Brookhaven National Laboratory

20 years of RHIC

What do the measurements at the LHC say about the collectivity in small collision systems

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CTU
CZECH TECHNICAL UNIVERSITY IN PRAGUE

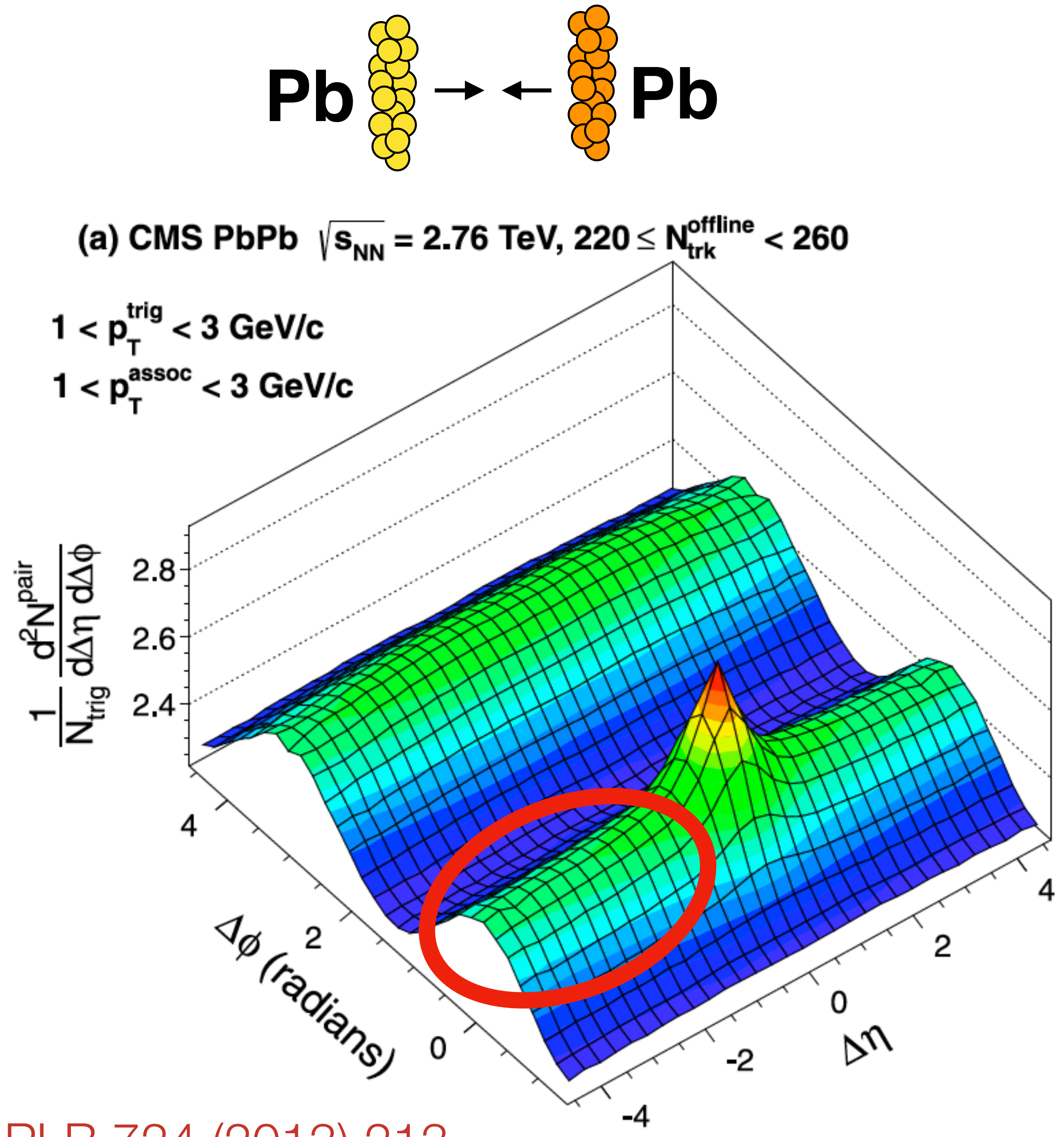
RHIC & AGS AUM Small System Workshop
22th October 2020

Supported by the Ministry of Education, Youth and Sports of the Czech Republic under grant „International Mobility of Researchers MSCA IF III at CTU in Prague"
CZ.02.2.69/0.0/0.0/16 027/0008465

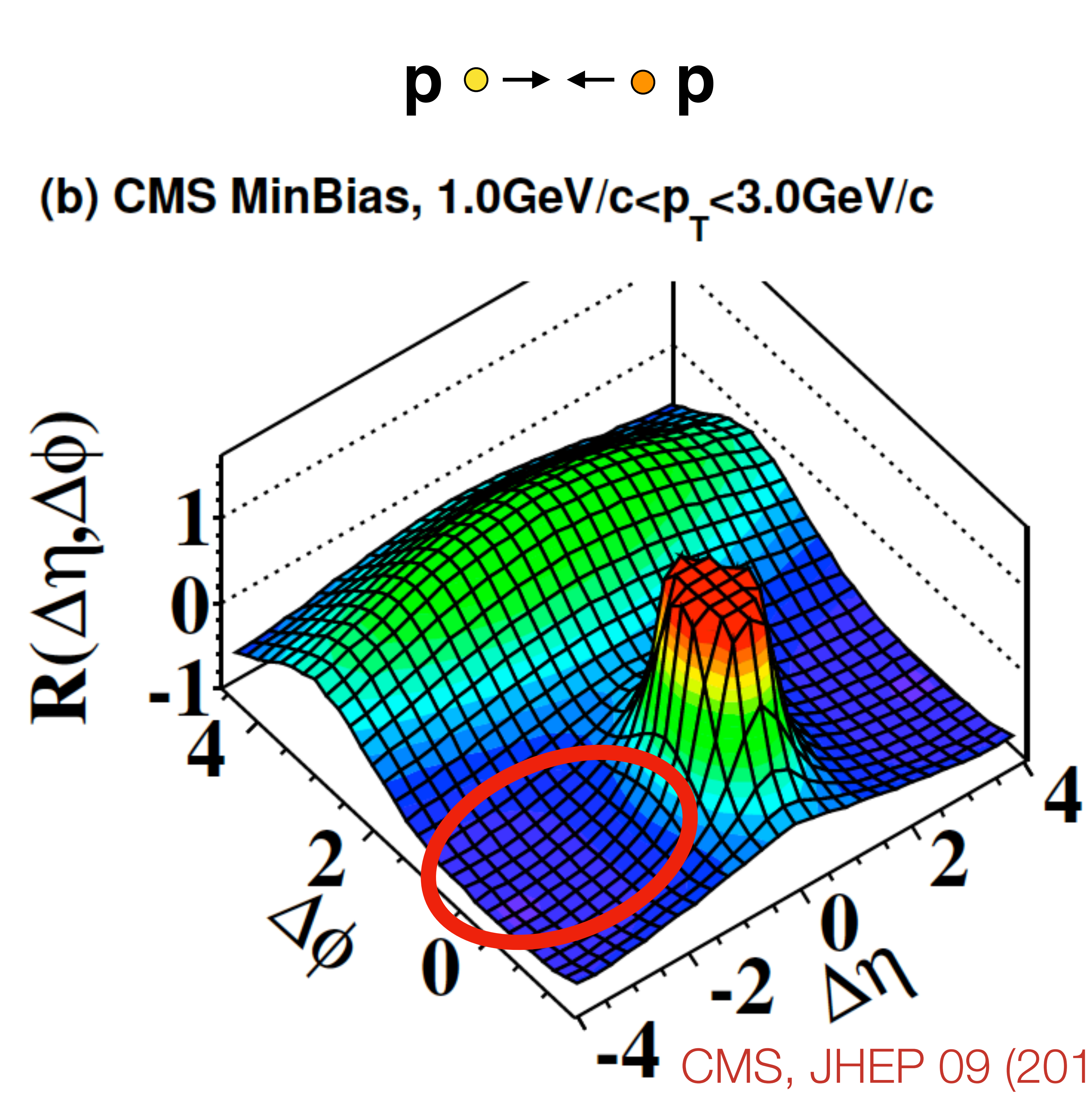
EVROPSKÁ UNIE
Evropské strukturální a investiční fondy
Operační program Výzkum, vývoj a vzdělávání

MINISTERSTVO ŠKOLSTVÍ, MLÁDEŽE A TĚLOVÝCHOVY

Small collision systems: the old picture



CMS, PLB 724 (2013) 213



CMS, JHEP 09 (2010) 091

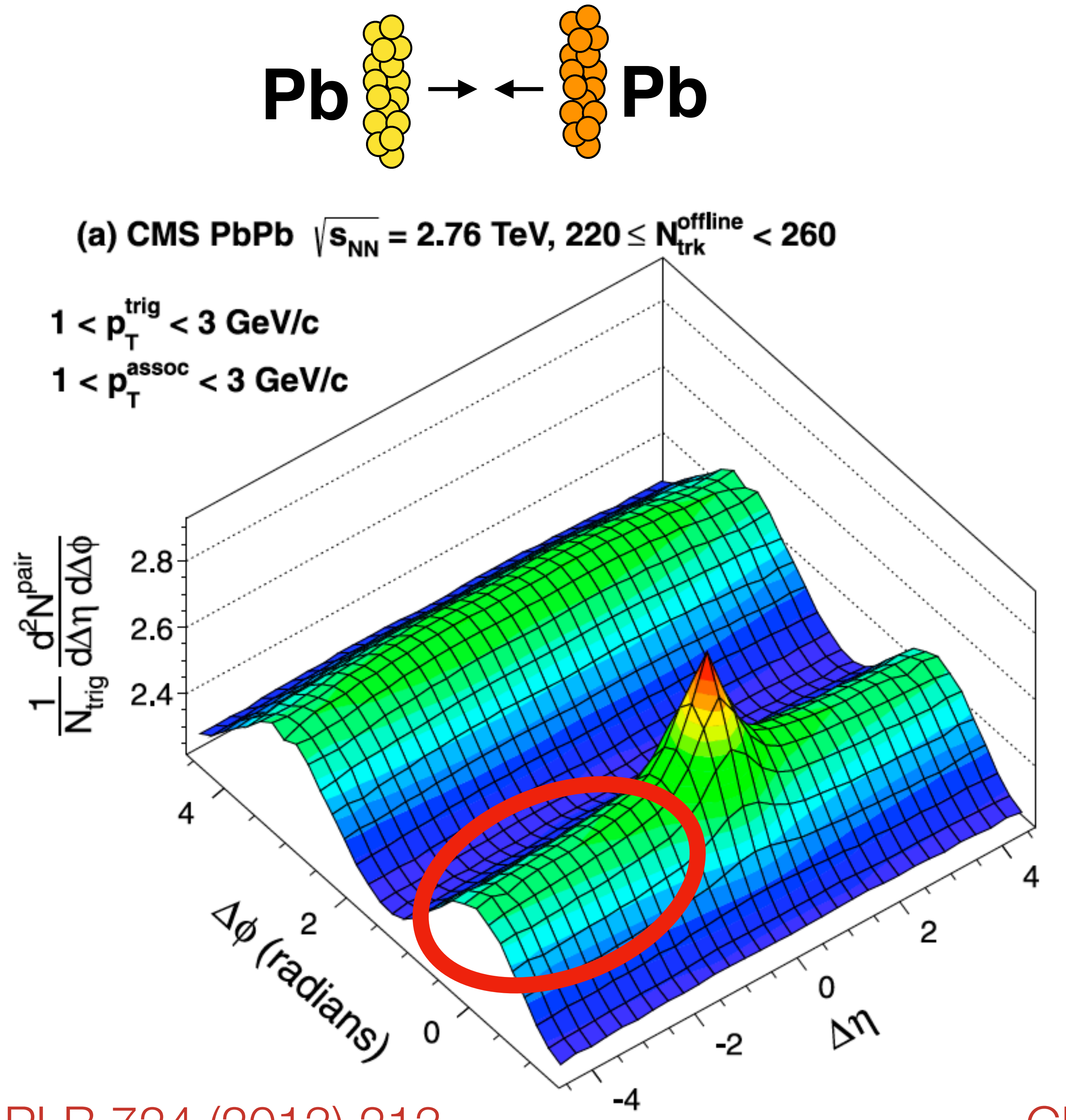
Large collision systems

- Long-range correlations
- Hydrodynamic flow

Small collision systems

- No long-range correlations
- No flow

Small collision systems: the new picture



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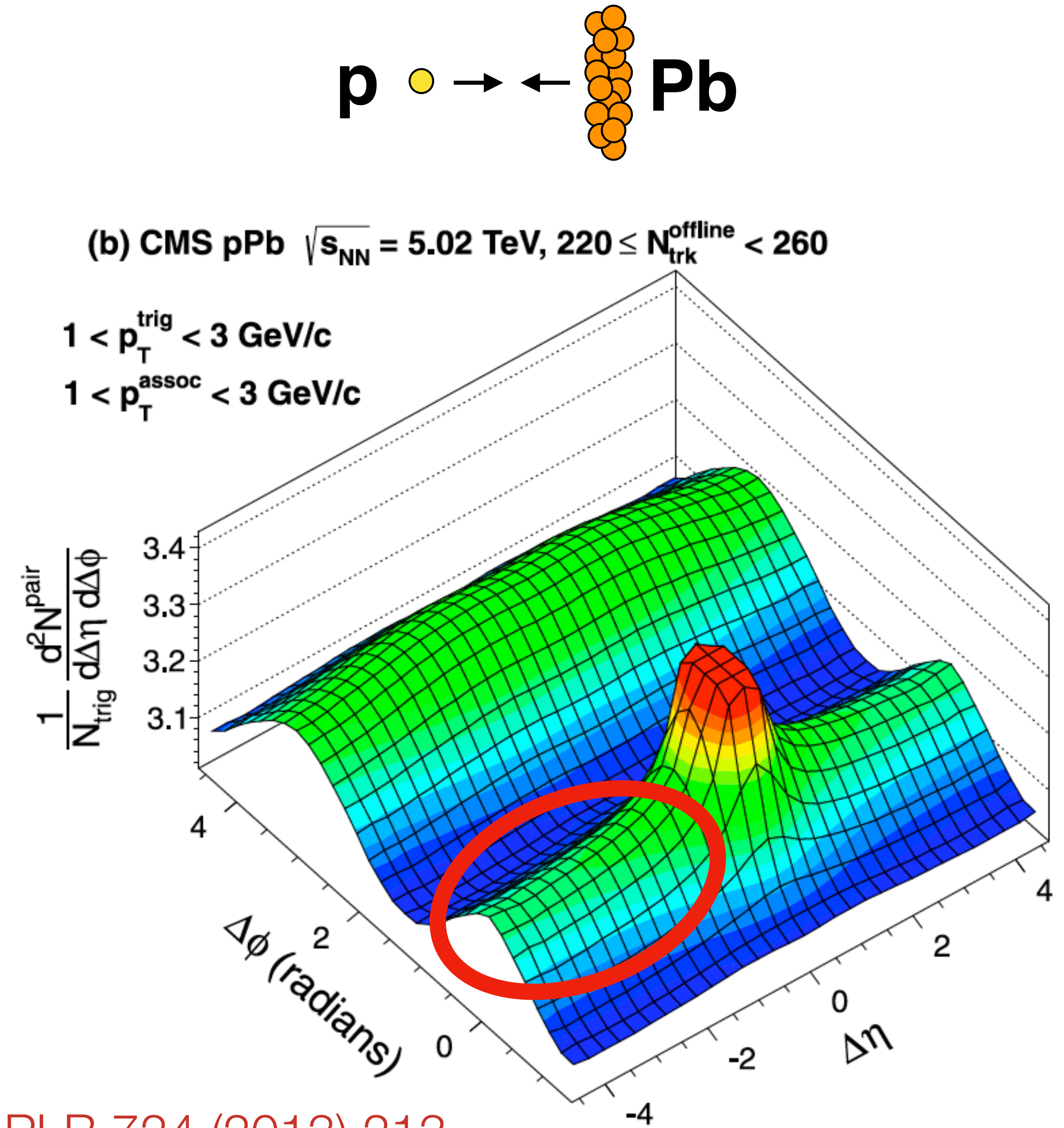

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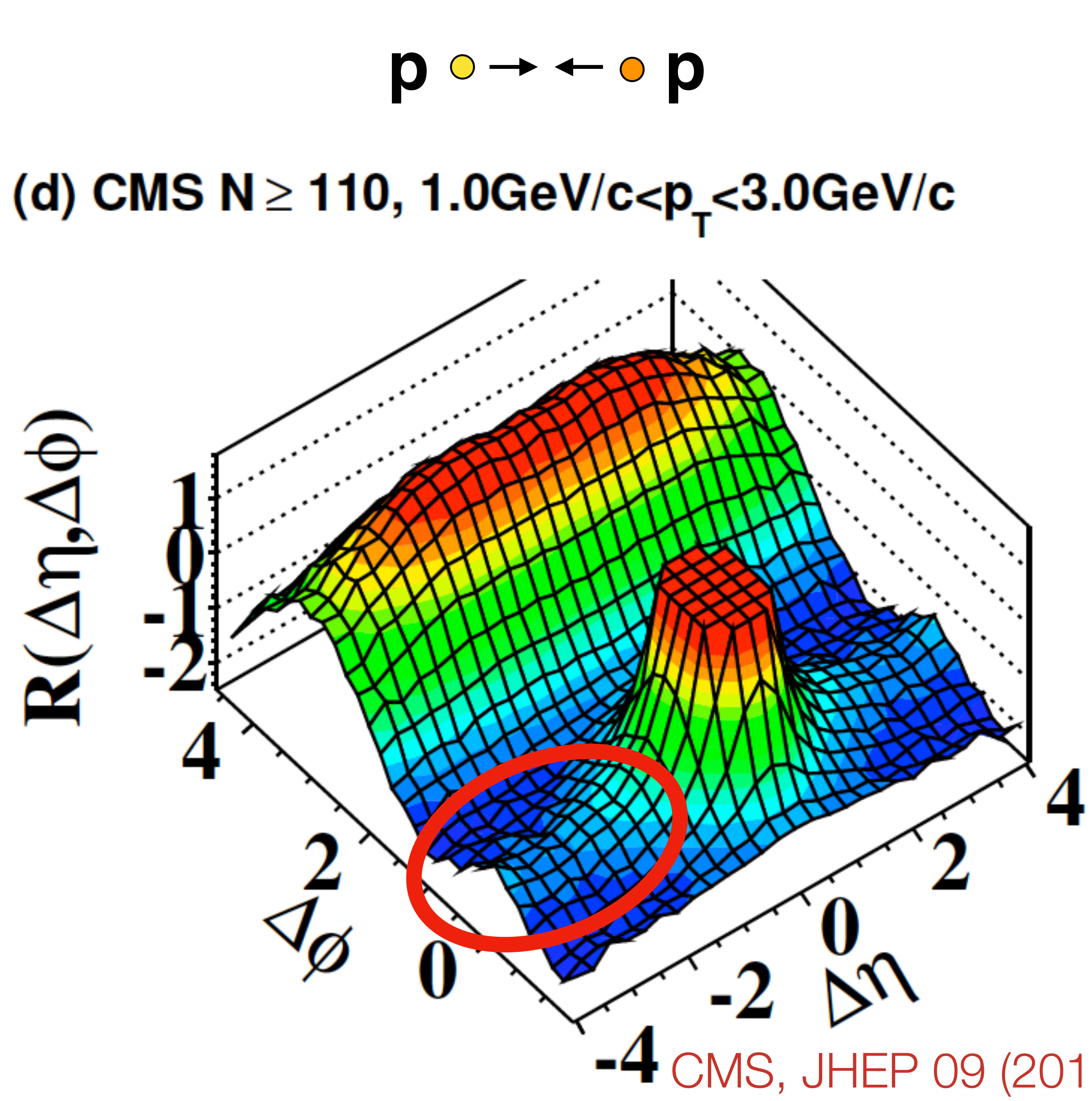


CMS, JHEP 09 (2010) 091

Large collision systems

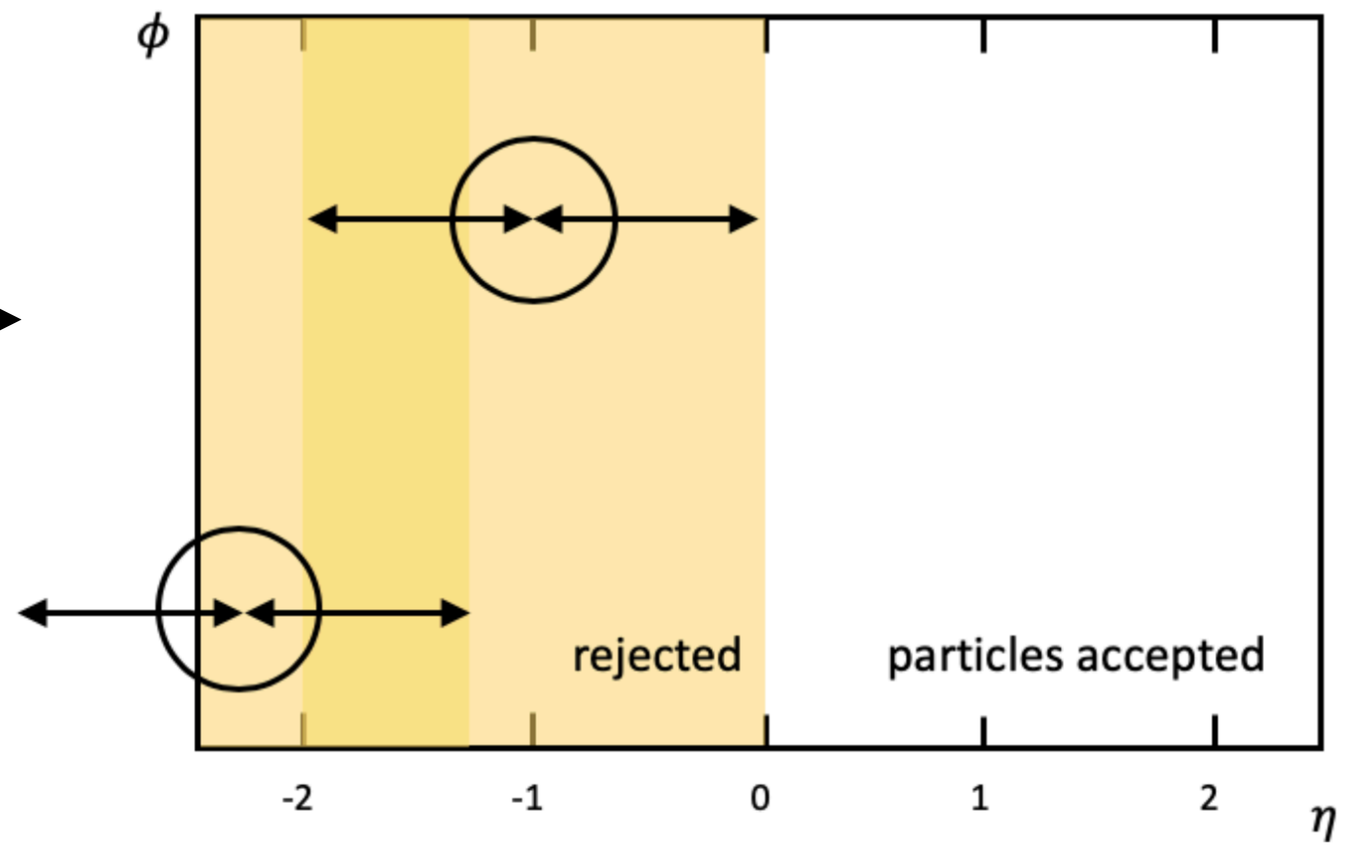
- Long-range correlations
- Hydrodynamic flow

High-multiplicity Small collision systems

- ~~No long-range correlations~~
- No flow
- Ridge observed in pp and p-Pb collisions

Sensitivity of the ridge to the presence of jets

- If the long-range ridge arises from hard or semi-hard processes:
  - Removing particles associated with jets may affect it
  - Selecting events with jets (while still removing particles associated with jets) may affect it



ATLAS-CONF-2020-018

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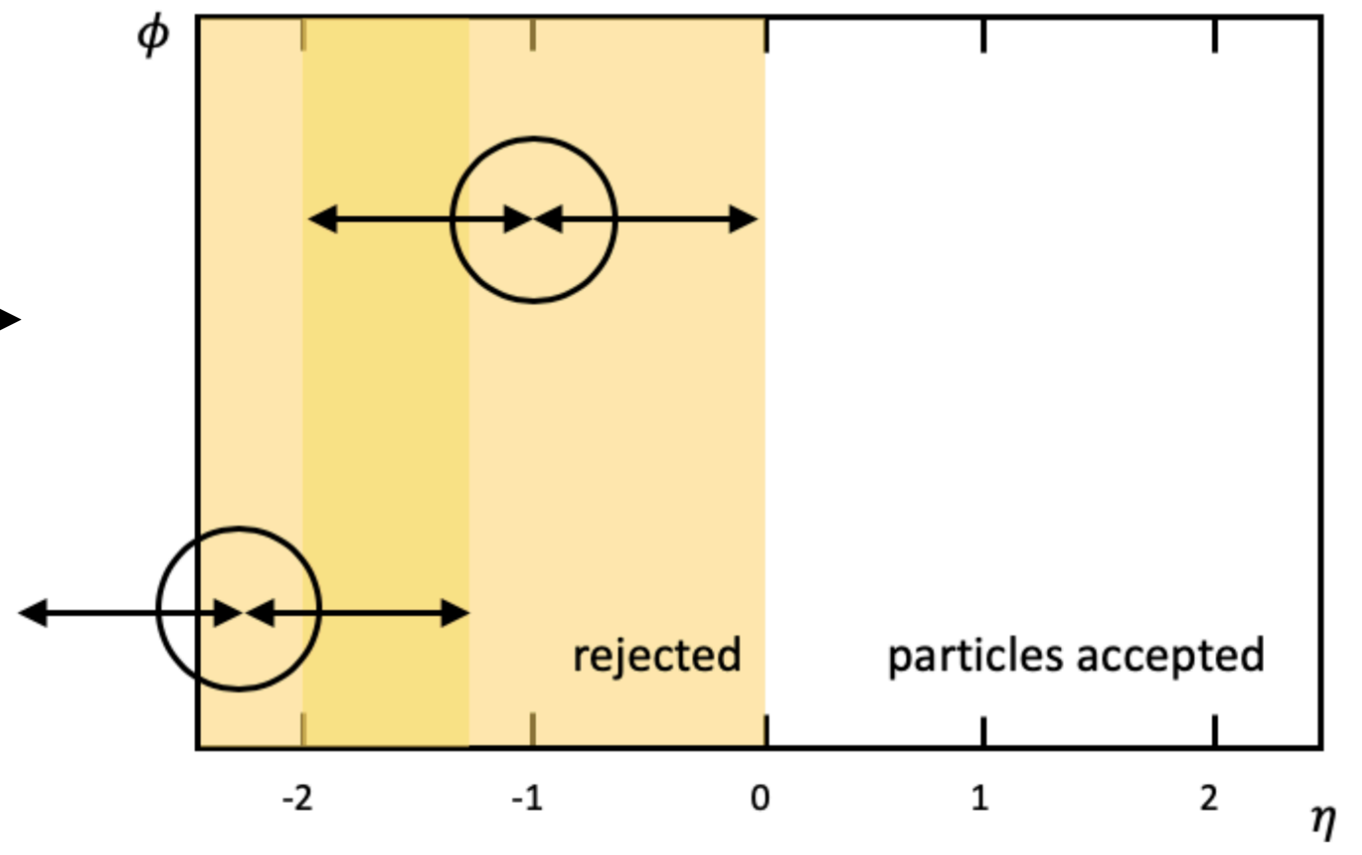

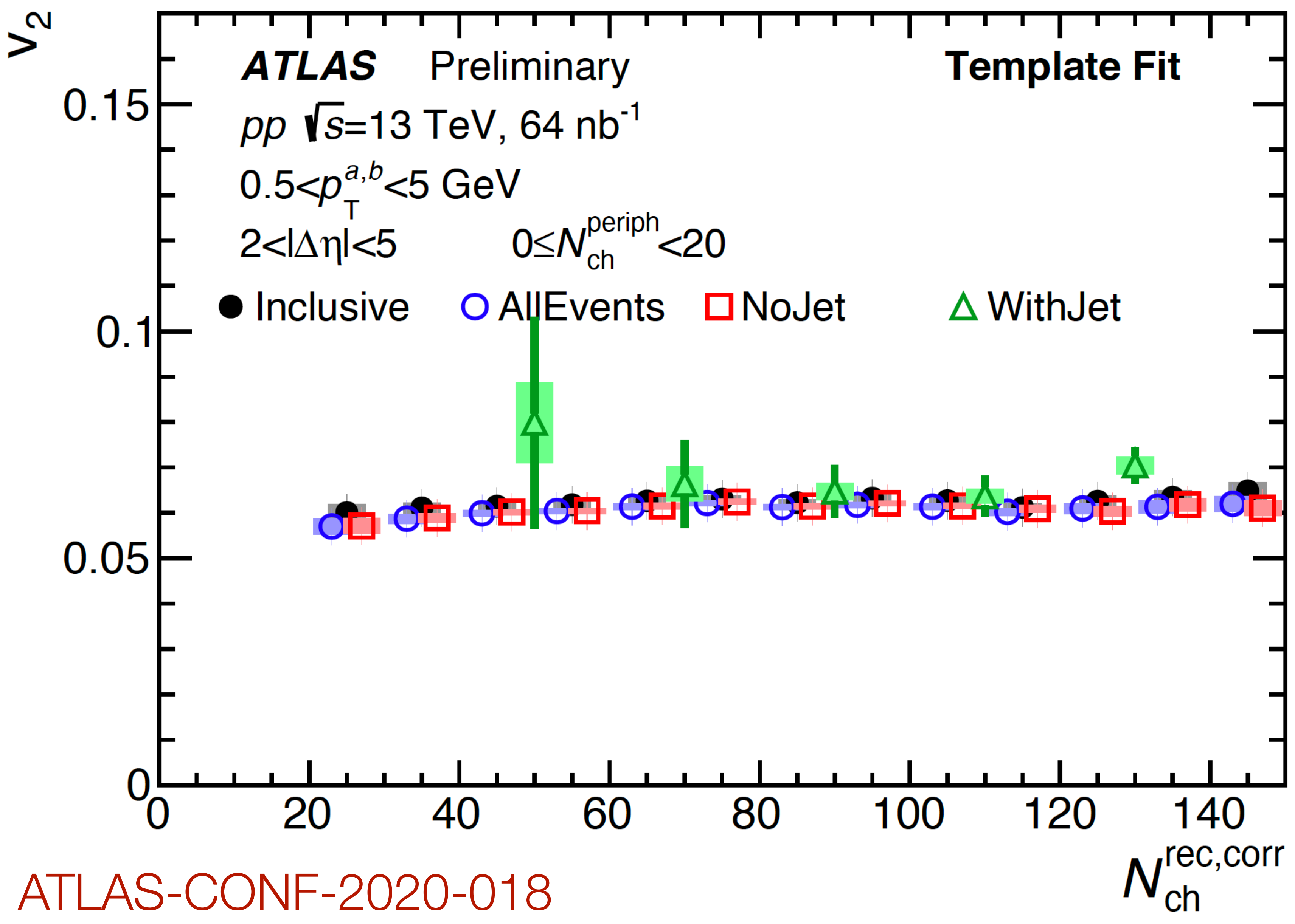

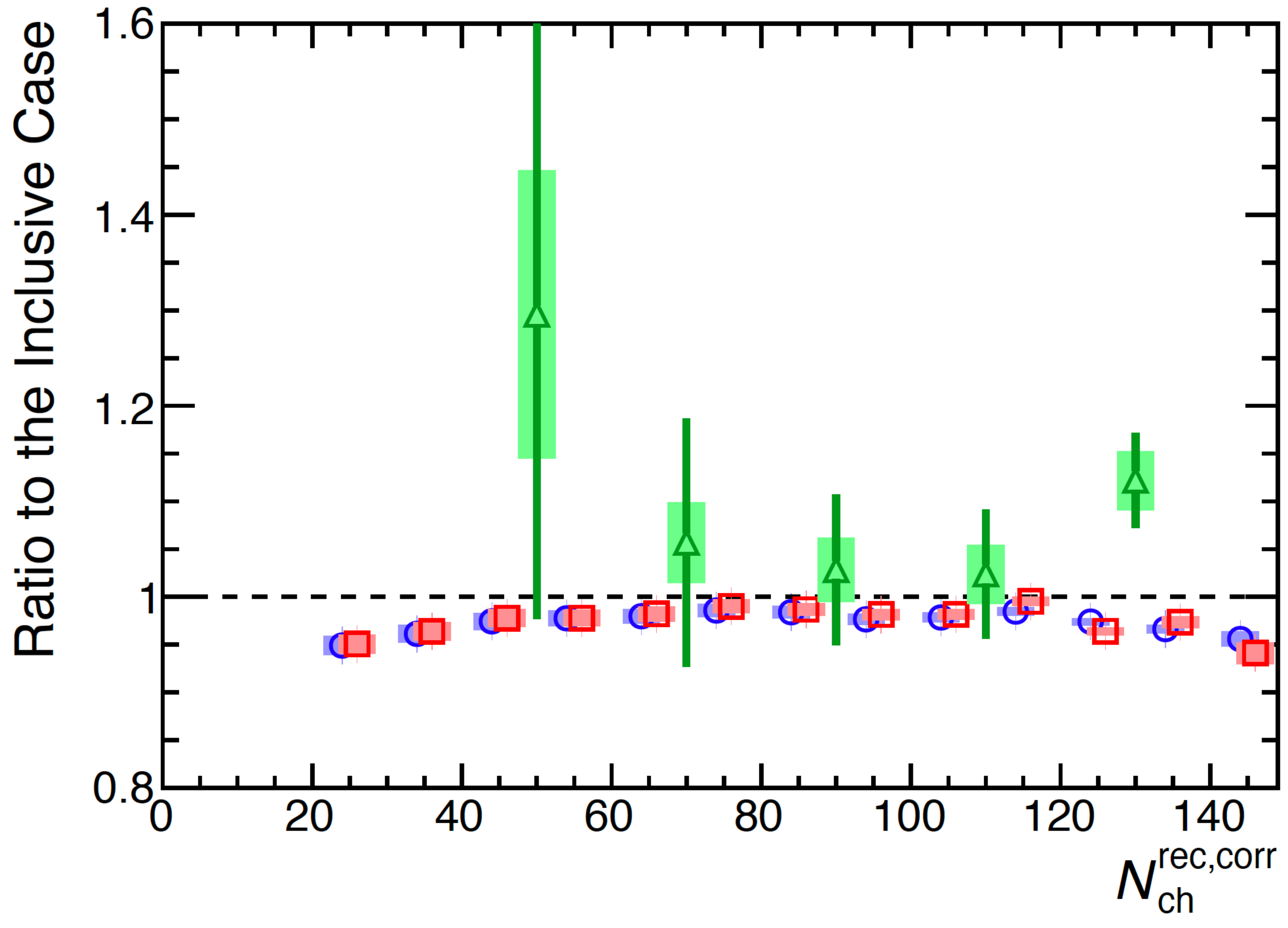

ATLAS-CONF-2020-018

		jet particle rejection
	Inclusive	no
NoJet+WithJet	**AllEvents**	yes
without jets	**NoJet**	yes
with jets only	**WithJet**	yes

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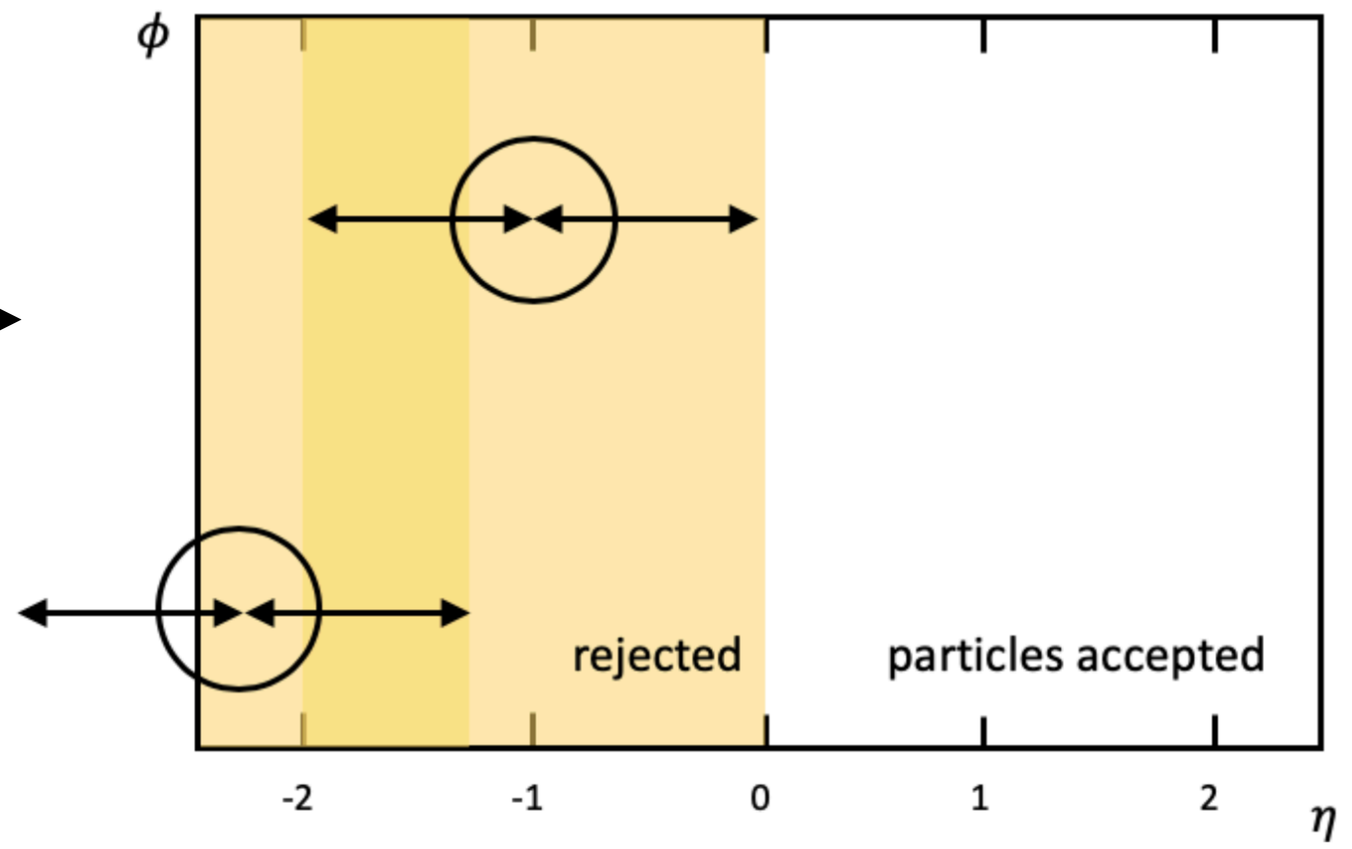
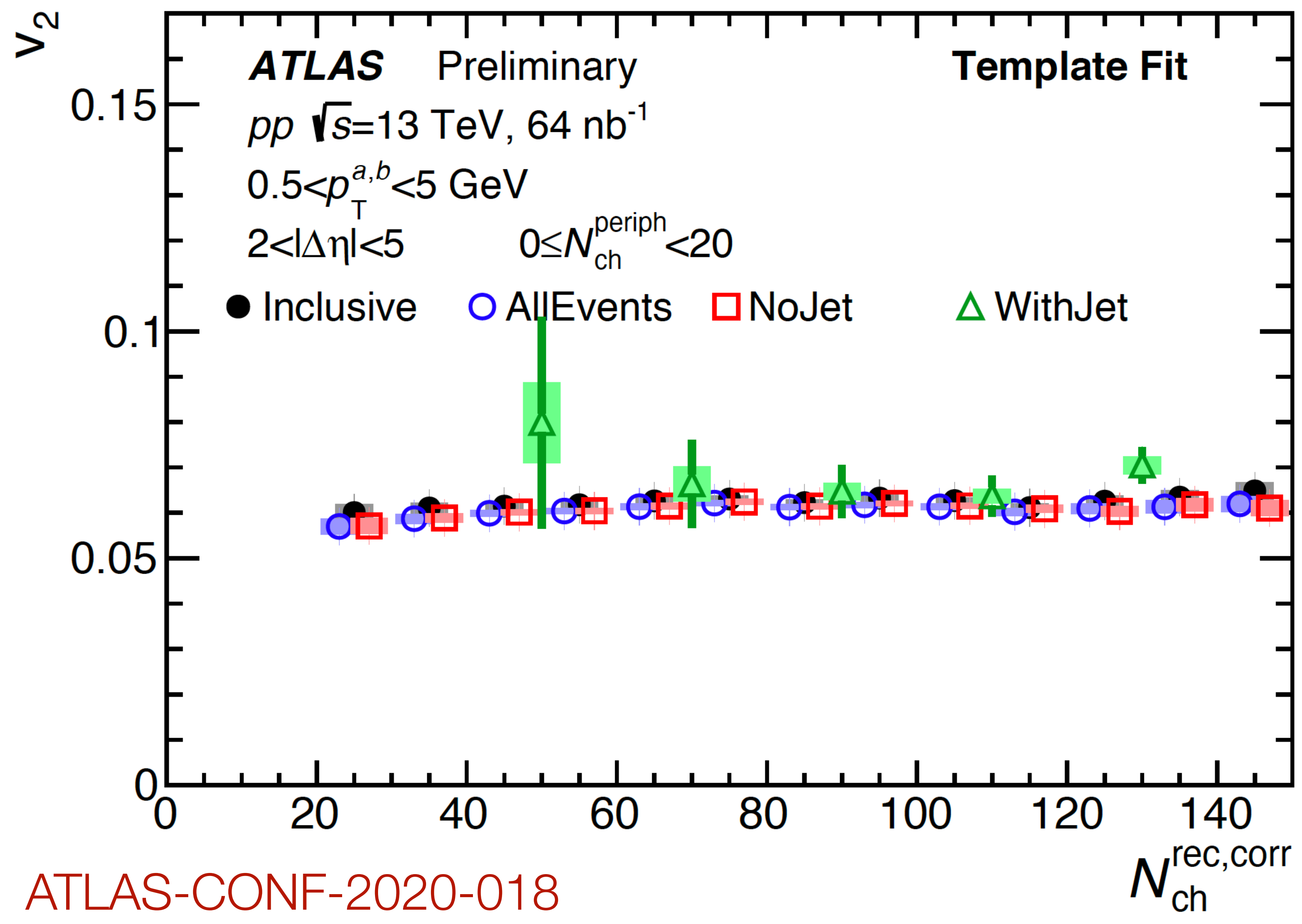
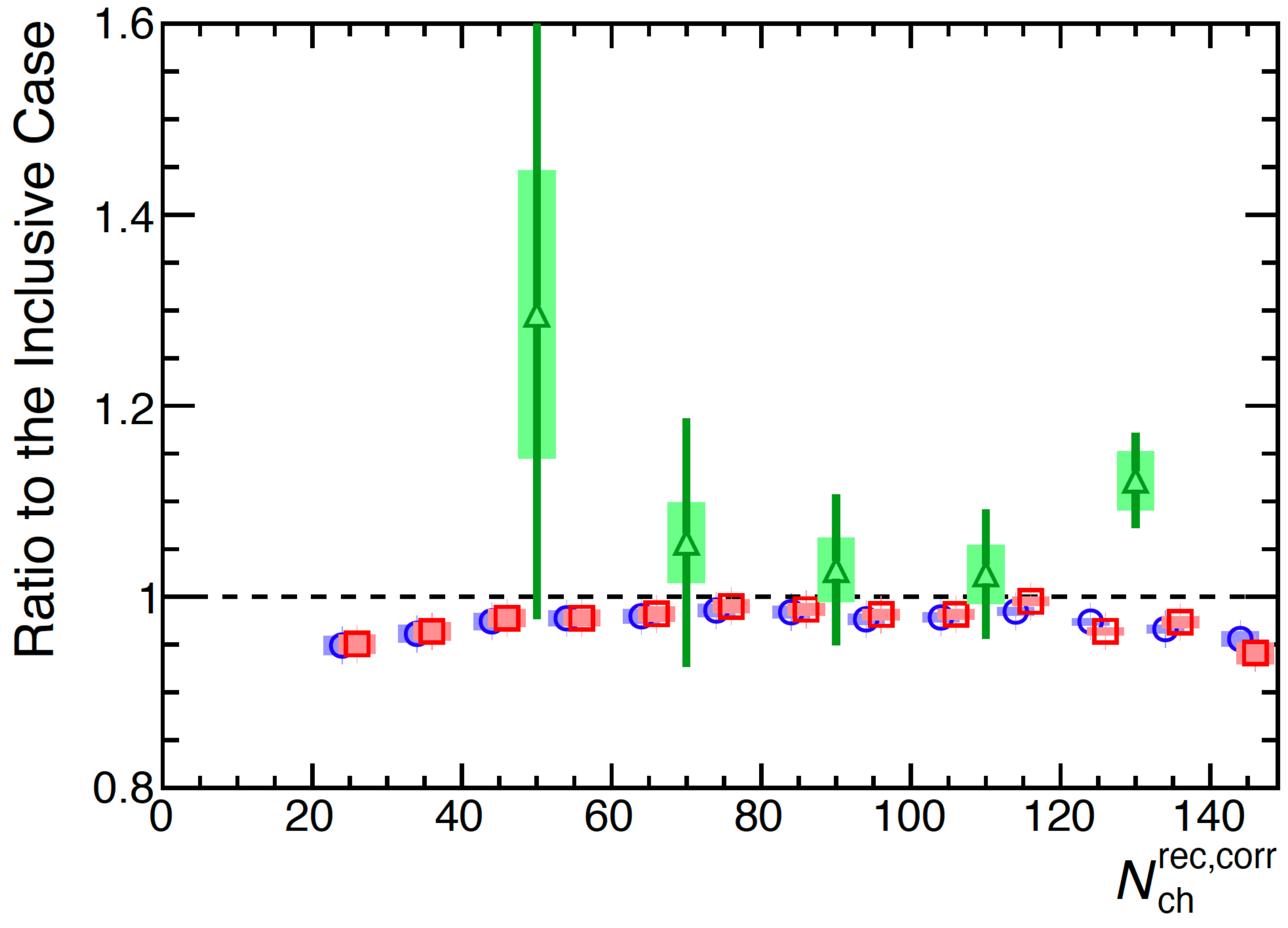


- Correlations are only slightly affected by the presence of hard or semi-hard processes



ATLAS-CONF-2020-018



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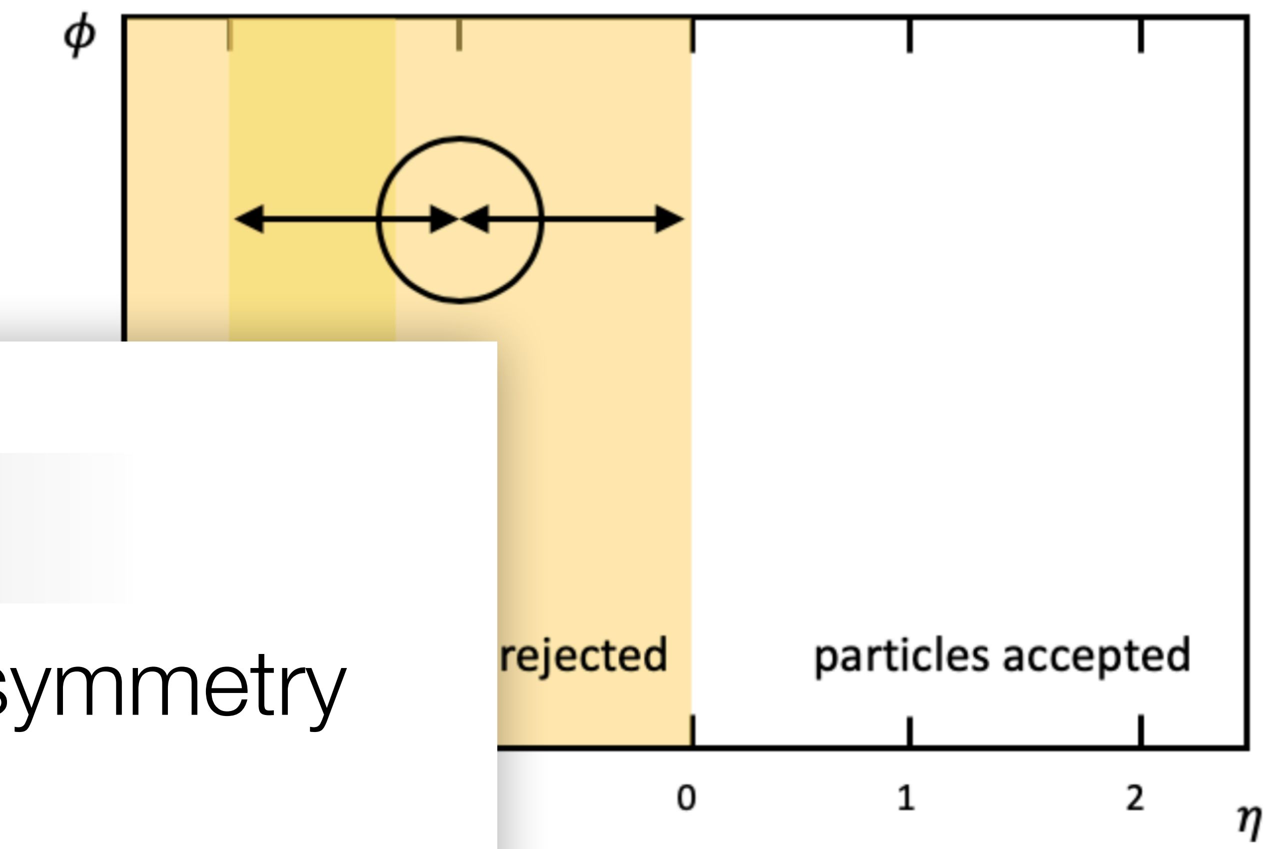


- Correla
  semi-h

Are small systems collective?

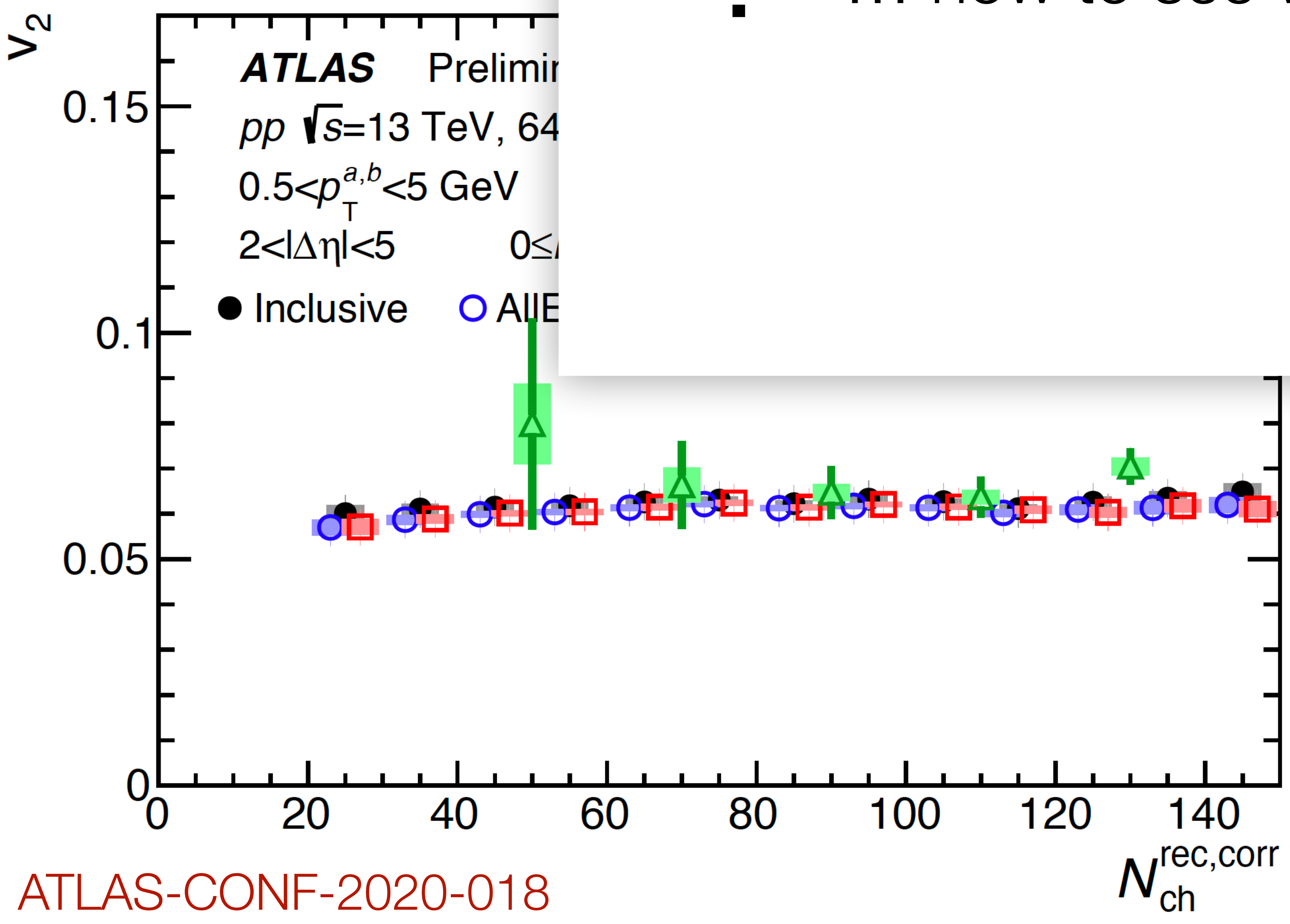
Collective = long-range multi-particle correlations w.r.t. common symmetry

✔ Ridge -> long-range correlations

? … how to see whether a large number of particles *"are acting in unison"*?

R. Bhalerao, arXiv: 2009.09586

… more investigations are needed



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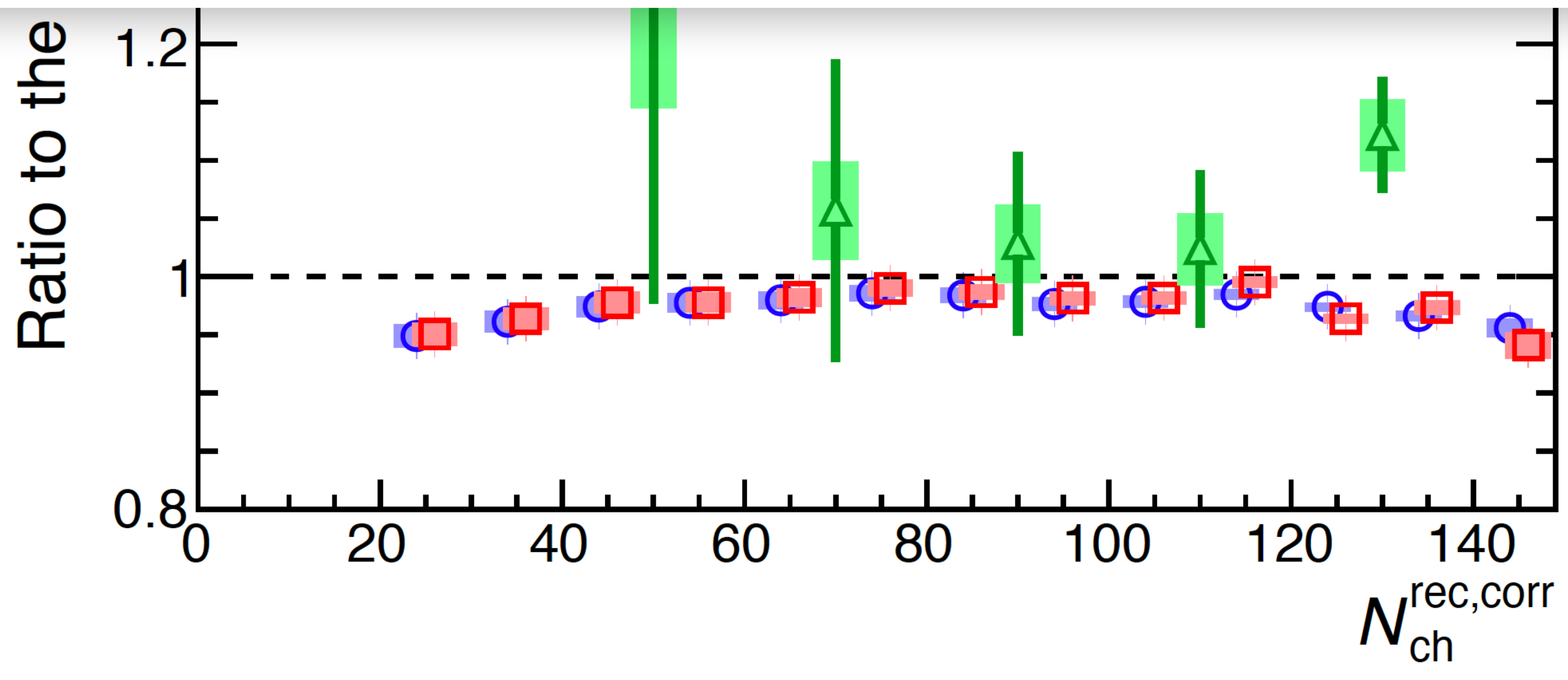

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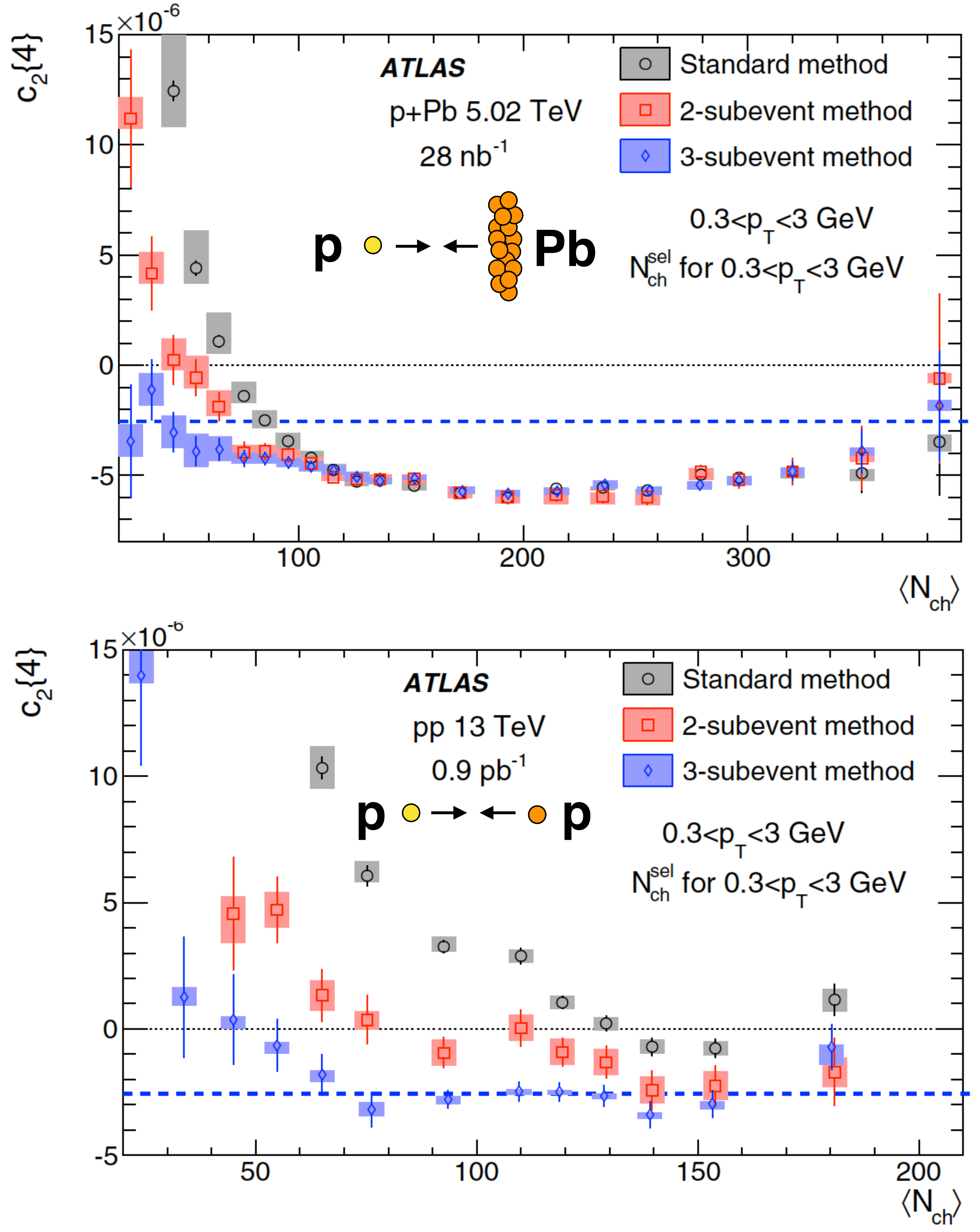
Multi-particle correlations



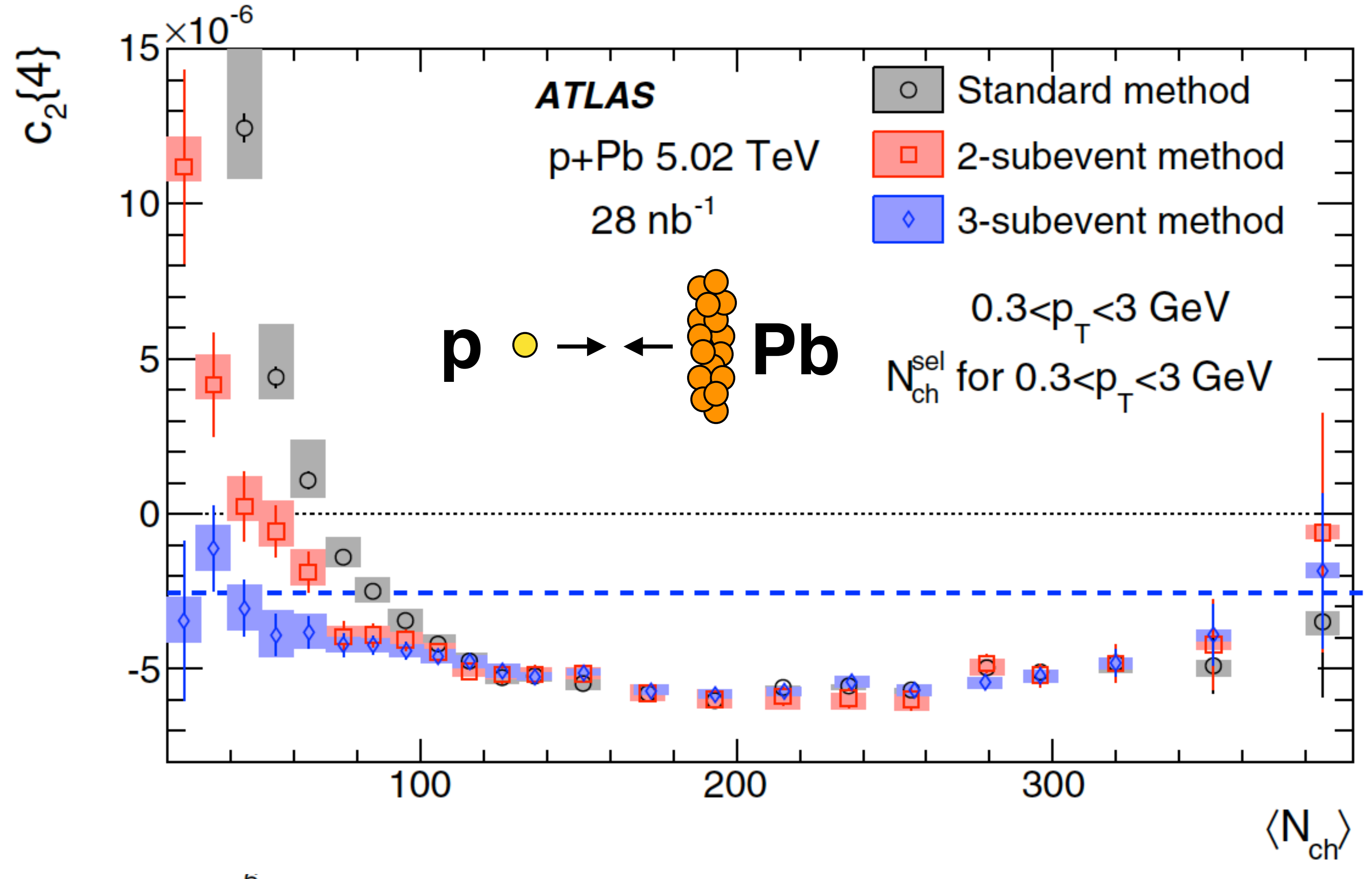
"Correct" sign of the four-particle cumulant

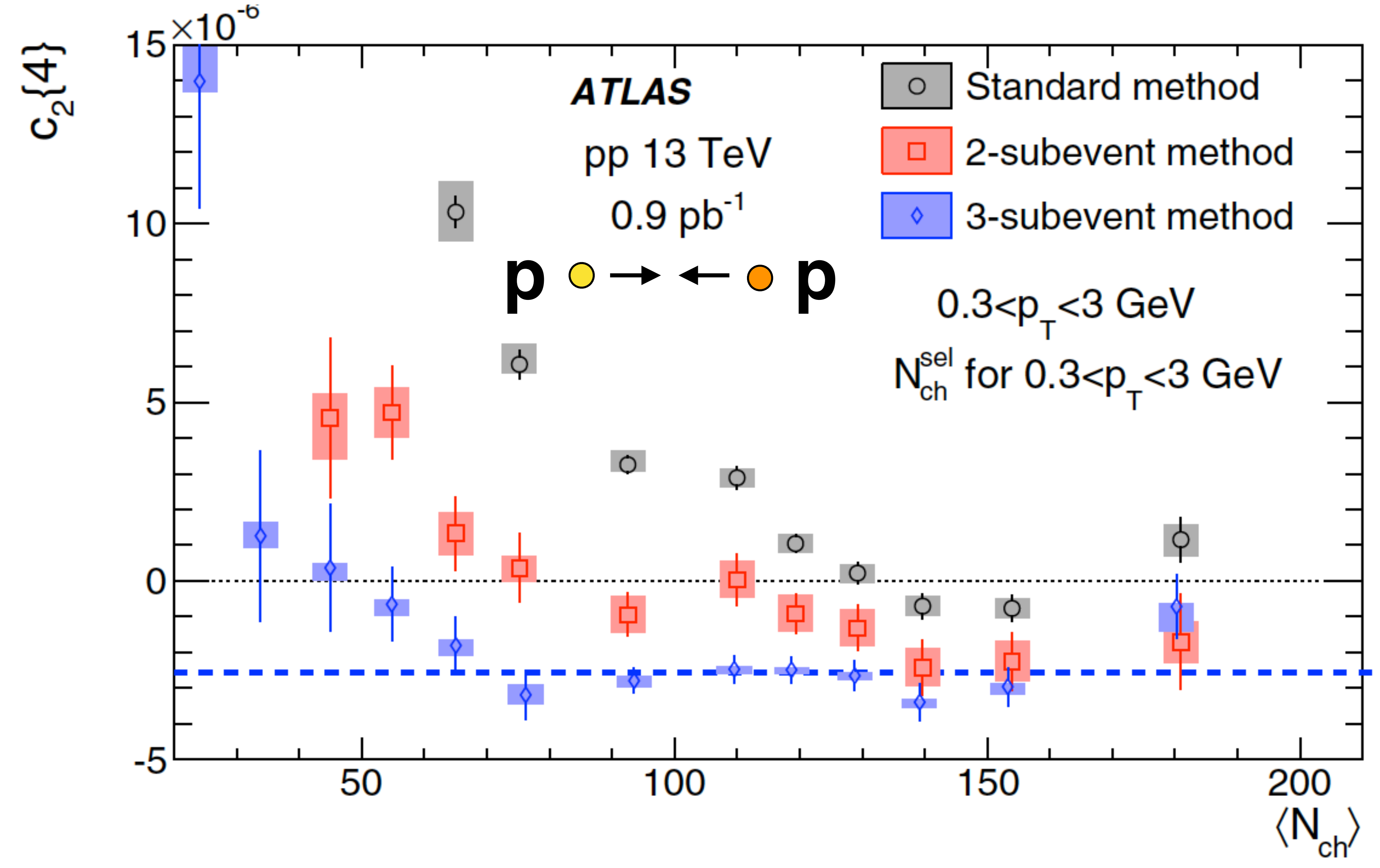
$$v_n\{4\} = \sqrt[4]{-c_n\{4\}}$$

- Negative four-particle cumulant in p-Pb and pp collisions
  - In pp collisions only possible with proper non-flow suppression

ATLAS, PRC 97, 024904 (2018)

Multi-particle correlations





ATLAS, PRC 97, 024904 (2018)

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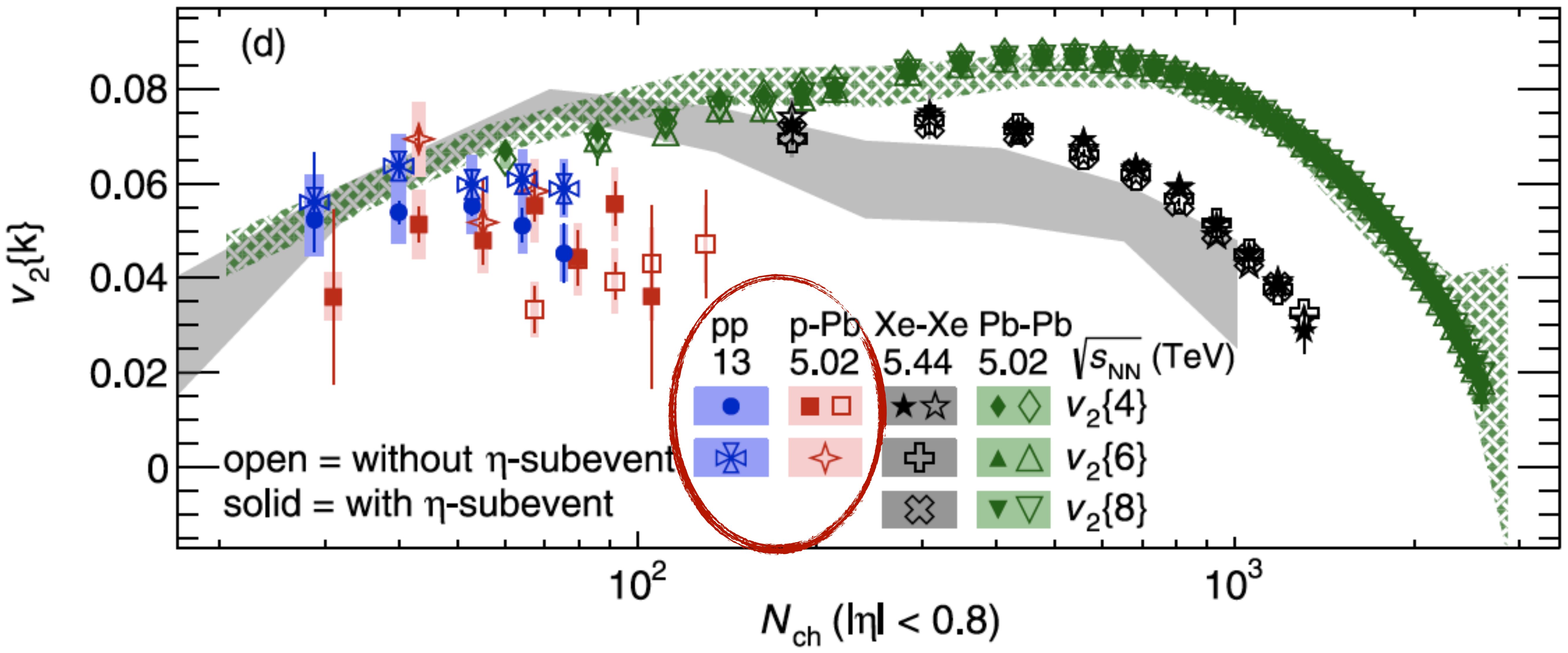
ALICE, PRL 123, 142301 (2019)



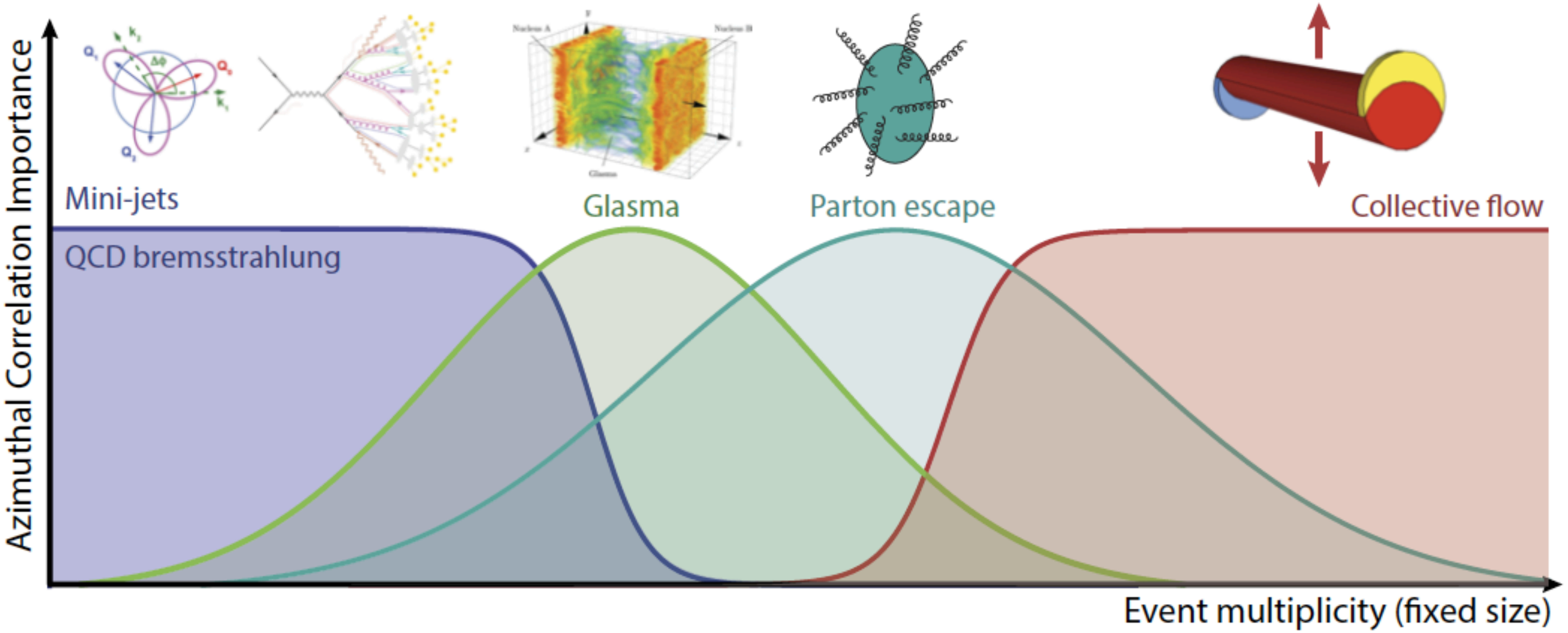
- Negative four-particle cumulant in p-Pb and pp collisions
  - In pp collisions only possible with proper non-flow suppression
- Similar v_2 signal using high orders of multi-particle correlations
  - Similar observation in small systems as in large systems

$$v_n\{4\} \approx v_n\{6\}$$

Long-range **multi-particle** correlations

Origin of long-range multi-particle correlations

M. Strickland, NPA 982 (2019) 92-98



Effects of the initial state:

Initial momentum correlations
Not correlated with the initial geometry

Effects of the final state:

Initial spatial anisotropy + interactions in the final state
Correlated with the initial geometry

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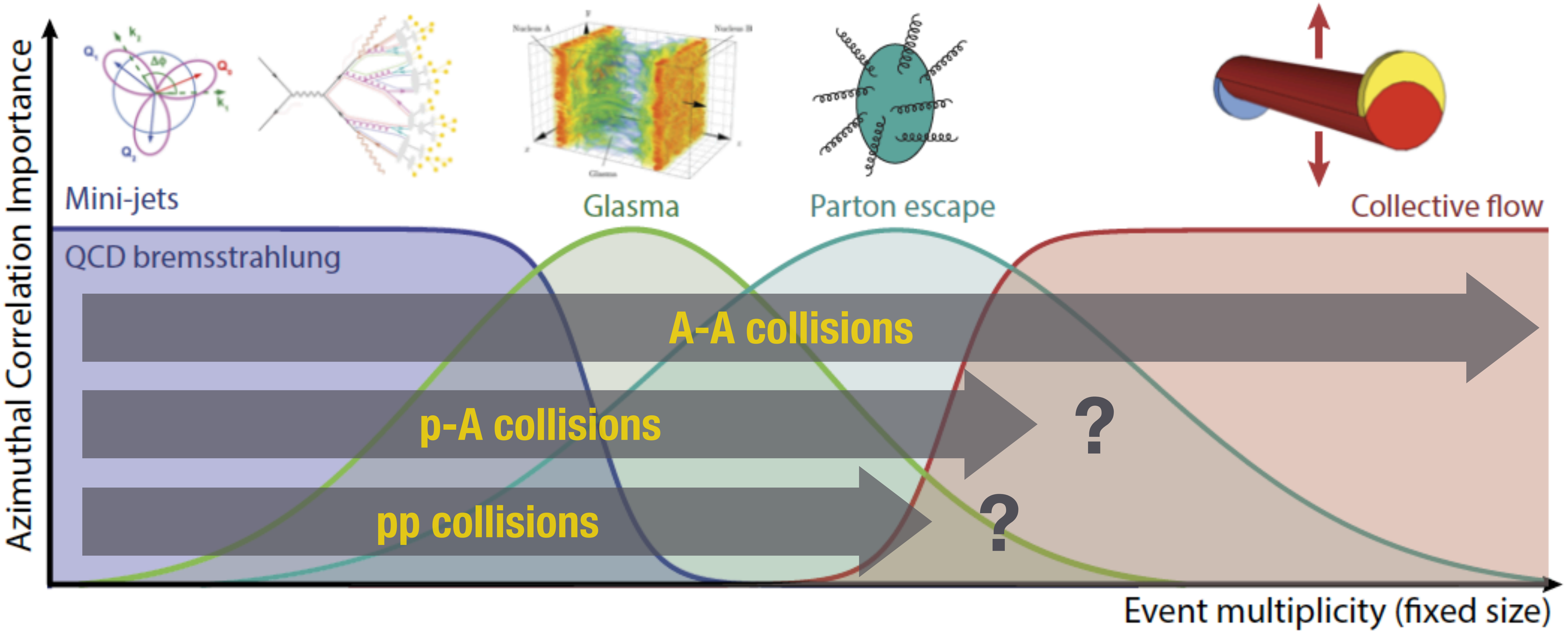

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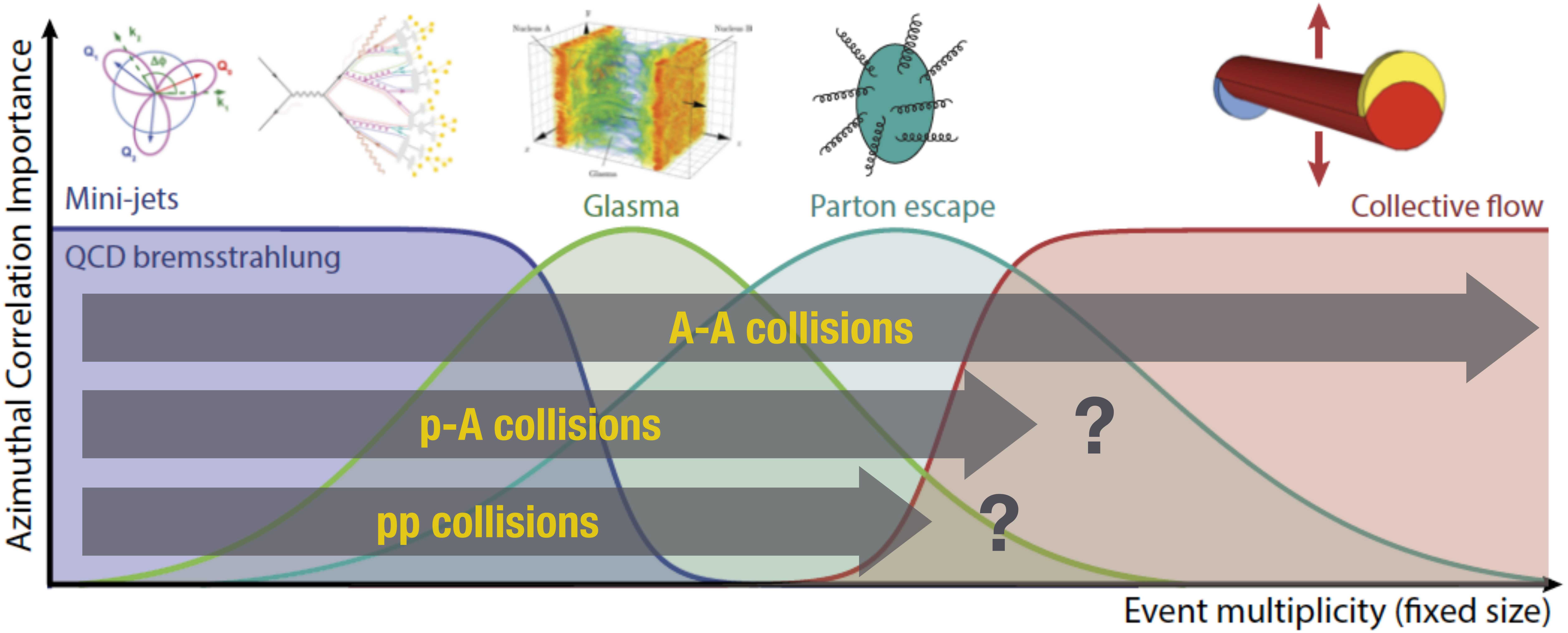

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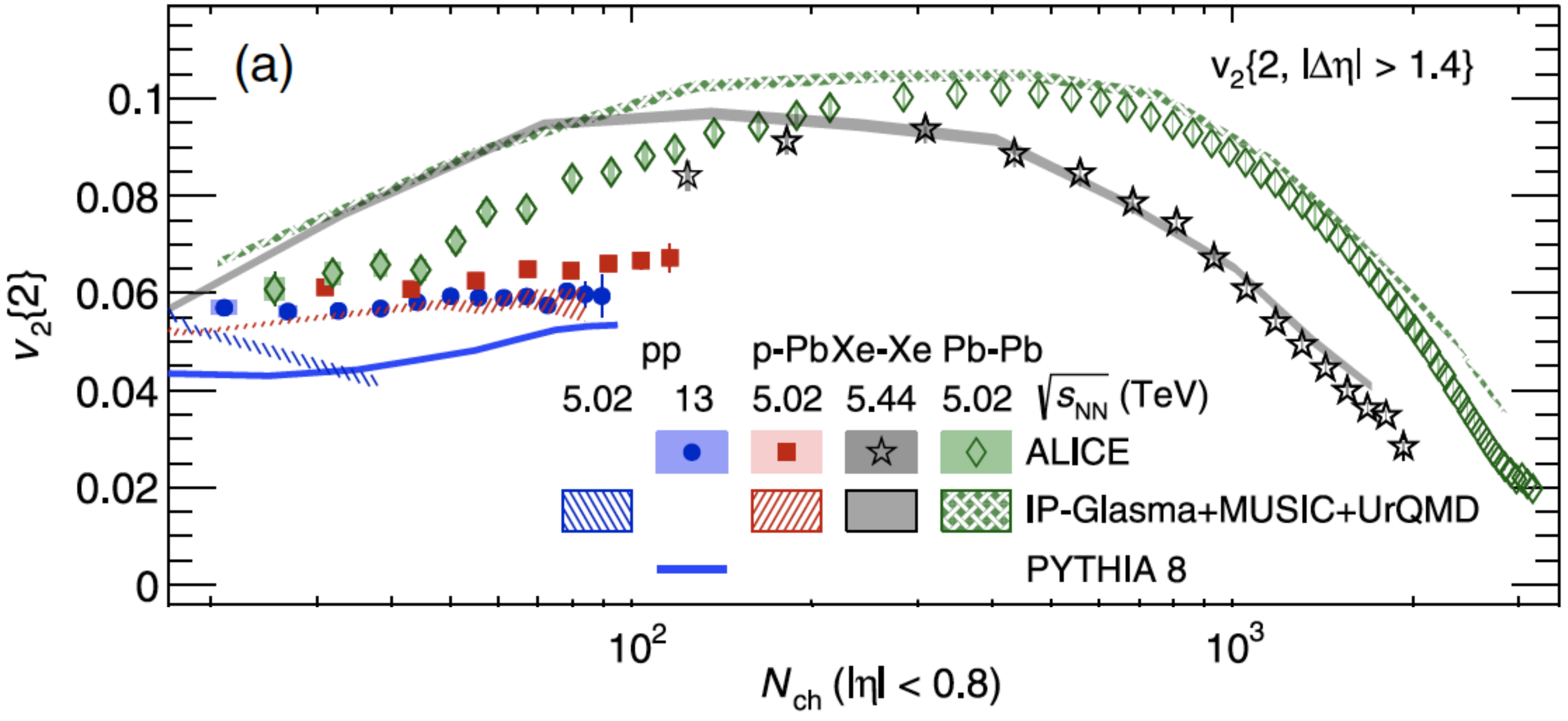
How to determine the scale on the x-axis?
How to determine the reach of the arrows?
→ … more measurements and theoretical comparisons with them

Description of two-particle correlations

Macroscopic models

ALICE, PRL 123, 142301 (2019)



Schenke et al., PRC 89, 024901 (2014)
Mäntysaari et al., PLB 772, 681 (2017)
update: Schenke et al., arXiv: 2005.14682

- IP-Glasma+MUSIC+UrQMD **describes $v_n\{2\}$** in all but pp collisions
- Note: iEBE-VISHNU hydrodynamic model reproduces the $v_2\{2\}$ measurements in pp collisions

Zhao et al., PLB 780 (2018) 495
Zhao et al., arXiv: 2001.06742

Description of two-particle correlations

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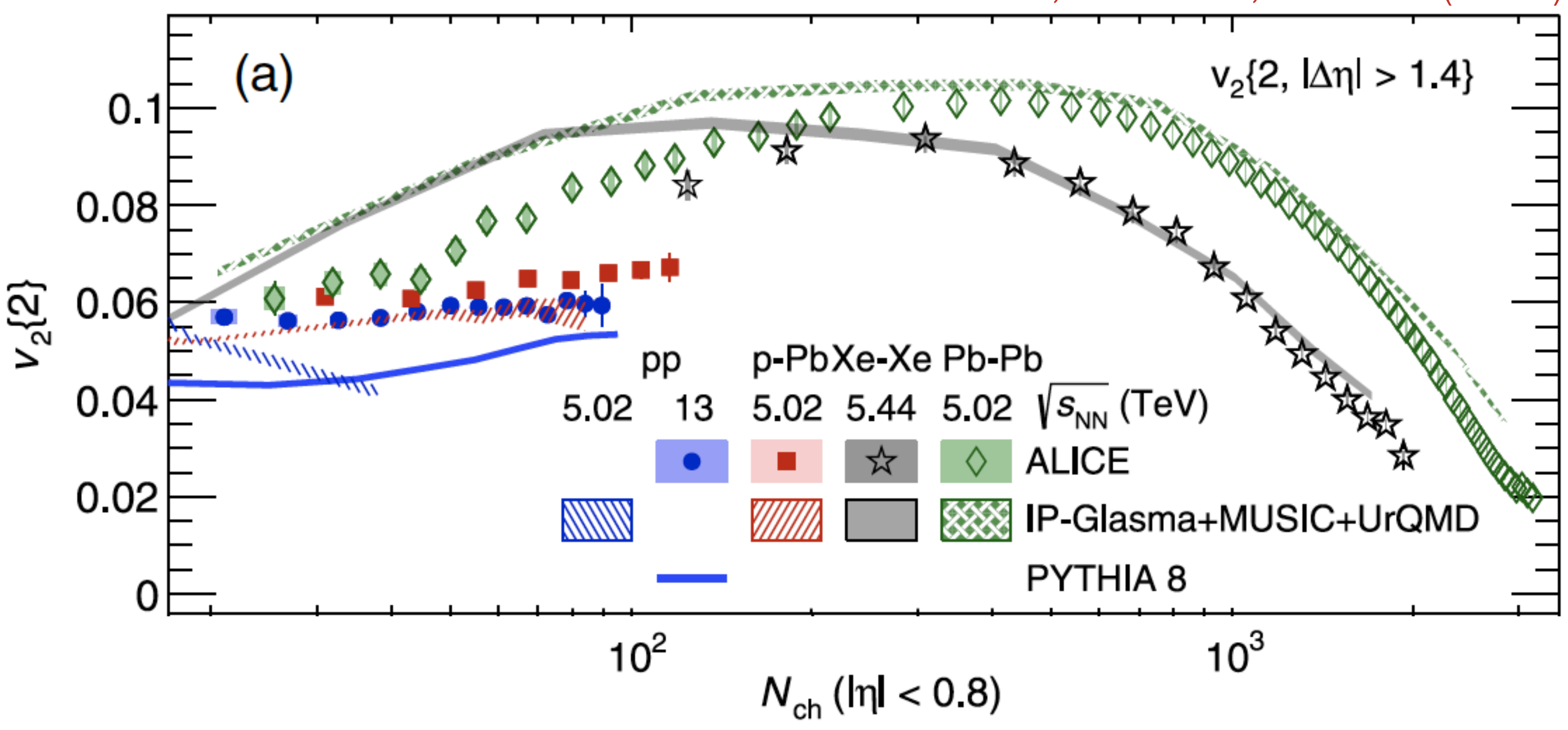

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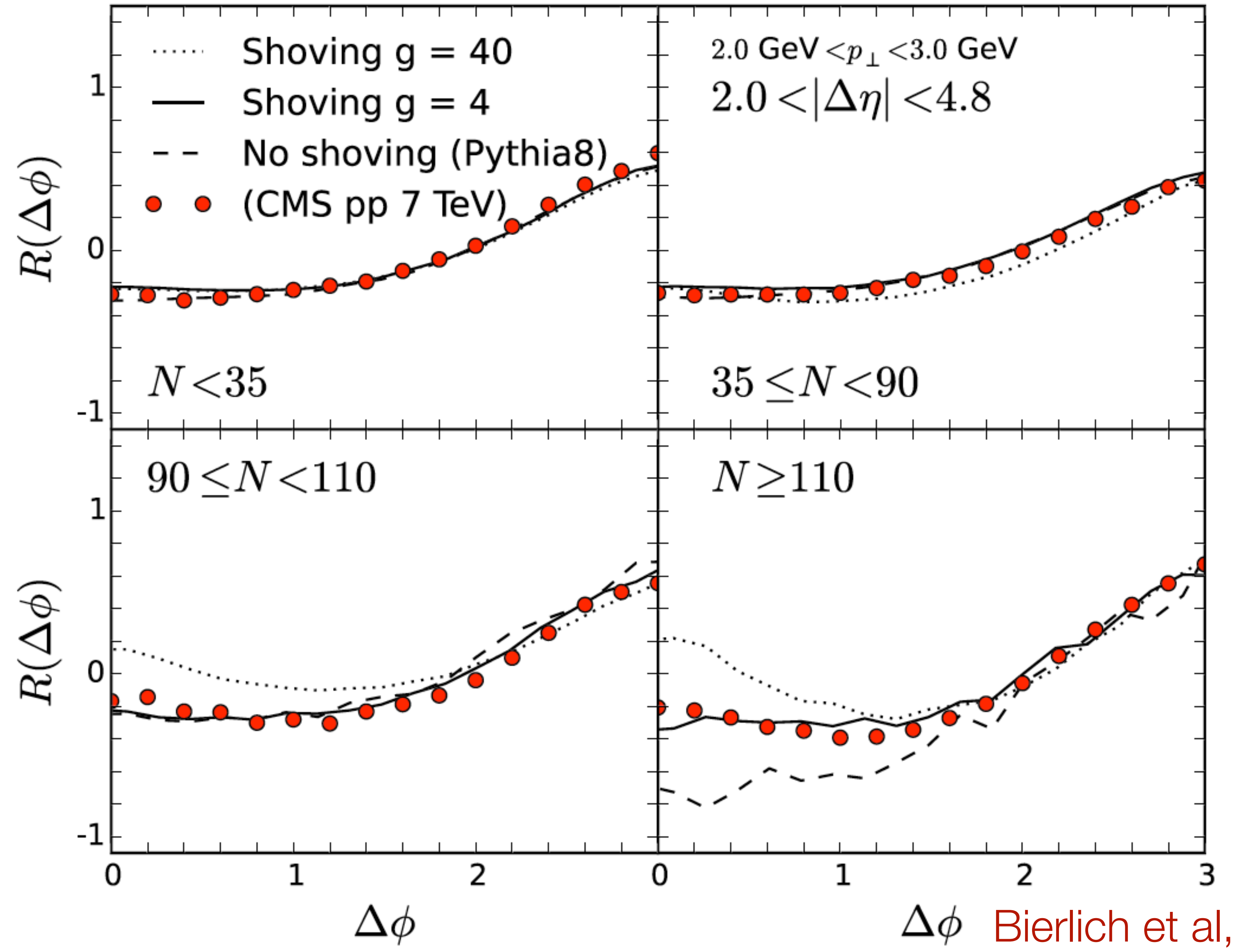
Microscopic models



Bierlich et al, PLB 779 (2018) 58

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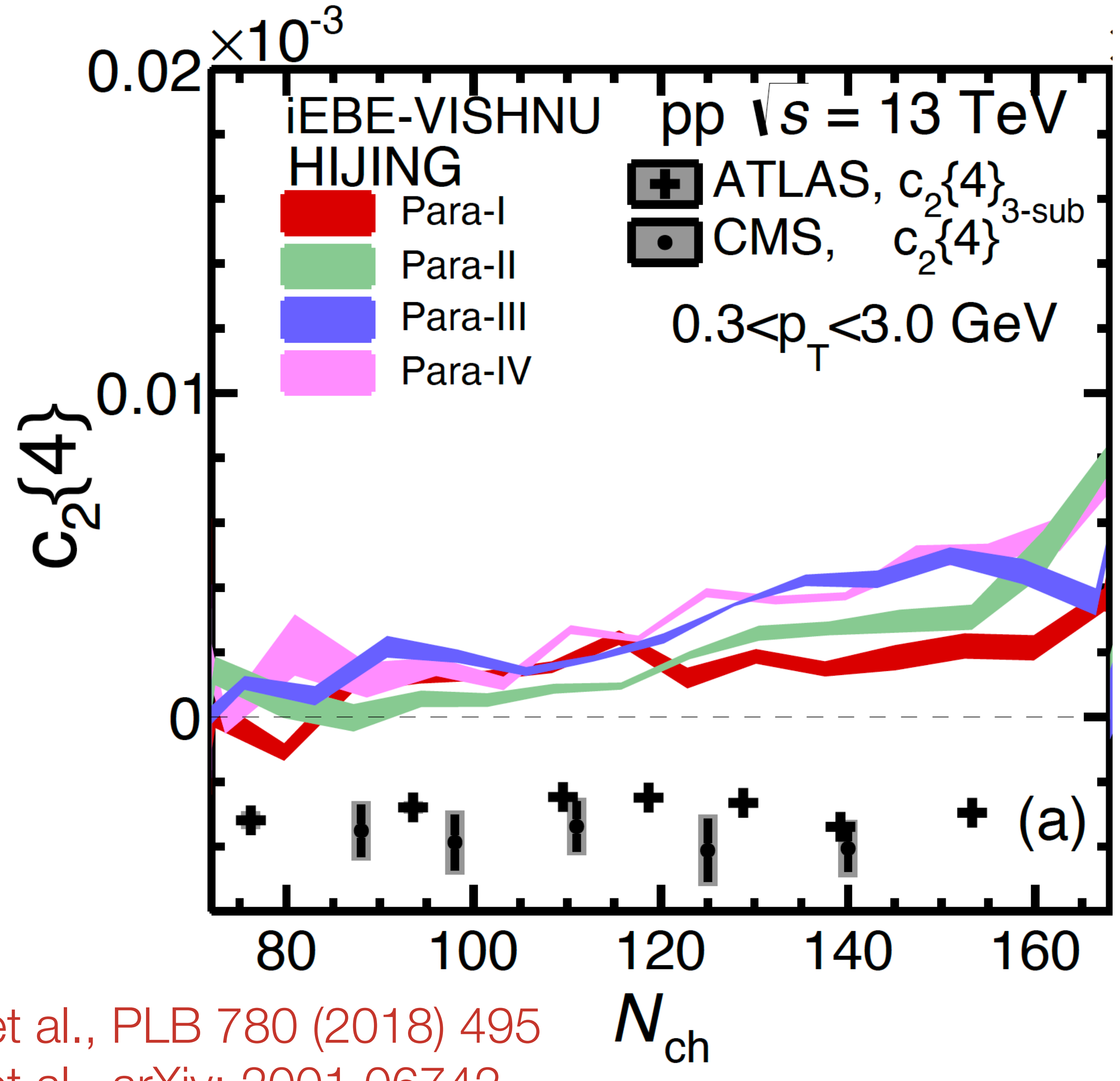
Zhao et al., PLB 780 (2018) 495
Zhao et al., arXiv: 2001.06742

- PYTHIA with the shoving mechanism can **describe the ridge**
- Transport theory: **collectivity** can be achieved via **few-particle scatterings** A. Kurkela et al, PLB 783 (2018) 274-279

Description of multi-particle correlations

Macroscopic models



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- pp collisions: iEBE-VISHNU **cannot reproduce** the negative sign of $c_2\{4\}$ from data
  - Importance of nonlinear hydrodynamic response in pp collisions
- p-Pb collisions: **qualitative agreement** with $v_2\{4\}$

Schenke et al., arXiv: 2005.14682

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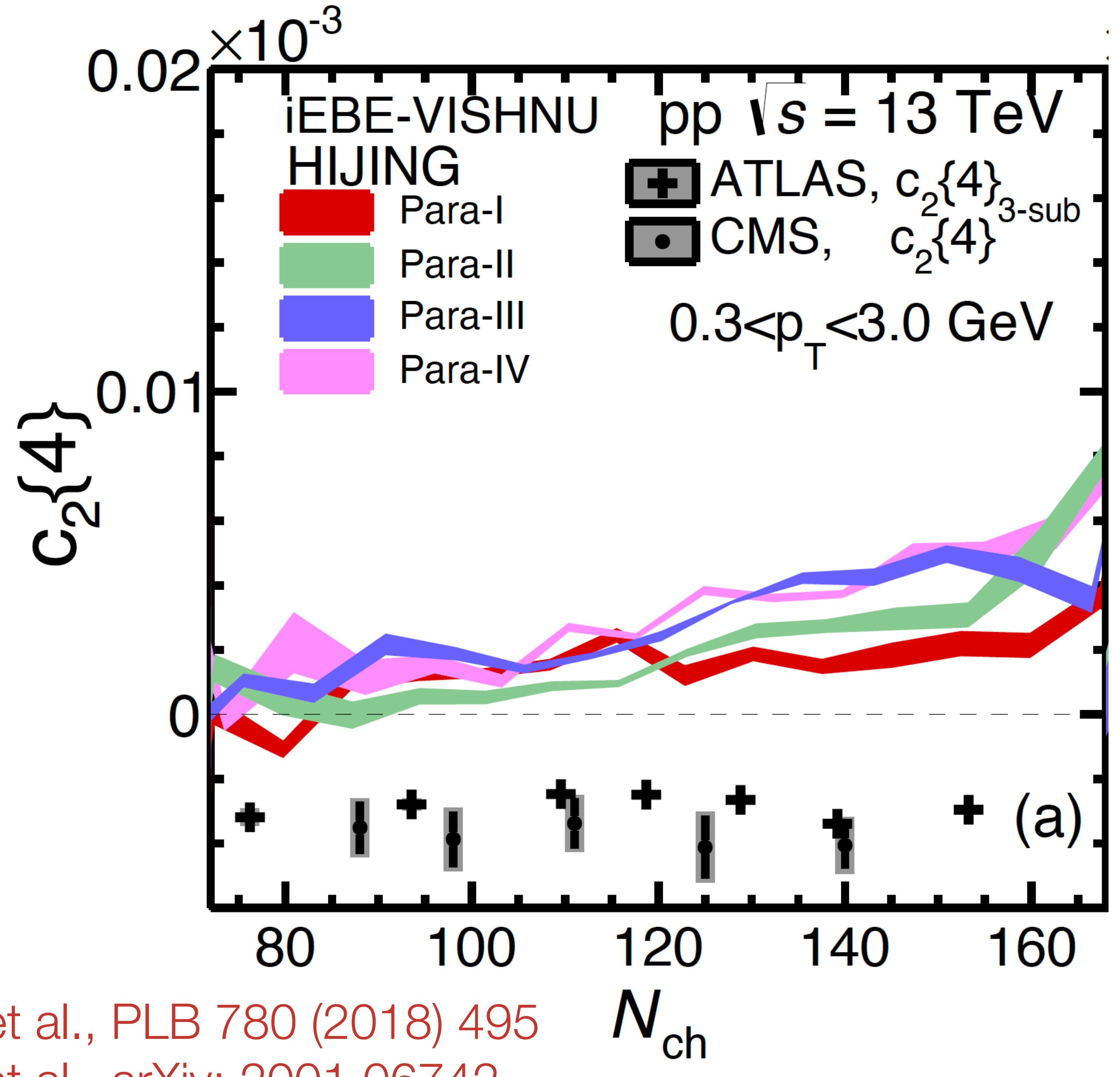

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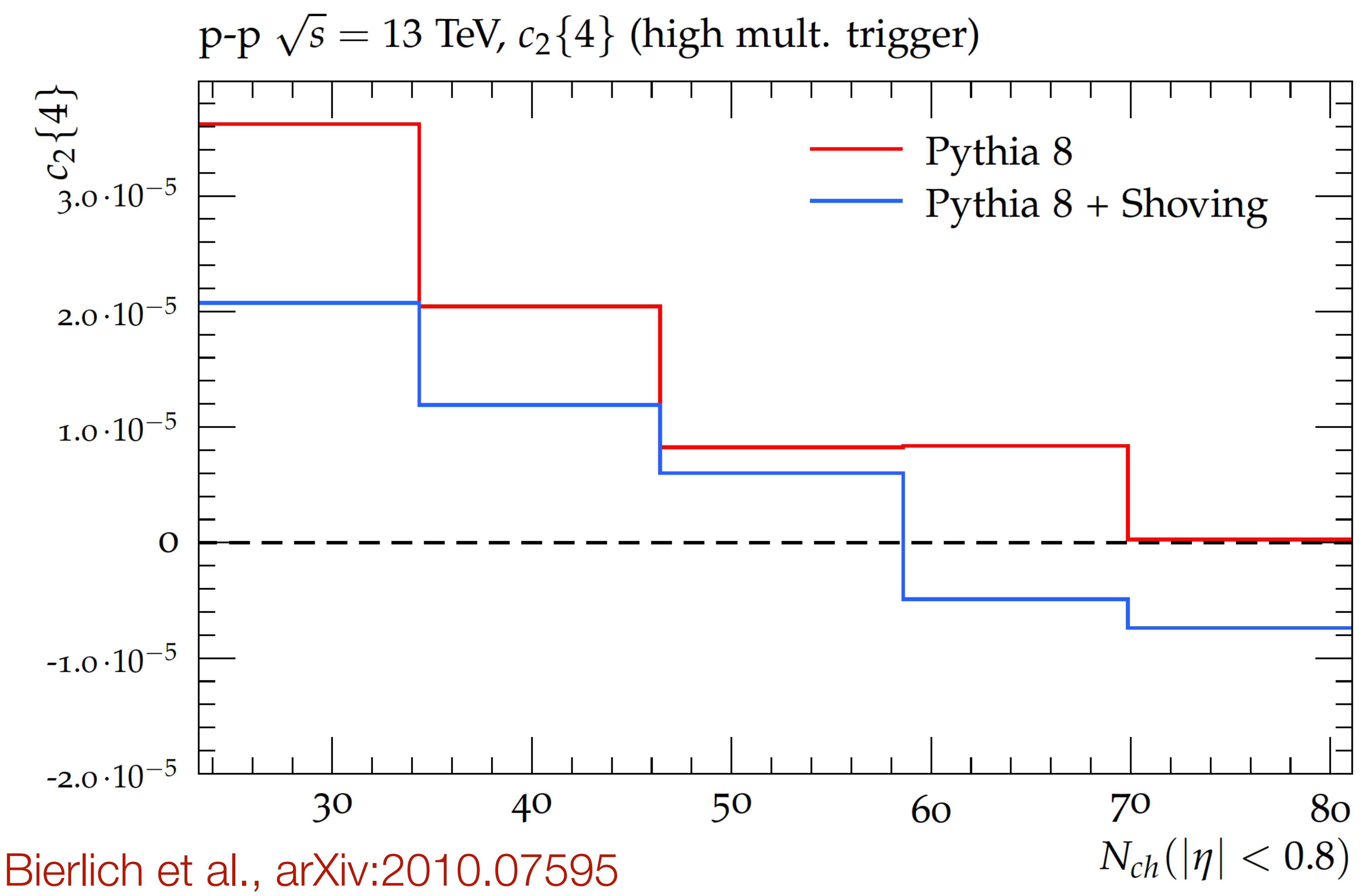


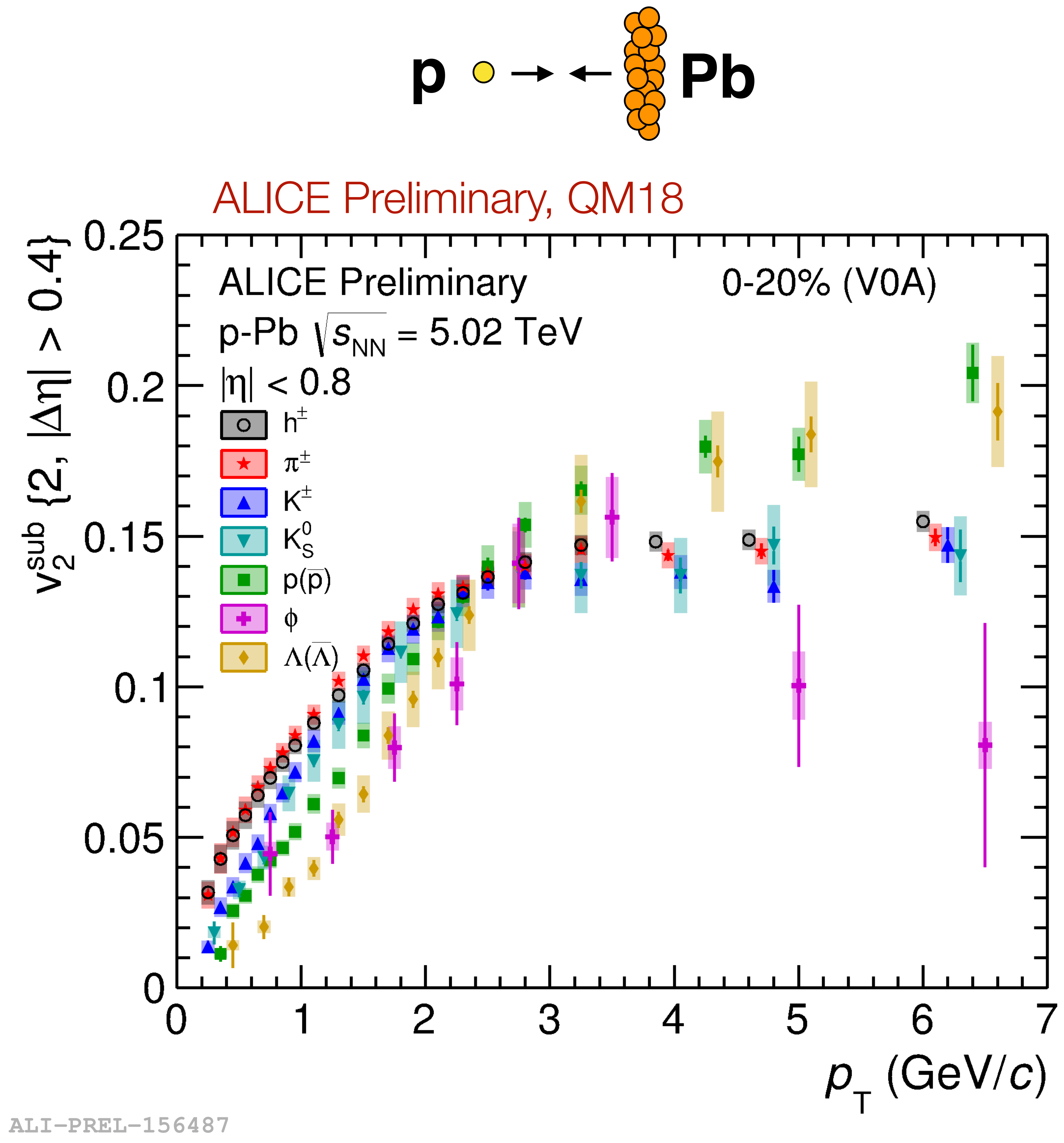
Bierlich et al., arXiv:2010.07595

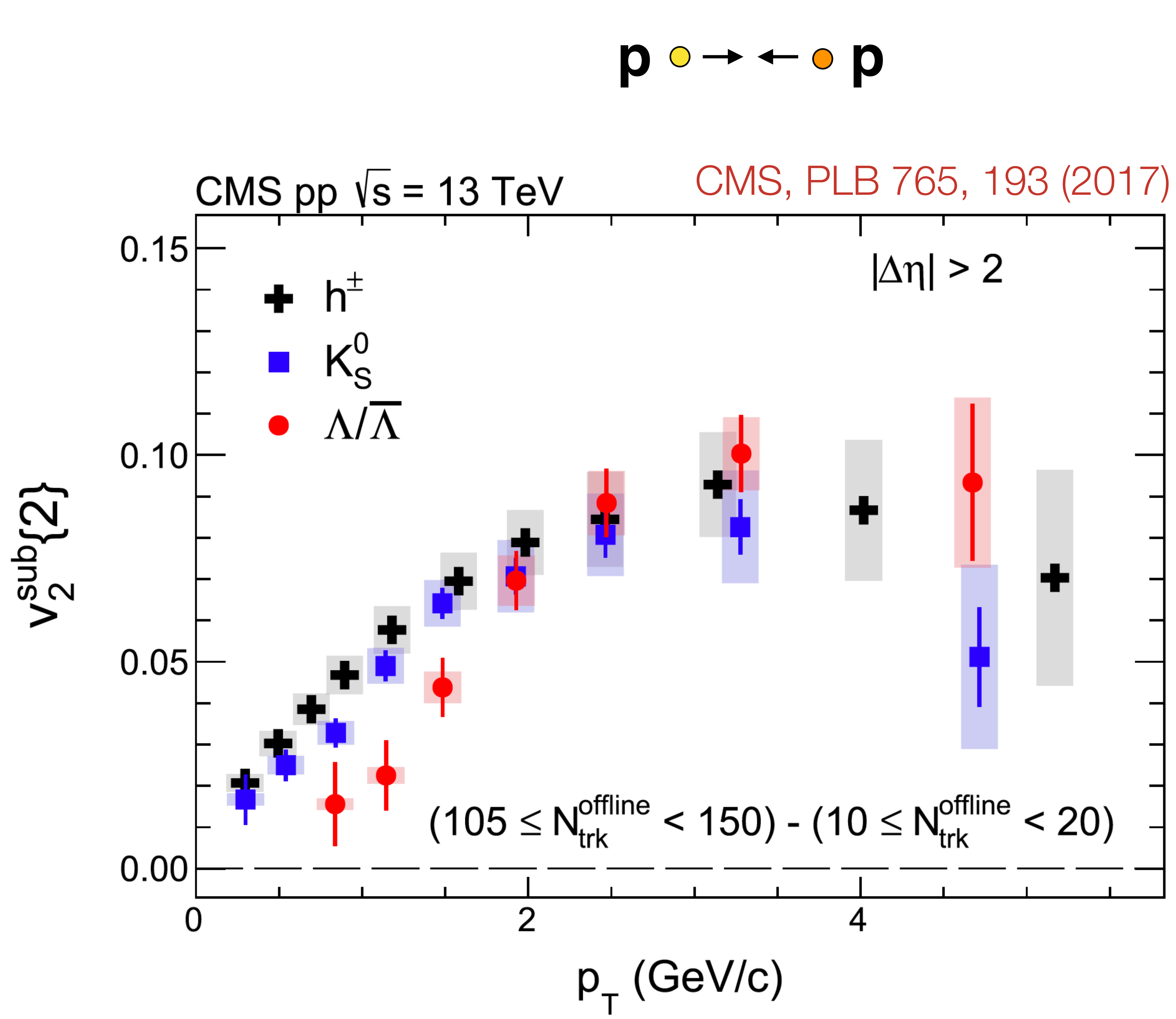
- <u>pp collisions</u>: iEBE-VISHNU **cannot reproduce** the negative sign of $c_2\{4\}$ from data
  - Importance of nonlinear hydrodynamic response in pp collisions
- <u>p-Pb collisions</u>: **qualitative agreement** with $v_2\{4\}$

Schenke et al., arXiv: 2005.14682

- PYTHIA with the shoving mechanism and simulated ALICE high-multiplicity trigger reveals **$c_2\{4\} < 0$ in pp collisions**
  - First look, should be further investigated

Flow of identified particles

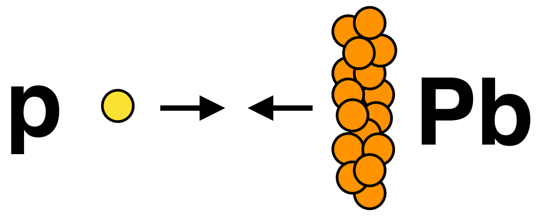




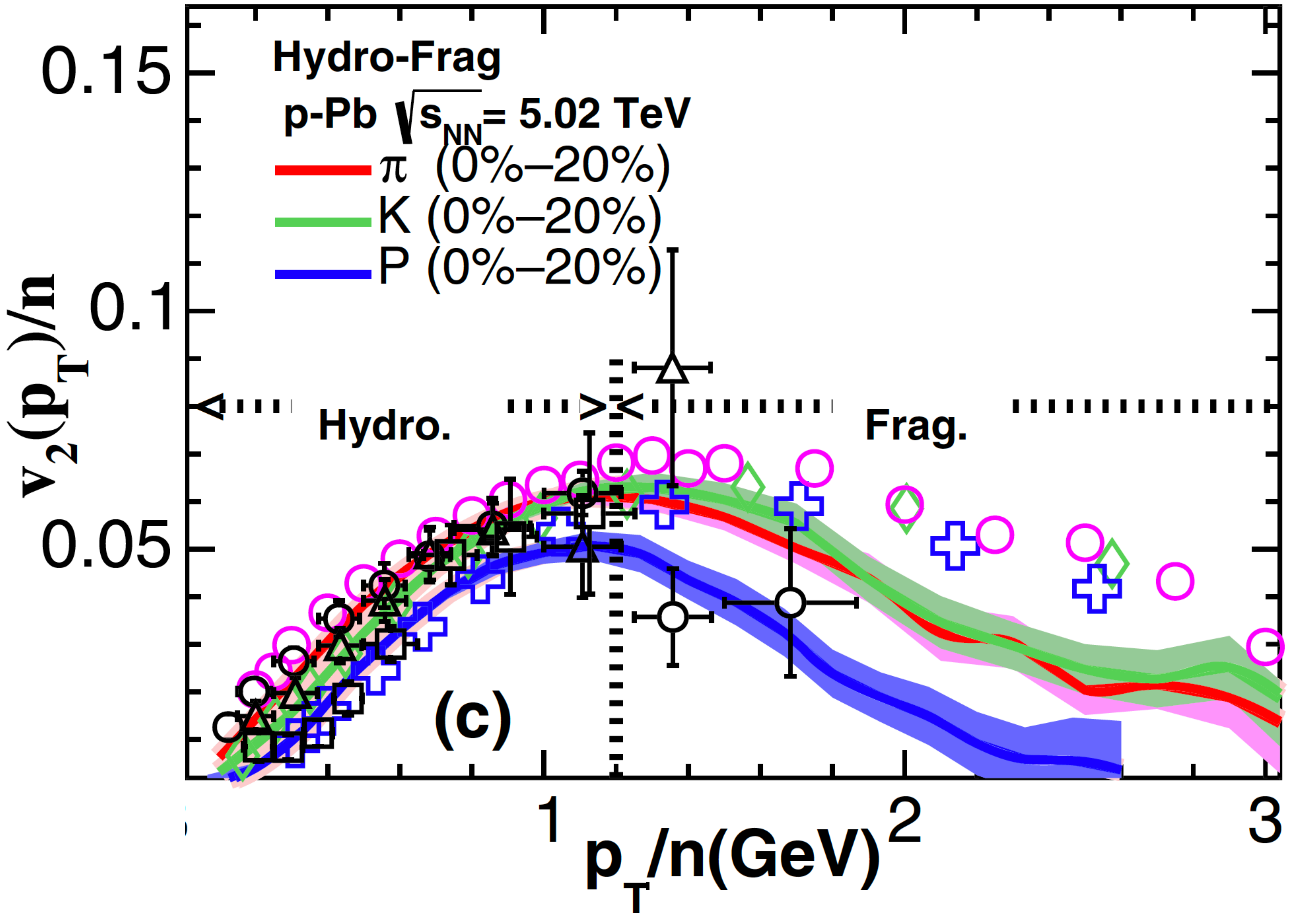
Similar observations as in Pb-Pb collisions:

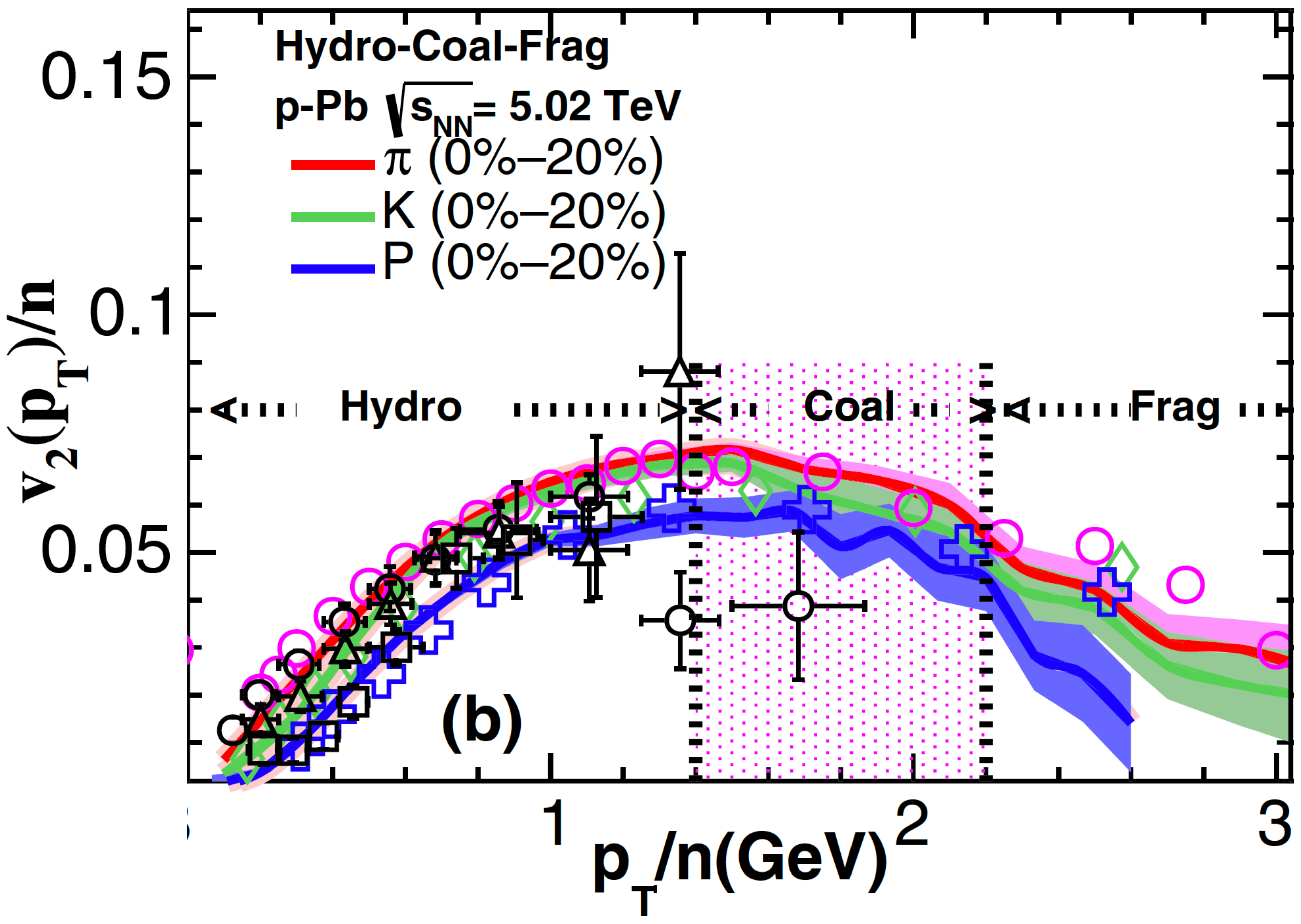
- **Mass ordering** at low p_T in p-Pb and pp collisions
- Hint for a **baryon-meson grouping** at intermediate p_T in p-Pb collisions

Description of flow of identified particles



Zhao et al., PRL 125, 072301 (2020)





- Mass ordering at **low p_T** is reproduced by hydrodynamic models

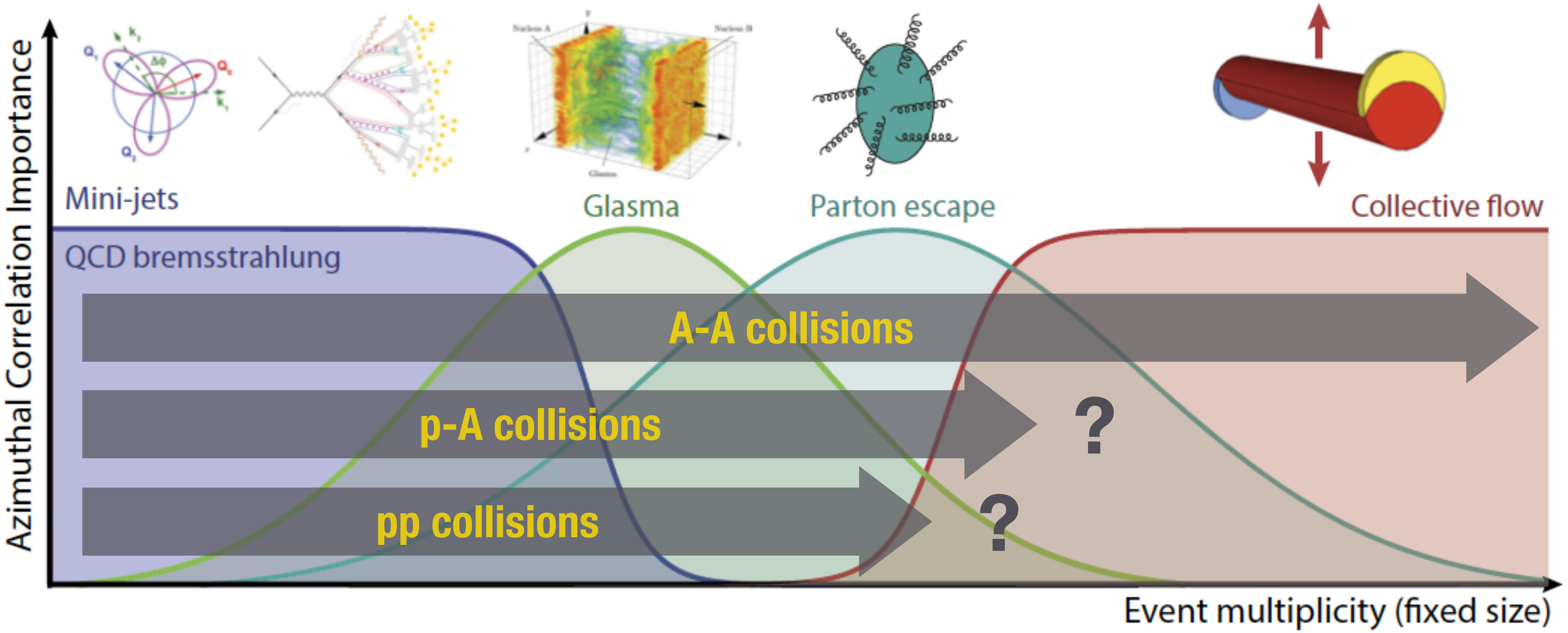
Mäntysaari et al., PLB 772, 681 (2017)

- Approximate NCQ scaling at **intermediate p_T** is reproduced by hydrodynamics
  - Only possible with the inclusion of the quark coalescence model

Possible existence of the partonic phase in high multiplicity p-Pb collisions

Origin of long-range multi-particle correlations

M. Strickland, NPA 982 (2019) 92-98



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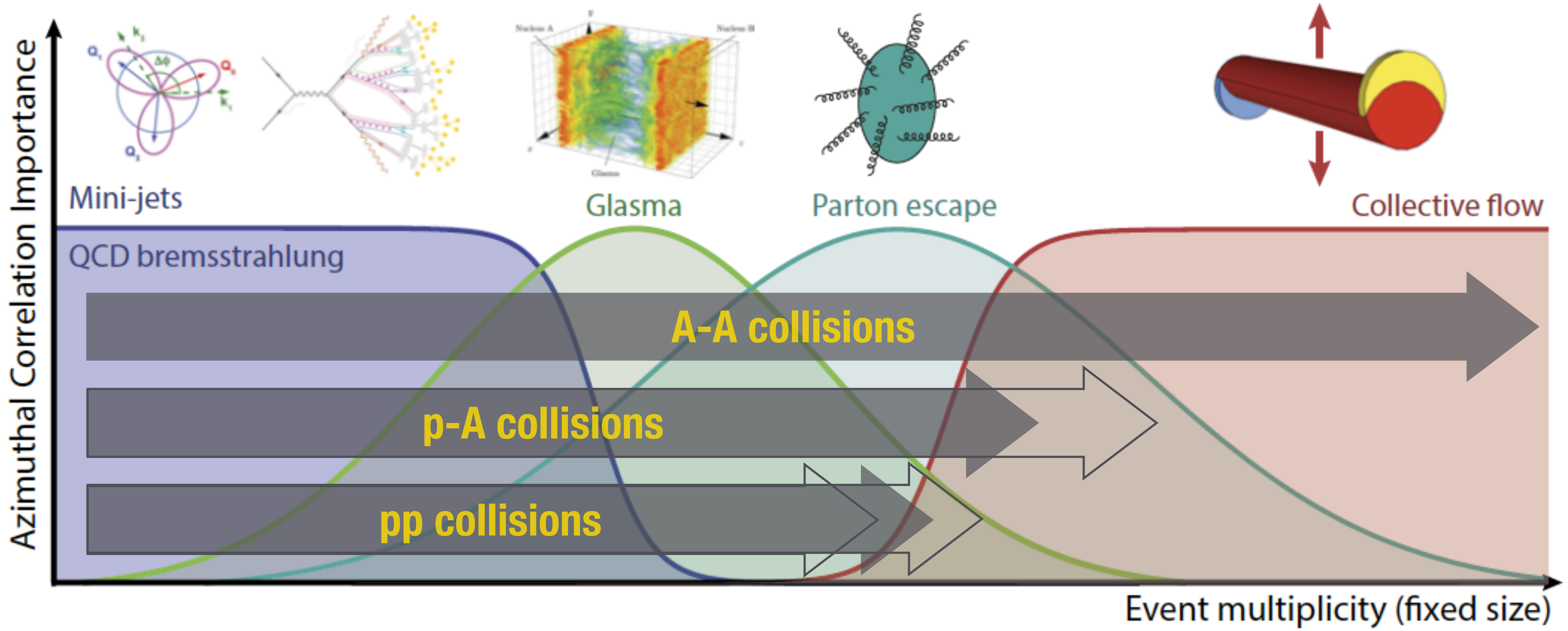

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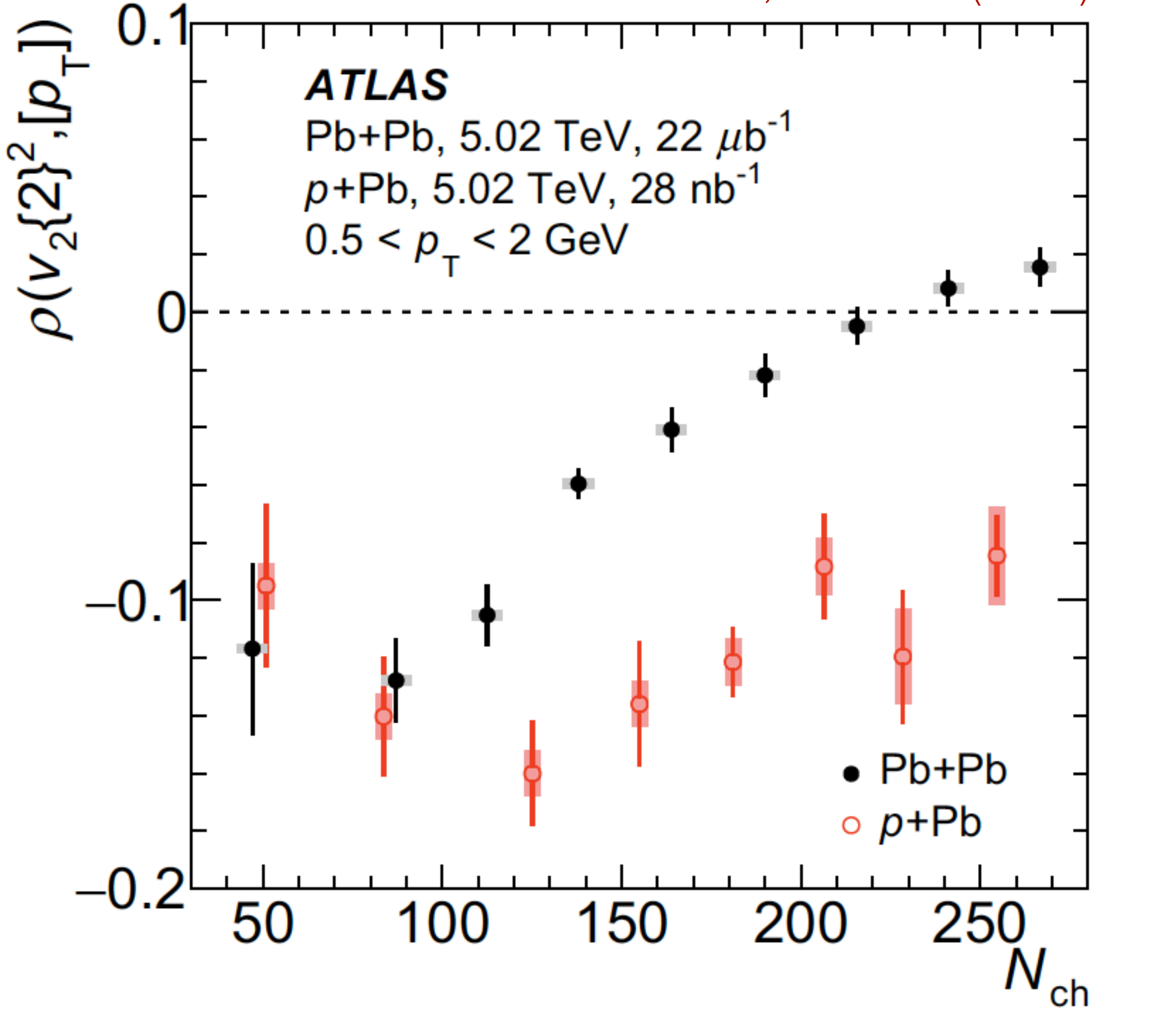
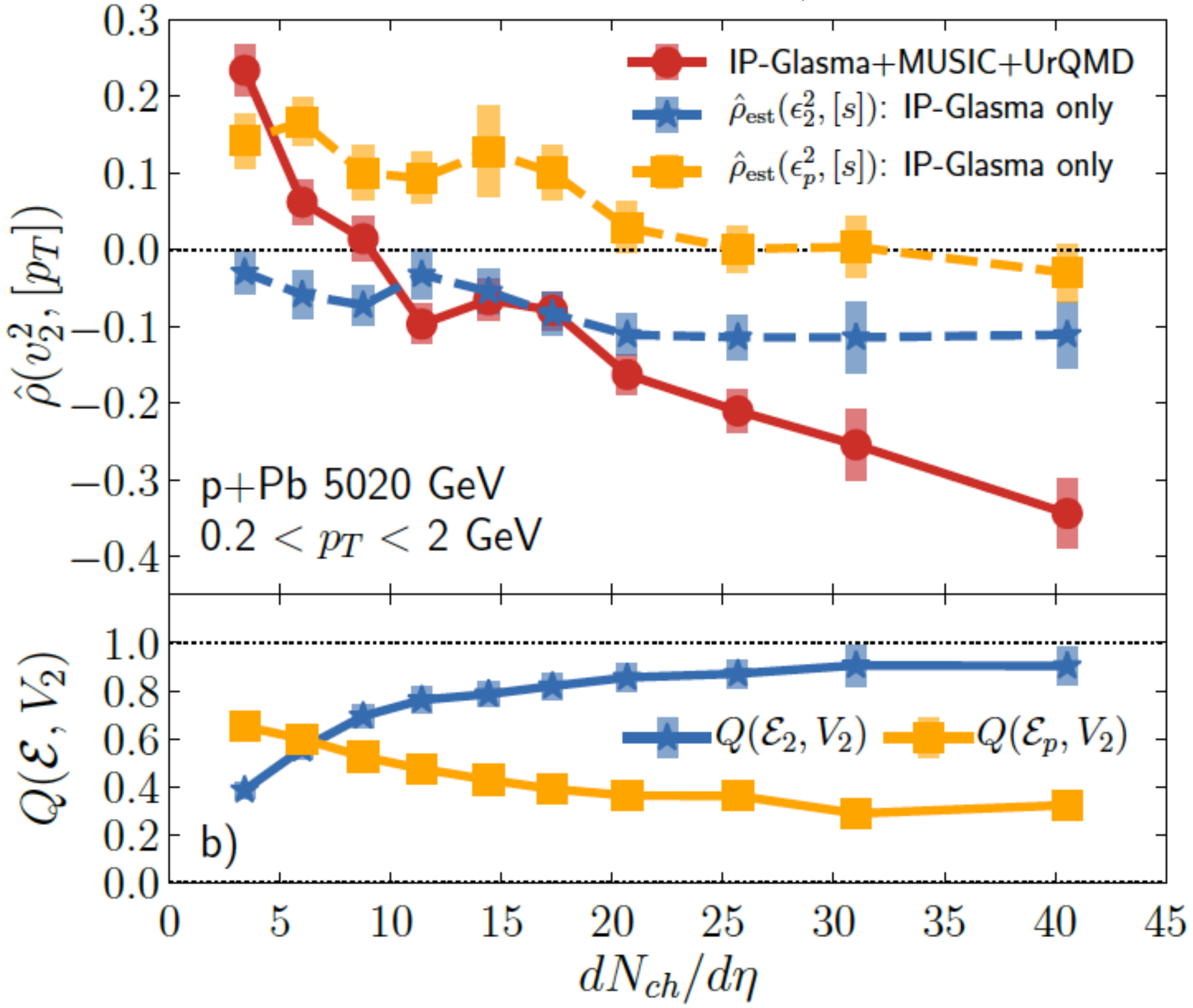
Probing the influence of the initial state

ATLAS, EPJC 79 (2019) 985



Giacalone et al., arXiv:2006.15721



- Initial (gluon) momentum anisotropy important at low multiplicities
- Initial spatial anisotropy important at high multiplicities

$$Q(\mathcal{E}, V_2) = \frac{\mathrm{Re}\langle \mathcal{E} V_2^* \rangle}{\sqrt{\langle |\mathcal{E}|^2 \rangle \langle |V_2|^2 \rangle}}$$

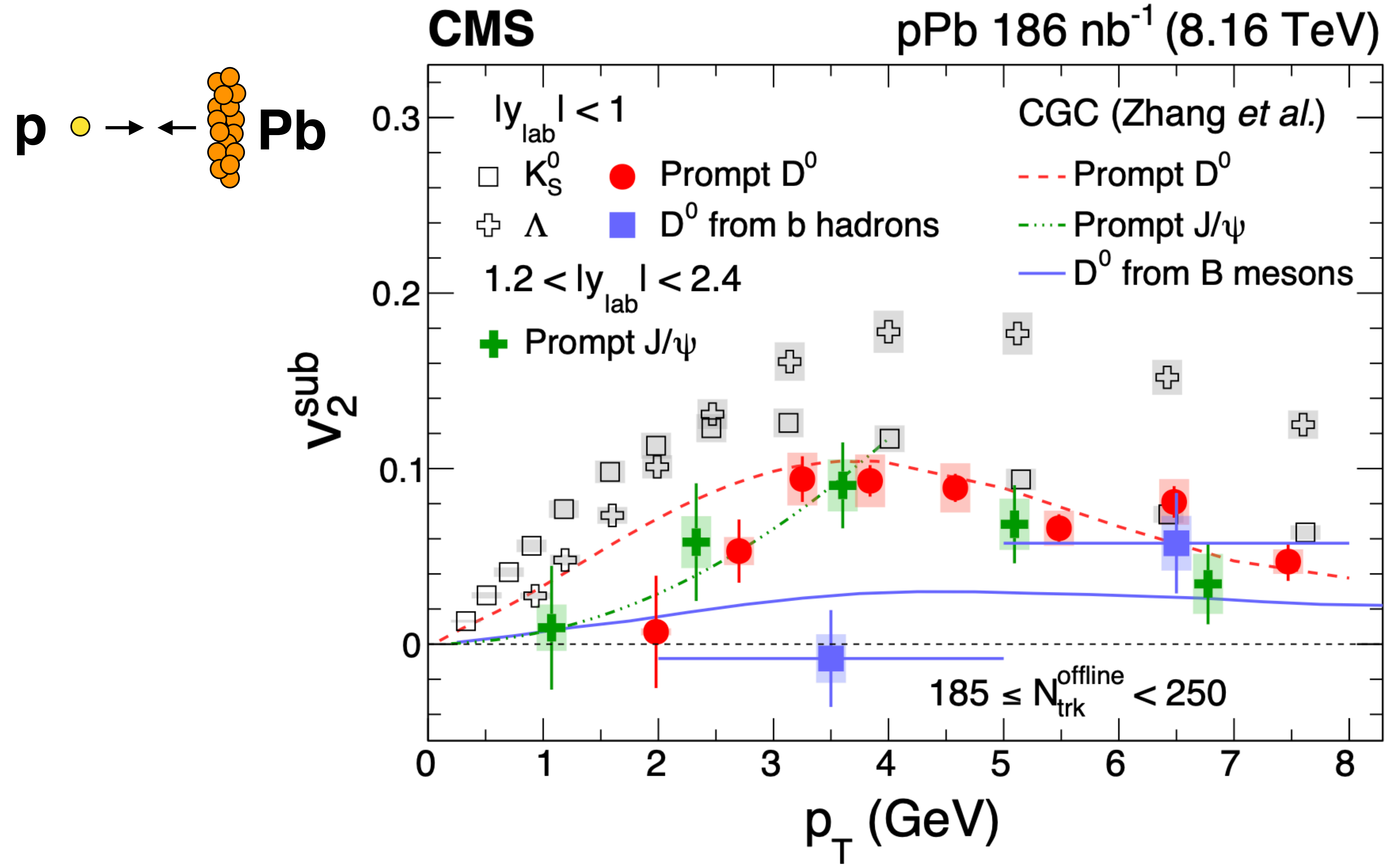
$$\rho = \frac{cov(v_n\{2\}^2, [p_T])}{\sqrt{Var(v_n\{2\}^2)_{dyn}}\sqrt{c_k}}$$

- The observable is predicted to exhibit a **sign change in the presence of initial momentum anisotropy**
- Measurements down to such low multiplicity in small systems would be very interesting, but very challenging

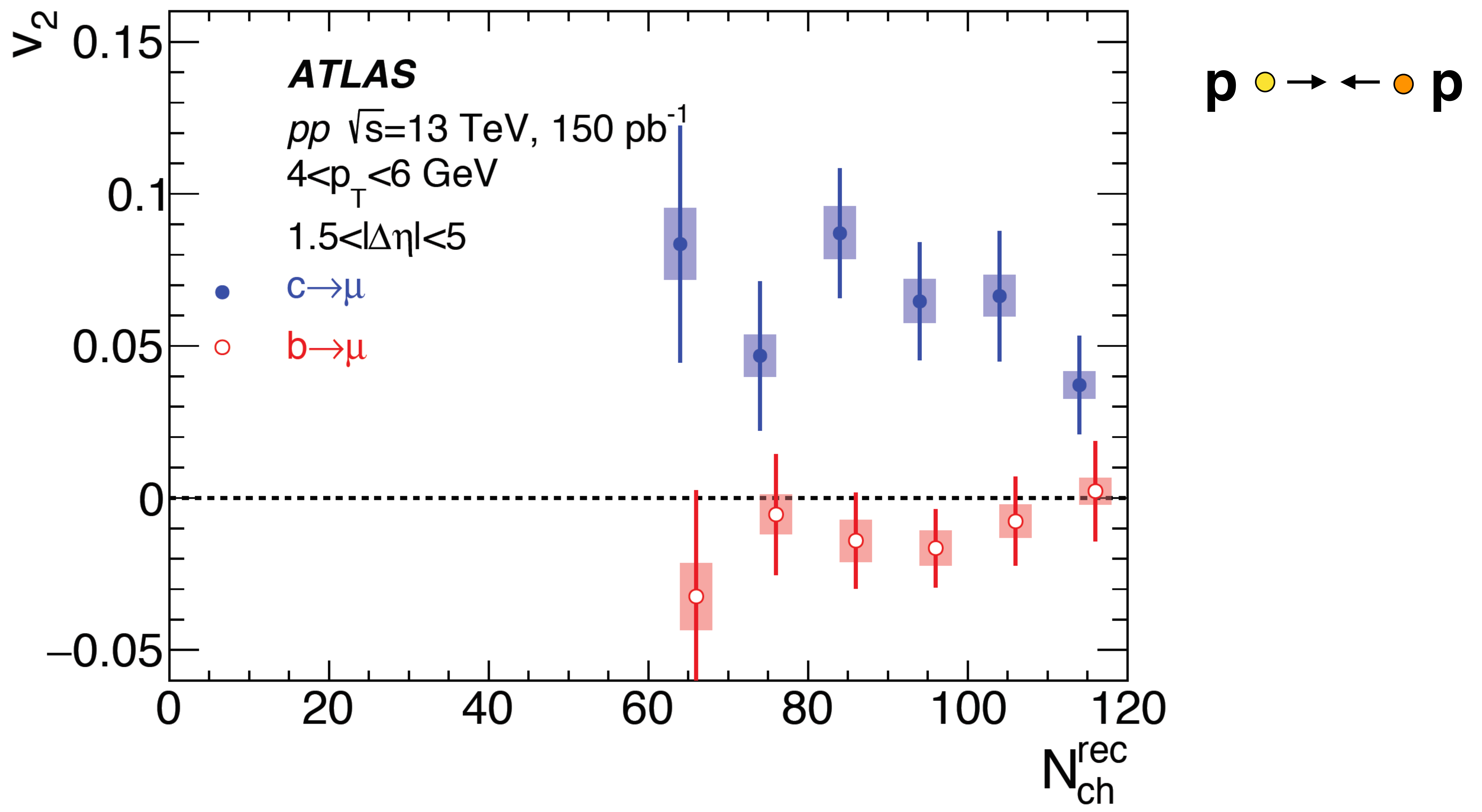
A new promising way to determine the origin of collectivity in small collision systems

Flow of identified (very heavy) particles

CMS, arXiv: 2009.07065



ATLAS, PRL 124, 082301 (2020)

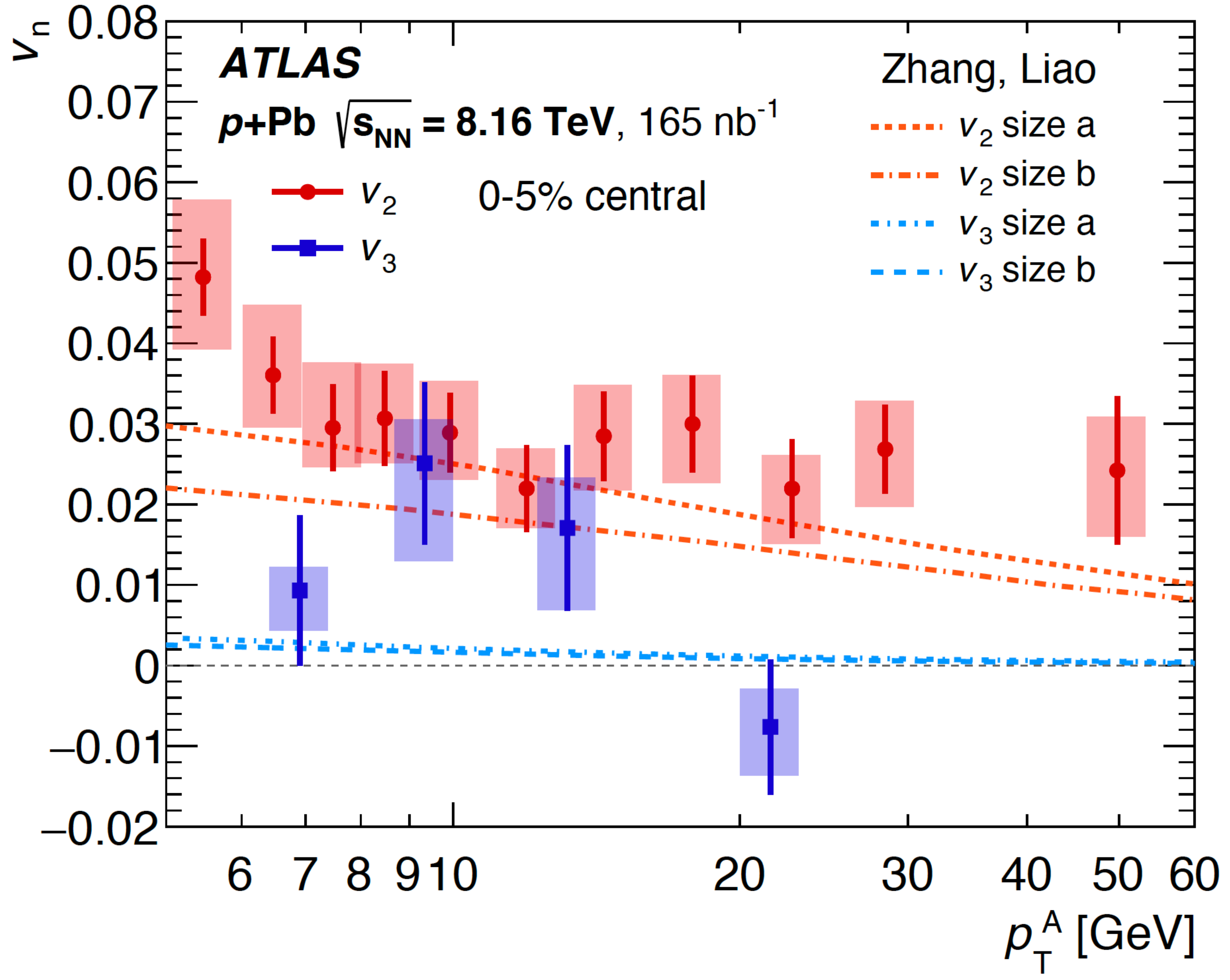


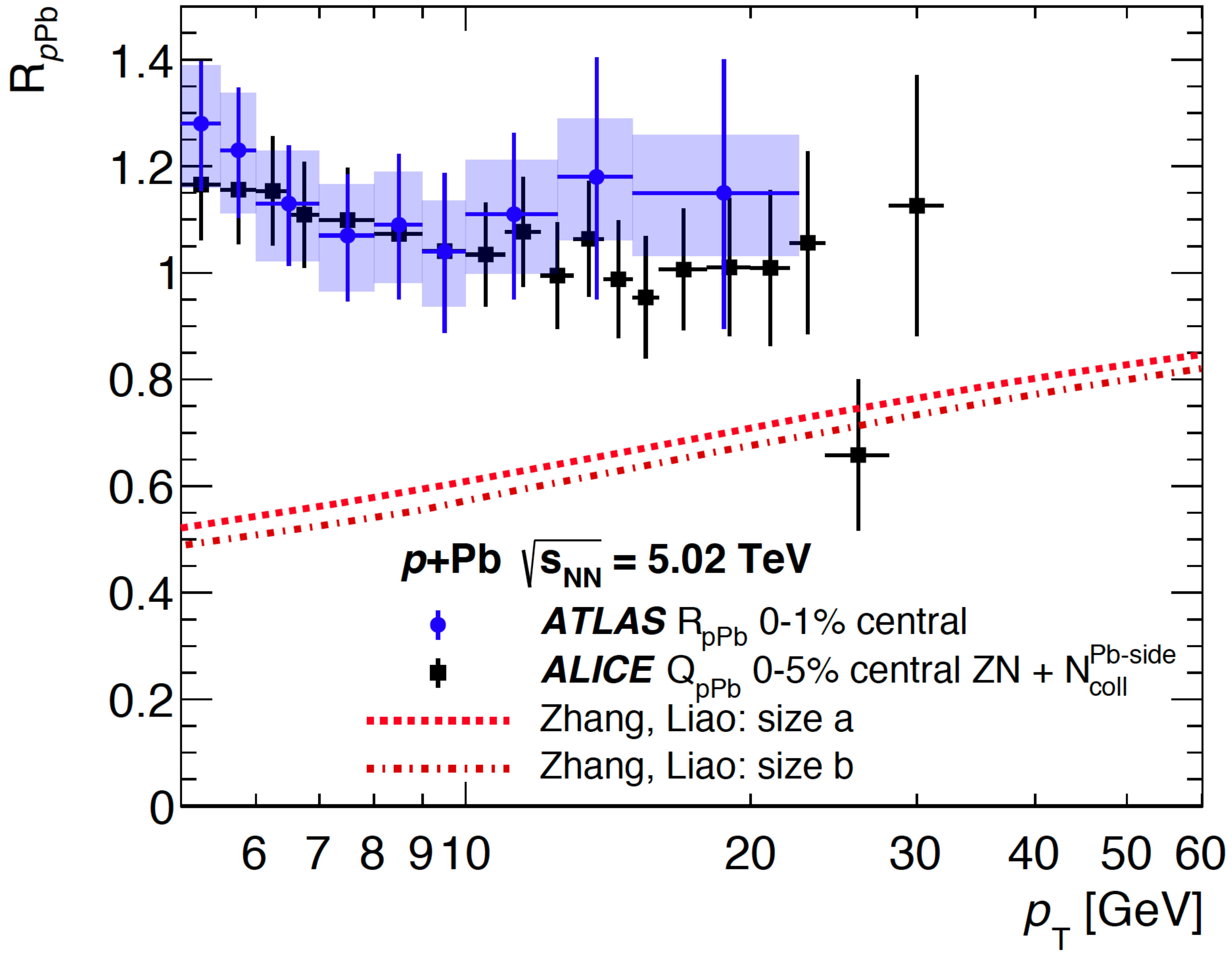
- Finite flow of heavy flavor particles in p-Pb and pp collisions
  - Separate charm and bottom contribution in both collision systems (bottom quark doesn't flow in pp collisions)
  - Description of the results in p-Pb collisions with the CGC model -> collectivity of heavy flavor particles may be **largely influenced by initial state effects**

Zhang et al., PRL 122, 172302 (2019)
Zhang et al., PRD 102, 034010 (2020)

Jet quenching ?

ATLAS, EPJC (2020) 80:73



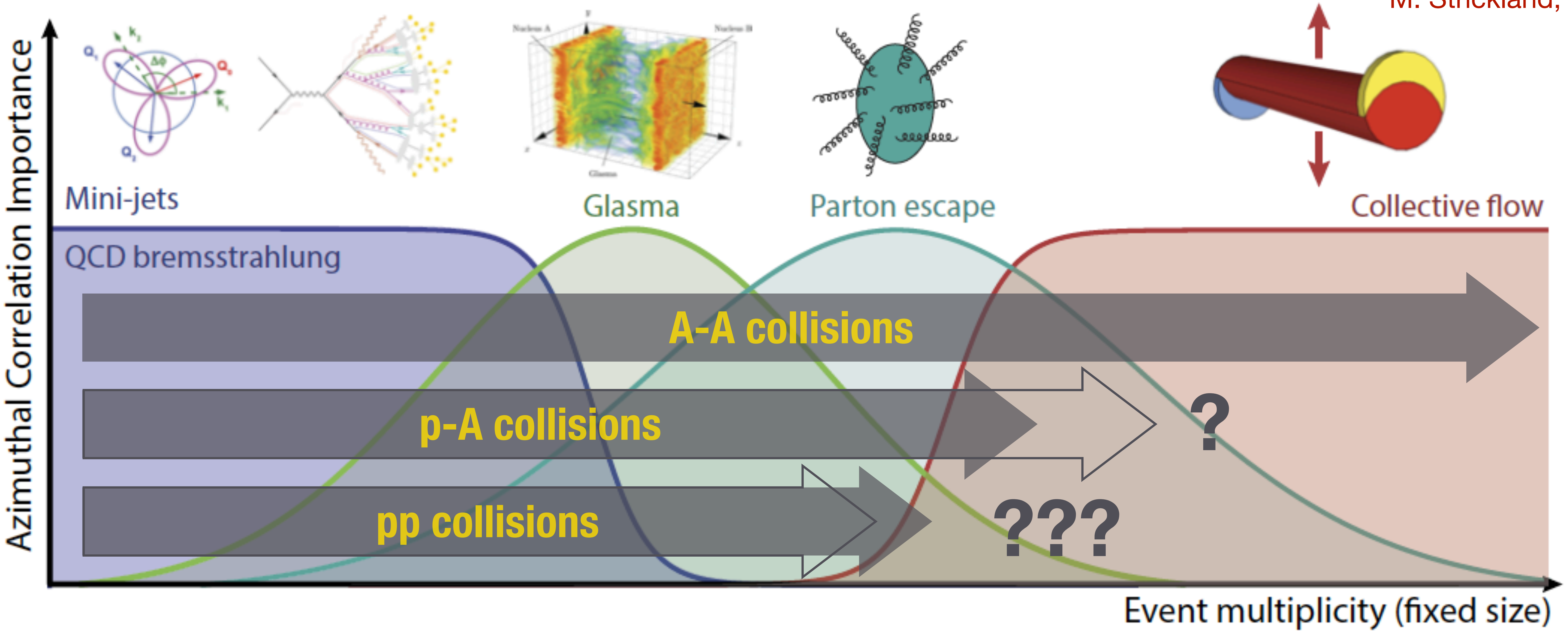


EXPERIMENT	THEORY
$v_2(p_T) > 0$	$v_2(p_T) > 0$
$R_{pPb} \approx 1$	$R_{pPb} < 1$

- Models with parton energy loss in a medium require both finite v_2 at high p_T and $R_{pPb} < 1$
  - Not supported by data
- **Other mechanisms responsible for the finite v_2 at high p_T ?**

Summary

M. Strickland, NPA 982 (2019) 92-98



- p-Pb collisions
  - Experimental data favor the hydrodynamic origin of long-range multi-particle correlations
- pp collisions
  - Hydrodynamic models are challenged by microscopic approaches
- Future Run 3 data will hopefully bring us closer to the understanding of the origin of collectivity in small collision systems

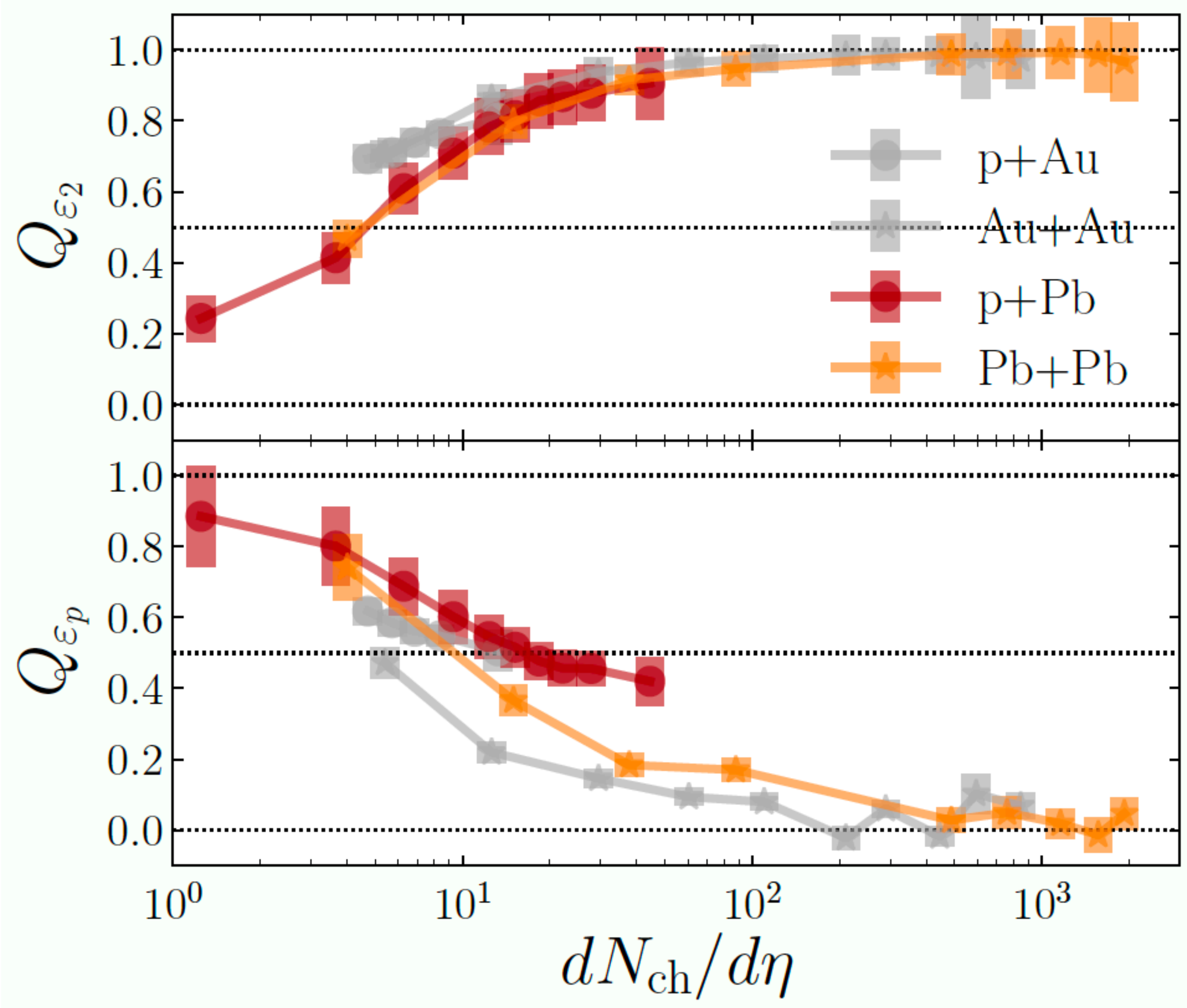
Backup

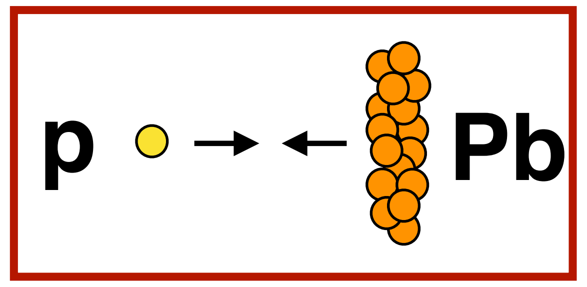
Importance of the initial state momentum anisotropy

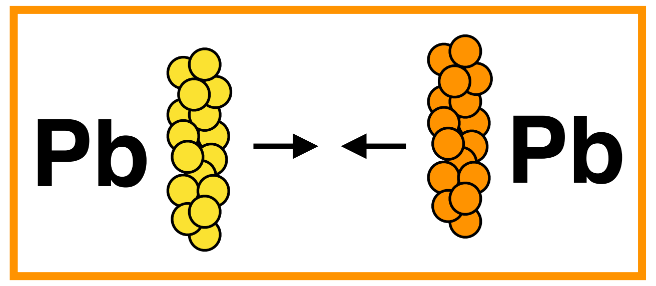
Schenke et al., PLB 803 (2020) 135322
Schenke et al., QM19

$$Q_{\varepsilon_2} = \frac{\mathrm{Re}\langle \vec{\mathscr{E}}_2 \cdot \vec{V}_2^* \rangle}{\sqrt{\langle |\vec{\mathscr{E}}_2|^2 \rangle \langle |\vec{V}_2|^2 \rangle}}$$

$$Q_{\varepsilon_p} = \frac{\mathrm{Re}\langle \vec{\mathscr{E}}_p \cdot \vec{V}_2^* \rangle}{\sqrt{\langle |\vec{\mathscr{E}}_p|^2 \rangle \langle |\vec{V}_2|^2 \rangle}}$$



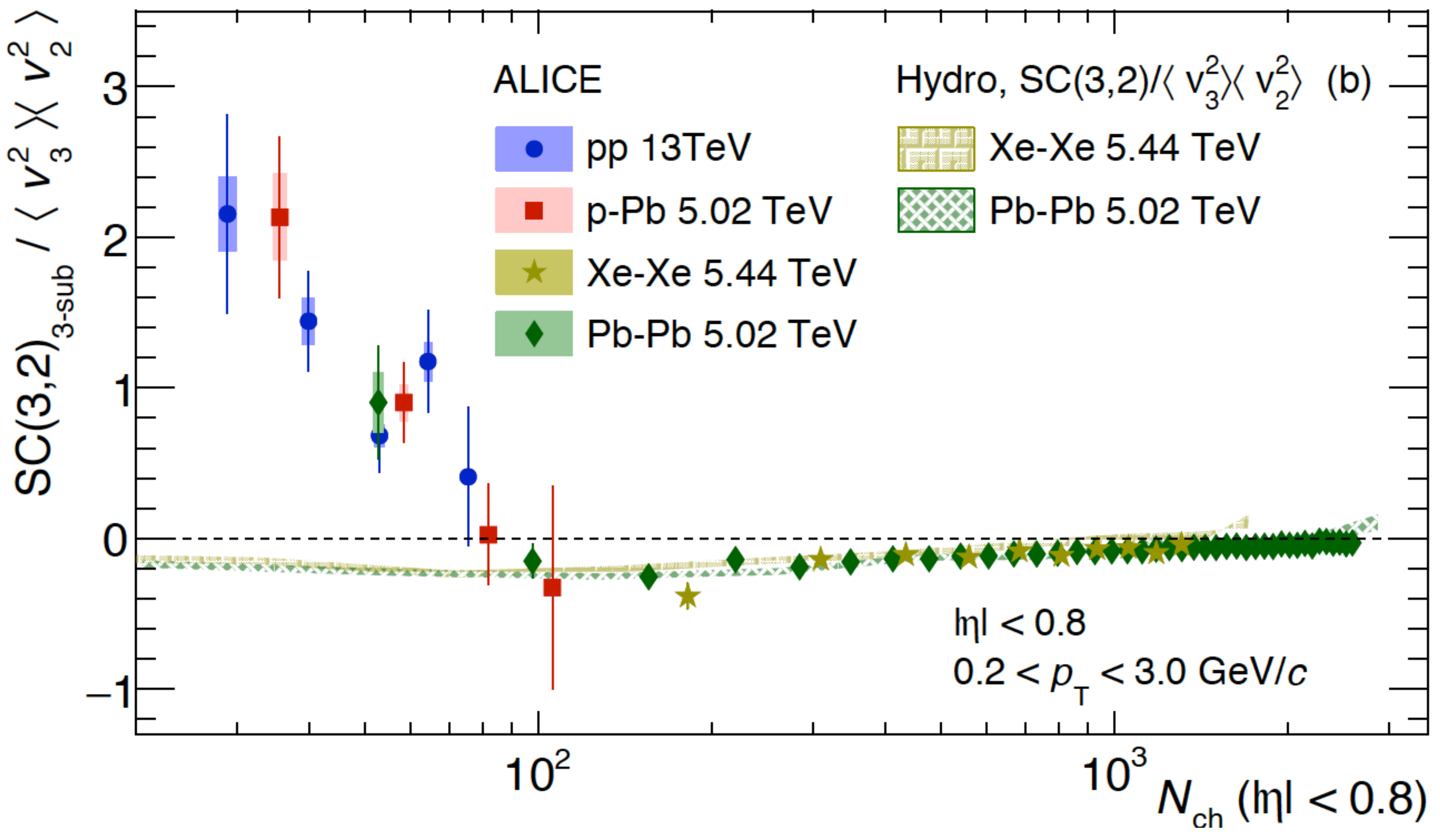




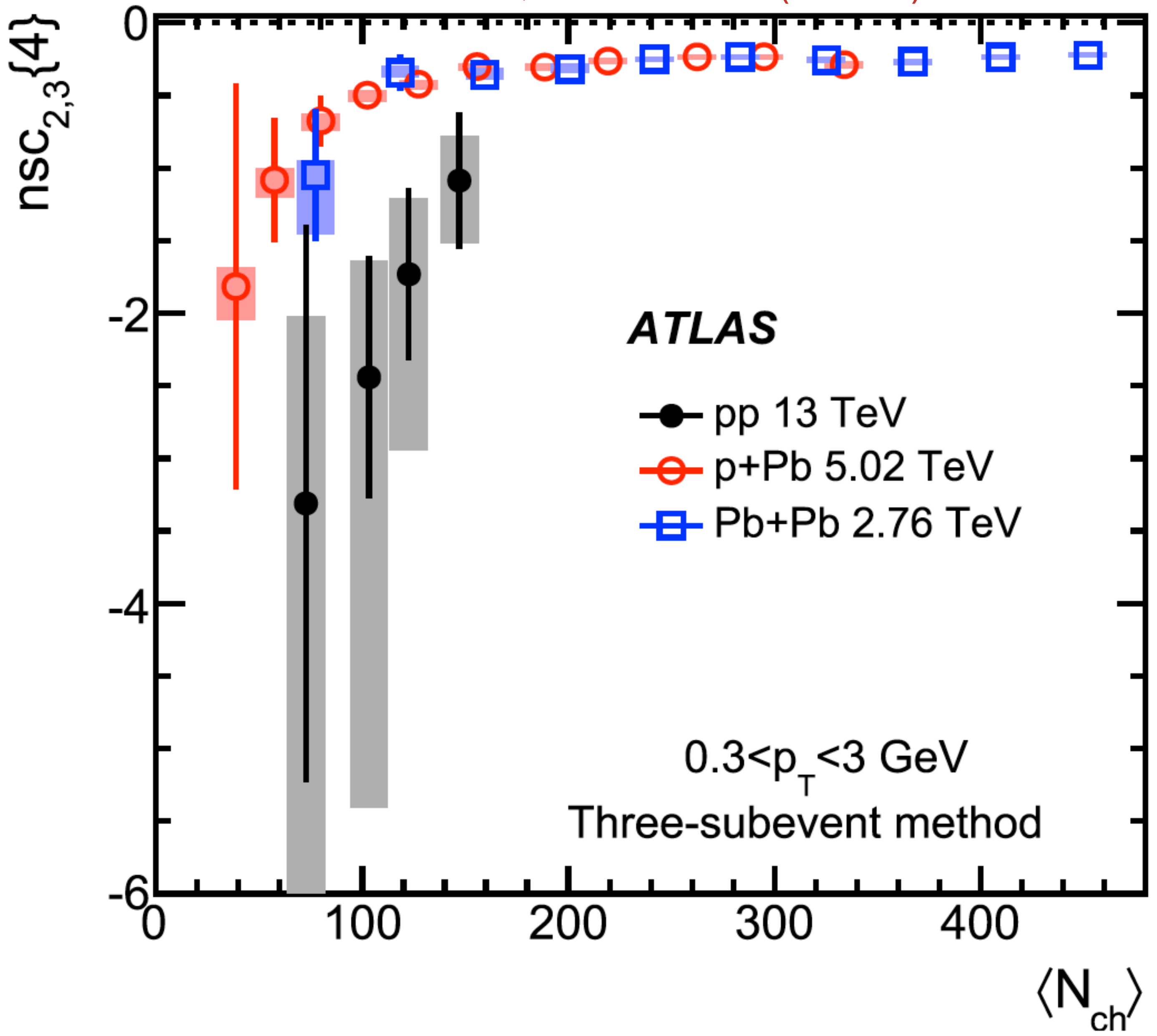
- Initial (gluon) momentum anisotropy important at low multiplicities
- Initial spatial anisotropy important at high multiplicities
  - Although the initial momentum anisotropy may have non-negligible effect in small systems even at high multiplicity

Symmetric Cumulants

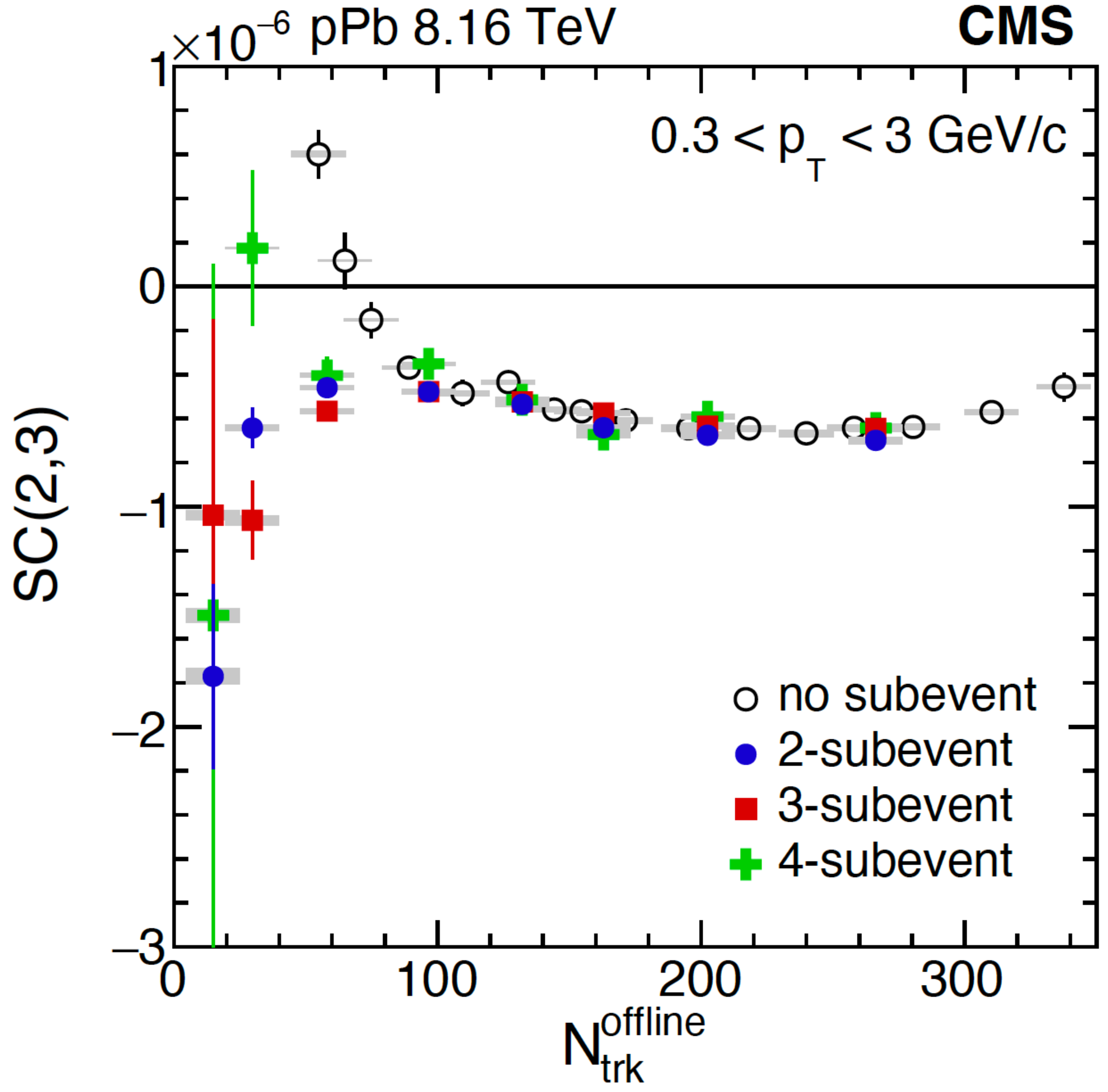
ALICE, PRL 123, 142301 (2019)



ATLAS, PLB 789 (2019) 444



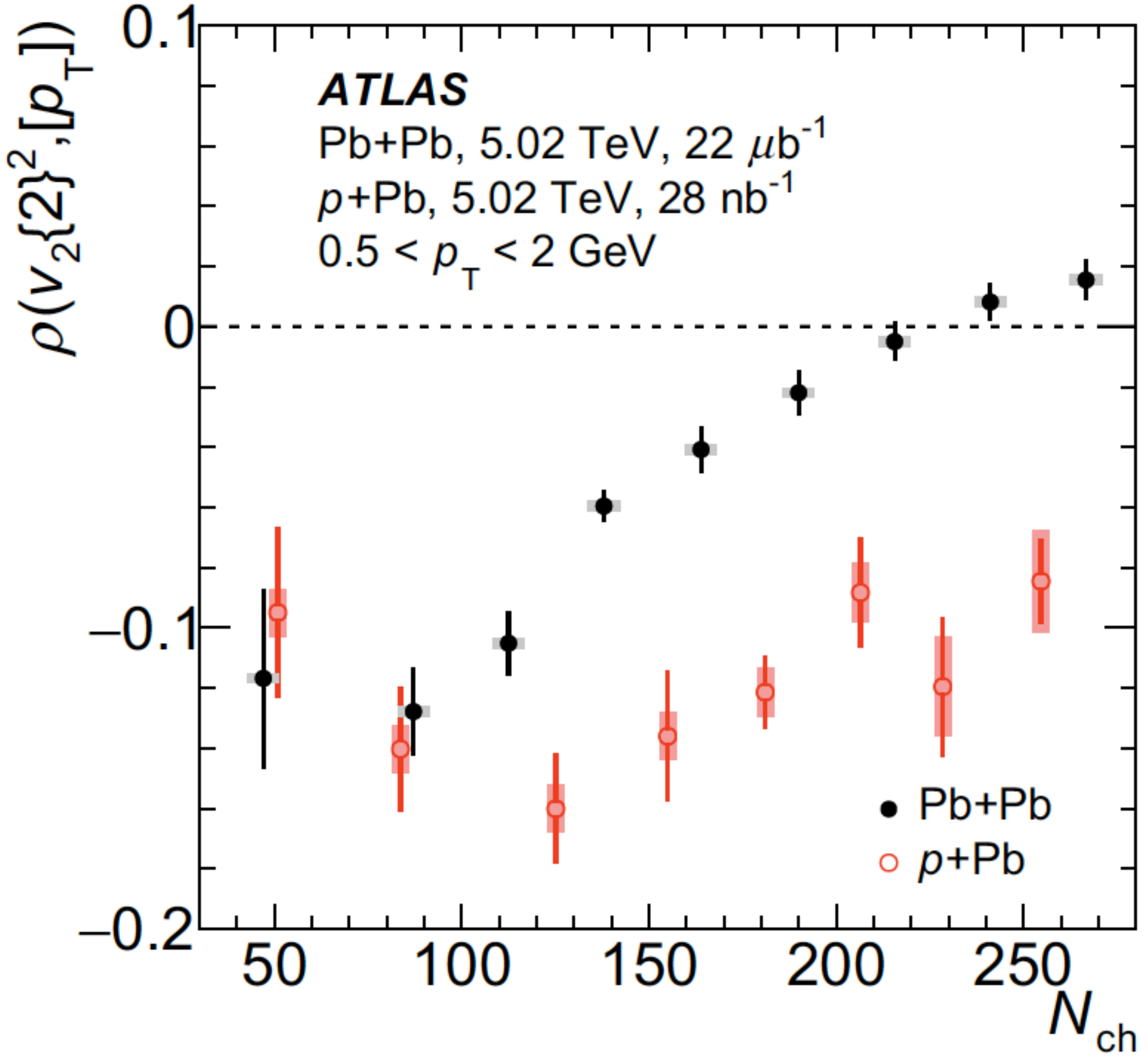
CMS, arXiv: 1905.09935



- SC(3,2): correlation between v_2 and v_3
- Dependence on multiplicity shows a common trend between different collision systems, smoothly with multiplicity
- May point to a common origin of the observed collectivity, which evolves with multiplicity
- Note: the trend at low multiplicities is different for ALICE and ATLAS & CMS -> probably due to different acceptance and subsequent decorrelation effects and/or residual non-flow

Correlations of v_2 and $[p_T]$

ATLAS, EPJC 79 (2019) 985



$$\rho = \frac{cov(v_n\{2\}^2, [p_T])}{\sqrt{Var(v_n\{2\}^2)_{dyn}\sqrt{c_k}}}$$

$$cov(v_n\{2\}^2, [p_T]) = \langle \frac{1}{N_{pairs}N} \sum_{a \neq b \neq c} e^{in(\varphi_a - \varphi_c)}(p_{T,b} - \langle [p_T] \rangle) \rangle$$

$$Var(v_n\{2\}^2)_{dyn} = \langle\langle 4 \rangle\rangle - \langle\langle 2 \rangle\rangle^2$$

$$c_k = \langle \frac{1}{N_B(N_B - 1)\sum_b \sum_{b \neq b'} (p_{T,b} - \langle [p_T] \rangle)(p_{T,b'} - \langle [p_T] \rangle)} \rangle$$

Z-tagged pp collisions

- Selection of events with a hard scattering of momentum transfer $Q^2 \geq (80\ \mathrm{GeV})^2$ (Z-boson tagged events)
- Measurements are compatible with inclusive pp collisions
- Long-range correlations are not significantly affected by the presence of a hard-scattering process

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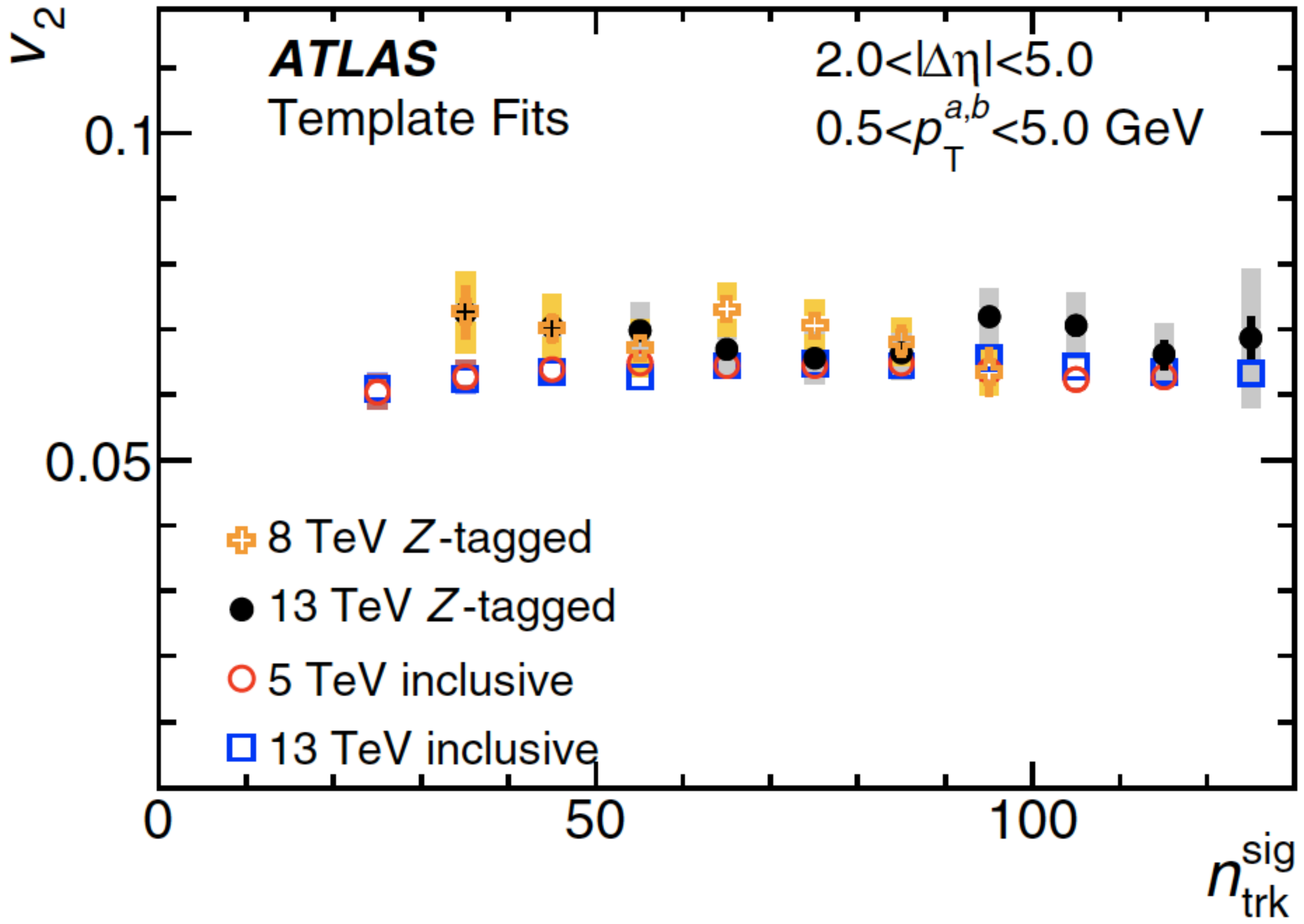
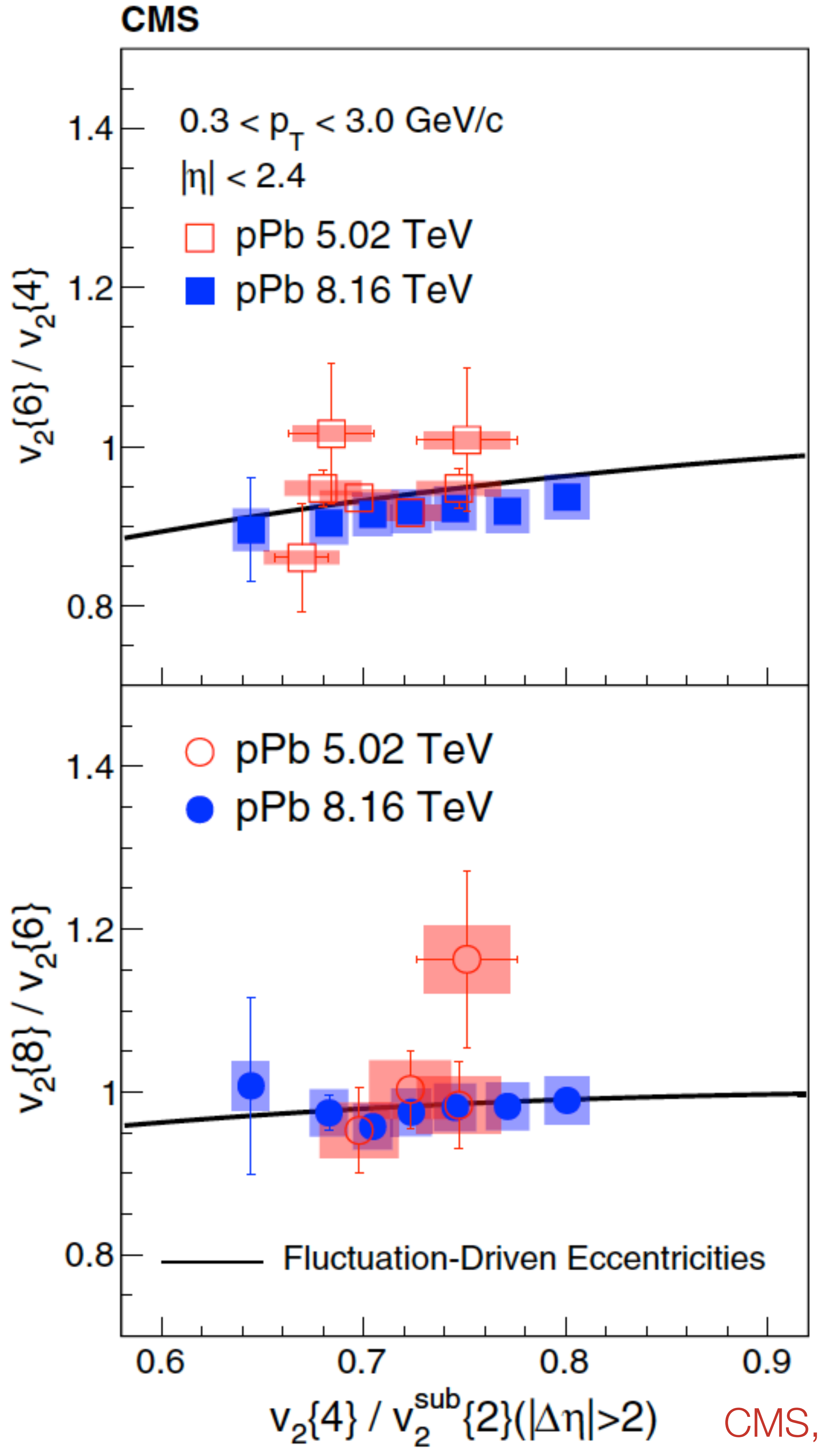


Ratio of multi-particle cumulants



CMS, PRC 101, 014912 (2020)

- Ratios of multi-particle cumulants are consistent with a purely fluctuation driven origin of azimuthal asymmetry (at the reported multiplicity range)
- Assumption of direct correspondence of ratios of $v_n\{m\}$ to ratios of $\varepsilon_n\{m\}$ within the hydrodynamic picture
  - Although, it was shown that a non-negligible cubic term is present in hydrodynamic calculations in pp collisions   Zhao et al., arXiv: 2001.06742