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

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Motivation

- Scalar Leptoquarks (SLQs) are hypothetical Beyond Standard Model (BSM) particles that appear in many extensions of the SM
- Experimental results hint toward the possible violation of lepton universality in flavor changing neutral and charged current B meson decay ratios (***flavor anomalies***) – SLQs are a possible explanation
- Ongoing searches at the LHCb, ATLAS, and CMS collaborations for SLQs – this analysis studies the possibility of measuring Drell-Yan (DY) t-channel SLQ production at a Central Acceptance and LHCb detectors

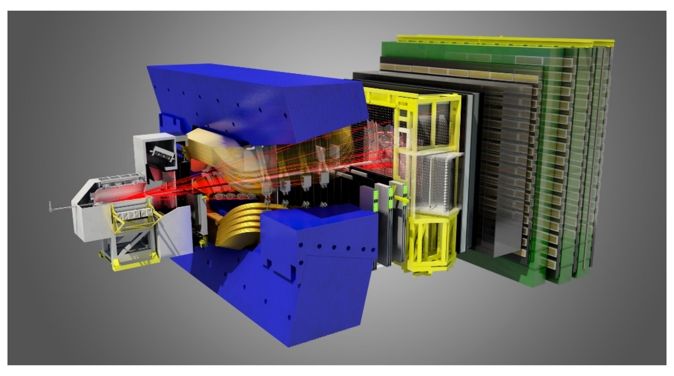


Figure 1: Image of the LHCb detector

Scalar Leptoquark Theory Overview

- SLQs couple simultaneously to both quarks and leptons – provide mechanism for quark/lepton interactions
- LQ models with large couplings to heavy quark flavors link flavor anomalies and modifications in DY dilepton distributions[1]

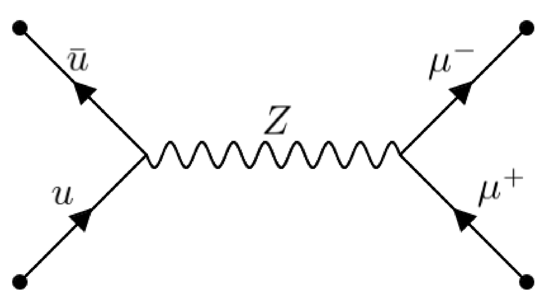


Figure 2: Feynman diagram of s-channel Z boson production via Drell-Yan (DY) process. Largest contributor to background.

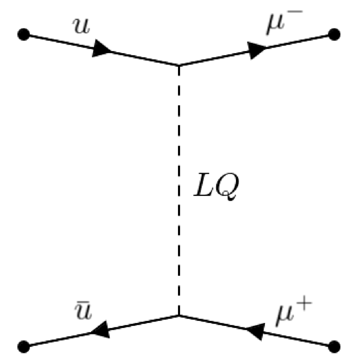


Figure 3: Feynman diagram of t-channel production of SLQ particle via Drell-Yan process.

Data Sets

- MadGraph5 software and SLQrules-UFO-CKM model[2] (default paramters) used to collect simulated event data for SM and SM+SLQ models up to LO
- Simulated only p p $\rightarrow \mu^+ \mu^-$ events

Table 1. SLQ representations and masses considered in this study.

SLQ Representation	Mass (GeV)
SU(2) triplet Φ_3	5000
SU(2) doublet Φ_2	3000
SU(2) doublet Φ_2	3000
SU(2) singlet Φ_1	1000
SU(2) singlet Φ_1	1000

- Kinematics studied : lepton transverse momentum pT, rapidity η, rapidity difference Δη, mean lepton invariant mass $M_{\ell\ell}$, and cos(Θ*) (Θ* defined as the angle between leptons in boosted frame of lepton 1)

Table 2. Generation level input parameters and cuts made to collect data used in study.

Generation Parameter	Central Acceptance	LHCb
Total # of events N	10^6	10^6
Collision energy (TeV)	13.6	13.6
Luminosity L (fb^{-1})	500	50
Lepton pT (GeV)	> 10	> 10
Lepton Rapidity η	-2.5 < η < 2.5	2 < η < 5
$M_{\ell\ell}$ (GeV)	> 500	> 500

Analysis

Table 3. Calculated cross sections σ for the SM and SM+SLQ for Central Acceptance and LHCb

Detector	SM σ (fb)	SM+SLQ σ (fb)
Central Acceptance	65.6	76.5
LHCb	1.39	1.51

- 3 cuts were made on the $M_{\ell\ell}$ kinematic in succession : > 600, 800, 1000 GeV
- Histograms were normalized by normalization constant
$$c = \frac{\sigma * L}{N}$$
- In below tables and plots, Signal is defined as
$$(SM+SLQ) - SM$$
and the Significance estimator used is
$$S = \frac{(SM+SLQ) - SM}{\sqrt{SM}}$$

Table 4. Table of fractions of SM and SM+SLQ events kept, total signal and background events for the 3 $M_{\ell\ell}$ cuts made (Central Acceptance).

$M_{\ell\ell}$ Cut	Fraction of SM Events	Fraction of SM+SLQ Events	Signal	Background
>600	0.017	0.021	4440	17000
>800	0.006	0.008	2660	5660
>1000	0.002	0.004	1520	2240

Table 5. Table of fractions of SM and SM+SLQ events kept, total signal and background events for the 3 $M_{\ell\ell}$ cuts made (LHCb).

$M_{\ell\ell}$ Cut	Fraction of SM Events	Fraction of SM+SLQ Events	Signal	Background
>600	$5.93*10^{-6}$	$6.64*10^{-6}$	0.70	5.94
>800	$4.76*10^{-7}$	$5.60*10^{-7}$	0.09	0.48
>1000	$3.66*10^{-8}$	$5.00*10^{-8}$	0.01	0.04

Kinematic Distributions

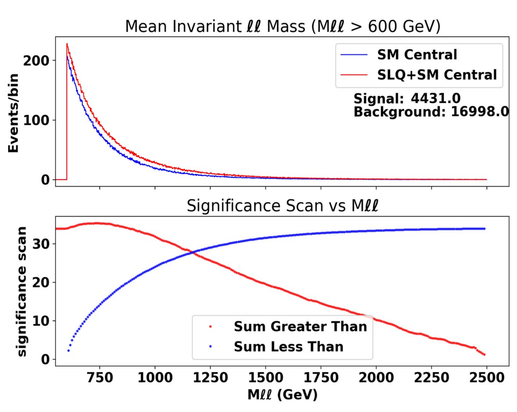


Figure 4: Histogram, significance scan of $M_{\ell\ell}$ for Central Acceptance

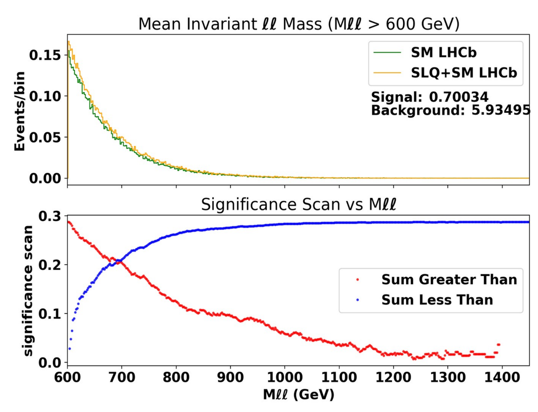
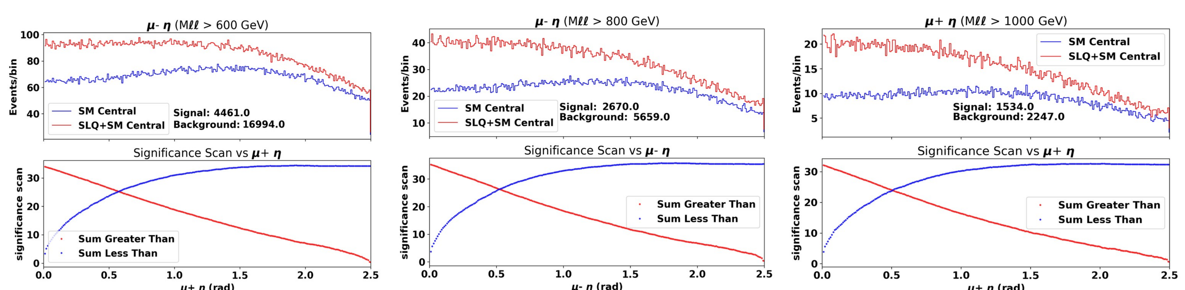
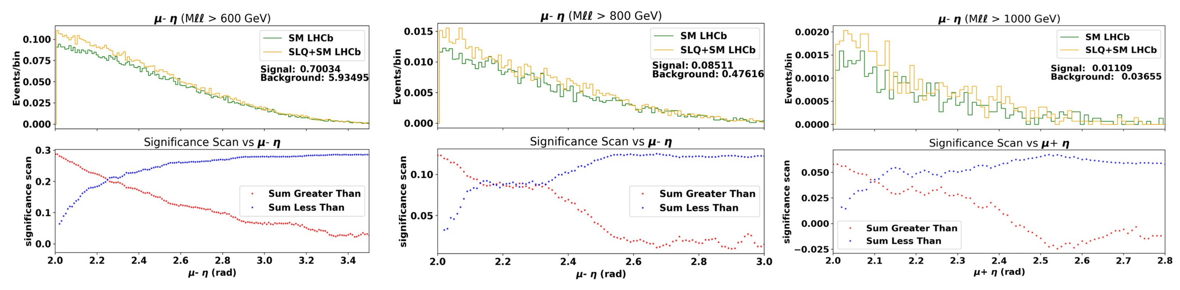


Figure 5: Histogram, significance scan of $M_{\ell\ell}$ for LHCb



Figures 6, 7, 8 (from left): Histogram, significance scan of absolute value of η distribution of μ^- at Central Acceptance at $M_{\ell\ell}$ >600, 800, 1000 GeV



Figures 9, 10, 11 (from left): Histogram, significance scan of η distribution of μ^- at LHCb at $M_{\ell\ell}$ >600, 800, 1000 GeV

- Strict η acceptance and lower luminosity of LHCb (Table 2) greatly decreases number of expected events and significance as compared to Central Acceptance detector
- $M_{\ell\ell}$ cuts had no major impact on significance enhancement for either detector

Machine Learning Application

- A Machine Learning classification technique to improve signal/background separation
- The first classifier implemented was the Histogram Gradient Boosting Classifier from the sklearn Python library
- A 5 hidden layer, fully connected neural network was also created to attempt to improve signal/background separation beyond limits of HGB classifier
- Neither classifier technique was able to significantly deconvolute the signal/background histograms for LHCb, however promising preliminary results were achieved for Central Acceptance

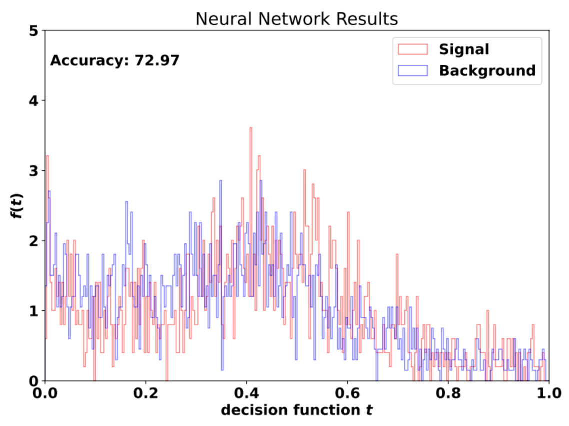


Figure 12: Histogram of decision function generated by the neural network based on LHCb data. Unable to separate the signal and background distributions

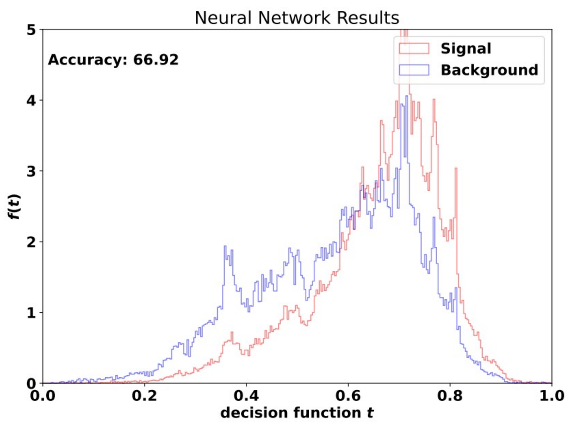


Figure 13: Histogram of decision function generated by the neural network based on Central Acceptance data. Better able to differentiate signal/background

Conclusions and Further Work

- SLQs are a particle predicted by some BSM theories that could explain anomalies detected at LHCb and other HEP collaborations
- Due to limitations on LHCb's acceptance and luminosity, no strong sensitivity to t-channel SLQ production is observed
- Other collaborations that have a wider rapidity acceptance (eg. ATLAS, CMS) will have a higher sensitivity – may be able to refine the ML techniques implemented in this study to perform a more sophisticated search
- **Opportunities for Further Work**
  - Further analysis needed to determine how changing free parameters of the SLQ model, such as SLQ mass, changes the DY kinematic distributions
  - Further efforts in developing a ML algorithm that is better able to enhance signal/background separation ; may use an optimization algorithm to select best hyperparameters

Acknowledgments

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References

[1] Haisch, U., Schnell, L., & Schulte, S. (2022). On Drell-Yan production of scalar leptoquarks coupling to heavy-quark flavours. Journal of High Energy Physics, 2022(11), 1-21.
[2] Crivellin, A., Schnell, L. Complete Lagrangian and Set of Feynman Rules for Scalar Leptoquarks. Computer Physics Communications, 271 (2022): 108188