Big Simulation Overview summary with Event Mixing

Patrick Schwendimann, 17. October

A Year Ago in Santa Cruz …

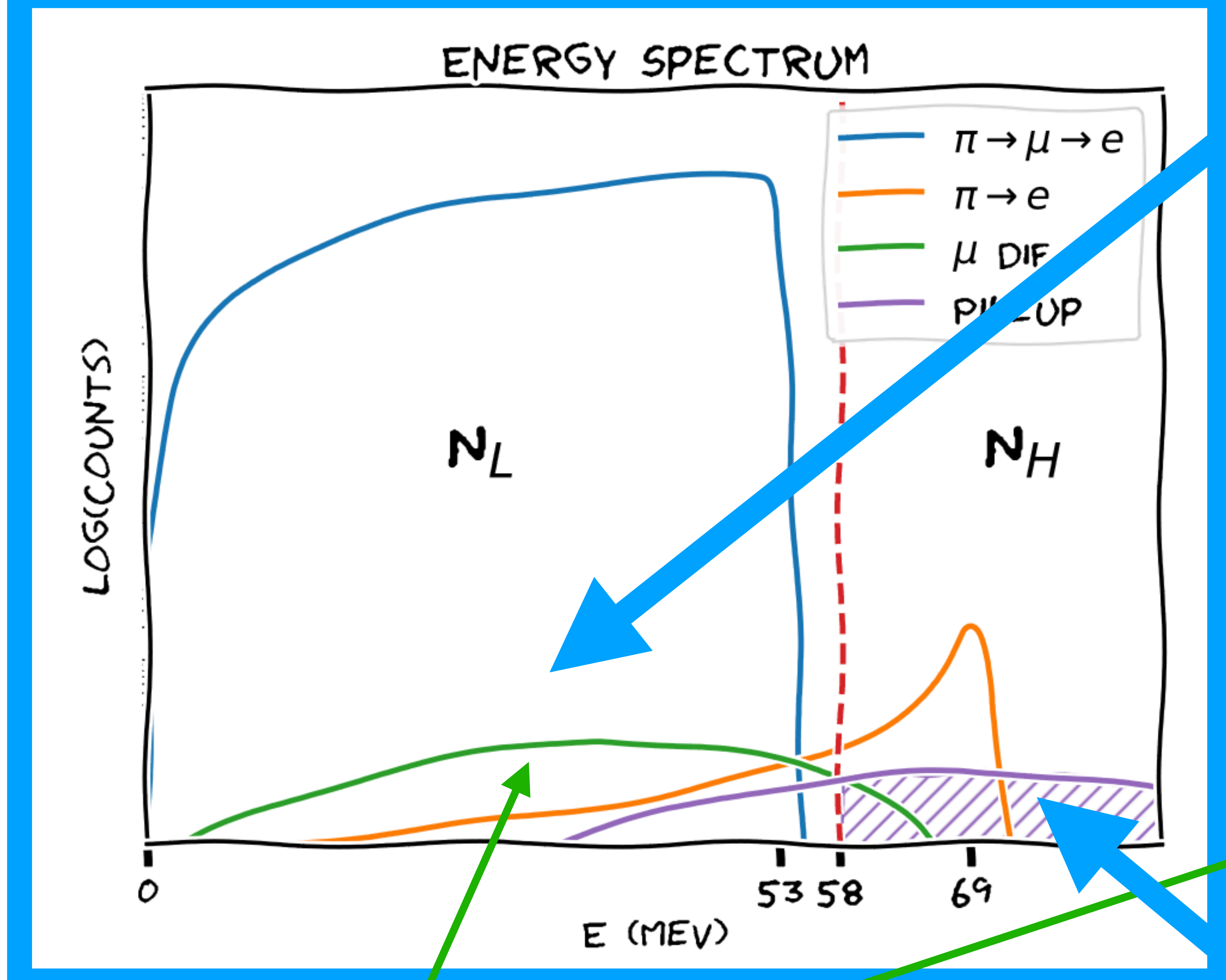
1. What does this figure look like now?

2. What will the Reconstruction do for us in terms of Muon Decay at Rest suppression? AKA: Are we able to reveal the tail?

Keeping the Corrections und…

LXe Pileup

- The Basic Idea
- Simulating the Detector
- LXe Calorimeter Event Reconstruction
- Pileup
- Conclusion
- Backup



$$R_{e/\mu} = \frac{N_H}{N_L} \frac{1 + c_T}{1 + c_{DIF} + c_{PU}}$$

To Reach our Sensitivity Goal

	Value	Precision
$R_{e/\mu}$	$\mathcal{O}(10^{-4})$	$\mathcal{O}(10^{-8})$
N_L	$\mathcal{O}(1)$	$\mathcal{O}(10^{-4})$
N_H	$\mathcal{O}(10^{-4})$	$\mathcal{O}(10^{-8})$
c_T	$\mathcal{O}(10^{-2})$	$\mathcal{O}(10^{-4})$
c_{DIF}	???	$\mathcal{O}(10^{-4})$
c_{PU}	???	$\mathcal{O}(10^{-4})$

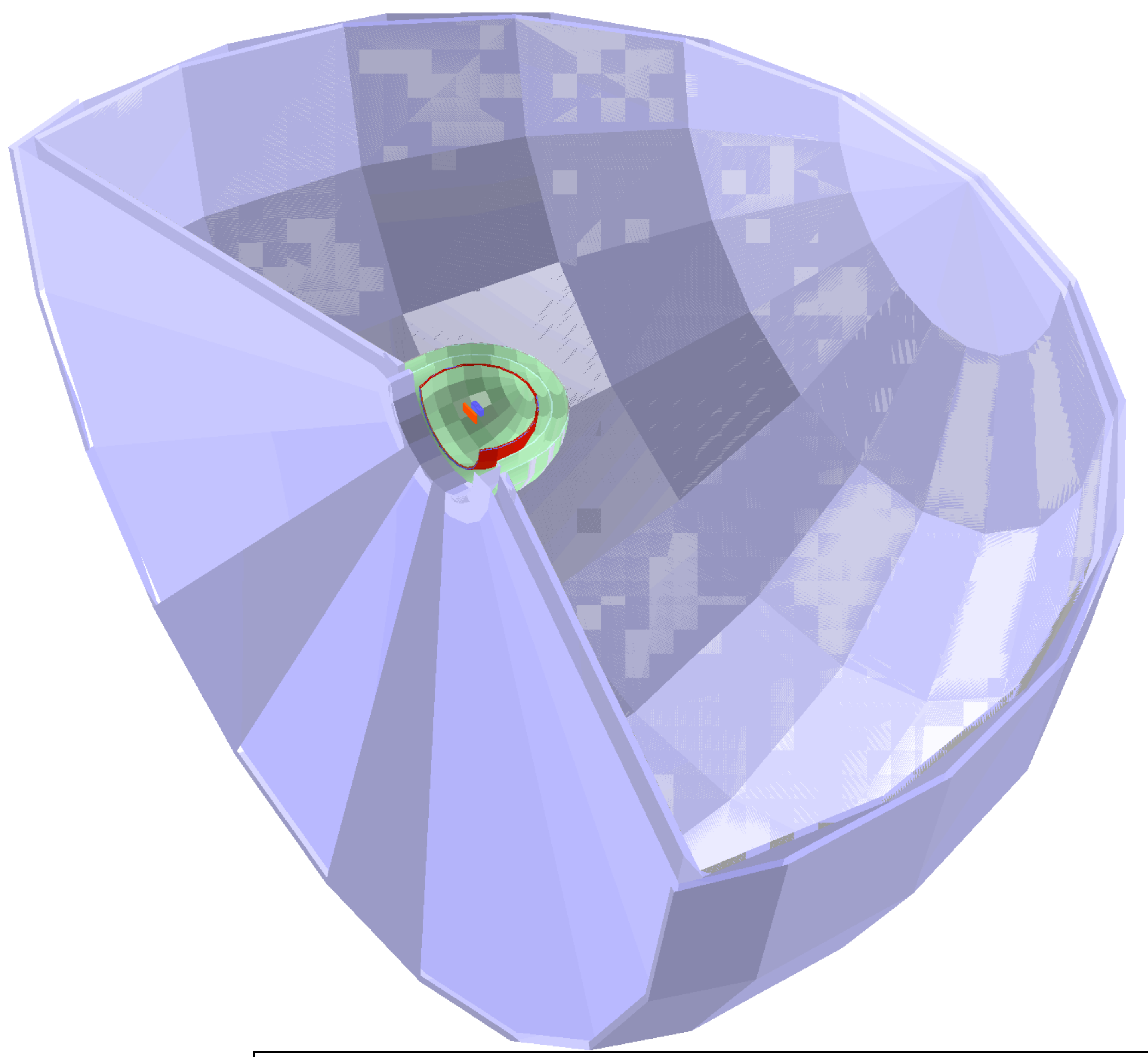
P. Schwendimann (UW) LXe Pileup RPD 2022/10/7 8 / 25

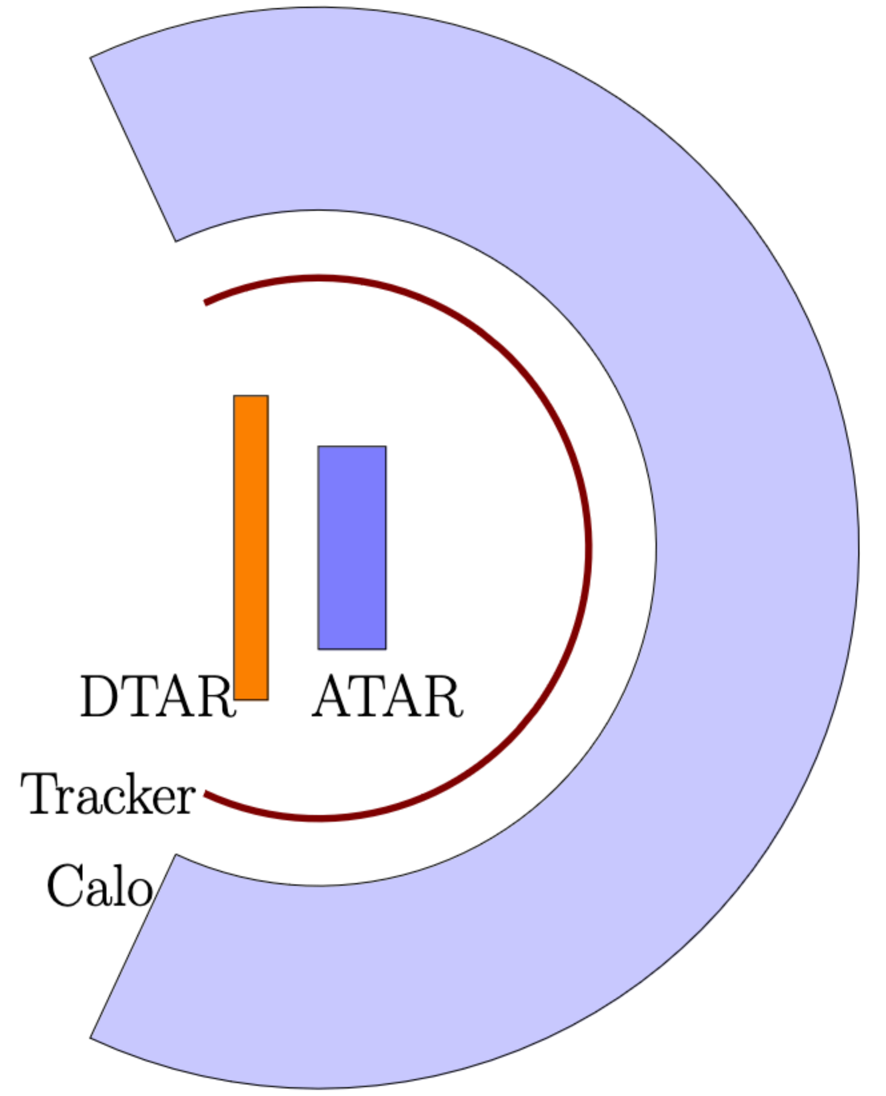
Note: Quentin did a lot of work in terms of Muon Decay in Flight.

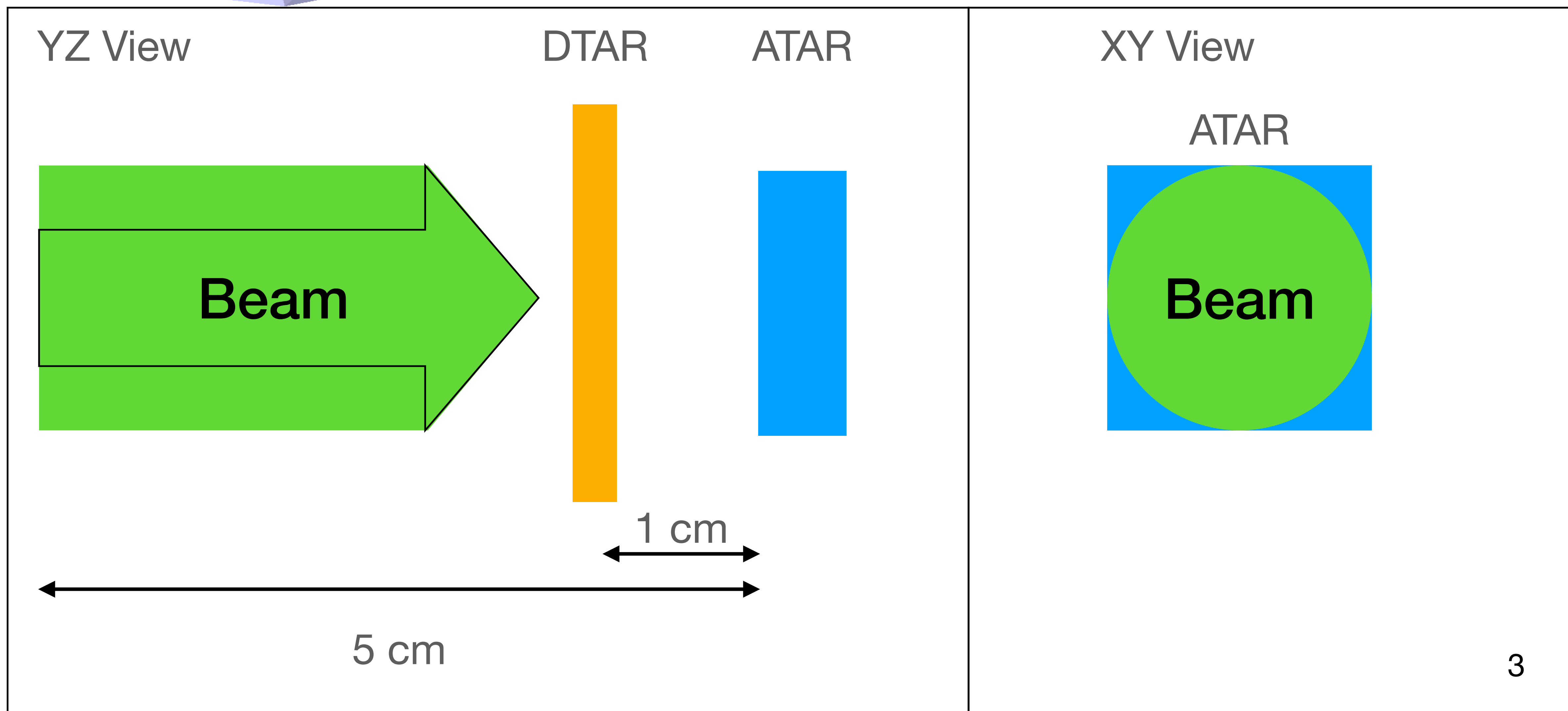
3. What about Pileup?

The Simulation Configuration
(Unless stated otherwise)

- Go With Baseline Design
- Beam:
    - Cylindric (2 cm diameter)
    - Pure 65 MeV/c Pions
    - 5 cm upstream
- Hardly any beam related backgrounds.
- Energy Smearing:
  ATAR: $10\,\%$
  Calo: $(3.5/\sqrt{E} + 1.6)\,\%$
  Omar's recipe, $2\,\%$ @70MeV





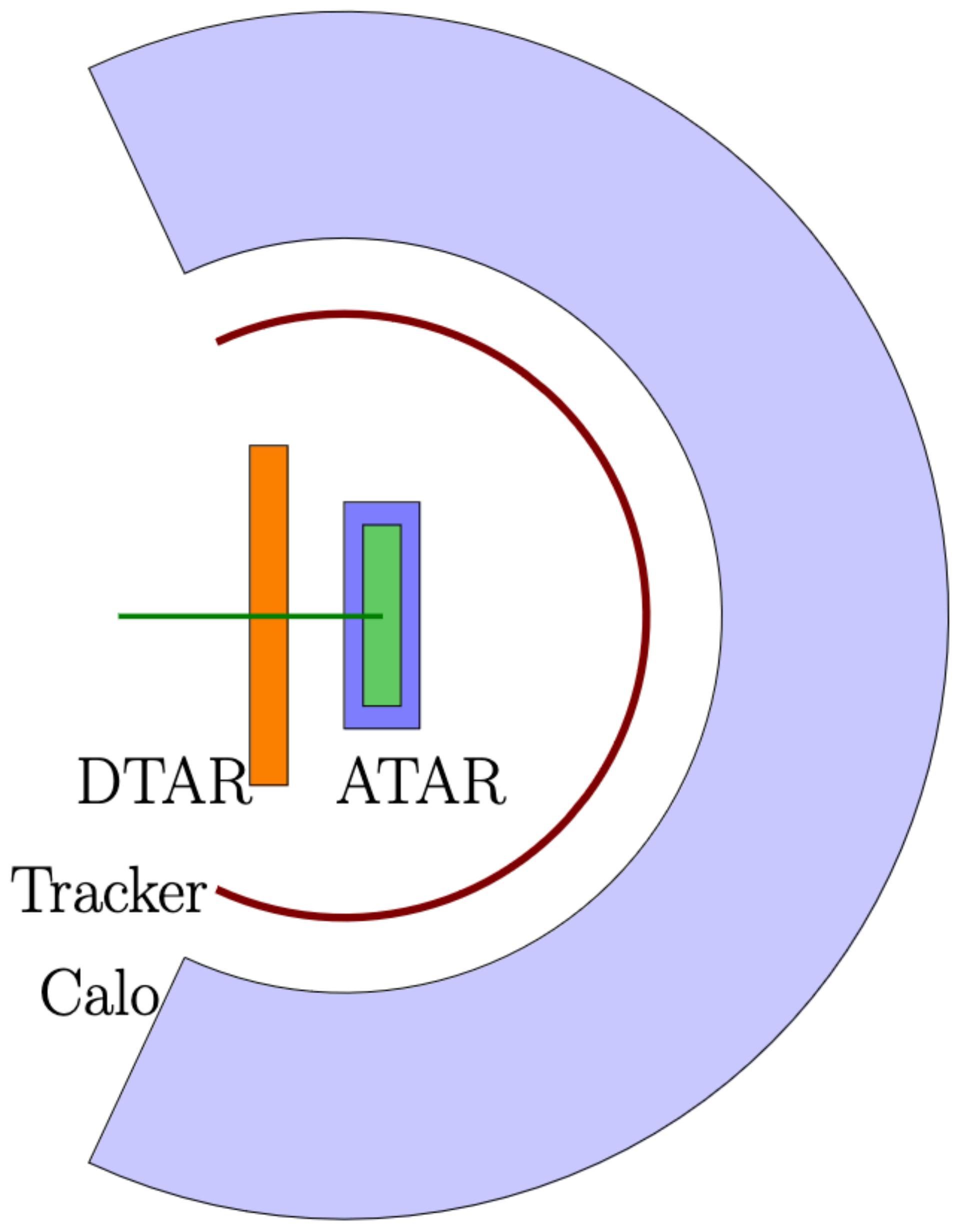


Event Selection

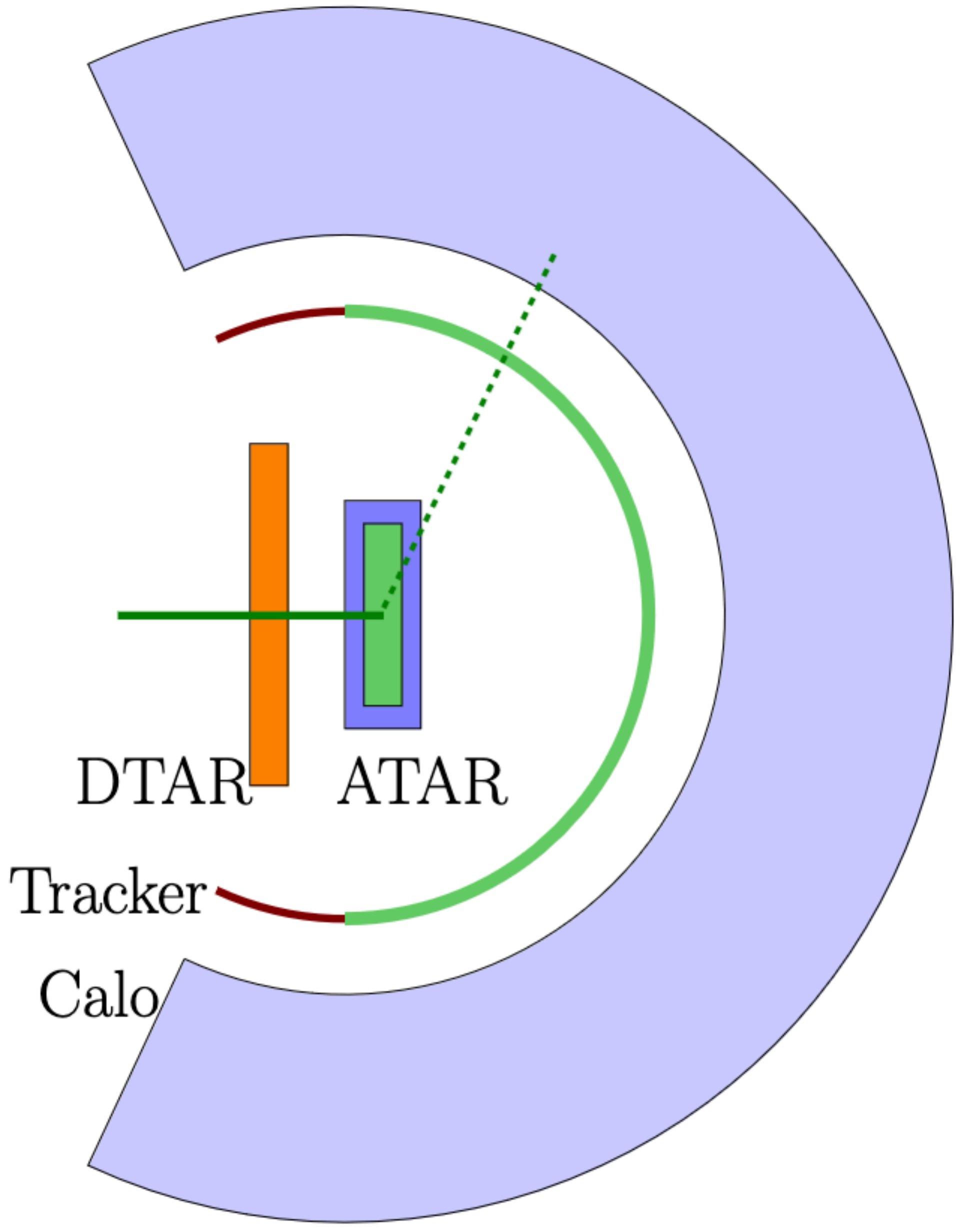
- **Target Box Selection**:
  Require a high ionising track (pion or muon) to hit DTAR and to end in the centre of ATAR (2 mm away from lateral sides, 1.5 mm away from front and back). Implicitly asks for a MIP to come out as a Muon's range is below 1 mm.

- **Time Selection** (applied by default):
  Request that a calo hit is delayed by at least by 5 ns with respect to the triggering DTAR hit. Also, drop Calo hits later than 100 ns (Energy Analysis) or 500 ns (Time Analysis).

- **Fiducial Volume Selection**:
  Require Tracker hit with $\vartheta < 90°$



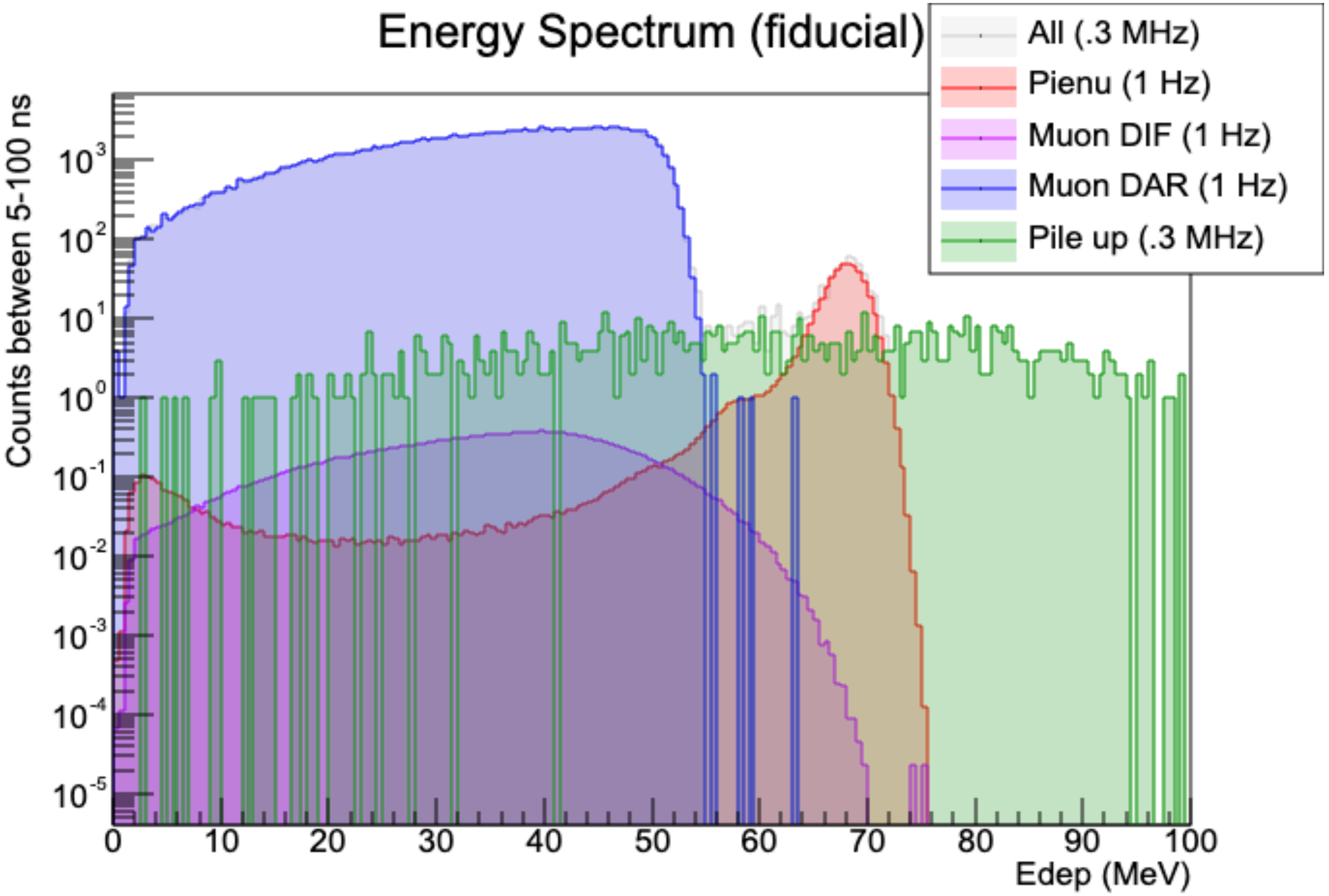
Box

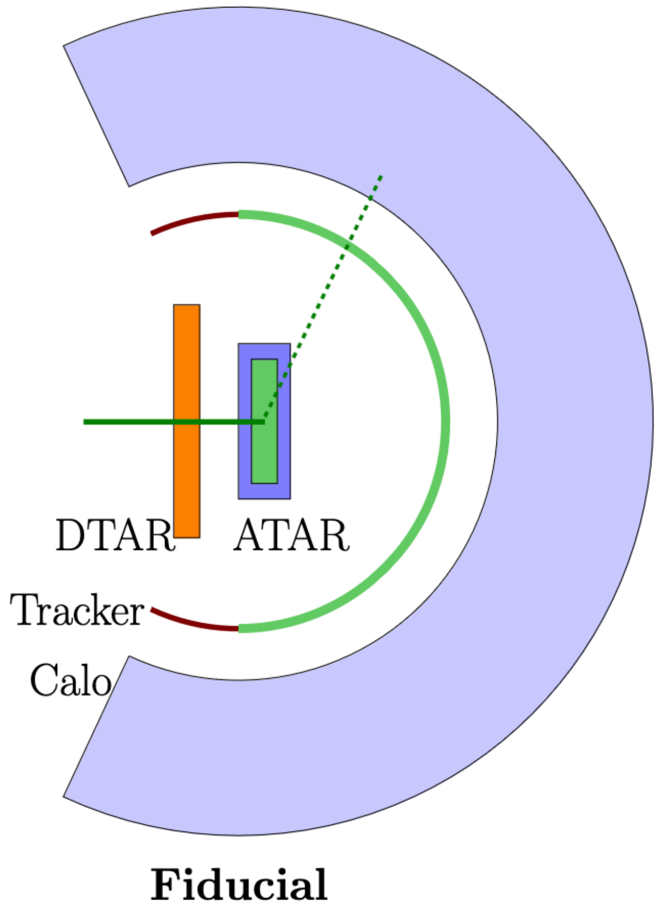


Fiducial

Energy spectrum

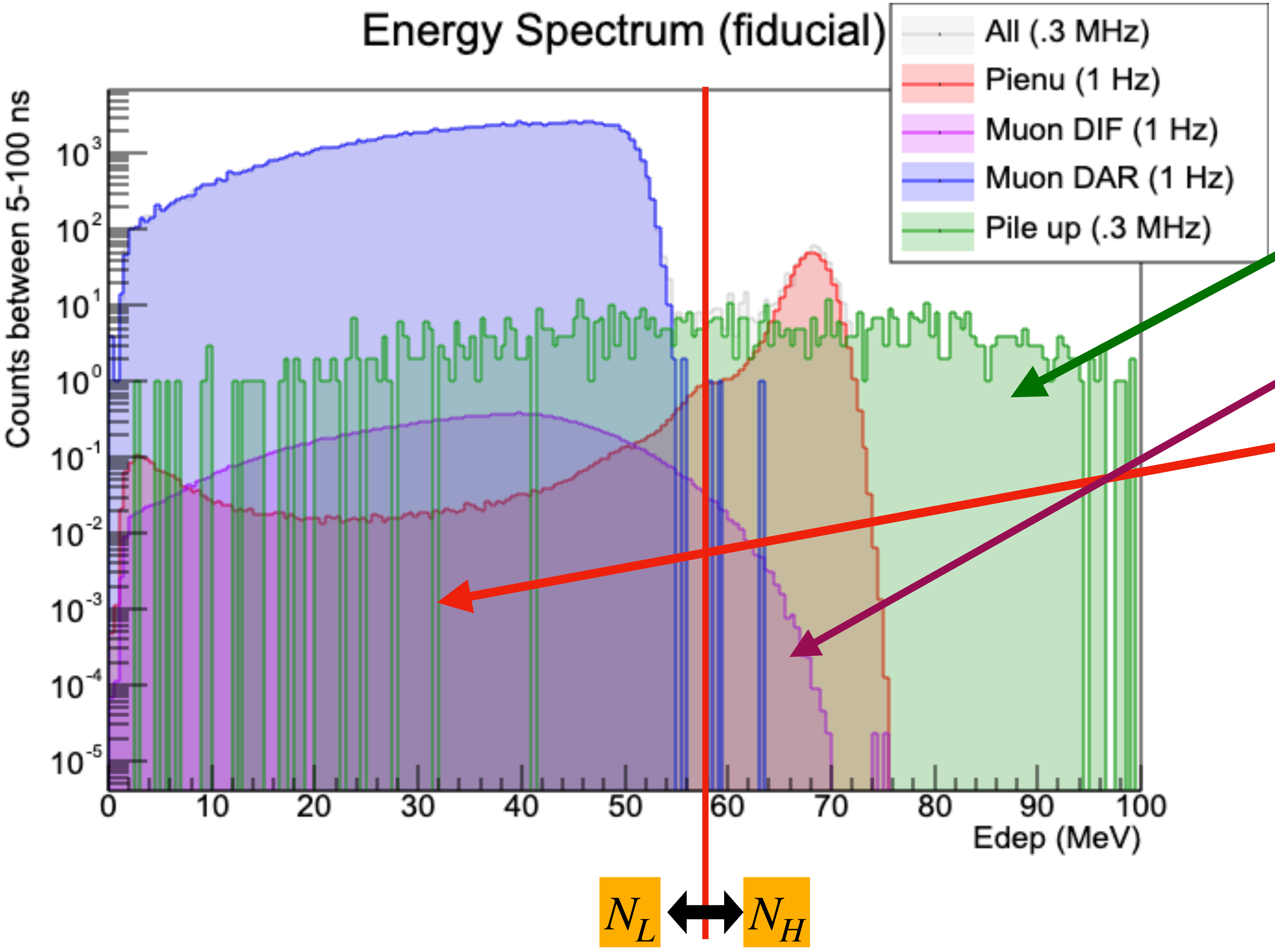
Events passing box, time (5 - 100 ns) and fiducial cut

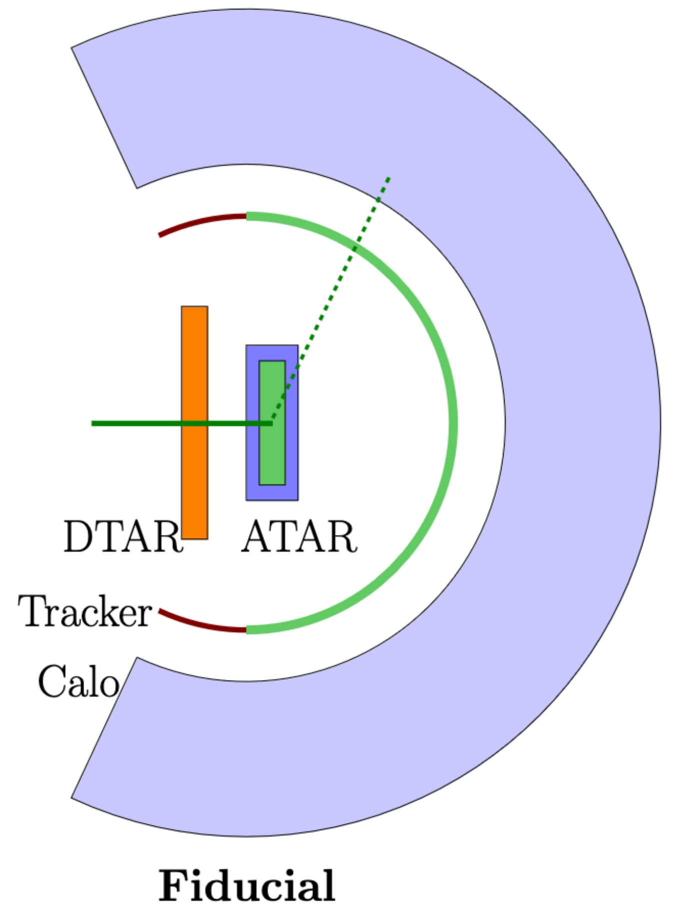




- Simulate unbiased and biased $\pi \rightarrow e\nu$ & muon decay in flight events.
- Run them through the detector response and reconstruction.
- Sort events according to their recorded truth event type.
- No further selection so far.

Estimating $R_{e/\mu} = \frac{N_H}{N_L} \times$ Corrections





Corrections include:

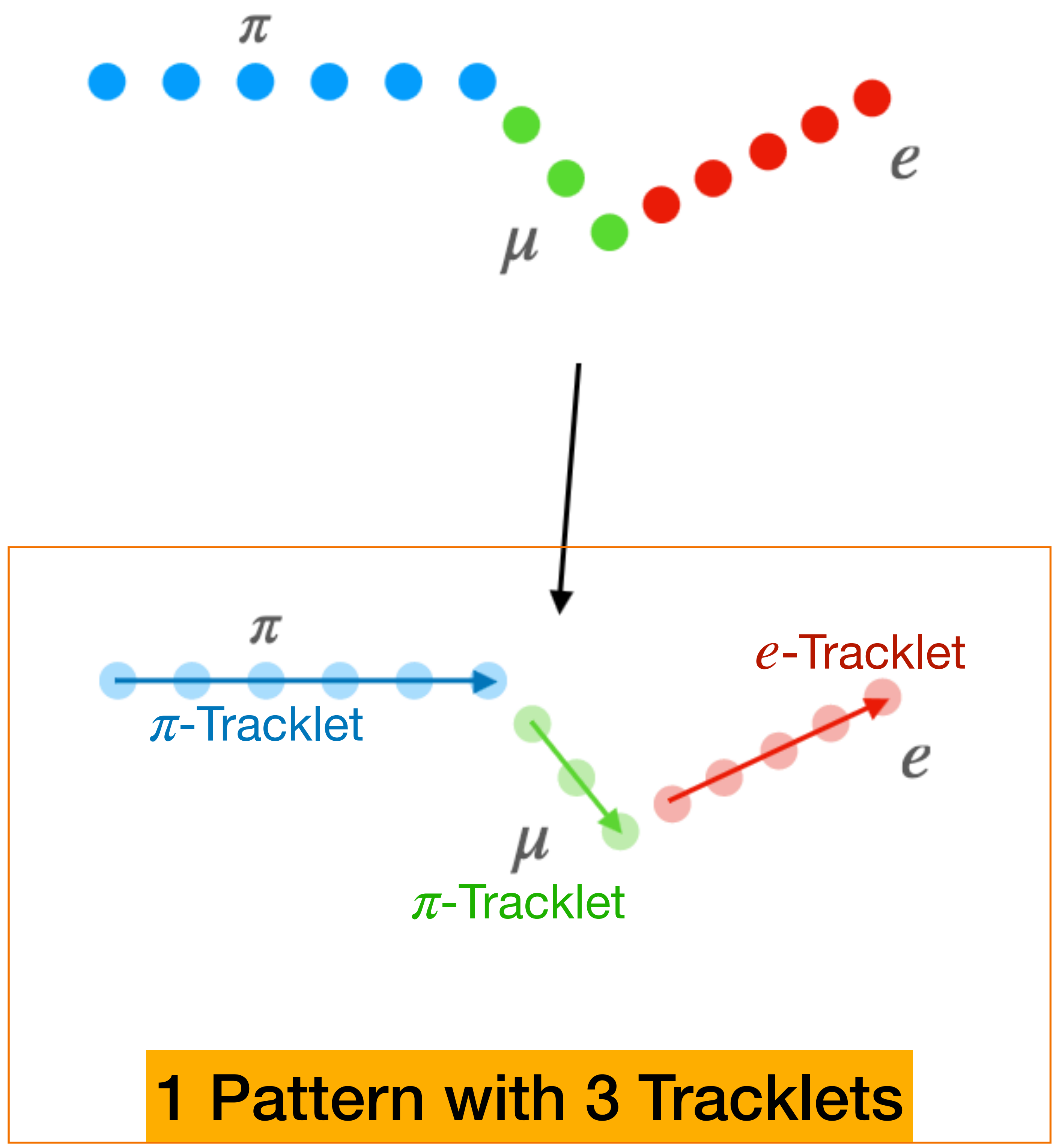
- Pileup
- Muon Decay In Flight
- Tail Correction

"ATAR will fix this! And this! And this as well"

-

But does it?

Tracklet and Pattern Reminder



- **Tracklet:**
  - Collection of all hits that stem from the same Geant4 particle.
  - Start either in DTAR or ATAR
- **Pattern:**
  - Collection of all tracklets that belong to the same event.
- **Expect:**

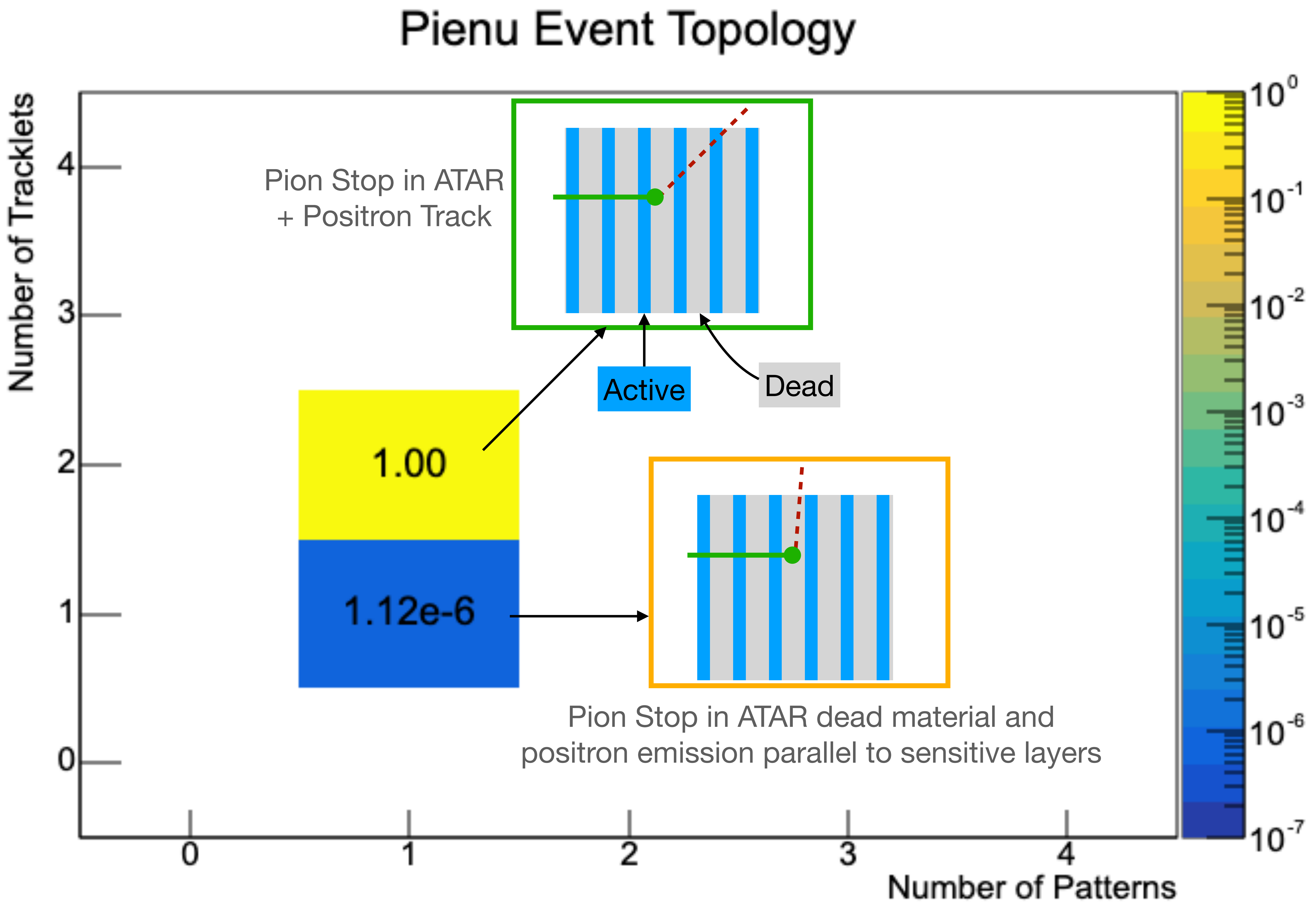
  1 Pattern with 2 Tracklets for $\pi \to e$

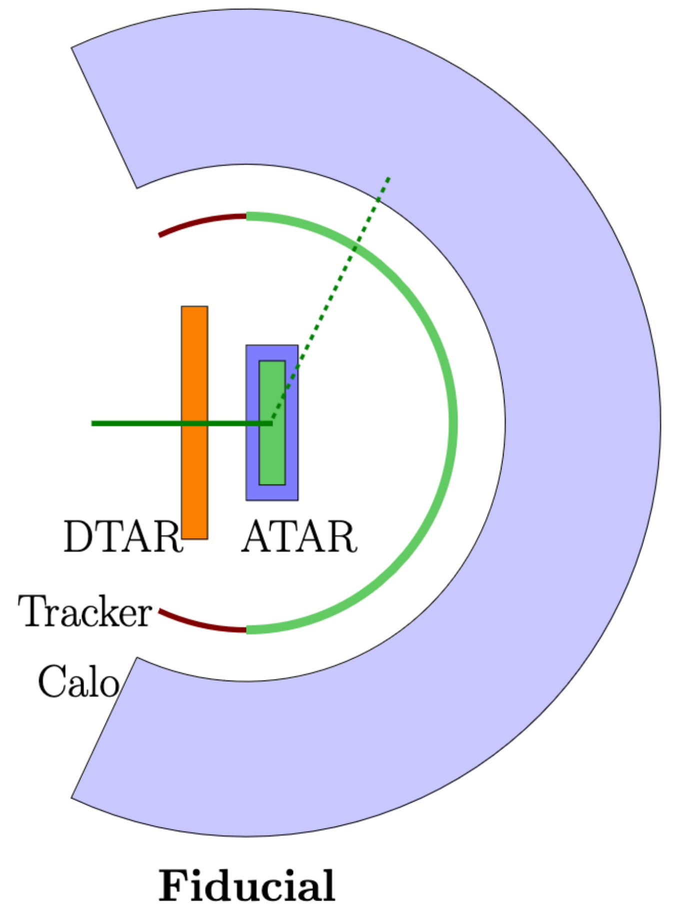
  1 Pattern with 3 Tracklets for $\pi \to \mu \to e$

  2+ Patterns can only happen when:
  a) events pile up
  b) in future, when reconstruction fails

Event Topologies

$\pi \to e\nu$ - Required Precision: below 10^{-4}

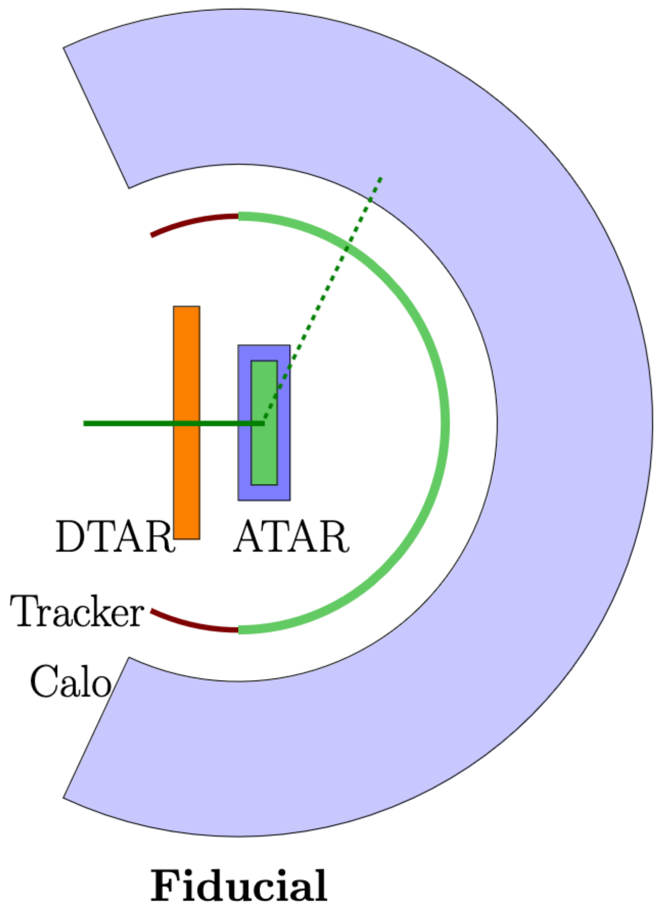


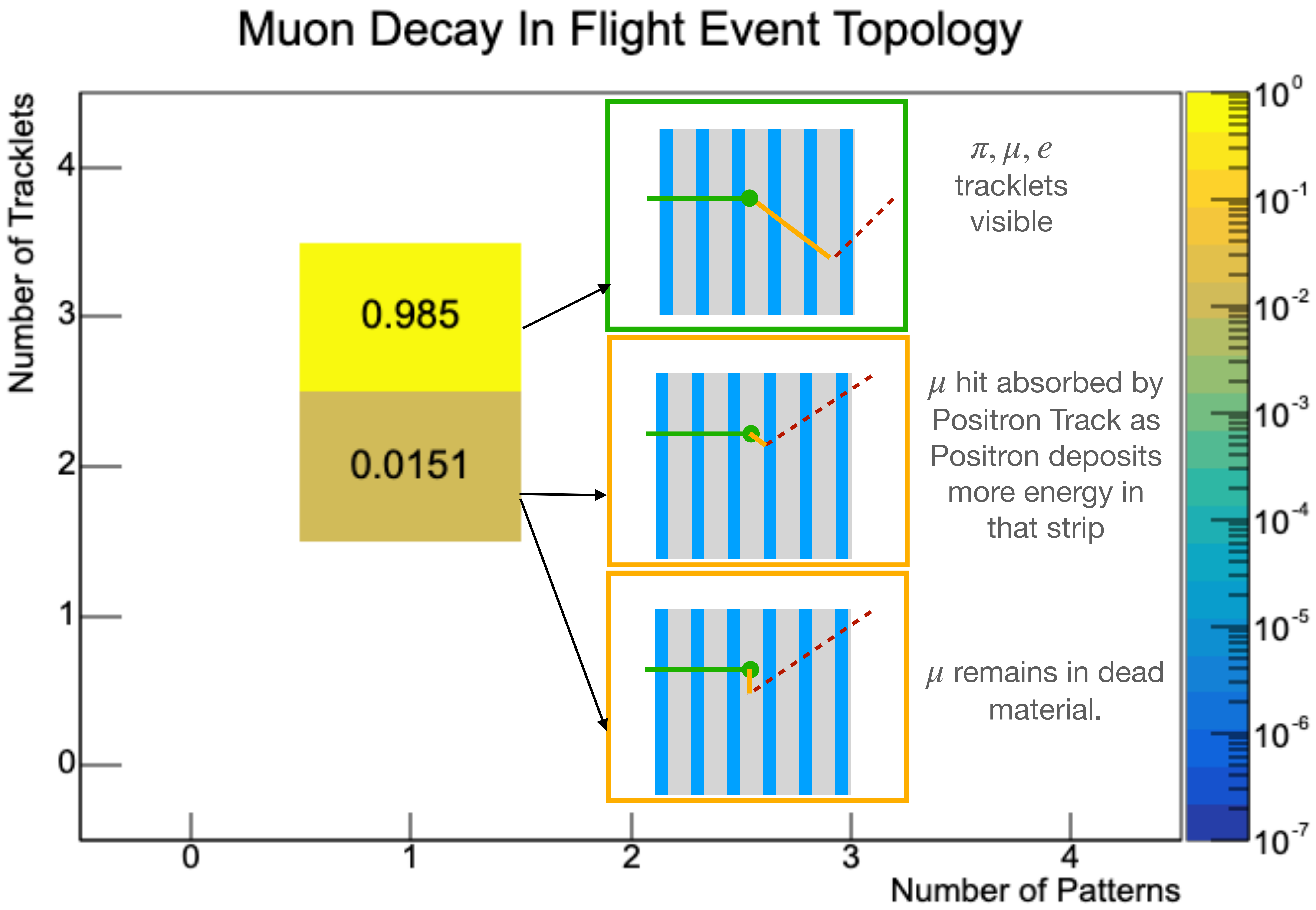


- Number of patterns is here synonymous with number of events that have ATAR hits.
- Number of Tracklets only counts Pions, Muons and positrons. Avoid confusion due to Bhabha Scattering or Delta Rays for now.

Event Topologies

Muon Decay in Flight, desired suppression: $\mathcal{O}(100)$

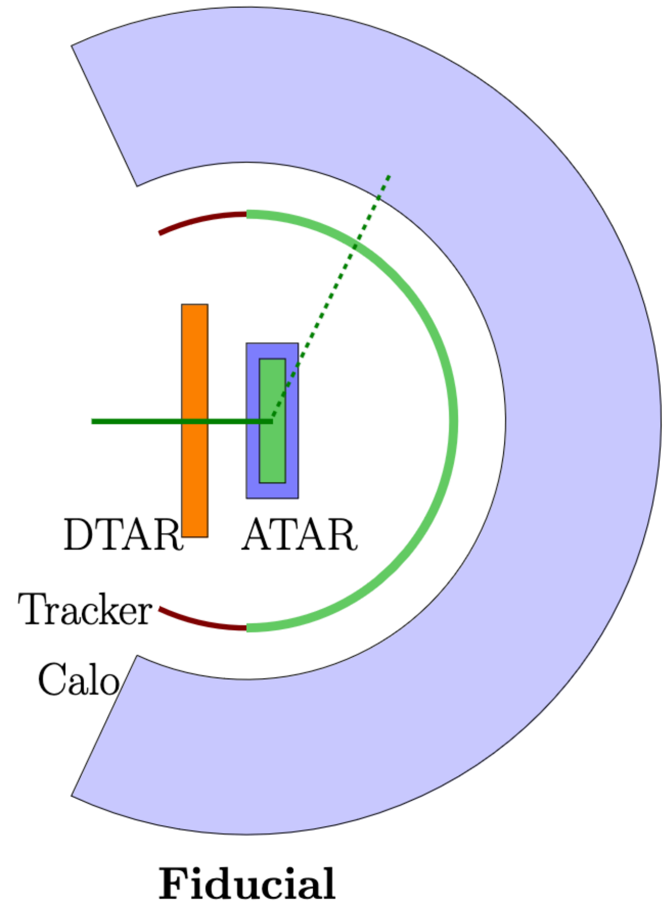


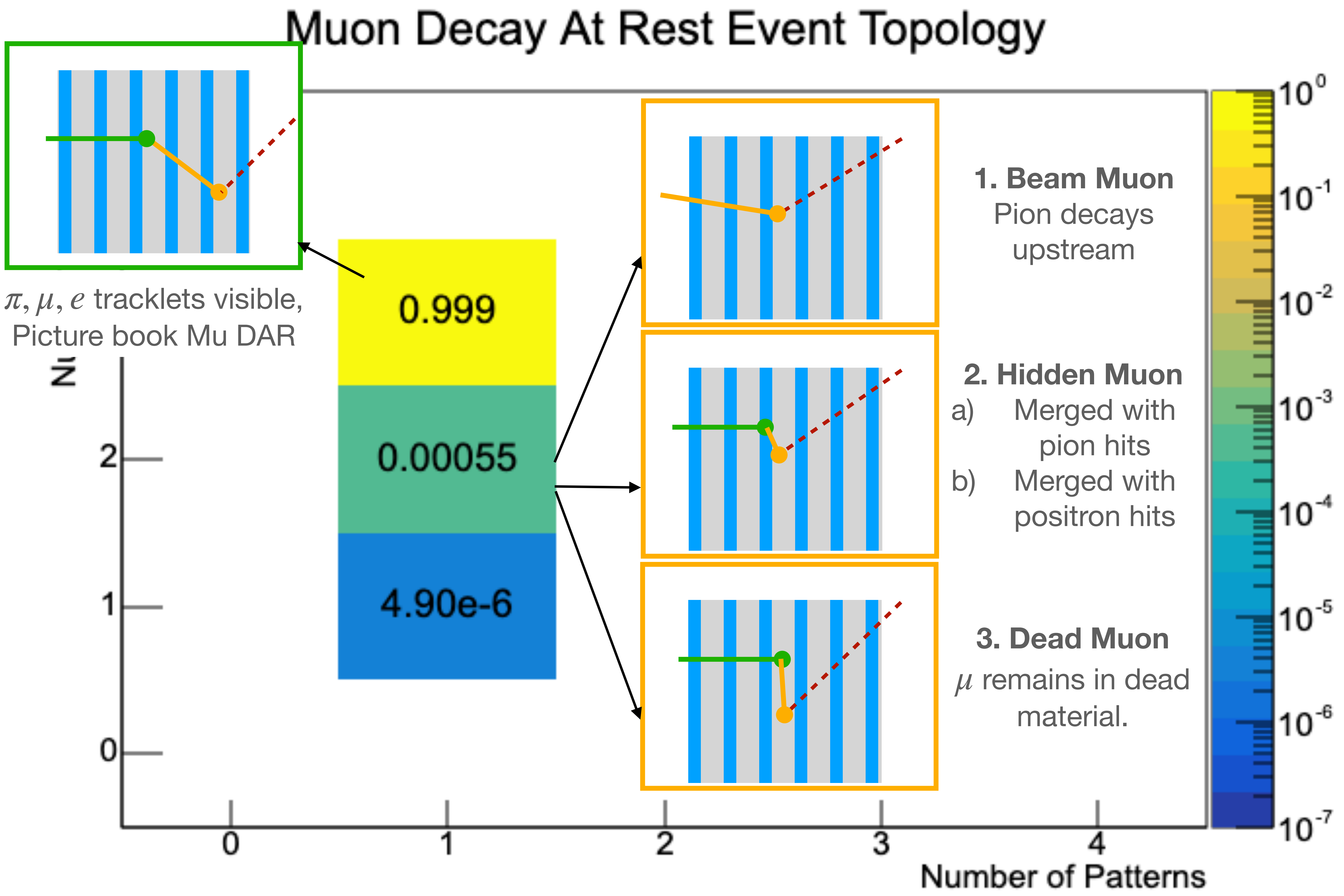


- Muon Decay in flight features shorter muon tracks.
- Guaranteed overlap and margin of muon and positron hit if in active volume.
- Discussed in detail by Quentin.

Event Topologies

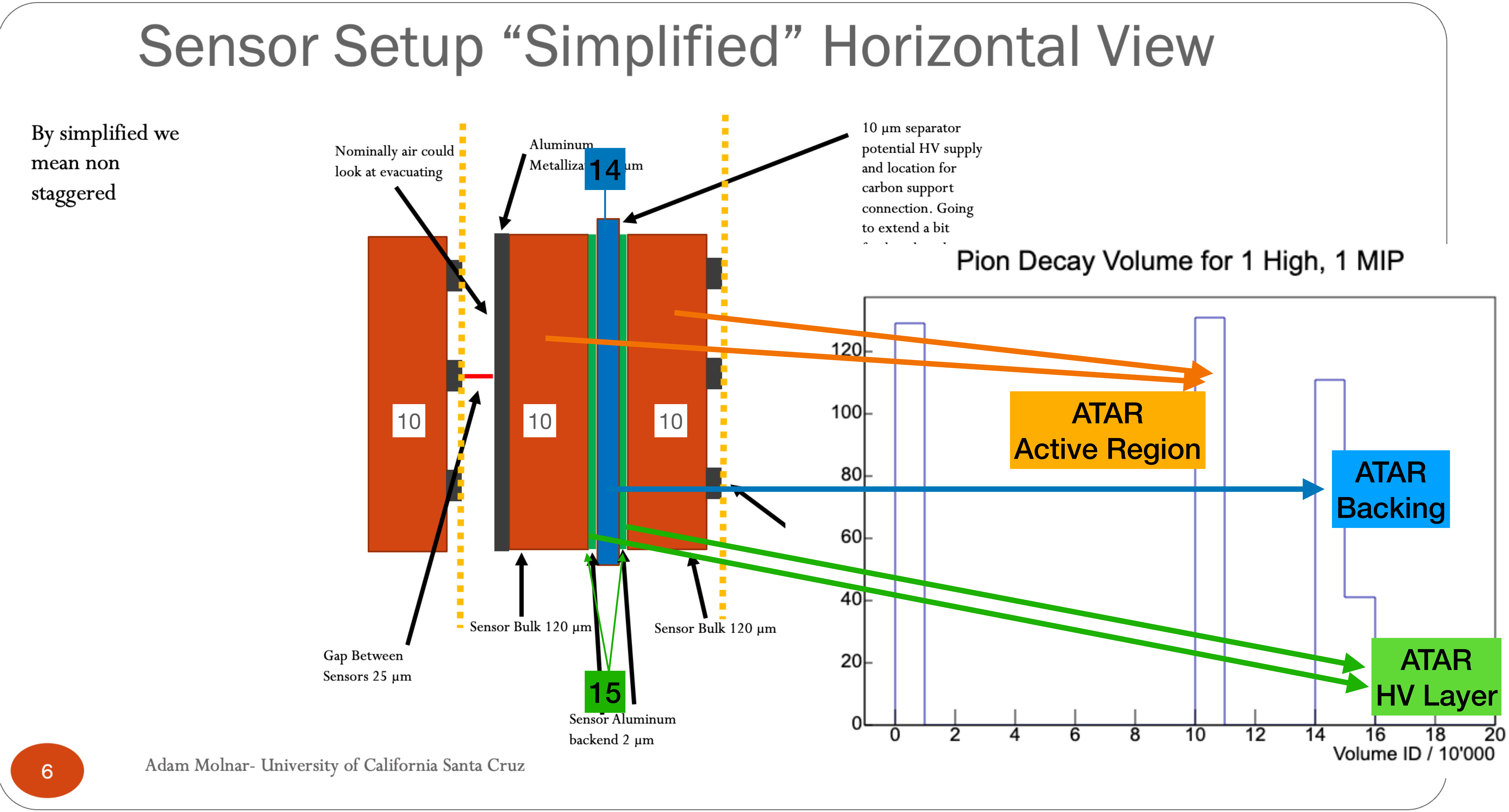
Muon Decay at Rest, Desired suppression $\mathcal{O}\left(10^7\right)$



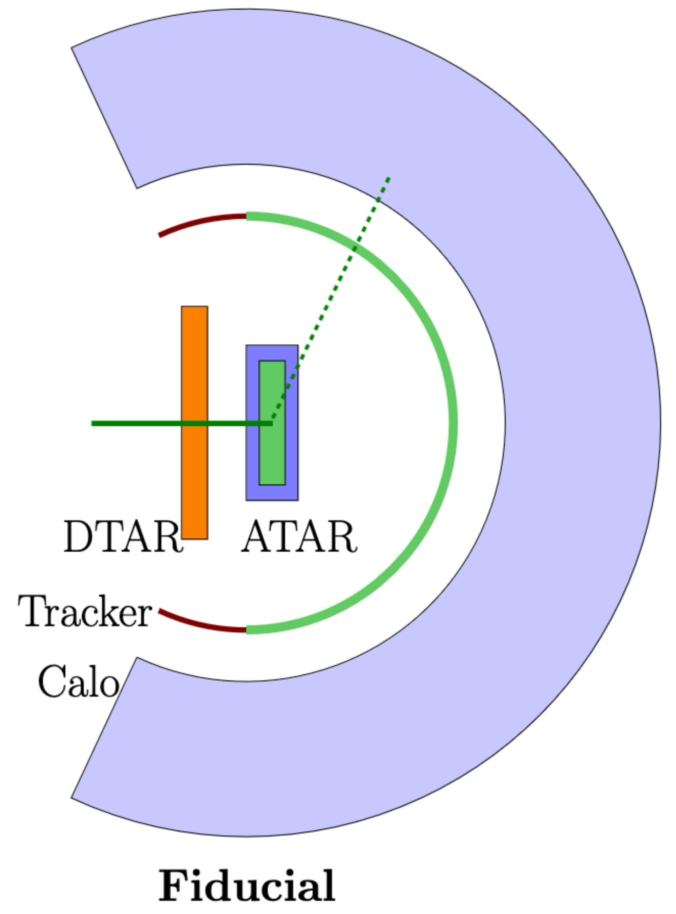


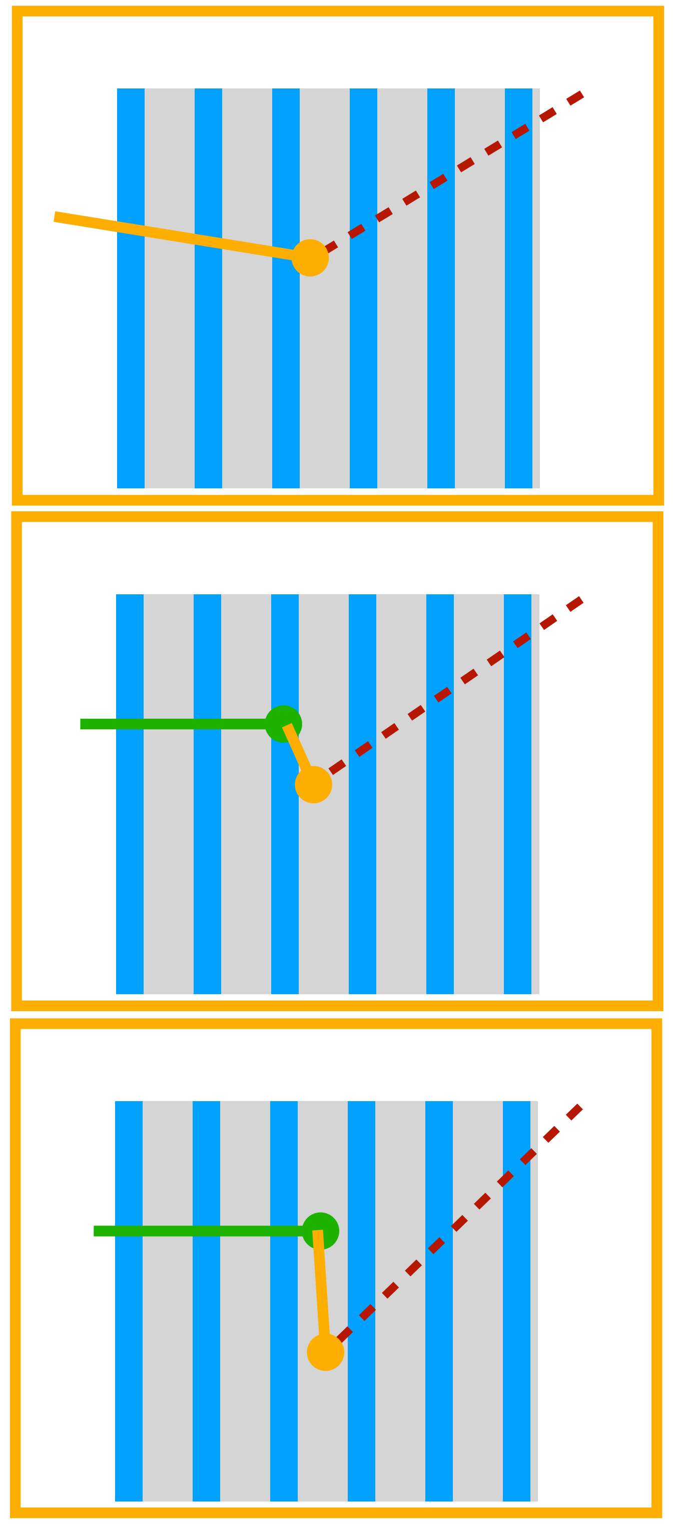
- Muon Decay at Rest is the most common event type.
- Beware: The rate of 1 pattern 2 tracklet events is five times larger than the $\pi \rightarrow e\nu$ events.
- Understanding those backgrounds and how to reduce them is essential.

Locating Decay Positions in ATAR



Pion Decay position

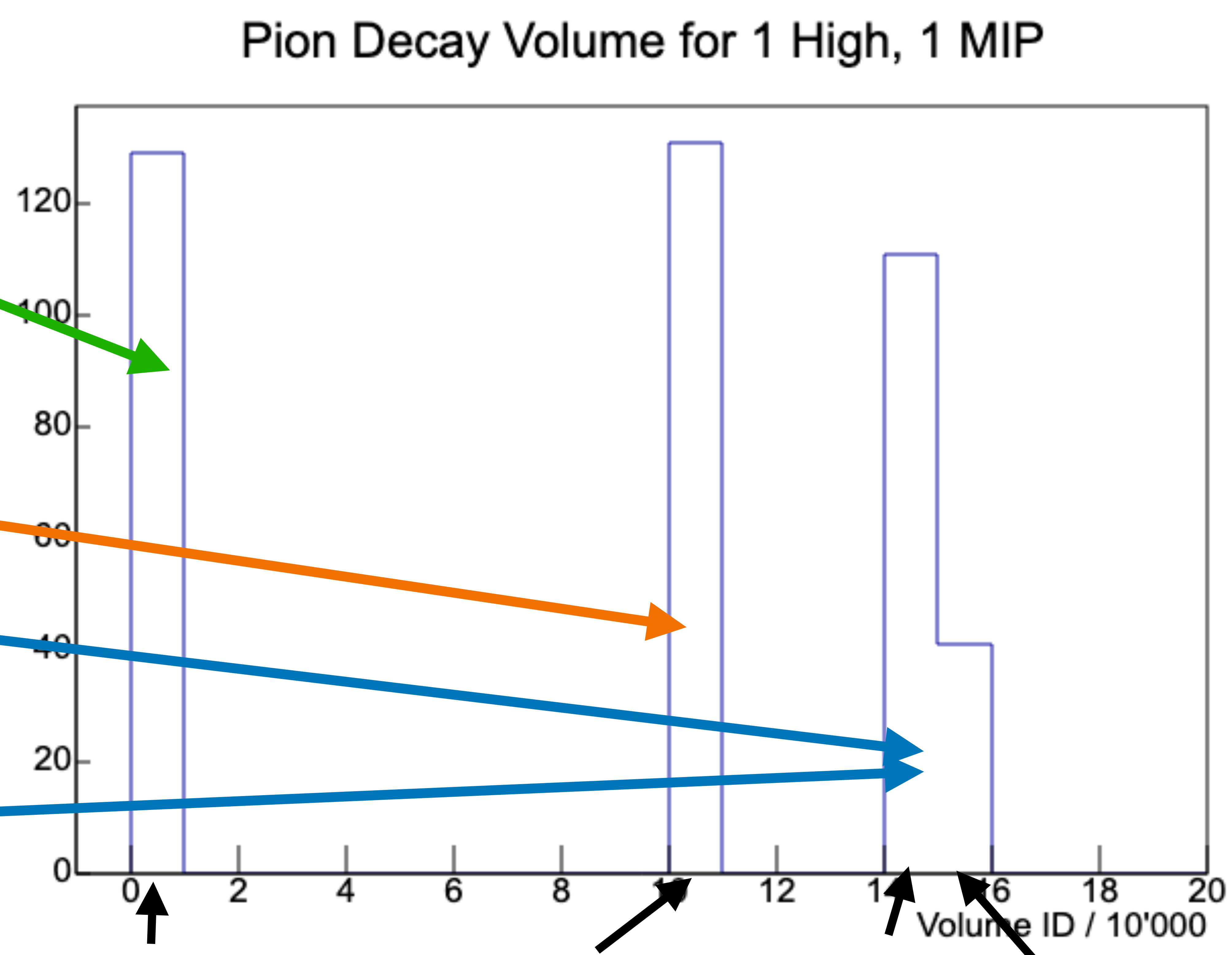




1. Beam Muon
Pion decays upstream

2. Hidden Muon
a) Merged with pion hits
b) Merged with positron hits

3. Dead Muon
μ remains in dead material.



0: Outside of Detector Upstream Decay

10: ATAR Sensitive Volume

14: ATAR HV Layer

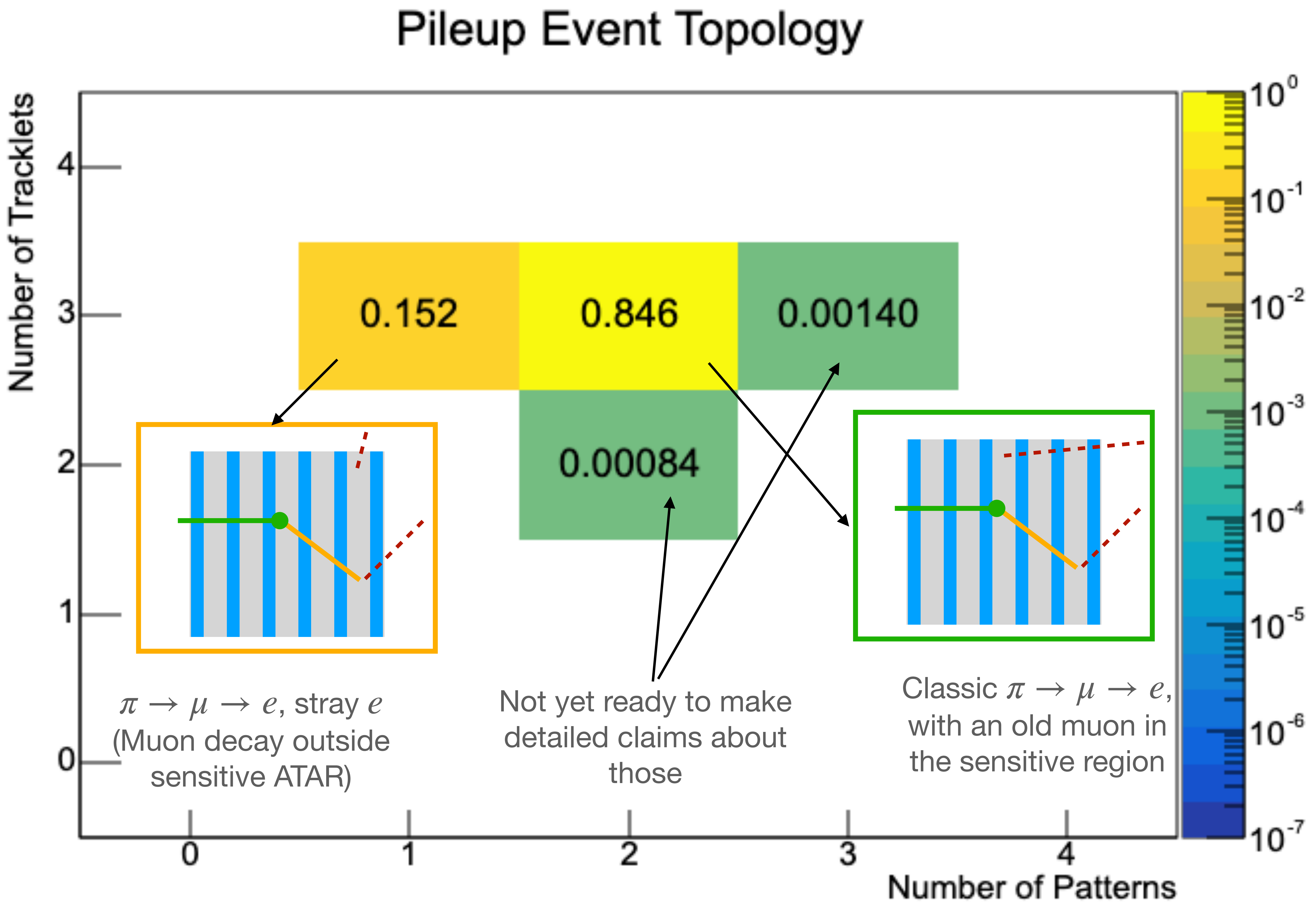
15: ATAR Back Layer

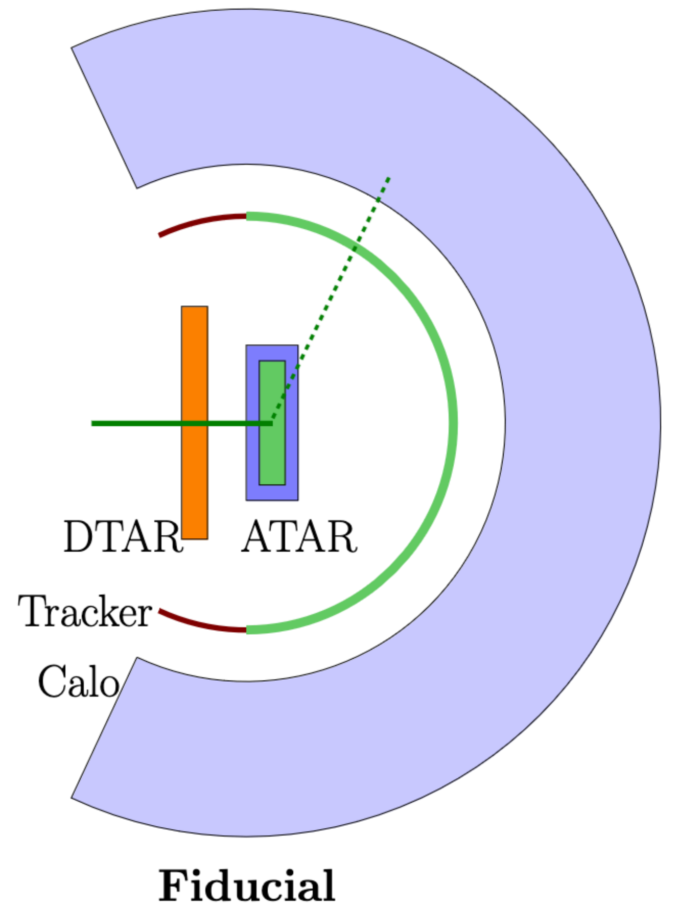
Disclaimer:
a) This is probably not complete. More sophisticated topologies remain hidden here
b) Beam Muons are now only from decays within 5 cm upstream. That will be worse!

Even ignoring beam muons, hidden muons ($1.6 \cdot 10^{-4}$) and dead muons ($1.9 \cdot 10^{-4}$) impose a limit to muon decay at rest suppression far larger than 10^{-7} Vincent reported last year. What happened to the three orders of magnitude?

Event Topologies

Pile Up, Desired suppression $\mathcal{O}\left(10^5\right)$

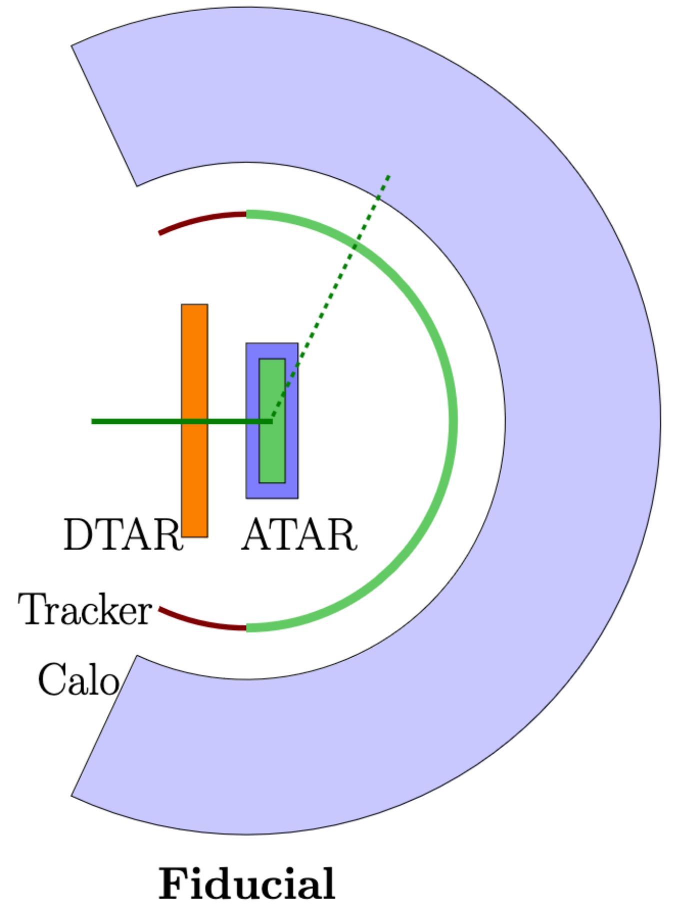




- Number of events is significantly lower for this event type.
- Number of Tracklets = number of tracklets of the pattern with the most tracklets.
- Many more rabbits to chase!
- Involvement of events that avoid ATAR completely.

Event Topology

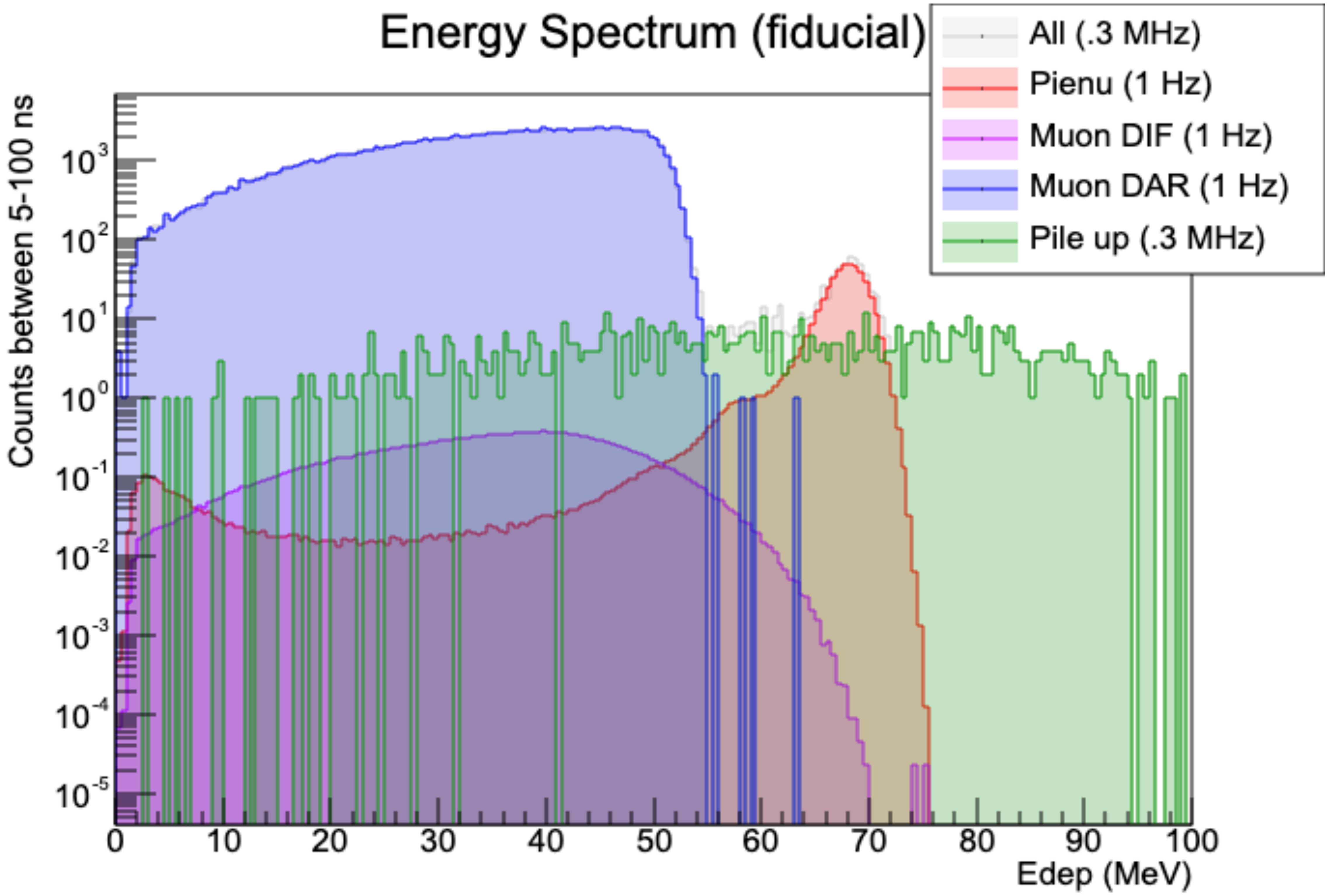
Recap

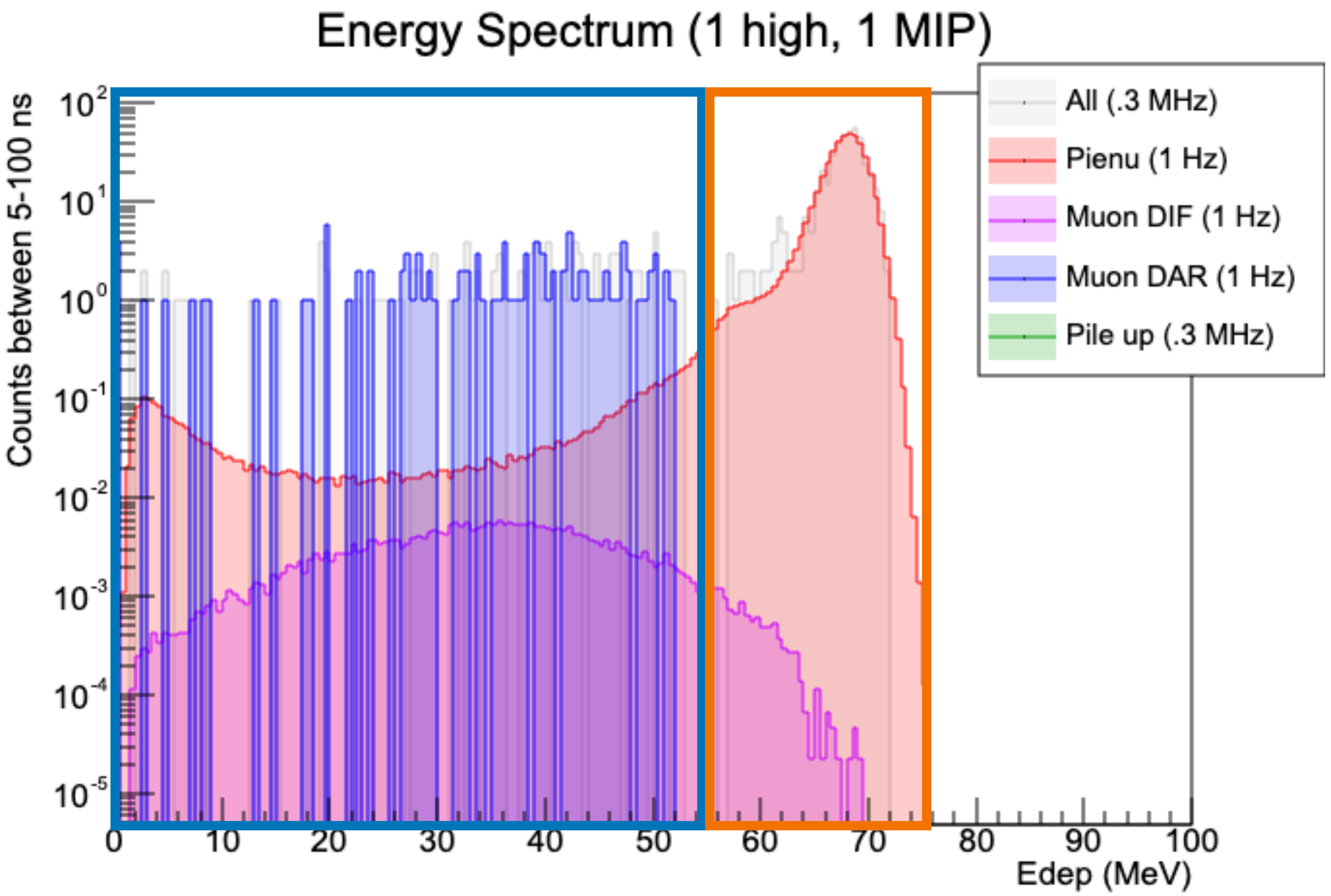


- Pienu events have almost always two tracklets, one high ionising from the pion, one MIP.
- Muon DIF mostly has 3 Tracklets, assuming we can use Quentin's study to separate muon and positron hits. Suppression of two orders of magnitude.
- Muon DAR almost always has 3 Tracklets. Notable exceptions are:
    - Beam Muons ($1.6 \cdot 10^{-4}$ of the cases)
    - Hidden Muons ($1.6 \cdot 10^{-4}$ of the cases)
    - Dead Muons ($1.9 \cdot 10^{-4}$ of the cases)
- Pileup typically features multiple patterns. Off-target decays can produce single-pattern topologies.

Selecting patterns with 1 highly ionising tracklet and a mip tracklet will help selecting a cleaner $\pi \to e\nu$ sample, e.g. for tail extraction.

Energy spectrum after Selection





$\pi \rightarrow e\nu$: 100%
μ DIF : 1.5 %
μ DAR: 0.05 %
Pileup: < 0.08%

I find the lack of suppression disturbing

Rel. Abundance	0 - 55 MeV	55 - 75 MeV
Pienu	0.014	1
Muon Decay at Rest	0.24	0
Muon Decay in Flight	7E-04	3E-05
Pileup	0	0

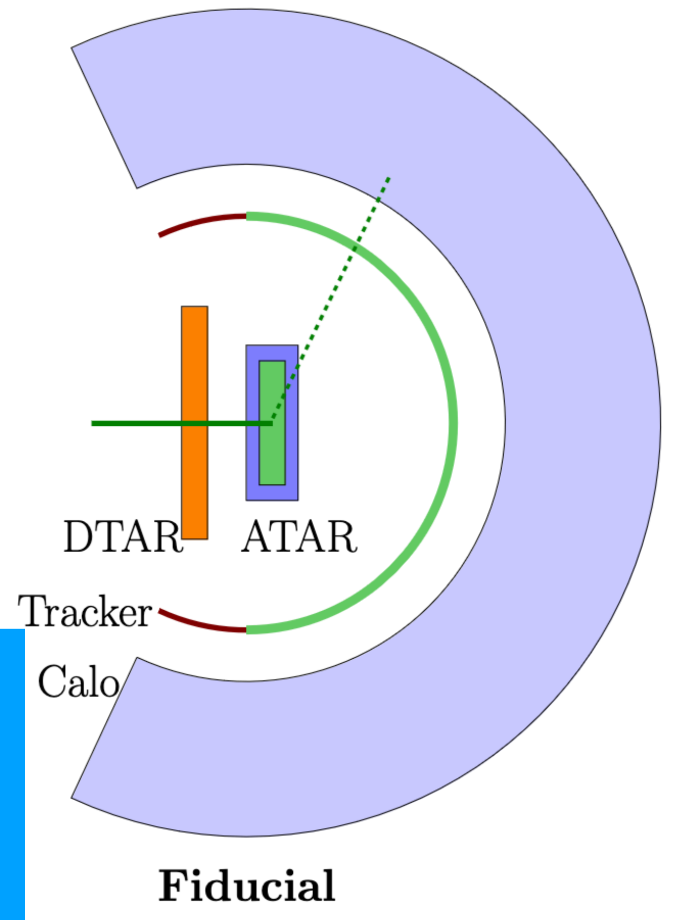
Changing the point of view

Analyse in time rather than energy

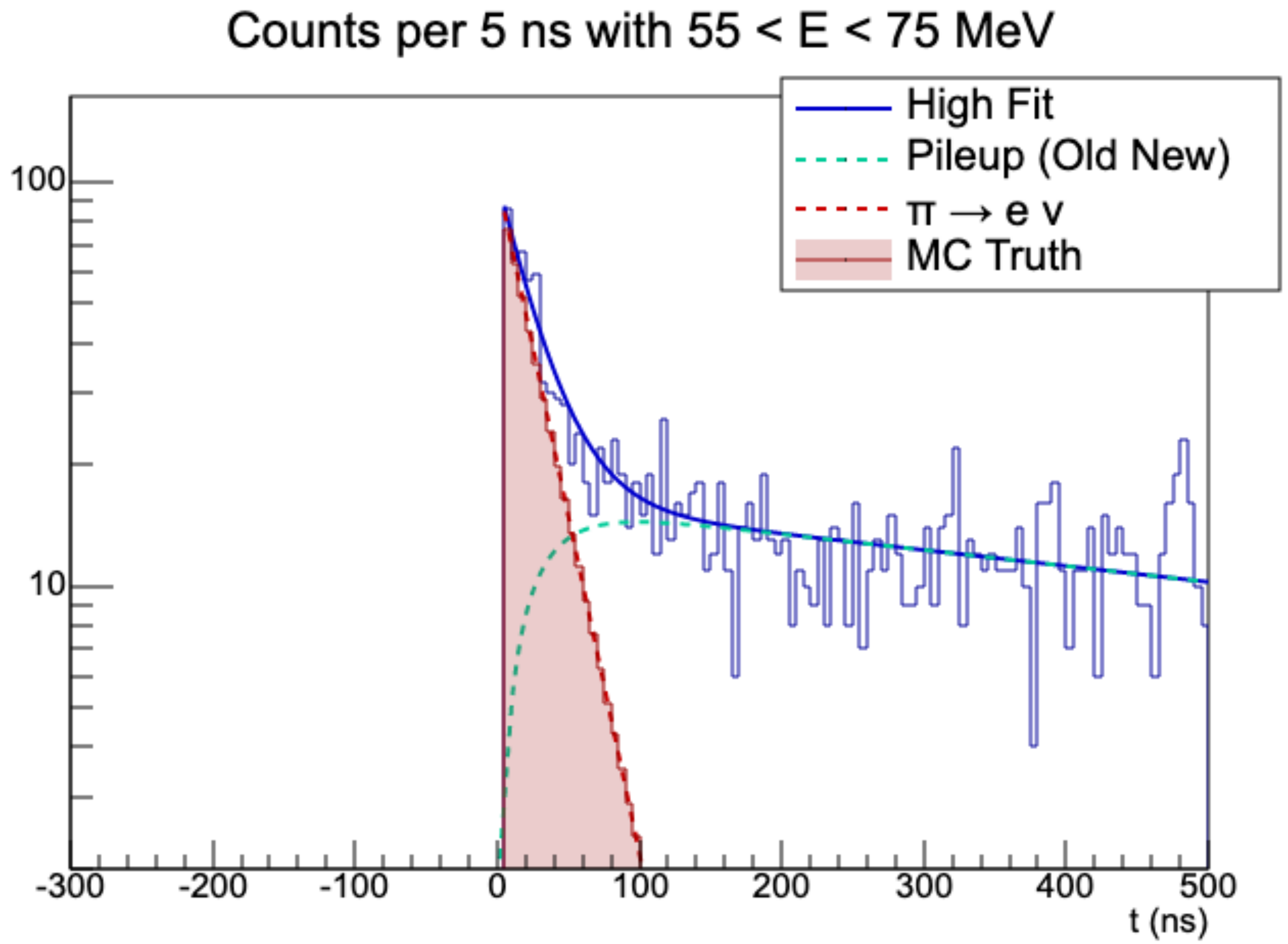
- Pienu is using time fits to extract the numbers.
- Works for pileup using only fiducial cut.
- Simplified fit consists of:

$$\underbrace{A \cdot e^{-t/\tau_\pi}}_{\pi \to e} + \underbrace{B \cdot e^{-t/\tau_\mu} \cdot \frac{\tau_\pi}{\tau_\pi - \tau_\mu}\left(e^{-t/\tau_\mu} - e^{-t/\tau_\pi}\right)}_{\text{Old-Muon + New Pion Pileup}}$$

Able to extract the fraction of $\pi \to e\nu$ events even with a large amount of pileup interfering



Fit Result:
$65 \pm 2\,\%$ of high energy events between 5 and 100 ns are $\pi \to e$, others are pileup

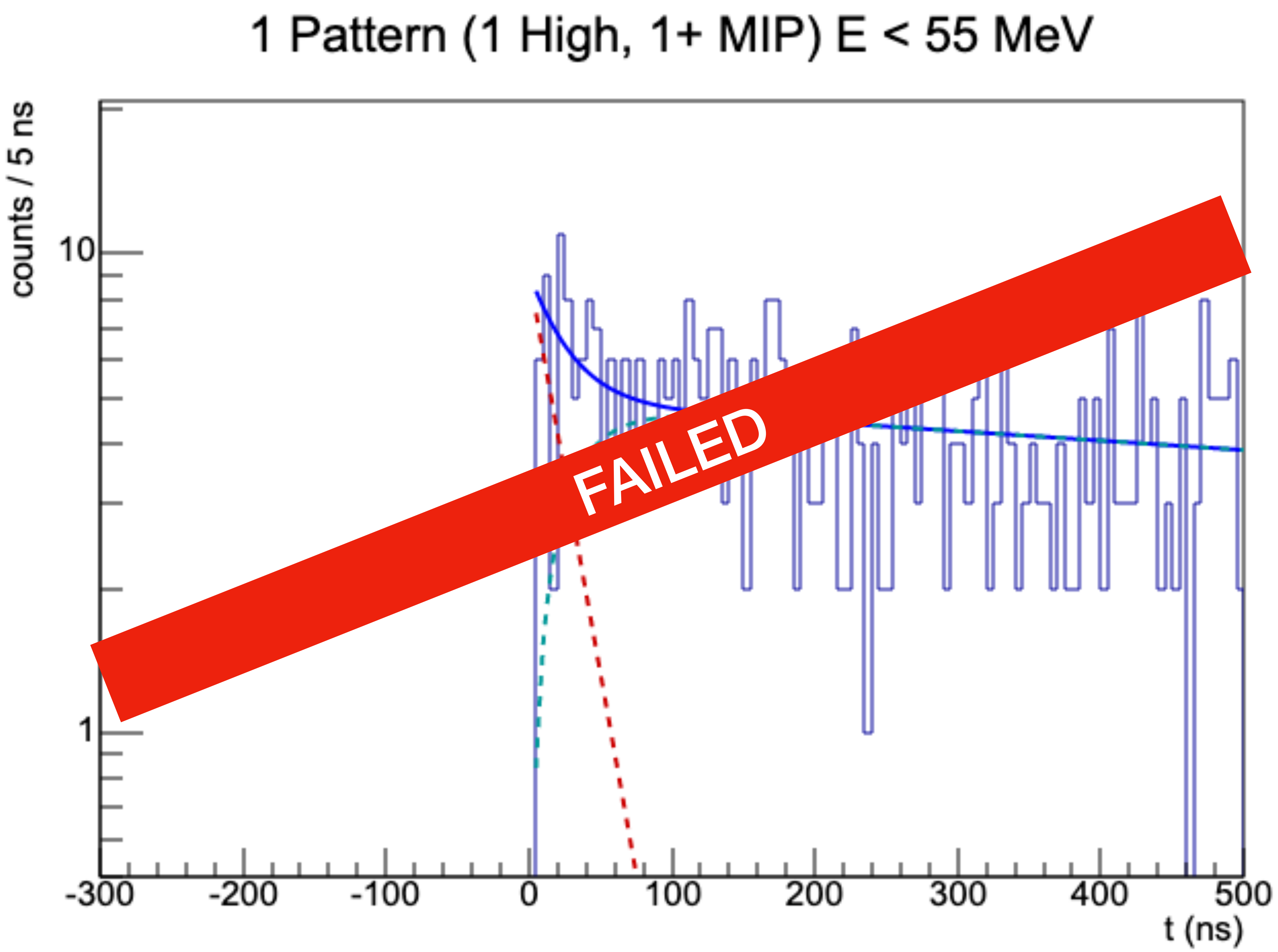


The Naive Approach …

- Try the same fitting strategy with only the tail events that feature one high ionising tracklet and MIPs.

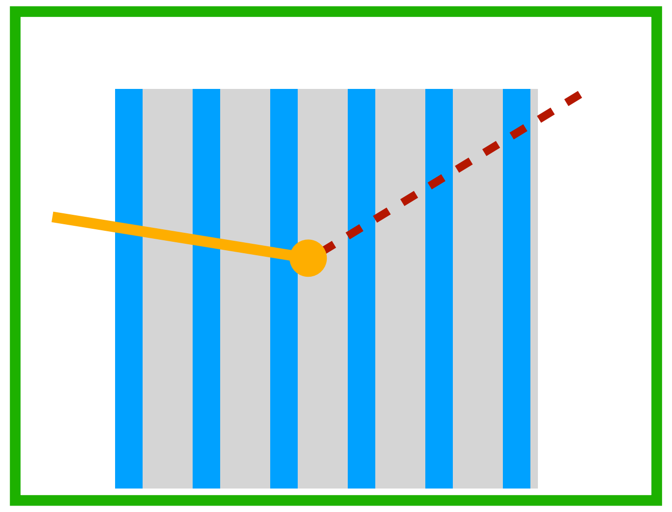
$$[0] \cdot e^{-t/\tau_\pi} + [1] \cdot \frac{\tau_\pi}{\tau_\pi - \tau_\mu}\left(e^{-t/\tau_\mu} - e^{-t/\tau_\pi}\right)$$

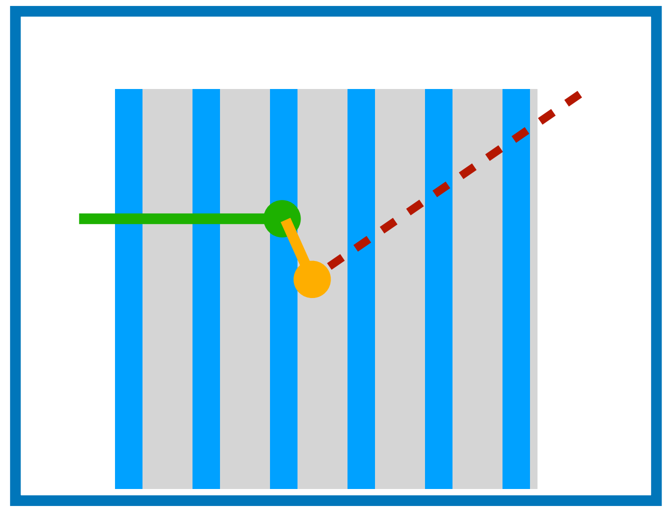
- The fit looks promising, but provides a ludicrously wrong result.

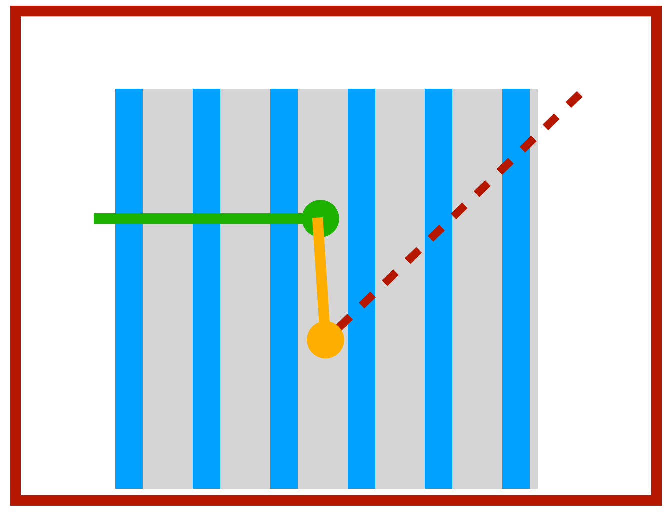


Why there is no easy way fitting out

Double back to the identified event topologies







Beam Muons and Hidden muons, type A (merged with pion) require imminent muon decay. Thus:

$$R_{1,2a}(t) = A \cdot e^{-t/\tau_\mu}$$

Hidden Muons type B (merged with positron) and Dead Muons have no such constraint, thus:

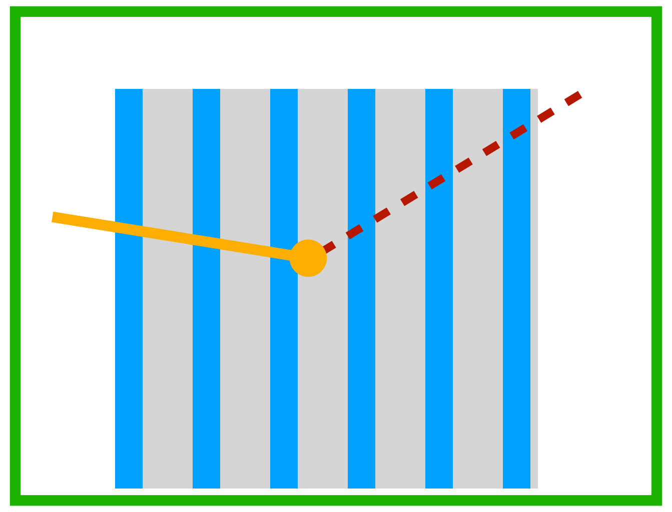
$$R_{2b,3}(t) = B \cdot \frac{\tau_\pi}{\tau_\pi - \tau_\mu}\left(e^{-t/\tau_\mu} - e^{-t/\tau_\pi}\right)$$

Some simple algebra later:

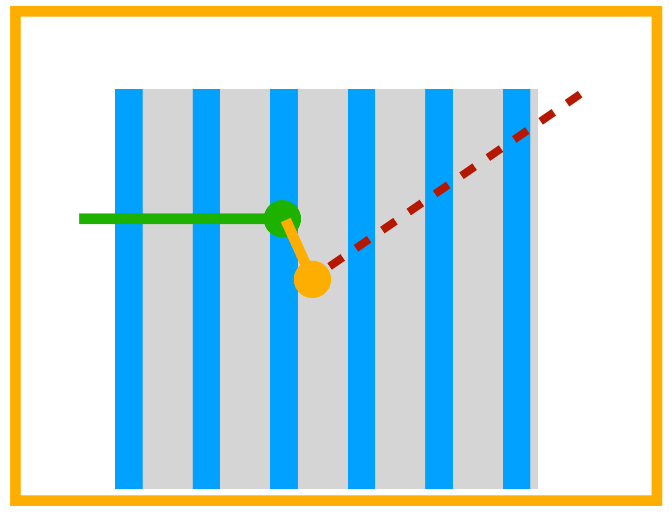
$$R(t) = R_{1,2a}(t) + R_{2b,3}(t) = K_1 \cdot e^{-t/\tau_\mu} + K_2 \cdot e^{-t/\tau_\pi}$$

The correct fitting formula can absorb the $\pi \rightarrow e$ contribution perfectly!

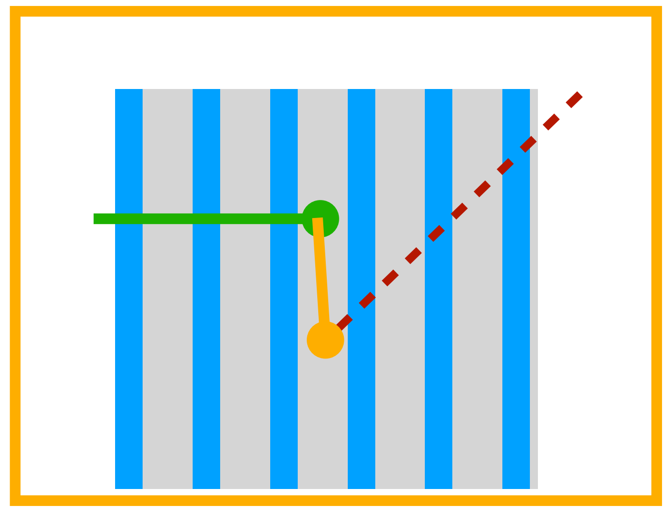
How to suppress them further



1. Beam Muon
Pion decays upstream



2. Hidden Muon
a) Merged with pion hits
b) Merged with positron hits



3. Dead Muon
μ remains in dead material.

- Identify what comes in. Make ATAR/DTAR distinguish between muons and pions.
- Can distinguish between muon and pion stopping position/energy deposition cuts?

Requires further understanding of the beam and DTAR.

- Reduction of dead material.
- Investigate tracking capabilities. Can we see the position mismatch between Pion and Positron track?
- Investigate distribution of well identified muon decay at rest. Extrapolate to the hidden region. Also, look for peculiar last pion hits/first positron hits.

Some of those investigations are soon to be started. The data waits to be analysed on the cluster and there are plenty of tasks for additional brains.

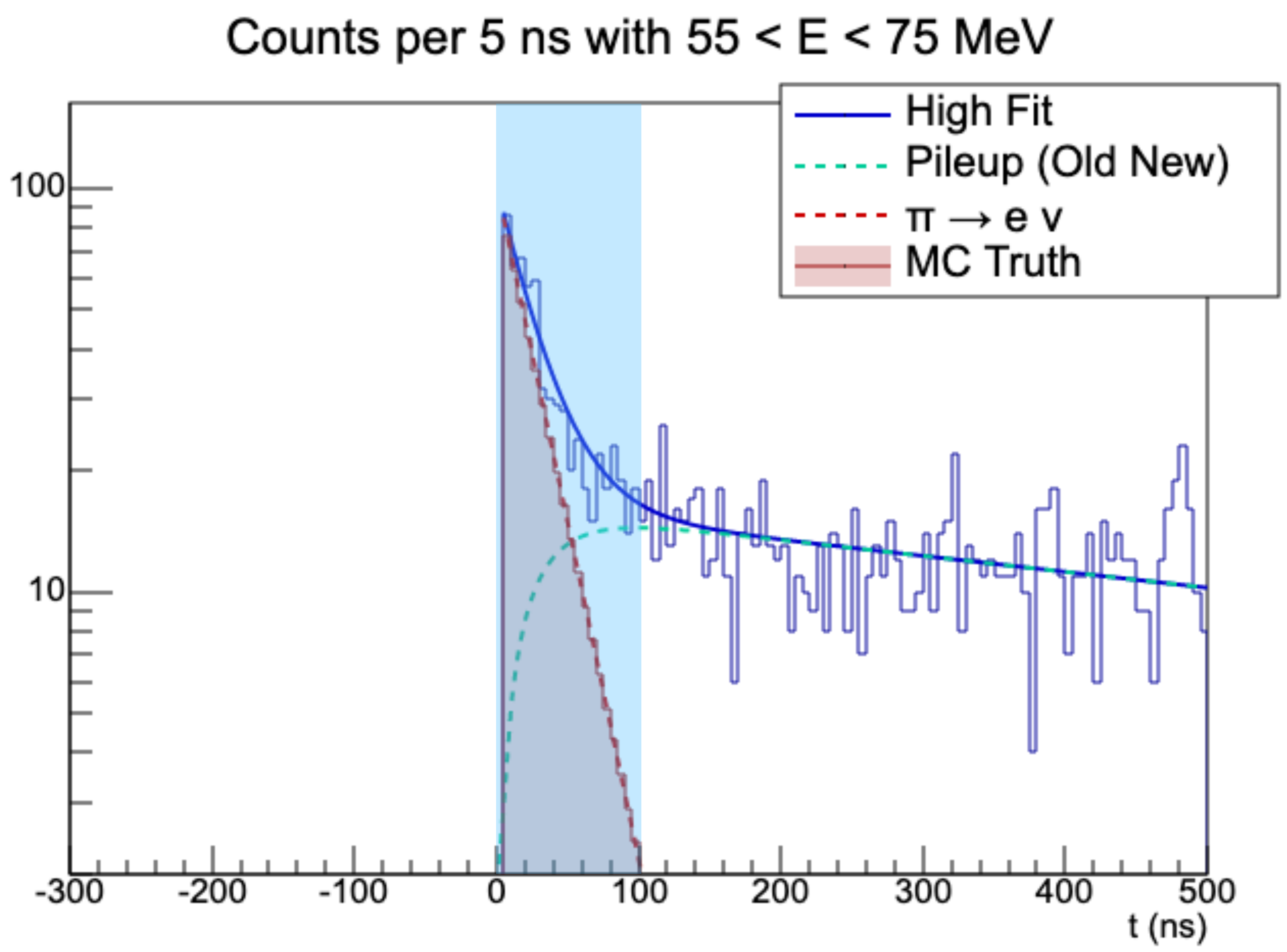
Examples for Muon Decay At Rest Studies

Definitely not complete, no guarantees

- **Angular distribution of muon tracks**
  Muons are emitted isotropically about 0.8 mm. If they travel perpendicular to a strip, they are guaranteed to cross active material and get detected.
  How well does the observed angular distribution match the isotropic prediction?

- **Time between pion and muon tracks**
  If their time difference is larger than 1 ns, they are easy to distinguish and an exponential decay pattern is expected.
  How well can this pattern be extended to no time delay? Does the extrapolation match?

What about pile up?



Fit Result:
$65 \pm 2\,\%$ of high energy events between 5 and 100 ns are $\pi \to e$, others are pileup

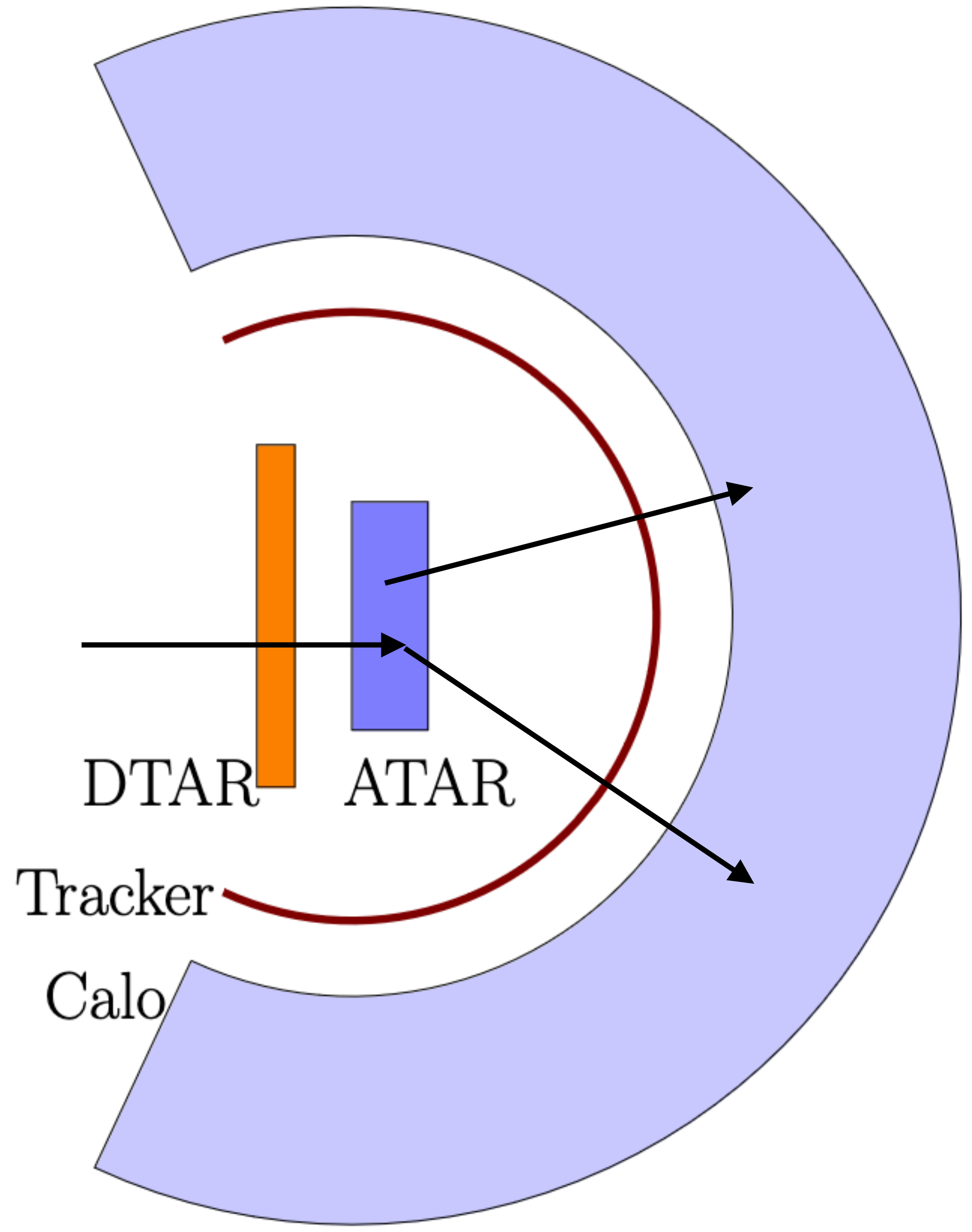
- What does our analysis strategy look like?

    A. Extract N_H based on all fiducial events:
    Fitting the time distribution will deal with pileup. Large correction factor required.

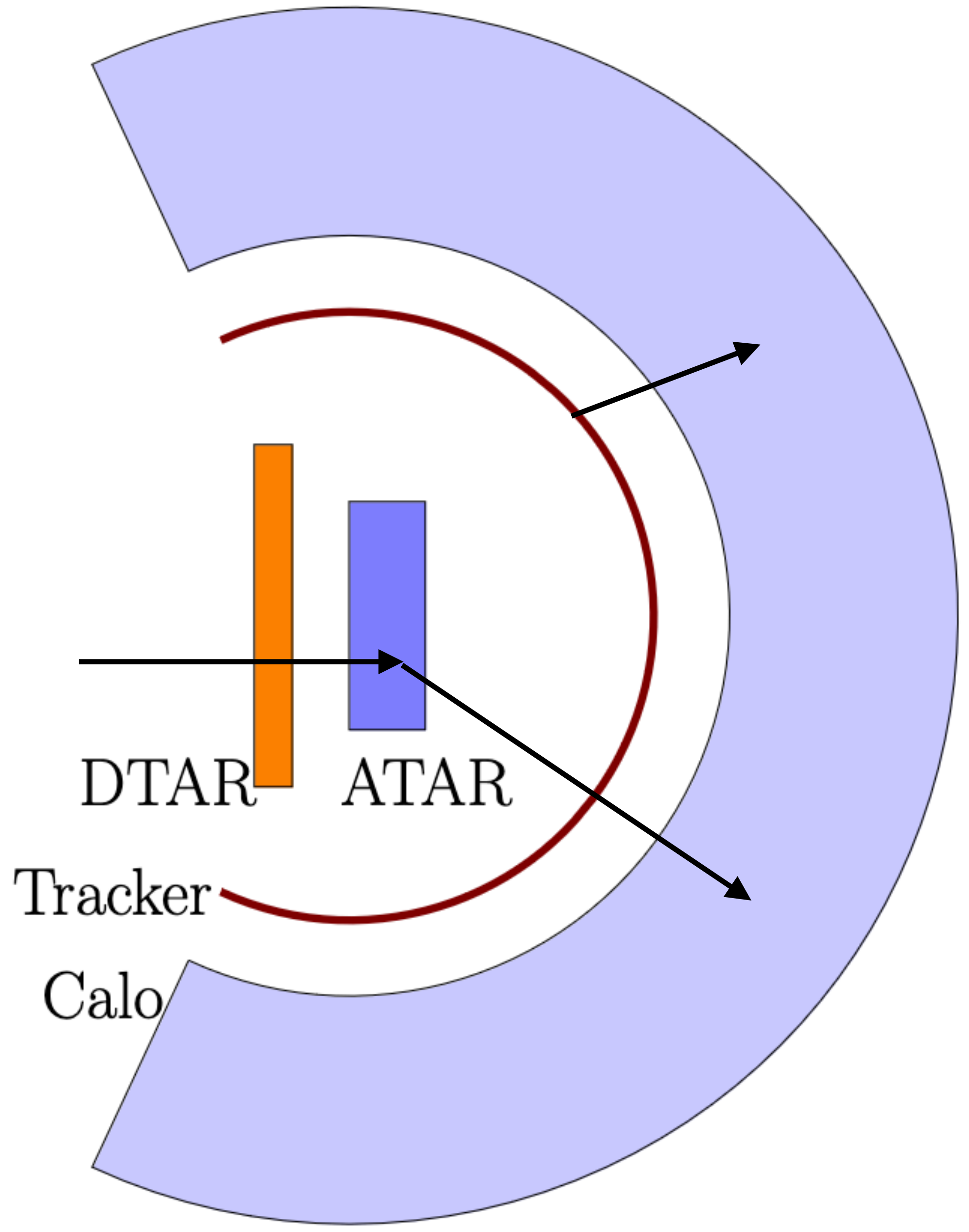
    B. Clean up sample with pattern cut first, require 1 high ionising and at least 1 MIP tracklet.
    Sounds very promising based on MC Truth Tracklet and Pattern finding. Will we bias the sample with a more realistic reconstruction approach?

Caveats piling up

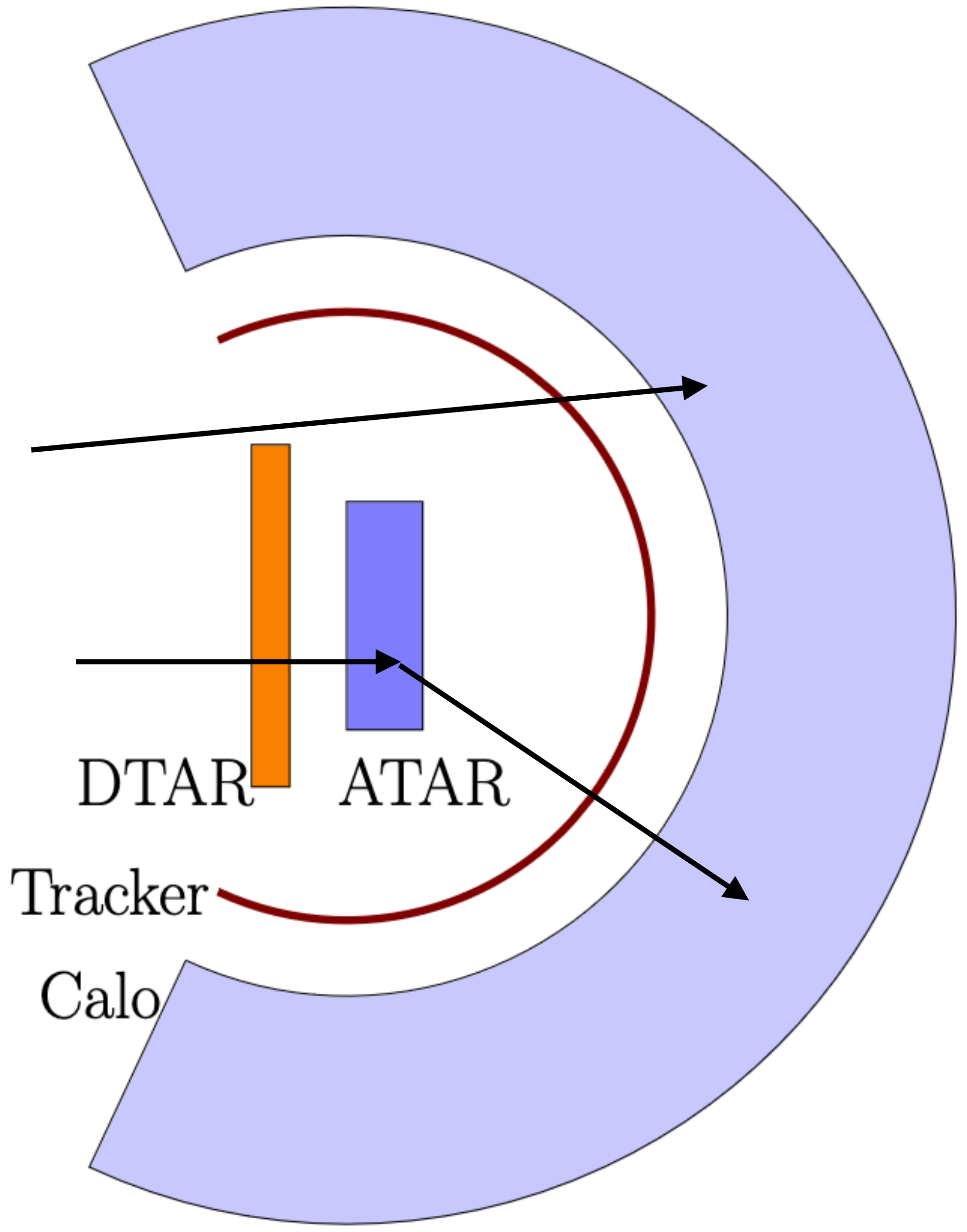
Only a fraction of possibilities has been covered so far …



Classic old muon:
Old muon decays on target. clearly identifiable by two pattern structure. The only case where the current dataset is suitable for. Either fit it or use ATAR for suppression



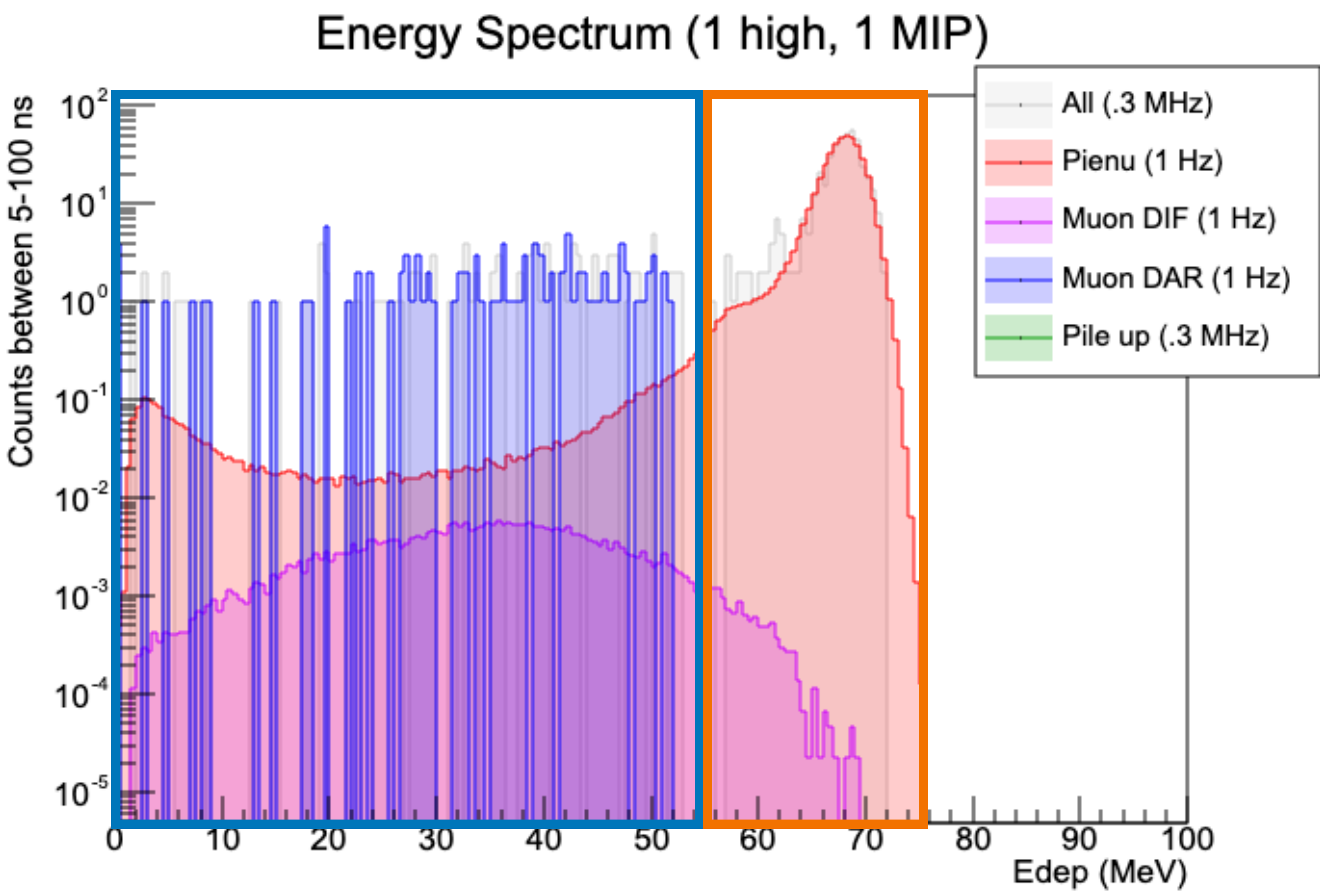
Stray old muon:
Old muon decays somewhere in dead material. The emitted positron may be seen by tracker or calo only. Their abundance will increase with future implementation of Cables and Supporting Structures.



Beam Pileup:
Some beam particles bypasses all our structures and hits the calo. Potential candidates are recent beam muons as suggested by Stefan. These require all support structures and cables as well as a dedicated simulation with a more realistic beam.

Summary

- Event identification based on number of high ionising and MIP tracklets
- This suppresses $\pi \rightarrow \mu \rightarrow e$ events and backgrounds (e.g. pileup).
- Not even close to reveal the tail. Missing few orders of magnitude.
- Dead ATAR material needs to be reduced.
- Old Muon pile up can be suppressed based on pattern or fitted based on time distribution.



Rel. Abundance	0 - 55 MeV	55 - 75 MeV
Pienu	0.014	1
Muon Decay at Rest	0.24	0
Muon Decay in Flight	7E-04	3E-05
Pileup	0	0

How to go forward - Inputs for other Teams

- **ATAR Builders**: How much can you reduce the backing layer and HV supply layer? *Those seem to be mostly involved with dead muons. Also hidden muons often vanish there.*

- **Geometry Coders**: Please implement cables and support structures in the target region.
  They will be crucial to get a good simulation of pile up as they harbour stray muons.

- **DTAR Developers:** What will this currently fictional detector look like?
  We need those informations as they will flow into the reconstruction and event identification.

- **Analysers:** There are many analysis tasks people can complete, ranging from nice undergrad intro projects to the grand analysis scheme.

- **Trigger Designers:** While not actively mentioned in the talk … What kind of events will actually make it into the reconstruction? Prescaling?