A note on the CDF high-$p_t$ charged particle excess

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Abstract

It has recently been pointed out that CDF data for the cross section of high-$p_t$ charged particles show an excess of up to three orders of magnitude over QCD predictions, a feature tentatively ascribed to possible violations of factorisation. We observe that for $p_t > 80\text{ GeV}$ the measured charged-particle cross sections become of the same order as jet cross sections. Combining this information with data on charged particle distributions within jets allows us to rule out the hypothesis that the CDF data could be interpreted in terms of QCD factorisation violation. We also comment on the difficulty of interpreting the excess in terms of new physics scenarios.

In reference \cite{1}, the CDF collaboration at the Tevatron collider has published measurements of the inclusive charged particle spectrum at transverse momenta, $p_t$, up to 150 GeV. These data are based on a minimum-bias trigger sample consisting of about 16000000 events and a smaller high track-multiplicity trigger sample. In its analysis, CDF compared the data to Monte Carlo predictions for a somewhat larger minimum-bias sample from the Pythia event generator \cite{2} and found that approaching 50 GeV the data exceeded predictions by about a factor of three. The comparison was not extended beyond 50 GeV.

Recently, Albino, Kniehl and Kramer \cite{3} presented a comparison of the CDF data to a NLO QCD calculation involving parton distribution functions and fragmentation functions from global fits. Such a calculation should be more precise than predictions from Pythia and should have better constrained uncertainties. Furthermore, it covers the full extent of the high-$p_t$ region in which there are data. The striking observation in \cite{3} is that in the highest $p_t$ bin, 100 – 150 GeV, the data exceed QCD predictions by a factor of up to $O(10^3)$. Independent work by Arleo, d’Enterria and Yoon \cite{4}, which appeared while our note was being finalised, made the same observation and also compared to a Pythia sample that covered the whole $p_t$ range, confirming the findings of a large excess. This excess is illustrated in fig. 1 where we compare the data to the combination of a Pythia minimum-bias sample in the low-$p_t$ range with dijet samples at high $p_t$.

In interpreting their findings, the authors of ref. \cite{3} argue that the comparison of data and theory challenges the validity of QCD factorisation, requiring a drastic modification
Figure 1: Comparison of the CDF charged-particle data [1] with predictions from Pythia 6.421 [2] using the DW tune [5].

either to the theoretical calculation or the experimental data. We can investigate the question of factorisation in more detail by comparing the charged-particle data to Tevatron data on inclusive jet production.

The particle and jet spectra are compared in fig. 2. The left-hand plot shows the inclusive charged particle data [1] together with data from CDF for the inclusive jet spectrum [6] (with the $k_t$ algorithm [7], using $R = 0.5$; results with other jet definitions and from DØ [8] are similar). The right-hand plot shows the ratio of the charged particle to jet spectra. One sees that for $p_t > 80$ GeV the charged particle cross sections become of the same order as the jet cross sections. If the CDF charged particles are normal hadrons, then the only explanation for the high-$p_t$ bins of fig. 2 would be that for the majority of jets, the whole jet momentum is accounted for by a single charged hadron.

Such a feature would not just be a violation of factorisation for fragmentation functions, but would imply that above some parton energy, collinear splitting, the mechanism by which a parton’s momentum is shared among multiple daughters in a parton shower, would turn off. Aside from violating fundamental properties of quantum field theory, an interpretation of this kind is in contradiction with CDF data on charged particle spectra within jets, such as fig. 3 taken from ref. [12]: for a dijet mass range of 200 – 260 GeV, corresponding to $p_{t,jet} \sim 100$ GeV, those data show that only about 0.1% of jets contain a charged hadron carrying at least 90% of the jet momentum.

1 Ref. [12] does not measure all particles inside the jet, but only those within a cone of limited radius. However, any particle carrying a large fraction of the jet’s momentum has to be near the centre of the jet. Furthermore, measurements of jet shapes [13] constrain the fraction of energy that can be in the outer parts of a jet (beyond an angle of 0.5 radians) to an average of 10 – 15%. A second restriction of [12] is that it only considers events in which the two hardest jets are well-balanced in $p_t$ and any 3rd or 4th jet is much softer than the two leading ones. While this does not affect conclusions about the validity of QCD
Figure 2: Left: comparison of the charged-particle data \cite{1} with CDF data on the inclusive jet spectrum \cite{6}, showing also predictions from Pythia and the NLO calculation for the jets from FastNLO and NLOJet++ \cite{9,10} with CTEQ66 PDFs \cite{11}. Right: ratio of the charged-particle spectrum to the (rebinned) CDF inclusive jet spectrum. Note that the charged-particle and jets data correspond to slightly different rapidity ranges. For the $p_t$ range of relevance, the mismatch in rapidity ranges implies only modest additional corrections, $\mathcal{O}(10\%)$ (which have not been applied).

Figure 3: Figure 20 of ref. \cite{12}, by the CDF Collaboration, showing the inclusive distribution of momentum fraction $x$ of charged particles in cones around each of the two jets axes in dijet events at the Tevatron (Run I).
The argument can be further refined by noting that the jet spectrum $d\sigma/dp_t$ falls as $p_t^{-n}$ with $n \simeq 6$ in the relevant $p_t$ range and that the measured inclusive charged particle momentum-fraction distribution within the jet, $C(x)$, does not depend too strongly on the jet $p_t$. By taking the $(n - 1)^{th}$ moment of $C(x)$, $\int_0^1 dx x^{n-1}C(x)$, as determined from the points in fig. 3 one then derives an expectation for the ratio of charged-particle and jet inclusive spectra. Numerically this turns out to be of order 0.006 with uncertainties of a few tens of percent (related to the exact choice of $n$ and the finite size of the bins of the data for $C(x)$). Such a result is consistent with the predictions of parton shower programs like Pythia (cf. the two Pythia curves in fig. 2 left). This should not be a surprise: the data of [12] had been compared to Herwig [14] simulations, showing near perfect agreement.

We therefore conclude that the large excess in charged-particle production at high transverse momenta cannot be explained by any modification of QCD fragmentation functions (or of other aspects of QCD factorisation), because this would lead to a strong contradiction with Tevatron data on charged tracks within jets in the same $p_t$ range.

The most likely explanation for the CDF excess, as argued already in [4], is probably some issue with the data. But it is worth considering what the implications would be if the tracks are real.

Unless somehow jets in multijet events fragment in a way so different from jets in dijet events that the plots of [12] are not applicable in multijet QCD, then the high $p_T$ tracks in [1] cannot form part of an ordinary jet – and so, if the tracks are real, they cannot be ordinary hadrons. Nor can they be electrons or muons; non-isolated electrons would appear as jets, while such high rates for muons, converted photons or isolated electrons are inconsistent with other data. Could a new metastable exotic object be responsible for these tracks? This seems unlikely but is not completely trivial to rule out.

Whatever these objects are, they must be produced with a very large cross-section. From the last 4 bins of the data, one sees that it must be of order 50 nanobarns, with large errors, if the track-objects are pair produced.

This big cross section is a major impediment to a new physics explanation. A colour octet fermion with mass of 25 GeV and $p_t > 50$ GeV would be pair produced with $\sim 10$ nb cross-sections at leading order. A wide resonance with a small branching fraction to dijets and a large branching fraction to exotica, such as a 150 GeV “coloron” in the spirit of [15], could have a few-nanobarn cross-section through mixing with the gluon, and a decay dominantly to an exotic final state, while drowning in dijet background. Still, even though a 50 nb cross-section pushes the limits of credulity, it seems worthwhile to try to exclude any exotica directly from searches for those objects.

For an object to leave a track, it must be ionising: it must carry electric charge or magnetic charge on an atomic scale. (It could be a neutral object with a large dipole...
moment.) In addition, to not affect the dijet fragmentation results in [12], it must not appear frequently in dijet events, or else must deposit only a fraction of its $p_T$ as calorimetric jet energy (so that it appears as a small contribution at negative $\xi$ in lower dijet-mass bins). A possible candidate, massive metastable charged particles (“CHAMPs” or “CMSPs”), if colourless and stable, are excluded by CDF [16] and DØ [17]. Even non-hadronic CHAMPs that decay in flight are excluded: given how many must leave tracks, too many would still reach the muon system and be detected by CDF’s CHAMP search. (The DØ search, requiring two “muons” per event, is less sensitive.)

Charged R-hadrons (bound states of an exotic coloured object $Q$ with quarks and gluons) are more subtle. Understanding of their behaviour in matter has continued to evolve (for a review see [19].) It certainly seems unlikely that a few million R-hadrons could escape the CDF CHAMP search, but it is not simple because of charge-flipping, by which an R-hadron colliding with a nucleus may shift its charge by 1 unit. Such flipping reduces dramatically the number of good “muon” candidates produced by R-hadrons, and makes the DØ search, with its requirement of two “muons”, one with tight isolation, far less sensitive. The CDF study directly considers stable top squarks, and, with some assumptions regarding their properties in matter, reports a detection efficiency greater than 3.5%. But loopholes might remain for lower-mass R-hadrons, for example those built from a charge-neutral colour-octet $Q$, which is only constrained at LEP [20, 21] to be above about 25 GeV. (Ref. [22] argues that indirect mass limits can be placed at 50 GeV.) And colour octets, less well understood than triplets, may well have a lower detection efficiency [19].

There are good reasons to expect substantial missing transverse momentum (MET) from R-hadrons [19]. One is that slow R-hadrons have much less kinetic energy than $p_T$. Another is that fast R-hadrons that are neutral (if any are produced) are expected to deposit only a fraction of their kinetic energy in the calorimeter. In association with initial state radiation (ISR), a substantial MET signal would then be generated. Indeed in [23] it is argued that a robust lower bound of 170 GeV can be placed on gluino masses: specifically, neutral R-hadrons leave too little energy to register as jets, and therefore contribute to monojet signals [24, 25]. But R-hadron energy deposition increases at low masses, so perhaps this argument might break down for sufficiently light R-hadrons. Moreover, even accepting the arguments of [23], R-hadrons decaying in flight with $c\tau\gamma \sim 1-2$ meters might still be allowed; such decays would further reduce the sensitivity of the CHAMP/CMSP searches. Still, it would be necessary either that the R-hadrons appear typically in events with more than two jets, or that their decay include invisible particles, so as to evade the constraints from [12] discussed above and not distort the jet spectrum.

We certainly think the R-hadron scenario unlikely. And while there may well be other allowed exotic objects that could give tracks of low curvature without producing corre-

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3 A fractionally charged CHAMP (still allowed by cosmology and direct searches if the CHAMP pair are quirks [18] that will always eventually find each other and annihilate) would have its track $p_T$ overestimated in [1], but the powerful CHAMP/CMSP bounds of [16, 17] still exclude it. Any decrease in efficiency in the muon system with the lower charge would be partly counterbalanced by a decreasing tracking efficiency, requiring an even larger cross-section.
sponding high-$p_T$ jets a plausible new physics scenario seems difficult to achieve. But because of the range of possibilities and the uncertainties on their dynamics, we cannot claim to have strictly eliminated this option.

We therefore suggest that CDF, with appropriate scepticism, might wish to exclude such possibilities directly from the data, if no technical problem with the data is immediately apparent. It would seem that any exotic explanation for the tracks is likely to become evident in a direct perusal of the signal events with the high-$p_T$ tracks in \[1\]. Signatures could include a systematic mismatch of a track’s $p_T$ with its associated energy deposition, unusual energy deposition patterns, time-of-flight delay or large $dE/dx$, evidence of a late decay, overall calorimeter MET, pairs of tracks per event, etc. (By contrast a fake track would not lead to calorimetric MET, and two such tracks per event would be very rare. Note that misreconstructed tracks with unphysically high momentum are removed from the CDF CHAMP search \[16\], though no details on this step are given.) Should a direct investigation of the existing events prove inconclusive, it is likely that the event sample can be enlarged by looking in other trigger streams, given the signal’s high rate and apparent high energy. At a minimum, ISR radiation should contribute events of this type to (prescaled) 20 or 50 GeV jet triggers.

To conclude, we have argued that the excess of high-$p_T$ tracks seen in \[1\] cannot be attributed to QCD factorisation violations, or to any other misunderstanding in QCD calculations of hadron production. The argument is largely based on data from the Tevatron itself, in the same $p_T$ range as the excess. We have not been able to eliminate fully the possibility that the excess is due to exotic new physics, though we view it as unlikely. Inspection of the data should be able to settle the question.

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4For instance, in some regimes a quirk bound state — an electric dipole formed from two charged particles bound together by a hidden-sector flux tube — could be misread as a high-$p_T$ track \[18\] and yet, because of unusual behaviour in matter, might not be easily detected by existing CHAMP/CMSP searches. However it seems very difficult to achieve the required cross-sections.
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