Fluctuations and correlations of net-conserved quantities at LHC energies with ALICE

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Outline

- Introduction
- Motivation
- ALICE detector
- Results
- Summary

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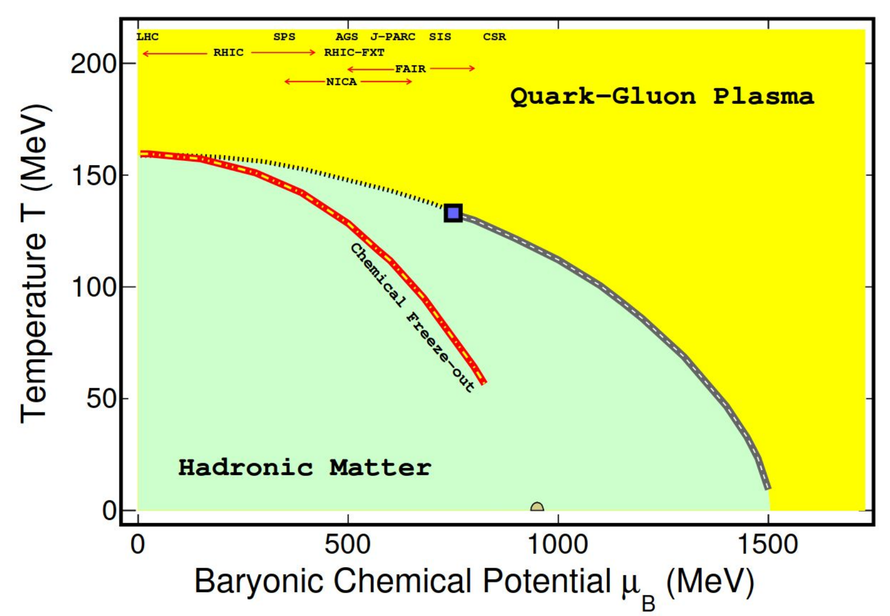
13th - 16th January, 2025, Mayfair Palm Beach Resort, Berhampur, Odisha, India

QCD phase diagram and phase structure

A. Pandav et al., *Prog. Part. Nucl. Phys.* 125 (2022) 103960



Phase structure	Remarks
Phases	De-confined: **Quark–Gluon Plasma** Confined: **Hadron gas**
Nature of transition	❖ **Crossover** at low μ_B ❖ **First order** at large μ_B ❖ **Second order** – Critical point
Transition temperature	Phase boundary as a function of μ_B
Freeze-out	Chemical freeze-out Kinetic freeze-out

LHC experiments ➡ $\mu_B \sim 0$

Fluctuations and correlations

- Fluctuations and correlations of net-conserved charges such as net-baryon (B), net-electric charge (Q), and net-strangeness (S) number can **provide valuable insights into the QCD phase structure**.

- They are sensitive probes for the equation of state and are directly **related to the QCD thermodynamic susceptibilities**. They can be studied in the Hadron Resonance Gas (HRG) model and lattice QCD simulations.

Theory → $$\chi^{l,m,n}_{\mathrm{B,Q,S}} = \frac{1}{VT^3}\sigma^{l,m,n}_{\mathrm{B,Q,S}}$$ ← Experiment

V, T → system's volume and temperature

- Observables are **diagonal and off-diagonal cumulants of net-conserved charges** (B, Q, and S).

$$\sigma^2_\alpha = \langle(\delta N_\alpha)^2\rangle$$
$$\sigma^{11}_{\alpha,\beta} = \langle(\delta N_\alpha)(\delta N_\beta)\rangle$$

$$\delta N_\alpha = (N_{\alpha^+} - N_{\alpha^-}) - \langle(N_{\alpha^+} - N_{\alpha^-})\rangle$$

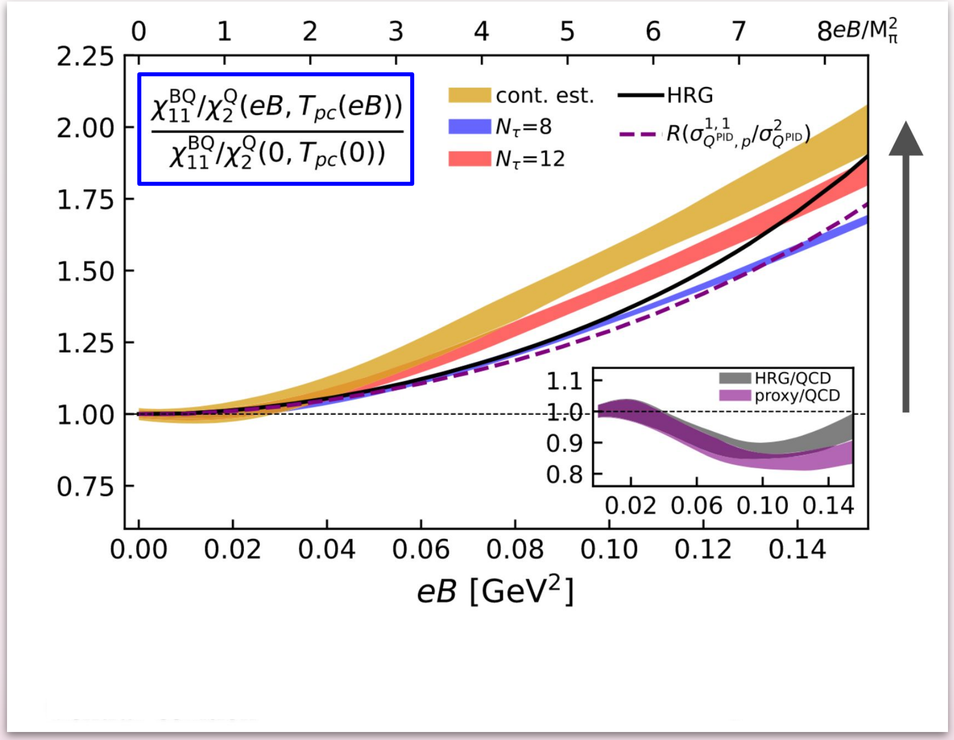
→
- α, β can be B, Q, or S
- net-proton and net-kaon considered as proxy of net-baryon and net-strangeness number

- The **ratio of the cumulants** cancels the *V* and *T* dependence.

$$C_{\mathrm{BS}} = \frac{\sigma^{11}_{\mathrm{BS}}}{\sigma^2_{\mathrm{S}}}, \quad C_{\mathrm{QS}} = \frac{\sigma^{11}_{\mathrm{QS}}}{\sigma^2_{\mathrm{S}}}, \quad C_{\mathrm{QB}} = \frac{\sigma^{11}_{\mathrm{QB}}}{\sigma^2_{\mathrm{B}}}$$

Lattice QCD and magnetic field

H.-T. Ding et al., *Phys. Rev. Lett 132 (2024) 201903*



Lattice QCD studies with magnetic fields show a significant effect on fluctuations of conserved charges.

Can we test this in experiments?

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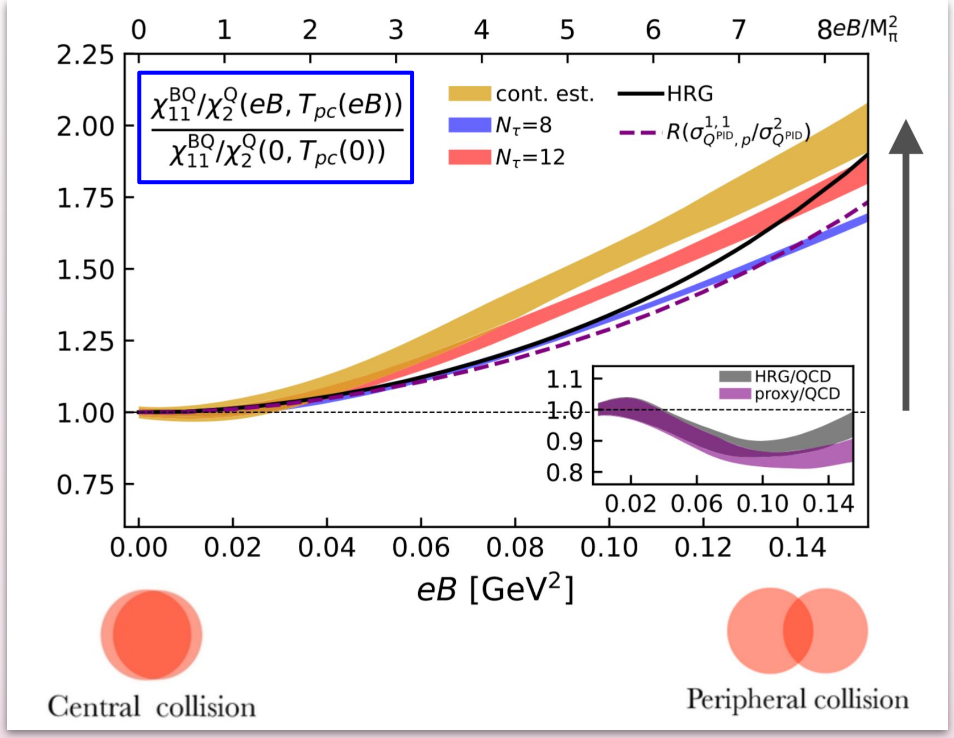

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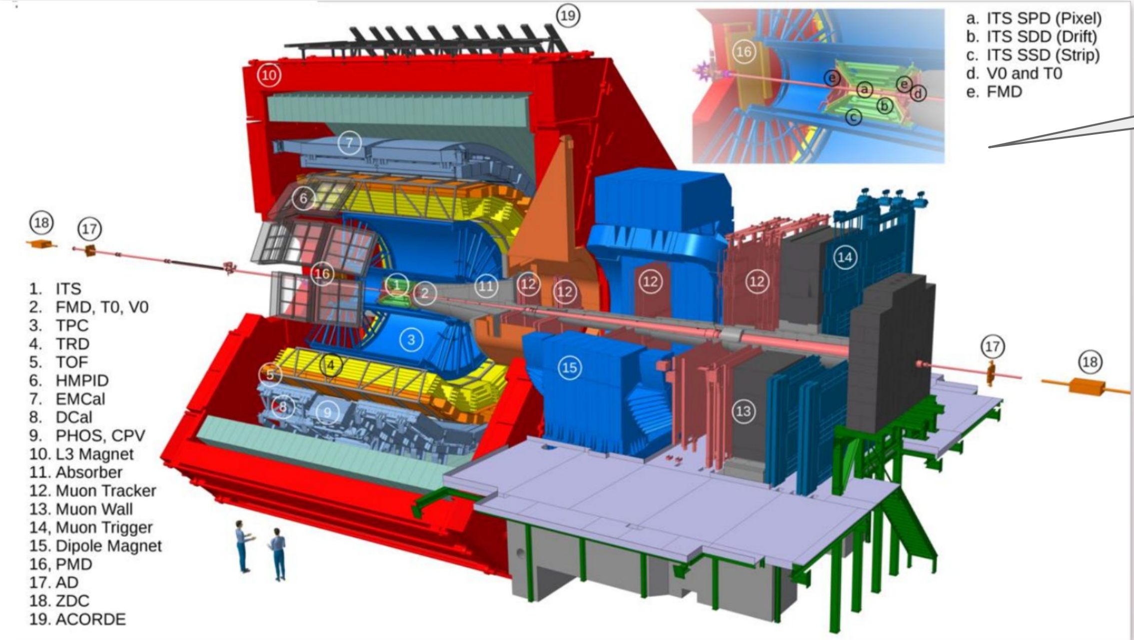
Can we test this in experiments?

$$\frac{\sigma^{11}_{Q,p}/\sigma^2_Q}{[\sigma^{11}_{Q,p}/\sigma^2_Q]_{0-5\%}}$$

ALICE detector



Uniform acceptance at mid-rapidity and excellent particle identification capability

- **Inner Tracking System (ITS)**
  tracking, vertexing, trigger
- **V0** ($2.8 < \eta < 5.1$ & $-3.7 < \eta < -1.7$)
  trigger, centrality estimation
- **Time Projection Chamber (TPC)**
  tracking, PID via dE/dx
- **Time-Of-Flight (TOF)**
  PID via time of flight

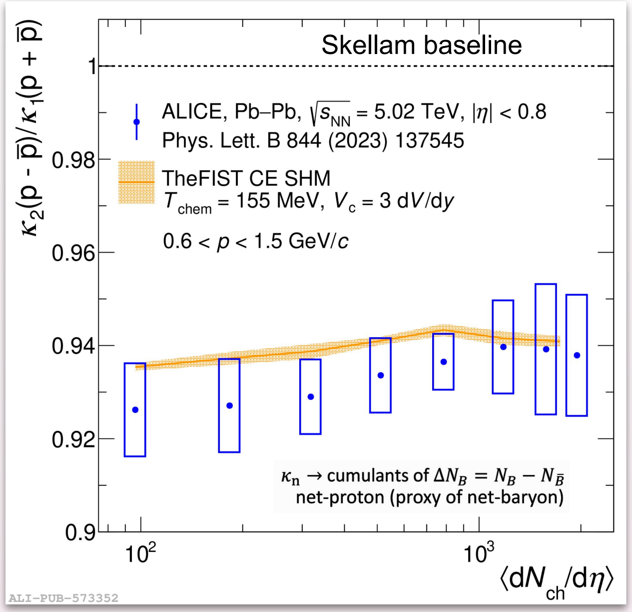
Run 2 data **Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV** collected in 2015
Statistics: 80 million (good events)

Results

2nd and 3rd order fluctuations of net-proton

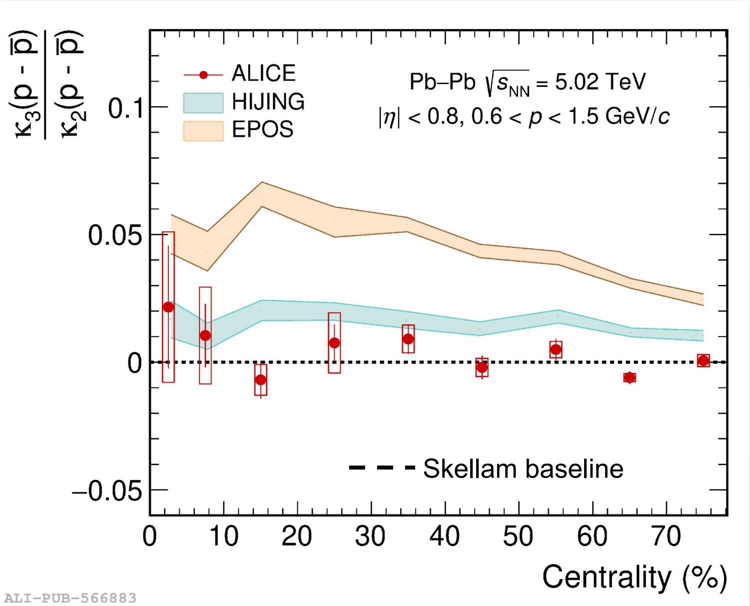
ALICE, *arXiv:2405.19890*

Normalized 2nd order cumulant



ALICE, *Phys. Lett. B 844 (2023) 137545*

Ratio of 3rd to 2nd order cumulant



- **Thermal-FIST[1,2] canonical ensemble (CE) predictions for baryon conservation in a correlation volume of 3d*V*/dy describes the measurements ⇒ long-range correlations**

[1] V. Vovchenko et al., *Comput. Phys. Commun. 244 (2019) 295-310*
[2] V. Vovchenko et al., *Phys. Rev. C* 100 (2019) 054906

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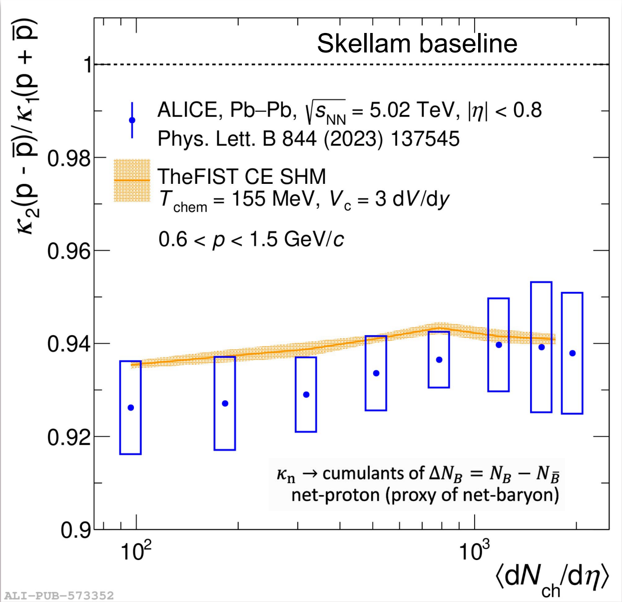

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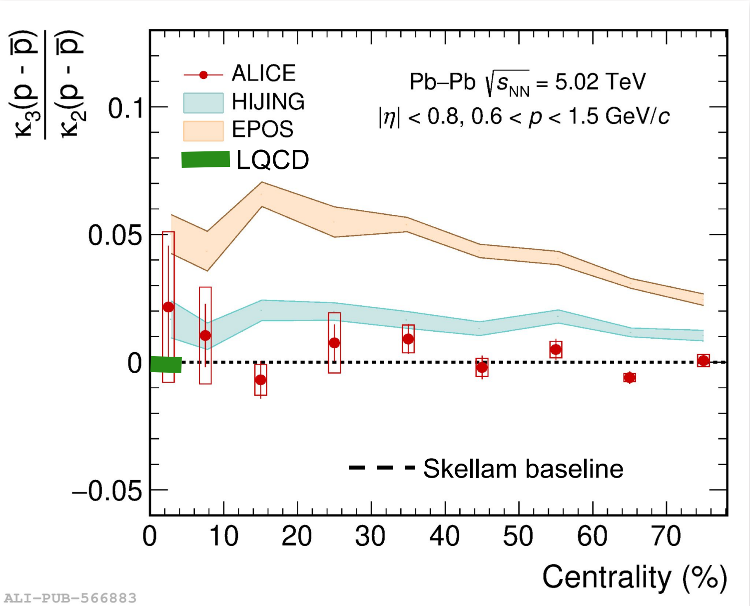
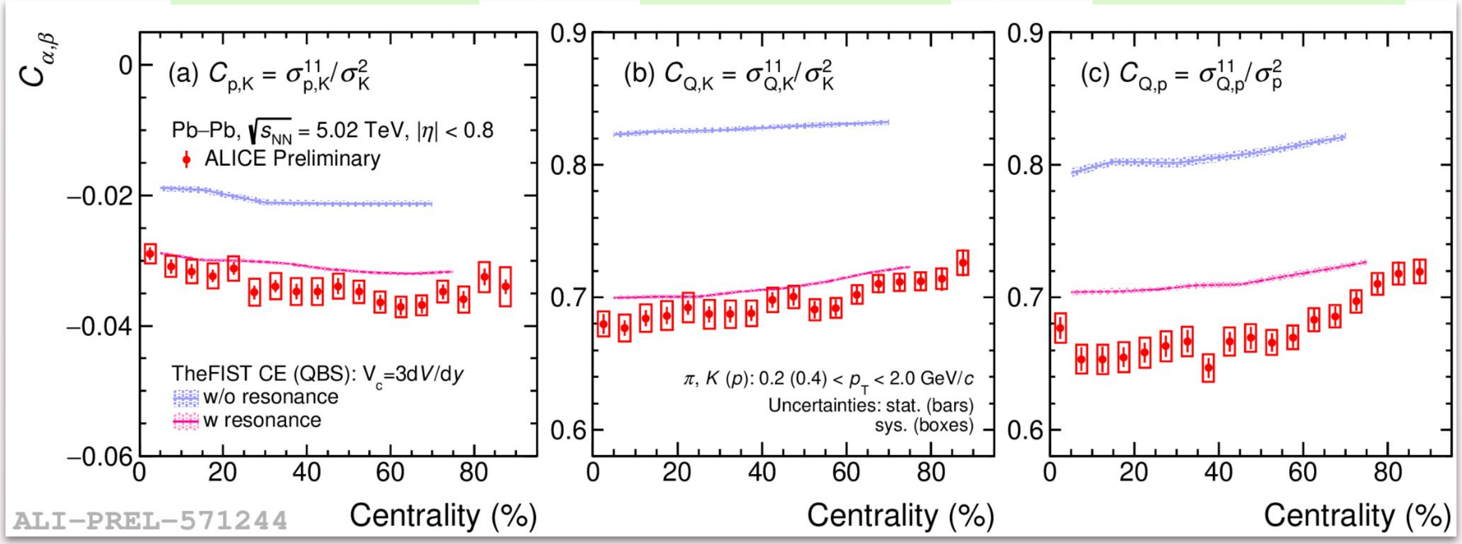


- Thermal-FIST[1,2] canonical ensemble (CE) predictions for baryon conservation in a correlation volume of 3d*V*/dy describes the measurements ⇒ long-range correlations
- Net-proton cumulants consistent with LQCD calculations up to 3rd order

[1] V. Vovchenko et al., *Comput. Phys. Commun. 244 (2019)* 295-310
[2] V. Vovchenko et al., *Phys. Rev. C* 100 (2019) 054906

Correlations among net-pion, net-kaon & net-proton

~ B-S correlation | ~ Q-S correlation | ~ Q-B correlation

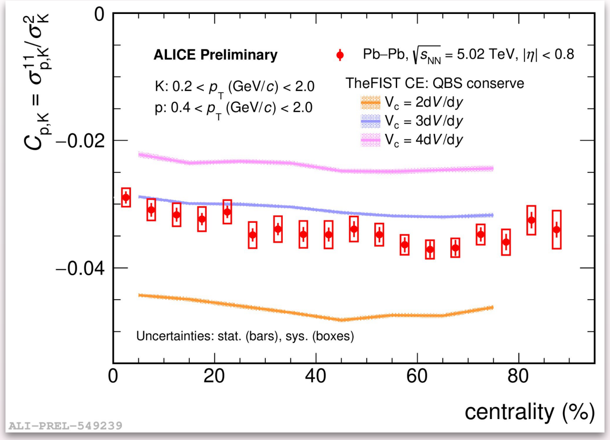


- Significant effect of resonance decays
- Thermal-FIST[1,2] canonical ensemble (CE) predictions for Q, B, and S conserved in a correlation volume of 3d*V*/d*y* describe the measurements better

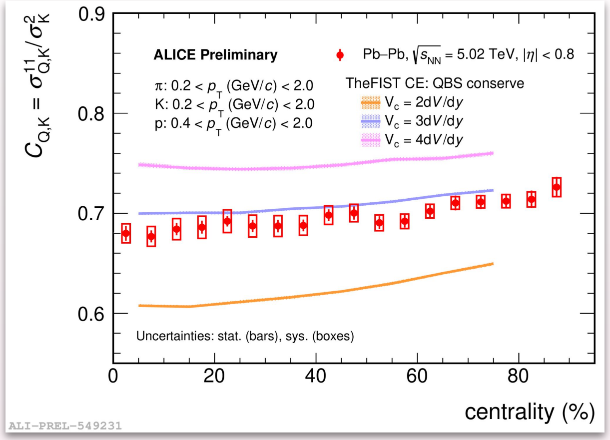
[1] V. Vovchenko et al., *Comput. Phys. Commun. 244 (2019)* 295-310
[2] V. Vovchenko et al., *Phys. Rev. C* 100 (2019) 054906

Effect of correlation volume

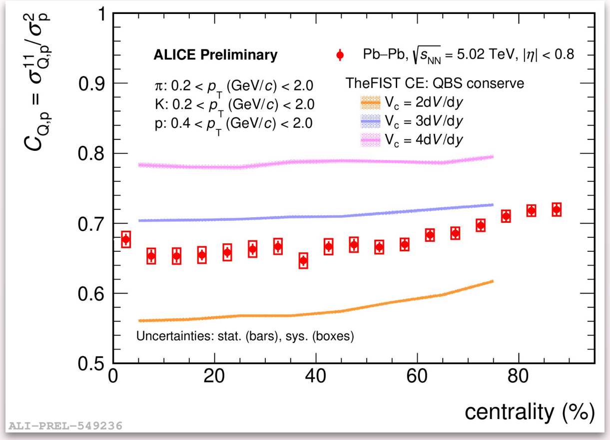
~ B-S correlation



~ Q-S correlation



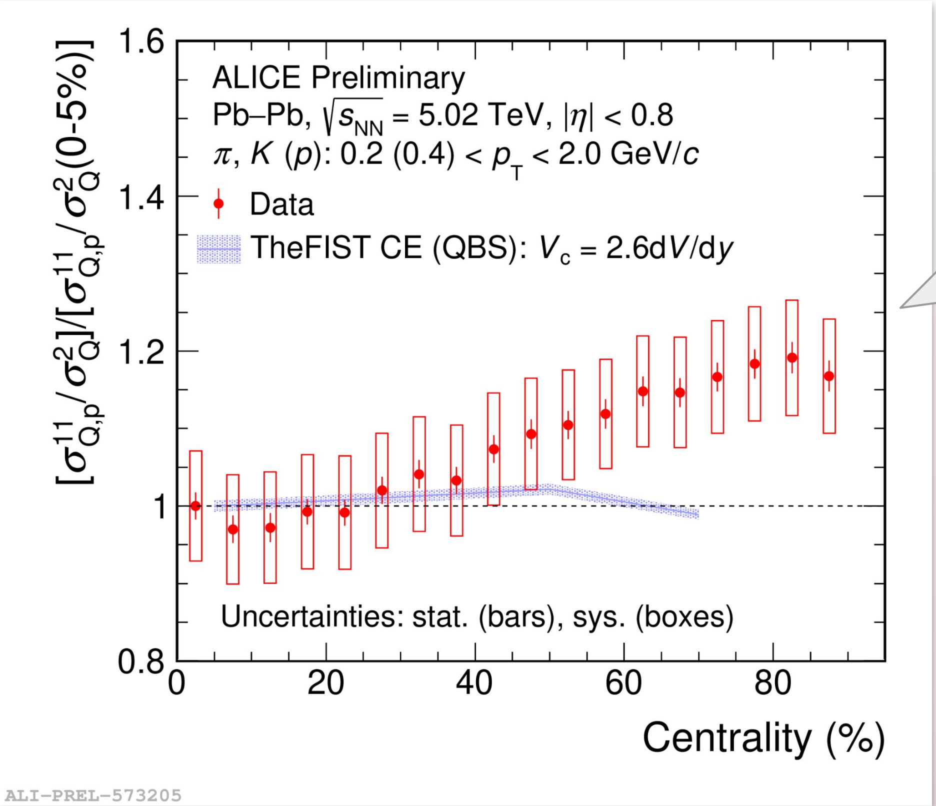
~ Q-B correlation



- **Sensitive to the correlation volume (V_c) in which Q, B, S are conserved exactly**
- **A quantitative estimation of V_c by chi-square minimization using Thermal-FIST[1,2] predictions for different V_c values give V_c~2.6d*V*/dy**

[1] V. Vovchenko et al., *Comput. Phys. Commun. 244 (2019)* 295-310
[2] V. Vovchenko et al., *Phys. Rev. C* 100 (2019) 054906

Effect of initial magnetic field on fluctuations



- Shows an increasing trend consistent with LQCD predictions.
- Deviates from unity by ~20% in peripheral collisions.
- The Thermal-FIST[1,2] model without magnetic field fails to describe the observed trend in data.

[1] V. Vovchenko et al., *Comput. Phys. Commun. 244 (2019)* 295-310
[2] V. Vovchenko et al., *Phys. Rev. C* 100 (2019) 054906

Summary

- Measurement of net-proton number fluctuations only up to 3rd order.

- The centrality dependence of correlations among net-charge, net-proton, and net-kaon are presented in Pb−Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV with ALICE.

- Experimental measurements show contributions from (a) resonance decays, (b) conservation of charges and (c) long-range correlations.

- Interesting results for observable claimed to be sensitive to initial magnetic field effects
    - Data shows a similar trend as in LQCD
    - Whether imprints of a strong magnetic field exist in the final stage of heavy-ion collisions?

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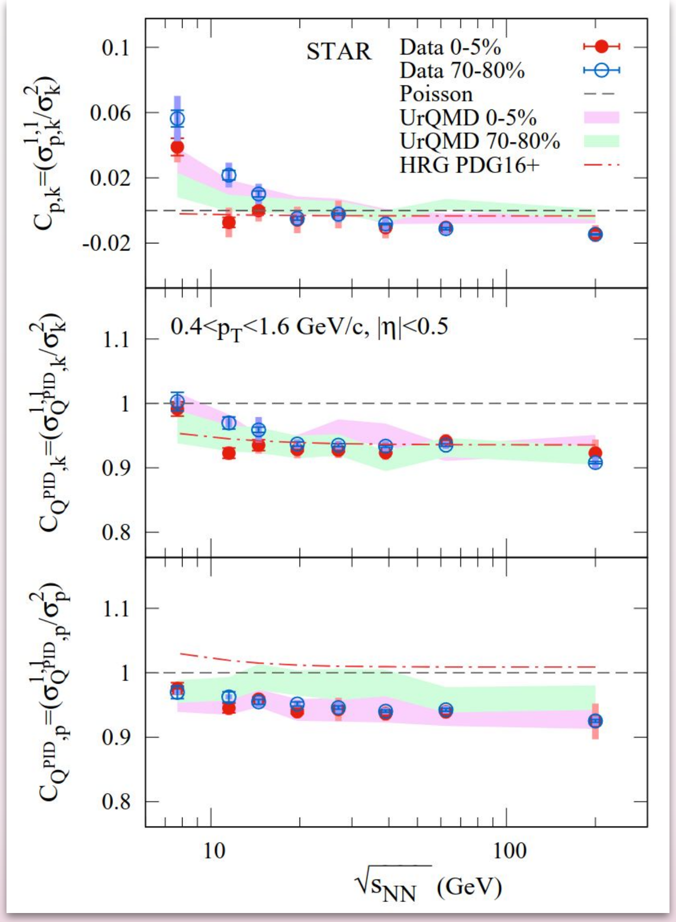
Thank you for your attention

Backup

STAR measurements of correlations

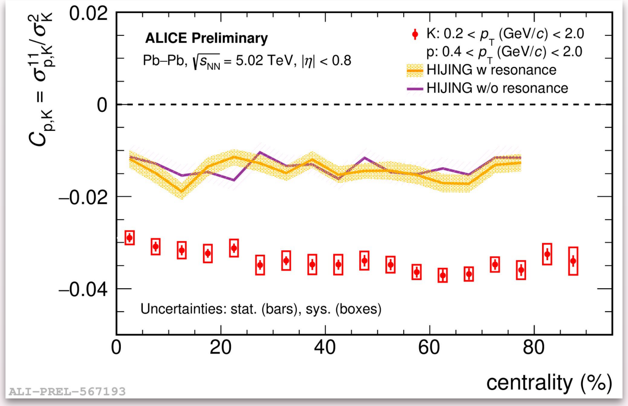
STAR, *Phys. Rev. C 105 (2022) 029901*



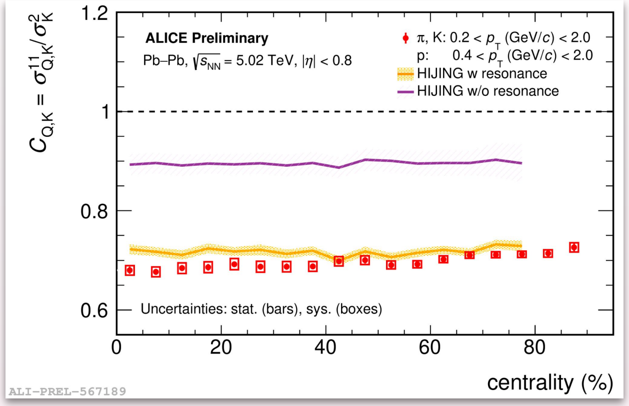
- Measurements of STAR experiment at RHIC

Comparison to HIJING model

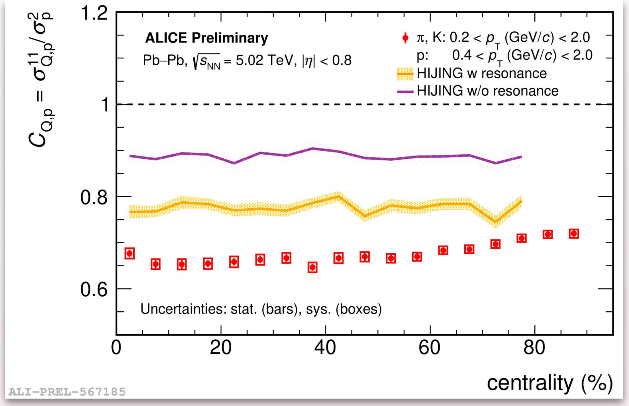
~ B-S correlation



~ Q-S correlation



~ Q-B correlation



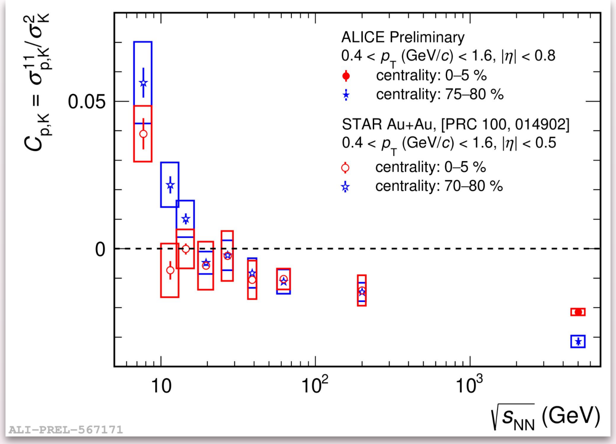
Measurements are compared to **predictions from the HIJING[1] model**

- ❑ **Significant effect of resonance decays**
- ❑ **Incomplete implementation of resonance decays in the HIJING model**
- ❑ **HIJING model fails to explain measurements for $C_{p,K}$ and $C_{Q,p}$**

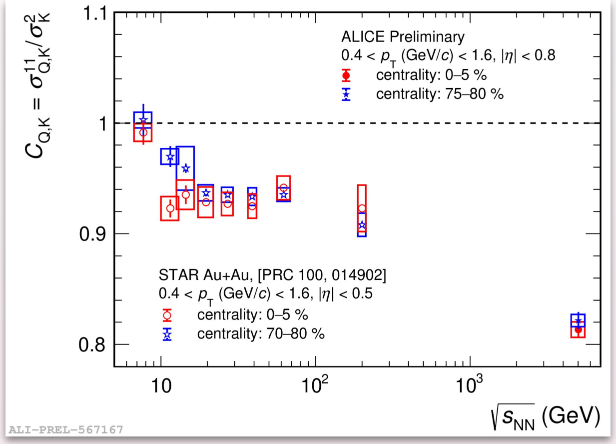
[1] X.-N. Wang et al., *Phys. Rev. D 44 (1991) 3501-3516*

Energy dependence of correlations

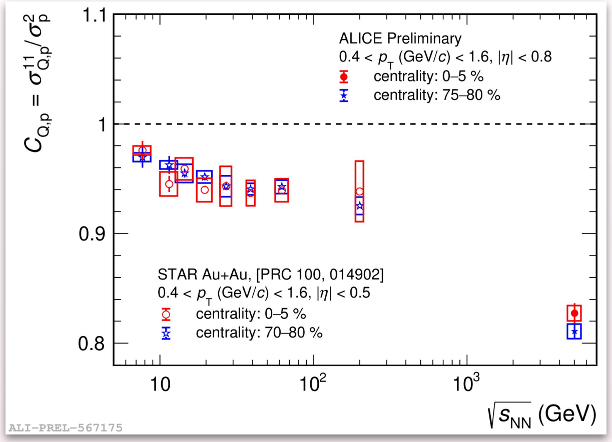
~ B-S correlation



~ Q-S correlation



~ Q-B correlation



- **Decrease in correlations with increase in beam energy**

Analysis details

Corrections & Uncertainties:

➔ Suppress volume fluctuations by **Centrality Bin Width Correction (CBWC)**

$$C_n = \frac{\sum_a n_a C_{n,a}}{\sum_a n_a}, \quad \delta_{C_n} = \sqrt{\frac{\sum_a (n_a \delta_{C_{n,a}})^2}{(\sum_a n_a)^2}}$$

n_a and $C_{n,a}$ are number of events and cumulant in a_{th} multiplicity bin

➔ Efficiency correction: **Considering the Binomial model of detector response, analytical expressions in Ref[1,2] are used to correct the cumulants**

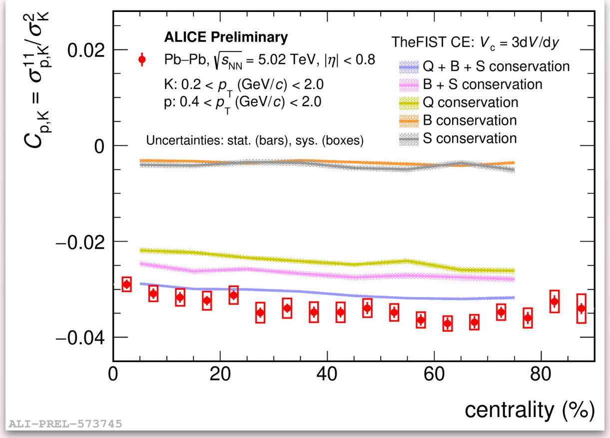
[1] T. Nonaka et al., *Phys. Rev. C* 95, 064912 (2017)
[2] X. Luo et al., *Phys. Rev. C* 99, 044917 (2019)

➔ Statistical uncertainty: **Bootstrap Sampling Method**

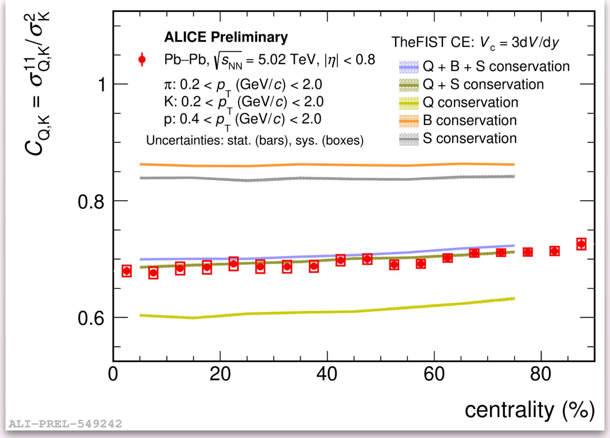
➔ Systematic uncertainties: **Varying event selection, track selection, and PID criteria**

Effect of charge conservation

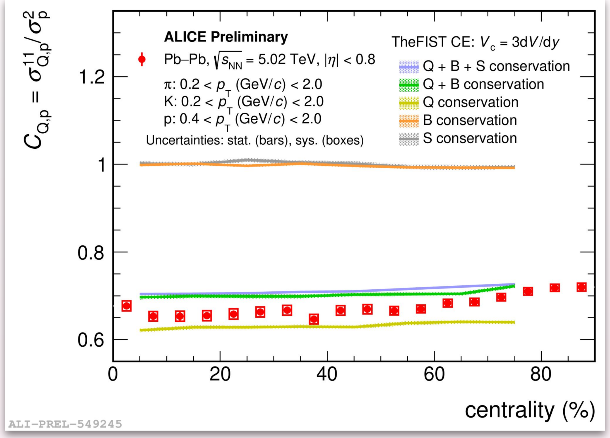
~ B-S correlation



~ Q-S correlation



~ Q-B correlation



- **Charge conservation plays an important role in these correlations**

TheFIST → Thermal-FIST[1,2]

[1] V. Vovchenko et al., *Comput. Phys. Commun. 244 (2019) 295-310*
[2] V. Vovchenko et al., *Phys. Rev. C* 100 (2019) 054906