EMMI WORKSHOP

NET-PROTON FLUCTUATIONS AND NON-DYNAMICAL CONTRIBUTIONS

FROM SPS TO LHC

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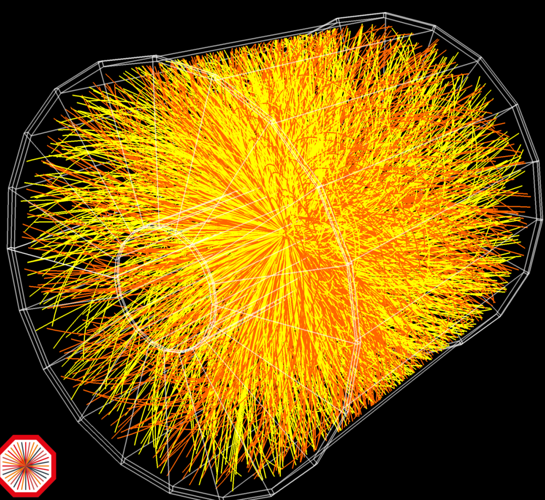


ALICE

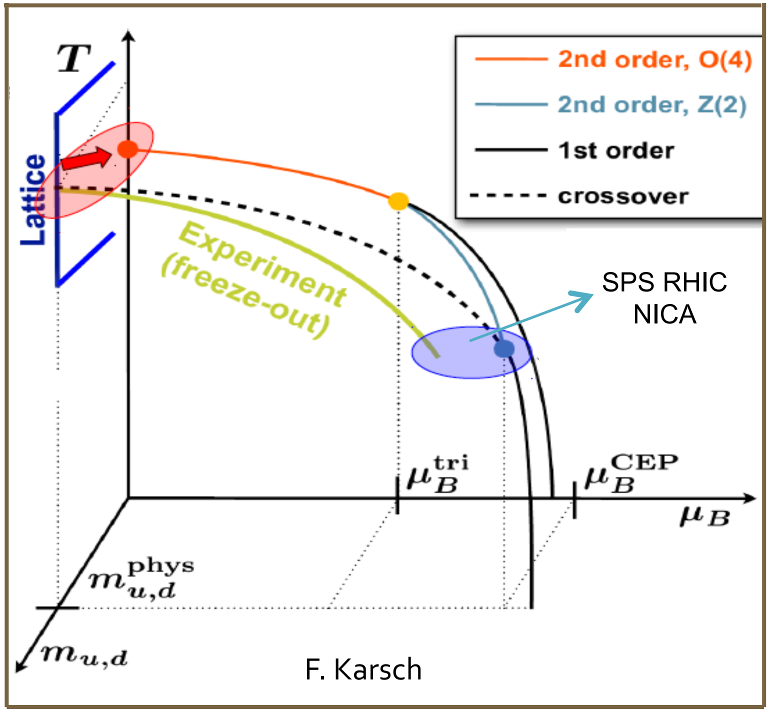
- Motivations
- News from SPS
- Results From ALICE
- Fluctuations in CE
- Summary

EMMI

ISOQUANT SFB1225

BMBF Forschungsschwerpunkt ALICE Experiment 202 ALICE

The Ultimate Goal



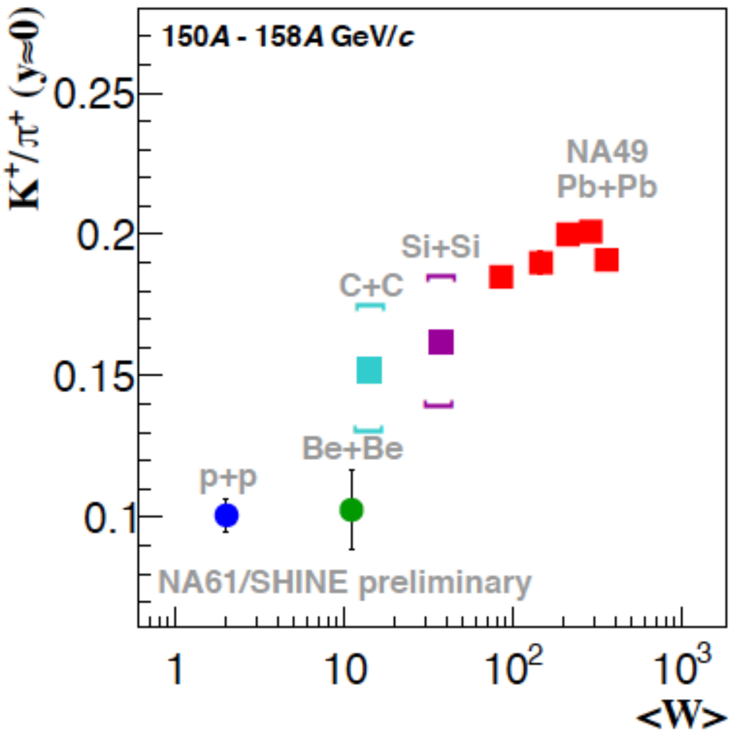
- To probe the structure of strongly interacting matter
  - Locate phase boundaries
  - Search for critical phenomena
  - …

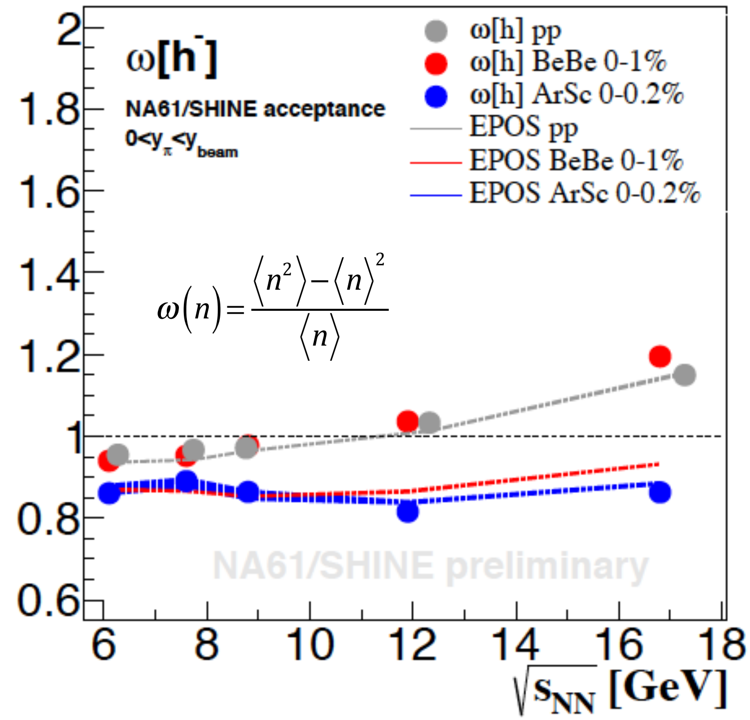
fingerprints of criticality for $m_{u,d} = 0$ survive at crossover with $m_{u,d} \neq 0$

A. Bazavov et al., Phys.Rev. D85 (2012) 054503

E-by-E fluctuations are predicted within Grand Canonical Ensemble

News from NA61/SHINE



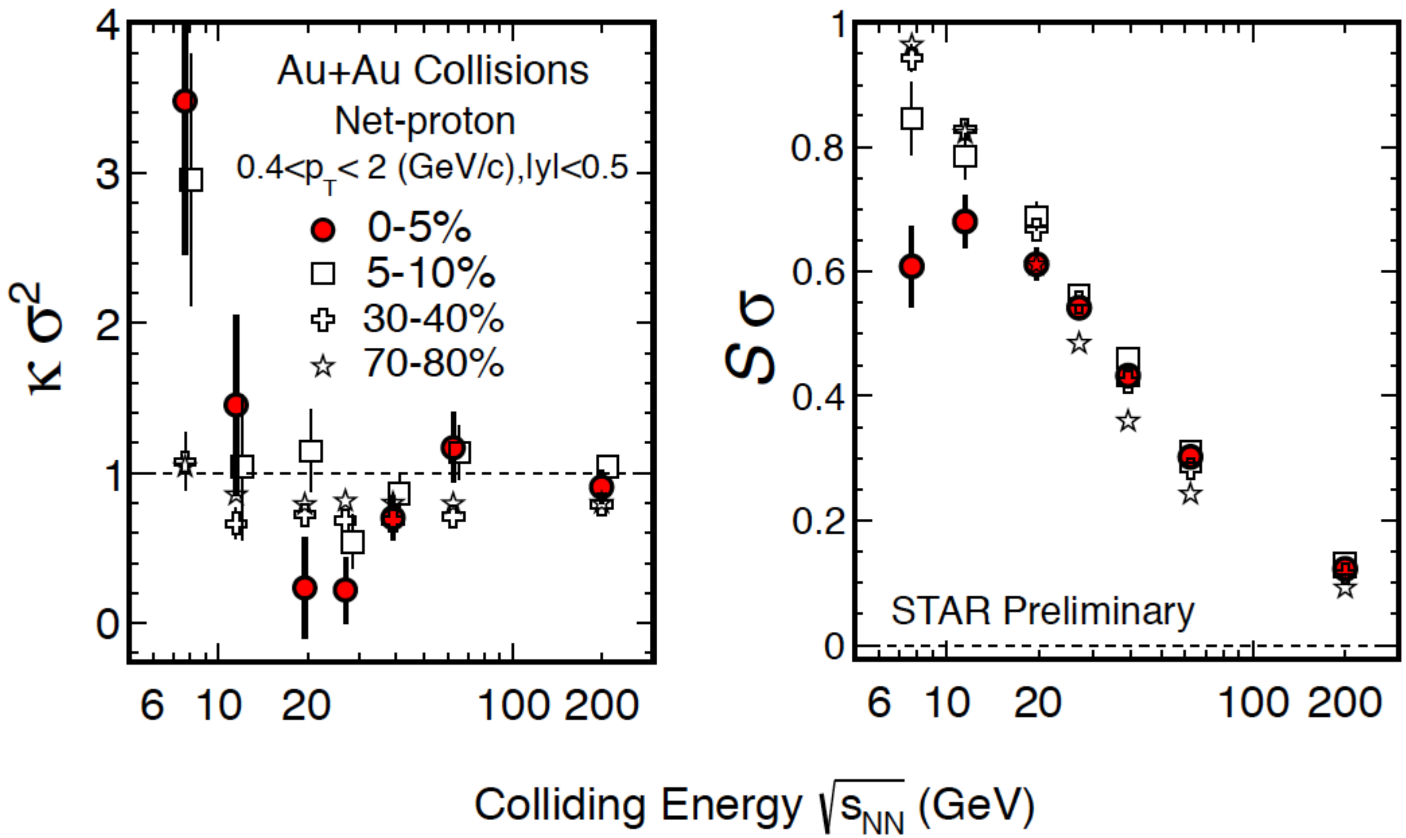


- Be+Be results are very close to p+p
- Consistent behavior between first and second moments

- Similar energy dependence for p+p and Be+Be
- Lower values for Ar+Sc (conservation laws)
- Deviation of Be+Be results from EPOS values

NA61 SPSC Status Report 2017

Results from STAR

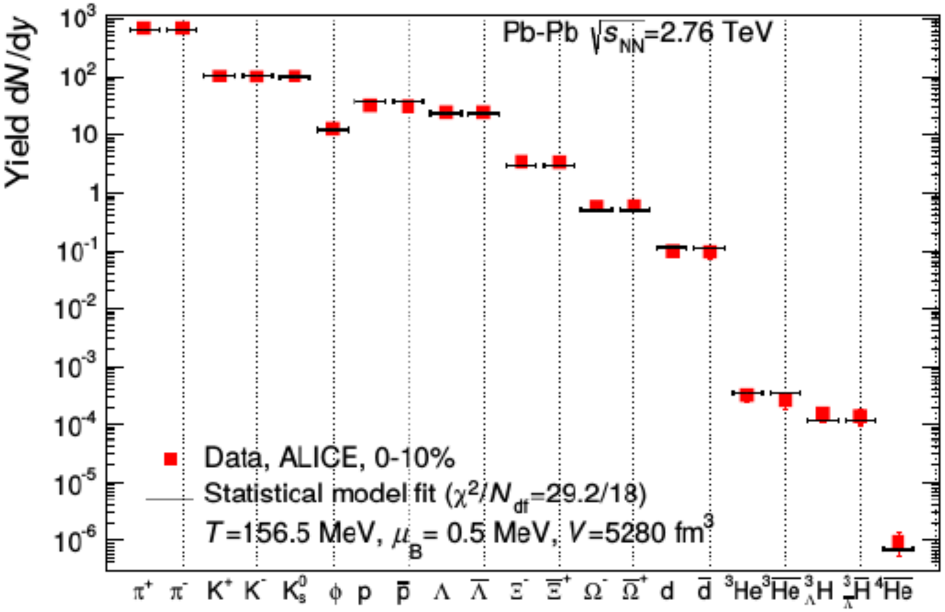


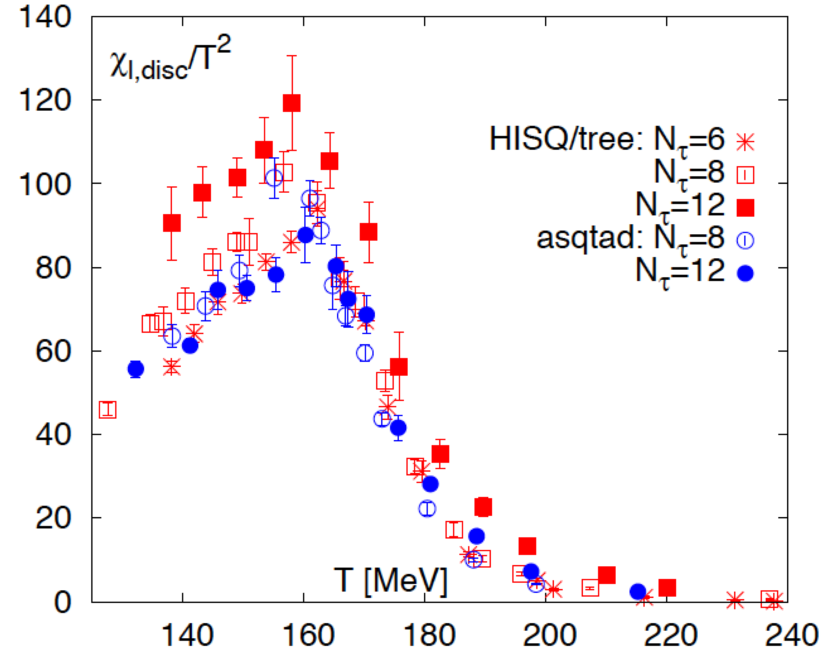
- Close to unity for peripheral collisions
- Below 39 GeV hints for a non-monotonic behavior
- ***More statistics and precise control of systematics are needed to explore this region***

Drop at 7.7 GeV for central events

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

Criticality at crossover





$$\langle N_i \rangle = V \frac{g_i}{2\pi^2} \int_0^\infty \frac{p^2 dp}{\exp\left[\left(E_i - \mu_i\right)/T\right] \pm 1}$$

freeze-out at the phase boundary

$$\mu_i = \mu_B B_i + \mu_s S_i + \mu_I I_i$$

$$T_c^{lattice} = 154 \pm 9\, MeV, \quad T_{fo}^{ALICE} = 156 \pm 3 MeV$$

ALICE, PLB 726 (2013) 610
J. Stachel, A. Andronic, P. Braun-Munzinger and K. Redlich
J. Phys. Conf. Ser. 509 (2014) 012019

A. Bazavov et al., Phys.Rev. D85 (2012) 054503

y axis: 9 orders of magnitude; works in the energy range spanning by 3 orders of magnitude

Bridge from experiment to theory

for a thermal system in a fixed volume V within the Grand Canonical Ensemble

$$\hat{\chi}_2^B = \frac{\langle \Delta N_B^2 \rangle - \langle \Delta N_B \rangle^2}{VT^3} = \frac{\kappa_2(\Delta N_B)}{VT^3}$$

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

- ***In experiments***
  - *Volume (participants) fluctuates from E-to-E*
  - *Global conservation laws are important*

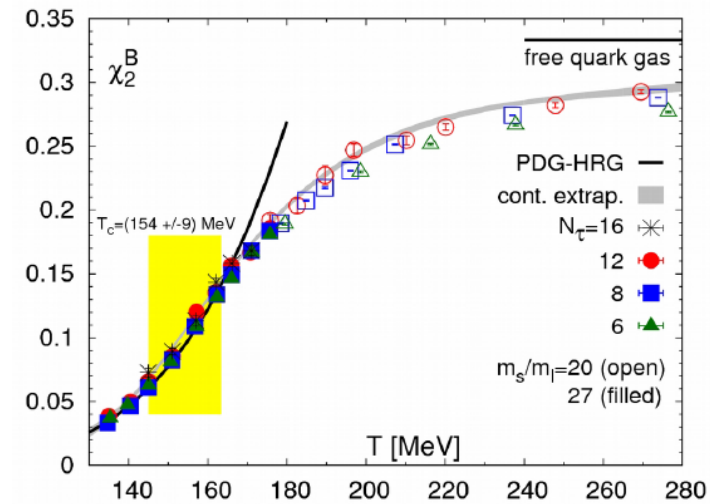
$$\frac{\kappa_4(\Delta N_B)}{\kappa_2(\Delta N_B)} \equiv \gamma_2\sigma^2 \neq \frac{\hat{\chi}_4^B}{\hat{\chi}_2^B} \qquad \frac{\kappa_3(\Delta N_B)}{\kappa_2(\Delta N_B)} \equiv \gamma_1\sigma \neq \frac{\hat{\chi}_3^B}{\hat{\chi}_2^B}$$

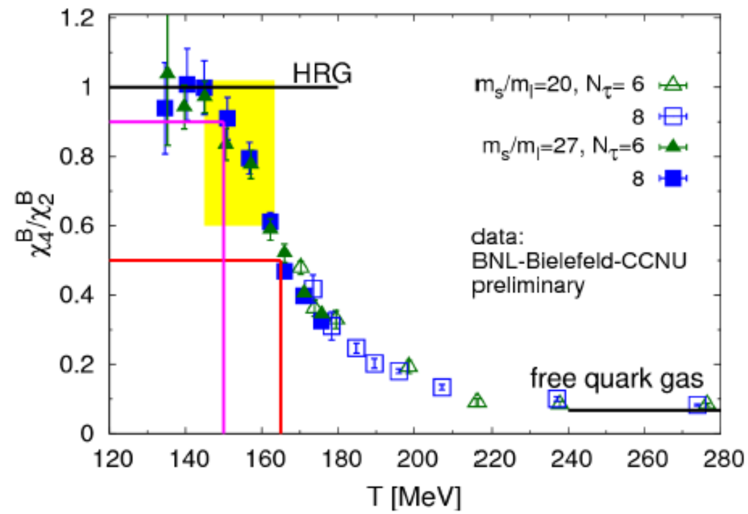
V. Skokov, B. Friman, and K. Redlich, Phys.Rev. C88 (2013) 034911

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

At $s^{1/2}$ > 10 GeV net-proton is a reasonable proxy for the net-baryon

M. Kitazawa, and M. Asakawa, Phys. Rev. C86 (2012) 024904





smaller than in HRG for T > 150 MeV

F. Karsch, QM17, arXiv:1706.01620

O. Kaczmarek, QM17, arXiv:1705.10682

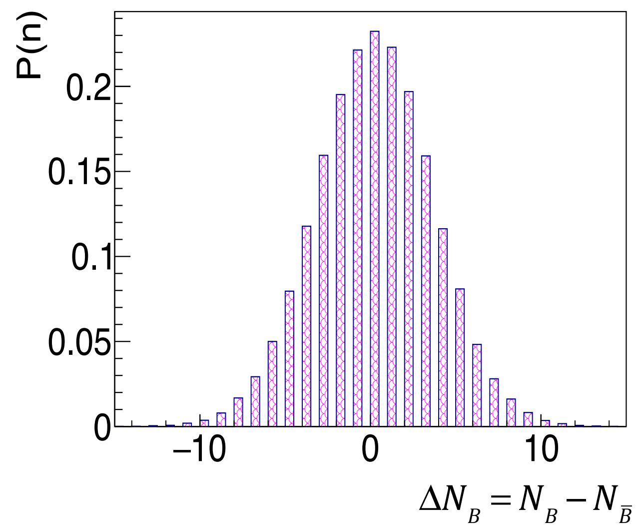
Net-cumulants, definitions

$$\kappa_1(X) = \langle X \rangle$$

$$\kappa_2(X) = \left\langle \left(X - \langle X \rangle\right)^2 \right\rangle$$

$$\kappa_3(X) = \left\langle \left(X - \langle X \rangle\right)^3 \right\rangle$$

$$\kappa_4(X) = \left\langle \left(X - \langle X \rangle\right)^4 \right\rangle - 3\kappa_2^2(X)$$



e.g., second cumulant of net-baryons

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

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

Correlation term may arise from:

1. Resonance contributions
2. Global conservation laws

Poisson limit:

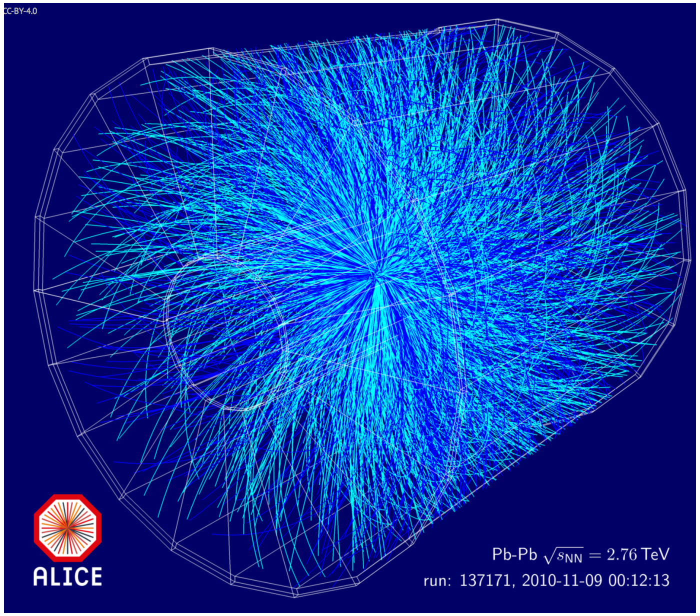
$$\kappa_2(N_B) = \langle N_B \rangle$$

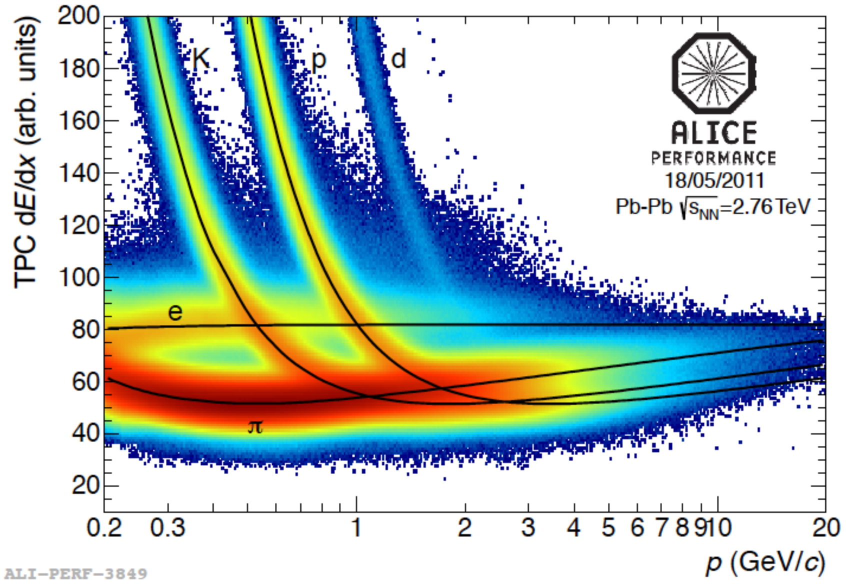
$$\kappa_2(N_{\bar{B}}) = \langle N_{\bar{B}} \rangle$$

$$\kappa_2(N_{\bar{B}} - N_B) \xrightarrow{\langle N_B N_{\bar{B}} \rangle = \langle N_B N_{\bar{B}} \rangle} \langle N_B \rangle + \langle N_{\bar{B}} \rangle$$

Skellam

ALICE Pb-Pb data at $\sqrt{s_{NN}} = 2.76\,\mathrm{TeV}$





Acceptance selection:

$$0.6 < p < 1.5\,\mathrm{GeV}/c, \quad |\eta| < 0.8$$

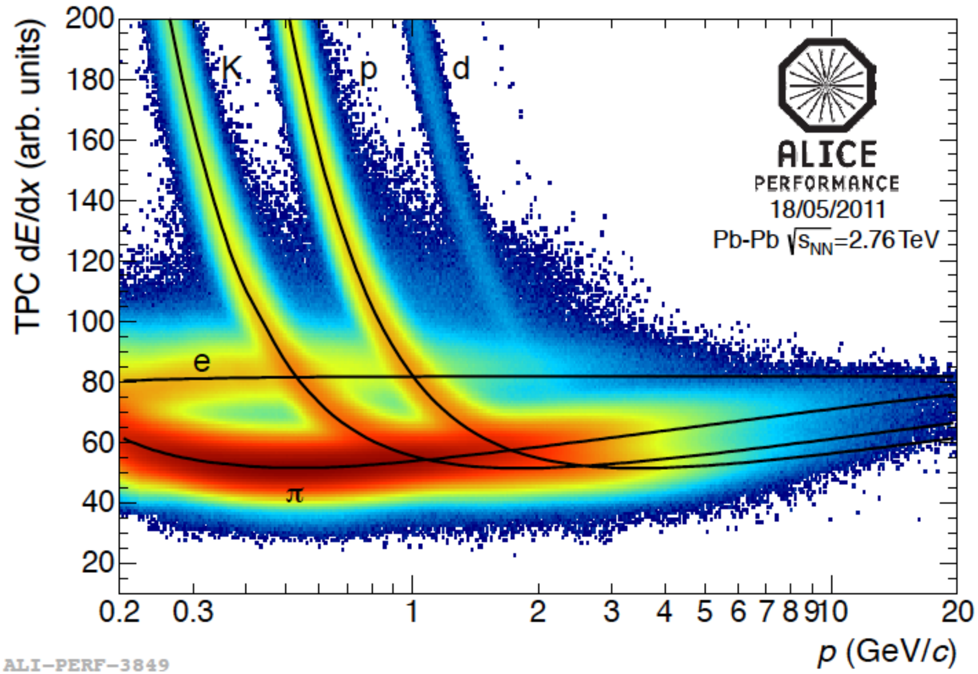
Centrality selection:

charged particle multiplicities in

$$2.8 < \eta < 5.1 \quad \text{and} \quad -3.7 < \eta < -1.7$$

Analysis technique: Identity Method

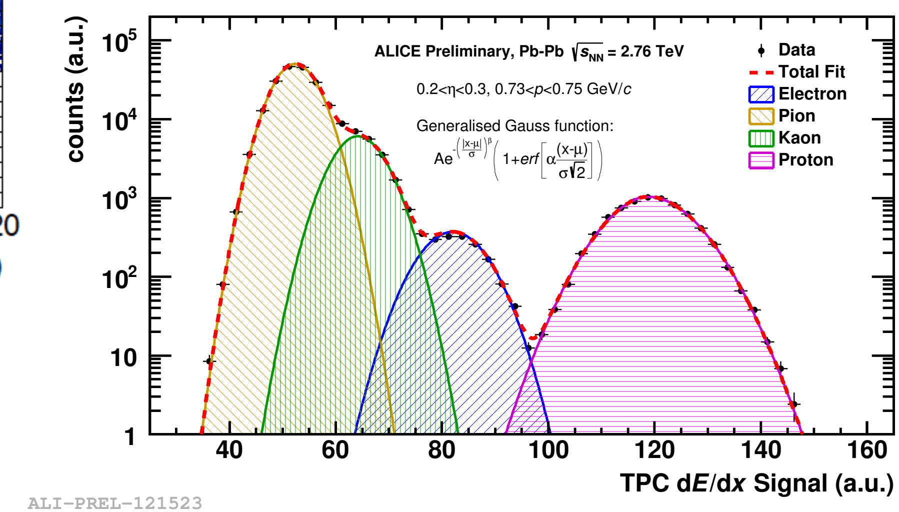
Analysis Strategy, PID



Tracking and cut efficiencies for protons:

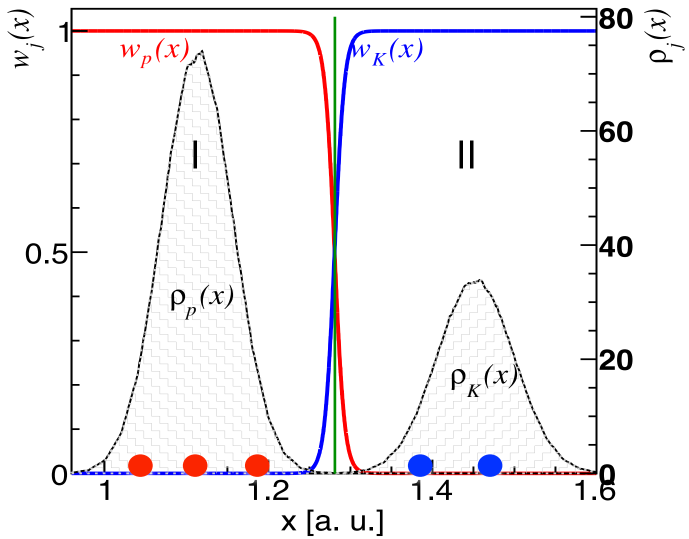
- 75-80 % for p_T > 0.5 GeV/c
- no centrality dependence

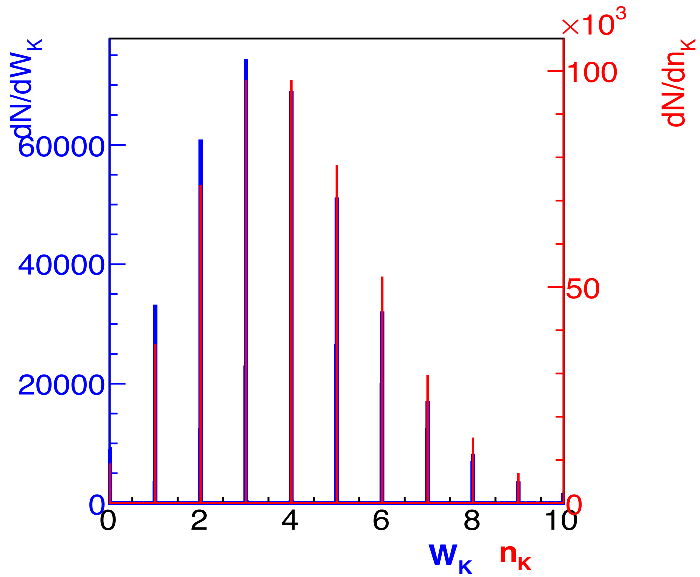
ALICE: Phys.Rev. C88 (2013) 044910



Analysis technique: Identity Method

Analysis method





single event example : 3 protons, 2 kaons

traditional approach

measurement in region I
count as proton
measurement in region II
count as kaon

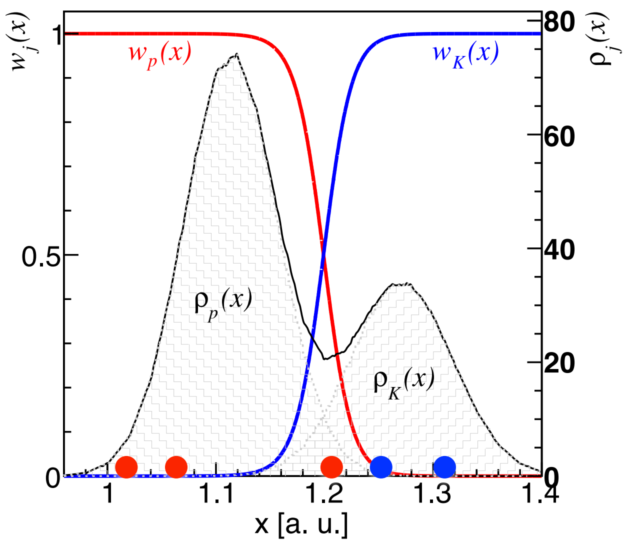
Identity method approach

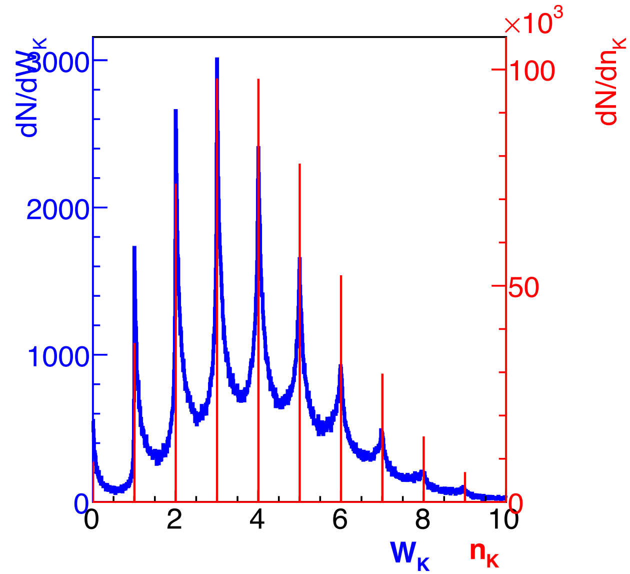
$$w_p(x_i) = \frac{\rho_p(x_i)}{\rho_p(x_i) + \rho_K(x_i)} \qquad W_p = \sum_{i=1}^{5} w_p(x_i)$$

$$w_K(x_i) = \frac{\rho_K(x_i)}{\rho_p(x_i) + \rho_K(x_i)} \qquad W_K = \sum_{i=1}^{5} w_K(x_i)$$

Analysis method

ALICE





$$\langle\vec{W}\rangle = A \times \langle\vec{N}\rangle$$

A: Fully defined by dE/dx fit functions

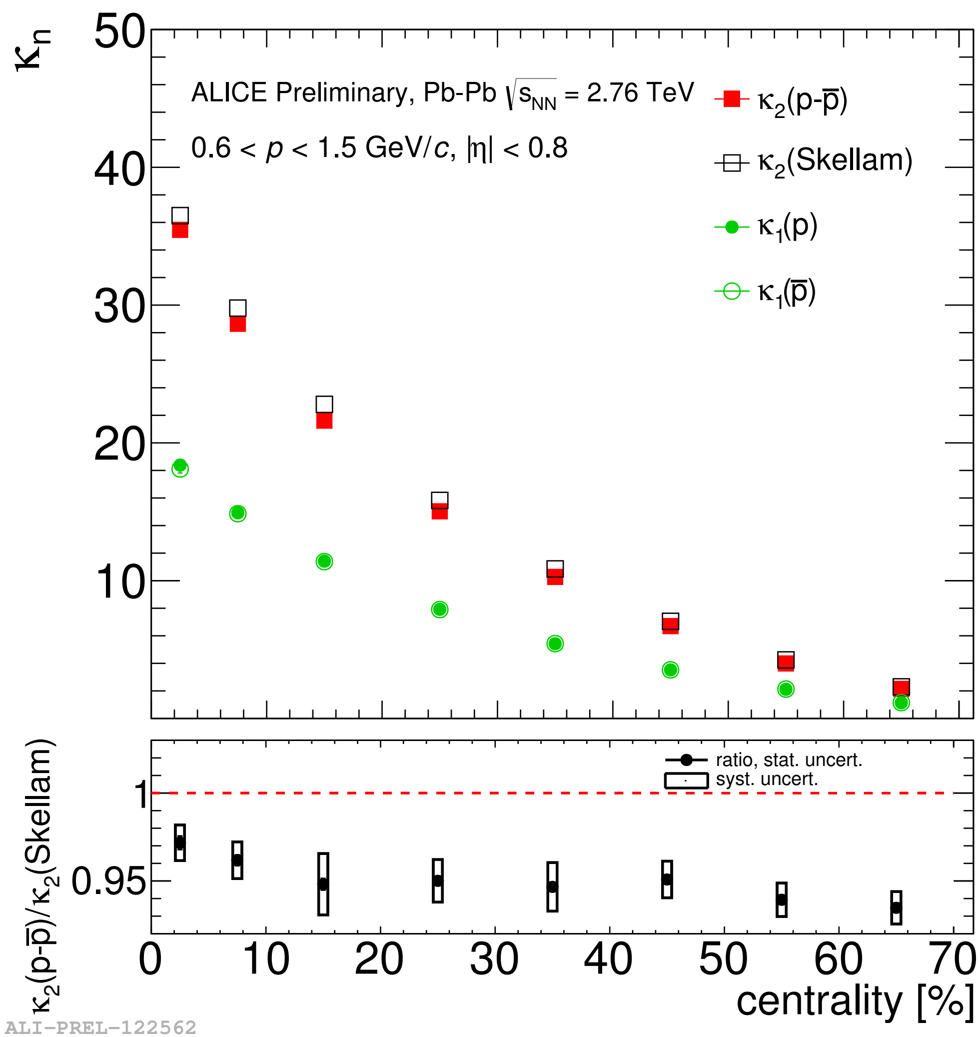
Identity method, basic idea:

$$\langle\vec{N}\rangle = A^{-1}\langle\vec{W}\rangle$$

M. Gazdzicki et al., PRC 83, 054907 (2011)
M. I. Gorenstein, PRC 84, 024902 (2011)
A. Rustamov, M. I. Gorenstein, PRC 86, 044906 (2012)

Used in NA49, NA61/SHINE, ALICE

Net-protons



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

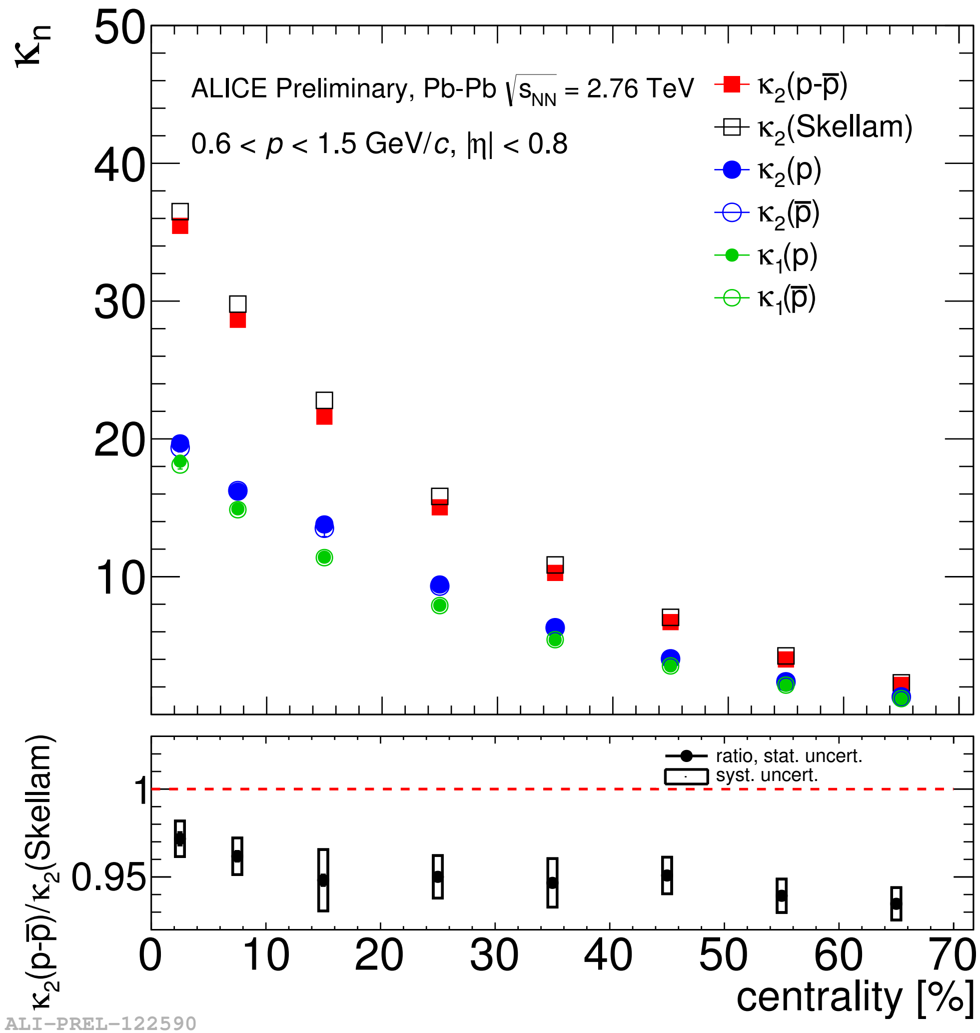
correlation term

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

● + ○ = □ ≠ ■

- correlation term?
- non Poisson (anti)protons?

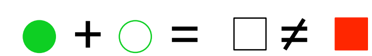
Net-protons, protons, antiprotons



$$\kappa_2(p-\bar{p}) = \kappa_2(p) + \kappa_2(\bar{p}) - 2(\langle p\bar{p}\rangle - \langle p\rangle\langle\bar{p}\rangle)$$

correlation term

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



- correlation term?
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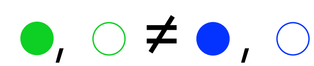
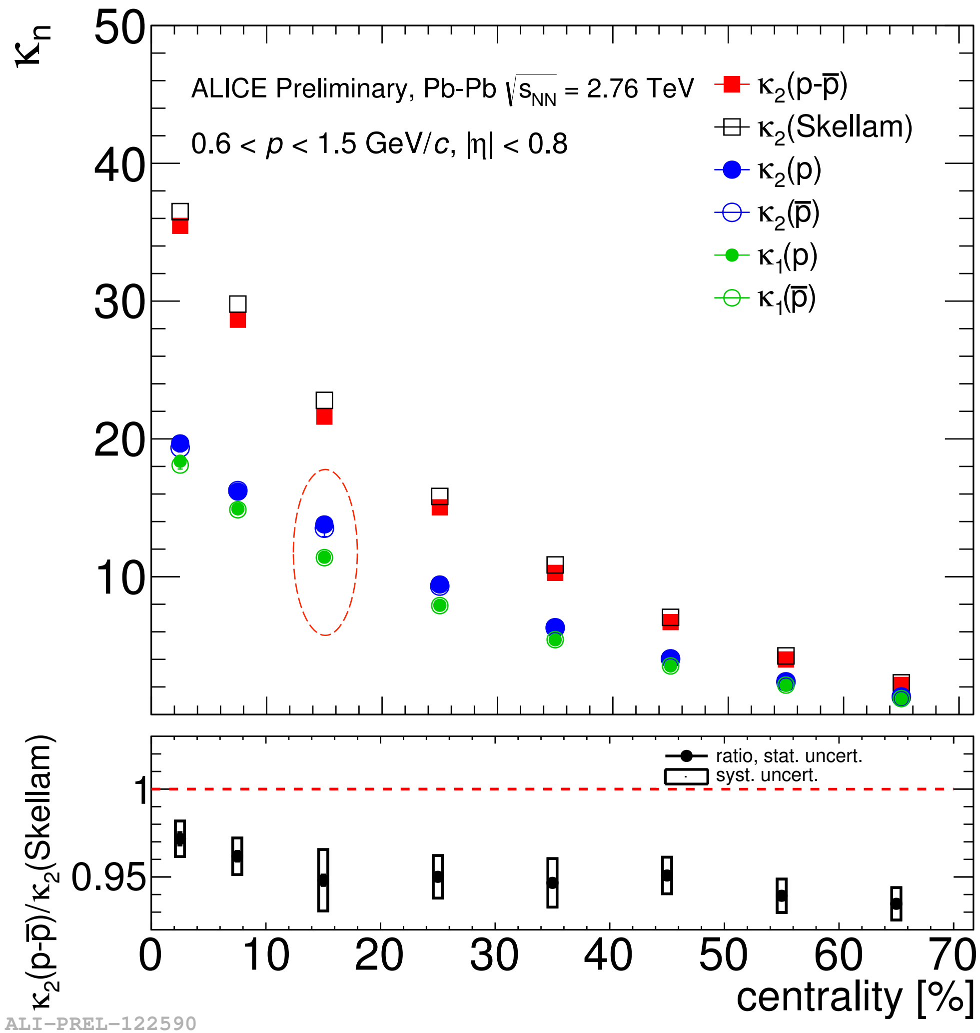


A. Rustamov, EMMI workshop on fluctuations, China, Wuhan, 10-13 October, 2017

Net-protons, protons, antiprotons



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

correlation term

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

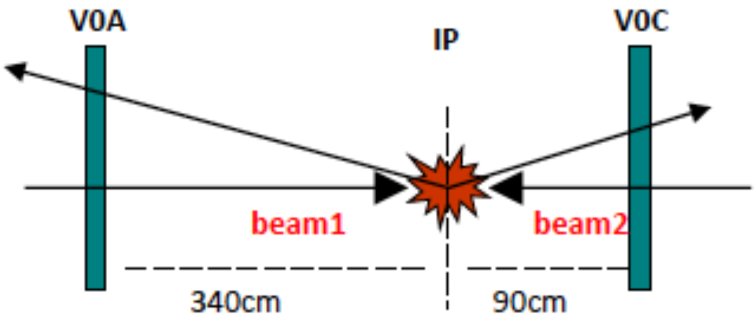
● + ○ = □ ≠ ■

- correlation term?
- non Poisson (anti)protons?

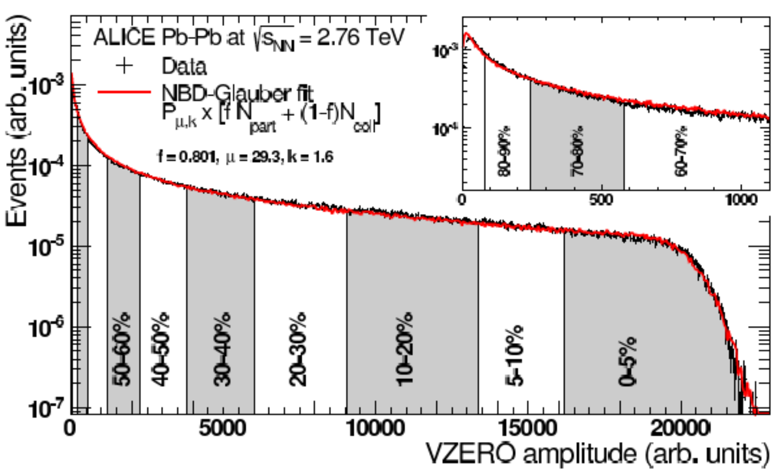
●, ○ ≠ ●, ○

- more evident in the third centrality class
- participant fluctuations ?

Centrality determination matters



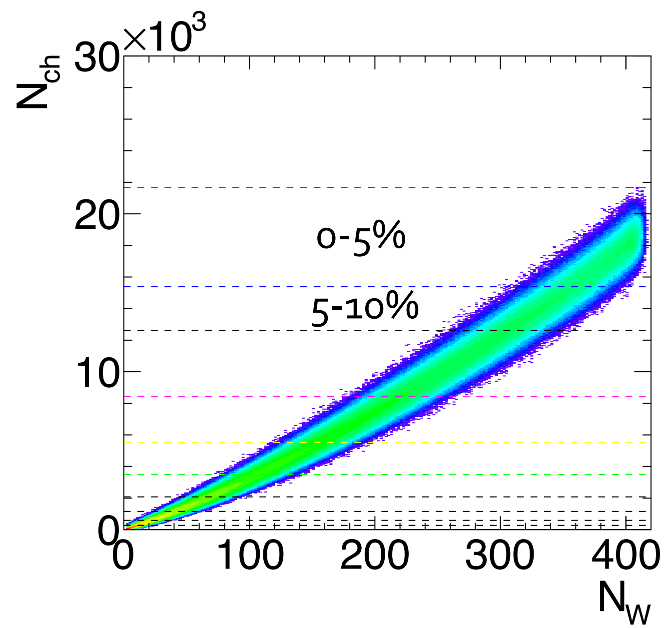
$2.8 < \eta < 5.1$ and $-3.7 < \eta < -1.7$



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

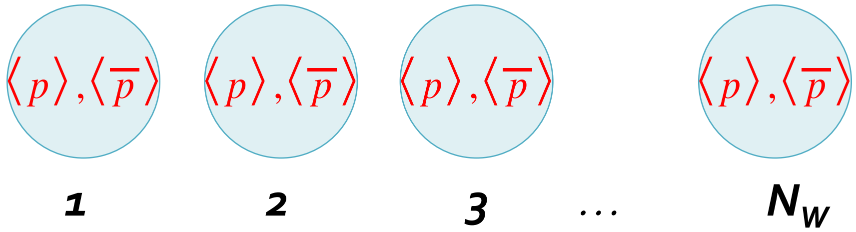
$$P_{\mu,k}(n) = \frac{\Gamma(n+k)}{\Gamma(n+1)\Gamma(k)} \frac{\left(\mu/k\right)^n}{\left(\mu/k+1\right)^{n+k}}$$

$$N = fN_W + (1-f)N_{coll}$$

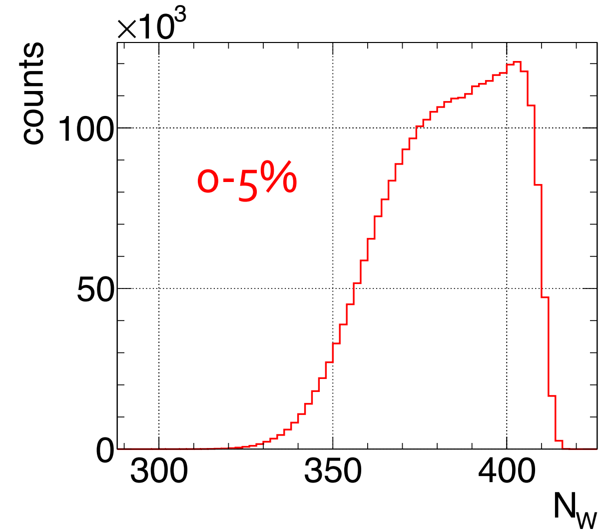


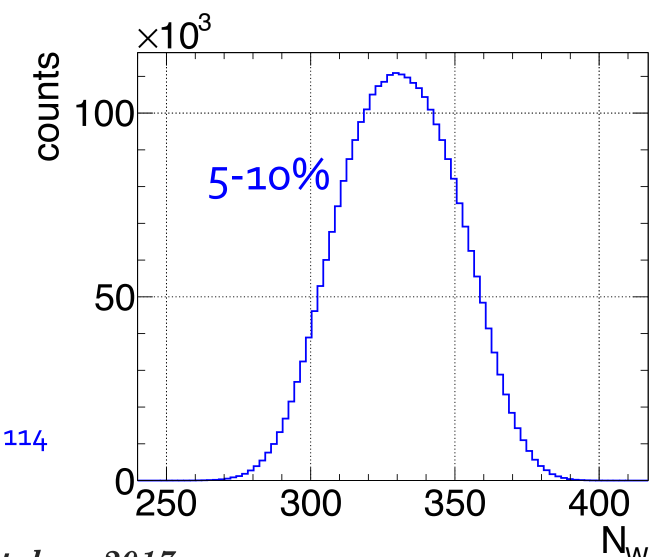
P. Braun-Munzinger, A. Rustamov, J. Stachel, arXiv:1612.00702, NPA in print

Participant (volume) fluctuations



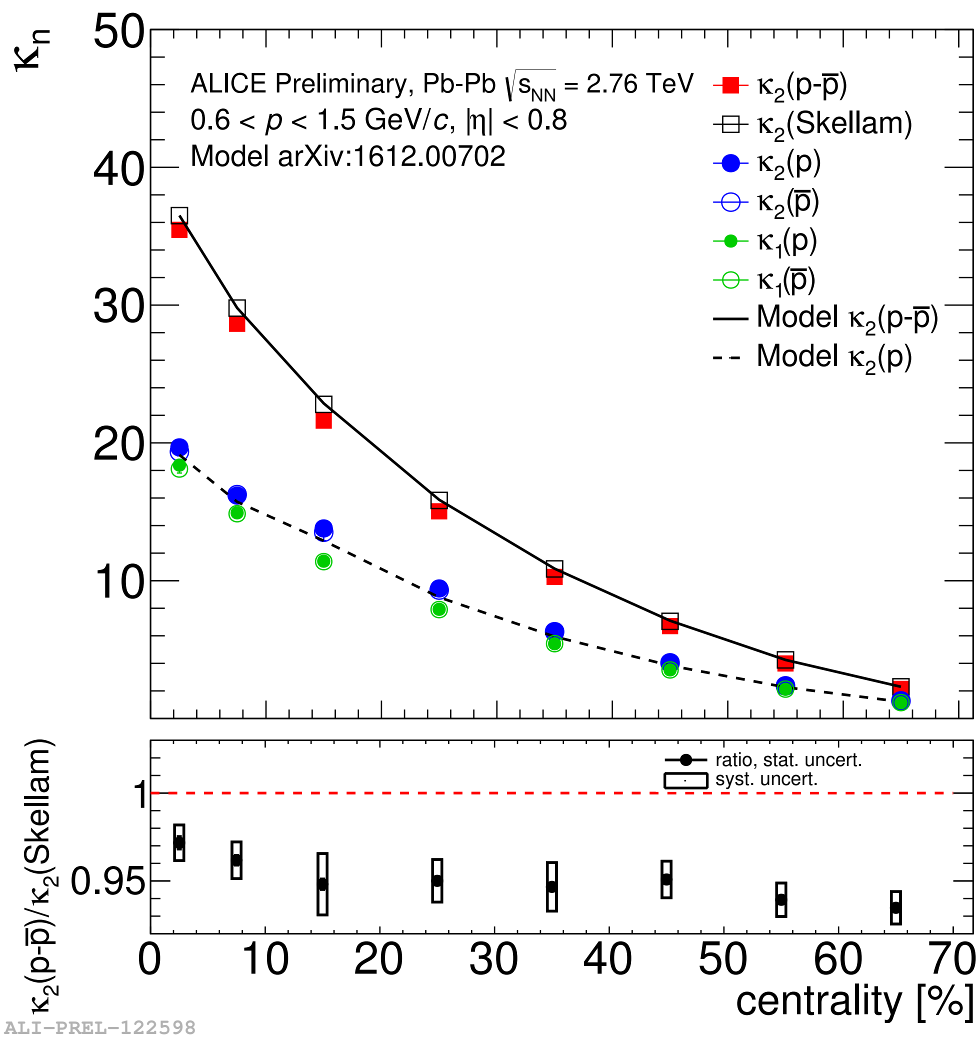
- ***N_W fluctuates with MC Glauber initial conditions***
- ***Particles are produced from each source (GCE)***
- ***Inputs:***
  - ***Mean proton multiplicities*** $\langle p \rangle$, $\langle \bar{p} \rangle$
  - ***Centrality selection like in experimental data***





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

Volume fluctuations



Analysis of higher cumulants is ongoing!

$$\kappa_2(n_B - n_{\bar{B}}) = \kappa_2(n_B) + \kappa_2(n_{\bar{B}}) - 2\left(\langle n_B n_{\bar{B}}\rangle - \langle n_B\rangle\langle n_{\bar{B}}\rangle\right)$$

Input to the Model

$\kappa_1(p)$, $\kappa_1(\bar{p})$

centrality selection procedure

Predictions

——— $\kappa_2(p-\bar{p})$

- - - - - $\kappa_2(p)$

participants — vanishes at LHC

$$\kappa_2(N_B - N_{\bar{B}}) = \langle N_W\rangle \kappa_2(n_B - n_{\bar{B}}) + \langle n_B - n_{\bar{B}}\rangle^2 \kappa_2(N_W)$$

from single participant

Second cumulants of net-particles at LHC are not affected by participant fluctuations

easy control of systematics

A. Rustamov, QM2017, arXiv:1704.05329

Acceptance dependence

Contribution from global baryon number conservation

$$\frac{\kappa_2(p-\bar{p})}{\kappa_2(Skellam)} = 1-\alpha \qquad \alpha = \frac{\langle p\rangle^{measured}}{\langle B\rangle^{4\pi}}$$

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

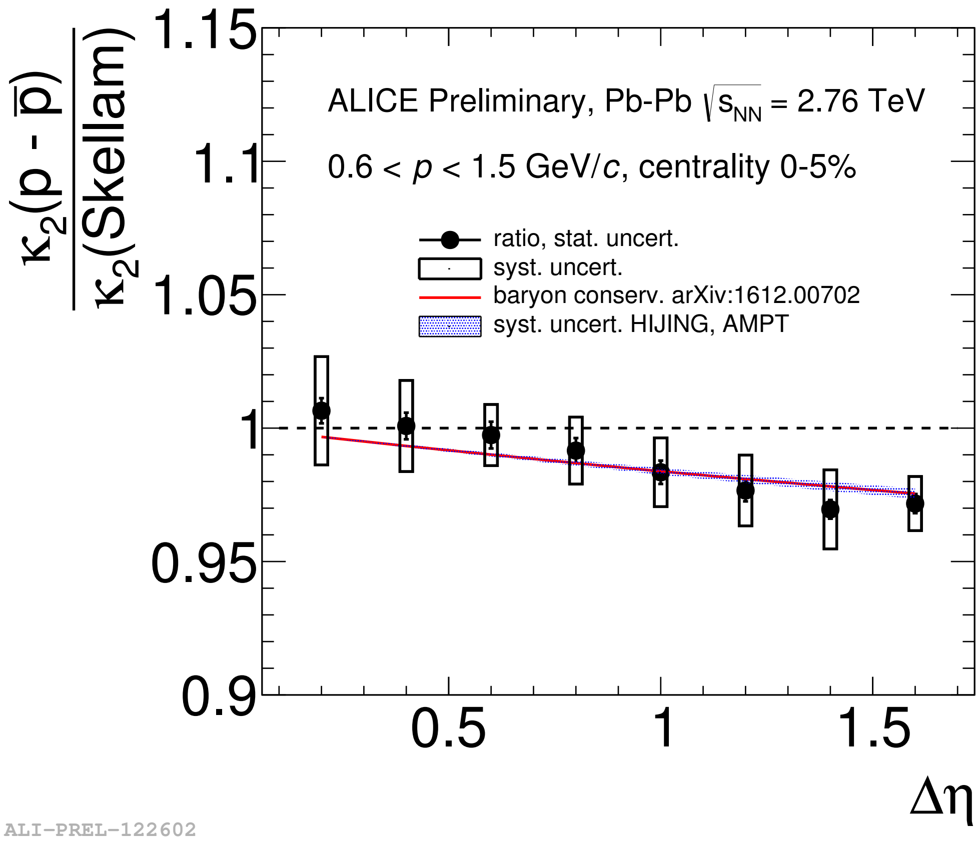
Inputs for $\langle B\rangle^{acc}$ from:

Phys. Lett. B 747, 292 (2015)
P. Braun-Munzinger, A. Kalweit, K. Redlich, J. Stachel

extrapolation from $\langle B\rangle^{acc}$ to $\langle B\rangle^{4\pi}$

using HIJING and AMPT models

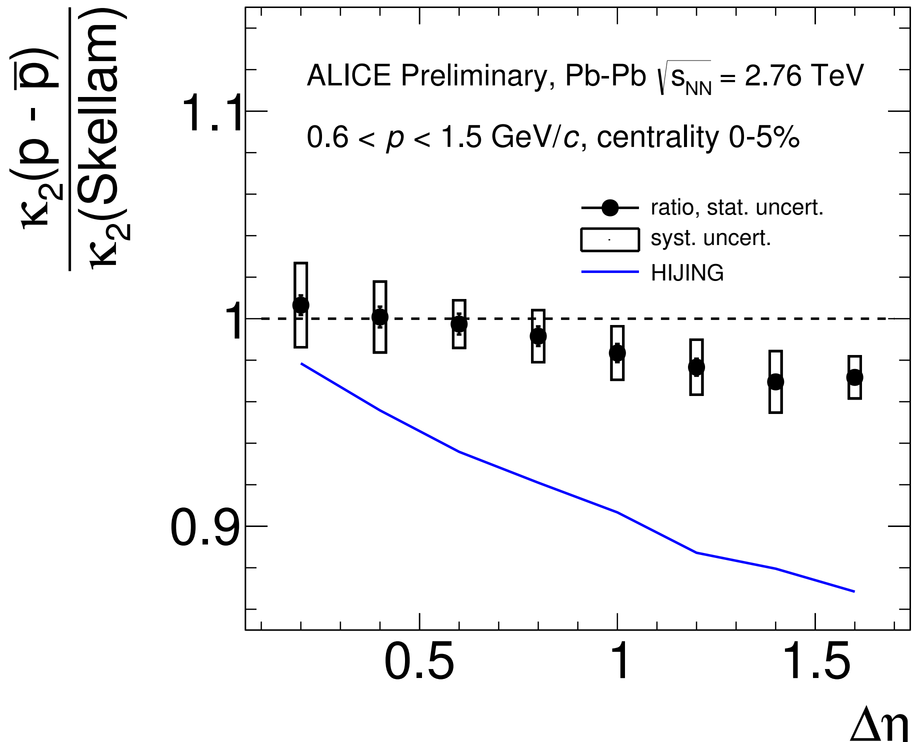
A. Rustamov, QM2017, arXiv:1704.05329

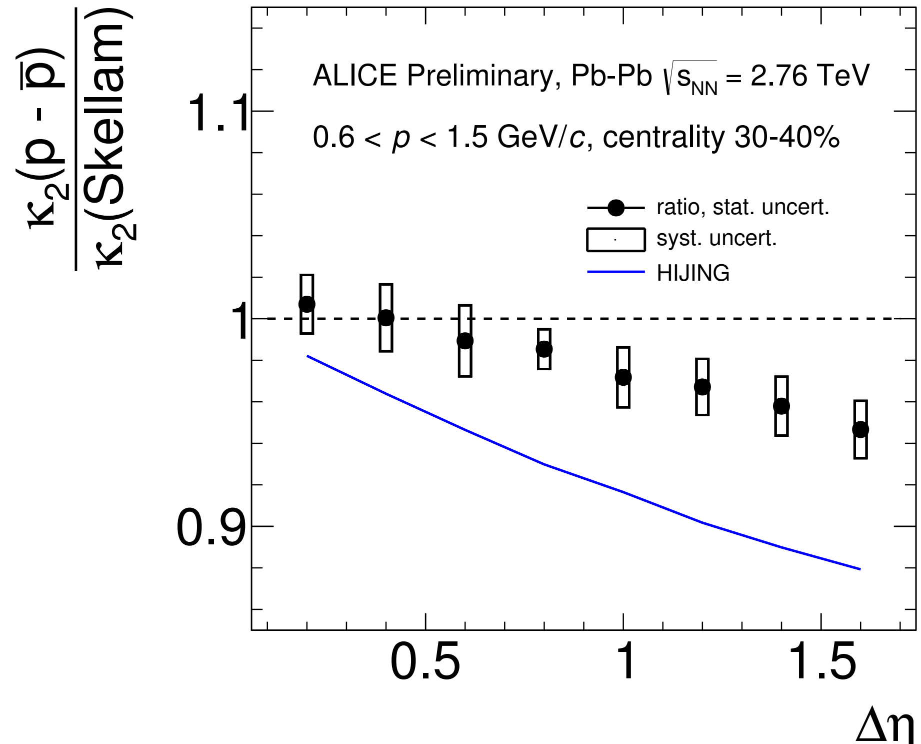


The deviation from Skellam is due to the global baryon number conservation.

Analysis of higher cumulants is ongoing!

Acceptance and centrality dependence

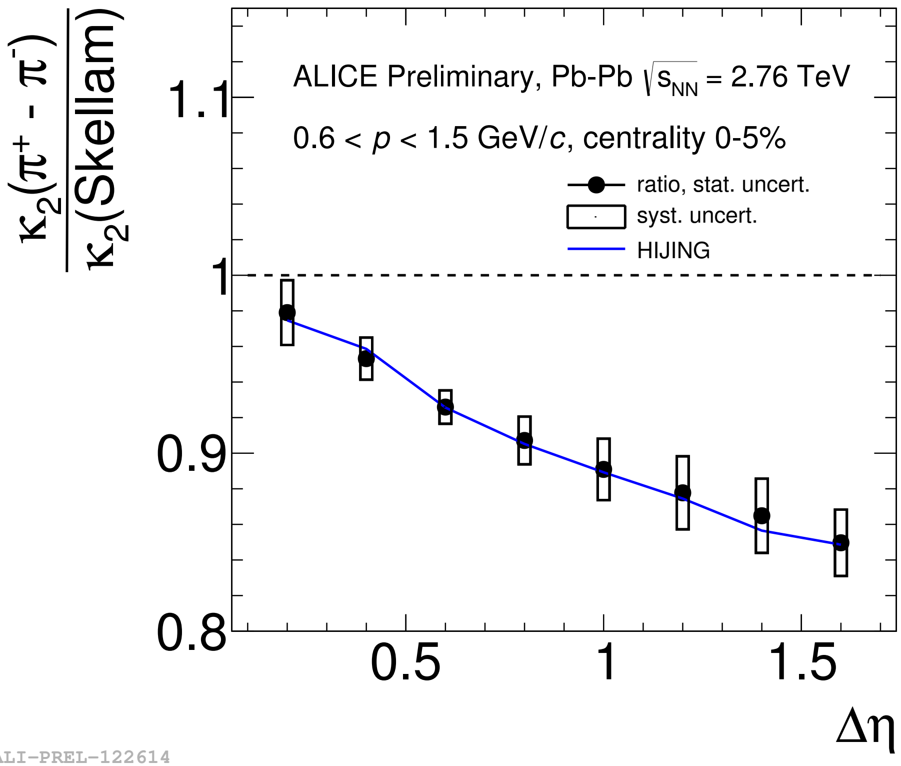




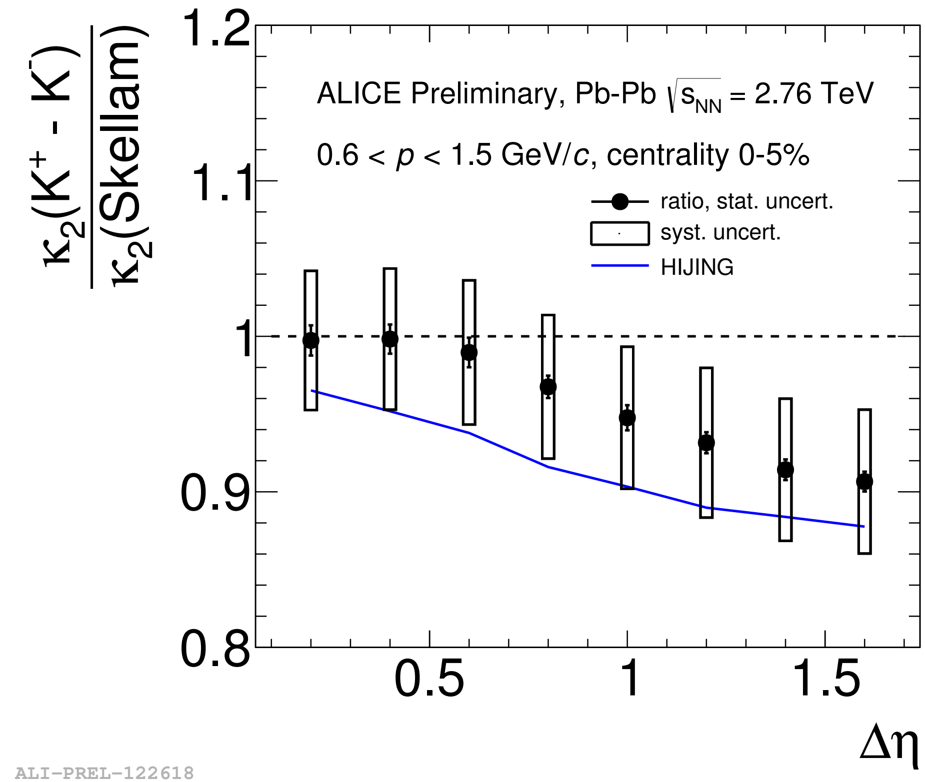
Not properly described in most string fragmentation based event generators

Net-pions and Net-kaons

net-pions



net-kaons



perfect agreement with HIJING

reasonable agreement with HIJING

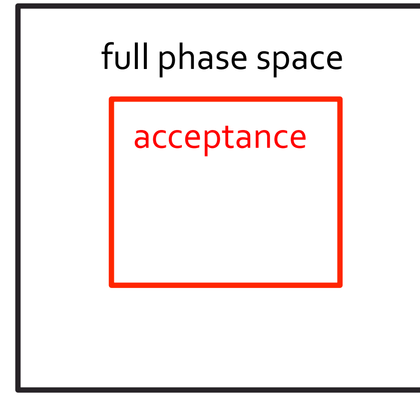
resonance pion and kaon production is likely to explain the measured trend

Warning: Skellam is not a proper baseline for net-pions and net-kaons

Effects of conservation laws on higher moments

Approach reported before

1. Poisson distributions for both baryons and anti-baryons in 4π
2. Folding into acceptance with binomial distribution
3. Counting net-baryons inside and outside acceptance



$P_1(n_1)$ – probability to measure n_1 net-baryons inside acceptance
$P_2(n_2)$- probability to measure n_2 net-baryons outside acceptance

Summing over net-baryons outside acceptance by imposing conservation in the full phase space

$$P_B(n_1)=\Sigma_{n2}P_1(n_1)P_2(n_2)\delta(n_1+n_2-B)$$

Input to the model:
number of baryons and anti-baryons in 4pi
experimental acceptance

A. Bzdak, V. Koch, V. Skokov, PRC87 (2013) 014901

Our approach: MC implementation of canonical ensemble

Two baryon species with the baryon numbers +1 and -1 in the ideal Boltzmann gas

$$Z_{GCE}(V,T,\mu)=\sum_{N_B=0}^{\infty}\sum_{N_{\bar{B}}=0}^{\infty}\frac{(\lambda_B z)^{N_B}}{N_B!}\frac{(\lambda_{\bar{B}} z)^{N_{\bar{B}}}}{N_{\bar{B}}!}=e^{2z\cosh\left(\mu/T\right)},\quad \lambda_{B,\bar{B}}=e^{\pm\frac{\mu}{T}}$$

$$Z_{GC}(V,T,B)=\sum_{N_B=0}^{\infty}\sum_{N_{\bar{B}}=0}^{\infty}\frac{(\lambda_B z)^{N_B}}{N_B!}\frac{(\lambda_{\bar{B}} z)^{N_{\bar{B}}}}{N_{\bar{B}}!}\delta\left(N_B-N_{\bar{B}}-B\right)=I_B(2z)\Big|_{\lambda_B=\lambda_{\bar{B}}=1}$$

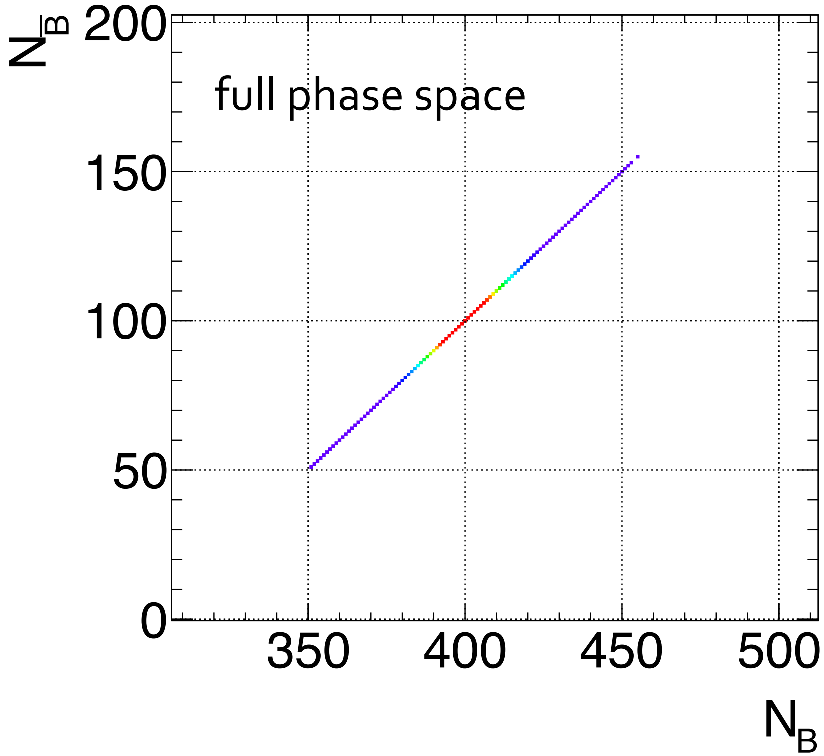
$$\left\langle N_{B,\bar{B}}\right\rangle_{GCE}=\lambda_{B,\bar{B}}\frac{\partial\ln Z_{GCE}}{\partial\lambda_{B,\bar{B}}}=e^{\pm\frac{\mu}{T}}z,\quad z=\sqrt{\left\langle N_B\right\rangle_{GCE}\left\langle N_{\bar{B}}\right\rangle_{GCE}}$$

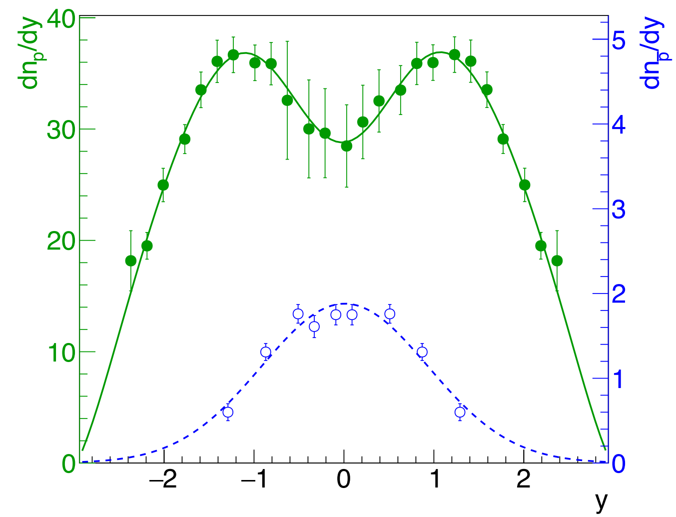
$$\left\langle N_{B,\bar{B}}\right\rangle_{CE}=\sqrt{\left\langle N_B\right\rangle_{GCE}\left\langle N_{\bar{B}}\right\rangle_{GCE}}\frac{I_{B\mp1}\left(2\sqrt{\left\langle N_B\right\rangle_{GCE}\left\langle N_{\bar{B}}\right\rangle_{GCE}}\right)}{I_B\left(2\sqrt{\left\langle N_B\right\rangle_{GCE}\left\langle N_{\bar{B}}\right\rangle_{GCE}}\right)}$$

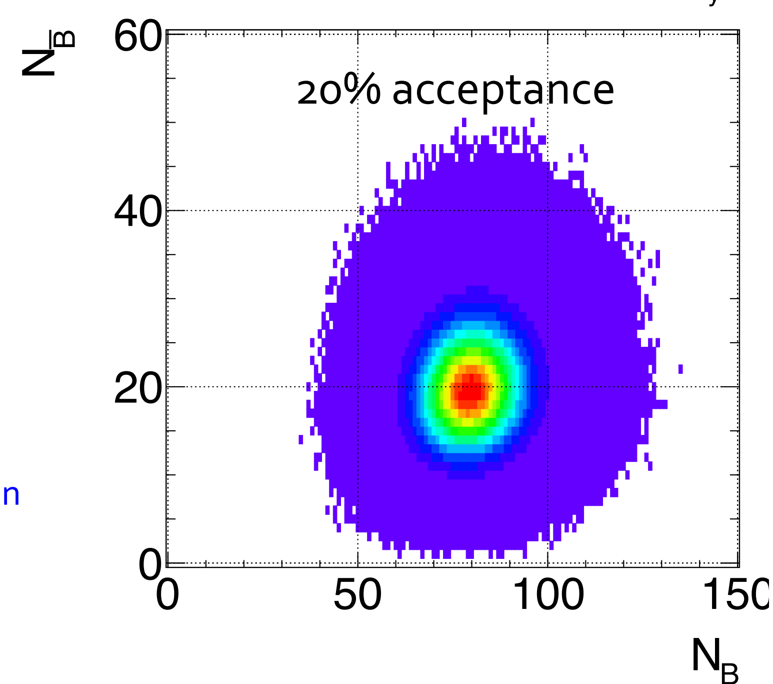
V.V. Begun, M. I. Gorenstein, O. S. Zozulya, PRC 72 (2005) 014902
M. I. Gorenstein, W. Greiner, A. R., PLB 731 (2014) 302-306
P. Braun-Munzinger, B. Friman, F. Karsch, K. Redlich, V. Skokov, NPA 880 (2012)

Technical details

$$N_B = 400, \quad N_{\bar{B}} = 100$$



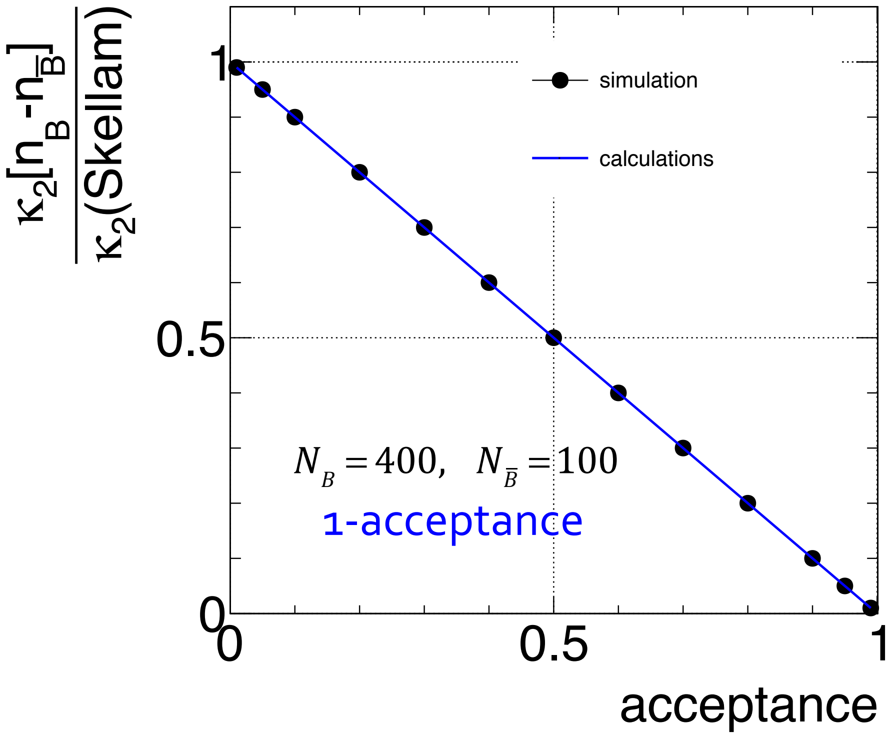


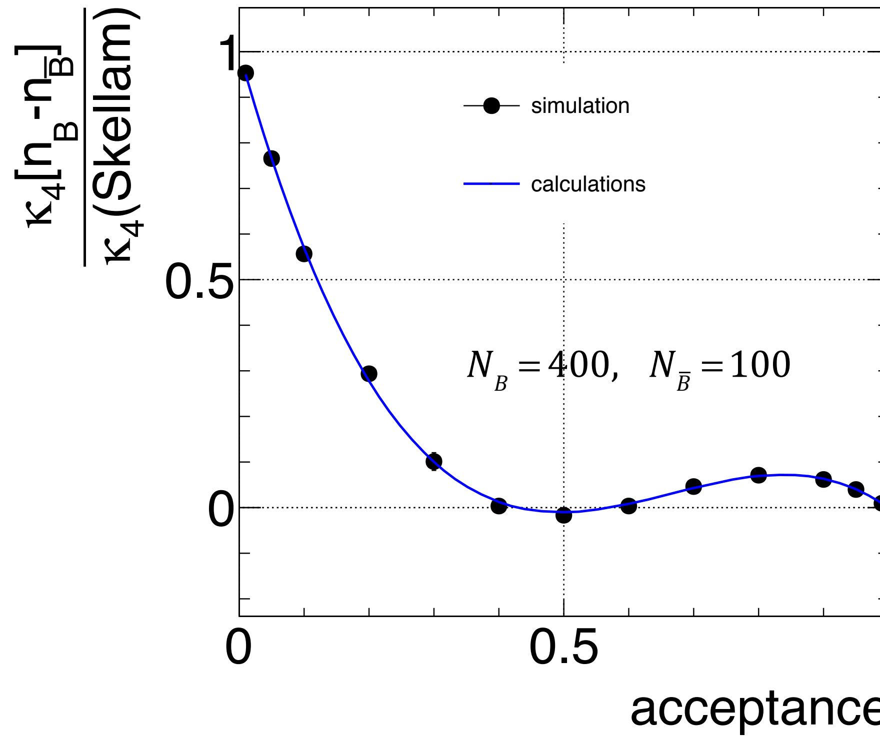


- Fluctuations of net-baryons appear only inside finite acceptance

P. Braun-Munzinger, A. Rustamov, J. Stachel, in preparation

Importance of acceptance

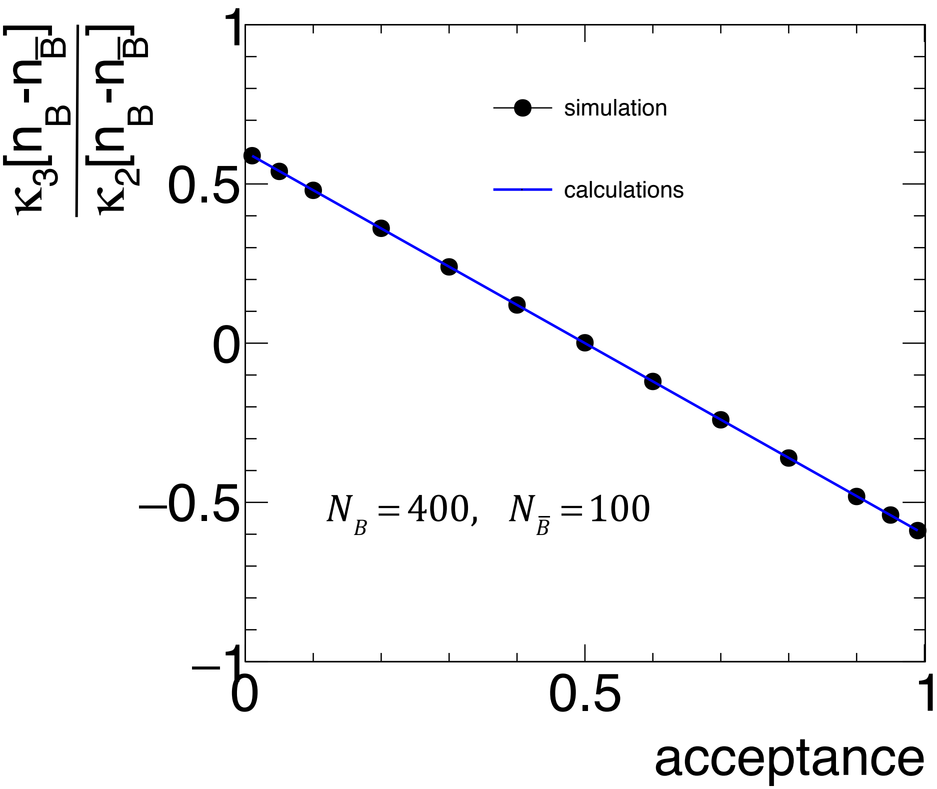


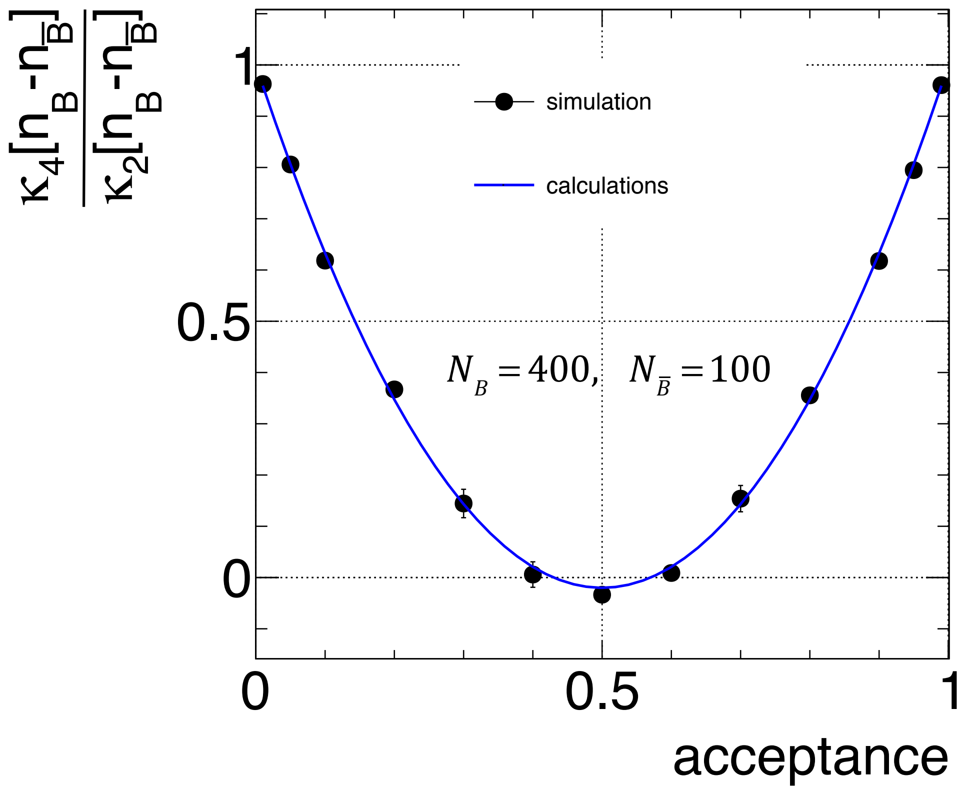


- Approach to independent Poisson (Skellam) for a small acceptance
- Approach to zero for full acceptance
- Acceptance is more crucial for the 4th cumulant

Third and fourth cumulants

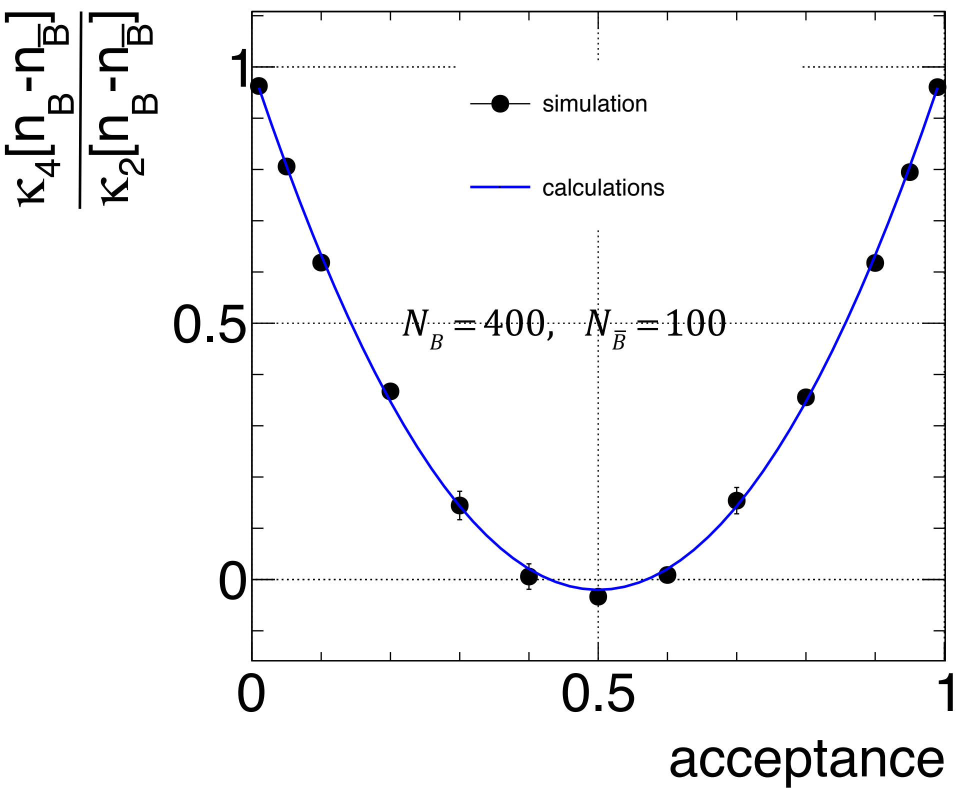
$$\frac{\kappa_3}{\kappa_2} = \frac{\langle n_B - n_{\bar{B}} \rangle_{CE}}{\langle n_B + n_{\bar{B}} \rangle_{CE}} (1-2\alpha) \xrightarrow{\langle n_{\bar{B}} \to 0 \rangle} (1-2\alpha)$$



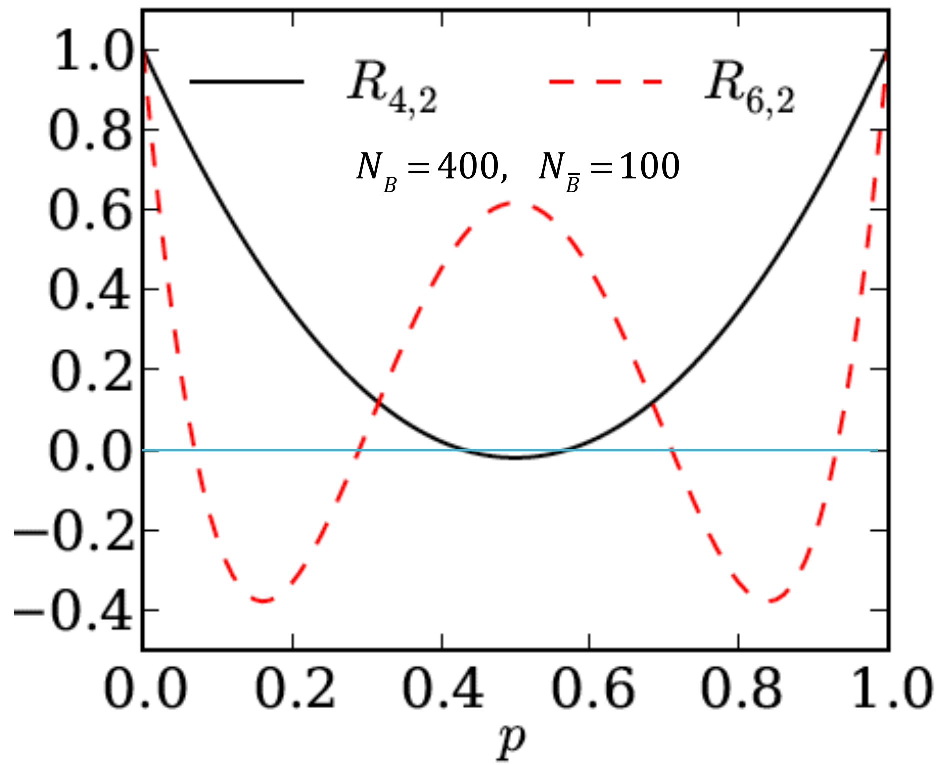


$$\frac{\kappa_4}{\kappa_2} = 1 - 6\alpha(1-\alpha)\left(1 - \frac{2}{\langle n_B + n_{\bar{B}} \rangle_{CE}} \left[\langle n_B \rangle_{GCE} \langle n_{\bar{B}} \rangle_{GCE} - \langle n_B \rangle_{CE} \langle n_{\bar{B}} \rangle_{CE} \right] \right)$$

Comparisons between the two



P. Braun-Munzinger, A. Rustamov, J. Stachel, in preparation

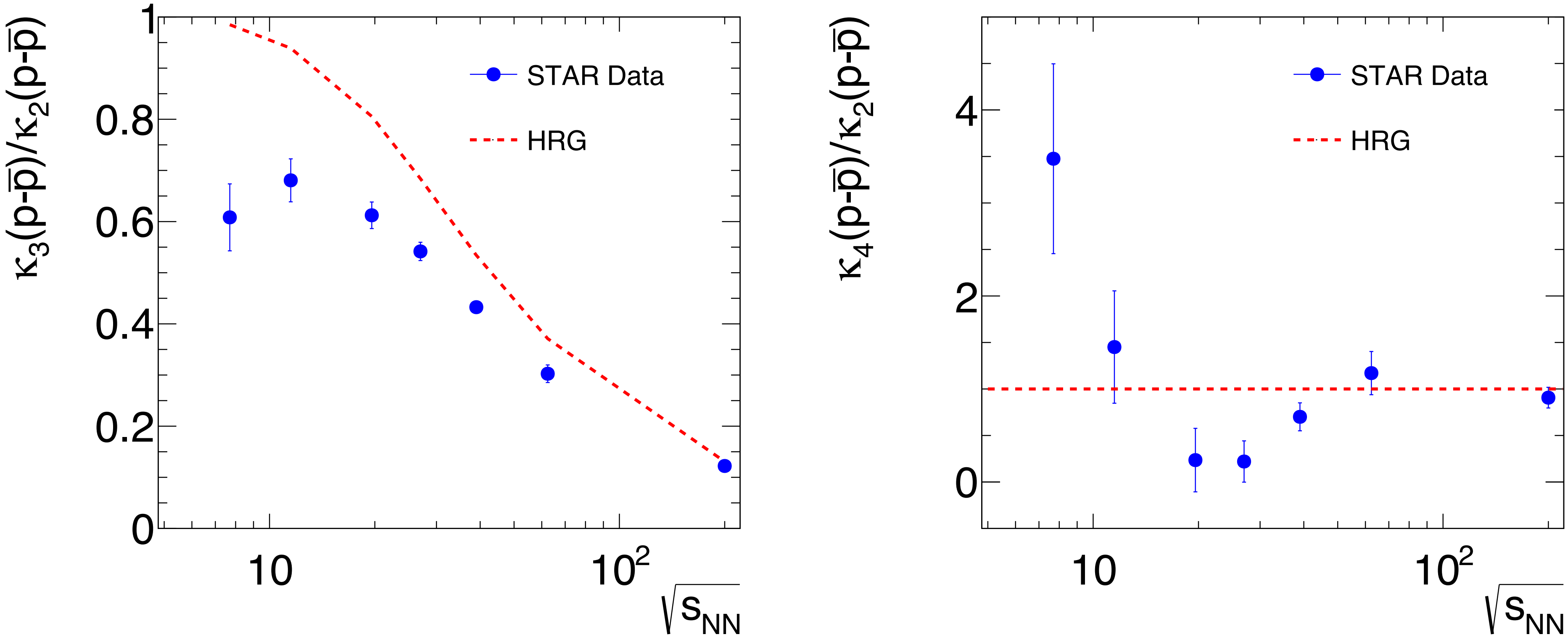


A. Bzdak, V. Koch, V. Skokov, PRC87 (2013) 014901

Same results in both approaches

Results from STAR, deviations from HRG

At low energies : opposite deviations from HRG baseline for 3rd and 4th cumulants!

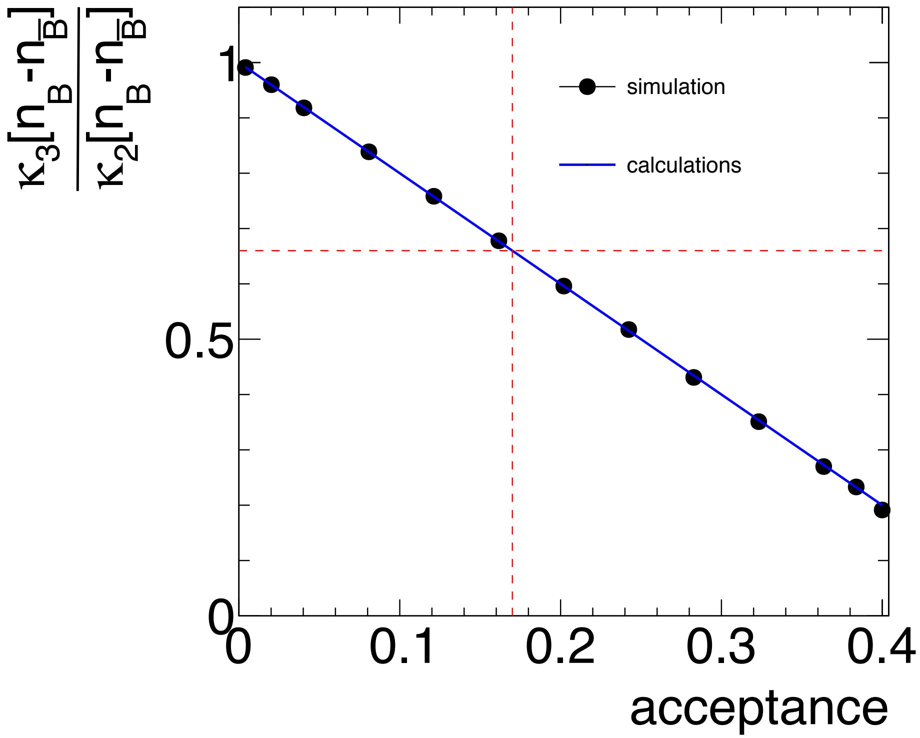


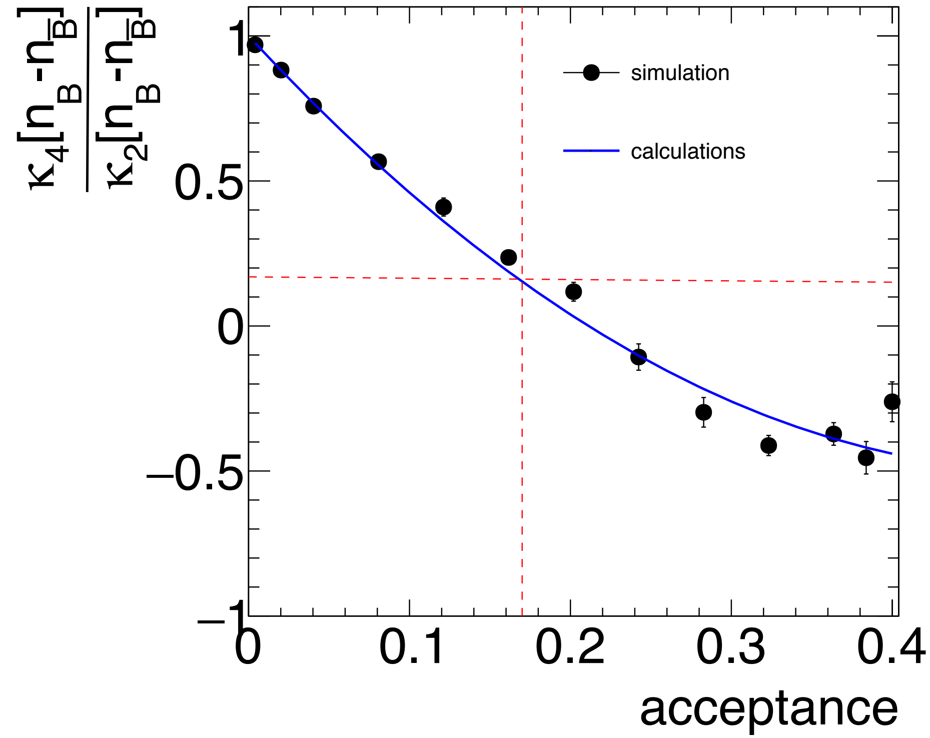
$$\frac{\kappa_3}{\kappa_2} = \frac{\langle n_B - n_{\bar{B}} \rangle_{CE}}{\langle n_B + n_{\bar{B}} \rangle_{CE}} (1 - 2\alpha), \quad \alpha_{\sqrt{s}=7.7GeV} = 0.19 \pm 0.03, \quad \alpha_{\sqrt{s}=19.6GeV} = 0.12 \pm 0.016$$

Based on data from X. Luo, PoS CPOD2014, 019 (2015)

40 GeV lab momentum, $s^{1/2} \approx 8.8$ GeV

Input to the model (in 4π): $\langle N_B \rangle = 351$, $\langle N_{\bar{B}} \rangle = 0$, experimentally measured rapidity dist.

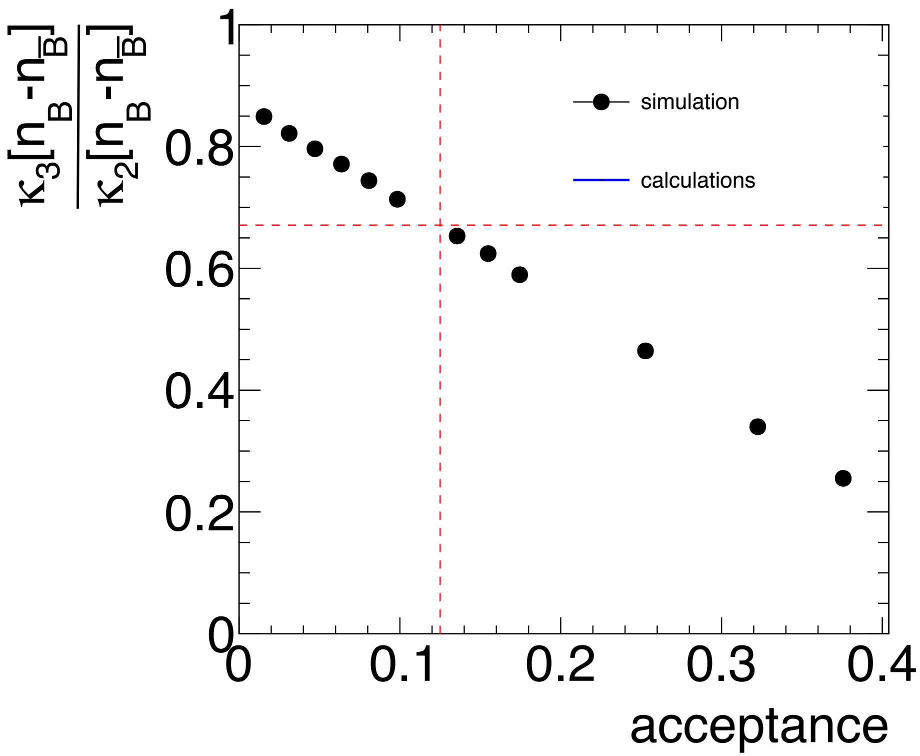


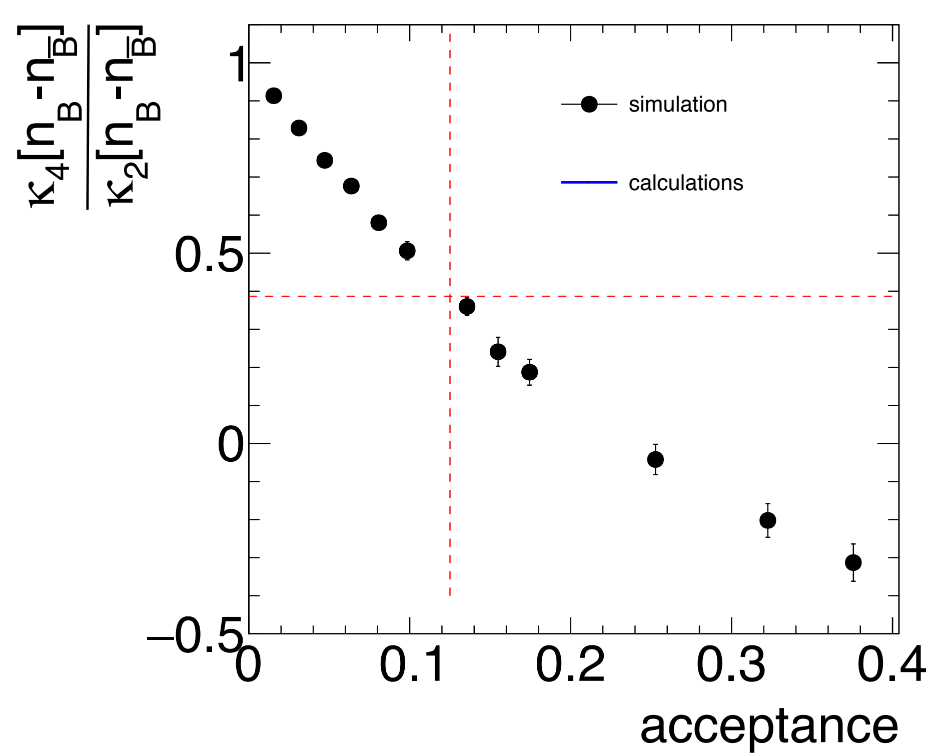


$\alpha_{\sqrt{s}=8.8GeV} = 0.17$ estimated from energy dependence

158 GeV lab momentum, $s^{1/2} \approx 17.3$ GeV

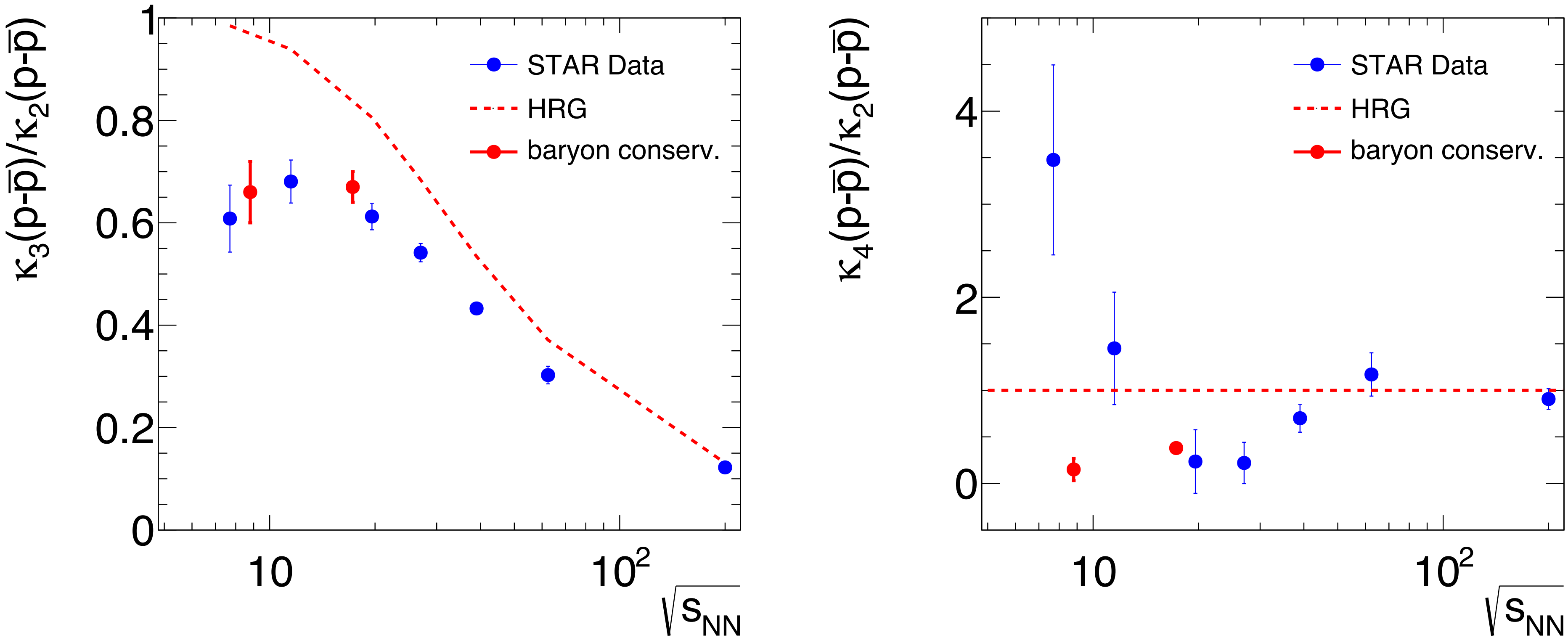
Input to the model (in 4π): $\langle N_B \rangle = 373$, $\langle N_{\bar{B}} \rangle = 20$, experimentally measured rapidity dist.





$\alpha_{\sqrt{s}=17.3GeV} = 0.125$ estimated from energy dependence

Our predictions



At 7.7 GeV k3/k2 and k4/k2 cannot be simultaneously explained

Summary

- NA61/SHINE data show a significant jump in K^+/π^+ ratio from light to heavy systems
- No anomalies are observed in the energy dependence of fluctuations for p+p, Be+Be and Ar+Sc.
- The measured second cumulants of net-protons at ALICE are, after accounting for baryon number conservation, in agreement with the corresponding second cumulants of the Skellam distribution.
    - LQCD predicts a Skellam behavior for κ_2 of net-baryons at 150 MeV.
- Net-proton measurements from STAR hint for a non-monotonic behavior for energies below 39 GeV. More statistics and control of systematics are needed.
- At 7.7 GeV the energy dependence of k3/k2 and k4/k2 of net-protons from STAR cannot be simultaneously described by baryon-number conservation
- At 19.6 GeV both k3/k2 and k4/k2 are in agreement with the baryon number conservation

The analysis of higher cumulants are ongoing in ALICE, which is extremely important for understanding the nature of transition at vanishing μ_B