ATAR Event Characterisation

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PIONEER Collaboration Meeting — Oct 17, 2023

Introduction

ATAR in PIONEER $R_{e/\mu}$ measurement

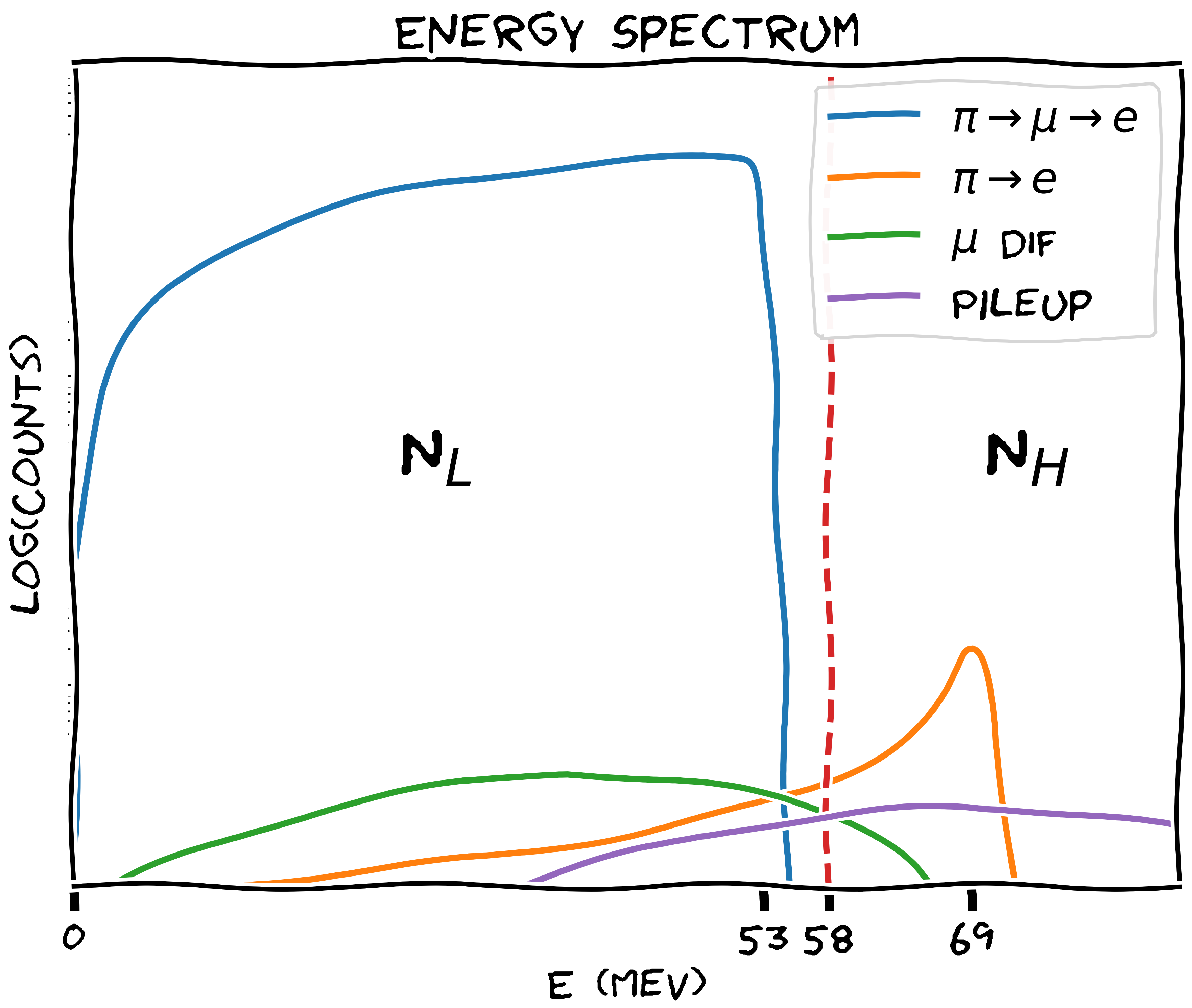
- Two important keys to successful measurement:
  - Mitigation of significant contributions from **pileup**
    - Outgoing positron track matching the pion/muon stopping vertex
  - Suppression of **decay-in-flight (DIF) backgrounds**
    - π-e timing, dE/dx and track topology

V. Wong - Overview of ATAR Physics Requirements and Simulation/Analysis

This talk → Suppression of decay-in-flight (DIF) backgrounds

Introduction

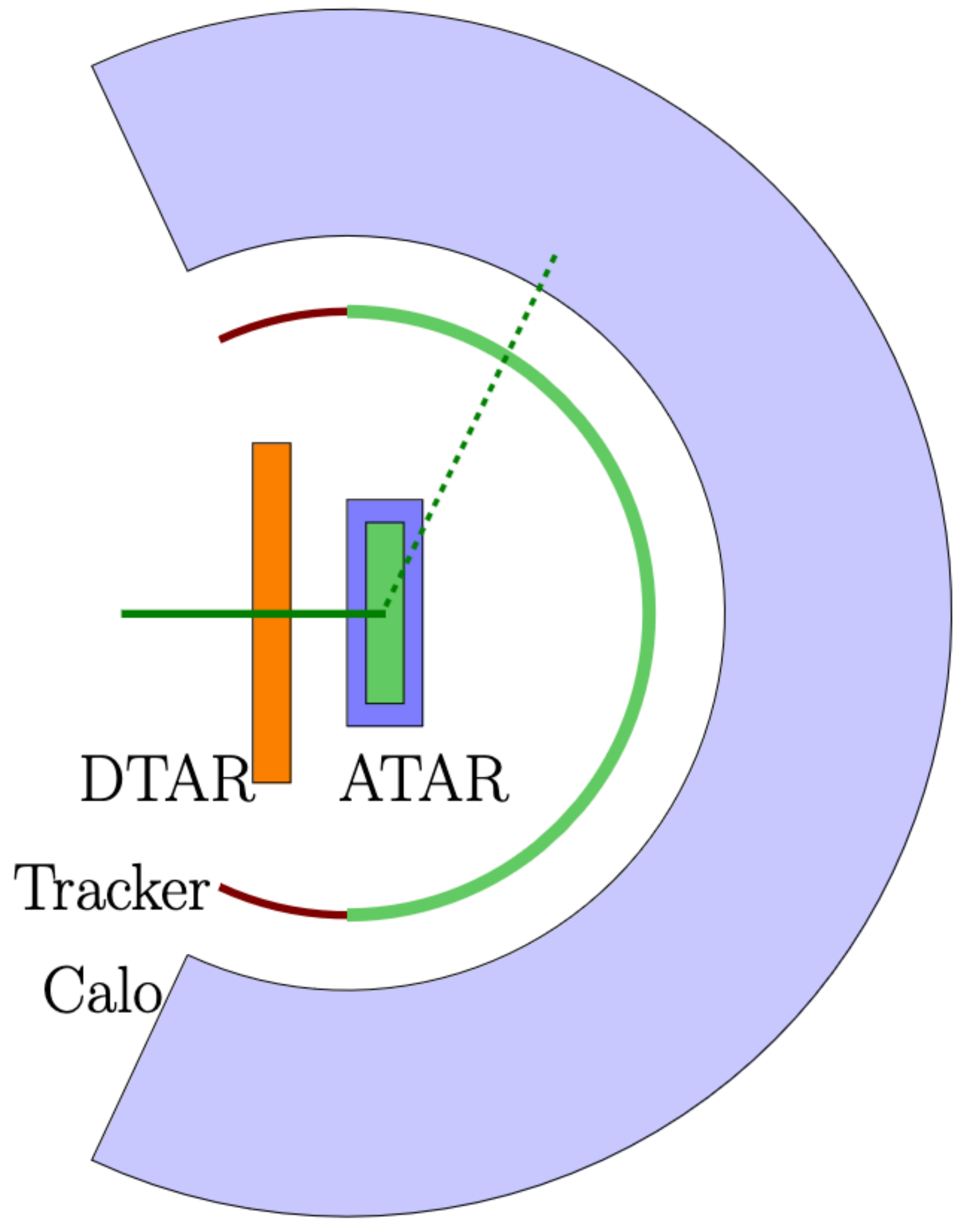
- **Assuming a tail fraction (TF) of 1%, tail analysis requirement:**
- We plan to collect 2.10^8 pi-enu events
  → it means 2.10^6 in the low energy bin
- To meet the 0.01% precision on $R_{e\mu}$, → ΔTF/TF=1%
- Low bin sample is overwhelming dominated by michel events:
  - Event reconstruction and identification are mandatory to reveal the tail
- Need $O(10^4)$ 'clean' pienu events for measuring tail correction with 1% statistical accuracy:
  - This places a constraint on signal efficiency of 1%
  - 'Clean' means essentially no background



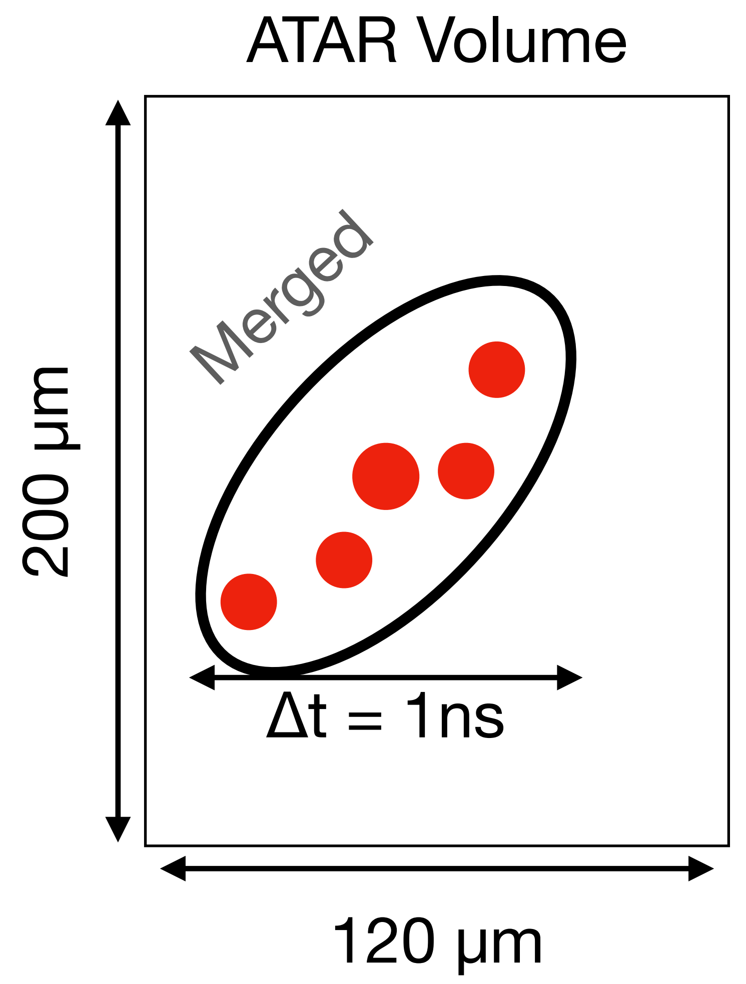
Simulation setup

Selection (*Signal efficiency = 23%*)

- Pion decays at rest enforced
- Pion and Muon decay inside ATAR
- Calo -Upstream time > 5 ns
- At least one tracker hit
- Acceptance cut using tracker hit: theta < **π/3**
- A single pattern (focus on pileup-free events)
- Pion stops inside a fiducial box in ATAR:
  -8 mm < X (Y) < +8 mm, 1.5mm < Z < 4.5mm)



Fiducial



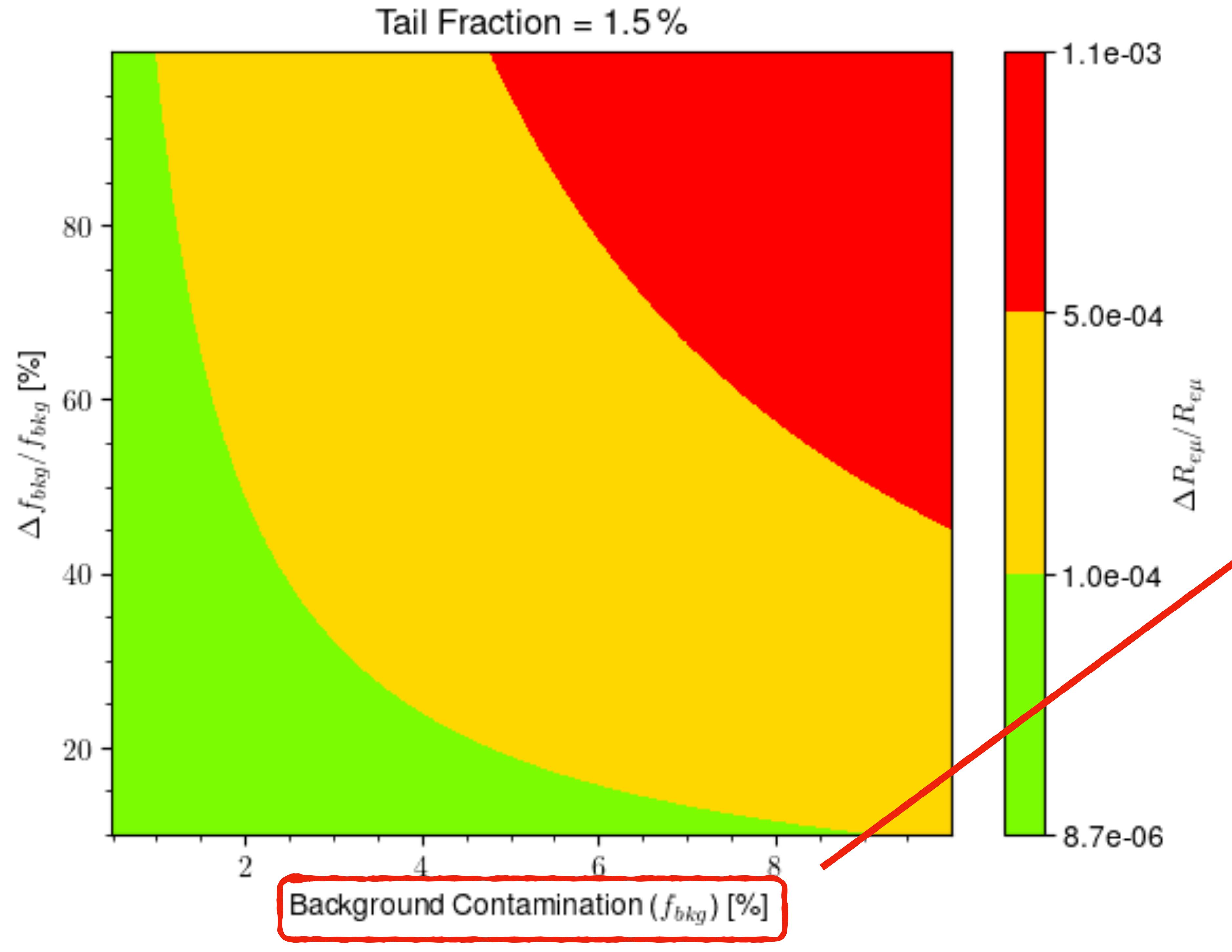
Hit merging scheme: all G4 steps within 1ns in a given active volume are merged together

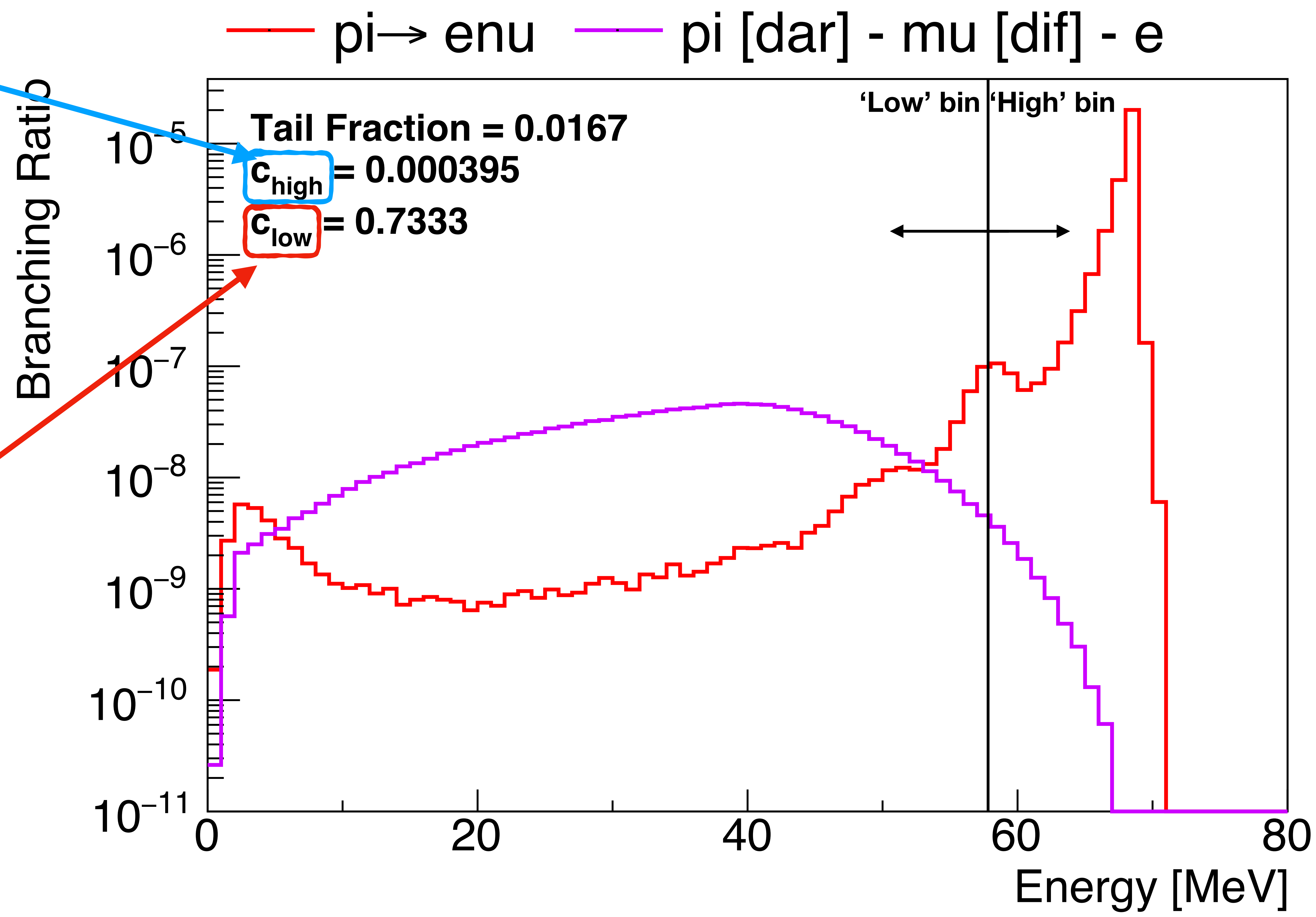
Merged hit quantities:

- Time: time of the first hit
- Energy: summed over all hits
- Position: position of the most energetic hit

Where do we start from?

A contamination in the high bin above 10^{-4} will need to be estimated carefully to not impact the measurement

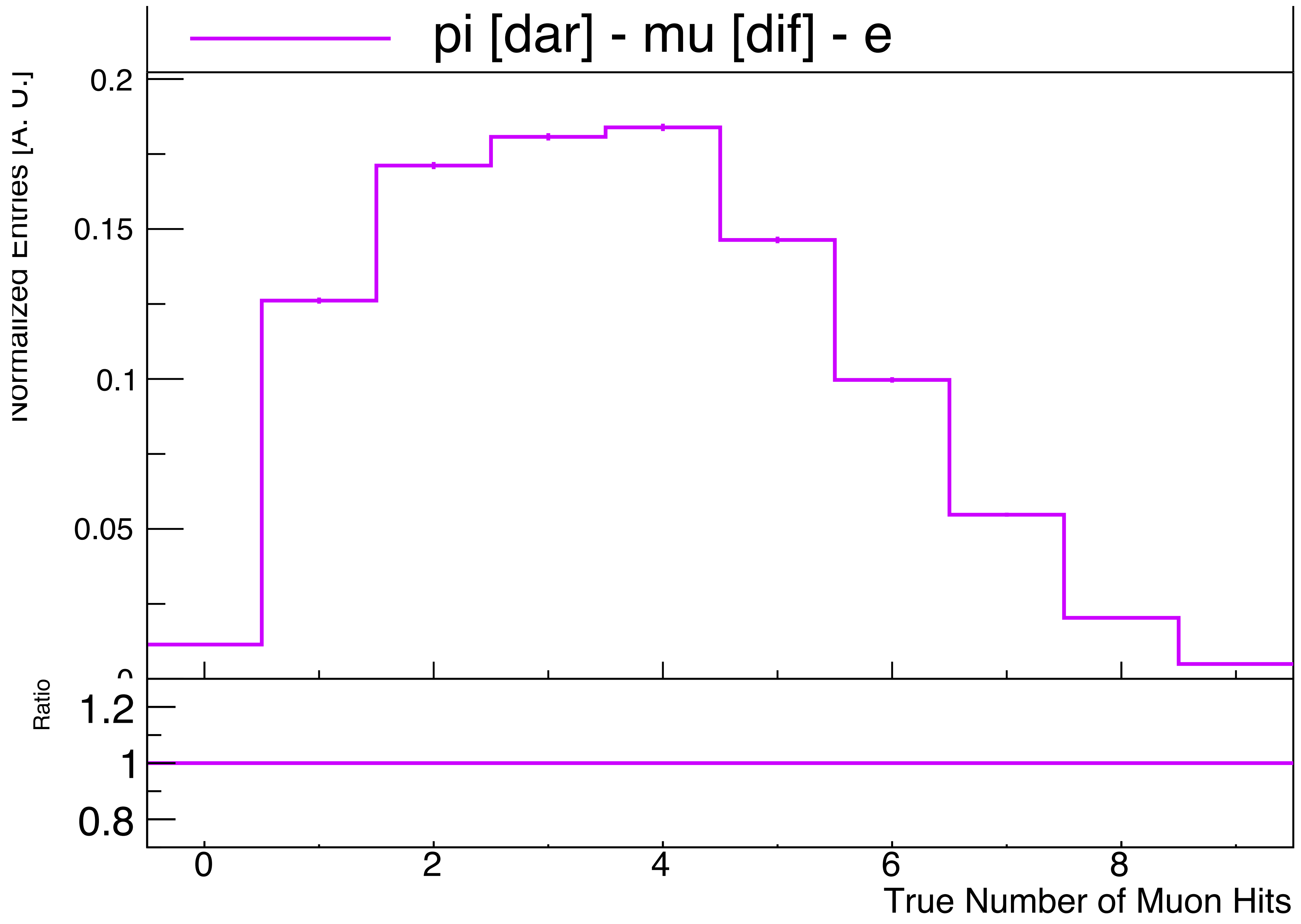


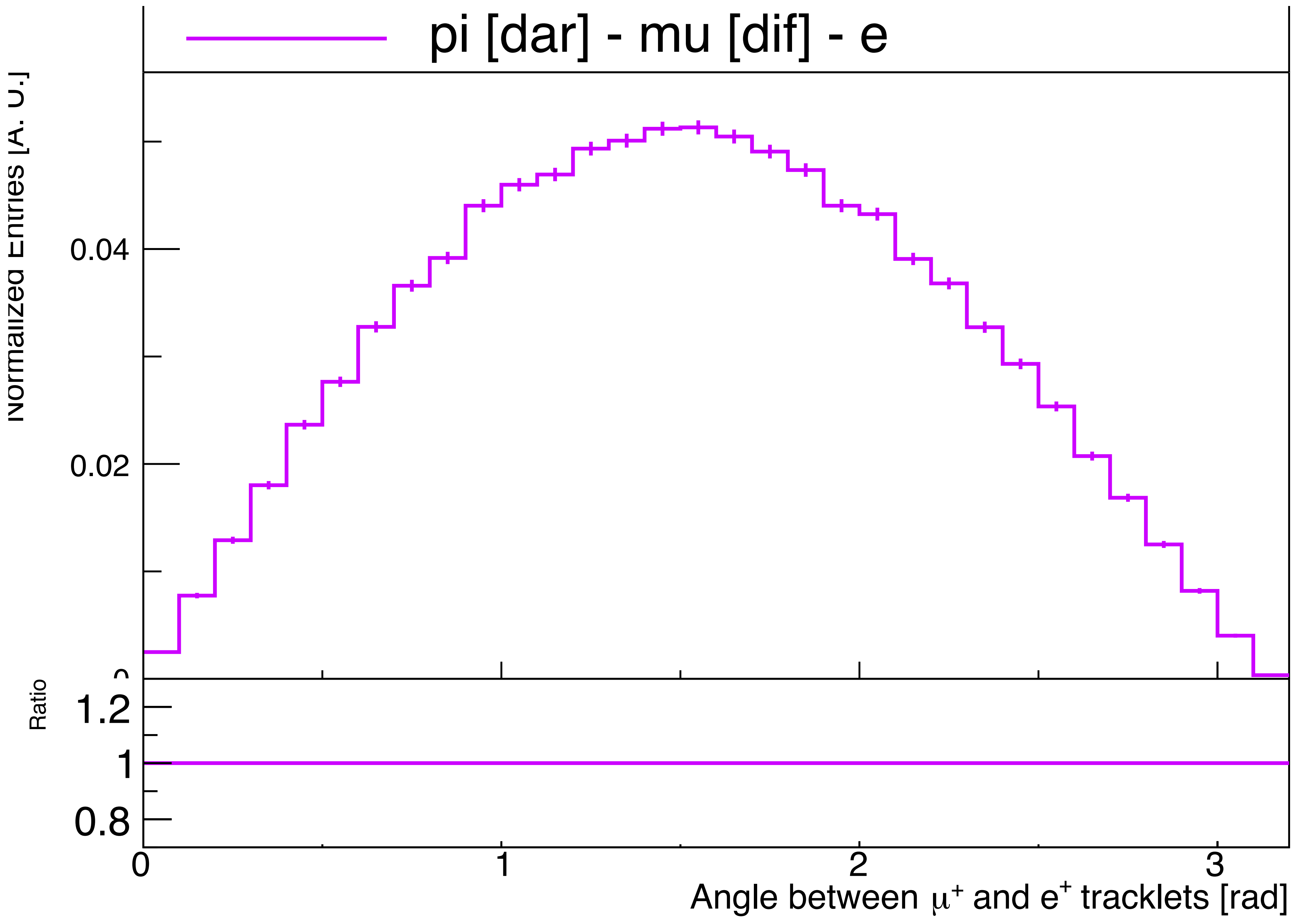


Rel. Uncert. On $R_{e\mu}$ as a function of c_{low} (X axis) and the rel. uncert. on c_{low} (y axis)

See elog-simulation-and-software-23 for details on how this plot is derived

Decay-In-Flight muon topology



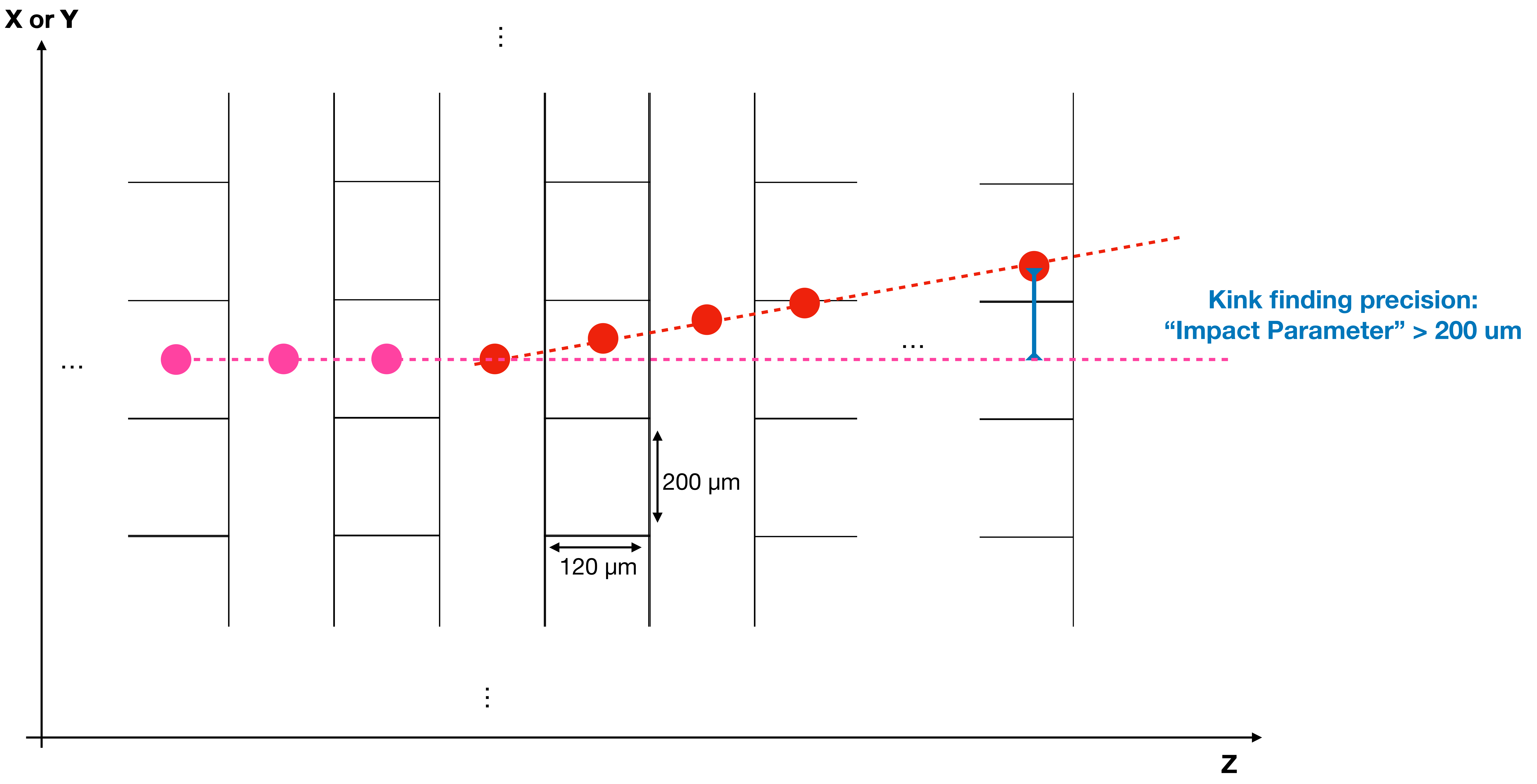


A large fraction of pi [dar] - mu [dif] - e events have a muon that travels several strips and decay to a positron with a significant opening angle

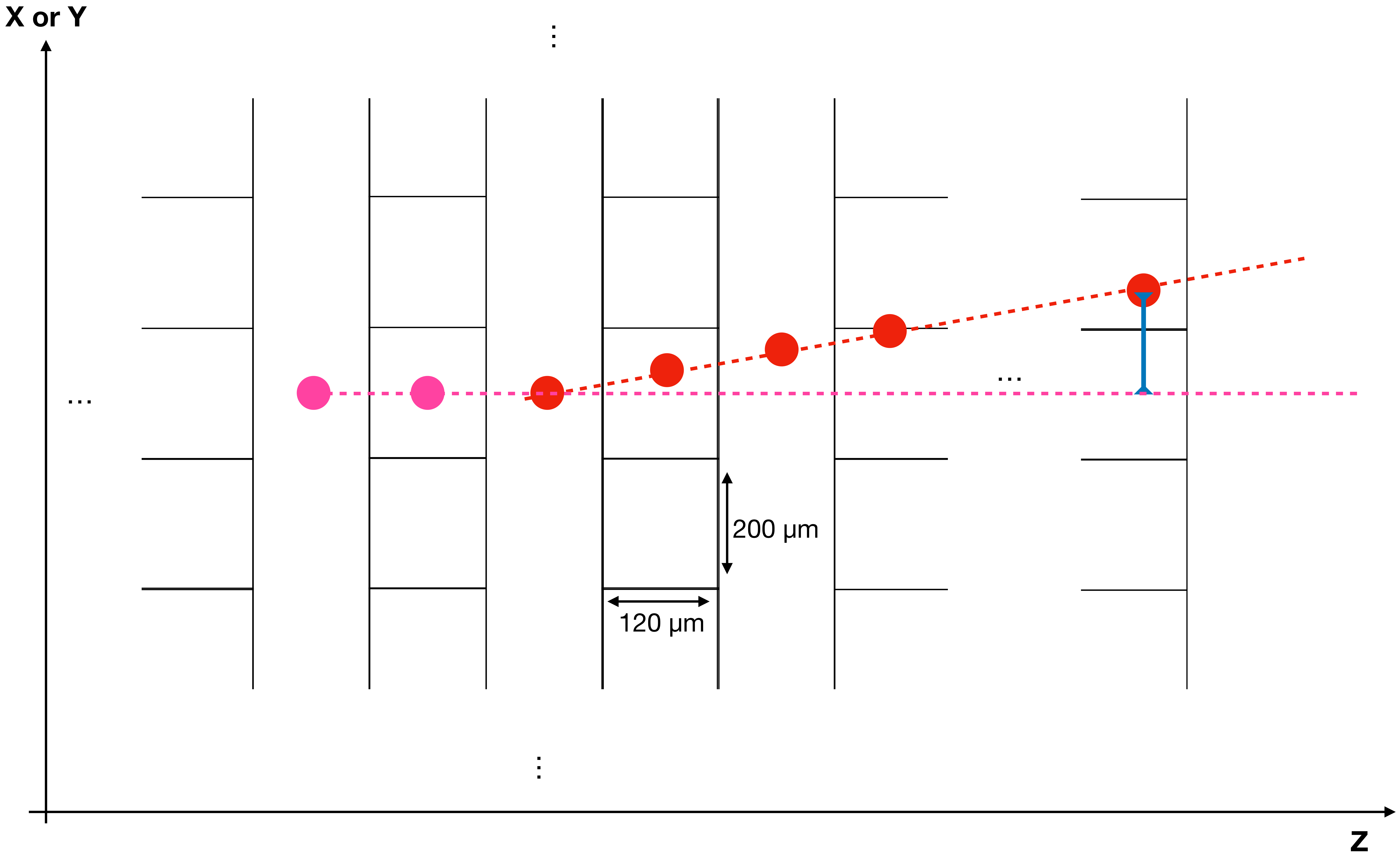
This can be leveraged with tracking in the ATAR

Using topology

3 muon hits



Using topology
2 muon hits



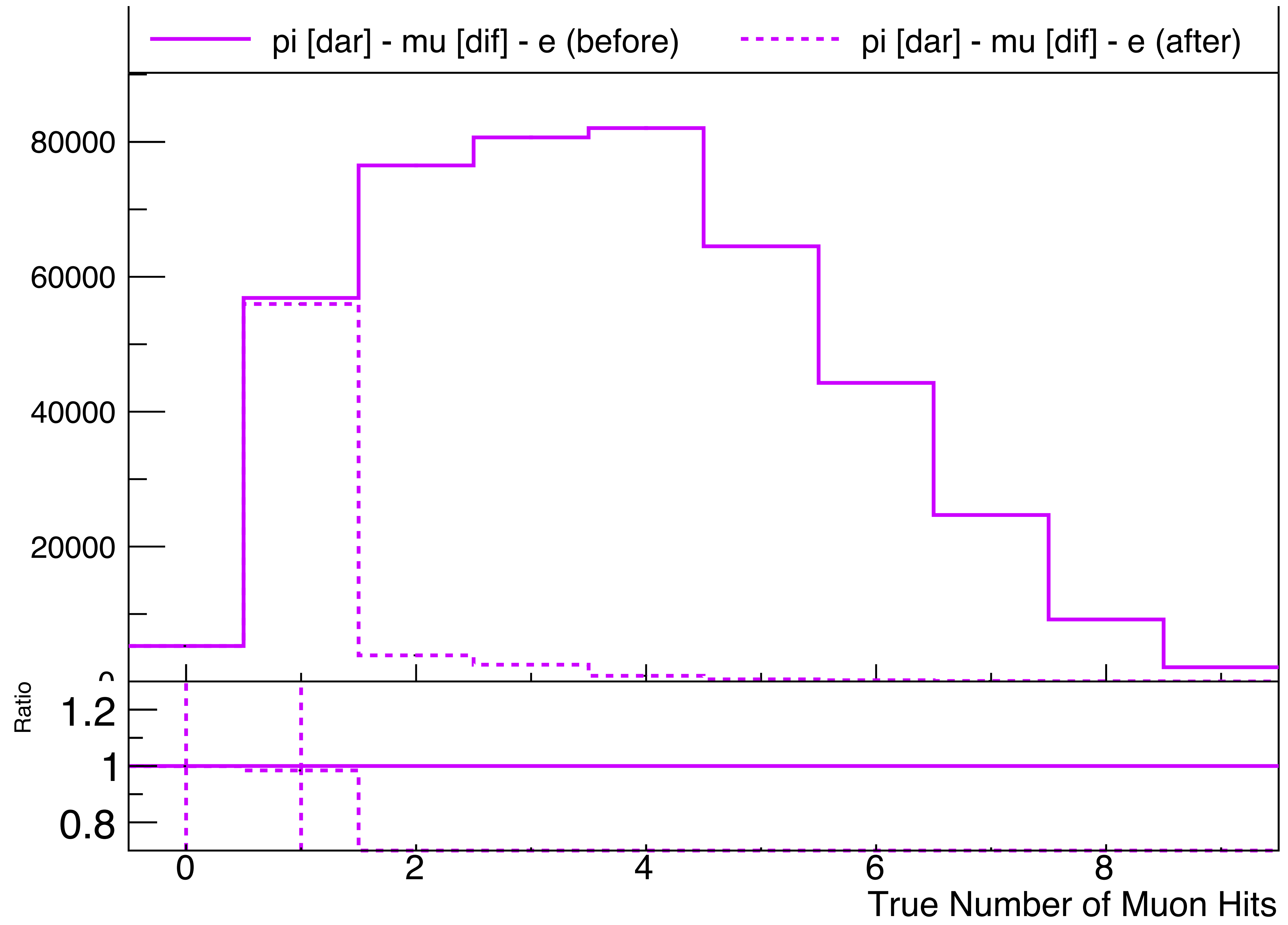
With only two hits, Y component of muon track only known within 200µm

Kink finding precision:

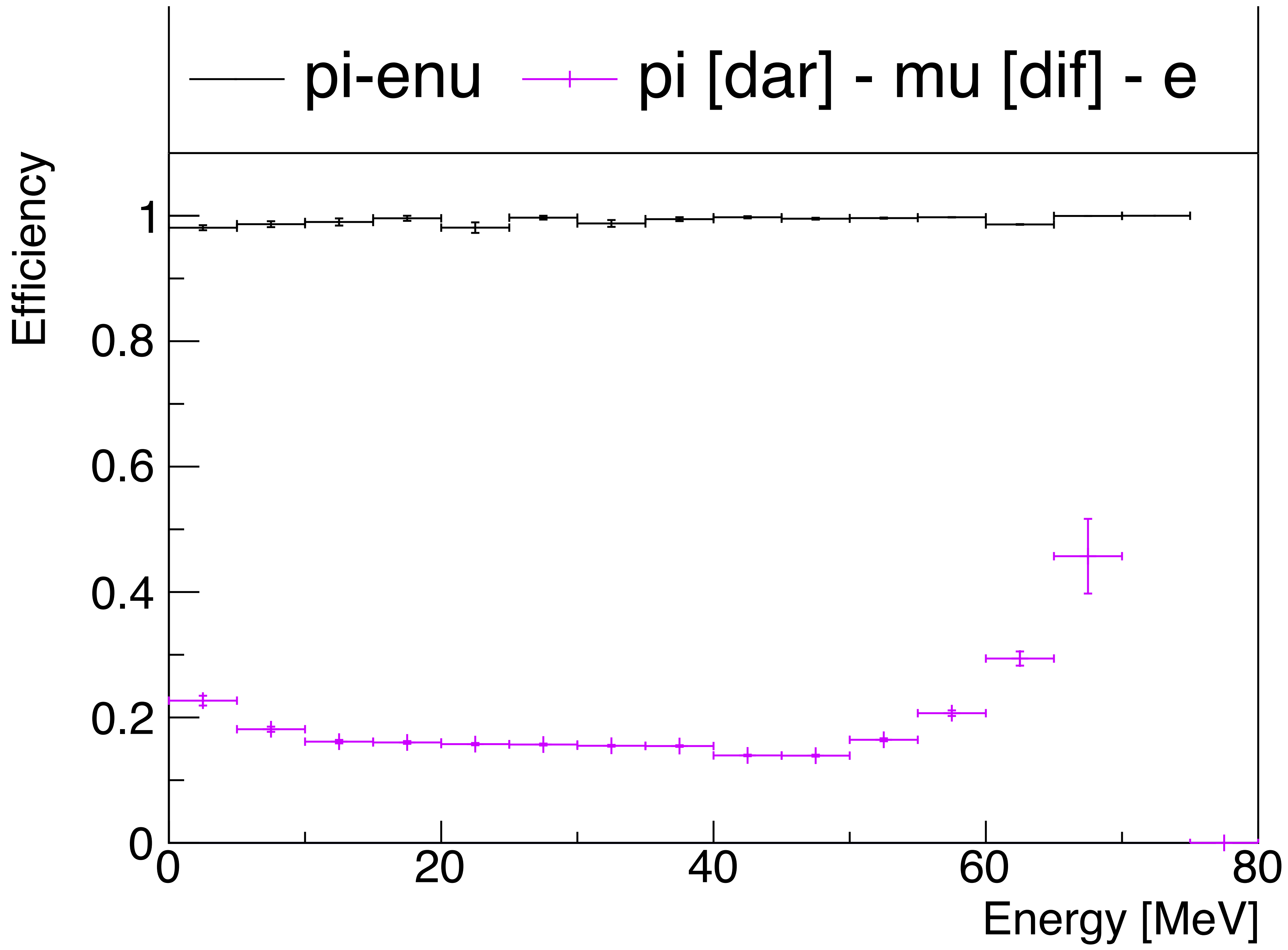
"Impact Parameter" > $\sqrt{200^2 + 120^2}$

DIF muon topology

Applying “impact parameter cut”



Efficiency wrt events passing the cuts listed on S4



Reduction of the pi[dar]-mu[dif]-e background by a factor ~ 5

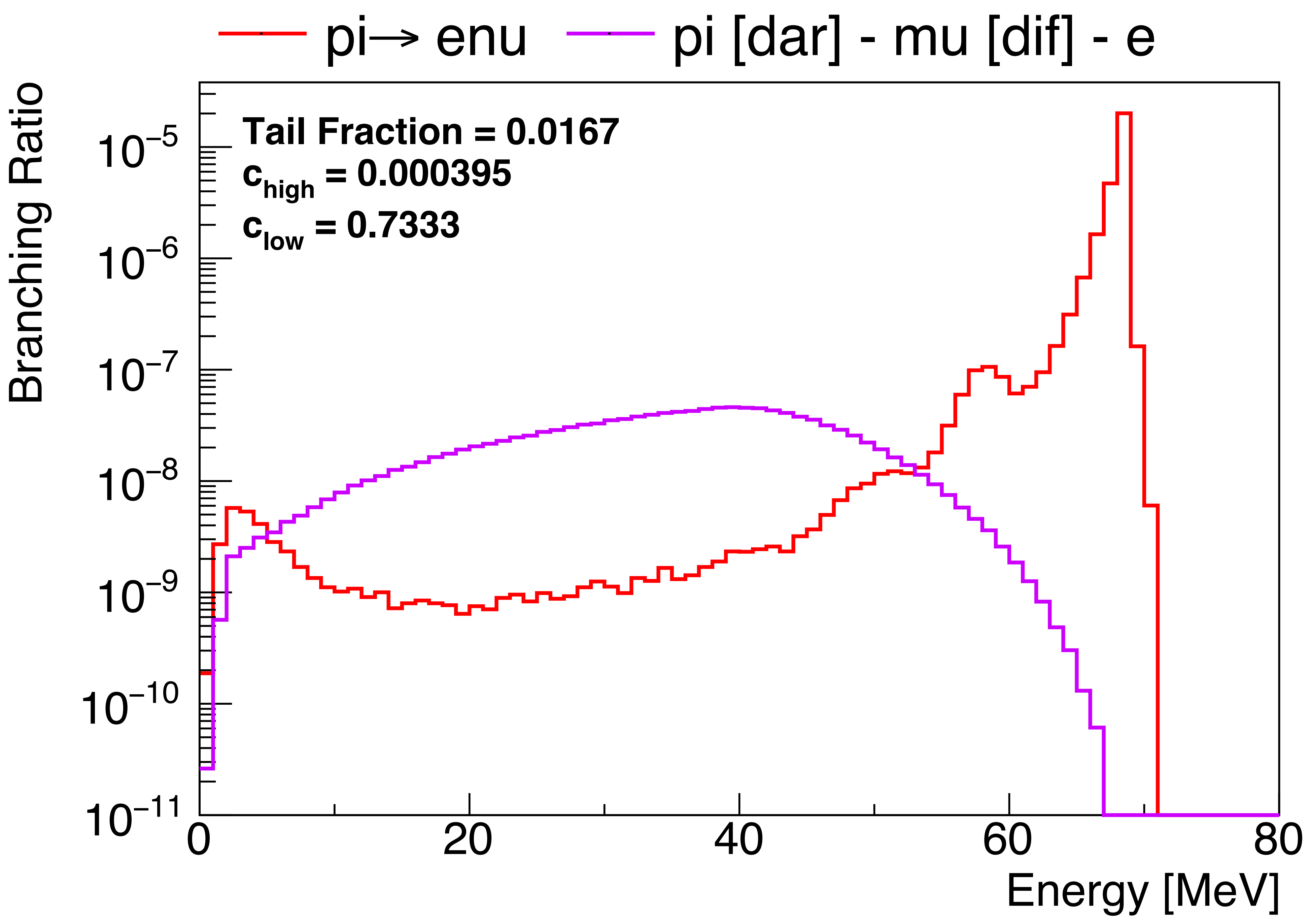
Cut on the signal is close to 100% efficient

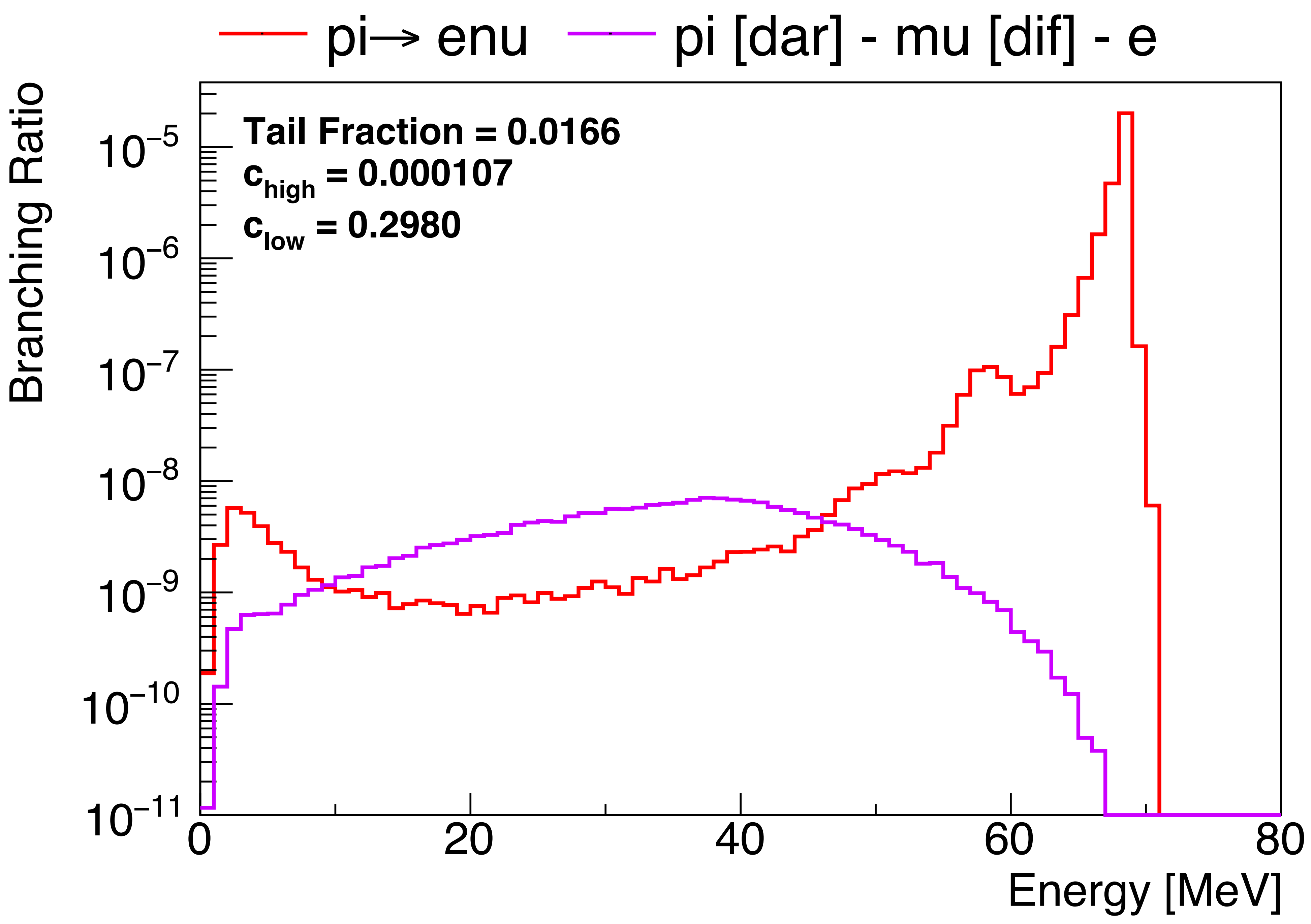
[TODO check some signal events that fail]

More realistic topological cuts need to be worked out
with track fitting using strip coordinates instead of G4 truth
(study to be done)

DIF muon topology

Applying "impact parameter cut"

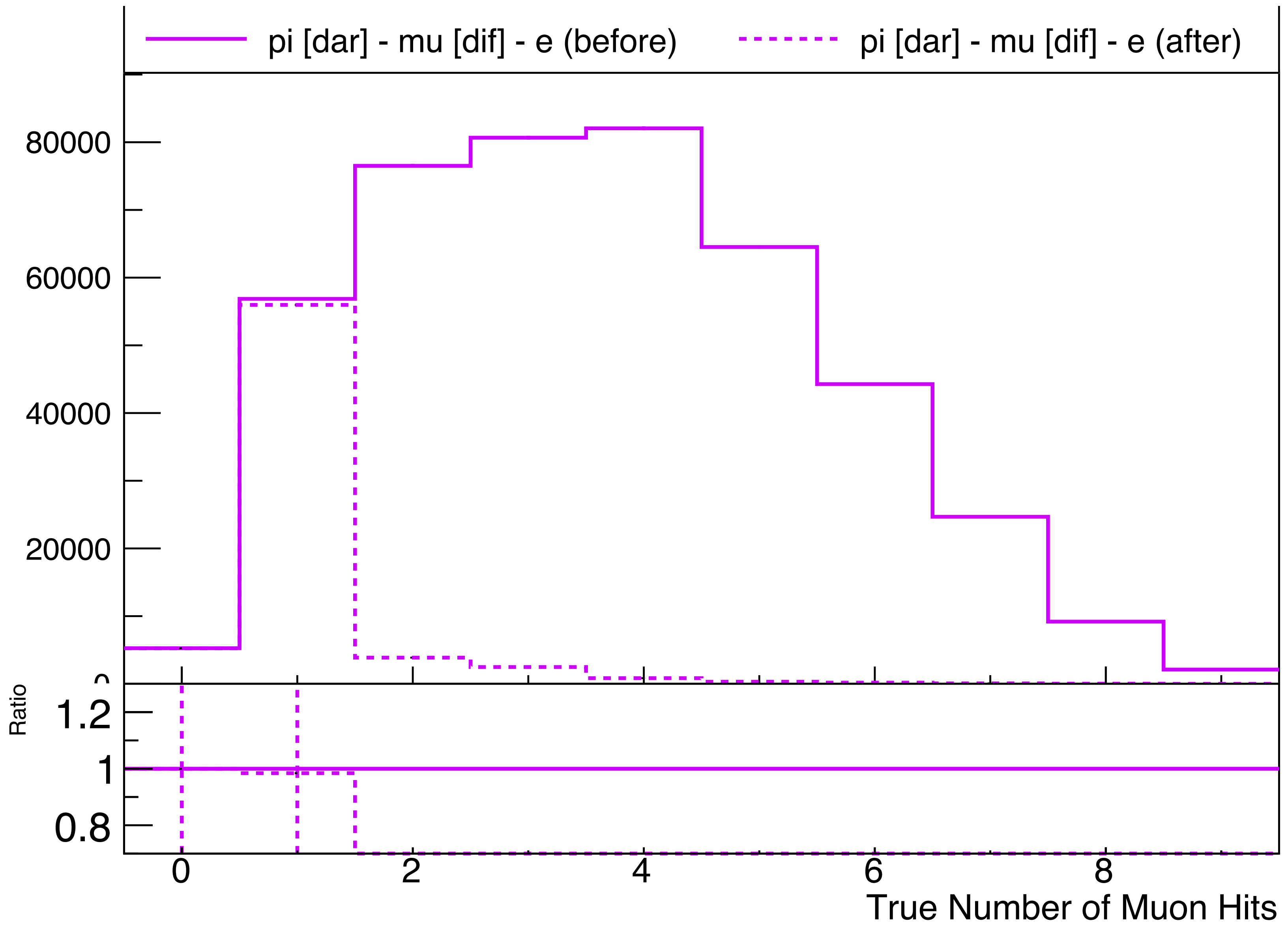




C_{low} reduced to 30% (still way above an acceptable level)

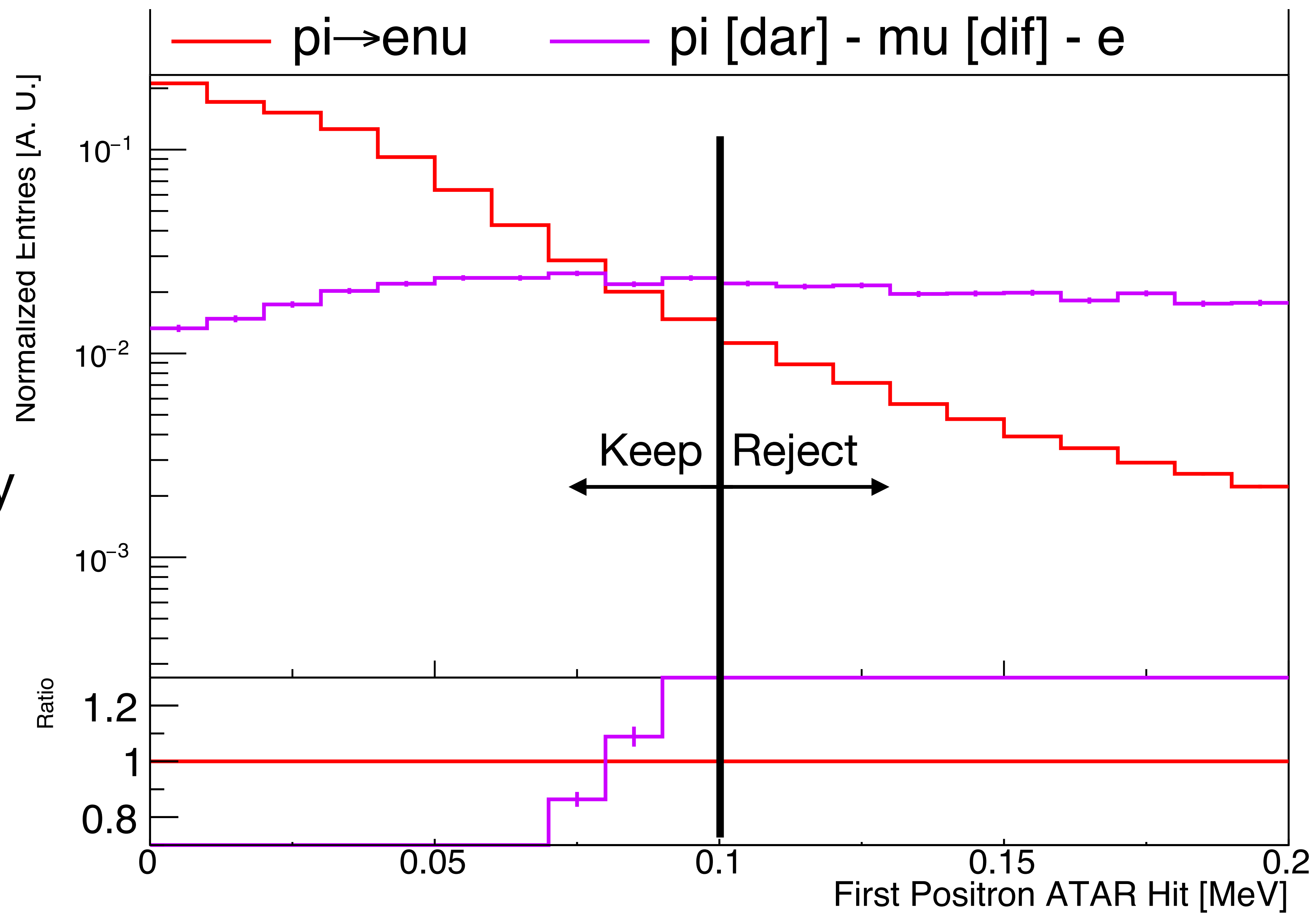
$C_{high} \sim 10^{-4}$

1-strip DIF muon
Energy measurement



After topology criteria, remaining DIF muons are single-strip events

Muon leaves in average more energy
=> Simple cut on the collected energy

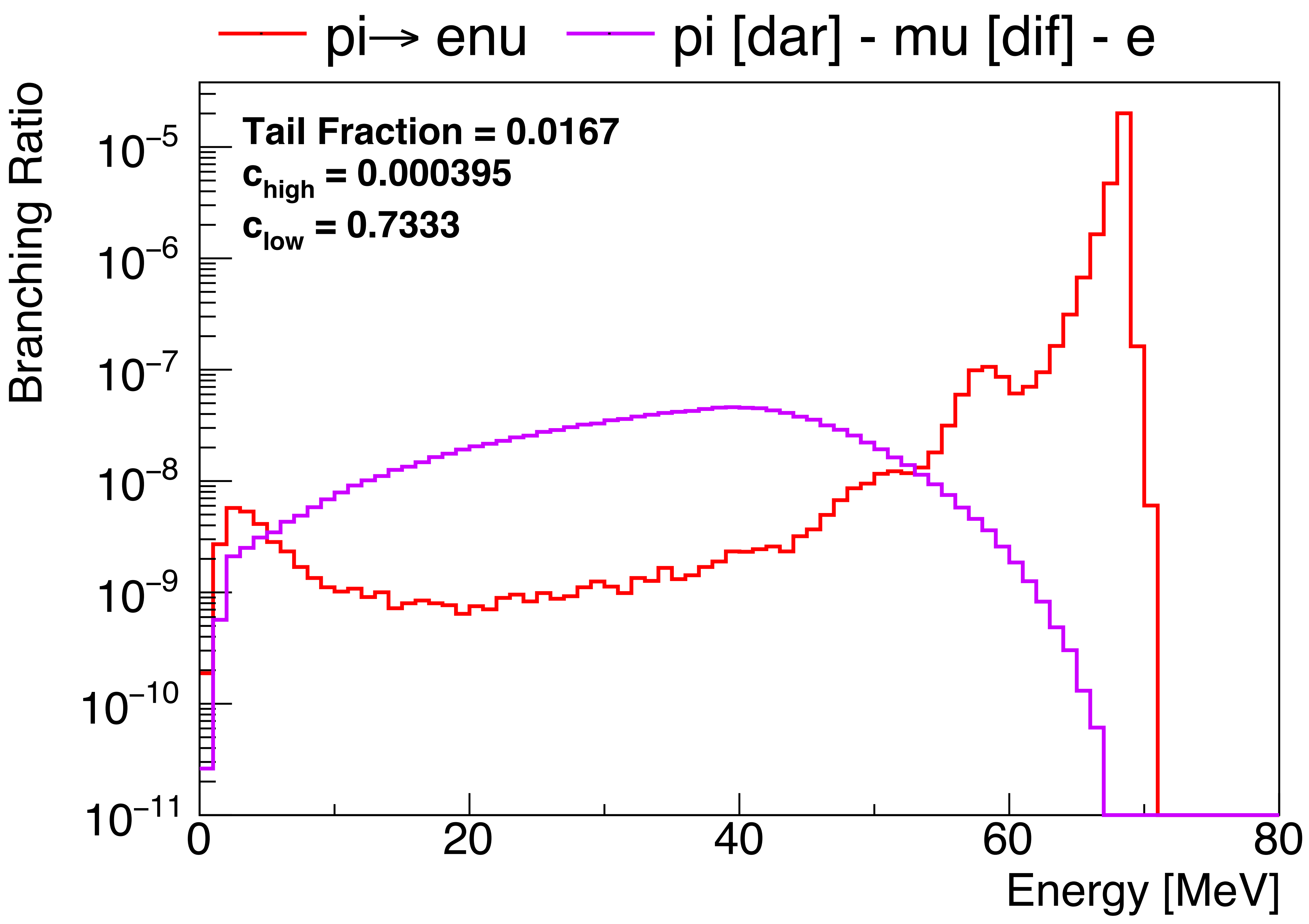


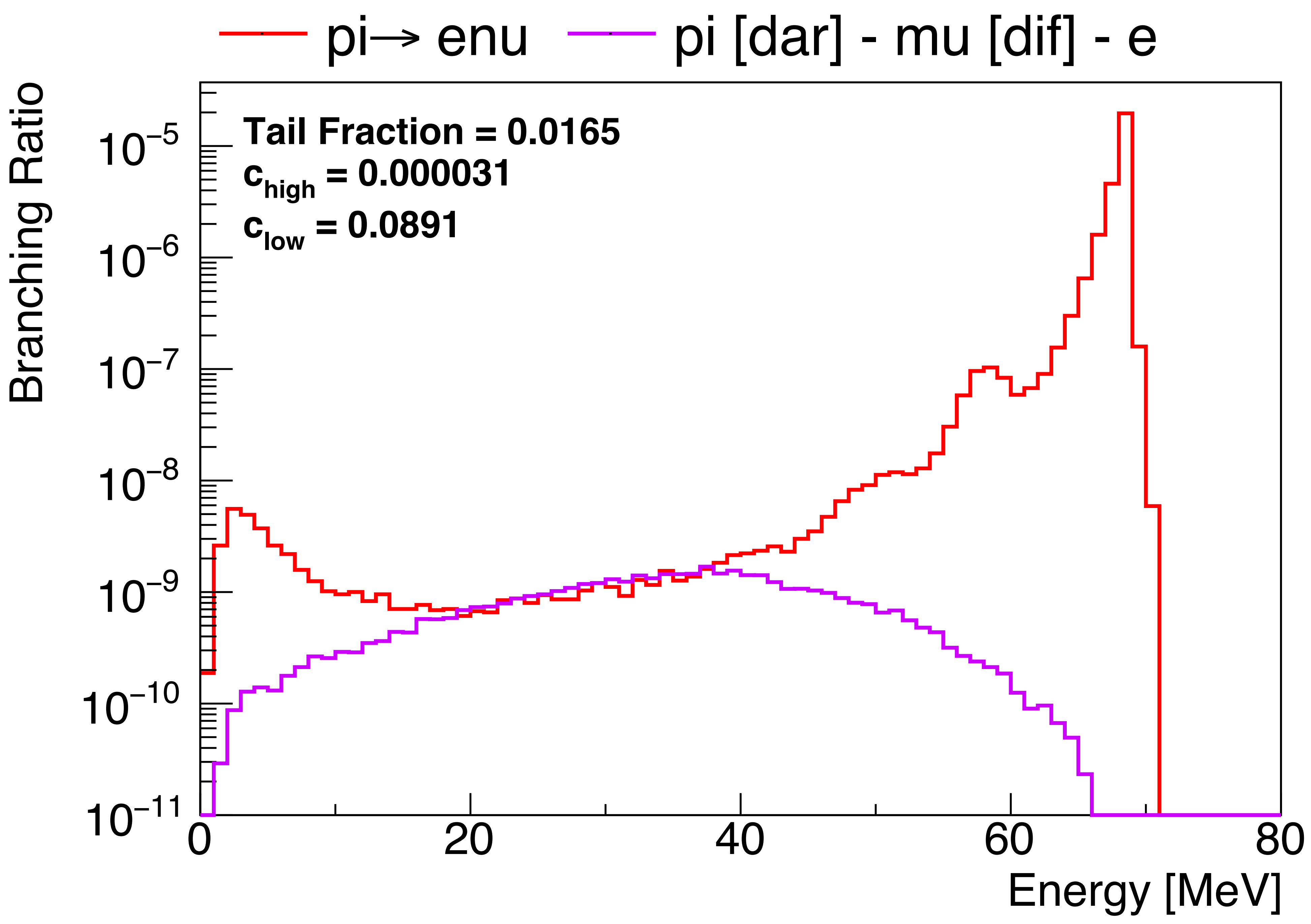
Cut at 100 keV (2-3 mips)

Due to the steeply falling nature of the signal spectrum,
even a slight mis-calibration could have dramatic effect on the performance of this cut

1-strip muon DIF

Impact of the single-strip energy cut

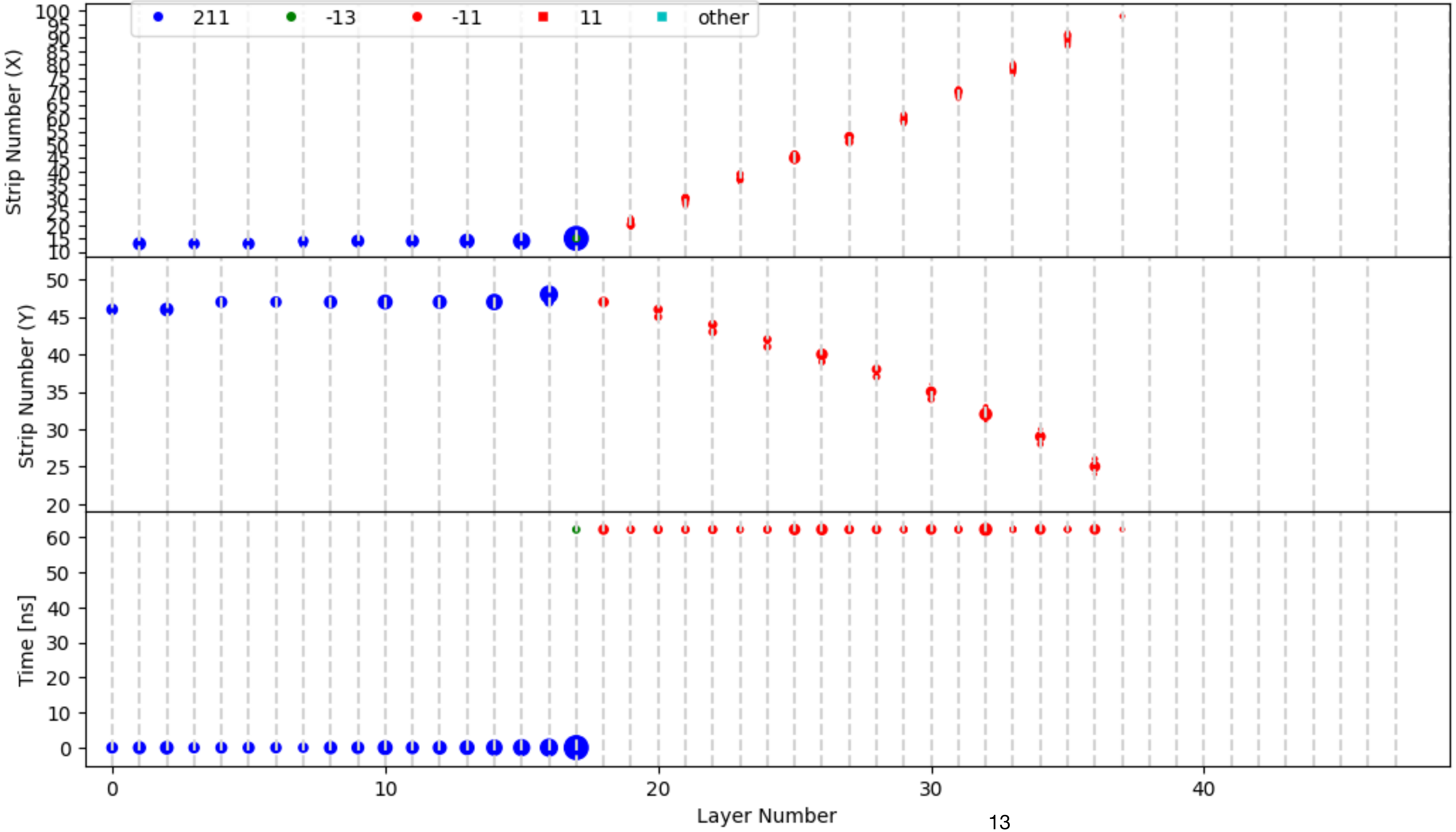




c_{low} of ~8% is acceptable if we can measure it with ~5% precision

What are the events we are left with?

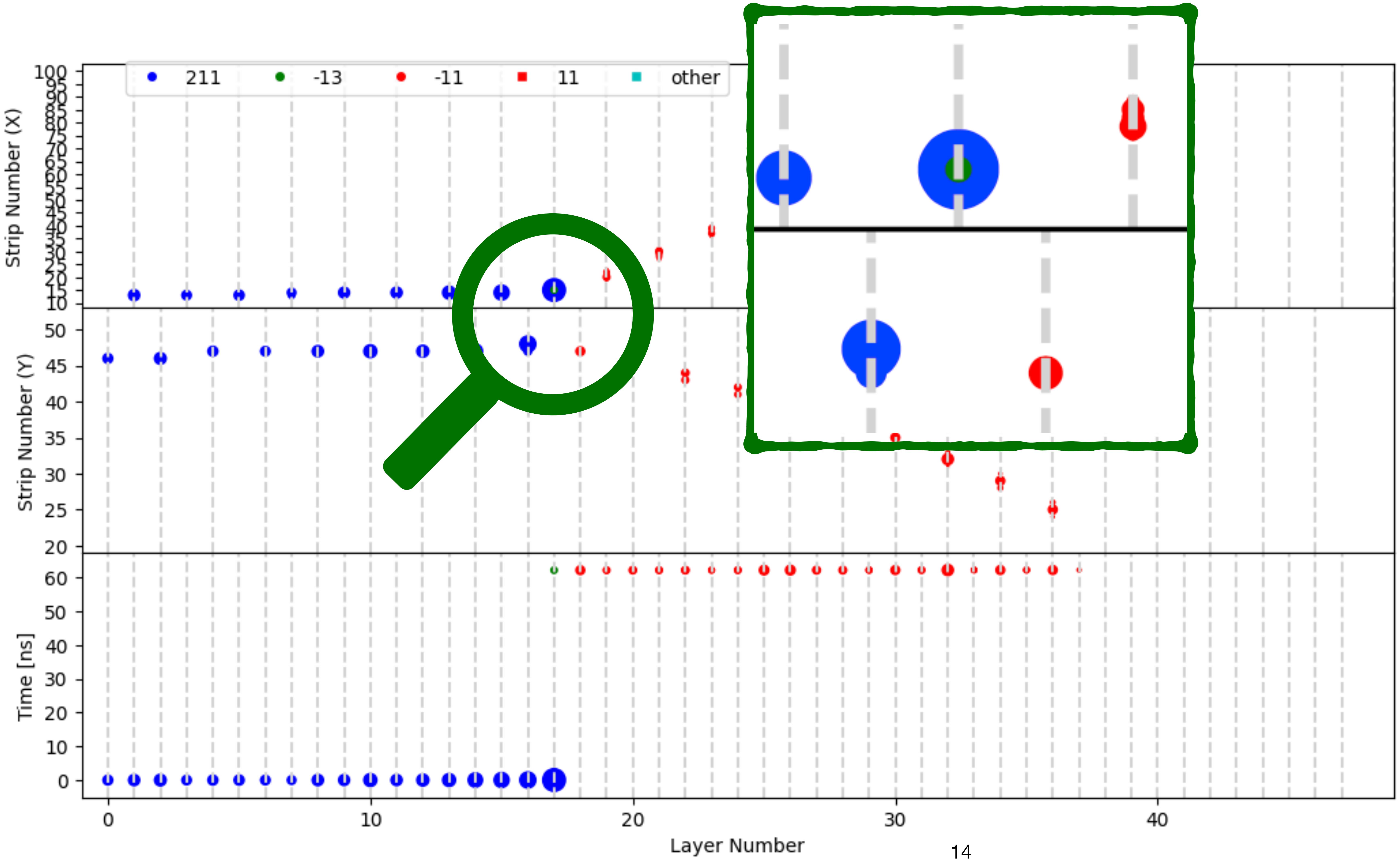
The difficult ones…



This event:
The μ+ only travels through a single strip and leave a positron-like energy deposit

What are the events we are left with?

The difficult ones…

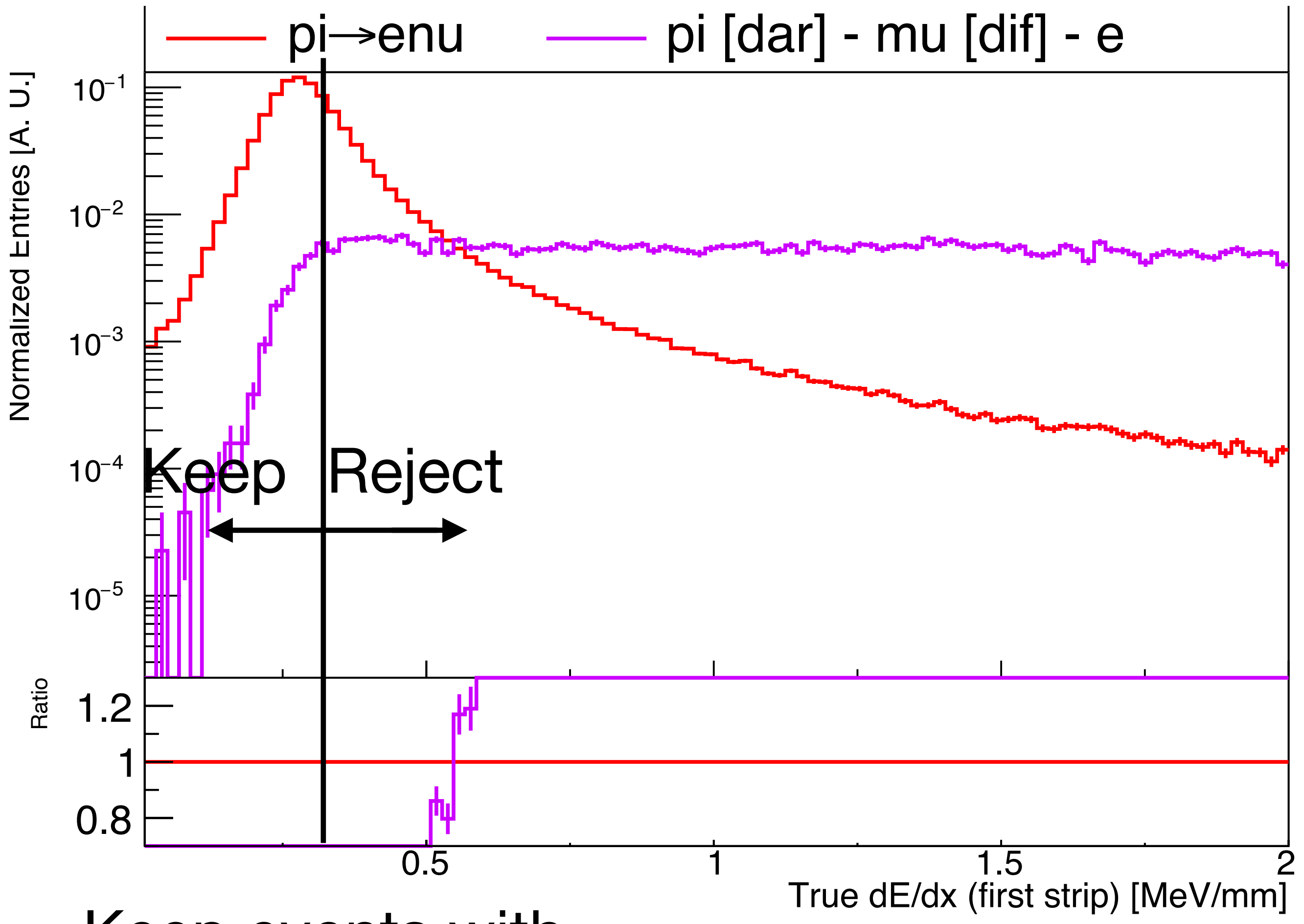


This event:
The μ+ only travels through a single strip and leave a positron-like energy deposit

With timing information we can easily remove incoming pion and use first positron-like hit in the same strip

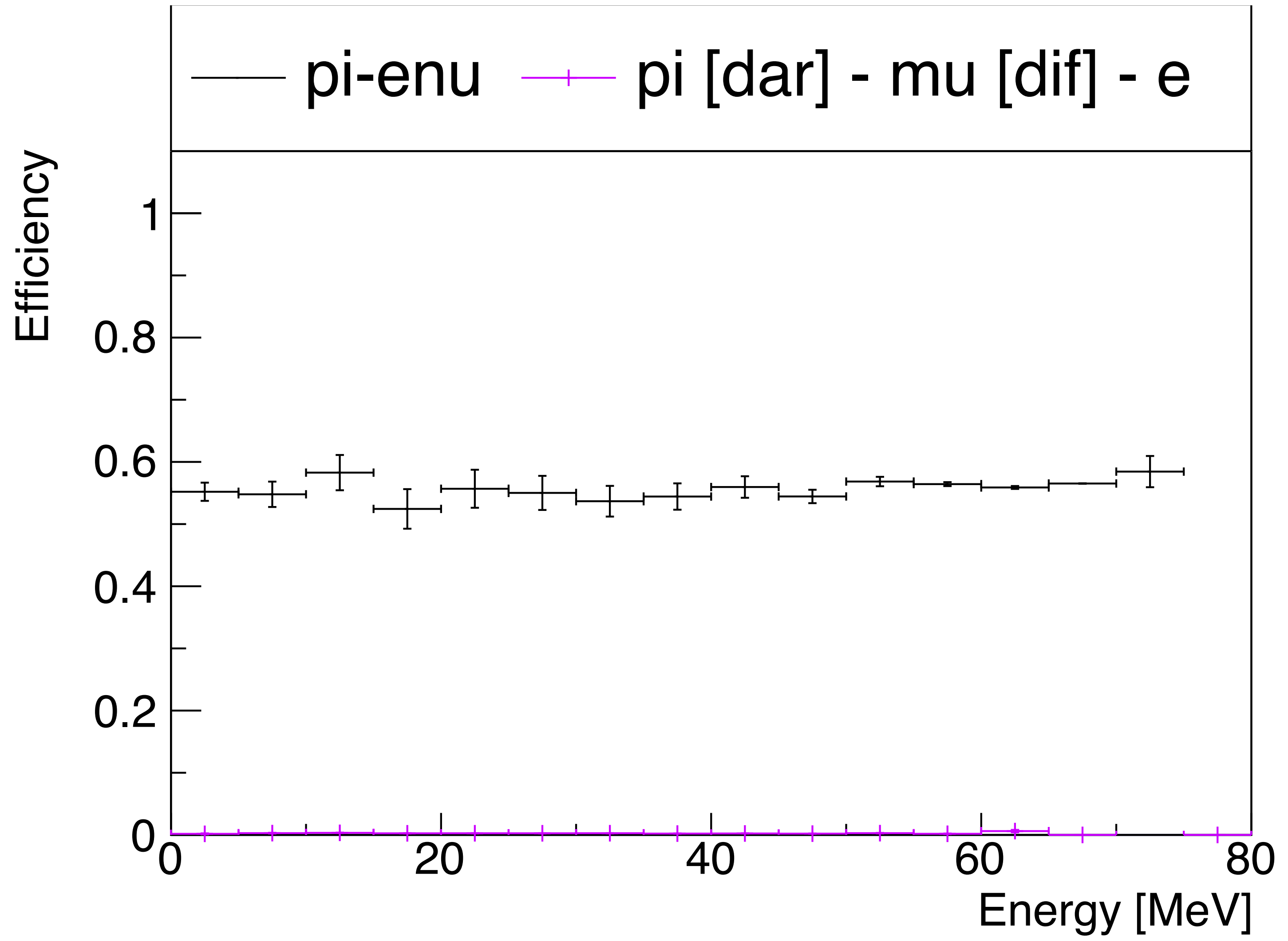
dE/dx

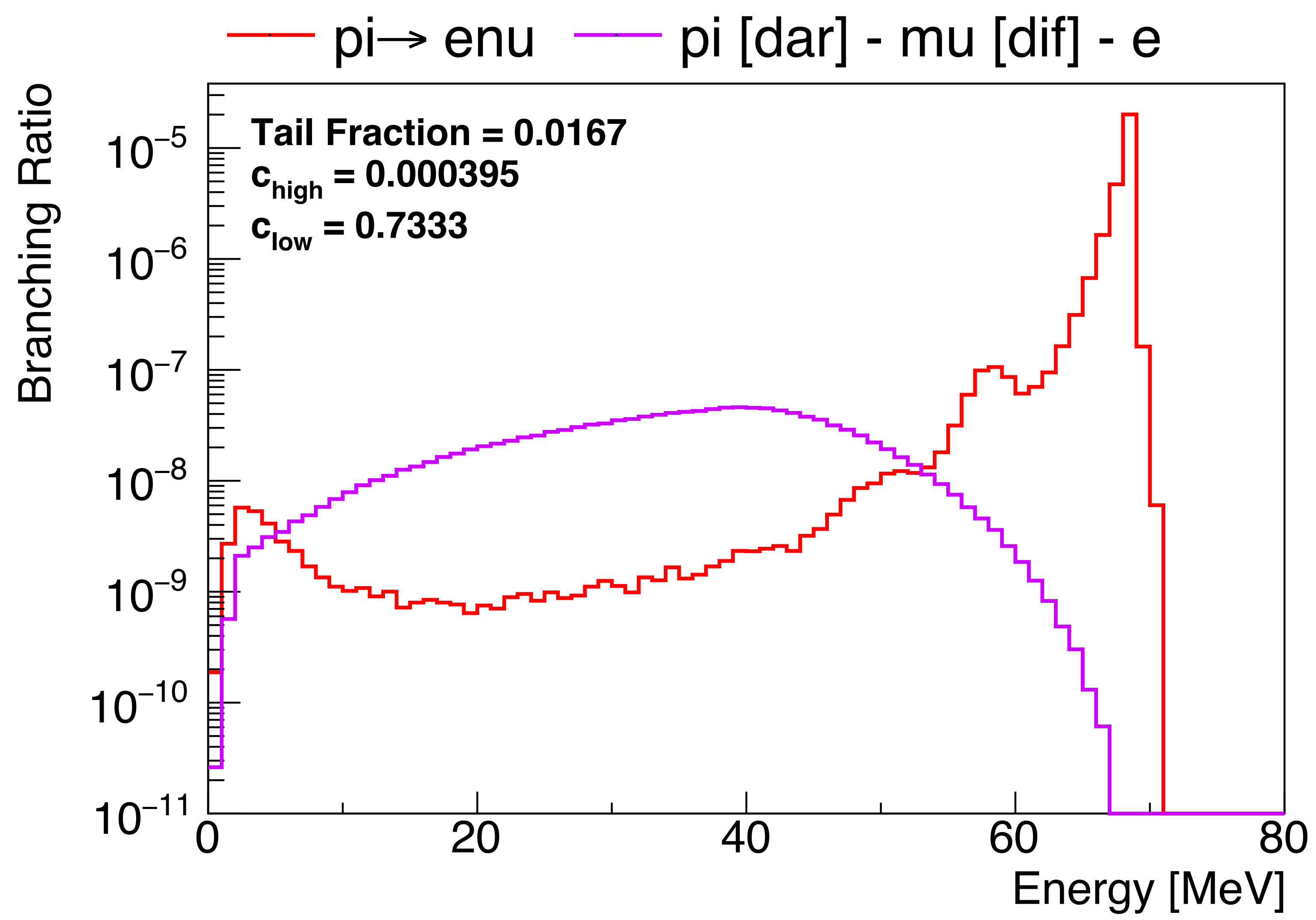
Using true muon+positron travel length

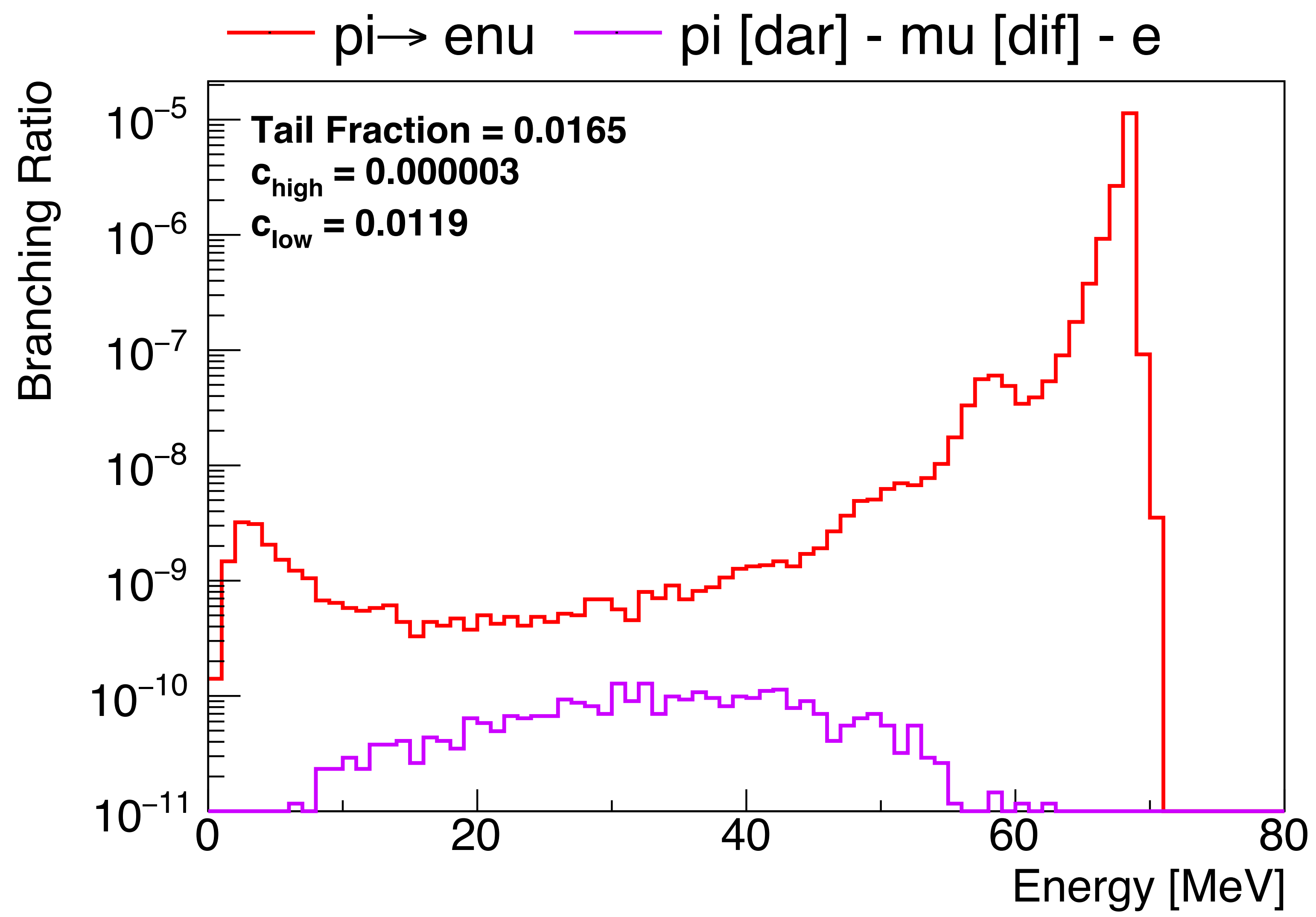


Keep events with dE/dx < 0.3

Efficiency wrt events passing the cuts listed on S4







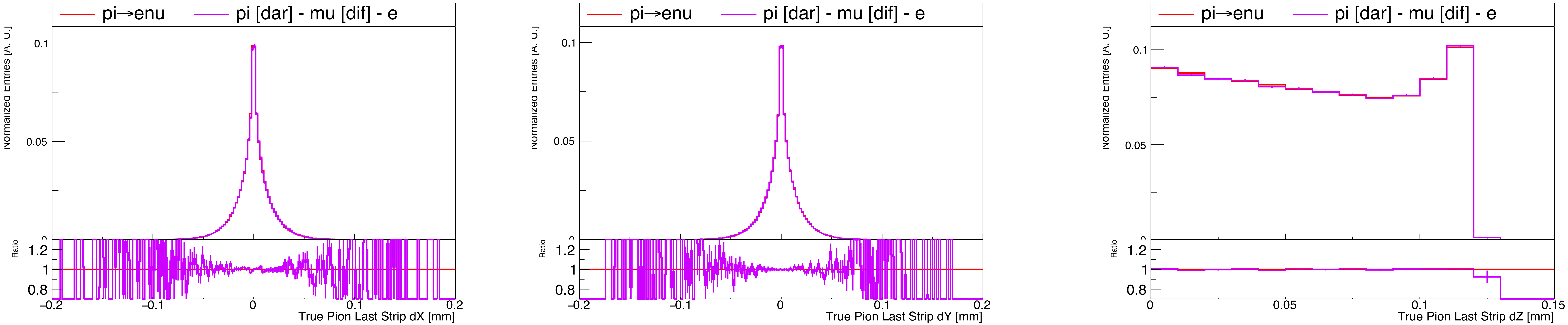
Key ingredients to leverage this separation power in PIONEER:

Determine the pion stopping position
(discussed in this talk)

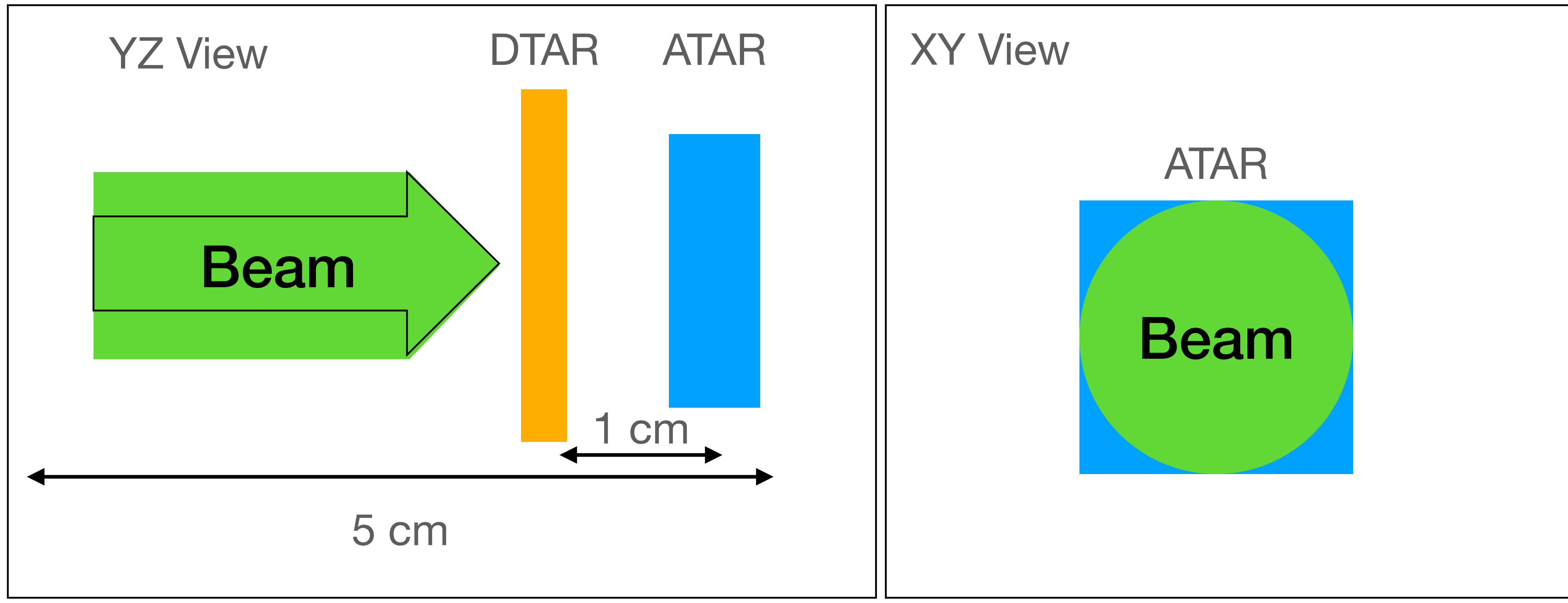
Determine where the positron track is born
(track fitting task, need to be investigated)

Pion stopping position

True Geant4 record

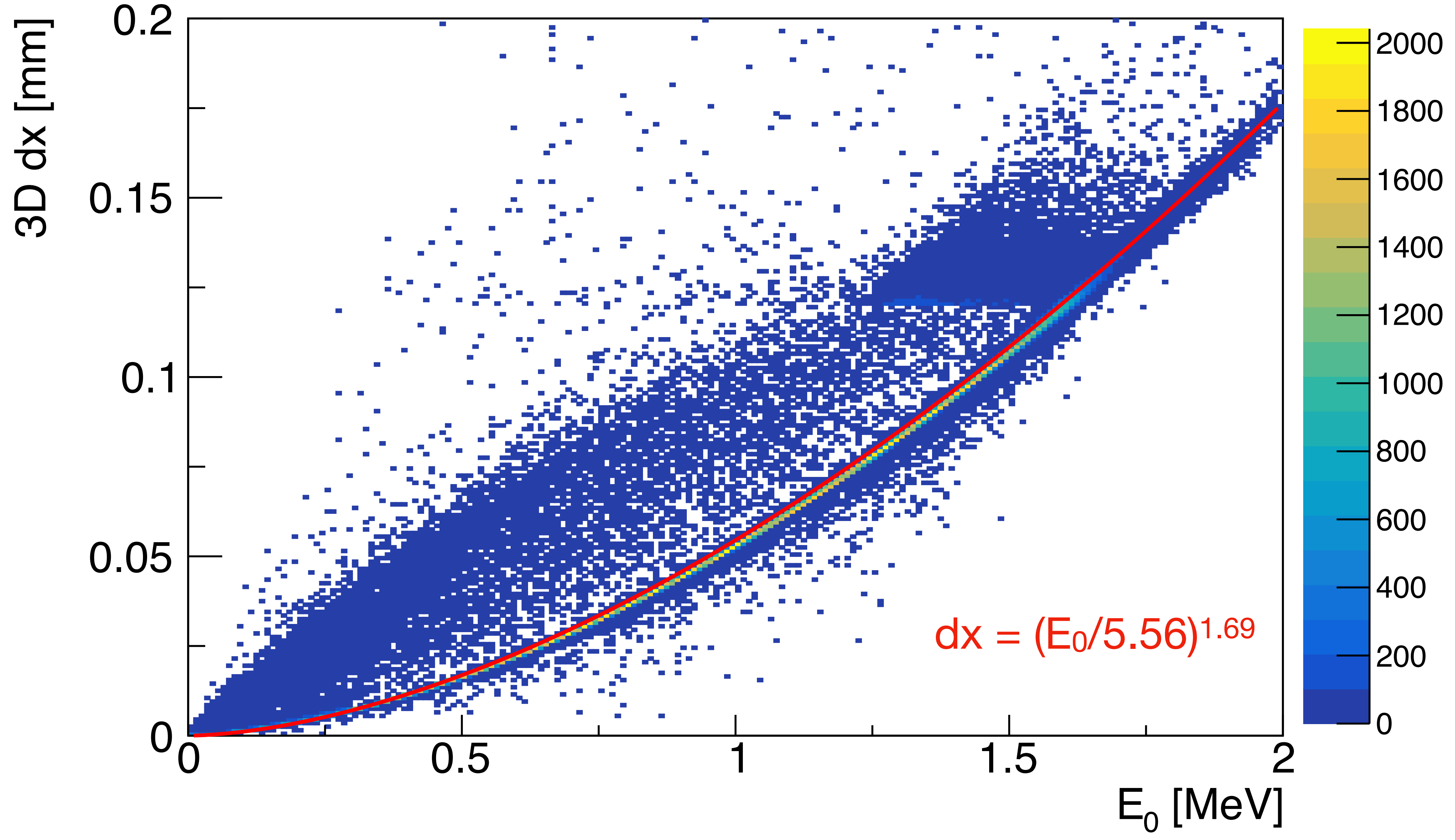


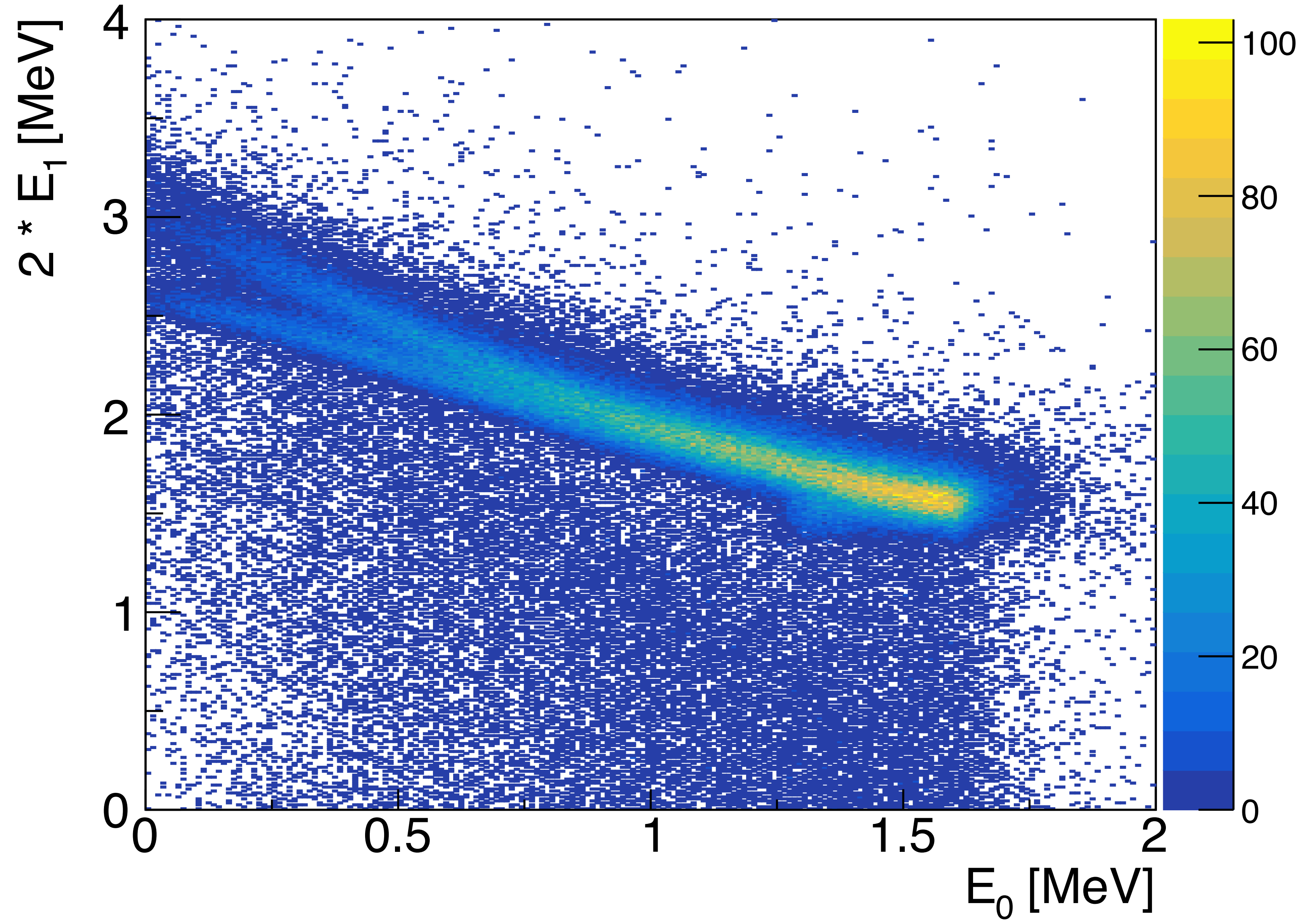
- Pion deviates very little in the transverse plane: ±18μm in each direction
- ~ uniform stopping along Z (modulo some edge effects due to dead material)
- NB: This can be impacted by beam profile



Pion stopping position

Characterising the energy deposit



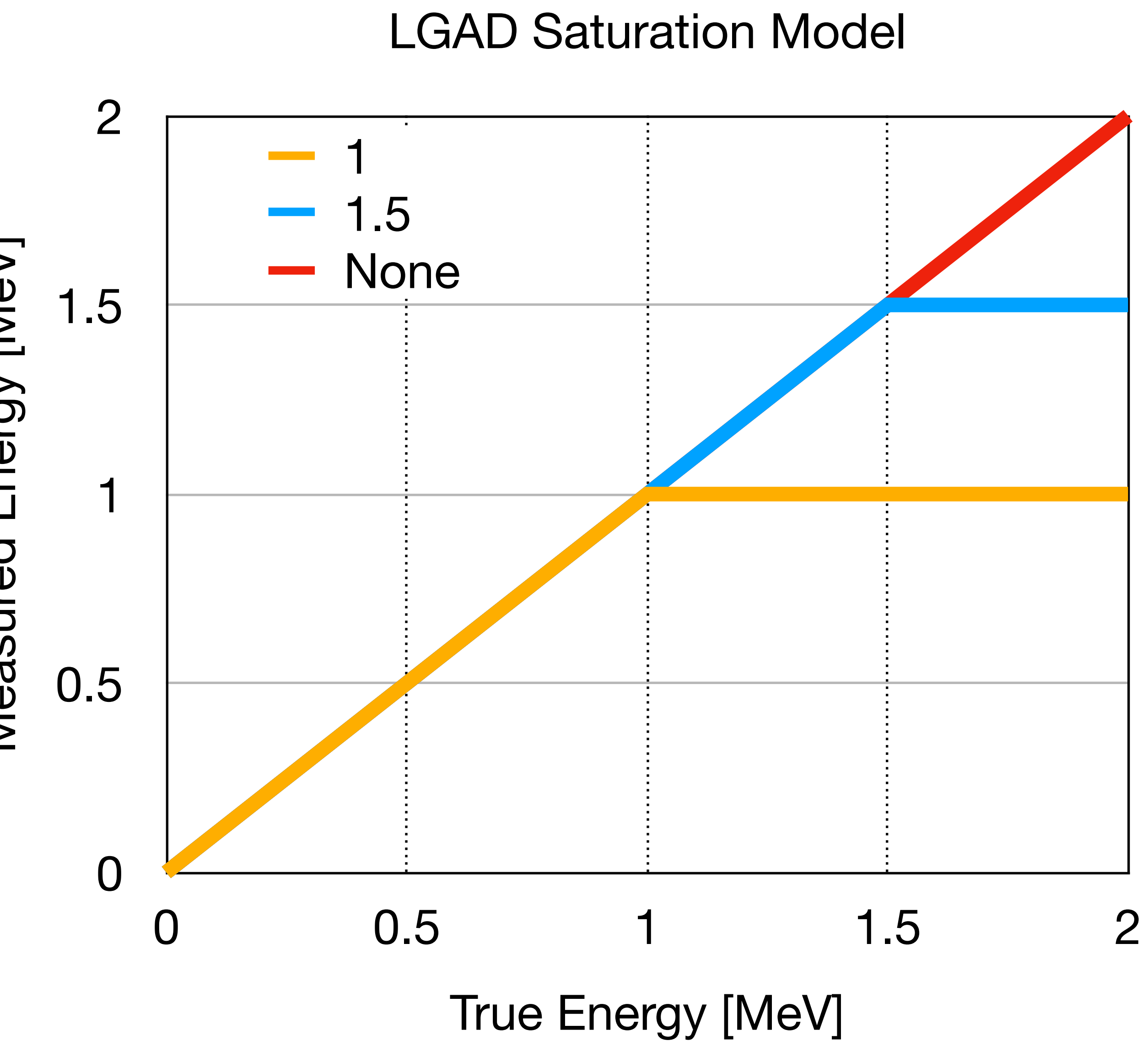


Derived criterion only uses E_0 but clear correlation observed between E_0 and E_1

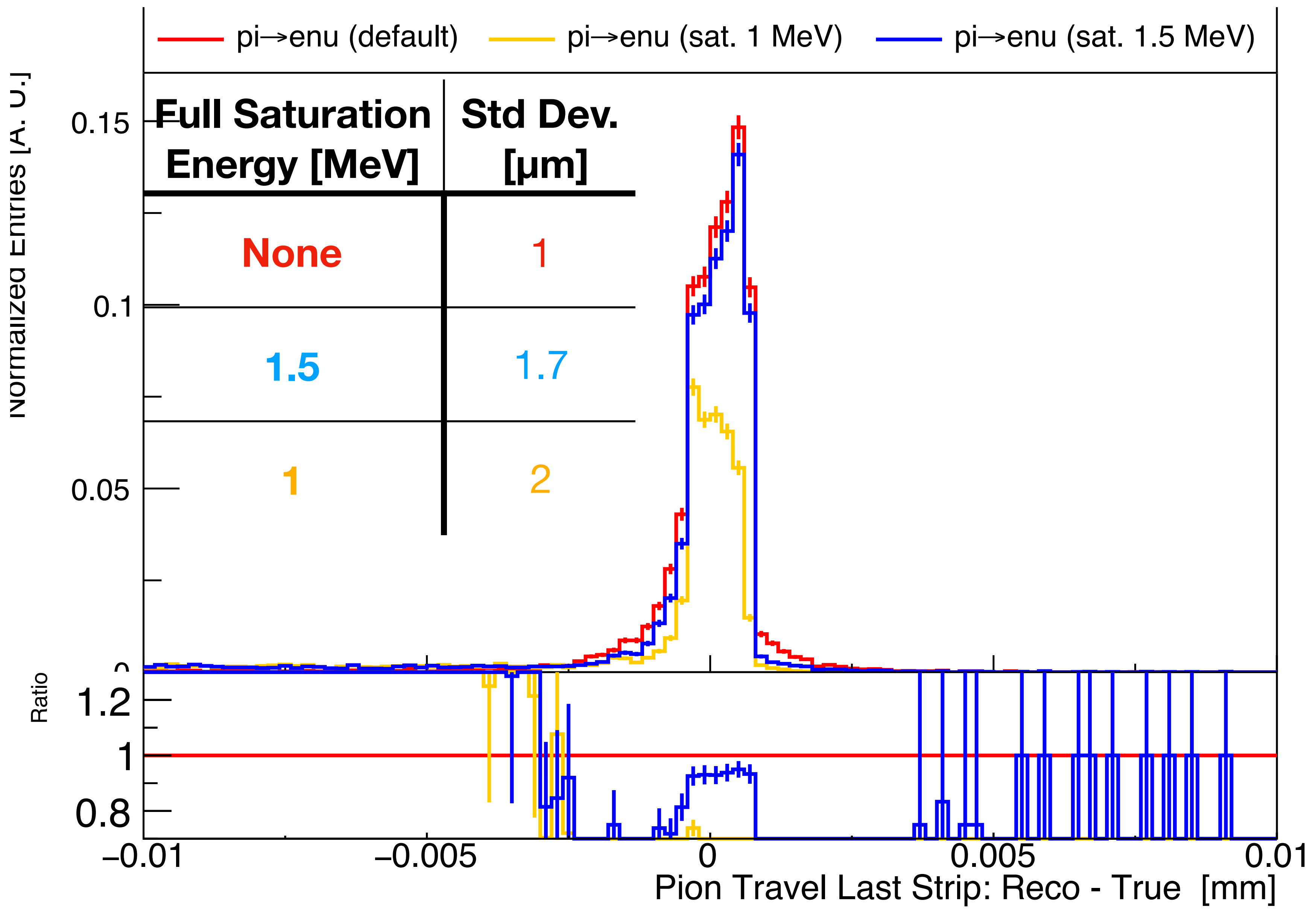
Additional study: build a more sophisticated dX = f(E0, E1) using ML or Likelihood model

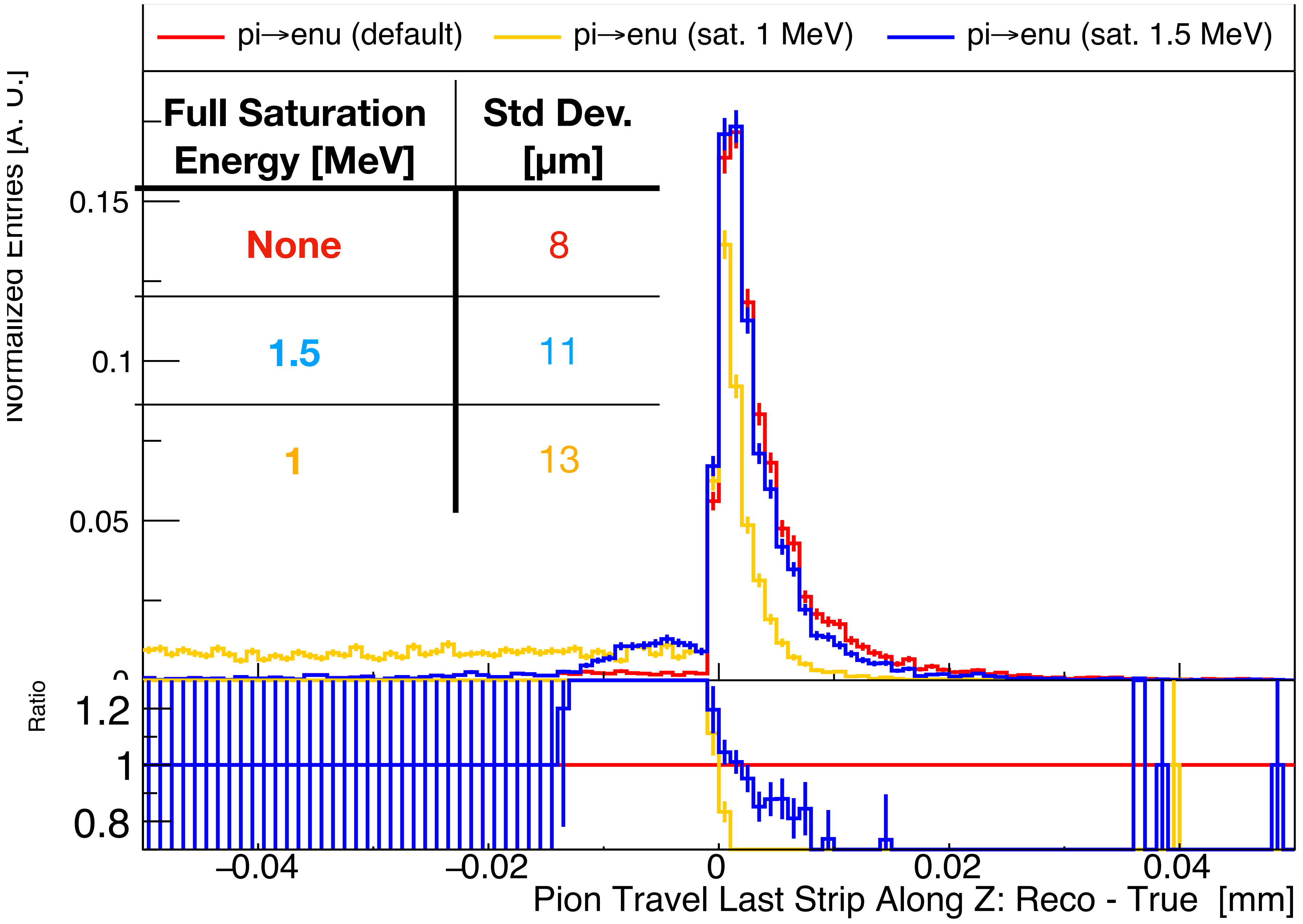
Pion stopping position

Characterising the energy deposit



Very crude LGAD saturation model

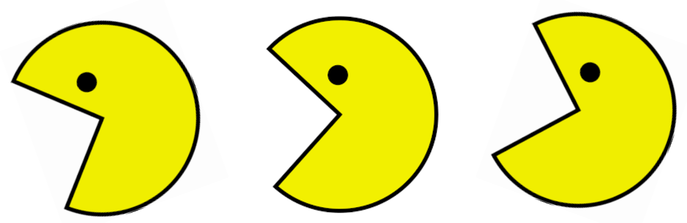




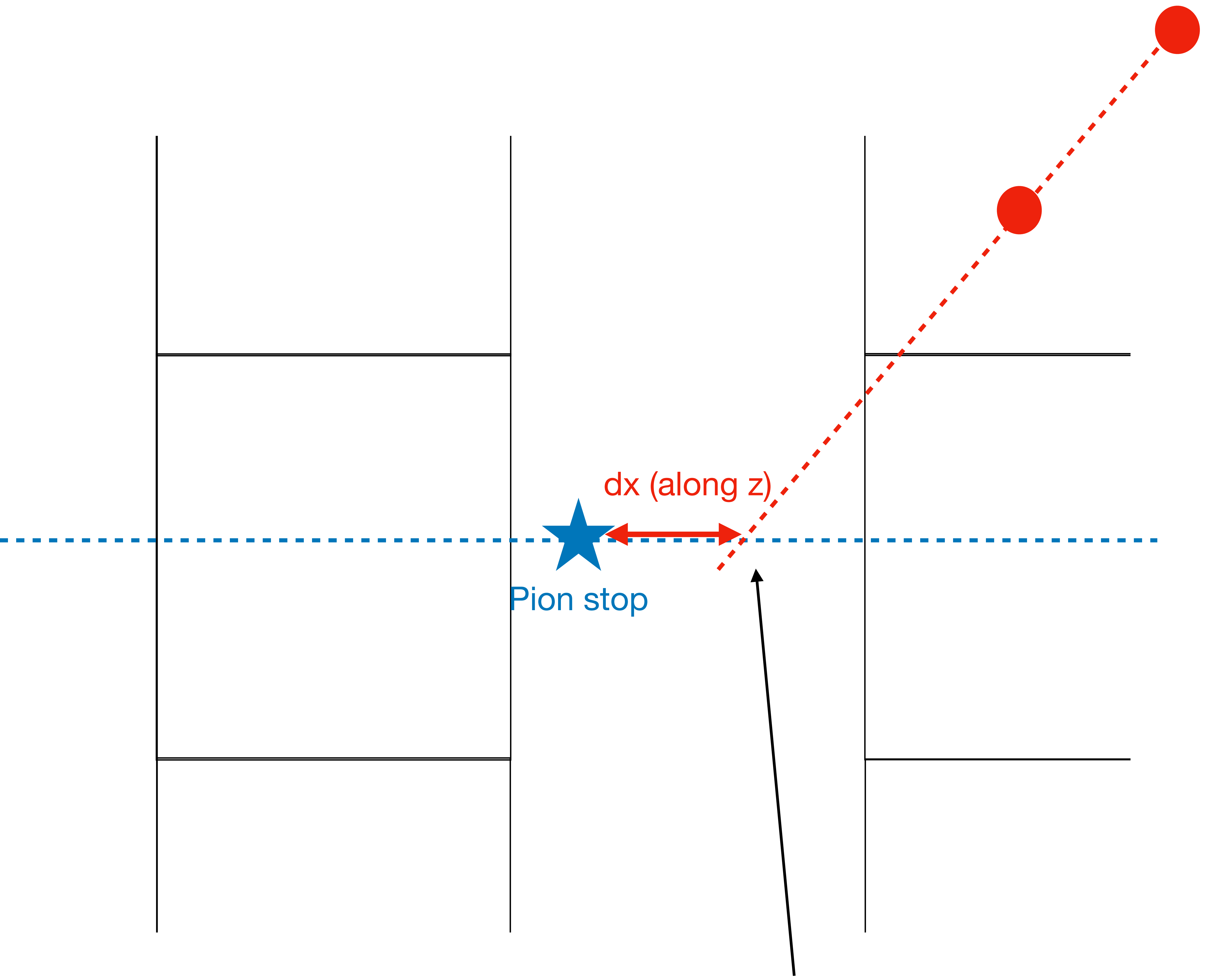
Clear degradation observed as saturation threshold decreases

Important note: Since pions go perpendicular to the strips,
→ X and Y precision is set by the pitch ($\pm 200/\sqrt{12}\ \mu$m)

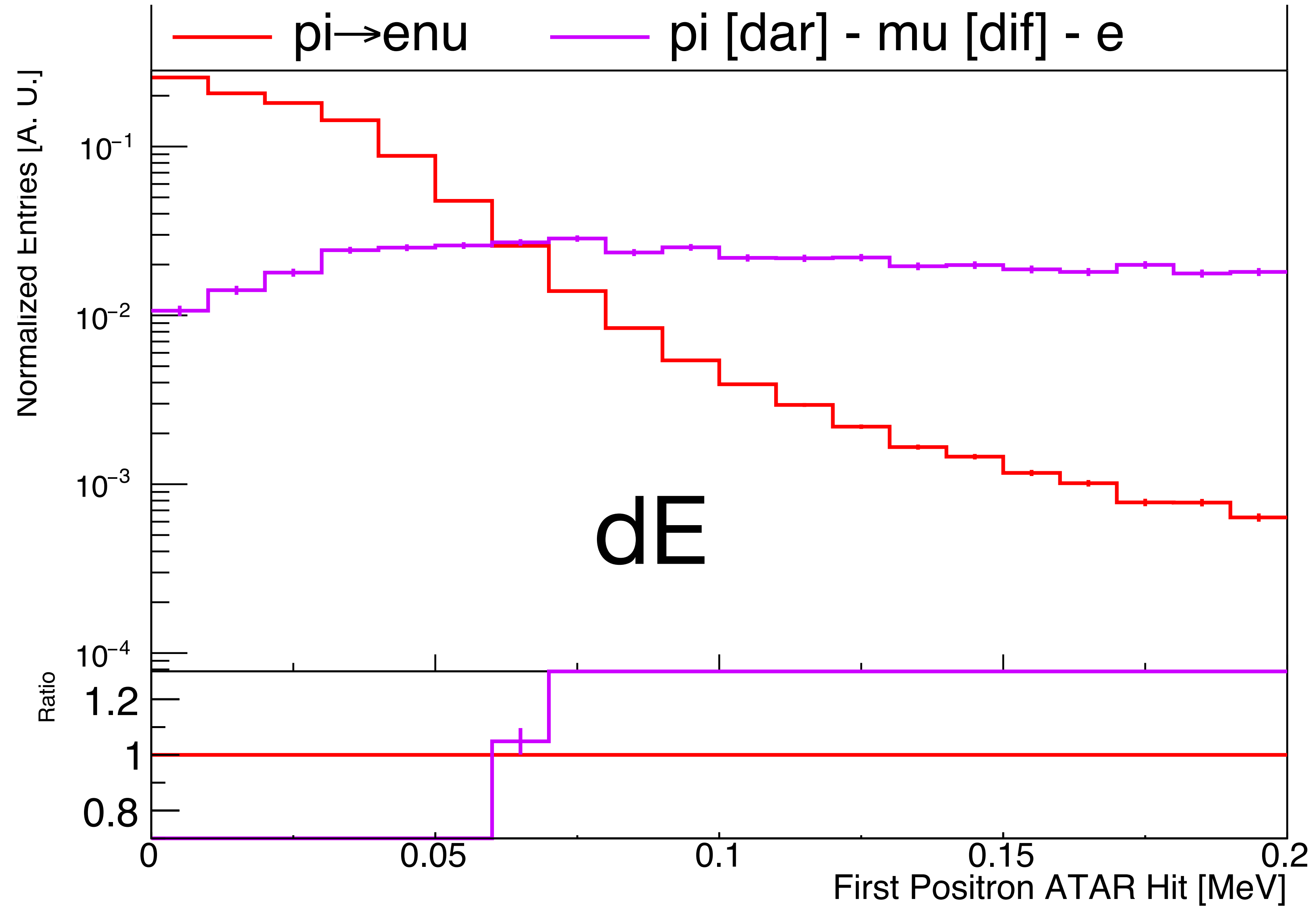
Tilting pioneer would improve our determination of the pion stopping in the transverse plane



Reco. dE/dx (along Z)



Study needed to determine how precisely we measure the position of the first non pion hit



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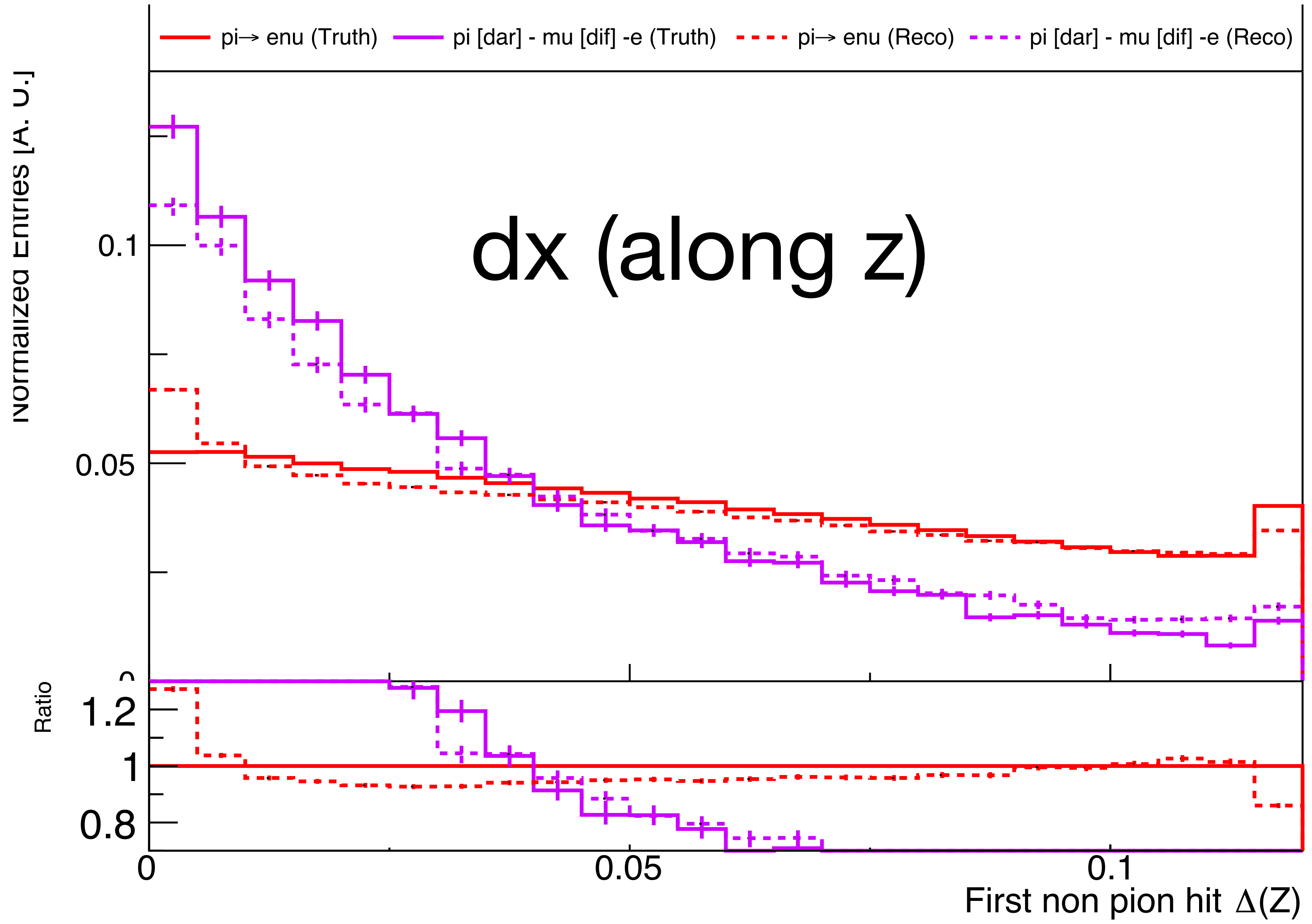
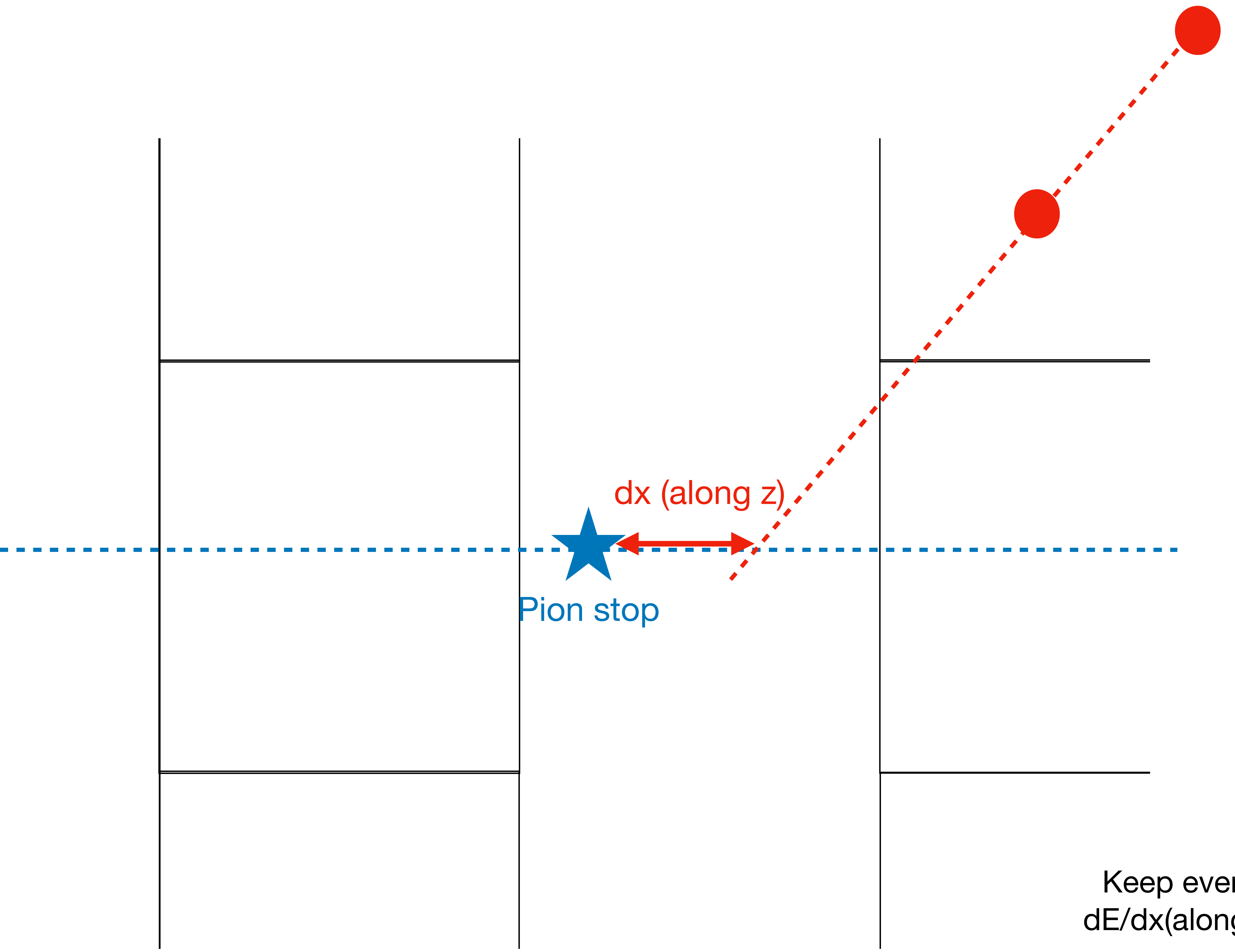
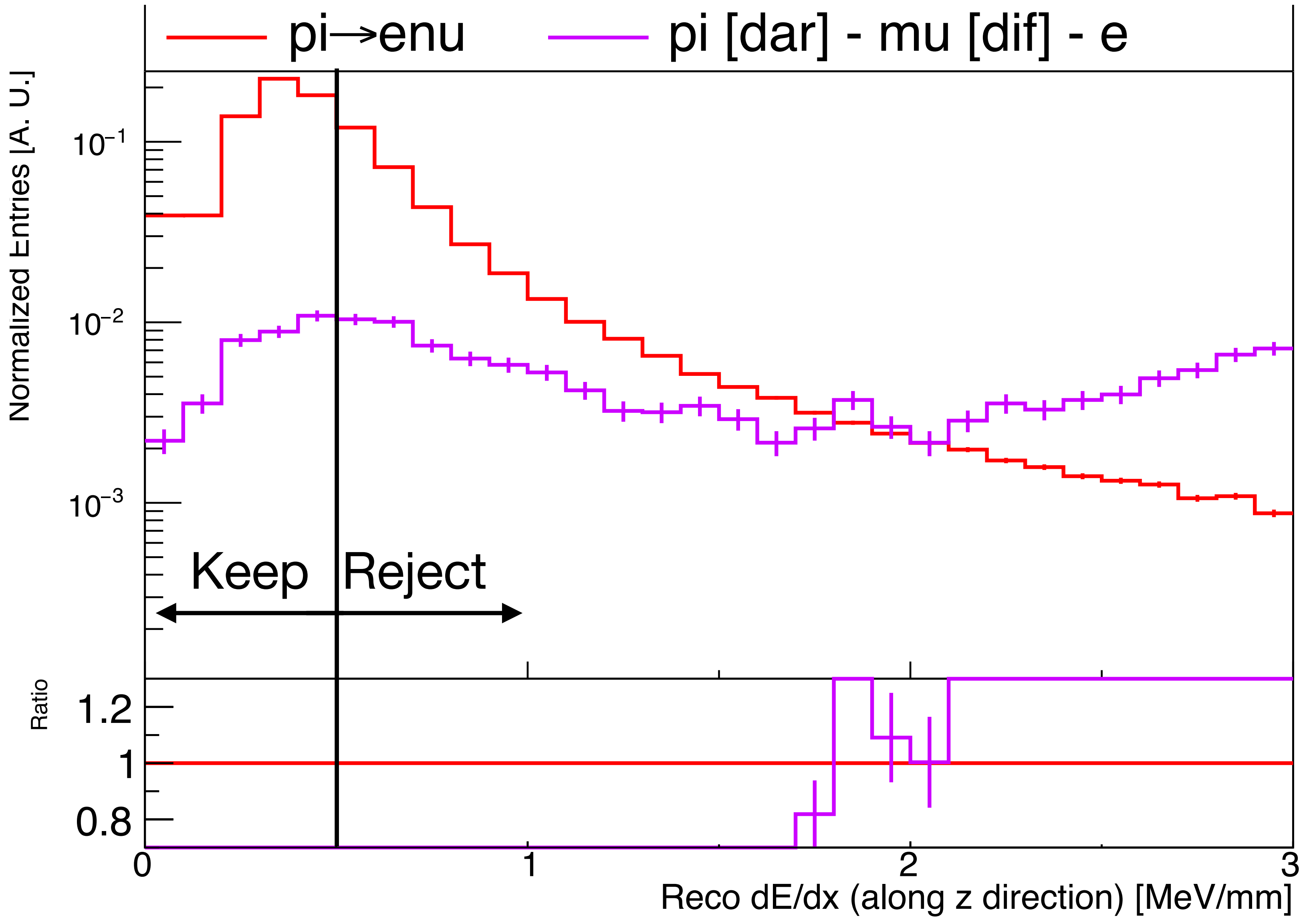
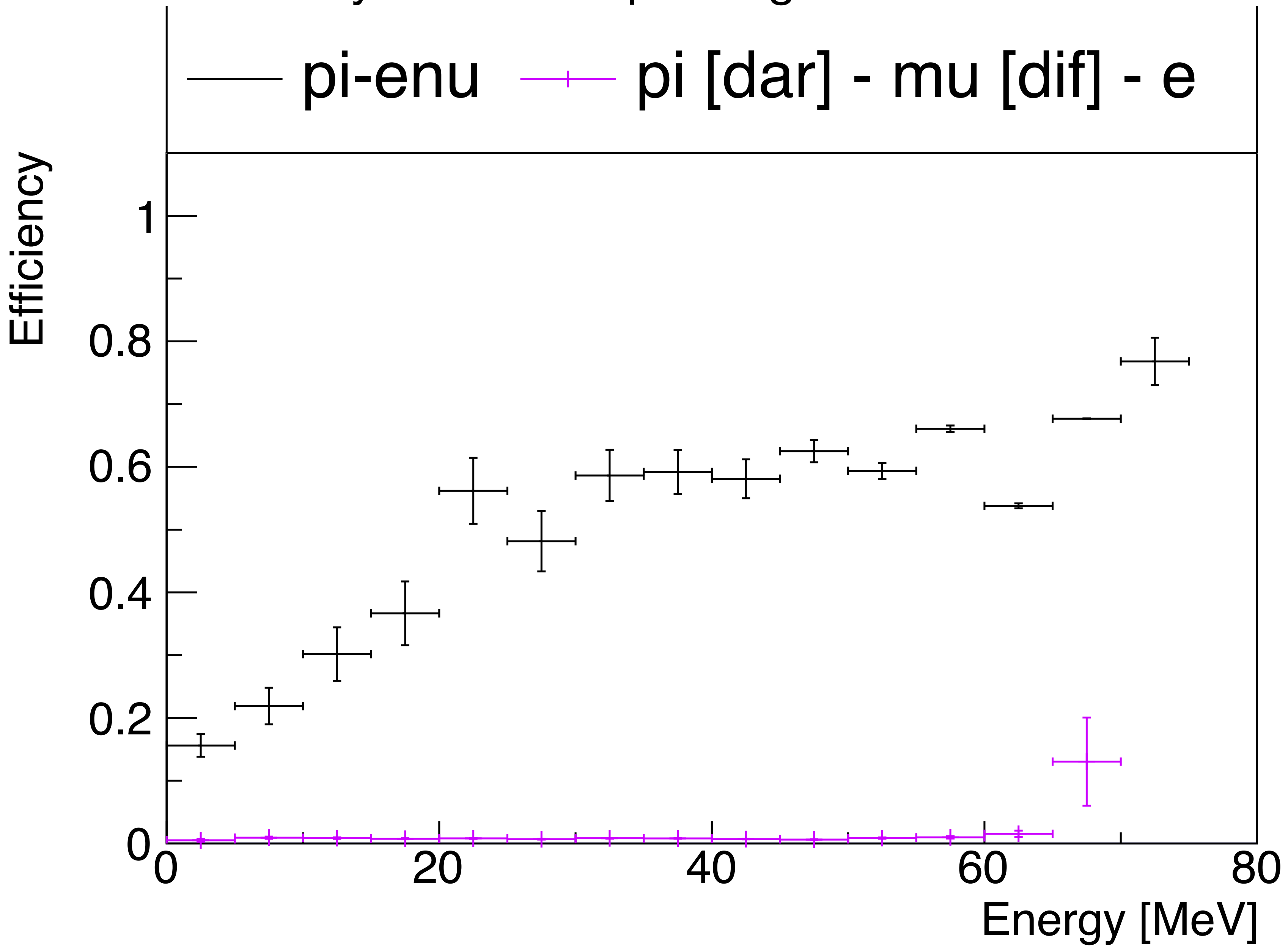


Reco. dE/dx (along Z)





Efficiency wrt events passing the cuts listed on S4

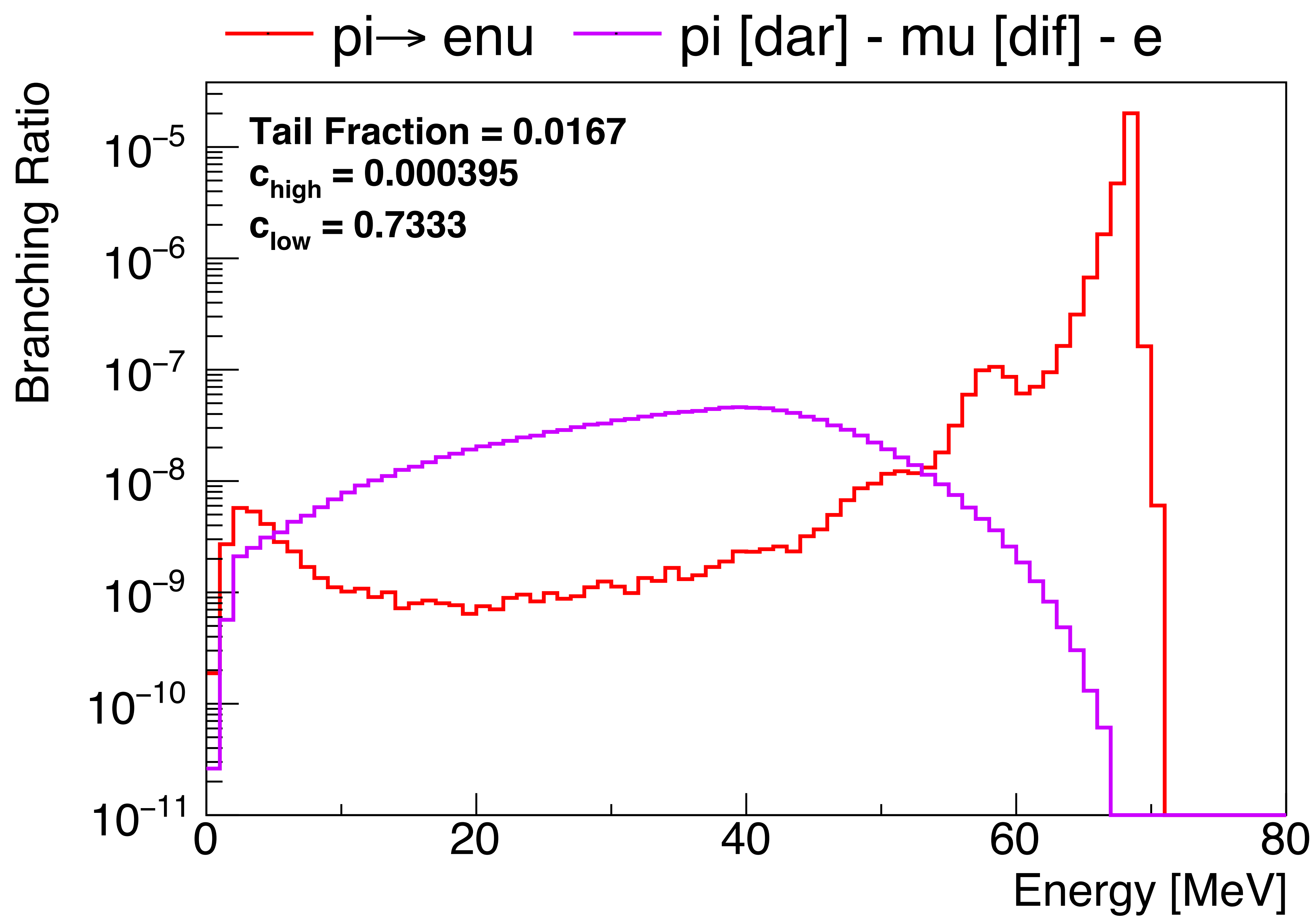


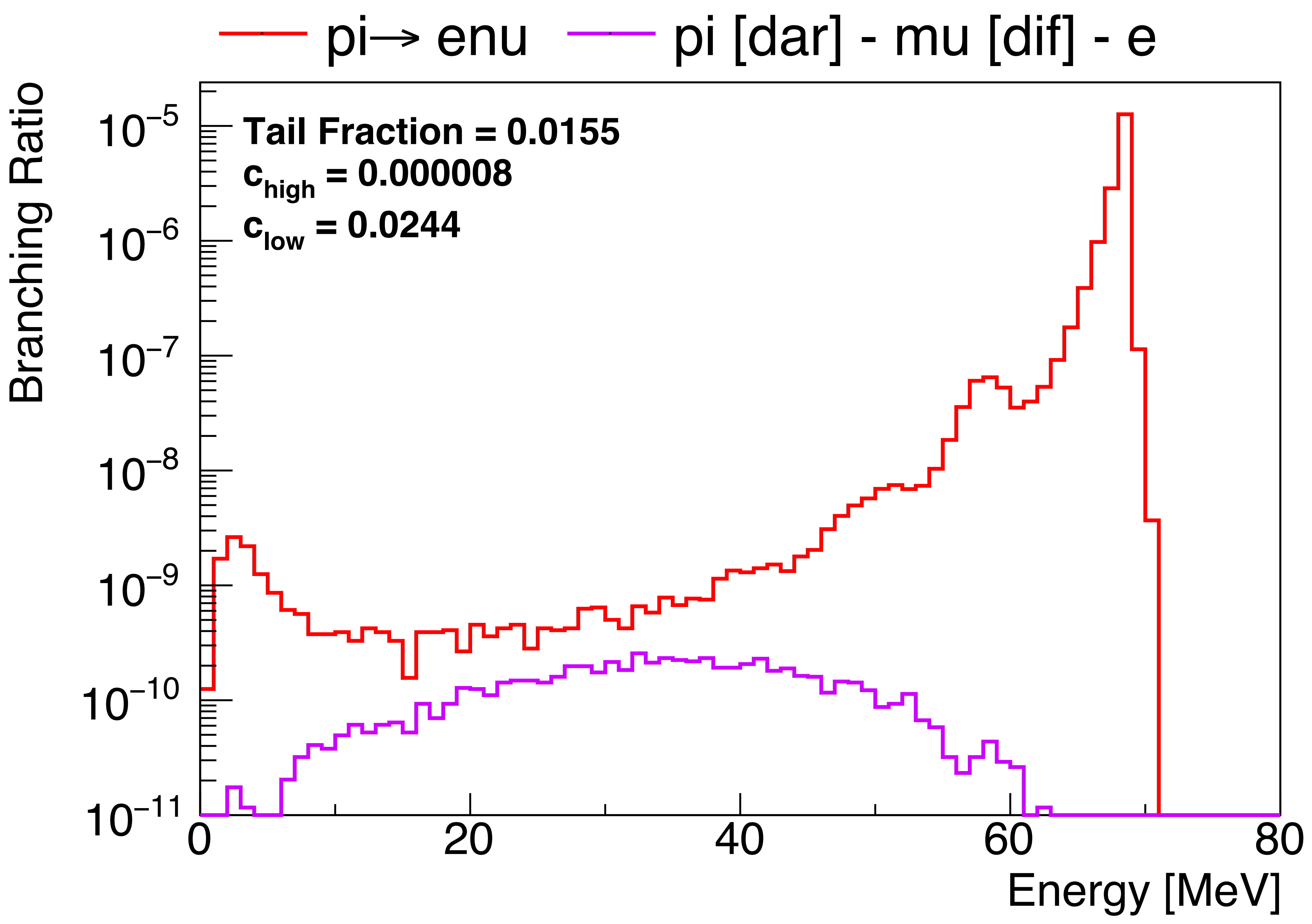
Keep events with
dE/dx(along z) < 0.5

Signal efficiency exhibits an energy dependency
needs to be investigated

Final selection

Applying dE/dx(along z) cut

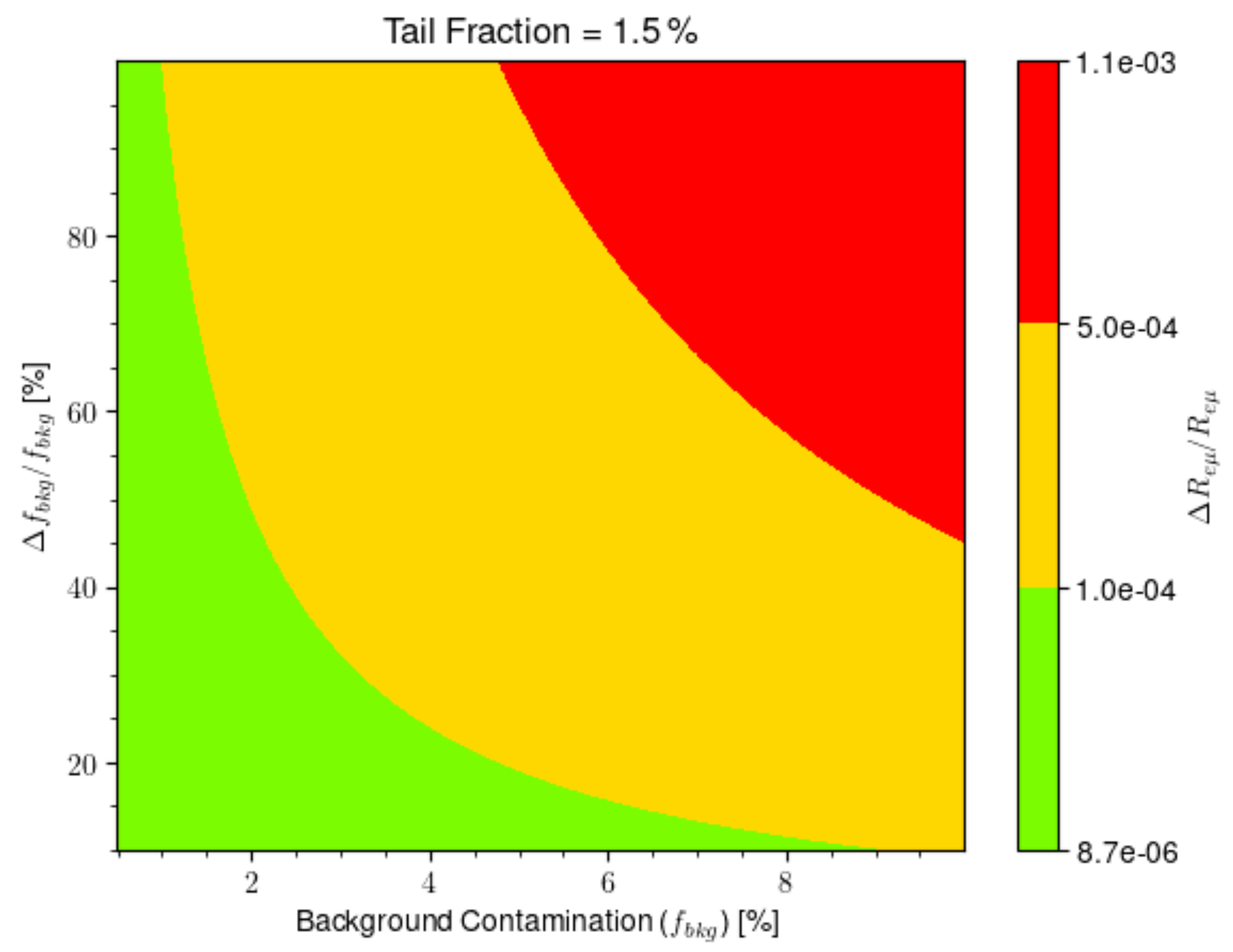


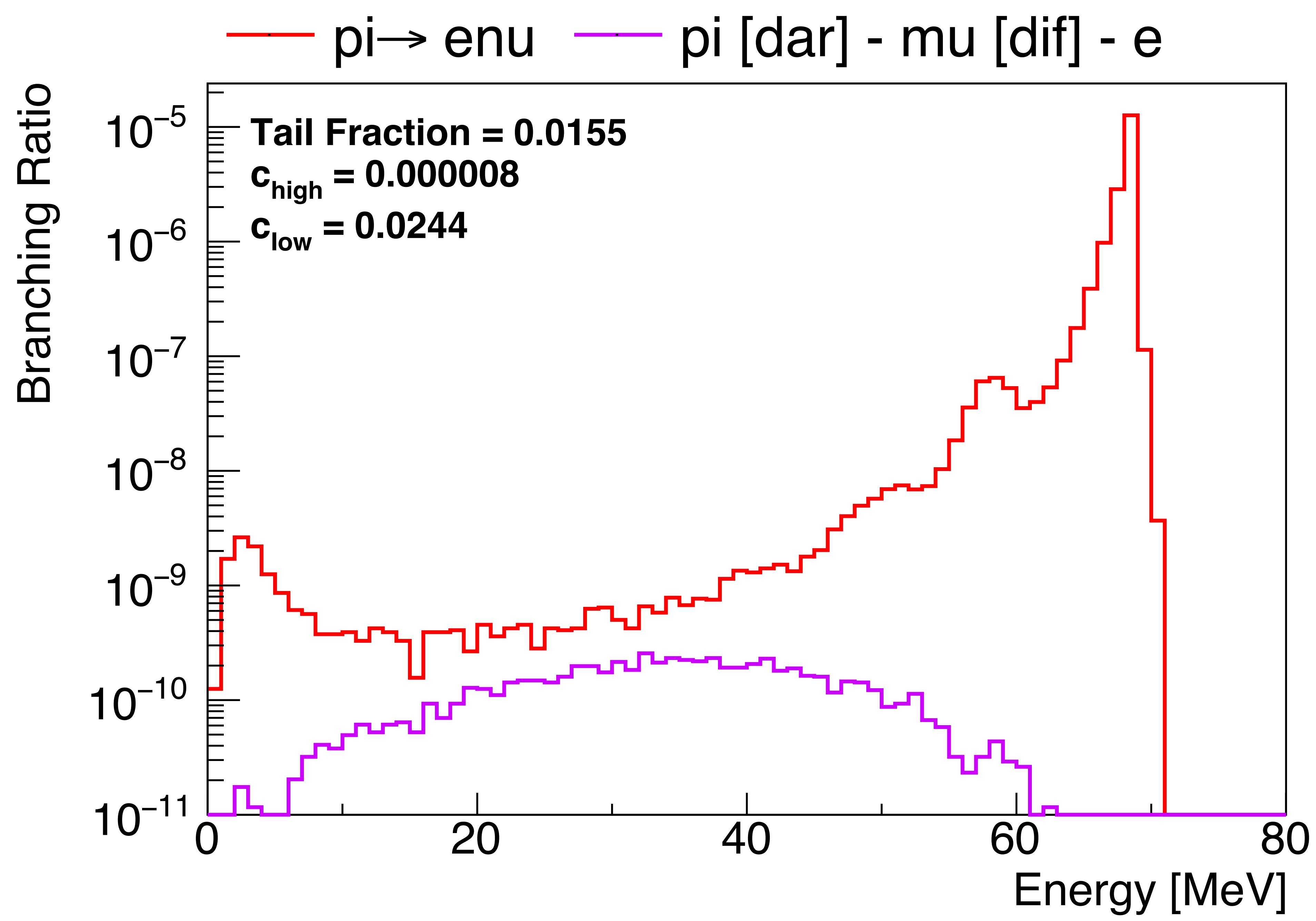


C_{low} reduced to 2.5%

Conclusions

- Muon decay in flight background seems to be manageable
    - ATAR is a fantastic tool to suppress it
    - Selection bias of the tail needs to be understood — and the impact on the measurement assessed
    - Impact of energy saturation and resolution needs to be studied in more details —> Decide on a few benchmark scenarios with ATAR experts?
- Precise pion stop determination can be achieved
    - Important for mu DIF but can also provide all around improvements (c.f. Patrick's talk)
    - Quantifying this precisely could provide a powerful benchmark for ATAR developments
- There is still room for improvement!
    - Tracking can provide precise x, y, z position of positron track. Can leverage this to build a 3D dx
    - Highlighted several studies that can be conducted toward a more 'realistic' criteria





Backup

Cutflows

Cutflow for pienu_cutflow

Step	Name	Entries
1	all	7855325
2	findsummary	7850422
3	PIMCInfoFlag	7670862
4	upstream_calo_match	6378463
5	found_tracker_position	6378463
6	pass_theta_cut	2305767
7	one_pattern	2305767
8	atar_fiducial	1822468
9	kink_cut	1821174
10	true_de_dx_cut	1029751
11	ene_onepix_cut	1778673
12	pattern_has_two_tracks	1548112
14	de_dx_cut	1130336

pioneer_reco_ana.analysis.utils:INFO:

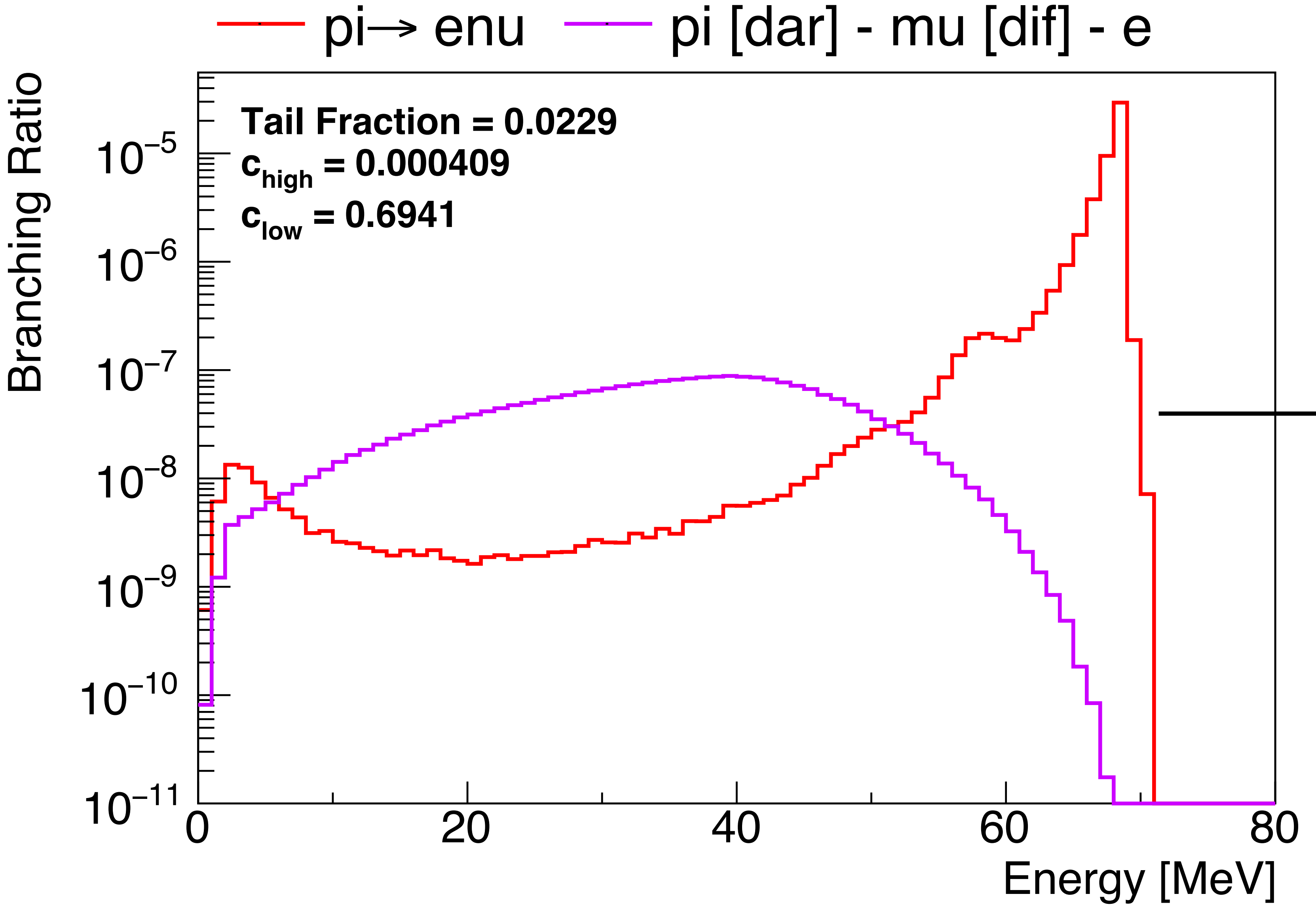
Cutflow for mudif_cutflow

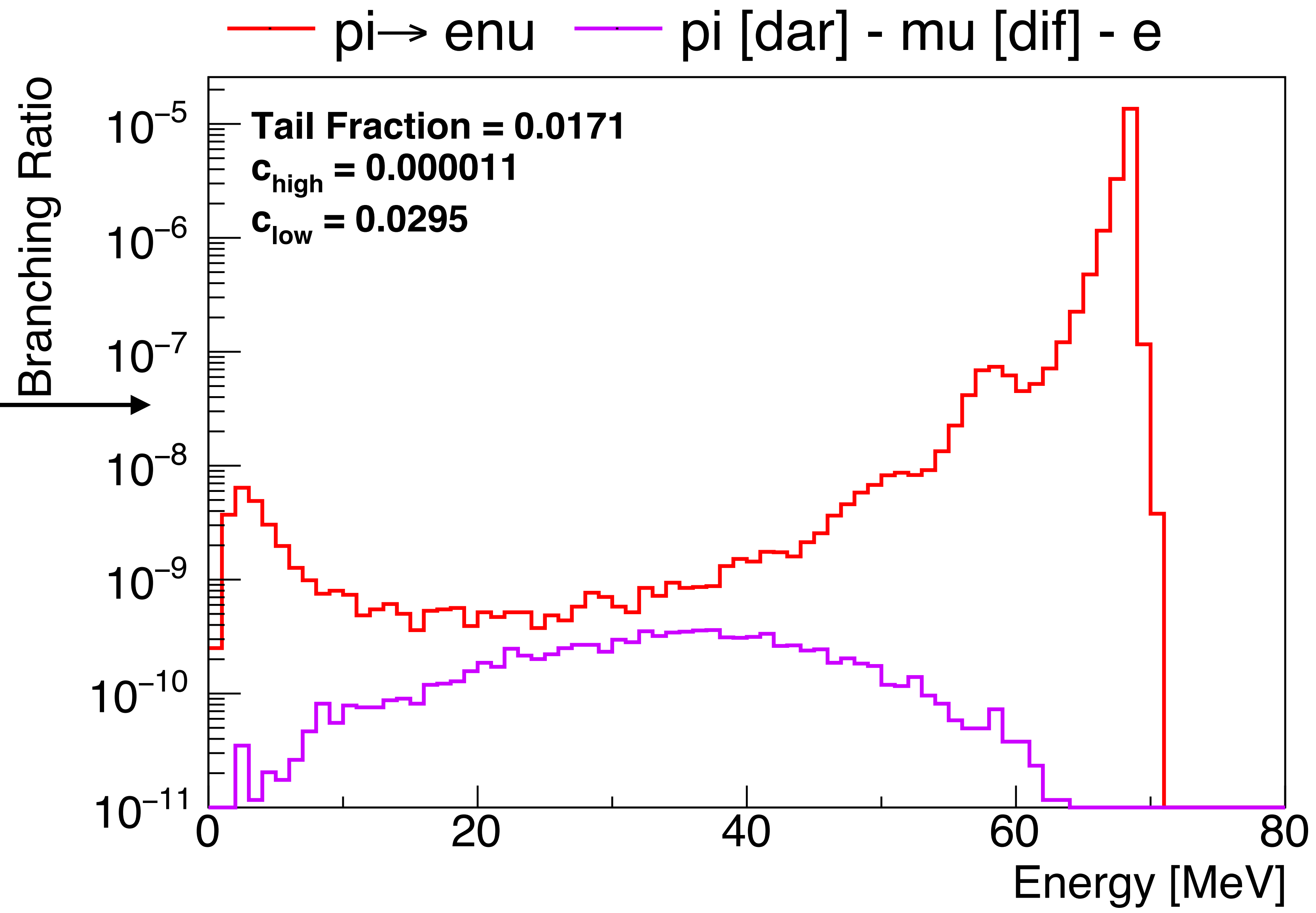
Step	Name	Entries
1	all	7822605
2	findsummary	7816234
3	PIMCInfoFlag	1854307
4	upstream_calo_match	1526307
5	found_tracker_position	1526307
6	pass_theta_cut	564671
7	one_pattern	564671
8	atar_fiducial	446398
9	kink_cut	69014
10	true_de_dx_cut	1107
11	ene_onepix_cut	15487
12	pattern_has_two_tracks	4389
14	de_dx_cut	2371

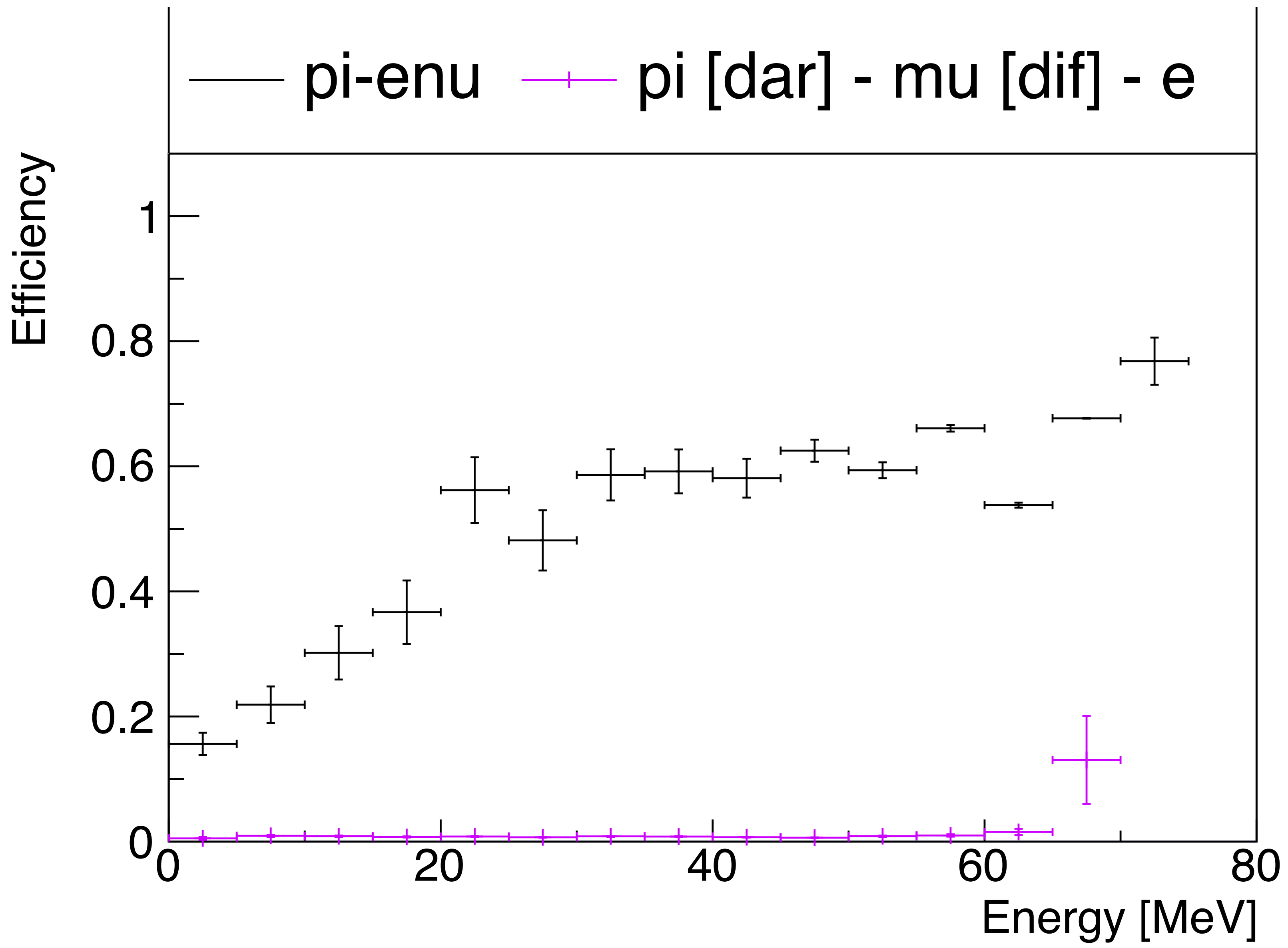
pioneer_reco_ana.analysis.utils:INFO:

Repeating the study with larger acceptance

Θ<π/2







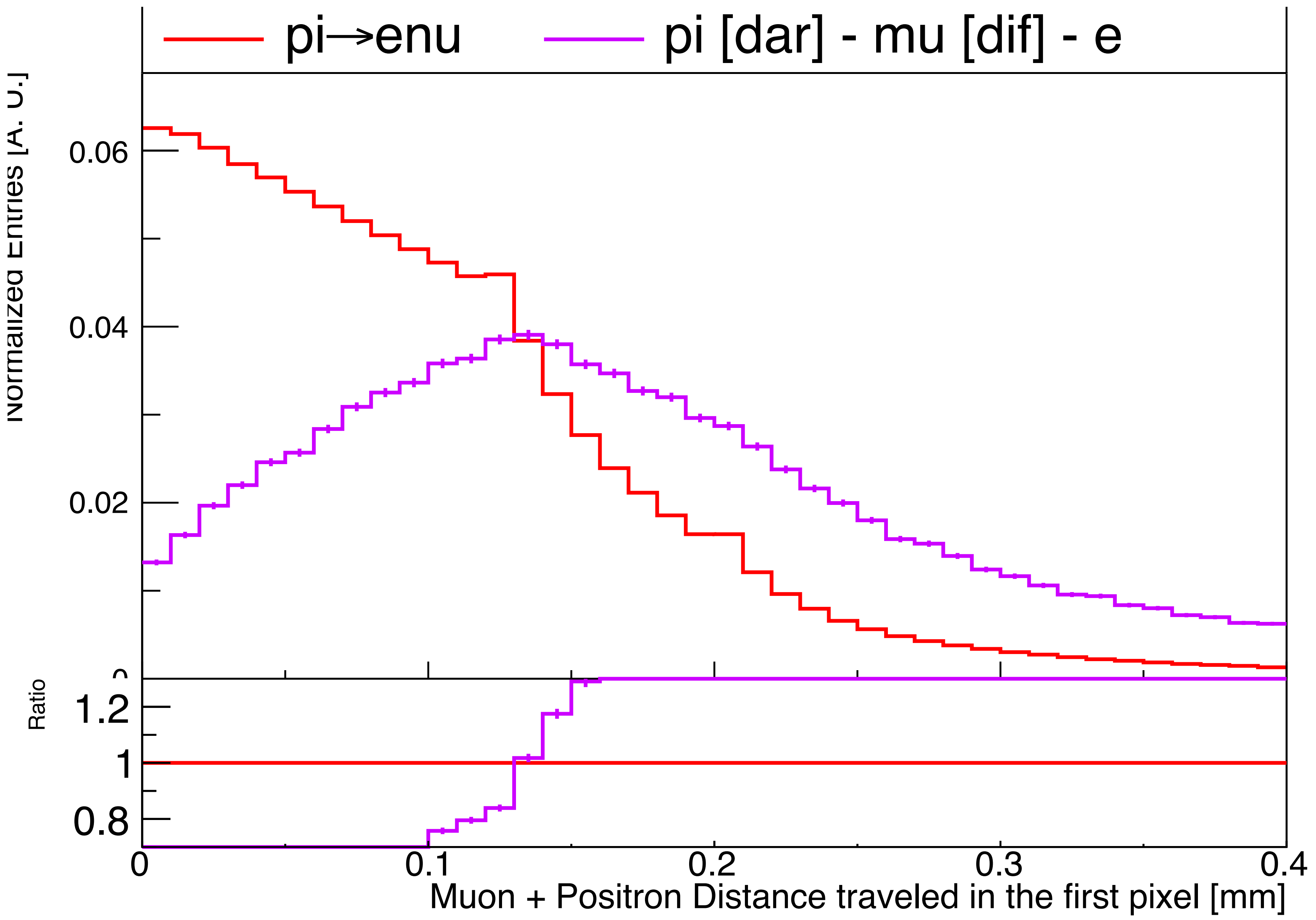
C_{low} reduced to 2.9%

Selection efficiency = 40%

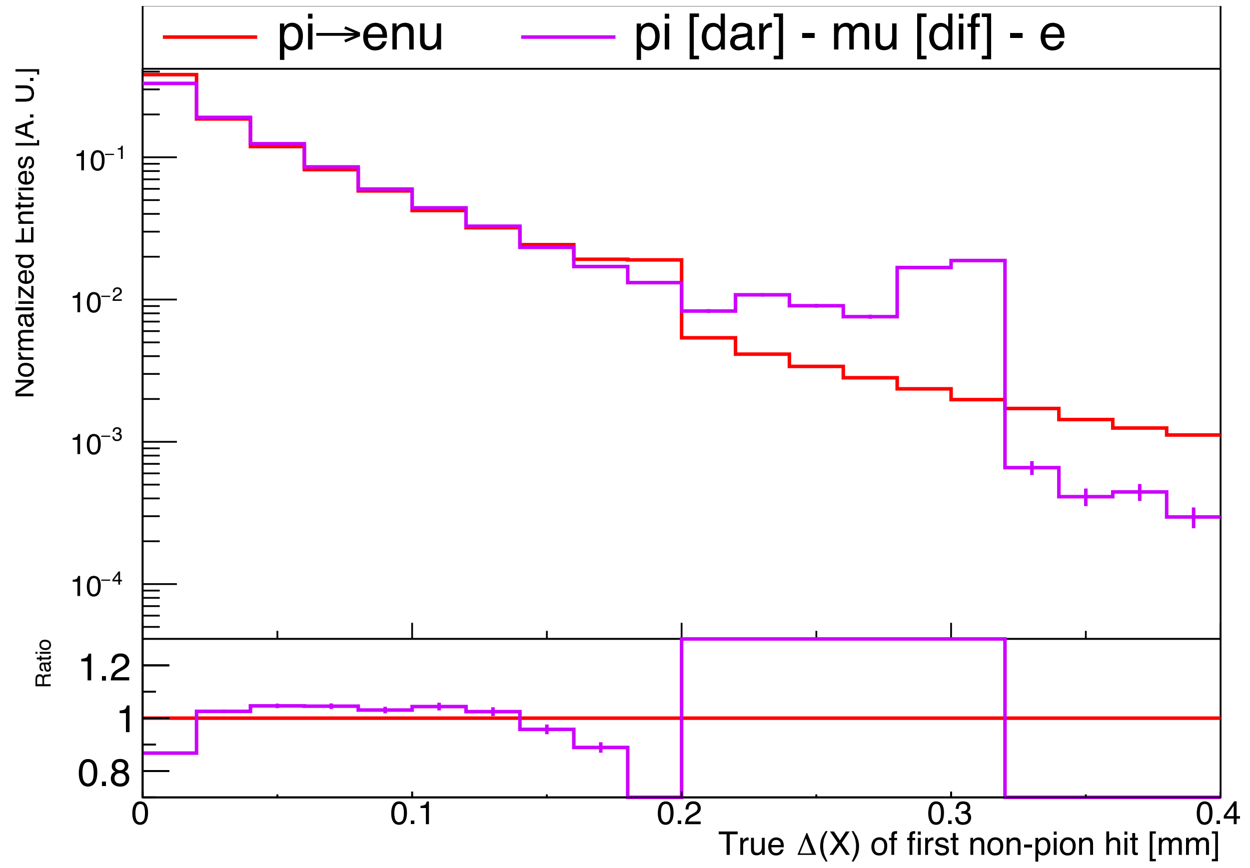
muDIF cuts efficiency = 40%

Signal efficiency=16%

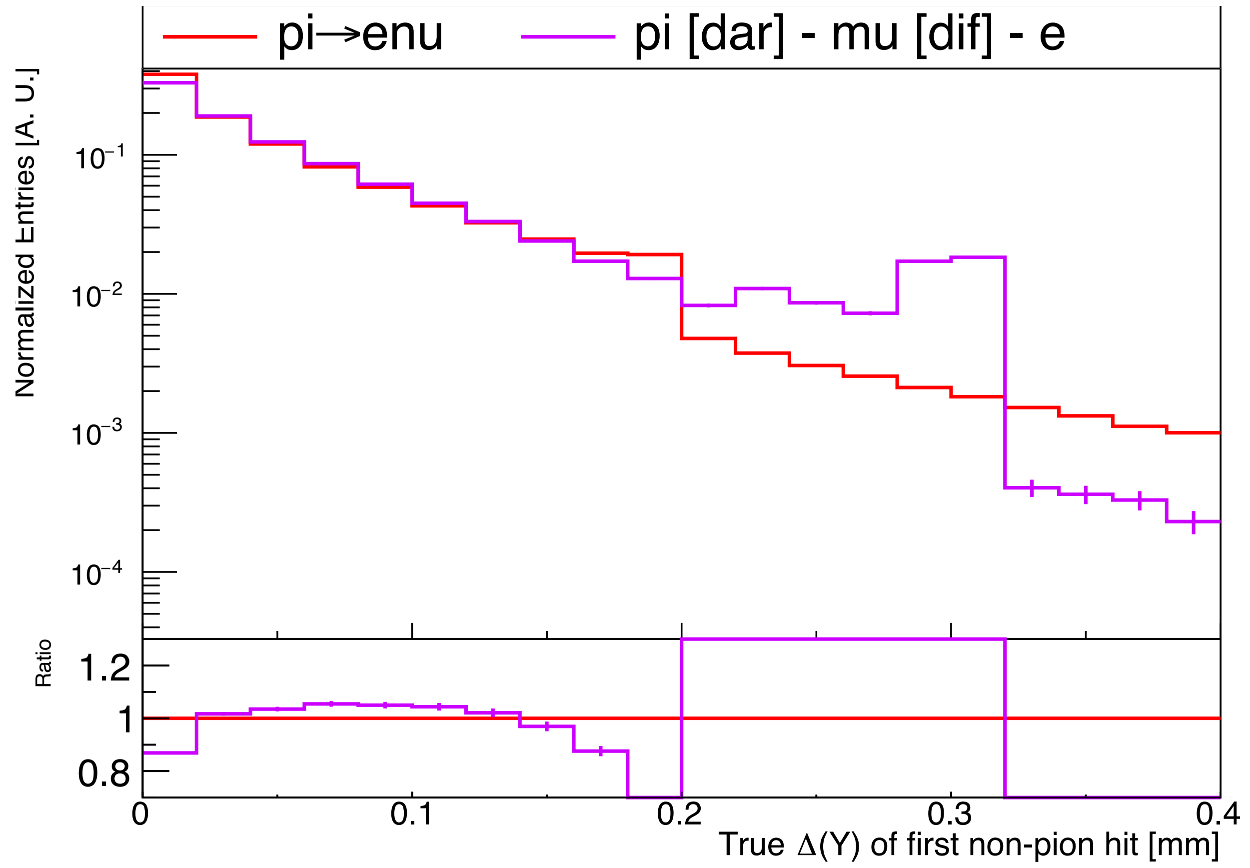
Muon Travel



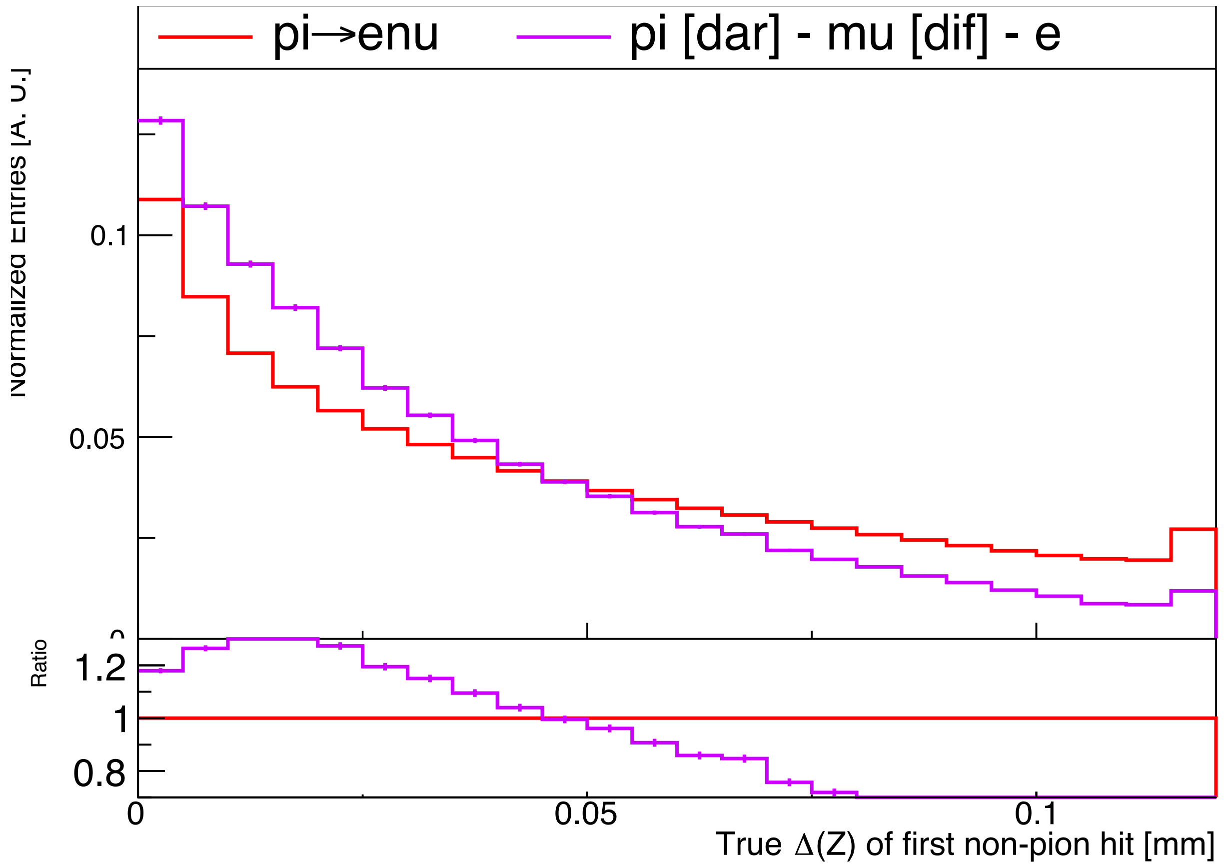
pi→enu
pi [dar] - mu [dif] - e
Normalized Entries [A. U.]
Ratio
Muon + Positron Distance traveled in the first pixel [mm]



pi→enu
pi [dar] - mu [dif] - e
Normalized Entries [A. U.]
Ratio
True Δ(X) of first non-pion hit [mm]



pi→enu
pi [dar] - mu [dif] - e
Normalized Entries [A. U.]
Ratio
True Δ(Y) of first non-pion hit [mm]



pi→enu
pi [dar] - mu [dif] - e
Normalized Entries [A. U.]
Ratio
True Δ(Z) of first non-pion hit [mm]