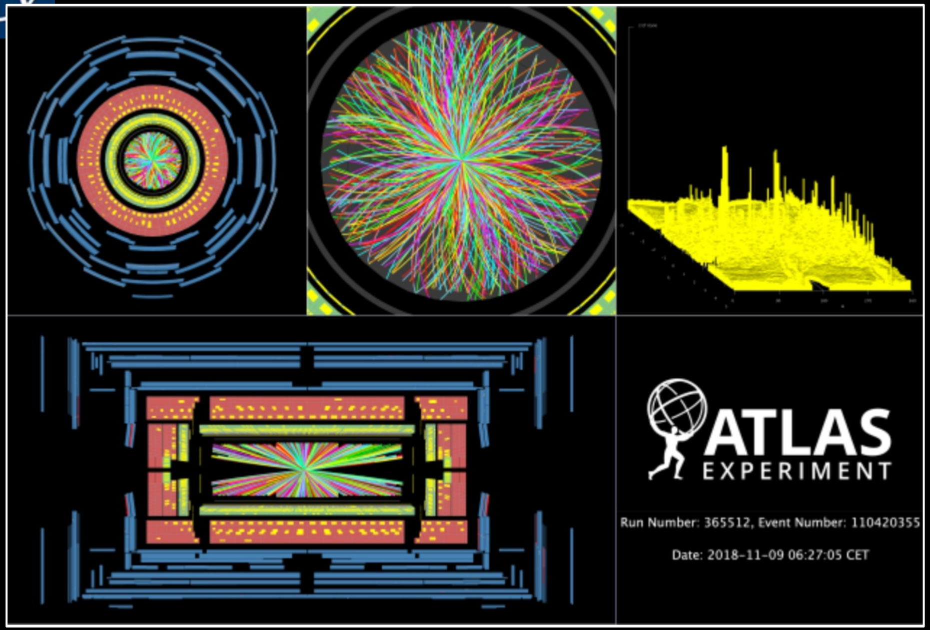
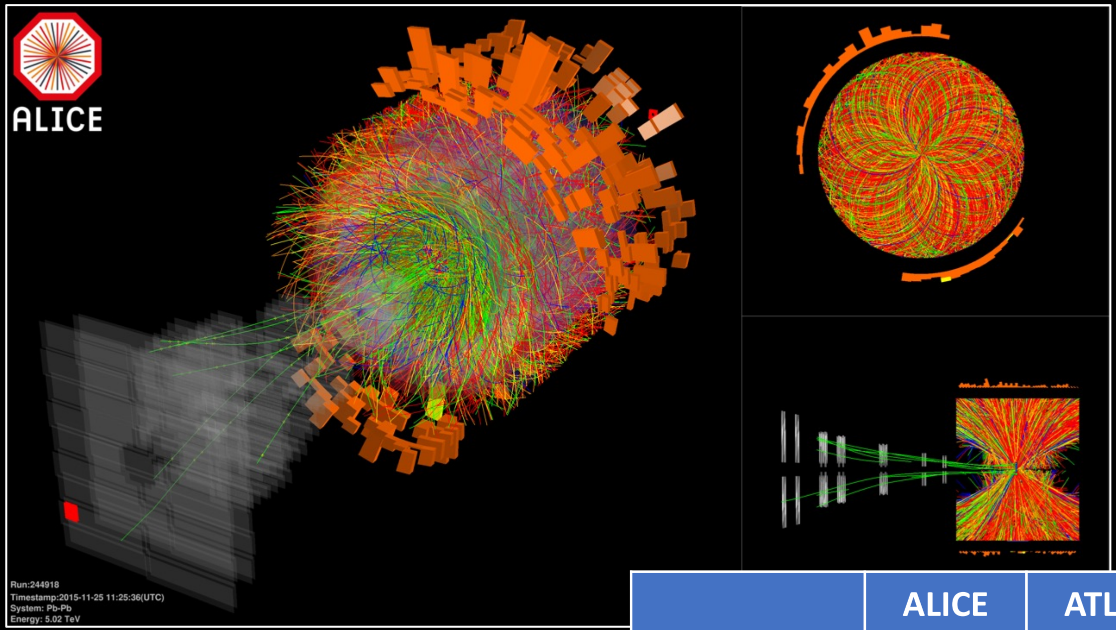
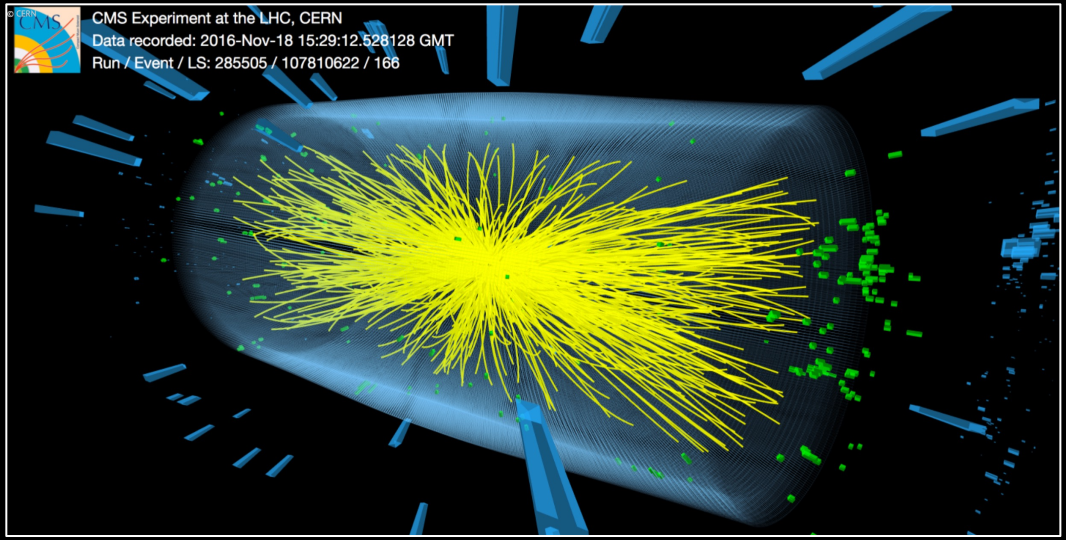
Event-by-event fluctuations at the LHC

Tapan Nayak (NISER/CERN) for ALICE, ATLAS & CMS collaborations





	ALICE	ATLAS	CMS
η - coverage	$\|\eta\|$<0.8	$\|\eta\|$<2.5	$\|\eta\|$<2.4
p_T coverage (GeV/*c*)	> 0.15	>0.3	>0.3

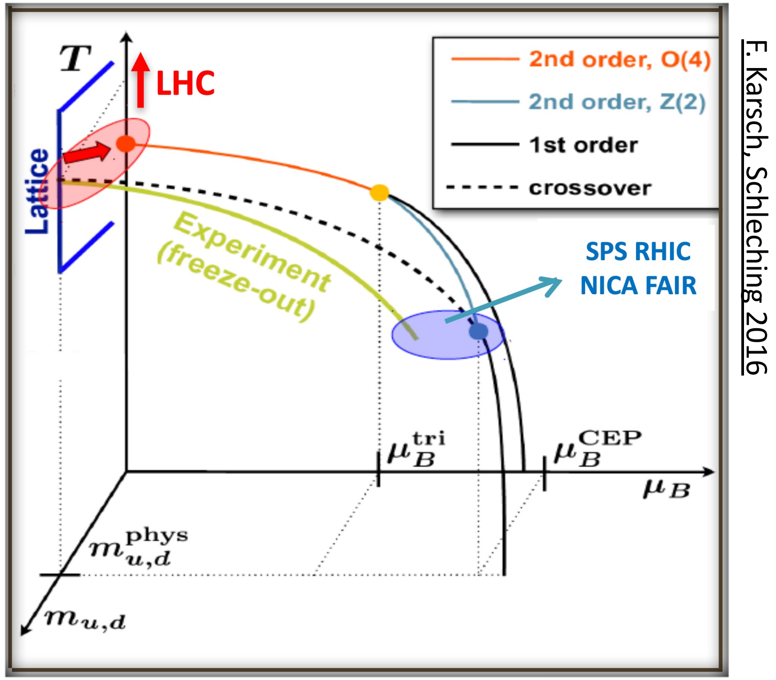


Event-by-event fluctuations of particle multiplicites:

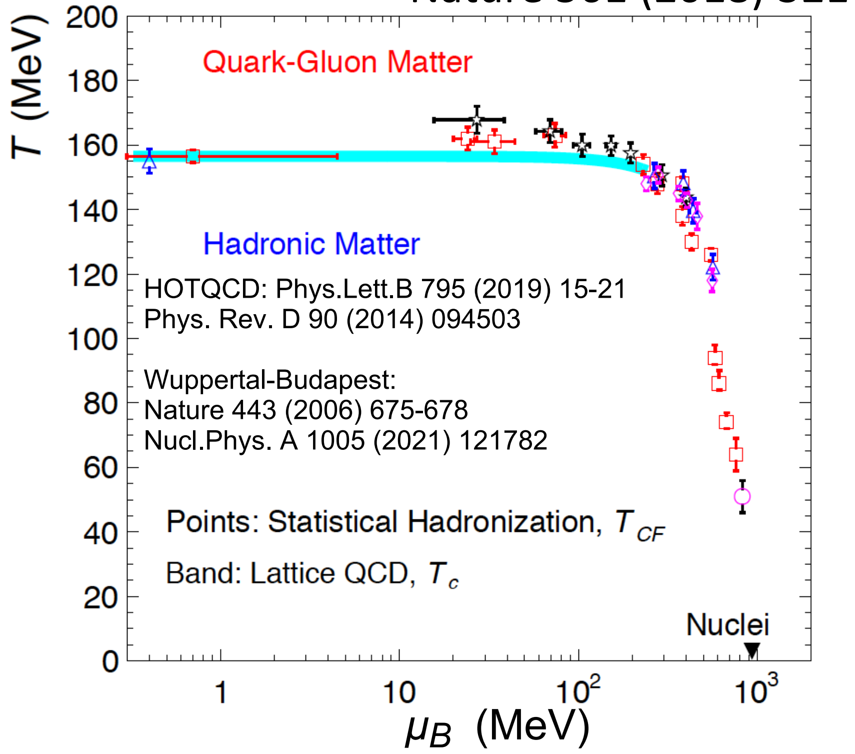
- probe the properties and phase structure of strongly-interacting matter, probing the nature of phase transition;
- are ideal to study thermodynamics of the produced system;
- test lattice QCD predictions at μ_B=0;
- complementary to RHIC Beam Energy Scan Program, FAIR, NICA, and J-PARC.

Nature of chiral phase transition

Lattice QCD calculations



Nature 561 (2018) 321



- Critical behavior in the limit of vanishing light quark masses --- the chiral Phase Transition
- Vanishing u, d quark masses
  $\Longrightarrow$ vicinity to 2nd order O(4) criticality
  $\Longrightarrow$ pseudocritical features at the crossover

➢ Quantitative **agreement** of chemical freeze-out parameters **with the most recent LQCD predictions** for $\mu_B < 300$ MeV

$$\Longrightarrow T_{pc}^{LQCD} \approx T_{fo}^{ALICE} = 156.5 \pm 3\ MeV$$

PLB 795 (2019) 15, PRL 125 (2020) 052001

Lattice QCD meets experiment

Thermodynamic susceptibilities (response of a thermalized system to changes in external conditions): **conserved charge fluctuations**

- **Lattice QCD calculations:** Taylor expansion of the QCD pressure:

$$\frac{P}{T^4} = \frac{1}{VT^3} \ln Z(T, V, \mu_B, \mu_Q, \mu_S) \Rightarrow \chi^{BQSC}_{klmn} = \left. \frac{\partial^{(k+l+m+n)}[P(\hat{\mu}_B, \hat{\mu}_Q, \hat{\mu}_S, \hat{\mu}_C)/T^4]}{\partial\hat{\mu}_B^k \partial\hat{\mu}_Q^l \hat{\mu}_S^m \partial\hat{\mu}_C^n} \right|_{\vec{\mu}=0}$$

<u>Deviations from the Baseline:</u>

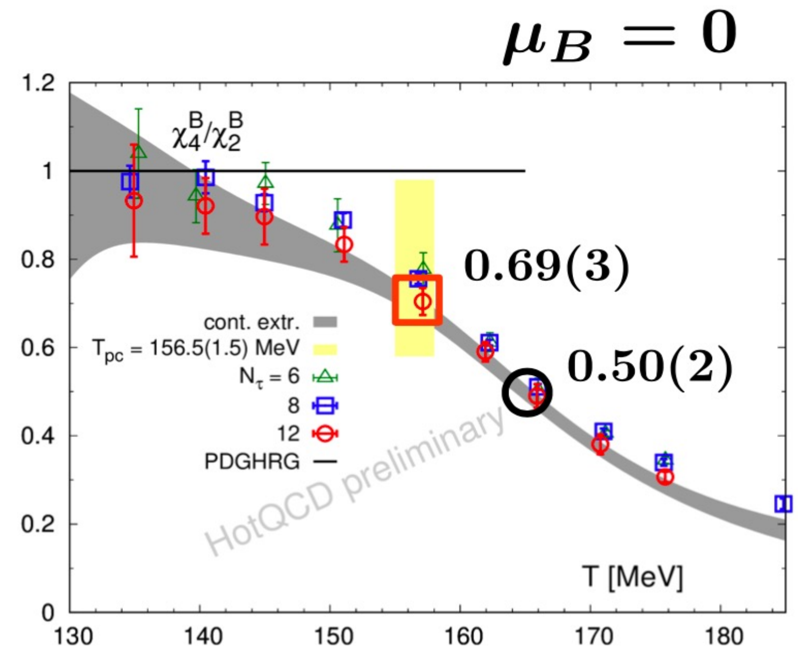
- ○ Baseline: difference of two Skellams: $\boldsymbol{\kappa_n/\kappa_2}$ is 0 (odd) or 1 (even);
- ○ up to 3rd order HRG model agrees with LQCD at μ_B = 0;
- ○ higher order → larger deviations: 4th order ~30%, 6th order ~150%.

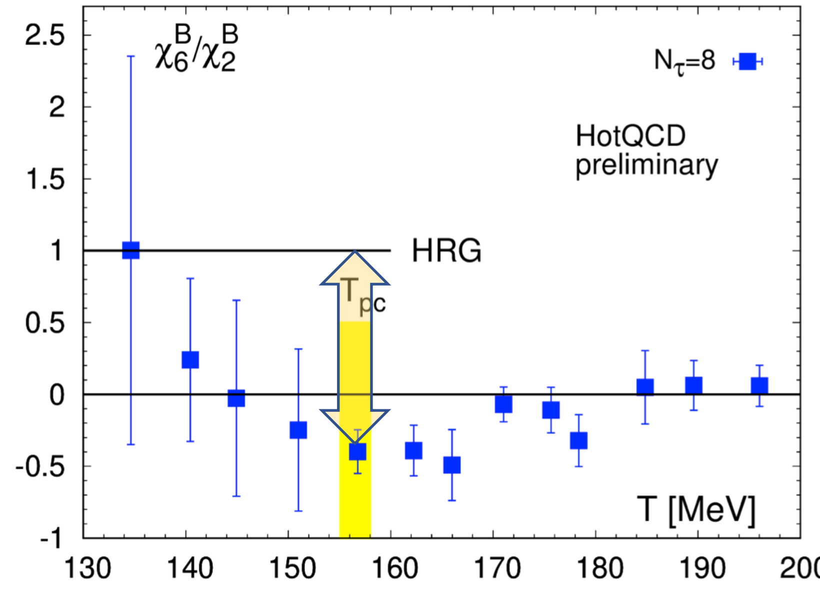
- **Experiment:** within GCE, susceptibilities are related to event-by-event fluctuations of the number of conserved charges.

$\Delta N_B = X = N_B - N_{\bar{B}}$, κ_n → central moments of X

$$\hat{\chi}_2^B = \frac{\kappa_2(\Delta N_B)}{VT^3} \Rightarrow \frac{\kappa_4(\Delta N_B)}{\kappa_2(\Delta N_B)} = \frac{\hat{\chi}_4^B}{\hat{\chi}_2^B}$$

Cumulants **Higher orders**



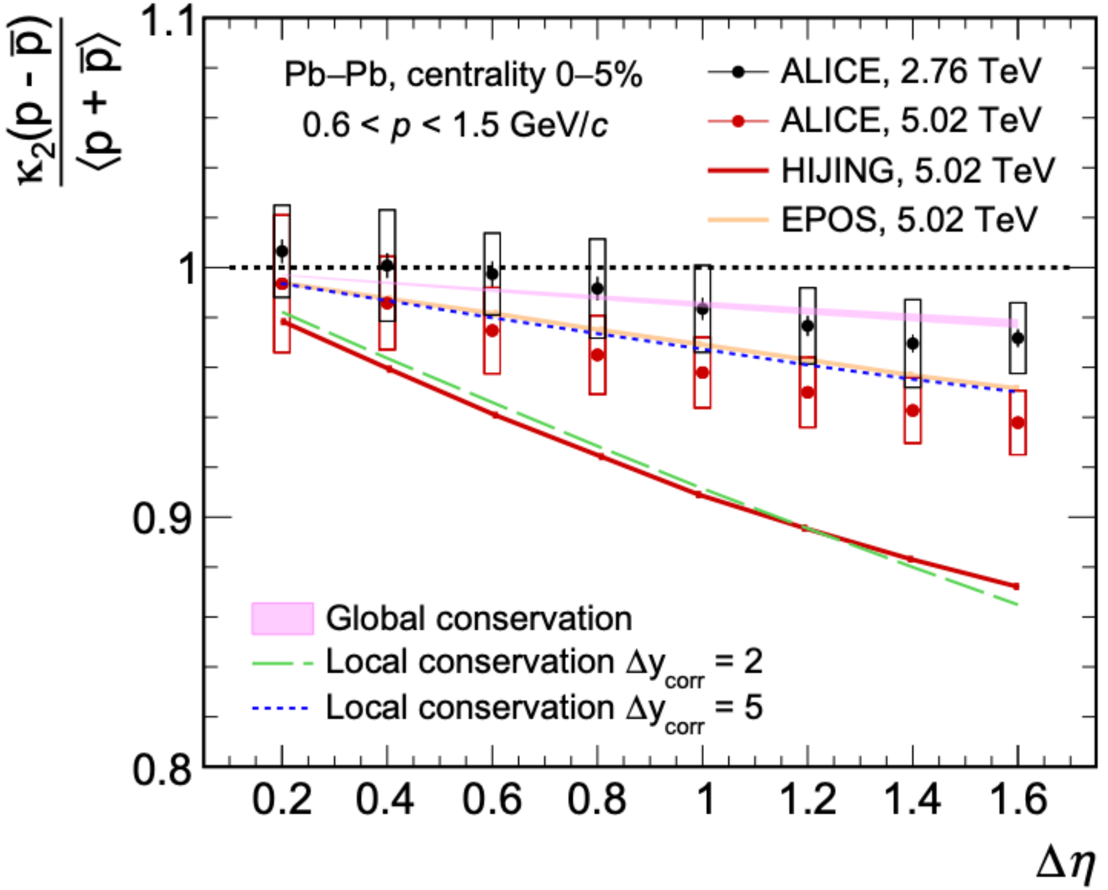


Phys. Rev. D 95 (2017), 054504

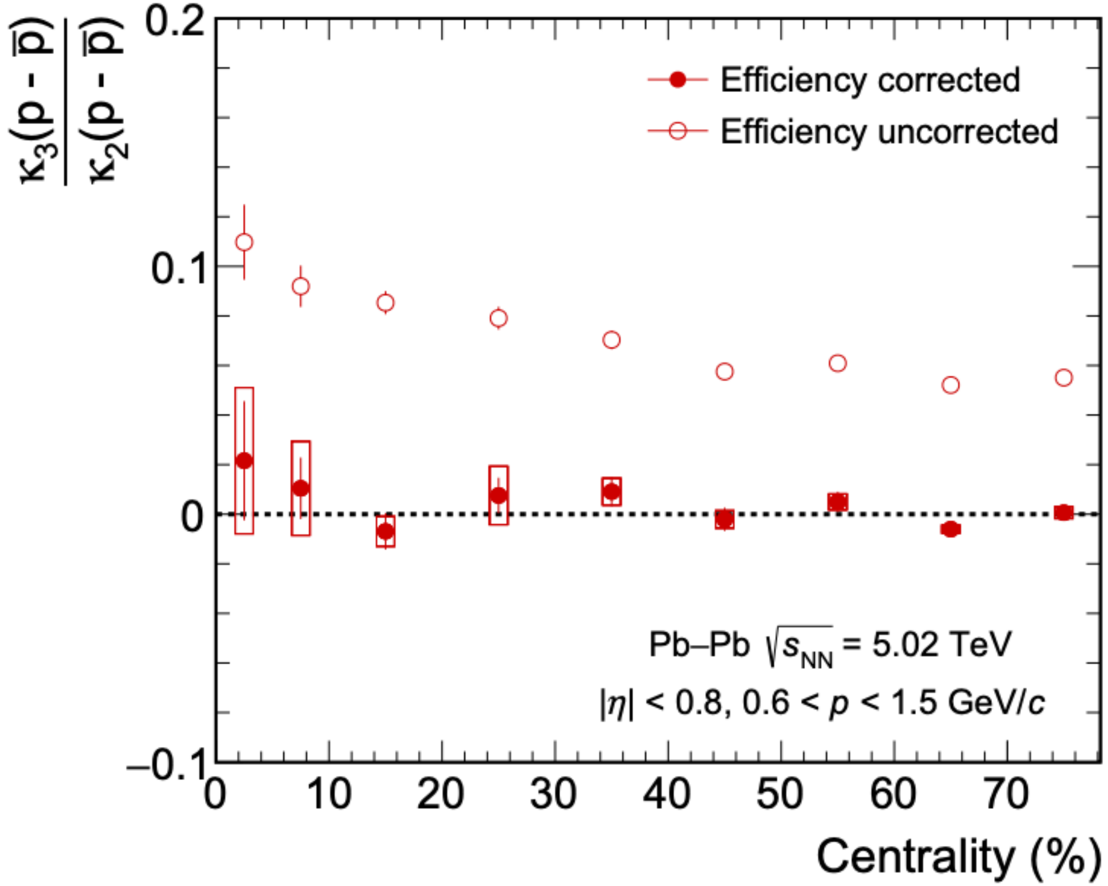
Net-proton fluctuations

ALICE collaboration, arXiv: 2206.03343

2nd order cumulants



3rd order cumulants

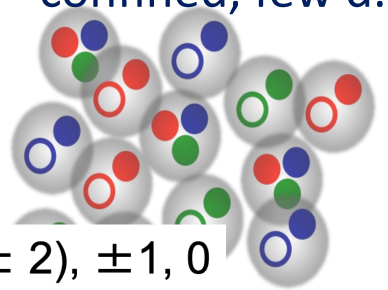


- 2nd order: **Deviation from Skellam baseline due to Baryon number conservation**
- long-range correlations ($\Delta\eta$ about ±2.5) originating from earlier in time

- 3rd order: data agree with Skellam baseline "0"

Net-charge fluctuations

Hadron gas:
confined, few d.o.f

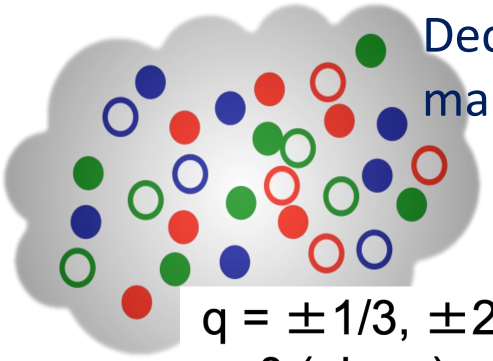


q = (± 2), ±1, 0

Dynamical net-charge fluctuations:

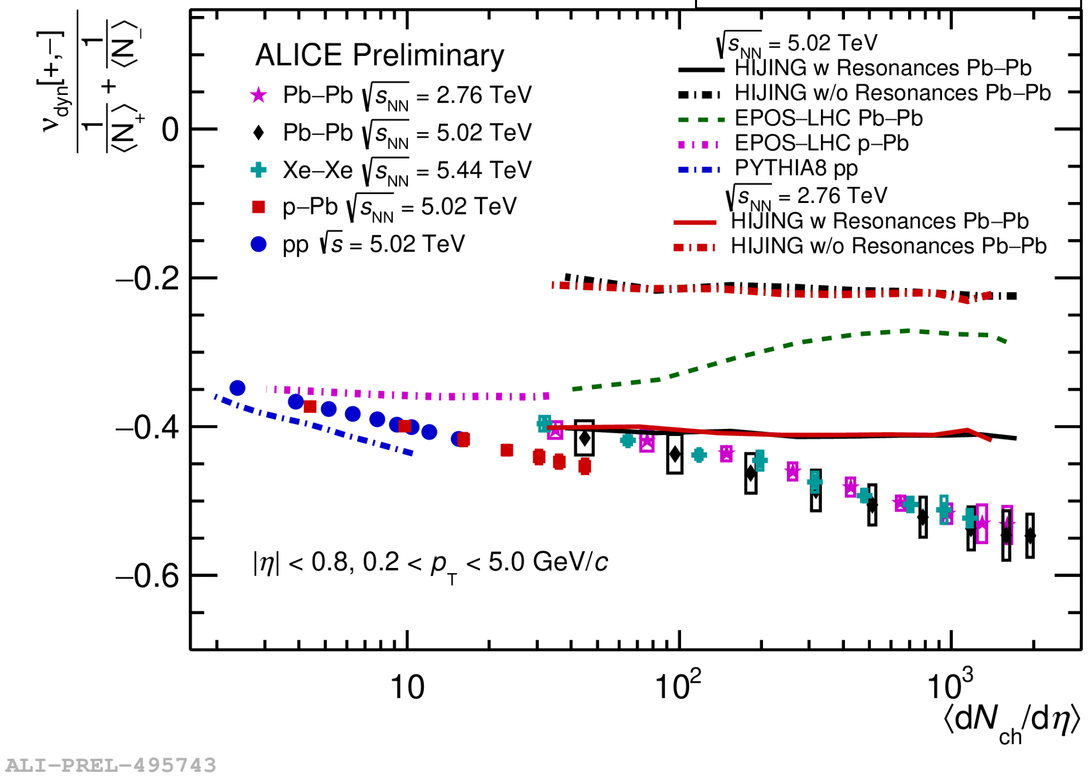
$$\nu_{[+-,dyn]} = \frac{\langle N_+(N_+-1)\rangle}{\langle N_+\rangle^2} + \frac{\langle N_-(N_--1)\rangle}{\langle N_-\rangle^2} - 2\frac{\langle N_+N_-\rangle}{\langle N_+\rangle\langle N_-\rangle}$$

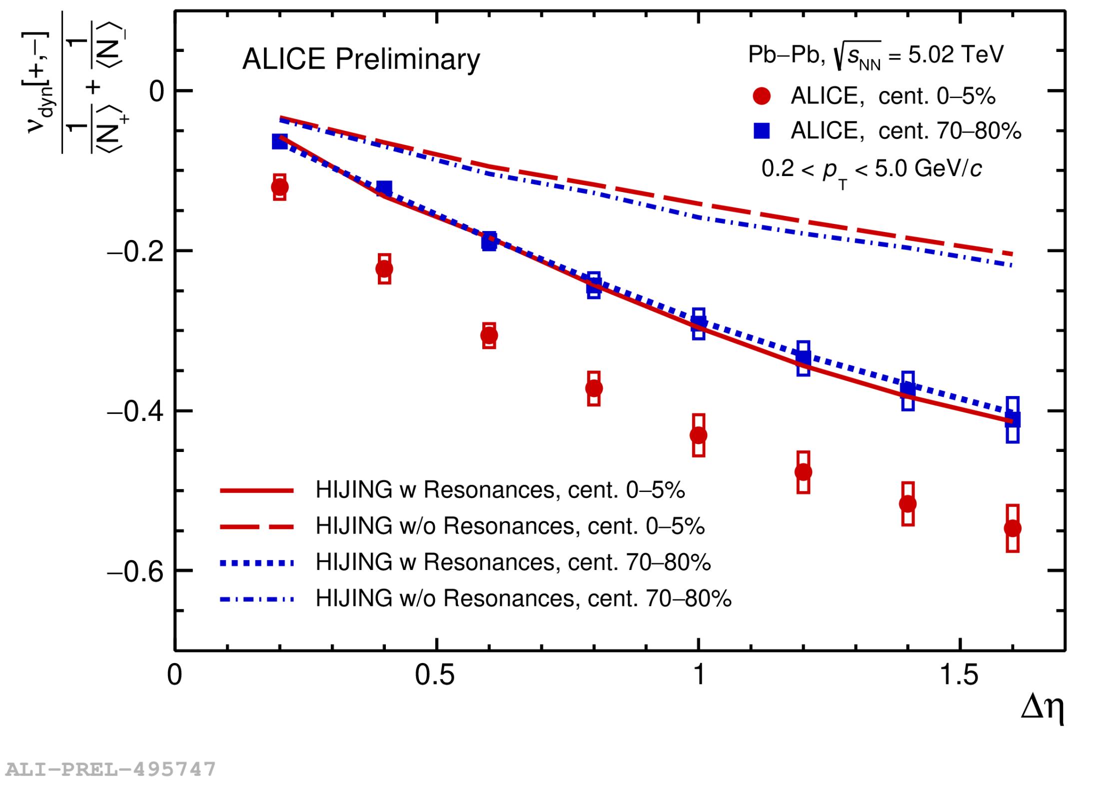
Deconfined:
many d.o.f.



q = ±1/3, ±2/3 (quark)
or 0 (gluon)

ALICE Preliminary

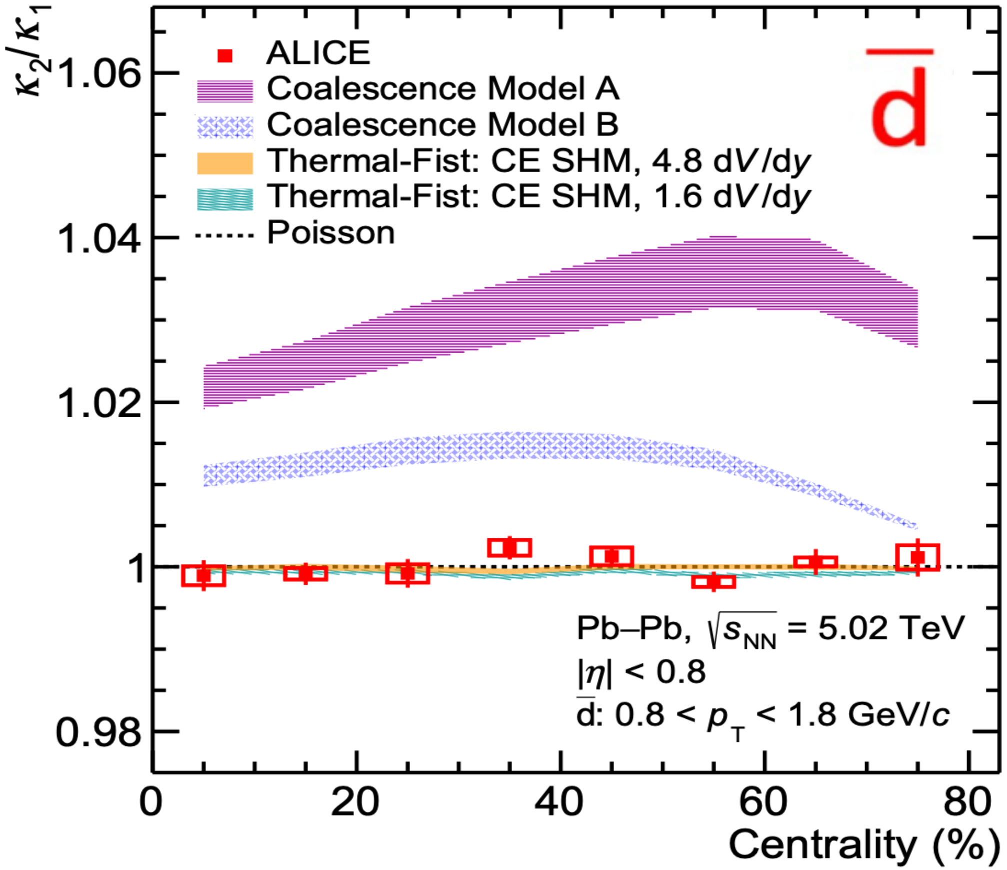




- Scaled $\nu_{dyn}[+,-]$ shows increasing correlations with increasing multiplicity for all systems,
- net-charge fluctuations are strongly dominated by resonance contributions.

Anti-deuteron number fluctuations

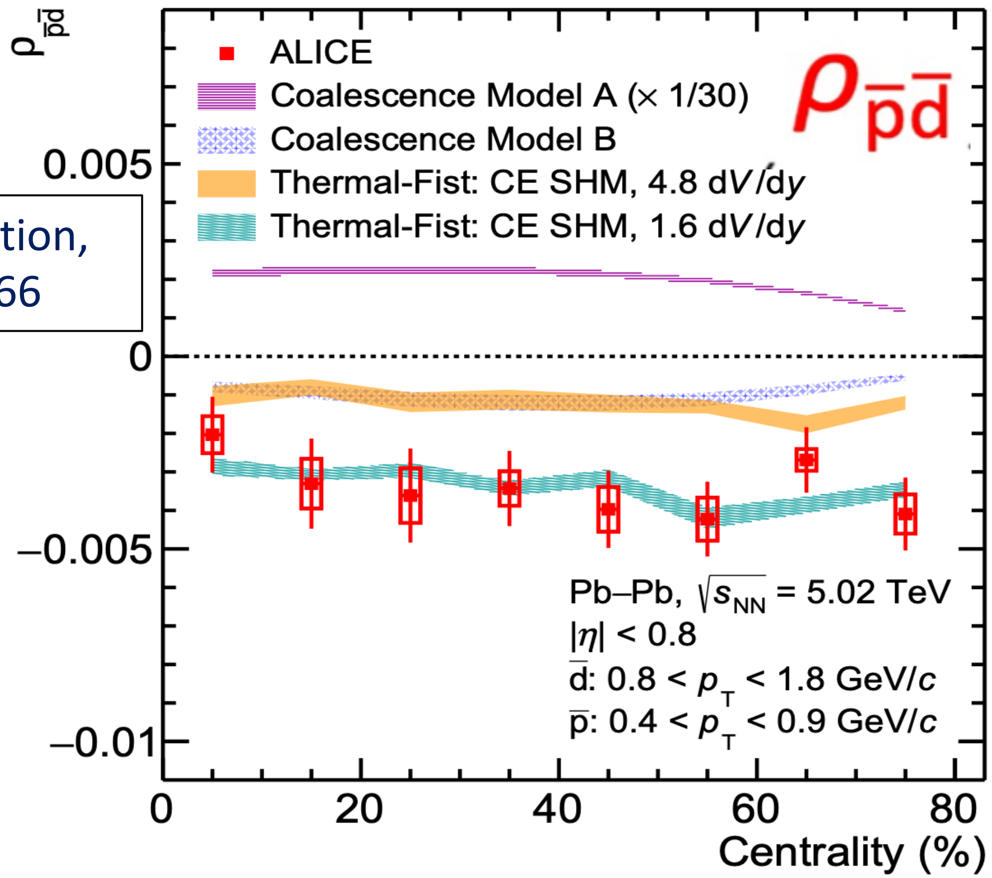
- to distinguish between nucleosynthesis models (thermal *vs*. coalesence)



ALICE collaboration, arXiv:2204.10166

Antiproton-antideuteron Pearson correlation

$$\rho_{ab} = \langle (n_a - \langle n_a \rangle)(n_b - \langle n_b \rangle) \rangle / \sqrt{\kappa_{2a}\kappa_{2b}}$$



- Anti-deuteron fluctuation is consistent with Poisson baseline,
- canonical Ensemble (CE) SHM consistent with data, with no significant effect of baryon number conservation.

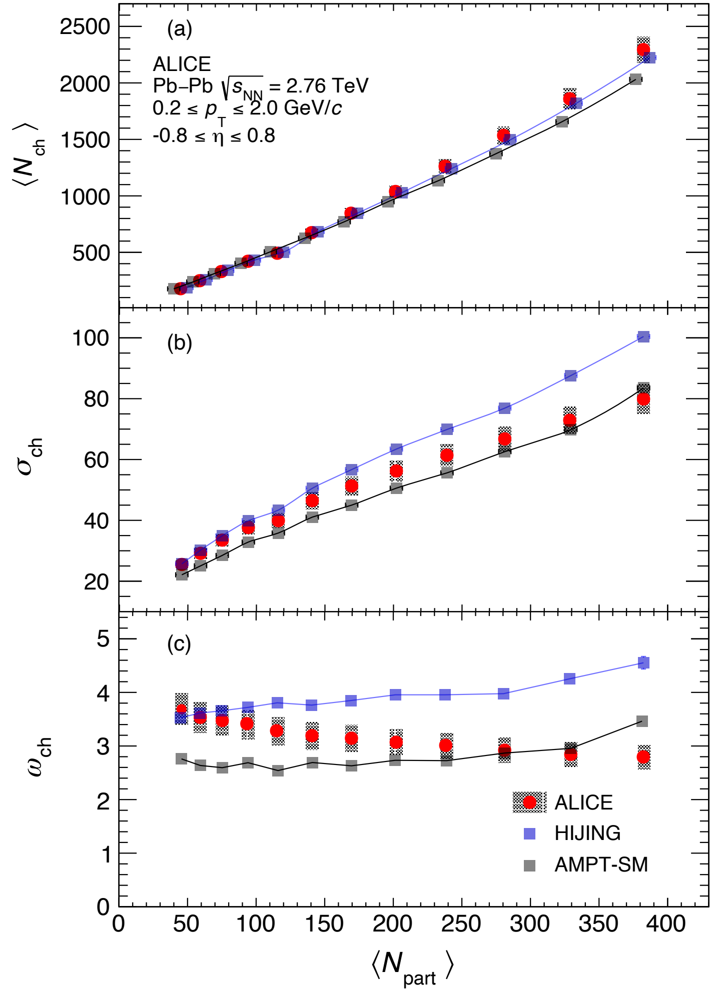
- Negative correlation: in events with at least one anti-deuteron, O(0.1%) less antiprotons than an average event.

Multiplicity fluctuations

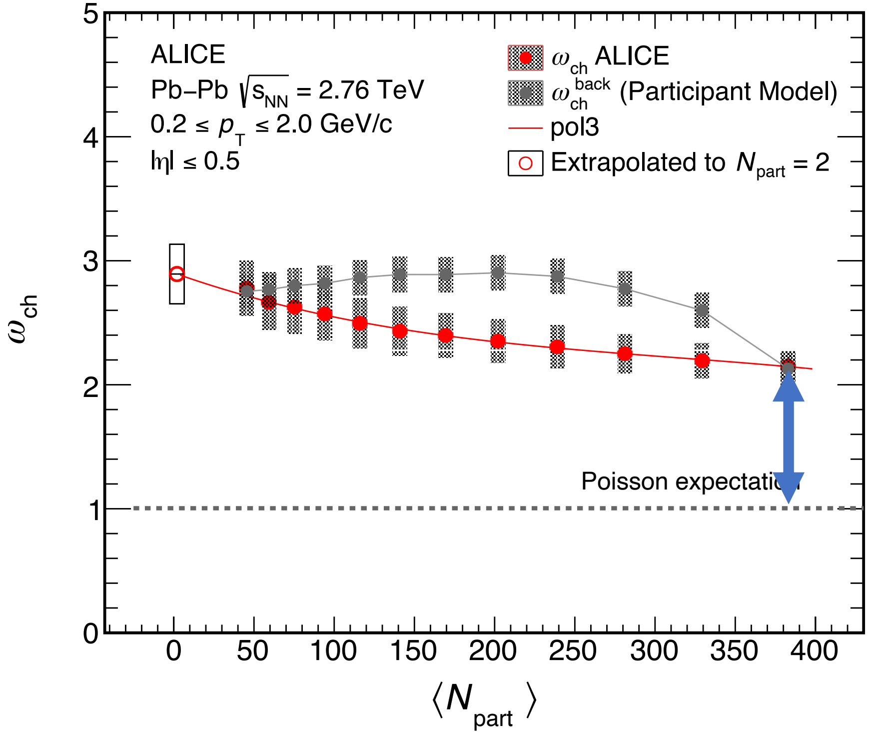
⇒ **Isothermal compressibility (**expresses how a system's volume responds to a change in the applied pressure.)

Charged-particle multiplicities

ALICE collaboration: EPJC 81 (2021) 1012



$$\omega_{\rm ch} = \frac{k_{\rm B} T \langle N_{\rm ch} \rangle}{V} k_T$$



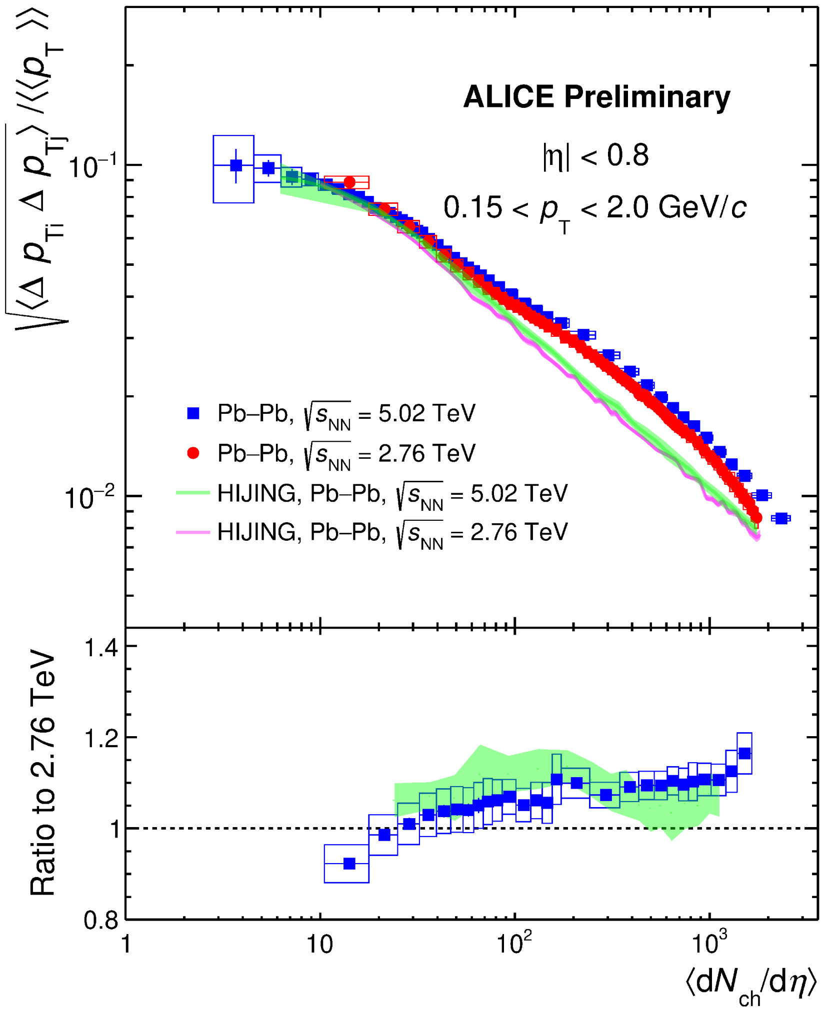
For central collisions:
- T_{ch} = 0.156 ± 0.002 GeV
- Volume= 5330 ± 505 fm^3
- $\langle N_{ch} \rangle$ = 1410 ± 47 (*syst*)

- Fluctuations above the Poisson estimation gives ω_{ch} = 1.15 ± 0.06.

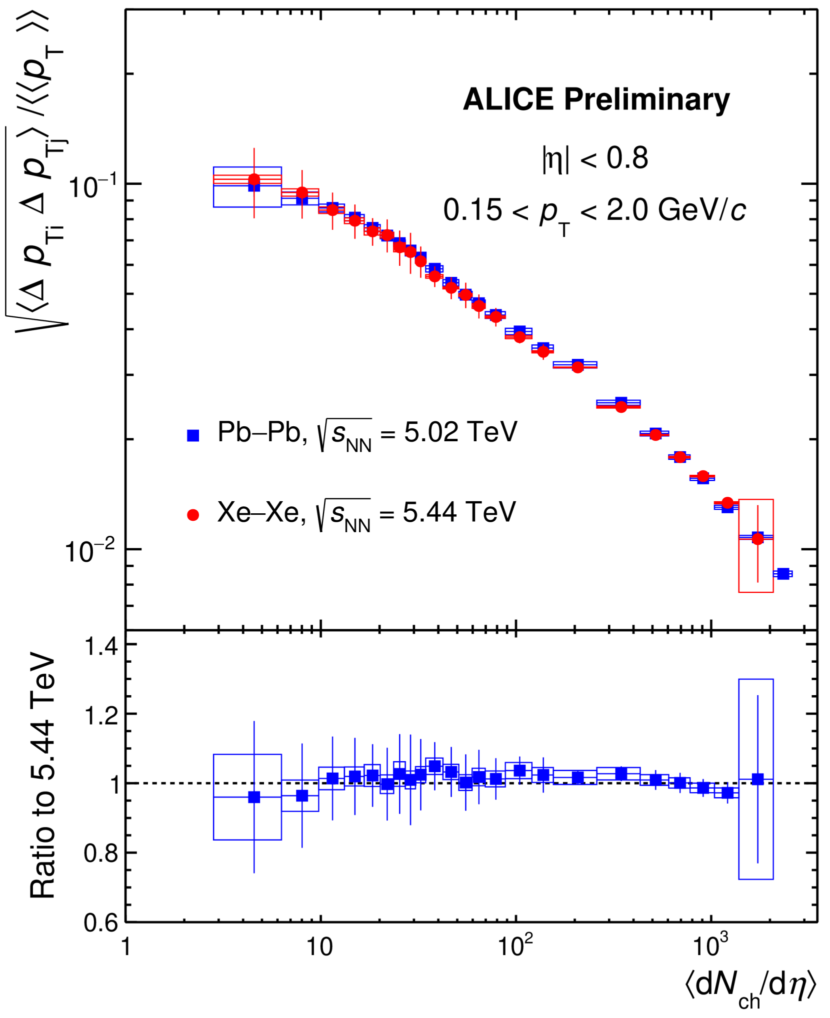
=> k_T upper limit = 27.9 ± 3.18 fm^3/GeV.

Fluctuations of mean p_T

- results from fluctuations of the energy of the fluid when the hydrodynamic expansion starts.
- $\langle p_T \rangle$ is a proxy to the system temperature => measure of **temperature fluctuations ⇒ heat capacity**.



ALI-PREL-526955



ALI-PREL-526499

ALICE Preliminary

$$\langle \Delta p_i \Delta p_j \rangle = \left\langle \frac{\sum_{i,j\neq i} (p_i - \langle p_T \rangle)(p_j - \langle p_T \rangle)}{N_{ch}(N_{ch} - 1)} \right\rangle$$

Scaled variance: $\sqrt{\langle \Delta p_{Ti} \Delta p_{Tj} \rangle} / \langle \langle p_T \rangle \rangle$

- Fluctuations decrease with increasing multiplicity and increase w/t beam energy.

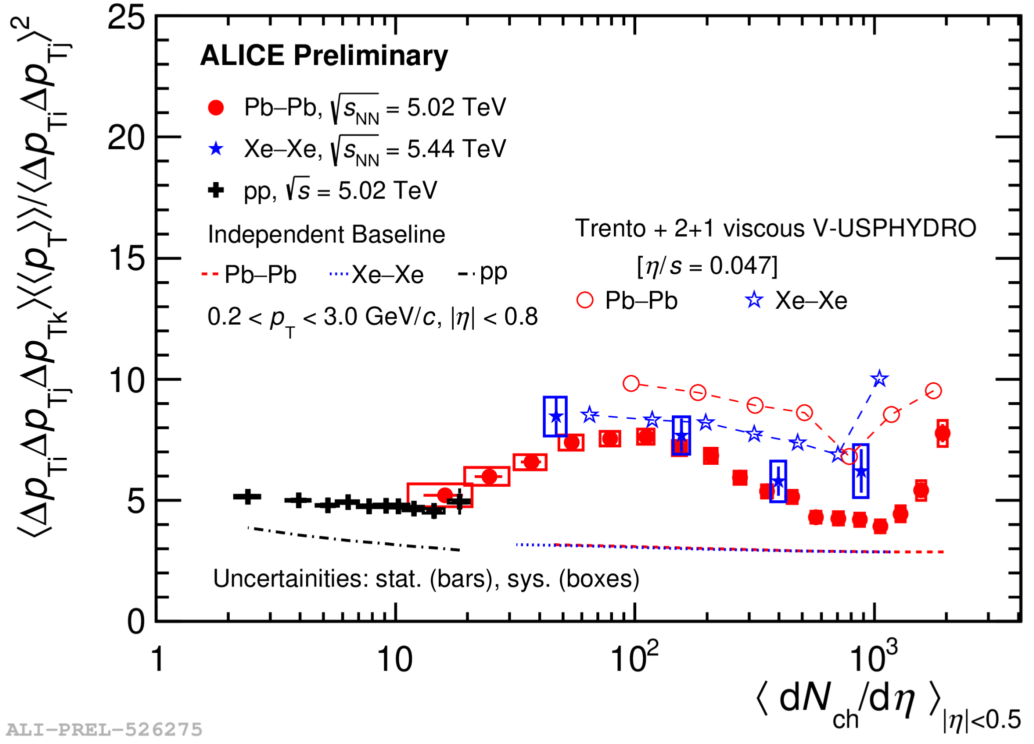
Higher-order fluctuations of mean p_T

⇒ detailed probes of QCD thermodynamics at higher T, achieved during the early stages of the collision.

ALICE Preliminary

Skewness (3-particle correlator):

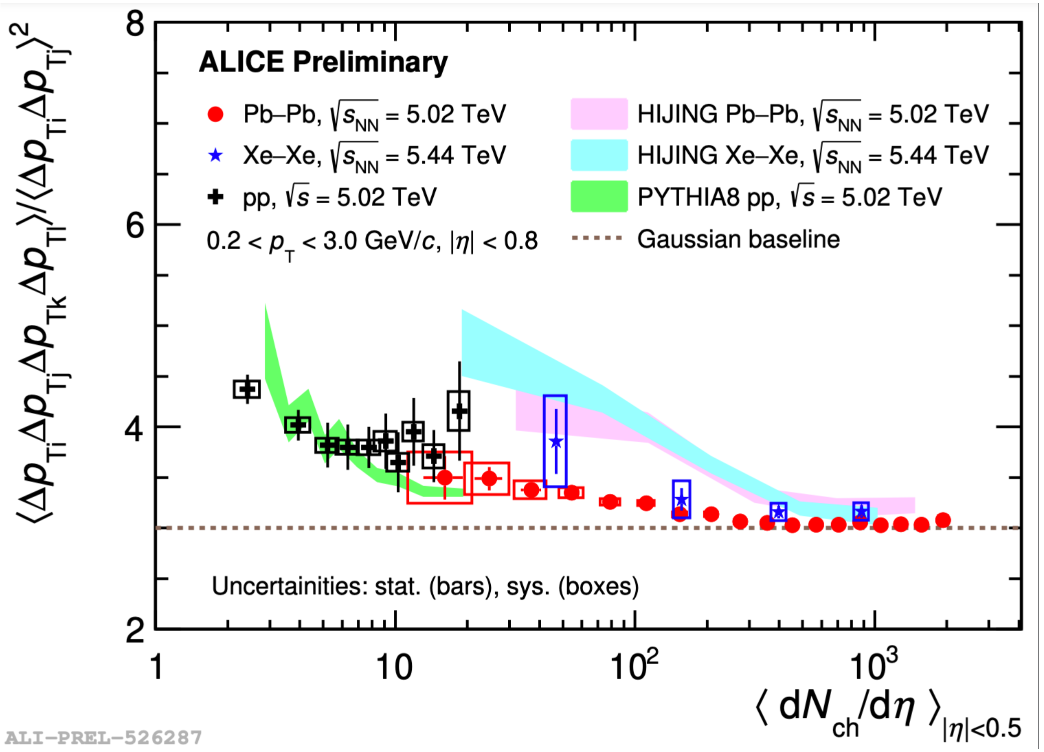
$$\langle \Delta p_i \Delta p_j \Delta p_k \rangle \equiv \left\langle \frac{\sum_{i,j\neq i,k\neq i,j} (p_i - \langle\langle p_t \rangle\rangle)(p_j - \langle\langle p_t \rangle\rangle)(p_k - \langle\langle p_t \rangle\rangle)}{N_{\rm ch}(N_{\rm ch}-1)(N_{\rm ch}-2)} \right\rangle$$



- Positive intensive skewness excess from its baseline value observed - indicates hydrodynamic evolution.

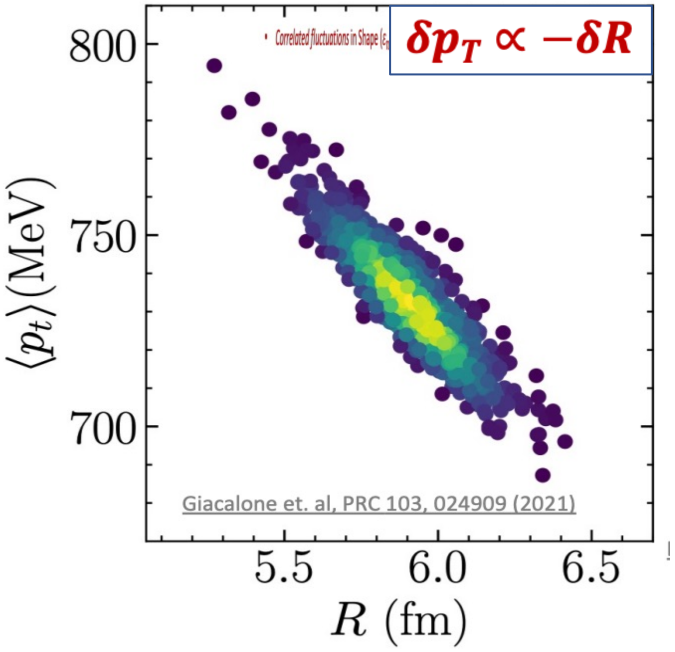
Kurtosis (4-particle correlator):

$$\langle \Delta p_i \Delta p_j \Delta p_k \Delta p_l \rangle \equiv \left\langle \frac{\sum_{i,i\neq j\neq k\neq l}^{N_{ch}} (p_i - \langle\langle p_{\rm T} \rangle\rangle)(p_j - \langle\langle p_{\rm T} \rangle\rangle)(p_k - \langle\langle p_{\rm T} \rangle\rangle)(p_l - \langle\langle p_{\rm T} \rangle\rangle)}{N_{ch}(N_{ch}-1)(N_{ch}-2)(N_{ch}-3)} \right\rangle$$



- Mild dependence on multiplicity,
- Approaches Gaussian baseline at high multiplicities.

Accessing precursor stage of QGP formation



Correlated fluctuations in shape (ε_n) and size (R) in the initial state: measured using Pearson Correlation:

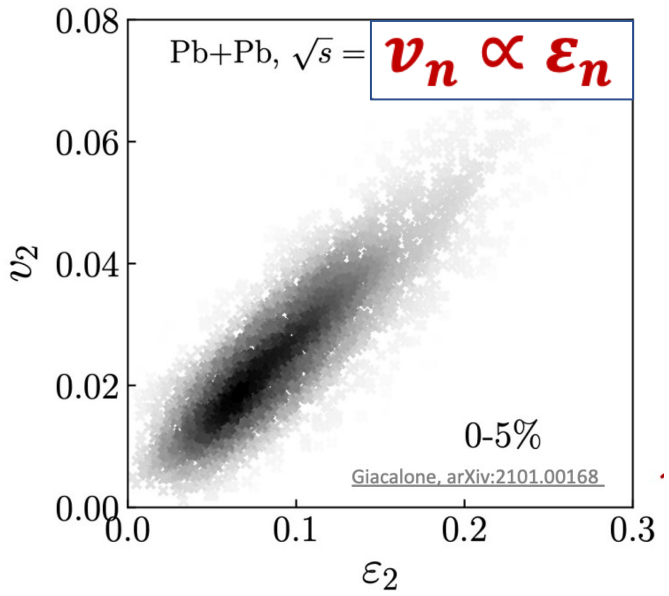
$$\rho(\epsilon_n^2, \delta R) = \frac{cov(\epsilon_n^2, \delta R)}{\sqrt{var(\epsilon_n^2) var(\delta R)}}$$

Initial State to Final State

$$cov(v_n^2, \delta p_T) = \langle\langle v_n^2, \delta p_T \rangle\rangle$$

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

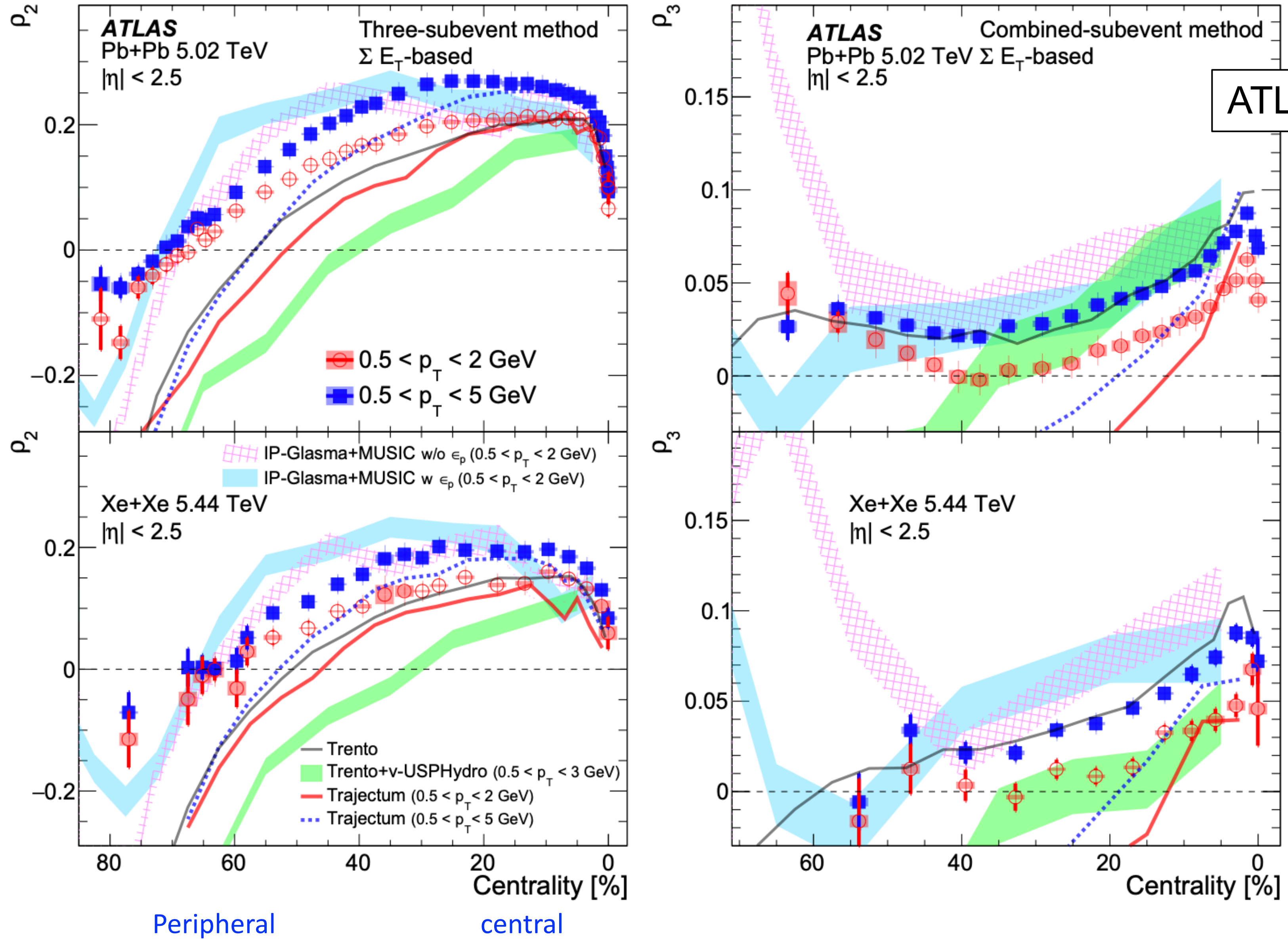
$$var(v_n^2\{2\}) = \langle v_n^4 \rangle - \langle v_n^2 \rangle^2 \qquad var(\delta p_T) = \langle\langle \delta p_T \delta p_T \rangle\rangle$$



=> v_n - mean-p_T correlations

(i) Constrain the initial state, and
(ii) nuclear deformation.

v_n – mean p_T correlations

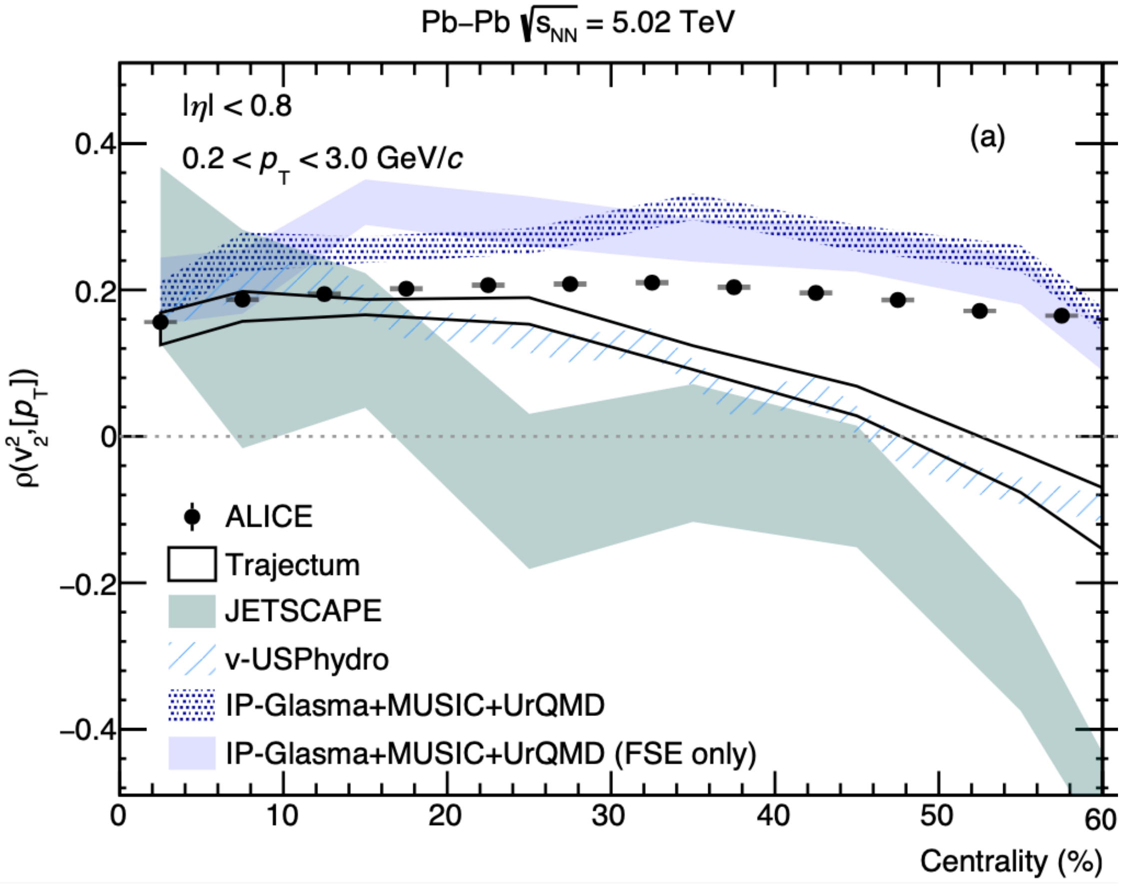


ATLAS collaboration, arXiV: 2205.00039

- ρ_2 has a geometric origin, ρ_3 originates mostly from fluctuations.
- ρ_n depends mildly on centrality fluctuations and final state p_T and η ranges, suggesting they are dominated by initial states.
- the comparison of the model to the Xe–Xe data suggests that the Xe nucleus is a triaxial ellipsoid.

v_n – mean p_T correlations

ALICE collaboration, PLB 834 (2022) 13793

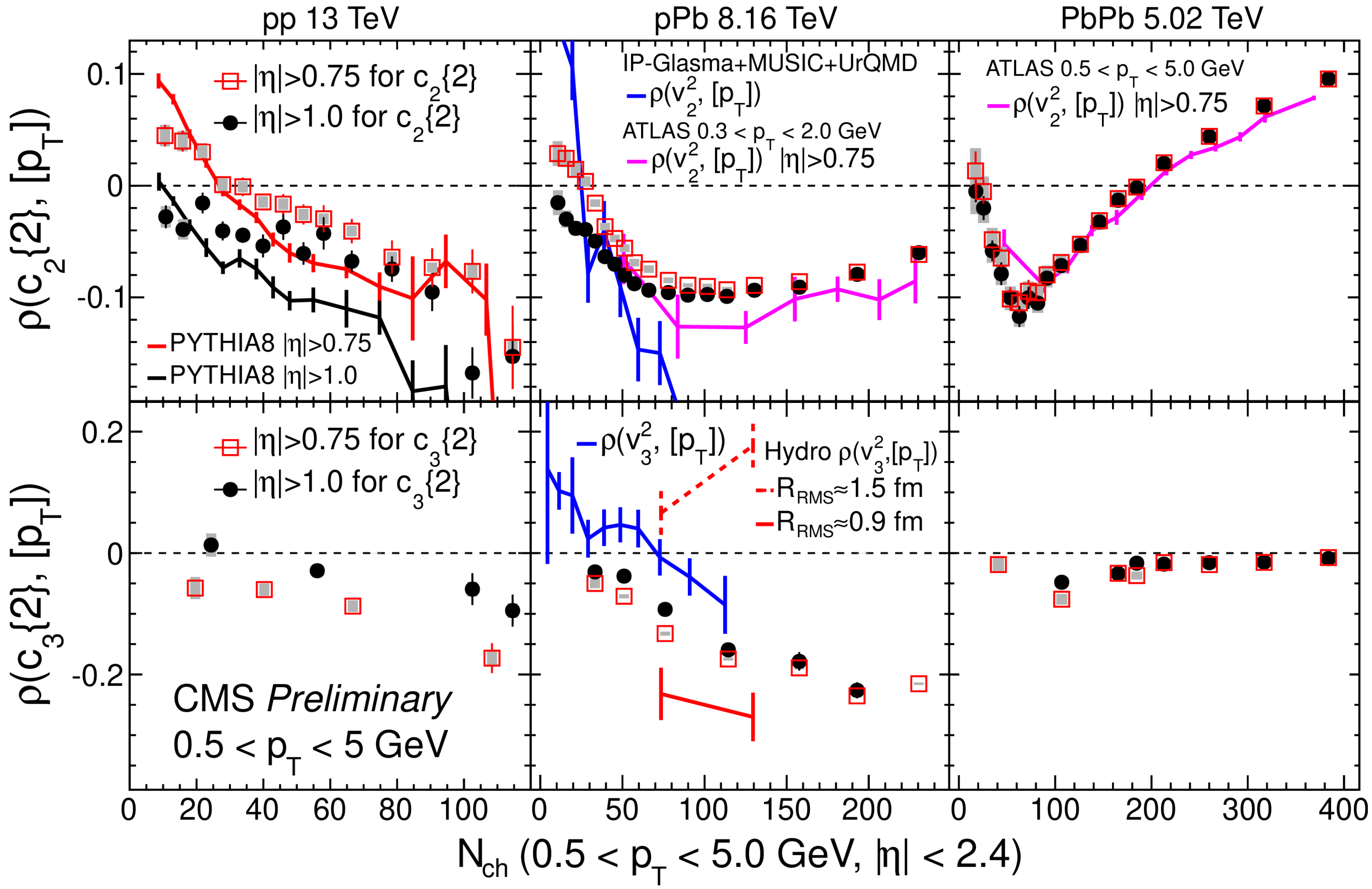


Central Peripheral

- Data shows positive correlation between v_n and $p_{T,}$
- The centrality dependence of ρ is better described by IP-Glasma than by Trento,
- These are sensitive to the nucleon width parameter (size of nucleon) => new constraints on the nucleon size,
- ALICE data agrees with an effective nucleon width of the order of 0.4 fm => transverse radius of 0.56 fm.

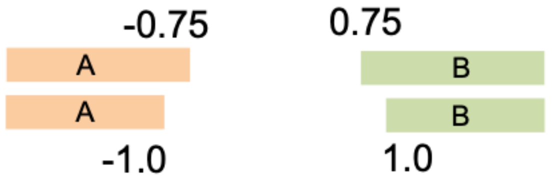
v_n – mean p_T correlations

CMS collaboration, CMS-PAS-HIN-21-012



Peripheral central

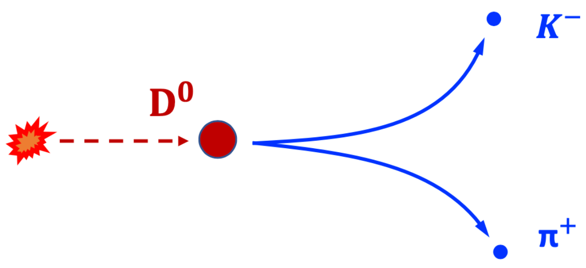
- Explore the correlator with different η gaps to study nonflow effects



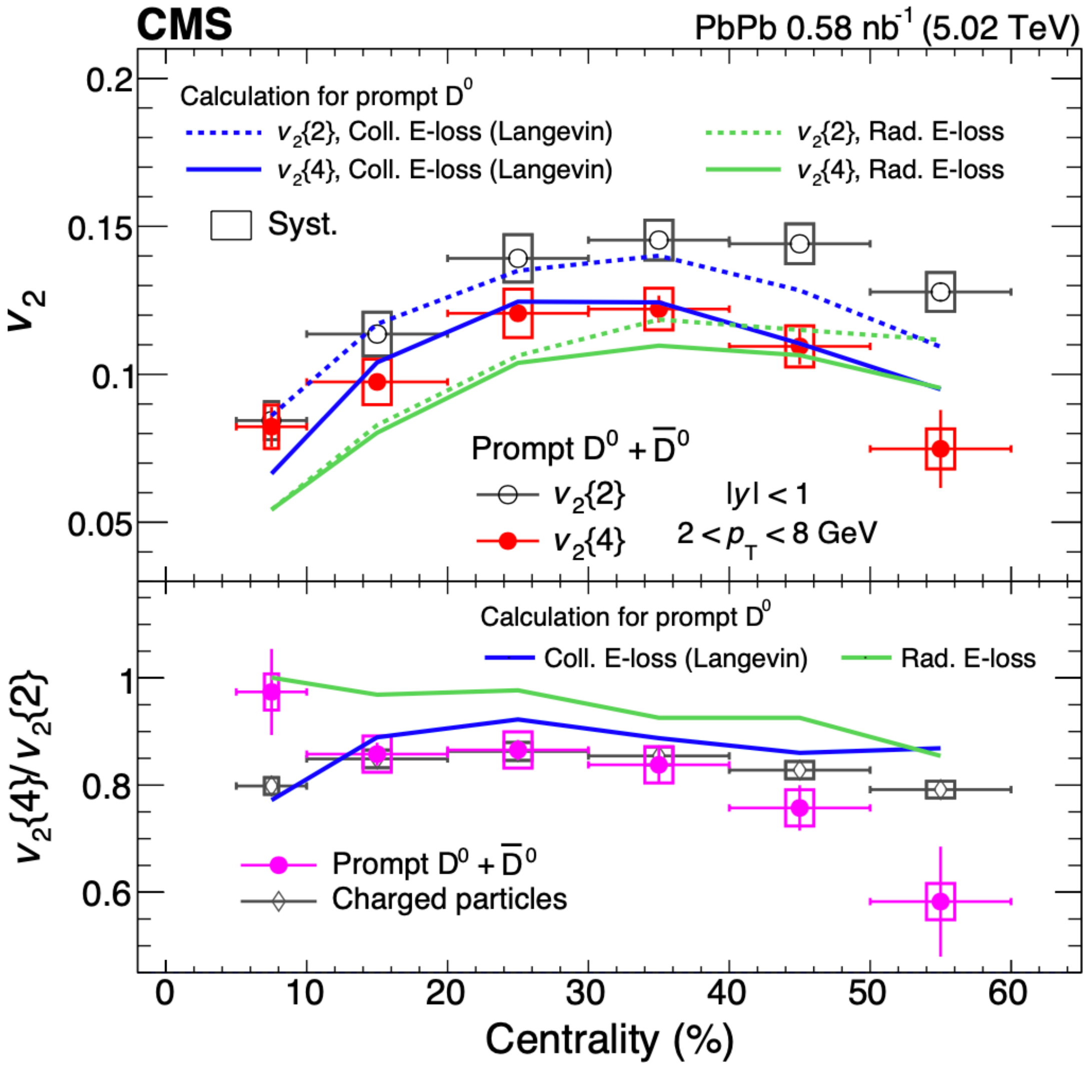
- apparent sign change is observed for $\rho(c_2\{2\}, [p_T])$ in pp and p–Pb,
- no sign change is observed in case of $|\eta|>1.0$,
- positive correlation at high multiplicities.

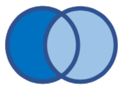
Fluctuations of charm quark azimuthal anisotropies

CMS collaboration, PRL 129 (2022) 022001



- Two-particle correlations: $v_2\{2\} \simeq \langle v_2 \rangle + \frac{1}{2}\frac{\sigma_{v_n}^2}{\langle v_2 \rangle}$
- Four-particle correlations: $v_2\{4\} \simeq \langle v_2 \rangle - \frac{1}{2}\frac{\sigma_{v_n}^2}{\langle v_2 \rangle}$





- D^0 compatible with charged hadrons in 10-40% centrality:
  - suggesting that initial fluctuations are dominant,
- indication of discrepancies in more peripheral collisions:
  - potential final-state effects.

Summary and outlook

- **Event-by-event fluctuations of conserved charges:**
  - effect of baryon number conservation to be understood.
- **Anti-deuteron fluctuation and correlation with anti-proton:**
  - coalescence models do not simultaneously describe both observables;
  - SHM: simultaneously describe both but with a small correlation volume.
- **Multiplicity fluctuation** => upper limit on isotheral compressibility.
- **Mean-p_T fluctuations** decrease with increasing multiplicity.
- **Higher-order fluctuations of mean-p_T :**
  - positive intensive skewness indicates hydrodynamic evolution.
- **v_n – mean p_T correlations:**
  - apparent sign change in correlation in pp and p–Pb;
  - positive correlation at high multiplicities;
  - small transverse radius of the nucleon.
- **Fluctuations of charm quark (D^0) azimuthal anisotropies:**
  - compatible with charged hadrons in 10-40% centrality.

The physics program of future experiments provides excellent opportunities for fluctuation measurements with large acceptance + excellent coverage down to low p_T.