Higher moments of net-particle fluctuations in Pb-Pb collisions from ALICE

Mesut Arslandok
Physikalisches Institut, Heidelberg University
on behalf of the ALICE Collaboration

The 18th International Conference on **Strangeness in Quark Matter**
10-15 June 2019, Bari, Italy

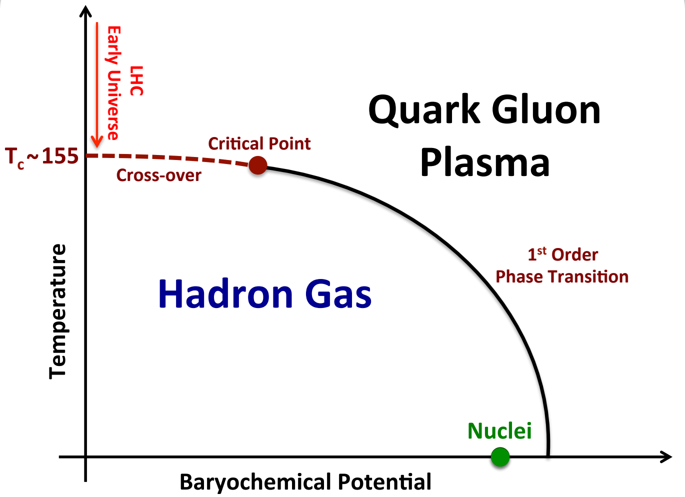
UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386

isoQuant SFB1225

BMBF Forschungsschwerpunkt ALICE Experiment 202

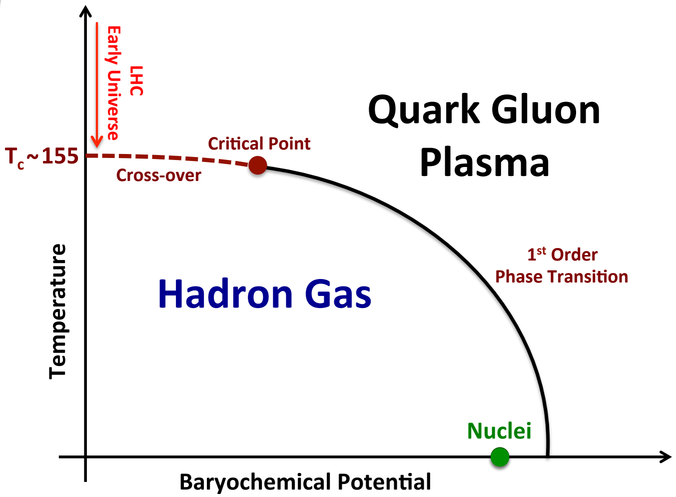
ALICE

Why Ebye fluctuations?

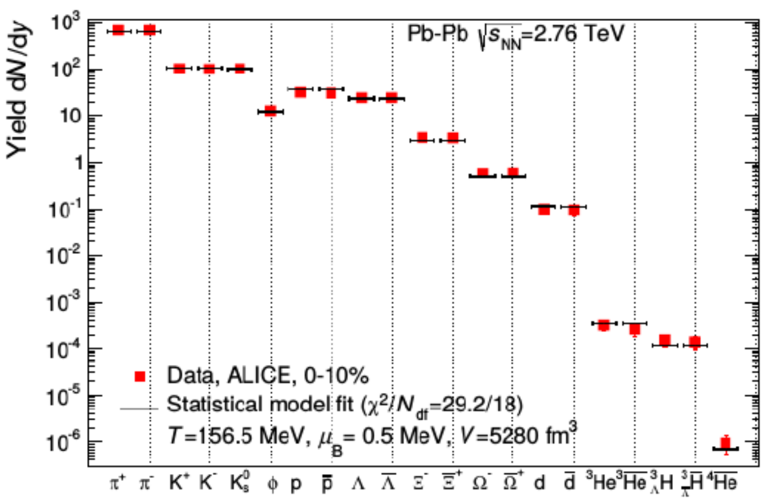


- Study dynamics of the **phase transitions**
- Locate **phase boundaries**

Why Ebye fluctuations?



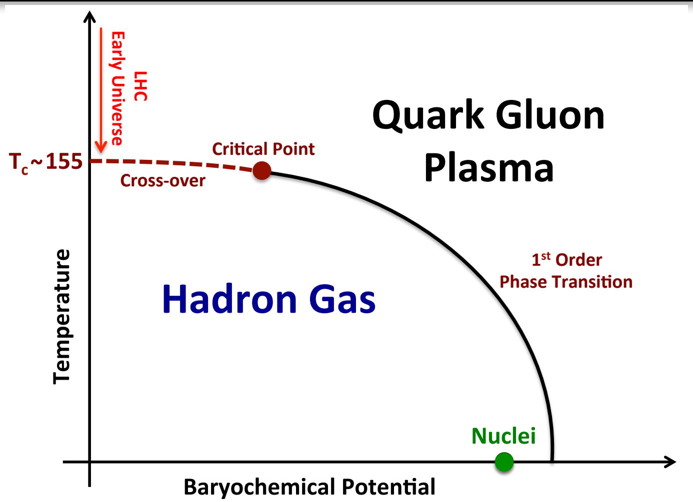
- Study dynamics of the **phase transitions**
- Locate **phase boundaries**



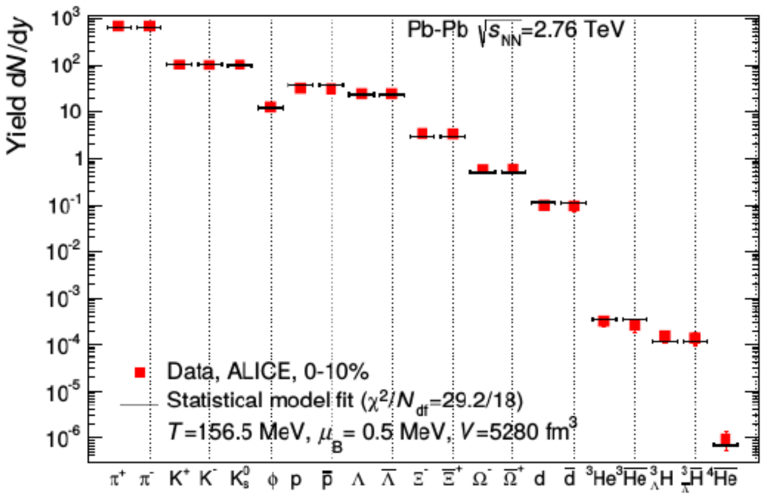
$$T_{fo}^{ALICE} = 156.5 \pm 3MeV$$

A. Andronic, P. Braun-Munzinger, J. Stachel and K. Redlich Nature 561, 321–330 (2018), ALICE, PLB 726 (2013) 610

Why Ebye fluctuations?



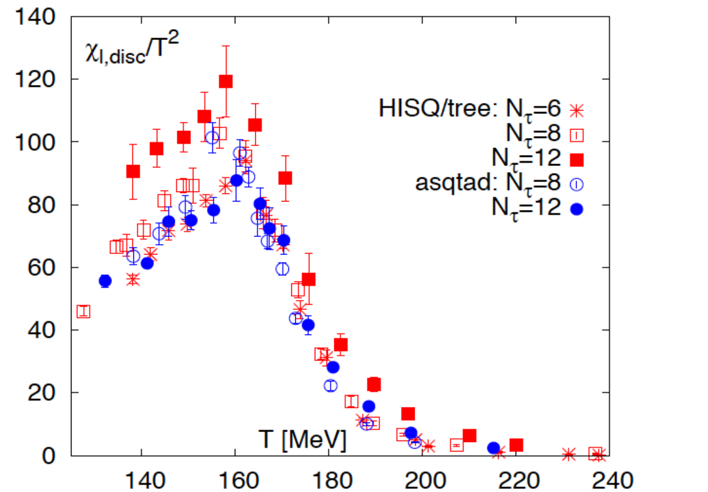
- Study dynamics of the **phase transitions**
- Locate **phase boundaries**



$$T_{fo}^{ALICE} = 156.5 \pm 3MeV$$

A. Andronic, P. Braun-Munzinger, J. Stachel and K. Redlich
Nature 561, 321–330 (2018), ALICE, PLB 726 (2013) 610

freeze-out at the phase boundary!



$$T_{pc} = 156.5 \pm 1.5MeV$$

HotQCD Collaboration
Phys.Rev. D85 (2012) 054503, arXiv:1904.09951

Why net-baryon fluctuations?

For a thermal system within the **Grand Canonical Ensemble**

$$\frac{P}{T^4} = \frac{1}{VT^3} \ln Z\left(V, T, \mu_{B,Q,S}\right) \Rightarrow \hat{\chi}_n^{N=B,S,Q} = \frac{\partial^n P/T^4}{\partial\left(\mu_N/T\right)^n}$$

Susceptibilities

Why net-baryon fluctuations?

For a thermal system within the **Grand Canonical Ensemble**

$$\frac{P}{T^4} = \frac{1}{VT^3} \ln Z\left(V, T, \mu_{B,Q,S}\right) \Rightarrow \hat{\chi}_n^{N=B,S,Q} = \frac{\partial^n P/T^4}{\partial\left(\mu_N/T\right)^n}$$

Susceptibilities

$$\hat{\chi}_2^B = \frac{\kappa_2\left(\Delta N_B\right)}{VT^3}$$

Cumulants

$$\frac{\kappa_4\left(\Delta N_B\right)}{\kappa_2\left(\Delta N_B\right)} = \frac{\hat{\chi}_4^B}{\hat{\chi}_2^B}$$

Higher orders

P. Braun-Munzinger, A. Rustamov, J. Stachel
Nuclear Physics A 960 (2017) 114–130

Why net-baryon fluctuations?

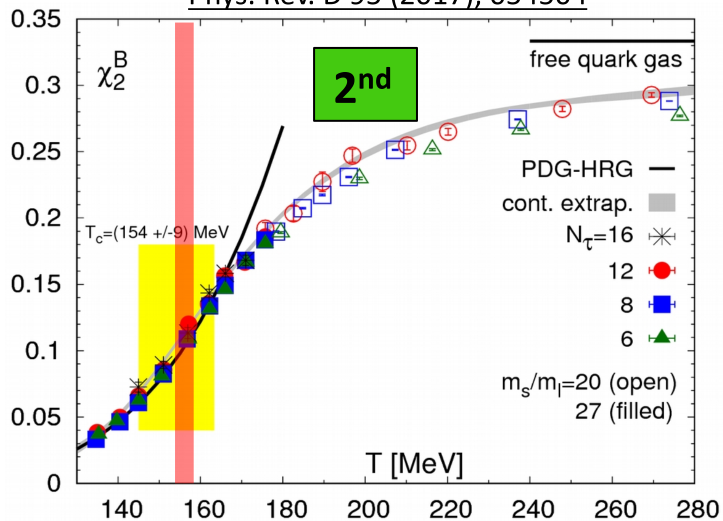
For a thermal system within the **Grand Canonical Ensemble**

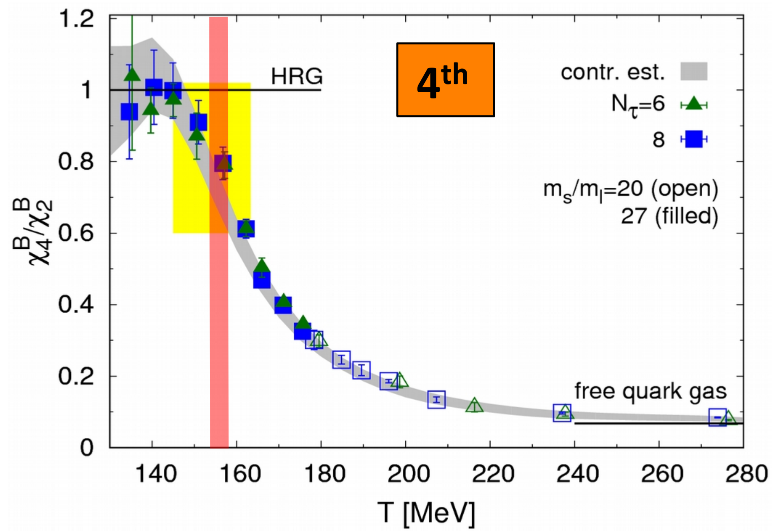
$$\frac{P}{T^4} = \frac{1}{VT^3}\ln Z\left(V,T,\mu_{B,Q,S}\right) \Rightarrow \hat{\chi}_n^{N=B,S,Q} = \frac{\partial^n P/T^4}{\partial\left(\mu_N/T\right)^n} \Rightarrow \hat{\chi}_2^B = \frac{\kappa_2\left(\Delta N_B\right)}{VT^3} \Rightarrow \frac{\kappa_4\left(\Delta N_B\right)}{\kappa_2\left(\Delta N_B\right)} = \frac{\hat{\chi}_4^B}{\hat{\chi}_2^B}$$

Susceptibilities **Cumulants** **Higher orders**

P. Braun-Munzinger, A. Rustamov, J. Stachel
Nuclear Physics A 960 (2017) 114–130

Phys. Rev. D 95 (2017), 054504





➢ **At 4th order** LQCD shows a **deviation** from Hadron Resonance Gas (HRG)

Interpretation of net-baryon fluctuations

We need a baseline: Skellam distribution

$$X = N_B - N_{\overline{B}}$$

- **rth central moment:**

$$\mu_r \equiv \langle (X - \langle X \rangle)^r \rangle = \sum_X (X - \langle X \rangle)^r P(X)$$

- **First four cumulants**

$$\kappa_1 = \langle X \rangle, \quad \kappa_2 = \mu_2,$$

$$\kappa_3 = \mu_3, \quad \kappa_4 = \mu_4 - 3\mu_2^2$$

We need a baseline: Skellam distribution

$$X = N_B - N_{\overline{B}}$$

- **r[th] central moment:**

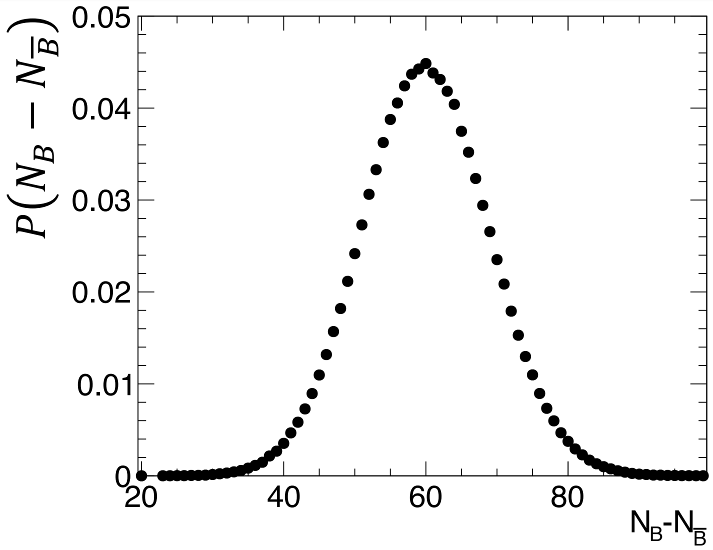
$$\mu_r \equiv \langle (X - \langle X \rangle)^r \rangle = \sum_X (X - \langle X \rangle)^r P(X)$$

- **First four cumulants**

$$\kappa_1 = \langle X \rangle, \quad \kappa_2 = \mu_2,$$
$$\kappa_3 = \mu_3, \quad \kappa_4 = \mu_4 - 3\mu_2^2$$

- **Uncorrelated Poisson limit:**

$$\langle N_B N_{\overline{B}} \rangle = \langle N_B \rangle \langle N_{\overline{B}} \rangle$$



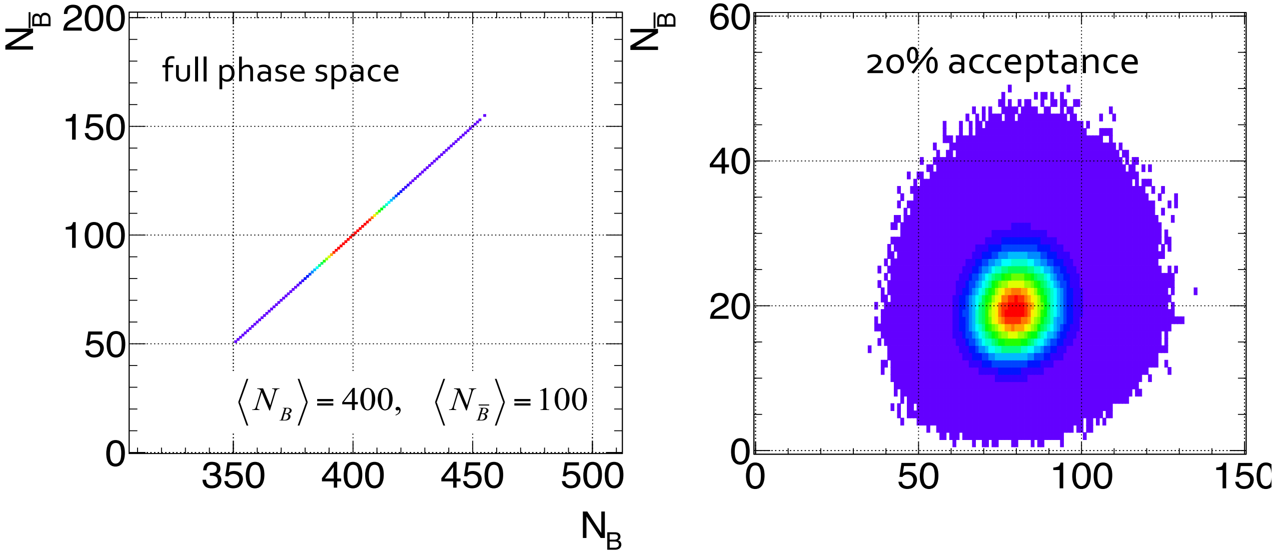
Difference between two independent Poissonian distributions

$$\kappa_n = \langle N_B \rangle + (-1)^n \langle N_{\overline{B}} \rangle$$

$$\frac{\kappa_{2n+1}}{\kappa_{2k}} = \frac{\langle n_B \rangle - \langle n_{\bar{B}} \rangle}{\langle n_B \rangle + \langle n_{\bar{B}} \rangle}$$

Importance of acceptance

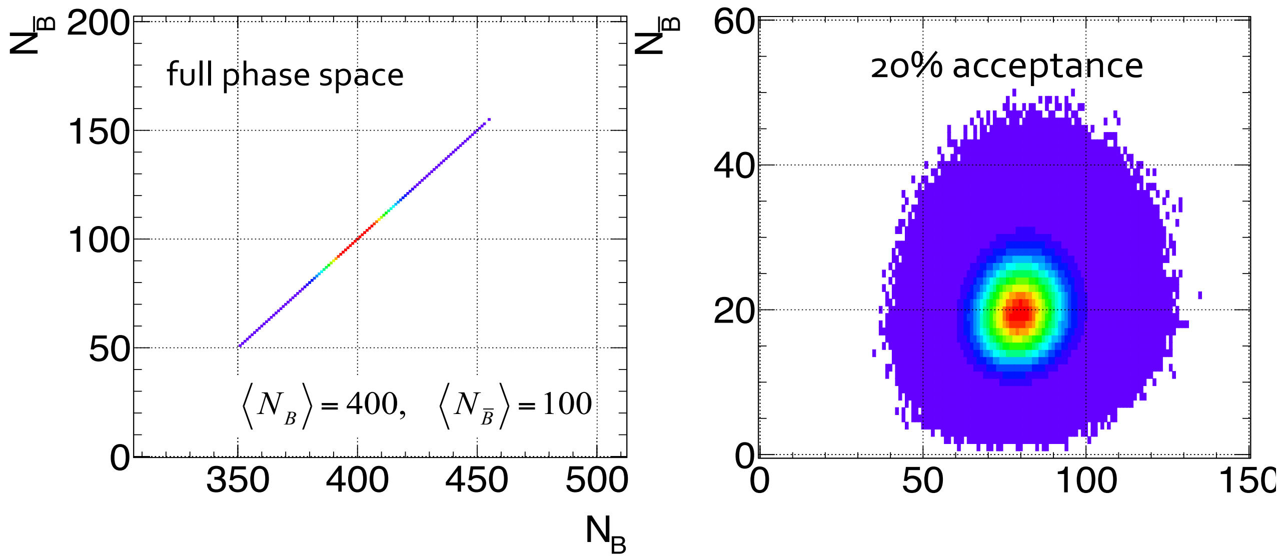
- Fluctuations of net-baryons appear only inside **finite acceptance**
- **Baryon number conservation** imposes subtle correlations



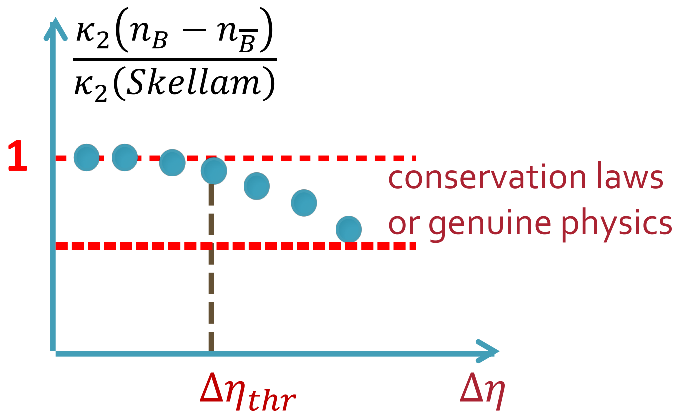
P. Braun-Munzinger, A. Rustamov, J. Stachel, QM18, NPA 982 (2019) 307-310

Importance of acceptance

- Fluctuations of net-baryons appear only inside **finite acceptance**
- **Baryon number conservation** imposes subtle correlations



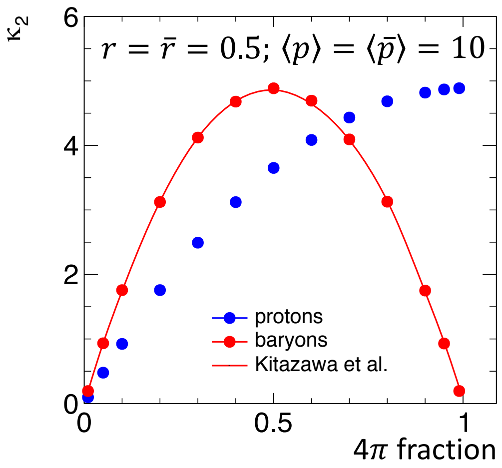
P. Braun-Munzinger, A. Rustamov, J. Stachel, QM18, NPA 982 (2019) 307-310



- **Limit of very small acceptance**
  - vanishing or invisible dynamical fluctuations
- **Acceptance has to be large enough**

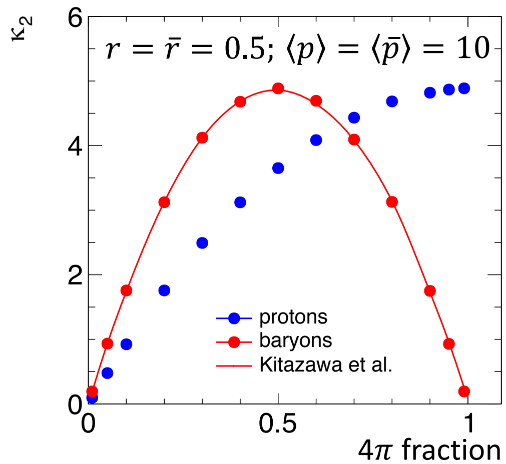
Net-proton vs Net-baryon

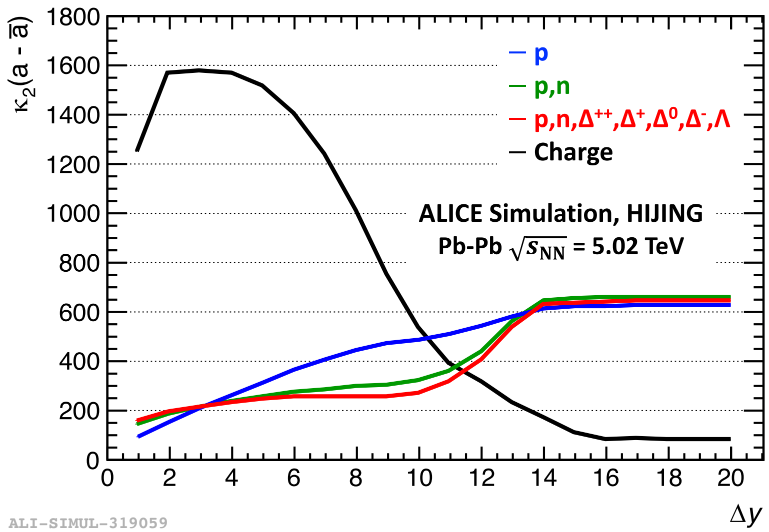
- Due to **isospin randomization,** at $\sqrt{s_{\mathrm{NN}}}$ > 10 GeV **net-baryon** fluctuations can be obtained from corresponding **net-proton** measurements (M. Kitazawa, and M. Asakawa, Phys. Rev. C 86, 024904 (2012))



Net-proton vs Net-baryon

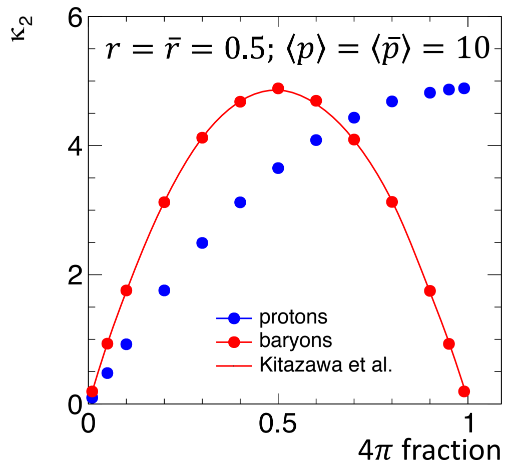
- Due to **isospin randomization,** at $\sqrt{s_{NN}}$ > 10 GeV **net-baryon** fluctuations can be obtained from corresponding **net-proton** measurements (M. Kitazawa, and M. Asakawa, Phys. Rev. C 86, 024904 (2012))

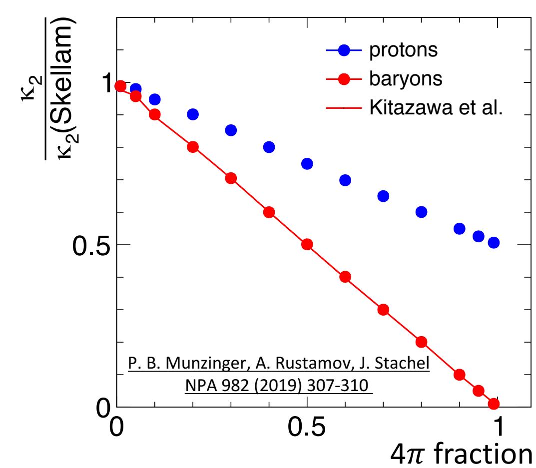


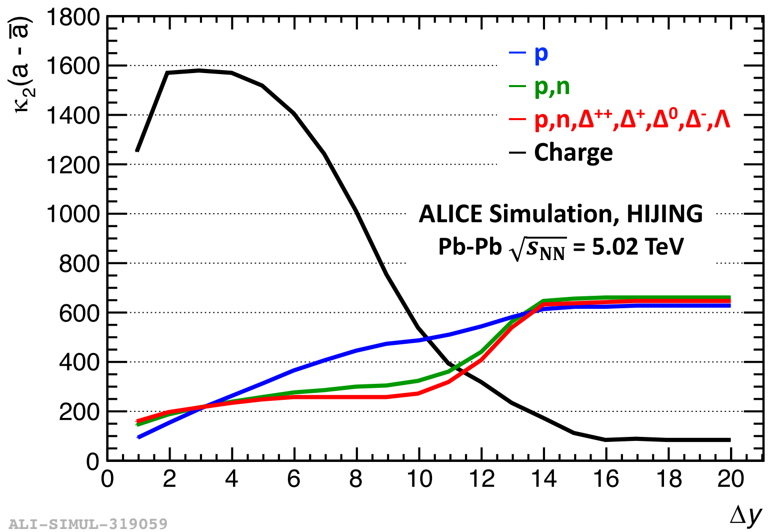


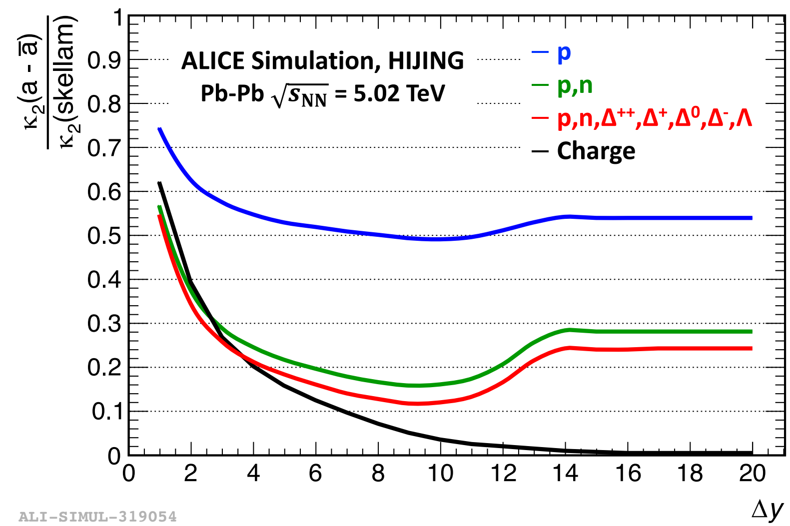
Net-proton vs Net-baryon

- Due to **isospin randomization,** at $\sqrt{s_{NN}}$ > 10 GeV **net-baryon** fluctuations can be obtained from corresponding **net-proton** measurements (M. Kitazawa, and M. Asakawa, Phys. Rev. C 86, 024904 (2012))









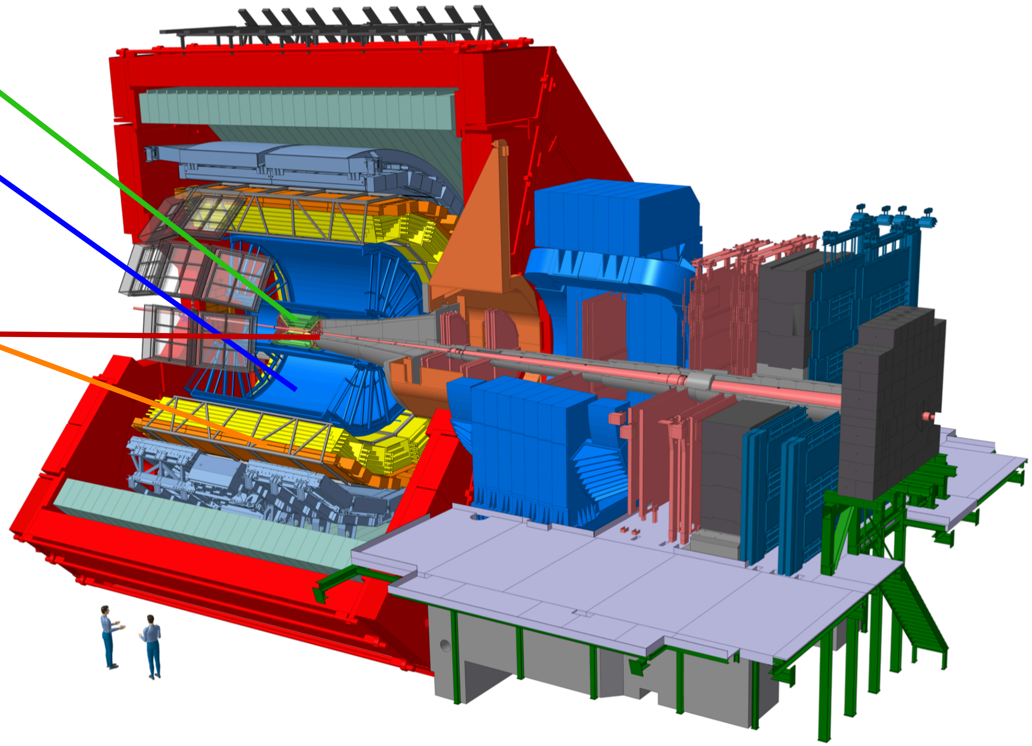
Effect of baryon number conservation has to be taken into account

RESULTS

A Large Ion Collider Experiment

Main detectors used:

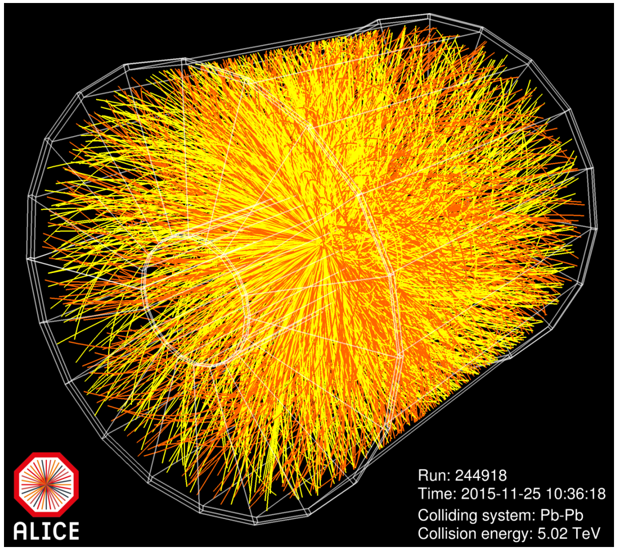
- **I**nner **T**racking **S**ystem **(ITS)**
  - Tracking and vertexing
- **T**ime **P**rojection **C**hamber **(TPC)**
  - Tracking and Particle identification (PID)
- **T**ime **O**f **F**light **(TOF)**
  - PID
- **V**ertex **0** **(V0)**
  - Centrality determination

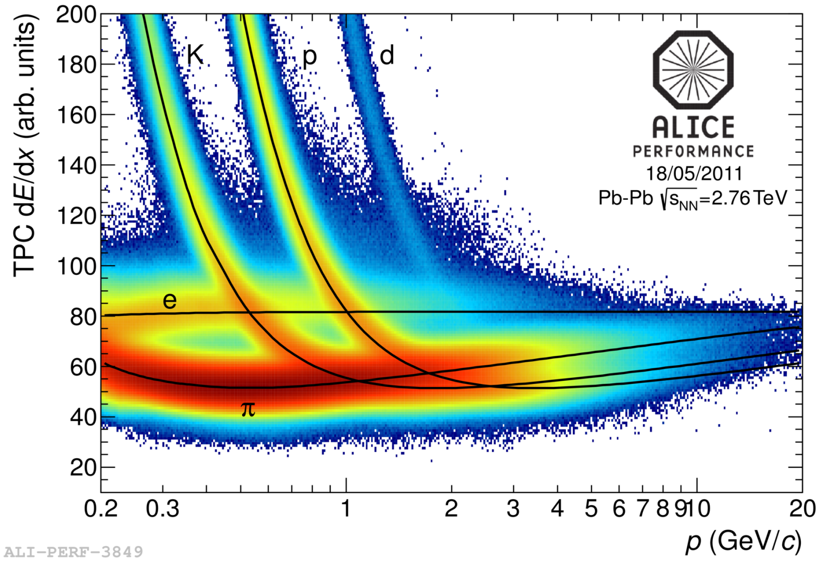


Data Set:

- **Pb-Pb collisions**
  - $\sqrt{s_{NN}} = 5.02$ TeV, ~60 M events
  - $\sqrt{s_{NN}} = 2.76$ TeV, ~12 M events
- **Model**
  - HIJING, ~6 M events

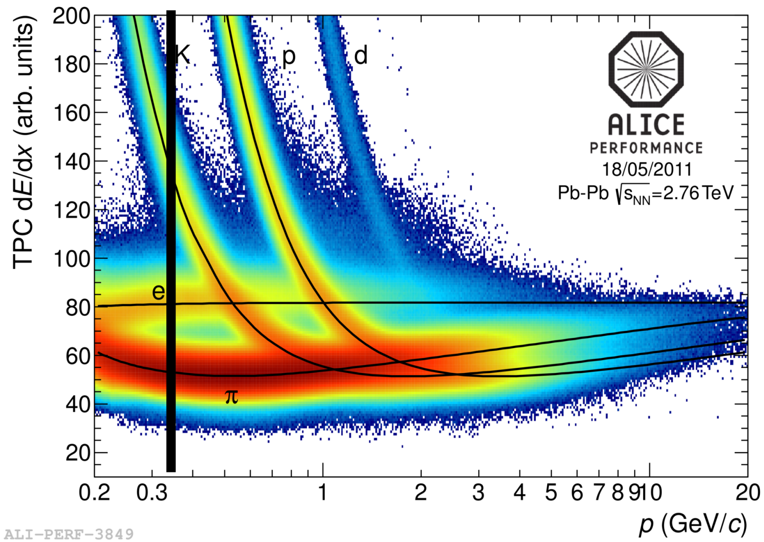
Particle Identification

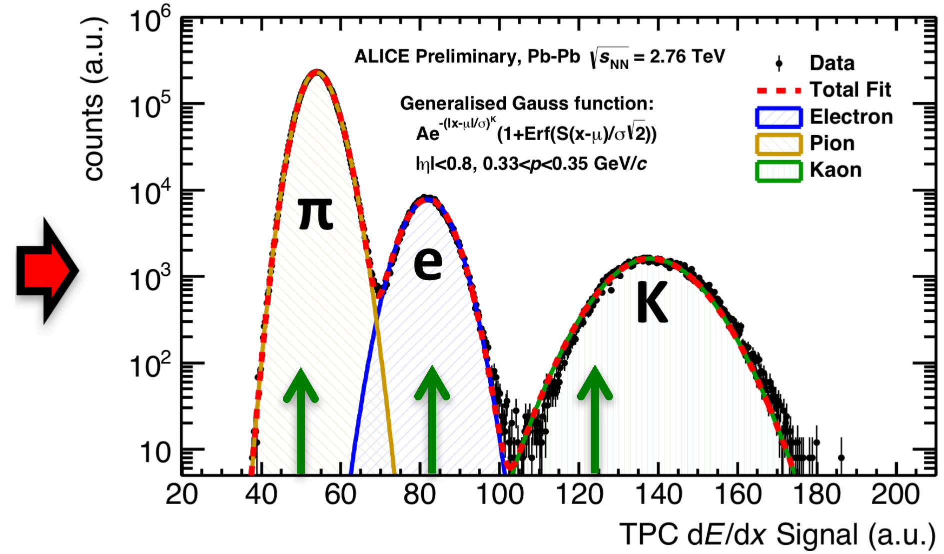




Cut-based vs Identity method

Cut-based approach: count tracks of a given particle type

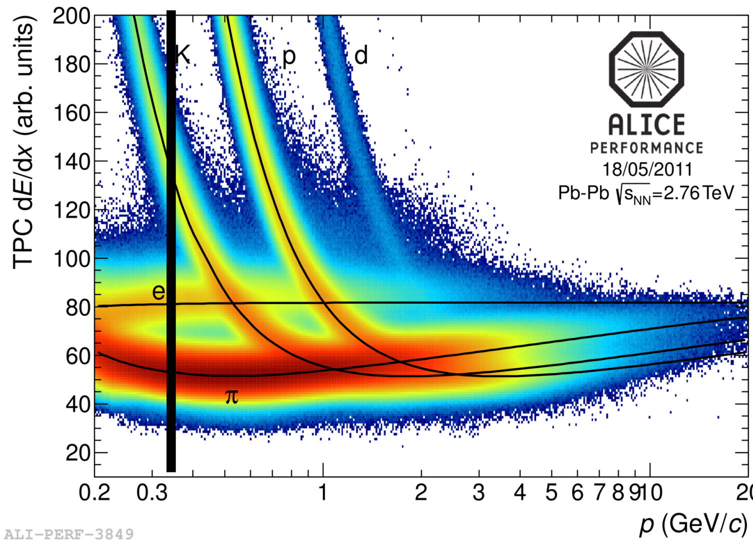


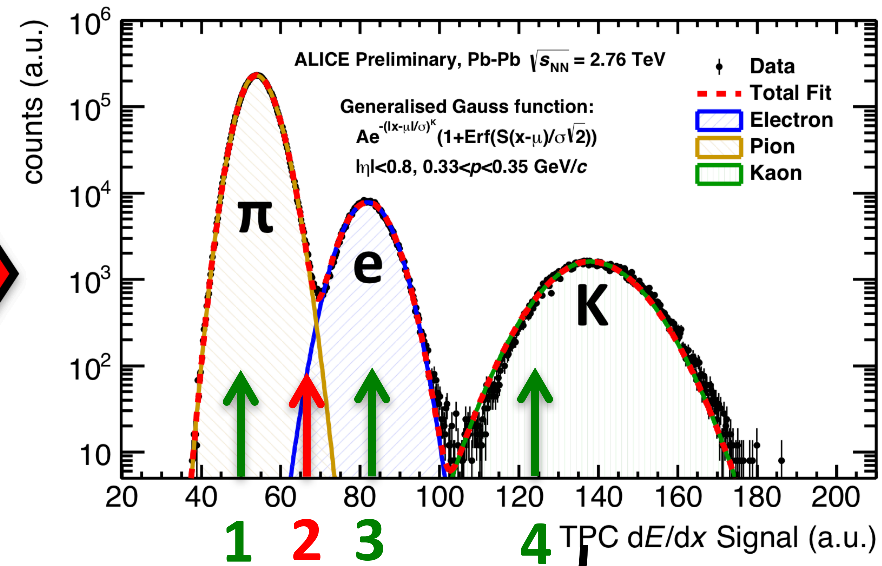


Cut-based vs Identity method

Cut-based approach: count tracks of a given particle type

Identity method: count probabilities to be of a given particle type



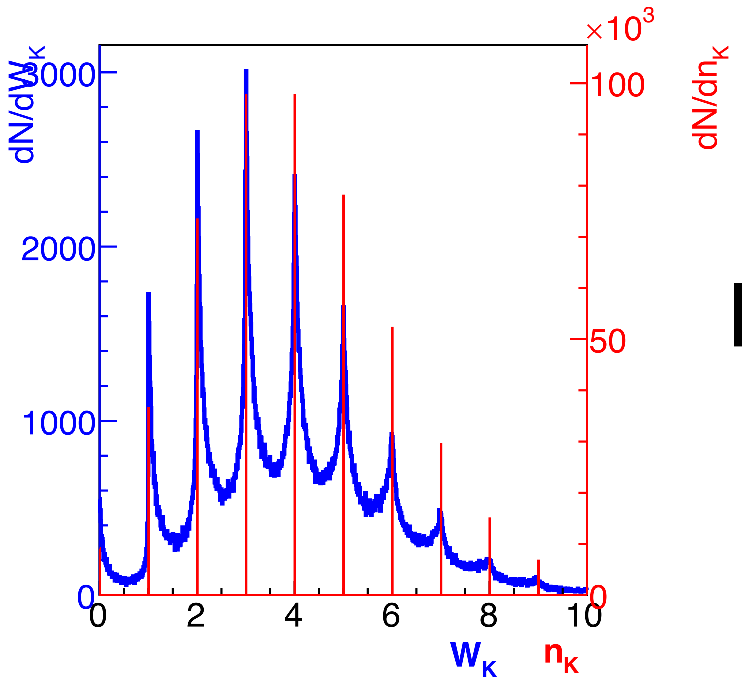


$$\omega_{\pi}^{(1)} = 1, \quad \omega_{\pi}^{(2)} \cong 0.6, \quad \omega_{\pi}^{(3)} = 0, \quad \omega_{\pi}^{(4)} = 0 \quad \Rightarrow \quad W_{\pi} = 1.6 \neq N_{\pi}$$

A. Rustamov, M. Gazdzicki, M. I. Gorenstein, PRC 86, 044906 (2012), PRC 84, 024902 (2011)

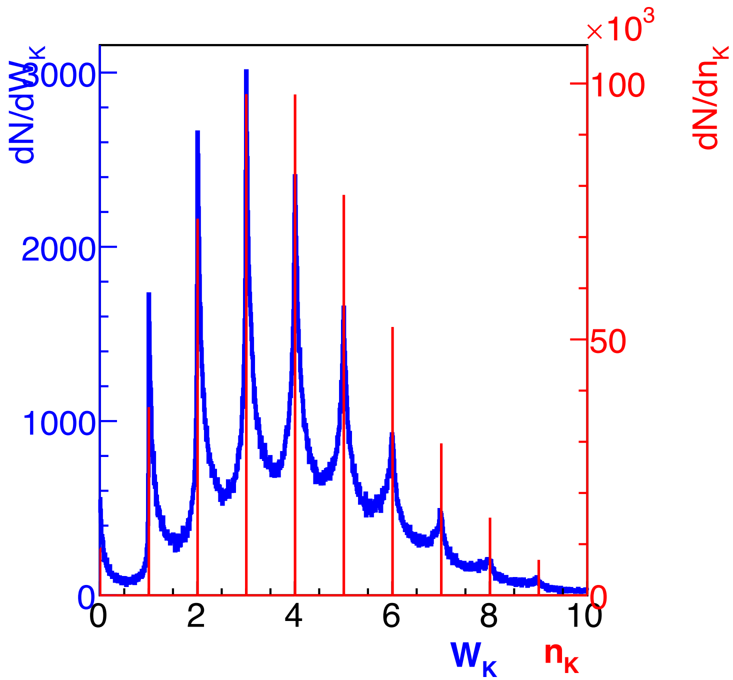
A. Rustamov, M. Arslandok, arXiv:1807.06370, NIM in print

Cut-based vs Identity method



$$\langle N_j^n \rangle = A^{-1} \langle W_j^n \rangle$$

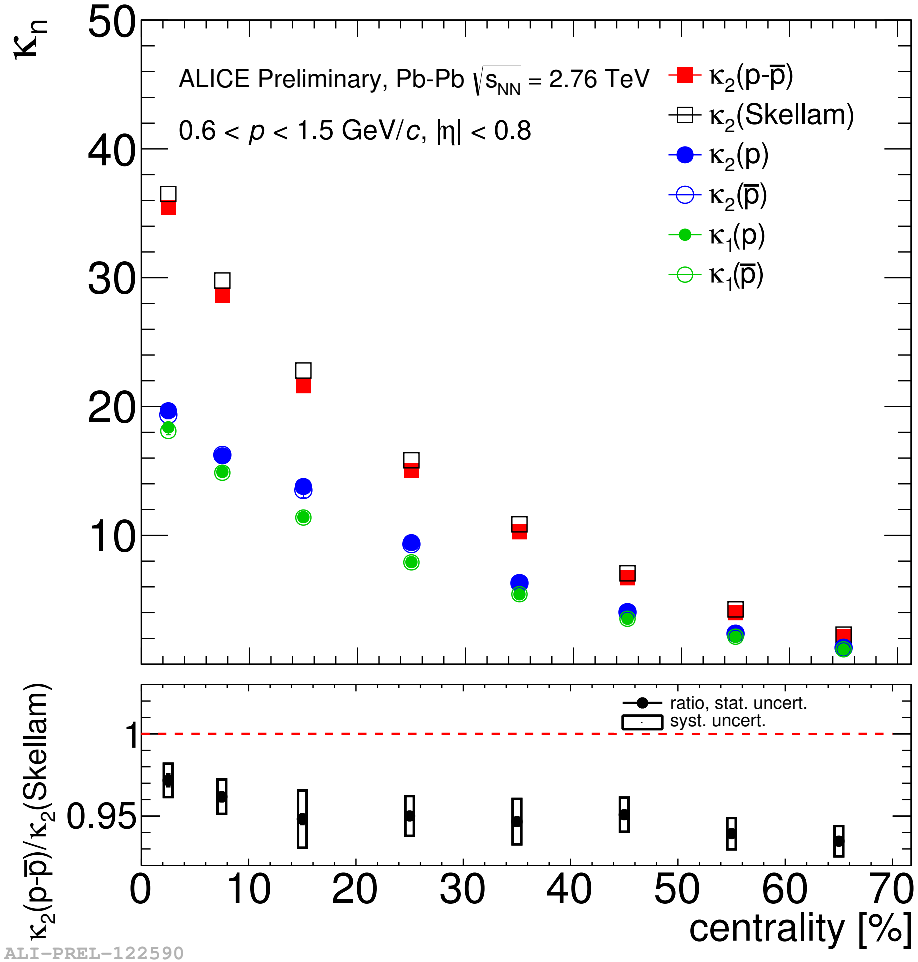
Cut-based vs Identity method



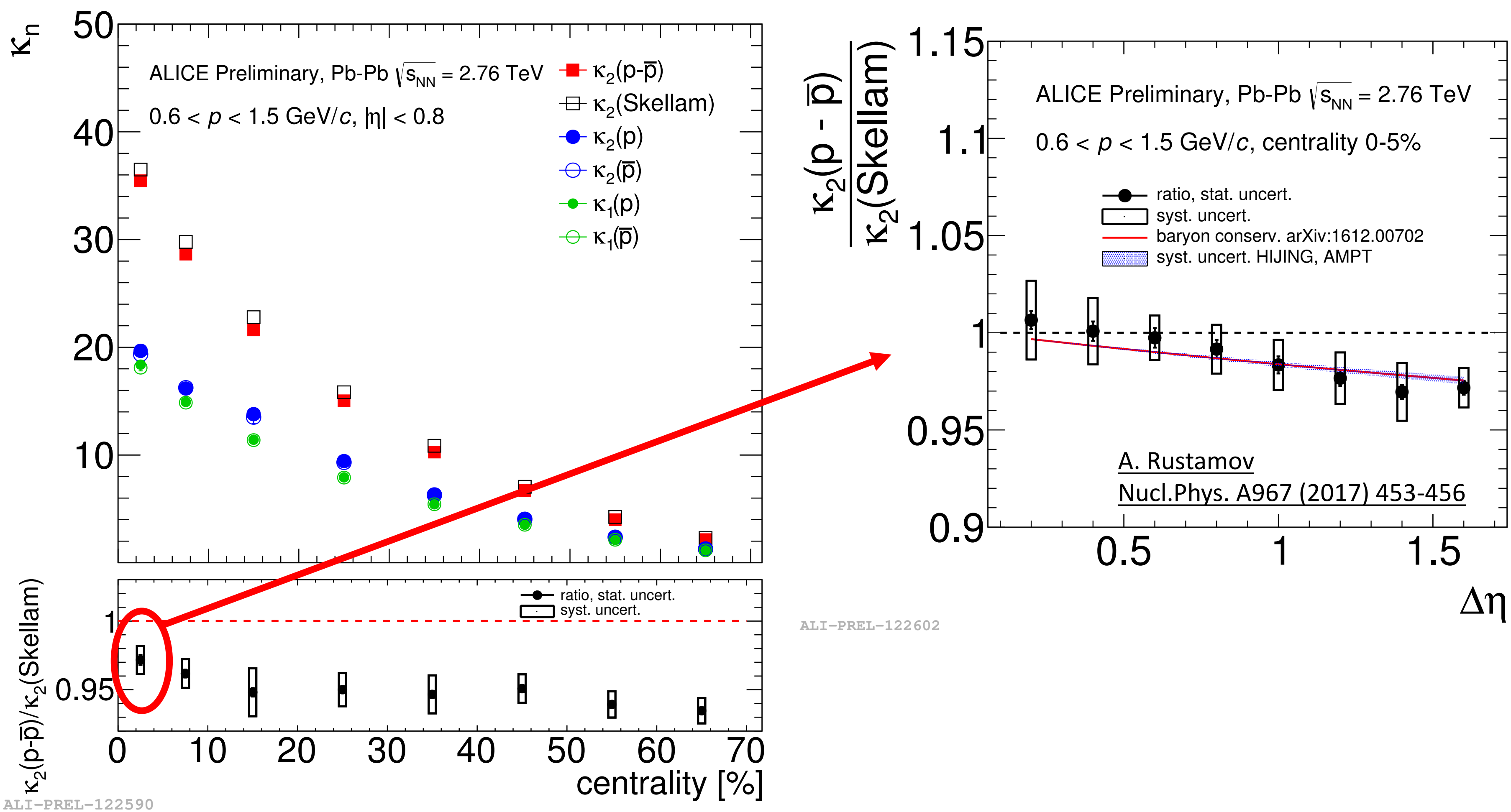
$$\langle N_j^n \rangle = A^{-1} \langle W_j^n \rangle$$

- **Cut-based approach**
  - Uses additional detector information or reject a given phase space bin
  - Challenge: efficiency correction and contamination
- **Identity Method**
  - Gives folded multiplicity distribution
  - Allows for larger efficiencies → smaller correction needed
  - Ideal approach for low momentum (p<2 GeV/c)

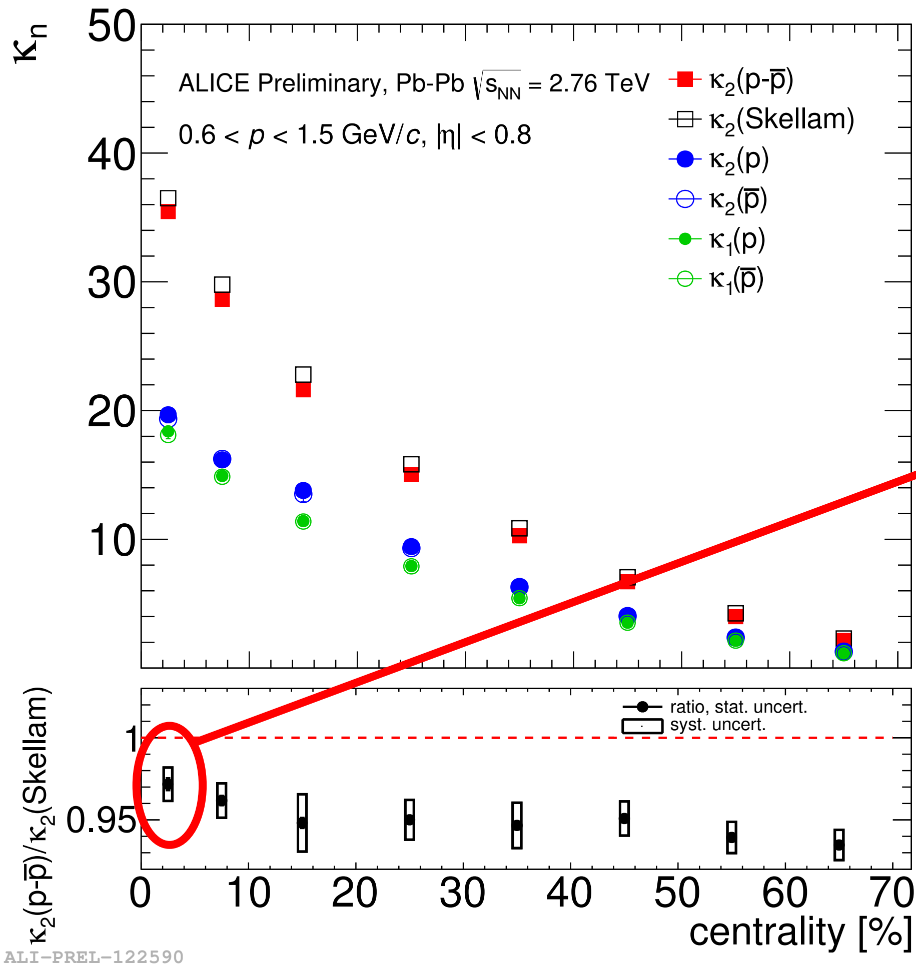
Identity Method: 2nd order cumulants of net-p

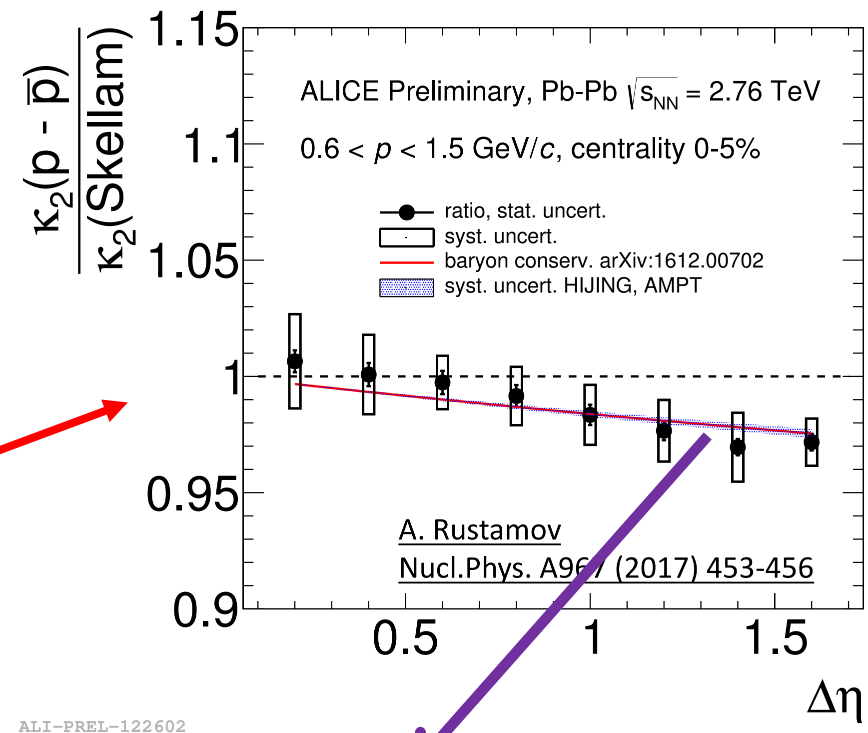


Identity Method: 2nd order cumulants of net-p



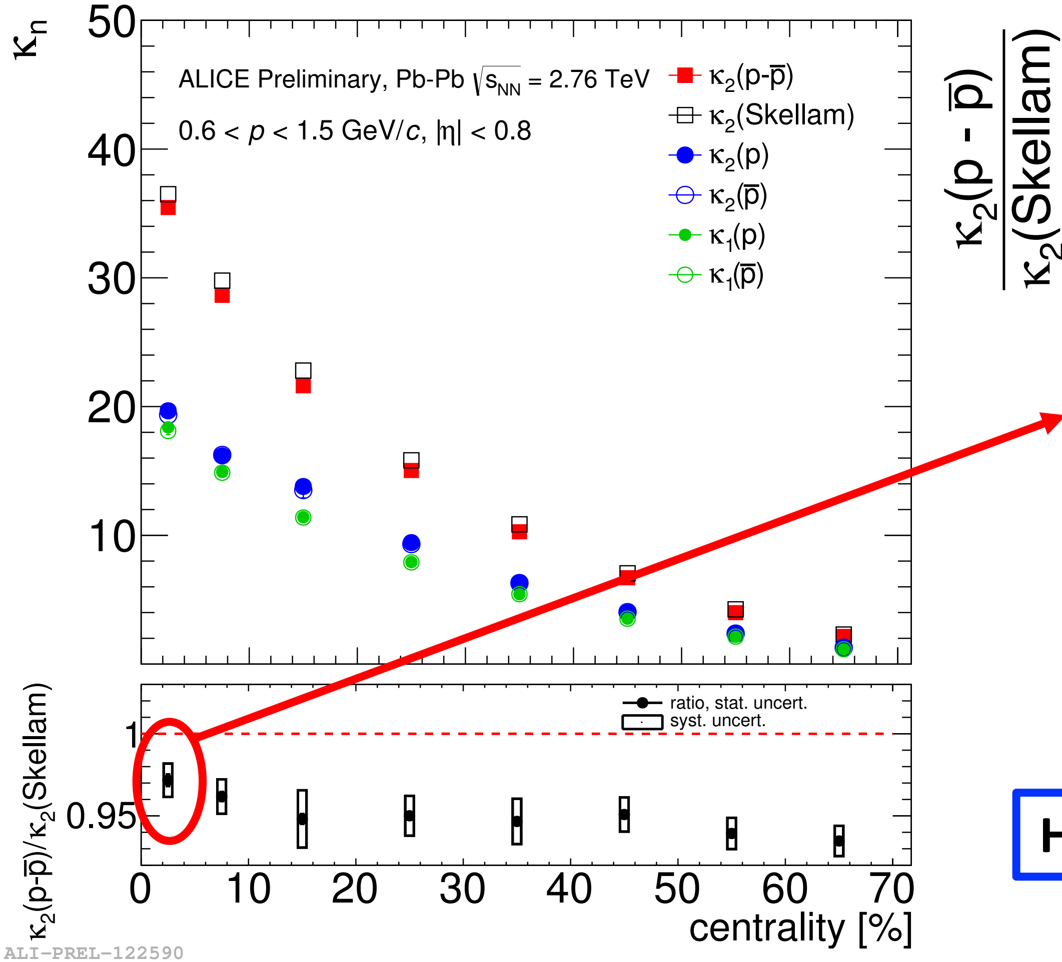
Identity Method: 2nd order cumulants of net-p

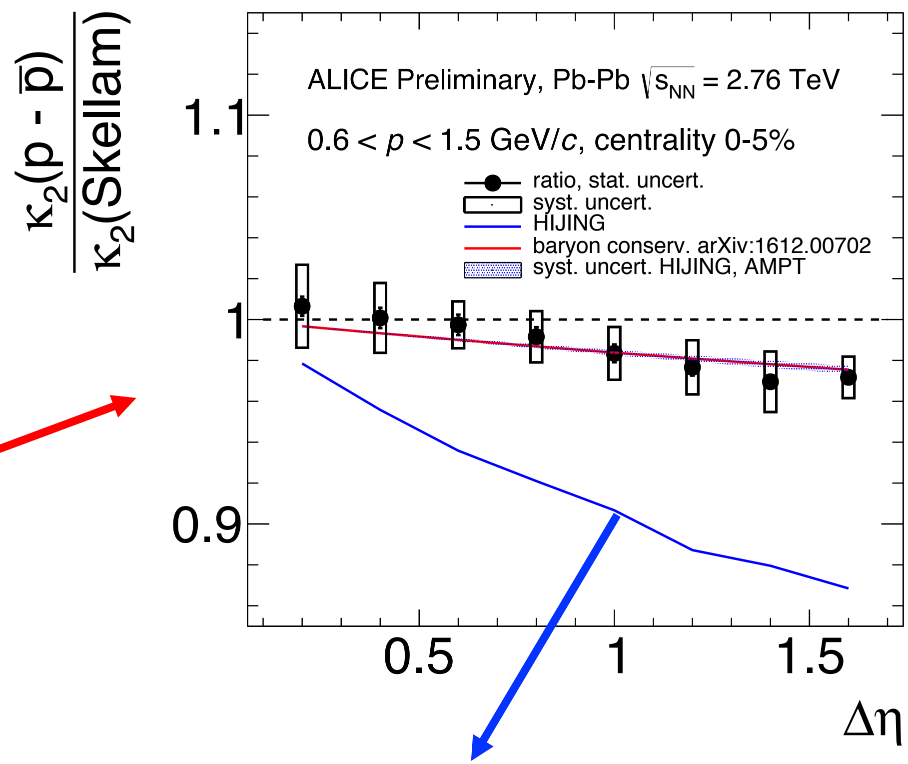




Deviation from Skellam is due to the global **baryon number conservation**

Identity Method: 2nd order cumulants of net-p

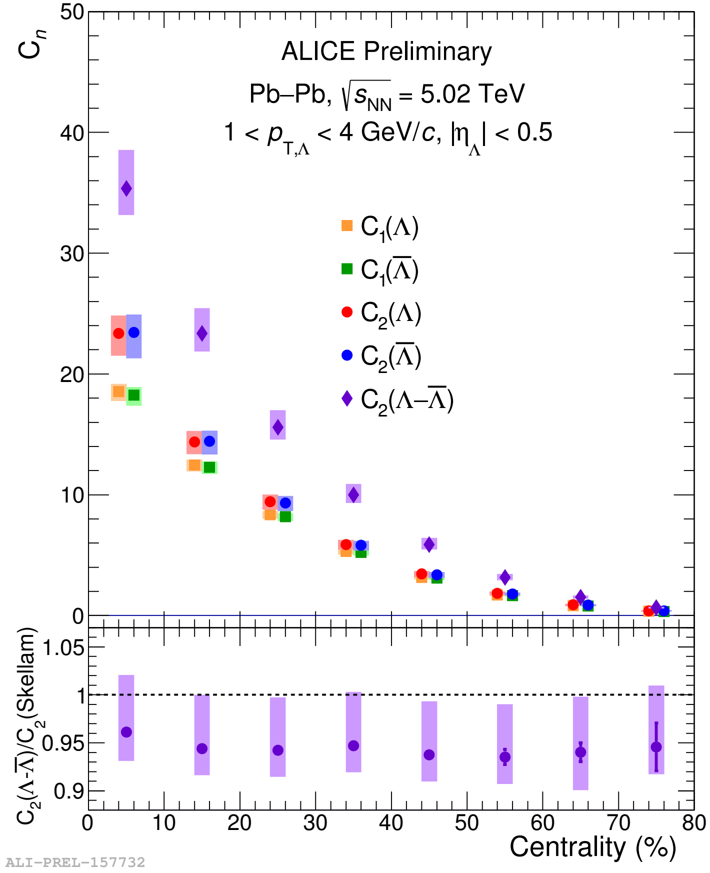




HIJING is not consistent with data

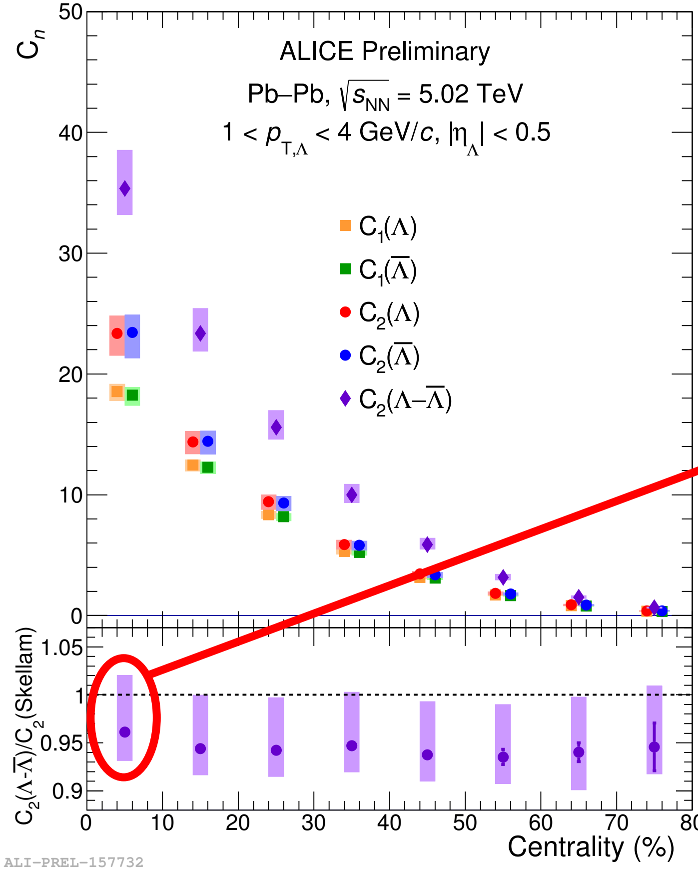
Identity Method: 2nd order cumulants of net-Λ

$$\kappa_2(n-\bar{n}) \equiv C_2(n-\bar{n})$$

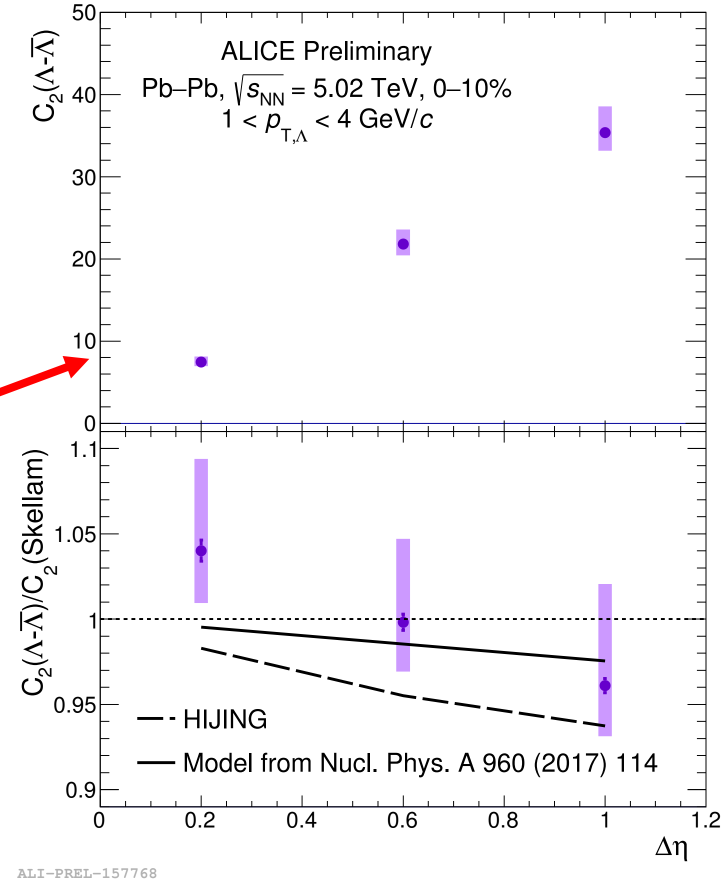


Identity Method: 2nd order cumulants of net-Λ

$$\kappa_2(n-\bar{n}) \equiv C_2(n-\bar{n})$$



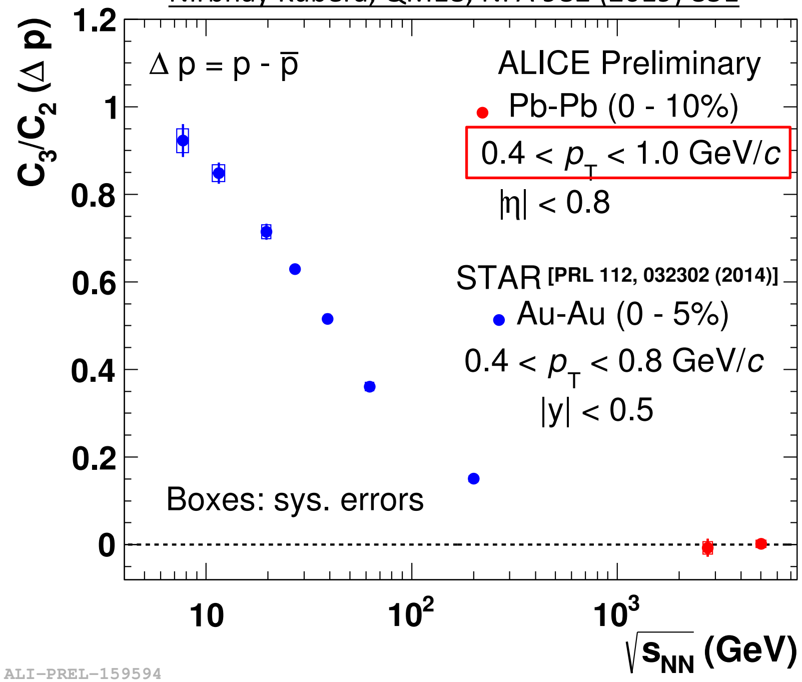
Alice Ohlson, QM2018, NPA 982 (2019) 299

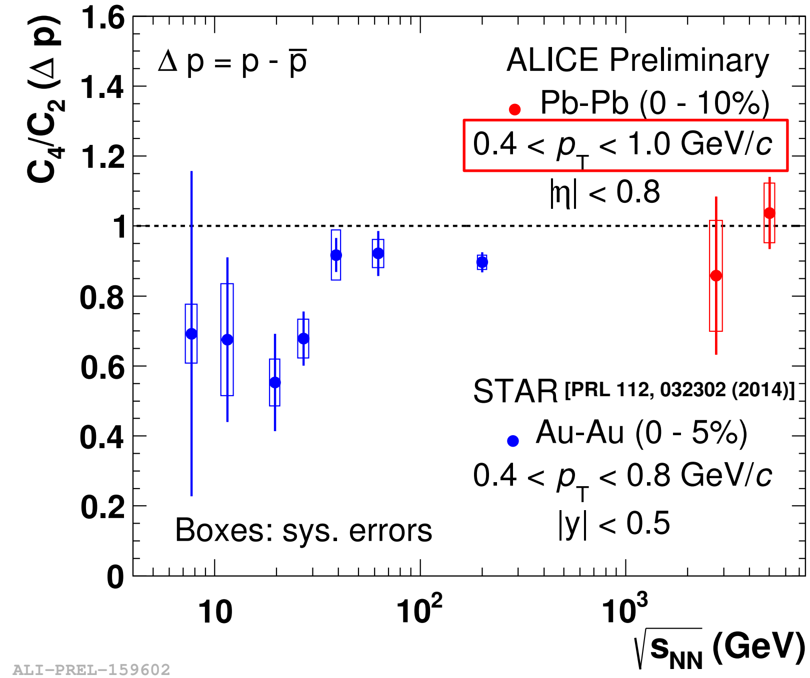


- Similar trend as for **net-p**
- Better precision is needed to disentangle global vs local conservation laws

3rd and 4th order net-p

Nirbhay Kubera, QM18, NPA 982 (2019) 851

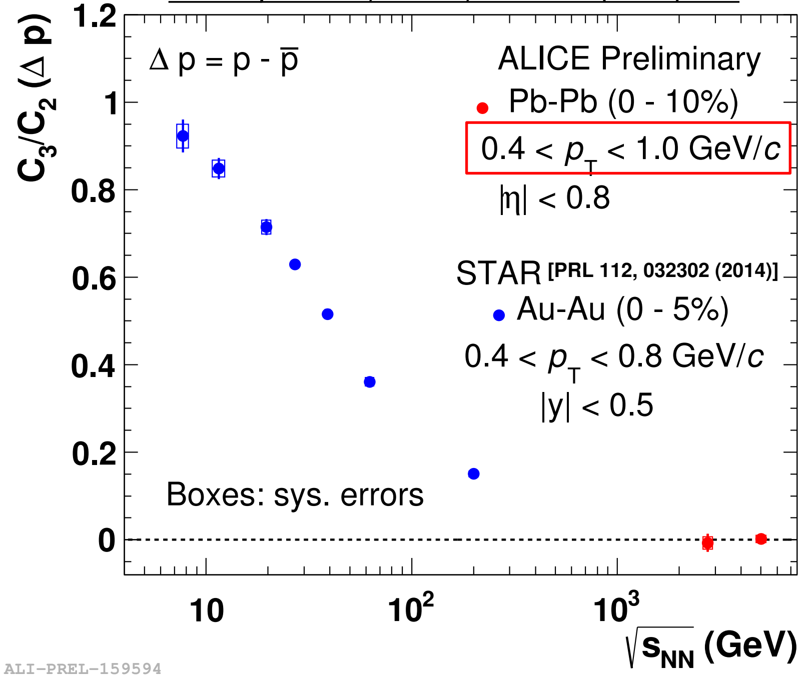


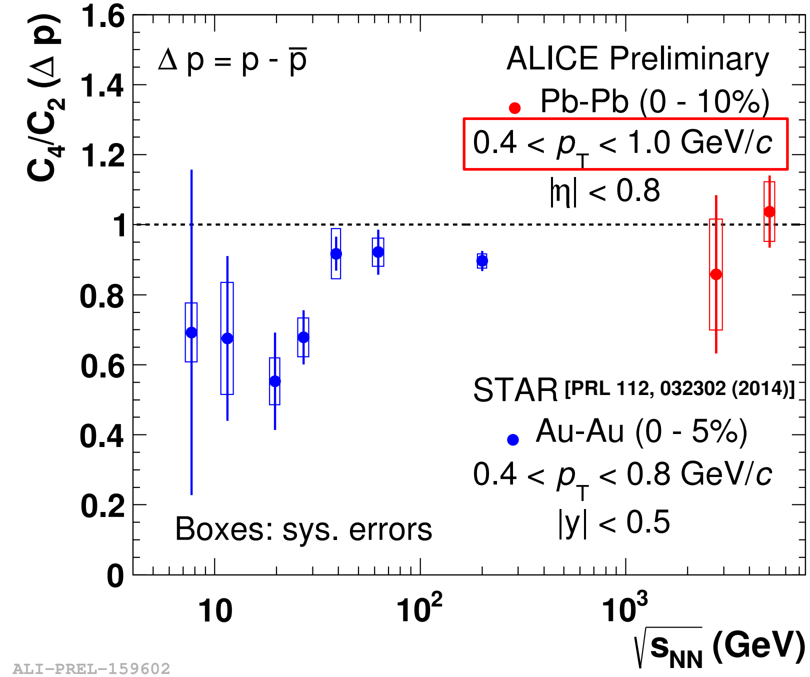


- So far only **cut-based results** within small kinematic acceptance

3rd and 4th order net-p

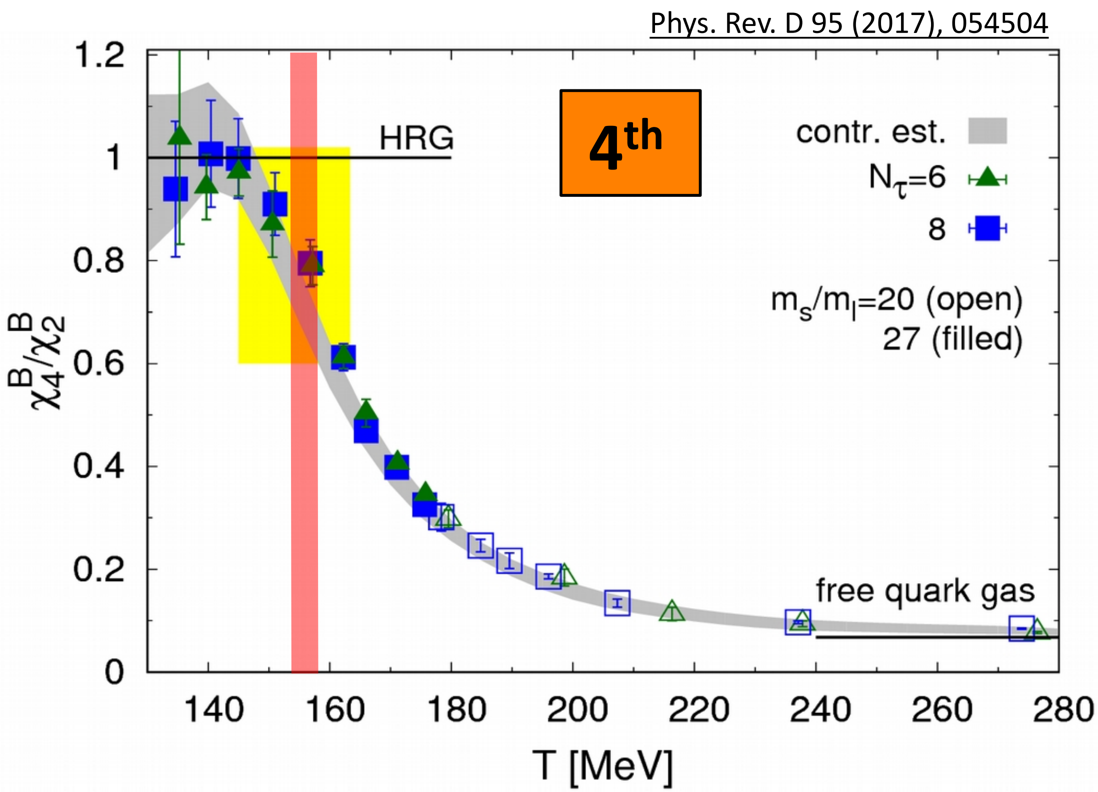
Nirbhay Kubera, QM18, NPA 982 (2019) 851





- So far only **cut-based results** within small kinematic acceptance
- **C_3/C_2 and C_4/C_2 at LHC** within uncertainties are consistent with Skellam?

3rd and 4th order net-p



- **~30% difference** between LQCD and HRG
- **Identity Method (in progress)** will increase acceptance leading to be a better sensitivity of these differences

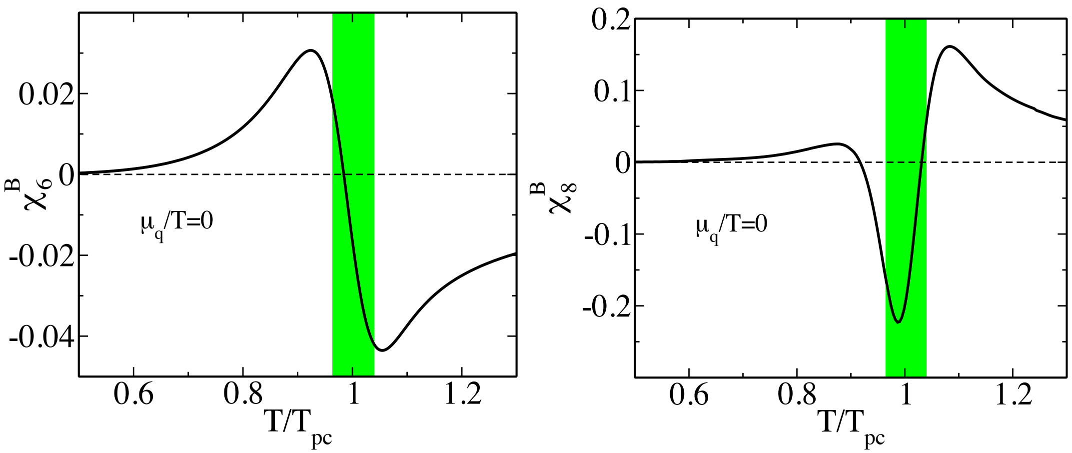
Summary

- **Technical:**
  - **Identity method** maximizes efficiency and solves misidentification problem
  - **Efficiency correction and volume fluctuations** are crucial.
  - **Acceptance** has to be large enough to see dynamical fluctuations
- **Physics:**
  - **Deviation** from Skellam baseline observed in the 2nd order level is due to baryon number conservation
  - Analysis of **3rd and 4th cumulants with identity method** in extended acceptance in p_T

Summary

- **Technical:**
  - **Identity method** maximizes efficiency and solves misidentification problem
  - **Efficiency correction and volume fluctuations** are crucial.
  - **Acceptance** has to be large enough to see dynamical fluctuations
- **Physics:**
  - **Deviation** from Skellam baseline observed in the 2nd order level is due to baryon number conservation
  - Analysis of **3rd and 4th cumulants with identity method** in extended acceptance in p_T

Holy grail: see critical behavior in 6th and higher order cumulants



B. Friman, F. Karsch, K. Redlich, V. Skokov Eur. Phys. J. C (2011) 71: 1694

RUN1: 2nd order (~13M min. bias events)

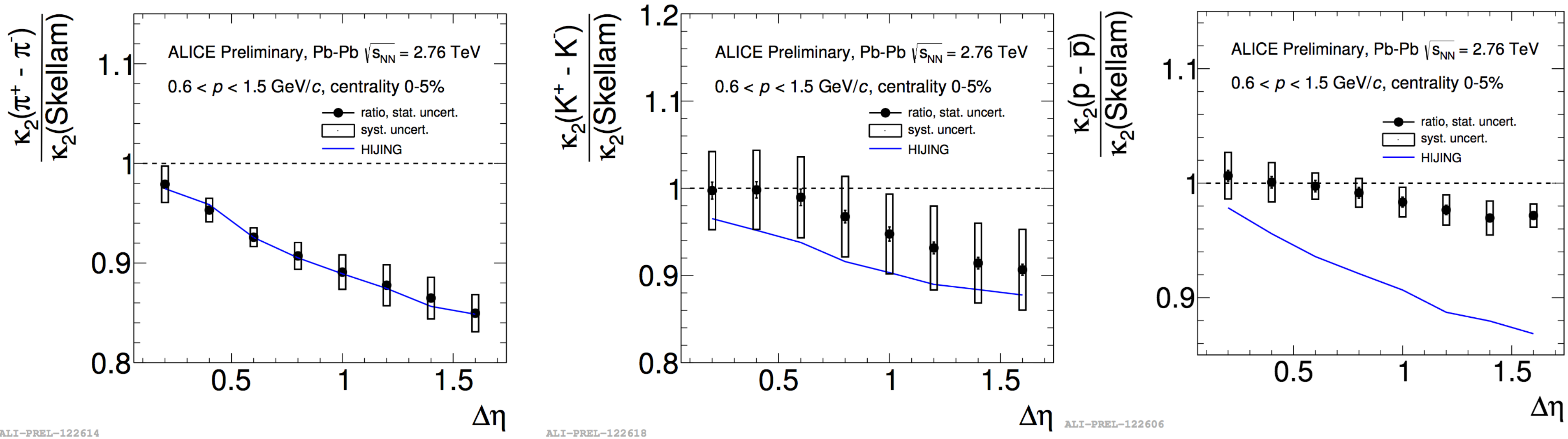
RUN2: 4th order (~150M central events)

RUN3: **6th …** (>1000M central events)

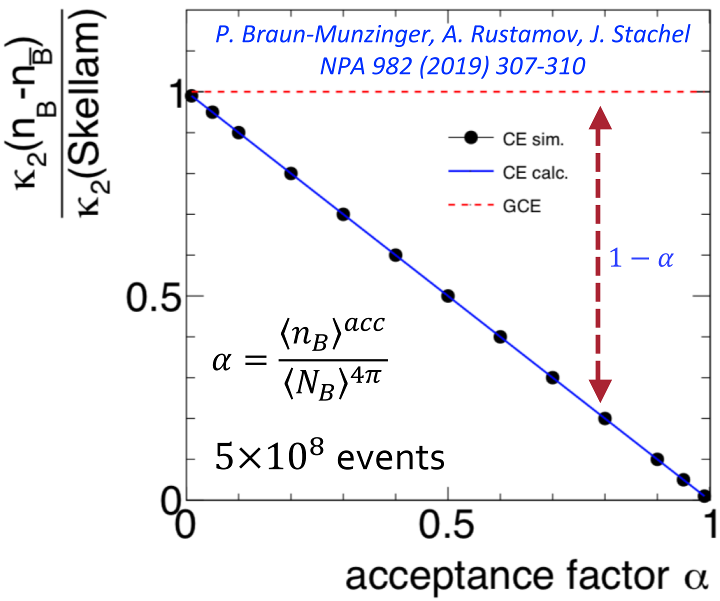
BACKUP

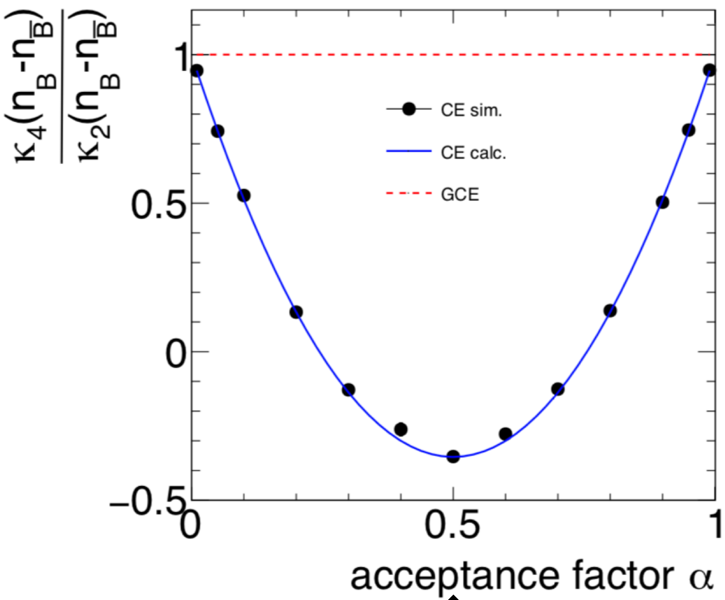
Net-particle fluctuations vs HIJING

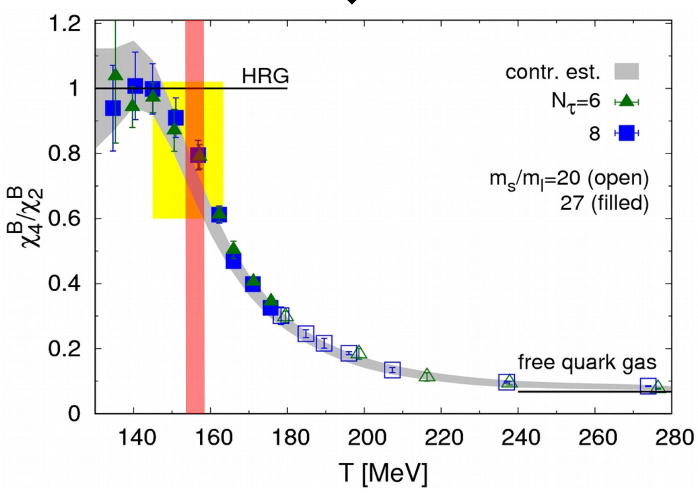
A. Rustamov
Nucl.Phys. A967 (2017) 453-456



Effects from conservation laws





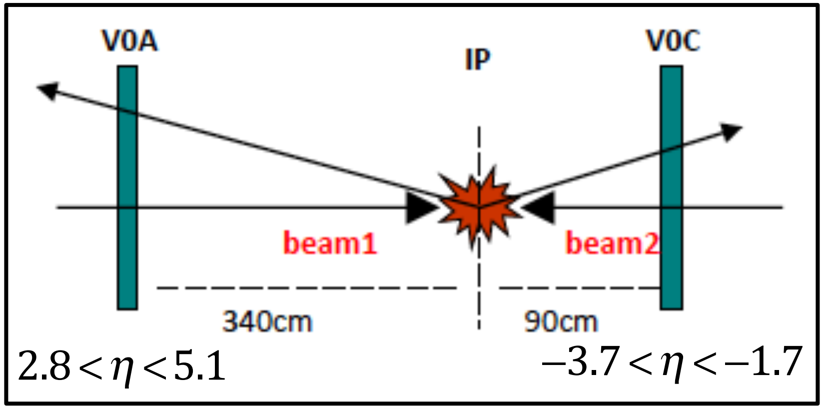


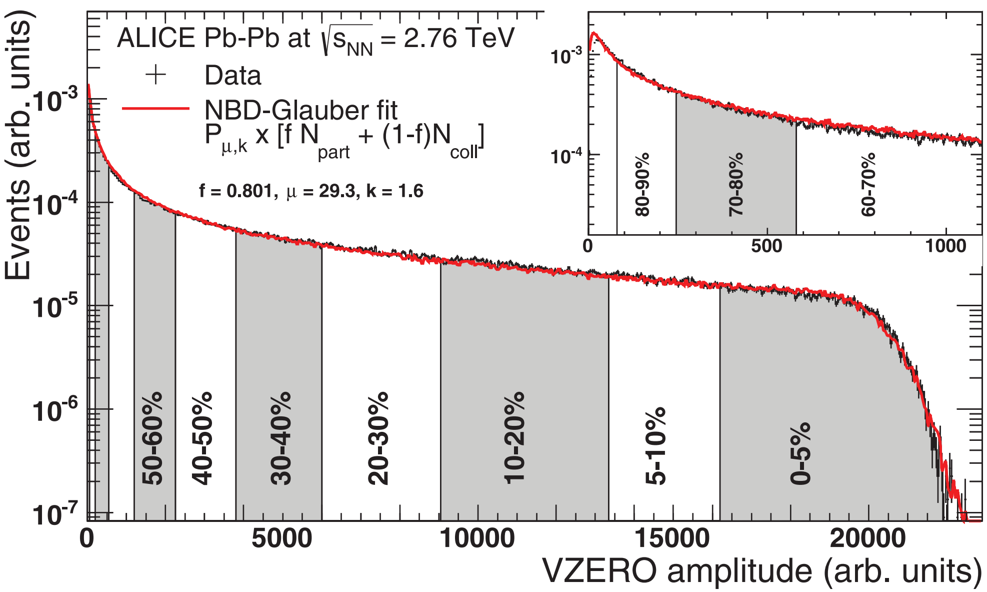
Deviations from unity are driven by different mechanisms

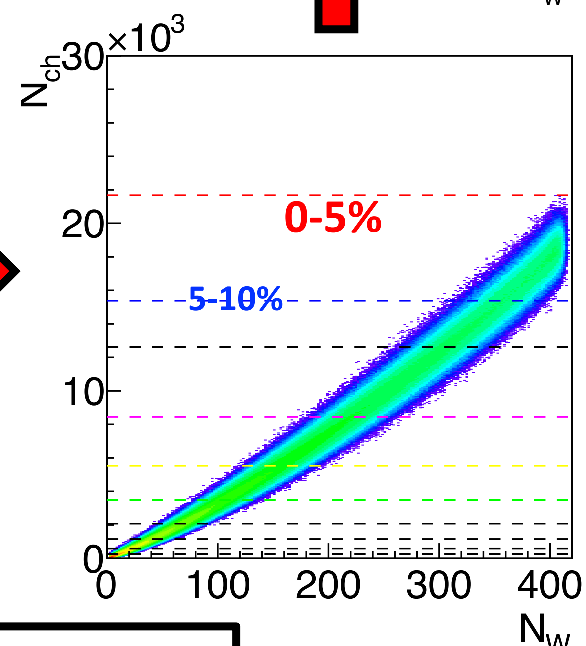
A. Bzdak, V. Koch, V. Skokov, PRC87 (2013) 014901
K. Redlich and L. Turko, Z. Phys. C5 (1980) 201

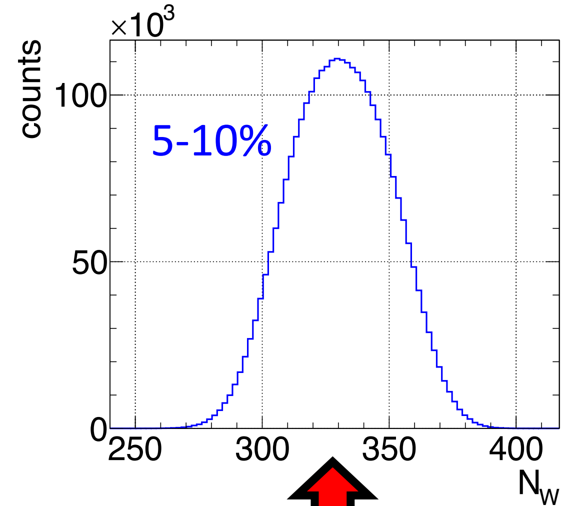
Volume Fluctuations

ALICE: Phys.Rev. C88 (2013) no.4, 044909





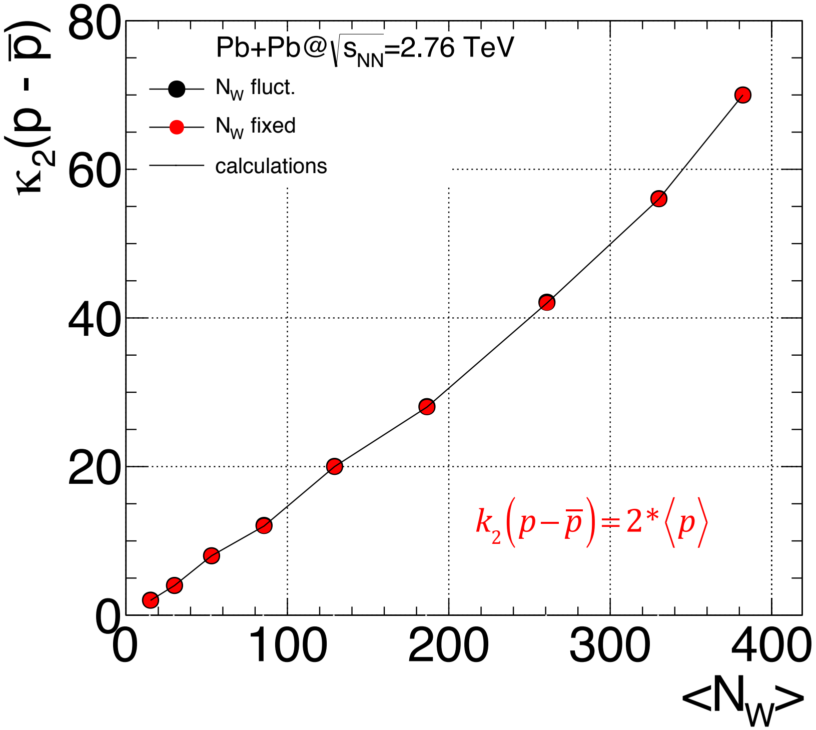


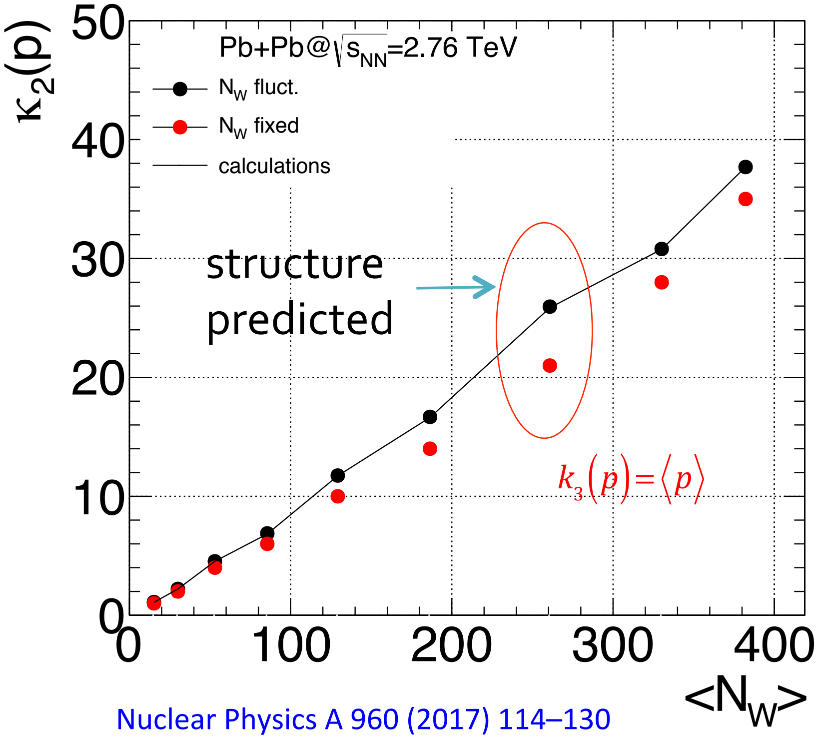


volume fluctuations has to be taken into account

Volume Fluct.: 2nd order

150*10^6 Events





Nuclear Physics A 960 (2017) 114–130

$$k_2(p-\bar{p}) = \langle N_w \rangle k_2(n-\bar{n}) + \langle n-\bar{n} \rangle^2 k_2(N_w)$$

vanishes for ALICE

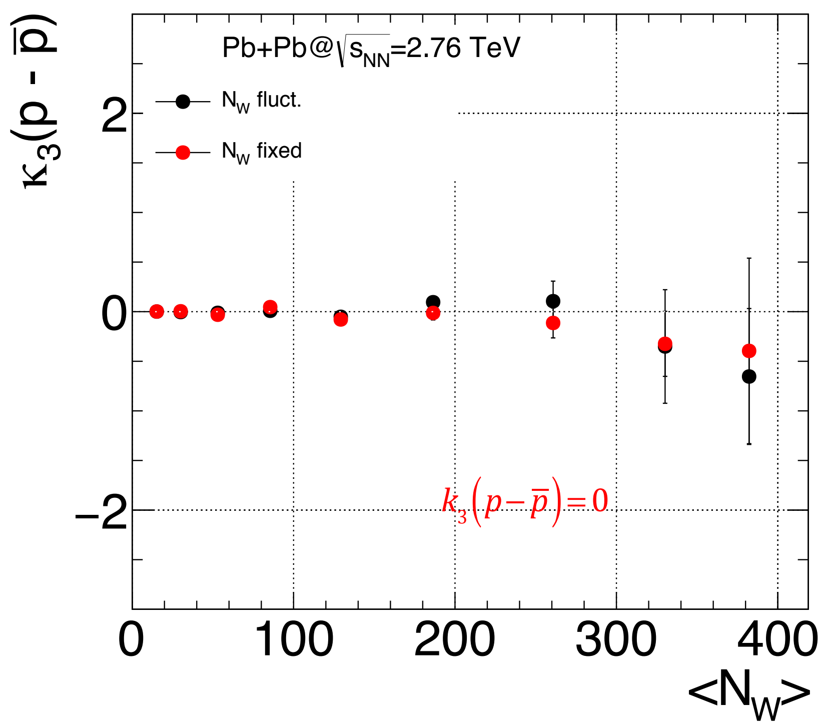
$$k_2(p) = \langle N_w \rangle k_2(n) + \langle n \rangle^2 k_2(N_w)$$

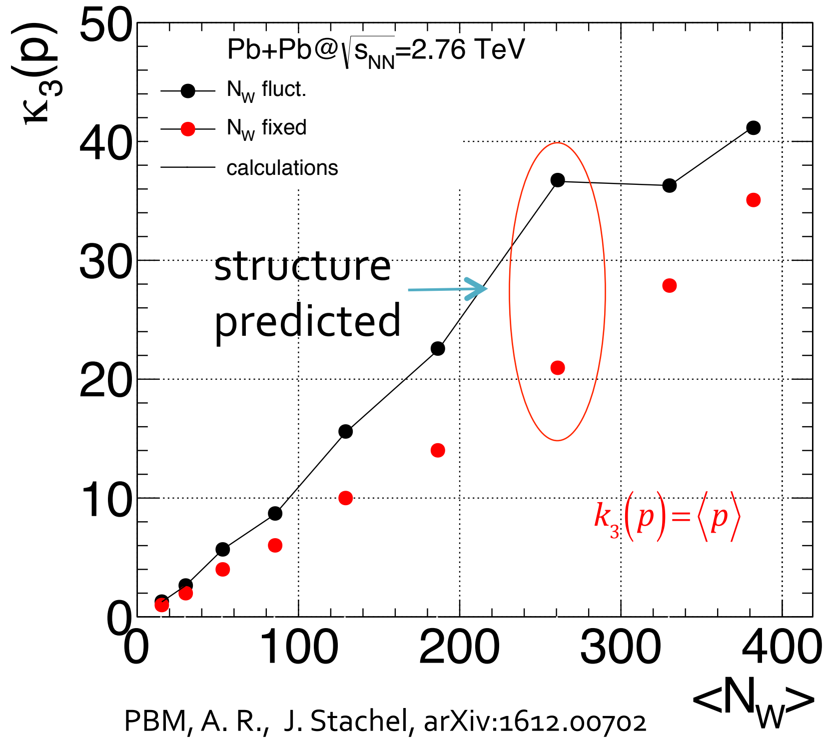
does not vanish

$n, \bar{n}$ from single wounded nucleon

Volume Fluct.: 3rd order

150*10^6 Events





PBM, A. R., J. Stachel, arXiv:1612.00702

$$k_3(p-\bar{p})=\langle N_w \rangle k_3(n-\bar{n})+\langle n-\bar{n} \rangle(\ldots)$$

↓ vanishes for ALICE

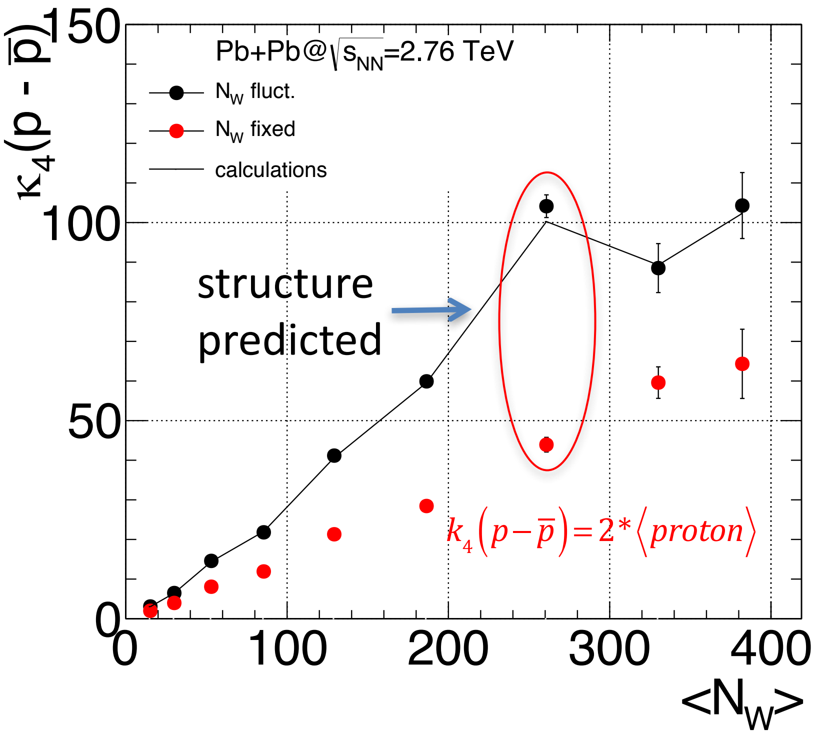
$$k_3(p)=\langle N_w \rangle k_3(n)+\langle n \rangle(\ldots)$$

↓ does not vanish

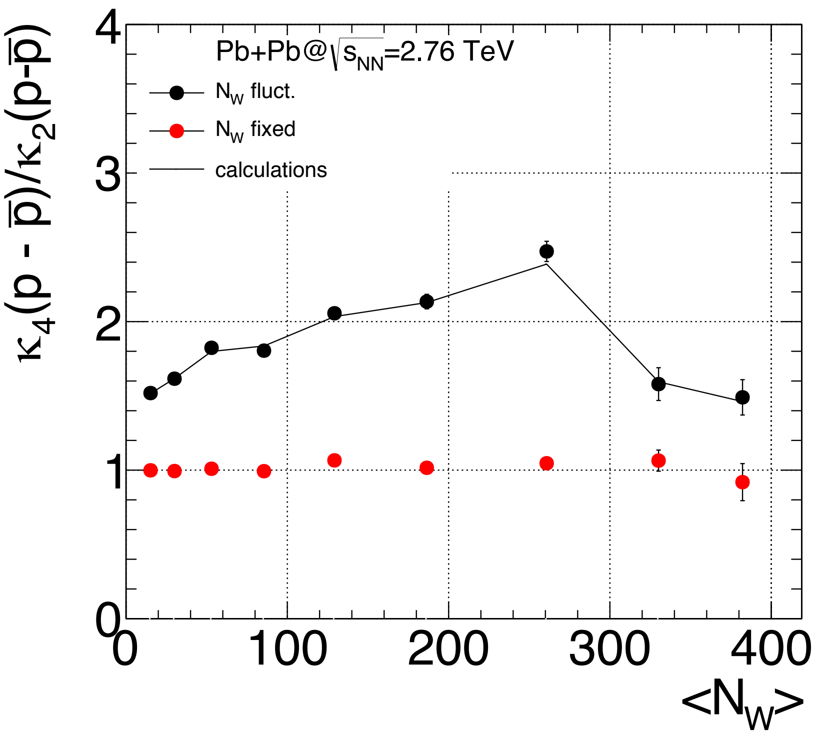
$n, \bar{n}$ from single wounded nucleon

Volume Fluct.: 4th order

150*10^6 Events



P. Braun-Munzinger, A. Rustamov, J. Stachel
Nuclear Physics A 960 (2017) 114–130



$$k_4(p-\bar{p}) = \langle N_w \rangle k_4(n-\bar{n}) + 3k_2(n-\bar{n})^2 k_2(N_w) + \langle n-\bar{n} \rangle (\ldots)$$

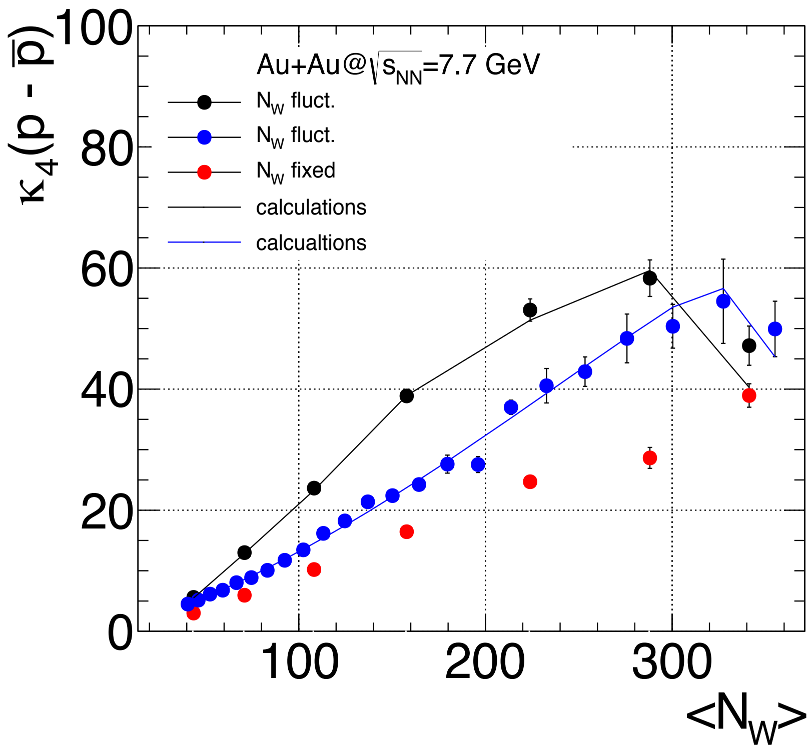
$n, \bar{n}$ → from single wounded nucleon

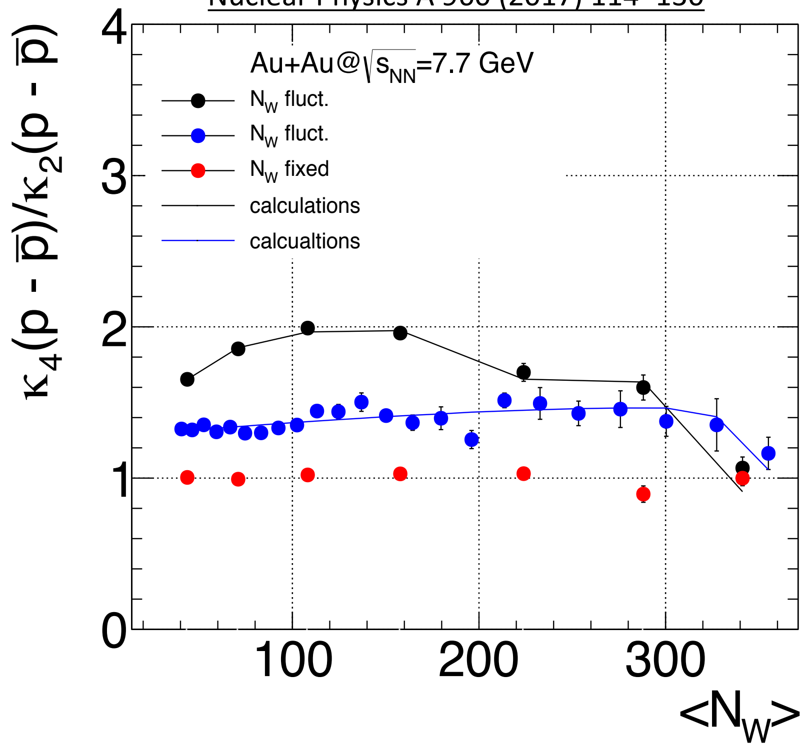
vanishes for ALICE

volume fluctuations has to be taken into account

Solution for volume fluct : CBWC ???

P. Braun-Munzinger, A. Rustamov, J. Stachel, Nuclear Physics A 960 (2017) 114–130

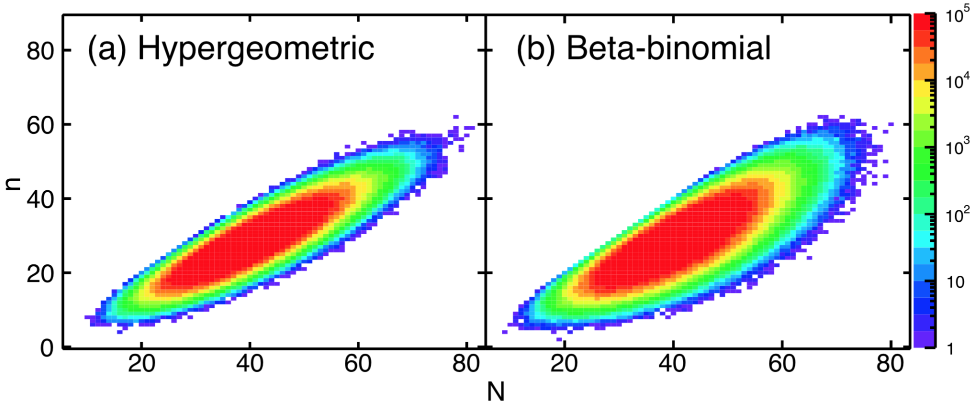




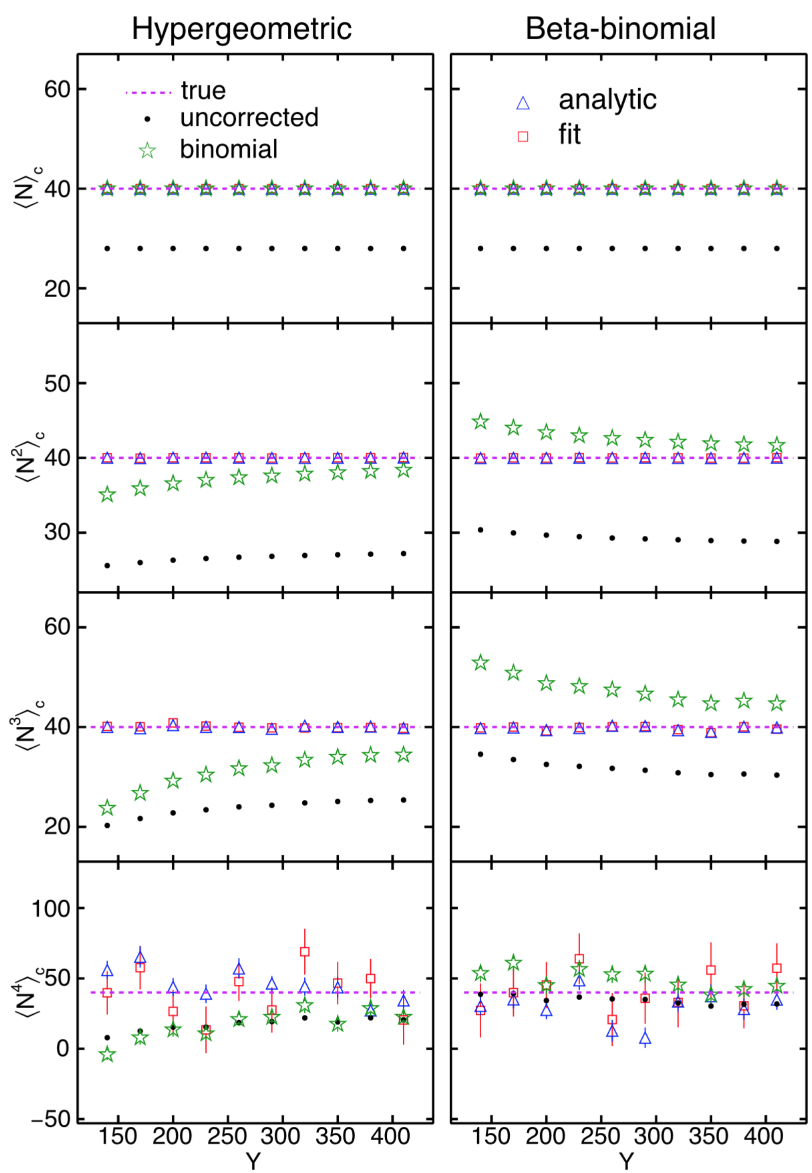
- Subdividing a given centrality bin into smaller ones and then merging them together incoherently.
- Incoherent addition of data from intervals with very small centrality bin width will eliminate true dynamical fluctuations.

Better publish uncorrected results

What if the efficiency loss is not binomial?



Draw N balls from the urn without returning balls to the urn	In each draw, when one draws a white ball, two white balls are returned to the urn

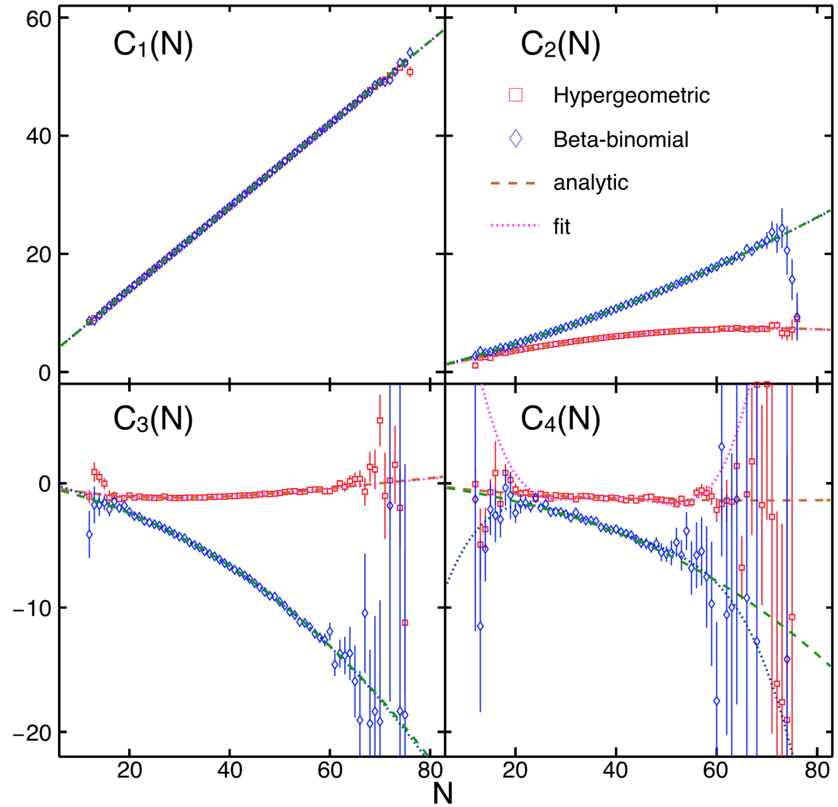


T. Nonaka, M. Kitazawa, S. Esumi, Nucl.Instrum.Meth. A906 (2018) 10-17

- Simulate efficiency loss
  - Correct with Binomial assumption
  - Correct with "detector response"

Efficiency loss shape has to be checked before

How does it work?



- Produce sample events of N assuming the **Poisson distribution** (N=number of particles in a given event)
- **Model the efficiency** loss with

$$\mathcal{R}_{\mathrm{HG}}(n;N) \text{ or } \mathcal{R}_{\beta}(n;N)$$

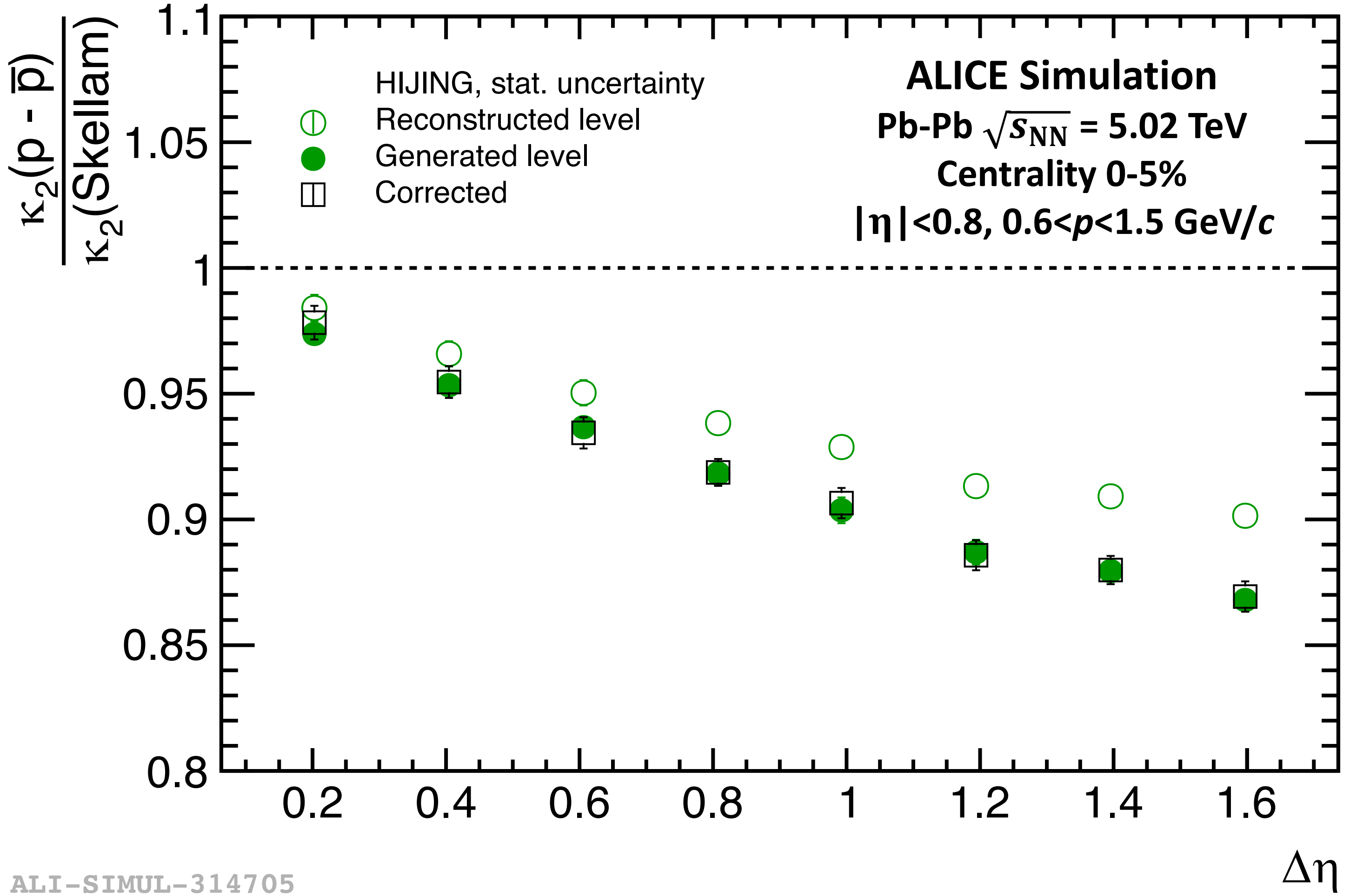
Measured moments — **Real moments**

$$\begin{bmatrix} \langle\langle n \rangle\rangle \\ \langle\langle n^2 \rangle\rangle \\ \vdots \\ \langle\langle n^L \rangle\rangle \end{bmatrix} = \begin{bmatrix} r_{10} \\ r_{20} \\ \vdots \\ r_{L0} \end{bmatrix} + \boldsymbol{R} \begin{bmatrix} \langle N \rangle \\ \langle N^2 \rangle \\ \vdots \\ \langle N^L \rangle \end{bmatrix}$$

Polynomial fit of the moments

$$R_m(N) = \sum_{j=0}^{L} r_{mj} N^j$$

Efficiency correction: $\kappa_2(p-\bar{p})/\kappa_2(Skellam)$

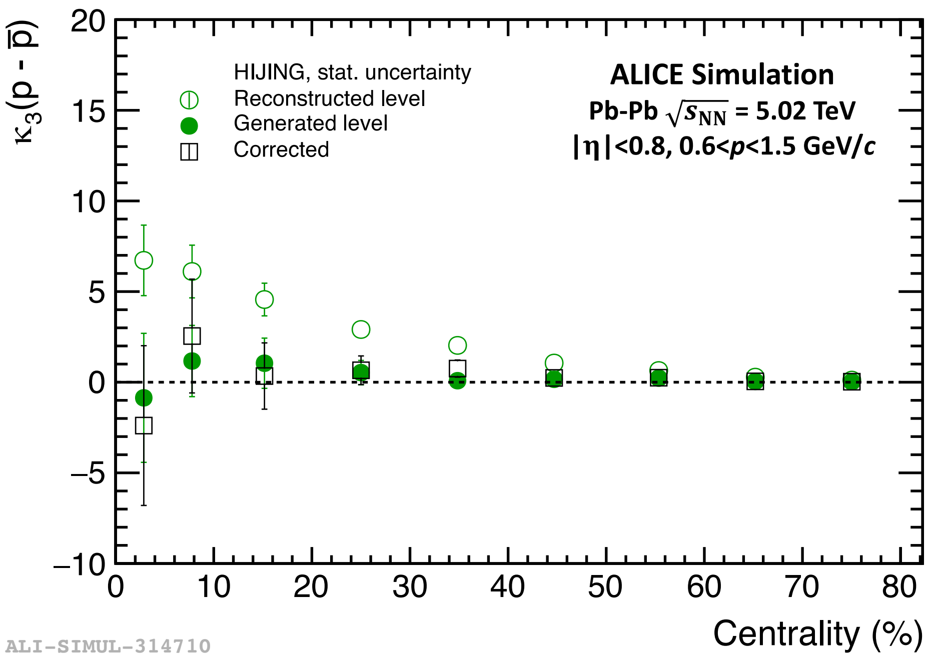


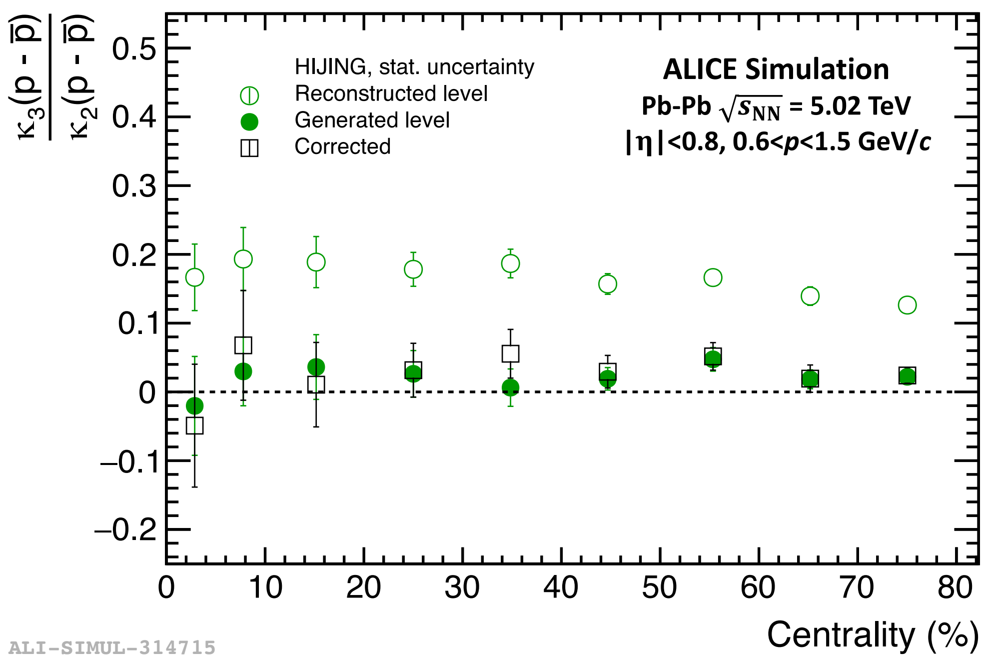
Efficiency correction with binomial assumption:

T. Nonaka, M. Kitazawa, S. Esumi, Phys. Rev. C 95, 064912 (2017)

Adam Bzdak, Volker Koch, Phys. Rev. C86, 044904 (2012)

Efficiency correction: $\kappa_3(p-\bar{p})/\kappa_2(p-\bar{p})$





Efficiency correction with binomial assumption:

T. Nonaka, M. Kitazawa, S. Esumi, Phys. Rev. C 95, 064912 (2017)

Adam Bzdak, Volker Koch, Phys. Rev. C86, 044904 (2012)