Sensitivity to Charged Lepton Flavor Violation via $e \to \tau$ Transitions in the Leptoquark Framework at the Electron-Ion Collider

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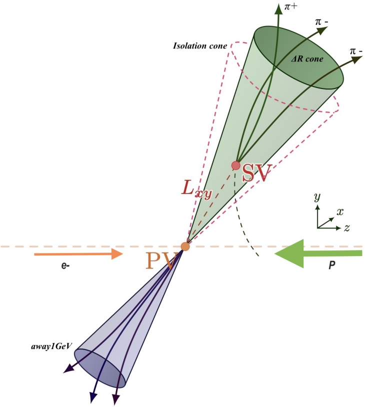
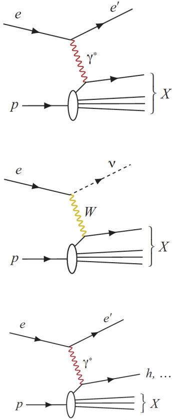
Univerrsity of Manitoba
Joint Inclusive/EW+BSM Meeting

May 20, 2026

Introduction

- Analysis carried for CLFV in DIS-like events mediated by LQs : $e + p \to \tau + X$ using the highest available center-of-mass energy configuration of $\sqrt{s} = 140$ GeV, corresponding to 18 GeV electron and 275 GeV proton beams.
- Current focus into 3-prong τ decays : $\tau^- \to \pi^- \pi^+ \pi^- \nu_\tau$

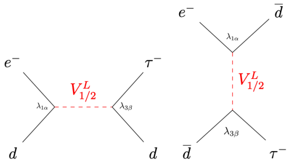


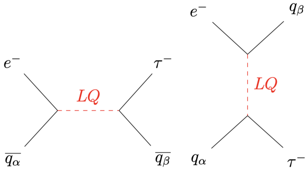


LQ5=$V^L_{1/2}$ Signal and DIS Background

- Presented results regarding the signal are based on s and u channel contributions for $e^- + q_i \rightarrow V^L_{1/2} \rightarrow \tau^- + q_j$ mediated by the Leptoquark(LQ) $V^L_{1/2}$

$$\sigma_{|F|=2} = \frac{s}{32\pi} \left[\frac{\lambda_{1\alpha}\lambda_{3\beta}}{M^2_{\mathrm{LQ}}} \right]^2 \int_0^1 dx \int_0^1 dy \left\{ x q_\alpha(x, Q^2) f(y) + x \bar{q}_\beta(x, Q^2) g(y) \right\} \quad (1)$$



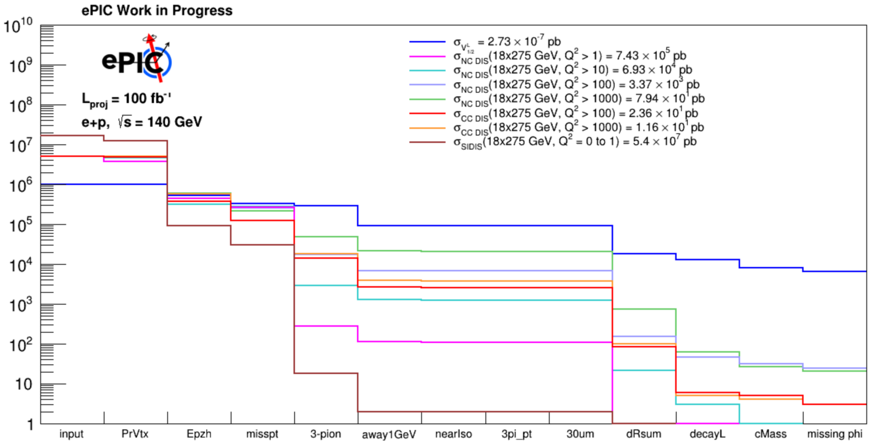


Extending to $\alpha\beta$ for all quark generations $\alpha, \beta \in \{1, 2, 3\}$, the leptoquark states to investigate will include:

- S^L_0, S^R_0, $\tilde{S}^R_0$, S^L_1, $S^L_{1/2}$, $S^R_{1/2}$, $\tilde{S}^L_{1/2}$
- V^L_0, V^R_0, $\tilde{V}^R_0$, V^L_1, $V^R_{1/2}$, $\tilde{V}^L_{1/2}$

Consecutive cuts on $V^L_{1/2}$, NC, CC, SIDIS events

- Number of events surviving each selection cut for $V^L_{1/2}$ signal, generated using LQGENEP, and the DIS background samples from the simulation campaign (**ePIC 26.03.0 ep 18x275 GeV**).



Scaling for LQ5=$V^{L}_{1/2}$, NCDIS, CCDIS, and SIDIS

Table: Generated events, and Monte Carlo events surviving selection cuts.

Process	$N_{\textbf{surviving}}$	$N_{\textbf{generated}}$
Signal	6437	1,000,000
NC $Q^2 > 1$	0	4,983,993
NC $Q^2 > 10$	0	4,980,621
NC $Q^2 > 100$	24	4,980,556
NC $Q^2 > 1000$	21	4,982,696
CC $Q^2 > 100$	3	4,981,635
CC $Q^2 > 1000$	3	4,979,393
SIDIS $Q^2 = 0\text{to}1$	0	16,777,216

$$w = \frac{\sigma \times L}{N_{\text{generated}}} \quad (2)$$

$$N_{\text{expected}} = \sigma \times L \times \varepsilon \quad (3)$$

$$\varepsilon = \frac{N_{\text{surviving}}}{N_{\text{generated}}} \quad (4)$$

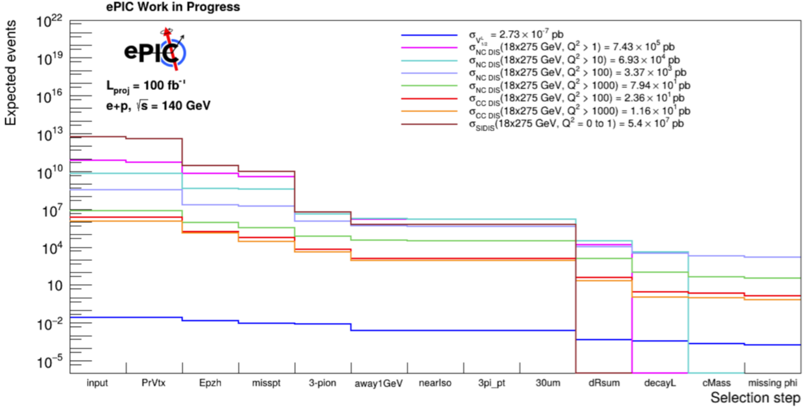
$$N_{\text{expected}} = w \times N_{\text{surviving}} \quad (5)$$

$$B = \sum_i w_i \quad (6)$$

where w_i are the event weights.

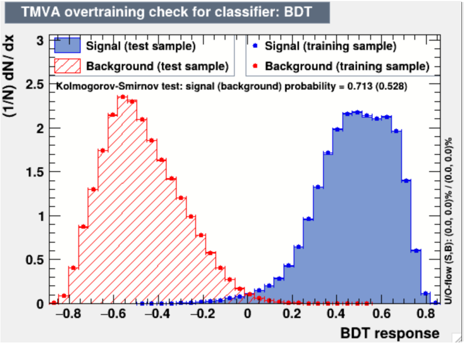
Scaling for LQ5=$V^{L}_{1/2}$, NCDIS, CCDIS, and SIDIS

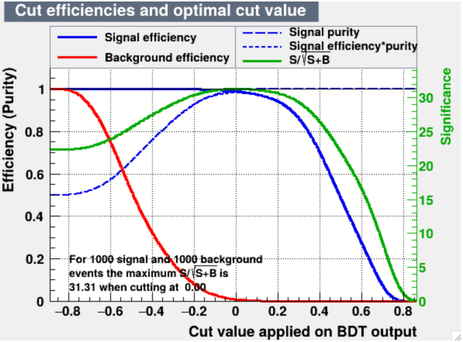
- Number of events that survived each selection cut, for an integrated luminosity of $\mathcal{L} = 100\ \text{fb}^{-1}$.



Boost Decision Trees(BDT)

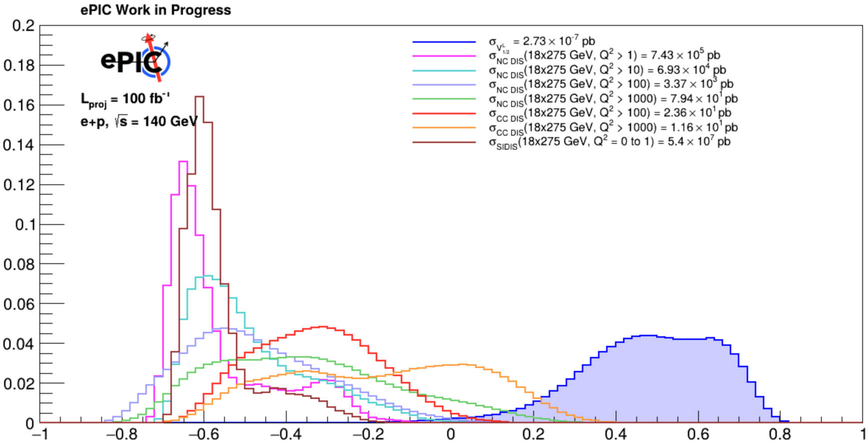
- Train the BDT Model (weights, scaling included...!)
- Signal training(500,000) and testing(500,000) events = 1,000,000.
- Background training (4,981,626) and testing events(4,981,626) = 9,963,252.
- Training was done with 600 Decision Tree
- dataset/weights/weights.xml



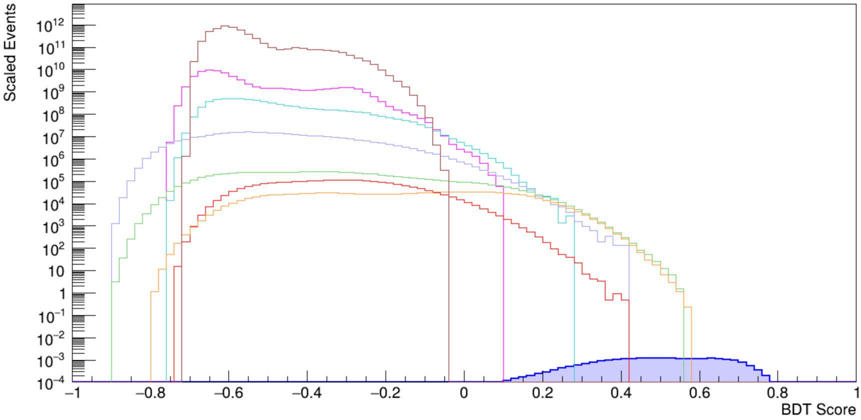


Boost Decision Trees(BDT)

- Apply the model on all other files, no need to train them all. BDT Model made it clear already what is S and B.



Boost Decision Trees(BDT)



$$B = 5.48158 \times 10^{12}$$

$$S = 2.73 \times 10^{-2}$$

Sensitivity projection for $V_{1/2}^{L}$

Signal events were generated with:

- Leptoquark mass: $M_{\text{LQ}} = 1.9365$ TeV $= 1936.5$ GeV
- Couplings: $\lambda_{11} = 0.3$, $\lambda_{31} = 0.3$
- EIC beam energies: $E_e = 18$ GeV, $E_p = 275$ GeV
- Process: $e + d \to \tau + d$ via $V_{1/2}^{L}$ leptoquark exchange

The LQGENEP generator produced:

- Total events (all τ decay modes): 7,000,000
- Total cross-section (all τ modes): $\sigma_{\text{total}} = 1.88 \times 10^{-15}$ mb $= 1.88 \times 10^{-3}$ fb

Applying 3-prong τ decay filter:

- 3-prong events: $=$1,016,946
- 3-prong cross-section:

$$\sigma_{\text{gen}} = 1.88 \times 10^{-3} \times BR(0.14527) = 2.73 \times 10^{-4} \text{ fb}$$

$$\sigma_{|F|=2} = \frac{s}{32\pi}\left[\frac{\lambda_{1\alpha}\lambda_{3\beta}}{M_{\text{LQ}}^2}\right]^2 \int_0^1 dx \int_0^1 dy \left\{x q_\alpha(x, Q^2) f(y) + x \bar{q}_\beta(x, Q^2) g(y)\right\}$$

Sensitivity projection for $V^L_{1/2}$

The exclusion boundary is defined where the theoretical cross-section equals the exclusion limit:

$$\sigma_{\text{theory}} = \sigma_{\text{exclusion}} \tag{7}$$

$$y = y_{\rm theory}\sqrt{\frac{\sigma_{95}}{\sigma_{\rm theory}}} \tag{8}$$

The upper limit on the cross section is

$$\sigma_{95} = \frac{S_{95}}{\mathcal{L}\,\epsilon} \tag{9}$$

The upper limit on the signal yield S_{95} is obtained by Gaussian approximation or CL$_s$ method

$$S_{95} = 1.645\sqrt{B} \tag{10}$$

Physical interpretation: We need at least X signal events at 100 fb^{-1} to distinguish signal from background fluctuations at the 1.645σ level.

$$y \propto B^{1/4} \tag{11}$$

The propagated MC statistical uncertainty on y is therefore

$$\sigma_y = \frac{y}{4B}\sqrt{\sum_i w_i^2} \tag{12}$$

where

$$B = \sum_i w_i \tag{13}$$

Sensitivity projection for $V_{1/2}^{L}$

Event counts follow Poisson statistics, the probability to observe n events given an expectation λ is

$$P(n|\lambda) = \frac{\lambda^n e^{-\lambda}}{n!}. \tag{14}$$

The cumulative Poisson probability is

$$P(n \leq n_{\text{obs}}|\lambda) = \sum_{n=0}^{n_{\text{obs}}} P(n|\lambda). \tag{15}$$

The CL$_s$ test statistic is defined as

$$CL_s = \frac{P(n \leq n_{\text{obs}}|s+b)}{P(n \leq n_{\text{obs}}|b)}, \tag{16}$$

where s is the signal contribution and $b = B$ is the expected background.
The 95% confidence level upper limit on the signal yield, S_{95}, is obtained by solving

$$CL_s = 0.05. \tag{17}$$

Sensitivity projection for $V_{1/2}^L$

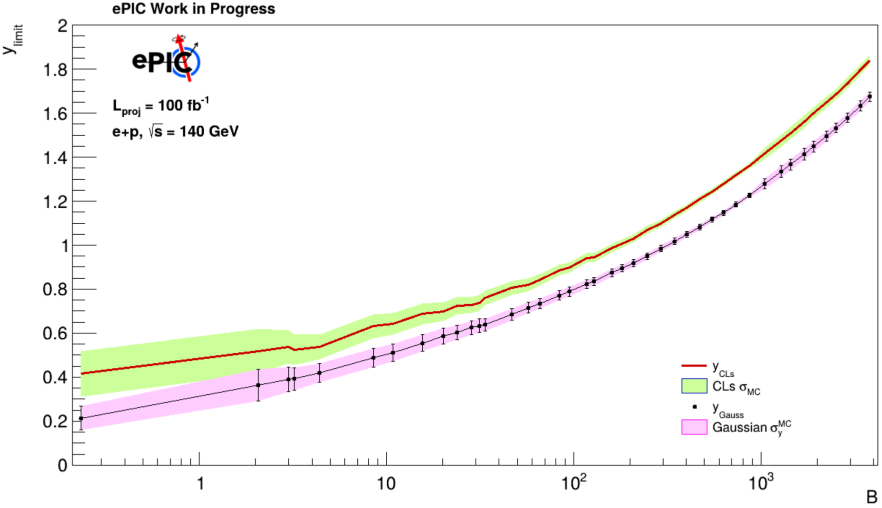


Figure: CL_s optimization study showing the expected limit y_{CLs} and the Monte Carlo statistical uncertainty along with Gaussian optimization $y_{Gaussian}$.

Sensitivity projection for $V^{L}_{1/2}$

- The best cut is chosen in the region where the background has sufficient effective statistics, reasonably small uncertainty, and the significance is maximized within that stable region. I want:
- large enough

$$N_{\text{eff}} = \frac{\left(\sum_i w_i\right)^2}{\sum_i w_i^2} \tag{18}$$

- small enough uncertainty

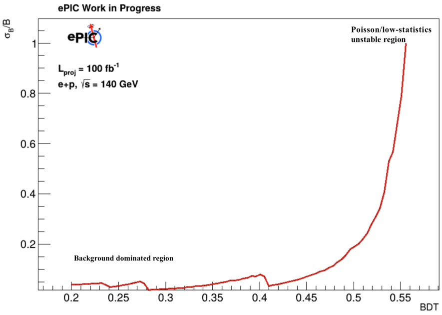
$$\sigma_y = \frac{y}{4B}\sqrt{\sum_i w_i^2} \tag{19}$$

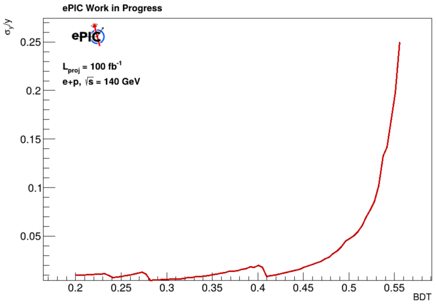
- high significance

$$Z = \frac{S}{\sqrt{S+B}},$$

Sensitivity projection for $V_{1/2}^{L}$

$$\frac{\sigma_y}{y} = \frac{1}{4B}\sqrt{\sum_i w_i^2} \tag{20}$$





Sensitivity projection for $V_{1/2}^L$

Table: BDT optimization summary showing signal yield S, background yield B, signal efficiency, coupling sensitivity y, number of MC background events (N_{MC}), and relative MC statistical uncertainty.

BDT Cut	S	B	Efficiency	y	N_{MC}	MC Error
0.400506	0.0190748	1290.18	0.6987	1.3358	2628	0.0263
0.405063	0.0188264	1052.66	0.6896	1.2779	2261	0.0226
0.409620	0.0185757	866.79	0.6804	1.2255	1957	0.0103
0.414177	0.0183278	737.504	0.6713	1.1849	1659	0.0109
0.418734	0.0180702	630.554	0.6619	1.1475	1416	0.0114
0.423291	0.0178130	549.985	0.6525	1.1169	1222	0.0119
0.427848	0.0175514	471.709	0.6429	1.0828	1032	0.0126
0.432405	0.0172895	401.978	0.6333	1.0482	867	0.0132
0.436962	0.0170250	345.843	0.6236	1.0173	737	0.0139
0.441519	0.0167562	293.472	0.6138	0.9842	629	0.0146
0.446076	0.0164852	246.655	0.6039	0.9501	539	0.0152
0.450633	0.0162181	208.197	0.5941	0.9181	444	0.0162
0.455190	0.0159474	181.201	0.5842	0.8943	369	0.0172
0.459747	0.0156720	160.029	0.5741	0.8745	319	0.0180
0.464304	0.0154003	128.206	0.5641	0.8347	270	0.0188
0.468861	0.0151261	117.601	0.5541	0.8242	242	0.0196
0.473418	0.0148562	95.1061	0.5442	0.7887	198	0.0208
0.477975	0.0145840	83.8026	0.5342	0.7712	167	0.0220
0.482532	0.0143119	66.1252	0.5242	0.7337	132	0.0235

Sensitivity projection for $V^L_{1/2}$

BDT Cut	S	B	Efficiency	y	$N_{\rm MC}$	MC Error
0.487089	0.0140381	57.3843	0.5142	0.7151	112	0.0248
0.491646	0.0137638	46.5840	0.5042	0.6855	89	0.0265
0.496203	0.0134914	33.5285	0.4942	0.6377	68	0.0285
0.500759	0.0132208	31.4319	0.4843	0.6339	59	0.0300
0.505316	0.0129510	28.4406	0.4744	0.6246	52	0.0314
0.509873	0.0126854	23.8558	0.4647	0.6040	44	0.0330
0.514430	0.0124164	20.1656	0.4548	0.5854	34	0.0357
0.518987	0.0121459	15.5808	0.4449	0.5549	26	0.0386
0.523544	0.0118776	10.8003	0.4351	0.5120	23	0.0396
0.528101	0.0116108	8.50791	0.4253	0.4879	19	0.0418
0.532658	0.0113454	4.38904	0.4156	0.4183	13	0.0426
0.537215	0.0110789	3.22424	0.4058	0.3919	8	0.0519
0.541772	0.0108156	2.99128	0.3962	0.3893	7	0.0551
0.550886	0.0102887	2.05944	0.3769	0.3635	3	0.0718
0.555443	0.0100307	0.23296	0.3674	0.2135	1	0.0534

Sensitivity projection for $V^L_{1/2}$

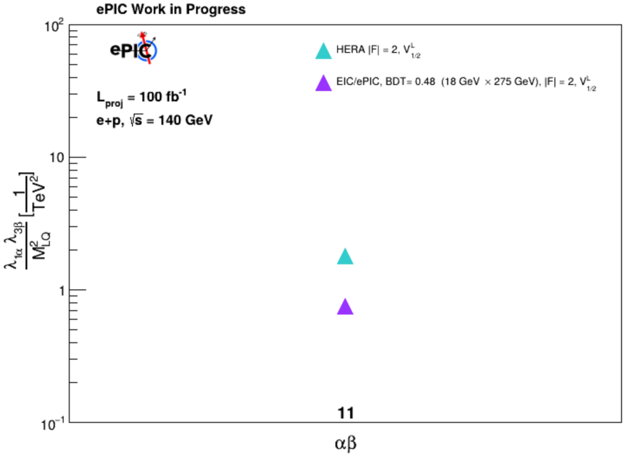


Figure: Comparison between HERA and EIC/ePIC limits on leptoquark $V^L_{1/2}$.

Any leptoquark model that satisfies: $\frac{\lambda_{11}\lambda_{31}}{M^2_{\text{LQ}}} > 0.75$ TeV^{-2} is **excluded**.

Future work

- Project the sensitivity for other 13 LQs based on the selection criteria and BDT.
- Compare the EIC/ePIC results with the existing limits from HERA experiment.