Searches for vector-like quarks, leptoquarks and quirks at DØ

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Brown University
on behalf of the

collaboration

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Outline

- Leptoquarks
- Vector-like quarks
- Quirks
Motivation

• Standard model is believed to be low energy effective theory
  – There are evidences of physics beyond SM
• Many additional models are proposed
• DØ performed extensive search for new particles and models over the years
DØ experiment in Run II

- Multipurpose detector:
  - Central tracking system embedded in a solenoid magnetic field:
    - Silicon vertex detector (SMT)
    - Central Fiber tracker (CFT)
  - Preshowers
  - Electromagnetic and hadronic calorimeters
  - Muon system

| Angular coverage | $|\eta|$ |
|------------------|-------|
| Muon ID          | ~2    |
| Tracking         | ~2.5  |
| EM / Jet ID      | ~4    |
More than 10.4 fb\(^{-1}\) on tape
More than 90% efficiency lately
Peak luminosity \(\sim 4.3 \times 10^{32}\)

Run IIa
Run IIb

Presented today
Leptoquarks
Motivation

• Leptoquark (LQ) is predicted by many extensions of the Standard Model (GUT, technicolor, SUSY, etc.)
  – LQ can be a mediating boson, allowing interaction between leptons and quarks
    • In the SM, leptons and quarks do not directly interact
  – Can be scalar or vector field
    • has three generations
  – Short-lived and decays to a lepton and a quark
Introduction

- LQ can be produced singly or in pairs
- Produced via quark-antiquark annihilation or gluon-gluon fusion:
  \[ q + q \rightarrow LQ + LQ \]
  \[ g + g \rightarrow LQ + LQ \]

- Assume no intergenerational mixing
  - search for the first generation
- LQ pair decays to 1 of 3 final states: \( e \bar{e} qq, eq\nu q, \) and \( vq\nu q. \)
  - Define branching ratio \( \beta = \text{Br}(LQ \rightarrow e + q), \) then probability of LQ pair decaying to \( eq\nu q \) is \( 2\beta(1 - \beta) \)
- Cross section times branching ratio is maximized for \( \beta = 0.5 \)
Previous results

- Previous published DØ result puts lower limit on a scalar LQ mass at 264 GeV in e+jj channel, and 284 GeV when combined with e+jj and v+jj (β = 0.5)

- ATLAS and CMS released their first searches this year excluding mass of 319 and 340 GeV at β = 0.5 (combined e+jj and e+ej channels)
Data and backgrounds

- **Data** – 5.4 fb\(^{-1}\) collected with DØ between 2002 and 2009
- **SM backgrounds:**
  - modeled with MC:
    - W/Z+jets, tt, single top, diboson (WW, WZ and ZZ)
    - Normalized to the (N)NLO
  - Multijet (MJ) background estimated from data
- **Leptoquark signal normalized to NLO**

**TABLE I: Scalar LQ pair production cross sections, calculated at NLO, for different \(m_{LQ}\).**

<table>
<thead>
<tr>
<th>(m_{LQ}) (GeV)</th>
<th>200</th>
<th>210</th>
<th>220</th>
<th>230</th>
<th>240</th>
<th>250</th>
<th>260</th>
<th>270</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\sigma) (fb)</td>
<td>270</td>
<td>190</td>
<td>140</td>
<td>100</td>
<td>76</td>
<td>56</td>
<td>42</td>
<td>31</td>
</tr>
<tr>
<td>(m_{LQ}) (GeV)</td>
<td>280</td>
<td>290</td>
<td>300</td>
<td>310</td>
<td>320</td>
<td>340</td>
<td>360</td>
<td></td>
</tr>
<tr>
<td>(\sigma) (fb)</td>
<td>23</td>
<td>17</td>
<td>13</td>
<td>10</td>
<td>7.4</td>
<td>4.2</td>
<td>2.4</td>
<td></td>
</tr>
</tbody>
</table>
Signal reconstruction

- **Channel LQLQ → eqνq;**
  - explored ways to pair jets and e/ν coming from the same LQ
- **Two possible combinations:** [(j1,e),(j2,ν)] and [(j1,ν),(j2,e)]
  1. matching by minimizing differences in $p_T$ from the combination of (jet,e) and (jet,ν)
  2. reconstruct LQ from both combinations, and pick the combination such that $Δφ(LQ1,LQ2)$ is closest to $π$
  3. matching by minimizing $Δφ$ between the decay products of LQs
  4. matching by minimizing the differences in $m_T$ reconstructed from (jet,e) and (jet,ν), since the LQs are produced with the same mass

<table>
<thead>
<tr>
<th>$m_{LQ}$ (GeV)</th>
<th>200</th>
<th>240</th>
<th>280</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T$</td>
<td>0.46</td>
<td>0.47</td>
<td>0.47</td>
</tr>
<tr>
<td>$Δφ(LQ_1,LQ_2)$</td>
<td>0.61</td>
<td>0.59</td>
<td>0.58</td>
</tr>
<tr>
<td>$Δφ(\text{dec. products})$</td>
<td>0.48</td>
<td>0.47</td>
<td>0.45</td>
</tr>
<tr>
<td>$m_{T1}=m_{T2}$</td>
<td>0.77</td>
<td>0.75</td>
<td>0.74</td>
</tr>
</tbody>
</table>

Success rate:
Selection

- Few very simple cuts to achieve higher sensitivity
- Preselection: 1 electron with $p_T > 15$ GeV, MET > 15 GeV, at least 2 jets with $p_T > 20$ GeV,
  MJ cleaning cut: MET/50 + $m_T(e, \text{MET})/70 \geq 1$

<table>
<thead>
<tr>
<th>Condition</th>
<th>Data</th>
<th>Total BG</th>
<th>LQ (m=260 GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preselection</td>
<td>65992</td>
<td>65703.4 ± 5957.5</td>
<td>50.4 ± 6.8</td>
</tr>
<tr>
<td>$m_T (e, \text{MET} &gt; 110$ GeV</td>
<td>990</td>
<td>986.3 ± 81.6</td>
<td>33.5 ± 4.6</td>
</tr>
<tr>
<td>$\Sigma(m_{LQ}) &gt; 350$ GeV</td>
<td>64</td>
<td>54.5 ± 4.1</td>
<td>27.3 ± 3.7</td>
</tr>
<tr>
<td>$\Sigma p_T (\text{rec. objects}) &gt; 450$ GeV</td>
<td>15</td>
<td>14.8 ± 1.1</td>
<td>24.4 ± 3.3</td>
</tr>
</tbody>
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Selection

- Few very simple cuts to achieve higher sensitivity
- $\Sigma(m_{LQ}) = m_{ej} + m^{vis}_{vj}$, $m^{vis}_{vj}$ is mass of jet and visible part of neutrino, i.e. $\nu^{vis} = (MET_x, MET_y, 0, MET)$

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![Graph](image1.png)

![Graph](image2.png)
Selection

- Few very simple cuts to achieve higher sensitivity
- $S_T = \Sigma p_T(\text{rec. objects}) = p_T(e) + \text{MET} + p_T(\text{jet}_1) + p_T(\text{jet}_2)$

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Result

- $S_T$ after final cut used to search for signal
- No excess in data $\Rightarrow$ limits set
  - For $\beta=0.5$ LQ with mass below 326 GeV is excluded
  - Below $\beta=0.3$ we set the best limits

\[ \text{arXiv:1107.1849 [hep-ex]} \]
Vector-like quarks
Motivation

• Many new theories predict vector-like quarks:
  – Little Higgs
  – Warped extra dimensions
  – Universal extra dimensions => lowest KK excitation of SM fermions comprises a vector-like 4th generation

• Vector-like quarks are:
  – Fermions despite the name
  – Their left- and right-handed components transform in the same way under SU(3)xSU(2)_L xU(1)
Introduction

- Vector-like quarks can be produced via strong or electroweak interaction

  - Pair production
  - Single production

- In some scenarios (e.g. warped extra dimensions), corrections to SM quark couplings due to mixing with vector-like quarks can cancel.

- No constraints from precision EW measurements

- Single weak production is possible at the Tevatron

\[ \kappa_{qQ} = \frac{v}{m_Q} \tilde{\kappa}_{qQ} \]

\[ \text{Coupling strength} \]

\[ \text{Heavy quark mass} \]

8/30/2011  L. Ž. Leptoquarks, heavy quarks and quirks
Previous result

- Search for pair-produced heavy quarks: heavily constrained by the kinematic reach of the Tevatron
  - CDF: $m_Q > 338 \text{ GeV}$ at 95% C.L. (PRL 104, 091801 (2010))
Vector-like quark signatures

- Vector-like quark can decay to $W+q$ and to $Z+q$
- We assume $\tilde{\kappa}_{uD} = 1$, $\tilde{\kappa}_{uU} = \sqrt{2}$, $\tilde{\kappa}_{dU} = \tilde{\kappa}_{dD} = 0$, i.e. $\text{BR}(Q_D \rightarrow Wq) = \text{BR}(Q_U \rightarrow Zq) = 100$

- One isolated lepton, $p_T > 15$ GeV, missing $E_T > 15$ GeV, and at least two jets, $p_T > 20$ GeV
- Main background $W$+jets
- Two isolated leptons, $p_T > 15$ GeV from a $Z$ boson, $70 < M_{ll} < 110$ GeV, and at least two jets $p_T > 20$ GeV; no MET, i.e. < 50 GeV
- Main background $Z$+jets
- Other backgrounds $tt$, single top, diboson ($WW$, $WZ$, $ZZ$) and instrumental multijet background
- Data – 5.4 fb$^{-1}$ collected with DØ between 2002 and 2009
Final selection

- **Single lepton channel:**
  - Lepton $p_T > 50$ GeV
  - Leading jet $p_T > 100$ GeV
  - $\Delta \phi(\text{lep}, \text{MET}) < 2.0$
  - $M_{TR} < 150$ GeV
  - MET $> 40(50)$ GeV
  - $Q_{lep} \times \eta_{jet2} > 0$

- **Dilepton channel:**
  - $Z \rightarrow \ell \ell$ $p_T > 100$ GeV
  - Leading jet $p_T > 100$ GeV
  - $\Delta R(l,l) < 2.0$

- 2nd jet in Qq->Wqq signal comes from SM quark produced in association with vector quark $\Rightarrow$ forward, relatively soft

- Direction of 2nd jet is correlated with production of VQ/anti-VQ, and therefore correlated with the sign of the lepton in W decay mode
Result

- **W+q**
  - $m_T(l+\nu+\text{lead jet})$ used to search for a signal

- **Z+q**
  - $m(l_1+l_2+\text{lead jet})$ used to search for a signal

- No significant excess
- Limits are set on production cross sections
Limit

- $W+q$
- $Z+q$

For $\tilde{\kappa}_{uD} = 1, \tilde{\kappa}_{uU} = \sqrt{2}, \tilde{\kappa}_{dQ} = 0$
  - $m_Q > 693$ GeV for $Q \to Wq$, $m_Q > 551$ GeV for $Q \to Zq$

For $\tilde{\kappa}_{dU} = 1, \tilde{\kappa}_{dD} = \sqrt{2}, \tilde{\kappa}_{uQ} = 0$
  - $m_Q > 403$ GeV for $Q \to Wq$, $m_Q > 430$ GeV for $Q \to Zq$
Quirks
Motivation

- Possible minimal extension of the standard model includes an addition of a new unbroken SU(N) gauge group new fermions, quirks, in the fundamental representation
  - Two parameters:
    - the new fermion mass $m_Q$
    - strength of new SU(N) gauge coupling, infracolor, is defined through scale $\Lambda$ where it becomes strong

- If quirks carry SM charges, they can be pair-produced at colliders

- Phenomenology in a case of $\Lambda \ll m_Q \approx 0.1-1$ TeV recently studied

- $\Gamma_{\text{break}} \sim \exp(-m_Q^2/\Lambda^2) \Rightarrow$ Infracolor strings are stable
Motivation

- Quirk-antiquirk pair stays connected by the infracolor string like a rubber band that can stretch to macroscopic length

\[ L \approx \frac{m_Q}{\Lambda} \approx 1 \mu m \left( \frac{m_Q}{100 \text{ GeV}} \right) \left( \frac{\Lambda}{100 \text{ keV}} \right)^{-2} \]

- We consider a case where quirks have electric charge, no strong color charge, \(10\text{ keV} < \Lambda < 1\text{ MeV}\), and \(60\text{ GeV} < m_Q < 1\text{ TeV}\).
  - Decay length of many centimeters
  - String size that is too small to be resolved in a detector, but large compared to atomic scales
    - for \(m_Q = 100\text{ GeV}\) the corresponding string size is less than 100 \(\mu\text{m}\), which is comparable to the resolution of the DØ tracking system.
Signature

• Experimental signature:
  - Quirk-antiquirk pair will be reconstructed in the detector as a single highly ionizing track
  - The net charge of the string is zero ⇒ the track will be straight ⇒ a pair of quirks will look like a single massive slow moving particle
    (1) High transverse momentum track with a large ionization-energy loss rate \( \frac{dE}{dx} \)
  - High ET jets from initial state radiation
    (2) Jet to trigger events
  - (3) Missing transverse energy (MET) aligned with the track
Event selection

- **High transverse momentum track with a large ionization-energy loss rate dE/dx:**
  - \( p_T > 40 \text{ GeV} \)
  - \(|\eta_{SMT}| < 1.6\)
  - \(N \text{ of SMT hits } \geq 4; \ N \text{ of CFT hits } \geq 12\)
  - Isolation: No additional tracks with summed \( p_T > 2.5 \text{ GeV} \) in a cone \( \Delta R < 0.5 \) around track

- **Jet to trigger events**
  - \( p_T^{\text{lead}} > 75 \text{ GeV}, \ |\eta| < 1.6\)
  - No additional jet with \( p_T > 25 \text{ GeV} \)

- **Missing transverse energy (MET) aligned with the track**
  - \( \text{MET} > 50 \text{ GeV} \) (muons \( p_T \) not included)
Signal reconstruction

- In addition to position, the SMT detector provides a measurement of ionization energy with a dynamic range up to ~1.4 MeV per strip.

- The quirk-antiquirk pair follow a trajectory which is a classical superposition of the motion of the center of mass (c.o.m.) of the quirk-antiquirk system and the motion of the quirk (or the antiquirk) in the c.o.m. frame.
  - To compute $dE/dx$ of a di-quirk system we integrate energy deposited by each quirk along its trajectory and normalize sum of both contributions by the displacement of c.o.m.
  - To simulate effect of detector resolution and noise we smear this $dE/dx$ with width of $dE/dx$ for muons in data.
  - Optimal $dE/dx$ cut depends on $mQ$.
Data and background

• Data is 2.4 fb\(^{-1}\) collected with DØ

• Backgrounds determined from data:
  - Electrons and Muons: W+jet
    • From Z\(\rightarrow\)ee(Z\(\rightarrow\)\(\mu\mu\)) events: at least one lepton to have a track that passes selection criterion and an invariant mass of two leptons to be consistent with Z boson
  - Hadrons
    • Tracks with \(p_T > 40\) GeV found inside jets
    • From the same primary vertex \(|Z_{\text{jet}} - Z_{\text{track}}| < 1\) cm
  - Fake Tracks
    • Tracks found in the vicinity of a jet (\(\Delta R < 0.5\))
    • Same track selection criteria except \(N_{\text{CFT}} \leq 1\)
Selection

- Electron/muon: track from lepton, obtained from $Z \rightarrow ee(\mu \mu)$
- hadrons: tracks found in the vicinity of jets
- fake tracks: no hits in CFT, crossing angles are wrong, thus wider $dE/dx$

- No excess of highly ionizing tracks above SM expectations
  - Proceed to set limits
Results

- The dE/dx cut is optimized to achieve the lowest 95% C.L. expected limit for each quirk mass.
- No excess of highly ionizing tracks
- Exclude charged quirks of mass up to 107 GeV, 119 GeV, and 133 GeV at the 95% C.L. with strong dynamics scale $\Lambda$ in the range from 10 keV to 1 MeV for SU(2), SU(3), and SU(5) gauge sectors

*Phys. Rev. Lett. 105, 211803 (2010)*
Summary

- Tevatron is running well and reliably and we are thankful to accelerator people that made it all happen – delivered more than 11 fb$^{-1}$.
- DØ has been searching for new physics signals over many years and produced dozens of papers
- LHC has started and surpassed many of our results
  - It used Tevatron experiences in the best possible way
- We present results on the search for the first generation scalar LQ pair production in e$\nu$jj final state
  - We exclude scalar LQ with mass below 326 GeV for $\beta=0.5$
- We also searched for the heavy vector-like quark
  - We set the most stringent limits to date on the production of the heavy vector-like quark
- Quirks:
  - The first limits on quirk-antiquirk production

Results: http://www-d0.fnal.gov/d0_publications/d0_pubs_list_runII_bytopic.html#np
Backup
LQ systematics

• Flat:
  - Production cross sections: on W/Z+jets (6%), ttbar (7%), diboson (10%) and signal (10%)
  - Multijet production (QCD): 20%
  - Luminosity: 6.1%
  - Lepton ID and trigger: Combined 4%

• Shape:
  - Jet energy scale (JES)
  - Jet energy resolution (JER)
  - Jet ID and reconstruction efficiency
  - PDF (signal only)
  - Jet pT missmodeling (W+jets only)
## Systematic Uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>Single Lepton Channel</th>
<th>Dilepton Channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integrated lumi</td>
<td>6.1%</td>
<td>--</td>
</tr>
<tr>
<td>Global MC norm.</td>
<td>--</td>
<td>5%</td>
</tr>
<tr>
<td>V+jets modeling</td>
<td>15%</td>
<td></td>
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<tr>
<td>top x-section</td>
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<tr>
<td>W/Z+jets x-section</td>
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<tr>
<td>diboson x-section</td>
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<tr>
<td>lepton ID</td>
<td>3%</td>
<td>--</td>
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<tr>
<td>Trigger</td>
<td>1% (electron)</td>
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<tr>
<td></td>
<td>4% (muon)</td>
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<td>Jet energy scale</td>
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<td>Jet vertex confirmation</td>
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<td>high-p_T muon modeling</td>
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</tr>
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<td>QCD modeling</td>
<td>6.5% (electron)</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>30% (muon)</td>
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</tbody>
</table>

*: shape-dependent systematic uncertainty