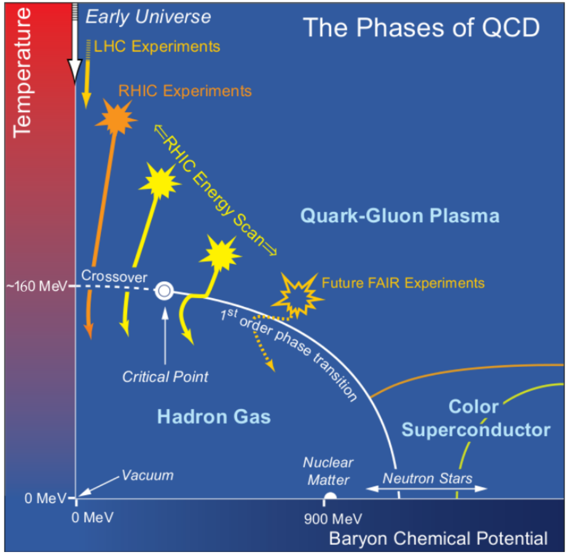
Investigating correlated fluctuations of conserved charges with net-Λ fluctuations in Pb-Pb collisions at ALICE

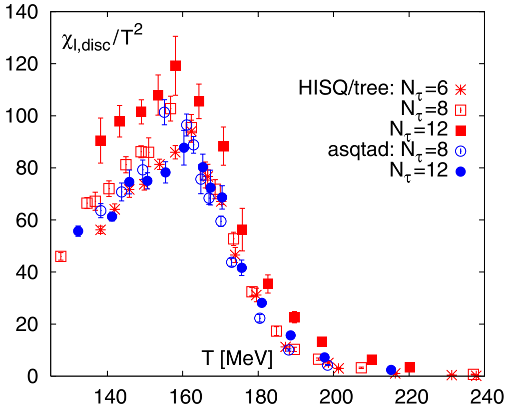
Alice Ohlson (Universität Heidelberg)
for the ALICE Collaboration

Quark Matter 2018, Venice, Italy

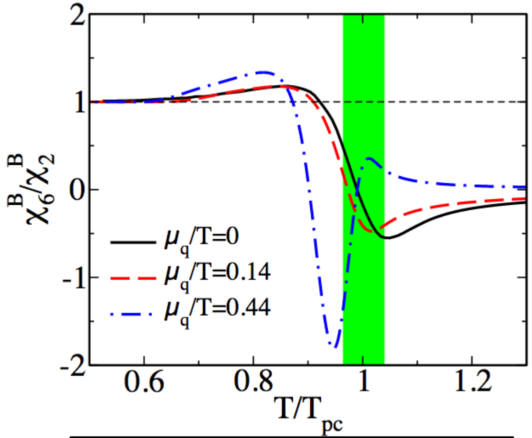
Fluctuations in heavy-ion collisions

- Event-by-event fluctuations of particle multiplicities are used to study properties and the phase structure of strongly-interacting matter
- In heavy-ion collisions at the LHC:
  - test lattice QCD predictions at $\mu_B = 0$
  - close to 2nd-order phase transition for vanishing quark masses → signs of criticality?





A. Bazavov et al. PRD 85 (2012) 054503, arXiv:1111.1710 [hep-lat]



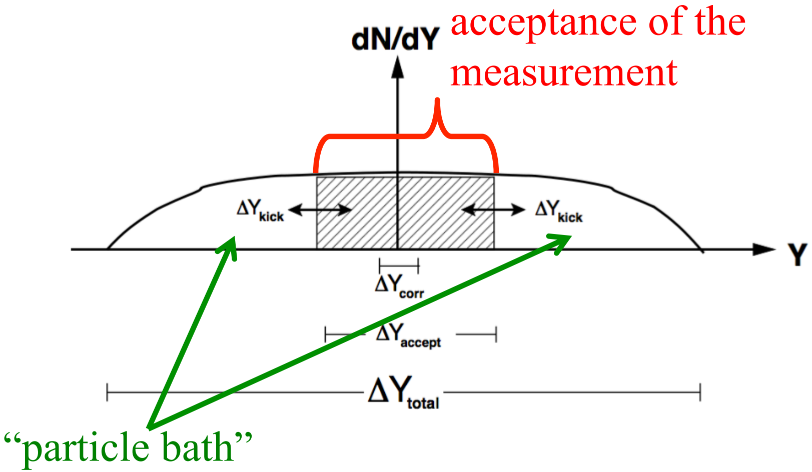
B. Friman, et al. EPJC 71 (2011) 1694, arXiv:1103.3511 [hep-ph]

Connecting theory to experiment

- Thermodynamic susceptibilities χ
  - describe the response of a thermalized system to changes in external conditions, fundamental properties of the medium
  - can be calculated within lattice QCD
  - within the Grand Canonical Ensemble, are related to event-by-event fluctuations of the number of conserved charges: electric charge, strangeness, baryon number

Theory:
susceptibilities

$$\chi_n^B = \frac{\partial^n \left(P/T^4\right)}{\partial \left(\mu_B/T\right)^n}$$



Experiment:
moments of net particle multiplicity distributions

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

Connecting theory to experiment

- Thermodynamic susceptibilities χ
  - describe the response of a thermalized system to changes in external conditions, fundamental properties of the medium
  - can be calculated within lattice QCD
  - within the Grand Canonical Ensemble, are related to event-by-event fluctuations of the number of conserved charges: electric charge, strangeness, baryon number

Theory:
susceptibilities

$$\chi_n^B = \frac{\partial^n \left(P/T^4\right)}{\partial\left(\mu_B/T\right)^n}$$

$$\langle \Delta N_B \rangle = VT^3 \chi_1^B$$

$$\left\langle \left(\Delta N_B - \langle \Delta N_B \rangle\right)^2 \right\rangle = VT^3 \chi_2^B = \sigma^2$$

$$\left\langle \left(\Delta N_B - \langle \Delta N_B \rangle\right)^3 \right\rangle \Big/ \sigma^3 = \frac{VT^3 \chi_3^B}{\left(VT^3 \chi_2^B\right)^{3/2}} = S$$

$$\left\langle \left(\Delta N_B - \langle \Delta N_B \rangle\right)^4 \right\rangle \Big/ \sigma^4 - 3 = \frac{VT^3 \chi_4^B}{\left(VT^3 \chi_2^B\right)^2} = k$$

Experiment:
moments of net particle multiplicity distributions

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

Connecting theory to experiment

- Thermodynamic susceptibilities χ
  - describe the response of a thermalized system to changes in external conditions, fundamental properties of the medium
  - can be calculated within lattice QCD
  - within the Grand Canonical Ensemble, are related to event-by-event fluctuations of the number of conserved charges: electric charge, strangeness, baryon number

Theory:
susceptibilities

$$\chi_n^B = \frac{\partial^n \left(P/T^4\right)}{\partial\left(\mu_B/T\right)^n}$$

$$\langle \Delta N_B \rangle = VT^3\chi_1^B$$

$$\left\langle \left(\Delta N_B - \langle \Delta N_B \rangle\right)^2 \right\rangle = VT^3\chi_2^B = \sigma^2$$

$$\left\langle \left(\Delta N_B - \langle \Delta \ldots \right. \qquad \frac{VT^3\chi_3^B}{\left(VT^3\chi_2^B\right)^{3/2}} = S$$

$$\boxed{\begin{aligned} S\sigma &= \chi_3^B / \chi_2^B \\ \kappa\sigma^2 &= \chi_4^B / \chi_2^B \end{aligned}}$$

$$\left\langle \left(\Delta N_B - \langle \Delta N_B \rangle\right)^4 \right\rangle \Big/ \sigma^4 - 3 = \frac{VT^3\chi_4^B}{\left(VT^3\chi_2^B\right)^2} = k$$

Experiment:
moments of net particle multiplicity distributions

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

Connecting theory to experiment

- Thermodynamic susceptibilities χ
  - describe the response of a thermalized system to changes in external conditions, fundamental properties of the medium
  - can be calculated within lattice QCD
  - within the Grand Canonical Ensemble, are related to event-by-event fluctuations of the number of conserved charges: electric charge, strangeness, baryon number

Theory:
fixed volume,
particle bath in GCE

$$\langle \Delta N_B \rangle \cancel{=} VT^3 \chi_1^B$$

$$\left\langle \left(\Delta N_B - \langle \Delta N_B \rangle \right)^2 \right\rangle \cancel{=} VT^3 \chi_2^B = \sigma^2$$

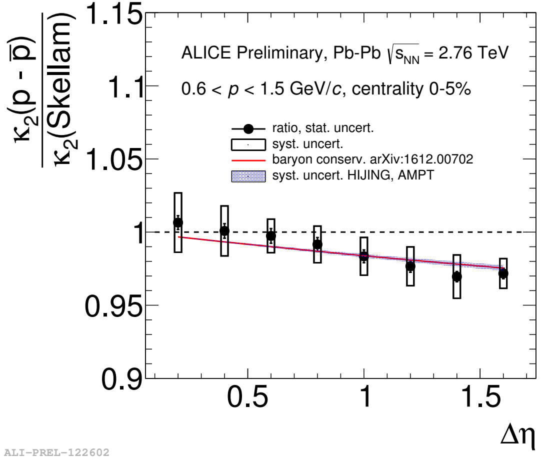
$$\left\langle \left(\Delta N_B - \langle \Delta N_B \rangle \right)^3 \right\rangle / \sigma^3 \cancel{=} \frac{VT^3 \chi_3^B}{\left(VT^3 \chi_2^B \right)^{3/2}} = S$$

$$\left\langle \left(\Delta N_B - \langle \Delta N_B \rangle \right)^4 \right\rangle / \sigma^4 - 3 \cancel{=} \frac{VT^3 \chi_4^B}{\left(VT^3 \chi_2^B \right)^2} = k$$

Experiment:
event-by-event
volume fluctuations,
global conservation
laws

What we have learned so far? What's next?

- Second moments of net-pions, net-kaons, net-protons measured as a function of centrality and $\Delta\eta$
- Deviation of net-protons from Skellam baseline fully accounted for by global baryon number conservation

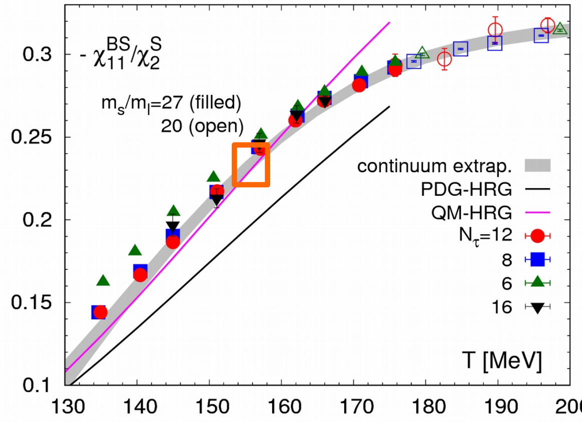


A. Rustamov, QM 2017, Nucl. Phys. A, 967 (2017) 453, arXiv:1704.05329

- Higher moments in ALICE!

N.Behera, Wed. 11:50

- Correlated fluctuations of net-charge, net-strangeness, net-baryon number
  - Access off-diagonal elements, mixed derivatives χ^{BS}, χ^{BQ}, χ^{QS}



F. Karsch, EMMI Workshop on Fluctuations, Wuhan, October 2017

Why measure net-Λ fluctuations?

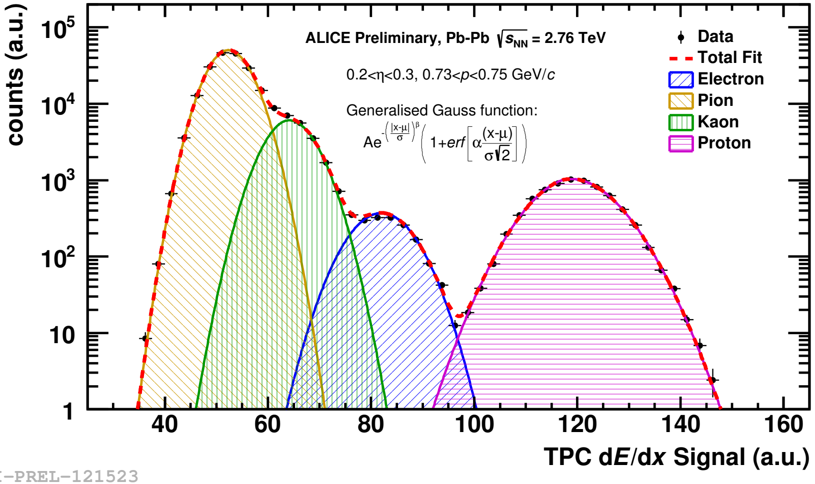
- Explore correlated fluctuations of baryon number and strangeness
- Critical fluctuations not expected for second moments, establish baseline for future measurements of higher moments in the strangeness sector
- Improve understanding of net-baryon fluctuations
  - different contributions from resonances, etc, than in net-proton measurement
- Λs can be "added" to net-proton or net-kaon results to get closer to net-baryon and net-strangeness fluctuations

- The challenge: event-by-event particle identification, signal extraction of $\Lambda \rightarrow p\pi$ complicated by significant combinatorial background
- Proposed solution: the Identity Method

Identity Method for π, K, p identification

- For any value of TPC d*E*/dx, probability that a particle is a π, K, p, is known from inclusive distribution
- Particles are identified statistically, weights (w) are assigned according to probability that particle is of a given species
- Calculate sum of weights (W) instead of sum of particles (N) in a given event
- Find moments of W distribution, then transform into true moments
- Identity Method makes it possible to account for misidentification/impurity without lowering efficiency by imposing strict selection cuts

ALICE, submitted to EPJC, arXiv:1712.07929



ALI-PREL-121523

M. Gazdzicki et al., PRC 83 (2011) 054907, arXiv:1103.2887 [nucl-th]

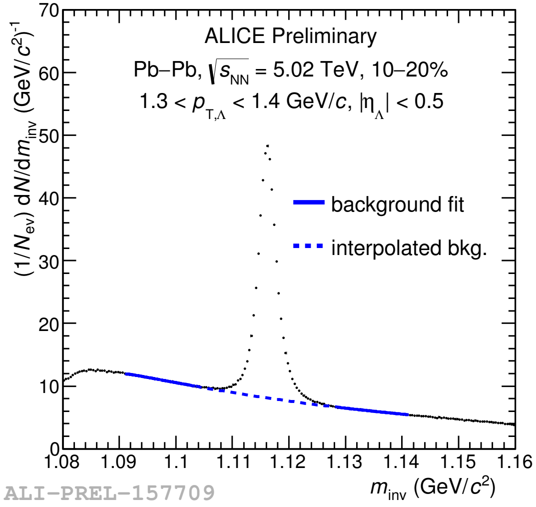
M. I. Gorenstein, PRC 84, (2011) 024902, arXiv:1106.4473 [nucl-th]

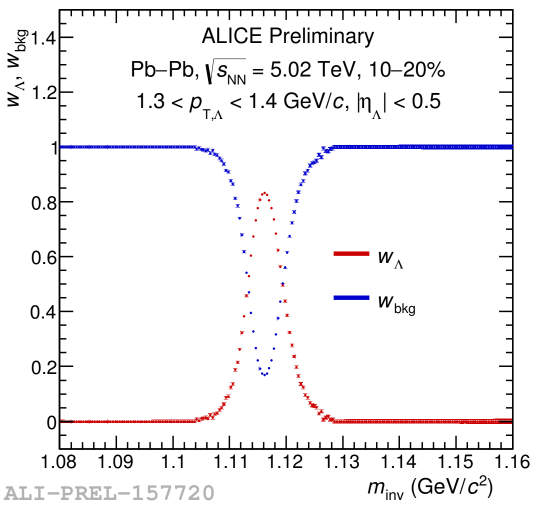
A. Rustamov, M. I. Gorenstein, PRC 86 (2012) 044906, arXiv:1204.6632 [nucl-th]

Identity Method for Λ

- For any value of m_{inv}, probability that a particle is a Λ or combinatoric pπ pair is known from inclusive distribution
- Identity Method formalism can be applied for four 'species': Λ, $\overline{\Lambda}$, combinatoric $p\pi^-$, combinatoric $\overline{p}\pi^+$
- Identity Method makes it possible to account for large combinatoric background
- Efficiency (ε ~10-30%) and secondary contamination (δ ~ 20-35%) corrections performed under binomial assumption

C. Pruneau, PRC 96 (2017) 054902, arXiv:1706.01333 [physics.data-an]

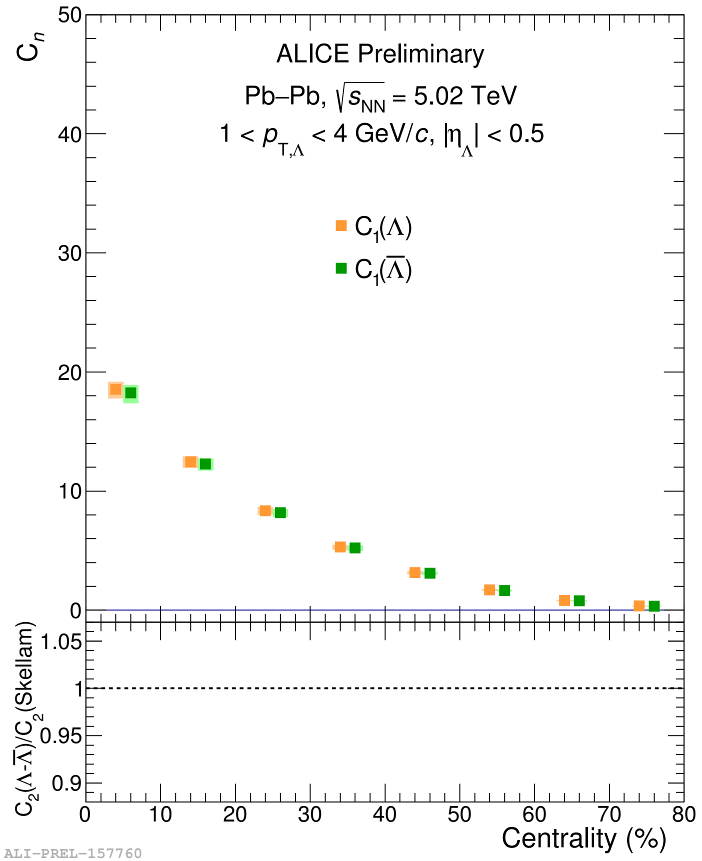




Results: Net-Λ fluctuations in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

Centrality dependence of 1st moments

$$C_1(\Lambda) = \langle N_\Lambda \rangle$$



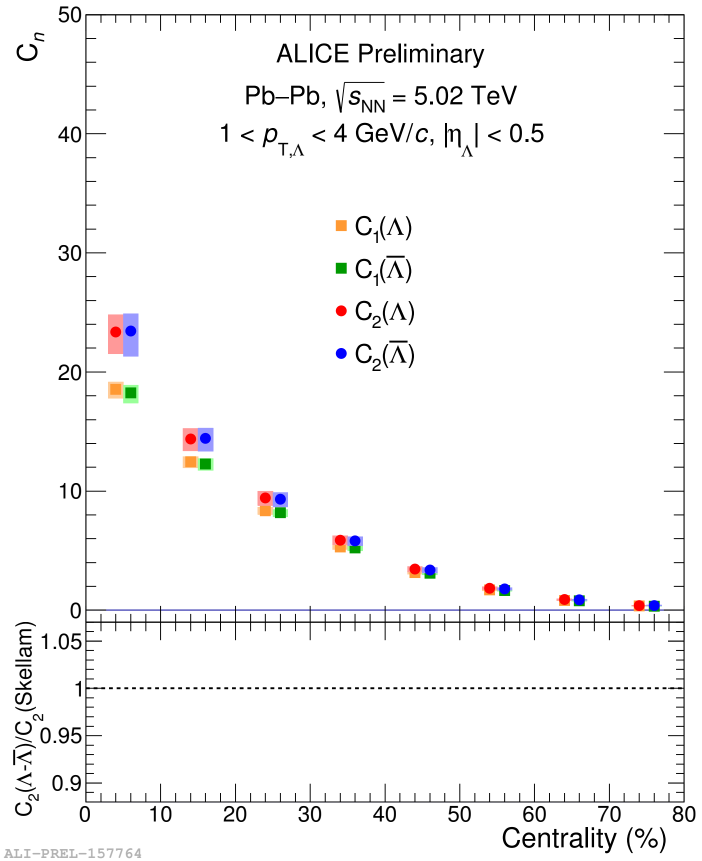
Centrality dependence of 2nd moments

$$C_1(\Lambda) = \langle N_\Lambda \rangle$$

$$C_2(\Lambda) = \left\langle \left(N_\Lambda - \langle N_\Lambda \rangle\right)^2 \right\rangle$$

- If multiplicity distributions of Λ and $\overline{\Lambda}$ are Poissonian

$$C_2(\Lambda) = C_1(\Lambda)$$



Centrality dependence of net-Λ 2nd moments

$$C_1(\Lambda) = \langle N_\Lambda \rangle$$

$$C_2(\Lambda) = \left\langle \left(N_\Lambda - \langle N_\Lambda \rangle\right)^2 \right\rangle$$

$$C_2(\Lambda - \overline{\Lambda}) = \left\langle \left(N_\Lambda - N_{\overline{\Lambda}} - \langle N_\Lambda - N_{\overline{\Lambda}} \rangle\right)^2 \right\rangle$$

$$C_2(\Lambda - \overline{\Lambda}) = C_2(\Lambda) + C_2(\overline{\Lambda}) - 2\left(\langle N_\Lambda N_{\overline{\Lambda}} \rangle - \langle N_\Lambda \rangle \langle N_{\overline{\Lambda}} \rangle\right)$$

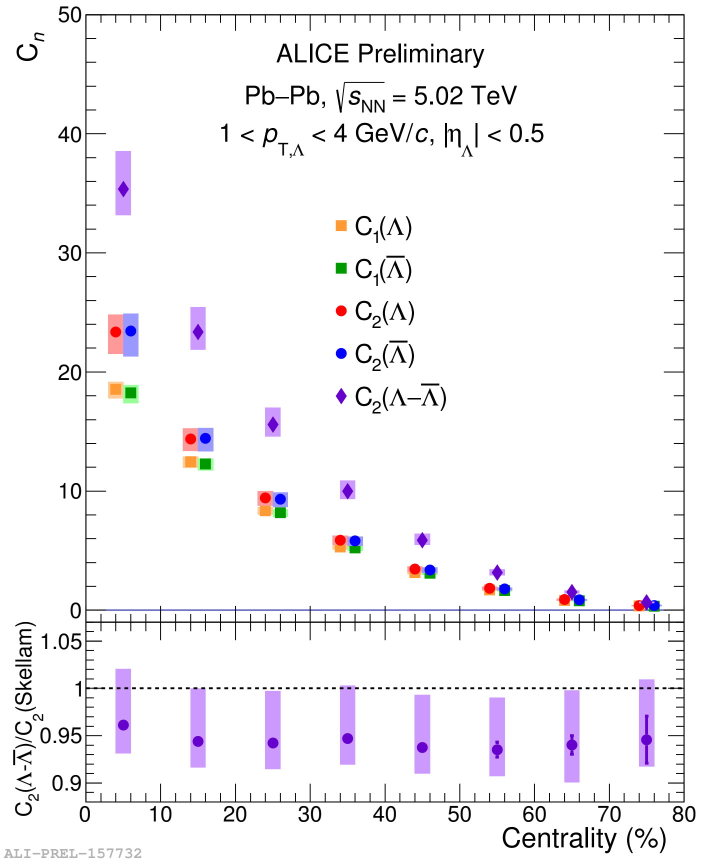
- If multiplicity distributions of Λ and $\overline{\Lambda}$ are Poissonian

$$C_2(\Lambda) = C_1(\Lambda)$$

$\rightarrow$ if uncorrelated, Skellam distribution for net-Λ

$$C_2(Skellam) = C_1(\Lambda) + C_1(\overline{\Lambda})$$

- Small deviations from Skellam baseline
  - correlation term? non-Poissonian Λ or $\overline{\Lambda}$ distributions? critical fluctuations?



Comparison to HIJING

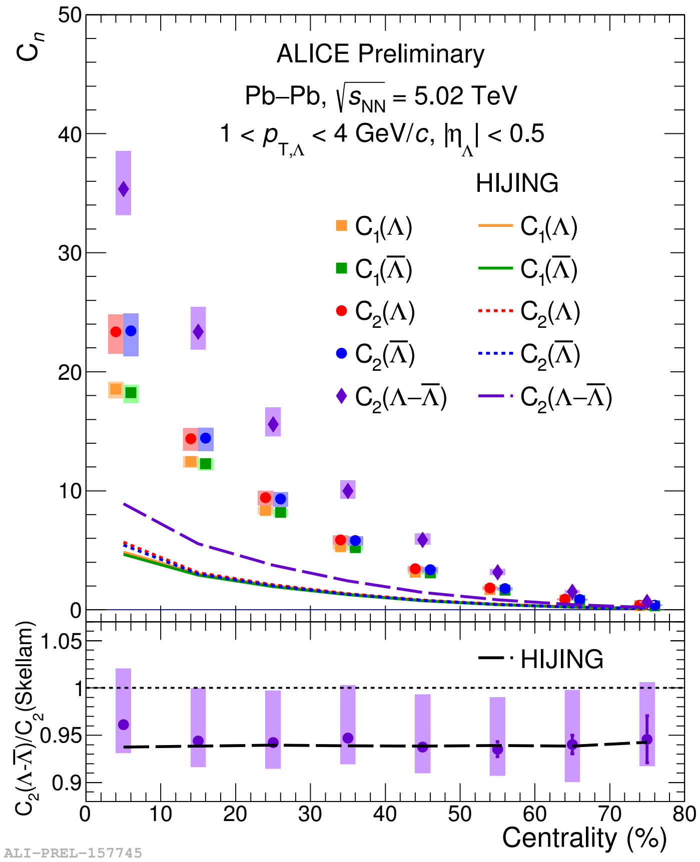
$$C_1(\Lambda) = \langle N_\Lambda \rangle$$

$$C_2(\Lambda) = \left\langle \left(N_\Lambda - \langle N_\Lambda \rangle\right)^2 \right\rangle$$

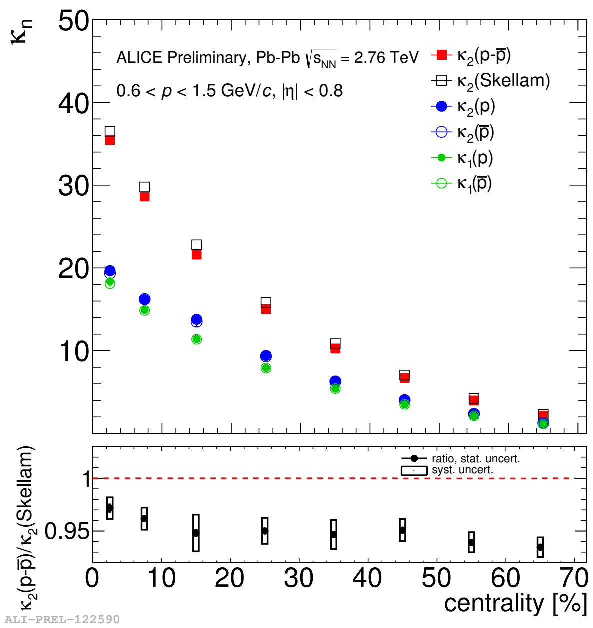
$$C_2(\Lambda - \overline{\Lambda}) = \left\langle \left(N_\Lambda - N_{\overline{\Lambda}} - \langle N_\Lambda - N_{\overline{\Lambda}} \rangle\right)^2 \right\rangle$$

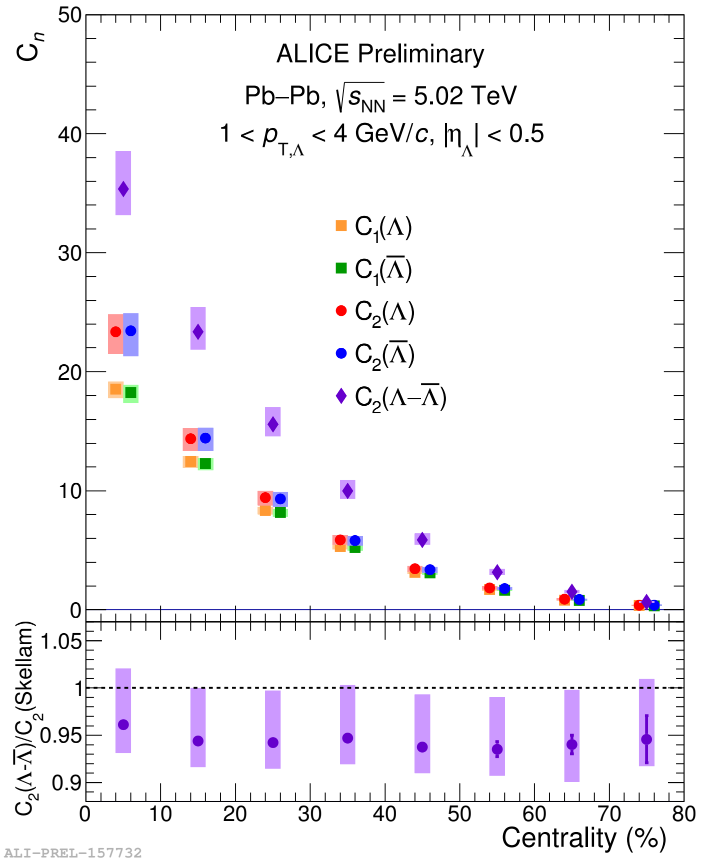
$$C_2(\Lambda - \overline{\Lambda}) = C_2(\Lambda) + C_2(\overline{\Lambda}) - 2\left(\langle N_\Lambda N_{\overline{\Lambda}} \rangle - \langle N_\Lambda \rangle \langle N_{\overline{\Lambda}} \rangle\right)$$

- HIJING does not describe strangeness production well
  - underestimates C_1 and C_2 by factor ~4
- $C_2(\Lambda\text{-}\overline{\Lambda})/C_2(\text{Skellam})$ ratio agrees with data
  - coincidence? or due to description of fluctuations and resonance contributions in HIJING?



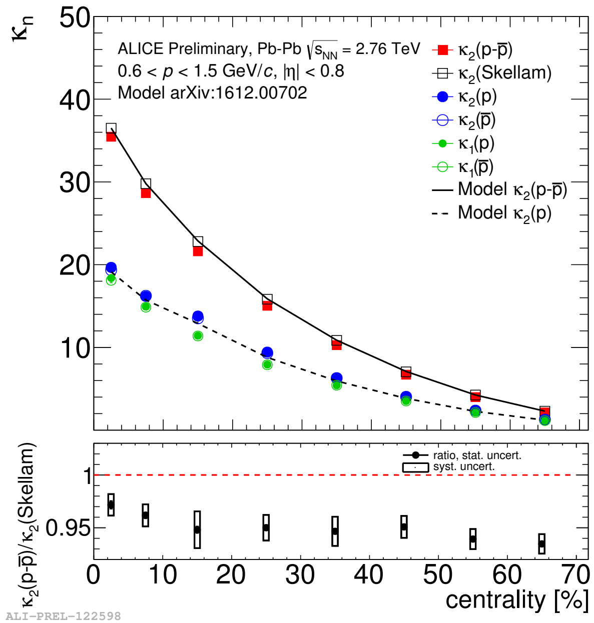
Comparison to net-protons

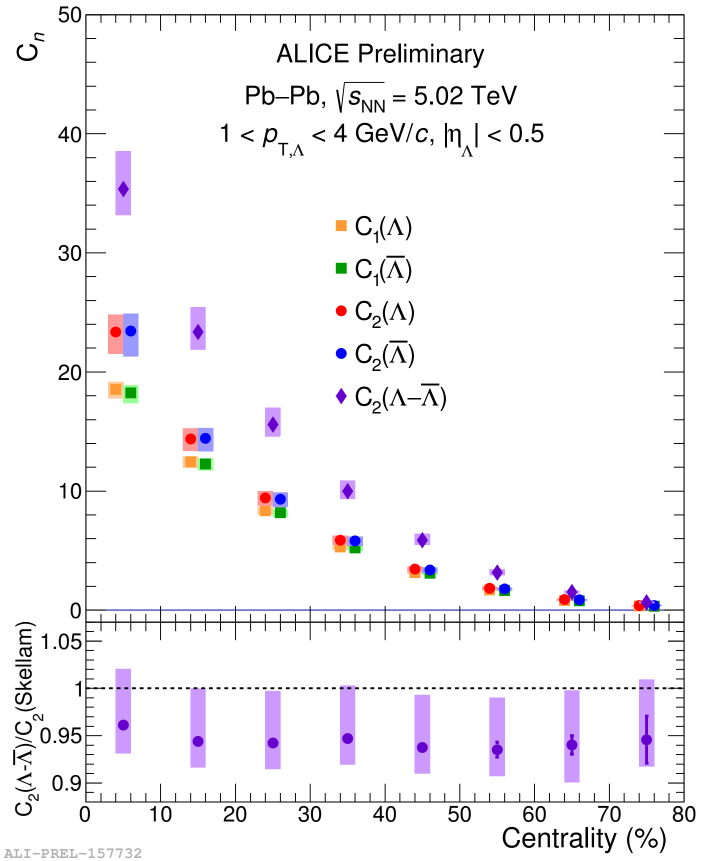




- Qualitatively similar results for net-protons
  - note different kinematic range
  - different contributions from resonance decays

Comparison to net-protons

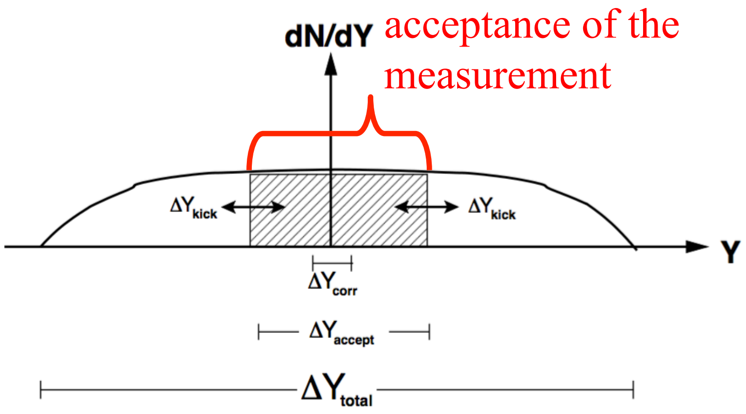




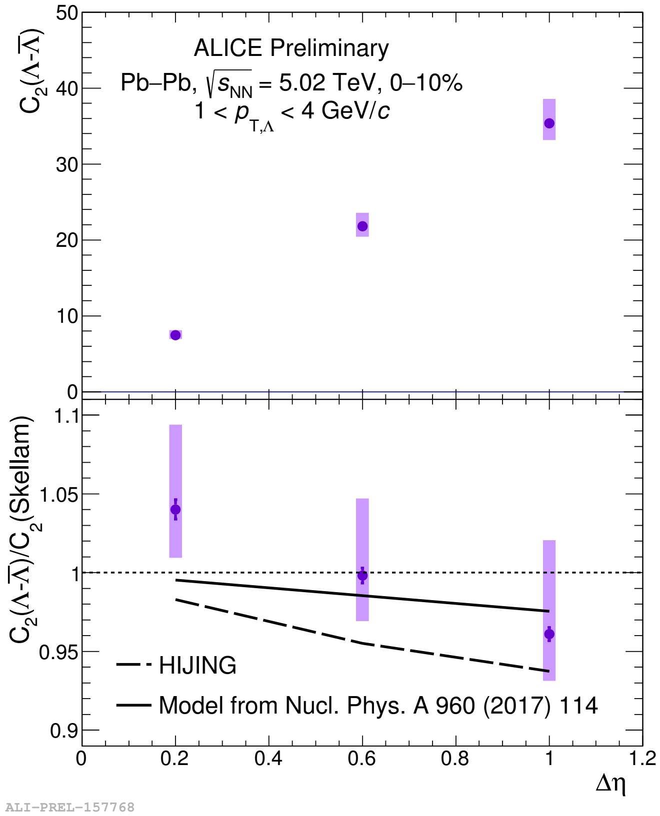
- Model including volume fluctuations and global baryon number conservation fully describes deviations from Poisson/Skellam expectation for net-protons

P. Braun-Munzinger, A. Rustamov, J. Stachel, NPA 960 (2017) 114, arXiv:1612.00702 [nucl-th]

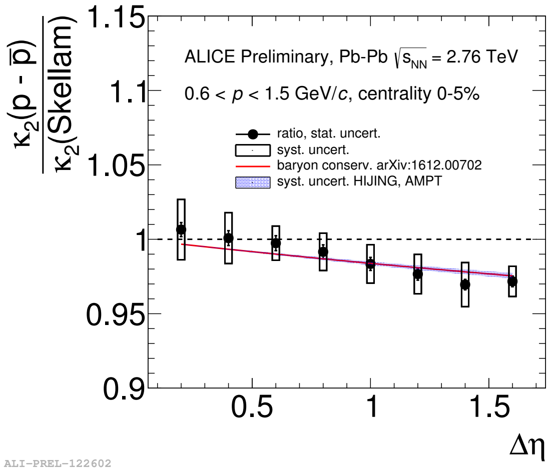
Δη dependence in central collisions

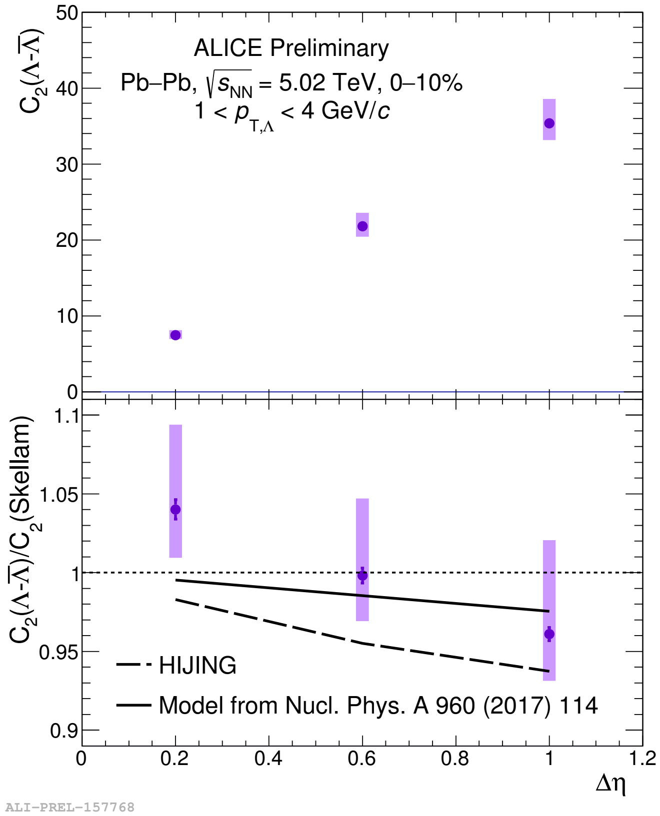


- Small Δη → Poissonian fluctuations, ratio to Skellam ~1
- Large Δη → global baryon number and strangeness conservation effects, ratio to Skellam < 1
- Systematic uncertainties are highly correlated point-to-point
- Δη dependence consistent with effects of baryon number conservation

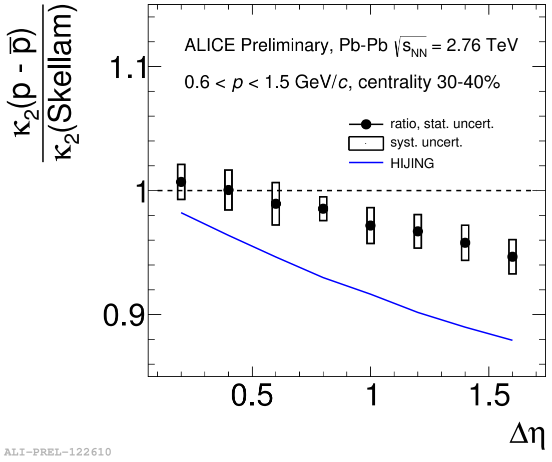


Δη dependence, comparison to net-protons

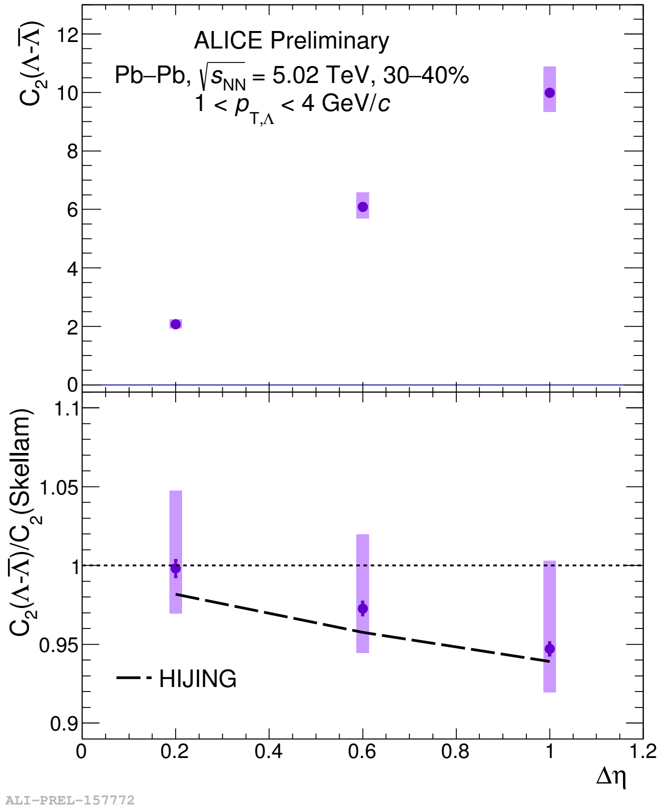




- $C_2(p-\bar{p})$ fully consistent with Skellam baseline after accounting for global baryon number conservation
- Similar trends for net-Λ
  - also strangeness conservation effects should be considered



- Net-protons results not described by HIJING, but net-Λ results are consistent



Conclusions

- First measurement of second moments of event-by-event net-Λ fluctuations as a function of centrality and $\Delta\eta$
- Ratio of C_2 to Skellam baseline ~0.95-1
  - qualitative agreement with net-proton measurement
  - deviation from Skellam understood due to global baryon number and strangeness conservation, not critical behavior
- Identity Method is applied on m_{inv} axis for the first time
- Opens new possibilities for future measurements of other particle species and higher moments!

Conclusions

- First measurement of second moments of event-by-event net-Λ fluctuations as a function of centrality and $\Delta\eta$
- Ratio of C_2 to Skellam baseline ~0.95-1
  - qualitative agreement with net-proton measurement
  - deviation from Skellam understood due to global baryon number and strangeness conservation, not critical behavior
- Identity Method is applied on m_{inv} axis for the first time
- Opens new possibilities for future measurements of other particle species and higher moments!

Thank you for your attention!

Any questions?

backup

Λ reconstruction

- Cuts on V0s
  - V0 radius > 5 cm
  - DCA of V0 daughters < 1 cm
  - DCA of daughters to secondary vertex > 0.1 cm
  - proper lifetime mL/*p* < 25 cm
  - p_T-dependent $\cos(\theta_{PA})$ cut
- Cuts on daughter tracks
  - $|\eta| < 0.8$
  - $p_{T,\pi} > 0.15$ GeV/*c*, $p_{T,p} > 0.6$ GeV/*c*
  - $n\sigma < 3$ for (anti-)proton
  - # crossed rows > 70, crossed rows / findable clusters > 0.8
- (Anti-)Lambda selection
  - $|\eta| < 0.5$
  - $1 < p_T < 4$ GeV/c