Event simulation and reconstruction in the active target

Vincent Wong
TRIUMF

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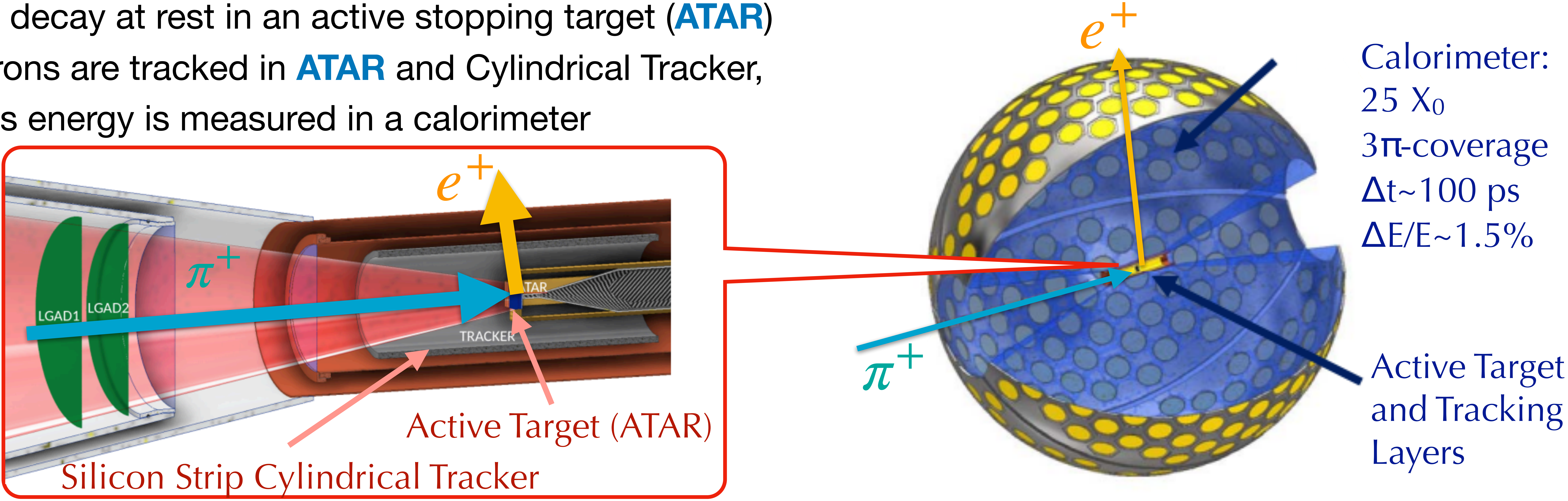
PIONEER experiment

- In Phase I of PIONEER, one of the main goals is to measure the branching ratio $R_{e/\mu} = \frac{\Gamma(\pi^+ \to e^+\nu(\gamma))}{\Gamma(\pi^+ \to \mu^+\nu(\gamma))}$ at the precision level of ≤ 0.01%
  - ✓ 20-fold improvement in the precision of the g_e/g_μ test, compared to current best results from PEN, PIENU
  - ✓ sensitive to BSM up to O(1000) TeV with coupling O(1), e.g. charged Higgs, leptoquarks…

PIONEER design to measure $\pi^+ \to e^+\nu$:

- Pions decay at rest in an active stopping target (**ATAR**)
- Positrons are tracked in **ATAR** and Cylindrical Tracker, and its energy is measured in a calorimeter



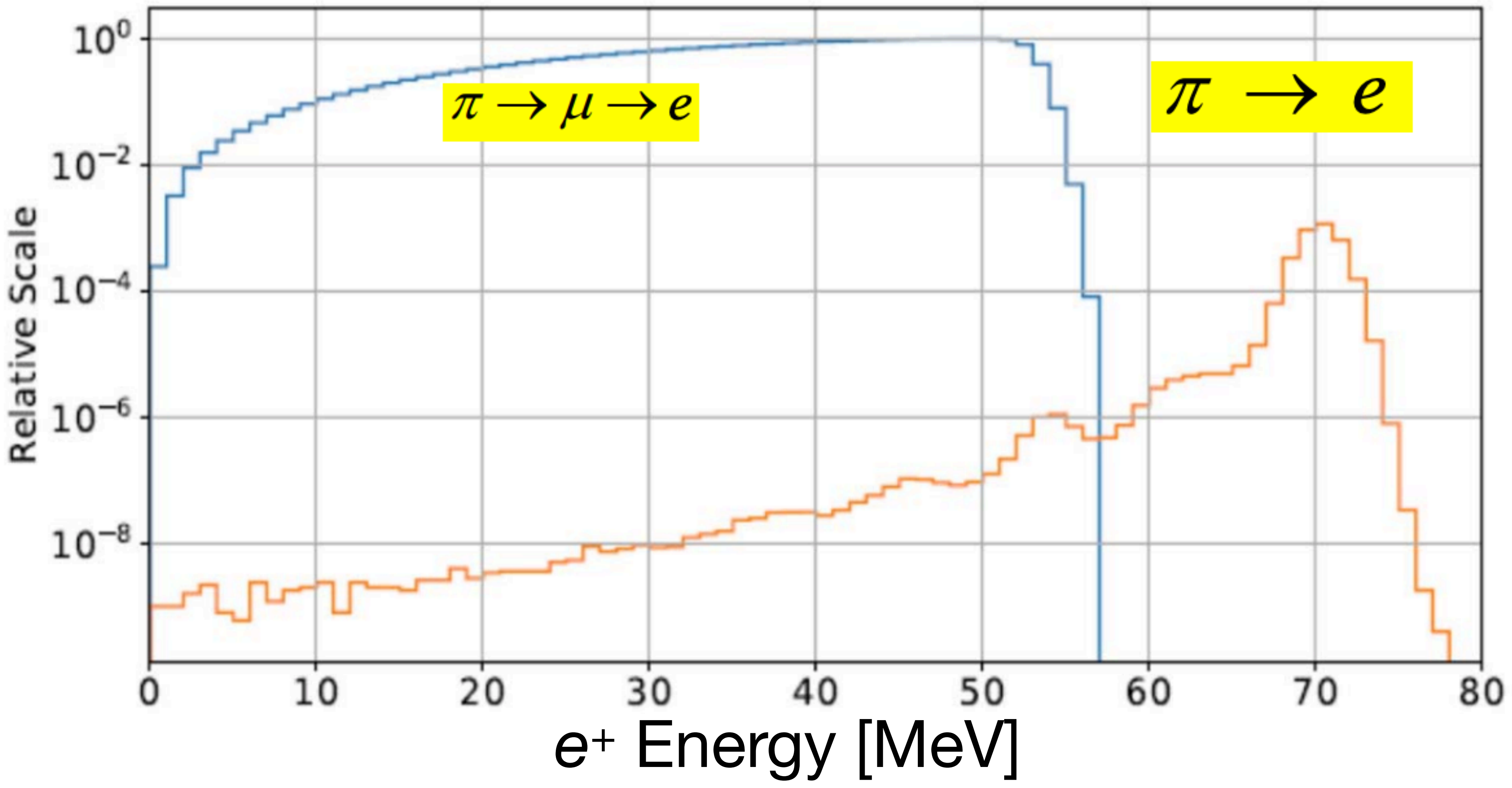
Tail fraction in low-energy spectrum

Principal challenge: Low energy "tail" of $\pi^+ \to e^+\nu$ events (from radiative decays) under $\pi^+ \to \mu^+(\to e^+\nu\bar{\nu})\nu$ background

- Silicon active target (ATAR) with 4D tracking
  - reduce pileup effects and $\pi^+ \to e^+\nu$ energy tail correction
  - directly identify $\pi^+ \to \mu^+ \to e^+$ "Michel" decay chain
- Calorimeter with high resolution and fast timing
  - improve $\pi^+ \to e^+\nu$ energy tail suppression
- Fast electronics and DAQ ⇒ improve efficiency

- The main systematic uncertainty for PIENU was the uncertainty in the tail correction for $\pi^+ \to e^+\nu$ events below 52 MeV, where the suppression of "Michel" decay chain is crucial

simulated decay spectrum before $\pi^+ \to \mu^+ \to e^+$ suppression

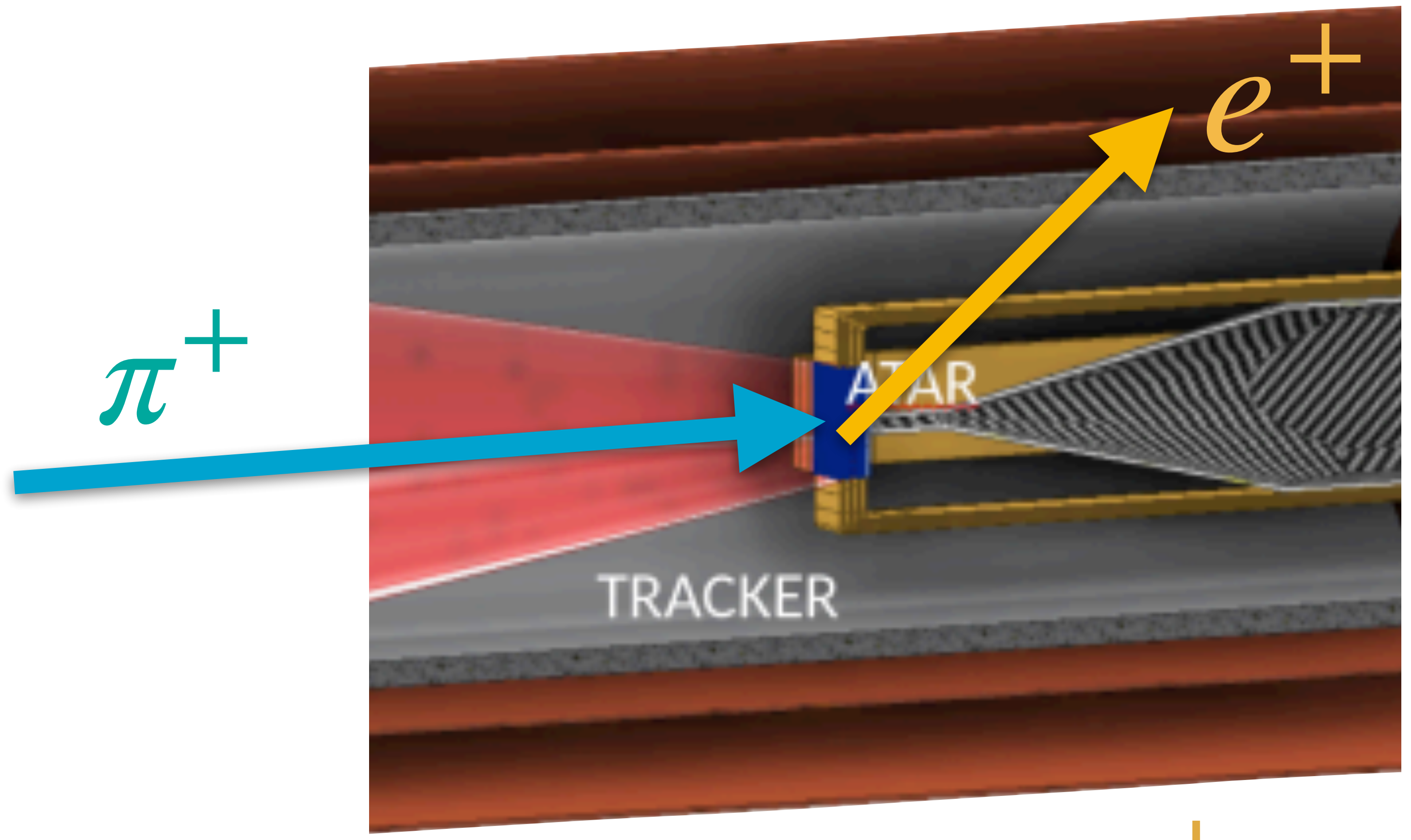


Error Source	PIENU 2015 %	PIONEER Estimate %
Statistics	0.19	0.007
Tail Correction	0.12	<0.01
t_0 Correction	0.05	<0.01
Muon DIF	0.05	0.005
Parameter Fitting	0.05	<0.01
Selection Cuts	0.04	<0.01
Acceptance Correction	0.03	0.003
Total Uncertainty	**0.24**	**≤ 0.01**

ATAR simulation

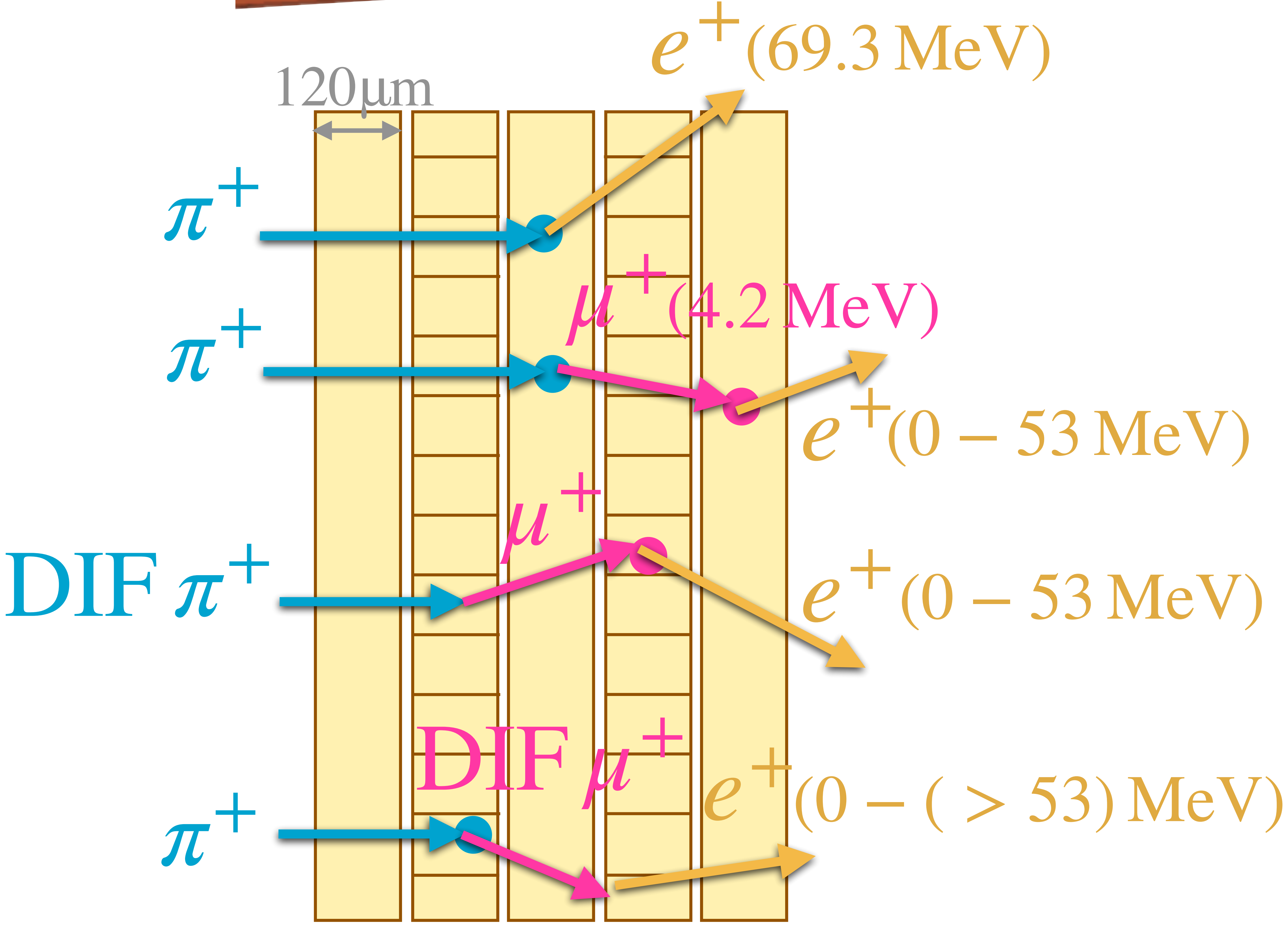
<u>Baseline design of the ATAR:</u>

- employs Low Gain Avalanche Detectors (LGAD)
- High granularity
  - consists of 48 layers of orthogonal X/Y Si strips
  - Strip size: *120 µm thick* x *200 µm wide* x *2 cm long*
  - 100 strips/layer



Beamline setup:

- 55 MeV/c π^+ with $\Delta p/p$=2% (from PSI $\pi E5$ beamline)
  - no degrader included upstream

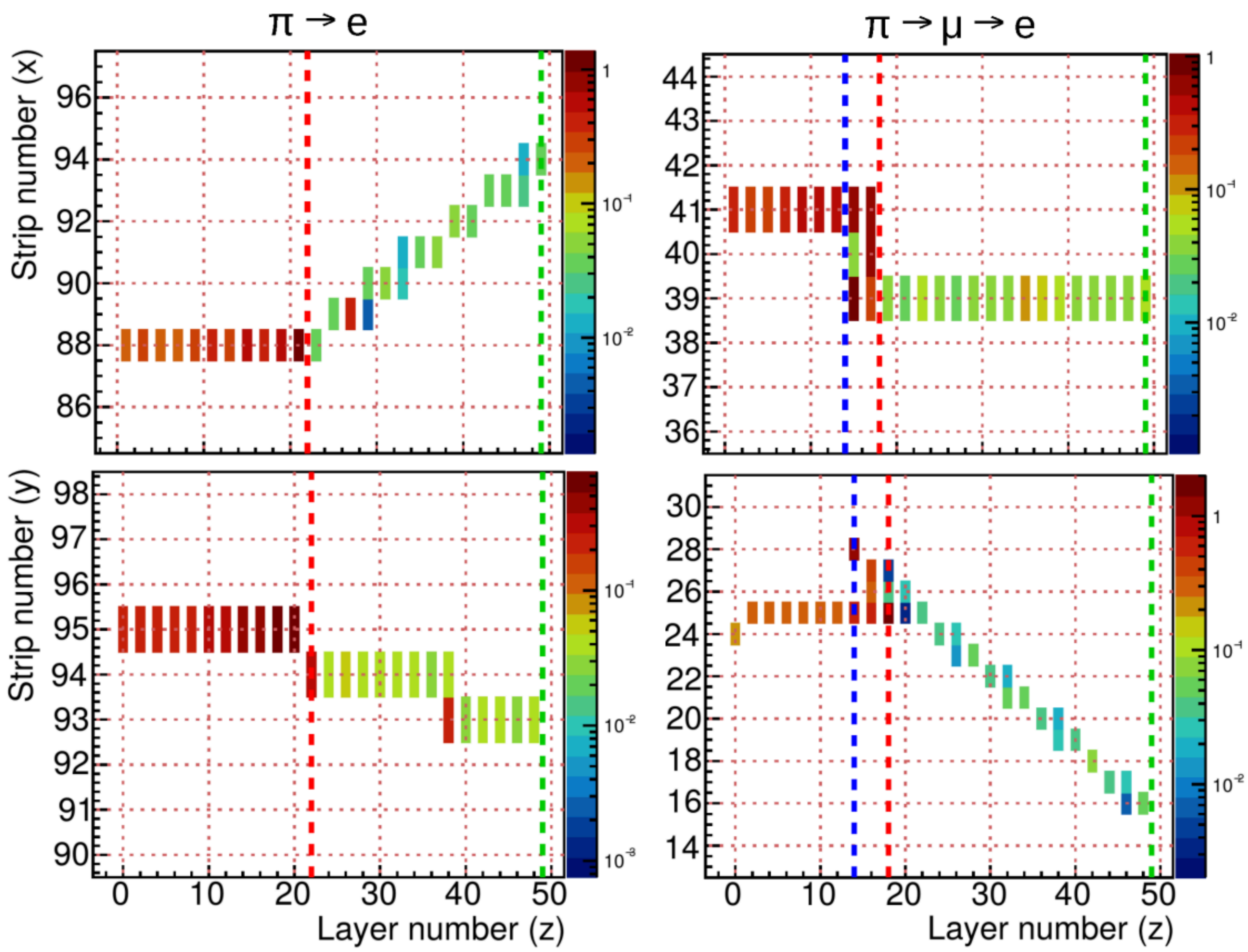


Pion decay modes considered:

- π^+ decay at rest (DAR) → e^+
- π^+ decay at rest (DAR) → μ^+ decay at rest (DAR) → e^+
- π^+ decay in flight (DIF) → μ^+ decay at rest (DAR) → e^+
- π^+ decay in flight (DAR) → μ^+ decay at rest (DIF) → e^+

ATAR simulation

Event display:



Suppression of $\pi \to \mu \to e$ events

	positron timing from pion hits	energy deposits	'pion' stopping plane	'pion' dE/dx	'pion' tracking	'positron' track
DAR $\pi \to e$	short	mostly in central volume and narrowly distributed	narrowly distributed	follows pion Bragg peak	straight track	positron-like
DAR π $\to$ DAR $\mu \to e$	long	4.1 MeV higher from muon	similar	similar	similar	similar
in-ATAR DIF π $\to$ DAR $\mu \to e$	long	partially in central volume and widely distributed	widely distributed	follows muon Bragg peak	track with a kink	similar
DAR π $\to$ DIF $\mu \to e$	similar	similar	similar	similar	similar	muon-like

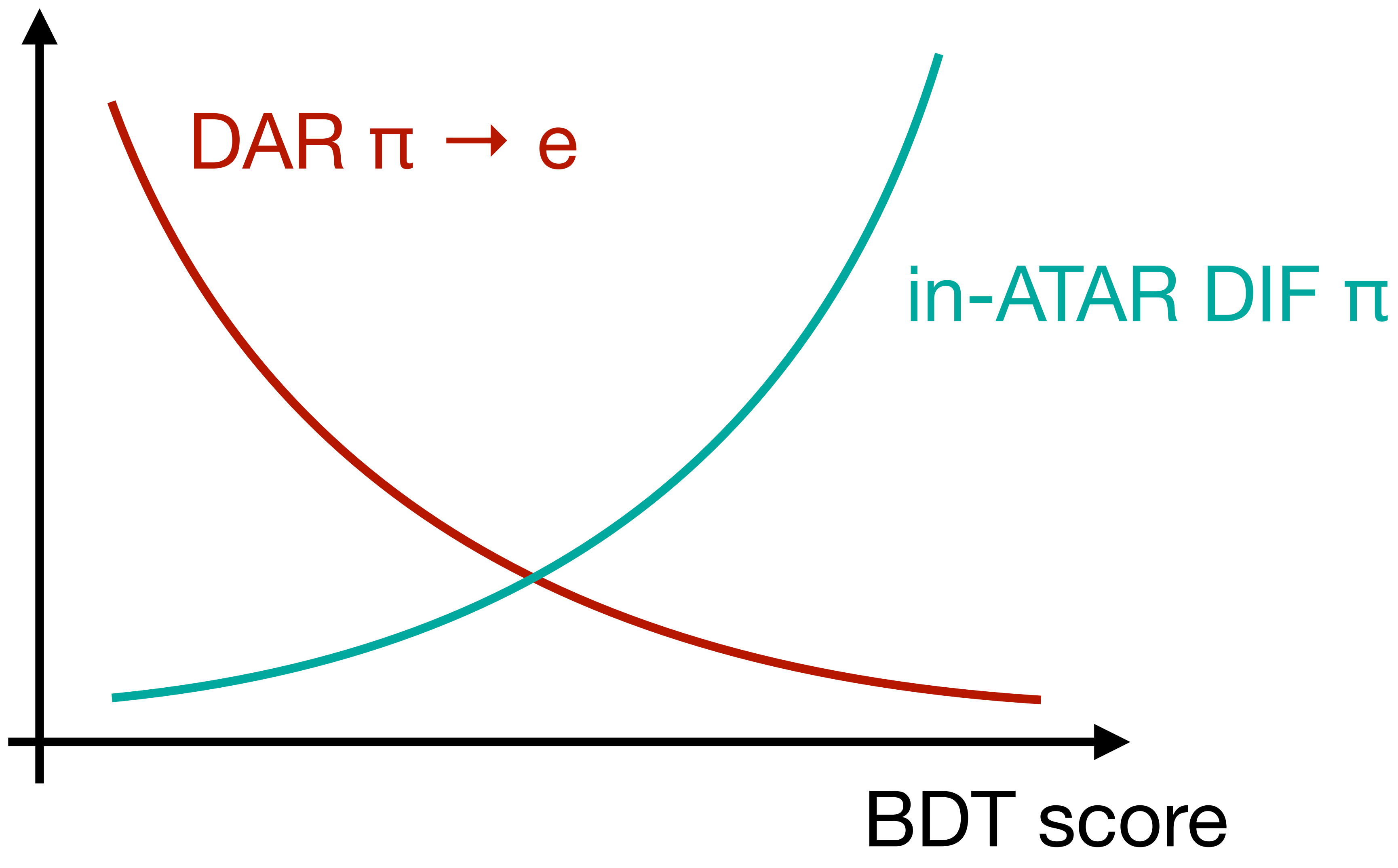
- With good pulse pair resolution, the presence of 4.1 MeV allows DAR $\pi \to \mu \to e$ suppression factor at a level of $O(10^7)$ or more ➡ simple cut on energy deposit
- ATAR can provide excellent tracking information to suppress in-ATAR DIF π, which dominated the background suppressed spectrum in PIENU ➡ BDT
- DIF μ looks similar to DAR $\pi \to e$, except local dE/dx along the positron track
  ➡ simple cut on energy deposit in the closest five positron hits to the pion stopping vertex

Suppression of in-ATAR DIF π

In order to optimize the suppression of in-ATAR DIF π, a gradient-boosted decision tree (BDT) is applied on ATAR information, like stopping position, dE/dx and tracking topology.

- pion stopping plane position
- plane position with max E
- total energy deposit
- goodness of linear track fit in x- & y-orientation
- individual energy deposits in the last five planes before the pion stopping plane

→ **XGBoost** →



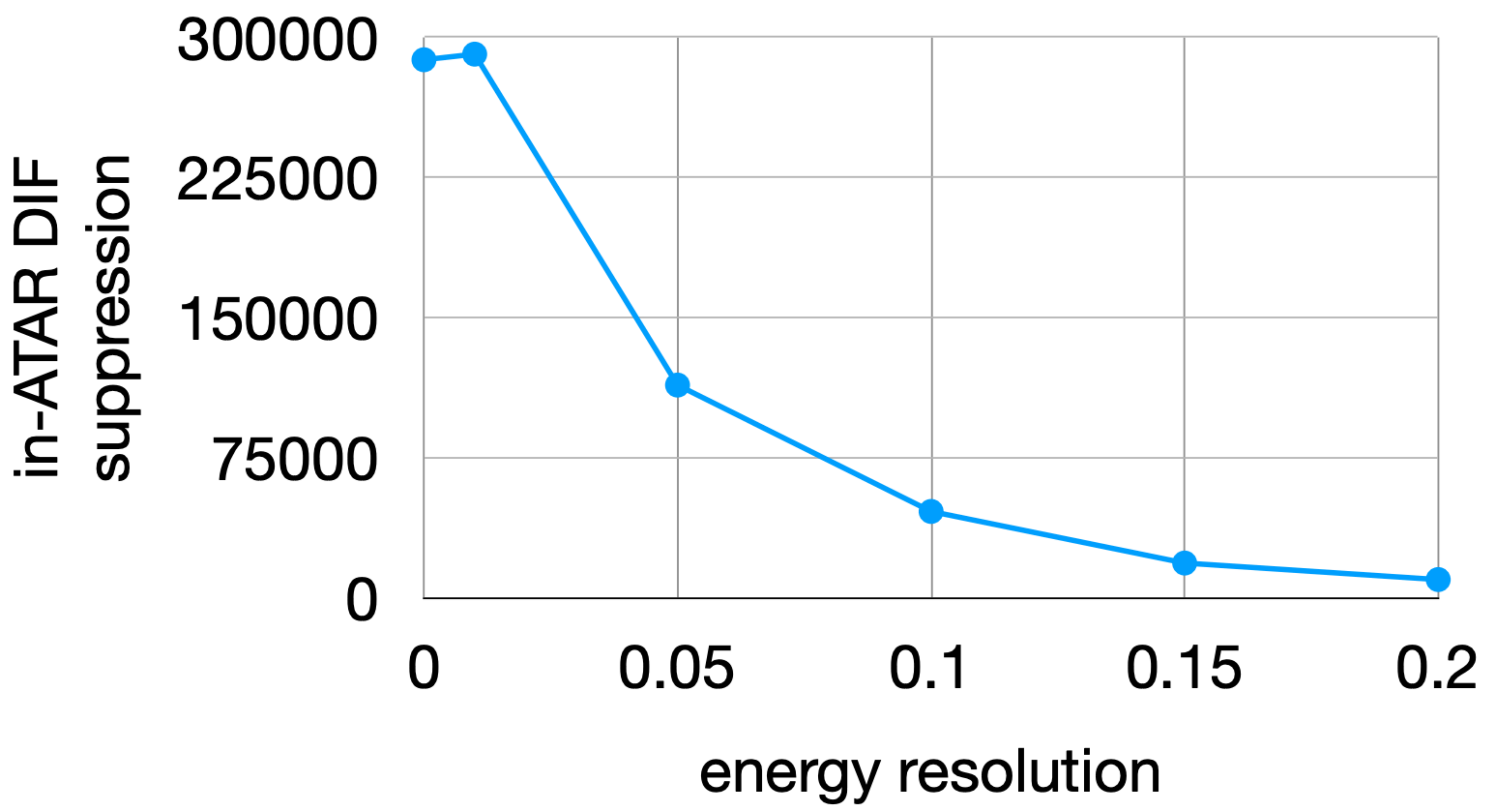
At a 10% energy resolution, "in-ATAR DIF π" has a misidentified rate of 0.35% when the "DAR π → e" efficiency is 75%, resulting in a suppression factor of ~650.

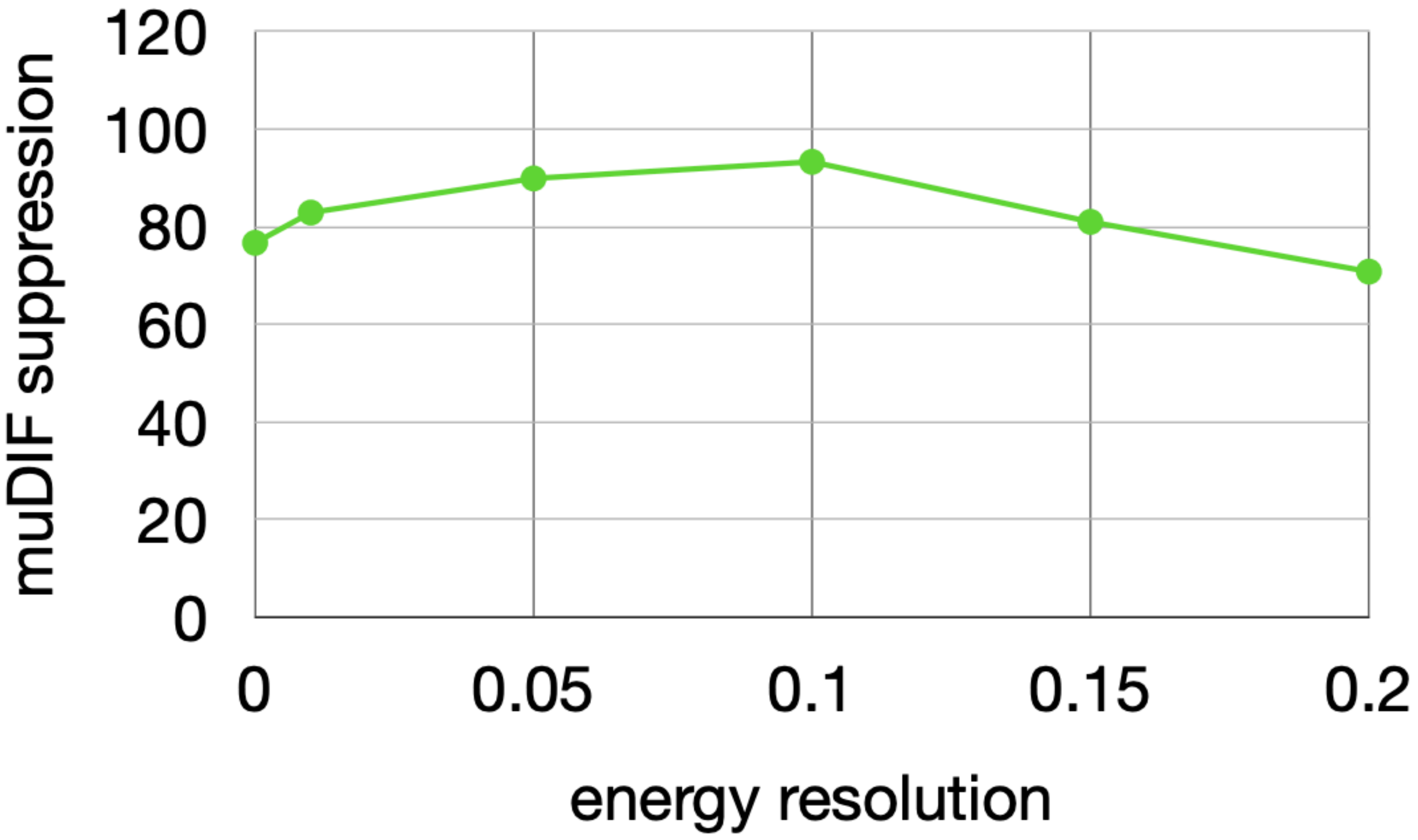
Additionally, there's a suppression factor of:
(i) ~50 by requiring $t_{e^+} \in [2, 32]\,\mathrm{ns}$, and
(ii) ~1.5 by requiring central energy deposit > 75%

suppression factor of O(40,000) in total

Suppression of DIF backgrounds

As a function of ATAR energy resolution:

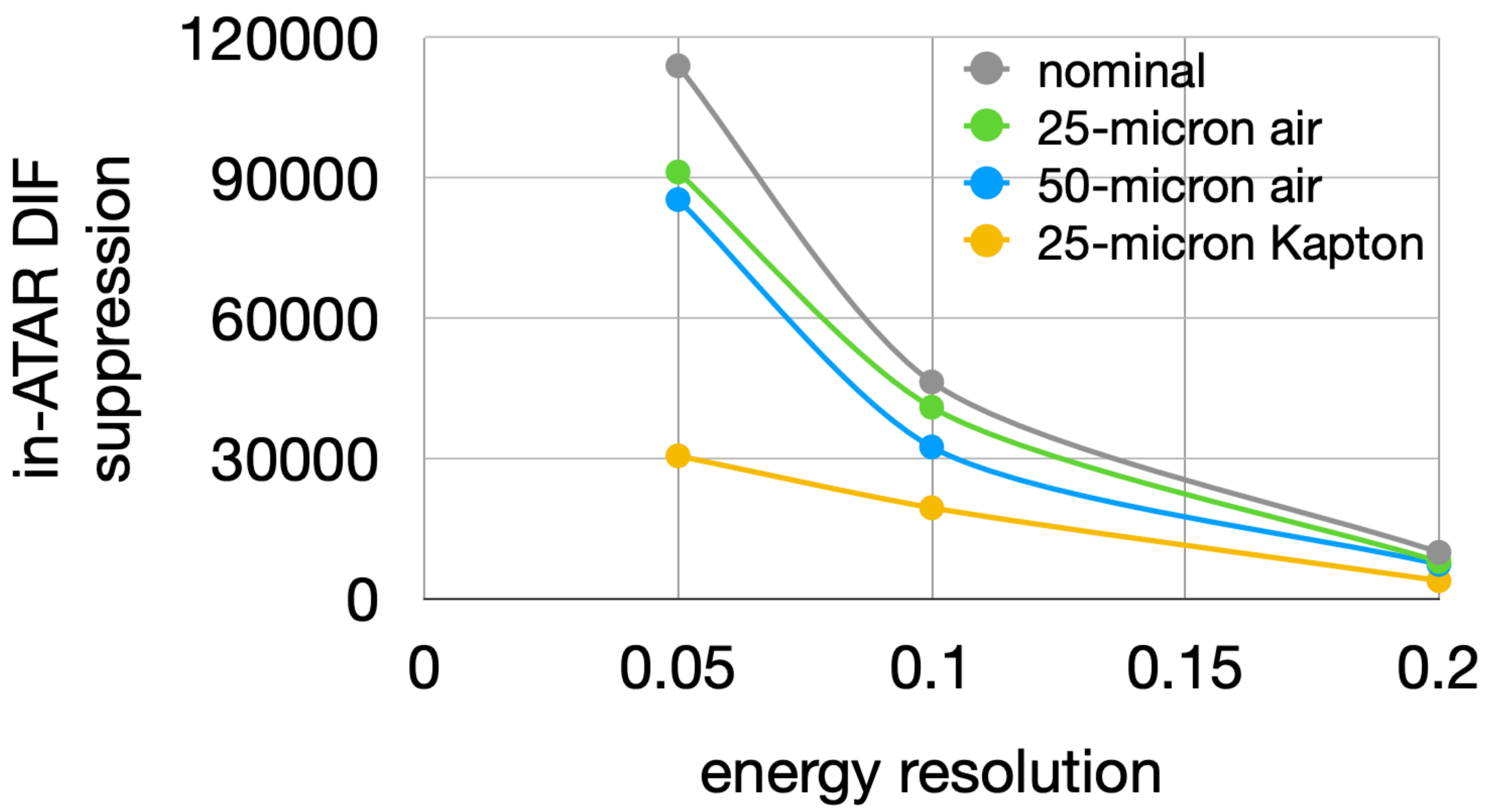


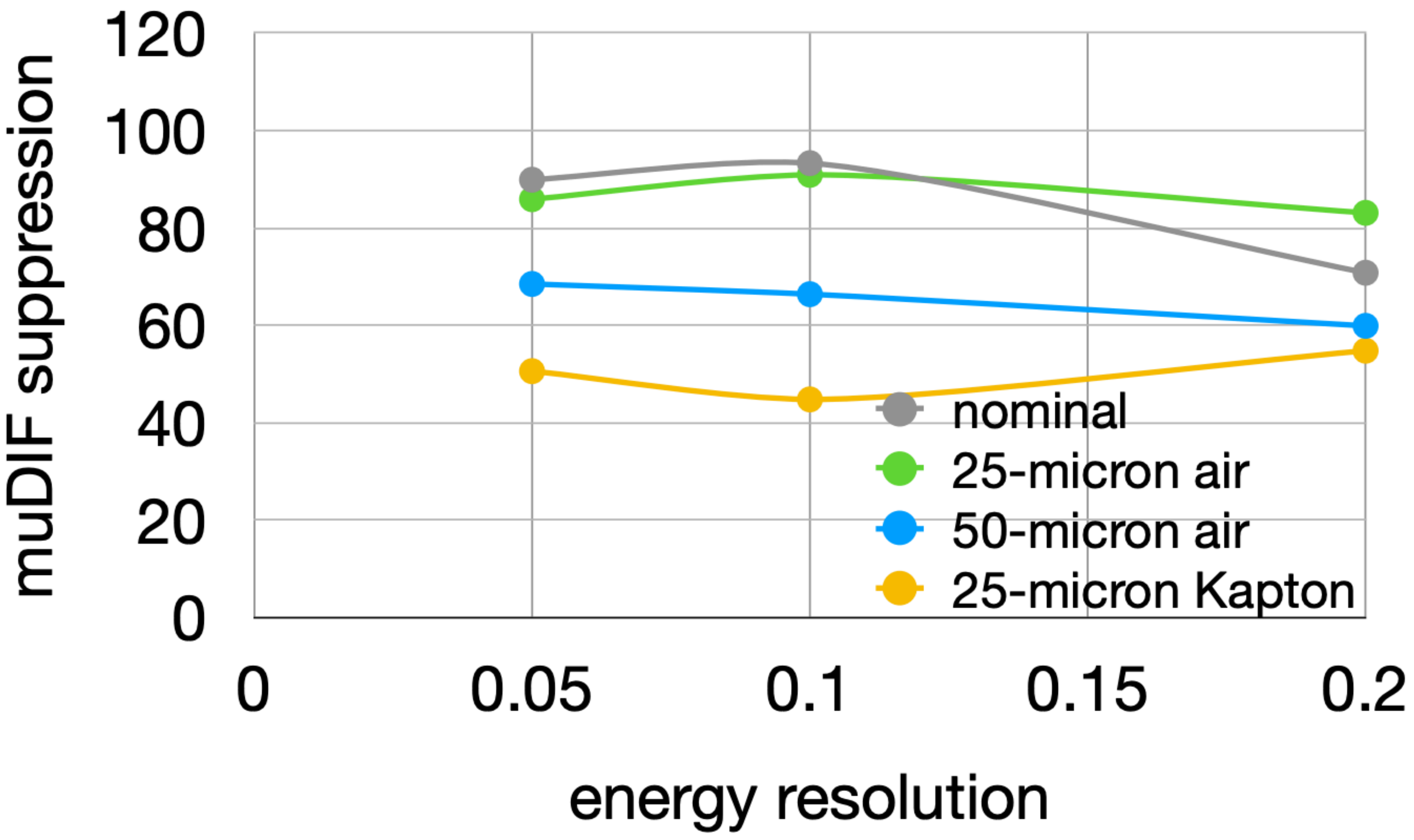


- "in-ATAR DIF π" suppression deceases and levels off as energy resolution gets worse (as separation power from track fit is not affected)
- "DIF μ" suppression is not affected much, as a muon-like hit is distinctive enough from a positron-like hit

Suppression of DIF backgrounds

Dead material study was performed to investigate the effect of dead material between layers for supporting structure:



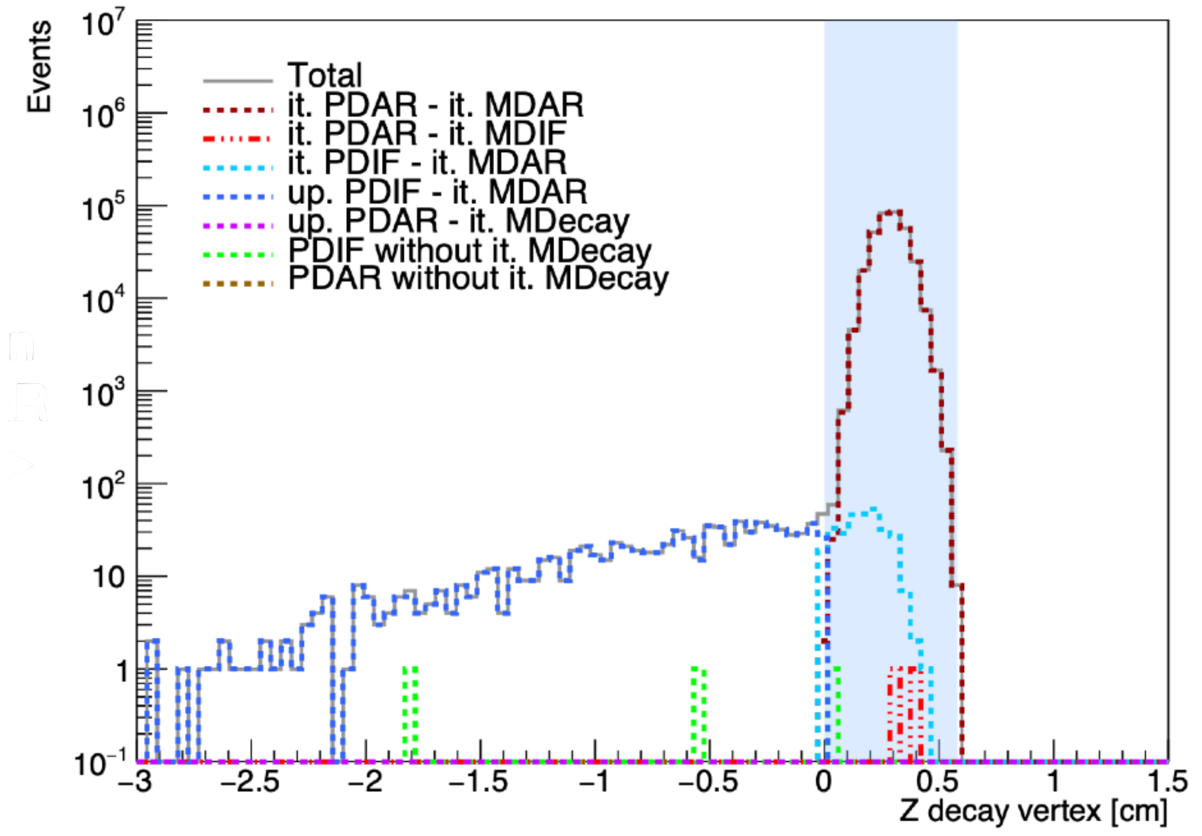


- Suppression is lower when Kapton is used instead of leaving an air gap in between layers.
- 25-micron of air gap does not affect the suppression very much.

Energy spectrum after π → μ → e suppression

$$R_{e/\mu} = \frac{\Gamma(\pi^+ \to e^+\nu(\gamma))}{\Gamma(\pi^+ \to \mu^+\nu(\gamma))} = 1.23 \times 10^{-4}$$

×



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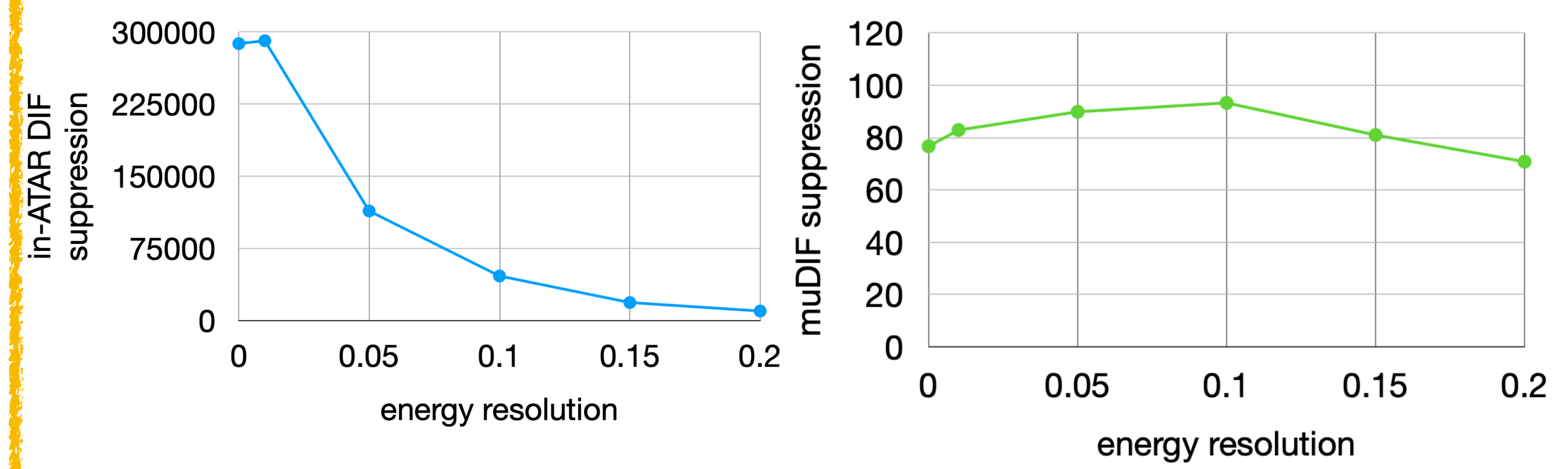

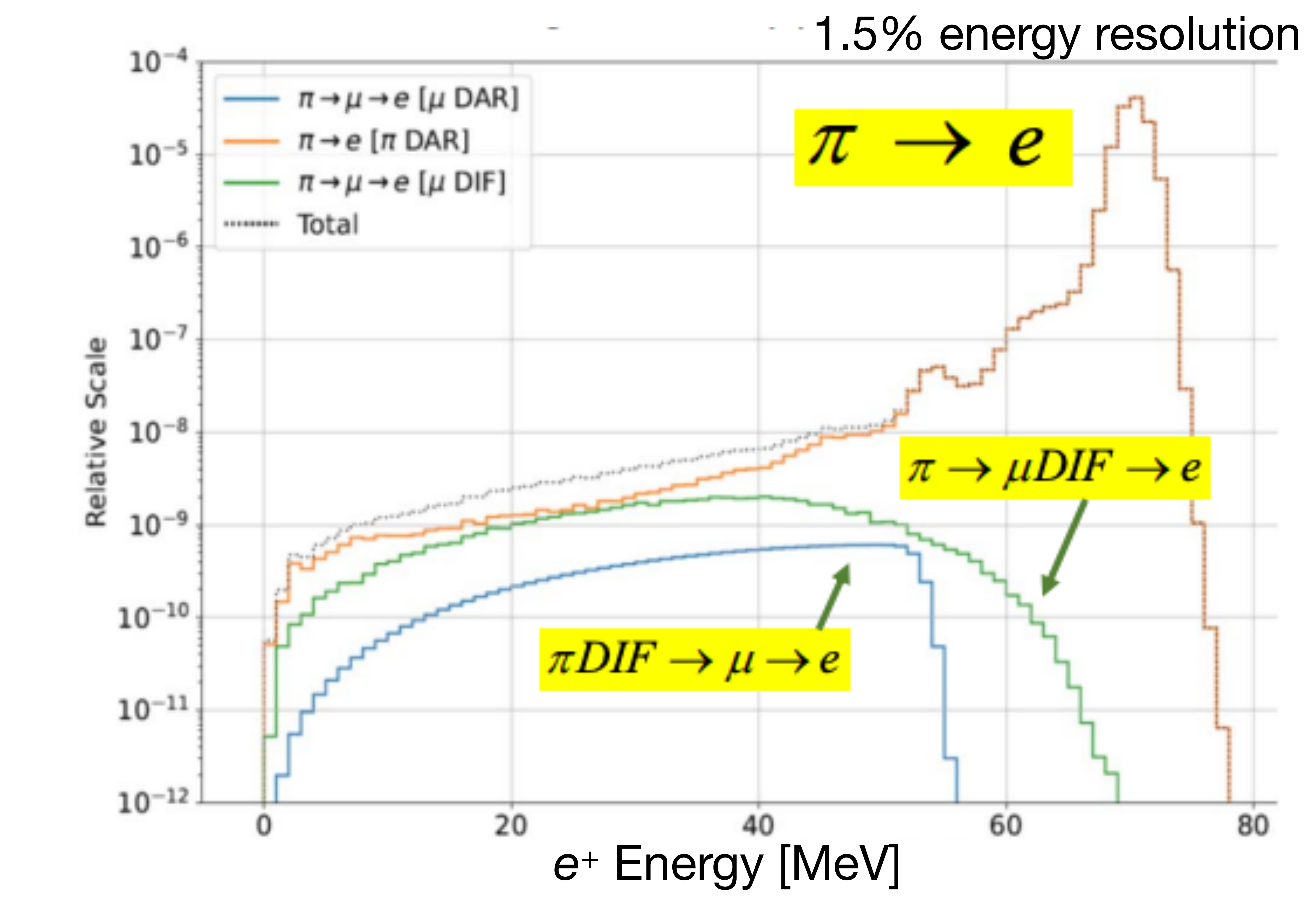

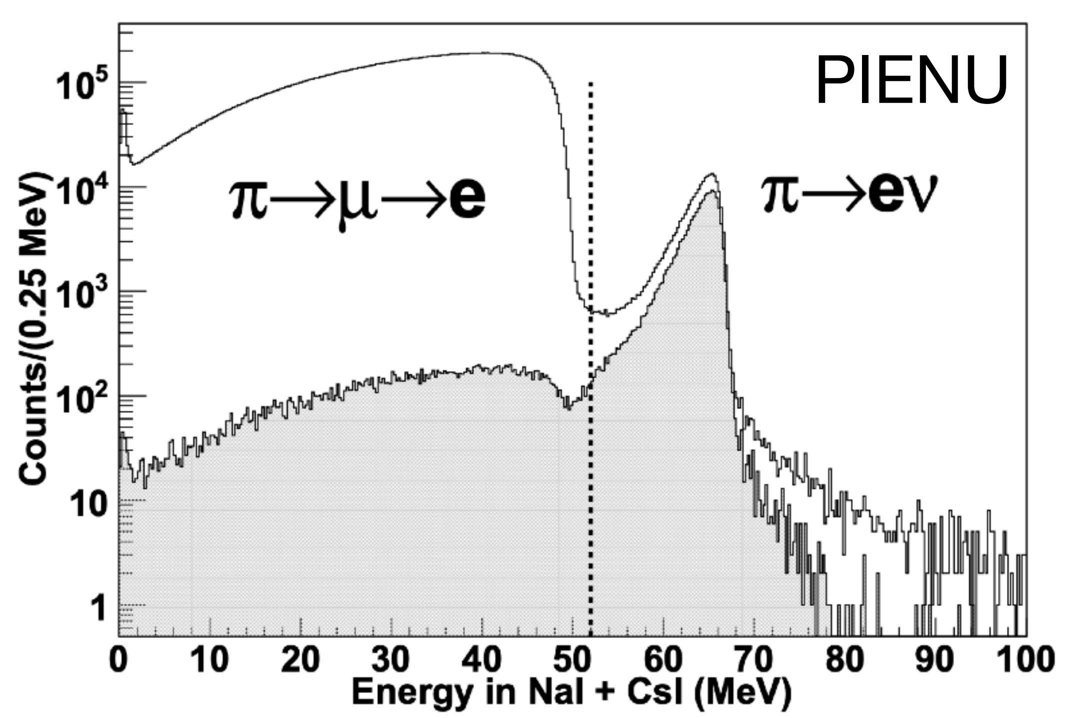

Conclusions & Outlooks

- ATAR can provide strong suppression power on π → μ → e, especially on the “in-ATAR DIF π” events. The π → μ → e background is now dominated by “DIF μ” events.

- Charge sharing in the case of AC-LGAD
  - A more realistic detector response in the simulation to study the impact on DIF suppression
- Ways to further suppress “DIF μ” suppression
  - The 4.1 MeV muon travels up to 0.8mm before it decays into positron
  - Thinner layers to help with muon track reconstruction?
- Optimizing the suppression of DIF backgrounds
  - Using advanced deep learning models (e.g. CNN, PointNet) on low-level ATAR hit information directly