

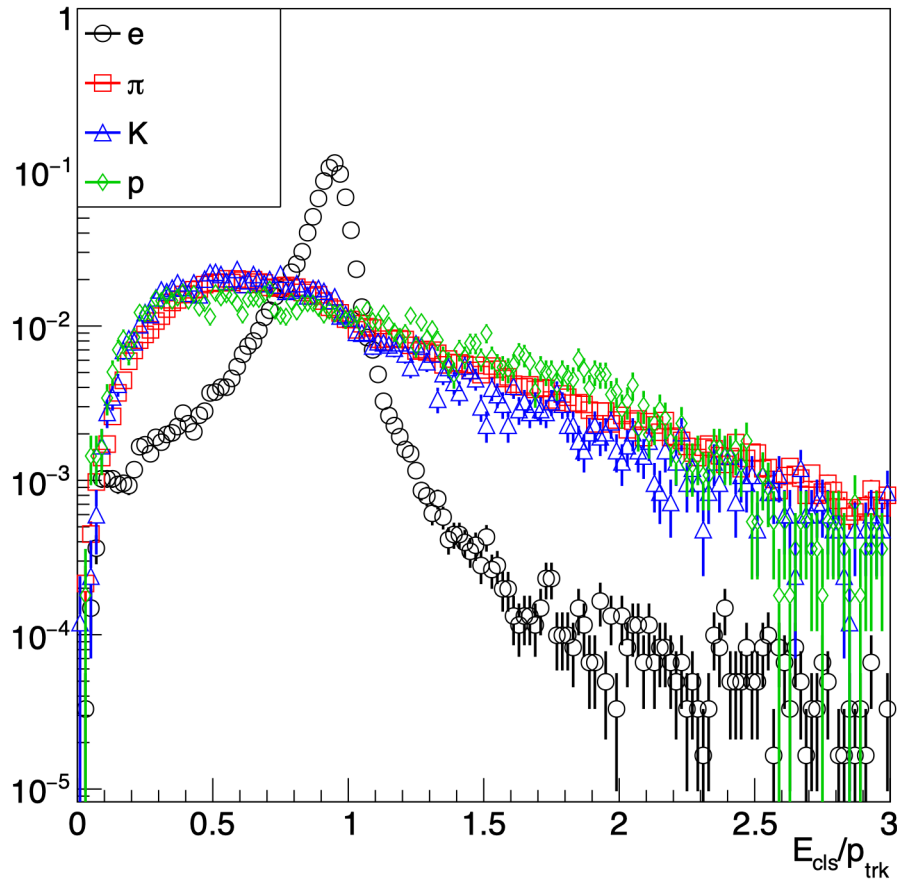
Transverse Spin Asymmetries in Inclusive ep DIS as a Probe of Quark Dipole Operator

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Knowledge gained from ALP study

ECAL response in BEMC to e and h

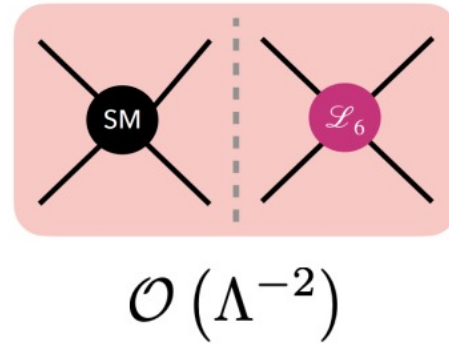
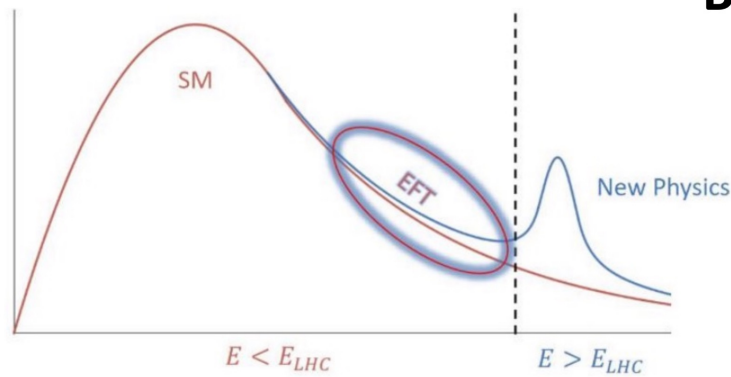


- Searches for Axion-Like Particle (ALP) ongoing
 - Currently investigating decay channels ($a \rightarrow \mu^+ \mu^-$, $e^+ e^-$) and finalizing non-decaying channel with BDT-based selection (Ganesh)
 - Event characterization based on identified electron in non-decaying channel
- eID based on ECal and Tracking
 - Good electron purity in DIS environment
 - Further improvement expected with input from PID detectors in terms of precision and kinematic reach

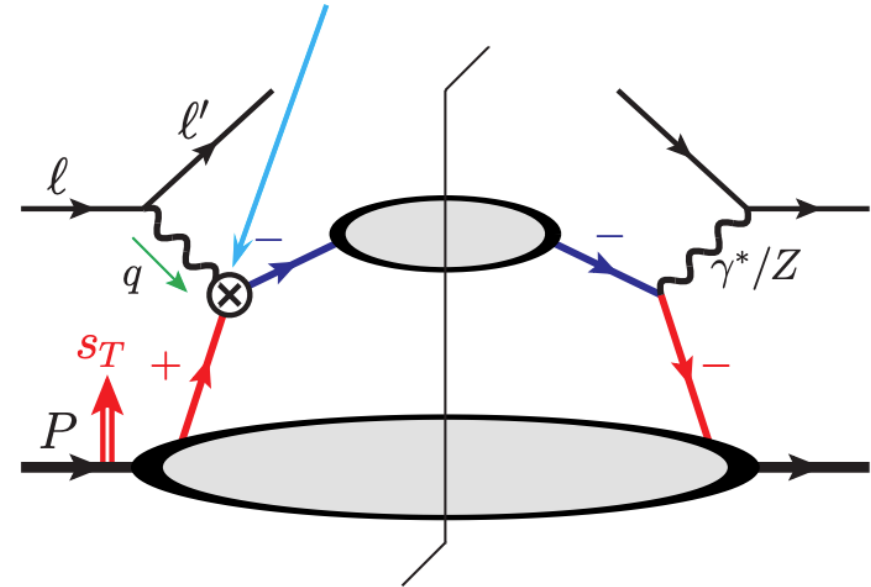
SMEFT and Quark Dipole Operator

- **SMEFT cross section:**

$$\sigma \propto |\mathcal{M}_{\text{SM}} + \Lambda^{-2} \mathcal{M}_{\text{NP}}|^2$$

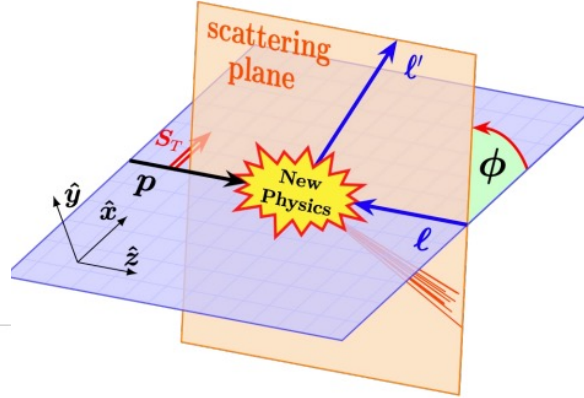
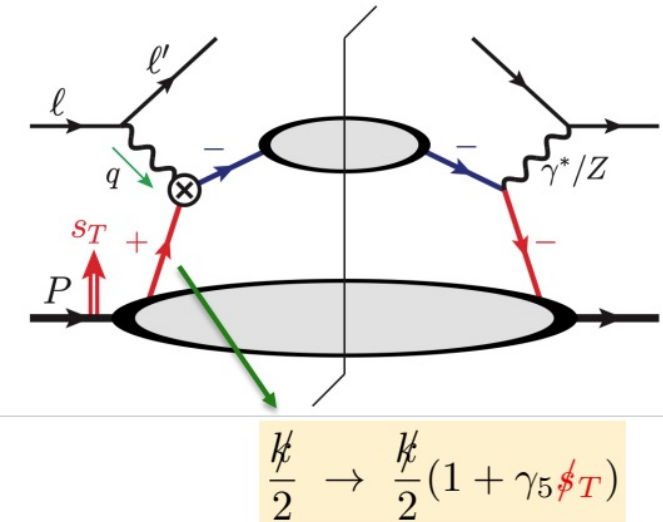


$$\bar{q}_L \sigma_{\mu\nu} q_R A^{\mu\nu}, \bar{q}_L \sigma_{\mu\nu} q_R Z^{\mu\nu}$$



- Within SMEFT framework, EW quark dipole operators (QDO) generate effective low-energy couplings between quarks and $\gamma, Z, W^\pm$
- Chirally-odd; Enhanced coupling from interference with SM transversity
- Observable $\rightarrow$ Transverse Spin Asymmetries

Quark Dipole Operator at ePIC/EIC



$$\frac{d\sigma_{AA}}{dx_B dQ^2 d\phi} = \Sigma_{UU}^{AA} + \lambda_e S_T \Sigma_{LT}^{AA}(\Delta\phi), \quad \Delta\phi \equiv \phi - \phi_S$$

$$\Sigma_{UU}^{AA} = \frac{\alpha_e^2}{Q^4} f_q(x_B) \cdot e_q^2 [1 + (1-y)^2],$$

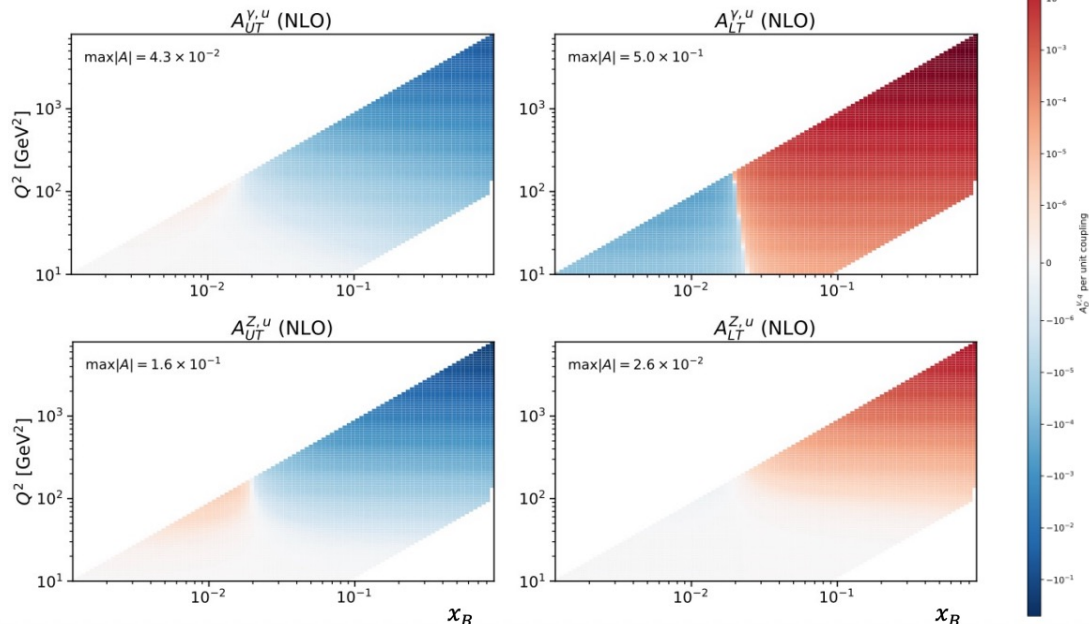
$$\Sigma_{LT}^{AA}(\Delta\phi) = -\frac{\alpha_e^2}{Q^4} \frac{2Q\sqrt{1-y}}{v} h_q(x_B) \cdot (e_q y) \left[\text{Re}(\Gamma_\gamma^q) \cos(\Delta\phi) - \text{Im}(\Gamma_\gamma^q) \sin(\Delta\phi) \right]$$

$$\frac{d\sigma_{AZ}}{dx_B dQ^2 d\phi} = \Sigma_{UU}^{AZ} + \lambda_e \Sigma_{LU}^{AZ} + S_T \Sigma_{UT}^{AZ}(\Delta\phi) + \lambda_e S_T \Sigma_{LT}^{AZ}(\Delta\phi)$$

$$\Sigma_{UT}^{AZ} = -\frac{\alpha_e \alpha_Z h_q(x_B)}{4Q^2(Q^2 + m_Z^2)} \frac{2Q\sqrt{1-y}}{v} \left\{ [g_V^e g_A^q (2-y) + g_A^e g_V^q y] \text{Re}(\Gamma_\gamma^q e^{i\Delta\phi}) + 2e_q g_A^e y \text{Re}(\Gamma_Z^q e^{i\Delta\phi}) \right\},$$

$$\Sigma_{LT}^{AZ} = \frac{\alpha_e \alpha_Z h_q(x_B)}{4Q^2(Q^2 + m_Z^2)} \frac{2Q\sqrt{1-y}}{v} \left\{ [g_A^e g_A^q (2-y) + g_V^e g_V^q y] \text{Re}(\Gamma_\gamma^q e^{i\Delta\phi}) + 2e_q g_V^e y \text{Re}(\Gamma_Z^q e^{i\Delta\phi}) \right\}$$

Asymmetry distribution



- Novel channel for QDO by R. Boughezal, et al. [2301.02304], calculated for ePIC/EIC kinematics by Z. Yu and S. Dawson
- Results in two (TSSA, LT DSA) transverse spin asymmetries in **inclusive *ep* DIS**
- Numeric calculation in progress

Strategy

- Probe experimental sensitivity of ePIC/EIC on QDO using ePIC detector sim.
- Simulation
 - Official ePIC/EIC simulation stack based on Pythia 8.3 and Geant4
 - $E_e = 5, 9(10), \mathbf{18} \text{ GeV}$ on $E_p = 41, 100, \mathbf{275} \text{ GeV}$ ($\sqrt{s} = 140 \text{ GeV}$)
 - $10 < Q^2(\text{GeV}^2) < 100$, $100 < Q^2(\text{GeV}^2) < 1000$, $1000 < Q^2(\text{GeV}^2) < \text{INF}$
 - Scaled to $L_{int} = 100 \text{ fb}^{-1}$
- Event selection
 - Kinematic selection
 - $0.01 < y < 0.8$ (upper limit can be extended to 0.95)
 - $W^2 > 20 \text{ GeV}^2$ (ePIC analyses commonly use $> 4 \text{ GeV}^2$)
 - $p_{T,e} > 1.5 \text{ GeV}$ (can go as low as 0.5 GeV or below)
 - Electron ID
 - ALP electron selection using E/p, cluster-isolation (backup)
 - DIS selection (WIP)
 - Based on $p_{T,miss}$ and $E - P_z$

Strategy

- Arbitrarily introduce electron and proton polarization:

- Event ID % 4 == 0 : $P_e, P_p = \uparrow, \uparrow$
- Event ID % 4 == 1 : $P_e, P_p = \downarrow, \uparrow$
- Event ID % 4 == 2 : $P_e, P_p = \uparrow, \downarrow$
- Event ID % 4 == 3 : $P_e, P_p = \downarrow, \downarrow$

*Only the proton polarization considered

- Asymmetry extraction (only looking at cos modulation)

$$** \phi = \phi_e - \phi_s$$

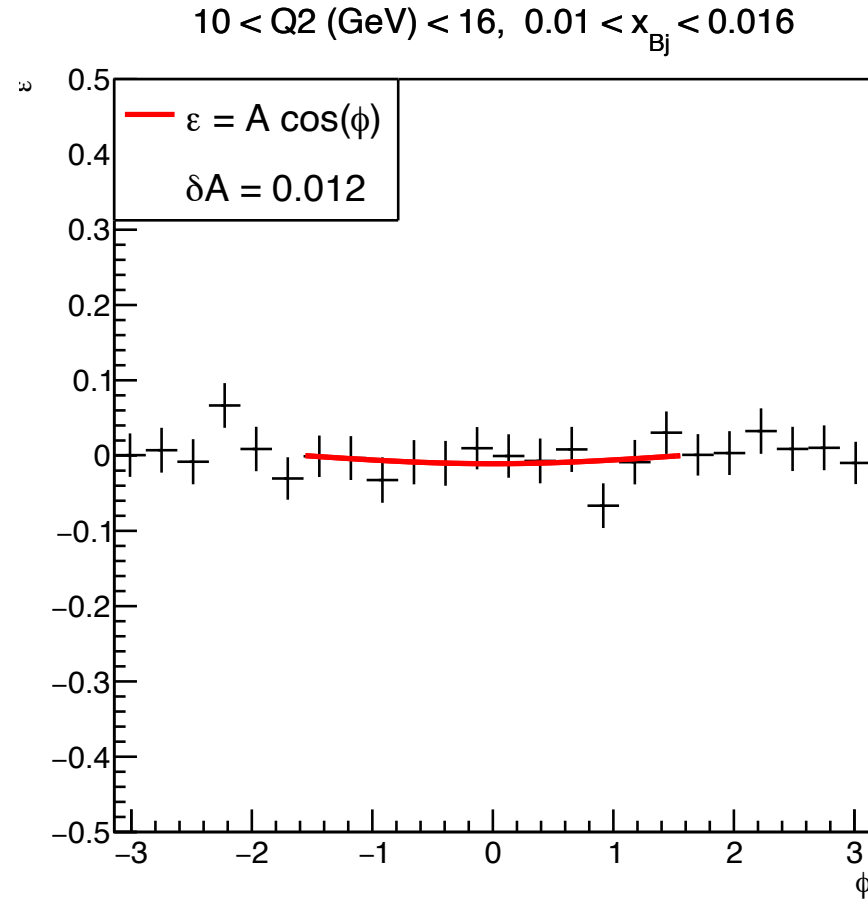
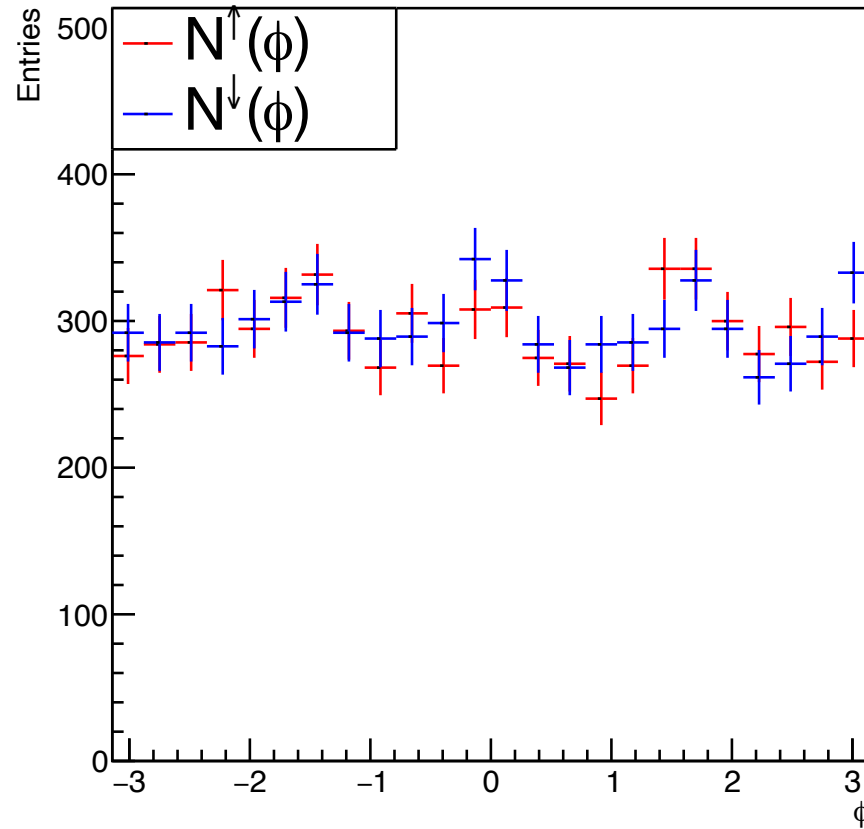
$$A_{UT} \cos \phi = \frac{1}{P(= 0.7)} \cdot \frac{\sigma^\uparrow(\phi) - \sigma^\downarrow(\phi)}{\sigma^\uparrow(\phi) + \sigma^\downarrow(\phi)} = \frac{1}{P} \frac{N^\uparrow(\phi)/L^\uparrow - N^\downarrow(\phi)/L^\downarrow}{N^\uparrow(\phi)/L^\uparrow + N^\downarrow(\phi)/L^\downarrow}$$

- Using cross-ratio formula, removing relative luminosity dependence

$$P \cdot A_{UT} \cos \phi = \epsilon = \frac{\sqrt{N^\uparrow(\phi)N^\downarrow(\phi + \pi)} - \sqrt{N^\downarrow(\phi)N^\uparrow(\phi + \pi)}}{\sqrt{N^\uparrow(\phi)N^\downarrow(\phi + \pi)} + \sqrt{N^\downarrow(\phi)N^\uparrow(\phi + \pi)}}$$

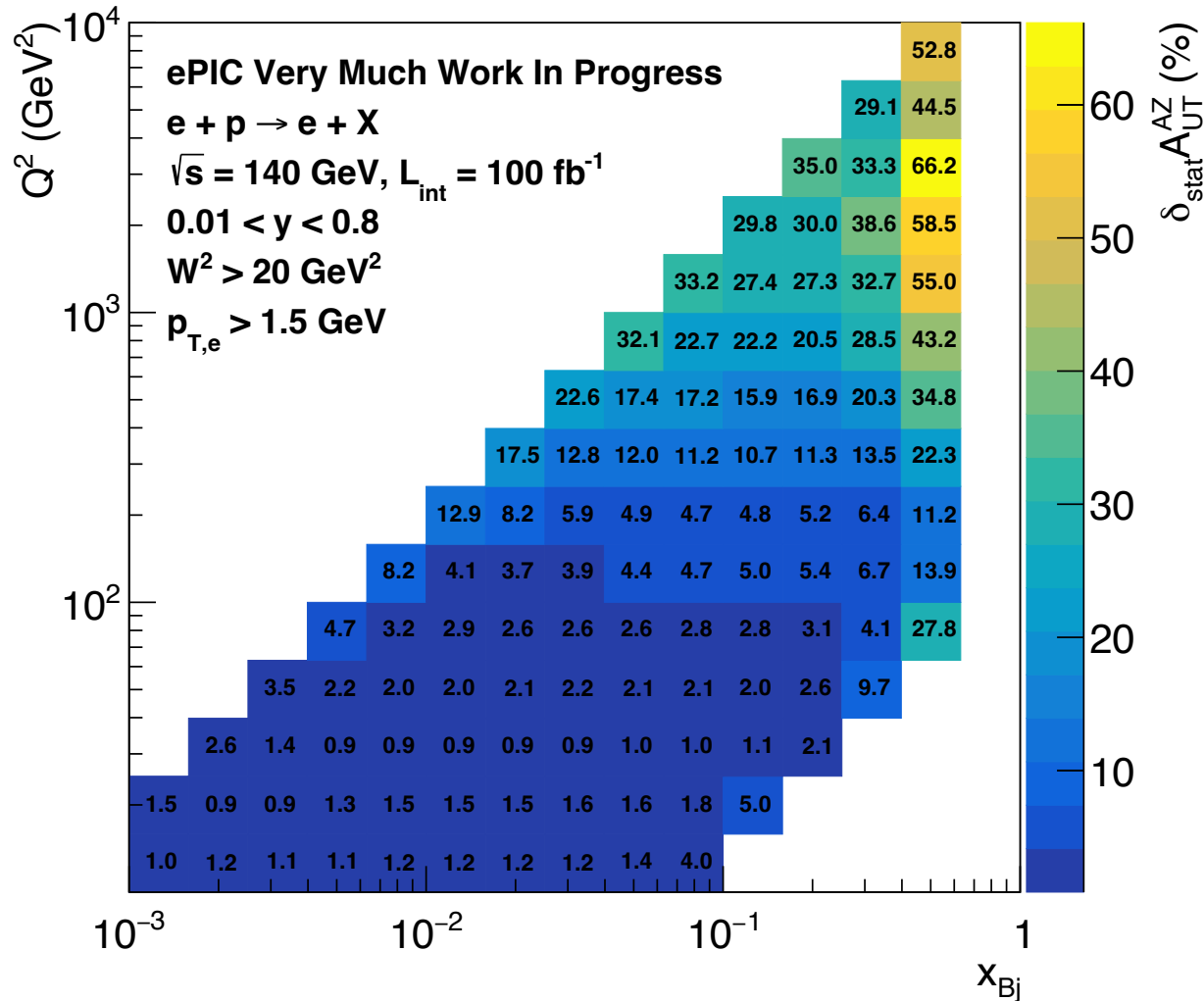
$$\delta\epsilon = \frac{1 - \epsilon^2}{4} \cdot \sqrt{\frac{1}{N_1} + \frac{1}{N_2} + \frac{1}{N_3} + \frac{1}{N_4}}$$

Asymmetry extraction



- Uncertainty extracted by fitting ϵ with $A \cos \phi$ between the range $[-\pi/2, \pi/2]$ to account for double counting

Asymmetry extraction



- Following corrections need to be applied:

- Polarization correction: $A_{UT} = \frac{1}{P} A$
- eID impurity & non-DIS background:

$$\begin{pmatrix} A_{e,raw} \\ A_{h,raw} \end{pmatrix} = \begin{pmatrix} f_e^{sig} & 1 - f_e^{sig} \\ f_e^{bg} & 1 - f_e^{bg} \end{pmatrix} \begin{pmatrix} A_e \\ A_h \end{pmatrix}$$

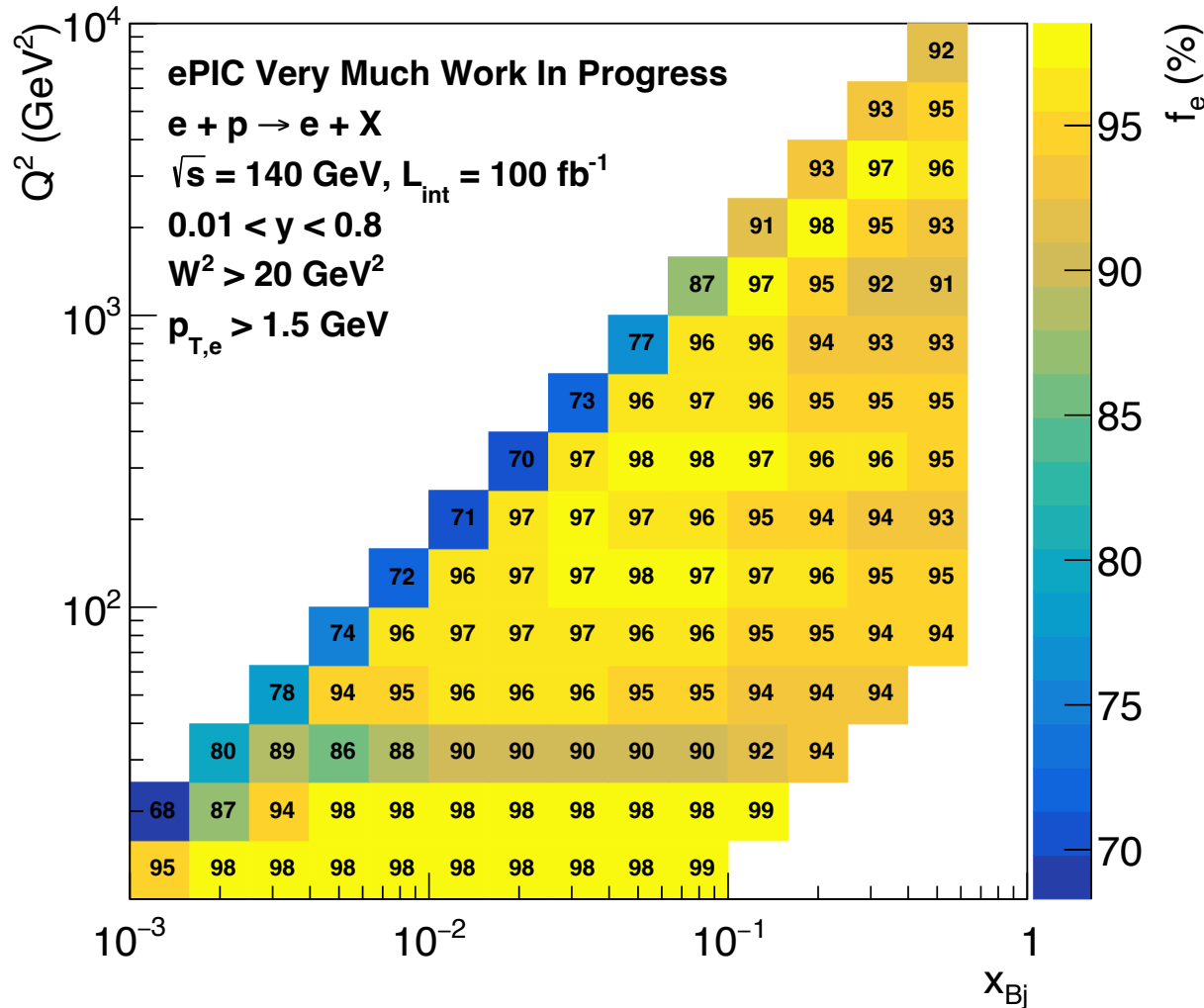
Assuming $A_h = 0 \rightarrow A_e = \frac{1}{f_e} A_{e,raw}$

- ϕ smearing (negligible): $A_{UT} = \frac{1}{c_\phi} A$

$$\delta A_{UT}[A_{UT}] = \frac{1}{P} \cdot \frac{1}{f_e} \cdot \frac{1}{c_\phi} \delta A[A]$$

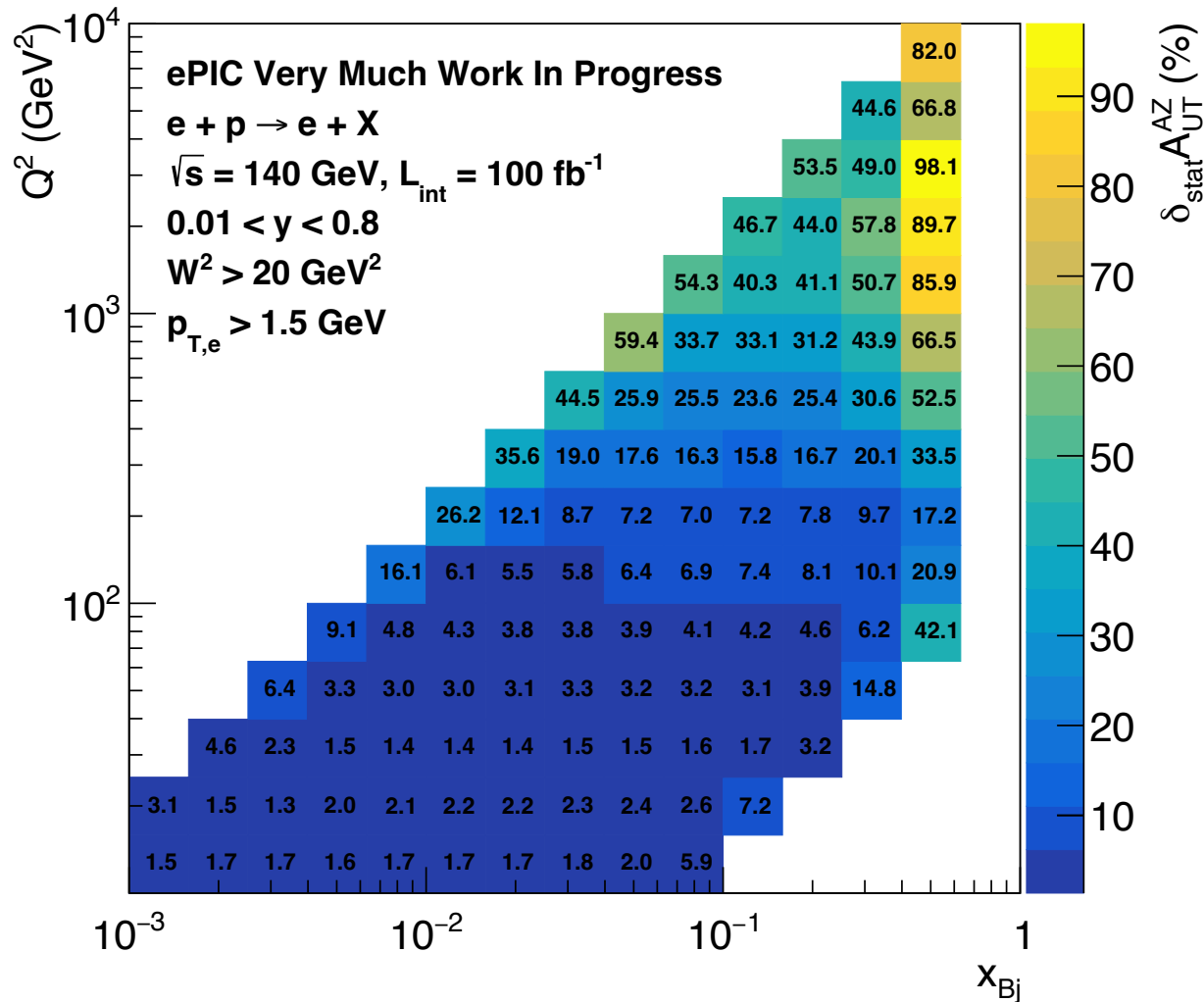
- Unfolding:** Currently using Truth $x, Q^2 \rightarrow$ Consult DIS experts

Electron purity



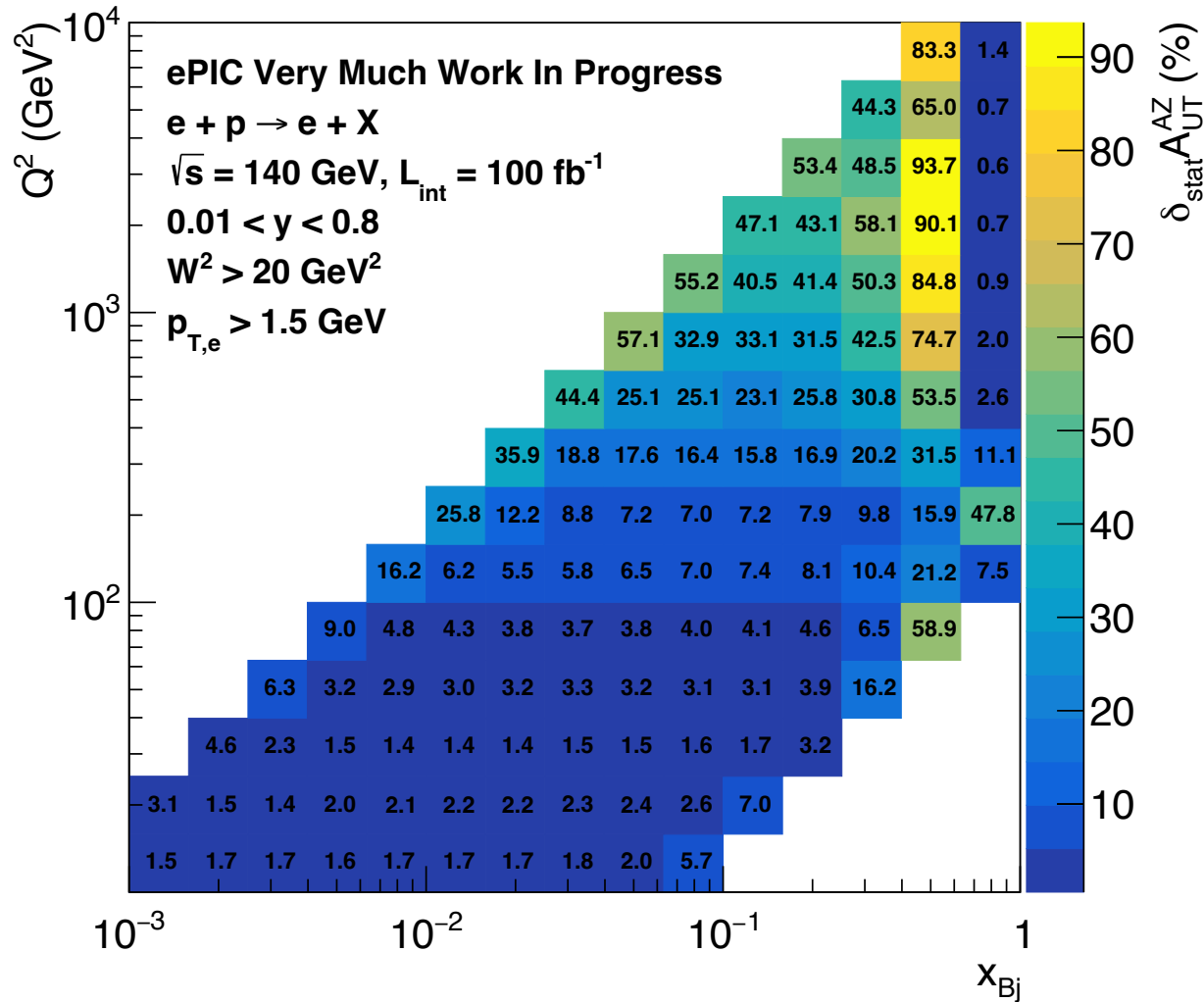
- eID based on ALP study ($\sim$ DIS)
- Electron purity $\geq 90\%$ over most of the kinematic space
- Further improvement expected incorporating PID detectors
- DIS selection scheme & background estimation need to be folded in for final asymmetry

Results: A_{UT}^{AZ}



- Estimated statistical uncertainty
 - Extracted via cross-ratio + cos fit
 - Missing BG est. & DIS selection
 - Missing ϕ smearing (exp. negligible)
 - Missing unfolding (truth kinematics)
 - Currently DIS convention for binning
 - Optimal binning based on guidance from theory
- ~ few percent to 50% statistical uncertainty in $Q^2 > 100 \text{ GeV}^2$ in the valence region

Results: A_{UT}^{AZ}

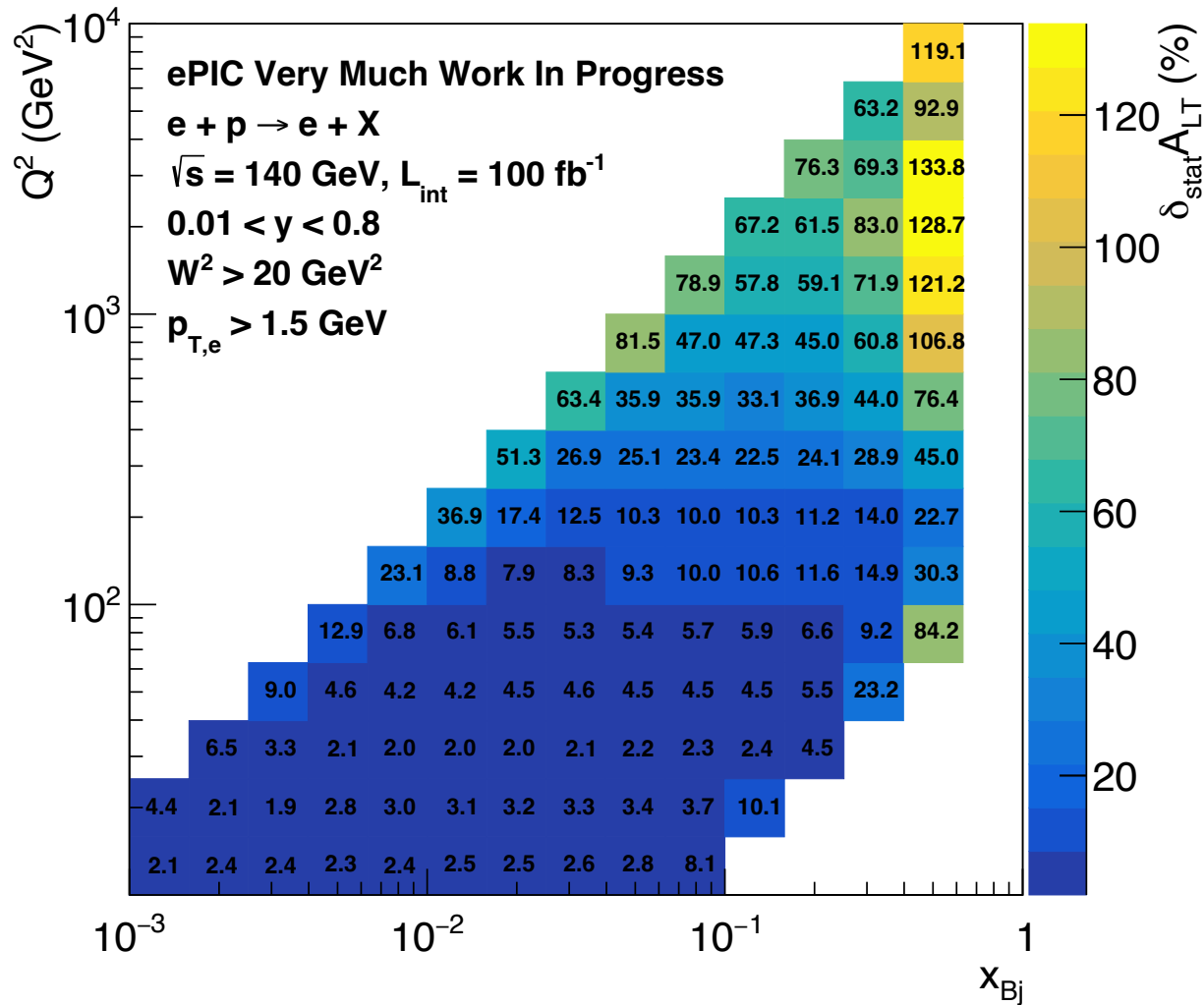


- Cross check with numeric method

$$\delta A_{UT} = \frac{1}{P} \cdot \sqrt{\frac{2}{N_{tot}}} \oplus \text{cor.}$$

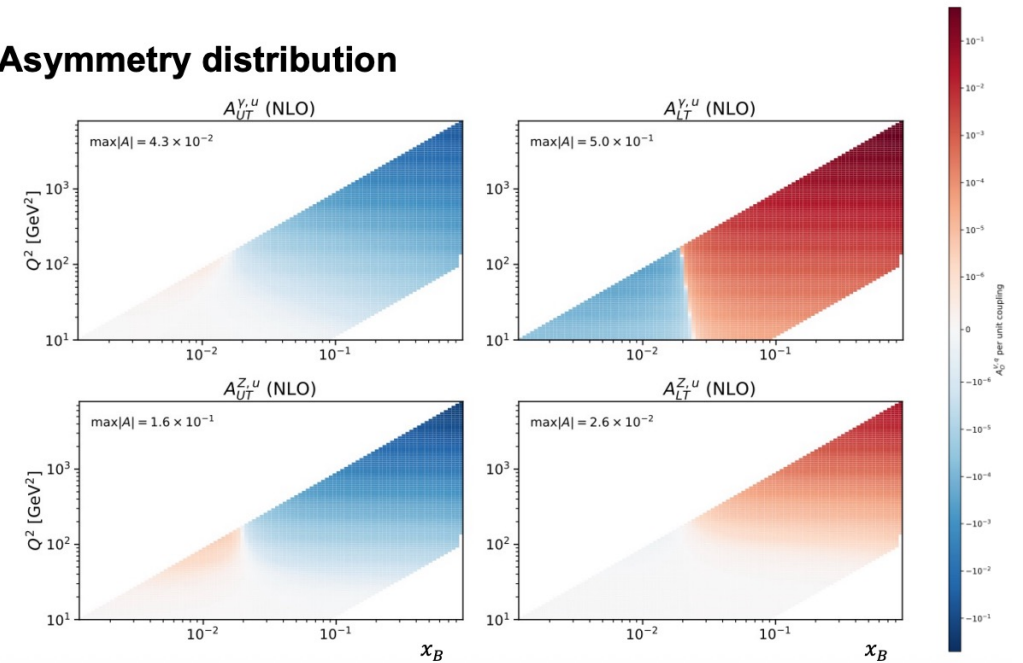
- Two results consistent down to decimal point except near kinematic limits
- Consult theory input + experimental limitations on final kinematic range

Results: A_{LT}



- Expected LT DSA uncertainty using the numeric method
 - Cross ratio extraction WIP
- Limits on the coupling of the dipole operator based on these results

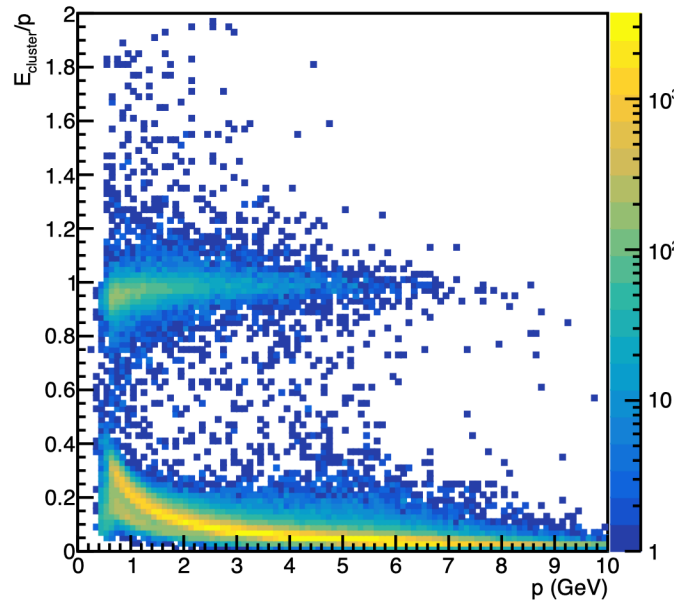
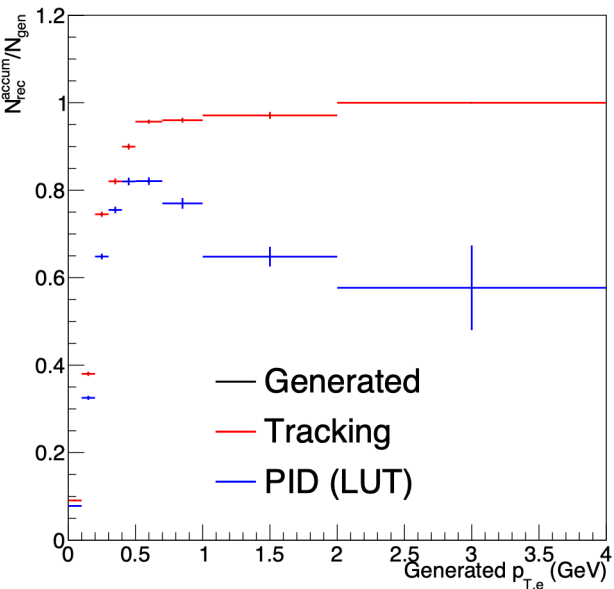
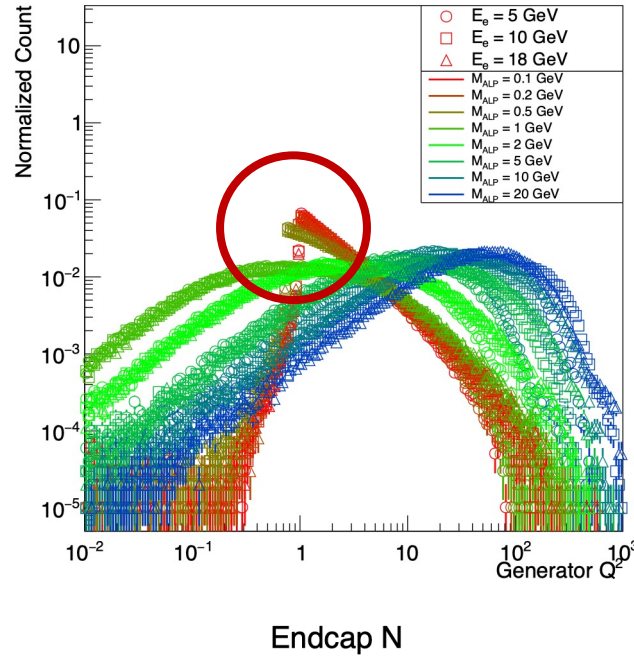
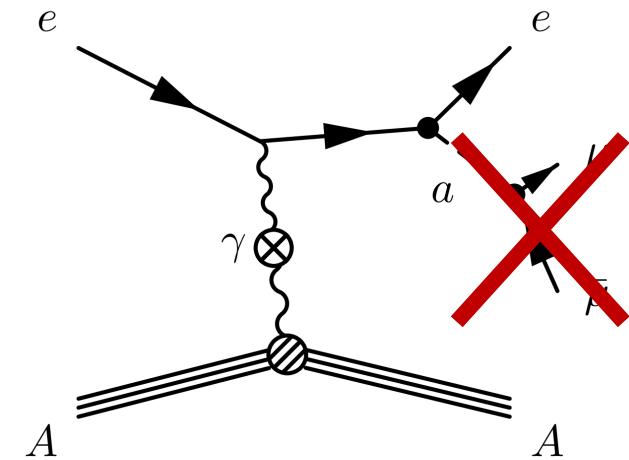
Asymmetry distribution



Summary

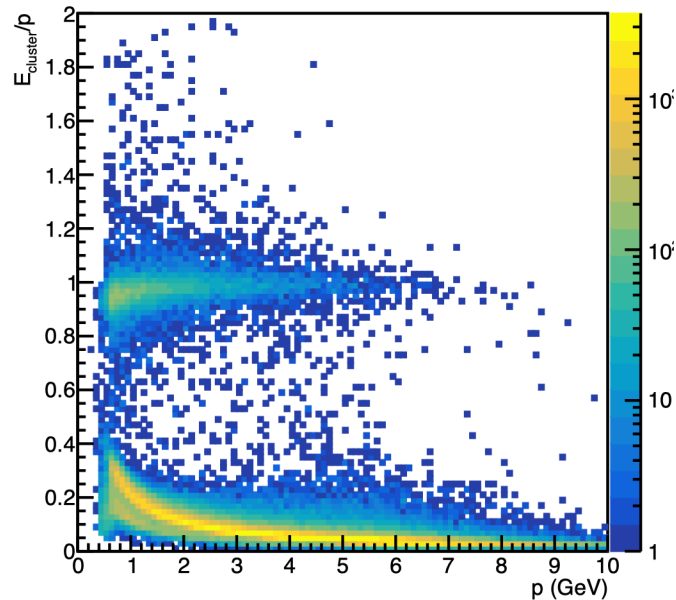
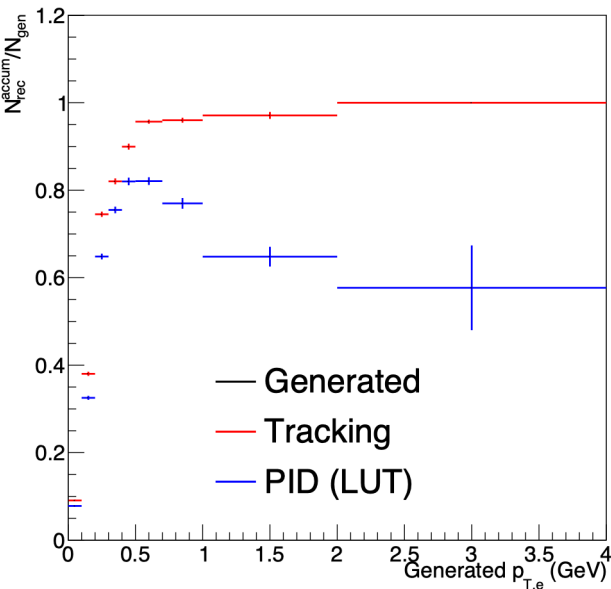
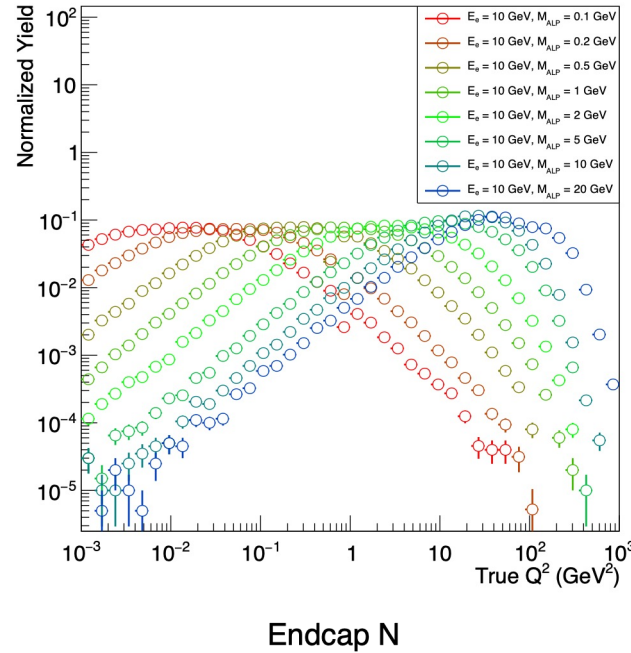
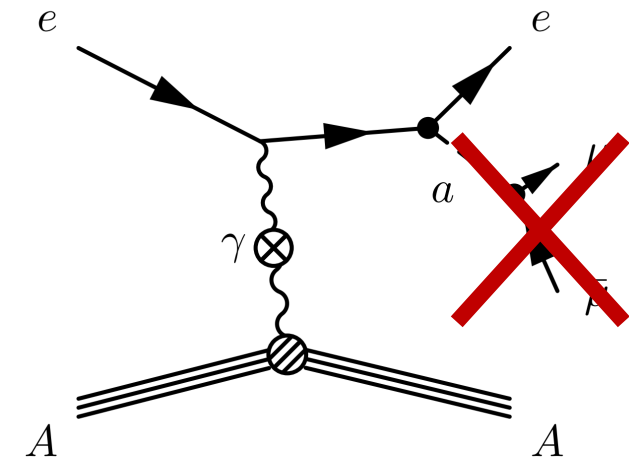
- Quark dipole operator within the SMEFT framework can be probed at ePIC/EIC via Transverse Spin Asymmetries in inclusive ep DIS
- Projection study has been performed for quark dipole operator for the EIC kinematics & ePIC detector using Pythia8 and Geant4 MC simulation
 - Currently missing DIS selection & BG contamination effects
 - Unfolding needs to be performed to obtain correct x_{Bj} and Q^2
 - Revisit kinematic scope of the measurement
- The resulting asymmetry will be used for dipole coupling limit extraction

Recap



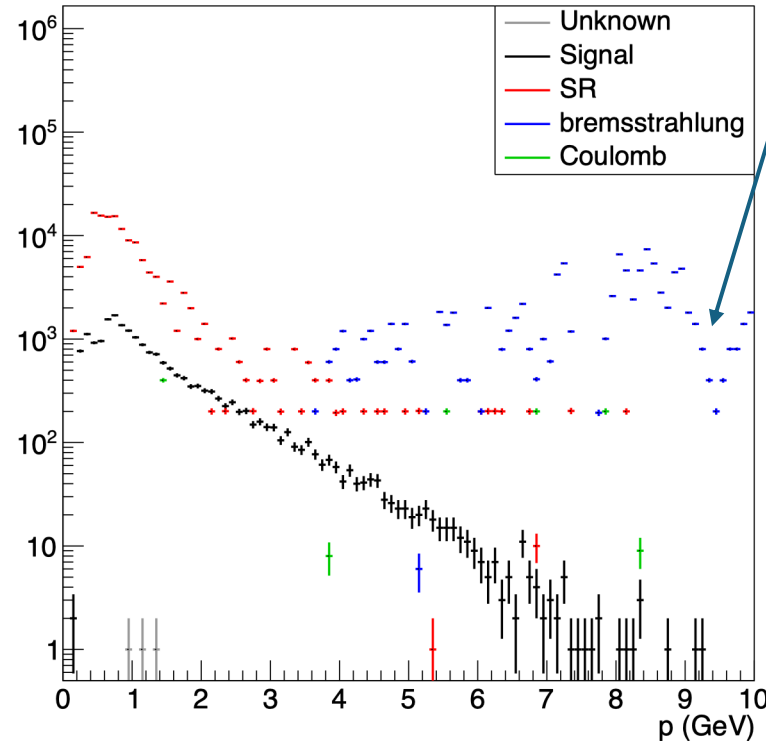
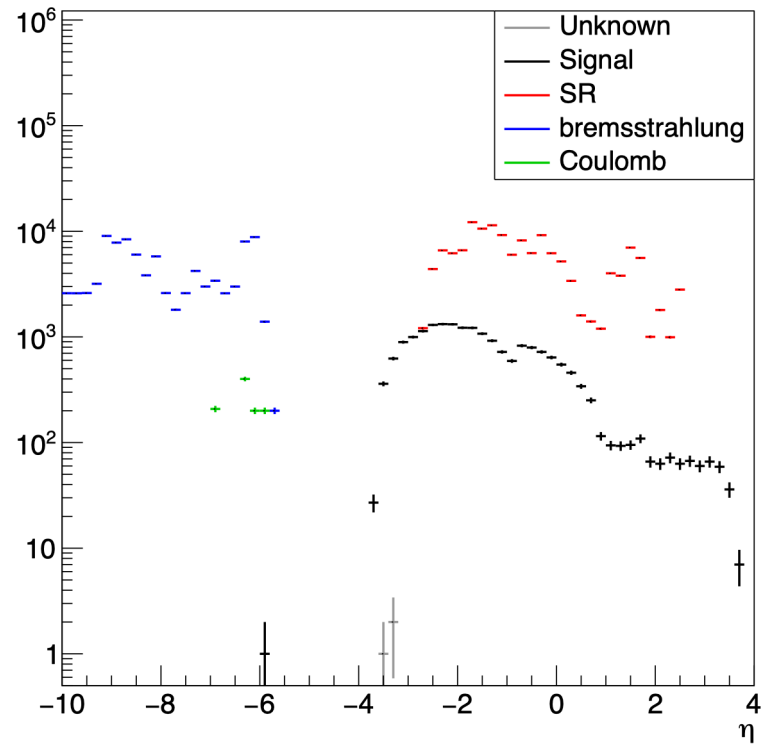
- Last update on May 18
- Focus: Non-decaying/ Invisibly-decaying ALP
- Event kinematics entirely defined by electron within central ePIC
- Bug with MadGraph5 event generation → has been addressed
- Strong ALP mass (m_a) dependence found in observed Q^2 (purely phenom. quantity)
- First look at ECal response

Recap

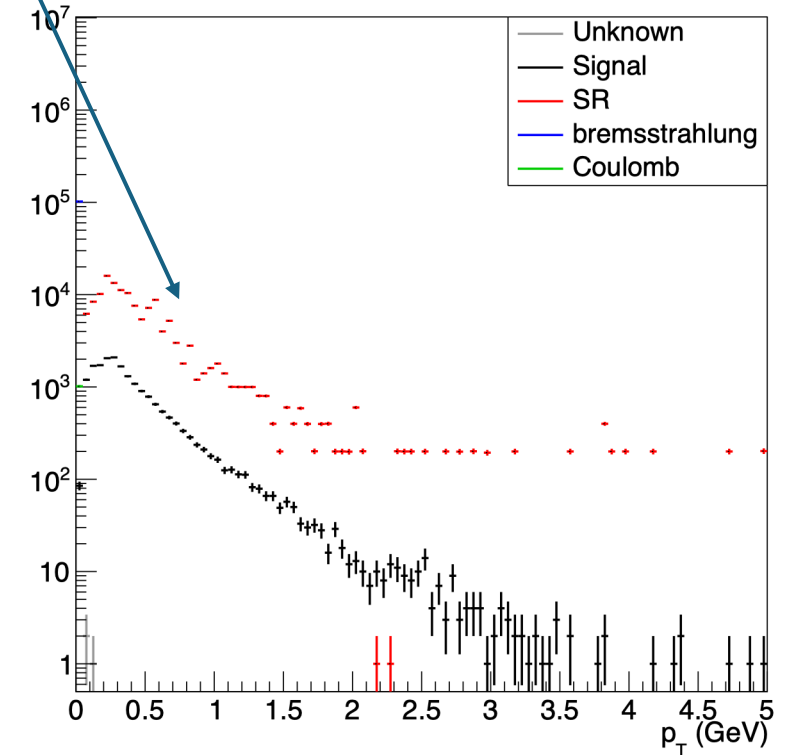


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- Focus: Non-decaying/ Invisibly-decaying ALP
- Event kinematics entirely defined by electron within central ePIC
- Bug with MadGraph5 event generation → has been addressed
- Strong ALP mass (m_a) dependence found in observed Q^2 (purely phenom. quantity)
- First look at ECal response
 - Invisibly-decaying ALP samples with beam BGR embedded into official ePIC sample
 - Finalize analysis selection strategy

Rejecting machine backgrounds

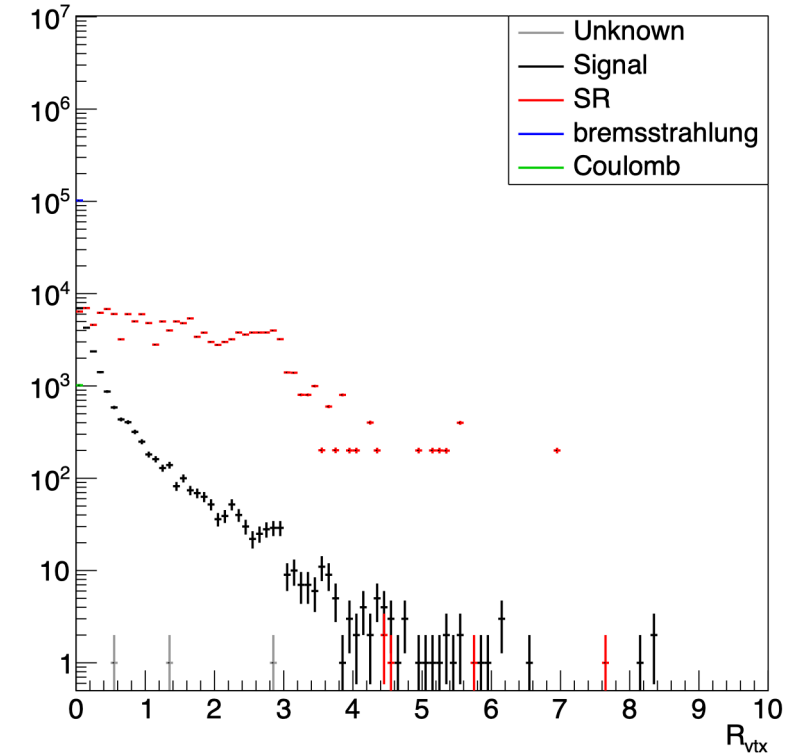
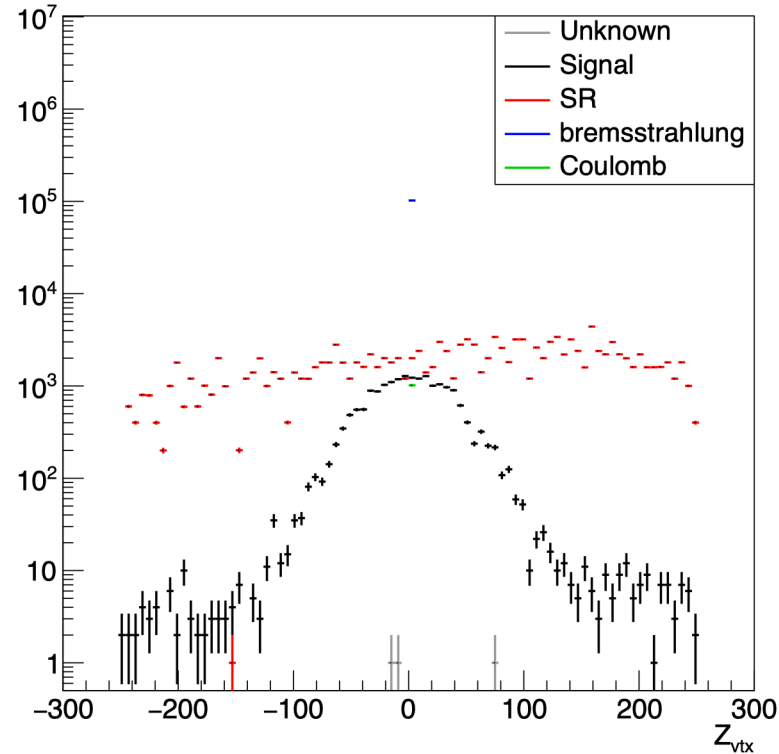
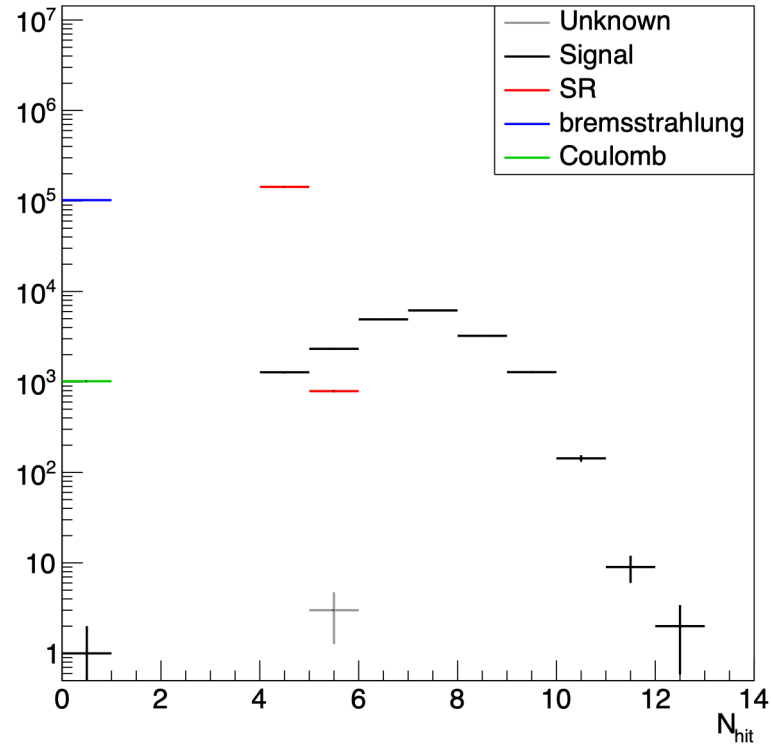


Correlated BG, should be resolved in July campaign



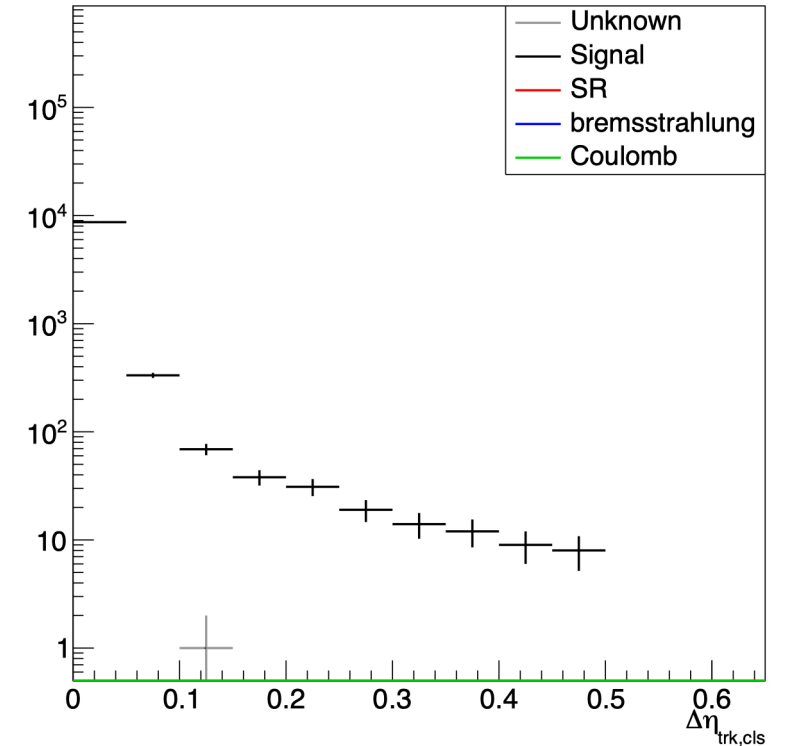
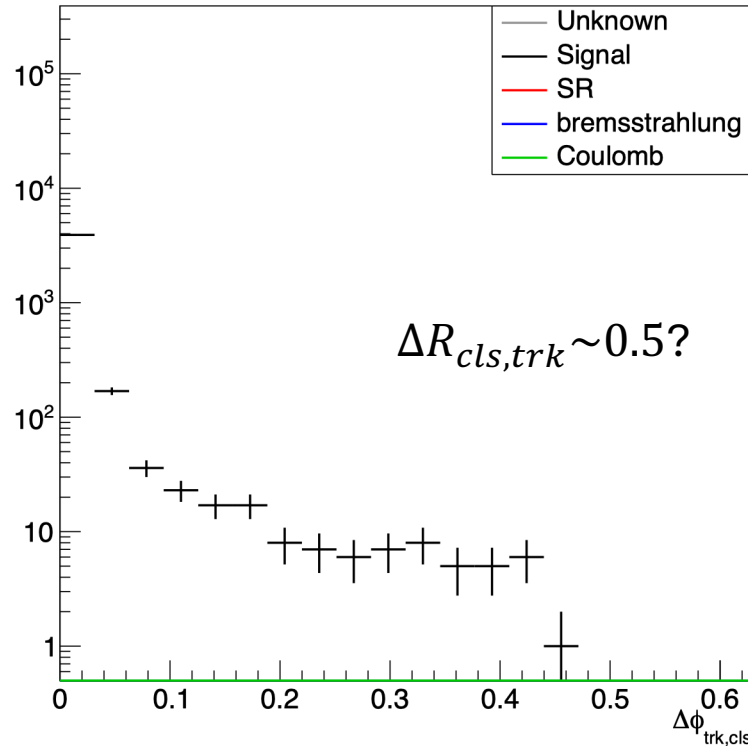
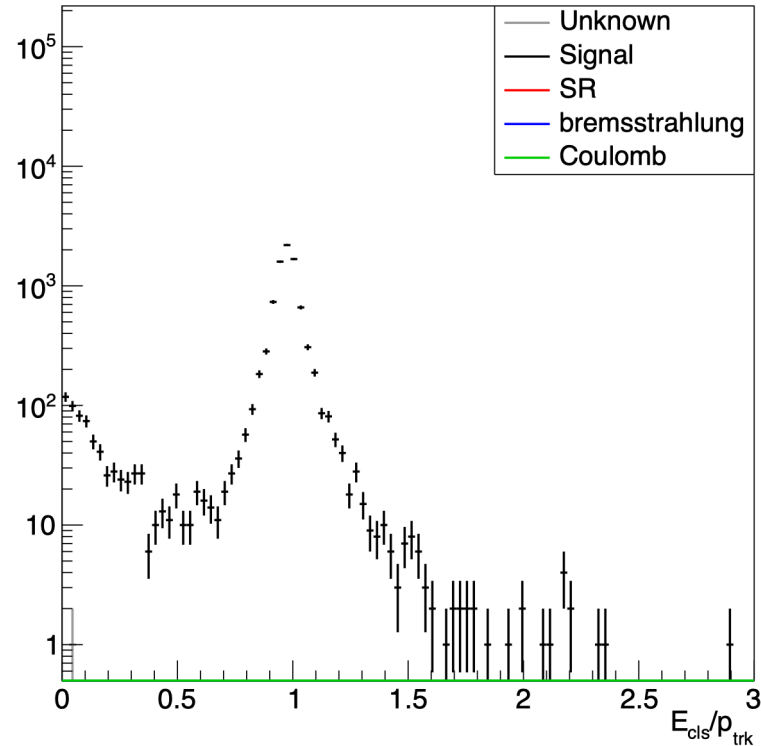
- Signal (ALP) tracks compared to machine backgrounds in June production
- brems and Coulomb tracks in low- Q^2 tagger
→ reject tracks in low- Q^2 tagger for now
- High-rate SR photons ($\sim 50k$ hits within $2\mu s$ window) → combinatoric fake tracks

Rejecting machine backgrounds



- N_{hits} cut at ≥ 5 (default) should reject most of the SR tracks
- Further beamline constraints should reject the remaining $\sim 50\%$

Rejecting machine backgrounds



- Geometric matching (“TrackClusterMatch”) to an ECal cluster, effectively requiring 6th hit, removes all of the SR fake tracks
- This effectively imposes a lower limit on momentum (e.g., $p_T > 0.5 \text{ GeV}$ in barrel)
- Current simulation infrastructure is limited in statistics, this study needs to be revisited with either more SR simulation or real data

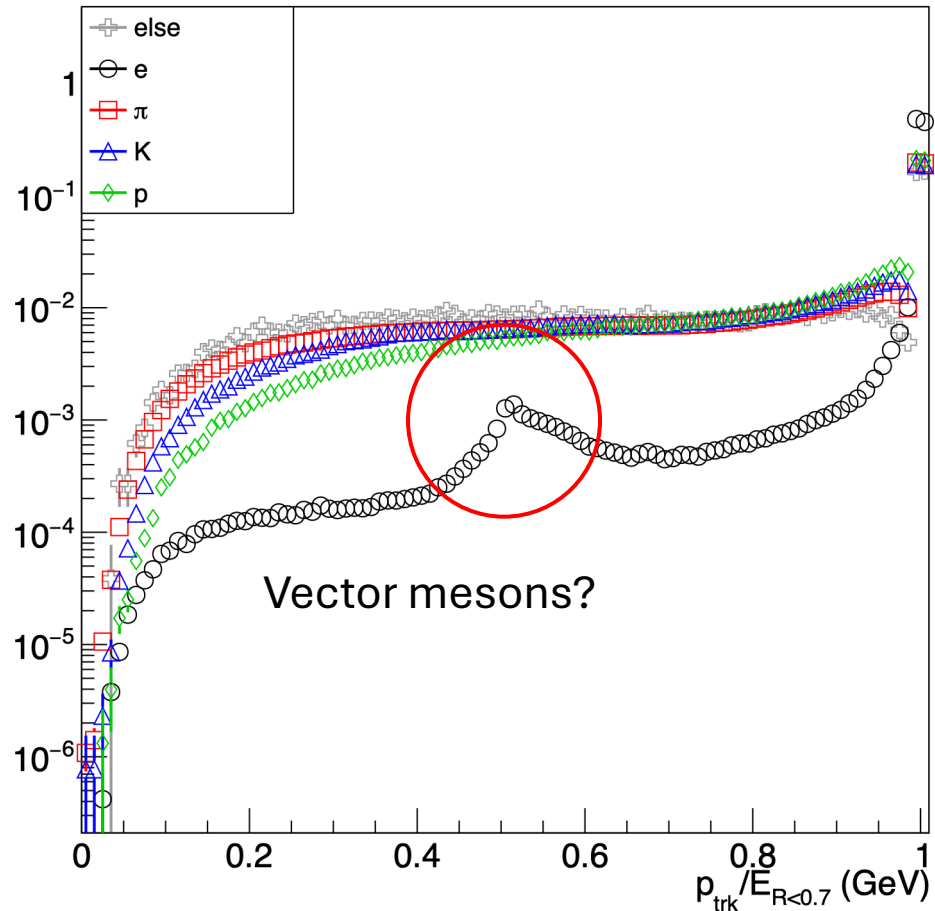
Selection cuts

Tracks	$p > 0.5 \text{ GeV}$ $\eta < 4$ $Z_{vtx} < 100 \text{ mm}$ $R_{XY,vtx} < 3 \text{ mm}$ $N_{hits} \geq 5$ (Truth-)matched cluster Reject Low-Q2 tagger
Electron	
Event	

- These are the selection cuts considered for NIM-A for track quality assurance
- Track **momentum** and **ECal** matching are motivated by SR background rejection, and may later be relaxed once PID detector information is incorporated
- Hit **multiplicity** will be either tightened or a hit in a specific detector component will be required to reject SR background with ECal restriction relaxed

Electron identification

* Based on DIS $1 < Q^2(\text{GeV}^2) < 10$ sample

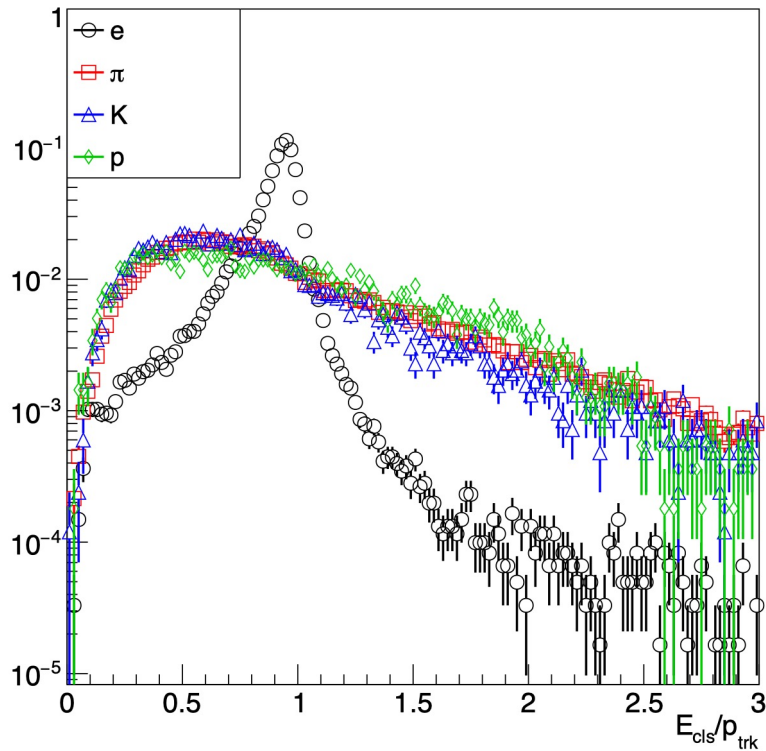


- Using inclusive DIS at $1 < Q^2(\text{GeV}^2) < 10$ sample for eID study
- The current strategy follows Inclusive PWG:
 - Track-cluster matching
 - Isolated cluster ($E/E_{\Delta R<0.7} > 0.9$)
 - $0.8 < E_{cls}/p_{trk} < 1.2$
 - Highest p_T track
- Isolation seems to work well for the most part, but perhaps some tuning required for non-primary electron ID.
- Also, requires cluster matching, which effectively imposes a lower momentum cut

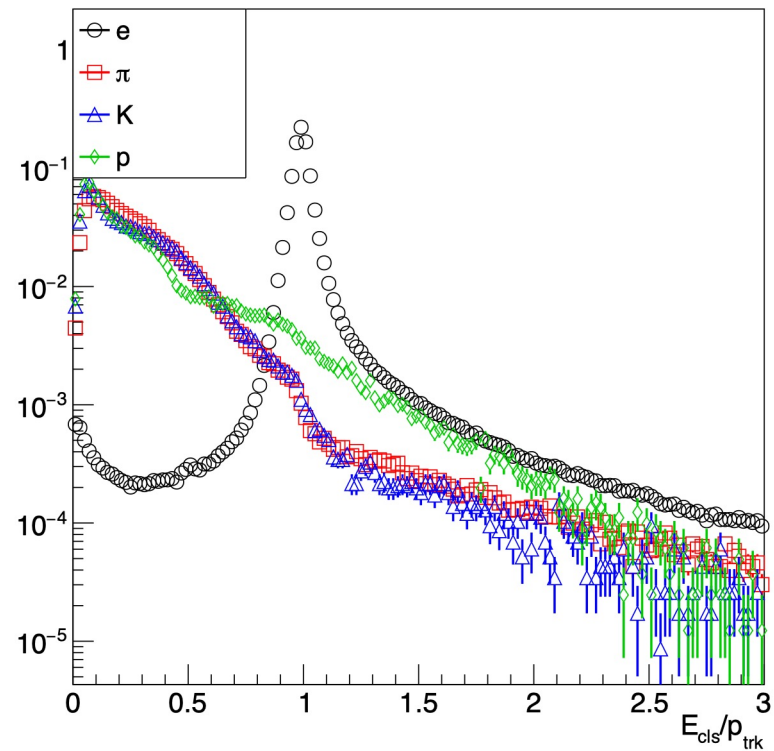
Electron identification

* Based on DIS $1 < Q^2(\text{GeV}^2) < 10$ sample

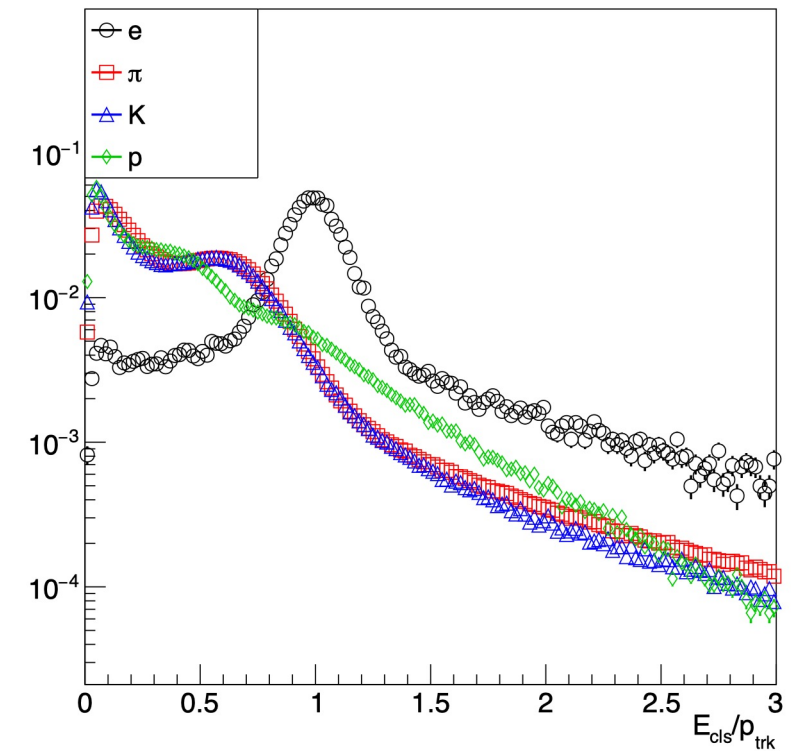
BEMC



N-Endcap EMC



P-Endcap EMC



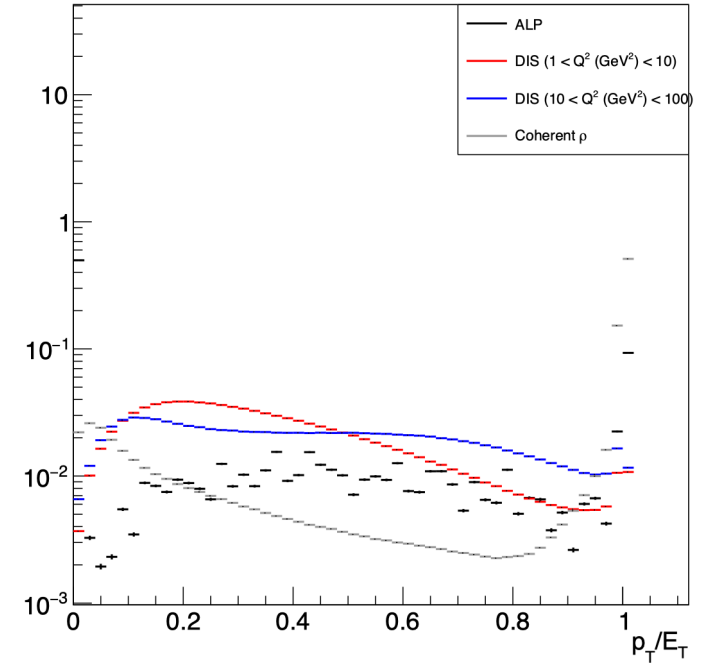
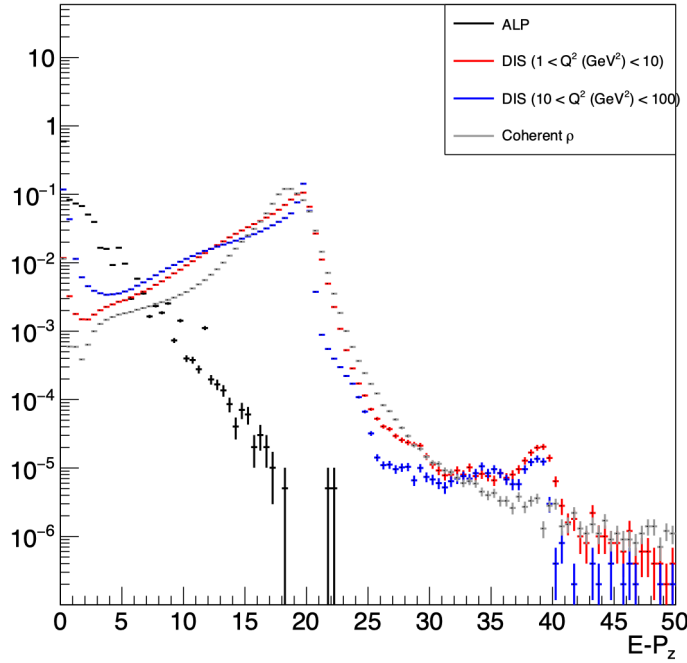
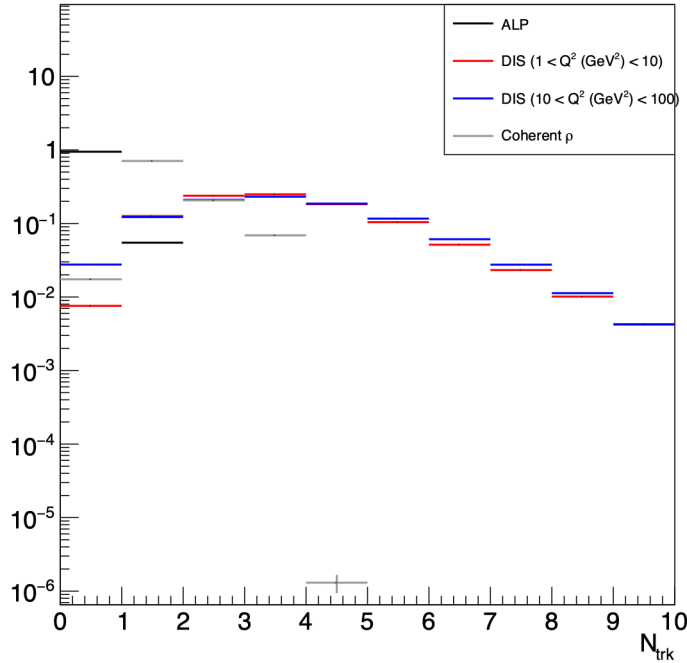
- E/p performs fairly well with varying degrees of success

Selection cuts

Tracks	$p > 0.5 \text{ GeV}$ $ \eta < 4$ $ Z_{vtx} < 100 \text{ mm}$ $ R_{XY,vtx} < 3 \text{ mm}$ $N_{hits} \geq 5$ (Truth-)matched cluster Reject Low-Q2 tagger
Electron	$0.8 < E_{cls}/p_{trk} < 1.4$ $E/E_{R<0.7} > 0.9$
Event	

- These were the selection cuts considered for NIM-A
- For now, ECal **cluster isolation** is required for scattered electron; will be relaxed or removed for ALP decay ($a \rightarrow e^+ e^-$)

Event selection



- Identified 3 variables to isolate ALP signal from physics background
 - N_{trk} : Invisibly-decaying ALP = 1
 - $E - P_z = \sum_i E_i - P_{z,i}$: For fully contained DIS $\sim 2 E_e$
 - $p_{T,miss}/E_T = \sum_i \vec{p}_{T,i} / \sum_i E_{T,i} \sim 1$ for ALP, < 1 for DIS

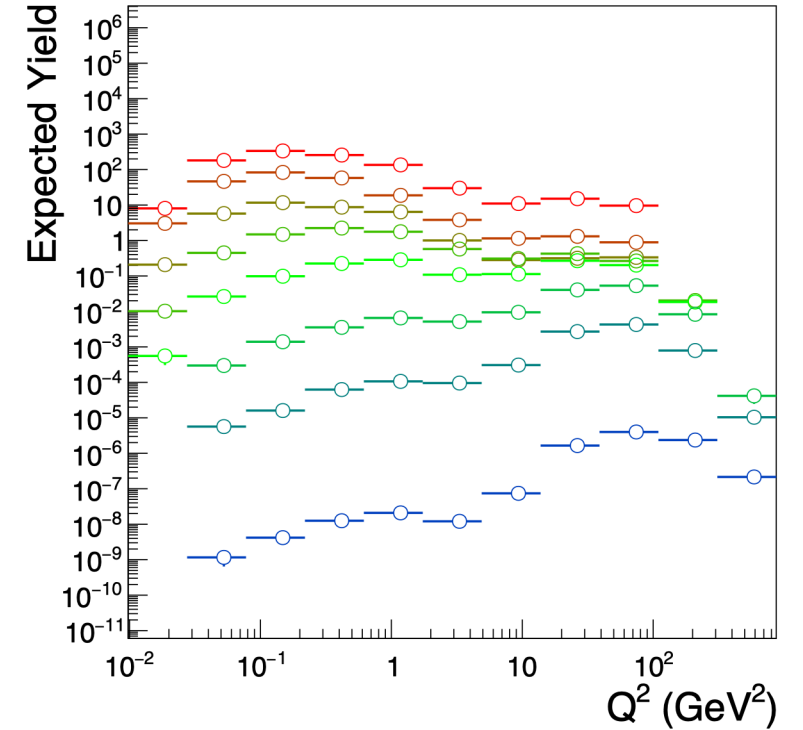
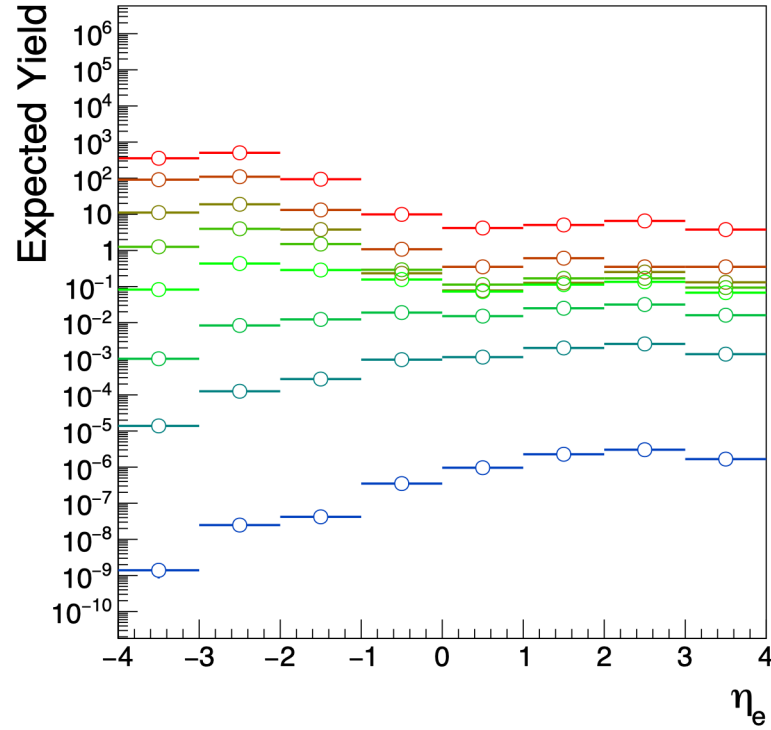
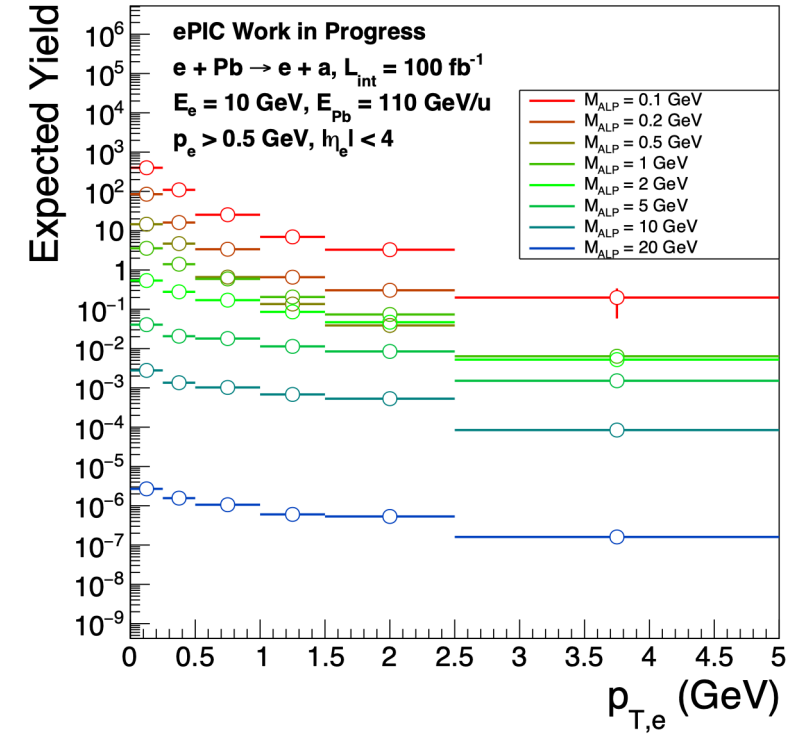
Selection cuts and Summary

Tracks	$p > 0.5 \text{ GeV}$ $ \eta < 4$ $ Z_{vtx} < 100 \text{ mm}$ $ R_{XY,vtx} < 3 \text{ mm}$ $N_{hits} \geq 5$ (Truth-)matched cluster Reject Low-Q2 tagger
Electron	$0.8 < E_{cls}/p_{trk} < 1.4$ $E/E_{R<0.7} > 0.9$
Event	$N_{trk} = 1$ $E - P_z < 10 \text{ GeV}$ $p_{T,miss}/E_T > 0.9$ Has ele candidate

- These were the selection cuts considered for NIM-A
- Ganesh (and Alyssa) performing BDT study to finalize event selection
- Electron decay channel
($e + \gamma \rightarrow e + a \rightarrow e + e^+ + e^-$) samples currently being produced and will be submitted to official ePIC simulation team soon

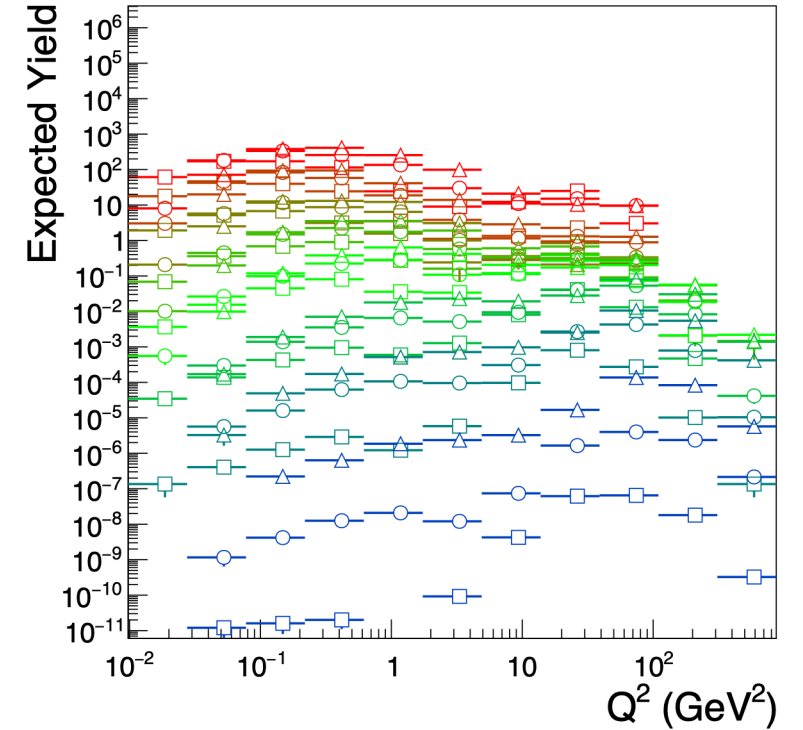
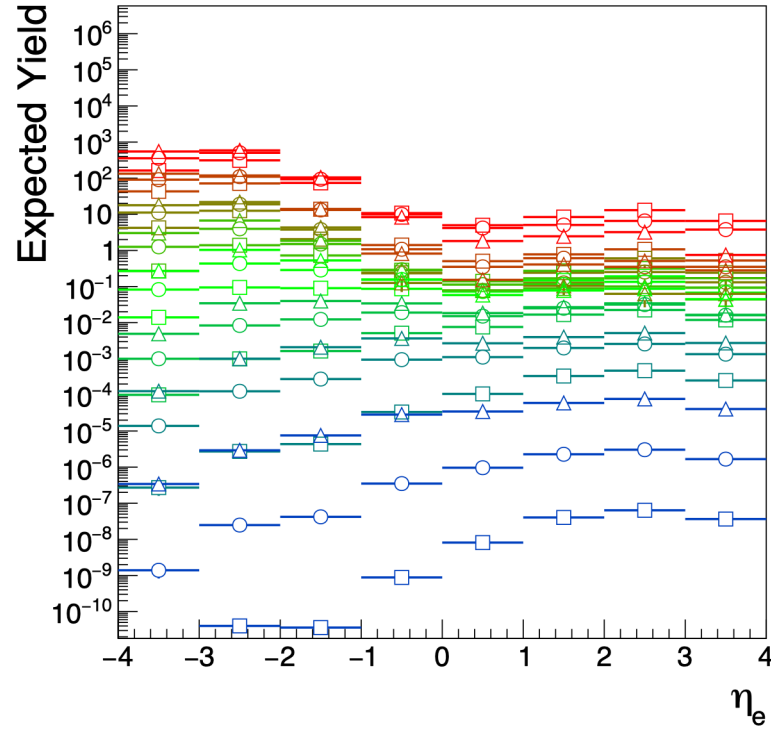
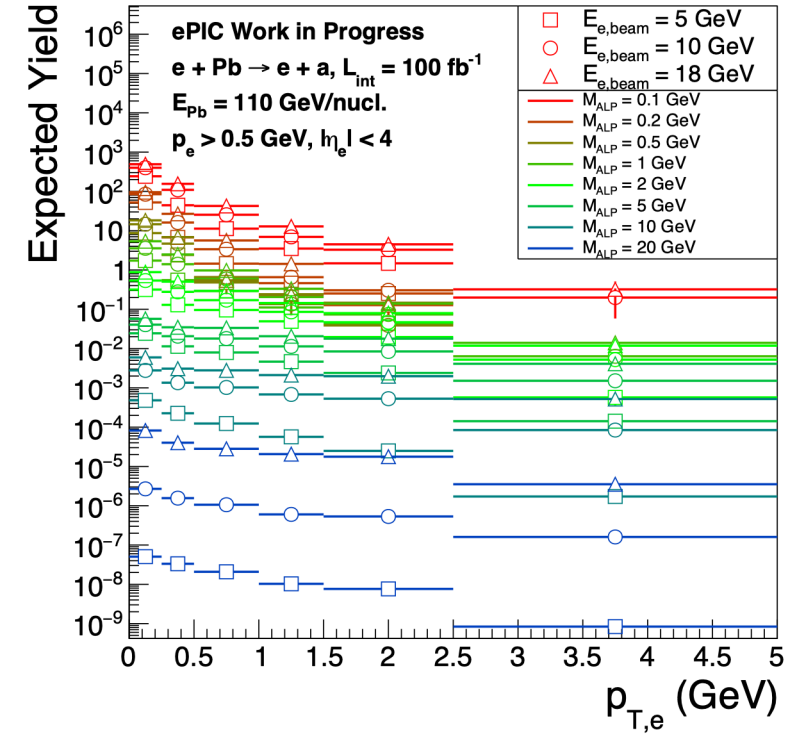
Backup

Expected signal



- Presented in EIC Asia Workshop
- Expected signal yield using “Tracking” cuts only
- Searches possible for low-mass ($M_{ALP} < 1 \text{ GeV}$) ALPs with $L_{int} = 100 \text{ fb}^{-1}$
- Limit-setting for high-mass ALPs

Expected signal



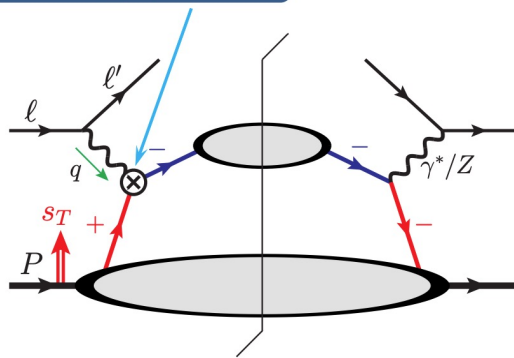
- Expected signal yield based on the tracking and clustering performance
 - Significant beam-energy dependence with high-mass ALP
 - Motivates $E_{e,beam} = 18 \text{ GeV}$ collisions

Conclusion

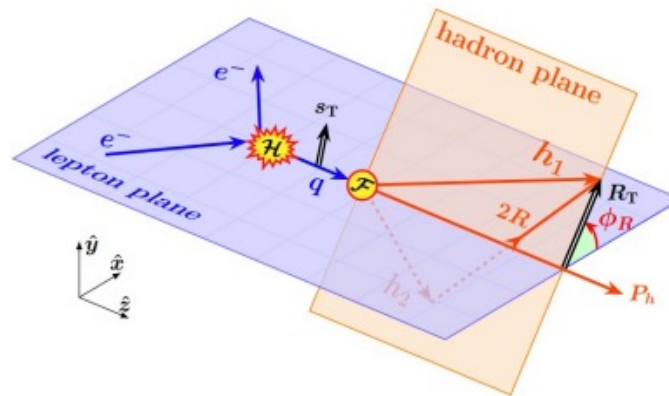
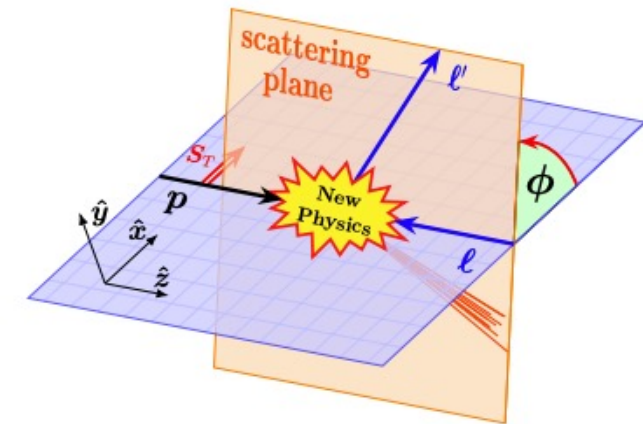
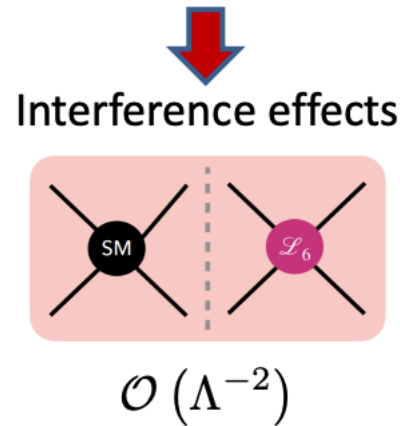
- Machine background rejection
 - Coulomb and bremsstrahlung most entirely fall in to low Q2 tagger
 - $N_{trk,hits} \geq 5$ rejects most of the SR
 - Requiring track-cluster matching rejects the rest
 - Some rejection provided by quality cuts
- Track-cluster matching
 - Several ideas have been tested
 - Without the presence of cluster splitting algo, the matching schemes tested here have their own limitations
 - Truth matching for now
- Electron Identification
 - The current scheme based on isolation and E/p performs well for cluster-matched tracks
 - Will investigate improvements from PID detectors for low momentum tracks

Dipole operators by Zhite

$$\bar{q}_L \sigma_{\mu\nu} q_R A^{\mu\nu}, \bar{q}_L \sigma_{\mu\nu} q_R Z^{\mu\nu}$$



$$\sigma \propto |\mathcal{M}_{\text{SM}} + \Lambda^{-2} \mathcal{M}_{\text{NP}}|^2$$



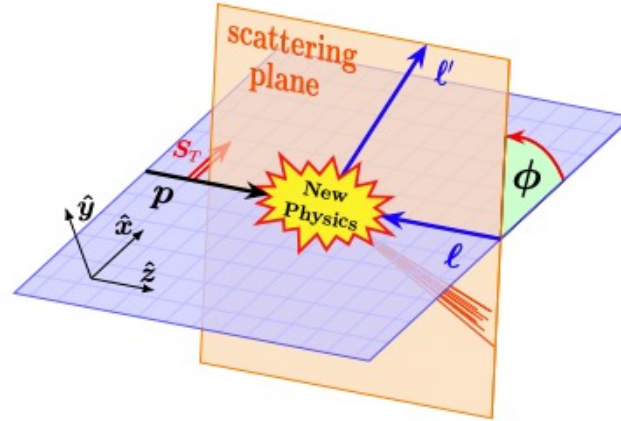
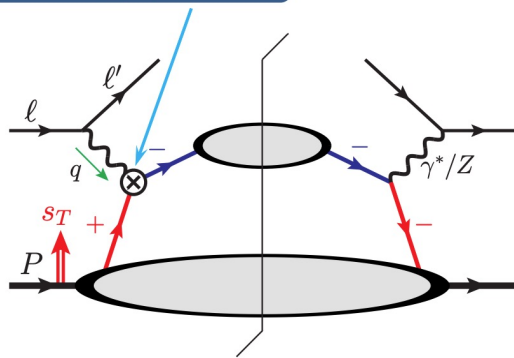
- From Apr 13, 2026

(https://indico.cern.ch/event/1668453/contributions/7014240/attachments/3255038/5810101/BSMEIC_meeting_dipole_ZhiteYu.pdf)

- Chirally-Odd dipole operators interfering with transversity PDF $\rightarrow \mathcal{O}(\Lambda^{-2})$ effect in SMEFT
- 2+ channels proposed
 - Inclusive DIS
 - SIDIS dihadron
 - ...
- Our knowledge so far
 - eID from invisibly-decaying ALP
 - dimuon decay of ALP (WIP)

Dipole operators by Zhite

$$\bar{q}_L \sigma_{\mu\nu} q_R A^{\mu\nu}, \bar{q}_L \sigma_{\mu\nu} q_R Z^{\mu\nu}$$



$$\frac{d\sigma_{AA}}{dx_B dQ^2 d\phi} = \Sigma_{UU}^{AA} + \lambda_e S_T \Sigma_{LT}^{AA}(\Delta\phi), \quad \Delta\phi \equiv \phi - \phi_S$$

$$\Sigma_{UU}^{AA} = \frac{\alpha_e^2}{Q^4} f_q(x_B) \cdot e_q^2 [1 + (1-y)^2],$$

$$\Sigma_{LT}^{AA}(\Delta\phi) = -\frac{\alpha_e^2}{Q^4} \frac{2Q\sqrt{1-y}}{v} h_q(x_B) \cdot (e_q y) \left[\text{Re}(\Gamma_\gamma^q) \cos(\Delta\phi) - \text{Im}(\Gamma_\gamma^q) \sin(\Delta\phi) \right]$$

$$\frac{d\sigma_{AZ}}{dx_B dQ^2 d\phi} = \Sigma_{UU}^{AZ} + \lambda_e \Sigma_{LU}^{AZ} + S_T \Sigma_{UT}^{AZ}(\Delta\phi) + \lambda_e S_T \Sigma_{LT}^{AZ}(\Delta\phi)$$

$$\Sigma_{UT}^{AZ} = -\frac{\alpha_e \alpha_Z h_q(x_B)}{4Q^2(Q^2 + m_Z^2)} \frac{2Q\sqrt{1-y}}{v} \left\{ [g_V^e g_A^q (2-y) + g_A^e g_V^q y] \text{Re}(\Gamma_\gamma^q e^{i\Delta\phi}) + 2e_q g_A^e y \text{Re}(\Gamma_Z^q e^{i\Delta\phi}) \right\},$$

$$\Sigma_{LT}^{AZ} = \frac{\alpha_e \alpha_Z h_q(x_B)}{4Q^2(Q^2 + m_Z^2)} \frac{2Q\sqrt{1-y}}{v} \left\{ [g_A^e g_A^q (2-y) + g_V^e g_V^q y] \text{Re}(\Gamma_\gamma^q e^{i\Delta\phi}) + 2e_q g_V^e y \text{Re}(\Gamma_Z^q e^{i\Delta\phi}) \right\}$$

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- Chirally-Odd dipole operators interfering with transversity PDF $\rightarrow \mathcal{O}(\Lambda^{-2})$ effect in SMEFT

- 2+ channels proposed

- **Inclusive DIS**

- SIDIS dihadron

- ...

- Results in 3 observable spin asymmetries

- $\Sigma_{LT}^{AA} \rightarrow A_{LT,c}^{AA} \cos(\phi) - A_{LT,s}^{AA} \sin \phi$

- $\Sigma_{LT}^{AZ} \rightarrow A_{LT}^{AZ} \cos(\phi)$

- **$\Sigma_{UT}^{AZ} \rightarrow A_{UT}^{AZ} \cos(\phi)$**

Strategy

- Official ePIC simulation sample from June
 - Inclusive DIS, ep 18X275 GeV2 ([5, 10, 18] X [41, 100, 275]), $10 < Q^2 < 1000 \text{ GeV}^2$
 - Generated luminosity = $\sim 75 \text{ fb}^{-1}$ (will be scaled later to 100 fb^{-1})
 - Polarization randomly chosen: spin pattern $(P_e, P_p) = (\uparrow, \uparrow), (\downarrow, \uparrow), (\uparrow, \downarrow), (\downarrow, \downarrow)$ [only P_p used]
- Electron ID from ALP study
 - No background (diffractive, CC DIS) estimated (for now)
 - No pion contamination estimated (for now)
 - No DIS selection (for now)

Asymmetry extraction

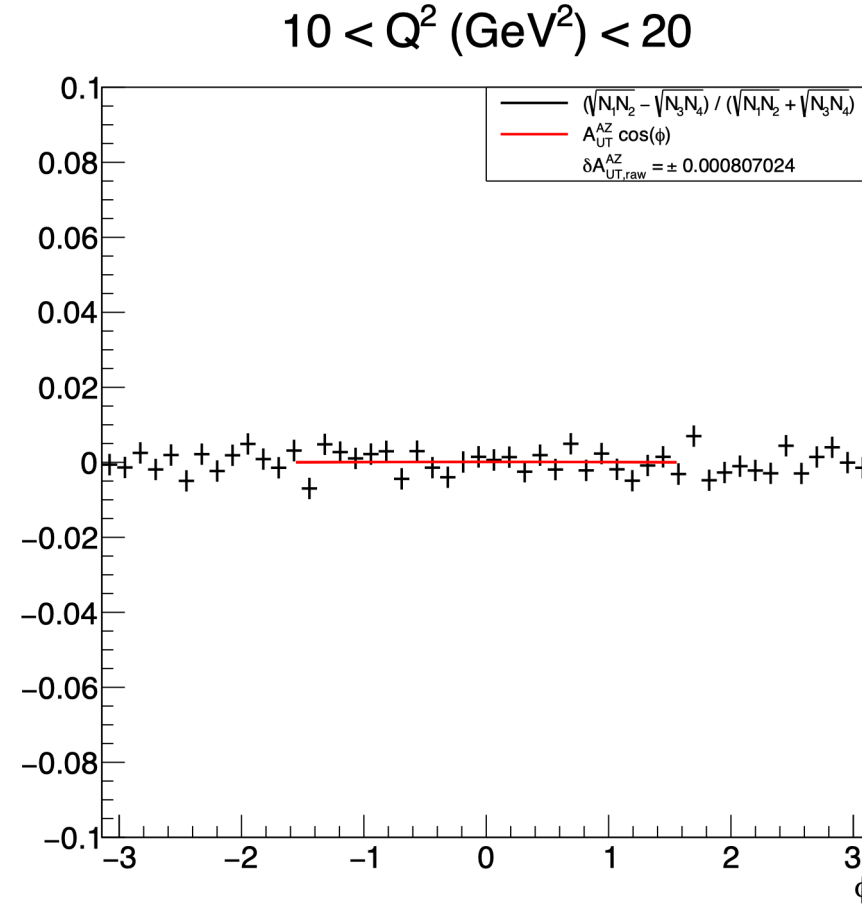
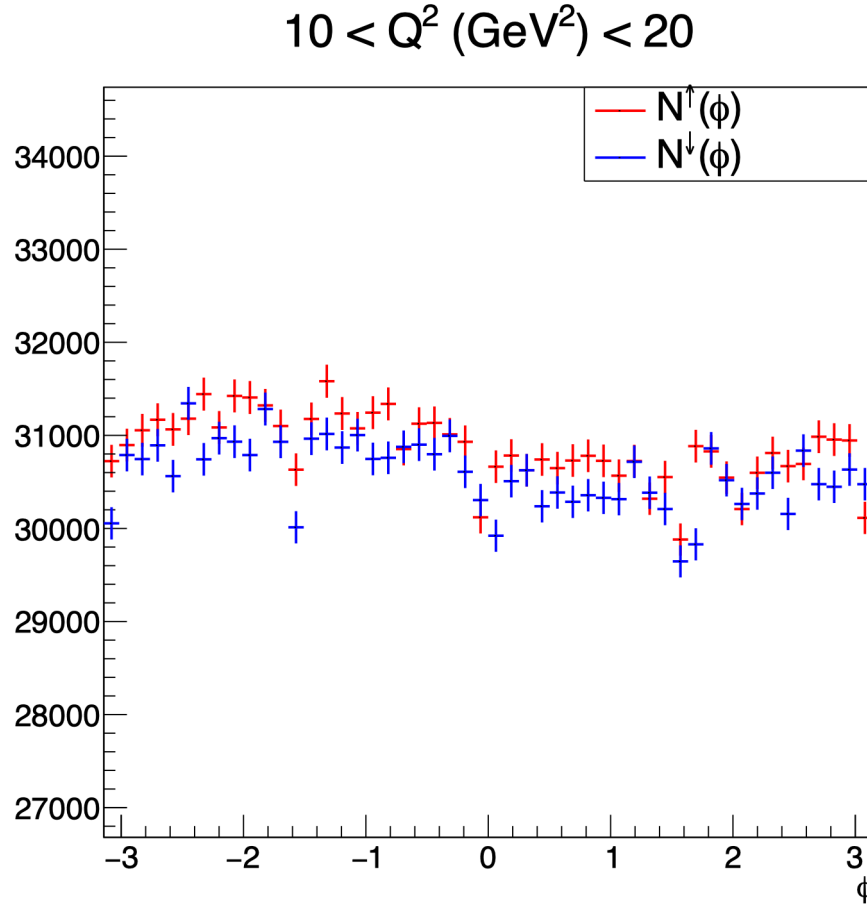
- $A_{UT}^{AZ} \cos \phi = \frac{1}{P} \frac{\sigma^\uparrow(\phi) - \sigma^\downarrow(\phi)}{\sigma^\uparrow(\phi) + \sigma^\downarrow(\phi)} = \frac{1}{P} \frac{N^\uparrow(\phi)/L^\uparrow - N^\downarrow(\phi)/L^\downarrow}{N^\uparrow(\phi)/L^\uparrow + N^\downarrow(\phi)/L^\downarrow}$

- Cross-ratio method $\rightarrow A_{UT}^{AZ} \cos \phi = \frac{1}{P} \frac{\sqrt{N^\uparrow(\phi)N^\downarrow(\phi+\pi)} - \sqrt{N^\uparrow(\phi)N^\downarrow(\phi+\pi)}}{\sqrt{N^\uparrow(\phi)N^\downarrow(\phi+\pi)} + \sqrt{N^\uparrow(\phi)N^\downarrow(\phi+\pi)}}$

- Uncertainty $\rightarrow \delta A_{UT}^{AZ} = \frac{1-A^2}{4} \sqrt{\frac{1}{N_1} + \frac{1}{N_2} + \frac{1}{N_3} + \frac{1}{N_4}}$

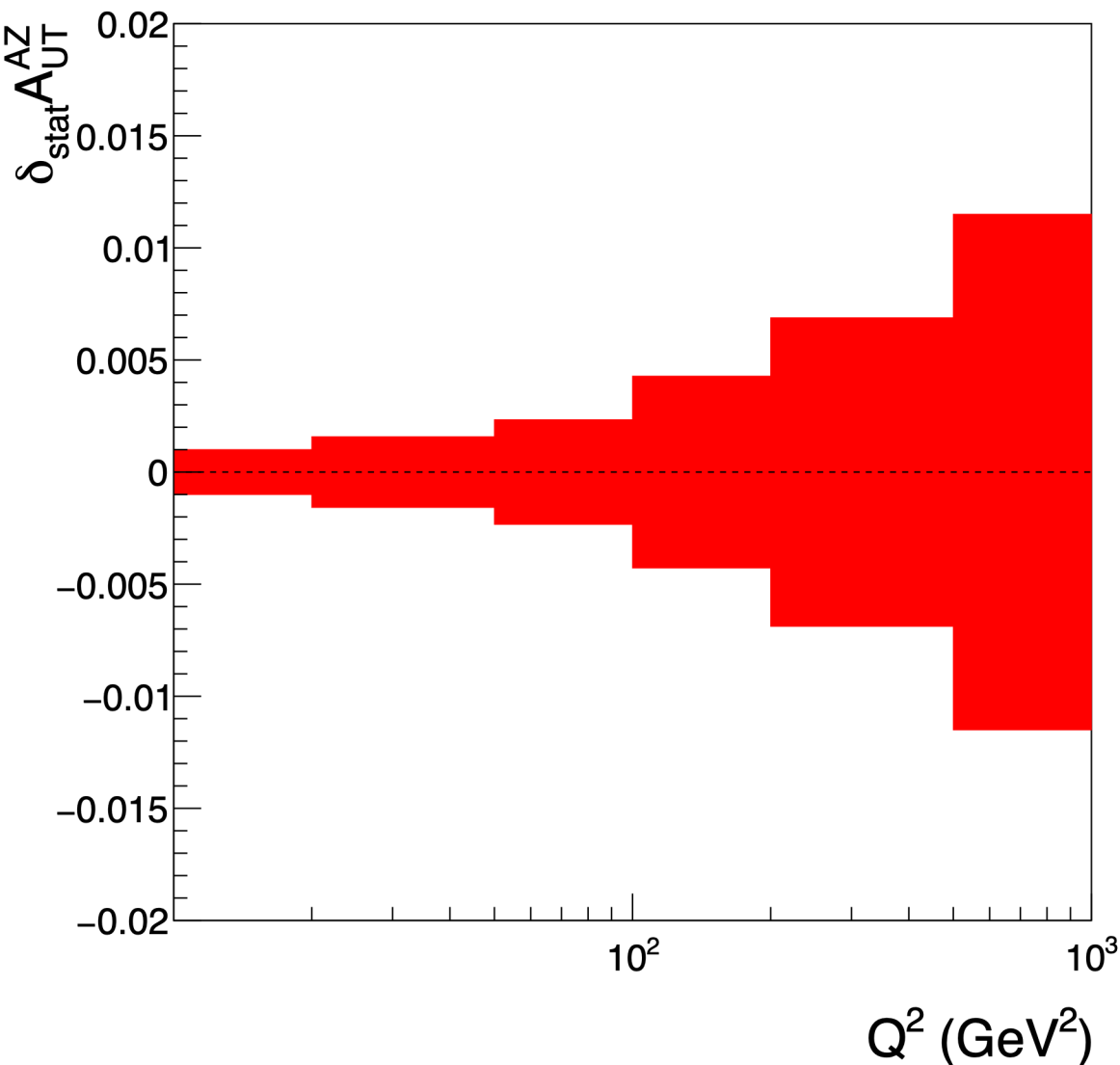
* $P = 0.7$ used

Asymmetry extraction



- $\phi (= \phi_e - \phi_s)$ distribution for $10 < Q^2 \text{ (GeV}^2\text{)} < 20$
- Fit range = $[-\frac{\pi}{2}, +\frac{\pi}{2}]$ to account for the double counting
- $\delta_{stat} A_{UT}^{AZ}$ extracted by $\delta_{stat} A_{UT}^{AZ} = \frac{1}{P} \frac{1}{\sqrt{L_{data}^{target} / L_{MC}^{sample}}} \delta A_{UT,raw}^{AZ} = \frac{1}{0.7} \frac{1}{\sqrt{100/75}} 0.000807$

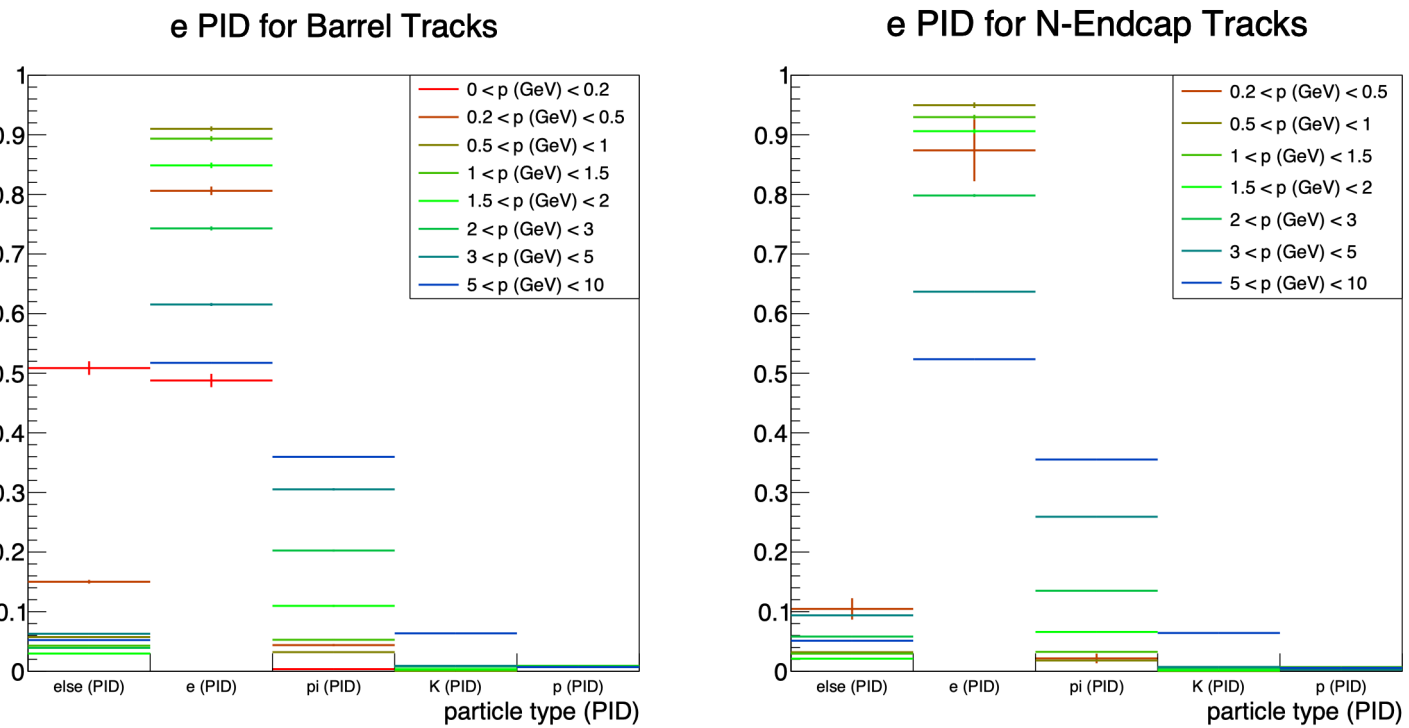
Results



- $\sim < 0.01$ stat. unc. expected from ep DIS
18X275GeV2, 70% pol., 100 fb⁻¹
- Remaining corrections
 - ϕ smearing: expected to be negligible
 - Purity:
 - $A_{\text{meas}} = MA \rightarrow A = M^{-1} A_{\text{meas}}$
 - $\begin{pmatrix} A_{\text{meas}}^e \\ A_{\text{meas}}^h \end{pmatrix} = \begin{pmatrix} f_{\text{sig}}^e & 1 - f_{\text{sig}}^e \\ f_{\text{bg}}^e & 1 - f_{\text{bg}}^e \end{pmatrix} \begin{pmatrix} A^e \\ A^h \end{pmatrix}$
 - Assume $A^h = 0$, $A^e = \frac{1}{f_{\text{sig}}^e} A_{\text{meas}}^e$
 - DIS Selection: < factor of 2
 - Bin migration in x_{Bj} and Q^2
- Systematics
 - Polarization
 - Efficiency for gluon- vs quark-initiated processes
 - etc.

Selection cuts

Tracks	$p > 0.5 \text{ GeV}$ $\eta < 4$ $Z_{vtx} < 100 \text{ mm}$ $R_{XY,vtx} < 3 \text{ mm}$ $N_{hits} \geq 5$ (Truth-)matched cluster Reject Low-Q2 tagger
Electron	$0.8 < E_{cls}/p_{trk} < 1.4$ $E/E_{R<0.7} > 0.9$
Event	$N_{trk} = 1$ $E - P_Z < 10 \text{ GeV}$ $p_{T,miss}/E_T > 0.9$ Has ele candidate



- Left: Selection cuts from previous meeting
- Top-right: PID detector performance
- Today: Incorporate PID detectors for eID

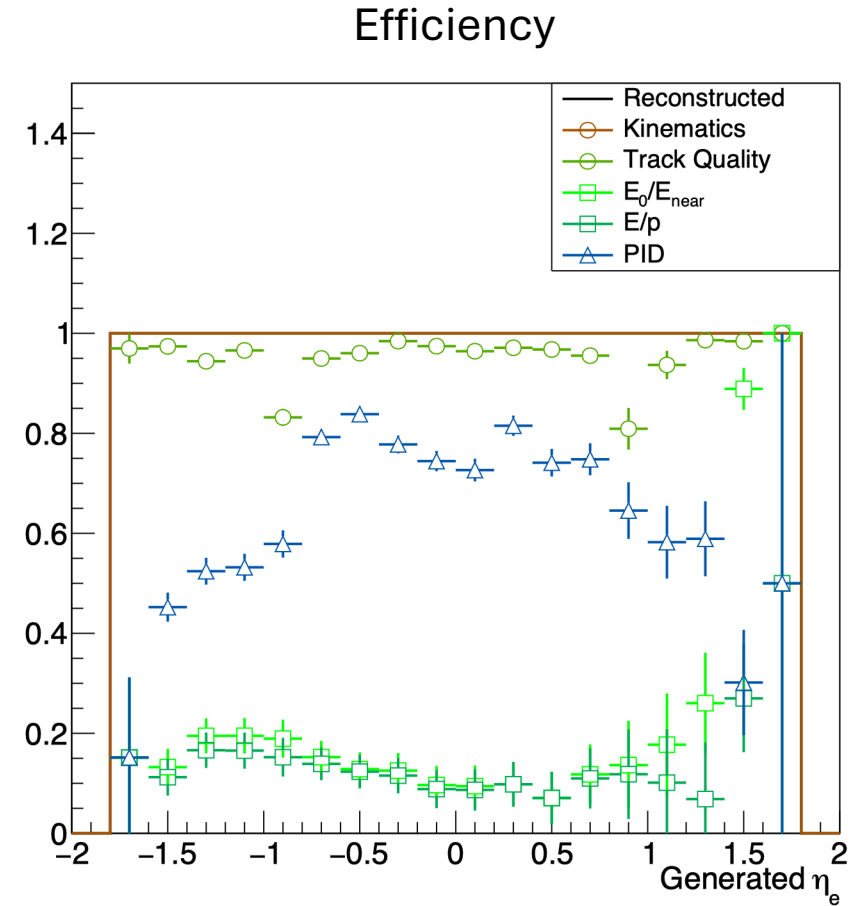
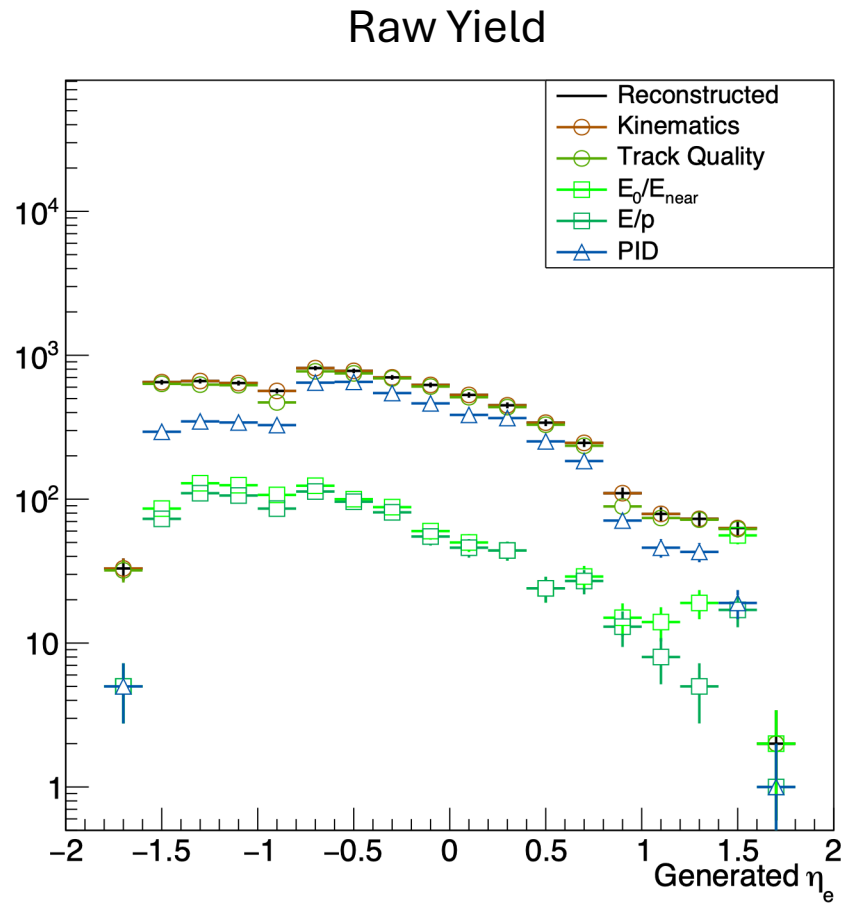
Selection cuts

Tracks	$p > 0.5 \text{ GeV}$ $\eta < 4$ $Z_{vtx} < 100 \text{ mm}$ $R_{XY,vtx} < 3 \text{ mm}$ $N_{hits} \geq 5$ (Truth-)matched cluster Reject Low-Q2 tagger	
Electron	$0.8 < E_{cls}/p_{trk} < 1.4$ $E/E_{R<0.7} > 0.9$	
Event	$N_{trk} = 1$ $E - P_Z < 10 \text{ GeV}$ $p_{T,miss}/E_T > 0.9$ Has ele candidate	

Tracks	$p > 0.2 \text{ GeV}$ $\eta < 4$ $Z_{vtx} < 100 \text{ mm}$ $R_{XY,vtx} < 3 \text{ mm}$ $N_{hits} \geq 5$ $N_{cls} > 0$ OR PDG != 0 Reject Low-Q2 tagger	
Electron	$N_{cls} > 0$ $0.8 < E_{cls}/p_{trk} < 1.4$ $E/E_{R<0.7} > 0.9$	$N_{cls} = 0$ AND $p < 1 \text{ GeV}$ PDG (LUT) = 11
Event	$N_{trk} = 1$ $E - P_Z < 10 \text{ GeV}$ $p_{T,miss}/E_T > 0.9$	

PID Performance (Barrel)

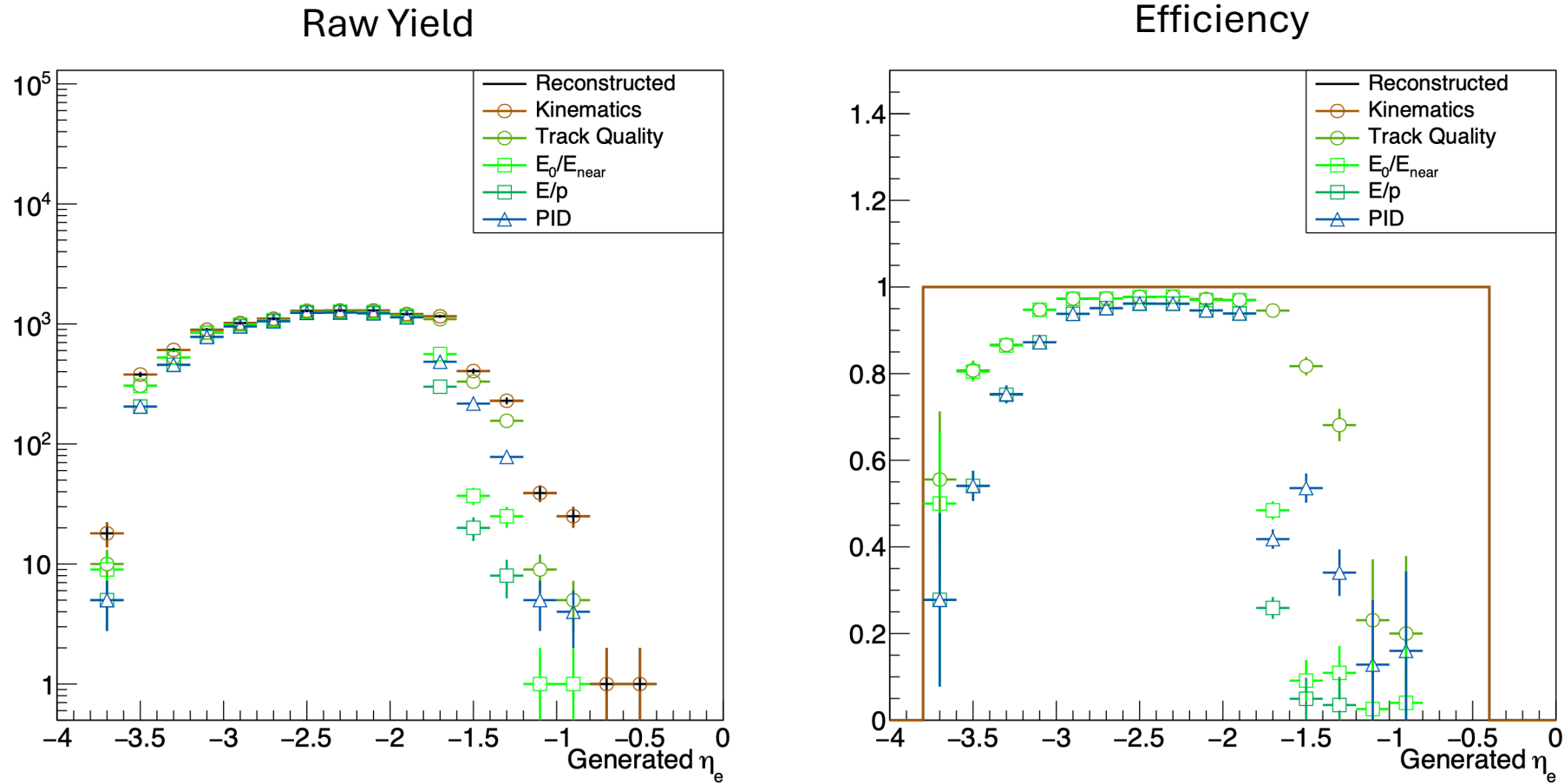
* $e + Pb \rightarrow e + Pb + a$, $10 \times 110 \text{ GeV}^2$, $m_a = 1 \text{ GeV}$



- Significant gain ($\sim 4\times$) in efficiency in the barrel region after removing the requirements on ECal match below $p < 1 \text{ GeV}$

PID Performance (N-End)

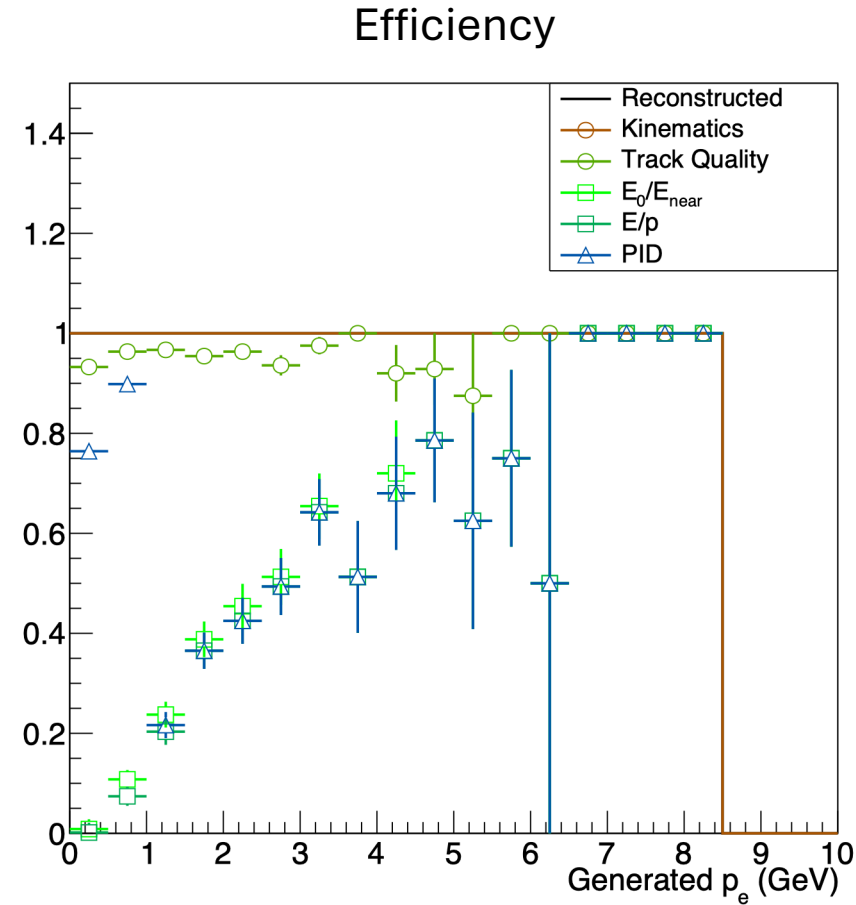
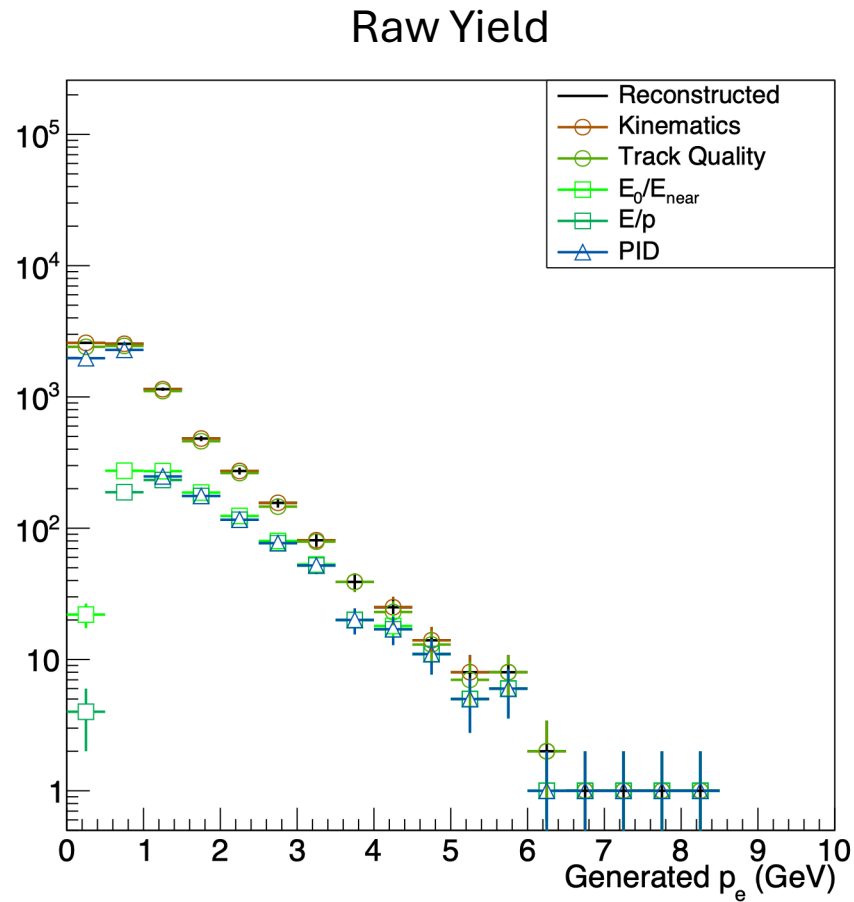
* $e + Pb \rightarrow e + Pb + a$, $10 \times 110 \text{ GeV}^2$, $m_a = 1 \text{ GeV}$



- No significant impact for N-Endcap (and P-Endcap) tracks, as expected

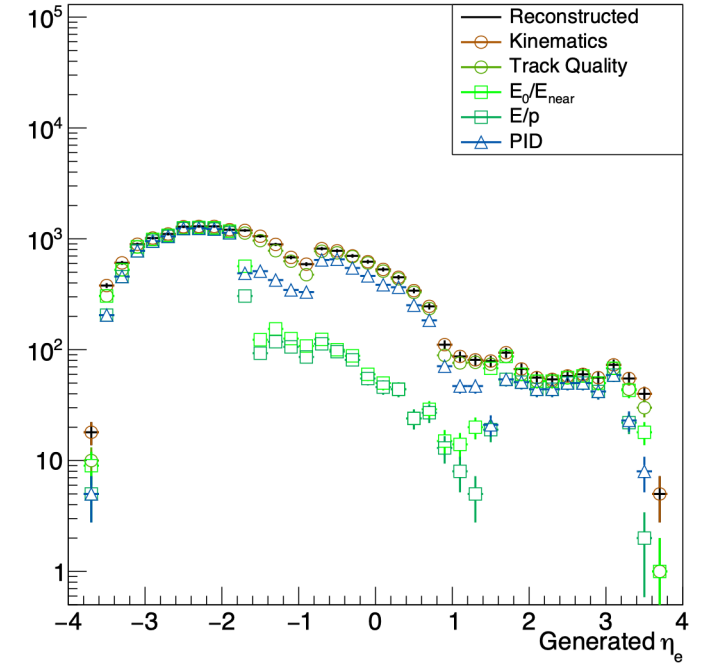
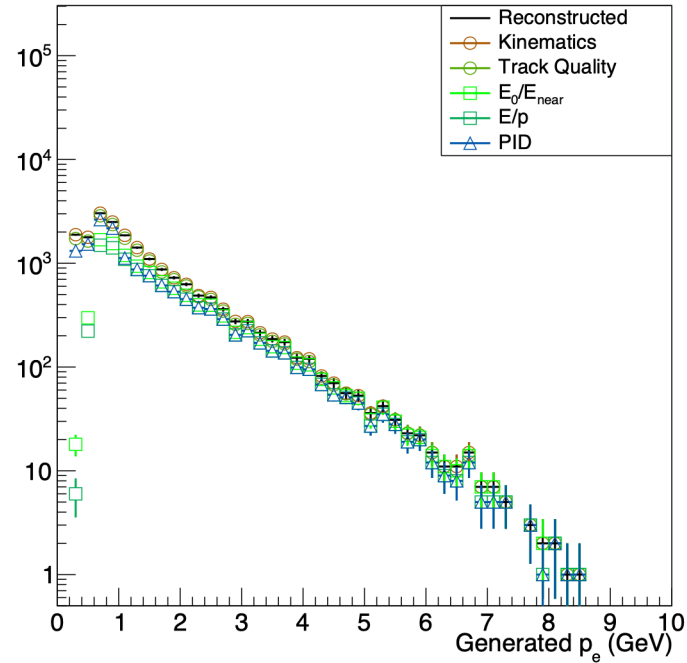
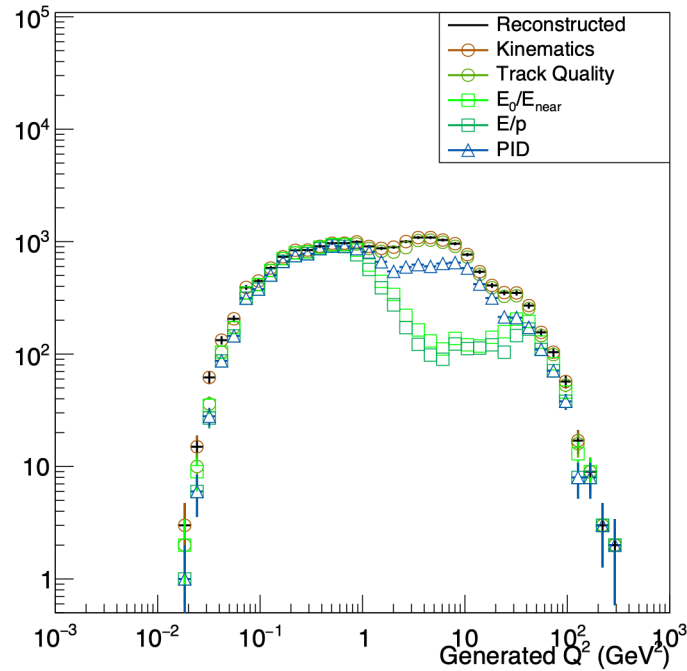
PID Performance (Barrel)

* $e + Pb \rightarrow e + Pb + a$, $10 \times 110 \text{ GeV}^2$, $m_a = 1 \text{ GeV}$



- Big jump in efficiency at the $p = 1 \text{ GeV}$ mark
- Large systematics expected from unfolding with real data
- Likelihood-based approach for eID in this regime (barrel, low-momentum)?

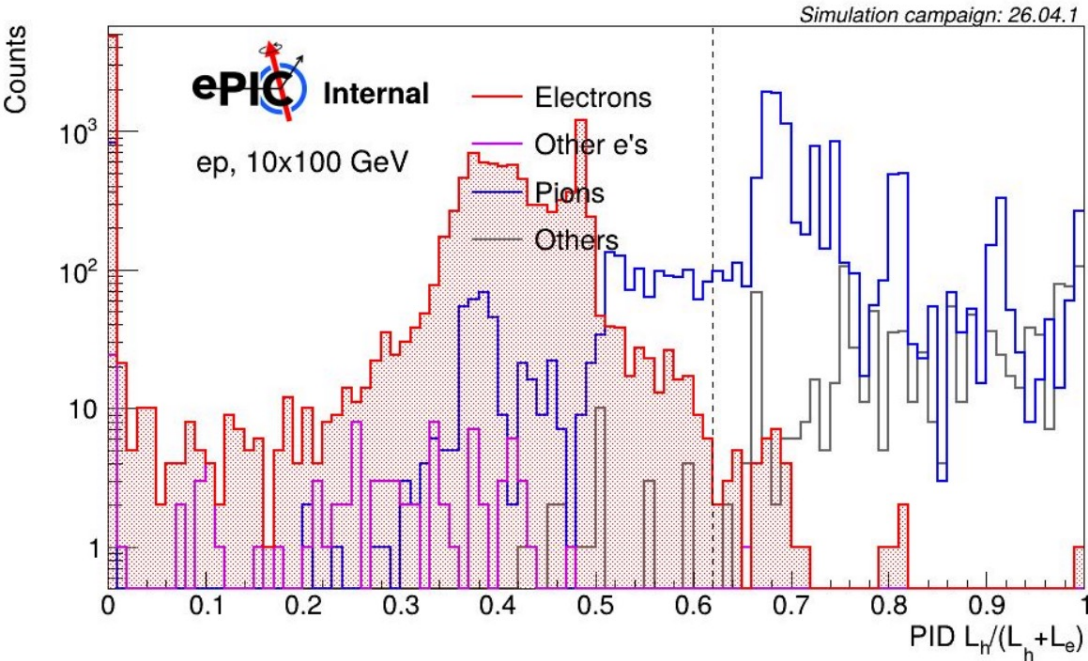
Summary



- By **relaxing the ECal matching** requirement, and relying on **PID detectors**, one should expect improvement in eID efficiency in the **low-momentum** ($\sim < 1 \text{ GeV}$, $y > 0.9$), **low Q^2** ($\sim 10 \text{ GeV}^2$), and **central** ($-2 < \eta < 2$) regime
- Likelihood-based approach might be worthwhile to address the “step function” behavior in electron momentum
- Pion contamination needs to be evaluated as well

Backup

eID via PID detectors

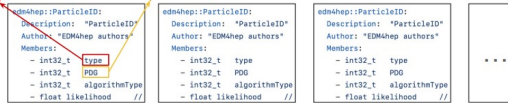


State of PID structures in our EDM

- Two implementations that rely on edm4hep::ParticleID:

- [1] [2] PID LUTs for *pfRICH, DIRC, TOF, DRICH*: $e^\pm, \pi^\pm, K^\pm, p^\pm$
- [3] ML on clusters for *EEEMCal*: e^-, π^-

```
edm4hep::ReconstructedParticle {
  Description: "ED Reconstructed Particle"
  Author: "W. Armstrong, S. Joosten, F. Sadeh"
  Members:
    - int32_t PID // PID code for this particle
    // ... Definitions for energy, momentum, mass, ...
    - float goodnessPID // overall goodness of the PID on a scale of [0,1]
  OneToManyRelations:
    // ...
    - edm4hep::ParticleID particleID used for this particle
  OneToManyRelations:
    // ... Definitions for relations to other clusters, track, particle ...
    - edm4hep::ParticleID particleID // All associated particle IDs for this particle (not yet)
```

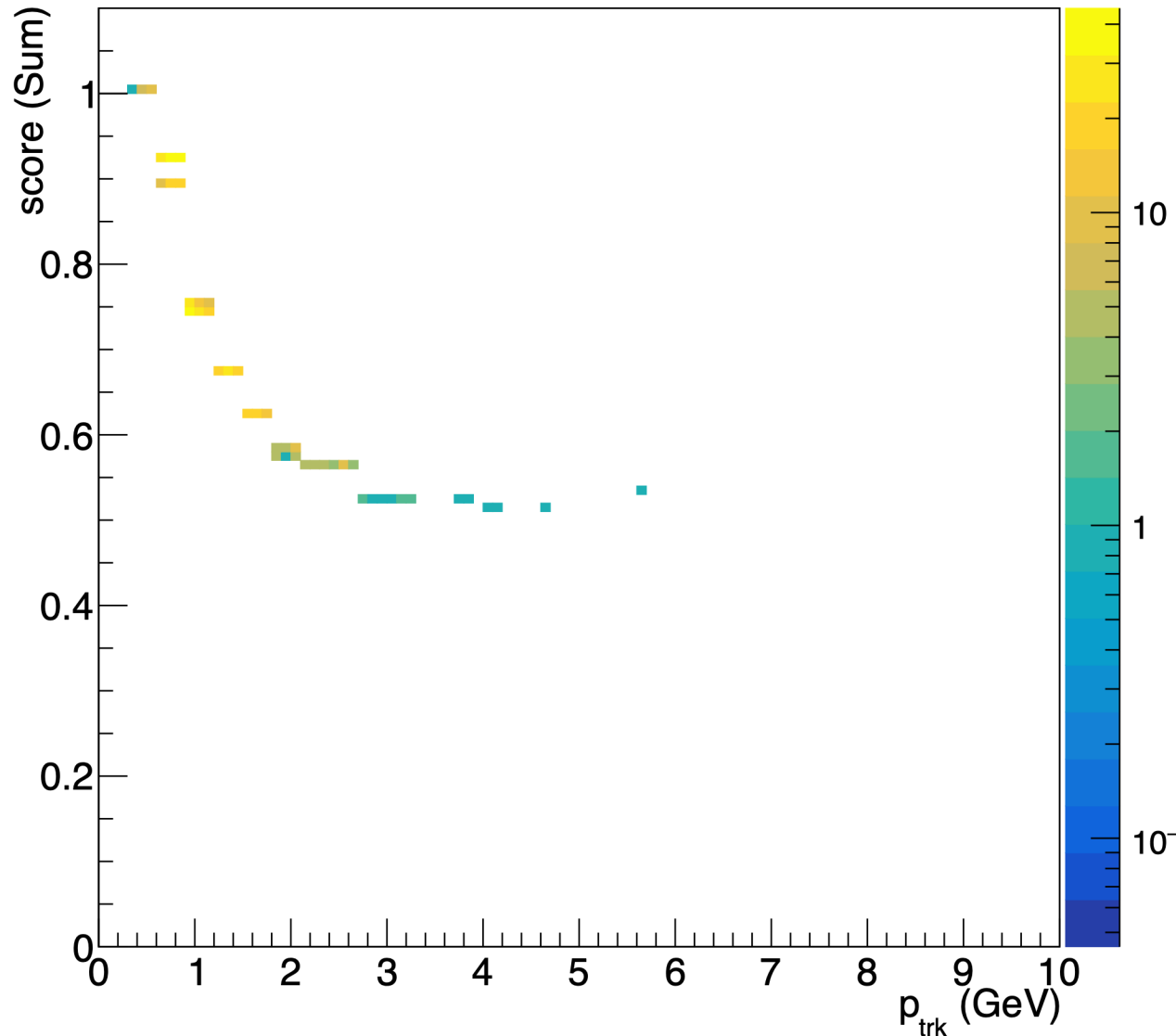


- EDM4hep insists on inverting the relation, i.e. ParticleID points to ReconstructedParticle [4] [5]
- The ML method currently “misuses” the **likelihood field** and provide posterior **P(hypot|meas)** instead of the **likelihood P(meas|hypot)**
- The LUTs also “misuse”, providing **distribution of model outputs conditioned by true class P(prediction|hypot)**. Main charge for LUTs was to fill the PDG field, reproducing a realistic misclassification distribution.

- eID based on the “likelihood” from PID detectors (LUT)
- Good e-h separation
- Score (nominal) = $\frac{\max(L_h|TOF,DIRC,...)}{\max(L_e)+\max(L_h)}$
- PID presentation from O. Hartbrich and D. Kalinkin in Joint SC-TC PID meeting
(<https://indico.bnl.gov/event/29822/contributions/113615/attachments/64927/111522/PID%20Data%20Model.pdf>)
- Discusses the misuse of Likelihood field
 $L_{current} = \langle \text{prediction} | \text{truth prior} \rangle$
 $= \langle \text{prediction} | \text{detector} \rangle \langle \text{detector} | \text{truth} \rangle$
- Detector level info integrated out!
- Whereas (depending on exactly what we are trying to do), what we want is either $\langle \text{prediction} | \text{detector} \rangle$ or $\langle \text{detector} | \text{truth} \rangle$

P-Endcap response

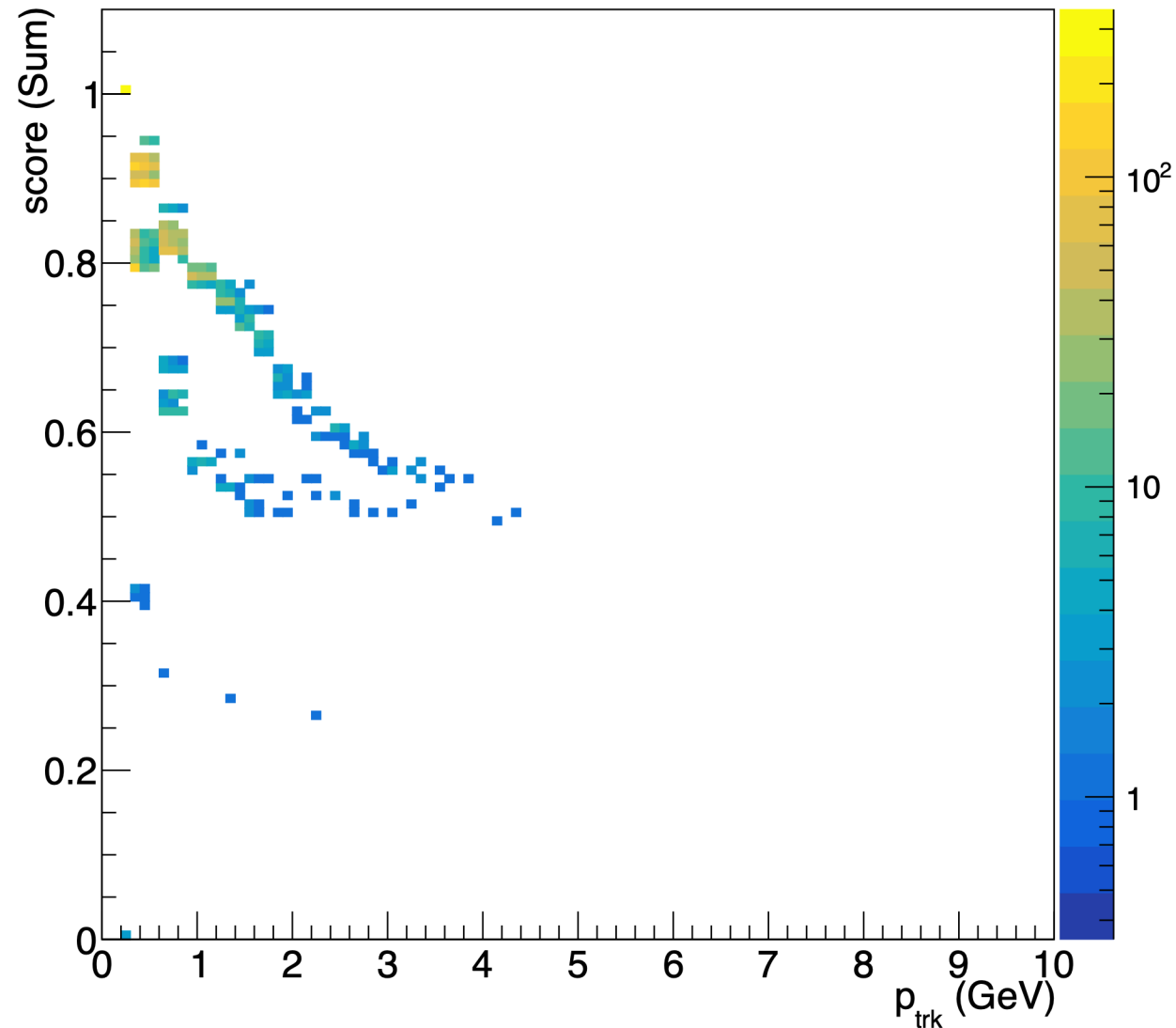
P-Endcap Tracks



- Looking at electrons from $e + Pb \rightarrow e + a$
- eID score (sum) =
$$\frac{\sum_{TOF, dRICH} L_e}{\frac{\sum L_e + \sum L_h}{L_e + L_h}}_{dRICH}$$
- Complete correlation between prior (momentum) and eID score (sum)

Barrel response

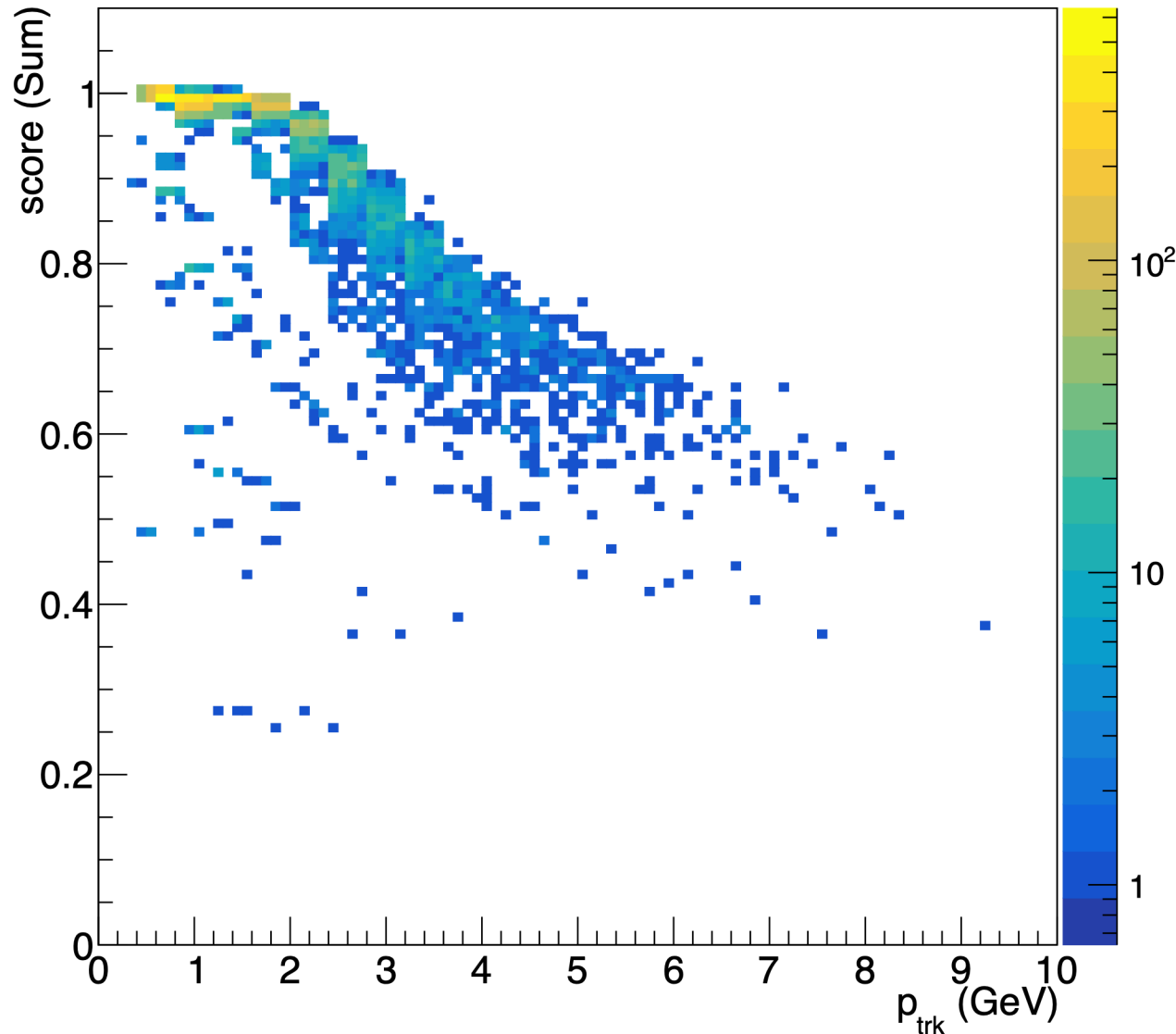
Barrel Tracks



- Three “bands” coming from
 - DIRC only
 - TOF only
 - DIRC + TOF
- Similar result as P-Endcap

N-Endcap response

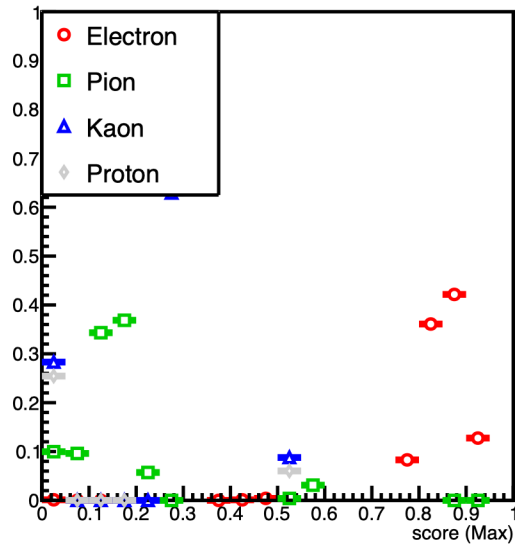
N-Endcap Tracks



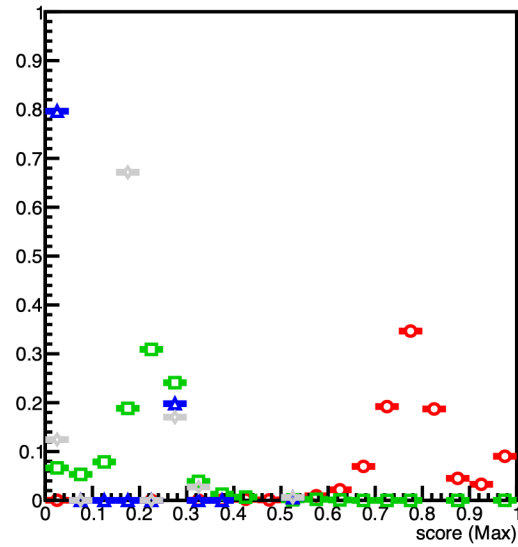
- Much more “smearing” then previous two
- Will investigate other significant priors (p, eta, phi, charge, truth PDG)

Barrel tracks

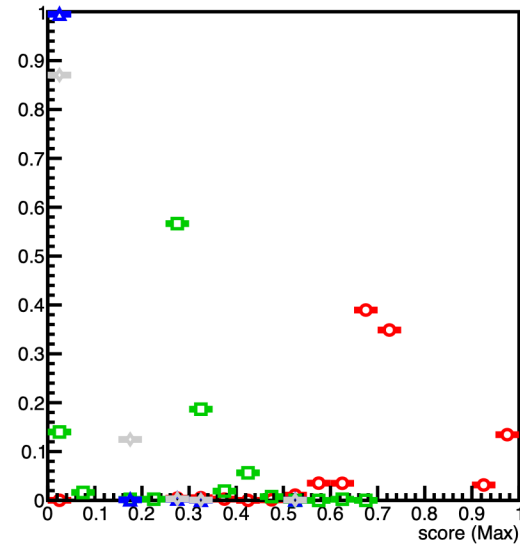
$0.2 < p_{\text{trk}} \text{ (GeV)} < 0.5 \text{ (Max)}$



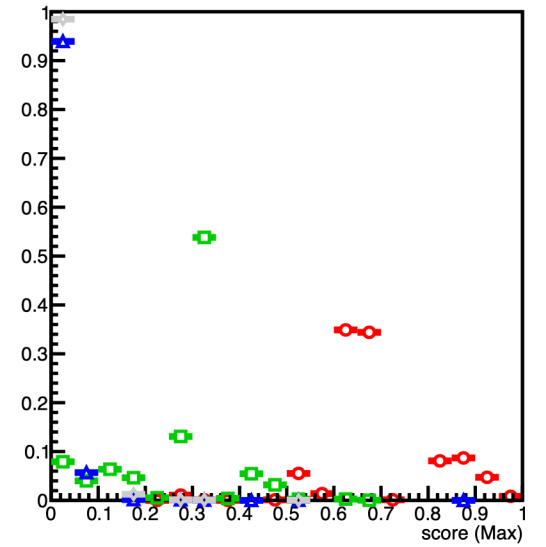
$0.5 < p_{\text{trk}} \text{ (GeV)} < 1 \text{ (Max)}$



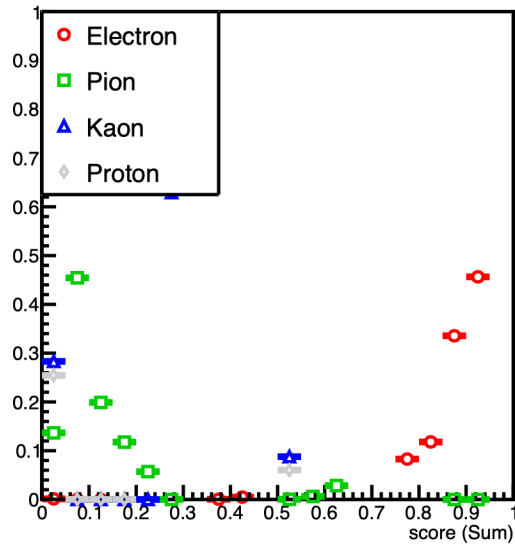
$1 < p_{\text{trk}} \text{ (GeV)} < 1.5 \text{ (Max)}$



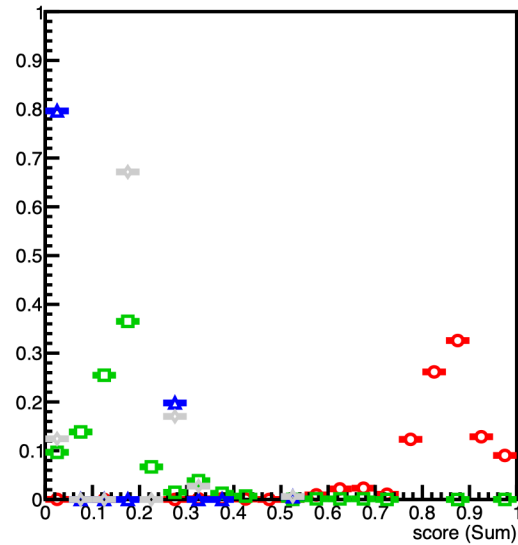
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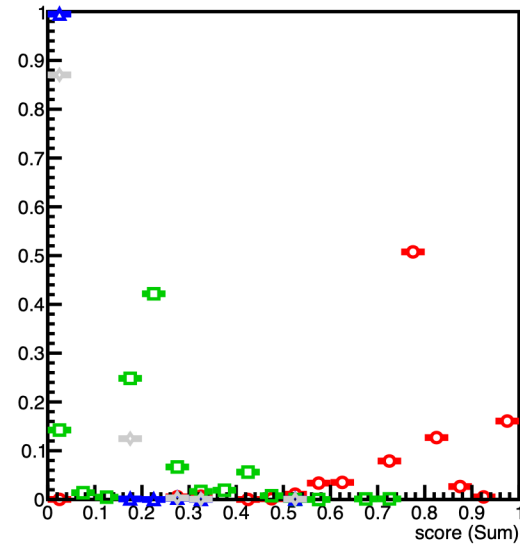
$0.2 < p_{\text{trk}} \text{ (GeV)} < 0.5 \text{ (Sum)}$



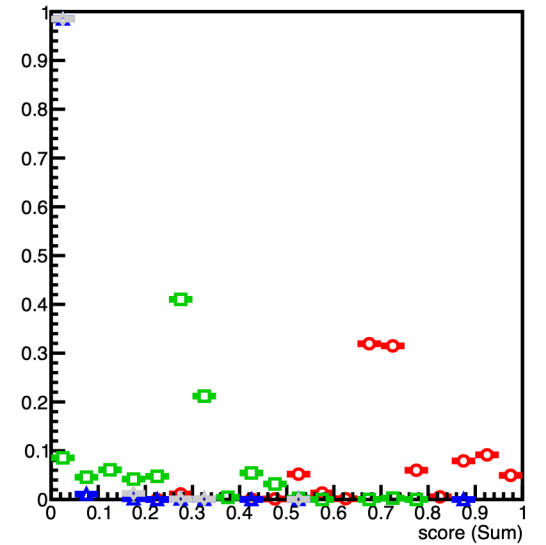
$0.5 < p_{\text{trk}} \text{ (GeV)} < 1 \text{ (Sum)}$



$1 < p_{\text{trk}} \text{ (GeV)} < 1.5 \text{ (Sum)}$

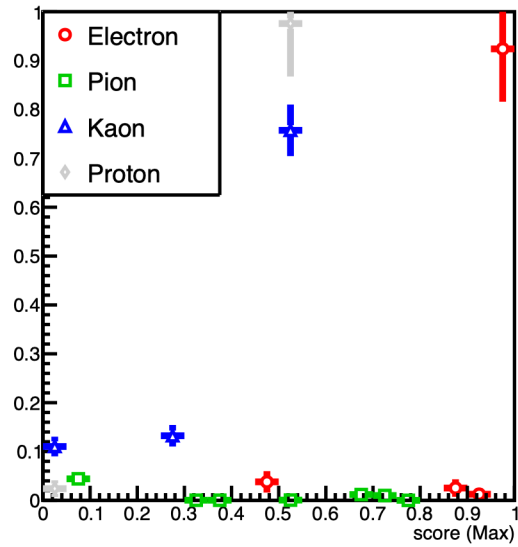


$1.5 < p_{\text{trk}} \text{ (GeV)} < 2 \text{ (Sum)}$

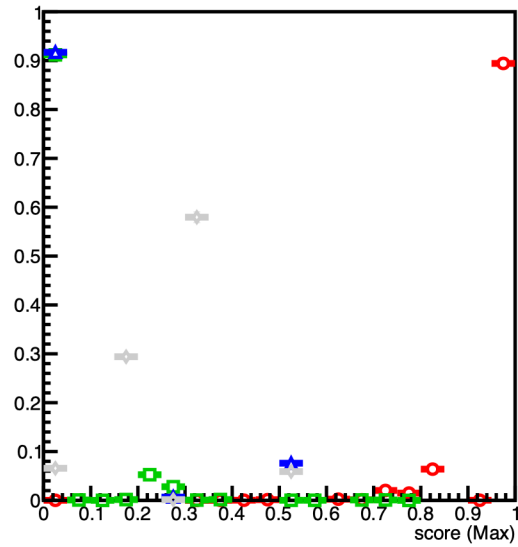


N-Endcap tracks

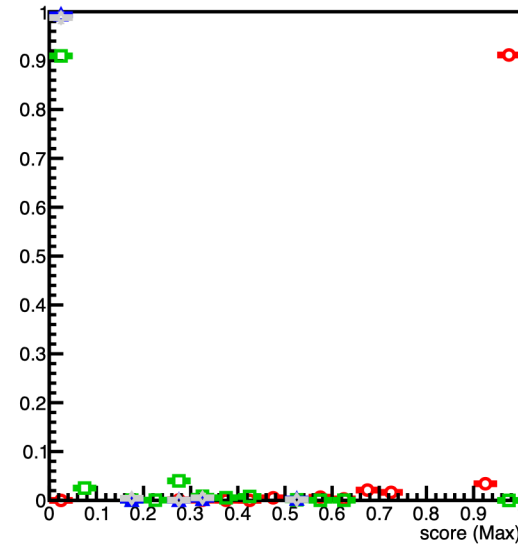
$0.2 < p_{\text{trk}} \text{ (GeV)} < 0.5 \text{ (Max)}$



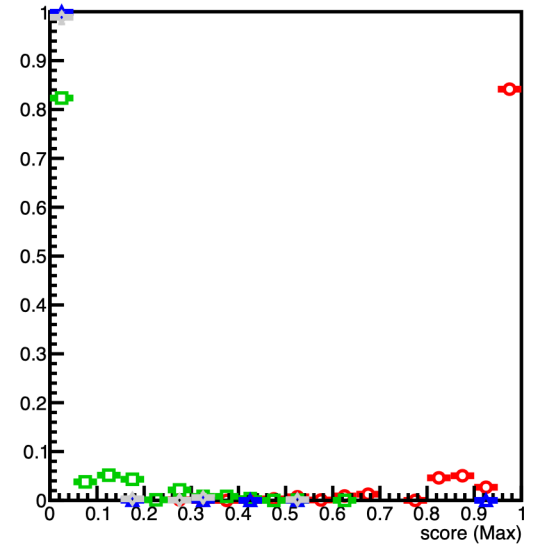
$0.5 < p_{\text{trk}} \text{ (GeV)} < 1 \text{ (Max)}$



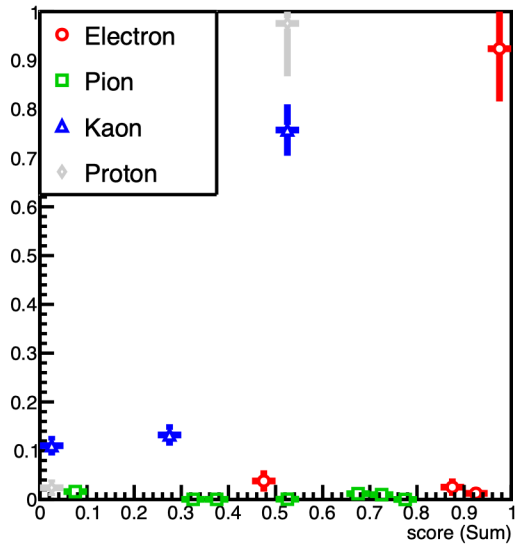
$1 < p_{\text{trk}} \text{ (GeV)} < 1.5 \text{ (Max)}$



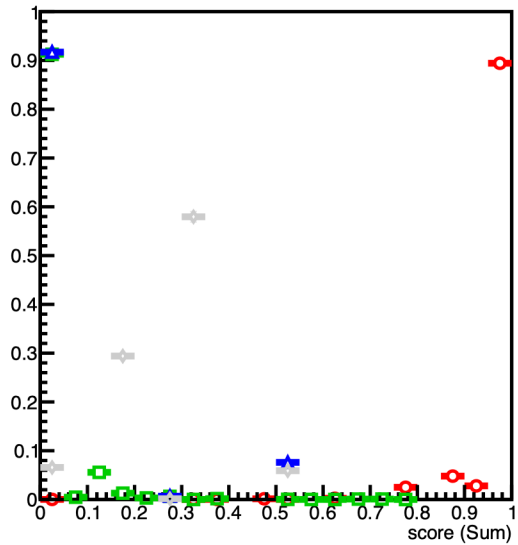
$1.5 < p_{\text{trk}} \text{ (GeV)} < 2 \text{ (Max)}$



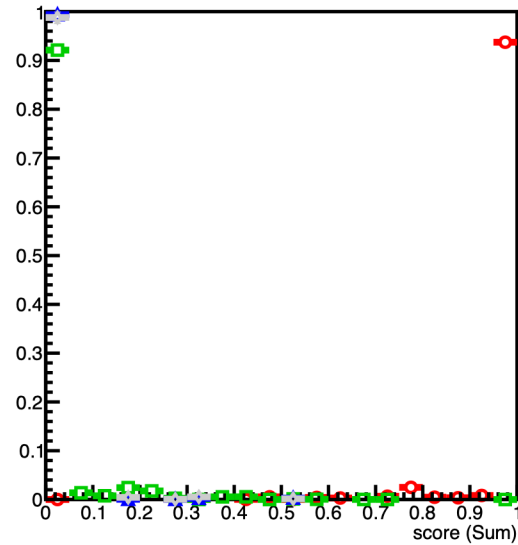
$0.2 < p_{\text{trk}} \text{ (GeV)} < 0.5 \text{ (Sum)}$



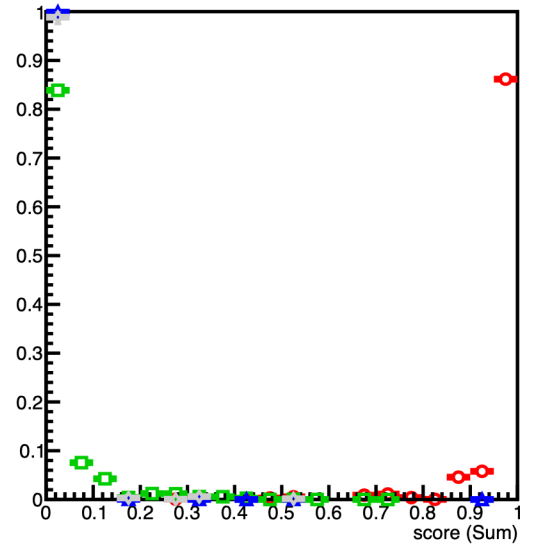
$0.5 < p_{\text{trk}} \text{ (GeV)} < 1 \text{ (Sum)}$



$1 < p_{\text{trk}} \text{ (GeV)} < 1.5 \text{ (Sum)}$

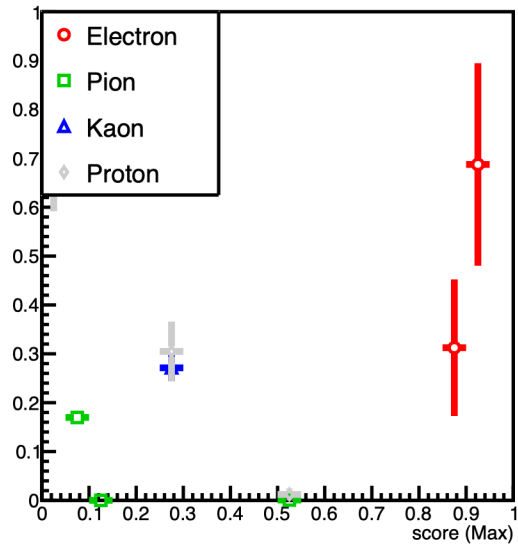


$1.5 < p_{\text{trk}} \text{ (GeV)} < 2 \text{ (Sum)}$

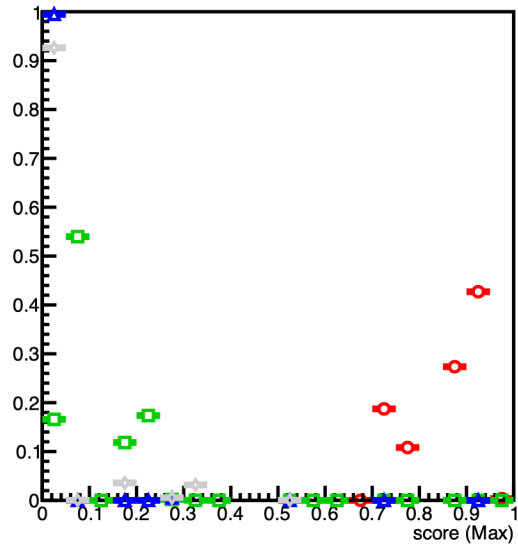


P-Endcap

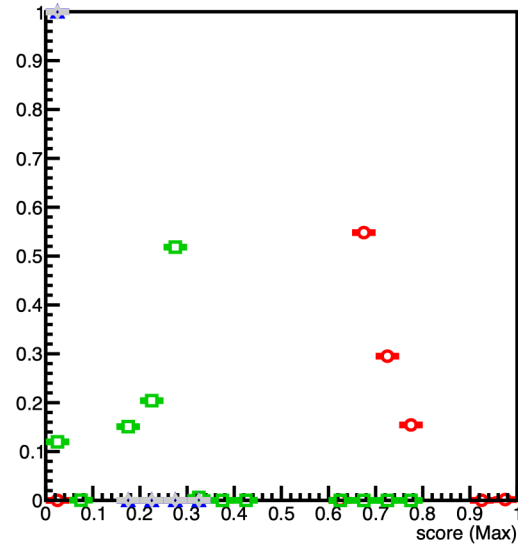
$0.2 < p_{\text{trk}} \text{ (GeV)} < 0.5 \text{ (Max)}$



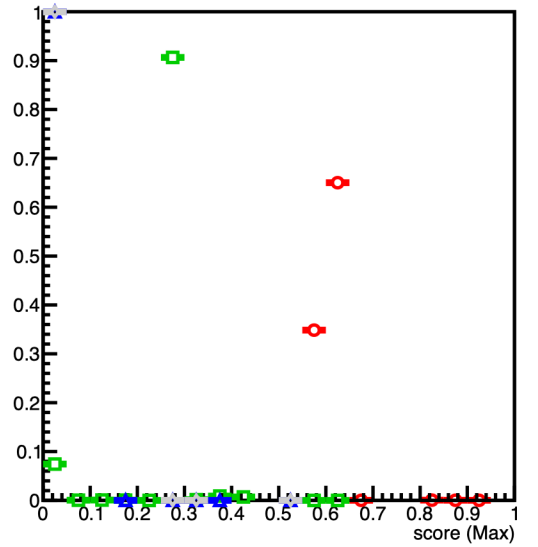
$0.5 < p_{\text{trk}} \text{ (GeV)} < 1 \text{ (Max)}$



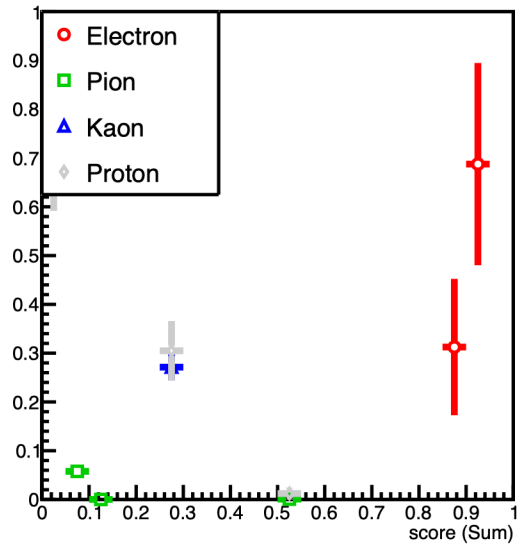
$1 < p_{\text{trk}} \text{ (GeV)} < 1.5 \text{ (Max)}$



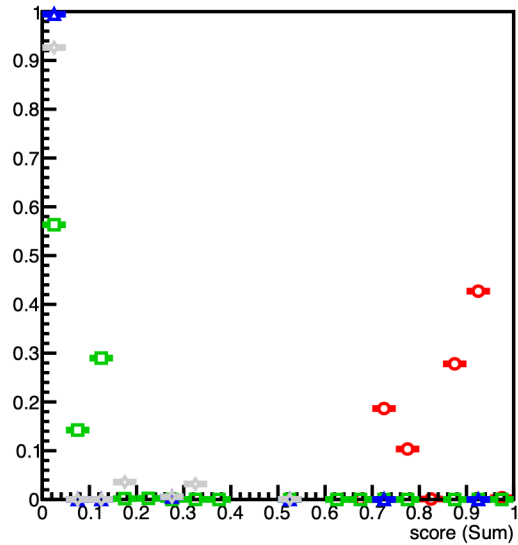
$1.5 < p_{\text{trk}} \text{ (GeV)} < 2 \text{ (Max)}$



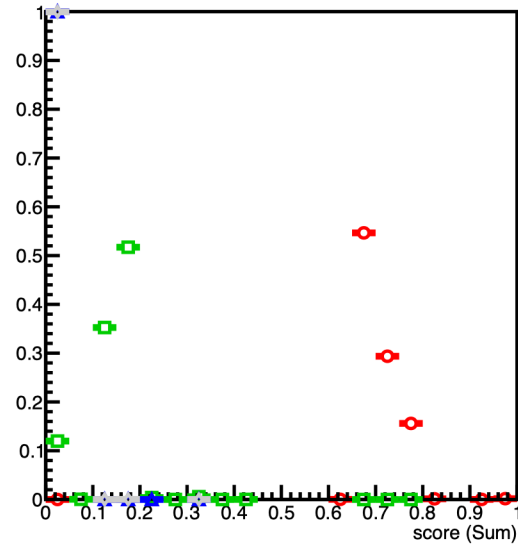
$0.2 < p_{\text{trk}} \text{ (GeV)} < 0.5 \text{ (Sum)}$



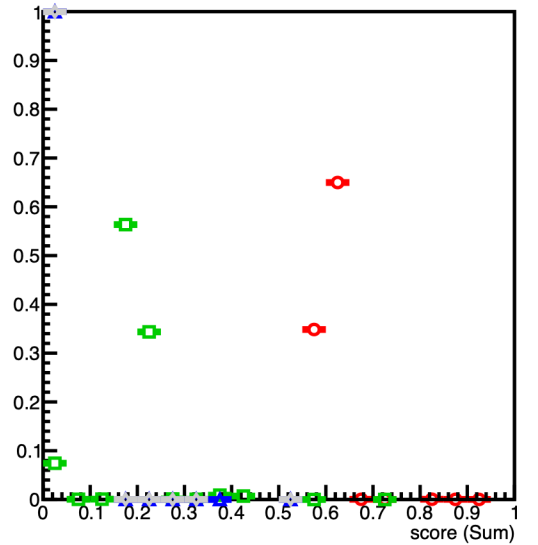
$0.5 < p_{\text{trk}} \text{ (GeV)} < 1 \text{ (Sum)}$



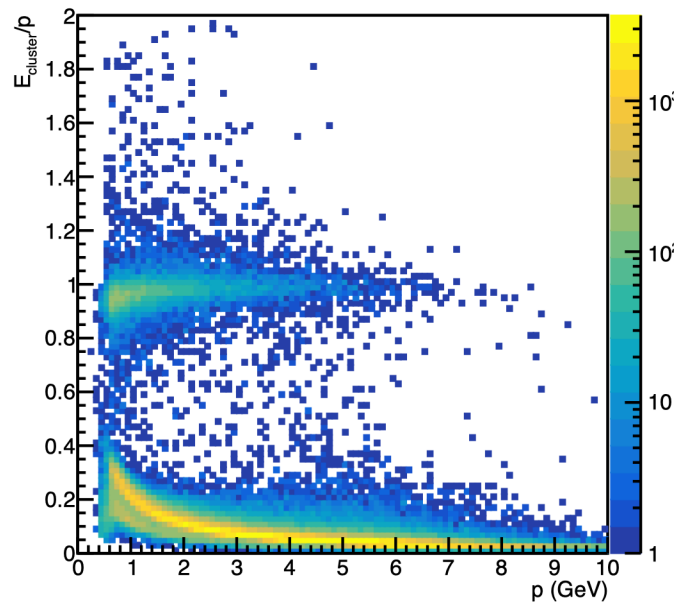
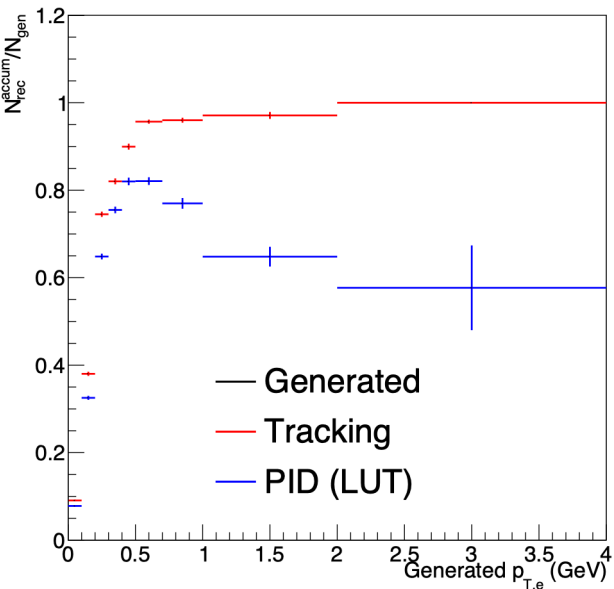
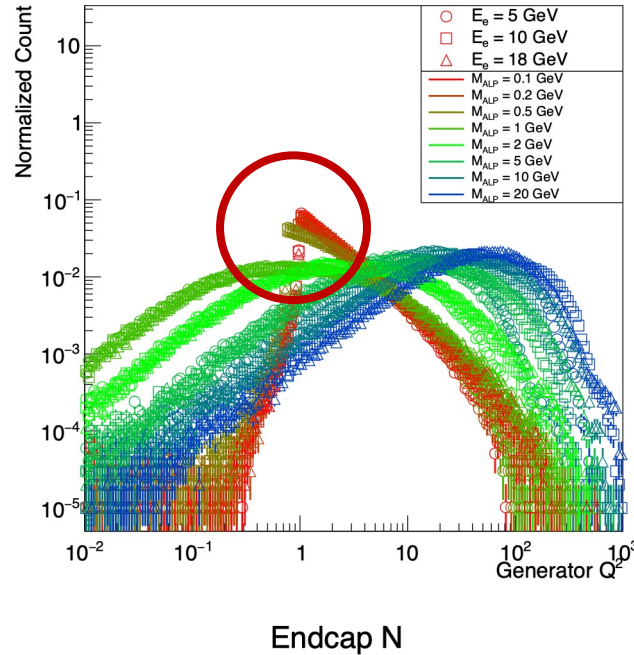
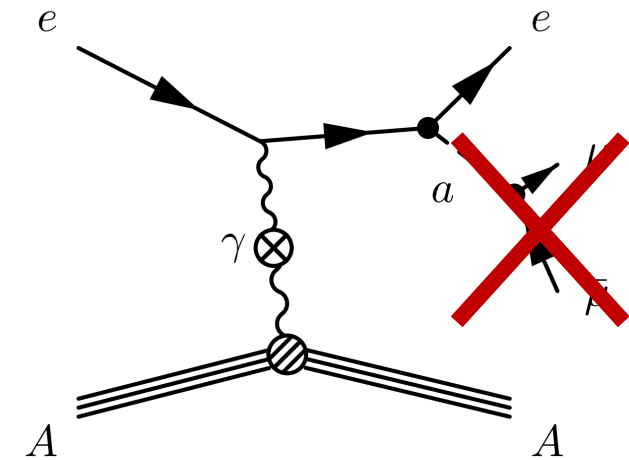
$1 < p_{\text{trk}} \text{ (GeV)} < 1.5 \text{ (Sum)}$



$1.5 < p_{\text{trk}} \text{ (GeV)} < 2 \text{ (Sum)}$

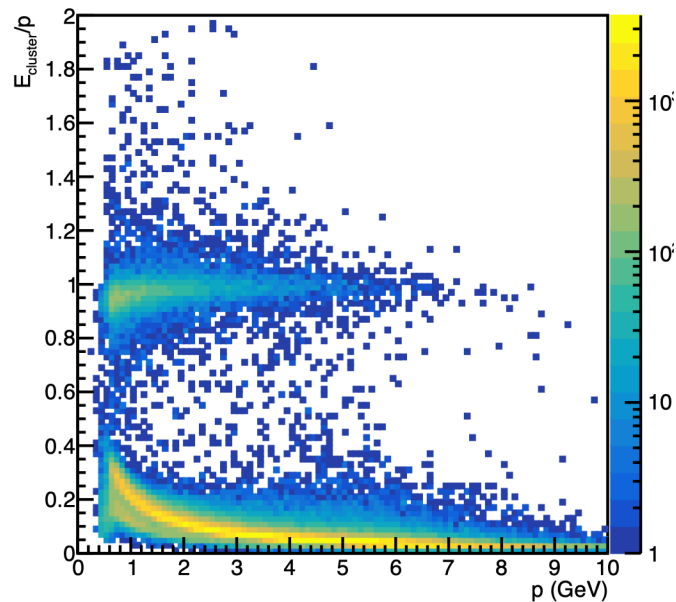
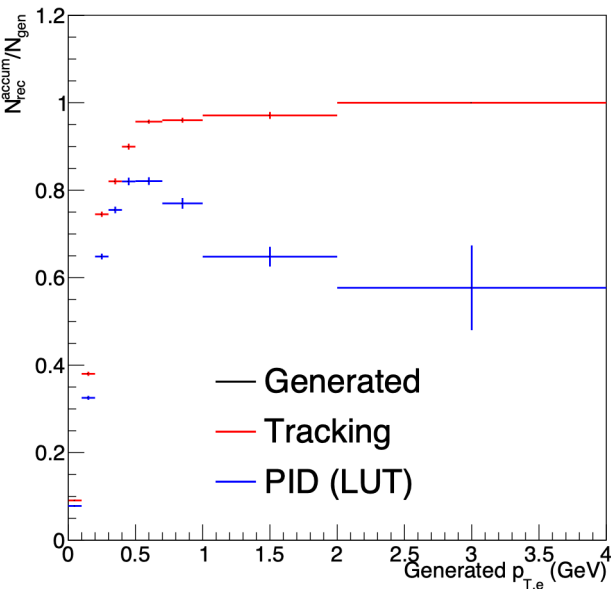
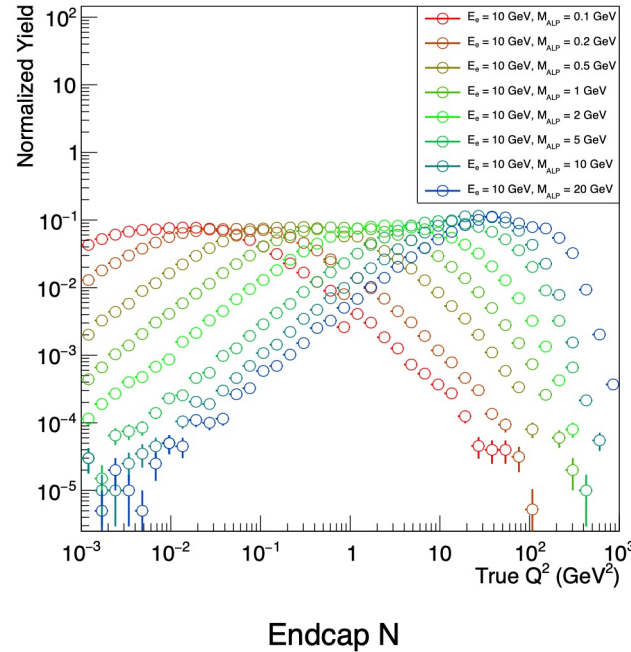
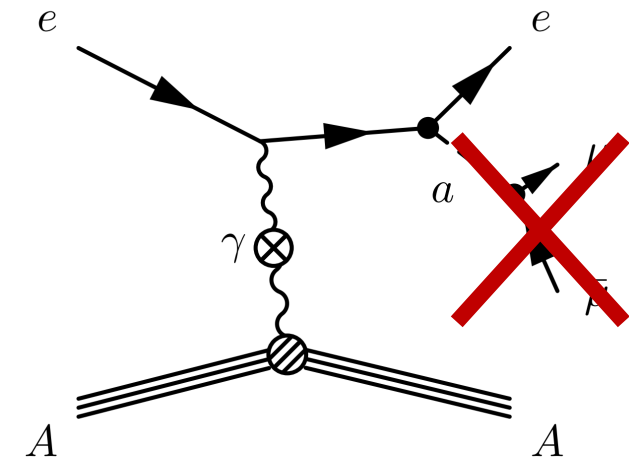


Recap



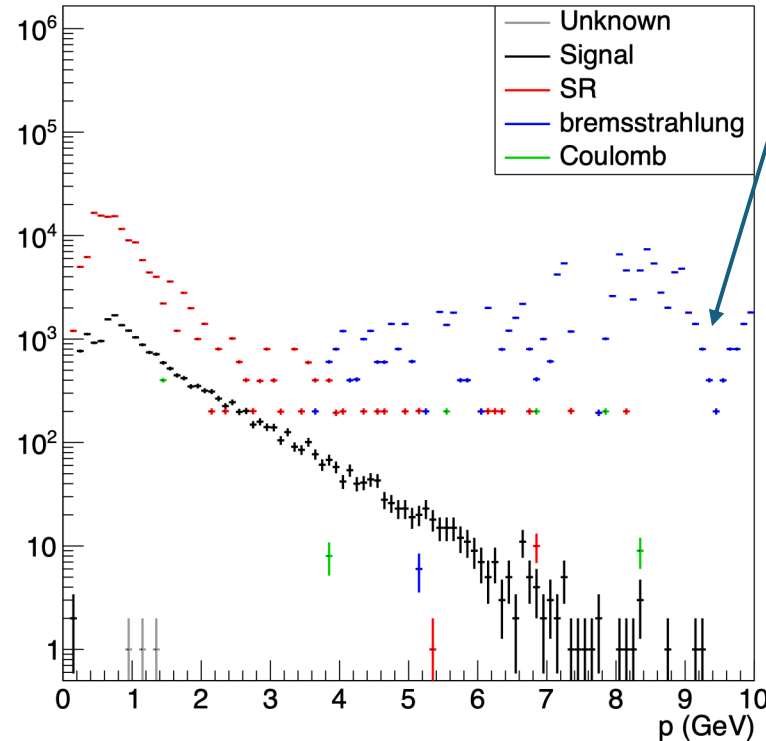
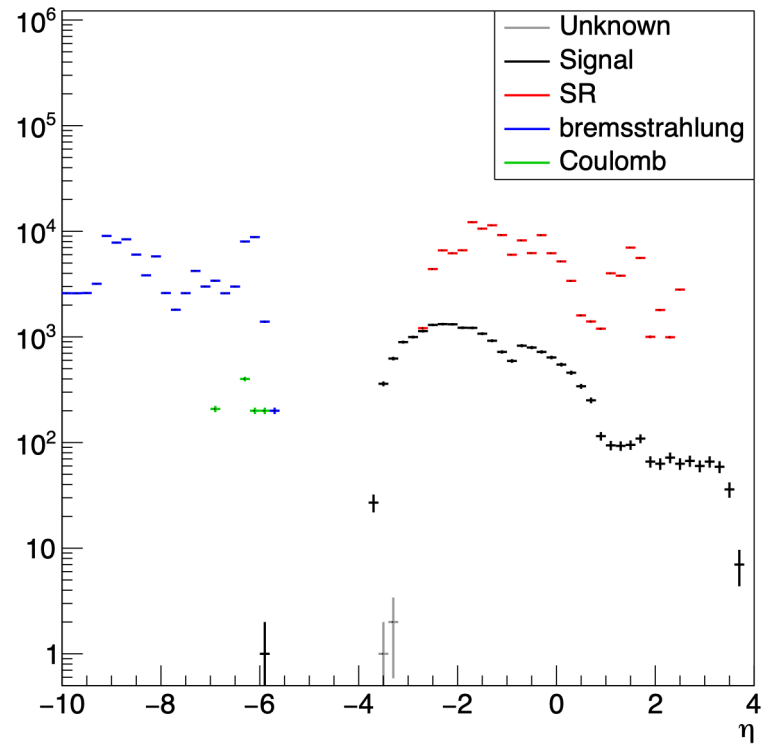
- Last update on Apr 21
- Focus: Non-decaying/ Invisibly-decaying ALP
- Event kinematics entirely defined by electron within central ePIC
- Bug with MadGraph5 event generation → has been addressed
- Strong ALP mass (m_a) dependence found in observed Q^2 (purely phenom. quantity)
- eID cannot entirely rely on PID systems?
- First look at ECal response

Recap

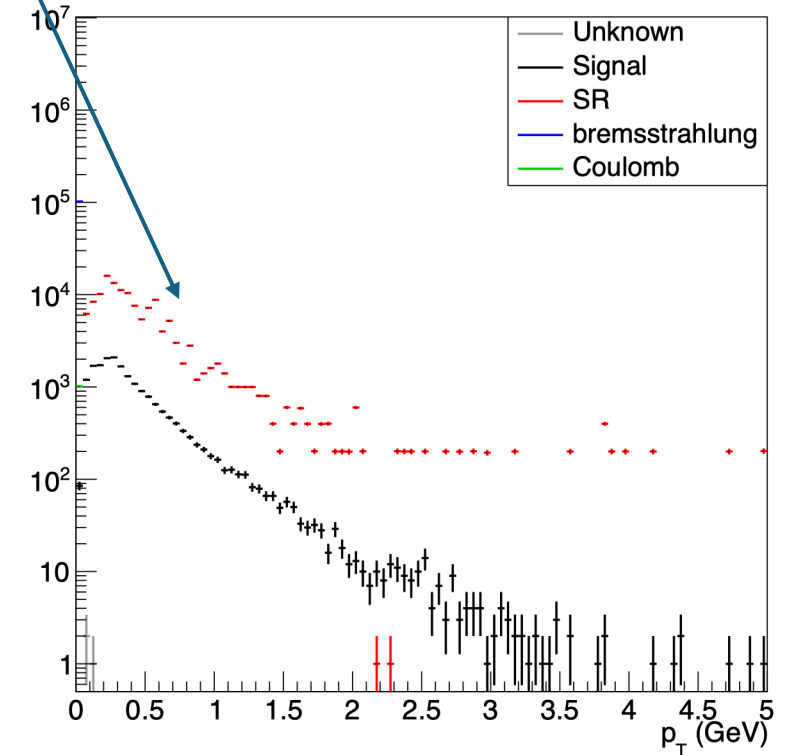


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Rejecting machine backgrounds

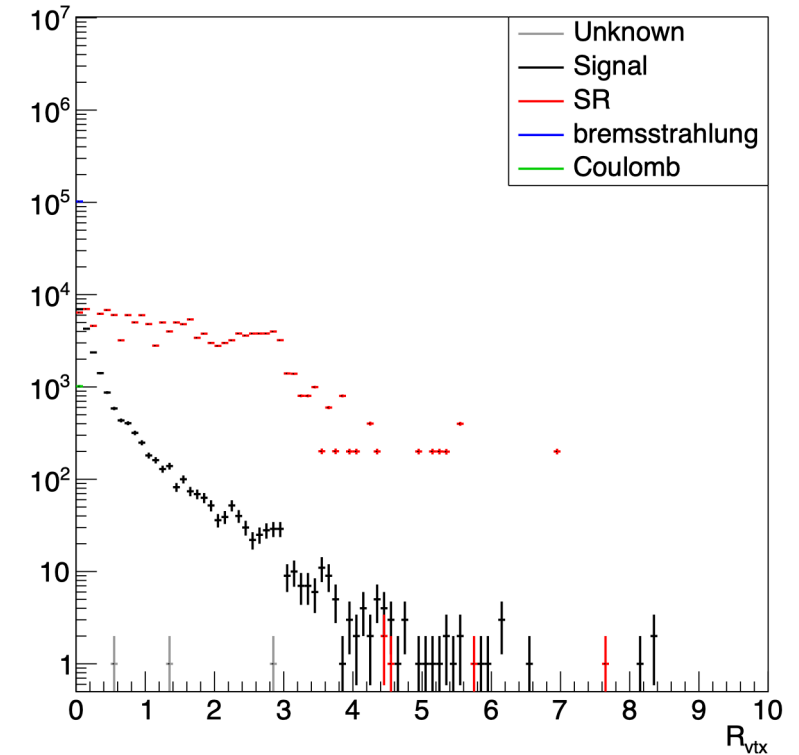
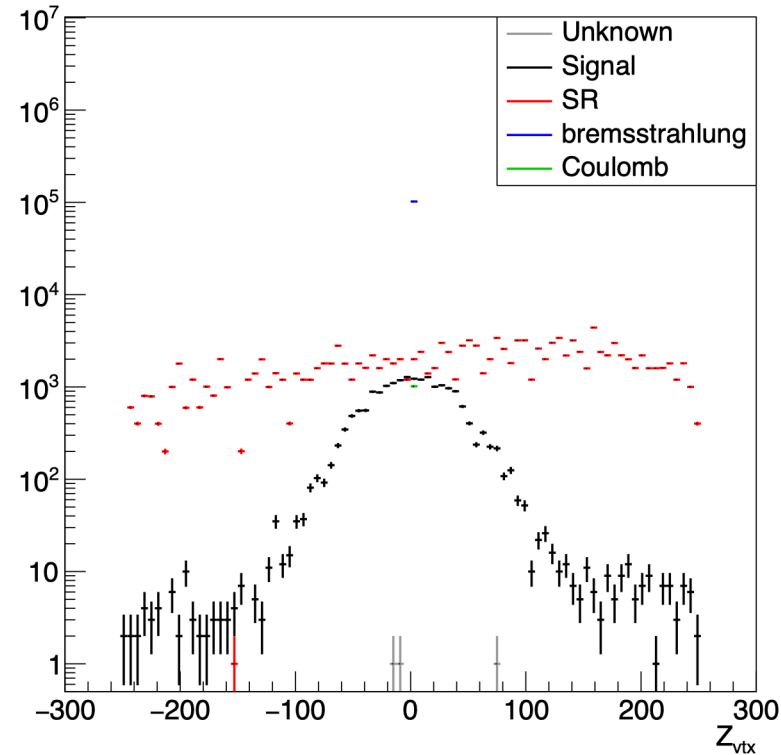
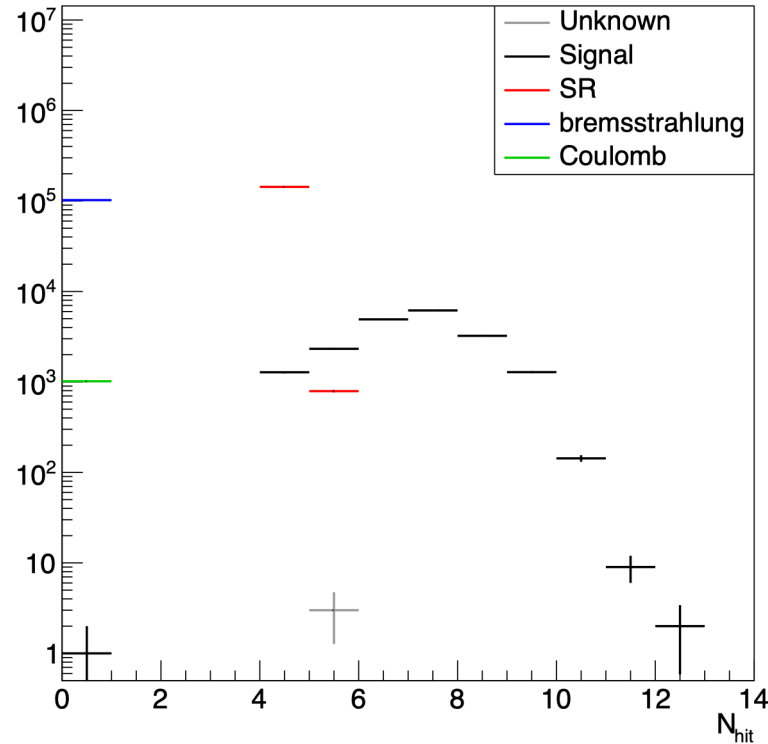


Correlated BG, should be resolved in July campaign



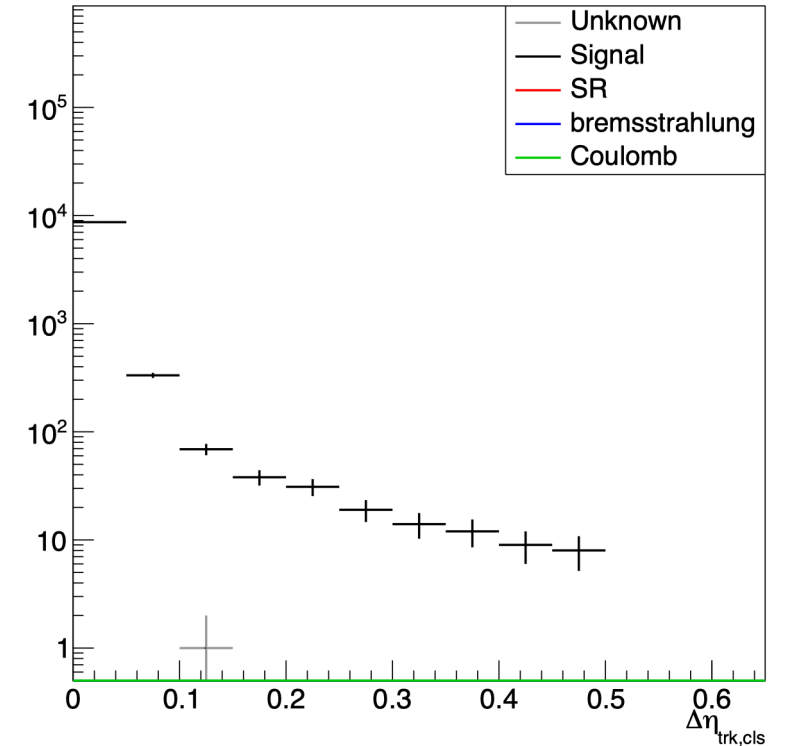
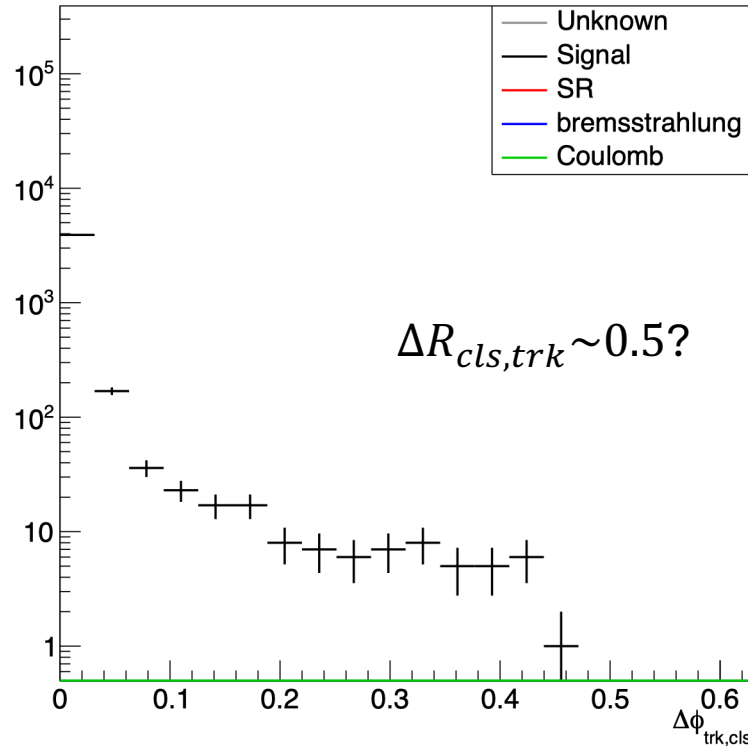
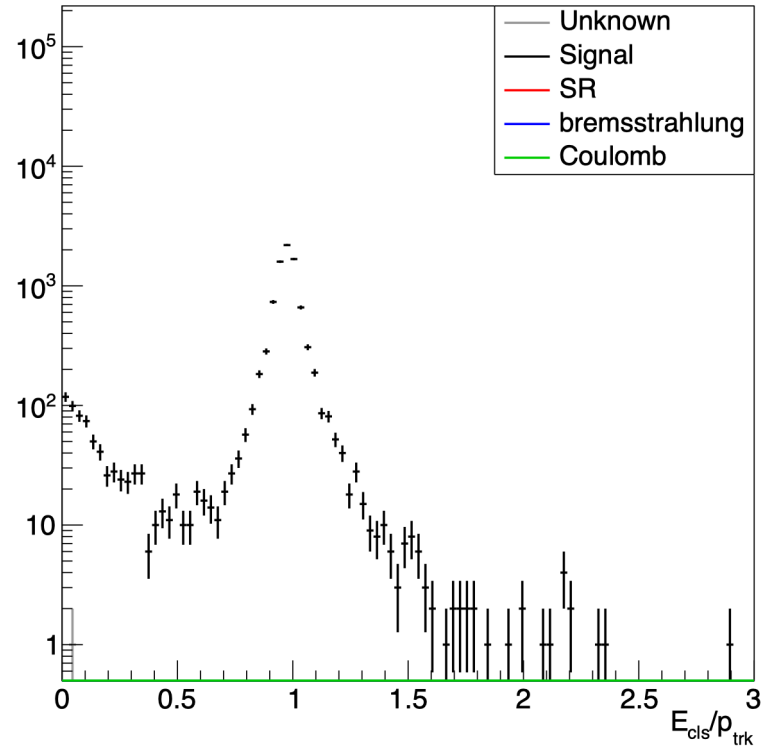
- Signal (ALP) tracks compared to machine backgrounds in June production
- brems and Coulomb tracks in low- Q^2 tagger
→ reject tracks in low- Q^2 tagger for now
- High-rate SR photons ($\sim 50k$ hits within $2\mu s$ window) → combinatoric fake tracks

Rejecting machine backgrounds



- N_{hits} cut at ≥ 5 (default) should reject most of the SR tracks
- Further beamline constraints should reject the remaining $\sim 50\%$

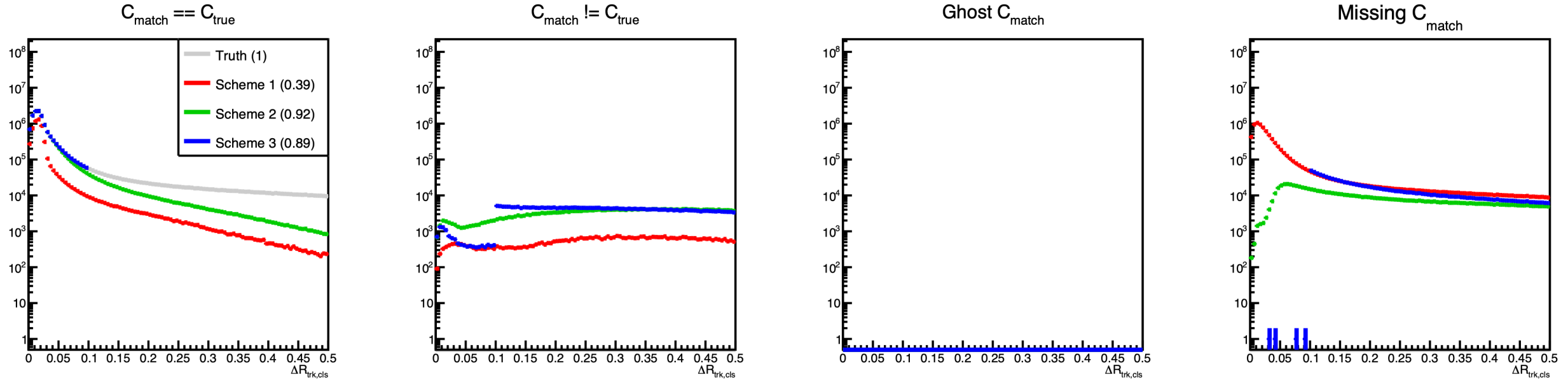
Rejecting machine backgrounds



- Geometric matching (“TrackClusterMatch”) to an ECal cluster, effectively requiring 6th hit, removes all of the SR fake tracks
- This effectively imposes a lower limit on momentum (e.g., $p_T > 0.5 \text{ GeV}$ in barrel)
- Current simulation infrastructure is limited in statistics, this study needs to be revisited with either more SR simulation or real data

Cluster matching tests

* Based on DIS $1 < Q^2(\text{GeV}^2) < 10$ sample



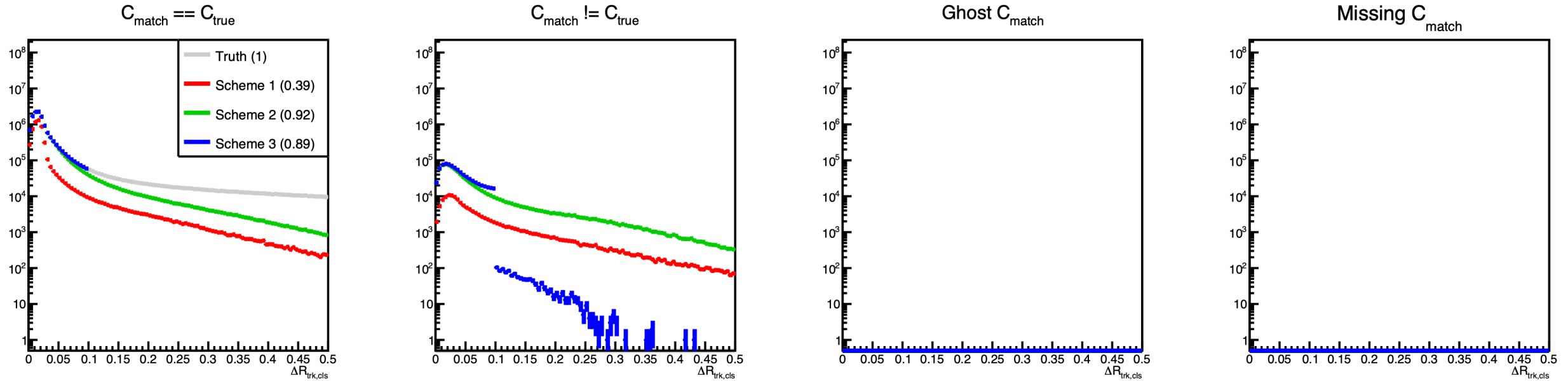
• Test of track-cluster matching algo

Truth-matched track-cluster

- Scheme 1: “TrackClusterMatch” (nearest cluster within 0.5 in $\Delta\eta \times \Delta\phi$)
- Scheme 2: Most energetic cluster within $R = \text{cluster radius} + 1$ cell size
- Scheme 3: Most energetic cluster within $R = 0.1$ in $\Delta\eta \times \Delta\phi$ space
- No clear “winner”, will revisit this topic with cluster splitting
- Further studies (for now) using truth matches

Cluster matching tests

* Based on DIS $1 < Q^2(\text{GeV}^2) < 10$ sample



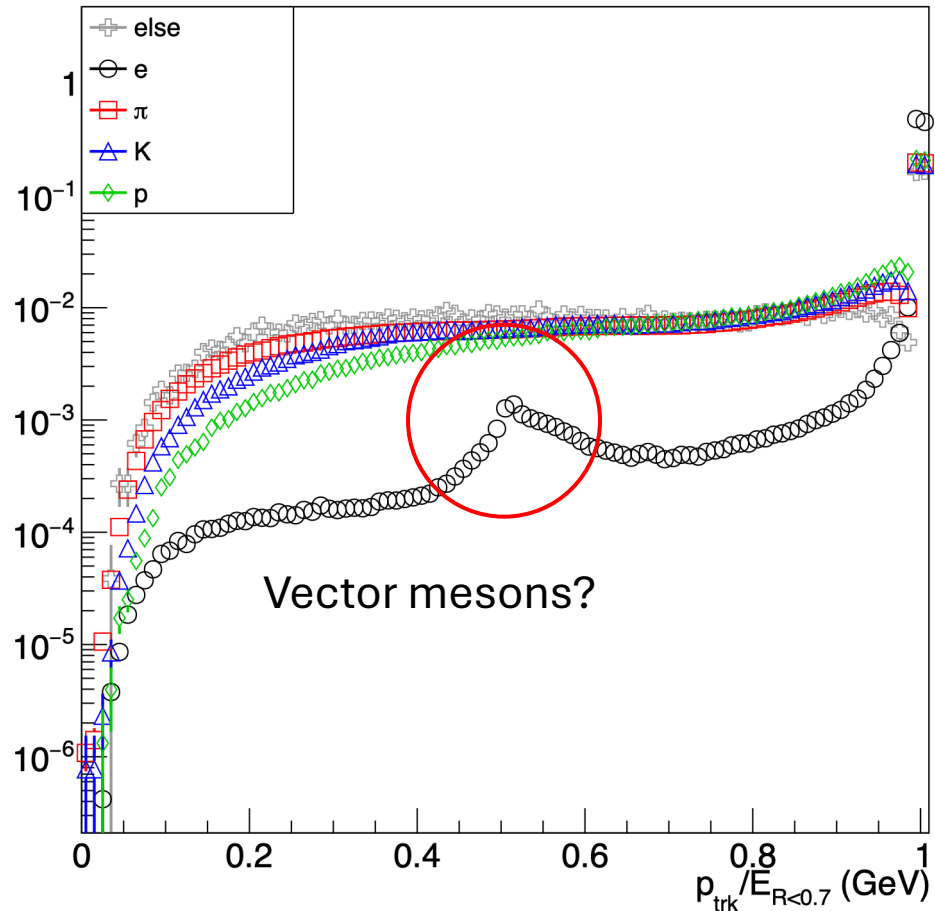
• Test of track-cluster matching algo

Algo-matched track-cluster

- Scheme 1: “TrackClusterMatch” (nearest cluster within 0.5 in $\Delta\eta \times \Delta\phi$)
- Scheme 2: Most energetic cluster within $R = \text{cluster radius} + 1$ cell size
- Scheme 3: Most energetic cluster within $R = 0.1$ in $\Delta\eta \times \Delta\phi$ space
- No clear “winner”, will revisit this topic with cluster splitting
- Further studies (for now) using truth matches

Electron identification

* Based on DIS $1 < Q^2(\text{GeV}^2) < 10$ sample

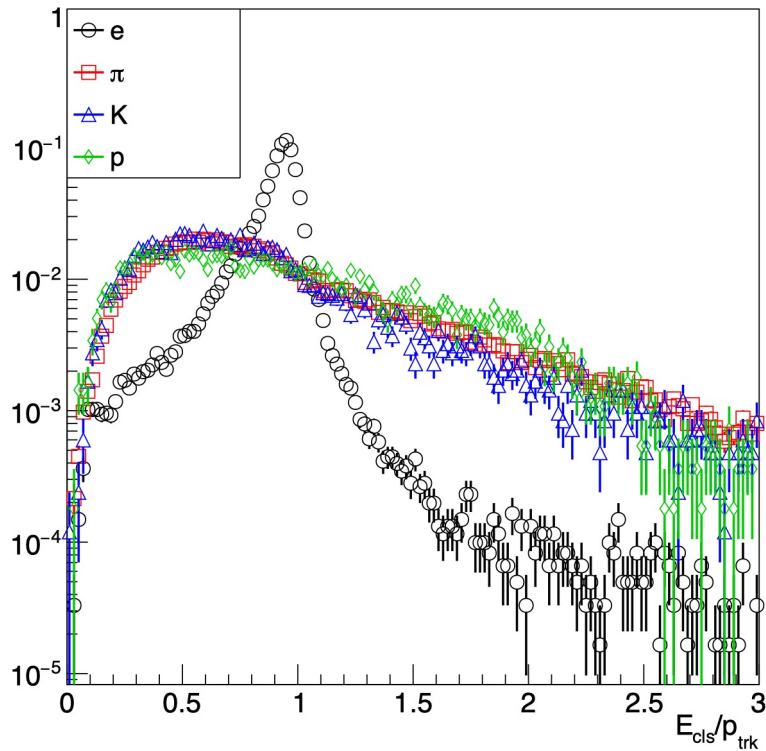


- Using inclusive DIS at $1 < Q^2(\text{GeV}^2) < 10$ sample for eID study
- The current strategy follows Inclusive PWG:
 - Track-cluster matching
 - Isolated cluster ($E/E_{\Delta R < 0.7} > 0.9$)
 - $0.8 < E_{cls}/p_{trk} < 1.2$
 - Highest p_T track
- Isolation seems to work well for the most part, but perhaps some tuning required for non-primary electron ID.
- Also, requires cluster matching, which effectively imposes a lower momentum cut

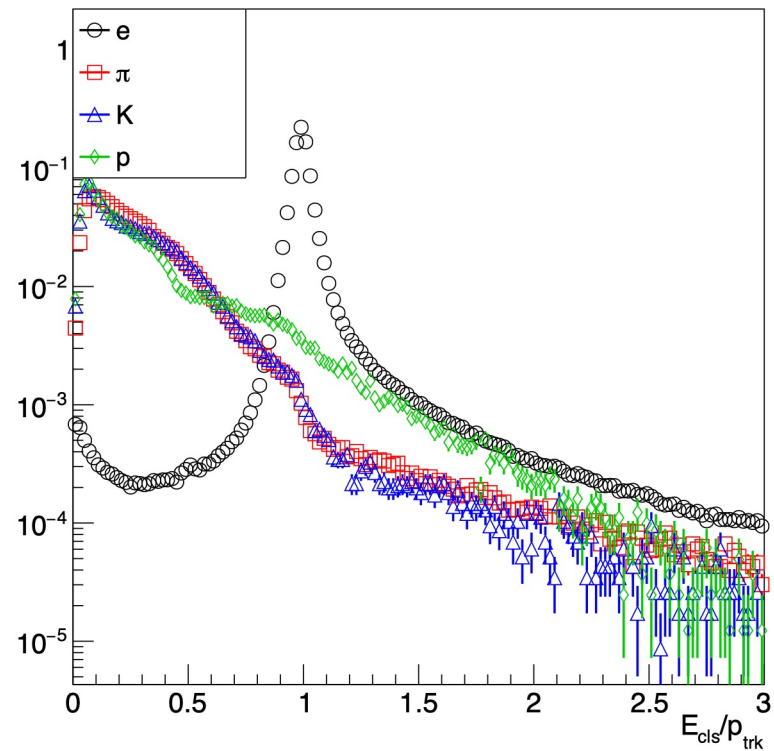
Electron identification

* Based on DIS $1 < Q^2(\text{GeV}^2) < 10$ sample

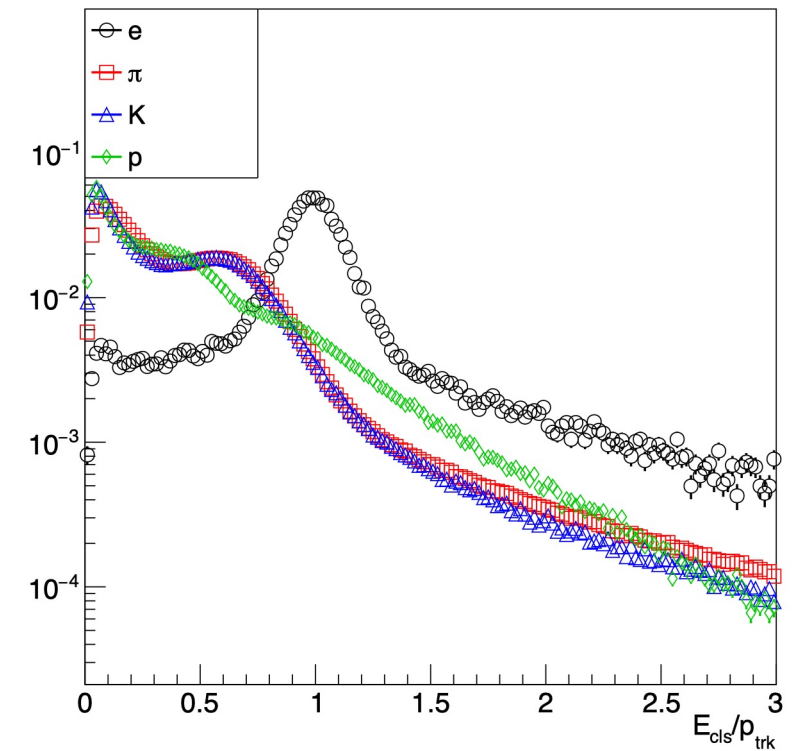
BEMC



N-Endcap EMC



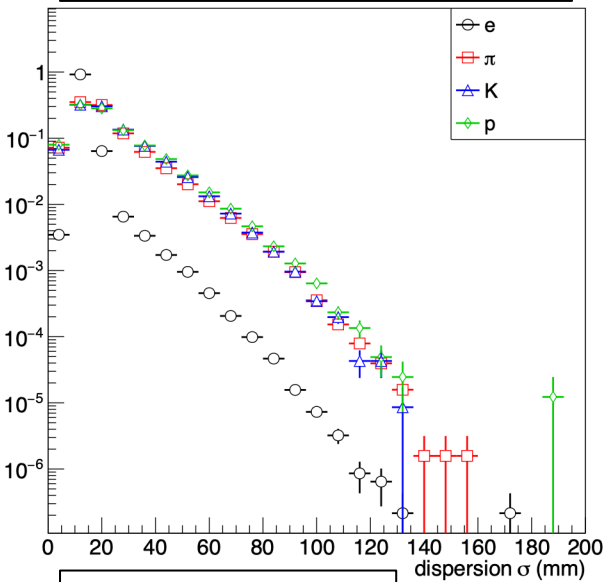
P-Endcap EMC



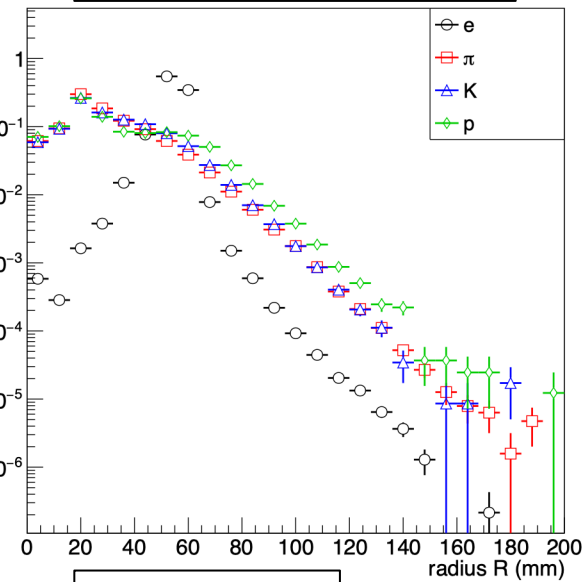
- E/p performs fairly well with varying degrees of success

Electron identification

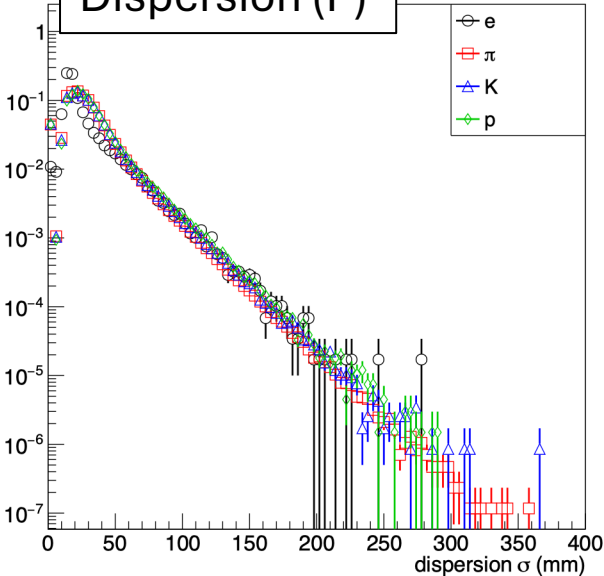
Dispersion (N-Endcap)



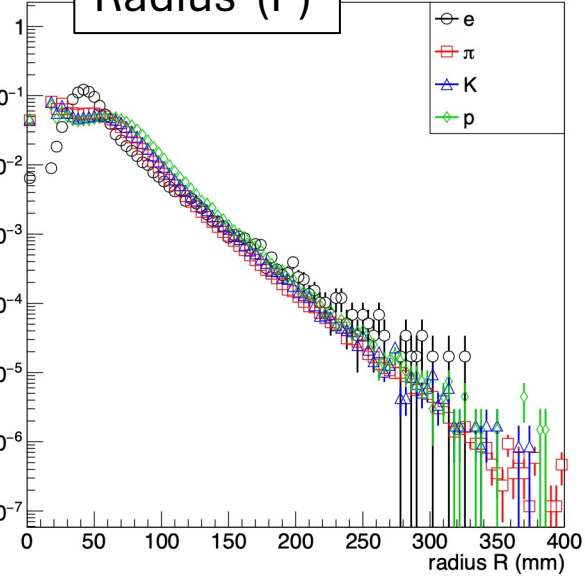
Radius (N-Endcap)



Dispersion (P)



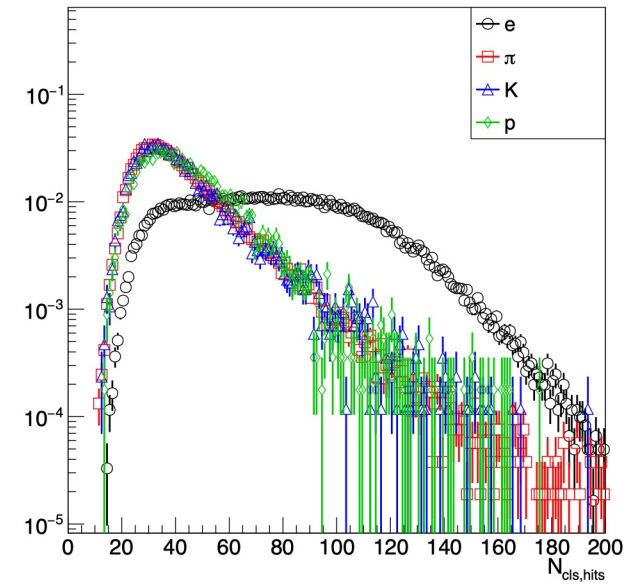
Radius (P)



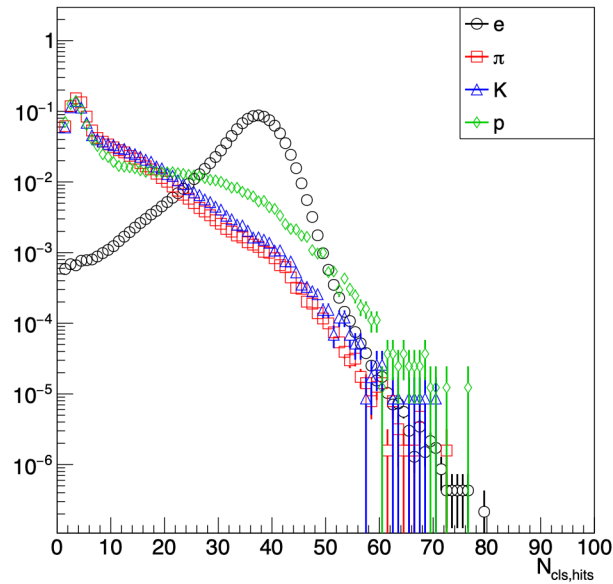
- Cluster energy deposit pattern explored for additional eID performance
- Radius and dispersion have...
 - **Some biasing** in **N-Endcap**;
 - **No biasing** in **P-Endcap**;
 - **Empty** (at the moment) in **Barrel**

Electron identification

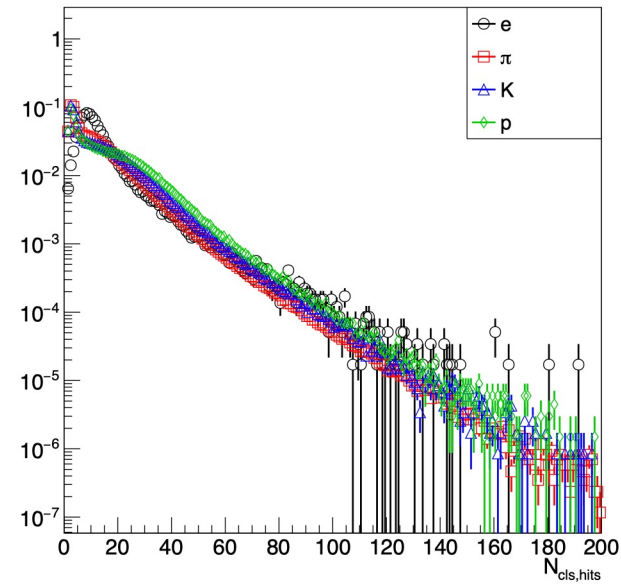
$N_{cls,hits}$ (Barrel)



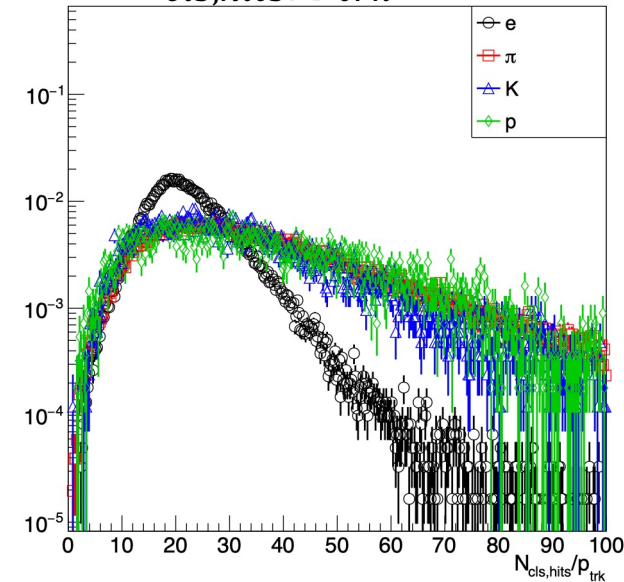
$N_{cls,hits}$ (N-Endcap)



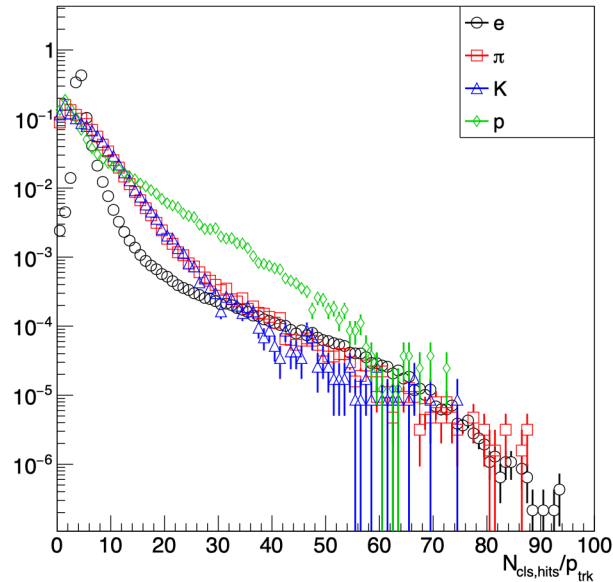
$N_{cls,hits}$ (P-Endcap)



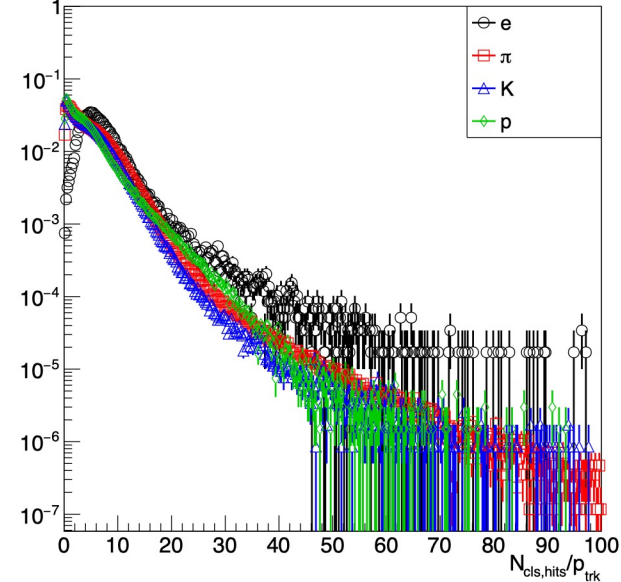
$N_{cls,hits}/p_{trk}$ (Barrel)



$N_{cls,hits}/p_{trk}$ (N-Endcap)



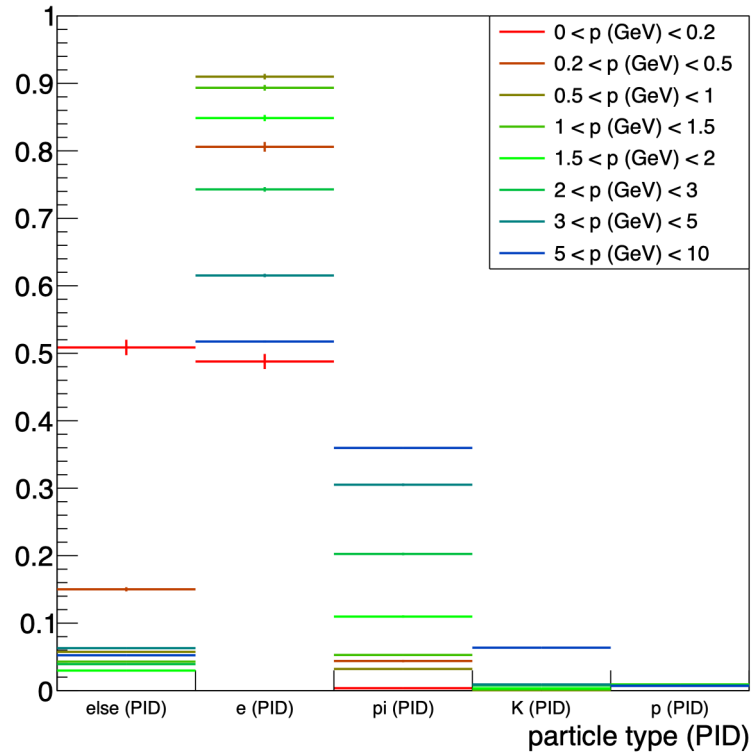
$N_{cls,hits}/p_{trk}$ (P-Endcap)



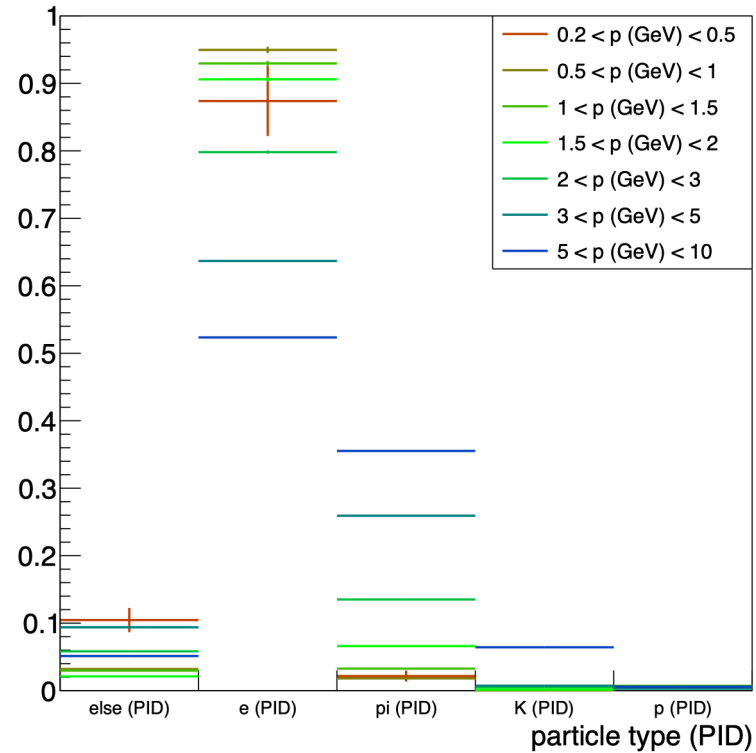
- N_{hits} naively looks usable;
- But more strongly correlated with momentum

Electron Identification

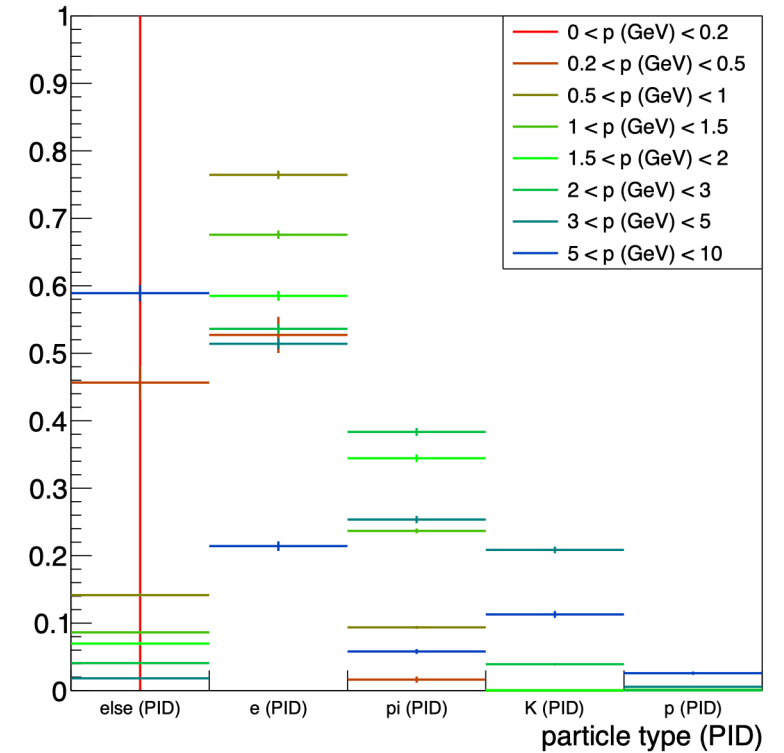
e PID for Barrel Tracks



e PID for N-Endcap Tracks



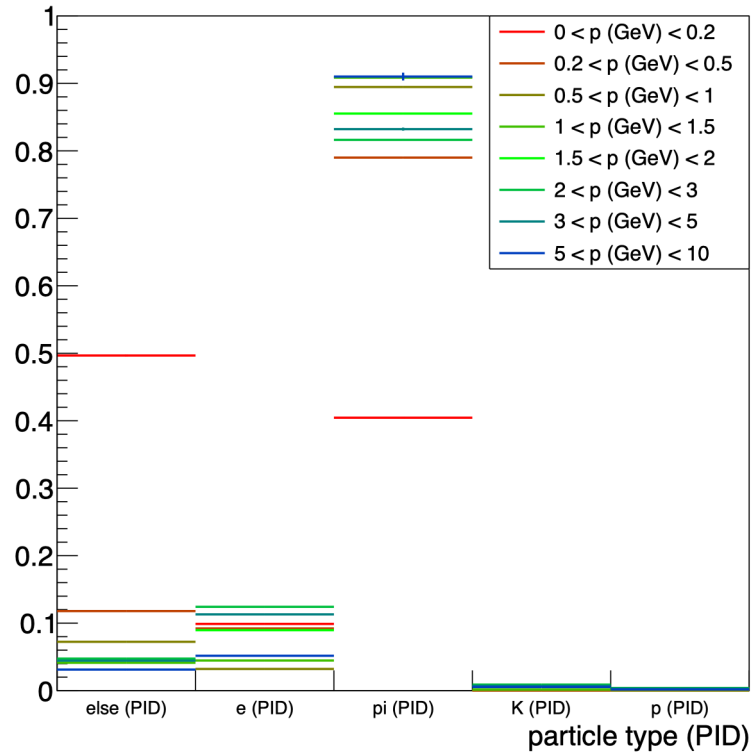
e PID for P-Endcap Tracks



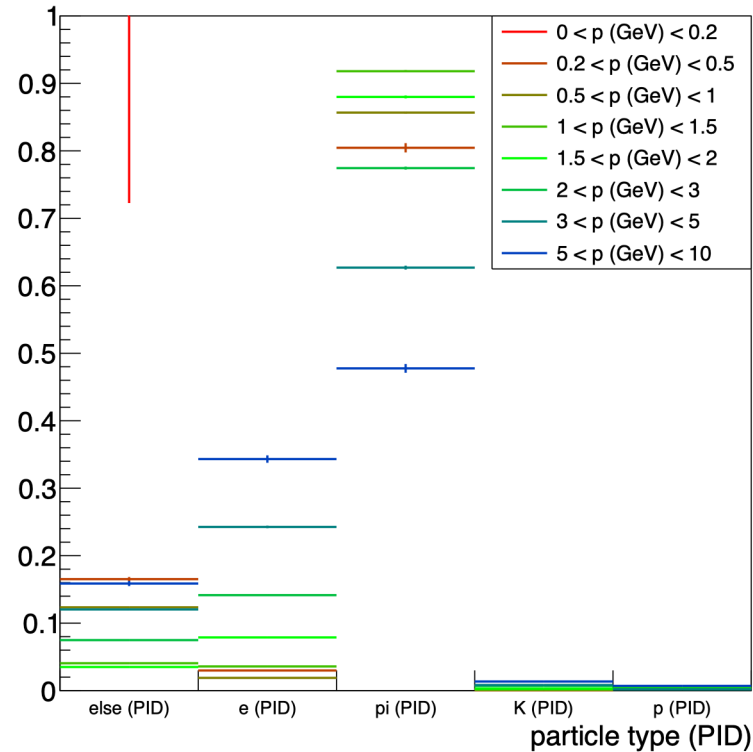
- PID detector perform well for low momentum electrons
 - $\sim 90\%$ up to $0.2 < p < 1.0$ GeV in Barrel, and $p < 2.0$ GeV in N-Endcap
- Will consider PID detectors for eID for tracks without a matched ECal cluster

Electron Identification

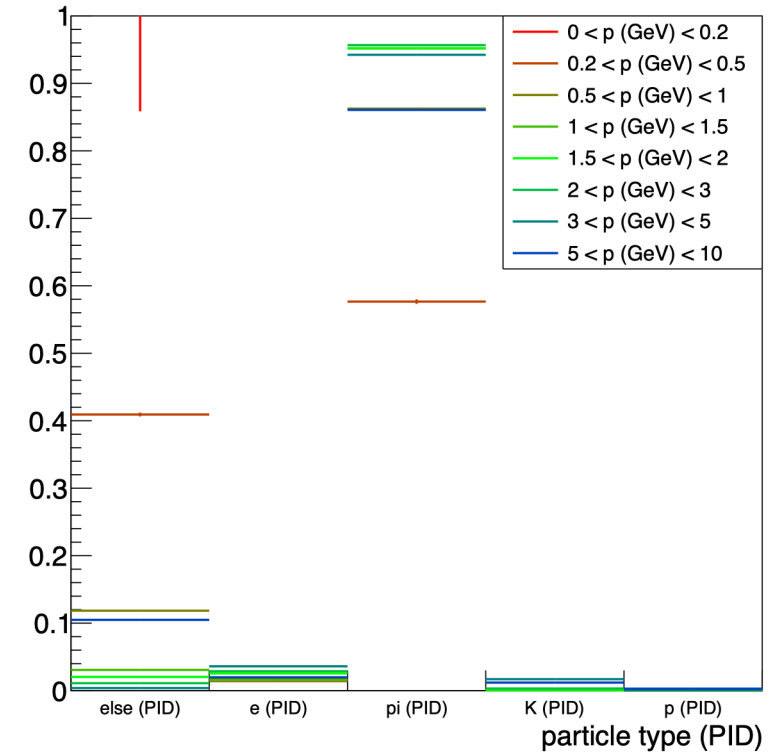
π PID for Barrel Tracks



π PID for N-Endcap Tracks



π PID for P-Endcap Tracks

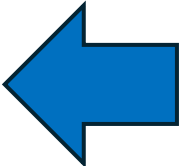


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Selection cuts

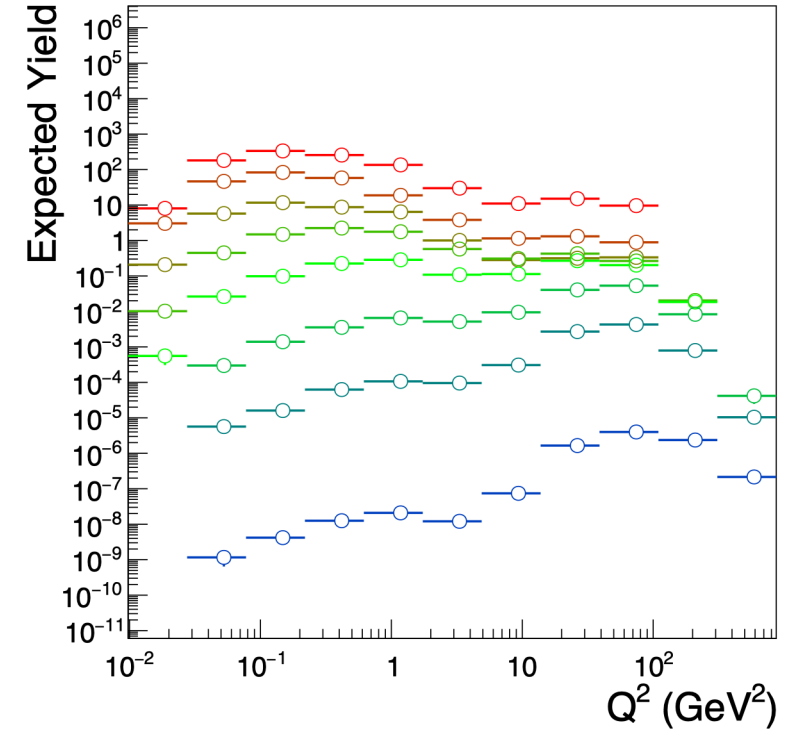
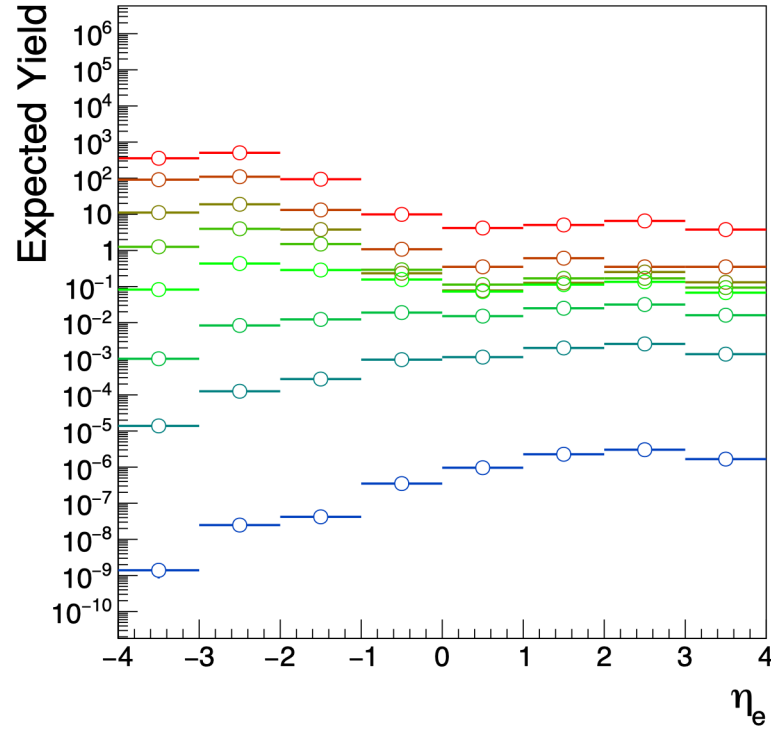
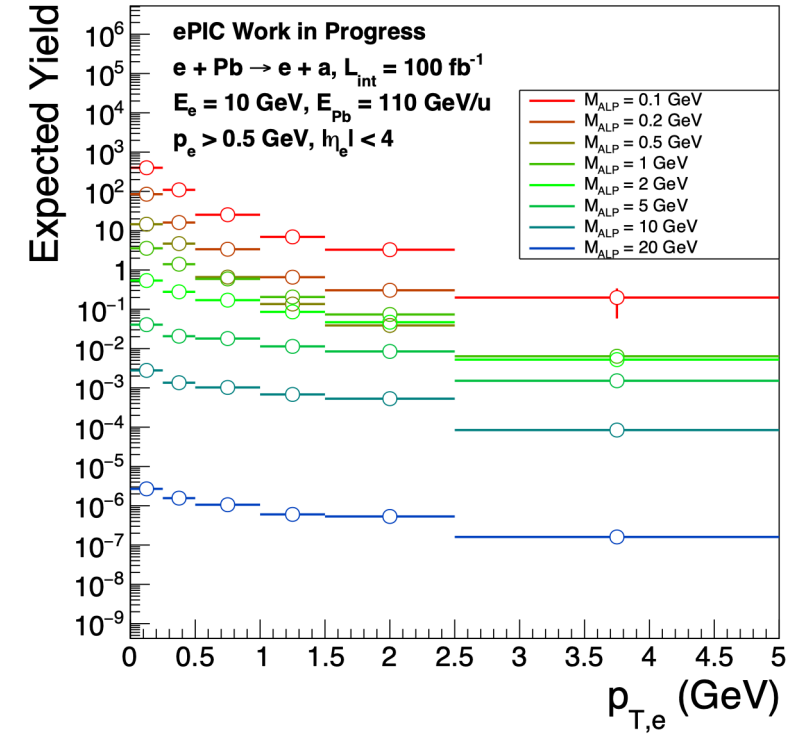
Tracks	$p > 0.5 \text{ GeV}$ $ \eta < 4$ $ Z_{vtx} < 100 \text{ mm}$ $ R_{XY,vtx} < 3 \text{ mm}$ $N_{hits} \geq 5$ (Truth-)matched cluster Reject Low-Q2 tagger
Electron	$0.8 < E_{cls}/p_{trk} < 1.4$ $E/E_{R<0.7} > 0.9$
Event	$N_{trk} = 1$ $E - P_z < 10 \text{ GeV}$ $p_{T,miss}/E_T > 0.9$ Has ele candidate

- These were the selection cuts considered for NIM-A
- Will consider relaxing **these** cuts related to eID, while including PID measurements
- Will consider tightening **these** cuts, to reject SR fake tracks without requiring ECal matching



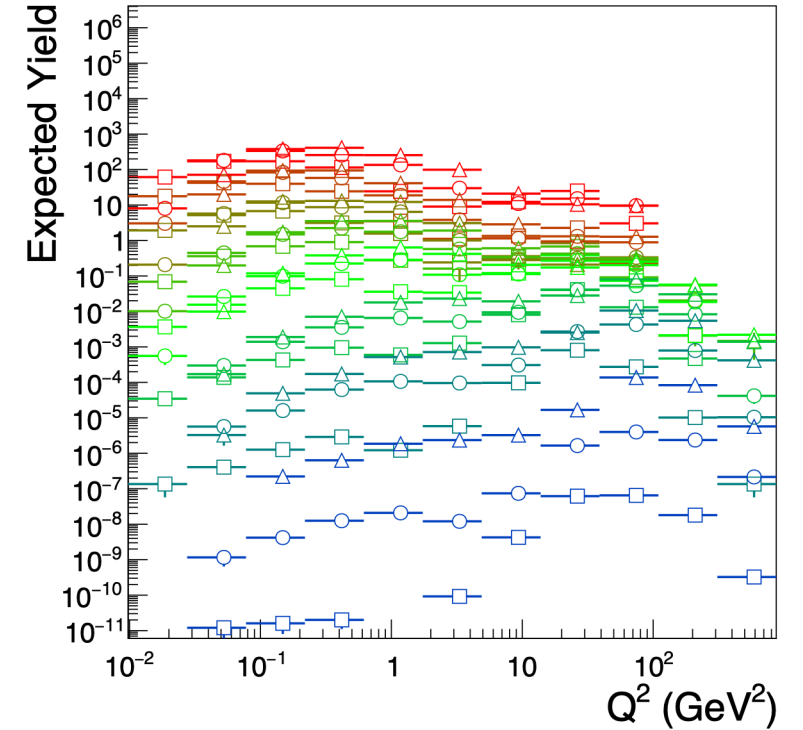
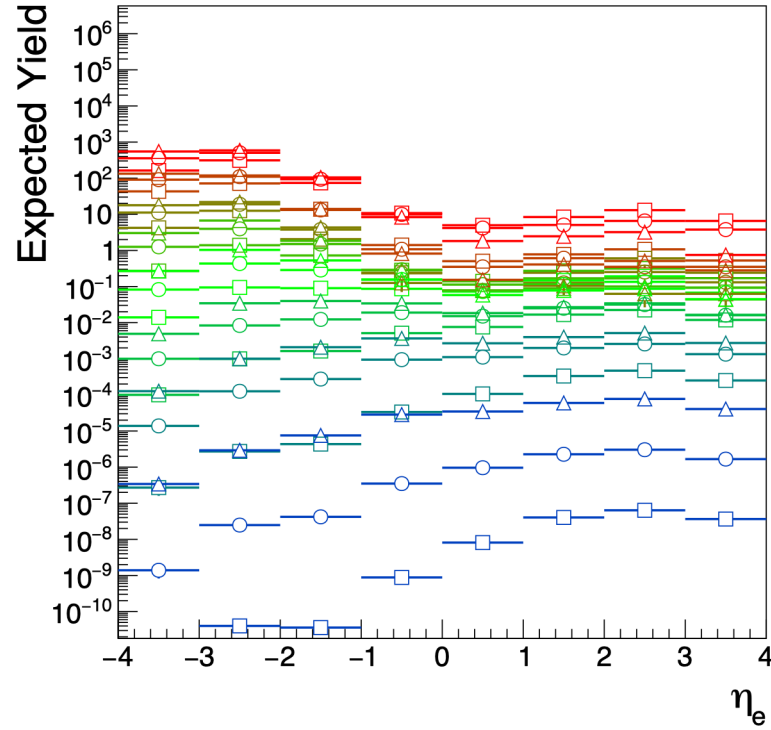
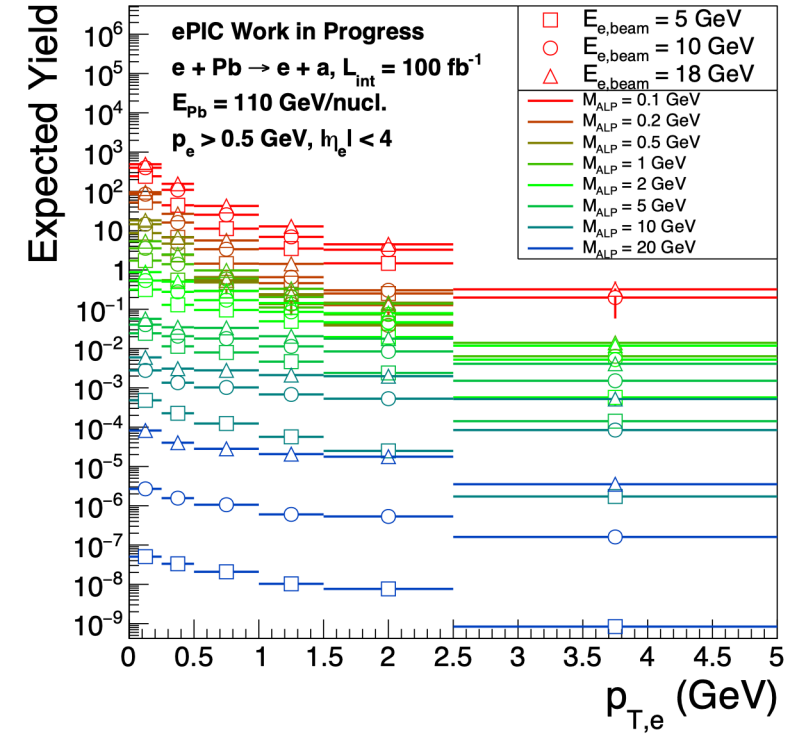
Will be discussed by **Ganesh & Alyssa**

Expected signal



- Presented in EIC Asia Workshop
- Expected signal yield using “Tracking” cuts only
- Searches possible for low-mass ($M_{ALP} < 1 \text{ GeV}$) ALPs with $L_{int} = 100 \text{ fb}^{-1}$
- Limit-setting for high-mass ALPs

Expected signal



- Expected signal yield based on the tracking and clustering performance
 - Significant beam-energy dependence with high-mass ALP
 - Motivates $E_{e,beam} = 18 \text{ GeV}$ collisions

Conclusion

- Machine background rejection
 - Coulomb and bremsstrahlung most entirely fall in to low Q2 tagger
 - $N_{trk,hits} \geq 5$ rejects most of the SR
 - Requiring track-cluster matching rejects the rest
 - Some rejection provided by quality cuts
- Track-cluster matching
 - Several ideas have been tested
 - Without the presence of cluster splitting algo, the matching schemes tested here have their own limitations
 - Truth matching for now
- Electron Identification
 - The current scheme based on isolation and E/p performs well for cluster-matched tracks
 - Will investigate improvements from PID detectors for low momentum tracks