Muon Detection Study in the forward region at ePIC (for 2nd Detector)

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Goal, Approach, and Pythia Sample

- **Worth having Muon ID in the forward region?**
  - Look at **muon kinematics in ep** using Pythia8 (big thanks to Brian)
  - Particles we interested in: Muon and Pion
    - Pick single momentum and pseudo-rapidity
  - Evaluate **pion/muon rejection factor** at current ePIC detector
    - Use single particle simulation
    - Check response from forward EMCAL and HCAL: Energy deposit and # of hits

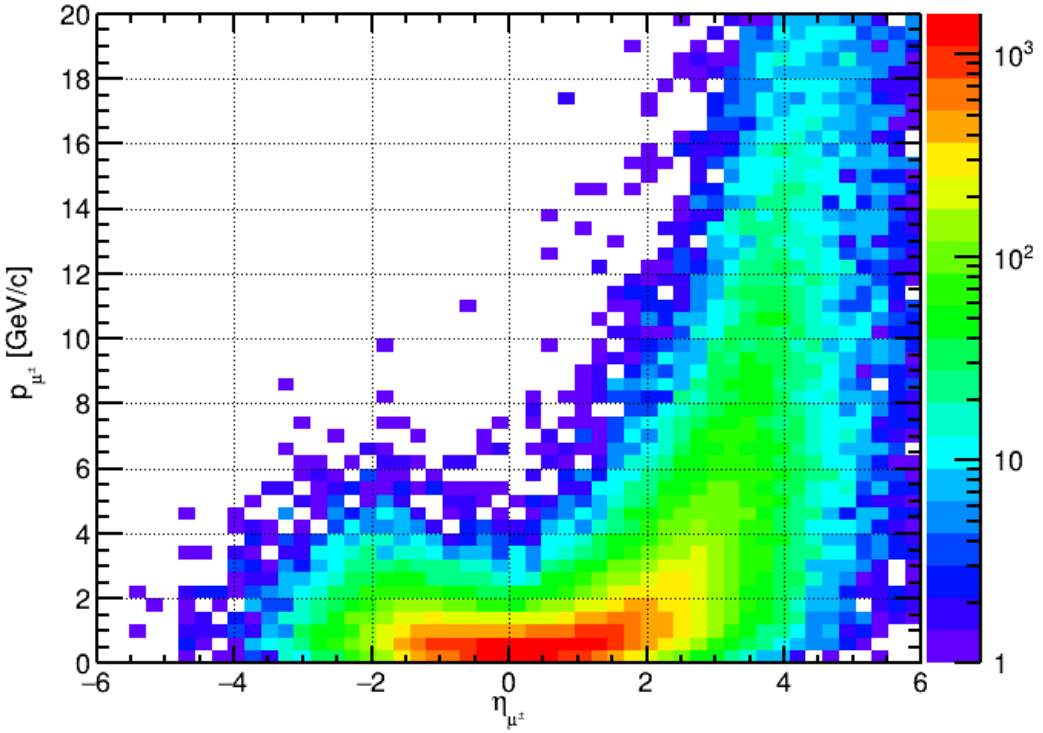
- **Pythia8 NC DIS ep 5×41, 10×100, and 18×275 GeV^2**
  - **10M** events each beam configuration
  - Q^2_{min} **> 1 GeV^2**
  - Look at **kinematics of muons and pions**

Pythia8 Events

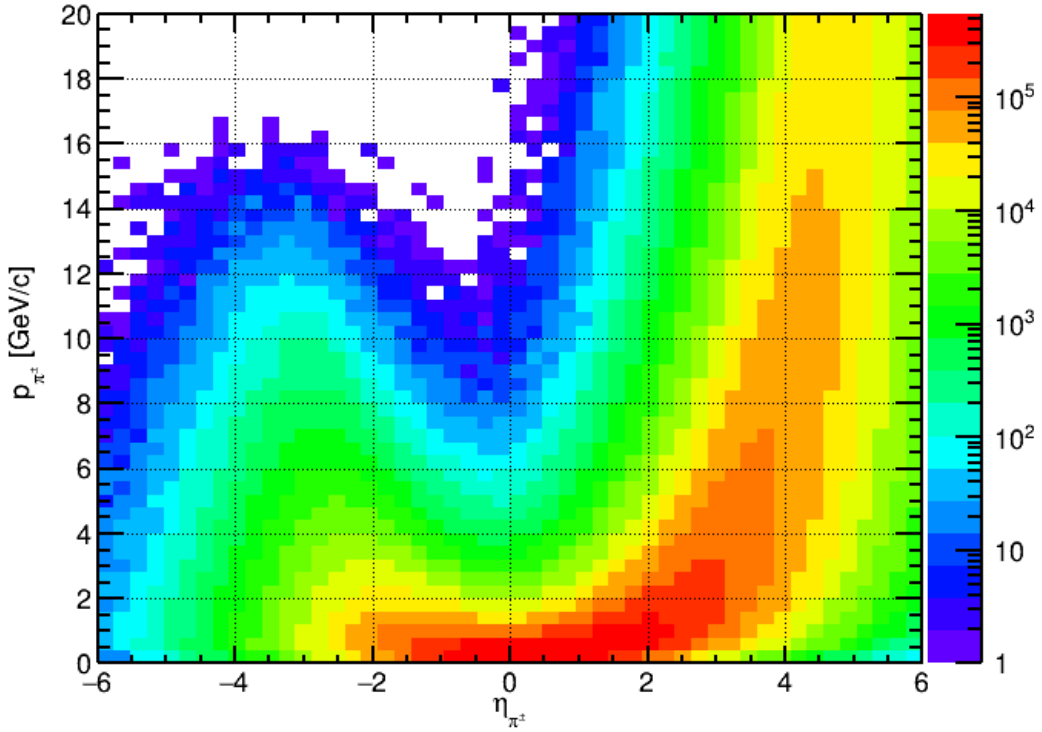
Pythia8 sample

Muon and Pion Kinematics – 18×275 GeV²

$\mu^{\pm}$



$\pi^{\pm}$

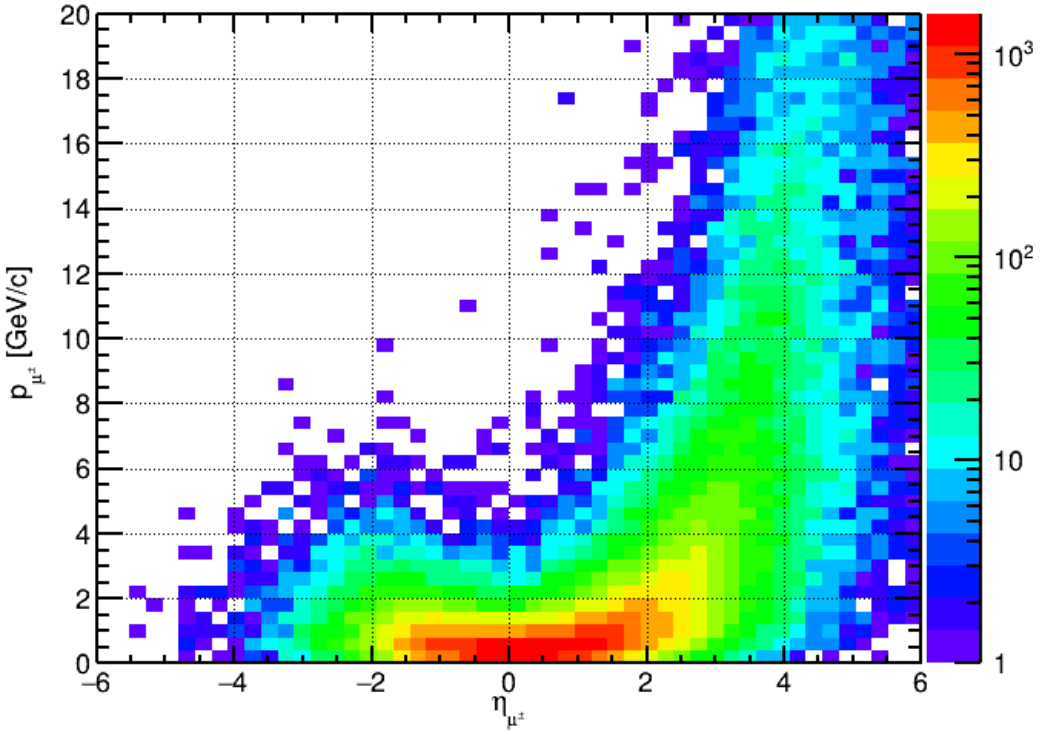


η = 1.74	1 GeV/c	2 GeV/c	5 GeV/c	10 GeV/c
Muons	736	271	22	2
Pions	368039	109691	7507	492
Ratio (Pions/Muons)	~ 500	~ 405	~ 342	~ 246

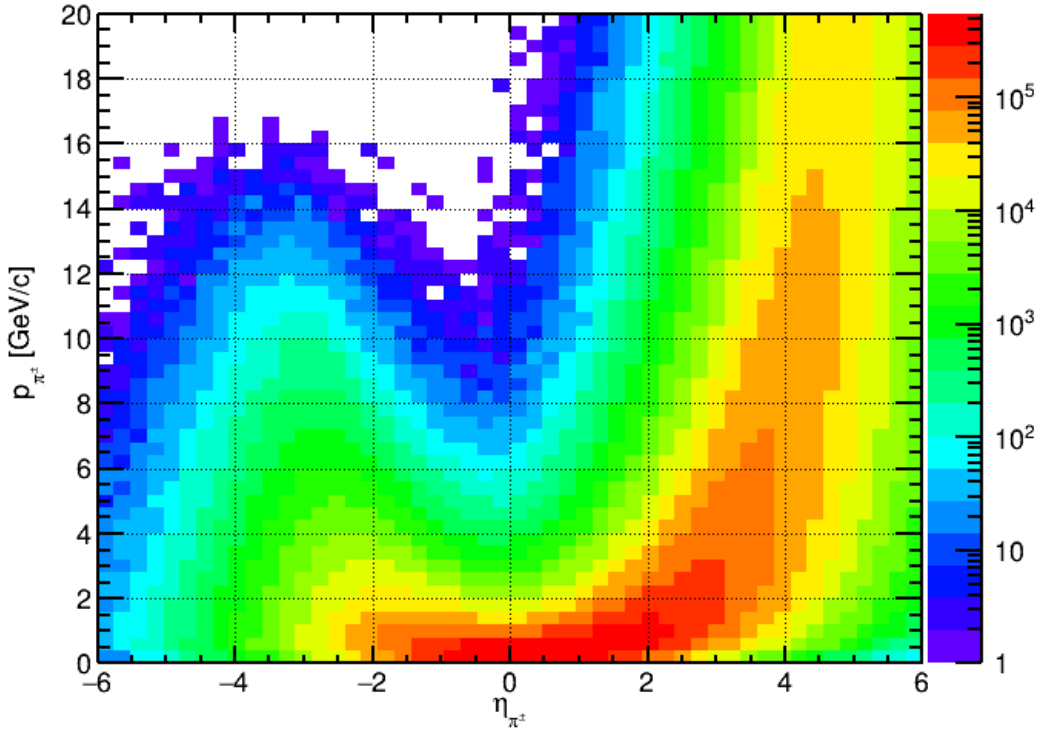
Pythia8 sample

Muon and Pion Kinematics – 18×275 GeV²

$\mu^{\pm}$



$\pi^{\pm}$



η = 3.13	1 GeV/c	2 GeV/c	5 GeV/c	10 GeV/c
Muons	76	110	93	34
Pions	80240	130908	97796	21590
Ratio (Pions/Muons)	~ 1056	~ 1190	~ 1052	~ 635

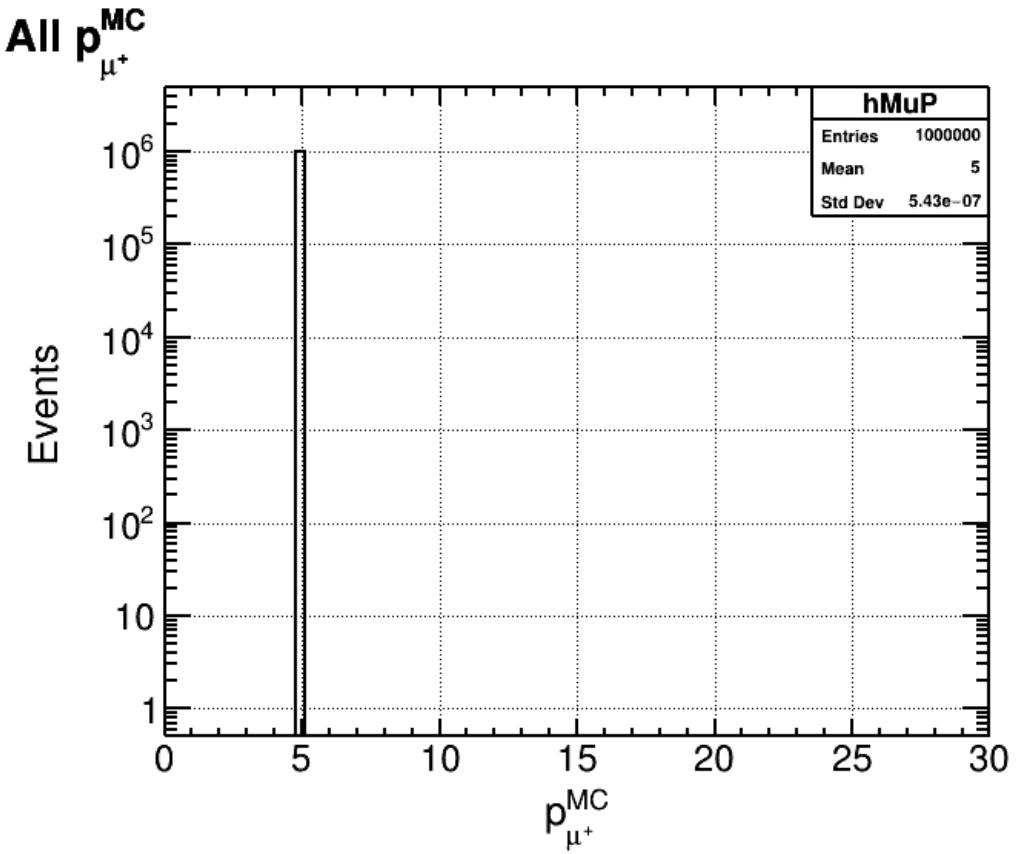
Simulation Sample

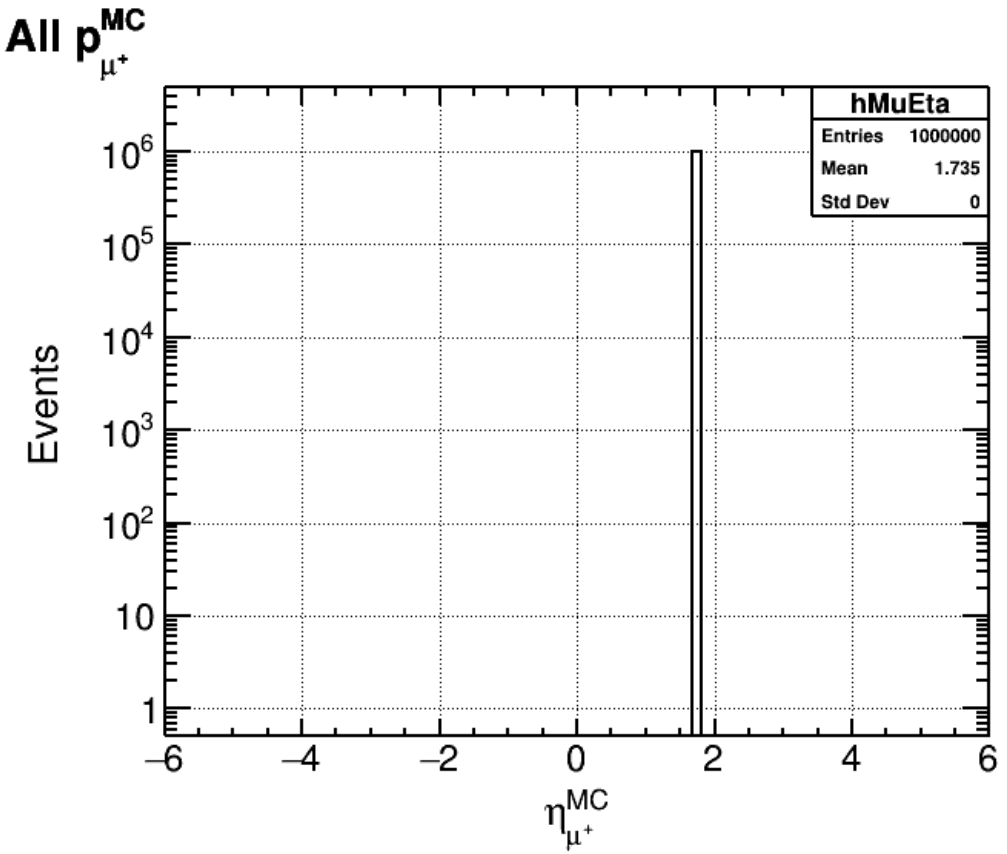
- Single particle simulation
  - Muon (μ^+) and Pion (π^+)
  - **p** = **1**, **2**, **5**, and **10** GeV/c
  - η = **1.74** (θ **= 20**°), and **3.13** (θ **= 5**°)
  - Detector responses from **Forward EMCAL** and **HCAL**
  - **Energy deposit** and **number of hits**
- Run **ePIC** simulation
  - Craterlake version
  - Forward ECAL – Tunsten power mixed with eposy + scintillating fibers, 5 cm × 5 cm × 17 cm blocks, 4 independent towers per block, 4 SiPM per tower, 50 μm pixel, and 23 X_0
  - Forward HCAL – Steel + Scintillator SiPM-on-tile, highly segmented longitudinally and 65 layers per tower (7 layers in reconstructed hit configuration)
- Muon sample used for efficiency and energy/nhit cut
- Pion sample used for contamination

ePIC Simulation – Muons

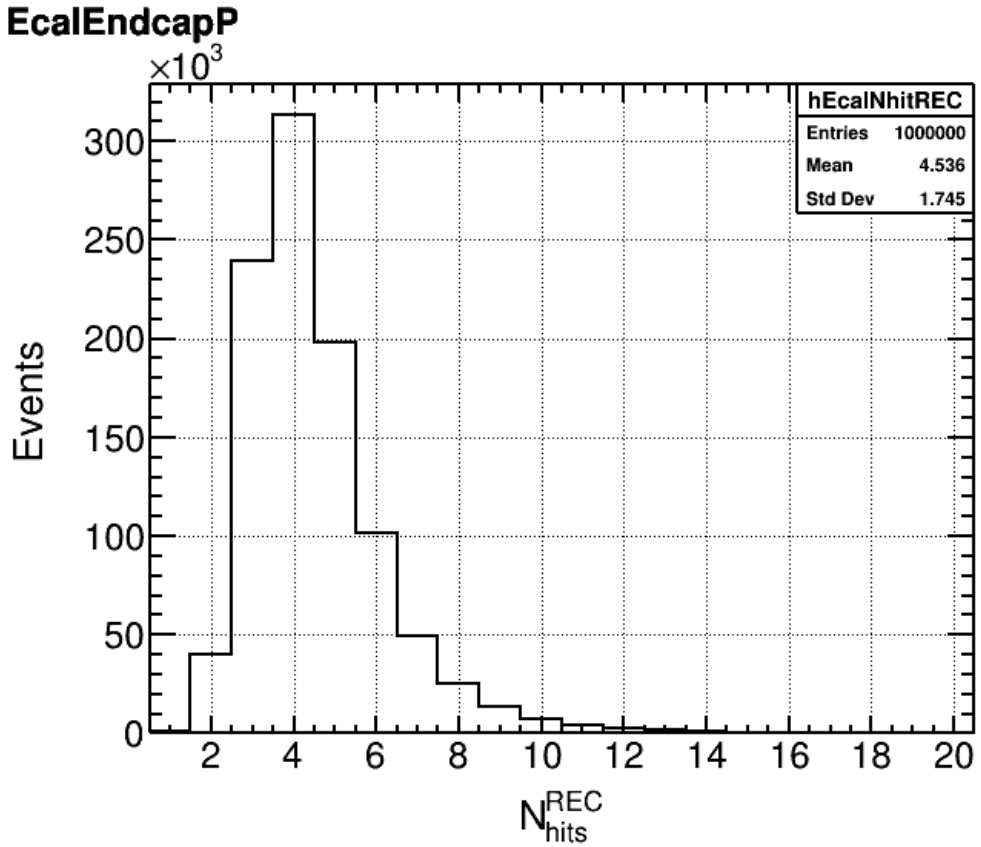
ex) 5 GeV at η = 1.74

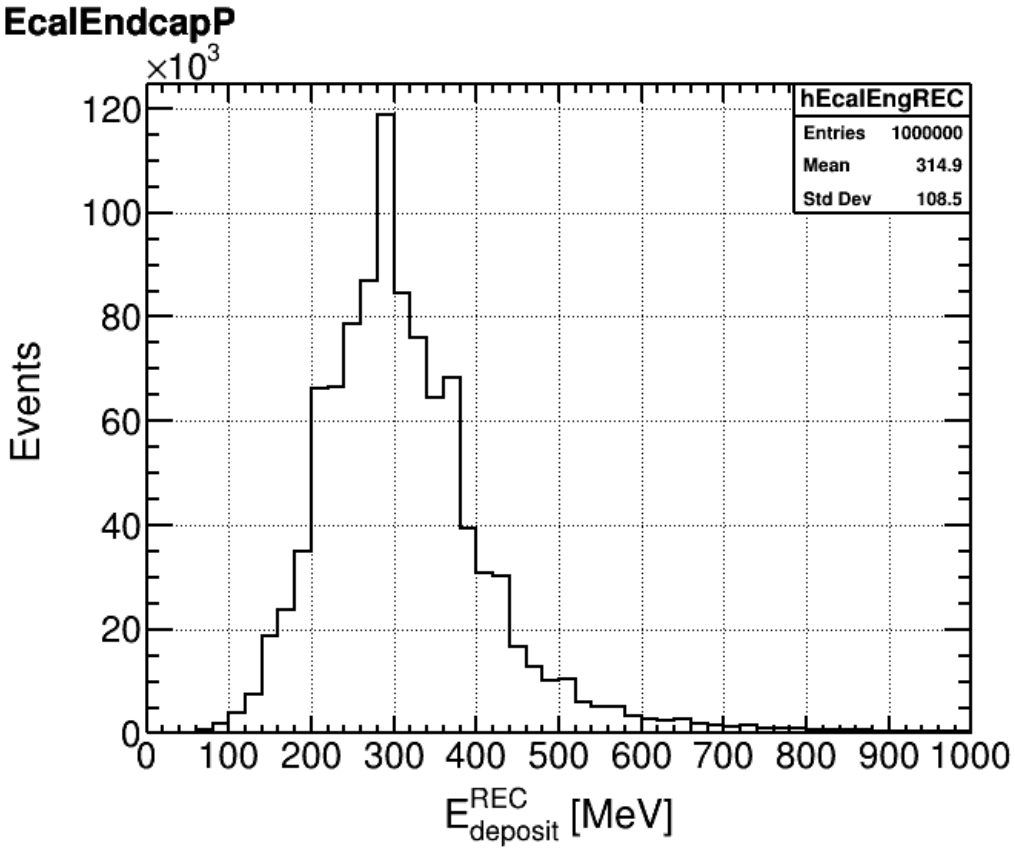
Muon Sample – Input Distribution





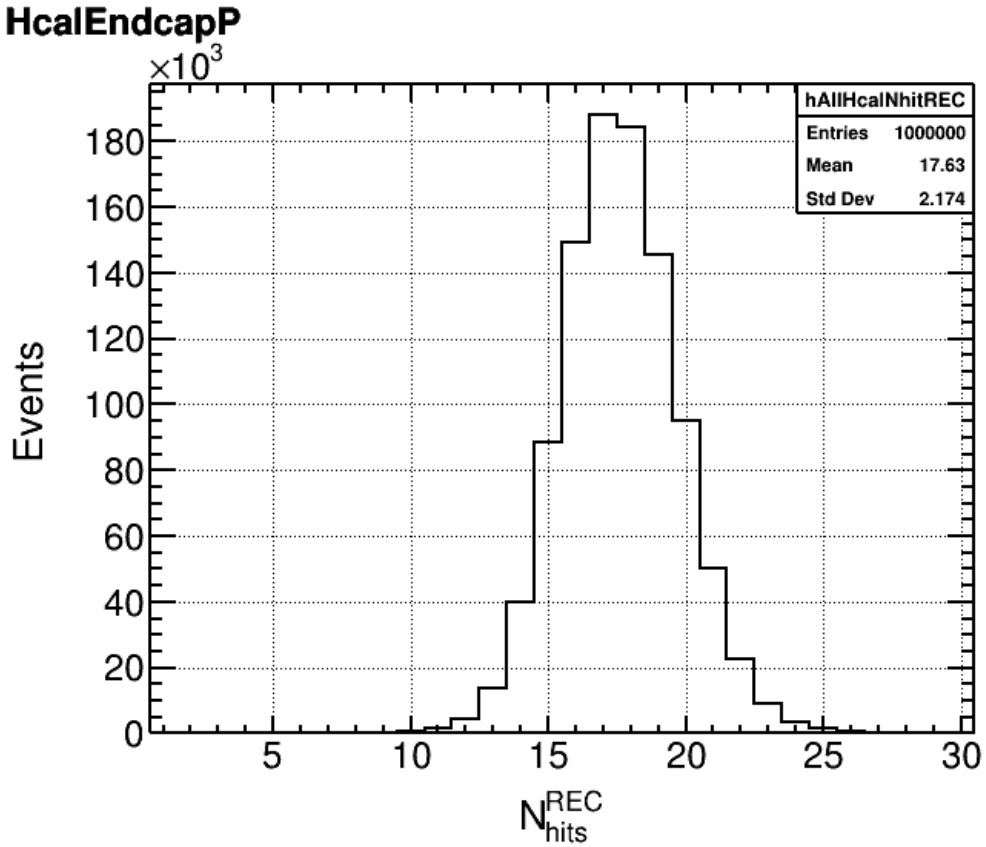
Muon Sample – Forward ECAL

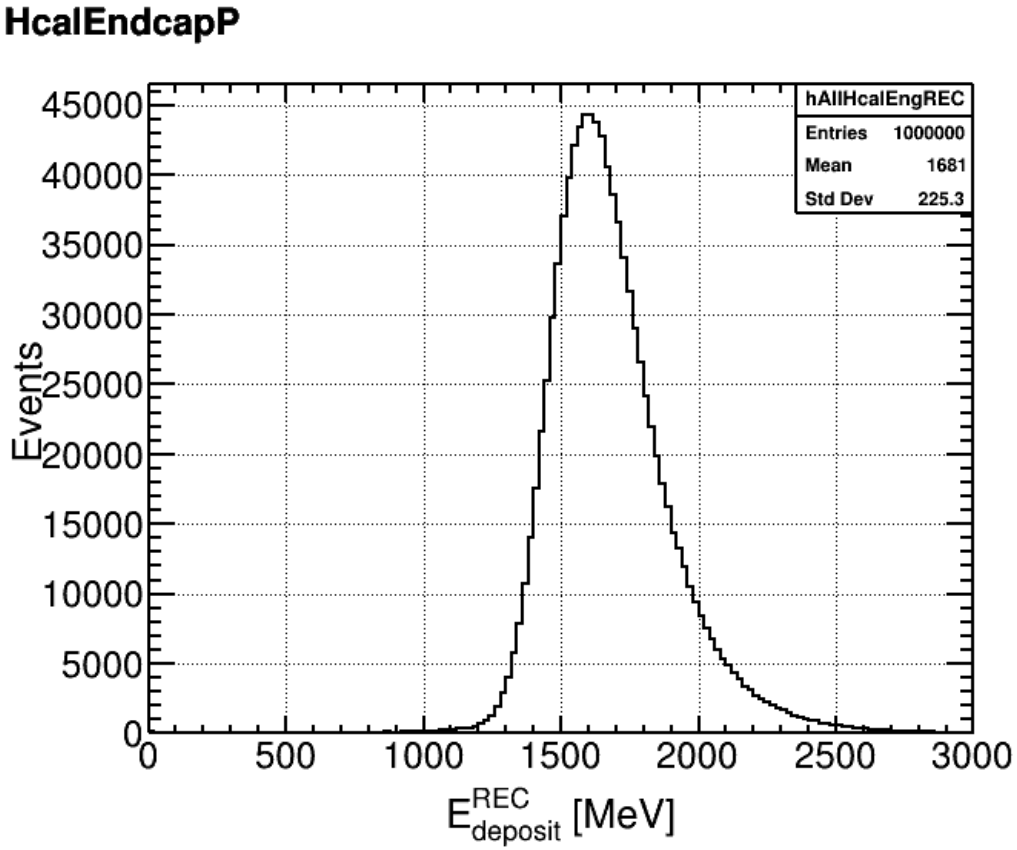




Total number of hits and total energy deposit in EMCAL

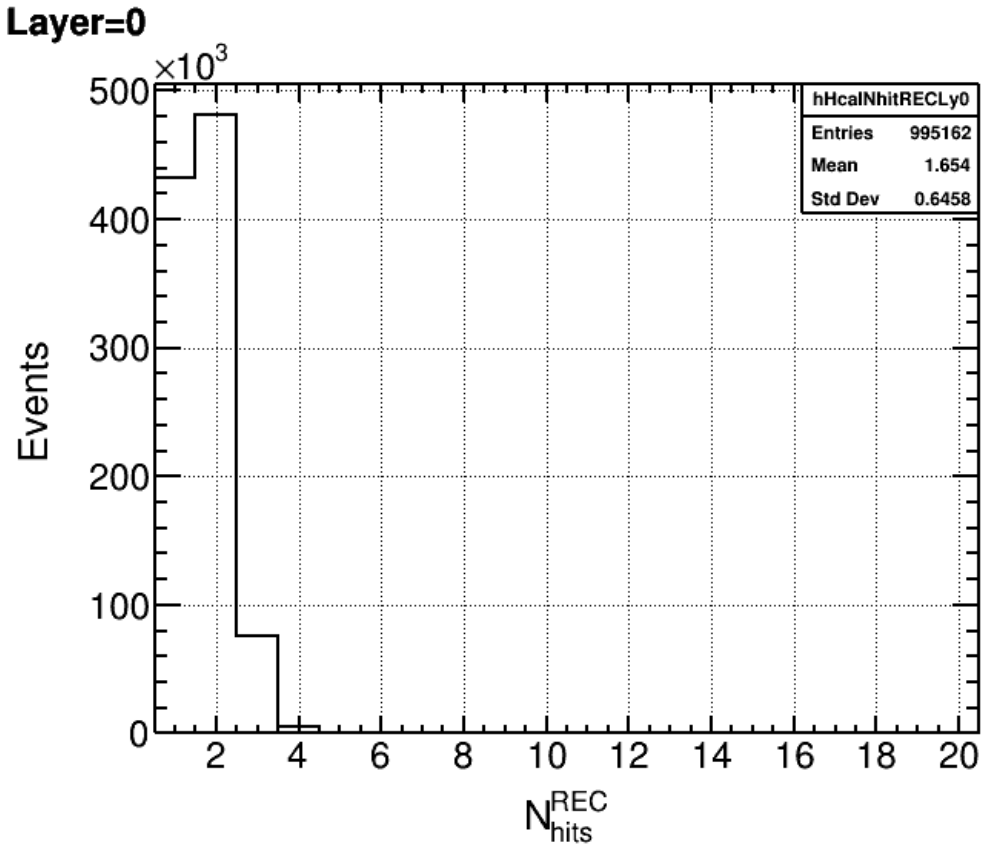
Muon Sample – Forward HCAL

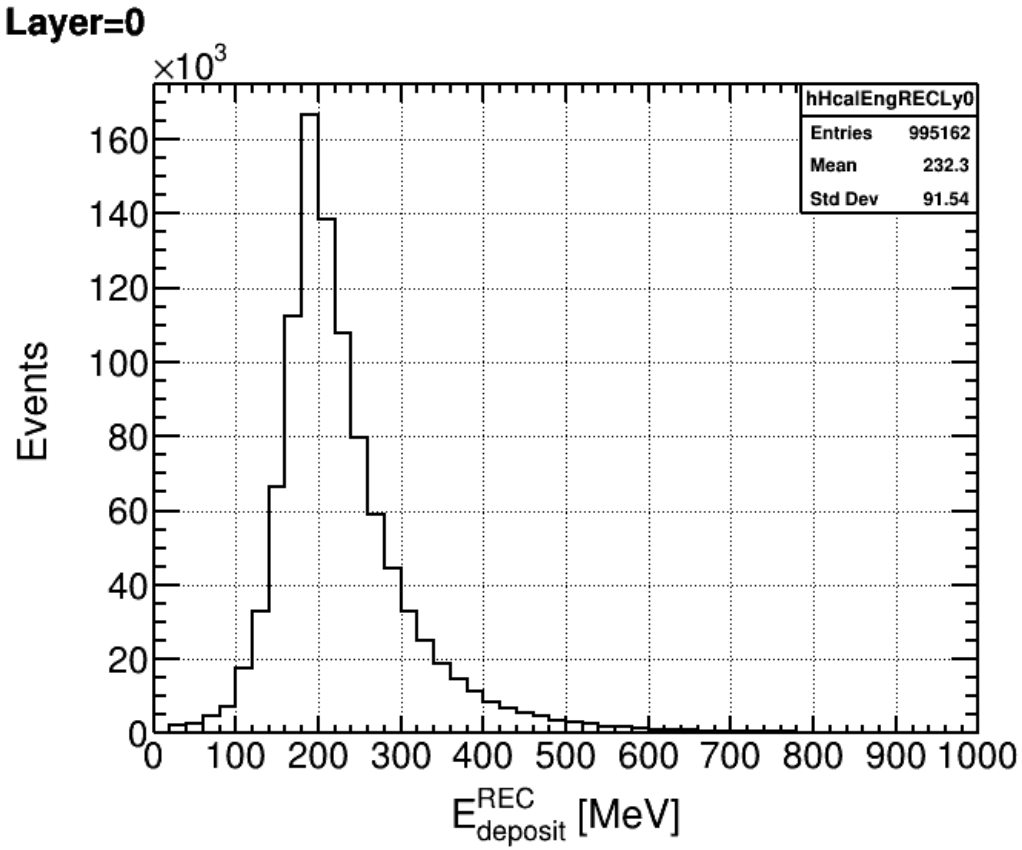




Total number of hits and total energy deposit in HCAL

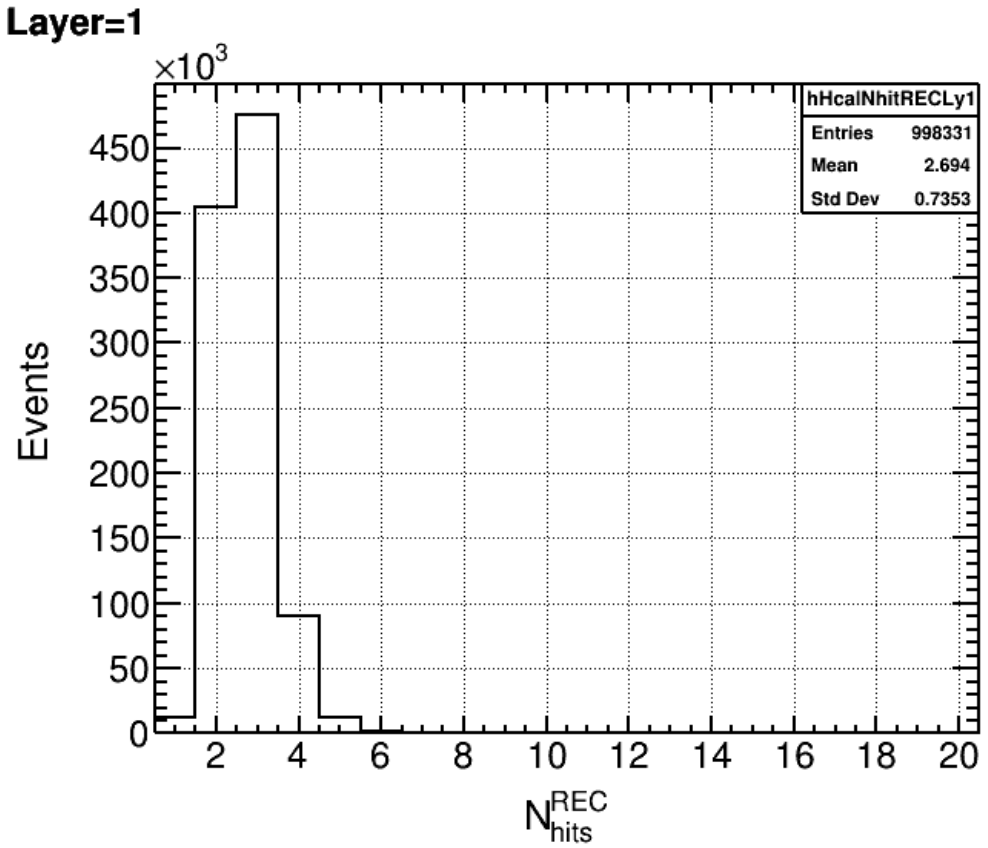
Muon Sample – Forward HCAL (Layer0)

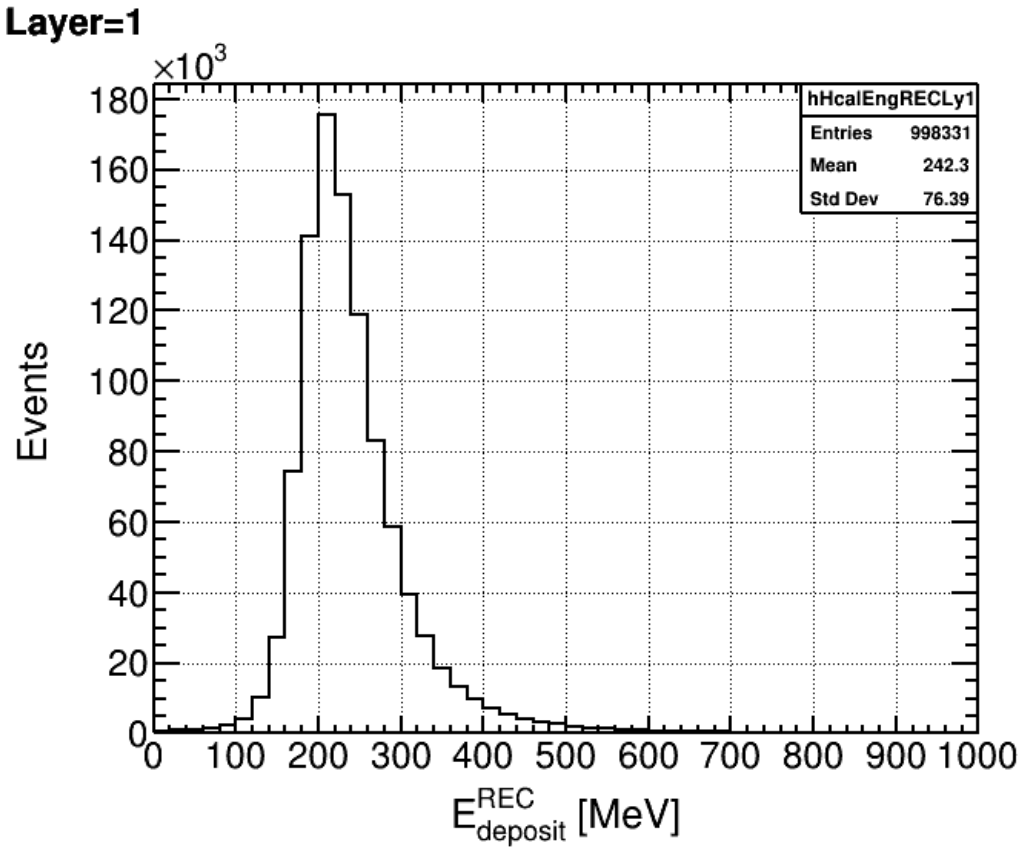




Number of hits and Energy deposit at each HCAL layer are consistent throughout entire HCAL

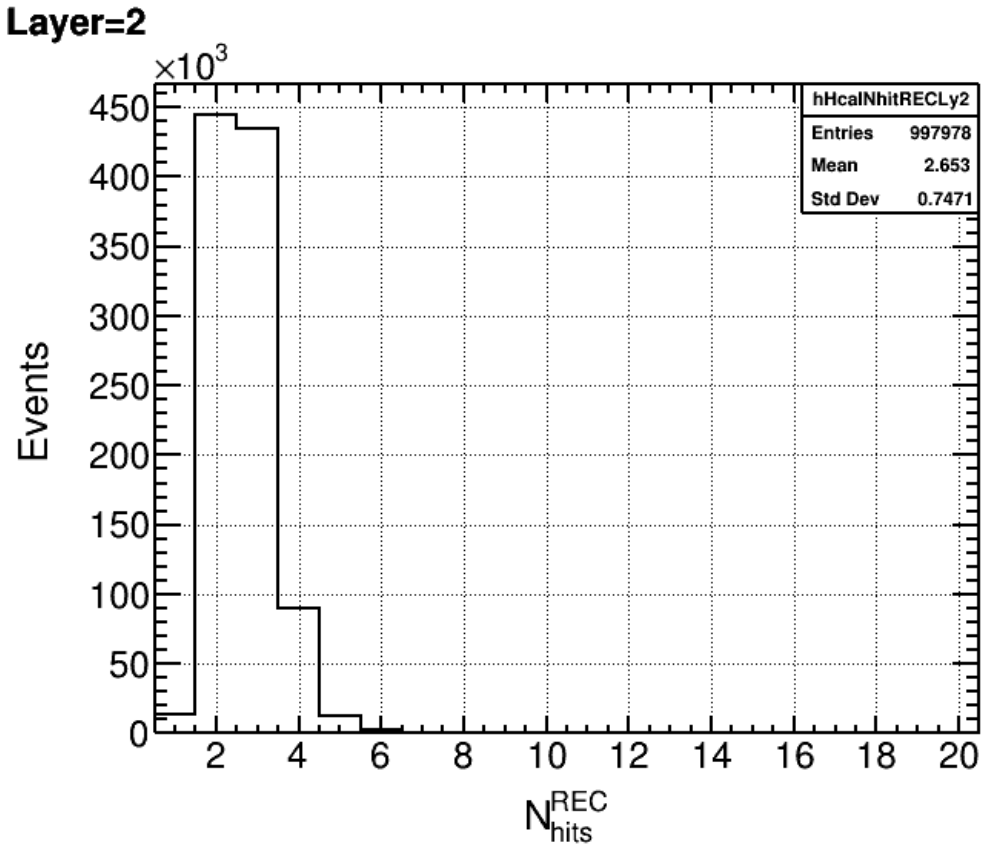
Muon Sample – Forward HCAL (Layer1)

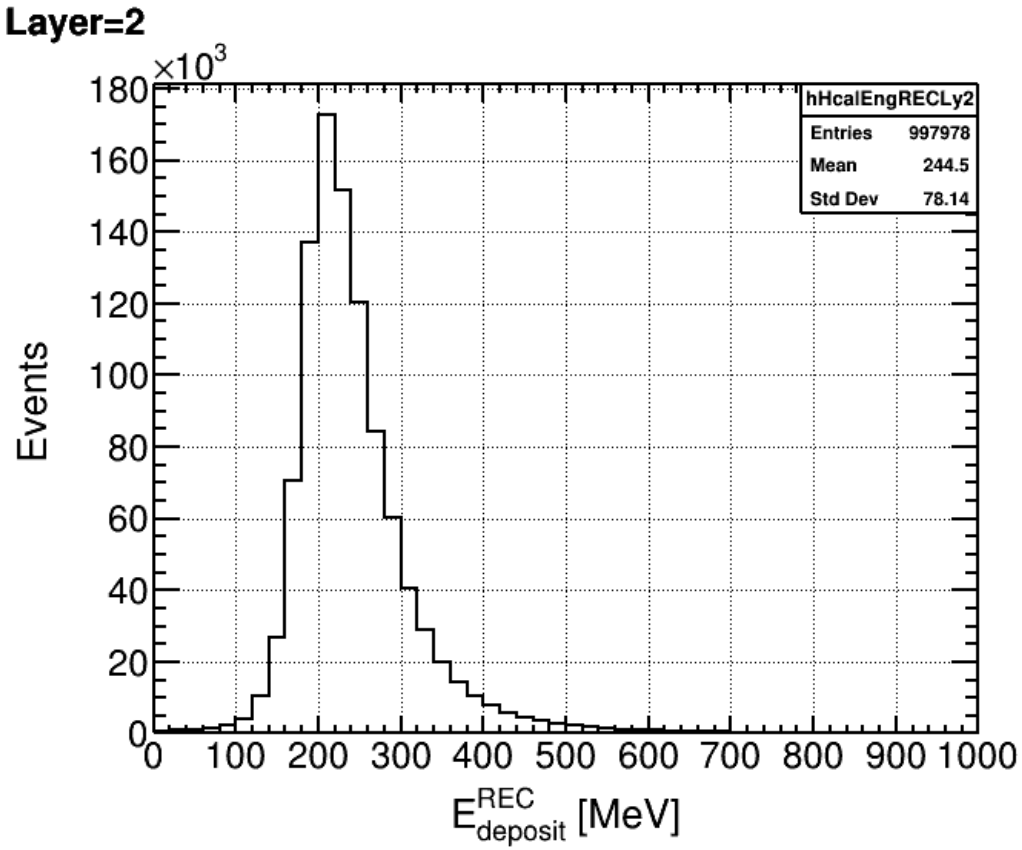




Number of hits and Energy deposit at each HCAL layer are consistent throughout entire HCAL

Muon Sample – Forward HCAL (Layer2)





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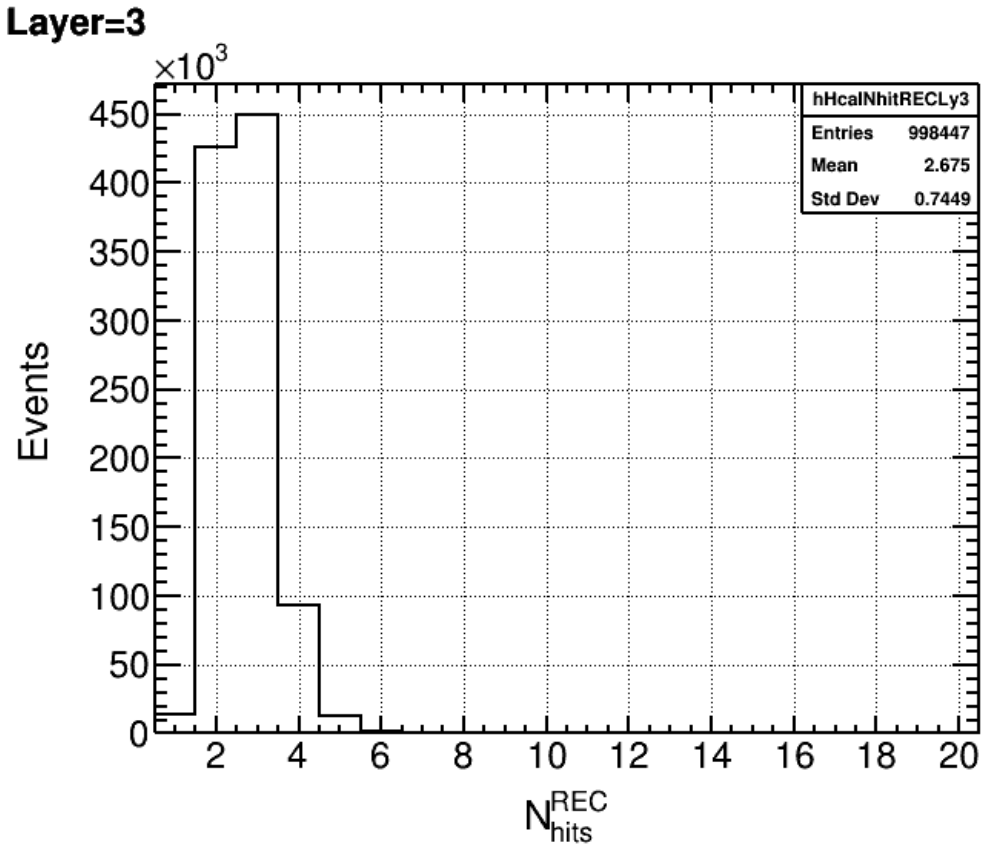
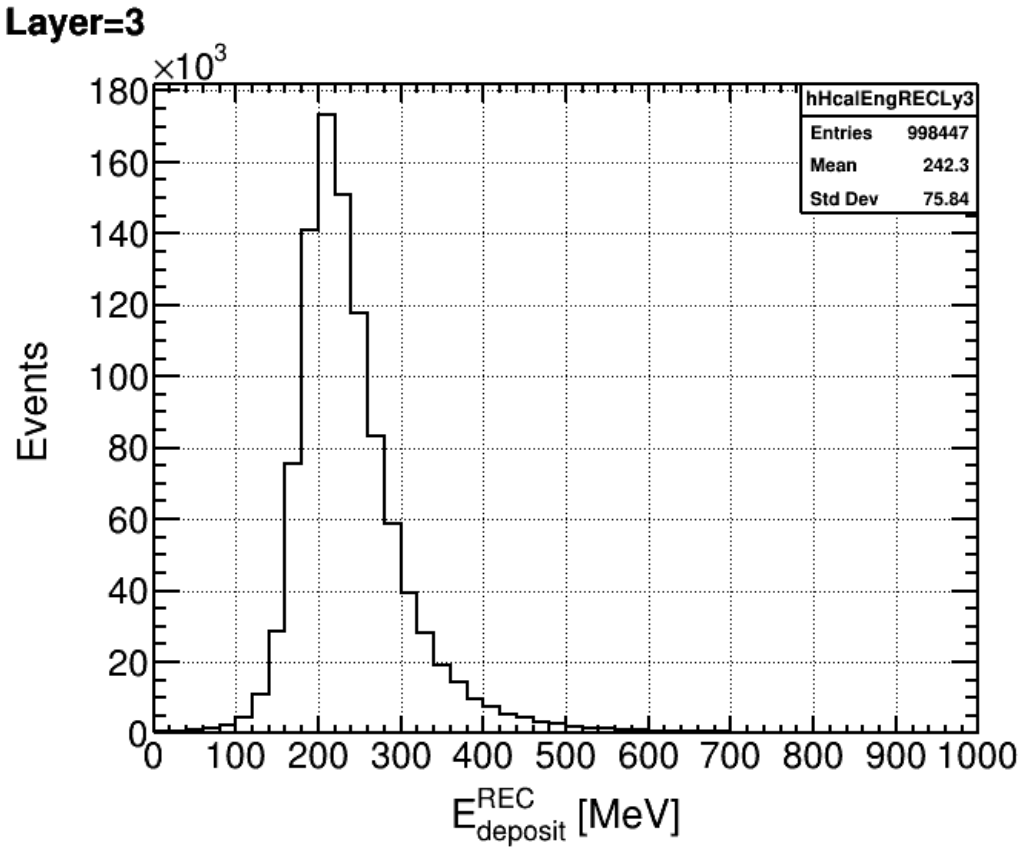
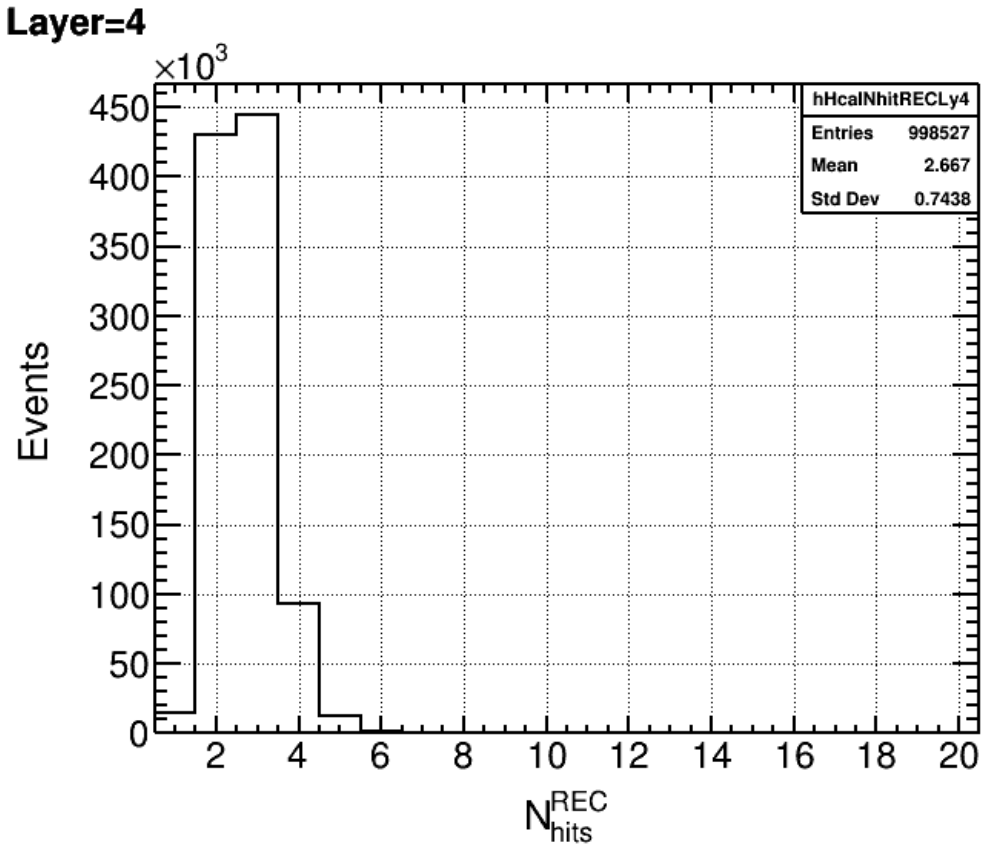
Muon Sample – Forward HCAL (Layer3)

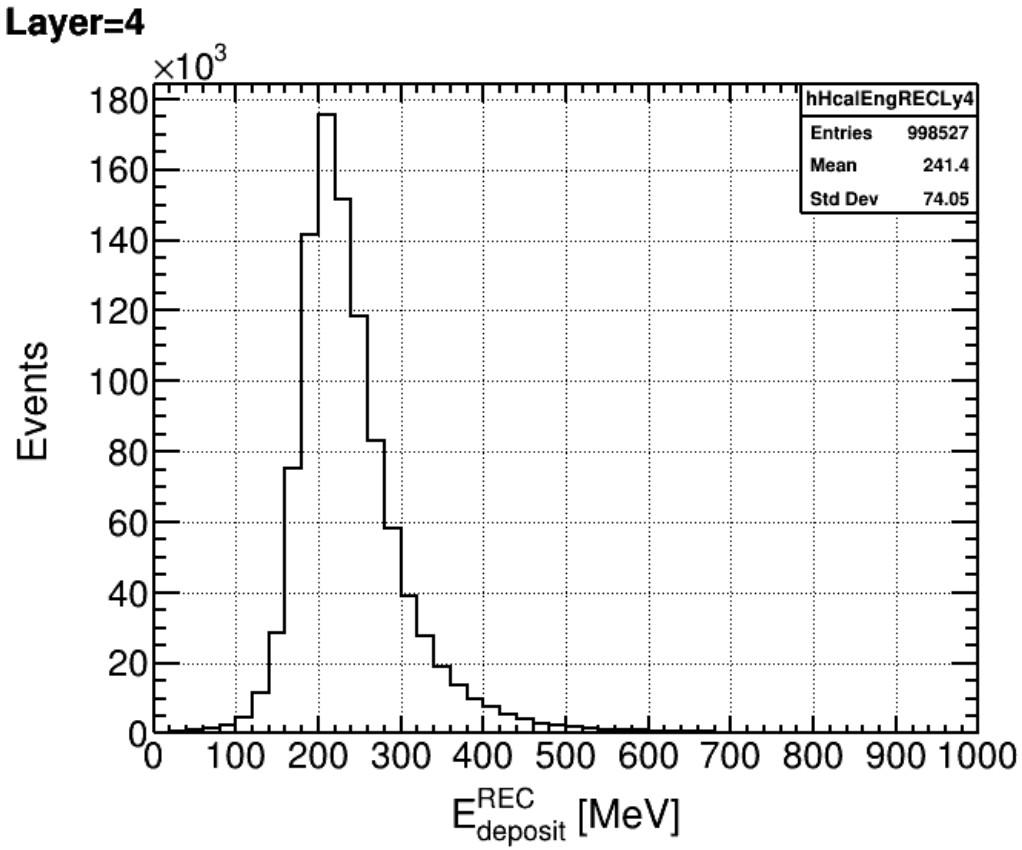




Number of hits and Energy deposit at each HCAL layer are consistent throughout entire HCAL

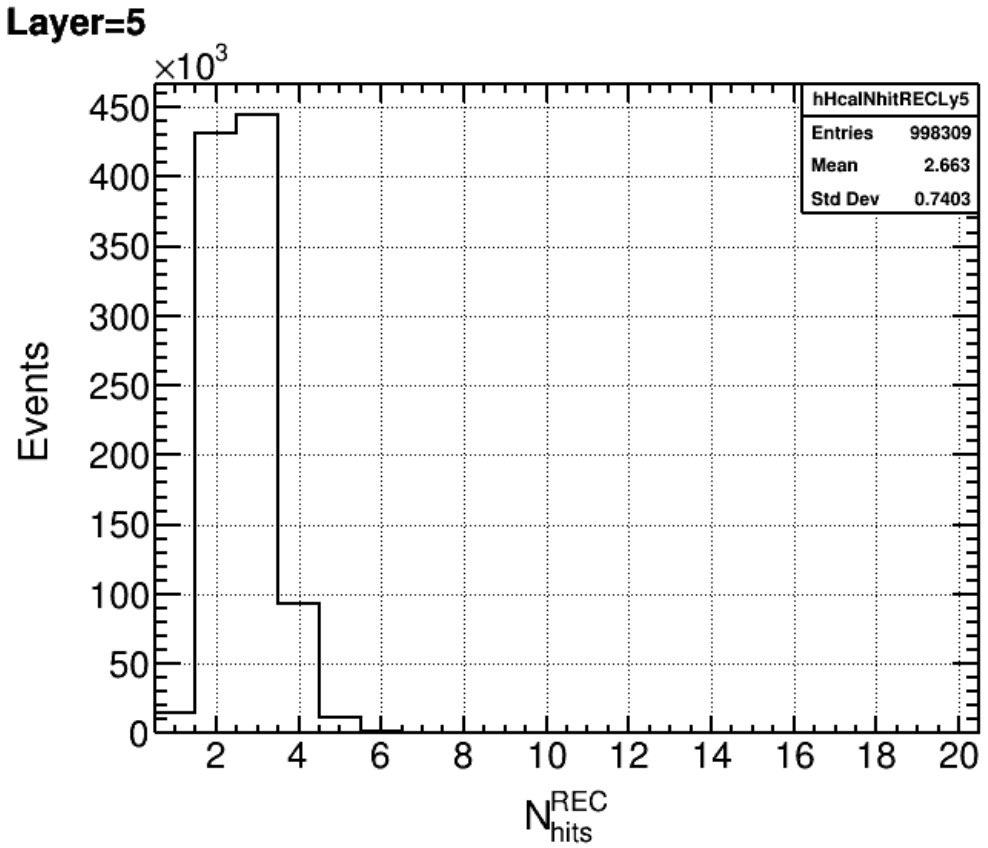
Muon Sample – Forward HCAL (Layer4)

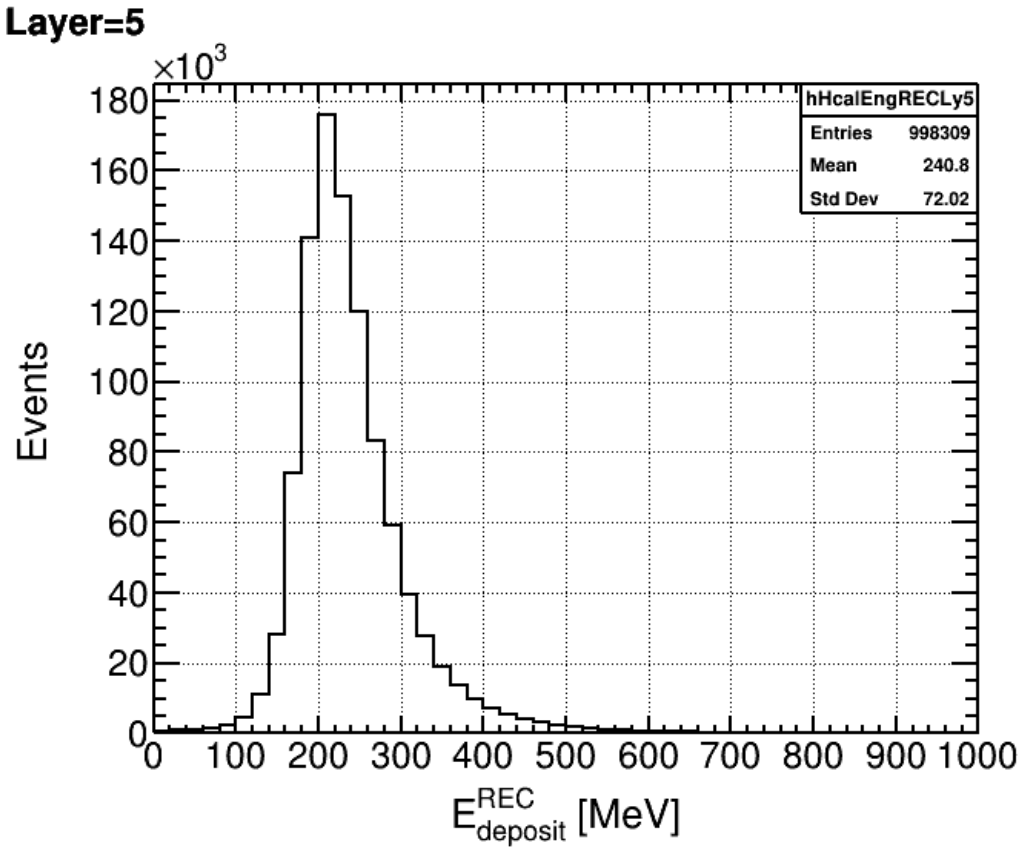




Number of hits and Energy deposit at each HCAL layer are consistent throughout entire HCAL

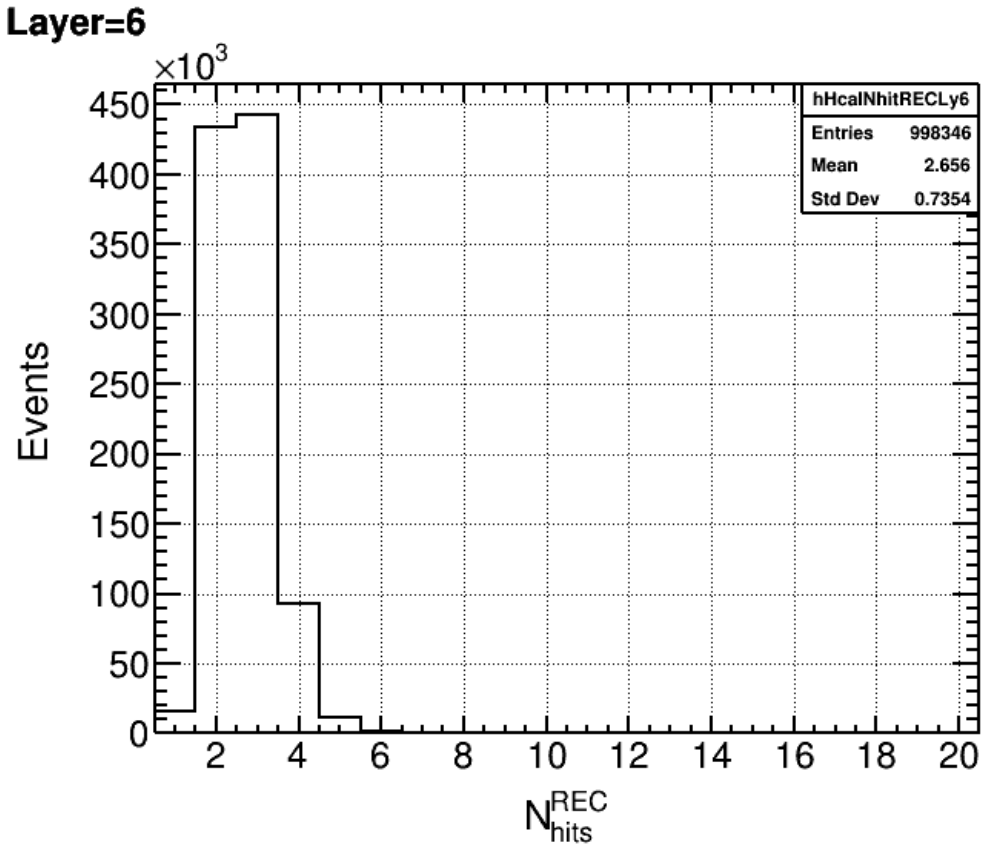
Muon Sample – Forward HCAL (Layer5)

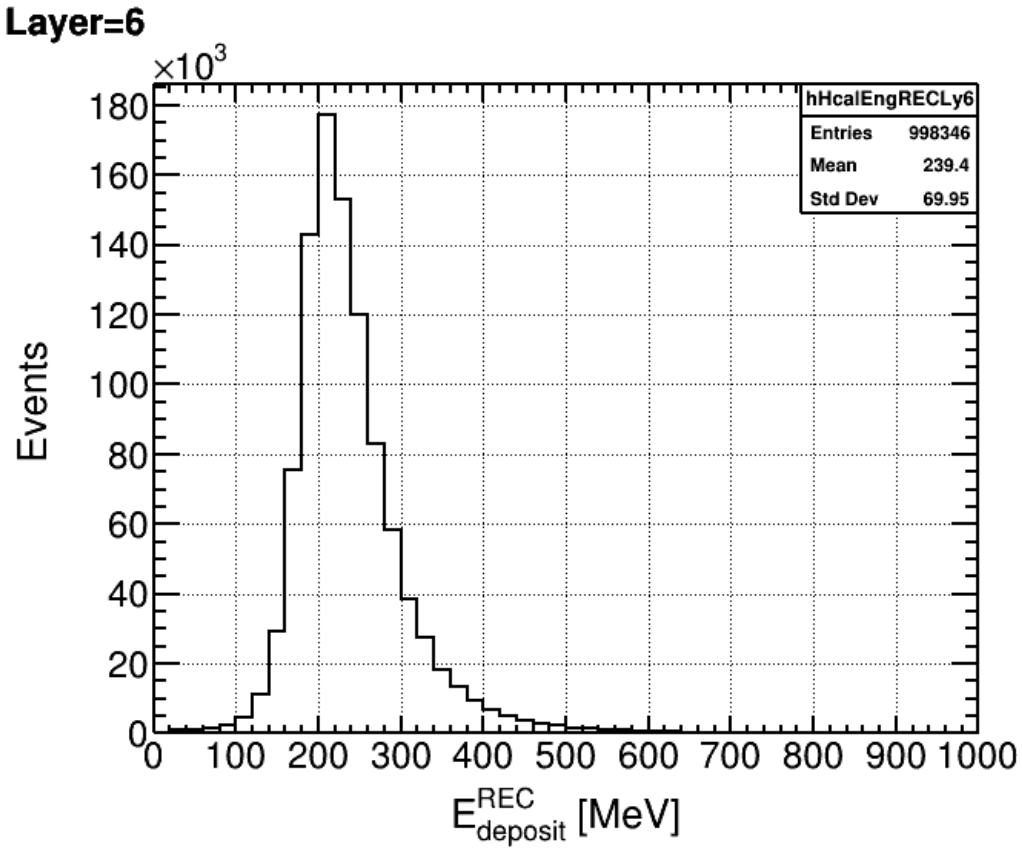




Number of hits and Energy deposit at each HCAL layer are consistent throughout entire HCAL

Muon Sample – Forward HCAL (Layer6)





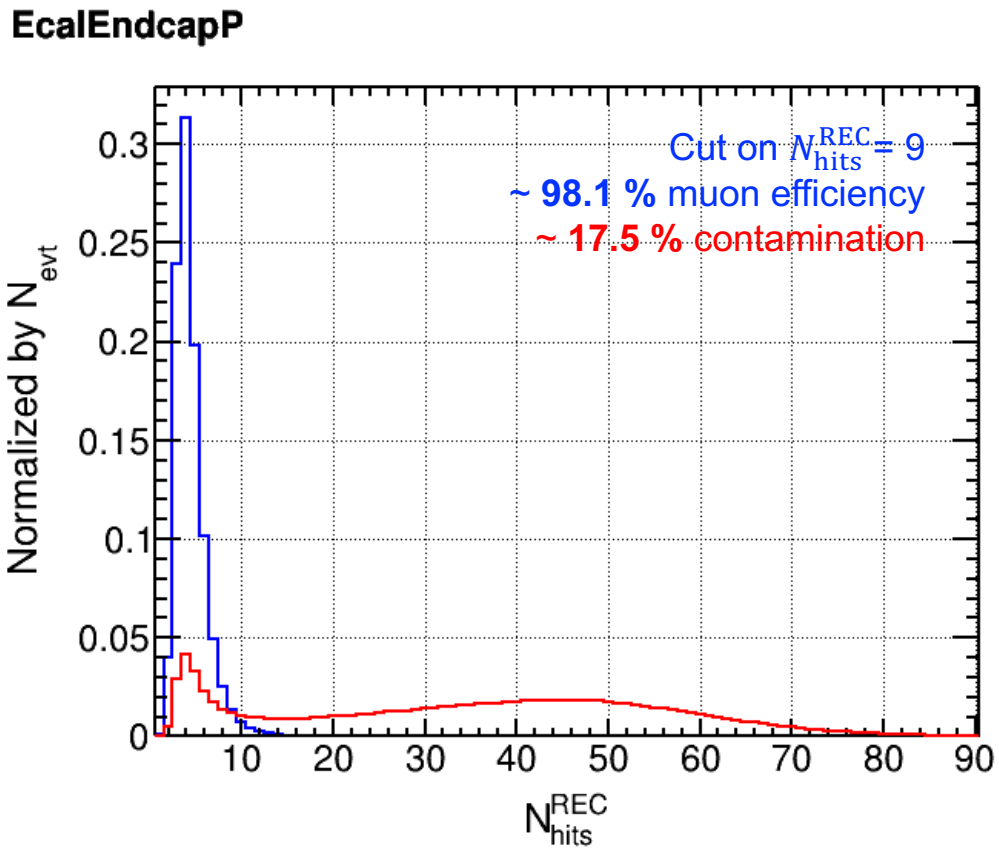
Number of hits and Energy deposit at each HCAL layer are consistent throughout entire HCAL

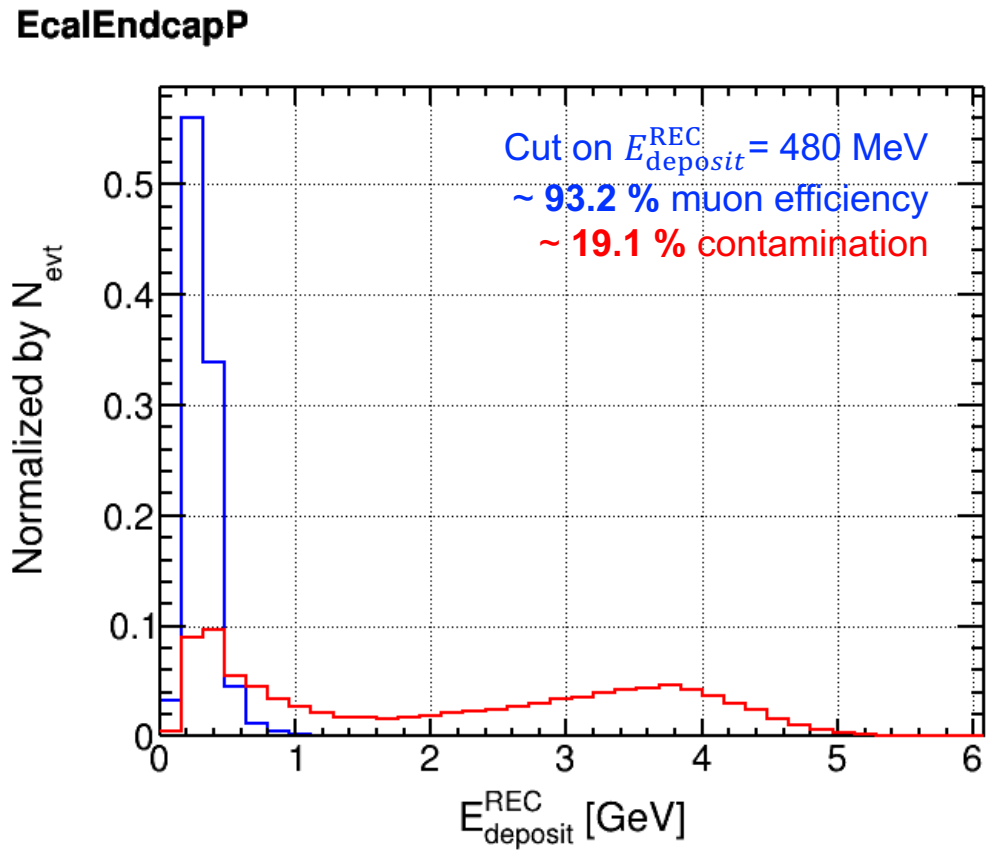
ePIC Simulation – Pions

ex) 5 GeV at η = 1.74

Muons Pions

Comparison – Forward ECAL

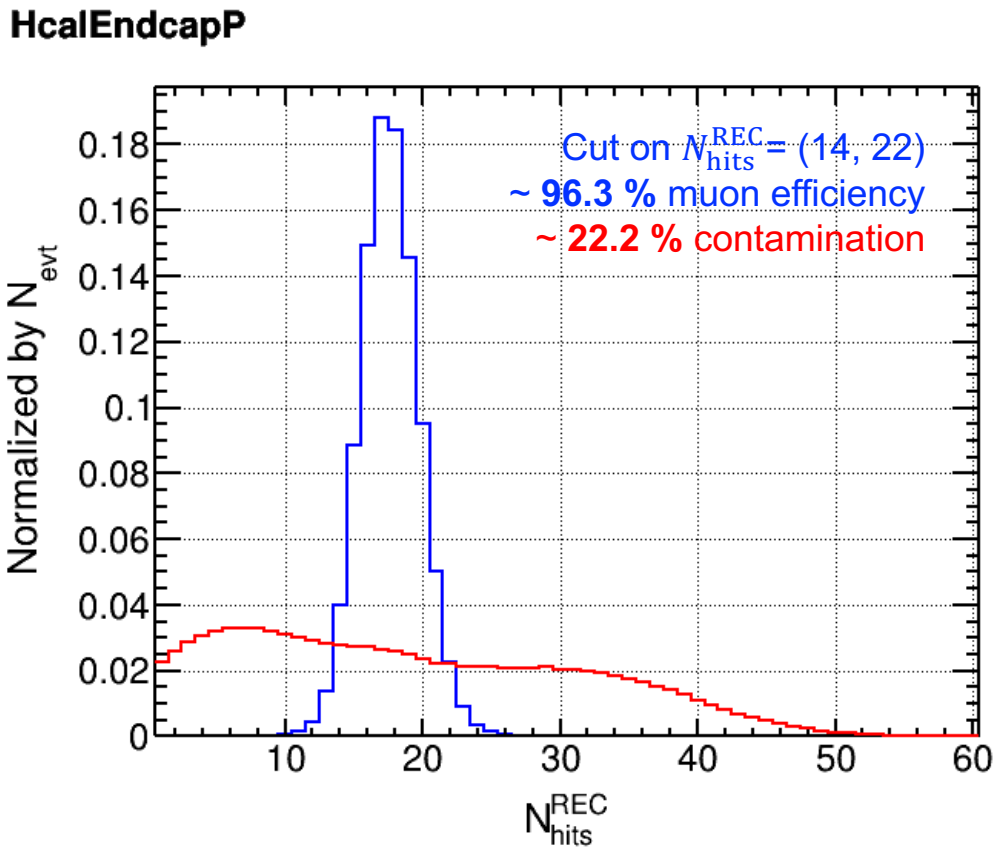


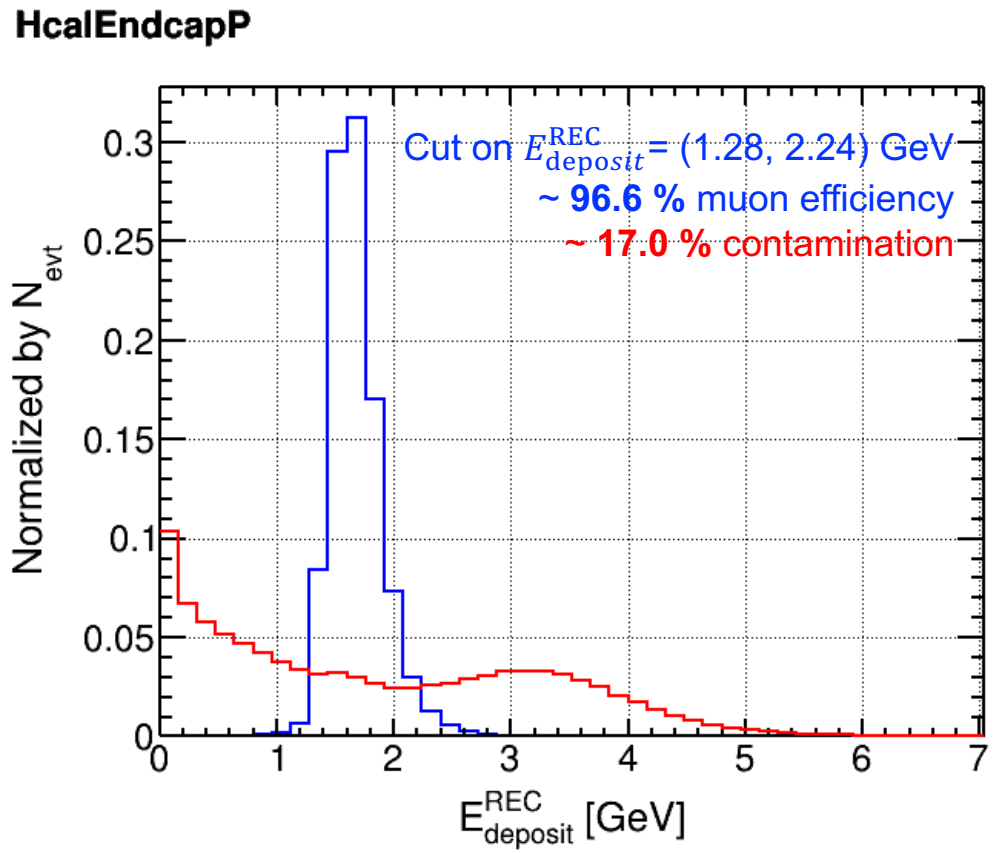


Comparing muon, pion has a long tail.
Defined a cut where muon (treated as a signal) is below pion (treated as a background)

Muons Pions

Comparison – Forward HCAL





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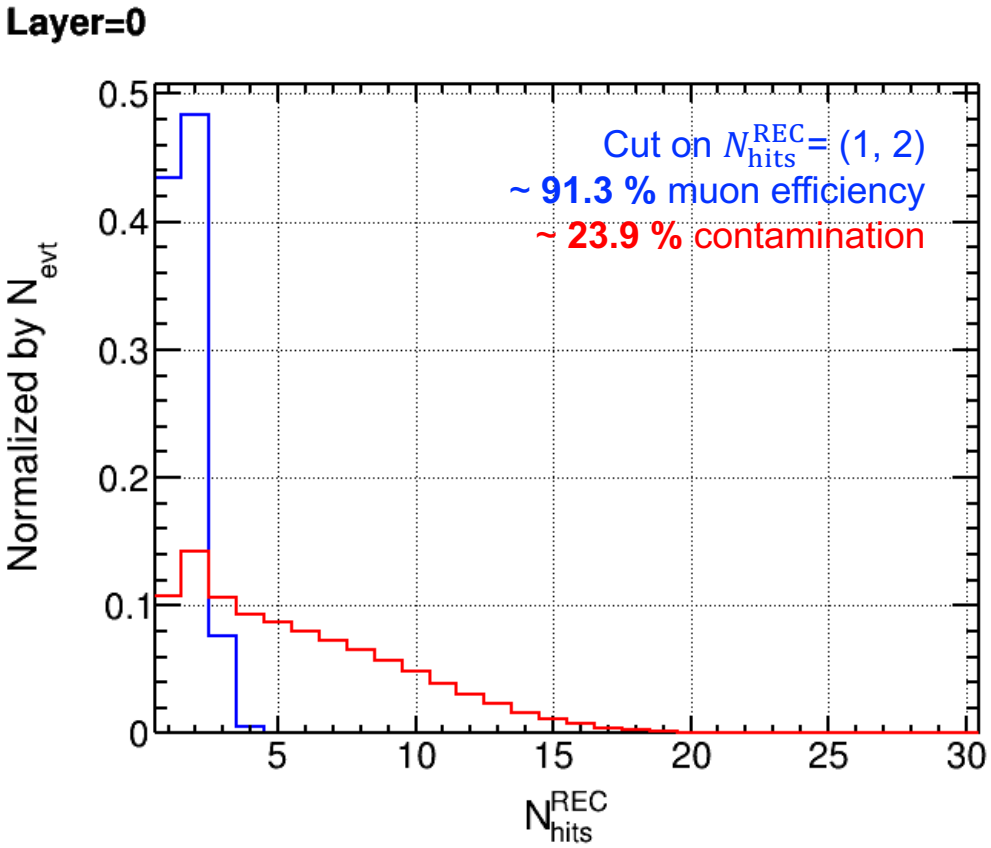
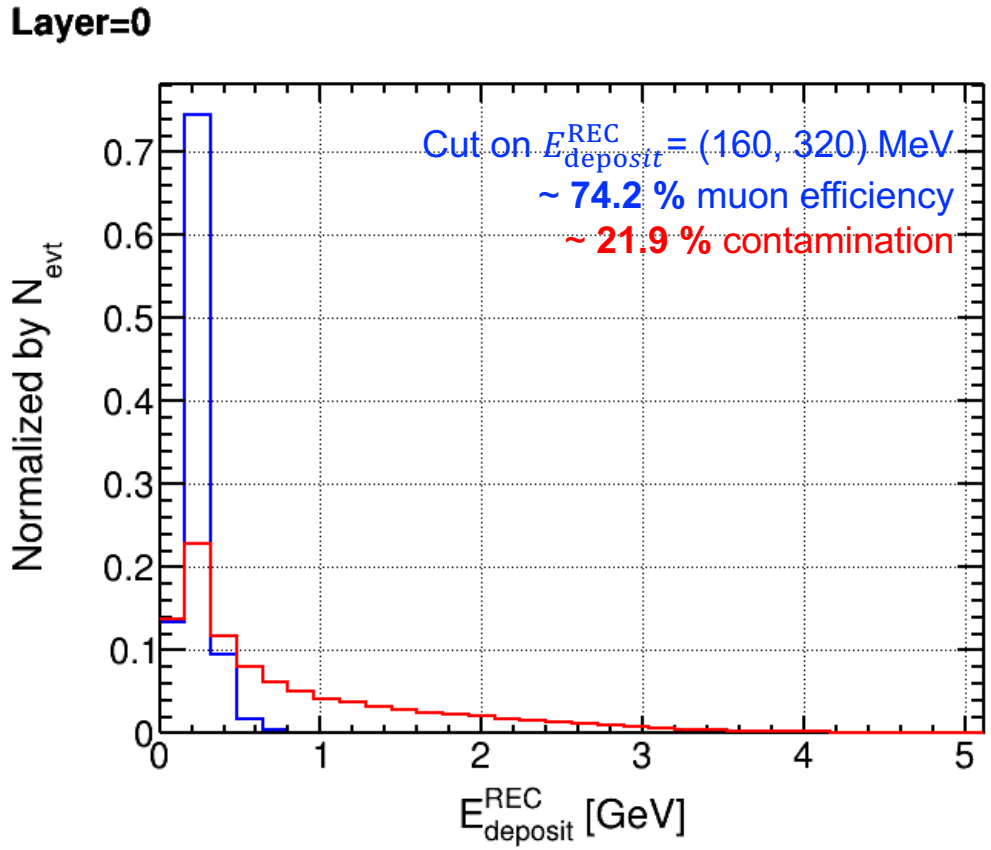
Muons Pions

Comparison – Forward HCAL (Layer0)





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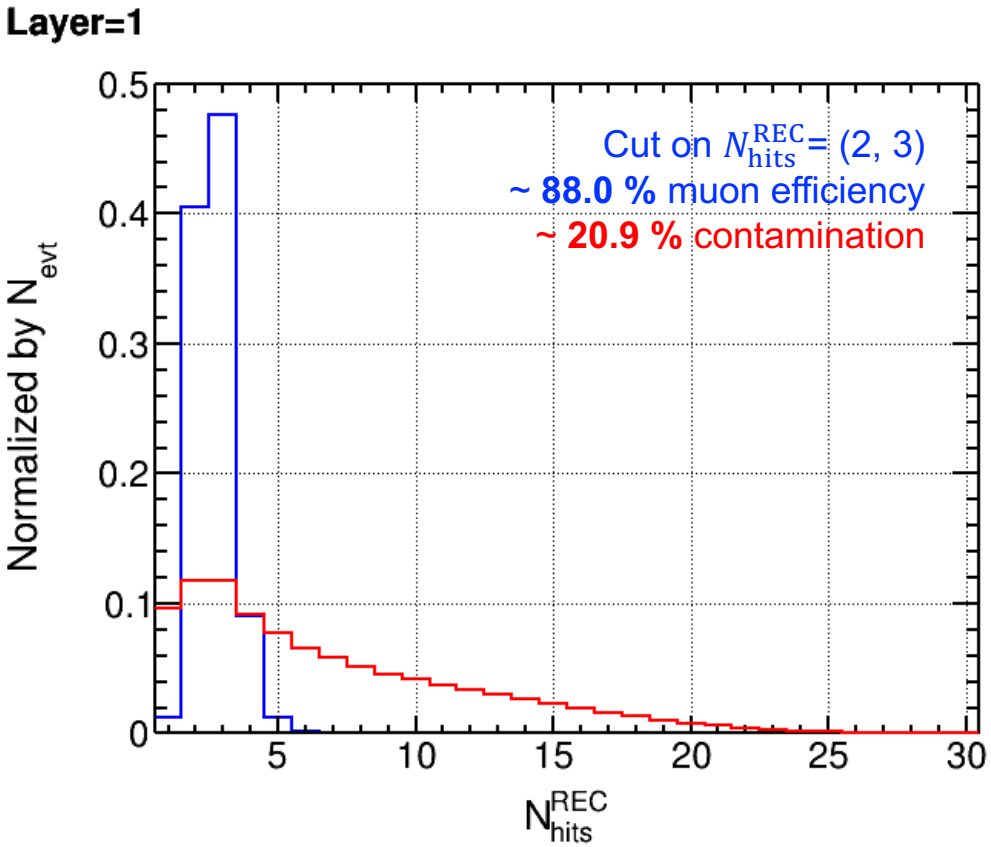
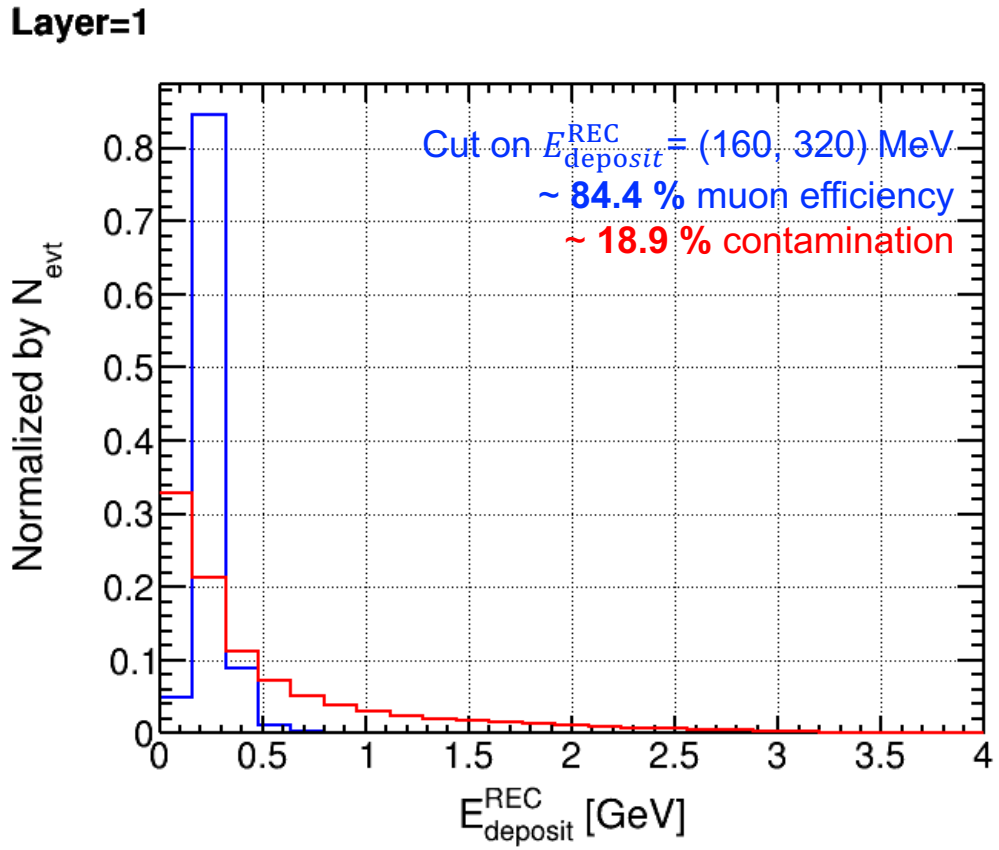
Muons Pions

Comparison – Forward HCAL (Layer1)





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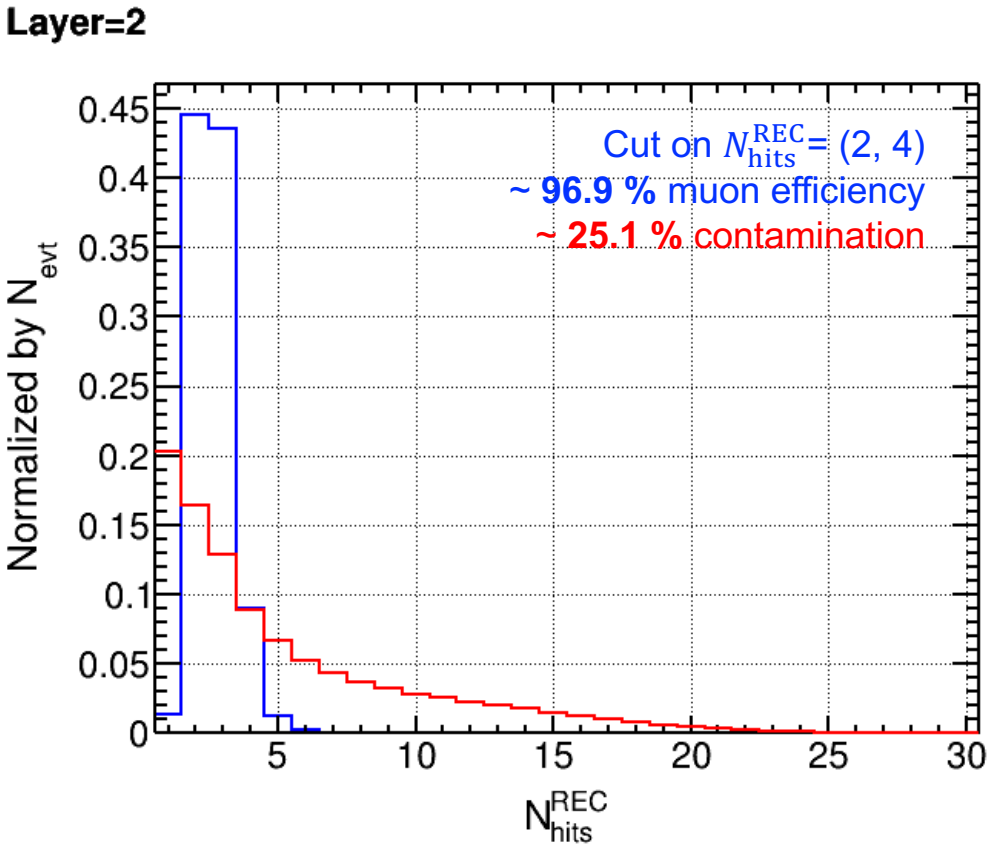
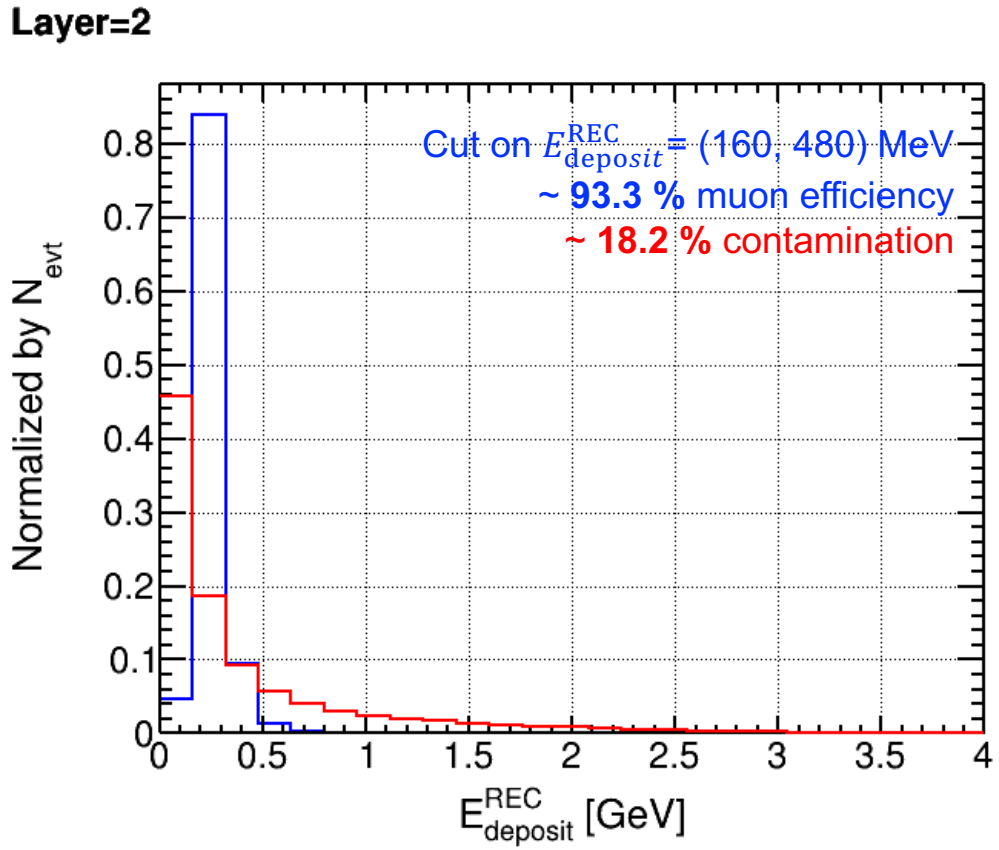
Muons Pions

Comparison – Forward HCAL (Layer2)





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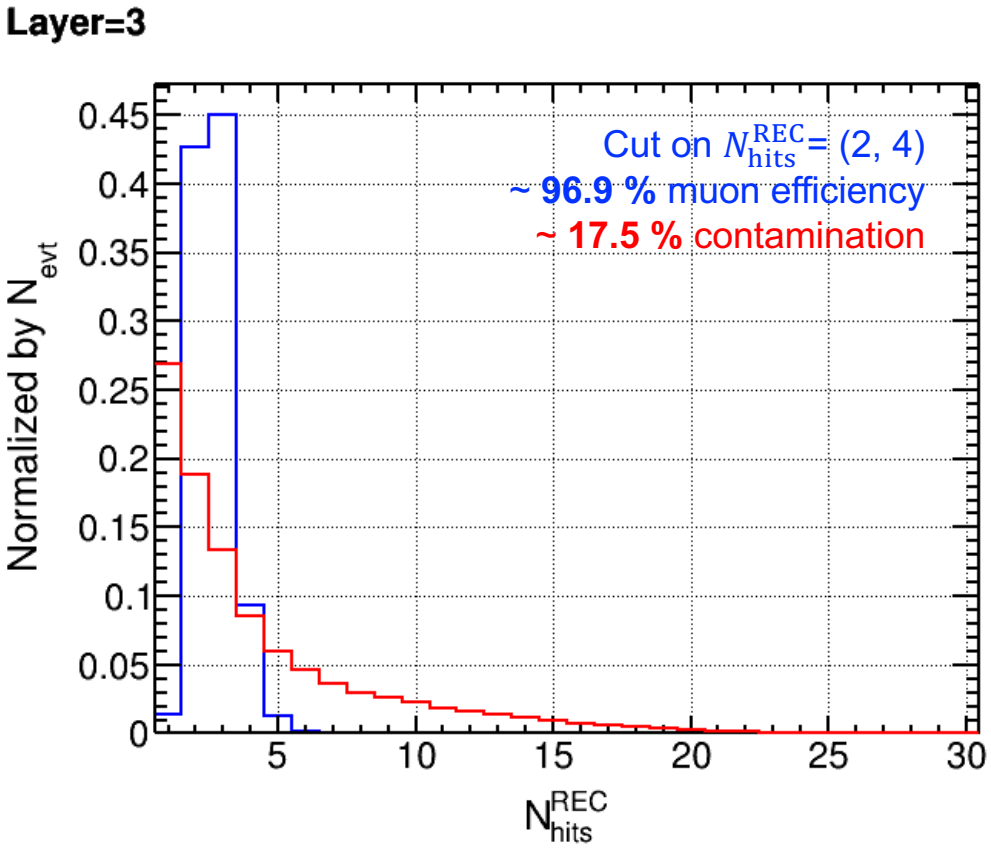
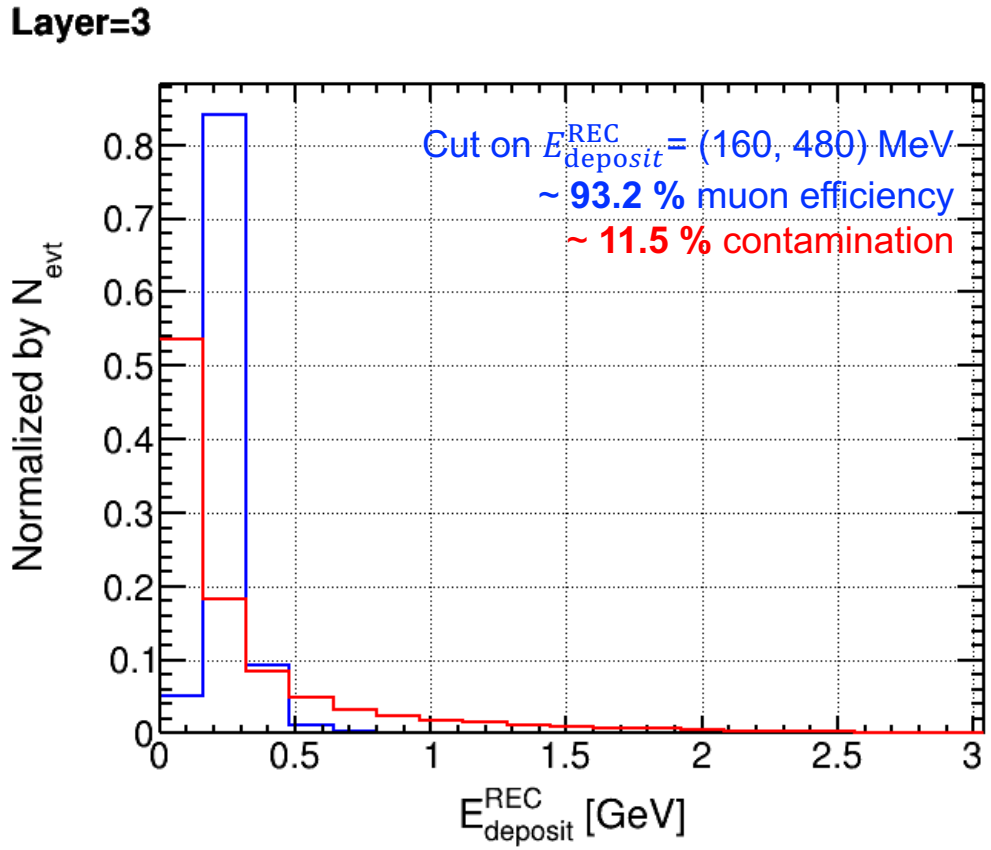
Muons Pions

Comparison – Forward HCAL (Layer3)





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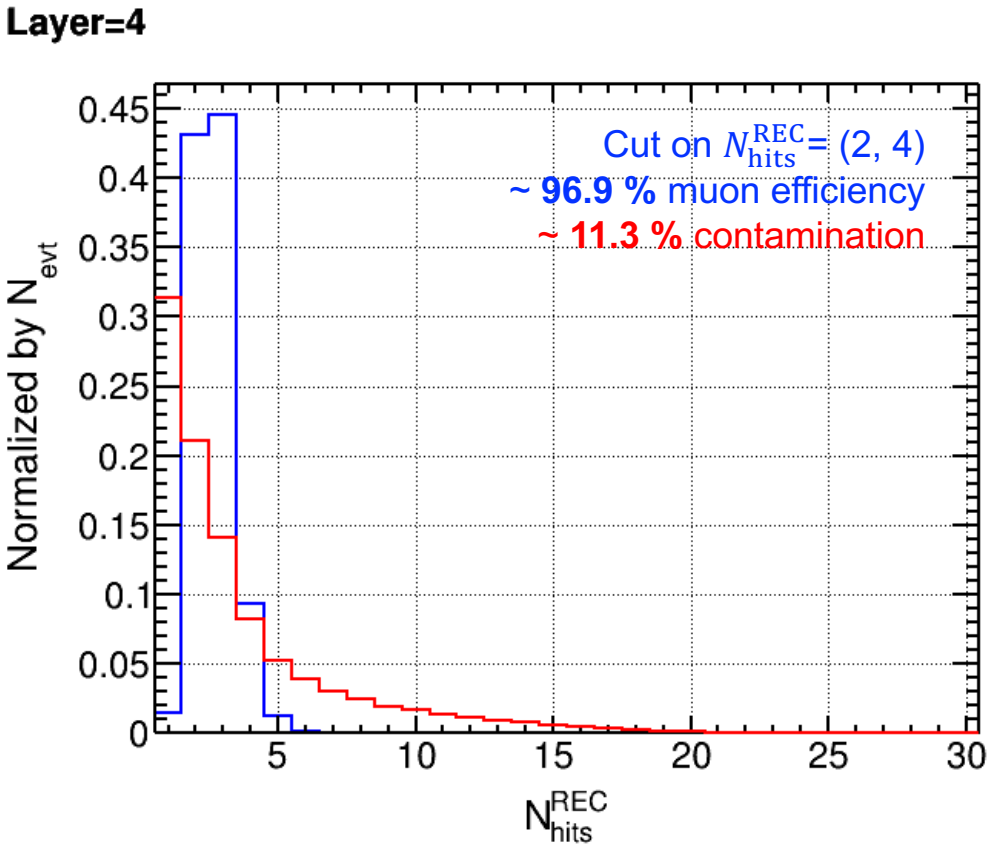
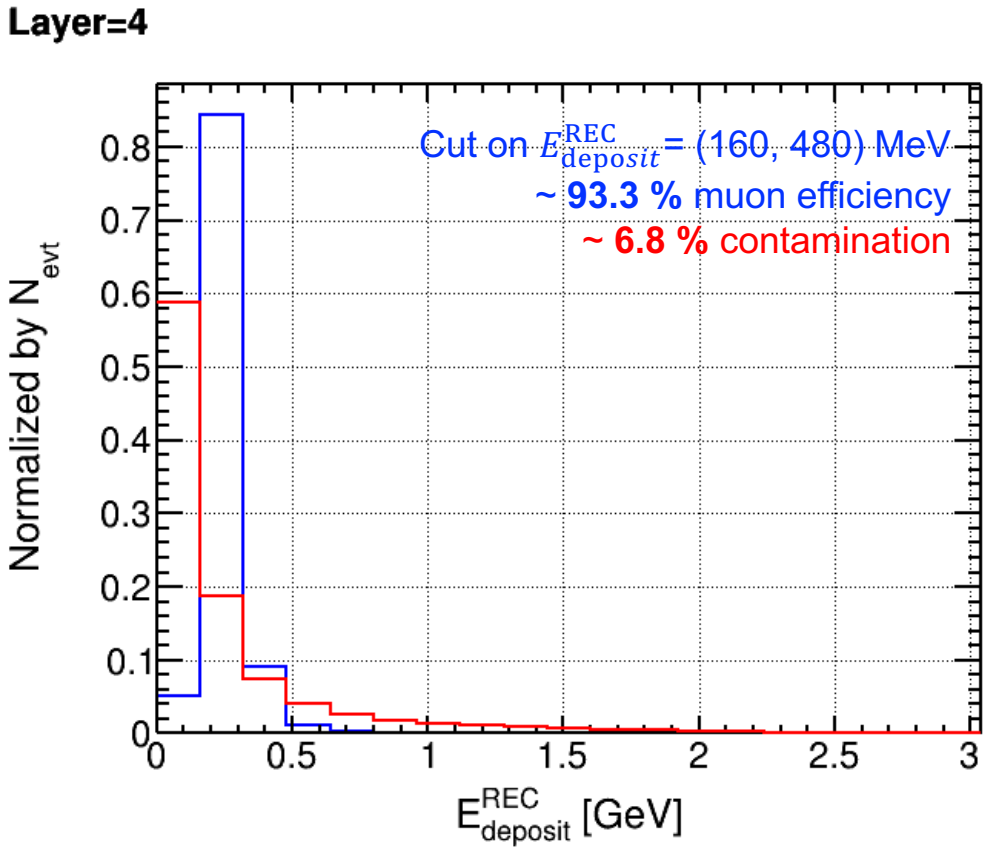
Muons Pions

Comparison – Forward HCAL (Layer4)





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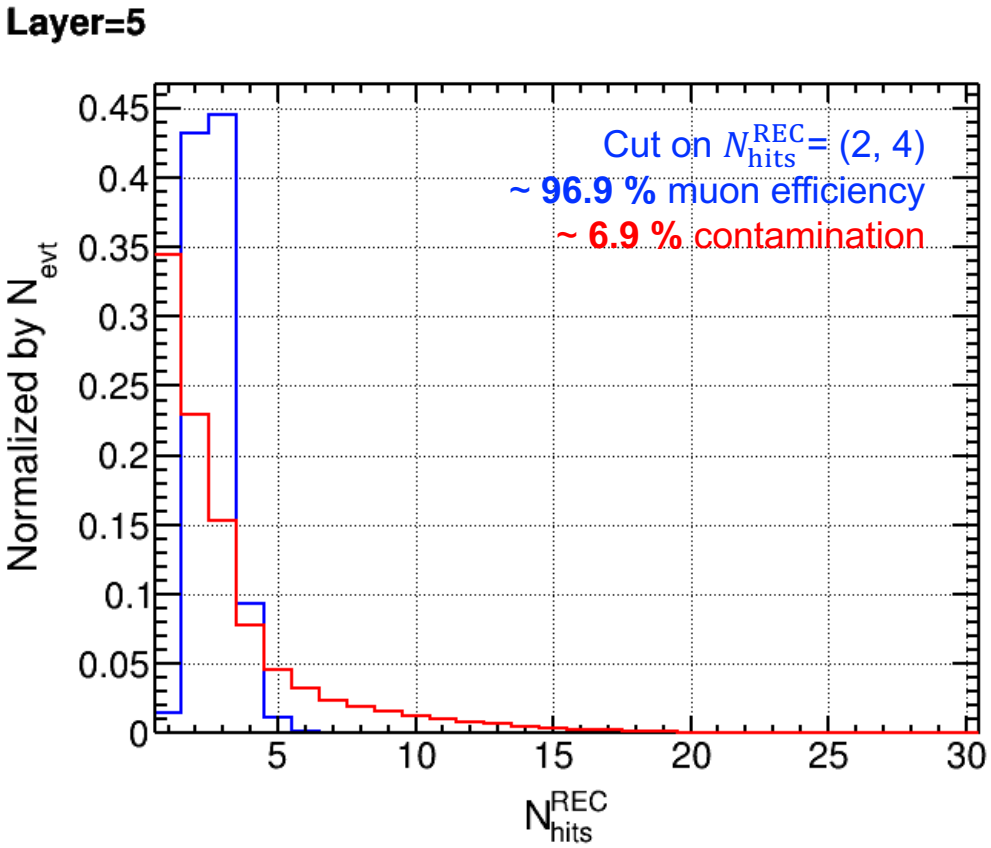
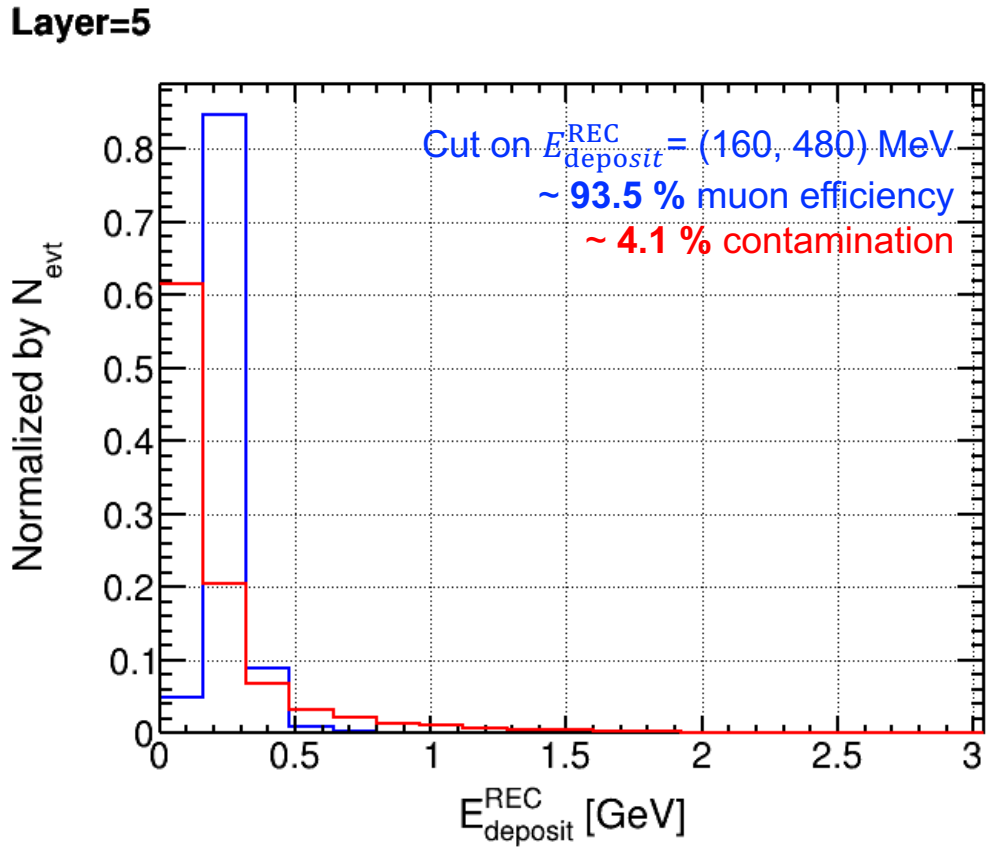
Muons Pions

Comparison – Forward HCAL (Layer5)





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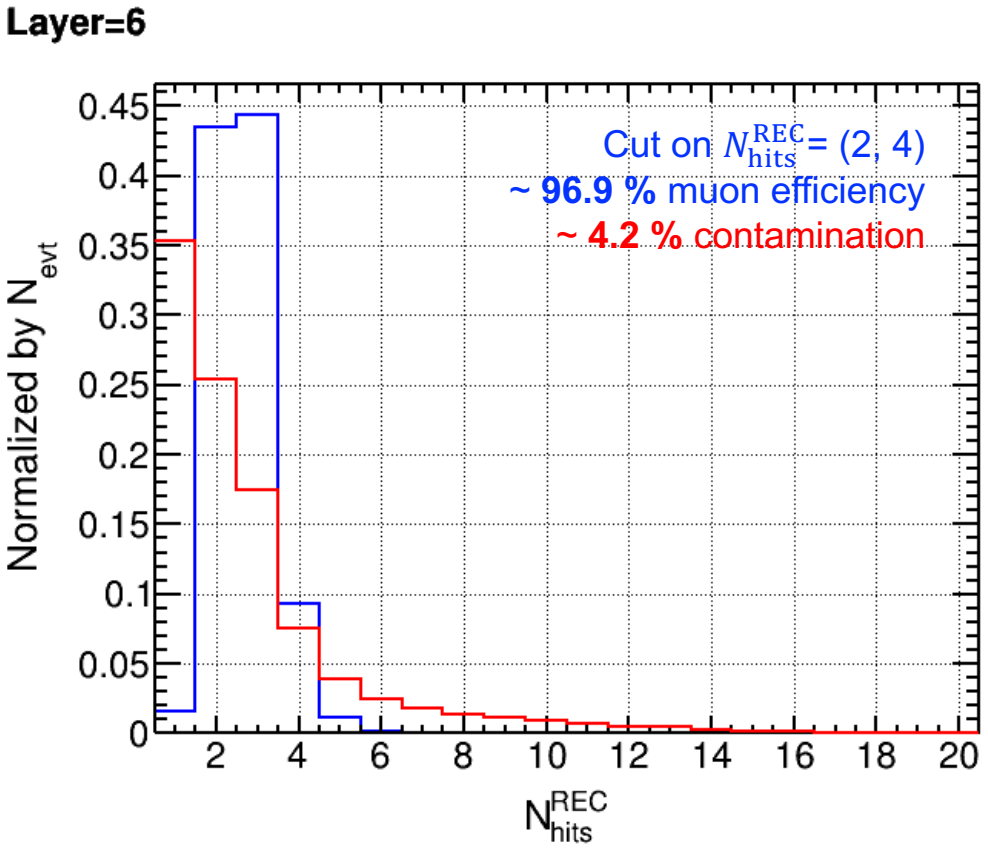
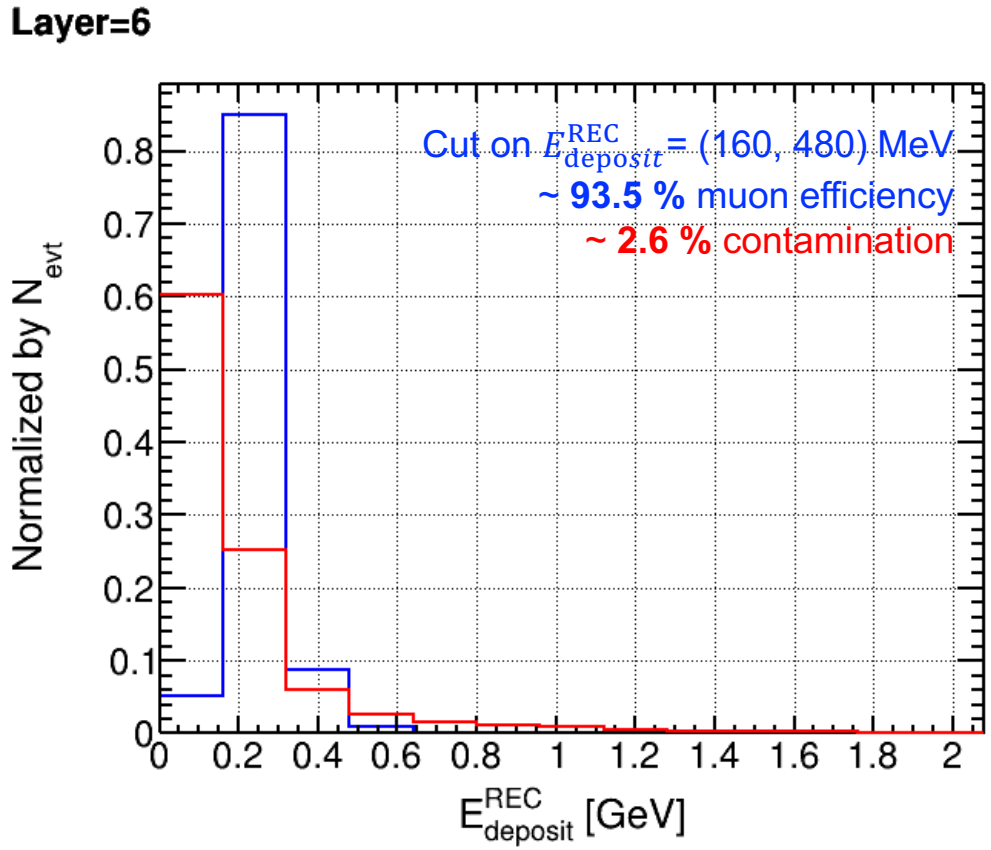
Muons Pions

Comparison – Forward HCAL (Layer6)





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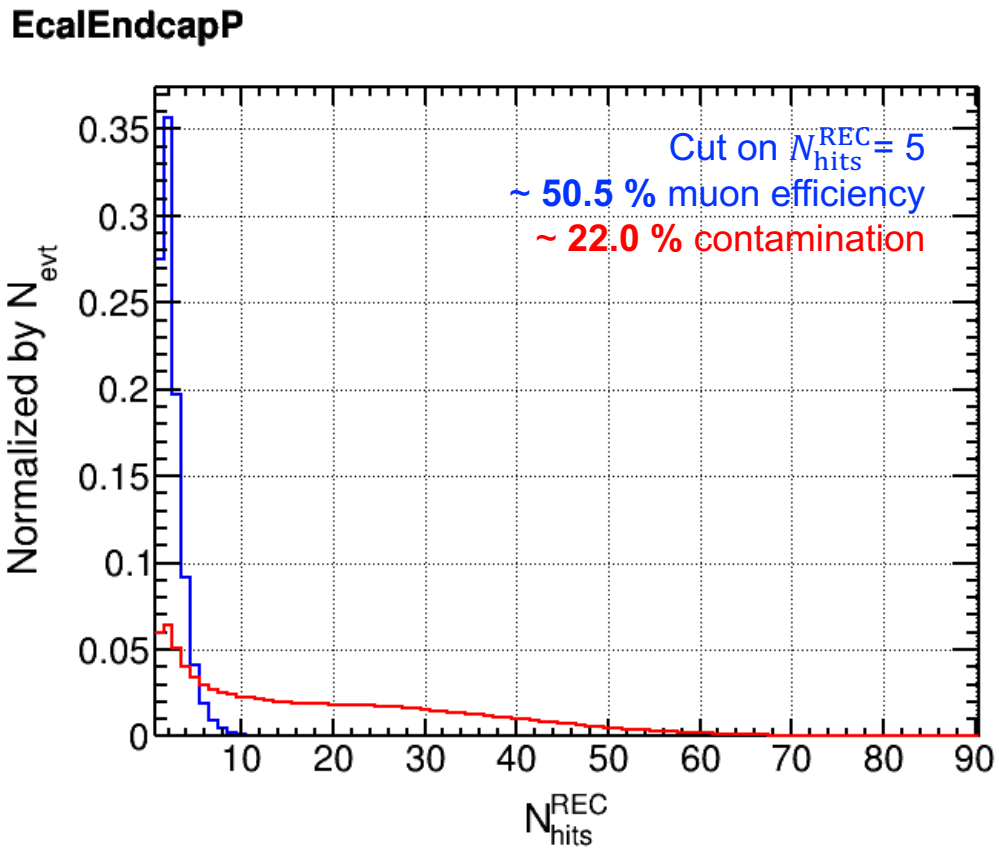
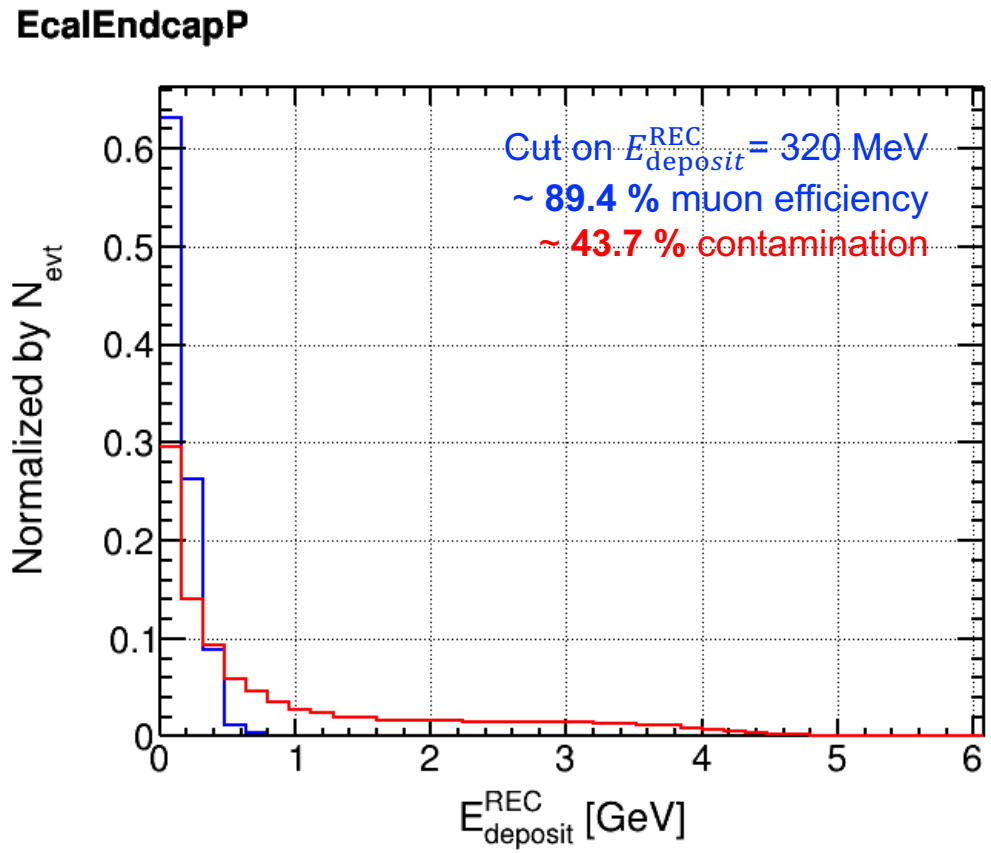
ePIC Simulation – Pions

ex) 5 GeV at η = 3.13

Muons Pions

Comparison – Forward ECAL

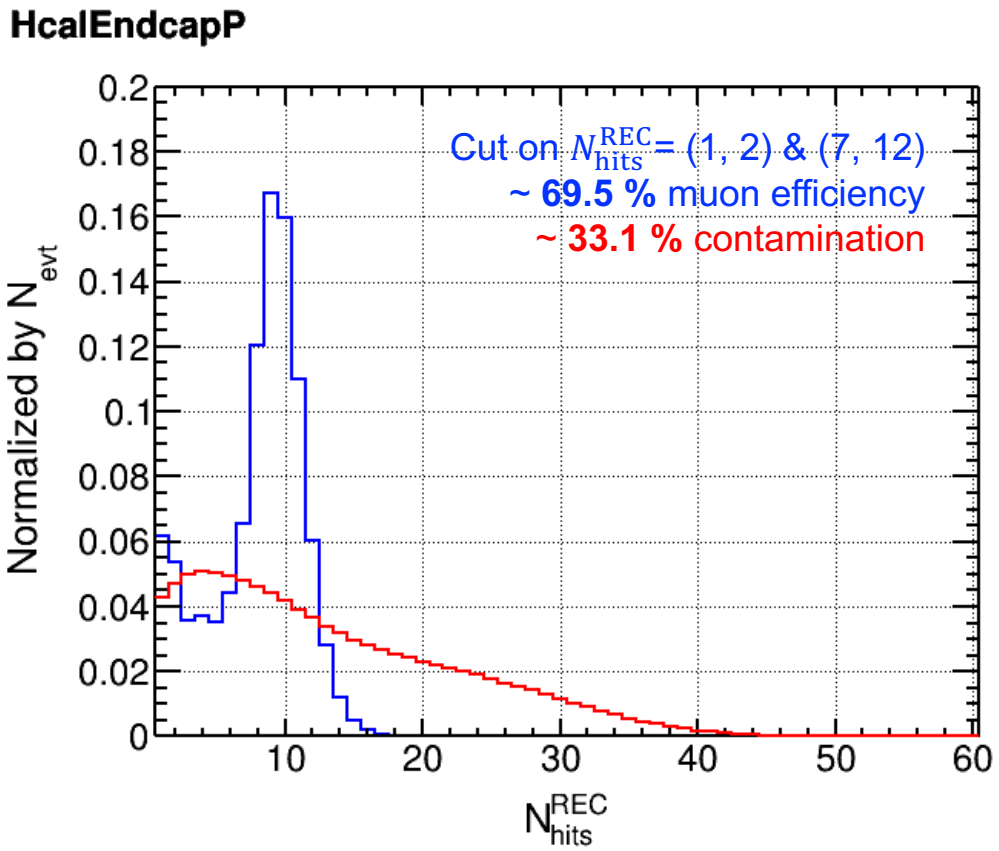


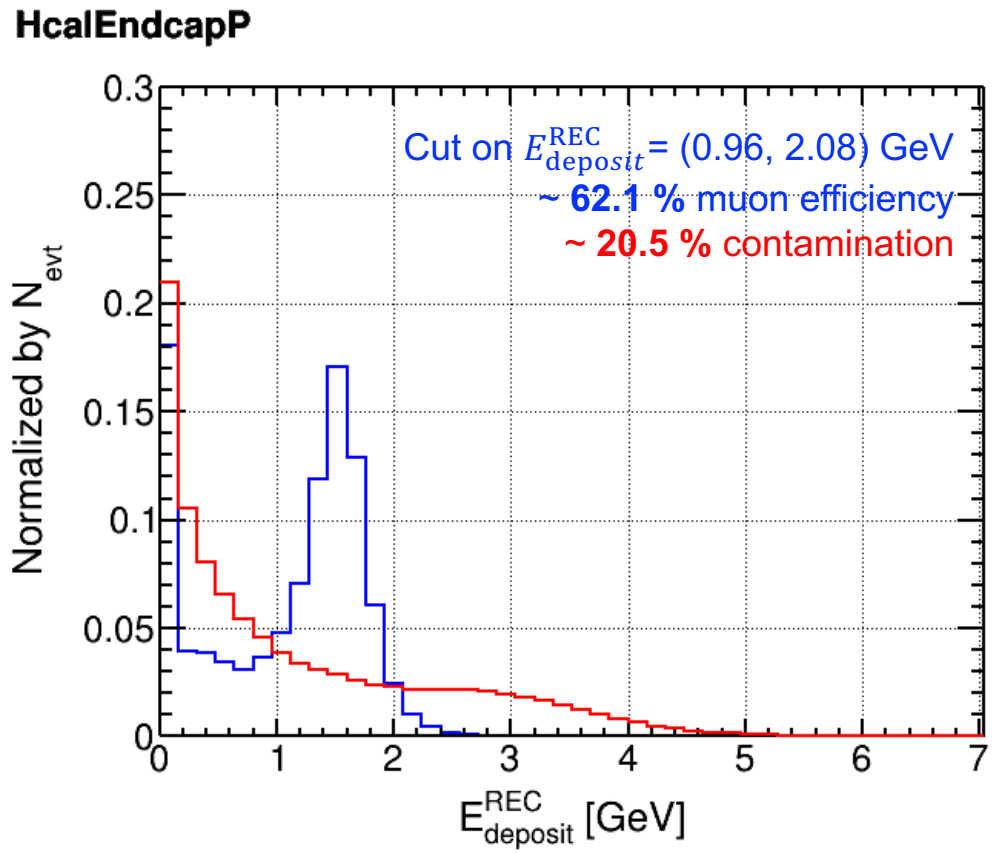


For more forward going muons, it has more less number of hits and less energy deposit in general. Lower efficiency is observed. Defined a cut where muon (treated as a signal) is below pion (treated as a background)

Muons Pions

Comparison – Forward HCAL





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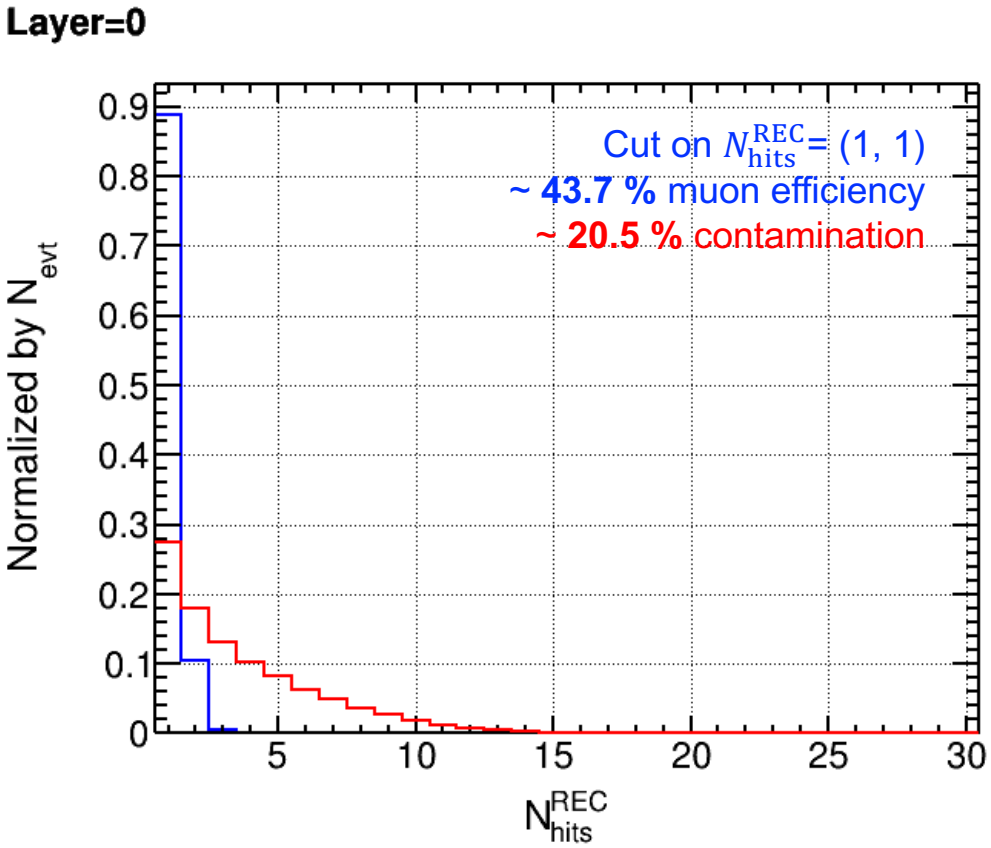
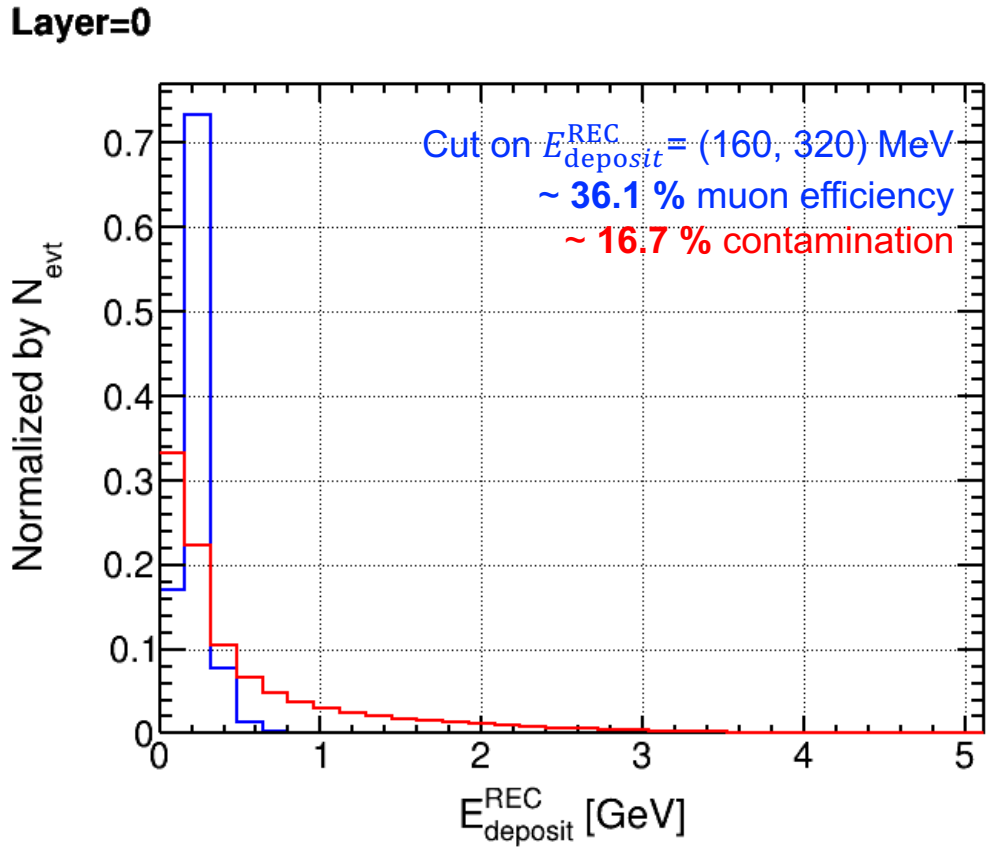
Muons Pions

Comparison – Forward HCAL (Layer0)





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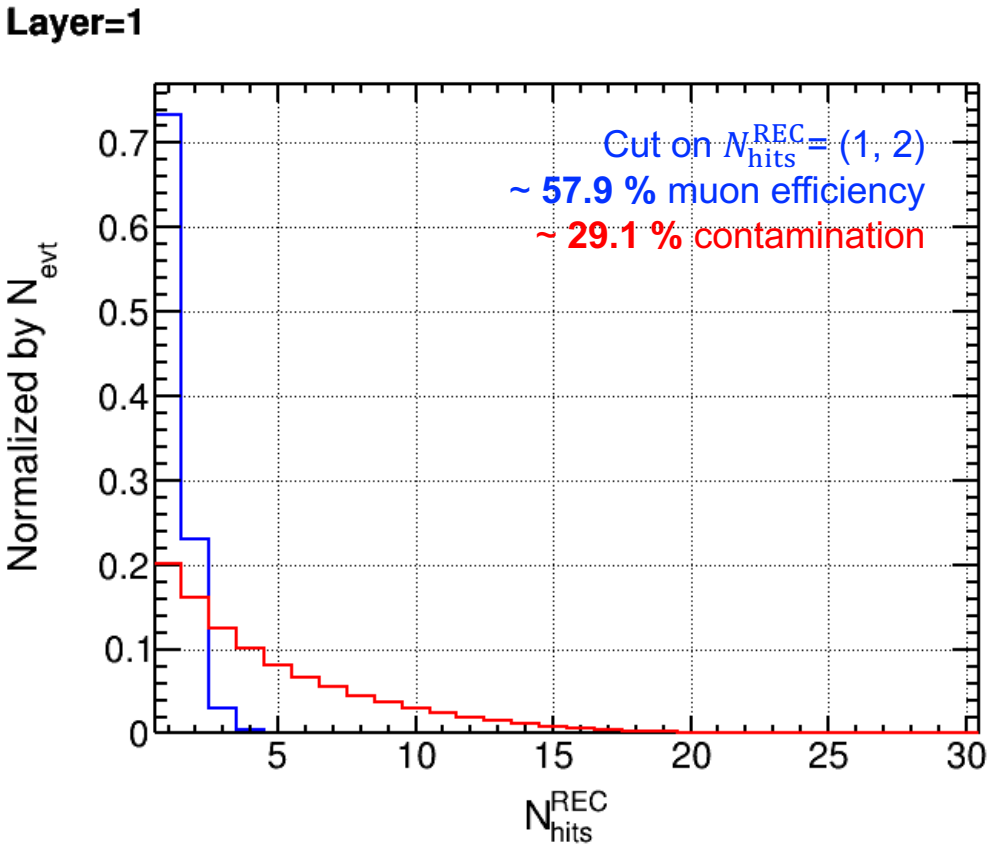
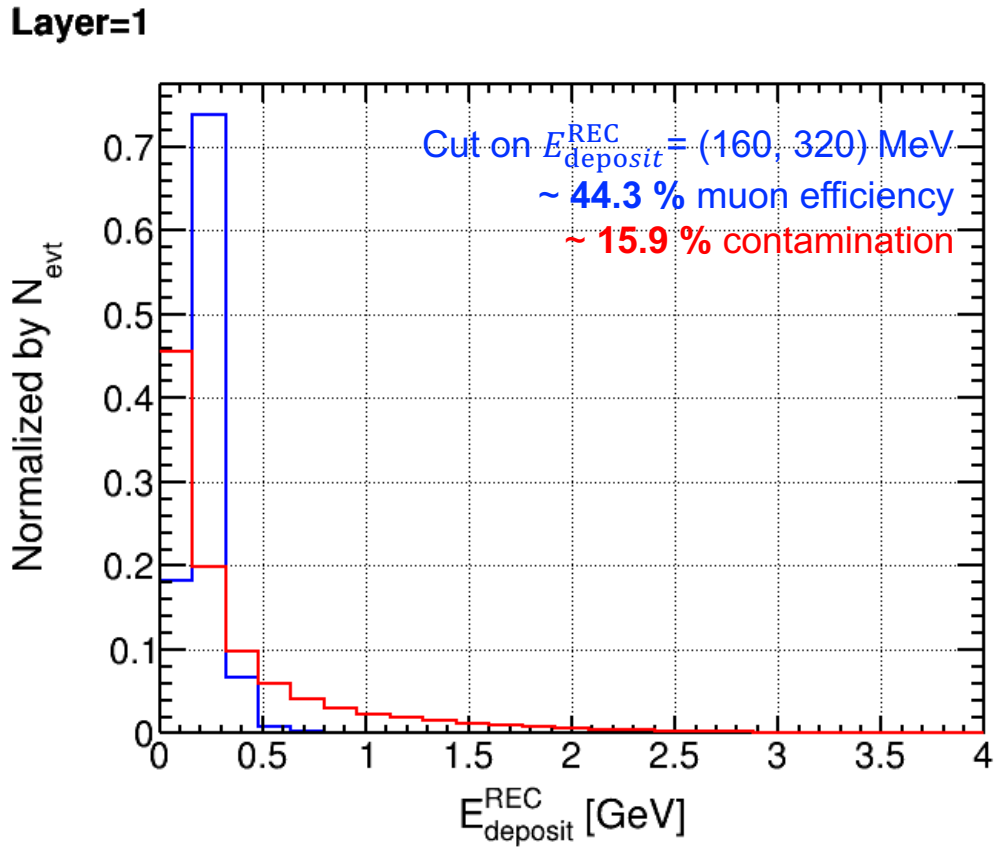
Muons Pions

Comparison – Forward HCAL (Layer1)

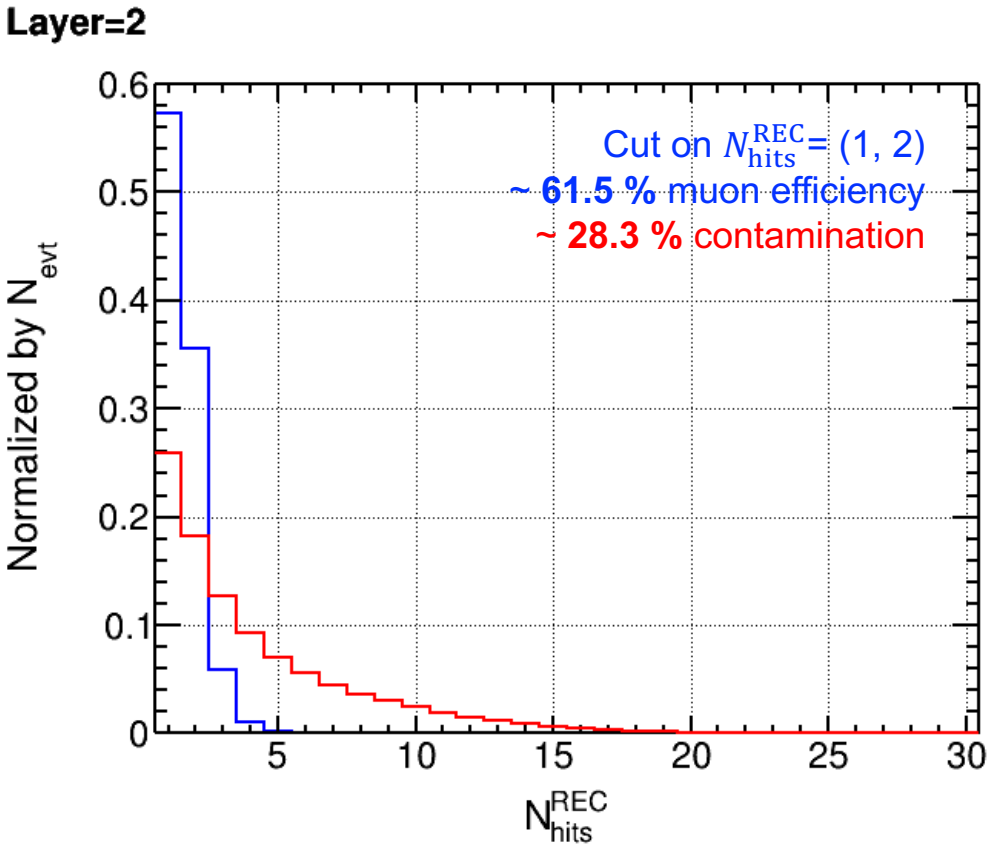


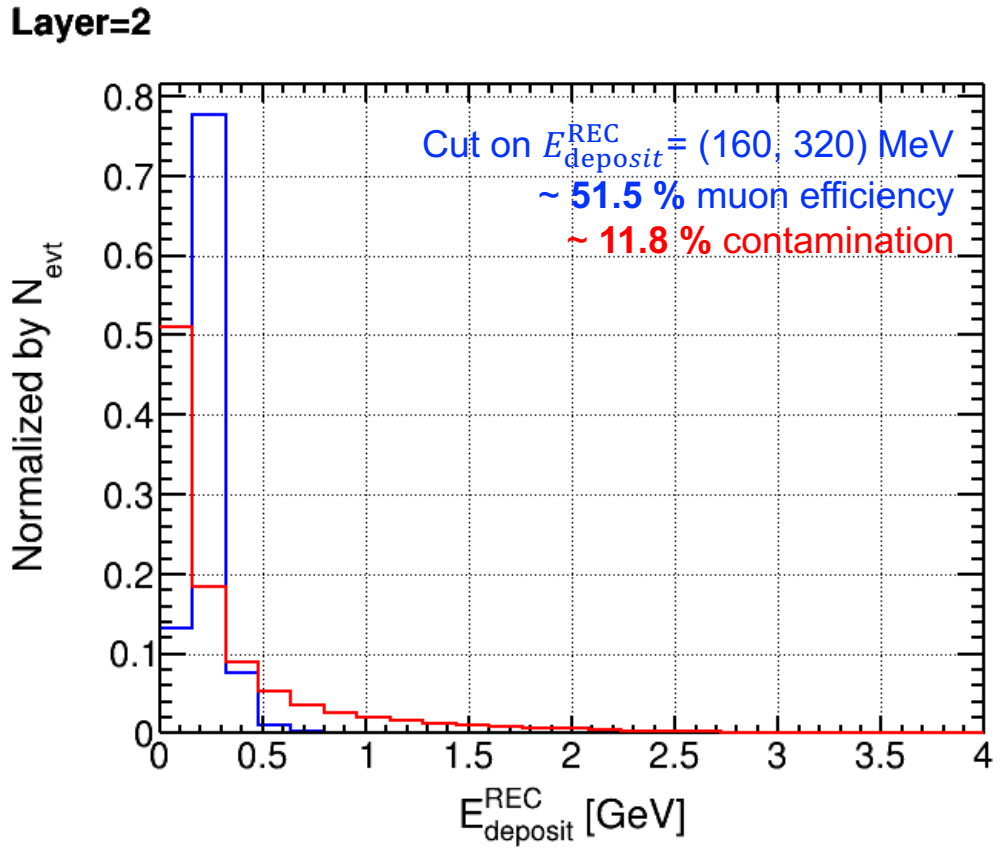


Comparing muon, pion has a long tail.
Defined a cut where muon (treated as a signal) is below pion (treated as a background)

Muons Pions

Comparison – Forward HCAL (Layer2)

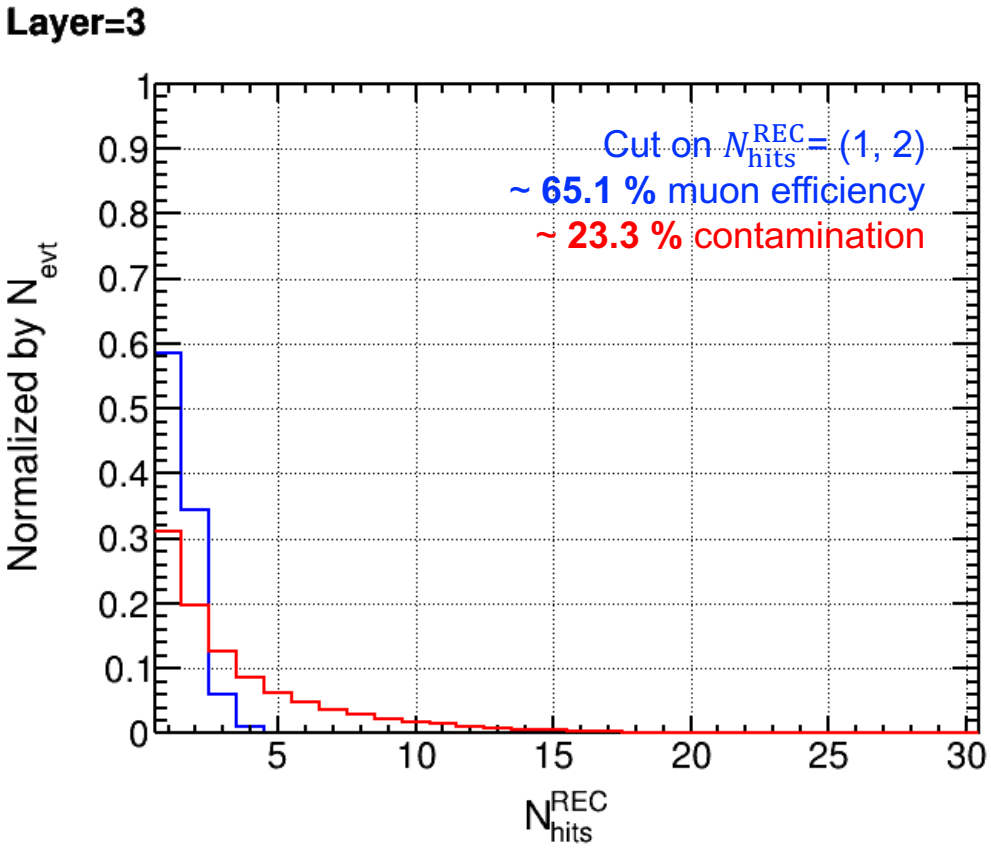


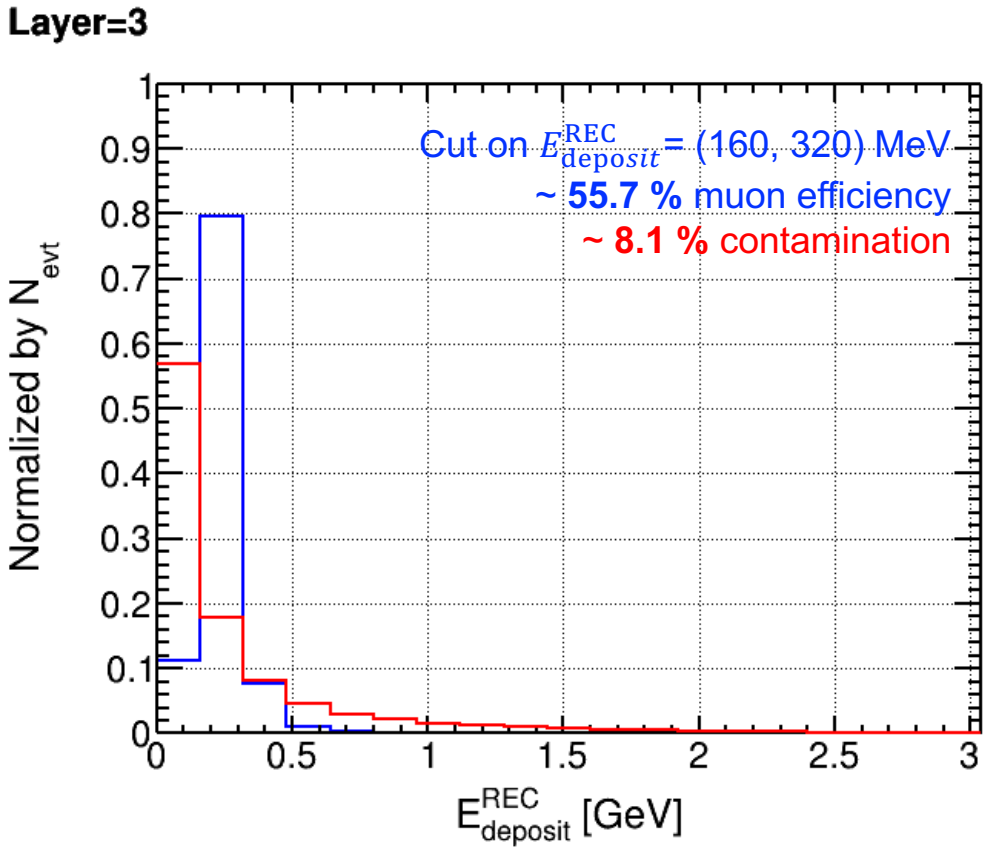


Comparing muon, pion has a long tail.
Defined a cut where muon (treated as a signal) is below pion (treated as a background)

Muons Pions

Comparison – Forward HCAL (Layer3)

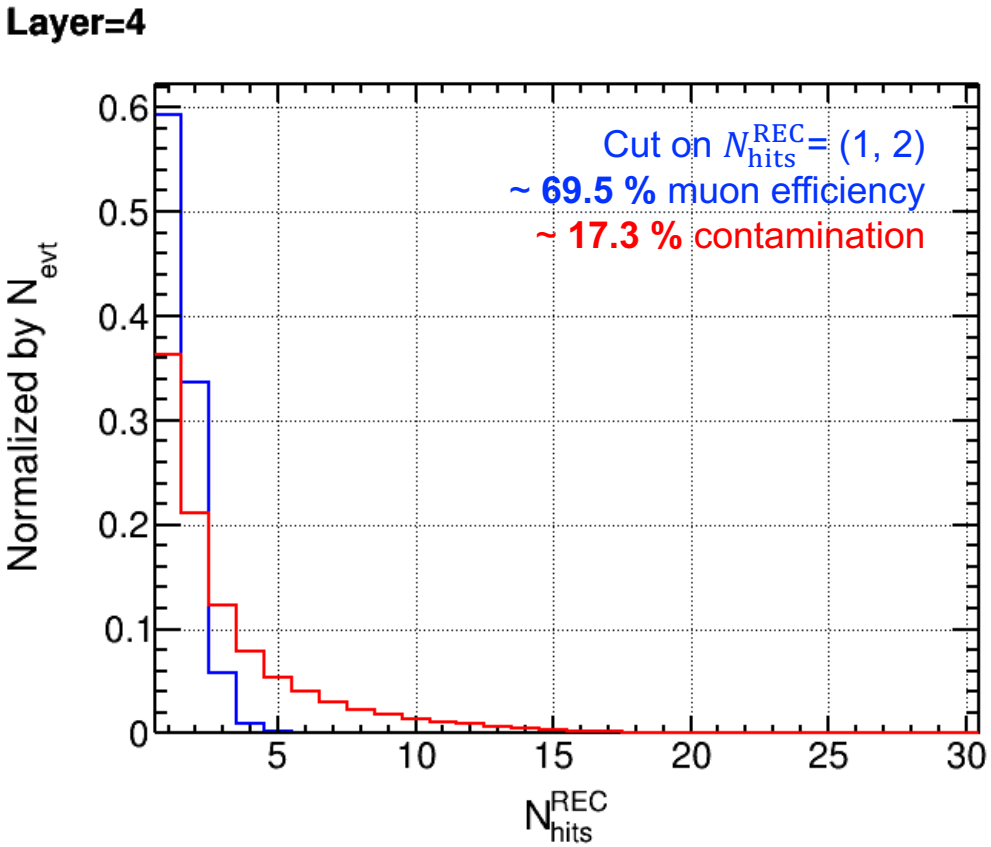


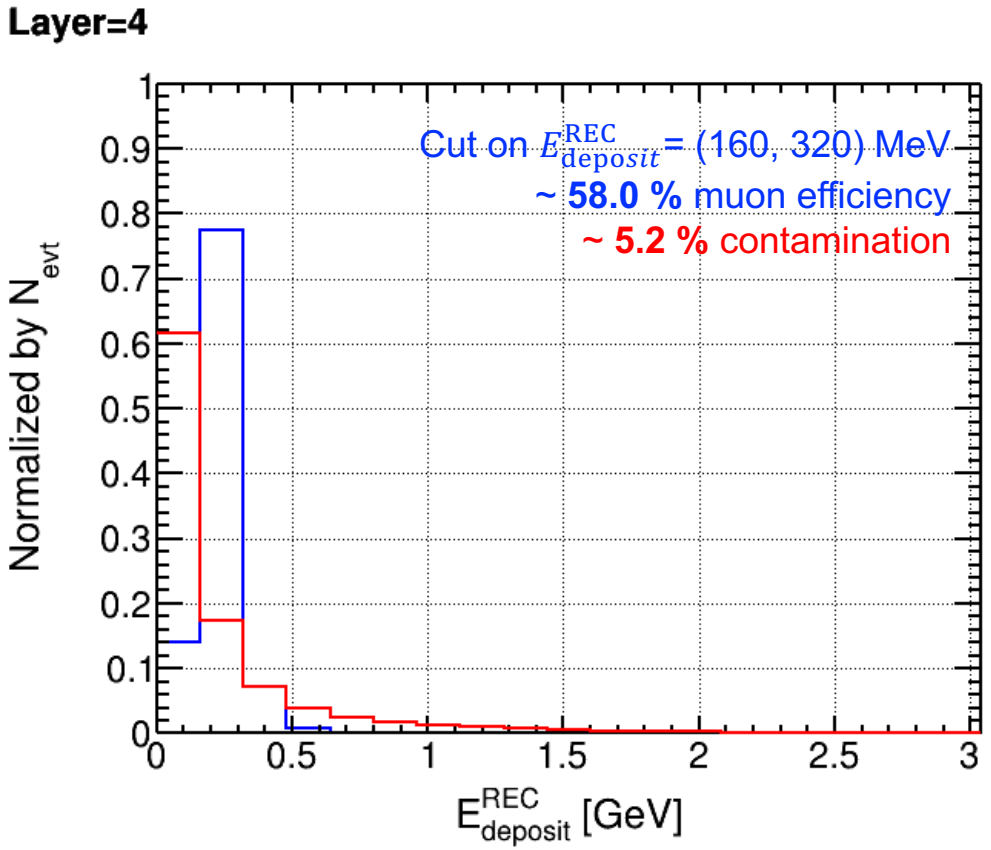


Comparing muon, pion has a long tail.
Defined a cut where muon (treated as a signal) is below pion (treated as a background)

Muons Pions

Comparison – Forward HCAL (Layer4)

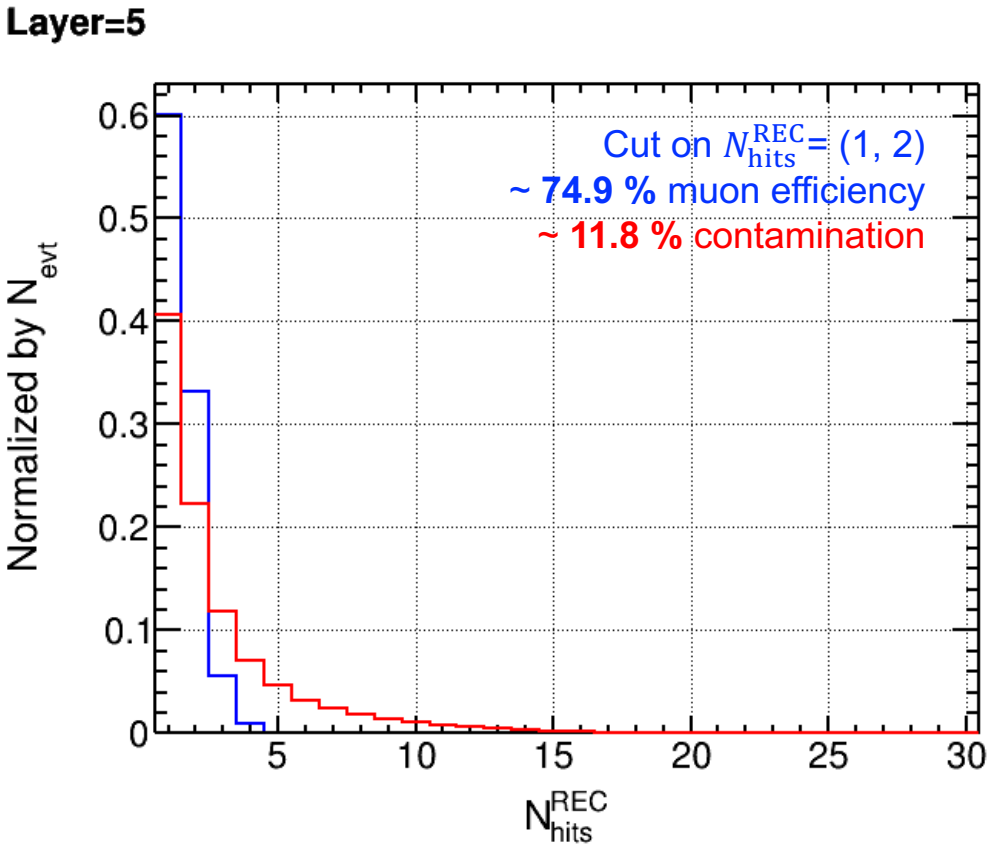


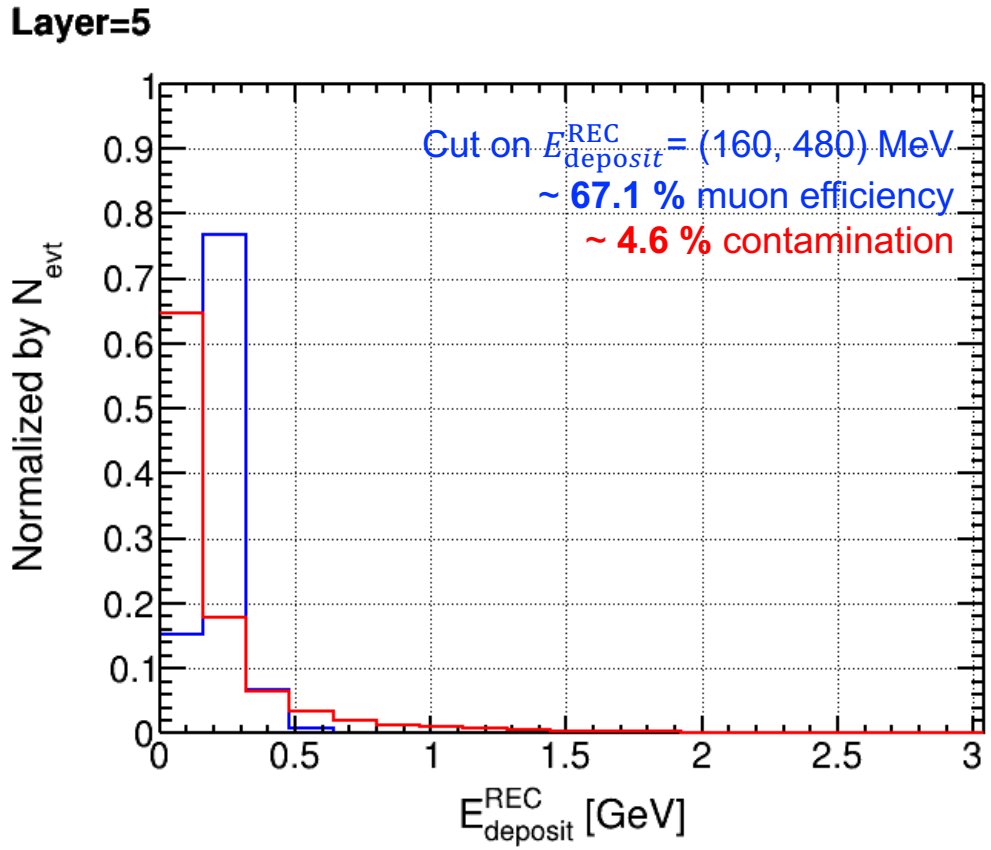


Comparing muon, pion has a long tail.
Defined a cut where muon (treated as a signal) is below pion (treated as a background)

Muons Pions

Comparison – Forward HCAL (Layer5)

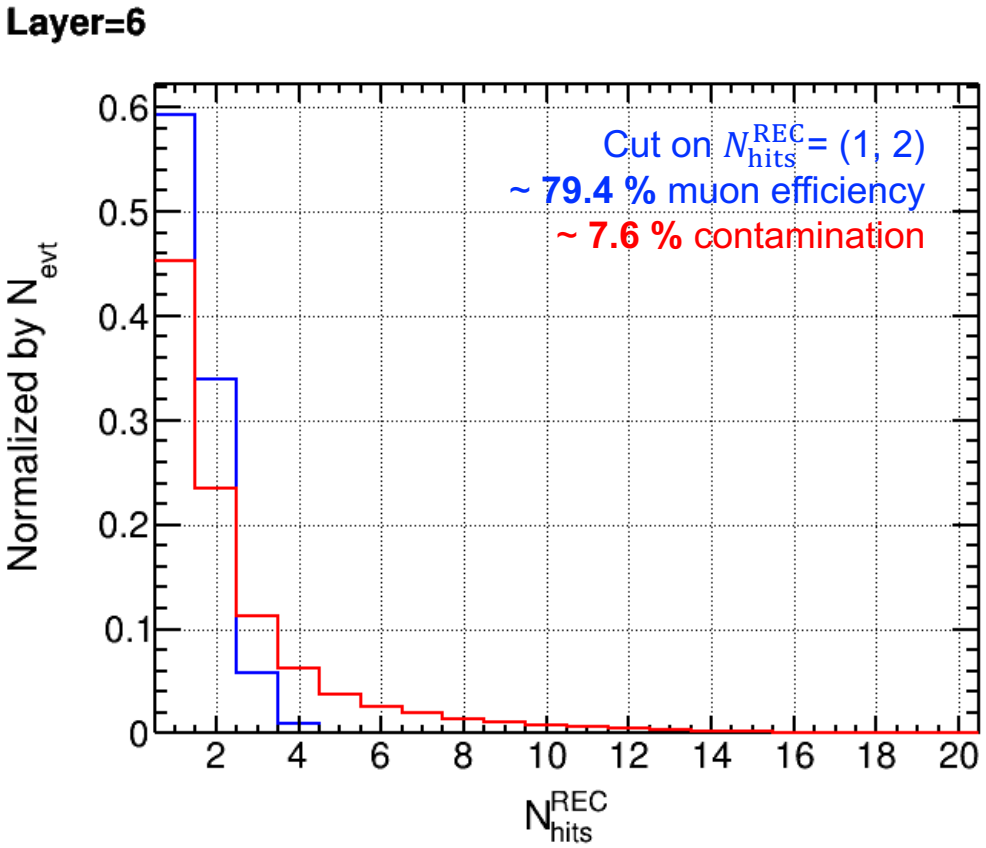


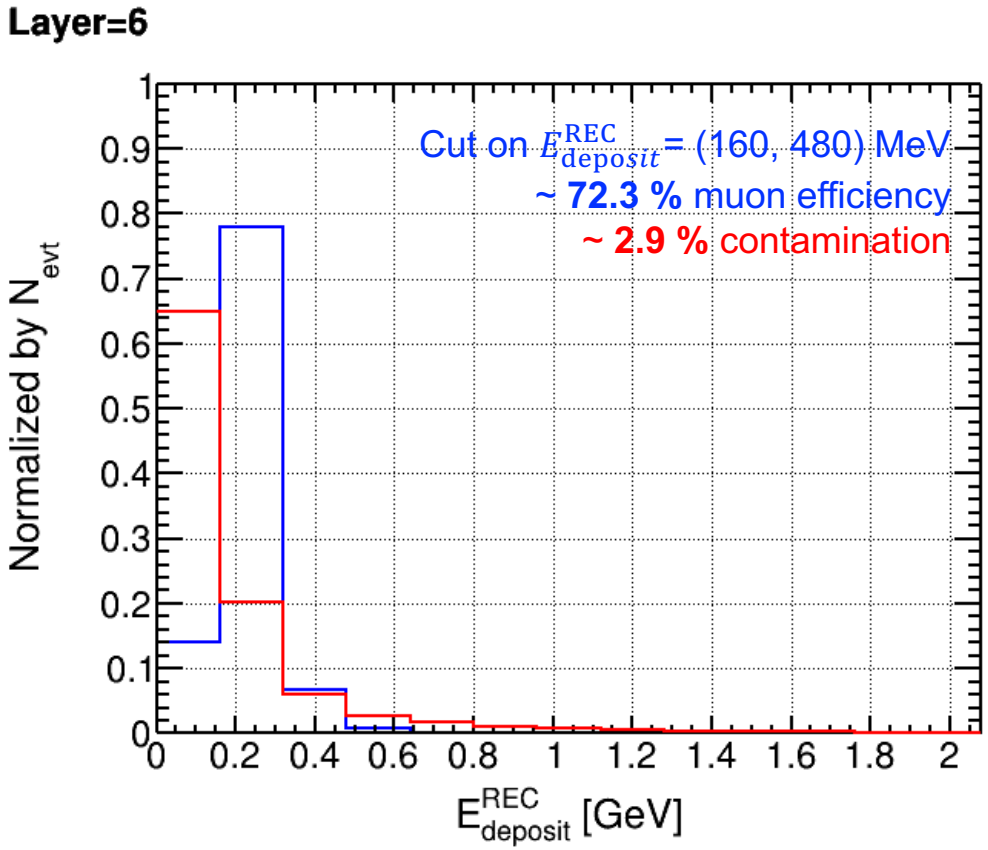


Comparing muon, pion has a long tail.
Defined a cut where muon (treated as a signal) is below pion (treated as a background)

Muons Pions

Comparison – Forward HCAL (Layer6)





Comparing muon, pion has a long tail.
Defined a cut where muon (treated as a signal) is below pion (treated as a background)

ePIC Simulation – Results

So, How We Apply Cut for Muon ID?

- Cut parameters based on comparison between muon and pion
  - Current "**pass-0**" on **whole ECAL** and **whole HCAL** $(N_{\text{hits}}^{\text{REC}}, E_{\text{deposit}}^{\text{REC}})$

η = 1.74 (θ = 20°)

Cut Params	p = 10 GeV	
Stage	ECAL	HCAL
$N_{\text{hits}}^{\text{REC}}$	> 9	14 < hits < 22
$E_{\text{deposit}}^{\text{REC}}$	> 600 MeV	1.20 GeV < E_{dep} < 2. 40 GeV
Cut Params	**p = 5 GeV**	
Stage	ECAL	HCAL
$N_{\text{hits}}^{\text{REC}}$	> 9	14 < hits < 22
$E_{\text{deposit}}^{\text{REC}}$	> 480 MeV	1.28 GeV < E_{dep} < 2.24 GeV
Cut Params	**p = 2 GeV**	
Stage	ECAL	HCAL
$N_{\text{hits}}^{\text{REC}}$	2 < hits < 7	13 < hits < 29
$E_{\text{deposit}}^{\text{REC}}$	> 480 MeV	1.28 GeV < E_{dep} < 1.92 GeV
Cut Params	**p = 1 GeV**	
Stage	ECAL	HCAL
$N_{\text{hits}}^{\text{REC}}$	2 < hits < 6	5 < hits < 11
$E_{\text{deposit}}^{\text{REC}}$	160 MeV < E_{dep} < 480 MeV	480 MeV < E_{dep} < 960 MeV

η = 3.13 (θ = 5°)

Cut Params	p = 10	
Stage	ECAL	HCAL
$N_{\text{hits}}^{\text{REC}}$	> 5	> 13
$E_{\text{deposit}}^{\text{REC}}$	> 400 MeV	E_{dep} < 0.20 GeV & 1 GeV < E_{dep} < 2. 20 GeV
Cut Params	**p = 5 GeV**	
Stage	ECAL	HCAL
$N_{\text{hits}}^{\text{REC}}$	> 5	hits < 2 & 7 < hits < 12
$E_{\text{deposit}}^{\text{REC}}$	> 320 MeV	0.96 GeV < E_{dep} < 2.08 GeV
Cut Params	**p = 2 GeV**	
Stage	ECAL	HCAL
$N_{\text{hits}}^{\text{REC}}$	> 4	7 < hits < 15
$E_{\text{deposit}}^{\text{REC}}$	> 320 MeV	0.80 GeV < E_{dep} < 1.92 GeV
Cut Params	**p = 1 GeV**	
Stage	ECAL	HCAL
$N_{\text{hits}}^{\text{REC}}$	> 3	4 < hits < 9
$E_{\text{deposit}}^{\text{REC}}$	> 320 MeV	320 MeV < E_{dep} < 960 MeV

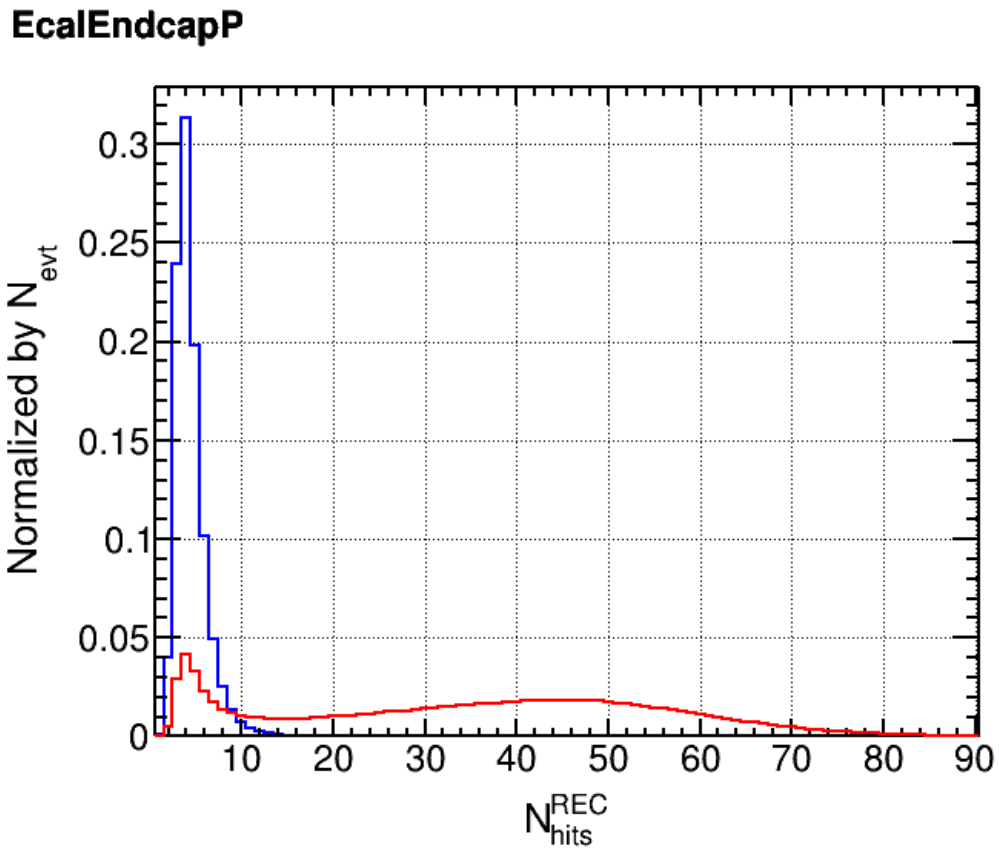
Muon Efficiency and Fake-ID Efficiency

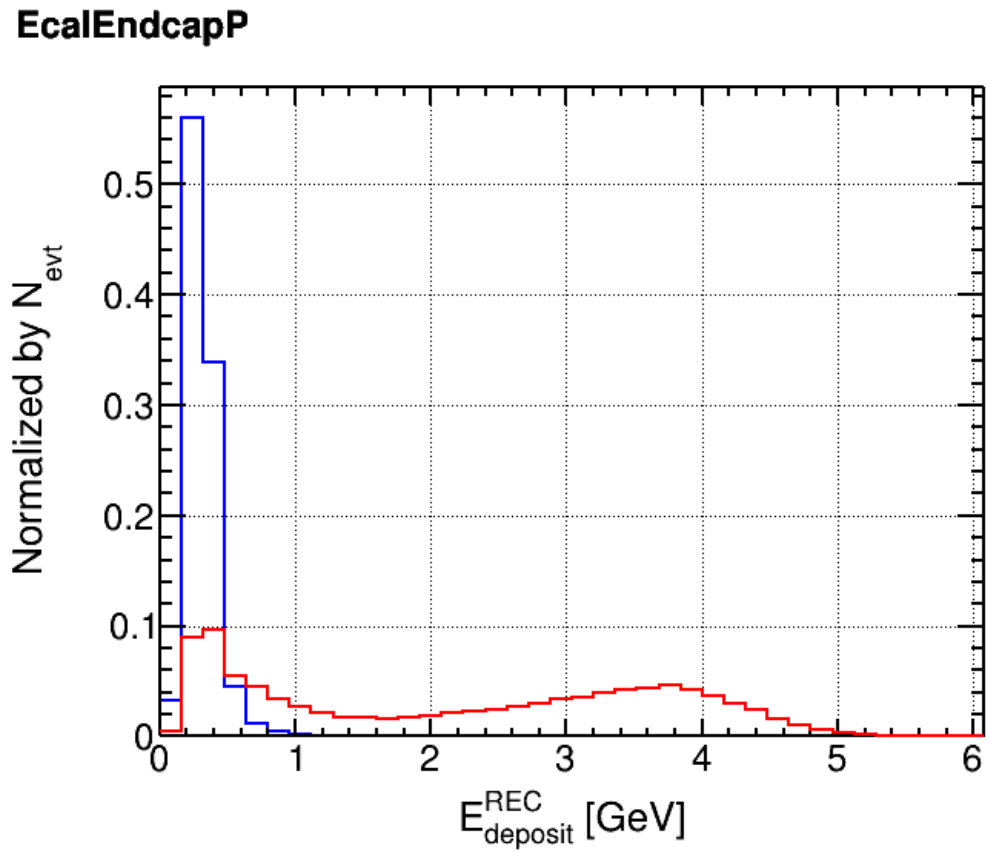
η = 1.74 (θ = 20°)	Muon Efficiency	Fake-ID Efficiency	Cut
p = 1 GeV/c	79.5 %	8.36 %	Whole ECAL **&** Whole HCAL
p = 2 GeV/c	88.6 %	6.33 %	Whole ECAL **&** Whole HCAL
p = 5 GeV/c	87.4 %	1.27 %	Whole ECAL **&** Whole HCAL
p = 10 GeV/c	86.9 %	0.68 %	Whole ECAL **&** Whole HCAL
η = 3.13 (θ = 5°)	**Muon Efficiency**	**Fake-ID Efficiency**	**Cut**
p = 1 GeV/c	41.1 %	7.99%	Whole ECAL **&** Whole HCAL
p = 2 GeV/c	50.5 %	8.07%	Whole ECAL **&** Whole HCAL
p = 5 GeV/c	47.1 %	1.40 %	Whole ECAL **&** Whole HCAL
p = 10 GeV/c	72 %	2.43 %	Whole ECAL **&** Whole HCAL

- Fake-ID efficiency (surviving pions for muon cut) level varies from 0.7 – 8.4 % and found that at higher momentum less pions are survived after muon cut
- There might be room for improvement on using layer information instead of whole HCAL
  - Consistent energy deposit and number of hits each layer throughout HCAL layers for muons

Muons Pions

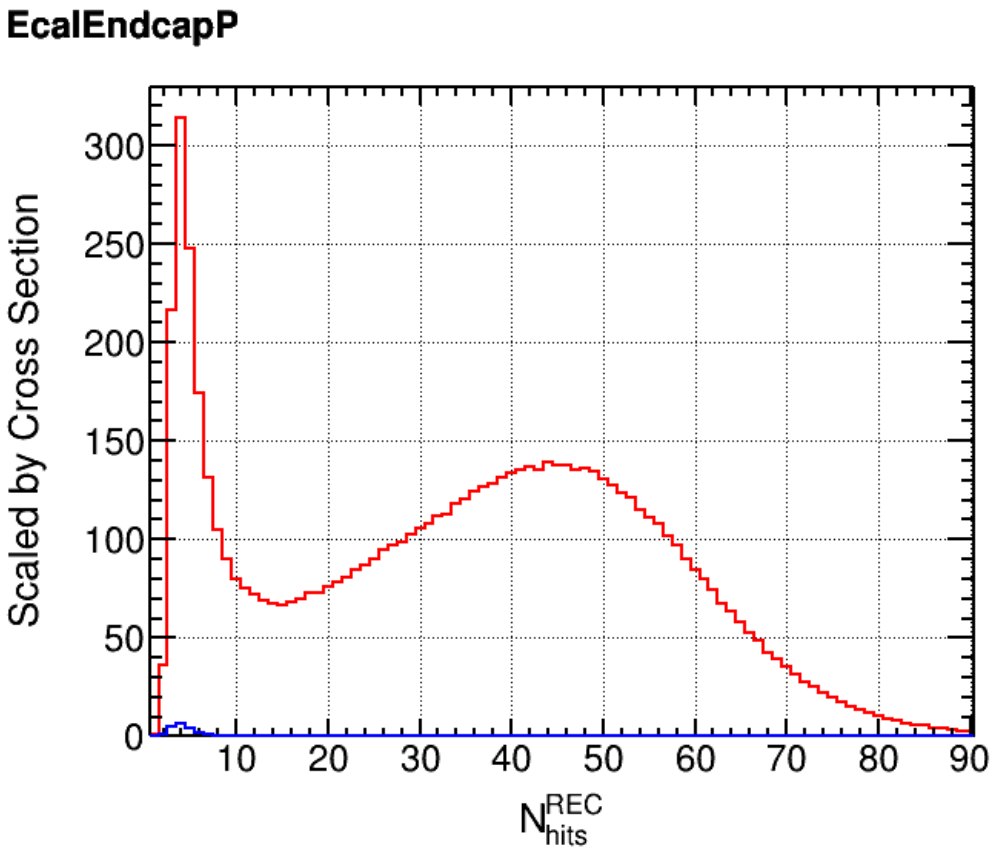
Next Step – Consider Cross Section?

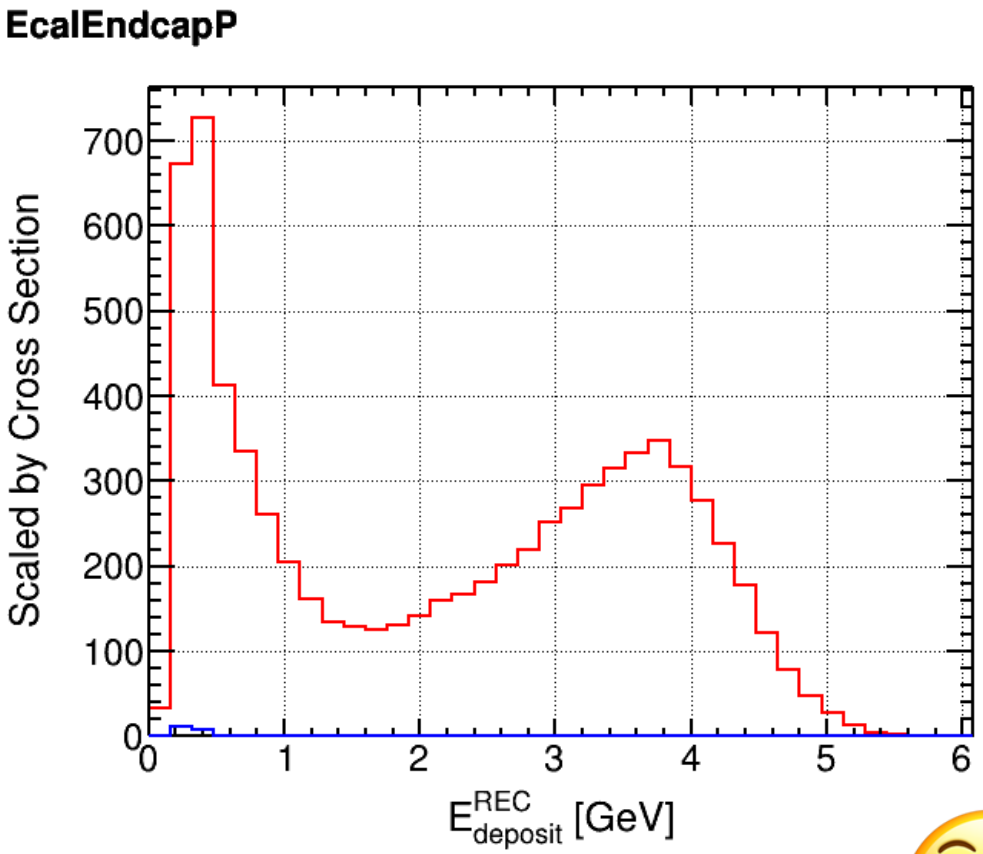




Muons Pions

Next Step – Consider Cross Section?

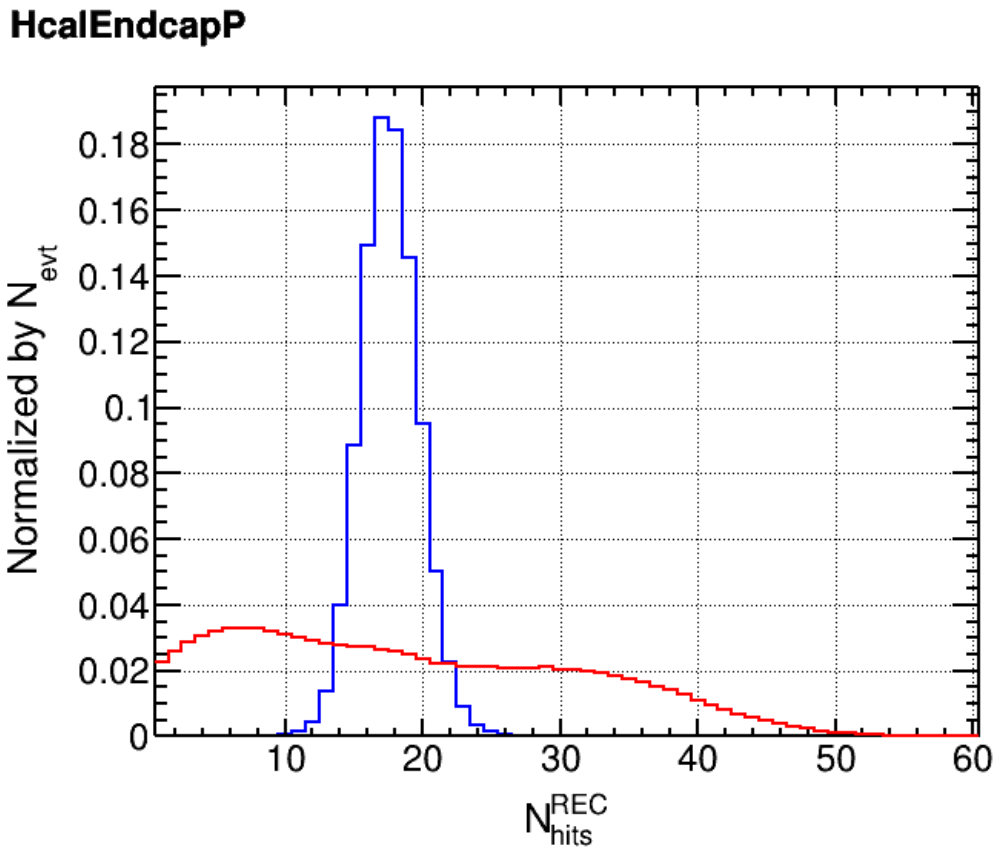


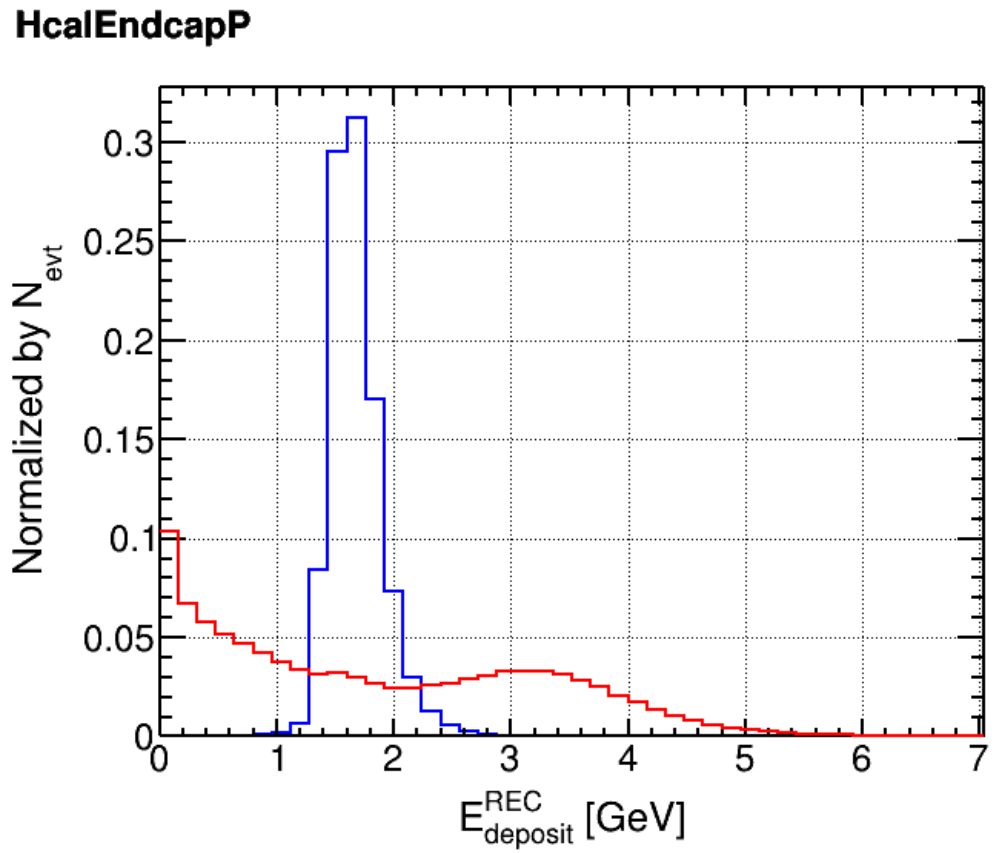


Overwhelming background from pion? 🤔

Muons Pions

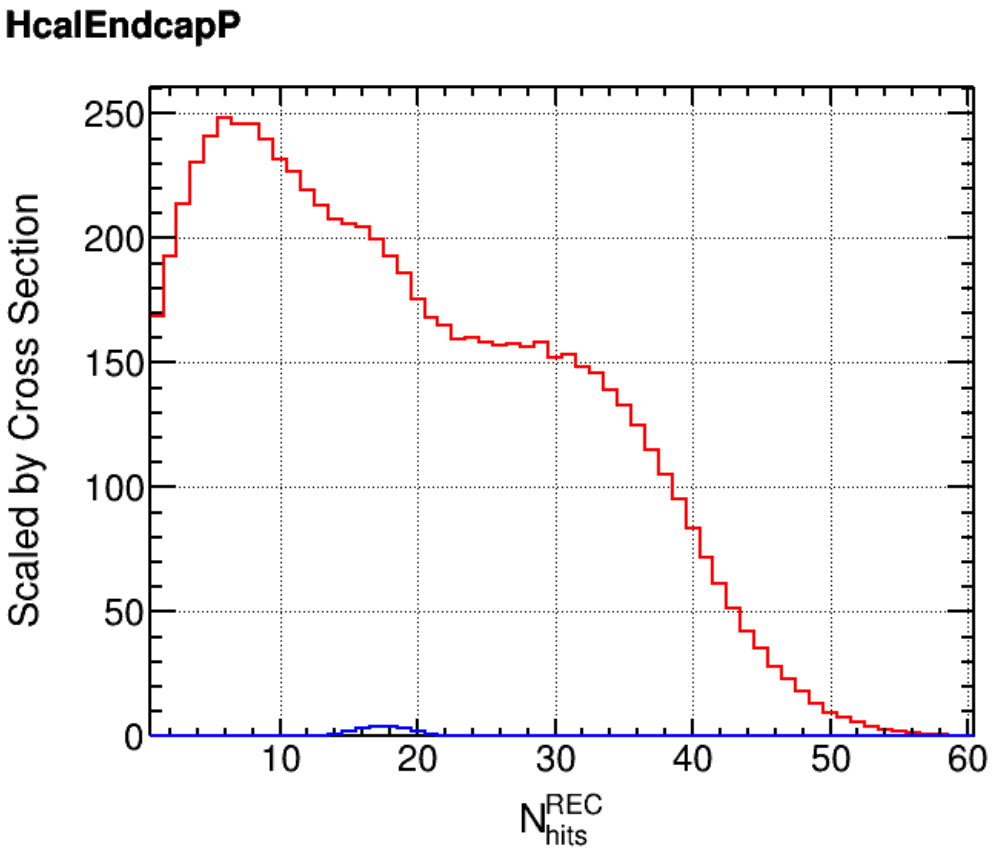
Next Step – Consider Cross Section?

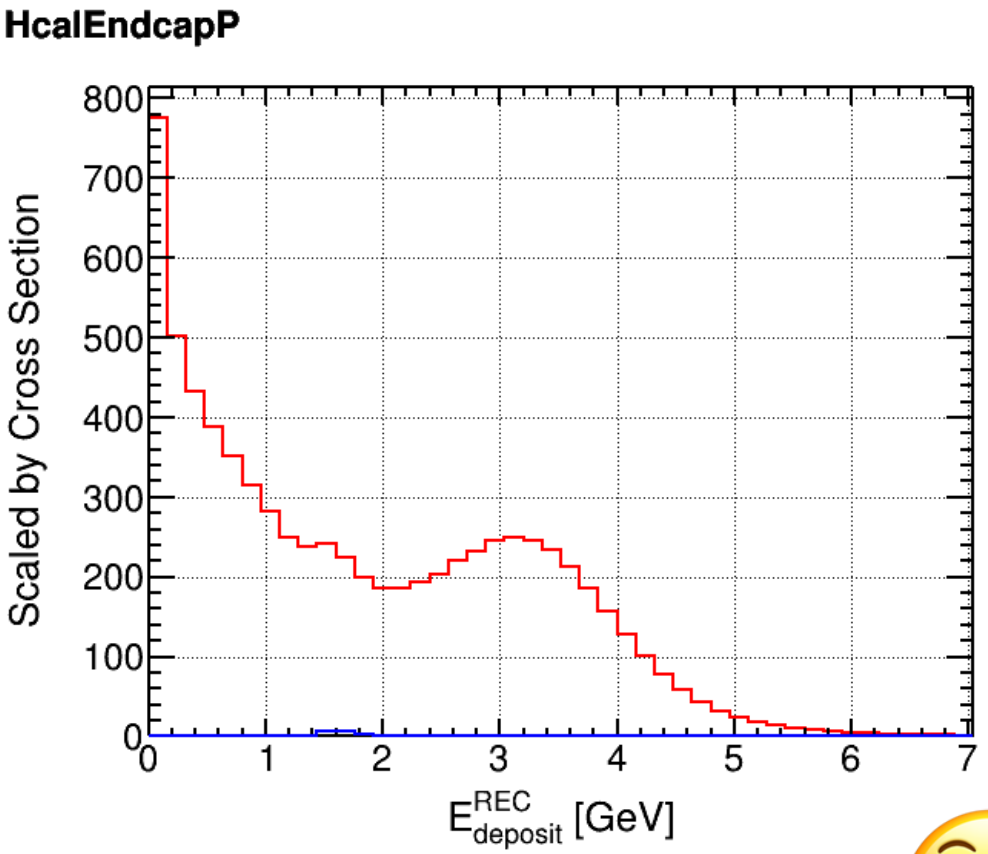




Muons Pions

Next Step – Consider Cross Section?

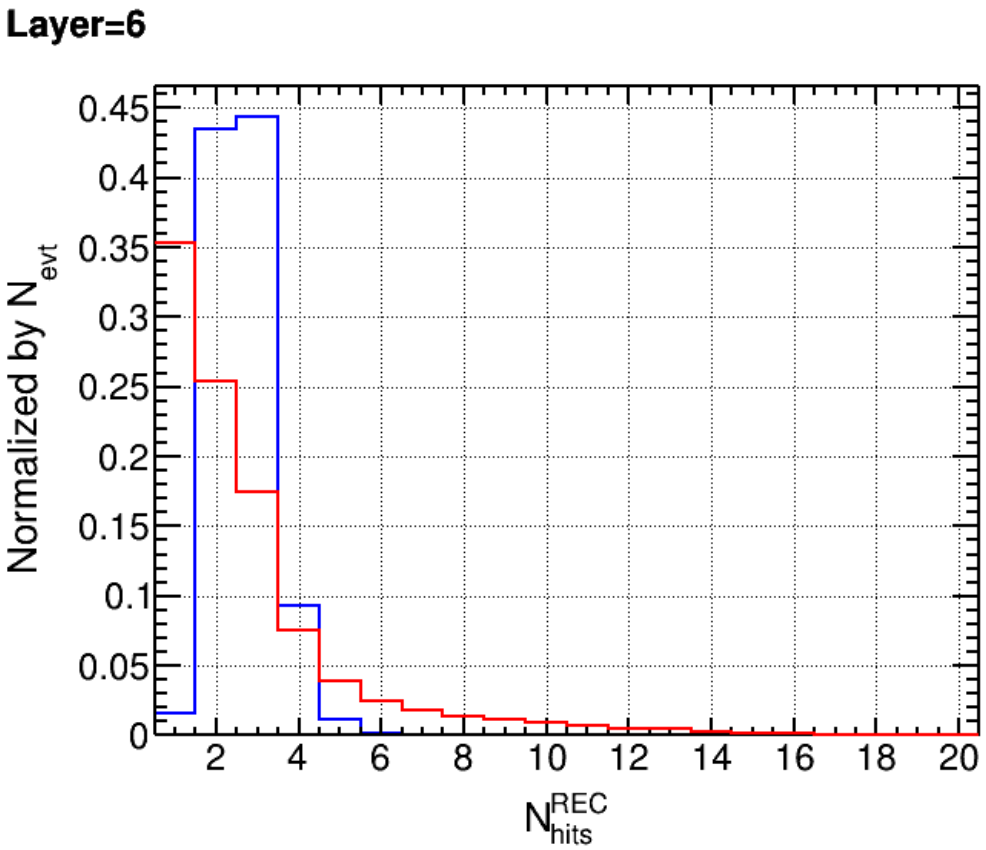


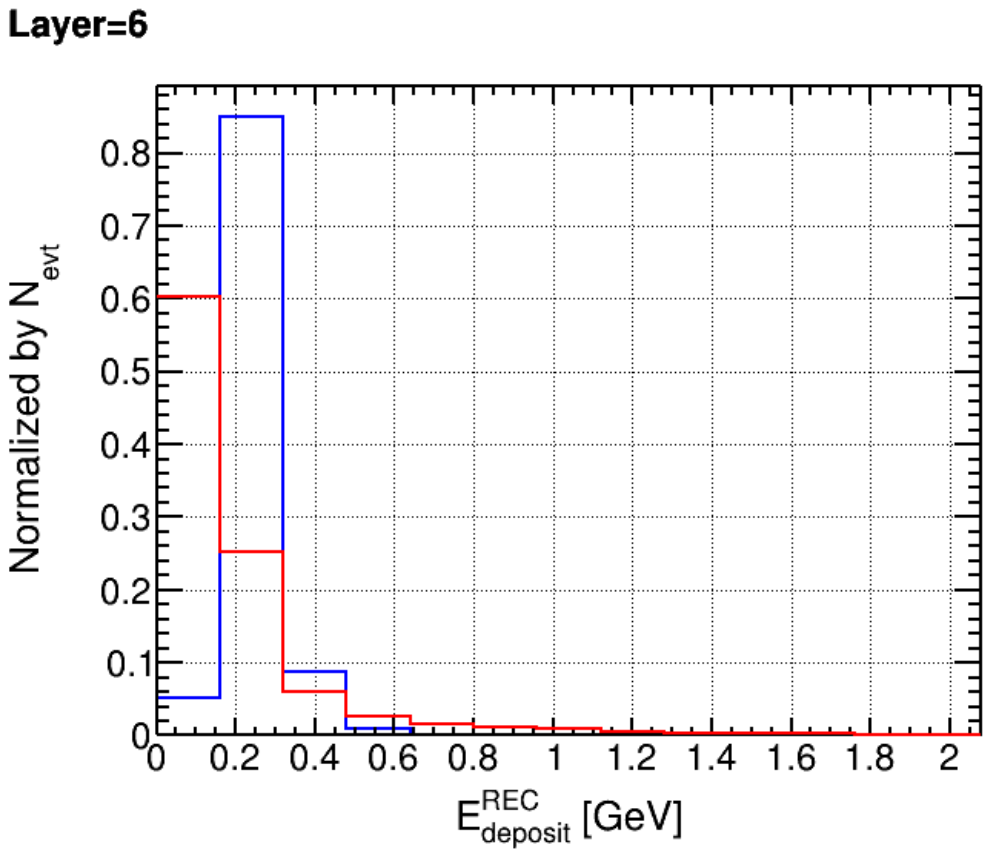


Overwhelming background from pion? 🤔

Muons Pions

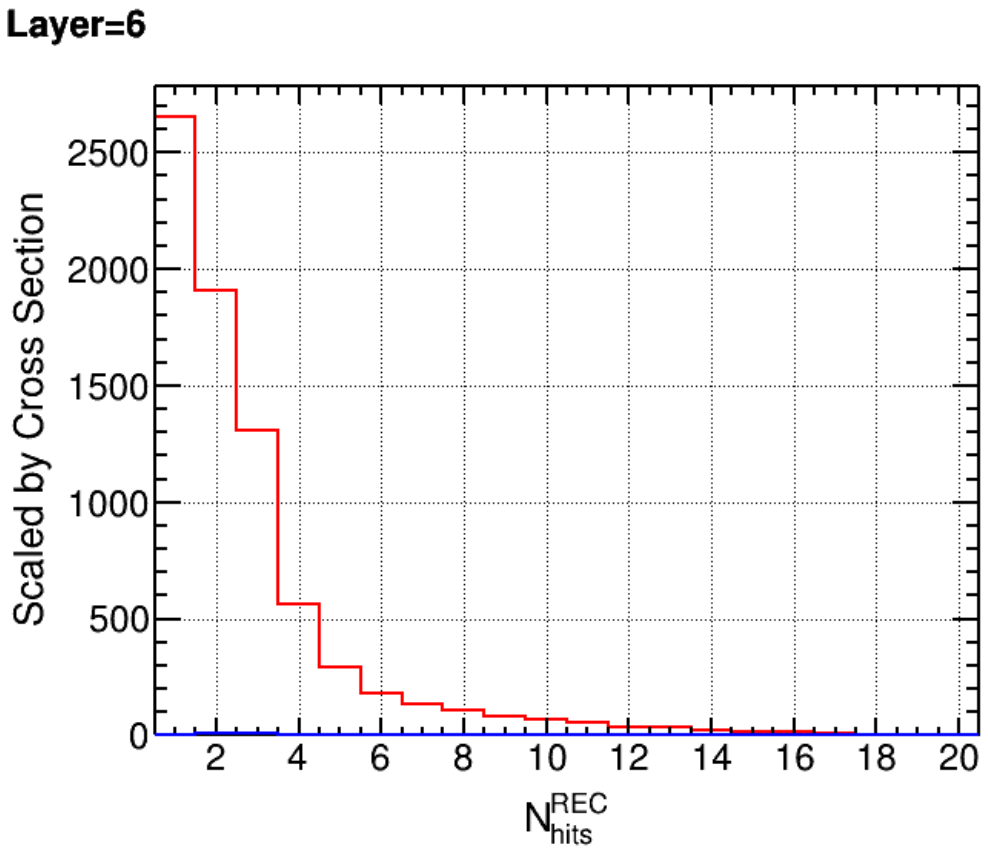
Next Step – Consider Cross Section?

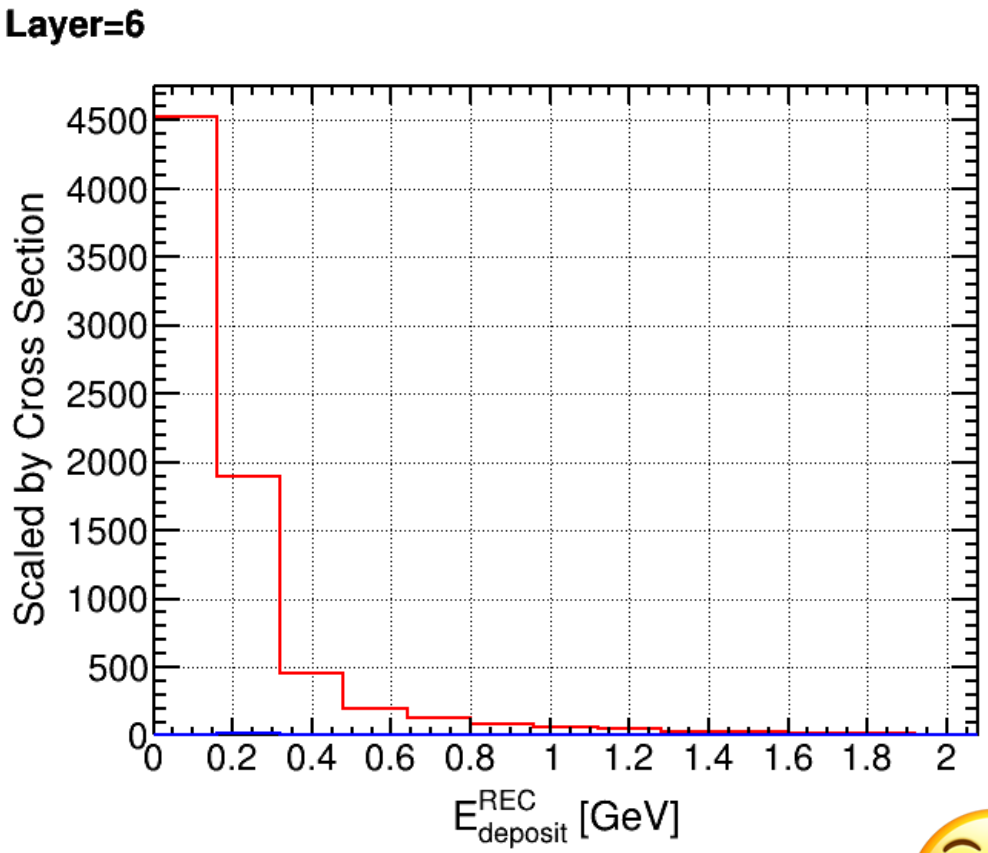




Muons Pions

Next Step – Consider Cross Section?





Overwhelming background from pion? 🤔

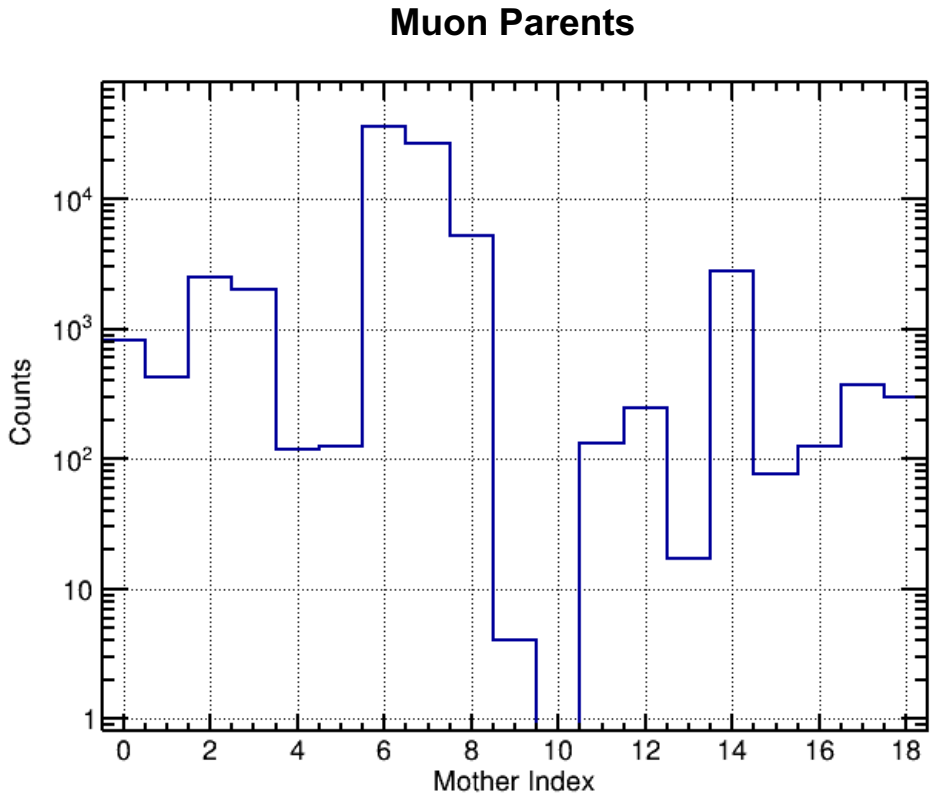
Status of IR-8 Vetoing Efficiency

- Draft of IR-8 vetoing efficiency on overleaf is **ready**
- Thinking of **EPJ C** or **PRD journal**
- https://www.overleaf.com/3628945327hgyctydxcpjp#b66c9d
- Primary message: Simple. Introduce pre-conceptual design of IR-8 and secondary focus feature. Show how powerful can be in terms of tagging and vetoing.
- Outline
  - **Introduction** – EIC, EIC 1st & 2nd detectors, and Exclusive Diffractive VM measurements
  - **Proposed IR-8 layout** – Interaction region and secondary focus feature
  - **Far-Forward Detectors** – Detector general layout and acceptance
  - **Event Generator** – BeAGLE and incoherent sample
  - **Results** – Vetoing procedure , impact of secondary focus, and neutron exit window impact
  - **Summary** – Physics case for 2nd detector ("secondary focus") will be dedicated to the next paper
- Please let me know if you have any **comments** and **feedback**. **I would appreciate it.**
- Thank you so much for your input! Xiaoxuan, Alex*, Kong, Elke, and Thomas (*English/Grammar)

Supplemental Slides

Pythia8 sample

Where Muons Come from – 18×275 GeV²

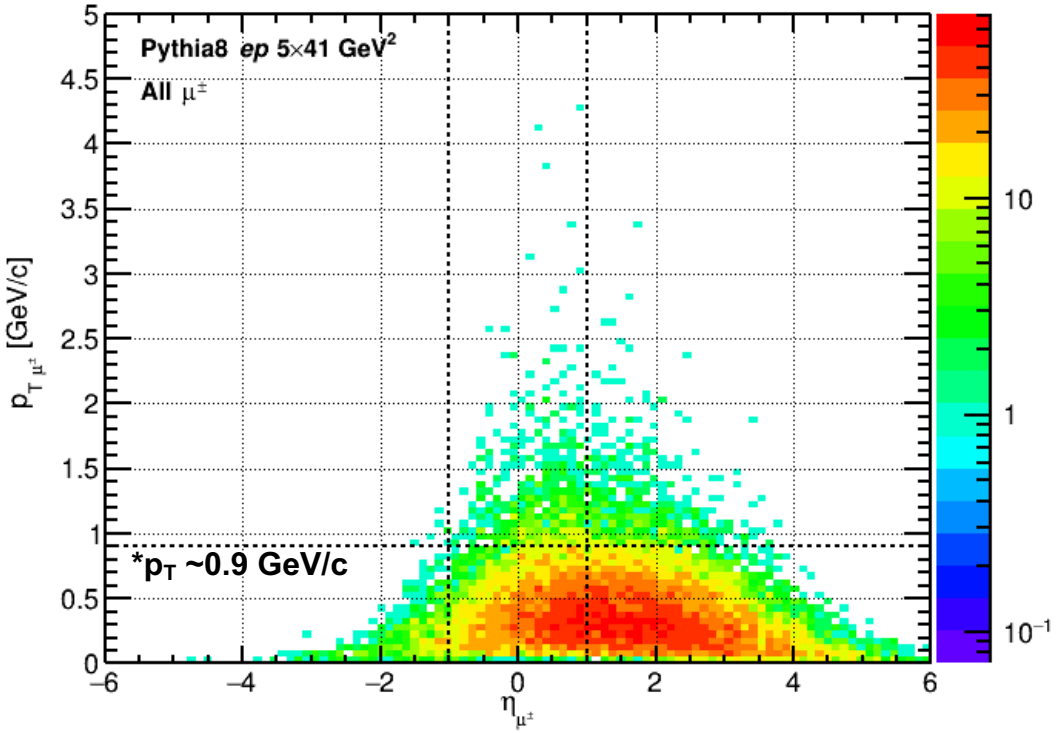


[0] τ
[1] ρ^0
[2] η
[3] ω
[4] η'
[5] ϕ
[6] D^+
[7] D^0
[8] D_s^+
[9] J/ψ
[10] Υ
[11] Σ^-
[12] Λ
[13] Ξ^-
[14] Λ_c^+
[15] Ξ_c^0
[16] Ξ_c^+
[17] $\gamma \rightarrow \mu^{\pm}$ pair production
[18] the rest (ex. B^+, B^0, …)

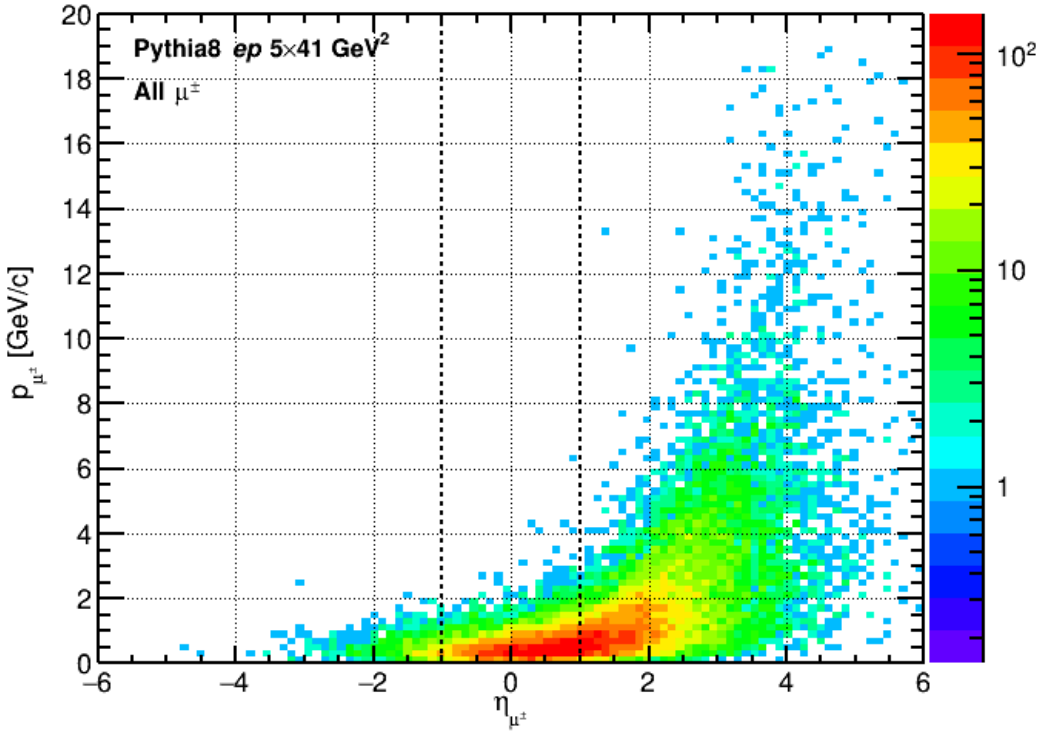
Pythia8 sample

Muon Kinematics – 5×41 GeV²

Transvers Momentum vs Pseudo-rapidity



Momentum vs Pseudo-rapidity

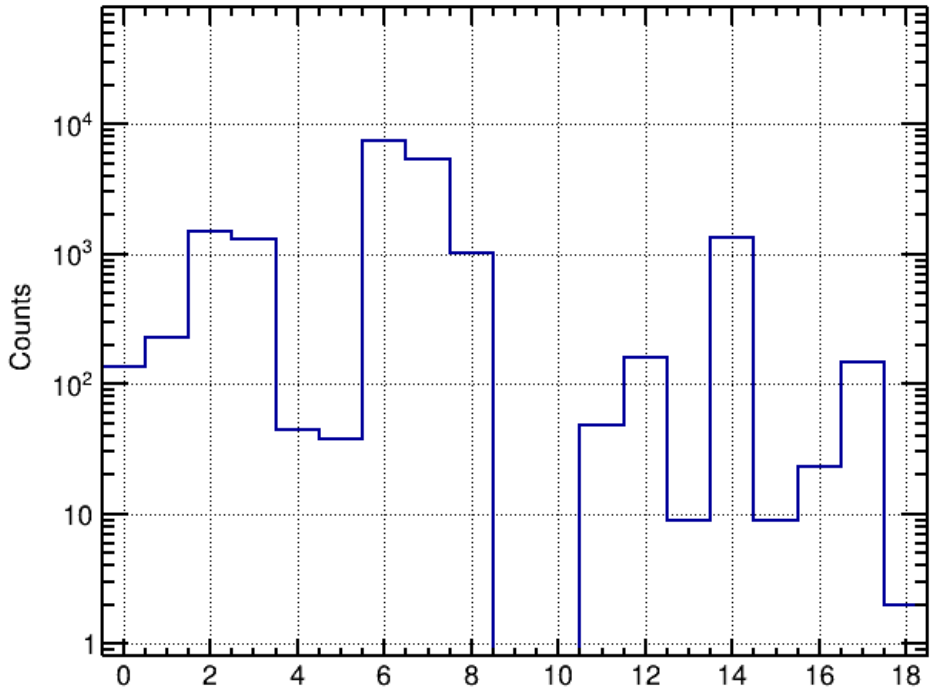


There are muons going beyond mid-rapidity ($|\eta| > 1$), but they are soft

*evaluated based on 1.7 T and R_{max} of solenoid of ePIC

Pythia8 sample

Where Muons Come from – 5×41 GeV²

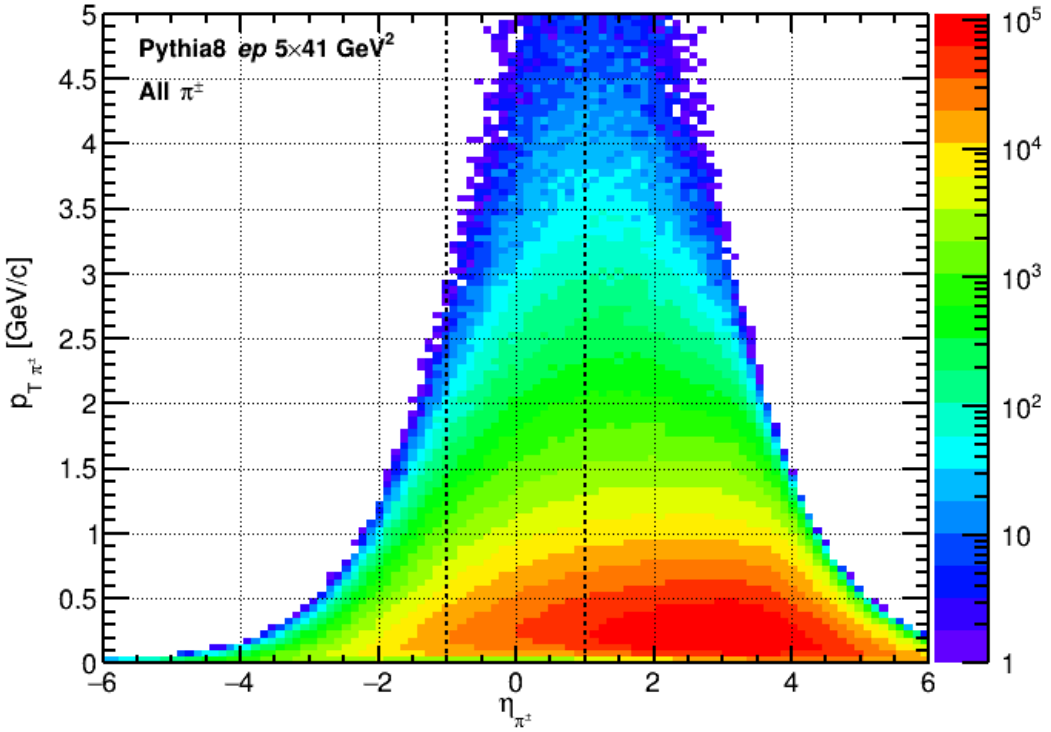


[0] τ
[1] ρ^0
[2] η
[3] ω
[4] η'
[5] ϕ
[6] D^+
[7] D^0
[8] D_s^+
[9] J/ψ
[10] Υ
[11] Σ^-
[12] Λ
[13] Ξ^-
[14] Λ_c^+
[15] Ξ_c^0
[16] Ξ_c^+
[17] $\gamma \rightarrow \mu^{\pm}$ pair production
[18] the rest (ex. B^+, B^0, …)

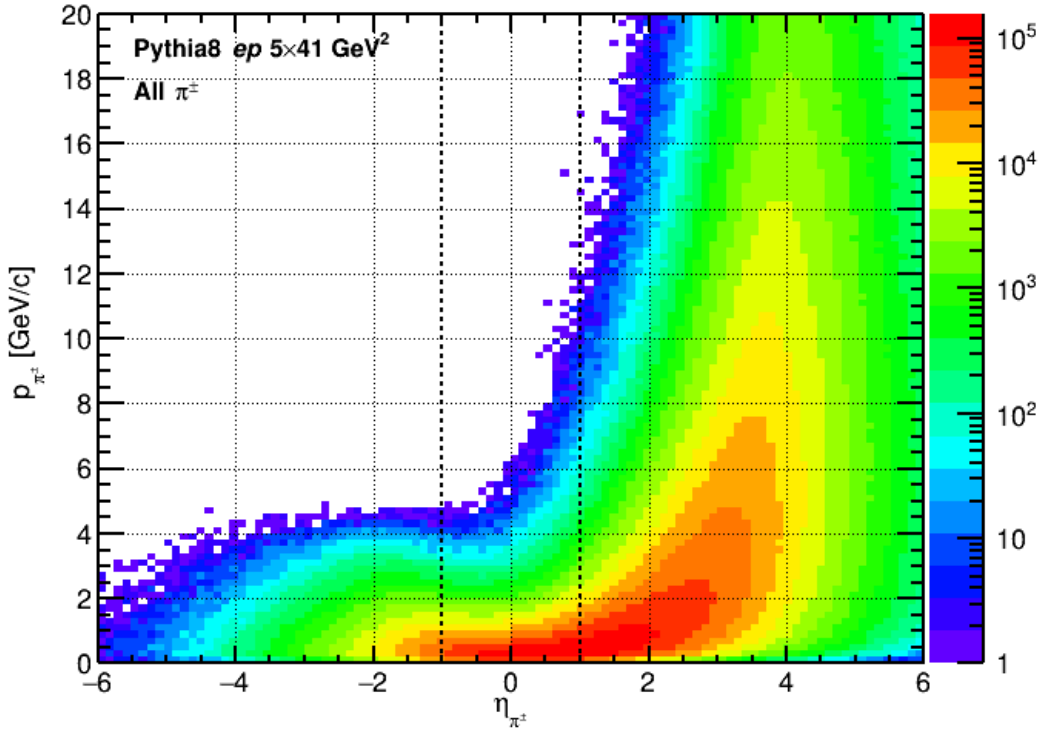
Pythia8 sample

Pion Kinematics – 5×41 GeV²

Transvers Momentum vs Pseudo-rapidity



Momentum vs Pseudo-rapidity

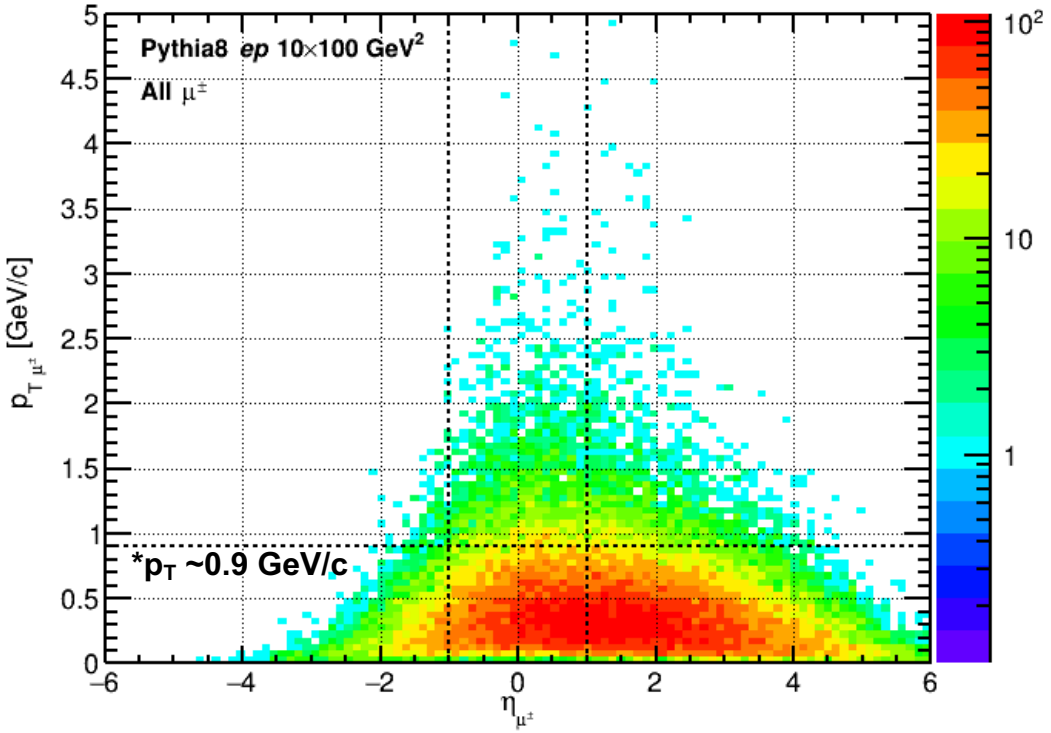


There are huge pions going forward

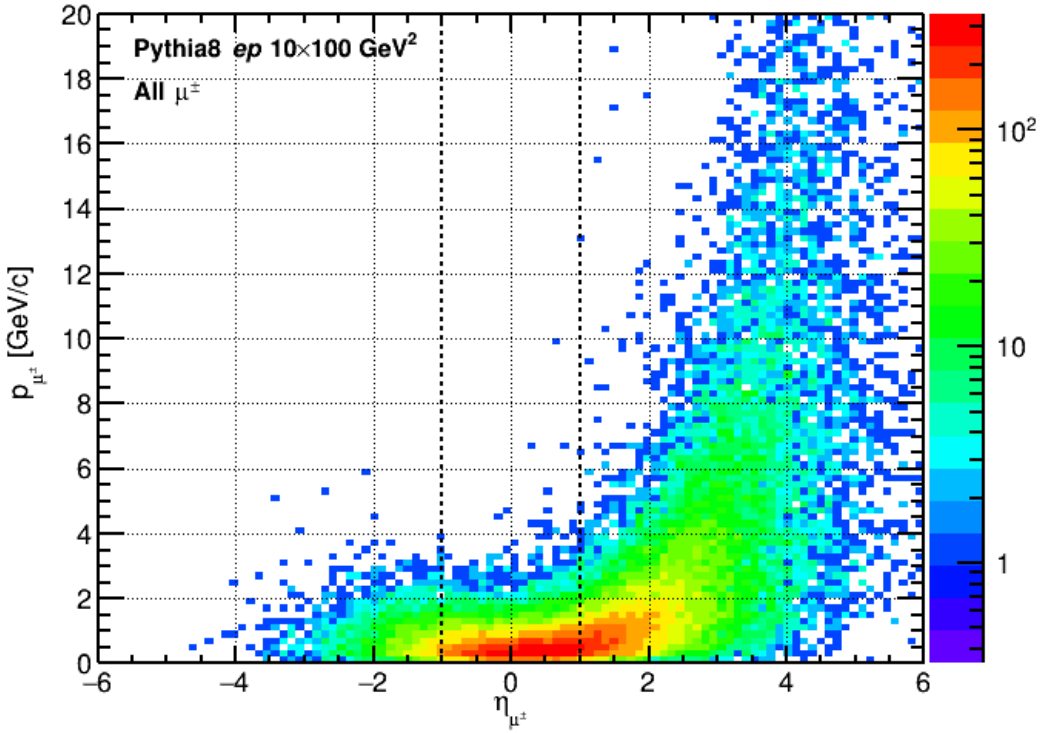
Pythia8 sample

Muon Kinematics – 10×100 GeV²

Transvers Momentum vs Pseudo-rapidity



Momentum vs Pseudo-rapidity

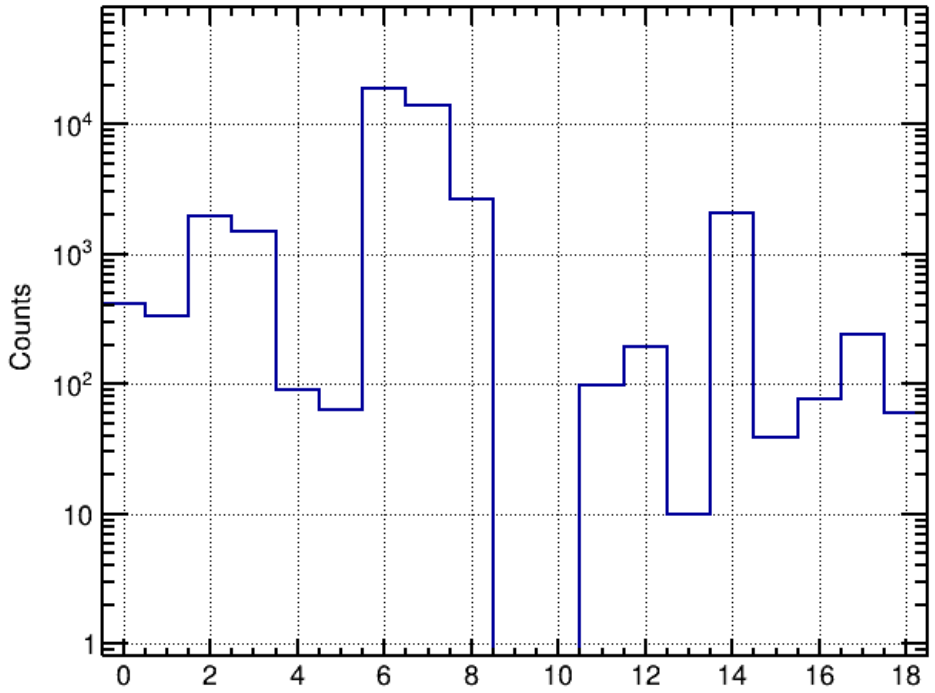


There are muons going beyond mid-rapidity ($|\eta| > 1$), but they are soft

*evaluated based on 1.7 T and R_{max} of solenoid of ePIC

Pythia8 sample

Where Muons Come from – 10×100 GeV²



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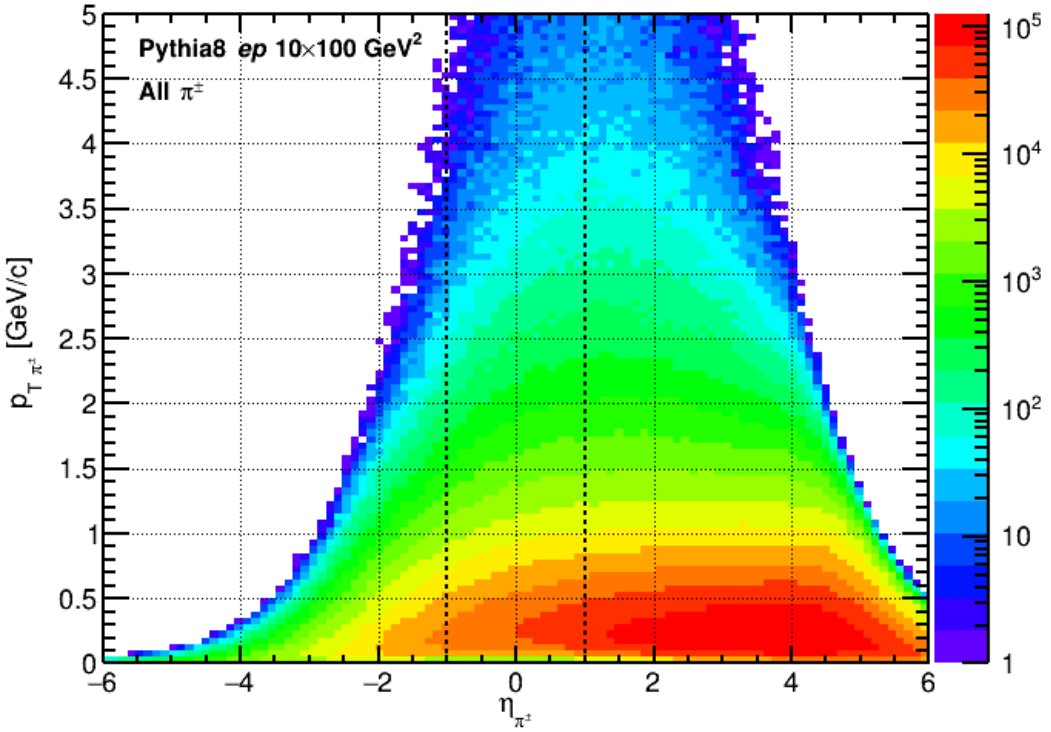
[13] Ξ^-
[14] Λ_c^+
[15] Ξ_c^0
[16] Ξ_c^+
[17] $\gamma \rightarrow \mu^{\pm}$ pair production
[18] the rest (ex. B^+, B^0, …)

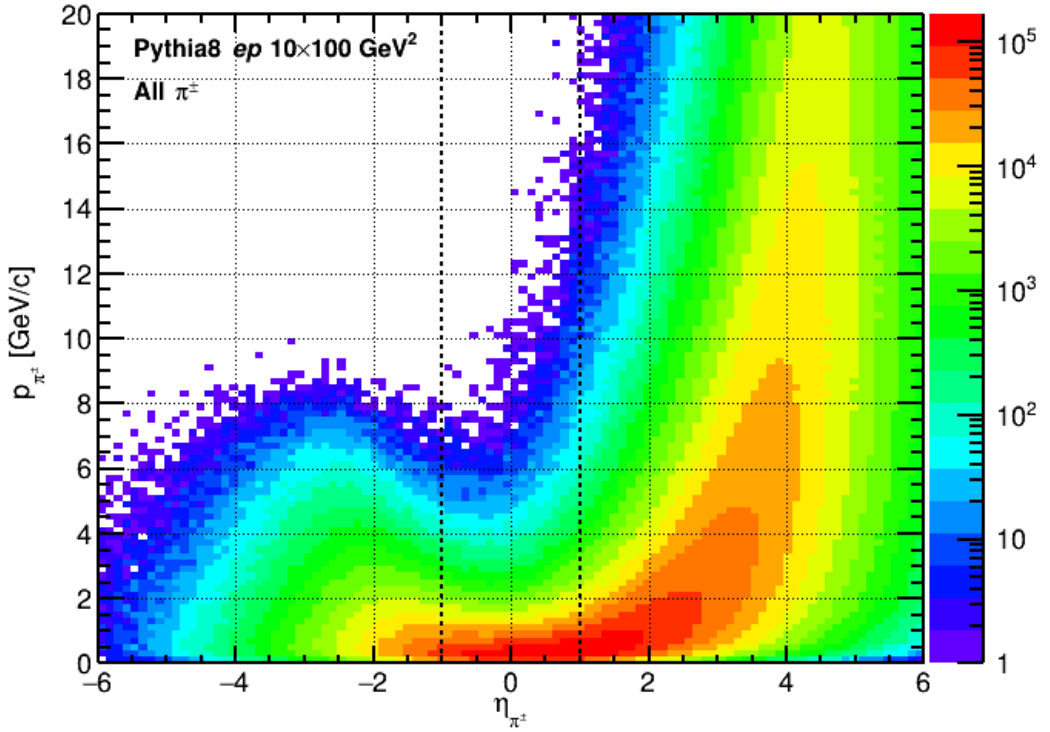
Pythia8 sample

Pion Kinematics – 10×100 GeV²

Transvers Momentum vs Pseudo-rapidity



Momentum vs Pseudo-rapidity



There are huge pions going forward

Backup Slides

Pythia8 Steering File

```
/*
Steering file for LO DIS with realistic EIC beam parameters
18x275 in High Divergence Mode
See CDR Table 3.3
*/

Main:numberOfEvents = 10000000

/*
Beam Parameters
*/

Beams:frameType = 2
Beams:idA = 2212
Beams:idB = 11

Beams:eA = 275
Beams:eB = 18

/*
PDF Selection 2 = CTEQ5L
PDF:GammaHardSet needed to try SAS Photon set, LHAPDF5 isn't linked yet ...
PDF:extrapolate = on allow extrapolations to low x
*/
PDF:pset = 2
PDF:lepton = off


/*
Subprocess Selection
*/
WeakBosonExchange:ff2ff(t:gmZ) = on


/*
Shower Settings
*/
SpaceShower:dipoleRecoil = on
SpaceShower:pTmaxMatch = 2
TimeShower:QEDshowerByL = off


/*
Photoproduction Settings and Kinematics
0 = All
1 = Resolved
2 = Direct
*/
```

```
/*
Photoproduction Settings and Kinematics
0 = All
1 = Resolved
2 = Direct
*/


/*
PhaseSpace Settings

PhaseSpace:pTHatMin = 1.0
PhaseSpace:pTHatMinDiverge = 0.5
*/
PhaseSpace:mHatMin = 1.0
PhaseSpace:pTHatMinDiverge = force 0.45
PhaseSpace:Q2Min = 1.0


/*
Hadronization and Radiation Settings
*/
HadronLevel:Decay = on
HadronLevel:all = on
PartonLevel:ISR = on
PartonLevel:MPI = off
PartonLevel:FSR = on
PromptPhoton:all = off


/*
Display Settings
*/
Init:showProcesses = off
Init:showChangedSettings = off
Init:showMultipartonInteractions = off
Init:showChangedParticleData = off

Next:numberShowInfo = 0
Next:numberShowProcess = 0
Next:numberShowEvent = 0
Next:numberCount = 10000

Random:setSeed = on
Random:seed = 0
```