CENTER for NUCLEAR STUDY
THE UNIVERSITY of TOKYO

ALICE

Flow & Correlation

Yuko Sekiguchi
Center for Nuclear Study, the University of Tokyo

Highlight in QM2022

- v_n-$[p_T]$ correlation
  - System size dependence and energy dependence
  - Deformation of Xe and U
- Precise measurements of Flow Fluctuation
  - High precision measurements of skewness, kurtosis, and super skewness of v_2
  - PID with four-particle correlation in Pb–Pb and p–Pb
- Flow in small systems
  - System size dependence in RHIC
  - PID Flow in LHC
- Collectivity in ee, ep, and γ+A
  - Onset of collectivity
- Strangeness enhancement vs effective energy in pp
- Charmed baryon enhancement
- Charm molecule
- Three-body interaction

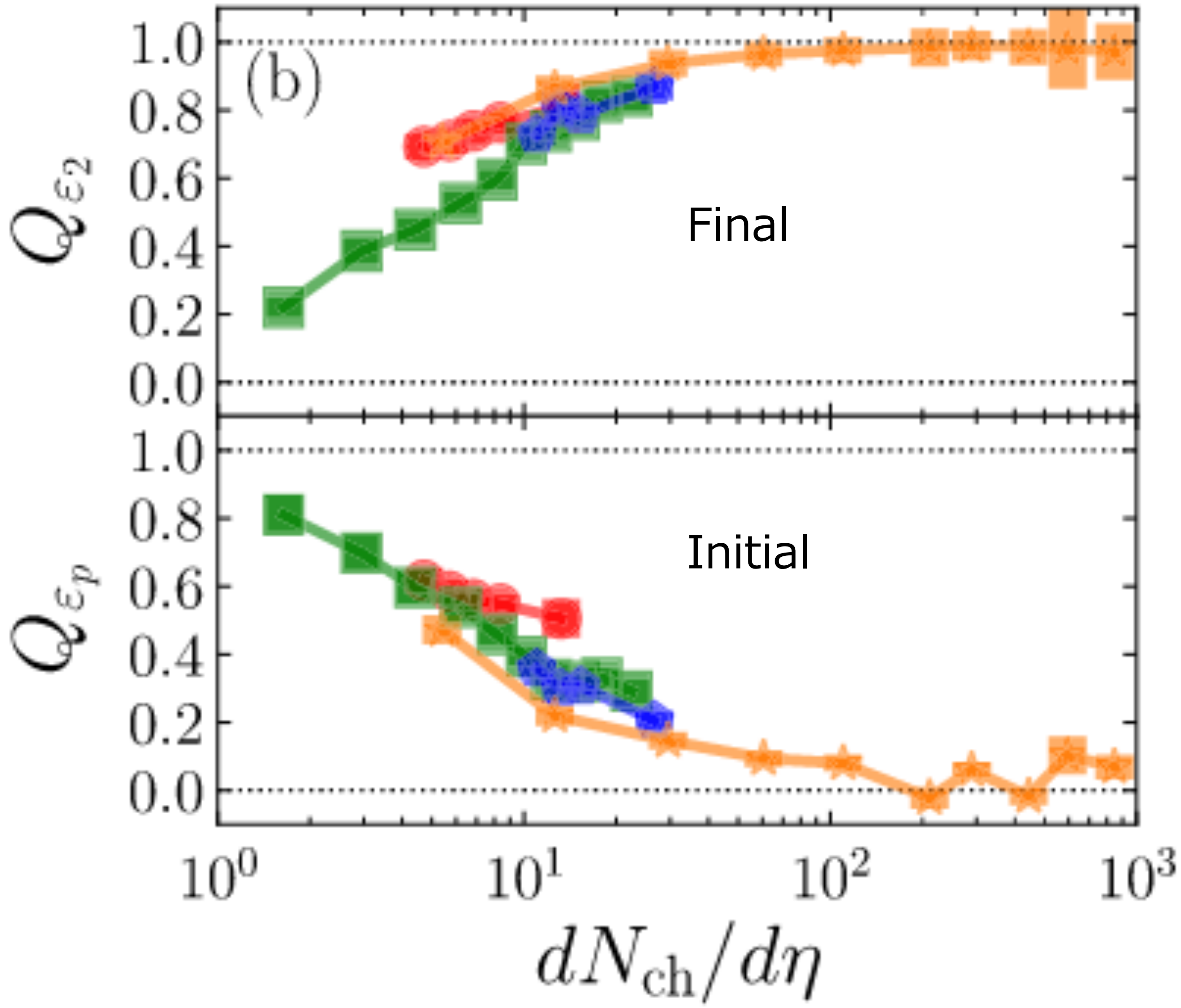
Origin of anisotropic flow

- Pearson correlations between initial geometry/initial momentum anisotropy and v_2.

$$Q_{\varepsilon} = \frac{\mathrm{Re}\langle \mathcal{E} V_2^* \rangle}{\sqrt{\langle |\mathcal{E}|^2 \rangle \langle |V_2|^2 \rangle}}$$

- At low multiplicity, final v_2 is correlated to initial momentum anisotropy rather than geometry.

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



v_n-$[p_T]$ correlation

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

Final State

- R ↑ ↔ [pT] ↓ Anti-correlated
- ε_2 ↑ ↔ v_2 ↑

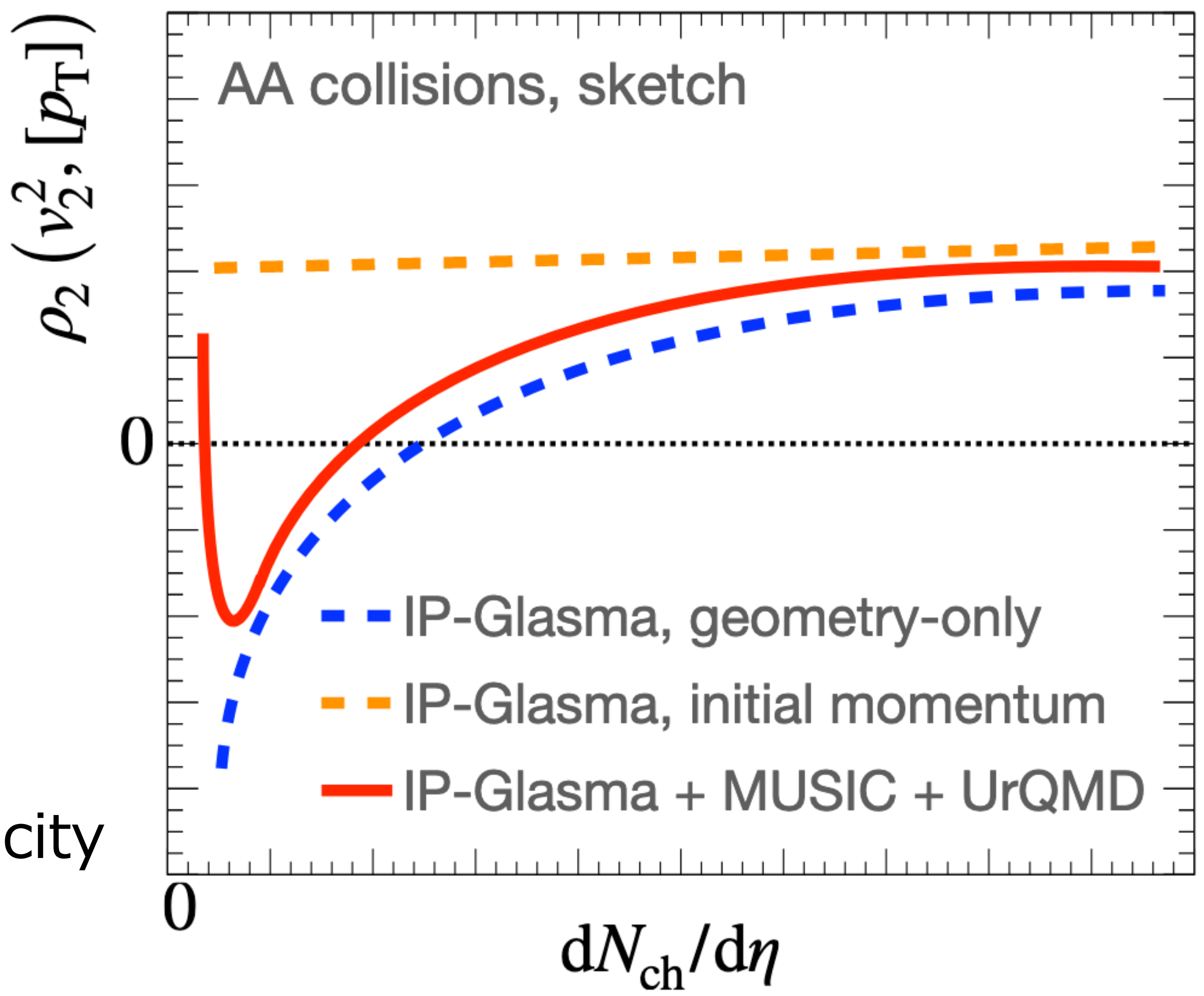
Initial State

R ↑ ↔ [pT] ↓ Correlated

$\varepsilon^p{}_2$ ↓ ↔ $v^p{}_2$ ↓

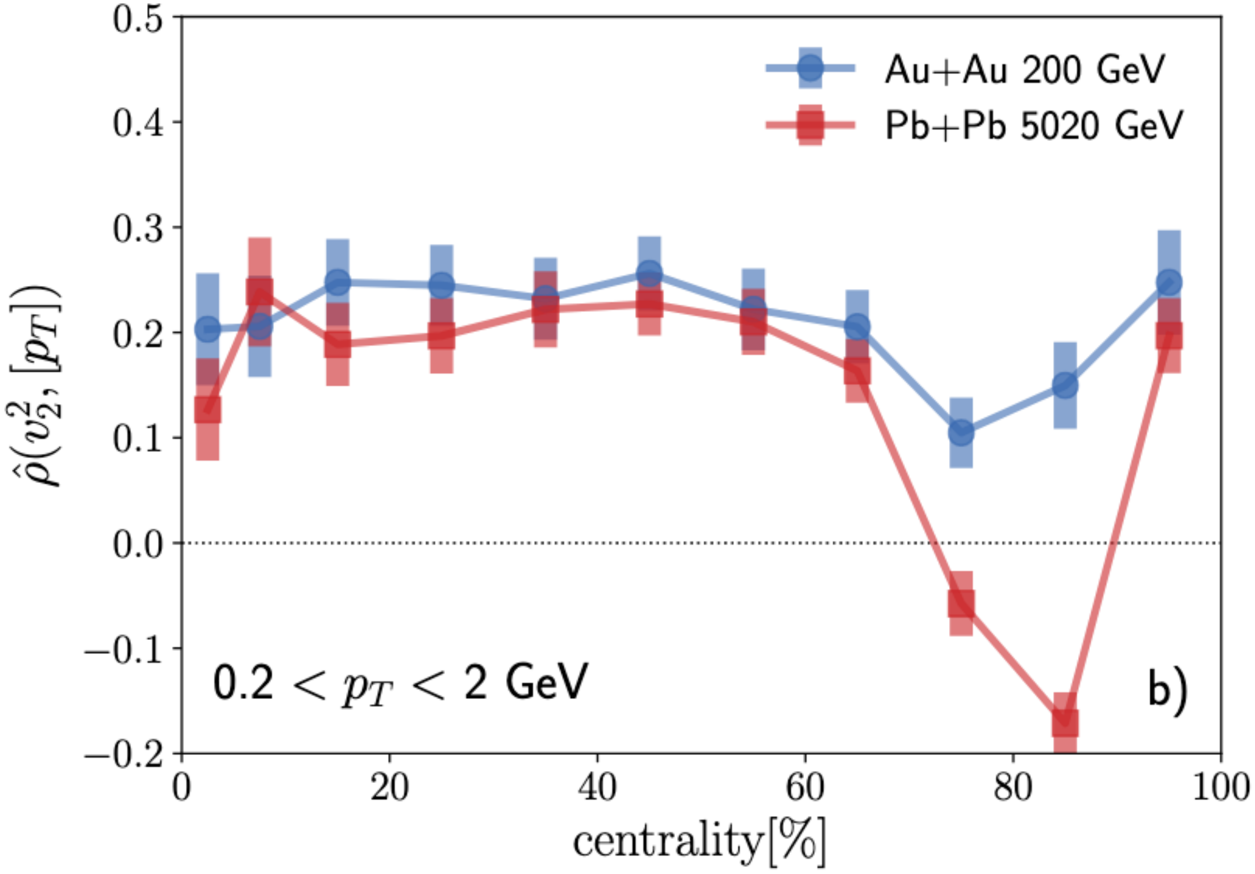
The correlation is sensitive to…

- Gluon saturation at low multiplicity
- Deformed nuclei

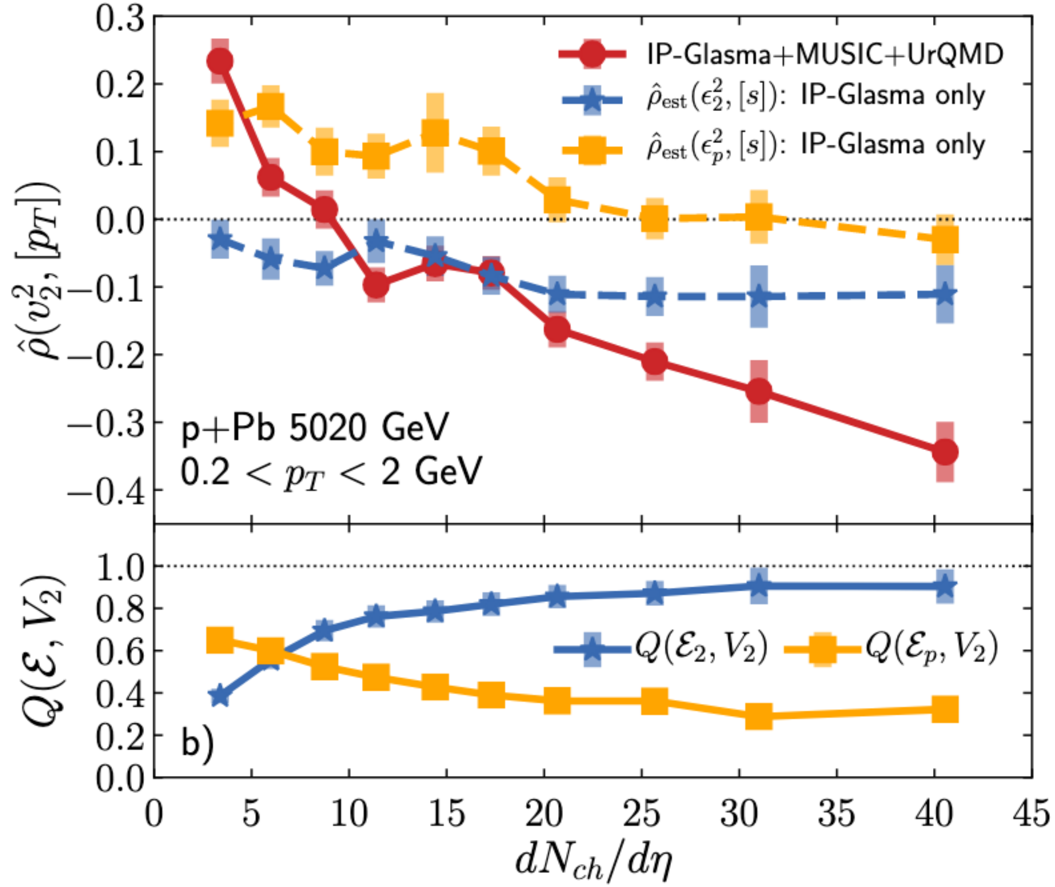


v_n-[p_T] correlation vs system/energy

- Two sign changes in Pb–Pb collisions in LHC, while no sign change in Au–Au collisions in RHIC due to weak final state response.
- One sign change in p–Pb/d–Au collisions



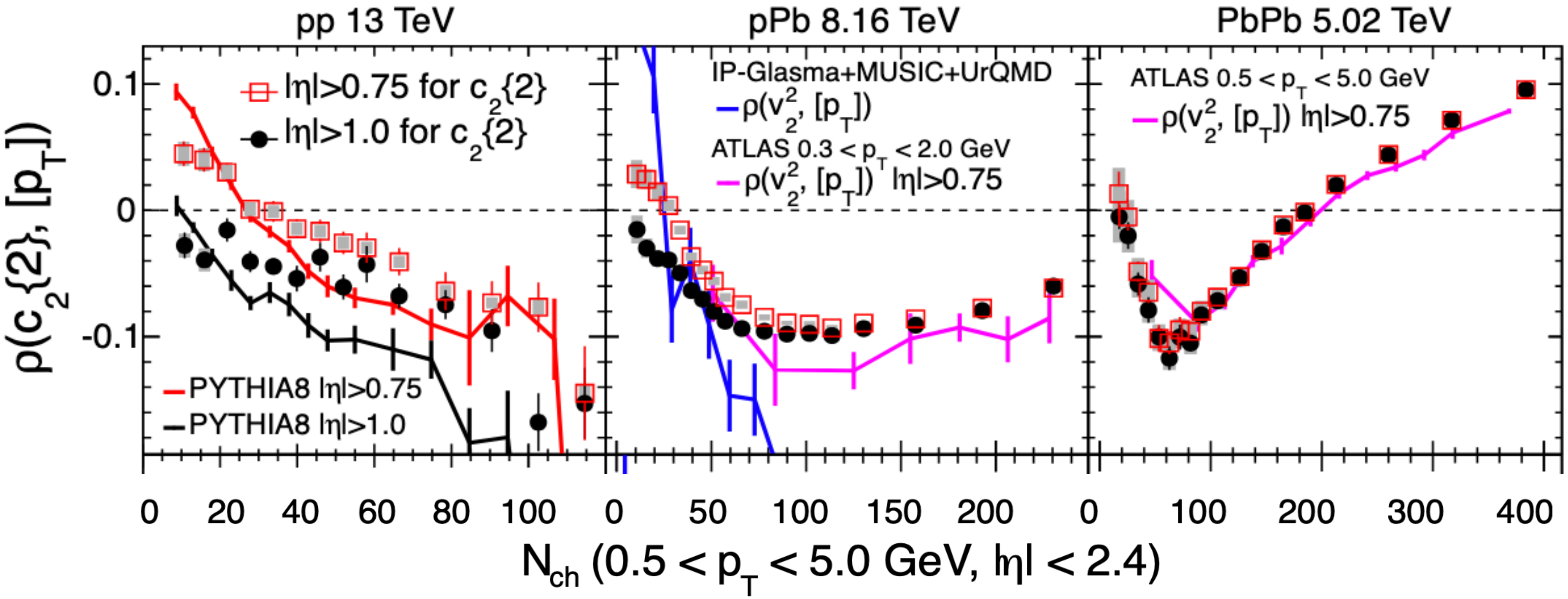
G. Giacalone, et. al., PRL,125, 192301(2020)



v_2-[p_T] correlation in LHC

- To reduce non-flow, three-subevent method is employed.
- Sign change is observed with a small rapidity gap, while no sign change with a large rapidity gap in pp and p–Pb collisions.
  - A theoretical model calculation indicates that initial momentum anisotropy is removed as well as non-flow by using a large rapidity gap (Talk by P. Singh)
    - ATLAS:|Δη|>1.5, CMS:|Δη|>1.5 or 2, ALICE:|Δη|>0.8
- Sign change is visible in Pb–Pb with a large rapidity gap.

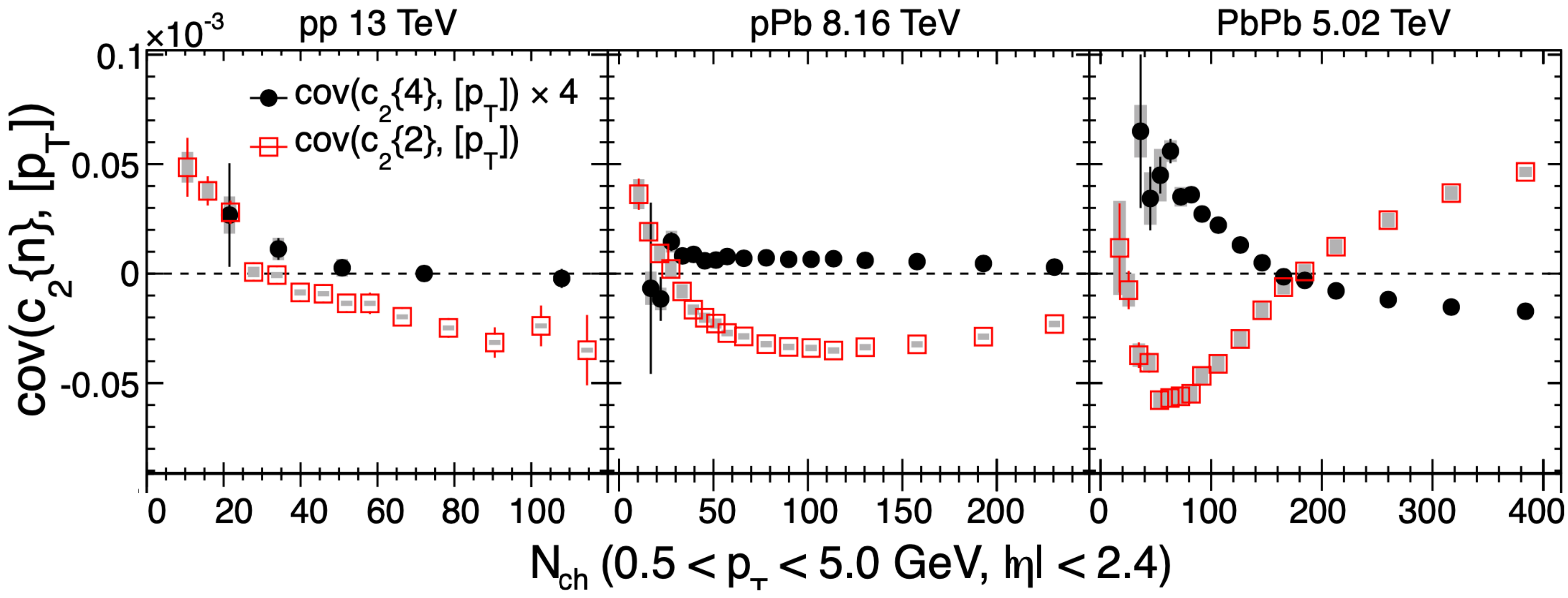
S. Tuo for CMS



v_2-[p_T] correlation in LHC

- No sign change with four-particle cumulant method in small systems
- The trend is different between $c_2\{4\}$ and $c_2\{2\}$ in Pb–Pb collisions

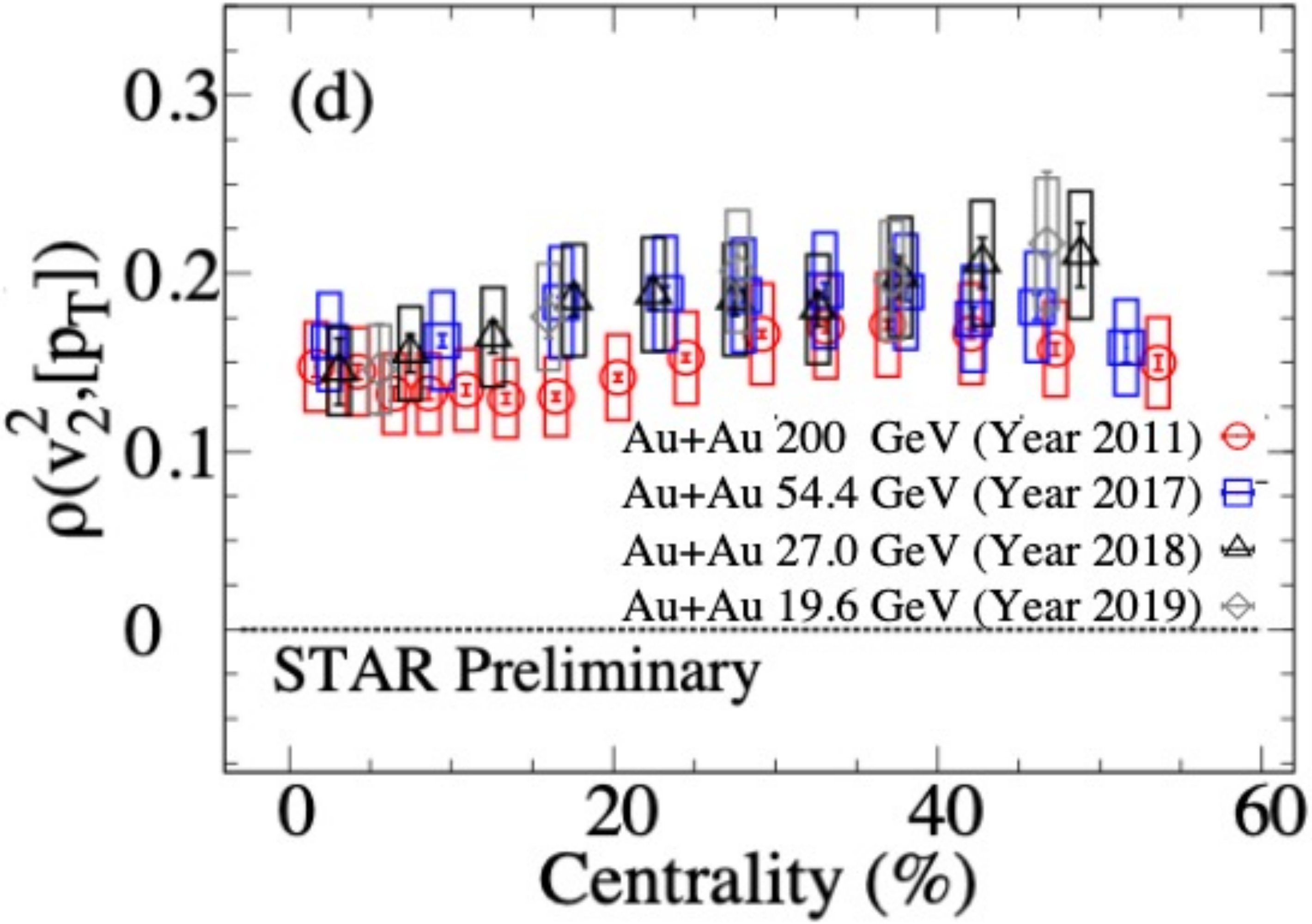
S. Tuo for CMS



v_2-$[p_T]$ correlation in RHIC

- No sign change as predicted by the model calculation
- The correlation shows hint of collision energy dependence.

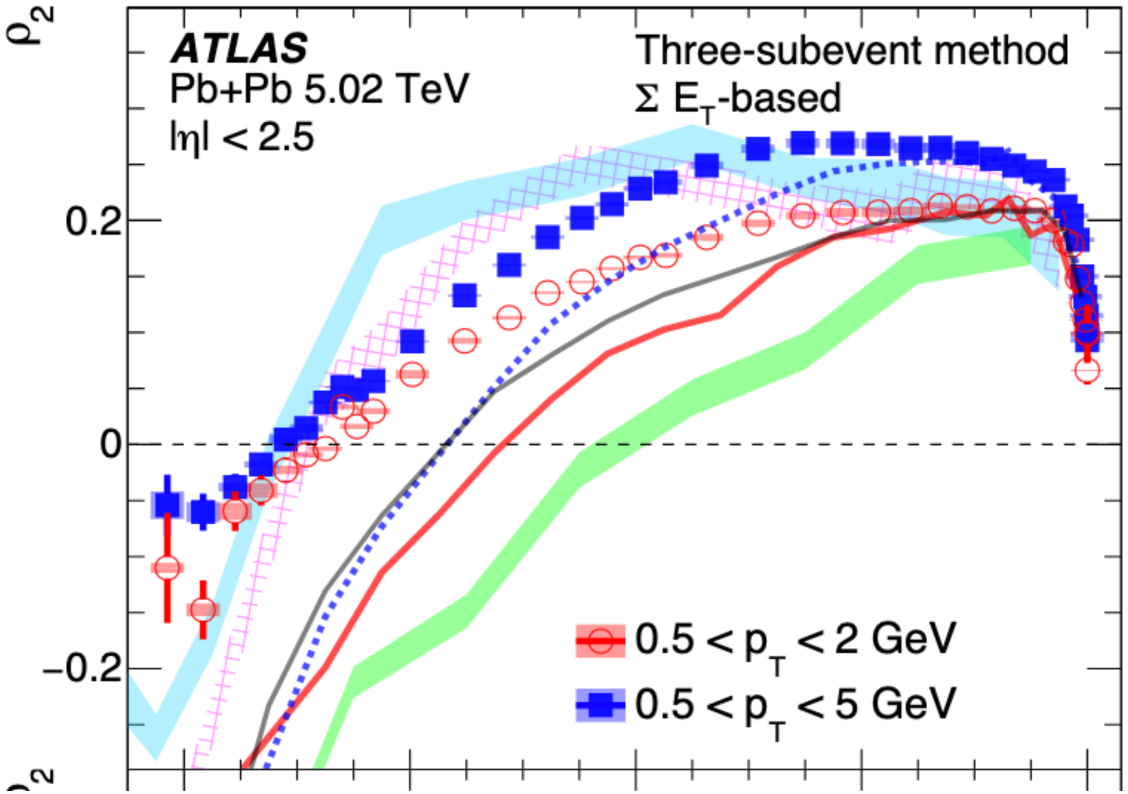
G. Yan for STAR



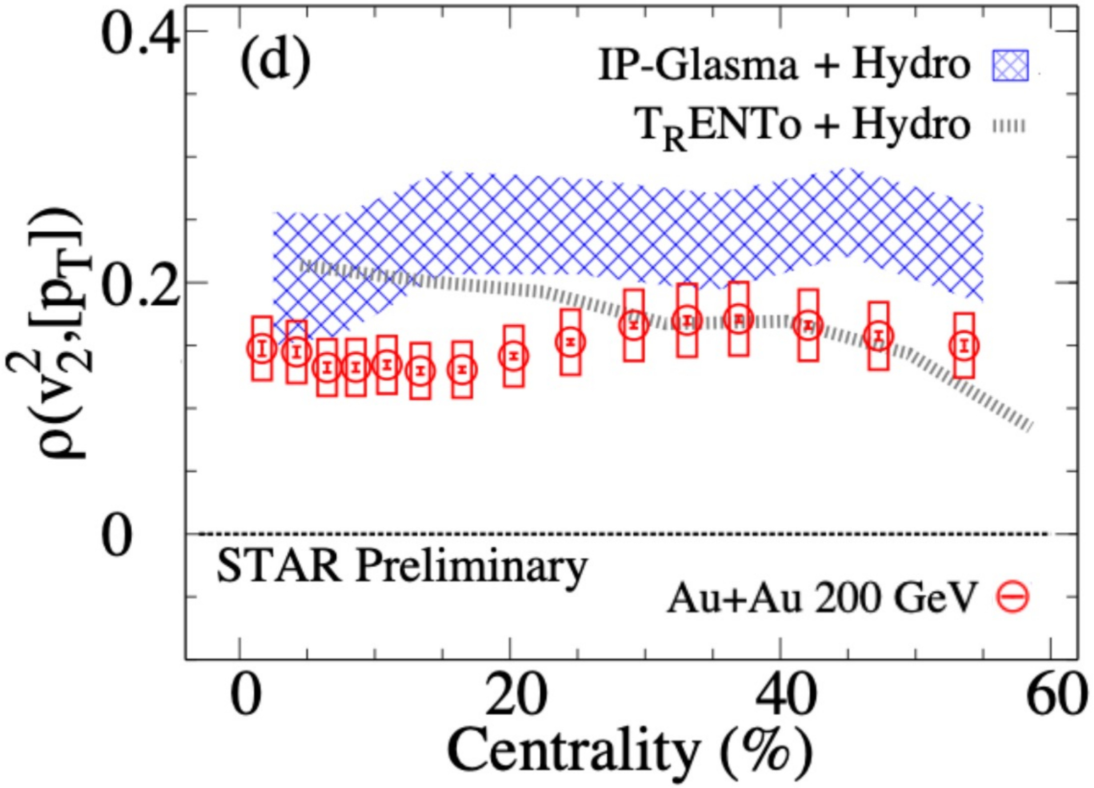
Hydro Model Comparisons

- IP-Glasma+Music describes the data qualitatively in Pb–Pb collisions in LHC.
- IP-Glasma+Hydro overestimates the data, and TRENTO+Hydro describes at mid-central while overestimates at most-central in Au–Au collisions in RHIC.

S. Bhatta for ATLAS



G. Yan for STAR



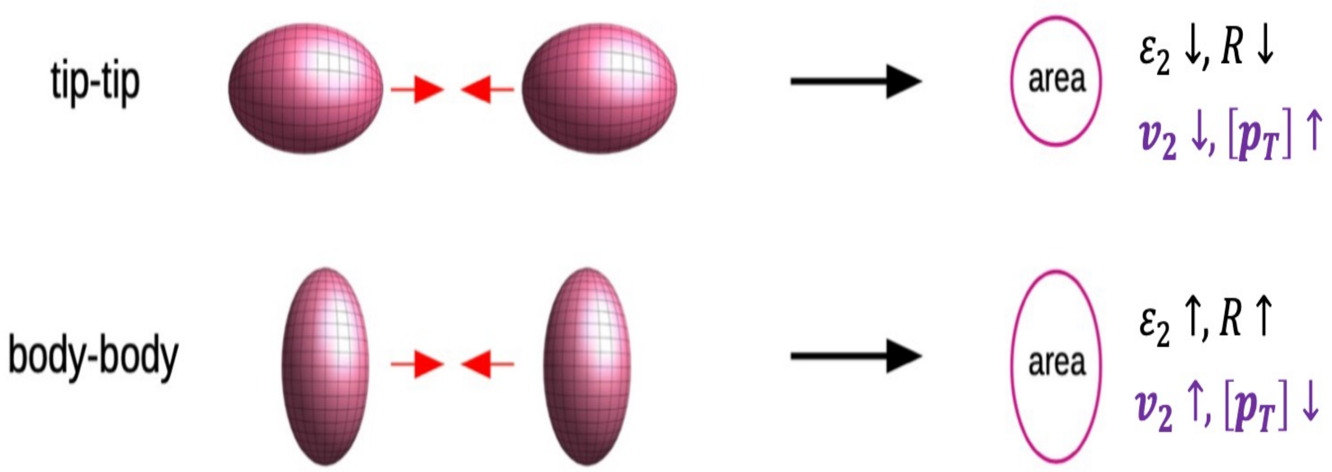
Study of nuclear geometry

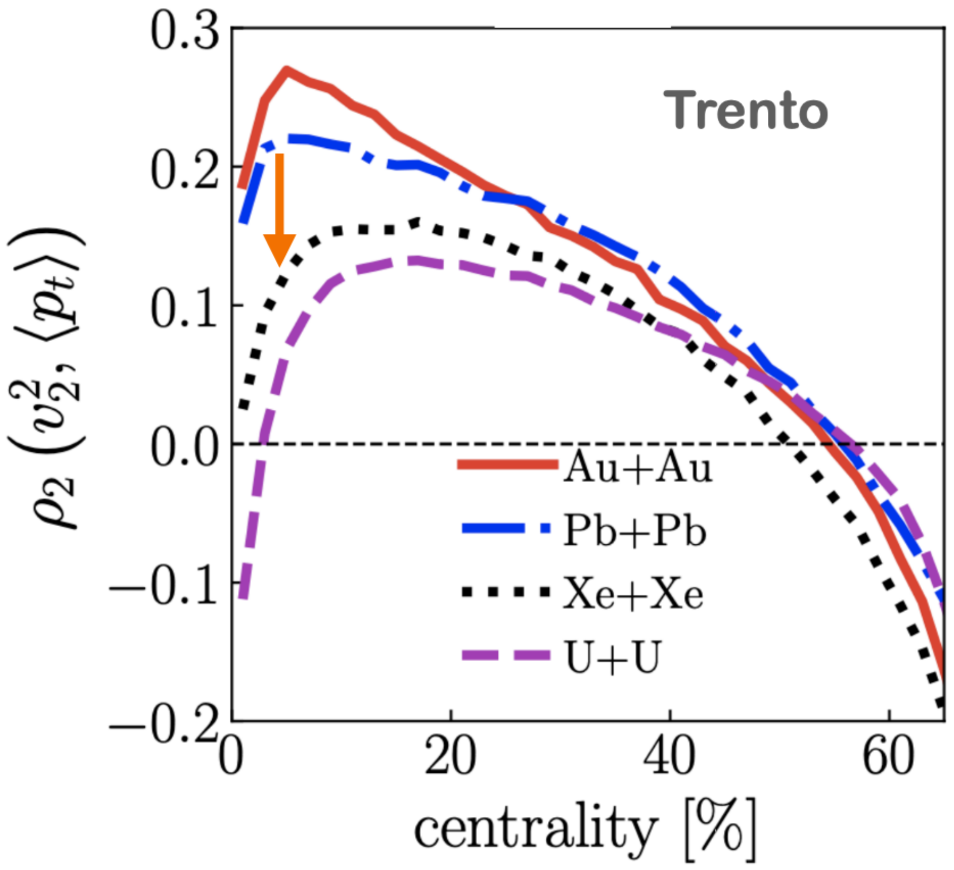
- Nuclear geometry parametrized by Woods-Saxon distribution

$$\rho(r,\theta,\phi) = \frac{\rho_0}{1+e^{[r-R(\theta,\phi)/a_0]}}$$

$$R(\theta,\phi) = R_0(1+\beta(cos\gamma Y_{20}(\theta,\phi) + sin\gamma Y_{22}(\theta,\phi)))$$

- v_2-$[p_T]$ correlation also sensitive to the shape of nuclei



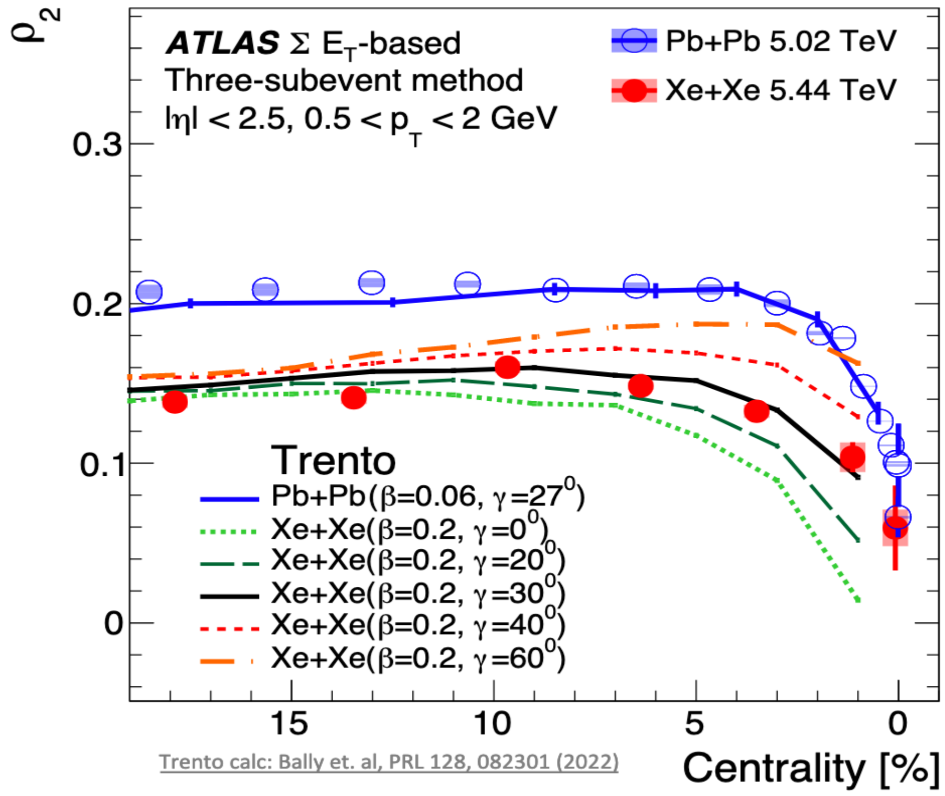


G. Giacalone, Phys. Rev. C 102, 024901 (2020)

Deformation of nuclei

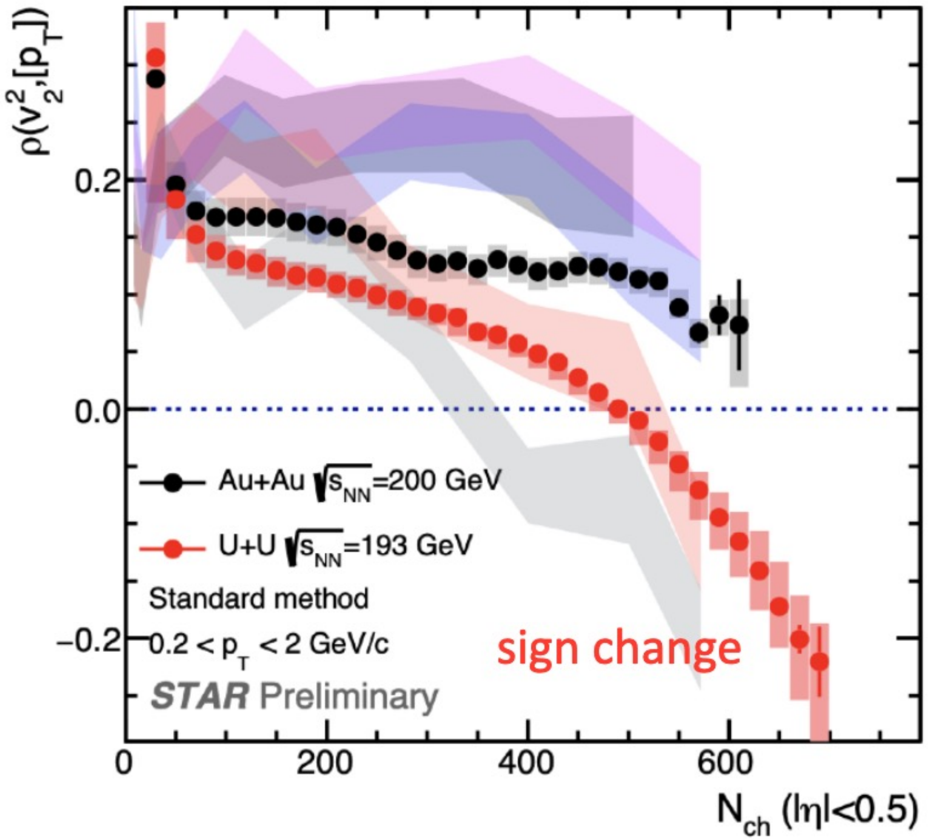
- Pb is almost a sphere, Xe is deformed by β=0.2.
- ρ_2 is sensitive to γ in central collisions
  - TRENTO with γ=30° describes the data.➡Xe deformed to triaxial nucleus
- U is prolate, β~0.28

S. Bhatta for ATLAS



Trento calc: Bally et. al, PRL 128, 082301 (2022)

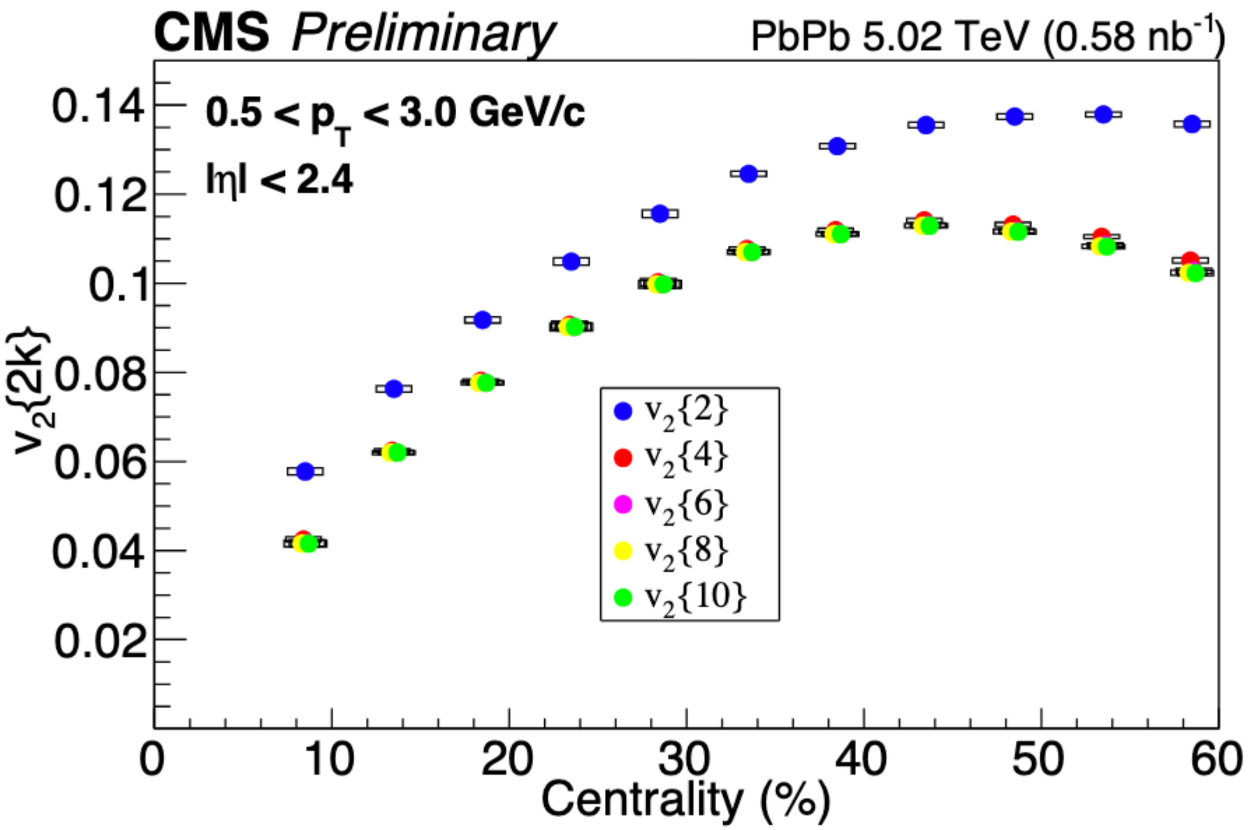
H. Xu for STAR

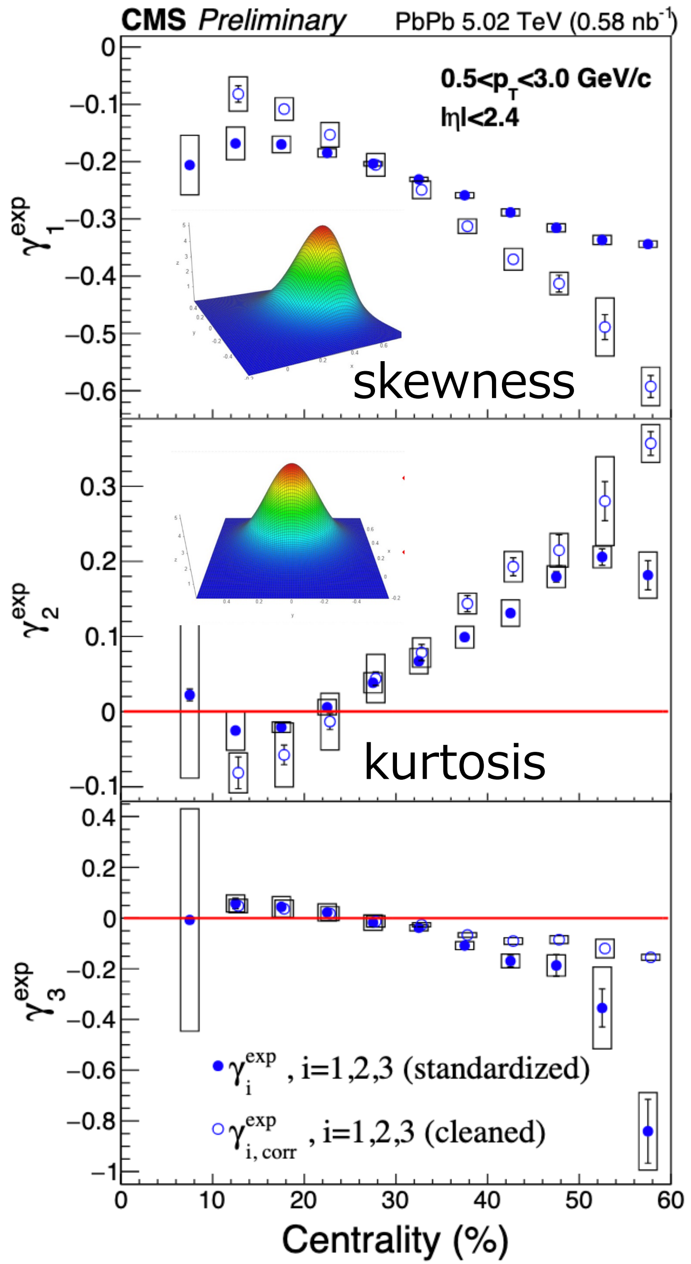


Initial geometry

- $v_2\{2k\}$ is measured up to k=5 with fine uncertainties.
  - $v_2\{4\} >\approx v_2\{6\} >\approx v_2\{8\} >\approx v_2\{10\}$
- Skewness, kurtosis, and superskewness are measured precisely
  - Constrains on the initial geometry

L. Nadderd for CMS

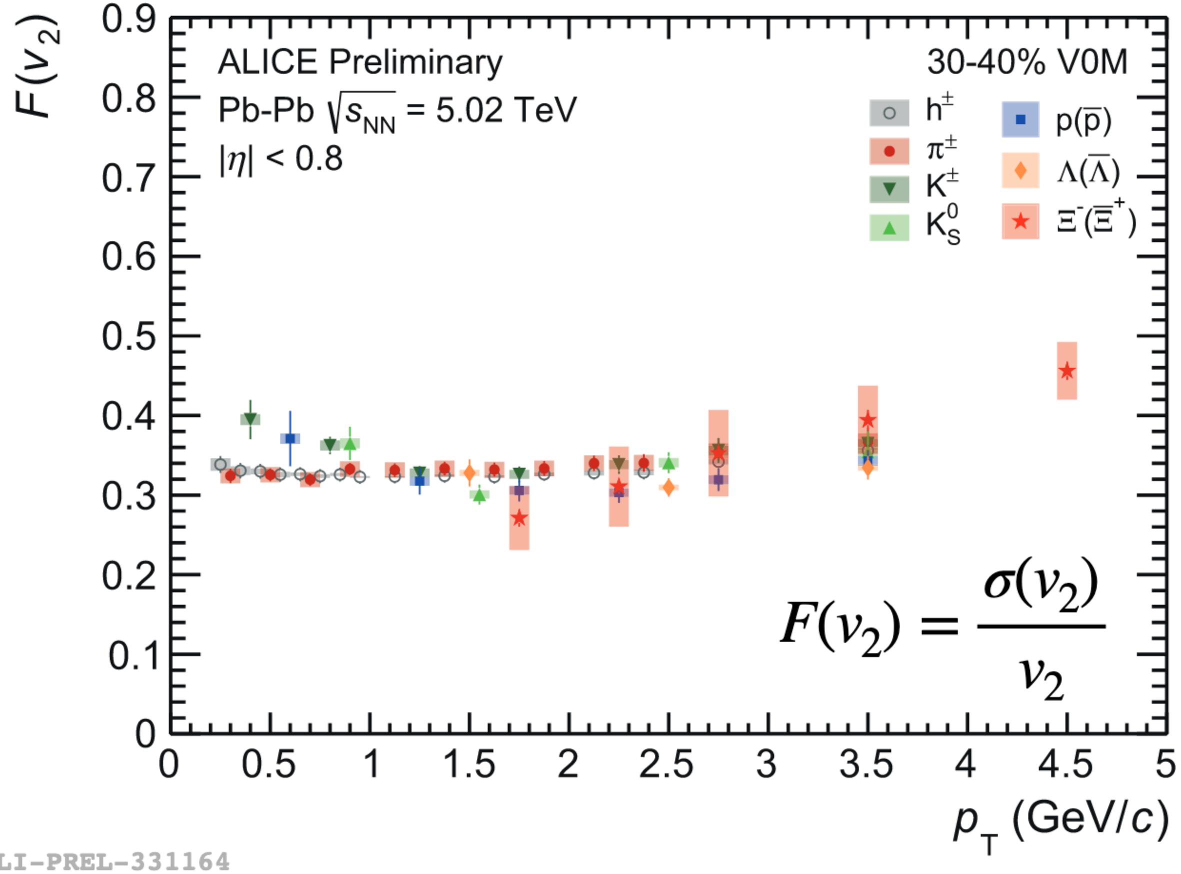




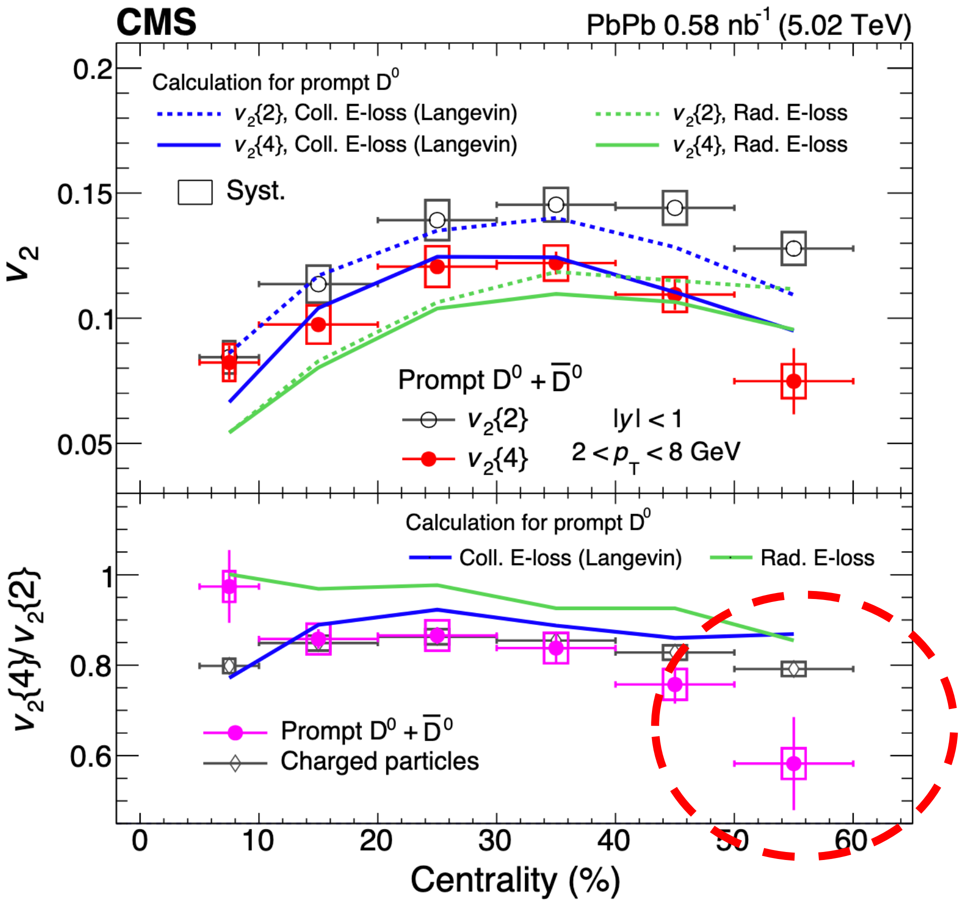
Flow Fluctuation of PID in Pb–Pb

- Relative fluctuation $F(v_2)$ does not depend on p_T and particle species, while v_2 has mass dependence.
- Difference between charged particle and prompt D in peripheral Pb–Pb
  - Hint of fluctuation on energy loss

V. Vislavicius for ALICE



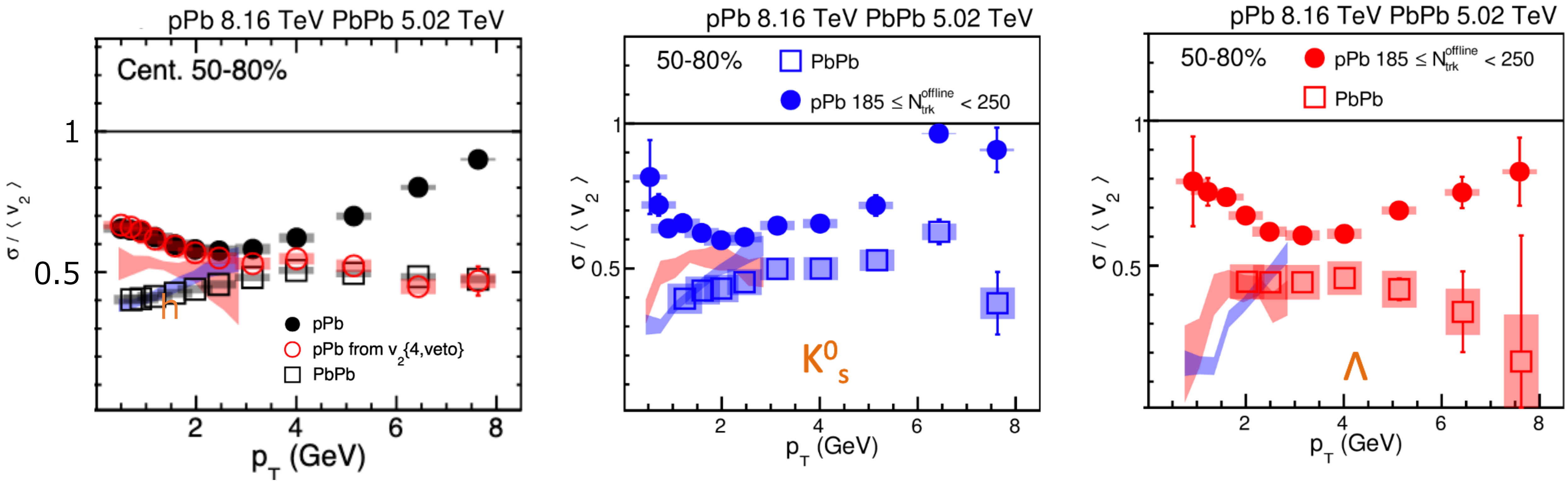
arXiv:2112.12236



Flow Fluctuation of PID in p–Pb

- $v_2\{4\}$ with veto jet method can more suppress non-flow
- The fluctuation in p–Pb is comparable with Pb–Pb at high $p_{T,}$ while the fluctuation in p–Pb is greater than Pb–Pb at low p_T.
- No dependence on particle species in p–Pb collisions as well as Pb–Pb

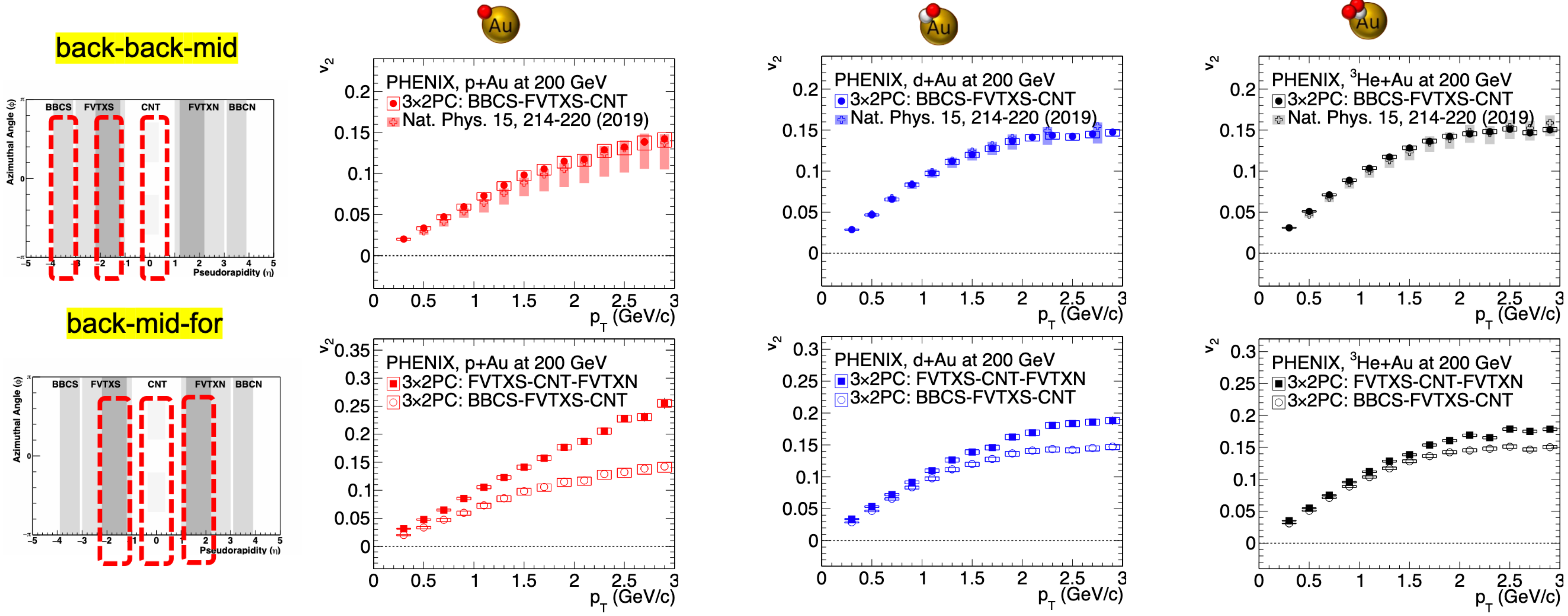
Q. Wang for CMS



Flow in small system at RHIC

- v_n by two-particle correlation method supports the result by event plane method in case of the same setup.
  - Kinematic selection has sizable effects for v_n due to non-flow contribution

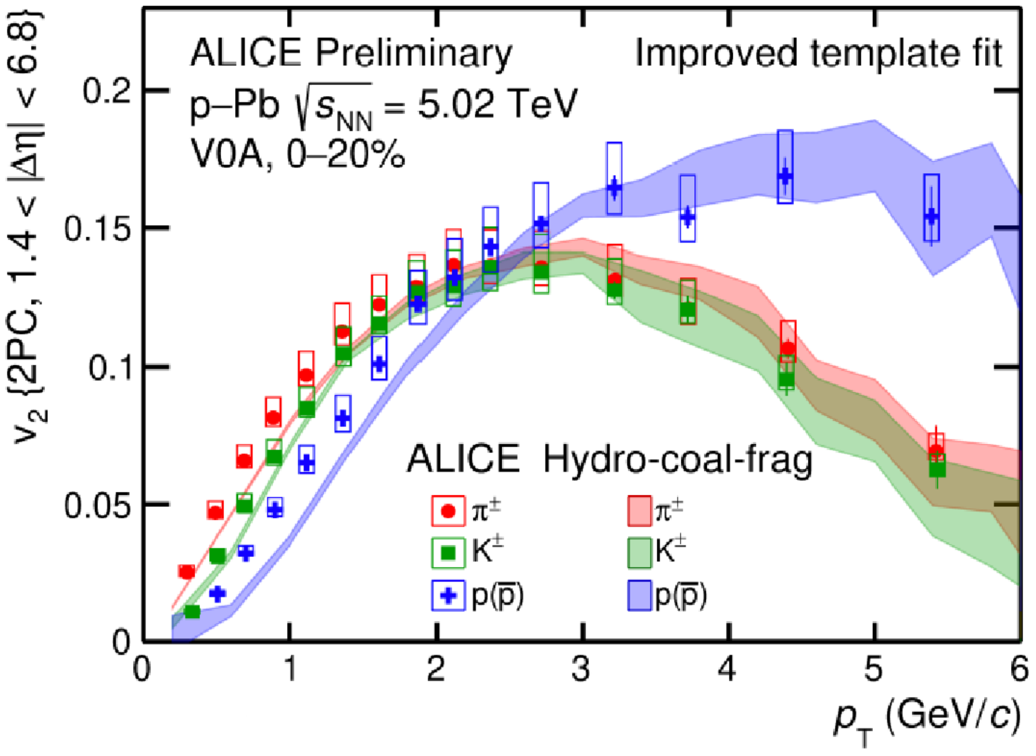
T. Todoroki for PHENIX

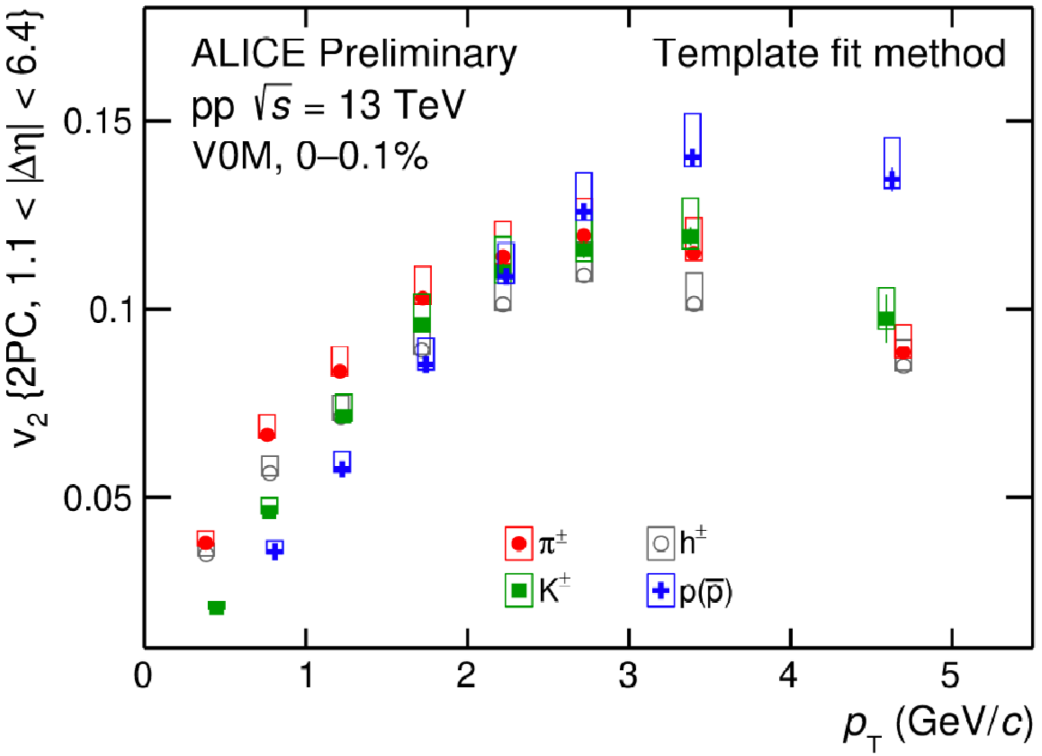


PID flow in small system

- Baryon/meson splitting and mass ordering are observed both in p–Pb and pp collisions as well as Pb–Pb.
- Comprehensive model[1] (Hydro+coalescence+jet fragmentation) can describes the data up to 6 GeV/c in p–Pb collisions.

Z. Moravcova´ for ALICE



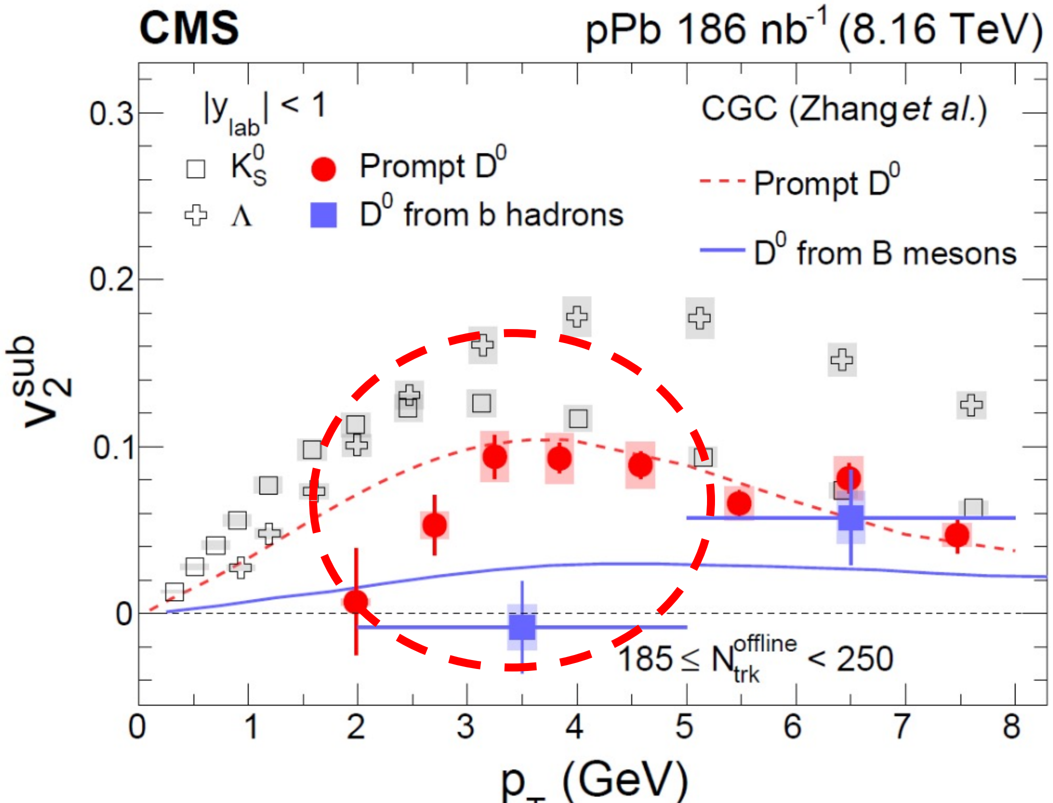


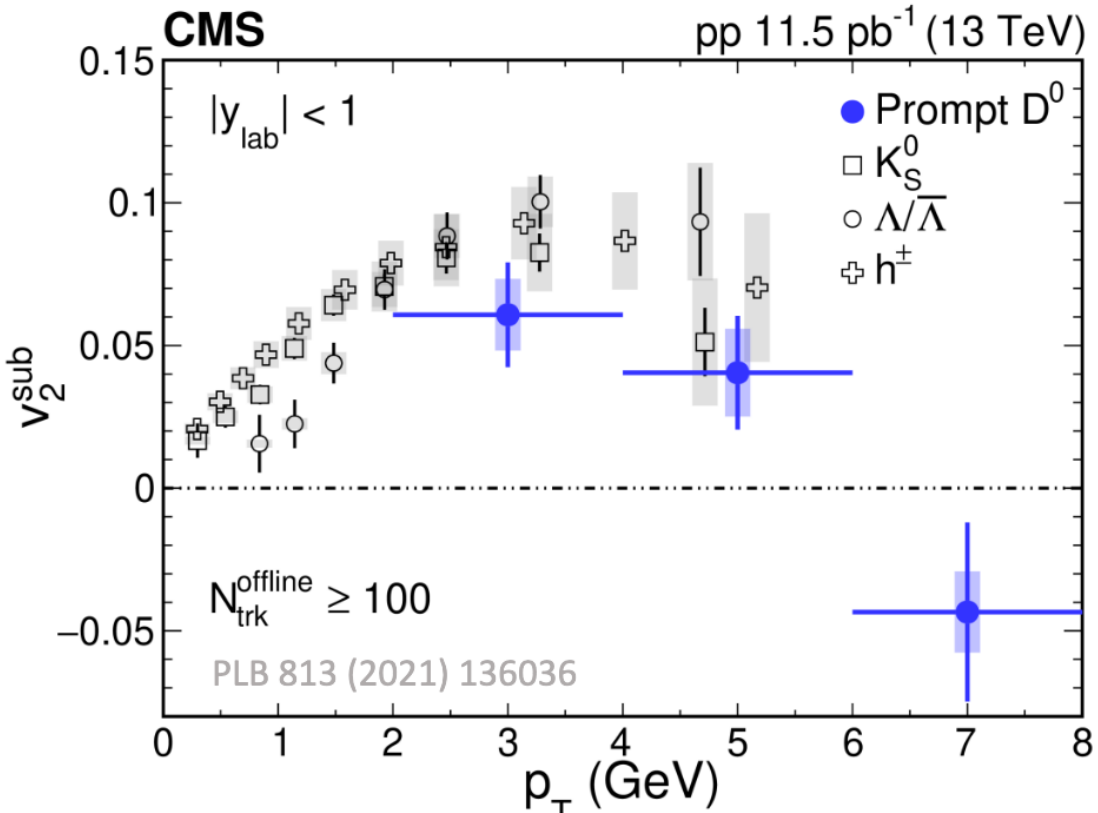
[1]W. Zhao et al., PRL, 125, 072301 (2020)

HF v_2 in small system

- Flavor hierarchy between charm and bottom is observed at $2<p_T<5$ GeV/c in p–Pb collisions
- D^0 v_2 in pp is comparable with p–Pb
  - On the other hand, Zero J/ψ v_2 in pp

Y. Zhang for CMS

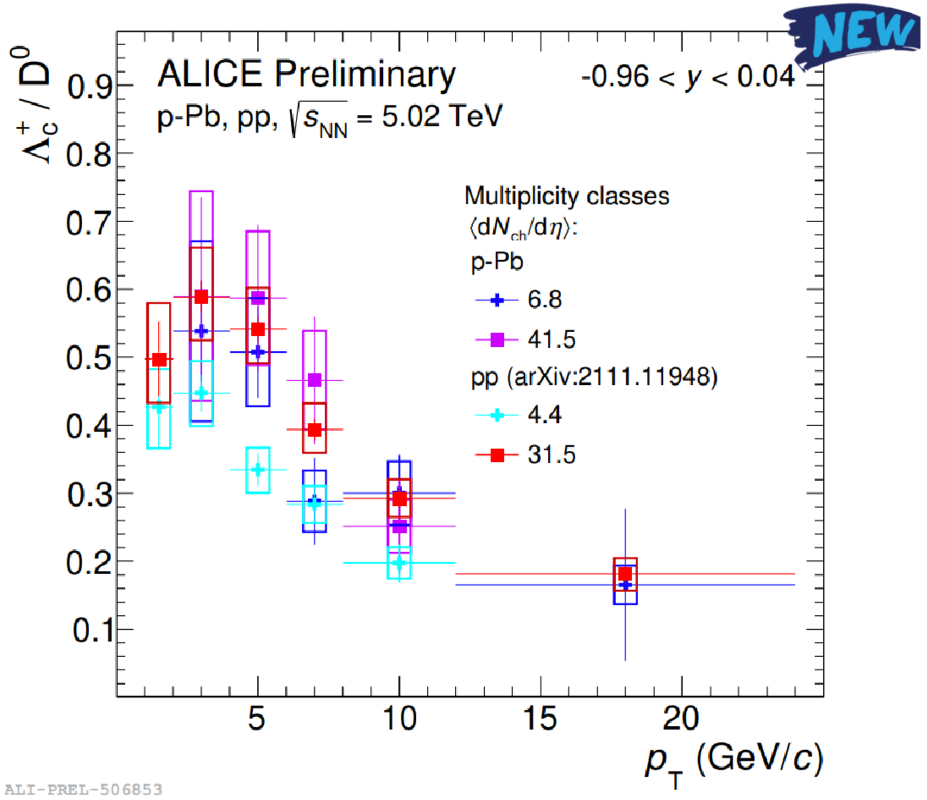


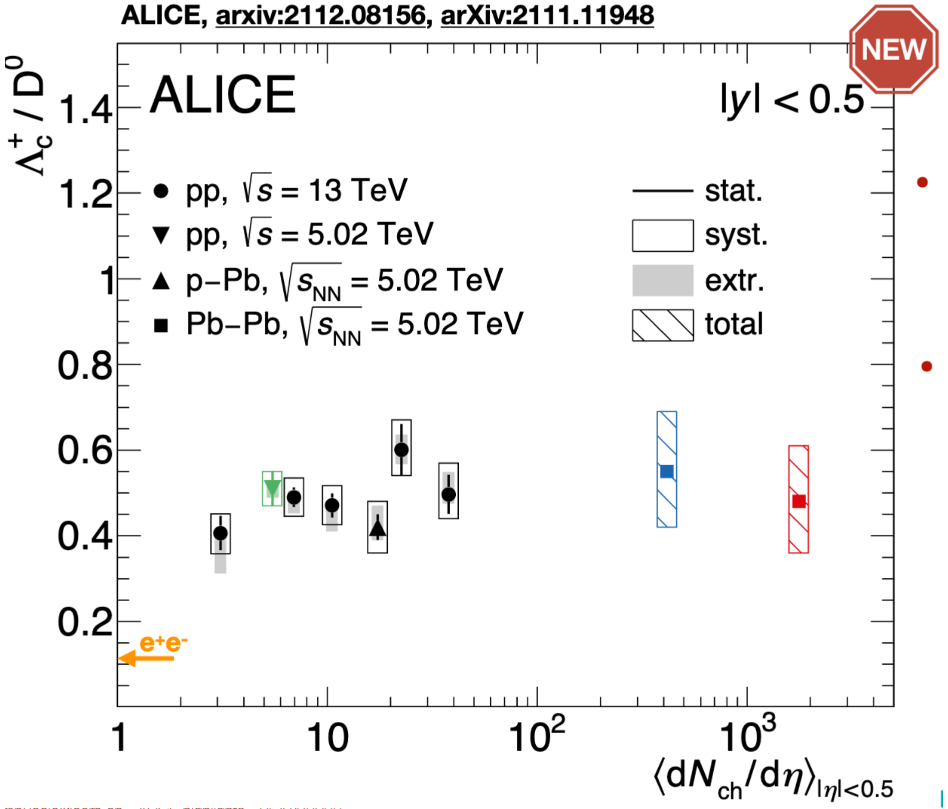


Charm baryon enhancement

- Significant baryon enhancement with respected to ee and ep in pp and p–Pb collisions
- Flat trend with multiplicity
  - Indication of same mechanism in all collision systems?
    - Charm recombination and radial flow?

L. Stritto for ALICE

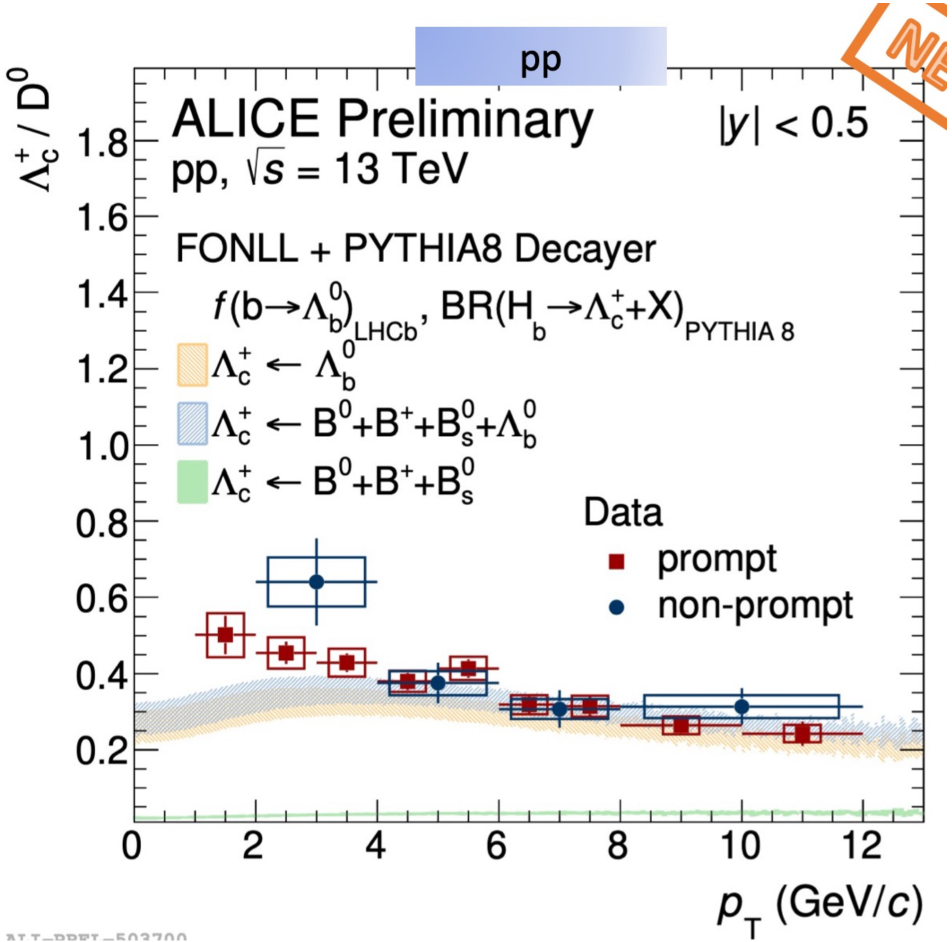




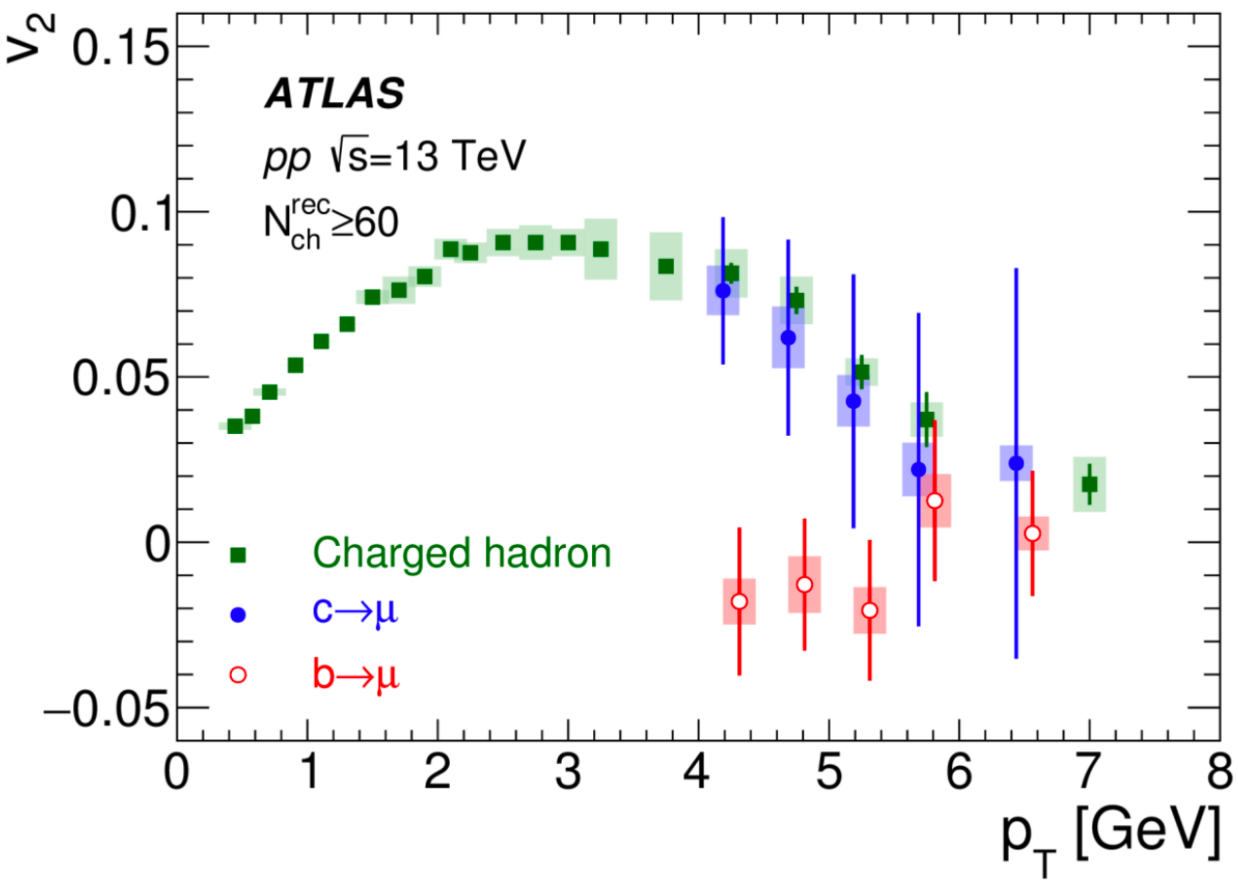
Non-prompt Λ_c/D enhancement

- Similar enhancement both in prompt and non-prompt Λ_c/D.
- Direct measurements of Λ_b/B in Run3 give more insight into the collectivity of beauty in a small system.

S. Perrin for ALICE



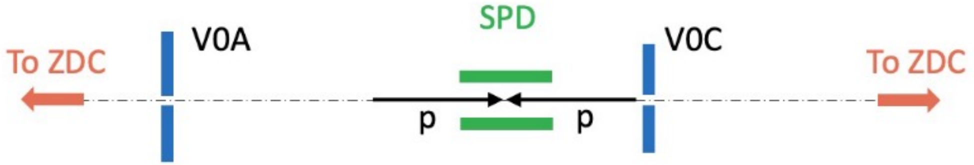
ATLAS, PRL, 124 (2020) 082301

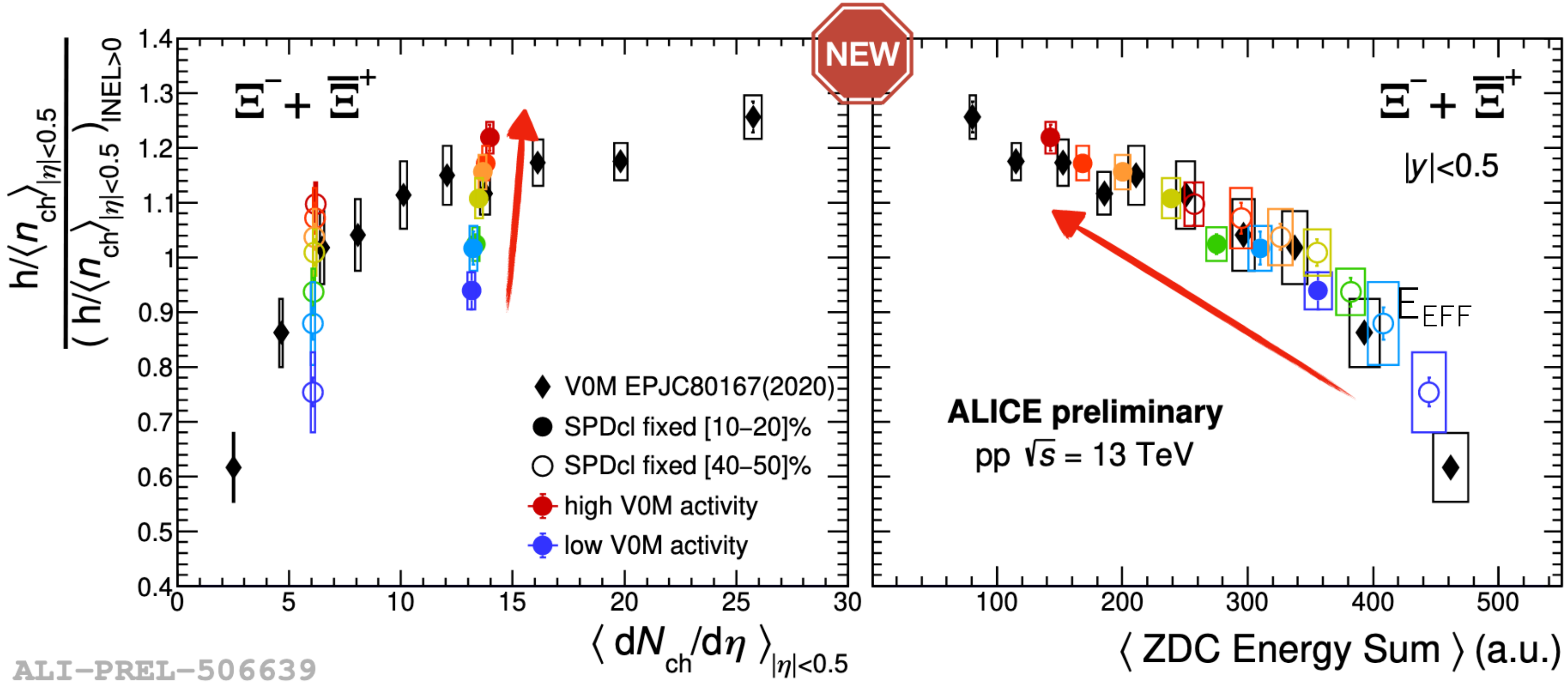


Strangeness enhancement

- Fix SPD multiplicity at mid-rapidity + select multiplicity in V0A+V0C
    - Clear Effective energy dependence is visible with Ξ and Ω
- Early-stage plays an important role in strangeness enhancement

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



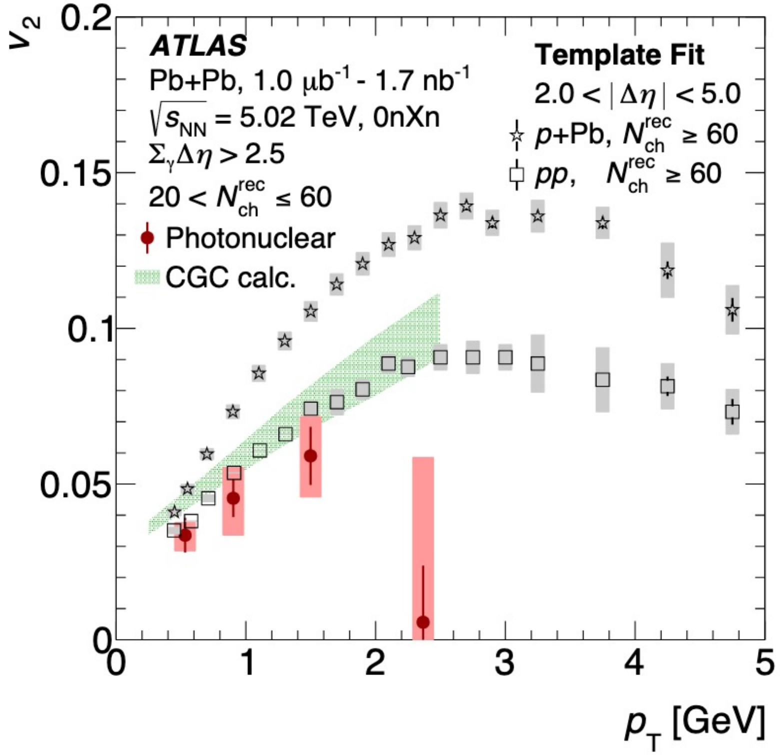


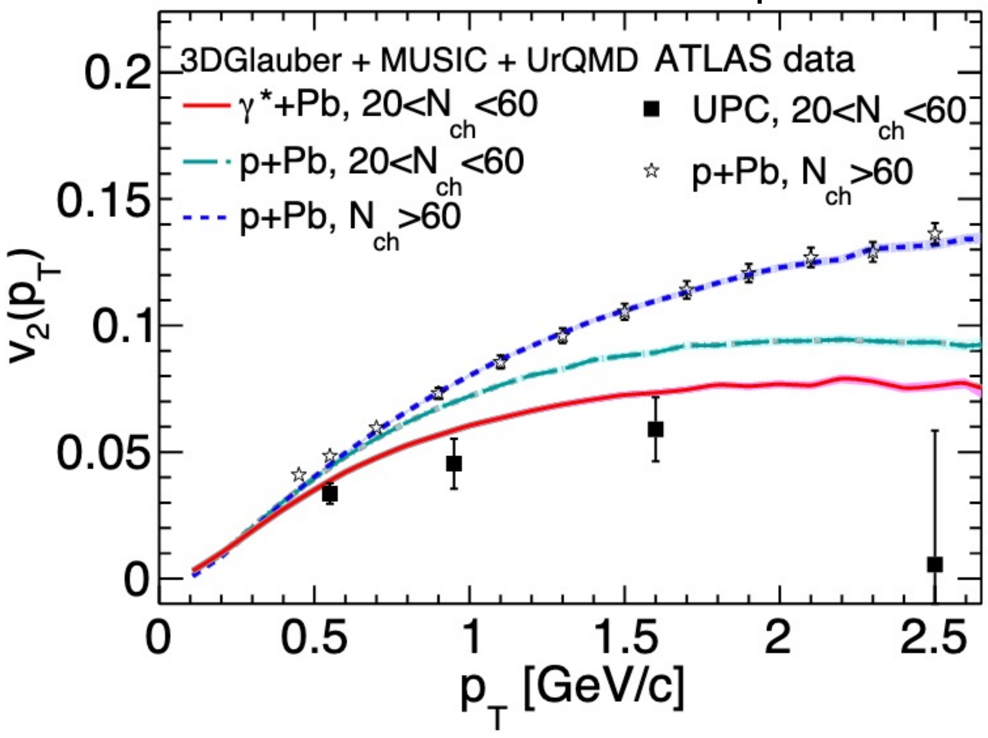
C. Martin for ALICE

γ-Pb

- In UPC Pb–Pb collisions, photons coherently emitted from one Pb nuclei interact with the other Pb nuclei
- CGC calculation describes the data
  - Benchmark for EIC?
- Hydro model describes the data.
  - The model claims larger longitudinal decorrelation and large rapidity boost in γ–Pb

D. Perepelitsa for ATLAS





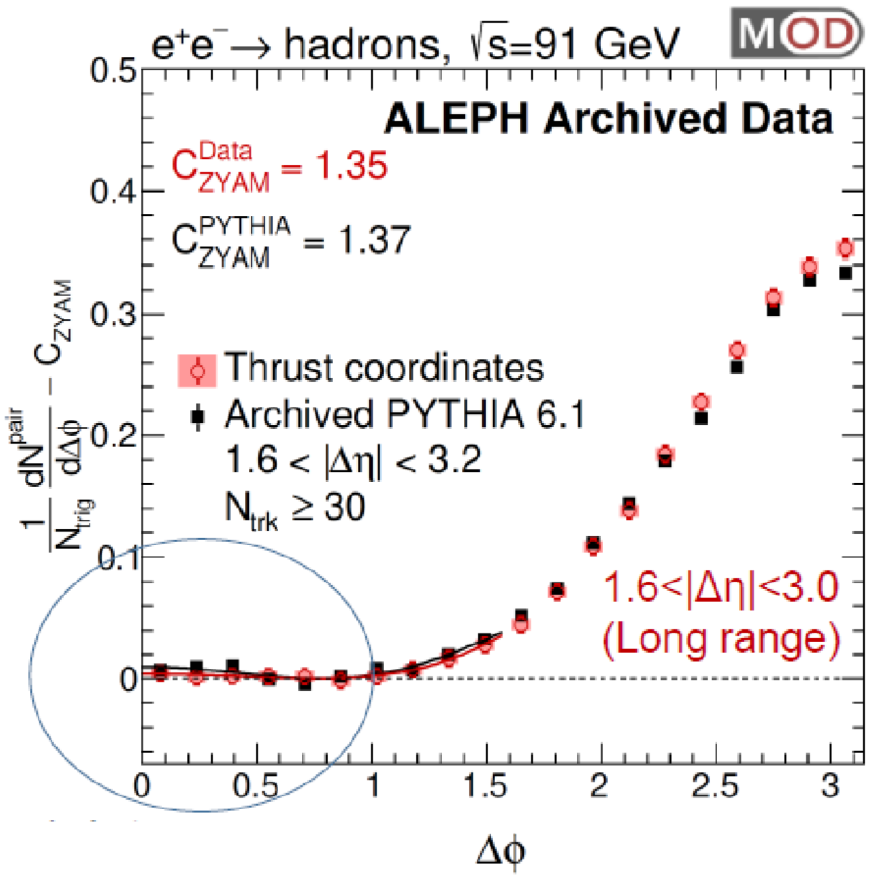
Outlook:

- Particle production
- γ–p
- γ–Au

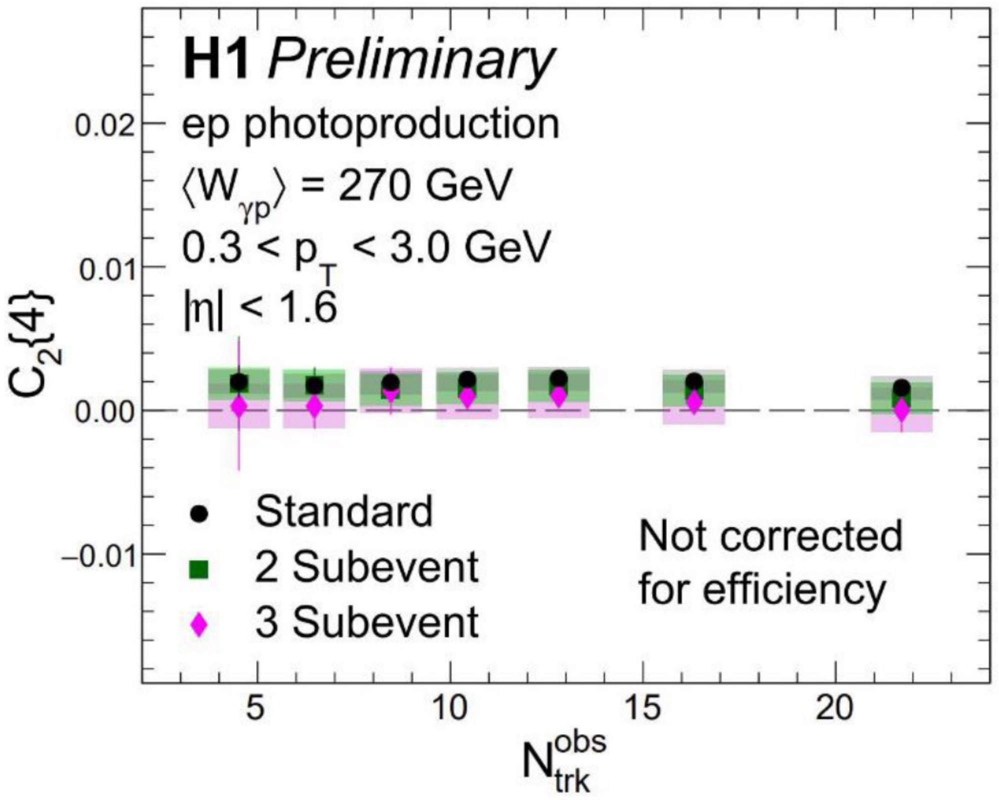
ee and ep collisions

- No collectivity is observed in ee and ep collisions.
- Does non-flow subtraction give non-zero v_2 as well as γ–A??
  - What might that be?

Y. Chen for ALEPH



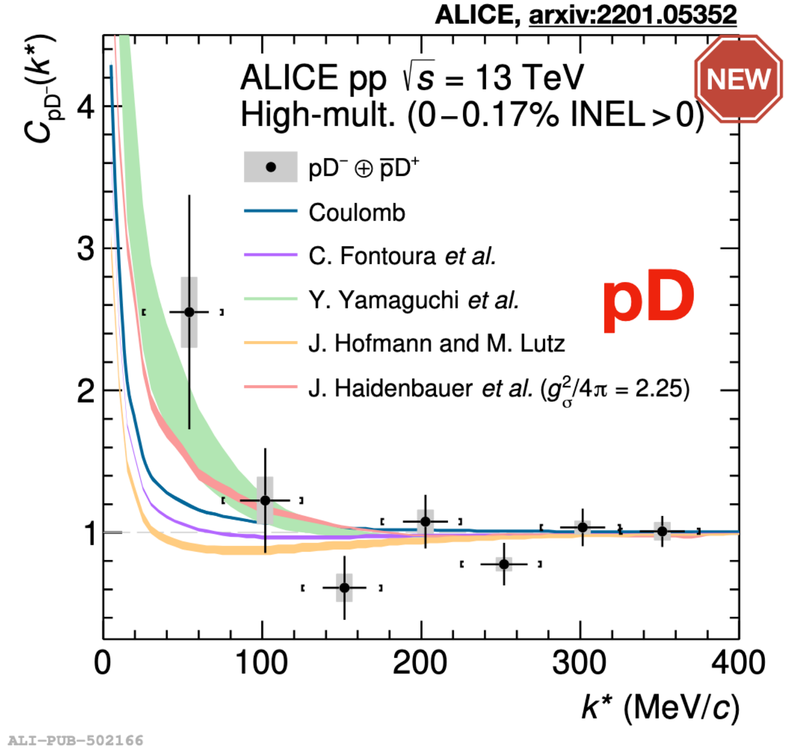
C .Sun for H1

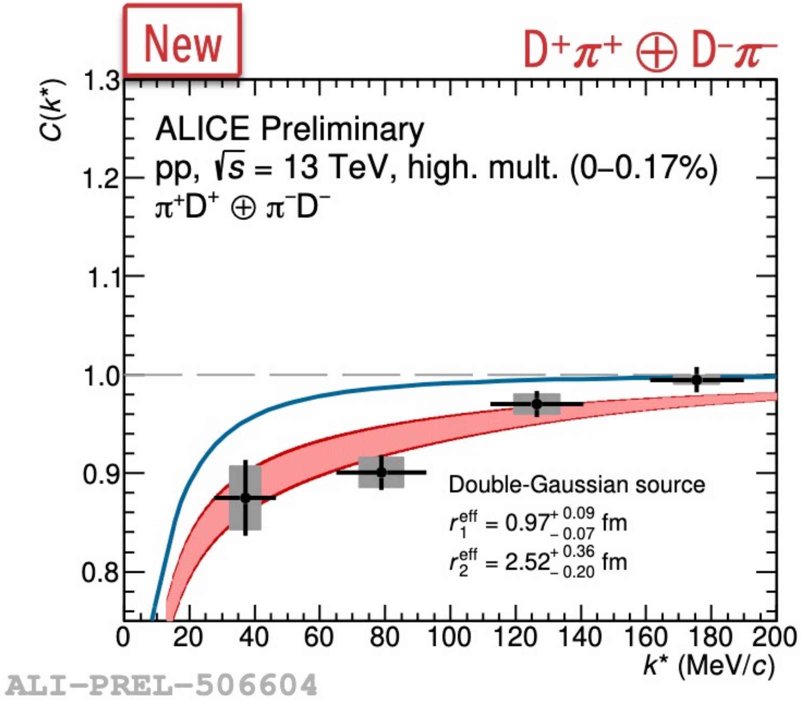


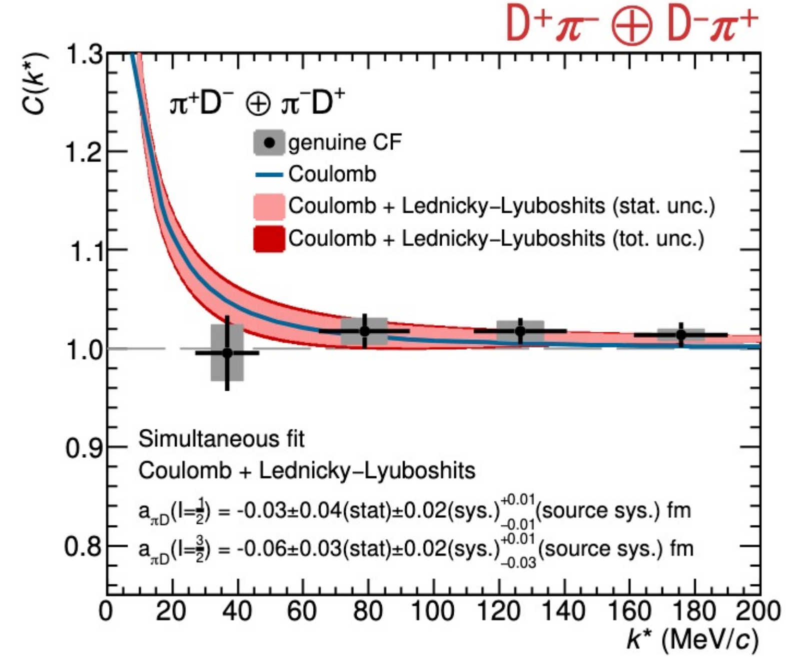
Charm molecule

- First measurement of πD and pD.
  - The data is compatible with Coulomb interaction and with shallow attractive strong interaction
  - The values indicate a small scattering of D mesons in the hadronic phase in heavy-ion collisions

F. Grosa for ALICE



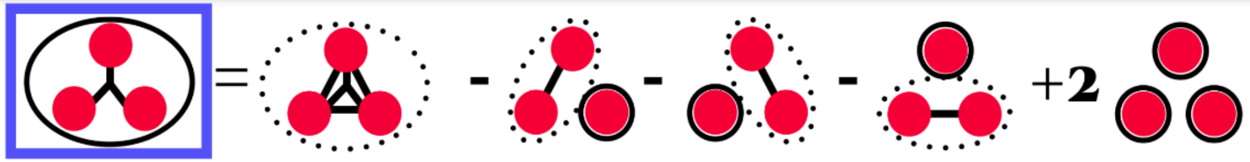




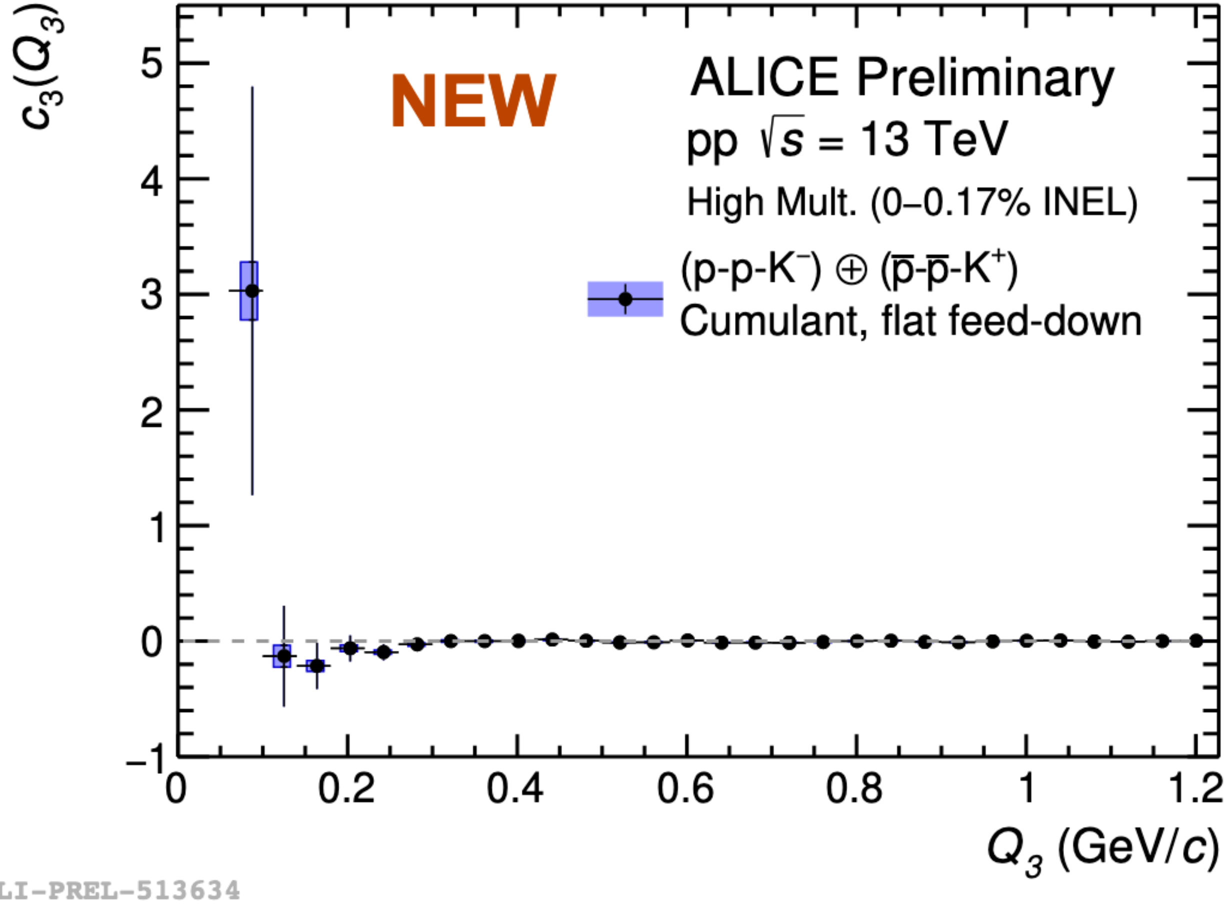
Three body hadron interaction

- Kaonic proton matter (KPM) is predicted by Y. Akaishi and Y. Yamazaki (PRC65 (2002) 044005)
- The result is consistent with zero within uncertainties
    - Genuine three-body effect is not significant in p-p-K$^-$.

  ➡ kaonic bound state formation driven by two-body forces.



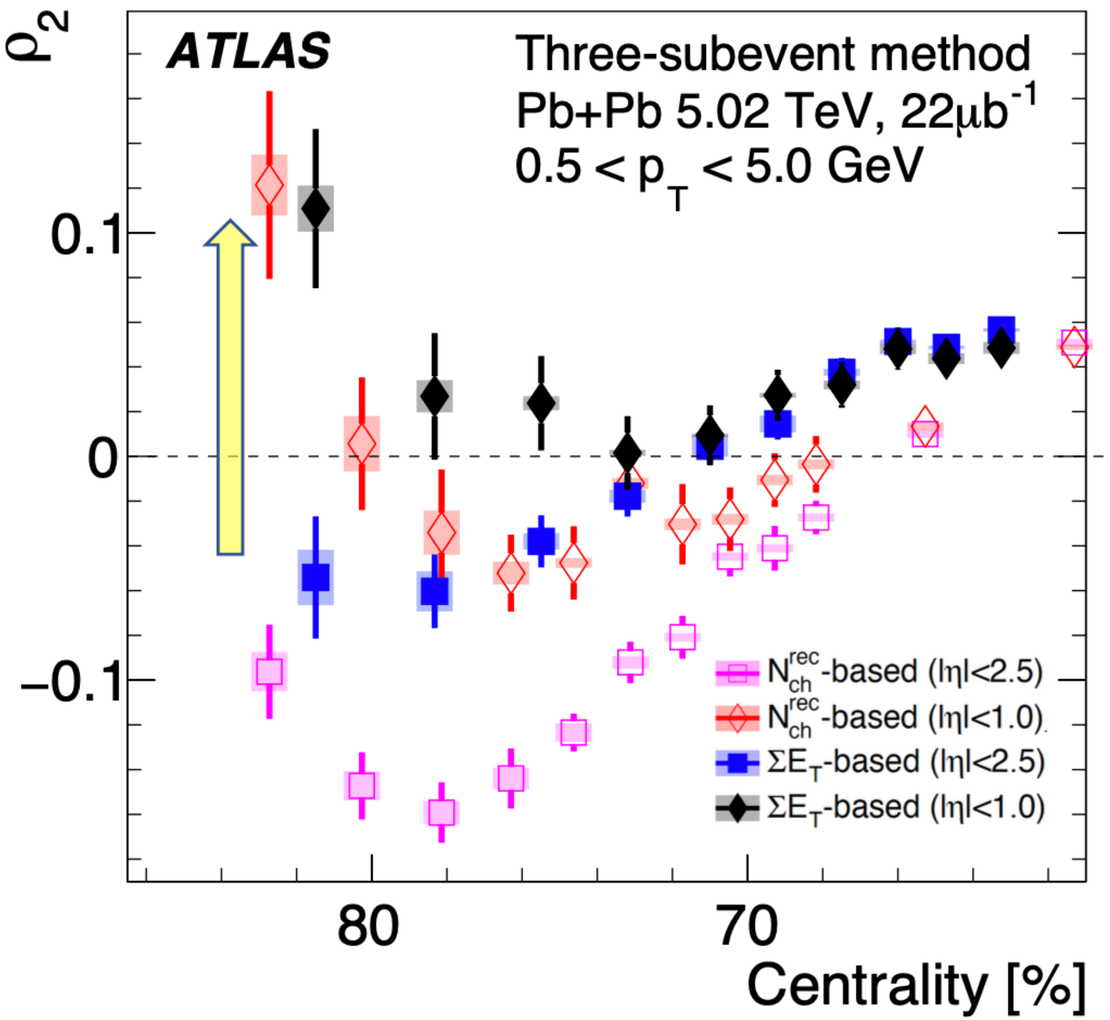
R. Del Grande for ALICE



Backup

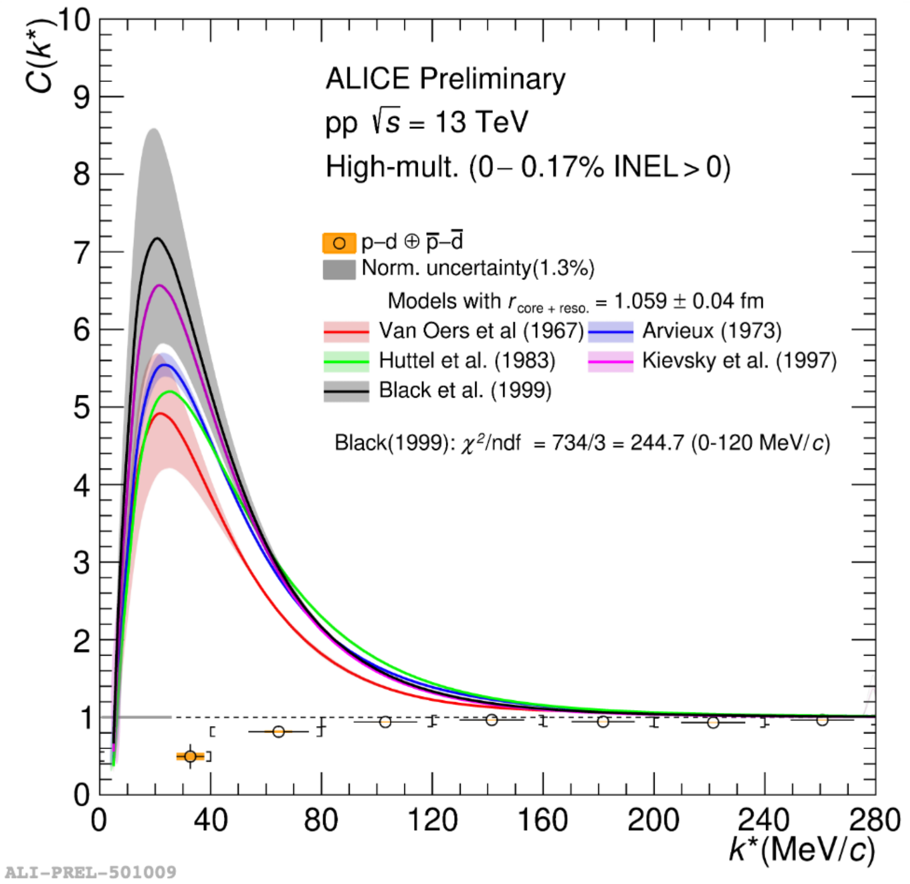
v_2-p_T correlation vs centrality determination

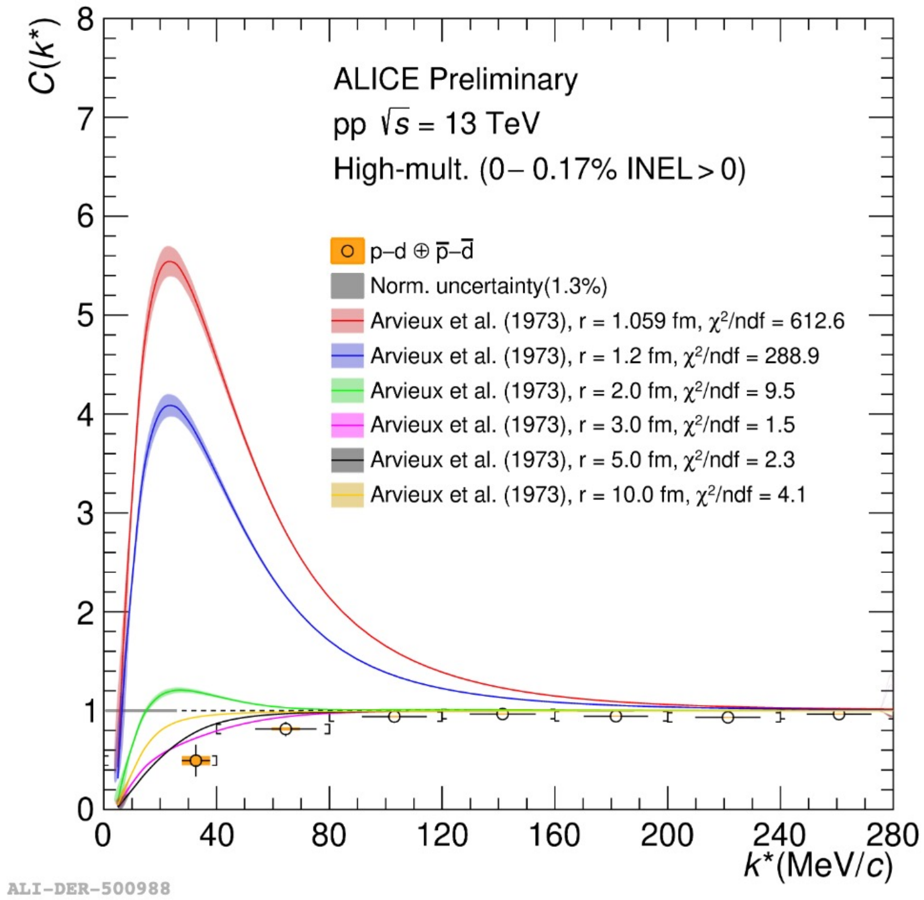
- At low multiplicity, large difference between different centrality determination in Pb−Pb collisions.



Proton-Deuteron correlations

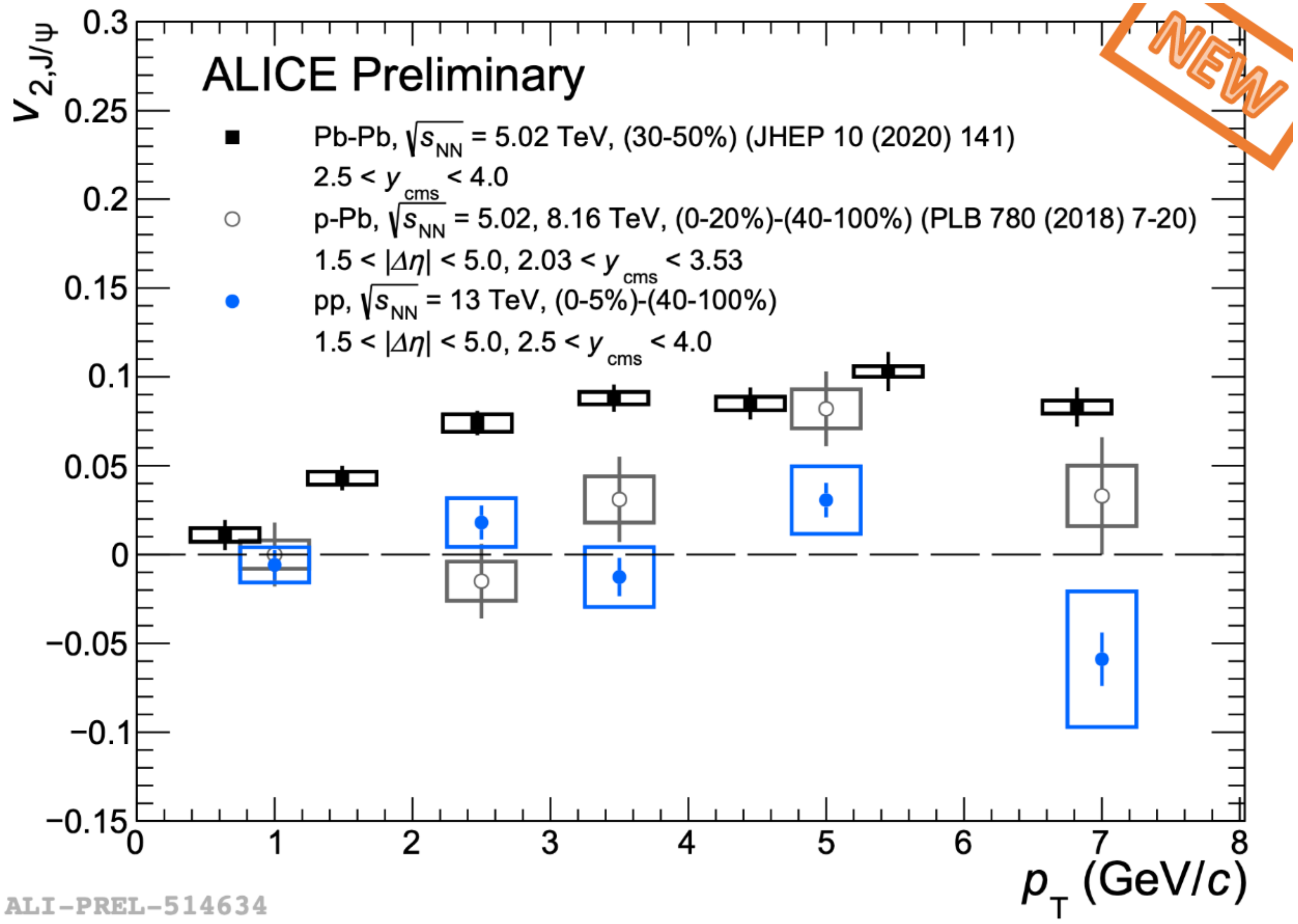
- The correlation gives an insight into the Formation mechanisms of light nuclei in hadron-hadron collisions.
- The LL prediction for small source radii described the data, while the modle with large source radii is comparable. ➡Insights into the production time of nuclei?

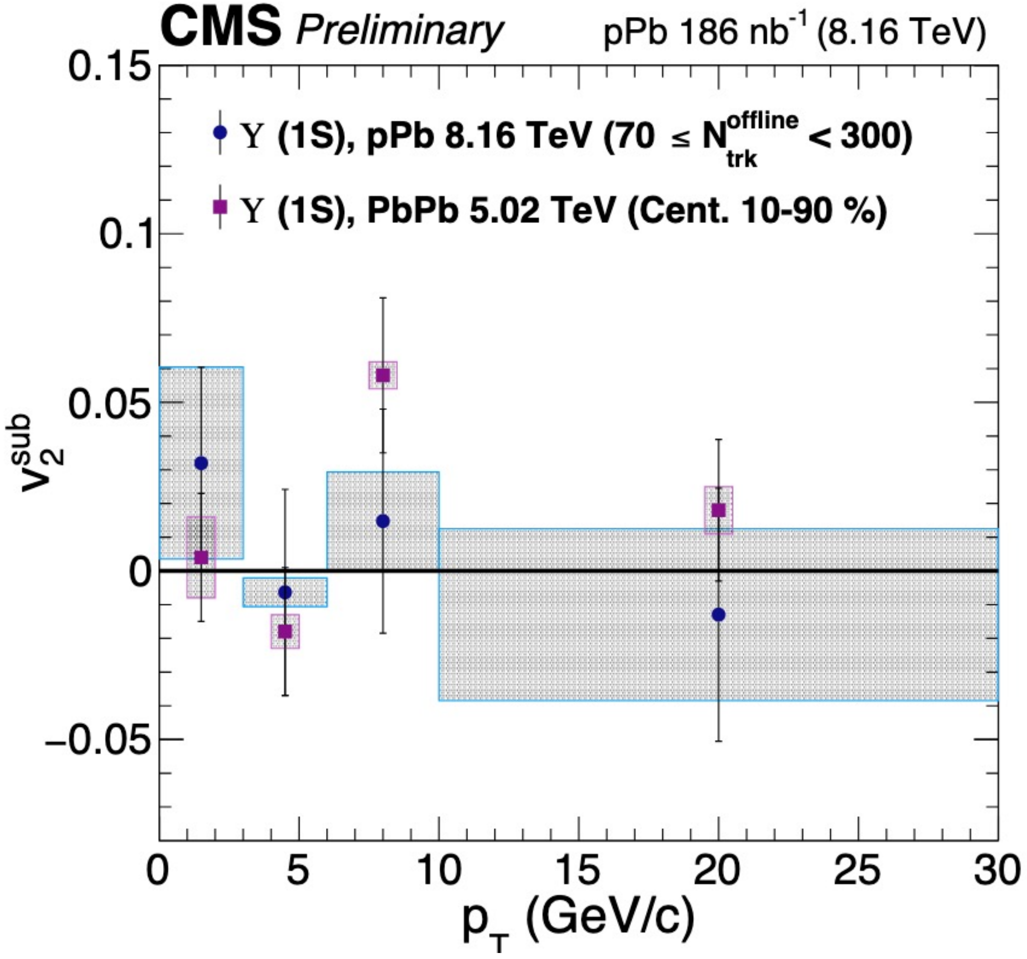




Charmonium v2 in pp, p–Pb, and Pb–Pb

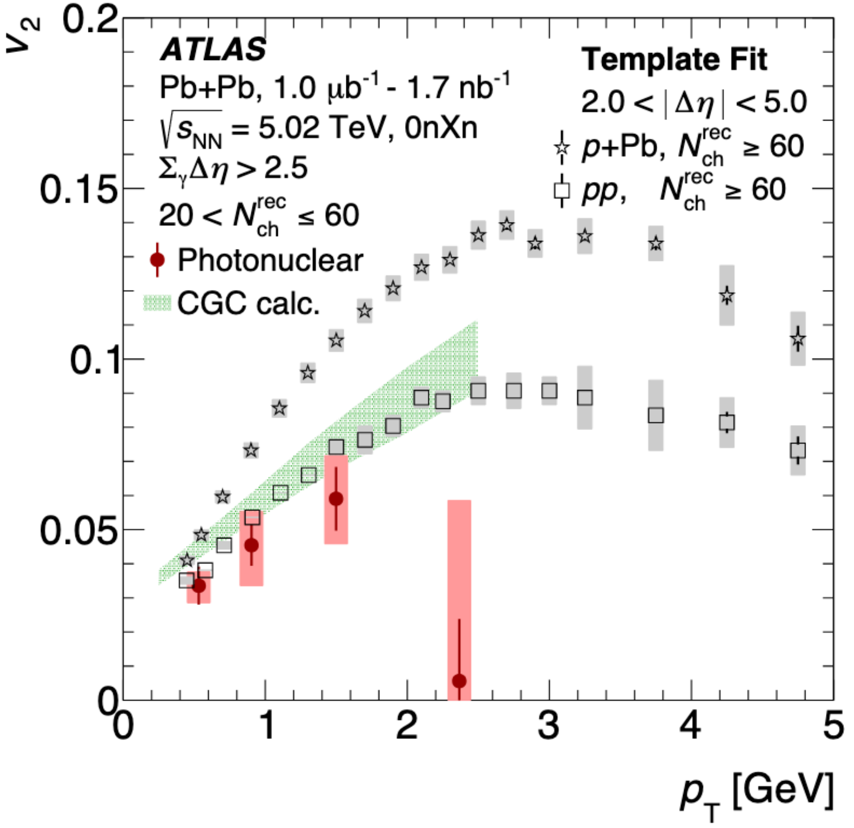
- J/psi v2 in pp is consistent with zero
- Υ(1S) v2 in Pb–Pb and p–Pb is consistent with zero

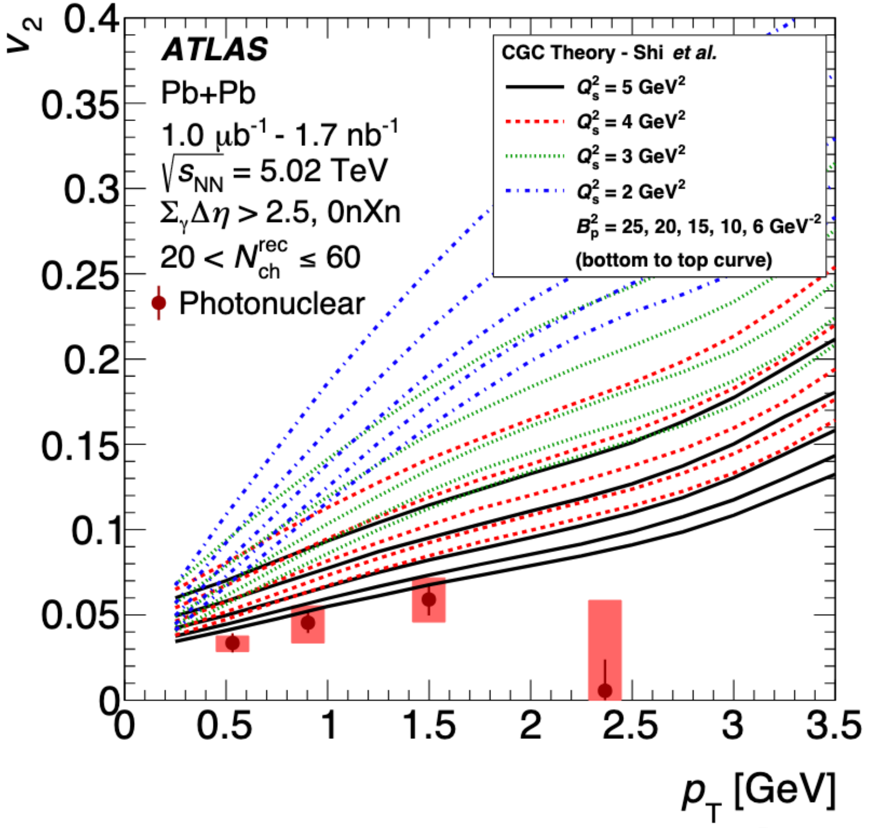




γ-Pb

- In UPC Pb–Pb collisions, photons coherently emitted from one Pb interact with the other Pb
- Non-zero v_2 in γ–Pb by non-flow subtraction
    - Comparable with pp within large uncertainties
    - Smaller than p–Pb due to larger longitudinal decorrelation and larger rapidity boost
- Good probe to constrain initial state?

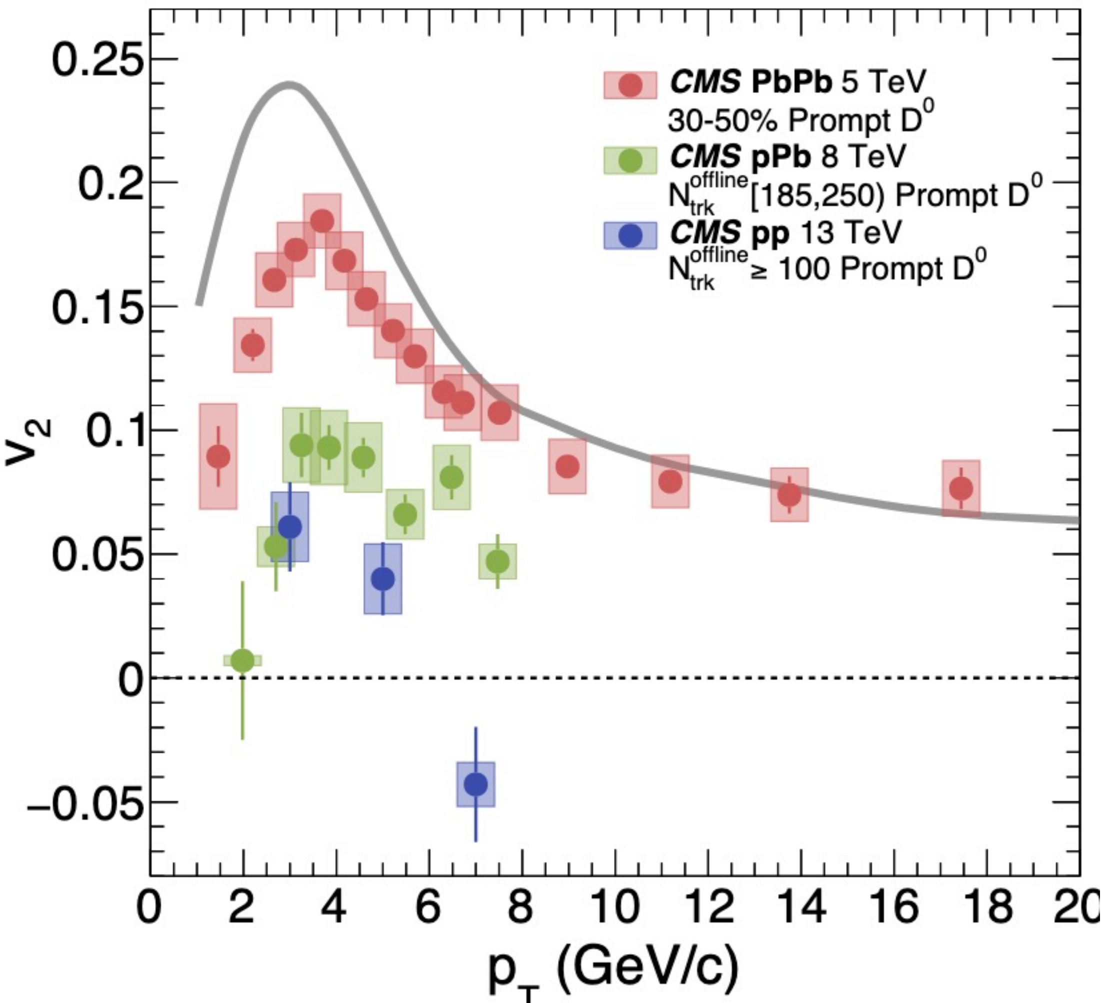


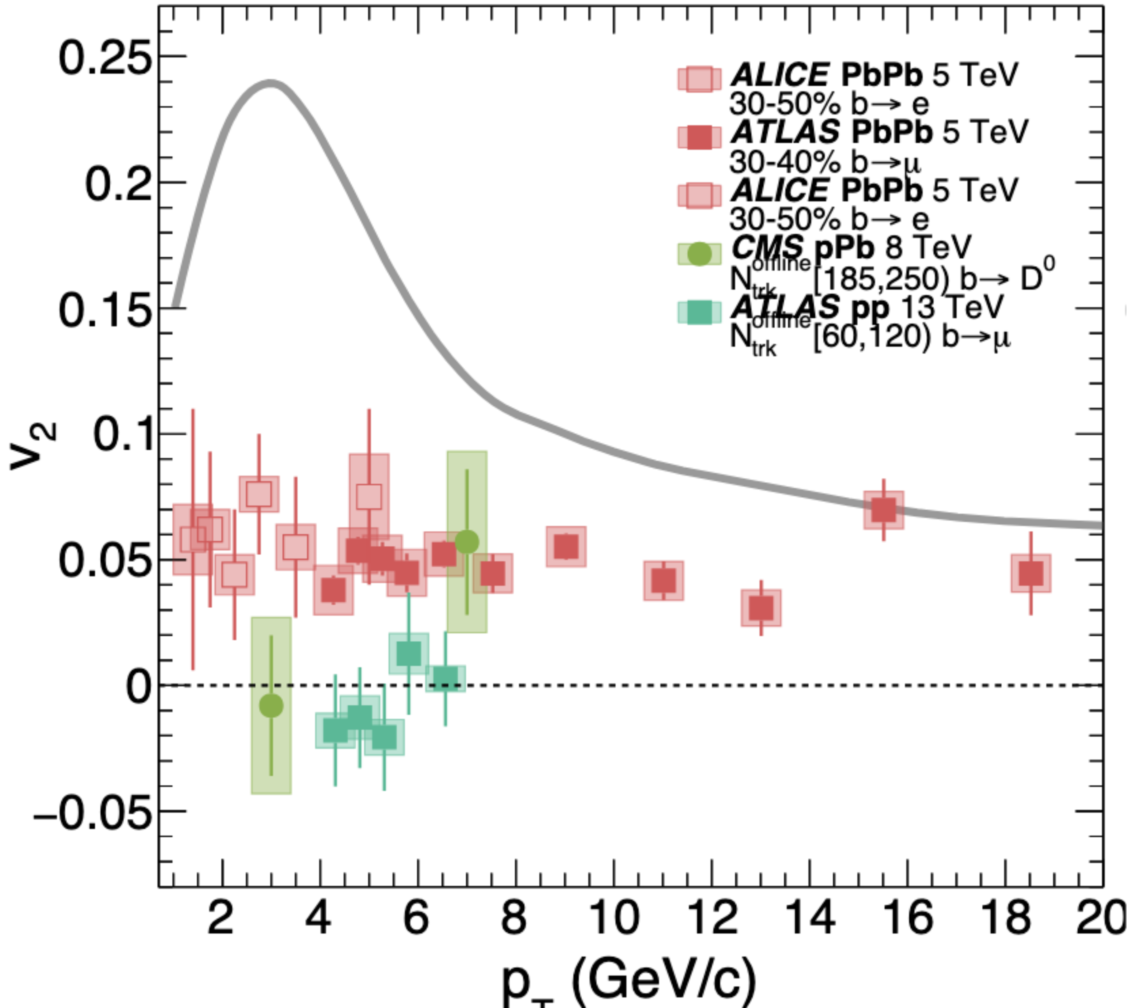


- Outlook:
    - Particle production
    - γ–p
    - γ–Au

HF v_2 in pp,p–Pb, and Pb–Pb

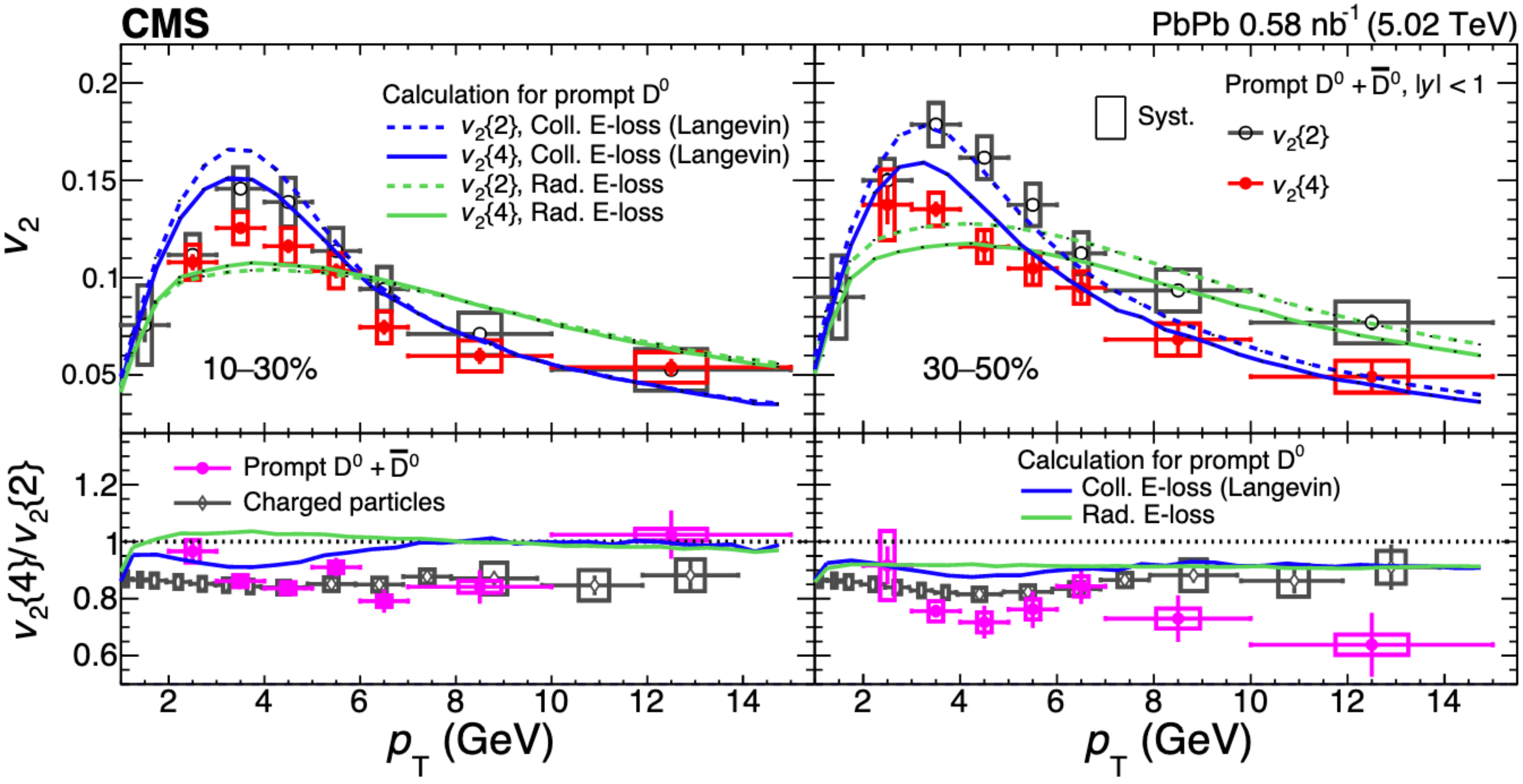
- Charm v2 is observed from pp to Pb–Pb.
- Non-zero beauty v_2 in Pb–Pb but not in pp and p–Pb





HF Flow Fluctuation vs p_T in Pb–Pb

- $v_2\{4\}/v_2\{2\}$ of Charged particle and D meson are comparable



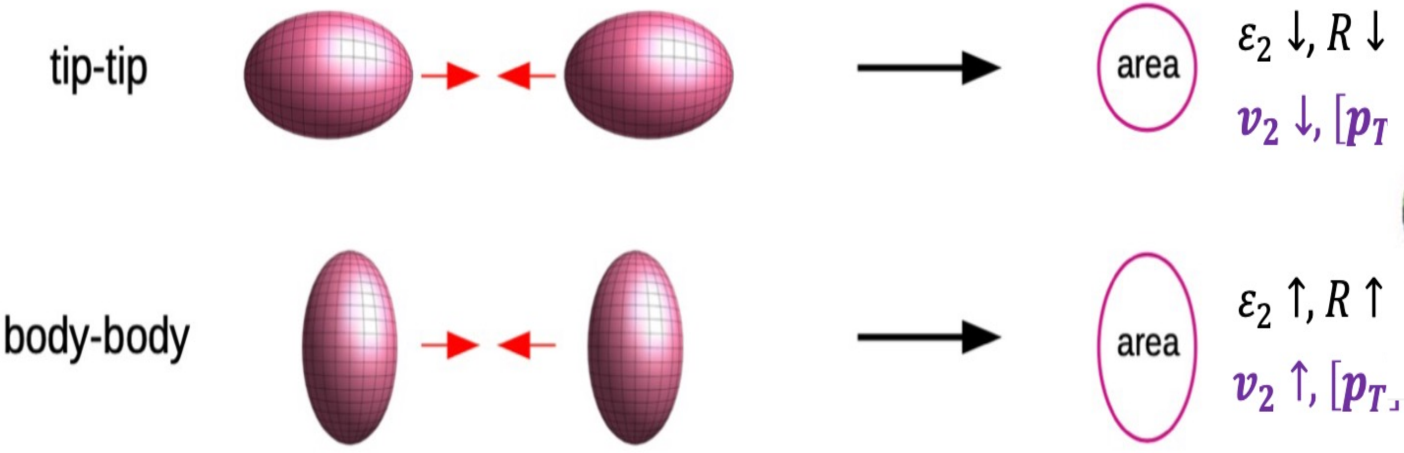
Deformed nuclei

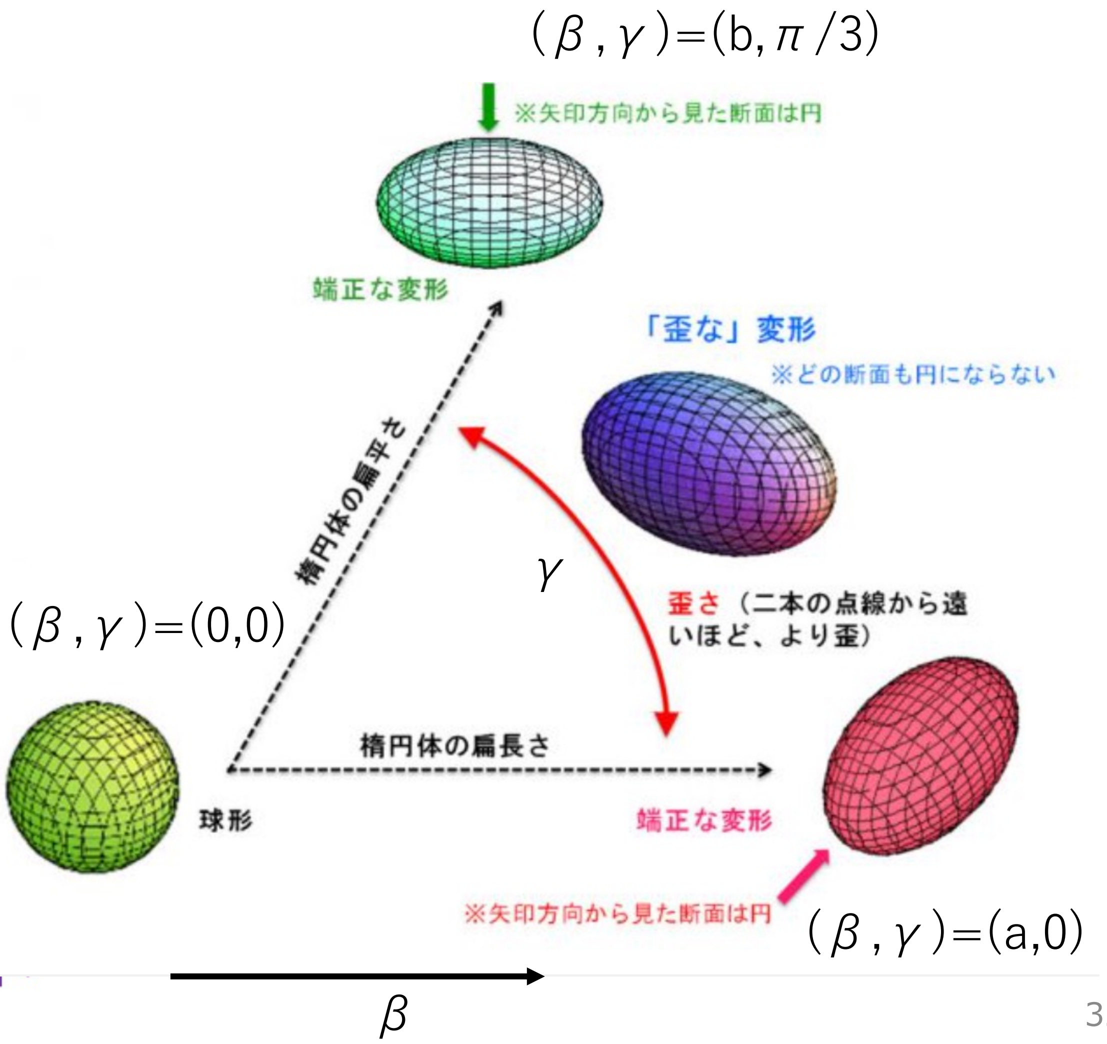
- Nuclear geometry parametrized by Woods-Saxon distribution

$$\rho(r,\theta,\phi) = \frac{\rho_0}{1+e^{[r-R(\theta,\phi)/a_0]}}$$

$$R(\theta,\phi) = R_0(1+\beta(cos\gamma Y_{20}(\theta,\phi) + sin\gamma Y_{22}(\theta,\phi)))$$

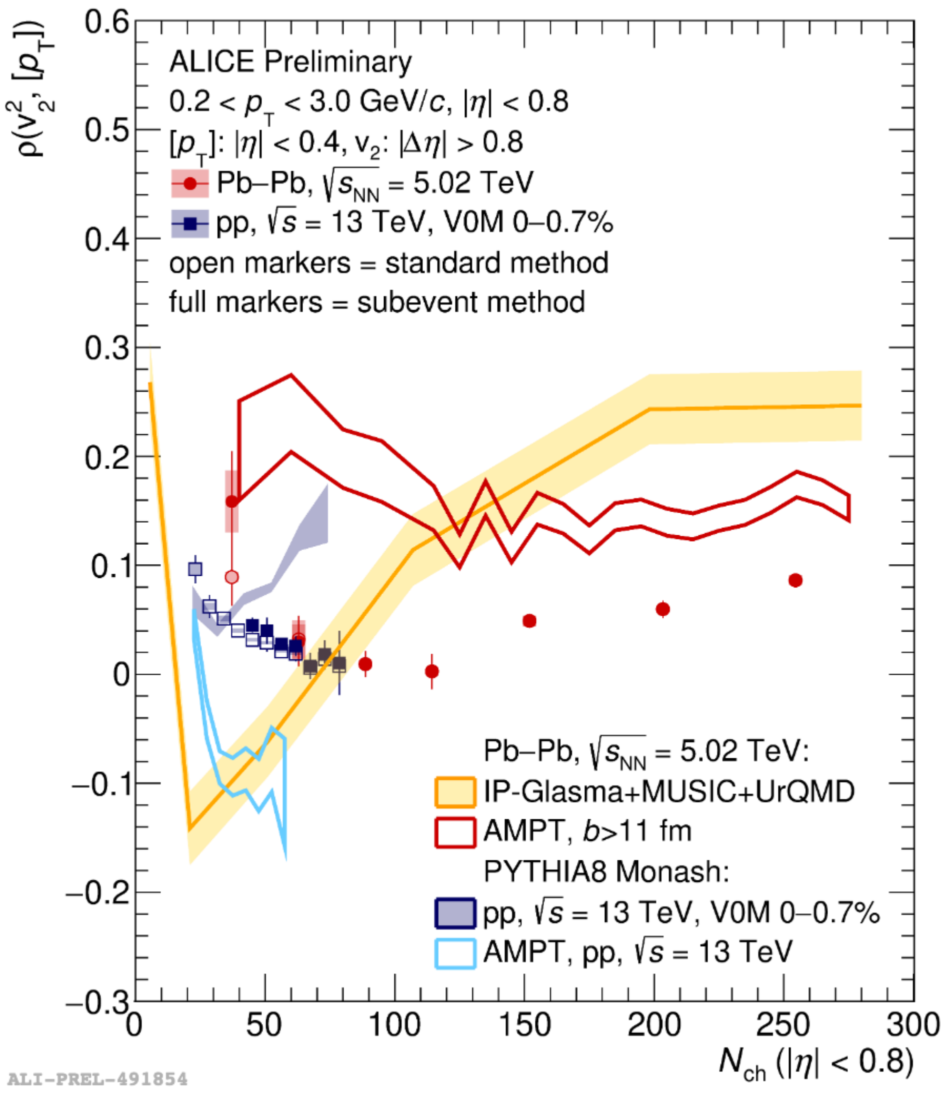
- v_2-$[p_T]$ correlation also sensitive to the shape of nuclei

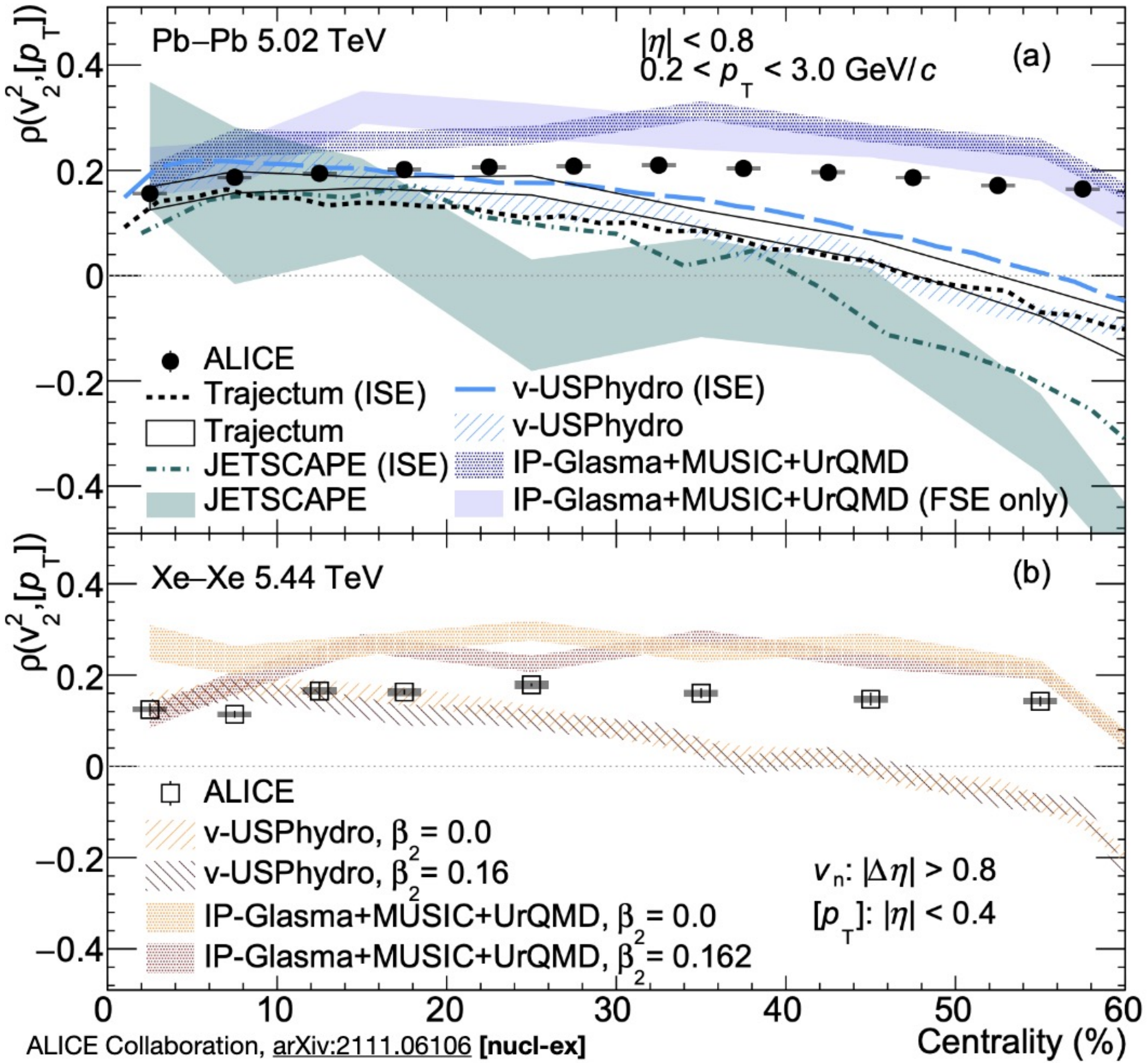




v_n-$[p_T]$ correlation by ALICE

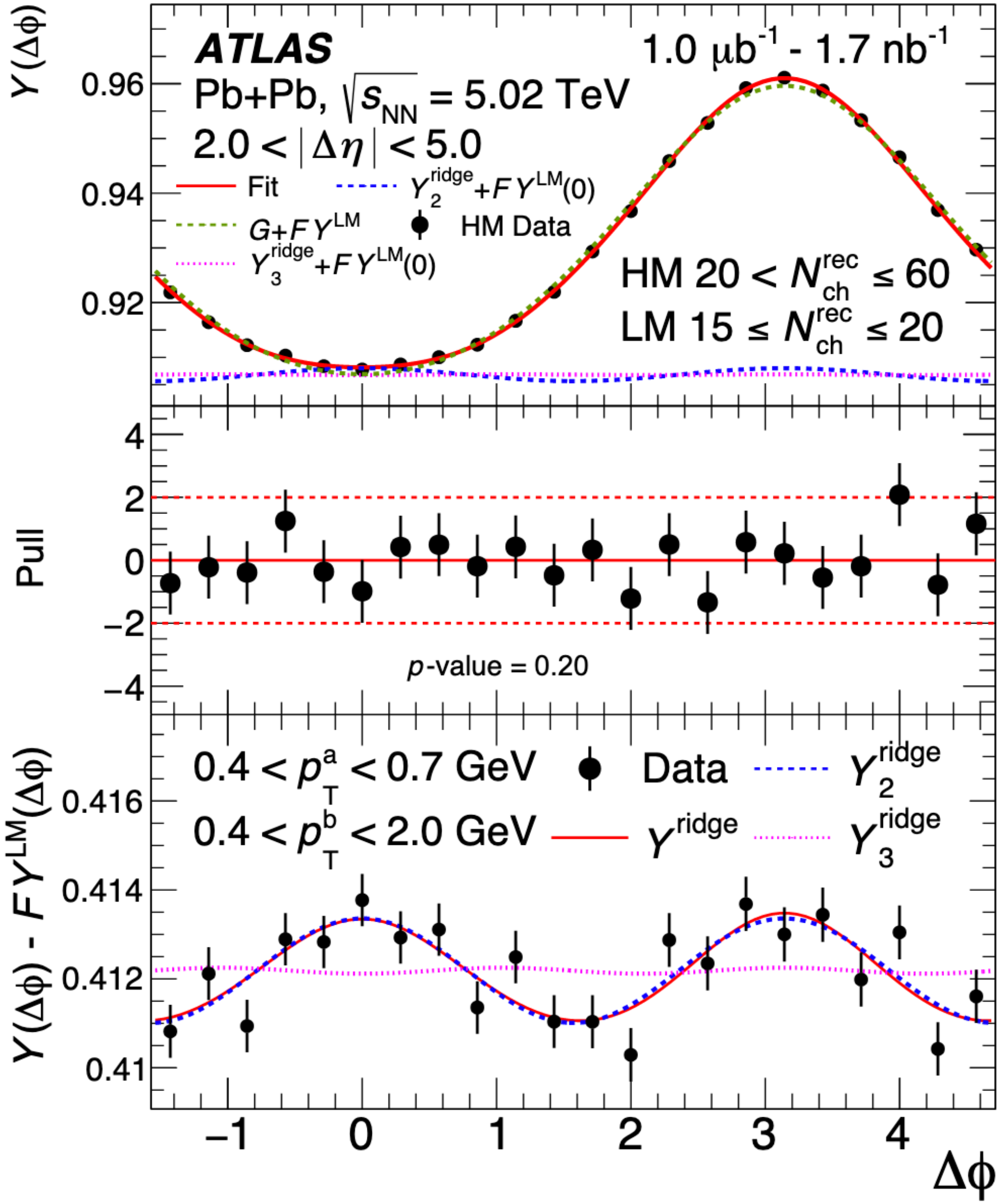
- No sign change is observed by ALICE





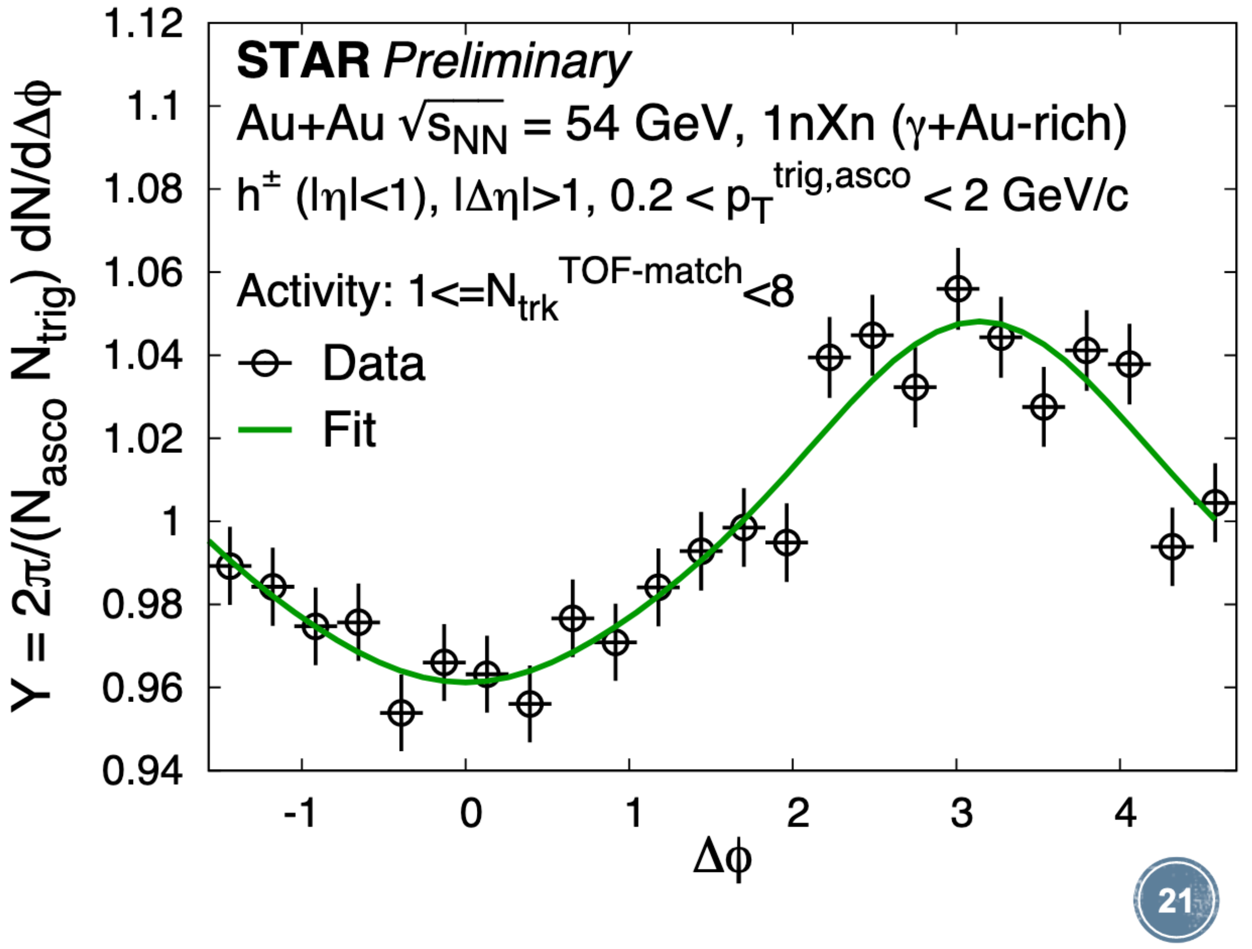
γ–Pb

- No significant near-side correlation
- After non-flow subtraction, double ridge is visible.



γ–Au

- No significant near-side ridge is visible
- non-flow flow subtraction is not applied.
- Improved measurements are available from 2023 by the forward upgrade.



Baryon-to-meson ratio

- Λc/D and Λ/K0s are comparable in pp an p–Pb collision