Reconstruction with Photon Detectors in a Liquid Argon TPC

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LBNE Physics Workshop
7/30/2012

Motivations

- The move to the surface has made the far detector a very busy place.
- Cosmic ray flux: 100 μ/m^2/sec
- Two 5 kton cryostat modules have a top surface area of 650 m^2.
  (Sides add extra, of course)
- ~90 muons per 1.4 ms TPC drift time
- ~ 0.7 muon per 10 μs beam spill window

Useful Numbers

Mostly based on docdb #3383-v31

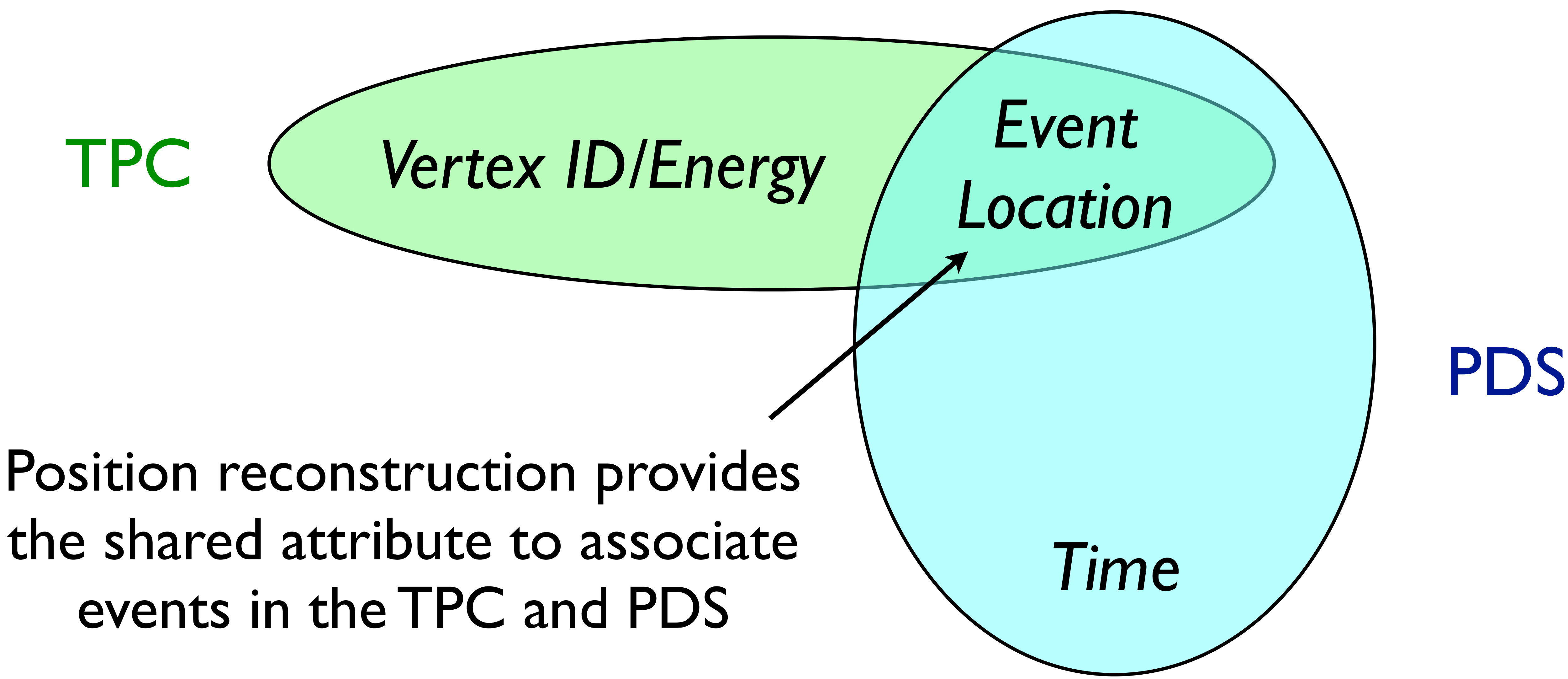
Energy loss for Minimum Ionizing Particle in LAr	2.12 MeV/cm
Average energy for a cosmic ray muon	5 GeV
Neutrino event energy	1-10 GeV
Average path length for a cosmic ray muon	23 m
# anode plane modules (2.5 m x 7 m)	2 (*z*) x 3 (*y*) x 10 (*x*) = 60
Expected # of cosmic rays per module *per TPC drift time*	~1-2
Expected # of cosmic rays per module *per beam spill*	*~0.01*

Two Detectors in One

- A MIP produces ~27,000 free electrons (after recombination) *and* ~20,000 UV photons per MeV in liquid argon.
- Opportunity for two orthogonal detectors in one volume!
- Electrons have good spatial resolution and poor temporal resolution.
  (Wires are cheap, electron diffusion is low, but electron drift is slow)
- Photons have poor spatial resolution and good temporal resolution.
  (Photons are fast, but Rayleigh scattering is frequent and PMT coverage is expensive.)

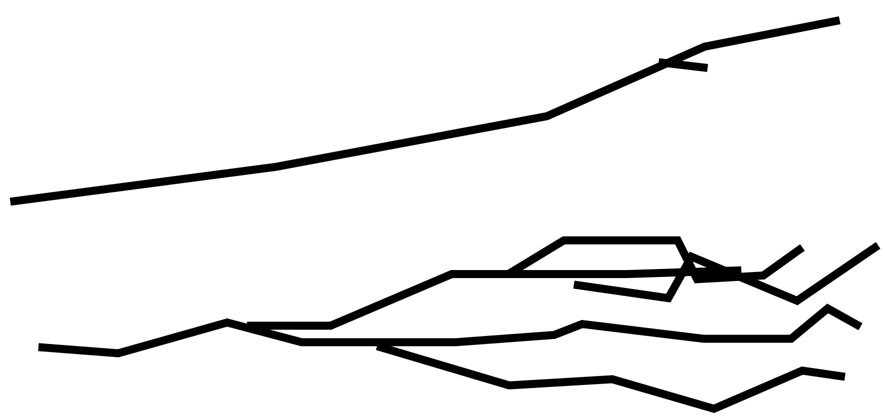
Best of Both Worlds

- Use the TPC for individual track/shower reconstruction, particle ID, and calorimetry.
- Use the photon detection system (PDS) to identify the time and rough location of each "event".



Event Sacrifice

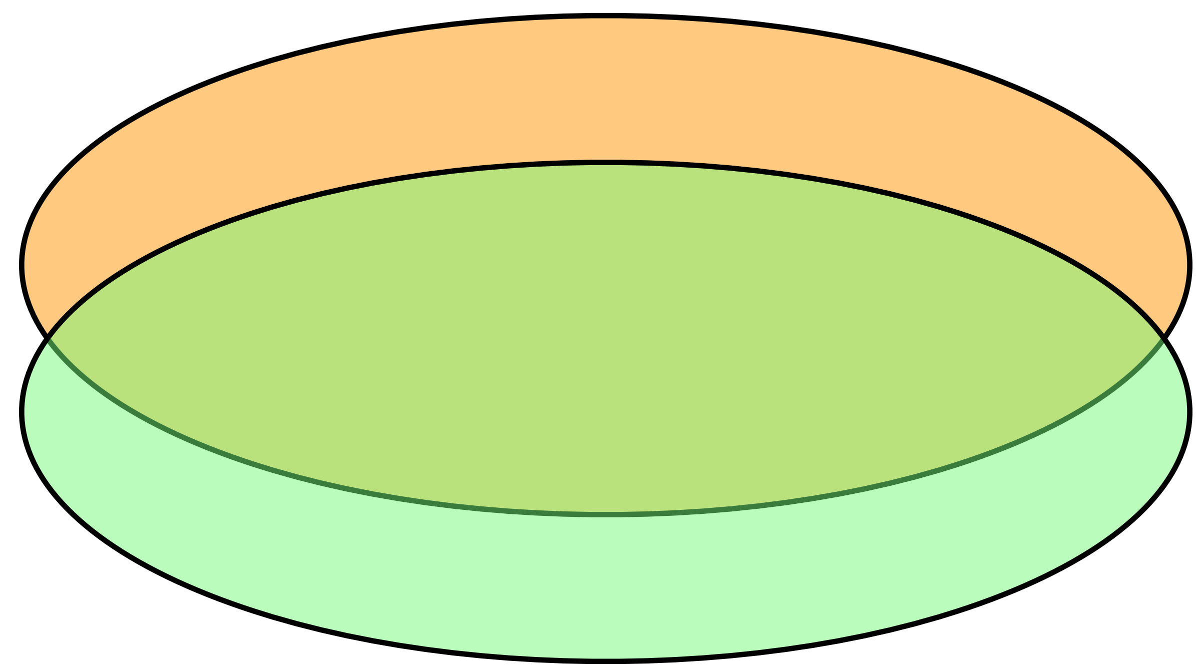
TPC



Events clearly resolved in space, but not in time

PDS

t_0 = 4 μs



t_0 = 500 μs

Events clearly resolved in time, but not in space

Can't tell which one is the signal!

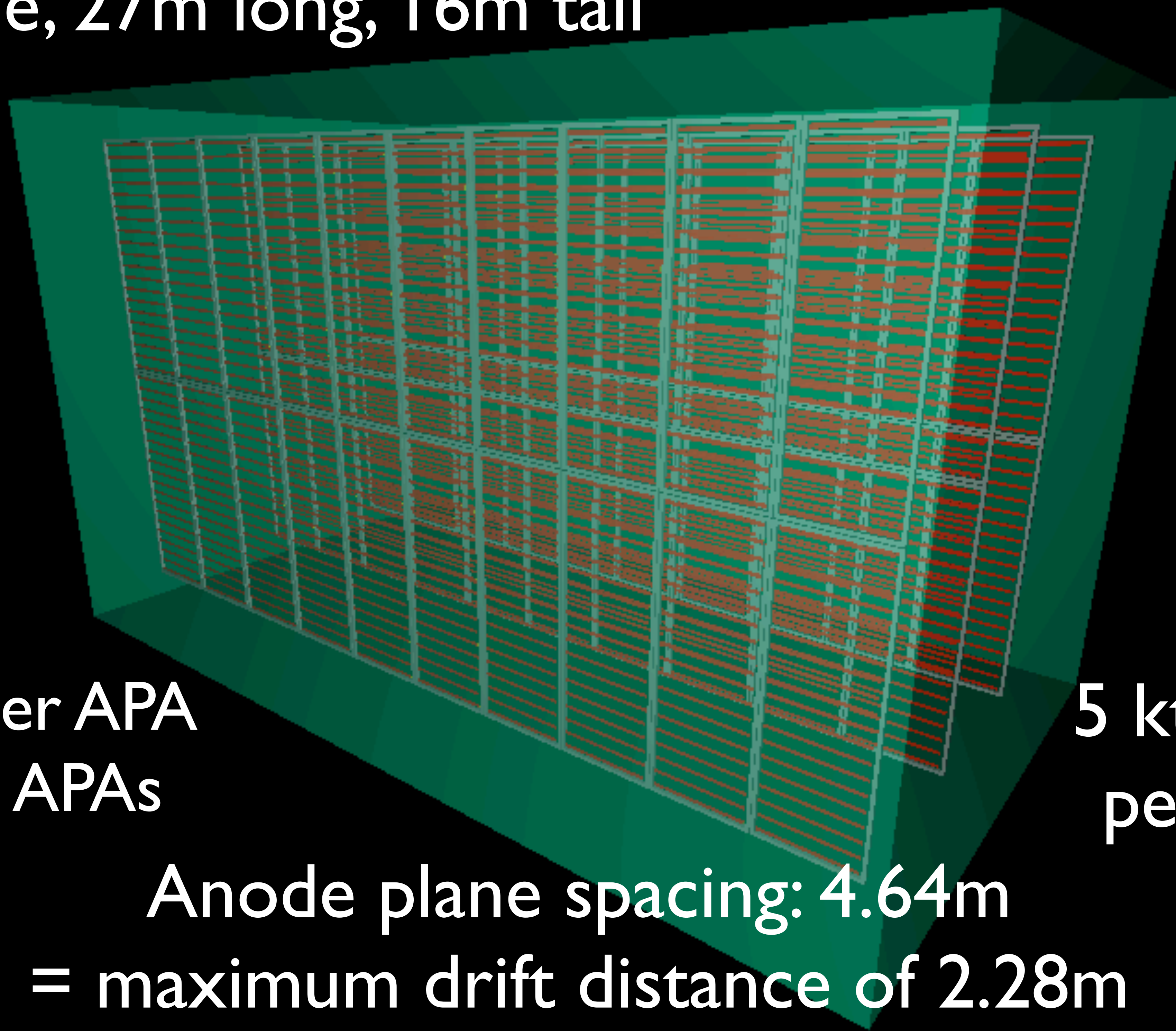
Requirements Flow

- The position resolution of PDS reconstruction will impact signal acceptance.
- If two piled-up events in the TPC are close enough in space that they cannot be resolved by the PDS, then a unique time cannot be assigned to the tracks, and we will (probably) be forced to cut both.
- So, the cosmic ray rate + maximum background acceptance / signal sacrifice we can tolerate → *required position resolution of PDS* → *required optical properties of PDS system.*

The Cryostat (for now)

(Imagine Darth Vader quote here)

16m wide, 27m long, 16m tall

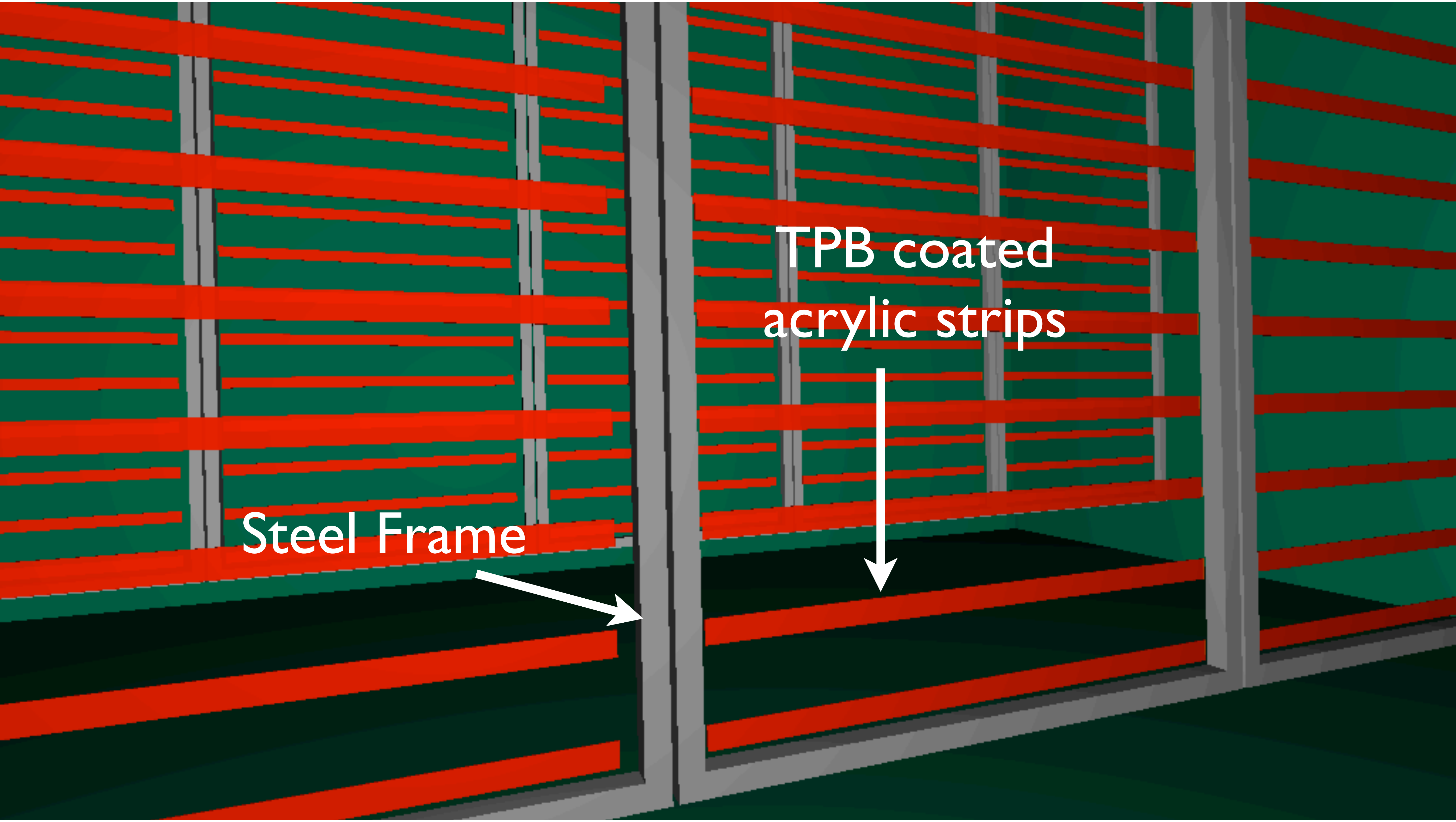


10 paddles per APA
10x3x2=60 APAs

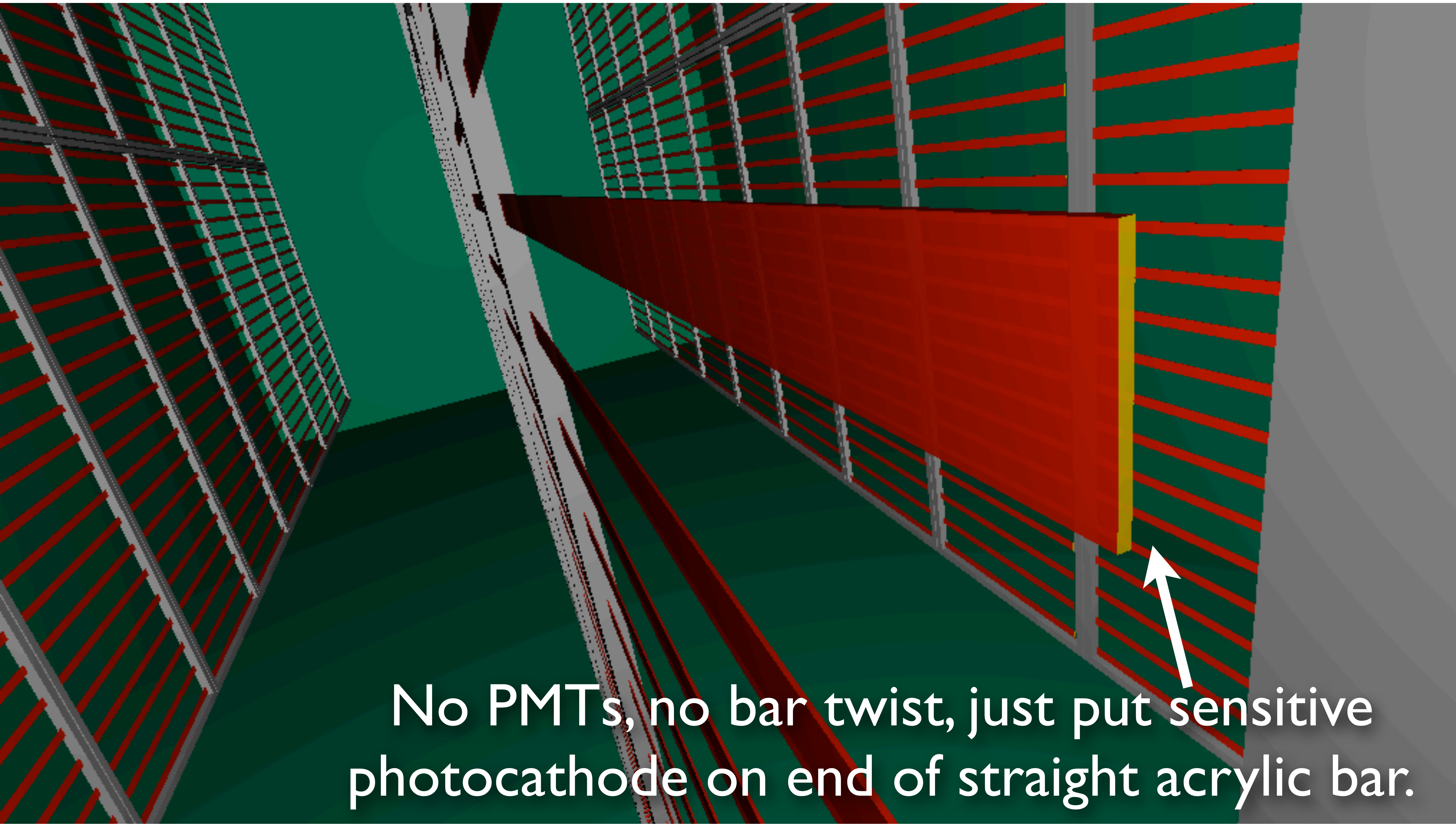
5 kton fiducial
per cryostat

Anode plane spacing: 4.64m
= maximum drift distance of 2.28m

APA Up Close



The Detector



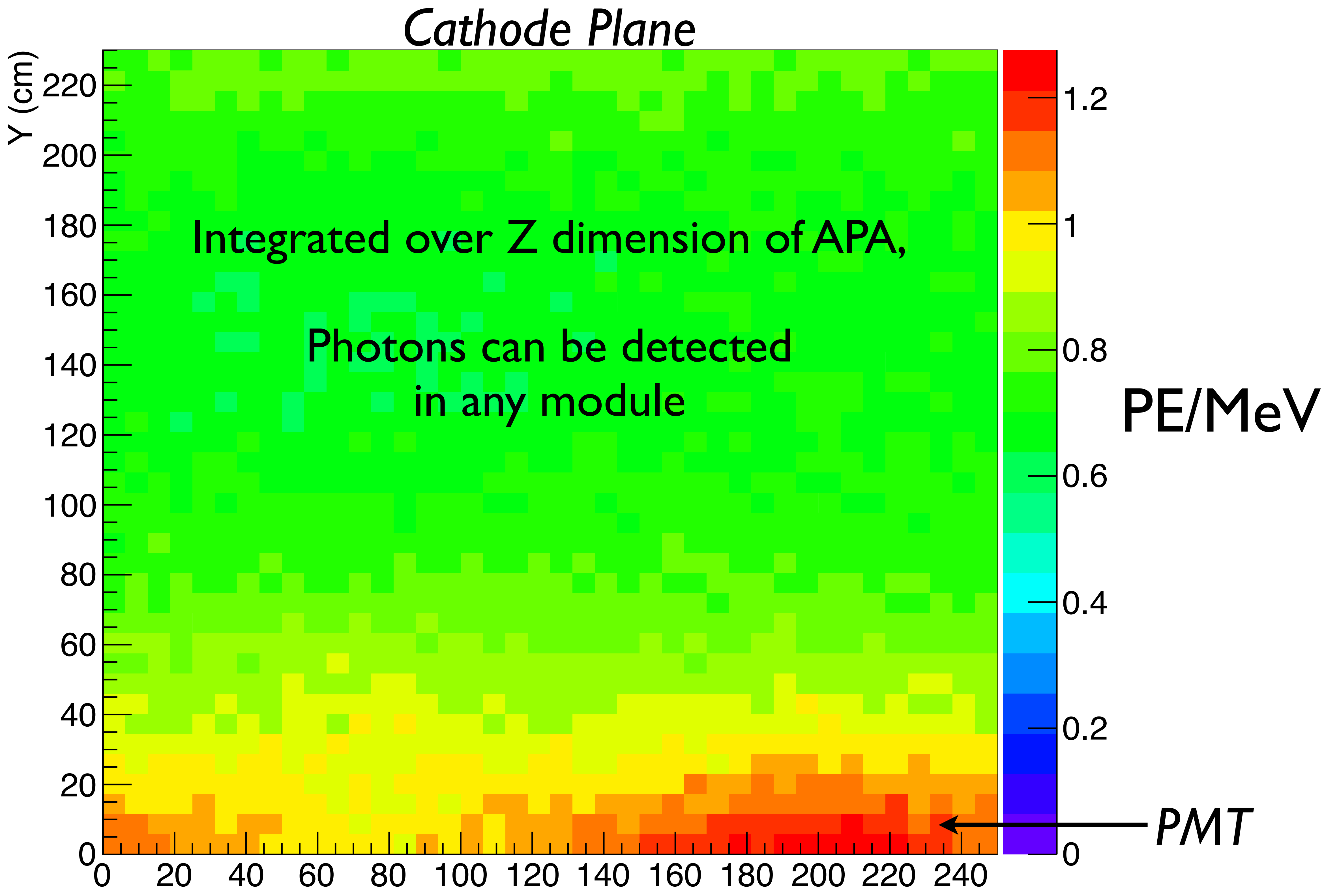
Photon Simulation

- 19,800 UV photons (128 nm) per MeV deposited
(this from CDR... LArSoft assumes 24,000, w/o E-field is 40,000)
- 90 cm Rayleigh scattering length @ 128 nm
- Full TPB re-emission spectrum, efficiency = 1.0
- Acrylic attenuation wavelength dependent
(based on acrylic from MiniCLEAN)
- PMT QE wavelength dependent (based on cryogenic R5912-02-MOD PMTs from MiniCLEAN, but scaled up to 25% peak efficiency assumed in CDR)
- *No adiabatic twist to map end of light guide onto square PMT surface.*
- Effective photocathode area is same as CDR
- Steel reflectivity in UV (25%) and visible (50%) taken from LArSoft
- *No other optical obstructions in tank*

Light Yield

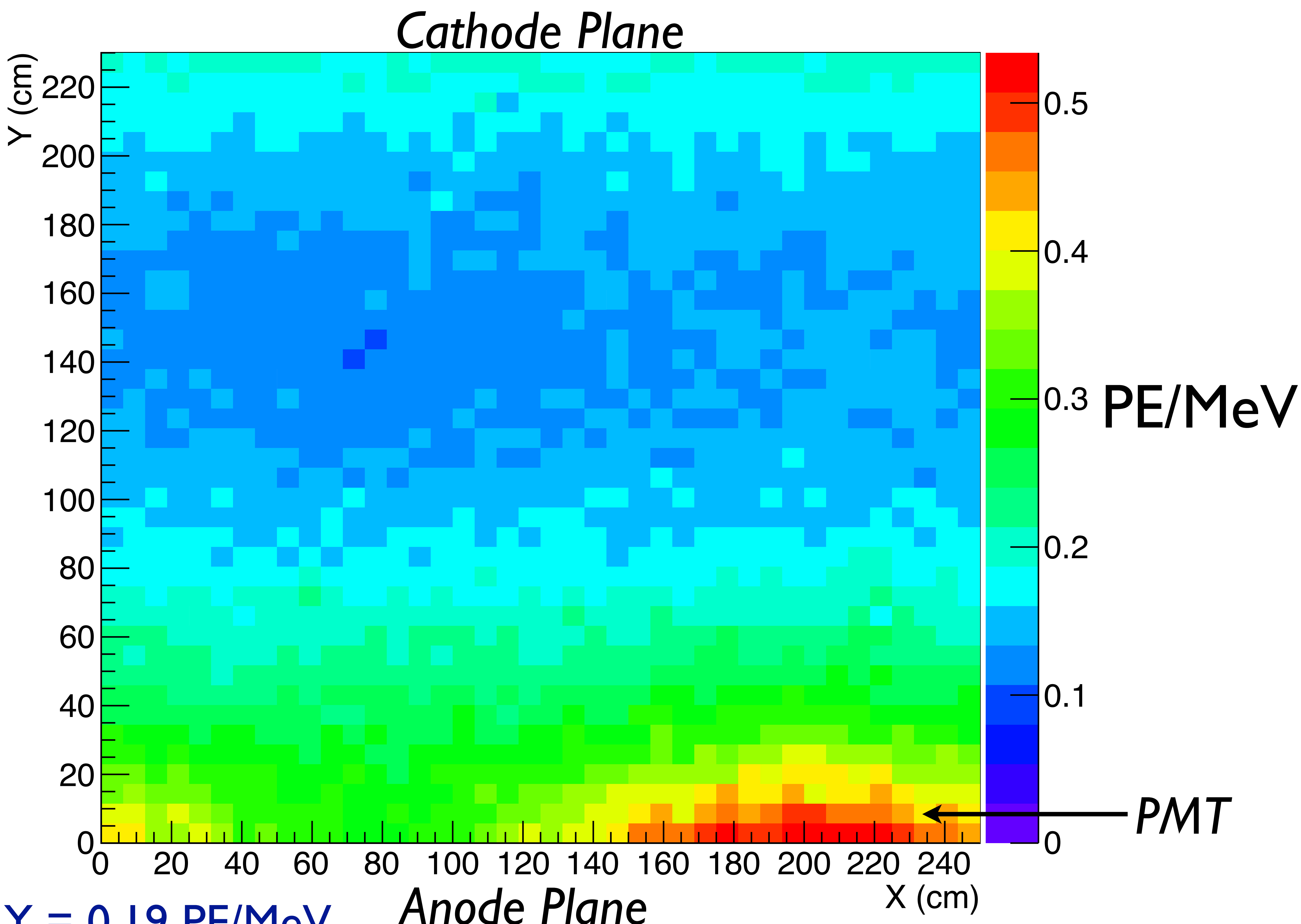
- Light yield will be one of the variables that controls reconstruction resolution. *(More photons = more information)*
- CDR estimates 0.2 photoelectrons per MeV using simple calculation that does not include absorption in liquid argon.
- LArSoft uses a 2 meter absorption length that comes from ICARUS. *(Note this is different than the Rayleigh scattering length, which is 90 cm @ 128 nm!)*
- Light yield depends significantly on absorption lengths in the argon, which is determined entirely by purity.
- O_2 is the primary concern for electron drift, but UV propagation also requires low N_2 and H_2O contamination.

LY in a Module: 100m Absorption



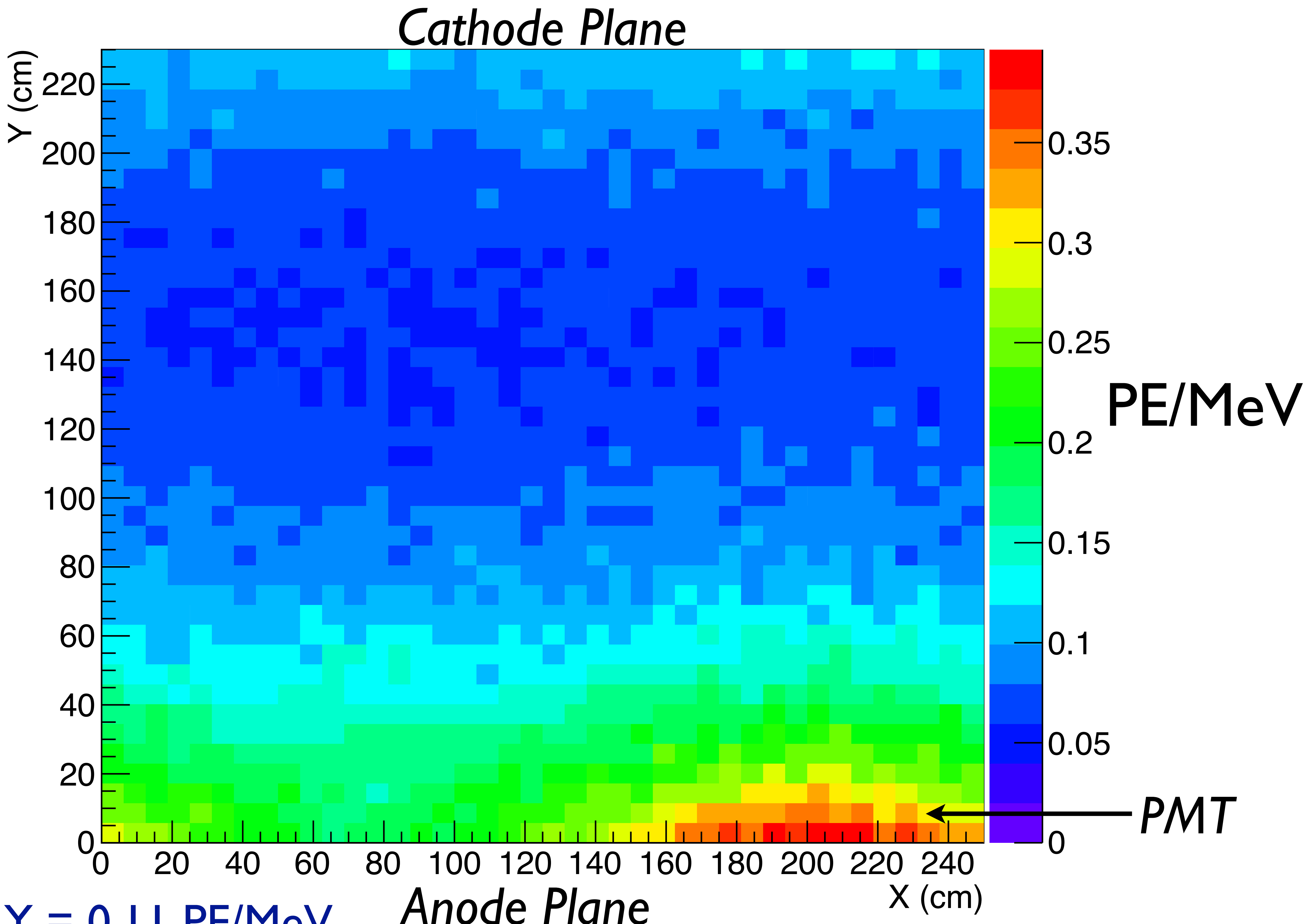
Average LY = 0.78 PE/MeV

LY in a Module: 3m Absorption



Average LY = 0.19 PE/MeV

LY in a Module: 2m Absorption



Average LY = 0.11 PE/MeV

Absorption vs. TPB Coverage

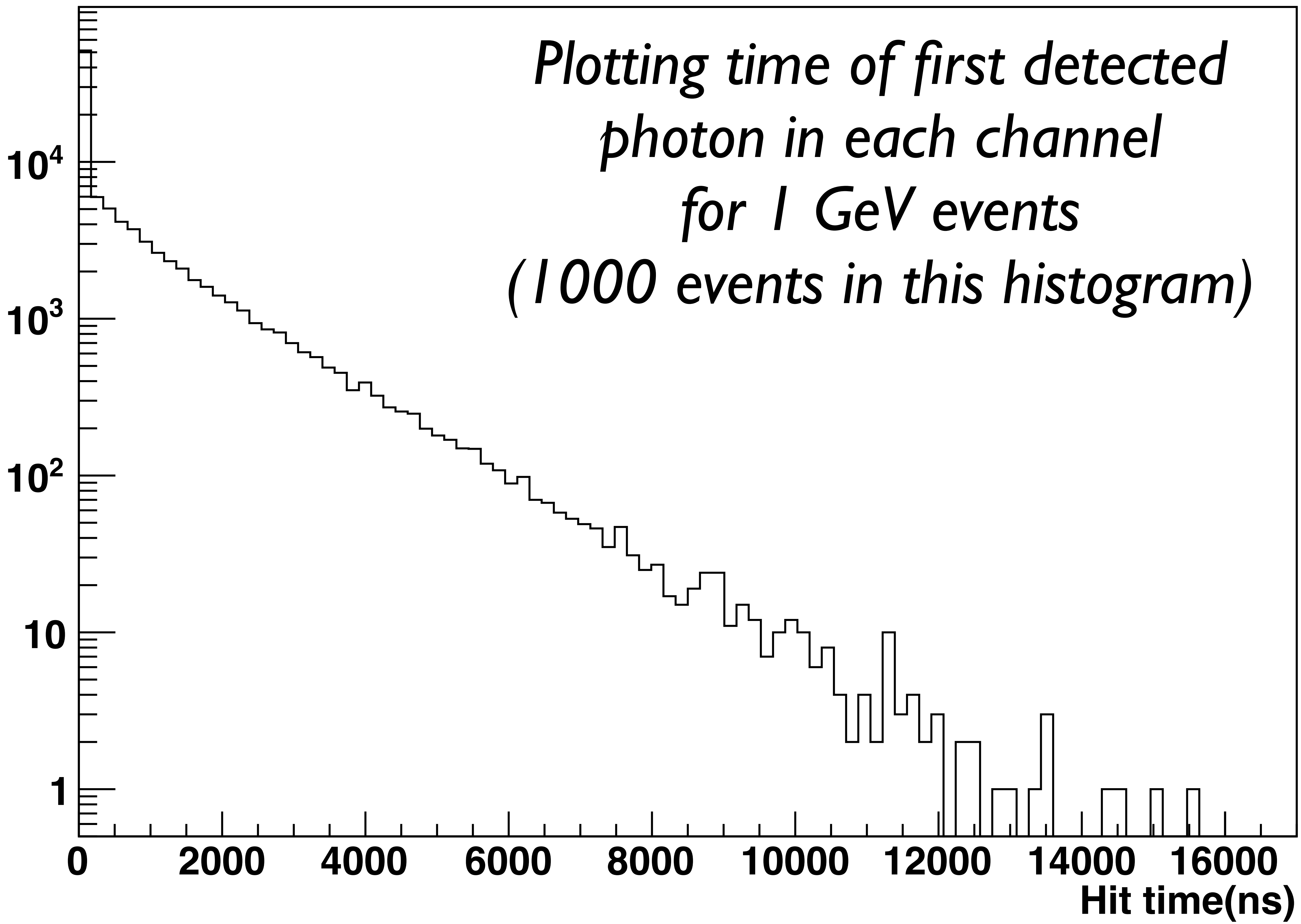
- Absorption lengths have a big effect on overall light yield.
- Longer absorption lengths increase light yield, but also de-localize the photons.
- This leads to increased probability of pileup of photons produced in one module in other modules. Noise floor from ^{39}Ar increases, etc.
- Modest absorption lengths + more TPB coverage increases light yield in a way that more directly improves reconstruction.
- More TPB coverage costs more, so will need to balance these effects.

How can we do reconstruction in the PDS?

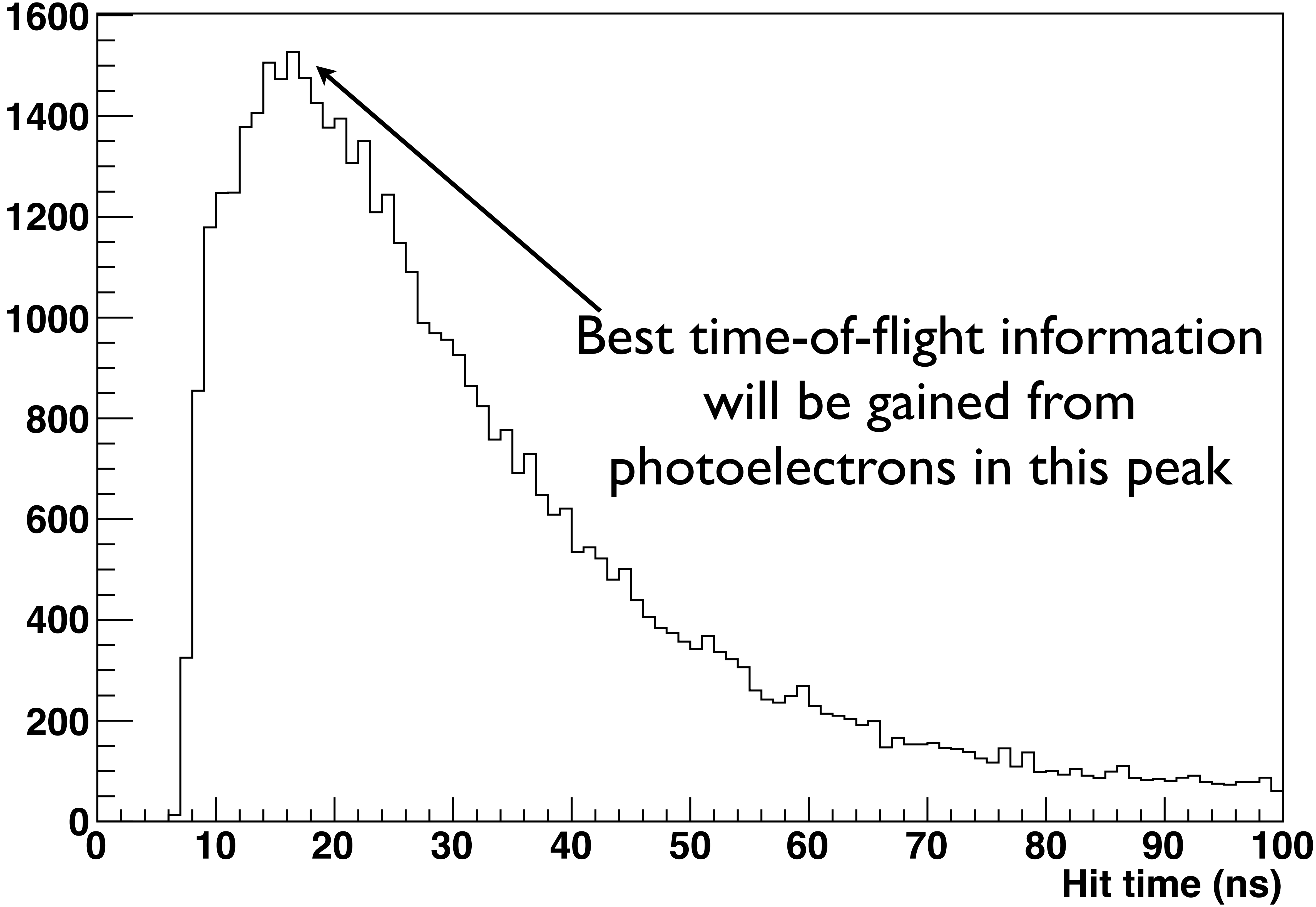
Time "Reconstruction"

- Finding the time of each event is the primary job of the PDS.
- Complicated by two factors:
  - Only 30% of the scintillation light is produced with a 6-12 ns time constant, the remaining 70% of the light is produced with a 1500 ns time constant.
  - The Rayleigh scattering length in liquid argon is 90 cm @ 128 nm, so the UV path length can be much longer than the straight-line distance from the event to the TPB surface.
- Complications are mitigated by two other factors:
  - Nearby light guides detect multiple photons, so the probability of seeing an early photon in those PMTs is higher than 30%.
  - UV absorption means the photons you are most likely to see have traveled the shortest distance, i.e. the fewest scatters.

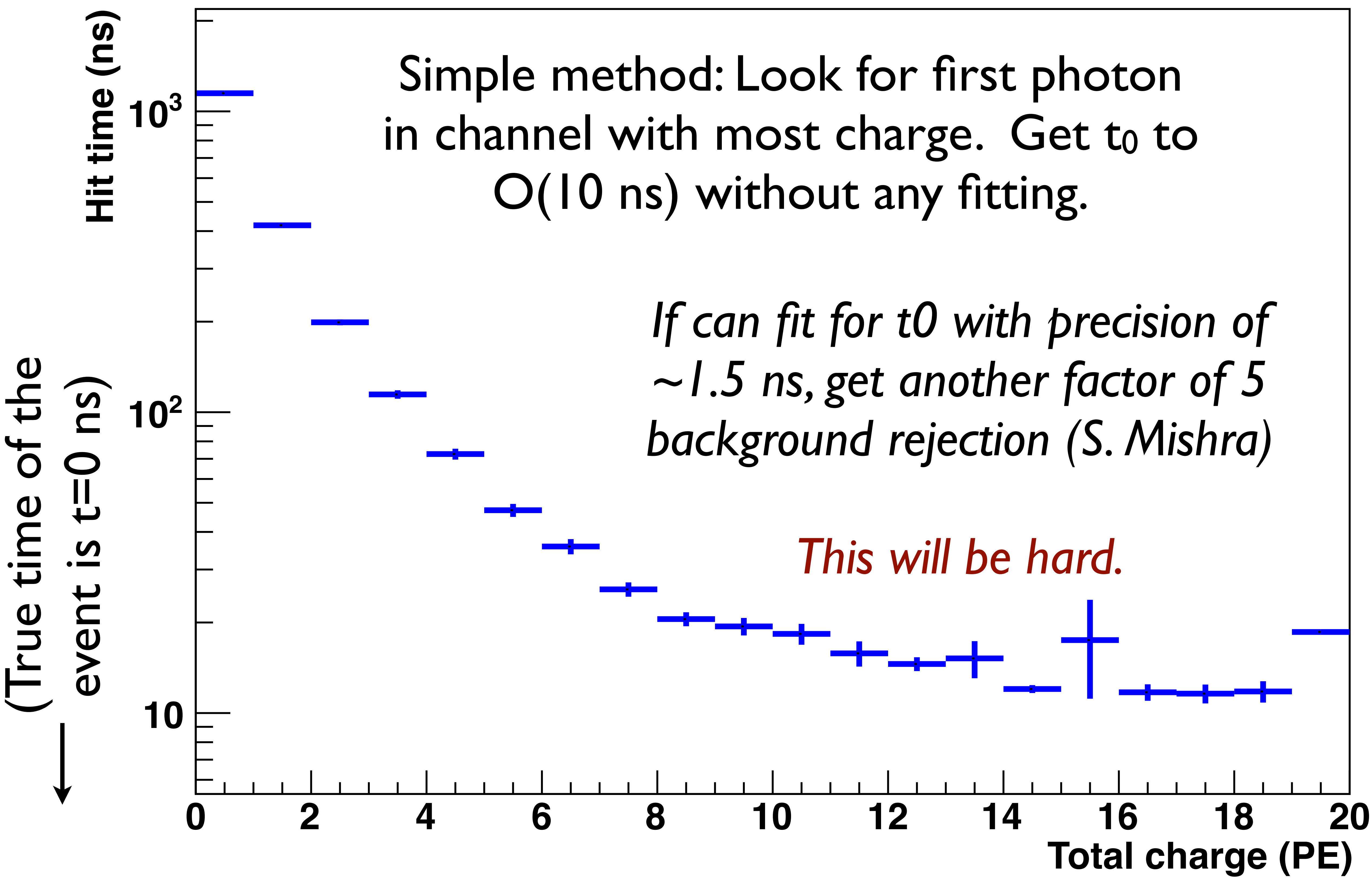
Time Distribution



Time Distribution: Early



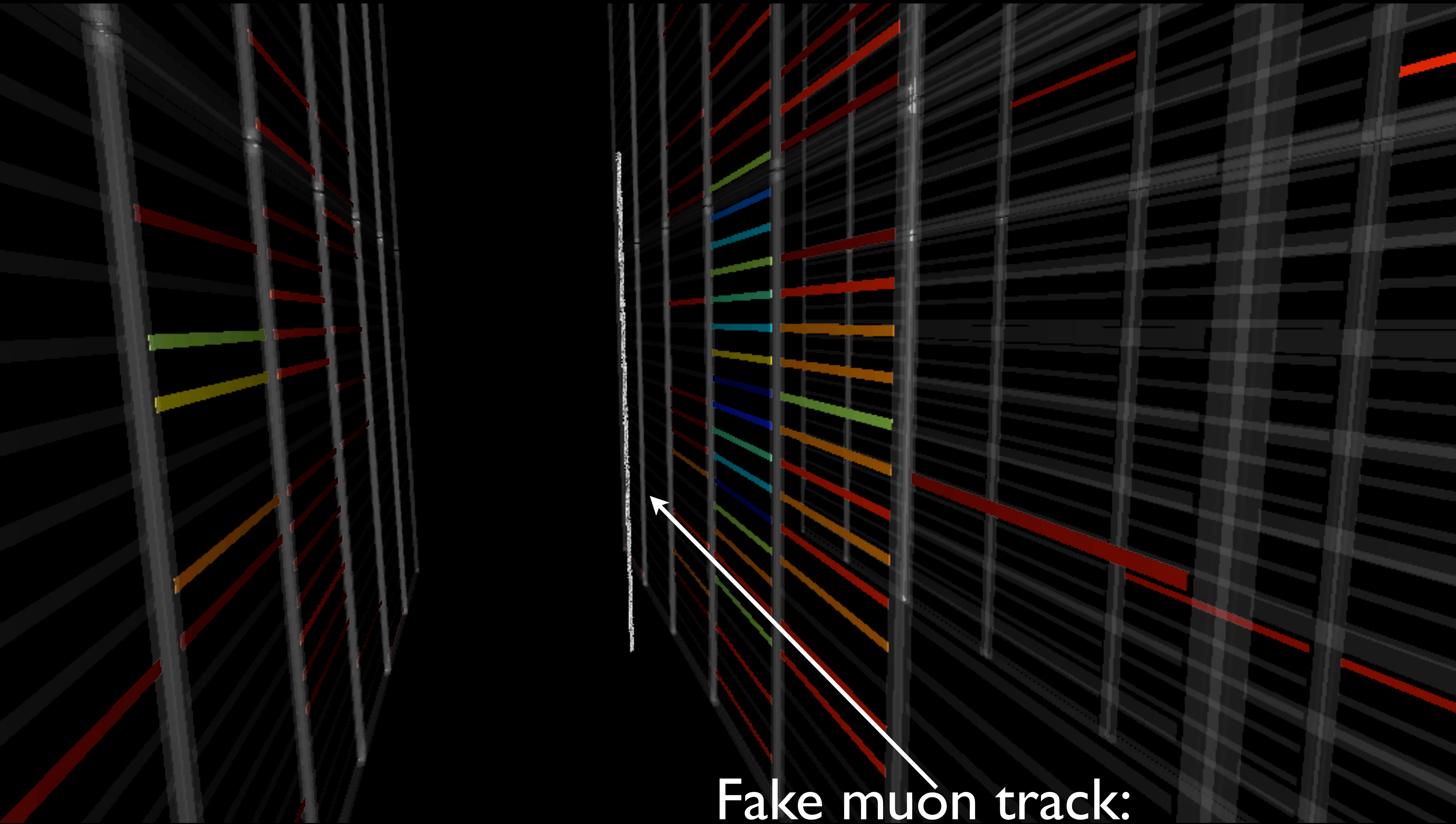
Time vs. Charge



Position Reconstruction

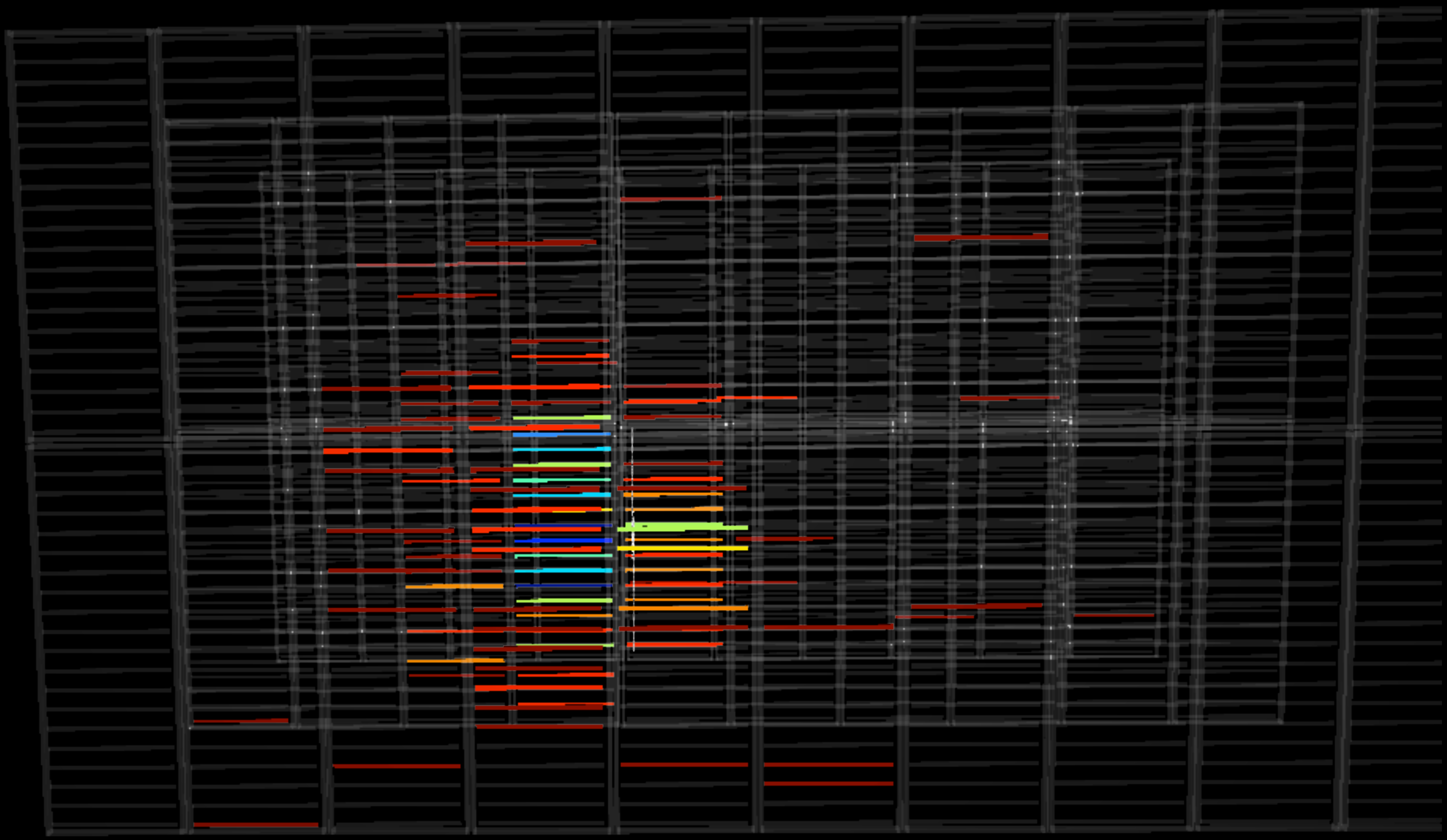
- Position reconstruction lets us link each t_0 to a specific collection of tracks in the TPC.
- Made difficult by two factors:
  - Short (6 ns) and long scintillation (1500 ns) time constants really smear out time-of-flight constraints on position. (Comparison: It takes photons 9 nanoseconds to traverse the 2.3 m drift distance, assuming no scatters.)
  - Rayleigh scattering scrambles the photon paths, complicating methods to estimate the time PDF for each channel.
- Hit pattern and charge are easier to predict, and should significantly constrain the position as well.

Example: GeV “muon”



Fake muon track:
20 million scintillation photons, 4.7 m long

Event Charge



Red = 1 photoelectron   Blue = ~20 photoelectrons

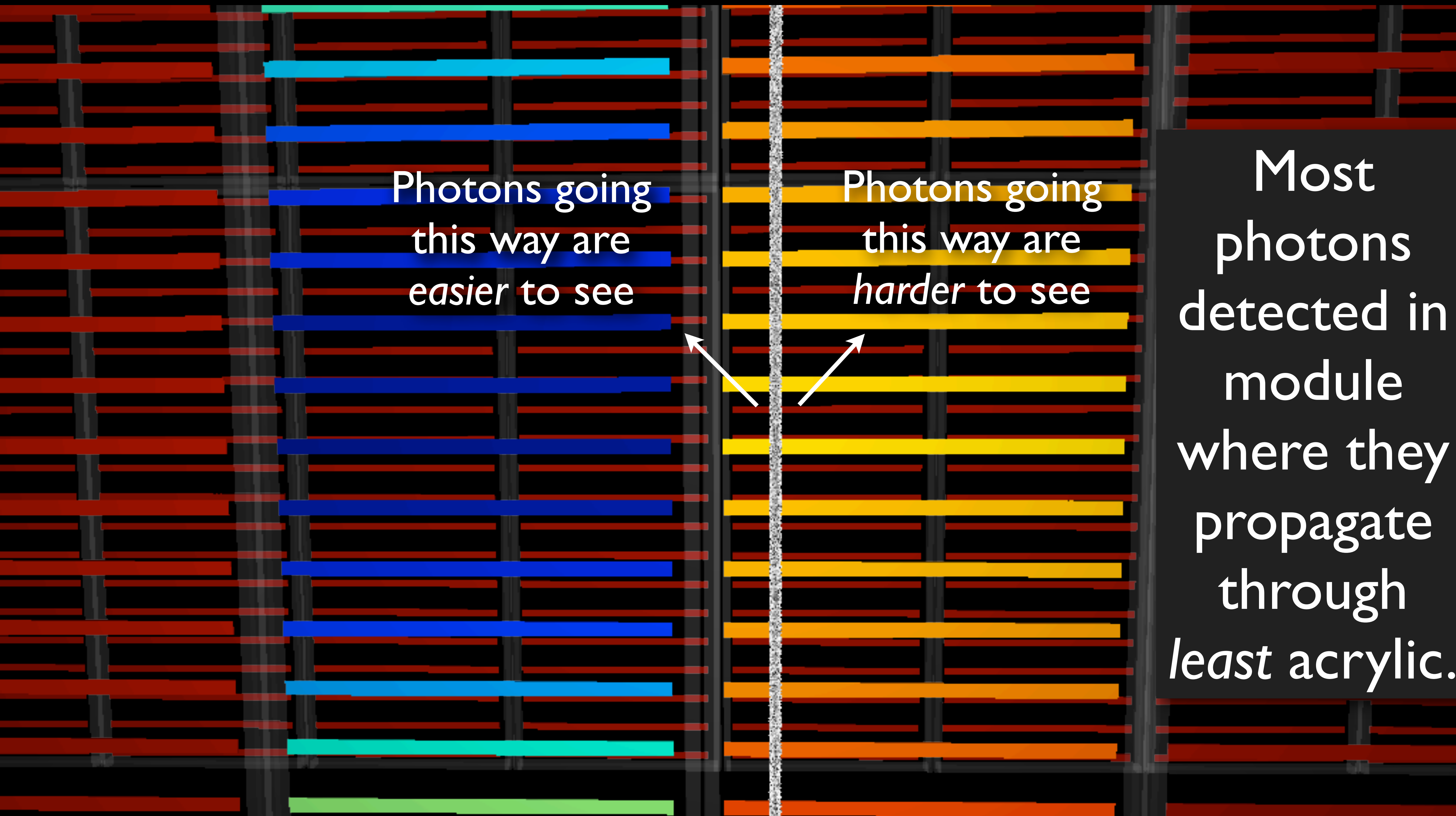
Event Time

Photon times are all over the place due to scintillation time constants

Red = Early

Blue = Late

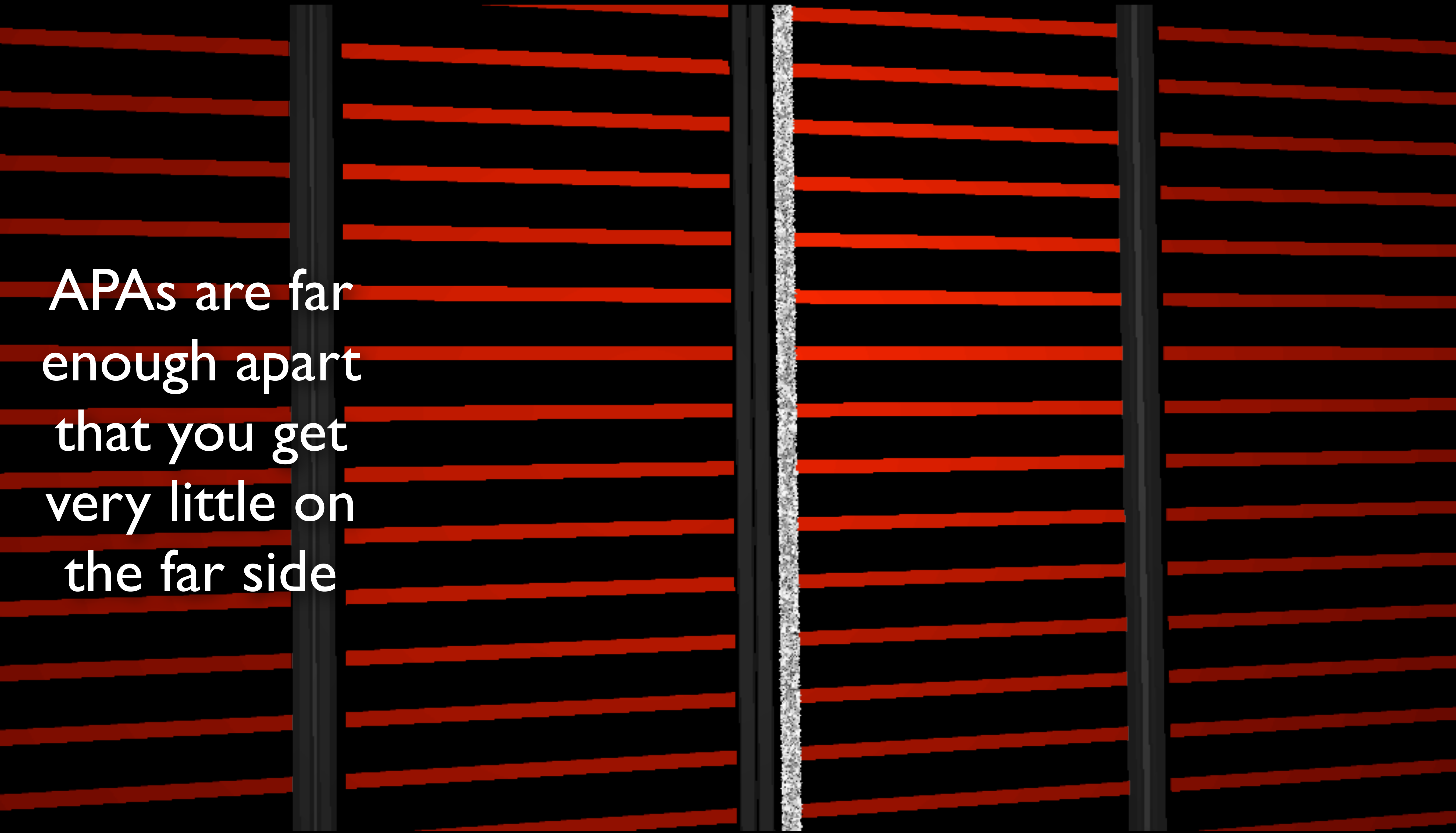
Expected Charge: Near Side



Red = Small # of PE

Blue = Large # of PE

Expected Charge: Far Side

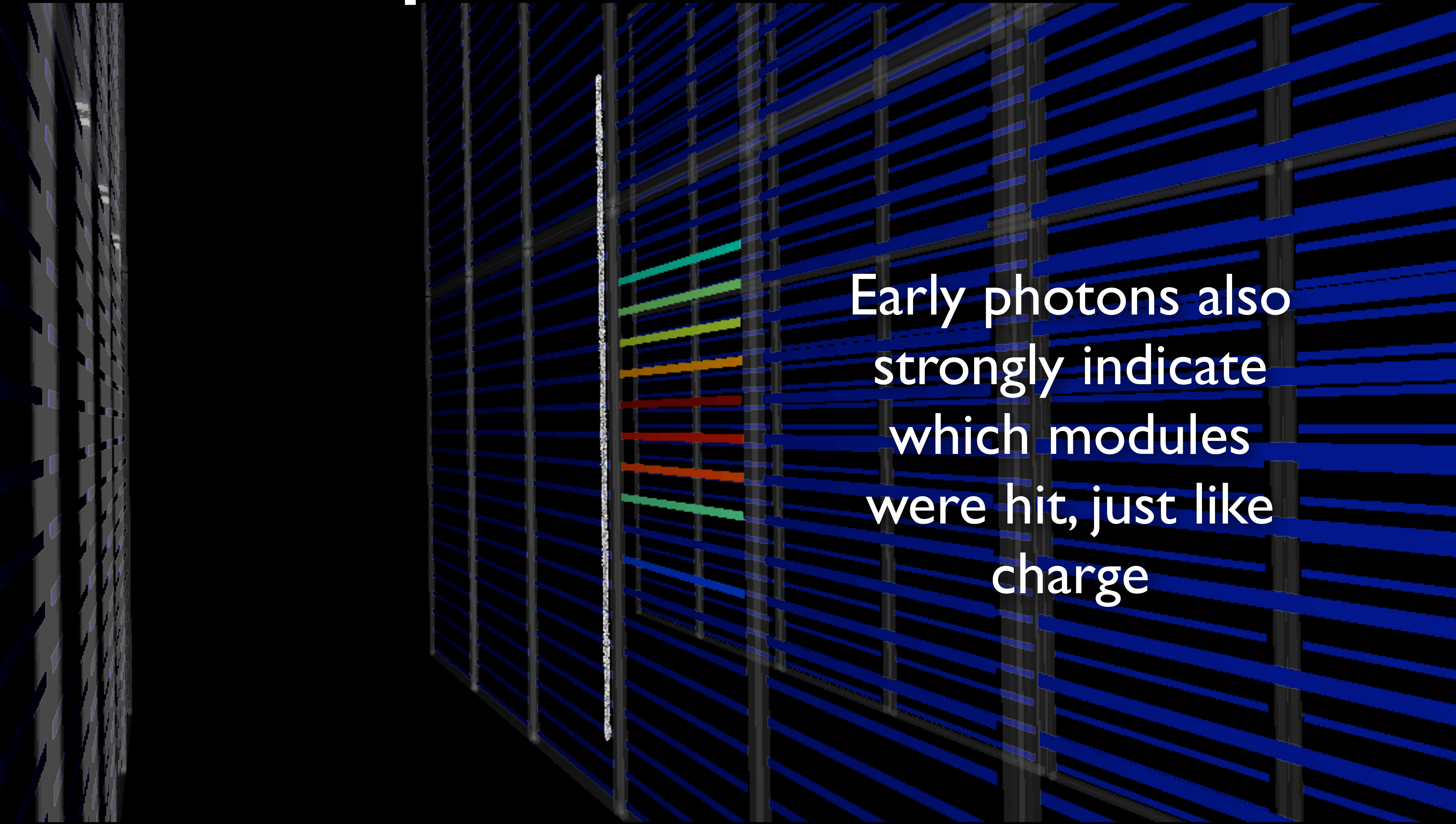


APAs are far enough apart that you get very little on the far side

Red = Small # of PE

Blue = Large # of PE

Expected Hit Time



Red = Early

Blue = >50 ns

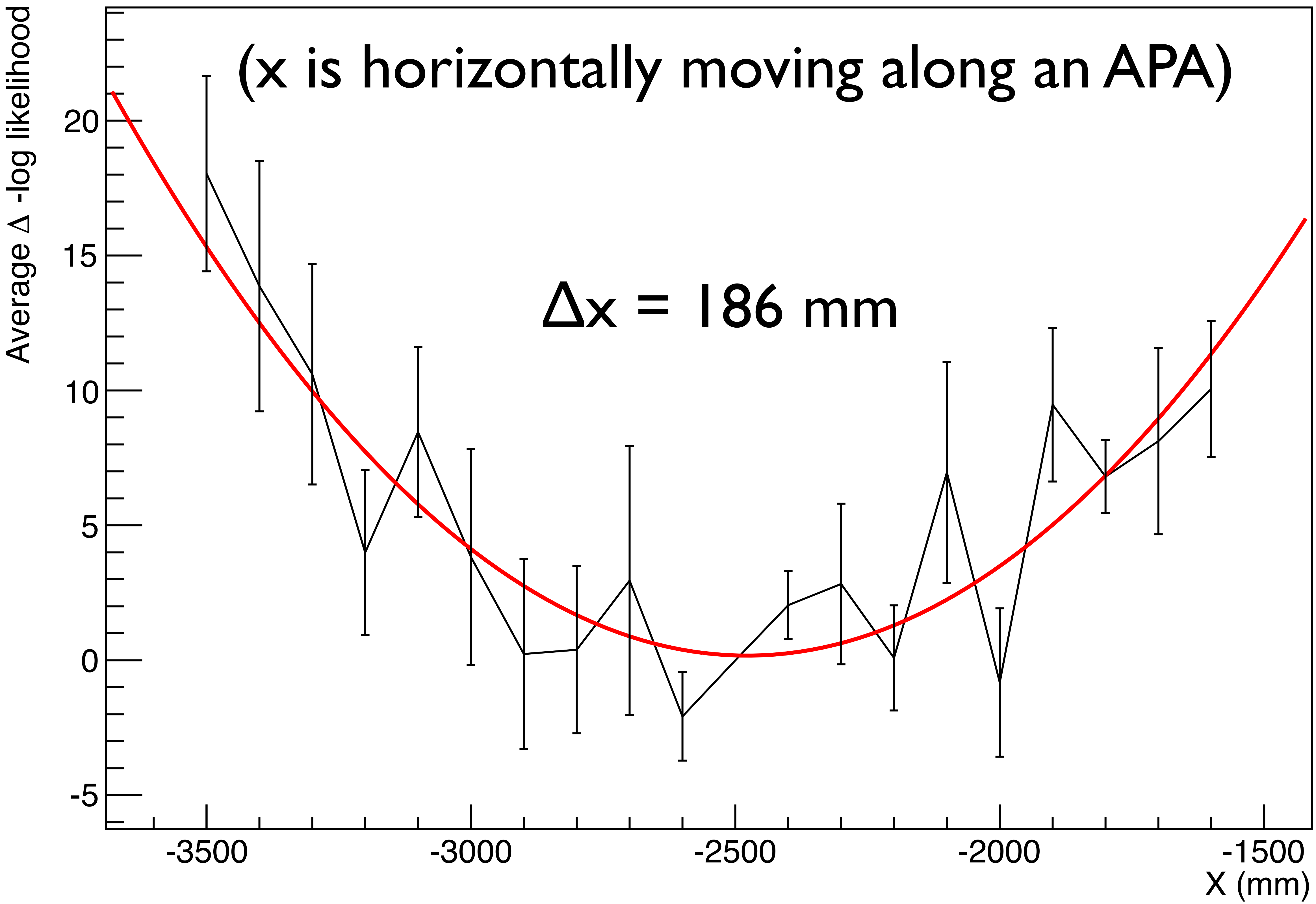
Likelihood Scans

- First attempt to reconstruct the position and direction of a simple track.
- This likelihood is using hit pattern *only*.
- Currently using the excruciatingly slow (in this detector) live Monte Carlo technique from Chroma.
- We will not do this for a real fitter (*each detected photon requires simulating 10^5 photons!*), but we will still use the Monte Carlo to generate lookup tables for the real fitter.

Test Case

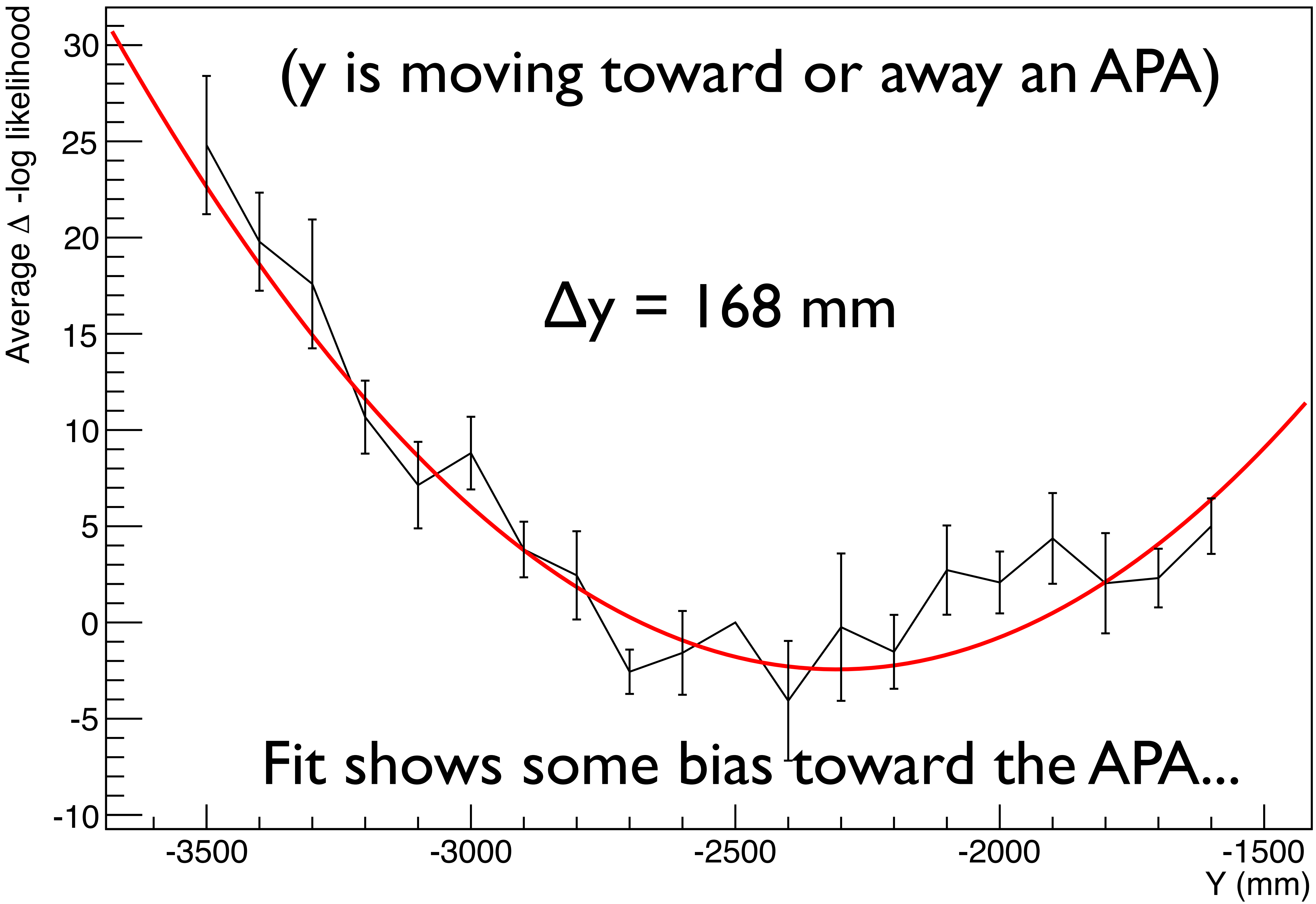
- All events are ~700 MeV straight tracks starting from (-2500 mm, -2500 mm, 0 mm), going down 4.7 meters.
- (This is actually a too long of a track for a 700 MeV muon, but I didn't discover I had the energy loss wrong until too late to redo everything.)
- Assuming we know the energy and length of the track already, *how well can we estimate the position of the starting point and the direction in a 1D scan*?
- Constrained 1D scans only give a *lower bound* on the final uncertainty that we can achieve in each parameter once we float all the free parameters.
- Each plot is the average of the likelihood scans of 9 events.

X Scan



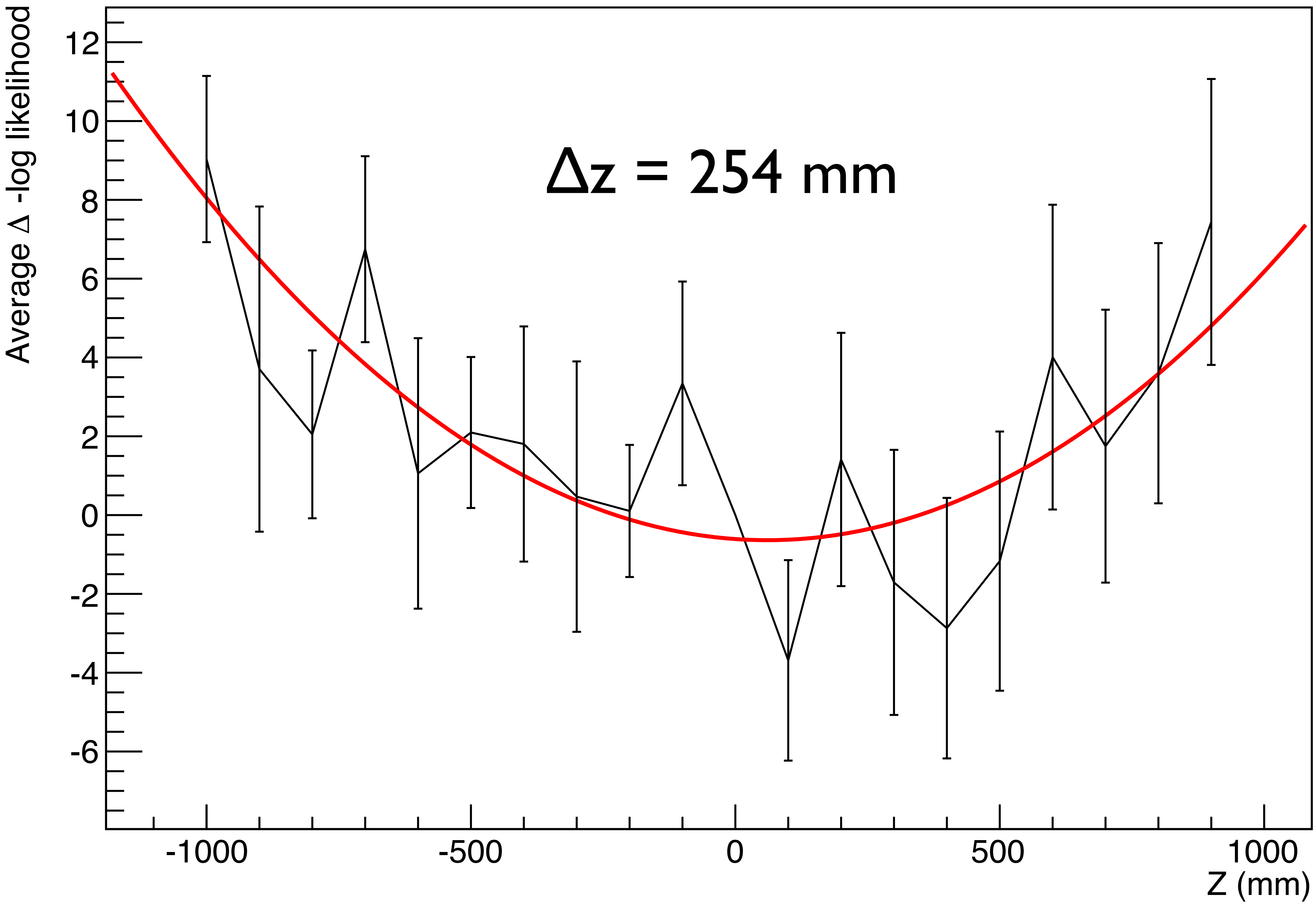
(x is horizontally moving along an APA)
Δx = 186 mm
Average Δ -log likelihood
20
15
10
5
0
-5
-3500
-3000
-2500
-2000
-1500
X (mm)

Y Scan

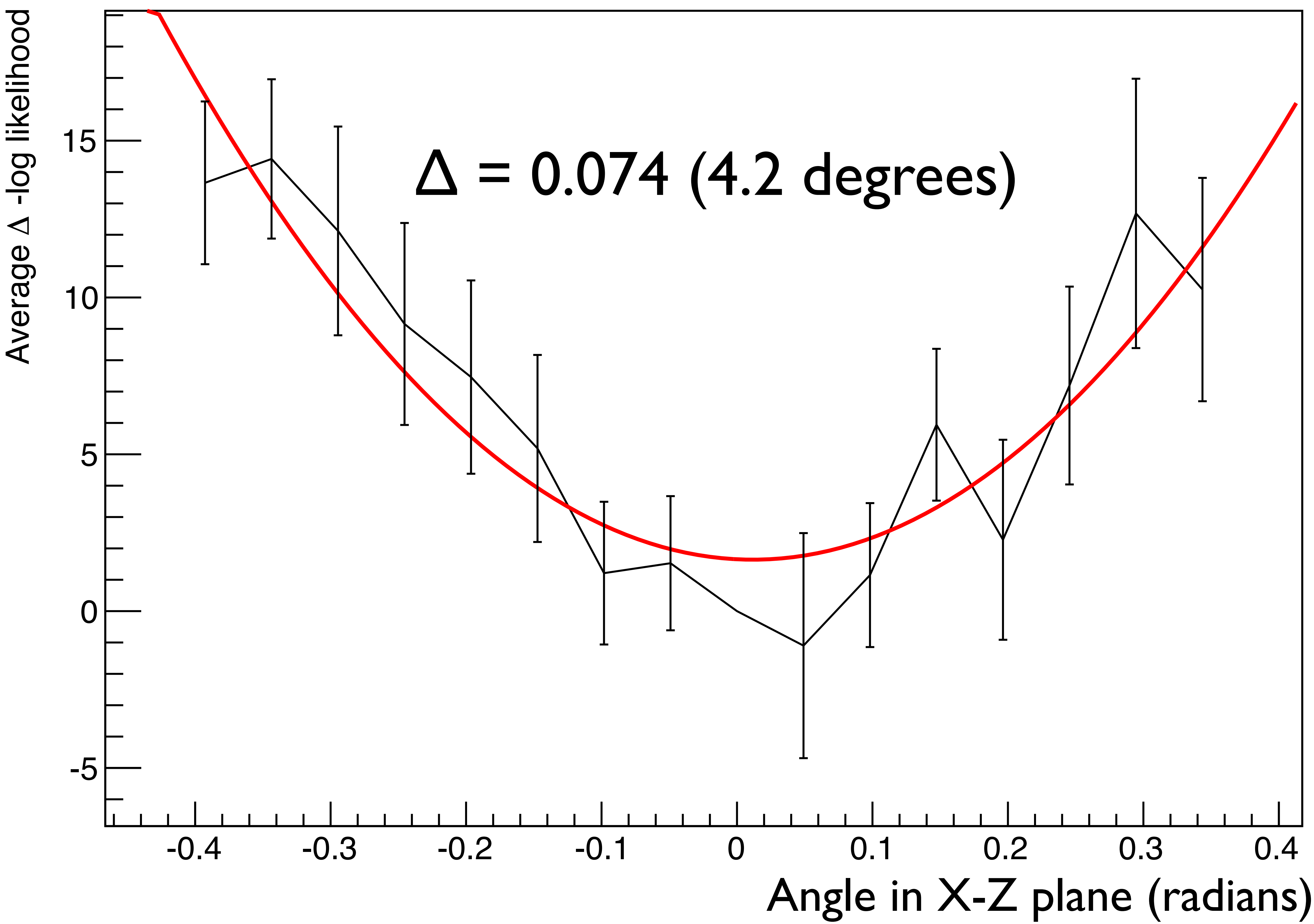


(y is moving toward or away an APA)
Δy = 168 mm
Fit shows some bias toward the APA...
Average Δ -log likelihood
Y (mm)
30
25
20
15
10
5
0
-5
-10
-3500
-3000
-2500
-2000
-1500

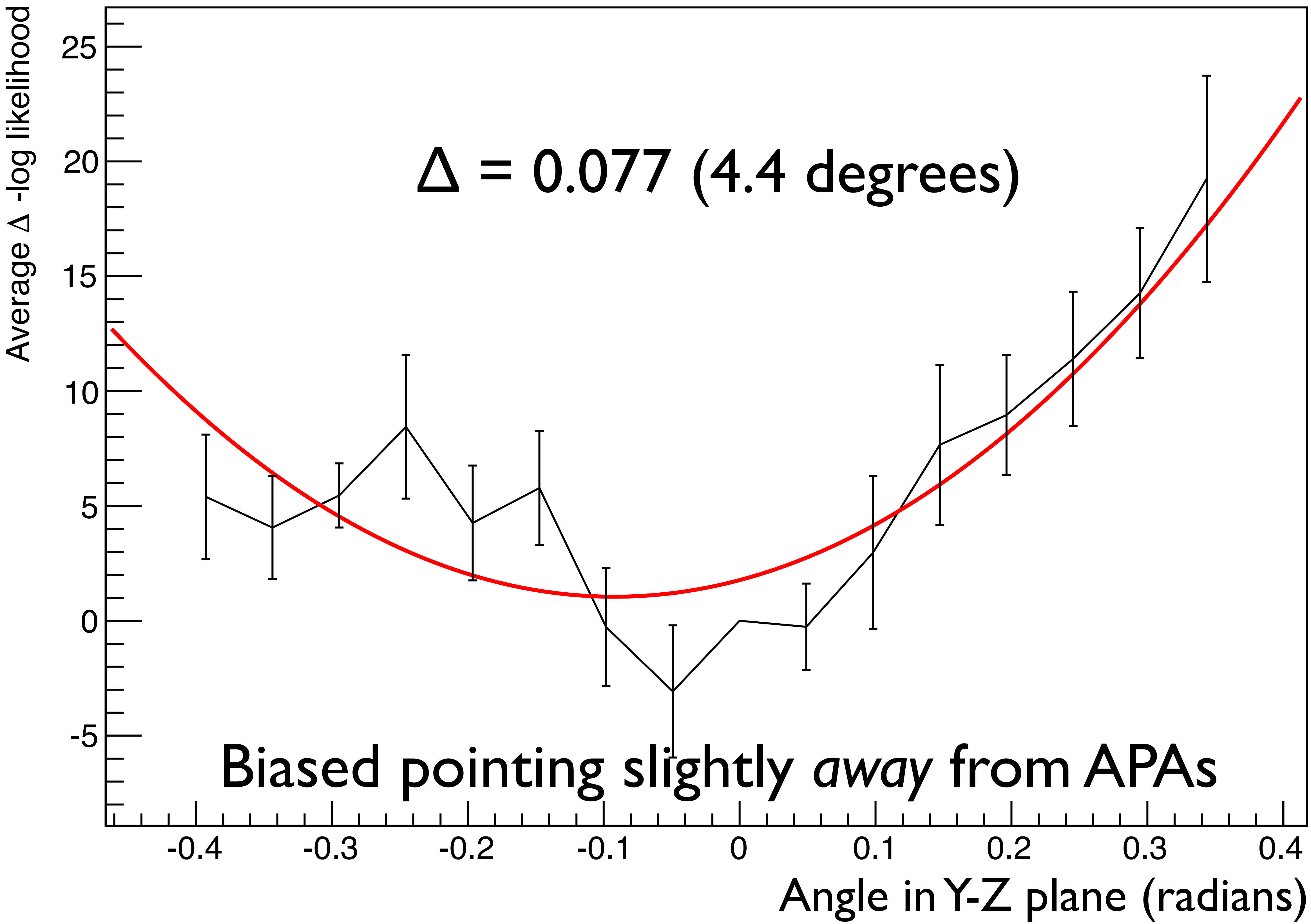
Z Scan


Δz = 254 mm
Average Δ -log likelihood
12
10
8
6
4
2
0
-2
-4
-6
-1000
-500
0
500
1000
Z (mm)

X-Z Angle Scan



Y-Z Angle Scan



What Does It Mean?

- Due to the geometry of the APAs, our information about each dimension is very different.
- Clearly the likelihood space is behaving oddly as the event moves you toward or away from the APAs.
- Indication that Rayleigh scattering and absorption are going to tend to pull events toward the APAs?
- Really need to see what happens when we let energy vary as at the same time as the other parameters. Likely to be highly covariant with the Y direction.
- Definitely want a faster likelihood function than pure Chroma.

Short / Medium Term

- Implement simple and fast time and position reconstruction algorithms.
- Time is relatively simple: Use the "early photons are on high charge channels" technique.
- Speeding up the a hit pattern/charge based likelihood for position:
  - Build a 4D lookup table for # of PE seen by each channel per MeV deposited at a point: [x, y, z, PMT ID #] (Only 3.5 MB for a 1 meter grid in the cryostat.)
  - Can create a likelihood function that interpolates this table along a track to figure out the expected # of PE for each PMT.
- Start running these algorithms on simple, synthetic tracks from Chroma. Characterize resolution as function of light yield.

Long Term

- Plug Chroma into LArSoft as a fast photon Monte Carlo option. (Coordinated with other alternative Monte Carlo options being discussed.)
- Use LArSoft as an event generator of realistic tracks and showers for PDS reconstruction.
- Run reconstruction on signal events piled up with cosmic rays and assess signal sacrifice vs. background leakage.
- Feed light yield requirements back to photon detection system working group to ensure physics goals are met.

Conclusions

- Near-surface operation escalates the PDS system from an enabler of non-beam physics to a critical background rejection tool.
- The TPC and PDS have orthogonal capabilities, but given the cosmic ray rate, events from each system *can only be associated if the PDS can perform rudimentary position reconstruction.*
- Position resolution in the PDS determines the level of signal sacrifice due to pileup, and sets the required light yield.
- Full optical simulations suggest that the light yield assumed in the CDR is achievable if we can maintain > *3 meter* absorption lengths in the liquid argon (or double the TPB coverage).
- In the short term, we can build a simple table-based reconstruction algorithm to study position resolution vs. light yield.
- Long term we can connect the fast simulation to LArSoft and look at realistic signal + background pileup.