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Hunting a Light $U(1)_B$ Gauge Boson Coupled to Baryon Number in Collider Experiments

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We analyze several signals at HERA and the Tevatron of a light $U(1)_B$ gauge boson (γ_B) coupling to baryon number. We show that the study of the production of $b\bar{b}$ pairs at the (upgraded) Tevatron can exclude γ_B with masses (m_B) in the range $40 \lesssim m_B \lesssim 300$ GeV for γ_B couplings (α_B) greater than 2×10^{-2} (3×10^{-3}). We also show that the HERA experiments cannot improve the present bounds on γ_B. Moreover, we demonstrate that the production at HERA and the Tevatron of di-jet events with large rapidity gaps between the jets cannot be explained by the existence of a light γ_B.

I. INTRODUCTION

Global symmetries of the standard model (SM), like baryon and lepton numbers, can be broken by quantum gravity effects [1]. In order to avoid an unacceptably large proton decay rate induced by this symmetry breaking we can elevate the conservation of baryon number to a local symmetry [2]. Moreover, there are string models that also gauge baryon number to protect the proton from decaying through higher-dimensional operators. In particular, models with low string scale, $E_{\rm string} \sim \mathcal{O}$(TeV), generally exhibit baryon number as a local symmetry [3].

In this work, we analyze the signals of a light gauge boson coupling to baryon number at the HERA and Tevatron colliders. We assumed that the $U(1)_B$ symmetry is spontaneously broken, giving a mass (m_B) to γ_B, and that the mixing between γ_B and the electroweak gauge bosons is negligible [4]. In the absence of mixing, the γ_B boson always decays into quark pairs; its signature is thus the presence of 2 jets with an invariant mass close to m_B. A previous analysis [5] studied its effect on Z-pole physics and constrained its coupling to be $\alpha_B \lesssim 0.2$ for masses $m_B \leq m_Z$. Moreover, $\Upsilon(1S)$ decays are modified by the γ_B boson, leading to stronger constraints on α_B for $m_B \lesssim 30$ GeV [5].

In our analysis we concentrate on the decay $\gamma_B \to b\bar{b}$ in order to reduce the QCD backgrounds. Using a muon trigger, we show that the study of the production of $b\bar{b}$ pairs at the (upgraded) Tevatron can exclude γ_B bosons with masses (m_B) in the range $40 \lesssim m_B \lesssim 300$ GeV for couplings $\alpha_B \gtrsim 2 \times 10^{-2}$ (3×10^{-3}). A displaced vertex trigger could increase the sensitivity at the upcoming Main Injector (MI) run by another factor of three. We also use the available search by the CDF collaboration for particles decaying into $b\bar{b}$ pairs [6]. Since this search uses a jet trigger which needs to be pre-scaled if the jet energies are not very large, the resulting limit turns out to be weaker than the sensitivity limit of current data based on a muon trigger. We also analyze γ_B production at HERA, however, the potential bounds derived from this study are weaker than the Z-pole or Tevatron ones due to the limited integrated luminosity.

In principle, γ_B boson exchange in the t-channel can give rise to events presenting a large rapidity gap between two jets [5]. Recently DØ studied the gap fraction as a function of E_T [7]. Our fit to this data in terms of γ_B exchange gives γ_B masses very close to zero and $\alpha_B \simeq 0.06$. However, this region is already excluded by the analysis of $\Upsilon(1S)$ decays [5]. Moreover, the HERA data on rapidity gaps can only be explained for $m_B \simeq 0$ and very large α_B. Therefore, the present data on the production of rapidity gaps cannot be explained by the existence of a γ_B boson.

In our analyses we assumed that the interaction between quarks and γ_B is described by the effective Lagrangian

$$\mathcal{L}_{\rm eff} = \frac{1}{3}\sqrt{4\pi\alpha_B}\ \bar{q}\gamma^\mu q\ B_\mu \ ,$$

where we denote the quark fields by q and the γ_B field by B_μ. Neglecting the fermions masses, the γ_B width is given by

$$\Gamma_B = \frac{N}{9}\ \alpha_B\ m_B \ ,$$

where N is the number of quark pairs to which γ_B can decay.

II. DIRECT SEARCHES AT TEVATRON AND HERA

In hadronic collisions γ_B bosons can be produced in the s-channel via quark–antiquark annihilation, leading to two-jet events. In order to reduce the large QCD backgrounds we focused on γ_B decays into $b\bar{b}$ pairs ($p\bar{p} \to q\bar{q} \to \gamma_B \to b\bar{b}$). The main backgrounds to this process are QCD $b\bar{b}$ production, mistagged QCD jets, and Z production for m_B close to M_Z. Since the two-jet event rate is too large for the present data acquisition system to be able to analyze all events, we need to choose a trigger to select a subset of the data. In our analyses of the Run I potential for γ_B searches, we considered only events containing a muon (from b decay) with $p_T^\mu > 7.5$ GeV and $|\eta_\mu| < 0.9$ (2 for the upgraded Tevatron) [8]. There is one useful byproduct of this requirement: together with the requirement that both b's be vertex tagged, the presence of this muon reduces the mistag background to a negligible level. Moreover, we also demanded that

- the jets should have $p_T > 15$ GeV;
- the jets should be separated by $\Delta R > 0.4$.

With these requirements the b tag efficiency is 0.24. In our analyses we evaluated the scattering amplitudes of the signal and backgrounds using the package Madgraph [9], taking into account the interference between γ_B and gluon/Z exchange diagrams.

We considered that a point of the (α_B, m_B) plane is within the reach of an experimental search, if the predicted signal has a 3σ significance when we restrict ourselves to $b\bar{b}$ invariant masses in the range $m_B - 10$ GeV $< m_{b\bar{b}} < m_B + 10$ GeV. We chose this rather high confidence level for an exclusion limit since our analysis does not allow for experimental resolutions or efficiencies (other than the $b-$tagging efficiency). We note, however, that CDF recently found [8] preliminary evidence for $Z \to b\bar{b}$ decays in their Run I data sample using cuts very similar to the ones applied by us. We show in Fig. 1a the region in the (α_B, m_B) plane which could be excluded by the CDF Run I data, *i.e.* for an integrated luminosity of 110 pb^{-1} and a b-tagging efficiency of 24%, if no signal is found. In this figure we also display the effect of having a larger integrated luminosity (2 fb^{-1}) and an extended rapidity acceptance for the muons ($|\eta_\mu| < 2$) at the MI. Notice that our p_T and ΔR cuts constrain the invariant mass of the $b\bar{b}$ pair in two-jet events to be larger than 30 GeV.

In order to explore smaller γ_B masses we considered its production in association with a jet. The processes that we analyzed are

$$p\bar{p} \to \gamma_B g \to b\bar{b}g \; ,$$
$$p\bar{p} \to \gamma_B q \to b\bar{b}q \; ,$$

where q can be any quark or antiquark. We present in Fig. 1b the potential limits on α_B and m_B originating from the study of b-$\bar{b}$-jet production for Run I and at the MI. In this analysis we applied the same cuts for the $b\bar{b}$ system and required the extra jet to have $p_T > 10$ GeV and to be separated from the b jets by $\Delta R > 0.4$.

It is also possible to search for γ_B using the Run I data but triggering on jets with a minimum E_T [6]. This choice of trigger requires pre-scaling, which leads to small effective integrated luminosities at low values of E_T. Using the CDF excluded production cross sections for particles decaying into $b\bar{b}$ pairs we obtained the limits on γ_B shown in Fig. 2. We emphasize that the bounds shown in this figure are directly based on an experimental analysis, including all resolution and efficiency effects. As we can see, for m_B up to a few hundred GeV the limits on γ_B from this search are weaker than the ones that should be obtainable using the muon trigger, if no signal is found.

The Tevatron experimental collaborations are studying the possibility of triggering events exhibiting displaced vertices for the upcoming Main Injector run. We access the impact of this trigger on the searches for γ_B eliminating the cuts on the muon coming from b decays and introducing the QCD mistag background with a rate of 1% per jet. All other cuts are unchanged. Fig. 3 contains the region of the (α_B, m_B) plane that can be probed at the MI with this new trigger. As we can see from this figure, this trigger can increase the sensitivity of the Tevatron for γ_B searches.

At HERA, γ_B bosons can be produced via the hadronic content of the photon:

$$\gamma p \to q\bar{q} \to \gamma_B \to q'\bar{q}' \; .$$

However, the two-jet signature of γ_B is immersed in a large background from resolved photons. It turns out that the signal can not be observed even for the largest couplings allowed by the Z physics ($\alpha_B \simeq 0.2$) for the presently available luminosities. In order to observe a γ_B signal for this large couplings one would need an integrated luminosity of at least 250–500 pb^{-1} depending on m_B. Therefore, the bounds on γ_B from HERA are much weaker than the Z pole or Tevatron ones.

III. RAPIDITY GAP ANALYSIS

Experiments at HERA and the Tevatron have observed events containing two jets with no hadronic activity between them. These occur with a frequency of order of one percent in hadron–hadron collisions [10]. This is just one example of an interaction mediated by the exchange of the "Pomeron", a state which carries no net color. Since γ_B is a color singlet, it can also give rise to rapidity gap events [5]. In this case the fraction of events presenting rapidity gaps as well as their kinematical distributions are determined by α_B and m_B, which allows us to constrain these parameters. Here we extract the bounds on γ_B from the study of rapidity gaps assuming that these are only due to γ_B exchange in the $t-$channel.

The DØ Collaboration has recently measured the production cross section of hard jets separated by a rapidity gap as a function of transverse momentum and gap size [7]. This data indicates that a large fraction of the gap events originates from quark–quark collisions [11], a feature that is present in the γ_B exchange. In order to obtain bounds on γ_B from this data, we evaluated

$$F_{\rm gap}(E_T) = \frac{d\sigma_B/dE_T}{d\sigma_{\rm total}/dE_T} ,$$

where σ_B and $\sigma_{\rm total}$ are the γ_B contribution and the total cross section for the production of jet pairs, respectively.

In our analysis, we fixed the value of m_B and determined α_B in order to fit the experimental E_T spectrum, using the cuts and E_T bins defined in Ref. [7]. We exhibit in Fig. 4 the region in the (α_B, m_B) plane obtained from the fits to the data. Although the χ^2 distribution as a function of α_B has a well-defined minimum for all values of m_B, the quality of the fit is good only at small m_B. This can be seen from Fig. 5, which shows the general trend of the predicted E_T distribution as m_B increases. Therefore, γ_B exchange cannot be the sole source of rapidity gap events at the Tevatron since the low mass allowed region in Fig. 4 has already been ruled out by the direct γ_B search in Υ decays [5]. Furthermore, for larger γ_B masses the fitted values of α_B fall well within the region that can be probed by the the direct search for γ_B using Run I data, see Fig. 1. It is interesting to notice that introducing a gap survival probability [12] $P_s < 1$ only worsens the problem since this will require larger values of α_B to fit the data, $\alpha_B \propto 1/\sqrt{P_s}$.

Hard jets separated by a rapidity gap have also been observed in photoproduction events at the *ep* collider HERA [13]. The ZEUS Collaboration measured that approximately 10% of the two-jet events with $p_T > 6$ GeV and $\Delta\eta > 3$ present a rapidity gap [13]. Assuming that these events stem from γ_B exchange in the t–channel we can constrain the mass and coupling of γ_B. We present in Table I the values of α_B that lead to the observed gap fraction of 0.1 at large rapidity separation, where we imposed the cuts of Ref. [13]. Here it is also clear that these events cannot be explained solely as being due to γ_B exchange.

IV. CONCLUSIONS

In this work we demonstrated that the presently available Tevatron data can be used to rule out the existence of bosons coupling to baryon number for masses in the range 40–300 GeV and $\alpha_B \gtrsim 0.02$, if no signal is found. In the near future, the Tevatron experiments should increase this sensitivity to $\alpha_B \gtrsim 0.003$ at the Main Injector. These bounds would preclude γ_B boson exchange as a significant source of events with rapidity gaps between hard jets.

V. ACKNOWLEDGMENTS

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m_B (GeV)	α_B
10.	1.05
20.	2.84
30.	4.59

TABLE I. Values of α_B needed to explain the formation of rapidity gaps in photoproduction events at HERA for several γ_B masses.

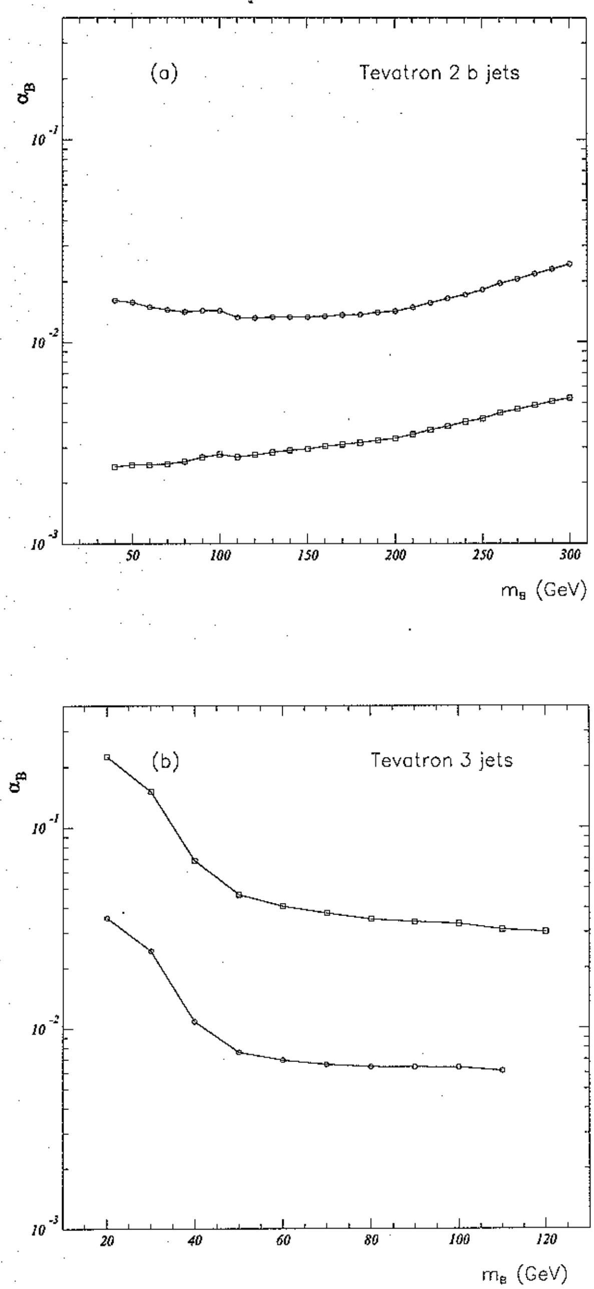

FIG. 1. The region that can be excluded at the 3σ level using the Run I or Main Injector data is given above the upper and lower lines respectively. In (a) we considered $b\bar{b}$ final states while in (b) we studied $b\bar{b}$+jet events.

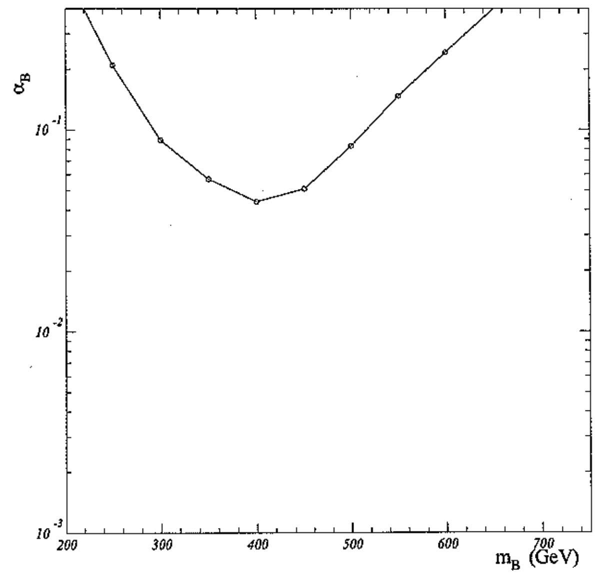

FIG. 2. The region that can be excluded at 95% CL from the CDF search [6] using a jet trigger at Run I.

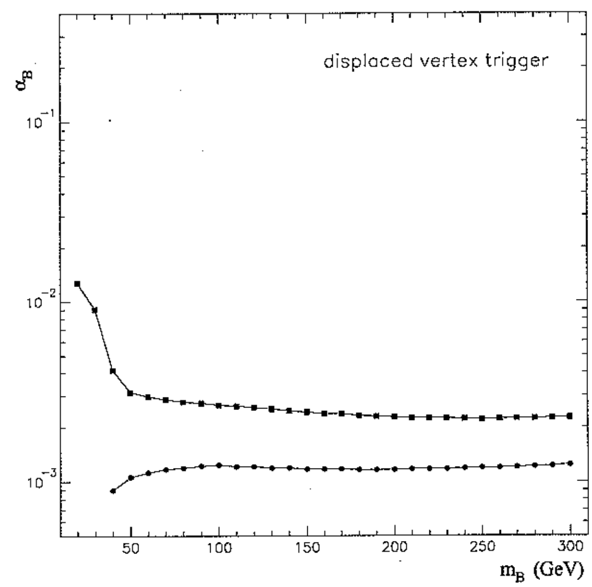

FIG. 3. The region that can be excluded at the 3σ level at the MI using a displaced vertex trigger. The upper (lower) line is due to the b-$\bar{b}$-jet ($b\bar{b}$) production.

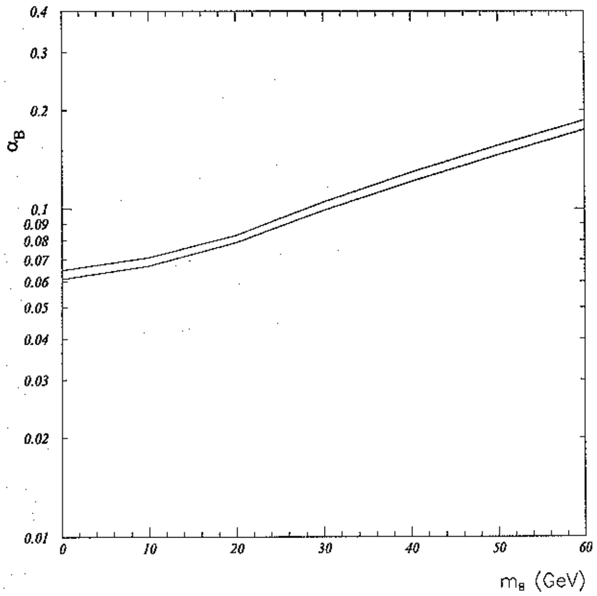

FIG. 4. The region between the solid lines is the 1σ allowed area obtained from our fitting procedure to the DØ data. We used the cuts and bins defined in Ref. [7].

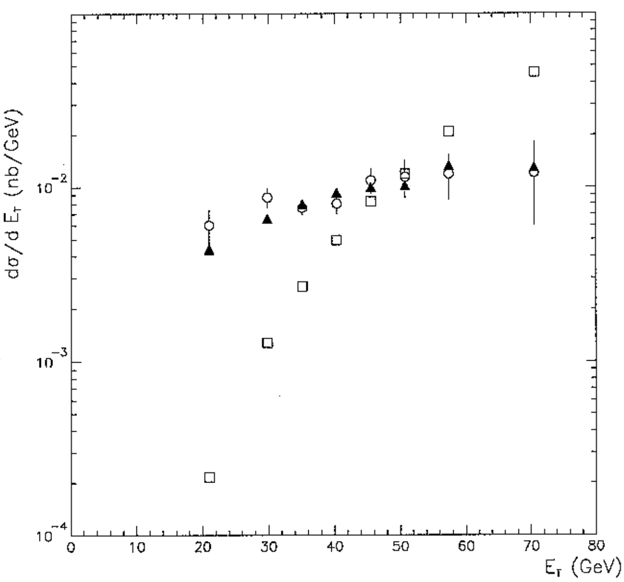

FIG. 5. Comparison of the experimental E_T spectrum of the rapidity gap fraction (open circles) with the γ_B predictions for $m_b = 0$ and 70 GeV (solid triangle and open squares, respectively) .