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THE STRUCTURE OF "TECHNI" JETS

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Abstract

The properties of jets associated with quarks carrying a non-Abelian gauge interaction which becomes strong at a momentum scale, Λ_{TC}, which is taken to be much larger than that appropriate for QCD, Λ_{QCD}, are studied. Such jets are shown to produce a unique experimental signal for new interactions.

At extremely high energies such as might be available at a $\bar{p}p$ collider of $E_{CM} \cong 10 - 40$ Tev, new degrees of freedom such as techni-quarks, constitutents of quarks and gluons and their ilk might be produced [F1]. Such new degrees of freedom should appear in high transverse momentum events, where the short distance structure of matter is probed. This is expected to occur at a momentum scale typical of these new degrees of freedom, which we shall refer to Λ_{TC} for lack of a better name. In the remainder of this paper we shall explore the dynamics of these new degrees of freedom when produced in high transverse momentum processes. We shall assume that these new degrees of freedom carry a charge of a confining gauge theory characterized by a confinement momentum scale Λ_{TC}. We shall refer to the new degrees of freedom of this confining gauge theory generically as techni-quarks, although our considerations should apply for any constituents of a confining gauge theory characterized by a confinement scale $\Lambda_{TC} > \Lambda_{QCD}$.

At very high transverse momentum, $p_T \cong \Lambda_{TC}$, production of techni-quarks may begin to dominate over conventional hard processes. For example, at energy transfers of several GeV (10-100 Λ_{QCD}), the composite nature of ordinary hadrons appear. Only at transverse momenta $p_T \cong 10 - 100\ \Lambda_{TC}$ do we expect that these techni-quarks may play a dominant role in jet processes [F2]. To understand this, recall that in order for a jet to develop, the techni-quark must be moving fast.

The leading techni-quark in the jet will typically have some uncertainty in its transverse mass (that is, the mass for degrees of freedom transverse to the jet axis determined by p_T) which is of the order of Λ_{TC}. The Lorentz gamma factor of the leading techni-quark is $\gamma \cong p_T/\Lambda_{TC}$, and $p_T \cong 10\ \Lambda_{TC}$ is probably needed. A larger factor may be required for the techni jets to stick out beyond the backgrounds for conventional jet processes, as is the case with quark jets at present $\bar{p}p$ collider energies. A detailed estimate of techni jet production cross sections and a comparison to conventional jet computations would be required to make a firm estimate of the required transverse momentum.

In the remainder of this paper, we shall discuss the properties of techni jets. All transverse momentum will be measured relative to the jet axis, and rapidities, $y = \ell n[(E+p)/m_T]$, will be measured along the jet axis. The typical transverse mass scales in the theory should be typical of the only momentum scale in the confining gauge theory, $m_T \sim \Lambda_{TC}$. The transverse momentum of particles relative to the jet axis are therefore extremely large, and this provides an unmistakable signal for a techni jet. The total rapidity interval should also be of order $y_{total} \cong \ell n(2E/\Lambda_{TC})$.

The estimation of the rapidity density of secondaries along the jet axis proceeds by first determining the rapidity density for primevally produced techni-hadrons, that is techni-singlet bound states, and then accounting for final state interactions which, as we shall soon see, dramatically increases the rapidity density. The primeval rapidity density should be determined by dynamics which are parallel to that of QCD [3]. We expect the density dN/dy to be approximately uniform, and since no scale appears in dN/dy, this distribution should be of order one, as in QCD. As far as the rapidity density reflects the primeval distributions of quark-antiquark pairs and gluons, the primeval distributions of techni-quarks and techni-gluons should not be so much different between QCD and the techni-color theory, at least so long as the number of colors of the techni-color theory is close to that of QCD.

There are at least two ways that this rapidity distribution might be modified by final state interactions. Unstable techni-hadron resonances may form which may subsequently decay into stable techni-hadrons. The entire dN/dy distribution may be increased by an undetermined scale factor. Without a detailed model, it is difficult to quantify this enhancement. Since most theories of new confining interactions suffer from particle proliferation, it is probably safe to assume that the rapidity density increase generated by this effect will be larger than the corresponding effect generated by ρ decay in QCD.

There is also a dynamical effect which may increase the rapidity density. The techni-hadrons primevally produced in the techni jet may have all manner of QCD colors. The time scale for the production of techni-hadrons is $t \cong \Lambda_{TC}^{-1}$ which is short compared to the time scale for QCD, $t \cong \Lambda_{QCD}^{-1}$. The techni-hadrons will be required to be singlets under the techni-color group, but the time is too short and the interactions of the techni-mesons are too energetic to force a QCD color singlet constraint. Since the colored techni-hadrons have transverse momentum of $p_T \cong \Lambda_{TC}$, the colored techni-hadrons may form ordinary QCD jets transverse to the techni jet axis. The multiplicity of hadrons will therefore be increased by a factor of $\ell n\ (\Lambda_{TC}/\Lambda_{QCD})$.

The overall increase in dN/dy relative to that appropriate for ordinary QCD jets may very well be a factor of 10 - 100. Such a tremendous increase might be easily detected. Also, the momentum distribution of the tertiaries produced in the QCD secondary jets may reflect the hadronization process. These tertiaries may be distributed along the QCD jet axis with distributions typical of QCD jets. There may also be high transverse momentum color singlet particles which appear in isolation with no tertiary QCD hadronization.

Another signal of the techni-quark nature of the jet might be in the exotic quantum numbers of the secondaries with high transverse momentum to the jet axis. These particles might be rich in techni-hadrons of unconventional variety. The jet may serve as a factory for these techni-mesons.

Since the multiplicity density of secondary hadrons produced along the jet axis is so large, a natural question to ask is whether any exotic high energy density forms of matter might be produced. For example, might a techni-quark techni-gluon plasma form? [F3]. This issue is at least as complicated as that for the formation of a quark-gluon plasma in jets for e^+e^- collisions, since all of our considerations scale up uniformly to this new energy scale. Since in average e^+e^- collisions, we do not expect quark-gluon plasma to form, the corresponding situation may hold for techni jets. Fluctuations yielding an exceptionally high rapidity density along the jet axis might occasionally generate a plasma, but this might be very rare and difficult to analyze. Since it is difficult to generate a plasma, other collective phenomenon which take place over large times in large spatial volumes, that is large relative to the natural scales at hand, may be difficult to induce.

Another question is whether due to the high multiplicity of secondaries in a techni jet, it might be possible to form a more prosaic quark-gluon plasma at temperatures much higher than might be produced in nucleus-nucleus collisions or, more speculatively in $\bar{p}p$ collisions. To assess this issue we need to use a space-time picture of the collision process and determine for what energy densities and at what temperature might the system be able to expand in local thermal equilibrium. This condition is that the rate of energy transfer per particle (through scattering) be larger than the rate of energy loss per particle (through expansion).

Such a computation assumes that prior to thermalization the distribution of particles are not too far from being locally in thermal distributions. This may depend strongly on the details of the formation of tertiary particles during the QCD hadronization process. If the formation time of colored matter remains $t = O(1fm/c)$ independent of multiplicity, this assumption might not be valid, and either no plasma, or a plasma with $T \lesssim O(\Lambda_{QCD})$ might be produced [4]. If the hadronization time depends upon multiplicity, as it does in color flux tube models, then we believe that the assumptions underpinning our computations have a better chance to be true. The validity of our assumptions is difficult to access a priori given our present understanding of soft hadronic processes. Our conclusion, stated in its most conservative form, is that extremely high temperatures, $T >> 1GeV$, are unlikely to occur although temperatures $T = O(1GeV)$ are not completely ruled out.

The rate of energy transfer per particle through scattering may be determined using kinetic theory. On dimensional grounds, this rate is proportional to T^2 where T is the temperature. Since the transfer may take place only through scattering processes, the rate must involve α_s^2 where α_s is the QCD fine structure constant. There are also logarithms of α_s which arise from regulating infrared divergences. This rate of energy loss has not yet been fully estimated in QCD, so we use this crude order of magnitude estimate. The order of magnitude estimate is

$$dE/dt|_{scattering} \cong \alpha_s^2 \, T^2 \, \ell n\alpha_s. \qquad (1)$$

Estimating the rate of energy loss through expansion involves invoking a space-time picture of the collision process.[5] We shall employ the inside-outside cascade picture of the formation of matter in the techni jet. Secondaries begin to form which are techni-color singlets, but may have all manner of color quantum numbers. As time goes on more and more secondaries are formed. These secondaries have transverse momentum $p_T \cong \Lambda_{TC}$. The sequential nature of their formation follows from Lorentz time dilation of the particle formation process. If the secondaries take a natural time of $t_o \cong \Lambda_{TC}^{-1}$ to form in their rest frame, this time becomes Lorentz time dilated by a factor of γ in the observer's frame. Since most of the secondaries have most of their momentum directed along the jet axis, the particles form at the position $x \cong \gamma v t_o$. The position and formation time are clearly correlated and $v = x/t$. This equation allows the identification of rapidity as

$$y = \frac{1}{2} \ln \{\frac{t+x}{t-x}\} = \frac{1}{2} \ln \{\frac{1+p/E}{1-p/E}\} \qquad (2)$$

Intrinsic to this picture of matter formation is that matter is initially formed while expanding. The length scale along the jet axix is ≅ t and is independent of any intrinsic momentum scales. This expansion is along the jet axis.

As the colored techni-singlet hadrons emerge transverse to the jet axis, a radially expanding matter distribution is formed. The typical transverse length scale is ≅ t, as was the case along the jet axis.

Combining these factors together gives a volume V which depends on time as t^3. This rate will be modified once the system begins to expand in thermodynamic equilibrium, and in general the expansion rate will increase, and a more thorough treatment would include this modification. The temperature dependence upon time is evaluated through the relationship $E/V \cong T^4 \cong \rho_o(t_o/t)^3$.

The rate of energy loss through transverse expansion is therefore

$$|dE/dt|_{expansion} \cong dT/dt \propto T/t. \qquad (3)$$

The condition that the system may begin to expand in thermal equilibrium

$$|dE/dt|_{expansion} < |dE/dt|_{scattering} \tag{4}$$

becomes

$$\alpha_s^6 \ln^3\alpha_s > T/\Lambda_{TC} \tag{5}$$

This relationship depends fairly sensitively upon undetermined numerical factors which appear in the scattering rate. This evaluation shows that $\alpha_s \sim .15 - .5$ might not be unexpected coupling values for which the system thermalizes. This range of couplings corresponds to temperatures of $T \cong .2 - 10$ GeV. A more reliable estimate must await more reliable estimates of energy loss mechanisms through scattering, and a more complete kinetic theory treatment.

The bottom line on the formation of a quark-gluon plasma in a techni jet is that such a plasma if formed has a temperature $T \ll \Lambda_{TC}$. The exact value of the temperature is quite difficult to reliably estimate, but may very well be much larger than is generated in ultra-relativistic nuclear collisions.

Finally, if a quark-gluon plasma does form, it probably does not affect the dN/dy distributions very much. This is so because the plasma should expand approximately isentropically, and the dN/dy distribution, which measures the local entropy density should be approximately invariant under expansion.

In conclusion, techni-quark production results in jets with secondary particles with very high momentum transverse to the jet axis, $p_T \cong \Lambda_{TC}$. The rapidity density along the jet axis should be a factor of $\ell n(\Lambda_{TC}/\Lambda_{QCD})$ larger than for jets generated by QCD. These jets should first become noticeable at energies $E \cong 10 - 100\ \Lambda_{TC}$, and may also produce matter in thermal equilibrium at temperatures much higher than obtainable through ordinary QCD interactions.

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Footnotes

[F 1] For a review of the present status of techicolor theories, see [1] and references therein.

[F 2] For a review of jet physics, see [2] and references therein.

[F 3] For a review of quark-gluon plasmas, see the many presentations in [4].

References

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