Optimizing Signal-to-Background for $e \to \tau$ Transitions via Leptoquarks at the Electron-Ion Collider

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

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 $V^L_{1/2}$ 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:

$$\sigma_{\text{gen}} = 1.88 \times 10^{-3} \times BR(0.1452) = 2.729 \times 10^{-4} \text{ fb}$$

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

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

Table: Number of events surviving selection cuts

Process	$N_{\textsf{surviving}}$
Signal	6862
NC1	0
NC10	8
NC100	55
NC1000	93
CC100	1
CC1000	2
SIDIS	0

- Expected number of events are found using:

$$N_{\text{expected}} = \sigma \times \mathcal{L} \times \varepsilon$$

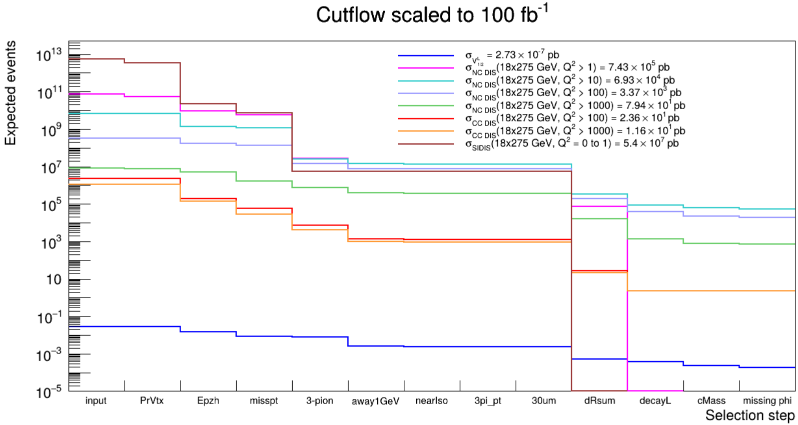
$$\varepsilon = \frac{N_{\text{surviving}}}{N_{\text{generated}}}$$

Integrated luminosity $\mathcal{L} = 100\ \text{fb}^{-1}$for 1M Signal & DIS Background events

Number of events surviving each selection cut for $V_{1/2}^{L}$ signal, generated using LQGENEP,

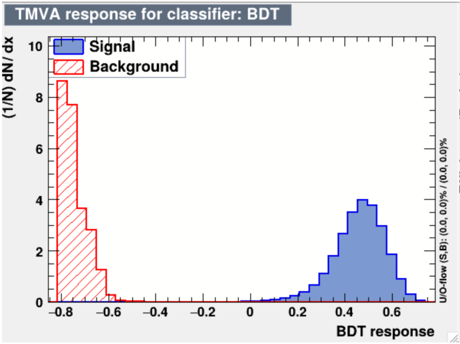
and the DIS background samples from the simulation campaign (**ePIC 25.10.0 ep 18x275 GeV**)

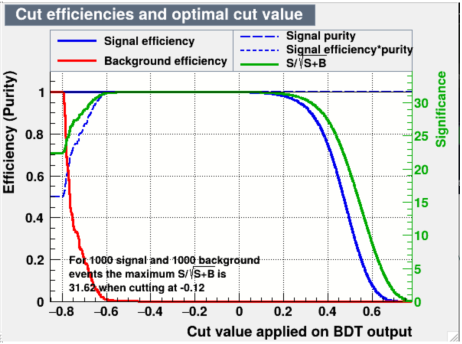
scaled to an integrated luminosity of $\mathcal{L} = 100\ \text{fb}^{-1}$, with focus into 3-prong τ decay : $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$



Boost Decision Trees(BDT)

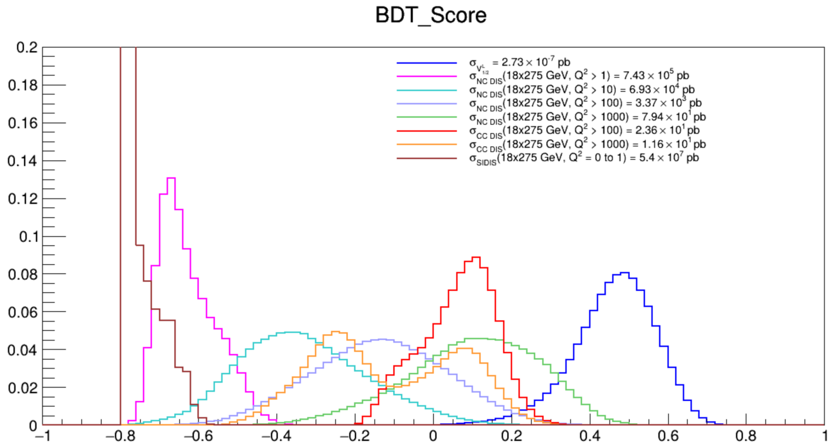
- Train the BDT Model (weights, scaling included...!)
- Signal training(499500) and testing(499500) events = 999000.
- Background training (3500000) and testing events(3500000) = 7000000.
- Training was done with 600 Decision Tree
- dataset/weights/weights.xml



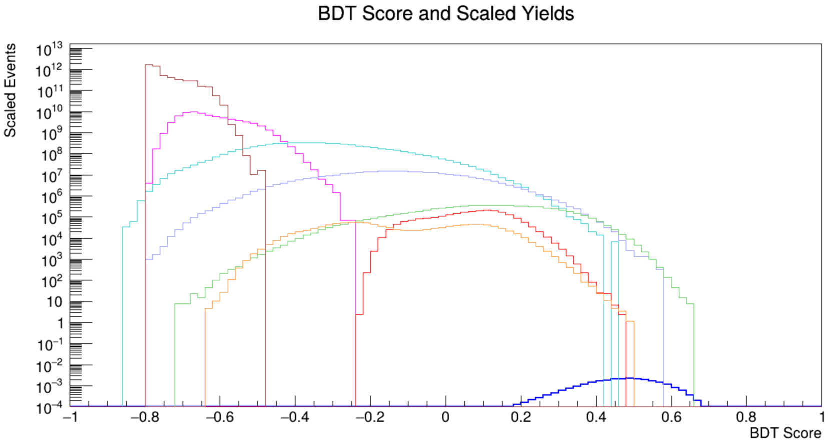


Boost Decision Trees(BDT)

- 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)



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

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

Boost Decision Trees(BDT)

$$S/B_{\text{before}} = 4.98 \times 10^{-15}$$

$$S/B_{\text{after}} = 9.84 \times 10^{-5}$$

$$\frac{S}{\sqrt{S+B}}_{\text{before}} = 1.16 \times 10^{-8}$$

$$\frac{S}{\sqrt{S+B}}_{\text{after}} = 2.77 \times 10^{-4}$$

- The improvement corresponds to an enhancement of approximately **10 orders of magnitude** for S/B and **4 orders of magnitude** for significance $\frac{S}{\sqrt{S+B}}$.

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

- Exclusion Cross-Section after BDT cut application

$$\sigma_s = \frac{999,000}{\mathcal{L}} = \frac{999,000}{100\ \text{fb}^{-1}} = 9,990\ \text{fb}$$

$$\sigma_{min} = \frac{9,990\ \text{fb}}{28,600} = 0.349\ \text{fb}$$

- Scaling for Background after best BDT cut would yield 7.94 B events
- **For 95% CL :** The exclusion cross-section will be:

$$\boxed{\sigma_{\text{exclusion}} = 0.349\ \text{fb} \times 1.64\sqrt{7.94} = 1.612\ \text{fb}}$$

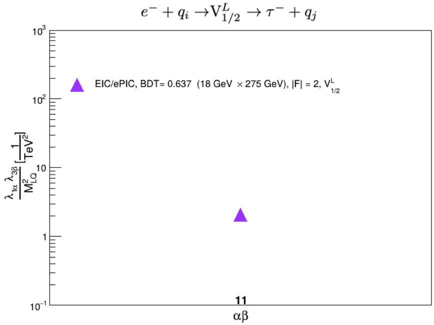
Sensitivity projection for $V^L_{1/2}$

The exclusion boundary is defined where the theoretical cross-section equals the exclusion limit: $\sigma_{\text{theory}} = \sigma_{\text{excl}}$

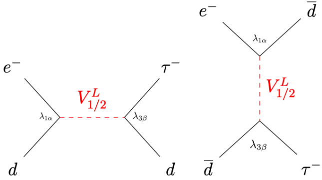
$y_{\text{excl}} = y_{\text{theory}}\sqrt{\frac{\sigma_{\text{excl}}}{\sigma_{\text{theory}}}}$, where $y = \frac{\lambda_{1\alpha}\lambda_{3\beta}}{M^2_{\text{LQ}}}$

The exclusion boundary is represented by a **purple triangle** at position:$(\alpha\beta = 11,\ y = 1.84\ \text{TeV}^{-2})$

Any leptoquark model satisfying: $\frac{\lambda_{11}\lambda_{31}}{M^2_{\text{LQ}}} > 1.84\ \text{TeV}^{-2}$ is **excluded**



Training with Boost Decision Trees (BDT)
The best significance is achieved with BDT_cut = 0.637.



Preliminary limits at 95% CL on $\frac{\lambda_{11}\lambda_{31}}{M^2_{\text{LQ}}}$ for $V^L_{1/2}$ leptoquark.

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, $V^R_{1/2}$, and $\tilde{V}^L_{1/2}$

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

Electroweak and BSM Physics at EIC with ECCE

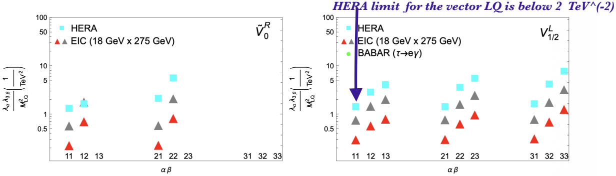


Figure 34: Limits on the vector leptoquarks with $F = 0$ $\tilde{V}_0^R$ (left) and $|F| = 2$ $V^L_{1/2}$ (right) from 100 fb^{-1} of ep 18×275 GeV data, based on a sensitivity to leptoquark-mediated $ep \to \tau X$ cross section of size 1.7 fb (red triangles) or 11.4 fb (grey triangles) from ECCE. Note that due to small value of $\sqrt{s}$, EIC cannot constraint the third generation couplings of $\tilde{V}_0^R$ to top quarks. Limits from HERA [34, 29, 35, 30] are shown as cyan solid squares. Limits from $\tau \to e\gamma$ decays [27] exist but require some work to convert to the 4-fermion contact term. This will be done in the future.

4.5 Remaining Analysis Tasks and Notes for the Future

- The $\tau \to e\gamma$ limit for vector leptoquarks needs to be added to Fig. 34. This needs to be looked up or extracted from the literature;
- Detector-based particle identification should be used instead of truth information.
- Detection efficiency of τ decay channels other than the 3-prong mode needs to be studied;
- Background study obviously affect the leptoquark sensitivity. However, simulation of SM processes at full statistics needs to be left for a later stage, once the detector design is finalized and/or EIC is built.