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Looking for the NB at the CCC*

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Abstract

Multiplicity distributions are considered in the range 10 GeV — 100 PeV, using the parton showering and string fragmentation models in the JETSET program. It is shown that reasonable agreement can be obtained with the negative binomial ansatz, with a k^{-1} increasing with energy. Some of the challenges of constructing an accelerator to confirm/repute this behaviour are addressed, and a 'modest proposal' is presented for a Ceres Central Collider.

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1 Introduction

Léon Van Hove has, together with Alberto Giovannini, successfully promoted the idea of a negative binomial (NB) type multiplicity distribution behaviour.[1)] This distribution is characterized by two parameters, $\overline{n}$ and k,

$$P_n(\overline{n},k) = \left(\frac{k}{\overline{n}+k}\right)^k \left(\frac{\overline{n}}{\overline{n}+k}\right)^n \frac{k(k+1)\cdots(k+n-1)}{n!}, \qquad (1)$$

where P_n is the probability to find multiplicity n.

At this meeting, we have repeatedly seen the NB confronted with data. However, if the negative binomial provides a good parametrization of data, there must be some underlying physics reason. One possibility was raised by Malaza and Webber,[2)] who showed (analytically) that a parton shower picture gives an asymptotic multiplicity distribution consistent with a negative binomial with $k = 3$ (at least to lowest order; when nonleading corrections are included, the picture becomes more complicated[3)]). This parton level picture could survive to the hadron level if fragmentation obeys a rule of local parton hadron duality[4)] (LPHD), at least in an average sense.

When I visited CERN two years ago, Giovannini and Van Hove engaged my help in running the JETSET parton shower[5)] plus string fragmentation[6)] program.[7)] The negative binomial fitting program was obtained from the Nijmegen group,[8)] who had used it in a previous study;[9)] it is based on the MINUIT package available inside HBOOK. Unfortunately, the fitting procedure becomes very slow at large CM energies. In fact, more time is spent in the fitting than in the generation of events. In addition, the evaluation of eq. (1) comes to involve intermediate results larger than can easily be represented in a computer. As a consequence, no systematic studies were made at energies above 2 TeV.

This is therefore a suitable opportunity to clear up unfinished business. The fitting procedure has been rewritten, so that time consumption is reduced by a careful choice of nesting of DO loops and saving of intermediate results, while machine representation problems are addressed by taking the logarithm of eq. (1).

2 Results

The primary process studied is $e^+e^- \to \gamma/Z^0 \to q\overline{q}$. For simplicity, top production is not included, i.e. the q flavour is either u, d, s, c or b. A parton shower is allowed to evolve from the primary $q\overline{q}$ pair, thus giving a complex multipartonic state. The Λ scale of the shower is taken to be 400 MeV (a scale not to be directly equated with the standard $\Lambda_{\overline{MS}}$), and the evolution is cut off below a virtuality $Q_0 = 1$ GeV. Subsequently, the Lund string model is used for the transformation into a set of hadrons, and unstable particles are allowed to decay. The whole process is included in JETSET version 7.1, which was recompiled in double precision so as to be able to handle kinematics at large energies.

Runs were made at CM energies spaced a factor 10 apart, at 10 GeV, 100 GeV, 1 TeV, 10 TeV, 100 TeV, 1 PeV, 10 PeV and 100 PeV. At lower energies, each run contains

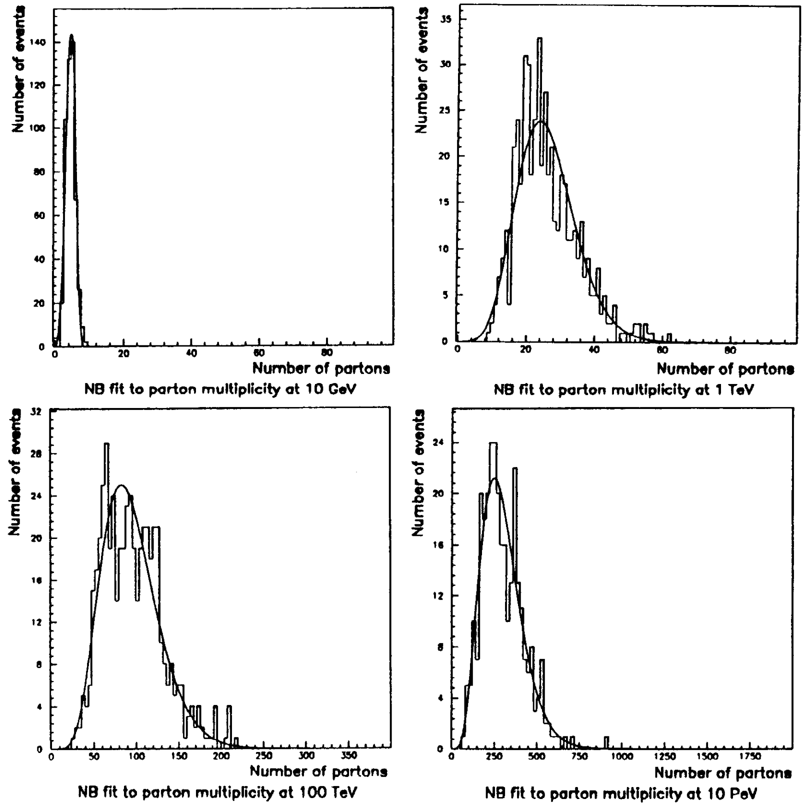

Figure 1: Parton multiplicity distributions at 10 Gev, 1 TeV, 100 TeV and 10 PeV. Histograms show Monte Carlo results and curves the negative binomial fits.

500 events, but at 10 (100) PeV only 300 (40) events were generated — at the top energy each event takes something like 10 s true IBM 3090 CPU time to generate. Distributions were obtained for the parton multiplicity at the end of the shower evolution, and for the final hadronic charged multiplicity. These are shown, for some of the energies, in Fig. 1 and Fig. 2, respectively, together with the negative binomial fits.

Are then the fits to the data good ones? The χ^2 per degree of freedom is typically around 1.5, and seldom larger than 2. One should not be too impressed by this, however, since the limited statistics makes the χ^2 measure a rather blunt tool. In this case, the visual picture is therefore just as revealing: the fits seem reasonable. This does not mean they are perfect. For instance, when looking at the charged multiplicity plots, one gets the impression that the negative binomial distributions continue on down to lower multiplicities than does the 'data'. This is not an unreasonable behaviour: the fragmentation of a simple straight string gives an (almost) Poissonian multiplicity

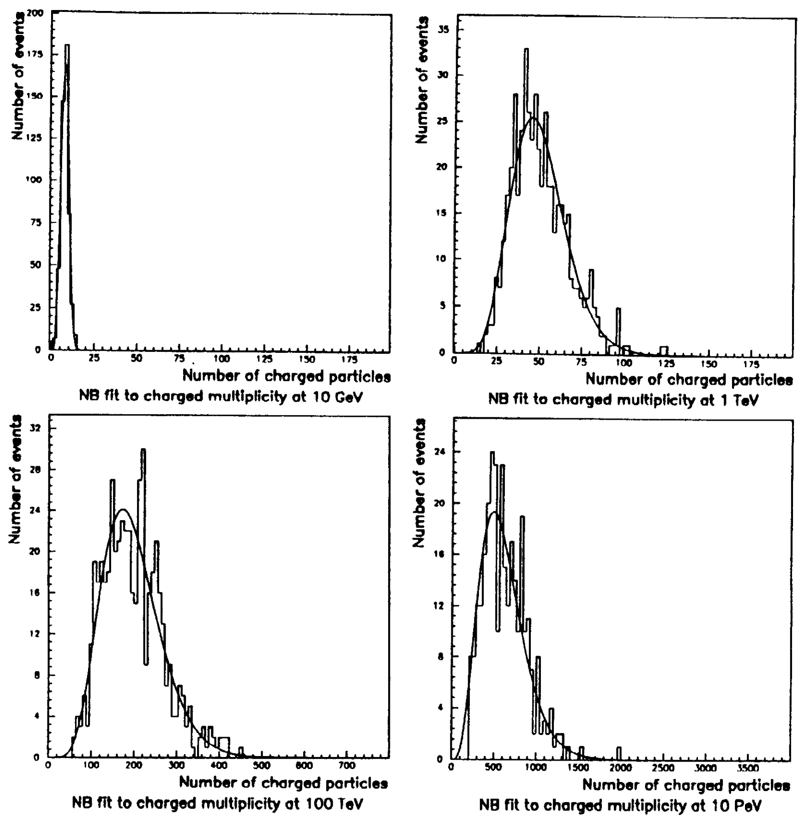

Figure 2: Charged multiplicity distributions at 10 Gev, 1 TeV, 100 TeV and 10 PeV. Notation as in Figure 1.

distribution. This means that, at large energies, the distribution falls off rapidly on either side of the mean value. The parton shower adds a mechanism whereby the multiplicity can be significantly increased, but not as easily decreased. Therefore a cutoff at low multiplicities is inherent in the string model framework, with no correspondence in the negative binomial approach.

The fitted negative binomial $\overline{n}$ values, which agree well with the average multiplicities, $\langle n \rangle$, are shown in Fig. 3, as functions of the CM energy. It is interesting to note that the the two curves trace each other very closely, separated by a constant factor, $\overline{n}_{charged}/\overline{n}_{parton} \approx 2$, as already found for lower energies.[10] The number 2 is not significant, since a different ratio would have been obtained for another Q_0 shower cutoff, but the constancy of the ratio when the energy is varied is a manifestation of an approximate LPHD built into the shower+fragmentation scenario.

The expected (asymptotic) energy dependence of the average parton multiplicity is

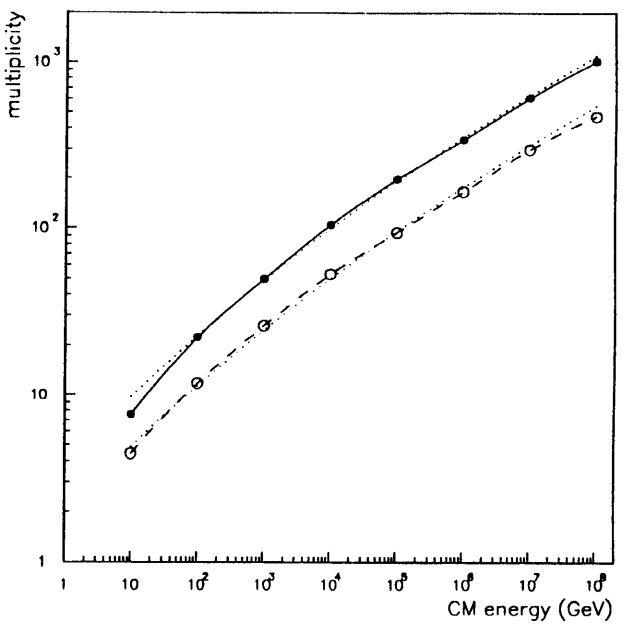

Figure 3: Fitted average parton (open circles) and charged (filled points) multiplicity $\overline{n}$ as a function of CM energy. Full and dashed curves are drawn to guide the eye. The dotted curves give the dependence of eq. (2) for $c = -1$; see the text for additional details.

given by the formula[11]

$$\langle n(t) \rangle = N\, t^c \exp\left(\sqrt{\frac{72}{33-2n_f}t}\right), \quad c = -\frac{1}{4}\left(1+\frac{5}{9}\frac{8n_f}{33-2n_f}\right) \approx -\frac{1}{2}, \qquad (2)$$

where $t = \log(Q^2/\Lambda^2)$, N is an undetermined normalization constant, and the effective number of flavours n_f is 5 in our exercise. Compared to a 'conventional' shower, where the reduction of emission by soft gluon interference effects[12] is not included, the 'coherent' shower has an additional factor 1/2 in the exponential. Therefore the conventional shower is expected to have a multiplicity growth, over the energy range considered, a factor 675 larger than that given by eq. (2). In real life, it would be difficult to find a conventional algorithm with that rapid a growth; also formally the growth could be slowed down by a different c value.

The multiplicity growth in JETSET is even slightly slower than that of eq. (2), by a factor of 2.3 between 10 GeV and 100 PeV. This discrepancy is probably attributable to subleading differences between the kinematics assumptions made in deriving eq. (2) and those that are used in the program. The differences can be reasonably well accounted for, either by a change of the c value, or by a change of the effective Q scale (i.e.

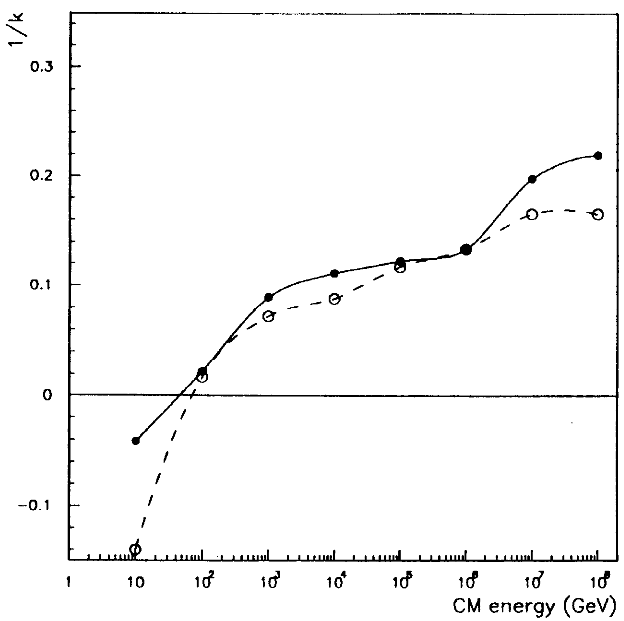

Figure 4: Fitted k^{-1} values for partons (open circles) and charged particles (filled points). Statistical errors on the fitted k^{-1} values are typically ± 0.03, so the kinks on the dashed and full curves that connect the points are not significant.

the Q entering into the definition of t need not be equal to the CM energy), or by a combination of the two. For the dotted curves in Figure 3 the c value has been changed from $-1/2$ to -1. The normalization constants are $N_{parton} = 0.35$ and $N_{charged} = 0.70$.

The k^{-1} values, as functions of the CM energy, are shown in Fig. 4. For small CM energies, k^{-1} is negative, i.e. the distribution is of the positive binomial type. The k^{-1} curves for partons and for charged particles almost coincide. In fact, the difference between the two curves is nowhere larger than are the statistical errors on the k^{-1} values themselves (with the exception of the 10 GeV results, where the absence of parton multiplicities 0 or 1 tends to narrow the parton distribution anomalously). Taken as a whole, there seems to be some indication that k^{-1} is larger for charged hadrons than for partons, however. This would correspond to some extra broadening of the multiplicity distribution by fragmentation effects, but still the basic picture is very close to the LPHD requirement of $k^{-1}_{parton} = k^{-1}_{charged}$.

The lasting impression of, in particular, Fig. 4 is that the k^{-1} values keep on rising right to the end of the plot, and are still a far way off from $k = 3$. To the extent that the model indeed has such an asymptotic behaviour (which is not entirely clear), we must conclude that the truly asymptotic regime is uncomfortably high up in mass,

maybe close to typical Grand Unification scales, or even the Planck mass. One lesson to draw is that one must keep apart asymptotic properties of parton showers from those properties that are accessed by current or planned experiments.

3 Accelerators

In the previous section we rapidly stepped up through the decades. It is easy to lose the sense of proportions, and not realize what a scale of 100 PeV means. Since Van Hove has a past as planner of big accelerators, it is maybe appropriate to spend a few minutes considering what is needed to confront the Monte Carlo simulations with data.

In fact, one is tempted to say that the task is impossible. A number of reasons could be raised.

- An extremely high acceleration gradient is required.
- Since the annihilation cross-section drops like $1/s$, where $s = E^2_{CM}$, the transverse dimensions of the two colliding beams should be made to drop like $1/E_{CM}$, in order that one may have a reasonable number of events. Had we not had the Z^0 peak to boost cross-sections, a 1 μm beam spot (combined with perfect running) would have been needed to have any events at all at a 100 GeV linear collider (SLC), so at 10 PeV one needs 0.01 nm = 0.1 Å— and these beams must be made to hit head on!
- Beam disruption, beamstrahlung and other beam-beam dynamics effects will be hard (impossible?) to master.
- Processes not dominated by s-channel exchange will have much larger cross-sections than the ordinary annihilation graphs. The obvious example is $\gamma\gamma$-physics, but at high energies the list of similar processes becomes much larger. We might end up in a situation where the 'old', 'interesting' physics of multiplicity distributions in annihilation events is swamped by 'new', 'dull' physics like W^+W^- fusion production of Higgs and other exotic particles. (Since the latter type of processes has a steeper fall-off in transverse momentum, this issue might be more manageable than many others, however.)

Now, the problems above will certainly have to be addressed by specialists in the field. One can, however make a few more mundane comments, to understand the dimensions of such a project, were it possible. For this, let us consider the case for a 10 PeV collider.

The first point to settle is what accelerating gradients to aim for. In the study of laser driven plasma beat wave accelerators, gradients of several GeV/m are often mentioned,[13] so let us be optimistic and take $k_{acc} = 10$ GeV/m as a realistic goal. In passing, one can note that access to this kind of accelerator technology would reduce LEP to a two-day exercise, part of the undergraduate program in any well-equipped University: in your (shielded) cellar you simply need two 10 m linacs, with the interaction point surrounded by simple counter hodoscopes. With the kind of beam spot size we have already mentioned above (for need at higher energies), it will be a straightforward task for the students to map out the Z^0 line shape day 1, and then study the W^+W^- threshold behaviour day 2, just by looking at multihadronic event rates.

It should come as no surprise that one needs linear colliders. Let us just repeat the argument. For a beam energy of E_b and a bending radius r, the beam energy lost per turn is

$$E_{loss} = k_{loss}\frac{E_b^4}{r}, \qquad k_{loss} \simeq 10^{-4}\ \mathrm{m}\cdot\mathrm{GeV}^{-3}. \tag{3}$$

If bending and acceleration machine components can be combined, the energy gain per turn is

$$E_{gain} = k_{acc}\cdot 2\pi r = k_{gain}r, \qquad k_{gain} \simeq 60\ \mathrm{GeV/m}, \tag{4}$$

based on our assumed k_{acc}. The two balance each other, $E_{gain} = E_{loss}$, for

$$E_b = \sqrt{\sqrt{\frac{k_{gain}}{k_{loss}}}r} = \sqrt{k_{bal}r}, \qquad k_{bal} \simeq 8\cdot 10^2\ \mathrm{GeV}^2/\mathrm{m}, \tag{5}$$

so even the radius of the Earth gives $E_{CM} = 2E_b \simeq 150$ TeV, two orders of magnitude below the desired result.

A linear accelerator, on the other hand, 'only' needs to have a total length of 1000 km, i.e. two arms of 500 km each, to reach 10 PeV. If we want to put the detector under the CERN site, the two beams could start out close to Toulouse and Munich, or Ajaccio and Brussels, or Angers and Venice, etc.

However, if the two beams are to hit head-on, the collision point will be 20 km underground, due to the curvature of the Earth. This is about twice as deep as the deepest drilling ever achieved so far, so the engineering task of building an access shaft and an experimental hall is not insignificant. In addition, the ambient temperature will be in the order of 400° C, i.e. a lot of cooling equipment will be needed. The high air pressure, if not addressed by a system of airlocks in the access shafts, will also cause problems: diver's bends for physicists returning to the surface, high inflammability, etc.

Of course, it would be possible to place the interaction region closer to the surface, 1 km down, say, and only have the linac tunnels go as deep as 6 km, but then the beams will cross at an angle, i.e., after travelling 500 km, they should arrive at the same spot no more than 10^{-19} s apart.

In either case, the Earth is not particularly stable: already tidal forces from the Moon and the Sun would deform the linacs by several metres diurnally, and earthquakes (man-made or natural) would add short-term oscillations.

It is therefore probably necessary to put an accelerator of this size away from Earth. The Moon is excluded, since tidal deformations are even more important there, and seismological disturbances not uncommon. An obvious idea might be to construct an accelerator at one of the Lagrange points of the Sun–Earth system. The linac would then actually be slightly bent, with a radius equal to the Sun-Earth distance, $1.5\cdot 10^8$ km. Plugging this into eq. (5), one obtains a maximum allowed CM energy of 22 PeV, comfortably above our target number (and so the total length only has to be increased from 1000 km to 1010 km to make up for synchrotron radiation losses). However, to leave an accelerator like this floating in open space might have its problems: the structure would be deformed by gravitational perturbations from other planets, from the solar wind, and from meteoroidal impacts.

So, after all, the safest place is probably to have the linacs protected inside a planetary body. After a look at the possibilities, it seems that the asteroids might be the best

choice, in terms of geological stability (as far as we know), absence of tidal effects, low ambient temperature, low gravity (which makes excavation work rather easier), etc. In particular, one may contemplate a Ceres Central Collider, with one linac starting at the north pole and the other at the south one, and with the experimental hall right in the middle of the asteroid. With this arrangement, one would have the added advantage of no net gravitational forces in the central cave — this would be the proverbial detector that could be held together with 'spit and chewing gum' — and hence dead zones for mechanical support would be a memory of the past. The one disadvantage is that even Ceres, the largest of the asteroids, only has a diameter of 700 km. One would therefore have to go for an accelerating gradient of 15 GeV/m, rather than the 10 GeV/m we proposed originally.

4 Outlook

Even a 10 PeV CCC project would not explore the asymptotic properties of showers, as we have seen. To go beyond these energies, it will probably be necessary to leave the Solar System behind altogether (unless even larger accelerating gradient can be achieved). As an example of what higher energies might hold in store, Fig. 5 contains the first event generated at 1 EeV (10^9 GeV). At these energies, multijets are clearly visible to the eye, as is (some kind of) local parton-hadron duality. And, to tie in with another main theme of this meeting, so is intermittency[14]: if the second factorial moment $\langle F_2\rangle$ is normalized to be unity for the rapidity range ± 3.2, then it reaches 13.8 for $\Delta y = 0.0125$, and 3117 for a simultaneous slicing in rapidity and azimuth, $\Delta y \times \Delta\phi = 0.0125 \times 0.0123$, and even larger results would have been obtained with smaller bin sizes. The only problem is that it is all a trivial consequence of the shower evolution.

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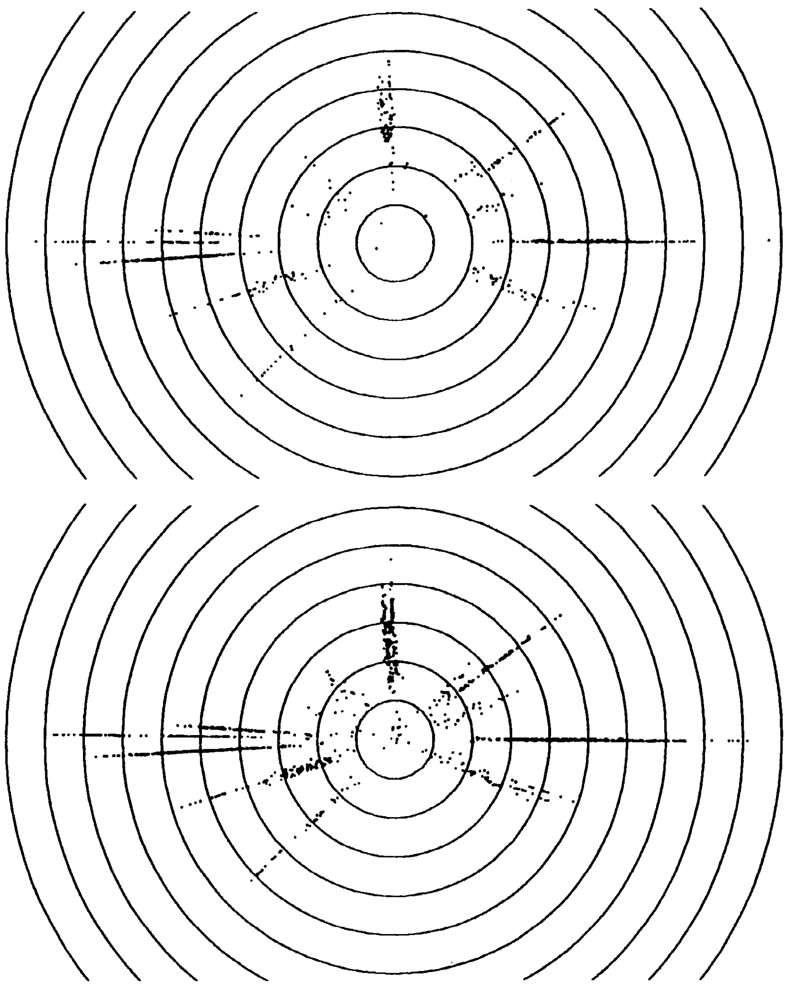

Figure 5: Parton (top) and charged particle (bottom) distribution in momentum space for one 1 EeV e^+e^- annihilation event. Each parton (multiplicity 671) or charged particle (multiplicity 1396) momentum vector is represented by a single point. Momentum components out of the event plane (determined by linear sphericity) are neglected. Angles in the plane are preserved, while the absolute momenta in the plane are displayed as follows: inside the innermost circle, a linear scale is used out to 1 GeV, thereafter a logarithmic scale is used, with each circle corresponding to an order of magnitude, so that the outermost circle would represent particles with absolute momentum 10^9 GeV in the plane.

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