Experimental Overview of QGP in small system

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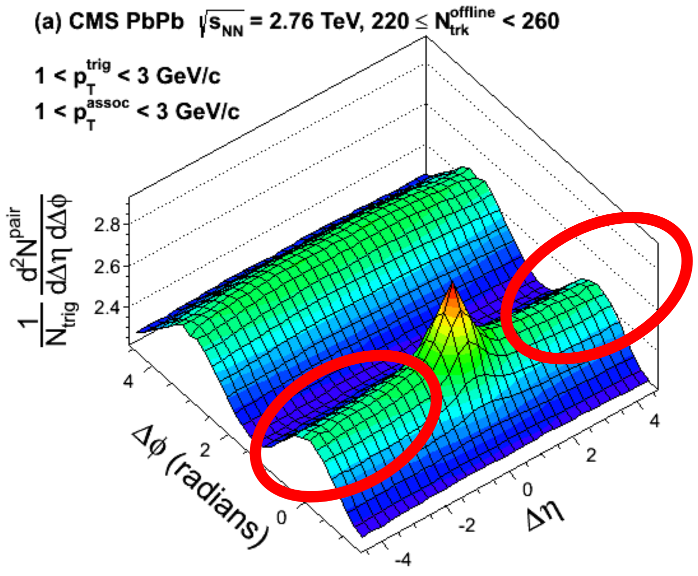
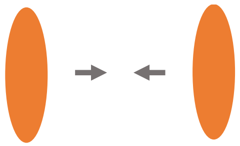
April 24 - 27, 2023

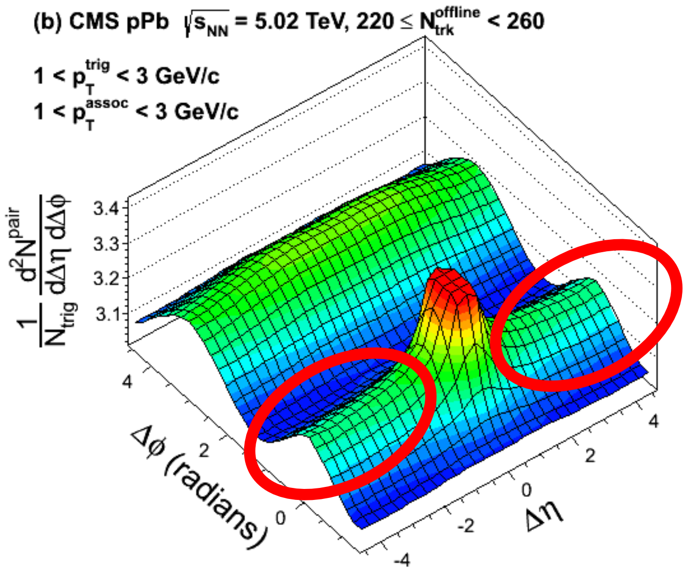
The 9th Asian Triangle Heavy-Ion Conference at JMS Aster Plaza, Hiroshima, Japan

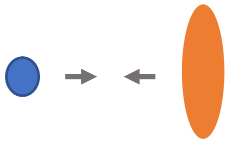
The first hint of QGP in small system

PLB 724, 213 (2013)

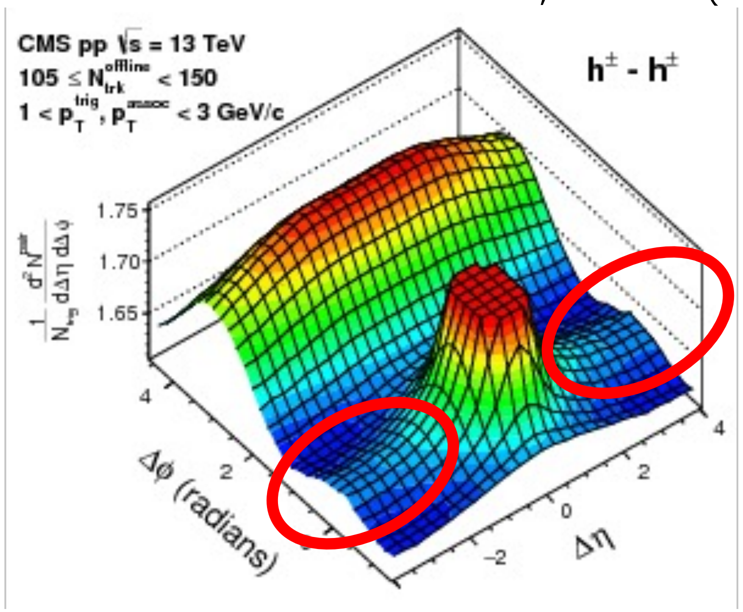


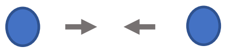






PLB 765, 193-220 (2017)



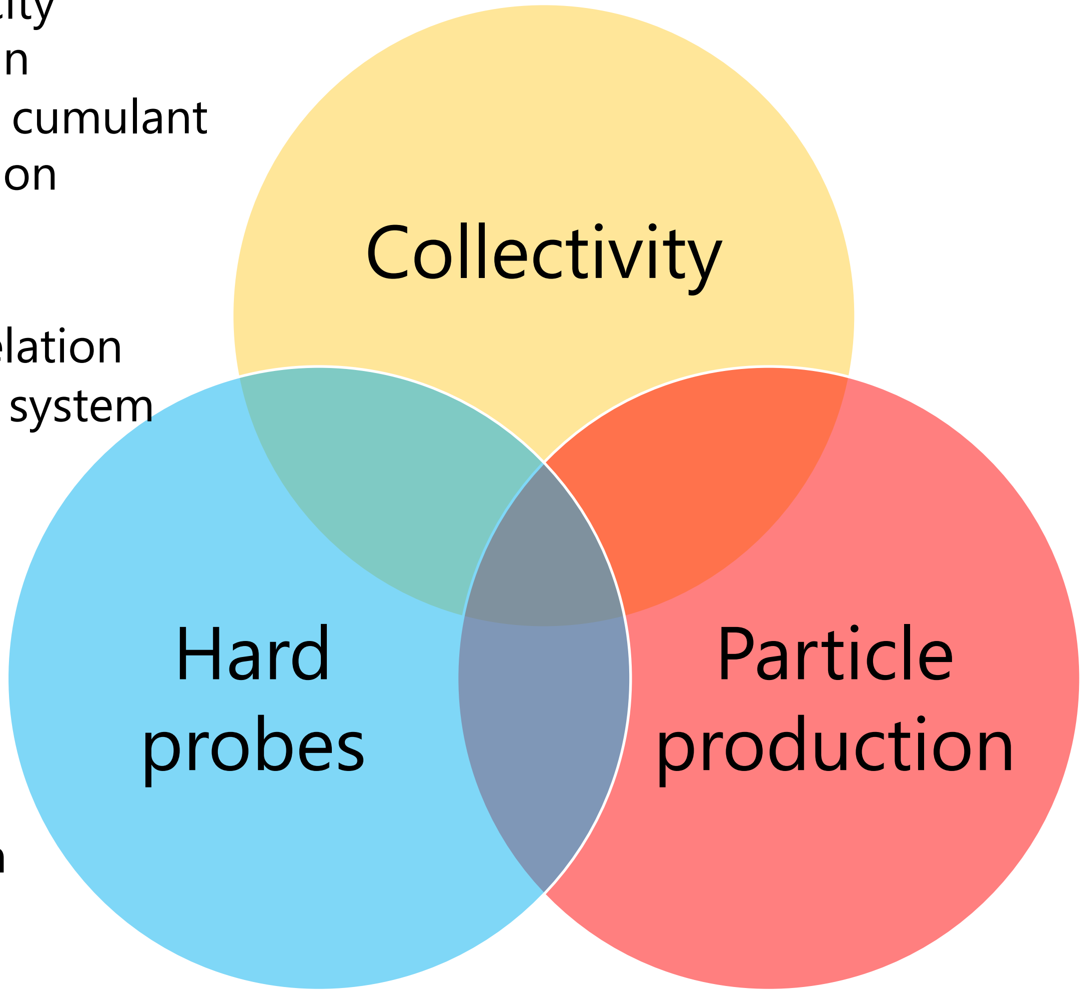


- Observation of long-range correlations at Δφ~0, so-called near-side "ridge", in Pb–Pb and high-multiplicity pp and p–Pb collisions.
  - Indication of collectivity in small systems.

Experimental measurements in small systems

- Many systematic measurements to investigate the properties of small system

  - v_n vs multiplicity
  - Geometry scan
  - Multi-particle cumulant
  - Flow Fluctuation
  - PID v_2
  - Energy scan
  - v_2-$\langle p_T \rangle$ correlation
  - Much smaller system

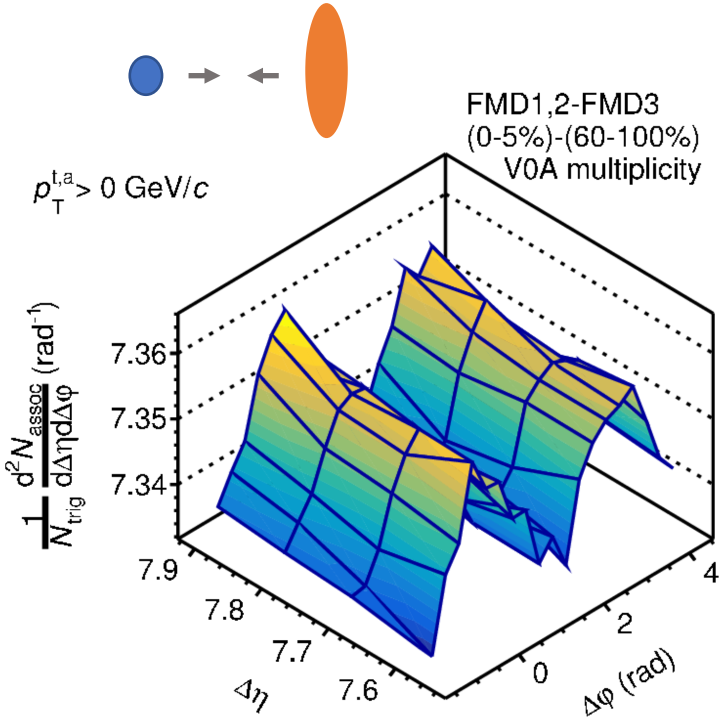


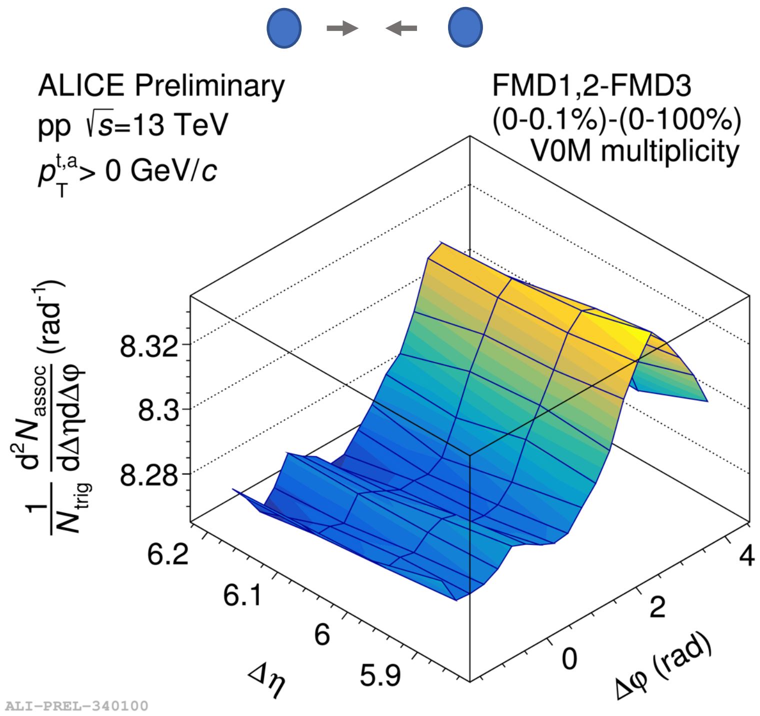
  - Strangeness enhancement
  - Baryon-to-meson ratio

  - Open charm production
  - HF Flow
  - Thermal photon

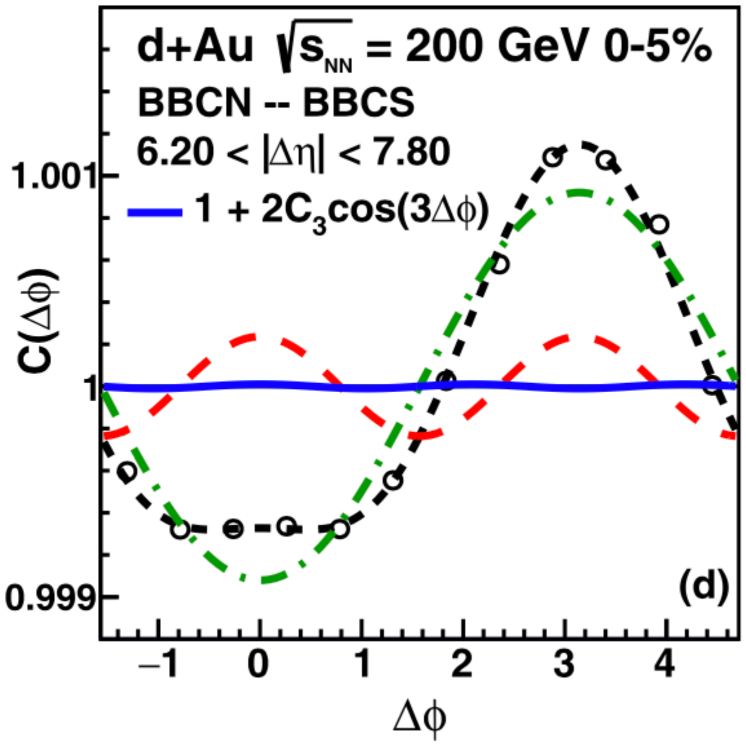
Systematic Measurements of Collectivity

Long-range two-particle correlation





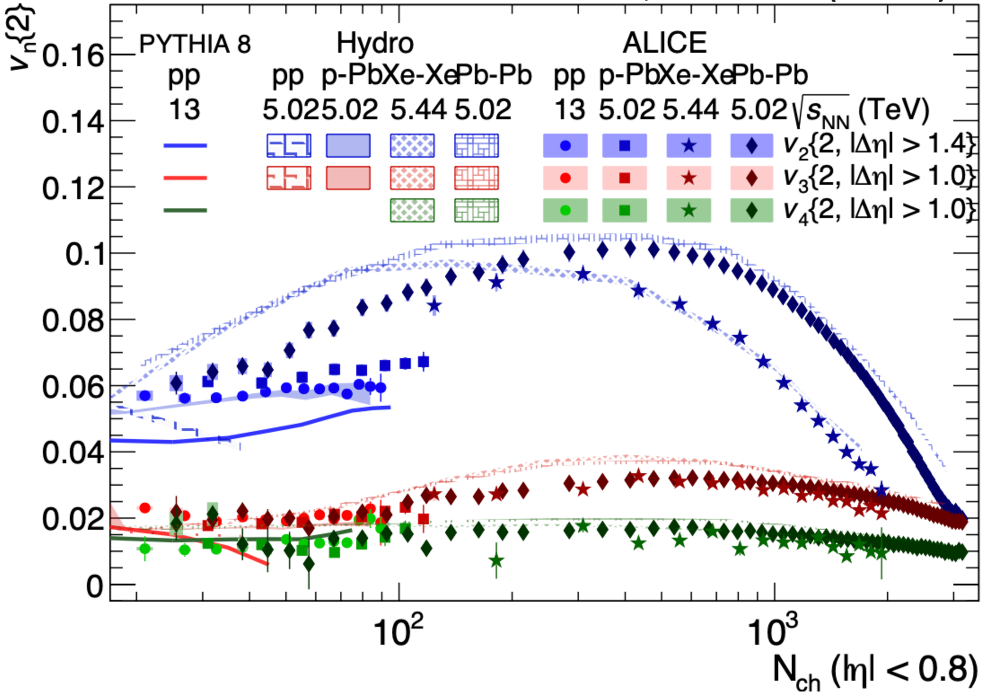
PRC 96, 064905 (2017)

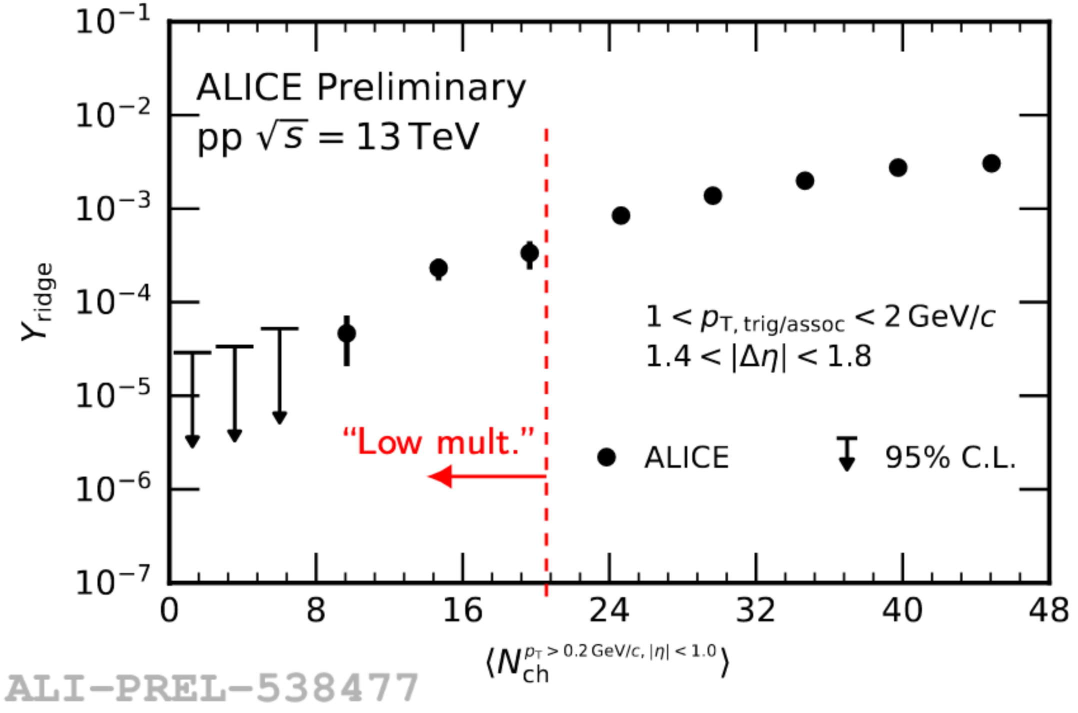


- Long-range correlations are observed up to very large Δη in high multiplicity small collision systems at RHIC and LHC.
  - p–Pb at Δη~8
  - pp at Δη~6
  - d–Au at Δη~7.8

v_n vs multiplicity

PRL 123, 142301 (2019)





- Non-zero ridge yield is observed in very low multiplicity regions.
- Smooth transition from small to large system
- ordering $v_2 > v_3 > v_4$
- PYTHIA8 underestimates $v_2\{2\}$ and can not reproduce the ordering in pp collisions.
- Hydro model (IP-Glasma+Music+UrQMD) underestimates $v_2\{2\}$ in pp collisions.

Multi-particle correlation: $C_2\{4\}$

- Negative $c_2\{4\}$ strongly indicates the emergence of collectivity.

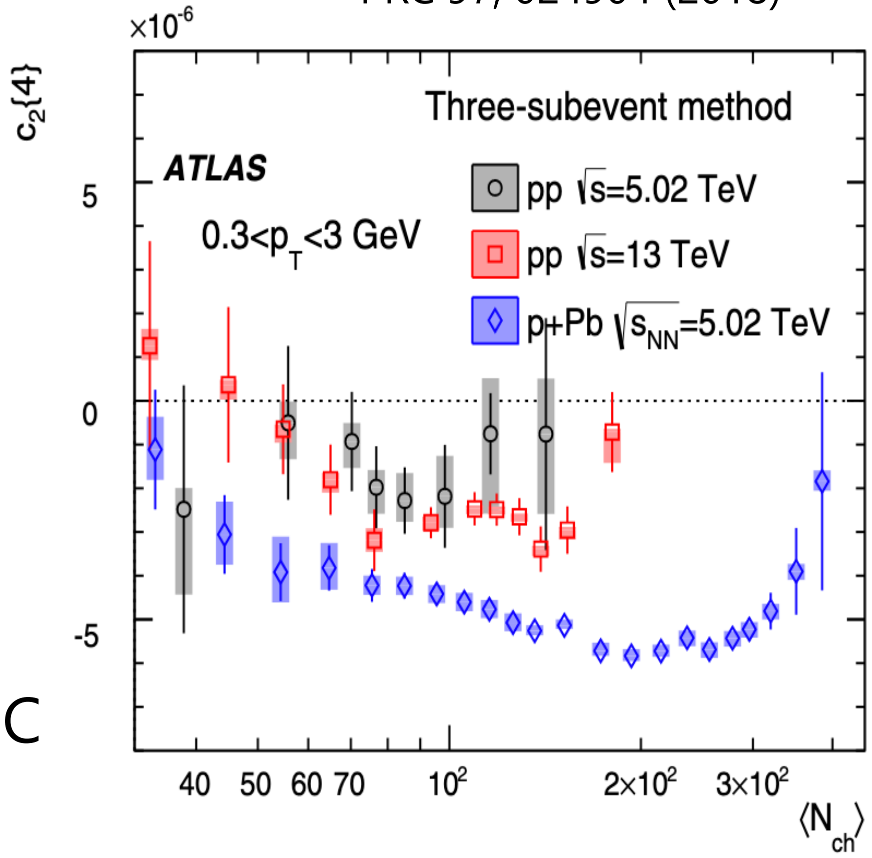
$$v_2\{4\} = \sqrt[4]{-c_2\{4\}}$$

$$v_2\{2\} = \langle v_2^2 \rangle + \sigma_2^2$$

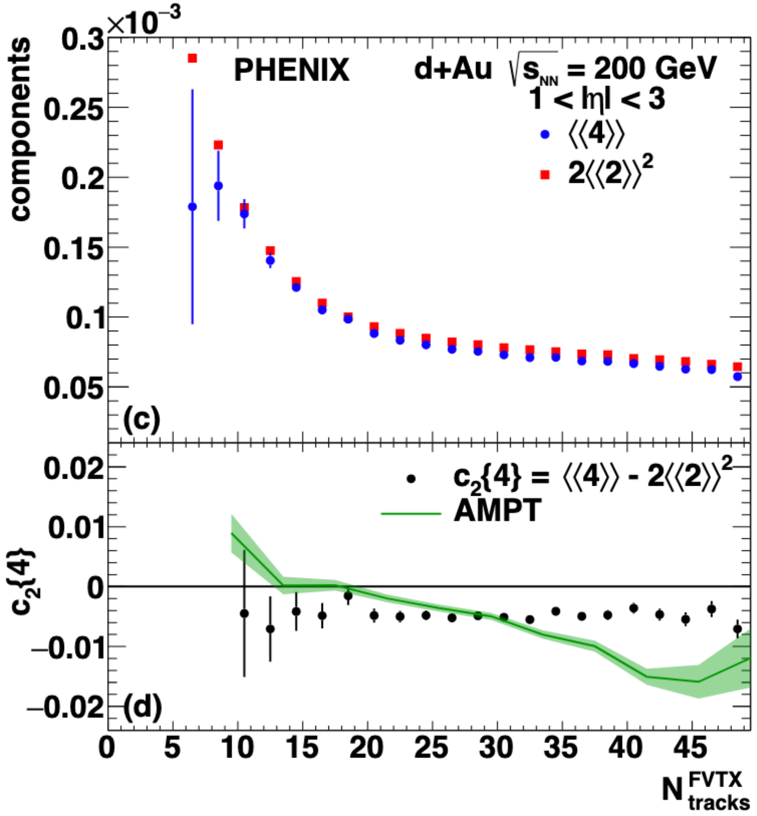
$$v_2\{4\} = \langle v_2^2 \rangle - \sigma_2^2$$

- Negative $c_2\{4\}$ is observed in pp, p–Pb, and Pb–Pb at the LHC.
- Negative $c_2\{4\}$ is observed in d–Au, but not in p–Au at RHIC w/o subevent method.

PRC 97, 024904 (2018)



PRL 120, 062302 (2018)



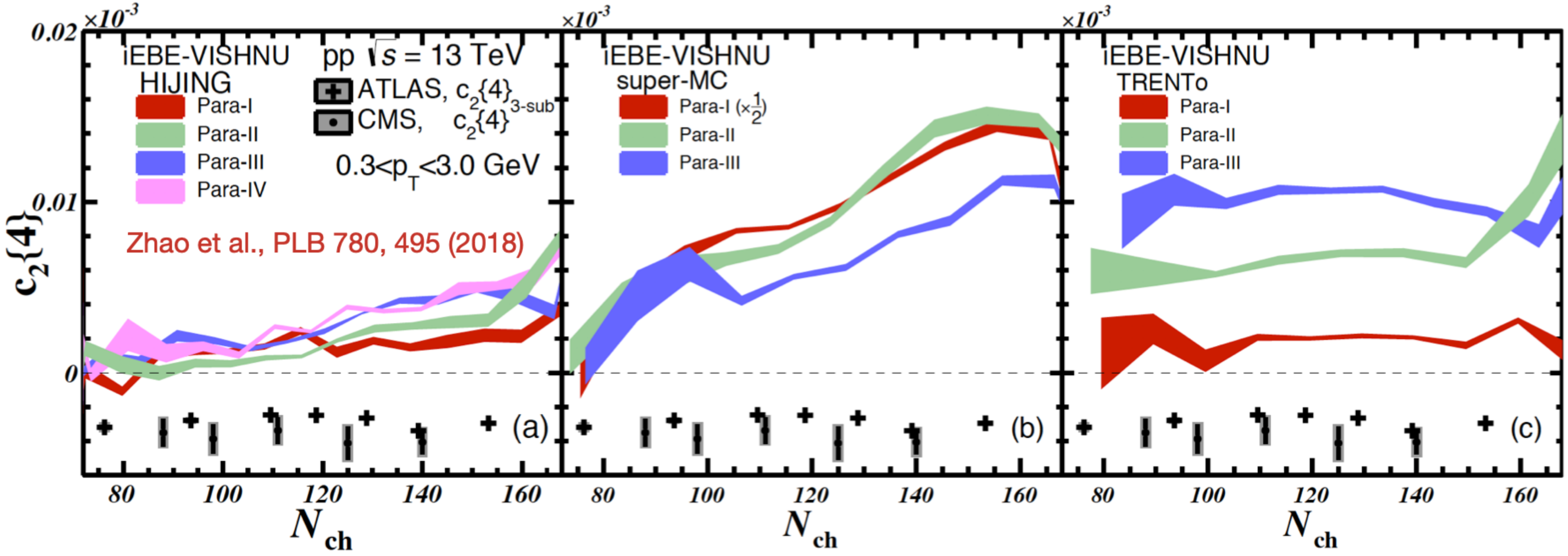
$c_2\{4\}$ vs hydro

- Negative $c_2\{4\}$ in pp collisions is not reproduced using various initial conditions.

☞ Importance of understanding Initial state

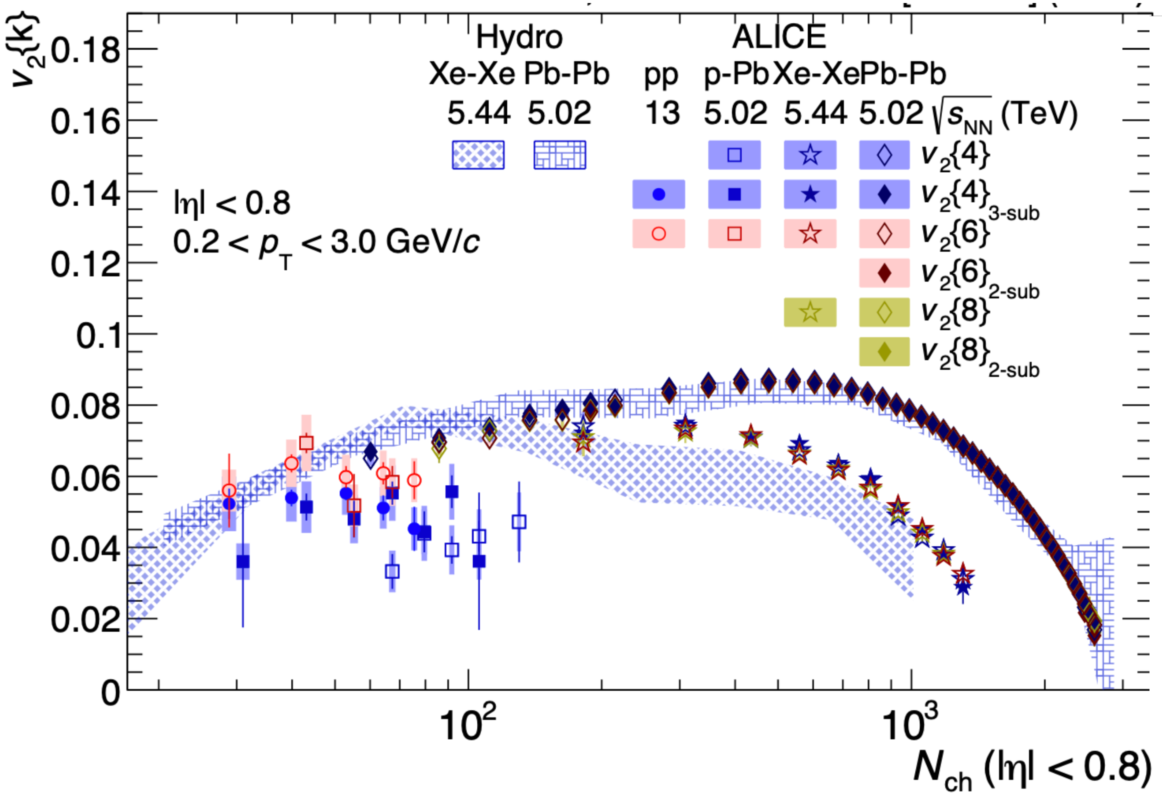
Y.Zhou@QM19

HIJING **SUPER-MC** **TRENTo**

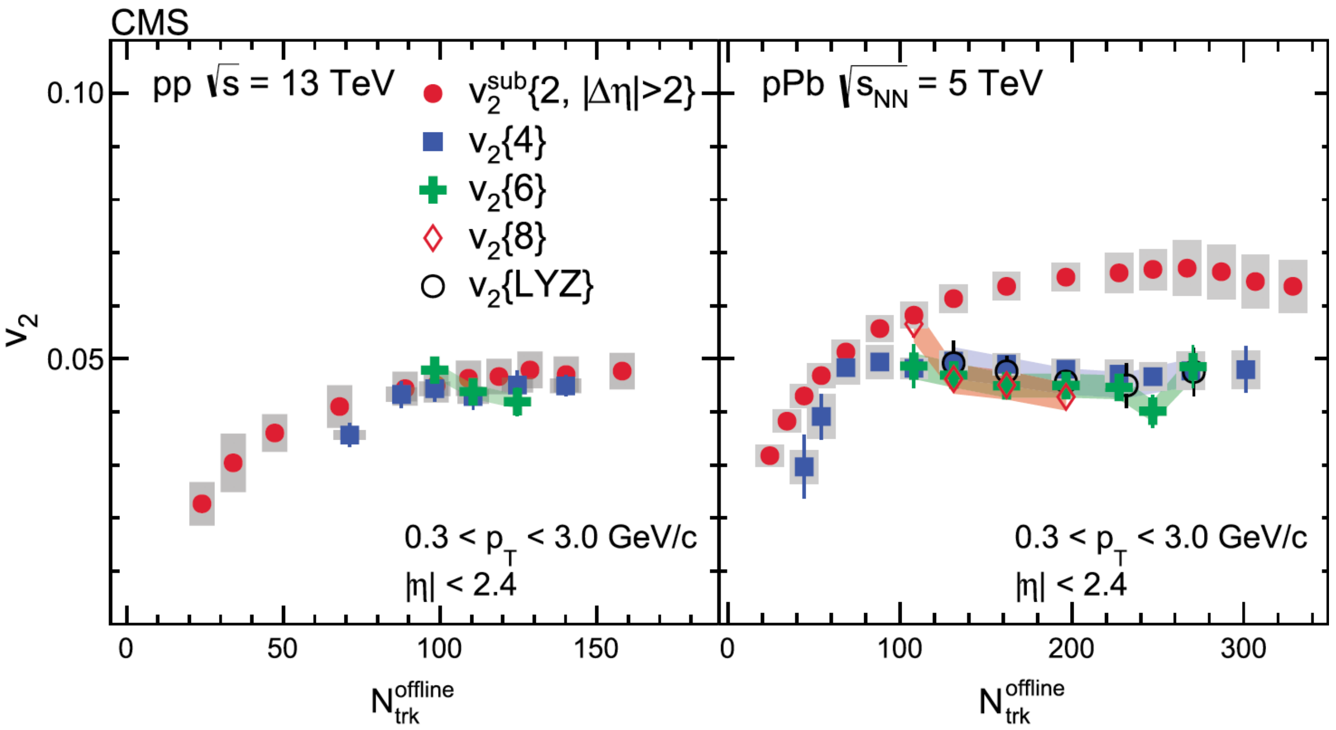


$v_2\{4,6,8\}$ from small to large system

PRL 123, 142301 (2019)



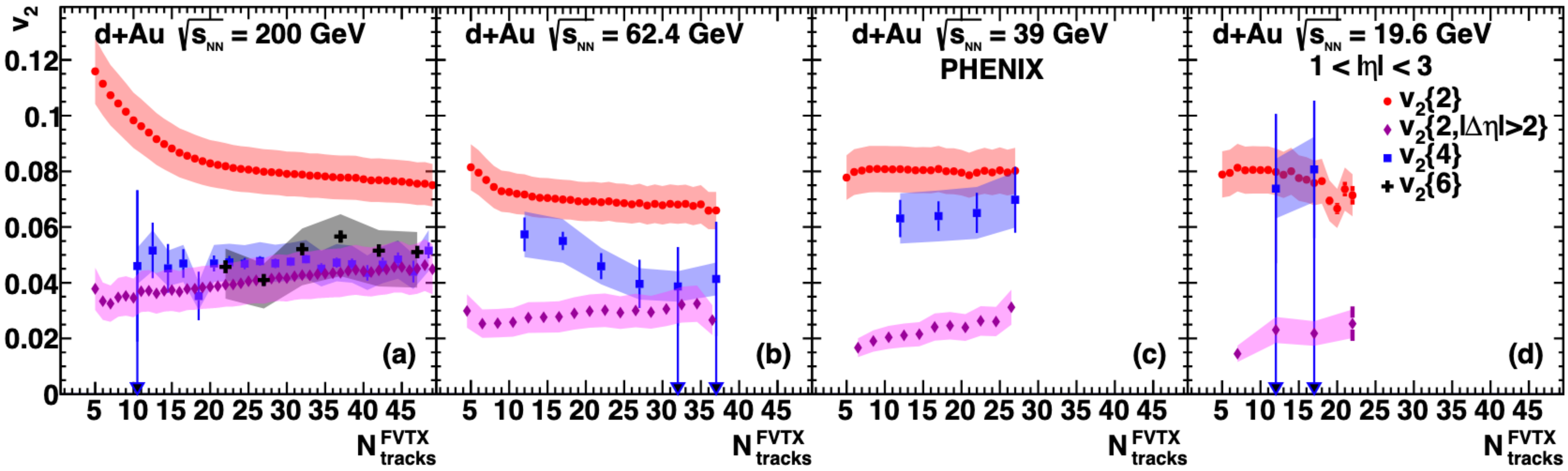
PLB 765, 193-220 (2017)



- v_2s by multi-particle correlations are comparable in pp and p–Pb same as Pb–Pb: $v_2\{4\}$~$v_2\{6\}$~$v_2\{8\}$
  - ☞<u>Evidence of collectivity in small system</u>

Energy dependence of multi-particle correlation

PRL 120, 062302 (2018)

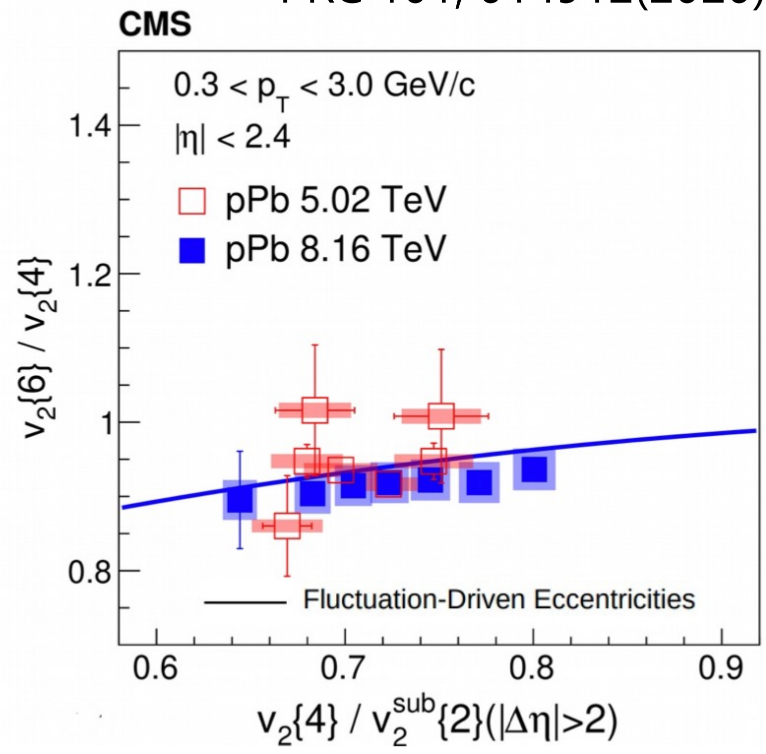


- v_2s by multi-particle correlations is observed in d–Au collisions down to $\sqrt{s_{NN}}$=19.6 GeV

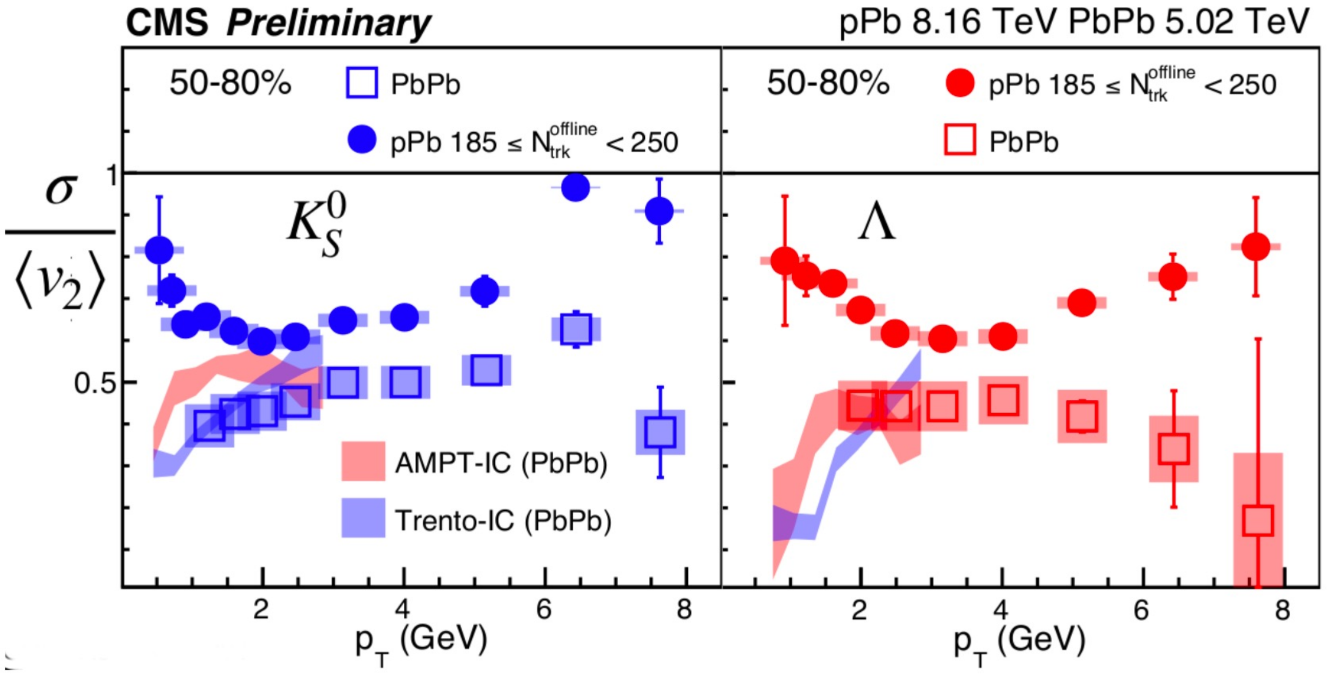
Flow Fluctuation

- Ratios of multi-particle cumulants are consistent with geometry driven assumptions.
- The fraction of flow fluctuation is larger in p–Pb than Pb–Pb.
- No obvious particle species dependence of fluctuation.
  - Fluctuation is originated from initial-state geometry.

PRC 101, 014912(2020)

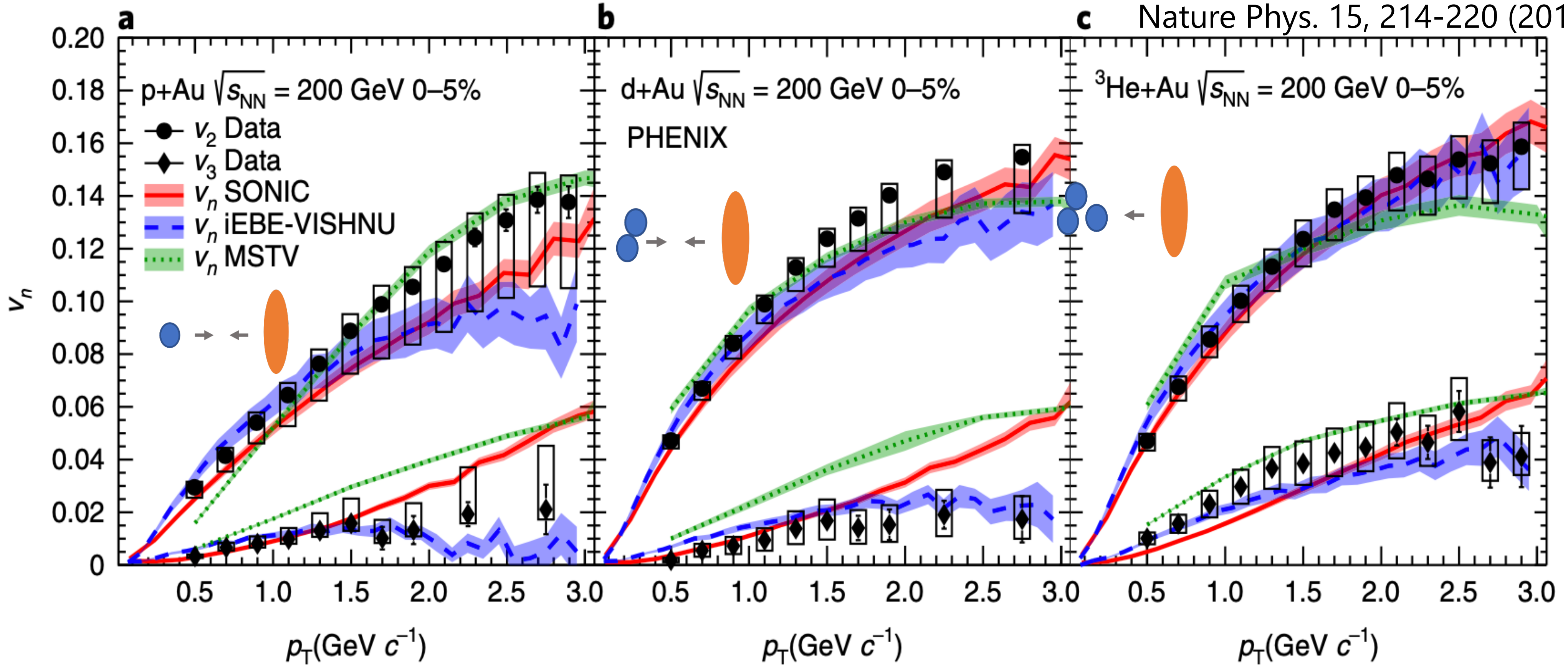


arXiv:2205.00080



v_n vs initial geometry

Nature Phys. 15, 214-220 (2019)



- The hydro model describes the data well

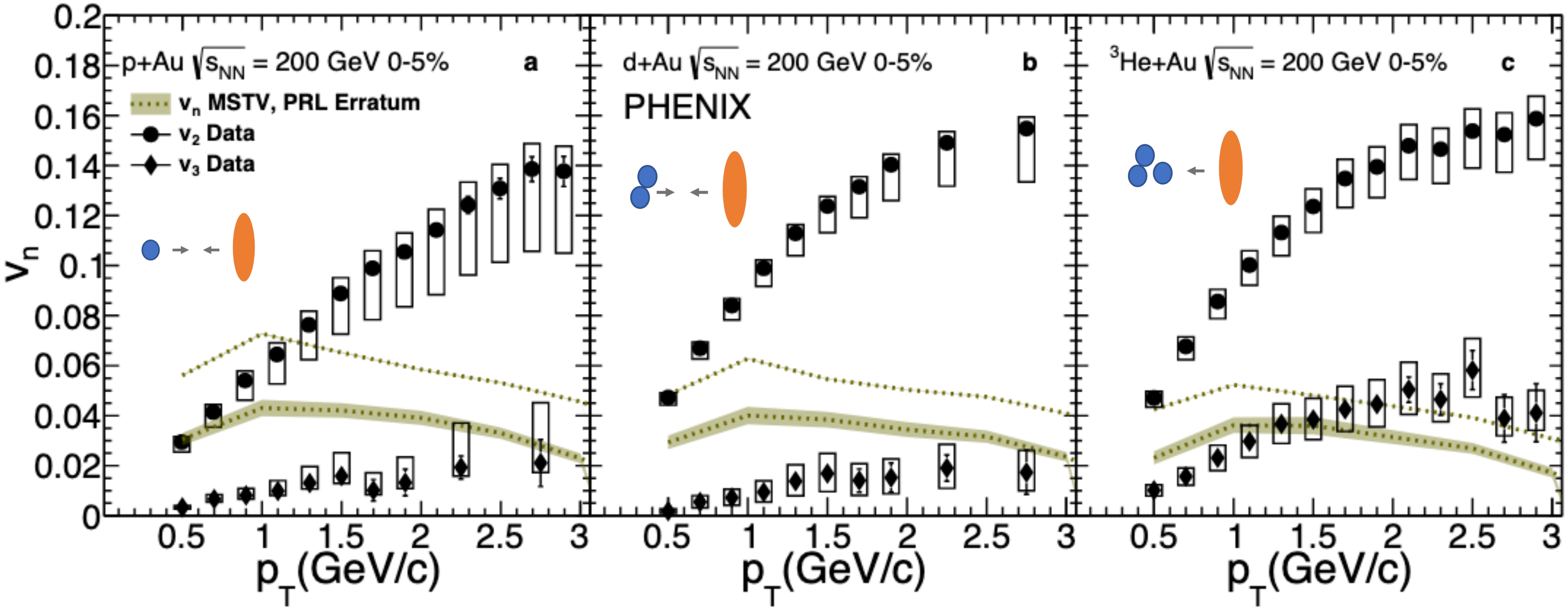
$$v_2^{pAu} < v_2^{dAu} \approx v_2^{HeAu} \qquad \varepsilon_2^{pAu} < \varepsilon_2^{dAu} \approx \varepsilon_2^{HeAu}$$

$$\longleftrightarrow$$

$$v_3^{pAu} \approx v_3^{dAu} < v_3^{HeAu} \qquad \varepsilon_3^{pAu} \approx \varepsilon_3^{dAu} < \varepsilon_3^{HeAu}$$

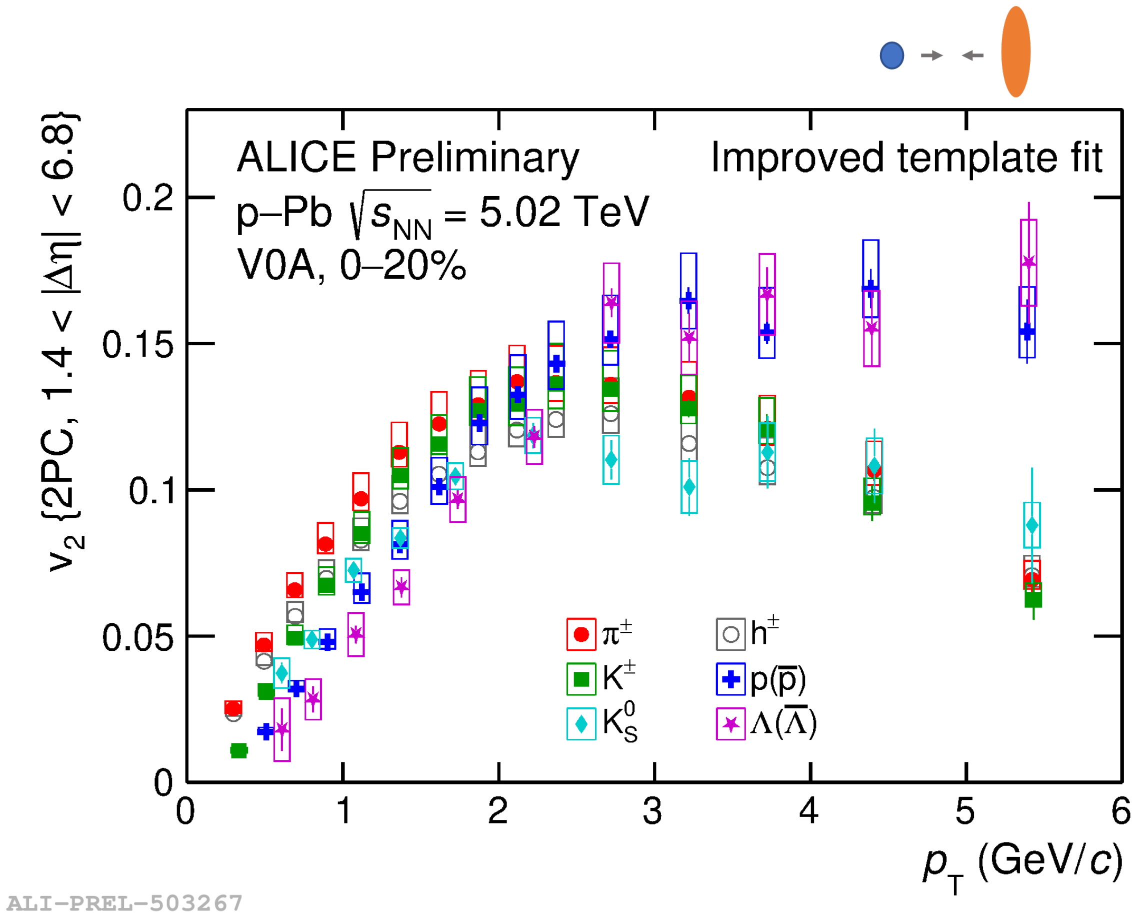
v_n vs initial geometry

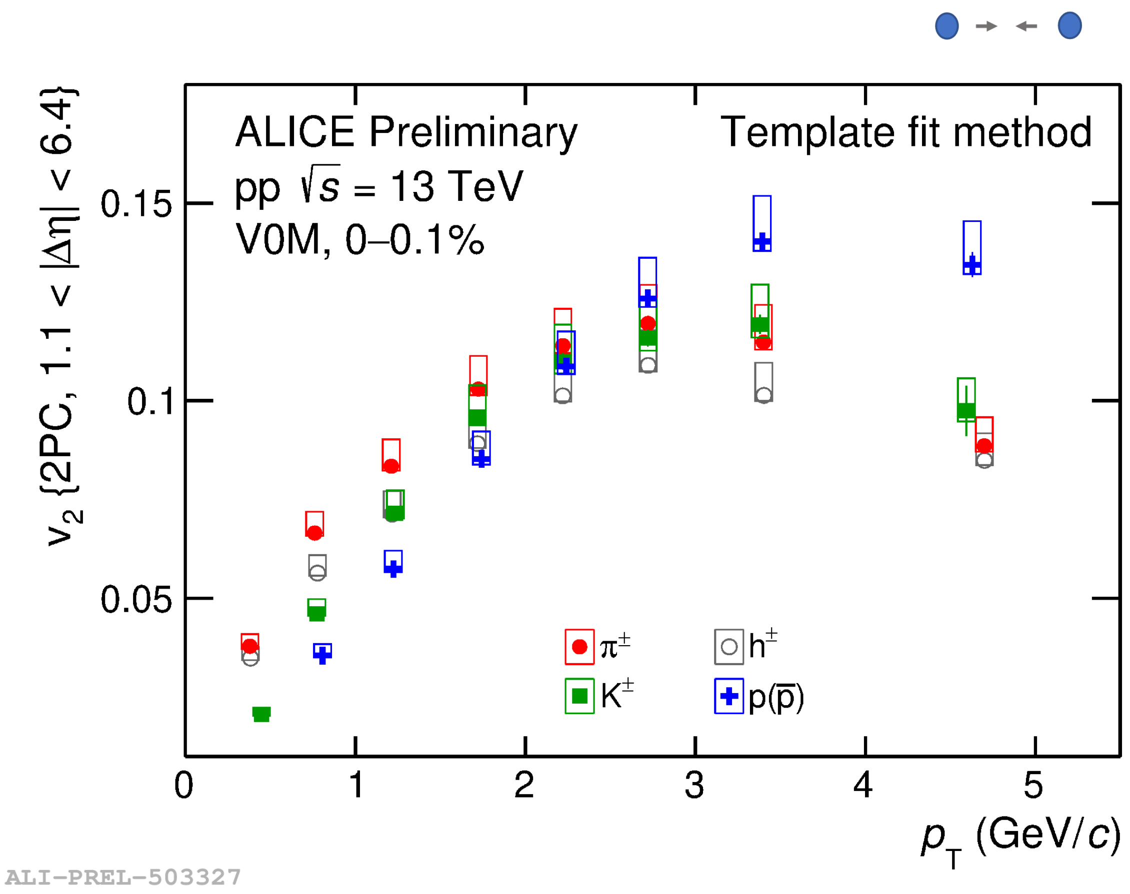
Nature Phys. 15, 214-220 (2019) , PRL 123, 039901 (2019)



- The initial state model (CGC) alone underestimates the data.
- <u>Interaction in the final state is essential to reproduce v_n</u>

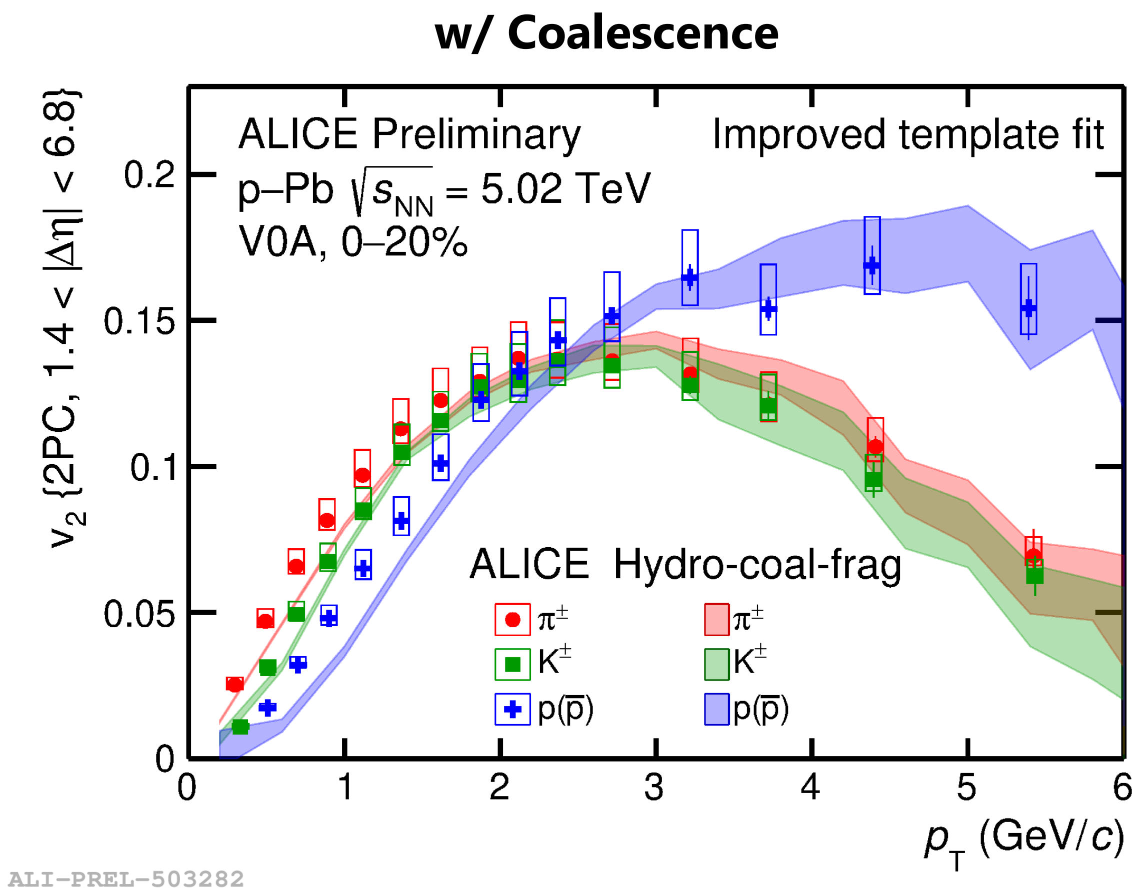
PID v_2 in pp and p–Pb

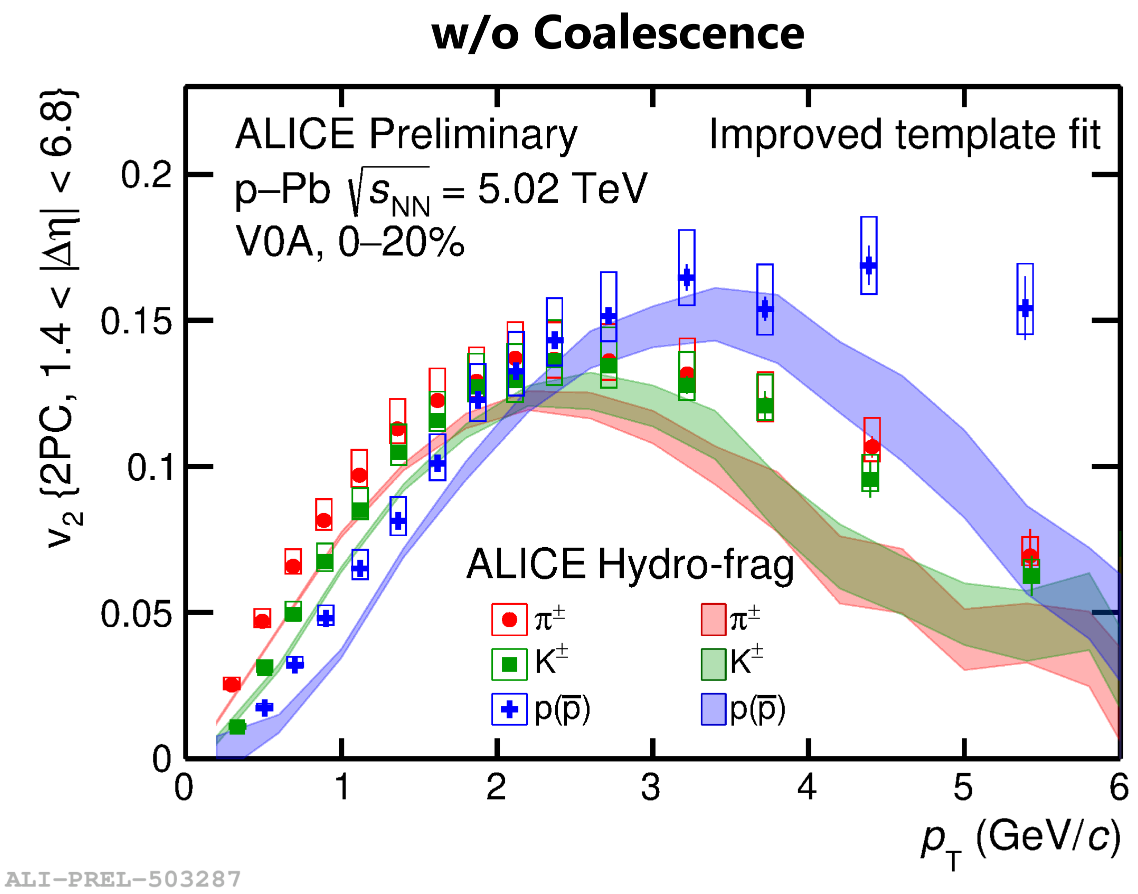




- v_2 in pp and p–Pb has a similar feature to Pb–Pb
  - Mass ordering at low p_T
  - Baryon/meson grouping at intermediate p_T

Model comparisons of PID v_2 in p–Pb





- The hydro model with coalescence and jet fragmentation describes the data well (PRL125 7, 072301 (2020)).

☞Partonic flow in small system

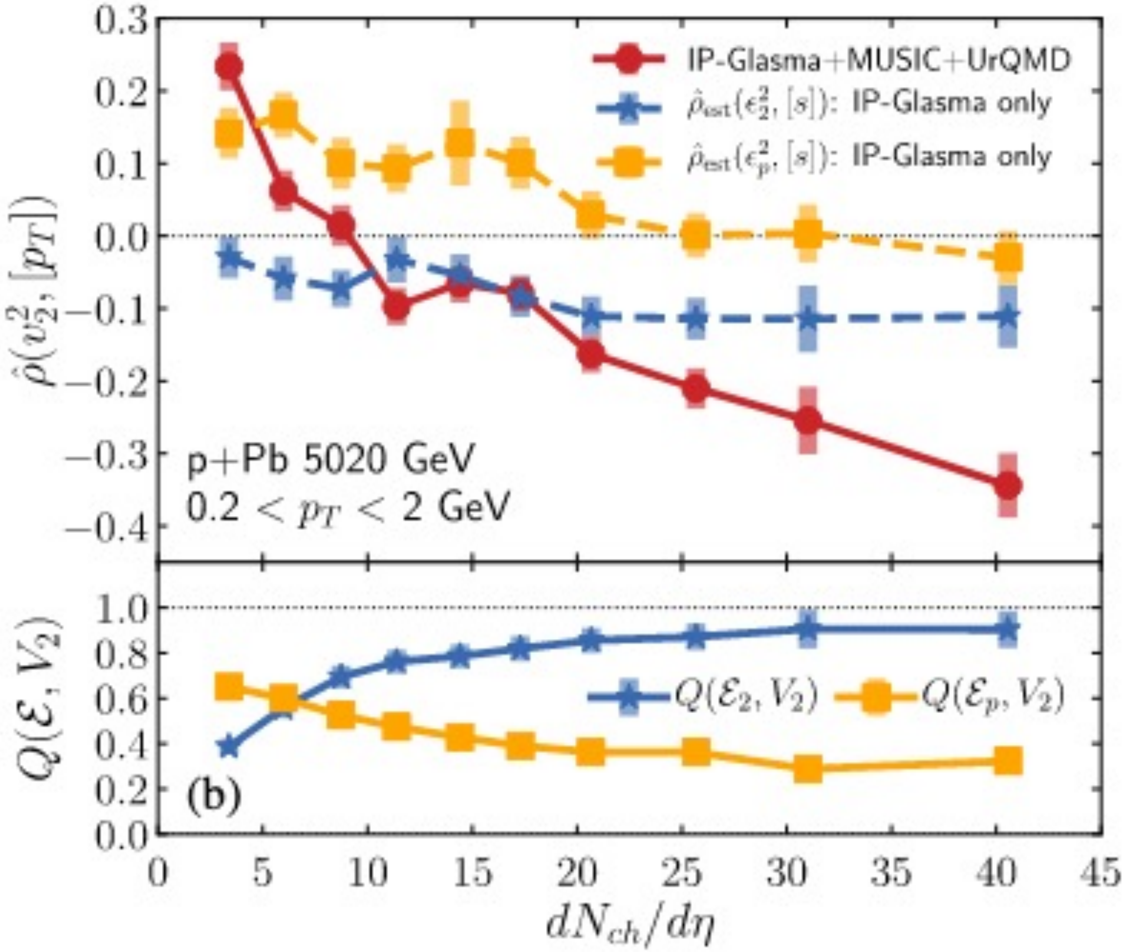
v_2-$\langle p_T \rangle$ correlation

- At low multiplicity, v_2 is correlated to initial momentum anisotropy rather than initial geometry.
- Correlation between v_2 and $\langle p_T \rangle$

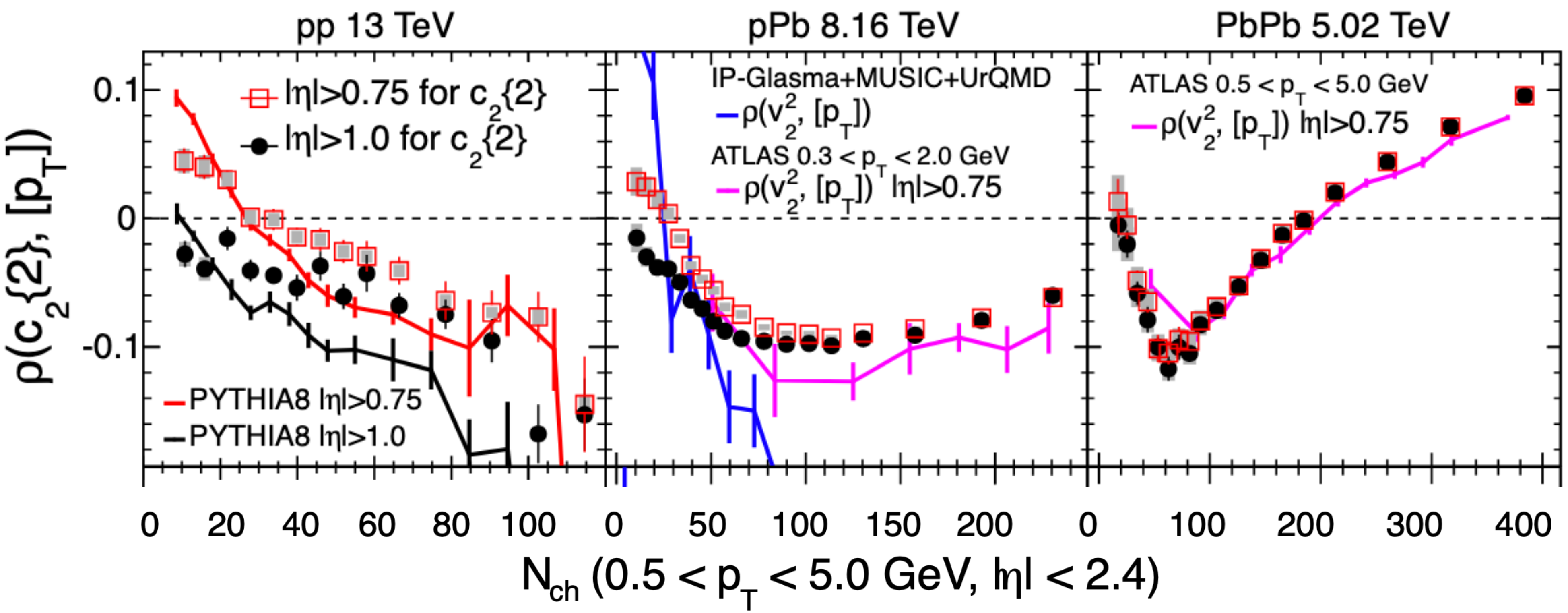
$$\rho_n(v_n^2, [p_T]) = \frac{cov(v_n^2, [p_T])}{\sqrt{var(v_n^2)}\sqrt{var([p_T])}}$$

  - Final effect: v_2-$\langle p_T \rangle$ correlated
  - Initial effect: v_2-$\langle p_T \rangle$ anti-correlate
  - Sign change is predicted at N_{ch}~10

PRL,125, 192301(2020)



v_2-<p_T> correlation

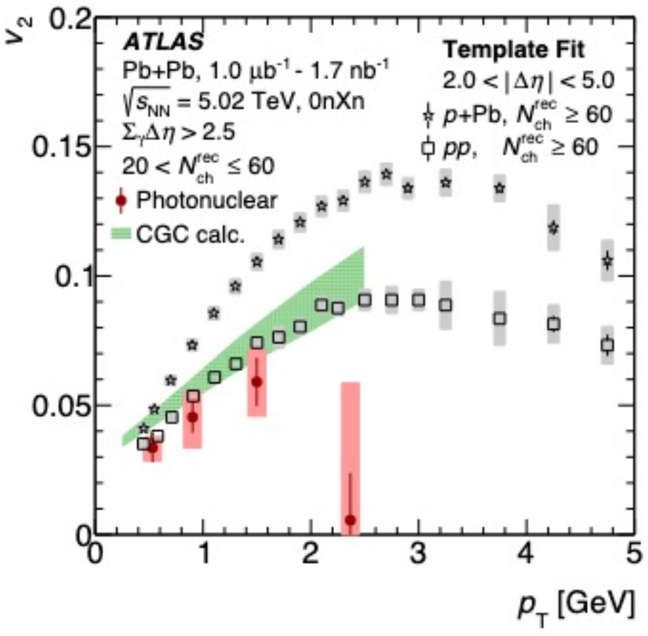


- Sign change of $\rho(c_2\{2\}, [p_T])$ is observed as the model predicted with $|\eta|>0.75$.
- However, the sign change disappears with a larger rapidity gap.
- Correlations in the initial stage are the short range? (PRD 105,094023 (2022))

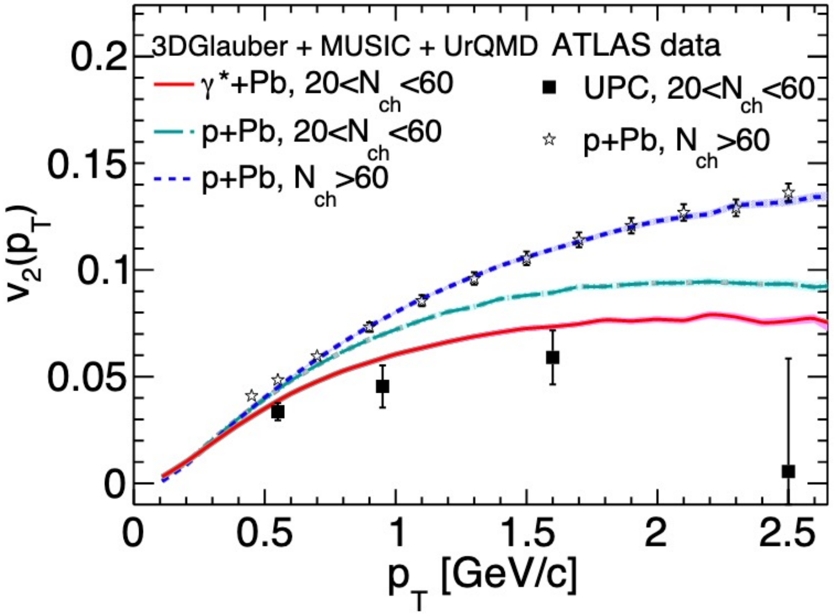
Flow in γ–A

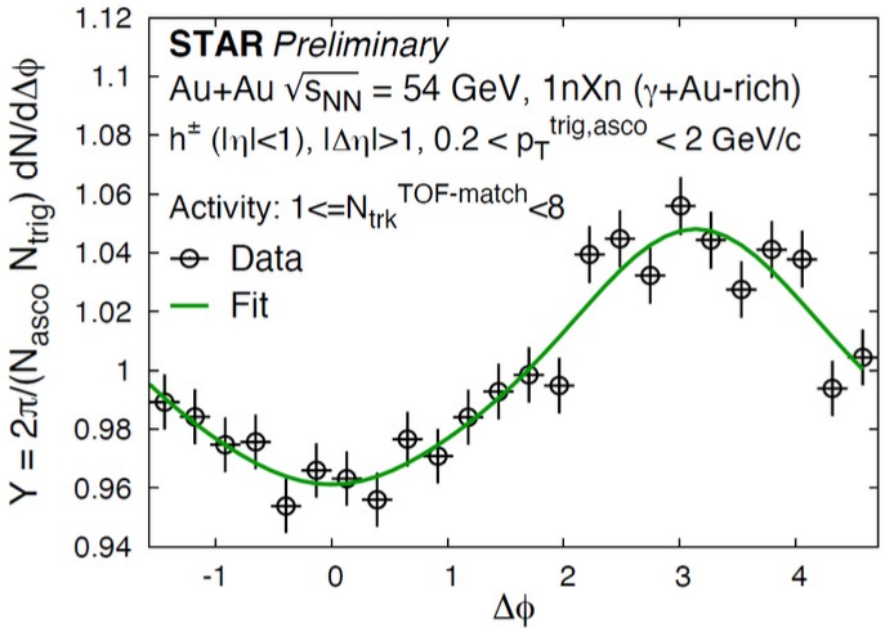
- In UPC A–A collisions, photons coherently emitted from one nuclei interact with the other nuclei.
- Long-range two-particle dihadron correlations are measured in γ–Pb and γ–Au.
- The Initial-only (CGC) and hydro (3DGlauber+MUSIC+UrQMD) models describe v_2 in γ–Pb qualitatively.

PRC 104 014903 (2021)



PRL 192, 252302 (2022)



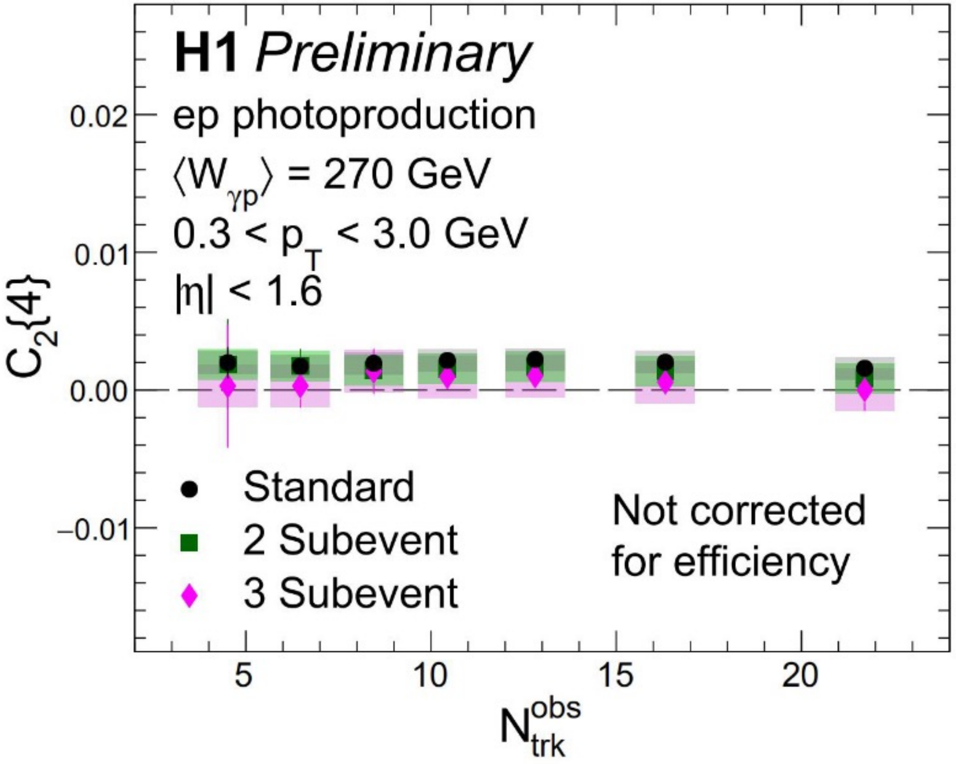


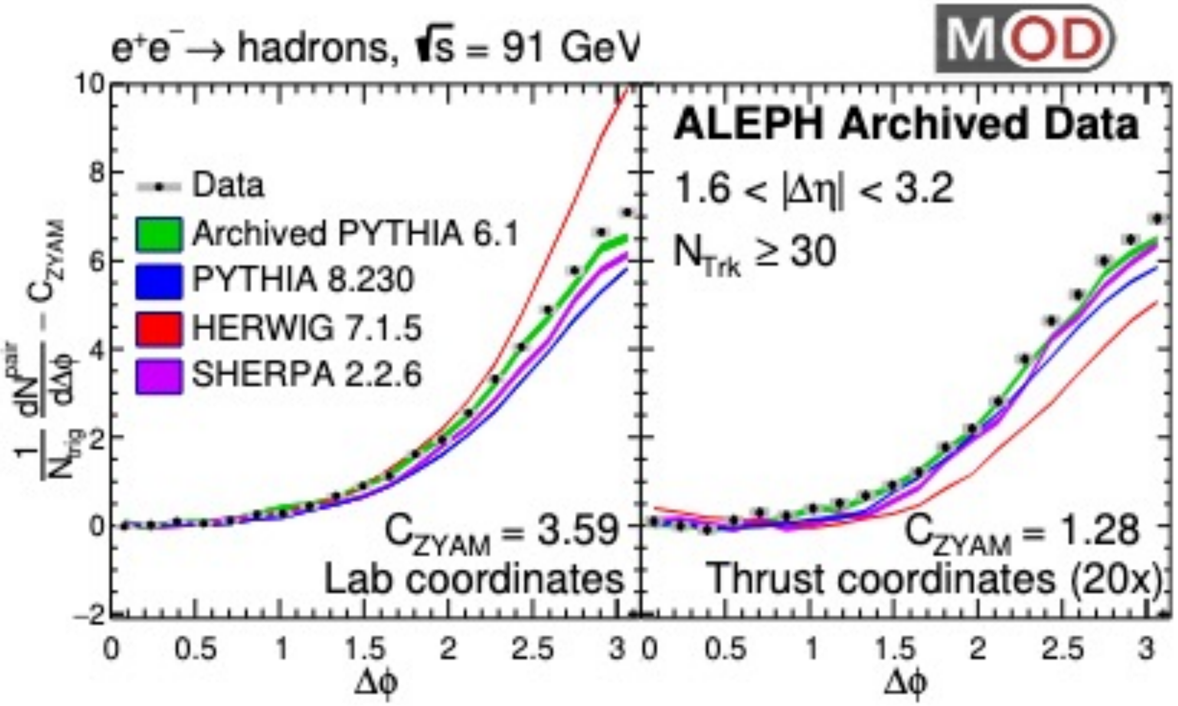
Collectivity in ep and e^+e^-

- Negative $c_2\{4\}$ is not observed in ep collisions
- Near-side "ridge" is not observed, and PYTHIA reproduces results in e^+e^- collisions.
  - Ridge yield is smaller than pp with more than 3σ in <N>=10~20.

☞<u>No collectivity in ep and e^+e^- collisions.</u>

PRL 123 21, 212002 (2019)



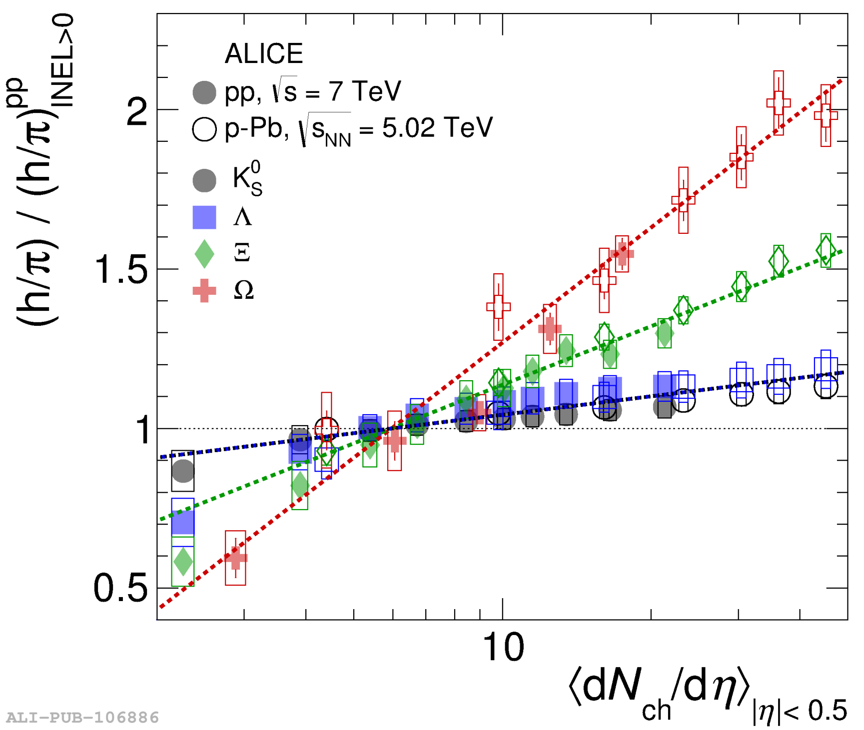


Particle Production

Strangeness Enhancement

- Smooth transition with multiplicity from small to large system.
- Enhancement is larger for the hadron with larger strangeness.

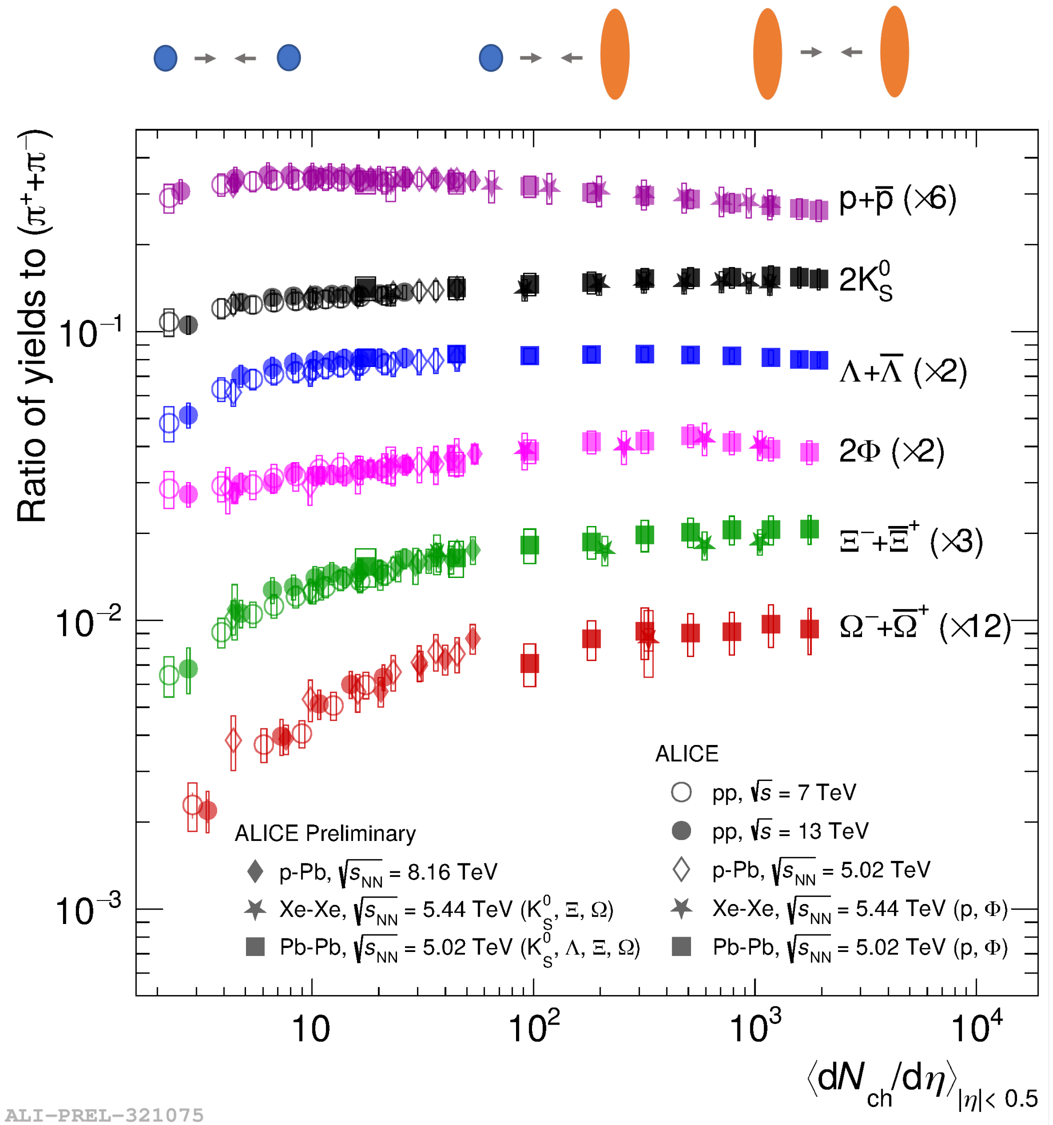
Nature Phys. 13, 535–539 (2017)



S=3

S=2

S=1

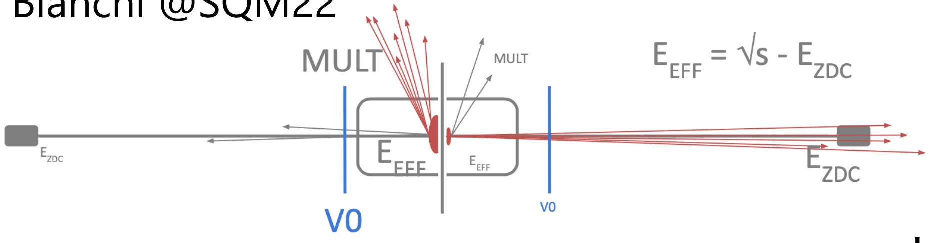


Initial effect for strangeness production

- Is the final particle multiplicity related only to the enhancement of strangeness, or does the initial stage play a role?

  The initial stage effect is investigated via effective energy

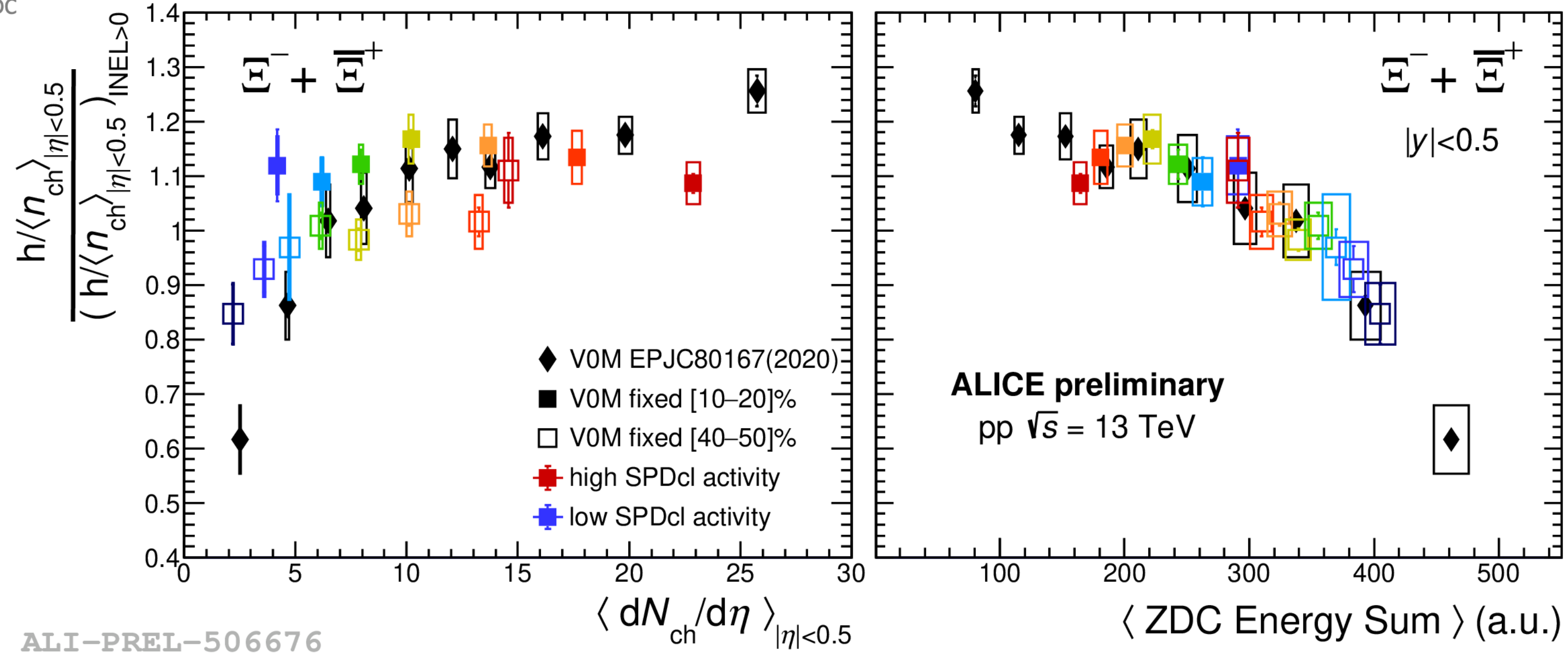
L. Bianchi @SQM22



$$E_{\mathrm{EFF}} \backsimeq \sqrt{s} - \langle \mathrm{ZDC\ energy\ sum} \rangle$$

Larger E_{EFF}

Smaller E_{EFF}

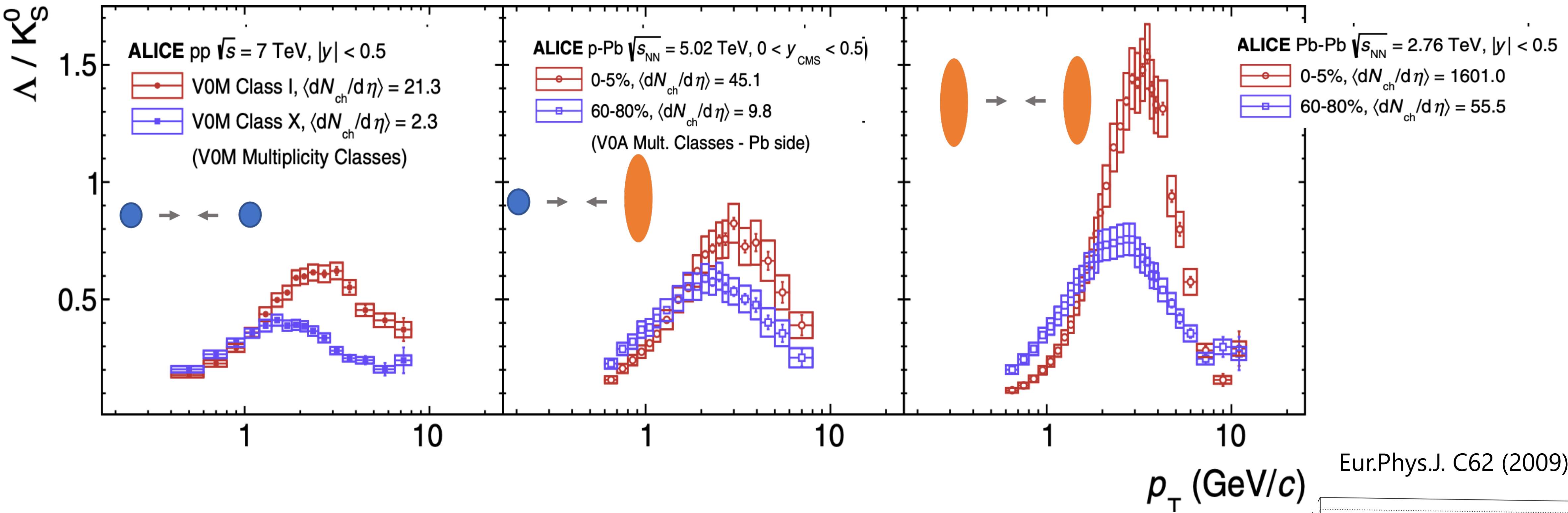


E_{EFF}

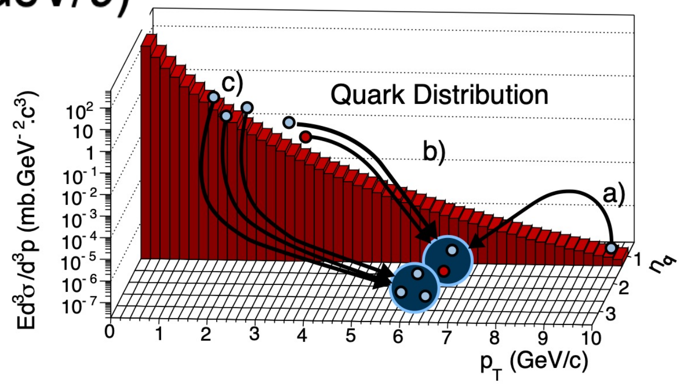
☞The initial stage plays an important role in the strangeness enhancement.

Baryon-meson ratio

PRC 99, 024906 (2019)



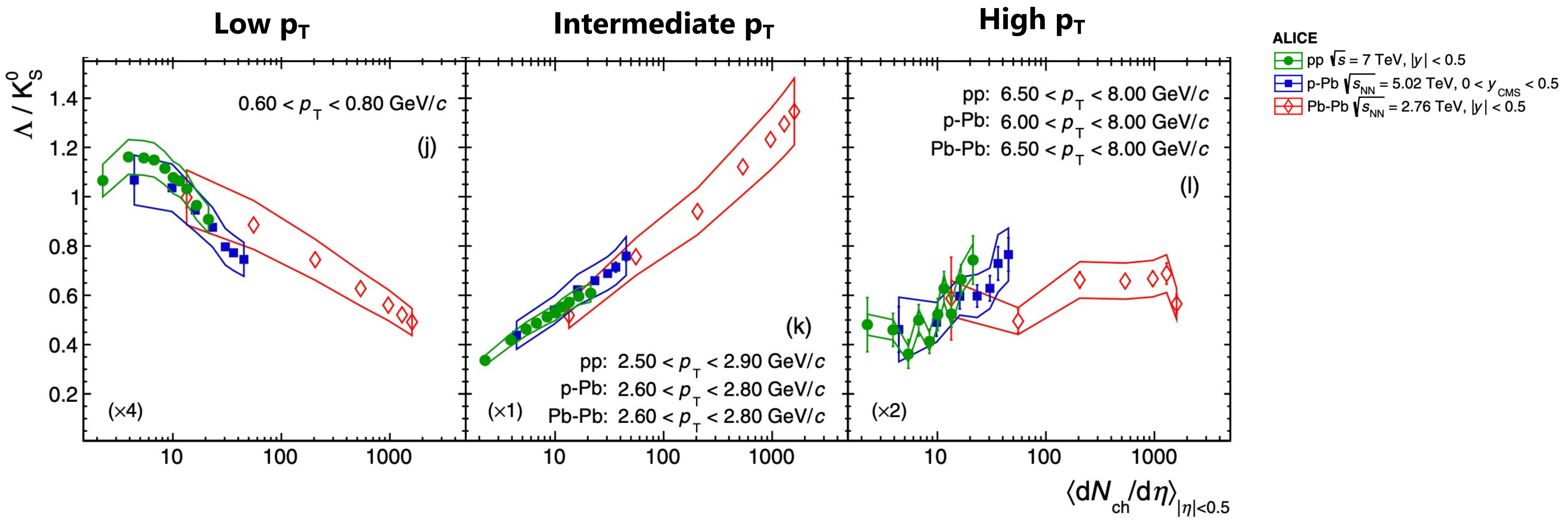
Eur.Phys.J. C62 (2009) 237-242



- Enhancement of baryon to meson ratio is observed at intermediate p_T in pp, p–Pb.

Baryon-meson ratio

PRC 99, 024906 (2019)

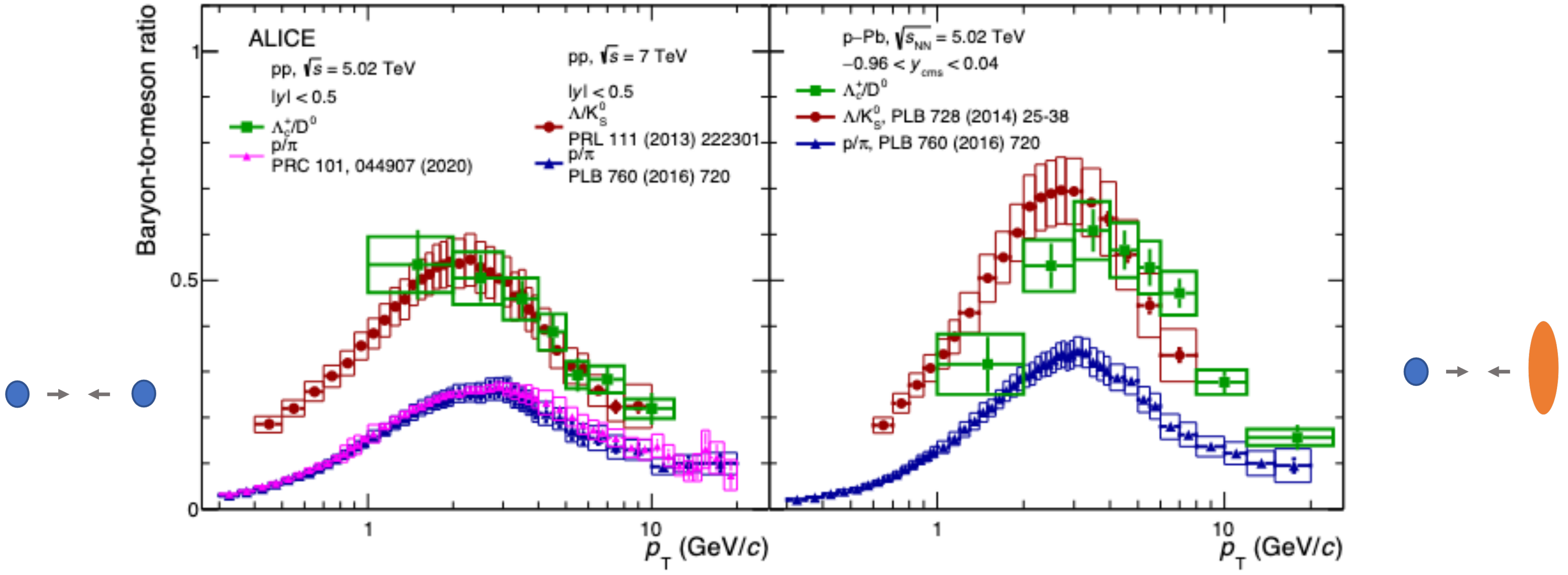


- Smooth transition from pp to Pb–Pb.
- Indication of common hadronization mechanism.

Hard Probes

Λ^+_c/D^0 ratio compared to Λ/K^0_s

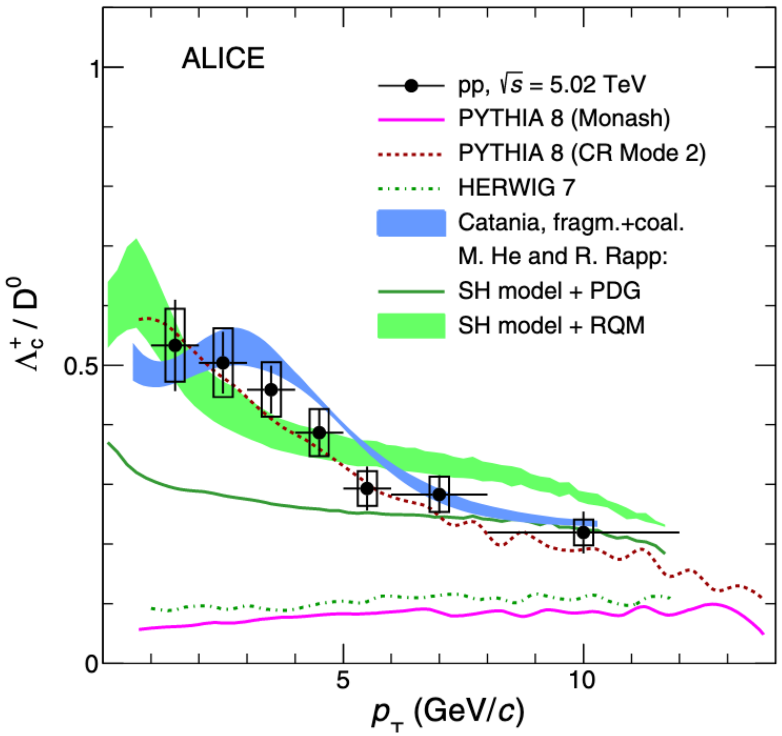
PRL 127, 202301 (2021)

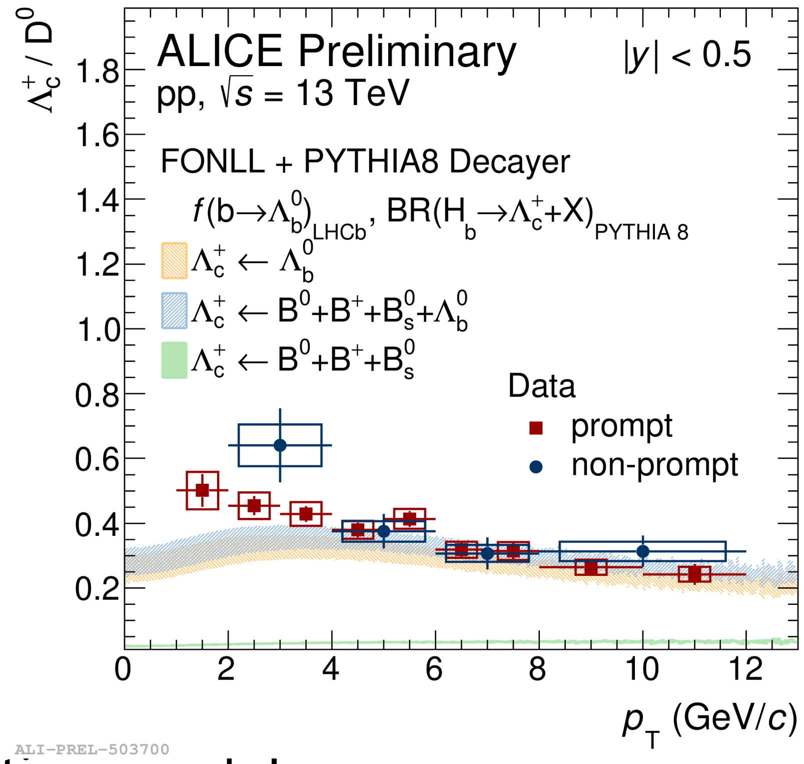


- Λ^+_c/D^0 is comparable with Λ/K^0_s
- A hint of common production mechanism for light- and charm- hadrons

HF baryon-meson ratio vs models

PRL 127, 202301 (2021)





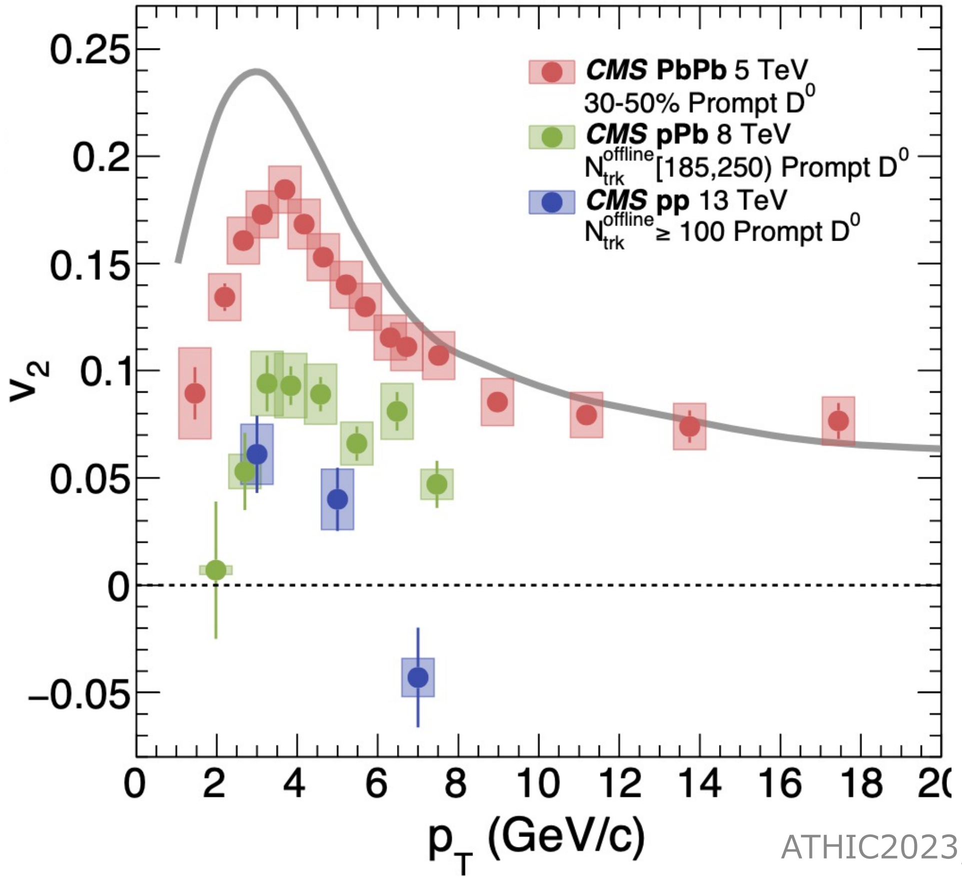
- Λ^{+}_{c}/D^{0} is enhanced from simple fragmentation model
- Models with color reconnection or quark coalescence describe the data qualitatively
- Non-prompt Λ^{+}_{c}/D^{0} is also enhanced at low p_{T}
  - Precision measurements of beauty baryons in Run3+Run4

Open HF Flow

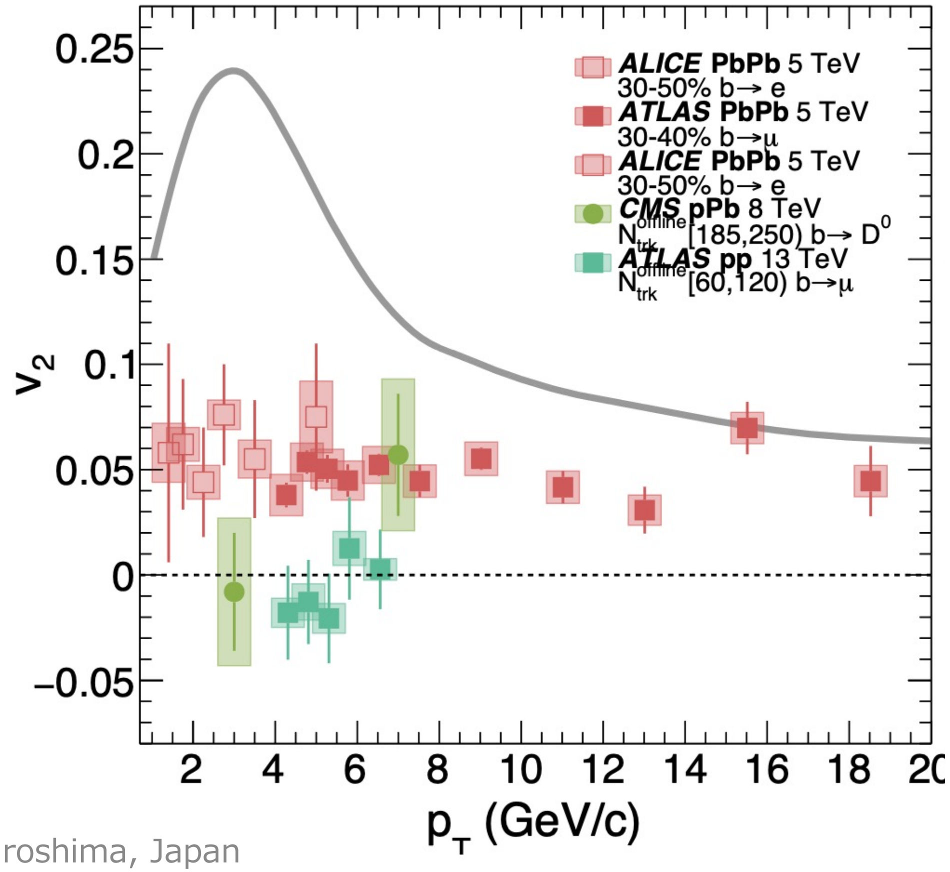
- Open charm flow is observed from small system to large system, while open beauty flow is observed in Pb–Pb but not in small system.

☞<u>A hint of "Onset" between charm and beauty processes in small system?</u>

Open Charm



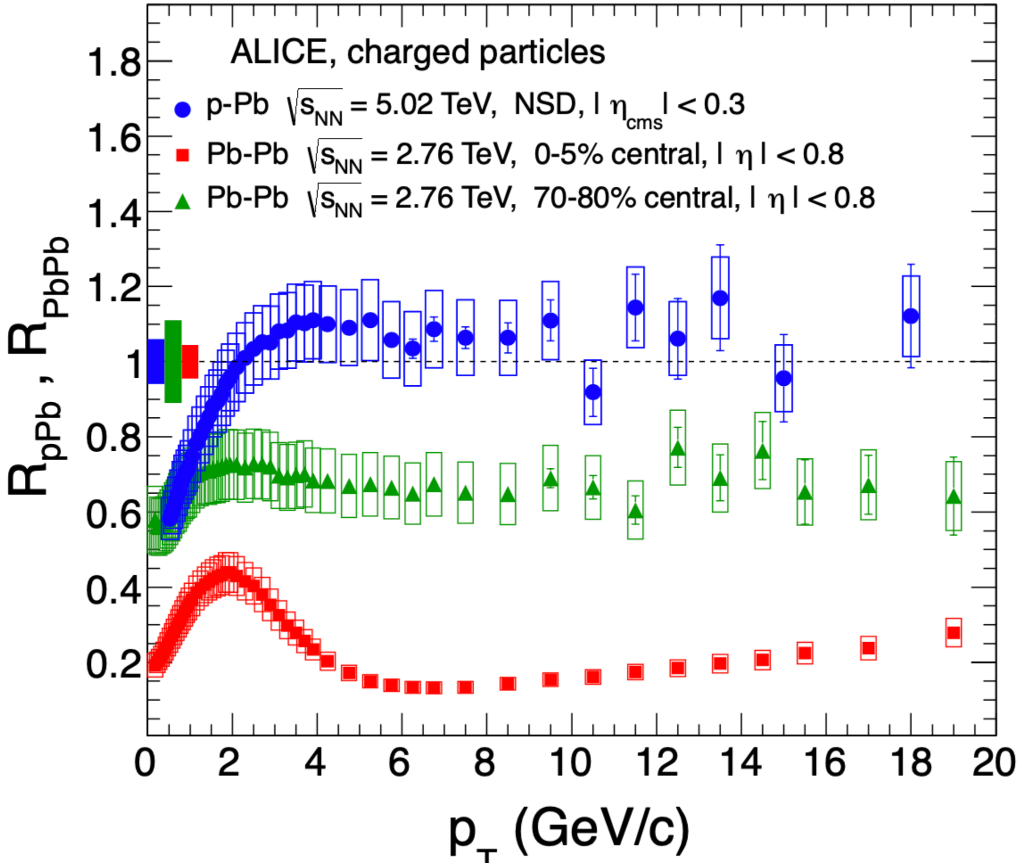
Open Beauty C. Mironov@HP20

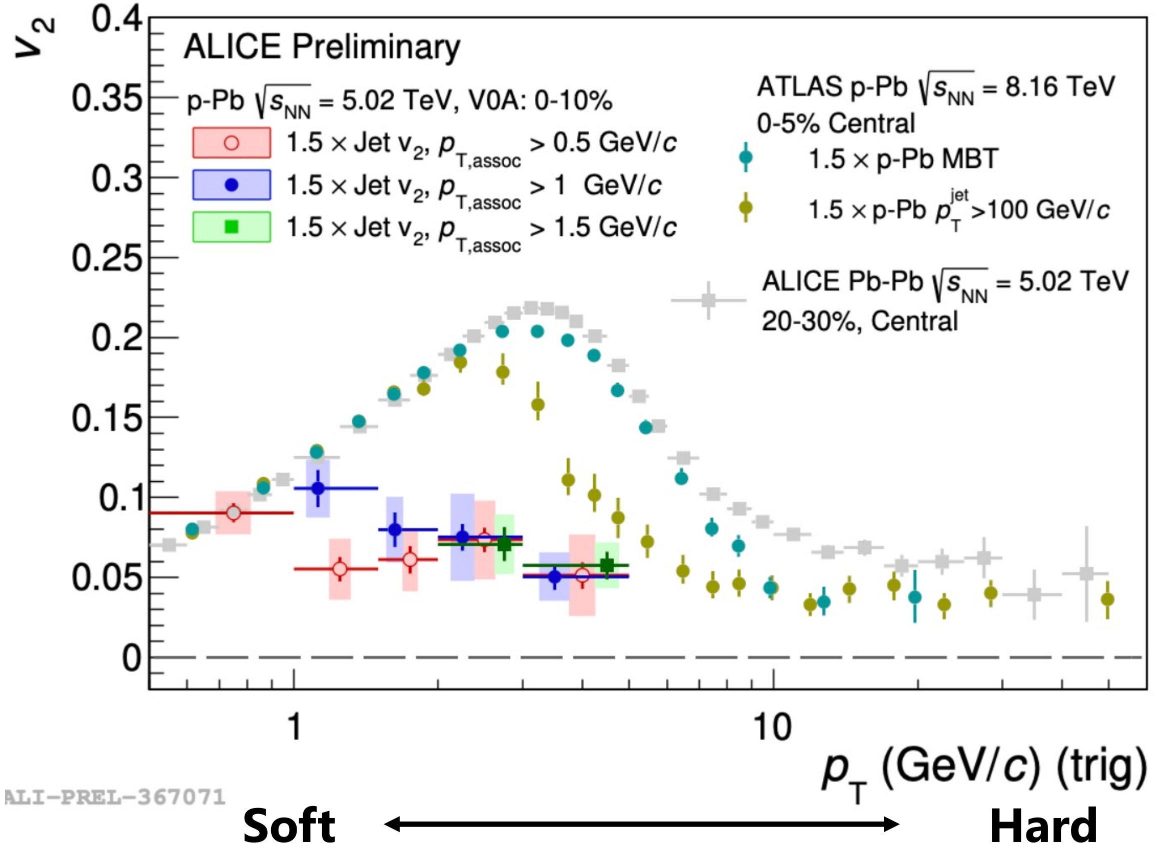


v_2 at high p_T

- v_2 at high p_T is due to jet energy loss in Pb–Pb collisions.
- R_{pA} ~1 and non-zero high p_T and jet particle v_2 in p–Pb collisions.
  - Indication of additional contribution to energy loss

arXiv:2212.12609





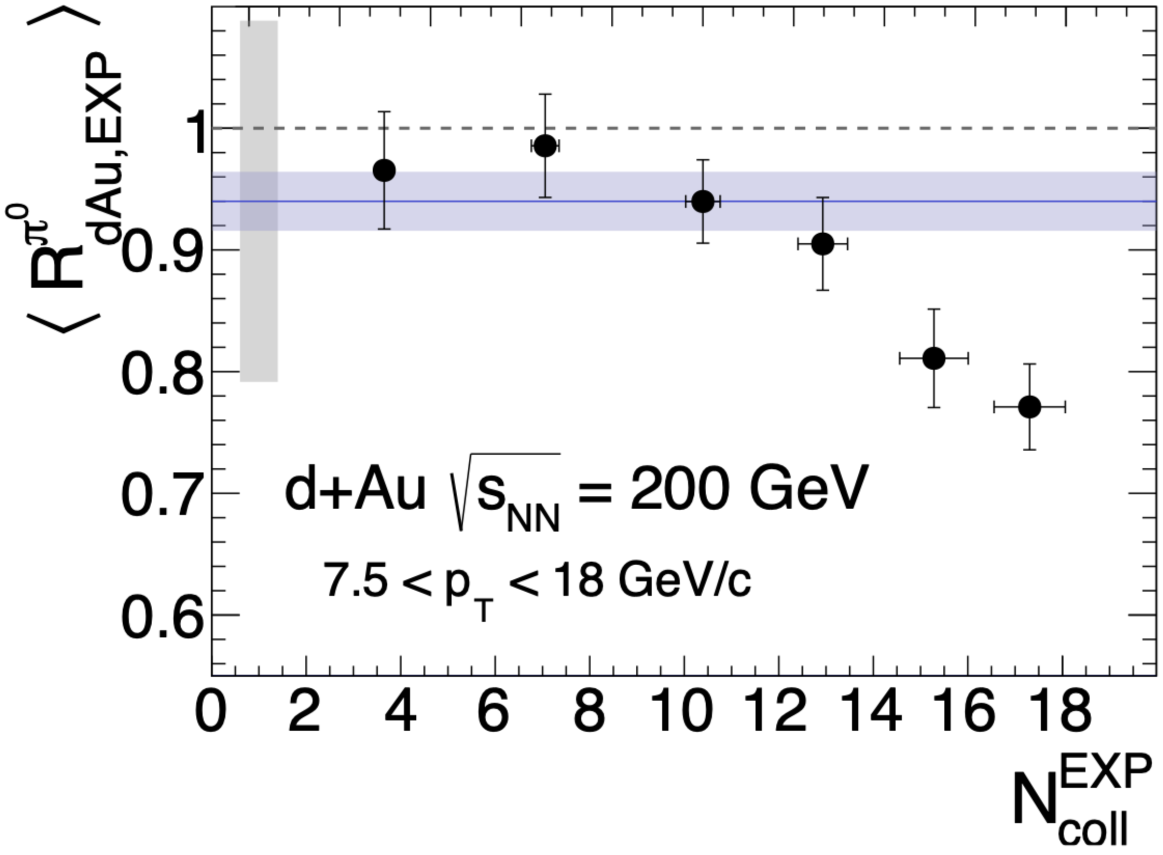
Energy loss in small system

- High-p_T π^0 R_{pA} using direct γ in d–Au collisions vs N_{coll}
  - Significant suppression at N_{coll}>14

$$\frac{R^{\pi^0}_{dAu,EXP}(0\%\text{–}5\%)}{R^{\pi^0}_{dAu,EXP}(0\%\text{–}100\%)} = 0.806 \pm 0.042$$

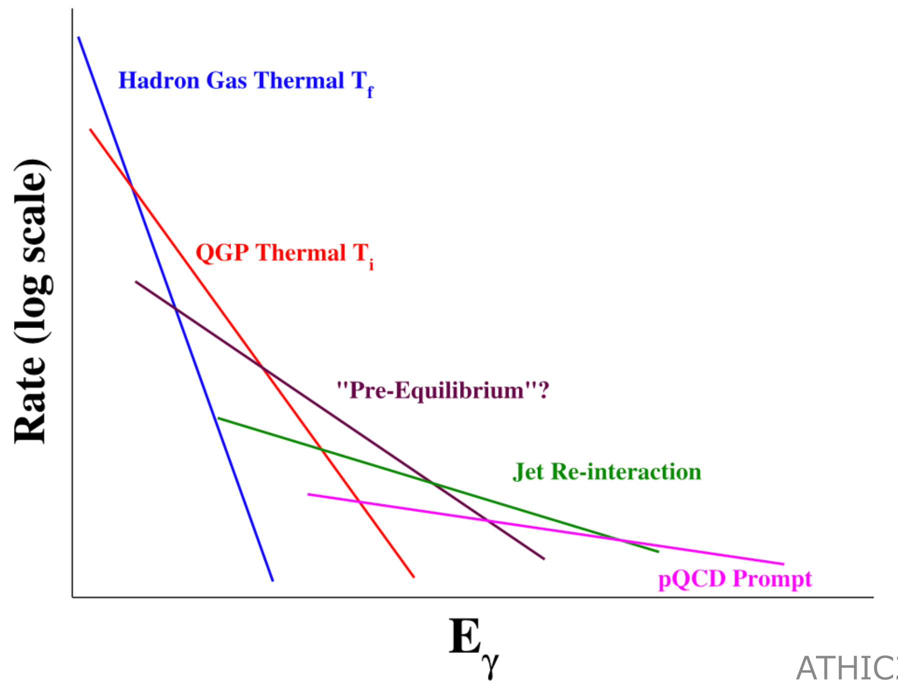
☞Hint of Energy loss in QGP in small system?

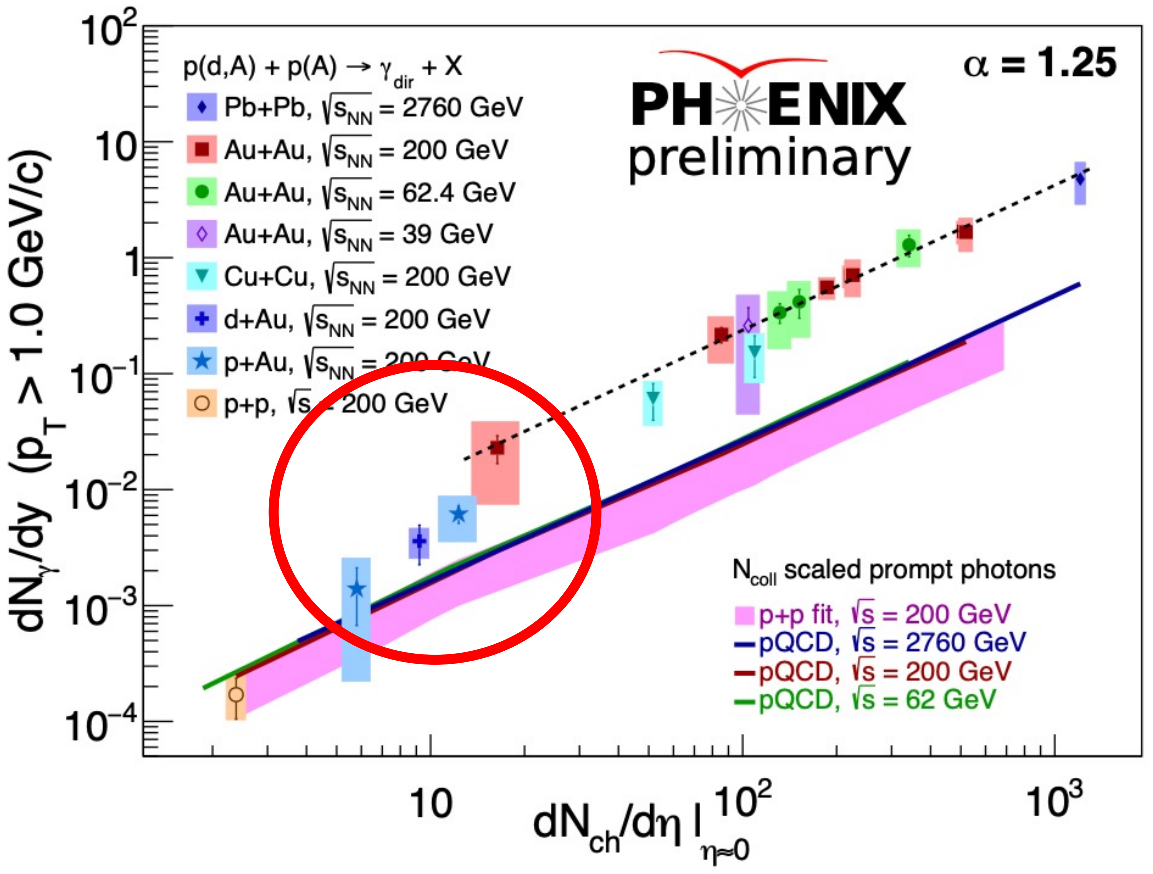
arxiv:2303.12899



Thermal photon

- If the system is thermalized, photons from thermal radiation are emitted.
- Excess for pQCD calculation at $N_{ch}>10$ in small system at RHIC
- A Hint of thermalization in small system?





Future measurements:

PHENIX: d+Au (2016) BES, ^{3}He+Au (2014)

ALICE: HM and MB pp

Summary

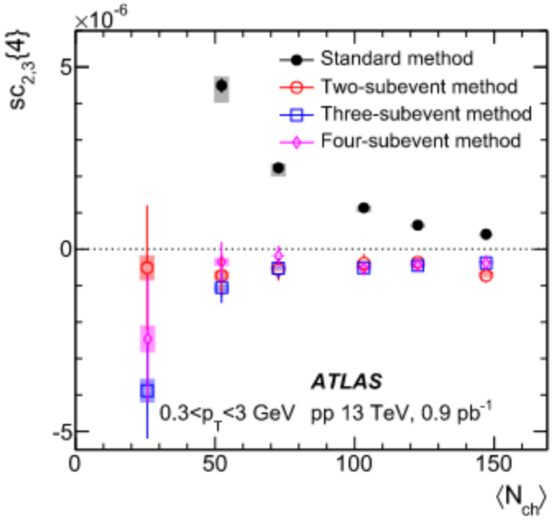
- Many systematic measurements to understand small system
  - The final state effect is essential to describe the flow measurement in small system, however, the initial state is also important.
  - Hints of unique features of small system
    - non-zero v_2 is observed in γ-Pb collisions
    - No collectivity is observed in much smaller systems such as ep and ee.
    - Charm v_2 is observed and zero beauty v_2 in small system.
    - Energy loss signal in d–Au

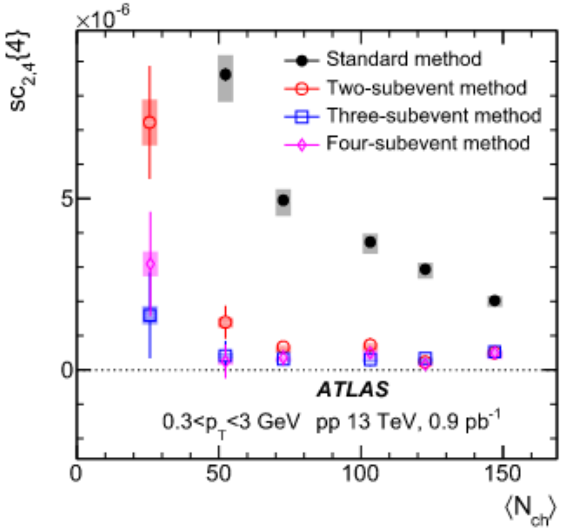
- Future measurements:
  - Precise measurements in Run3+4 at the LHC
    - charm and beauty hadron
    - Direct photon
  - O–O collision in Run3 at the LHC
    - Simple initial geometry and similar multiplicity to p–Pb
    - Energy loss
  - HF flow in small system by sPHENIX at RHIC

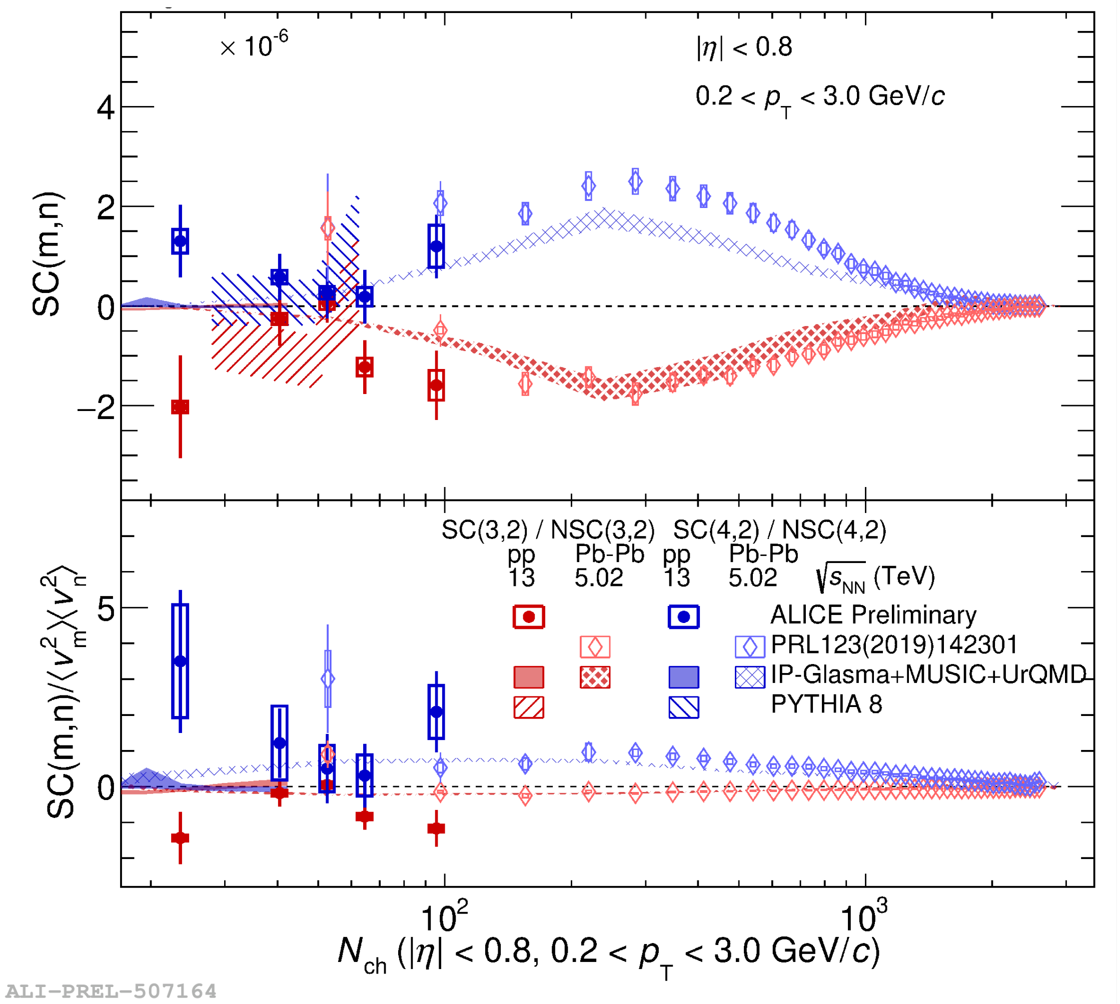
Backup

Symmetric cumulant

- Correlation between different flow harmonics
  - SC(4,2): Sensitive to the initial condition and the medium evolution
  - SC(3,2): Sensitive to the initial condition
- Same sign in pp and Pb–Pb collisions
  - Non-flow subtraction is very sensitive







PLB 789 444 (2019)

Long-range correlations in γ–p

- Long-range two-particle correlations are measured in γ–p events in UPC p–Pb collisions at 8.16 TeV without low multiplicity subtraction
- At low p_T, v_2 is reproduced by PYTHIA and HIJING, which have no collective effect.

arXiv:2204.13486