Event-by-event fluctuation measurements with ALICE

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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 ($\mu_B \approx 0$ at LHC energies).

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

Thermodynamic susceptibilities $\chi$:
- 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: electric charge, strangeness, baryon number
Connection between theory and experiment

**Theory:** susceptibilities
\[
\chi^B_n = \frac{\partial^n \left( \frac{P}{T^4} \right)}{\partial \left( \frac{\mu_B}{T} \right)^n}
\]
(fixed volume, particles in GCE)

\[\kappa_n \text{ – cumulants}\]

**Experiment:** moments of net-particle multiplicity distributions
\[
\Delta N_B = N_B - \bar{N}_B
\]
(volume fluctuations, global conservation laws)

\[dN/dY\]

\[\Delta Y \text{ kicks}\]

\[\gamma_{\text{acceptance}}\]

\[\gamma_{\text{total}}\]

\[\frac{\kappa_3(\Delta N_B)}{\kappa_2(\Delta N_B)} \leftrightarrow \frac{\chi^B_3}{\chi^B_2}\]

\[\frac{\kappa_4(\Delta N_B)}{\kappa_2(\Delta N_B)} \leftrightarrow \frac{\chi^B_4}{\chi^B_2}\]

(cancel \(VT^3\))
Connection between theory and experiment

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\]

(volume fluctuations, global conservation laws)

\[
\kappa_n - \text{cumulants}
\]

\[
\chi^B_n = \frac{\kappa_n(\Delta N_B)}{VT^3}
\]

\[
\kappa_1 = \langle \Delta N_B \rangle = VT^3 \chi^B_1
\]

\[
\kappa_2 = \sigma^2 = \left\langle \left( \Delta N_B - \langle \Delta N_B \rangle \right)^2 \right\rangle = VT^3 \chi^B_2
\]

\[
\kappa_3/\sigma^3 = S = \left\langle \left( \Delta N_B - \langle \Delta N_B \rangle \right)^3 \right\rangle / \sigma^3 = \frac{VT^3 \chi^B_3}{\left(VT^3 \chi^B_2\right)^{3/2}}
\]

\[
\kappa_4/\sigma^4 = k = \left\langle \left( \Delta N_B - \langle \Delta N_B \rangle \right)^4 \right\rangle / \sigma^4 - 3 = \frac{VT^3 \chi^B_4}{\left(VT^3 \chi^B_2\right)^2}
\]

**Ratios from experiment:**

\[
\frac{\kappa_3(\Delta N_B)}{\kappa_2(\Delta N_B)} \Leftrightarrow \frac{\chi^B_3}{\chi^B_2}
\]

\[
\frac{\kappa_4(\Delta N_B)}{\kappa_2(\Delta N_B)} \Leftrightarrow \frac{\chi^B_4}{\chi^B_2}
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(cancel \(VT^3\))

Igor Altsybeev, E-by-E measurements with ALICE
Connection between theory and experiment

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(fixed volume, particles in GCE)

**Experiment:** moments of net-particle multiplicity distributions
\[ \Delta N_B = N_B - N_{\overline{B}} \]
(volume fluctuations, global conservation laws)

\[ \kappa_1 = \left\langle \Delta N_B \right\rangle = VT^3 \chi^B_1 \]
\[ \kappa_2 = \sigma^2 = \left\langle \left( \Delta N_B - \left\langle \Delta N_B \right\rangle \right)^2 \right\rangle \neq VT^3 \chi^B_2 \]
\[ \kappa_3 / \sigma^3 = S = \left\langle \left( \Delta N_B - \left\langle \Delta N_B \right\rangle \right)^3 \right\rangle / \sigma^3 \neq \frac{VT^3 \chi^B_3}{\left( VT^3 \chi^B_2 \right)^{3/2}} \]
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Ratios from experiment:
\[ \frac{\kappa_3(\Delta N_B)}{\kappa_2(\Delta N_B)} \neq \frac{\chi^B_3}{\chi^B_2} \]
\[ \frac{\kappa_4(\Delta N_B)}{\kappa_2(\Delta N_B)} \neq \frac{\chi^B_4}{\chi^B_2} \]
(cancel $VT^3$)

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


Igor Altsybeev, E-by-E measurements with ALICE
**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, $\approx 14 \times 10^6$ events

2015: $\sqrt{s_{NN}}=5.02$ TeV, $\approx 60 \times 10^6$ events
**Net-proton fluctuations in Pb-Pb: the 2nd moment**

Protons and antiprotons with $0.6 < p < 1.5$ GeV/c and $|\eta| < 0.8$

1st and 2nd cumulants:

$$
\kappa_1(\Delta n_B) = \langle \Delta n_B \rangle \\
\kappa_2(\Delta n_B) = \langle \Delta n_B^2 \rangle - \langle \Delta n_B \rangle^2 = \kappa_2(n_B) + \kappa_2(n_{\bar{B}}) - 2(\langle n_B n_{\bar{B}} \rangle - \langle n_B \rangle \langle n_{\bar{B}} \rangle)
$$

if Skellam

**Skellam distribution:**

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

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

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

\[ \frac{\kappa_2(p - \bar{p})}{\kappa_2(Skellam)} = 1 - \alpha \]
\[ \alpha = \frac{\langle p \rangle_{\text{measured}}}{\langle B \rangle_{4\pi}} \]

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

No evidence for dynamical fluctuations

Why measure net-Λ fluctuations?

→ to explore correlated fluctuations of baryon number and strangeness
  • different contributions from resonances, etc., than in net-proton measurement

\[ \kappa_2(\Delta n_B) = \left\langle \Delta n_B^2 \right\rangle - \left\langle \Delta n_B \right\rangle^2 = \kappa_2(n_B) + \kappa_2(n_{\bar{B}}) - 2(\left\langle n_B n_{\bar{B}} \right\rangle - \left\langle n_B \right\rangle \left\langle n_{\bar{B}} \right\rangle) \]
**Net-Λ fluctuations in Pb-Pb: the 2\textsuperscript{nd} moment**

**Why measure net-Λ fluctuations?**

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\kappa_2(\Delta n_B) = \langle \Delta n_B^2 \rangle - \langle \Delta n_B \rangle^2 = \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)
\]

**Results:**

Net-Λ fluctuations in Pb-Pb collisions at \( \sqrt{s_{NN}} = 5.02 \text{ TeV} \):

<table>
<thead>
<tr>
<th>Centrality (%)</th>
<th>( C_2(\Lambda) )</th>
<th>( C_2(\Lambda^-) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.95</td>
<td>0.95</td>
</tr>
<tr>
<td>10</td>
<td>0.95</td>
<td>0.95</td>
</tr>
<tr>
<td>20</td>
<td>0.95</td>
<td>0.95</td>
</tr>
<tr>
<td>30</td>
<td>0.95</td>
<td>0.95</td>
</tr>
<tr>
<td>40</td>
<td>0.95</td>
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<tr>
<td>50</td>
<td>0.95</td>
<td>0.95</td>
</tr>
<tr>
<td>60</td>
<td>0.95</td>
<td>0.95</td>
</tr>
<tr>
<td>70</td>
<td>0.95</td>
<td>0.95</td>
</tr>
</tbody>
</table>

Note changed notations:

\( \kappa_n \rightarrow C_n \)

- different kinematic range
- different contributions from resonance decays

Recall net-proton fluctuations

Qualitatively similar conclusion as for net-protons.

QM2018 talk by A. Ohlson
**Study acceptance dependence:**

![Graph showing fluctuations in Pb-Pb collisions](image)

\[ C_2(\Lambda^-\Lambda) \text{ and } C_2(\Lambda^-\Lambda)^{(\text{Skellam})}/C_2 \text{ vs } \Delta \eta \]

- **ALICE Preliminary**
  - Pb-Pb, \( \sqrt{s_{NN}} = 5.02 \text{ TeV}, 0-10\% \)
  - \( 1 < p_{T,\Lambda} < 4 \text{ GeV/c} \)

\[ \Delta \eta \text{ dependence for net-\( \Lambda \) 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.

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**Note:** Systematic uncertainties are highly correlated point-to-point.
**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 $|\eta| < 0.8$.

For both energies, cumulants $C_1$, $C_2$, $C_3$, $C_4$ of net-proton distributions are the same within statistical and systematic errors.
**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.
**Net-proton fluctuations in Pb-Pb: higher moments**

**3**

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

\[
\frac{C_3}{C_2} \text{ follows the decreasing trend with } \sqrt{s_{NN}},
\]

\[
\frac{C_4}{C_2} \text{ approaches Skellam baseline at LHC energies.}
\]
F-B correlations between mean transverse momenta

\[ B \equiv p_{TB} = \frac{\sum_{i=1}^{n_B} p_T^{(i)}}{n_B} \]

\[ F \equiv p_{TF} = \frac{\sum_{j=1}^{n_F} p_T^{(j)}}{n_F} \]

Quantify correlations using the correlation coefficient:

\[ b_{\text{corr}}^{p_T} = \frac{\langle p_F \ p_B \rangle - \langle p_F \rangle \langle p_B \rangle}{\langle p_F^2 \rangle - \langle p_F \rangle^2} \]

ALICE Preliminary
\(0.2 < p_T < 2.0 \text{ GeV/c} \)
\(\sqrt{s_{NN}} = 2.76 \text{ TeV} \)
\(\eta_{\text{gap}} = 0.8, \delta\eta = 0.4 \)

class 0-5%

\(\rightarrow\) Correlation coefficient \(b_{\text{corr}}\) is the slope of the linear fit.
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
- pressure gradients in the fireball reflect the fluctuations of the density in the fireball.

String fusion model
- strings overlap
  - modification of string tension
  - increased $p_T$ of particles from the fused strings

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

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**F-B correlations: comparison with models**

- **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

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**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 $\kappa_3/\kappa_2, \kappa_4/\kappa_2$ also agree with Skellam.

- Second moments of net-$\Lambda$ 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!

This work is supported by the Russian Science Foundation, grant 17-72-20045.
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In addition to critical fluctuations, the correlation term may emerge from the global conservation laws.

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\[ \alpha = \frac{\langle p \rangle_{\text{measured}}}{\langle B \rangle_{4\pi}} \]

\[ \kappa_2(p - \bar{p}) = \kappa_2(\text{Skellam}) \]

\[ \Delta \eta \]

→ Study acceptance dependence:

(\text{most central 0-5\% events})

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

No evidence for dynamical fluctuations

ALICE Preliminary, Pb-Pb \( \sqrt{s_{NN}} = 2.76 \) TeV
0.6 < \( p < 1.5 \) GeV/\( c \), centrality 0-5\%

Comparison with HIJING: