Cumulants of net-proton number fluctuations from ALICE at the LHC

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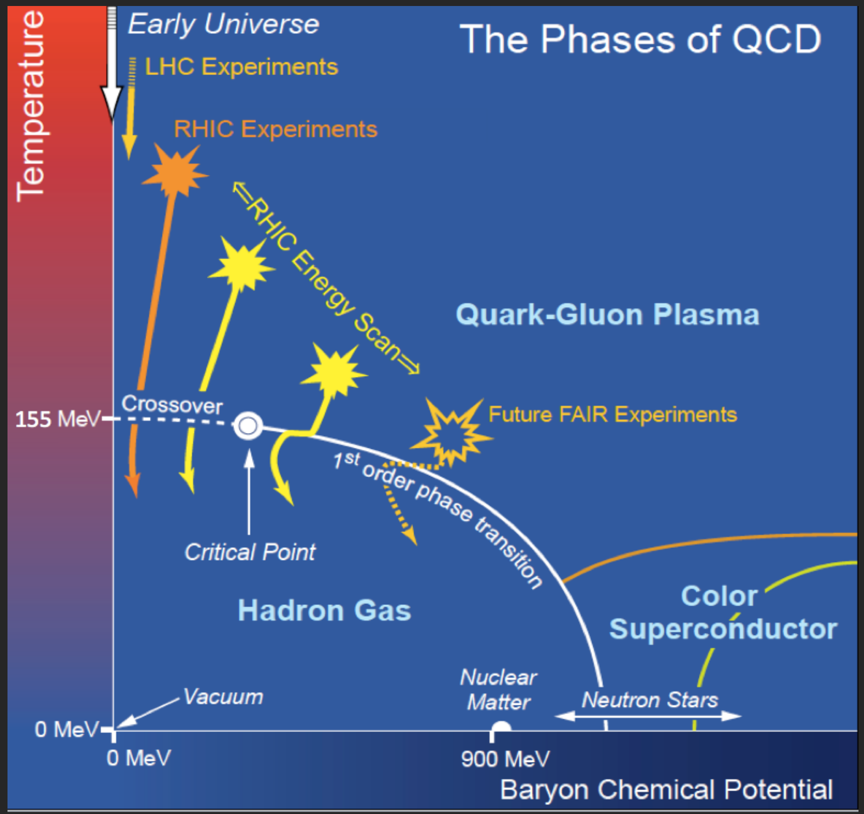
23rd May 2018, WPCF 2018, IFJ PAN, Krakow, Poland

Motivation: To map the QCD phase diagram



(Y. Akiba et al, arXiv:1502.02730v1)

- At LHC energies, $\mu_B \simeq 0$.
- Lattice QCD: $T_c \simeq 154 \pm 9$ MeV

Estimation from models with ALICE data:

- $T_{\text{freeze-out}}$: ~156 ± 3 MeV

  [J. Stachel et al J. Phys.Conf. Ser. 509, 012019, (2014)]

➢ Chemical freeze-out line is close to the crossover line!

Precise determination of freeze-out parameters (T and μ_B) at the LHC can help to locate the phase boundary at $\mu_B \simeq 0$.

S. Borsányi *et al,* PRL 111, 062005 (2013), **Frithjof Karsch**, Central Eur.J.Phys. 10 (2012) 1234-1237

Motivation: Connecting experiment with lattice QCD

In lattice QCD, the cumulants (C_n) of the distributions of conserved charges (net-charge, net-baryon, net-strangeness) are related to the generalized quark-number susceptibilities (χ_n^q)

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

We measure — We are interested in

Experiment — Lattice QCD

$$C_n = VT^3 \chi_n^q$$

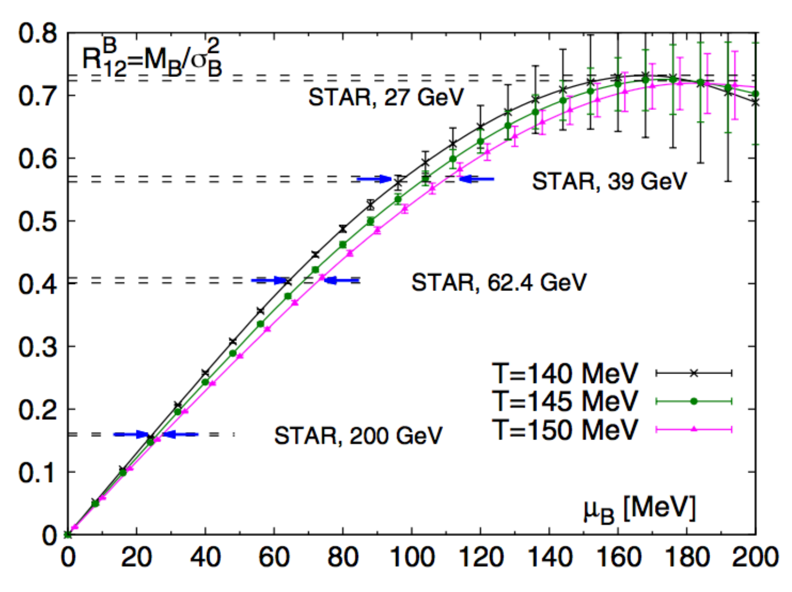
$$\frac{C_4}{C_2} = \frac{\chi_4^q}{\chi_2^q}$$

$$\frac{C_3}{C_2} = \frac{\chi_3^q}{\chi_2^q}$$

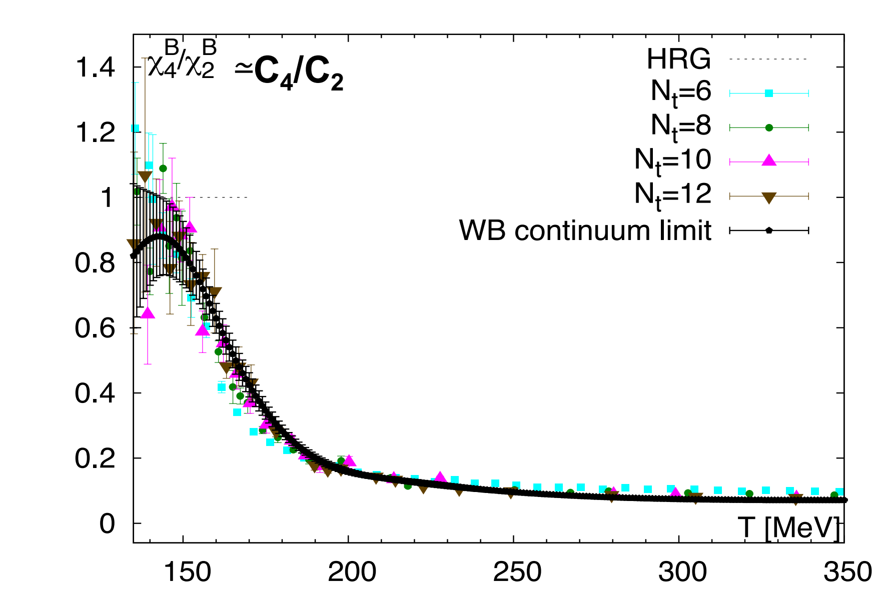
A direct comparison of experimental results with lattice QCD!

Motivation: Connecting experiment with lattice QCD

Freeze-out temperature from the ratio of cumulants of net-baryons



S. Borsányi *et al* PRL 113, 052301 (2014)



S. Borsányi *et al* PRL 111, 062005 (2013)

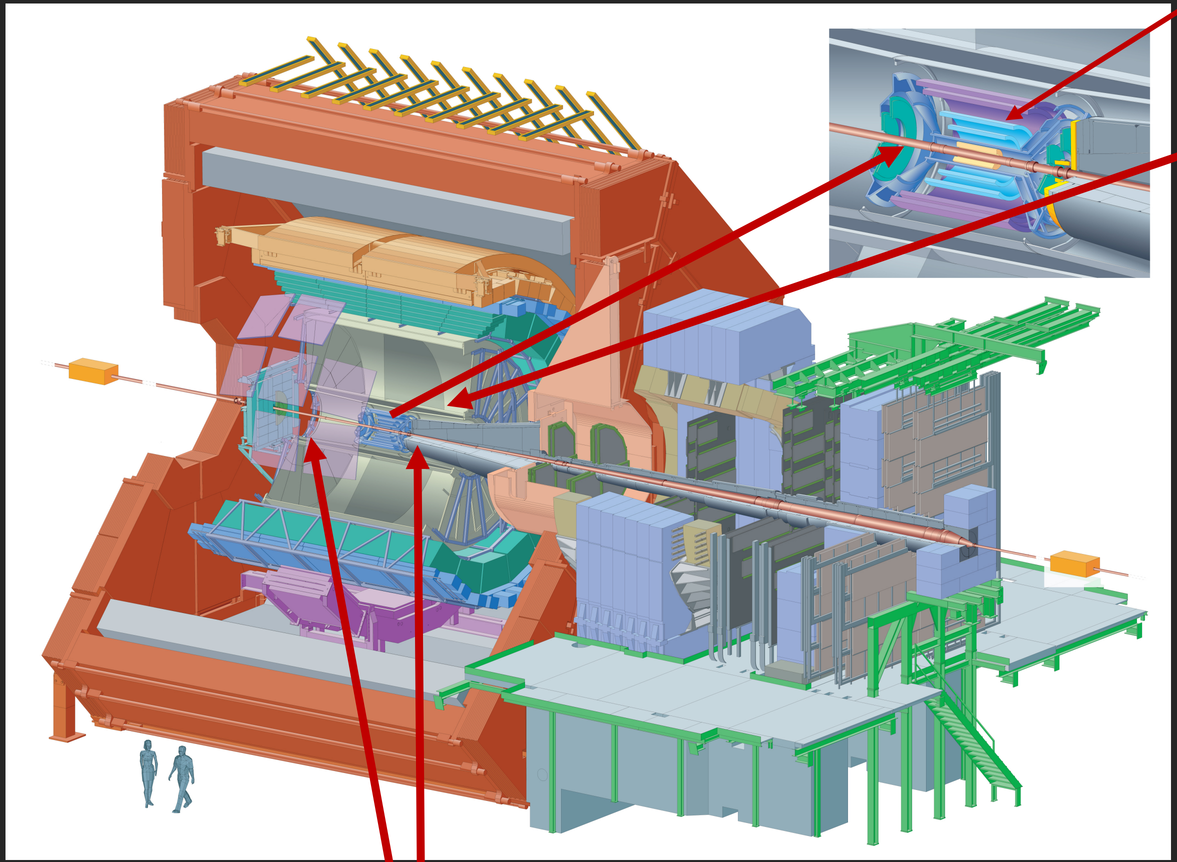
- From lattice QCD, freeze-out parameters can be extracted from experimental results at $\mu_B = 0$.
- Net-proton fluctuations are a good proxy for net-baryon number fluctuations.

[Y. Hatta, M.A. Stephanov, PRL 91 102003 (2003)]

Experimental measurements of the ratio of cumulants of net-protons at the LHC will help to constrain the lattice QCD predictions in a model independent way.

Experimental setup and dataset

ALICE detector



Inner Tracking System (ITS): Vertex, tracking, PID

Time Projection Chamber (TPC): Tracking, PID

V0 detector:
Trigger, centrality estimation
V0A: $2.8 < \eta < 5.1$, V0C: $-3.7 < \eta < -1.7$

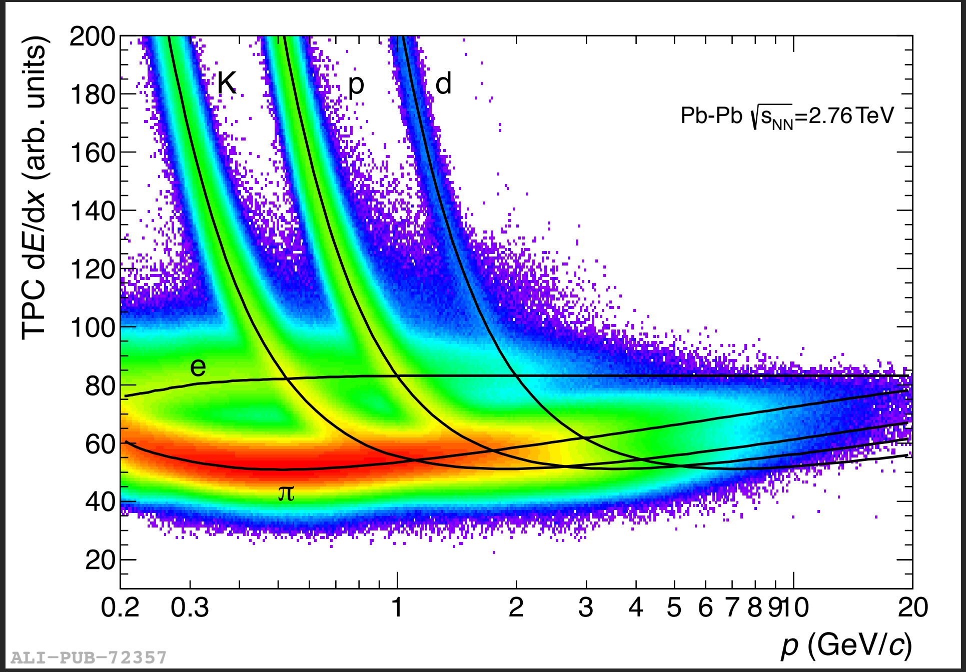
Minimum-bias Pb-Pb collision data

Collision energy	**Pb-Pb 2.76 TeV (Run1)**	**Pb-Pb 5.02 TeV (Run2)**
Number of events	14×10^6	59×10^6

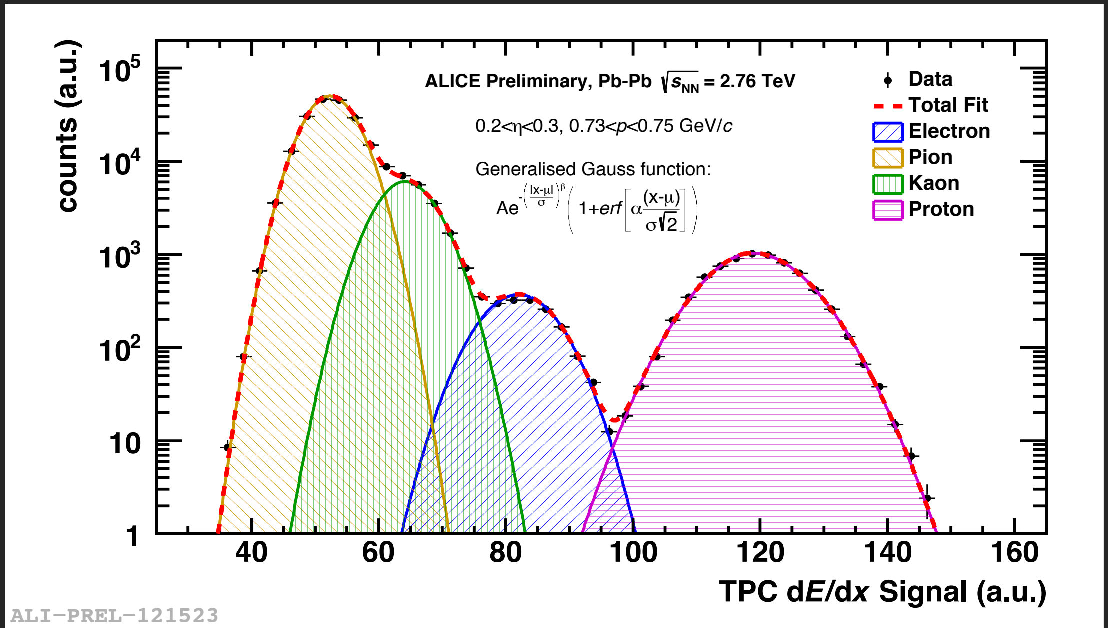
- **Kinematic cuts: $0.4 < p_T < 1.0$ GeV/c, $|\eta| < 0.8$**
- **Proton identification: TPC (next slide)**

Proton Identification

Energy loss (dE/dx) of particles in TPC gas



Generalized Gaussian fit to TPC dE/dx



- (Anti-)Proton identified using the nσ cut around the expected value of energy loss of particles in TPC detector (this presentation).

- Proton identification using Identity method: Assign a Bayesian probability for each particle species.
- Get the true numbers using response matrix built from the parameterization of TPC dE/dx.

C_2 results from both the methods agree with each other

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

Higher moments and cumulants

- Measure net-proton numbers on event-by-event basis: $\mathbf{\Delta p = p - \bar{p}}$
- The n[th] moments: $m'_n = <(\Delta\mathrm{p})^n>$

Cumulants from moments

$$C_1 = m'_1$$

$$C_2 = m'_2 - {m'_1}^2$$

$$C_3 = m'_3 - 3m'_1 m'_2 + 2{m'_1}^3$$

$$C_4 = m'_4 - 4m'_1 m'_3 - 3\,{m'_2}^2 + 12{m'_1}^2 m'_2 - 6{m'_1}^4$$

Analysis methodology

1) Detector efficiency correction: method 1

- A. Bzdak and V. Koch, PRC 91, 027901 (2015).
- Assumption: detector efficiency follows Binomial distribution.

Factorial moments

$$F_{i,k} = \sum_{x_1,\ldots,x_i} \sum_{\bar{x}_1,\ldots,\bar{x}_k} \frac{a_{i,k}(x_1,\ldots,x_i;\bar{x}_1,\ldots,\bar{x}_k)}{\epsilon(x_1)\ldots\epsilon(x_i)\bar{\epsilon}(\bar{x}_1)\ldots\bar{\epsilon}(\bar{x}_k)}.$$

where

$$a_{i,k}(x_1,\ldots,x_i;\bar{x}_1,\ldots,\bar{x}_k) = \langle n(x_1)[n(x_2)-\delta_{x_1,x_2}]\cdots[n(x_i)-\delta_{x_1,x_i}-\cdots-\delta_{x_{i-1},x_i}] \bar{n}(\bar{x}_1)[\bar{n}(\bar{x}_2)-\delta_{\bar{x}_1,\bar{x}_2}]\cdots[\bar{n}(\bar{x}_k)-\delta_{\bar{x}_1,\bar{x}_k}-\cdots-\delta_{\bar{x}_{k-1},\bar{x}_k}]\rangle.$$

Cumulants from factorial moments

$$\begin{aligned}
K_1 &= \langle N_1\rangle - \langle N_2\rangle\,,\\
K_2 &= N - K_1^2 + F_{02} - 2F_{11} + F_{20},\\
K_3 &= K_1 + 2K_1^3 - F_{03} - 3F_{02} + 3F_{12} + 3F_{20} - 3F_{21} + F_{30}\\
&\quad - 3K_1(N + F_{02} - 2F_{11} + F_{20}),\\
K_4 &= N - 6K_1^4 + F_{04} + 6F_{03} + 7F_{02} - 2F_{11} - 6F_{12} - 4F_{13}\\
&\quad + 7F_{20} - 6F_{21} + 6F_{22} + 6F_{30} - 4F_{31} + F_{40}\\
&\quad + 12K_1^2(N + F_{02} - 2F_{11} + F_{20}) - 3(N + F_{02} - 2F_{11} + F_{20})^2\\
&\quad - 4K_1(K_1 - F_{03} - 3F_{02} + 3F_{12} + 3F_{20} - 3F_{21} + F_{30}),
\end{aligned}$$

where $N \equiv \langle N_1\rangle + \langle N_2\rangle = F_{10} + F_{01}.$

Analysis methodology

1) Detector efficiency correction: method 2 (Used here)

- Recent method: T Nonaka et al ,PRC 95, 064912, (2017)
- Assumption: detector efficiency follows Binomial distribution.

$$\langle Q\rangle_c = \langle q_{(1,1)}\rangle_c,$$

$$\langle Q^2\rangle_c = \langle q_{(1,1)}^2\rangle_c + \langle q_{(2,1)}\rangle_c - \langle q_{(2,2)}\rangle_c,$$

$$\langle Q^3\rangle_c = \langle q_{(1,1)}^3\rangle_c + 3\langle q_{(1,1)}q_{(2,1)}\rangle_c - 3\langle q_{(1,1)}q_{(2,2)}\rangle_c + \langle q_{(3,1)}\rangle_c - 3\langle q_{(3,2)}\rangle_c + 2\langle q_{(3,3)}\rangle_c,$$

$$\begin{aligned}\langle Q^4\rangle_c = {} & \langle q_{(1,1)}^4\rangle_c + 6\langle q_{(1,1)}^2 q_{(2,1)}\rangle_c - 6\langle q_{(1,1)}^2 q_{(2,2)}\rangle_c + 4\langle q_{(1,1)}q_{(3,1)}\rangle_c + 3\langle q_{(2,1)}^2\rangle_c + 3\langle q_{(2,2)}^2\rangle_c - 12\langle q_{(1,1)}q_{(3,2)}\rangle_c \\ & + 8\langle q_{(1,1)}q_{(3,3)}\rangle_c - 6\langle q_{(2,1)}q_{(2,2)}\rangle_c + \langle q_{(4,1)}\rangle_c - 7\langle q_{(4,2)}\rangle_c + 12\langle q_{(4,3)}\rangle_c - 6\langle q_{(4,4)}\rangle_c,\end{aligned}$$

Moments

where

$$q_{(r,s)} = q_{(a^r/p^s)} = \sum_{i=1}^{M} (a_i^r/p_i^s)n_i.$$

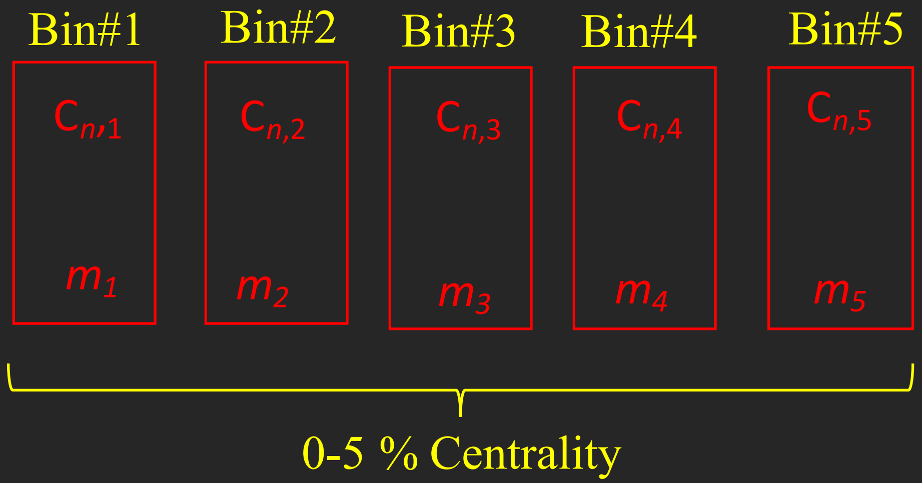
a_i = 1 for proton, -1 for anti-proton
p_i = Efficiency in i^{th} p_T bin.
n_i = Number of observed (anti-) proton
M = Total Number of p_T bins

- Simpler and faster than method 1.
- Method 1 and 2 give the same results!

Analysis methodology

2) Centrality bin-width correction (CBWC):

- To minimize the impact parameter (or volume) variations due to the finite centrality bin. [X. Luo et al **J. Phys. G 40, 105104 (2013)**]



$$C_n = \frac{\sum_{i=1}^{k} m_i C_{n,i}}{\sum_{i=1}^{k} m_i}$$

$C_{n,i}$ = n[th] order cumulant measured in i[th] centrality bin
m_i = number of events in i[th] centrality bin
k = numbers of centrality bins

- With or without CBWC, the results are consistent for ALICE measurements.
- Cumulants up to 3[rd] order are not sensitive to volume fluctuations!

[P. Braun-Munzinger, A. Rustamov, J. Stachel, NPA 960, 114 (2017)]

Analysis methodology

3) Statistical error estimation:

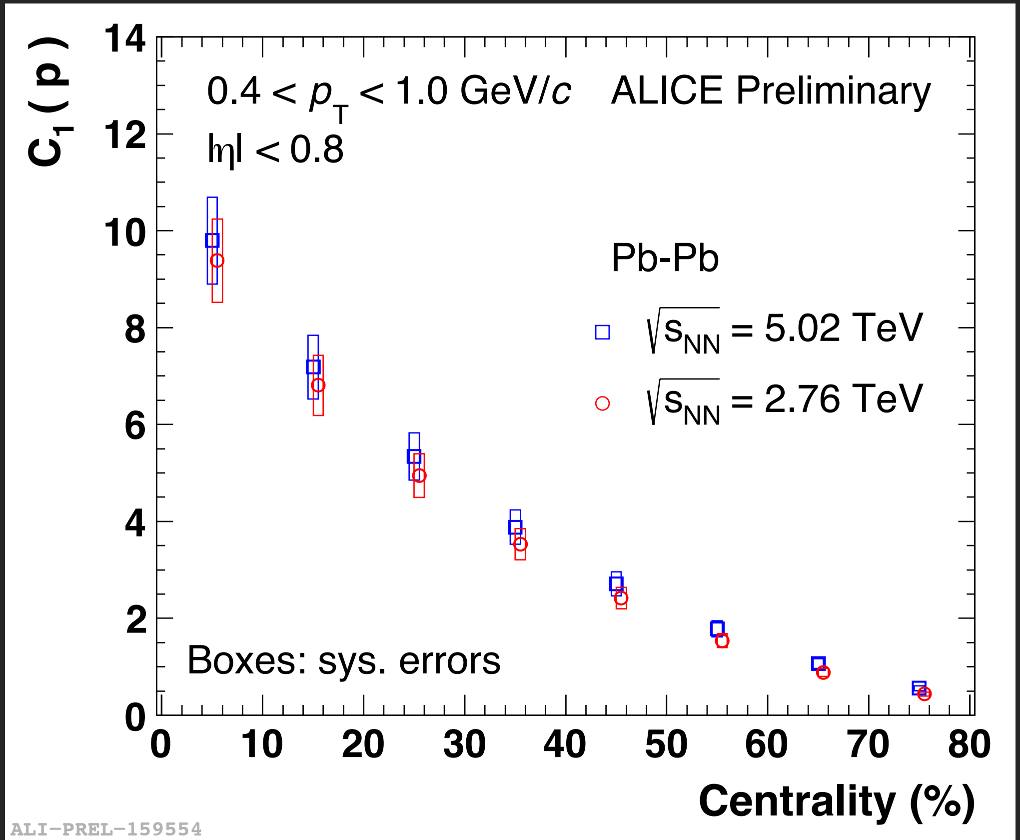
- Subgroup method: Divide the data sample into '*k*' subsamples randomly.

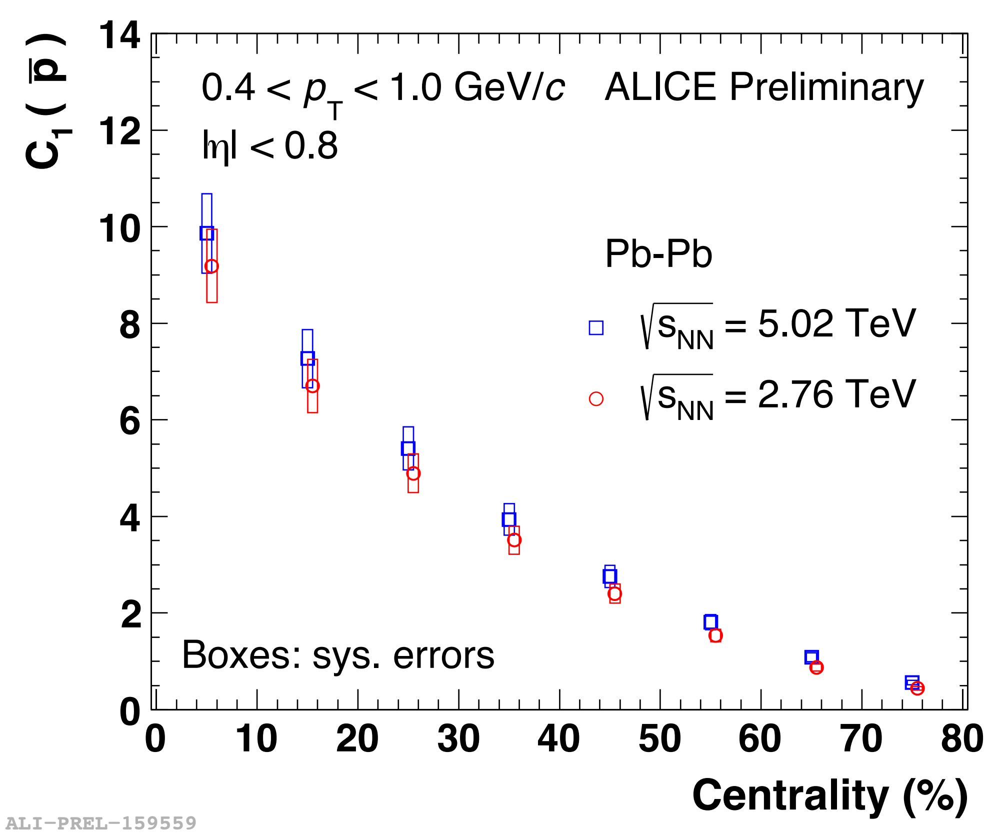
$$C_n = \frac{\sum_i^k C_n^i}{k}$$

Statistical error $$\delta C_n = \frac{\sigma}{\sqrt{k}}$$ where $$\sigma = \sqrt{\frac{\sum_{i=1}^k \left(C_n^i - \langle C_n \rangle\right)^2}{k-1}}$$

- Number of subsamples used : 30
- Statistical errors estimated from Bootstrap and Subgroup method agree with each other.

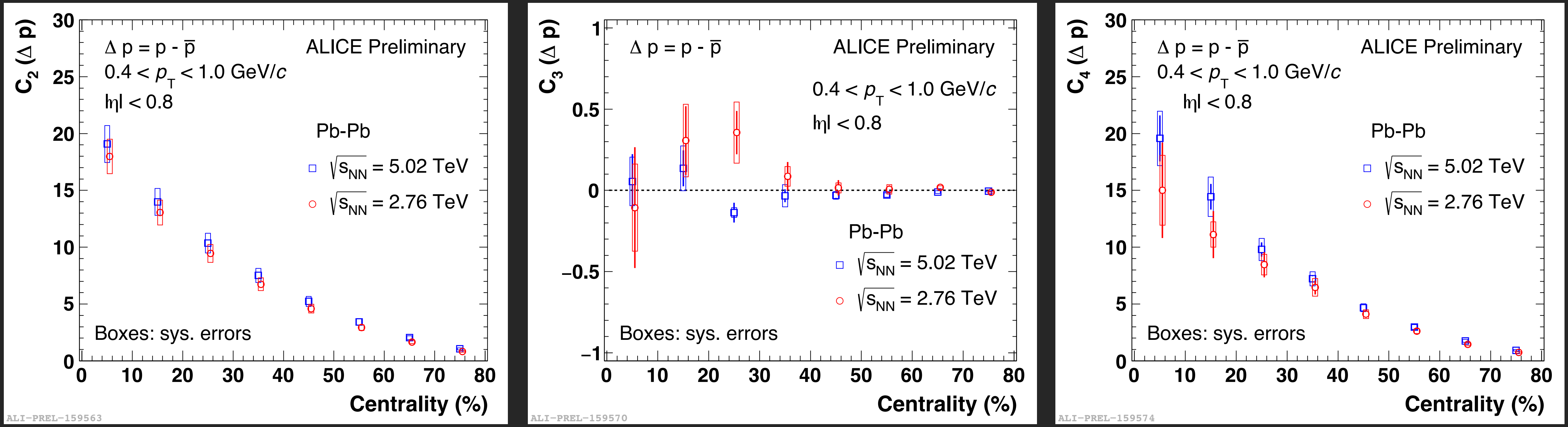
Results: proton and anti-proton C_1





- For both energies, proton and anti-proton numbers are similar within systematic errors.

Results: Cumulants of net-proton distributions



- Cumulants of net-proton distributions for both energies are the same within statistical and systematic errors.

- C_2 results are consistent with Identity method. [A. Rustamov NPA, 967 (2017) 453–456 (QM 2017)]

Baseline estimation

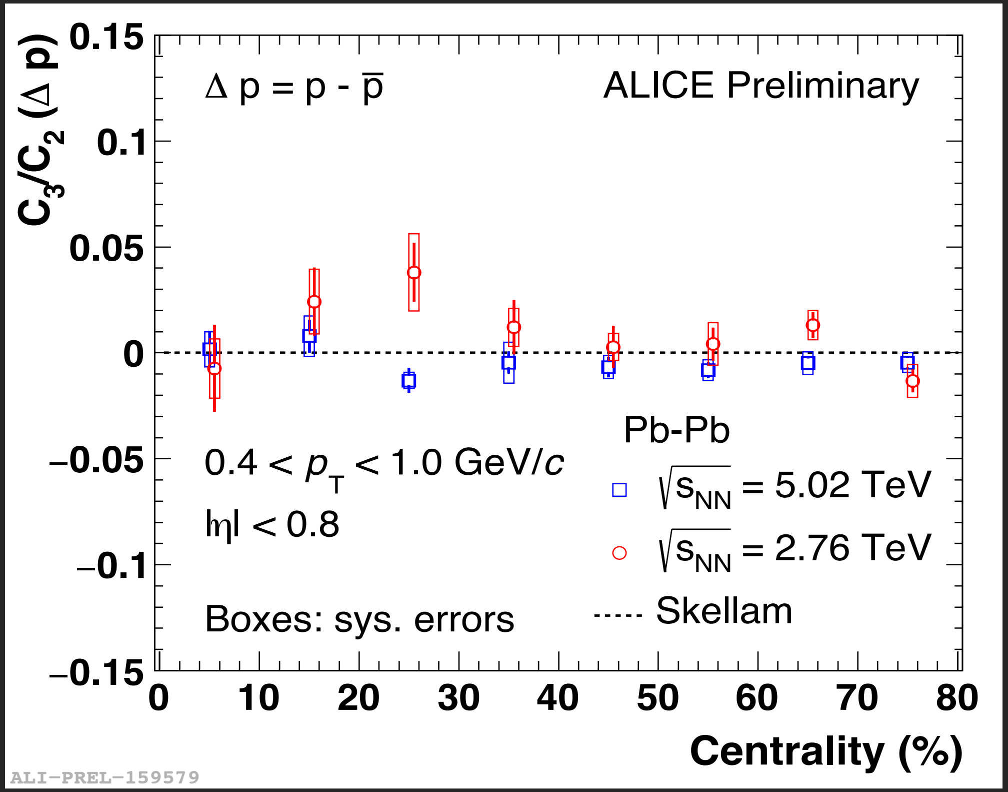
- Assume proton and anti-proton distributions are independent Poissonian distributions => net-proton distribution is a Skellam distribution.

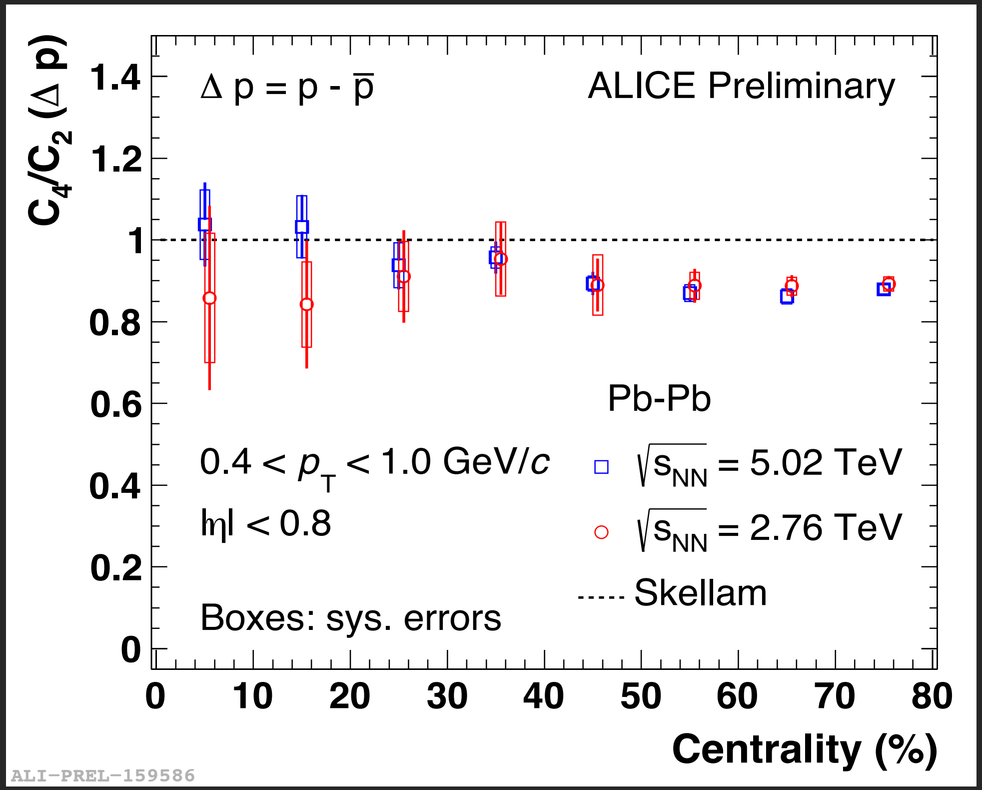
- $C_n(\text{Skellam}) = C_1(p) + (-1)^n C_1(\bar{p})$
- $C_1(\Delta p) = C_3(\Delta p) = C_1(p) - C_1(\bar{p})$
- $C_2(\Delta p) = C_4(\Delta p) = C_1(p) + C_1(\bar{p}) \Rightarrow C_4/C_2 = 1.$

- Used in Hadron Resonance Gas (HRG) model calculations.

  [P. Braun-Munzinger *et al* PLB 747, 292 (2015), P. Garg *et al* PLB 726, 691 (2013)]

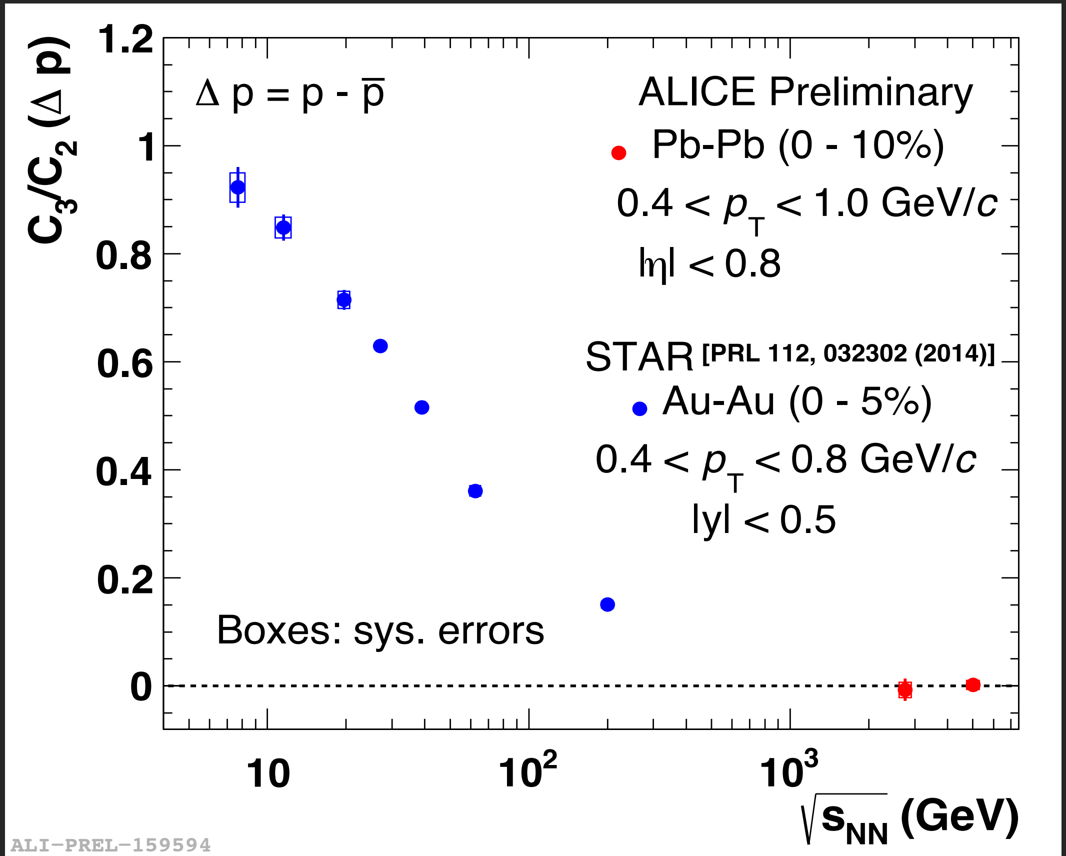
Results: Ratio of cumulants of net-proton distributions

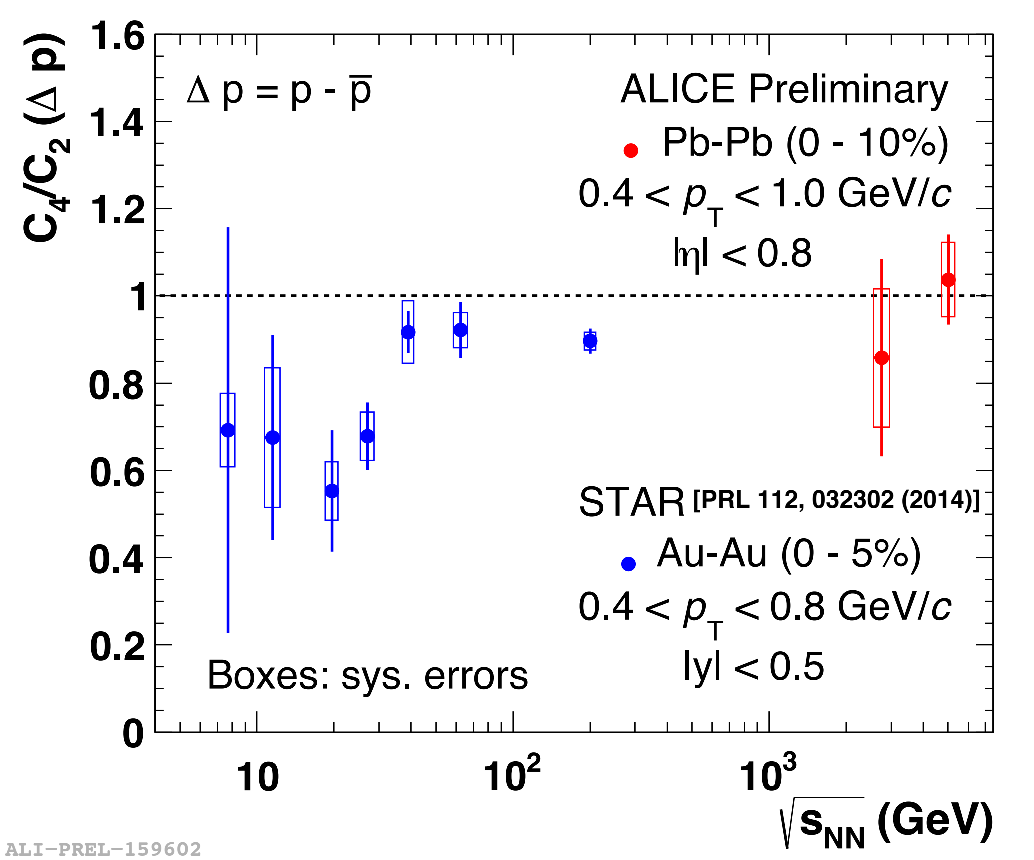




- C_3/C_2 and C_4/C_2 results for 2.76 TeV and 5.02 TeV are the same within the statistical error bars.
- C_3/C_2 and C_4/C_2 of central events agree with Skellam expectations within statistical errors.

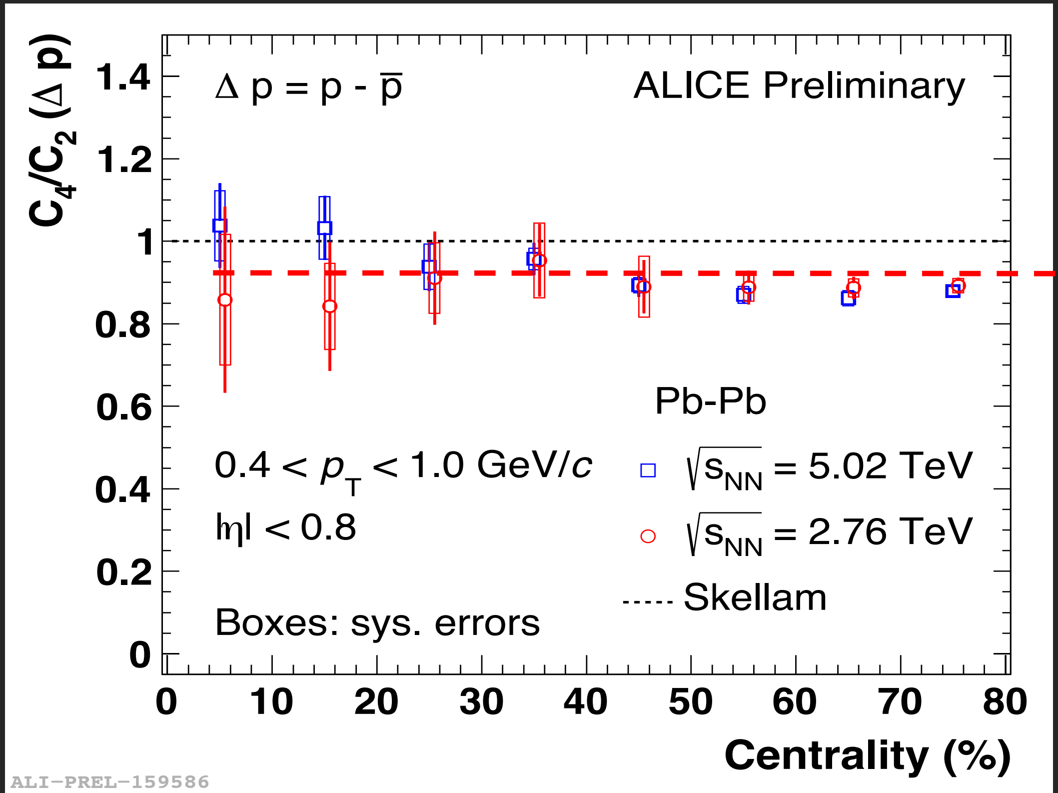
Results: RHIC to LHC

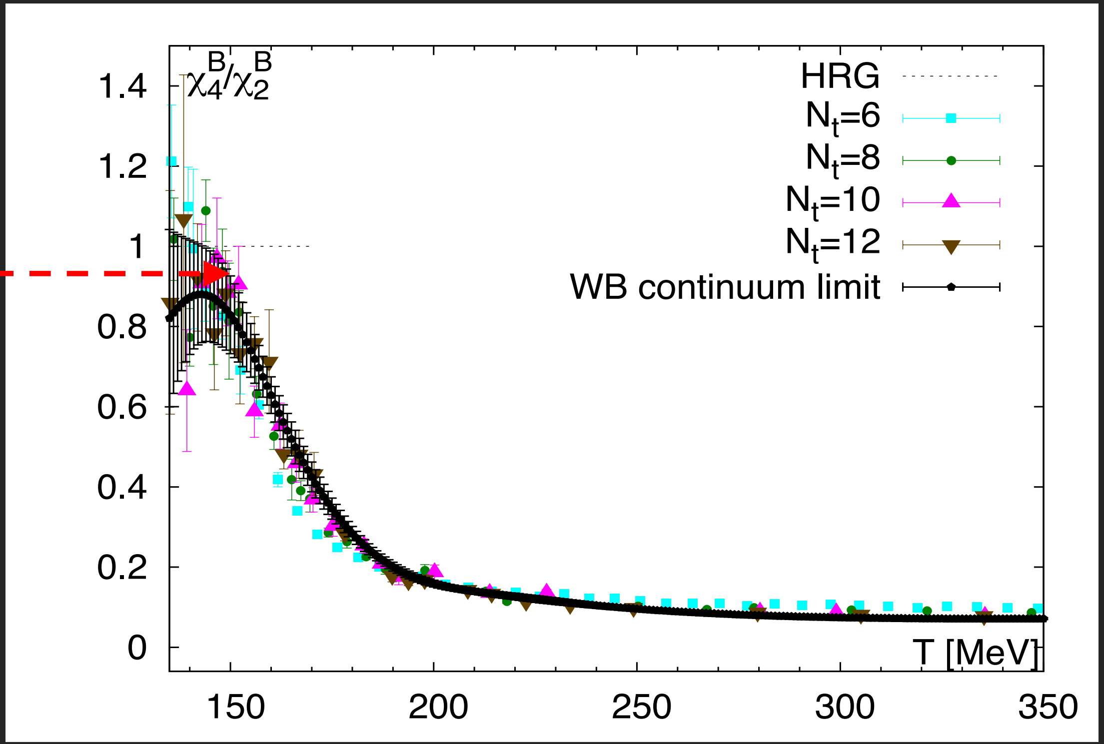




- C_3/C_2 follows a decreasing trend as a function of collision energy.
- Within experimental uncertainties C_4/C_2 at the LHC agrees with the Skellam baseline.

Freeze-out temperature at the LHC





S. Borsányi *et al* PRL 111, 062005 (2013)

Implied freeze-out temperature from C_4/C_2 consistent with thermal fits to particle yields.
(assuming net-protons are good proxy to net-baryons on the lattice)

- Need more precise data to further constrain the freeze-out temperature.

Summary

- The net-proton higher order cumulants up to 4th order and their ratios in Pb-Pb collisions at 2.76 and 5.02 TeV are presented as a function of centrality.
- C_{3}, C_4 and their ratios with respect to C_2 generally agree with Skellam expectations within the uncertainties.
- From RHIC to LHC the ratios of cumulants approach the Skellam baseline.
- The results may be used in conjunction with lattice calculations to estimate the freeze-out temperature.
- News: Second cumulants of net-Λ fluctuations are measured in ALICE (see A. Ohlson talk in QM 2018)

Outlook

- The analysis will be extended for higher p_T (up to 2 GeV/c) and for other particle species in different pseudo-rapidity windows.
- Measurement of net-proton higher order cumulants with Identity method.
- Off-diagonal cumulants of net-particles.
- The upcoming dedicated Pb-Pb run at 5.02 TeV will increase the statistics to further constrain the freeze-out parameters.

THANK YOU

Backup slides

Efficiency correction method

$N_{rec.} = N_{rec.primary} + N_{cont.}$

where $N_{cont.} = N_{material} + N_{secondary} + N_{mis.Identified}$

Now $N_{rec.primary} = N_{rec}$ - $N_{cont.}$

$$\Rightarrow N_{gen.primary} = N_{rec.} \frac{(1-\delta)}{\varepsilon}$$

where contamination factor $(\delta) = \frac{N_{cont.}}{N_{rec.}}$

Efficiency $(\varepsilon) = \frac{N_{rec.primary}}{N_{gen.primary}}$

$$\Rightarrow N_{gen.primary} = \frac{N_{rec.}}{\omega}$$

correction factor $\boldsymbol{\omega} = \frac{\boldsymbol{\varepsilon}}{(\mathbf{1}-\boldsymbol{\delta})}$