Recent results on collectivity in small collision systems

Shengquan Tuo
(Vanderbilt University)

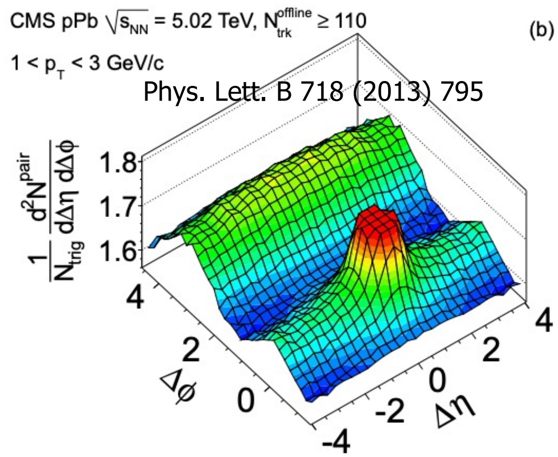
September 3, 2022

U.S. DEPARTMENT OF ENERGY | Office of Science

VANDERBILT UNIVERSITY

ABOUT COLLECTIVITY

- Nonflow
  - Jets
  - BEC
  - Momentum Conservation
  - …



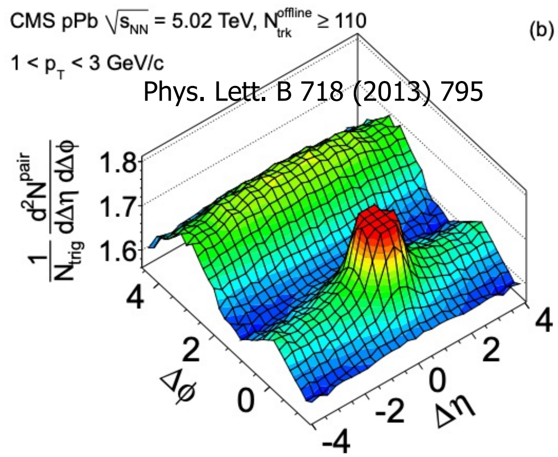
v_n

Azimuthal anisotropy

$$dN/d\phi \propto 1 + \sum_n v_n \cos(n(\phi - \Psi_n))$$

ABOUT COLLECTIVITY - METHODS

- Nonflow
  - Jets
  - BEC
  - Momentum Conservation
  - …



v_n

Azimuthal anisotropy

$$dN/d\phi \propto 1 + \sum_n v_n \cos(n(\phi - \Psi_n))$$

v_n analysis method with nonflow removal:

- Two particle correlation method with $v_n\{EP\}$, $v_n\{SP\}$, $v_n^{sub}\{2,|\Delta\eta|>2\}$, …

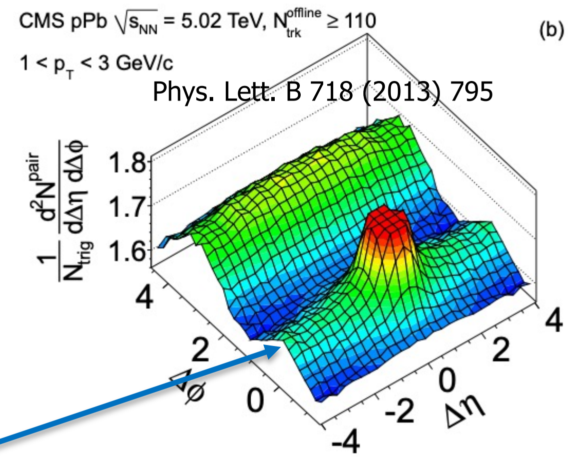
v_n fluctuations

- Multiparticle correlations with $v_n\{4, 6, 8, 10, …, LYZ\}$

  (Better removing nonflow)

ABOUT COLLECTIVITY - RIDGE

- Nonflow
  - Jets
  - BEC
  - Momentum Conservation
  - …



- Ridge: Near-side long range correlations

v_n

Azimuthal anisotropy

$$dN/d\phi \propto 1 + \sum_n v_n \cos(n(\phi - \Psi_n))$$

v_n analysis method with nonflow removal:

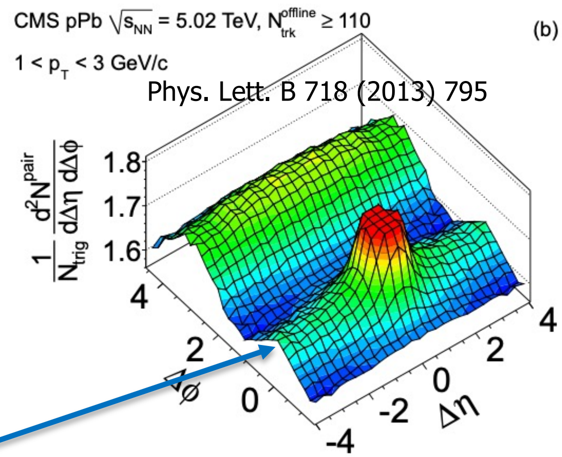
- Two particle correlation method with $v_n\{EP\}$, $v_n\{SP\}$, $v_n^{sub}\{2,|\Delta\eta|>2\}$, …

v_n fluctuations

- Multiparticle correlations with $v_n\{4, 6, 8, 10, …, LYZ\}$
  (Better removing nonflow)

ABOUT COLLECTIVITY - PHYSICS

- Nonflow
  - Jets
  - BEC
  - Momentum Conservation
  - …



- Ridge: Near-side long range correlations

v_n analysis method with nonflow removal:

- Two particle correlation method with $v_n\{EP\}$, $v_n\{SP\}$, $v_n^{sub}\{2,|\Delta\eta|>2\}$, …

v_n fluctuations

- Multiparticle correlations with $v_n\{4, 6, 8, 10, …, LYZ\}$
  (Better removing nonflow)

v_n

Azimuthal anisotropy

$$dN/d\phi \propto 1 + \sum_n v_n \cos(n(\phi - \Psi_n))$$

- CGC
- Color Reconnection and Rope Hadronization

Ridge and v_n but not related to FLOW or QGP

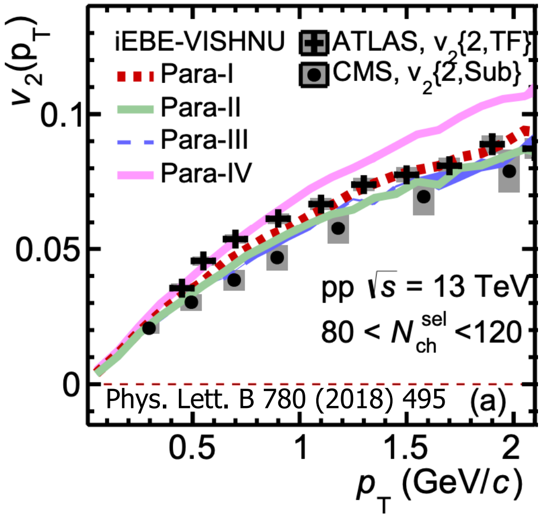
- Initial geometry + Hydrodynamics
- Transport models

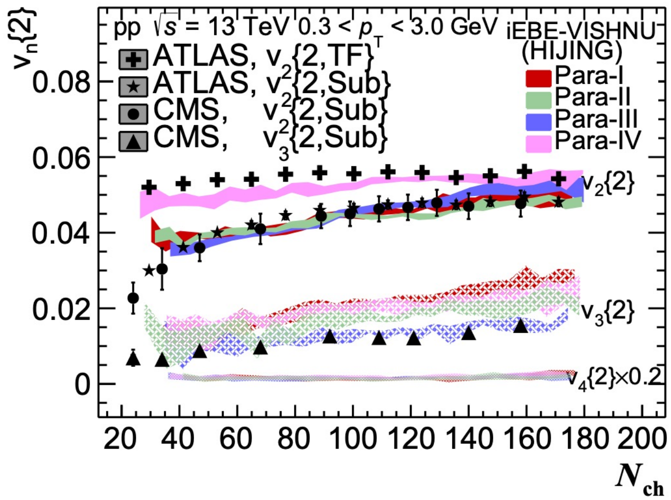
FLOW and QGP

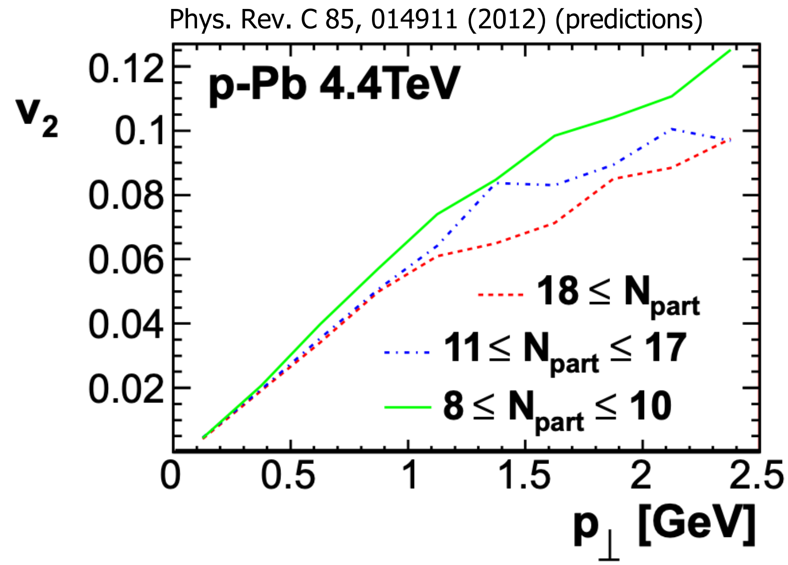
- Path length dependence
  - Jet energy loss
  - Quarkonium suppression

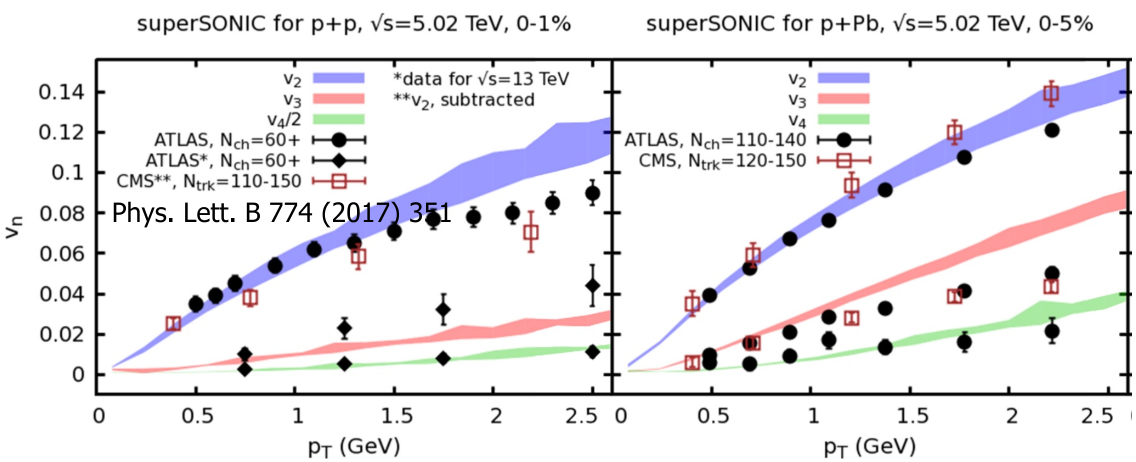
v_n is not hydrodynamic FLOW but probes QGP

PREVIOUS FLOW STUDY IN SMALL SYSTEMS

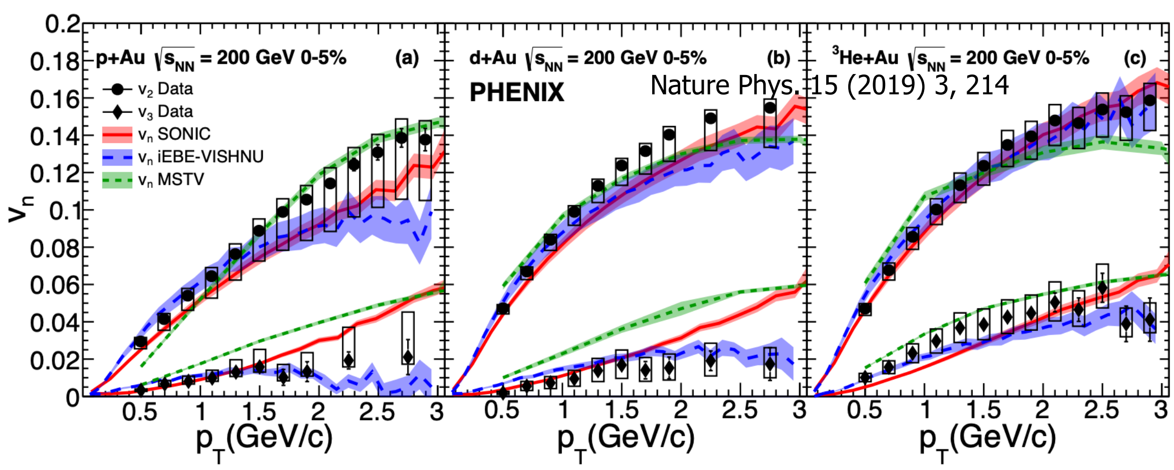


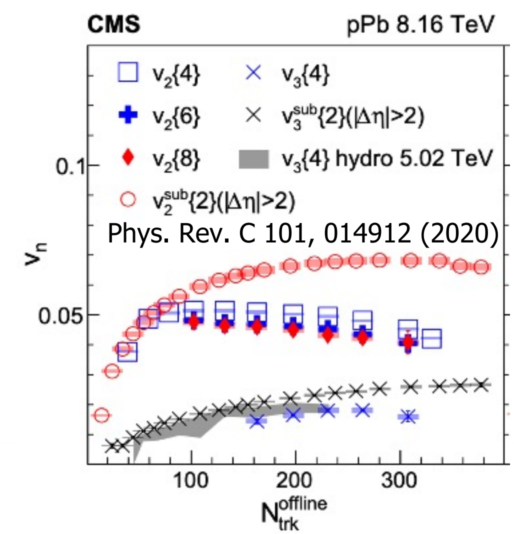






- Hydrodynamic models describe the small system FLOW data
- Difficulties for theories with multiparticle correlations

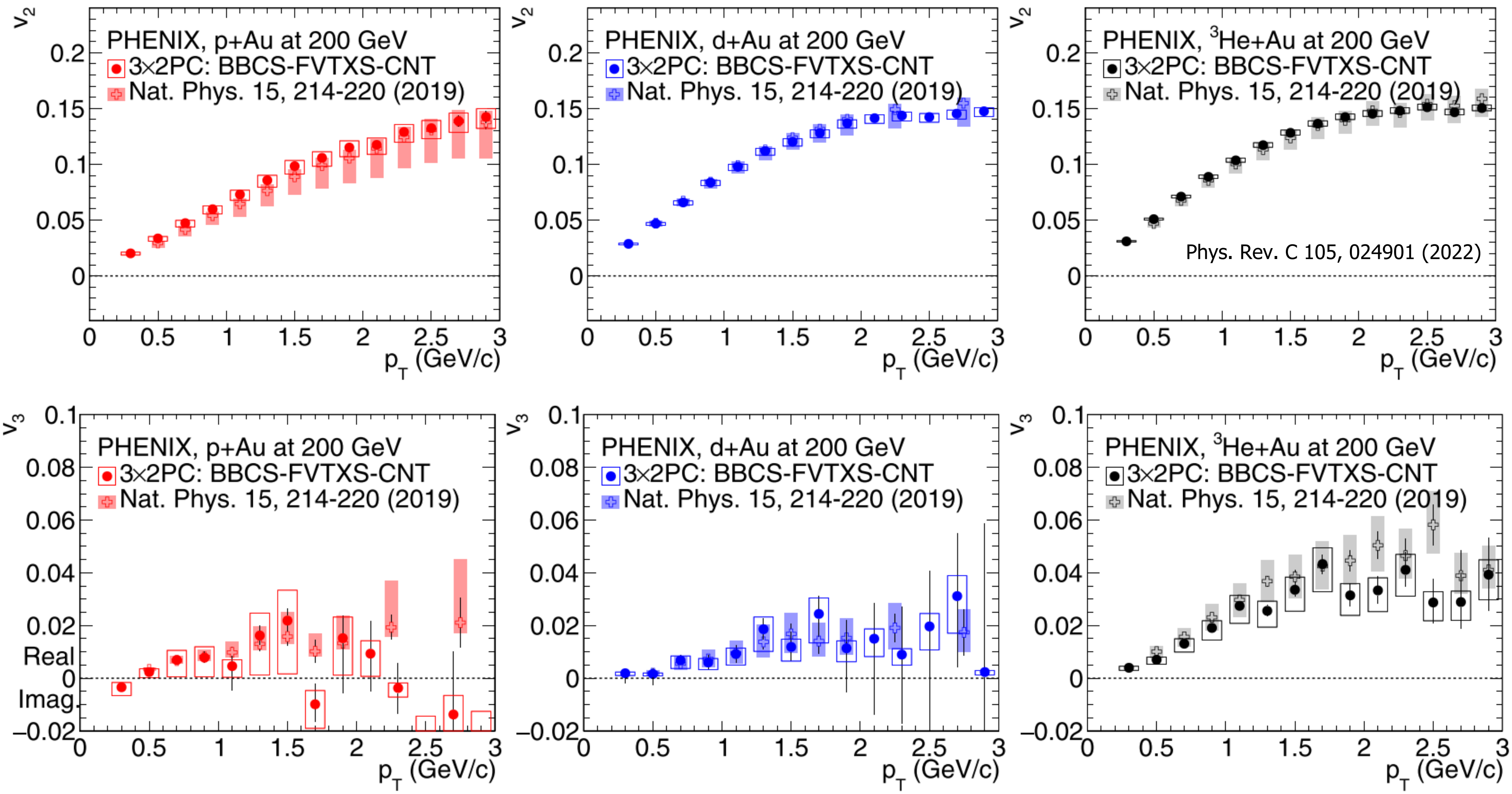


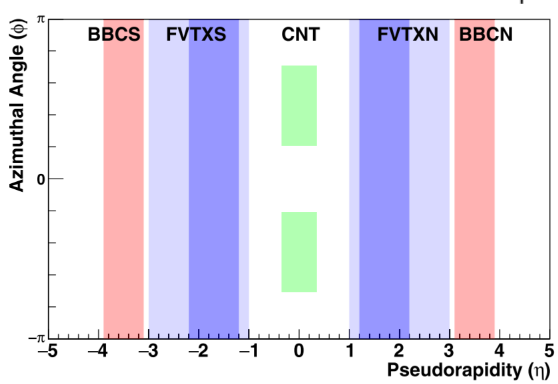


OUTLINE FOR RECENT STUDIES

- Results for charged hadrons
  - v_2 and v_3 from PHENIX
  - Symmetry cumulants and nonlinear v_n response from ALICE
  - v_n decorrelations from ATLAS
  - v_n-[p_T] correlations from ALICE and CMS
- Identified particles
- Challenges in small systems
- Summary and outlook

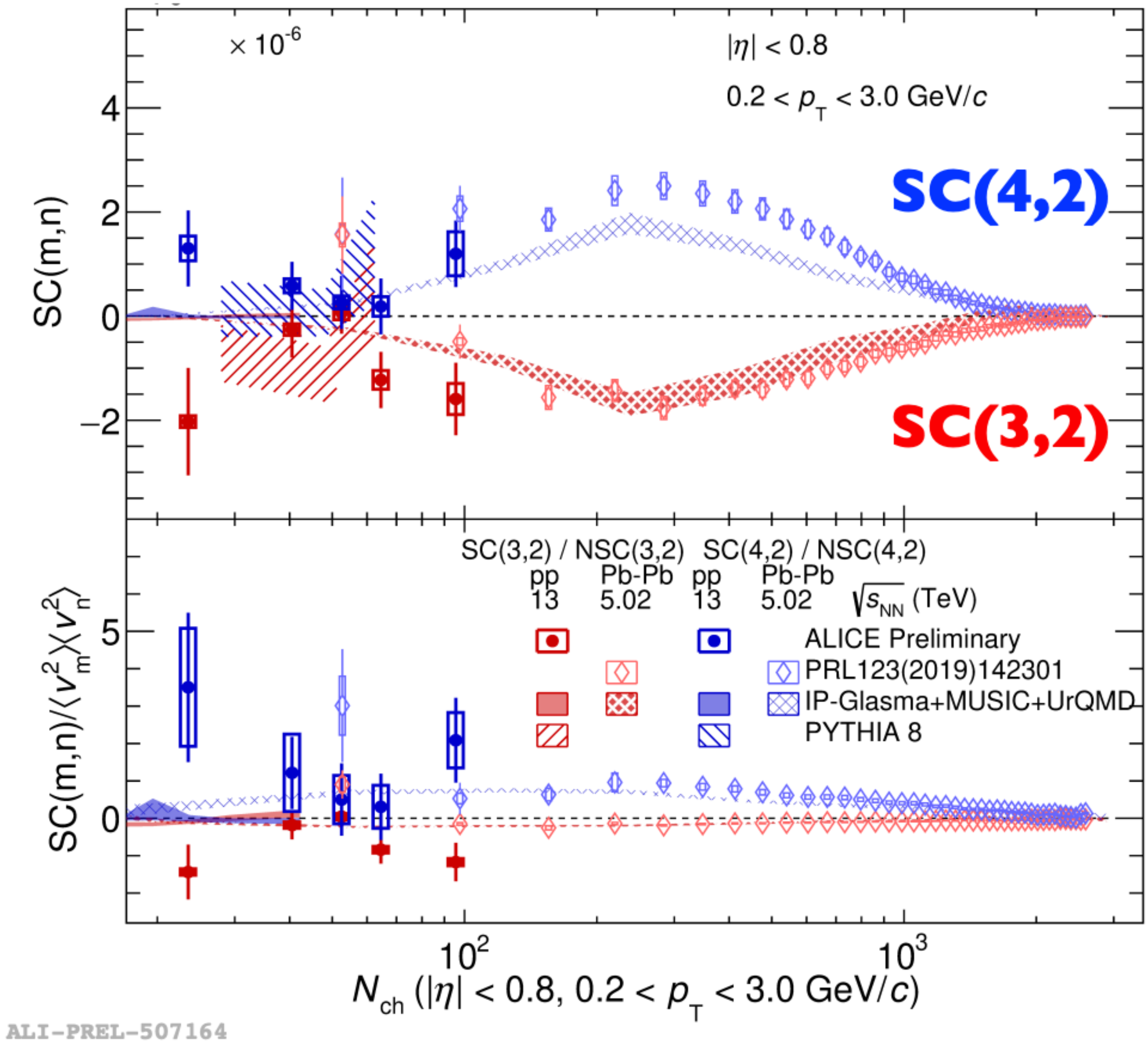
V_2 AND V_3 FROM PHENIX





- New analysis with two particle correlations
- The results for both v_2 and v_3 are consistent with previous measurements

SYMMETRY CUMULANTS IN PP

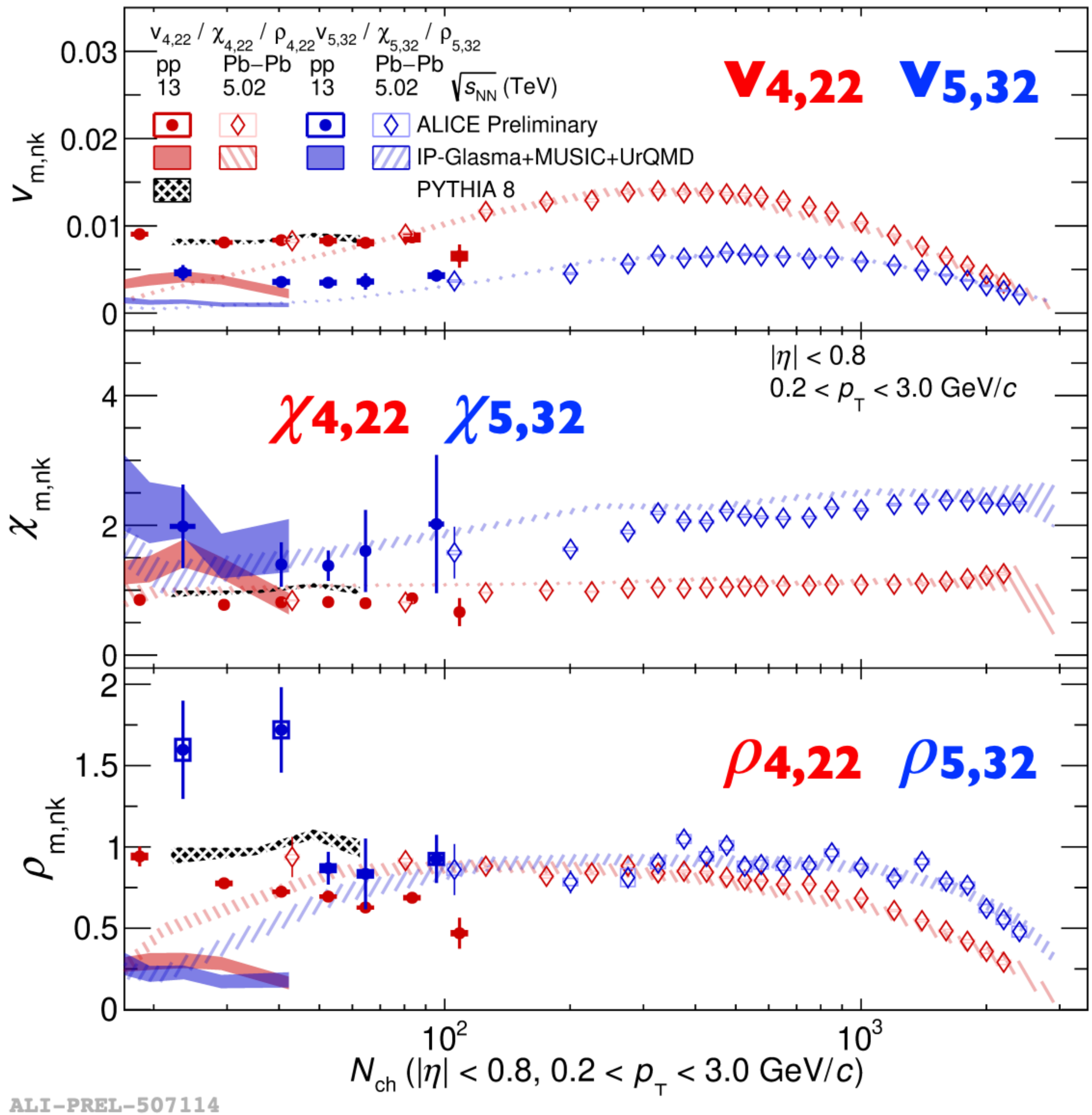


- Correlations between different harmonics of v_n coefficients

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

- Observation of the same ordering of SC(m,n) in both pp and PbPb collisions

NONLINEAR RESPONSE



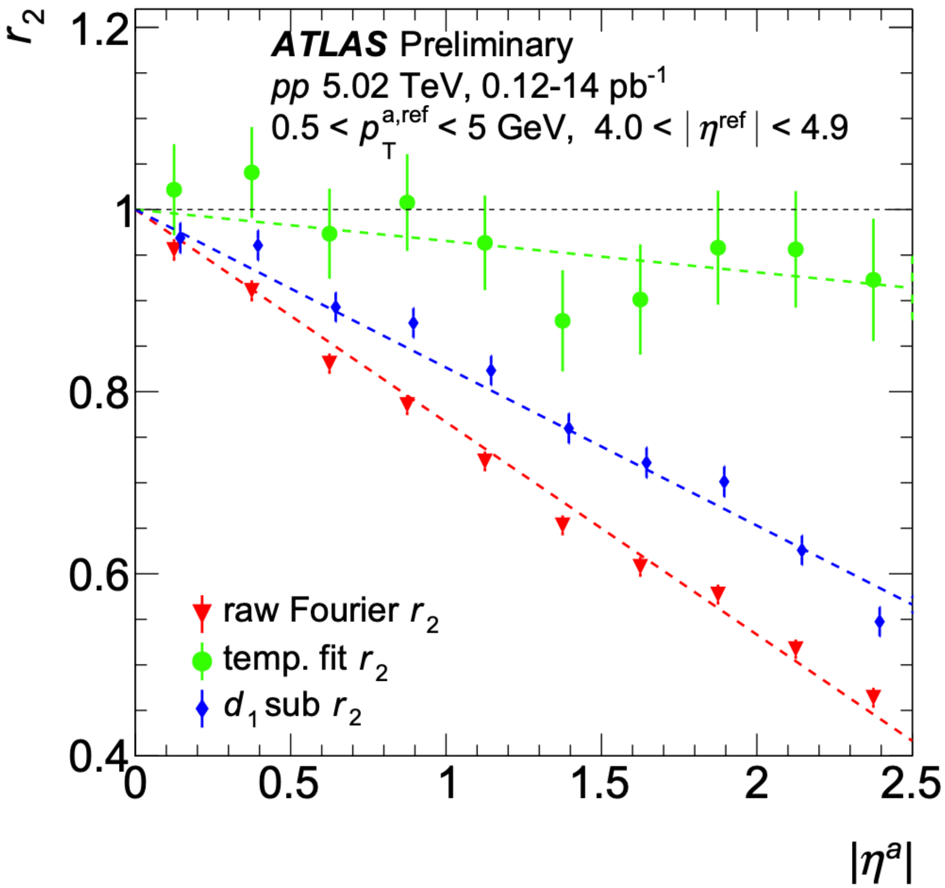
- Higher order flow coefficients contain a non-linear contribution from lower orders

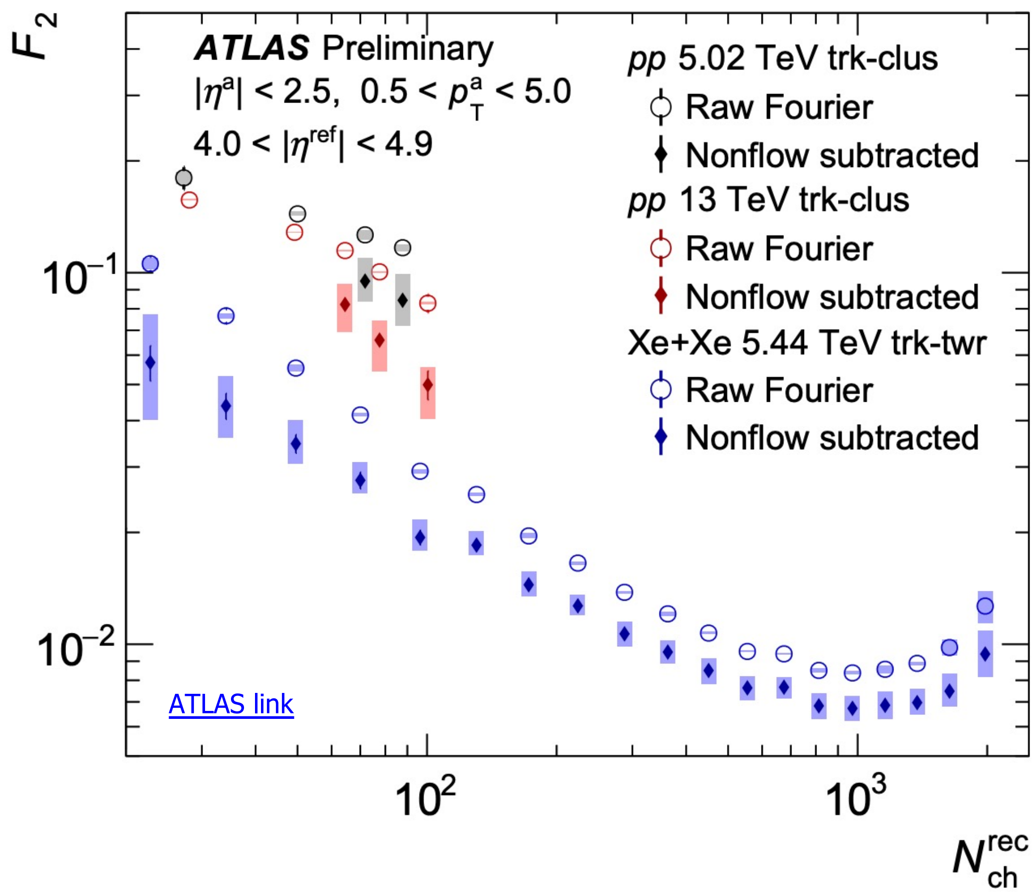
$$V_4 = V_4^L + V_4^{NL} = V_4^L + \chi_{4,22}(V_2)^2$$

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

- IP-Glasma+MUSIC+UrQMD fails to describe data at low multiplicity, but agrees for PbPb
- PYTHIA does not describe v_2 well, but does a good job for $v_{4,22}$

DECORRELATIONS IN PP





$$r_n(|\eta^a|) = \frac{c_n(-|\eta^a|)}{c_n(|\eta^a|)}$$

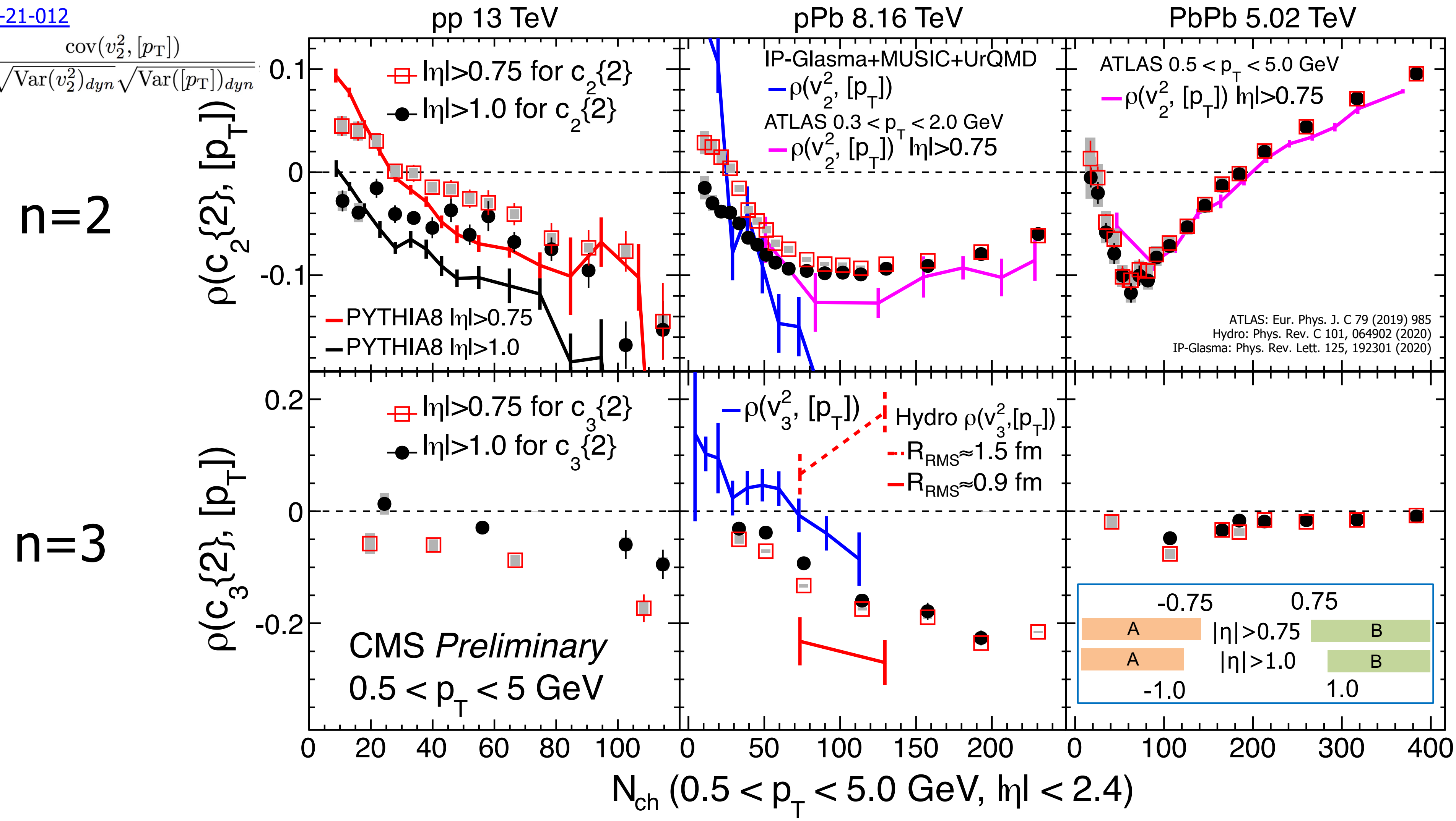
$$r_n(|\eta^a|) = \frac{c_2|^{\eta^a=0}(1 - F_2|\eta^a|)}{c_2|^{\eta^a=0}(1 + F_2|\eta^a|)} \approx 1 - 2F_2|\eta^a|$$

- Larger decorrelation in pp than Xe+Xe at similar multiplicities
- Peripheral XeXe and pp decorrelation follow a power-law decrease
- AMPT can not describe the data at low multiplicity

V_2 - MEAN PT CORRELATIONS

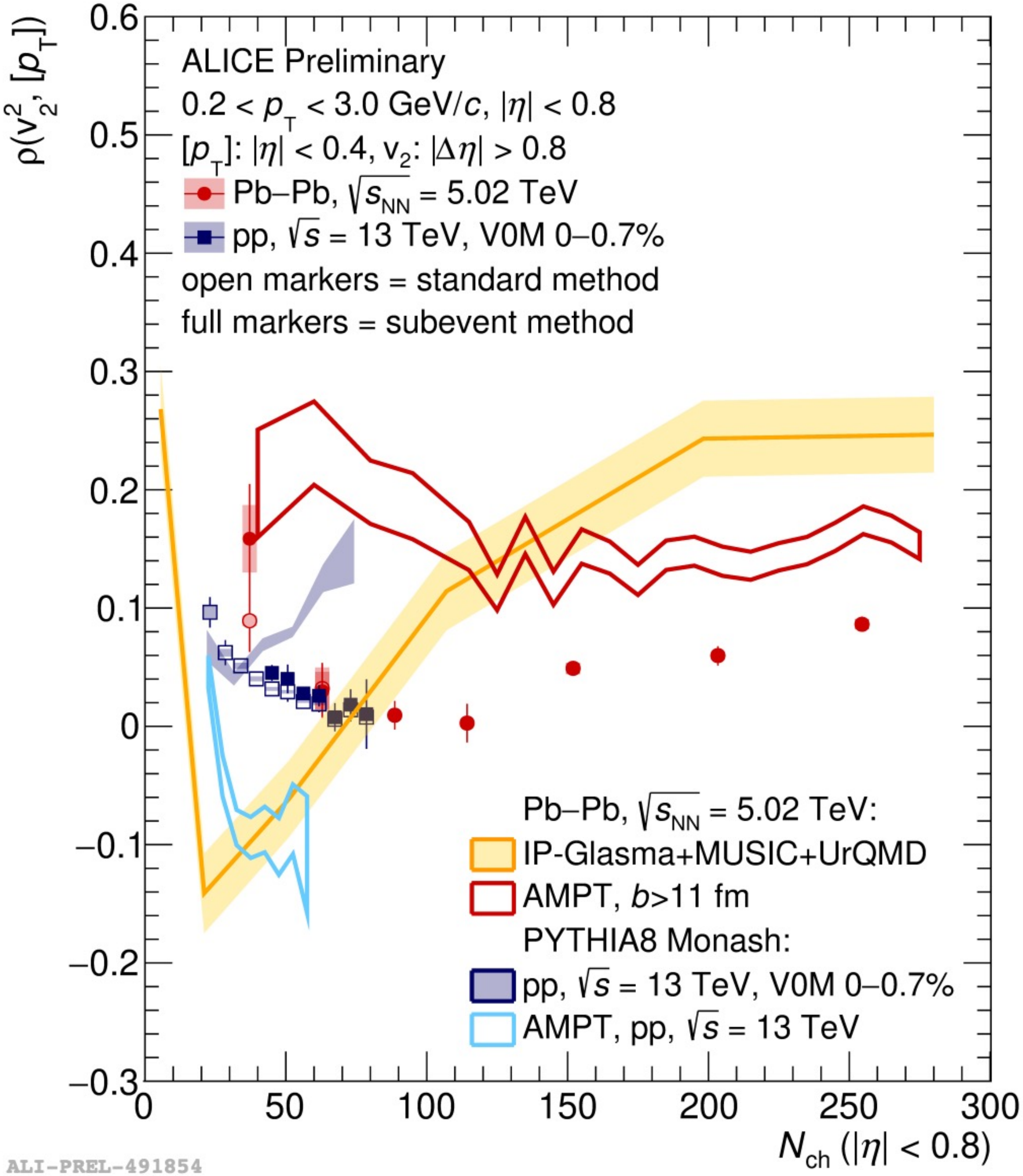
CMS-PAS-HIN-21-012

$$\rho(v_2^2,[p_T]) = \frac{\mathrm{cov}(v_2^2,[p_T])}{\sqrt{\mathrm{Var}(v_2^2)_{dyn}}\sqrt{\mathrm{Var}([p_T])_{dyn}}}$$



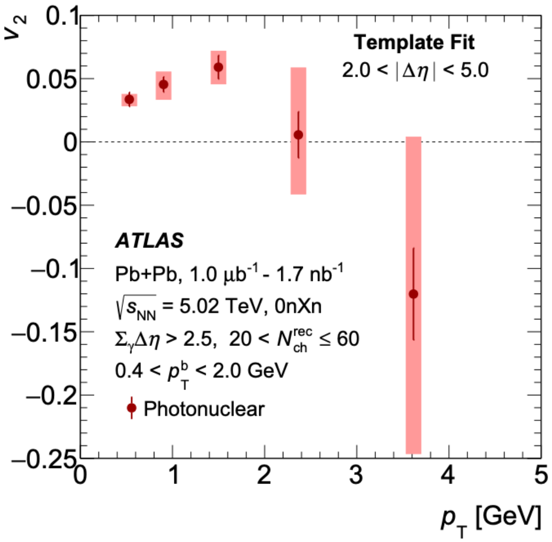
- Apparent sign change for $\rho(c_2\{2\}, [p_T])$ in pPb -> agree with IP-Glasma+Hydrodynamics
- However, no sign change is observed when using $|\eta|>1.0$ ($|\Delta\eta|>2.0$) for $c_2\{2\}$
  - The sign change signal is not a long-range effect in data
- n=3 results better described by the smaller initial fireball $R_{RMS}=0.9$ fm in hydrodynamics

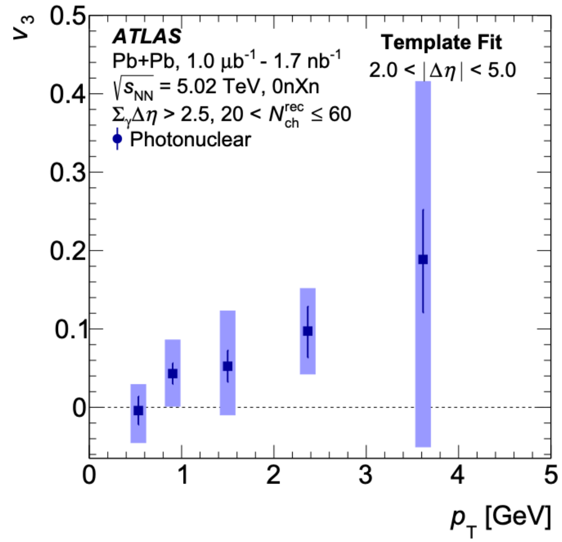
V2-[PT] CORRELATIONS - PP



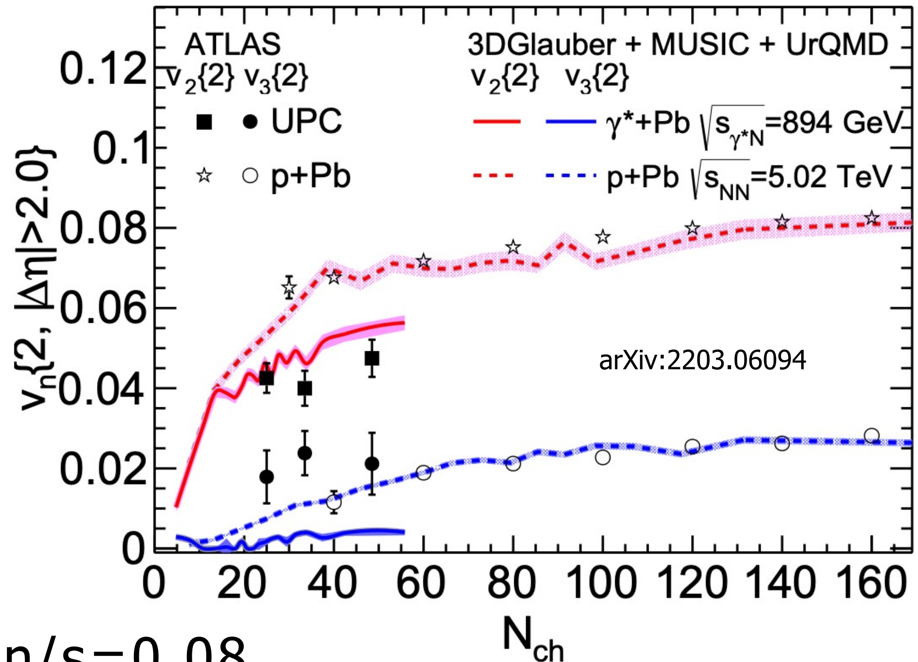
- Decreasing trend with N_{ch}
- Consistent with PbPb at low multiplicity
- Underestimated by AMPT
- Overestimated by PYTHIA

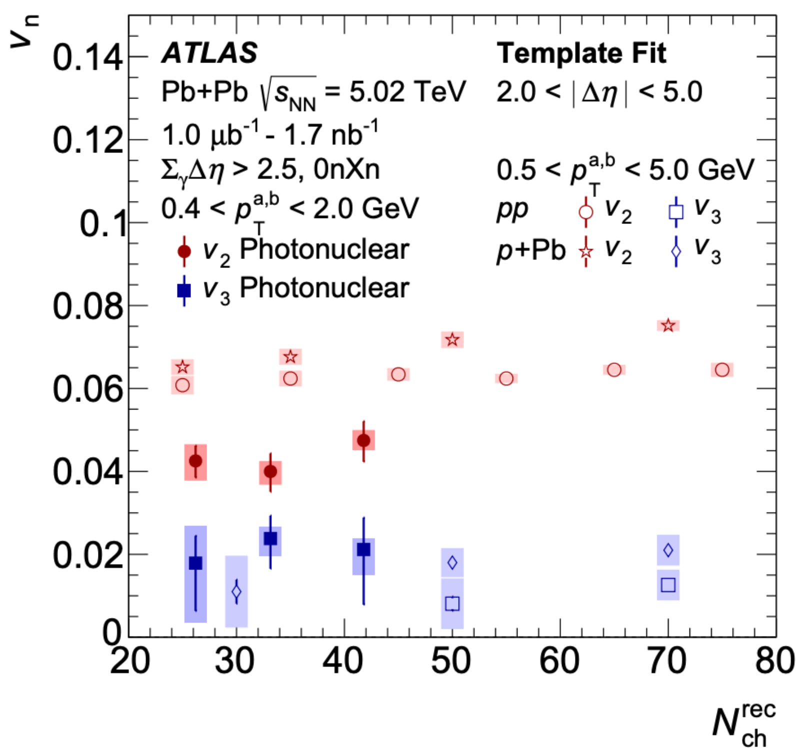
“FLOW” IN PHOTON-PB COLLISIONS



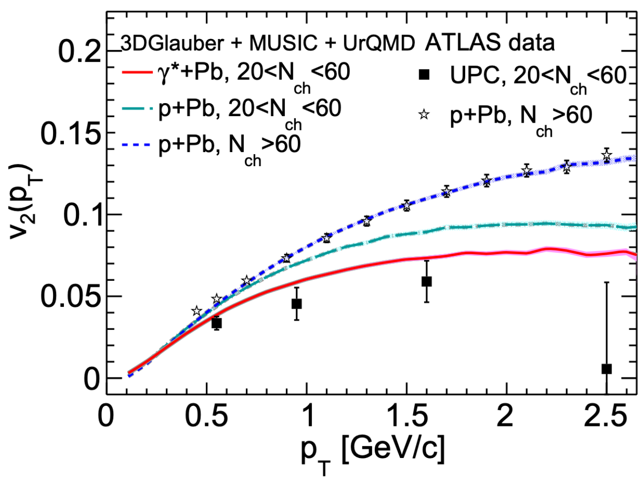


Phys. Rev. C 104, 014903 (2021)





η/s=0.08



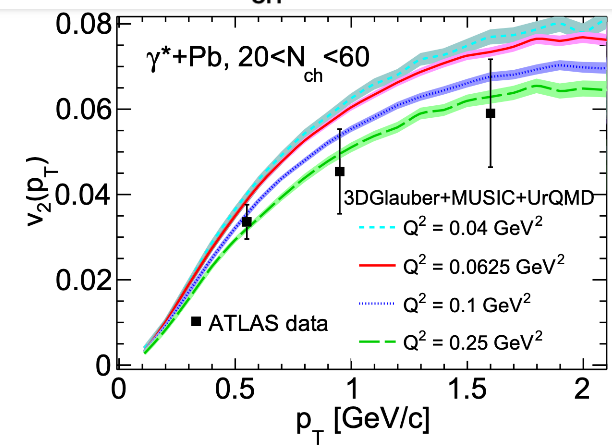
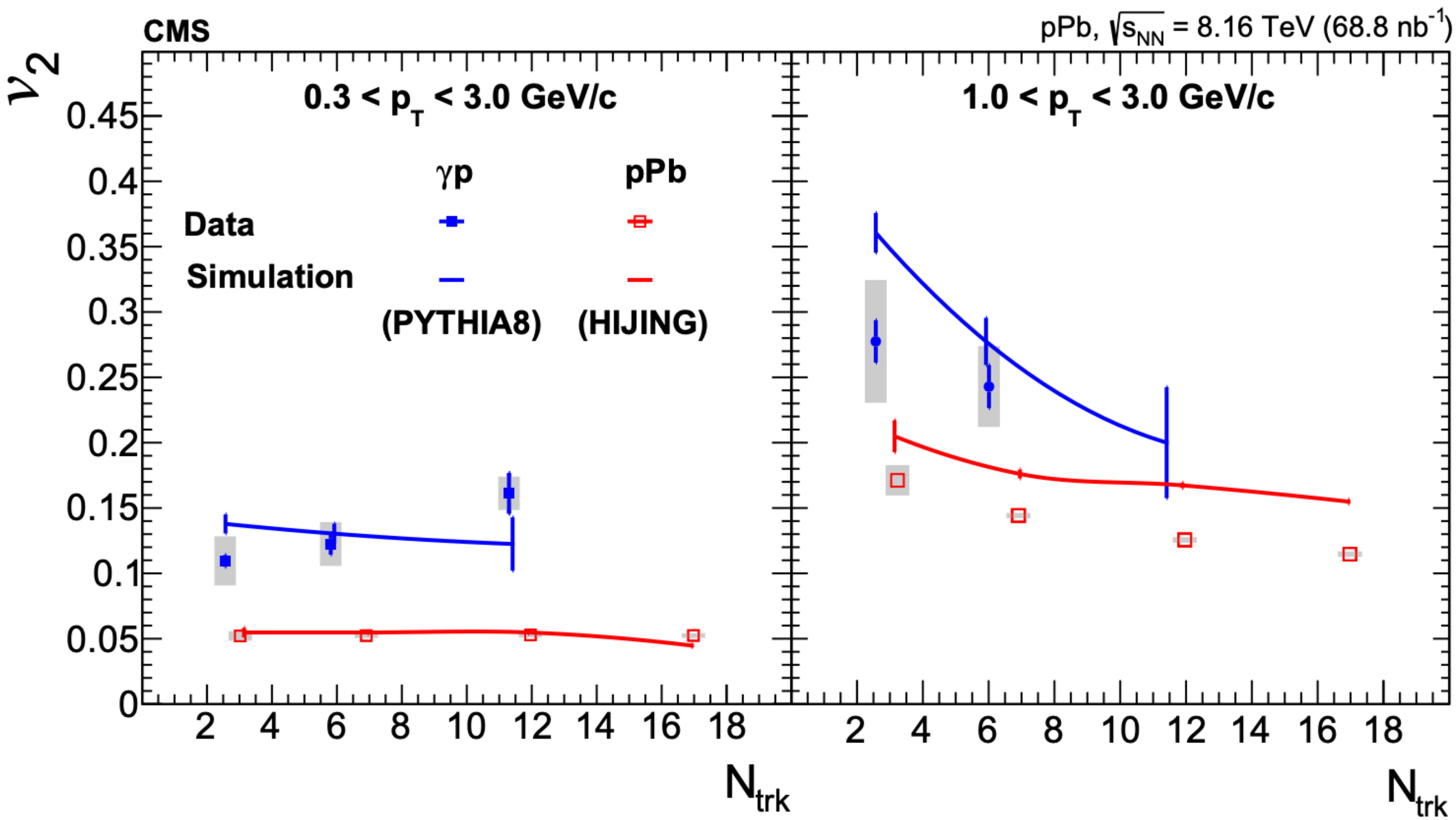


FIG. 5. (Color online) The p_T-differential elliptic flow coefficient $v_2(p_T)$ of charged hadrons in γ^*+Pb collisions from the 3D-GLAUBER+MUSIC+URQMD simulations with different photon virtualities are compared to the ATLAS data [24].

- Evidence of hydrodynamic FLOW in PbPb UPC

v_2 IN PHOTON-P COLLISIONS

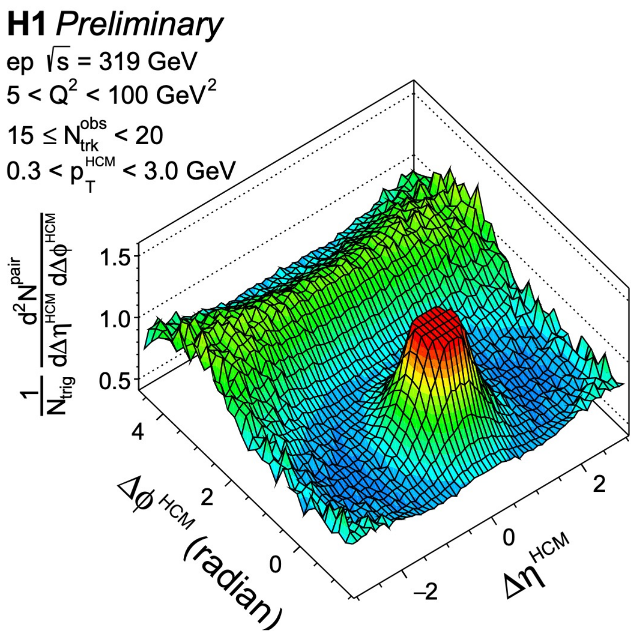
arXiv:2204.13486

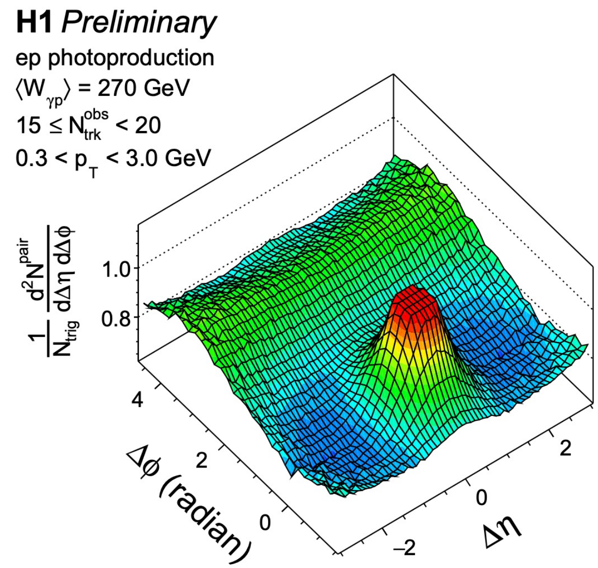


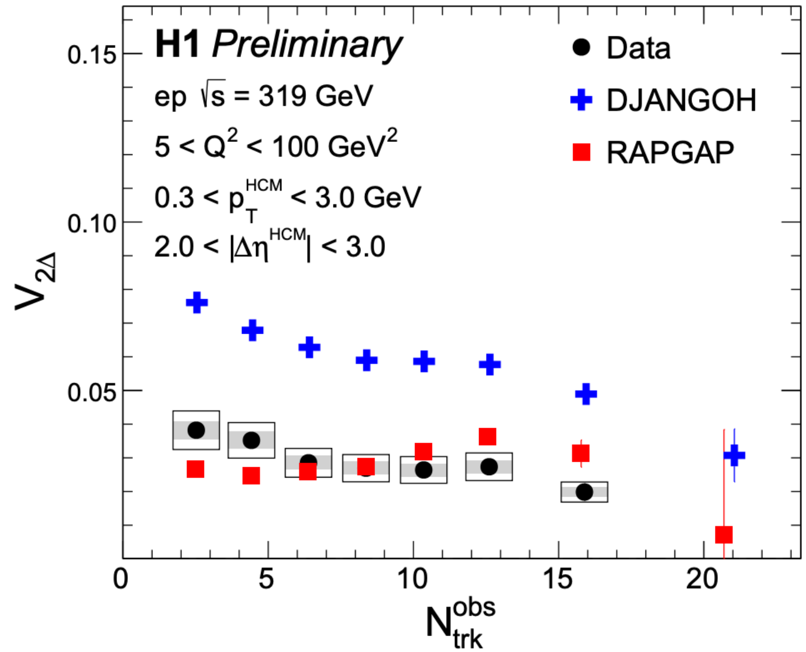
- Search for azimuthal anisotropy in γp interactions with pPb UPC
- Nonflow peripheral subtraction not applied
- Consistent with simulations without collective effects for both γp and pPb in the N_{trk} range

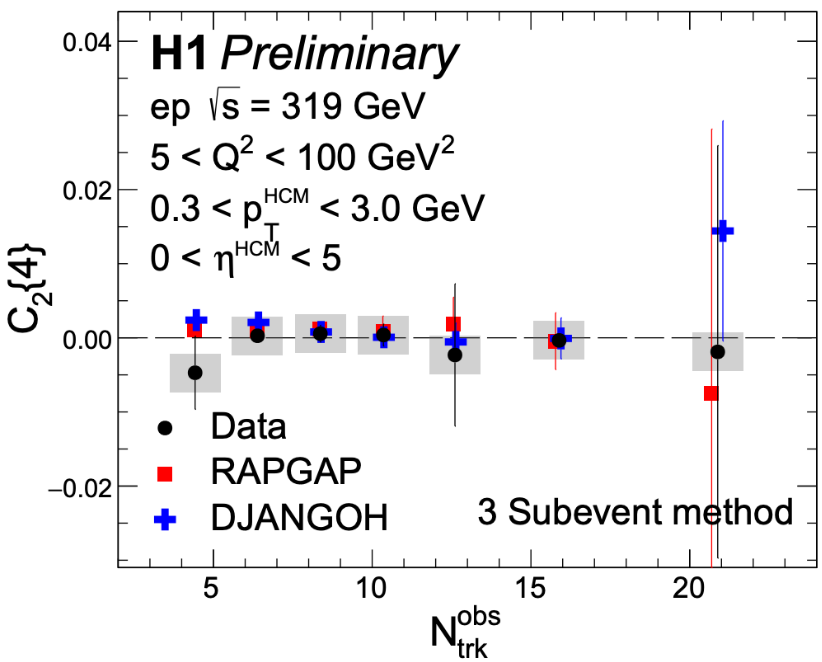
V_2 IN DIS

https://www-h1.desy.de/psfiles/confpap/IS2021/H1prelim-20-033.pdf







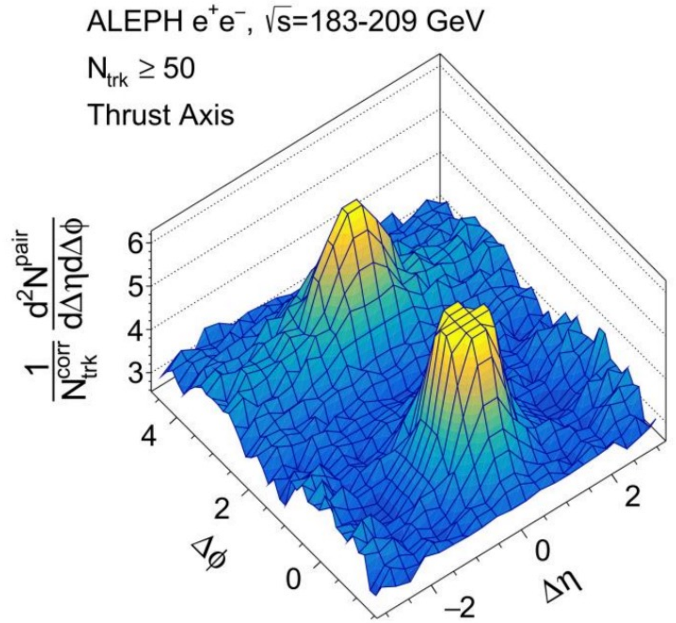


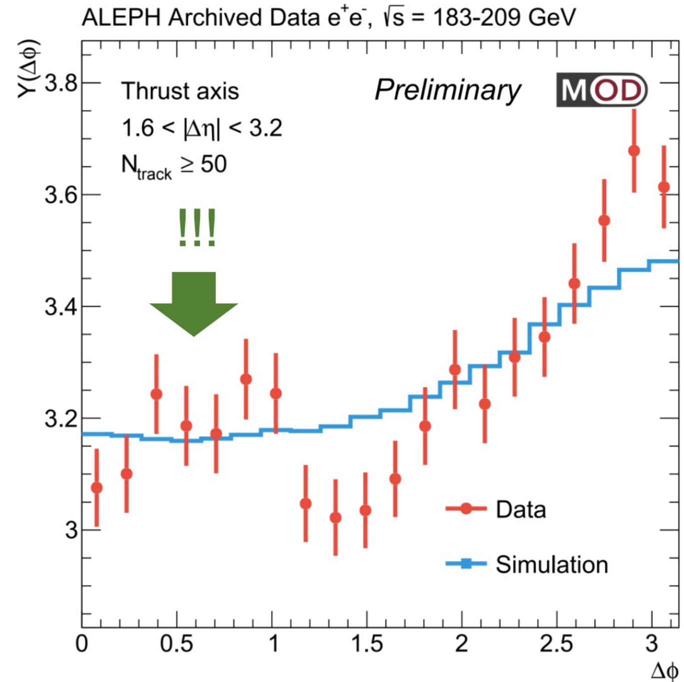
- Data described by model without collectivity
- No negative $c_2\{4\}$
- No collectivity observed in DIS
  - Multiplicity not high enough?

- Looking for the EIC results

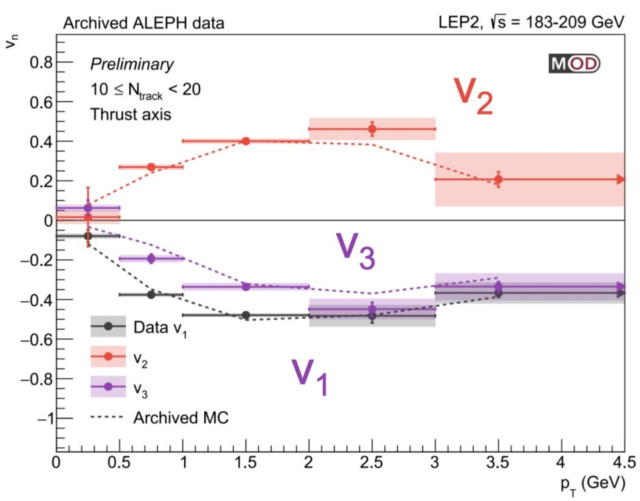
V_2 IN ELECTRON-POSITRON

Yen-Jie Lee ICHEP 2022



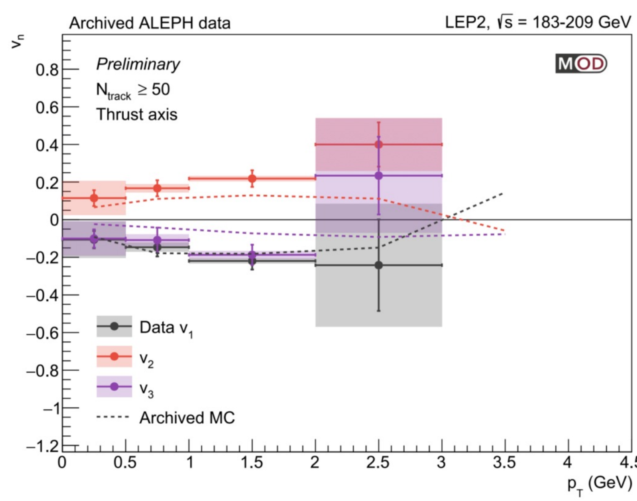


Low multiplicity 10<=N_{track}<20

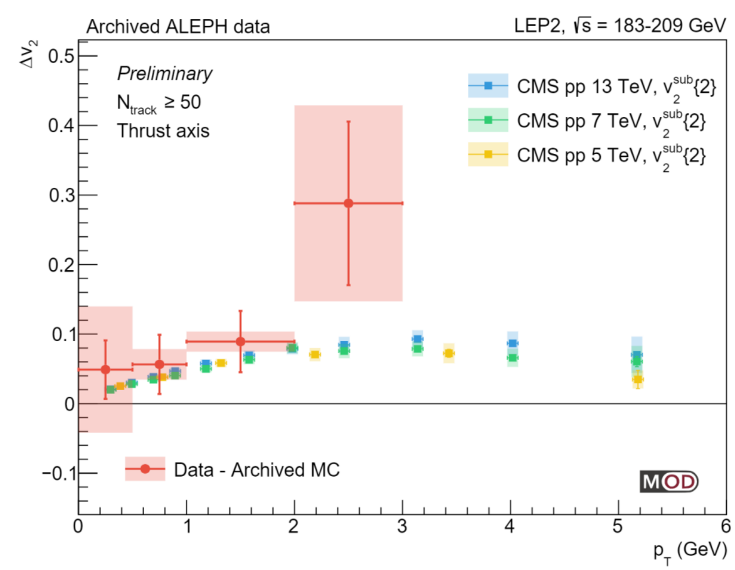


Good agreement between data and MC

High multiplicity N_{track}>=50

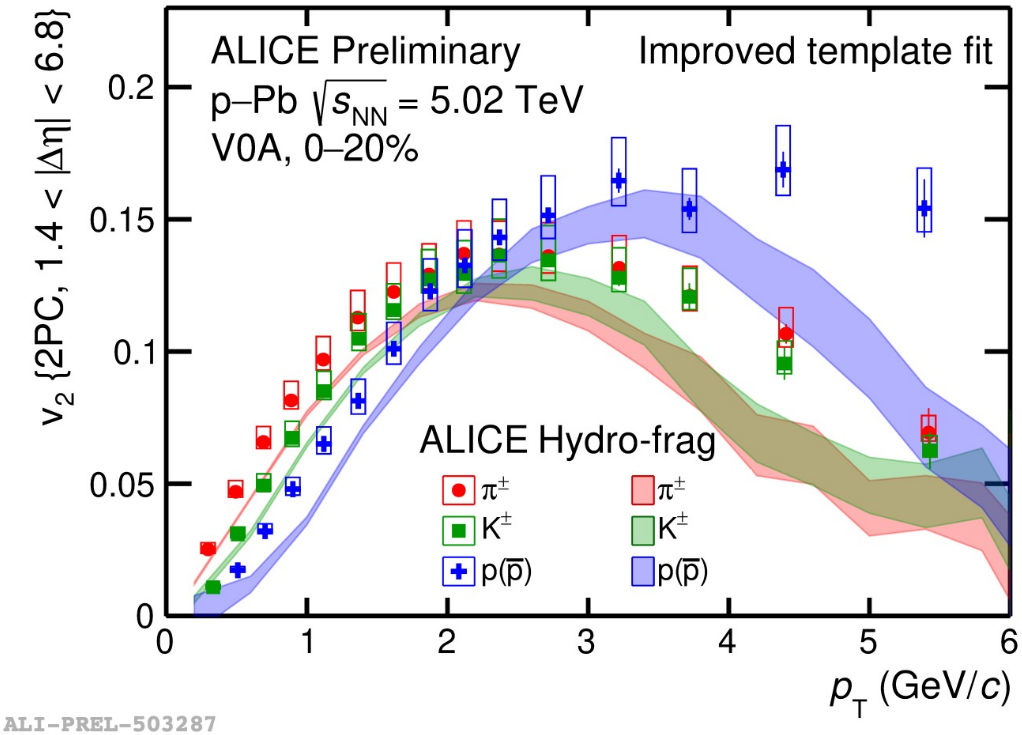


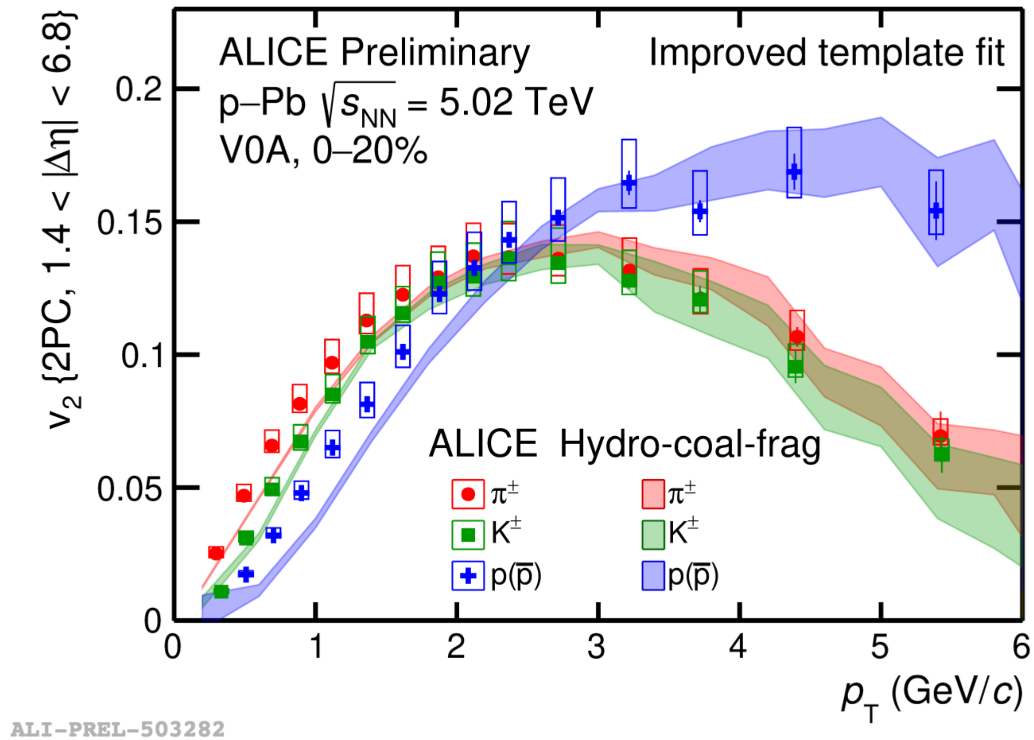
Larger v_2 and v_3 magnitudes than MC



- Difference between data and MC observed with N_{track}>=50

CHARGED PION, KAON AND PROTON FLOW - PPB



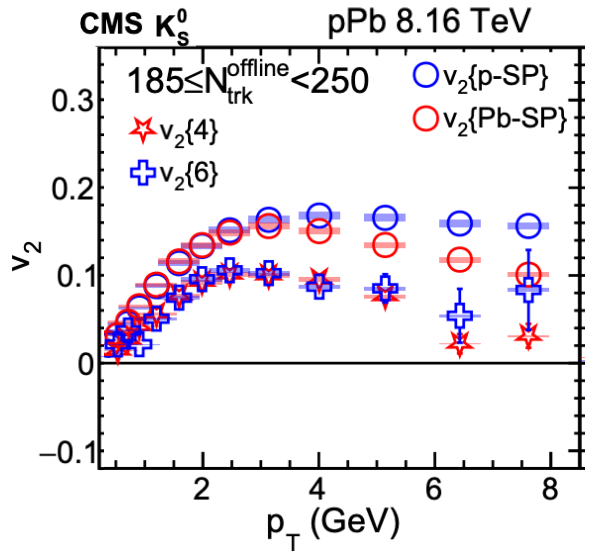


- Model without quark coalescence cannot qualitatively describe trends seen in data
- Partonic collectivity observed in p-Pb collisions

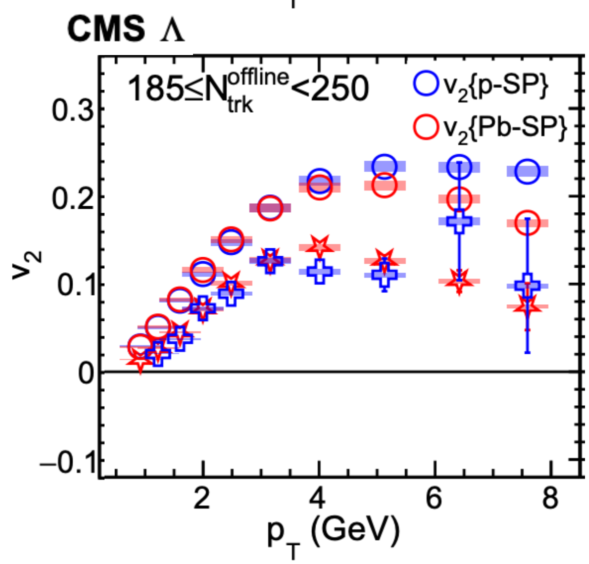
STRANGE PARTICLE V_2 - PPB

arXiv:2205.00080

K^0_S

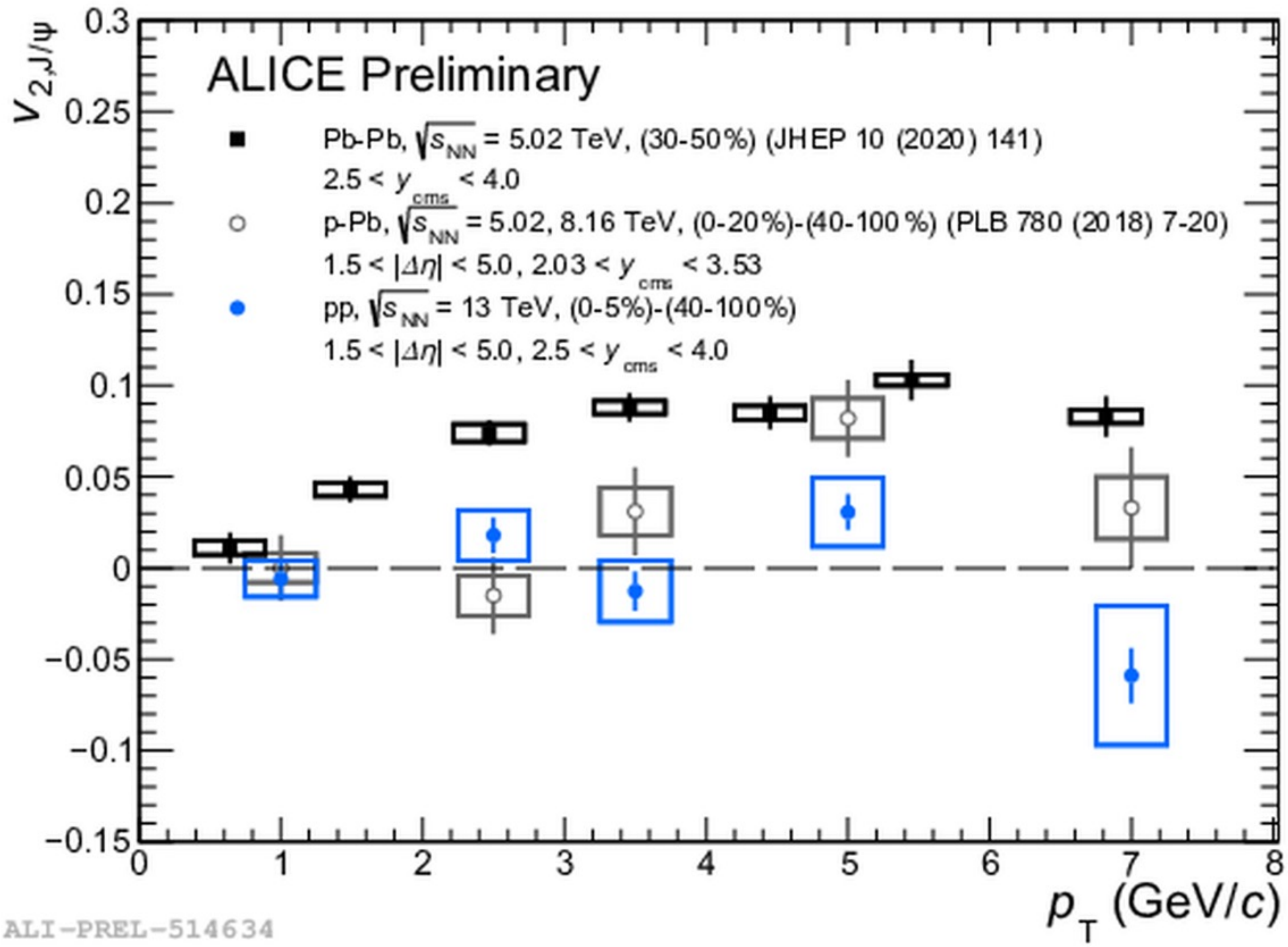


Λ



- K^0_s and Λ flow studied with multiparticle correlations
- Four and six particle correlations are nearly identical
- Compared with PbPb to illustrate the system size dependence of event-by-event fluctuations

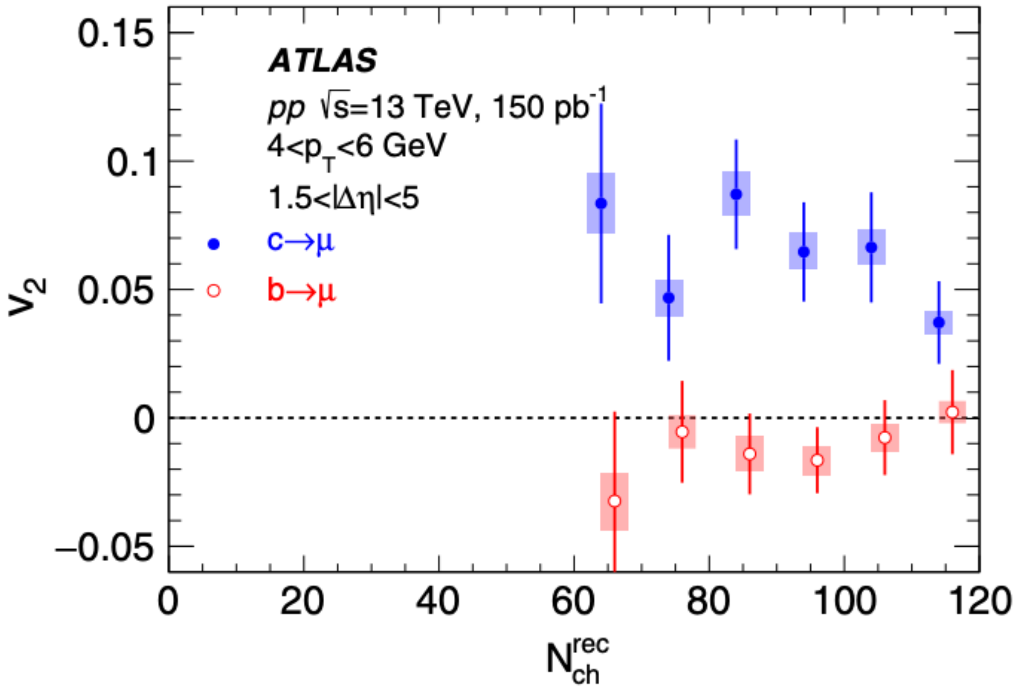
J/Ψ V_2 - PP

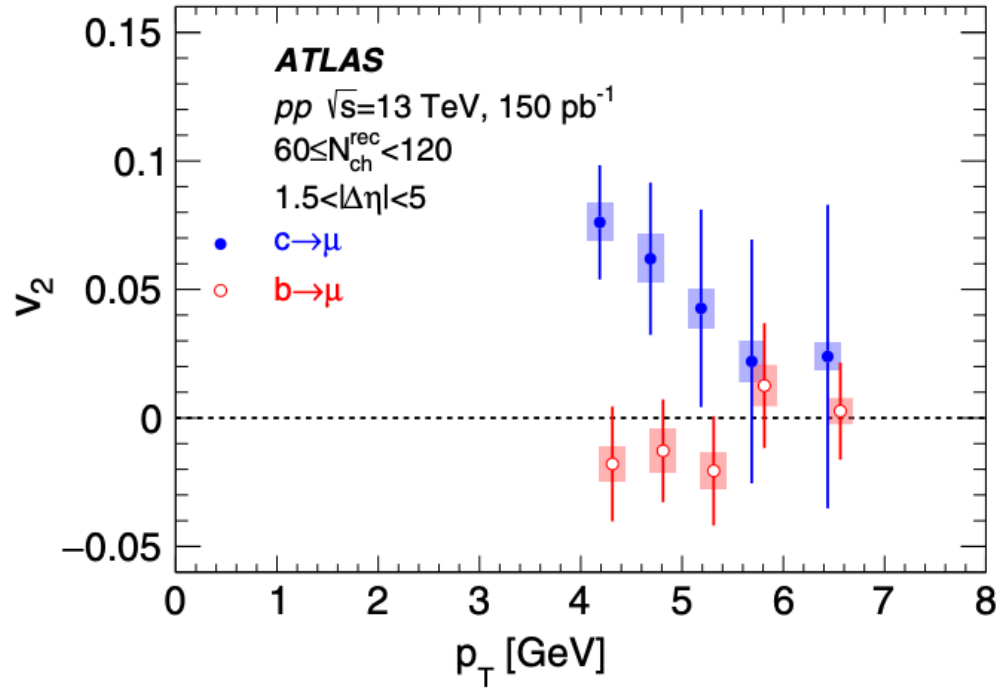


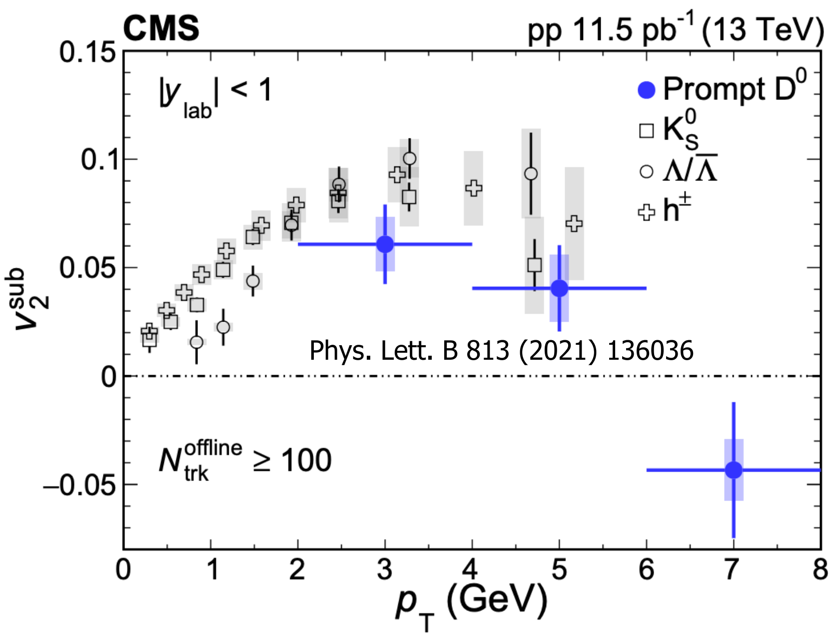
- J/ψ v_2 is significant in pPb
- The result in pp is compatible with 0 with current statistics

HEAVY FLAVOR V_2 - PP

Phys. Rev. Lett. 124, 082301



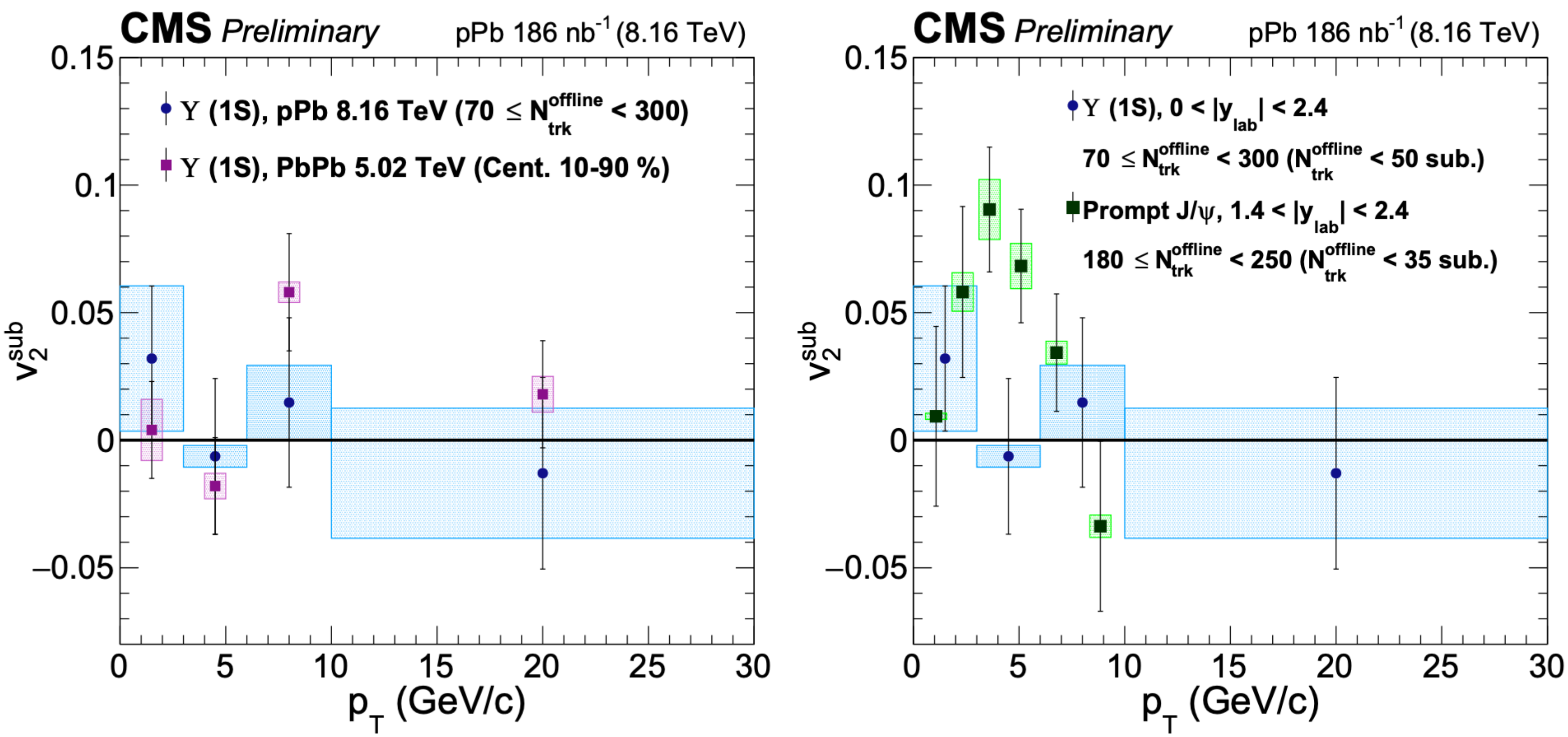




- Significant azimuthal anisotropy for charm muon in high multiplicity pp events
- v_2 from b decay ~ 0
- Charm and bottom difference is significant

Υ(1S) v_2 - PPB

CMS-PAS-HIN-21-001



- Υ(1S) v_2 consistent with 0 in pPb, similar in PbPb

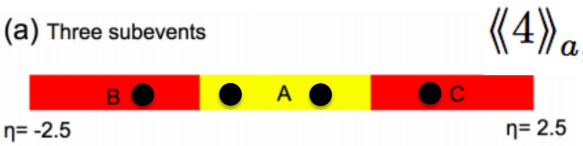
CHALLENGES - NONFLOW

Two particle correlations

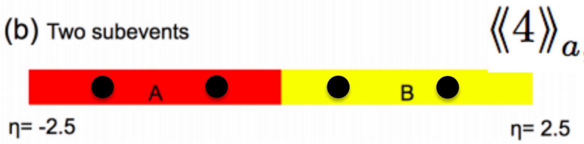
- Subtracting nonflow
  - Peripheral subtractions
  - Template fitting
  - Methods should be checked with different models
  - Careful with over subtractions

Multiparticle particle correlations

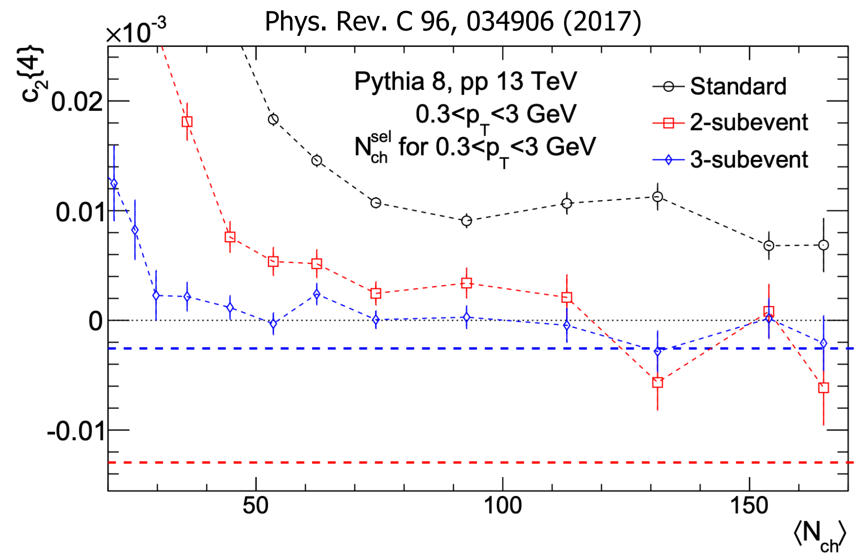
- Still affected by nonflow, need subevent event method
- 2-sub, 3-sub, 4-sub, …



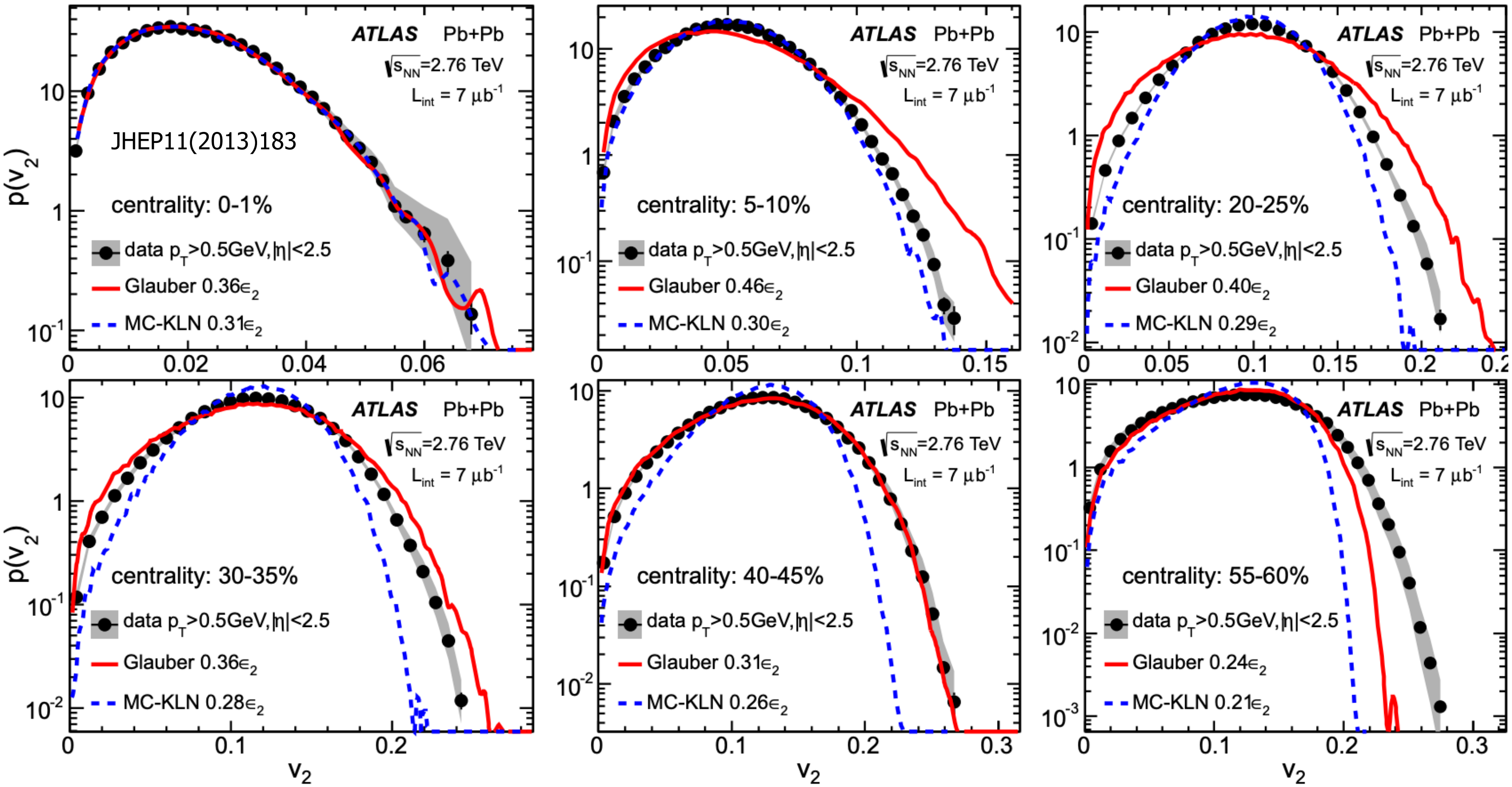
$$\langle\langle 4\rangle\rangle_{a,a|b,c} \equiv \left\langle\left\langle e^{in(\phi_1^a+\phi_2^a-\phi_3^b-\phi_4^c)}\right\rangle\right\rangle$$

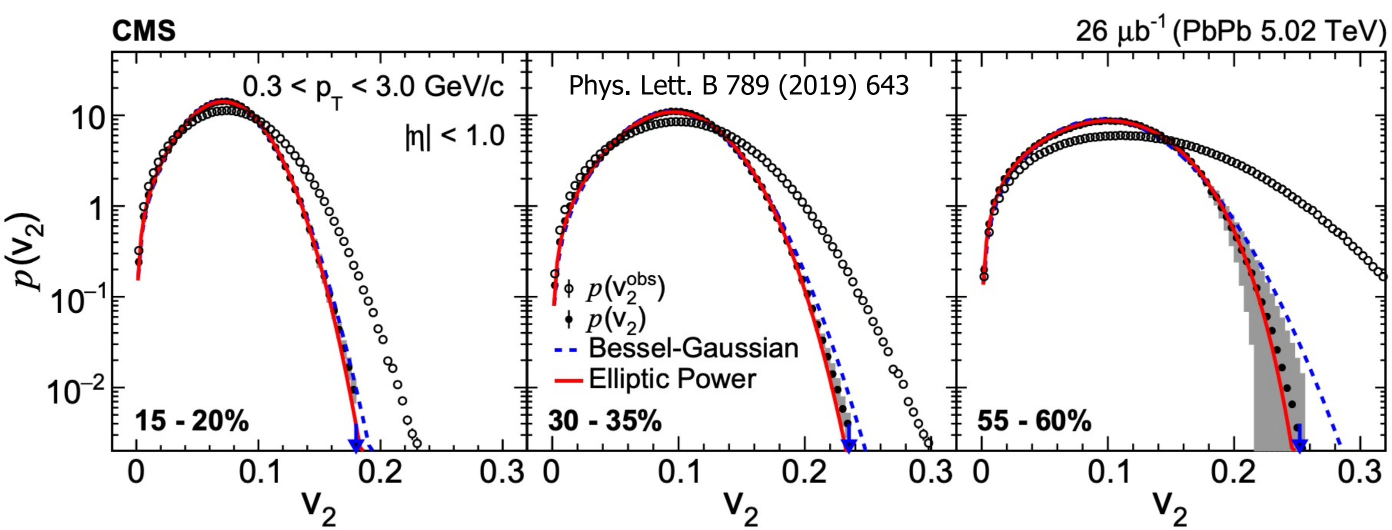


$$\langle\langle 4\rangle\rangle_{a,a|b,b} \equiv \left\langle\left\langle e^{in(\phi_1^a+\phi_2^a-\phi_3^b-\phi_4^b)}\right\rangle\right\rangle$$



CHALLENGES – FLOW FLUCTUATIONS





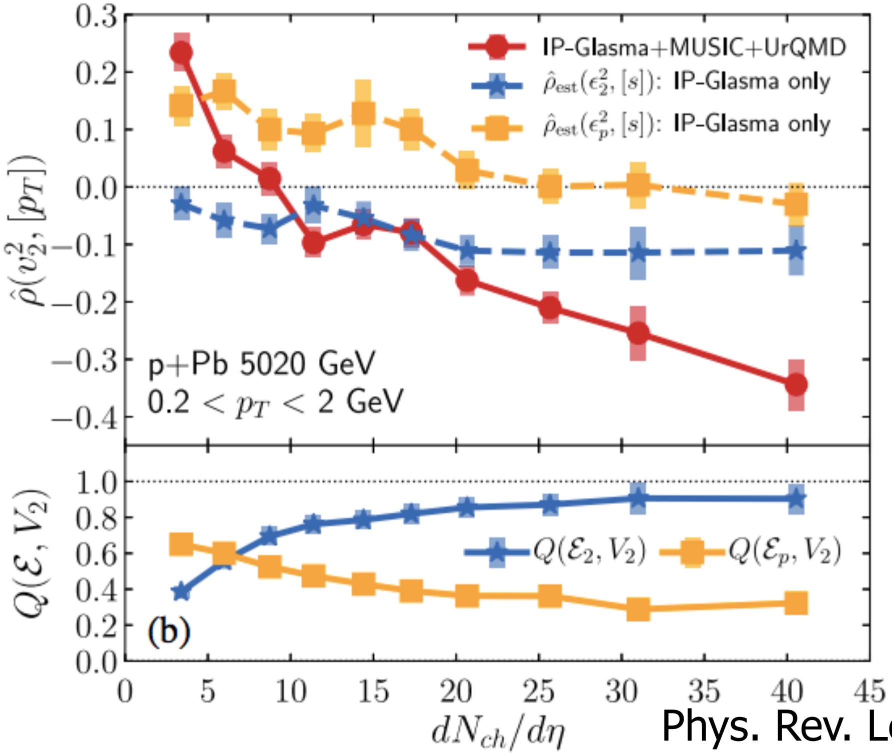
- True v_n distribution removing statistical fluctuations not measured yet at small systems
- Challenging for unfolding to work

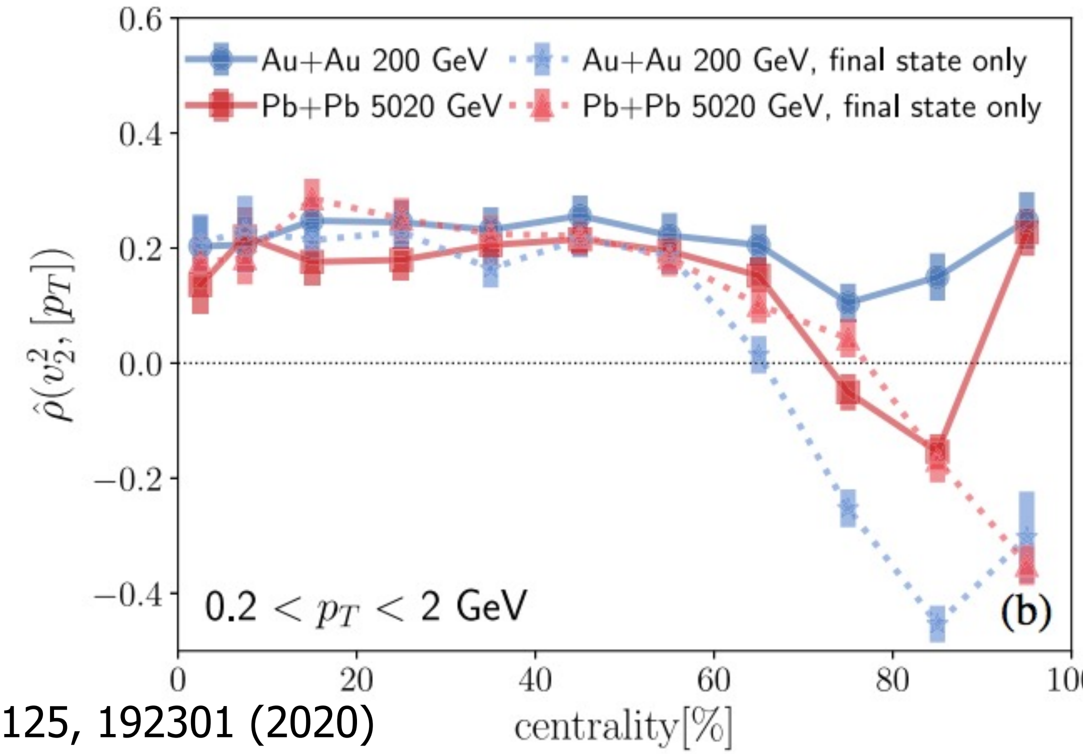
SUMMARY AND OUTLOOK

- Lots of measurements are done in both experiments and theories for collectivity in small systems
- More studies from theories for identified particles are needed
- So far, the smallest system that can be described by hydrodynamic calculations (some evidence of QGP) is the photon-Pb collision with $20<N_{ch}<60$
- Future measurements in small systems:
  - proton-Oxygen and Oxygen-Oxygen collisions
  - Flow in EIC?
- More questions we need to answer
  - What is the smallest possible size for collectivity to emerge?
  - Jet quenching in small systems?
  - Is there a phase transition to QGP for small systems?

BACKUP

BACKUP – V_N-[P_T] CORRELATIONS





Phys. Rev. Lett. 125, 192301 (2020)

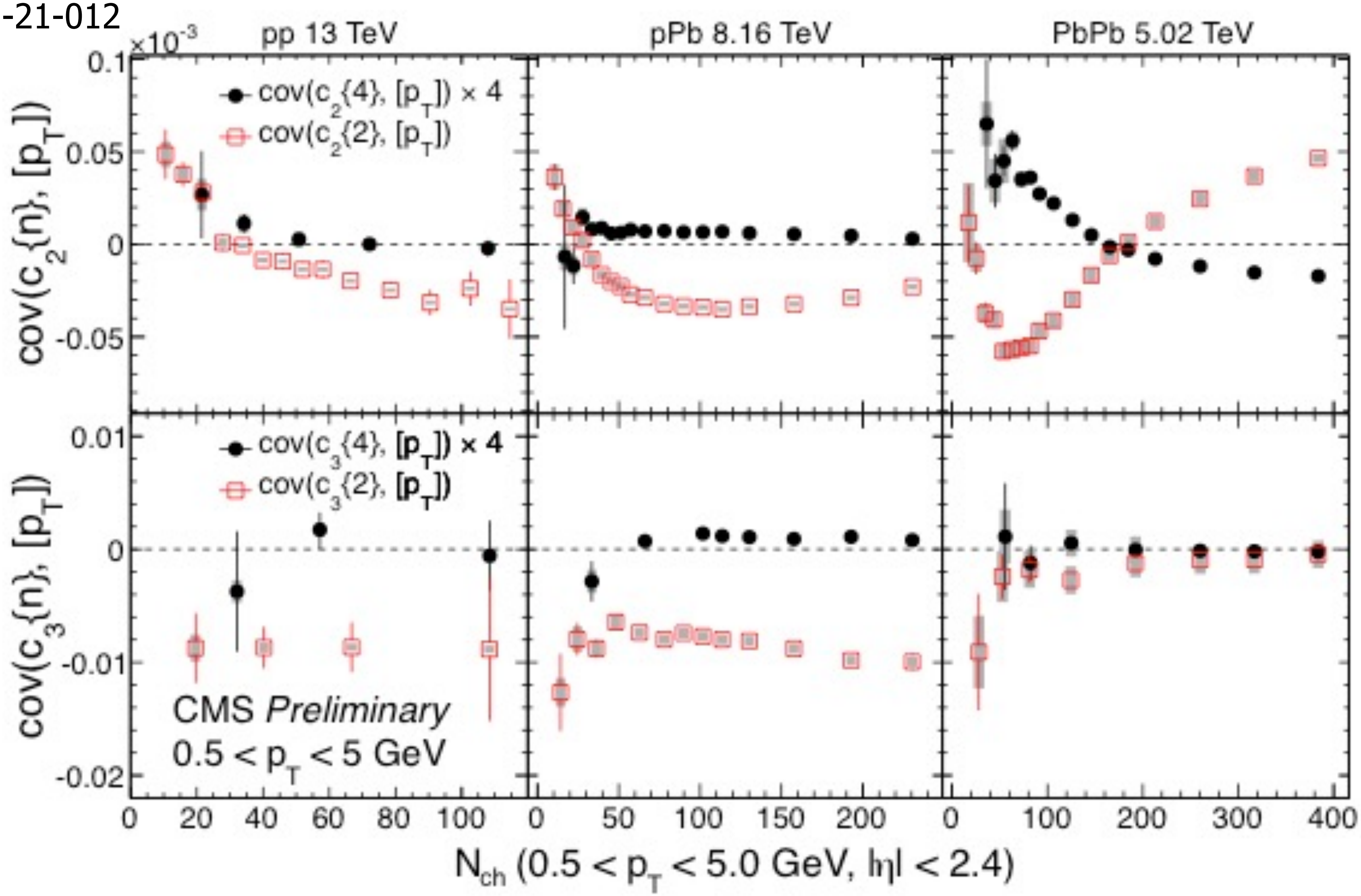
- The correlations carry information about the origin of the observed momentum anisotropy
- No sign change at low multiplicity without initial v_2 from CGC

BACKUP - COVARIANCE

CMS-PAS-HIN-21-012

n=2

n=3



- Clear sign change for pp and pPb collisions with $c_2\{2\}$
- No sign change at low N_{ch} using multiparticle correlations with current statistics