Event-by-event fluctuation measurements with ALICE

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Valday, Russia

What do we mean by "event-by-event"

In central Pb-Pb collisions at LHC energies, ~2000 particles within $|\eta|<0.5$.

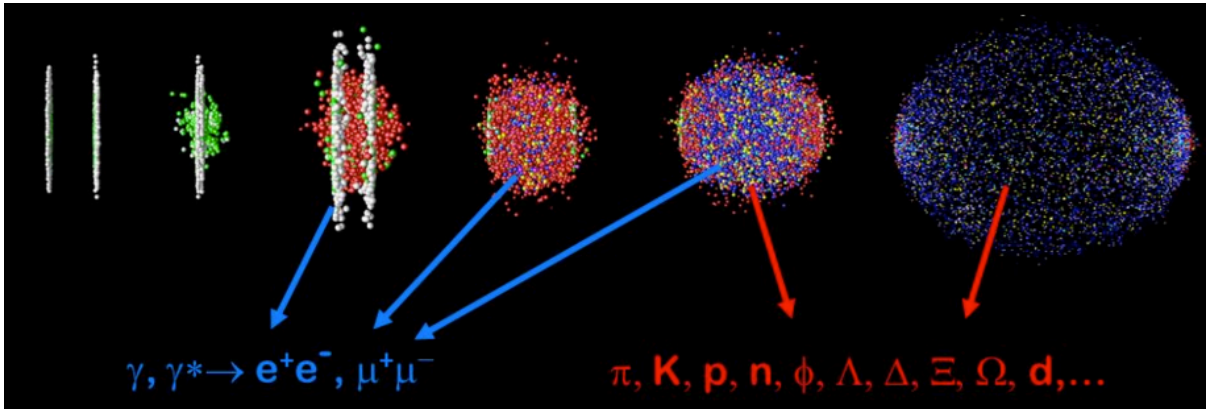
Many "event-averaged" observables can be studied:
particle yields, spectra, flow harmonics, two-particle correlations…

Event-by-event measurements:
when a given observable is measured on *an event-by-event basis,*
and the fluctuations are studied over the ensemble of the events.

- fluctuating net-charge, number of protons, mean p_T, forward-backward yields, etc.

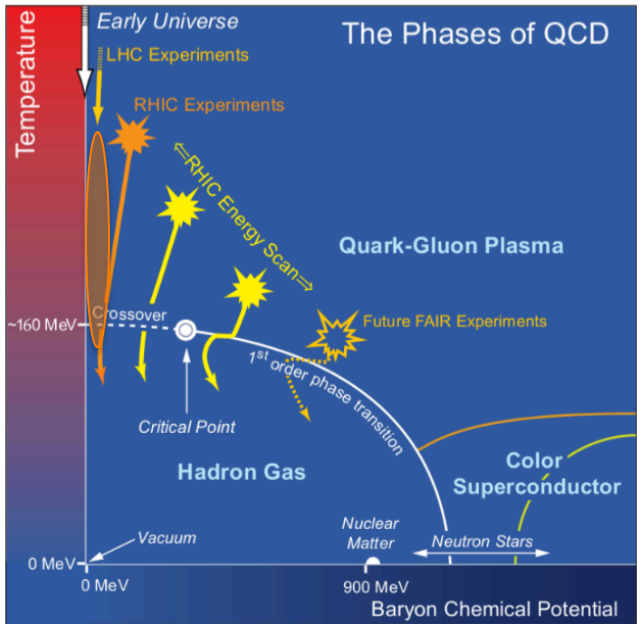
Why e-by-e fluctuations:

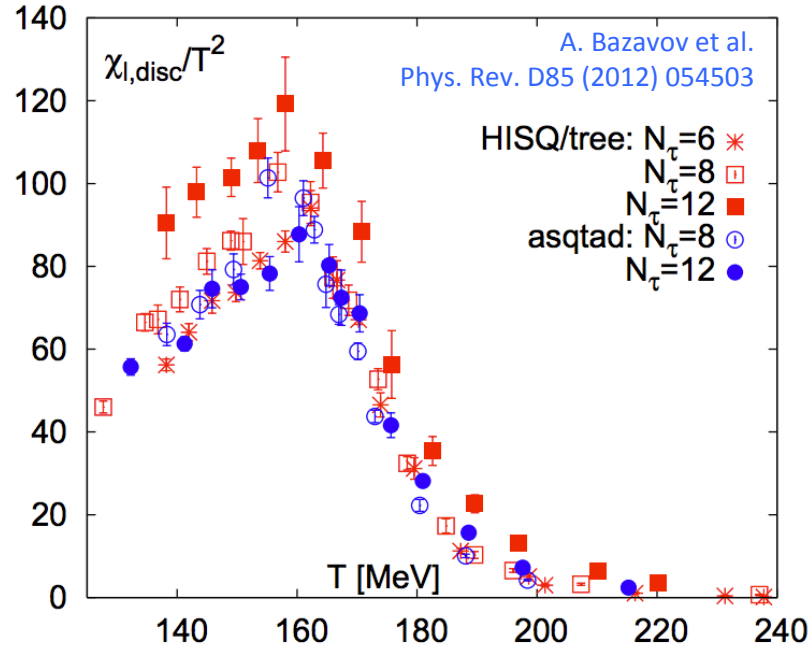
- they help to characterize the **properties of the "bulk" of the system**
- fluctuations also are closely related to **dynamics of the phase transitions**



Phase transitions at the LHC

Event-by-event fluctuations in heavy-ion collisions at the LHC make it possible to verify lattice QCD calculations at small values of baryon chemical potential ($\mu_B \simeq 0$ at LHC energies).





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

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

Thermodynamic susceptibilities χ:

- describe the response of a thermal system to changes in external conditions, fundamental properties of the medium
- can be calculated within lattice QCD
- within the Grand Canonical Ensemble, are related to e-by-e fluctuations of conserved charges: <u>electric charge</u>, <u>strangeness</u>, <u>baryon number</u>

$$\chi_n^B = \frac{\partial^n \left(P/T^4\right)}{\partial \left(\mu_B/T\right)^n}$$

Connection between theory and experiment

Theory: susceptibilities

$$\chi_n^B = \frac{\partial^n \left(P/T^4\right)}{\partial\left(\mu_B/T\right)^n}$$

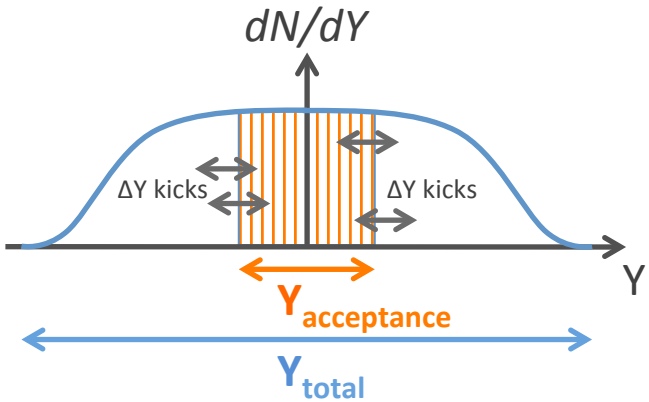
(fixed volume, particles in GCE)

⇔

Experiment:
moments of net-particle multiplicity distributions

$$\Delta N_B = N_B - N_{\bar{B}}$$

(volume fluctuations, global conservation laws)



κ_n – cumulants

$$\chi_n^B = \frac{\kappa_n(\Delta N_B)}{VT^3}$$

Ratios from experiment:

$$\frac{\kappa_3(\Delta N_B)}{\kappa_2(\Delta N_B)} \Leftrightarrow \frac{\chi_3^B}{\chi_2^B}$$

$$\frac{\kappa_4(\Delta N_B)}{\kappa_2(\Delta N_B)} \Leftrightarrow \frac{\chi_4^B}{\chi_2^B}$$

(cancel VT^3)

Connection between theory and experiment

Theory: susceptibilities

$$\chi_n^B = \frac{\partial^n \left(P/T^4\right)}{\partial\left(\mu_B/T\right)^n}$$

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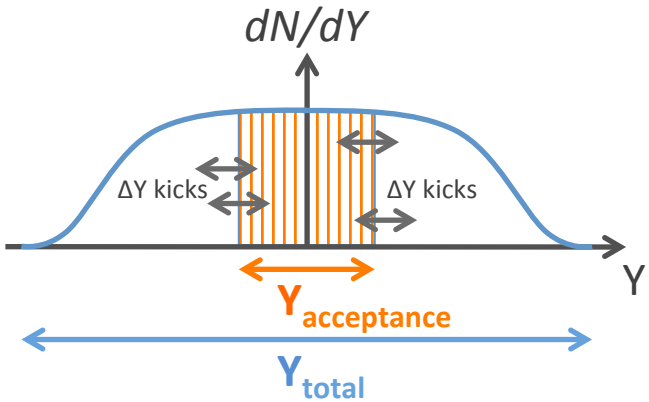

κ_n – cumulants

$$\chi_n^B = \frac{\kappa_n(\Delta N_B)}{VT^3}$$

$$\kappa_1 = \langle \Delta N_B \rangle = VT^3 \chi_1^B$$

$$\kappa_2 = \sigma^2 = \left\langle \left(\Delta N_B - \langle \Delta N_B \rangle\right)^2 \right\rangle = VT^3 \chi_2^B$$

variance

$$\kappa_3/\sigma^3 = S = \left\langle \left(\Delta N_B - \langle \Delta N_B \rangle\right)^3 \right\rangle / \sigma^3 = \frac{VT^3 \chi_3^B}{\left(VT^3 \chi_2^B\right)^{3/2}}$$

skewness

$$\kappa_4/\sigma^4 = k = \left\langle \left(\Delta N_B - \langle \Delta N_B \rangle\right)^4 \right\rangle / \sigma^4 - 3 = \frac{VT^3 \chi_4^B}{\left(VT^3 \chi_2^B\right)^2}$$

kurtosis

Ratios from experiment:

$$\frac{\kappa_3(\Delta N_B)}{\kappa_2(\Delta N_B)} \Leftrightarrow \frac{\chi_3^B}{\chi_2^B}$$

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(cancel VT^3)

Connection between theory and experiment

Theory: susceptibilities

$$\chi_n^B = \frac{\partial^n \left(P/T^4\right)}{\partial\left(\mu_B/T\right)^n}$$

(fixed volume, particles in GCE)

Experiment:
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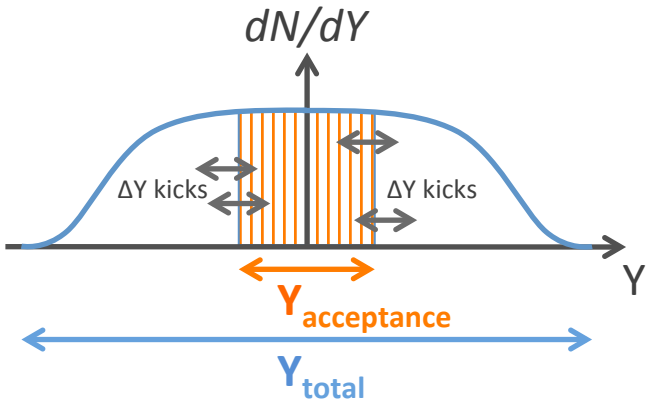

κ_n – cumulants

$$\chi_n^B \neq \frac{\kappa_n(\Delta N_B)}{VT^3}$$

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variance

$$\kappa_3/\sigma^3 = S = \left\langle \left(\Delta N_B - \langle \Delta N_B \rangle\right)^3 \right\rangle / \sigma^3 \neq \frac{VT^3 \chi_3^B}{\left(VT^3 \chi_2^B\right)^{3/2}}$$

skewness

$$\kappa_4/\sigma^4 = k = \left\langle \left(\Delta N_B - \langle \Delta N_B \rangle\right)^4 \right\rangle / \sigma^4 - 3 \neq \frac{VT^3 \chi_4^B}{\left(VT^3 \chi_2^B\right)^2}$$

kurtosis

Ratios from experiment:

$$\frac{\kappa_3(\Delta N_B)}{\kappa_2(\Delta N_B)} \not\Leftrightarrow \frac{\chi_3^B}{\chi_2^B}$$

$$\frac{\kappa_4(\Delta N_B)}{\kappa_2(\Delta N_B)} \not\Leftrightarrow \frac{\chi_4^B}{\chi_2^B}$$

~~(cancel VT^3)~~

However, at LHC energies net-proton is a reasonable *proxy* for net-baryon

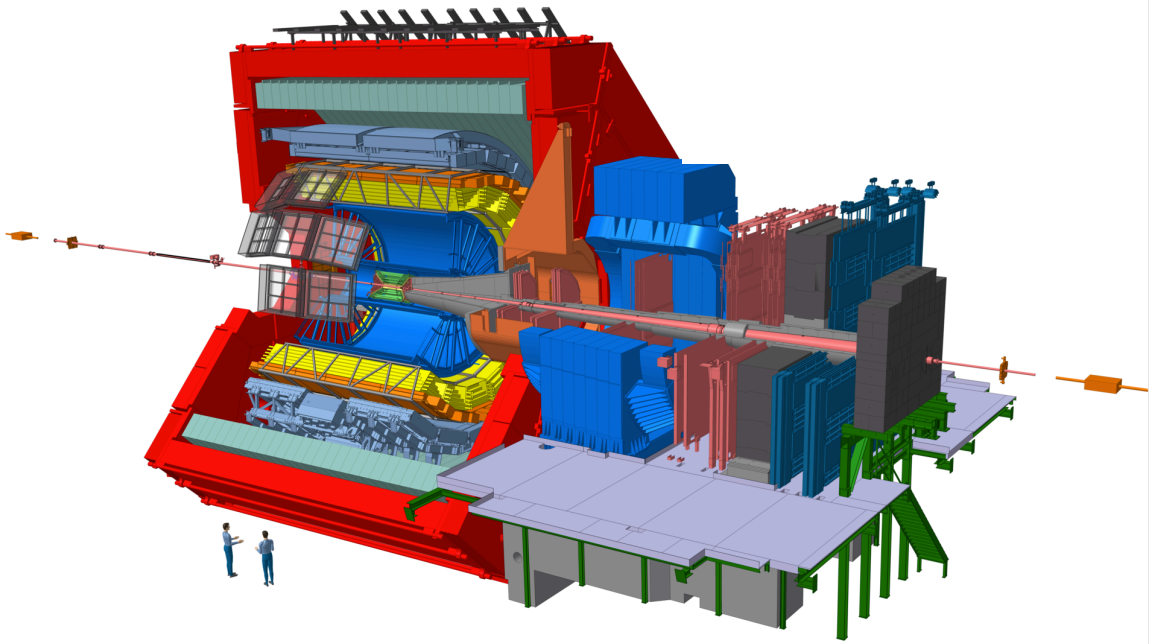
A.Rustamov et al., Nucl.Phys.A 960 (2017) 114, arXiv:1612.00702

ALICE detector and Pb-Pb data samples

Tracking $|\eta|<0.9$
Inner Tracking System
Time Projection Chamber (TPC)

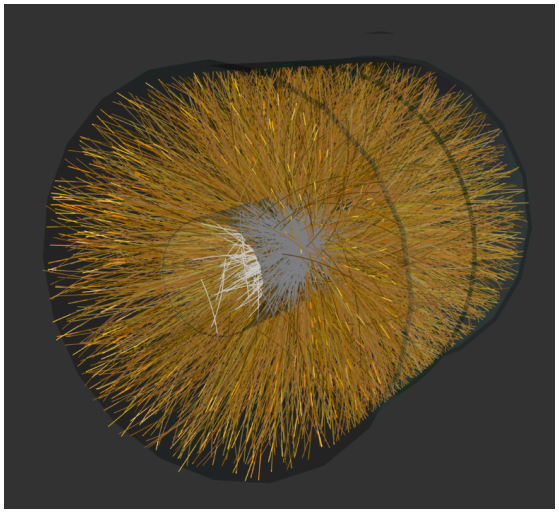
Particle identification:
this talk: TPC

Centrality of collisions:
V0 detector
(two forward scintillator arrays)

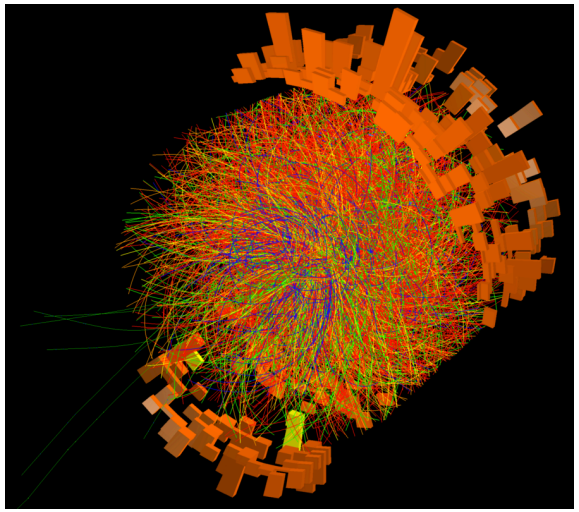


Pb-Pb data samples:

2010: **$\sqrt{s_{NN}}$=2.76 TeV**, ≈14×10^6 events



2015: **$\sqrt{s_{NN}}$=5.02 TeV**, ≈60×10^6 events



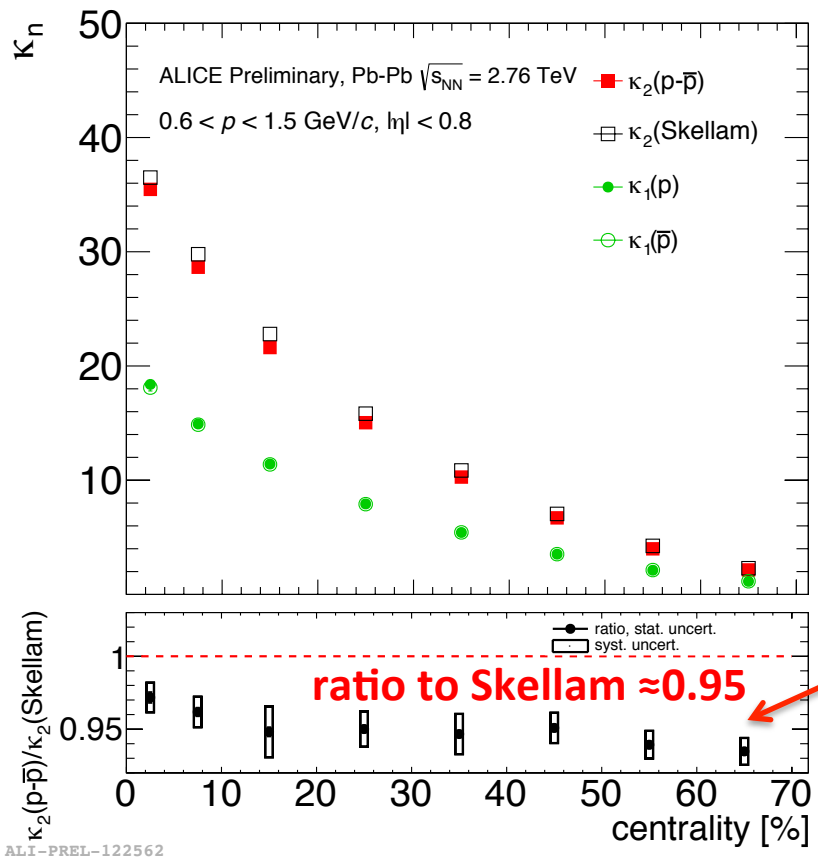
1 Net-proton fluctuations in Pb-Pb: *the 2nd moment*

Protons and antiprotons with **0.6<*p*<1.5 GeV/*c*** and **|η|<0.8**

1st and 2nd cumulants:

$$\kappa_1(\Delta n_B) = \langle \Delta n_B \rangle$$

$$\kappa_2(\Delta n_B) = \left\langle \Delta n_B^2 \right\rangle - \langle \Delta n_B \rangle^2 = \underbrace{\kappa_2(n_B) + \kappa_2(n_{\bar{B}})}_{\text{if Skellam}} - \underbrace{2\left(\langle n_B n_{\bar{B}} \rangle - \langle n_B \rangle \langle n_{\bar{B}} \rangle\right)}_{\text{correlation term}}$$



Skellam distribution:
prob. distribution of *difference of two random variables*, each generated from *statistically independent* Poisson distributions.

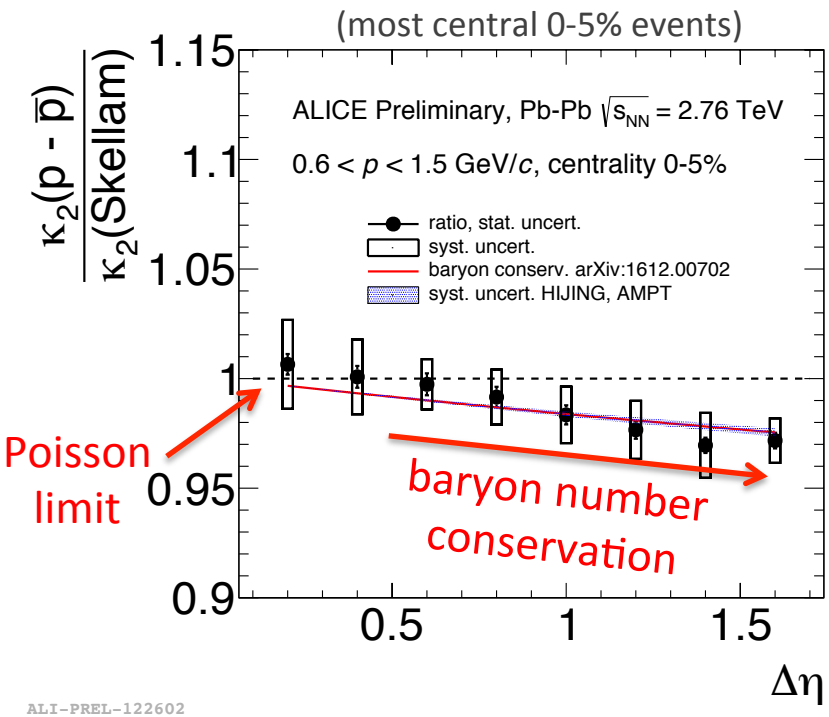
$$\kappa_n(Skellam) = \langle X_1 \rangle + (-1)^n \langle X_2 \rangle$$

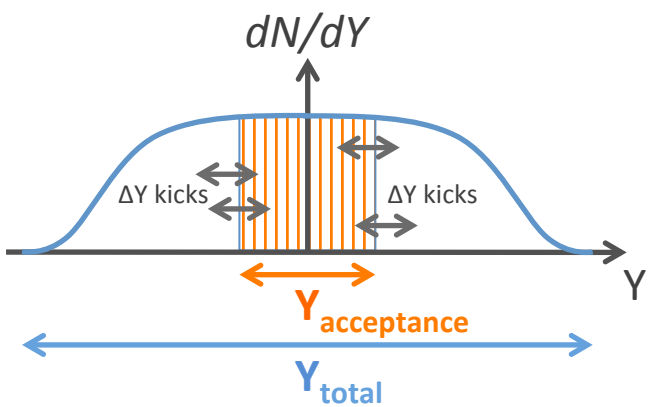
Deviation from Skellam:
genuine physics or non-dynamical contributions?

1 Net-proton fluctuations in Pb-Pb: *the 2nd moment*

In addition to critical fluctuations, the correlation term may emerge from the **global conservation laws**.

→ Study acceptance dependence:





→ Deviation from Skellam can be well explained by global baryon number conservation.

No evidence for dynamical fluctuations

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

Model by A.Rustamov et al., Nucl.Phys.A 960 (2017) 114, arXiv:1612.00702

2 Net-Λ fluctuations in Pb-Pb: *the 2nd moment*

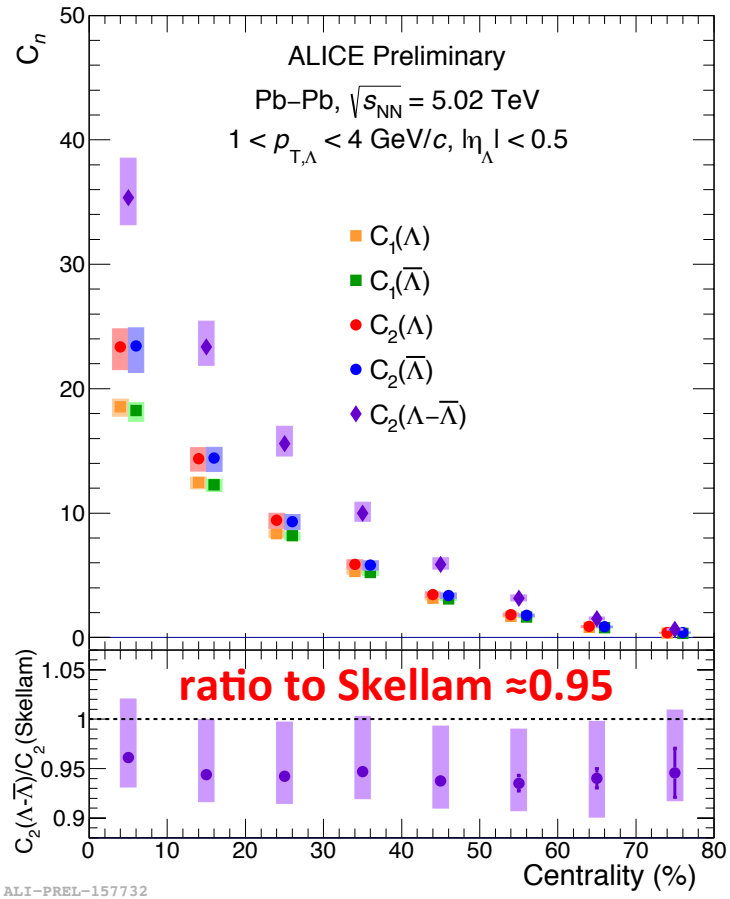
Why measure net-Λ fluctuations?

QM2018 talk by A.Ohlson

→ to explore correlated fluctuations of baryon number and strangeness

- different contributions from resonances, etc., than in net-proton measurement

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



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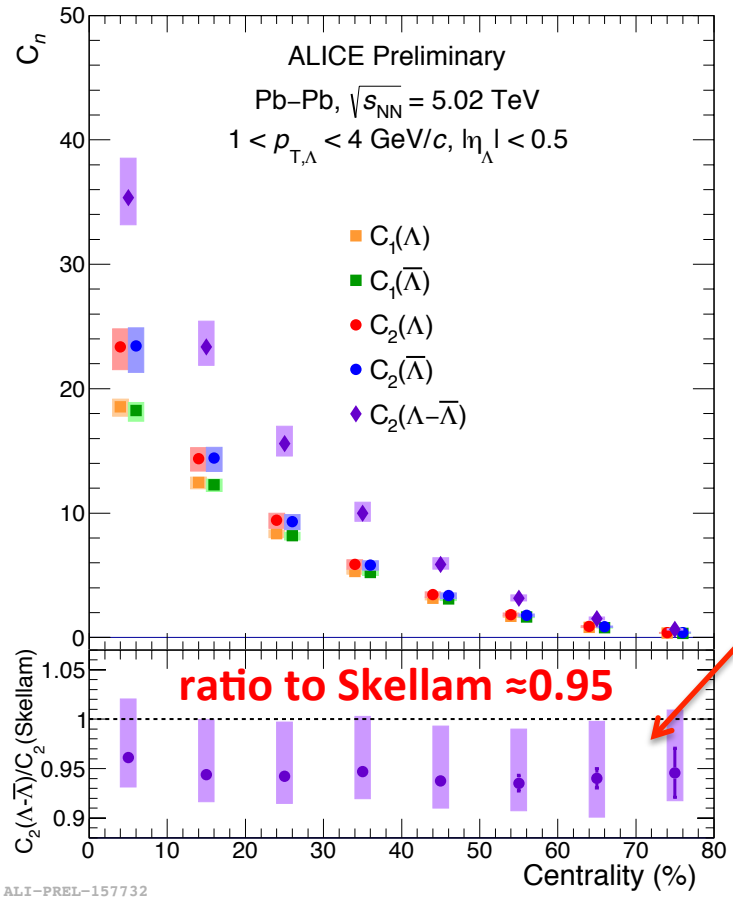
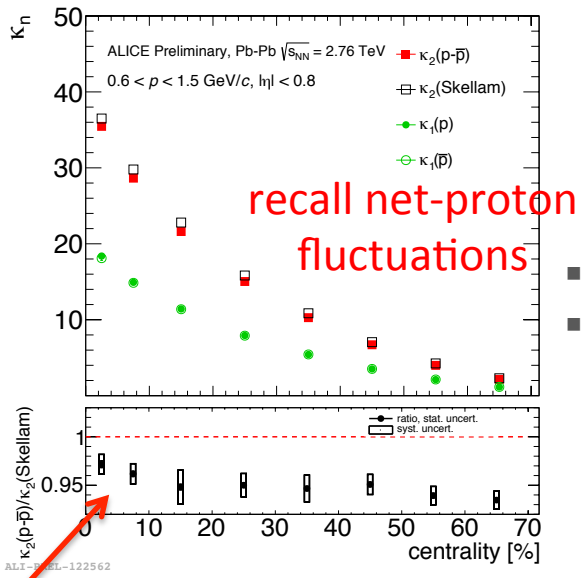




Note changed notations:
κ_n → C_n

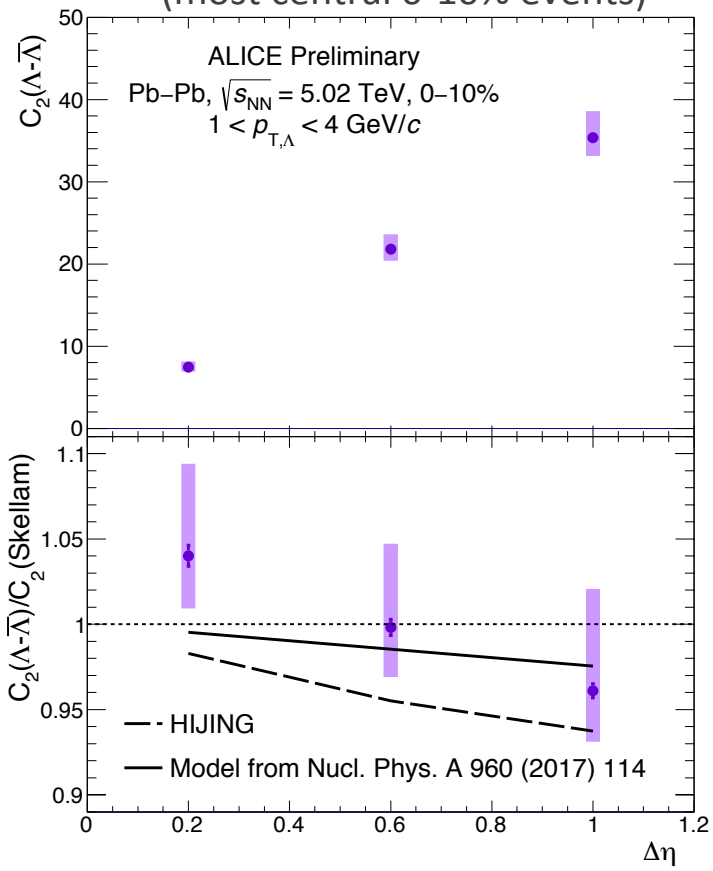
- different kinematic range
- different contributions from resonance decays

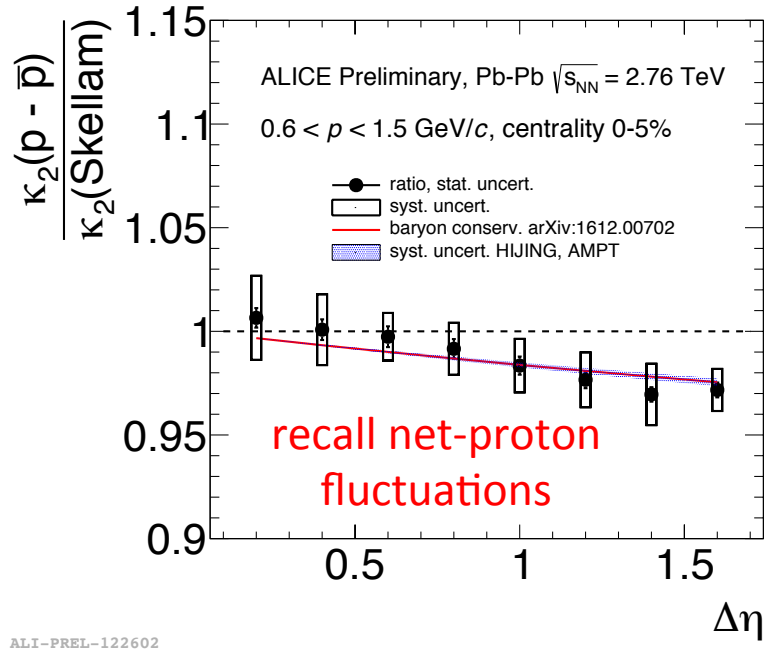
Qualitatively similar conclusion as for net-protons.

2 Net-Λ fluctuations in Pb-Pb: *the 2nd moment*

Study acceptance dependence:

(most central 0-10% events)





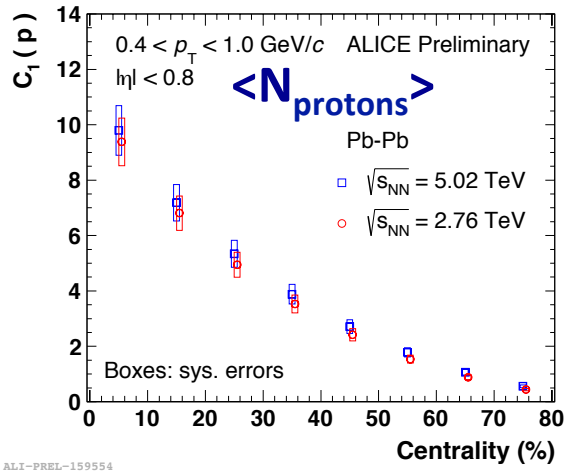
Note: systematic uncertainties are highly correlated point-to-point.

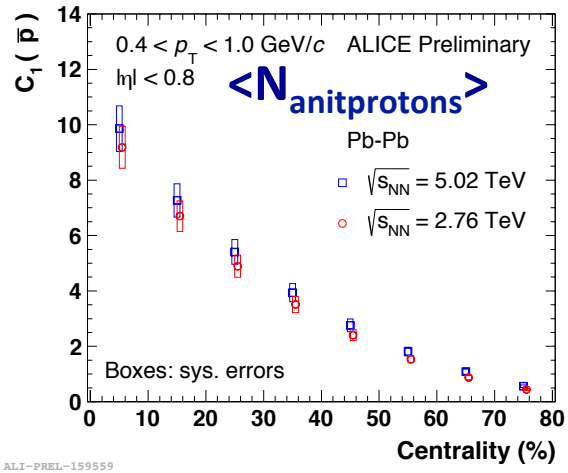
Δη dependence for net-Λ is consistent with the Skellam baseline **after accounting for global baryon number conservation** (as was seen for the net-protons).

- however, effect from strangeness conservation should be also considered.

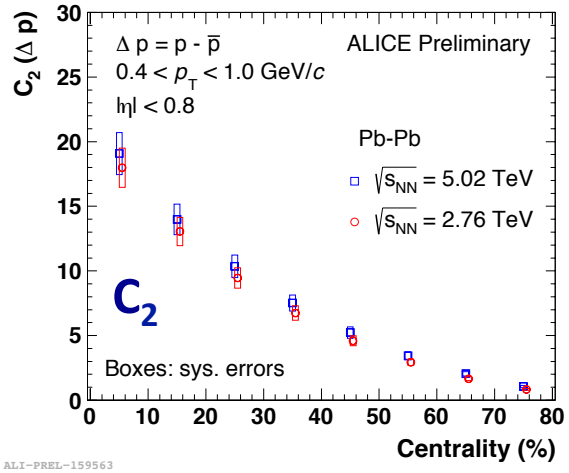
3 Net-proton fluctuations in Pb-Pb: *higher moments*

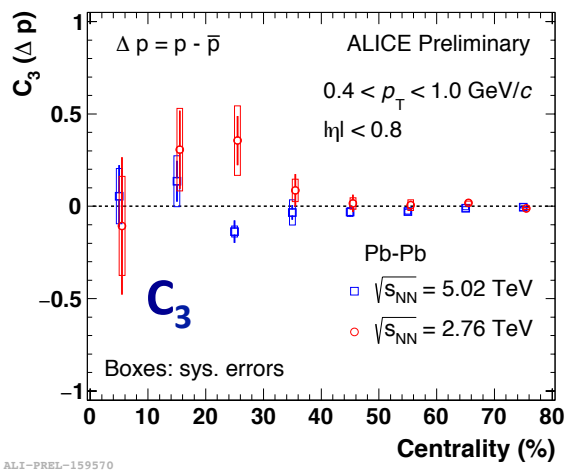
Pb-Pb@2.76, 5.02 TeV: protons and antiprotons with **0.4<p_T<1.0 GeV/*c*** and **|η|<0.8**.

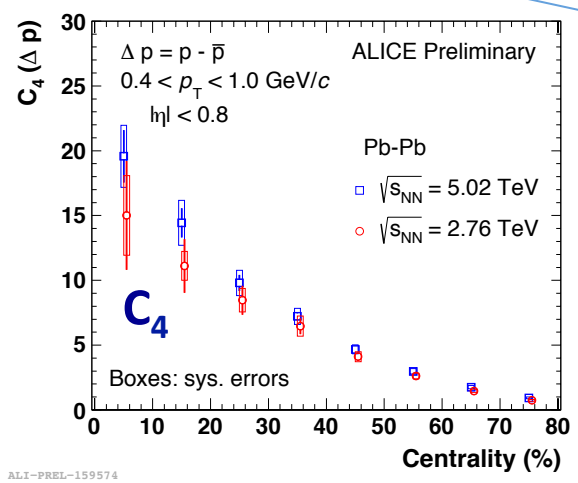




QM2018 talk by N.Behera



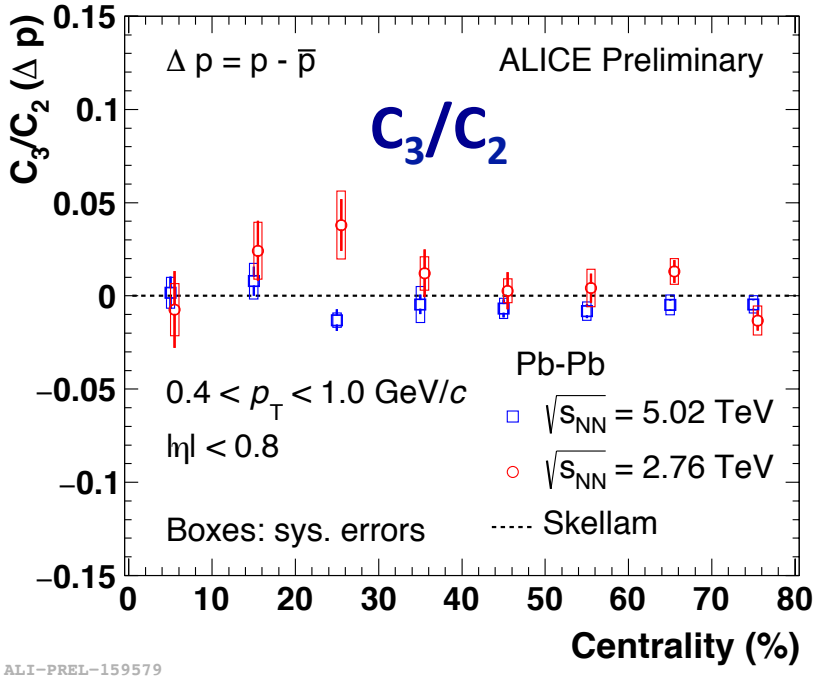


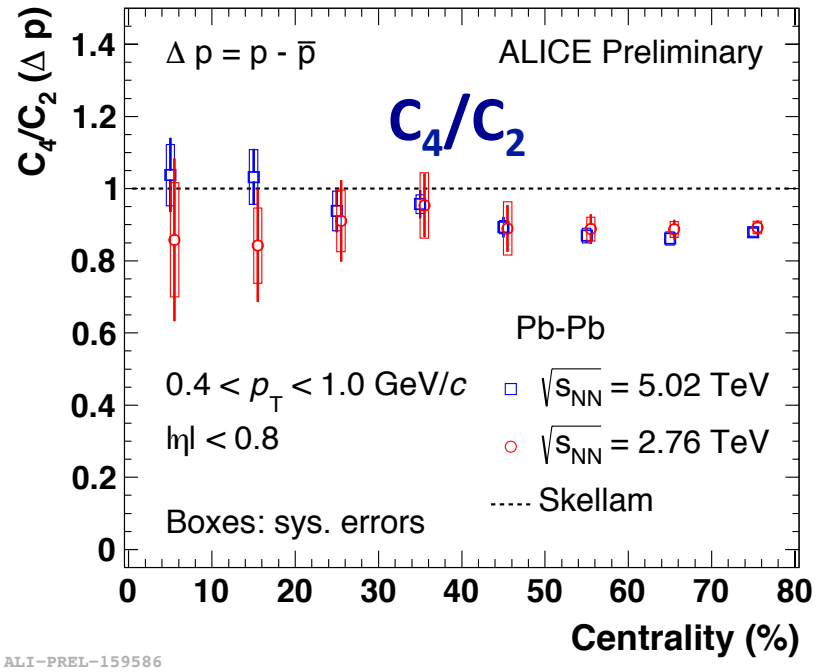


For both energies, cumulants **C_1, C_2, C_3, C_4** of net-proton distributions are the same within statistical and systematic errors.

3 Net-proton fluctuations in Pb-Pb: *higher moments*

Reminder: the connection to theory is actually through the ***ratios*** of cumulants.



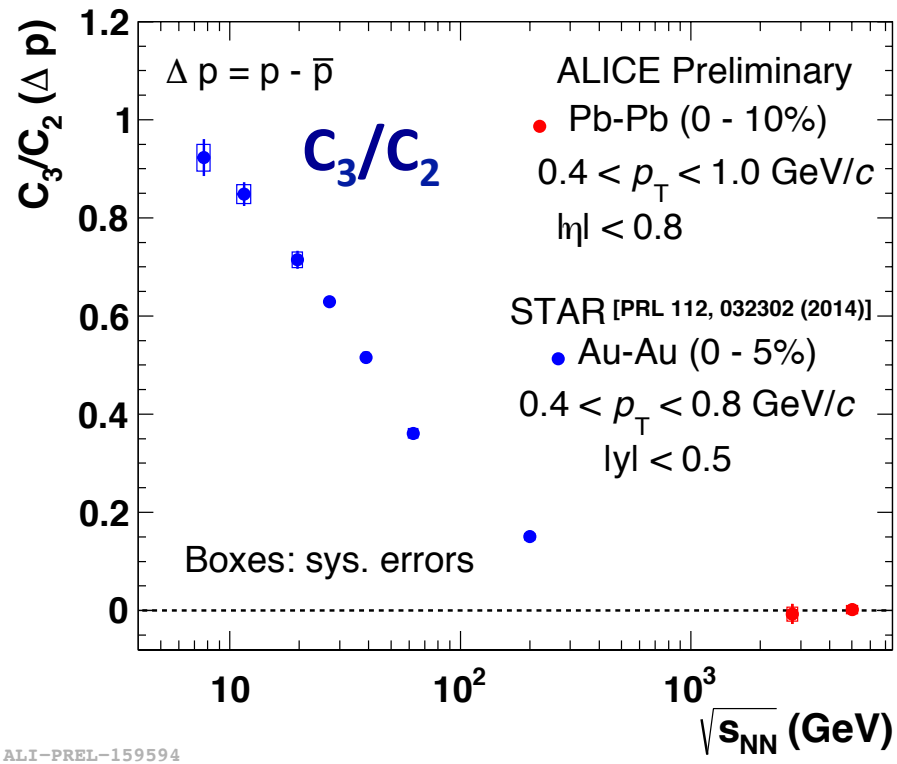


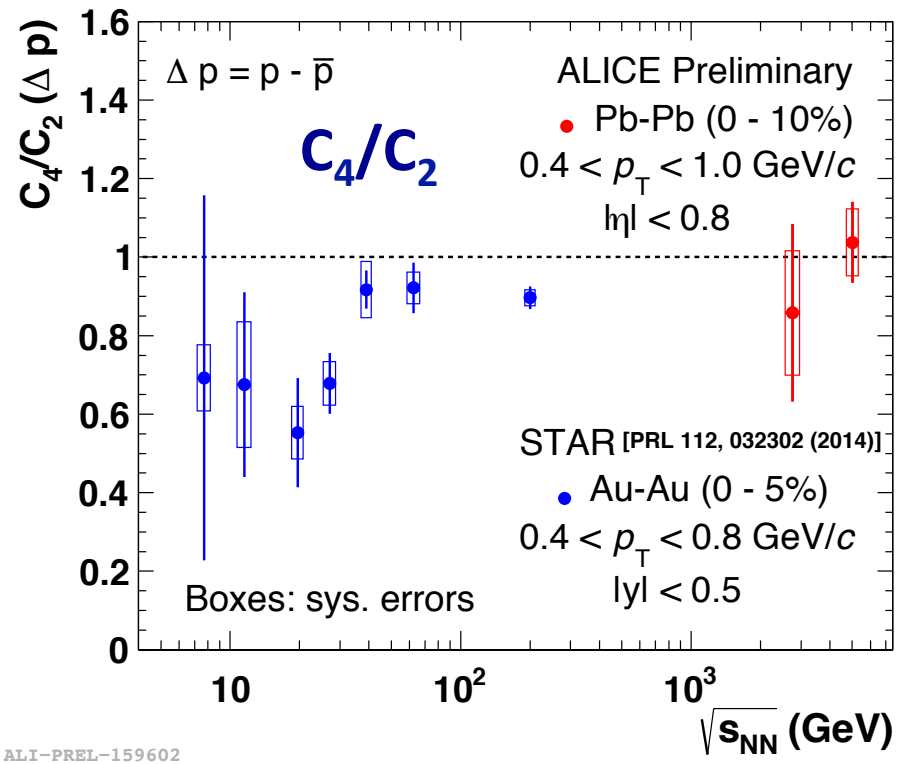
C_3/C_2 and **C_4/C_2** are consistent at 2.76 and 5.02 TeV within uncertainties, in central events agree with Skellam expectations.

In order to put constraints on the freeze-out temperature, correction for non-dynamical contributions (volume fluctuations, baryon number conservation) should be done.

3 Net-proton fluctuations in Pb-Pb: *higher moments*

Ratios of cumulants in most central events – from RHIC to LHC energies:

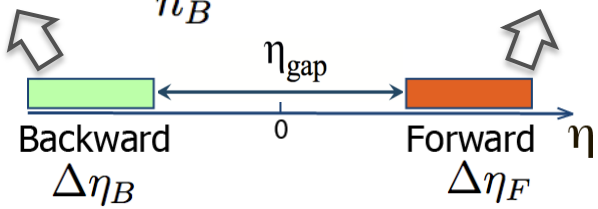




C_3/C_2 follows the decreasing trend with $\sqrt{s_{NN}}$,
C_4/C_2 approaches Skellam baseline at LHC energies.

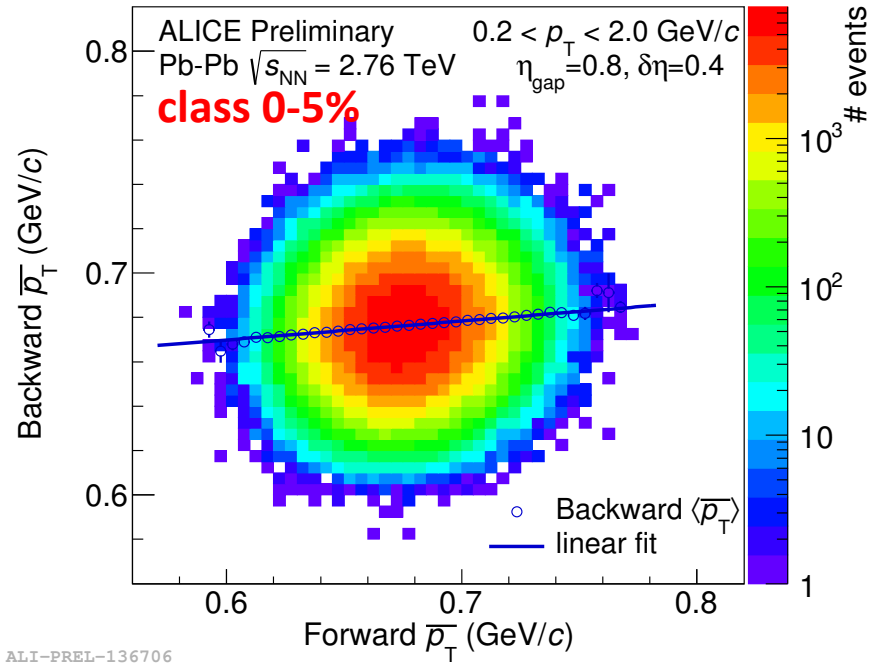
4 F-B correlations between mean transverse momenta

$$B \equiv \overline{p_{\mathrm{T}}}_B = \frac{\sum_{i=1}^{n_B} p_{\mathrm{T}}^{(i)}}{n_B} \qquad F \equiv \overline{p_{\mathrm{T}}}_F = \frac{\sum_{j=1}^{n_F} p_{\mathrm{T}}^{(j)}}{n_F}$$



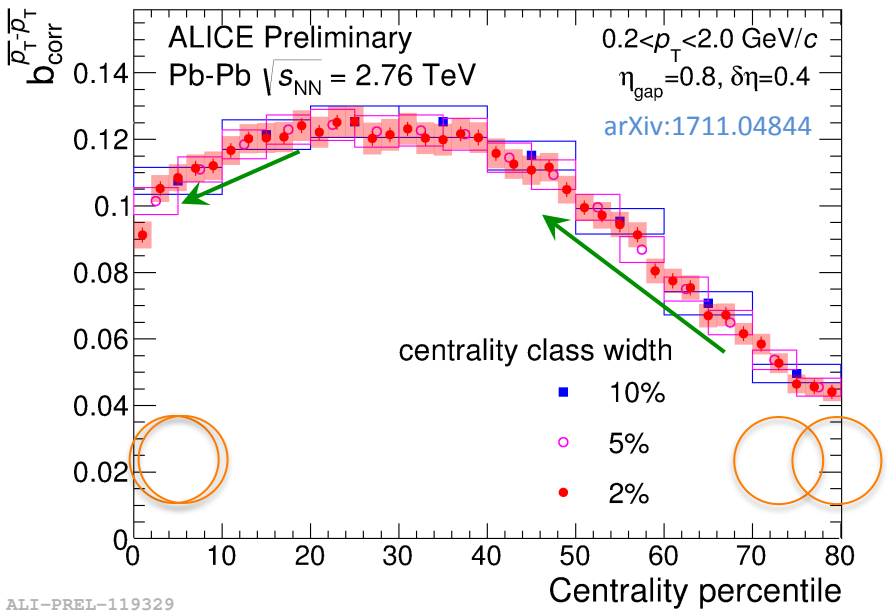
Quantify correlations using the correlation coefficient:

$$b_{\mathrm{corr}}^{p_T - p_T} = \frac{\langle \overline{p_{\mathrm{F}}}\, \overline{p_{\mathrm{B}}} \rangle - \langle \overline{p_{\mathrm{F}}} \rangle \langle \overline{p_{\mathrm{B}}} \rangle}{\langle \overline{p_{\mathrm{F}}}^2 \rangle - \langle \overline{p_{\mathrm{F}}} \rangle^2}$$



→ Correlation coefficient b_{corr} is the slope of the linear fit.

4 F-B correlations between mean transverse momenta

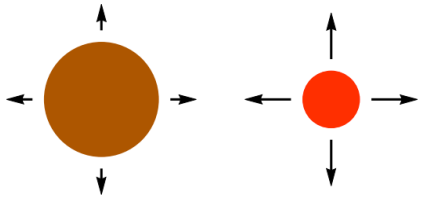


Correlation strength:

- rises from peripheral to mid-central
- **drops towards central collisions.**

What can cause mean-p_T FB correlations?

Size fluctuations ↔ p_T fluctuations

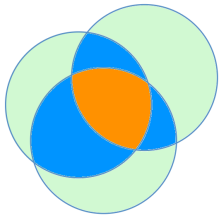


Phys. Rev. C 96, 014904 (2017)

– pressure gradients in the fireball reflect the fluctuations of the density in the fireball.

String fusion model

Nucl. Phys. B 390 542–558 (1993)

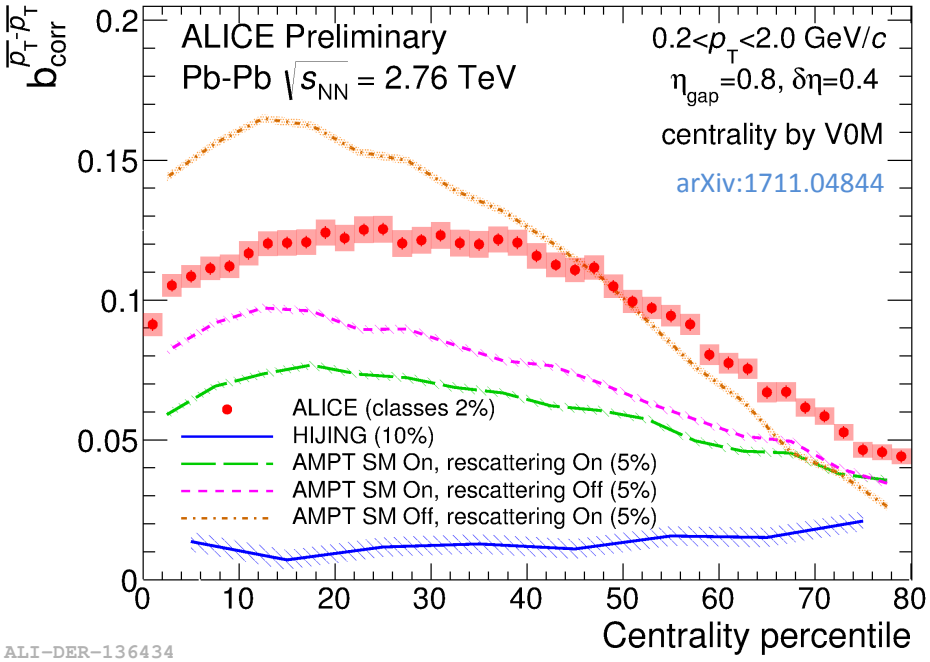


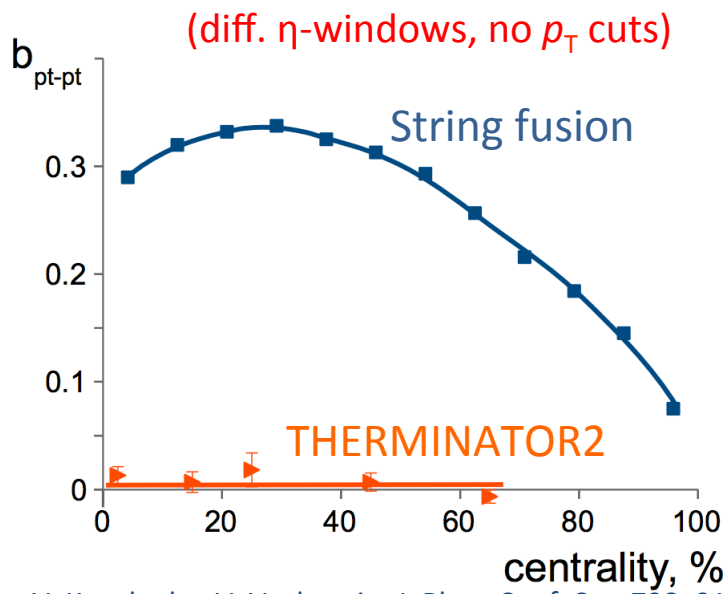
strings overlap
→ modification of string tension
→ increased p_T of particles from the fused strings

MC realization: arXiv:1308.6618

What is non-trivial to explain:
trend of mean-p_T correlations *vs* centrality.

4 F-B correlations: comparison with models





V. Kovalenko, V. Vechernin, J. Phys. Conf. Ser. 798, 012053 (2017)
arXiv:1611.07274

- **HIJING:** weak correlations, no dependence on centrality
- **AMPT:** generally reproduces the shapes, not the magnitude in detail

- **THERMINATOR:** freeze-out hypersurface, Cooper-Frye + decays
  → no mean-p_T correlations due to absence of e-by-e fluctuations
- **String fusion** → qualitatively describes behaviour with centrality

Mean-p_T correlations provide sensitivity to the properties of the initial state and evolution of the medium created in A-A collisions.

Summary

- Event-by-event measurements help to characterize the properties of the "bulk" of the system and also are closely related to dynamics of the phase transitions.

- **The cumulants of net-protons** are used as a proxy for net-baryons.
  - measured up to 4th order in Pb-Pb at 2.76 and 5.02 TeV with ALICE
  - the 2nd cumulants are, after accounting for baryon number conservation, in agreement with the Skellam baseline. Ratios κ_3/κ_2, κ_4/κ_2 also agree with Skellam.

- **Second moments of net-Λ** fluctuations are measured at the LHC for the first time.
  - qualitative agreement with net-protons, deviation from Skellam understood due to global baryon number and strangeness conservation, not critical behavior.

- **Forward-backward mean-p_T correlations** provide sensitivity to the properties of the initial state and evolution of the medium created in A-A collisions.

Thank you for your attention!

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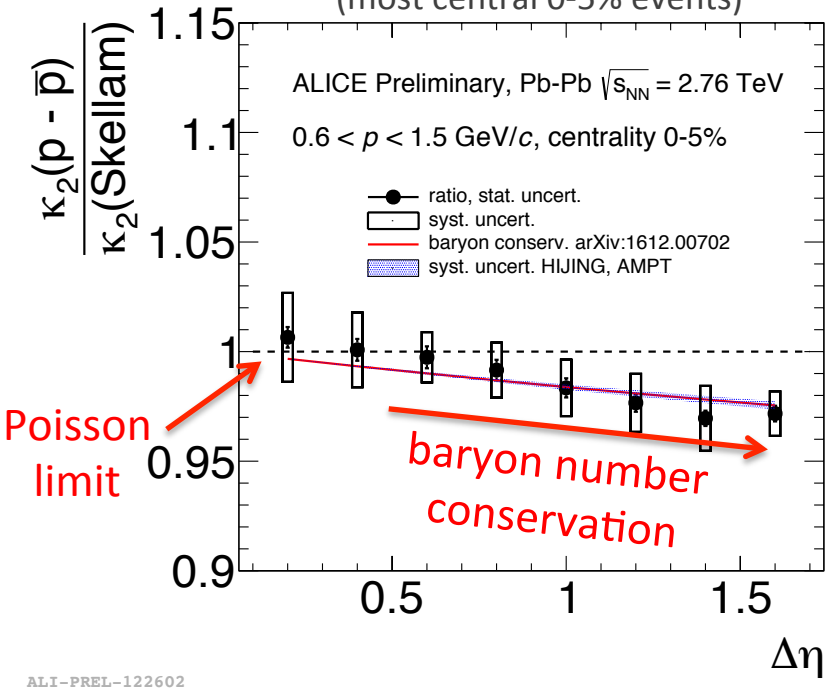
1 Net-proton fluctuations in Pb-Pb: *the 2nd moment*

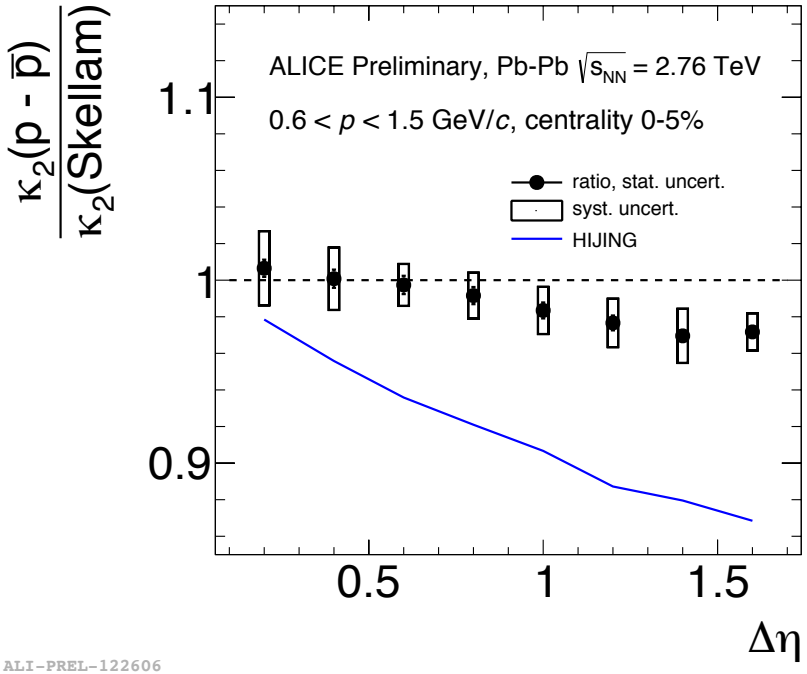
In addition to critical fluctuations, the correlation term may emerge from the **global conservation laws**.

→ Study acceptance dependence:

(most central 0-5% events)



Comparison with HIJING:



→ Deviation from Skellam can be well explained by global baryon number conservation.

No evidence for dynamical fluctuations

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

Model by A.Rustamov et al., Nucl.Phys.A 960 (2017) 114, arXiv:1612.00702