Charge Fluctuations in Fixed Target Hadron-Hadron Experiments

At fixed target experiments in hadronic multi-particle production it was possible to measure all charges of forward particles. In this way significant results could be obtained even with low energies available at the seventies\textsuperscript{1}:

- The charge fluctuations involve a restricted rapidity range.
- Qualitative agreement was obtained the Quigg-Thomas relation.

The Quigg-Thomas relation\textsuperscript{2} was initially based on intermediately produced neutral clusters\textsuperscript{3,4}. It postulates for charge fluctuation across a rapidity $y$ boundary

$$<\delta Q^2_{>y}> = <(Q_{>y} - \langle Q_{>y} \rangle)^2> = c \cdot dN_{\text{leading}}^{\text{charge}} / dy. \quad (1)$$

To quantitatively fit the constant $c$ with known resonances links with $q$ resp. $\bar{q}$ exchanges had to be added\textsuperscript{5}.

Such links appear in string models. We re-checked this old result using the Dual Parton Model code DPMJET\textsuperscript{6}: For pp-scattering at laboratory energies of 205 GeV good agreement is obtained.

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Strings as Ordering Mechanism

In QED real and virtual soft or collinear emissions cancel as the final states cannot be distinguished in measurement. For QCD such contributions involve long time scales leaving the perturbative regime. With the comparatively compact hadronic final states the emissions now cancel as the final states are equal.

In string models the hadronic final state is thought to be composed of color singlets called strings. If different soft or collinear contributions to a string production amplitude are summed their phases can lead to cancellations. In this way strings can act as infrared regulators.

It is possible that the usual soft phenomenology would emerge as extension of PQCD, if these cutoffs could be properly implemented. Strings can play an essential role as ordering mechanism of the dynamics of their production.

What changes for Heavy Ion Scattering?

With more interactions per nucleon strings will get more numerous and shorter. There are two possible quite distinct consequences:

- Denser strings should interact and find a different, possibly more efficient way to hadronize.
- A very large number of interactions can be expected to essentially destroy the strings as infrared regulator or ordering mechanism. The ensemble needed to describe the scattering then involves a much larger number of states.

Reasonable expectations for both cases are respectively:

- a reduction in density, an increase in baryon pairs and in strangeness,
- an increase in density, possibly looking like local thermalization.

RHIC data seem to favor the first option. Unfortunately explicit models show large uncertainties. Clarification can come from charge fluctuation measurements.

Charge Fluctuations in Heavy-Ion Scattering Experiments

In heavy ion experiments the charge distribution of the particle contained in a central box with a given rapidity range $[-y_{\text{max}}, +y_{\text{max}}]$ can be measured and the dispersion of this distribution $\langle \delta Q^2 \rangle$ can be obtained to sufficient accuracy. In comparison to the fluctuations in the forward backward charge distributions the charge distribution into a central box (having to have two sufficiently separated borders) can be expected to require roughly twice the rapidity range to obtain information about long range charge flow.

Within the framework of equilibrium models the dispersion was proposed to distinguish between particles emerging from an equilibrium quark-gluon gas or from an equilibrium hadron gas. It should be pointed out that this estimate is not without theoretical problems having to do with the hadronisation process.

Besides the classic charge dispersion

$$\langle \delta Q^2 \rangle = \langle (Q - \langle Q \rangle)^2 \rangle$$

(2)
where \( Q = N_+ - N_- \) is the net charge inside the box, it was proposed to just measure the mean standard deviation of the ratio \( R \) of positive to negative particles or the ratio \( F \) of the net charge to the total number of charged particles in the box. The motivation for choosing these ratios was to reduce the dependence of multiplicity fluctuations caused by the event structure. These quantities have problems for hadron-hadron or non-central heavy-ion events\(^{11,13} \). As any conclusion will have to depend on a comparison of central processes with minimum bias and proton-proton events, there is a clear advantage to stick to the dispersion of the net charge distribution.

The \( \phi \) - and \( \Gamma \) - measures also considered\(^{14} \) are closely related to \( \langle \delta Q^2 \rangle \).

### Quark Line Structure and Fluctuations in the Charge Flow

To visualize the meaning of charge flow measurements it is helpful to introduce the hypothesis that the flavor distribution of individual quarks factorizes. It is an adequate approximation, especially if long range fluctuations are considered.

The hypothesis leads to a generalization of the Quigg-Thomas relation\(^{5} \) determining the correlation of the charges exchanged across two arbitrary boundaries. A combination of such correlations yields the fluctuation of the charge within a \([−y_{\text{max}}, +y_{\text{max}}]\) box:

\[
\langle \delta Q[^{\text{box}}] \rangle^2 = n_{\text{quark lines entering box}}^\text{quark lines} \langle (\delta q)^2 \rangle
\]

where \( Q[^{\text{box}}] \) is the charge in the box, where \( n_{\text{quark lines entering box}} \) is the number of quark lines entering or leaving the box, and where \( q \) is the charge of the quark on such a line. With the notation: \( \delta Q = Q - \langle Q \rangle \), values \( \langle \delta q^2 \rangle = 0.22 \cdots 0.25 \) can be obtained.

The relation allows to easily evaluate simple situations like the thermalized limit of a small box with an infinite reservoir outside. In an “hadron gas case” all particles contain two independent quarks coming from outside; in the so-called “quark gluon gas case” one of the quarks of each meson comes from the outside the other is ignored as a local hadronisation affair (one ignores \( \langle q \rangle \neq 0 \)).

### Expanding Box

For a tiny box — considering only at the first order in \( \Delta y \) — one trivially obtains the hadron gas value \( \langle \delta Q^2 \rangle / \langle N_{\text{charged}} \rangle = 1 \). If the box size increases to one or two units of rapidity on each side this ratio will decrease, as realistic models contain a short range component in the charge fluctuations.

After a box size passed the short range the decisive region starts. In all global equilibrium models the ratio will have to reach a flat value.

If a large box involves a significant part of the phase space the overall charge conservation has to be considered with a correction factor \( \propto 1 - y_{\text{max}} / Y_{\text{kin,max}} \).

At present energies the decisive and large region are not separated.
String Model Predictions

Charges are locally compensated as the range spanned by quark lines in links or during resonance decays is limited. The total contribution will be determined by the density of quark lines reflecting the number of strings at the boundaries:

\[< \delta Q^2 > \propto \rho_{\text{charged}}(y_{\text{max}}). \quad (4)\]

This resulting scaling is illustrated in a DPMJET\(^6\) comparison between both quantities in (4) shown in Fig. 1 for RHIC and LHC energies. For smaller boxes there is a correction as some of the quark lines intersect both boundaries. For large rapidity sizes there is a minor increase from the leading charge flow \(Q_L\) originating in the incoming particles\(^{12}\). In a more careful consideration\(^3\) one can subtract this contribution \(< Q_L > (1- < Q_L >)\) and concentrate truly on the fluctuation. A simple estimate — with a width of neighboring string break ups and a width from resonance decays — leads to consistent values\(^{11}\).

A comparable result was obtained for the proton-proton case\(^{11}\).

String Model versus “Hadron Gas”

It was argued\(^9\) that the experimental results should be “purified” to account for charge conservation. We prefer a reference model with a posteriori randomized charges. This unbiased method can be obviously also directly applied to experimental data. Using DTMJET for RHIC and LHC energies for proton-proton and central lead-lead collisions we obtain the “statistical” prediction shown in Fig. 2.

We employed the correction factor \((1 - \int_0^{y_{\text{max}}} \rho_{\text{charge}} \, dy) / \int_0^{Y_{\text{kin, max}}} \rho_{\text{charge}} \, dy\) proposed by\(^9\) to check consistency and obtained expected the flat distribution.
Figure 2. Charge fluctuations with a posteriori randomized charges for p-p scattering and the most central 5% in Pb-Pb scattering at RHIC energies ($\sqrt{s} = 200$ A GeV) and at LHC energies ($\sqrt{s} = 6000$ A GeV). The results are also shown with a correction factor to account for the overall charge conservation.

Figure 3. Comparison of the charge fluctuations obtained in a string model DPMJET with a model using a posteriori randomized charges for p-p scattering and the most central 5% in Pb-Pb scattering at RHIC energies ($\sqrt{s} = 200$ A GeV) and at LHC energies ($\sqrt{s} = 6000$ A GeV). Taking the DPMJET string model and the randomized “hadron gas” version as extreme cases the decisive power can be tested. As shown in Fig. 3 there is a measurable distinction at RHIC energies and sizable one at LHC energies.

The spectra change roughly by a factor of 400 between simple proton-proton scattering and central lead lead scattering. The suprising similarity between p-p and Pb-Pb in the Fig. 3 can be understood as collective effects to a large part not included in the model. Also no dependence on the centrality was observed in DPMJET for Pb-Pb scattering at RHIC energies ($\sqrt{s} = 200$ A GeV)\textsuperscript{11}. This experimentally measurable centrality dependence allows to directly observe collective effects without reference to a particular model.
Conclusion

The dispersion of the charge distribution in a central box of varying size is an extremely powerful measure. It allows to directly and quantitatively test the presence of equilibrizing processes and remaining dynamical corrections to equilibrated distributions.

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