Cosmic Ray Event Reconstruction in the Mu2e Experiment

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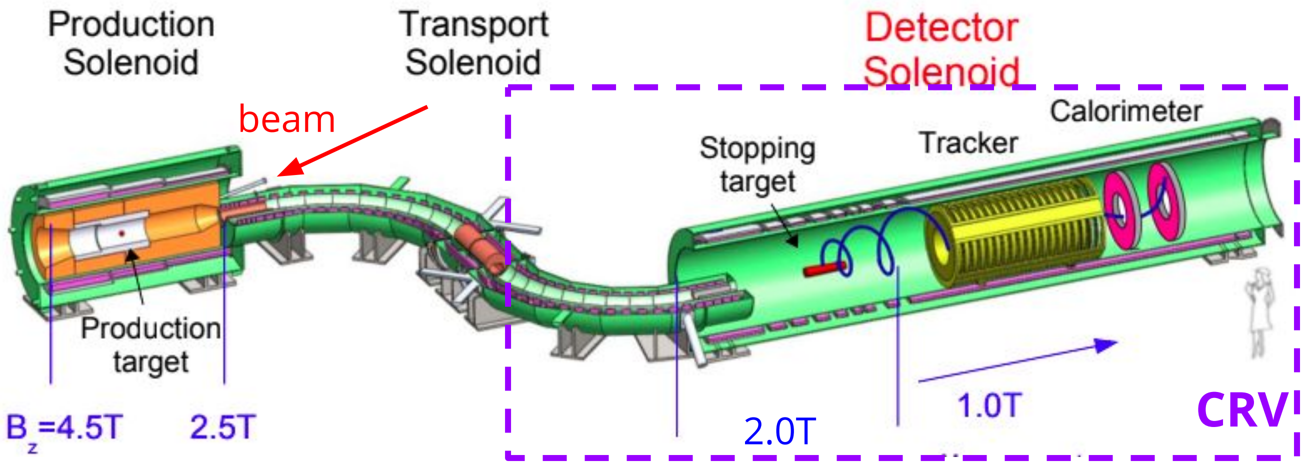
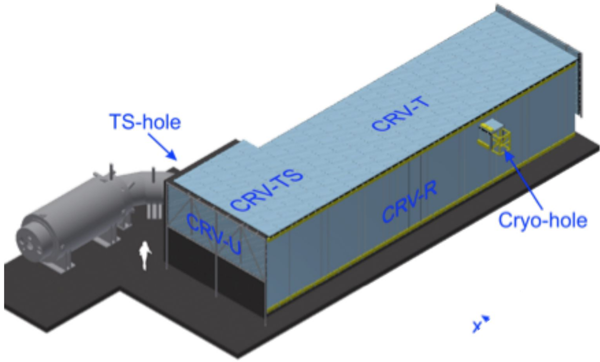
On behalf of the Mu2e Collaboration

Introduction to Mu2e Cosmic Reconstruction

- Reminder: Mu2e has an active detector called the **Cosmic Ray Veto** that surrounds the detector solenoid to monitor cosmics
- Mu2e's largest background source!





Mu2e Cosmic Rejection Requirements at a Glance

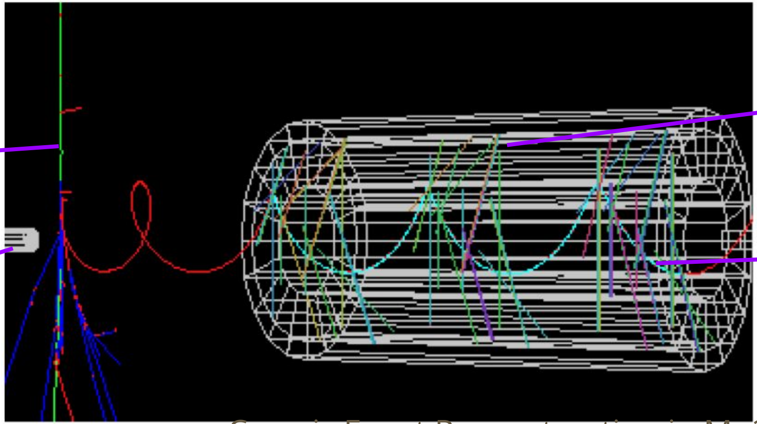
- SM prediction for μ→e conversion: $R_{\mu e} < 10^{-50}$
- Mu2e expected single event sensitivity: 8×10^{-17}
- Mu2e will run for several years, expecting roughly ~3×10^{20} protons on target throughout the duration of the experiment
- If cosmics were completely unmitigated, they would cause 1 background fake conversion electron signal **per day**
  - Mu2e: fewer than 1 background event after mitigation over ~1000 days of run time
  - Thus, we need the CRV to be > 99.99% efficient at rejecting cosmics!
  - **'CRV stub'**: cosmic signal is detected in adjacent counters in 3 out of 4 active layers

Cosmic Event Signatures

- Cosmic ray particles:
  1. enter the Mu2e detector solenoid from the environment, passing through the CRV
  2. interact and leave a secondary to travel or travel directly in a helical path through the tracker
  3. end in the calorimeter

….. so they ideally leave signatures in multiple Mu2e detectors that can be used to reject these events from being considered as signal candidates

Activated CRV bars would have been above the tracker in this case



Cosmic muon track

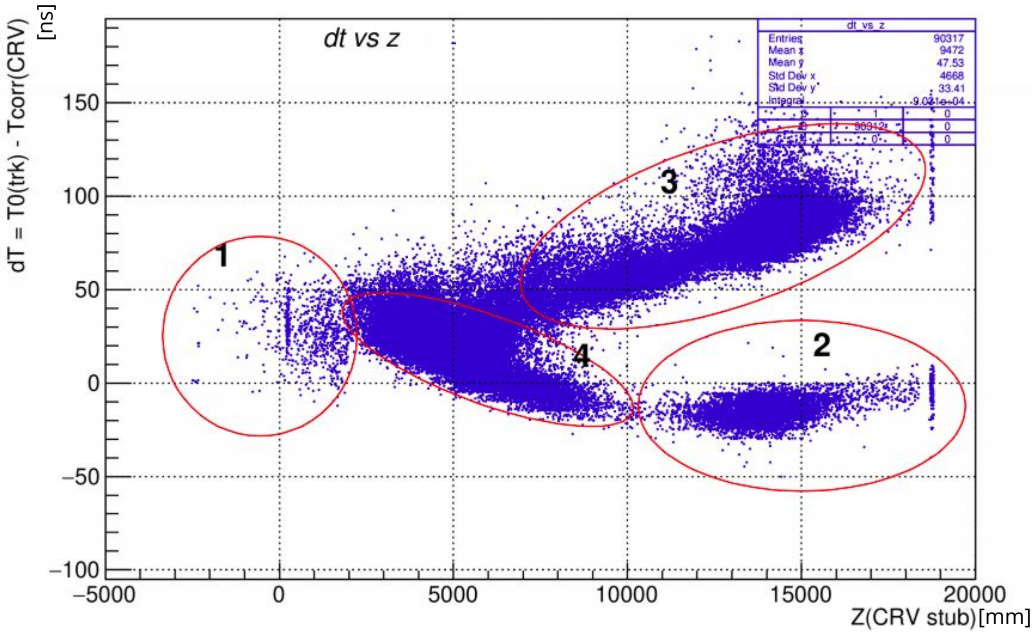
Stopping target

Straw tube tracker, with activated straws as colored lines

Electron track (blue)

dT vs. Z(CRV) … When and where are cosmics?

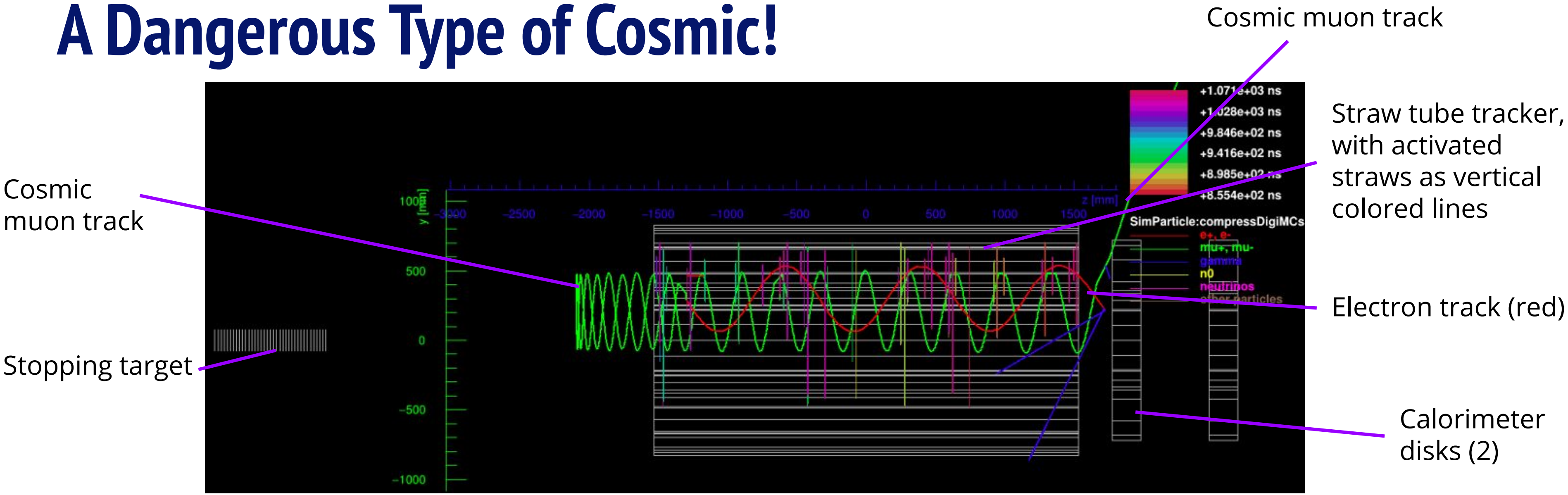
- The plot to the right tells us a great deal about cosmic reconstruction
- X axis: Z(CRV) stub
  - Position along the beam axis of CRV stub signal in CRV
- Y axis: dT = $T_{Z=0}$(track) - T_{start}(CRV)
  - Difference in time between track and CRV stub time
- This plot has an odd shape, where we can identify 4 regions:



1. (and 4.) Downstream cosmic muons with downstream tracks
2. Upstream cosmic muons with upstream tracks reconstructed as downstream tracks
3. Upstream cosmic muons with both upstream and downstream track components

Width in Y-direction… length of dead-time window needed for rejecting cosmics!

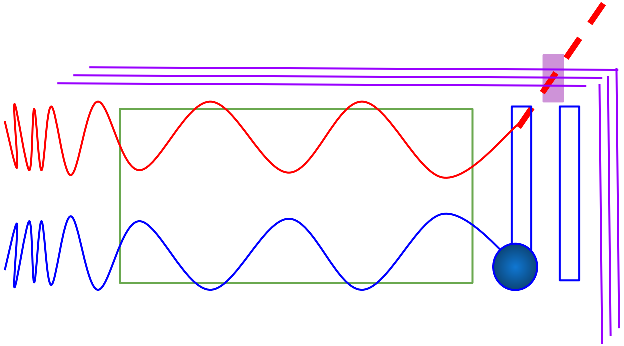
A Dangerous Type of Cosmic!



- Mu2e event displays are a powerful tool for visualizing events
- Here, a cosmic ray muon:
  1. enters on the calorimeter edge of the DS
  2. travels upstream towards the stopping target
  3. reflects at the magnetic bottle, and begins traveling back downstream toward the calorimeter
  4. Somewhere near the front of the tracker, the muon interacts and becomes an electron (red track)

What are ‘bouncing’ signatures?

- These ‘bouncing’ cosmic particles have a very distinct event topology since they travel through the tracker twice in most cases
- To identify these events, we look for:
  - The presence of a CRV stub ‘early’ in time
  - The presence of a time cluster, track, and helix ‘early’ in time
  - The presence of a time cluster, track, and helix ‘late’ in time
  - The presence of a calorimeter cluster ‘late’ in time



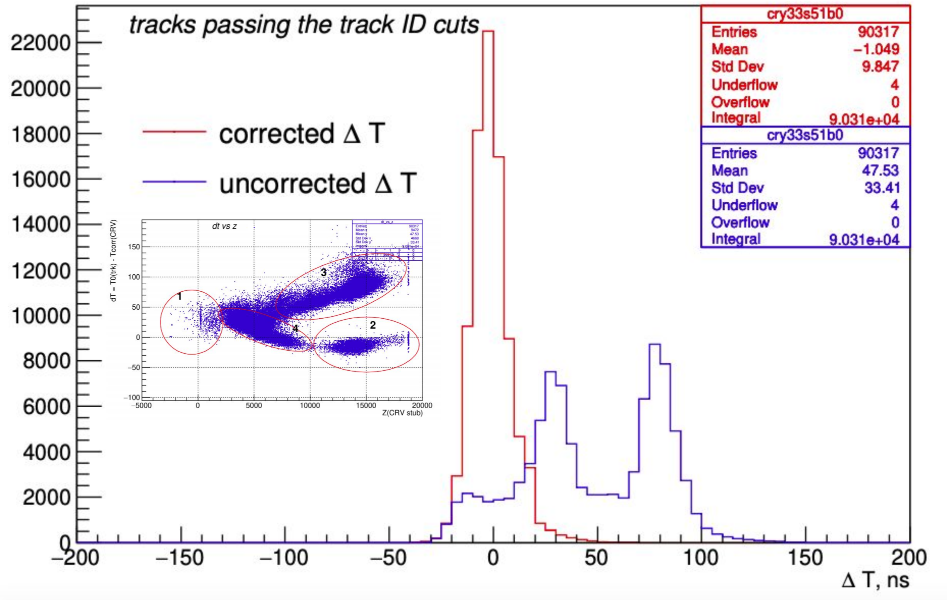
- These kind of events should have two distinct groups of timing information: some pieces early in time from the upstream component and some late in time from the downstream component, **~100ns separation**

Two Time Corrections to Close the dT Gap

- I recently implemented two timing corrections to the reconstructed cosmic stub time to bring the CRV time closer to the tracker time
- This allows bouncing events to fall well within the analysis veto window and surely be rejected with the application of that window
- Corrections:
  - Propagation of CRV signal in CRV scintillator bars
  - Time of flight of particle between CRV and tracker
- $T_{corrected} = T_{start}(CRV) - T_{propagation} - T_{TOF}$

Rejection of Bouncing Events and Final 1-D dT

- If we take a 1-D projection of the dT vs. Z plot and just view the dT axis, we can determine the length of the required dead-time window for rejecting cosmics
- With all rejections and timing corrections applied, the red distribution shows that we need 125ns window for appropriate cosmic rejection



Summary

- Cosmic rays are Mu2e's largest source of background, so we take great care to detect them with the active **Cosmic Ray Veto** detector and reject them using reconstruction tools and an **analysis veto window**
- We can calculate corrections to reconstructed cosmic ray signal timing to ensure that all cosmic events fall within the analysis veto window
- Using these corrections, Mu2e can set the **length of the analysis veto window to 125 ns** to provide adequate cosmic rejection power

Other Mu2e Talks at DPF!

Tuesday

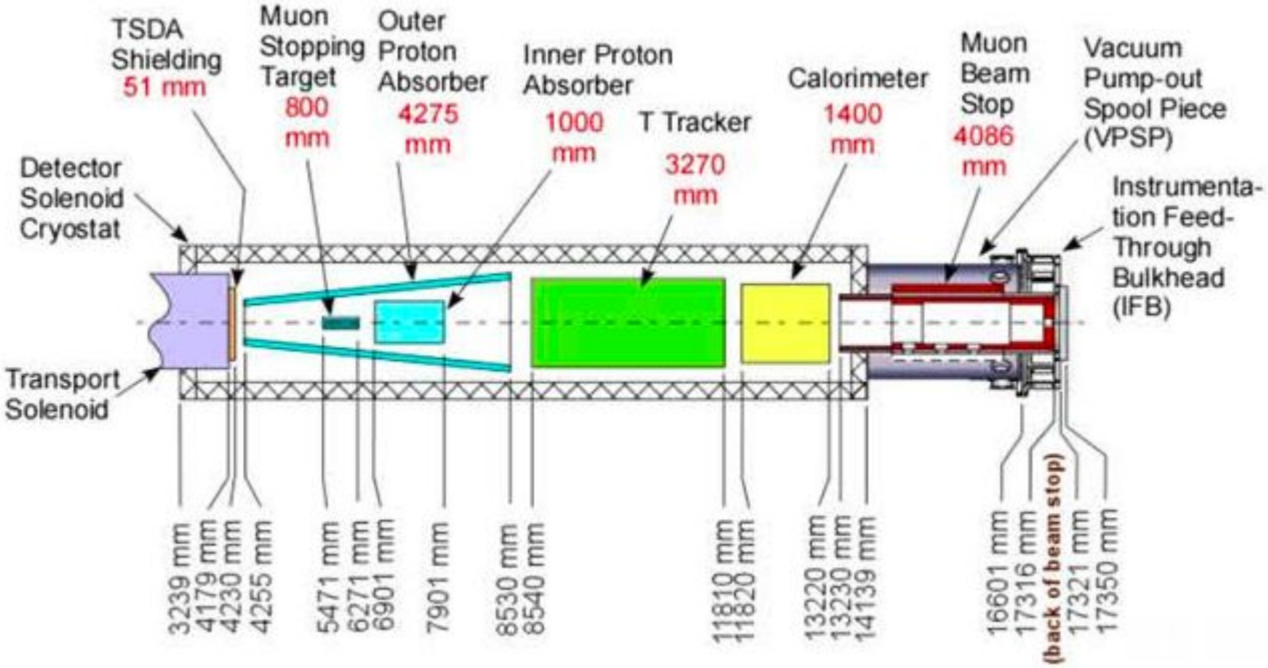
Helenka Casler: Pion Production Optimization for Mu2e, 4:15pm E
Vitaly Pronskikh: Pion Production Target Design Studies for Mu2e-II, 4:30pm E
Craig Group: Fabrication of a High Efficiency Cosmic Ray Veto for Mu2e, 4:15pm E
Sydney Roberts: Performance of Enhanced Wavelength-shifting Fibers for the Mu2e CRV, 4:30pm E
Craig Dukes: A Novel Scintillator for the Mu2e-II Experiment, 4:45pm E
Yongyi Wu: Mu2e Straw Tube Tracker Panel Performance Studies, 5:00pm E
Haichuan Cao: Design for Mu2e Branching Ratio Normalization Detectors, 5:15pm E

Wednesday

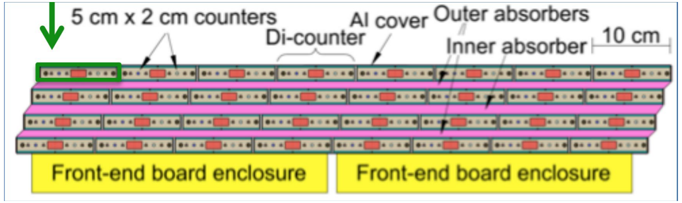
Kate Ciampa: The Mu2e Experiment Overview, 2:30pm E
Yuri Oksuzian: Simulation of the Cosmic Ray Background for Mu2e, 2:45pm E
Mackenzie Devilbiss: Cosmic Ray Event Reconstruction in Mu2e, 3:00pm E
Xiaobing Shi: Calibration of Mu2e Absolute Momentum Scale Using $\pi^+ \rightarrow e^+\nu$, 3:15pm E
Digvijay Roy Varier: Machine Learning for Background Hit Rejection in the Mu2e Tracker, 3:30pm E
Shihua Huang: A Familon Search Using the Mu2e Calibration Run, 3:45pm E
Jijun Chen: Normalization of the Mu2e Experiment, 4:15pm E
Nam Tran: Photons after Muon Capture on Aluminum and Titanium, 4:30pm E

Backup

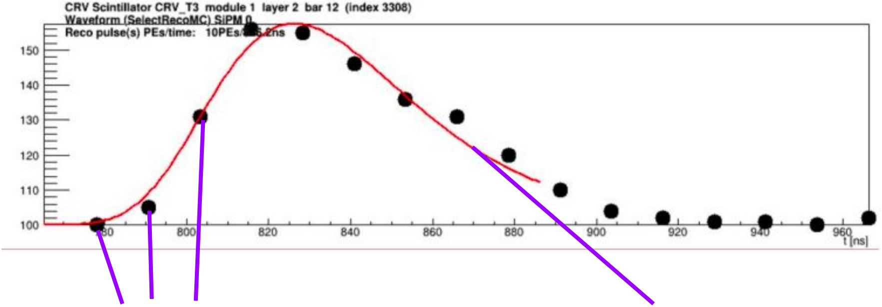
DS Elements (Mu2e-docDB 1383, figure 2)

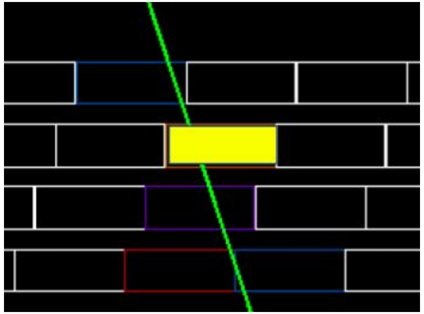


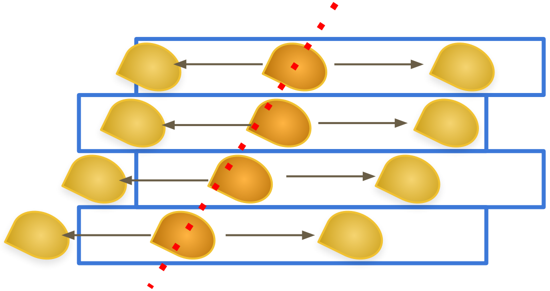
Cosmic Event Reconstruction Flow



10 PE – 826.2 ns







CRV Digis

- Digis are the raw light signals detected by the front end ADCs
- CRV ADC digitization period = 12.55ns
- We can plot these digis into waveforms in time, like above

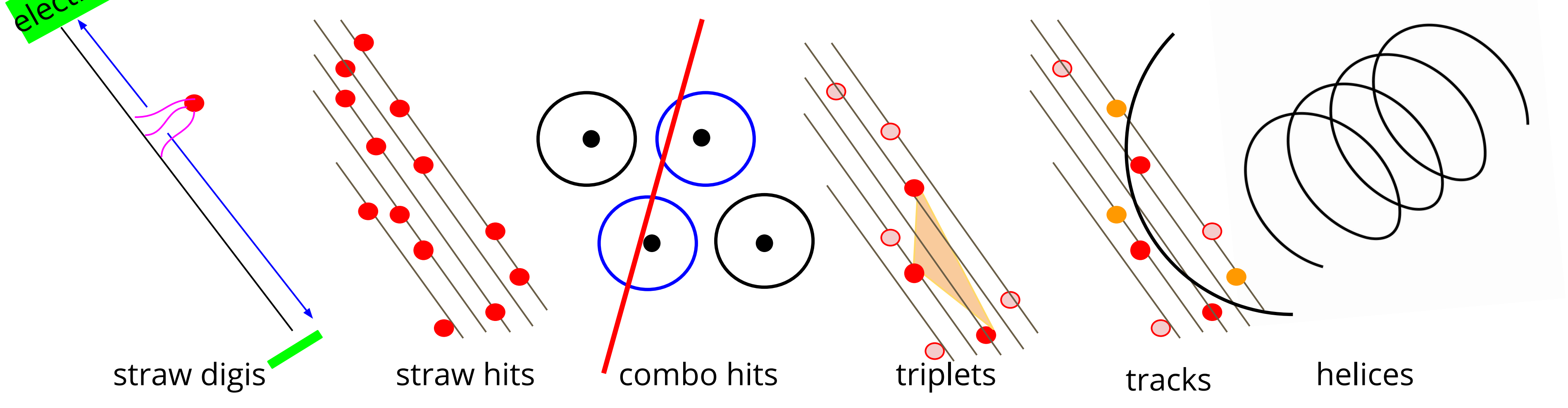
CRV Reco Pulses

- ADC digi waveforms are fit into CRV reco pulses
- Threshold of amp. for pulse
- These reco pulses have identifying information:
  - CRV bar and SiPM indices
  - Time (max and LE)
  - Fit amplitude and Chi^2

CRV Stubs

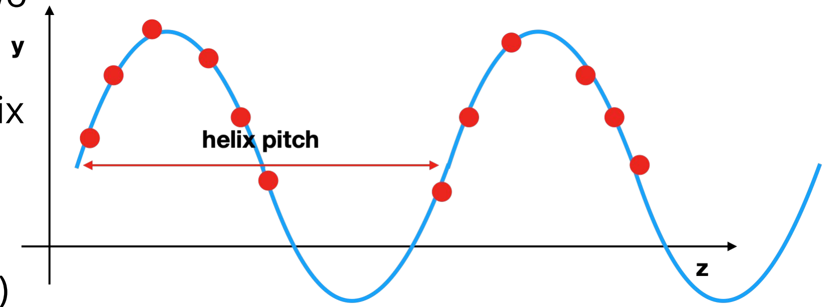
- A cluster of bars detect reco pulses when a cosmic passes through the CRV
- If bars in 3 of the 4 CRV layers are activated within 10ns of each other and are all adjacent, we reconstruct a ‘CRV stub’
- This is the true cosmic ray marker

Cosmic Event Reconstruction Flow

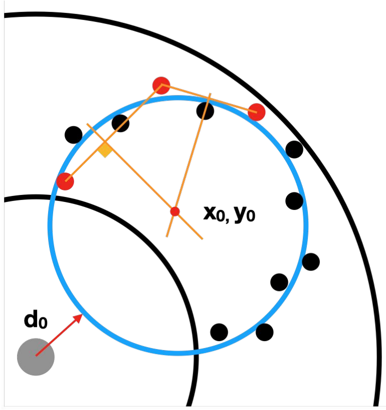


Pattern recognition occurs in two stages:

1. phi angle and z axis of helix
2. x, y cross section of helix



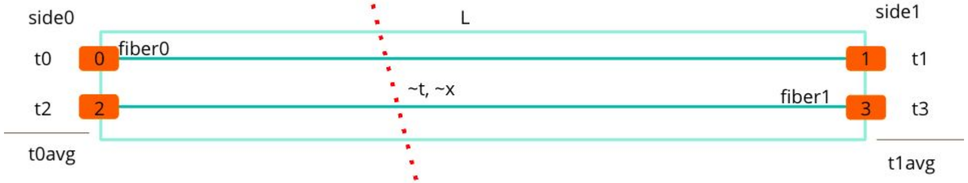
Two algorithms: TPR and CPR
(I detail TPR here by experience)



Time Corrections for Sensitivity Expectation Update

Propagation of Signal through CRV Bars

- Speed of light in scintillators is slowed by a function of the index of refraction



- Two-sided bars: solve system to right
- One-sided bars: just add LETime of each one-sided bar and take time average

$$t0_{avg} = t^* + x^* * v^{-1}$$
$$t1_{avg} = t^* + (L - x^*) * v^{-1}$$

$$t^* = \frac{1}{2}(t1_{avg} + t0_{avg} - L/v)$$
$$x^* = \frac{1}{2}(L - (t1_{avg} - t0_{avg}) * v)$$

Time of Flight between CRV and Tracker

- We can subtract off the time of flight of the particle traveling between the CRV and tracker to match the times

The right plot shows a profile of the upper leg of the dT vs. Z plot, with a linear fit. This gives is the slope, or Z traveled over time for TOF!