First results on the event-by-event fluctuations and correlations in Pb—Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV

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The presence of the phase transition can manifest itself by characteristic behavior of several observables which may vary dramatically from one event to the other.

- Thus the study of various quantities on an event-by-event basis offers the possibility for studying the QGP phase transition and the nature of the QGP matter.

The large particle production at the LHC allows one to make precision event-by-event measurements.

The challenge of event-by-event studies is to disentangle between the two components having a statistical and a dynamical origin. The latter consists of

- fluctuations which do not change event-to-event, e.g. those from Bose-Einstein (BE) correlations, resonance decays, etc.
- the fluctuations which have a new physics origin and may vary from event-to-event.
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ALICE has a detailed event-by-event physics program under way

- Charge fluctuations (+ higher moments)
- Transverse momentum fluctuations
- Multiplicity fluctuations
- Balance functions
- Identified particle ratios
- long range correlations
Motivation

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Studies in ALICE: Analysis details

- **Analysis of pp @ \( \sqrt{s} = 0.9, 2.76 \) and 7 TeV and Pb–Pb events @ \( \sqrt{s_{NN}} = 2.76 \) TeV**
  - Event sample split in two sets having different magnetic field polarities (results used for the systematic uncertainties)

- **The trigger consists of the following criteria:**
  - two pixel chips hit in the outer layer of the SPD,
  - signal in VZERO-A detector,
  - signal in VZERO-C detector.

- **The centrality in Pb–Pb is selected using the VZERO magnitude as the default estimator**
  - Centrality bins used in the analysis: 0-5%, 5-10%, 10-20%, ..., 70-80%
  - Different centrality estimators (TPC tracks, SPD clusters) investigated
    - Results used for the systematic uncertainty

- **Due to the nature of the studies, applying corrections is highly non-trivial; we need to have the acceptance corrections under control:**
  - The TPC tracks provide a uniform acceptance with minimal corrections
  - Disadvantage: contamination from secondaries
    - Investigated by varying the cut on the distance of closest approach (results used for the systematic uncertainty).
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- Possibility to have really fine bins in centrality, reducing the fluctuations due to the impact parameter
Transverse momentum fluctuations

- Event-by-event fluctuations of mean transverse momentum contain information on the dynamics and correlations in pp and heavy-ion collisions.
- Reference measurements in pp serve as a baseline with ‘known’ physics like $p_T$ correlations due to resonance decays, HBT, (mini-)jets etc.
- In heavy-ion collisions, fluctuations may also be related to other effects like a critical behaviour of the system in the vicinity of a phase boundary or the onset of thermalisation of the system.

- The tool used to quantify the fluctuations is the 2–particle correlator:

$$C_m = \left< \Delta p_{T,i}, \Delta p_{T,j} \right> = \frac{1}{n_{ev}} \sum_{k=1}^{n_{ev}} \sum_{i=1}^{N_k} \sum_{j=i+1}^{N_k} (p_{T,i} - \langle p_T \rangle_m) (p_{T,j} - \langle p_T \rangle_m)$$

- $C_m = 0$ in the presence of stat. fluctuations
Transverse momentum fluctuations in pp

- Significant non-statistical fluctuations
  - 'Dilution' with multiplicity
- Moderate energy dependence of the 2-particle correlator

![Graph showing transverse momentum fluctuations](image)

- Preliminary

PP: \( \sqrt{s} = 7 \text{ TeV} \)
- \( \sqrt{s} = 2.76 \text{ TeV} \)
- \( \sqrt{s} = 0.9 \text{ TeV} \)

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Transverse momentum fluctuations in pp

- Significant non-statistical fluctuations
  - 'Dilution' with multiplicity
- No apparent energy scaling of the relative fluctuations

- Good description of the relative fluctuations by PYTHIA
  - Discrepancies at low multiplicities ($N_{acc} < 7$)
- Poor description by PHOJET
Transverse momentum fluctuations in Pb–Pb

- Same trend as in pp
  - Significant fluctuations in the peripheral bins the magnitude of which is decreasing when moving to more central collisions
- pp and peripheral Pb–Pb indicate a common scaling

- Experimental values are not described by HIJING both in magnitude and in their centrality dependence
  - HIJING points show also significant non-statistical fluctuations with a decreasing trend vs centrality
Transverse momentum fluctuations: Data vs models

\[ f(N_{\text{acc.}}) \sim (N_{\text{acc.}})^a \]

Preliminary
Transverse momentum fluctuations: Data vs models

- Fit the pp baseline with a power law from $N_{acc.} > 8$
- The fit with the same parameters describe the Pb—Pb points up to the 30—40% centrality bin.
  - Moving to more central collisions leads to significant additional reduction of the relative fluctuations

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- HIJING points deviate following their own monotonic decrease with centrality
- Different slopes between experimental data points and HIJING
- No indication for a deviation from the power law fit for central collisions in HIJING
The relative fluctuations for both energies are described well by the pp baseline fit from peripheral up to mid-central collisions.

RHIC data were explained in terms of percolation of strings, thermalization, deconfinement.

We need to have a model incorporating the two important contributions: jets and flow.
Charge fluctuations

- In the presence of the QGP, the relevant carriers of the charge are the quarks.

- Thus in the QGP phase, the unit of charge is 1/3 while in the hadronic phase, the unit of charge is 1.

- Charge fluctuations depend on the squares of the charges and hence strongly depend on which phase they originate from.

- The measure of the net charge fluctuations should not be sensitive to:
  - Volume fluctuations (i.e. fluctuations in the impact parameter)
  - Detector effects

- The tool used to quantify the fluctuations is the $v_{\text{dyn}}$, which is not sensitive to detector effects, provided that the detection efficiency is uniform over the measured kinematic range:

$$v_{(+,-,\text{dyn.})} = \frac{\langle N_+ (N_+ - 1) \rangle}{\langle N_+ \rangle^2} + \frac{\langle N_- (N_- - 1) \rangle}{\langle N_- \rangle^2} - 2 \frac{\langle N_+ N_- \rangle}{\langle N_+ \rangle \langle N_- \rangle}$$

Charge fluctuations: Centrality dependence

- $v_{\text{dyn}}$ studied for different centralities and pseudo-rapidity windows.
- The centrality dependence shows a saturation pattern, already observed at RHIC.
  - $|v_{\text{dyn}}|$ decreases when moving from peripheral to central collisions
  - Can this be attributed to the larger yield of resonances that don't contribute to the charge fluctuations but only to the multiplicity?
- Relative decrease in $\Delta \eta$ of the $|v_{\text{dyn}}|$ twice as much in central than in peripheral collisions

\begin{itemize}
\item Pb-Pb events at $\sqrt{s_{\text{NN}}} = 2.76$ TeV ($0.2 \text{ GeV/c} < p_T < 5 \text{ GeV/c}$)
\item Preliminary
\end{itemize}
Charge fluctuations: LHC vs RHIC

- Nice evolution of the \( v_{\text{dyn.}} \) as a function of the centrality
- The ALICE points, when plotted vs \( N_{\text{part}} \), demonstrate a higher value of \( v_{\text{dyn.}} \) for each centrality bin.
- When plotted against the pseudo-rapidity density, there is a nice agreement between the LHC peripheral and mid-peripheral and the RHIC mid-peripheral and central points.
  - The ALICE points extend further in \( dN/d\eta \), exhibiting an additional reduction of the fluctuations.

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Preliminary
Charge fluctuations: Looking for the proper scaling

- Observed centrality dependence of the scaled (with the $dN/d\eta$) $v_{dyn}$
  - In case of independent nucleon-nucleon collisions, then the scaled $v_{dyn}$ should not show any dependence on centrality
  - Indication of a change in the collision dynamics when going from peripheral to central collisions.

- Additional 7.5% reduction of the fluctuations compared to the highest RHIC energy.
Initial estimate by Jeon and Koch about the values of the parameter $D$ in case of a pion gas and the QGP phase.

The relevant values were further refined by the same authors taking into account the contributions from resonances.

The experimental values are larger than the QGP prediction (ideal QGP) but still lower than the expectation for a hadron gas with the inclusion of resonances.


$$D \approx \left\langle N_{ch} \right\rangle \left\langle \Delta R^2 \right\rangle \approx \begin{cases} 4, (\pi - \text{gas}) \\ 3, (\text{hadron} - \text{gas}) \\ 1, (\text{QGP}) \end{cases}$$

$$N_{ch} \nu_{(+-,\text{dyn.)}} \approx D - 4$$
Charge fluctuations: Comparison with theory

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- The relevant values were further refined by the same authors taking into account the contributions from resonances.
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Initial fluctuations diluted by the hadronization and the final state interactions

- Introduction of the diffusion parameter to trace the initial magnitude of the fluctuations

$D \approx \langle N_{ch} \rangle \langle \Delta R^2 \rangle \approx \begin{cases} 4, (\pi - \text{gas}) \\ 3, (\text{hadron} - \text{gas}) \\ 1, \text{(QGP)} \end{cases}$

$N_{ch} \cdot \nu_{(+,-,\text{dyn.})} \approx D - 4$


First ebye observables studied at the LHC with the ALICE experiment in pp collisions @ $\sqrt{s} = 0.9, 2.76$ and $7$ TeV and Pb—Pb events @ $\sqrt{s_{\text{NN}}} = 2.76$ TeV

The transverse momentum fluctuations demonstrate:
- a universal scaling with energy in pp collisions,
- a nice evolution of the relative fluctuations from pp to mid-peripheral Pb—Pb collision with an additional reduction for the more central events,
- the centrality dependence of the fluctuations can’t be described by standard models (i.e. HIJING).

The charge fluctuations indicate:
- a further reduction of the magnitude of the fluctuations measured in $v_{\text{dyn}}$, going from RHIC to LHC,
- a change in the collision dynamics when $v_{\text{dyn}}$ is scaled with the $dN/dn$,
- the resulting fluctuations have a magnitude which resides between the expectations from theory for a hadron gas with the inclusion of resonances and the corresponding value for a QGP phase transition.

More things to come:
- Balance functions ➔ time of hadronization, radial flow
- Identified particle ratios
- long range correlations
Transverse momentum fluctuations in pp

- Significant non-statistical fluctuations
  - 'Dilution' with multiplicity
- Moderate energy dependence of the 2-particle correlator
- No apparent energy scaling of the relative fluctuations

![Graph](graph.png)

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Transverse momentum fluctuations: LHC vs RHIC

- The relative fluctuations for both energies are described well by the pp baseline fit from peripheral up to mid-central collisions.
- RHIC data were explained in terms of percolation of strings, thermalization, deconfinement.
- We need to have a model incorporating the two important contributions: jets and flow.
Charge fluctuations: Looking for the proper scaling

- Observed centrality dependence of the scaled (with the $dN/d\eta$) $v_{\text{dyn}}$
  - In case of independent nucleon-nucleon collisions, then the scaled $v_{\text{dyn}}$ should not show any dependence on centrality
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Preliminary
Charge fluctuations: Looking for the proper scaling

- No centrality dependence of the scaled (with the number of participants) $v_{\text{dyn}}$
- Fluctuations/participant show no centrality dependence?
- A strong energy dependence is observed
Several attempts were made to trace the initial fluctuations. According to Shuryak and Stephanov, the initial fluctuations are diluted by the final state interactions and the limited experimental acceptance. Based on a refined formulation of the previous idea, Gavin et al. introduced the notion of the causal diffusion.