We report on the preliminary results from the search for second-generation leptoquarks (LQ$_2$) in $pp$ collisions at a center-of-mass energy of $\sqrt{s} = 1.96$ TeV using an integrated luminosity of $(294 \pm 19)$ pb$^{-1}$ Since no evidence for leptoquark signal in the $\mu j + \mu j$ channel has been observed, upper bounds to the product of cross section times branching fraction $\beta = \text{Bf}(LQ_2 \rightarrow \mu j)$ into a quark and a muon were calculated for scalar second-generation leptoquarks. This yields a lower mass limit of $m_{LQ_2} > 247$ GeV for $\beta = 1$ and $m_{LQ_2} > 182$ GeV for $\beta = 1/2$. Combining these limits with previous results from DØ Run I, the lower limits on the mass of scalar second-generation leptoquarks are $m_{LQ_2} > 251$ GeV and $m_{LQ_2} > 204$ GeV for $\beta = 1$ and $\beta = 1/2$, respectively.
The observed symmetry in the spectrum of elementary particles between leptons and quarks motivates the existence of leptoquarks [1]. Leptoquarks are bosons carrying both quark and lepton quantum numbers and fractional electric charge. Leptoquarks could in principle decay into any combination of a lepton and a quark. Experimental limits on lepton number violations, on flavor-changing neutral currents and on proton decay, however, lead to the assumption that there would be three different generations of leptoquarks. Each of these leptoquark generations couples to one quark and one lepton generation only and, therefore, individually conserves the family lepton numbers. [2]

While the cross section for the single leptoquark production also depends on the a-priori unknown leptoquark-lepton-quark coupling, the production of pairs of scalar leptoquarks only depend on the leptoquark mass.

This analysis focuses on the search for pair-produced second generation leptoquarks (LQ2). Assuming 100\% branching fraction to a charged lepton and a quark, \( \beta = BF(\text{LQ}_2 \rightarrow \mu j) = 1 \), a pair of second-generation leptoquarks, LQ2LQ2, decays into two highly energetic muons and two highly energetic jets with no or little missing transverse energy.

The DØ detector consists of several layered elements. First, is a magnetic central-tracking system, which is comprised of a silicon microstrip tracker (SMT) and a central fiber tracker (CFT), both located within a 2 T superconducting solenoidal magnet [3]. The muon momenta are measured from the curvature of the muon tracks in the central-tracking system. Jets are reconstructed from energy depositions in the three liquid-argon/uranium calorimeters: a central section (CC) covering \( |\eta| \) up to \( \approx 1 \), and two end calorimeters (EC) extending coverage to \( |\eta| \approx 4 \), all housed in separate cryostats [4]. Scintillators between the CC and EC cryostats provide sampling of developing showers at \( 1.1 < |\eta| < 1.4 \). A muon system resides beyond the calorimetry, and consists of a layer of proportional-wire tracking detectors and scintillation trigger counters before 1.8 T toroids, followed by two more similar layers after the toroids. The muon system is used for triggering and identifying muons.

The data used in this analysis were collected between August 2002 and July 2003. The integrated luminosity is \((294 \pm 19)\text{pb}^{-1}\). Only events which pass a combination of single- or di-muon triggers were considered. At the first trigger level, a muon was triggered by a coincidence of hits in at least two of the three scintillator layers of the muon system within a time window consistent with muons coming from the interaction point. At the second trigger level, a muon track was identified from the hits in the drift-tube detectors and the scintillators of the muon system, allowing the rejection of low-momentum muons. Events passing the single- or di-muon triggers at first level were then required to have a second muon in the events or a track in the central-tracking system above a \( p_T \) threshold needed to be identified at level 2 or 3 of the DØ trigger system. The efficiency of the trigger combination for \( \mu j + \mu j \) events was measured with data.

Muons in the region \( |\eta| < 1.9 \) were reconstructed from hits in the three layers of the muon system which could be identified with isolated tracks in the central-tracking system. Cosmic muon events were rejected by cuts on the timing in the muon scintillators and by removing back-to-back muons. Jets are reconstructed using the iterative, midpoint cone algorithm [5] with a cone size of 0.5. The jet energies were calibrated as a function of the jet transverse energy and \( \eta \) by balancing energy in photon plus jet events. Only jets which were well contained within the detector were considered by requiring \( |\eta| < 2.4 \).

Due to the isolation requirement and the excellent shielding of the muon detectors, the background is dominated by Z-Boson/Drell-Yan (Z/DY) \( \gamma \rightarrow \mu \mu \) events. To estimate the uncertainty of the jet transverse energy shape. Additional samples of Monte Carlo (MC) events were generated with \( \text{pythia} [6] \) and \( \text{alpgen} [7] \) samples were generated to estimate the uncertainty of the jet transverse energy shape. Additional samples of \( \text{pythia} t\bar{t} \) events \((m_t = 175\text{GeV})\) and \( \text{pythia} WW \) samples were used to estimate the background contributions from top quark and W pair processes, respectively. The signal efficiencies were calculated using \( \text{pythia} \) samples of \( \text{LQ}_2\text{LQ}_2 \rightarrow \mu j \mu j \) Monte Carlo events for leptoquark masses from 140 to 300 GeV in steps of 20 GeV. All Monte Carlo events were processed using a full simulation of the DØ detector based on \( \text{geant} [8] \) and the event reconstruction. Differences in the trigger and reconstruction efficiencies between data and Monte Carlo were taken into account using proper weightings of the MC events.

This analysis required two muons with transverse momentum exceeding \( p_T = 15\text{GeV} \) and two jets with transverse energy (\( E_T \)) greater than 25 GeV. In order to reduce Z/DY background at high di-muon masses due to badly reconstructed muon tracks, the muon momentum was corrected taking advantage of the fact that no or little missing transverse energy is expected in both signal and Z/DY events. The missing transverse energy was approximated from the energy balance of all muons and jets \((E_T > 20\text{GeV})\) in the event and the momentum of the muon opposite to the direction of the missing transverse energy in the \( r-\phi \) plane was corrected such that the missing transverse energy parallel to the muon vanished. The resulting degraded resolution and the shift to lower values of the di-muon mass in both data and MC due to this correction was outweighed by the suppression of badly reconstructed Z events in the high mass region where the search for leptoquarks took place. To further reduce the background from Z/DY events a \( Z\)-veto cut \((m(\mu\mu) > 105\text{GeV})\) is applied. Six events survive this last cut while \( 6.7 \pm 0.7\text{(stat.)} \pm 1.8\text{(syst.)} \) are expected from standard model background, which is comprised of Drell-Yan \( Z+jets (6.0) \), top-antitop \((0.7) \), and W pair \((0.01) \) events.
Dé Run II Preliminary Data = 240 GeV

$\tilde{L}Q_2 \tilde{L}Q_2 \rightarrow \mu\mu jj$ events are expected to have both high di-muon masses and large values of $S_T$ which is the scalar sum of the transverse energies of the $\mu\mu jj$ system (see Fig. 1).

The remaining events after the $Z$-veto cut were arranged in four bins, from bin 0 to bin 3. The cut for bin $i$ ($i \in \{1, 2, 3\}$) is defined as:

$$S_T > 0.003 \cdot (m(\mu\mu) - 250 \text{ GeV})^2 + 180 \text{ GeV} + i \cdot 70 \text{ GeV},$$

where $m(\mu\mu)$ is the invariant di-muon mass. Since each event is allowed to contribute only once, the event is assigned to the highest possible bin for which it passes the corresponding cut. The remaining events with the lowest signal over background ratio end up in the first bin, i.e. bin 0. The binning of the remaining events is illustrated by the curved lines in Fig. 2 at the example of second-generation leptoquarks with a mass of 240 GeV.

The distribution of the four signal bins is shown in Fig. 3. Table I summarizes the efficiency for two leptoquarks mass points as well as the number of expected background events and the distribution of the data into the four signal bins.

The dominant errors on the predicted number of background events are Monte Carlo statistics, varying between 7 and 25% for the four signal bins. The jet-energy scale error (2 - 12%) and the jet-energy shape error in Drell-Yan $Z$ events (20%), which has been estimated by a comparison of the PYTHIA [6] simulation with Monte Carlo events.
The branching fraction for the process \( LQ_2 \rightarrow \mu j \) is \( \beta^2 = \text{Br}(LQ_2 \rightarrow \mu j)^2 \). Figure 5 shows the excluded region in the \( \beta \) versus \( m_{LQ_2} \) parameter space. The lower limit to the mass of scalar second generation leptoquarks was determined to \( m_{LQ_2} > 247 \text{ GeV} \) and \( m_{LQ_2} > 182 \text{ GeV} \) for \( \beta = 1 \) and \( \beta = 1/2 \), respectively. The corresponding expected limits, calculated from Monte Carlo events only, are \( m_{LQ_2}^{\text{expected}} > 251 \text{ GeV} \) and \( m_{LQ_2}^{\text{expected}} > 199 \text{ GeV} \).

A similar analysis in the \( \mu j + \mu j \) channel was performed with the DØ Run I data [12] using \((94 \pm 5) \text{ pb}^{-1} \) at
Another Run II analysis in the earlier results have been combined with the Run II analysis presented in this document. The results are summarized in Tab. II and the excluded parameter regions are shown in Fig. 5. The combined upper limit for scalar leptoquarks is

\[ m_{LQ_2} > 251 \text{ GeV} \quad (m_{LQ_2} > 204 \text{ GeV}) \] for \( \beta = 1 \) \((\beta = 1/2)\).

The smaller cross section for scalar leptoquark production at the Run I centre-of-mass energy to-leading-order (NLO) cross section \([10]\) originates from a variation of the renormalisation and factorisation scale between \( m_{LQ}/2 \) and \( 2m_{LQ} \) and the PDF errors, added in quadrature.

TABLE II: Efficiencies and NLO cross sections for scalar leptoquark pair production at Run I and II, 95 % C.L. upper cross section limits for the analysis described in this document, and the results from the Run I + Run II combination. The cross sections shown are calculated using CTEQ6.1M as PDF \([11]\) and \( m_{LQ} \) as the factorization/normalization scale \([10]\).

<table>
<thead>
<tr>
<th>Leptoquark mass ( m_{LQ_2} ) [GeV]</th>
<th>( \varepsilon ), Run I ( \mu j + \mu j )</th>
<th>( \varepsilon ), Run I ( \mu j + \nu j )</th>
<th>( \sigma_{\text{Run I}} ) ( \sqrt{s} = 1.8 \text{ TeV} )</th>
<th>( \sigma_{\text{Run II}} ) ( \sqrt{s} = 1.96 \text{ TeV} )</th>
<th>( \sigma_{\text{Run II}}^\text{95 % C.L.} ) ( \sqrt{s} = 1.96 \text{ TeV} )</th>
<th>( \sigma_{\text{Run I + II}} ) ( \sqrt{s} = 1.96 \text{ TeV} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>140</td>
<td>0.103 ( \pm 0.011 )</td>
<td>0.072 ( \pm 0.011 )</td>
<td>1.8 pb</td>
<td>2.380 ( ^{+0.250}_{-0.205} ) pb</td>
<td>0.181 pb</td>
<td>0.144 pb</td>
</tr>
<tr>
<td>160</td>
<td>0.145 ( \pm 0.016 )</td>
<td>0.103 ( \pm 0.015 )</td>
<td>8 pb</td>
<td>1.080 ( ^{+0.205}_{-0.206} ) pb</td>
<td>0.131 pb</td>
<td>0.104 pb</td>
</tr>
<tr>
<td>180</td>
<td>0.190 ( \pm 0.021 )</td>
<td>0.122 ( \pm 0.018 )</td>
<td>0.379 pb</td>
<td>0.525 ( ^{+0.111}_{-0.096} ) pb</td>
<td>0.105 pb</td>
<td>0.083 pb</td>
</tr>
<tr>
<td>200</td>
<td>0.218 ( \pm 0.021 )</td>
<td>0.134 ( \pm 0.020 )</td>
<td>0.188 pb</td>
<td>0.268 ( ^{+0.057}_{-0.045} ) pb</td>
<td>0.081 pb</td>
<td>0.064 pb</td>
</tr>
<tr>
<td>220</td>
<td>0.226 ( \pm 0.024 )</td>
<td>0.141 ( \pm 0.021 )</td>
<td>0.0958 pb</td>
<td>0.141 ( ^{+0.030}_{-0.025} ) pb</td>
<td>0.066 pb</td>
<td>0.052 pb</td>
</tr>
<tr>
<td>240</td>
<td>0.235 ( \pm 0.025 )</td>
<td>0.152 ( \pm 0.023 )</td>
<td>0.0499 pb</td>
<td>0.076 ( ^{+0.017}_{-0.015} ) pb</td>
<td>0.051 pb</td>
<td>0.045 pb</td>
</tr>
<tr>
<td>260</td>
<td>0.243 ( \pm 0.026 )</td>
<td>0.155 ( \pm 0.023 )</td>
<td>0.0265 pb</td>
<td>0.042 ( ^{+0.009}_{-0.008} ) pb</td>
<td>0.047 pb</td>
<td>0.042 pb</td>
</tr>
<tr>
<td>280</td>
<td>0.260 ( \pm 0.028 )</td>
<td>0.163 ( \pm 0.024 )</td>
<td>0.0142 pb</td>
<td>0.023 ( ^{+0.005}_{-0.004} ) pb</td>
<td>0.044 pb</td>
<td>0.038 pb</td>
</tr>
<tr>
<td>300</td>
<td>0.253 ( \pm 0.028 )</td>
<td>0.157 ( \pm 0.023 )</td>
<td>0.0076 pb</td>
<td>0.013 ( ^{+0.003}_{-0.002} ) pb</td>
<td>0.042 pb</td>
<td>0.037 pb</td>
</tr>
</tbody>
</table>

The error band fo the next-leading-order (NLO) cross section \([10]\) originates from a variation of the renormalisation and factorisation scale between \( m_{LQ}/2 \) and \( 2m_{LQ} \) and the PDF errors, added in quadrature.
FIG. 5: Excluded parameter space for scalar second-generation leptoquarks at 95% confidence level.

Acknowledgments

We thank the staffs at Fermilab and collaborating institutions, and acknowledge support from the DOE and NSF (USA); CEA and CNRS/IN2P3 (France); FASI, Rosatom and RFBR (Russia); CAPES, CNPq, FAPERJ, FAPESP and FUNDUNESP (Brazil); DAE and DST (India); Colciencias (Colombia); CONACyT (Mexico); KRF (Korea); CONICET and UBACyT (Argentina); FOM (The Netherlands); PPARC (United Kingdom); MSMT (Czech Republic); CRC Program, CFI, NSERC and WestGrid Project (Canada); BMBF and DFG (Germany); SFI (Ireland); Research Corporation, Alexander von Humboldt Foundation, and the Marie Curie Program.

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