Rapidity Gap of Weakly Coupled Leptoquark

Production in $ep$ Collider

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Abstract

We show that the current bounds on the leptoquark couplings imply that if leptoquarks are produced in $ep$ collisions, a significant fraction of them could form a leptoquark-quark bound state. The decay of the bound state has a distinct event shape with rapidity gap. A possible application of this observation in the leptoquark search at HERA is discussed.
There has been a considerable interest in the possible existence of leptoquarks. However, the couplings to quarks and leptons of leptoquarks which are accessible in the lepton-proton collider are severely bounded by various low energy physics. Generally the couplings from these bounds are very weak, of order electromagnetic interaction, or weaker [1, 2]. Because of this the lifetime of a light leptoquark is in the QCD hadronization time scale, and thus leptoquarks produced in $ep$ collisions could form a leptoquark-quark bound state before their decay. Because the leptoquark-quark bound state is a color singlet, its eventual decay should leave a distinct event shape which might be characterized by the presence of rapidity gap [3]. This rapidity gap could provide a unique tool in the search of leptoquarks in $ep$ collisions. To our knowledge, this idea has not been explored in the search of leptoquarks [4, 5].

To be specific, we consider a scalar leptoquark with non-zero fermion number, with coupling to the left-handed quarks and leptons only. Choosing this specific leptoquark is for the sake of simplicity only, and applying our discussion to other leptoquarks is straightforward. Then the most general effective lagrangian that preserves baryon and lepton number conservation and the standard model symmetry is given by [6]

$$\mathcal{L} = \lambda \Phi \bar{q}_L^c i\sigma_2 l_L + h.c.$$ (1)

where $q_L, l_L$ denote the left-handed quark and lepton doublets.

The coupling $\lambda$ is bounded by the quark-lepton universality [1]:

$$\lambda \leq \frac{m_{LQ}}{1.7\text{TeV}}$$ (2)

which corresponds to $\lambda \leq 0.1$ for the leptoquark mass $m_{LQ} = 200\text{GeV}$. This bound assumes
that leptoquarks are the only deviation to the standard model. Without the assumption the bound could be weakened.

The decay width of the leptoquark from the effective lagrangian in eq. (1) is

$$\Gamma_\Phi = \frac{\lambda^2}{8\pi} m_{LQ}. \quad (3)$$

For $\lambda = 0.1, m_{LQ} = 200$ GeV we have a very narrow width

$$\Gamma_\Phi \approx 80 \text{ MeV}. \quad (4)$$

Indeed this narrow decay width is a generic feature of leptoquarks accessible at collider [3]. Also note that the decay width is small even when compared to the leptoquark hadronization scale. In terms of QCD hadronization-time scale the leptoquark is quasi-stable. This observation is the central basis of the discussion in this letter.

Leptoquarks with very narrow decay width could be produced asymptotically in the s-channel in $ep$ collisions. The cross section for leptoquark production from the effective lagrangian in eq. (1) is

$$\sigma = \frac{\pi}{4s} \lambda^2 f_q \left( \frac{m_{LQ}^2}{s} \right) \quad (5)$$

where $f_q(x)$ is the quark distribution function in proton, and $\sqrt{s}$ is the c.m. energy.

The s-channel production of leptoquark combined with its long lifetime leads to rapidity gap in the final state. To see this, consider the lepton-proton collision in the c.m. frame. An s-channel production of a leptoquark would leave the leptoquark on the beam axis (See Fig.1). Since the leptoquark carries color, there would be a color electric string attached
Figure 1: Schematic of leptoquark production in the c.m. frame. The shaded blob denotes proton remnant, and the zigzag line denotes color electric string.

between the leptoquark and the outgoing proton remnant. This color string will eventually decay into hadrons. In the leptoquark rest frame, the hadronization of the color string would occur at the leptoquark end first, and then propagates toward the proton remnant. This picture is also true in the c.m. frame if we ignore the relativistic effect due to the small leptoquark velocity in the c.m. frame, which is

\[
\frac{v}{c} \approx 0.37
\]  

for \( m_{LQ} = 200 \text{GeV} \) at the HERA energy \( \sqrt{s} = 296 \text{GeV} \). Thus in the c.m. frame, the
leptoquark forms a leptoquark-quark bound state, denoted by $\Psi_{\Phi q}$, at the early stage of the color string hadronization, and decouples from the rest of the hadronization process. The bound state $\Psi_{\Phi q}$ will eventually decay into a lepton and a jet. The appearance of a jet in the decay of the bound state is easy to understand. At the decay of the bound state, an energetic lepton and a quark will be emitted from the center of the bound state in a back-to-back direction, and the primary quark from the center would drag the spectator valence quark along its motion, forming a jet.

The invariant mass of the jet can be easily estimated to be

$$M_{\text{jet}} = \sqrt{m_{LQ}(m_{\Psi_{\Phi q}} - m_{LQ})}. \quad (7)$$

The mass difference between the bound state and leptoquark is

$$m_{\Psi_{\Phi q}} - m_{LQ} \approx m_B - m_b \approx 1 \text{ GeV} \quad (8)$$

For $m_{LQ} = 200 \text{ GeV}$

$$M_{\text{jet}} \approx 14 \text{ GeV}. \quad (9)$$

Since $\Psi_{\Phi q}$ is color singlet, a rapidity gap should appear between the jet from the decay of the bound state and the proton remnant on the forward direction. One might worry about the contamination of the rapidity gap from the hadronization of the color string. However, the contamination from the hadronization of the color string should be minimal. This is because the s-channel production of leptoquark would confine the color string on the beam axis, and hence the hadrons from the string decay should move along the beam axis, leaving a clean gap between the jet and the proton remnant.
The cross section for $\Psi_{q\Phi}$ production can be estimated by counting the number of the leptoquarks that survive beyond the leptoquark hadronization-time $T_0$. Here we assume that all leptoquarks surviving beyond $T_0$ form bound states. For the leptoquark hadronization-time we assume that the average radius of the valence quark to the center of a heavy meson is a reasonable estimation of $T_0$. From the B-meson, we have [7]

$$T_0 \approx (400 \text{ MeV})^{-1}. \quad (10)$$

Using the decay width and cross section in eqs. (3), (5), we can readily derive a relation

$$\frac{N(\lambda)}{N(\lambda_0)} = \left( \frac{\lambda}{\lambda_0} \right)^2 e^{-\left( \frac{\lambda}{\lambda_0} \right)^2} \quad (11)$$

where $N(\lambda)$ is the number of leptoquarks surviving beyond $T_0$ at a given luminosity, and $\lambda_0$ is defined by

$$\Gamma(\lambda_0)T_0 = 1. \quad (12)$$

For $m_{LQ} = 200 \text{ GeV}$

$$\lambda_0 = 0.22 \quad (13)$$

and at HERA energy $\sqrt{s} = 296 \text{ GeV}$,

$$N(\lambda_0) = \frac{\pi}{4s} \lambda_0^2 f_q \left( \frac{m_{LQ}^2}{s} \right) e^{-1} = 2000 \cdot \frac{L}{100 \text{ pb}^{-1}}, \quad (14)$$

where $L$ is the luminosity.

A plot of the function in eq. (11) is shown in Fig. 2. With the HERA luminosities, an observable number of $\Psi_{q\Phi}$ can be produced with the coupling in the range

$$0.01 \leq \lambda \leq 0.6. \quad (15)$$
Figure 2: Relative number of leptoquarks that survive beyond the leptoquark hadronization time.

Thus the rapidity gap in the final state jet could be an effective tool in the search of leptoquarks over a wide range of couplings.

The main background for the leptoquark production is the $t$-channel lepton-proton deep inelastic scattering (DIS). However, jets from DIS are not expected to have large rapidity gap because the hadrons from the decay of the color string between the struck quark and proton remnant would fill the rapidity space between the jet and proton remnant [8, 9]. The
detailed effect on the events with rapidity gap from DIS should be reliably estimated using Monte Carlo simulation.

In conclusion, we have presented an intuitive picture of leptoquark hadronization that leads to event shape with rapidity gap. This rapidity gap in the final state jet could be exploited to enhance the signal to background ratio in the search of leptoquarks in HERA. The background from DIS for the signal with rapidity gap could be estimated with Monte Carlo simulation. We encourage a detailed Monte Carlo study incorporating the idea discussed here.

We are grateful to V. Barnes for useful discussion.
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