Soft Probes in Heavy Ion Collisions with CMS, ATLAS and ALICE

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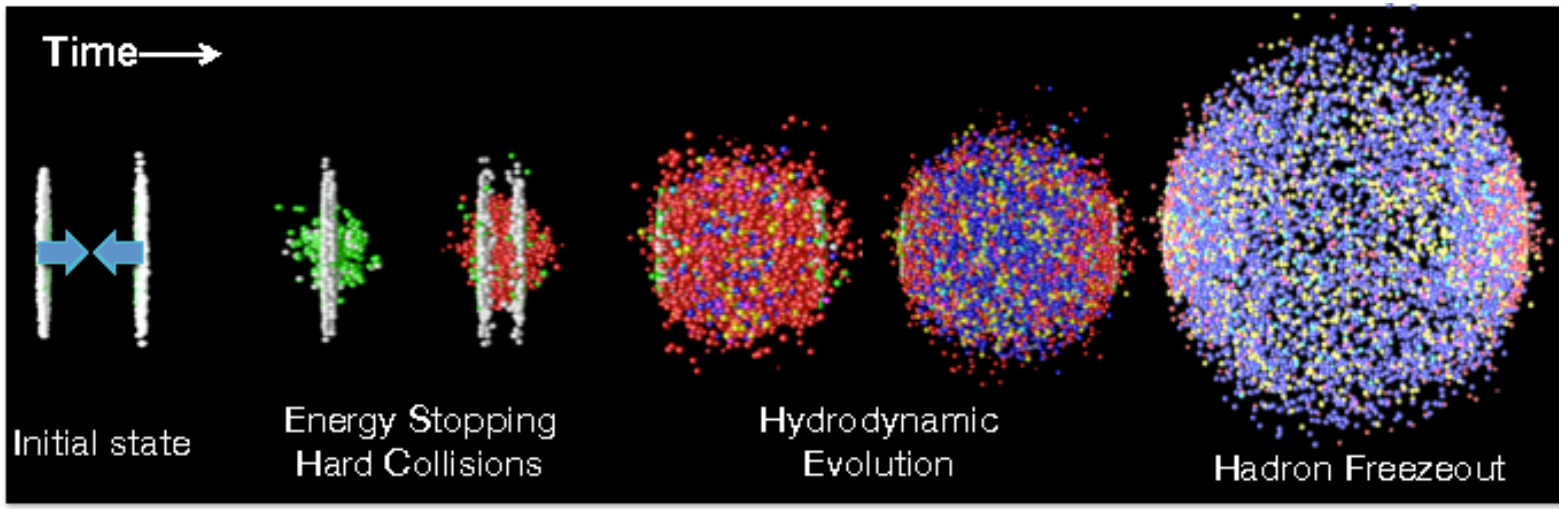
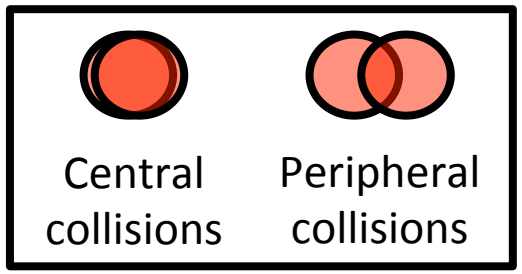
12th International workshop on
multiple partonic interactions
at the LHC, 11-15 Oct 2021, Lisbon

Hot QCD medium properties in heavy-ion (A-A) collisions





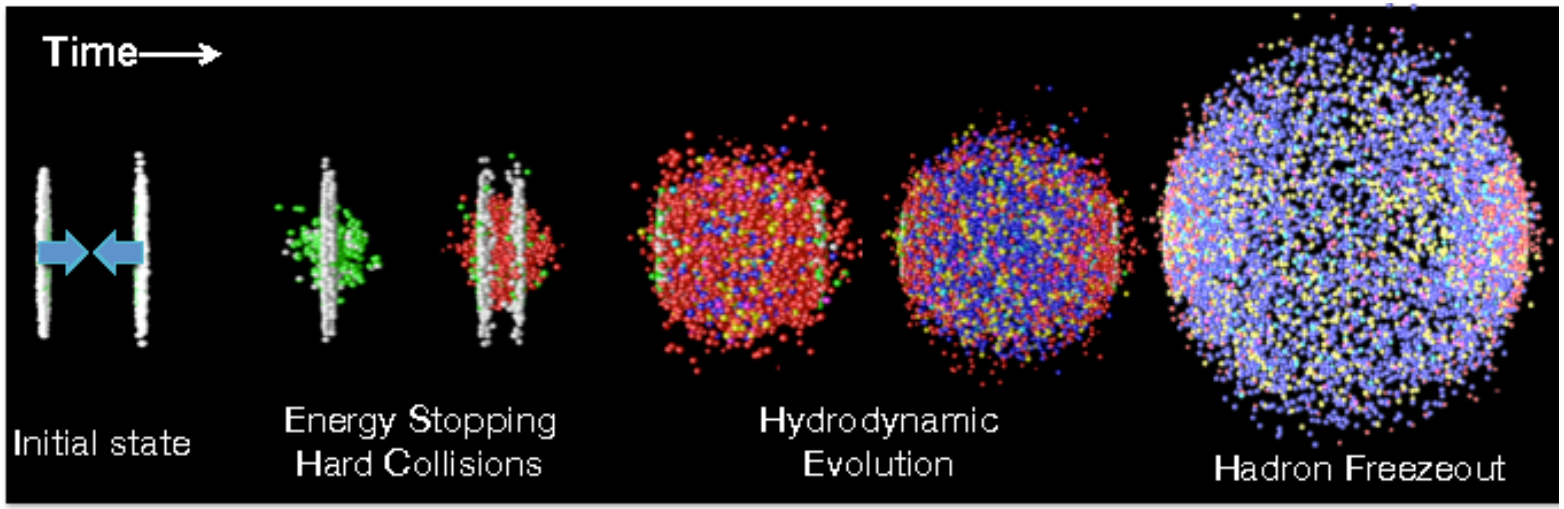
In A-A collisions:

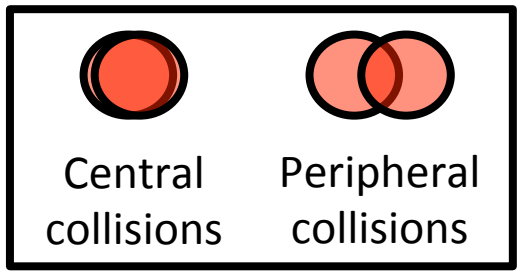
1) What are the properties of the medium created ?
2) How partons interact with the medium ?

In small systems (p-p & p-A):

1) Do we observe similar effects in small systems as in A-A collisions ?

Hot QCD medium properties in heavy-ion (A-A) collisions





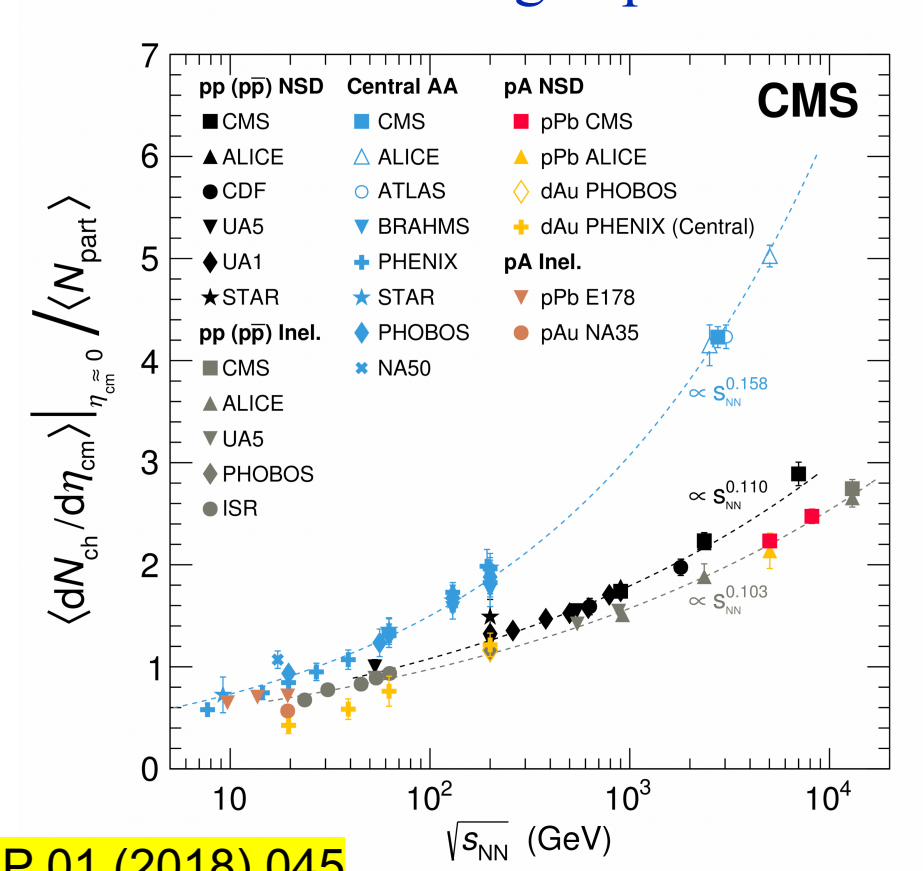
Outline:

I) Soft probes

II) Hard probes

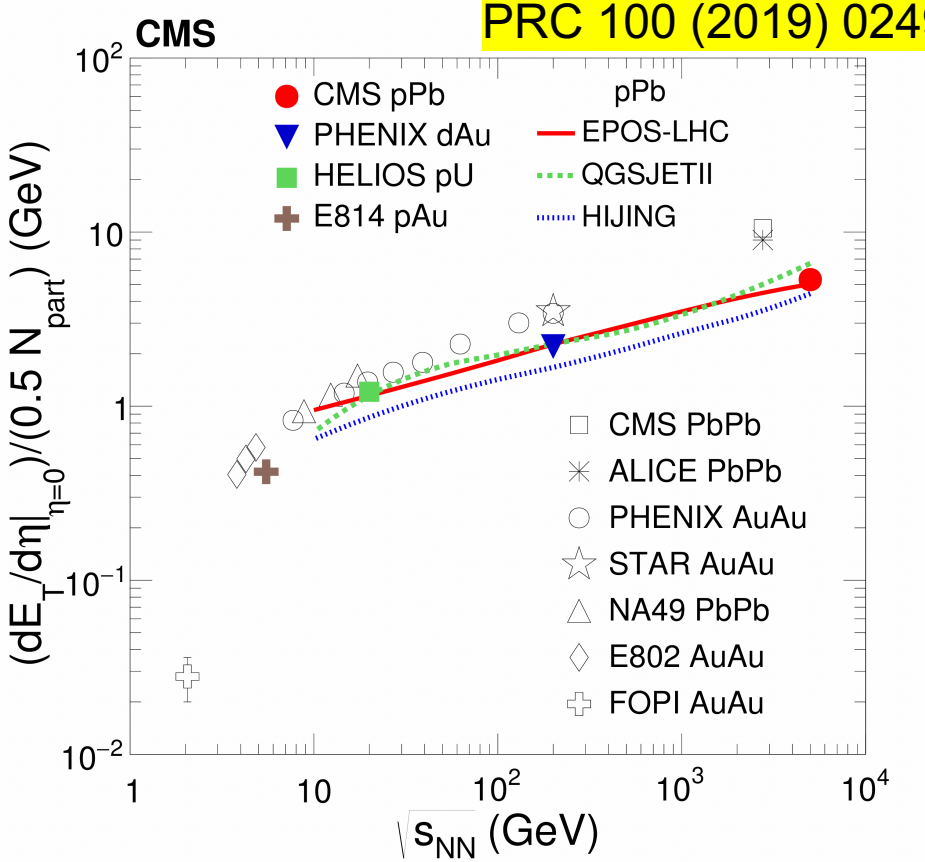
How did it evolve with energy ?

Charged particle multiplicity and transverse energy density



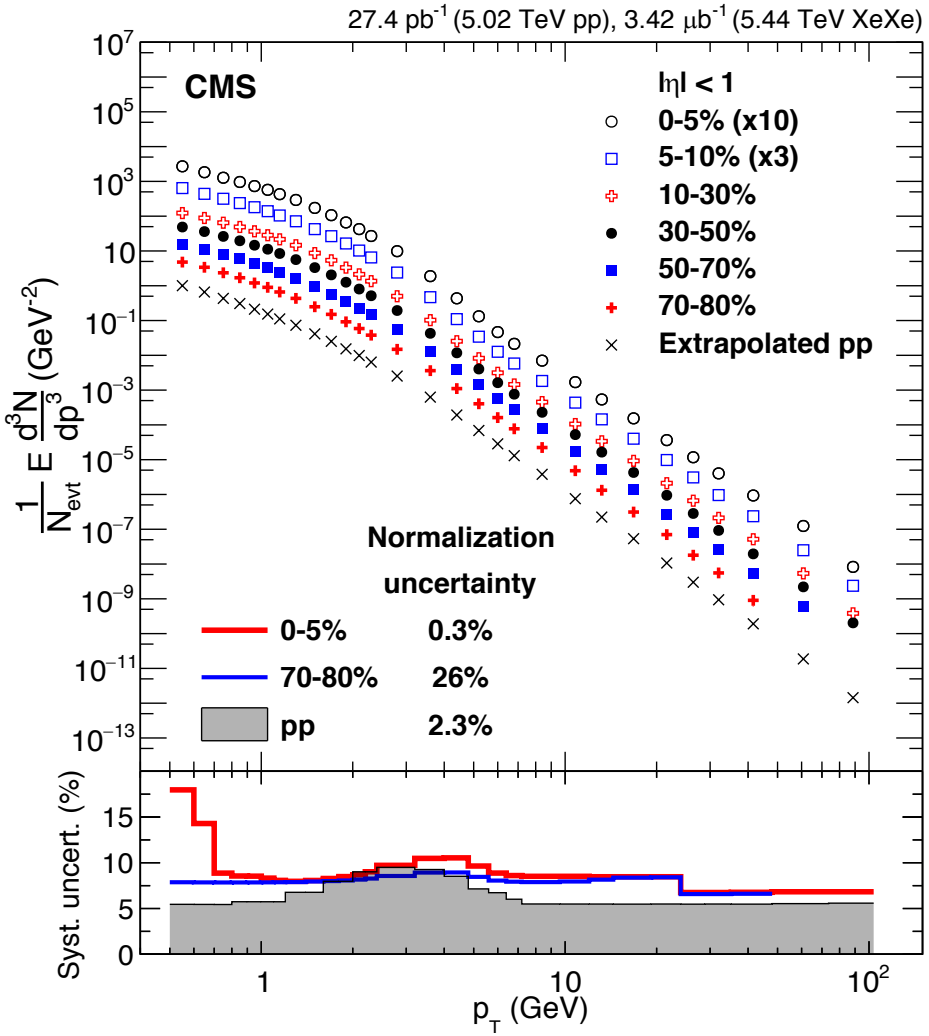
JHEP 01 (2018) 045

PRC 100 (2019) 024902

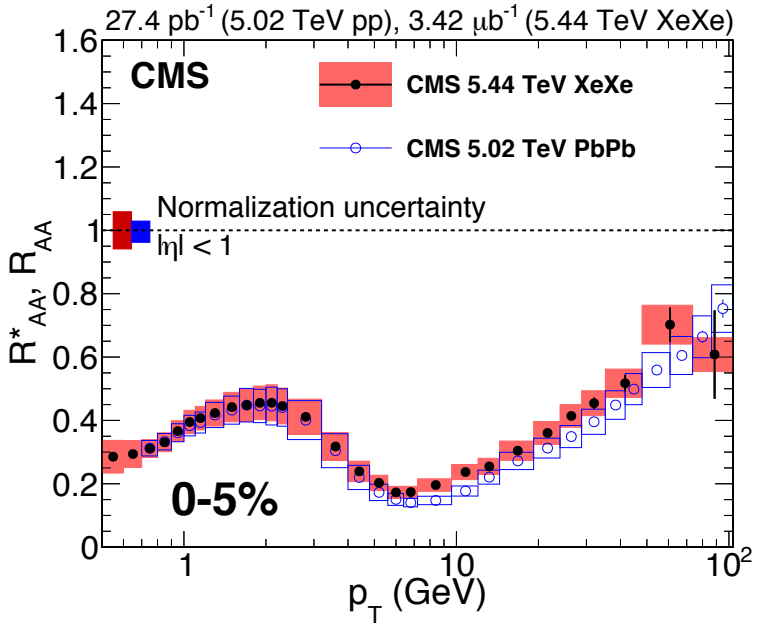


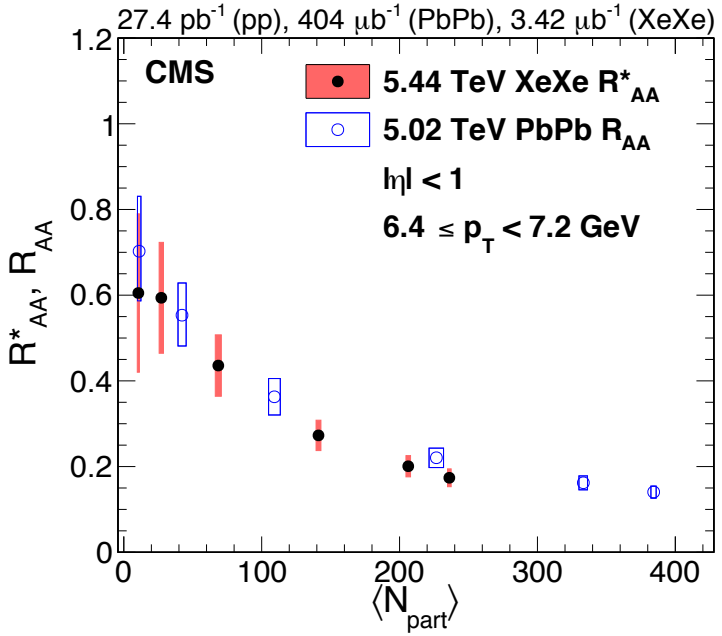
√s dependence - pp, pPb, PbPb follow power law

Charged-particle spectra and R^*_{AA} in XeXe collisions



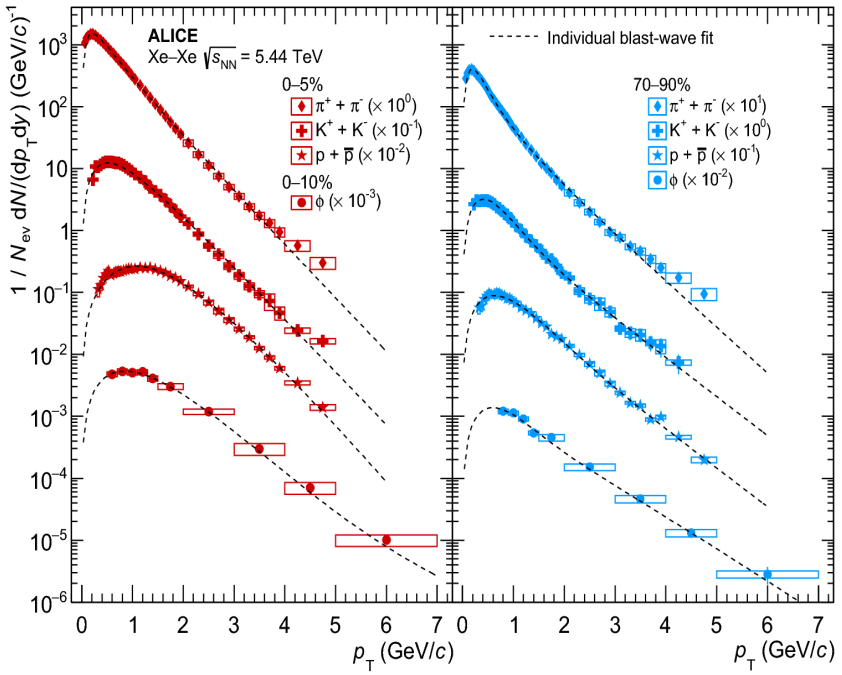
JHEP10(2018)138

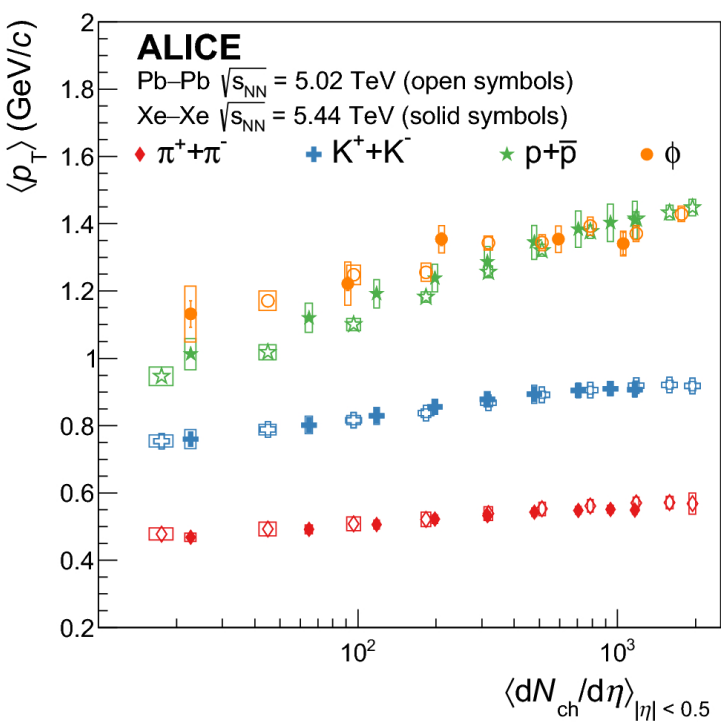




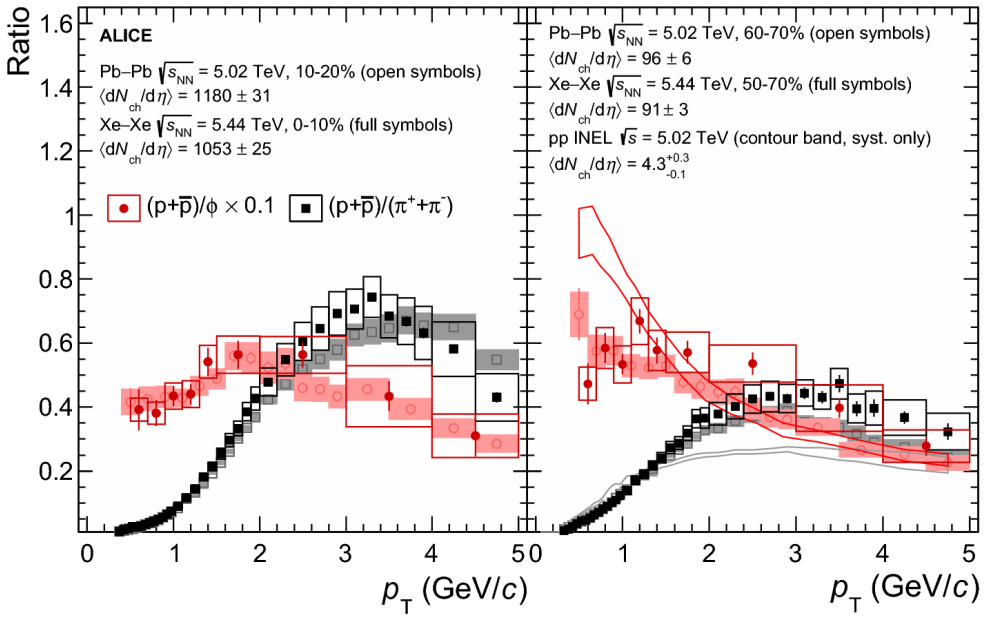
- In central (0-5%) collisions, the suppression in XeXe is less compared to PbPb in the p_T range of 6-8 GeV/c
- Charged-particle production in XeXe is slightly more suppressed than in PbPb at the same N_{part}

Identified-particle spectra and ratio in XeXe collisions





Eur. Phys. J. C 81 (2021) 584



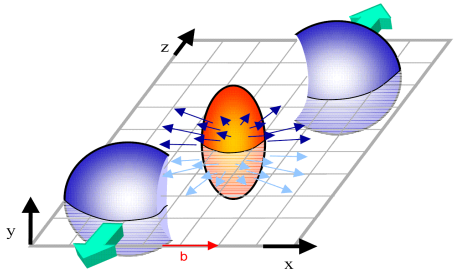
- Particle mass dependent spectra at intermediate p_T and depletion at low p_T
- Effect is more pronounced in central collisions -> presence of radial flow

- Mass dependent $\langle p_T \rangle$: $M_\pi < M_K < M_p < M_\phi$
- $\langle p_T \rangle$ of proton and ϕ-meson are similar for the same $dN_{ch}/d\eta$

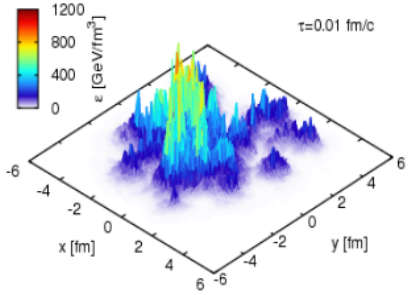
- More depletion of the baryon-to-meson ratio for p/π than p/ϕ at the low p_T – in agreement with the expectation from radial flow effect

Perfect fluid paradigm

Initial state



$\varepsilon(x, y, \eta^s)$



Event by Event

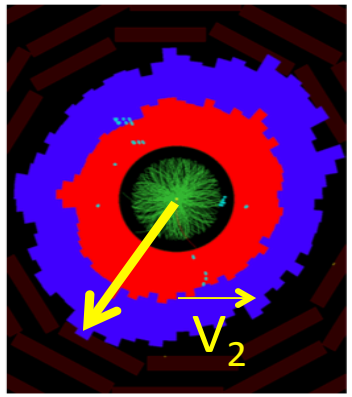
Pre-equilibrium

Hydrodynamics
$\delta_\mu T^{\mu\nu} = 0 + (\eta, \zeta, \ldots)$

Freeze-out
Hadronic transport

Final state

$f(p_T, \eta, \phi)$

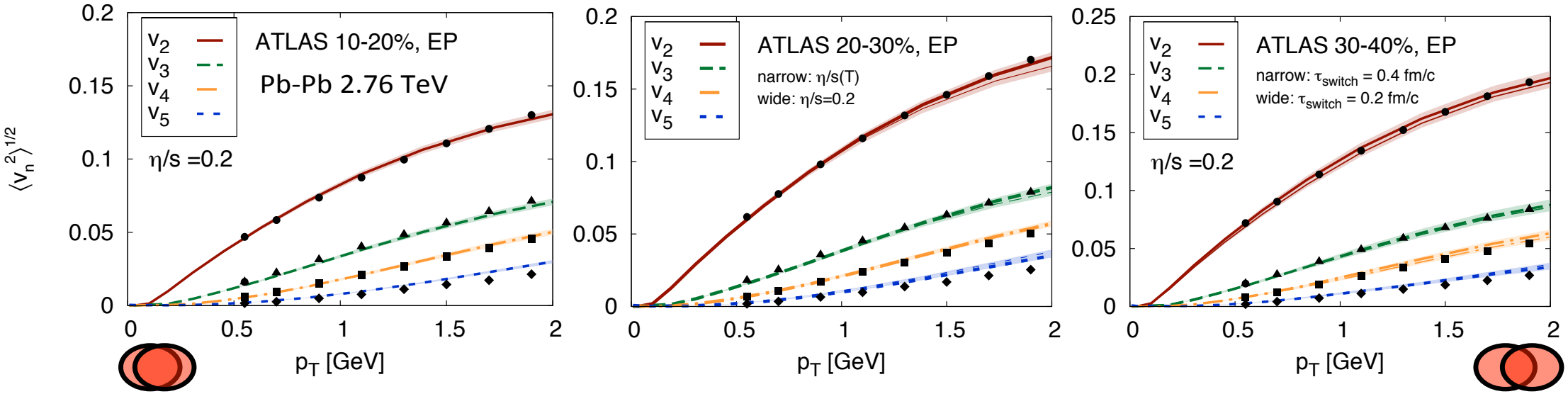


QGP behave like a nearly perfect fluid
(small η/s)

Fourier bases: $f(p_T, \eta, \phi) = N(p_T, \eta) \sum_{n=-\infty}^{+\infty} \vec{V}_n(p_T, \eta) e^{-in\phi}$

Anisotropic flow

A perfect fluid



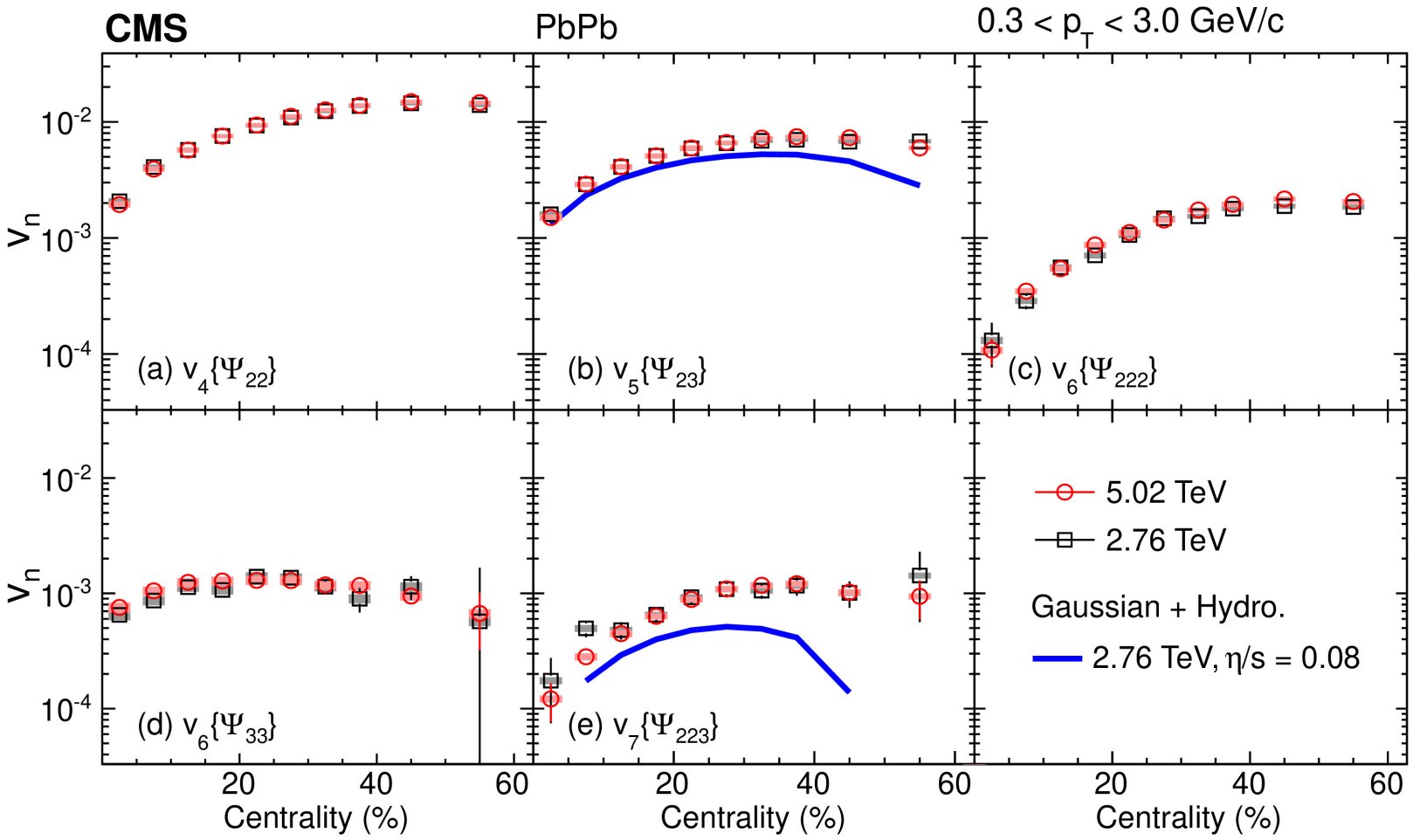
Phys. Rev. C 86, 014907 **ATLAS results**

Phys. Rev. Lett. 110, 012302 **IP glasma + MUSIC**

- v_n measurements well described by hydrodynamic models with very low sheared viscosity to entropy $(0.07 \leq \eta/s \leq 0.2)$ ⟶ almost perfect fluid
- v_2 mainly driven by geometry of the initial state (IS)
- v_3 driven by fluctuations of the IS

Mixed higher-order anisotropic flow in PbPb

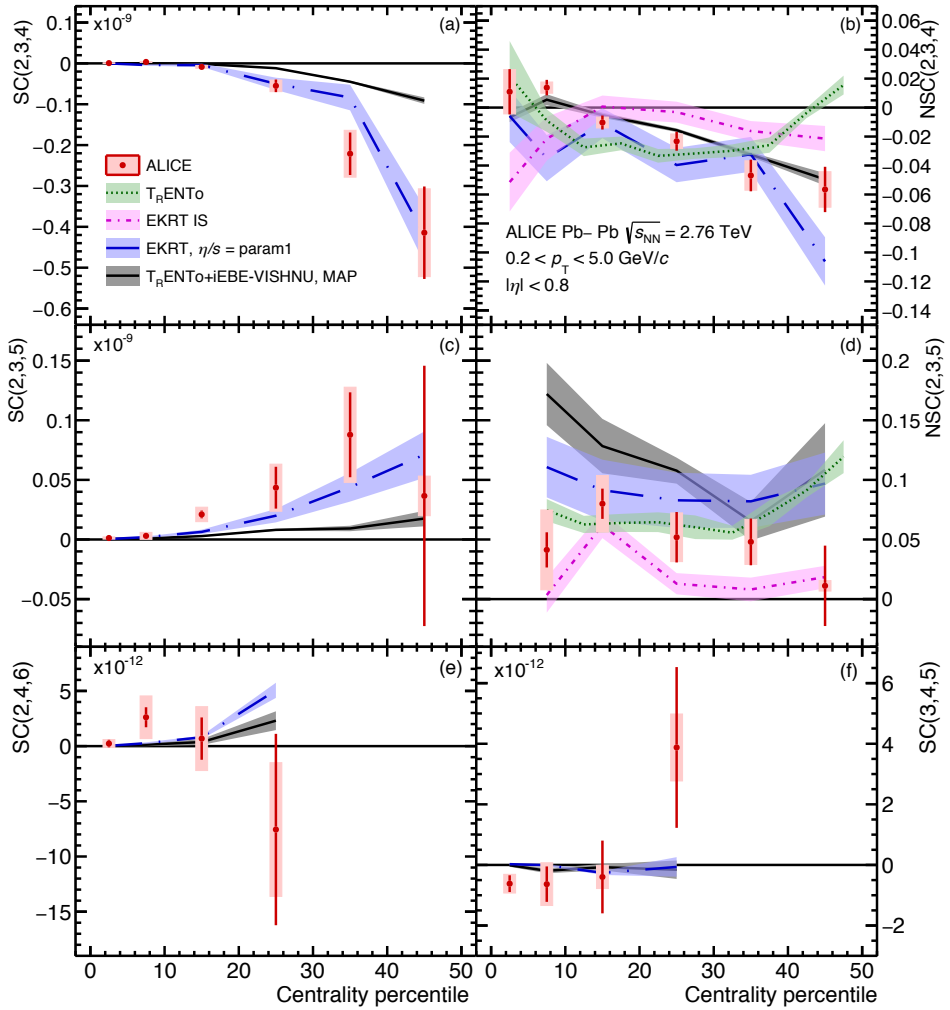
EPJ C 80 (2020) 534



- The mixed higher-order flow harmonics have a qualitatively similar centrality dependence
- Viscous hydrodynamic with Glauber initial conditions and shear viscosity don't provide a simultaneous description

Multi-harmonic flow correlations in PbPb collisions

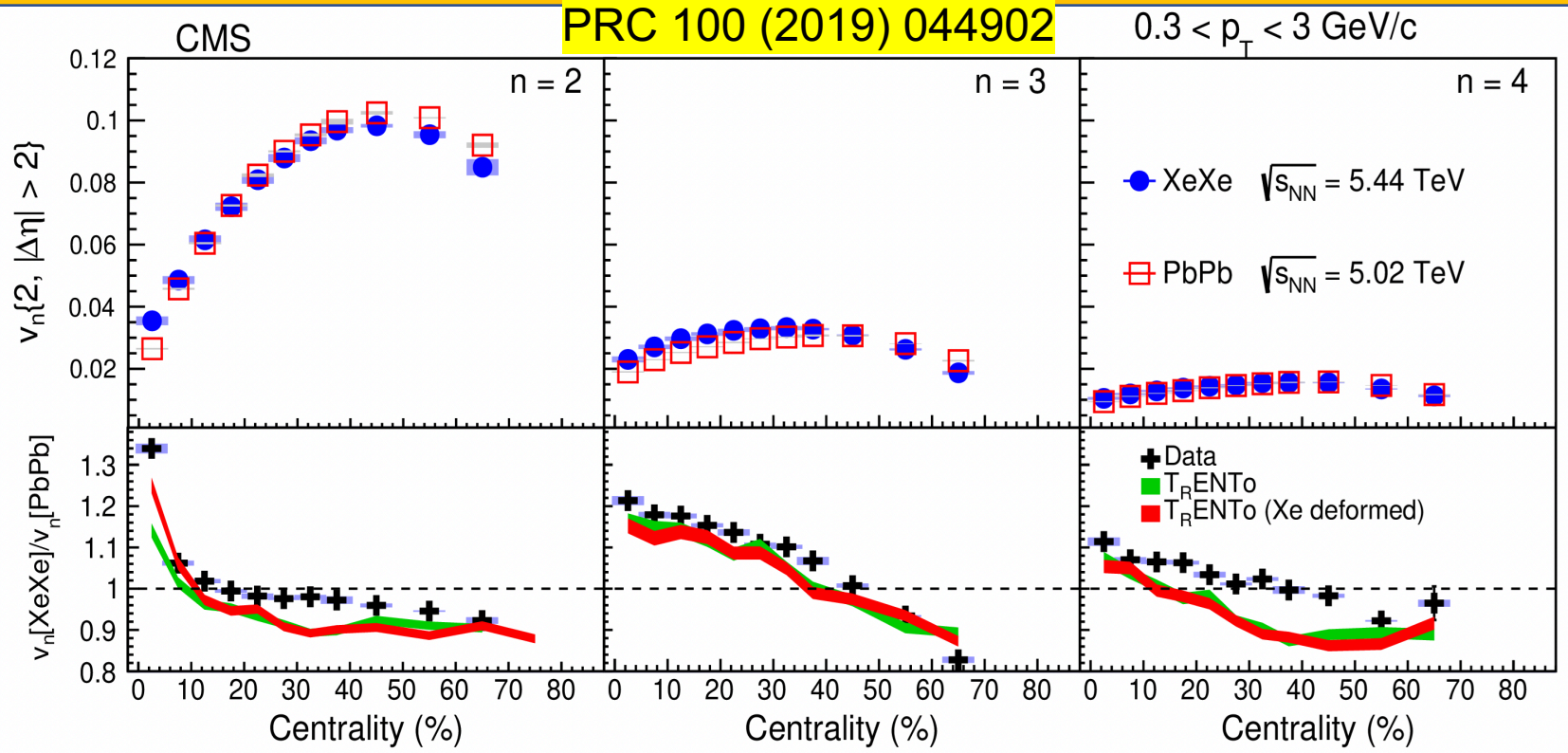
Phys. Rev. Lett. 127, 092302



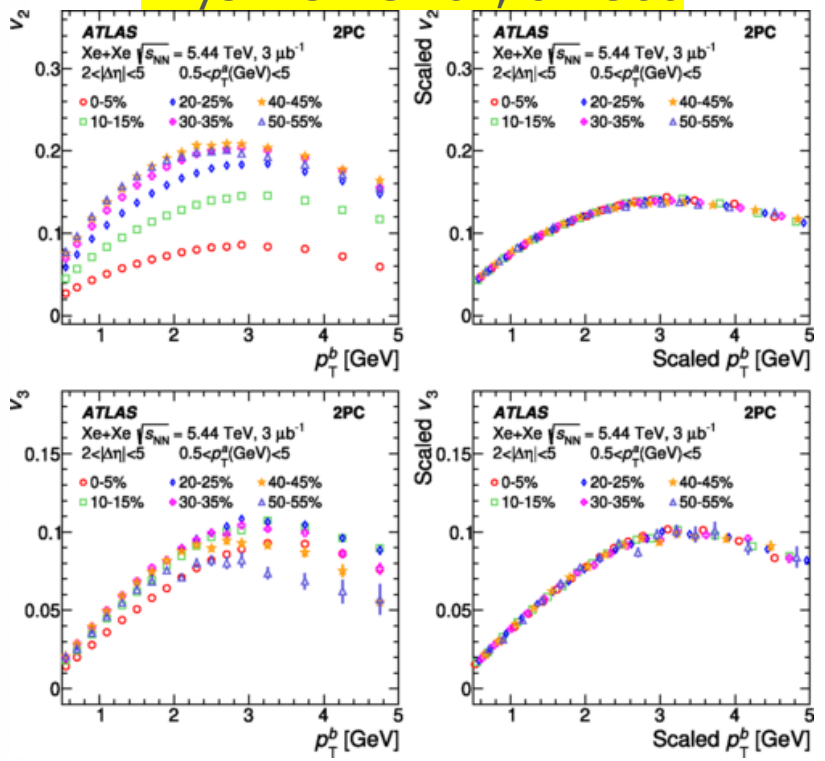
- Centrality dependence of the SC(k,l,m) are in good agreement with the predictions from the hydrodynamical models
- Indication of correlation between flow harmonics (v_2, v_3, v_4) during the medium evolution
- Provides new constraints for the initial conditions of the matter created in heavy-ion collisions

$v_{n=2,3,4}$ XeXe vs. PbPb

PRC 100 (2019) 044902

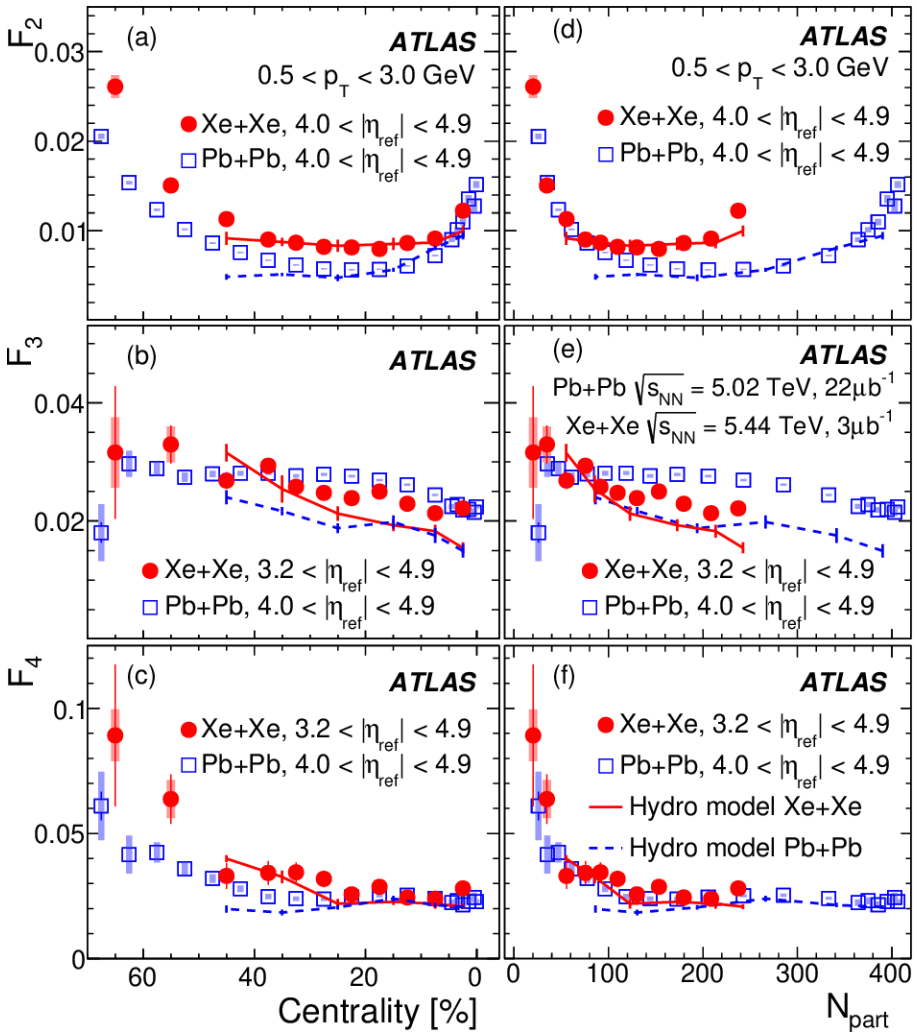


Phys. Rev. C 101, 024906

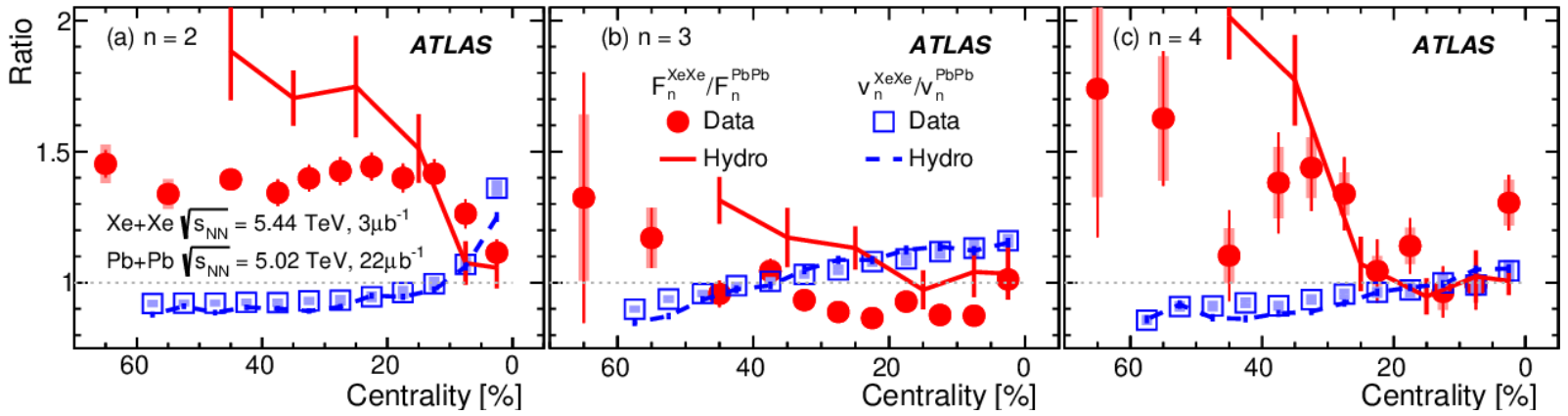


- v_2 for XeXe are larger than PbPb for the most central collisions
- Hydro models with Xe nuclear deformation better describe the v_2[XeXe]/v_2[PbPb] compared to models assuming spherical Xe shape for n=2 in central collisions

Longitudinal flow decorrelations in XeXe collisions



Phys. Rev. Lett. 126 (2021) 12230



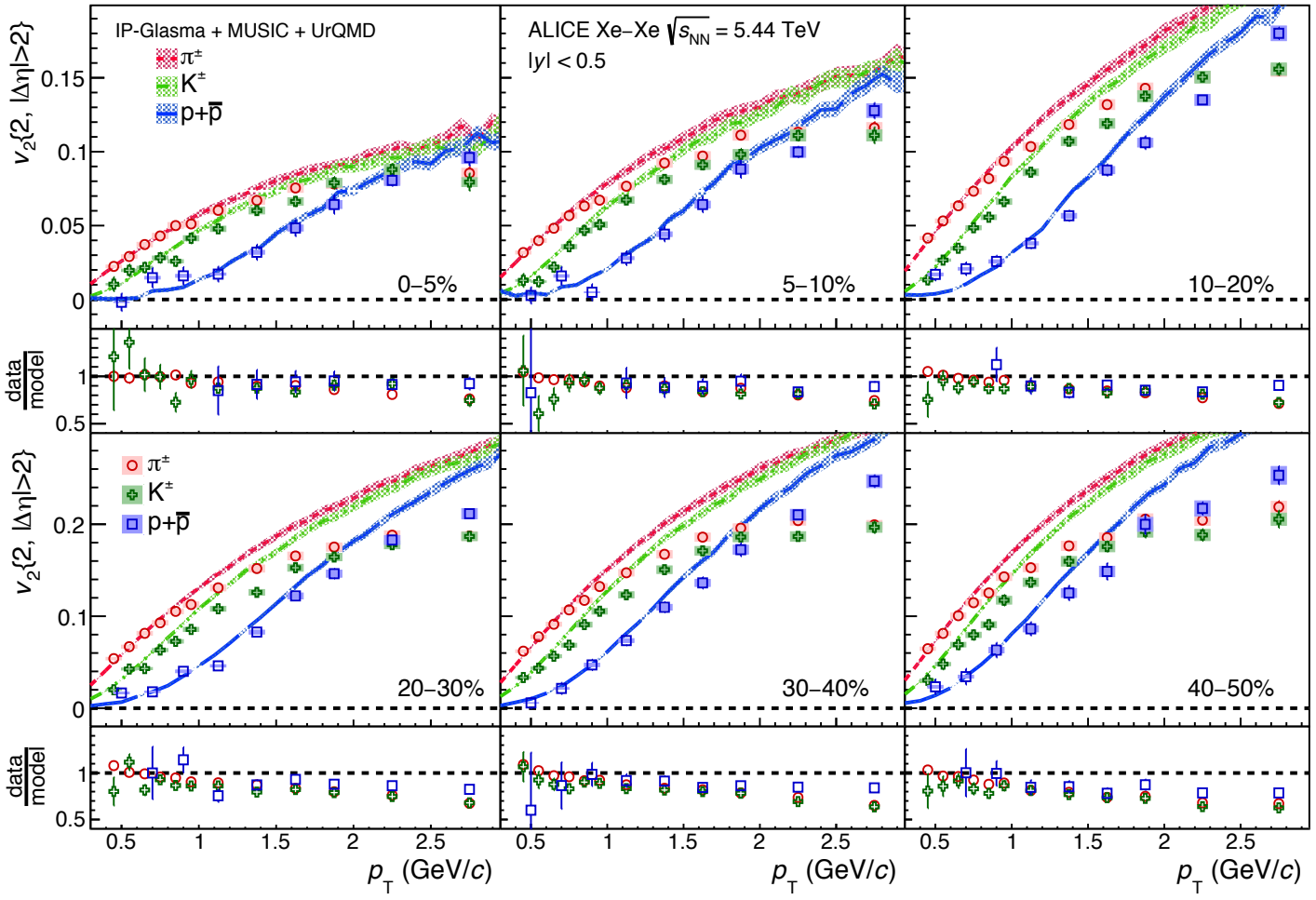
- $F_2^{XeXe} > F_2^{PbPb}$
- $F_3^{XeXe} < F_3^{PbPb}$
- $F_4^{XeXe} \approx F_4^{PbPb}$

Reverse ordering for n=2 and 3

- Hydrodynamical models fail to describe the longitudinal flow decorrelations between XeXe and PbPb collisions

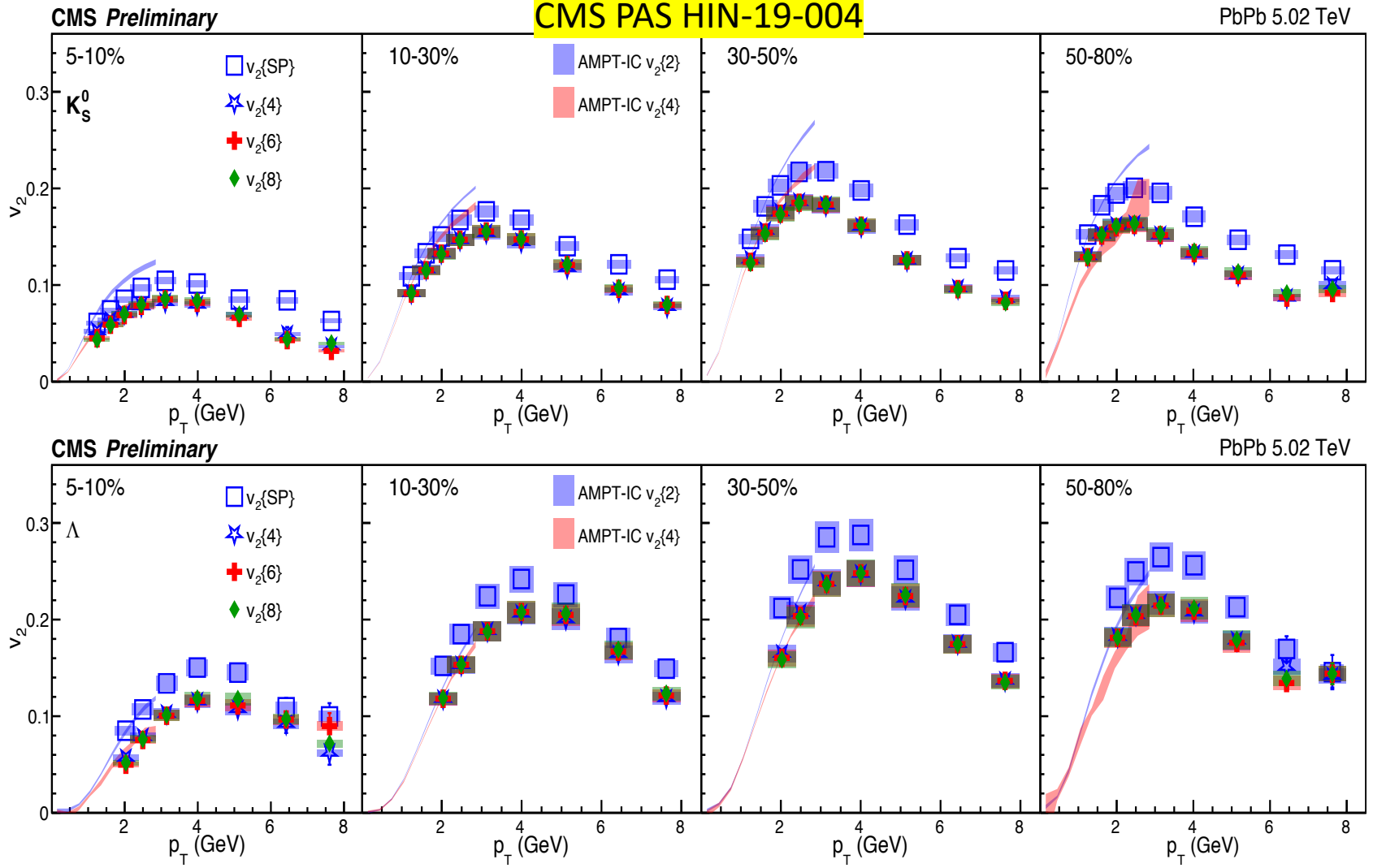
PID v_2 in XeXe collisions

ALICE, arXiv:2107.10592 [nucl-ex]



- For $p_T < 3$ GeV/c, v_2 shows a mass ordering attributed to the interplay between anisotropic flow and radial flow
- Hydrodynamical models qualitatively reproduce the mass ordering at $p_T < 1$ GeV/c
- A better agreement between data and model is observed in central collisions compared to peripheral

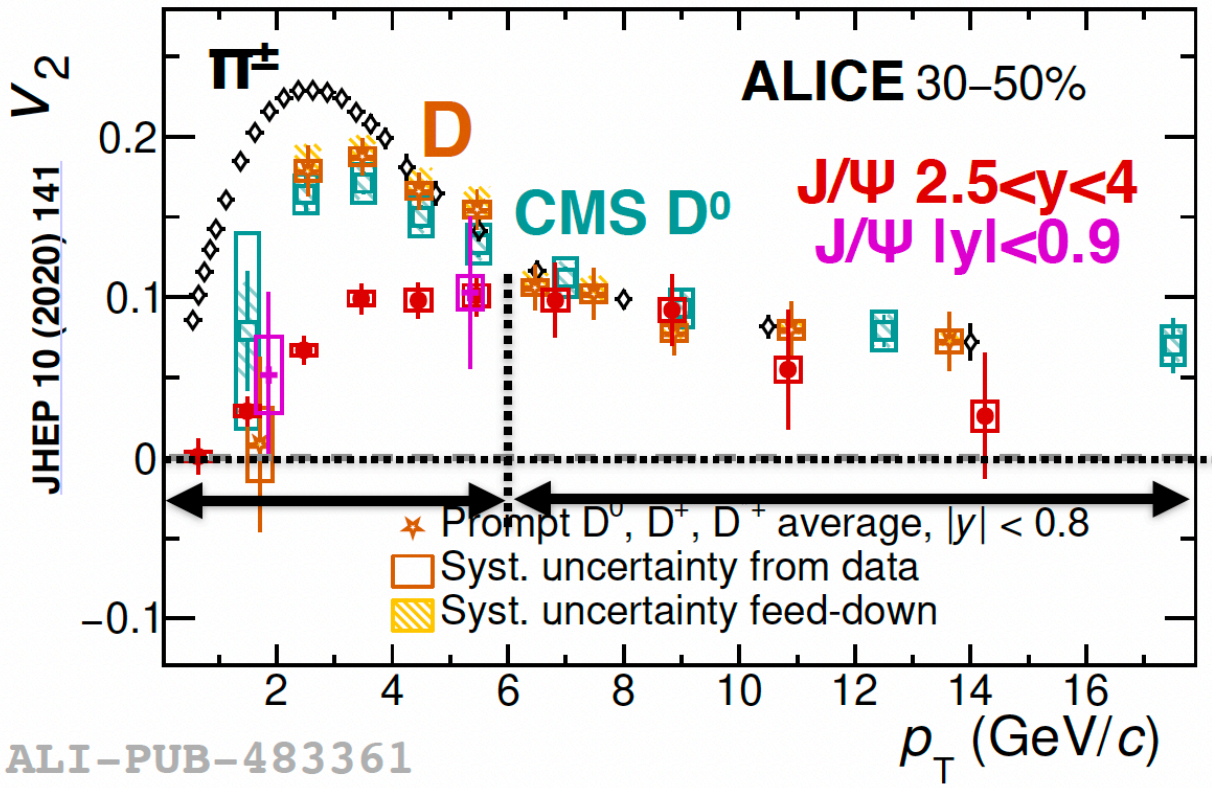
Strange hadrons v_2 in PbPb collisions



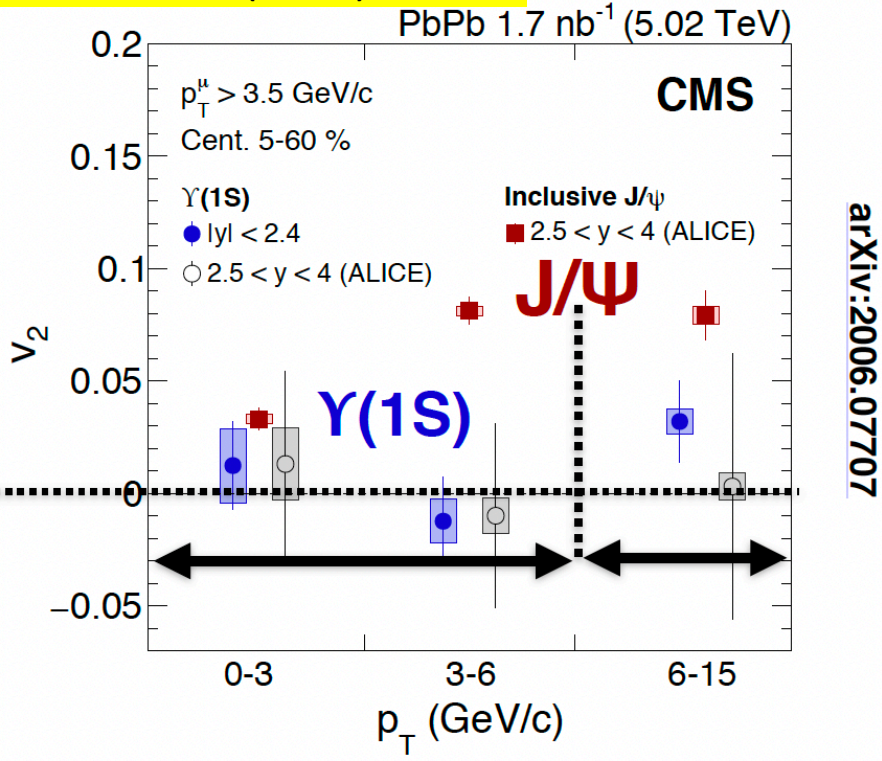
- Hydrodynamic calculations of 2- and 4-particle v_2 with AMPT initial conditions qualitatively consistent with the data

Heavy quarks collectivity in PbPb

JHEP 10 (2020) 141

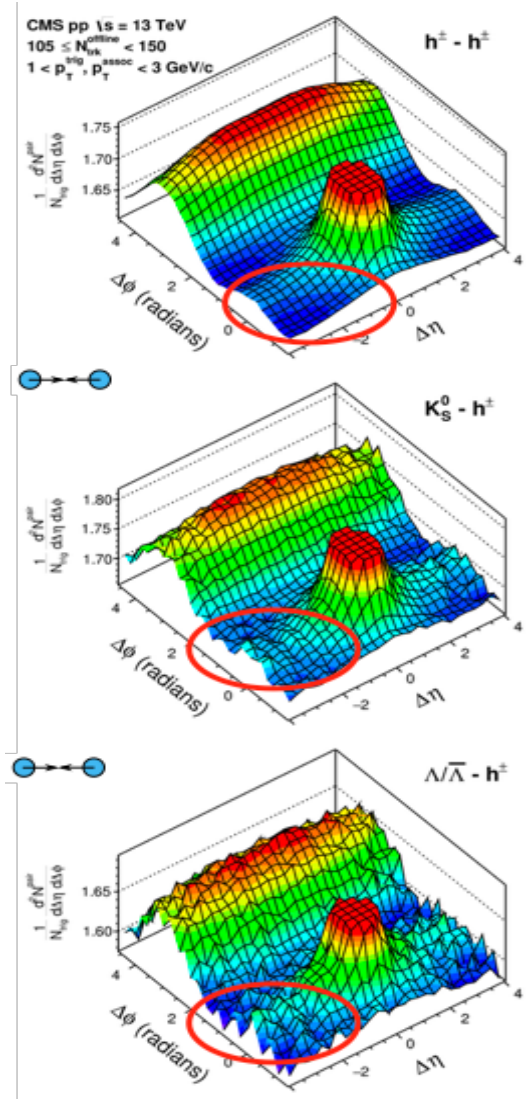


Phys. Lett. B 819 (2021) 136385

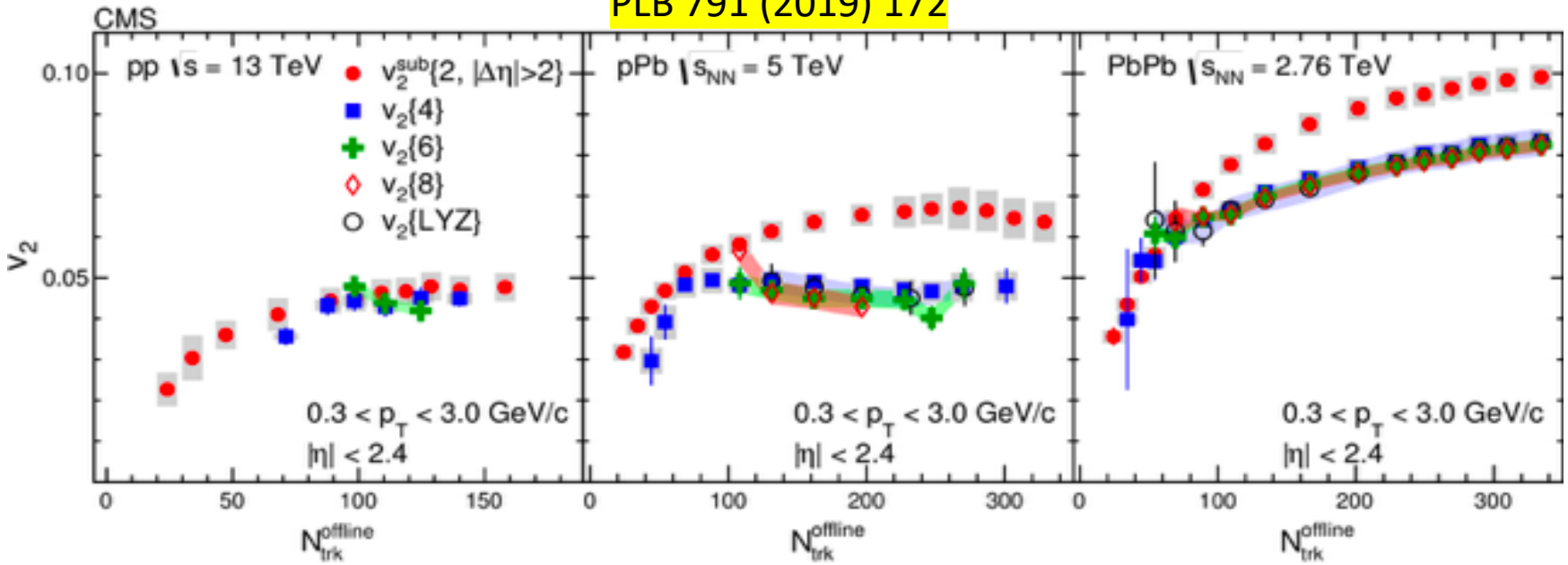


- Inclusive J/ψ v_2 at forward and midrapidity are in agreement with each other and positive up to $12 < p_T < 20$ GeV/c
- The v_2 values for $\Upsilon(1S)$ is consistent with zero in contrasts with positive J/ψ v_2

Nature of the "Ridge" – the small system puzzle



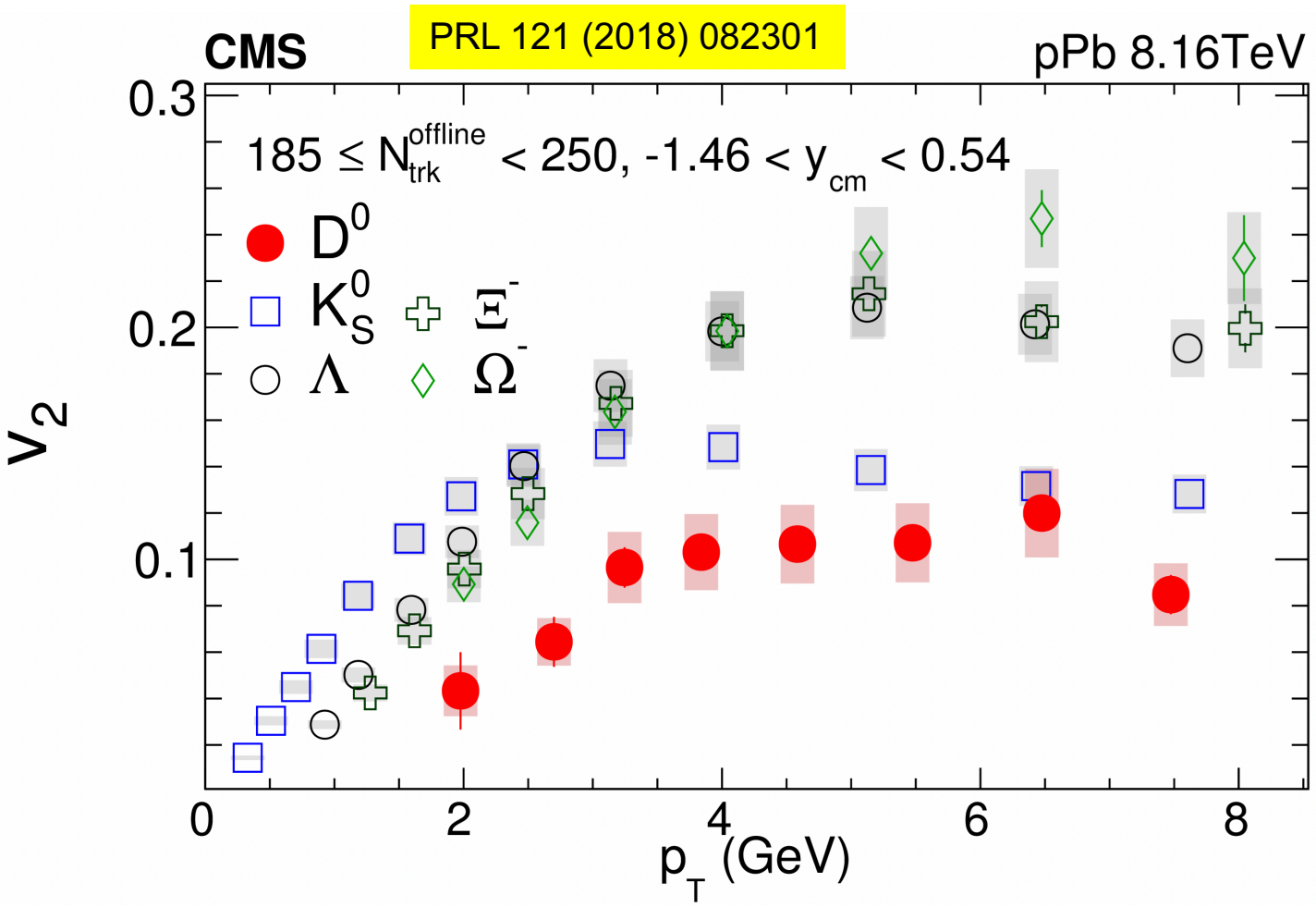
PLB 791 (2019) 172



- ❑ Collective nature: $v_2\{2\} \approx v_2\{4\} \approx v_2\{6\}$ in pp
- ❑ $v_2\{2\} > v_2\{4\} \approx v_2\{6\}$ in pPb and PbPb

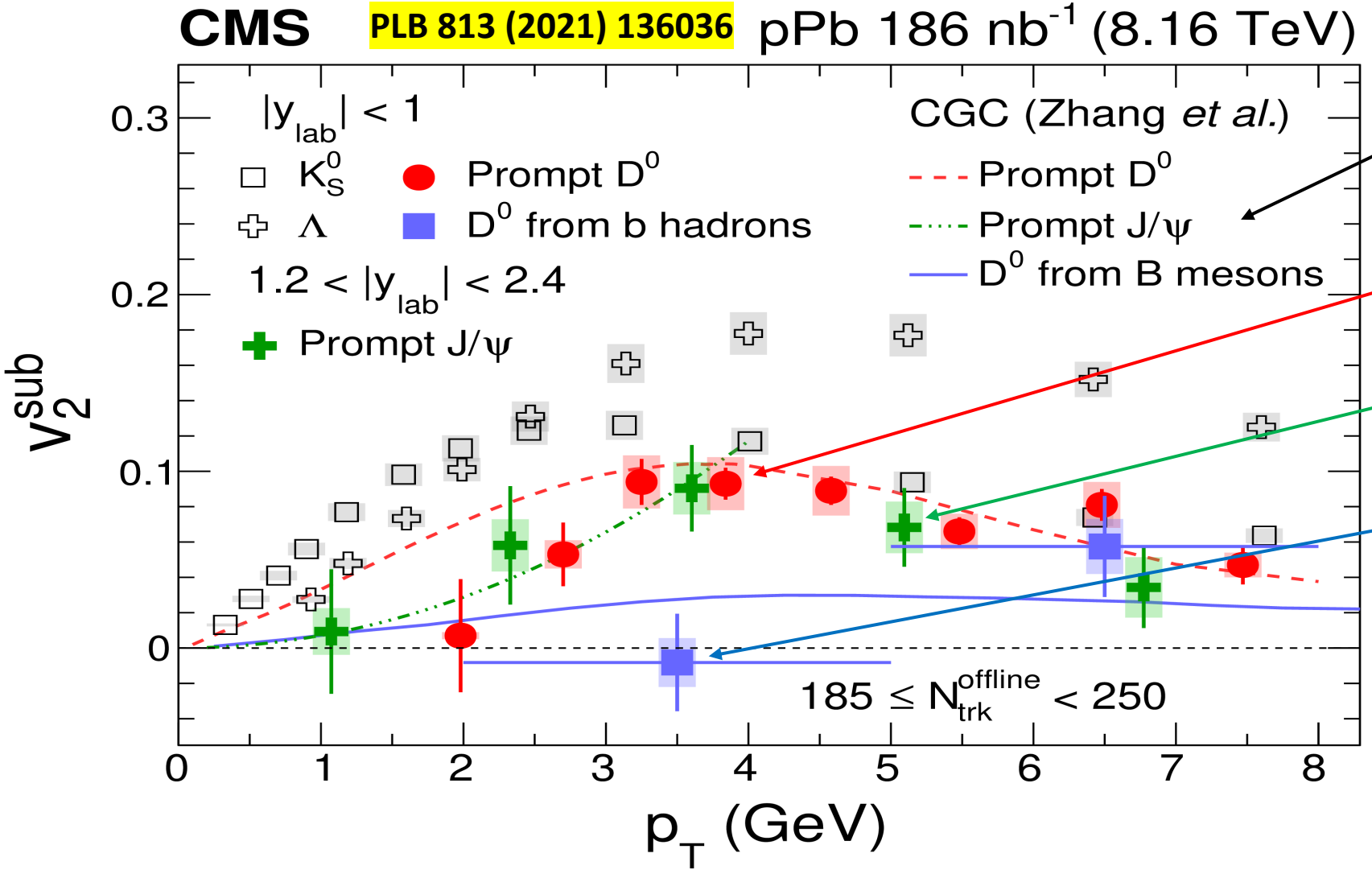
- ✓ Multi-particle correlation
- ✓ Similar patterns for all systems
- ✓ Initial state fluctuations play an important role

Heavy quarks collectivity in small system



- Significant positive v_2 values are observed for D^0 mesons with $p_T > 2$ GeV/c
- The collective behavior of charm quarks in high-multiplicity pPb collisions is weaker than that of the light-flavor quarks

Charm and beauty long-range correlations in pPb



Theory

Open charm

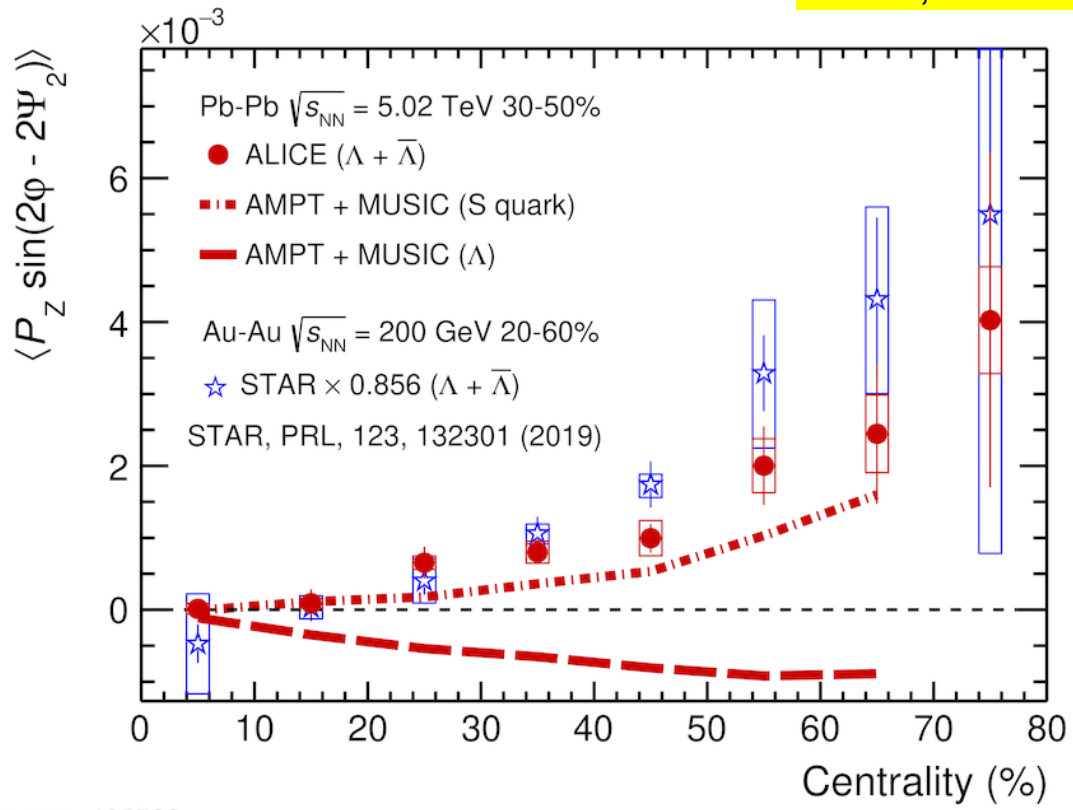
Hidden charm

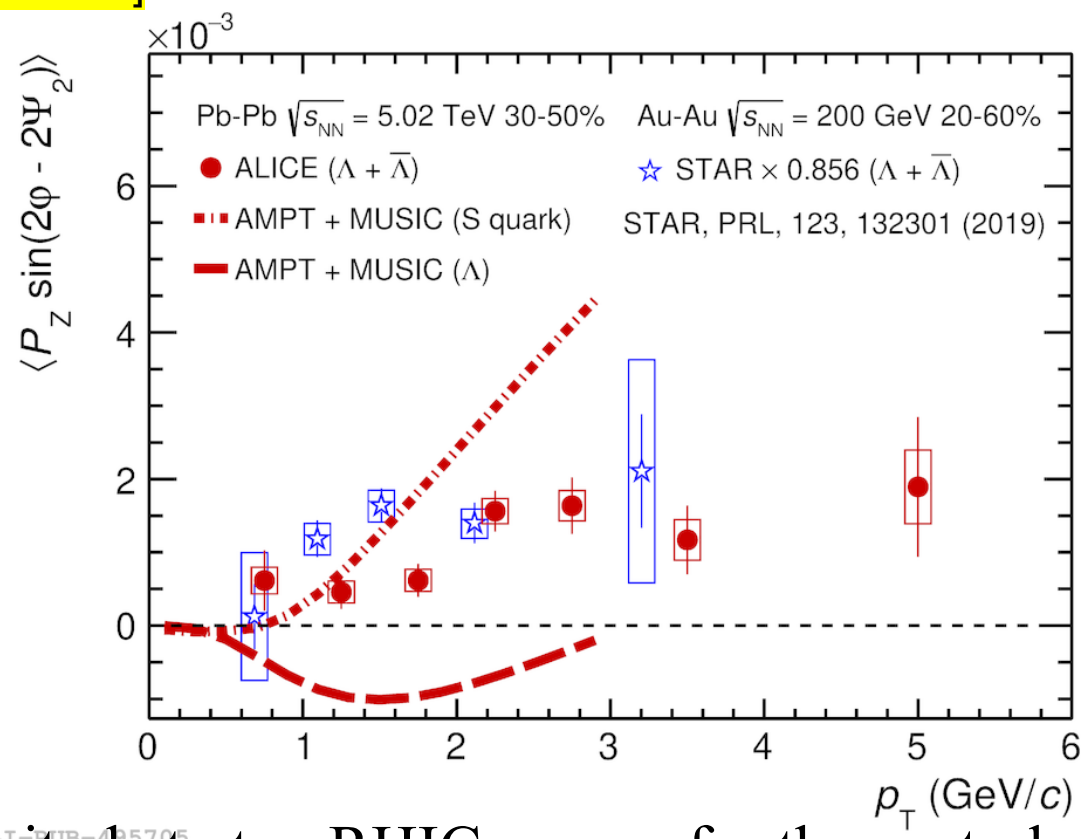
Open beauty

- **No significant flow for nonprompt D^0**

Longitudinal local Λ+Λ̄ polarization in PbPb

ALICE, arXiv:2107.11183 [nucl-ex]

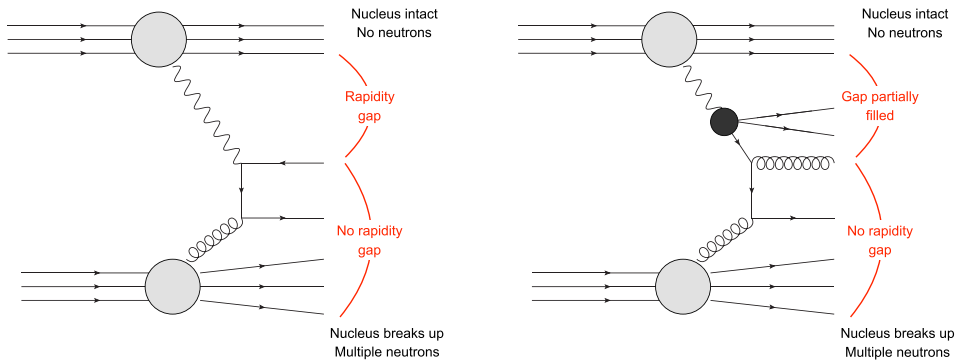


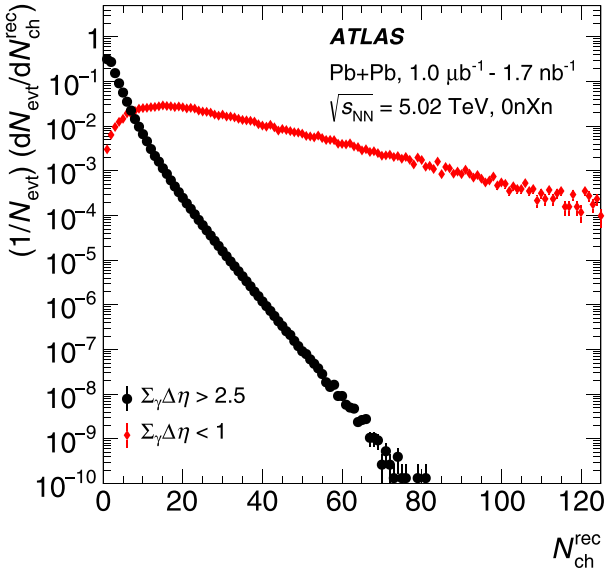


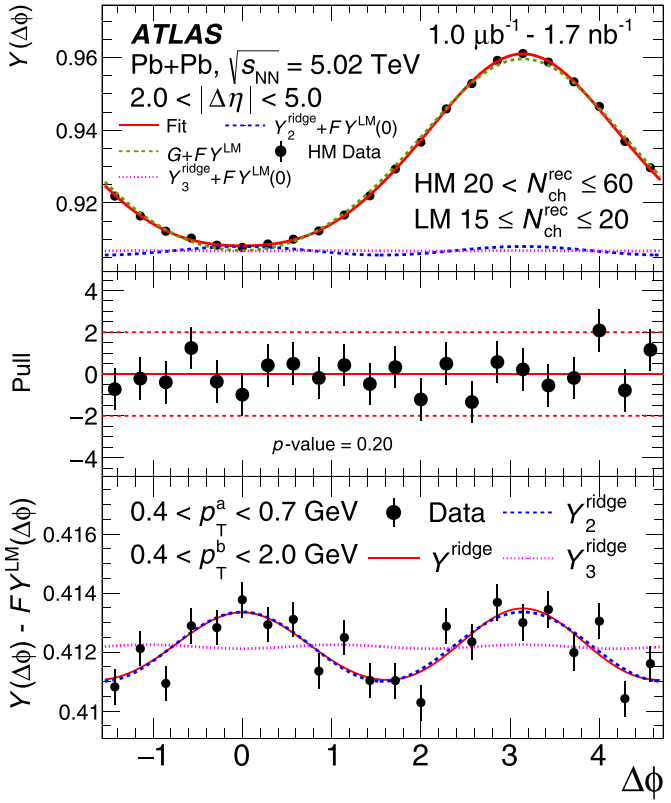
- Hyperon polarization at the LHC is similar in magnitude to top RHIC energy for the central collisions and smaller in semi-central collisions
- At $p_T < 2.0$ GeV, polarization at the LHC is smaller than the RHIC in semi-central collisions

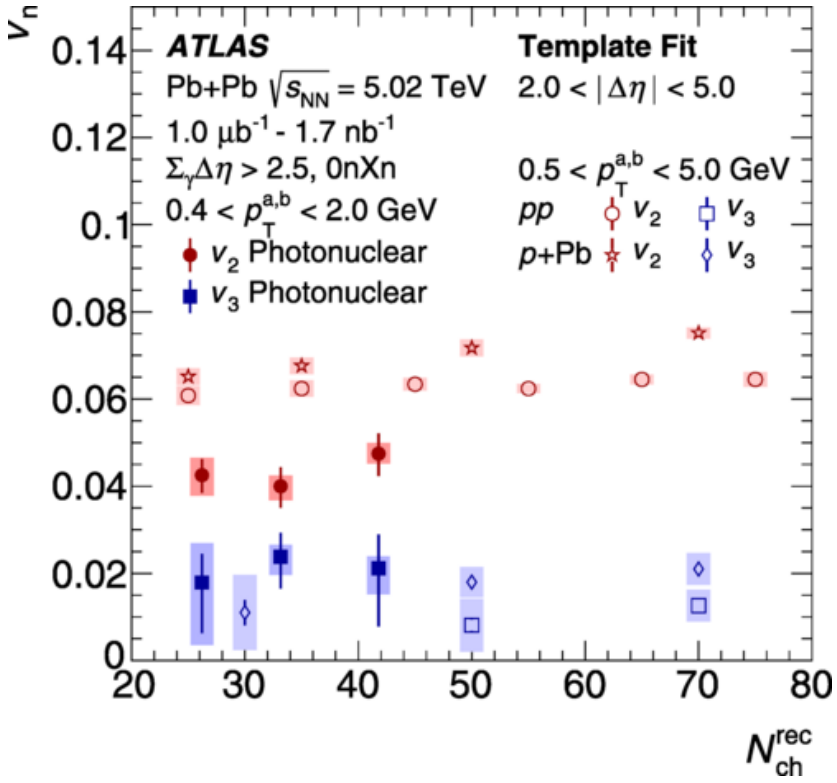
Long range correlations in ultraperipheral PbPb collisions

Phys. Rev. C 104, 014903







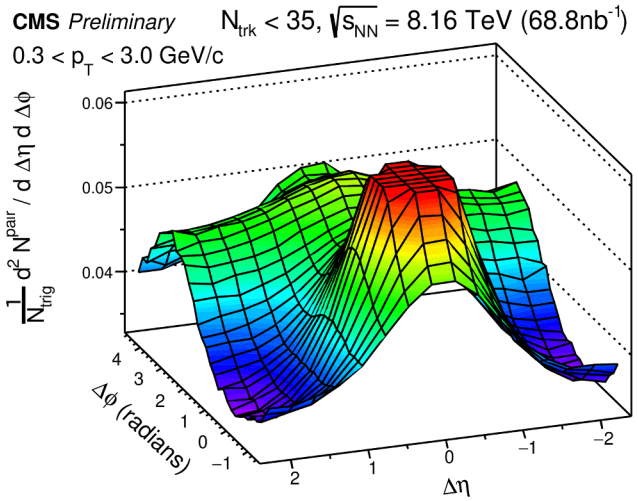


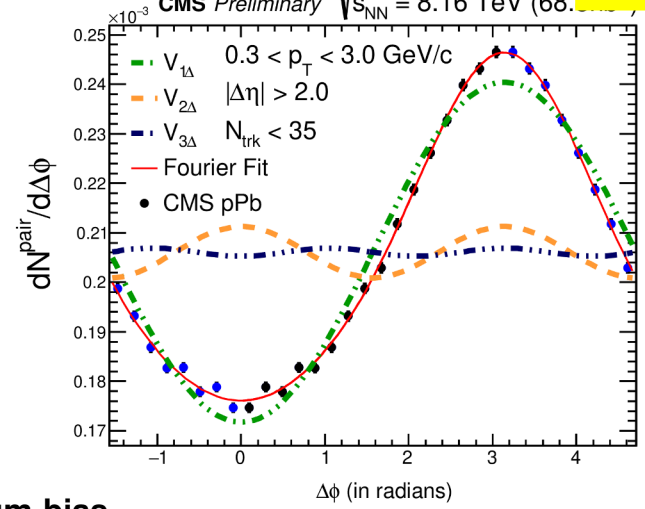
- Significant nonzero values for v_2 and v_3 flow coefficients as a function of N_{ch}
- Provide new information to probe the origin of collectivity

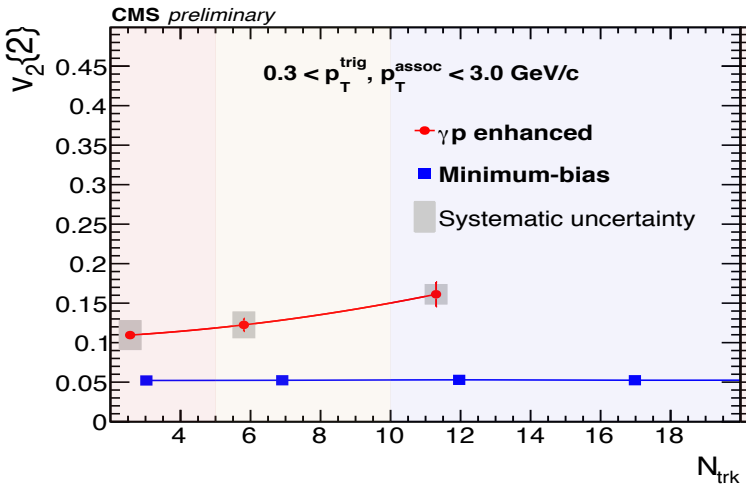
γp interactions within ultra-peripheral p+Pb collisions

γp enhanced

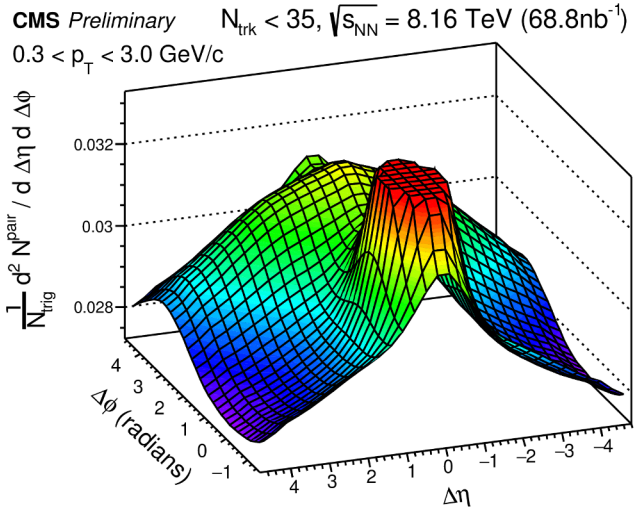
CMS-PAS-HIN-18-008

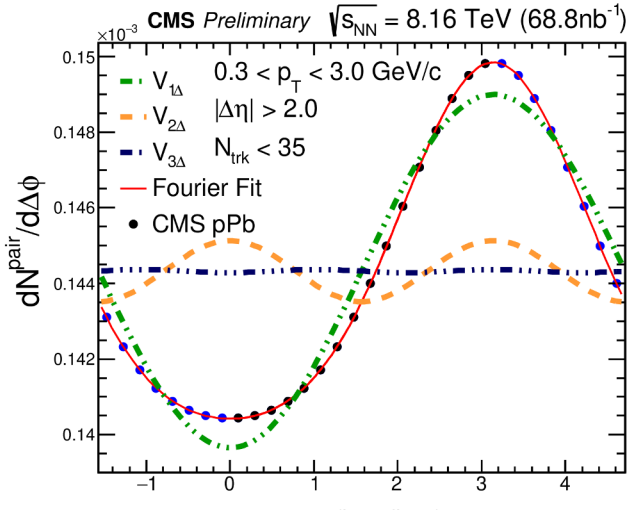






Minimum-bias





- For both **γp** and MB samples, significant negative $V_{1\Delta}$ and positive $V_{2\Delta}$ are observed, $V_{3\Delta}$ values are consistent with zero
- Single particle flow coefficient $\mathbf{v_2}$ is larger for **γp**-enhanced events than for MB collisions

Summary

We did create a strongly interacting medium in A-A collisions at the LHC!

- ❖ Behave like a perfect fluid and explain with hydro
- ❖ No strong energy dependence of the evolution of the system is observed
- ❖ Collectivity observed in small system? Which mechanism lies behind?

- ✓ Many interesting physics results in large, medium and small collision systems at the LHC
- ✓ Future heavy-ion program at the LHC (Run 3 and 4) with the upgraded detector systems will provide more exciting opportunities!

🙏 *Thank you*