Event-by-event fluctuations of identified particles in heavy-ion collisions

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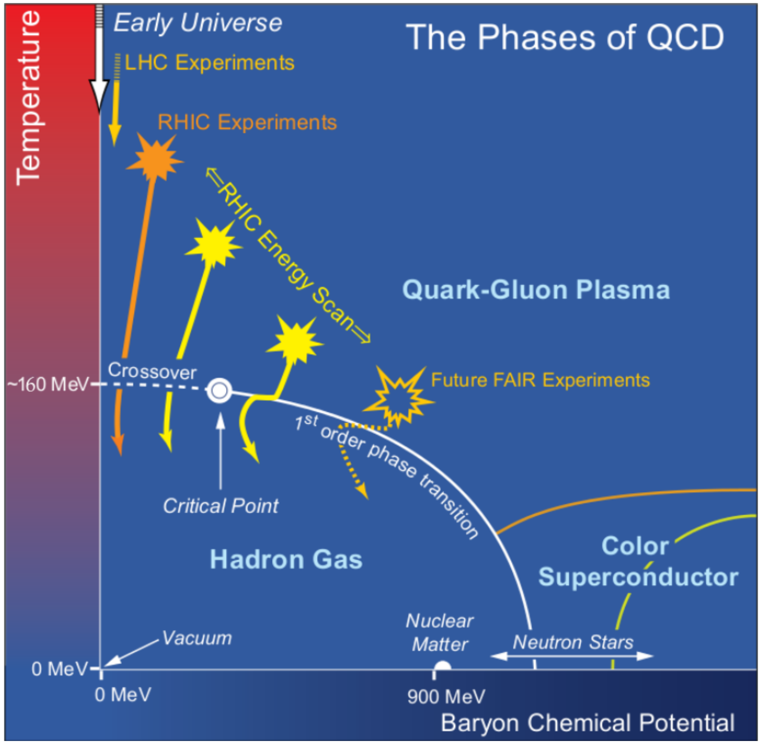
Alexander von Humboldt Stiftung/Foundation

Fluctuations in heavy ion collisions

- Event-by-event fluctuations of particle multiplicities are used to study properties and phase structure of strongly-interacting matter



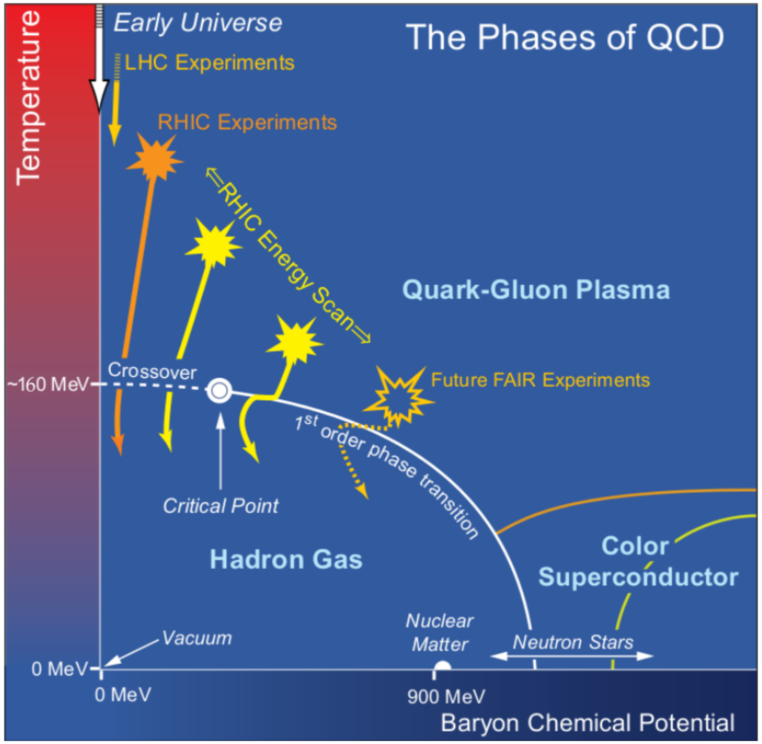
- Fluctuations grow in the region near a phase transition and/or critical point
  - can we observe signs of criticality?

Critical opalescence in CO_2
J.V. Sengers, A.L Sengers, Chem. Eng. News, June 10, 104–118, 1968

$T > T_c$ $T >\sim T_c$ $T <\sim T_c$ $T < T_c$

Fluctuations in heavy ion collisions

- Event-by-event fluctuations of particle multiplicities are used to study properties and phase structure of strongly-interacting matter



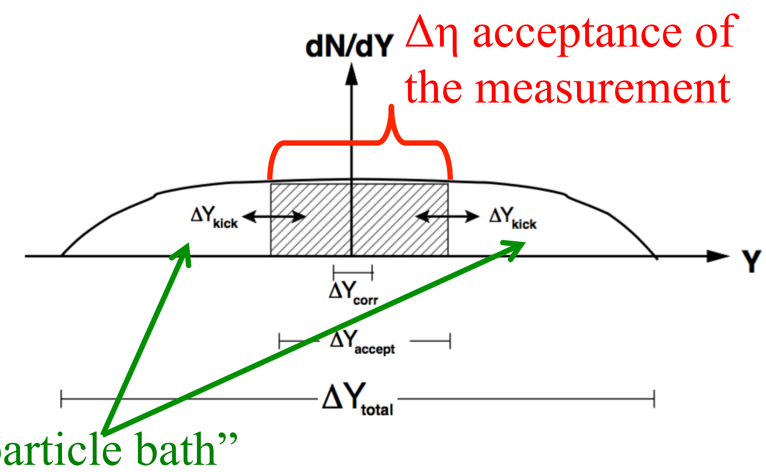
- Fluctuations grow in the region near a phase transition and/or critical point
  - can we observe signs of criticality?
- Fluctuations of conserved charges can be related to susceptibilities calculable in lattice QCD
  - precision test of LQCD at $\mu_B \approx 0$

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

Theory: susceptibilities

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



Experiment: moments of particle multiplicity distributions

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

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Theory: susceptibilities

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

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

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

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

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

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Theory: susceptibilities

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

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

$$\langle (\Delta N_B - \langle \Delta N \ldots \sigma^2$$

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

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

$$S\sigma = \chi_3^B / \chi_2^B$$

$$\kappa\sigma^2 = \chi_4^B / \chi_2^B$$

Experiment: moments of 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

Theory: fixed volume, particle bath in GCE

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

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

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

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

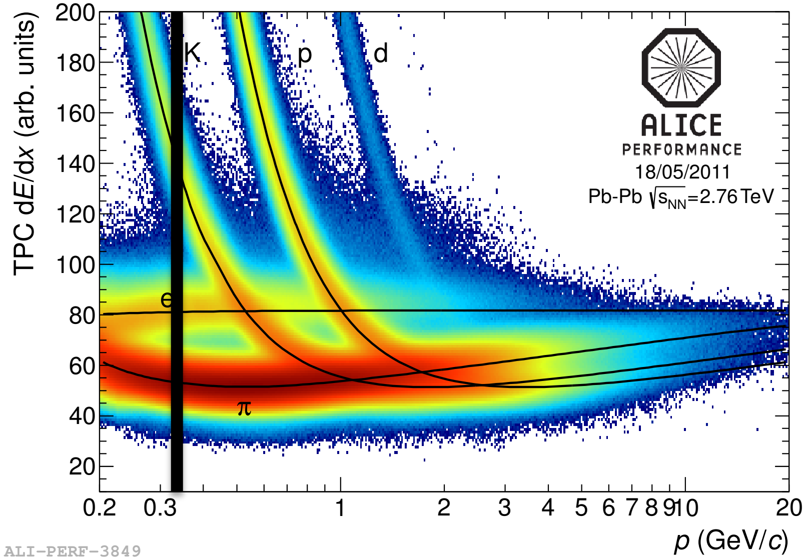
Experiment: event-by-event volume fluctuations, global conservation laws

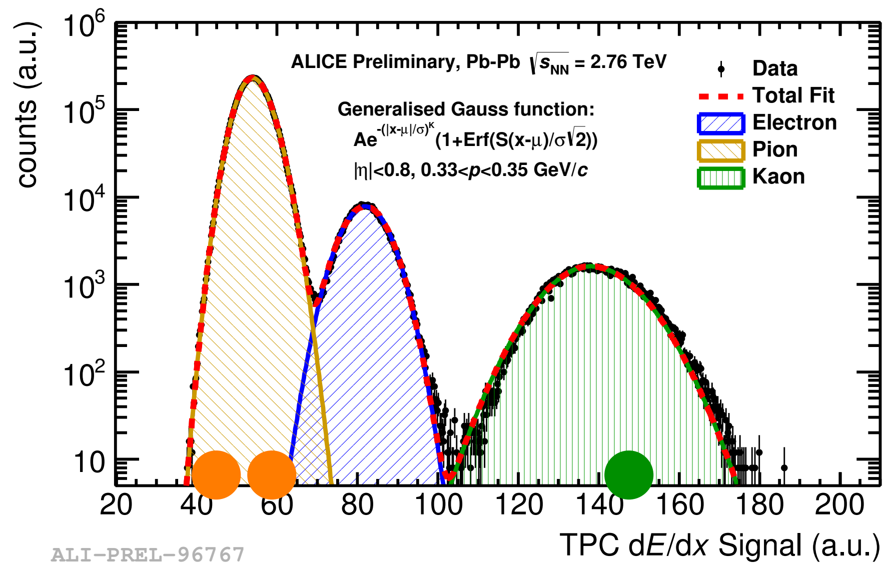
Experimental Challenges

1. Event-by-event particle identification
2. Event-by-event efficiency correction

We know how to correct the first moments, but what about the higher moments?

The challenge: event-by-event PID



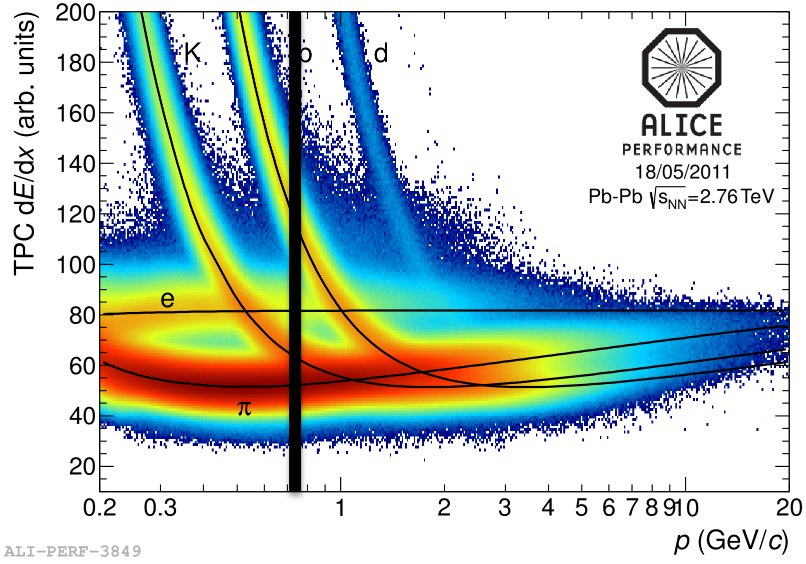


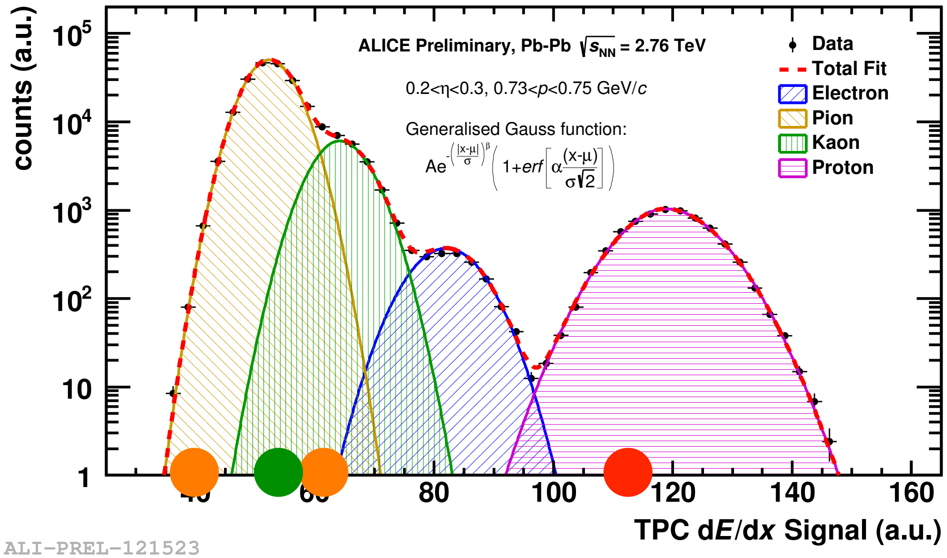
- Traditional method:
  - count number of pions (N_π), kaons (N_K), protons (N_p) in each event

$$N_p = \sum_{i}^{\#tracks} \begin{cases} 1 & \text{particle } i \text{ is a proton} \\ 0 & \text{particle } i \text{ is not a proton} \end{cases}$$

  - find moments of distributions of N_π, N_K, N_p, ...

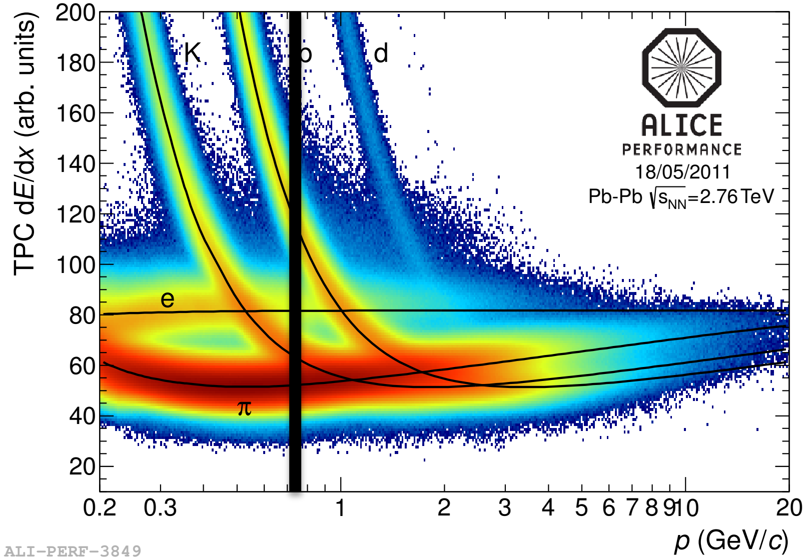
Traditional method

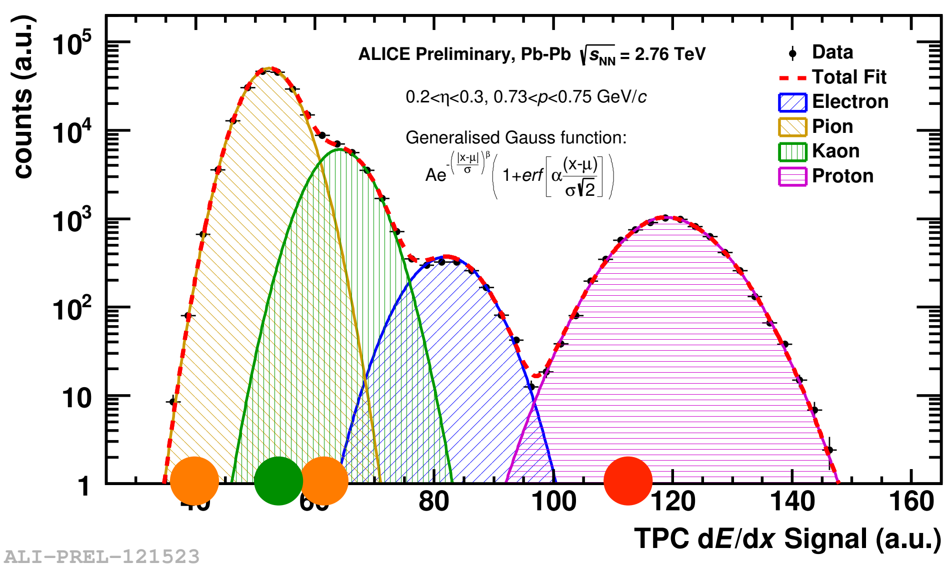




- What if PID is unclear?
  - use other detector information or reject phase space bin
  - results in lower efficiency

Identity method





- As a function of the PID variable m, determine probability w that particle is of a given species
- Calculate event-by-event sum of weights W_π, W_K, W_p, ….

$$W_p = \sum_i^{\#tracks} w_p(m_i)$$

- Using knowledge of inclusive m distributions, unfold moments of W distributions to get moments of N
- Contamination is accounted for, full phase space can be used

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 et al., PRC 86 (2012) 044906, arXiv:1204.6632 [nucl-th]

M. Arslandok and A. Rustamov, arXiv: 1807.06370 [hep-ex]

Efficiency corrections: several ideas

- Simple scaling of moments using HIJING and/or AMPT
- Correction of factorial moments assuming binomial track loss

A. Bzdak and V. Koch,
Phys. Rev. C86, 044904 (2012),
arXiv:1206.4286 [nucl-th].

A. Bzdak and V. Koch,
Phys. Rev. C91, 027901 (2015),
arXiv:1312.4574 [nucl-th].

  – extension to Identity Method

C. Pruneau, Phys. Rev. C96 (2017) 054902,
arXiv:1706.01333 [physics.data-an]

- Correction using moments of detector response matrix

T. Nonaka et al., Nucl. Inst. Meth. A 906 (2018) 10,
arXiv:1805.00279 [physics.data-an]

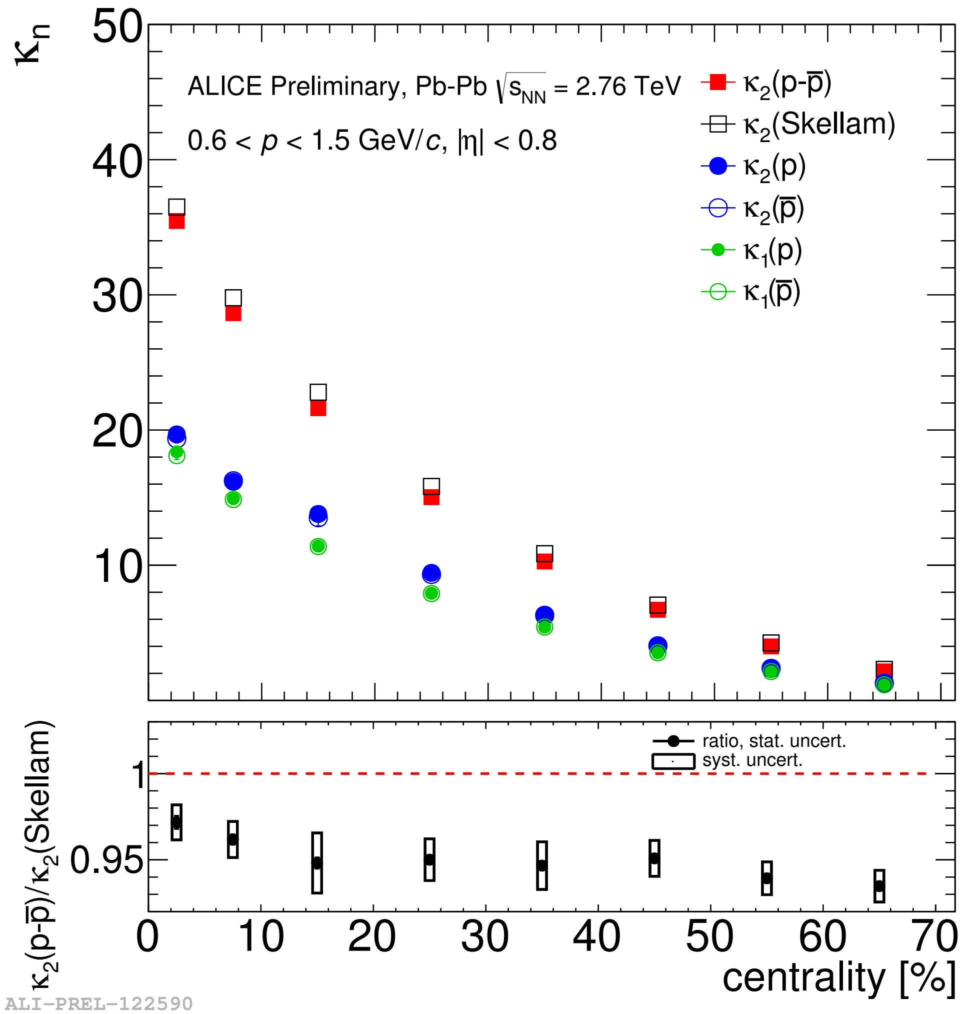
- Full unfolding of moments

All correction methods rely on different assumptions, which must be assessed and tested carefully!

Second moments from the LHC

Net-proton fluctuations

A. Rustamov for ALICE, QM2017



$$\kappa_1(p) = \langle N_p \rangle \qquad \kappa_2(p) = \left\langle \left(N_p - \langle N_p \rangle \right)^2 \right\rangle$$

$$\kappa_2(p-\bar{p}) = \left\langle \left(N_p - N_{\bar{p}} - \langle N_p - N_{\bar{p}} \rangle \right)^2 \right\rangle$$

$$= \kappa_2(p) + \kappa_2(\bar{p}) - 2\left(\langle N_p N_{\bar{p}} \rangle - \langle N_p \rangle \langle N_{\bar{p}} \rangle \right)$$

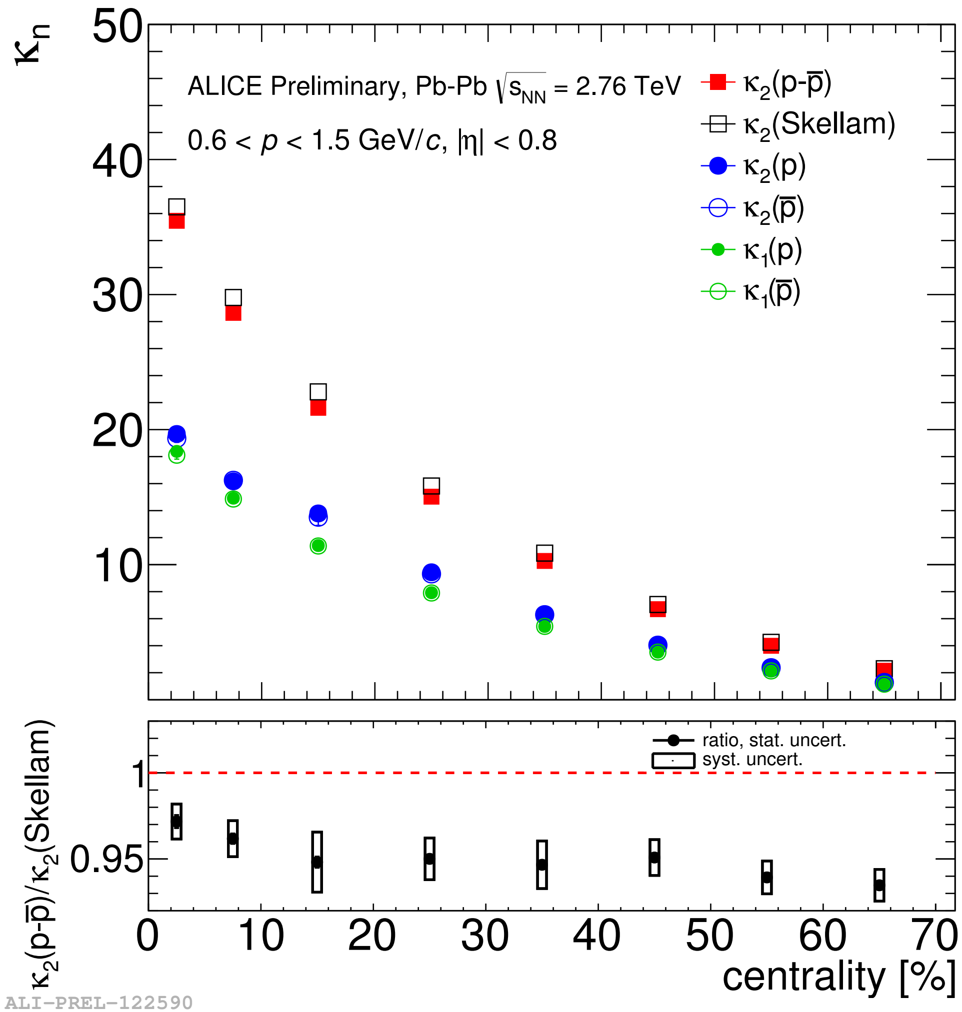
correlation term

- If multiplicity distributions of protons and anti-protons are Poissonian and uncorrelated
  → Skellam distribution for net-protons

$$\kappa_2(Skellam) = \kappa_1(p) + \kappa_1(\bar{p})$$

Net-proton fluctuations

A. Rustamov for ALICE, QM2017



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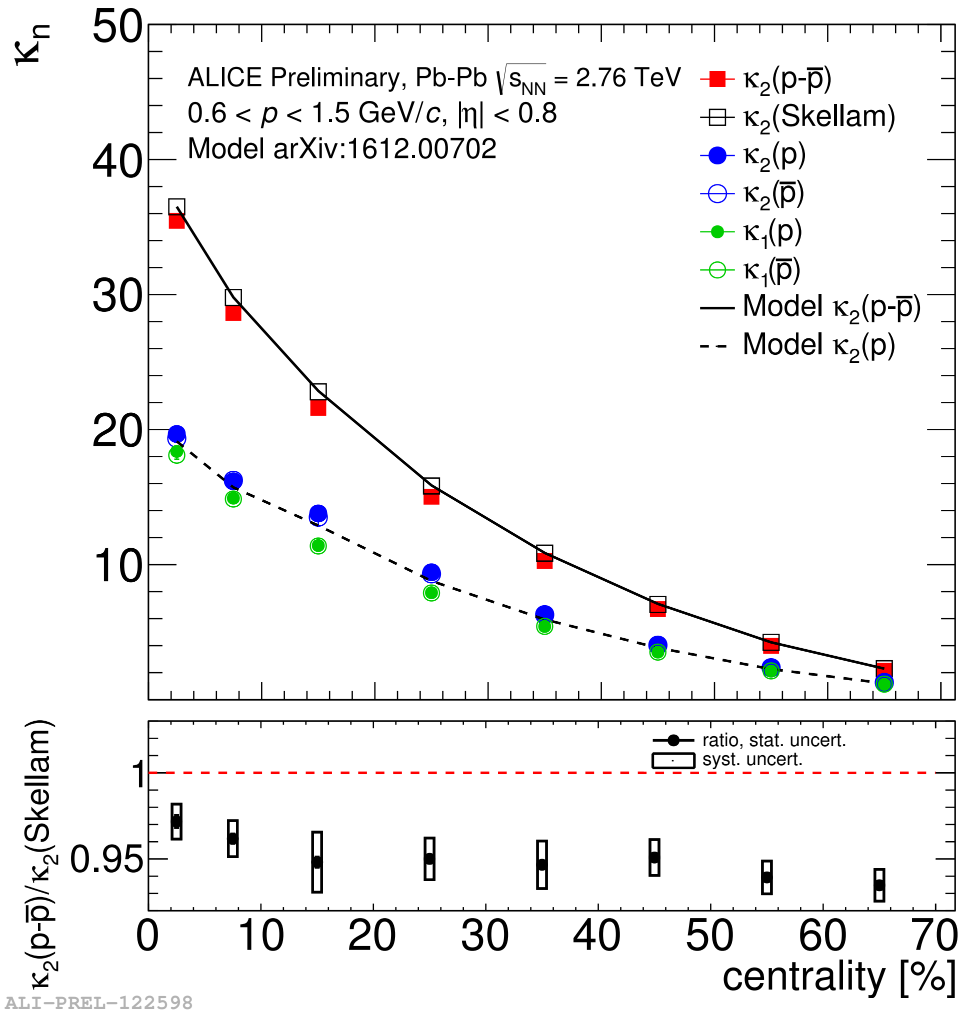
$$= \kappa_2(p) + \kappa_2(\bar{p}) - 2\underbrace{\left(\langle N_p N_{\bar{p}} \rangle - \langle N_p \rangle \langle N_{\bar{p}} \rangle\right)}_{\text{correlation term}}$$

- $\kappa_2(p-\bar{p})$ shows deviation from Skellam prediction
  - due to correlation term?
  - are protons and anti-protons Poissonian?

$$\kappa_2(Skellam) = \kappa_1(p) + \kappa_1(\bar{p})$$

Net-proton fluctuations

A. Rustamov for ALICE, QM2017

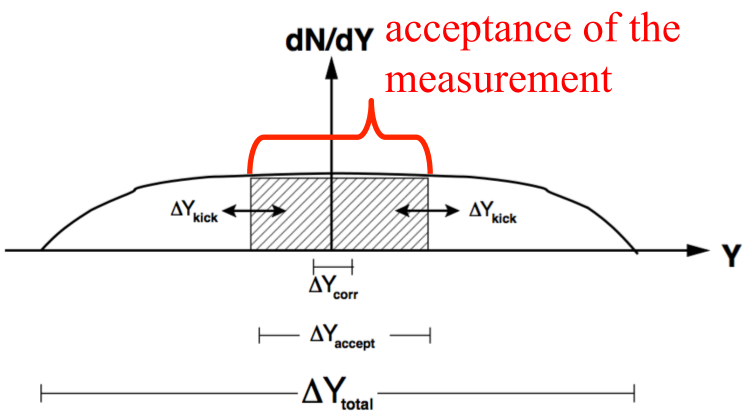


- Modeling the effects of participant fluctuations

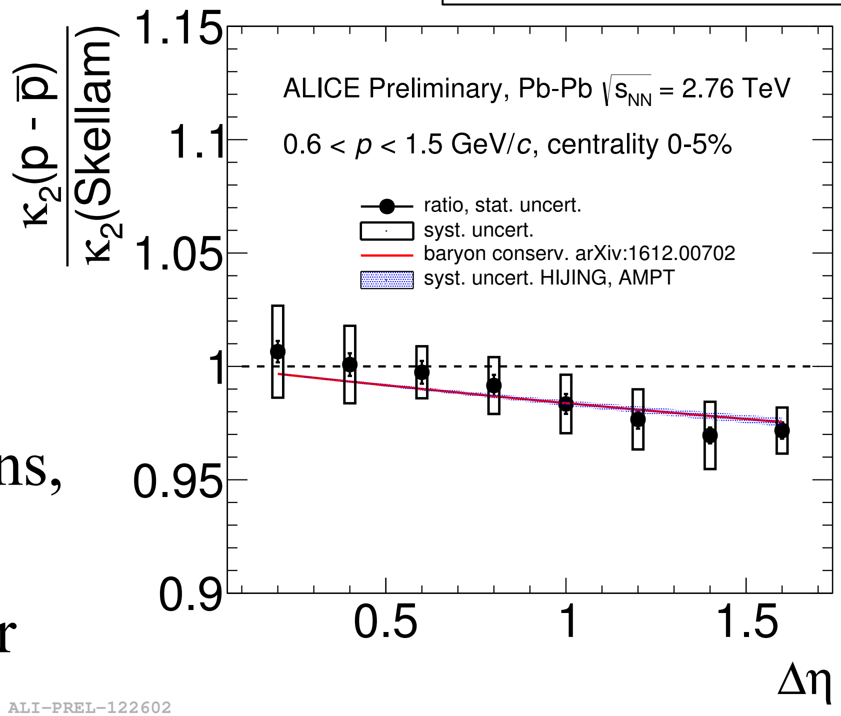
P. Braun-Munzinger et al., NPA 960 (2017) 114, arXiv:1612.00702 [nucl-th]

- Inputs to the model: $\kappa_1(p)$, $\kappa_1(\bar{p})$, centrality determination procedure
- Model gives a consistent picture of $\kappa_2(p)$, $\kappa_2(\bar{p})$ and $\kappa_2(p-\bar{p})$ without need of correlations or critical fluctuations

Global conservation laws



A. Rustamov for ALICE, QM2017



- Small $\Delta\eta \rightarrow$ Poissonian fluctuations, ratio to Skellam ~1
- Large $\Delta\eta \rightarrow$ global baryon number and strangeness conservation effects, ratio to Skellam < 1
- $\Delta\eta$ dependence consistent with effects of baryon number conservation

P. Braun-Munzinger et al., NPA 960 (2017) 114, arXiv:1612.00702 [nucl-th]

Global conservation laws

A. Rustamov for ALICE, QM2017

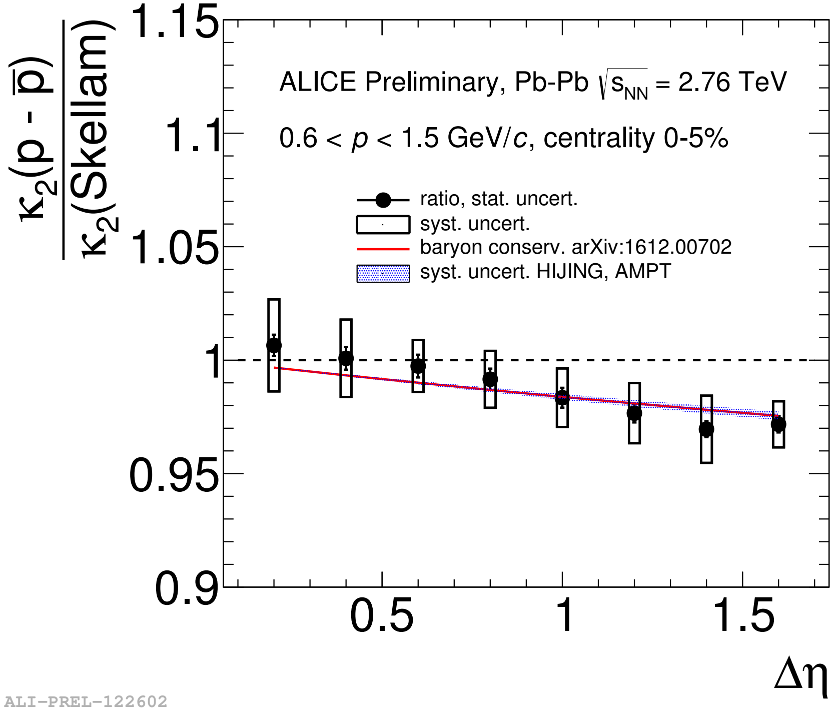
- Contribution from global baryon number conservation calculated as

$$\frac{\kappa_2(p-\bar{p})}{\kappa_2(Skellam)} = 1 - \frac{\langle N_p^{meas} \rangle}{\langle N_B^{4\pi} \rangle} = 1 - \alpha$$

- Inputs for $<N_B^{acc}>$ from

P. Braun-Munzinger et al., PLB 747 (2015) 292, arXiv:1412.8614 [hep-ph]

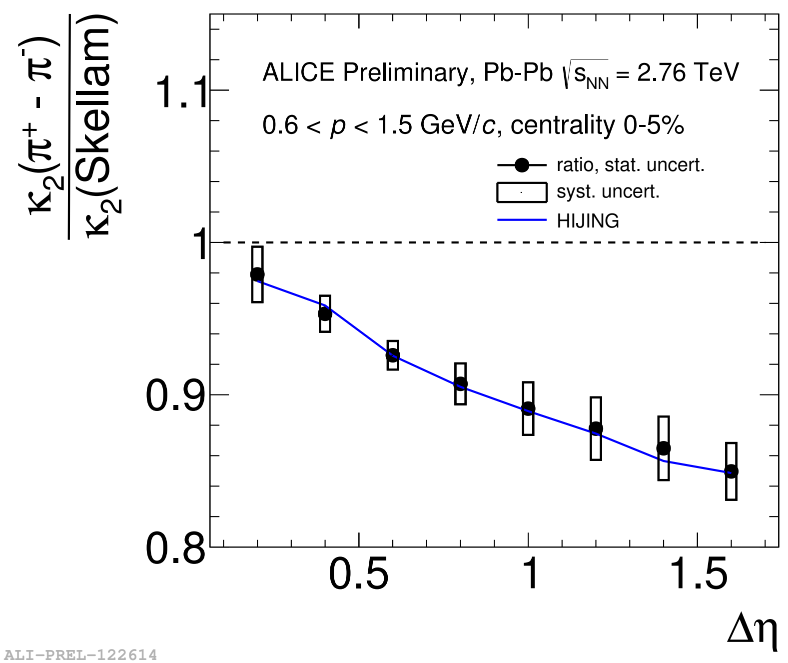
Extrapolation from $<N_B^{acc}>$ to $<N_B^{4\pi}>$ using AMPT and HIJING

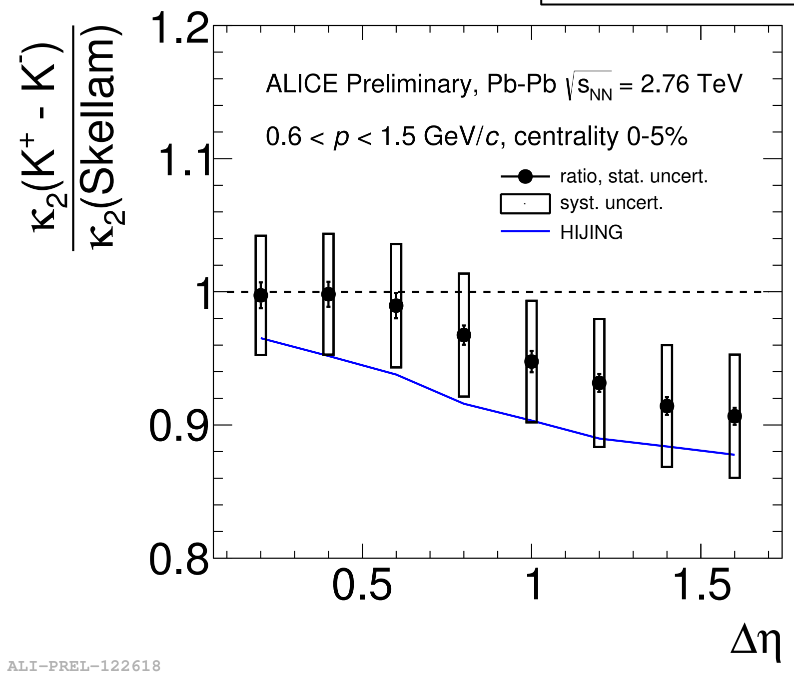


- Deviation from Skellam baseline accounted for by global baryon number conservation

Net-pion and net-kaon fluctuations

A. Rustamov for ALICE, QM2017



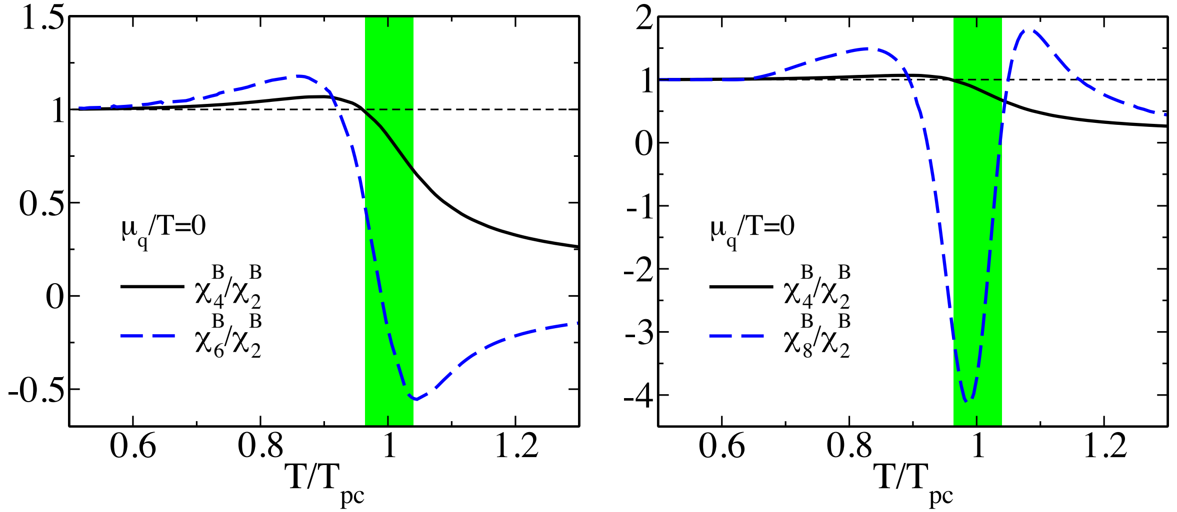


- Pions show good agreement with HIJING
- Production of pions and kaons from resonance decays contributes significantly to the measurement
- Skellam distribution is not a proper baseline for net-pions and net-kaons

Higher moments from the LHC

Higher moments

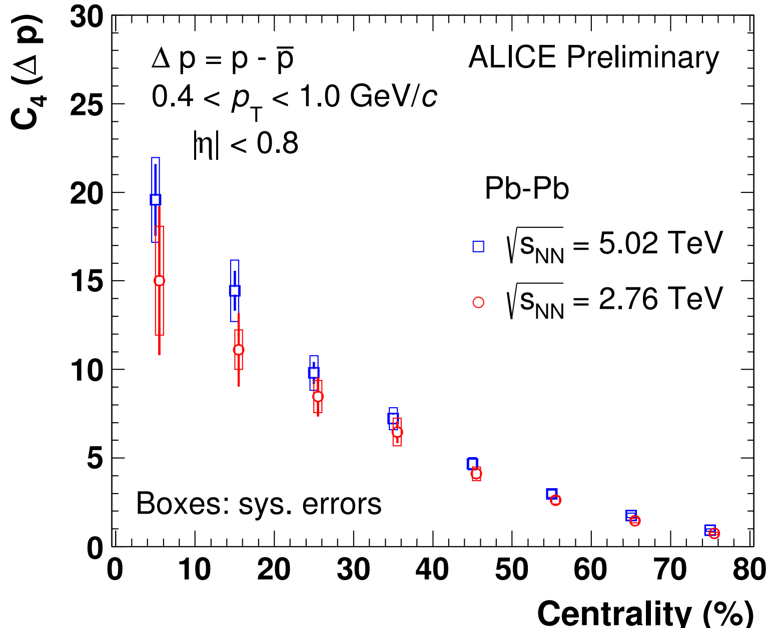
- Deviations from unity and signs of criticality are greatly enhanced for the higher moments (4th, 6th, 8th,...)



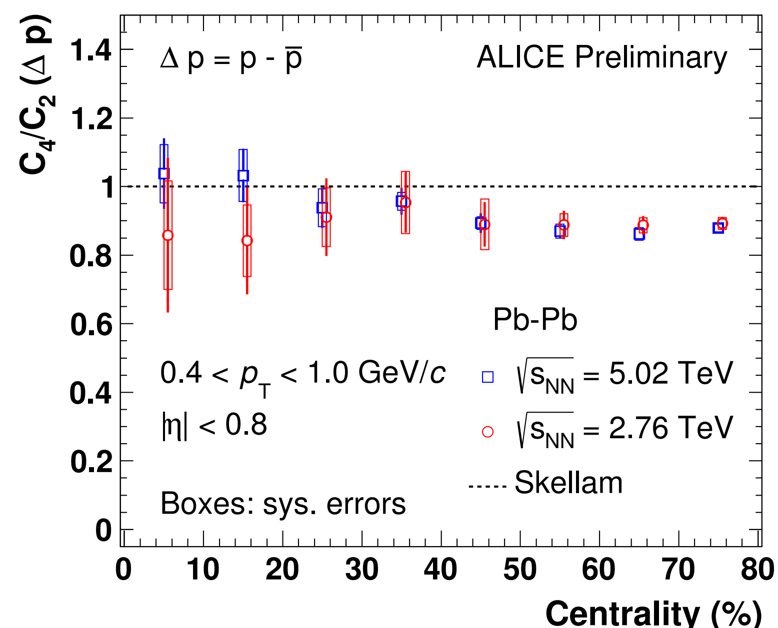
Friman, B., et al. Eur. Phys. J. C 71 (2011) 1694, arXiv:1103.3511 [hep-ph]

- But huge statistics are needed and experimental effects must be carefully controlled

First higher moments from ALICE



ALI-PREL-159574



ALI-PREL-159586

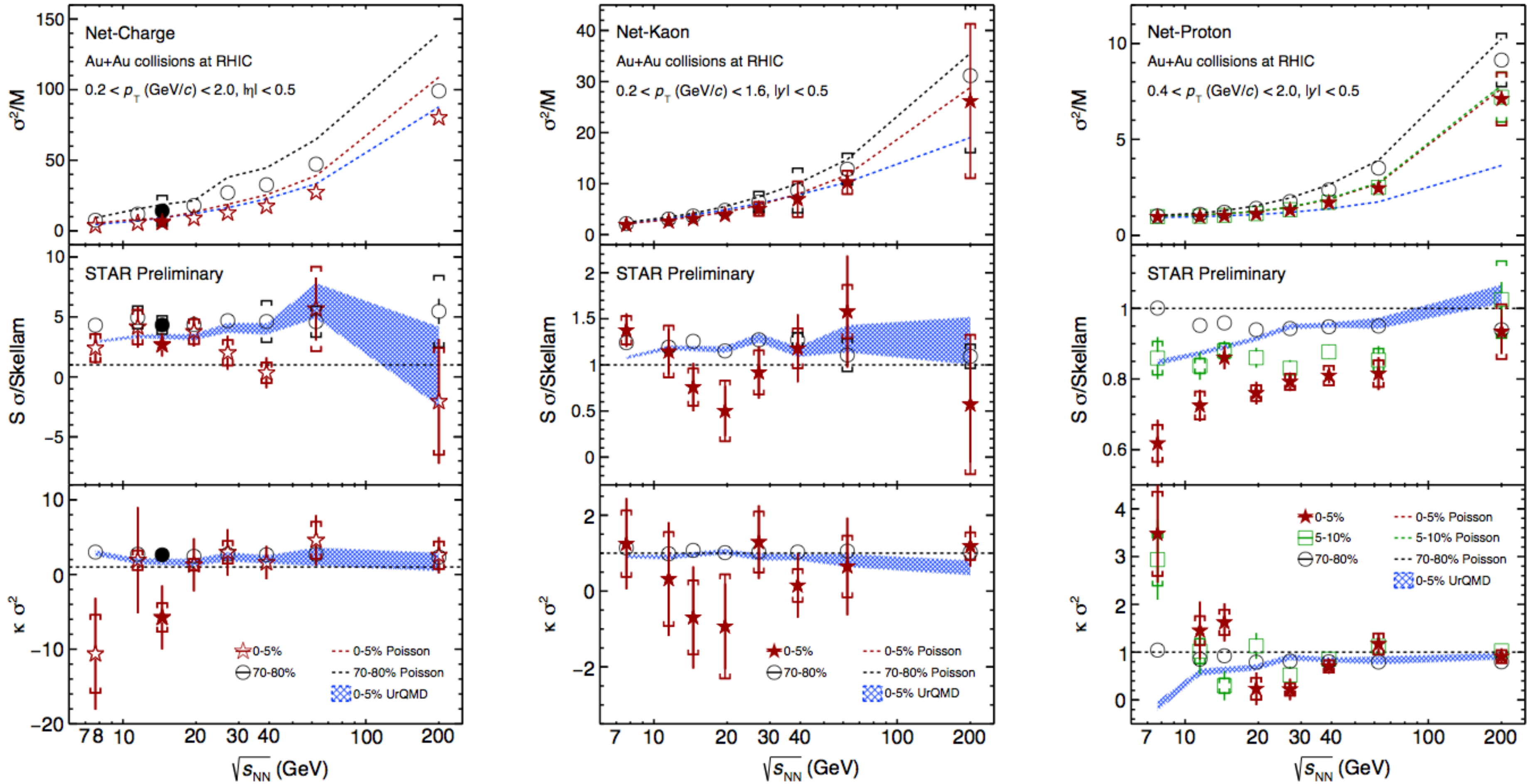
- Consistent results between $\sqrt{s_{NN}} = 2.76$ TeV and 5.02 TeV within statistical and systematic uncertainties
- In central events, consistency with Skellam baseline ($C_4/C_2 = 1$)
- Higher statistics and improved understanding of systematics are needed to obtain the precision needed for LQCD comparisons

N. Behera for ALICE, QM2018

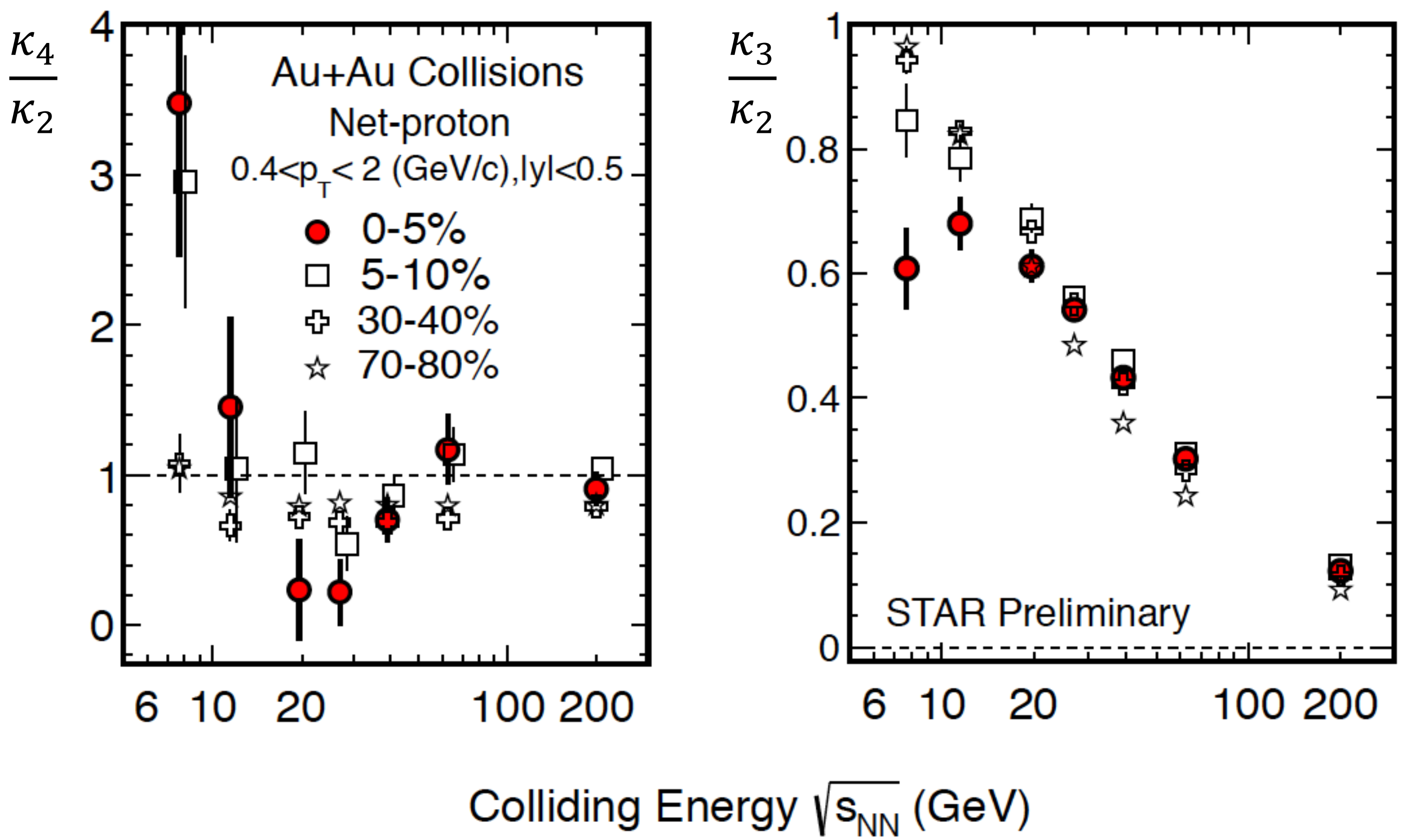
Higher moments at RHIC

STAR results: net-charge, net-K, net-p

J. Thäder for STAR, QM2015



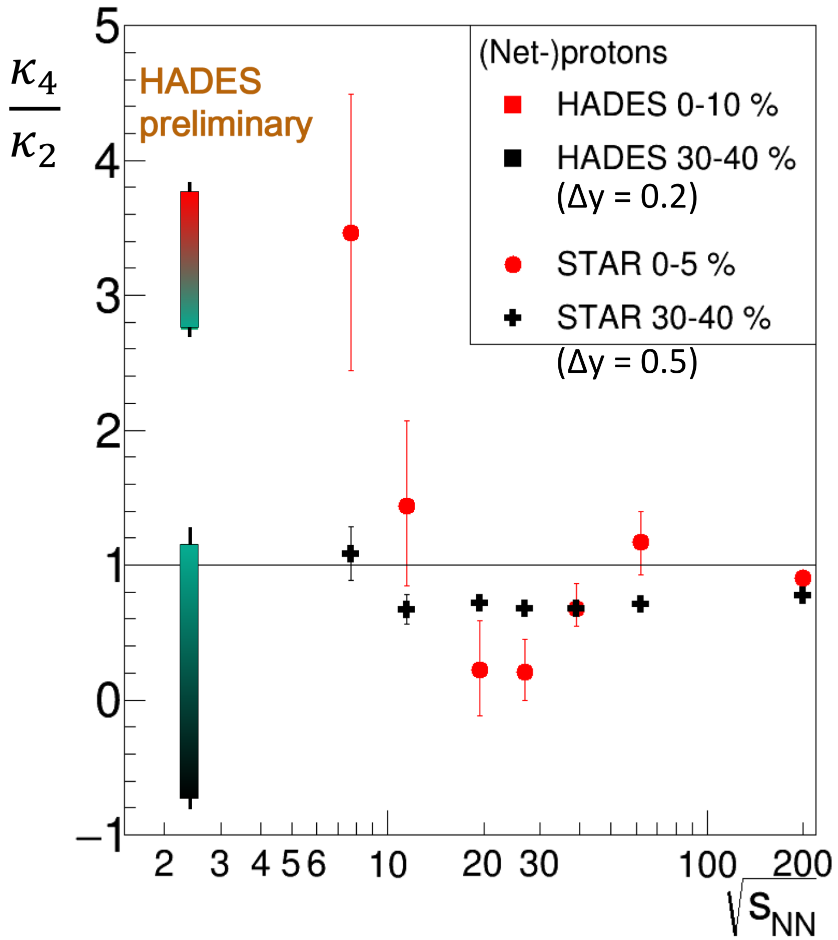
STAR results: net-protons in the BES



- non-monotonic behavior observed below $\sqrt{s_{NN}} = 39$ GeV

X. Luo, PoS CPOD2014 (2015) 019
STAR, PRL 112 (2014) 032302

STAR + HADES: net-protons vs $\sqrt{s_{NN}}$

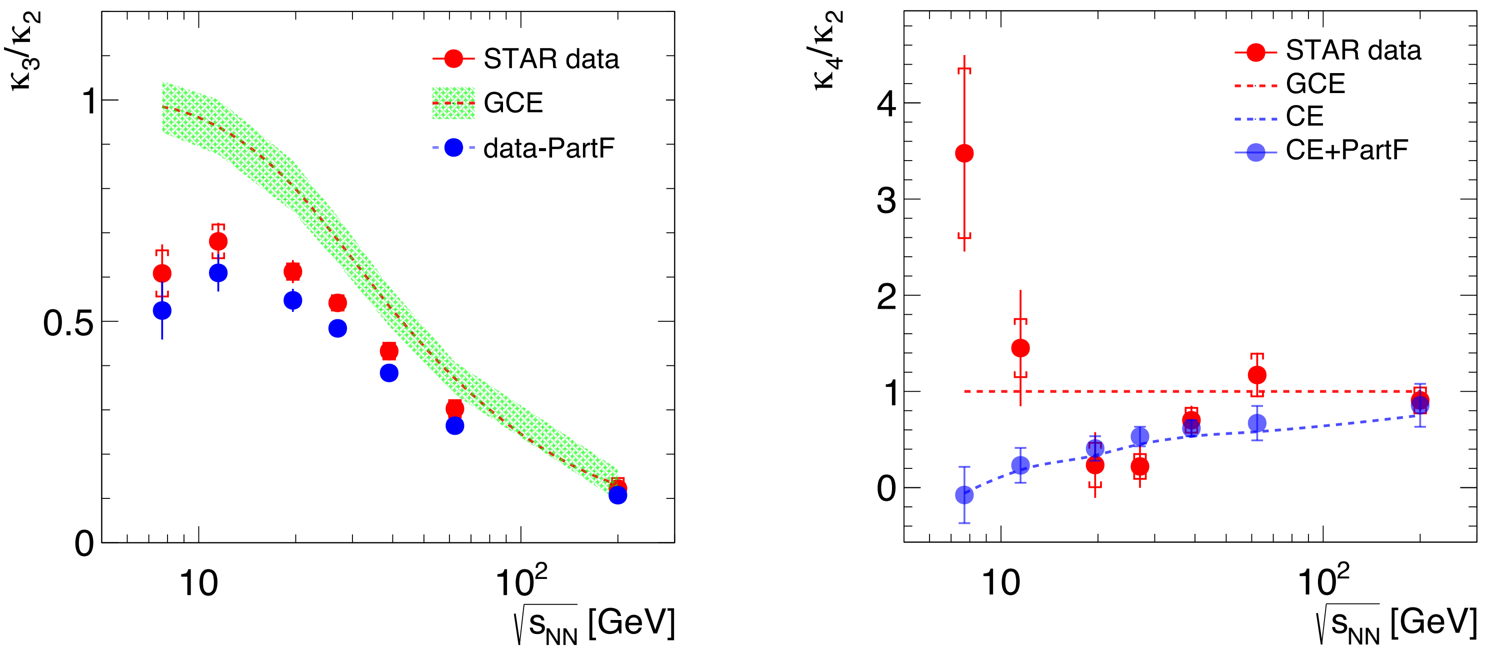


T. Galatyuk, CPOD 2018

- different correction methods:
  - unfolding + volume fluctuation correction
  - E-by-E correction of factorial moments + vol. fluct. corr.

  → large differences in results (still under investigation)

Effects of conservation laws + vol. fluct.



- At RHIC, proton and anti-proton multiplicities not equal

$$\frac{\kappa_3(n_p - n_{\overline{p}})}{\kappa_2(n_p - n_{\overline{p}})} = \frac{\langle n_p - n_{\overline{p}}\rangle_{CE}}{\langle n_p + n_{\overline{p}}\rangle_{CE}}(1-2\alpha)$$

$$\frac{\kappa_4(n_B - n_{\overline{B}})}{\kappa_2(n_B - n_{\overline{B}})} = 1 - 6\alpha(1-\alpha)\left[1 - \frac{2}{\langle N_B + N_{\overline{B}}\rangle_{CE}}\left(\langle N_B\rangle_{GCE}\langle N_{\overline{B}}\rangle_{GCE} - \langle N_B\rangle_{CE}\langle N_{\overline{B}}\rangle_{CE}\right)\right]$$

P. Braun-Munzinger, A. Rustamov, J. Stachel, arXiv:1807.08927 [nucl-th]

- Above $\sqrt{s_{NN}}$ = 11.5 GeV: deviation from unity can be described by global baryon number conservation

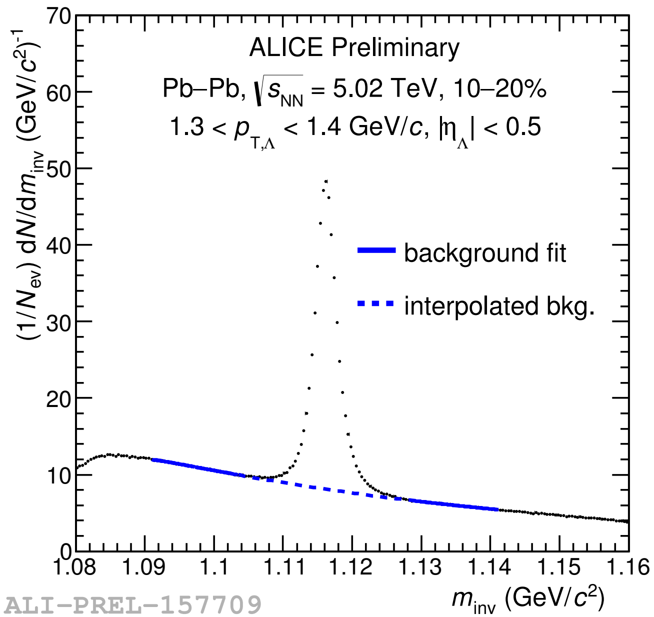
Net-Λ moments

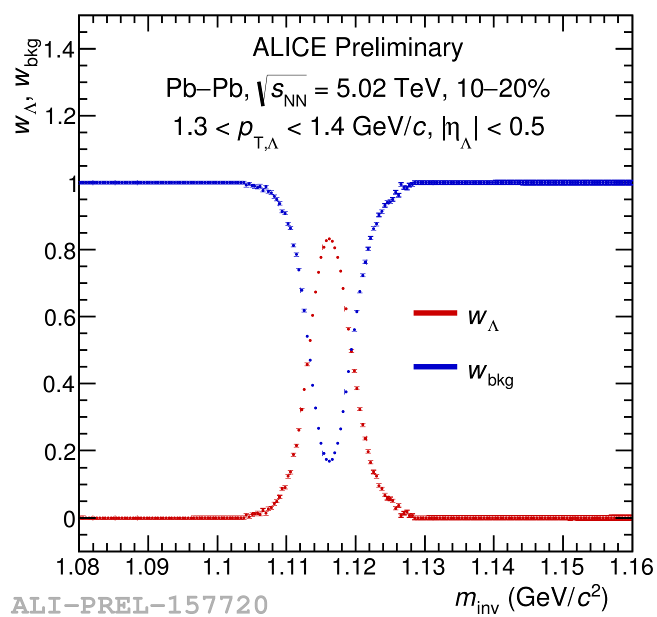
From net-π, K, p to net-Λ moments

- Explore correlated fluctuations of baryon number and strangeness
- 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

Identity method for invariant mass

- For any value of m_{inv}, the probability that a πp pair comes from the decay of a Λ baryon is known
- Apply Identity Method for four "species": Λ, $\bar{\Lambda}$, combinatoric $\pi^- p$, combinatoric $\pi^+ \bar{p}$

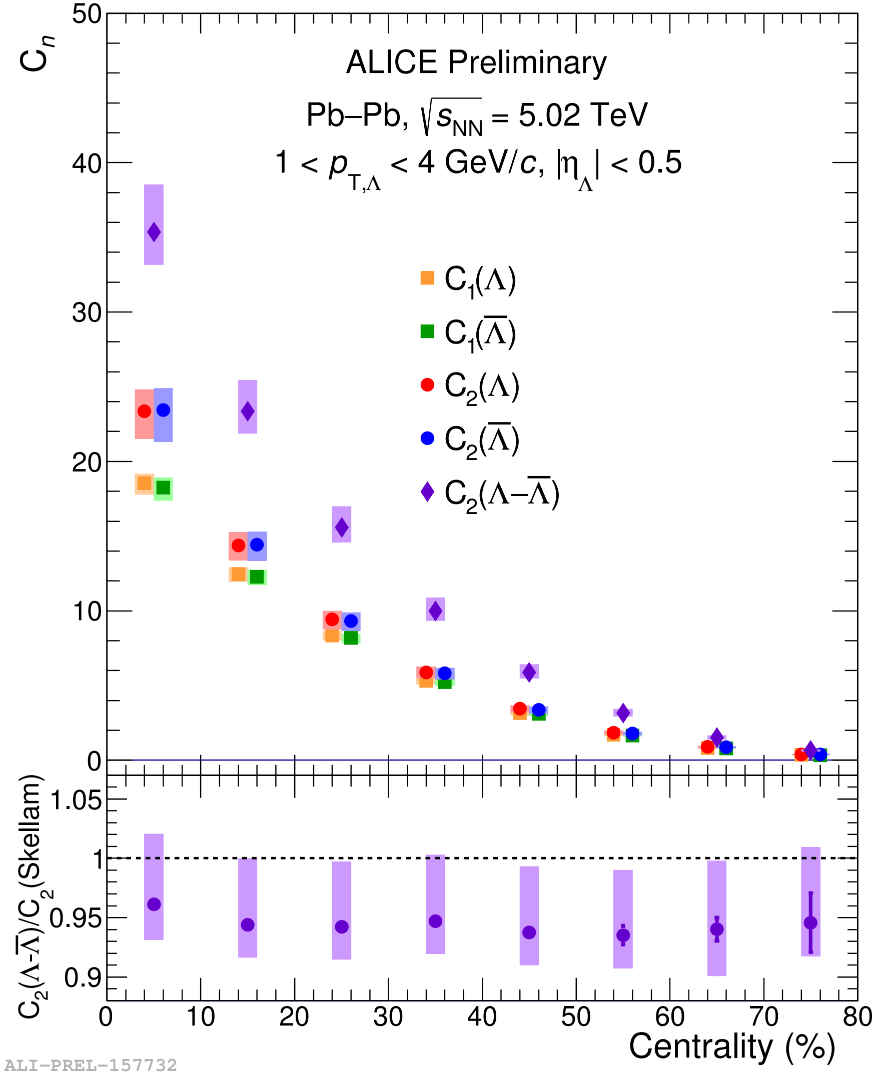




A. Ohlson for ALICE, QM2018

Net-Λ fluctuations

A. Ohlson for ALICE, QM2018



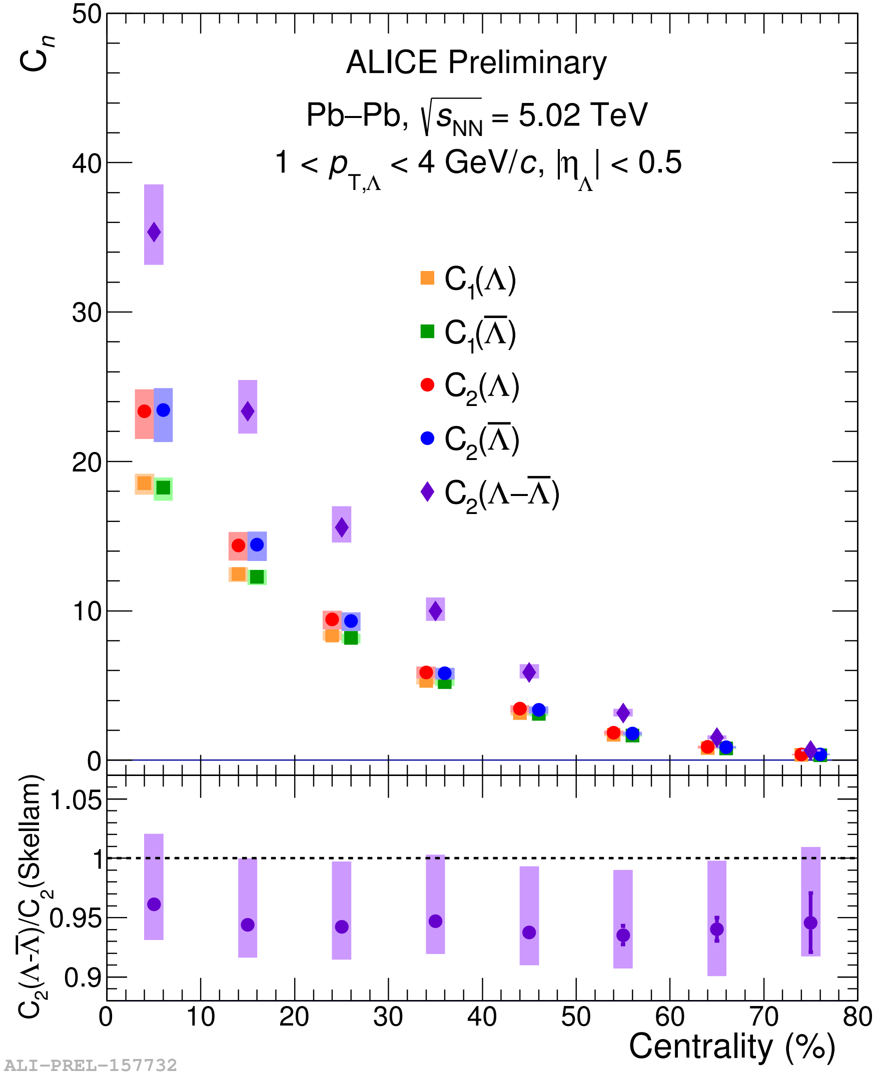
$$C_1(\Lambda) = \langle N_\Lambda \rangle \qquad C_2(\Lambda) = \left\langle \left(N_\Lambda - \langle N_\Lambda \rangle\right)^2 \right\rangle$$

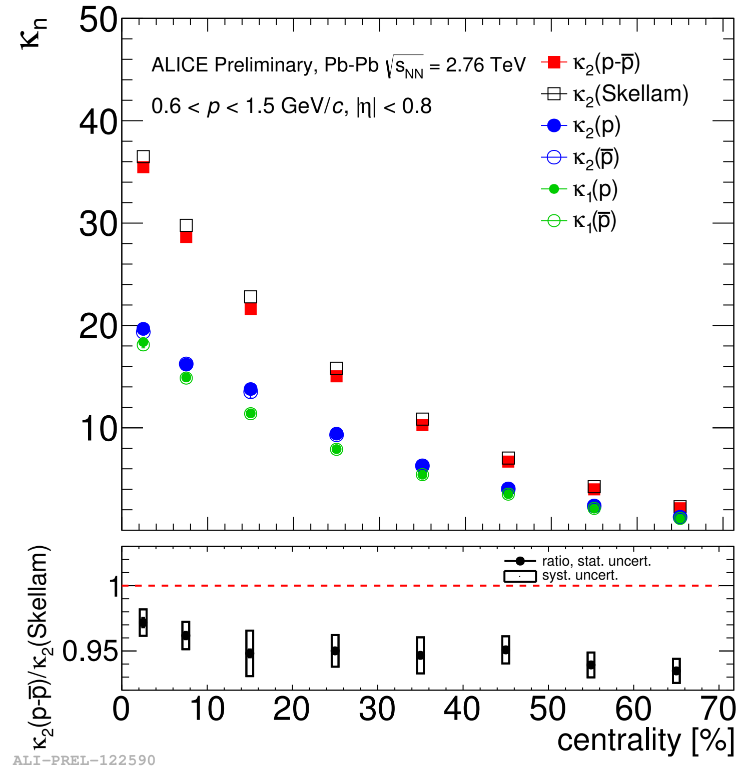
$$C_2(\Lambda - \bar{\Lambda}) = \left\langle \left(N_\Lambda - N_{\bar{\Lambda}} - \langle N_\Lambda - N_{\bar{\Lambda}} \rangle\right)^2 \right\rangle$$

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

- Small deviations from Skellam baseline → correlation term? non-Poissonian Λ or $\bar{\Lambda}$ distributions? critical fluctuations? effects of volume fluctuations and global conservation laws?

Comparison to net-protons

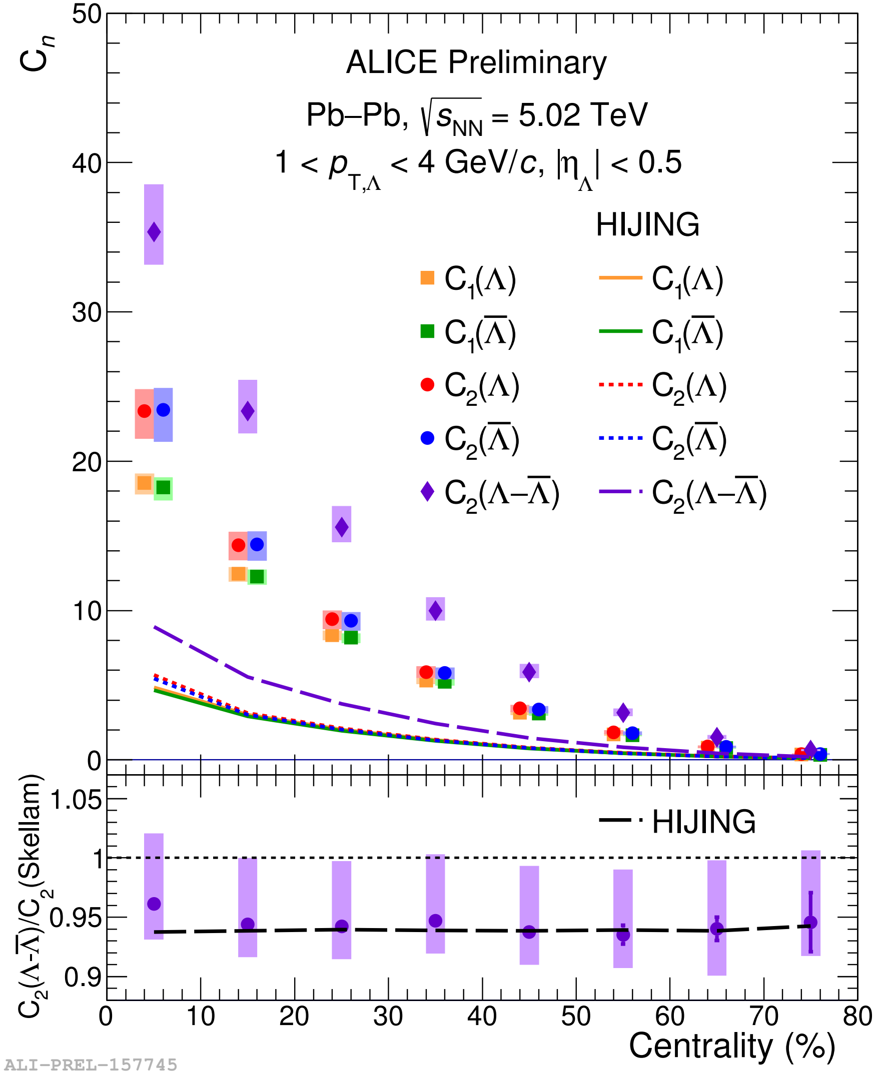




- Qualitatively similar results for net-protons
  - different kinematic range, different contributions from resonance decays

Comparison to HIJING

A. Ohlson for ALICE, QM2018

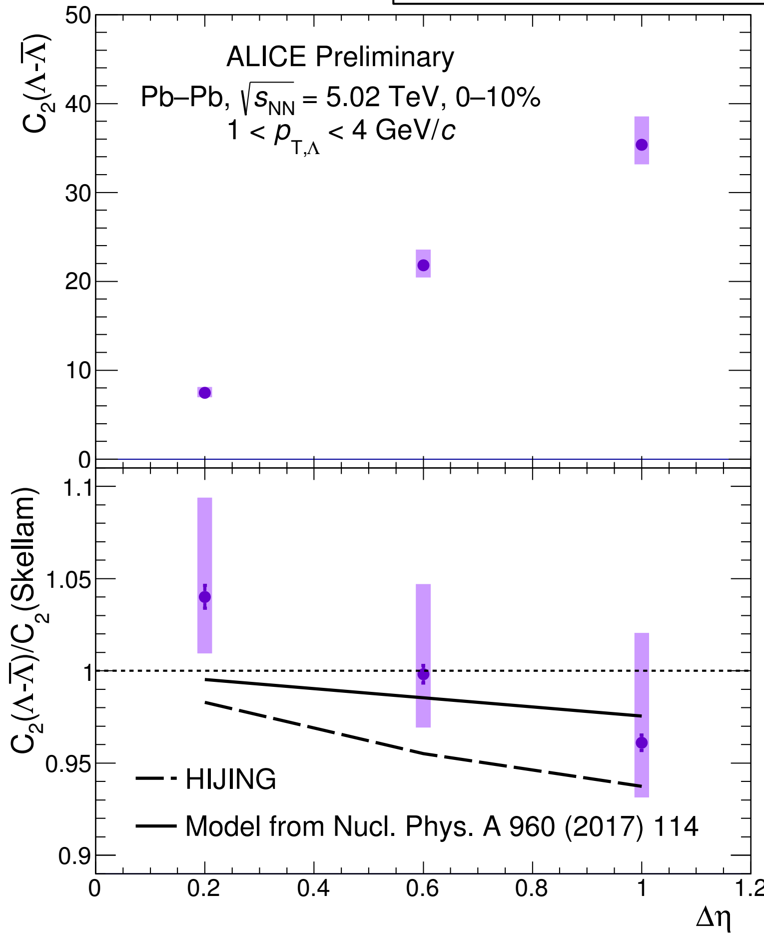


- HIJING does not describe strangeness production well
  - underestimates C_1 and C_2 by factor ~4
- However, $C_2(\Lambda\text{-}\bar{\Lambda})/C_2(\text{Skellam})$ ratio agrees with data
  - coincidence? or due to description of fluctuations and resonance contributions in HIJING?

Δη dependence of net-Λ fluctuations

- 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 → strangeness conservation should also be considered
- consistency also with HIJING

A. Ohlson for ALICE, QM2018

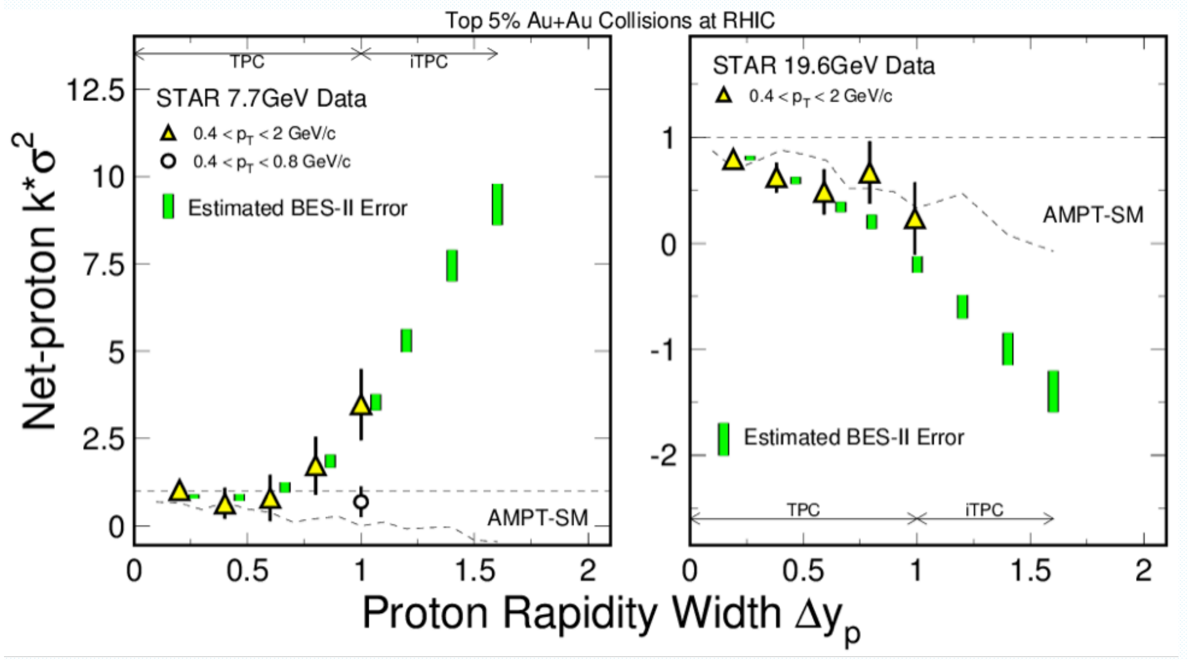


Outlook

- Runs 3+4 at the LHC will allow us to measure the fourth and sixth moments of the net-proton distribution with unprecedented precision

LHC Yellow Report: arXiv:1812.06772 [hep-ph]

- BES-II + detector upgrates at RHIC will allow us to probe fluctuations across a wide range of the phase diagram



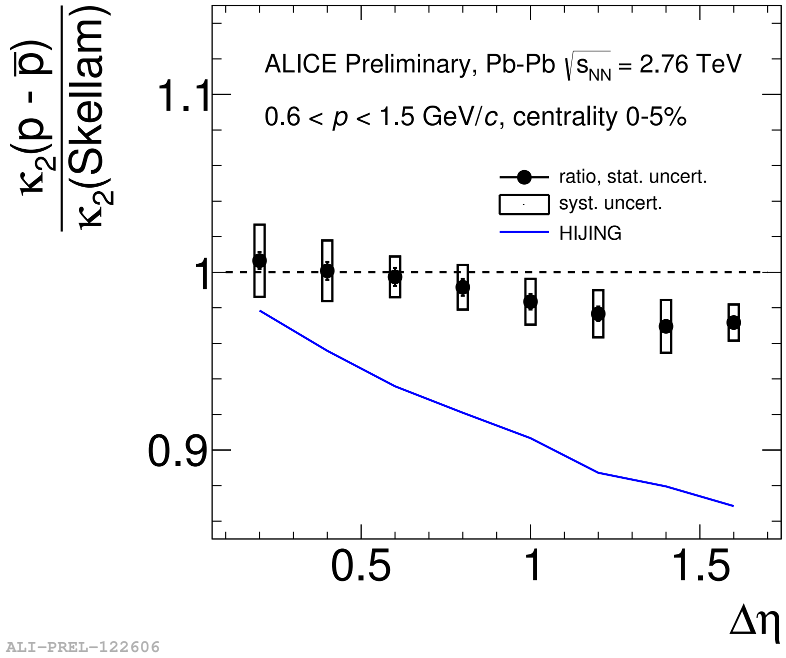
https://drupal.star.bnl.gov/STAR/starnotes/public/sn0619

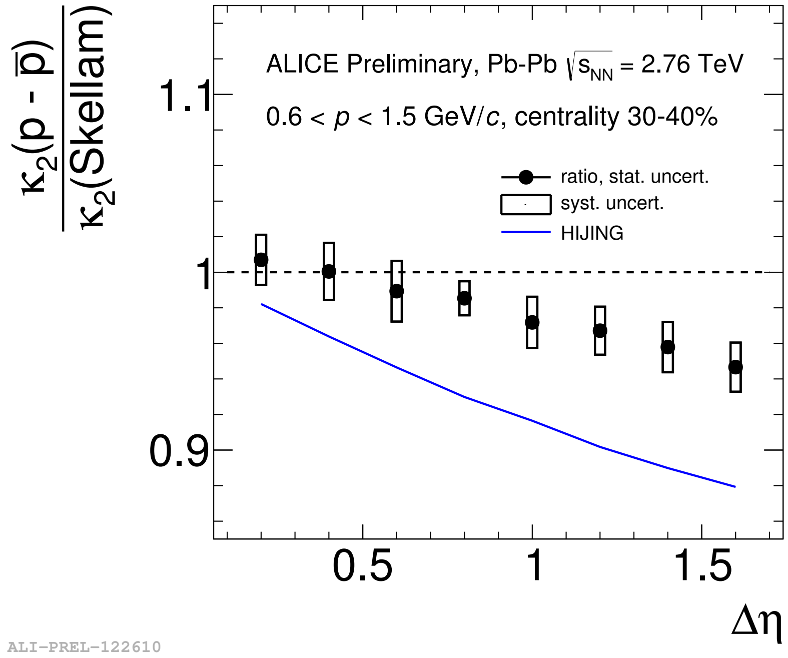
Conclusions

- Event-by-event fluctuations of identified particles
  - yield information on properties of the QGP medium
  - test lattice QCD predictions at $\mu_B = 0$
  - allow us to look for effects of criticality
- Effects of detector inefficiency and particle misidentification being brought under control
- Effects of volume fluctuations and global baryon number conservation are assessed
- Net-proton and net-Λ fluctuations at LHC energies: no deviations from Skellam baseline observed after accounting for baryon number conservation, agreement with LQCD predictions
- Net-proton fluctuations at RHIC energies: can be described above $\sqrt{s_{NN}}$ = 11.5 GeV by baryon number conservation

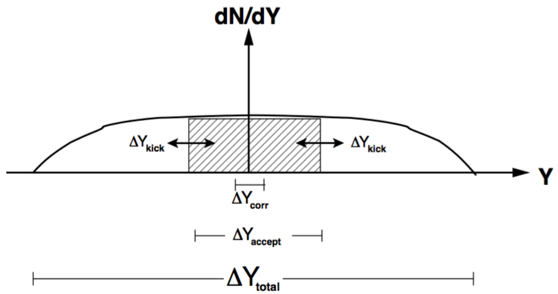
backup

Centrality dependence



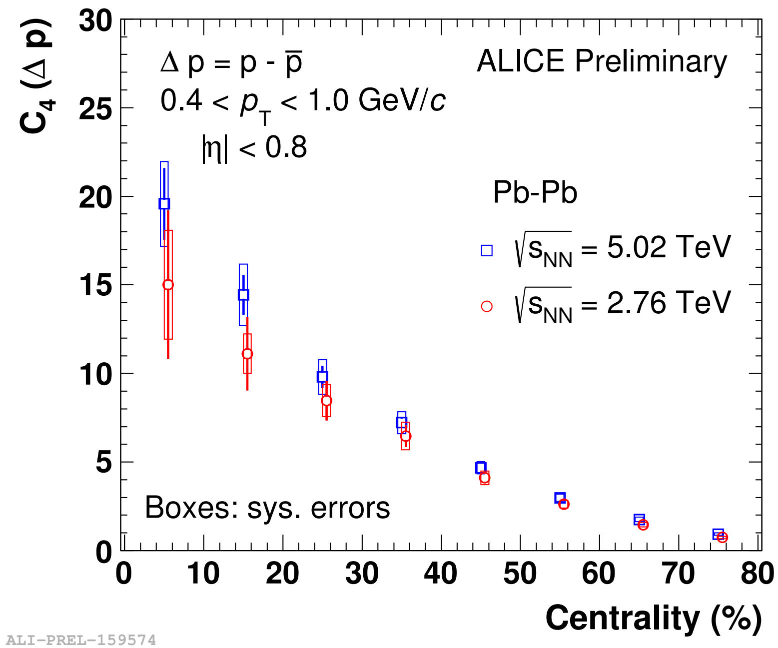


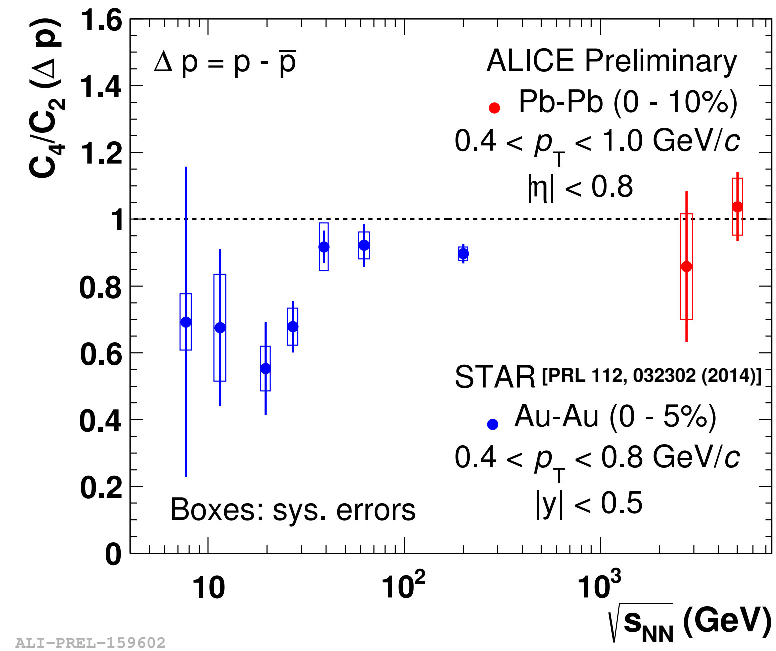
- Deviations from Skellam can be attributed global baryon number conservation, more significant in more peripheral collisions
- Disagreement with HIJING



A. Rustamov for ALICE, QM2017

First higher moments from ALICE!





- Measured with traditional (cut-based) PID method
- Consistent results between $\sqrt{s_{NN}} = 2.76$ TeV and 5.02 TeV within statistical and systematic uncertainties
- In central events, consistency with Skellam baseline ($C_4/C_2 = 1$) at LHC energies

N. Behera for ALICE, QM2018