

ALP@ePIC Update

Alyssa Wheeler, Jae Nam, Alessandro Tricoli

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BNL LDRD-A: EW and BSM Physics at EIC

- **PI:** Alessandro Tricoli
- **Co-PI:** S. Dawson, H. Davoudiasl, R. Szafron, Y. Hatta, P. Steinberg, Z. Tu
- **Collaborators:**
 - Theory: Hongkai Liu, Keping Xie
 - Experiment: Alex Jentsh
- **Postdocs:**
 - Theory: Zhite Yu
 - Experiment: Jae Nam, Ganesh Parida
- **Student:**
 - Experiment: Alyssa Wheeler

BNL LDRD-A: EW and BSM Physics at EIC

- **Objectives**

- Consortium of experimentalists and theorists in **HEP** and **NP** to study precision of **EW** measurements and **BSM** reach with the *ePIC detector* and *2nd Detector* at the EIC

- **Methodologies**

- Phenomenological Studies:
 - Identification and simulation of benchmark signals of new physics at the EIC in the EW sector
 - Complementarity between EIC and LHC discovery potential
- Experimental Studies:
 - Detector/software development and optimization to enhance BSM detection capabilities in EW processes, utilizing ML/AI techniques
 - Provide benchmarks based on similar signatures in ultra-peripheral heavy-ion collisions as well as forward proton-proton physics using LHC Run-3 dataset

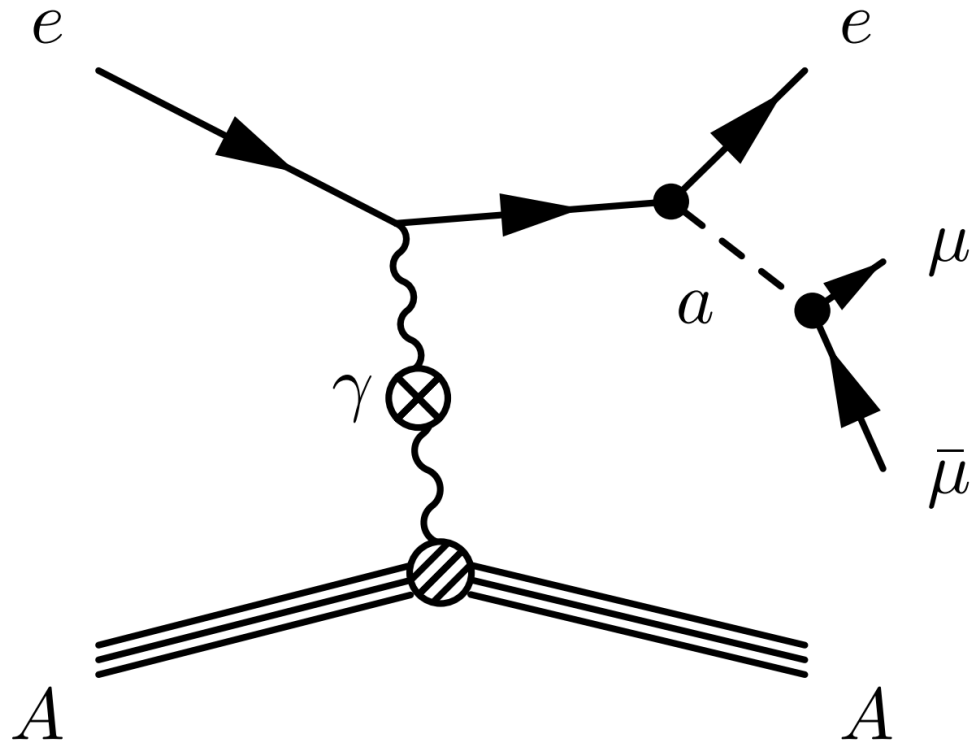
Processes of Interest

Channels under investigation

→ Electrophilic ALP ($0.1 < M_{ALP} < 20 \text{ GeV}$)

- **Fermion-coupled ALP**

- Compton-like scattering
- Long-lived decay signal at low ALP mass+coupling



*coherent scattering, scaling as Z^2

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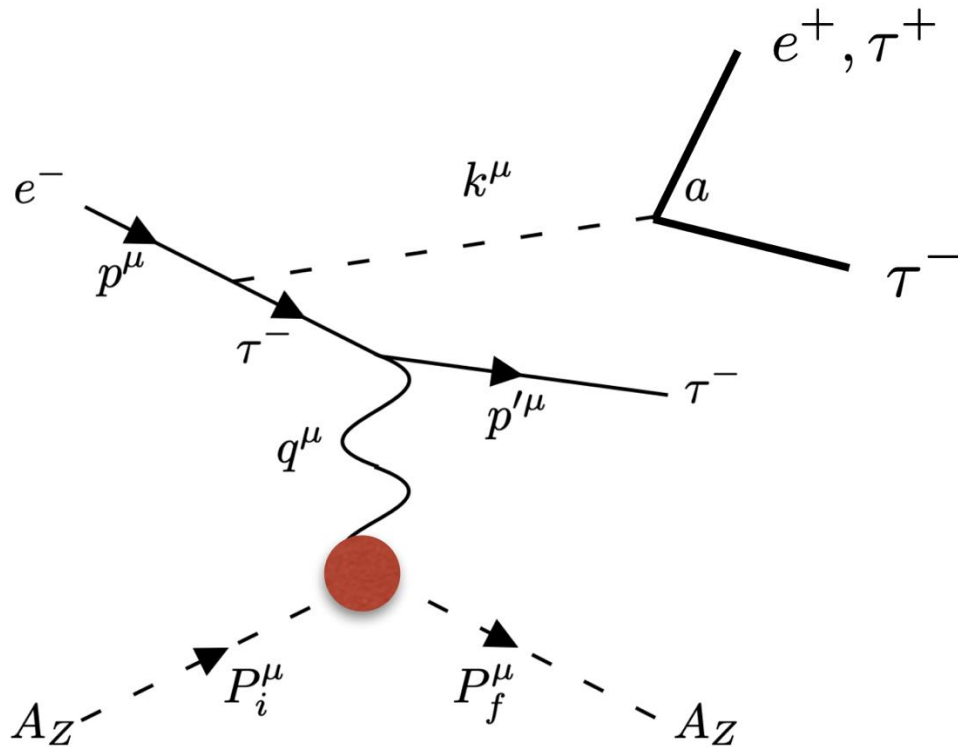
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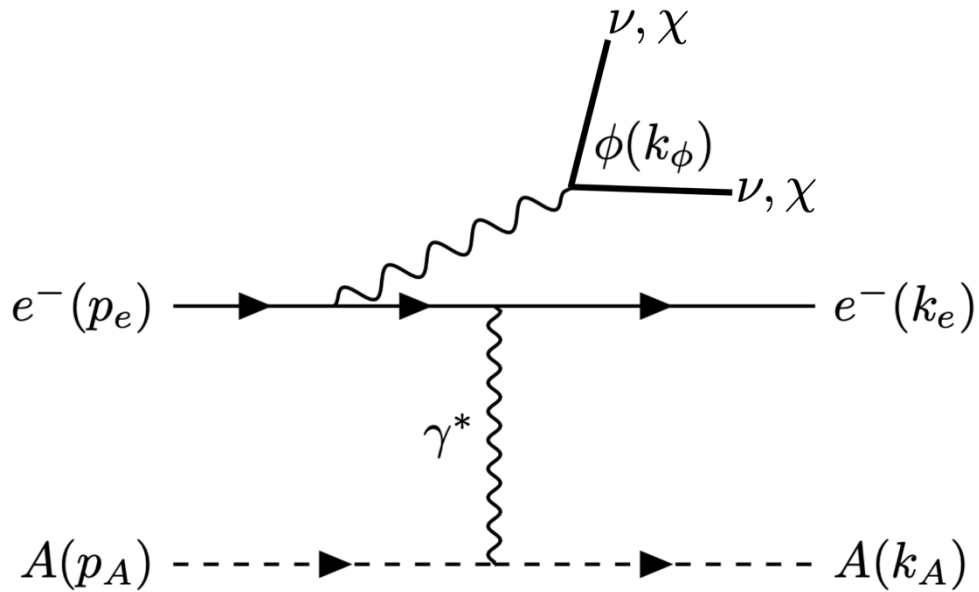
- **Lepton Flavor Violating ALP**

- $e^- + A$ into $\tau^- + e^+ + \tau^-$ final state
- $e + \tau$ mass and missing momentum reconstruction via ML/AI



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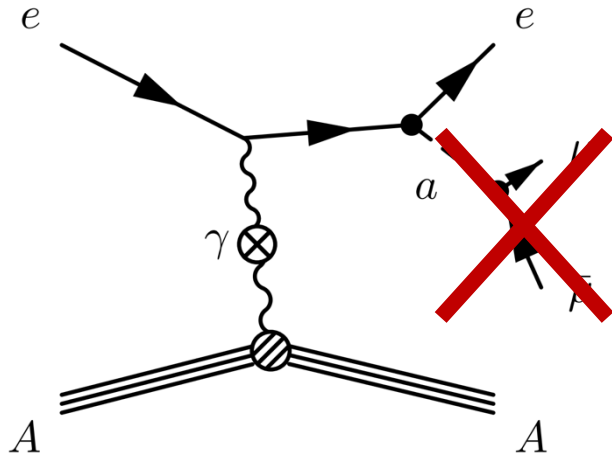
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- **U(1) gauge extension**

- Anomaly free U(1) gauge extensions involving electrons: $B - L, B - 3L_e, L_e - L_\mu, L_e - L_\tau$
- $\chi (= l, j)$ will inform about the underlying BSM mechanism

Near-term objectives



Channels under investigation

→ Electrophilic ALP ($0.1 < M_{ALP} < 20 \text{ GeV}$)

- **Fermion-coupled ALP**

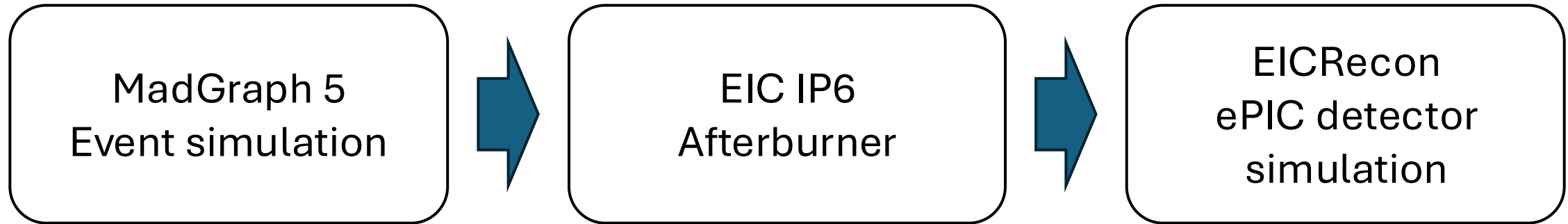
- Compton-like scattering
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- Current focus: **Non-decaying ALP**

- Low multiplicity events;
one-electron final state → detector veto
- Missing p_T
- ePIC/EIC will provide sensitivity for $0.1 < M_{ALP} < 20 \text{ GeV}$,
complementary to **LHC** ($> 20 \text{ GeV}$) and **non-collider** ($\lesssim \text{MeVs}$)
- Aiming to contribute to NIM-A in **Oct**, and ePIC/EIC Asia in **June**

Overview of Event Simulation

MG5-to-EICRecon simulation routine

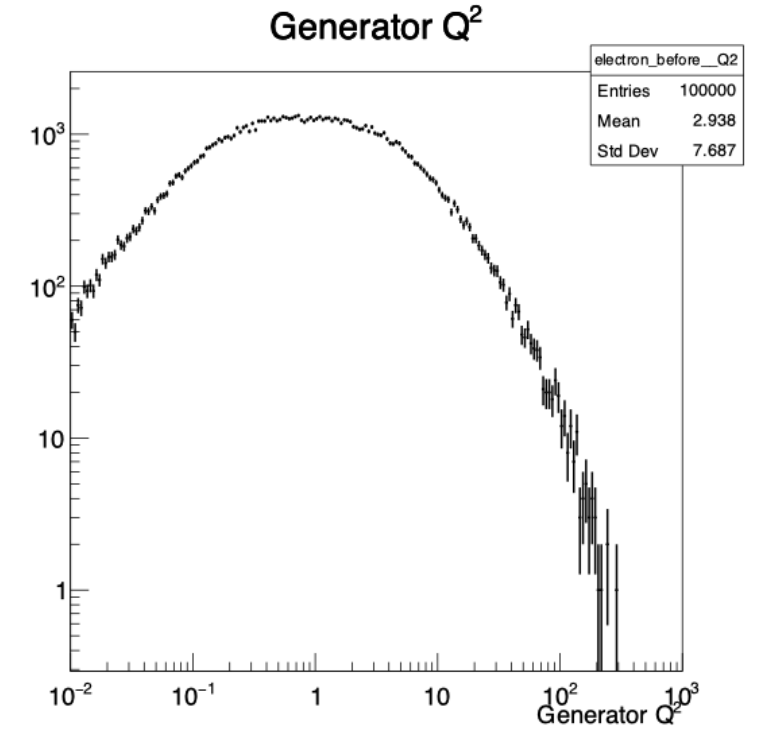
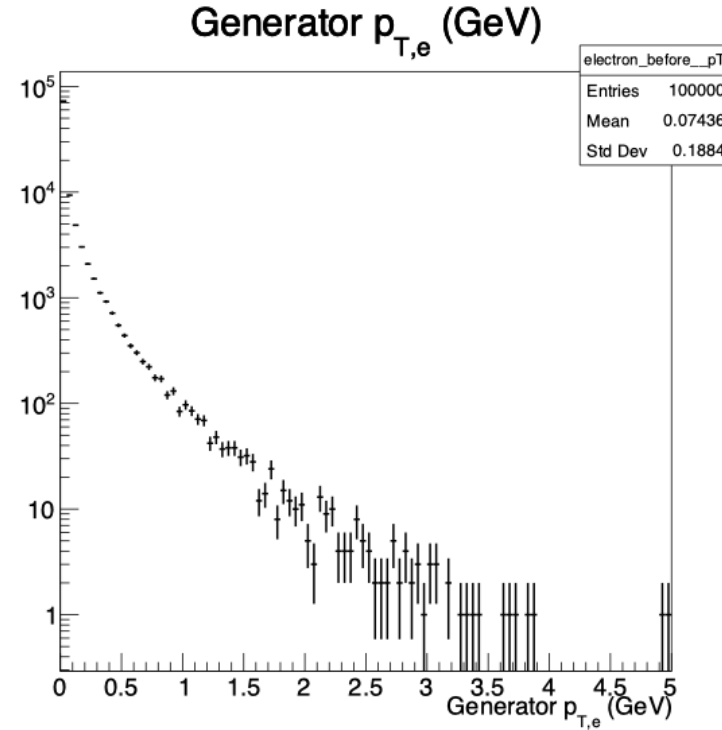
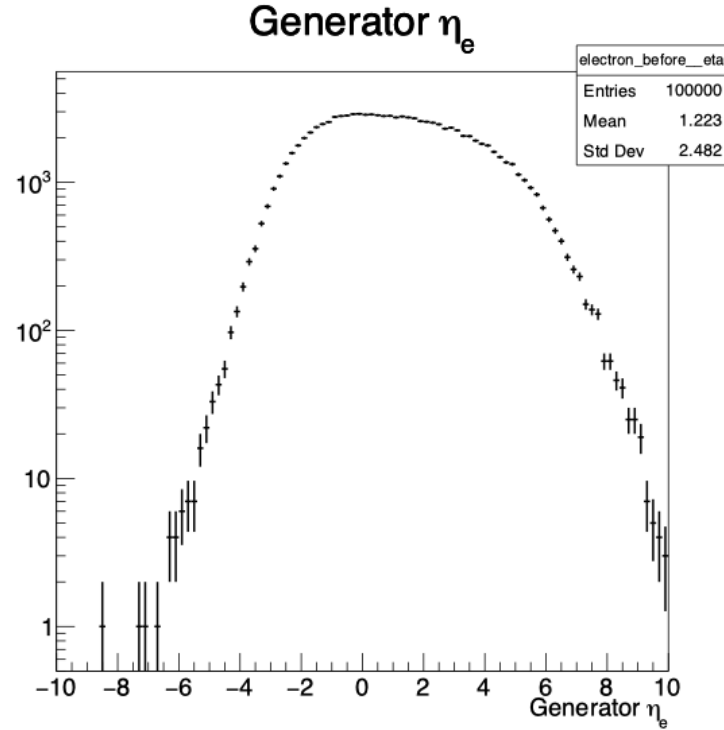


- Primarily using MG5 3.5.13/3.7.0
- Custom **ALP models** and heavy ion **PDF for photon** required
 - Currently looking at $e + Pb$ ($e + Au$ available)
 - Produced by Keping Xie (TD Lee), Verified by Honkai Liu (BNL)
 - Steering files (+PODIO analysis framework) available <https://github.com/eic/ALP-ePIC>
- Parton-showering available via Pythia8 (currently unused)
- Particle reconstruction based on “Reconstructed**Charged**Particles”
- Truth-level matching with ECAL and HCAL
- PID via LUT (Cherenkov? TOF?)
- Official simulation request submitted for April campaign
https://docs.google.com/spreadsheets/d/1BJeq3AYwefNC9m3palH6T0SHMxmRmHpOzLTsa_6SZIU/edit?gid=0#gid=0
- Custom installation of software stack can be found in `/gpfs/mnt/gpfs02/eic/namjae/madgraph`

First look at $e + Pb \rightarrow e + a$

Truth-level kinematics

* $e + Pb$ at 10×110 , with $M_{ALP} = 1\text{GeV}$



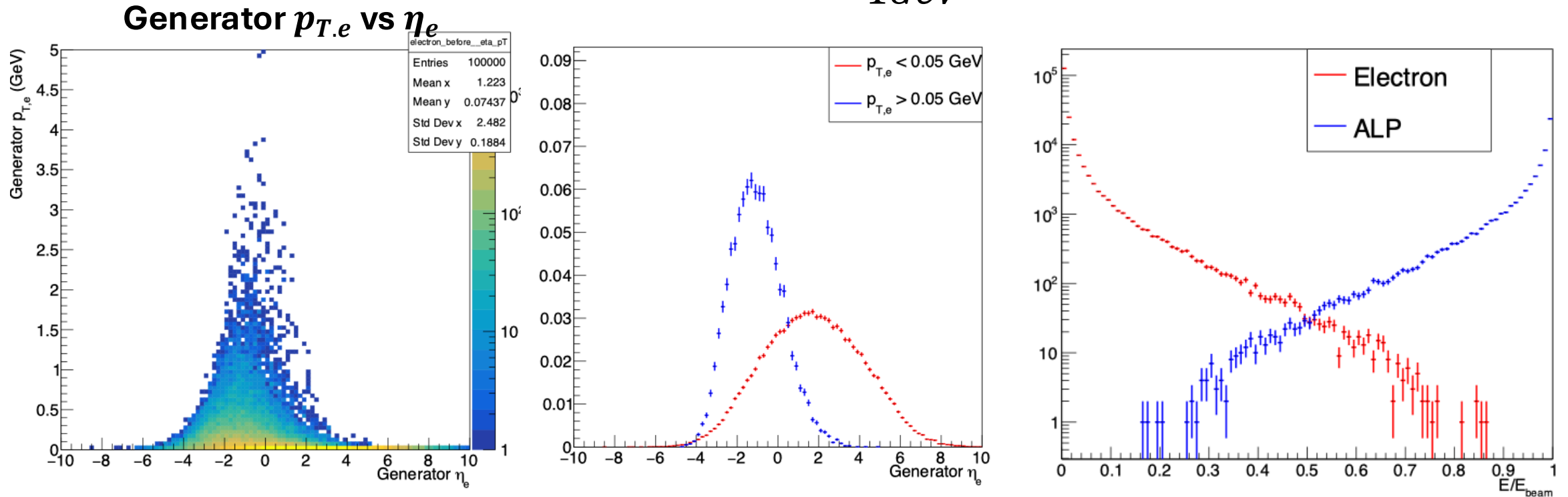
• Generated events

- $e + Pb \rightarrow e + a$
- $E_{Pb} = 110 \text{ GeV/nucleon}$
- $E_e = 5, \mathbf{10}, 18 \text{ GeV}$
- $M_{ALP} = 0.1, \dots, \mathbf{1}, \dots, 20 \text{ GeV}$

- The momentum transfer information is lost in Keping's EPA scheme
- Phenomenological scale $Q^2 = -(l - l')^2$
- Soft and central electrons

Truth-level kinematics

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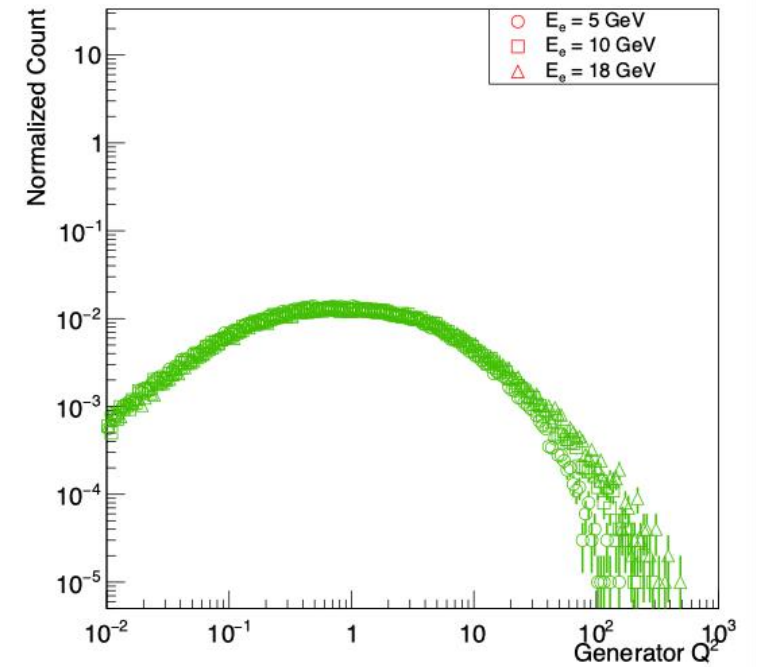
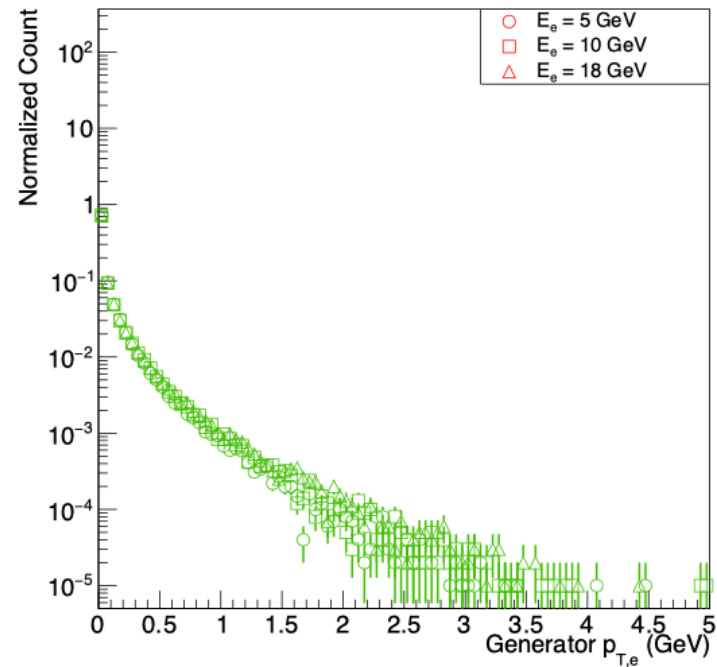
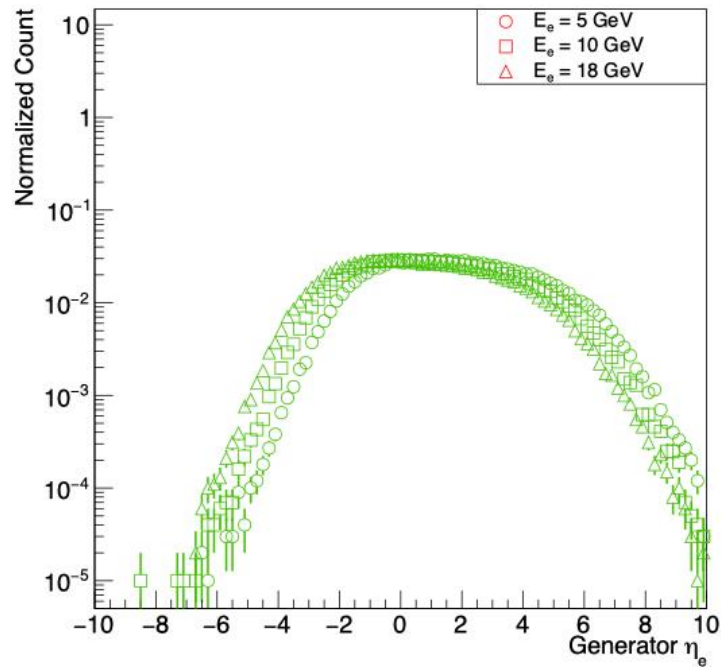


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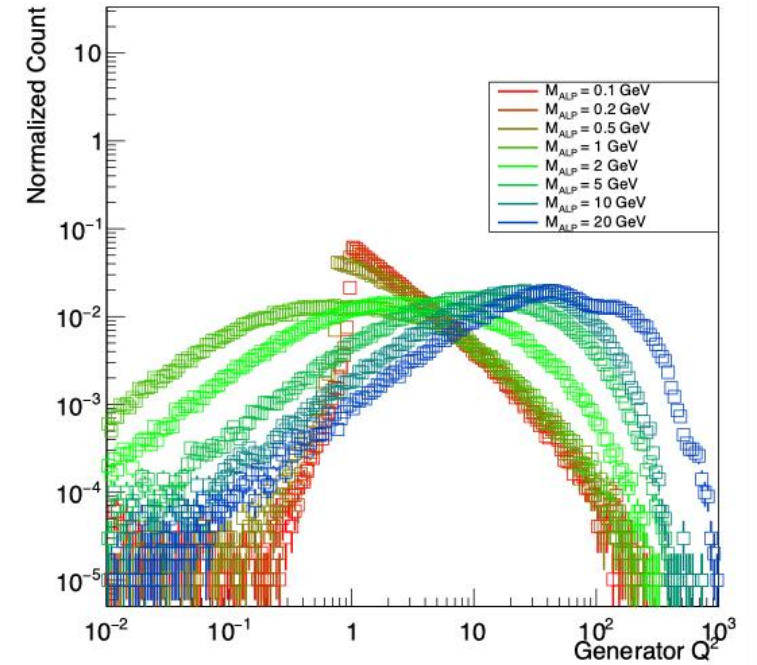
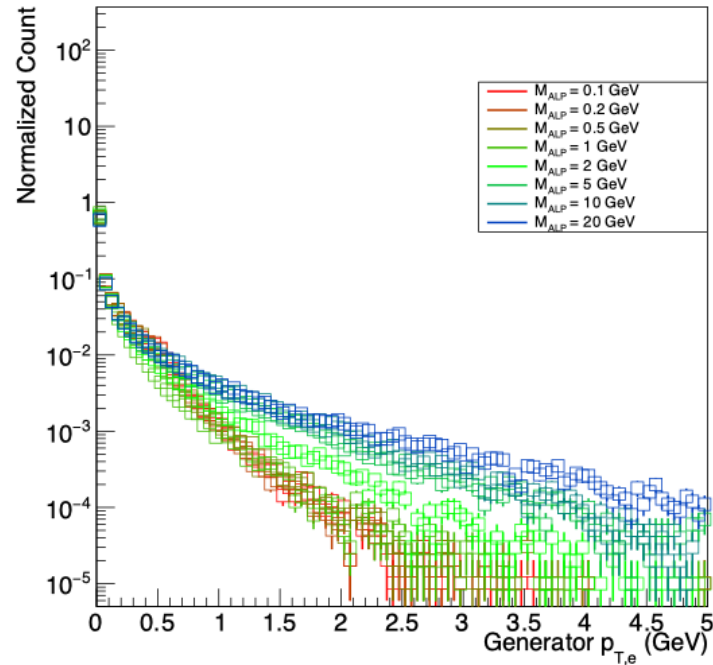
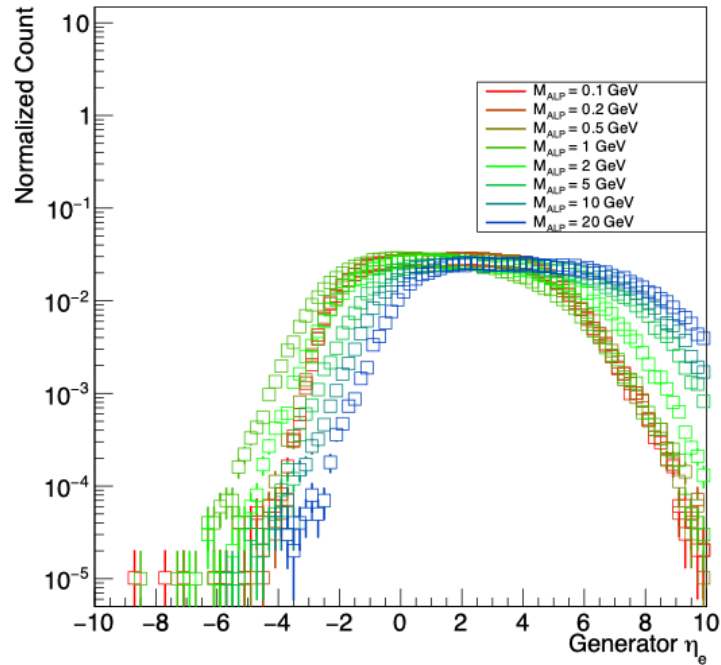
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Event Kinematics based on E_e and M_{ALP}



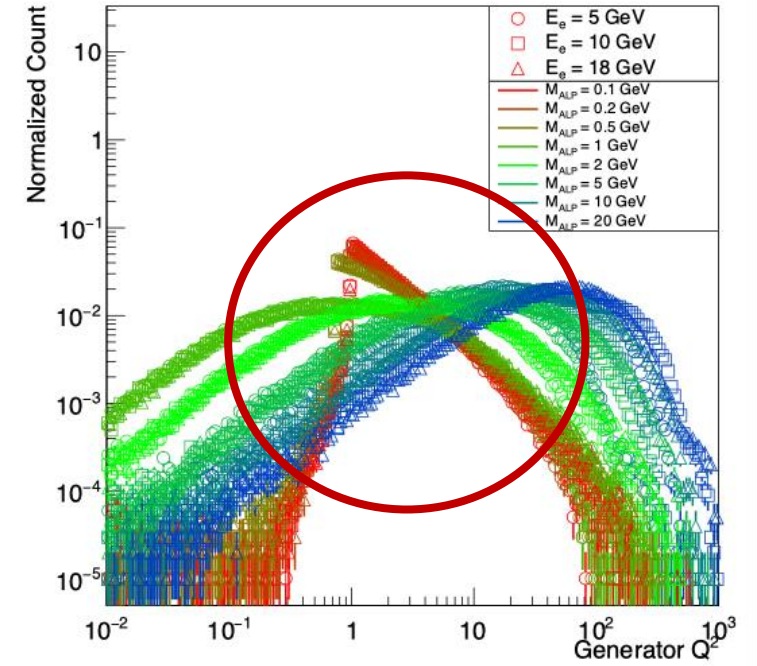
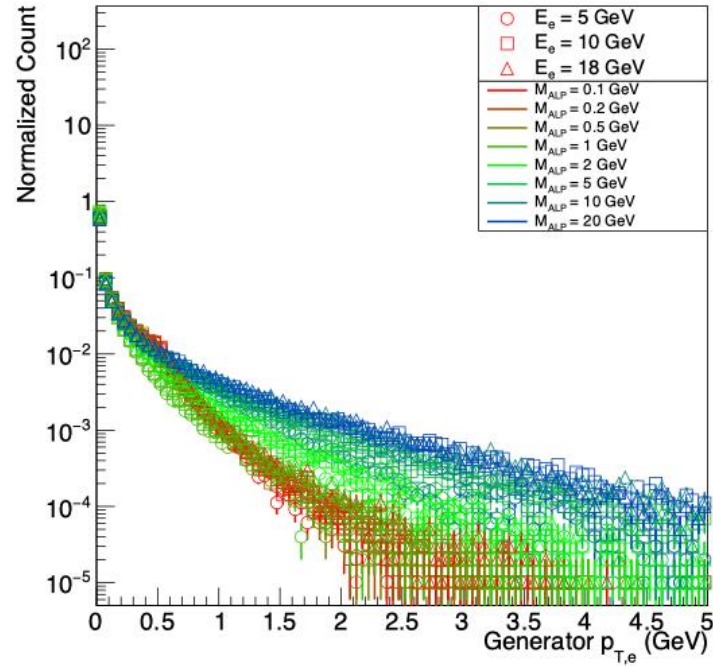
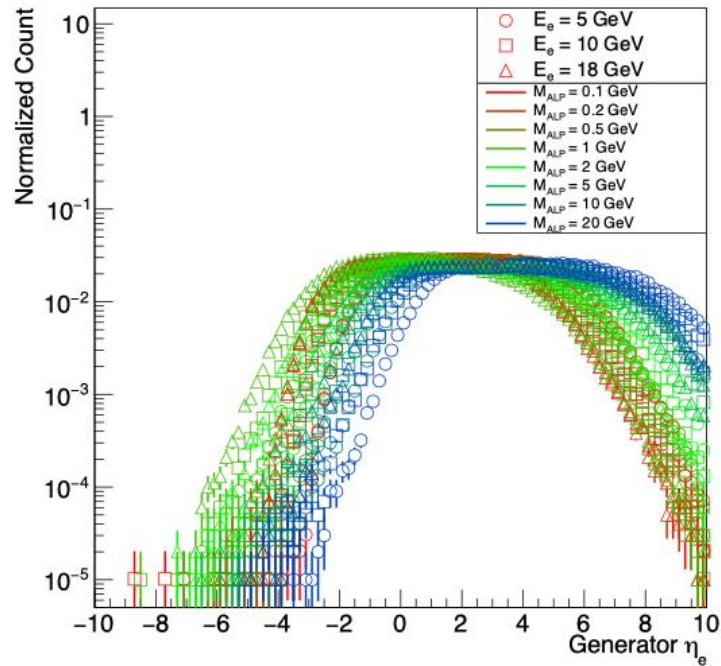
- $E_e = 5, 10, 18$ GeV
- In general, weak impact from E_e
(increase in $E_e \rightarrow$ slightly more backward, higher p_T tail)

Event Kinematics based on E_e and M_{ALP}



- $M_{ALP} = 0.1 - 20 \text{ GeV}$
- In general, weak impact from E_e
(increase in $E_e \rightarrow$ slightly more forward, higher p_T tail)
- Strong M_{ALP} dependence in η_e , $p_{T,e}$ and Q^2

Event Kinematics based on E_e and M_{ALP}



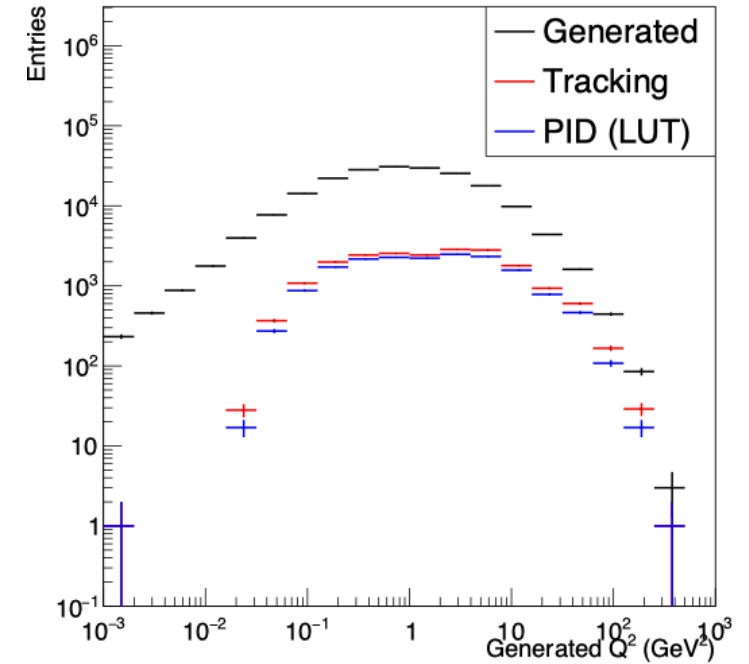
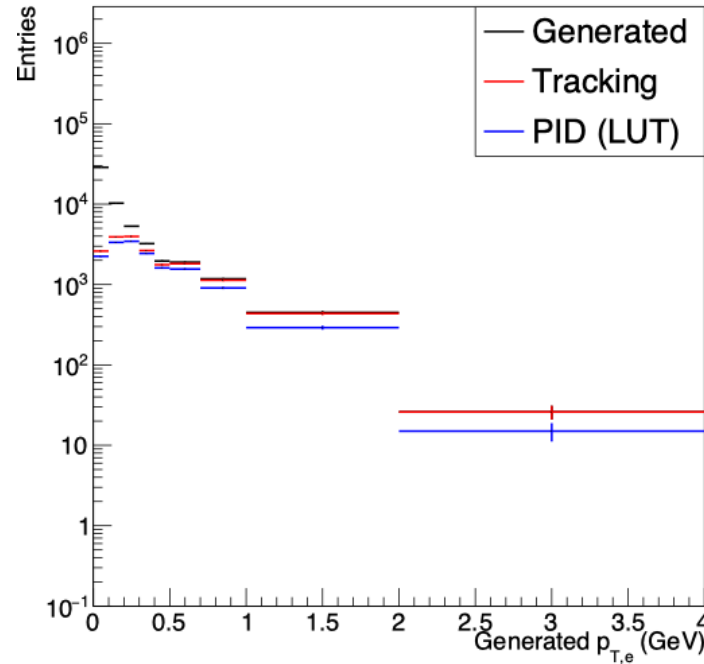
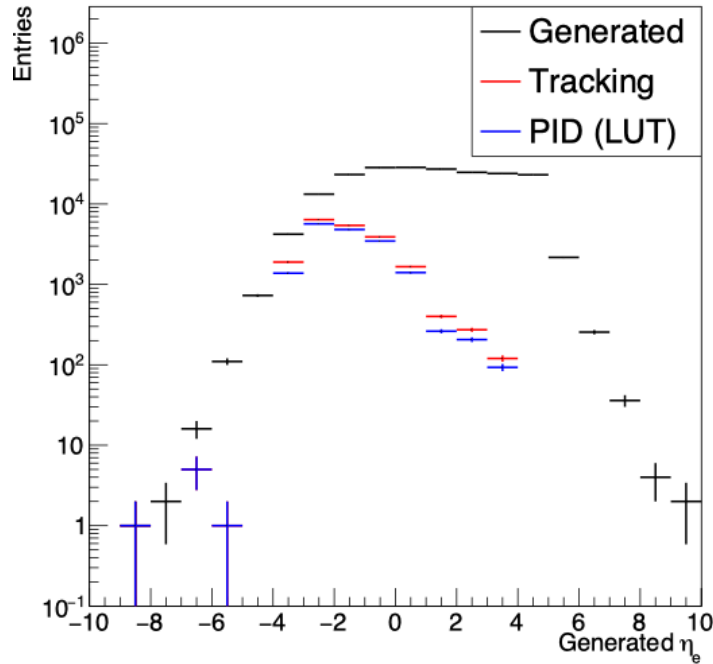
- Issues with simulations with $M_{ALP} < 1$ GeV (0.1, 0.2, 0.5 GeV)
- This has been addressed by fixing the upper limit MG5 integration scale ($\hat{s} = 4E_{pb}E_e$, dsqrt_shatmax)

Event Reconstruction

Tracking and PID Efficiency

*In-depth review by Alyssa next meeting

*generated = post-afterburner

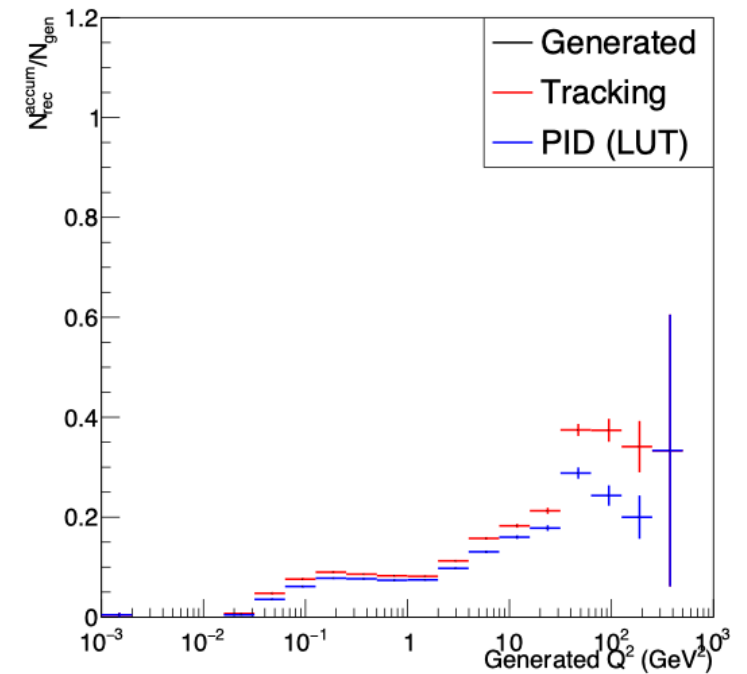
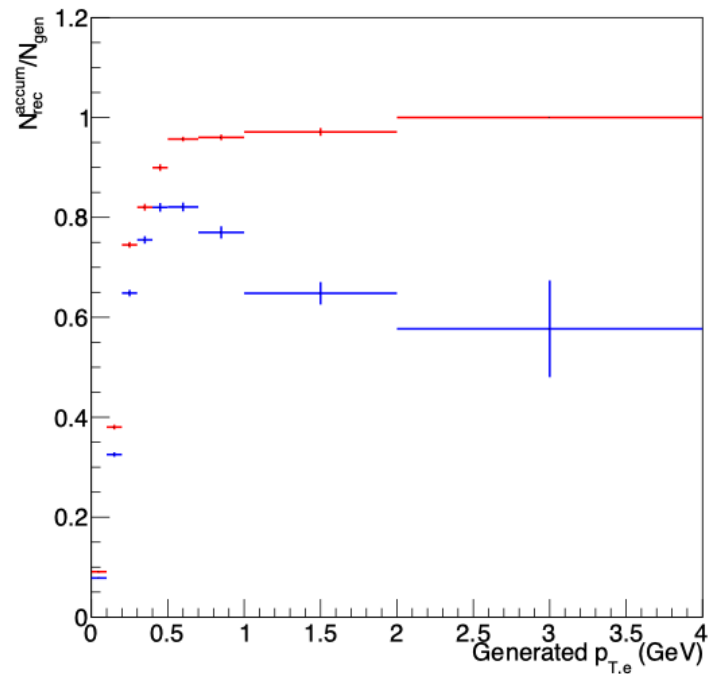
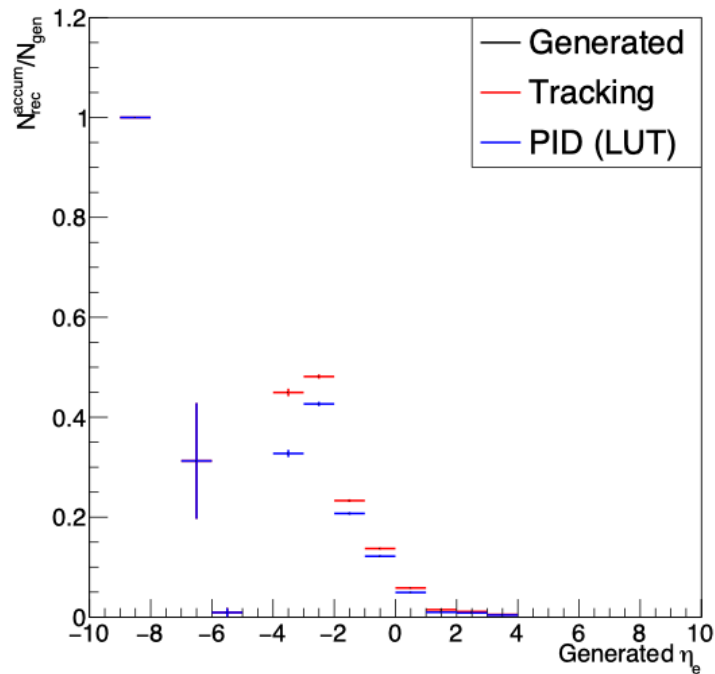


- High- η kink due to angular divergence effect (afterburner; in backup slide)
- Tracking efficiency
 - Overall $> 95\%$ for $p_T > 0.5$ GeV
 - High in Endcap-N; Endcap-P suffers from very soft electrons
 - Low in barrel due to geometry (disk vs cylinder)
 - Needs to be revisited with proper p_T cut (also accounting for background)

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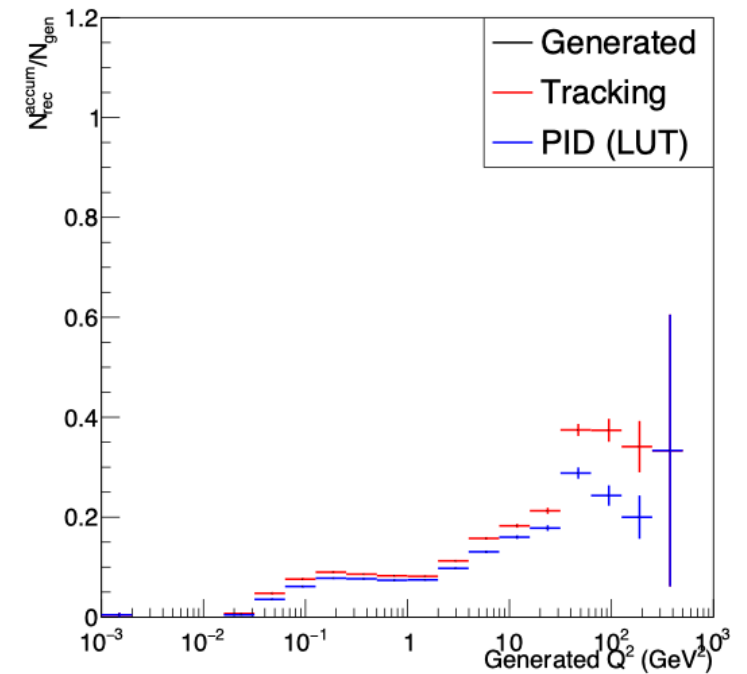
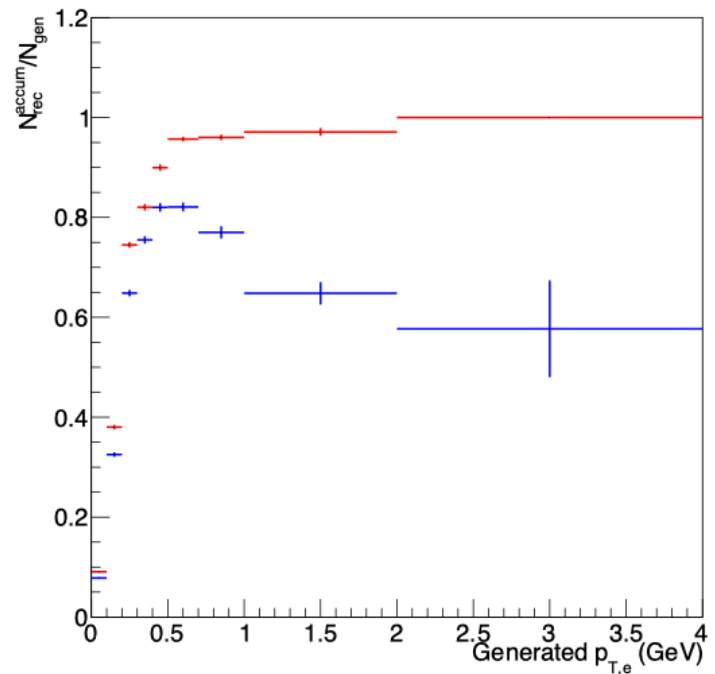
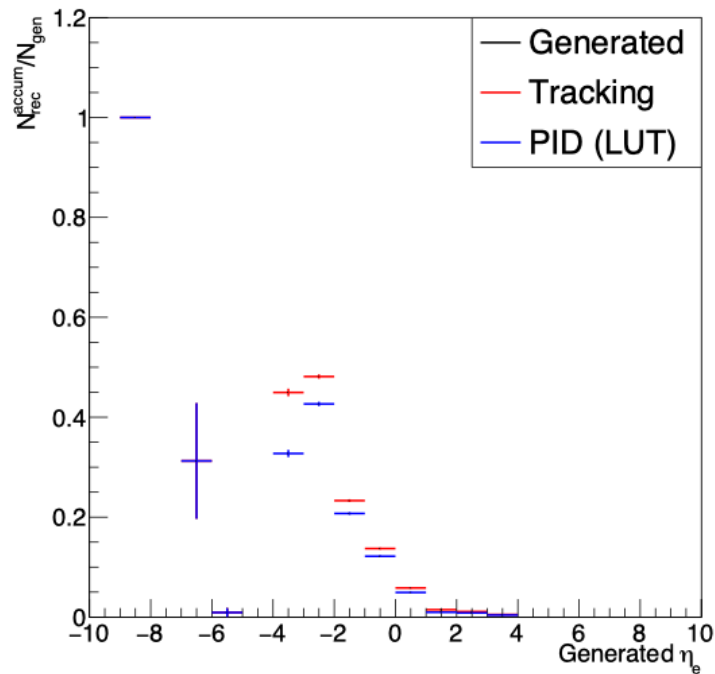


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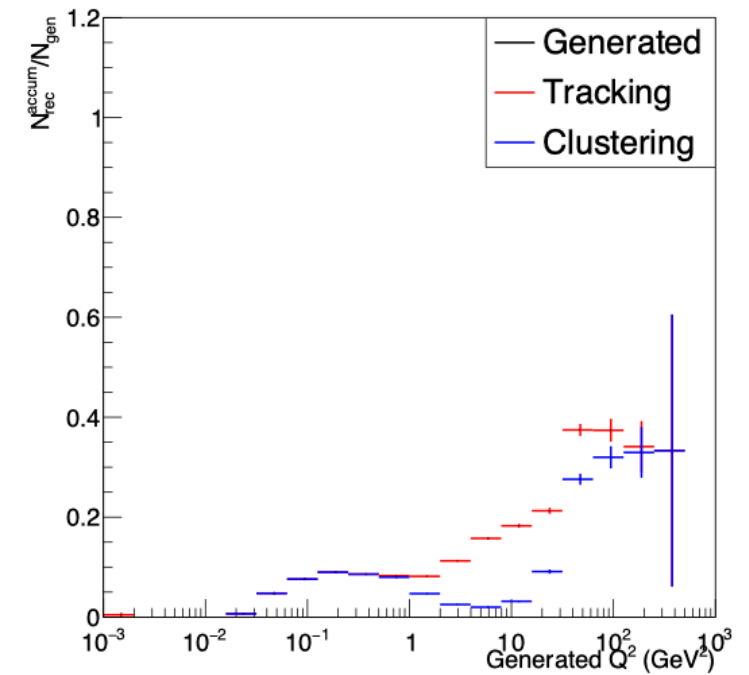
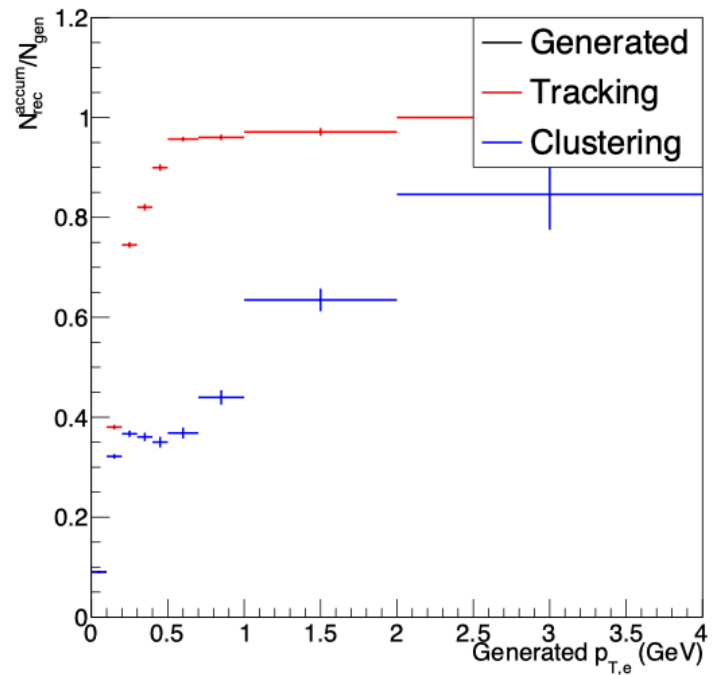
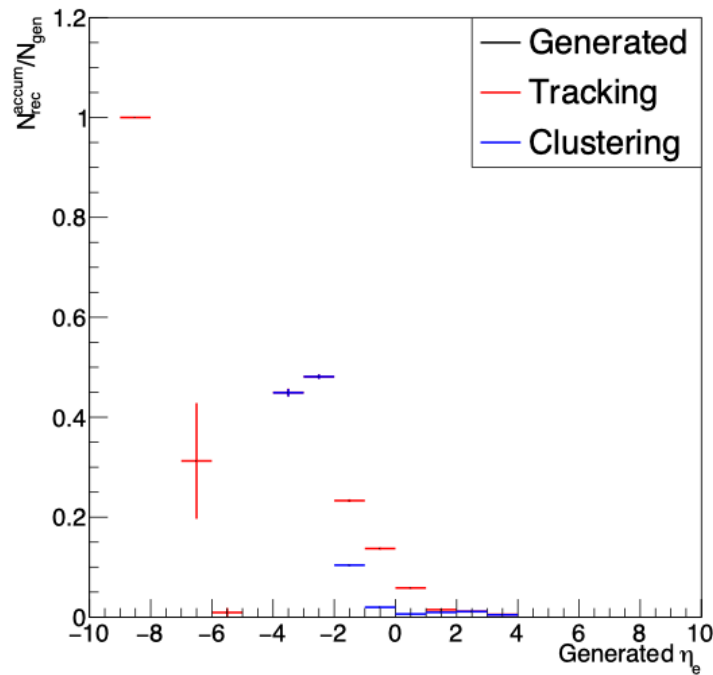


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 - Decreases as a function of p_T ; Surprising low (60~70%) at $p_{T,e} > 1$ GeV
 - Detector contribution in the LUT needs to be investigated (Cherenkov? TOF?)
 - Potential for complementary electron ID (e.g., ECAL)

Tracking and Calorimetry

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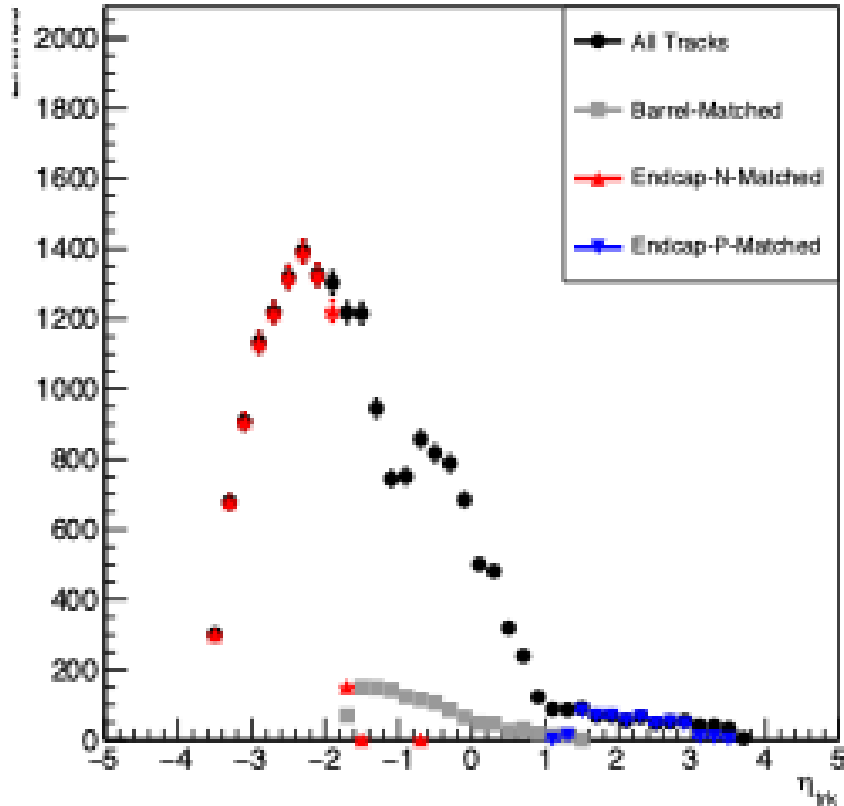
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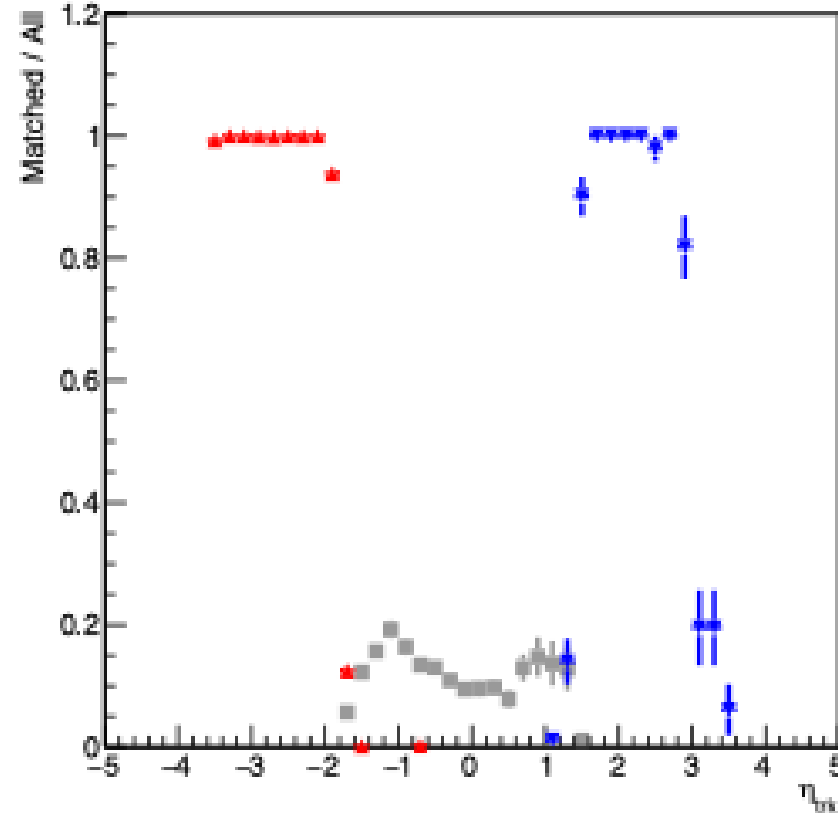
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(Plot only shows Track-Clustering matching ratio)

ECAL Response

All tracks vs Cluster-matched



Clustering rate



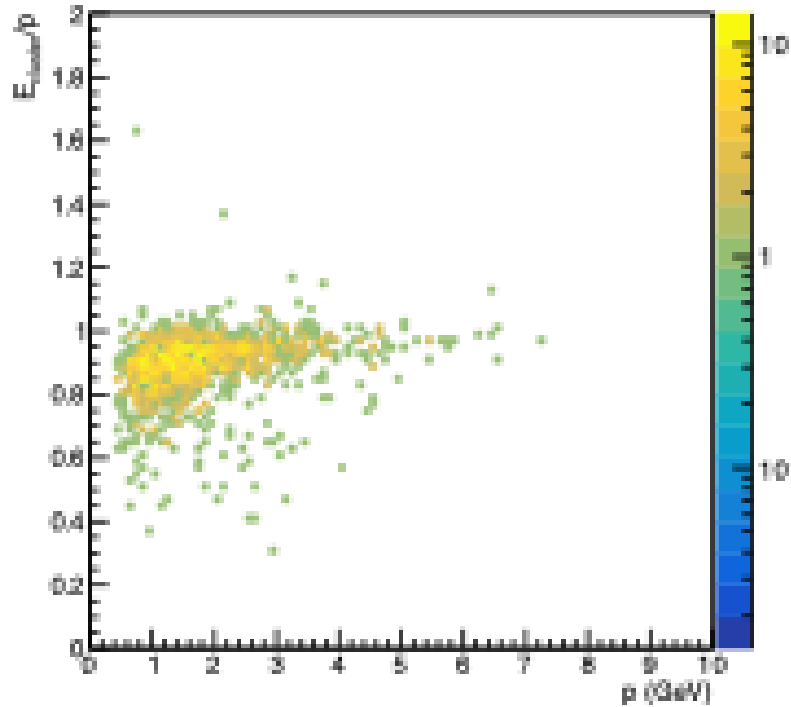
- Nearly all tracks in the endcap accompanied by reconstructed ECAL cluster
- Low ECAL clustering rate in the barrel due to low p_T threshold ~ 0.5 GeV

$$(\rho(\text{m})) = \frac{p_T (\text{GeV})}{0.3 \times B (\text{T})} = \frac{0.5}{0.3 \times 2} \sim 0.8\text{m} = \text{BECAL inner radius})$$

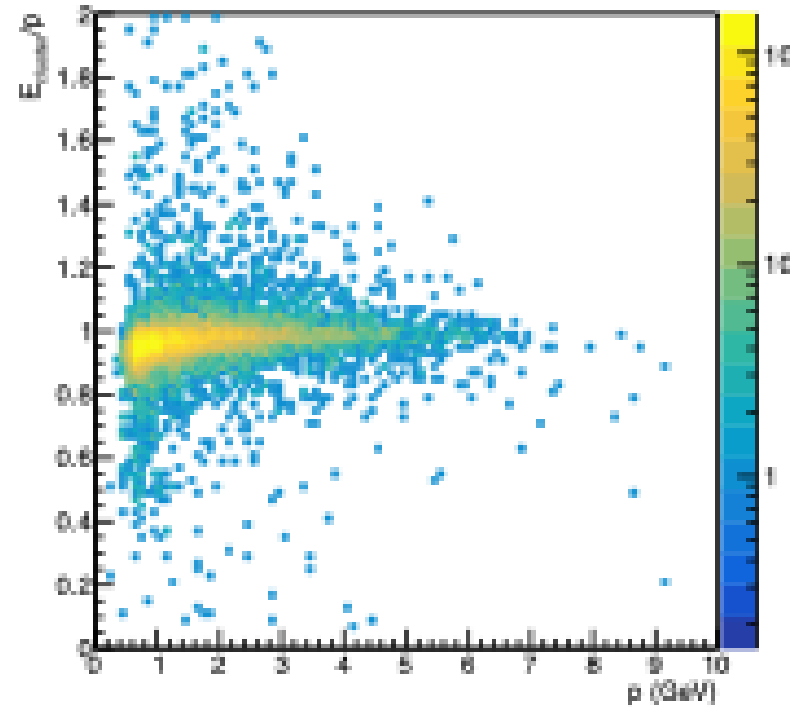
ECAL Response

Non-decaying ALP

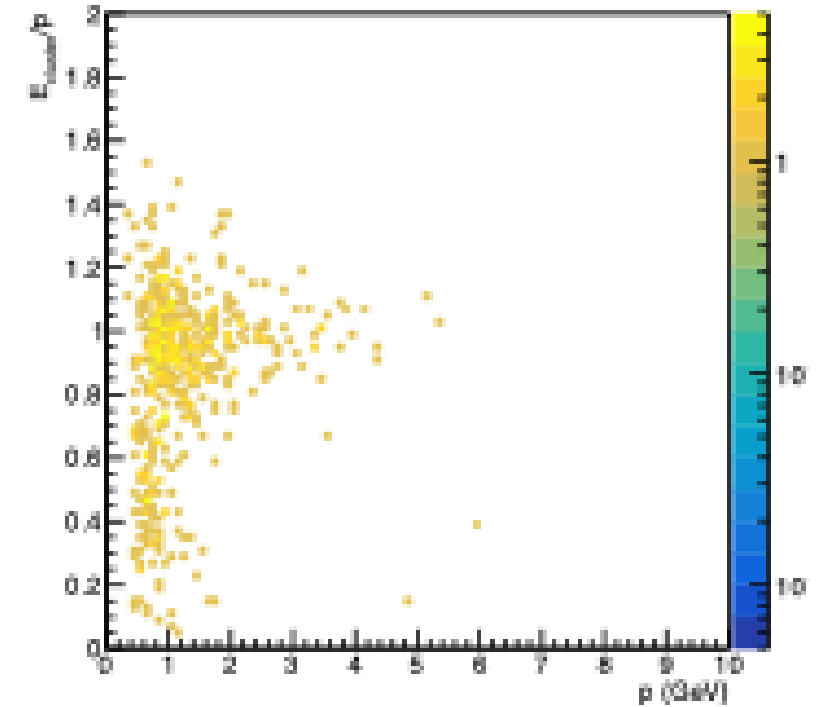
Barrel



Endcap N



Endcap P

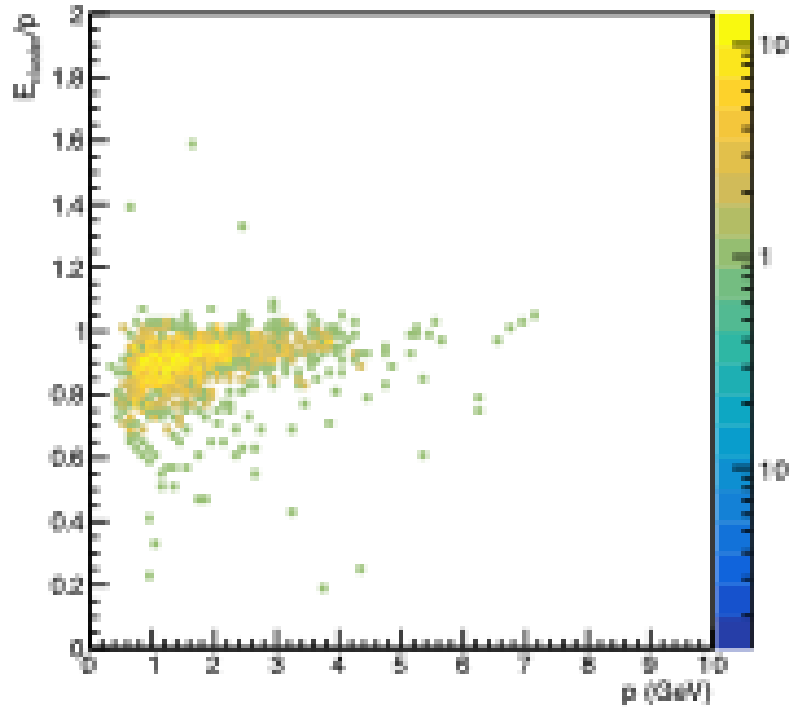


- Initial look at E/p response for soft electrons, complementary to DIS
- Endcap-P appears to have worse E_e reconstruction (revisit with high mass)

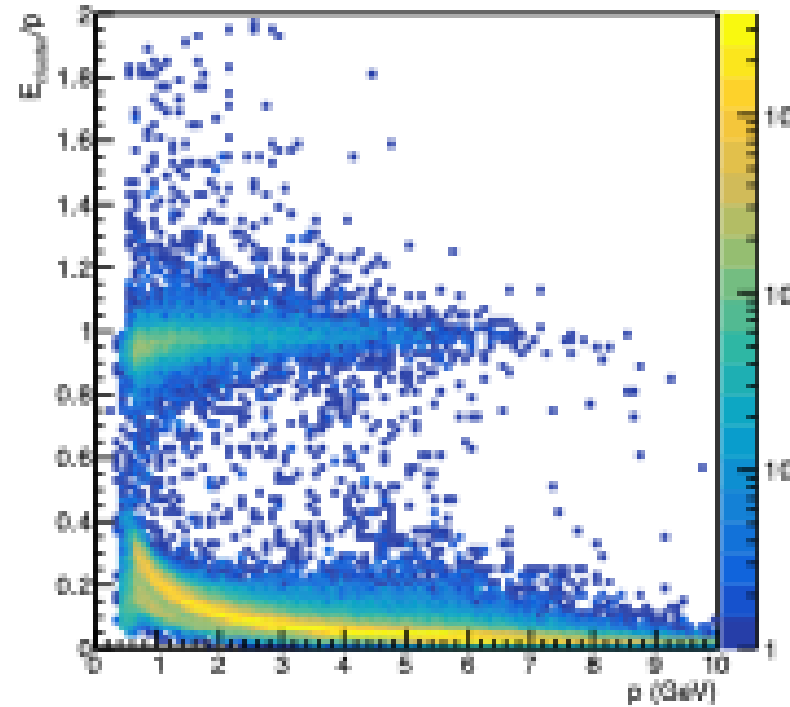
ECAL Response

Dimuon-decaying ALP

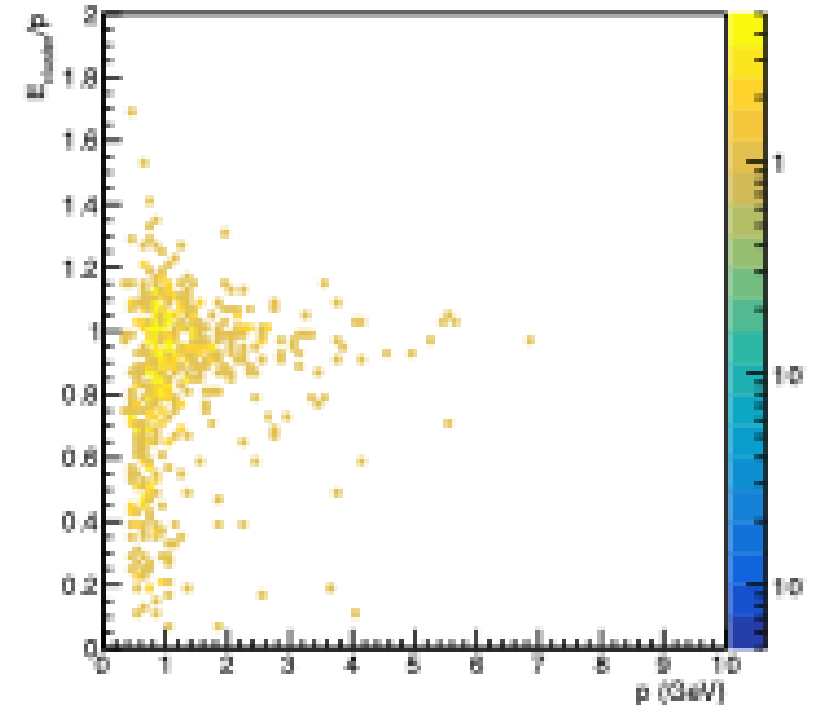
Barrel



Endcap N



Endcap P



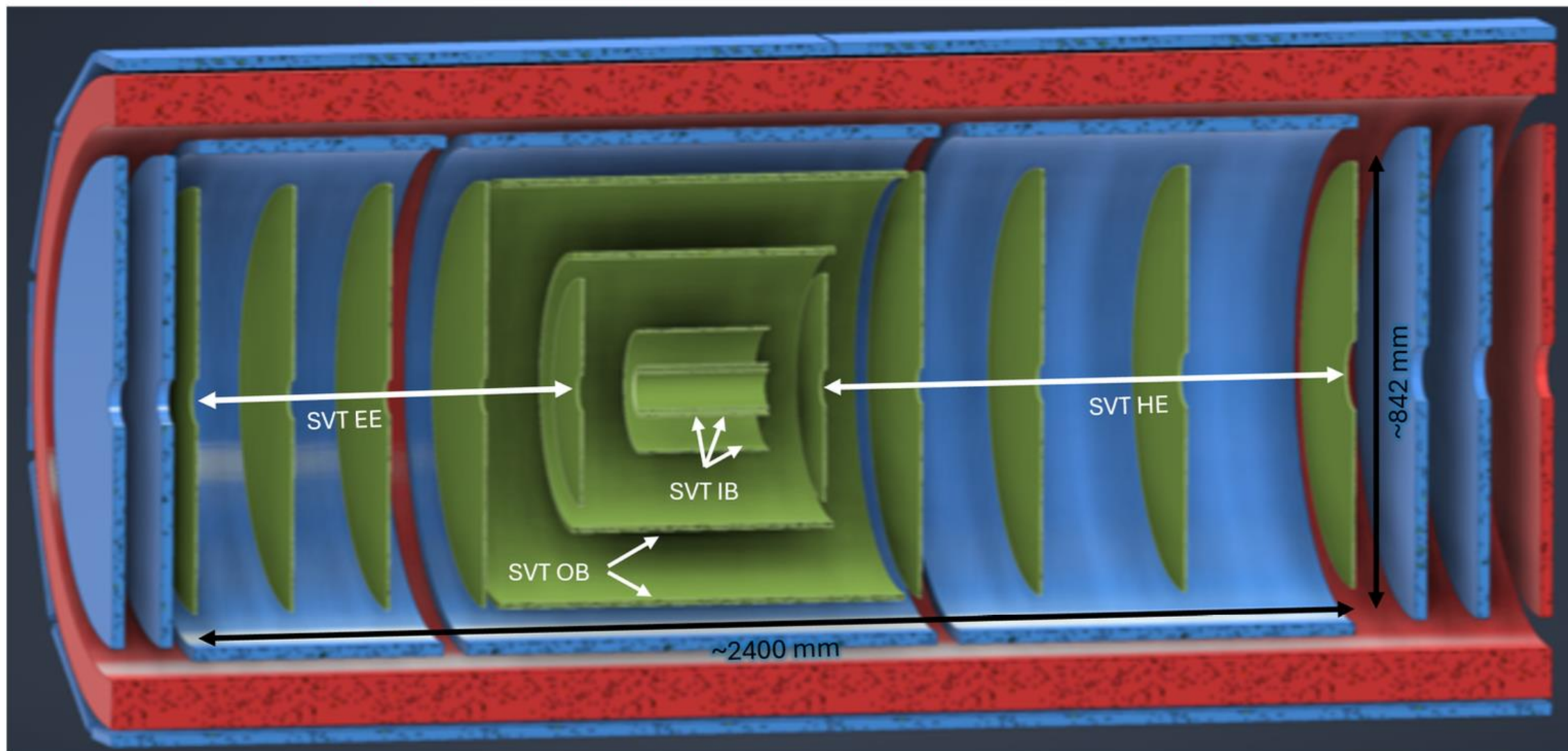
- Initial look at E/p response for soft electrons, complementary to DIS
- Endcap-P appears to have worse E_e reconstruction (revisit with high mass)
- Can clearly separate e from μ ; (μ mostly exist in Endcap-N)

Summary

- Feasibility study of electrophilic ALP search has been initiated
 - ePIC/EIC sensitive to **intermediate mass** ALPs ($0.1 < M_{ALP} < 20 \text{ GeV}$), complementary to LHC and non-collider experiments
 - **Near-term** focus: **non-decaying ALP** channel
 - Aiming to contribute to **NIM-A** special issue and **ePIC/EIC Asia** Workshop
- Investigation at Truth-level
 - **Soft** and **central** FS electron with ALP taking away most of beam energy
 - Electron-ALP relation: $p_{T,e}$ tail and η_e range $\propto M_{ALP}$
- Event reconstruction
 - Currently focusing on electron ID using PID info and ECAL
 - Complementary to Exclusive, DIS, and DIS-like BSM studies
 - WIP: Investigation of HCAL and forward systems (Roman Pot, ZDC, etc.)
 - Official ePIC simulation request submitted for the April campaign

Backup

SVT ; MPGDs ; TOF (fiducial volume) ;



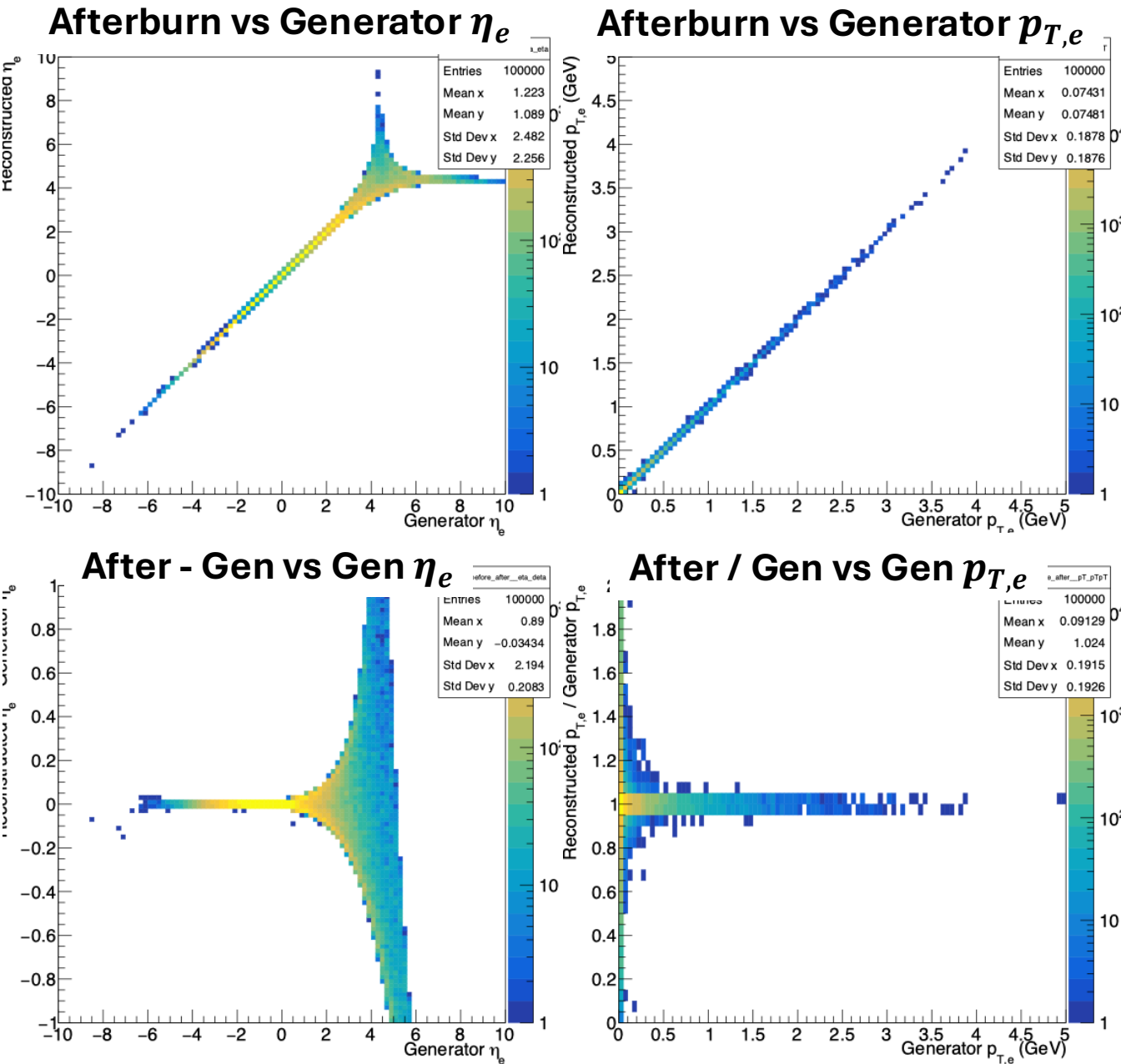
Hadron beam

Electron beam

Acceptance Requirements (Pre-TDR 3.1)

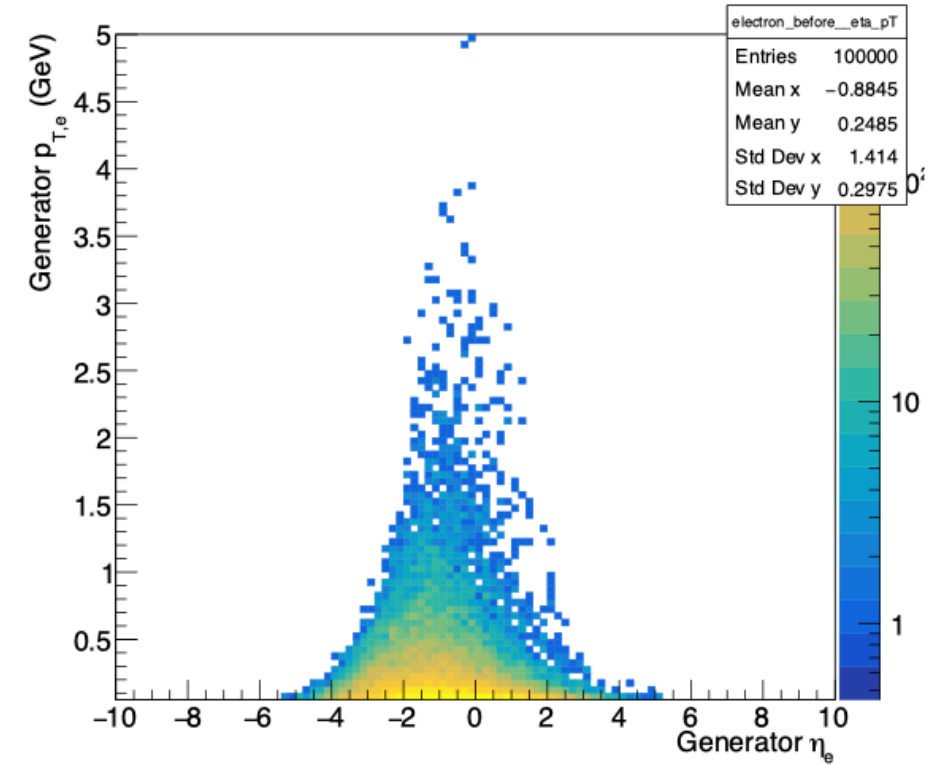
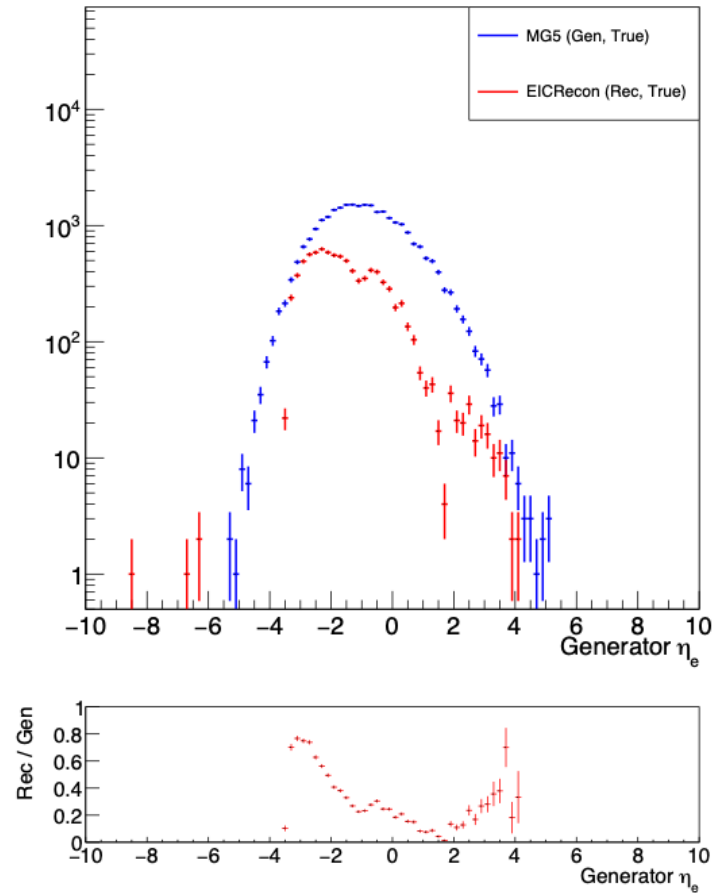
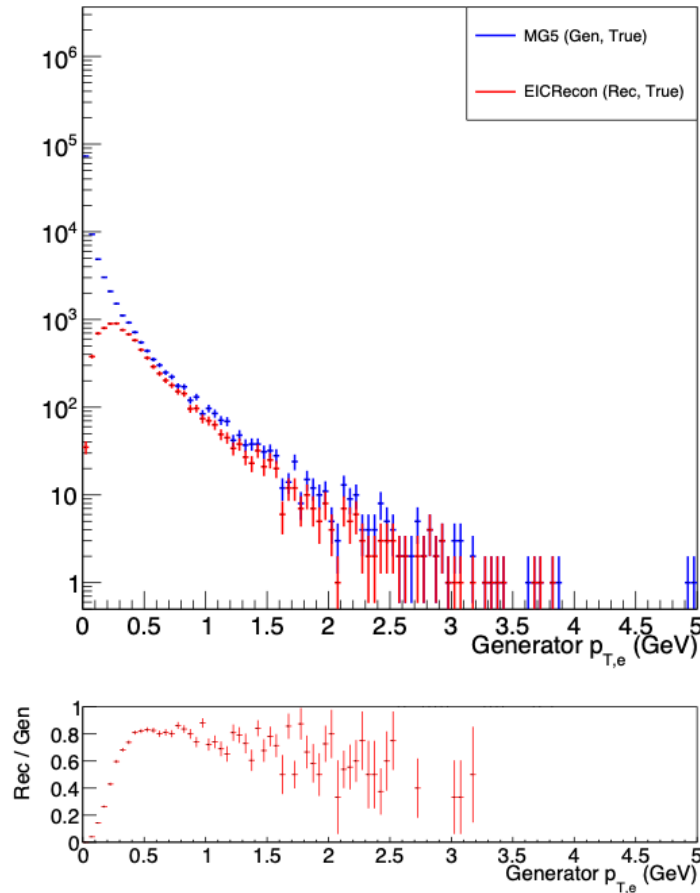
η	Nomenclature		Tracking				Electrons and Photons			$\pi/K/p$		HCAL		
			Resolution σ_p/p [GeV/c]	max X/X_0	min p_T	transverse pointing $dca(xy),$ p_T [GeV/c]	Resolution σ_E/E [GeV]	PID	E_{min}	Momentum range	Separation	Resolution σ_E/E [GeV]	E_{min}	
< -4.6	↓ p/A	Far Backward Detectors	low- Q^2 tagger	< 5%				$10\%/\sqrt{E}$ ⊕3%						
-4.6 to -4.0		Not Accessible												
-4.0 to -3.5		Reduced Performance												
-3.5 to -3.0		Central Detector	Backward Detector		< 5%	100 MeV/c (pions) 130 MeV/c (kaons)	30 $\mu\text{m}/p_T$ ⊕40 μm	$< (2 - 3)\%/\sqrt{E}$ ⊕(1 - 2)%	π supp. up to 10^4	20 MeV	< 10 GeV/c	> 3 σ	100%/ \sqrt{E} ⊕10%	500 MeV
-3.0 to -2.5				0.1% * p ⊕2%										
-2.5 to -2.0			Barrel				30 $\mu\text{m}/p_T$ ⊕20 μm	$< 10\%/\sqrt{E}$ ⊕(2 - 3)%	π supp. up to $10^3 - 10^2$	100 MeV	< 6 GeV/c			
-2.0 to -1.5				0.05% * p ⊕1%										
-1.5 to -1.0			Forward Detector				20 $\mu\text{m}/p_T$ ⊕5 μm	π supp. up to 10^2	100 MeV	< 6 GeV/c				
-1.0 to -0.5				0.05% * p ⊕0.5%										
-0.5 to 0.0				30 $\mu\text{m}/p_T$ ⊕20 μm	$< (10 - 12)\%/\sqrt{E}$ ⊕(2 - 3)%	3σ e/ π up to 15 GeV/c	100 MeV	< 50 GeV/c	50%/ \sqrt{E} ⊕10%					
0.0 to 0.5		Reduced Performance												
0.5 to 1.0		Not Accessible												
1.0 to 1.5		Far Forward Detectors	B0 Spectrometer	< 7% $p_T > 1$ GeV	< 5%			$< 20\%/\sqrt{E}$ ⊕3%		100 MeV				
1.5 to 2.0			Off Momentum Spectrometer	< 10% $p_T > 1$ GeV										
2.0 to 2.5			Roman Pots	< 5% $p_T > 0.5$ GeV										
2.5 to 3.0	Zero Degree Neutral Detection						$< 20\%/\sqrt{E}$ ⊕5%		100 MeV		< 50%/ \sqrt{E} ⊕5%			
3.0 to 3.5	↑ e													
3.5 to 4.0														
4.0 to 4.6														
> 4.6														
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15

Effect of Afterburner



- Asymptotic beam divergence starting at $\eta \sim 4$
- Only a small divergence effects in the backward direction
- Only a small p_T smearing at low p_T ($< 0.5 \text{ GeV}$) due to beam effect / rotation

Event reconstruction with EIC Recon

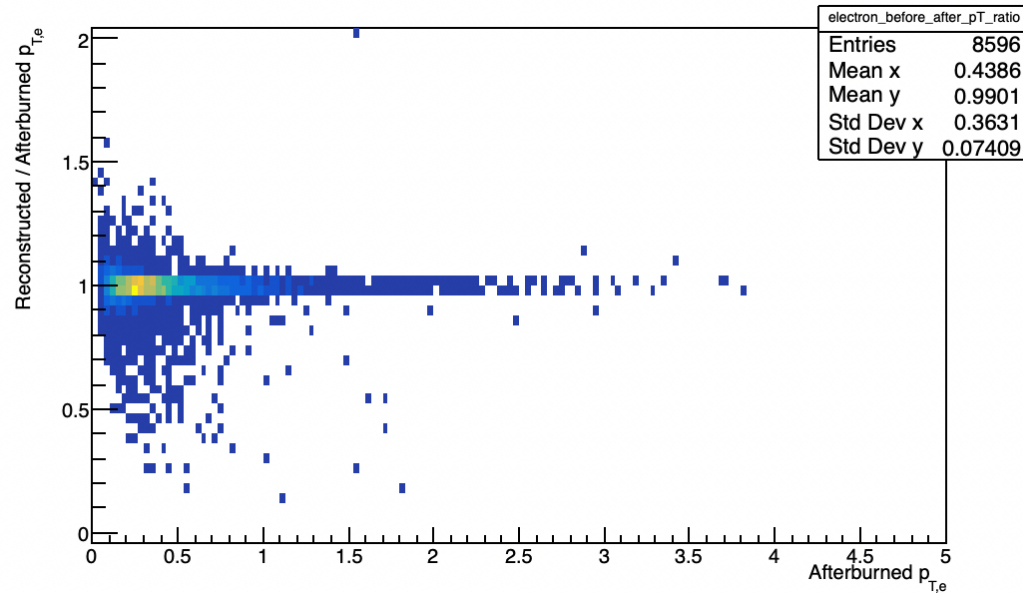


$p_T (> 0.05 \text{ GeV})$ vs η
No strong eta dependence in p_T found

- Only looking at $p_T > 0.05 \text{ GeV}$
- Higher efficiency in the **backward** and **forward**

Tracking Performance

*In-depth review by Alyssa next meeting



Graph of **Mean** p_T ratio vs p_T for different η
[Endcap-N vs Barrel vs Endcap-P]

- p_T smearing 6 – 8%
 - Pre-TDR requirements:
 - Endcap $\sim 2\%$
 - Barrel
- shifting $< 2\%$
- [Comment about barrel vs endcap]
- Small smearing/shifting effects in η_e

Tracking Performance

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2D histogram pT ratio vs pT

Graph of **RMS** pT ratio vs pT for different η
[Endcap-N vs Barrel vs Endcap-P]

- p_T smearing 6 – 8%
 - Pre-TDR requirements:
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- shifting $< 2\%$

- [Comment about barrel vs endcap]

- Small smearing/shifting effects in η_e

Tracking Performance

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2D histogram eta diff vs eta

Graph of **Mean** eta diff vs eta

Graph of **RMS** eta diff vs eta

- p_T smearing 6 – 8%
 - Pre-TDR requirements:
 - Endcap $\sim 2\%$
 - Barrel
- shifting $< 2\%$
- [Comment about barrel vs endcap]
- Small smearing/shifting effects in η_e