IDENTIFIED PARTICLE NUMBER FLUCTUATIONS FROM ALICE AT THE CERN LHC

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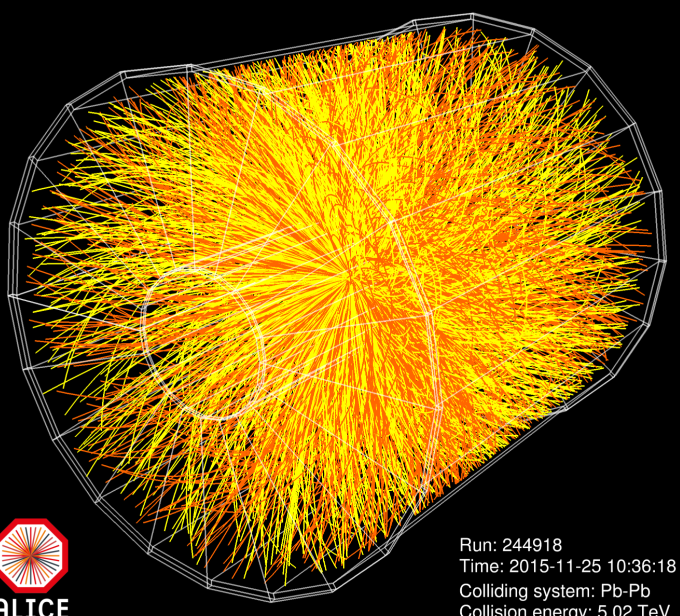
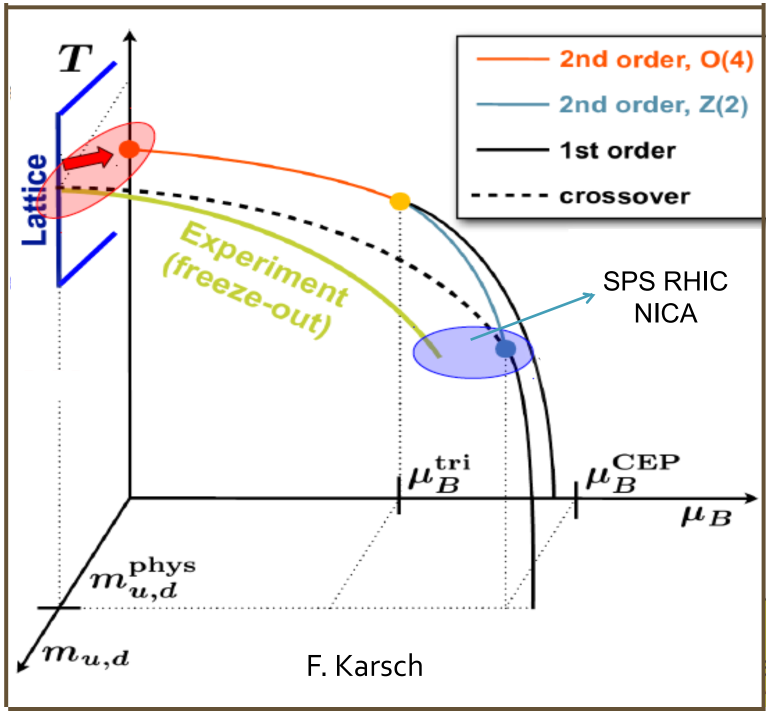
for the ALICE Collaboration



- Why fluctuations?
- Net-proton fluctuations
- Non-dynamical contributions
- Net-Lambda fluctuations
- Future possibilities
- Summary

Why fluctuations?



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

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

$$\frac{\langle N^2\rangle - \langle N\rangle^2}{\langle N\rangle^2} = \frac{T\chi}{V}, \quad \chi = -\frac{1}{V}\frac{\partial V}{\partial P}$$

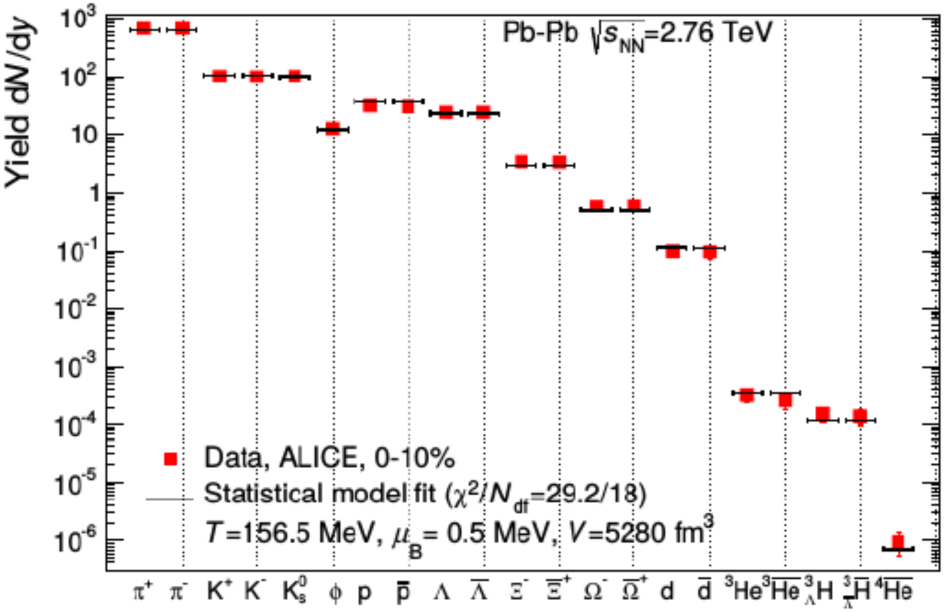
direct link to the EoS

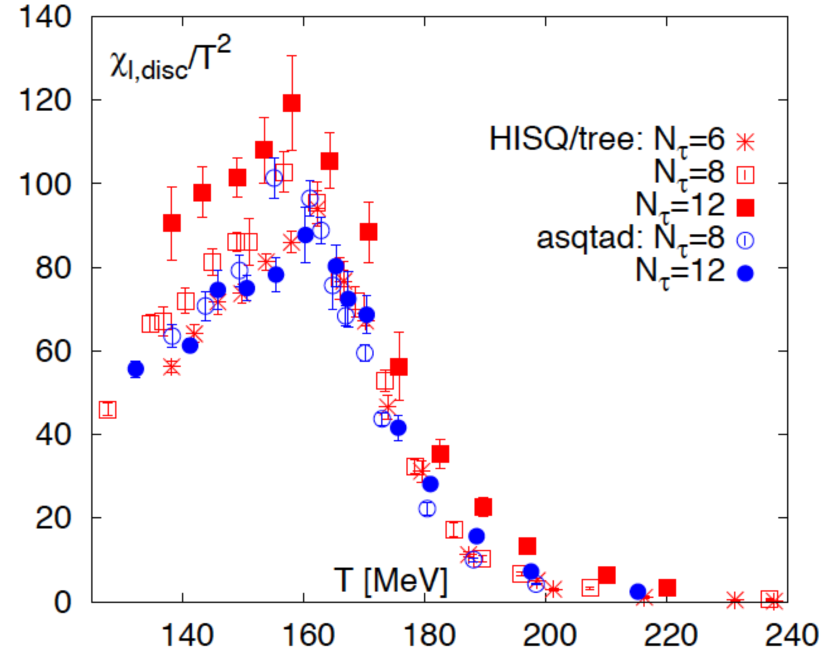
fingerprints of criticality for $m_{u,d} = 0$ survive at crossover with $m_{u,d} \neq 0$

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

probing the response of the system to external perturbations

Criticality at crossover





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

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

freeze-out at the phase boundary

$$T_c^{LQCD} = 156.5 \pm 1.5\ MeV$$

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

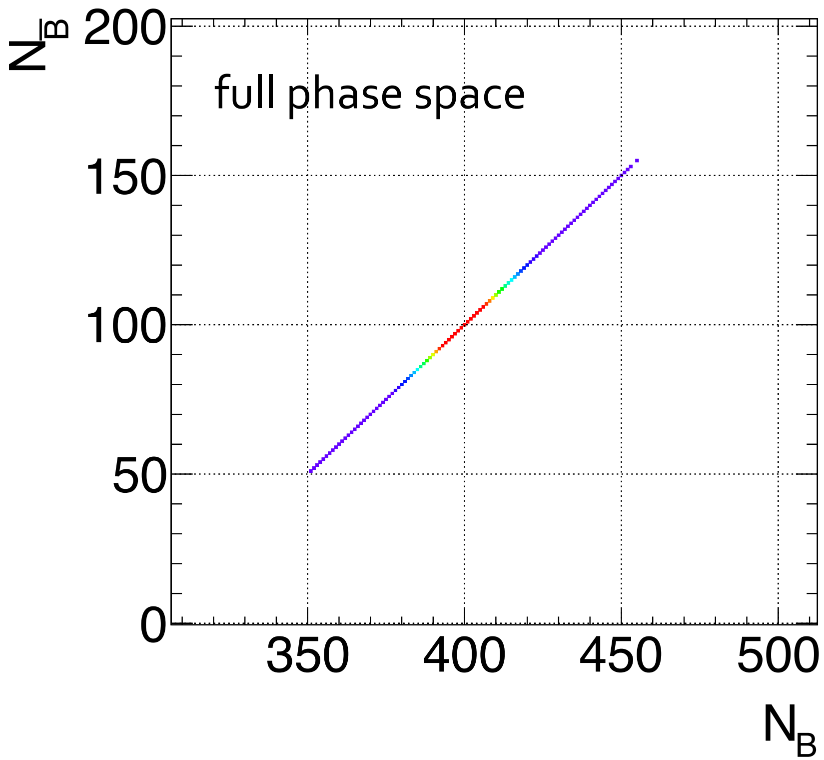
ALICE, PLB 726 (2013) 610
A. Andronic, P. Braun-Munzinger, K. Redlich and J. Stachel, Nature 561, 321–330 (2018)

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

What fluctuates?

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



conservation of the net-baryon number

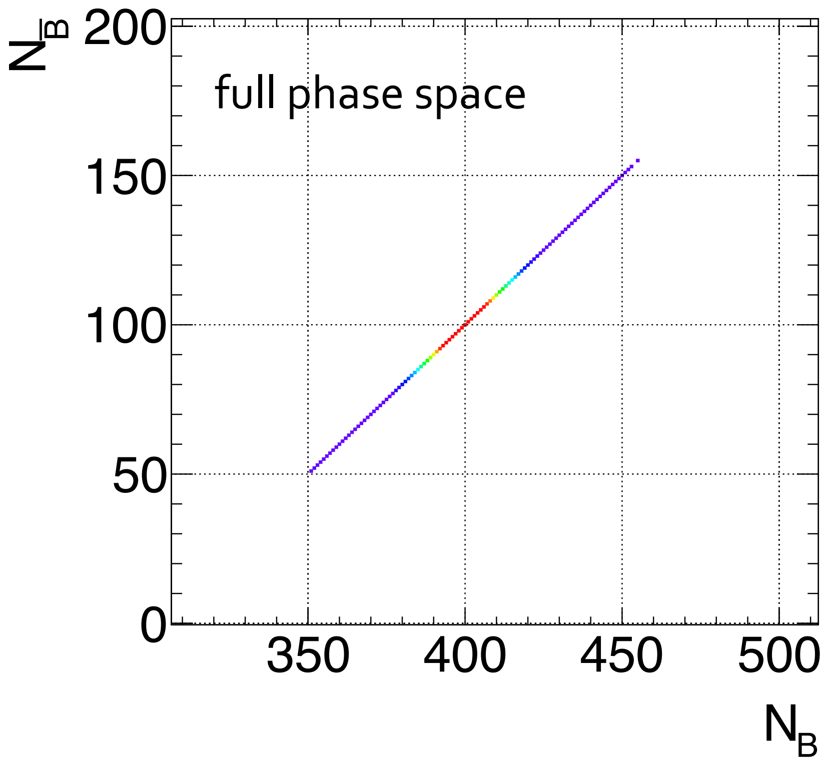
fluctuations of conserved quantities

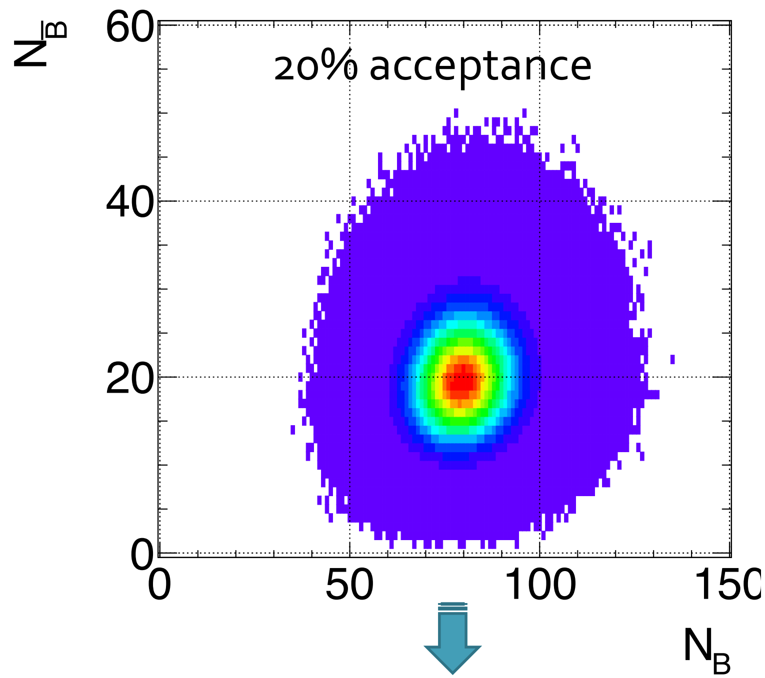
e.g., $N_B - N_{\bar{B}}$

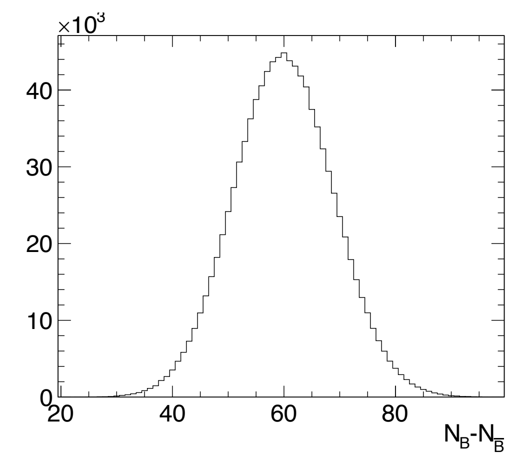
P. Braun-Munzinger, A. R., J. Stachel; QM18, arXiv:1807.08927

What fluctuates?

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







- **fluctuations of net-baryons appear only inside finite acceptance**

P. Braun-Munzinger, A. R., J. Stachel; QM18, arXiv:1807.08927

Net-particle cumulants, definitions

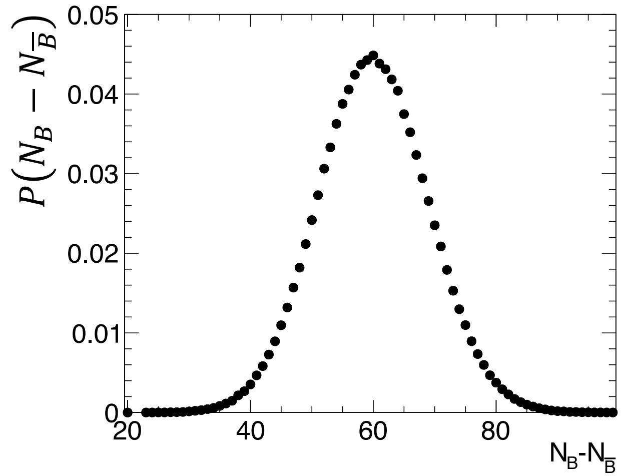
$$X = N_B - N_{\overline{B}}$$

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

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



Uncorrelated Poisson limit: $\langle N_B N_{\overline{B}} \rangle = \langle N_B \rangle \langle N_{\overline{B}} \rangle$

Net-Baryons → Skellam

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

$$\frac{\kappa_{2n+1}}{\kappa_{2k}} = \tanh\left(\frac{\mu}{T}\right) = \frac{\langle N_B \rangle - \langle N_{\overline{B}} \rangle}{\langle N_B \rangle + \langle N_{\overline{B}} \rangle}$$

Baselines from LQCD

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

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

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

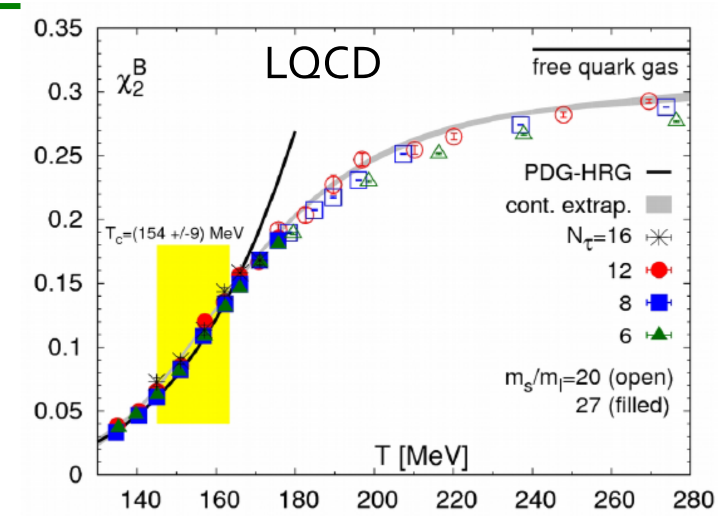
$$\frac{\kappa_4(\Delta N_B)}{\kappa_2(\Delta N_B)} = \frac{\hat{\chi}_4^B}{\hat{\chi}_2^B} \qquad \frac{\kappa_3(\Delta N_B)}{\kappa_2(\Delta N_B)} = \frac{\hat{\chi}_3^B}{\hat{\chi}_2^B}$$

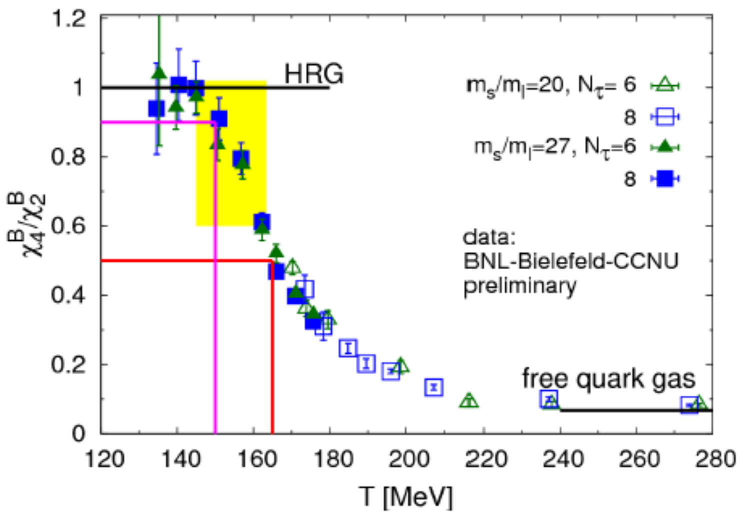
valid only for a fixed system volume

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

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

- *In experiments*
  - *Volume (participants) fluctuates from E-to-E*
    - *Centrality selection is crucial*
  - *Global conservation laws are important*
    - *Acceptance selection is crucial*





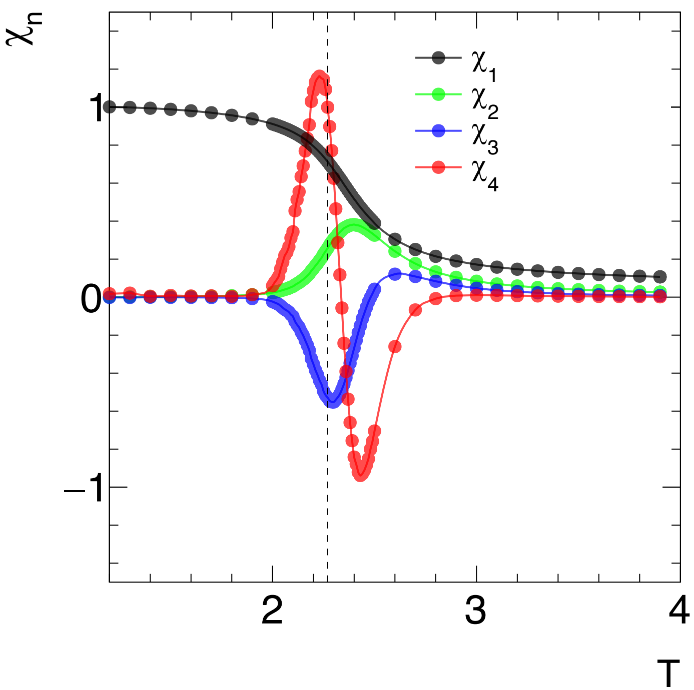
smaller than in HRG for T > 150 MeV

F. Karsch; QM17, arXiv:1706.01620

O. Kaczmarek; QM17, arXiv:1705.10682

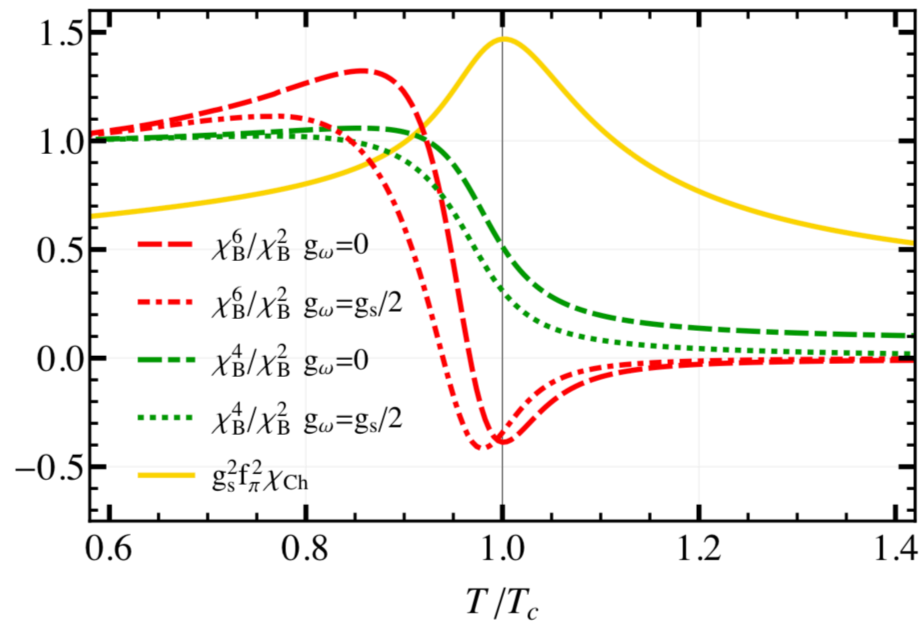
Importance of higher order cumulants

higher order cumulants are
more sensitive to the critical behavior



2D Ising Model (16x16)

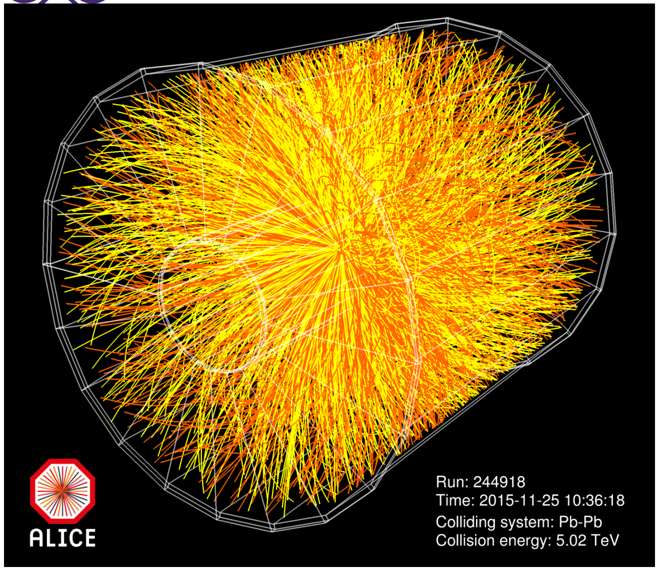
A. R. In progress



Polyakov-loop extended
Quark Meson Lagrangian

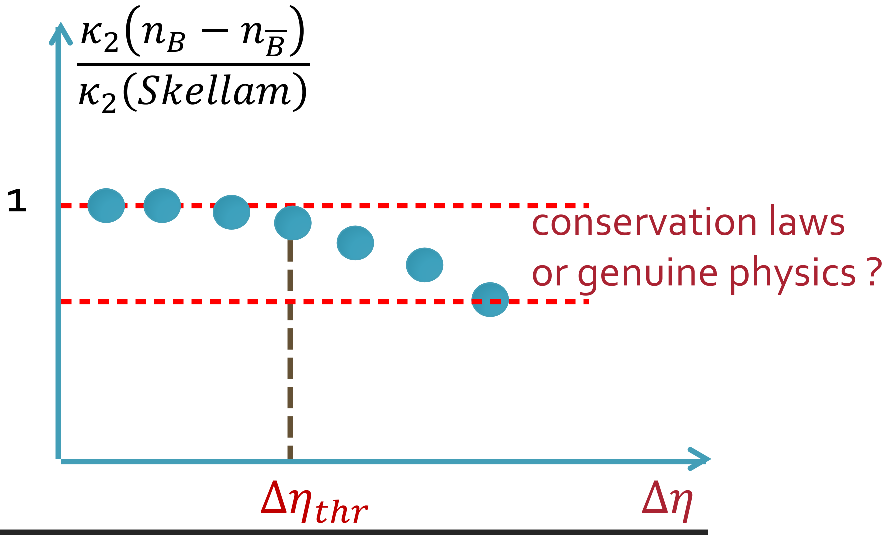
G. A. Almasi, B. Friman, K. Redlich, P.R.D96 (2017) 1, 014027.

Acceptance selection



$\Delta\eta > \Delta\eta_{thr}$: conservations laws dominate

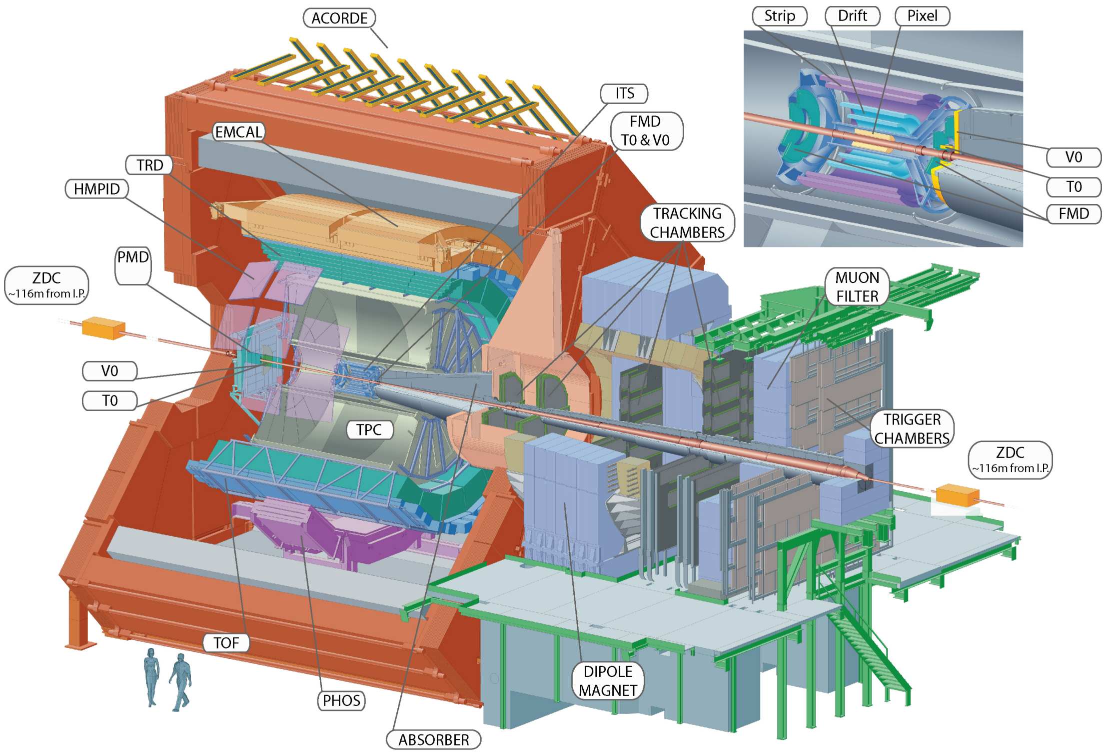
$\Delta\eta < \Delta\eta_{thr}$: dynamical fluctuations may disappear



- **The strategy**
  - Perform analysis for $\Delta\eta > \Delta\eta_{thr}$
  - Correct for non-dynamical contributions
    - Conservation laws
    - Volume fluctuations
    - etc.
  - Compare to theory

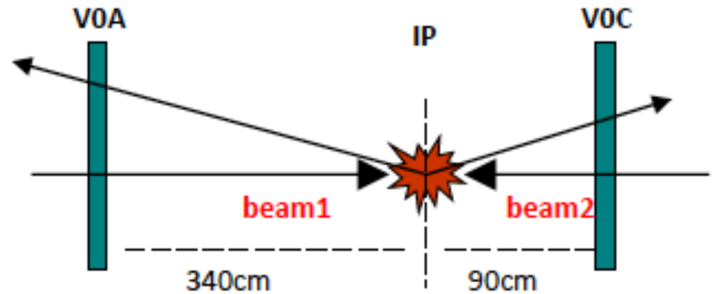
P. Braun-Munzinger, A. R., J. Stachel, NPA 960 (2017) 114

The ALICE apparatus

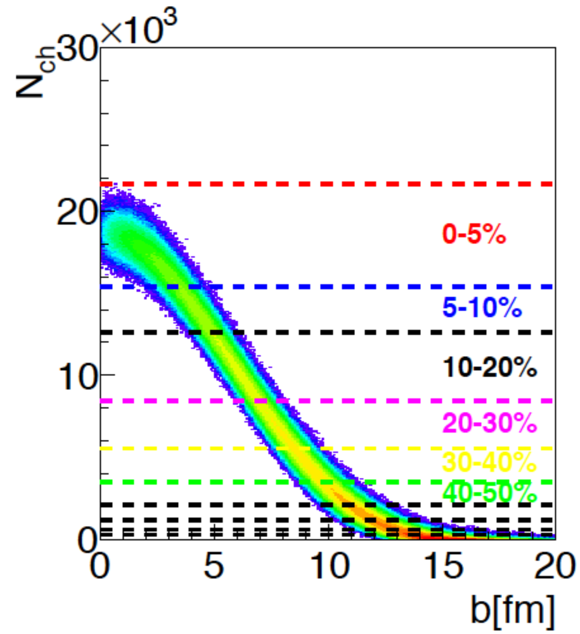


Used in this analysis: ITS, TPC, V0

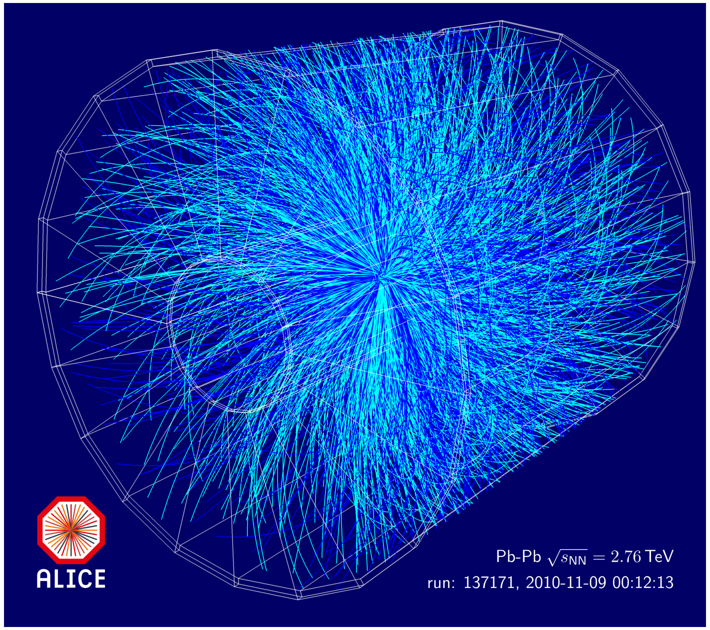
Centrality selection

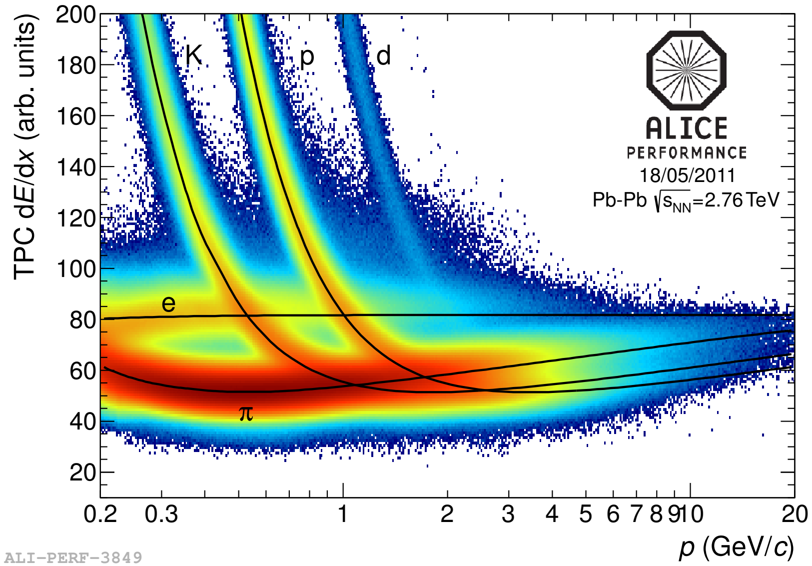


$2.8 < \eta < 5.1$ $-3.7 < \eta < -1.7$



Particle Identification





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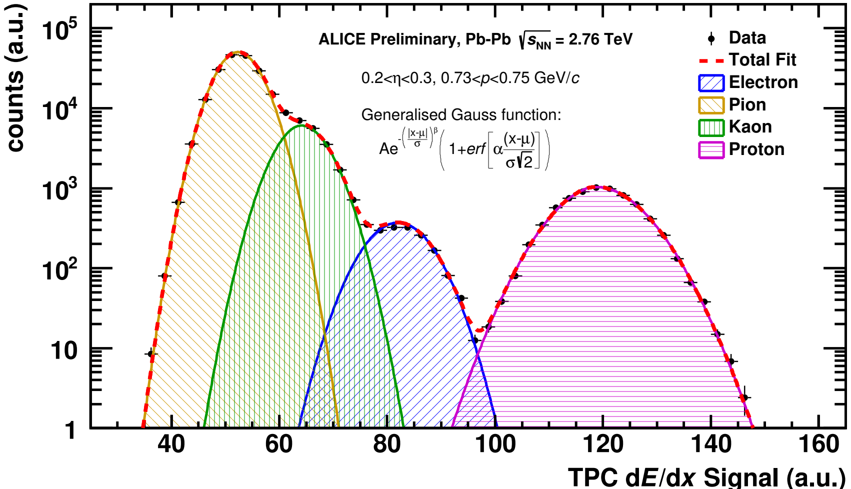

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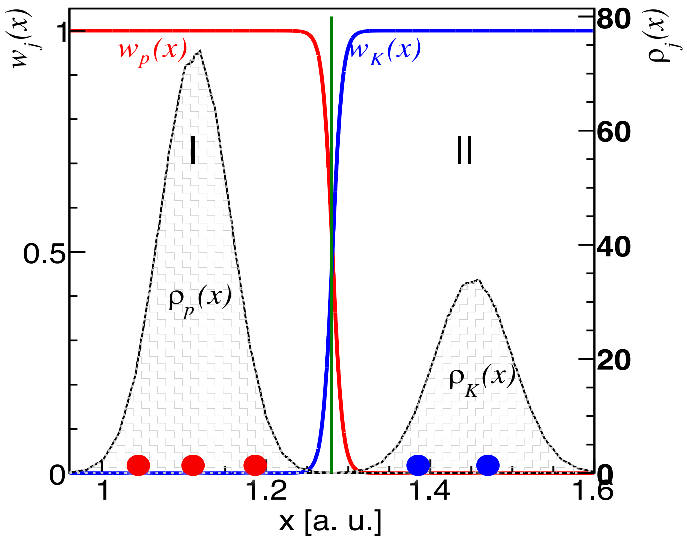
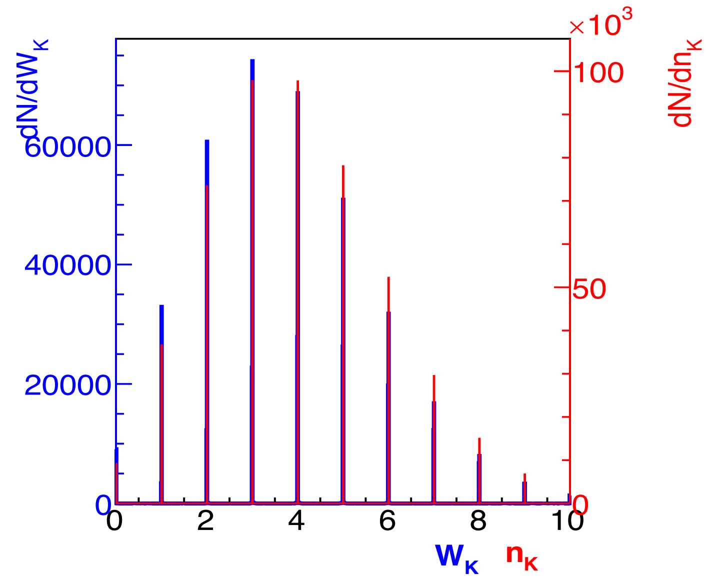
Analysis Techniques





single event example : 3 protons, 2 kaons

traditional approach

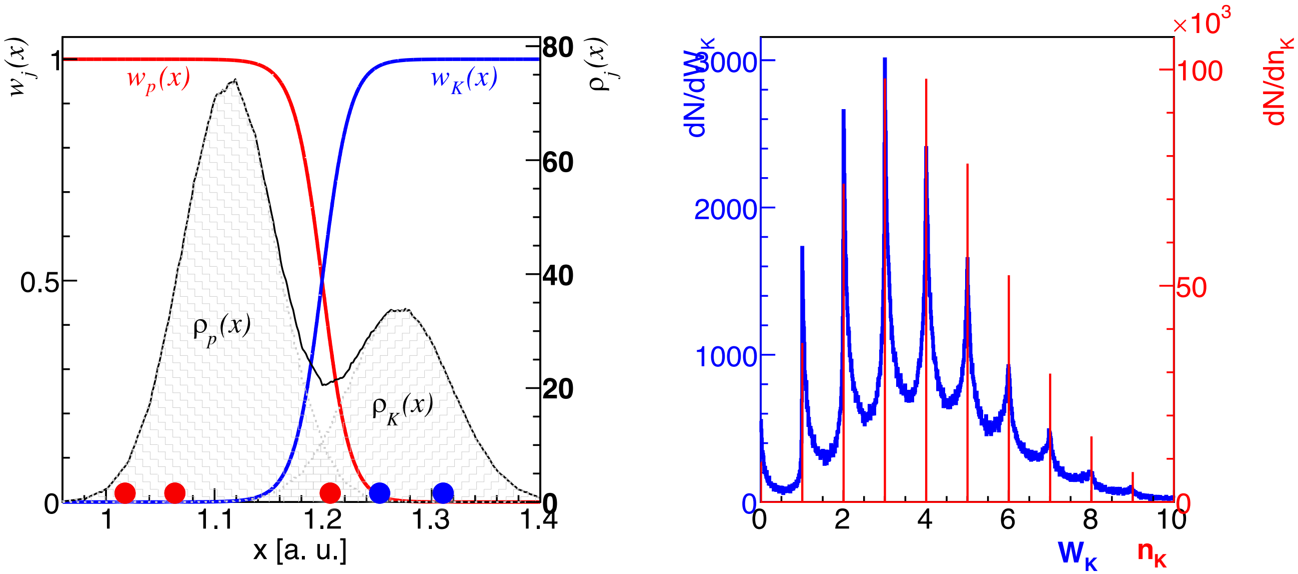
measurement in region I
count as proton
measurement in region II
count as kaon

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 Techniques



single event example : 3 protons, 2 kaons

traditional approach

Use additional detector information
Or reject a given phase space bin

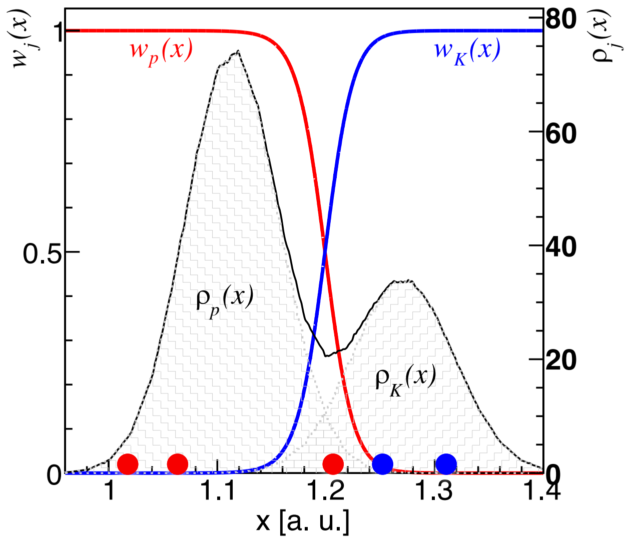
(challenge: efficiency correction)

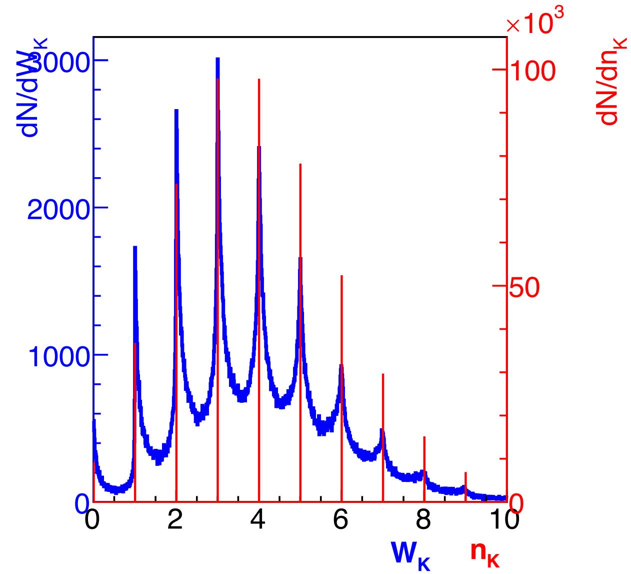
Identity method approach

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

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

The Identity Method





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

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)
M. Arslandok , A. Rustamov, arXiv:1807.06370

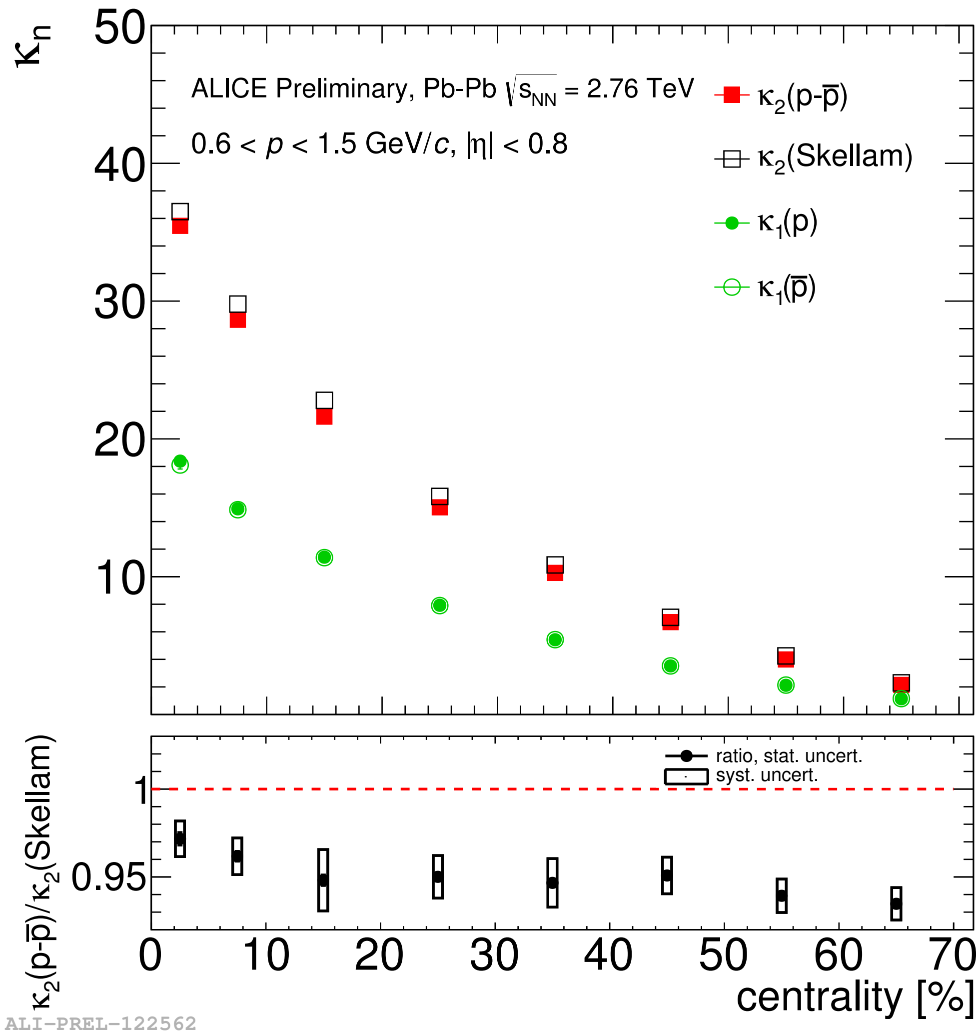
Used in ALICE, NA49, NA61/SHINE

NET-PROTON FLUCTUATIONS

- At LHC energies net-proton is a reasonable proxy for net-baryon

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

Net-protons, protons, antiprotons



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

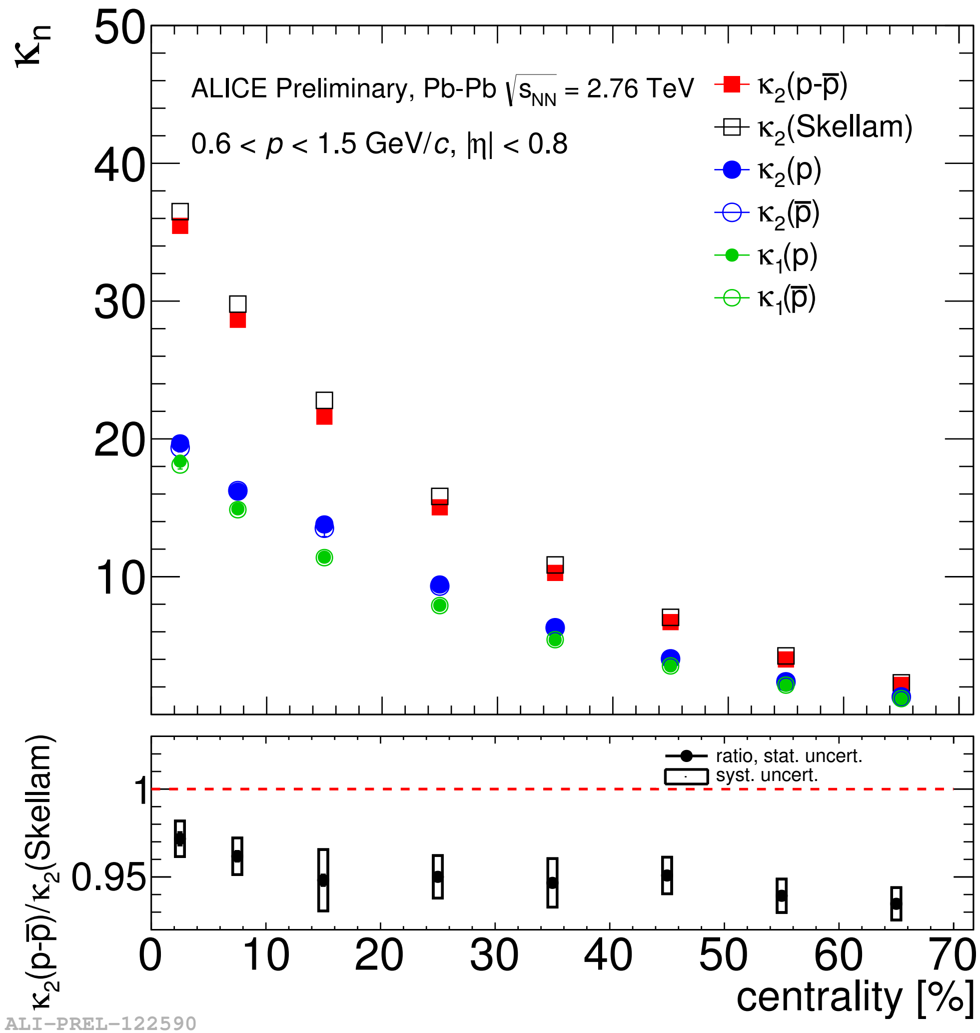
correlation term

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

● + ○ = □ ≠ ■

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

Net-protons, protons, antiprotons



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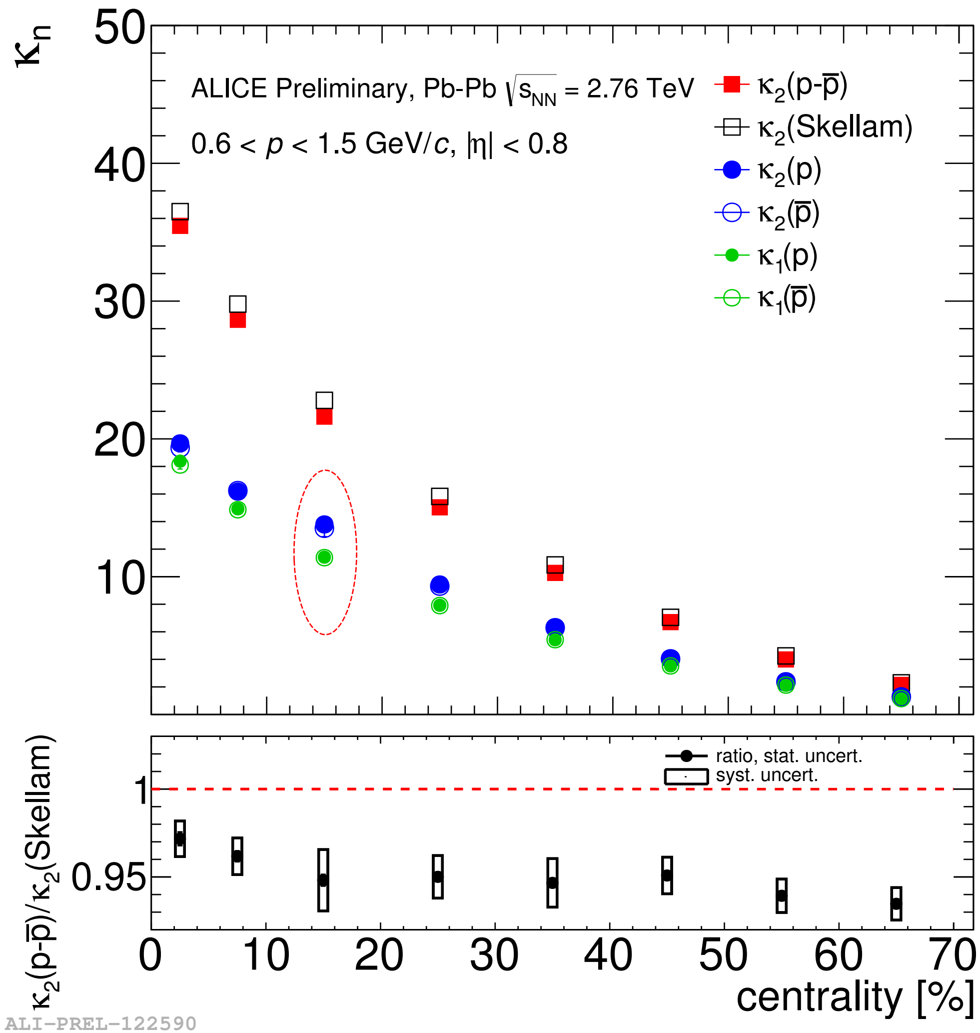
●, ○ ≠ ●, ○

Net-protons, protons, antiprotons



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correlation term

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

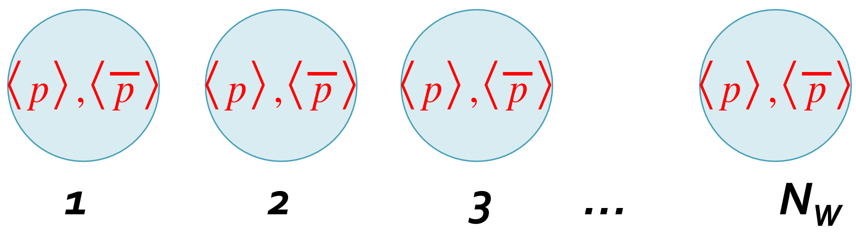
● + ○ = □ ≠ ■

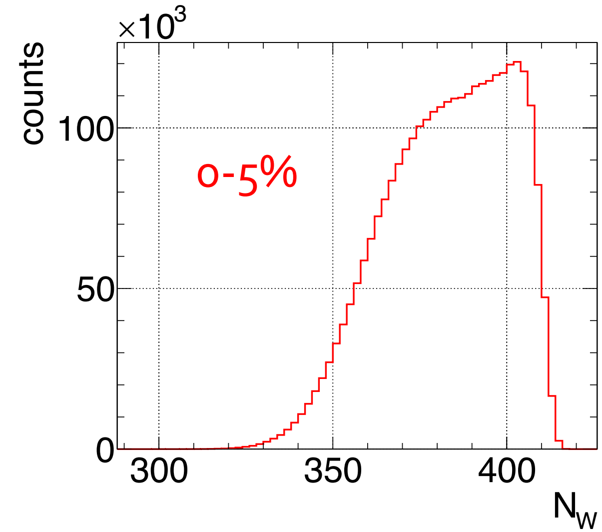
- correlation term?
- non Poisson (anti)protons?

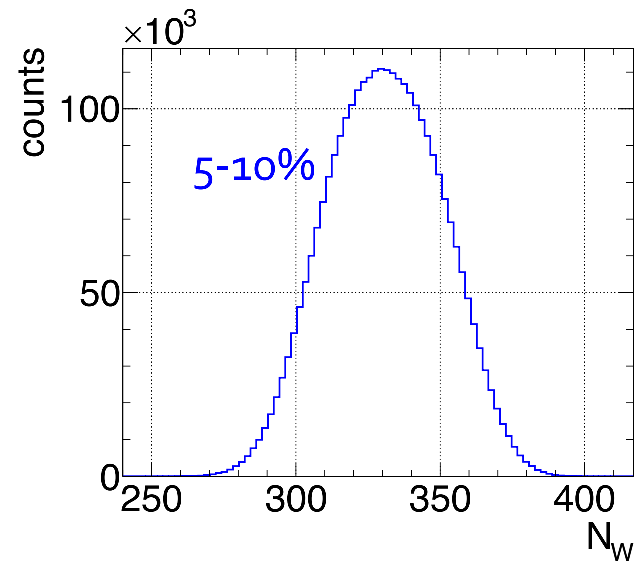
●, ○ ≠ ●, ○

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

Modeling participant fluctuations





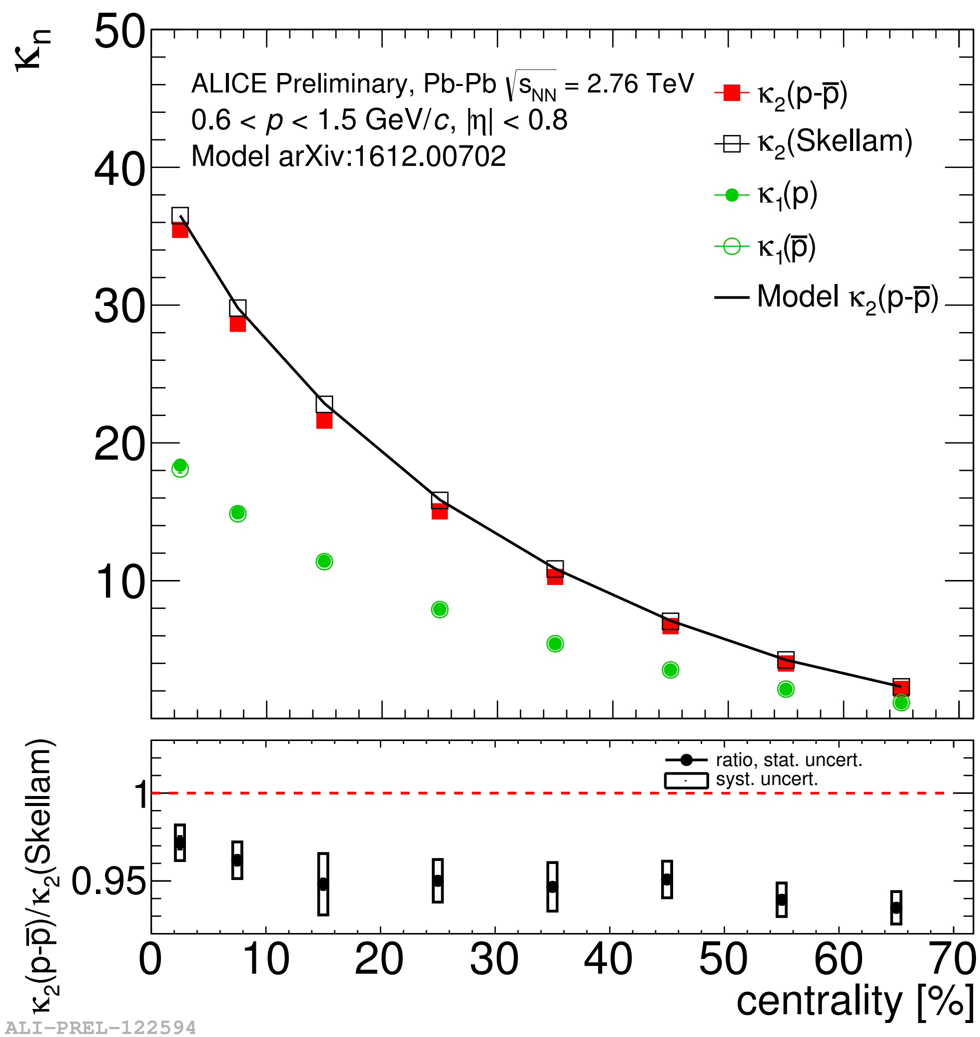


- ***N_W fluctuates with MC Glauber initial conditions***
- ***Each source is treated Grand Canonically***
- ***Mean proton multiplicities $\langle p \rangle$, $\langle \bar{p} \rangle$ from this analysis***
- ***Centrality selection like in experimental data***

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

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

Modeling participant fluctuations



Input to the Model

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

centrality selection procedure

Predictions

——— $\kappa_2(p-\bar{p})$

participants — vanishes at LHC

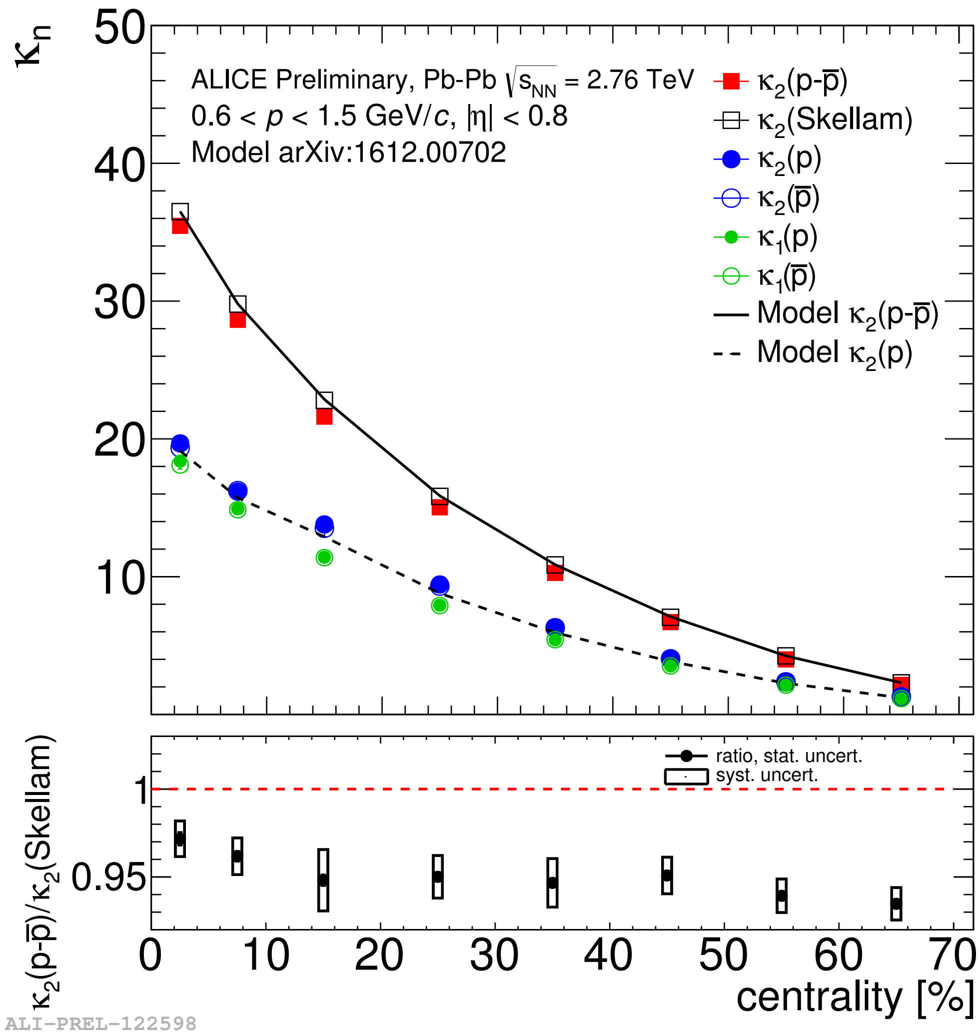
$$\kappa_2(N_B - N_{\bar{B}}) = \langle N_W \rangle \kappa_2(n_B - n_{\bar{B}}) + \langle n_B - n_{\bar{B}} \rangle^2 \kappa_2(N_W)$$

from single participant

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

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

Modeling participant fluctuations



Input to the Model

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

centrality selection procedure

Predictions

———— $\kappa_2(p-\bar{p})$

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

participants

$$\kappa_2(N_B) = \langle N_W \rangle \kappa_2(n_B) + \langle n_B \rangle^2 \kappa_2(N_W)$$

from single participant

Consistent predictions for net-protons, protons and antiprotons

Net-protons, acceptance dependence

Contribution from global baryon number conservation

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

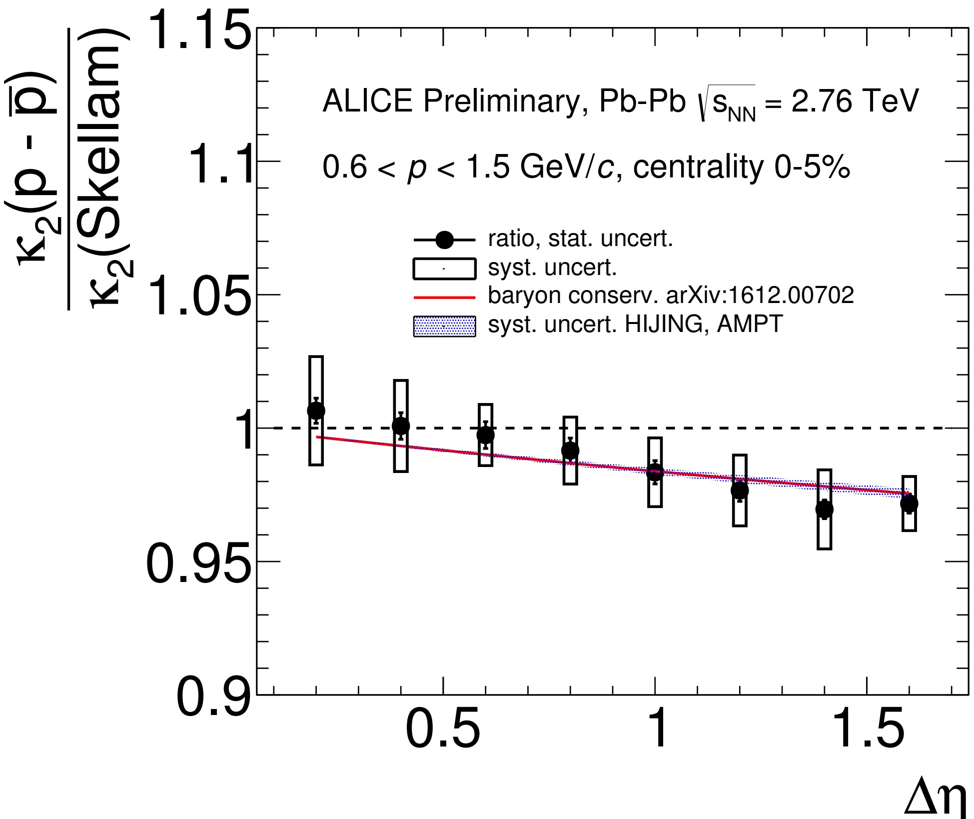
P. Braun-Munzinger, A. R., J. Stachel, arXiv:1807.08927

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 $\langle B \rangle^{4\pi}$

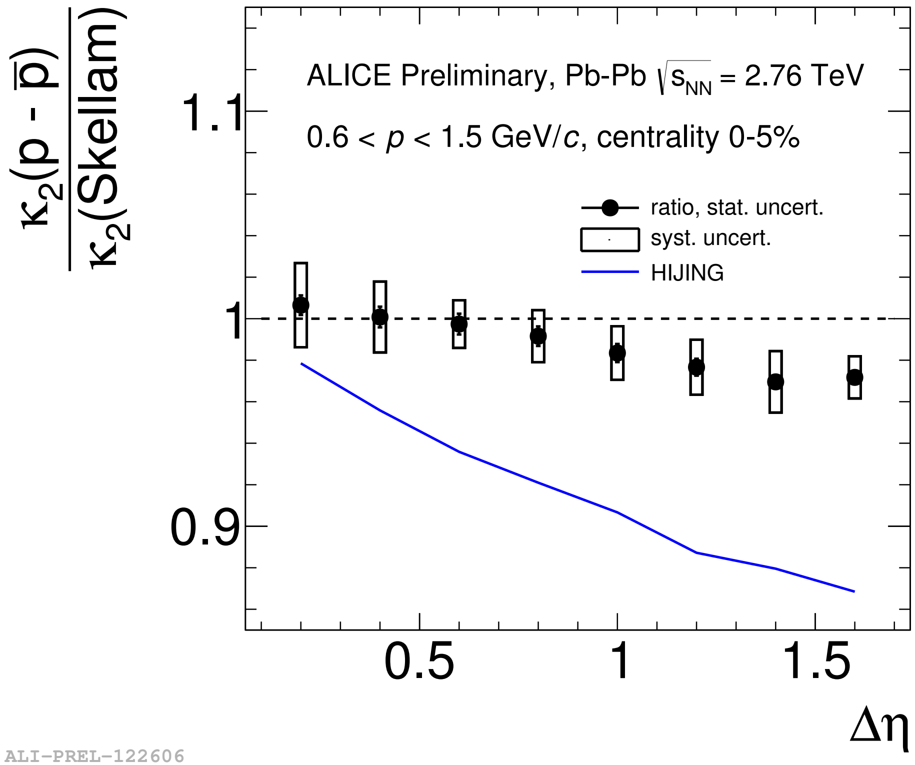
using HIJING and AMPT models

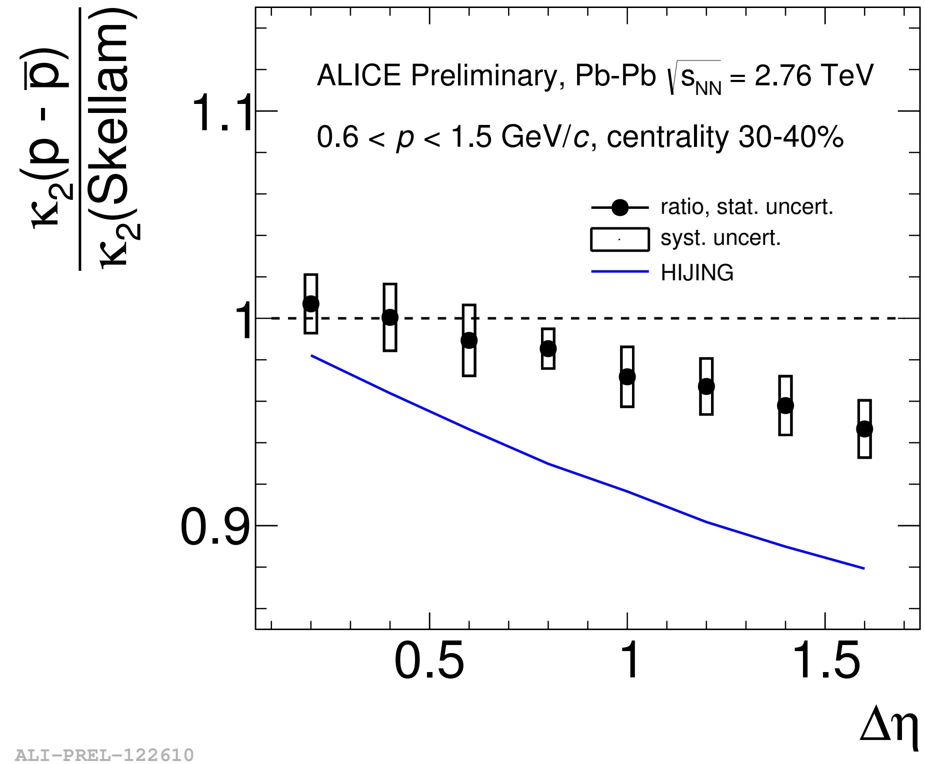


ALI−PREL−122602

The deviation from Skellam is due to global baryon number conservation

Acceptance and centrality dependence

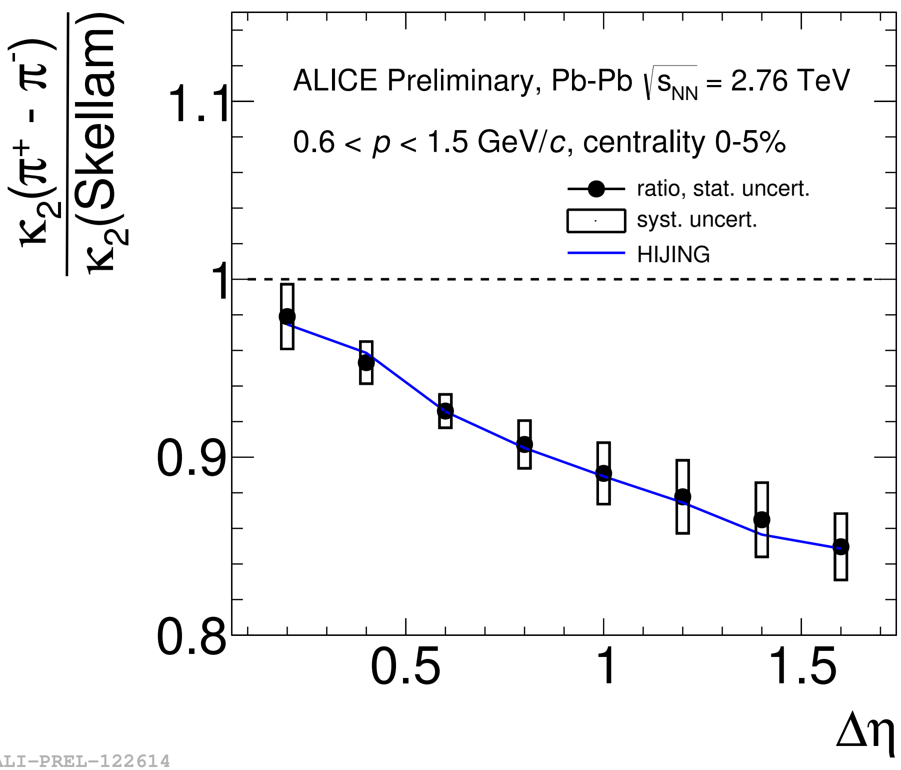




Effect of global baryon number conservation is more significant in peripheral collisions

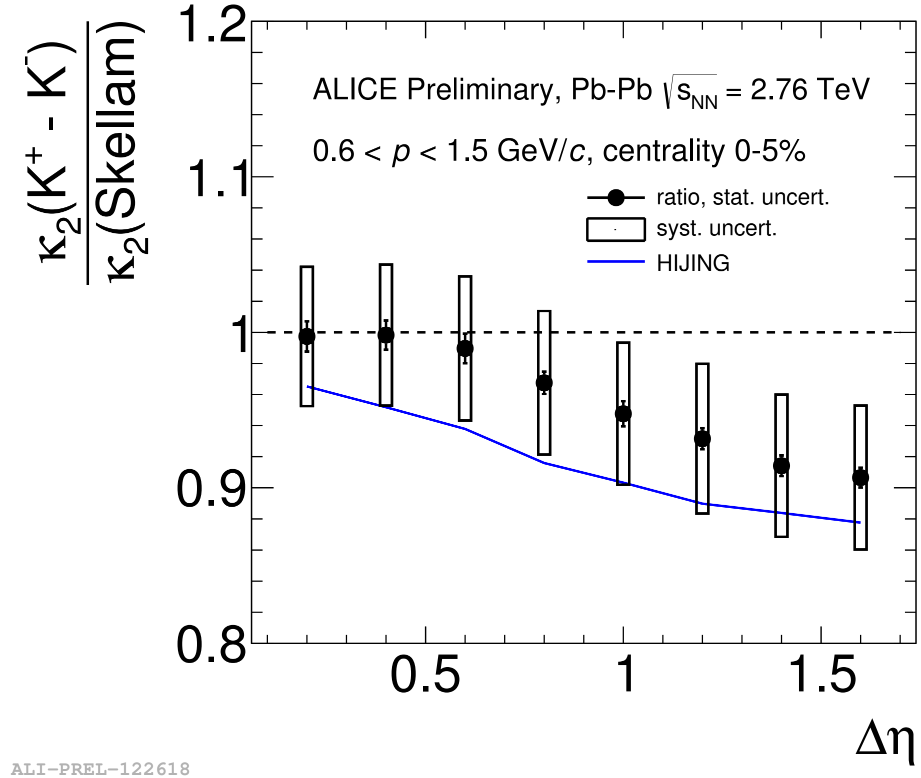
Net-pions and Net-kaons

net-pions



perfect agreement with HIJING

net-kaons

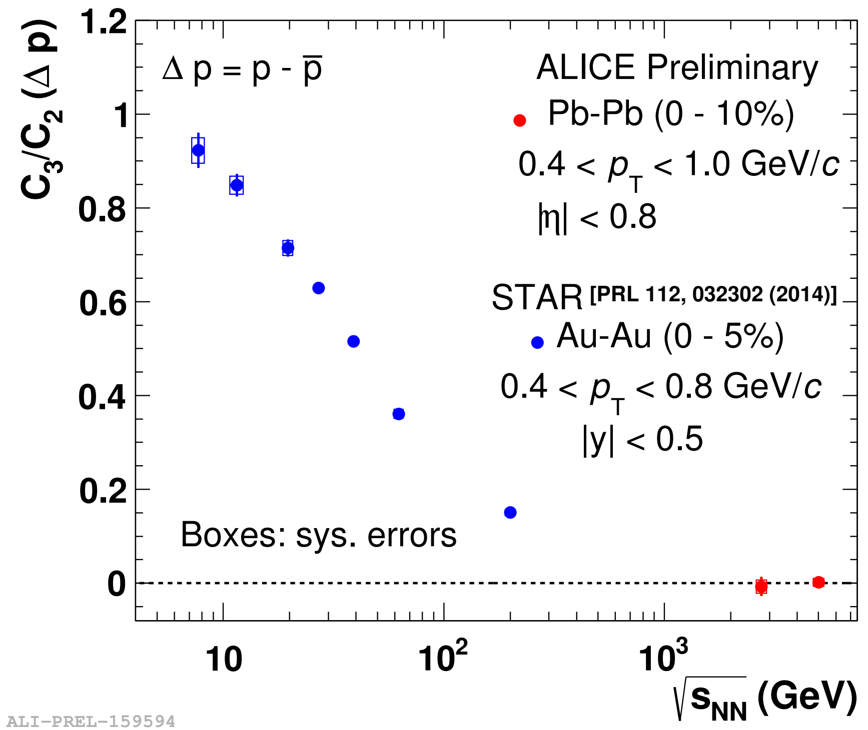


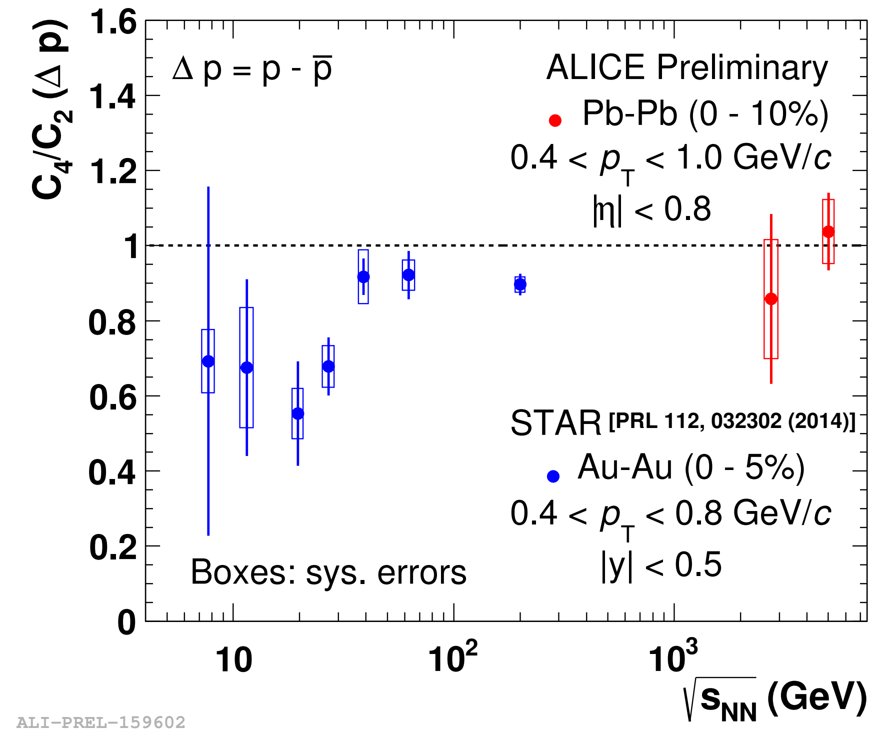
reasonable agreement with HIJING

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

Net-protons, Higher cumulants





ALICE, QM18, arXiv:1807.06780

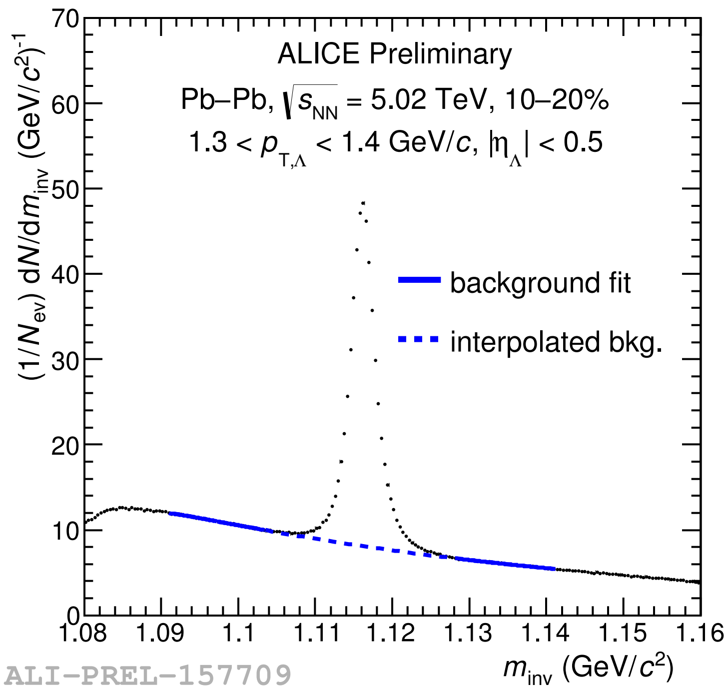
measured with the traditional approach in a rather small p_T acceptance

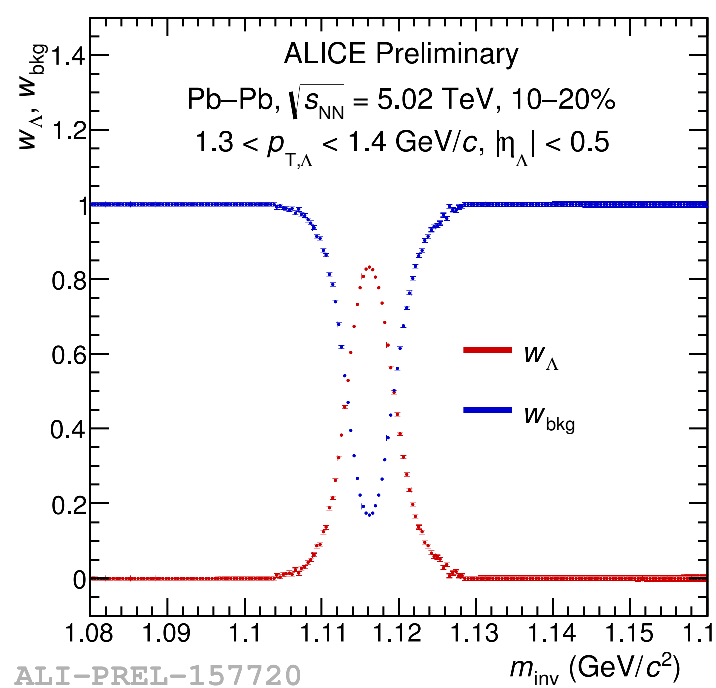
Both ALICE and STAR attempting to improve p_T acceptance

NET-LAMBDA FLUCTUATIONS

- To study correlated baryon-strangeness fluctuations
- To improve understanding of net-baryon baseline

Identity Method for Λ



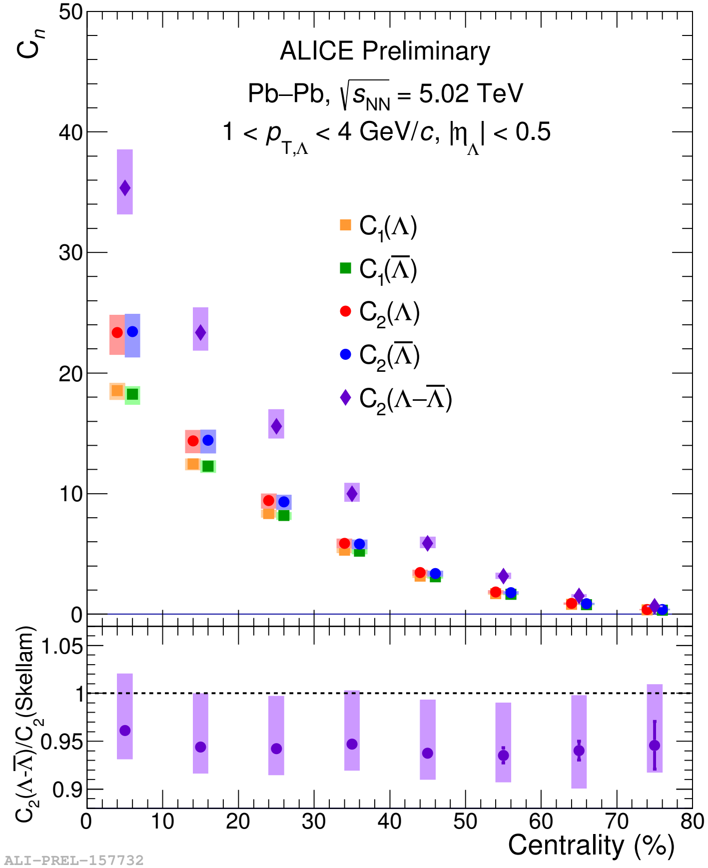


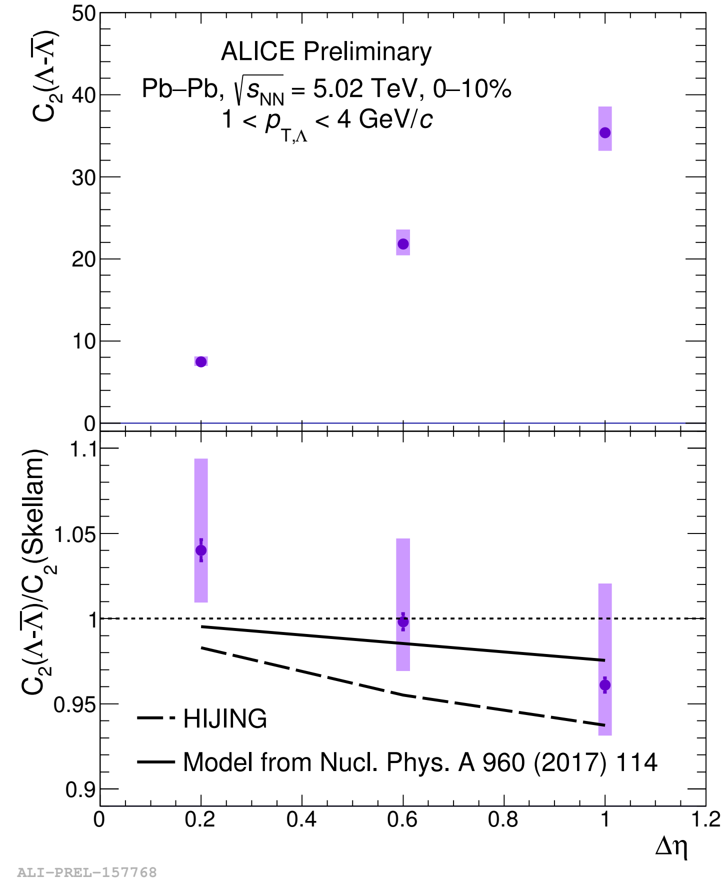
similar to the Identity method for 2 particle species (signal and background in this case)

ALICE, QM18

Net-Lambdas

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





ALICE, QM18

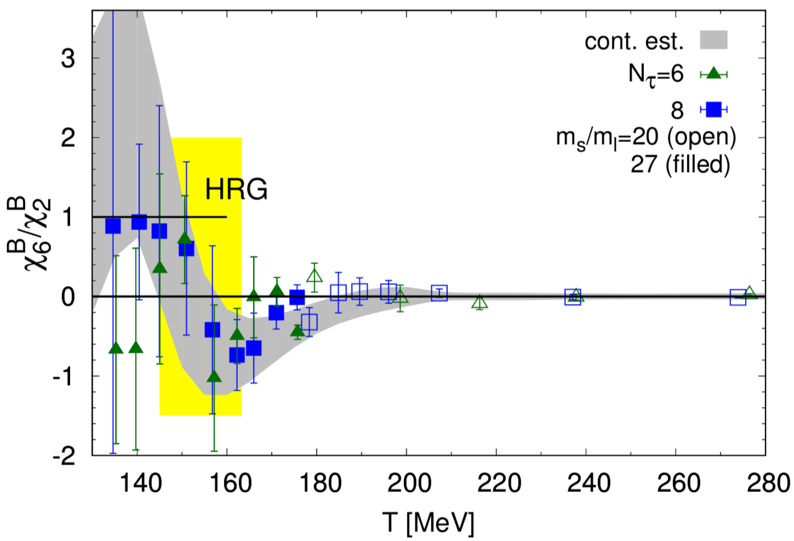
Similar trend as for net-protons

Future Possibilities

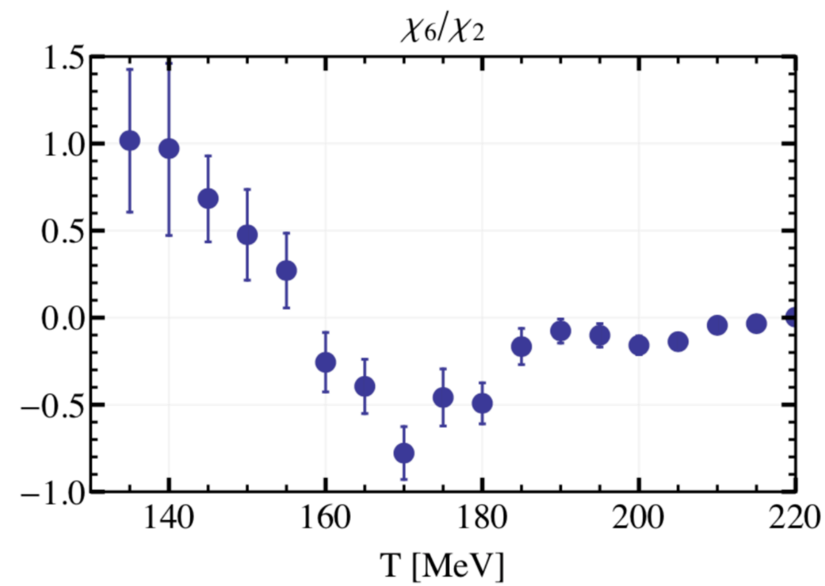
Run3/Run4 will provide 100 times more statistics (several billion events)

One of the ultimate goals is to explore higher order cumulants

Predictions from LQCD



A. Bazavov et al., Phys.Rev. D95 (2017) 054504



S. Borsanyi et al., arXiv:1805.04445

Summary

- The measured second order 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 the second cumulants of net-baryon distributions at a pseudo-critical temperature of about 155 MeV
- The Identity Method is applied for a signal + background combination for the first time
- Net-Lambda measurements show qualitative agreement with the net-proton results
  - The deviation of κ_2 from Skellam is explained by conservation laws

The analysis of higher order cumulants in a larger acceptance is ongoing

Bonus Slides

Fluctuations in GCE

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

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

z – single baryon partition function

Uncorrelated Poisson limit: $\langle N_B N_{\bar{B}}\rangle = \langle N_B\rangle\langle N_{\bar{B}}\rangle$

Net-Baryons → Skellam

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

$$\frac{\kappa_{2n+1}}{\kappa_{2k}} = \tanh\left(\frac{\mu}{T}\right) = \frac{\langle N_B\rangle - \langle N_{\bar{B}}\rangle}{\langle N_B\rangle + \langle N_{\bar{B}}\rangle}$$

Fluctuations in CE

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

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

z – single baryon partition function

Uncorrelated Poisson limit: $\langle N_B N_{\bar{B}}\rangle = \langle N_B\rangle\langle N_{\bar{B}}\rangle$

Net-Baryons → Skellam

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

$$\frac{\kappa_{2n+1}}{\kappa_{2k}} = \tanh\left(\frac{\mu}{T}\right) = \frac{\langle N_B\rangle - \langle N_{\bar{B}}\rangle}{\langle N_B\rangle + \langle N_{\bar{B}}\rangle}$$

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

- Non-Poisson single particles → **Canonical Suppression**
- Strong correlations $\langle N_B N_{\bar{B}}\rangle \neq \langle N_B\rangle\langle N_{\bar{B}}\rangle$
- **Net-Baryons do not fluctuate!**

K. Redlich and L. Turko, Z. Phys. C5 (1980) 201, V.V. Begun, M. I. Gorenstein, O. S. Zozulya, PRC 72 (2005) 014902
P. Braun-Munzinger, B. Friman, F. Karsch, K. Redlich, V. Skokov, NPA 880 (2012), A. Bzdak, V. Koch, V. Skokov, PRC87 (2013) 014901