New possibilities to study collectivity in small systems opened with the future high-energy pp programme at the LHC

Katarína Křížková Gajdošová
Czech Technical University in Prague

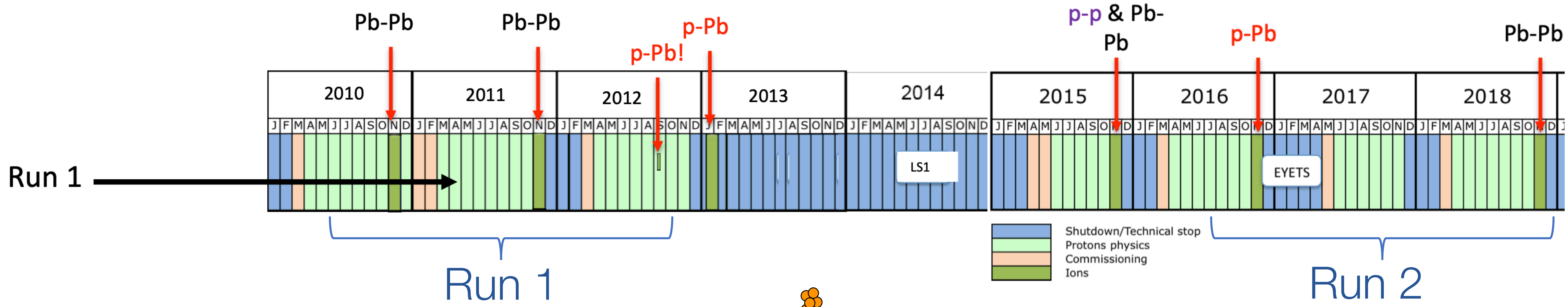
EF07: High Density QCD in Small Collision System
28th October 2020

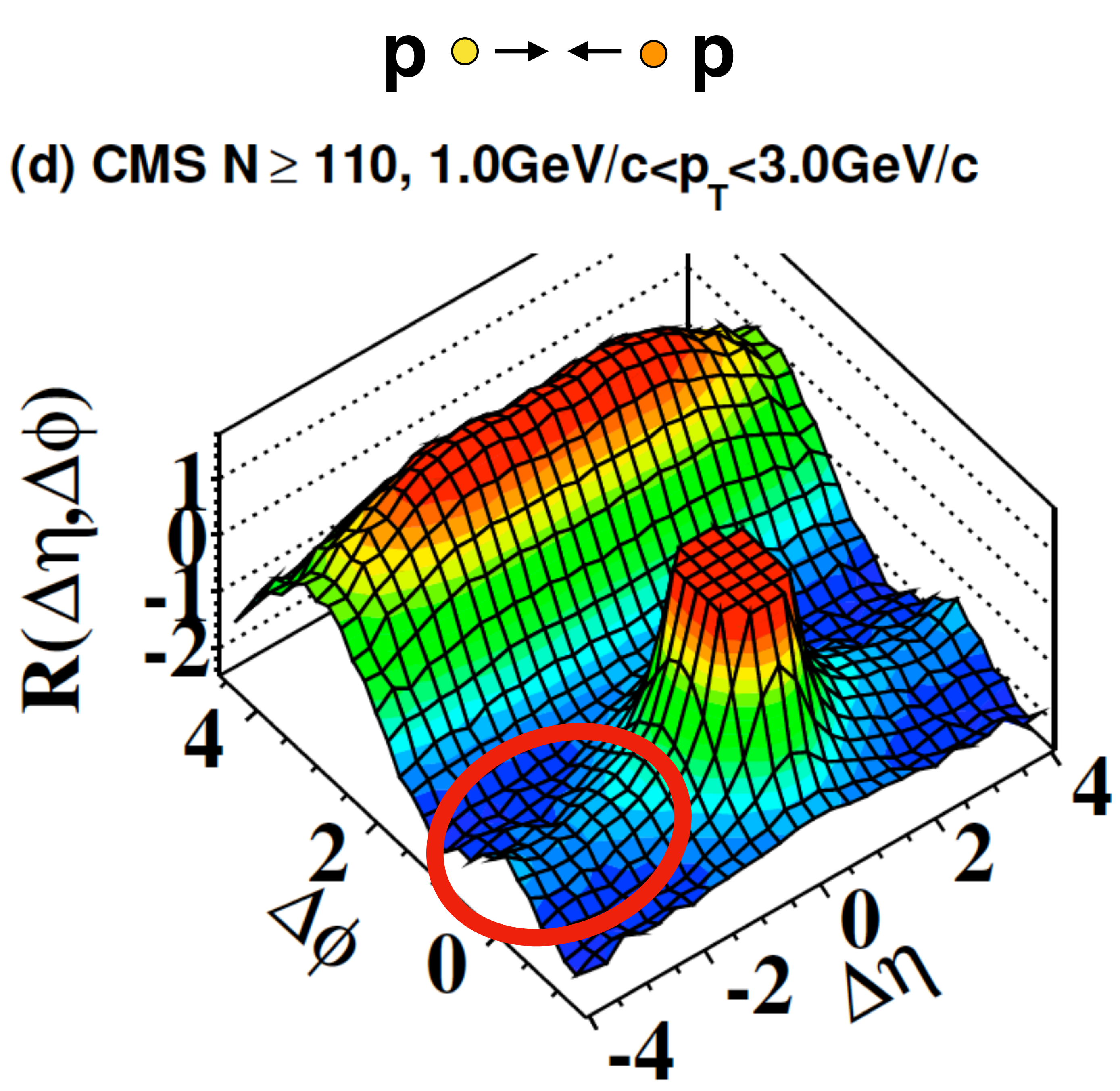
Supported by the Ministry of Education, Youth and Sports of the Czech Republic under grant „International Mobility of Researchers MSCA IF III at CTU in Prague“ CZ.02.2.69/0.0/0.0/16 027/0008465

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

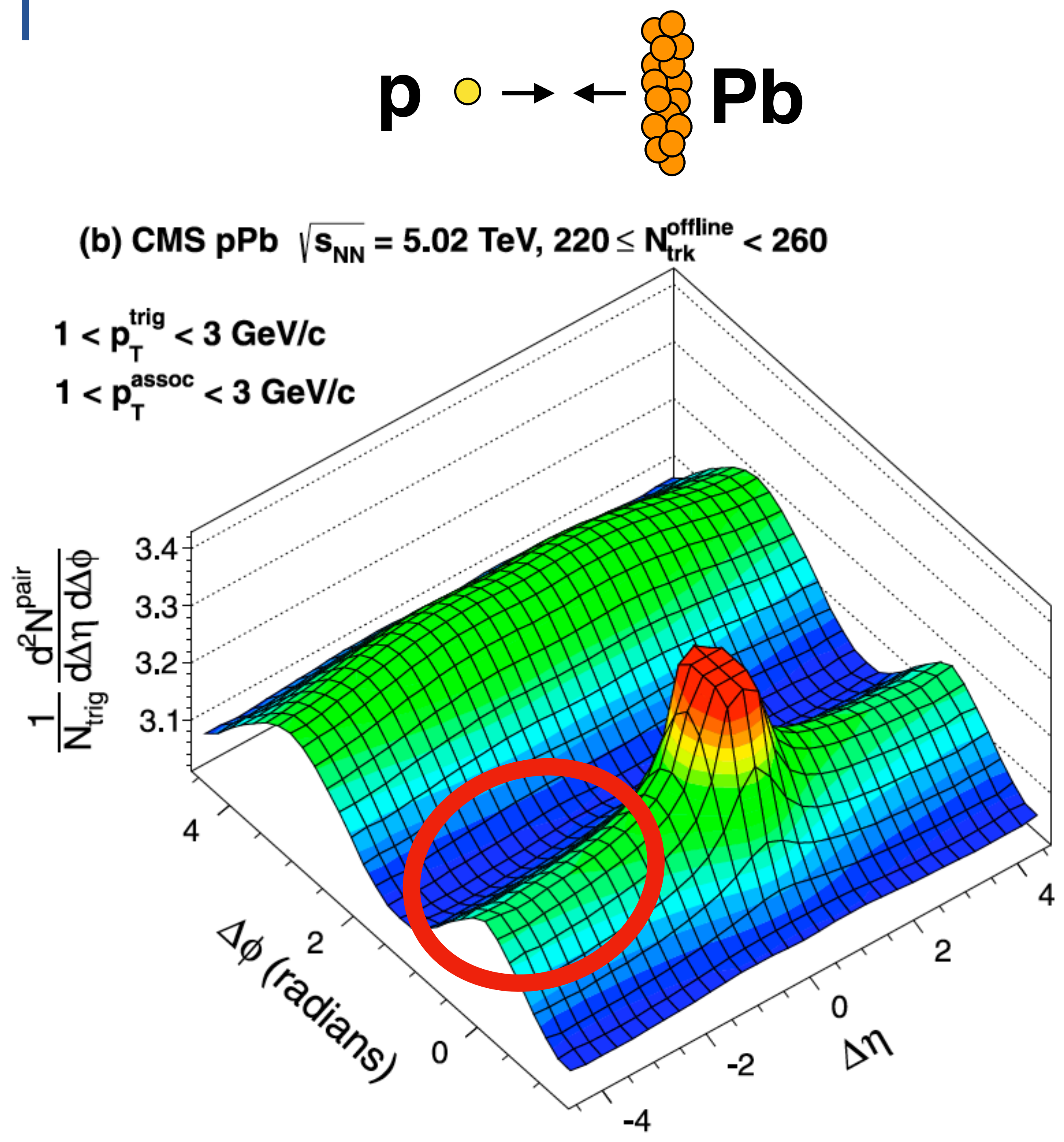
MINISTERSTVO ŠKOLSTVÍ, MLÁDEŽE A TĚLOVÝCHOVY

Fruitful results during Run 1 and Run 2





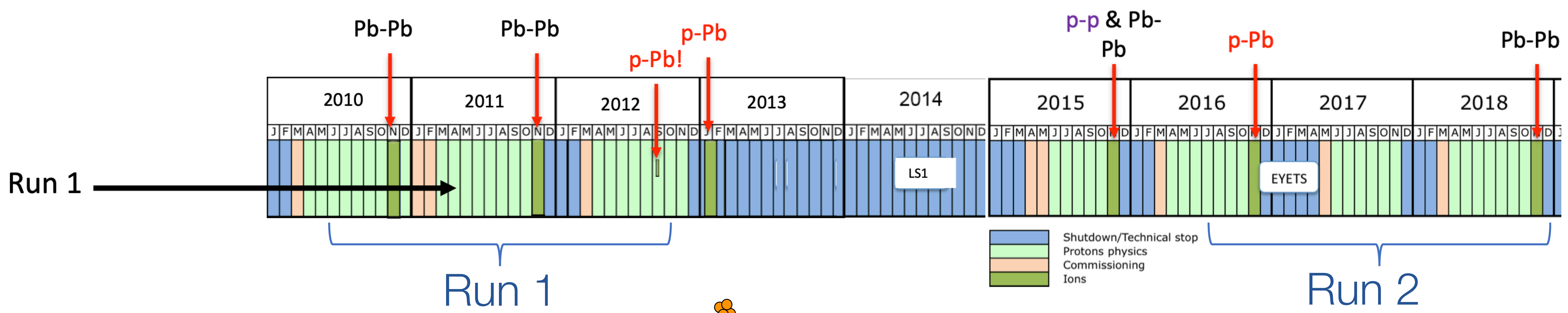
CMS, JHEP 09 (2010) 091

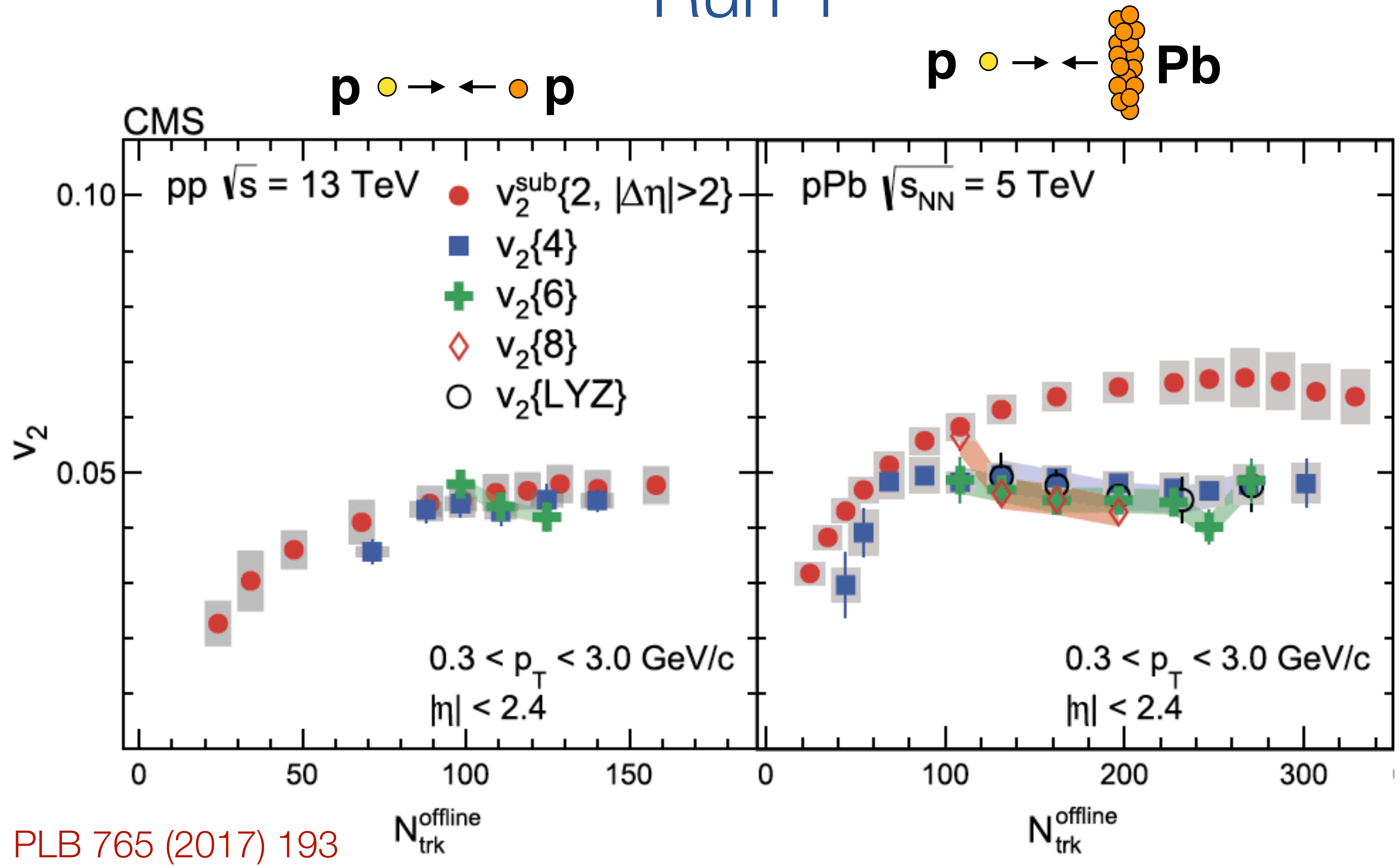


CMS, PLB 724 (2013) 213

- Near-side ridge found in high-multiplicity collisions

Fruitful results during Run 1 and Run 2

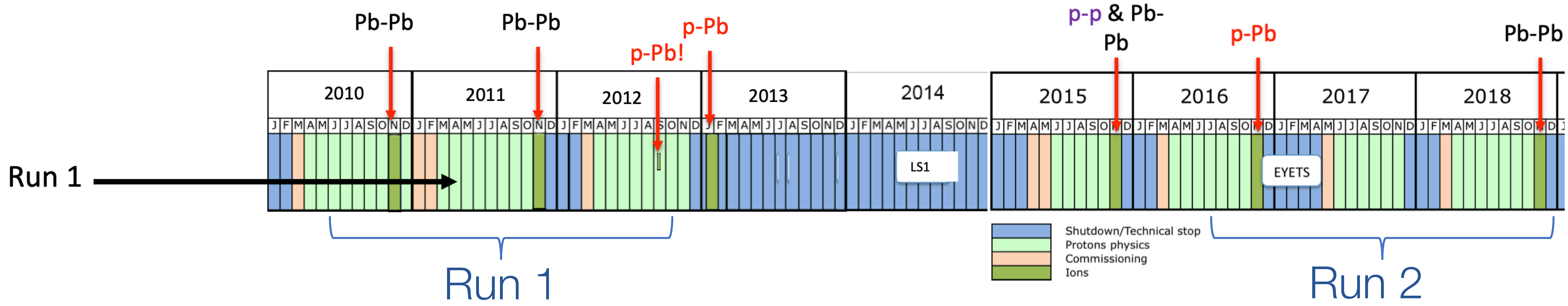


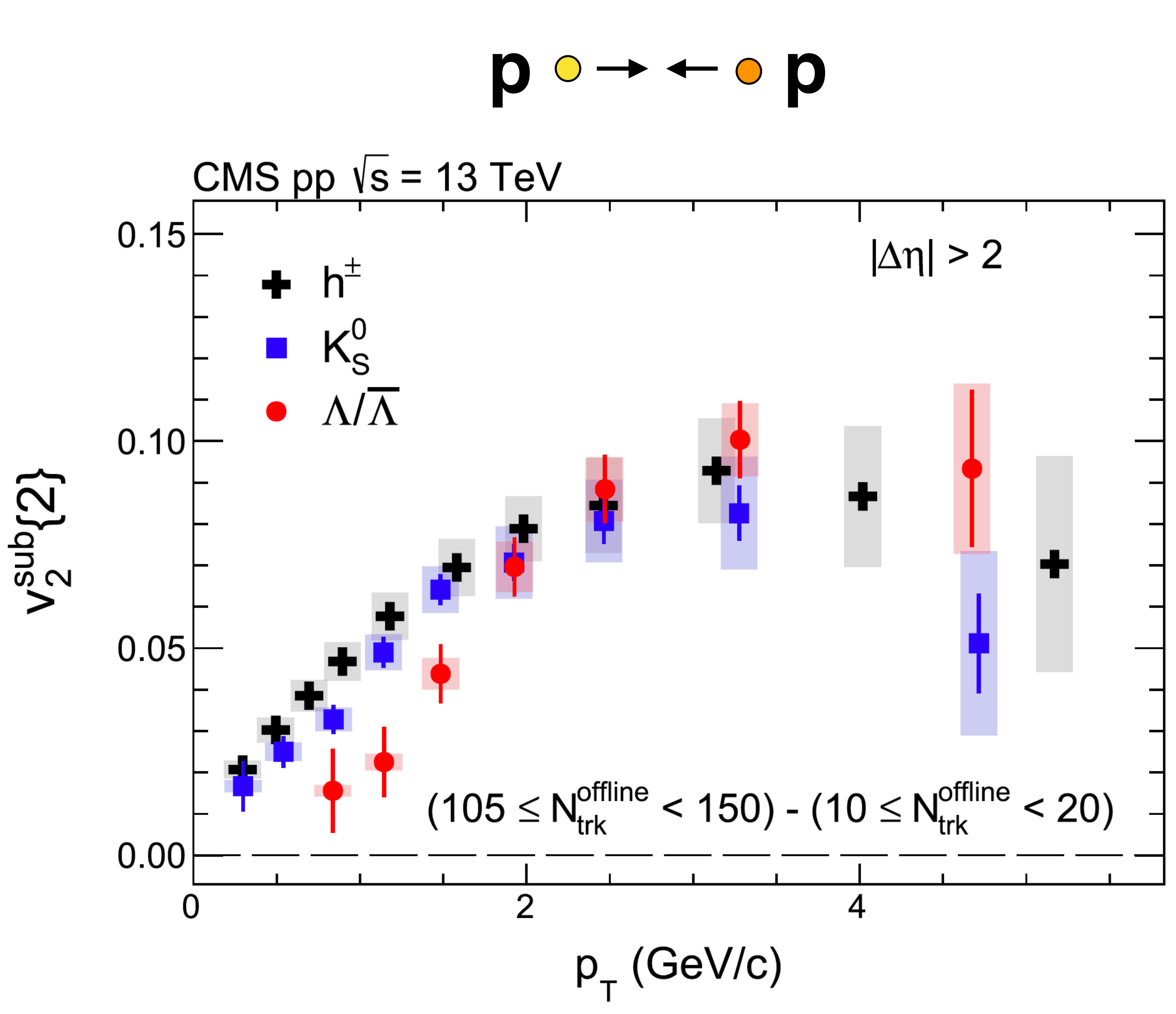


CMS, PLB 765 (2017) 193

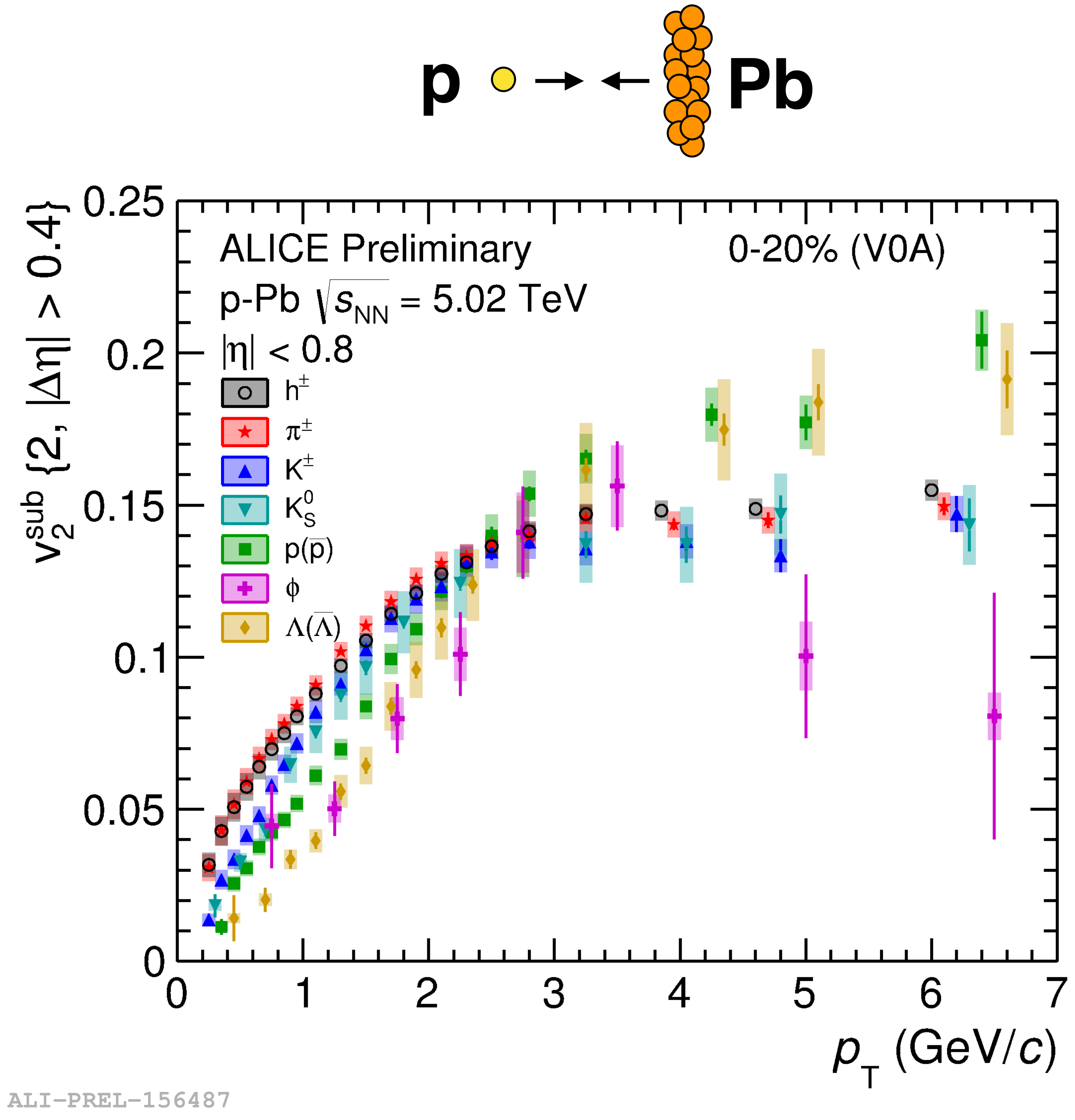
- Near-side ridge found in high-multiplicity collisions
- Multi-particle correlations confirmed in pp and p-Pb collisions

Fruitful results during Run 1 and Run 2





CMS, PLB 765 (2017) 193



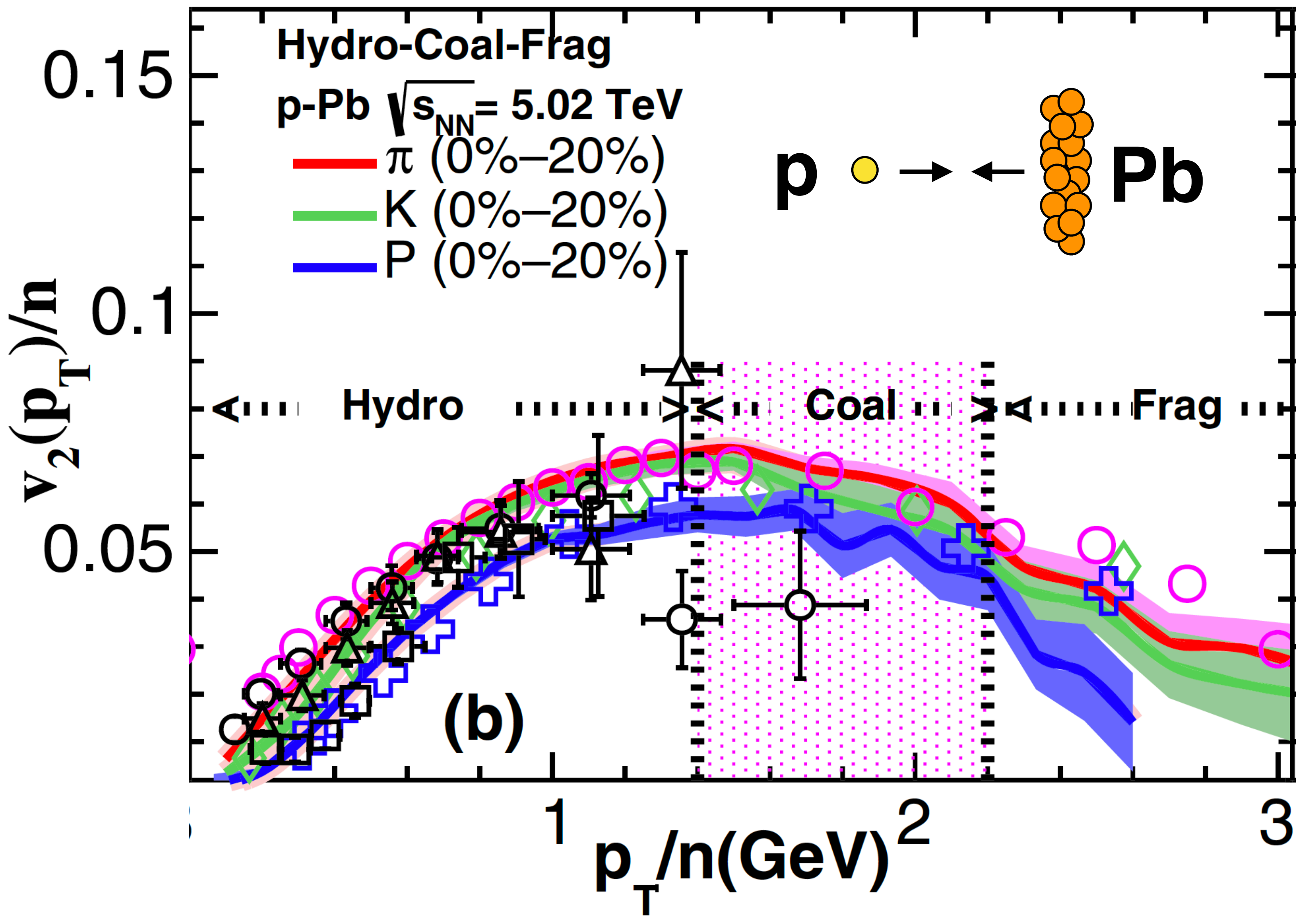
- Near-side ridge found in high-multiplicity collisions
- Multi-particle correlations confirmed in pp and p-Pb collisions
- Mass ordering (and baryon/meson grouping)

Theoretical description

Initial state effects	Final state effects
Initial momentum correlations Not correlated with initial geometry	*Interactions in the final state* Correlated with initial geometry
CGC	Hydrodynamics Transport theory

Pb-Pb

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



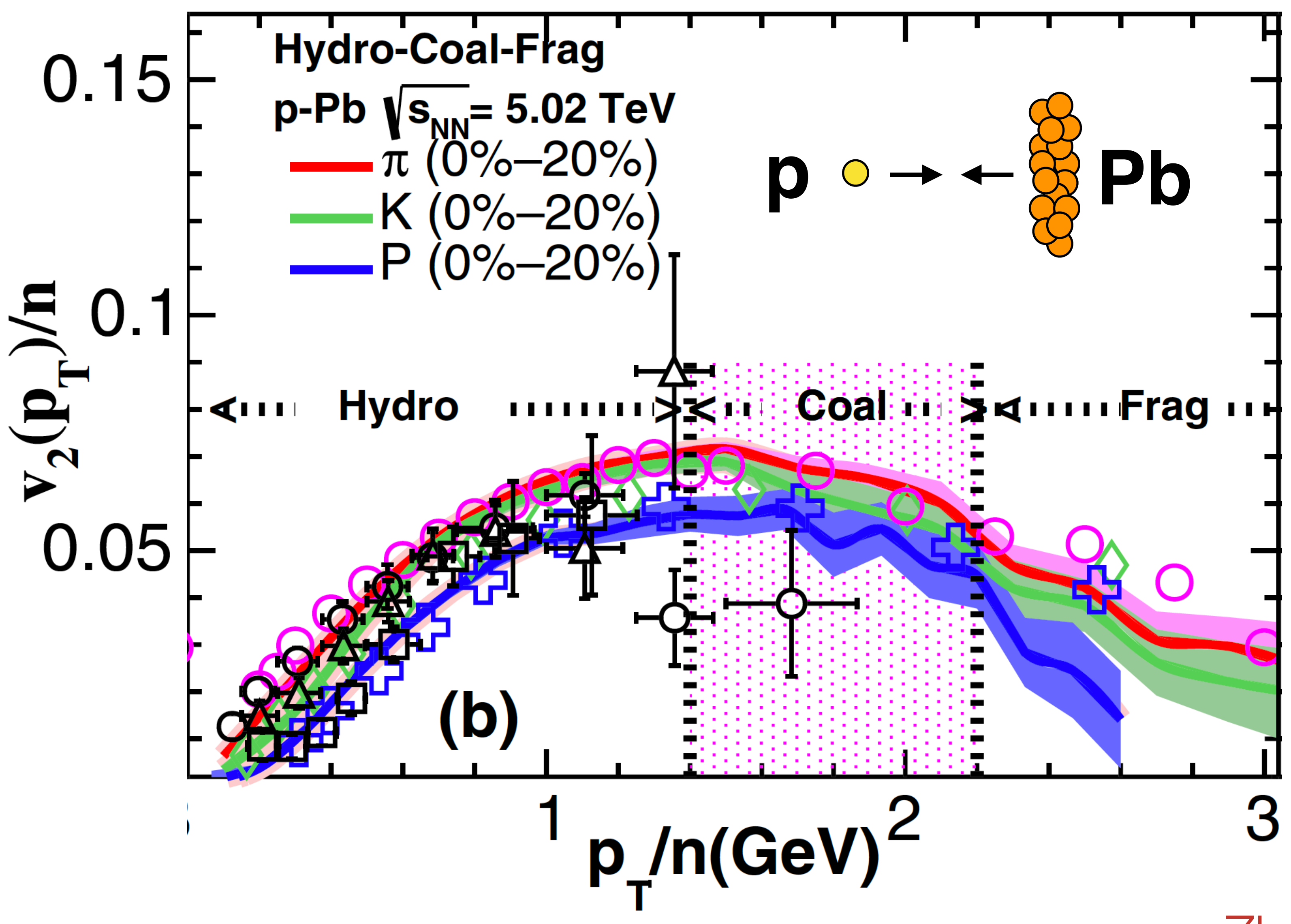
- Final state models provide good description of p-Pb collisions

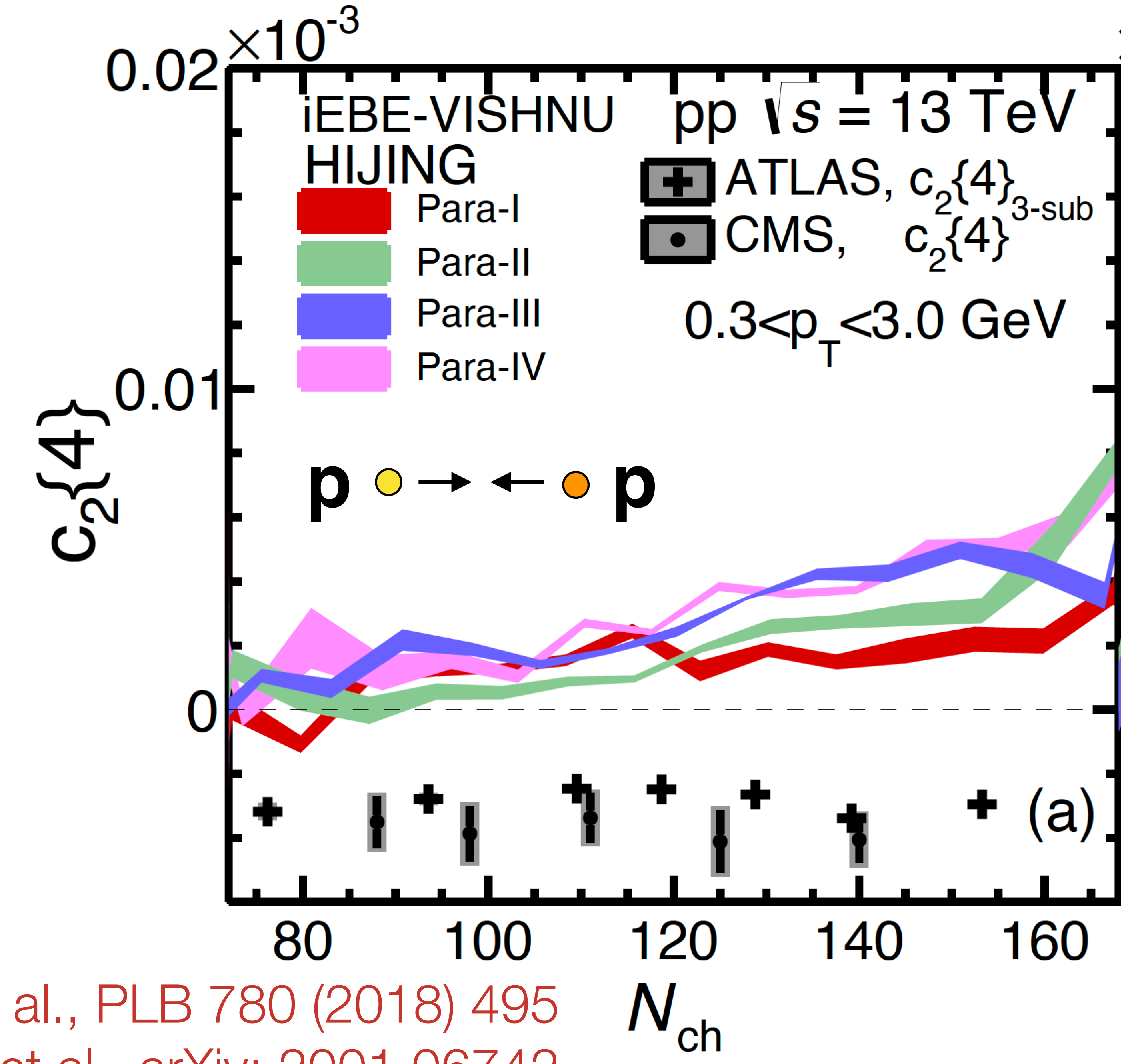
Initial state effects	Final state effects
Initial momentum correlations	*Interactions in the final state*
Not correlated with initial geometry	Correlated with initial geometry
CGC	Hydrodynamics Transport theory

p-Pb Pb-Pb

Theoretical description

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





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

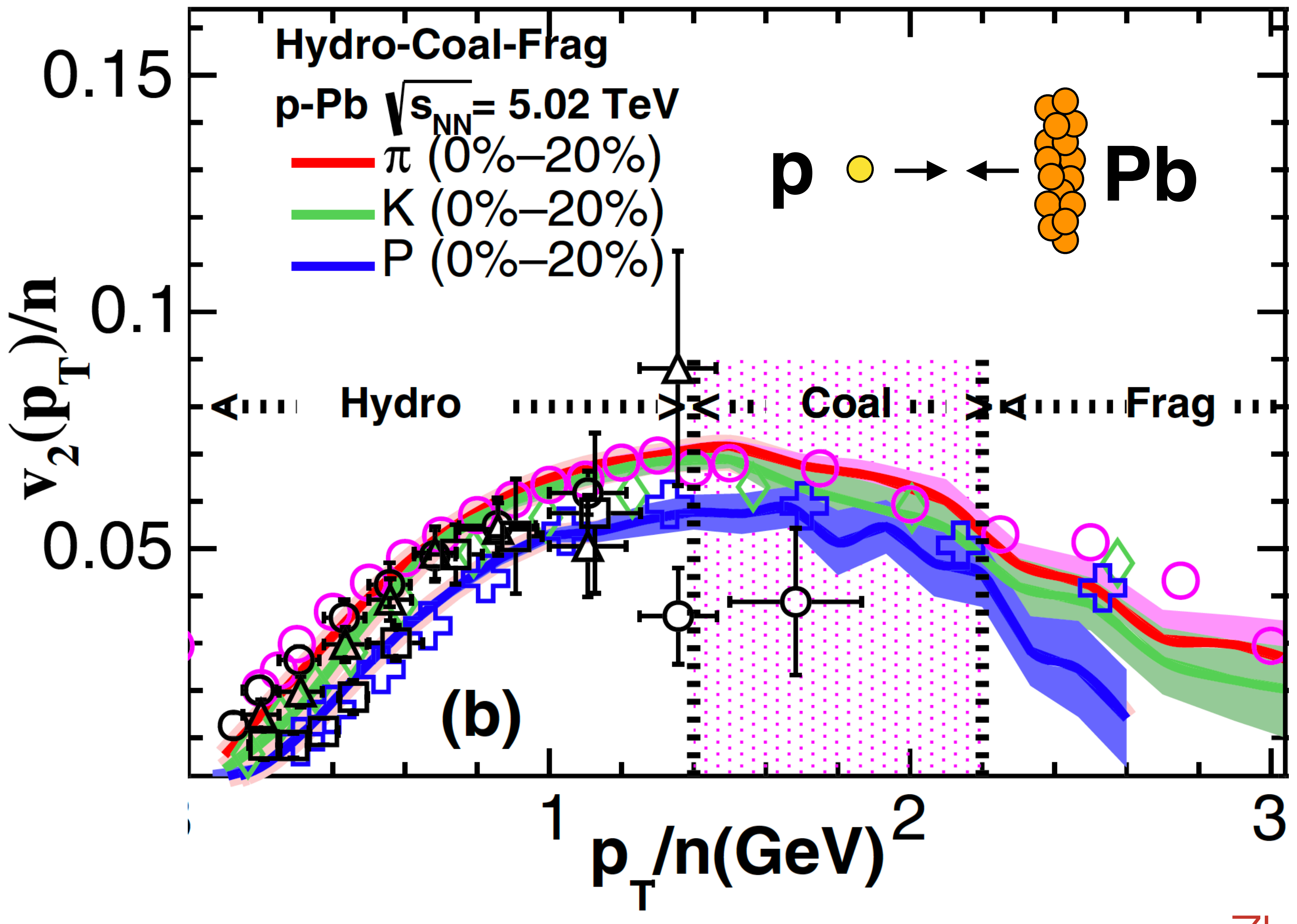
- Final state models provide good description of p-Pb collisions
- Description of pp collisions has its limits

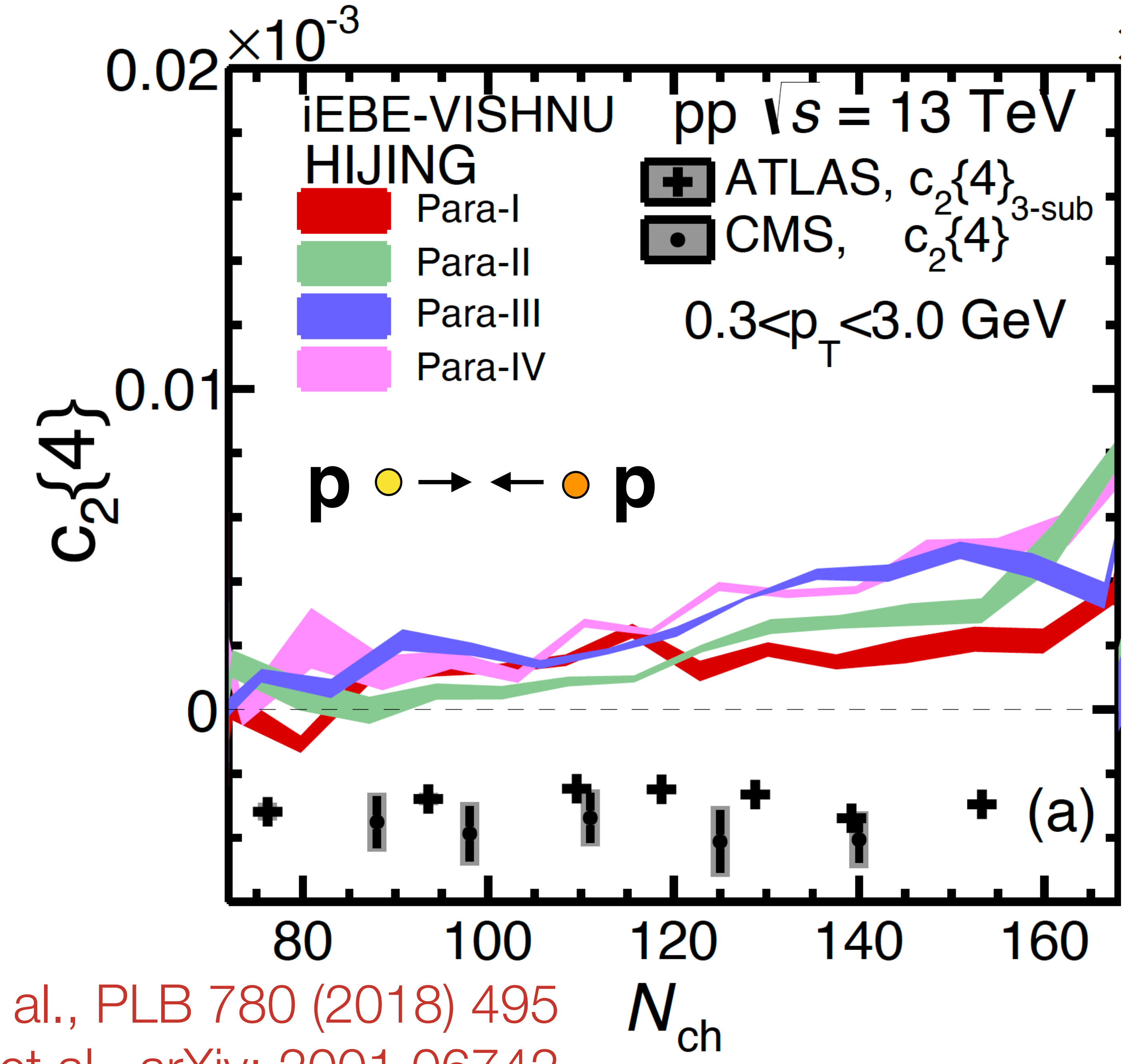
Initial state effects	Final state effects
Initial momentum correlations Not correlated with initial geometry CGC	*Interactions in the final state* Correlated with initial geometry Hydrodynamics Transport theory

? pp p-Pb Pb-Pb

Theoretical description

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

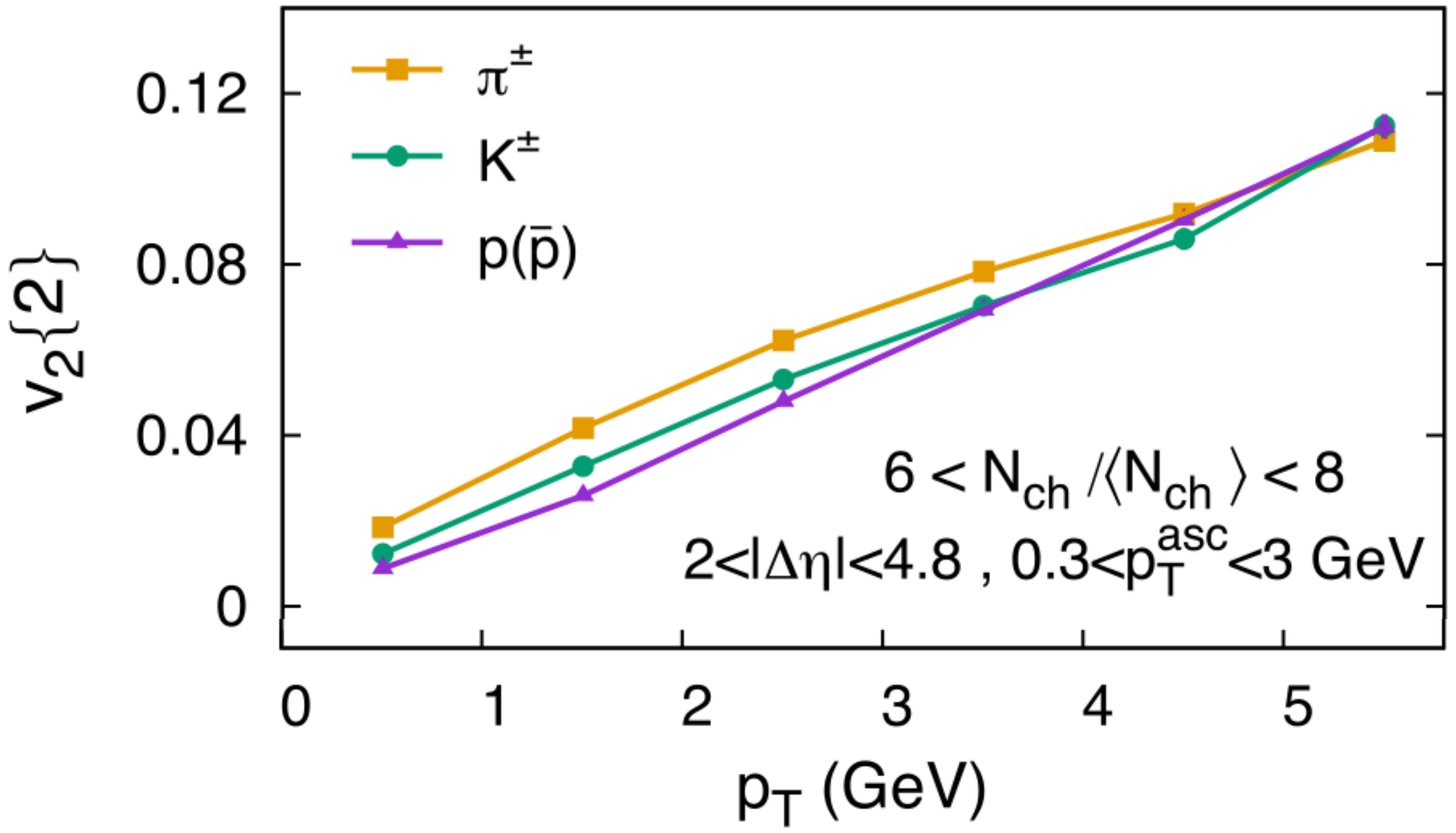




Zhao et al., PLB 780 (2018) 495

Zhao et al., arXiv: 2001.06742

Schenke et al., PRL 117, 162301 (2016)



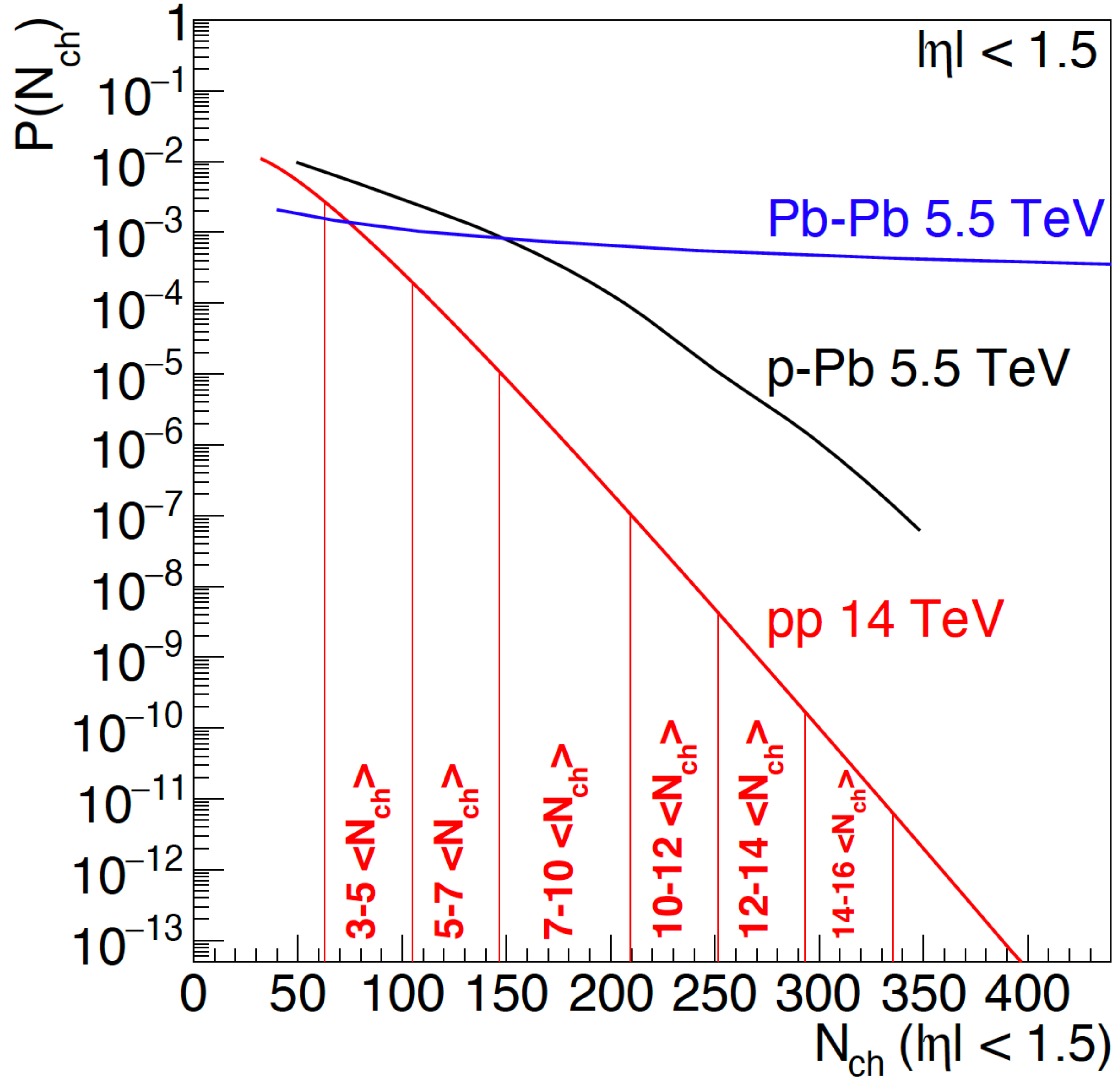
- Final state models provide good description of p-Pb collisions
- Description of pp collisions has its limits
- Models with initial state correlations only, or with few scatterings in the final state without a medium, catch some features of data, too

Initial state effects	Final state effects
Initial momentum correlations	*Interactions in the final state*
Not correlated with initial geometry	Correlated with initial geometry
CGC	Hydrodynamics Transport theory

? pp p-Pb Pb-Pb

LHC in Run 3 (and beyond)

LHC in Run 3 (and beyond)



ALICE-PUBLIC-2020-005
WG5 HL-LHC report: arXiv:1812.06772

Developing a unified picture of QCD collectivity across system size:

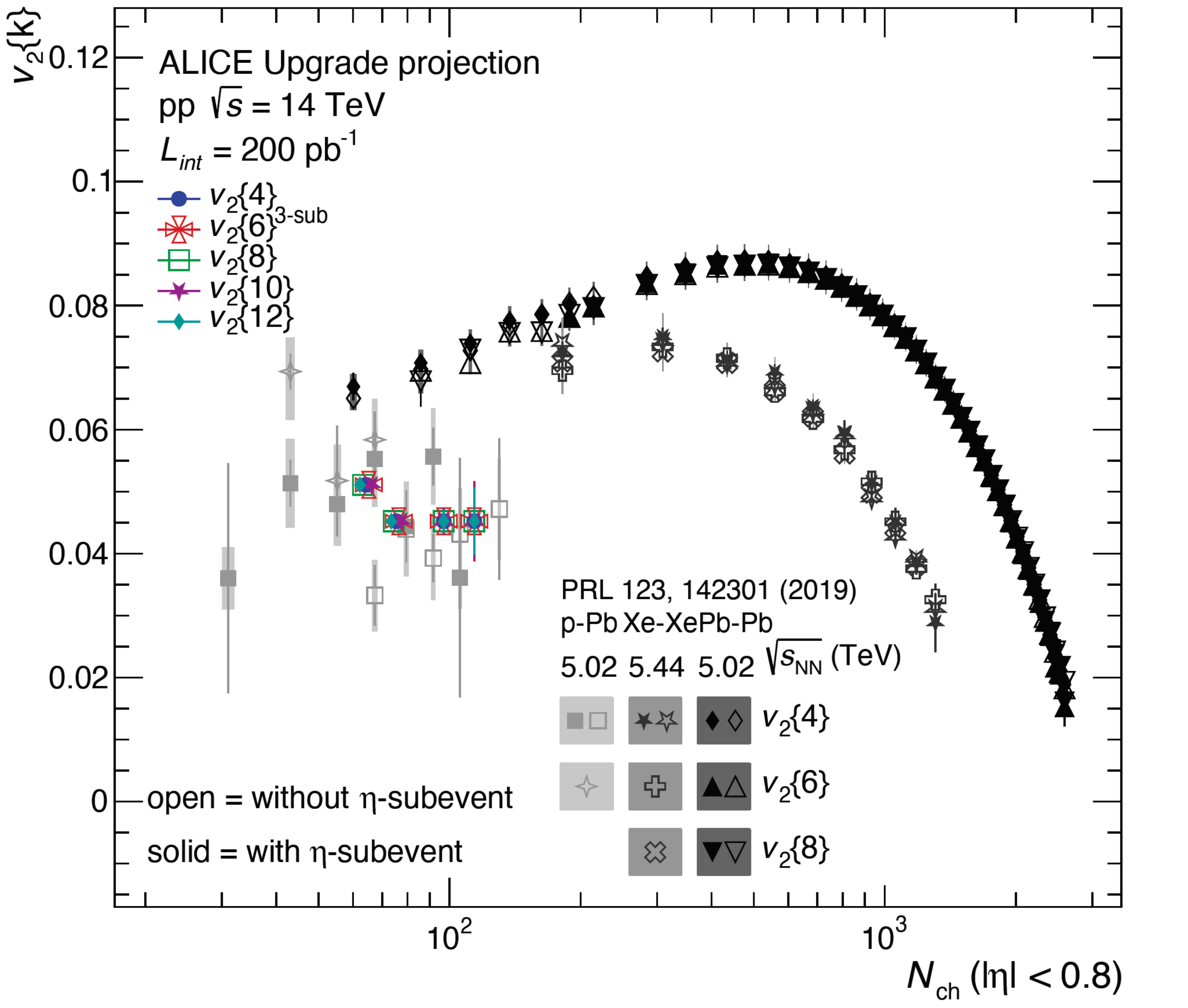
- ***Flow measurements in pp and pA systems: Onset and higher-order correlations***
- ***Flow of heavy flavor and quarkonium in smaller systems***
- *Strangeness production as a function of system size*
- *Searching for onset/existence of energy-loss effects in small systems*
- *Searching for the onset/existence of thermal radiation in small systems*

- Very high multiplicities in pp and p-Pb collisions
  - Similar to ~65% central Pb-Pb collisions
- Possibility to run p-O and O-O collisions

Multi-particle cumulants of charged hadrons

- (Very) high order cumulants Moravcova, Gulbrandsen, Zhou, arXiv:2005.07974
  - Suppression of non-flow without the need for the subevent method -> free from longitudinal decorrelations

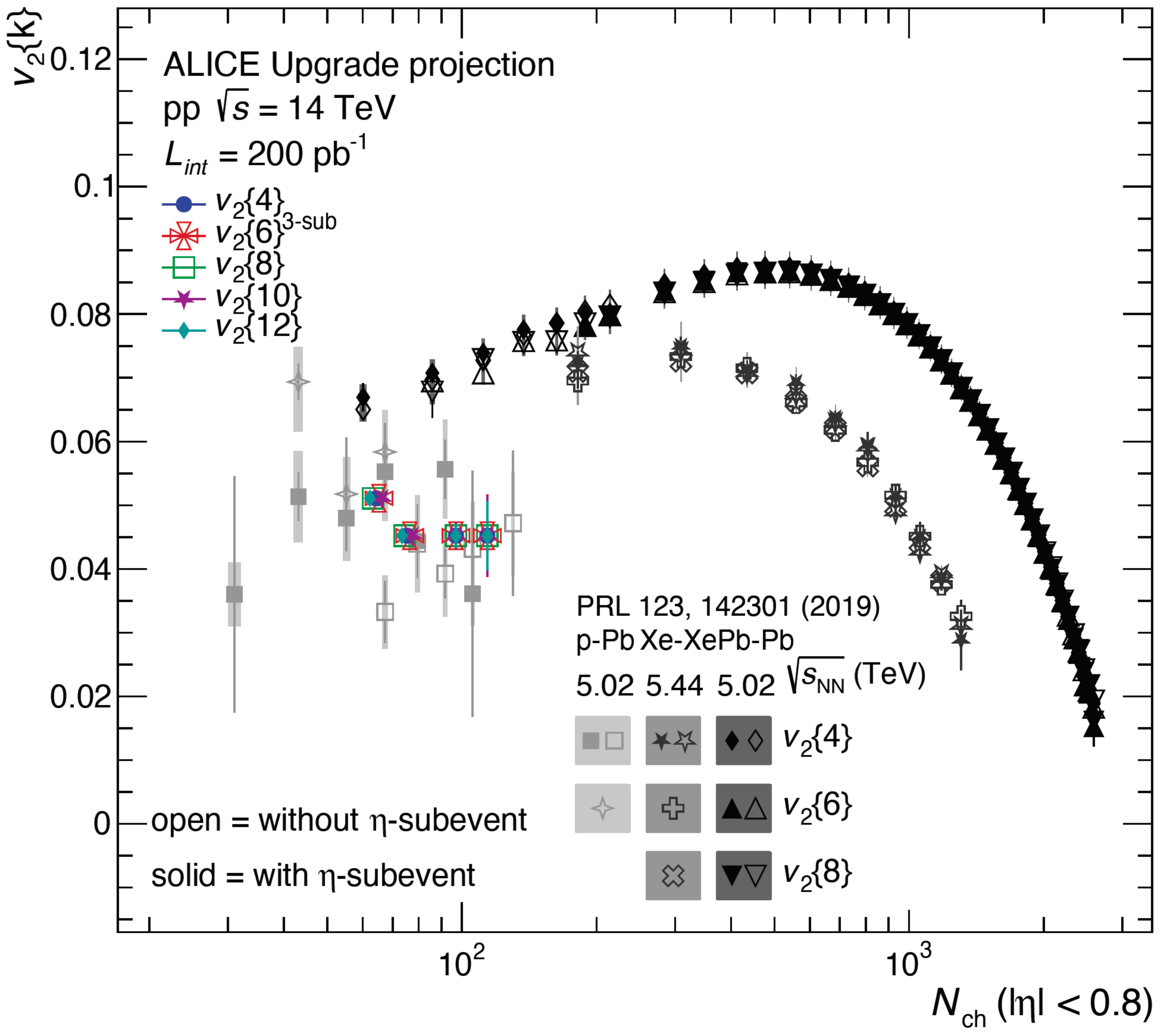
ALICE-PUBLIC-2020-005

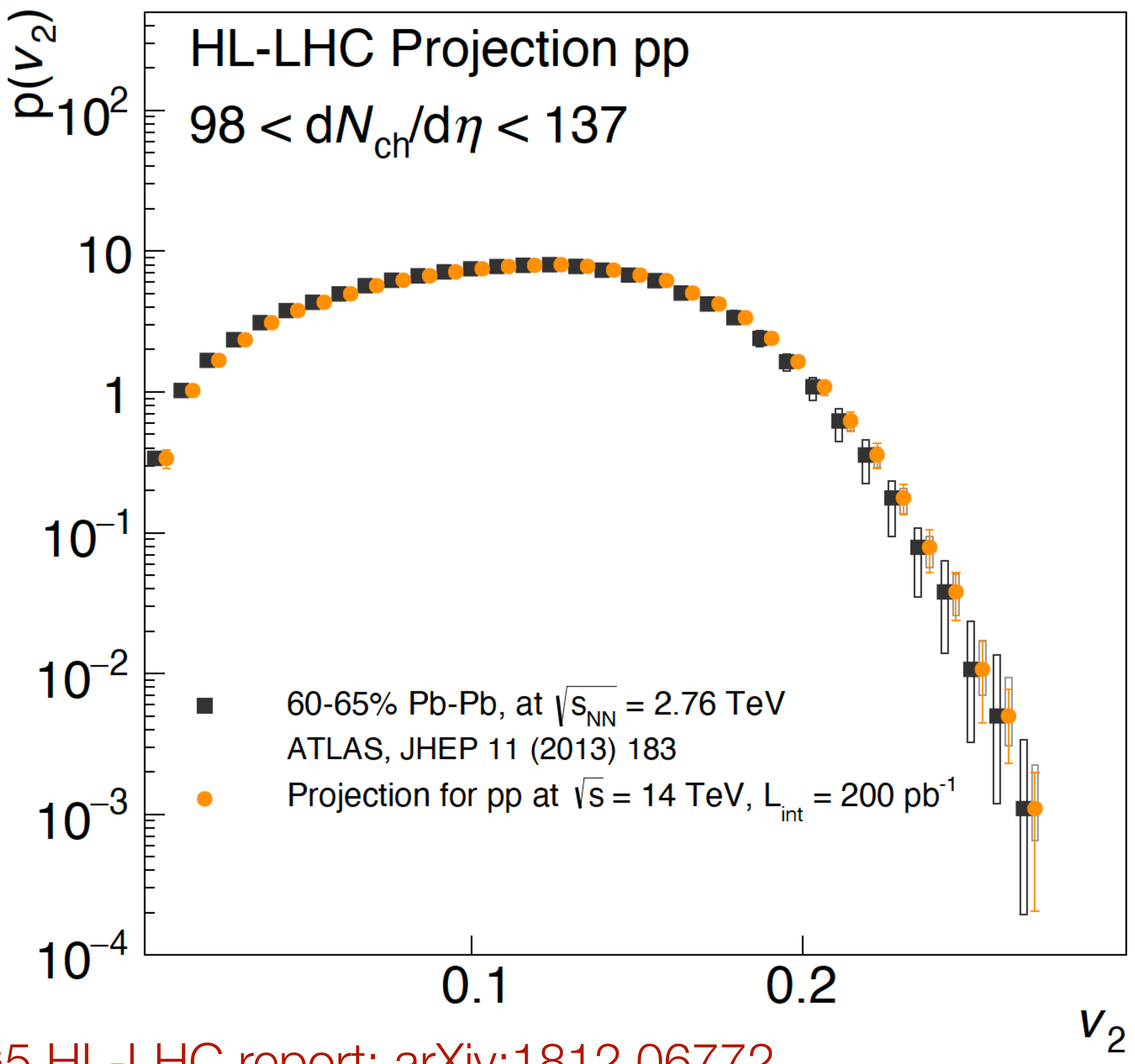


Multi-particle cumulants of charged hadrons

- (Very) high order cumulants Moravcova, Gulbrandsen, Zhou, arXiv:2005.07974
  - Suppression of non-flow without the need for the subevent method -> free from longitudinal decorrelations
- Extraction of $P(v_n)$ -> not measured in small systems yet
  - Constrain $P(\varepsilon_n)$ of the initial state (poorly understood in small systems)

ALICE-PUBLIC-2020-005

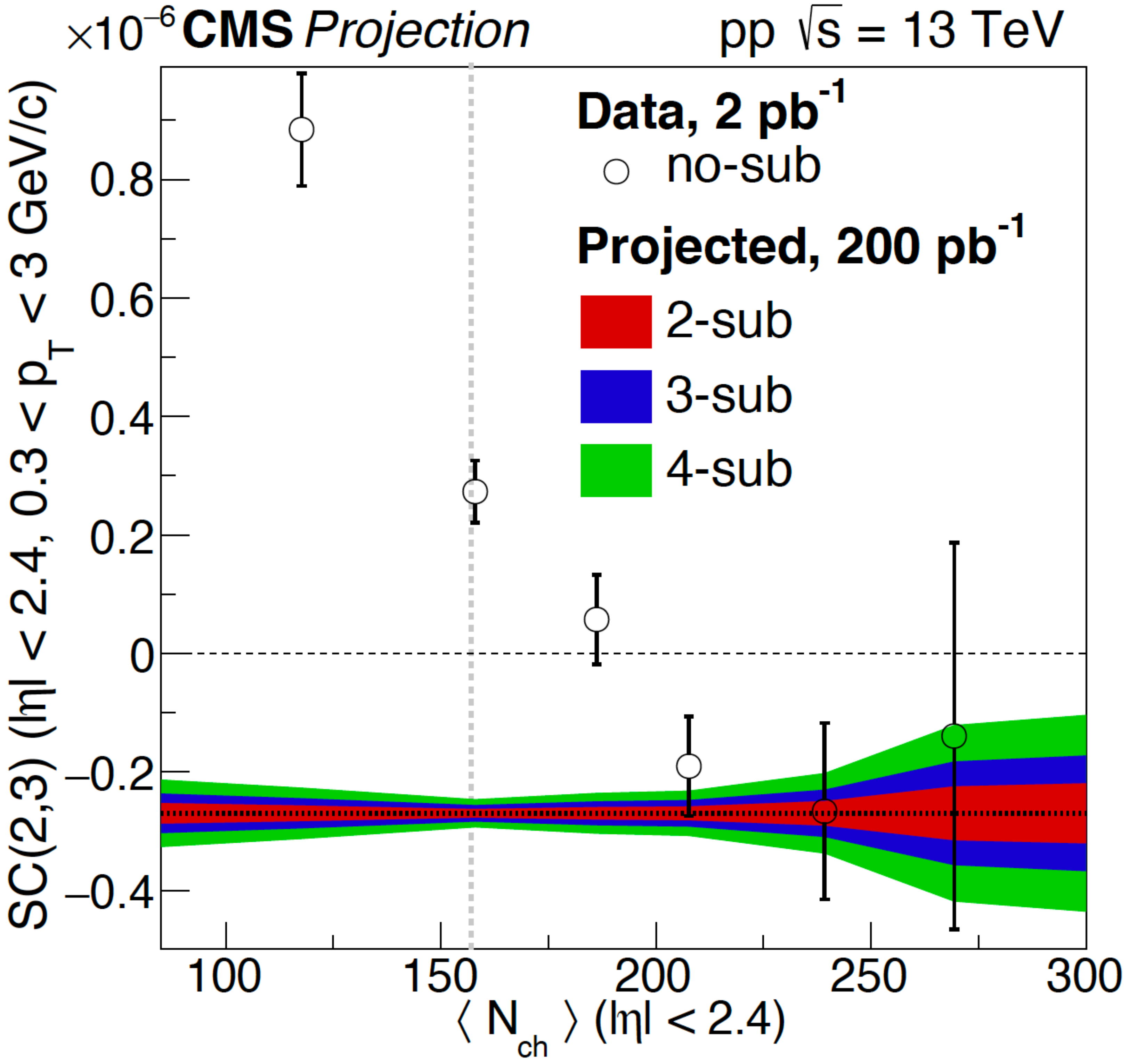




WG5 HL-LHC report: arXiv:1812.06772

Multi-particle cumulants of charged hadrons

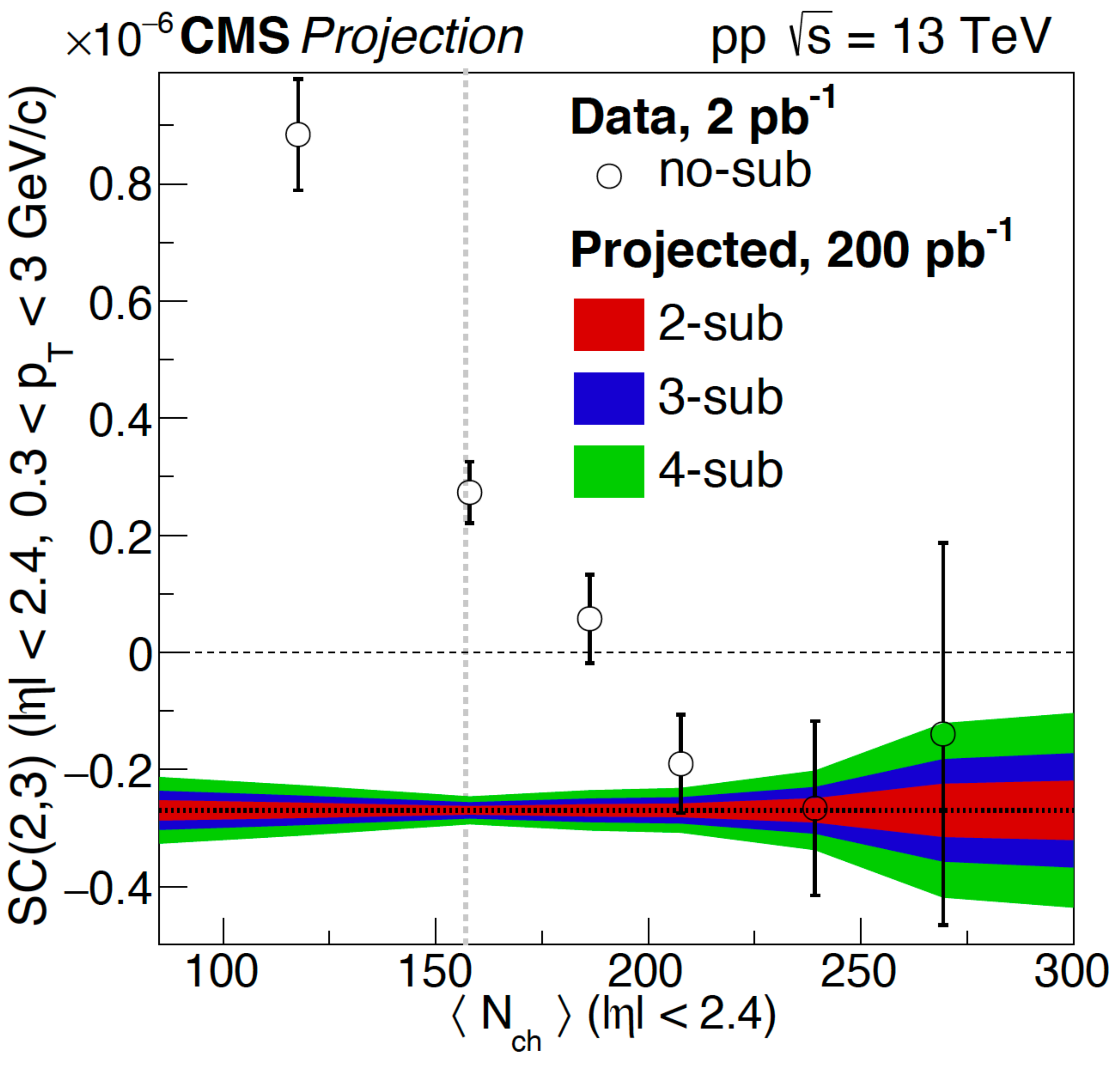
WG5 HL-LHC report: arXiv:1812.06772



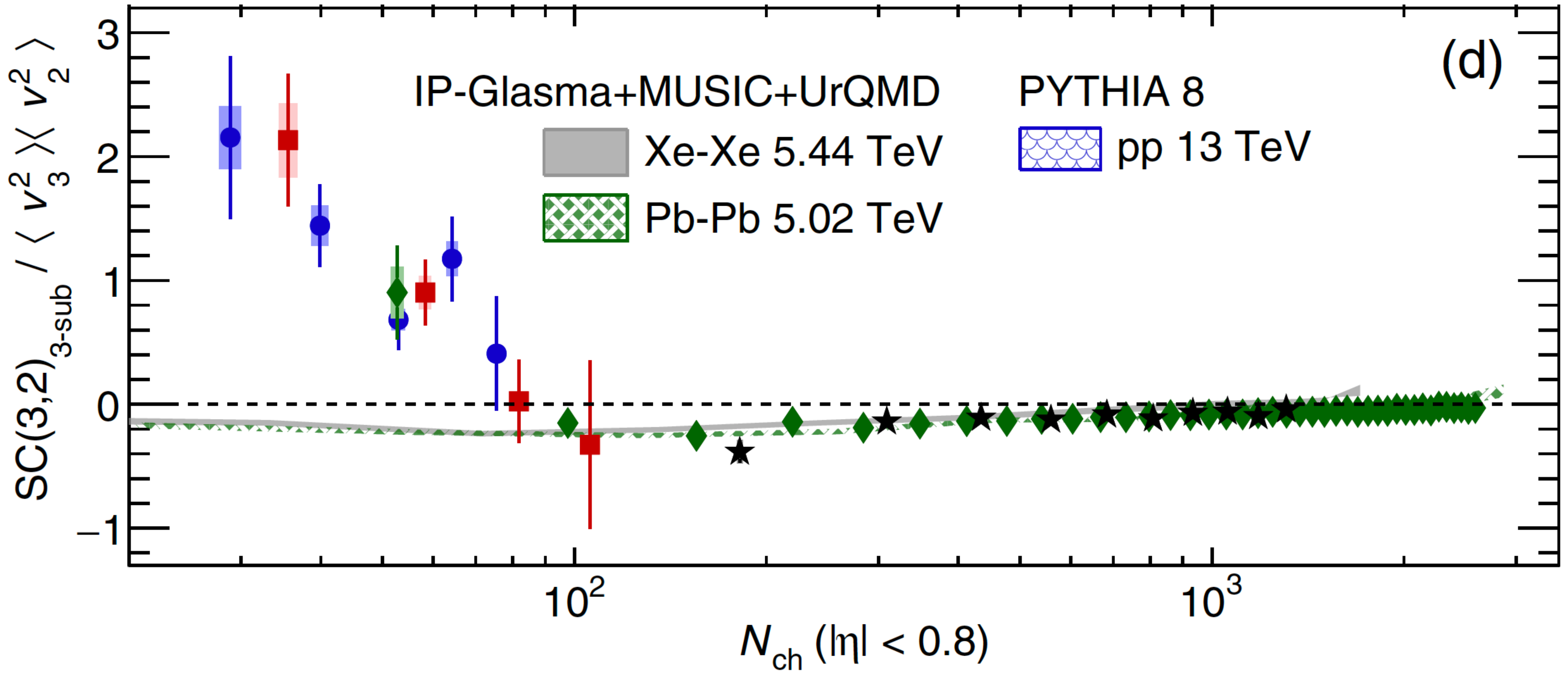
- Precise measurements of $SC(m,n)_{sub}$ and normalised $SC(m,n)_{sub}$
  - Access to initial conditions and/or dynamics of the medium

Multi-particle cumulants of charged hadrons

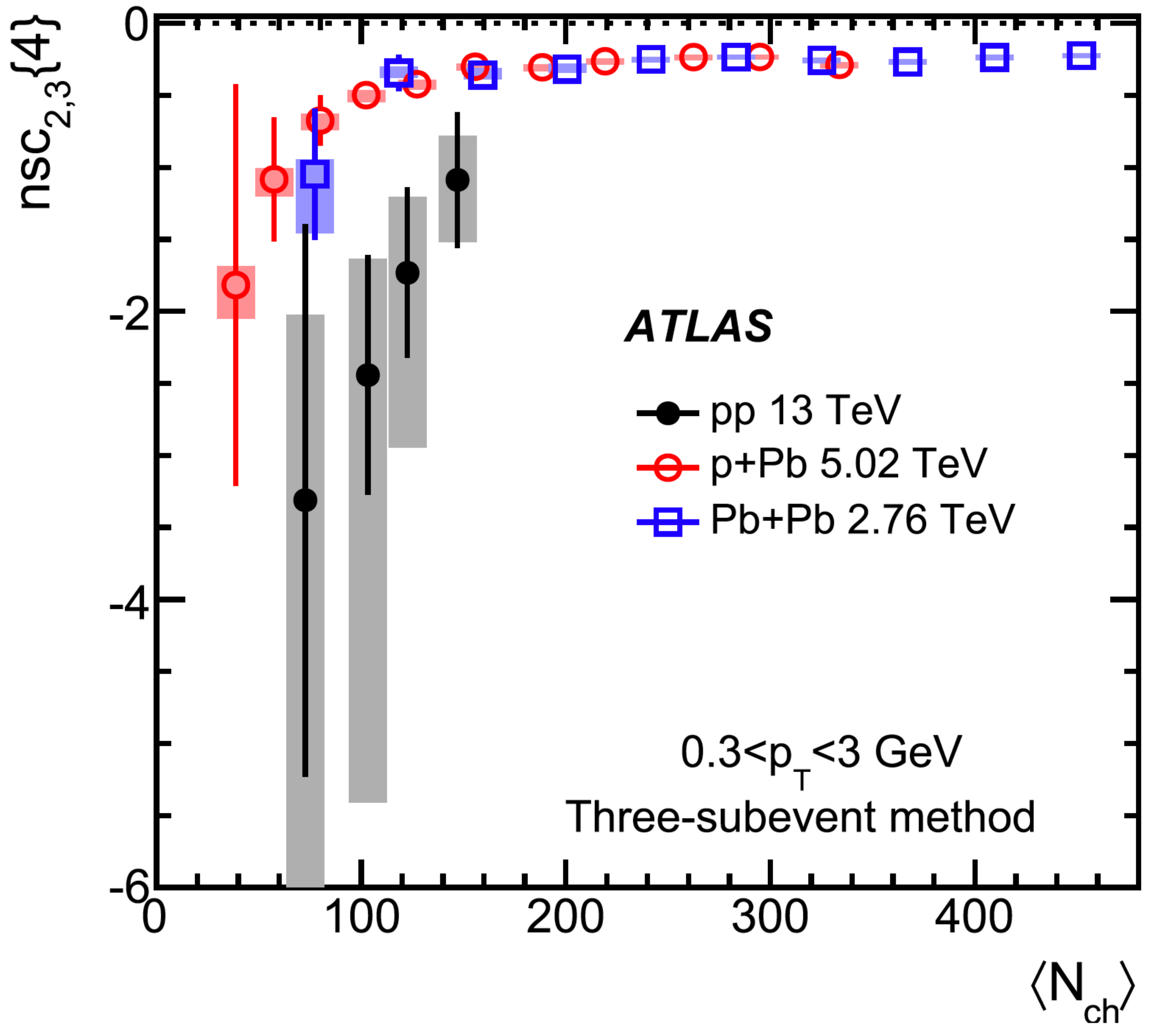
WG5 HL-LHC report: arXiv:1812.06772



ALICE, PRL 123, 142301 (2019)



ATLAS, PLB 789 (2019) 444

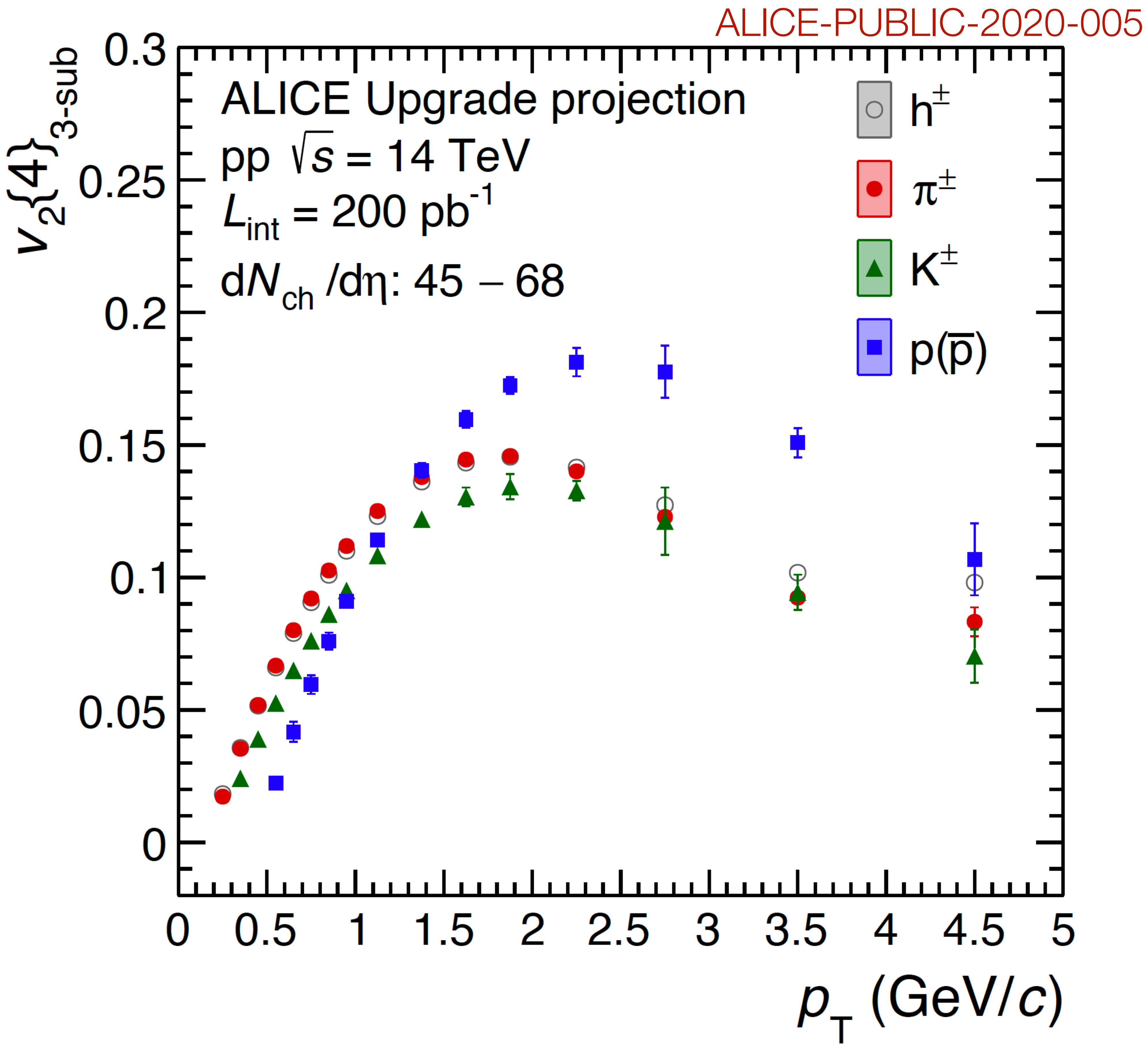


- Precise measurements of $SC(m,n)_{sub}$ and normalised $SC(m,n)_{sub}$
  - Access to initial conditions and/or dynamics of the medium

- Disagreement with ATLAS & CMS at low N_{ch} -> can we solve it in Run 3 ?
- Multi-harmonic correlations (using higher order moments)

Moravcova, Gulbrandsen, Zhou, arXiv:2005.07974

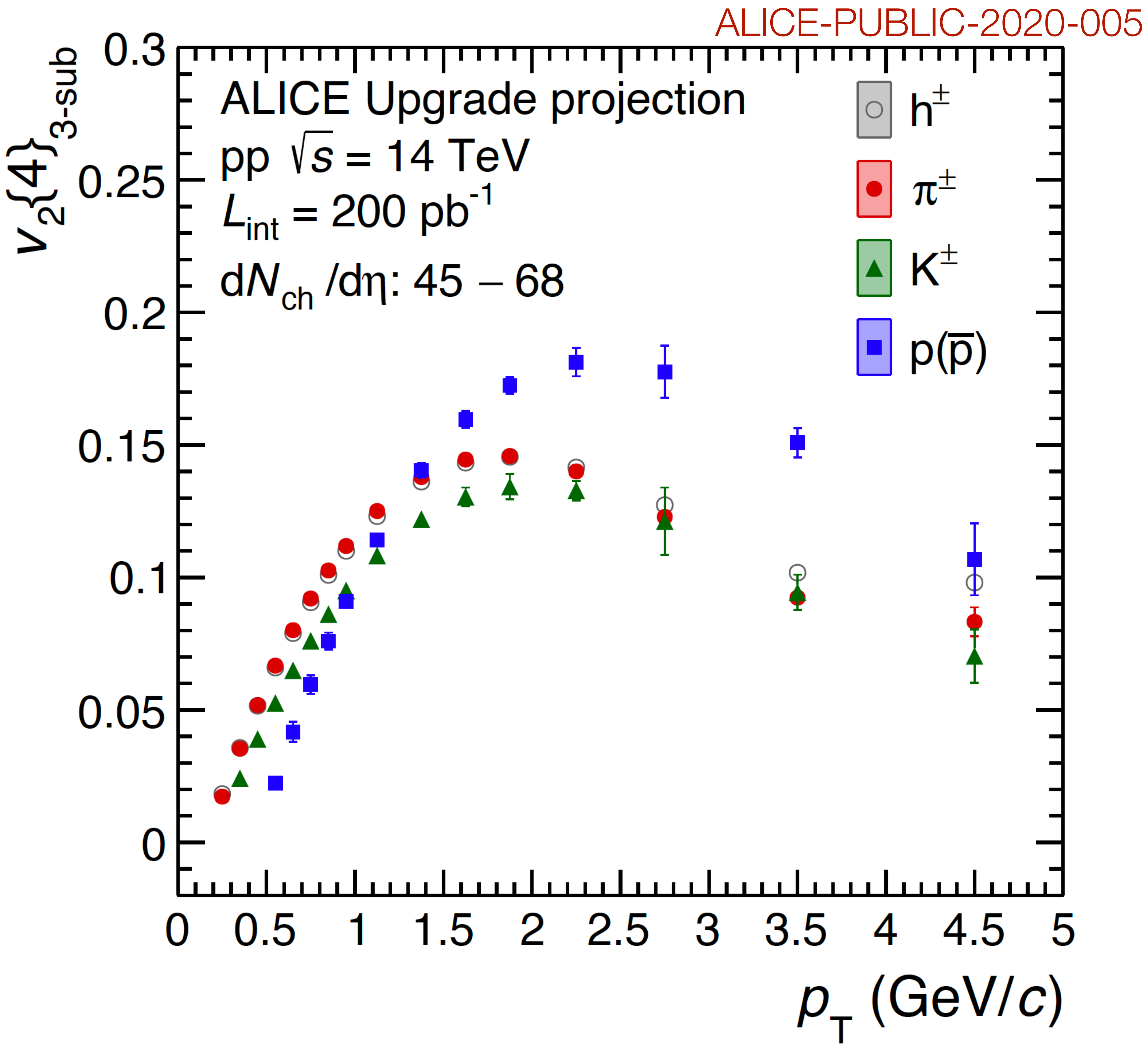
Flow of identified hadrons



- Flow of π, K and p not measured in pp collisions yet
  - Confirm the mass ordering with more particle species
  - Confirm whether there is baryon/meson grouping at intermediate p_T

measurement	pp	p-Pb
π, K, p, ϕ	X	✔
Λ, K^0_s	✔	✔
Ω, X	X	✔

Flow of identified hadrons



- Flow of π, K and p not measured in pp collisions yet
  - Confirm the mass ordering with more particle species
  - Confirm whether there is baryon/meson grouping at intermediate p_T
- Results using multi-particle cumulants with subevent method
  - More reliable in non-flow suppression than standard subtraction methods performed so far on two-particle correlations (subtraction of low multiplicity events)

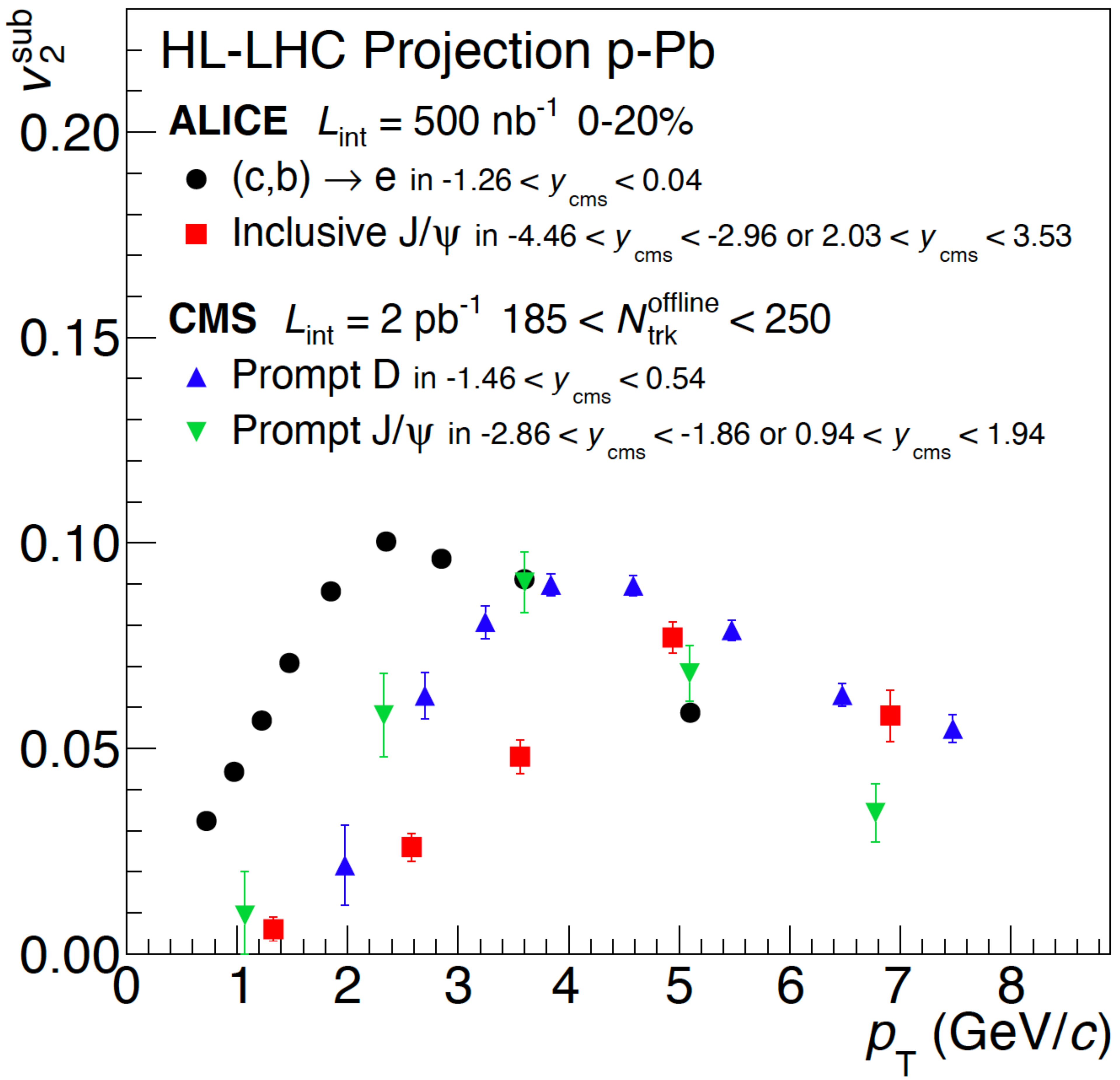
measurement	pp	p-Pb
π, K, p, ϕ	X	✔
Λ, K^0_s	✔	✔
Ω, X	X	✔

Two-particle correlations

Different methods of non-flow subtraction

Flow of heavy flavor hadrons

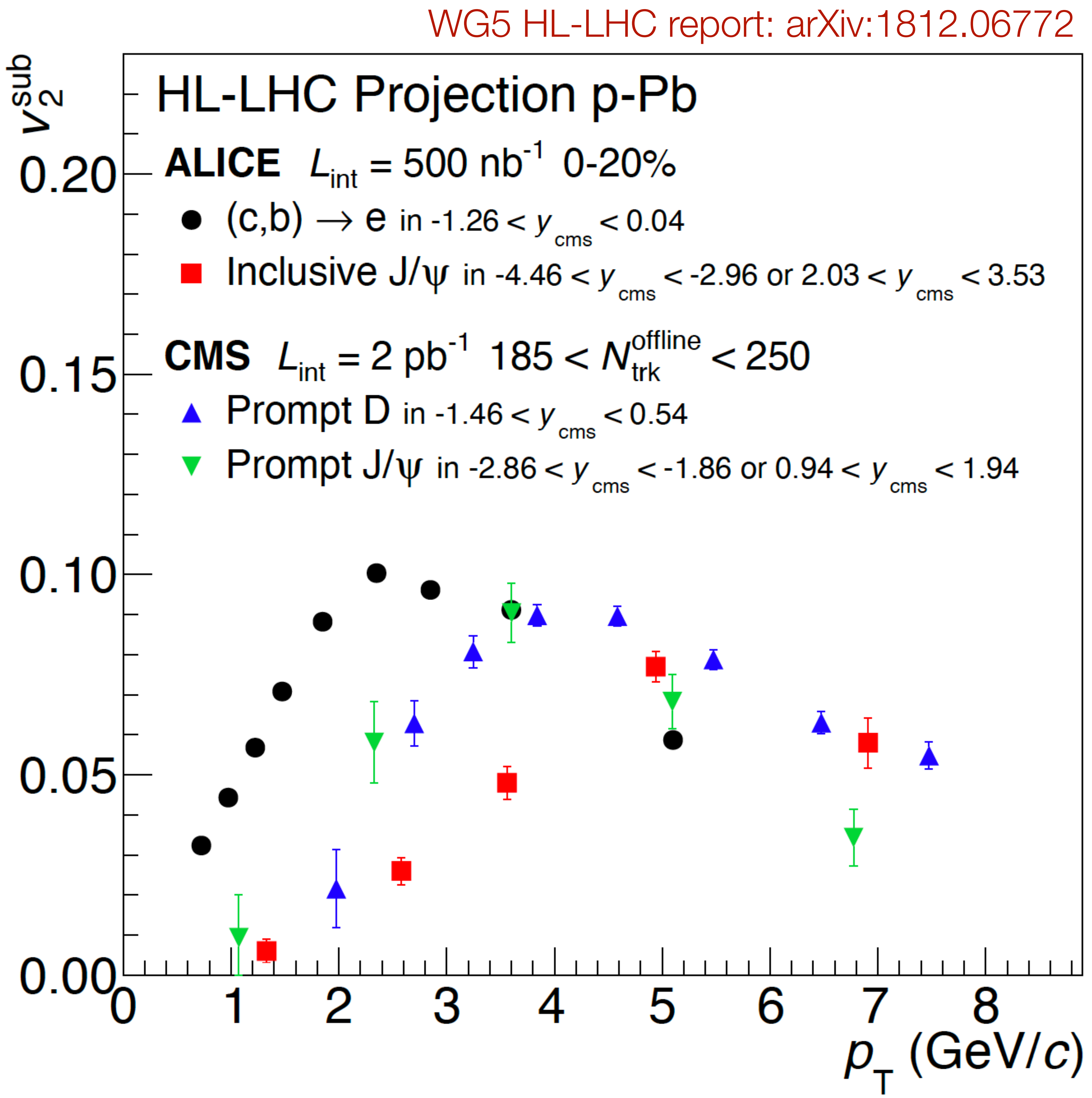
WG5 HL-LHC report: arXiv:1812.06772



- More (precise) measurements in pp (and p-Pb) collisions

measurement	pp	p-Pb
HFe HFμ	X	✔
HFμ (isolated c/b)	✔	X
Prompt D^0	X	✔
J/Ψ	X	✔
Non-prompt D^0	X	✔

Flow of heavy flavor hadrons



- More (precise) measurements in pp (and p-Pb) collisions
- Measurements using multi-particle correlations?
  - So far, only two-particle correlations with different non-flow suppression methods were used

measurement	pp	p-Pb
HFe HFμ	X	✔
HFμ (isolated c/b)	✔	X
Prompt D^0	X	✔
J/Ψ	X	✔
Non-prompt D^0	X	✔

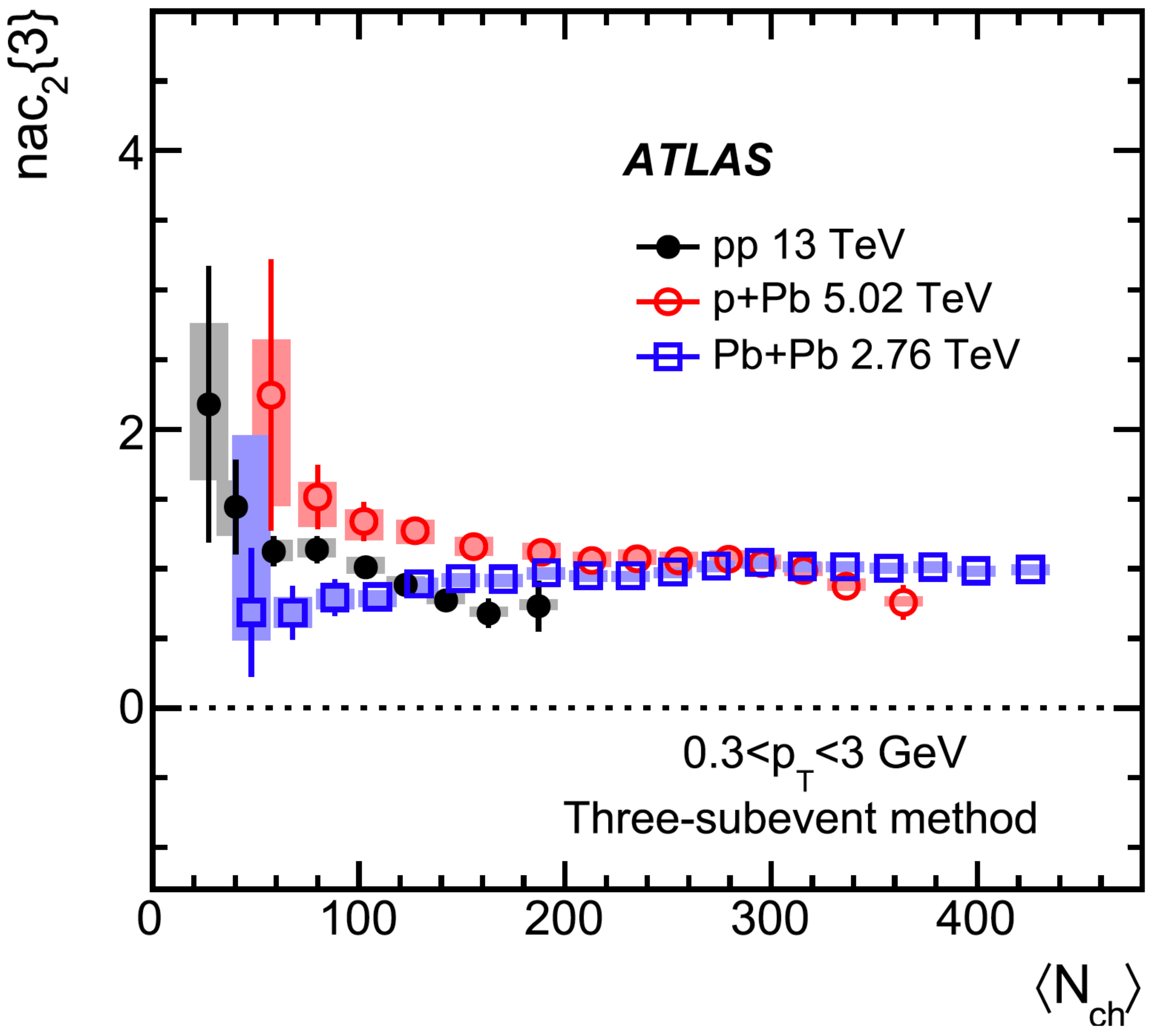
Two-particle correlations

Different methods of non-flow subtraction

Further possibilities

equivalent to $\langle \cos 4(\Psi_2 - \Psi_4) \rangle$

ATLAS, PLB 789 (2019) 444

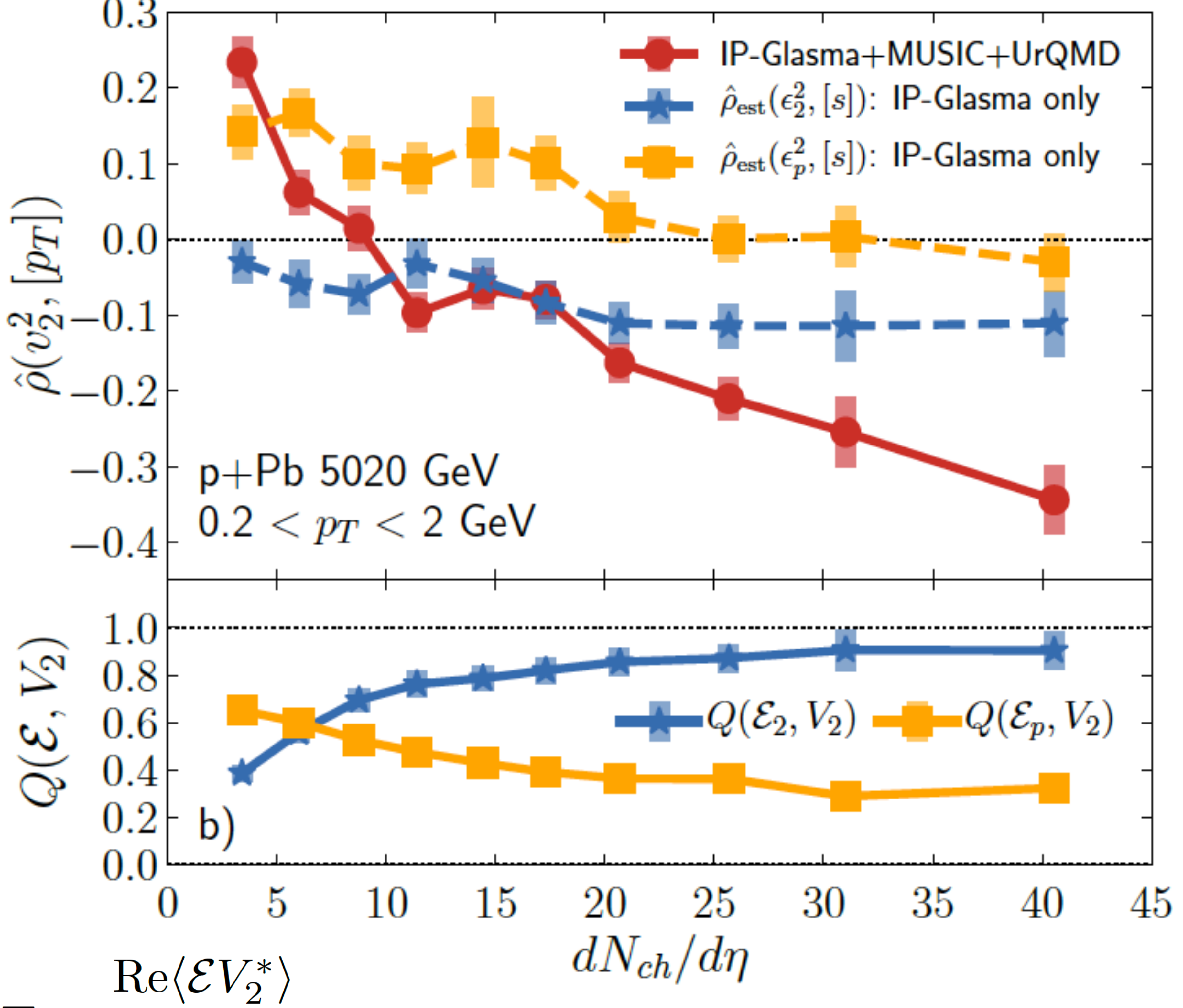


- Nonlinear response to initial state eccentricities/fluctuations
  - Insight into the (hydrodynamic?) evolution of the system

Further possibilities

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

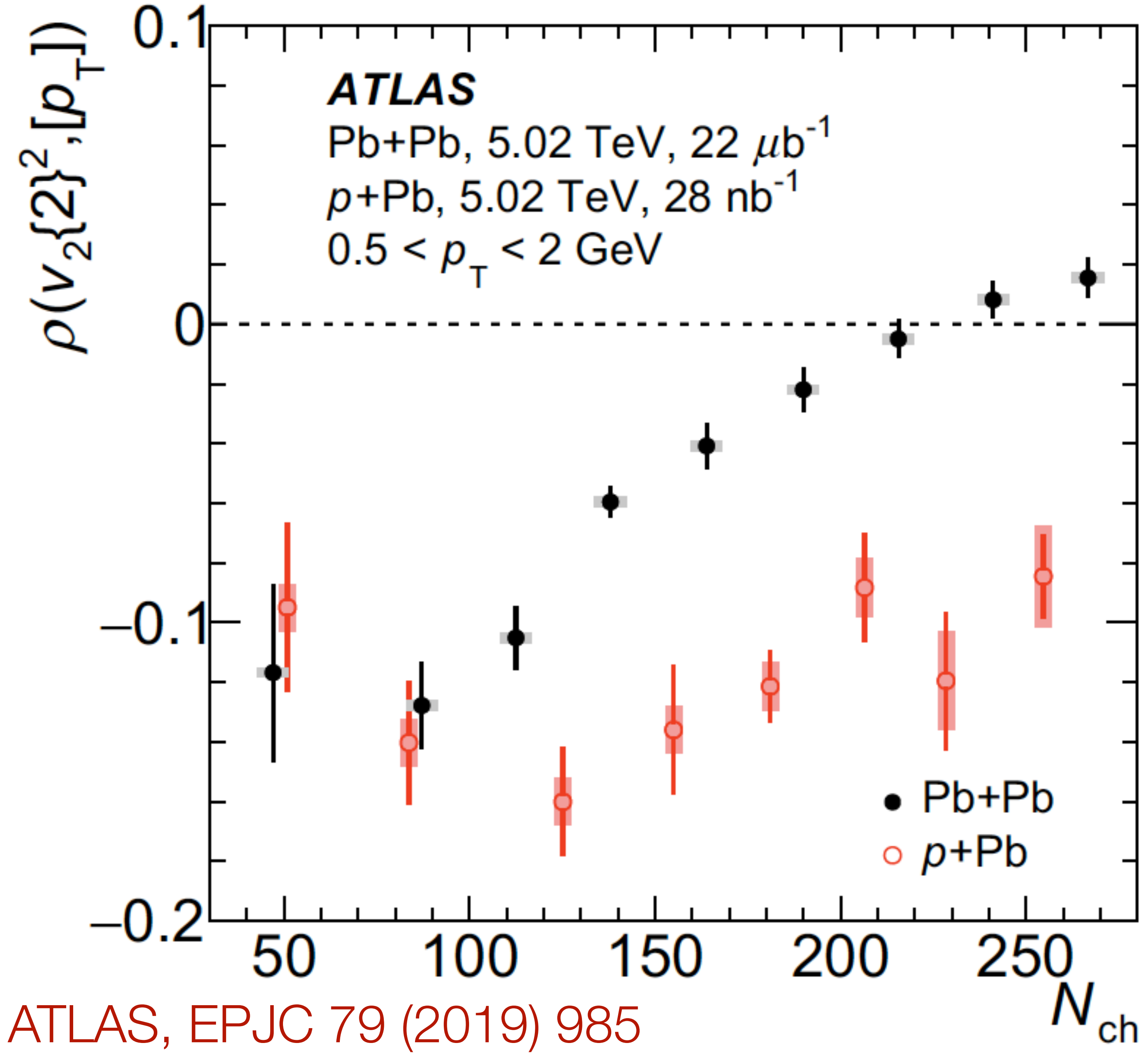
Giacalone et al., arXiv:2006.15721



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

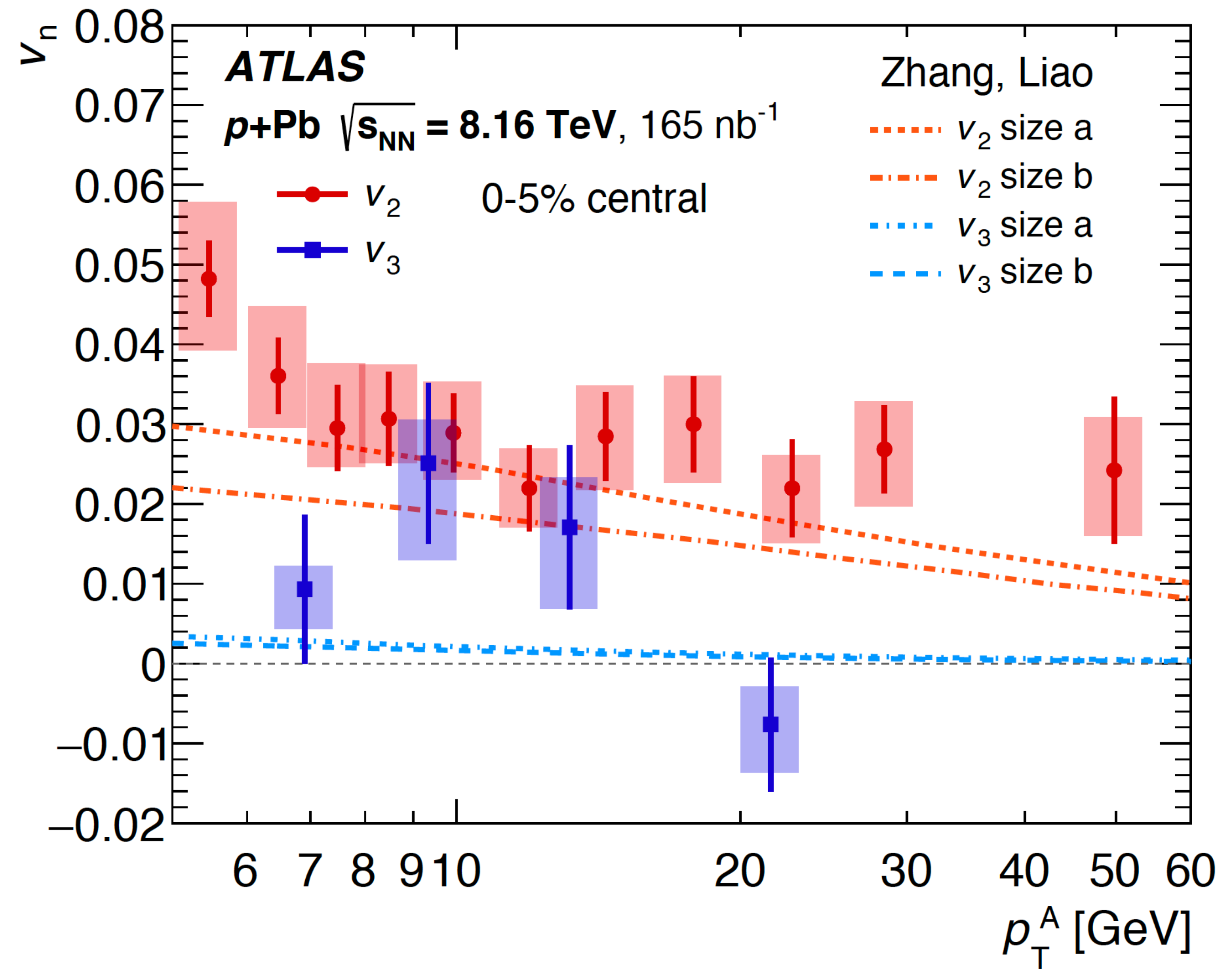
- Initial (gluon) momentum anisotropy important at low multiplicities
- Initial spatial anisotropy important at high multiplicities

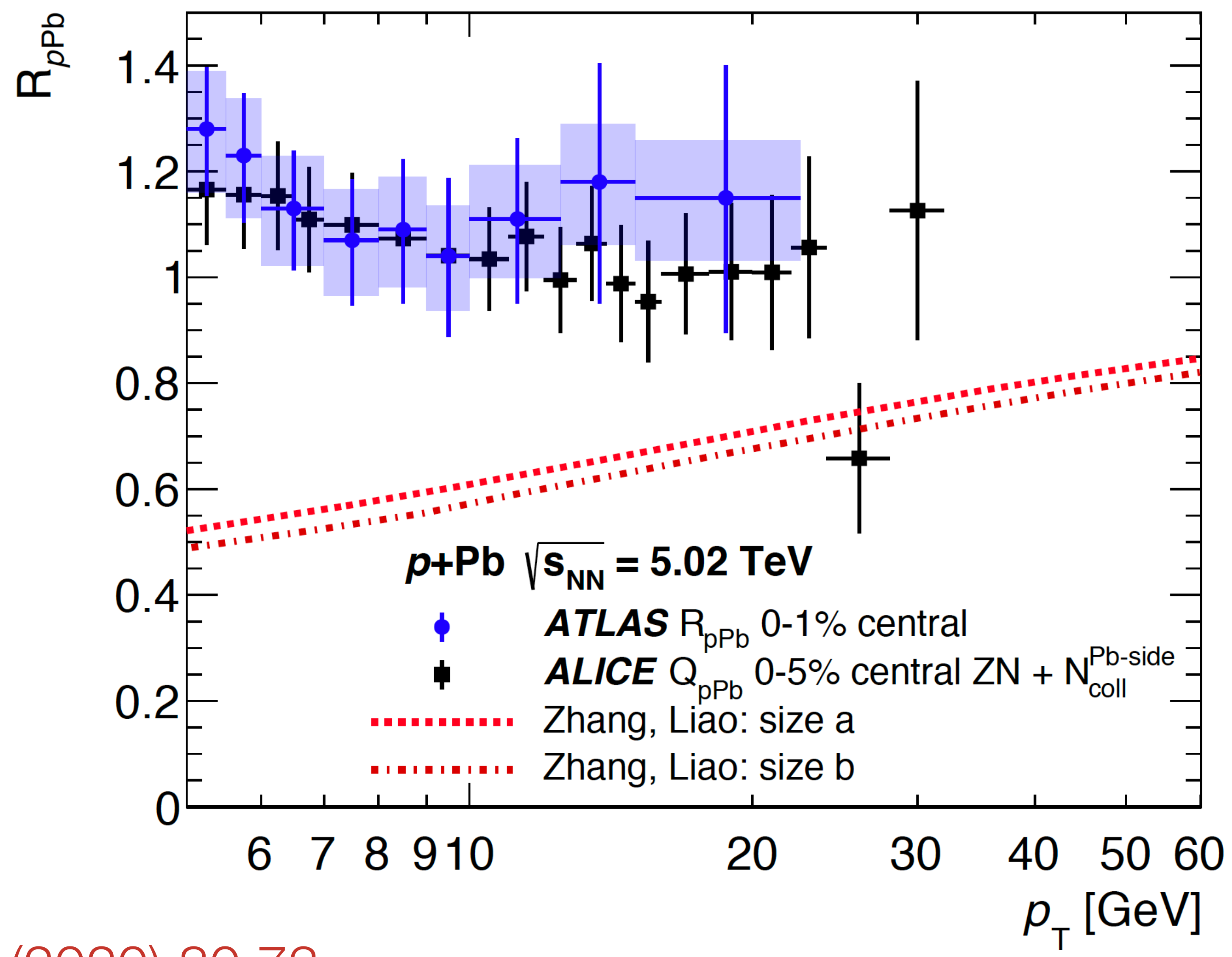
- Nonlinear response to initial state eccentricities/fluctuations
  - Insight into the (hydrodynamic?) evolution of the system
- Correlations of <pT> and flow
  - New promising tool to determine the importance of initial state correlations
  - More precise measurements needed … but at low multiplicities (it is anticipated to mostly run high-multiplicity triggers)



ATLAS, EPJC 79 (2019) 985

Further possibilities

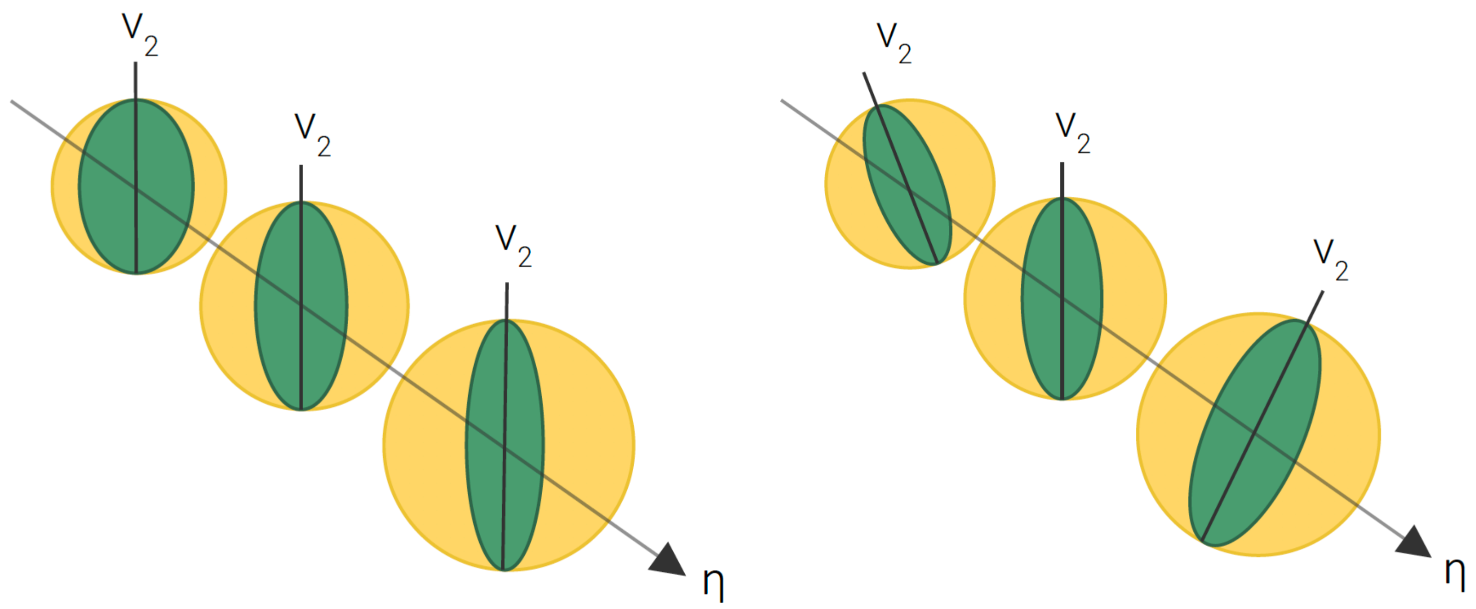


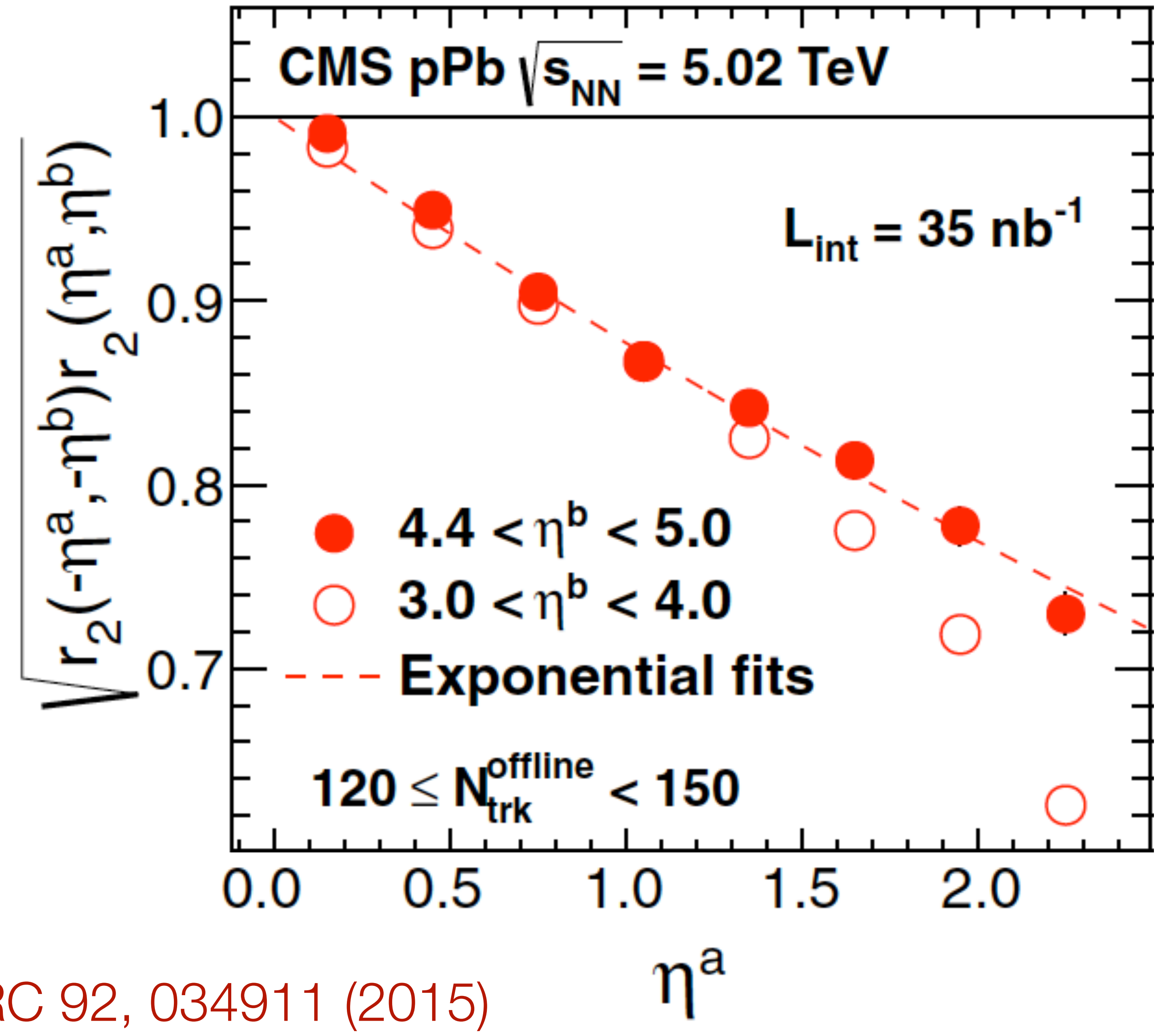


ATLAS, EPJC (2020) 80:73

- Nonlinear response to initial state eccentricities/fluctuations
  - Insight into the (hydrodynamic?) evolution of the system
- Correlations of <pT> and flow
  - New promising tool to determine the importance of initial state correlations
  - More precise measurements needed … but at low multiplicities (it is anticipated to mostly run high-multiplicity triggers)
- High-order cumulants at high-p_T
  - Complementary way to address the presence of jet quenching, however this region is very sensitive to possible non-flow contamination

Further possibilities





CMS, PRC 92, 034911 (2015)

- Nonlinear response to initial state eccentricities/fluctuations
  - Insight into the (hydrodynamic?) evolution of the system
- Correlations of <pT> and flow
  - New promising tool to determine the importance of initial state correlations
  - More precise measurements needed … but at low multiplicities (it is anticipated to mostly run high-multiplicity triggers)
- High-order cumulants at high-p_T
  - Complementary way to address the presence of jet quenching, however this region is very sensitive to possible non-flow contamination
- Flow vector fluctuations
  - Constrain fluctuating initial conditions
  - Investigate possible effects of decorrelation when using subevent method / Δη gap in small systems

Summary

- In Run 1 & 2 we learned about the presence of collectivity in small systems

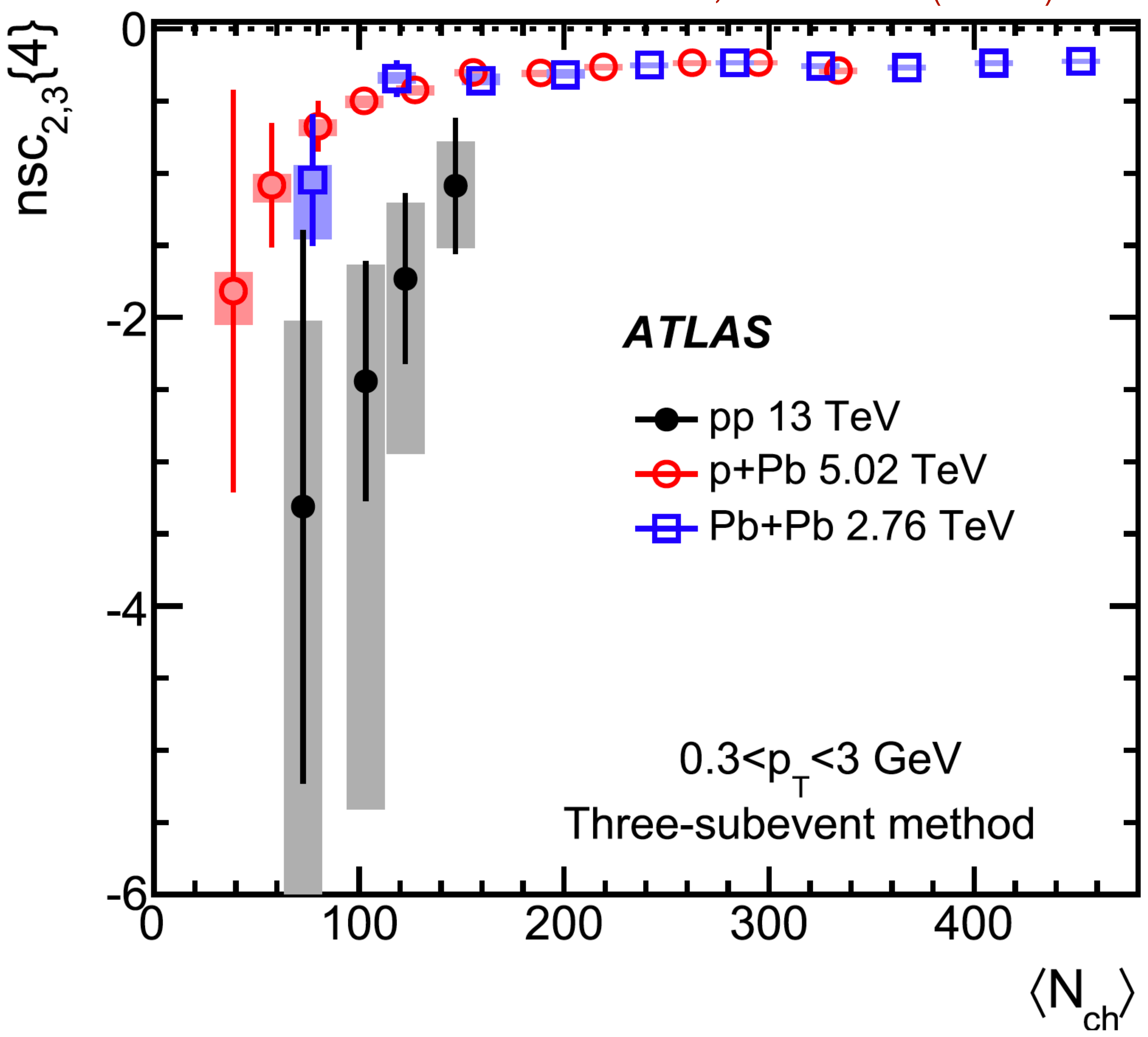
- In Run 3 and beyond we have an opportunity to understand its origin

- Effort from both theoretical and experimental side is crucial

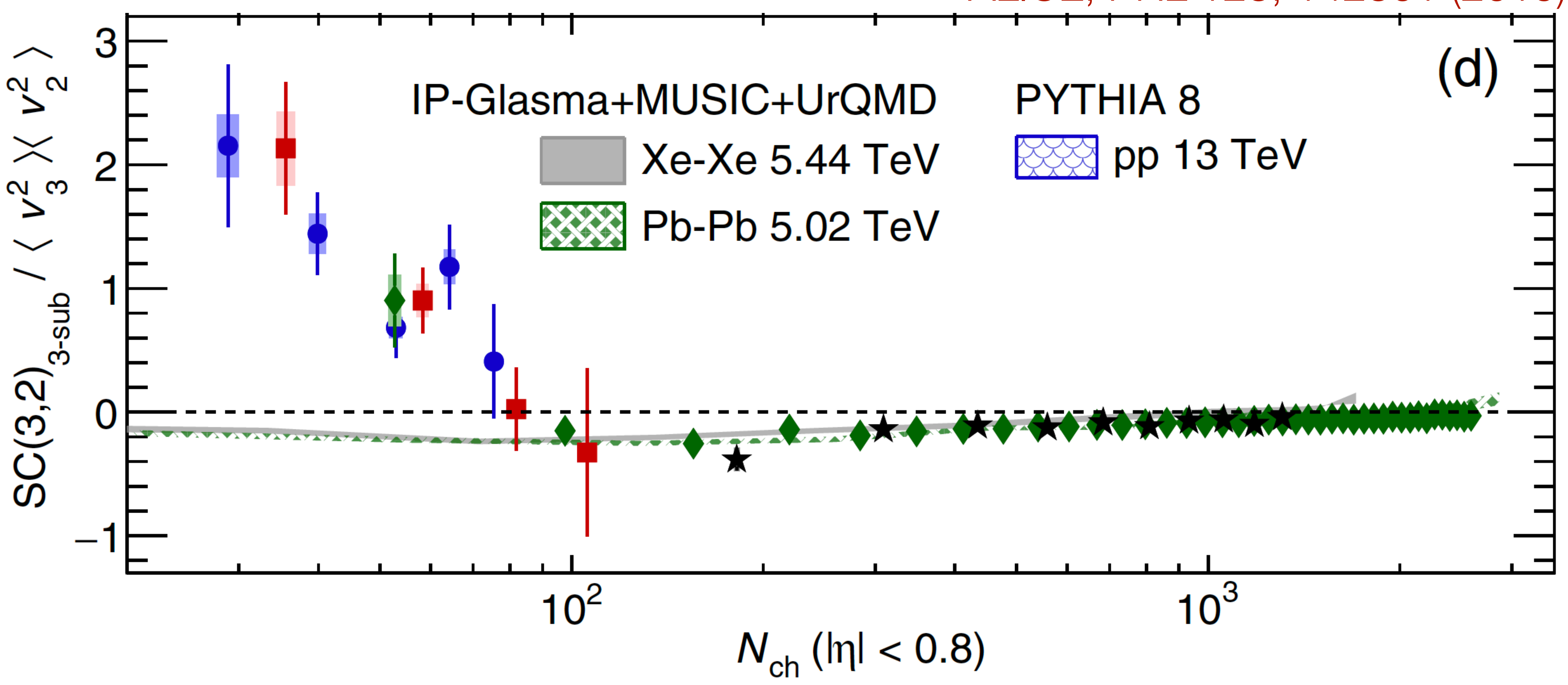
Backup

Symmetric cumulants at the LHC

ATLAS, PLB 789 (2019) 444



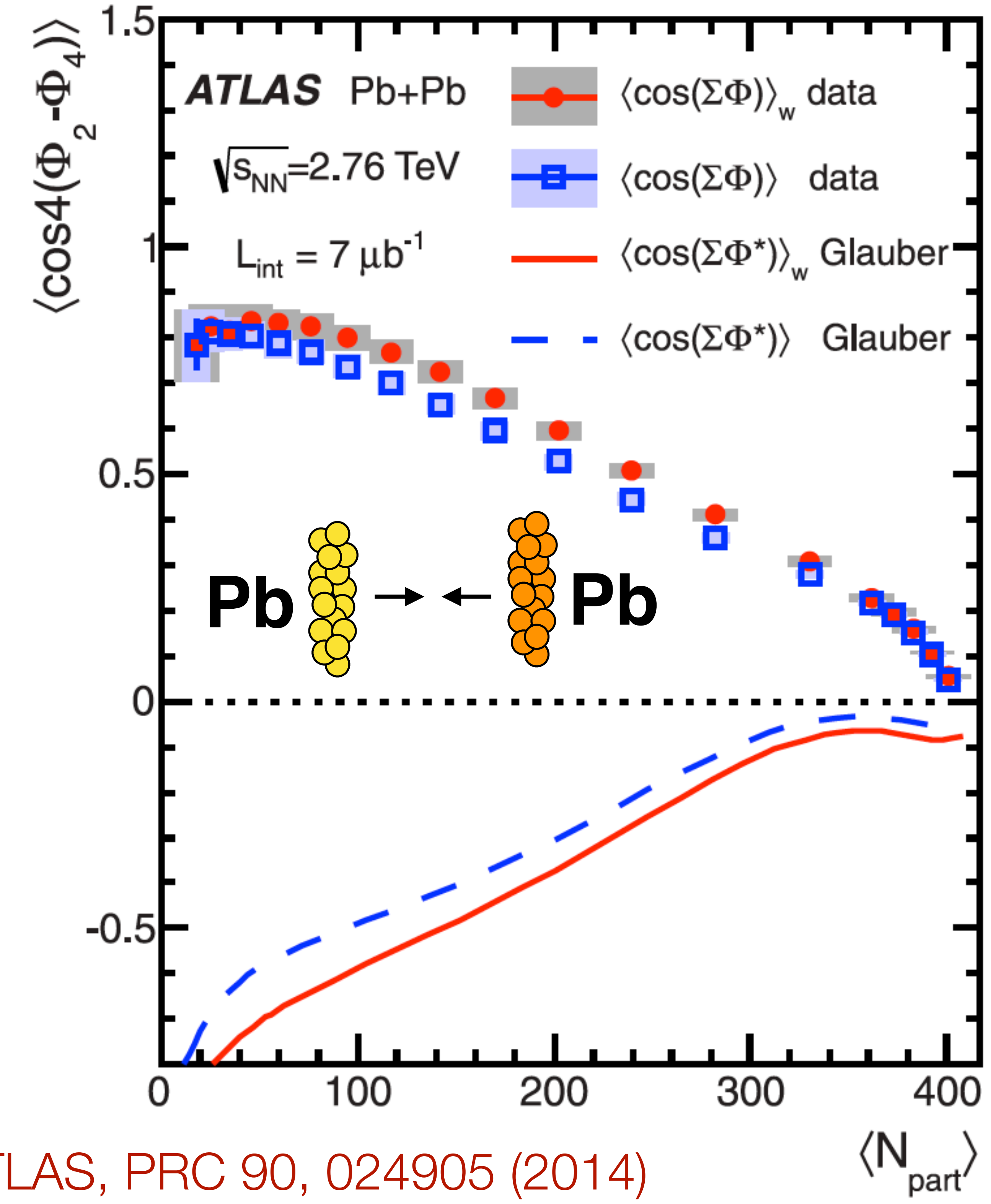
ALICE, PRL 123, 142301 (2019)



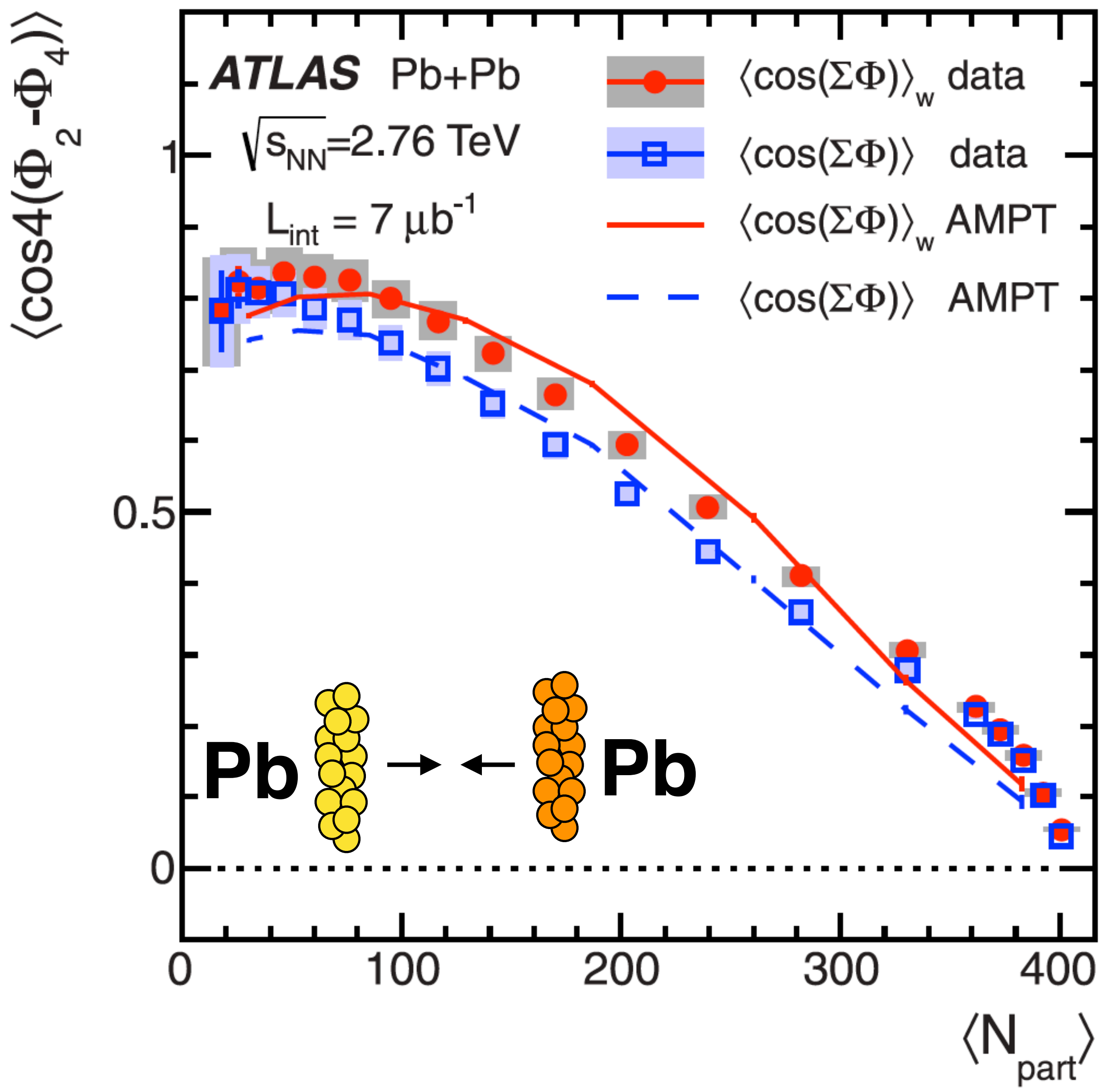
- Different sign of $SC(3,2)_{sub}$ and $NSC(3,2)_{sub}$ at low N_{ch}
- ALICE: positive sign
- ATLAS & CMS: negative sign

Nonlinear hydrodynamic response

- Nonlinear response to initial state eccentricities/fluctuations
  - Insight into the (hydrodynamic?) evolution of the system

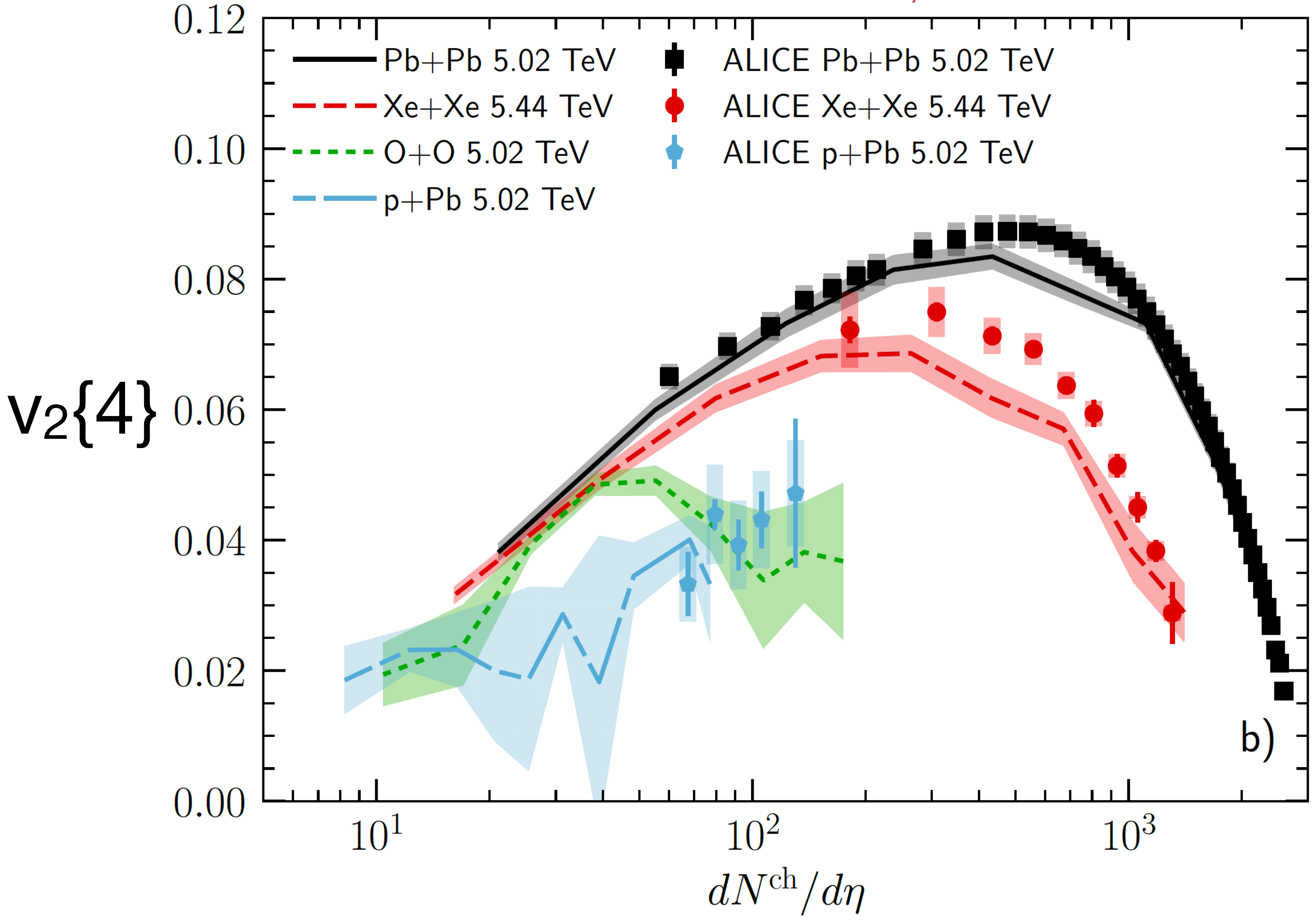


ATLAS, PRC 90, 024905 (2014)

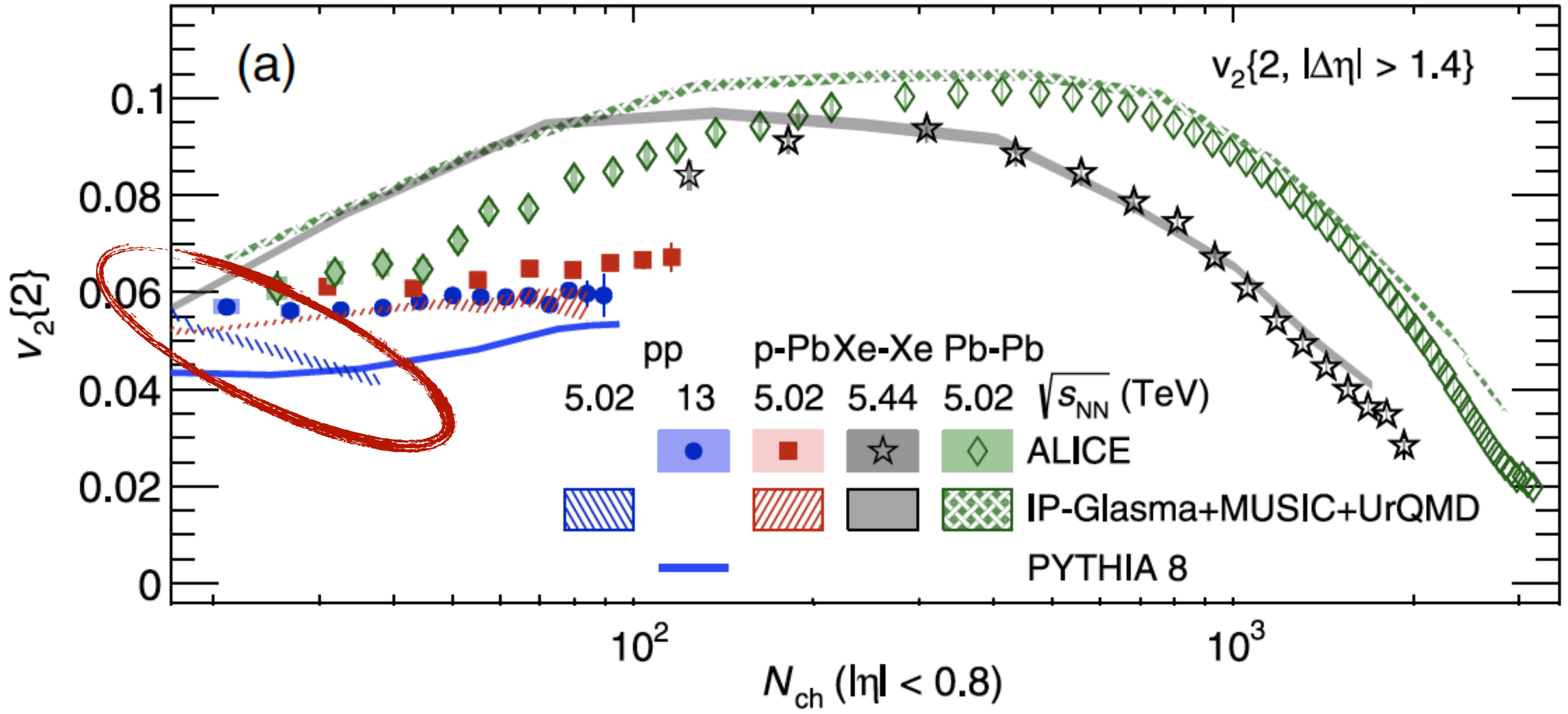


Theoretical description

Schenke et al., arXiv: 2005.14682



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

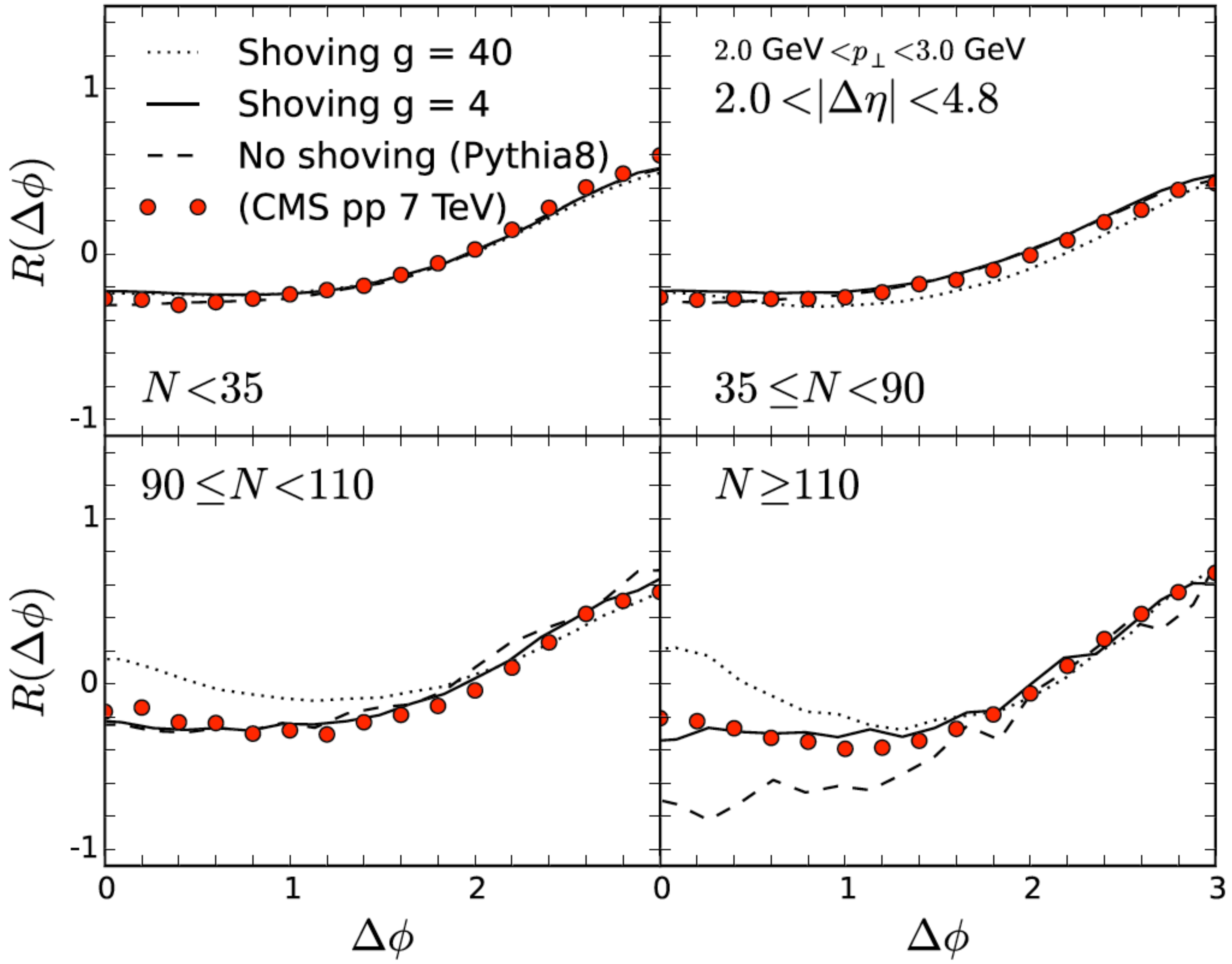
- Final state models provide good description of p-Pb collisions
- Description of pp collisions has its limits
- Models with initial state correlations only, or with few scatterings in the final state without a medium, catch some features of data, too

Initial state effects	Final state effects
Initial momentum correlations	*Interactions in the final state*
Not correlated with initial geometry	Correlated with initial geometry
CGC	Hydrodynamics Transport theory

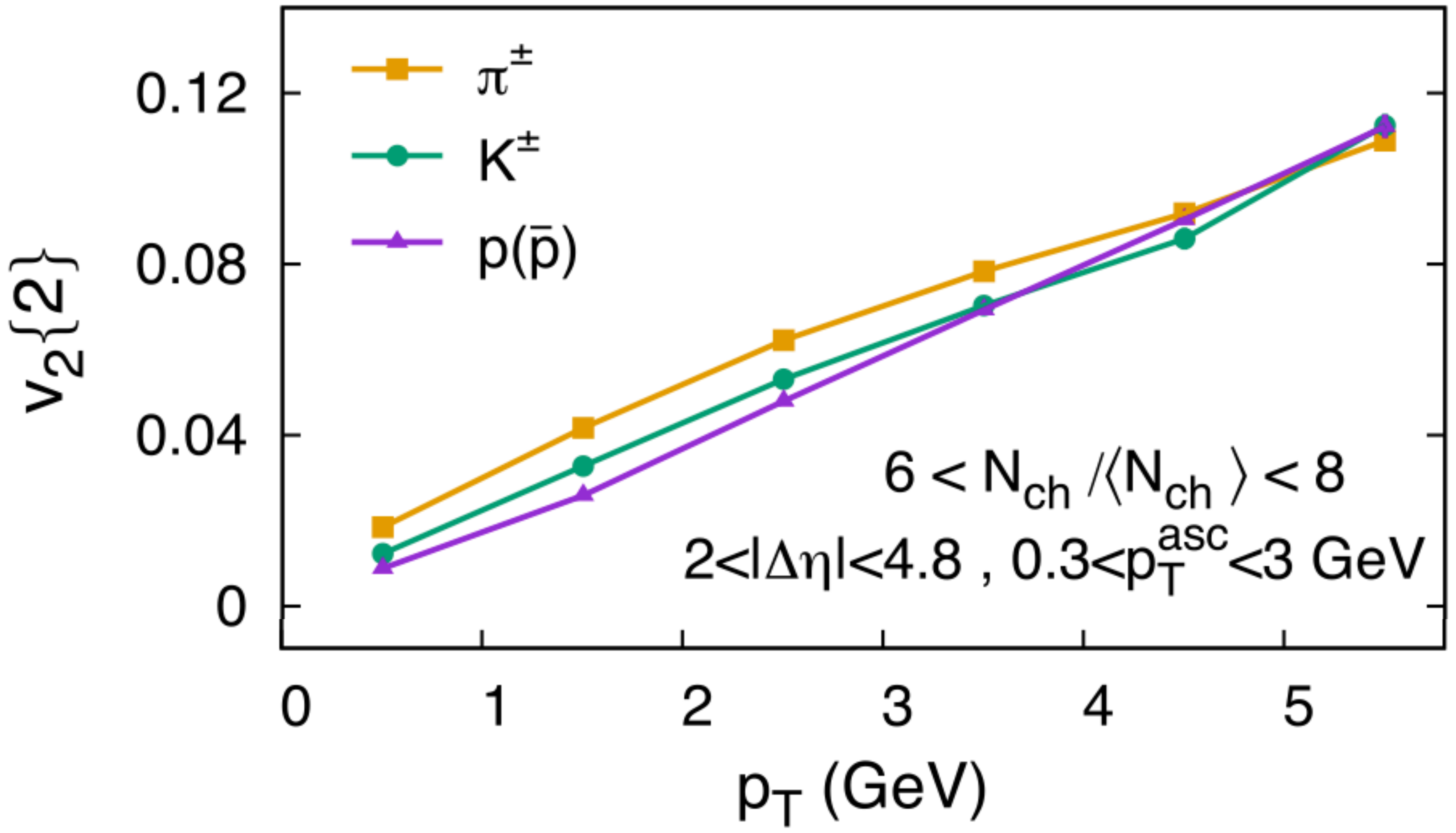
? pp ······ p-Pb ······ Pb-Pb ······

Theoretical description

Bierlich et al, PLB 779 (2018) 58



Schenke et al., PRL 117, 162301 (2016)



- Final state models provide good description of p-Pb collisions
- Final state model description of pp collisions has its limits
- Models with initial state correlations only, or with few scatterings in the final state without a medium, catch some features of data, too

Initial state effects	Final state effects
Initial momentum correlations	*Interactions in the final state*
Not correlated with initial geometry	Correlated with initial geometry
CGC	Hydrodynamics Transport theory

? pp p-Pb Pb-Pb

Multi-particle cumulants

$$v_n\{2\}^2 = \langle v_n^2 \rangle,$$

$$v_n\{4\}^4 = -\left(\langle v_n^4 \rangle - 2\langle v_n^2 \rangle^2 \right),$$

$$v_n\{6\}^6 = \frac{1}{4}\left(\langle v_n^6 \rangle - 9\langle v_n^4 \rangle \langle v_n^2 \rangle + 12\langle v_n^2 \rangle^3 \right),$$

$$v_n\{8\}^8 = -\frac{1}{33}\left(\langle v_n^8 \rangle - 16\langle v_n^6 \rangle \langle v_n^2 \rangle - 18\langle v_n^4 \rangle^2 + 144\langle v_n^4 \rangle \langle v_n^2 \rangle^2 - 144\langle v_n^2 \rangle^4 \right).$$

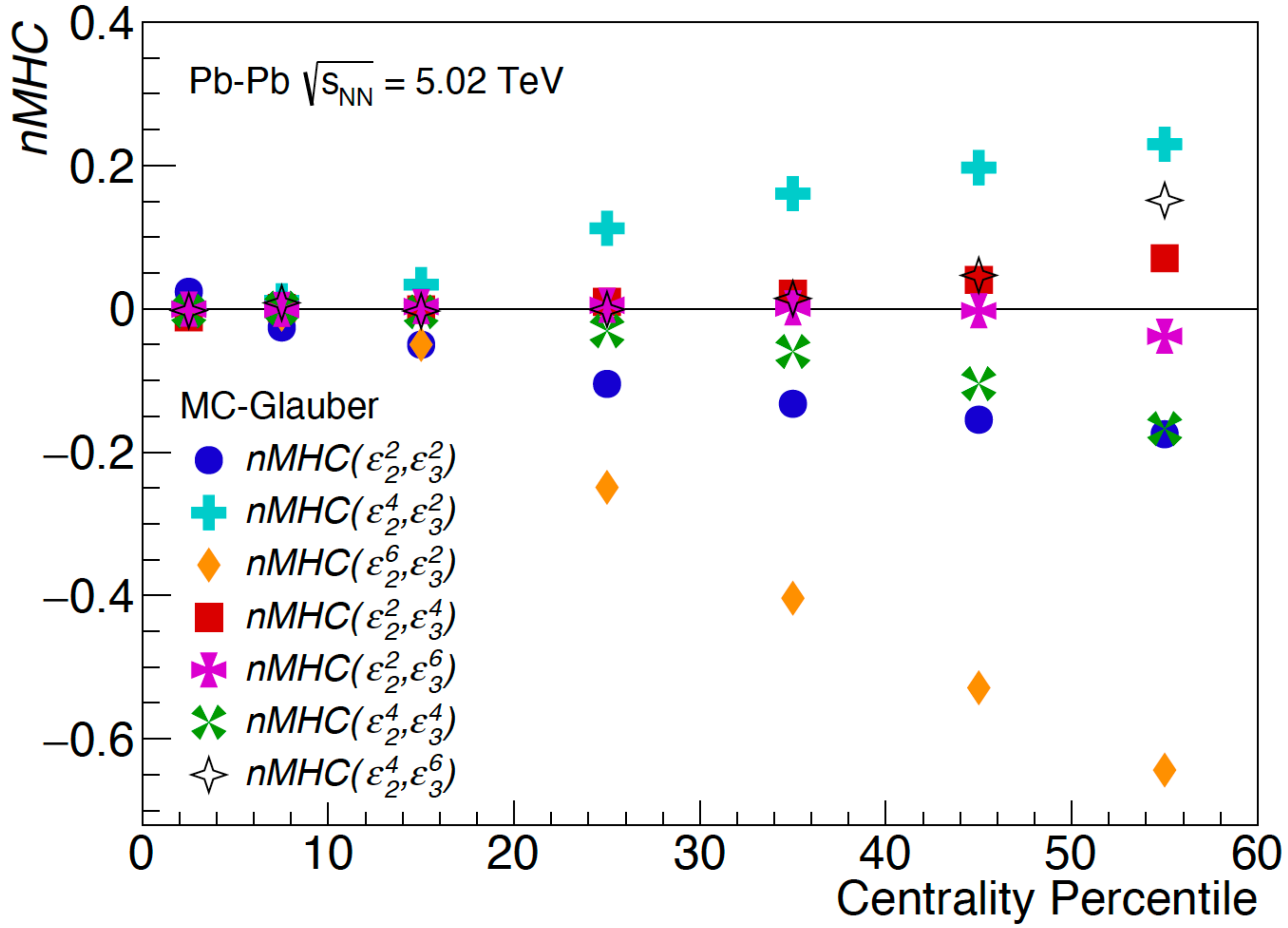
$$v_n\{10\}^{10} = \frac{1}{456}\Big(\langle v_n^{10} \rangle - 25 \langle v_n^8 \rangle \langle v_n^2 \rangle - 100 \langle v_n^6 \rangle \langle v_n^4 \rangle + 400 \langle v_n^6 \rangle \langle v_n^2 \rangle^2 + 900 \langle v_n^4 \rangle^2 \langle v_n^2 \rangle - 3600 \langle v_n^4 \rangle \langle v_n^2 \rangle^3 + 2880 \langle v_n^2 \rangle^5 \Big)$$

$$v_n\{12\}^{12} = -\frac{1}{9460}\Big(\langle v_n^{12} \rangle - 36 \langle v_n^{10} \rangle \langle v_n^2 \rangle - 225 \langle v_n^8 \rangle \langle v_n^4 \rangle + 900 \langle v_n^8 \rangle \langle v_n^2 \rangle^2 - 200 \langle v_n^6 \rangle^2 + 7200 \langle v_n^6 \rangle \langle v_n^4 \rangle \langle v_n^2 \rangle - 14400 \langle v_n^6 \rangle \langle v_n^2 \rangle^3 + 2700 \langle v_n^4 \rangle^3 - 48600 \langle v_n^4 \rangle^2 \langle v_n^2 \rangle^2 + 129600 \langle v_n^4 \rangle \langle v_n^2 \rangle^4 - 86400 \langle v_n^2 \rangle^6 \Big)$$

Moravcova, Gulbrandsen, Zhou, arXiv:2005.07974

Multi-harmonic correlations

- Multi-harmonic correlations using high order cumulants
- Higher order cumulant correlations have stronger signal than the lower order (e.g. SC(m,n))
- Sign change -> would it remain in small systems?



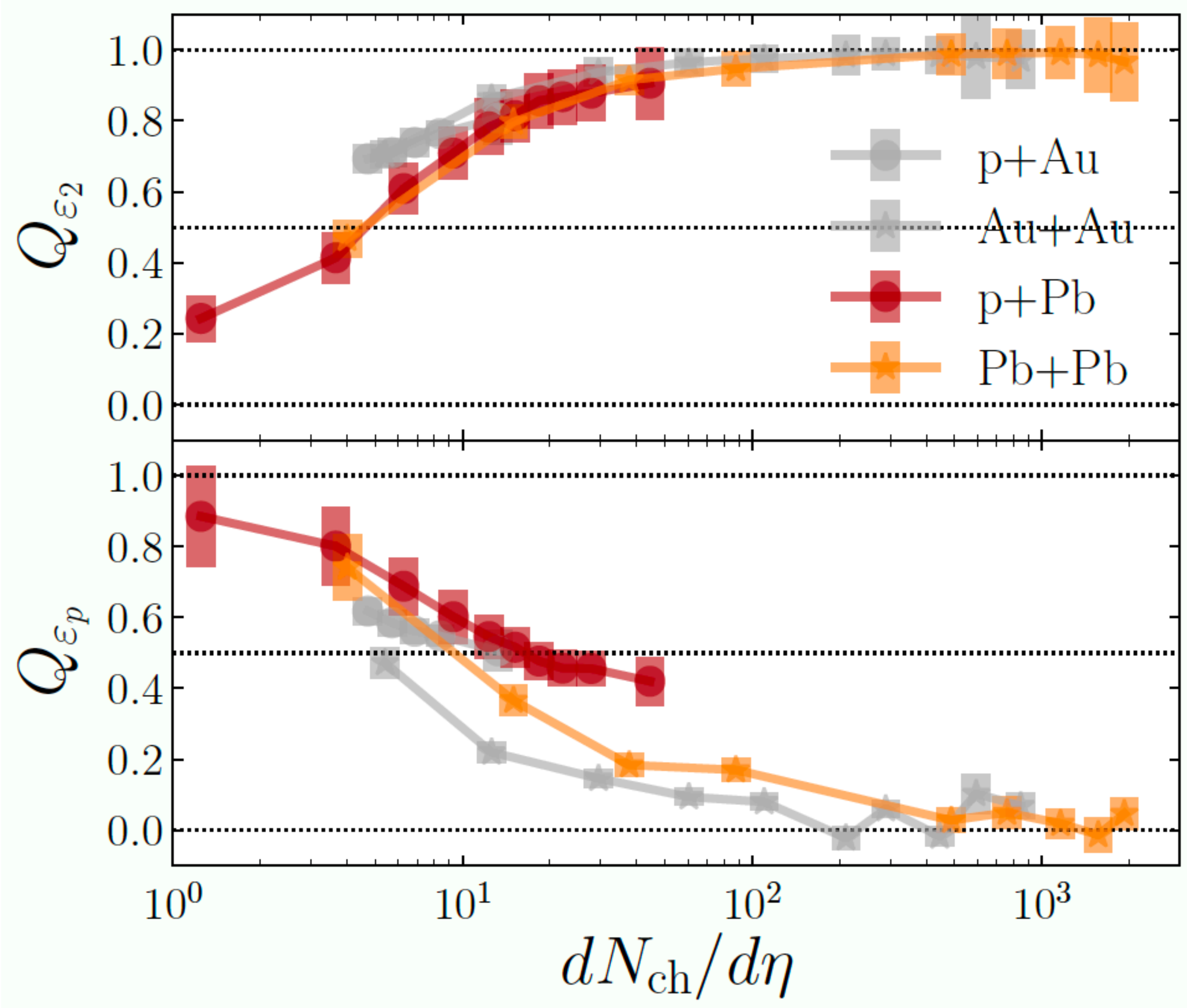
Moravcova, Gulbrandsen, Zhou, arXiv:2005.07974

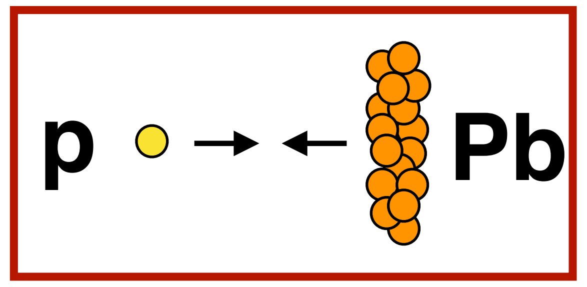
Influence of the initial state

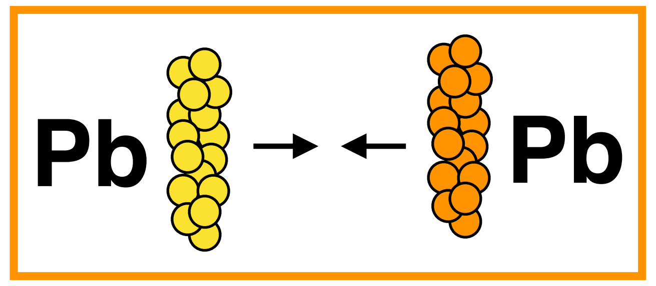
Schenke et al., PLB 803 (2020) 135322
Schenke et al., QM19

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

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







- 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