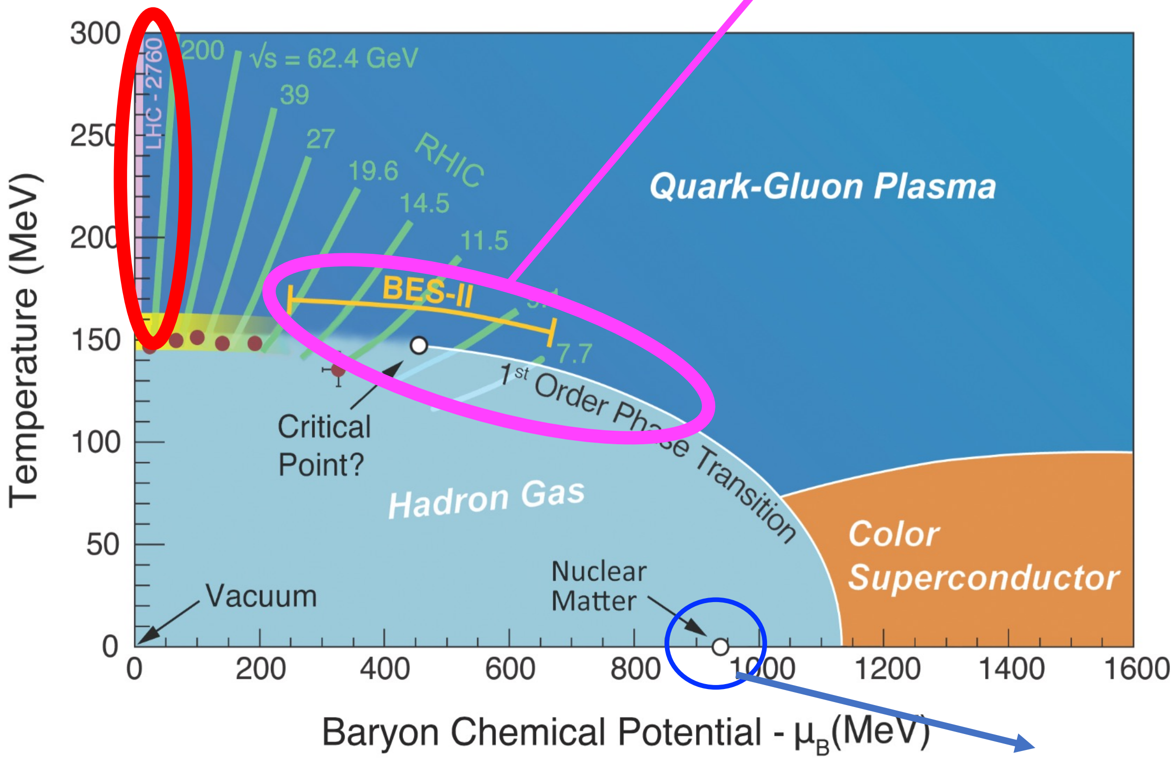
Tapan Nayak

RHIC
LHC (ALICE, **ALICE 3**)

The high-energy frontier

RHIC BES, SPS, SIS,
FAIR, J-PARC, NICA

Matter at high baryon density



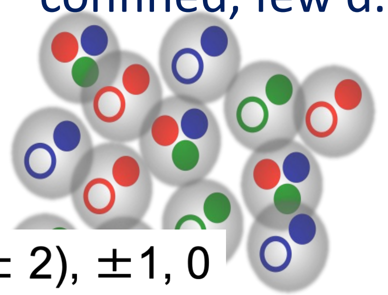
Cold Nuclear Matter

Correlation/Fluctuation techniques are the main tools for:

- Studying the nature of phase transition
- Probing the QCD critical point.

Net-charge fluctuations

Hadron gas:
confined, few d.o.f

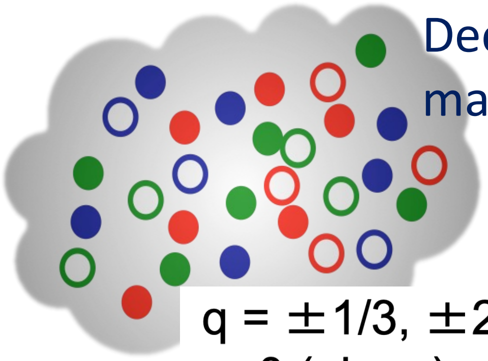


q = (± 2), ±1, 0

Dynamical net-charge fluctuations:

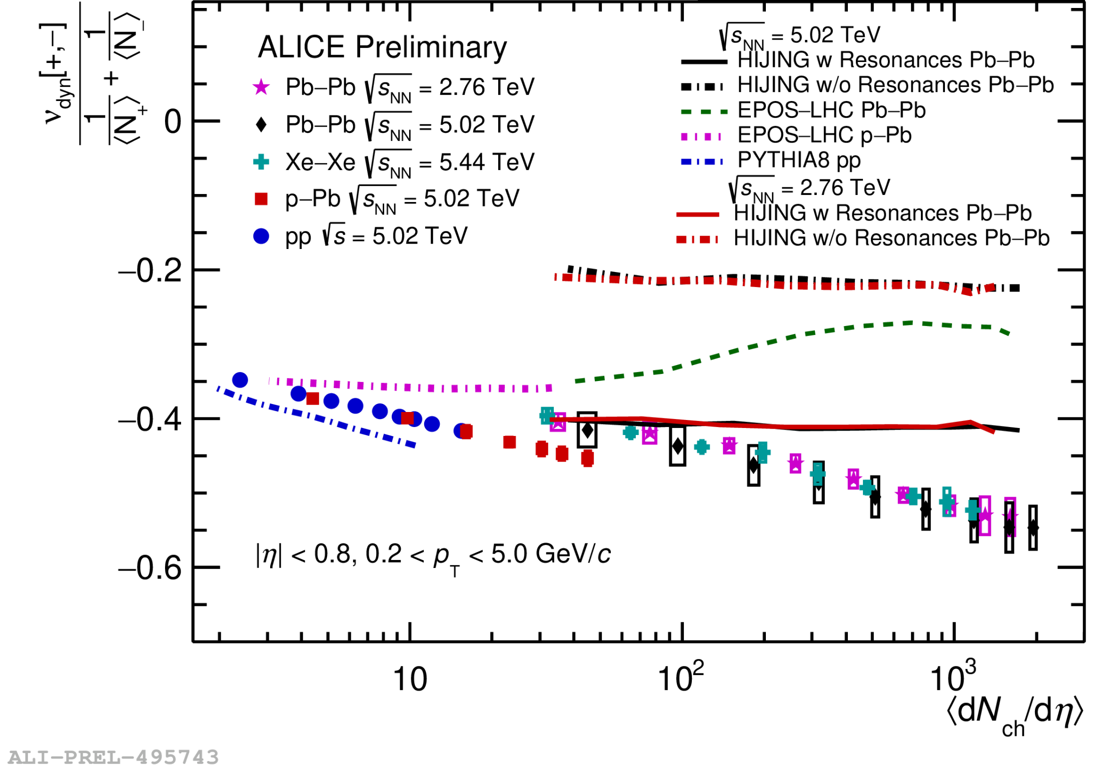
$$\nu_{[+-,dyn]} = \frac{\langle N_+(N_+-1)\rangle}{\langle N_+\rangle^2} + \frac{\langle N_-(N_--1)\rangle}{\langle N_-\rangle^2} - 2\frac{\langle N_+N_-\rangle}{\langle N_+\rangle\langle N_-\rangle}$$

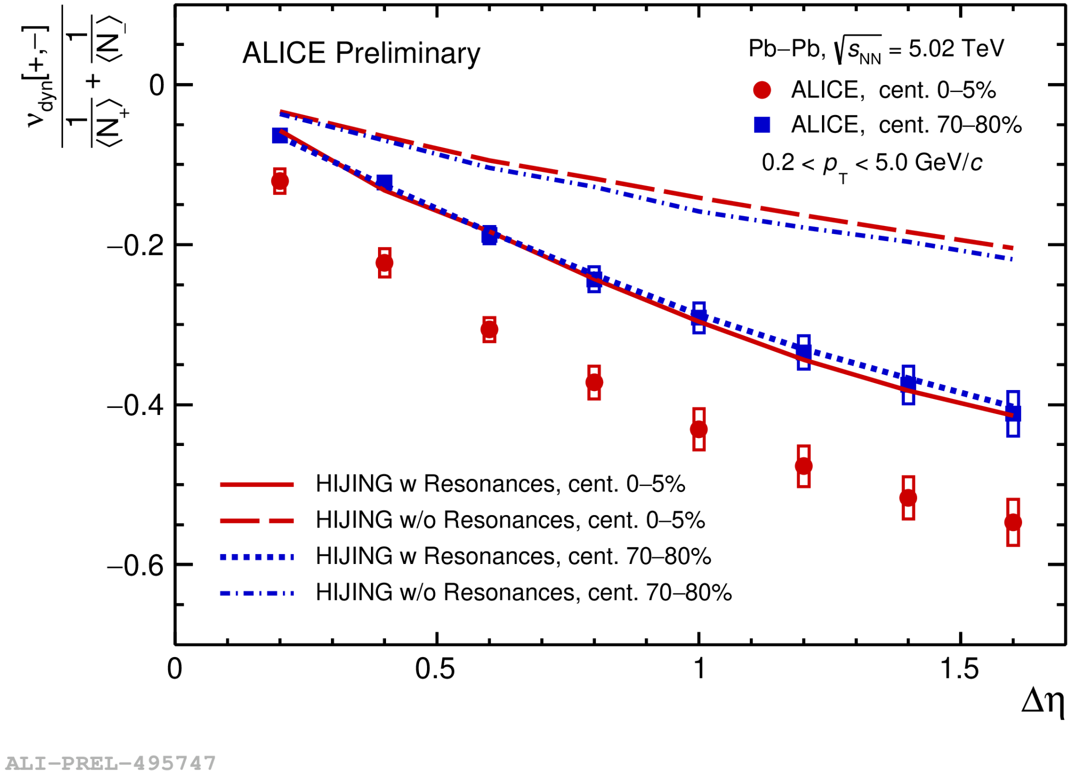
Deconfined:
many d.o.f.



q = ±1/3, ±2/3 (quark)
or 0 (gluon)

ALICE Preliminary





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

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:

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

Deviations from the Baseline:

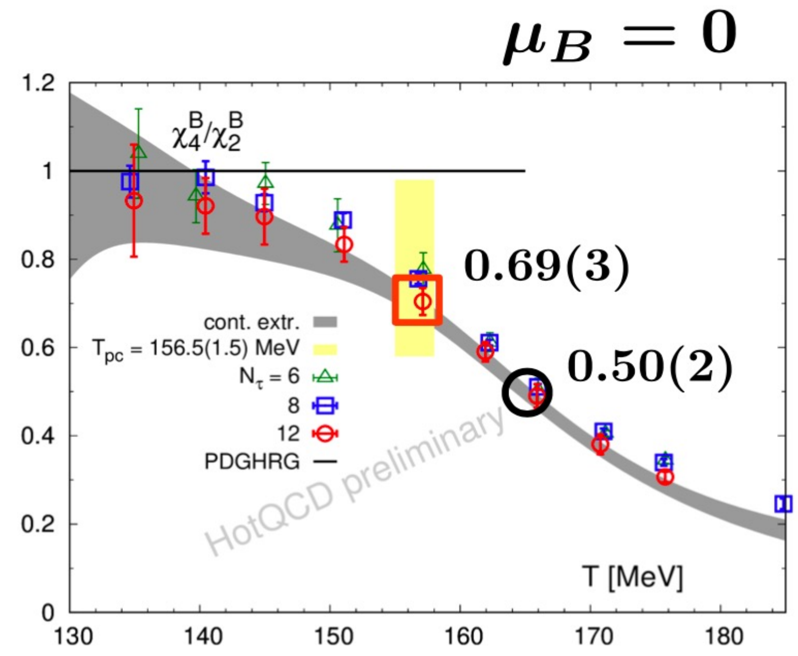
- ○ Baseline: difference of two Skellams: κ_n/κ_2 is 0 (odd) or 1 (even);
- ○ up to 3rd order HRG model agrees with LQCD at $\mu_B = 0$;
- ○ higher order → larger deviations: 4th order ~30%, 6th order ~150%.

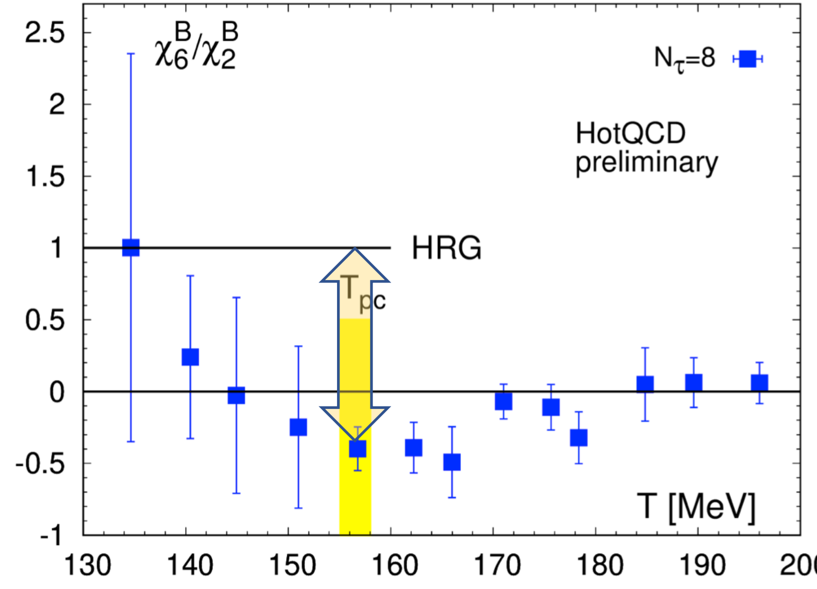
- **Experiment:** within GCE, susceptibilities are related to event-by-event fluctuations of the number of conserved charges.

$\Delta N_B = X = N_B - N_{\bar{B}}$, 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**



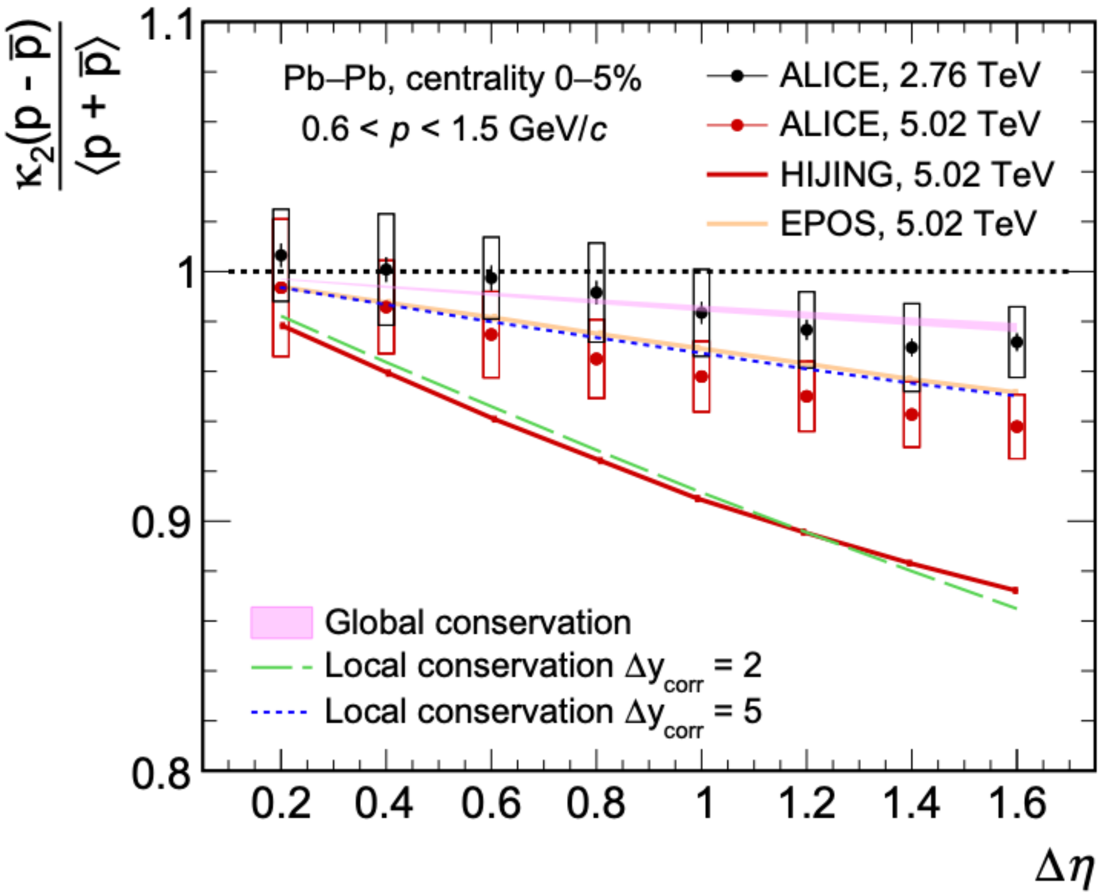


Phys. Rev. D 95 (2017), 054504

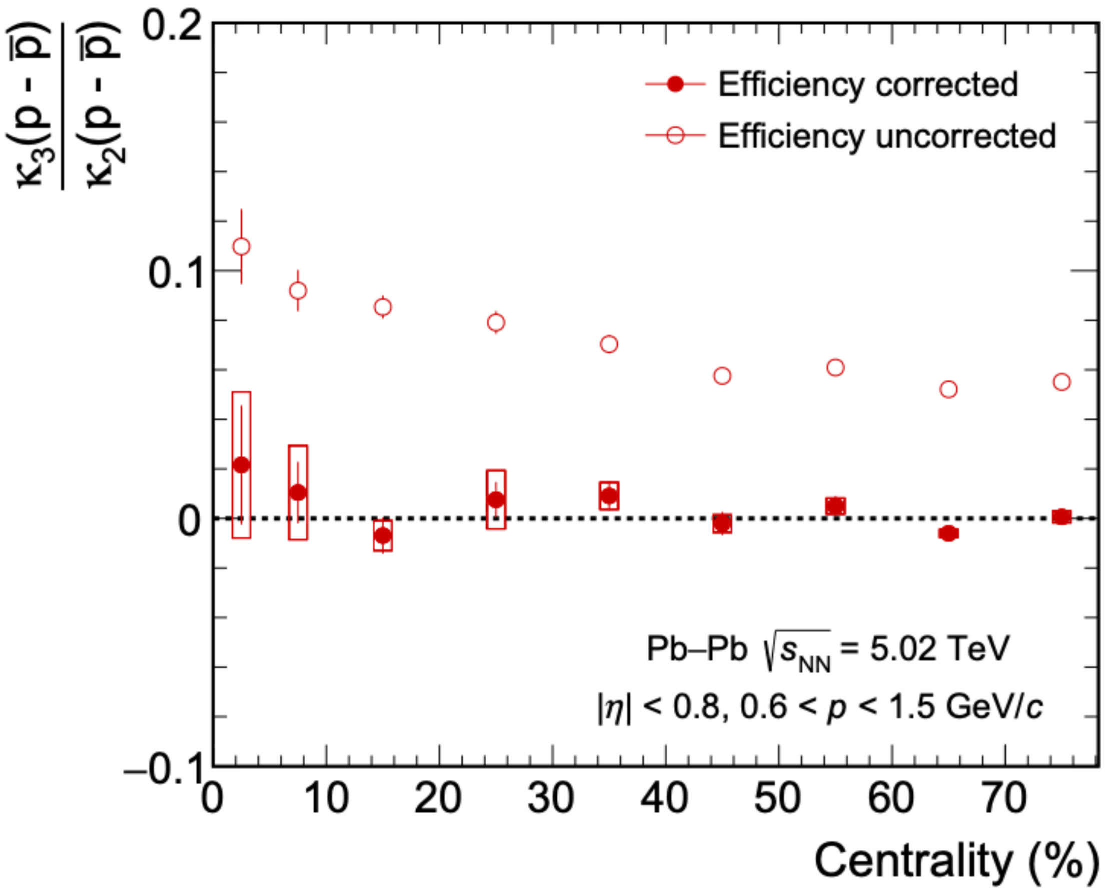
Net-proton fluctuations at LHC energies

ALICE collaboration, arXiv: 2206.03343

2nd order cumulants



3rd order cumulants

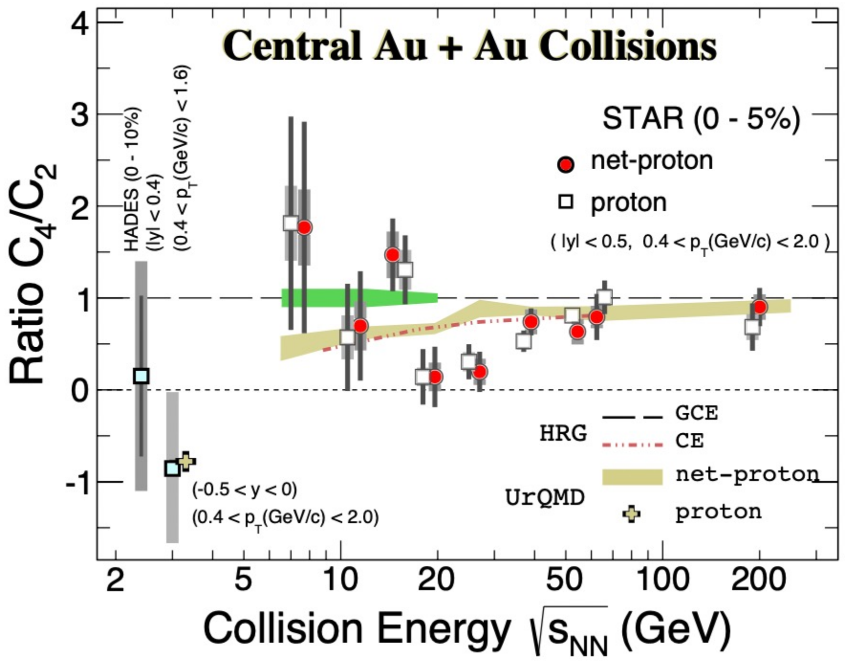


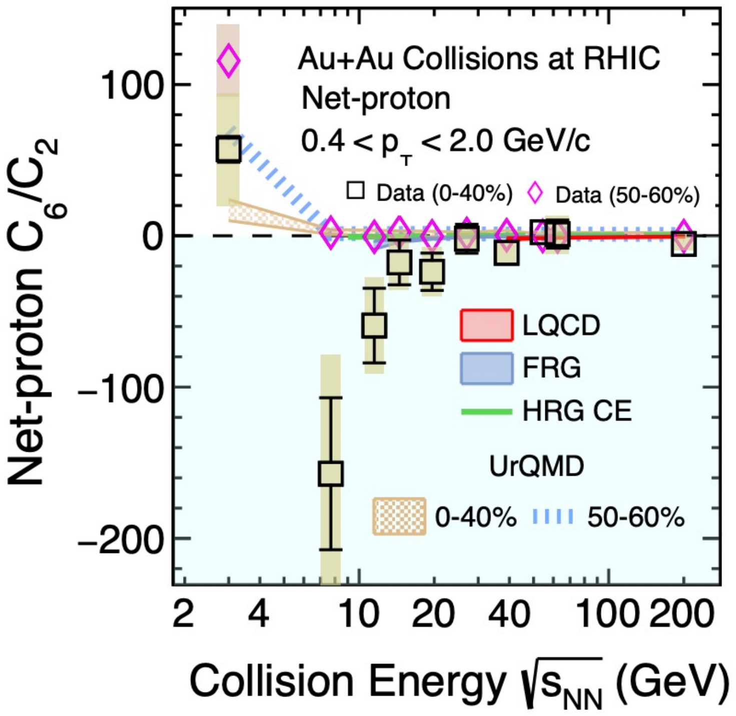
- 2nd order: **Deviation from Skellam baseline due to Baryon number conservation.**
- long-range correlations (Δη about ±2.5) originating from earlier in time.
- 3rd order: data agree with Skellam baseline "0"

Lattice meets experiment:
fluctuation of conserved quantities

Probing the QCD Critical Point

Moments of Net-proton STAR: PRL 130 , 82301 (2023)





What other observables can be used to get a better handle on the locaton of the critical point?

- Net-proton kurtosis ratio shows non-monotonic behavior as a function of collision energy.
- At 3 GeV, the fluctuations are driven by baryon number conservation (matter hadron dominated).
- Higher order moments can pin-point the nature of phase transition (cross-over).

Isothermal compressibility

Equation of State

Heat capacity

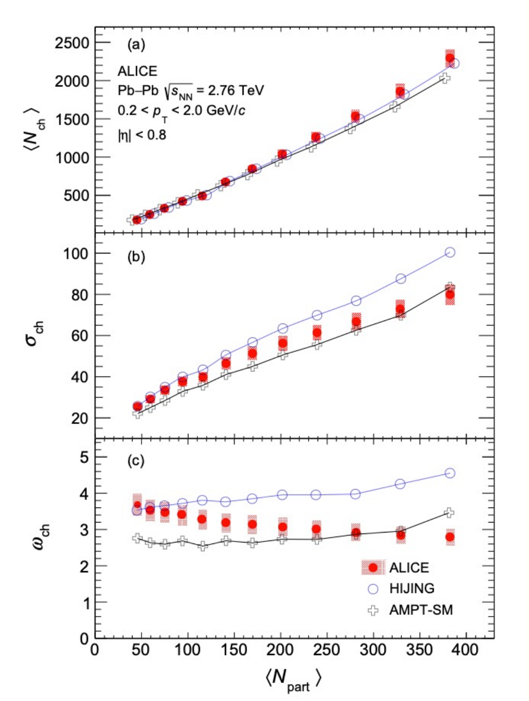
- S. Mrowczynski, Phys. Lett. B 430 (1998) 9
- M. Mukherjee, S. Basu, TN et al. PLB 784 (2018) 1-5
- A. Khuntia, R. Sahoo, TN et al. PRC 100 (2019) 014910

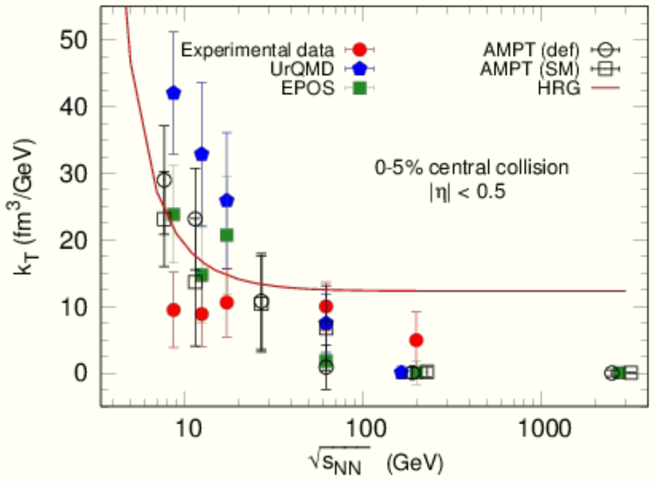
$$k_T = -\frac{1}{V}\left(\frac{\partial V}{\partial P}\right)_T$$

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

SPS, RHIC data, UrQMD, EPOS & HRG

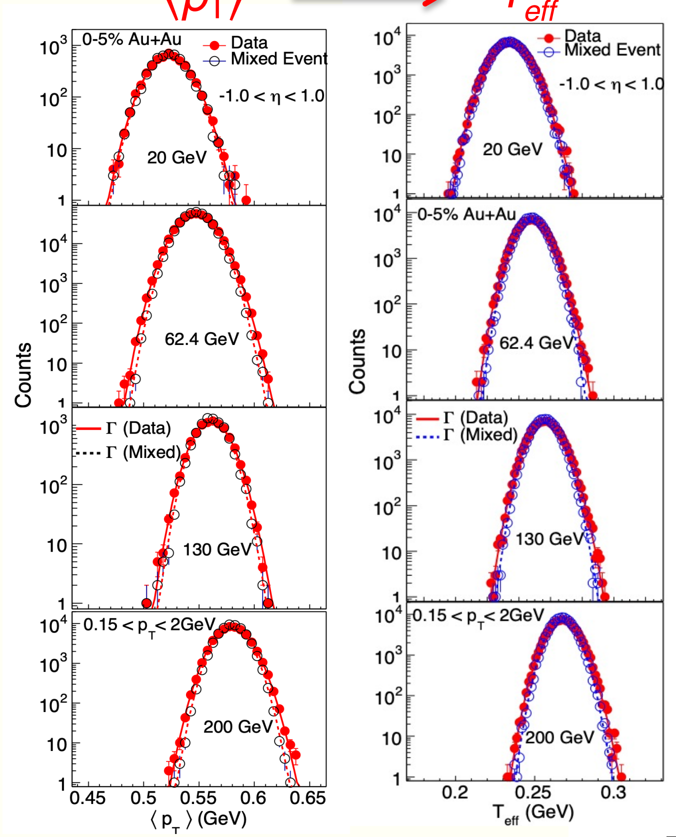
ALICE: Eur. Phys. J. C (2021) 81:1012





How to address the non-physical fluctuations (background)?

$\langle p_T \rangle$ → T_{eff}



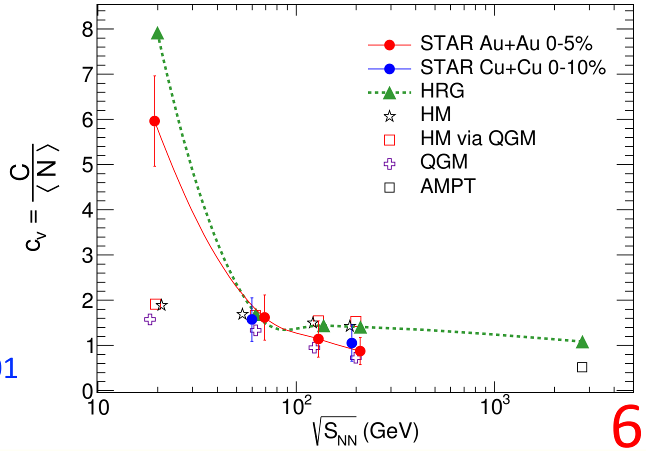
- L. Stodolsky, PRL 75, 1044 (1995))
- S. Basu, TN et al PRC 94 (2016) 044901

$$C = \left(\frac{\partial E}{\partial T}\right)_v$$

$$\frac{1}{C_v} = \frac{(\langle T^2\rangle - \langle T\rangle^2)}{\langle T\rangle^2}.$$

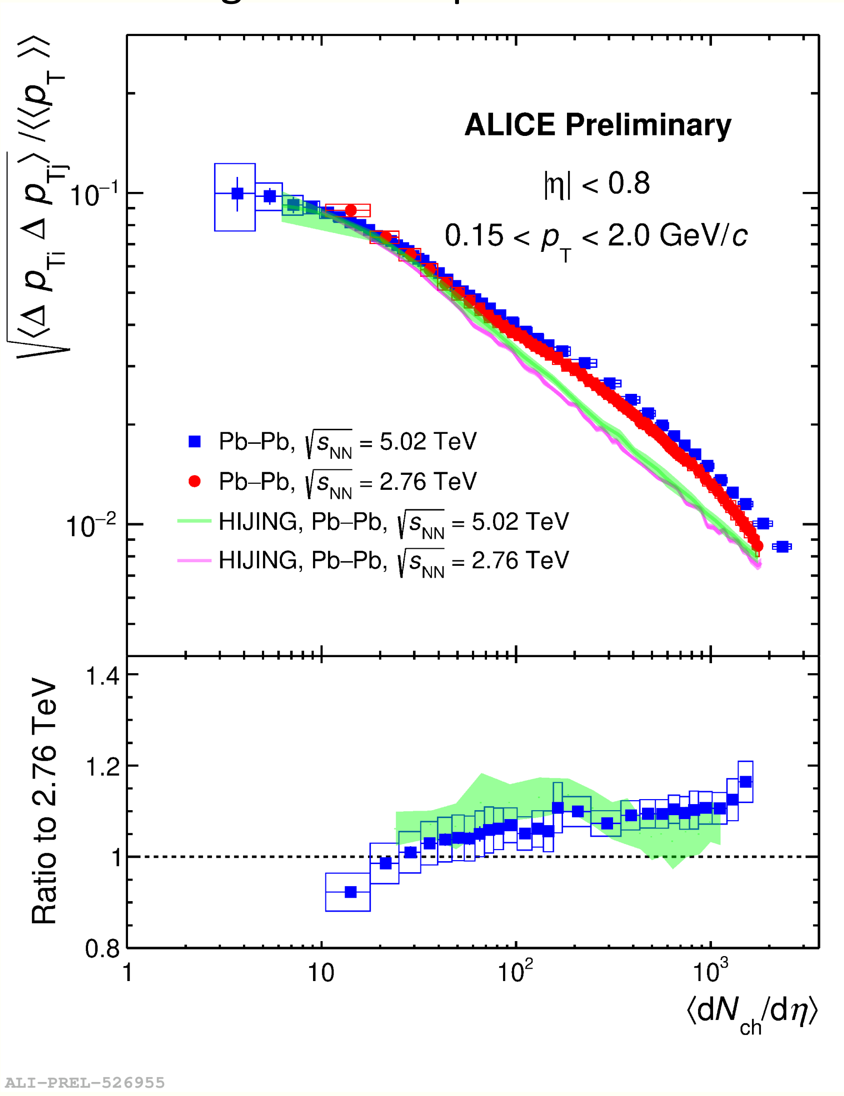
$$\frac{1}{C} = \frac{(\Delta T_{\rm eff}^{dyn})^2}{\langle T_{\rm kin}\rangle^2}.$$

Role of radial flow fluctuation in temperature fluctuation

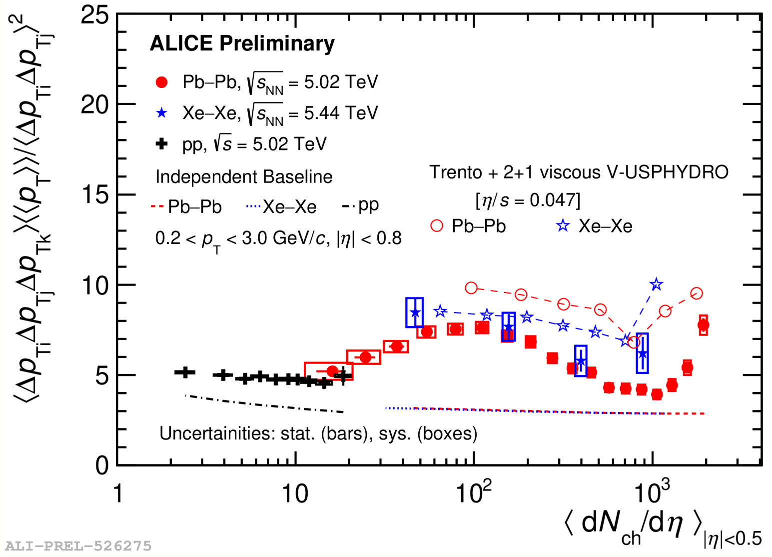


Fluctuations of mean p_T

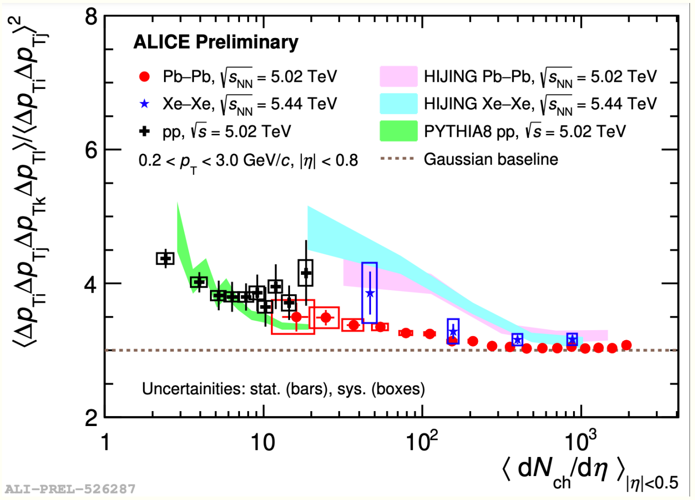
- $\langle p_T \rangle$ fluctuations result from fluctuations of the energy of the fluid when the hydrodynamic expansion starts.
- $\langle p_T \rangle$ is a proxy to the system temperature => measure of **temperature fluctuations ⇒ heat capacity**.
- Higher order: probes of QCD thermodynamics at higher T, achieved during the early stages of the collision.



Skewness (3-particle correlator):



Kurtosis (4-particle correlator):



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