

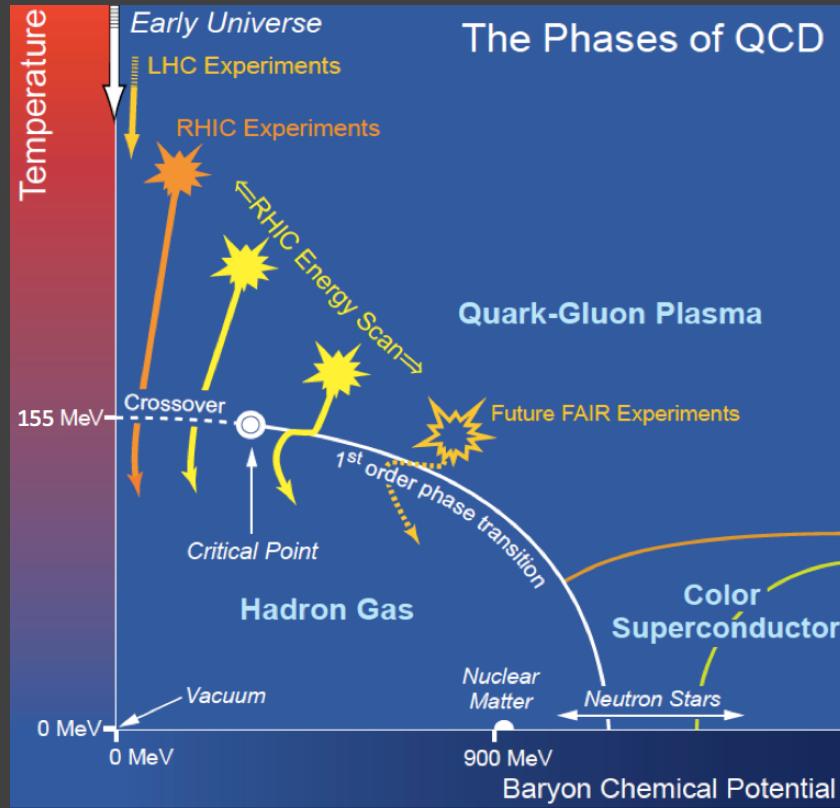
Higher moment fluctuations of identified particle distributions from ALICE

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for the ALICE collaboration

16th May 2018, QM2018, Venice, Italy



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:

- $T_{\text{freeze-out}}: \sim 156 \pm 3$ 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)

We measure
Experiment

We measure

We are interested in

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

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

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

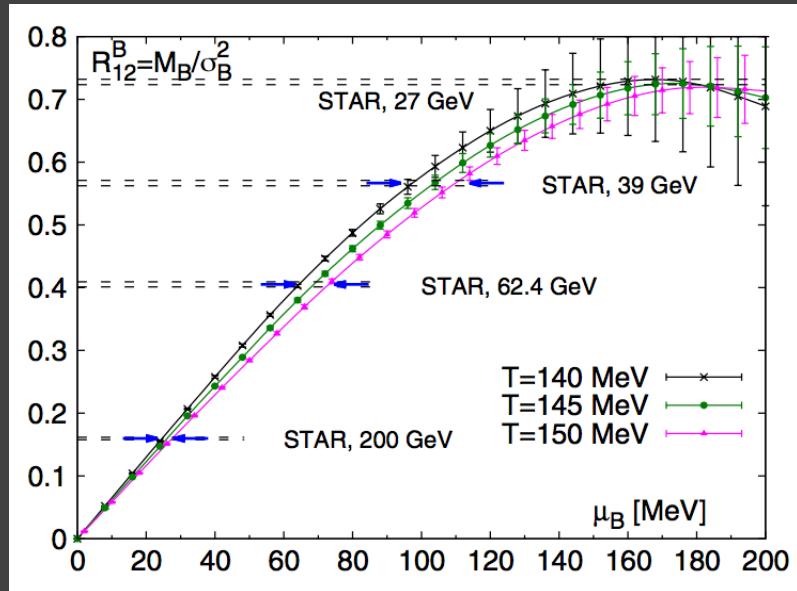
Lattice QCD

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

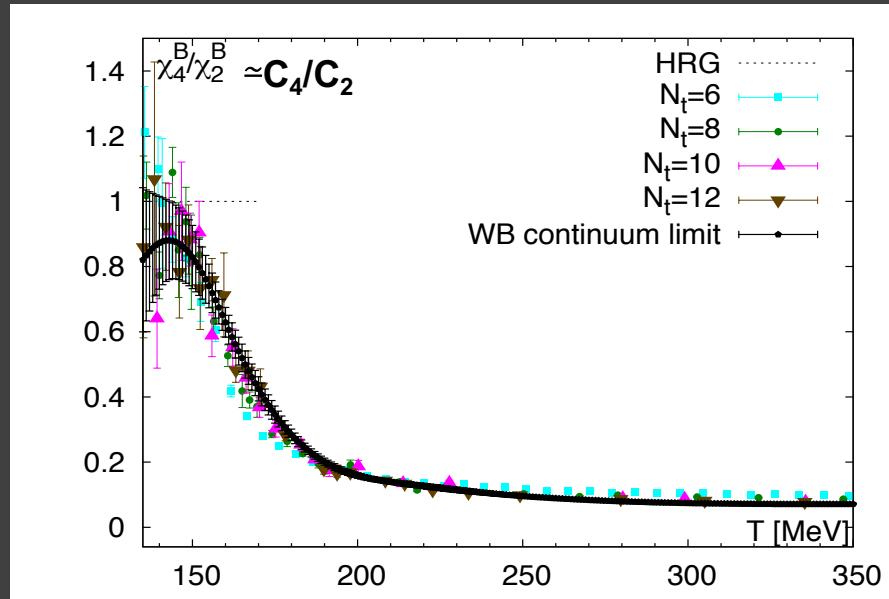
A direct comparison of experimental results with lattice QCD!

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)



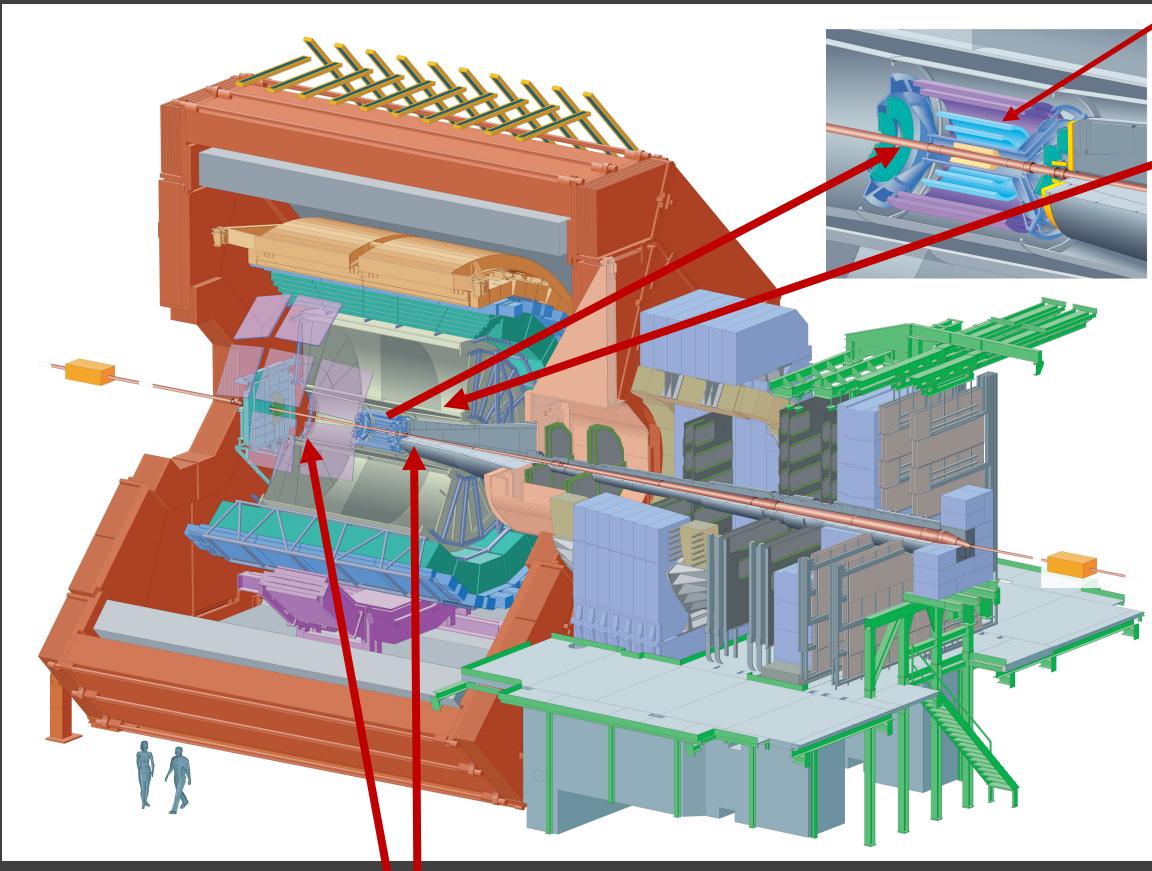
S. Borsányi *et al* PRL 111, 062005 (2013)

- From the first principle of lattice QCD, freeze-out parameters can be extracted from experimental results at $\mu_B = 0$.
- Net-proton is a good proxy of net-baryon number. [Y. Hatta, M.A. Stephanov, PRL 91 102003 (2003)]

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

Experimental setup and dataset

ALICE detector



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

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

Time Projection Chamber (TPC): Tracking, PID

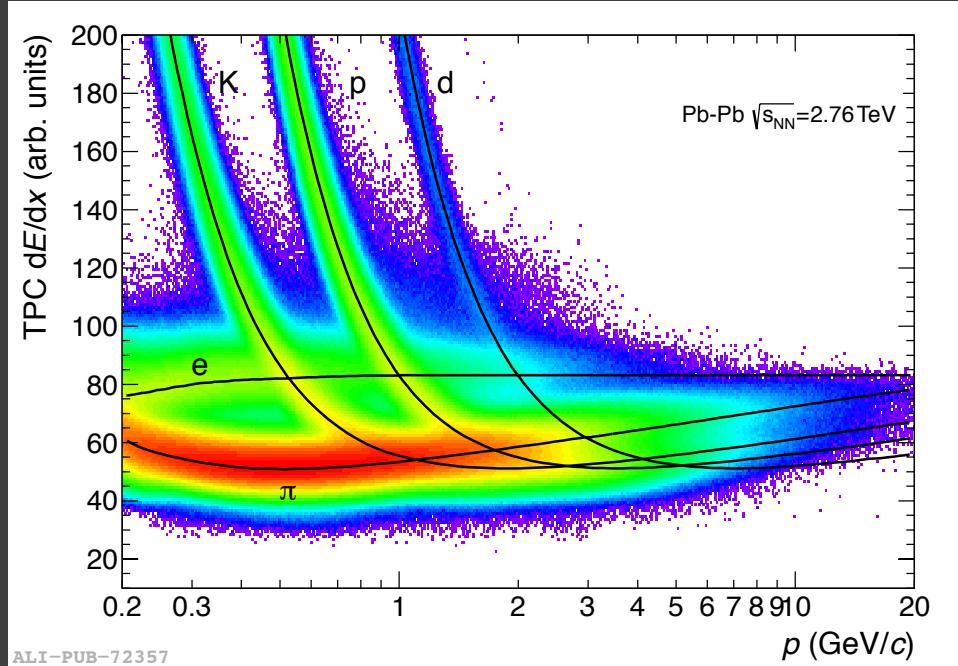
Minimum-bias Pb-Pb collision data

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

Proton Identification

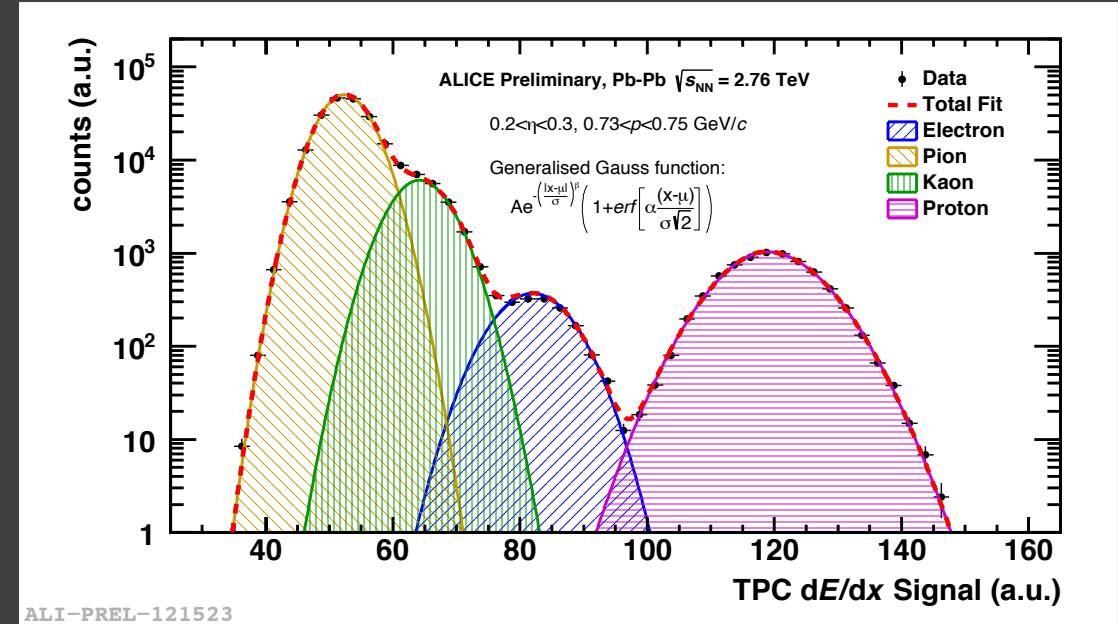
Energy loss (dE/dx) of particles in TPC gas



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

C₂ results from both the methods agree with each other

Generalized Gaussian fit to TPC dE/dx



- 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 .

M. Gazdzicki et al., PRC 83, 054907 (2011)

M. I. Gorenstein, PRC 84, 024902 (2011)

A. Rustamov, M. I. Gorenstein, PRC 86, 044906 (2012)

Analysis methodology

1) Detector efficiency correction:

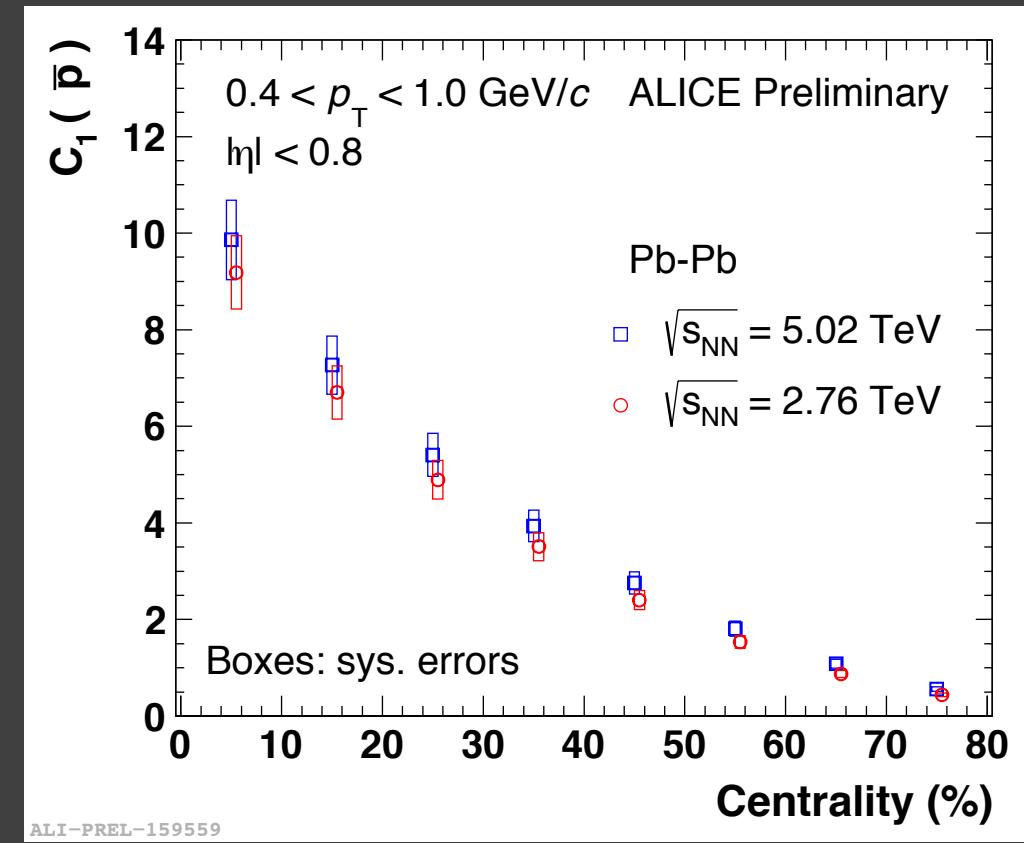
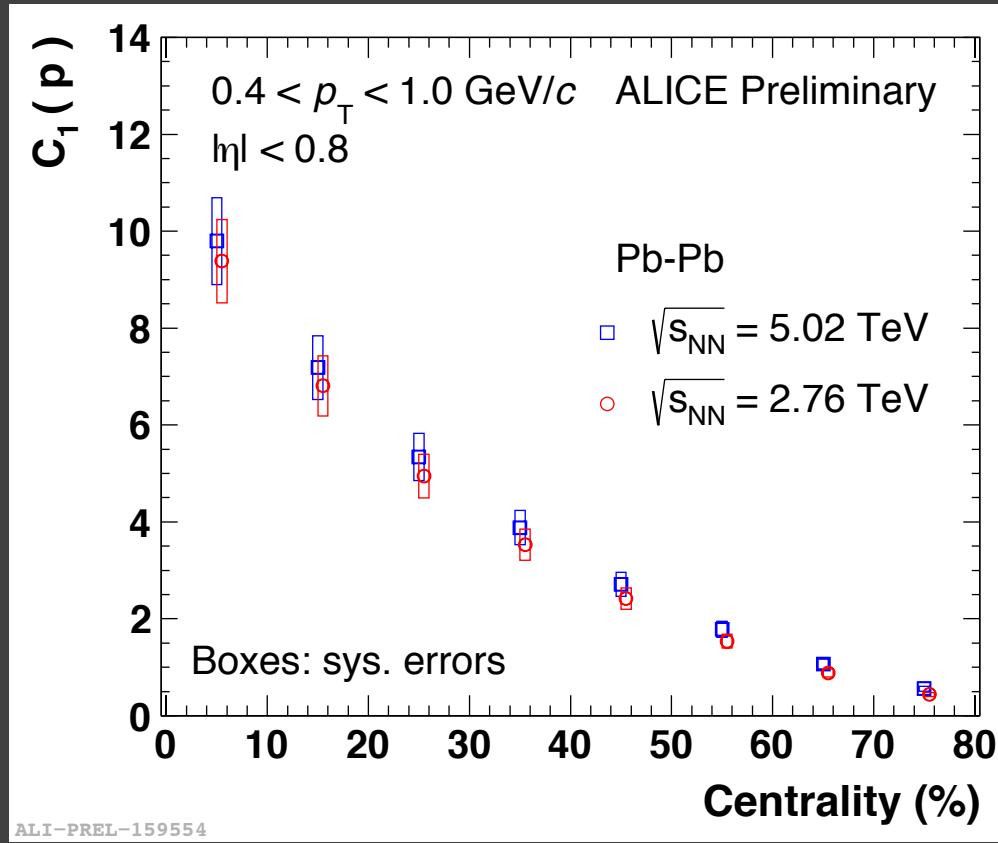
- Efficiency correction is done using Binomial efficiency loss assumptions.
- Transverse momentum (p_T) dependent efficiency correction methods:
 - A. Bzdak, V. Koch [PRC 91, 027901 (2015)].
 - T. Nonaka *et al* [PRC 95, 064912, (2017)] (used here!).
- The feed-down and contamination due to mis-identification are taken into account in the efficiency correction and contribute to the systematic uncertainties.

2) Centrality bin-width correction (CBWC):

- To eliminate/minimize the impact parameter (or volume) variations due to the finite centrality bin. [X. Luo et al J. Phys. G 40, 105104 (2013)]
- With and without CBWC results are the same within the statistical uncertainties.
- Cumulants up to 3rd order are not sensitive to volume fluctuations!

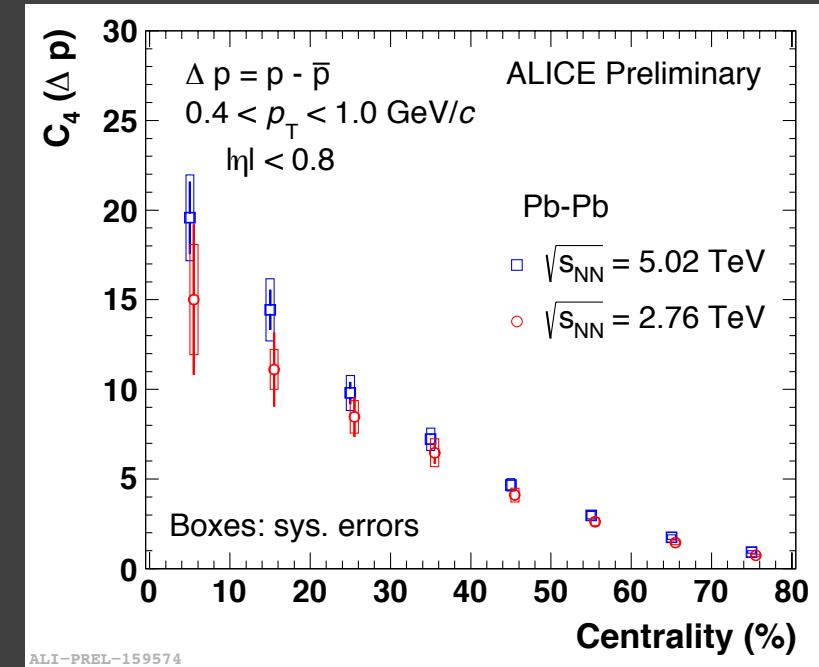
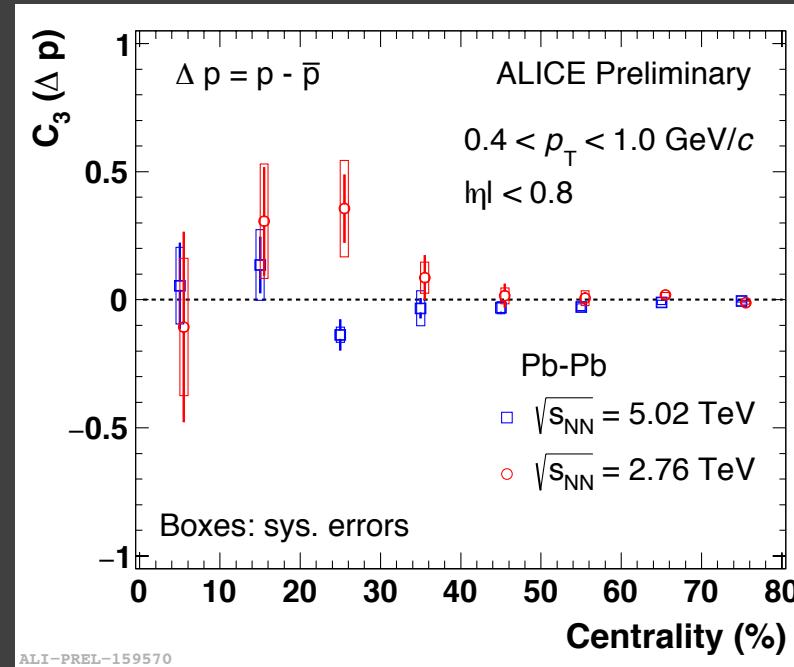
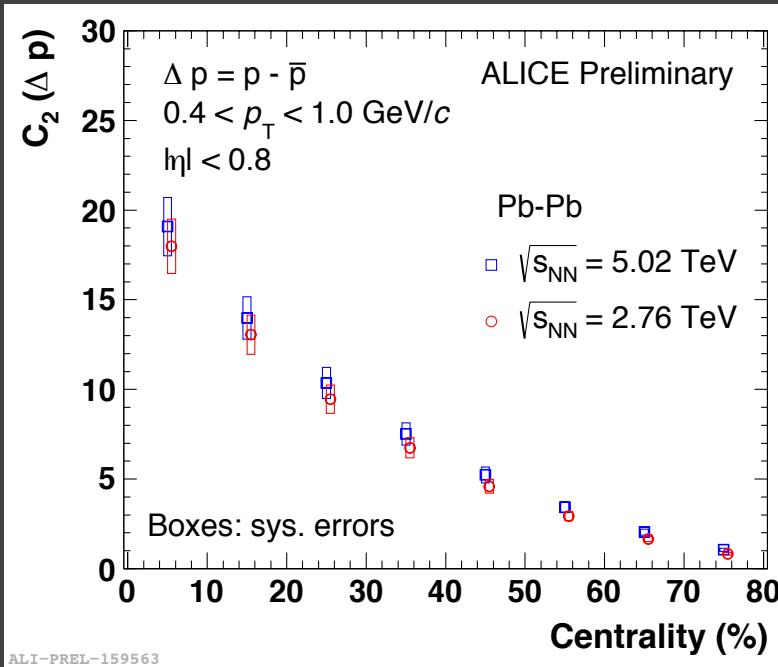
[P. Braun-Munzinger, A. Rustamov, J. Stachel, NPA 960, 114 (2017)]

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

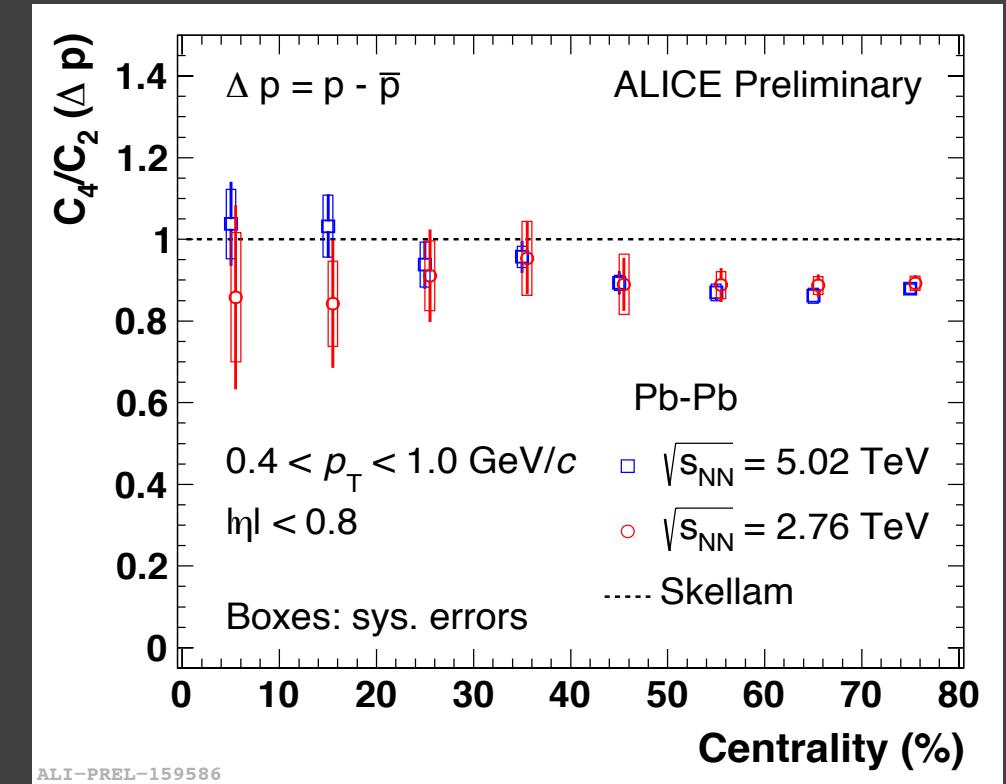
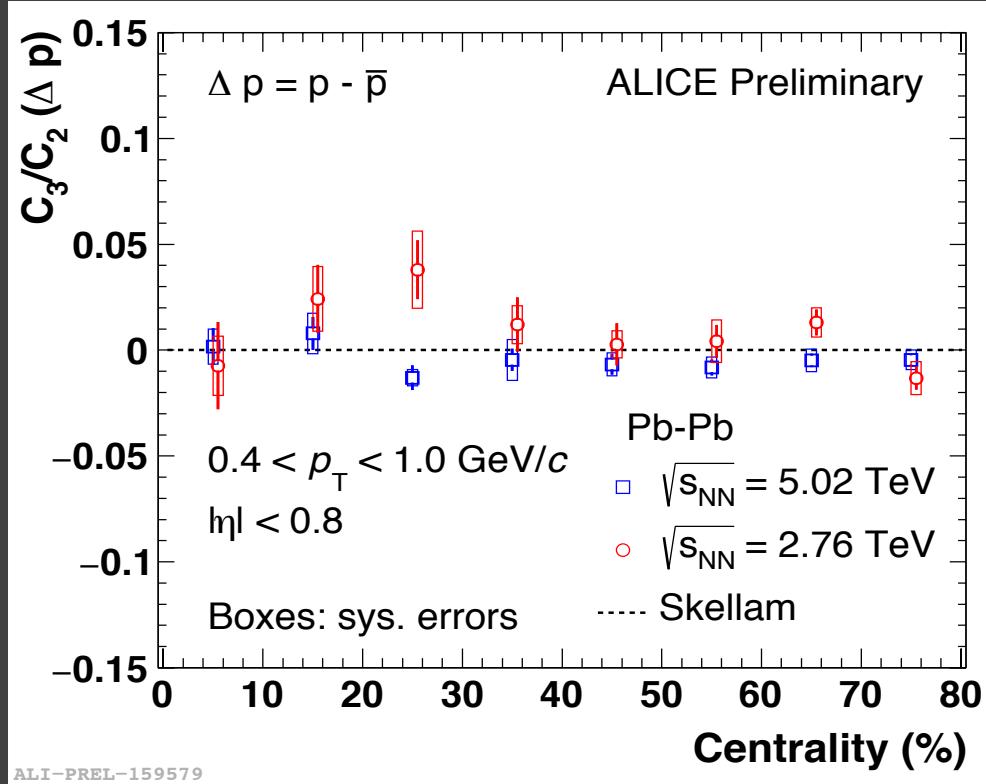


- Cumulants of net-proton distributions for both energies are the same within statistical and systematic errors.
- C₂ results are consistent with Identity method. [A. Rustamov NPA 967 (2017) 453–456 (QM 2017)]

Baseline estimation

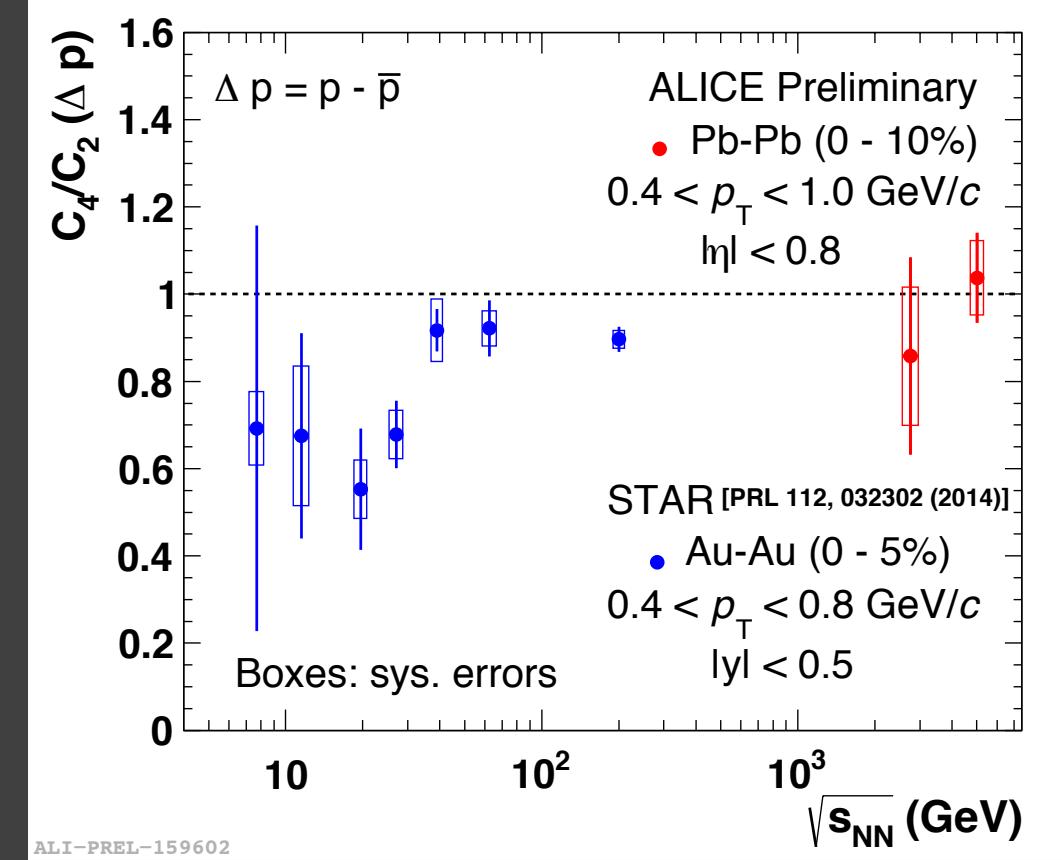
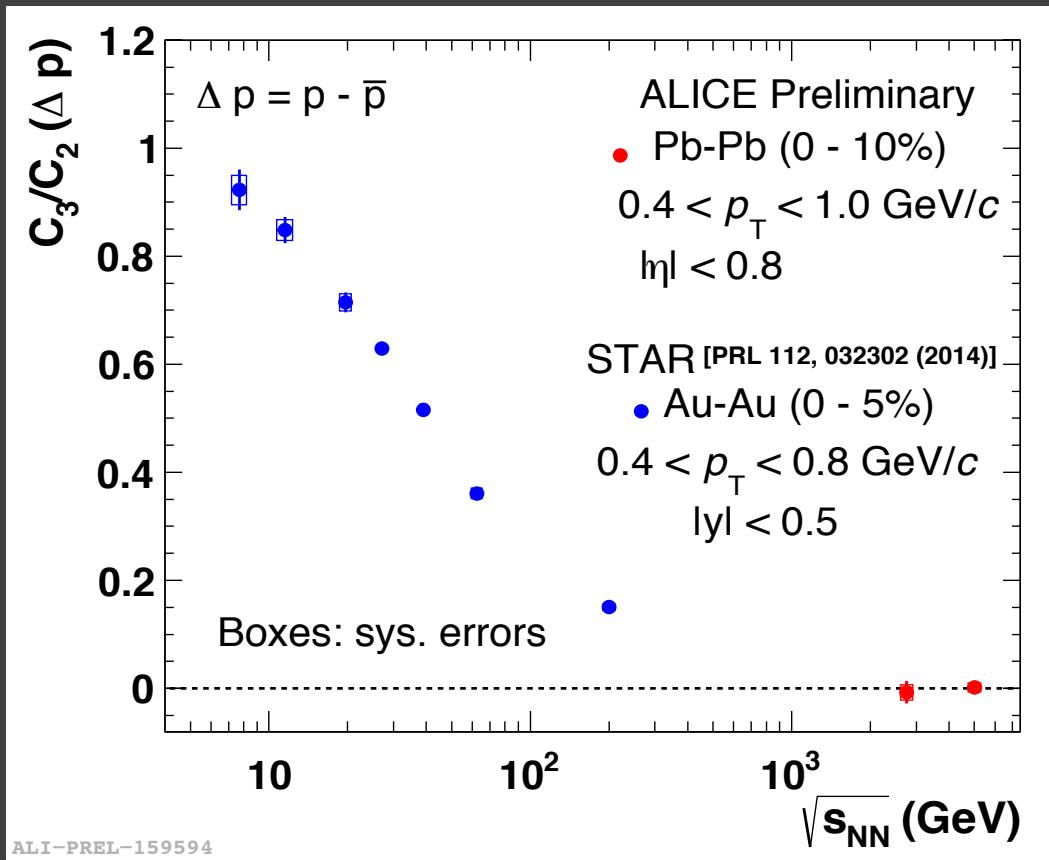
- Assume proton and anti-proton distributions are independent Poissonian distributions => net-proton distributions is a Skellam distribution.
- $C_n(\text{Skellam}) = C_1(p) + (-1)^n C_1(\bar{p})$
- $C_1(\Delta p) = C_3(\Delta p) = C_1(p) - C_1(\bar{p})$
- $C_2(\Delta p) = C_4(\Delta p) = C_1(p) + C_1(\bar{p}) \Rightarrow C_4/C_2 = 1.$
- 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



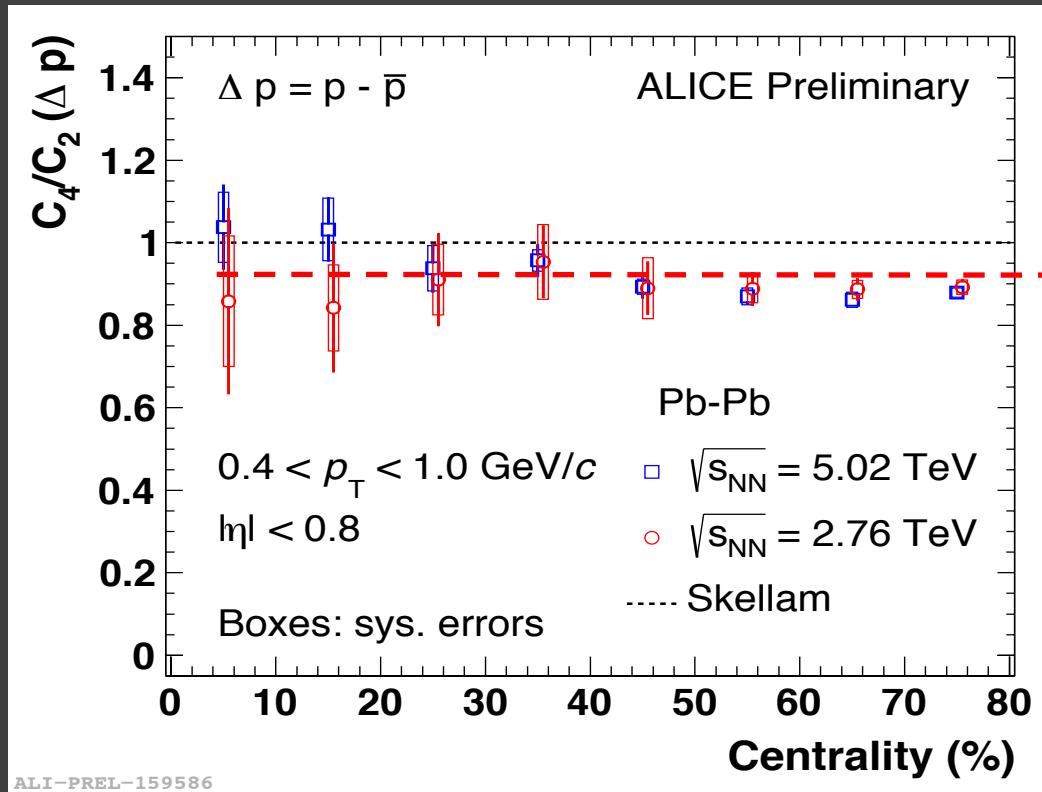
- The C_3/C_2 and C_4/C_2 results of 2.76 TeV and 5.02 TeV are same within the statistical error bars.
- The C_3/C_2 and C_4/C_2 of central events agree with Skellam expectations within statistical error.

Results: RHIC to LHC

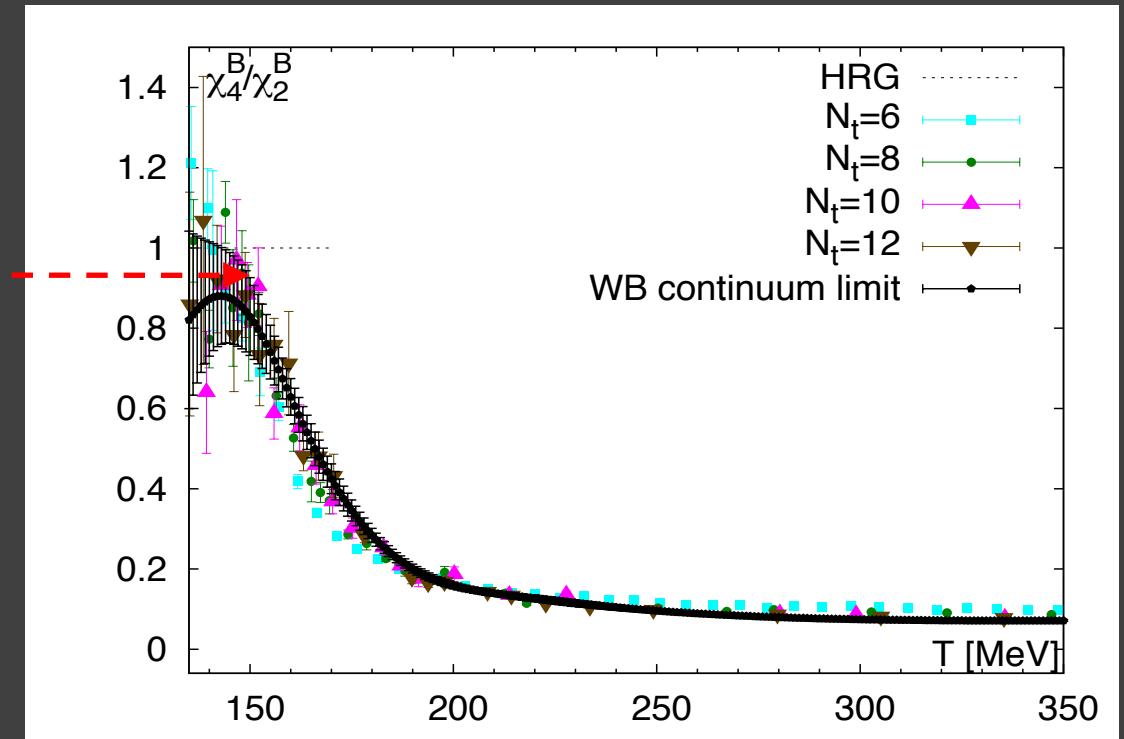


- C_3/C_2 follows the decreasing trend as a function of collision energy.
- Within experimental uncertainties C_4/C_2 at the LHC agrees with the Skellam baseline.

Freeze-out temperature at the LHC



ALI-PREL-159586



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

freeze-out temperature $\leq 155 \text{ MeV}$
(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 agree with Skellam expectations within the uncertainties.
- From RHIC to LHC the ratio of cumulants approach the Skellam baseline.
- The results may be used in conjunction with lattice calculations to estimate the freeze-out temperature.

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.
- 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

Higher moments and cumulants

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

Cumulants from moments

$$C_1 = m'_1$$

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

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

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

Efficiency correction method -1

- A. Bzdak and V. Koch, PRC 91, 027901 (2015).
- Use binomial model for efficiency loss.
- Involve many iterations, depends on event number and pt bins and order of cumulants.
- Efficiency correction by factorial moments method:

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

where

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

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

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

Efficiency correction method -2

- Recent method: T Nonaka et al ,PRC 95, 064912, (2017):
- Use binomial model for efficiency loss.

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

Moments
↑

where

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

Efficiency correction method

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

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

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

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

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

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

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

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