1

Charged particle fluctuations in heavy-ion collisions

Fritz W. Bopp and Johannes Ranft

Published in Eur.Phys.J.C22:171-177,2001
and in Acta Phys.Polon.B33:1505-1520,2002
e-Print Archive: hep-ph/0105192 and hep-ph/0204010

Fixed target hadron-hadron experiments

All forward charges can be observed experimentally.

With forward-backward fluctuations ***significant results*** were obtained in the 70'ties ***at low energies***:

- The charge fluctuations involve a ***restricted rapidity range.***
- Qualitative agreement was even obtained just with ***neutral resonance decays***.

The ***Quigg-Thomas relation*** for fluctuation across a rapidity y boundary

$$< \delta Q^2_{>y} >=< (Q_{>y} - < Q_{>y} >)^2 >= c \cdot dN^{\text{non incoming}}_{\text{charge}} / dy$$

was found to be satisfied.

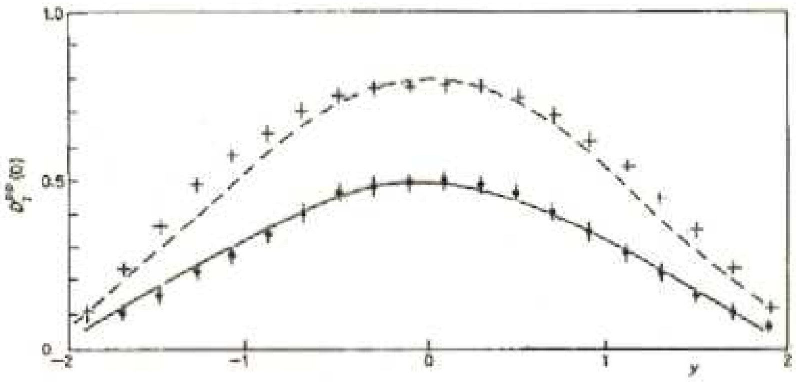
To quantitatively fit the constant c with known resonances ***links with q resp. $\bar{q}$ exchanges*** had to be added.

Such links exist in string models. We re-checked this old result using the ***Dual Parton Model*** code DPMJET: For pp-scattering at laboratory energies of 205 GeV good agreement is obtained. The required constant in the Quigg-Thomas relation was: $c = 0.70$. Within uncertainty this corresponds to the experimentally preferred value of: $c = 0.72$.

–drop page–

Example of early experiments data

Taking the rapidity of the forward-backward border as variable the ***data for 24 GeV proton-proton scattering*** were presented in the following way



The measured dispersion (+) and the produced charge dispersion (*), which is corrected for leading charge flow, is compared with the suitably normalized negative (produced) particle spectrum. The top and bottom lines and points correspond to with and without a ***correction for the leading charges*** discussed below.

(aus: A. Bialas, K. Fialkowski, M. Jezabek and M. Zielinski, Acta Phys. Polon. B **6**, 39 (1975).)

See also

F. W. Bopp, "The Cluster Model," Riv. Nuovo Cim. **1**, 1 (1978)

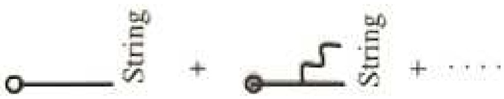
Strings as infrared regulators

The circles below correspond to arbitrary processes with one emitted fermion. In perturbative calculations **infrared singularities** appear:

which mutually cancel.

In **QED** such emissions have to be summed - or neglected- if the final states cannot be **distinguished**.

In **QCD** such emissions have to be summed - or neglected- if the final hadronic states are **equal.**



In **string models** the final hadronic state is composed of independently decaying color singlets called strings. If the different contributions and phases are summed, **only** gluons which lead to a **new string configuration** should survive. Strings act as **infrared regulators.**

The concept is that the **usual soft phenomenology** would emerge as **extension of PQCD,** if these **cutoffs** could be properly implemented.

What changes for Heavy Ion Scattering?

With more interactions per nucleon
strings will get more numerous and shorter.

There are two quite distinct consequences:

- denser **strings should interact** and find a more efficient way to hadronize.
- A very large number of interactions will essentially **destroy the strings** as regulator of the theory. The theory then changes in a fundamental way.

The simple-minded expectations are respectively:

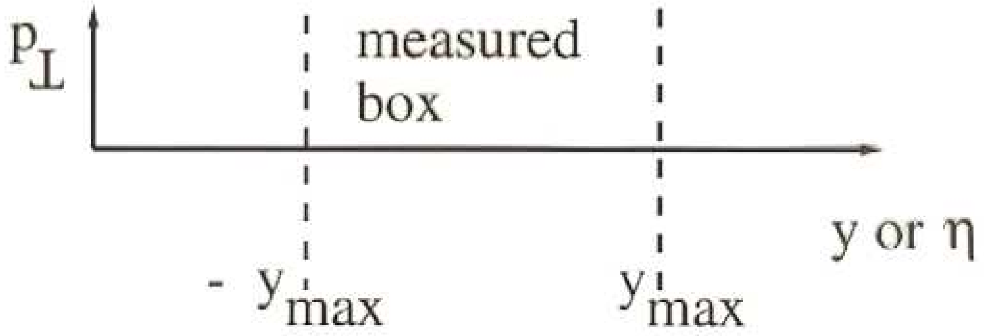
- a **reduction** in density, an increase in baryon-antibaryon production and possibly an increase in strangeness
- an **increase** in density, possibly looking like an almost instant local thermalisation

These predictions are quite divergent.

One needs experimental input. RHIC data seem to favor the first option. Clarification can come from charge fluctuations.

Charge fluctuation in heavy ion scattering

The charges of particles can be measured in a central rapidity box:



The dispersion of this distribution

$$< \delta Q^2 > = < (Q - < Q >)^2 >$$

can be obtained.

For sufficiently large gaps it contains information about long range charge flow.

Various Measures for Charge Fluctuations

Classically: ***Dispersion*** of the ***charge Q***

$$< \delta Q^2 >=< (Q- < Q >)^2 >$$

1. Mean standard deviation of ***ratio R*** involving positive to negative particles:

$$< \delta R^2 >=< \left(\frac{N_+}{N_-} - < \frac{N_+}{N_-} > \right)^2 >$$

2. Mean standard deviation of ***ratio F*** of $Q = N_+ - N_-$ to $N_{\text{charged}} = N_+ + N_-$

$$< \delta F^2 >=< \left(\frac{Q}{N_{\text{charged}}} - < \frac{Q}{N_{\text{charged}}} > \right)^2 >$$

Motivation for ratios "1" and "2":
less dependence on multiplicity fluctuation

The ϕ, ν **and** Γ **- measures** also considered in literature are closely related to $< \delta Q^2 >$.

(→ papers of S. Voloshin et al.)

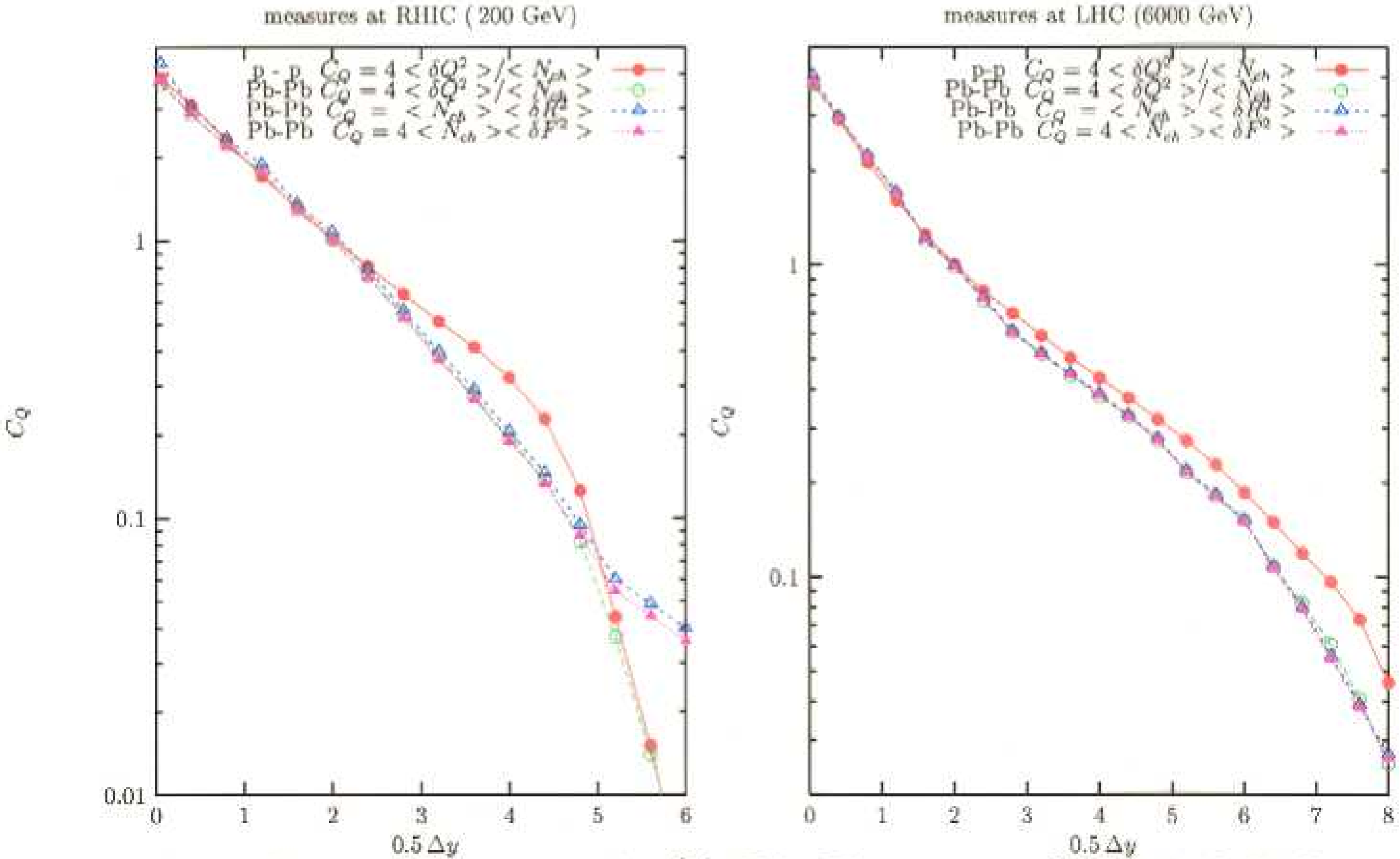
Evaluation of the measures

For large nuclei, high energies, and strong centrality the **charge component** of the fluctuations dominates.

In these region all measures are simply connected by a **relation given by Jeon** et al.:

$$< N_{\text{charged}} >< \delta R^2 >= 4 < N_{\text{charged}} >< \delta F^2 >= 4 \cdot \frac{< \delta Q^2 >}{< N_{\text{charged}} >}.$$

We check this with **Dual Parton model (DPMJET)**

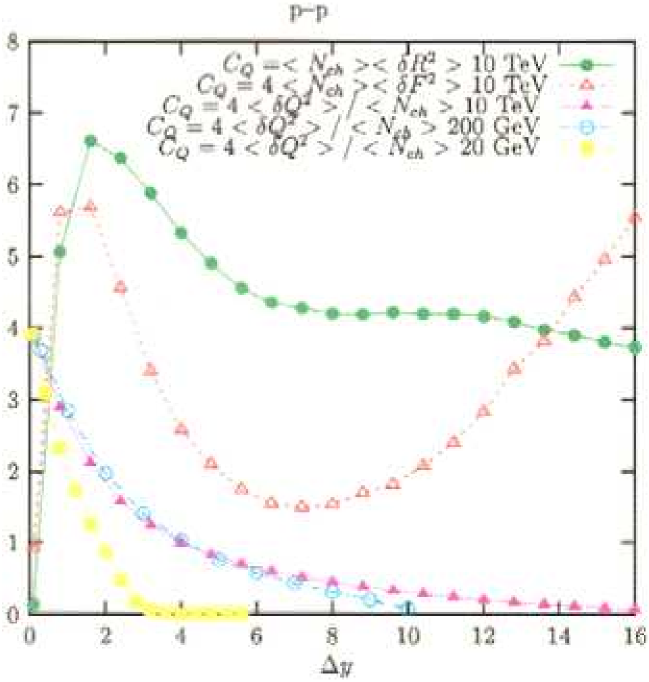


For the most central 5% Pb-Pb scattering at ***LHC*** energies ($\sqrt{s} = 6000$ A GeV) *perfect agreement*.

Agreement stays true for analogous Pb-Pb data at ***RHIC*** energies ($\sqrt{s} = 200$ A GeV)

The new measures are **not suitable** for small Δy boxes in less dense events

- As 0/0 or ∞ is undefined.
- As their mutual relation is lost.



Any conclusion will depend on a comparison of central with minimum bias and proton-proton events.

For this purpose the more regular behaving $< \delta Q^2 >$ is best suited.

A Simple Relation between Quark Line Structure and Charge Fluctuations

A parton factorization hypothesis postulates that the individual quark flavor distribution factorizes.

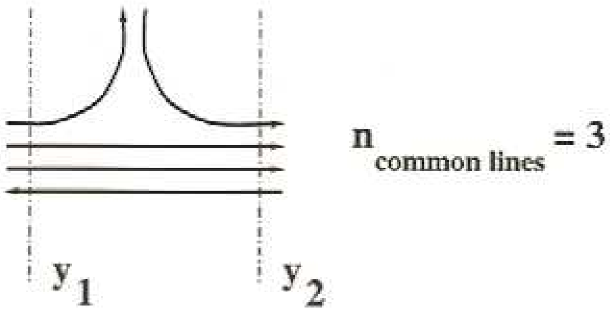
(based on isospin symmetry and degeneracy. As corrections are small, the transparency considering them is dropped)

$\Longrightarrow$ ***Generalized Quigg-Thomas relation***:

$$< \delta Q(y_1) \cdot \delta Q(y_2) >= n_{\text{common lines}} < \delta q^2 > .$$

- where the charges $\delta Q(y_i) = Q(y_i) - < Q(y_i) >$ were exchanged across two kinematic boundaries y_1 & y_2,
- where $n_{\text{common lines}}$ counts the number of quark lines intersecting both borders, and
- where q is the charge of the quark on such a line. Values $< \delta q^2 > = < (q - < q >)^2 = 0.22 \cdots 0.25$ are obtained.

Example:



drop this page:

To be more precise with strings

The proportionality factor for the case of *mere short range fluctuations* would be roughly a factor one.

In string models primordial particles are responsible for a wider range charge transfer coming from the *contributions of the fragmentation chains*.

Taking everything together one obtains

$$< \delta Q^2 >=$$

$$= \sum_{\text{left+right}} \{ n_{\text{strings}} \cdot 2 < \delta q^2 > + \sigma \, \frac{1}{2} \, \rho^{\text{not primary}}_{\text{charged secondary}}(y) \, \}$$

where $n_{\text{strings}} = \rho_{\text{charged primary}} / \rho_{\text{single string}}$
is the number of strings and

where the width of the local fluctuations σ
is roughly unity.

The fluctuation of the **charges within a box** is:

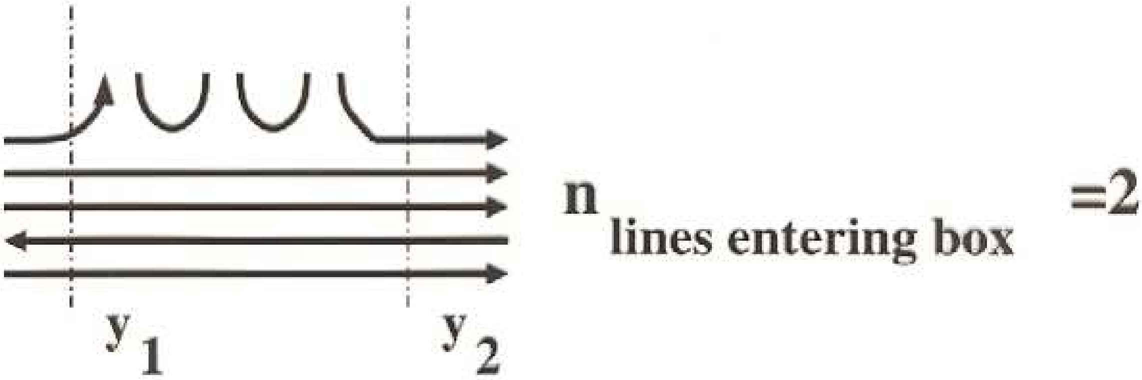
$$< \delta Q[\text{box}]^2 >= n_{\text{lines entering box}} < \delta q^2 >$$

where

$$n_{\text{lines entering box}}$$

counts the number of quark lines entering the box.

Example:



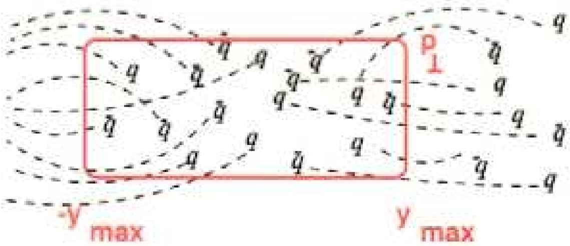
Equilibrium expectations

Hadron gas of Poisson-distributed particles with charges 0 and ± 1 yields:

$$< \delta Q^2 > = < N_{\text{charged}} > .$$

Inclusion of resonances with correlated secondaries a $*0.7$ reduction was estimated (Jeon & Koch).

In our quark line picture this corresponds to a small box in a large reservoir. No quark-antiquark pairs stay inside and all lines will connect to the outside.



Ignoring baryons all particles (50% charged) contain two quarks (each contributing roughly 1/4 yielding to $< N_{\text{charged}} >$) the above estimate is obtained with $< \delta q^2 > = 0.25$.

A second case considered in literature (Koch) was the ***quark-gluon gas***

Identifying quark charges q_i with final charges they obtain a quite distinct relation:

$$< \delta Q^2 >= \sum_i q_i^2 < N_i >= 0.19 < N_{\text{charged}} >$$

using a largely empirical multiplicity (Jeon & Koch):

$$N_{\text{charged}} = \tfrac{2}{3}(N_{\text{glue}} + 1.2 N_{\text{quark}} + 1.2 N_{\text{antiquark}})$$

Charges are said to be *frozen during hadronization.*

This can only concern long range charge transfers. The parton-hadron transition has to involve local, short range charge transfers.

A sensible assumption about hadronisation is that only one quark of each hadron originates in the initital parton process.
The other partons are assumed to be short range. In this way we recover their result for the long range part:

$$< \delta(Q- < q > \cdot 3 \cdot (\text{Baryon number}))^2 >= \sum \delta q_i^2 < N_i >$$

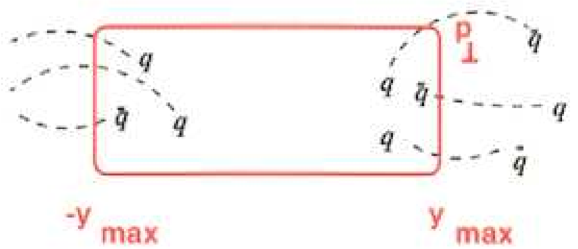
where numerically small corrections for non-vanishing quark charges $< q >$are included.

The reduction was proposed as ***distinctive measure*** between hadron- and quark-gluon gas. A definite decision is rather unlikely (≈Fialkowski) as there is no model-independent way to determine N_{charged}.
There is no evidence to support the hadron gas as starting point.

String model predictions

Charges are locally compensated as the range spanned by quark lines in links or during the resonance decay is limited.

Drawing *only quark lines which intersect* the boundary and contribute to the charge flow one obtains:



The total contribution will be determined by the density of quark lines reflecting the *number of strings.*

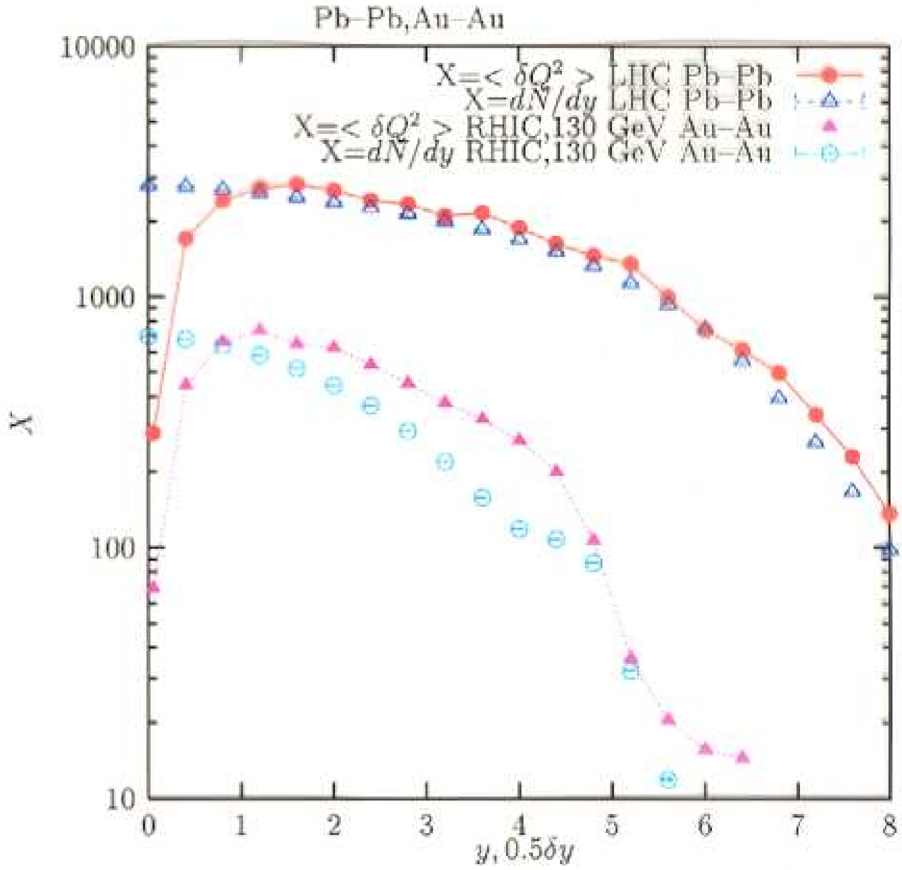
It is proportional to the particle density at the boundaries:

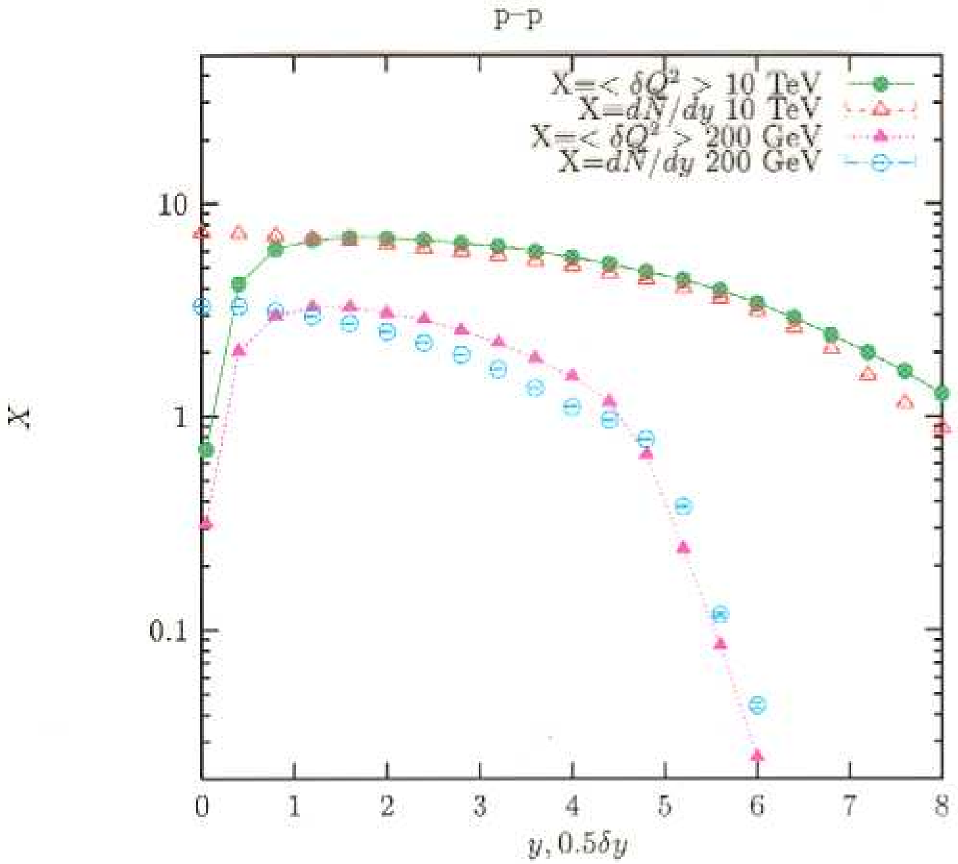
$$< \delta Q^2 > \propto \rho_{\text{charged}}(y_{\text{max.}}).$$

basically keeping the ***Quigg-Thomas*** relation.

The Dual Parton model DPMJET predictions

We compare both quantities for RHIC and LHC energies for central gold gold resp. lead lead scattering





Agreement is comparable to the proton-proton case

Expanding Box

Limit of a tiny box: At the first order in Δy *always hadron gas value*:

$$< \delta Q^2 > / < N_{\text{charged}} >= 1$$

One or two rapidity box: As there has to be a *short range component* the charge fluctuations decrease.

Decisive region box: In all *global equilibrium models* the ratio will have to reach a **constant value** outside short range region. The observed behaviour strongly constrains the dynamics. Unfortunately RHIC experiments so far did not reach this region.

Large box: If the box involves large part of total rapidity, *charge conservation* forces a *correction factor* approximately

$$\left(\int_{y_{\text{max}}}^{Y_{\text{kin.max}}} \rho_{\text{charge}}^{\text{new}} dy\right) / \left(\int_{0}^{Y_{\text{kin.max}}} \rho_{\text{charge}}^{\text{new}} dy\right) \propto 1 - y_{\text{max.}} / Y_{\text{kin.max.}}$$

At present energies the "decisive" and the "large" box are not really seperated (see Bleicher, Jeon, Koch)

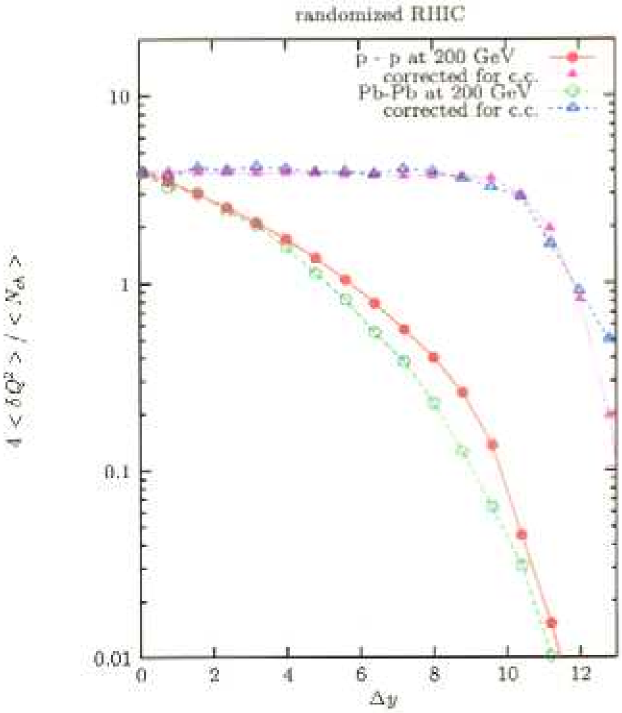
As there are uncertainties in the charge conservation correction factor for large boxes we use:

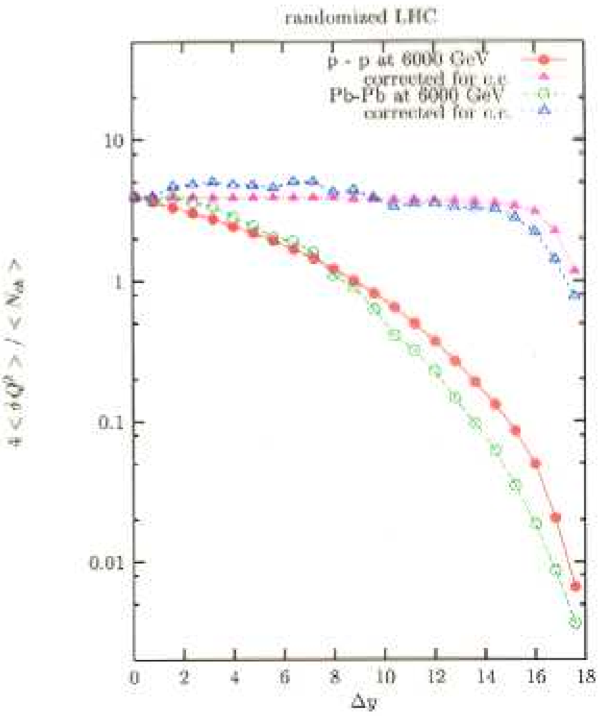
A reference model with statistical fluctuation

For such a model we ***a posteriori randomize charges***, separately for pions, kaons and nucleons.

This unbiased method can be also ***directly applied to experimental data***, at least in a simplified way.

Using DTMJET events we obtain for **RHIC** and **LHC** energies for ***proton-proton*** and ***central lead-lead*** collisions the following statistical results.

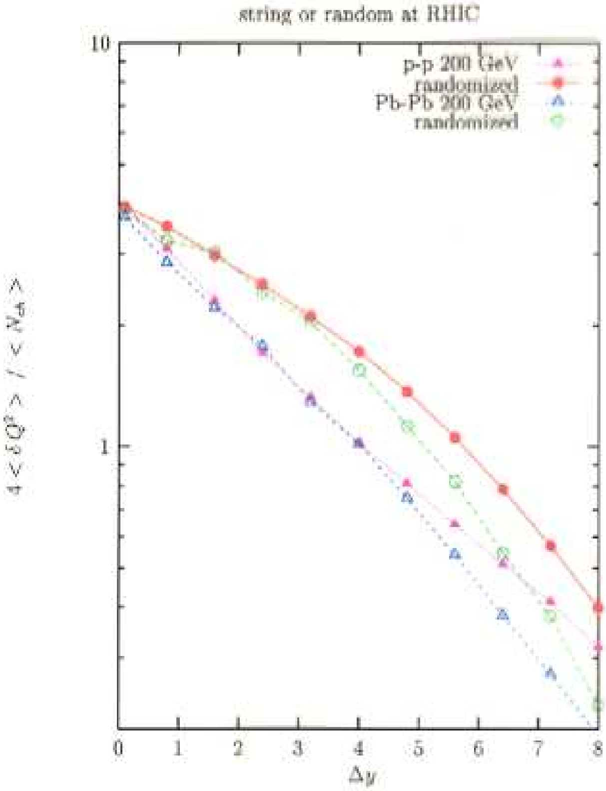


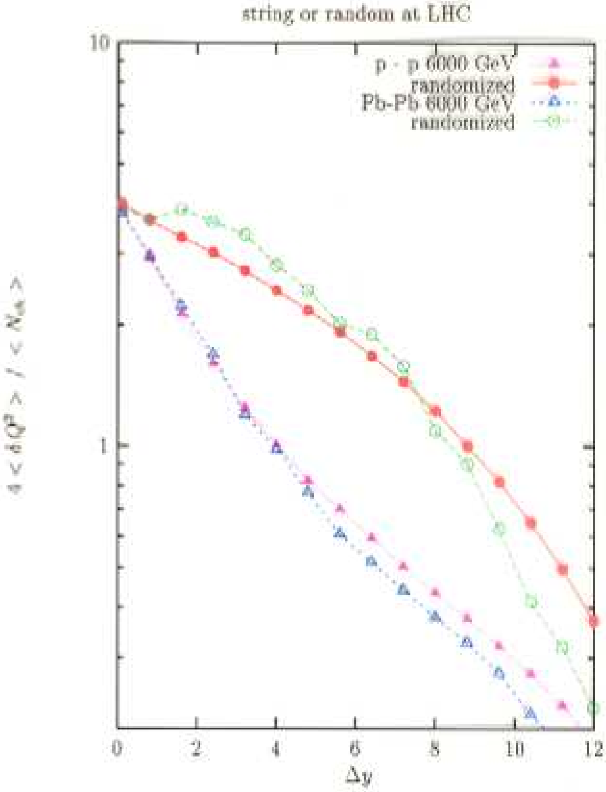


We also employed the correction factor $1 - \int_0^{y_{\text{max}}} \rho_{\text{charge}}\, dy / \int_0^{Y_{\text{kin.max}}} \rho_{\text{charge}}\, dy$ and indeed obtained the ***flat distribution*** expected for a "hadron gas".

String model versus randomized "hadron gas"

Taking DPMJET model pure and with randomization the decisive power of the measure can be tested.





The measure

unsuitable for SPS energies

There is

a measurable distinction at RHIC energies

and

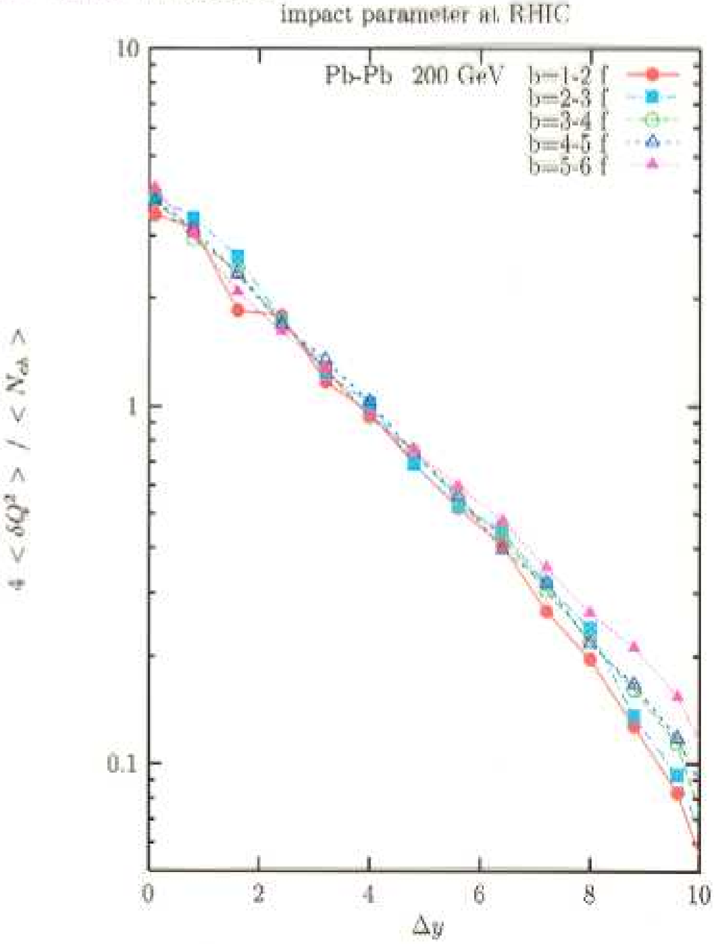
a sizable distinction at LHC.

A measured charge correlation somewhere in between quantitatively reflects the position between both extreme scenarioes.

The b dependence of the charge fluctuations

The similarity between p-p and Pb-Pb in the last transparency is expected as collective effects are to a large part not included in the model.

Without collective effects also no dependence on the centrality is observed for Pb-Pb scattering at RHIC energies ($\sqrt{s} = 200$ A GeV).



This experimentally measurable centrality dependence allows to directly **observe any dynamical change** without dependence on a particular model.

Conclusion

Within string model calculation the dispersion seen in relation to the spectra shows ***no significant difference*** between simple ***proton-proton*** and ***Pb-Pb*** scattering even though both quantities change roughly by a factor of 400.

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 equilibrized distributions.