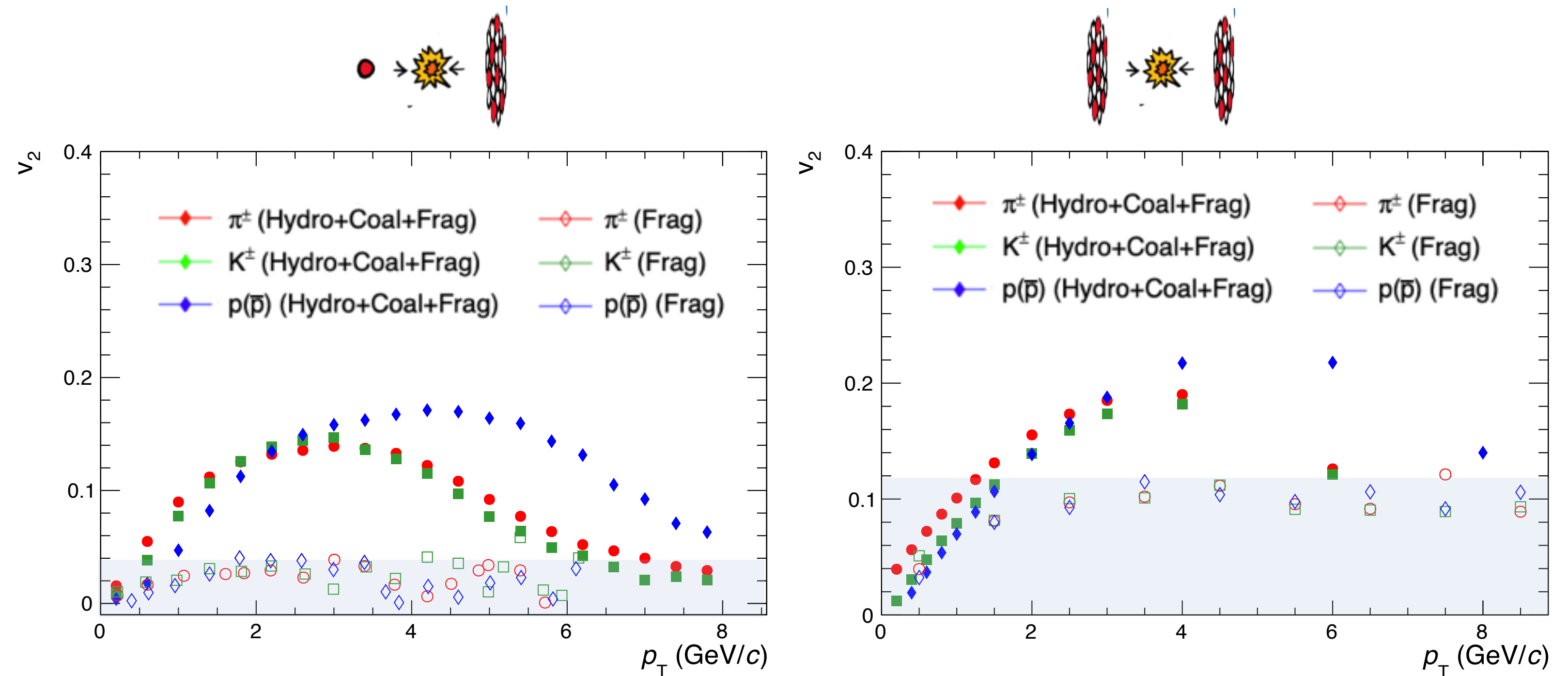


## ❖ $v_2$ from jet-fragmentation with LBT (one possible explanation)

- $v_2(\text{jet-frag})$  in Pb-Pb is significant/dominant at high  $p_T$   $\rightarrow$  large parton energy loss

Calculations: Yuanyuan W etc  
Figures from Wenya W.

# Large $v_2$ but no parton energy loss: Puzzle (?)



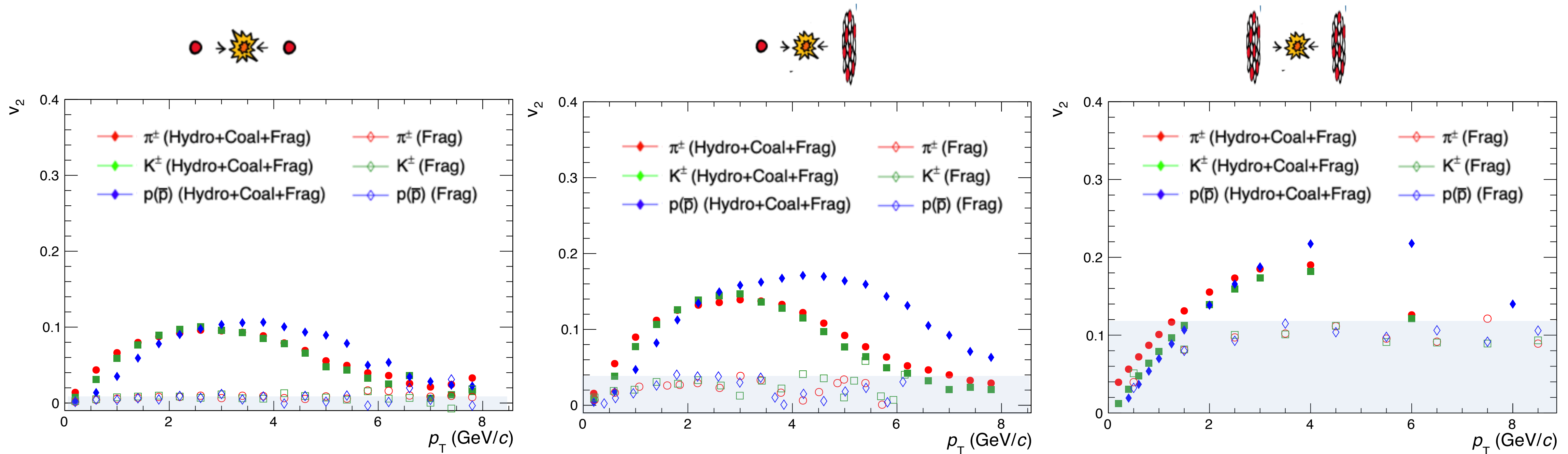
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- $v_2(\text{jet-frag})$  in p-Pb is very small and close to zero  $\rightarrow$  little to no parton energy loss

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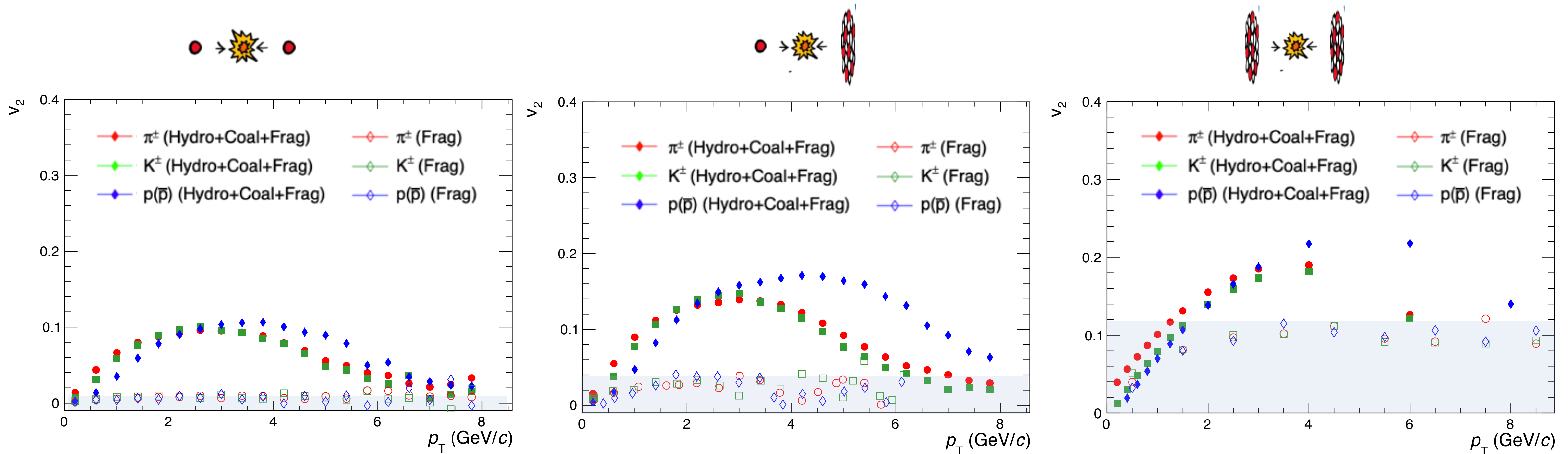


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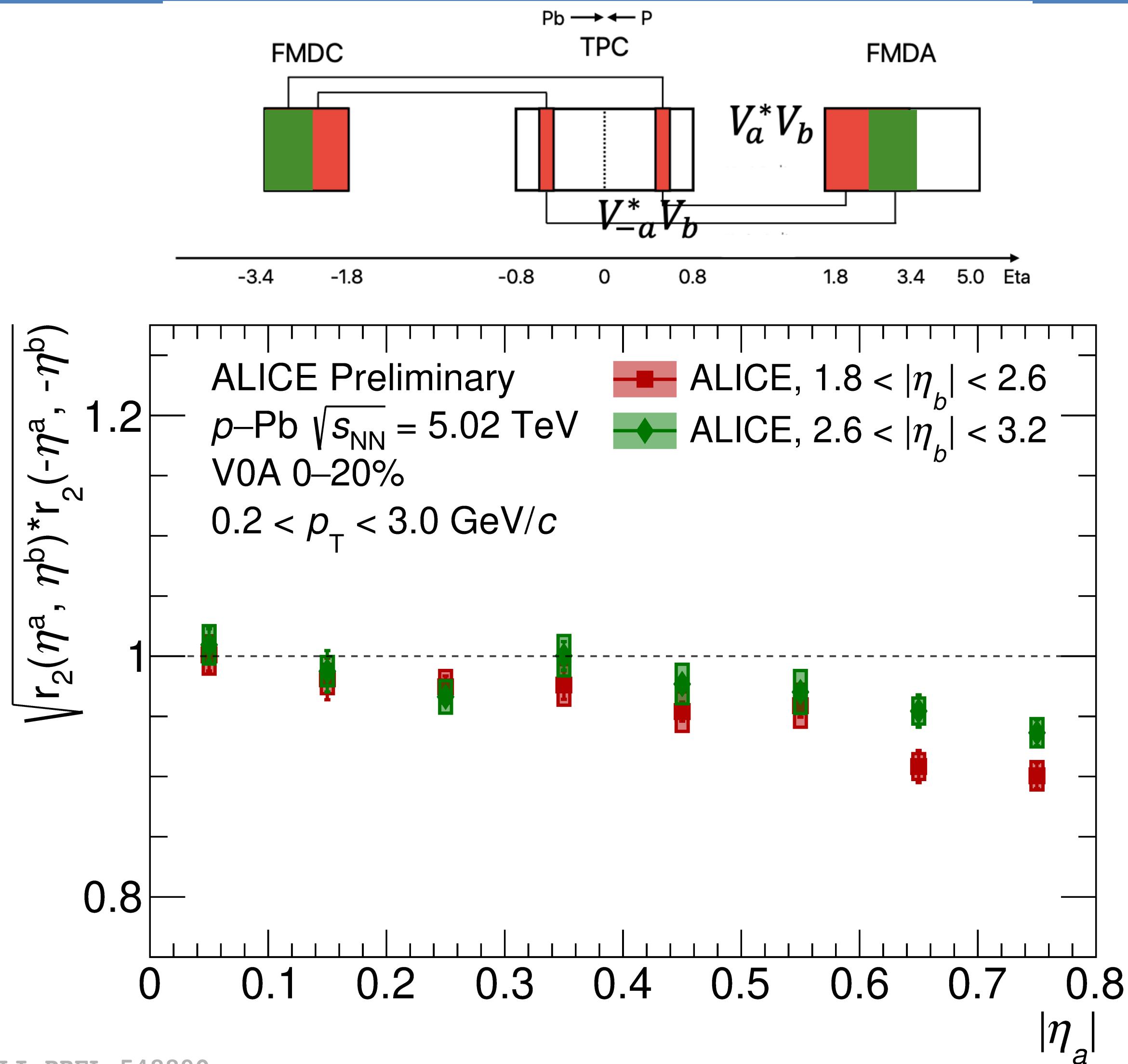
## ❖ Observed finite $v_2$ for the presented $p_T$ in small systems

$\rightarrow$  contributions mainly from left-over hydro and/or quark-coalescence, not parton energy loss.

Calculations: Yuanyuan W etc  
Figures from Wenya W.



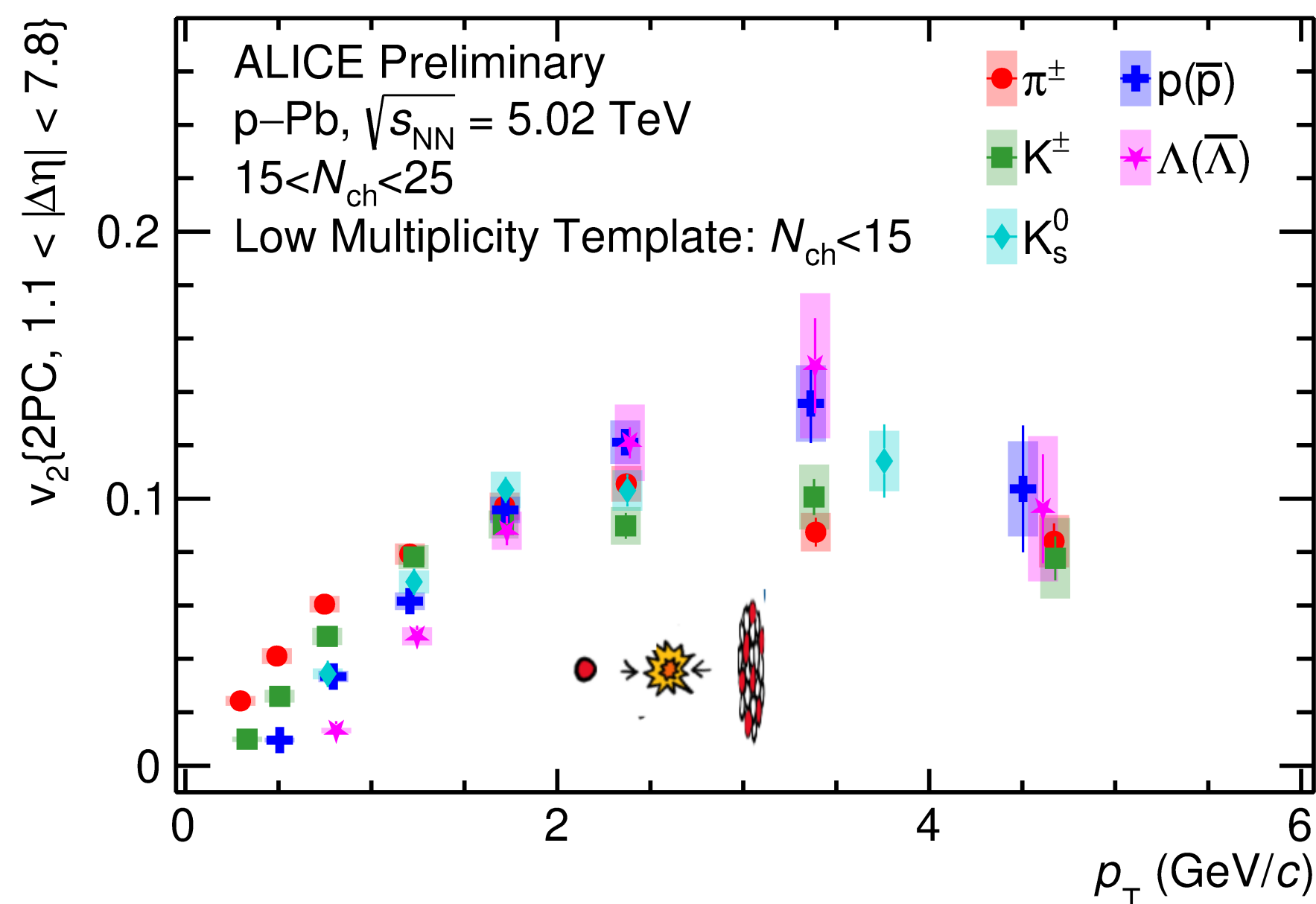
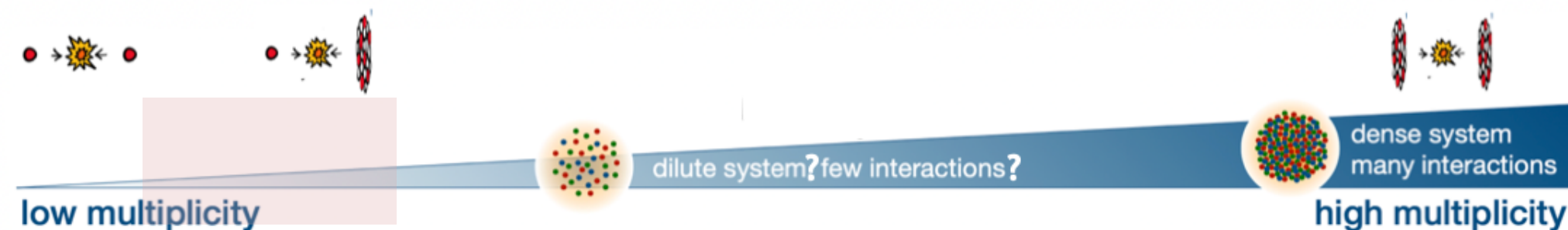
# Flow vector decorrelations in $\eta$ for p-Pb



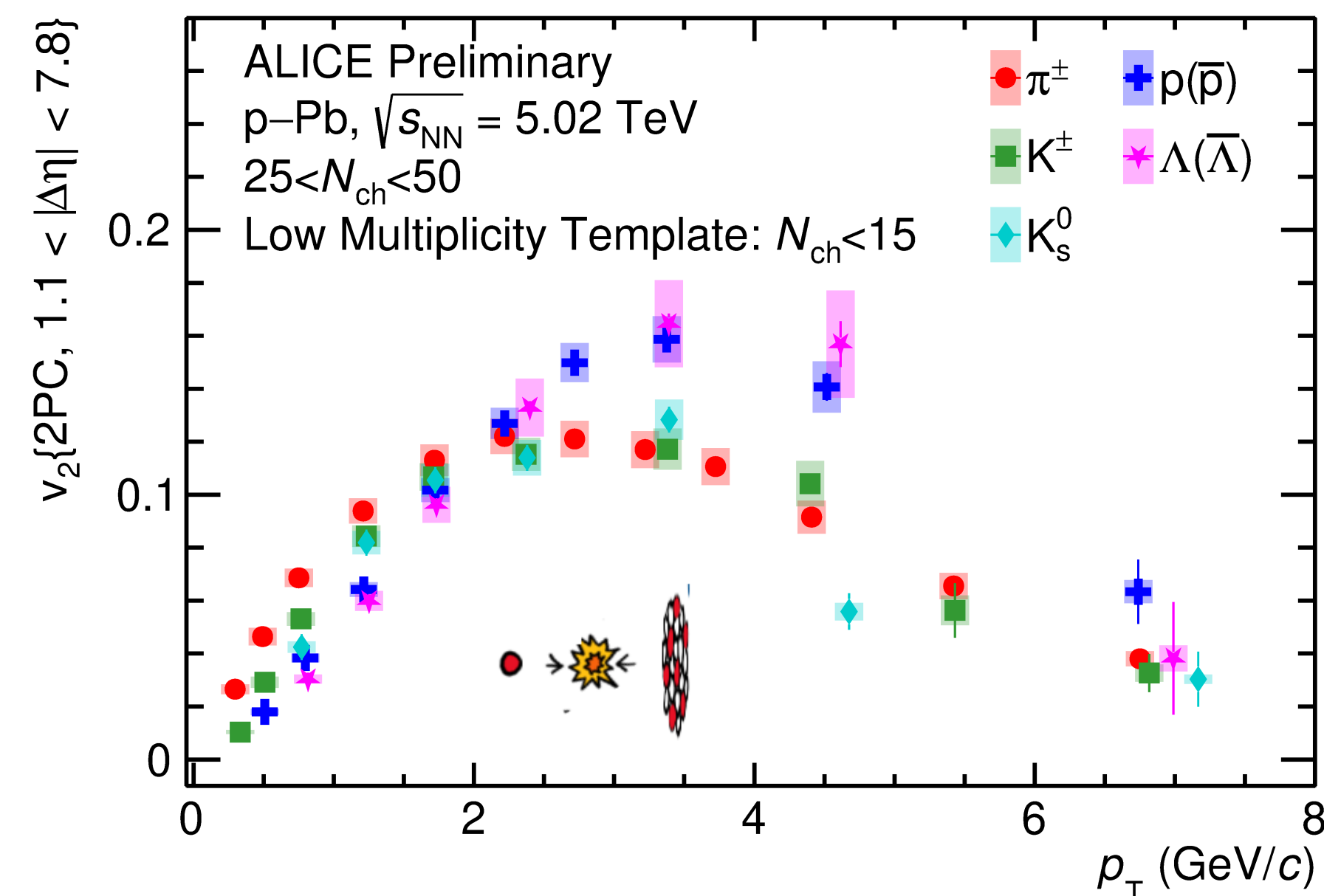
ALI-PREL-548890

- ❖ Deviation from unity in data indicates  $\eta$ -decorrelations
- ❖ First measurement of pseudorapidity-dependent flow vector fluctuations in ALICE for p-Pb collisions

# PID $v_2$ for low $N_{ch}$ **p-Pb** collisions



ALI-PREL-573055



ALI-PREL-573060

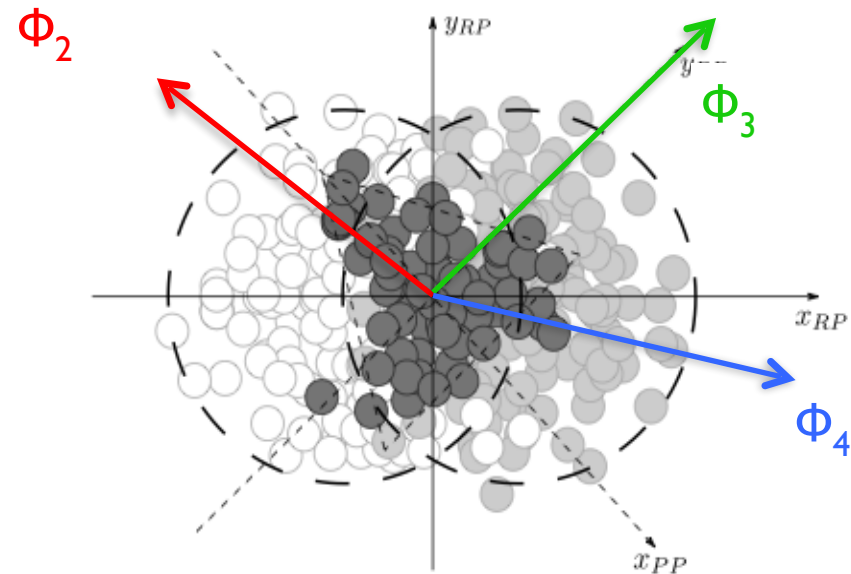
## ❖ For **p-Pb** collisions:

- $N_{ch} > 25$ : Baryon-meson grouping ( $\sim 1\sigma$  confidence) and splitting ( $> 5\sigma$  confidence) of  $v_2$  at intermediate  $p_T$
- $15 < N_{ch} < 25$ : grouping and splitting (within  $2\sigma$  confidence), partonic flow picture is not very clear
- Full investigations through careful data & model comparisons are ongoing

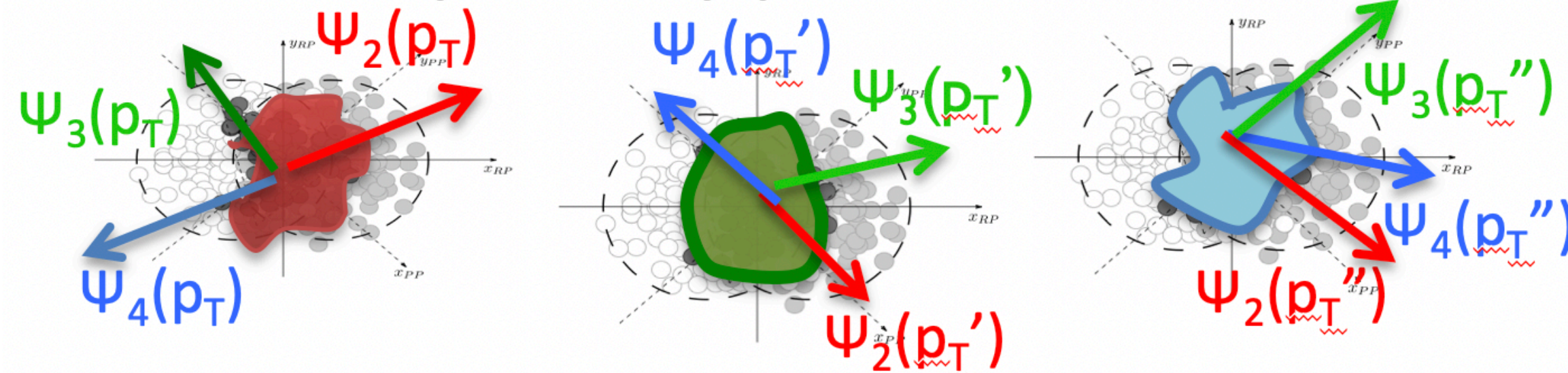


# Flow vector decorrelations

Initial symmetry planes



Final symmetry planes ??



Initial proposal:

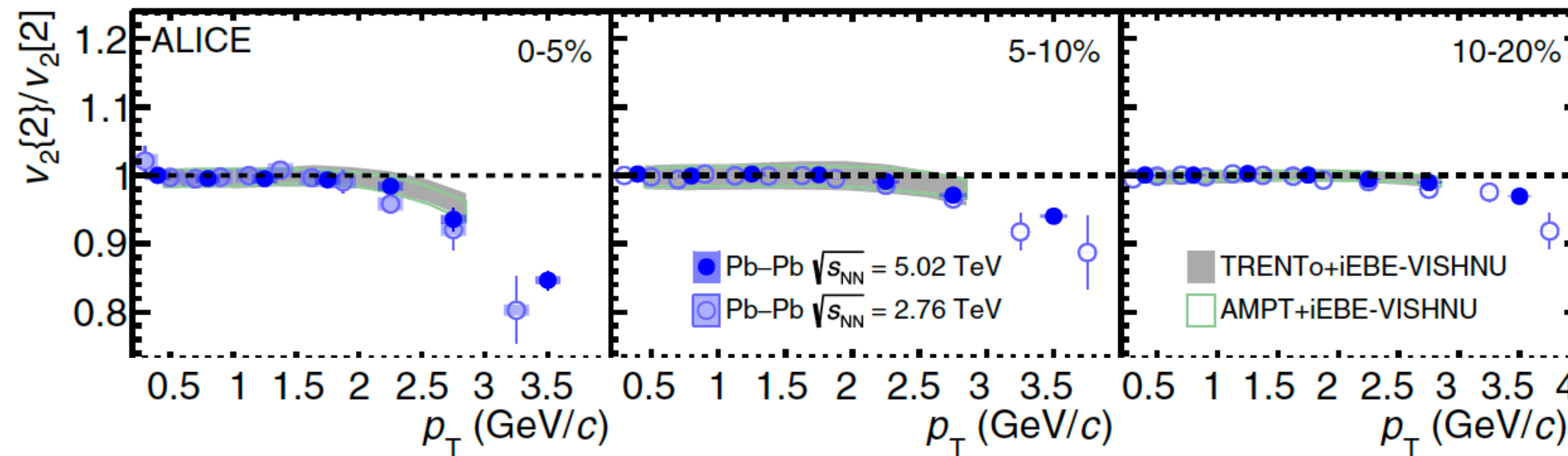
U. Heinz etc., PRC87, 034913 (2013)

F. G. Gardim etc., PRC 87, 031901(R) (2013).

$$\frac{v_2\{2PC\}}{v_2[2PC]} = \frac{V_{2\Delta}(p_T^a, p_T^{\text{ref}})}{\sqrt{V_{2\Delta}(p_T^a, p_T^a)} \sqrt{V_{2\Delta}(p_T^{\text{ref}}, p_T^{\text{ref}})}} = \frac{\langle v_2(p_T^a) v_2^{\text{ref}} \cos[n(\psi_2(p_T^a) - \psi_2)] \rangle}{\sqrt{\langle v_2(p_T^a)^2 \rangle} \sqrt{\langle v_2^{\text{ref}2} \rangle}}$$

→ Flow angle fluctuations (blue arrow)

→ Flow magnitude fluctuations (red arrow)

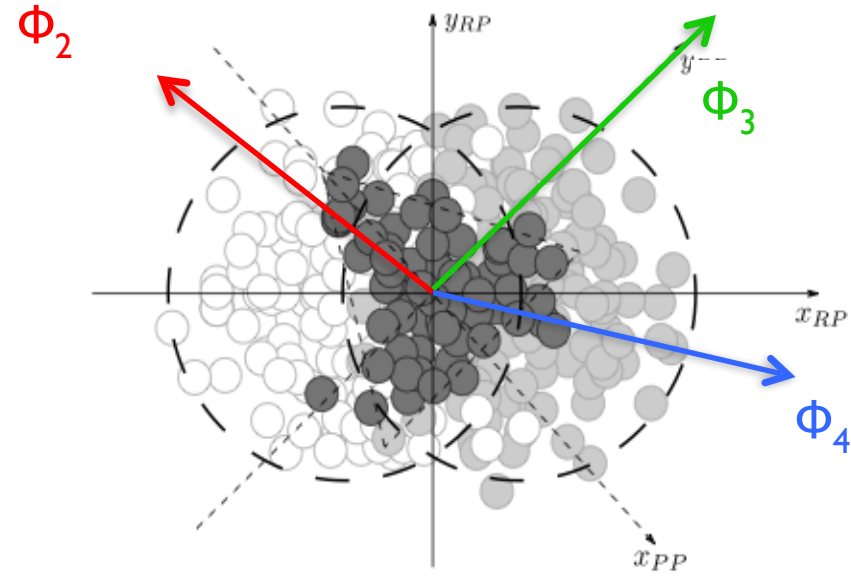


E.G. Nielsen, YZ, EPJC 83 (2023) 6, 545

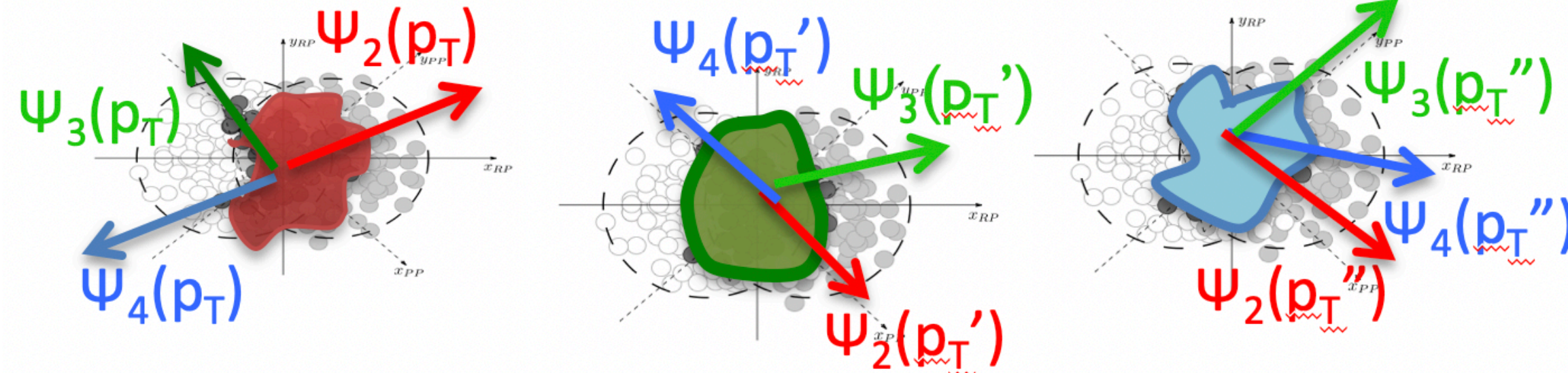


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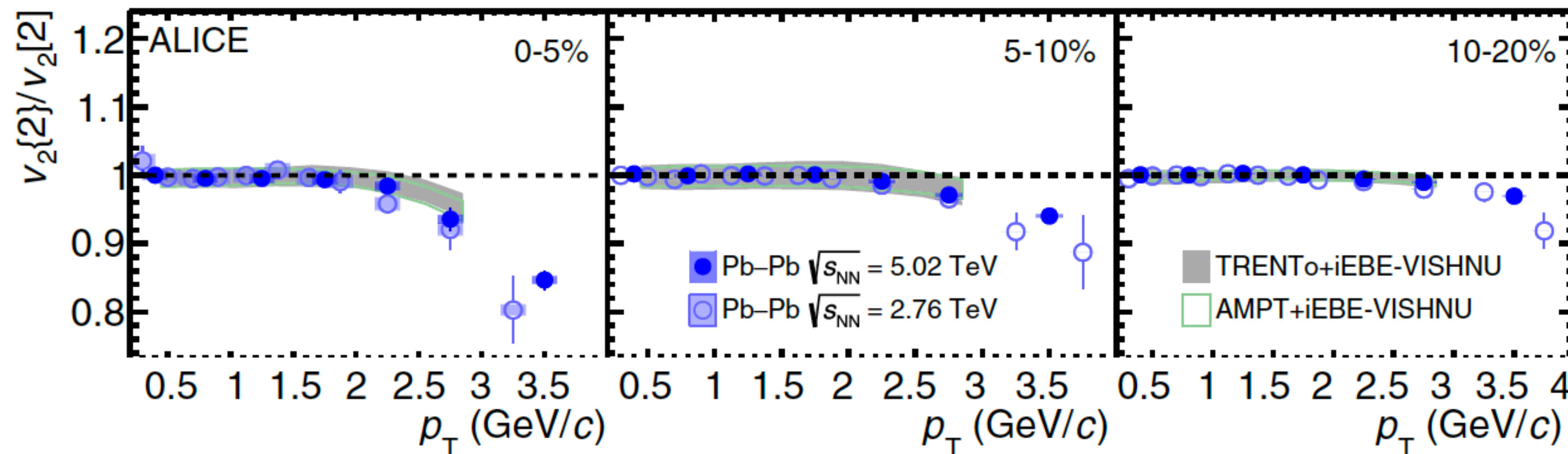
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$$\frac{v_2\{2PC\}}{v_2[2PC]} = \frac{V_{2\Delta}(p_T^a, p_T^{\text{ref}})}{\sqrt{V_{2\Delta}(p_T^a, p_T^a)} \sqrt{V_{2\Delta}(p_T^{\text{ref}}, p_T^{\text{ref}})}} = \frac{\langle v_2(p_T^a) v_2^{\text{ref}} \cos[n(\psi_2(p_T^a) - \psi_2)] \rangle}{\sqrt{\langle v_2(p_T^a)^2 \rangle} \sqrt{\langle v_2^{\text{ref}2} \rangle}}$$

→ Flow angle fluctuations  
→ Flow magnitude fluctuations



ALICE, JHEP 09 (2017) 032

ALICE, PRC107 (2023) L051901

ALICE, PRC109 (2024) 065202

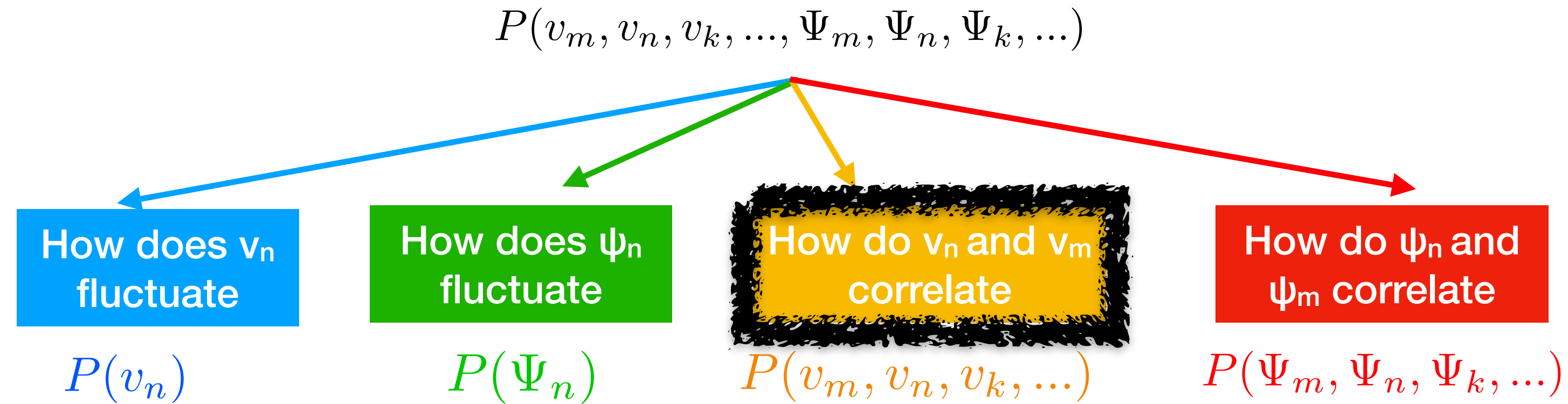
❖  $v_2\{2\}/v_2[2]$  deviates from unity, observation of flow-vector fluctuations in Pb-Pb collisions

- Driven by the initial geometrical fluctuations

E.G. Nielsen, YZ, EPJC 83 (2023) 6, 545



# Correlations between $v_m$ and $v_n$

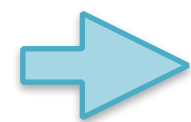


## Symmetric cumulants:

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

(Suggested by Jean-Yves in QM15 to look at normalised SC)

$$\begin{aligned} v_2 &\propto \varepsilon_2 \\ v_3 &\propto \varepsilon_3 \end{aligned}$$



$$\frac{\langle v_2^2 v_3^2 \rangle - \langle v_2^2 \rangle \langle v_3^2 \rangle}{\langle v_2^2 \rangle \langle v_3^2 \rangle} = \frac{\langle \varepsilon_2^2 \varepsilon_3^2 \rangle - \langle \varepsilon_2^2 \rangle \langle \varepsilon_3^2 \rangle}{\langle \varepsilon_2^2 \rangle \langle \varepsilon_3^2 \rangle}$$

Or:  $NSC^v(3, 2) = NSC^\varepsilon(3, 2)$

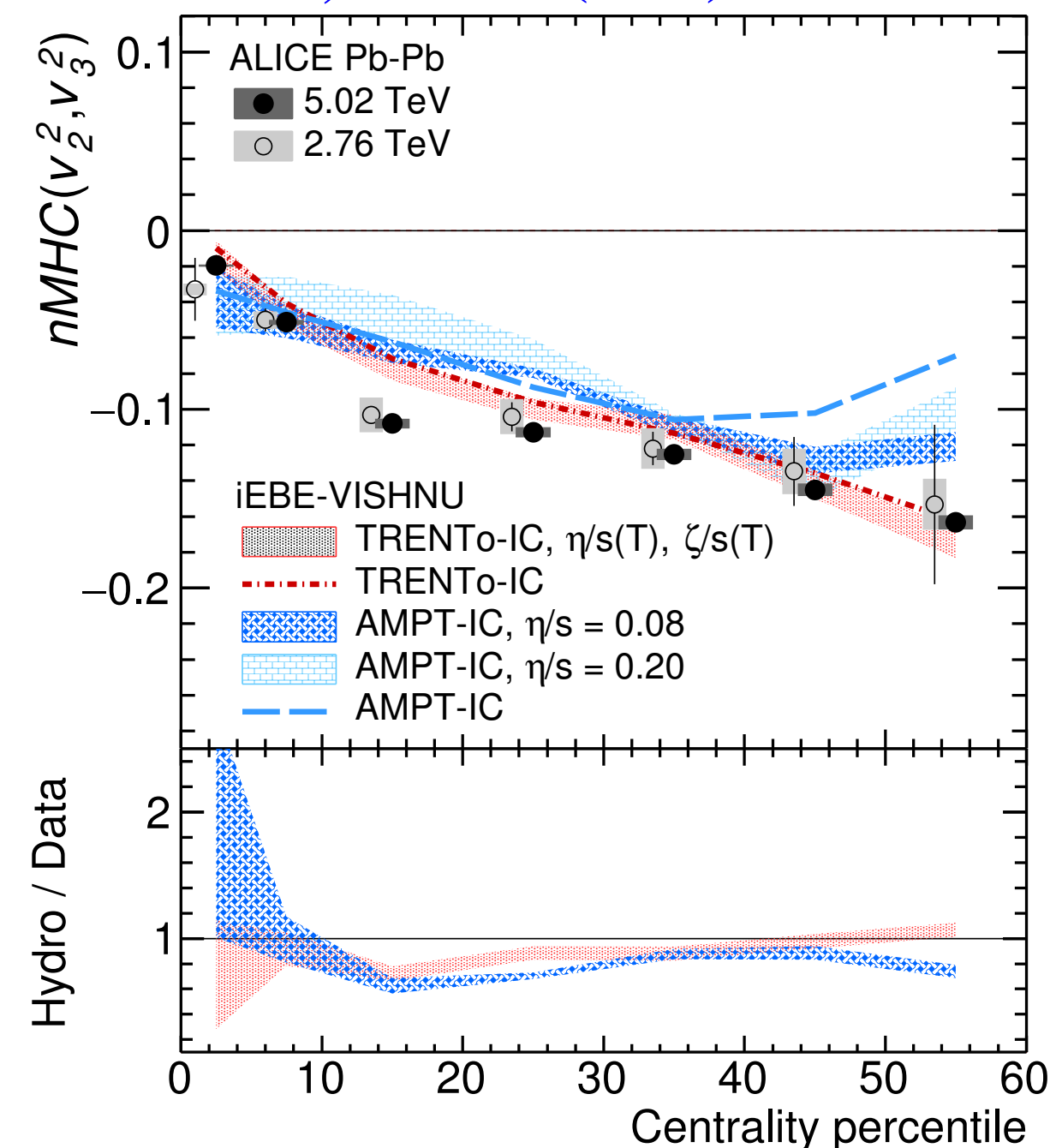
YZ, K. Xiao, F. Zhao, F. Liu, R. Snellings, PRC93, 034909 (2016)

X. Zhu, YZ, H. Xu, and H. Song, PRC95, 044902 (2017)

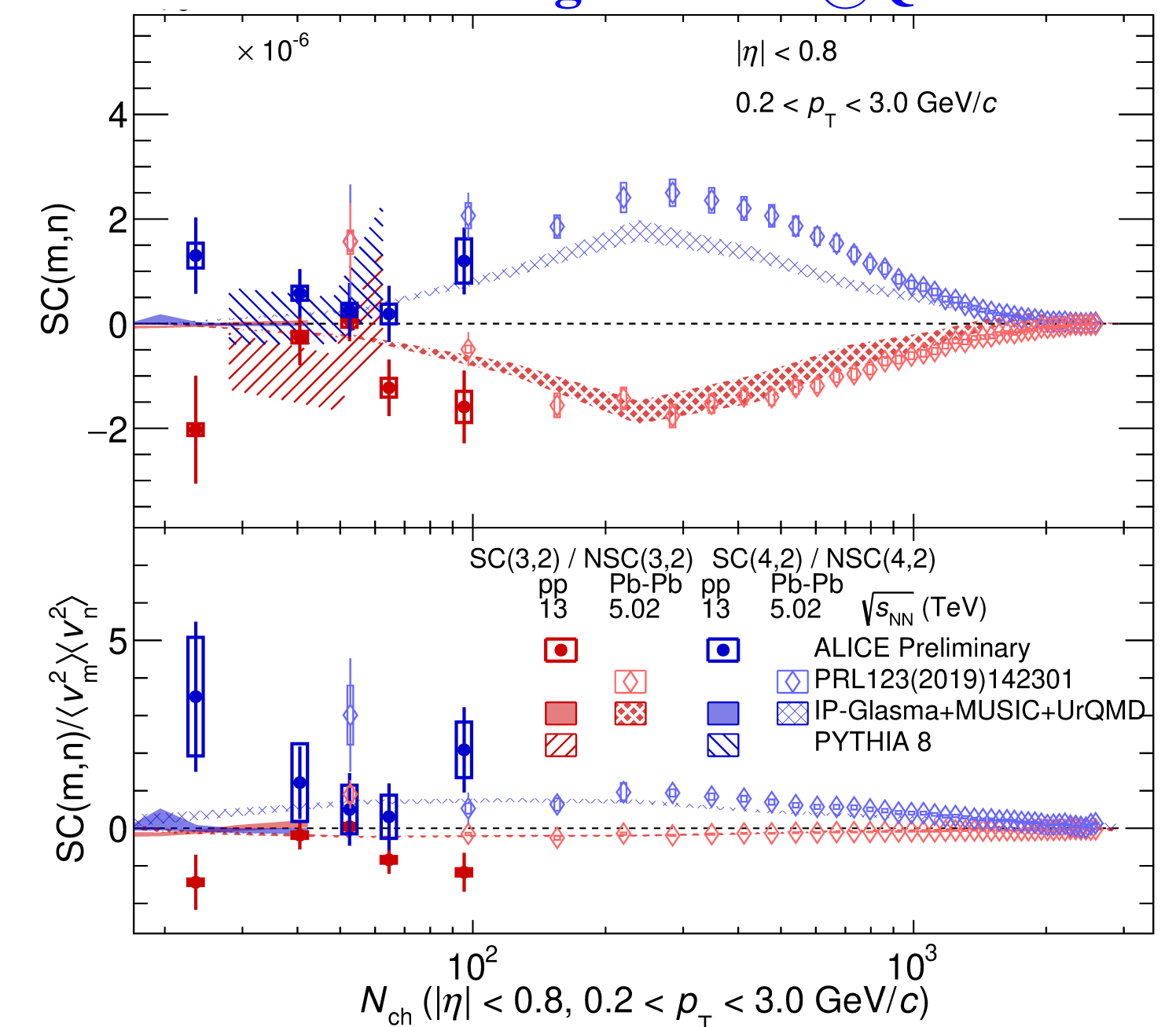
Z. Moravcova, K. Gulbrandsen, YZ, PRC103, 024913 (2021)

M. Li, YZ, ...H. Song, PRC104.024903(2021)

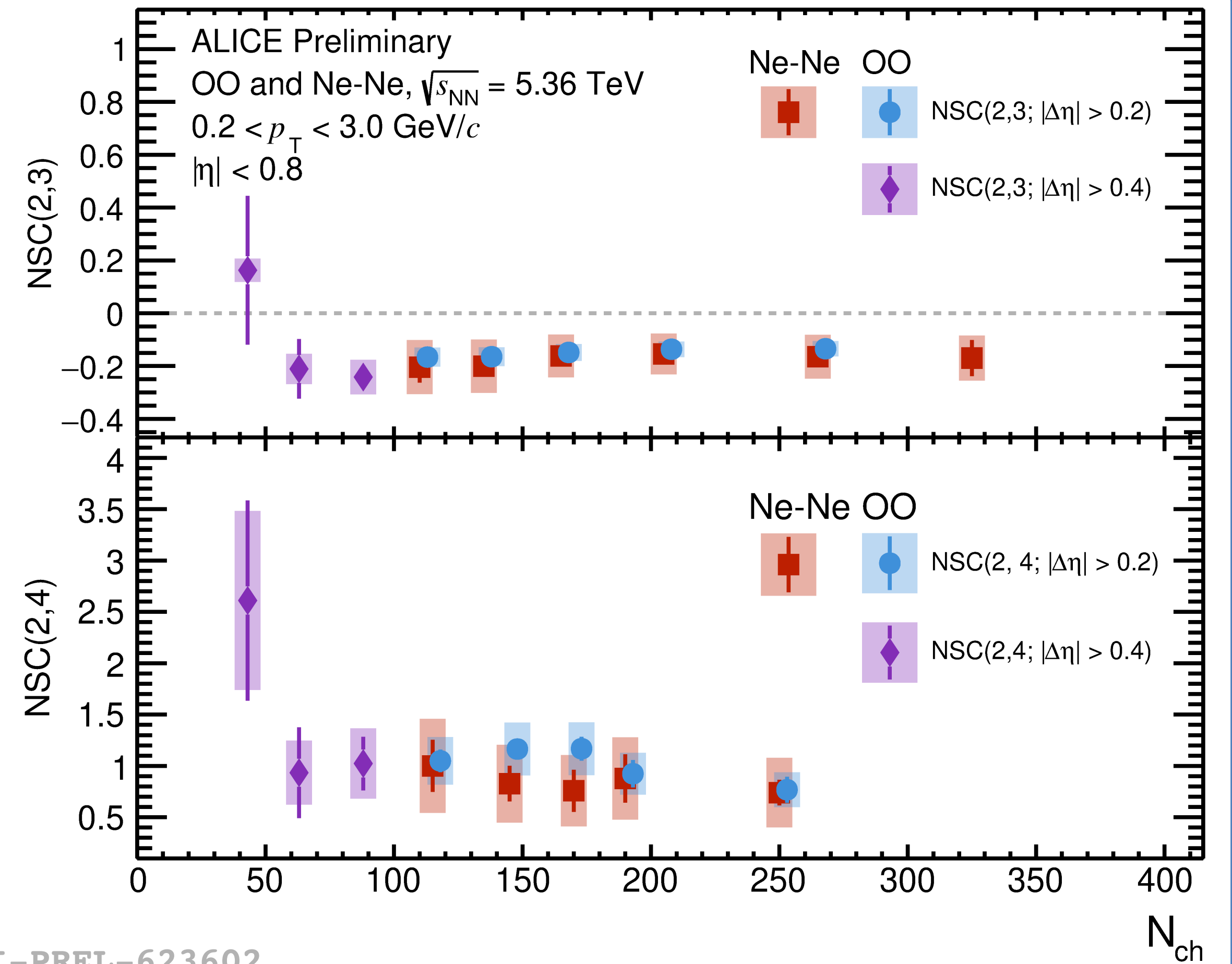
ALICE, PLB818 (2021) 136354



Mingrui Zhao @QM2023



ALI-PREL-507164



ALI-PREL-623602



# Correlations between $\Psi_m$ and $\Psi_n$

Early proposal:

Z. Qiu, U. Heinz, PLB717, 261 (2012)

$$P(v_m, v_n, v_k, \dots, \Psi_m, \Psi_n, \Psi_k, \dots)$$

How does  $v_n$   
fluctuate

$$P(v_n)$$

How does  $\psi_n$   
fluctuate

$$P(\Psi_n)$$

How do  $v_n$  and  $v_m$   
correlate

$$P(v_m, v_n, v_k, \dots)$$

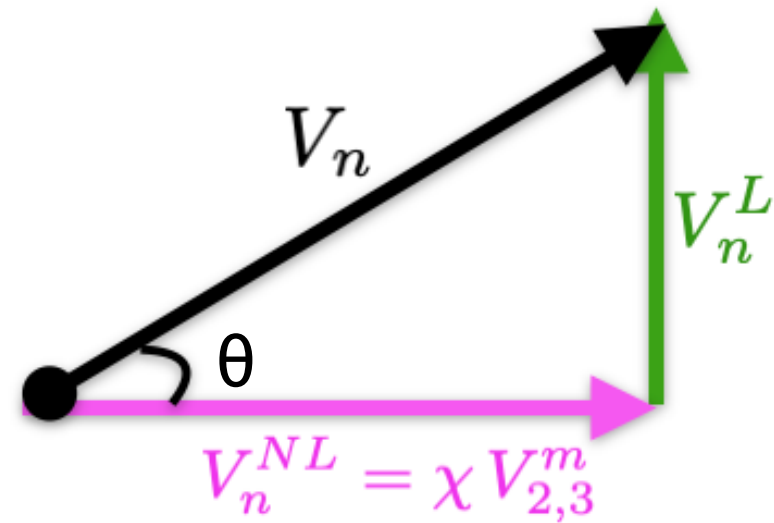
How do  $\psi_n$  and  
 $\psi_m$  correlate

$$P(\Psi_m, \Psi_n, \Psi_k, \dots)$$

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

non-linear flow mode

linear flow mode

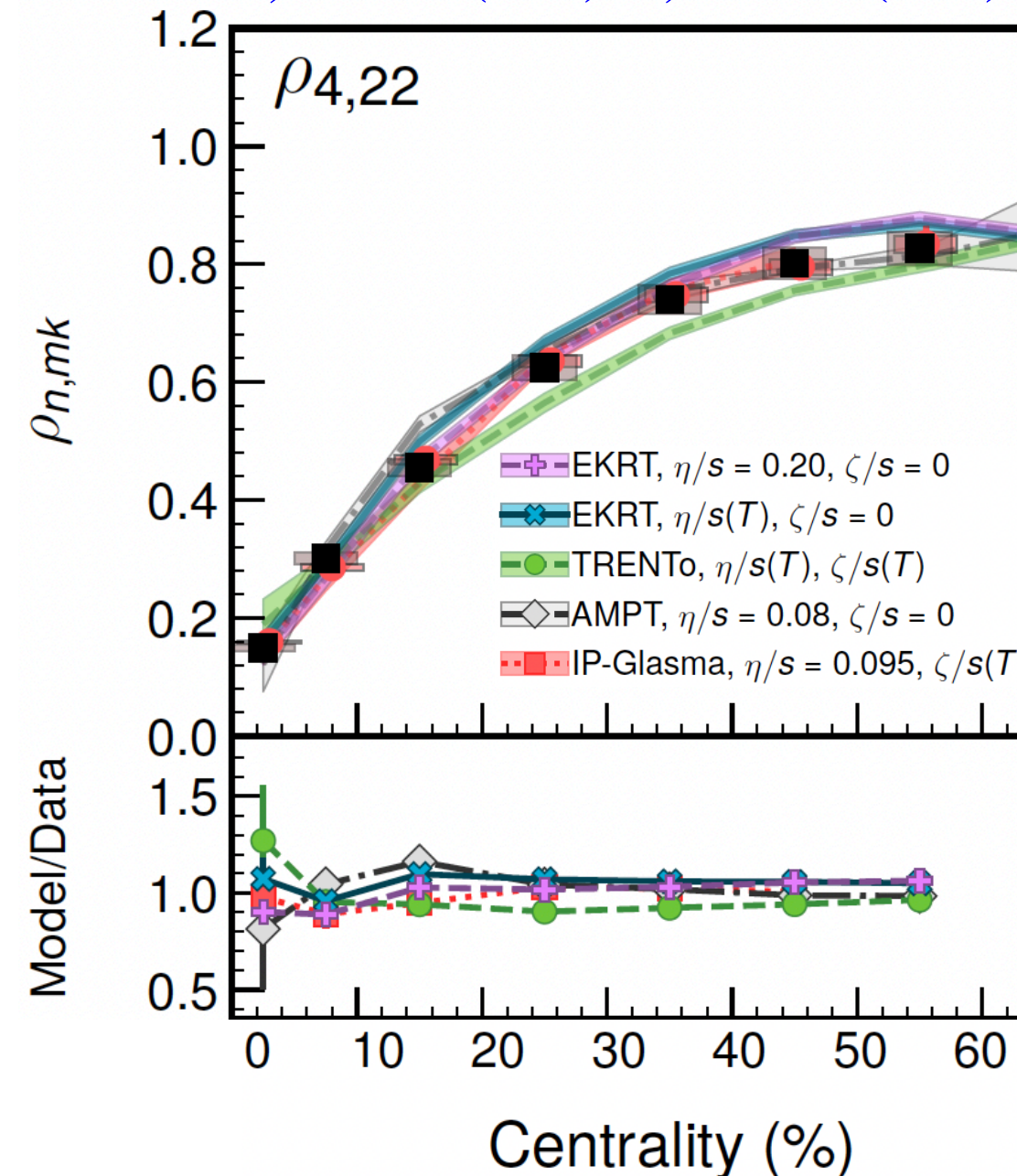


L. Yan et al,  
PLB744 (2015) 82

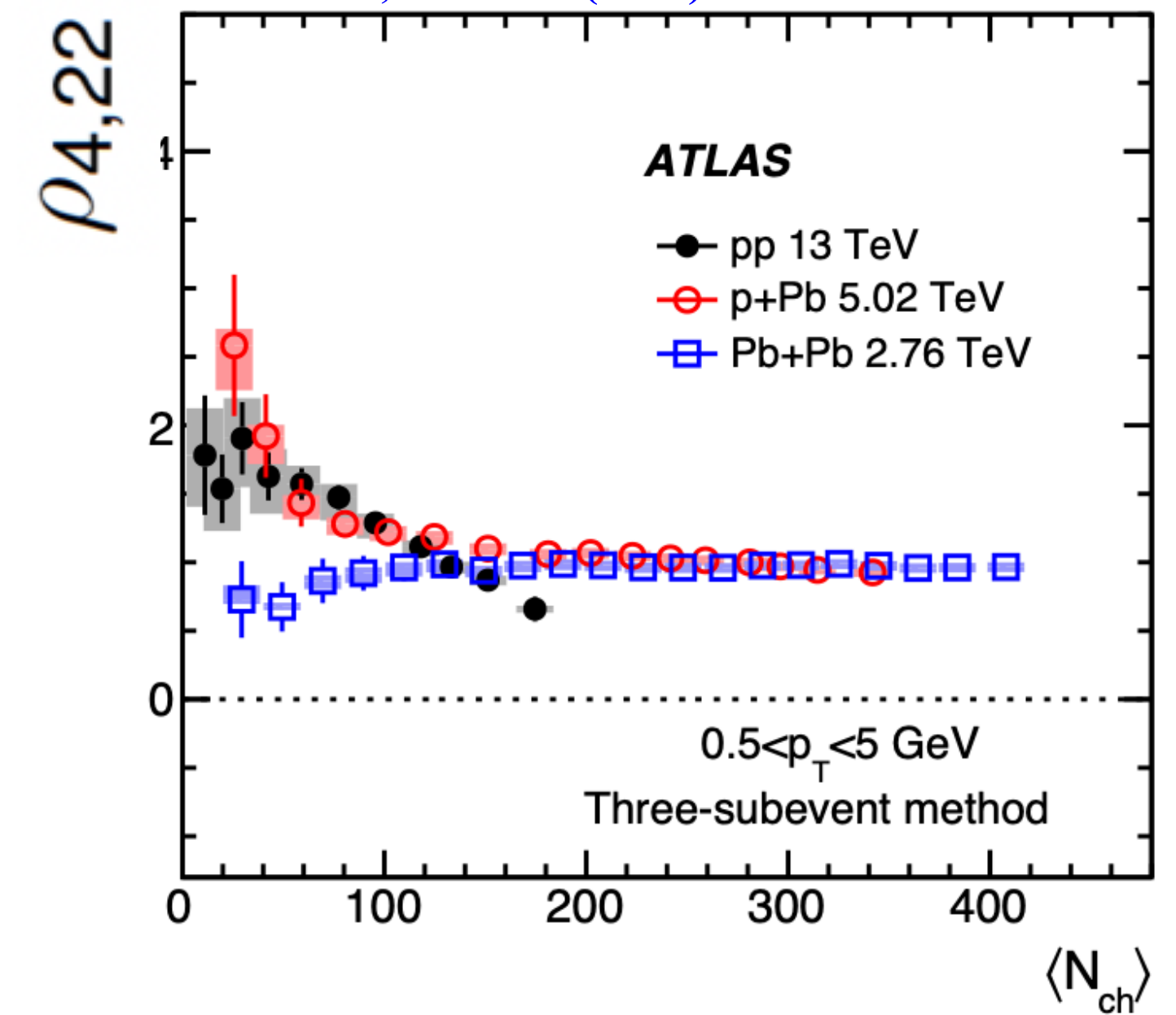
J. Qian, U. Heinz  
PRC 93, 064901 (2016)

$$\rho_{4,22} = \frac{v_{4,22}}{v_4\{2\}} \approx \langle \cos(4\Psi_4 - 4\Psi_2) \rangle$$

ALICE, PLB773 (2017) 68, JHEP05 (2020) 085



ATLAS, PLB 789 (2019) 444



# Elliptic power function reconstruction



$$v_n\{2\} = \sqrt{c_n\{2\}}, v_n\{4\} = \sqrt{-c_n\{4\}},$$

$$v_n\{6\} = \sqrt{\frac{1}{4}c_n\{6\}}, v_n\{8\} = \sqrt{-\frac{1}{33}c_n\{8\}}$$

## Construction via measured cumulants

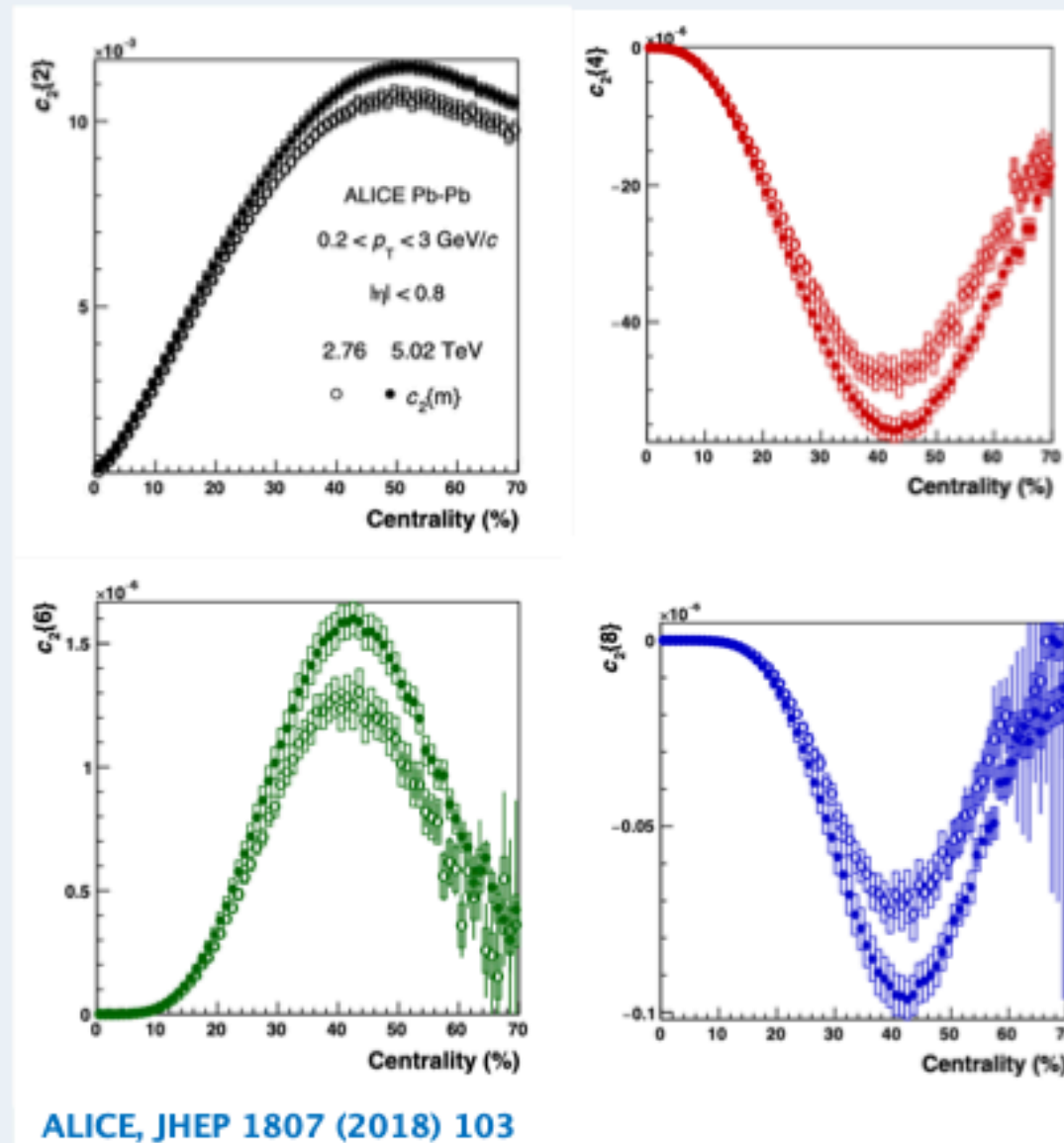
$$c_2\{2\} = k_2^2(1 - f_1),$$

$$c_2\{4\} = -k_2^4(1 - 2f_1 + 2f_1^2 - f_2),$$

$$c_2\{6\} = k_2^6(4 + 18f_1^2 - 12f_1^3 + 12f_1(3f_2 - 1) - 6f_2 - f_3),$$

$$c_2\{8\} = -k_2^8(33 - 288f_1^3 + 144f_1^4 - 66f_2 + 18f_2^2 - 24f_1^2(-11 + 6f_2^2) - 12f_3 + 4f_1(-33 + 42f_2 + 4f_3) - f_4),$$

$$f_k = \frac{\alpha}{\alpha + k} (1 - \varepsilon_0^2)^k {}_2F_1\left(k + \frac{1}{2}, k; \alpha + k + a, \varepsilon_0\right)$$

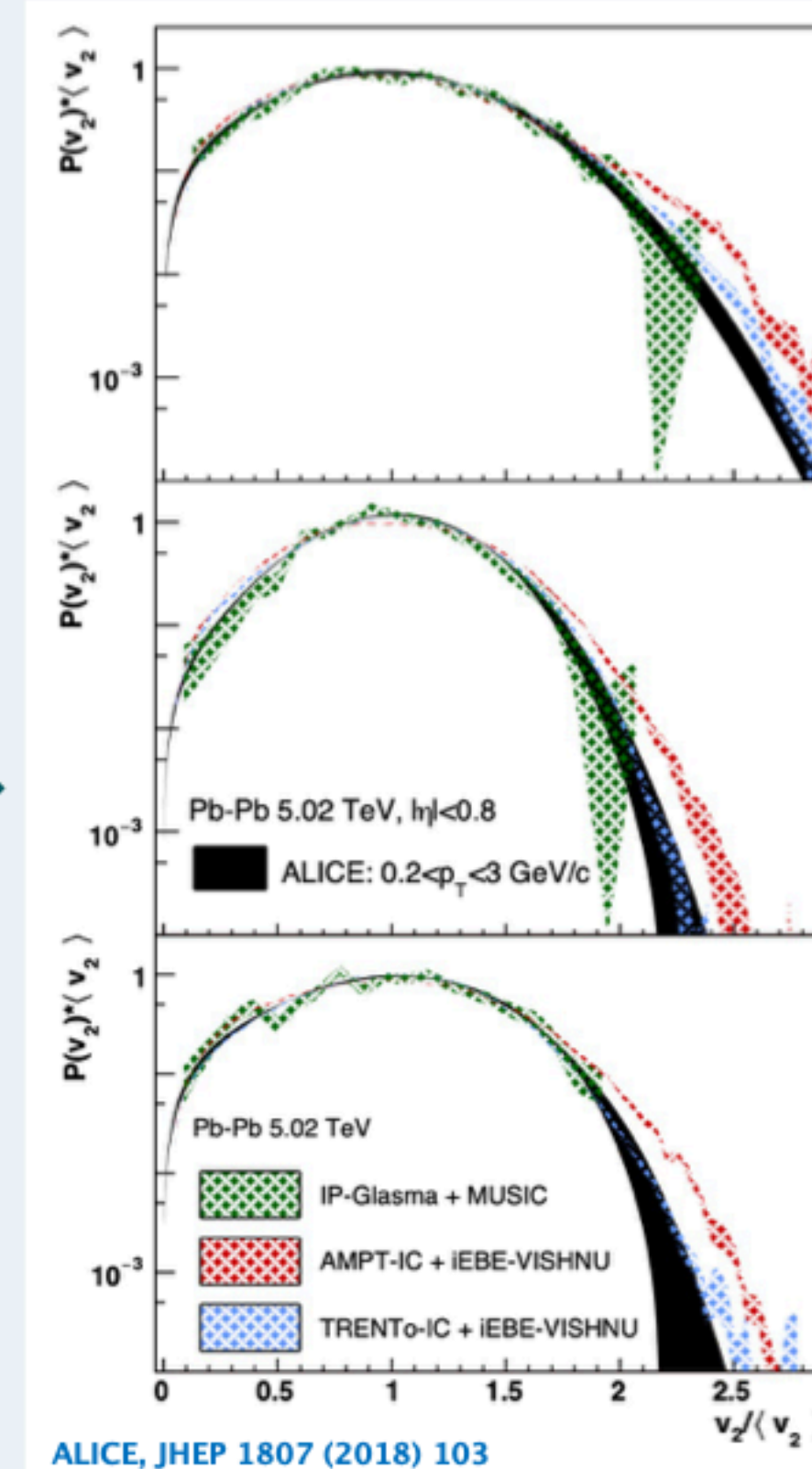


$$P(v_2) = \frac{2\alpha v_2}{k_2^2} \left(1 - \frac{v_2^2}{k_2^2}\right)^{\alpha-1} \left(1 - \frac{v_2 \varepsilon_0}{k_2}\right)^{-1-2\alpha} (1 - \varepsilon_0^2)^{\alpha+\frac{1}{2}} {}_2F_1\left(\frac{1}{2}, 1 + 2\alpha; 1, \frac{2v_2 \varepsilon_0}{v_2 \varepsilon_0 - k_2}\right)$$

$$\alpha \gg 1 \wedge \varepsilon_0 \ll 1$$

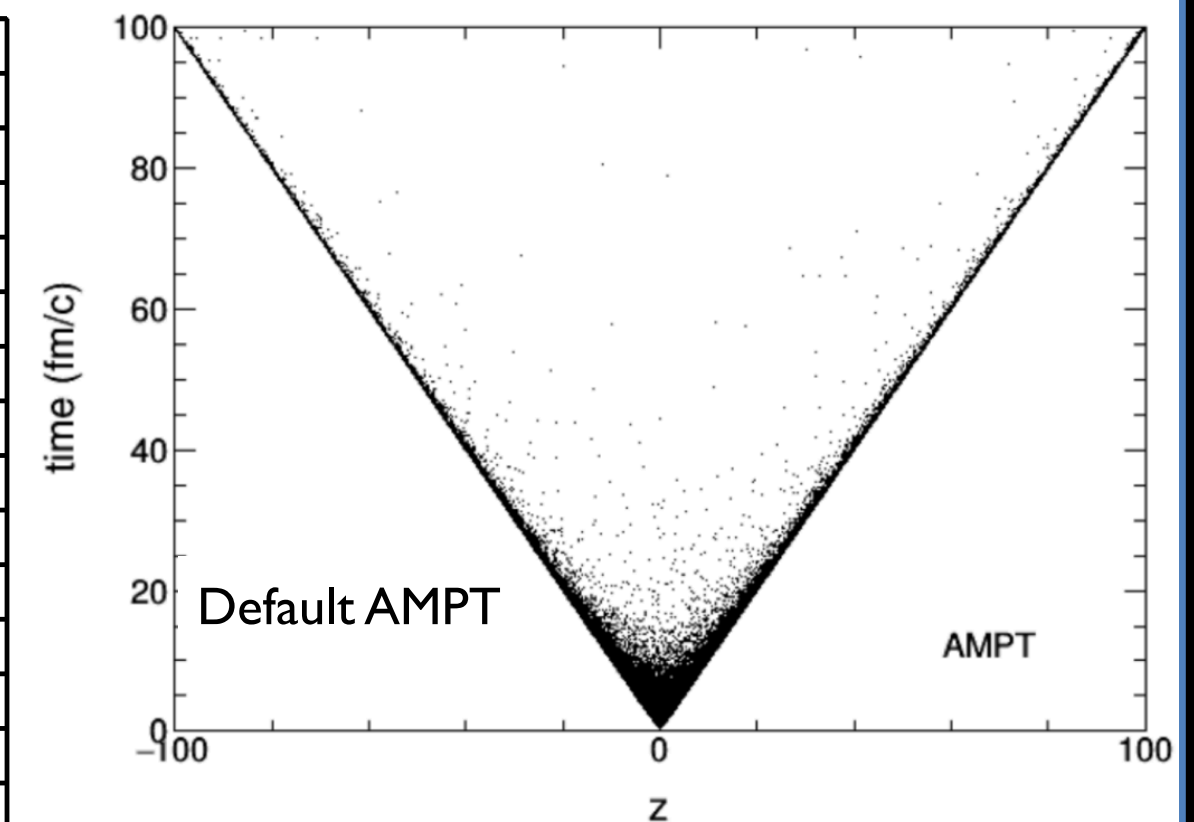
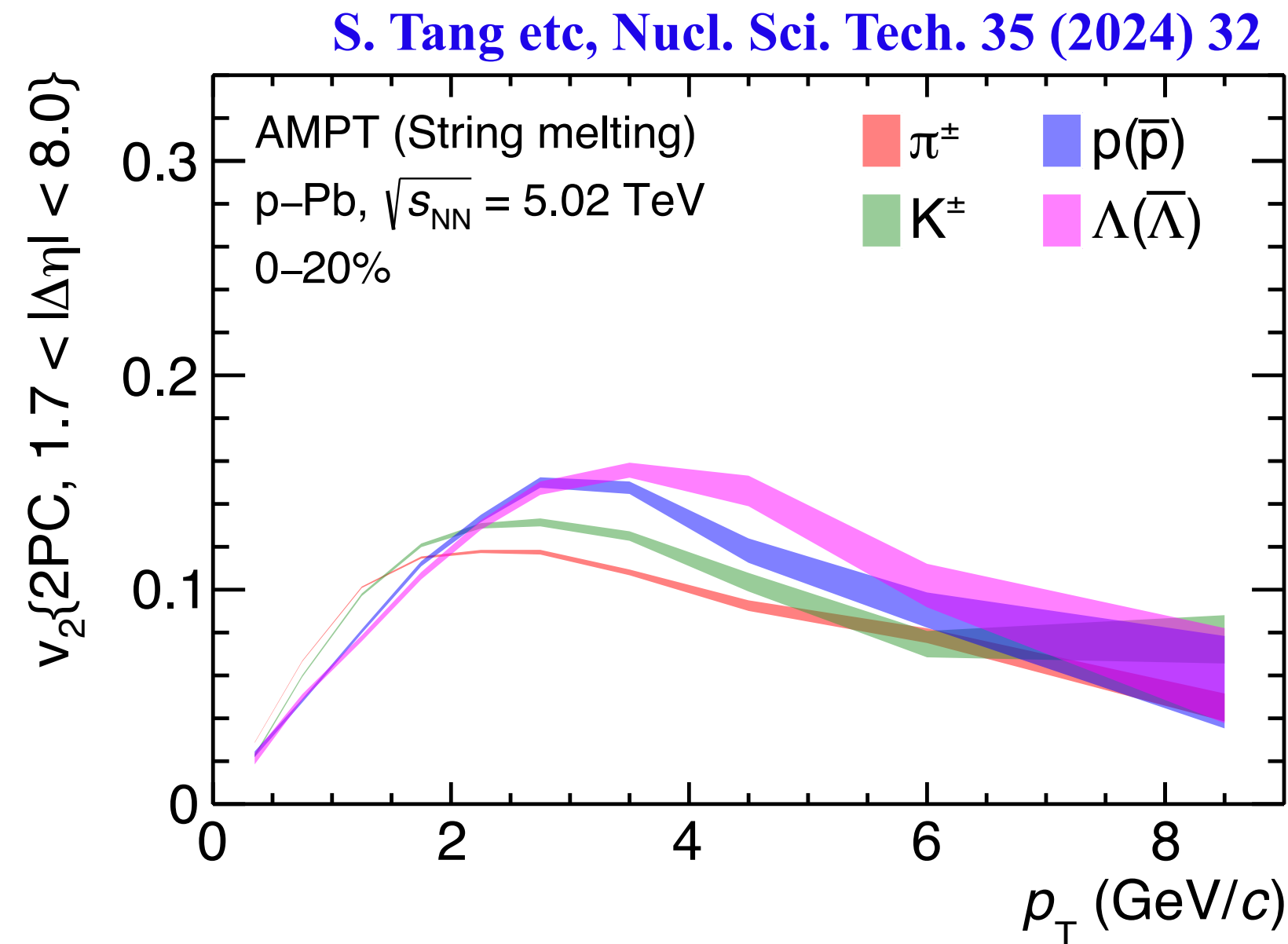
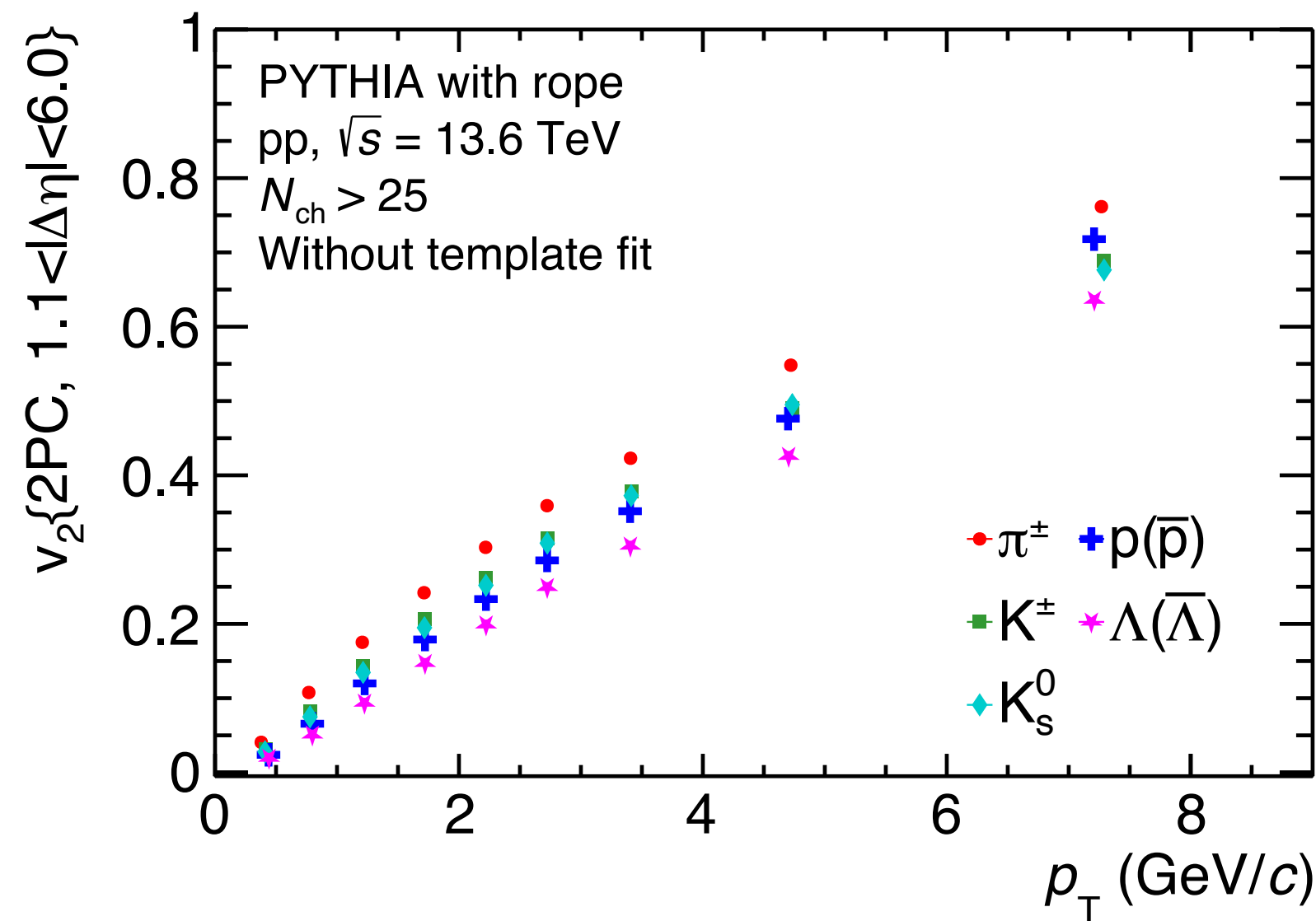
$$P(v_2) = \frac{2\alpha v_2}{k_2^2} \exp\left(-\alpha \frac{v_2^2 + k_2^2 \varepsilon_0^2}{k_2^2}\right) I_0\left(\frac{2\alpha \varepsilon_0 \varepsilon_2}{k_2}\right)$$

Bessel-Gaussian function



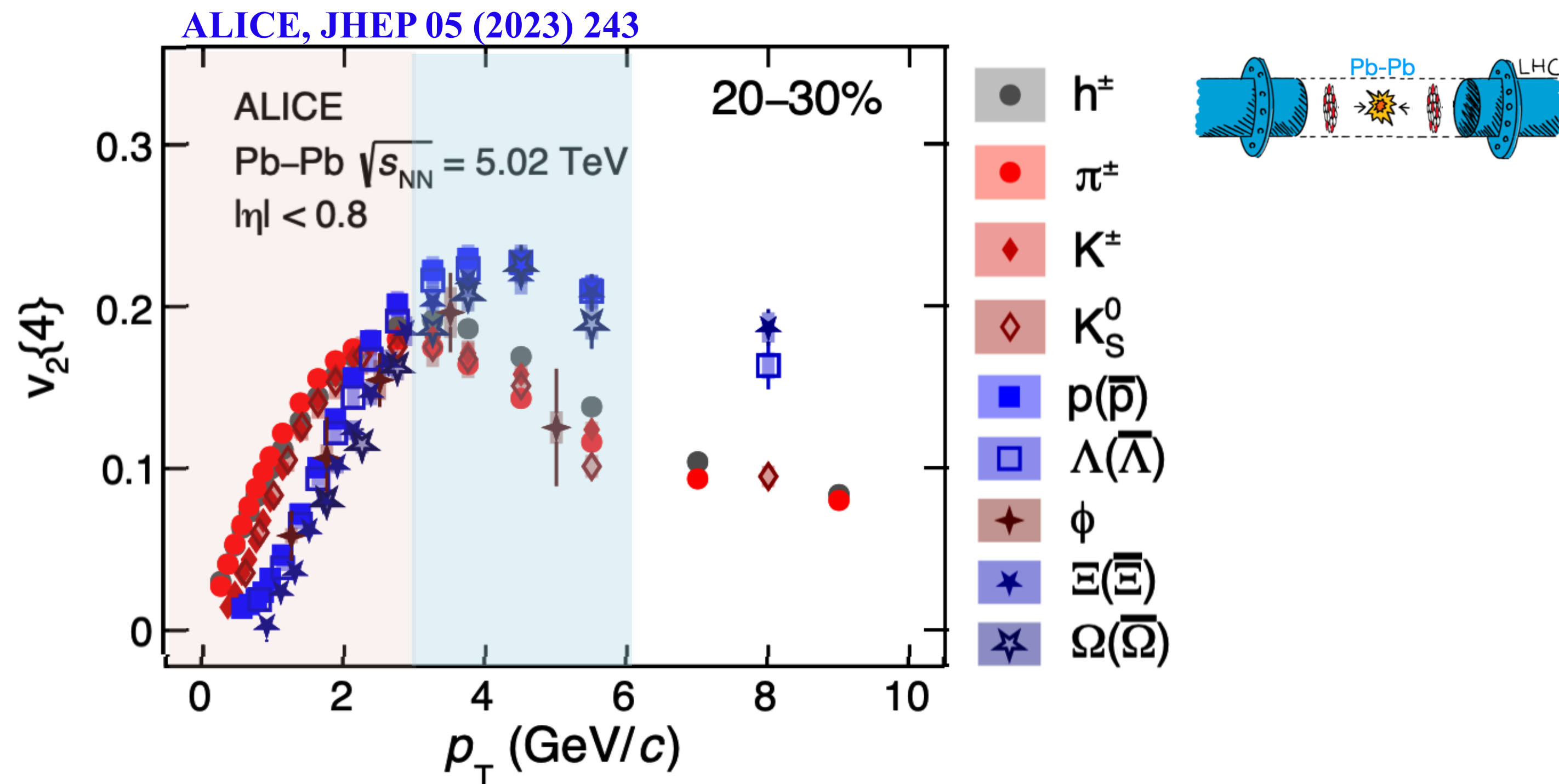


# Dense partonic matter (?)



- ❖ PYTHIA with rope, which well explains the *strangeness enhancement without QGP formation*, fails to predict the baryon/meson splitting and grouping, similar for UrQMD -> **Importance of partonic matter**
- ❖ Transport model with coalescence (AMPT) predicts only mass dependence.
  - Even using same quark-coalescence code, AMPT fails to reproduce the baryon/meson grouping and splitting. -> System is too diluted to have a sufficient quark-coalescence.
- ❖ Further suggests that one needs **dense partonic matter with quark-coalescence** to reproduce the data.

# Partonic flow in Pb-Pb collisions

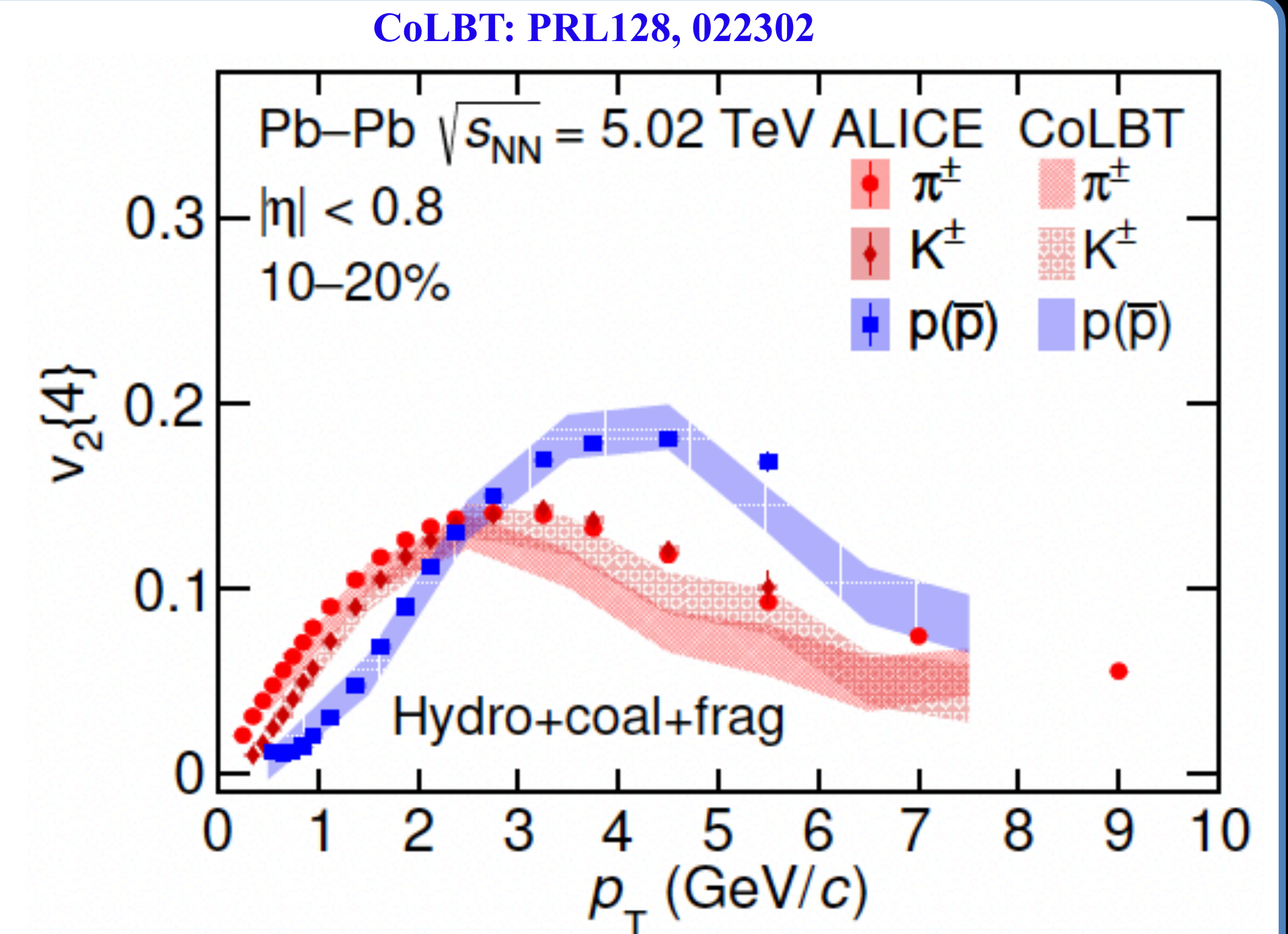
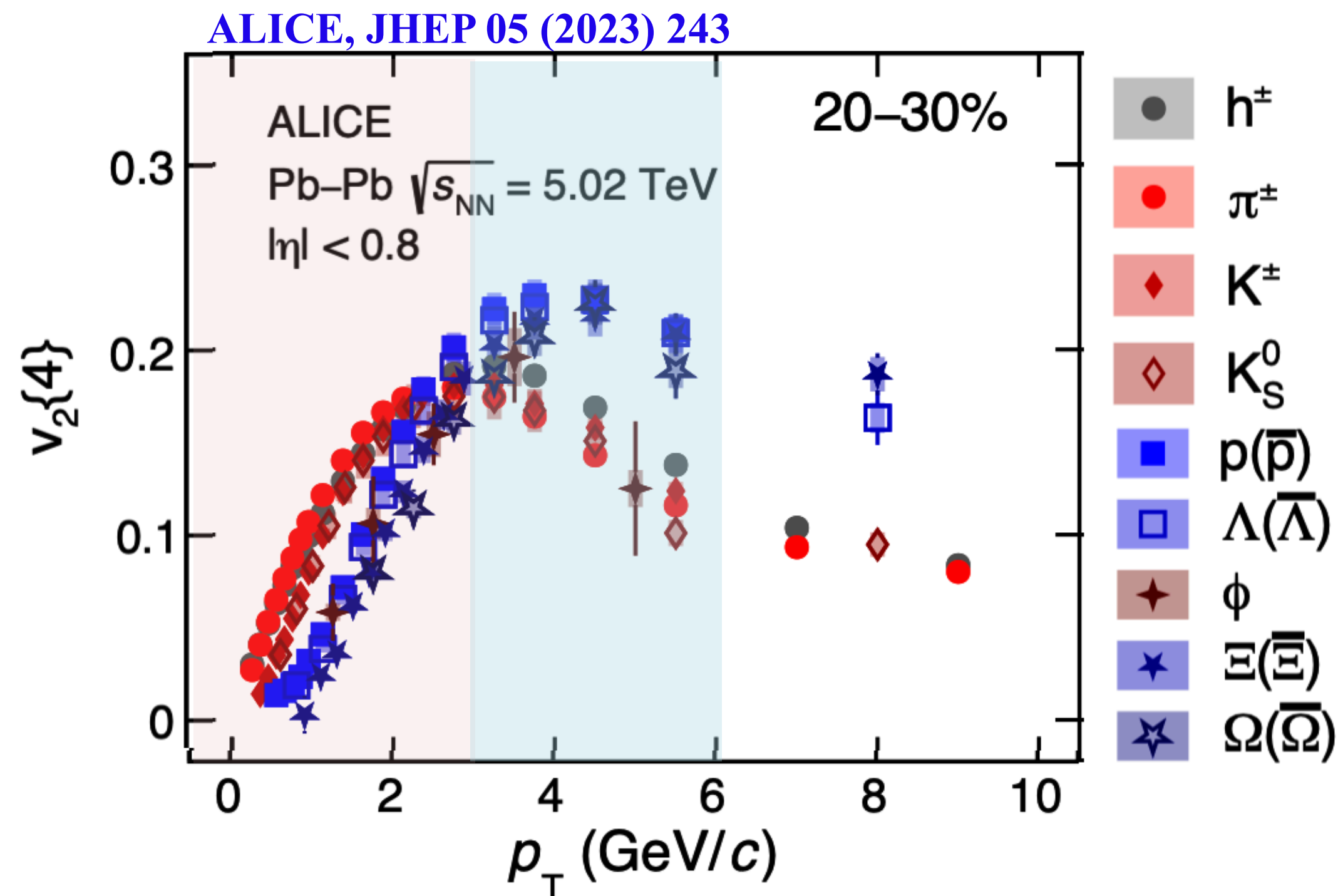


## ❖ **Partonic flow** in Pb-Pb.

- low  $p_T$  ( $p_T < 3$  GeV/c) - Mass ordering.
- Intermediate  $p_T$  ( $3 < p_T < 6$  GeV/c)
  - Baryon-meson grouping ( $\sim 1\sigma$  confidence)
  - Splitting between baryons and mesons  $v_2$  ( $> 5\sigma$  confidence)
  - **Smoking gun evidence of partonic flow in Pb-Pb**



# Partonic flow in Pb-Pb collisions

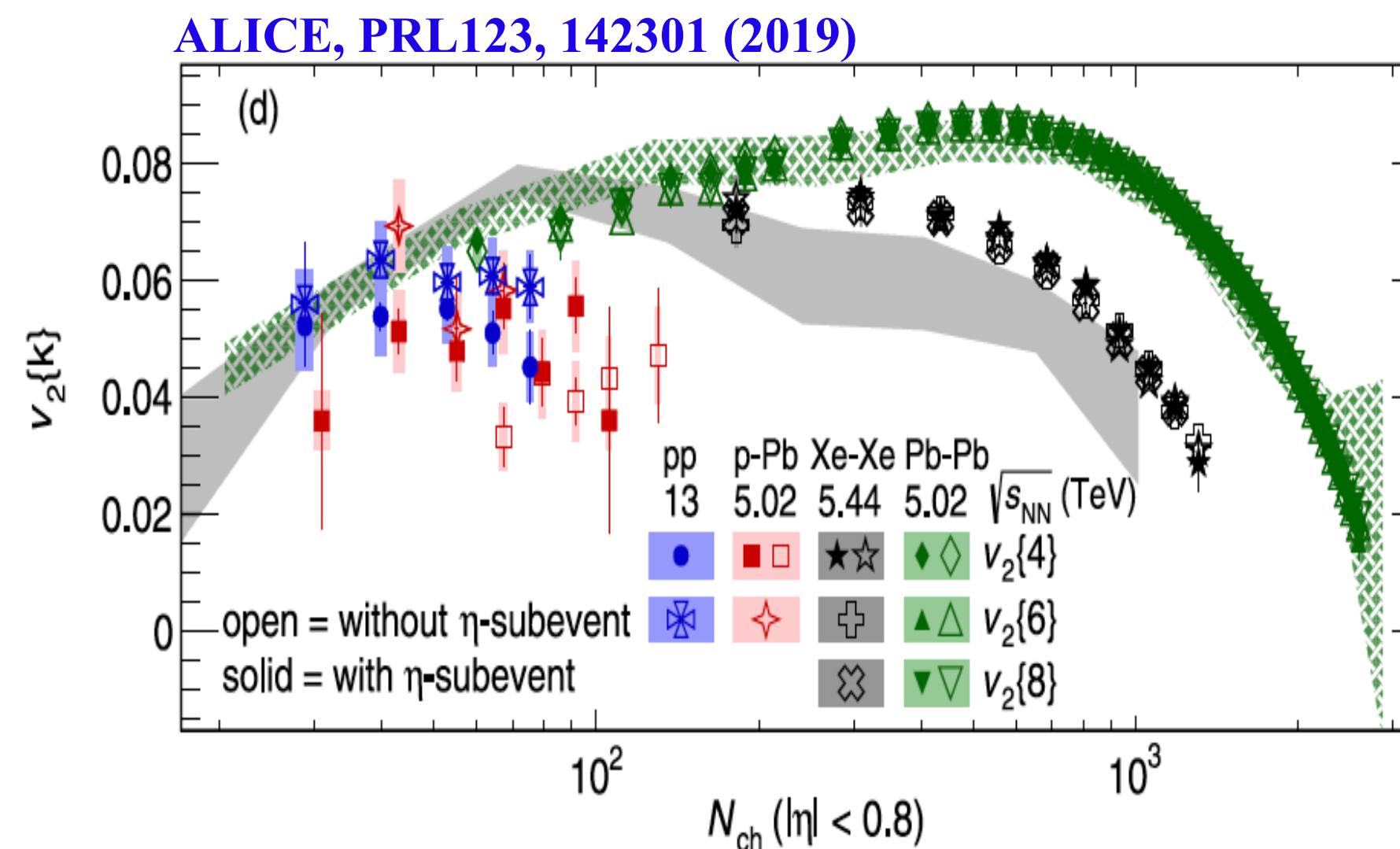
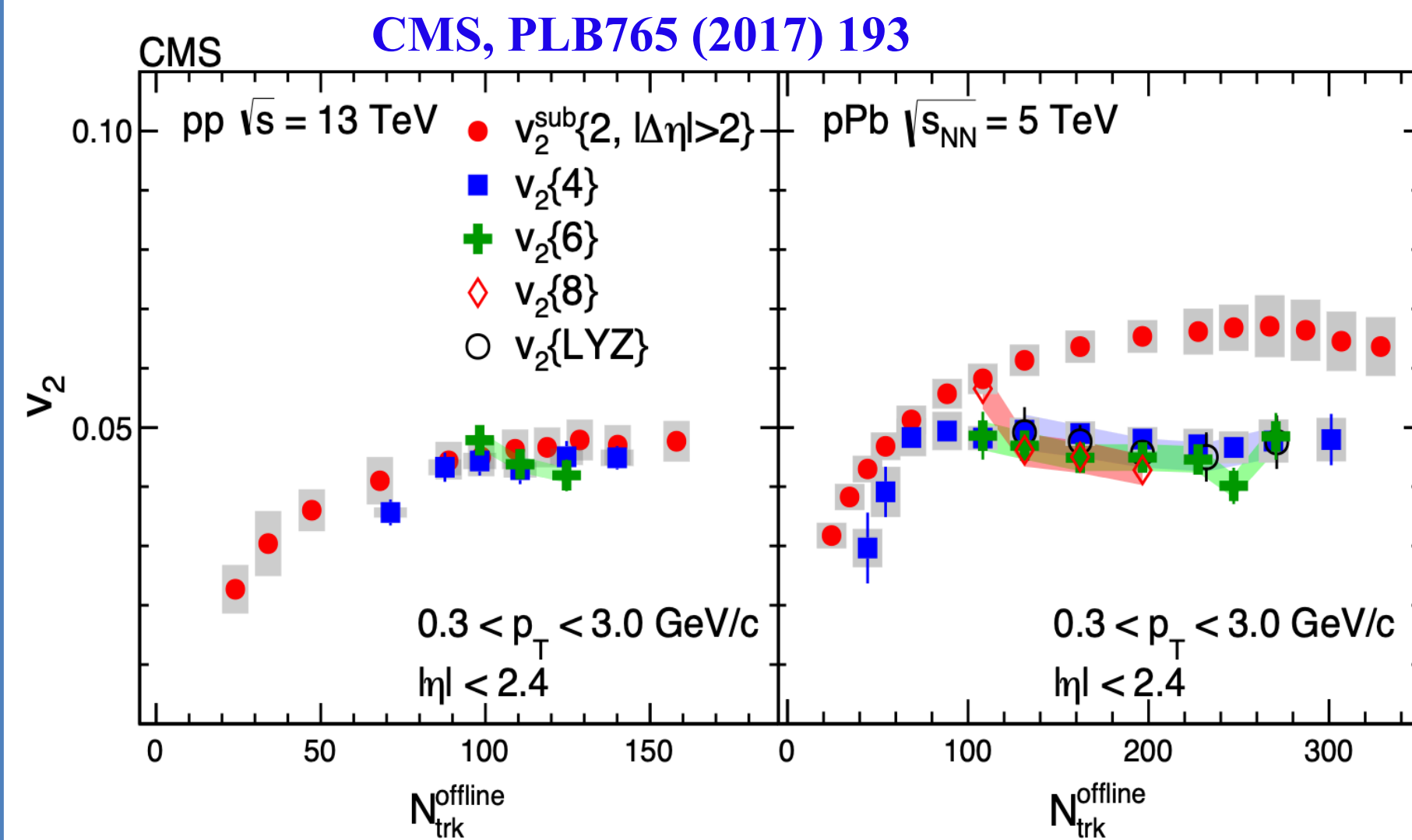


❖ **Partonic flow** in Pb-Pb. Well described by the model with hydro and quark-coalescence

- low  $p_T$  ( $p_T < 3$  GeV/c) - Mass ordering.
- Intermediate  $p_T$  ( $3 < p_T < 6$  GeV/c)
  - Baryon-meson grouping ( $\sim 1\sigma$  confidence)
  - Splitting between baryons and mesons  $v_2$  ( $> 5\sigma$  confidence)
  - **Smoking gun evidence of partonic flow in Pb-Pb**

# Working definition for small systems

## ❖ Working definition: Long-Range Multi-particle correlations

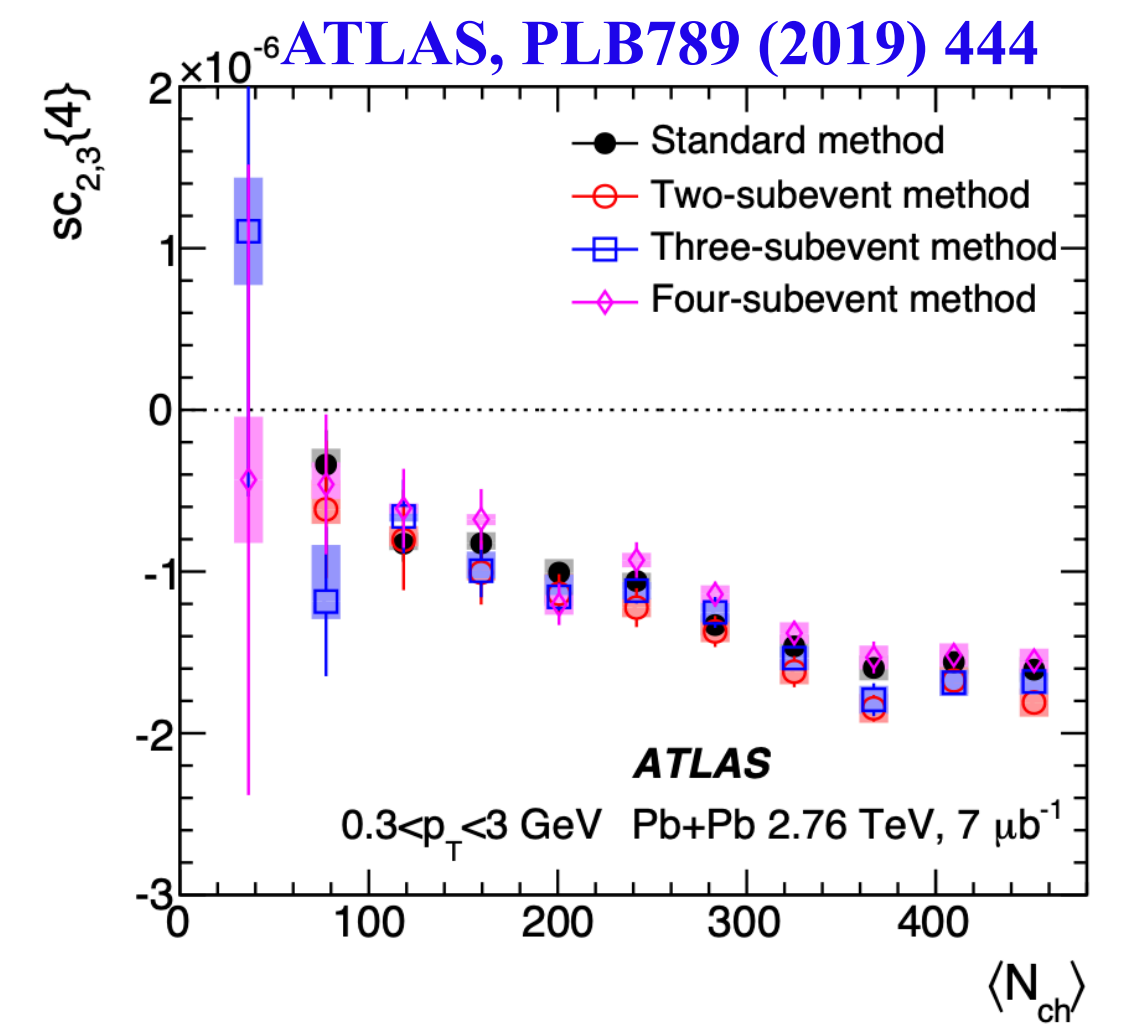
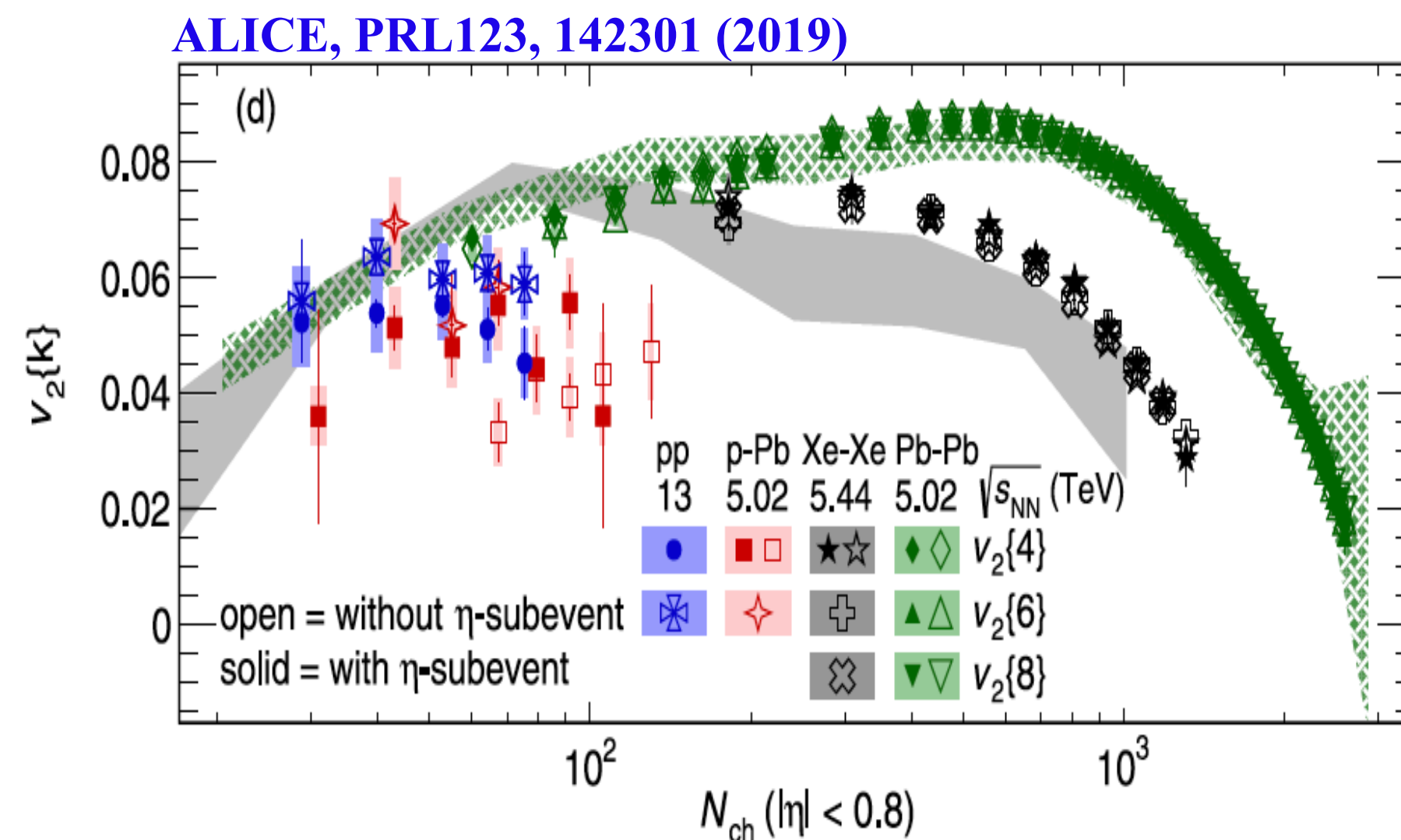
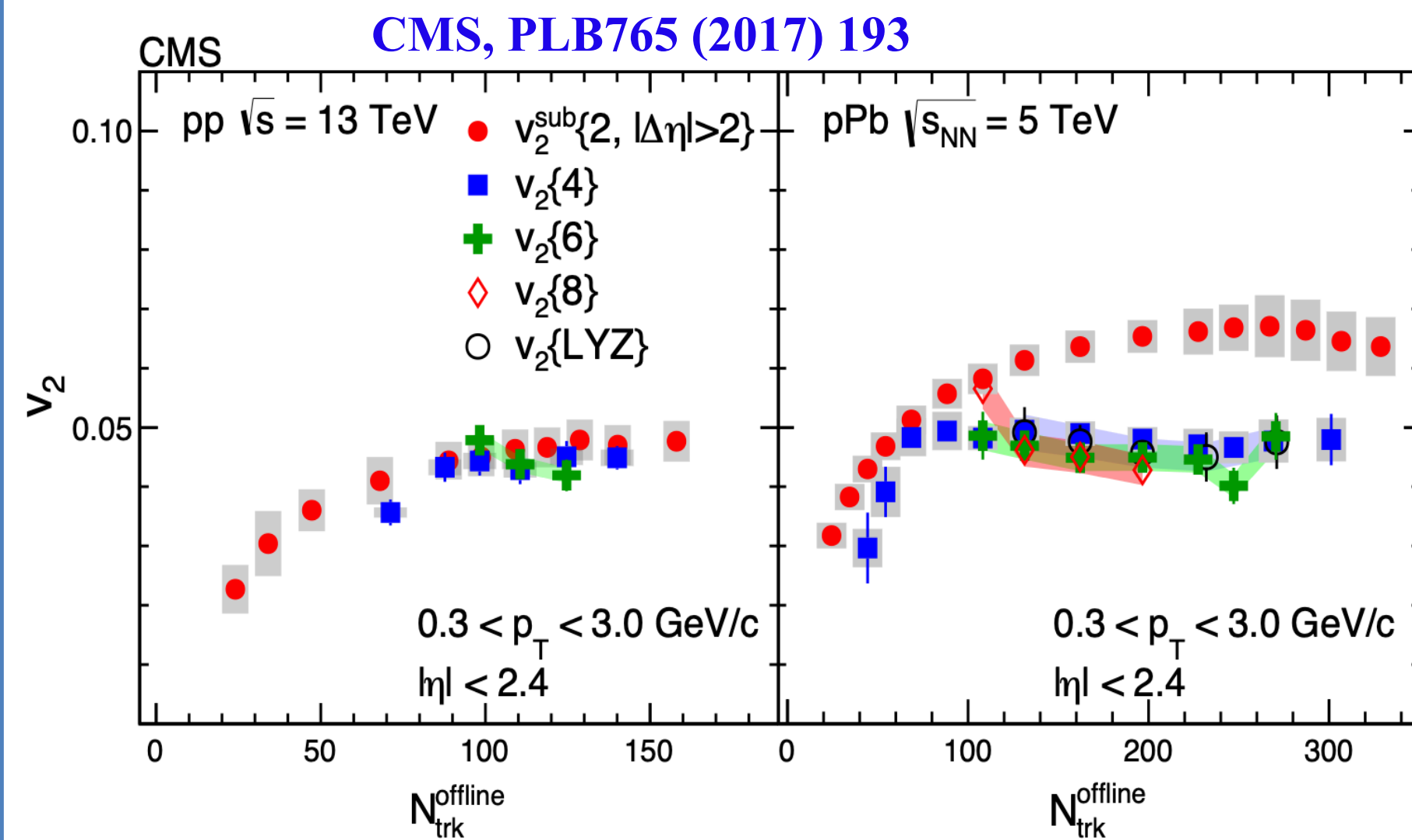


- Multi-particle correlations:  $v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$



# Working definition for small systems

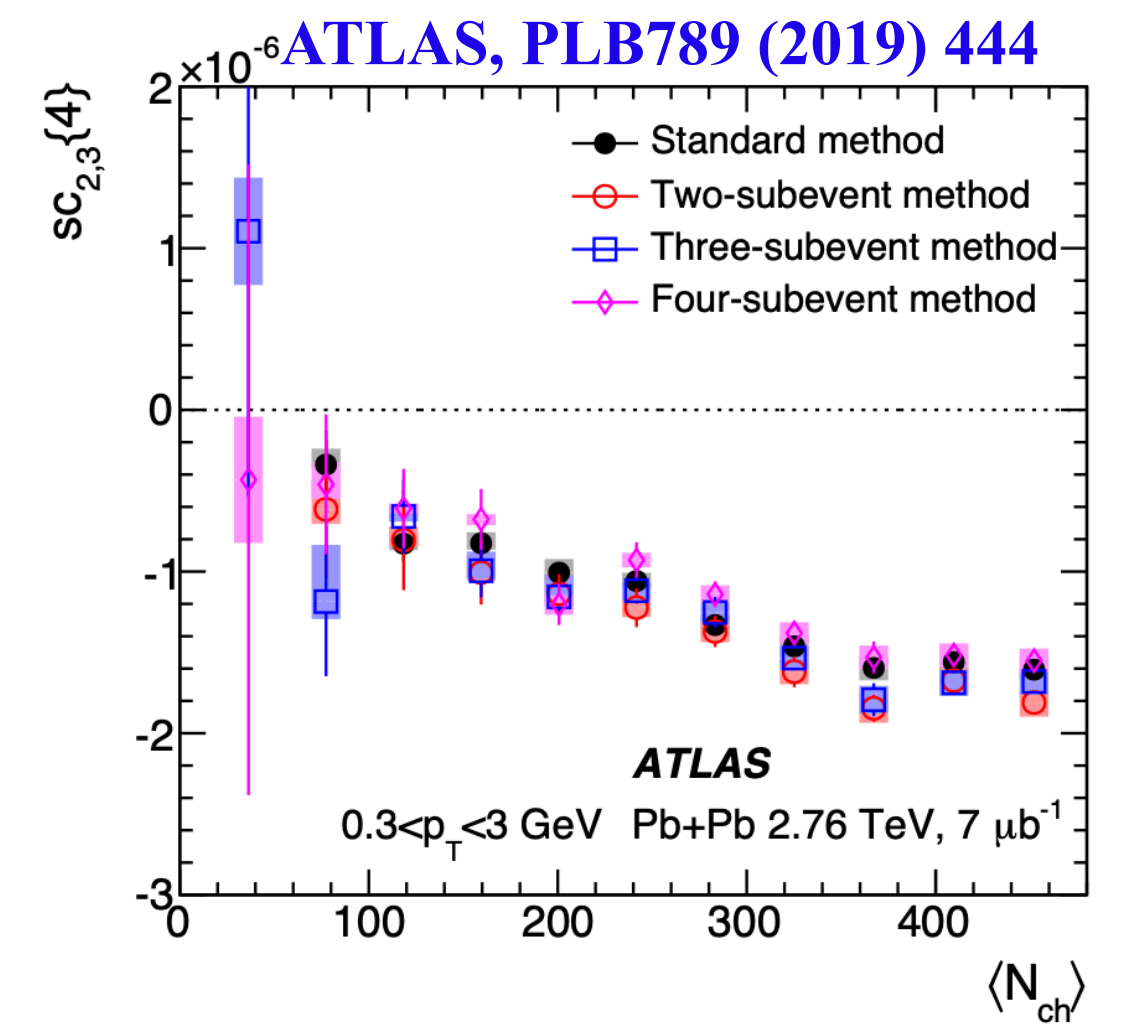
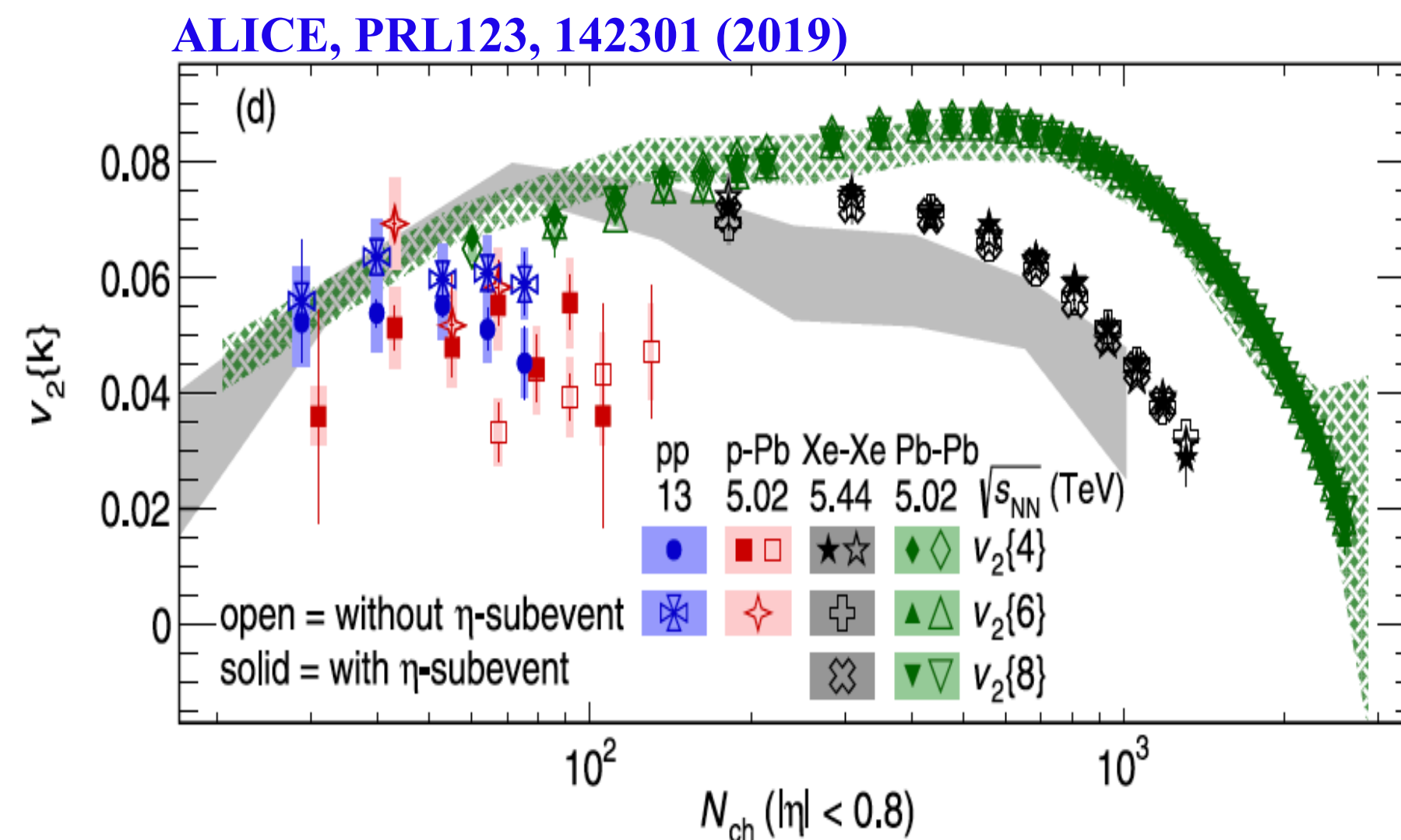
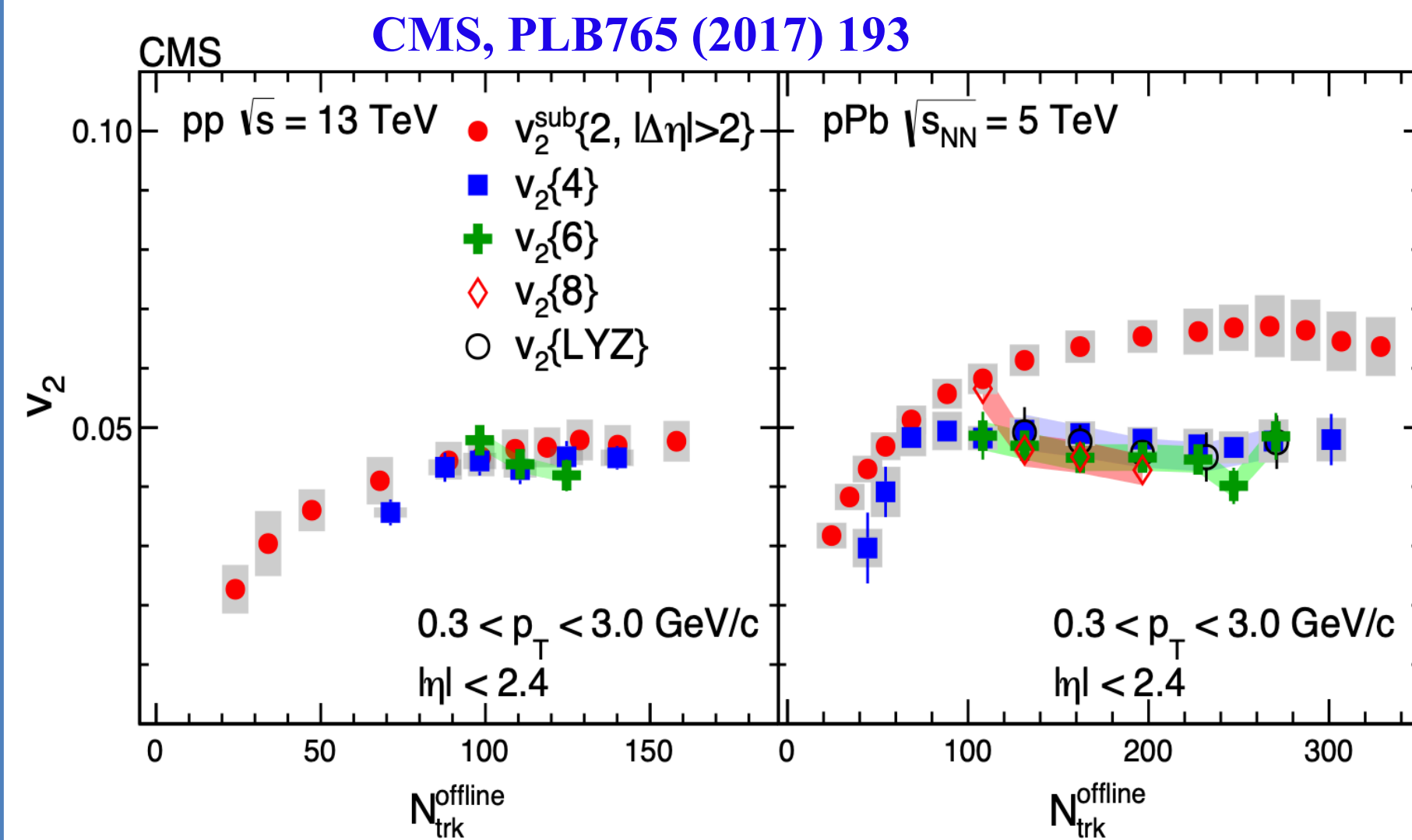
## ❖ Working definition: Long-Range Multi-particle correlations



- Multi-particle correlations:  $v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$
- Long-range: Compatible results with two-sub, three-sub and four-subevent methods

# Working definition for small systems

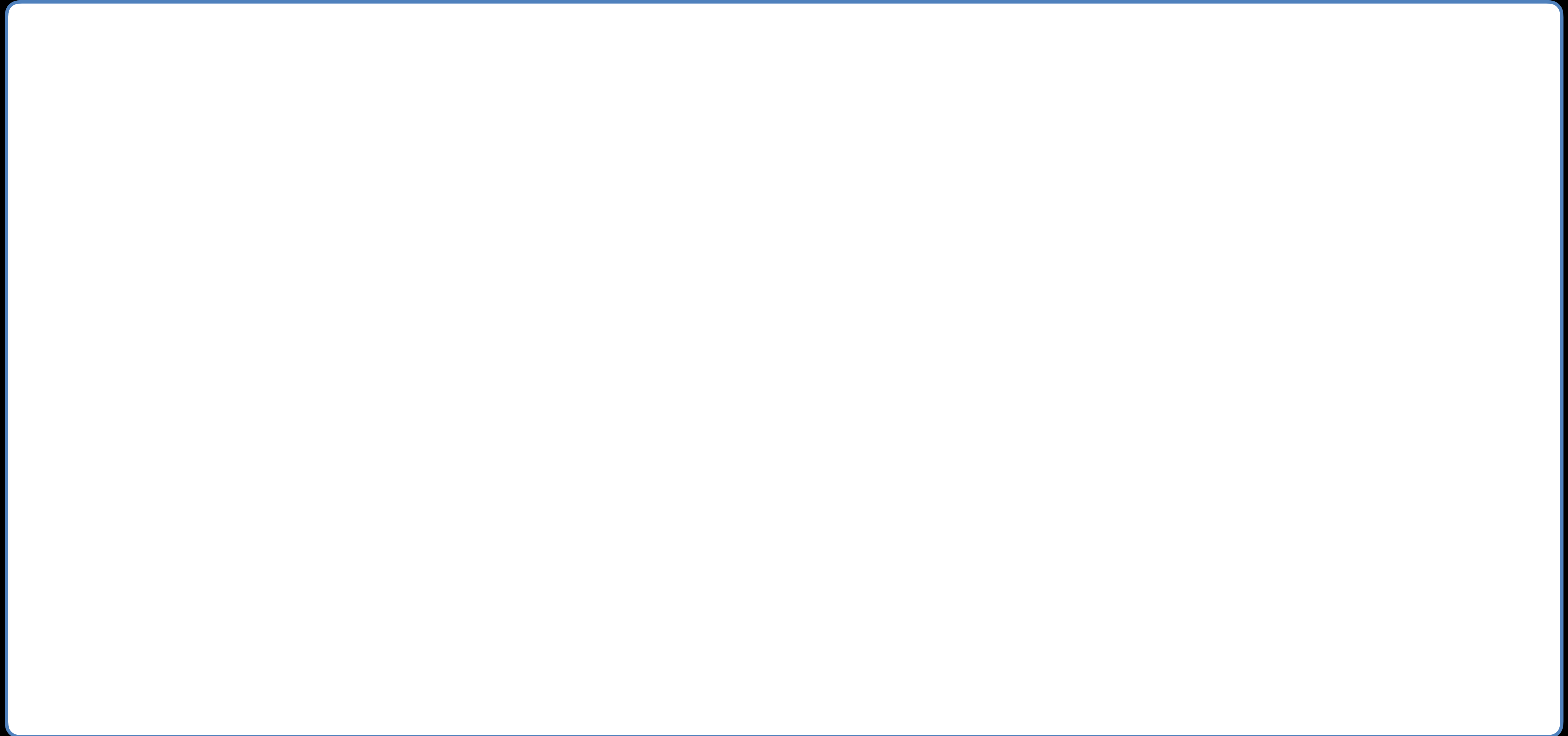
## ❖ Working definition: Long-Range Multi-particle correlations



- Multi-particle correlations:  $v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$
- Long-range: Compatible results with two-sub, three-sub and four-subevent methods
- Evidence of flow in small collisions systems at the LHC



# Working definition for small systems



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❖ How about **2**-particle (di-hadron) correlations?

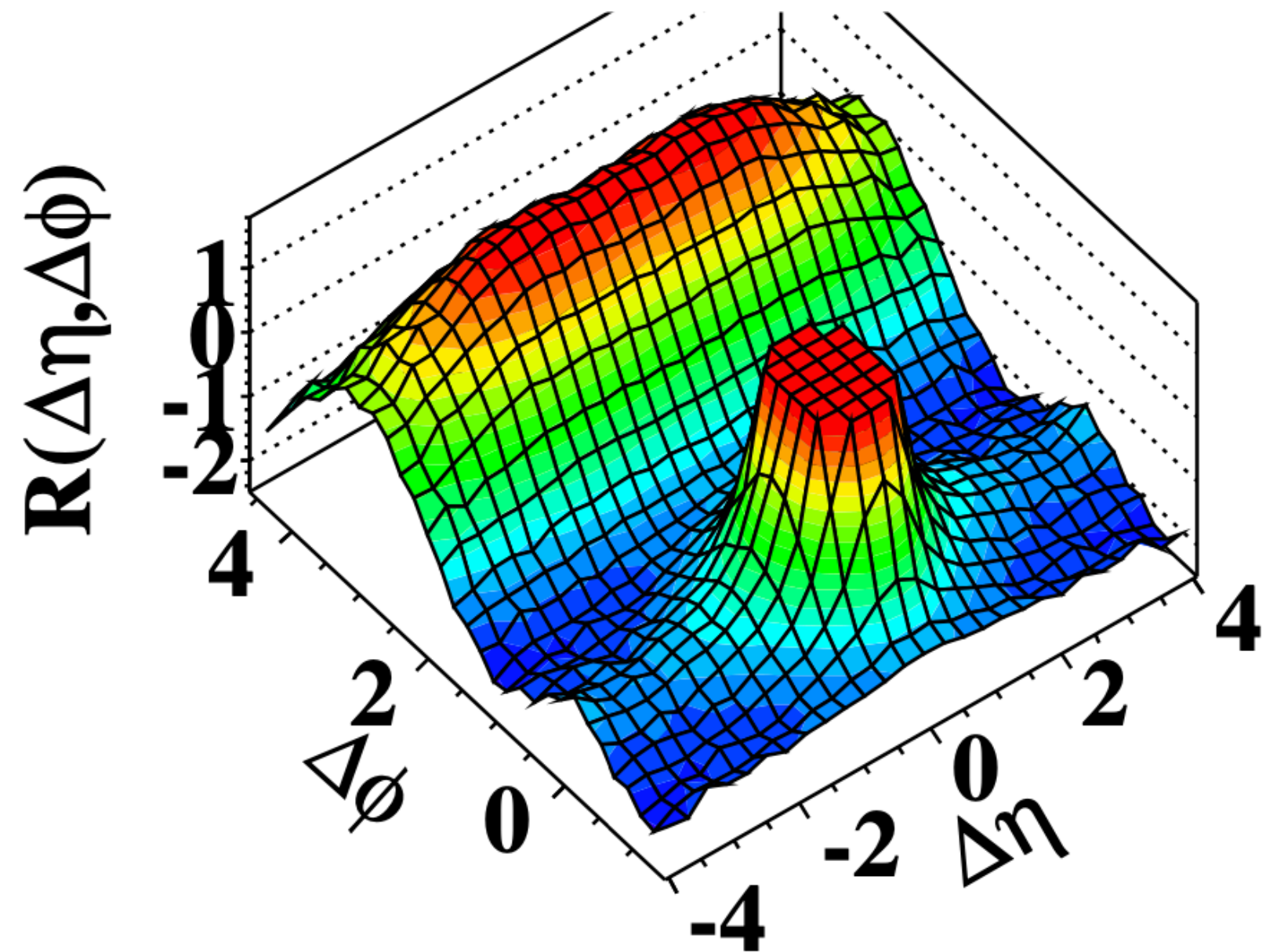


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CMS, JHEP 09 (2010) 091

(d) CMS  $N \geq 110$ ,  $1.0 \text{ GeV}/c < p_T < 3.0 \text{ GeV}/c$

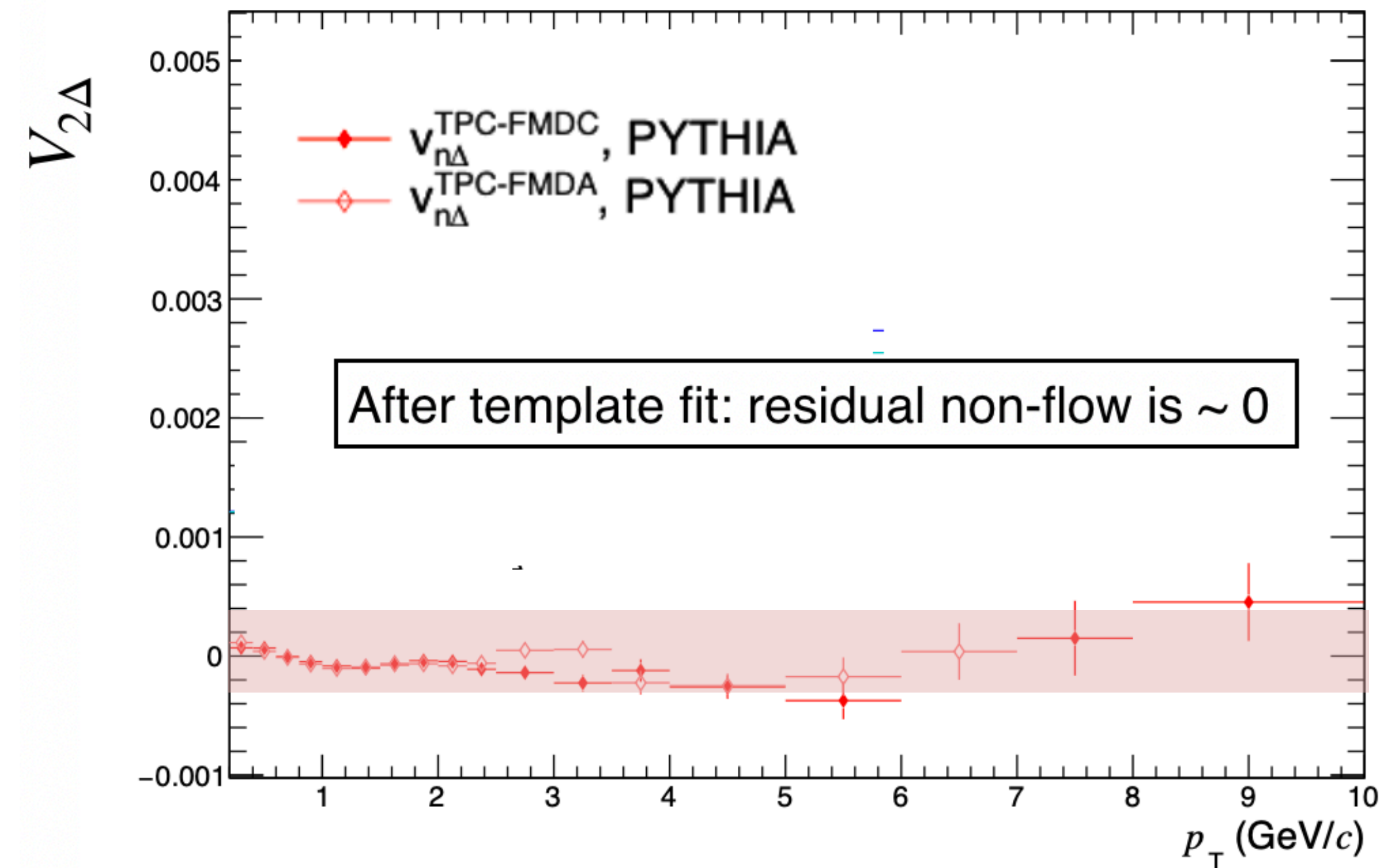
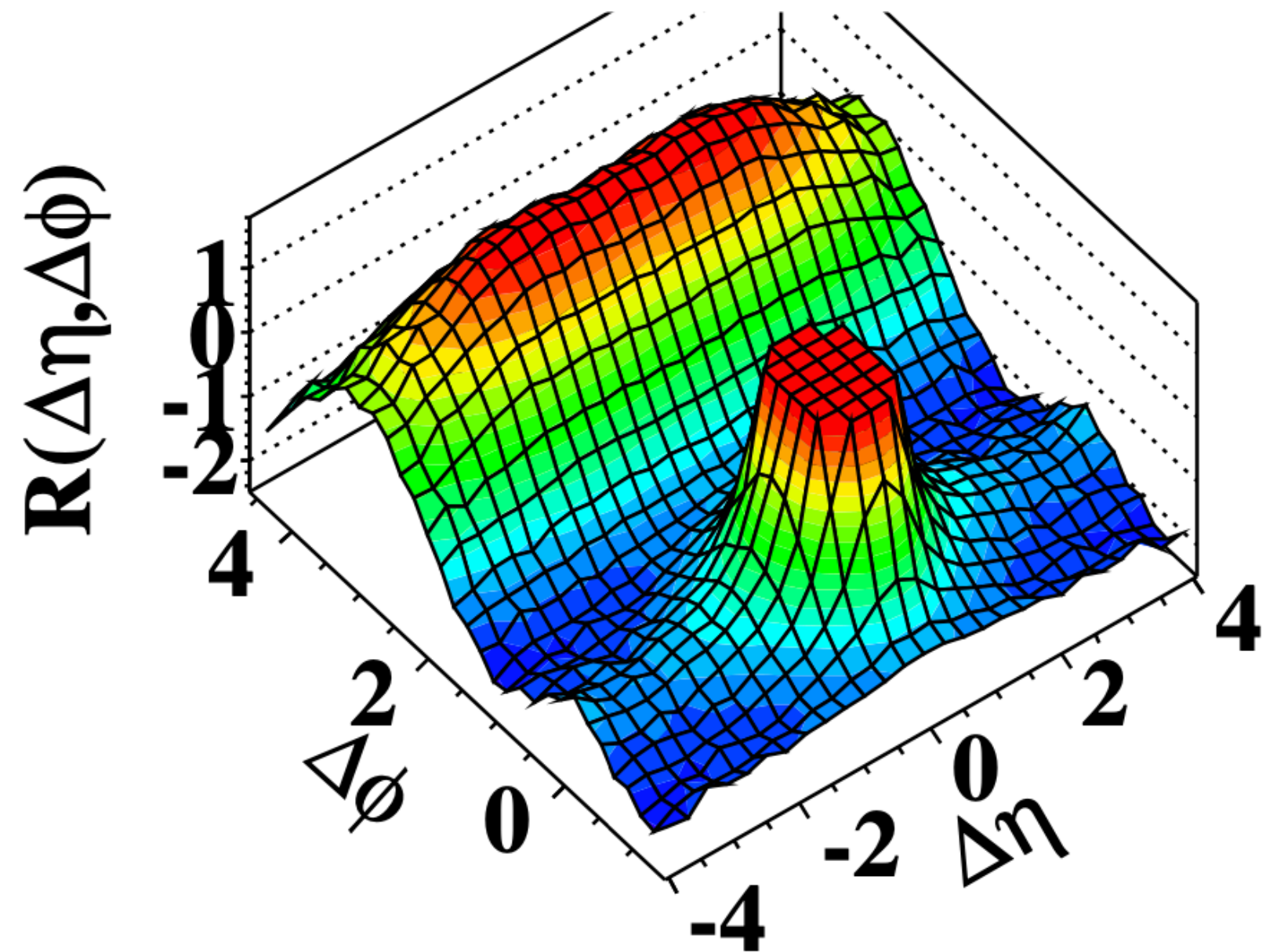


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- The 2-particle correlations in the **nonflow** model, after subtraction, are compatible with zero (necessary conditions)