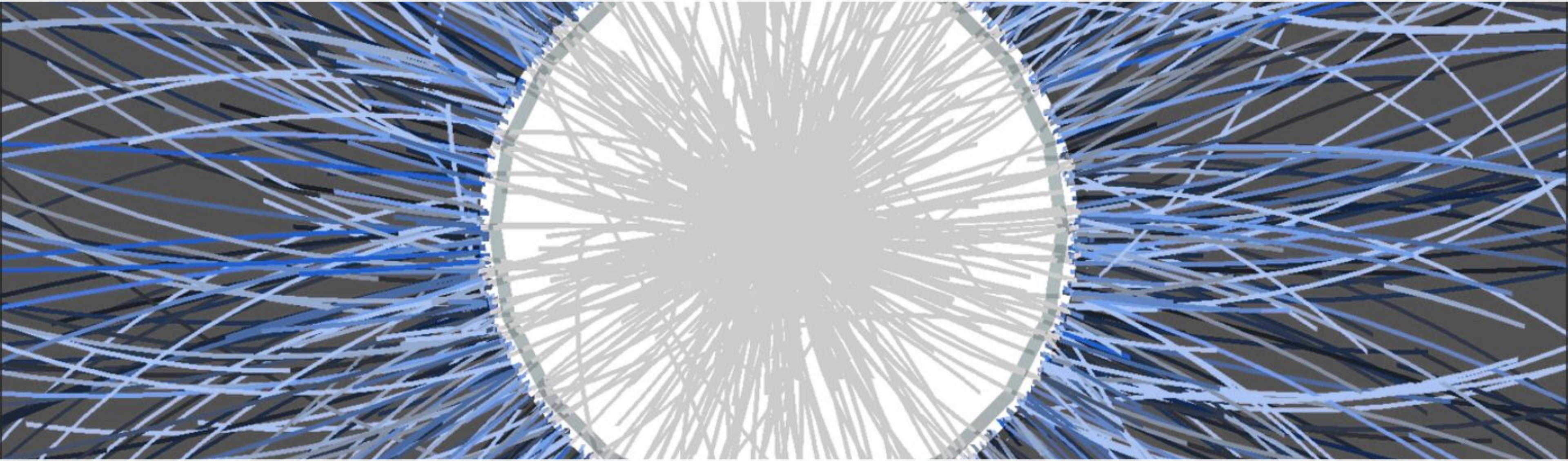
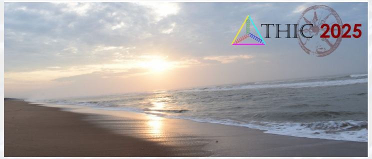
Baryon number and strangeness number fluctuations at LHC energies

Sourav Kundu (for the ALICE Collaboration)

ALICE

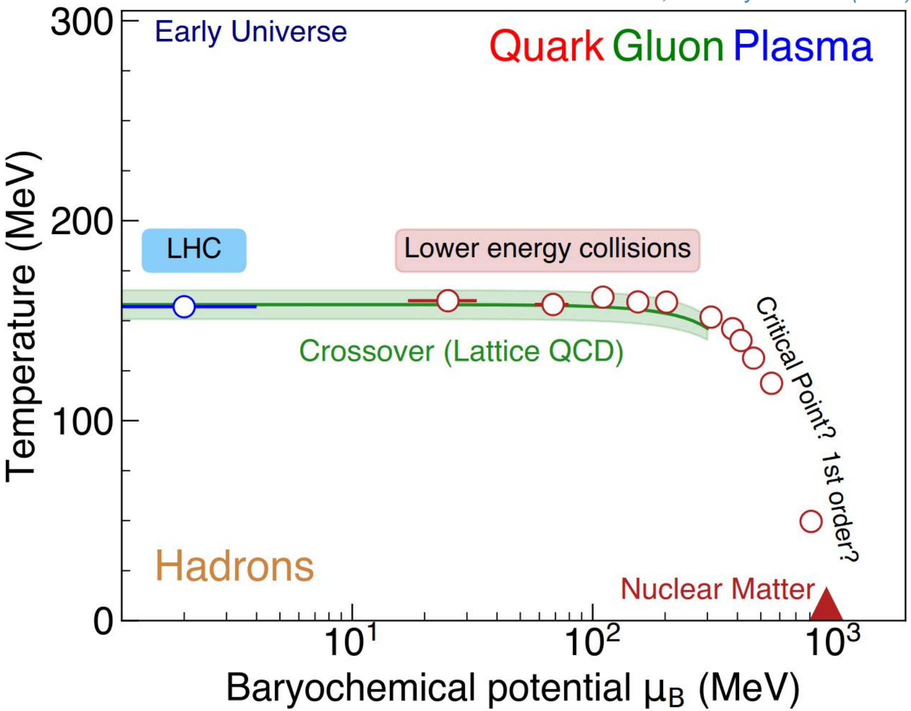




10th Asian Triangle Heavy-Ion Conference
13th to 16th January 2025

QCD phase diagram and phase structure

ALICE, Eur. Phys. J. C 84 (2024) 813



- Lattice QCD calculations predict a crossover transition at LHC energies → $\mu_B \approx 0$ MeV
  - $T_{pc}^{LQCD} \approx T_{fo}^{ALICE} \approx 156.5 \pm 3$ MeV

    A. Andronic et al., Nature 561 (2018) 321
  - no experimental confirmation of crossover

- E-by-E fluctuations of net-conserved charges (eg. net-baryon number) provide valuable insights into the QCD phase structure

Link to lattice QCD: Cumulants of net-conserved charges

LQCD

net-baryon (B), net-electric charge (Q), net-strangeness (S), net-charm (C) number

$$\chi^{BQSC}_{klmn} = \left. \frac{\partial^{(k+l+m+n)}[P(\hat{\mu}_B, \hat{\mu}_Q, \hat{\mu}_S, \hat{\mu}_C)/T^4]}{\partial \hat{\mu}^k_B \partial \hat{\mu}^l_Q \hat{\mu}^m_S \partial \hat{\mu}^n_C} \right|_{\vec{\mu}=0}$$

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

$\kappa_n \rightarrow$ central moments of X

Experiment

$$\hat{\chi}^B_2 = \frac{\kappa_2(\Delta N_B)}{VT^3} \Rightarrow \frac{\kappa_4(\Delta N_B)}{\kappa_2(\Delta N_B)} = \frac{\hat{\chi}^B_4}{\hat{\chi}^B_2}$$

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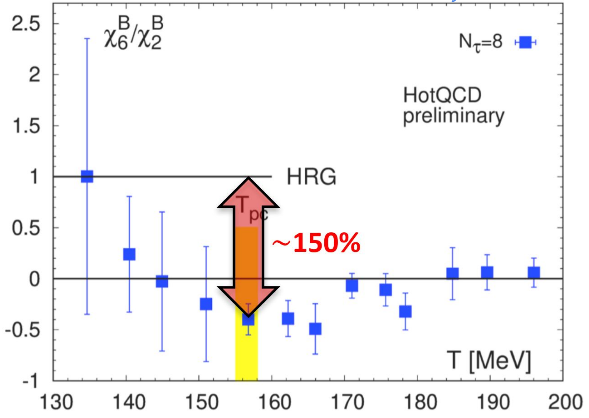
LQCD expectations at LHC:

1) Baseline: Difference between two independent Poissonian distributions (Skellam distr.)
   → κ_n/κ_2 is 0 (odd) or 1 (even)

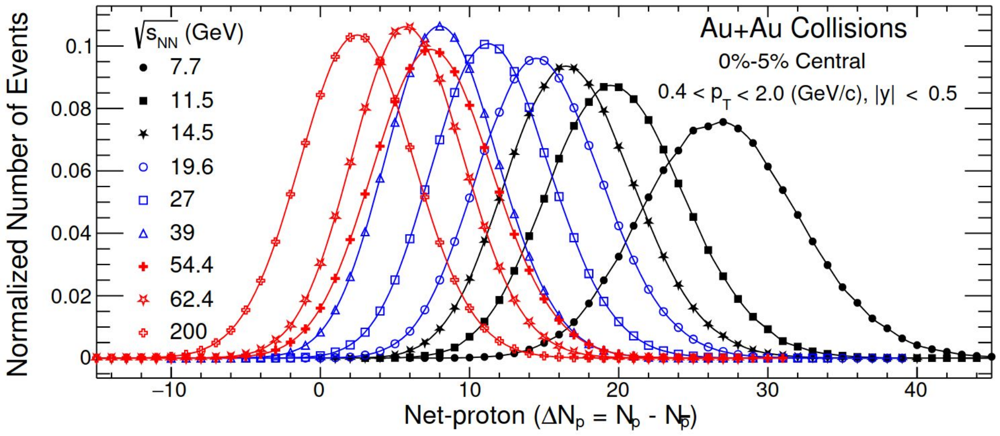
2) Up to 3rd order Hadron Resonance Gas (HRG) model agrees with LQCD at μ_B = 0

3) Higher order → larger deviation from baseline
   → 4th order ~30%, 6th order ~150%

A. Bazavov et al., Phys. Rev. D 95 (2017), 054504

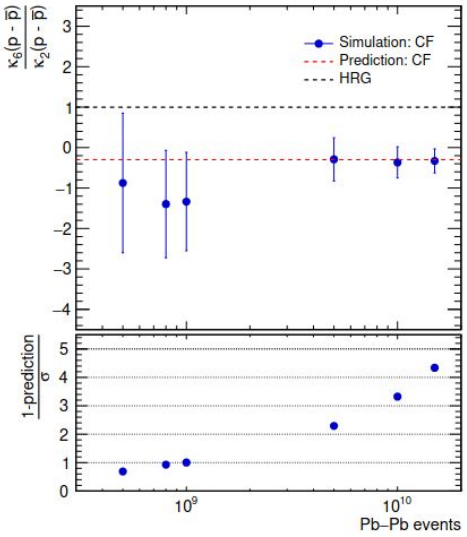


Required statistics for experimental measurements



STAR, Phys. Rev. Lett. 126, 092301

ALICE, arXiv:2211.02491



- Cumulants are obtained from the multiplicity distribution of net-conserved charges

- Higher-order cumulants are sensitive to the tail of the distribution
  → required very high statistics (e.g. for 6th order ~ $O(10^9)$ events in central Pb–Pb collisions)
  → feasible by the end of LHC Run 3 and Run 4

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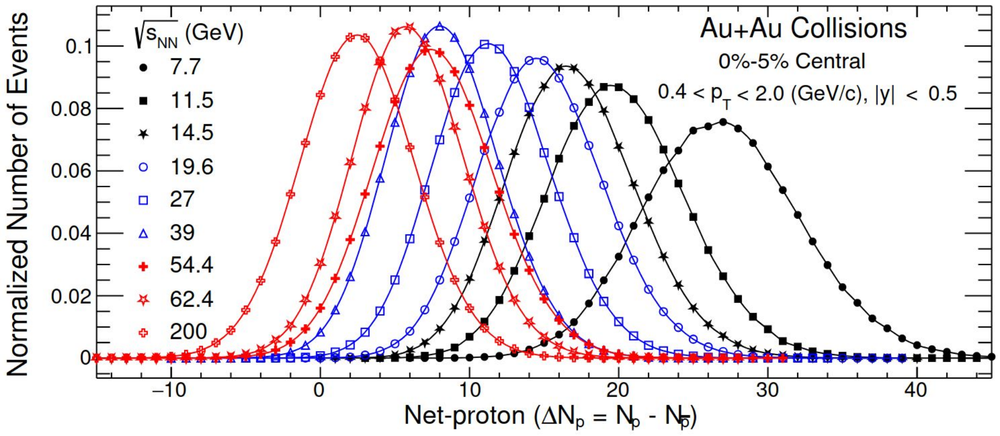

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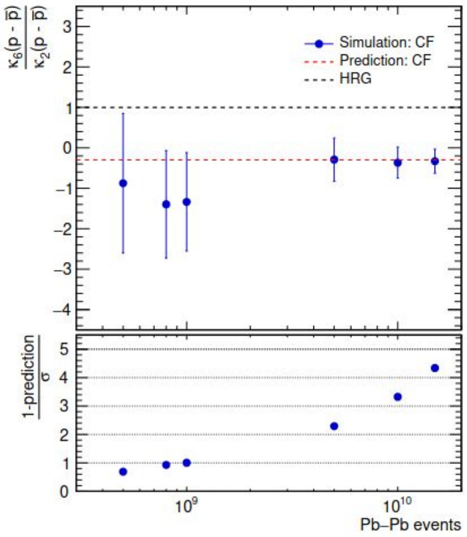

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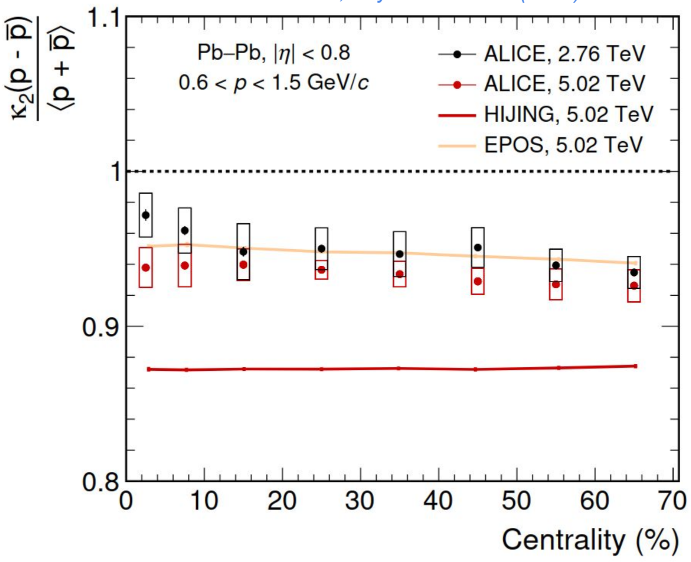
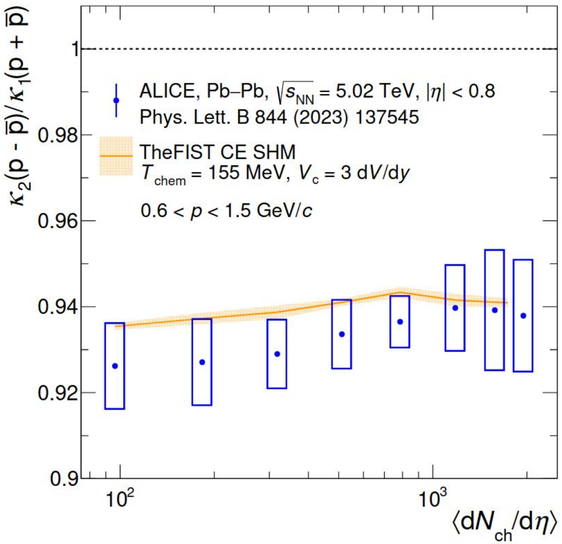
This talk focuses only on Run 2 results up to 2nd and 3rd order cumulants

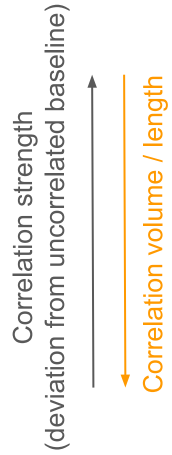
2nd order cumulants of net-p

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



ALICE, arXiv:2405.19890 (accepted by PRL)

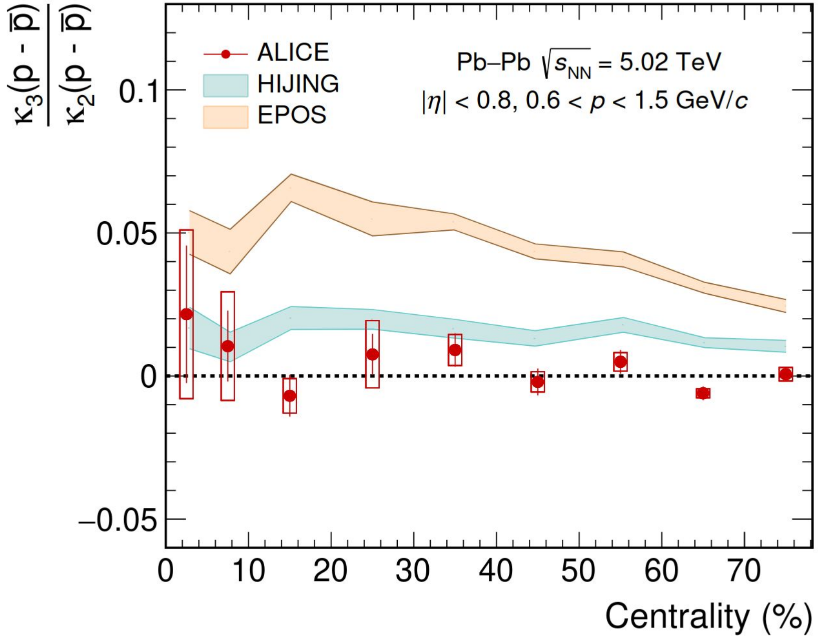




- Deviation from Skellam baseline due to local baryon number conservation
- HIJING overestimates the measurements → string models conserve baryon number over smaller rapidity
- Measurement supports baryon number conservation over a large conservation volume 3 dV/dy in canonical ensemble (CE) based Thermal-FIST model equivalent to a correlation length of 3 units of rapidity
  → originates earlier in time

3rd order cumulants of net-p

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



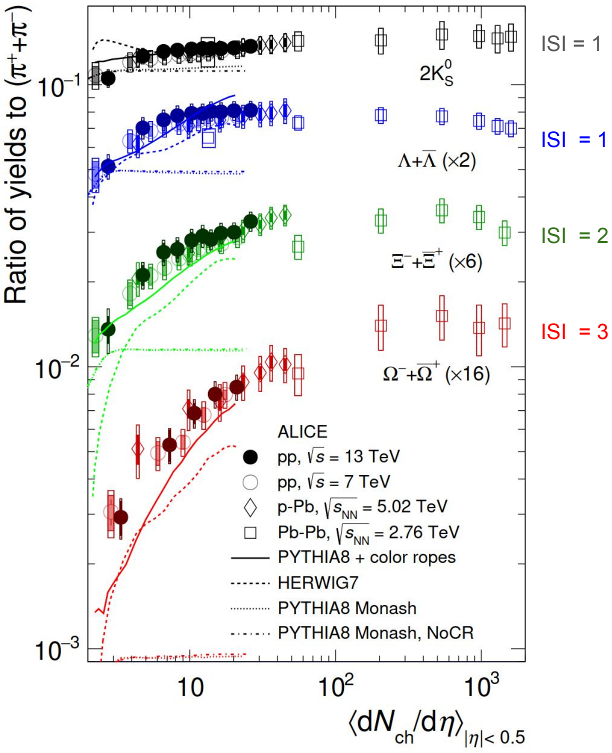
- Data agree with Skellam baseline "0" as expected at LHC energies
- Models deviate from "0" due to different particle to anti-particle ratio than data and effect of multiplicity fluctuation in models

Probing strange hadron production with e-by-e fluctuation

– Enhanced production of strange hadrons in heavy-ion collisions compared to the elementary collisions, originally proposed as a signature of QGP

– Similar observation in high multiplicity pp collisions

ALICE, Nature Physics, 13, (2017) 535



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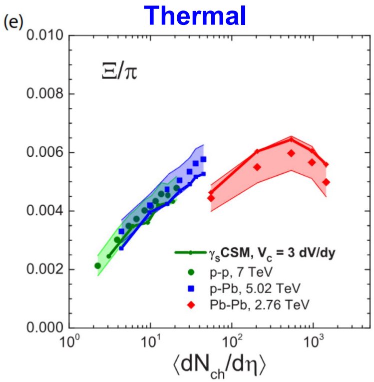
– To describe multiplicity evolution very different hadronization models are used:
Thermal model: Statistical Hadronization Model (SHM)
→effect of global conservation of strange quantum number

V. Vovchenko et al.,
Phys. Rev. C 100, 054906 (2019)



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Thermal model: Statistical Hadronization Model (SHM)
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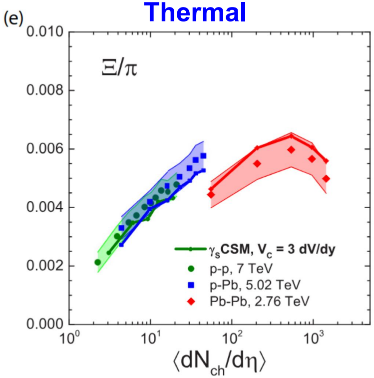
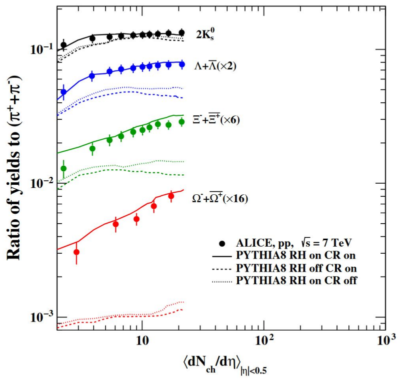
Non-thermal string model: PYTHIA8 + color ropes
→ hadrons formed from the breaking of color string/rope
→ formation of baryon junction

V. Vovchenko et al., Phys. Rev. C 100, 054906 (2019)

Thermal



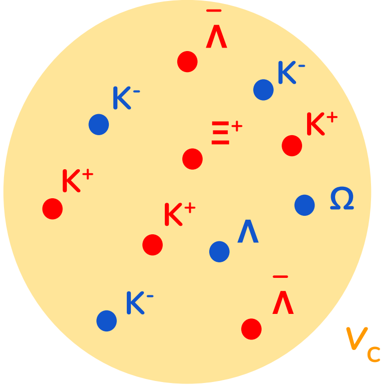
Non-thermal



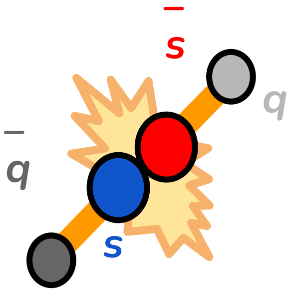
R. Nayak et al., Phys. Rev. D 100, 074023 (2019)

How to disentangle? Nature of strange quantum number conservation

- Canonical statistical hadronisation
  - Conservation over finite volume (V_c)
    → Long-range correlation length over rapidity
    → Both like- and unlike-sign correlations



- String fragmentation
  - Local conservation due to qq pair creation
    → Short range correlation length over rapidity
    → Mostly unlike-sign correlations



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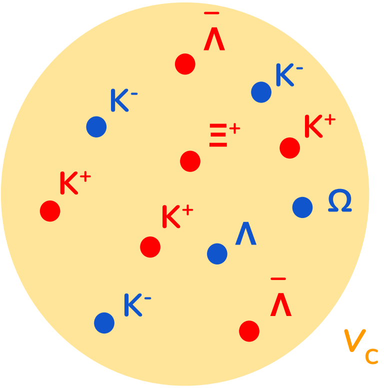

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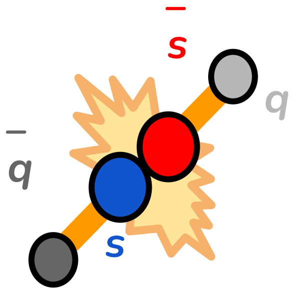


Observables: cumulant ratios of the net-particles

Cumulants

$\kappa_1 = \langle n \rangle$ Mean value

$\kappa_2 = \langle (n - \langle n \rangle)^2 \rangle$ (Co)variance

$\kappa_{11}(n,m) = \langle (n - \langle n \rangle)(m - \langle m \rangle) \rangle$

Net-particles

$\Delta\Xi = n_{\Xi^+} - n_{\Xi^-}$

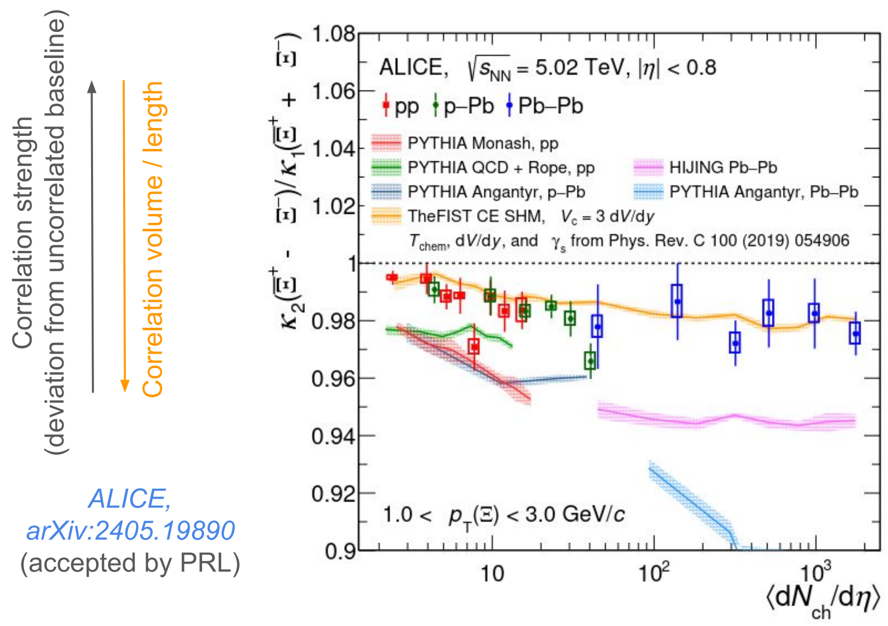
$\Delta K = n_{K^+} - n_{K^-}$

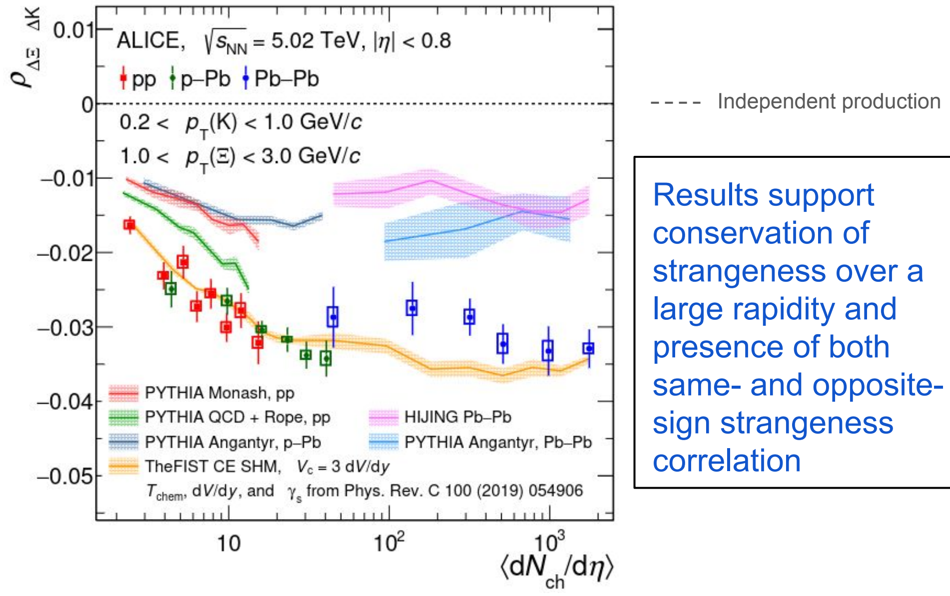
$$\kappa_2(\overline{\Xi}^+ - \Xi^-) = \kappa_2(\overline{\Xi}^+) + \kappa_2(\Xi^-) - 2\kappa_{11}(\overline{\Xi}^+, \Xi^-)$$

$$\rho_{\Delta\Xi\Delta K} = \frac{\kappa_{11}(\Delta\Xi, \Delta K)}{\sqrt{\kappa_{2,\Delta\Xi}\kappa_{2,\Delta K}}}$$

$$\kappa_{11}(\Delta\Xi, \Delta K) = \underbrace{\kappa_{11}(\overline{\Xi}^+, K^+) + \kappa_{11}(\Xi^-, K^-)}_{\text{same-sign}} - \underbrace{\kappa_{11}(\overline{\Xi}^+, K^-) - \kappa_{11}(\Xi^-, K^+)}_{\text{opposite-sign}}$$

E-by-E fluctuation of multi-strange hadrons



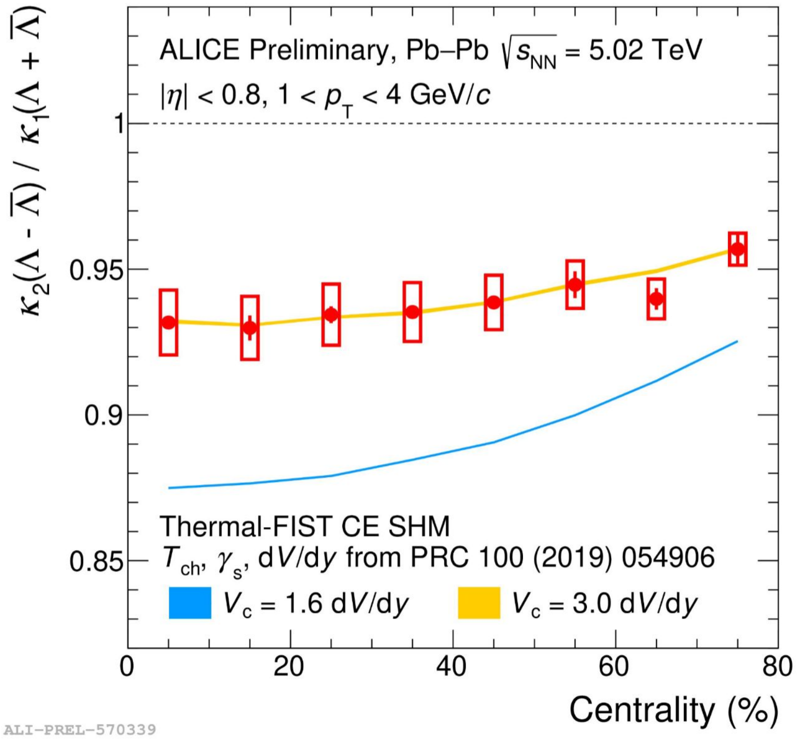


ALICE, arXiv:2405.19890 (accepted by PRL)

Results support conservation of strangeness over a large rapidity and presence of both same- and opposite-sign strangeness correlation

- Significant correlation among strange hadrons due to strange quantum number conservation
- **Thermal model SHM:**
  → described both the observables with a large conservation volume 3 d*V*/d*y* equivalent to a correlation length of 3 units of rapidity and has both the same and opposite sign correlation
- **Non-thermal model PYTHIA:**
  → κ_2/κ_1 is overestimated (larger deviation from independent baseline) due to short range rapidity correlation
  → ρ is underestimated (smaller deviation from independent baseline) due to the absence of same-sign correlation

Comparison with Λ baryon



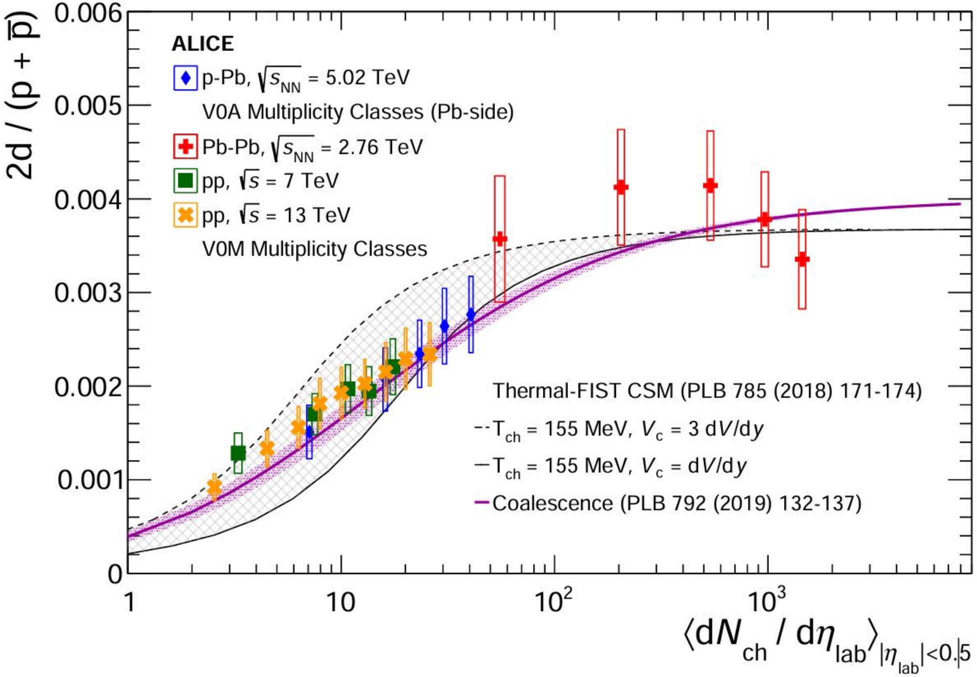
Net-Λ → V_c = 3 dV/dy matches the measured fluctuations

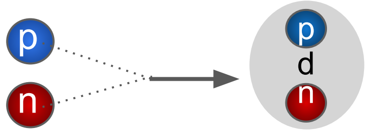
– Common volume parameter for different quantum-number content???

Probing (anti)nucleosynthesis mechanisms with e-by-e fluctuation

- Thermal production of proton and deuteron at freeze-out vs. late production of deuteron through coalescence

ALICE, Eur. Phys. J. C 80 (2020) 889

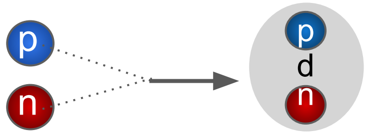




Probing (anti)nucleosynthesis mechanisms with e-by-e fluctuation

- Thermal production of proton and deuteron at freeze-out vs. late production of deuteron through coalescence

- Antideuteron–antiproton correlation has two possible sources of correlation:
  (1) anti-correlation due to baryon number conservation
  (2) anti-correlation due to coalescence



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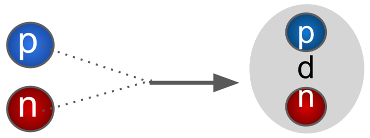

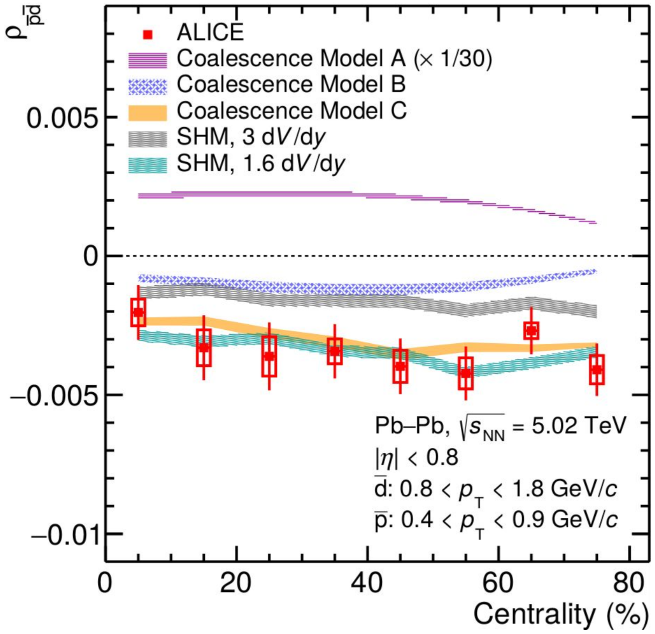

ALICE, Phys. Rev. Lett. 131, (2023) 041901

- Simple coalescence → convolution of proton and neutron distributions
  - Model A: fully correlated nucleons
  - Model B: independent nucleons
  - Model C: anticorrelated nucleons using SHM with 3 d*V*/dy
- Canonical Statistical Model
  - Correlation only due to baryon number conservation

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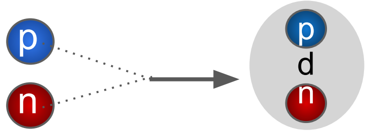

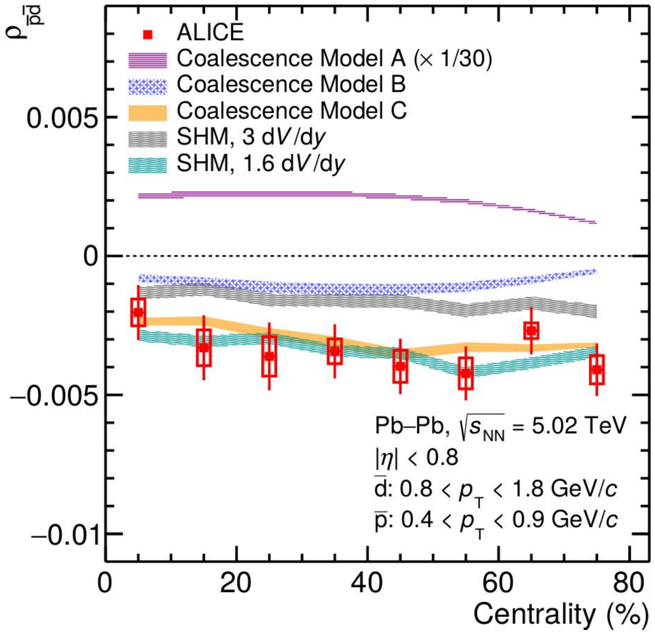

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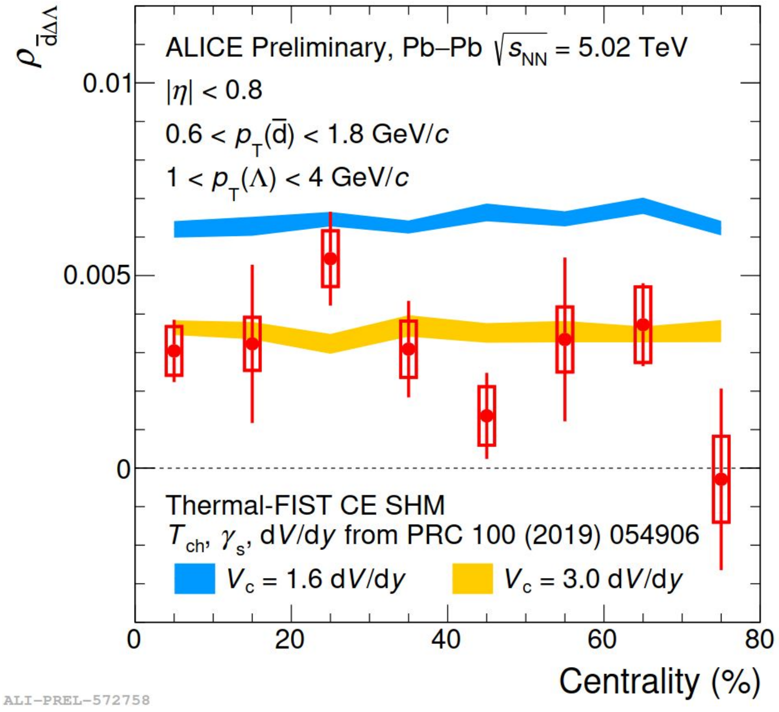
- Measurement can be described by SHM but only with a relatively smaller correlation volume 1.6 dV/dy than other hadrons indicating presence of additional correlation compared to the V_c = 3 dV/dy
- Model C that incorporate deuteron production from the coalescence of thermally produced nucleons with V_c = 3 dV/dy gives more consistent picture with other hadrons

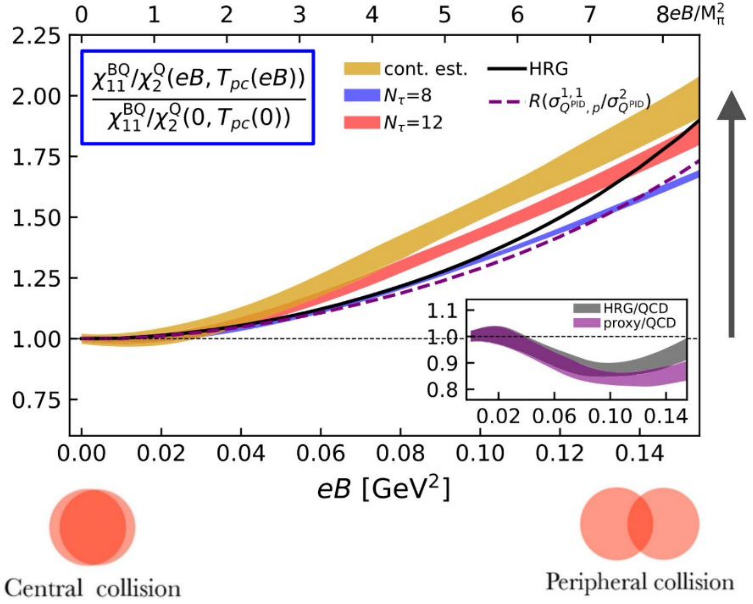
Correlation between deuteron and Lambda baryon
– deuterons are not produced from the coalescence of Lambda baryon
→ the only source of correlation is baryon number conservation



Consistent with V_C = 3 dV/dy
– baryon number conservation in the underlying processes is consistent with other hadrons

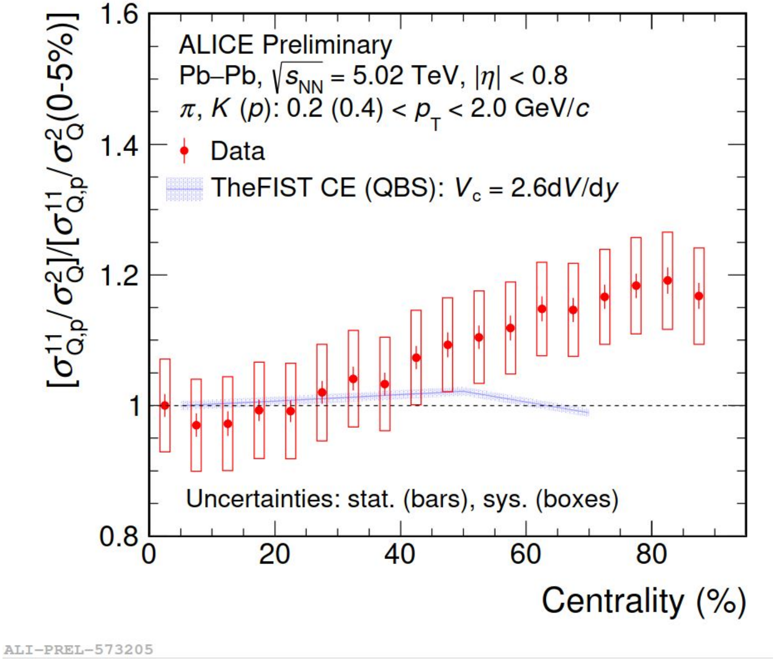
Probing initial magnetic field using e-by-e fluctuation

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

Probing initial magnetic field using e-by-e fluctuation



Shows an increasing trend consistent with LQCD predictions
– deviates from unity by ~20% in peripheral collisions.
– Thermal-FIST model without magnetic field fails to describe the observed trend in data

Summary

- Measurements of net-proton fluctuation upto 3rd order is consistent with SHM expectations
- Deviation of 2nd order fluctuations from Skellam baseline is mainly due to Quantum number conservation
- Measurement suggests conservation of baryon and strange quantum number over a larger correlation volume (3 dV/dy) compared to the string models
- Fluctuation measurements can be a useful tool to distinguish between different hadronization models of strangeness and nuclei
- $\sigma^{11}_{Q,p}$ / σ^{2}_{Q} increases from peripheral to central Pb–Pb collisions, qualitatively consistent with LQCD calculation in the presence of a magnetic field

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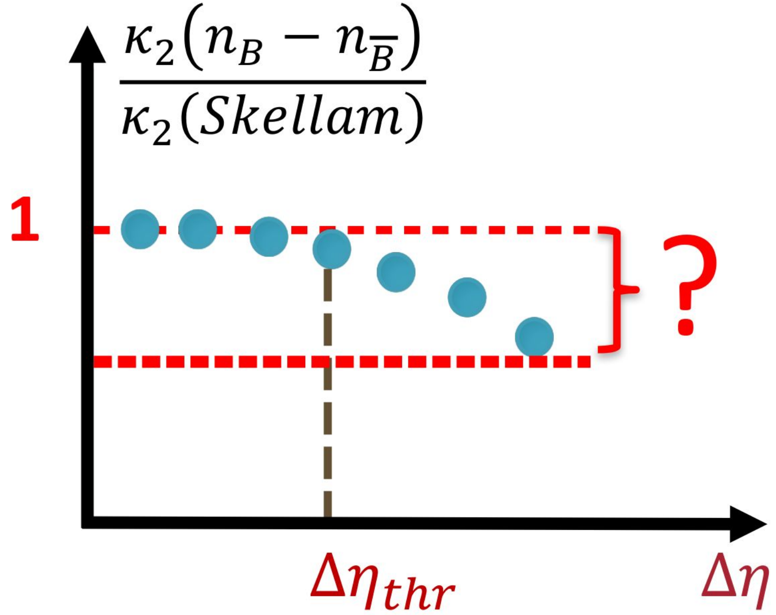
Thank you for your attention

Back up

What do we expect to see in the data?

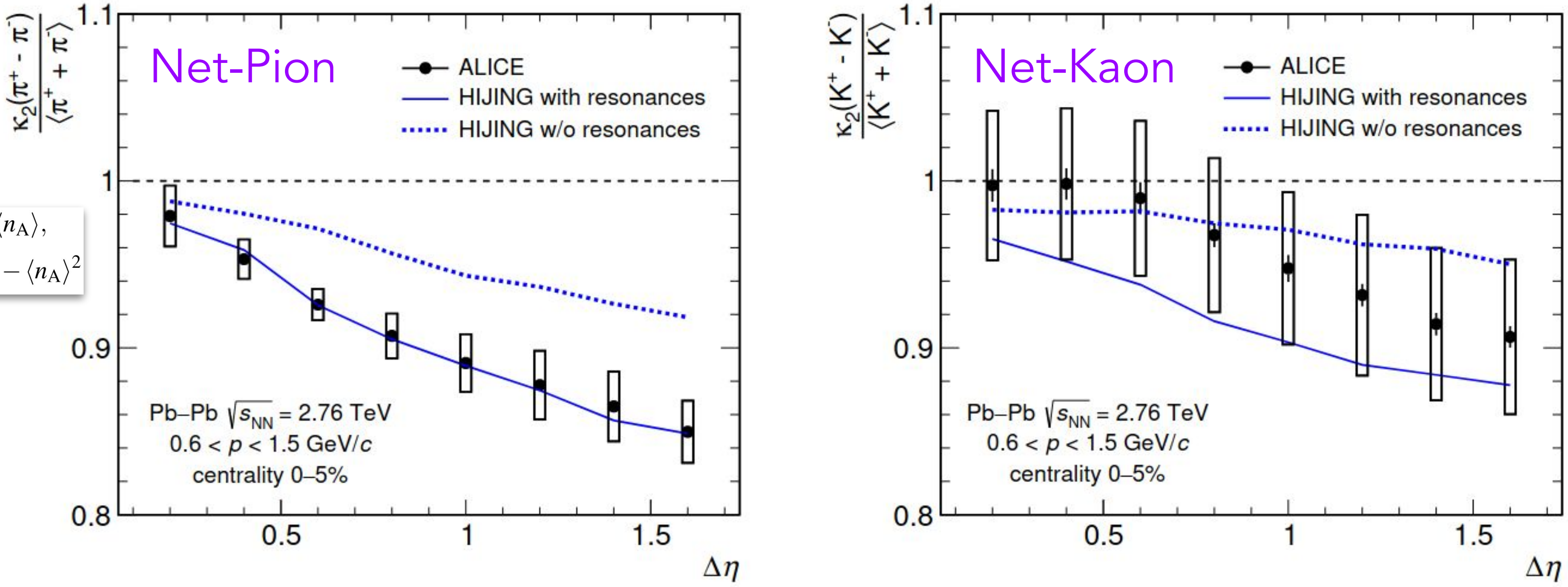


- Fluctuations of conserved charges appear only inside finite acceptance
- In the limit of very small acceptance → only Poissonian fluctuations
- Test if the deviation is consistent with HRG / LQCD

Net-Q,S fluctuations

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

$$\kappa_1(\mathrm{A}) = \langle n_\mathrm{A} \rangle,$$
$$\kappa_2(\mathrm{A}) = \langle n_\mathrm{A}^2 \rangle - \langle n_\mathrm{A} \rangle^2$$



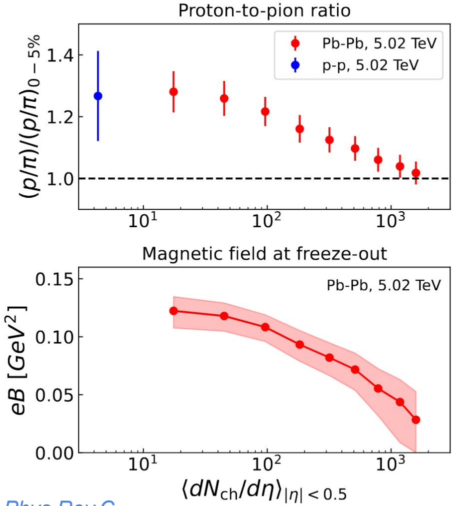
- Net-Q, S: → strongly dominated by resonance feed-down

- Net-B:
  – no resonance feed-down to p-p̄ pair
  – the best suitable candidate for measuring charge susceptibilities is net-p

Probing initial magnetic field using e-by-e fluctuation

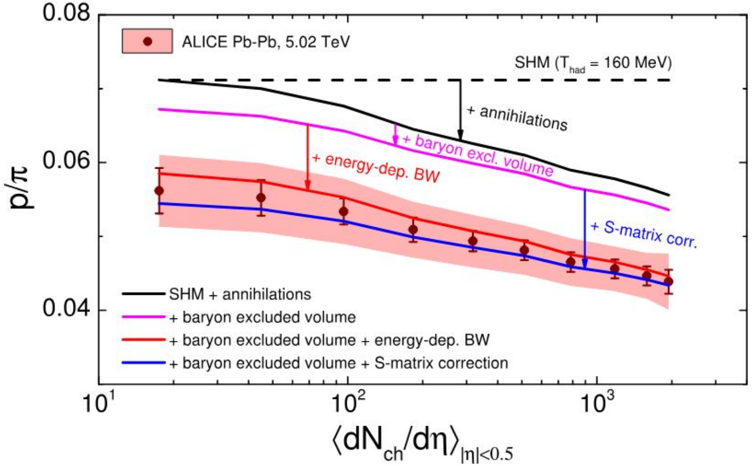
- Qualitatively, in the HRG model $\sigma^{11}_{Q,p} \sim \langle p \rangle$ due to proton self-correlation, while the net charge susceptibility is driven by pion multiplicity, $\sigma^2_Q \sim \langle \pi \rangle$. Therefore, in first-order $\sigma^{11}_{Q,p} / \sigma^2_Q$ is proportional to $\langle p \rangle / \langle \pi \rangle$

HRG with Magnetic Field



V. vovchenko et al., Phys.Rev.C 110 (2024) 3, 034914

HRG with final state interaction (baryon annihilation)



V. Vovchenko et al., Phys. Lett. B 835, (2022) 137577

- $\langle p \rangle / \langle \pi \rangle$ ratio can be changed due to the magnetic field or due to other effects such as baryon annihilation
  → More insight on magnetic field can be obtained from the simultaneous comparison of $\sigma^{11}_{Q,p}$ and $\langle p \rangle / \langle \pi \rangle$ ratios as well as from the measurement of $\sigma^{11}_{Q,p}$ in pp collisions as a null test