Study of t-Channel Production of Scalar LeptoQuarks at LHCb and Central Acceptance Detector

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Background and Motivation

- Scalar Leptoquark (SLQ): hypothetical beyond standard model particle that couples simultaneously to quarks and leptons
- Provides possible explanation for flavor anomalies detected at LHCb and other experiments
- Appear as propagator in Drell-Yan process – models with large couplings to heavy quarks link flavor anomalies with modifications in DY dilepton distributions

![Diagram of t-channel SLQ production](image1)

![Diagram of SM s-channel Z boson, photon production](image2)
Method

- Examine various simulated kinematic distributions for SM alone and then SM+SLQ model
- Compare the SM and SM+SLQ results for the Central Acceptance and LHCb detectors
- Make strategic cuts to enhance signal/background significance
- Significance estimator used is defined as:

\[ S = \frac{(SM + SLQ) - SM}{\sqrt{SM}} \]
SLQ Model

- Used default parameters specified in SLQRules-UFO-CKM Madgraph model (default masses, default couplings set to unity)
- Simulated SM processes alone in Madgraph using default settings, then imported SLQ model and simulated SM and SLQ processes together
- Ran LO, fixed order simulation for both models (no showering effects included)

<table>
<thead>
<tr>
<th>SLQ Representation</th>
<th>Mass (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SU(2) triplet $\Phi_3$</td>
<td>5000</td>
</tr>
<tr>
<td>SU(2) doublet $\Phi_2$</td>
<td>3000</td>
</tr>
<tr>
<td>SU(2) doublet $\Phi_2$</td>
<td>3000</td>
</tr>
<tr>
<td>SU(2) singlet $\Phi_1$</td>
<td>1000</td>
</tr>
<tr>
<td>SU(2) singlet $\Phi_1$</td>
<td>1000</td>
</tr>
</tbody>
</table>
Data Sets – LHCb, Central Acceptance

<table>
<thead>
<tr>
<th>Generation Parameter</th>
<th>LHCb</th>
<th>Central Acceptance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total # of events N</td>
<td>$10^6$</td>
<td>$10^6$</td>
</tr>
<tr>
<td>Collision Energy (TeV)</td>
<td>13.6</td>
<td>13.6</td>
</tr>
<tr>
<td>Luminosity L (fb$^{-1}$)</td>
<td>50</td>
<td>500</td>
</tr>
<tr>
<td>Lepton $p_T$ (GeV)</td>
<td>&gt; 10</td>
<td>&gt; 10</td>
</tr>
<tr>
<td>Lepton Rapidity $\eta$</td>
<td>$2 &lt; \eta &lt; 5$</td>
<td>-2.5 &lt; $\eta$ &lt; 2.5</td>
</tr>
<tr>
<td>$M_{\ell\ell}$ (GeV)</td>
<td>&gt; 500</td>
<td>&gt; 500</td>
</tr>
</tbody>
</table>

- Simulation results normalized by normalization constant $c$:

$$c = \frac{\sigma L}{N}$$
## Analysis

<table>
<thead>
<tr>
<th>LHCb:</th>
<th>(M_{\ell\ell}) Cut</th>
<th>Fraction of SM Events</th>
<th>Fraction of SM+SLQ Events</th>
<th>Signal</th>
<th>Background</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&gt;600</td>
<td>5.93\times10^{-6}</td>
<td>6.64\times10^{-6}</td>
<td>0.70</td>
<td>5.94</td>
</tr>
<tr>
<td></td>
<td>&gt;800</td>
<td>4.76\times10^{-7}</td>
<td>5.60\times10^{-7}</td>
<td>0.09</td>
<td>0.48</td>
</tr>
<tr>
<td></td>
<td>&gt;1000</td>
<td>3.66\times10^{-8}</td>
<td>5.00\times10^{-8}</td>
<td>0.01</td>
<td>0.04</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Central Acceptance:</th>
<th>(M_{\ell\ell}) Cut</th>
<th>Fraction of SM Events</th>
<th>Fraction of SM+SLQ Events</th>
<th>Signal</th>
<th>Background</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&gt;600</td>
<td>0.017</td>
<td>0.021</td>
<td>4,440</td>
<td>17,000</td>
</tr>
<tr>
<td></td>
<td>&gt;800</td>
<td>0.006</td>
<td>0.008</td>
<td>2,660</td>
<td>5,660</td>
</tr>
<tr>
<td></td>
<td>&gt;1000</td>
<td>0.002</td>
<td>0.004</td>
<td>1,520</td>
<td>2,240</td>
</tr>
</tbody>
</table>

- \(\text{SM}\) \(\sigma=1.39\) (fb)
- \(\text{SM+SLQ}\) \(\sigma=1.51\) (fb)

- \(\text{SM}\) \(\sigma=65.6\) (fb)
- \(\text{SM+SLQ}\) \(\sigma=76.5\) (fb)

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LHCb:

- SM \(\sigma=1.39\) (fb)
- SM+SLQ \(\sigma=1.51\) (fb)

Central Acceptance:

- SM \(\sigma=65.6\) (fb)
- SM+SLQ \(\sigma=76.5\) (fb)
Central Acceptance Distributions - Mean Lepton Invariant Mass ($M_{\ell\ell}$)

Mean Invariant $\ell\ell$ Mass ($M_{\ell\ell} > 600 \text{ GeV}$)

Signal: 4431.0  
Background: 16998.0

Significance Scan vs $M_{\ell\ell}$

- Sum Greater Than
- Sum Less Than
Central Acceptance Distributions – $p_T$, $\mu^+$

*lepton 1 and lepton 2 $p_T$ distributions are identical*
Central Acceptance Distributions – $\eta$, $\mu^-$ (absolute value)

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LHCb Distributions – $M_{ll}$

Mean Invariant $ll$ Mass ($M_{ll} > 600$ GeV)

Signal: 0.70034
Background: 5.93495

Significance Scan vs $M_{ll}$

- Sum Greater Than
- Sum Less Than
LHCb Distributions – pT, $\mu^+$

*lepton 1 and lepton 2 pT distributions are identical*
LHCb Distributions – $\eta$, $\mu$-

**$\mu \cdot \eta$ (M$\ell\ell > 600$ GeV)**

- SM LHCb
- SLQ+SM LHCb

Signal: 0.70034
Background: 5.93495

**$\mu \cdot \eta$ (M$\ell\ell > 800$ GeV)**

- SM LHCb
- SLQ+SM LHCb

Signal: 0.08511
Background: 0.47616

**$\mu \cdot \eta$ (M$\ell\ell > 1000$ GeV)**

- SM LHCb
- SLQ+SM LHCb

Signal: 0.01109
Background: 0.03655

Significance Scan vs $\mu \cdot \eta$

- Sum Greater Than
- Sum Less Than

Significance scan versus $\mu \cdot \eta$ (rad)
Machine Learning Application

- To enhance signal/background separation, attempted ML classifier technique using the kinematic distributions as input
- Compared results from two types of classifiers: Histogram Gradient Boosting Classifier and a fully connected 5 hidden layer Neural Network Classifier
- Generated new sample set of SLQ events alone to train classifiers
Classifier Results (Preliminary) – Central Acceptance

Permutation Feature Importance Across Models

HGBC Results

Neural Network Results

Accuracy: 65.84

Accuracy: 66.92
Summary

- Very low sensitivity to t-channel production of SLQs detected at LHCb, due to low luminosity and strict eta acceptance
- Much higher sensitivity found for central acceptance, higher luminosity detectors
- Machine learning classifiers can be used to increase signal/background signal deconvolution more than simple box cuts – further work to be done on optimizing algorithms and selecting appropriate cuts

What I learned...
- Using MadGraph and ROOT, improved python skills, first time using ML classification techniques
- The structure of a BSM analysis – how to choose what kind(s) of events to examine, how simulations are built and what we can use them for, choosing what data might be interesting to look at, and analyzing results to ensure they are consistent with expectations
Questions?
Thank you!
References

Additional Slides
Central Acceptance Distributions – pT, $\mu^-$

*lepton 1 and lepton 2 pT distributions are identical*
Central Acceptance Distributions – $\eta$, $\mu^+$ (absolute value)
Central Acceptance Distributions – $\Delta \eta$ (absolute value)

$\Delta \eta$ (Mll > 600 GeV)

- Signal: 4352.0
- Background: 16571.0

$\Delta \eta$ (Mll > 800 GeV)

- Signal: 2600.0
- Background: 5503.0

$\Delta \eta$ (Mll > 1000 GeV)

- Signal: 1491.0
- Background: 2181.0
Central Acceptance Distributions – $\cos(\theta^*)$ (absolute value)

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LHCb Distributions – pT, μ⁻

*lepton 1 and lepton 2 pT distributions are identical*
LHCb Distributions – $\eta$, $\mu^+$

- $\mu^+ \eta$ ($M_{\ell\ell} > 600$ GeV)
  - SM LHCb
  - SLQ+SM LHCb
  - Signal: 0.70034
  - Background: 5.93495

- $\mu^+ \eta$ ($M_{\ell\ell} > 800$ GeV)
  - SM LHCb
  - SLQ+SM LHCb
  - Signal: 0.08511
  - Background: 0.47616

- $\mu^+ \eta$ ($M_{\ell\ell} > 1000$ GeV)
  - SM LHCb
  - SLQ+SM LHCb
  - Signal: 0.01109
  - Background: 0.03655

Significance Scan vs $\mu^+ \eta$

- Sum Greater Than
- Sum Less Than

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LHCb Distributions – $\Delta \eta$ (absolute value)
LHCb Distributions – $\cos(\theta^*)$ (absolute value)
Kinematic Distributions – Half SLQ Masses, 2x L

Lepton1_pT (Mll > 800 GeV)

Significance Scan vs pT_Lep1

ETa_Diff (Mll > 800 GeV)

Significance Scan vs ETA_Diff

Lepton1_ETA (Mll > 800 GeV)

Significance Scan vs ETA_Lep1

cos(theta*) (Mll > 800 GeV)

Significance Scan vs cos(theta*)

Lepton2_ETA (Mll > 800 GeV)

Significance Scan vs ETA_Lep2

Mean Invariant LL Mass (Mll > 800 GeV)

Significance Scan vs Mll
cos(θ*) And η Acceptance
Additional Slides – \( \cos(\Theta^*) \) And \( \eta \) Acceptance
Classifier Results (Preliminary) – LHCb

Permutation Feature Importance Across Models

Model Results

HGBF Results

Accuracy: 59.90

Signal
Background

Neural Network Results

Accuracy: 72.97

Signal
Background