On signals of new physics in global event properties in pp collisions in the TeV energy domain

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Abstract

In the framework of the weighted superposition mechanism of different classes of minimum bias events (or substructures), described by the negative binomial multiplicity distribution, in possible scenarios for pp collisions in the TeV energy domain, we explore global properties of an eventual new class of events, characterised by high hadron and clan densities, to be added to the soft (without minijets) and semihard (with minijets) ones. It turns out that the main signal of the mentioned new physical expectations at 14 TeV c.m. energy would be an “elbow structure” in the tail of the total charged particle multiplicity distribution in complete disagreement with the second shoulder structure predicted by Pythia Monte Carlo calculations: a challenging problem for new experimental work.
1 Introduction

Possible scenarios for pp collisions in the TeV energy domain, based on extrapolations from data and fits in the GeV region to charged particle multiplicity distributions, \( P_n \), and on the weighted superposition mechanism of two classes of events, i.e., soft (without minijets) and semihard (with minijets), each described by a negative binomial multiplicity distribution (NBMD) with characteristic parameters \((\bar{n}_{\text{soft}}, k_{\text{soft}})\) and \((\bar{n}_{\text{sh}}, k_{\text{sh}})\), respectively, have been discussed both in full phase space \[1\] and rapidity intervals \[2\]. (For an experimental investigation of the substructures see Ref. \[3\].)

It has been pointed out that in the semihard component either with a strongly KNO scaling violating mechanism (parameter \(k_{\text{sh}}\) decreases with c.m. energy \(\sqrt{s}\) as \(\sim 1/\log \sqrt{s}\)) or with a QCD inspired KNO scaling violating behaviour, (which is milder than the previous one as parameter \(k_{\text{sh}}\) decreases as \(\sim 1/\sqrt{\log s}\)), the average number of clans, \(\bar{N}_{\text{sh}}\), becomes smaller as the c.m. energy increases (from \(\approx 23\) and \(22\), resp., at 900 GeV, to \(\approx 11\) and \(18\), resp., at 14 TeV) and the corresponding average number of particles per clan, \(\bar{n}_{\text{c,sh}}\), much larger (from \(\approx 2.5\) and \(2.6\), resp., at 900 GeV, to \(\approx 7\) and \(5\), resp., at 14 TeV), favouring clan aggregation and higher average particle population within clans. This behaviour was considered suggestive and indicative of a class of events with high particle density.

Motivated by this remark, we decided to explore in the same framework the consequences of an eventual more dramatic decrease of the average number of clans towards 1, i.e., towards a class of events with the maximum clan and particle aggregation, a situation which implies a \(k_{\text{sh}}\) value less than one but which is unfortunately met in the semihard component only asymptotically at an extraordinary high c.m. energy in the KNO scaling violating extrapolations of \(k_{\text{sh}}\). This result contrasts sharply with the main properties of the class of events belonging to the semihard component at non-asymptotic energies, where \(k_{\text{sh}}\) is always larger than or equal to one. It raises the intriguing question whether a very high clan and particle density is only an asymptotic behaviour of the semihard component, or the property of an effective new class of events, different from (maybe harder than) the semihard one, and whose onset might happen already at 14 TeV c.m. energy: if this is the case, its contribution to the total charged particle multiplicity distribution, \(P_{n}^{\text{(total)}}\), in terms of a new weighted NB(Pascal)MD, should be added to those of the soft and semihard ones of Ref. \[1\] and \[2\]. The claim is that the benchmark of this third new class of events (called ‘th’ from now on) is \(k_{\text{th}} < 1\).

It should be recalled that the average number of clans is in general a non trivial function of the average number of particles of each component, \(\bar{n}_i\), and of the parameter \(k_i\),

\[
\bar{N}_i = k_i \ln(1 + \bar{n}_i/k_i)
\]

with \(i=\text{soft, sh and th}\), enumerating the three classes. Whereas \(k_{\text{soft}}\) is taken constant in our scenarios in the new energy domain and therefore \(\bar{N}_{\text{soft}}\) depends only on the average multiplicity \(\bar{n}_{\text{soft}}\) as the c.m. energy increases, the decrease of \(k_{\text{sh}}\) with c.m. energy suggested by our assumptions on KNO scaling violations remains at non-asymptotic energies always larger than or equal to one in the semihard component.
and is only in part contrasted by the increase of $\bar{n}_{\text{sh}}$, a fact which outlines $k_{\text{sh}}$ dominance in the general $\bar{N}_{\text{sh}}$ behaviour. As already mentioned the request of an average number of clans, $\bar{N}_{\text{th}}$, of few units in the third component leads to values of $k_{\text{th}}$ less than one whereas that of $\bar{N}_{\text{th}} \approx 1$ implies $k_{\text{th}} \rightarrow 0$ for large $\bar{n}_{\text{th}}$. Notice that in this last extreme situation the average number of particle per clan, $\bar{n}_{c,\text{th}}$ coincides of course with the average number of particles of the new component $\bar{n}_{\text{th}}$. In addition when $\bar{n}_{\text{sh}} \gg k_{\text{sh}}$—a quite normal situation at large c.m. energies—the NB(Pascal)MD describing the final charged particle MD of the component is well approximated by a log-concave gamma MD for $k_{\text{sh}}$ larger than one which becomes an exponential when $k_{\text{sh}}$ is equal to one: the maximum of the gamma distribution occurs at $n/\bar{n}_{\text{th}} = 1 - k_{\text{th}}^{-1}$. (See Fig. 1). This behaviour should be compared with what happens in the third component under the condition $k_{\text{th}} \ll \bar{n}_{\text{th}}$: in this case the NBMD is in fact well approximated by a log-convex gamma distribution which for a certain value of the above parameter close to zero leads to the average number of clans $\approx 1$ and to the total MD well described by a logarithmic one. This result is consistent with the standard interpretation of the occurrence of the negative binomial MD for final charged multiplicity at hadron level as a two step process in which the independently emitted clans contain logarithmically distributed charged particles [4].

Finally in consequence of the assumed quite extreme clan and particle aggregation into few clans, events with quite large forward-backward multiplicity correlations close to the maximum allowed leakage from one hemisphere to the opposite one [5] are also expected. At partonic level the mentioned remarks would suggest for the third component high parton density clan production with huge colour exchange processes originated from a relatively small number of high virtuality ancestors, which would indicate probably an emission mechanism harder than that seen in the semihard component.

In conclusion it might well be that one could observe already at 14 TeV c.m. energy in pp collisions three classes of events or components instead of two, the first and the second class being those examined in Refs [1] and [2] and the third one fully characterised by the reduction of the the average number of clans to the minimum allowed by the condition $k_{\text{th}} < 1$. The classes of events or components contributing to the total $n$ charged particle multiplicity distributions would therefore be the following:

I) the class of soft events (events with no minijets), which in clan structure analysis would be characterised by quite large values of $\bar{N}_{\text{soft}}$ and quite small $\bar{n}_{c,\text{soft}}$; $P_n^{(\text{soft})}$ obeys KNO scaling and $k_{\text{soft}}$ is assumed to be constant from the GeV region to the new energy domain;

II) the class of semihard events (events with minijets), for which $\bar{N}_{\text{sh}}$ decreases quickly with c.m. energy and $\bar{n}_{c,\text{sh}} > \bar{n}_{c,\text{soft}}$; $k_{\text{sh}}$ decreases also with c.m. energy but its value is larger than or equal to one and KNO scaling is violated;

III) the new class of events (events generated probably by quite hard partons) with $k_{\text{th}} < 1$, $\bar{n}_{\text{th}} \gg k_{\text{th}}$ (and quite small $\bar{N}_{\text{th}}$), with large forward-backward multiplicity correlations.
Accordingly, the total charged particle MD will have the following expression in terms of the weighted composition of the three NBMD’s, one for each component:

\[
P_n^{(\text{total})} = \alpha_{\text{soft}} P_n^{(\text{soft})} + \alpha_{\text{sh}} P_n^{(\text{sh})} + (1 - \alpha_{\text{soft}} - \alpha_{\text{sh}}) P_n^{(\text{th})}
\]

where \(\alpha_{\text{soft}}\) and \(\alpha_{\text{sh}}\) are the fraction of soft and semihard events, respectively.

At 14 TeV c.m energy the weight of the third component is expected to be of course quite small, in our calculations we assumed it to be between 1 and 3 percent of the total number of events.

Since the quantitative properties of the classes of soft and semihard events have been extensively discussed in Refs. [1] and [2] we focus our attention in this paper on the global properties of the new class of events, which we would be tempted to call hard events.

2 A new class of events, a third component in pp collisions?

Assuming for simplicity that the new class of events is described —as are the soft and semihard ones— by a NBMD with parameters \(\bar{n}_{\text{th}}\) and \(k_{\text{th}}\), we decided to examine under such conditions possible signals of new physics which should be easily detectable already at 14 TeV c.m. energy in pp collisions by studying the general behaviour of the various sets of parameters characterising the final charged particles MD of the component \(P_n(\bar{n}_{\text{th}}, k_{\text{th}})\). In order to stress the properties of the new class of events, the extreme case \(\bar{N}_{\text{th}} = 1\) will be discussed in the following.

2.1 Consequences in terms of the \(\bar{n}_{\text{th}}, k_{\text{th}}\) parametrisation of the NBMD.

The request that \(\bar{N}_{\text{th}} = 1\), through its definition Eq. (1), leads to the straightforward relation between \(\bar{n}_{\text{th}}\) and \(k_{\text{th}}\):

\[
\bar{n}_{\text{th}} = k_{\text{th}}(e^{1/k_{\text{th}}} - 1)
\]

with (being \(\bar{n}_{\text{th}} \gg k_{\text{th}}\))

\[
k_{\text{th}} < 1.
\]

In Fig. 2 are plotted \(\bar{n}_{\text{th}} P_n\) vs \(n/\bar{n}_{\text{th}}\) in KNO form for \(\bar{N}_{\text{th}} = 1\) and different average multiplicities, with the respective values of \(k_{\text{th}}\) obtained via Eq. (3), which highlights the general trend of the exponential behaviour of the MD and \(k_{\text{th}} < 1\) dominance. In addition we notice that for \(k_{\text{th}} < 1\), as for the gamma distribution corresponding to the limit \(\bar{n} \gg k\) of the NBMD, we can distinguish two regions: \(n > \bar{n}_{\text{th}}\) and \(n < \bar{n}_{\text{th}}\). In the former a smooth behaviour of \(\bar{n}_{\text{th}} P_n\) is seen as \(n\) increases (events with large multiplicities) whereas in the latter a dramatic decrease of \(\bar{n}_{\text{th}} P_n\) is visible (events with low multiplicities). The fact that the distribution decreases so slowly for \(n > \bar{n}_{\text{th}}\) and so fast for \(n < \bar{n}_{\text{th}}\) produces more easily events with very large or very small charged multiplicity, which reminds us of what occurs in cosmic rays for centauro and anti-centauro events. A provocative result to be tested in experiments.
2.2 Consequences in terms of clan structure analysis

In Fig. 3 are plotted $N$ and $\bar{n}_c$ for the three components as a function of c.m. energy in full phase space: the first two components are those discussed in [1], notice that $k_{\text{sh}}$ behaviour corresponds to that suggested by a strong KNO scaling violation. The lack of experimental data on the third component at lower c.m. energies and the consequent impossibility to guess its behaviour in terms of extrapolations as it was done for the soft and semihard components in Ref. [1], led us to show a band of possible values. A conservative guess that the total multiplicity variation due to the third component over the extrapolation of Ref. [1] is limited to 10% leads to $\bar{n}_{\text{th}}$ values from 3 to 10 times larger than the total multiplicity, i.e., to a third component weight ranging from 1 to 3%. Notice that to a small variation of $k_{\text{th}}$ according to Eq. (3) corresponds a quite large variation of $\bar{n}_{\text{th}}$. This is clearly shown in the figure, where $\bar{N}_{\text{th}} = 1$ whereas $\bar{n}_{c,\text{th}}$ is 3 times larger in one case with respect to the other. Last but not least, $\bar{n}_{c,\text{th}}$ is, as assumed, much larger than in the two other components.

2.3 Consequences in terms of parameters $a_{\text{th}}, b_{\text{th}}$ of the NBMD.

Since

$$\frac{(n+1)P_{n+1}^{(\text{th})}}{P_n^{(\text{th})}} = a_{\text{th}} + b_{\text{th}}n, \quad (5)$$

with

$$a_{\text{th}} = \frac{k_{\text{th}}\bar{n}_{\text{th}}}{k_{\text{th}} + \bar{n}_{\text{th}}}, \quad (6)$$

and

$$b_{\text{th}} = \frac{\bar{n}_{\text{th}}}{k_{\text{th}} + \bar{n}_{\text{th}}}, \quad (7)$$

it follows that

$$a_{\text{th}} = \bar{N}_{\text{th}}P_{\log}(1) = \bar{N}_{\text{th}}\frac{-b_{\text{th}}}{\ln(1 - b_{\text{th}})}, \quad (8)$$

(where $P_{\log}$ is the logarithmic distribution) which for $\bar{N}_{\text{th}} = 1$ leads to

$$a_{\text{th}} = -b_{\text{th}}/\ln(1 - b_{\text{th}}) = P_{\log}(1). \quad (9)$$

It should be noticed that in the limit $k_{\text{th}} \to 0$ (it corresponds to $a_{\text{th}} \to 0$ and $b_{\text{th}} \to 1$) a truncated NBMD (i.e., with zero multiplicity missing) and with constant $\bar{n}_{\text{th}}/k_{\text{th}}$ (i.e., constant $b_{\text{th}}$) leads to a logarithmic MD, i.e., to the MD of a single average clan:

$$P_n^{(\text{th})} \to \frac{(b_{\text{th}})^{n-1}}{n}P_{\log}(1) \quad a_{\text{th}} \to 0 \quad = \frac{(b_{\text{th}})^n}{n\ln(1 - b_{\text{th}})} = P_{\log}(n). \quad (10)$$

This result is of course consistent with the standard interpretation of the occurrence of the NBMD as a two step process (independently produced clans with at least one particle ancestor decay according to a logarithmic MD) when the average number of clans is reduced to one.
In Fig. 4 are plotted the c.m. energy dependence of $a$ and $b$ for the three components which highlight the general trend of $a_{th} \to 0$ and $b_{th} \to 1$ for $\bar{N}_{th} \to 1$. Notice that in general, for $\bar{n}_i \gg k_i$, one has $a_i \sim k_i$.

2.4 Clan aggregation and correlations.

Being the probability of two particles of the hard component to join the same clan $1/k_{th}$ times larger than the probability to join two different clans it is clear that $k_{th} < 1$ is enhancing particle aggregation properties within clans.

Being $\bar{n}_{th}^2/k_{th}$ much larger than in the semihard component, from the relation

$$\bar{n}_{th}^2/k_{th} = \int C_2(\eta'_1, \eta''_2)d\eta'_1d\eta''_2$$

(11)

two particle correlations are also expected to be larger. Since cumulants are dependent on $1/k_{th}$, which is again much larger than $1/k_{sh}$, higher order cumulants are also expected to be quite large in the third component.

Concerning forward-backward multiplicity correlations and leakage parameter behaviour, it should be pointed out, as discussed in Ref. [5], that the forward-backward multiplicity correlation strength is given for each component by

$$b_{FB,i} = \frac{2b_ip_i(1-p_i)}{1-2b_ip_i(1-p_i)},$$

(12)

where $p_i$ is the average fraction of particles, within each clan, which remain in the same hemisphere where the clan was emitted and do not ‘leak’ to the opposite hemisphere. In the third component, in presence of only one clan, the leakage is expected to be maximum ($p_{th} \to 1/2$); being at the same time, as we have seen, $b_{th} \to 1$, one obtains $b_{FB,th} \to 1$.

Accordingly forward-backward multiplicity correlations in the third component are expected to be quite stronger than in the semihard component.

2.5 What Monte Carlo event generators say on the third component at 14 TeV c.m. energy in pp collisions

It is interesting to point out that the total charged particle MD, $P_n$, of the events generated with the last version of the Pythia Monte Carlo model both in full phase space and in a restricted rapidity interval ($|\eta| < 0.9$) cannot be fitted in terms of the weighted superposition of two NBMD’s and that the plot of $P_n$ vs $n$ shows two shoulders (see Fig. 5). These two shoulders appearing in the total multiplicity distribution come, in our framework, from the weighted superpositions of the first with the second and of the second with the third component. This is true also in the pseudo-rapidity interval. It would be tempting to identify the third component with the hard one discussed above, but striking differences between the third class of events generated with Pythia Monte Carlo and that one discussed above prevent us from doing this identification.
Table 1: Parameters for the third component at 14 TeV, assuming two cases: (a) $\bar{N}_{\text{th}} = 1$ and (b) $k_{\text{th}} = 0.5$.

|   | $\alpha_{\text{th}}$ | $\bar{n}_{\text{th}}$ | $k_{\text{th}}$ | $\bar{N}_{\text{th}}$ | $\bar{n}_{c,\text{th}}$ |
|---|----------------------|-----------------------|---------------|------------------|-------------------|
| (a) | 0.03 | 200 | 0.1370 | 1 | 200 |
| | 0.01 | 700 | 0.1147 | 1 | 700 |
| (b) | 0.03 | 200 | 0.5 | 3.62 | 193 |
| | 0.01 | 700 | 0.5 | 3.00 | 67 |

An “elbow structure” is expected in $P_n^{(\text{total})}$ as the result of the weighted superposition of the NB MD of the semihard component with the gamma log-convex MD of the hard one, as shown in Fig. 6.

In the figure are shown in addition to the weighted superposition of the soft with the semihard components already seen in Ref [1] the results of the weighted superposition of the semihard and hard components at 14 TeV c.m. energy.

2.6 The case of few clans

It should be pointed out that similar results to those discussed so far for the extreme case $\bar{N}_{\text{th}} = 1$ can be obtained with a small average number of clans, provided that $k_{\text{th}} < 1$, as illustrated in Table 1. The closer $k_{\text{th}}$ is to 1, the less evident becomes the elbow structure discussed above.

3 Conclusions

Signals of new physics could be visible in the tail of the $n$ charged particle multiplicity distribution $P_n$ in complete disagreement with Pythia Monte Carlo predictions under the assumption that the aggregation of the average number of clans in the semihard component reaches its minimum not asymptotically but at lower c.m. energy. The occurrence of this minimum would suggest the onset of a third (maybe hard) component to be added to the soft and semihard ones discussed in previous work.

In the paper we examined the main consequences of the occurrence of the mentioned situation already at 14 TeV c.m energy in pp collision, assuming that the new class of events is between 1 and 3 percent of the total.

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Figure 1: Multiplicity distributions, in KNO form, with various values of $k$ and the same average multiplicity $\bar{n}$, show different curvatures.
Figure 2: Multiplicity distributions in KNO form for two values of $\bar{n}$, with the respective values of $k$ (0.1611 for $\bar{n} = 80$ and 0.1128 for $\bar{n} = 800$) obtained from Eq. (3), i.e., requiring $N = 1$. 
Figure 3: Energy dependence of the average number of clans (top panel) and of the average number of particles per clan (bottom panel) for the three components (the band illustrates different choices for $\bar{n}_{th}$, see discussion in section 2.2).
Figure 4: Energy dependence of $a$ (top panel) and $b$ (bottom panel) parameters for the three components (see discussion in section 2.3; no band is visible for these variables, as they are little sensitive to the exact value of $\bar{n}_{th}$).
Figure 5: $n$ charged particle multiplicity distribution $P_n$ predicted for minimum bias events in full phase space by Pythia Monte Carlo (version 6.210, default parameters using model 4 with a double Gaussian matter distribution) at 14 TeV c.m. energy, showing two shoulder structures.
Figure 6: $n$ charged particle multiplicity distribution $P_n$ expected at 14 TeV in presence of a third (maybe hard) component with $\bar{N}_{\text{th}} = 1$, showing one shoulder structure and one ‘elbow’ structure. The band illustrates the range of values of parameters $\bar{n}_{\text{th}}, k_{\text{th}}$ and $\alpha_{\text{th}} = 1 - \alpha_{\text{soft}} - \alpha_{\text{sh}}$ discussed in the text.