Measuring Charged Lepton Flavor Violation at the EIC

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New Opportunities for BSM Searches at the EIC
Center for Frontiers in Nuclear Science
July 22, 2025

Outline

- Background
  - Flavor violation
  - HERA measurements
  - Current Limits
- Ongoing studies with ePIC
  - τ - decays
    - $\pi\pi\pi\nu$
    - $\mu\nu\nu$
  - Event selection / background suppression
- Muon ID using ePIC
- Future Work

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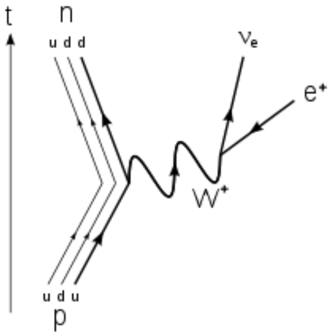
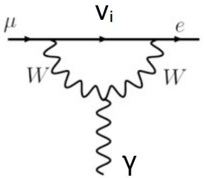
Flavor Violation

- Known Flavor violation
  - Quark Flavor violation
    - Beta decay first characterized in the early 1900s
    - Leads to the development of EW theory
  - Neutrino Flavor Oscillation
    - First hinted at through the solar neutrino problem
    - Observed BSM physics!
- Charged Lepton Flavor Violation
  - Unobserved so far
  - SM + Neutrino Masses allow for CLFV but suppressed
    - $BR(e \to \mu\gamma) \propto \Sigma(\Delta m_{ij}/M_W)^4$

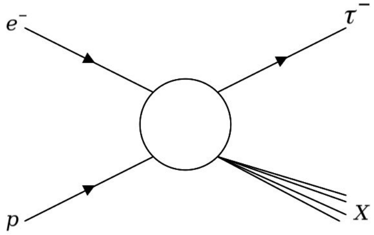




Charged Lepton Flavor Violation (CLFV)

- Due to the suppressed SM rate ($<10^{-54}$) of CLFV, observation ⇒ BSM signal
- Non-observations provides constraints on many BSM models that allow CLFV
- The $e \to \tau$ process has not been as constrained by experiment as much as the $e \to \mu$ process
  - $\Gamma(\tau \to e\gamma) < 3.3*10^{-8}$
  - $\Gamma(\mu \to e\gamma) < 4.2*10^{-13}$

    Particle Data Group, Prog. Theor. Exp. Phys. **2022**, 083C01 (2022) and 2023
  - EIC could improve on $\Gamma(\tau \to e\gamma)$ limits set by HERA and BABAR



τ - decay and ID

- τ-decay signature
  -

3-prong decays	15.2(0.06)%
$\pi^-\pi^+\pi^-\nu$	9.31(0.05)%
$\pi^-\pi^+\pi^-\pi^0\nu$	4.62(0.05)%
Others	

1-prong decays	85.24(0.06)%
$e^-\nu\nu$	17.82(0.04)%
$\mu^-\nu\nu$	17.39(0.04)%
$\pi^-\nu$	10.82(0.05)%
$\pi^-\pi^0\nu$	25.49(0.09)%
$\pi^-\pi^0\pi^0\nu$	9.26(0.10)%
Others	

  - Lifetime = $290.3(.5)\times10^{-15}$s
  - M_τ = 1776.86(0.12) MeV
- Identifying a displaced vertex and the missing p from the decay significantly improves ID

HERA Direct CLFV Search

Tau decays

- Leptonic decays
  - $\tau \rightarrow e\nu_e\nu_\tau$
  - $\tau \rightarrow \mu\nu_\mu\nu_\tau$
    - μ-ID with missing momentum and (in ZEUS) Forward μ Detector
- Hadronic decays
  - Selected as τ-Jets
- No displaced vertex

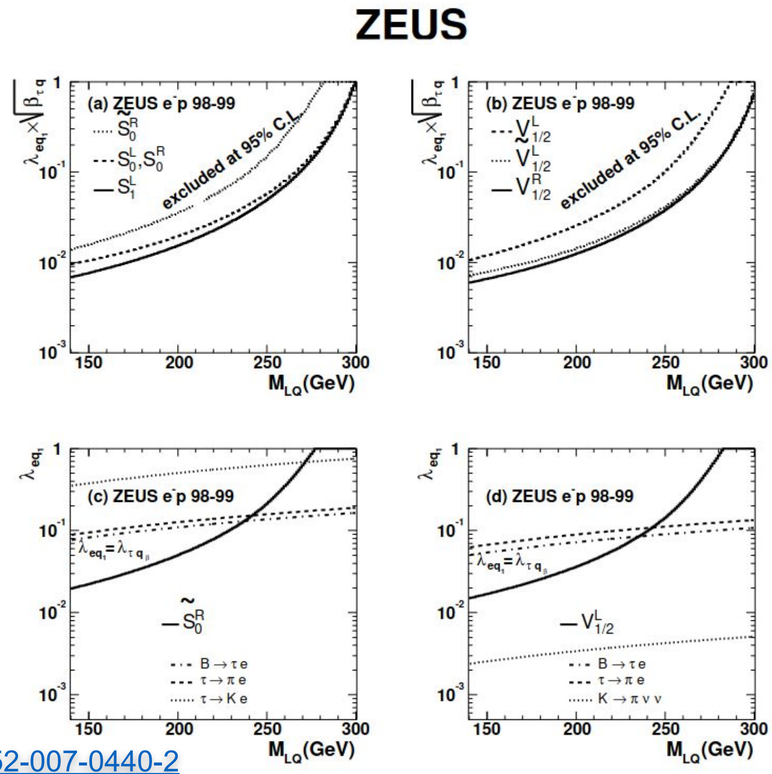
Main Backgrounds

- NC DIS
  - $ep \rightarrow eX$
- CC DIS
  - $ep \rightarrow \nu X$
- Photoproduction
  - $\gamma p \rightarrow X$
- Dilepton production
  - $ep \rightarrow e\ell^+\ell^- X$
- W production
  - $ep \rightarrow eWX$

The Zeus Collaboration https://doi.org/10.1140/epjc/s2005-02399-1
Aktas, A., Alexa, C., Andreev, V. *et al.* https://doi.org/10.1140/epjc/s10052-007-0440-2

HERA Direct CLFV Search Results

- No signal seen consistent with low mass or high mass leptoquarks in ZEUS or H1
- Set leading leptoquark limits in $e \rightarrow \tau$
  - E.g. low-mass LQ limits from $e^{-}p$ at ZEUS



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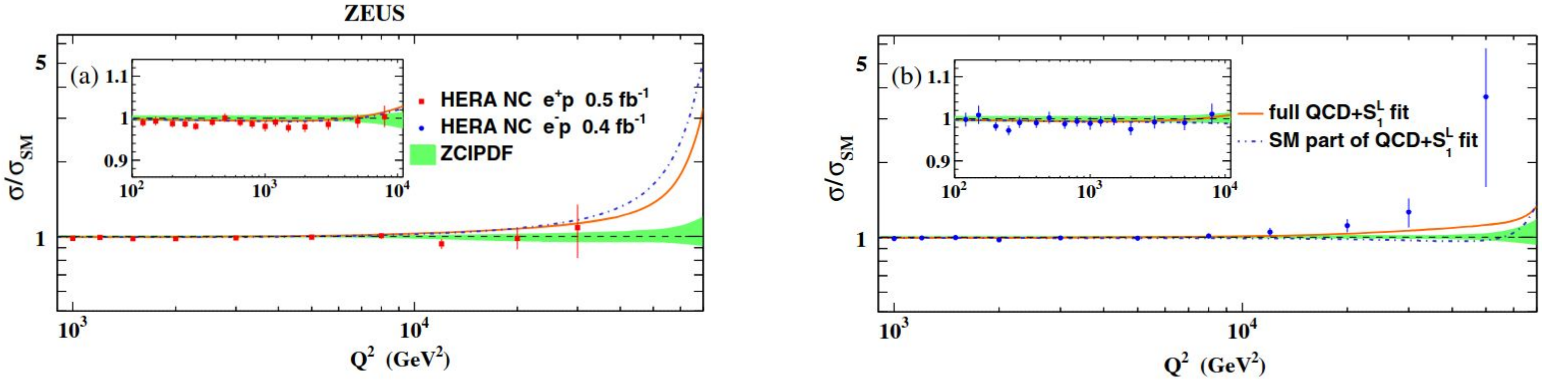
HERA Fit to Data 1

- Fit the NC DIS cross section with a SM + LQ model
  - $\mathscr{L}_{LQ} = a^{eq}_{ij}(\lambda_{LQ}/M_{LQ})^2(e\gamma^{\mu}e)(q\gamma_{\mu}q)$
- SM + LQ (LQ = S_1^L) fit example:



H1, A. Aktas et al., Search for lepton flavour violation in ep collisions at HERA, Eur. Phys. J. C 52 (2007) 833, DOI: 10.1103/PhysRevD.99.092006

Previous e→ τ Experimental Limits

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Leptoquark framework:
with coupling $\lambda_{e\alpha}\lambda_{\tau\beta}$ / M^2_{LQ}

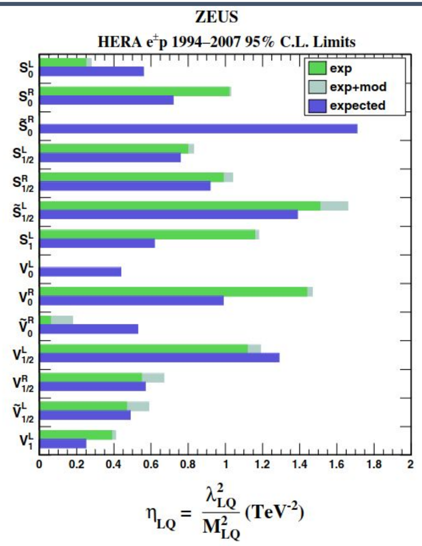
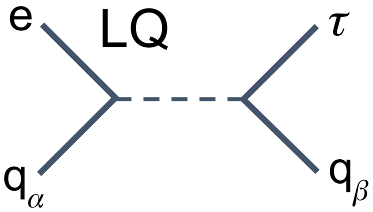
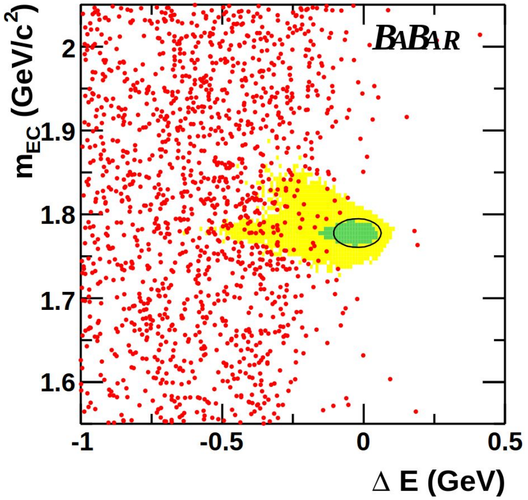


FIG. 5. Upper 95% C.L. limits on the LQ coupling strength, $\eta_{LQ} = \lambda^2_{LQ}/M^2_{LQ}$. Compared are the limits calculated without (dark upper bars) and with (light upper bars) modeling uncertainties, and the expected limits (lower bars).



Extracted from
~1fb^{-1} of e$^{\pm}$p data
√s ~ 300 GeV



➢ $\Gamma(\tau \rightarrow e\gamma) < 3.3*10^{-8}$

H1, A. Aktas et al., Search for lepton flavour violation in ep collisions at HERA, Eur. Phys. J. C 52 (2007) 833, DOI: 10.1103/PhysRevD.99.092006

BaBar, B. Aubert et al., Searches for Lepton Flavor Violation in the Decays τ + →e+γ and τ + → μ+γ, Phys. Rev. Lett. 104 (2010) 021802,

EIC Event Selection Sketch

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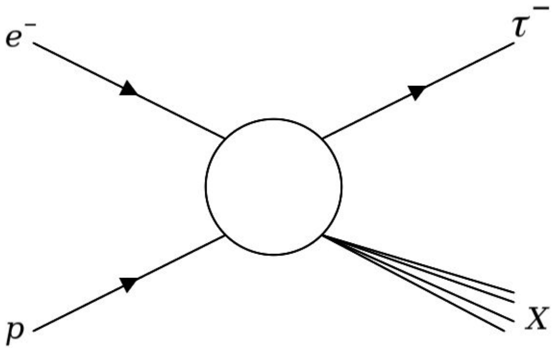
- Primary vertex is reconstructed (PrVtx)
- $\Sigma_h(E-p_z) > 18$ GeV (Epzh)
- 1 GeV $< p_{T,missing} <$ 9 GeV (misspt)
  - Photoproduction events
  - DIS events with large missing P_T
- High P_T jet back-to-back of the τ (away1GeV)
- τ-decay signature



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- Lifetime = $290.3(.5)\times10^{-15}$s
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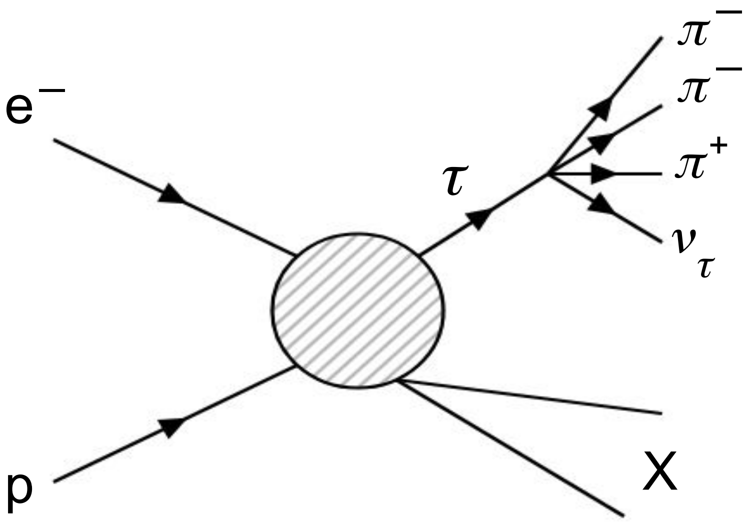
E→τ with a "3-prong" Decay in EIC

<u>3-prong decay</u>
$\tau \rightarrow \pi^{-}\pi^{+}\pi^{-}\nu_{\tau}$

Pro: event identification is relatively easy

Con: only a ~9% branching ratio

Studied for the ECCE detector and discussed in the following few slides



Zhang et al. Search for e → τ Charged Lepton Flavor Violation at the EIC with the ECCE Detector (2022)
https://doi.org/10.1016/j.nima.2023.168276

3-prong Decay Event Selection

- Primary vertex is reconstructed (PrVtx)
- $\Sigma_h(E\text{-}p_z) > 18$ GeV (Epzh)
- 1 GeV < $p_{T,missing}$ < 9 GeV (misspt)
  - 1 GeV < $p_{T,missing}$: Photoproduction events
  - $p_{T,missing}$ < 9 GeV: DIS events with large missing P_T
- 3 charged pions in a cone $\sqrt{(\Delta\phi^2+\Delta\eta^2)} < 1$ (3-pion)
- High P_T jet back-to-back of the τ (away1GevV)

Zhang et al. Search for e → τ Charged Lepton Flavor Violation at the EIC with the ECCE Detector (2022)
https://doi.org/10.1016/j.nima.2023.168276

3-prong Decay Event Selection cont

- 3 separate cuts using pairs of the 3-pions to constrain the secondary vertex (30μm, dRsum, decayL)
  - 30μm: “decay length reconstructed from any pair of the 3-pions is >30μm
  - dRsum: sum of decay vectors is < 0.4
  - decayL: average pion pair decay lengths >0.5mm

- Cuts that require the event to have P_T imbalance and missing mass in the τ jet from the undetected neutrino (cMass, missing phi)

ECCE 3-prong study: Event Selection

18x275 GeV

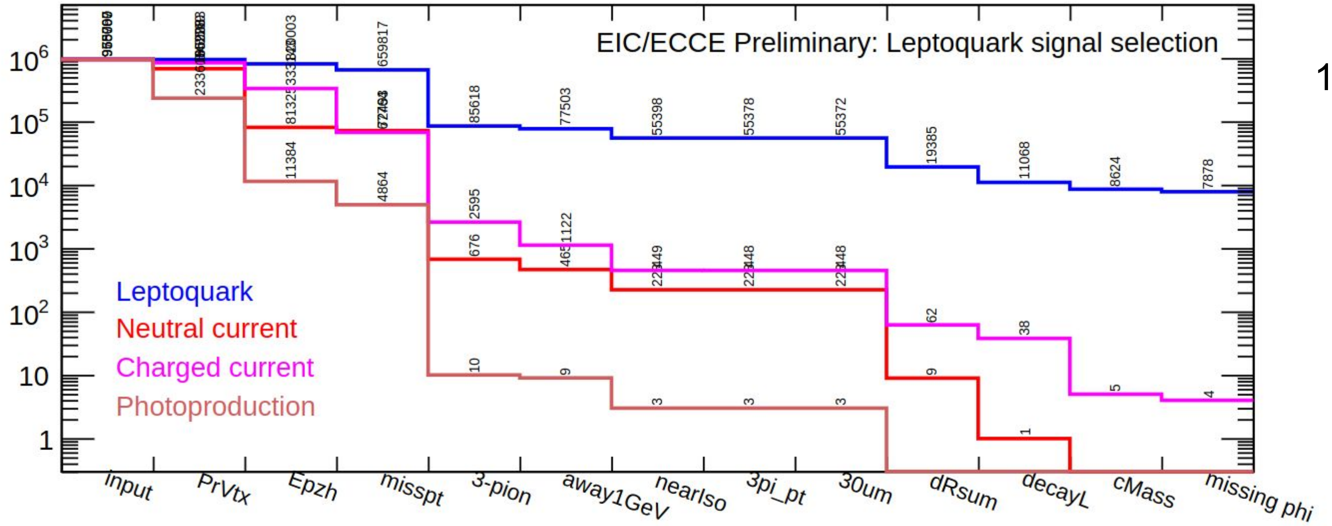


Figure 4: MC statistics of leptoquark (blue), DIS CC (red), DIS NC (magenta), and photoproduction (orange) events, as ten selection criteria are progressively applied on 1 M input events for each channel. Please see text for details.

3) Zhang et al. Search for e ⟶ τ Charged Lepton Flavor Violation at the EIC with the ECCE Detector (2022)
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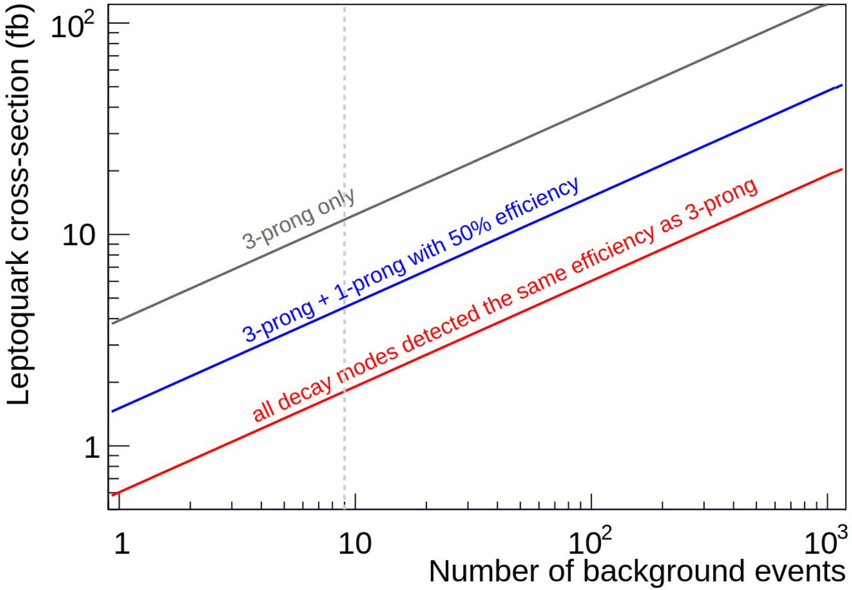
ECCE 3-prong Sensitivity



sensitivity for leptoquark cross section vs # remaining background

Calculated assuming 100 fb^{-1} integrated luminosity.

3) Zhang et al. Search for e ⟶ τ Charged Lepton Flavor Violation at the EIC with the ECCE Detector (2022)
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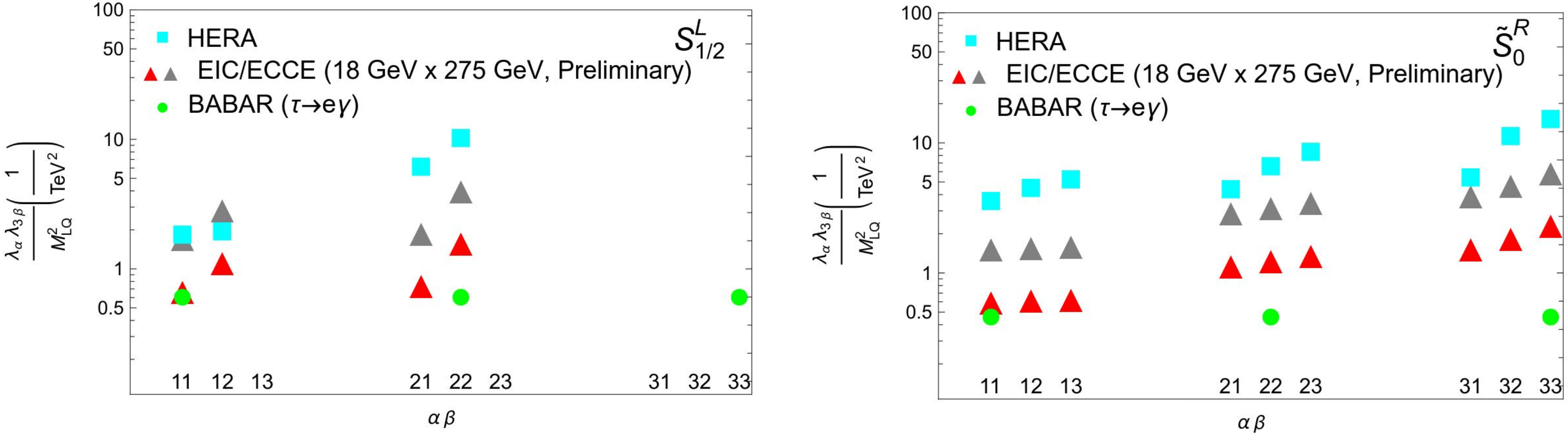
Scalar Leptoquark Sensitivity



3) Zhang et al. Search for e ⟶ τ Charged Lepton Flavor Violation at the EIC with the ECCE Detector (2022)
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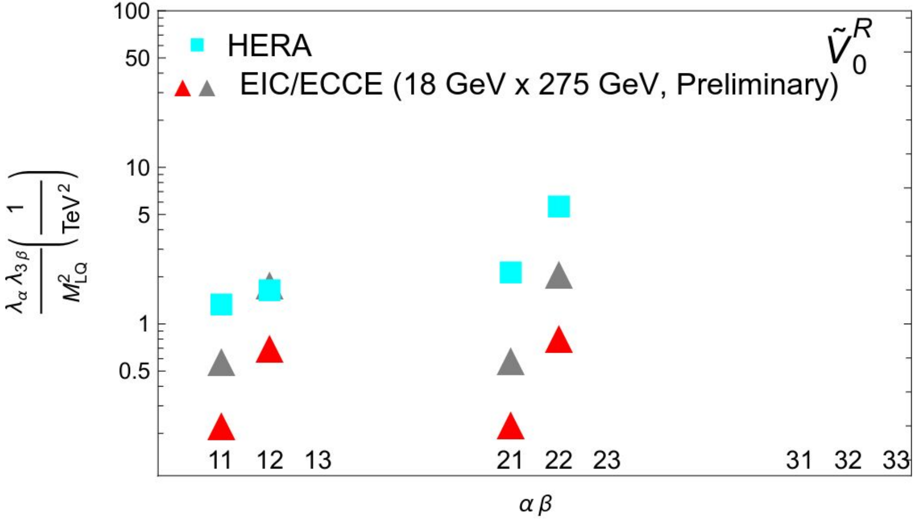
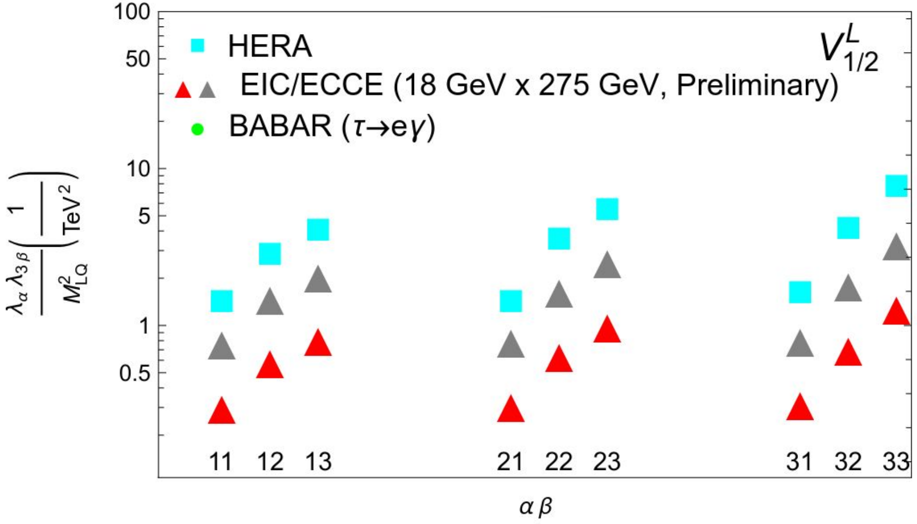
Vector Leptoquark Sensitivity





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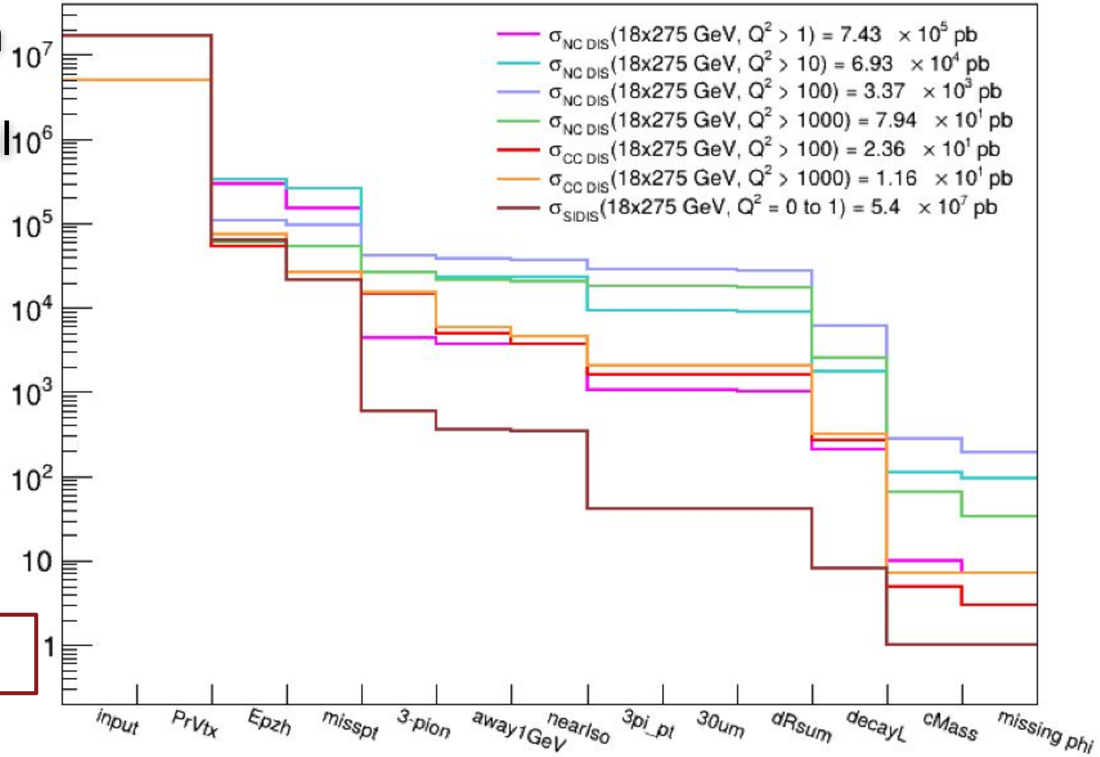
Repeating the $3\pi\nu$ in ePIC

- Repeating the ECCE study in the ePIC detector simulation
- Larger simulation, more detail



Bardh Quni - U. Manitoba PhD Student

Repeating the $3\pi\nu$ in ePIC

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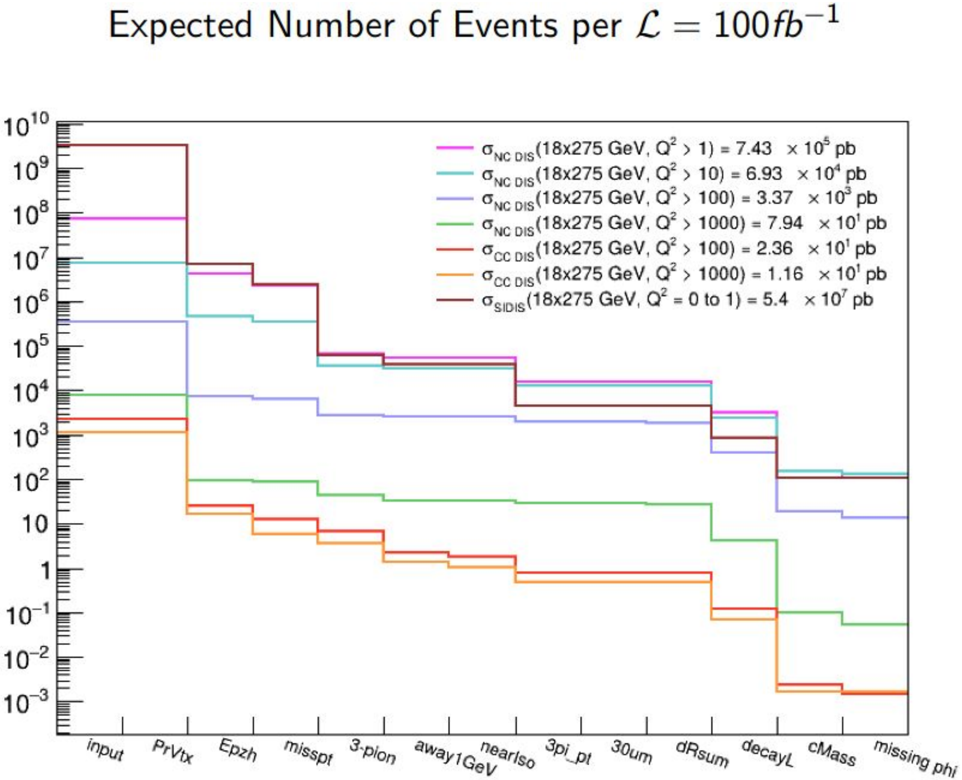
- Repeating the ECCE study in the ePIC detector simulation
- Larger simulation, more detail
- With relative scaling of the background



Bardh Quni - U. Manitoba PhD Student

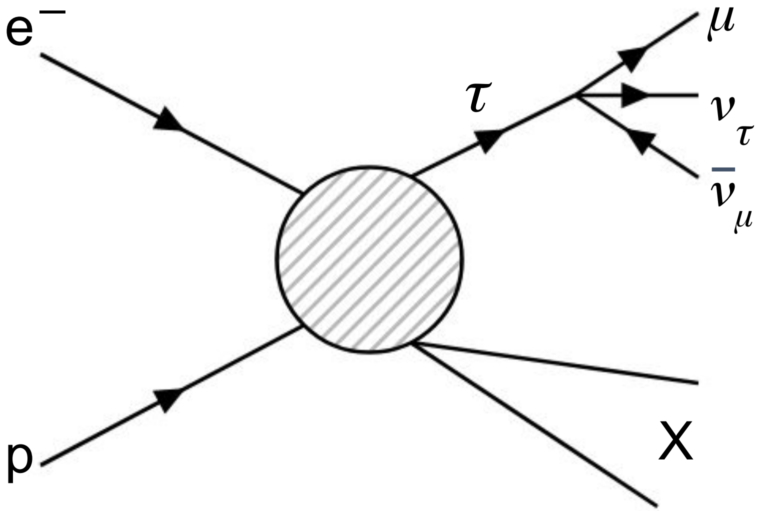
“1-prong” Muon Decay

$$\tau \rightarrow \mu \bar{\nu}_\mu \nu_\tau$$

Pros:
Suppression of SM background around $p^{\mu}_{t} > 15$ GeV

~17% branching ratio

Con: requires good muon identification



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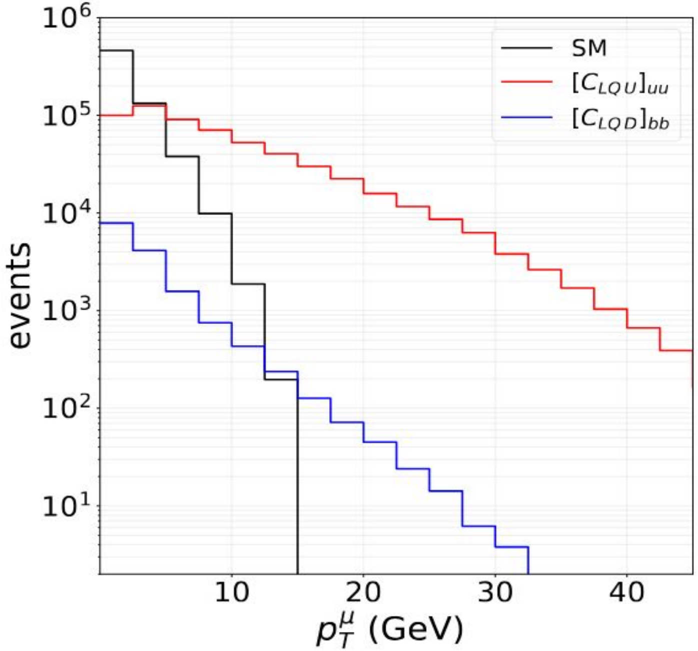

https://doi.org/10.1007/JHEP03(2021)256

μ/π PID Separation Overview

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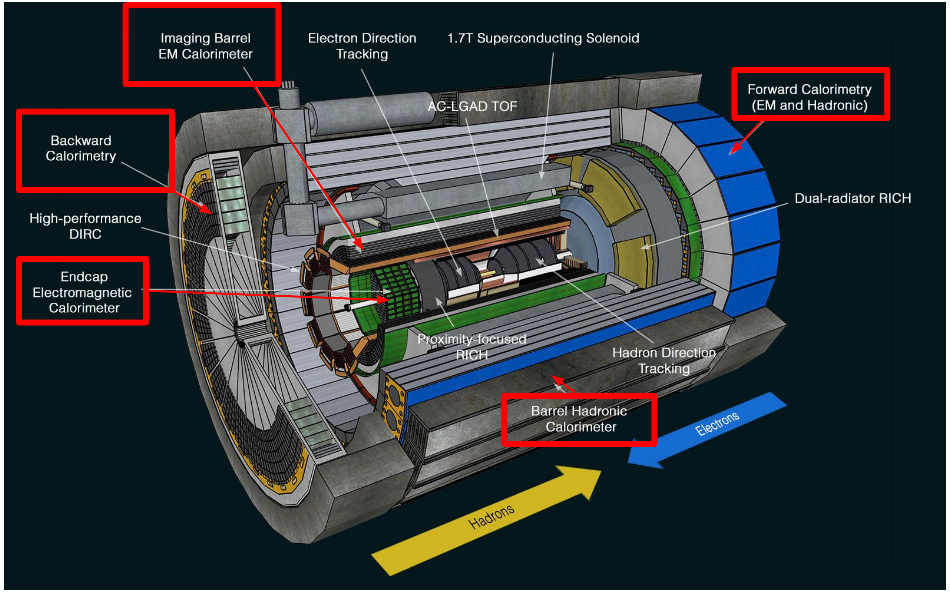
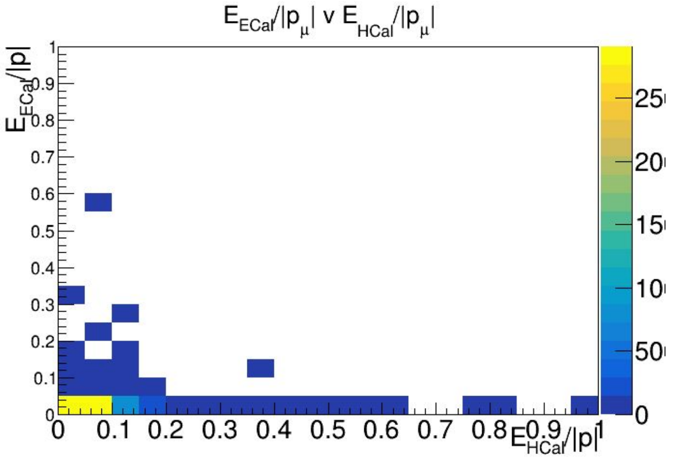
Detectors used for μ/π separation

- Hadronic calorimeters (HCals) are a natural starting point for μ/π separation.
- Combining information from the electromagnetic calorimeters with the HCals improves μ/π separation in the following study.
- The following study focuses on the barrel region.
  - Near future plans to extend the study to the backward endcap.

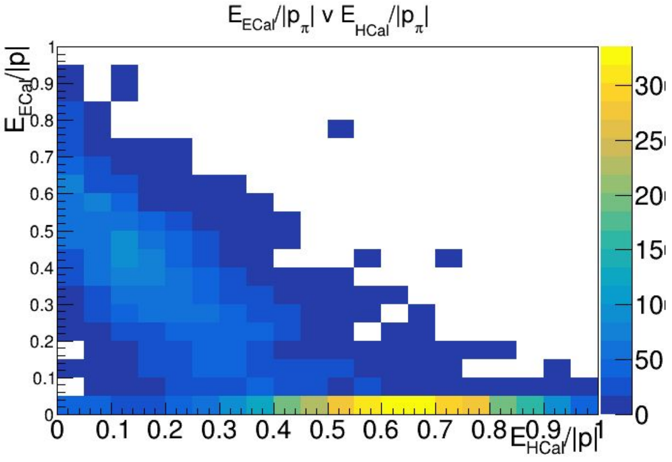


Using E/p in Both Barrel Calorimeters

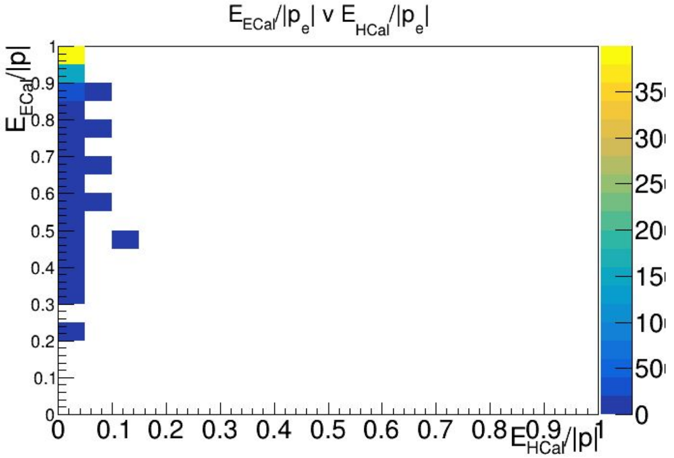
μ-



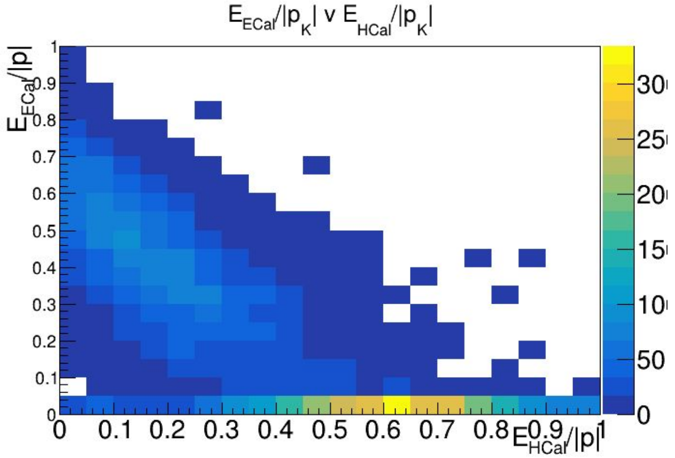
π-



e-



K-



HCal E/p < 0.2 + ECal E/p < 0.1

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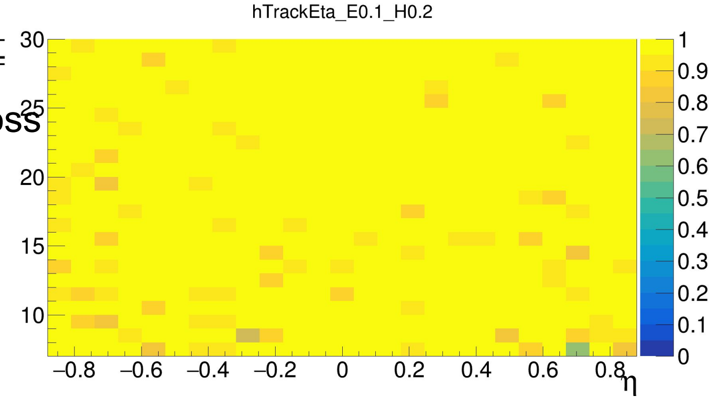
Z axis = events after combined E/p cut / events generated

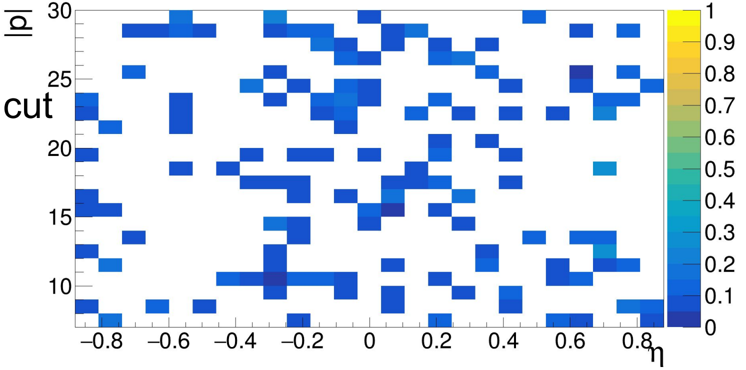
μ-

~1% loss



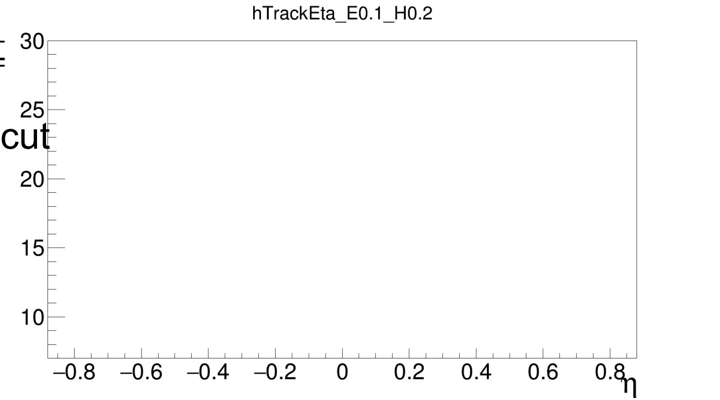
π-

98% cut



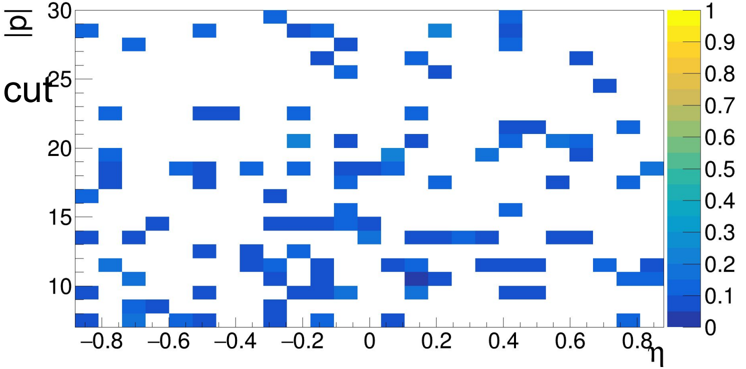
e-

>99% cut



K-

96% cut



μ/π PID Study Data Set

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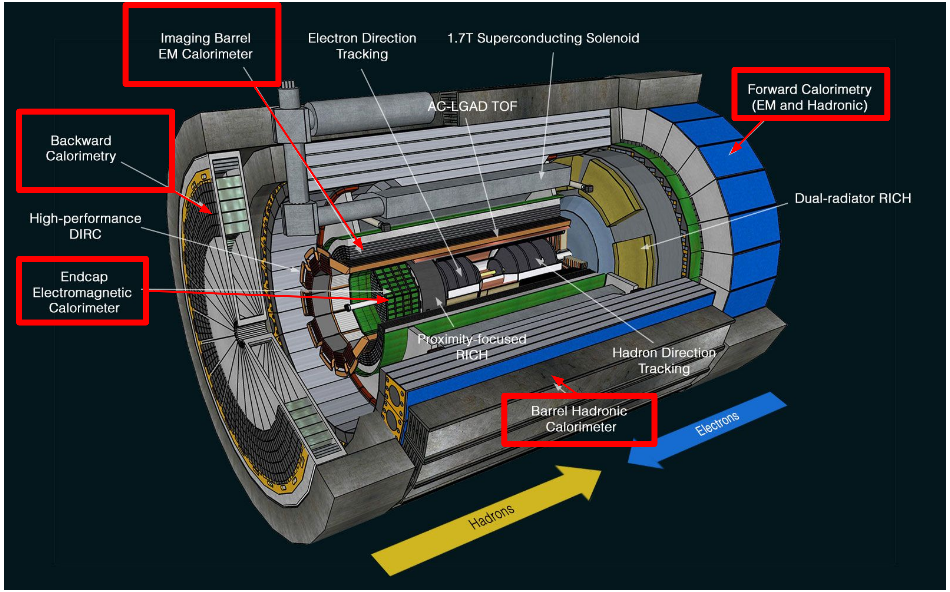
Simulation Details

- Single particle simulation using ddsim
  - 100K μ and π at various momenta and production angles:
    - $|p|$ = 1 to 15 GeV in 1GeV steps.
    - θ = 90° to 150° in 10° steps.
- Simulated in the ePIC detector
- Reconstructed using the EICrecon package



μ/π PID Values Used

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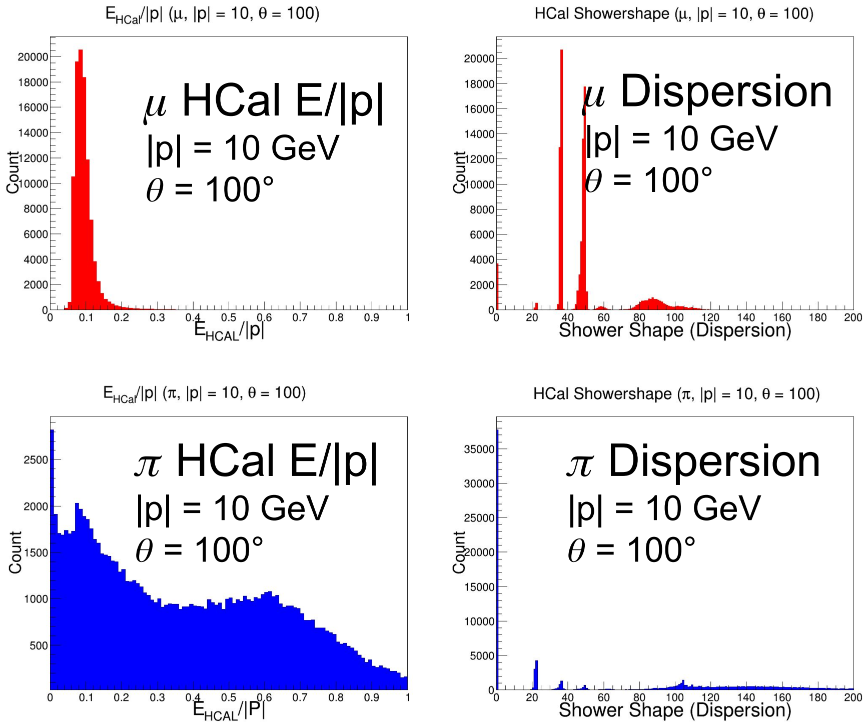
Reconstructed values used in this study

- Calorimeter E_{cal} seems to be the most useful value in μ/π separation
  - $E_{cal}/|p|$ used for convenience.
- Dispersion (Energy weighted radius) improves separation somewhat.
  - Named 'Shower Shape' in the following slides.

Example Distributions



μ/π PID, Log-likelihood Approach

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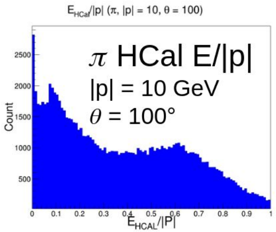
- Using a log-likelihood reduces the PID separation to a single variable to which cuts can be tuned for any given analysis.
  - Easy to incorporate additional reconstruction values given sufficient data/simulation.
- Method:
  - Take distributions such as: 

and treat them as probability distributions

$P(q_{\pi,HCal\ E/|p|})$

  - Calculate the log-likelihood for each track:
    - $L_j = \ln(\mathcal{L}_j) = \ln(\Pi_i\, p(q_{ji})) = \Sigma_i \ln(p(q_{ji}))$.
    - where j is the PID hypothesis (μ or π in this case).
    - i is each reconstructed value used (e.g. HCal E/|p|).
    - $p(q_{ji})$ is the probability a track has a value q_{ji} for the given PID hypothesis and reconstructed variable.
  - Cut on the log-likelihood difference $L_\mu - L_\pi$

μ/π PID, Log-likelihood Example

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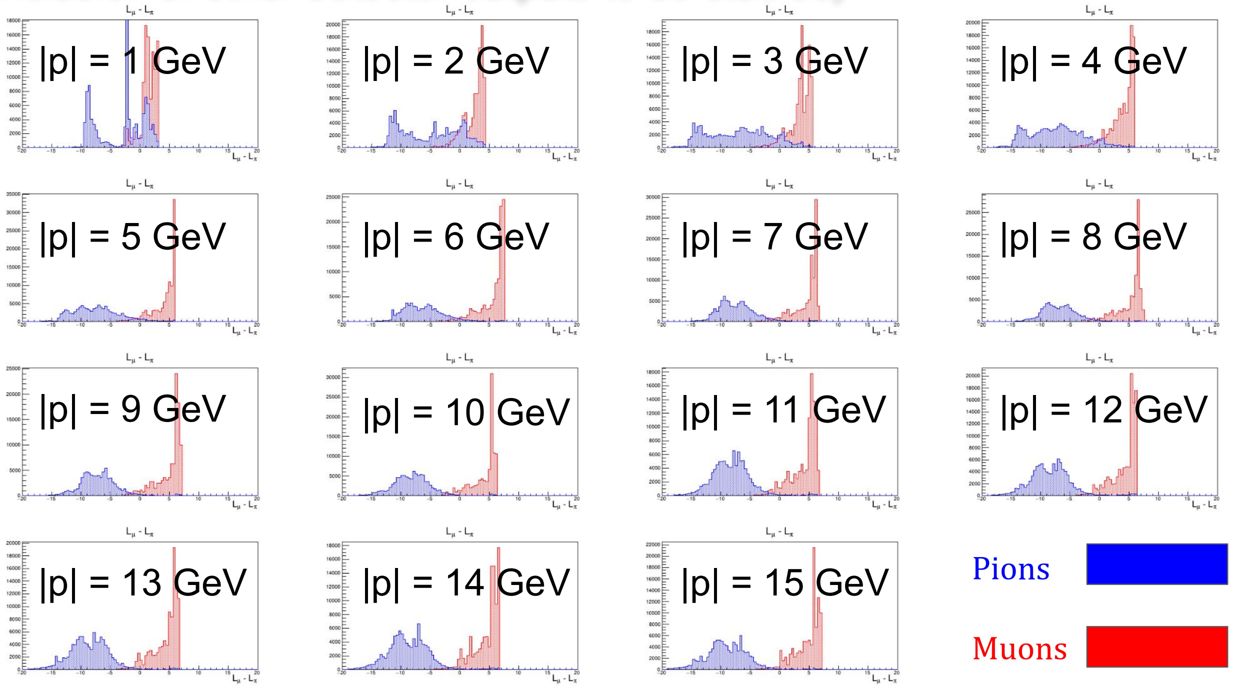
- L_μ - L_π for μ and π at θ = 90° with |p| = 1 GeV to 15 GeV in 1 GeV Steps.
- L_μ - L_π calculated using HCal E/|p|, HCal Shower Dispersion, ECal E/|p|, and ECal Shower Dispersion. (Inclusion of other detector outputs to be studied)



μ/π PID, Log-Likelihood (cont.)

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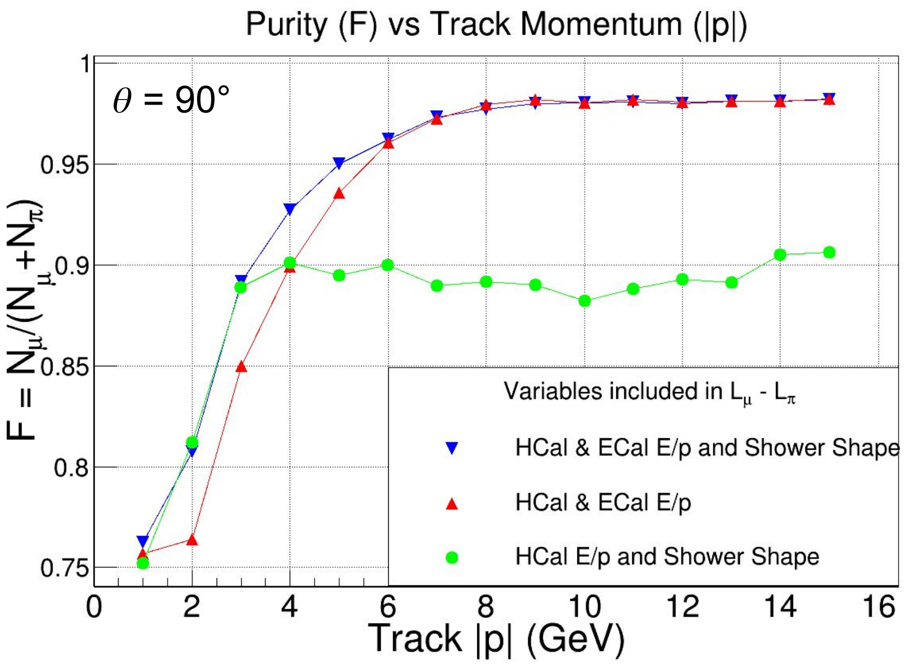
For μ/π same sample size:

- Effect on L_μ - L_π calculated using different combinations of HCal E/|p|, HCal Shower Dispersion, ECal E/|p|, and ECal Shower Dispersion.
- Cut on L_μ - L_π > 0
  - Somewhat arbitrary. Cut can be tuned to balance purity and efficiency for individual analyses.
- Chose a purity ($N_\mu/(N_\mu+N_\pi)$) as a figure of merit to compare the following input value combinations:
  - HCal & ECal E/|p| and Shower Shape
  - HCal & ECal E/|p|
  - HCal E/|p| and Shower Shape



μ/π PID, Log-Likelihood (cont.)

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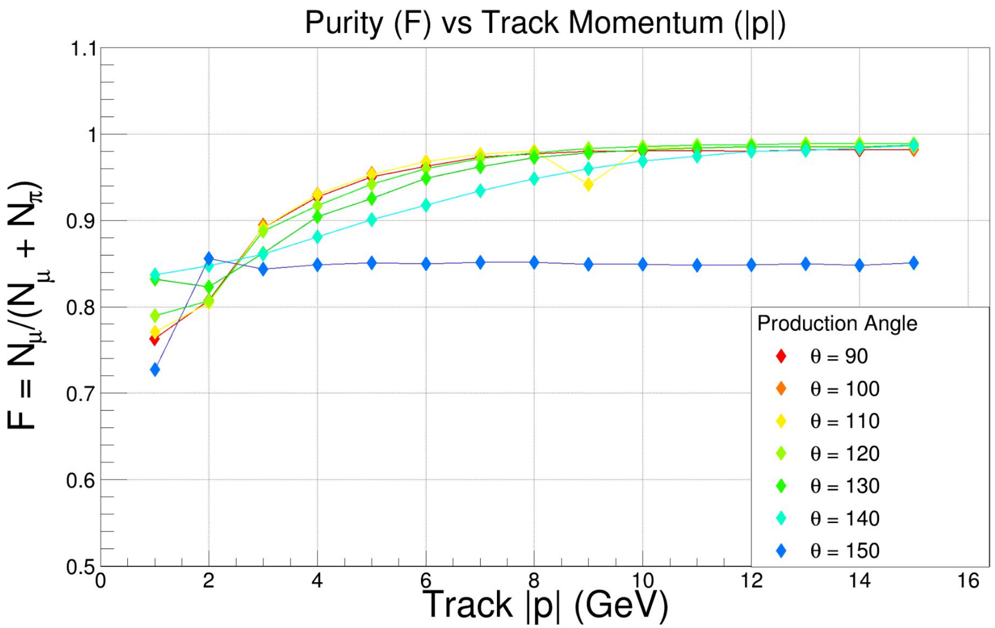
- L_μ - L_π calculated using HCal E/|p|, HCal Shower Dispersion, ECal E/|p|, and ECal Shower Dispersion.
- Now plotting the purity figure of merit for samples generated at different angles
  - 90° to 150° in 10° steps



Work to be done $e \rightarrow \tau$

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- Improving μ/π separation:
  - Extend study to other regions of the ePIC detector.
  - Including additional detector information.
    - Calorimeter shower profiles.
    - Study signals from other detector systems.
  - Implementing Machine Learning tools.
- $ep \rightarrow \tau X$ Signal simulation:
  - LQGENEP
    - Newer EIC CLFV generators available?
  - Analyse cuts for signal/background optimization.
    - Traditional 'by hand' cuts.
    - AI/ML tools.

What About the Other τ-decays?

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Others	

- $\tau \rightarrow e^-\nu\nu$
  - Displaced vertex to separate events from scattered e- events
- $\tau \rightarrow \pi^-\nu$
  - Displaced vertex and pion-ID
- $\tau \rightarrow \pi^-\pi^0\nu$
  - Displaced vertex, pion-ID, and π^0 reconstruction

Summary

- Studies on the ECCE detector design showed that EIC can make an impact on the CLFV/LQ limits.
  - ePIC simulation studies progressing.
    - Answering “how good is ePIC at measuring CLFV and how can a second detector improve upon it?” is the ultimate goal.

- μID has some legs but effectiveness will ultimately be determined by background size.
  - Tools for μID useful for many other analyses (e.g. $e^{-}p \rightarrow \mu^{+}jjj$).

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μ/π PID, Log-likelihood Example

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