Quark resonances and high $E_T$ jets

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Abstract

Possible spin-3/2 quark resonances would have a significant effect on high $E_T$ jet production through their contribution to the subprocess $q + \bar{q} \rightarrow g + g$. Such enhancements are compared to a, recently reported, anomaly in inclusive jet production at the CDF detector.

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The possible existence of spin 1/2 quark resonances has been looked at, both theoretically [1] and experimentally [2]. In the latter two works excluded regions in the mass–coupling constant plane were obtained; these analyses were based on the absence of the direct production of such states. In this article we study the effect of a possible spin-3/2 quark resonance, $q^*$, on the production rate of high $E_t$ jets; the exchange of such a particle in the reaction $q + \bar{q} \rightarrow g + g$ will enhance high $E_t$ gluon jet production. This study is motivated by the recently observed excess of such jets in 1.8 GeV $p\bar{p}$ collisions [3].

The $q - q^* - g$ interaction Lagrangian with a minimum number of derivatives is

$$\mathcal{L} = \frac{g_s \kappa}{2M^*} (\bar{q}^*_\nu \gamma_{\lambda} - \bar{q}^*_\lambda \gamma_{\nu}) \frac{\lambda^\alpha}{2} q G^{\nu\lambda}_\alpha + \text{h.c.}.$$  \hspace{1cm} (1)

$q^*_\nu$ is the Rarita-Schwinger field for a spin-3/2 particle, $G^{\nu\lambda}_\alpha$ is the gluon field strength tensor, $M^*$ is the resonance mass, $g_s$ is the strong coupling constant and $\kappa$ parameterizes the strength of this interaction. The quark $q$ and the corresponding $q^*$ can represent either the $u$ or the $d$ quark. In subsequent discussion we shall take the masses of $u^*, d^*$ to be degenerate.

To order $\alpha_s$, the amplitude for $q + \bar{q} \rightarrow g + g$ is given by the usual QCD diagrams, Fig. 1, and by the exchange of a $q^*$, Fig. 2. For a spin-3/2 $q^*$ the amplitude due to latter will grow by one power of $\hat{s}$, the quark-antiquark center of mass energy squared, faster than the amplitude described by Fig. 1. Such growth cannot go on indefinitely as at high enough $\hat{s}$ an exchange of a spin-3/2 particle will violate unitarity. However, depending on the strengths of various couplings, this increase can persist to large values of $\hat{s}$ values, typically up to $\hat{s} \sim M^{*2}/(\alpha_s \kappa^2)$; this limit is well beyond the range of $\hat{s}$ needed at present.

The effect of such exchanges on $E_t$ distributions can be seen in Fig. 3, where we show the transverse energy distribution, at rapidity $y = 0$, for gluon jets from the parton reactions $u + \bar{u} \rightarrow g + g$ plus $d + \bar{d} \rightarrow g + g$. In all calculations presented here we used the MRSA’ [4] parton distribution functions ($\Lambda_{QCD} = 231$ MeV) with renormalization scale $\mu = E_t/2$. Values for $M^*$, the mass of the spin-3/2 resonance and for its coupling strength, $\kappa$ (cf. Eq. (1)), are the ones used below in comparing to the data of Ref. [3]. For $E_t < 200$ GeV the contribution the exchange of the spin-3/2 resonances is small; this exchange rapidly dominates the QCD
contributions for larger values of $E_t$.

In Fig. 4 we plot the sum of the square of the amplitude due to the exchange of a spin-3/2 particle (Fig. 2) and the interference of this and the QCD amplitude (Fig. 1) as a percentage of the corresponding next to leading order QCD calculation [3] of the single jet inclusive cross section and compare to the experimental results of Ref. [3]; the extra contributions is averaged over the pseudorapidity range $0.1 \leq \eta \leq 0.7$. We restricted the comparison to $\kappa \leq 1.0$. For $\kappa = 1.0$, $M^* = 400$ GeV is largest resonance mass that the data can accommodate; for smaller $M^*$ we restricted the comparison to $M^* \geq 100$ GeV and for the latter we obtain a good fit with $\kappa = 0.13$.

As mentioned earlier, restrictions on masses and couplings of spin-1/2 quark resonances exist [1,2]. As we are dealing with a spin-3/2 system these restrictions cannot be taken over directly; namely, restrictions on $f_s$ of Refs. [1,2] do not translate into restrictions on $\kappa$. These analyses also assume that analogous couplings of spin-1/2 $q^*$’s to photons and $W$’s are proportional to $f_s$. The only unambiguous carry over of the spin-1/2 analysis to the spin-3/2 case is for the process of quark-gluon fusion where we find [3] $\sigma(g + q \rightarrow q^*_s = 3/2) = 0.5 \sigma(g + q \rightarrow q^*_s = 1/2)$ and thus it is somewhat harder to produce the spin-3/2 state. Should we anyway make such a comparison, it is comforting that these are not far off; $M^* = 100$ GeV, $f_s = 0.13$ is in the allowed range, while for $f_s = 1.0$ the spin-1/2 analysis would limit $M^*$ to $M^* > 560$ GeV, again not far away from the value $M^* = 400$ GeV used in this work. A reanalysis of the data of Ref. [2] using spin-3/2 excited quarks is needed.

In this study we have shown that spin-3/2 quark resonances can account for the observed large high $E_t$ cross section.

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FIGURES

FIG. 1. QCD Feynman diagrams for the process $q + \bar{q} \rightarrow g + g$.

FIG. 2. Feynman diagrams for the exchange of a spin-3/2 quark resonance in the process $q + \bar{q} \rightarrow g + g$.

FIG. 3. Transverse energy distribution for $p + \bar{p} \rightarrow g + g$, at 1.8 TeV center of mass energy and rapidity $y = 0$, from the subprocess $q + \bar{q} \rightarrow g + g$, for several values of the spin-3/2 quark resonance mass $M^*$ and coupling strength $\kappa$ (cf. Eq. 1); the solid line is for $\kappa = 0$, the dashed one for $\kappa = 0.13$, $M^* = 100$ GeV and the dotted one for $\kappa = 1.0$, $M^* = 400$ GeV.

FIG. 4. The percent difference between the experimental inclusive jet transverse energy distribution (Ref. 3), the contributions due to the exchange of a spin-3/2 quark resonance and pure QCD predictions used in Ref. 3; solid curve is for $\kappa = 0.13$, $M^* = 100$ GeV and the dashed one for $\kappa = 1.0$, $M^* = 400$ GeV.
Figure 1
Figure 2
Figure 3

\[ \frac{d\sigma}{dE_t} \text{ (nb-GeV}^{-1}) \]

- \( \kappa = 0.13, M^* = 100 \text{ GeV} \)
- \( \kappa = 1.0, M^* = 400 \text{ GeV} \)

\( E_t \) (GeV)
Figure 4

M* = 100 GeV; κ = 0.13

M* = 400 GeV; κ = 1.0