Muon ID Study in the Forward Region at ePIC for EIC 2nd Detector

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Goal of This Study

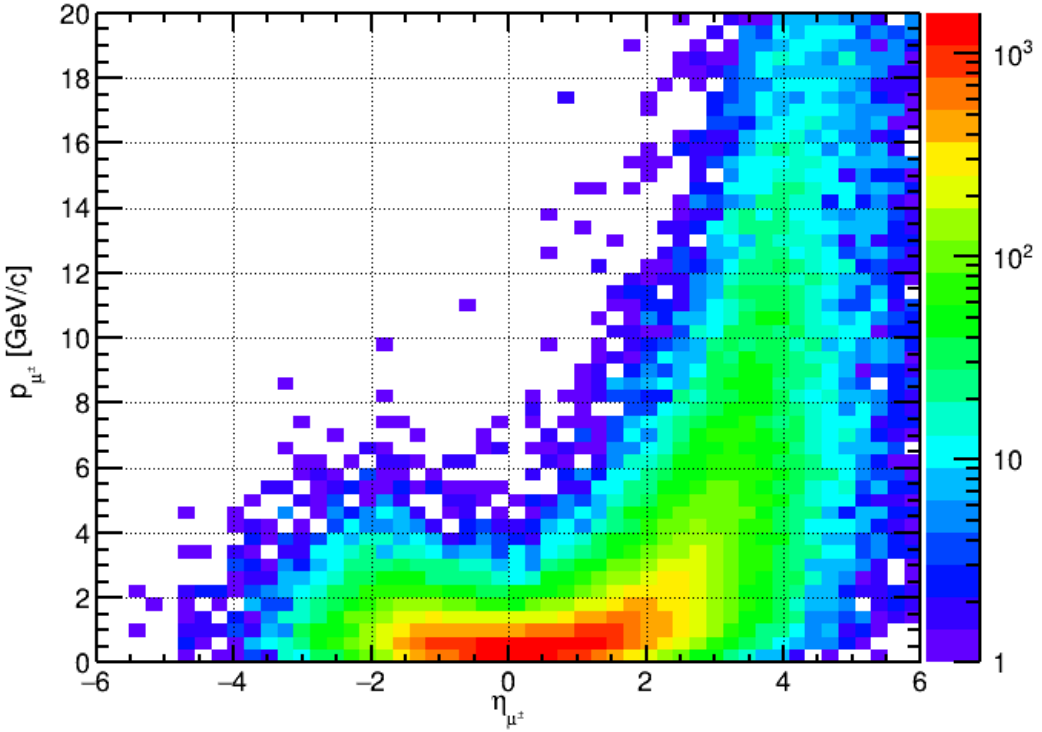
- Evaluate muon ID performance in the forward region at ePIC
  - A dedicated muon ID detector can complement project detector and a second detector
  - In currently proposed EIC 2nd detector design, only barrel region is considered

- How-To and Inputs
  - Use EMCAL and HCAL information to identify MIP-like events
    - EMCAL: Use energy and # of hits from the entire detector
    - HCAL: Use energy from each individual layer

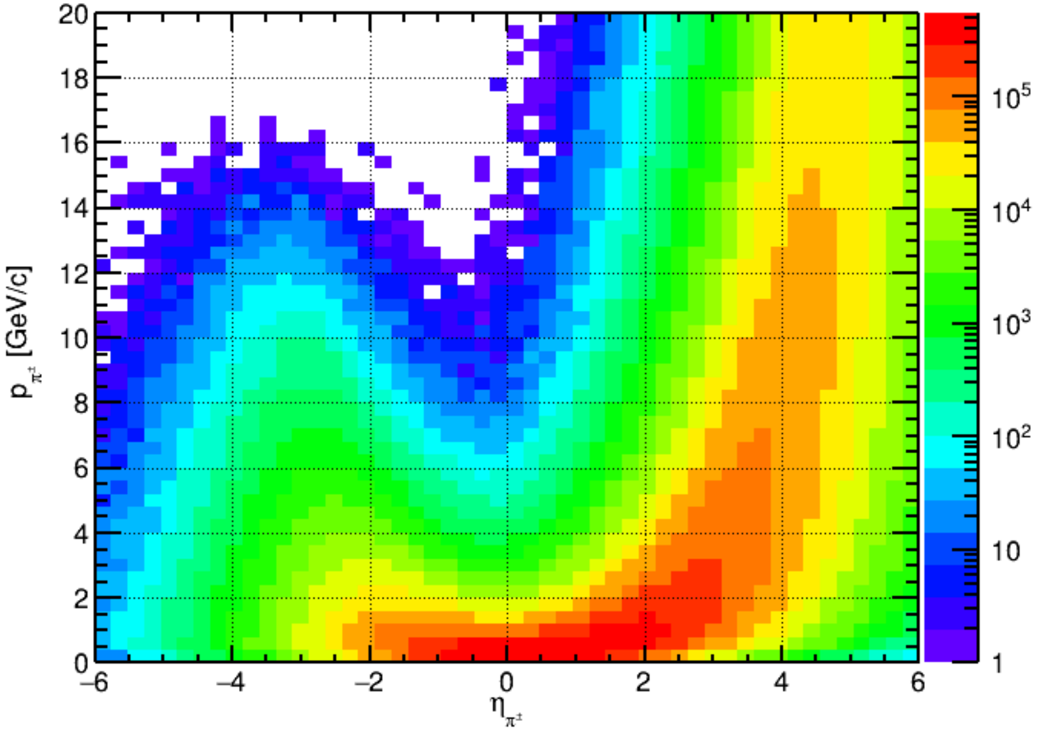
- This study serves as a good example for applying Machine Learning with ROOT TMVA module ep 18×275 GeV^2 10M in high divergence mode (EIC CDR Table 3.3)

Cross Section from PYTHIA Sample

$\mu^{\pm}$



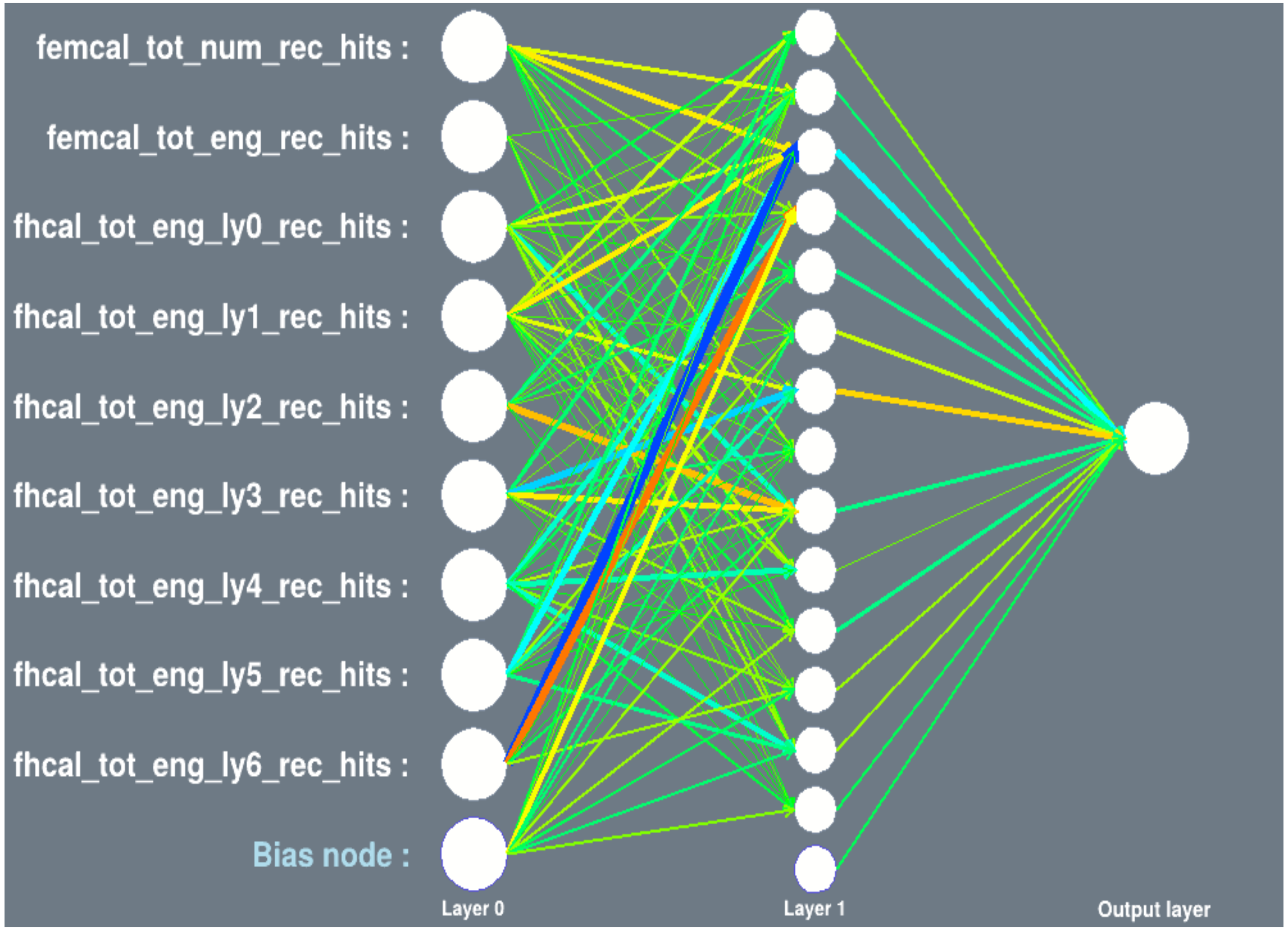
$\pi^{\pm}$



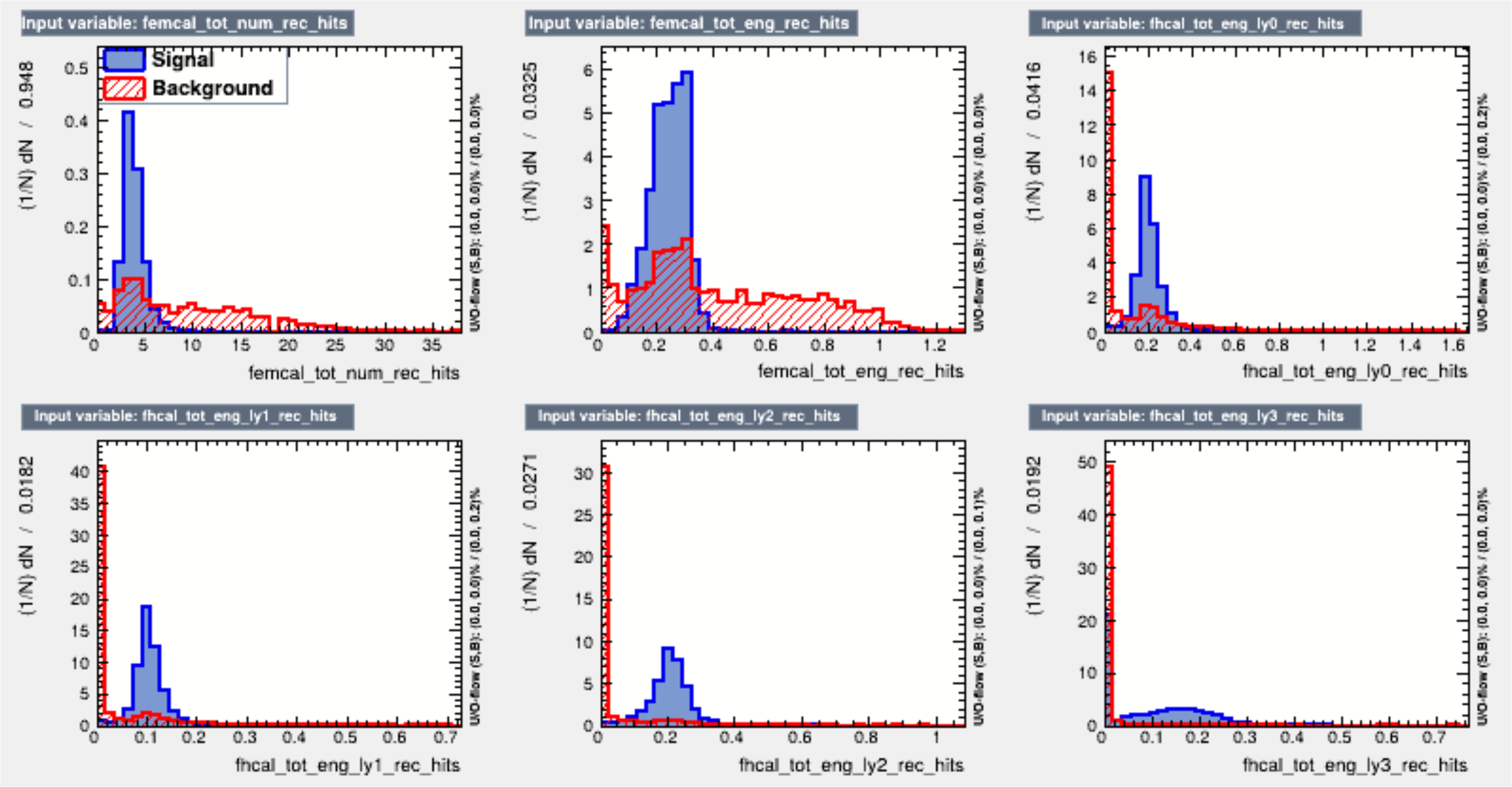
η = 1.74	1 GeV/c	2 GeV/c	5 GeV/c	10 GeV/c
N_μ	736	271	22	2
N_π	368039	109691	7507	492
N_π/N_μ	~ 500	~ 405	~ 342	~ 246

Input Variables

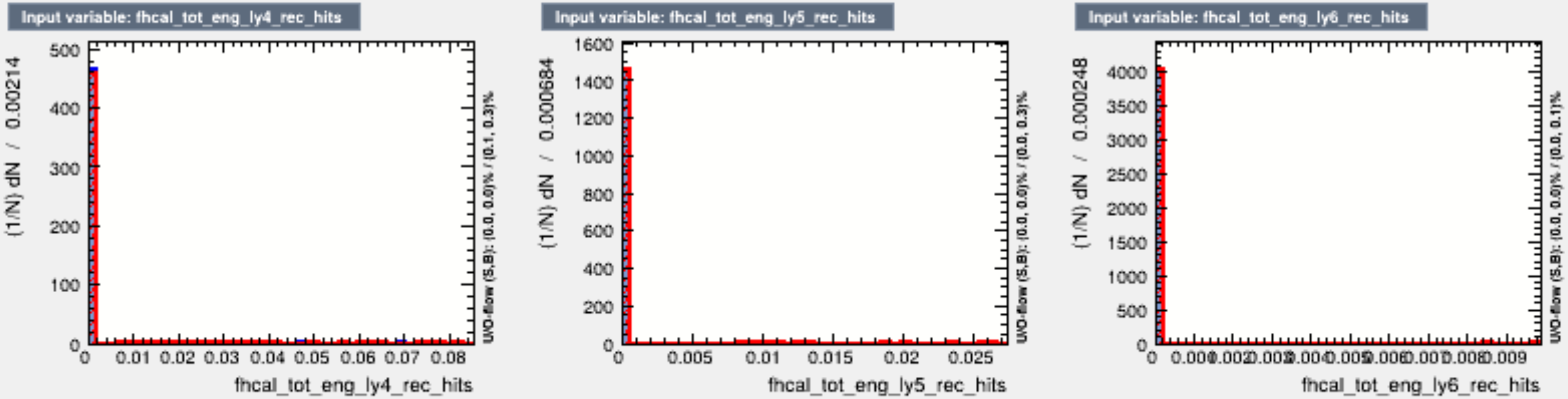
- Use TMVA: Toolkit for Multivariate Data Analysis with ROOT
  - Artificial Neural Networks (MultiLayer Perceptron)
- Default configuration
  - One hidden layer
  - N_{var}+5 neurons
- 10k events
  - 5k is used for training
  - Another 5k is used for testing
  - 9 inputs
- EMCAL: Energy, # hits
- HCAL per layer: Energy



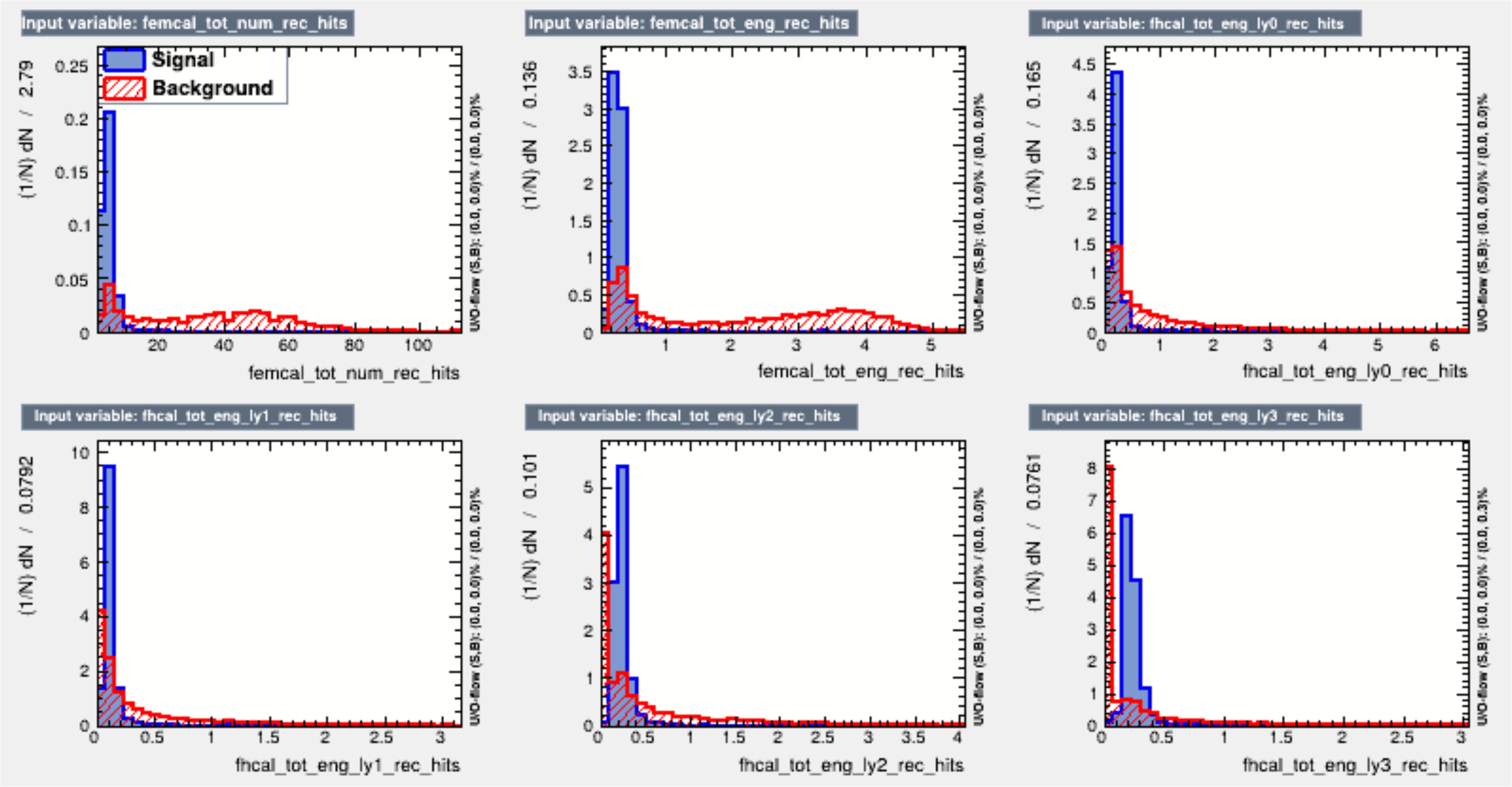
Input Distribution for 1 GeV μ^+ and π^+



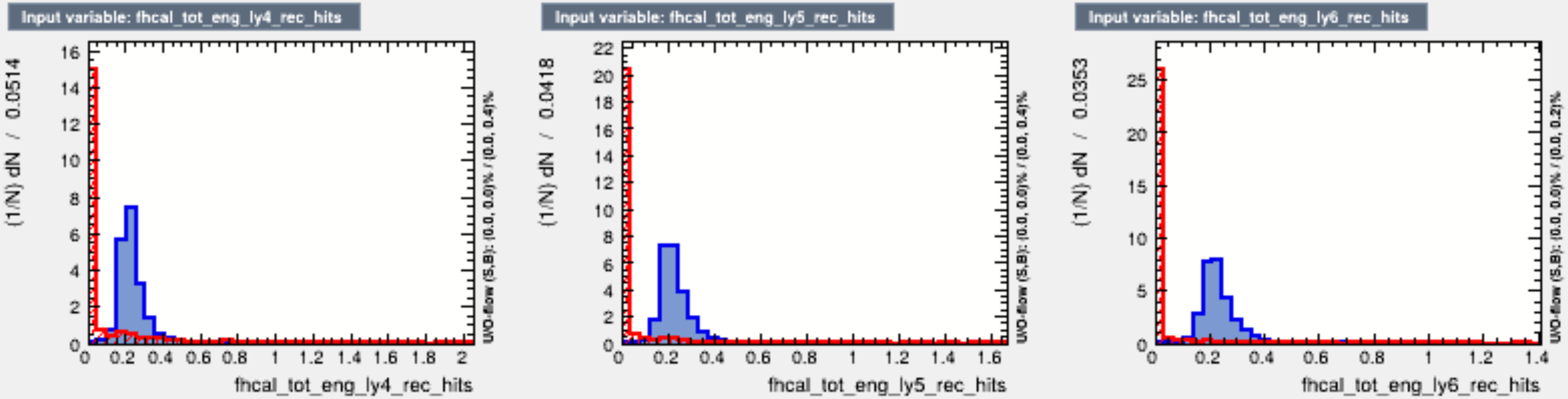
Input Distribution for 1 GeV μ^+ and π^+



Input Distribution for 5 GeV μ^+ and π^+

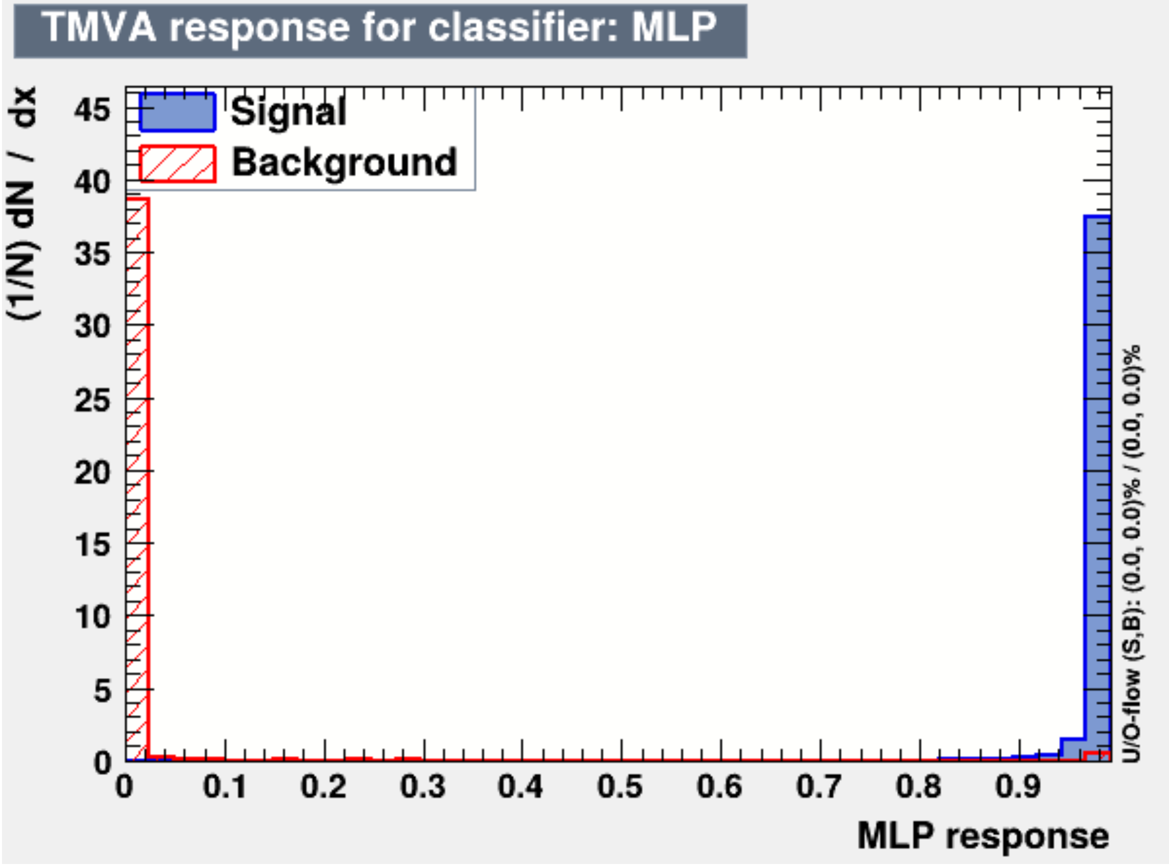


Input Distribution for 5 GeV μ^+ and π^+

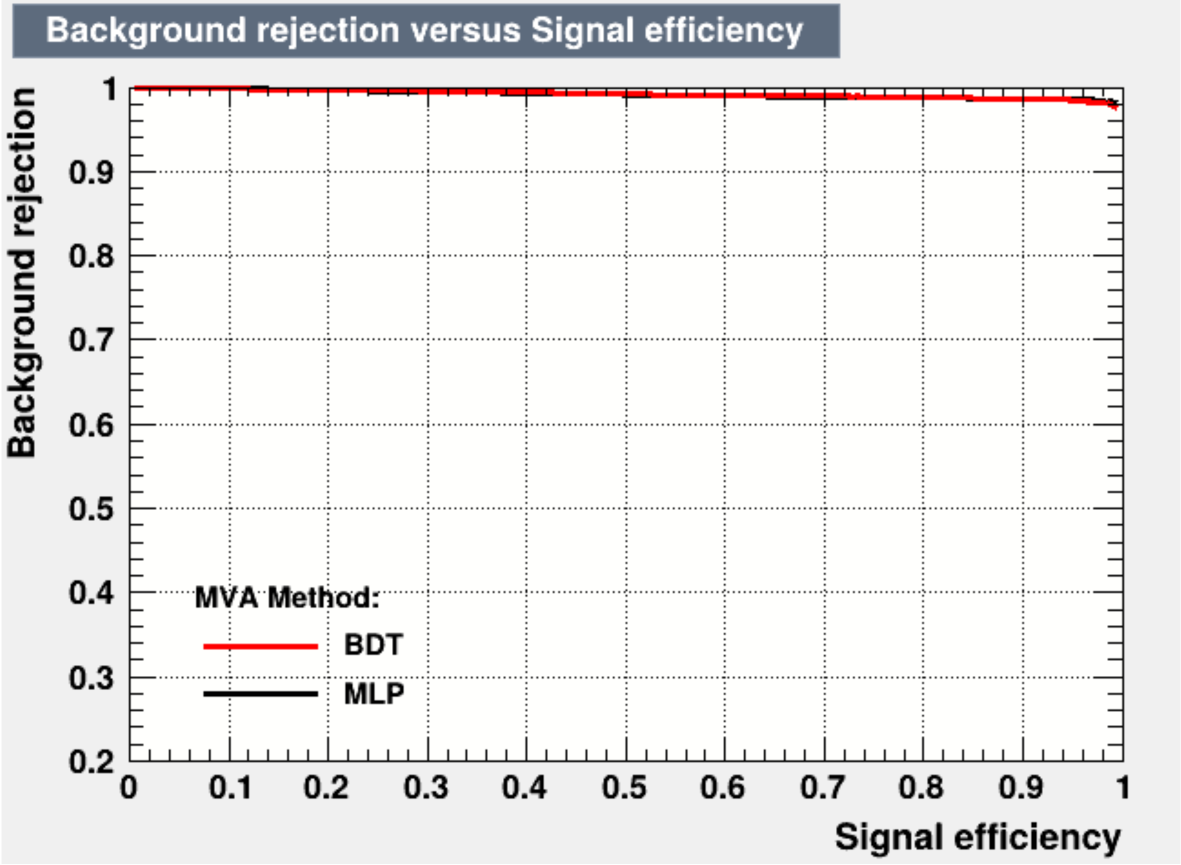


Singal/Background Efficiency

5 GeV



5 GeV



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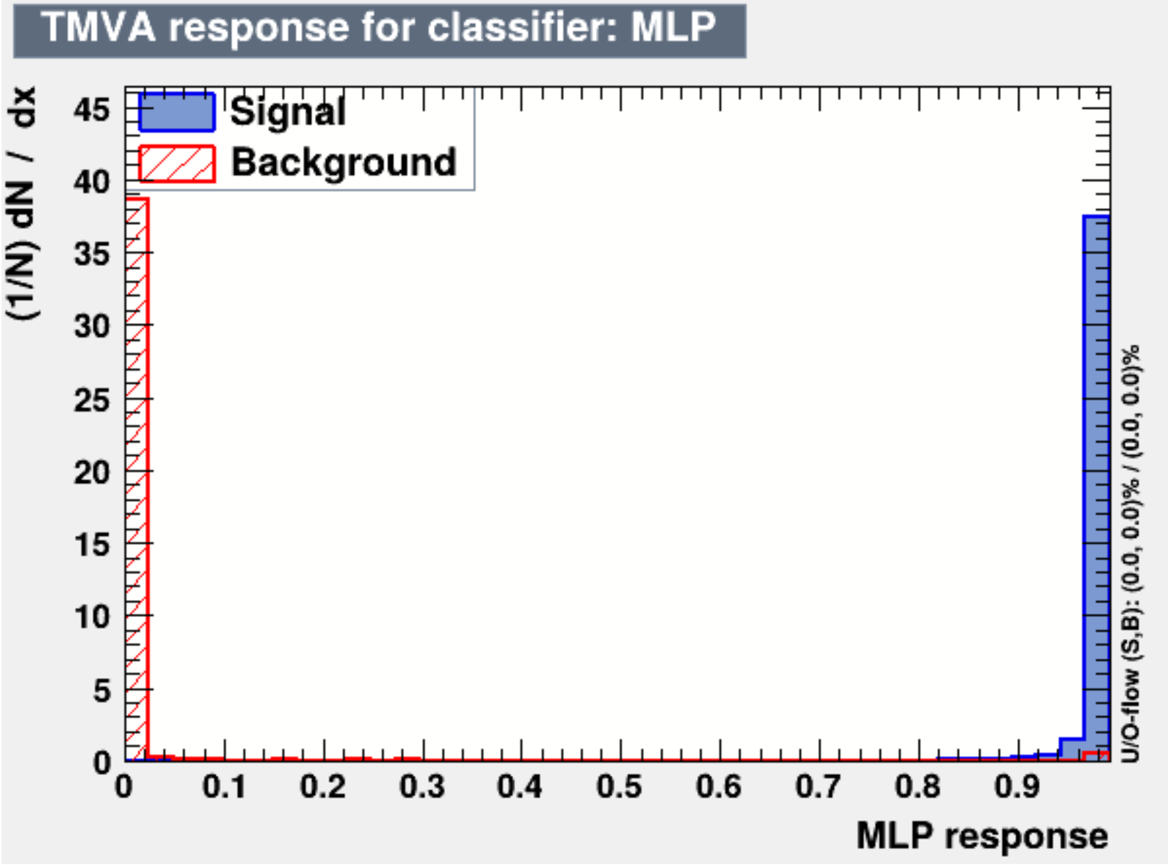
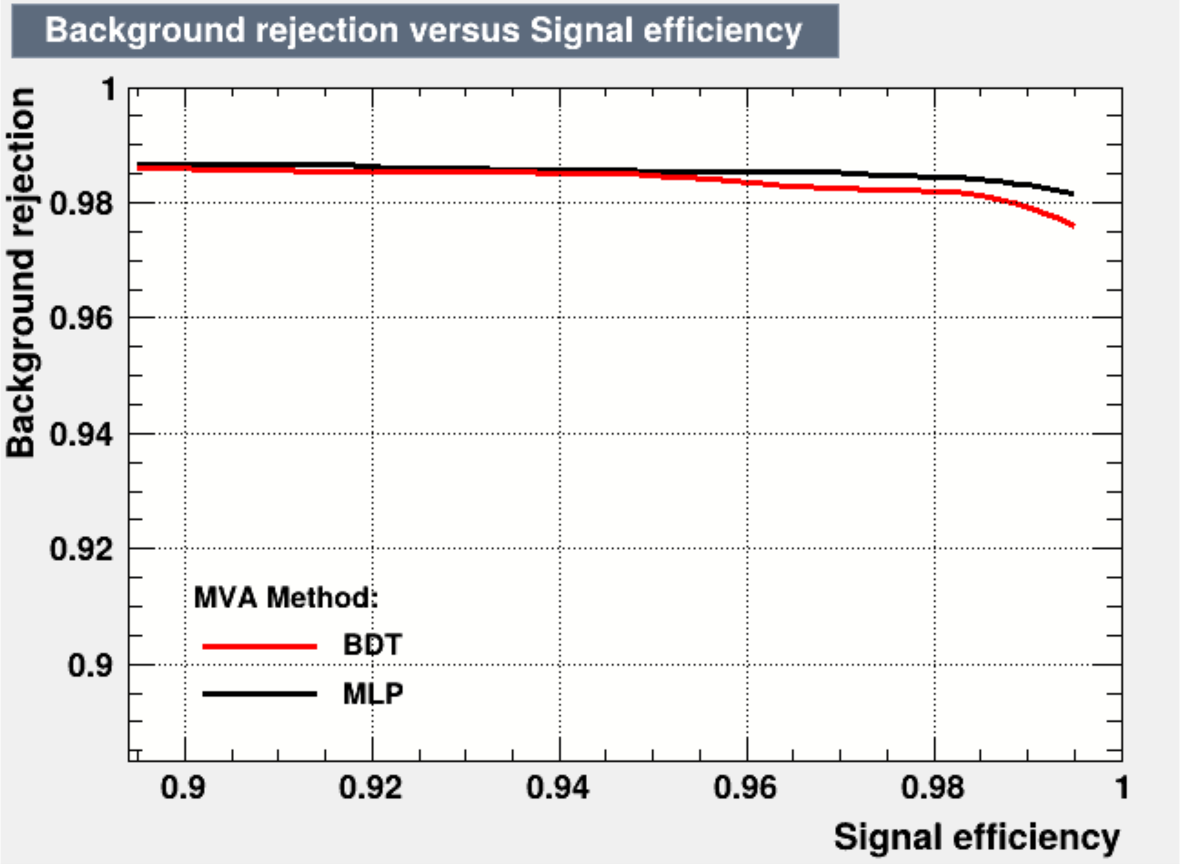
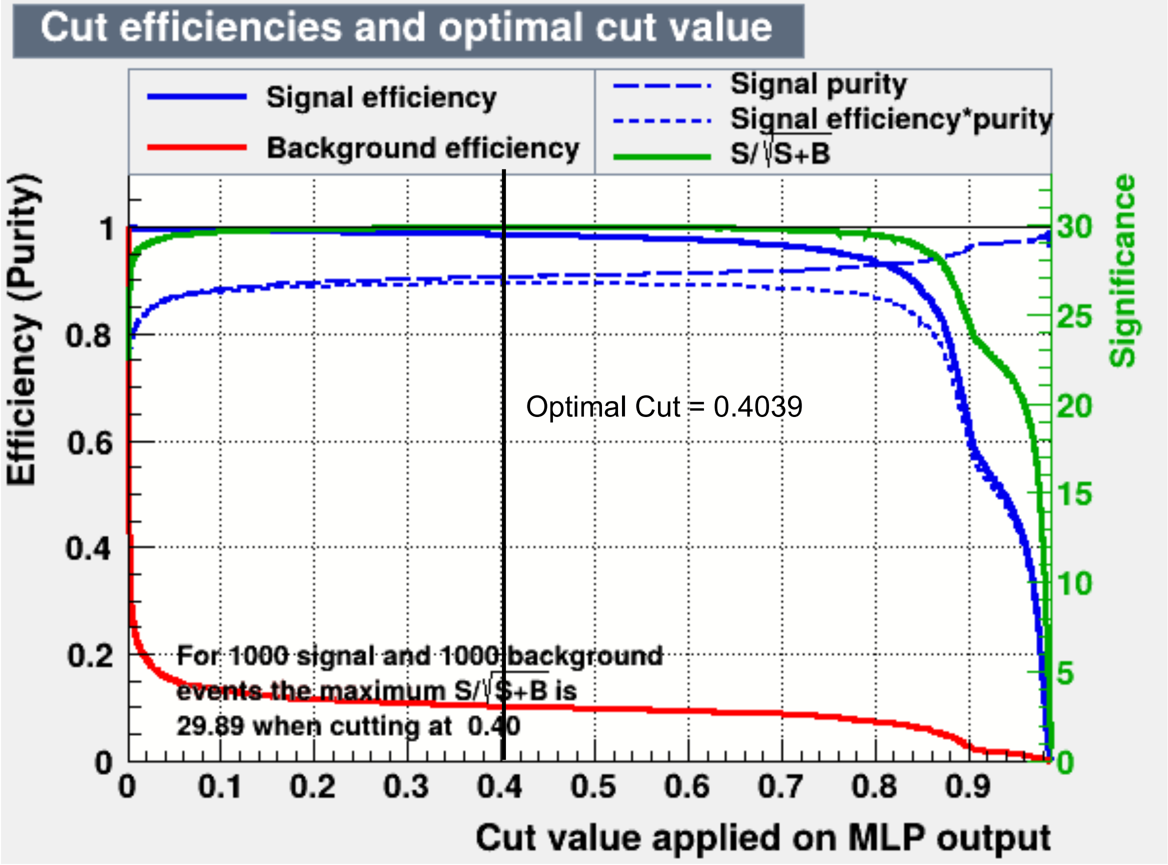


5 GeV



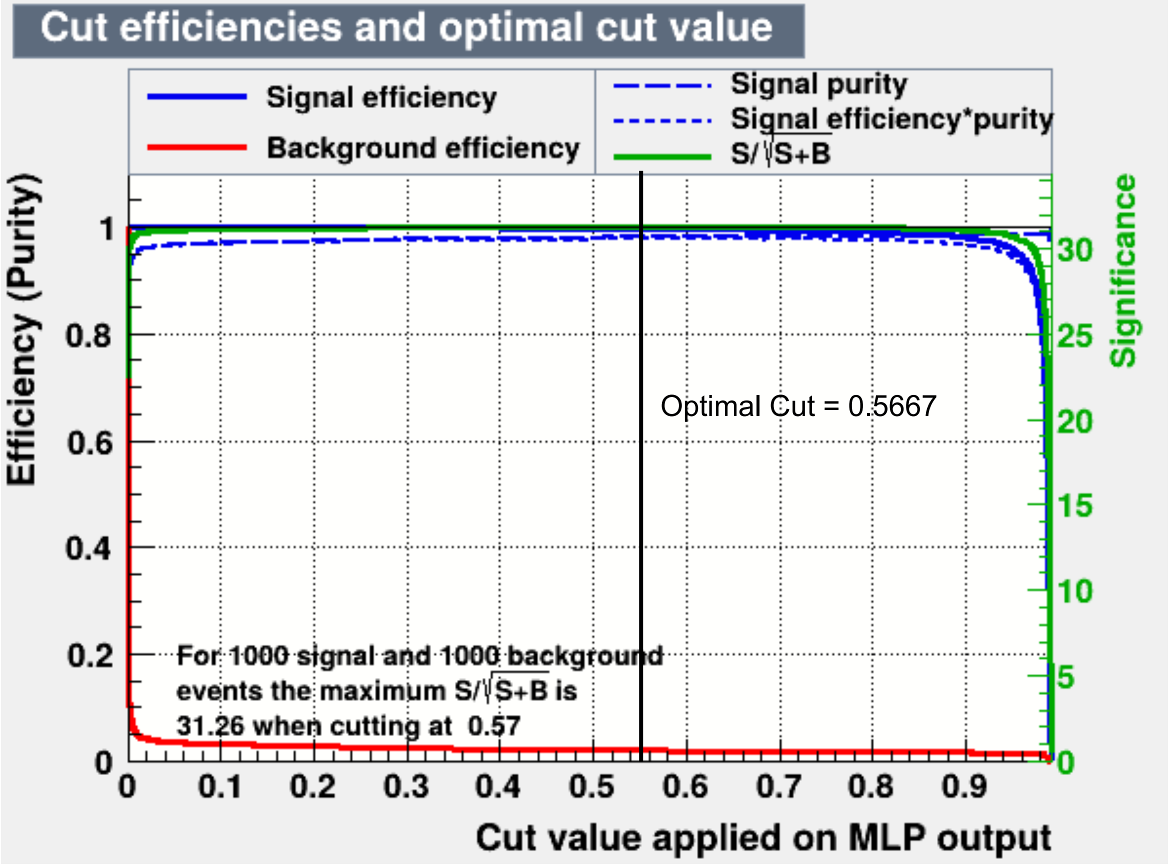
Singal/Background Efficiency

1 GeV



$\varepsilon_{Bg} = 0.1024$ for $\varepsilon_{Sg} = 0.9864$

5 GeV



$\varepsilon_{Bg} = 0.0112$ for $\varepsilon_{Sg} = 0.9968$

Results

Events with angle η = 1.74 or θ = 20°
Given 1M muon and 1M pion simulation samples

Momentum [GeV/c]	Muon Efficiency	Background Rejection Efficiency	Mis-ID Efficiency
1	0.607108	0.968002	0.031998
2	0.9904	0.986889	0.013111
5	0.996242	0.982436	0.017564
10	0.995968	0.9897	0.0103

where

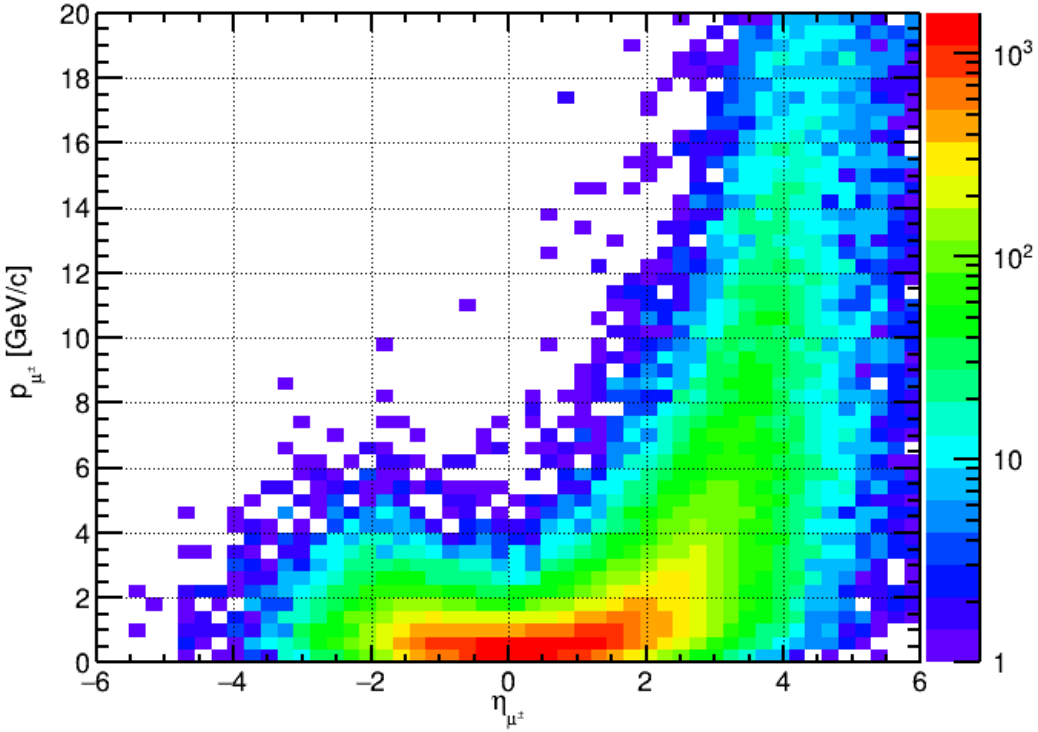
Muon Efficiency: Muon to Muon = $\frac{N_{\mu\rightarrow\mu}}{N_{\mu}}$

Background Rejection Efficiency: Pion to Pion = $\frac{N_{\pi\rightarrow\pi}}{N_{\pi}}$

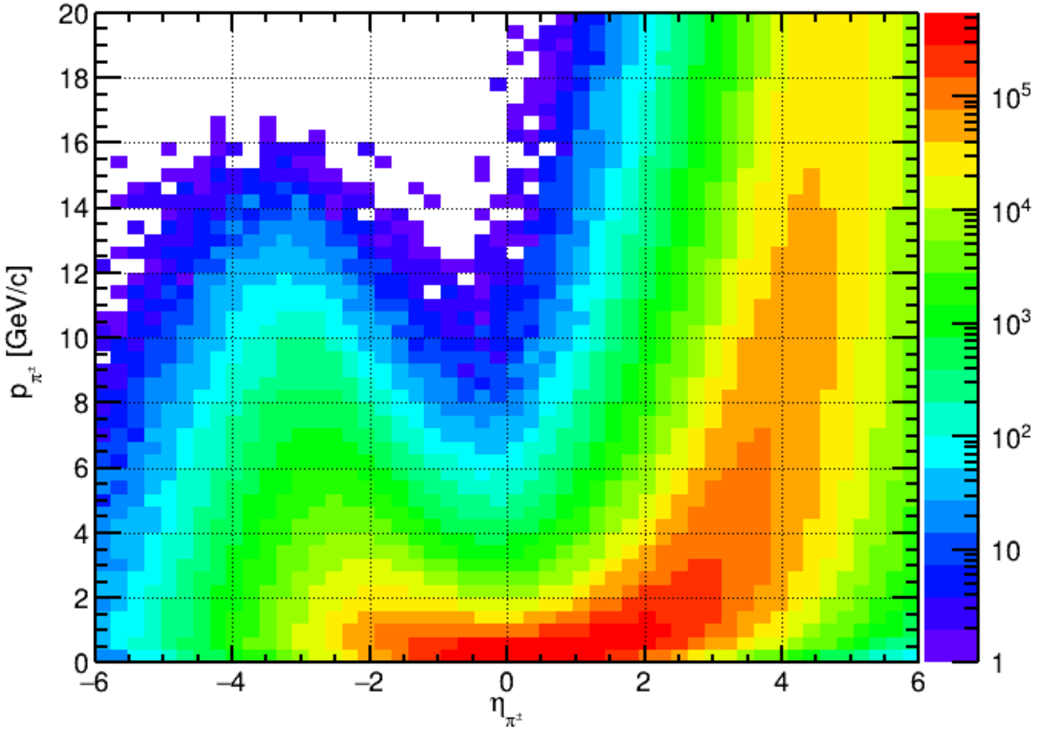
Mis-ID Efficiency: Pion to Muon = $\frac{N_{\pi\rightarrow\mu}}{N_{\pi}}$

Going Back to PYTHIA Sample

$\mu^{\pm}$



$\pi^{\pm}$



η = 1.74	1 GeV/c	2 GeV/c	5 GeV/c	10 GeV/c
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N_π/N_μ	~ 500	~ 405	~ 342	~ 246

Results – Cross Section

Events with angle η = 1.74 or θ = 20°
Given cross section from PYTHIA

Let's calculate mis-ID rate with proper cross section

Mis-ID Rate = $\frac{(N_{\pi\rightarrow\mu})*(\text{cross section})}{N_{\mu\rightarrow\mu}+(N_{\pi\rightarrow\mu})*(\text{cross section})}$

Results – Cross Section

Events with angle η = 1.74 or θ = 20°
Given cross section from PYTHIA

Let's calculate mis-ID rate with proper cross section

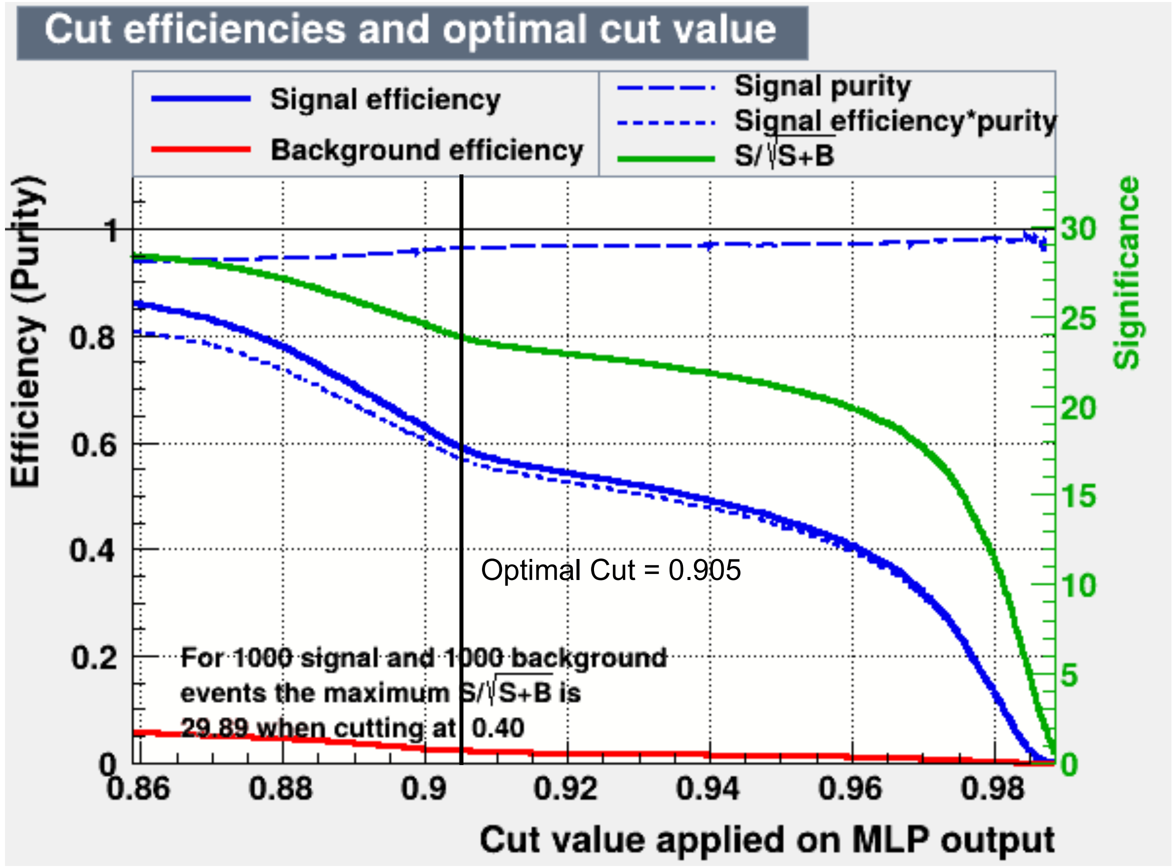
Mis-ID Rate = $\frac{(N_{\pi\to\mu})*(\text{cross section})}{N_{\mu\to\mu}+(N_{\pi\to\mu})*(\text{cross section})}$

Momentum [GeV/c]	Muon Efficiency	Background Rejection Efficiency	Mis-ID Rate
1	0.607108	0.968002	0.96344068
2	0.9904	0.986889	0.84280251
5	0.996242	0.982436	0.85774332
10	0.995968	0.9897	0.71783755

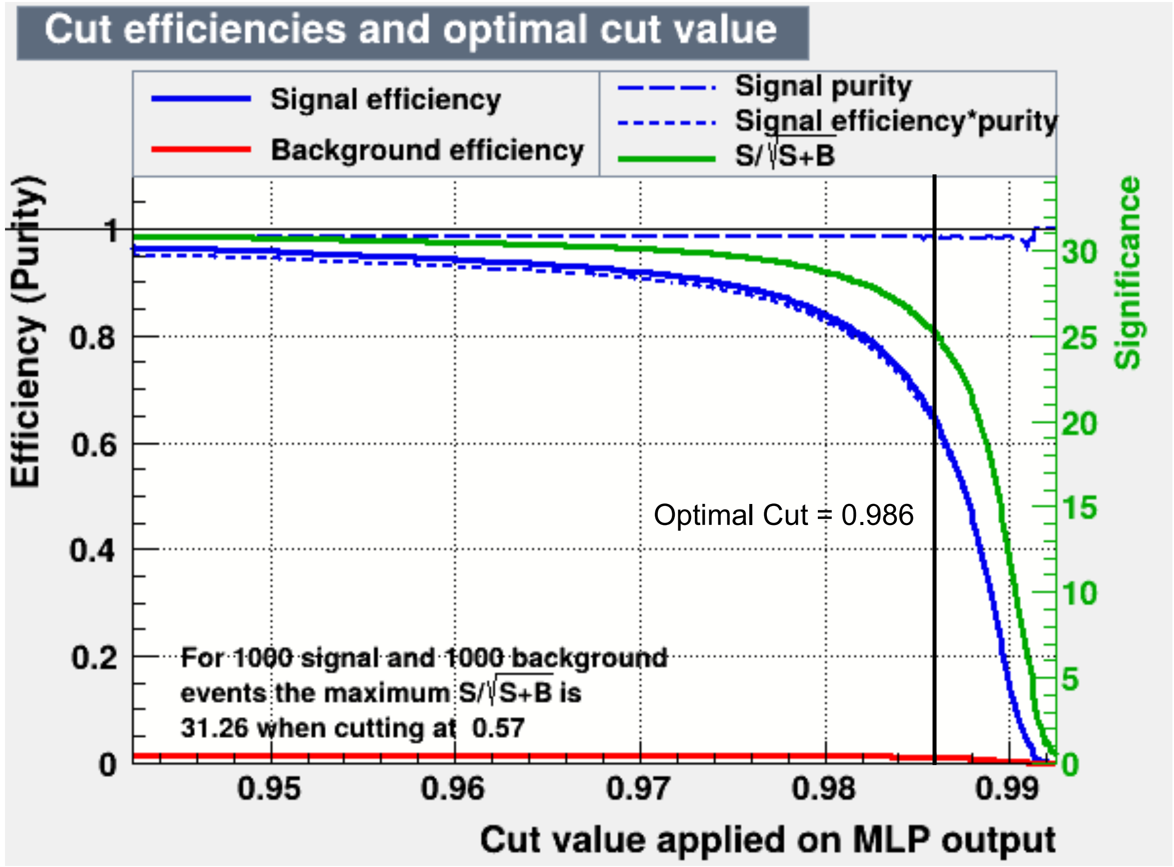
To achieve effective background suppression,

Consider Sacrificing Muon Efficiency

1 GeV



5 GeV



Results – Cross Section (Sacrifice Muon)

Events with angle η = 1.74 or θ = 20°
Given cross section from PYTHIA

Momentum [GeV/c]	Muon Efficiency	Background Rejection Efficiency	Mis-ID Efficiency
1	0.074805	0.998882	0.001118
2	0.510752	0.99578	0.00422
5	0.522971	0.99209	0.00791
10	0.666486	0.994741	0.005259

where

Muon Efficiency: Muon to Muon = $\frac{N_{\mu\rightarrow\mu}}{N_{\mu}}$

Background Rejection Efficiency: Pion to Pion = $\frac{N_{\pi\rightarrow\pi}}{N_{\pi}}$

Mis-ID Efficiency: Pion to Muon = $\frac{N_{\pi\rightarrow\mu}}{N_{\pi}}$

Results – Cross Section (Sacrifice Muon)

Events with angle η = 1.74 or θ = 20°
Given cross section from PYTHIA

Momentum [GeV/c]	Muon Efficiency	Background Rejection Efficiency	Mis-ID Rate
1	0.074805	0.998882	0.88197474
2	0.510752	0.99578	0.76991619
5	0.522971	0.99209	0.83799874
10	0.666486	0.994741	0.65999082

Let's calculate mis-ID rate with proper cross section

Mis-ID Rate = $\frac{(N_{\pi\rightarrow\mu})*(\text{cross section})}{N_{\mu\rightarrow\mu}+(N_{\pi\rightarrow\mu})*(\text{cross section})}$

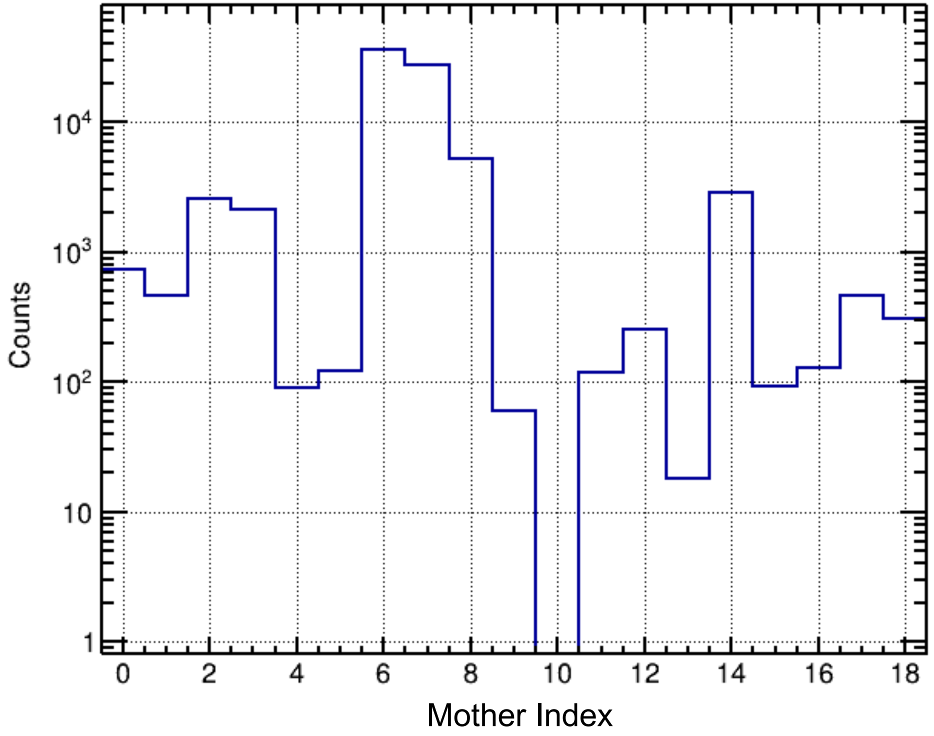
Summary

- Looked at muon ID performance using machine learning algorithm
  - Use forward EMCAL as a whole (energy and # hits) and forward HCAL layer (energy)
  - Consider cross section from PYTHIA ep sample
  - Vary optimal cuts
- Mis-ID rate (even sacrificing muon efficiency) after applying cross section
  - Lowest 66 % at 10 GeV
  - Highest 88 % at 1 GeV
- There might be room for improvement? Maybe tracker and PID detector?
  - Tracker and Calorimeter: E/p?
  - PID: similar mass between m_{π} (140 MeV) and m_{μ} (106 MeV)
- Or we need a dedicated muon ID detector in forward region for EIC 2nd Detector?
  - Exclusive quarkonium production – simpler and cleaner environment (background suppression)
  - Other channels such as TCS*, DDVCS**, HEMP***, etc?

*Timelike Compton Scattering (TCS)
**Double Deep Virtual Compton Scattering (DDVCS)
***Hard Exclusive Meson Production (HEMP)

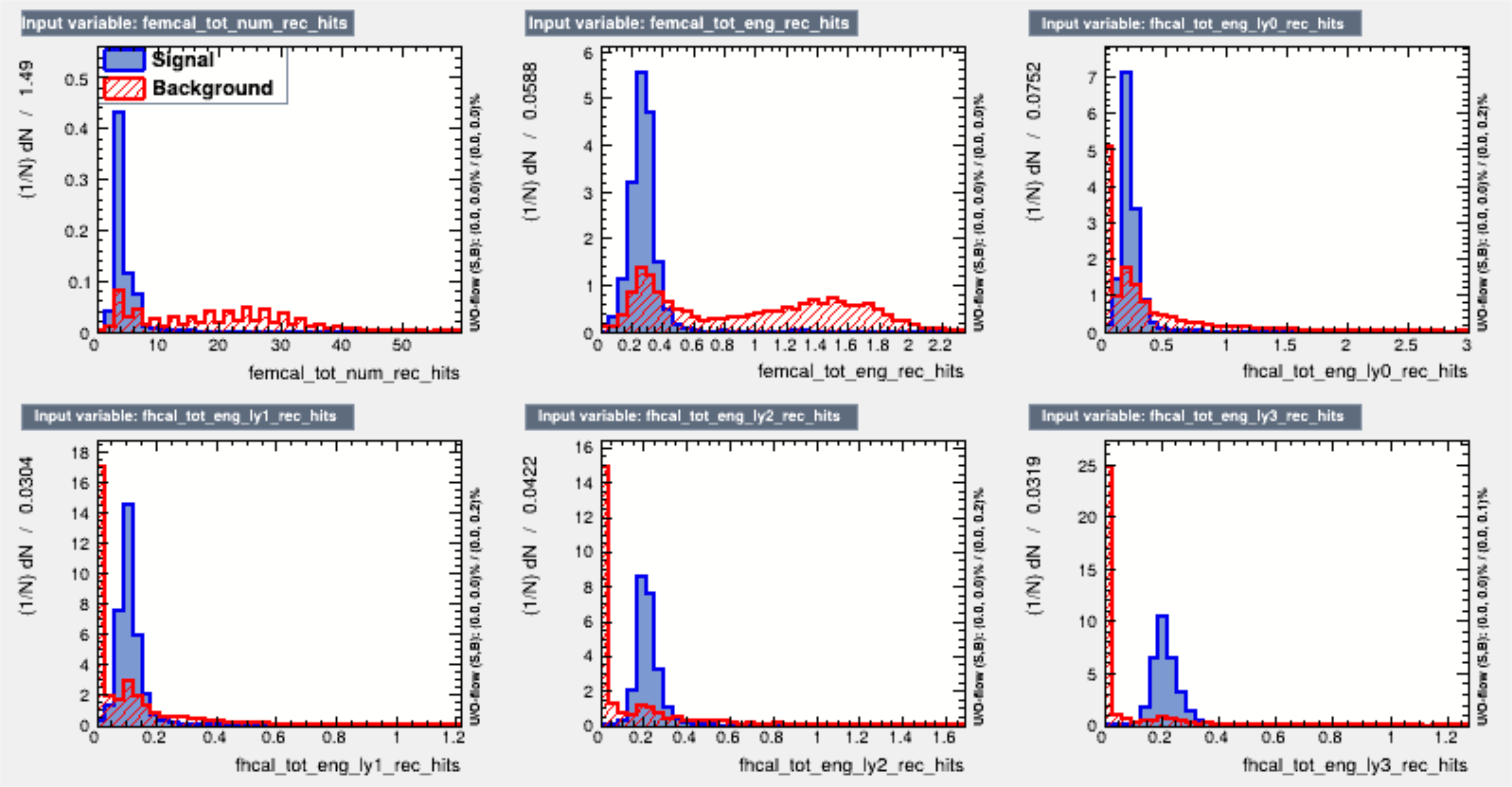
Backup Slides

Kinematics – 18×275 GeV^2

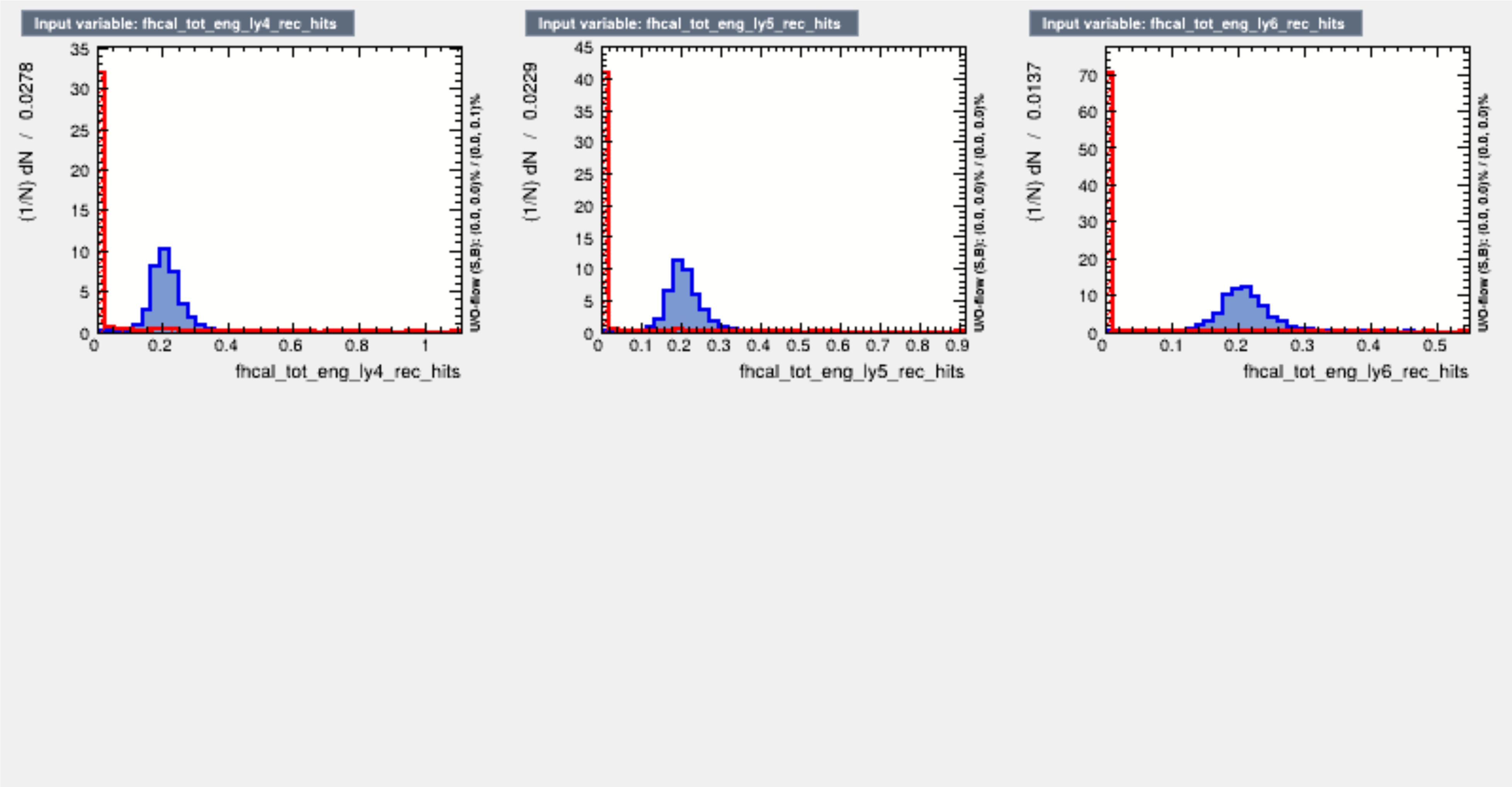


[0] τ
[1] ρ^0
[2] η
[3] ω
[4] η'
[5] ϕ
[6] $\boldsymbol{D^+}$
[7] $\boldsymbol{D^0}$
[8] D_s^+
[9] J/ψ
[10] Υ
[11] Σ^-
[12] Λ
[13] Ξ^-
[14] Λ_c^+
[15] Ξ_c^0
[16] Ξ_c^+
[17] $\mu^\pm$
[18] the rest (ex. B^+, B^0, …)

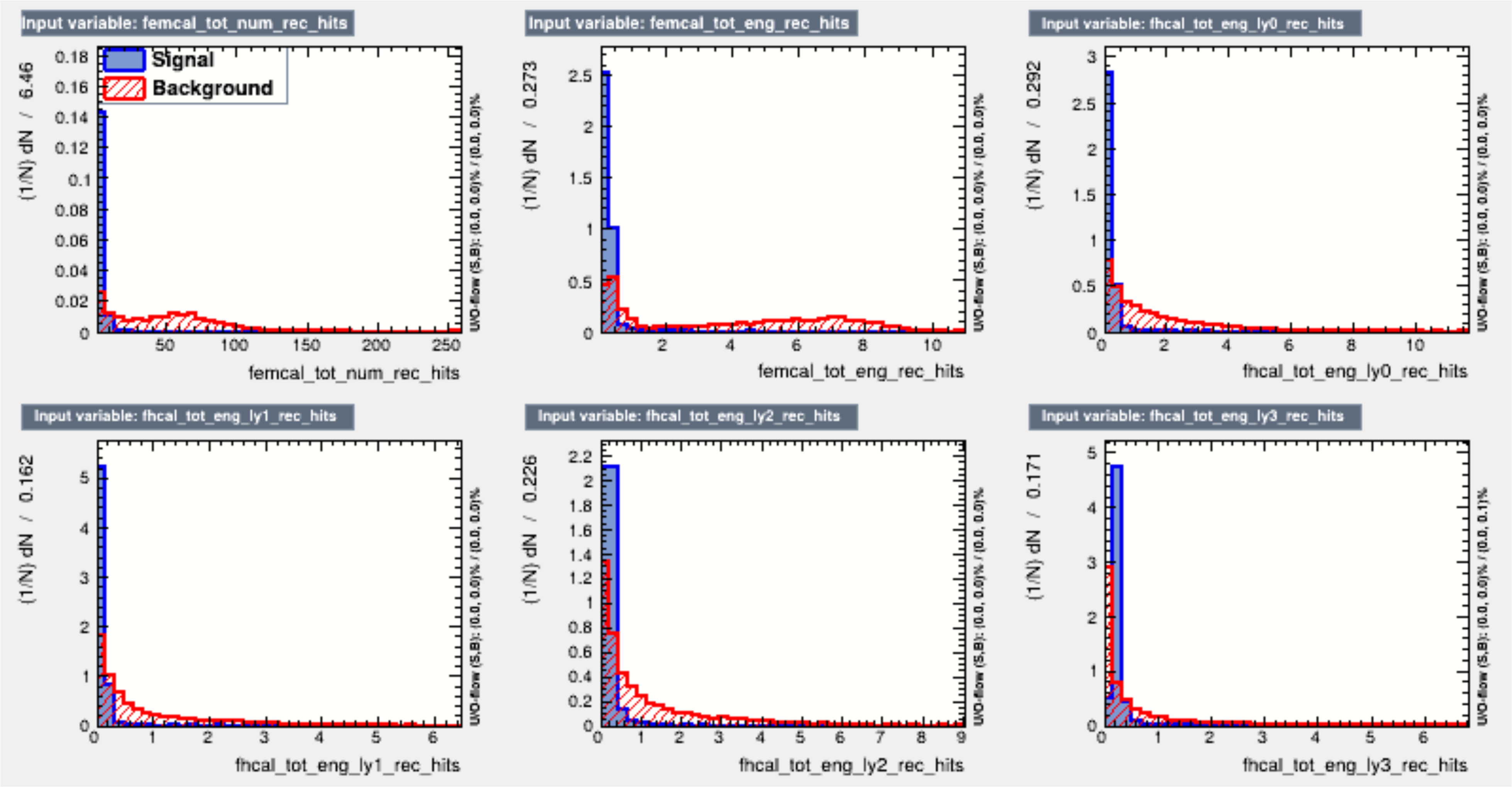
Input Distribution for 2 GeV μ^+ and π^+



Input Distribution for 2 GeV μ^+ and π^+



Input Distribution for 10 GeV μ^+ and π^+



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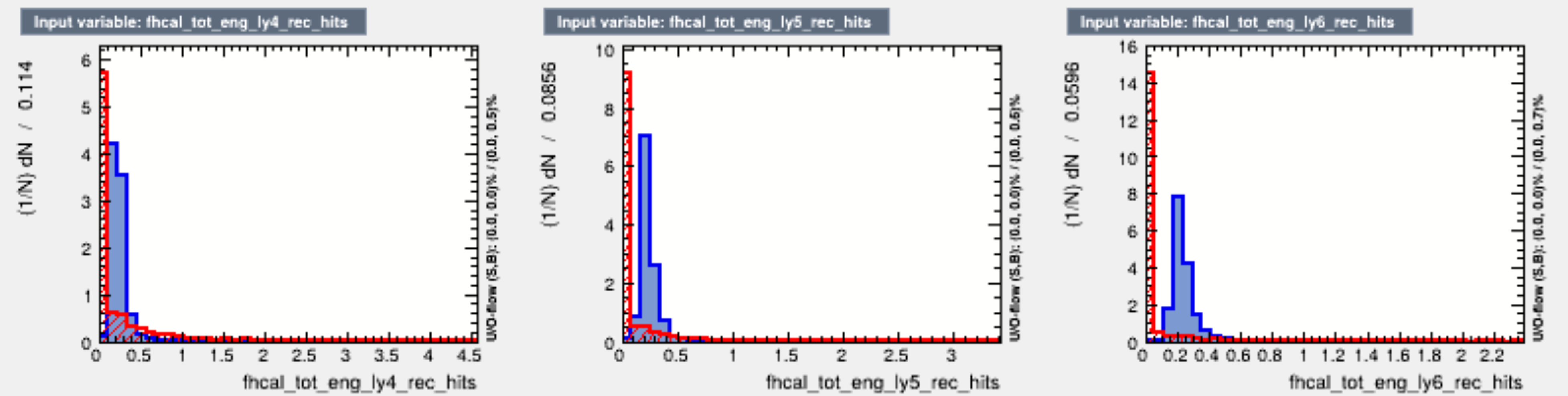
Input Distribution for 10 GeV μ^+ and π^+

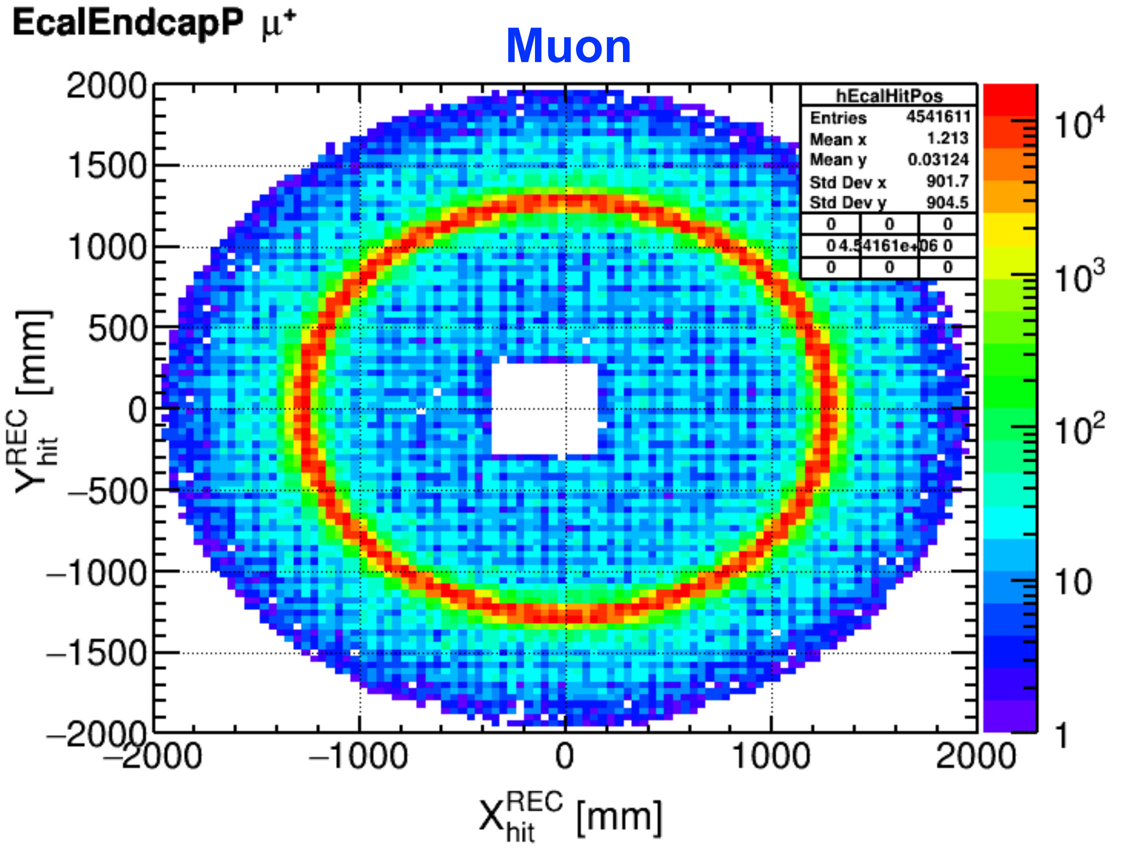


For Forward EMCAL

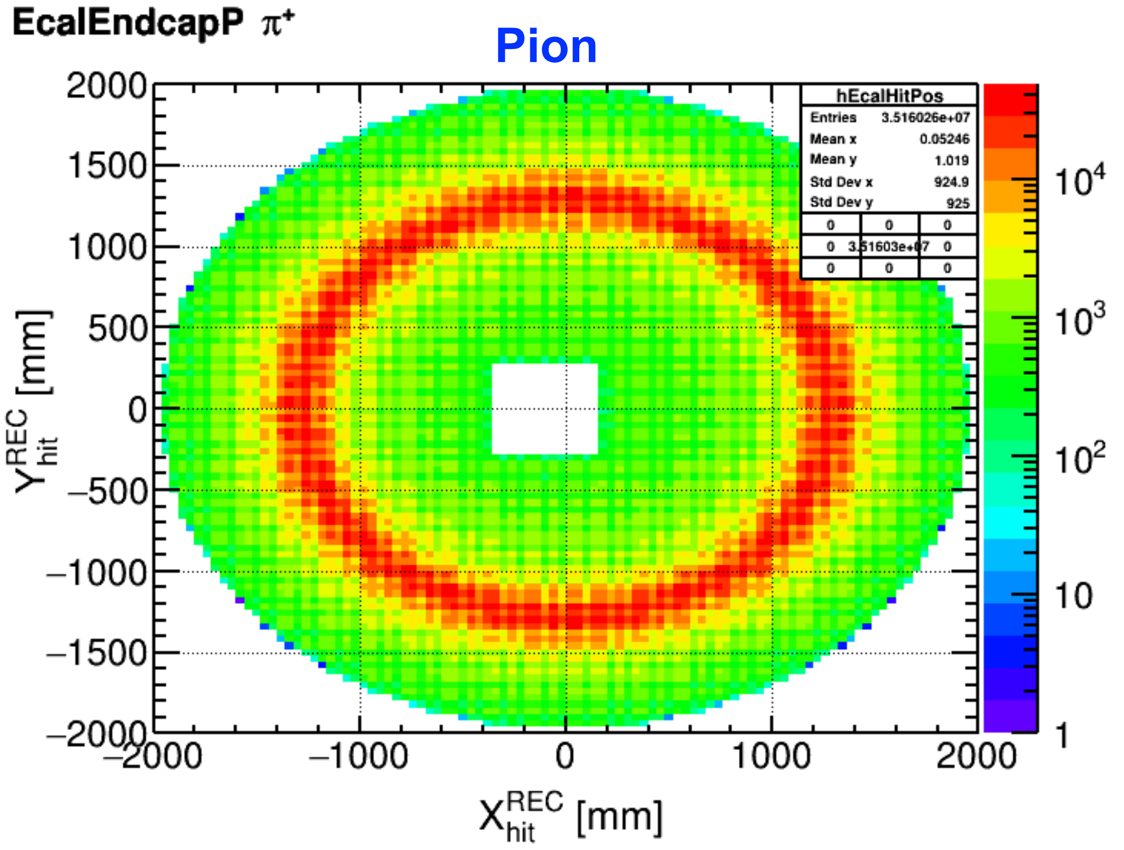
p = 5 GeV and η = 1.74

Position of Reconstructed Hits

Muon

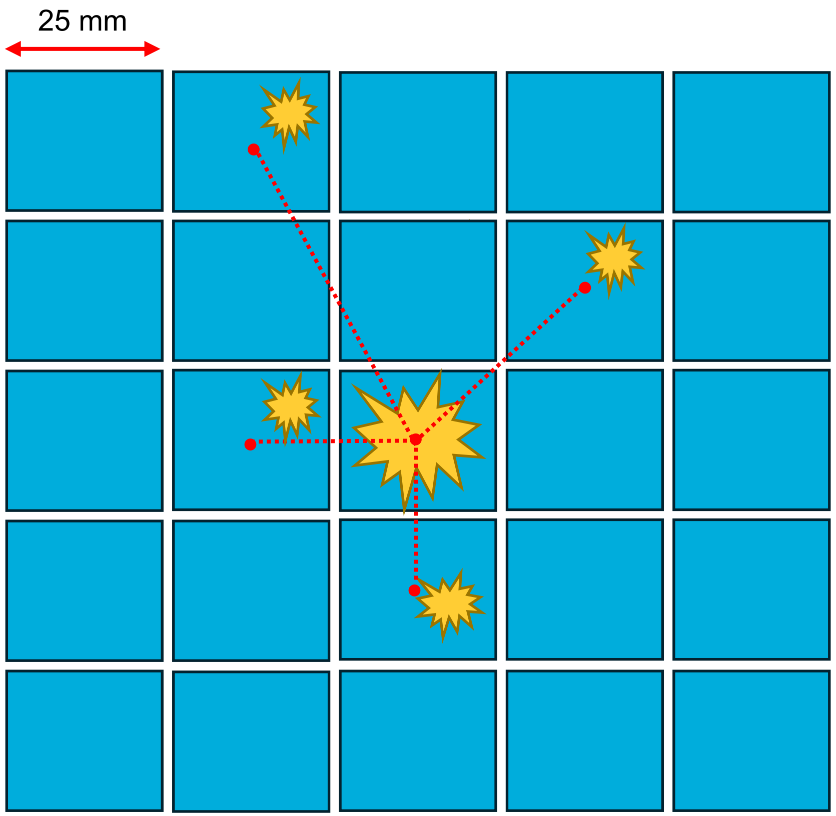


Pion



Based on muon sample (left), MIP events shows **localized hits in EMCAL**

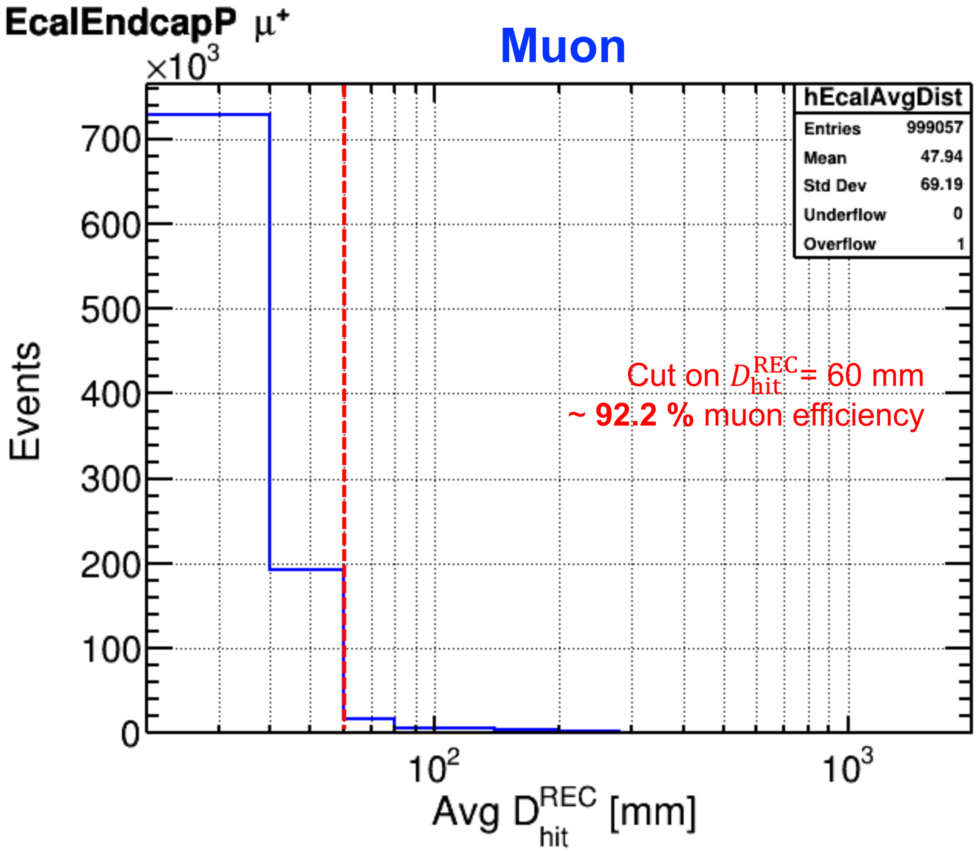
Avg Distance BTW Reconstructed Hits

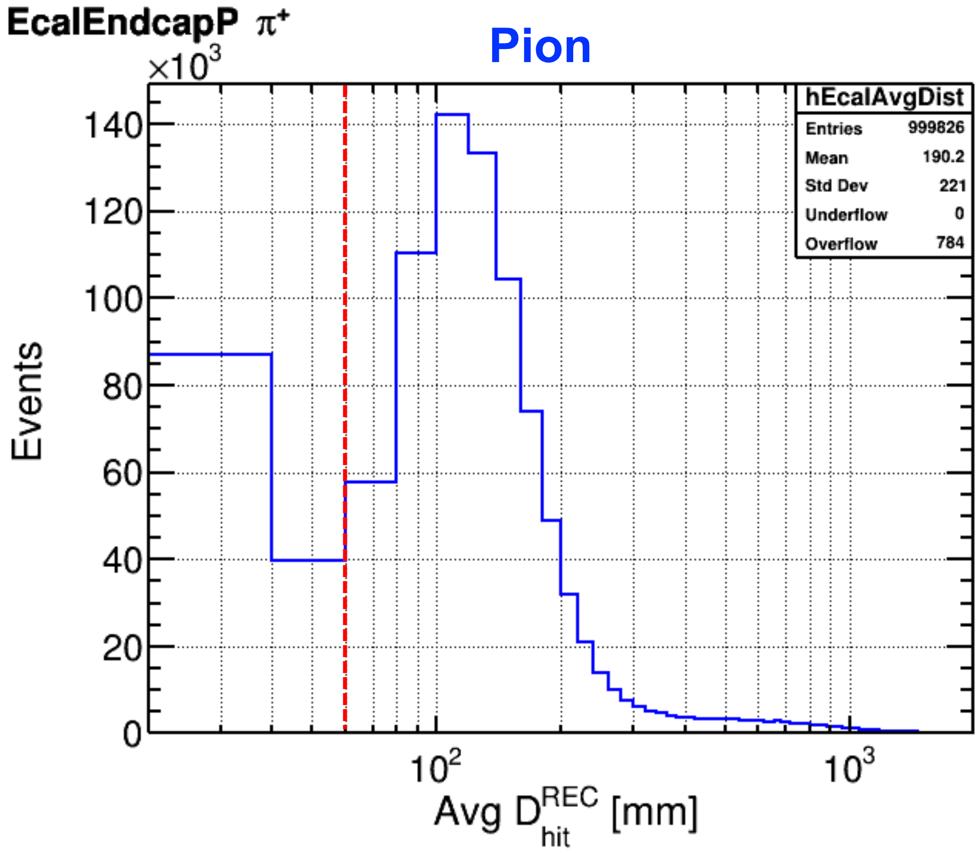


- Pick one hit with largest reconstructed energy
- Calculate distance to every other hit from the hit with the largest reconstructed energy
- Sum all calculated distances and divide by number of pairs
  - Small average distance – narrow distribution (MIP)
  - Large average distance – wide distribution (showering)

p = 5 GeV and η = 1.74

Avg Distance BTW Reconstructed Hits



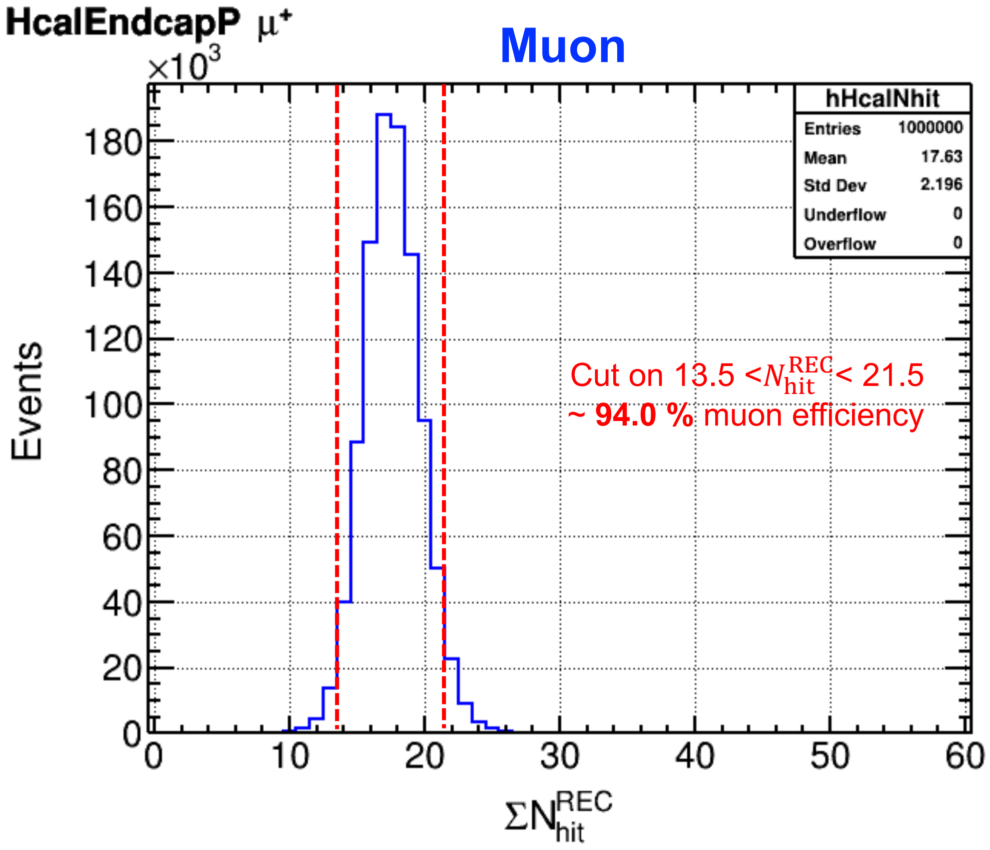


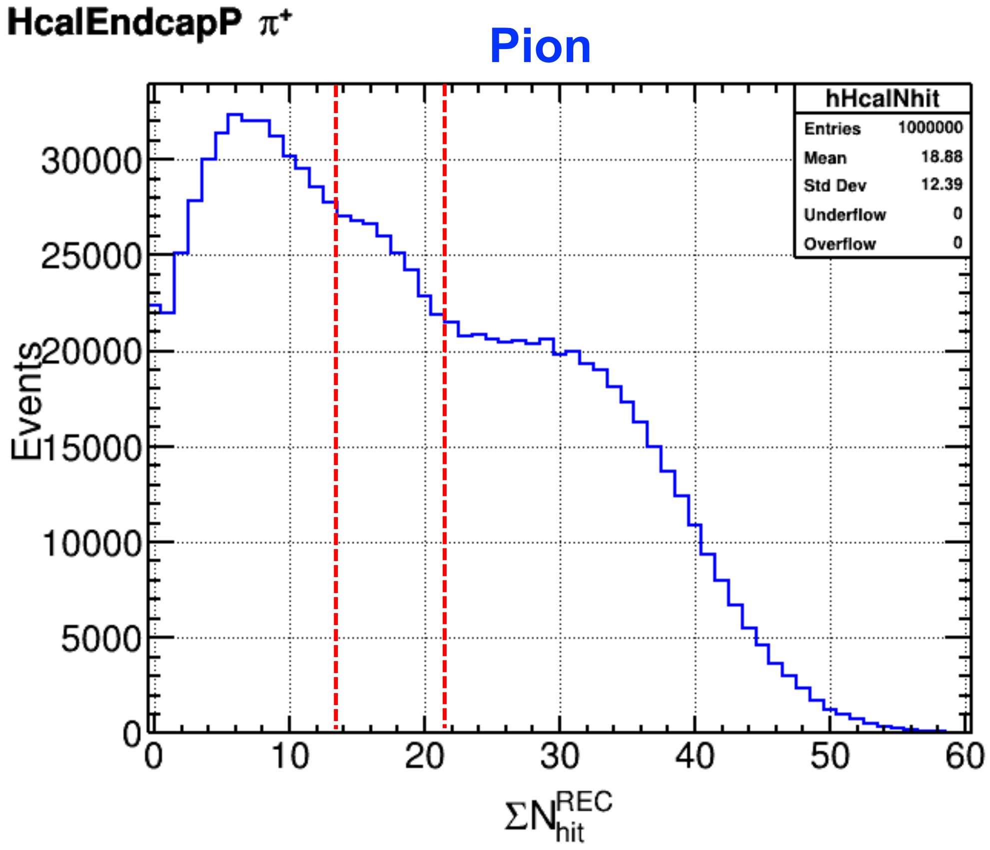
Based on muon sample (left),
MIP events have **average distance between hits up to 60 mm in EMCAL** (ref. tower size 25 mm)

For Forward HCAL

p = 5 GeV and η = 1.74

Number of Reconstructed Hits



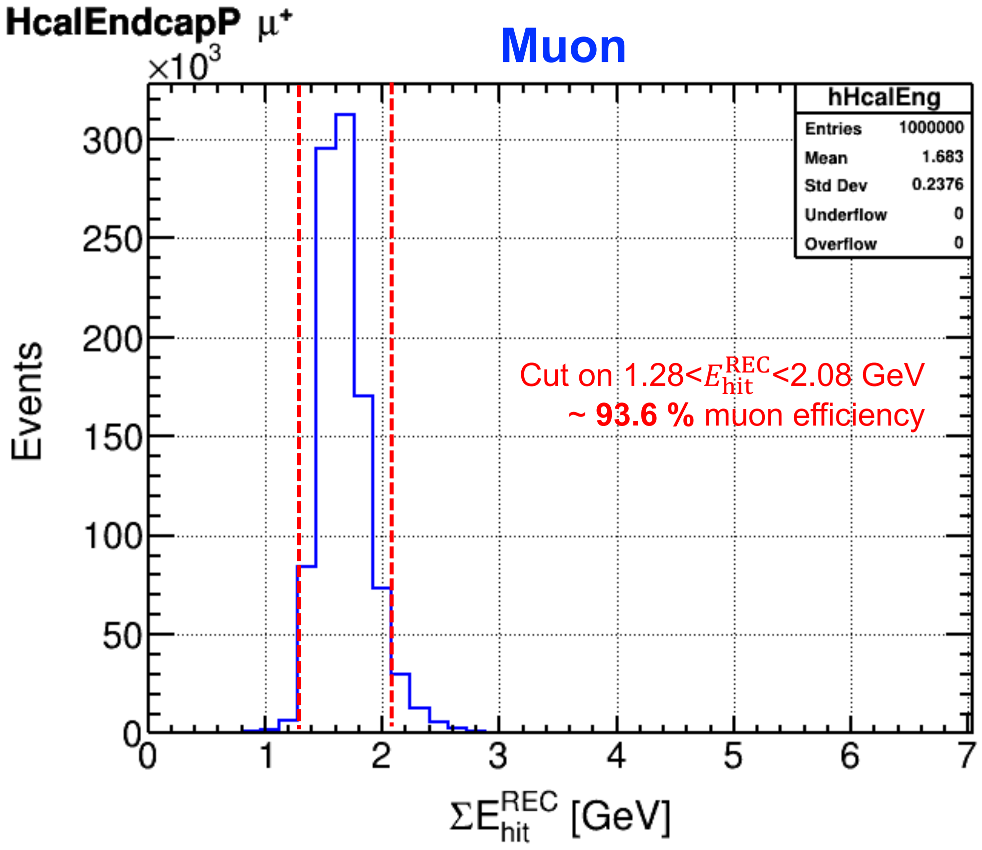


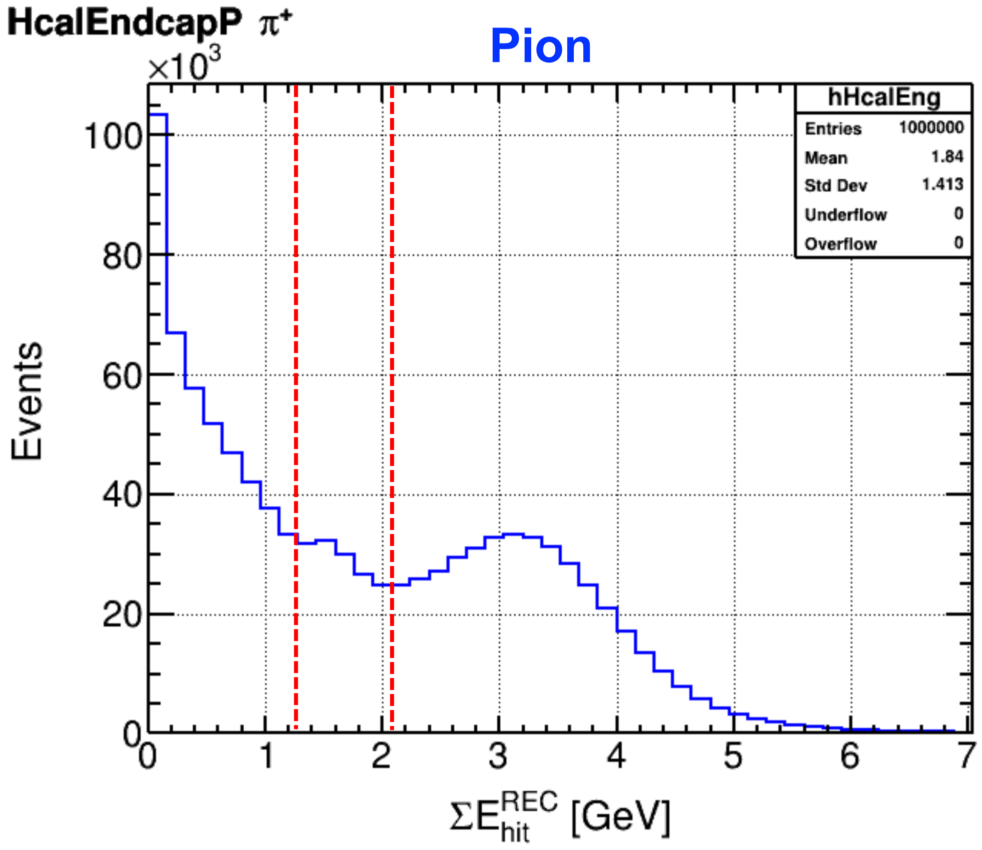
Based on muon sample (left), MIP events have **14 – 21 hits in HCAL**

Note y-axis scale difference between muon and pion samples

p = 5 GeV and η = 1.74

Sum of Reconstructed Energy



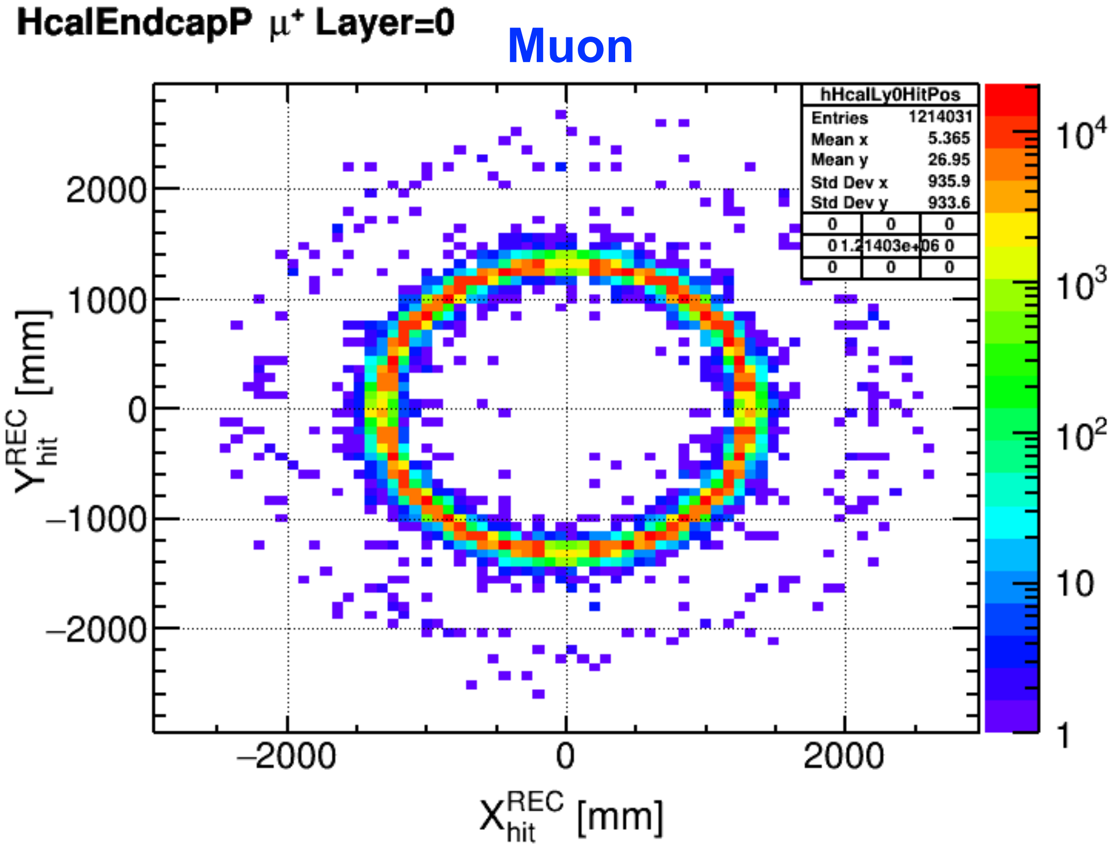


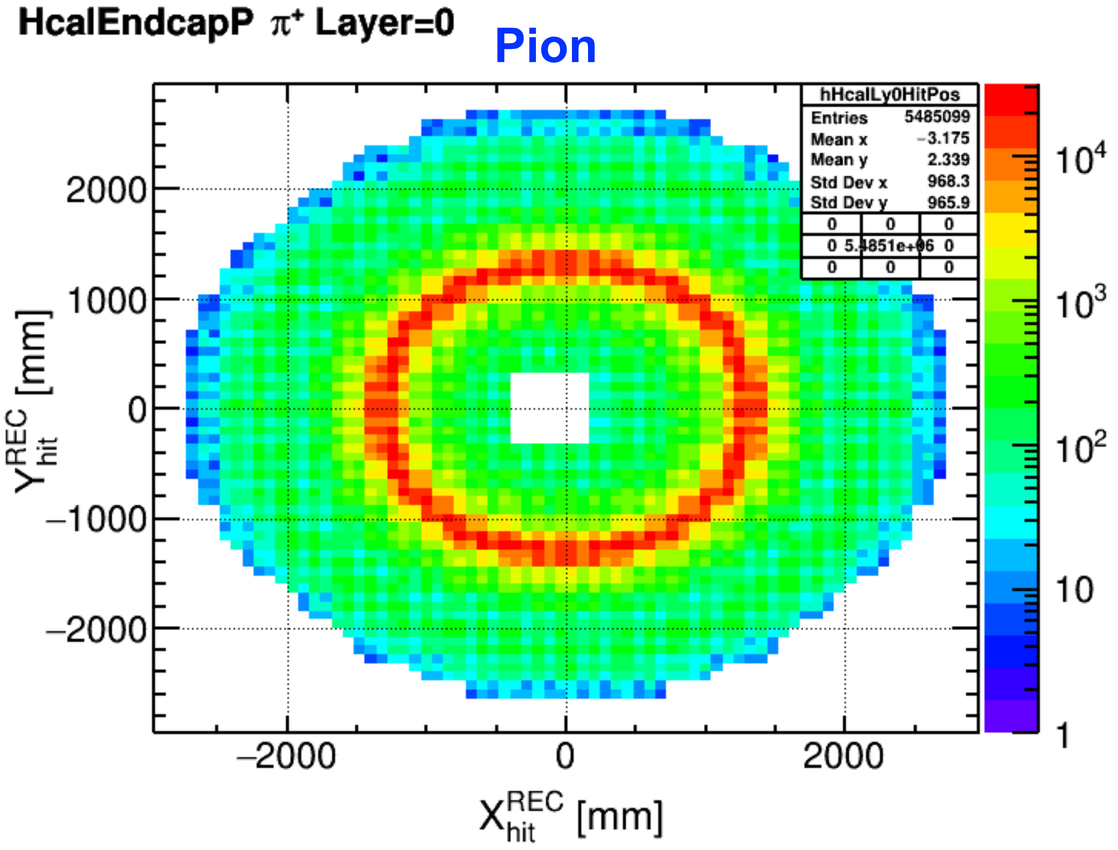
Based on muon sample (left), MIP events deposit its **energy 1.28 – 2.08 GeV in HCAL**

Note y-axis scale difference between muon and pion samples

p = 5 GeV and η = 1.74

Position of Reconstructed Hits – Layer 0

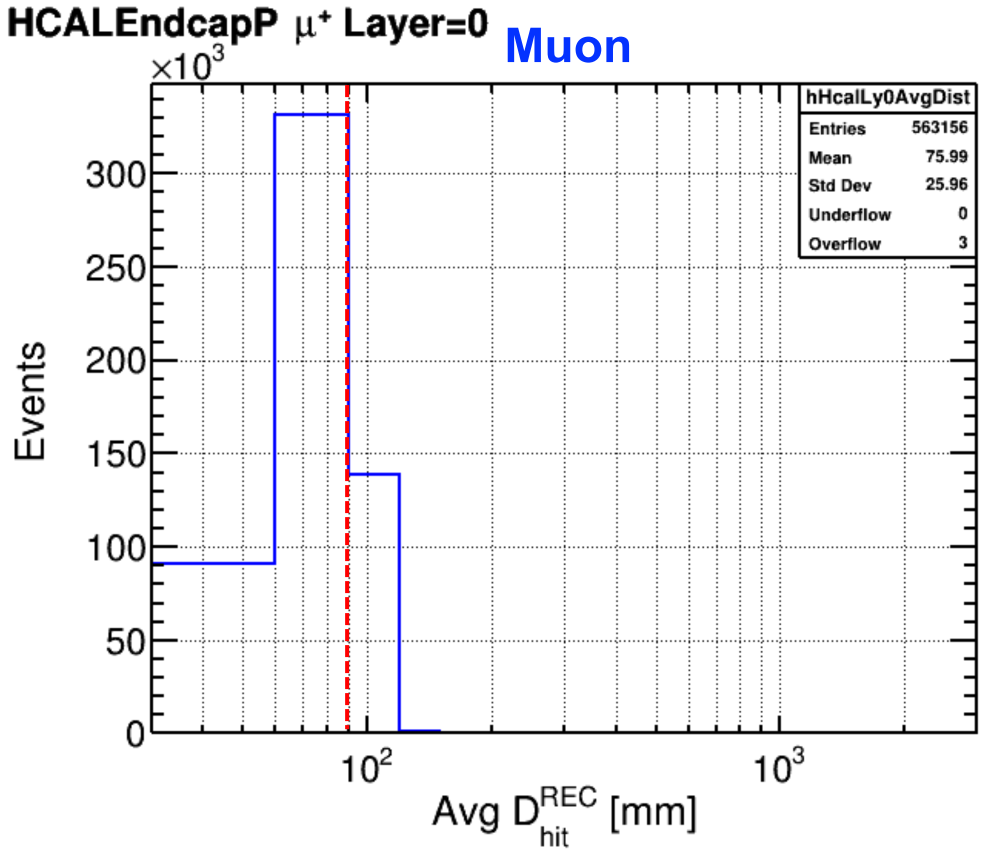


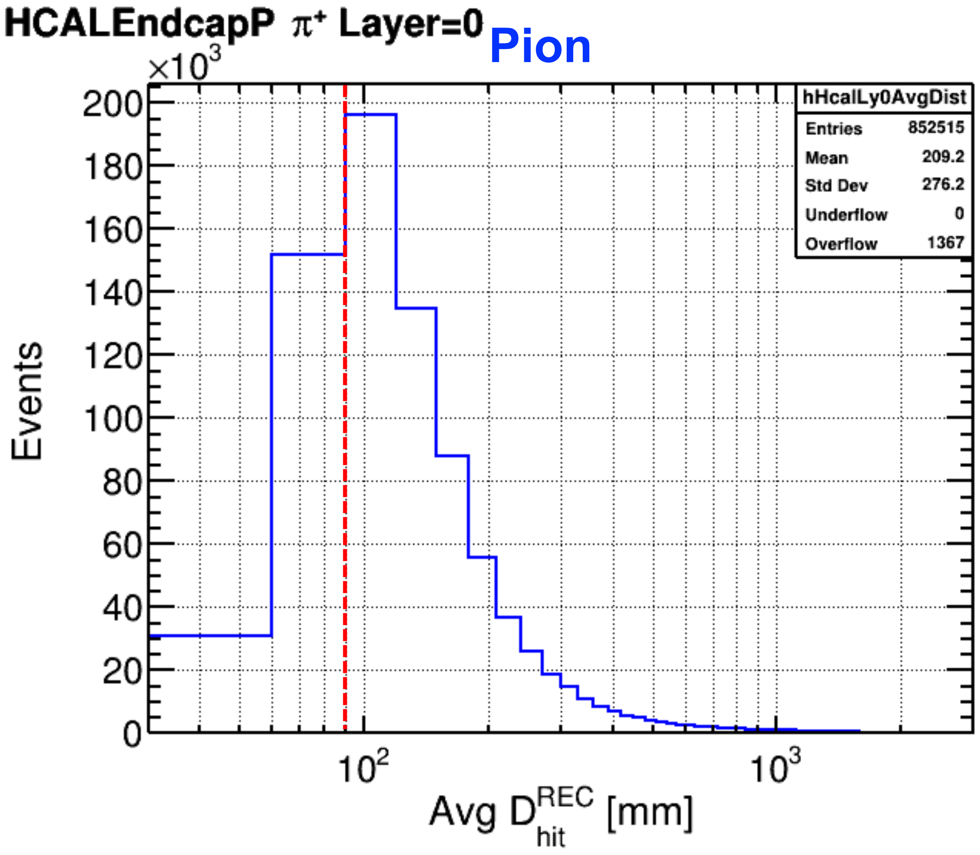


Based on muon sample (left), MIP events shows **localized hits in HCAL**

p = 5 GeV and η = 1.74

Avg Distance BTW Reconstructed Hits





Based on muon sample (left),

MIP events have **average distance between hits up to 90 mm in EMCAL** (ref. tower size 25 mm)