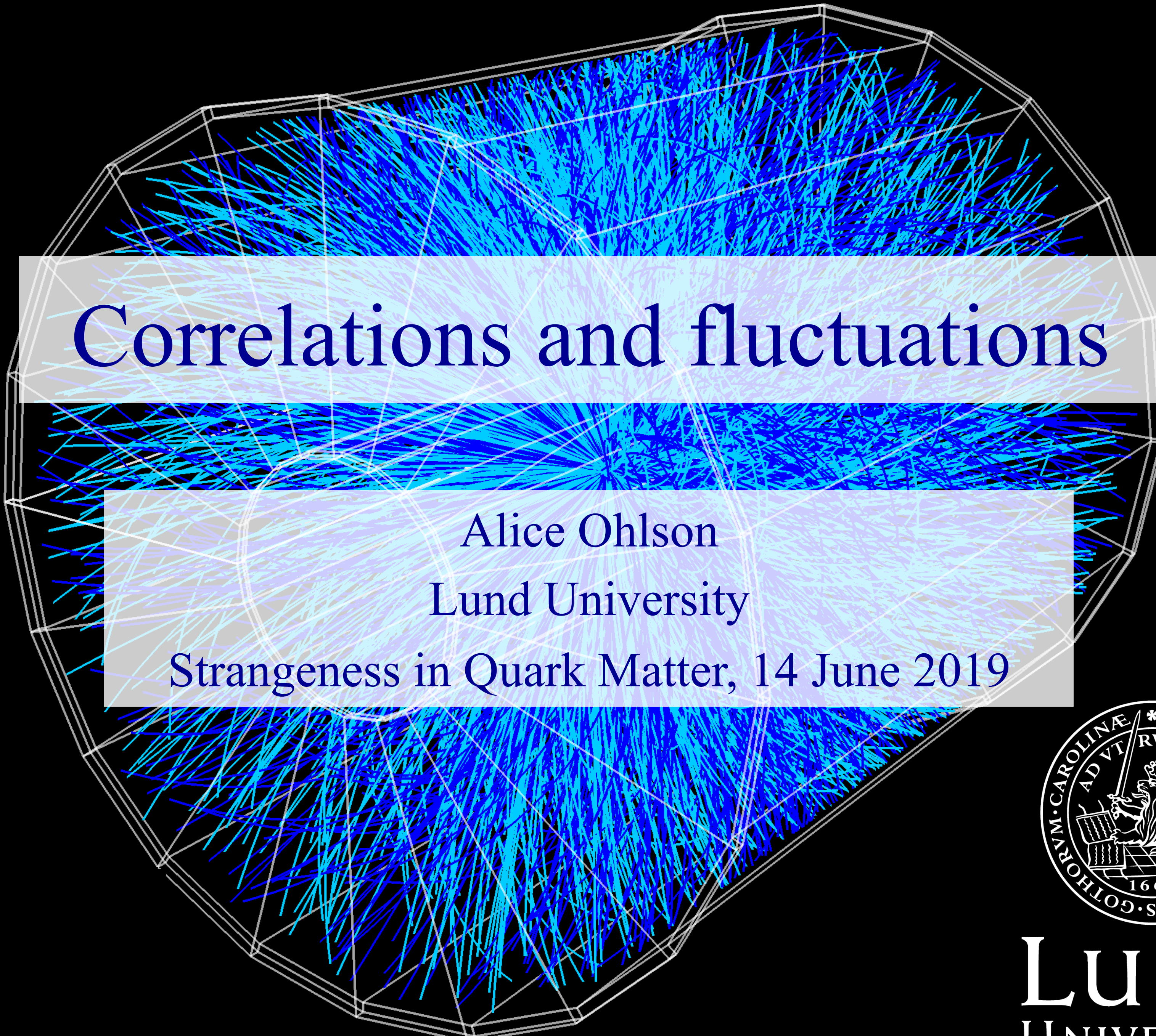


Correlations and fluctuations

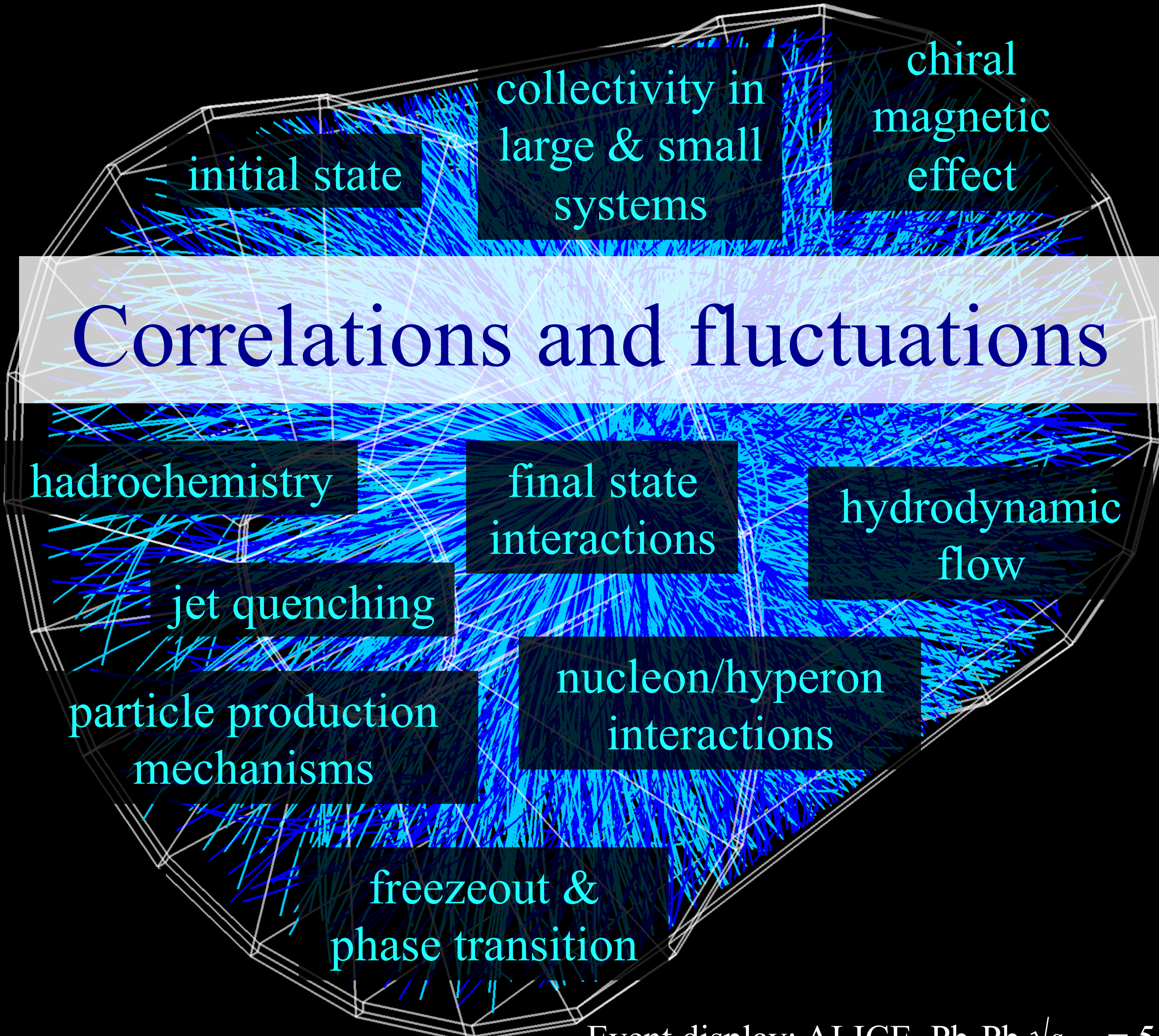
Alice Ohlson

Lund University

Strangeness in Quark Matter, 14 June 2019

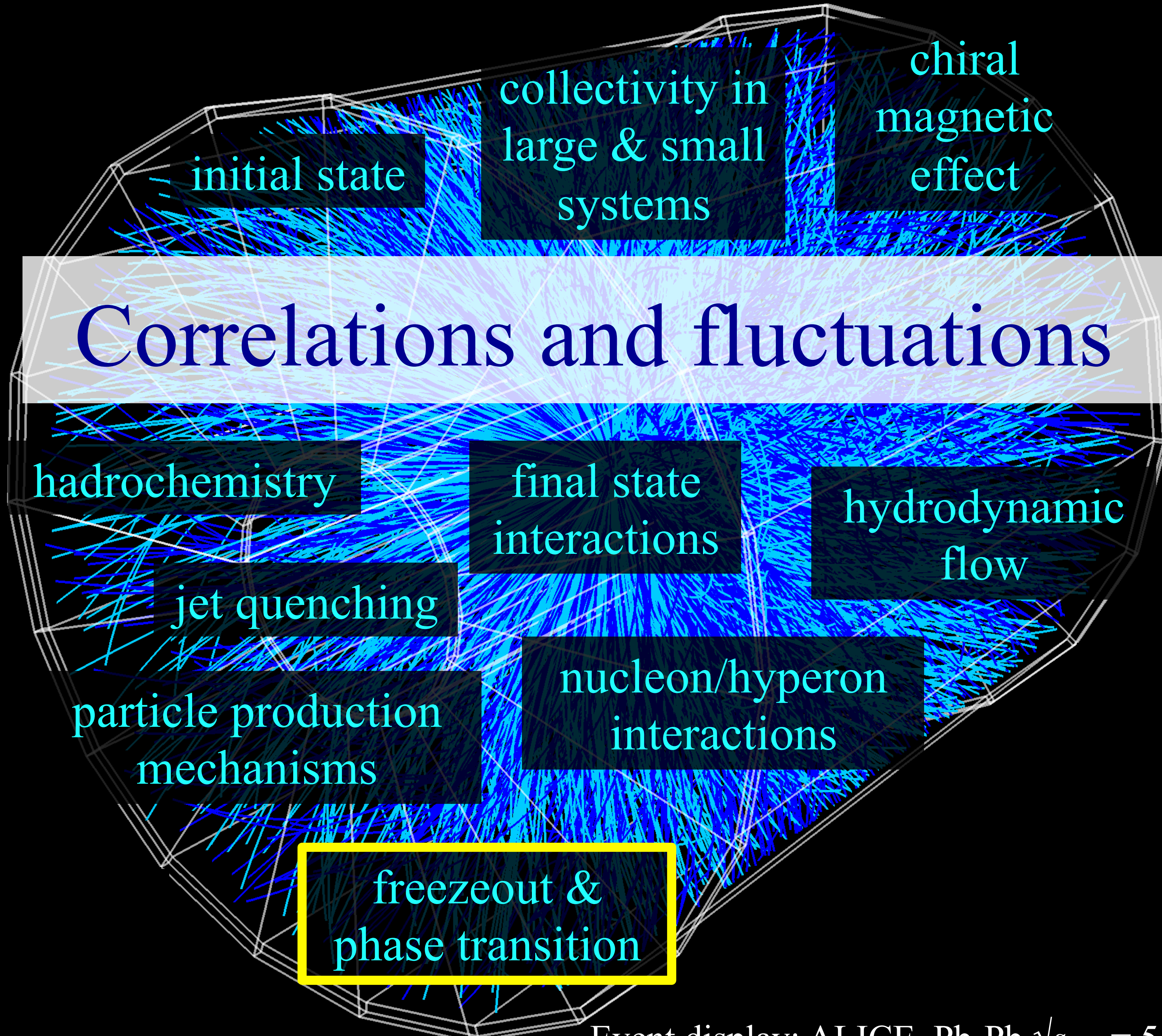
Lund University

Correlations and fluctuations



Event display: ALICE, Pb-Pb $\sqrt{s_{NN}}$ = 5.02 TeV

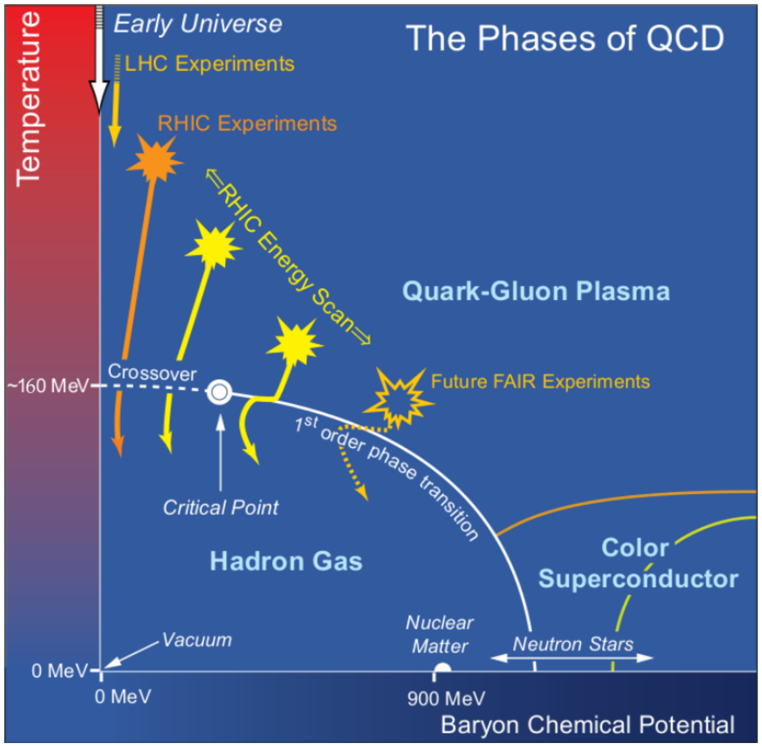
Correlations and fluctuations



Event display: ALICE, Pb-Pb $\sqrt{s_{NN}}$ = 5.02 TeV

Fluctuations in heavy ion collisions

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



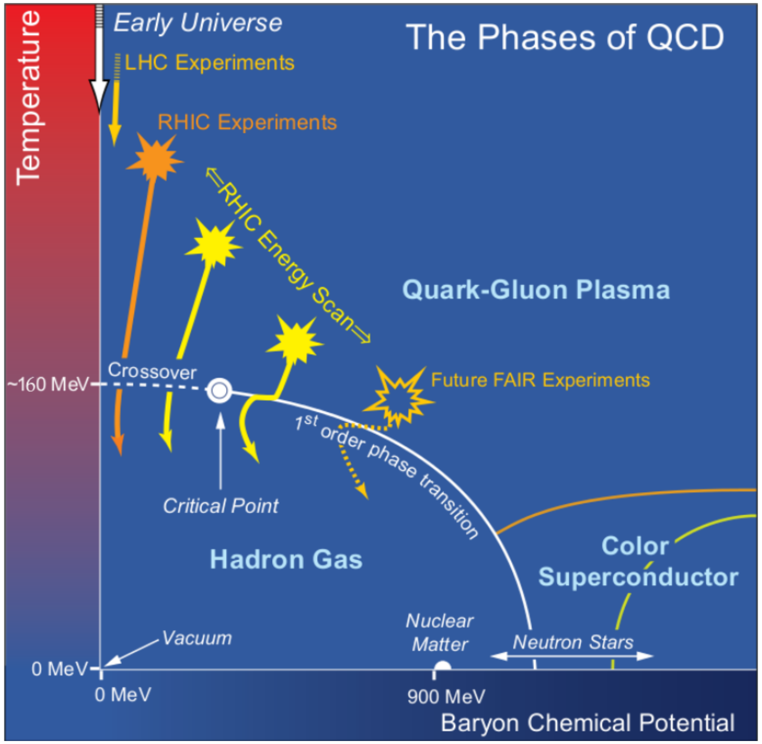
- Fluctuations grow in the region near a phase transition and/or critical point
  - can we observe signs of criticality?

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



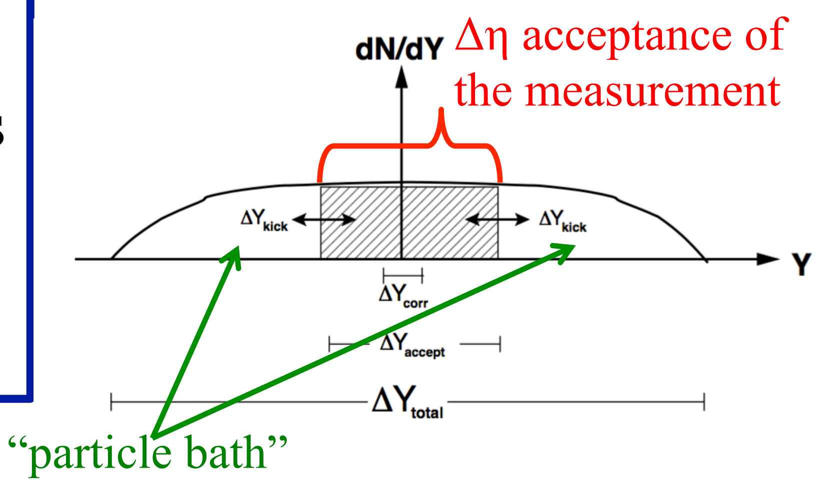
- Fluctuations grow in the region near a phase transition and/or critical point
  - can we observe signs of criticality?
- Fluctuations of conserved charges can be related to susceptibilities calculable in lattice QCD
  - precision test of LQCD at $\mu_B \approx 0$

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 net-charge, net-strangeness, net-baryon number 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: susceptibilities

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

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

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

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

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

Experiment: moments of net-charge, net-strangeness, net-baryon number 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:
susceptibilities

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

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

$$\left\langle \left(\Delta N_B - \langle \Delta N_B \rangle\right)^2 \right\rangle = \ldots \sigma^2$$

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

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

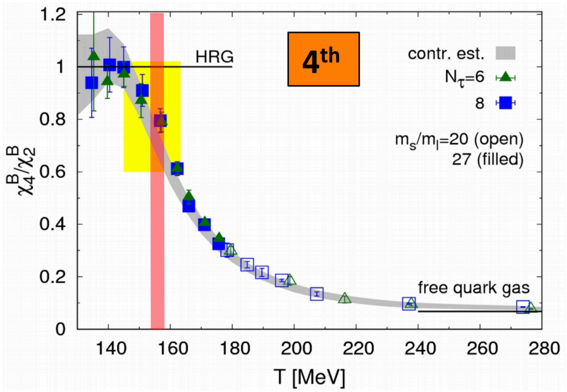
$$S\sigma = \chi_3^B / \chi_2^B$$

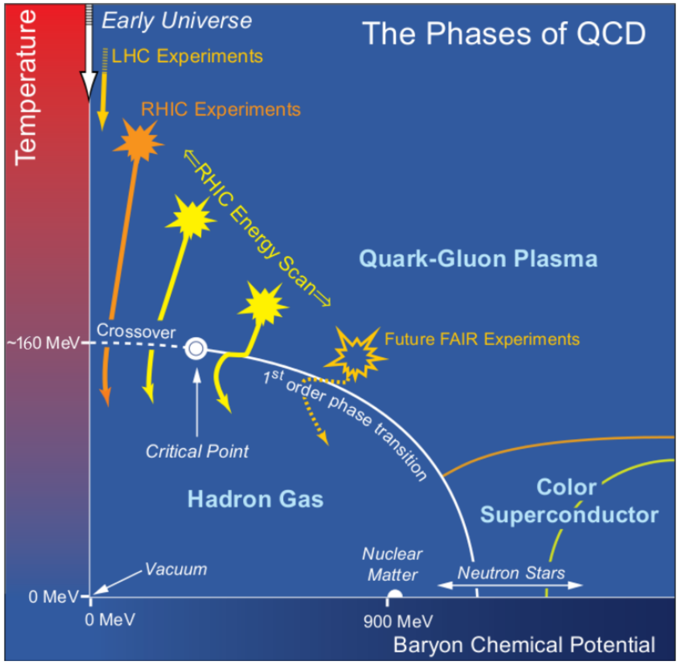
$$\kappa\sigma^2 = \chi_4^B / \chi_2^B$$

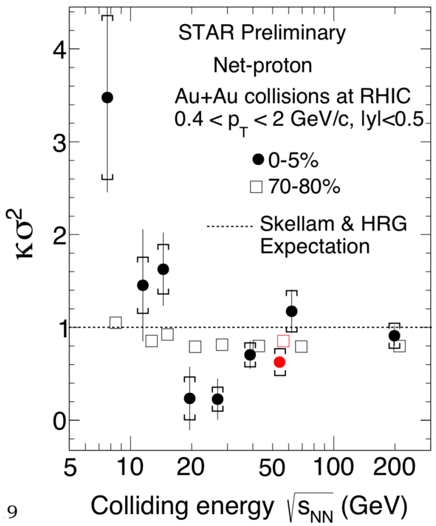
Experiment:
moments of net-charge, net-strangeness, net-baryon number distributions

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

Connecting theory to experiment







9

Theory: susceptibilities calculated in a fixed volume, particle bath in GCE

Experiment: event-by-event multiplicities of identified particles in a detector

Connecting theory to experiment

- experimental particle misidentification

  cut-based PID or Identity Method

  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]

- detector (in)efficiency

  A. Bzdak and V. Koch, PRC 86 (2012) 044904, arXiv:1206.4286 [nucl-th]
  A. Bzdak and V. Koch, PRC 91 (2015) 027901, arXiv:1312.4574 [nucl-th]
  T. Nonaka et al., NIM-A 906 (2018) 10, arXiv:1805.00279 [physics.data-an]

- net-π,K,p ⇔ net-Q,S,B

  M. Kitazawa and M. Asakawa, PRC 86 (2012) 024904, arXiv:1205.3292 [nucl-th]

- global conservation laws

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

- infinite ⇔ finite volume

  talk by Marcus Bluhm

- volume fluctuations

  talk by Sukanya Sombun

- resonance decays

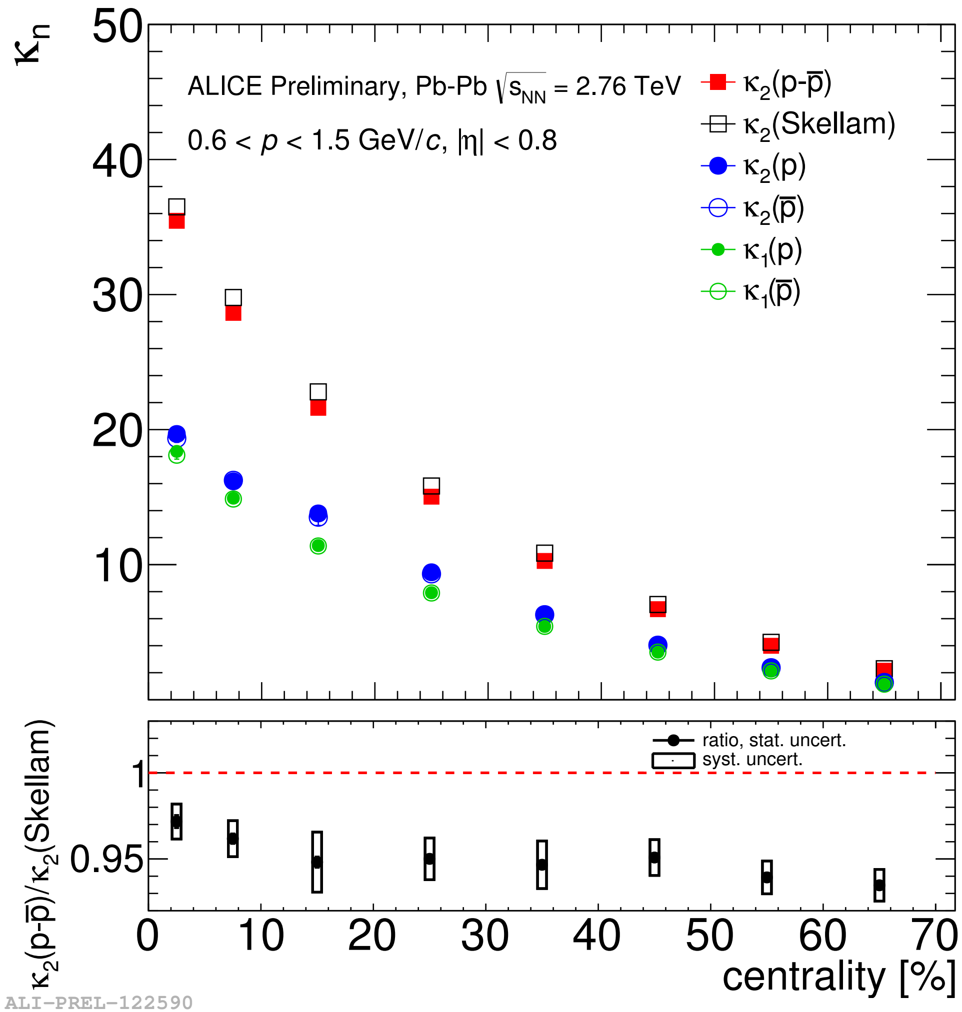
  talk by Mesut Arslandok (ALICE)

Precision test of the LQCD baseline at $\mu_B = 0$

-- second moments at the LHC --

Net-proton fluctuations

A. Rustamov for ALICE, QM2017



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

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

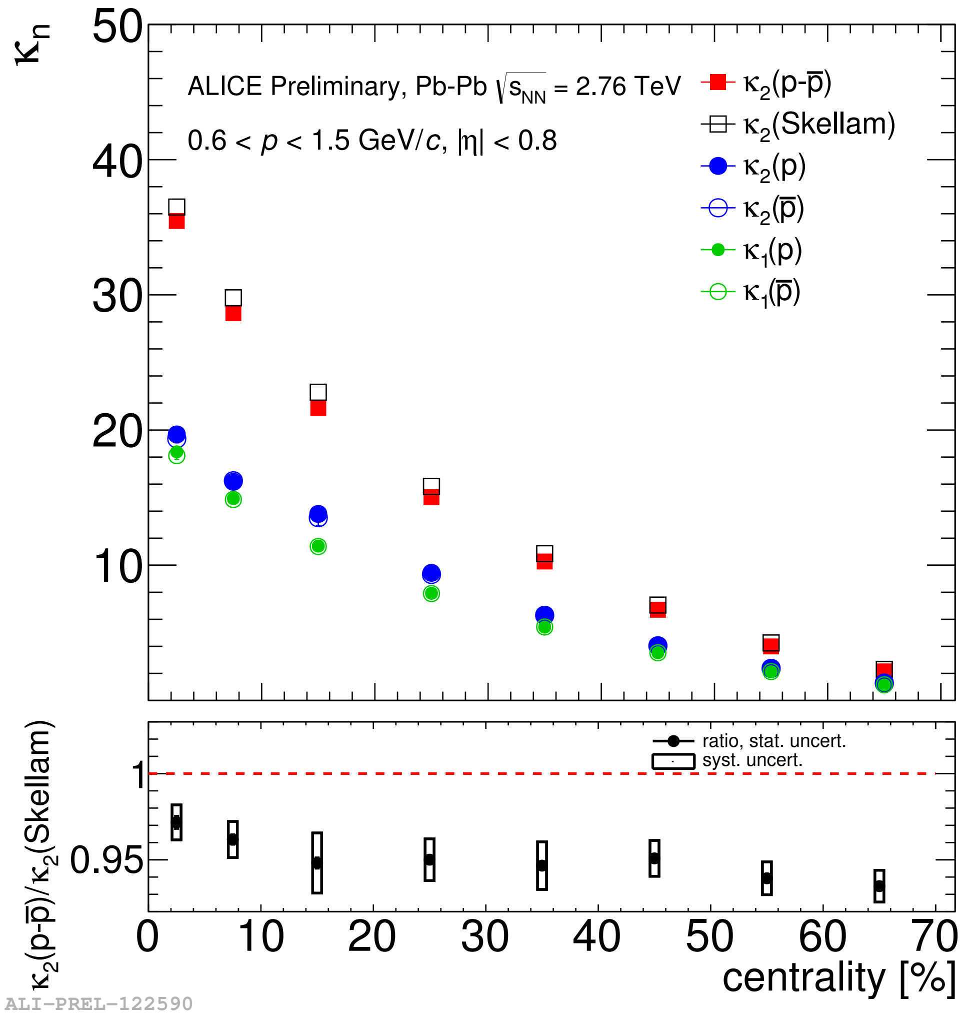
$$= \kappa_2(p) + \kappa_2(\bar{p}) - 2\underbrace{\left(\langle N_p N_{\bar{p}} \rangle - \langle N_p \rangle \langle N_{\bar{p}} \rangle\right)}_{\text{correlation term}}$$

- 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



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

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

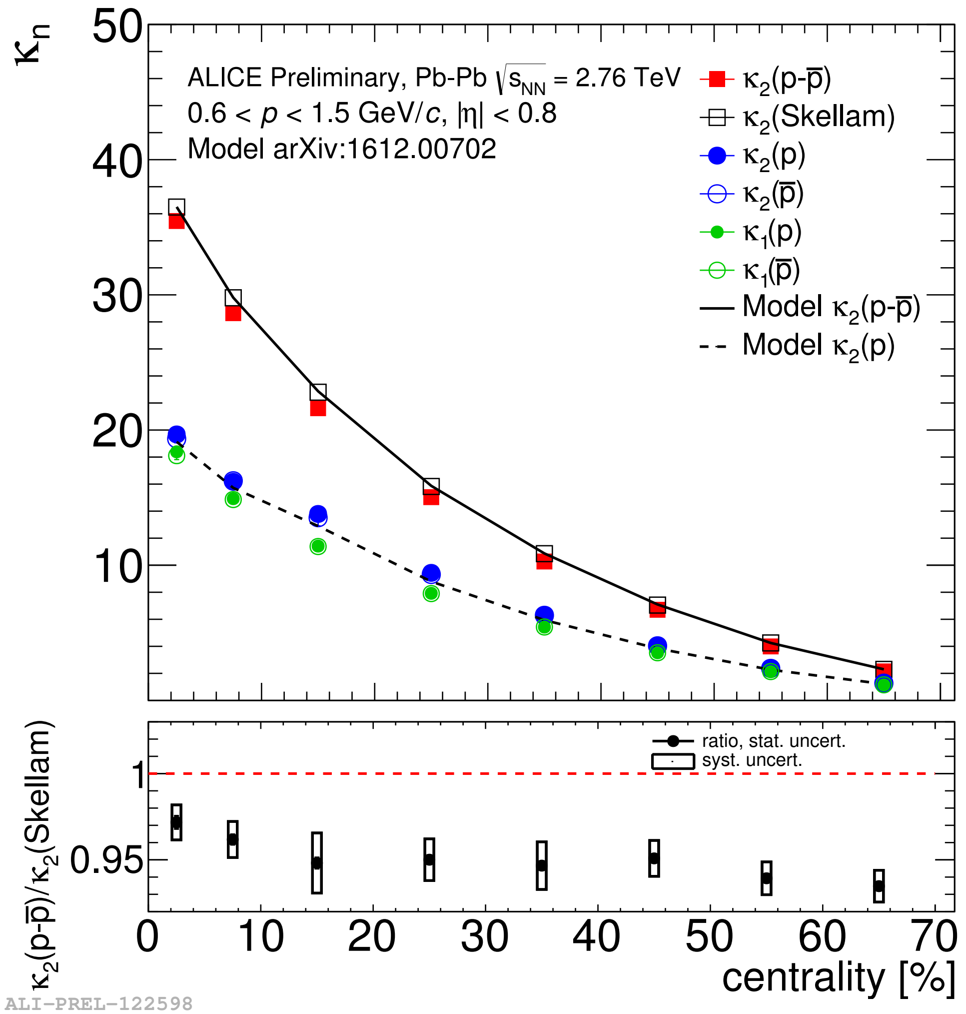
$$= \kappa_2(p) + \kappa_2(\bar{p}) - 2\underbrace{\left(\langle N_p N_{\bar{p}} \rangle - \langle N_p \rangle \langle N_{\bar{p}} \rangle \right)}_{\text{correlation term}}$$

- $\kappa_2(p-\bar{p})$ 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

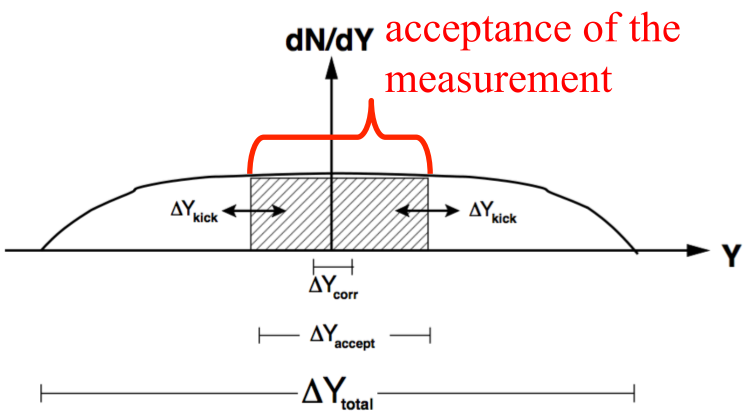


- Modeling the effects of participant fluctuations and global baryon number conservation

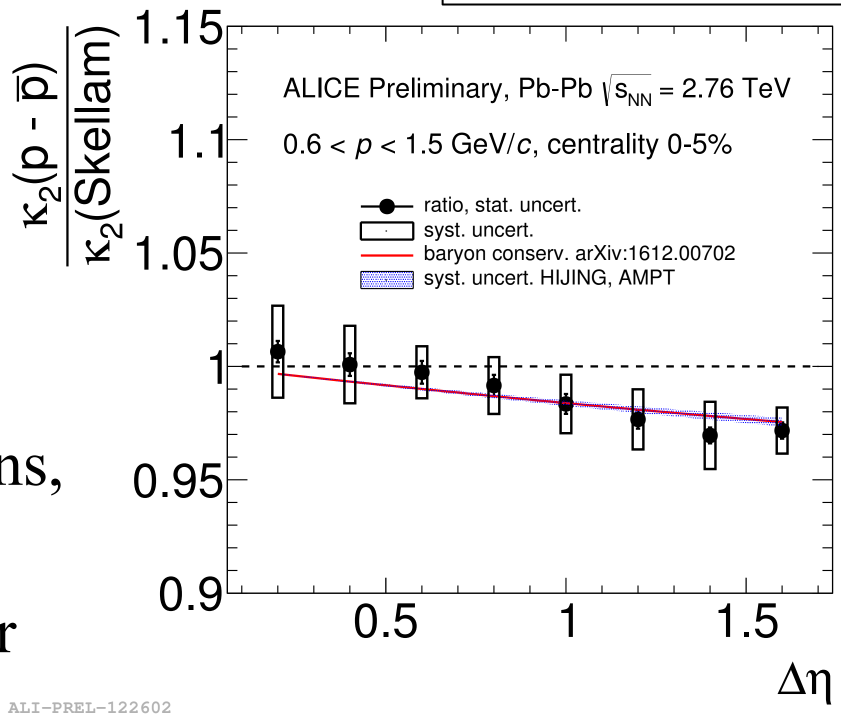
P. Braun-Munzinger et al., NPA 960 (2017) 114, arXiv:1612.00702 [nucl-th]

- 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

- Contribution from global baryon number conservation calculated as

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

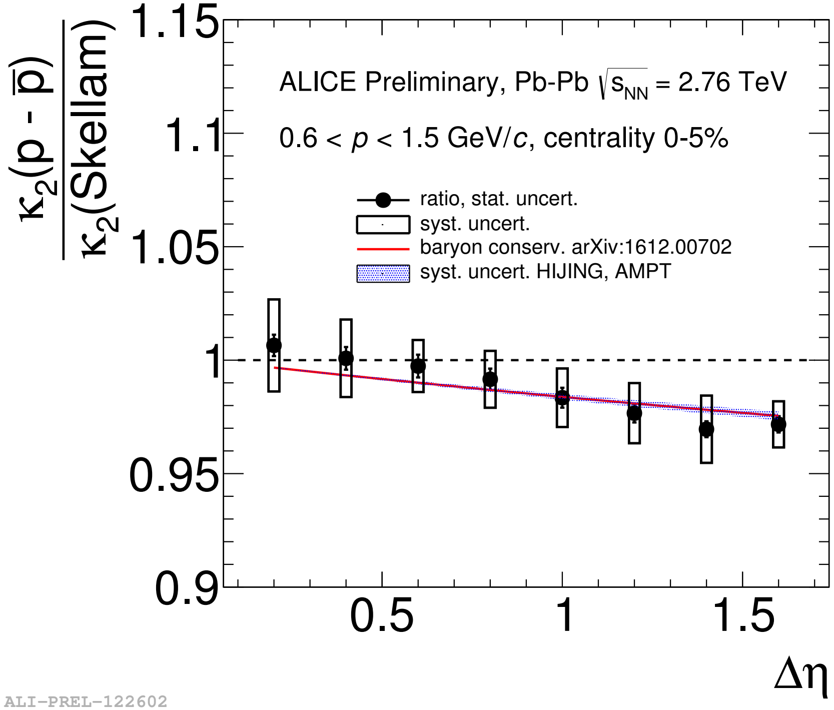
- Inputs for $\langle N_B^{acc} \rangle$ from

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

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

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

A. Rustamov for ALICE, QM2017

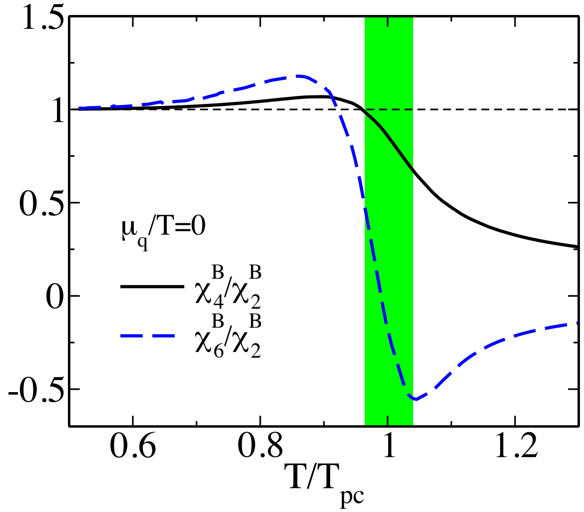


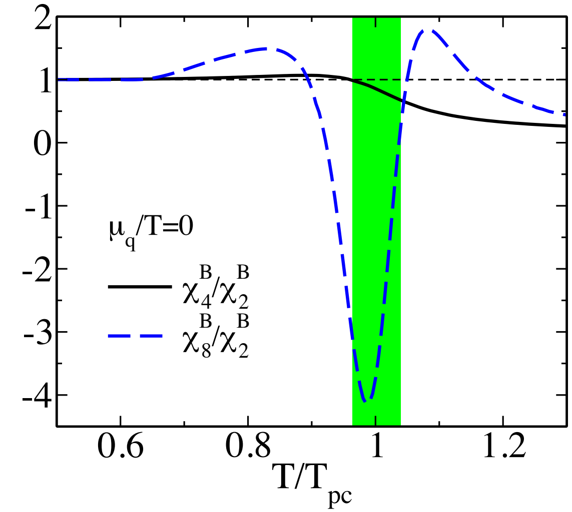
Looking for signs of criticality at $\mu_B = 0$

-- higher moments at the LHC --

Higher moments

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

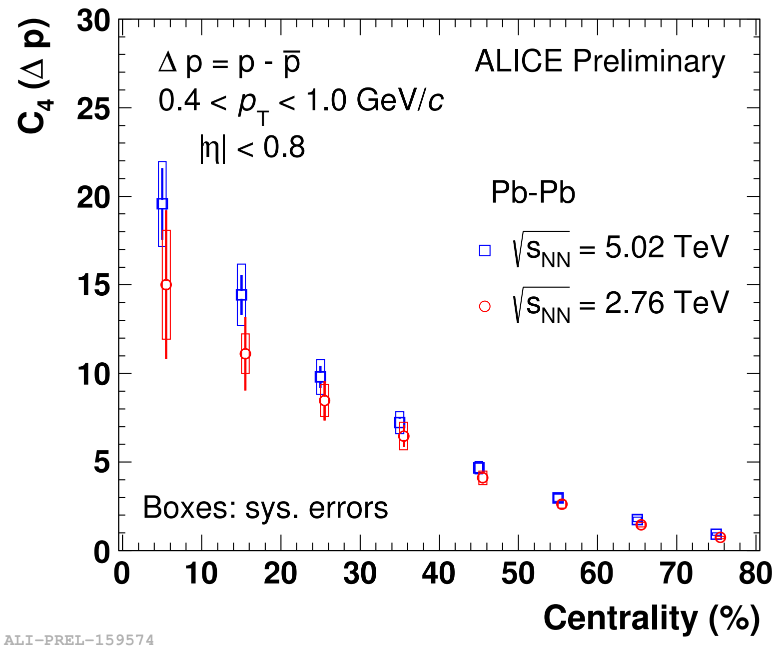


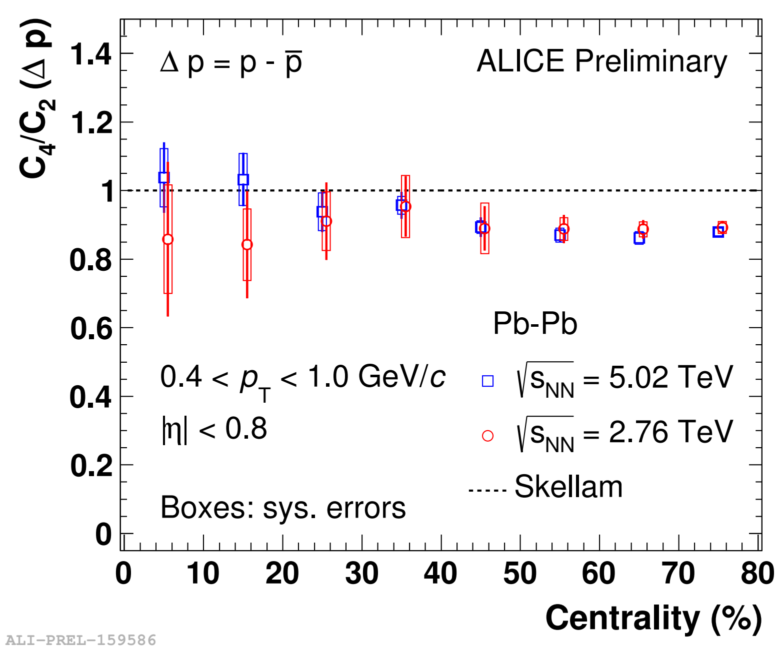


Friman, B., et al. Eur. Phys. J. C 71 (2011) 1694, arXiv:1103.3511 [hep-ph]

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

First higher moments from ALICE





- 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

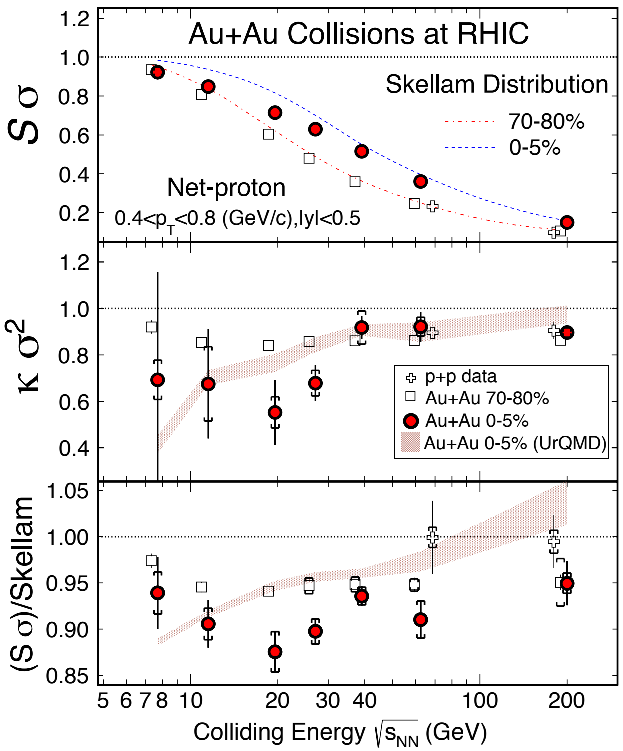
N. Behera for ALICE, QM2018

Exploring the phase diagram and searching for the critical point

-- higher moments at RHIC and SIS --

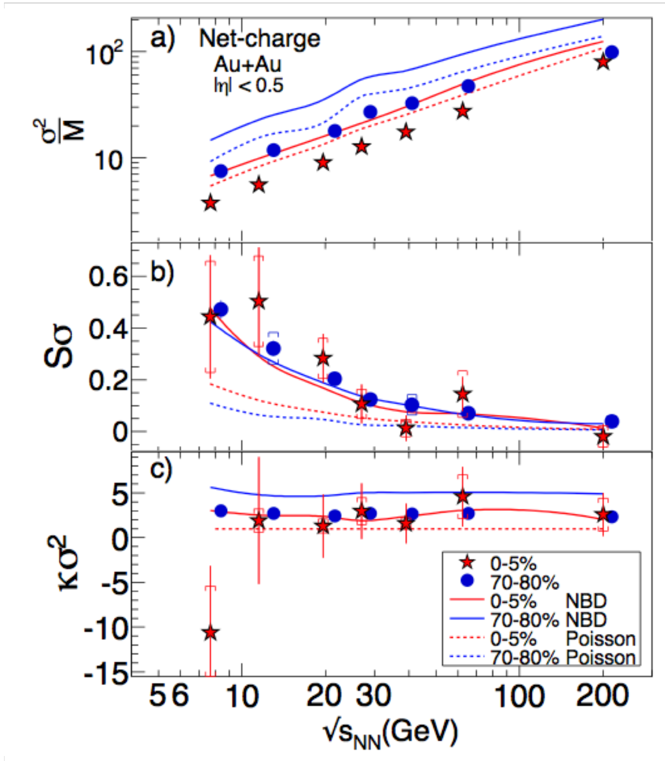
STAR results: net-charge, net-K, net-p

Net-Proton



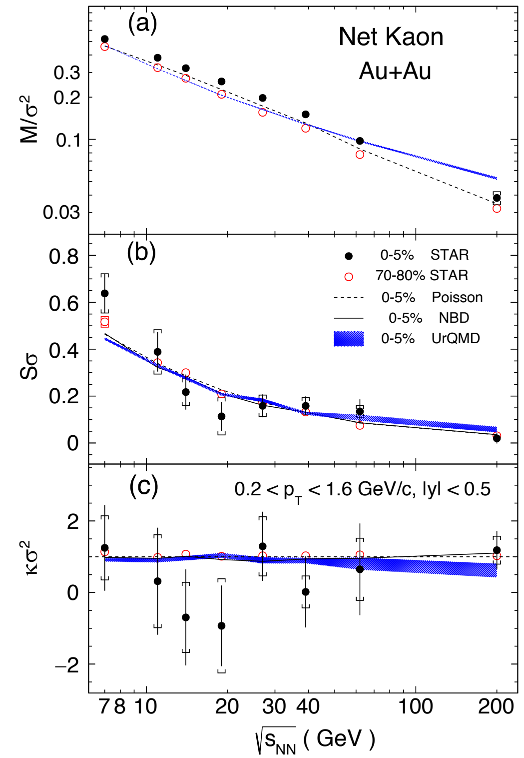
Phys. Rev. Lett. 112, 032302 (2014).

Net-Charge



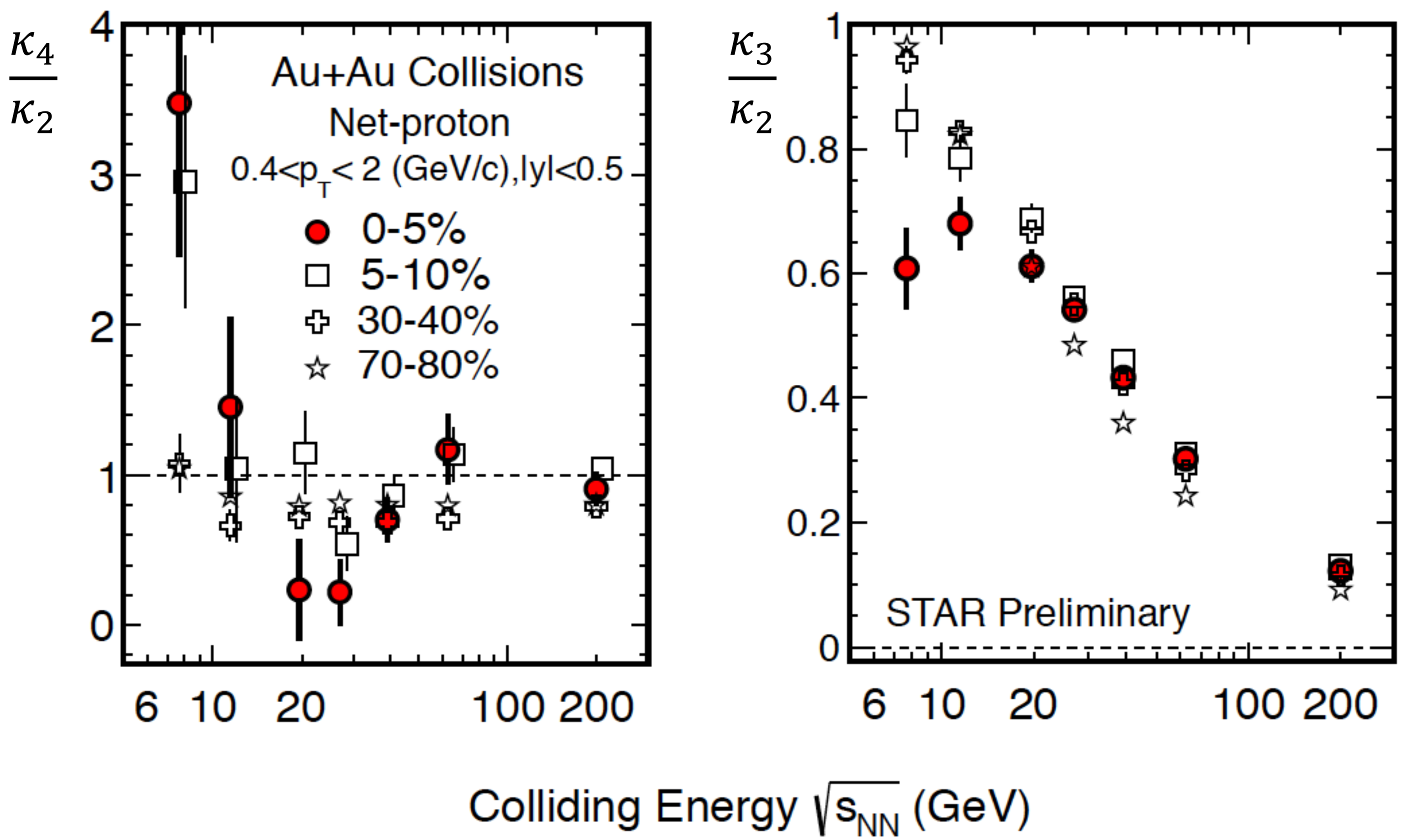
Phys. Rev. Lett. 113 092301 (2014).

Net-Kaon



Phys. Lett. B 785, 551 (2018).

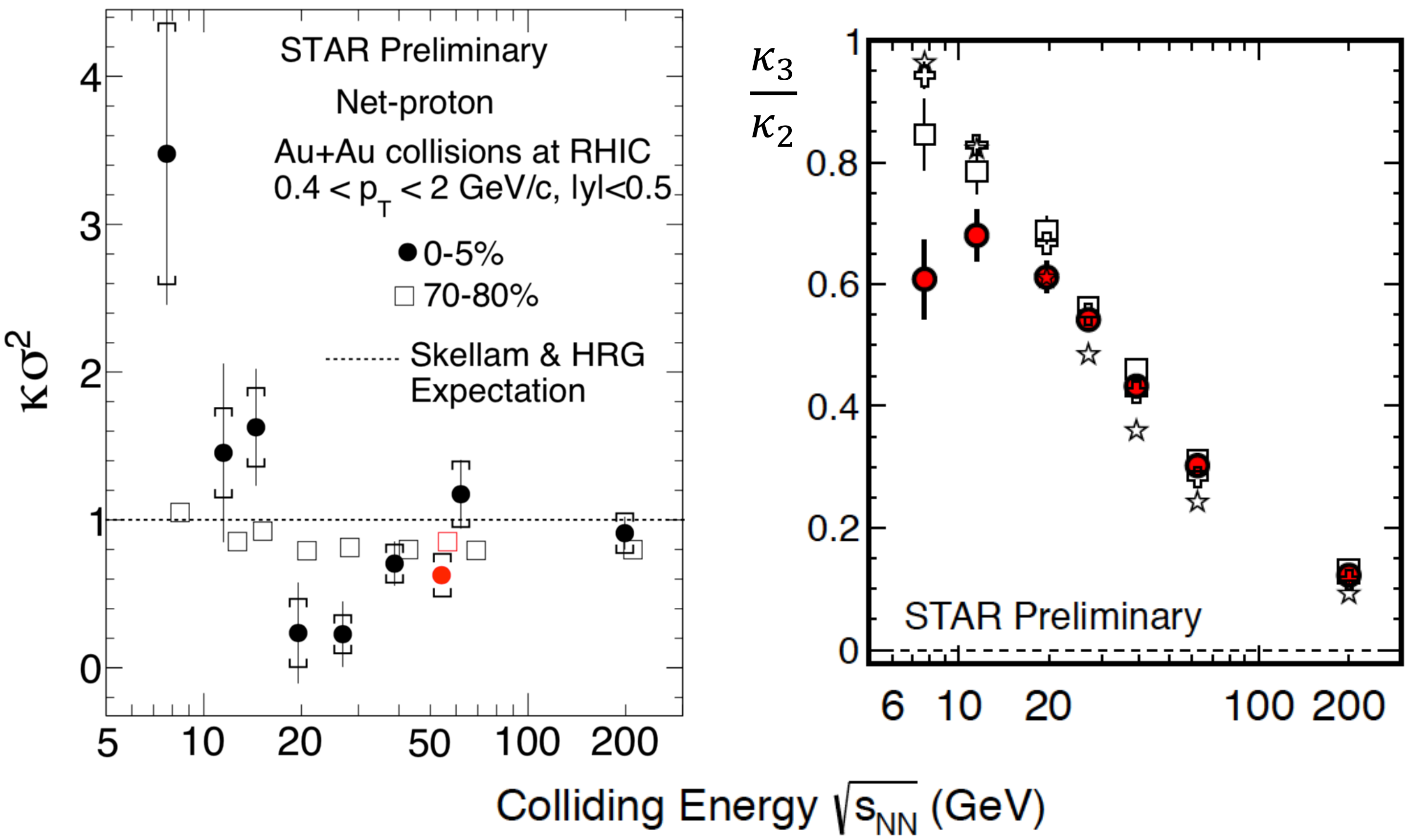
STAR results: net-protons in the BES



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

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

STAR results: net-protons in the BES

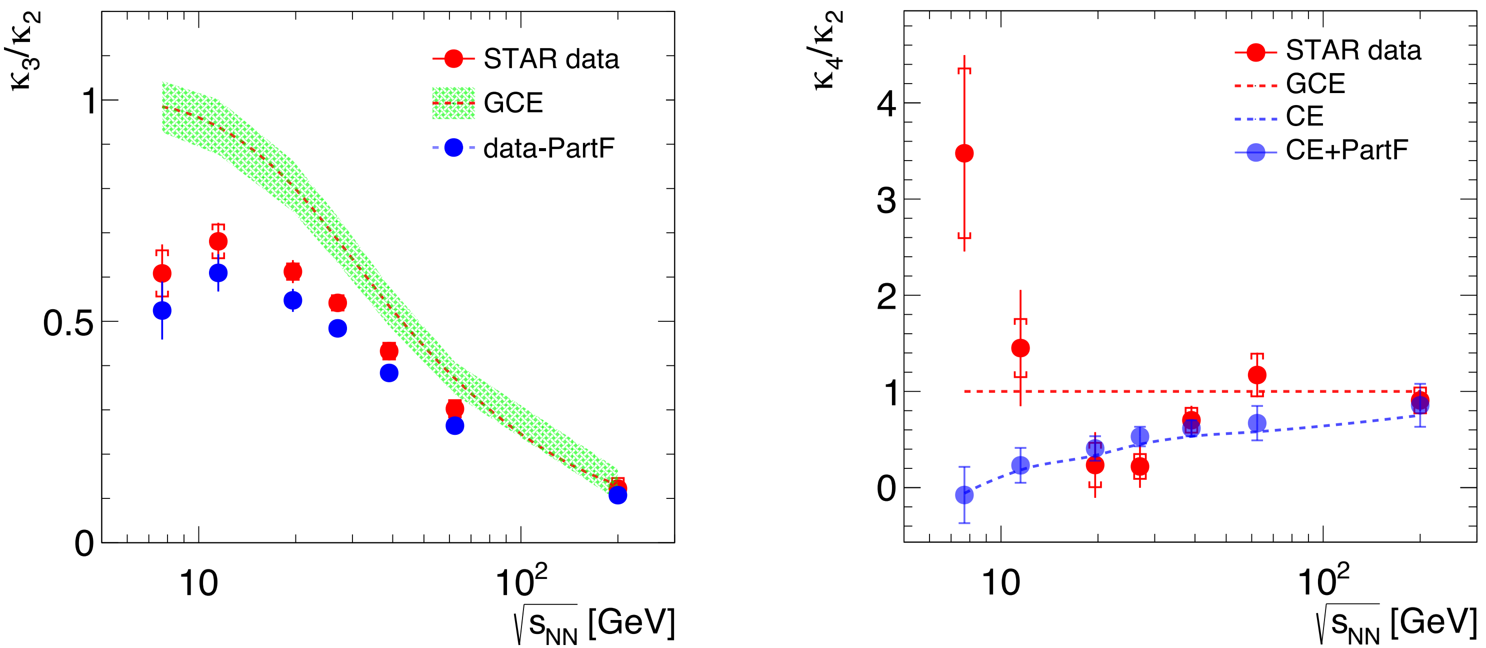


- non-monotonic behavior observed below $\sqrt{s_{NN}} = 39$ GeV

talk by Ashish Pandav (STAR)

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

Effects of conservation laws + vol. fluct.



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

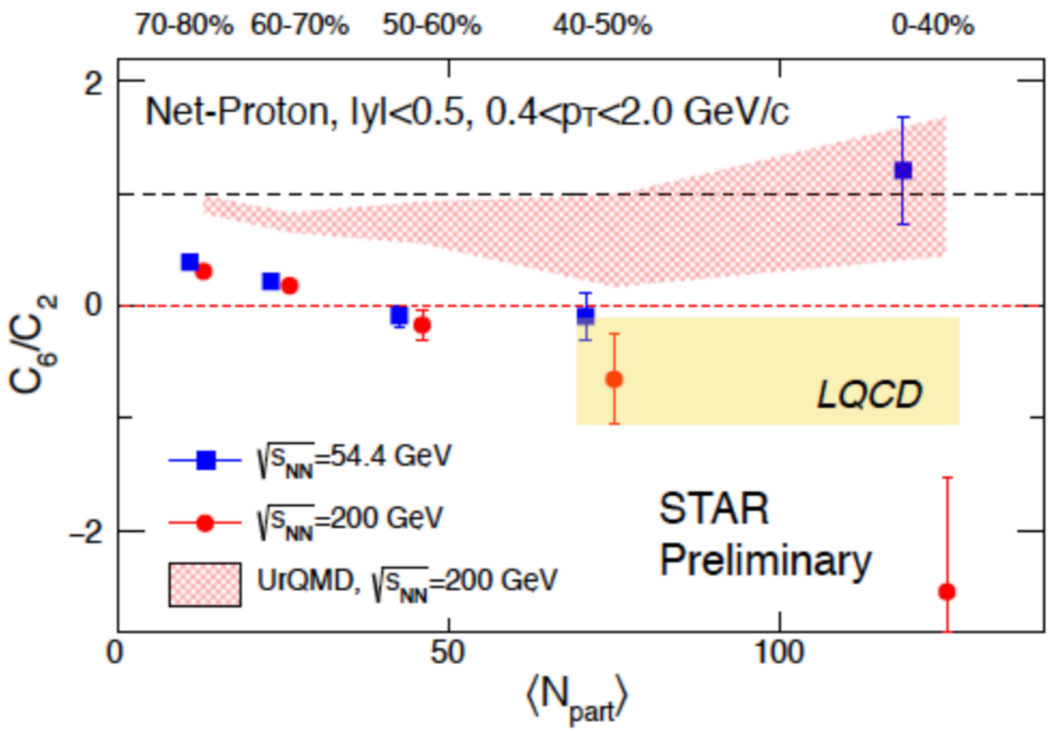
$$\frac{\kappa_3(n_p - n_{\bar{p}})}{\kappa_2(n_p - n_{\bar{p}})} = \frac{\langle n_p - n_{\bar{p}} \rangle_{CE}}{\langle n_p + n_{\bar{p}} \rangle_{CE}}(1 - 2\alpha)$$

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

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

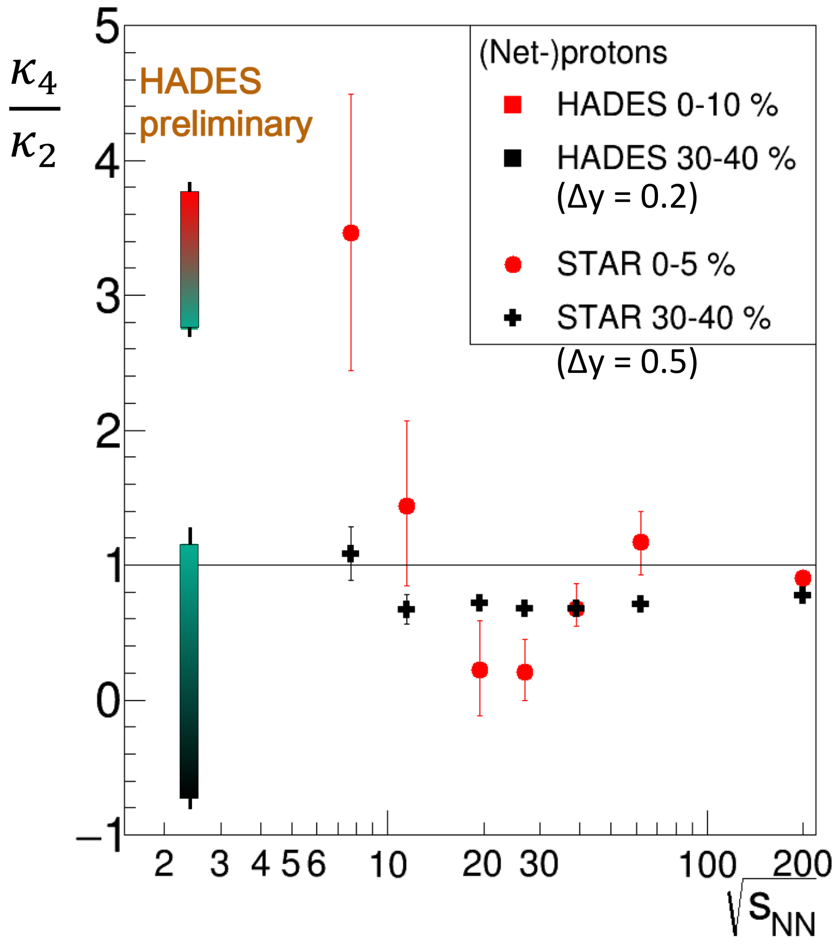
STAR: reaching towards sixth moments



- experimental effects and systematic uncertainties must be very precisely controlled before drawing conclusions, but sixth moments appear to be within the statistical reach
  → stay tuned for updates!

talk by Ashish Pandav (STAR)

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)

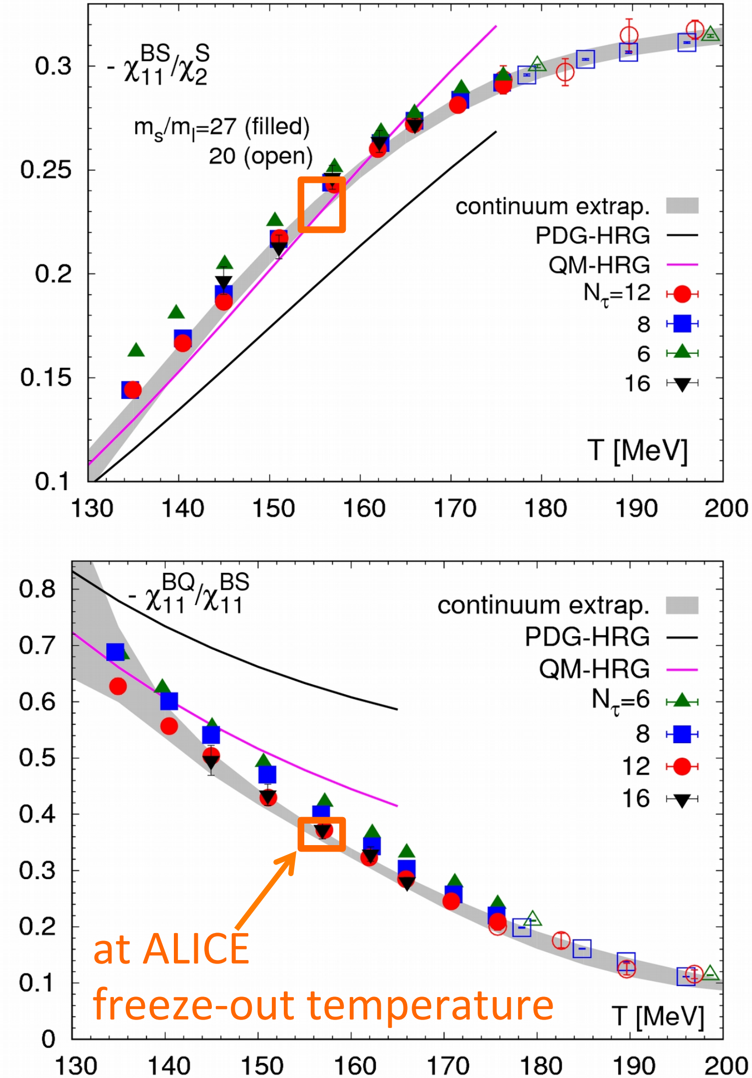
Correlated fluctuations of conserved quantities

-- net-Λ fluctuations and mixed cumulants --

Correlated fluctuations

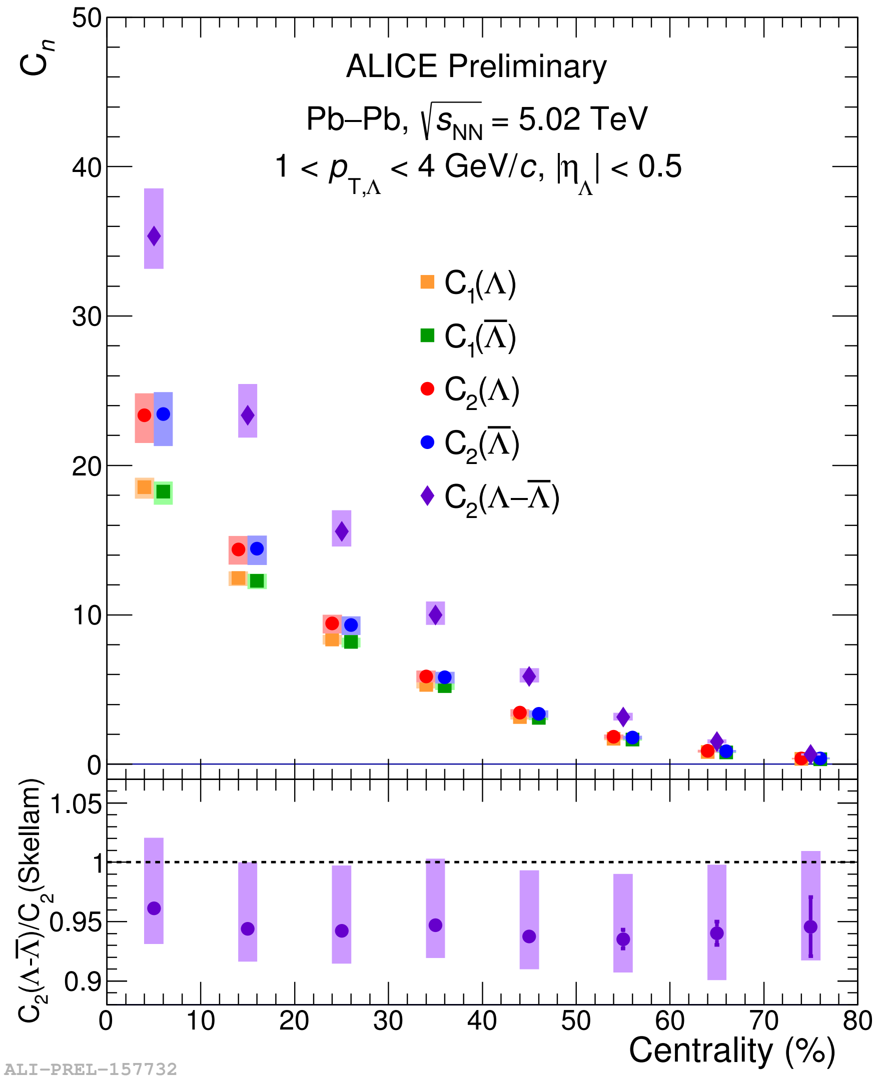
- Probe correlated fluctuations of net-charge, net-strangeness, net-baryon number
- Access off-diagonal elements, mixed derivatives χ^{BS}, χ^{BQ}, χ^{QS}
- Provides a more complete set of comparisons to LQCD predictions

- Experimental observables:
  - Net-Λ fluctuations
  - Cross-cumulants



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

Net-Λ fluctuations



A. Ohlson for ALICE, QM2018

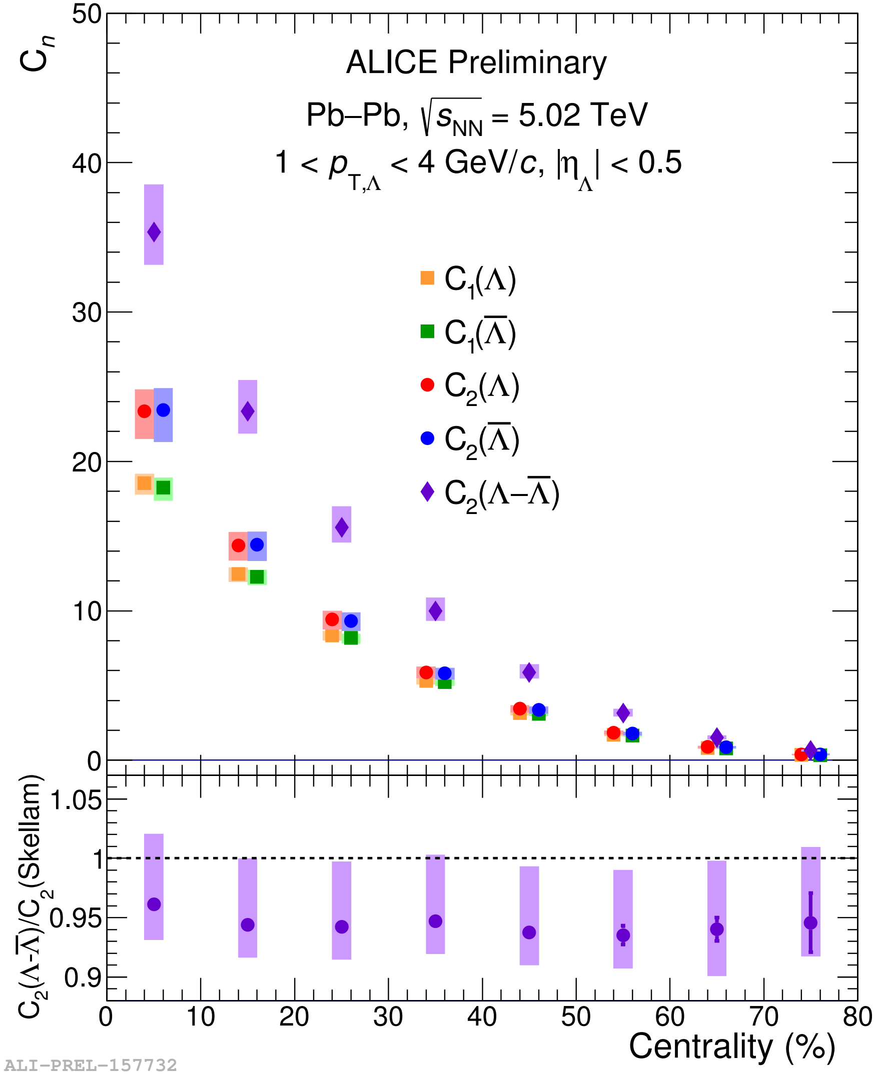
$$C_1(\Lambda) = \langle N_\Lambda \rangle \qquad C_2(\Lambda) = \left\langle \left(N_\Lambda - \langle N_\Lambda \rangle\right)^2 \right\rangle$$

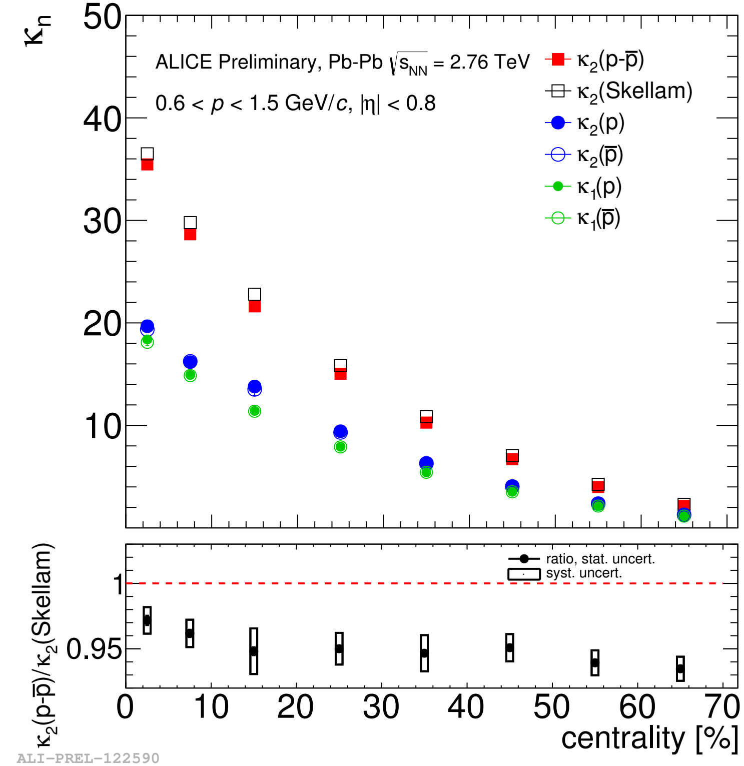
$$C_2(\Lambda-\bar{\Lambda}) = \left\langle \left(N_\Lambda - N_{\bar{\Lambda}} - \langle N_\Lambda - N_{\bar{\Lambda}} \rangle\right)^2 \right\rangle$$

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

- 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



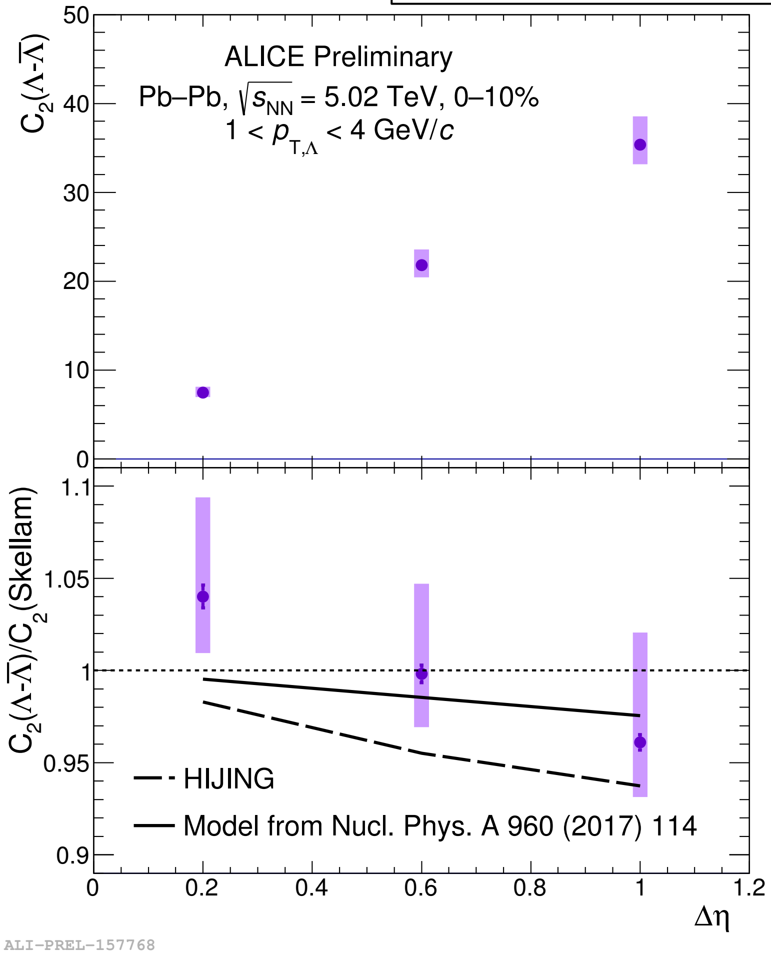


- Qualitatively similar results for net-protons
  - different kinematic range, different contributions from resonance decays

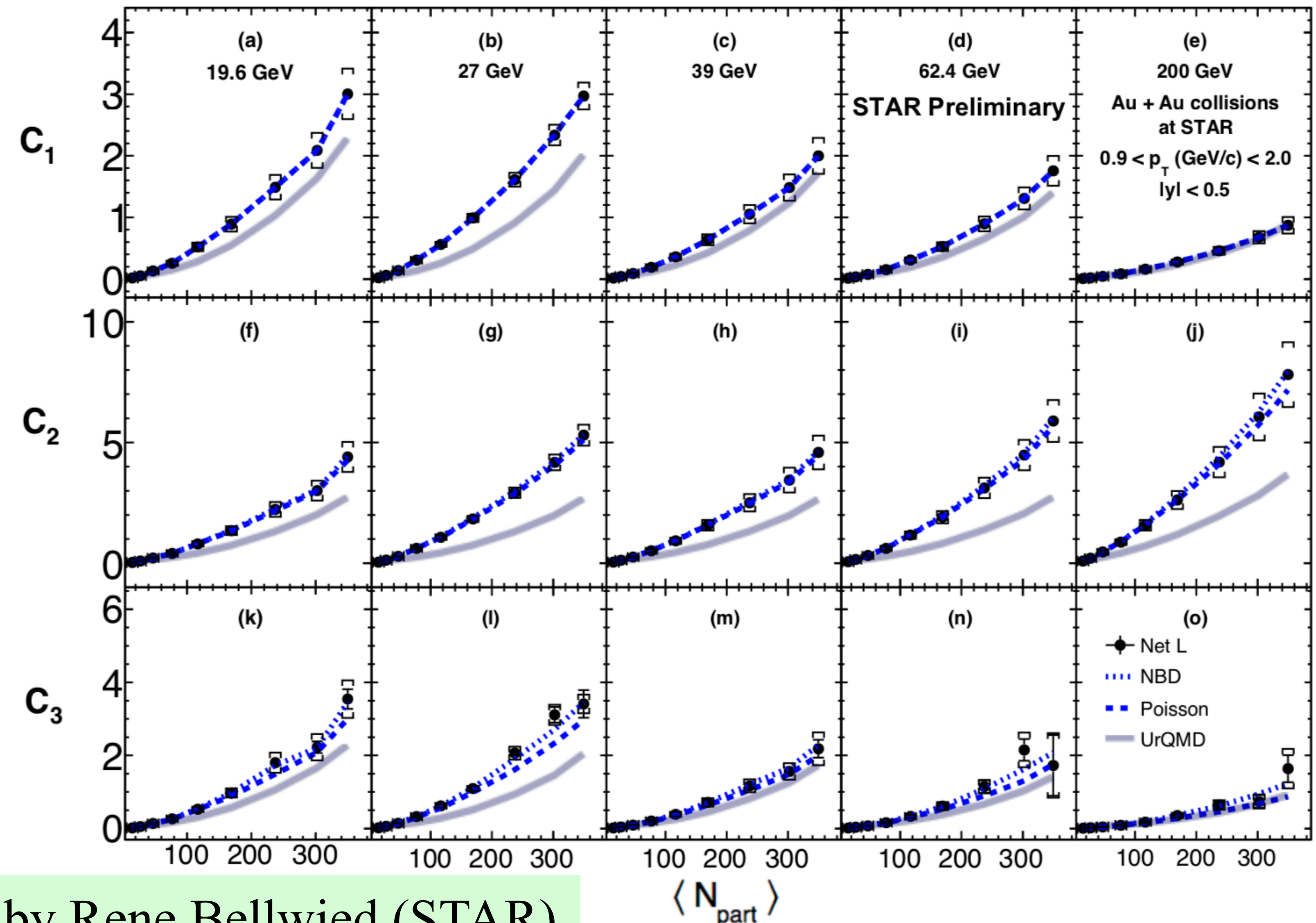
$\Delta\eta$ dependence of net-Λ fluctuations

A. Ohlson for ALICE, QM2018

- 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
- Systematic uncertainties are highly correlated point-to-point
- $\Delta\eta$ dependence consistent with effects of baryon number conservation $\rightarrow$ strangeness conservation should also be considered
- consistency also with HIJING

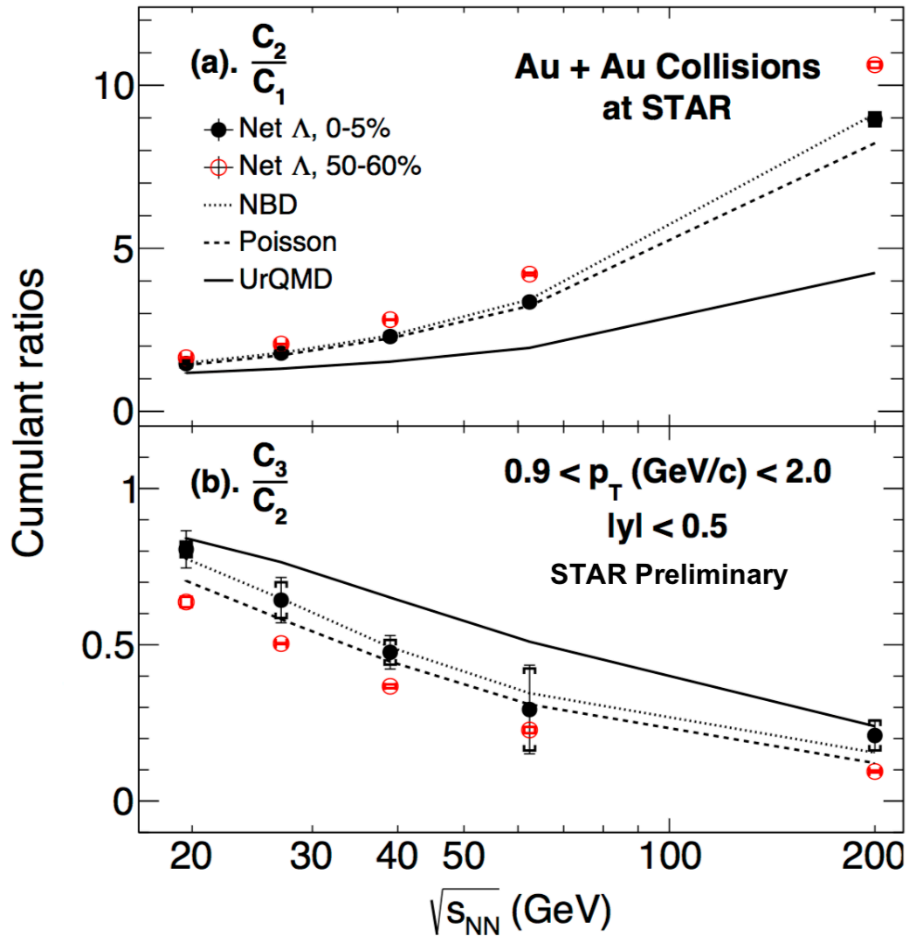


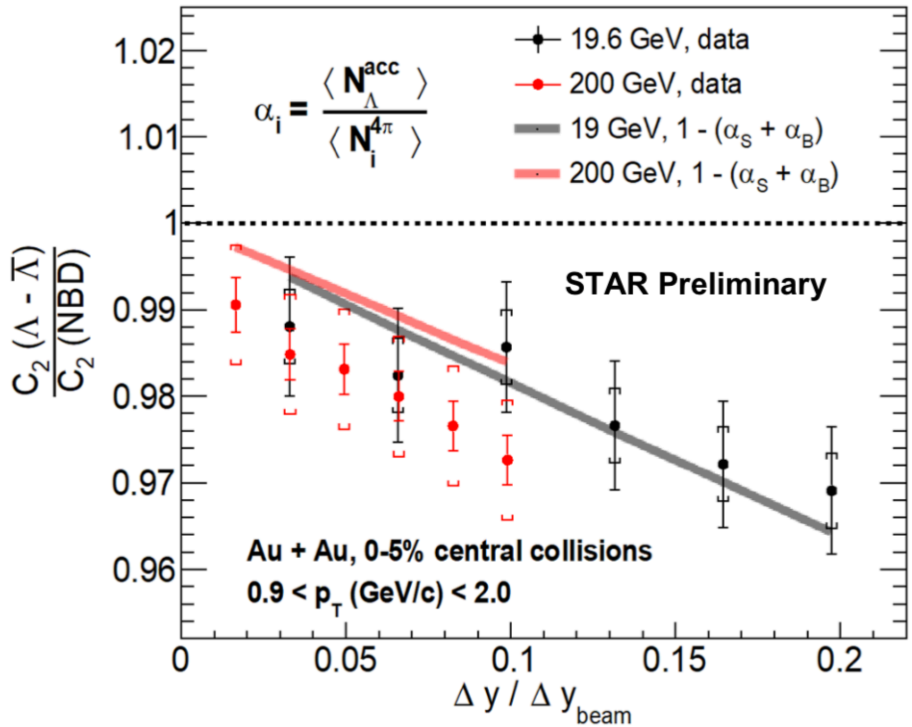
Net-Λ fluctuations at STAR



talk by Rene Bellwied (STAR)

Net-Λ fluctuations vs $\sqrt{s_{NN}}$ and Δη



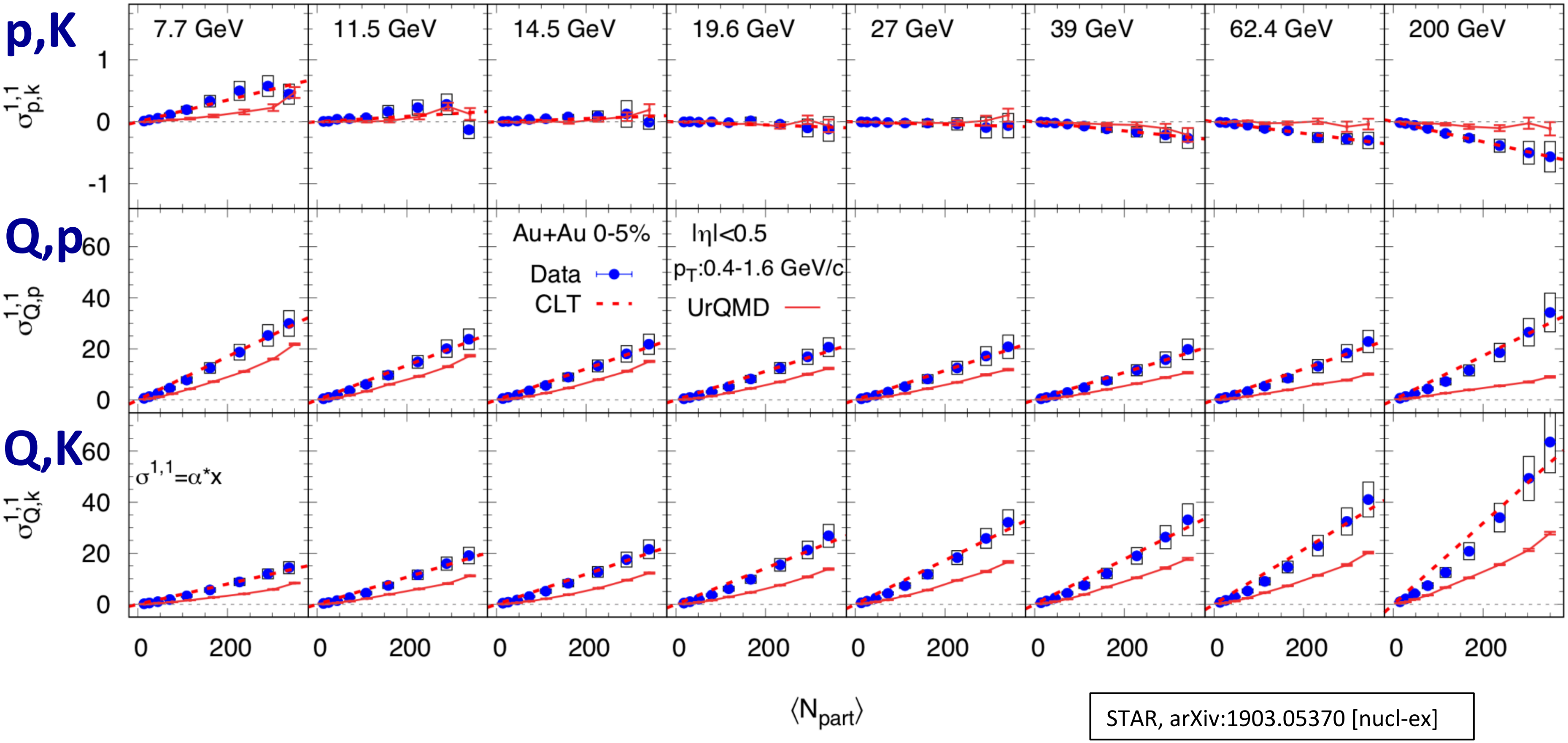


- Effect of net-baryon number conservation → can describe the data if B and S conservation treated additively

talk by Rene Bellwied (STAR)

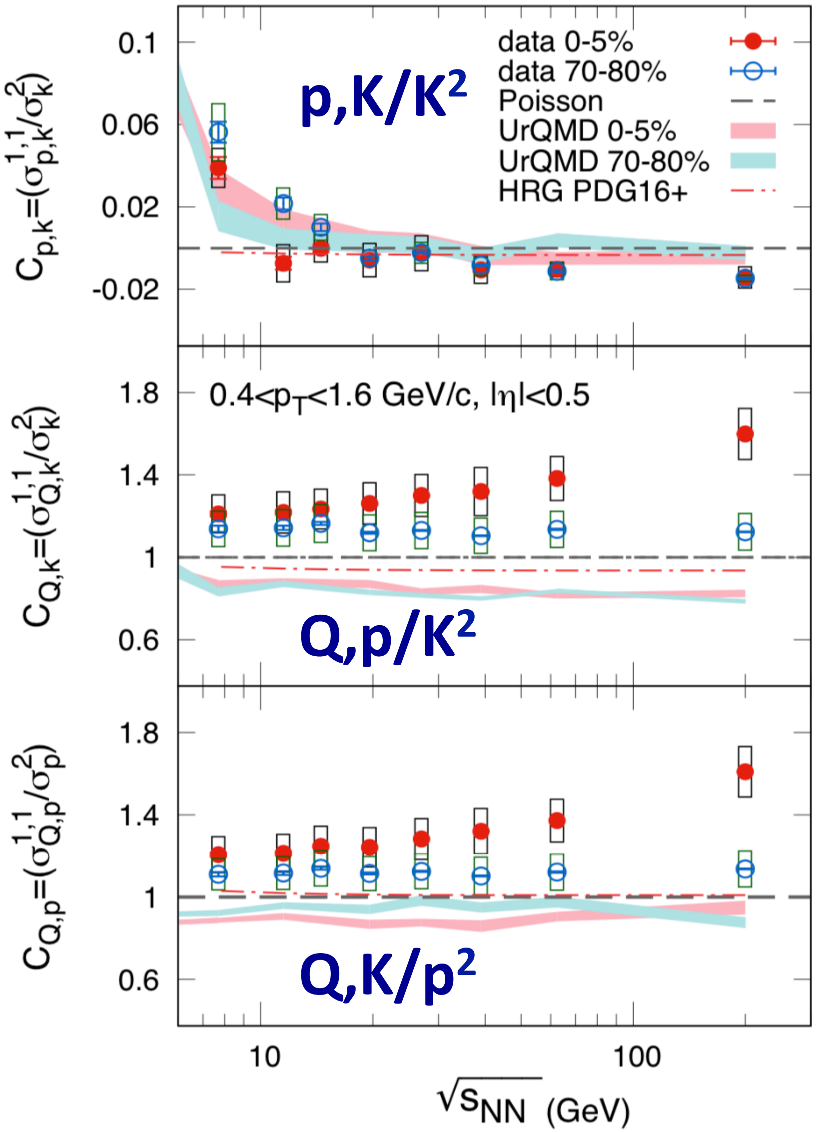
Cross-cumulants at STAR

- Full matrix of cross-cumulants of Q, p, K, up to second order measured in the BES $\sigma^{1,1}_{\alpha,\beta} = \langle (\delta N_\alpha - \langle \delta N_\alpha \rangle)(\delta N_\beta - \langle \delta N_\beta \rangle) \rangle$



STAR, arXiv:1903.05370 [nucl-ex]

Cross-cumulants in the BES



- Take ratios to remove volume dependence and self-correlations
  - effects of resonance decays must be quantitatively assessed
- Measurements do not agree with Poisson baseline, UrQMD or HRG predictions

STAR, arXiv:1903.05370 [nucl-ex]

What have we learned so far?
Where do we go from here?

Conclusions

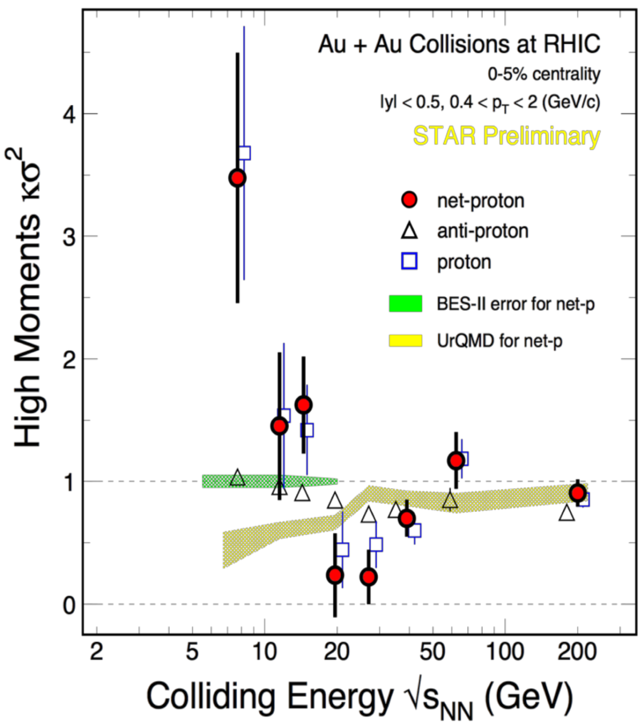
- Event-by-event fluctuations of identified particles
  - yield information on properties of the QGP medium
  - test lattice QCD predictions at $\mu_B = 0$
  - allow us to look for effects of criticality
- Progress in bringing experimental and theoretical effects under control in order to perform quantitative comparison
- A wealth of data from ALICE, STAR, and HADES
  - 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
  - Net-Λ fluctuations and cross-cumulants allow large set of comparisons to theory including LQCD

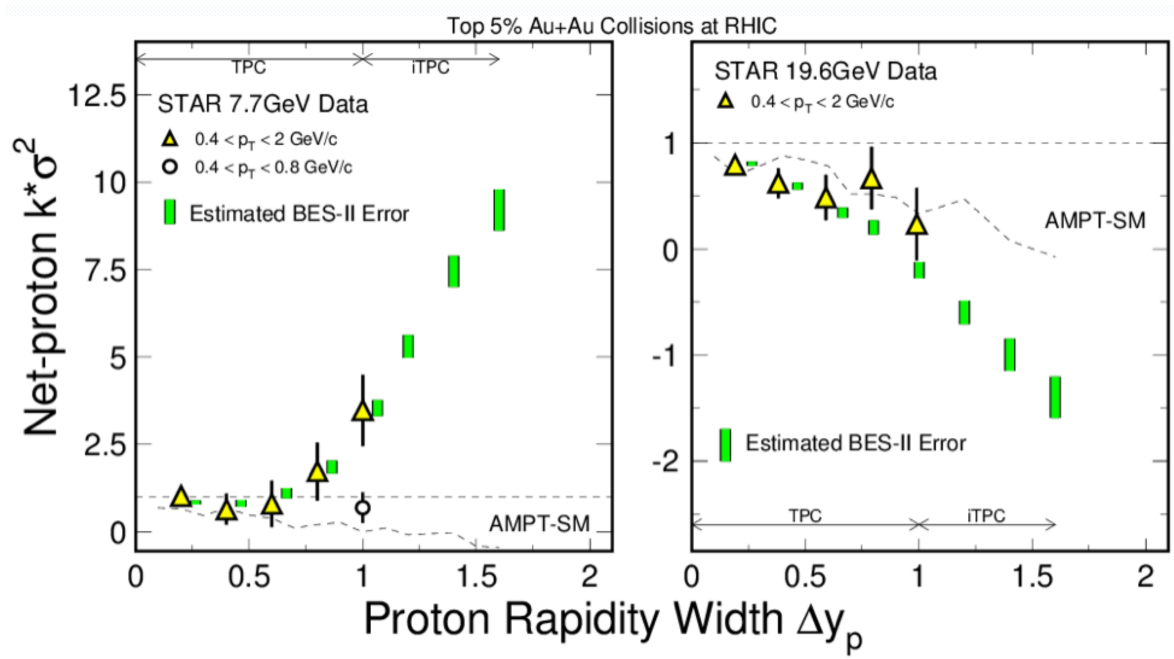
Outlook

- 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 upgrades 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

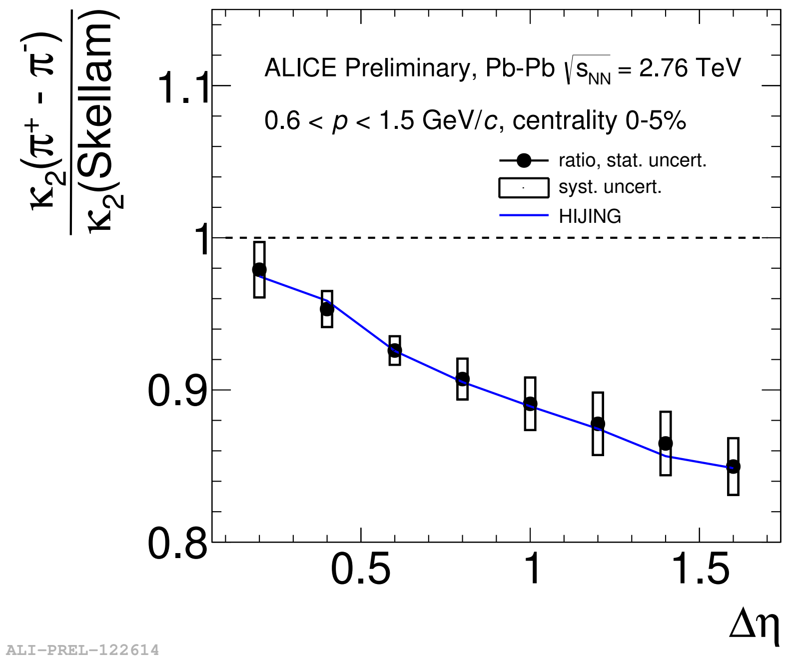
Grazie!

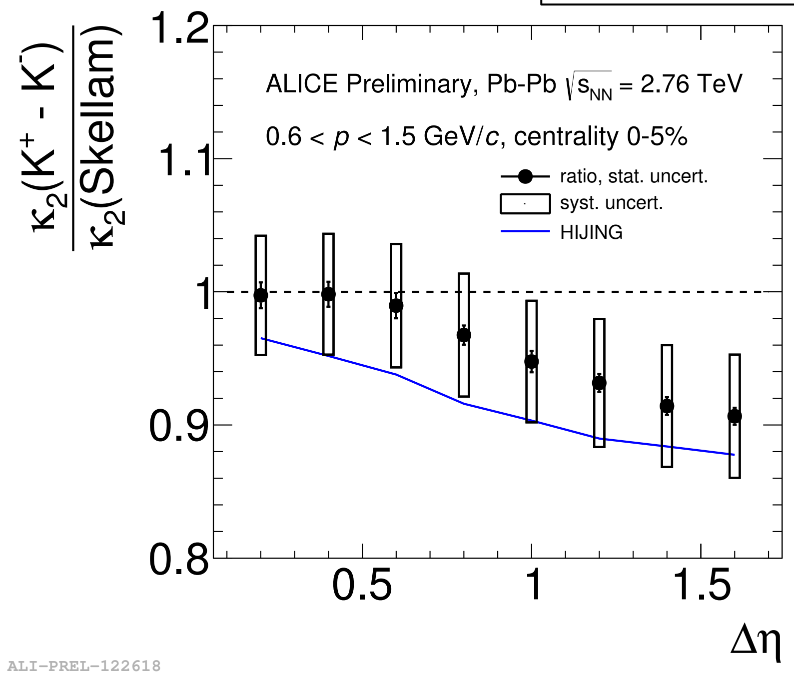
Matera
June 12, 2019

backup

Net-pion and net-kaon fluctuations

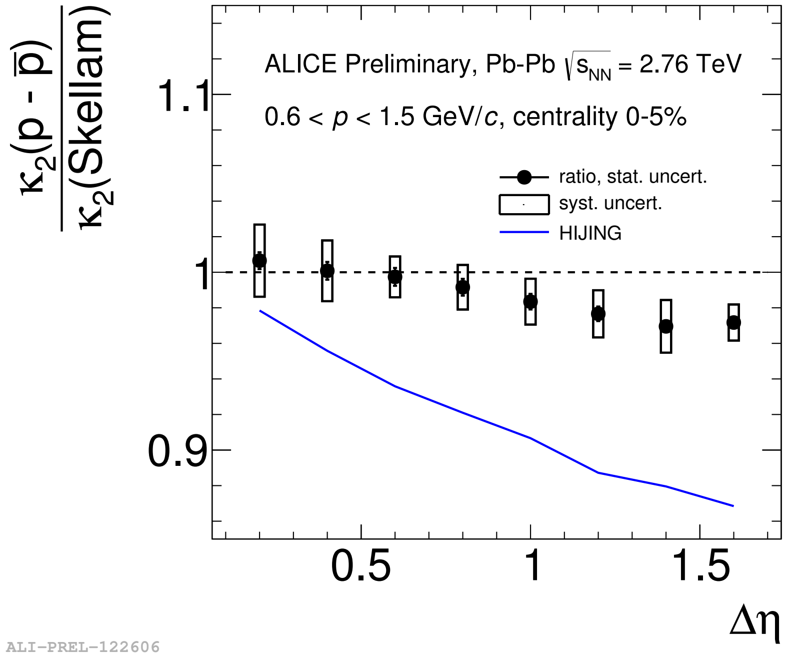
A. Rustamov for ALICE, QM2017

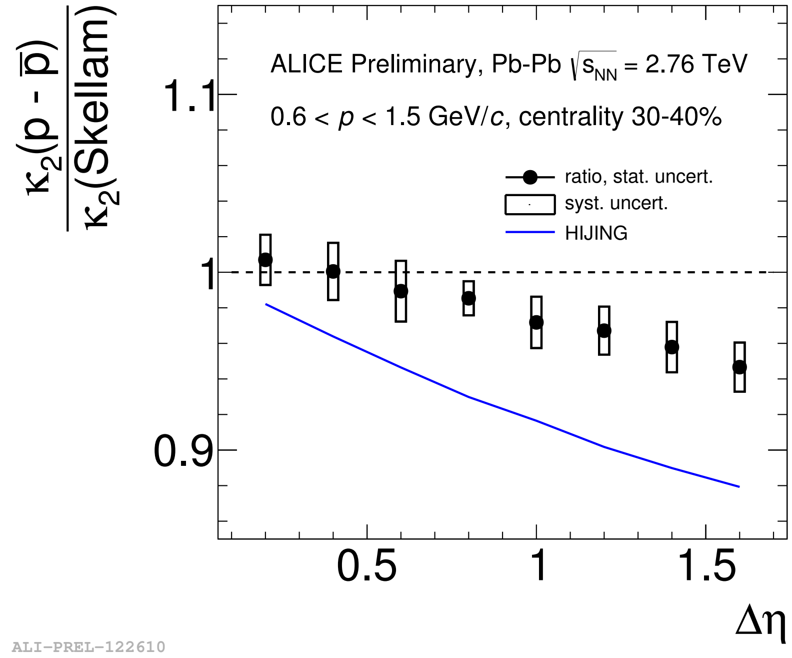




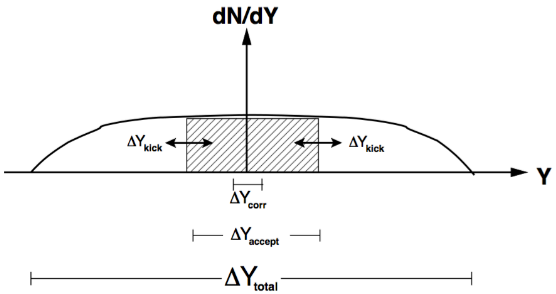
- Pions show good agreement with HIJING
- Production of pions and kaons from resonance decays contributes significantly to the measurement
- Skellam distribution is not a proper baseline for net-pions and net-kaons

Centrality dependence



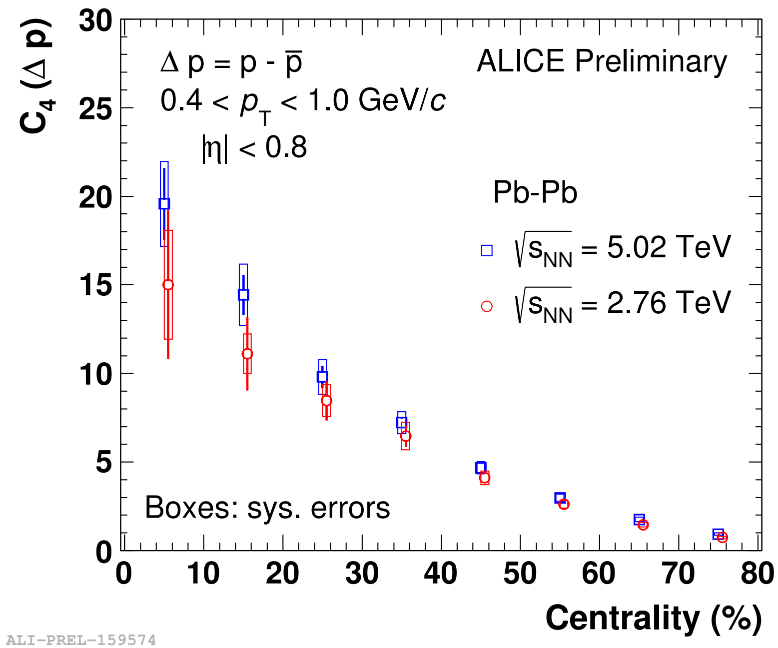


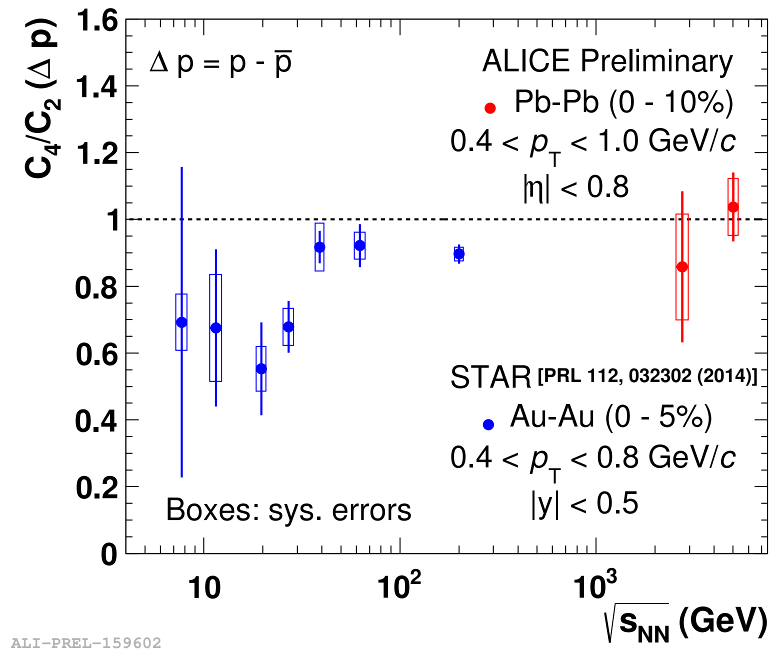
- Deviations from Skellam can be attributed global baryon number conservation, more significant in more peripheral collisions
- Disagreement with HIJING



A. Rustamov for ALICE, QM2017

First higher moments from ALICE!

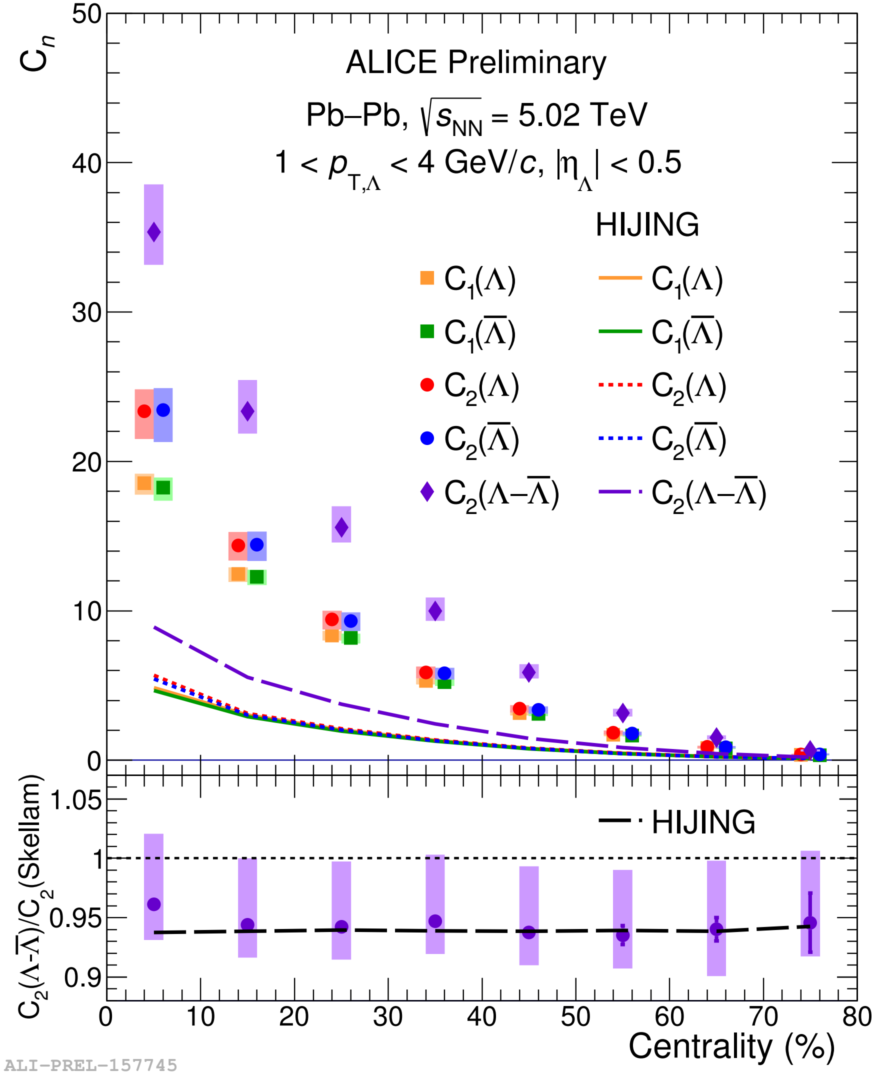




- Measured with traditional (cut-based) PID method
- Consistent results between $\sqrt{s_{NN}}$ = 2.76 TeV and 5.02 TeV within statistical and systematic uncertainties
- In central events, consistency with Skellam baseline ($C_4/C_2 = 1$) at LHC energies

N. Behera for ALICE, QM2018

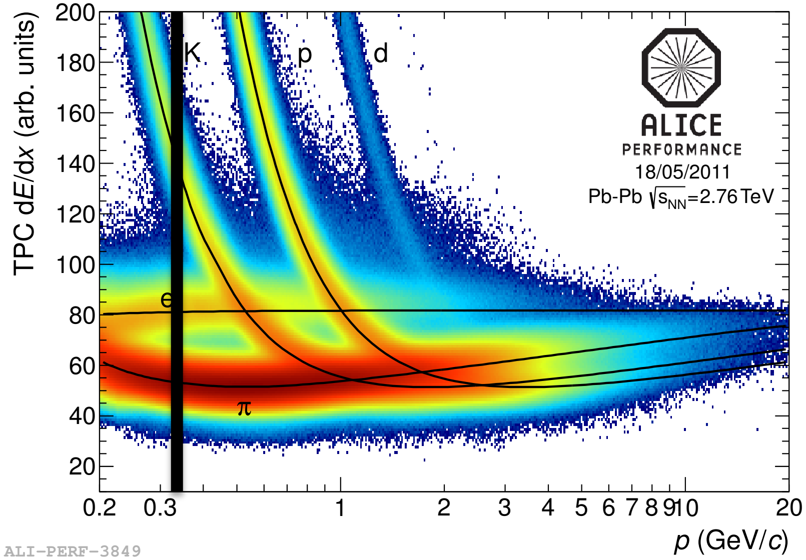
Comparison to HIJING

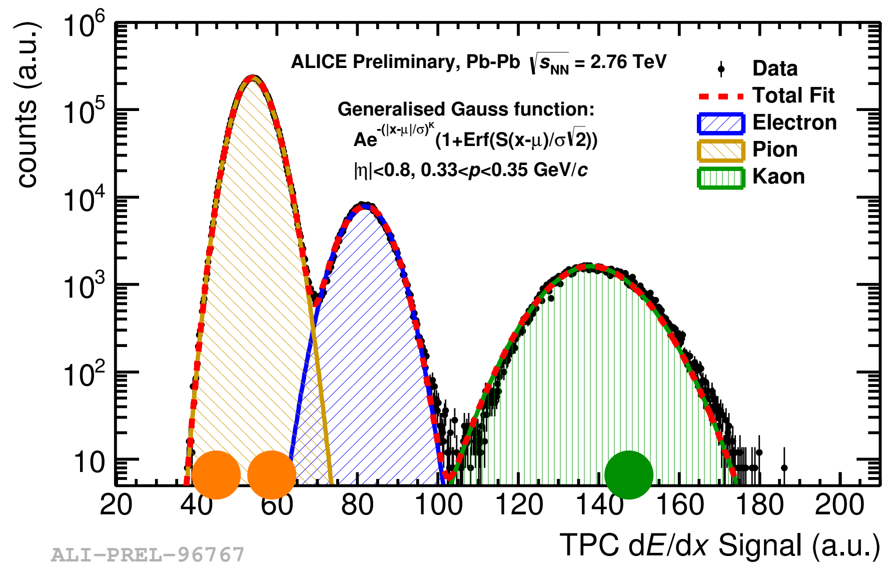


A. Ohlson for ALICE, QM2018

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

The challenge: event-by-event PID



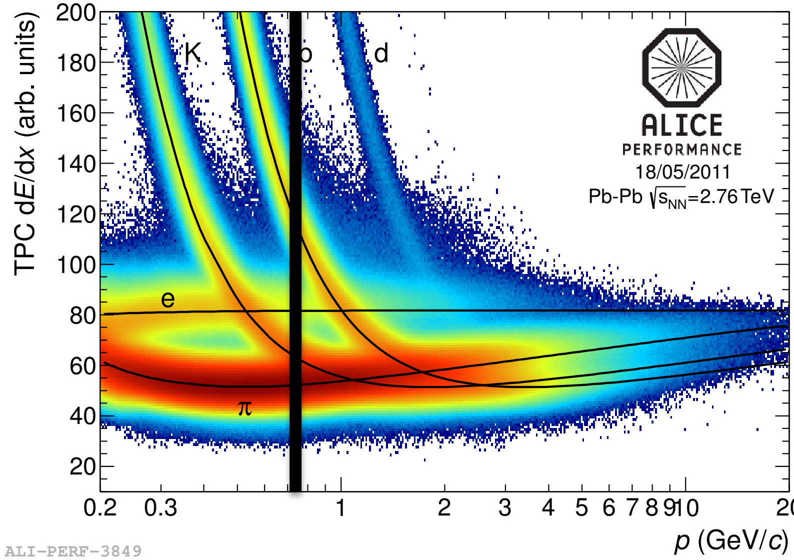


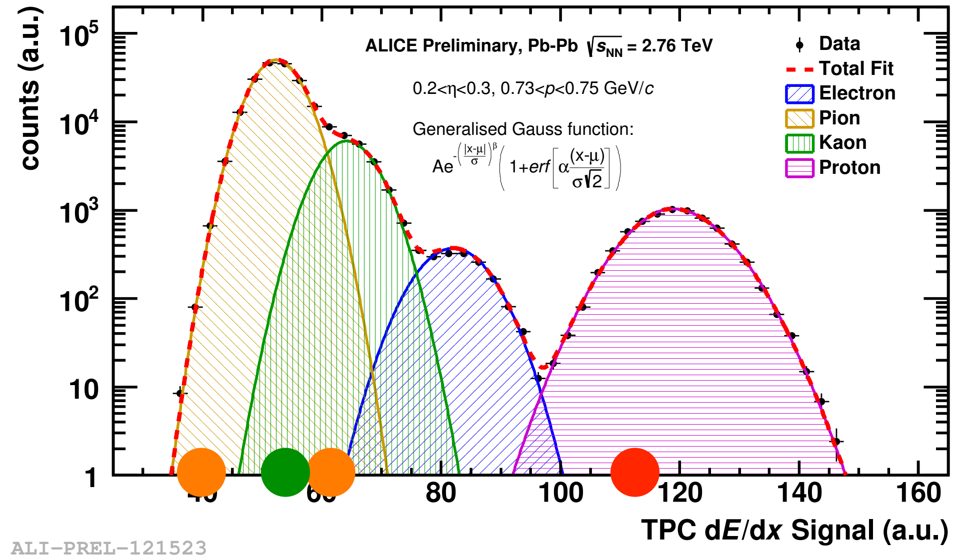
- Traditional method:
  - count number of pions (N_π), kaons (N_K), protons (N_p) in each event

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

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

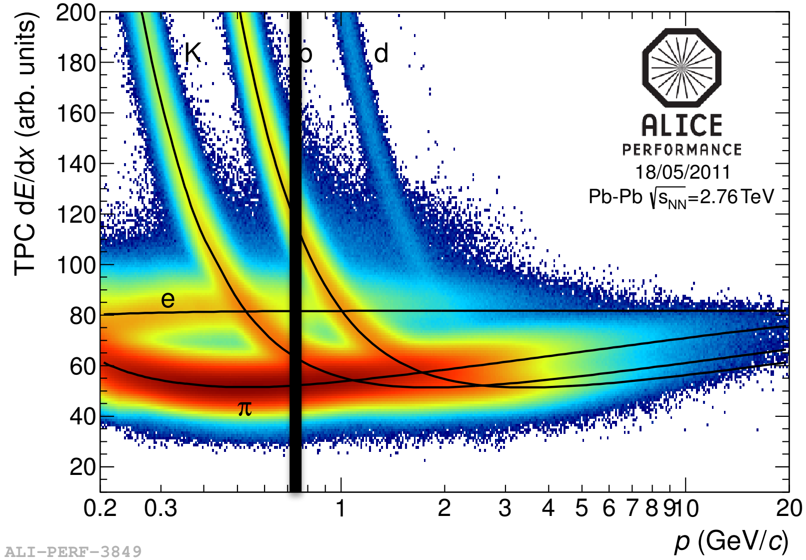
Traditional method

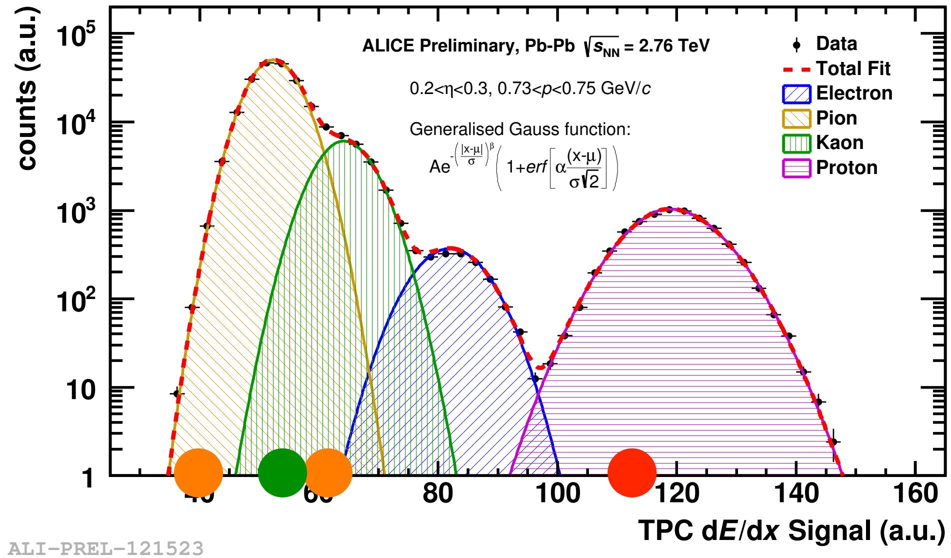




- What if PID is unclear?
  - use other detector information or reject phase space bin
  - results in lower efficiency

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]

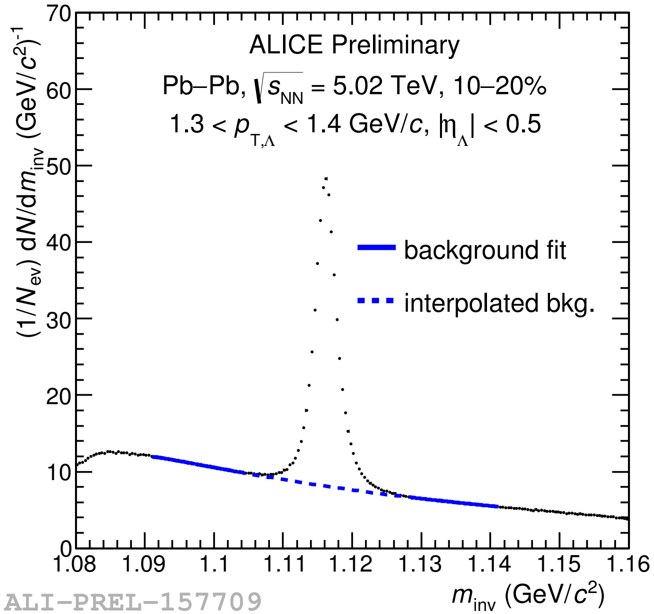
A. Rustamov et al., PRC 86 (2012) 044906, arXiv:1204.6632 [nucl-th]

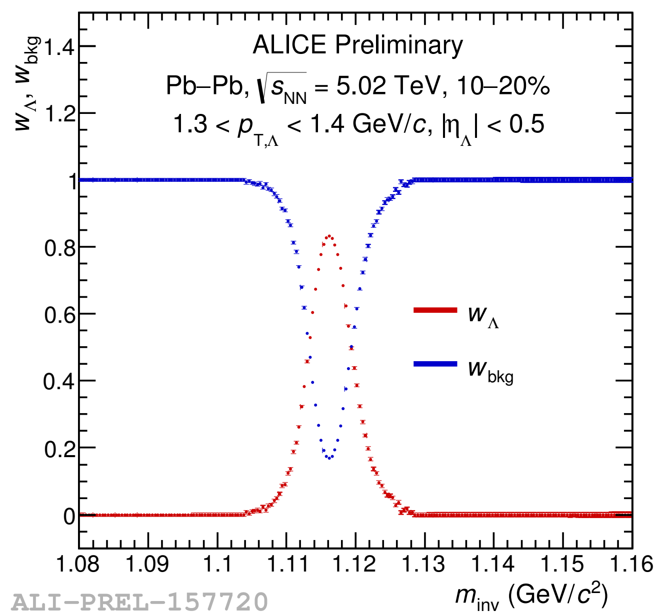
M. Arslandok and A. Rustamov, arXiv: 1807.06370 [hep-ex]

Identity method for invariant mass

A. Ohlson for ALICE, QM2018

- Net-Λ fluctuations: explore correlated fluctuations of baryon number and strangeness
- 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, $\overline{\Lambda}$, combinatoric $\pi^{-}p$, combinatoric $\pi^{+}\overline{p}$





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]

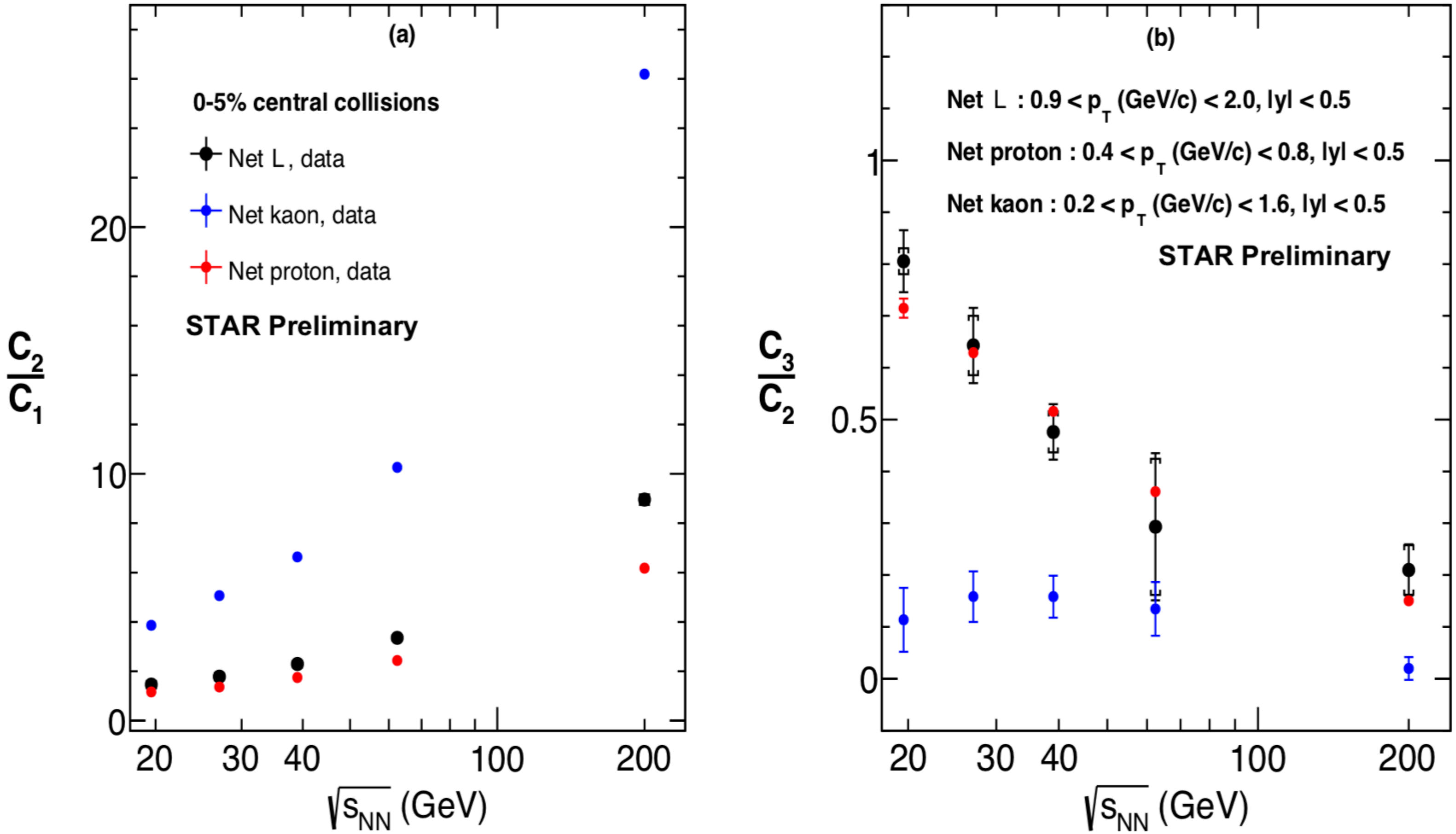
- Correction using moments of detector response matrix

  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!

Net-Λ fluctuations at STAR



What is the correlation length?

J. Pan for ALICE, QM2018

- Balance functions of identified particles

ALICE

$$B(\Delta y) = \frac{1}{2}\left[C_2^{+-} - C_2^{++} + C_2^{-+} - C_2^{--}\right]$$

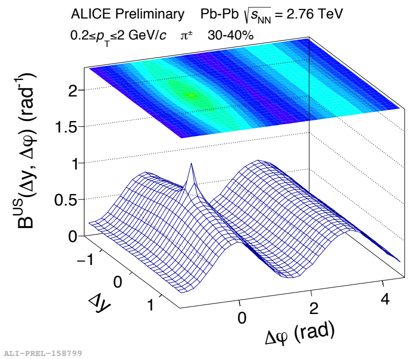
Bass, Danielewicz, Pratt PRL. 85, 2689 *(2000)*

$$C_2^{a,b}(\Delta y) = \frac{\langle N^{a,b}(\Delta y)\rangle}{\langle N^a(y_1)\rangle} \qquad a,b \in \{+,-\}$$

same for Δφ and Δp_T

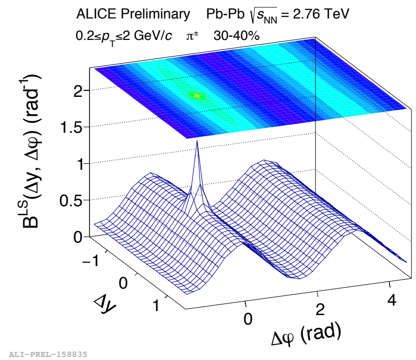
General charges:
- e: (±)electric charge
- S: (anti)strangeness
- B: (anti)baryon number

$$B^{US}(\Delta y) = \frac{1}{2}\left[C_2^{+-} + C_2^{-+}\right]$$



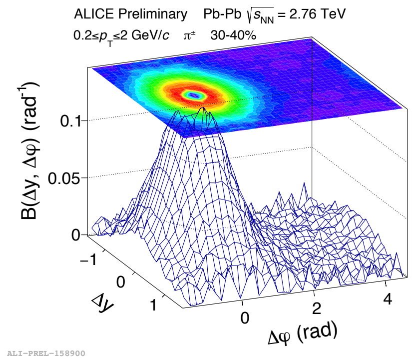
$-$

$$B^{LS}(\Delta y) = \frac{1}{2}\left[C_2^{++} + C_2^{--}\right]$$



$=$

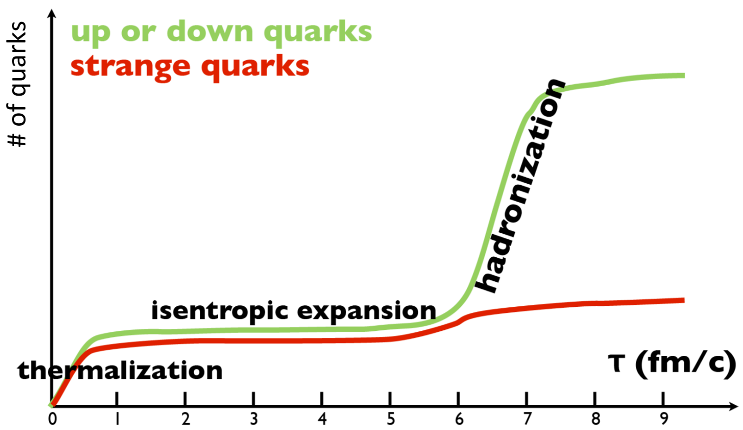
$$B(\Delta y) = B^{US}(\Delta y) - B^{LS}(\Delta y)$$



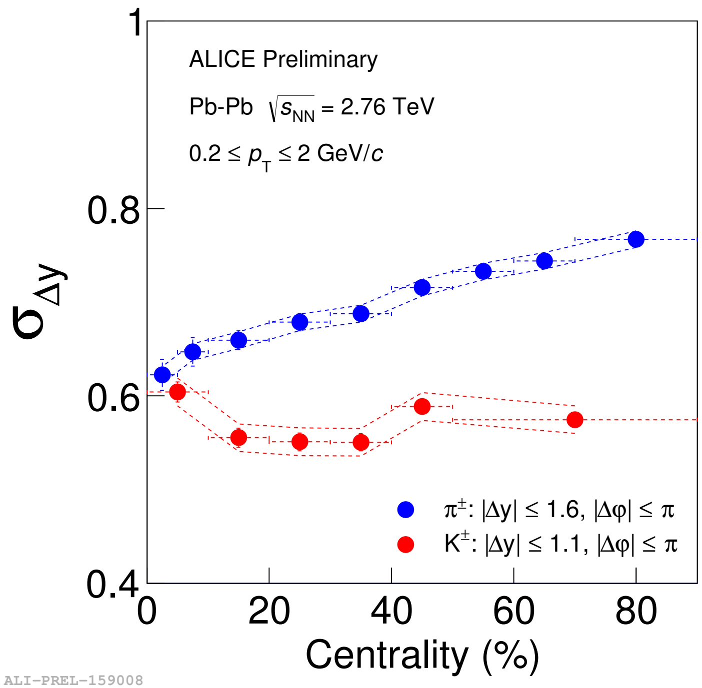
- Sensitive to physics of balancing charges:
  - Charge production mechanisms, two-wave production scenario, radial flow, quantum statistics, ...

Balance functions

J. Pan for ALICE, QM2018



Pratt PRL. 108, 212301 (2012)



- Width of π balance function shows centrality dependence, K balance function width is independence of centrality → consistent with two-wave production model, but other physical effects (e.g. radial flow) must be considered
- Full species matrix (including protons) coming soon!