Experimental view on $e \rightarrow \tau$ CLFV at the EIC

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INT Workshop 24-87W:
EW and BSM Physics at the EIC

Outline

- Background and Motivation
- Studying $e \to \tau$ at the EIC
  - 3-prong tau decay
  - 1-prong decay with muons
    - How well can muons be identified with the current ePIC detector design
- Summary

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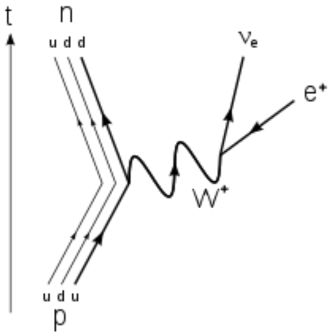
Background

- 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!
- CLFV
  - Unobserved so far
  - SM + Neutrino Masses allow for CLFV but suppressed
    - $BR(e \rightarrow \mu\gamma) \propto \Sigma(\Delta m_{ij}/M_W)^4$



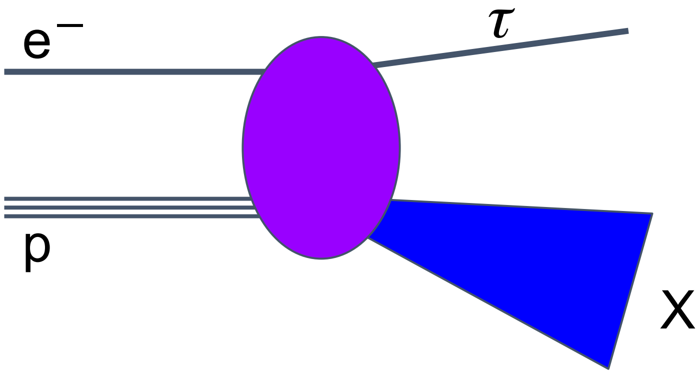
Motivation

- Observation of CLFV ⇒ BSM physics
  - Probe the neutrino mass mechanism
  - Constrain BSM theories
    - E.g. SUSY, GUTs, Leptoquark theories
  - New BSM interactions?

$e^{-} \rightarrow \tau^{-}$ CLFV

- The $e \rightarrow \tau$ process has not been as constrained by experiment as much as the $e \rightarrow \mu$ process
  - $\Gamma(\tau \rightarrow e\gamma) < 3.3*10^{-8}$
  - $\Gamma(\mu \rightarrow e\gamma) < 4.2*10^{-13}$

    Particle Data Group, Prog. Theor. Exp. Phys. **2022**, 083C01 (2022) and 2023



- SMEFT[1] and leptoquark[2] model calculations suggest that the EIC could make a competitive constraint or measurement of $e \rightarrow \tau$

1) Cirigliano, V., Fuyuto, K., Lee, C. et al. Charged lepton flavor violation at the EIC. J. High Energ. Phys. 2021, 256 (2021). https://doi.org/10.1007/JHEP03(2021)256

2) Gonderinger, M., Ramsey-Musolf, M.J. Electron-to-tau lepton flavor violation at the Electron-Ion Collider. J. High Energ. Phys. 2010,45 (2010). https://doi.org/10.1007/JHEP11(2010)045

Previous e→ τ Experimental Limits

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

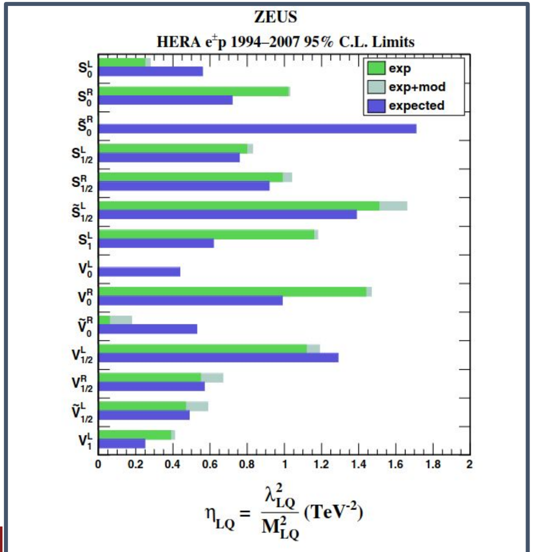
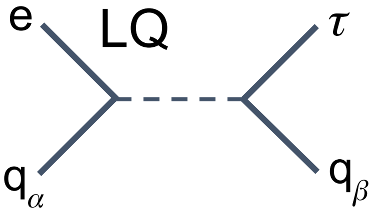
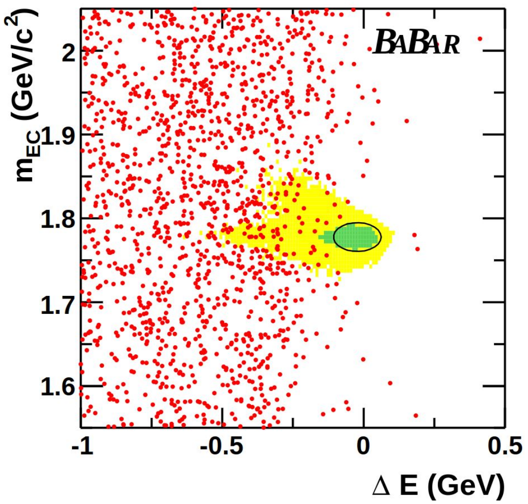


FIG. 5. Upper 95% C.L. limits on the LQ coupling strength, $\eta_{LQ} = \lambda^2_{LQ}/M^2_{LQ}$. Compared are the limits calculated without (dark upper bars) and with (light upper bars) modeling uncertainties, and the expected limits (lower bars).



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



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

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,

τ^{-} Properties

- M_{τ} = 1776.86(0.12) MeV
- Lifetime = 290.3(.5)x10^{-15}s
- Numerous decay modes
  - Multiple decays modes will likely need to analysed to produce strong CLFV limits

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)%
$e^{-}\bar{\nu}\nu$	17.82(0.04)%
$\mu^{-}\bar{\nu}\nu$	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	

E→τ with a "3-prong" Decay in EIC

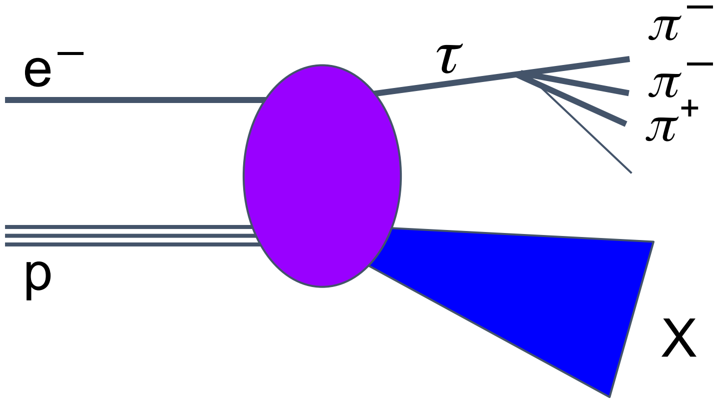
3-prong decay

$\tau \rightarrow \pi^{-}\pi^{+}\pi^{-}\nu_{\tau}$

Pro: event identification is relatively easy

Con: only a ~9% branching ratio

Studied for the ECCE detector[3] 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 < : Photoproduction events
  - < 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)

- 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

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18x275 GeV

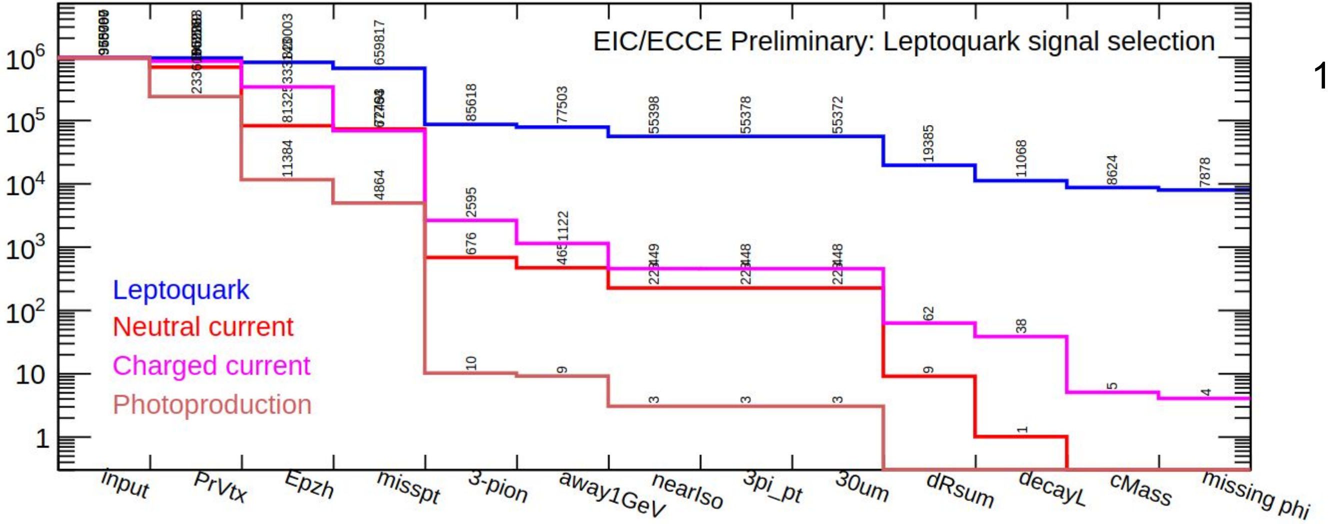
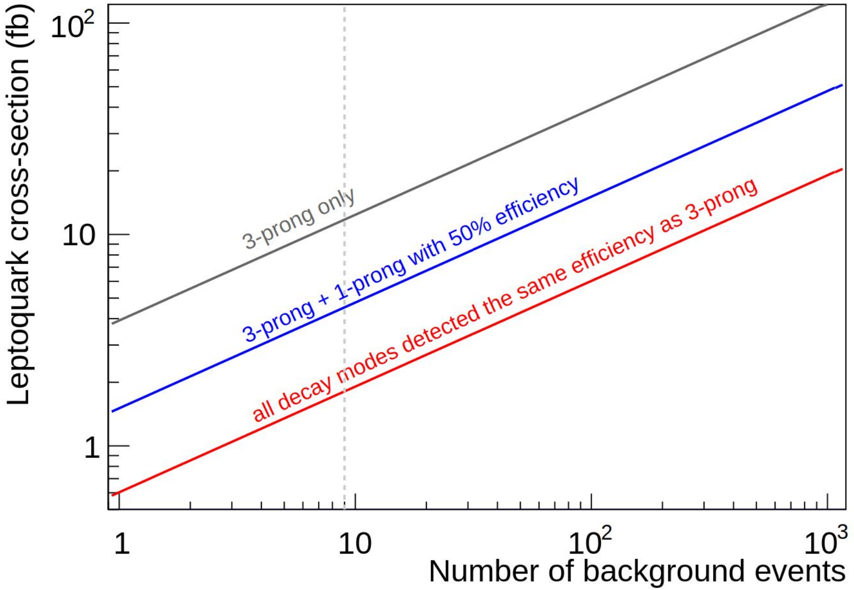


Figure 4: MC statistics of leptoquark (blue), DIS CC (red), DIS NC (magenta), and photoproduction (orange) events, as ten selection criteria are progressively applied on 1 M input events for each channel. Please see text for details.

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

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)
https://doi.org/10.1016/j.nima.2023.168276

Scalar Leptoquark Sensitivity

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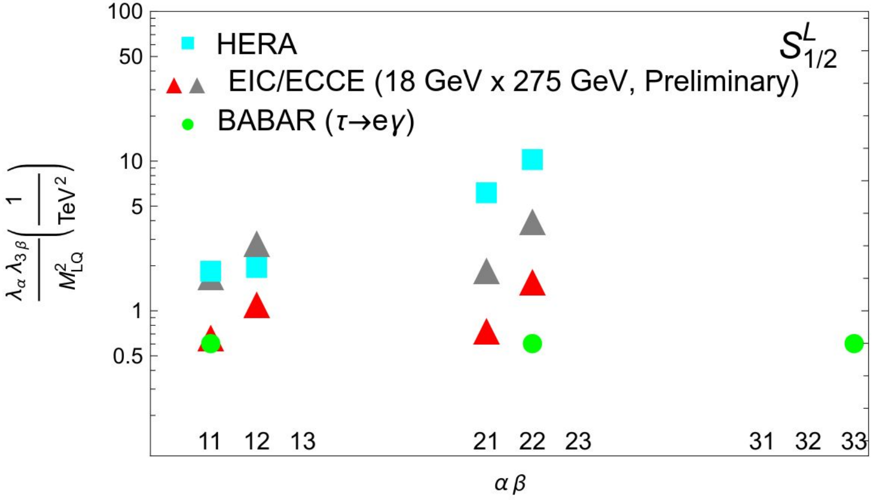

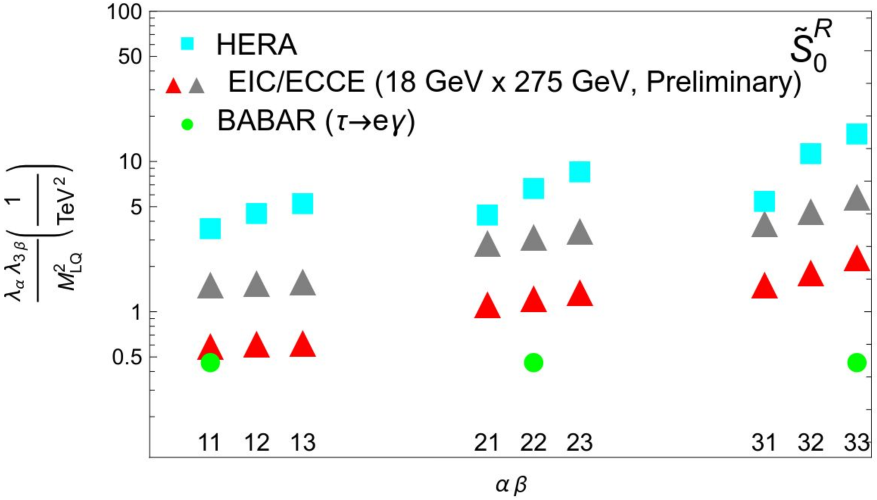

3) Zhang et al. Search for e ⟶ τ Charged Lepton Flavor Violation at the EIC with the ECCE Detector (2022)
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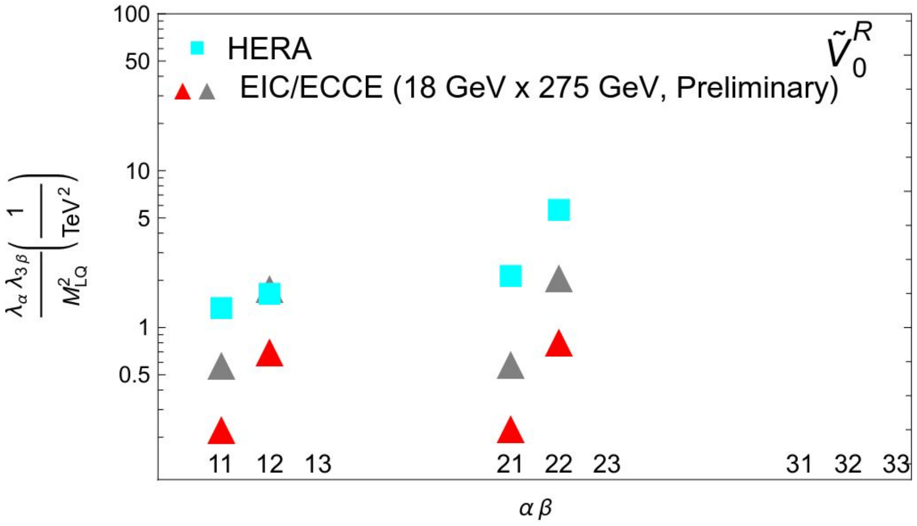
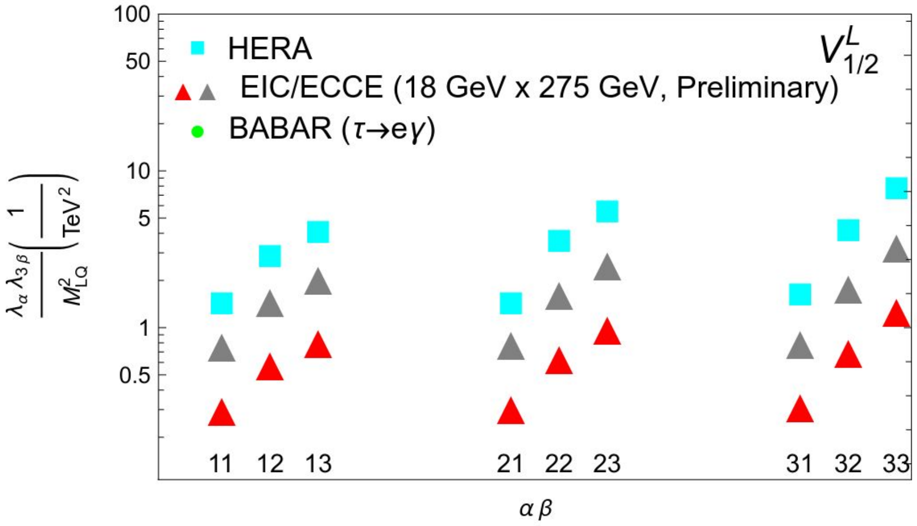
Vector Leptoquark Sensitivity





3) 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

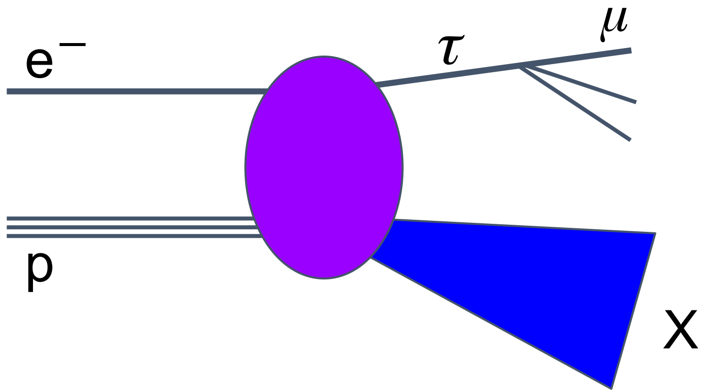
“1-prong” Muon Decay

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

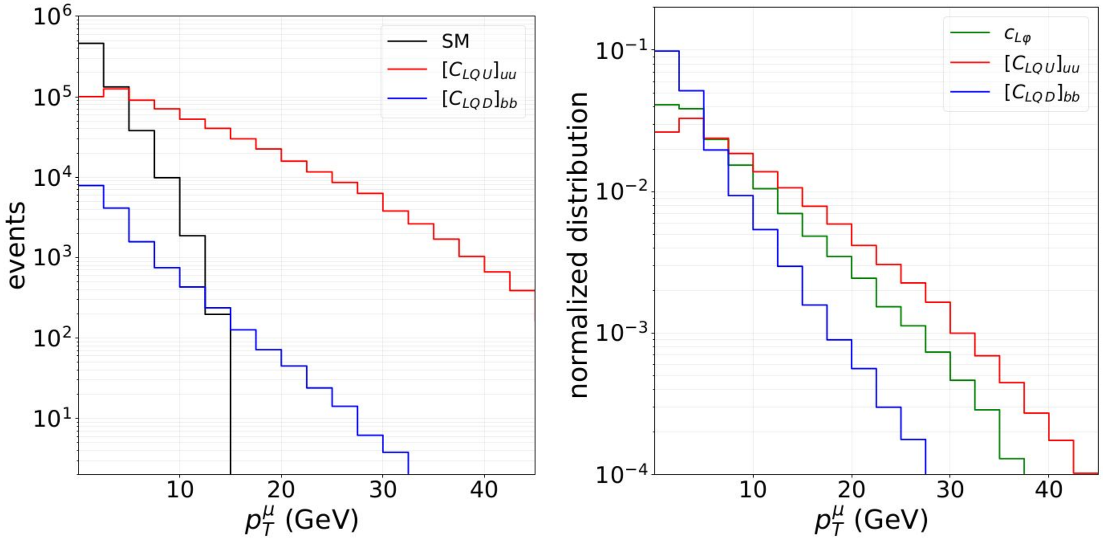
Pros:
Suppression of SM background.

~17% branching ratio

Con: requires good muon identification



Muon channel



- too much background in e channel, μ channel much more promising!
- in SM, μ come from hadron decays, typically at small p_T

$$p_T^\mu > 10\,\mathrm{GeV}, \quad \not{E}_T > 15\,\mathrm{GeV}, \quad p_T^{j_1} > 20\,\mathrm{GeV}$$

eliminates all SM background

- smaller signal efficiency for Z couplings, heavy quarks

Slide courtesy of Emanuele Mereghetti

Event Selection Sketch

- 1 charged track identifiable as a muon
- Displaced muon vertex
- Cuts to reject mis-ID'd hadrons or electrons
- P_T imbalance caused by undetected neutrinos
- Large Hadronic Jet P_T
- Hadronic Jet is back-to-back with the τ Jet
- TBD additional cuts to suppress backgrounds

muon ID in the ePIC Detector

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- EPIC does not have a dedicated muon detector currently in its design
  - First attempt at muon identification is to look for negatively charged tracks that are minimally ionizing in the calorimeters
  - Main suspected mis ID tracks using only calorimeters is pions

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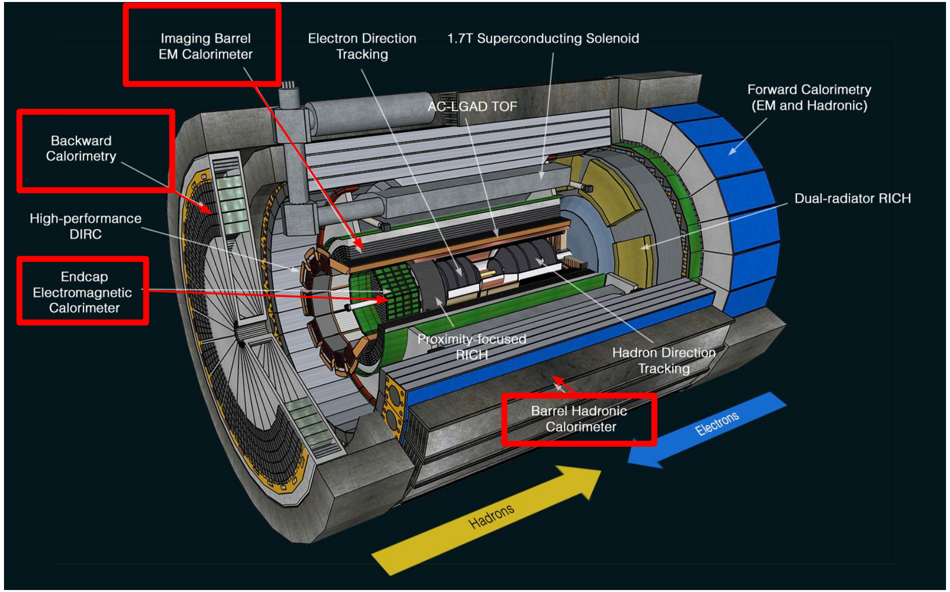
Single tracks ePIC calorimeters

- Simulate single, negatively charged particle events
  - Evaluate how well E/p cuts can suppress non-muon tracks while keeping as many muons as possible
  - No shower shape information has been used yet



E/p of Charged Tracks in endcap ECal

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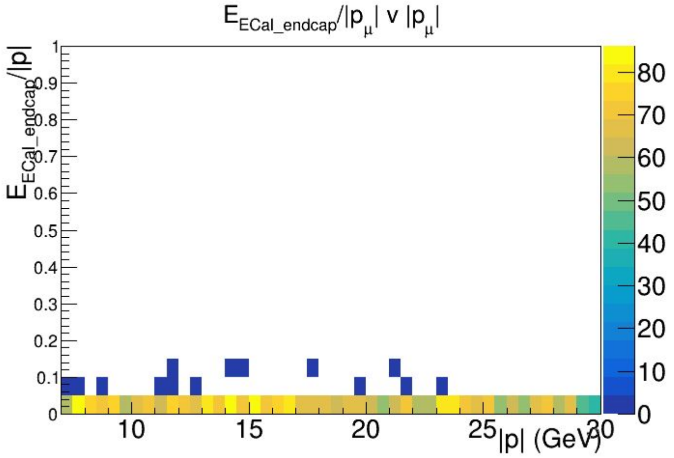
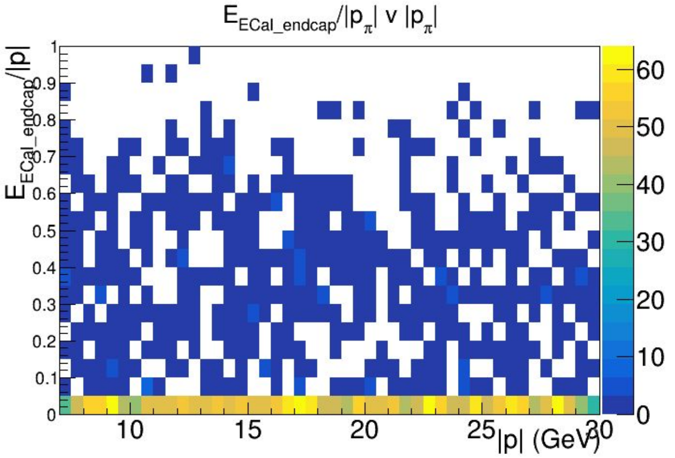
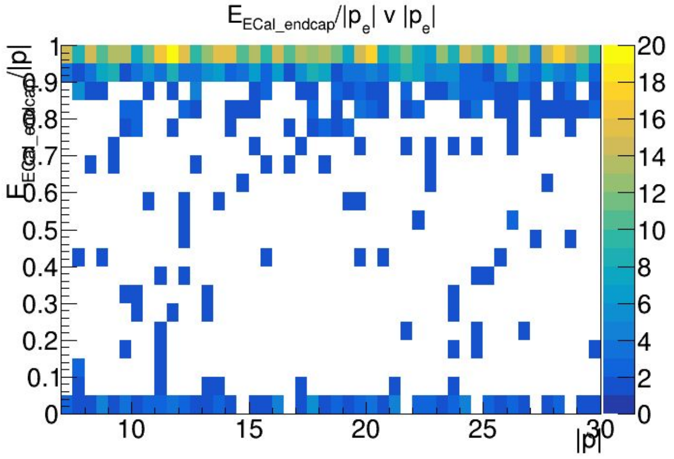
μ-



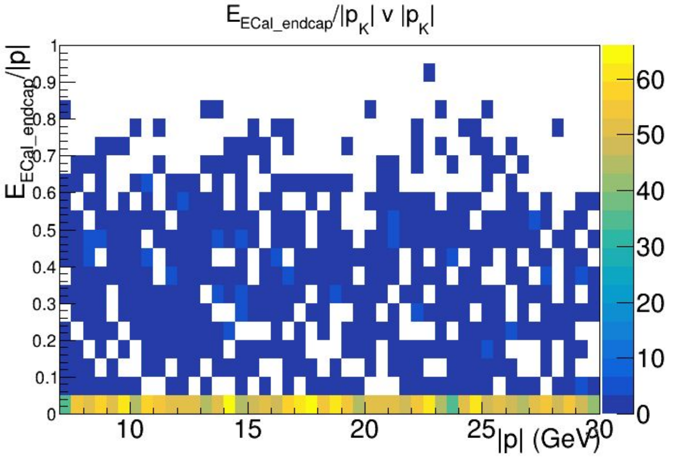
π-



e-

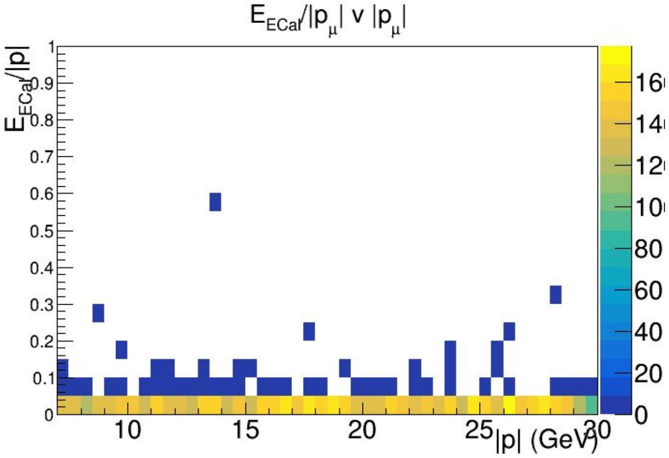


K-

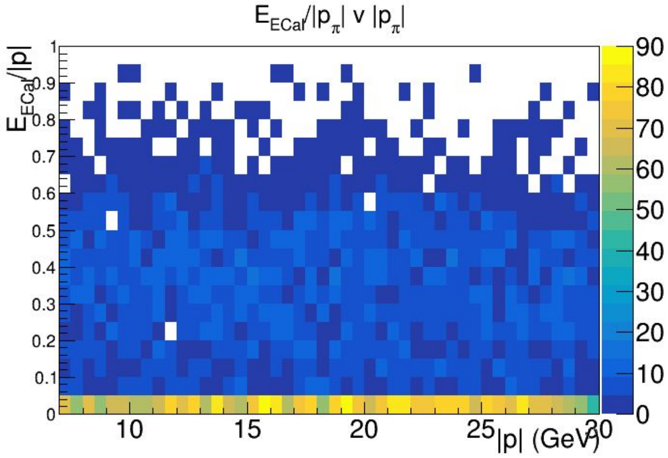


E/p of Charged Tracks in Barrel ECal

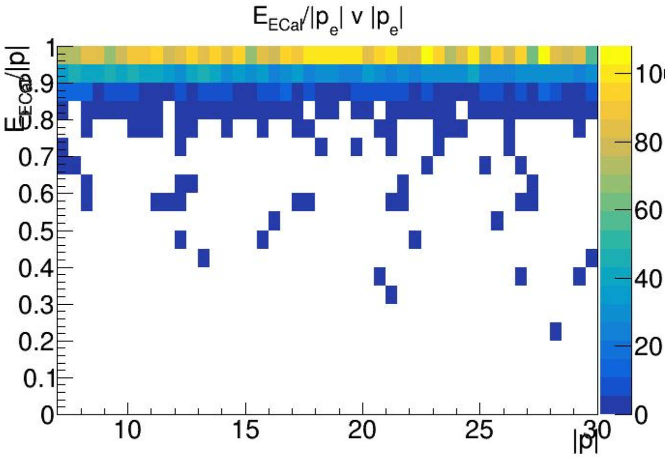
μ-



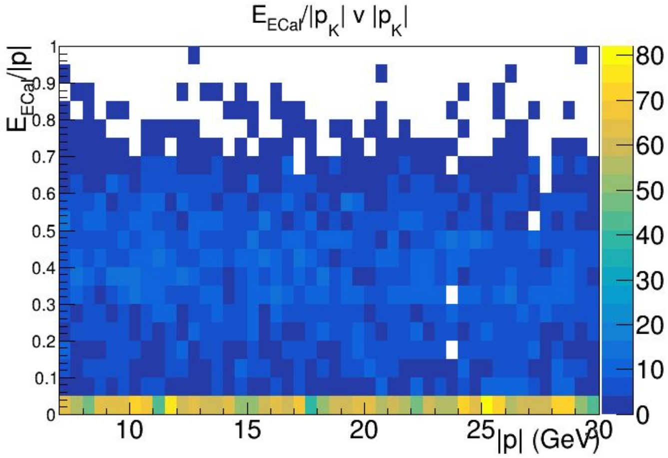
π-



e-



K-



E/p of Charged Tracks in Barrel HCal

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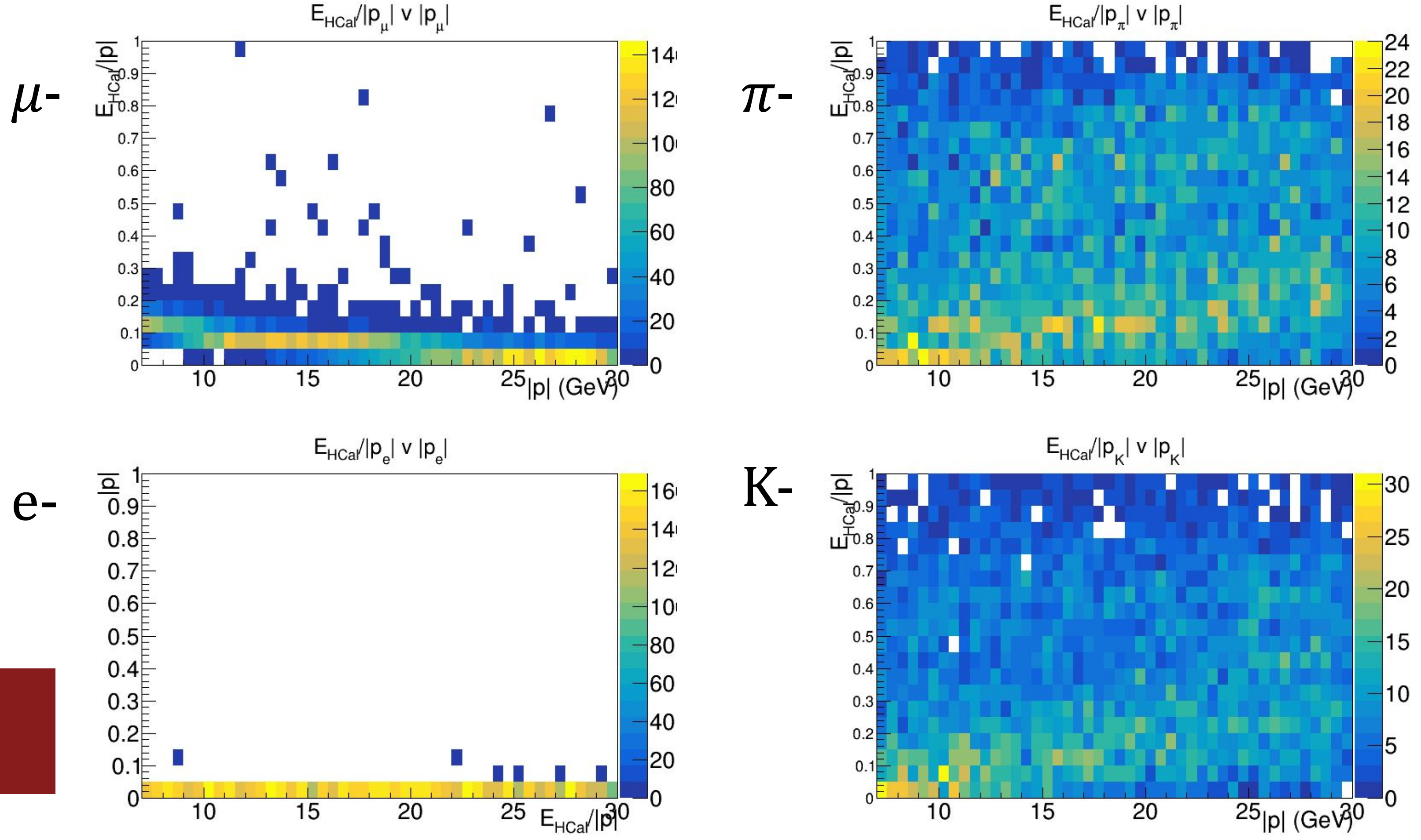

Using Multiple Calorimeters

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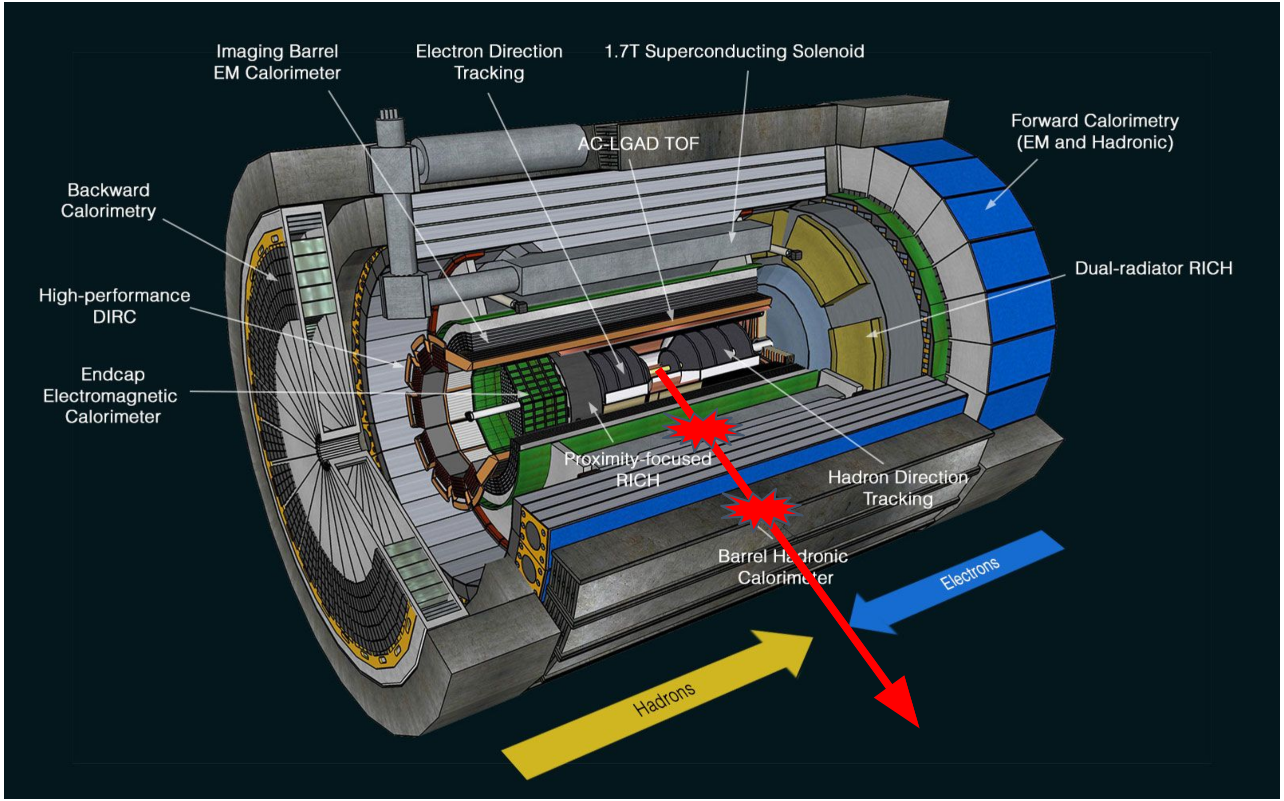

Using E/p in Both Barrel Calorimeters

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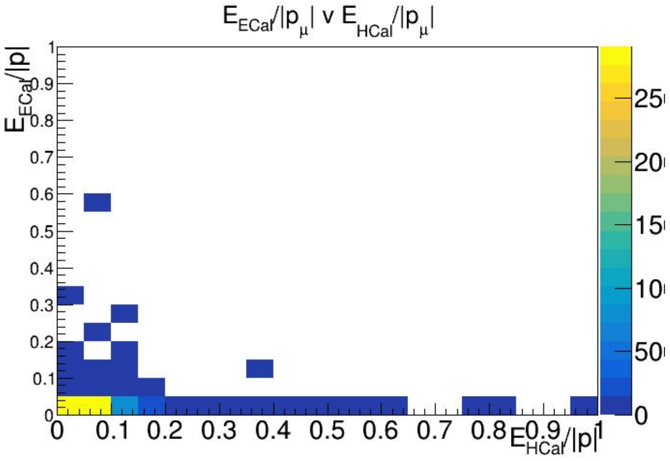
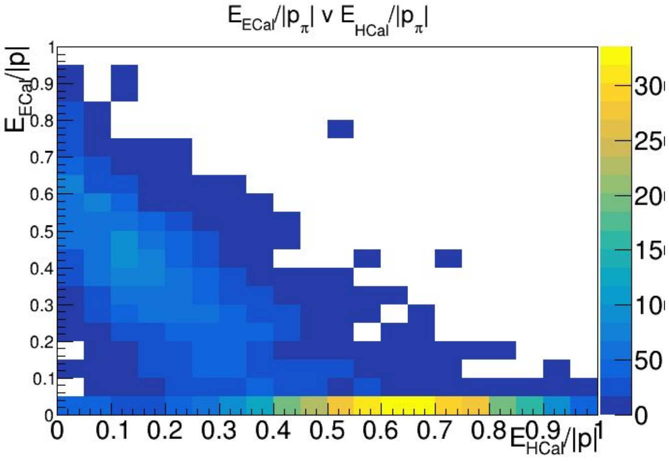
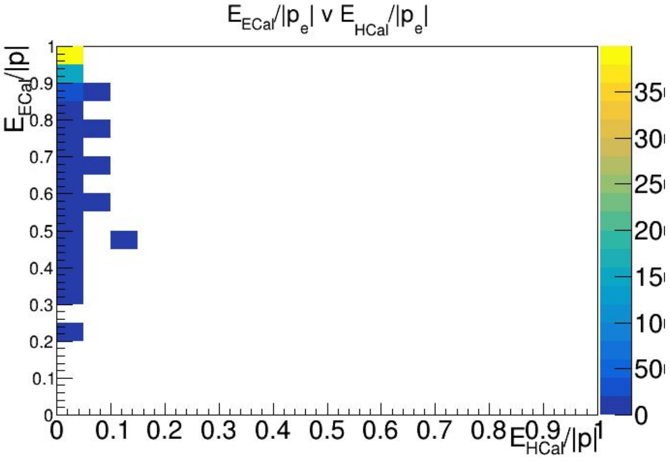
μ-



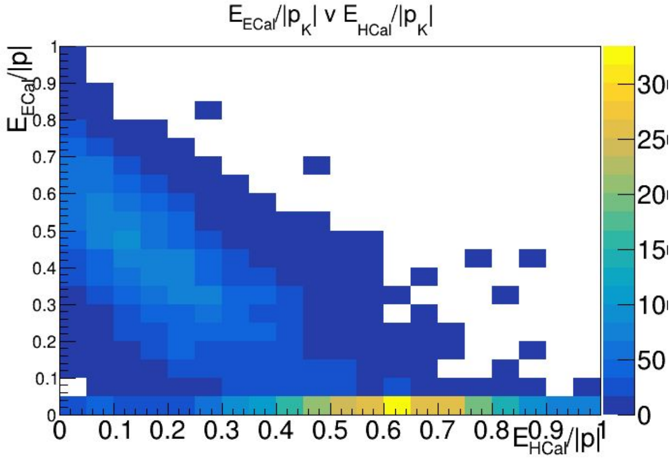
π-



e-



K-

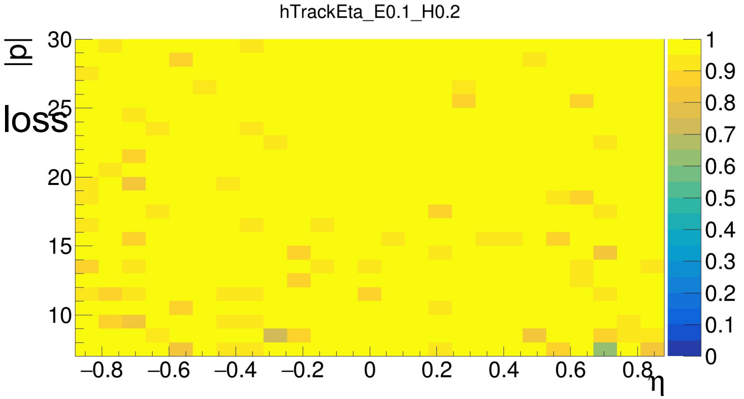


HCal E/p < 0.2 + ECal E/p < 0.1

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

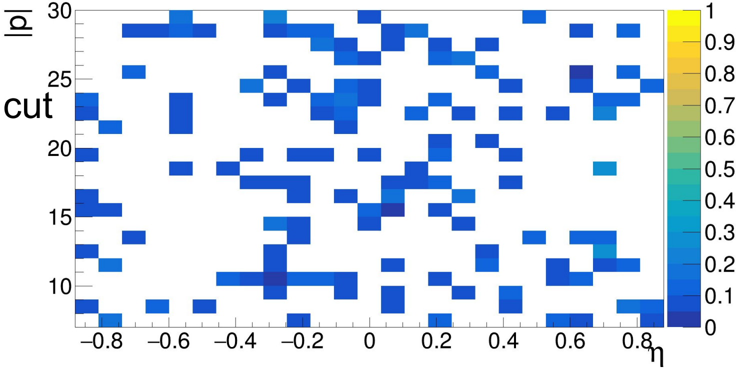
μ-

~1% loss



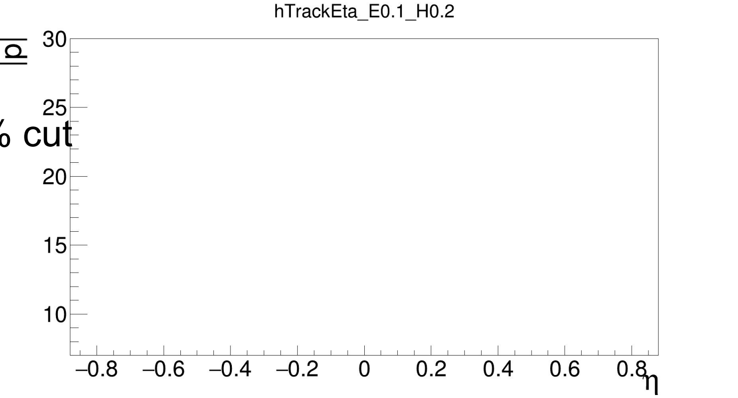
π-

98% cut



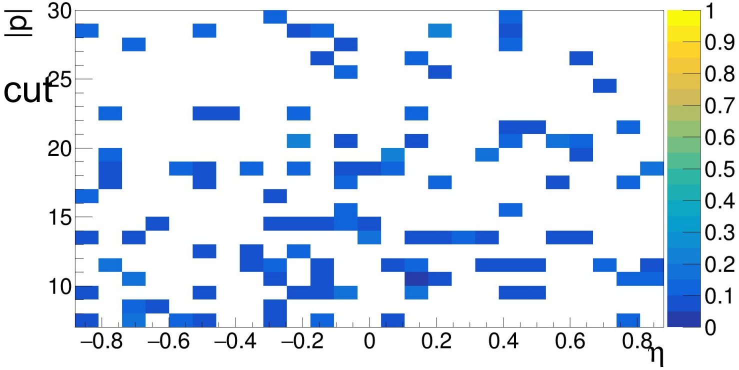
e-

>99% cut



K-

96% cut



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Muon channel outlook

- Study the shower shapes to see if calorimeter based separation can be improved
- Study the use of other detector systems to identify muons/reject other particles
- Implement event selection cuts, e.g:
  - Displaced muon vertex
  - P_T imbalance caused by undetected neutrinos
  - Large Hadronic Jet P_T
  - Hadronic Jet is back-to-back with the τ Jet
  - TBD additional cuts to suppress backgrounds
- Apply cuts to SM Monte Carlo to evaluate how much background is suppressed

Summary

- CLFV measurement offers an undeniable signature of BSM physics if observed.
  - The EIC can be competitive in probing the $e \rightarrow \tau$ coupling.
    - Many of the τ decay modes will need to be analyzed.
- Muon identification combining the E/p of multiple calorimeters along a muons path shows some promise.
  - Whether the background suppression is sufficient or not will depend on the specific analysis and the size of its background.
  - Future studies will focus on incorporating additional detectors as well as shower shapes.

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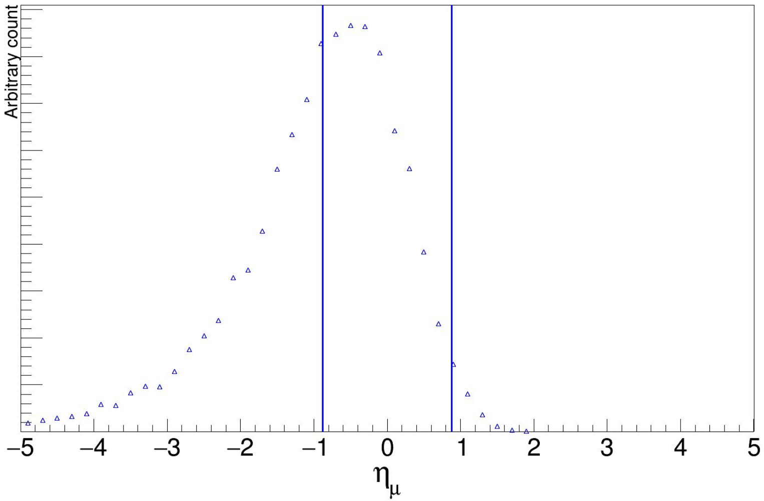
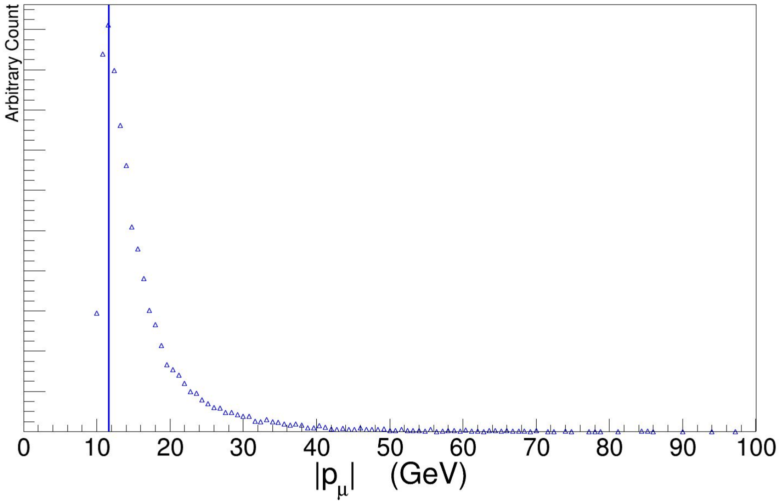
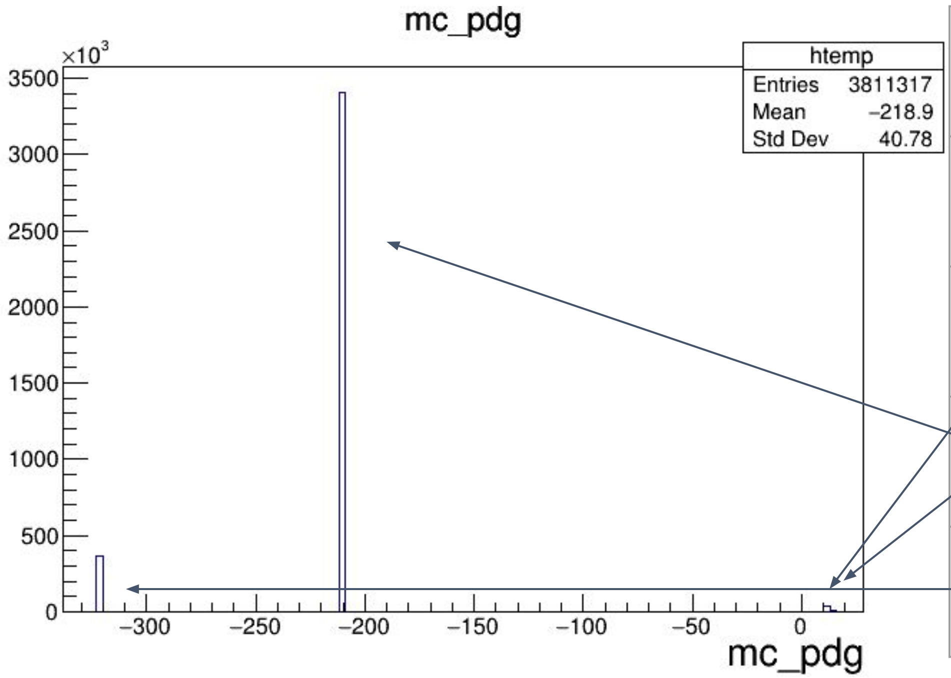
η and |p| of e→τ muons

- LQGENEP simulation
  - Q^2 = 300GeV
  - E_e x E_p = 18 x 275





CC DIS Example of e/mu/pi/K ratios. 18x275. minQ2 = 100



mc pid	~Total
e	~39,000 (3K)
μ	~5,000 (570)
π	~3,400,000 (560K)
K	~360,000 (80K)

Cuts on μ tracks

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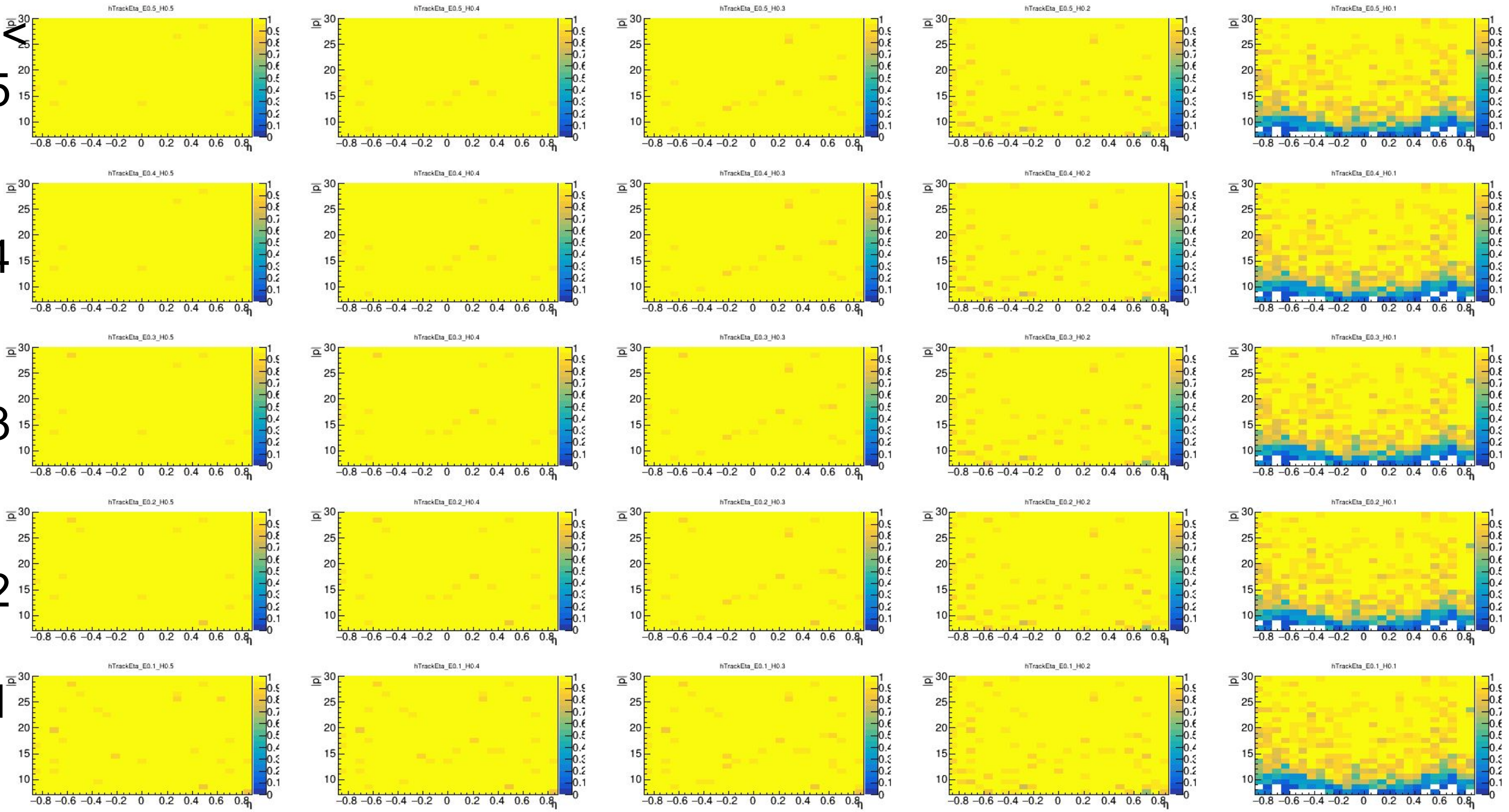
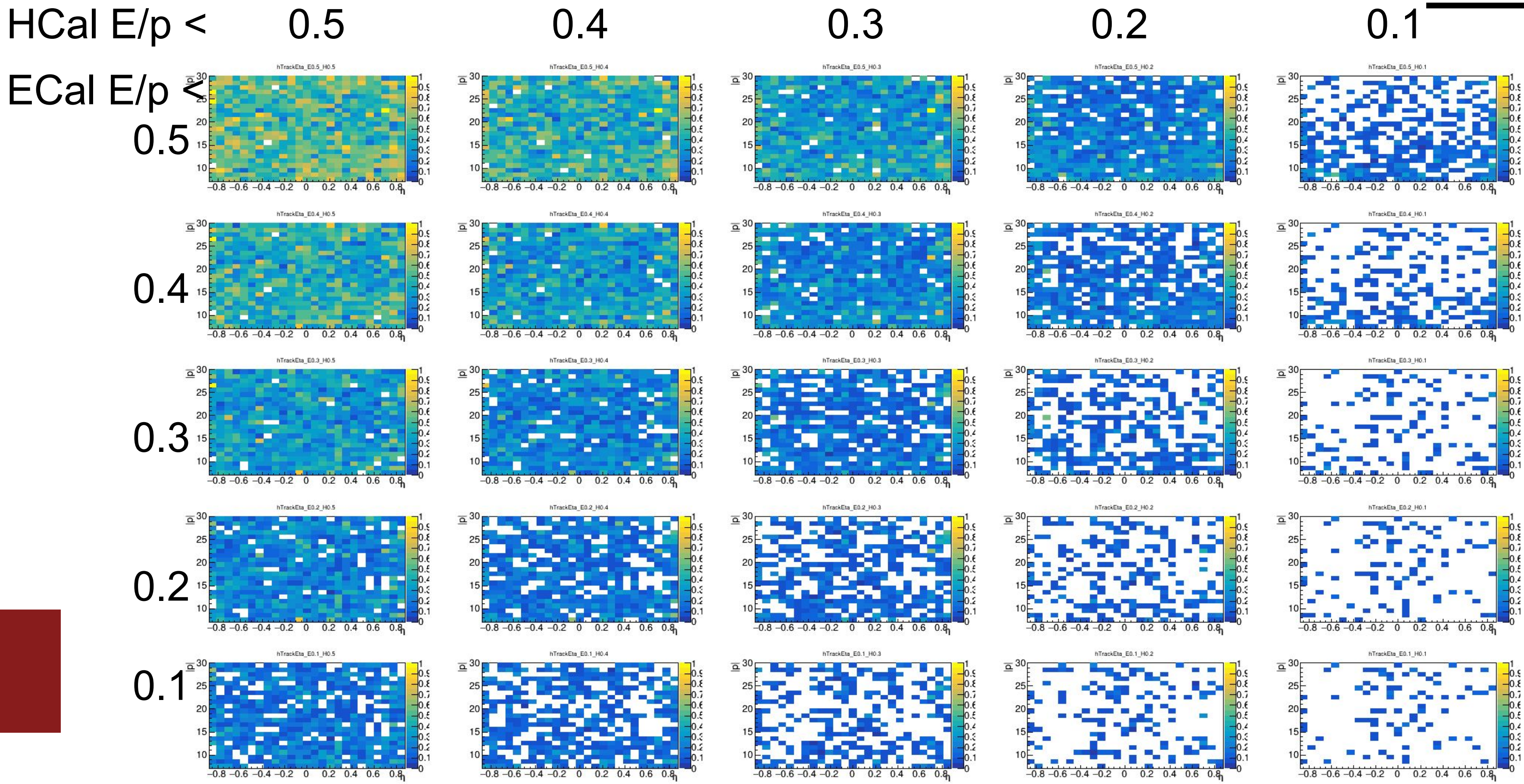
HCal E/p < 0.5 0.4 0.3 0.2 0.1

ECal E/p < 0.5 0.4 0.3 0.2 0.1



Cuts on π tracks



Cuts on e tracks

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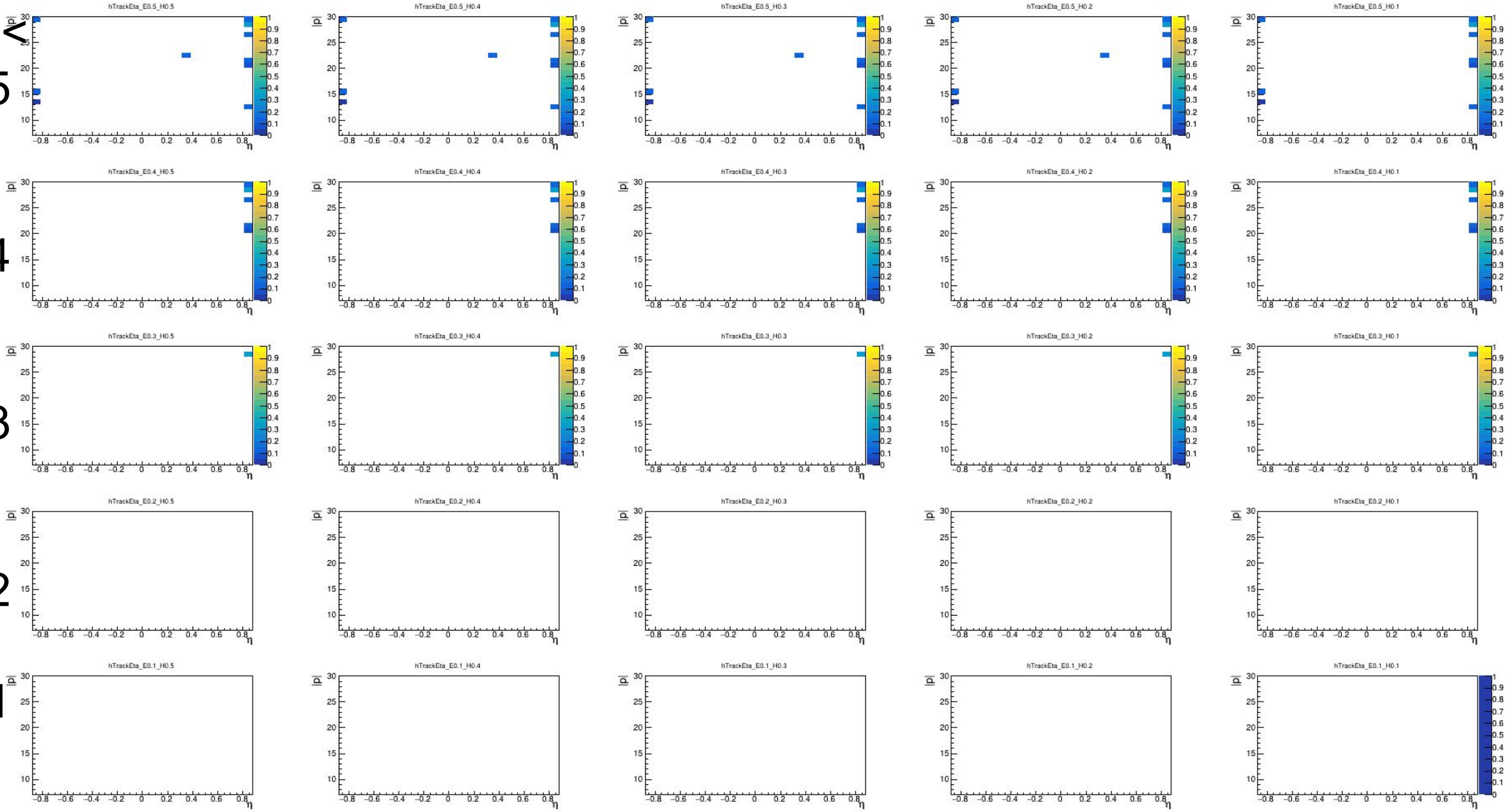
HCal E/p < 0.5 0.4 0.3 0.2 0.1

ECal E/p < 0.5 0.4 0.3 0.2 0.1



Cuts on K tracks

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HCal E/p < 0.5 0.4 0.3 0.2 0.1

ECal E/p <

0.5

0.4

0.3

0.2

0.1