Main results of a search on multiplicity distributions in $pp$ collisions: is anybody afraid of a new class of hard events?

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based on
For a general review see: hep-ph/0405251
Outline of this talk

1. The framework: the weighted superposition model
   - Clan structure analysis
2. Extrapolations from GeV to the TeV energy range
   - The picture in full phase-space
   - The picture in pseudo-rapidity intervals
   - High energy densities
3. Summary
The weighted superposition model

The weighted superposition mechanism of two classes of events in high energy collisions explains a series of experimental facts assuming that the multiplicity distribution (MD) $P_n$ for each class of events is described in terms of a Pascal (NB) MD with characteristic parameters $\bar{n}$ and $k$.

Weighted superposition of soft and semihard components:

$$ P_n = \alpha_{\text{soft}} P_n^{(\text{Pascal})} (\bar{n}_{\text{soft}}, k_{\text{soft}}) + \alpha_{\text{semihard}} P_n^{(\text{Pascal})} (\bar{n}_{\text{semihard}}, k_{\text{semihard}}) $$

$$ \alpha_{\text{soft}} + \alpha_{\text{semihard}} = 1 $$

$\bar{n}$ is the average charged multiplicity

$$ D^2 = \frac{1}{\bar{n}} + \frac{1}{k} $$

$D^2$ is the variance of the MD

The weighted superposition model (II)

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A. Shoulder structure in the intermediate multiplicity range.

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Relevance of Pascal (NB) regularity for classifying different classes of events
and
its interpretation in terms of clan concept

The Pascal (NB) distribution...

The multiplicity distribution

\[ P_n(\bar{n}, k) = \frac{k(k + 1) \cdots (k + n - 1)}{n!} \frac{\bar{n}^n k^k}{(\bar{n} + k)^{n+k}} \]

The generating function:

\[ G_{\text{Pascal}}(z; \bar{n}, k) \equiv \sum_{0}^{\infty} z^n P_n(\bar{n}, k) = G_{\text{Poisson}} \left( G_{\text{log}}(z; b); \bar{N} \right) \]

with

\[ G_{\text{Poisson}}(z; \bar{N}) = \exp \left[ \bar{N} (z - 1) \right] \]
\[ G_{\text{log}}(z; b) = \frac{\log(1 - bz)}{\log(1 - b)} \]
\[ b = \bar{n}/(\bar{n} + k) \]

\[ \bar{N} = k \log(1 + \bar{n}/k) \]
\[ \bar{n}_c = \bar{n}/\bar{N} \]
...its interpretation

Clan structure and the two-step mechanism

\[ \text{CLAN} = \text{set of particles of common ancestry} \]

- Each clan contains at least one particle (the ancestor)
- Clans are independently produced — they follow a Poisson distribution in \( \bar{N} = k \ln(1 + \bar{n}/k) \)
- Particles in a clan follow a logarithmic distribution in \( \bar{n}_c = \bar{n}/\bar{N} \)
- Correlations among particles are exhausted within each clan

At parton level

\[ \text{CLAN} = \text{bremsstrahlung gluon jet} \]

String formation is replaced by parton shower formation.

Extrapolations to the TeV region

We extrapolated to high energy the two components, starting from Sp\bar{p}S results, considering the following:

- **I** - the soft component satisfies KNO scaling
- **II** - three scenarios for the semihard component:
  ① also obeys KNO scaling
  ② $k^{-1}$ grows as $\ln s$ (max violation)
  ③ $k^{-1}$ grows as $k_{\infty} - a/\sqrt{\ln s}$ (QCD-inspired)

Scenario ① is disfavoured by CDF and E735 measurements at Tevatron

The unexpected increase of aggregation

Behaviour of the semihard component from 900 GeV to 14 TeV:
\[ \bar{N} \ (900 \ \text{GeV}) – (14 \ \text{TeV}) \quad \bar{n_c} \ (900 \ \text{GeV}) – (14 \ \text{TeV}) \]

\[ k_{sh} \sim (\ln s)^{-1} \quad 23 \searrow 11 \quad 2.5 \swarrow 7 \]
strong KNO violation

\[ k_{sh} \sim k_{\infty} - a/\sqrt{\ln s} \quad 22 \searrow 18 \quad 2.6 \swarrow 5 \]
QCD-inspired behaviour

From GeV to TeV, \( \bar{N} \) decreases and \( \bar{n_c} \) increases, implying clan aggregation and higher particle population per clan.
Minimum: \( \bar{N} = 1 \Leftrightarrow \bar{n} = k(e^{1/k} - 1) \) and being \( \bar{n} > k \) it implies

\[ k < 1 \]

An asymptotic property of the semihard component, or the characteristic property of an effective third class of events to be added to the soft and semihard ones?
Three classes

**I class:** soft events (no minijets)

\[ \bar{N}_{\text{soft}} \text{ large and growing,} \quad \bar{n}_{c,\text{soft}} \text{ quite small} \]

\[ P_{n,\text{soft}} \text{ obeys KNO scaling} \quad \Rightarrow k_{\text{soft}} \text{ constant} \]

**II class:** semihard events (with minijets)

\[ \bar{N}_{\text{semihard}} \text{ decreasing,} \quad \bar{n}_{c,\text{semihard}} > \bar{n}_{c,\text{soft}} \]

KNO scaling is violated

\[ k_{\text{semihard}} \text{ decreases} \]

**III class:** \( k_{\text{third}} < 1 \): the benchmark of the new class of events.

At parton level, huge colour exchange from a relatively small number of high vituality ancestors would probably indicate a mechanism harder than in both other components and lead to a situation of high density.
Three classes

I class: soft events (no minijets)
\( \bar{N}_{\text{soft}} \) large and growing, \( \bar{n}_{c,\text{soft}} \)
\( P_{n,\text{soft}} \) obeys KNO scaling \( \Rightarrow k_{\text{soft}} \)

II class: semihard events (with minijets)
\( \bar{N}_{\text{semihard}} \) decreasing, \( \bar{n}_{c,\text{semihard}} > n_{c,\text{soft}} \)
KNO scaling is violated \( k_{\text{semihard}} \) decreases

III class: \( k_{\text{third}} < 1 \): the benchmark of the new class of events.
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Distributions with different $k$: shape comparison

- log-convex gamma MD ($\bar{n} \gg k$) well approximated for $k \to 0$ by a logarithmic MD
- exponential MD (geometric)
- log-concave Pascal MD

$\frac{n}{\bar{n}}$
Clan parameters

\[ \bar{N} \text{ avg number of clans} \]

\[ \bar{n}_c \text{ avg num of particles per clan} \]
Clan aggregation and correlations

\( k_{\text{third}} < 1 \) implies:

\[
\frac{\bar{n}_{\text{third}}^2}{k_{\text{third}}} = \int C_2(\eta', \eta'') d\eta' d\eta'' > \frac{\bar{n}_{\text{semihard}}^2}{k_{\text{semihard}}}
\]

- Cumulants depend on \( 1/k_{\text{third}} \) and are expected to be also much larger than in the semihard component
- Forward-backward multiplicity correlations

\[
b_{\text{FB,th}} = \frac{2b_{\text{th}}p_{\text{th}}(1 - p_{\text{th}})}{1 - 2b_{\text{th}}p_{\text{th}}(1 - p_{\text{th}})},
\]

\( \bar{N}_{\text{third}} = 1 \iff \) maximum leakage, i.e., \( p_{\text{th}} = 1/2 \); since \( b_{\text{th}} \approx 1 \) then

\( b_{\text{FB,th}} \to 1 \) (i.e., \( b_{\text{FB,th}} \gg b_{\text{FB,sh}} \))
New shape!

shoulder

elbow

superposition of I and II class

shoulder = superposition of I and II class

elbow = superposition of II and III class
New shape!

![Graph showing multiplicity distributions]

- **Shoulder**: superposition of I and II class
- **Elbow**: superposition of II and III class
- Green: comp I
- Blue: comp II
- Red: comp III
Going to rapidity intervals: soft and semi-hard

Extend the FPS scenario in a consistent way in $|\eta| < \eta_c$.

- The weight of each component is the same as in FPS: semi-hard events are defined by the presence of (mini)-jets in the final state. The $\eta_c$ dependence comes from $\bar{n}$ and $k$ parameters only.

- In FPS it was assumed that each component has an average multiplicity which grows linearly with $\ln \sqrt{s}$; since the width of available phase space also grows linearly with $\ln \sqrt{s}$, the simplest consequence is that the single particle density must show some energy independent plateau around $\eta = 0$ which extends some units in each direction.

$$\bar{n}_i(\eta_c) = 2\bar{n}_{0,i}\eta_c \quad \text{with} \quad \bar{n}_{0,\text{soft}} \approx 2.45, \quad \bar{n}_{0,\text{semi-hard}} \approx 6.4$$

$$\bar{n}_{\text{total}}(\eta_c, \sqrt{s}) = \alpha_{\text{soft}}(\sqrt{s})\bar{n}_{\text{soft}}(\eta_c) + (1 - \alpha_{\text{soft}}(\sqrt{s}))\bar{n}_{\text{semi-hard}}(\eta_c)$$

...dispersion (soft)...

The width of the multiplicity distribution is characterised by the parameter $k$:

$$
\frac{1}{k} \equiv \frac{D^2}{\bar{n}^2} - \frac{1}{\bar{n}} \equiv \frac{\langle (n - \bar{n})^2 \rangle}{\bar{n}^2} - \frac{1}{\bar{n}} = \frac{\bar{n}^2 - \bar{n}^2 - \bar{n}}{\bar{n}^2}
$$

with the relation

$$
\bar{n}_{\text{total}}^2 \left(1 + \frac{1}{k_{\text{total}}}\right) = \alpha_{\text{soft}} \bar{n}_{\text{soft}}^2 \left(1 + \frac{1}{k_{\text{soft}}}\right) + (1 - \alpha_{\text{soft}}) \bar{n}_{\text{sh}}^2 \left(1 + \frac{1}{k_{\text{sh}}}\right)
$$
...dispersion (semi-hard)

- The soft component is taken to have $1/k$ constant with energy for each $\eta$ interval, but variable with the width of the interval. In low energy experimental data, $1/k$ is not constant but KNO scaling holds. Consequently, also constant with $\sqrt{s}$ are the clan parameters. $\bar{n}$, $\bar{N}$ and $\bar{n}_c$ all grow with $\eta_c$, while $1/k$ decreases.

- For the semi-hard part we choose to violate KNO scaling by making $1/k_{\text{total}}$ continue to grow with energy as it does up to UA5 energies with a linear behaviour in $\ln \sqrt{s}$. Consequently, the average number of clans is seen to decrease very rapidly with the energy for the semi-hard component, $\bar{n}_c$ is seen to increase with energy; it also increases with $\eta_c$, and the increase is faster when the energy is higher.
The third component in $|\eta| < 0.9$

Two extreme behaviours:

(i) the third component is distributed uniformly over the whole of phase space;

(ii) the third component has a very narrow and tall plateau and falls entirely within the interval $|\eta| < 0.9$.

These two extreme scenarios are represented as a band in the following figures.

In the first case, the value of $k_{th}$ has again been determined from the asymptotic behaviour of the average number of clans in the second (semihard) component, where it is a fixed fraction of the same quantity in FPS.

$$P_n = \sum_i \alpha_i(\sqrt{s}) P_n^{\text{NB}}(\bar{n}_i(\sqrt{s}, \eta_c), k_i(\sqrt{s}, \eta_c))$$
The third component in $|\eta| < 0.9$ (II)

At LHC, the elbow structure is clearly visible, the narrow peak at very low $n$ is hidden by the other components shifted to smaller $\bar{n}$.
Numerical details at LHC

<table>
<thead>
<tr>
<th></th>
<th>%</th>
<th>$\bar{n}$</th>
<th>$k$</th>
<th>$\bar{N}$</th>
<th>$\bar{n}_c$</th>
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<td><strong>FPS</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
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<td>41</td>
<td>40</td>
<td>7</td>
<td>13.3</td>
<td>3.0</td>
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<td>semi-hard</td>
<td>57</td>
<td>87</td>
<td>3.7</td>
<td>11.8</td>
<td>7.4</td>
</tr>
<tr>
<td>third</td>
<td>2</td>
<td>460</td>
<td>0.1212</td>
<td>1</td>
<td>460</td>
</tr>
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<td></td>
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<td>$</td>
<td>\eta</td>
<td>&lt; 0.9$</td>
<td></td>
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</tr>
<tr>
<td>soft</td>
<td>41</td>
<td>4.9</td>
<td>3.4</td>
<td>3.0</td>
<td>1.6</td>
</tr>
<tr>
<td>semi-hard</td>
<td>57</td>
<td>14</td>
<td>2.0</td>
<td>4.2</td>
<td>3.4</td>
</tr>
<tr>
<td>third (i)</td>
<td>2</td>
<td>40</td>
<td>0.056</td>
<td>0.368</td>
<td>109</td>
</tr>
<tr>
<td>third (ii)</td>
<td>2</td>
<td>460</td>
<td>0.1212</td>
<td>1</td>
<td>460</td>
</tr>
</tbody>
</table>

(i) the single clan is uniformly spread over the whole of phase space (37% of the clan is contained within $|\eta| < 0.9$), $k_{th}$ is even much less than 1.
(ii) the single clan is fully contained in $|\eta| < 0.9$, (same characteristic parameters as those seen in FPS, but much higher particle density.)
Energy density?

Bjorken formula for the energy density:

\[ \varepsilon = \frac{3}{2} \langle E_T \rangle \left. \frac{dn}{dy} \right|_{y=0} \]

where \( \langle E_T \rangle \) is the average transverse energy per particle, \( V \) the collision volume and \( dn/dy \) the particle density at mid-rapidity.

<table>
<thead>
<tr>
<th>our scenarios</th>
<th>soft</th>
<th>semi-hard</th>
<th>(i) third</th>
<th>(ii)</th>
<th>(i) total</th>
<th>(ii)</th>
</tr>
</thead>
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<tr>
<td>( dn/dy )</td>
<td>2.5</td>
<td>7</td>
<td>20</td>
<td>230</td>
<td>10.8</td>
<td>19.2</td>
</tr>
<tr>
<td>( \langle E_T \rangle ) (MeV)</td>
<td>350</td>
<td>500</td>
<td>500</td>
<td>500</td>
<td>500</td>
<td>500</td>
</tr>
<tr>
<td>( \varepsilon ) (GeV/fm(^3))</td>
<td>0.4</td>
<td>1.6</td>
<td>4.7</td>
<td>54</td>
<td>2.5</td>
<td>4.5</td>
</tr>
</tbody>
</table>

Compare with

- AGS – O + Cu – \( \sqrt{s_{NN}} = 5.6 \) GeV – \( \varepsilon \approx 1.7 \) GeV/fm\(^3\)
- RHIC (Phenix) – Au + Au – \( \sqrt{s_{NN}} = 130 \) GeV – \( \varepsilon \approx 4.6 \) GeV/fm\(^3\)
The possibility was explored of events in pp collisions with one (or few) clans, i.e., $k < 1$ with $\bar{n} \gg 1$.

It implies very few high-virtuality initial partons (bremsstrahlung gluon jets) developing high partonic densities and energy densities with large colour exchanges.

Measurable signatures were found in the high multiplicity tail, very strong long-range correlations, small size of the BEC region and, conceivably, reduced increase of the number of jets.