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A SEARCH FOR SCALAR LEPTOQUARKS AT THE CERN $\bar{p}p$ COLLIDER

The UA2 Collaboration

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Abstract

A search has been made for scalar leptoquark pair production with the upgraded UA2 detector at the CERN $\bar{p}p$ Collider at $\sqrt{s} = 630 \text{ GeV}$, investigating decays of the leptoquark into a quark and either an electron or an electron neutrino. From an event sample corresponding to an integrated luminosity of 13 pb^{-1} a lower limit has been determined for the mass of first generation leptoquarks, yielding 67 GeV (95% CL) for a scalar leptoquark decaying with a 50% branching ratio into a quark and an electron.

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1 Introduction

The symmetry between lepton and quark generations in the Standard Model (SM) naturally inspires the hypothesis about the existence of *leptoquarks* (S), particles carrying both lepton and quark quantum numbers. A framework however is given only by theories extending beyond the SM [1], like the Strong-Coupling version of the SM, Superstring Models or Grand Unified Theories. In several of these models [2] leptoquarks can have masses m_S lower than 100 GeV, and could be accessible at the CERN $\bar{p}p$ Collider.

The leptoquark quantum numbers are model-dependent. The present search considers only scalar leptoquarks. It is assumed that each generation has its own leptoquark. Couplings occur only within a given generation in order to satisfy the experimental constraints on Flavour Changing Neutral Currents [3]. The first family of leptoquarks is therefore expected to manifest itself with decays containing a light quark (u, d) and an electron (or positron) with a branching ratio b , or a light quark and an electron neutrino with a branching ratio $(1 - b)$.

In $\bar{p}p$ collisions, one expects single leptoquark production associated with a lepton (ℓ), via $qg \rightarrow S\ell$, as well as pair production through gg fusion and $\bar{q}q$ annihilation (q stands for quark and g for gluon). Single production is proportional to the model-dependent $q\ell S$ coupling, while in pair production only the contribution from the t-channel $\bar{q}q$ annihilation is affected by this dependence. Pair production is expected to dominate over single production at the CERN $\bar{p}p$ Collider [4]. Furthermore, the t-channel contribution in pair production is small and can be neglected, so that in practice no model dependence is left in the graphs contributing to the cross section, and therefore no assumptions need to be made about the $q\ell S$ coupling, nor the leptoquark charge.

Pair production of leptoquarks could be observed in three channels, namely 2 charged leptons + 2 jets, 1 charged lepton + 2 jets + ν and 2 jets + $\nu\bar{\nu}$ where the neutrino(s) would give rise to missing transverse momentum $\cancel{p}_T$ which can be experimentally observed. In the present Letter a search is reported for first generation leptoquarks at the CERN $\bar{p}p$ Collider at $\sqrt{s} = 630$ GeV, based on the data collected within the full 1988 to 1990 UA2 running periods, corresponding to an integrated luminosity of 13 pb^{-1} . In Section 2, the UA2 detector components relevant for this search are described. The event selection is given in Section 3 for the two charged leptons + two jets channel (Sect. 3.1) and for one charged lepton + two jets + $\cancel{p}_T$ (Sect. 3.2) topologies. Section 4 describes the Monte Carlo acceptance calculation for leptoquark pairs and the systematic error sources which can affect the measurement, while the final results are given in Section 5.

2 The UA2 detector

The detector features relevant for the detection of electrons, jets and $\cancel{p}_T$ can be found in Refs. [5] and [6], and only the major points are repeated here.

The Pb- and Fe-scintillator sampling calorimeter had full azimuthal coverage and extended to pseudorapidities of $-3 < \eta < 3$. The calorimeter was composed by a central part (CC) within $|\eta| < 1$ and two end cap regions (EC) over $0.9 < |\eta| < 3$. Granularity was provided in the CC by a lateral segmentation constant in azimuth and in polar

angle ($\Delta\phi = 15^\circ, \Delta\theta = 10^\circ$). In the end caps, the two cells closest to the beam axis ($2.5 < |\eta| < 3.0$ and $2.2 < |\eta| < 2.5$) covered 30° in azimuth, and the other cells had a constant segmentation of $\Delta\phi = 15^\circ, \Delta\eta = 0.2$. In the CC, each cell was divided into an electromagnetic (EM) section and two hadronic sections adding up to a total thickness of 4.5 absorption lengths (λ). The EC cells with $1.0 < |\eta| < 2.5$ had one EM and one hadronic section with 6.5λ or more, depending on θ . There was no EM section for the higher η regions nor for additional cells ($0.9 < |\eta| < 1.0$) overlapping with the CC edge cells used to measure particles which could otherwise escape from the interface between CC and EC. Details about the calorimeter calibration and resolution can be found in Ref. [6]. An uncertainty of $\pm 1\%$ affects the electromagnetic energy scale. The corresponding value for the hadronic energy scale is $\pm 2\%$.

The central detector consisted of the following elements. Two arrays of Silicon counters at radii of 3.5 cm and 14.5 cm were used for tracking and ionization measurements [7]. A cylindrical drift chamber with jet geometry (the jet vertex detector) [8] was located between the two arrays. Outside the inner tracking detectors was a transition radiation detector [9] consisting of two sets of radiators and proportional chambers, followed by a scintillating fibre detector [10] consisting of 60000 fibres arranged on cylinders in 8 stereo triplet layers. The scintillating fibre detector included a preshower detector used to localize the early development of electromagnetic showers.

In the end cap region, the end cap proportional tubes [11] provided tracking and preshower information.

Two arrays of 20 scintillator time of flight counters for the selection of inelastic $\bar{p}p$ interactions were positioned just inside the EC calorimeters at 1.2 m from the interaction point. They had full azimuthal coverage and extended in pseudorapidity over $2.3 < |\eta| < 4$.

3 Data analysis and reduction

3.1 The two-charged leptons + jets channel

In this channel two electrons are expected in the final state, and therefore the search has been based on data samples also used to study $Z \rightarrow e^+e^-$ decays. The search for $S\bar{S}$ -pairs in this channel was based for the 1988/89 running periods on the inclusive electron trigger which was obtained by requiring an electromagnetic cluster within $|\eta| < 2$ with a transverse energy exceeding 12 GeV and with a longitudinal and lateral shower profile compatible with those of an electromagnetic shower. For the 1990 running period, at least two electromagnetic clusters with $E_T > 7.5 \text{ GeV}$ were required in the calorimeter within $|\eta| < 2$, separated by more than 60° in azimuth and with an invariant mass above 10 GeV .

In the offline event selection, electron candidates [12] were required to have a track pointing to an electromagnetic cluster in the calorimeter, originating from a vertex within 250 mm from the detector centre along the beam direction. The lateral and longitudinal shower profiles in the calorimeter had to be consistent with those of a single electron, as determined from test beam data. Furthermore, there had to be a preshower cluster associated with the track, with a charge as expected for an electron. The electron energy

was corrected for the impact point dependence of the calorimeter response and the energy lost in the preshower detector, according to test beam measurements. After this selection 678 events were left.

A further event selection aimed at searching for a $S\bar{S}$ -pair signal in a kinematical region free of the background expected from $Z + \text{jets}$ and Drell-Yan production, and from misidentified electrons from QCD jet production.

- ▷ The highest- E_T electron was required to have $E_T > 18 \text{ GeV}$, to suppress most of the low- E_T Drell-Yan and QCD backgrounds.
- ▷ A minimal requirement of 9 GeV was applied to the E_T of the second electron.
- ▷ At least two jets with $E_T > 10 \text{ GeV}$ were required, the jets being reconstructed within a cone radius of 0.7 in the $\eta - \phi$ space.

After these requirements, the data sample contained 9 events, all falling into an electron-electron mass region between 80 and 100 GeV , compatible with $Z + 2 \text{ jet}$ production. Thus by excluding this mass region from the search, no event was left in the data sample.

3.2 The charged lepton + jets + $\cancel{p}_T$ channel

The decay of one of the pair-produced leptoquarks into an electron and a quark and of the other into a neutrino and a quark leads to a final state containing an electron, $\cancel{p}_T$ and two jets. In the 1988/89 running periods, the same trigger was used as in the previously described search. In the 1990 running period, the data sample was obtained with a higher electron E_T threshold of 16 GeV . In addition, the transverse momentum imbalance of the event, $\cancel{p}_T$, was calculated at the trigger level and required to be greater than 15 GeV .

In the offline event selection, the same electron identification criteria were applied as described in Sec. 3.1, yielding 4619 events. The further analysis optimized the acceptance for leptoquark pairs while minimizing the presence of background, which mainly arises from the associated production of W bosons and jets. Jets were reconstructed according to the algorithm described in Ref. [13]. While $W + \text{jet}$ events have a jet transverse energy distribution following a bremsstrahlung spectrum, peaked at low energies, in leptoquark pair production two jets with large transverse energies are expected, resulting from the decay of high mass particles. Furthermore, one can consider the transverse mass $M_T^{e\nu}$ of the electron-neutrino system, defined as $M_T^{e\nu} = \sqrt{2P_T^e P_T^\nu (1 - \cos \Delta\phi)}$, where $\Delta\phi$ is the azimuthal separation between the electron (P_T^e) and neutrino (P_T^ν) transverse momenta. While in W production the $M_T^{e\nu}$ spectrum is peaked around 80 GeV , in leptoquark production the spectrum is broader, with a maximum at about half this value or lower for the S -mass range covered by this search.

The following selection criteria were applied:

- ▷ A minimal requirement of 15 GeV (20 GeV) on the E_T of the electron candidates in the 1988/89 (1990) data samples.
- ▷ A missing transverse momentum larger than 20 GeV .

- ▷ At least two jets with a transverse energy greater than 20 GeV in the pseudorapidity range $|\eta| < 2$.
- ▷ A transverse mass $M_T^{e\nu}$ of the electron-neutrino system greater than 25 GeV , to suppress background events resulting from QCD two-jet production.

After this selection, 6 events were left in the data sample. They all had $M_T^{e\nu}$ in the range between 60 and 90 GeV , compatible with QCD calculations of $W + 2$ -jet production, which predict, within large theoretical uncertainties, 5 events in the 60 to 90 GeV mass range and 0.8 events outside this interval [14]. After events with $60\text{ GeV} < M_T^{e\nu} < 90\text{ GeV}$ were rejected, no event was left in the data sample.

4 Calculation of expected rates

The expected detector response and the acceptance for leptoquark production were investigated with detailed Monte Carlo simulations. For these studies, large samples of $\bar{p}p \rightarrow S\bar{S}$ events were generated for various leptoquark masses between 30 and 80 GeV . Leptoquark pair production and decays according to the formulae of Ref. [3] were implemented into the generator of Ref. [15]. As a default the structure function parametrization of Ref. [16] was adopted, with a first order running α_S calculation using $\Lambda = 200\text{ MeV}$ and a momentum transfer scale chosen as $Q^2 = m^2 + P_T^2$. In order to set a safe limit, corrections for higher order terms, which would increase the cross section [17], were ignored. Typically, cross section values for $S\bar{S}$ pair production of 6.9 (2.4) pb were obtained for a leptoquark mass of 60 (70) GeV . The uncertainty on these values due to the choice of the structure function parametrization, which amounts to $\pm 10.4\%$, was taken as a contribution to the overall systematic error. The final state quarks were hadronized following the scheme of Ref. [18] and for all final state particles a detailed UA2 calorimeter response simulation was applied as obtained from extensive test beam measurements. In the Monte Carlo simulation, the response of the tracking, vertex reconstruction and preshower detectors were not simulated; their effect was instead taken into account by efficiency factors [12]. Additional effects due to the presence of jets in the events could degrade the efficiency of the requirements on the electron shower profiles and on the matching between track and preshower detector signal. These effects were studied and taken into account in the present analysis.

For each channel of the leptoquark search, the calculated acceptance was folded with the appropriate efficiencies. The results are shown in Fig. 1 as a function of m_S . In the determination of the lower limits for leptoquark masses, systematic uncertainties had to be taken into account. For this purpose, all the sources of possible errors were studied. The resulting uncertainties were added in quadrature, and the overall detection efficiency was reduced by the full error (pessimistic assumption). The expected rates were then calculated using these resulting “reduced” efficiency values.

Systematic uncertainties were estimated assuming a leptoquark mass of 60 GeV , applied to the two-charged-leptons channel, unless specified otherwise. Only the contributions which lower the acceptance (and therefore the leptoquark mass limit) are discussed here and are given below *relative* to the values shown in Fig. 1.

The uncertainty on the absolute calorimeter calibration results in a 1% (2%) error on the energy scale for the electromagnetic (hadronic) calorimeter. The cell energies were rescaled accordingly in the Monte Carlo simulation. The resulting acceptance drop amounts to 1.6%.

The uncertainty on the calorimeter response to low energy particles was taken into account by reprocessing the Monte Carlo events using a calorimeter response function modified so as to include extreme variations still compatible with test beam measurements. Its contribution to the overall uncertainty on the detector acceptance is negligible.

The contribution of the underlying event structure possibly affects directly the electron signal, since it can spoil the electron identification, and can distort the measured jet energy. At the generator level an important part of the underlying event is produced by the initial and final state parton shower mechanisms. In an alternative approach, the underlying event was simulated by ignoring the initial and final state parton showering and instead superposing two minimum bias events. In this way an uncertainty of 13% was estimated for the detector acceptance.

Varying the fragmentation scheme allows an estimate of the uncertainty related to its choice. The fragmentation scheme of Ref. [18] was replaced with the one of Ref. [19] using parameters compatible with existing jet fragmentation data from e^+e^- and $\bar{p}p$ collider experiments. The standard fragmentation scheme yields the lowest acceptance values. Nevertheless, half the acceptance excursion was adopted as an estimate of the systematic uncertainty, which amounts to 9%.

The uncertainty introduced from the measurement of the integrated luminosity is 5.6%, as described in Ref. [12].

Statistical and systematic uncertainties affect the calculation of the different electron detection efficiencies as given in Ref. [12]. All the contributions were added in quadrature. For the charged-lepton + jets + $\cancel{p}_T$ channel, a total uncertainty of 4.2% is obtained, while for the two-charged-leptons + jets case it amounts to 7.7%.

All the above uncertainties combined give relative errors on the acceptance of 21.7% in the one-electron channel and of 20.3% in the two-electron channel.

5 Results and conclusions

No candidate events likely to have resulted from leptoquark pair production were observed in either of the two decay channels considered in this analysis. The maximum cross section σ^{MAX} compatible with this search allows the setting of a limit on the leptoquark mass, since

$$N_{CL} = [\varepsilon_{ee} b^2 + 2\varepsilon_{e\nu} b(1-b)] \mathcal{L} \sigma^{MAX} \quad (1)$$

where N_{CL} is the number of events corresponding to the chosen confidence level, b the branching ratio for the decay mode with a charged lepton, ε_{ij} the efficiency for the channel ij , (i and j stand for either e or ν), and $\mathcal{L}$ is the total integrated luminosity.

Figure 2 shows the lower limit on m_S at 95% CL as a function of b for the individual channels. The shaded area corresponds to the excluded region in the (b, m_S) plane. If one assumes a 50% branching ratio b , lower limits at 95% CL on the mass of first generation

leptoquarks are determined to be 58 GeV from the electron-neutrino channel, 60 GeV from the electron-electron channel and 67 GeV from the two channels combined. For branching ratios $b > 0.12$ this analysis improves the limits from LEP experiments [20], reaching a limit of 74 GeV at a branching ratio b of 100%.

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FIGURE CAPTIONS

Figure 1: Total acceptance for the two electrons + 2 jets channel and for the electron + $\cancel{p}_T$ + 2 jets channel, as a function of M_S , the mass of the scalar leptoquark.

Figure 2: Leptoquark mass limit at 95% CL as a function of the branching ratio b ($S \rightarrow eq$) for the two-electron channel (ee), the electron-neutrino channel ($e\nu$), and for both channels combined. Also indicated is the limit obtained by the LEP experiments [20]. The shaded area represents the combined excluded mass region from UA2 and LEP experiments.

FIG. 1

FIG. 2