UCDAVIS

ANNIE reconstruction using LAPPDs

Jingbo Wang
Department of Physics, UC, Davis

annie

UCDAVIS
UNIVERSITY OF CALIFORNIA

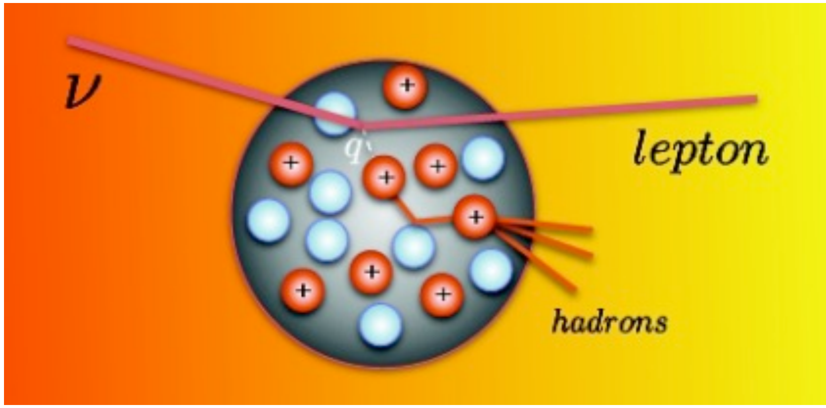
April 12, 2018, Theia workshop, UC Davis

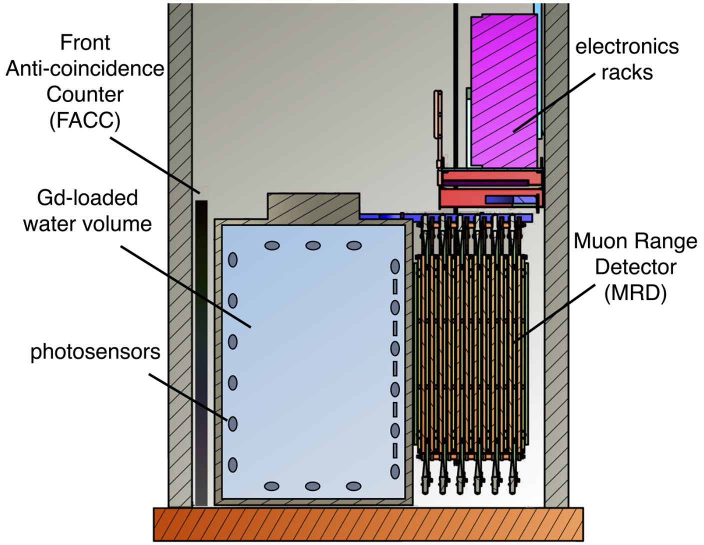
Outline

- ANNIE goals
- LAPPDs in ANNIE
- Phase II simulation
- Phase II reconstruction using LAPPDs
  - Two detector configurations (w/o 5 LAPPDs)
  - Vertex and track reconstruction
  - Energy reconstruction
  - Momentum transfer study
- Summary

ANNIE

- **ANNIE: A**ccelerator **N**eutrino **N**eutron **I**nteraction **E**xperiment
- **26-ton Gd-loaded water Cherenkov detector** placed downstream of the Booster Neutrino Beam (BNB) at Fermilab (flux peaked at 700 MeV, relevant to atmospheric neutrinos)
- **Two main goals:**
  - Measure the **neutron multiplicity** from neutrino-nucleus interactions in water
  - Demonstrate the use of **fast-timing LAPPDs** for event reconstruction
- Finished taking background data (Phase I), soon to be taking physics data (Phase II)

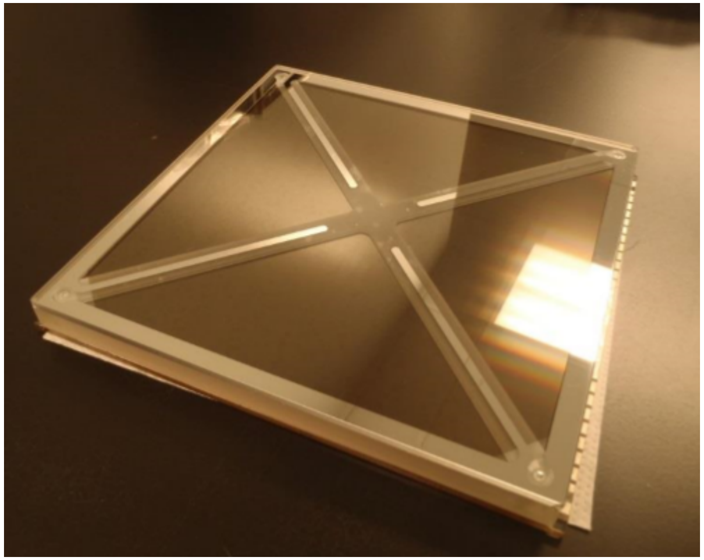




LAPPDs in ANNIE

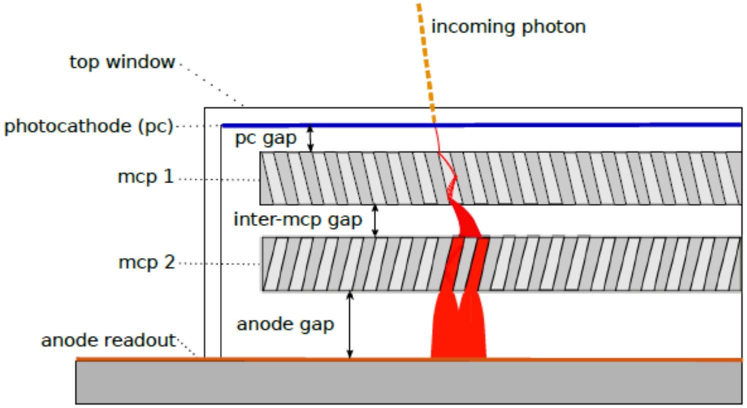
ANNIE is the first application of LAPPDs in HEP experiment

- LAPPDs have been commercialized by Incom. (ANNIE already has a few.)
- LAPPDs are tested at ISU (Matt's talk tomorrow)



Large Area Picosecond Photodetectors (LAPPDs) are MCP-based photodetectors

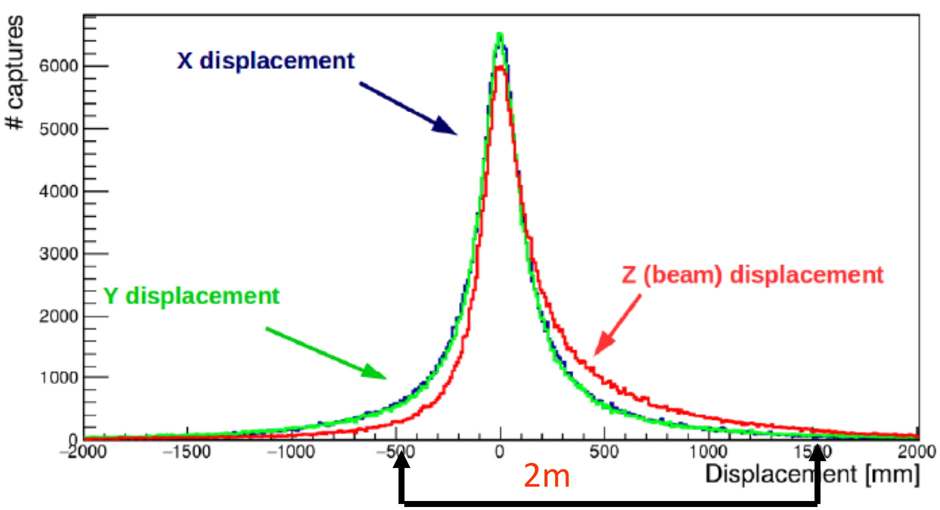
- Flat, Large-area: 20 cm × 20 cm
- Picosecond timing: <100 ps for SPE
- Quantum efficiency: >20%
- Position resolution: sub-mm
- Lower Cost per Unit Area
- Atomic Layer Deposited MCP

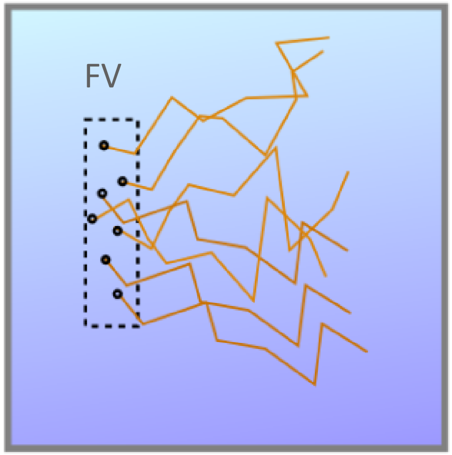


Why does ANNIE need LAPPDs?

LAPPDs are key detectors for the ANNIE physics measurement

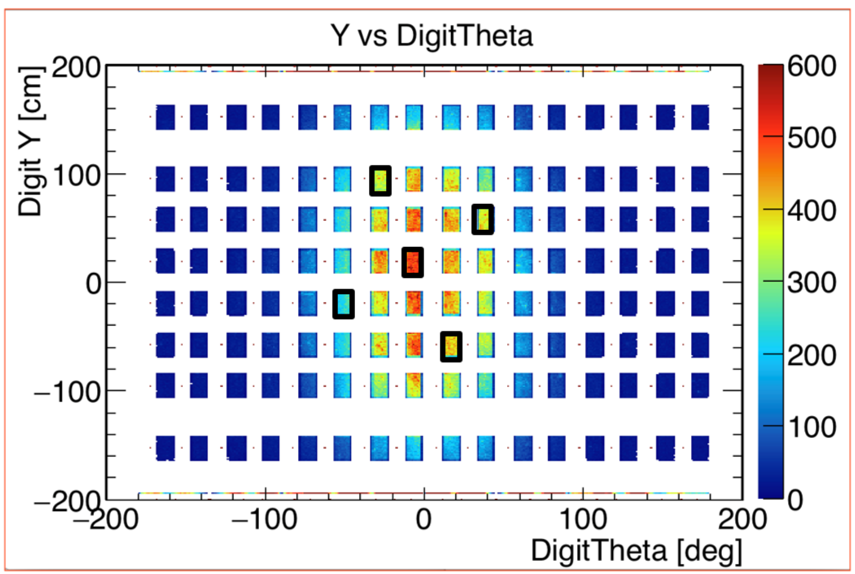
- Simulation shows that neutrons created in ANNIE can drift up to 2 meters.
  - In the direction transverse to beam, drift is symmetric
  - In the direction along the beam, drift is mostly forward with respect to the interaction point.
- In order to get a clean sample of neutrons, the analysis must be restricted to a small ~1 ton fiducial volume far from the walls of the tank to capture the neutrons
- To properly identify events in FV, vertex resolution of ~ 10 cm is needed
  - **This is beyond the capability of traditional PMTs!**
  - **LAPPDs use fast-timing to localize the vertices, which is essential for ANNIE analysis**

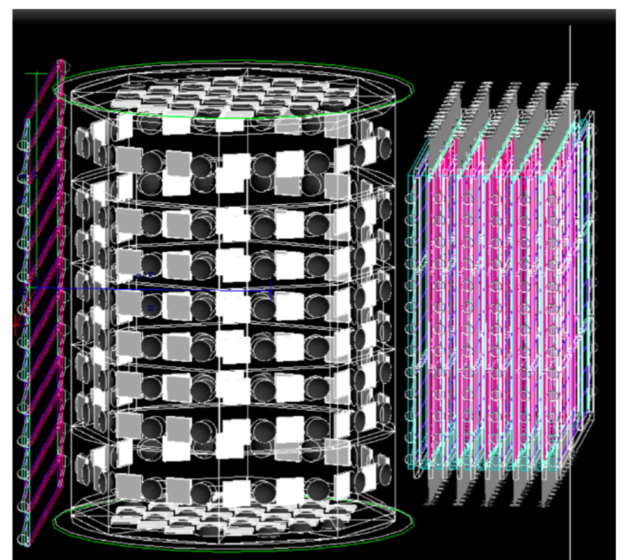




Simulation to study the LAPPD capability

- ANNIE Phase II proposal: WCSim simulation
- Investigated event reconstruction capability using two different photodetector configurations:
  - **PMT-only configuration** including 128 8-inch traditional PMTs (about 20% coverage of the inner surface of the tank).
  - **LAPPD+PMT Combined configuration** including 128 8-inch conventional PMTs and additional **5 LAPPDs** on the downstream wall of the tank.

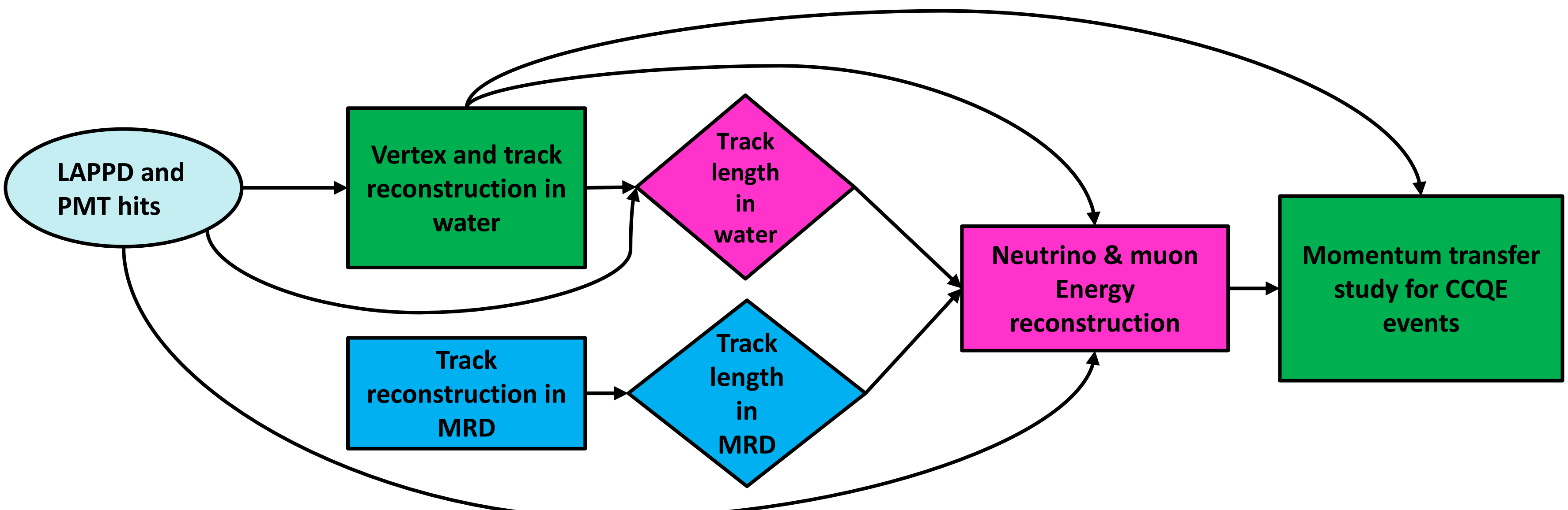




Phase II Reconstruction Strategy

We are developing reconstruction techniques

1) Vertex and track are reconstructed using maximum likelihood fit. The challenge is to handle two different types of photodetectors in the same framework
2) Track length in MRD is reconstructed by fitting the hit position in all MRD layers
3) Track length in water is reconstructed using **Deep Learning Neural Network** machine learning algorithm
4) Neutrino and muon energies are reconstructed using **Boosted Decision Tree** machine learning algorithm
5) Q^2 is calculated assuming CCQE events

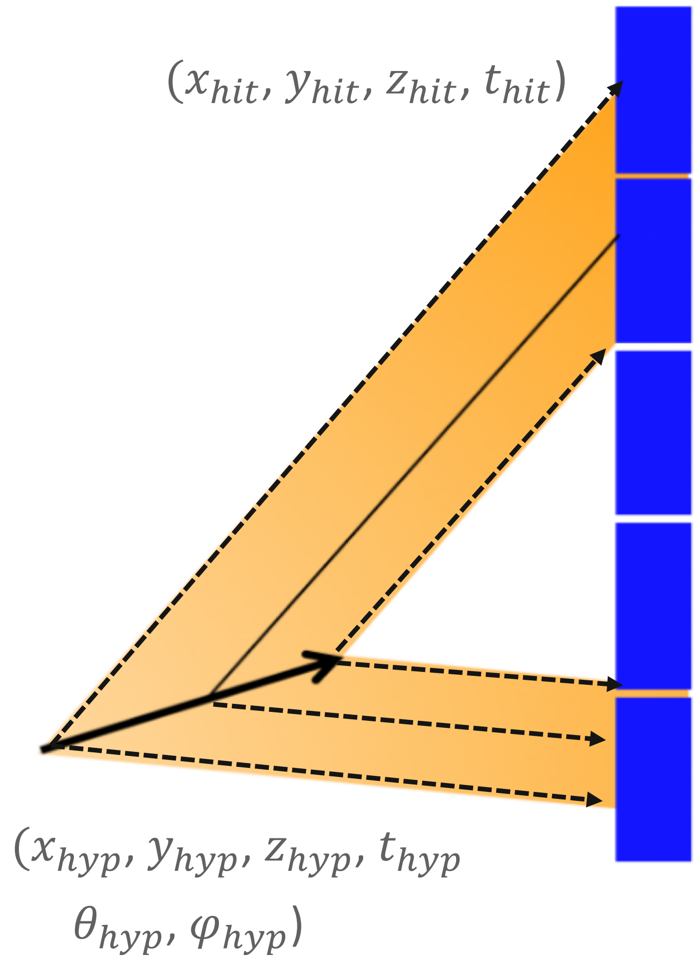


Vertex and track reconstruction

- A single muon track can be specified by **6 kinematic variables:**
  - A vertex position **(X, Y, Z)**
  - A vertex time **(T)**
  - A track direction **(θ, ϕ)**
- Measurement from photodetectors
  - Hit position and time
  - Hit charge

Basic strategy:

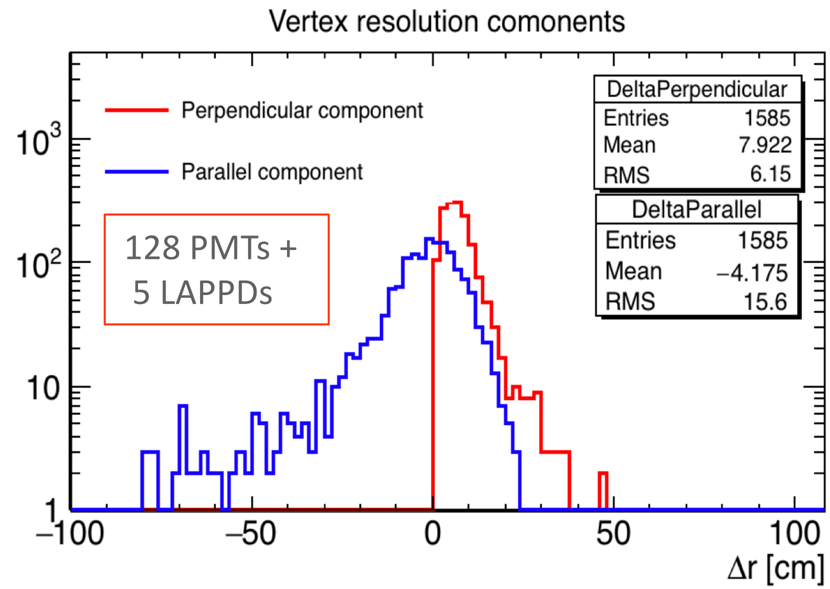
1) A timing-based likelihood (**FOM**$_{\text{time}}$) function is used to fit the vertex position and time
2) A charge-based likelihood function (**FOM**$_{\text{cone}}$) is used to fit the cone-edge then the track direction
3) Six parameters are varied and the combined likelihood functions is used to fit the track

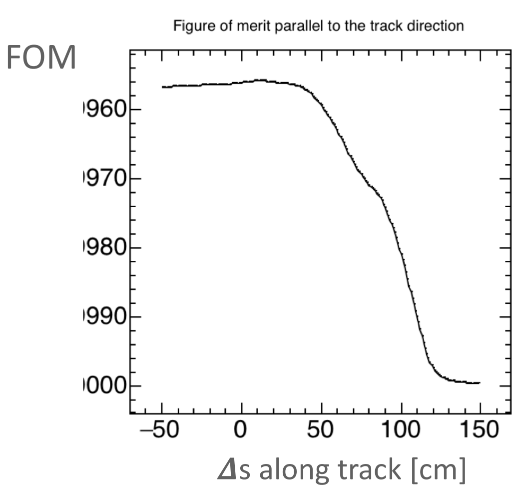


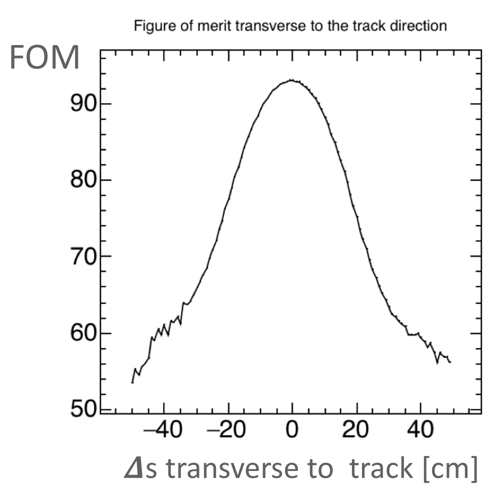
Constraints in two directions

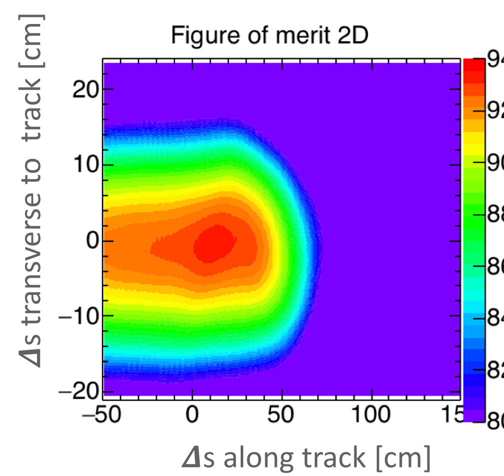
- With timing, constraint transverse to the muon direction is much stronger
- Along the muon direction there is an ambiguity issue of T_0
- Timing places a weak constraint on T_0. Scattered light helps a little bit, but it's not enough
- Cone-edge offers better constraint to T_0, which depends on the photodetector coverage and position resolution
- In ANNIE, the strong transverse constraint is dominated by 5 downstream LAPPDs, and the longitudinal constraint is strengthened by the PMT coverage

Distance between truth and reconstruction in two directions





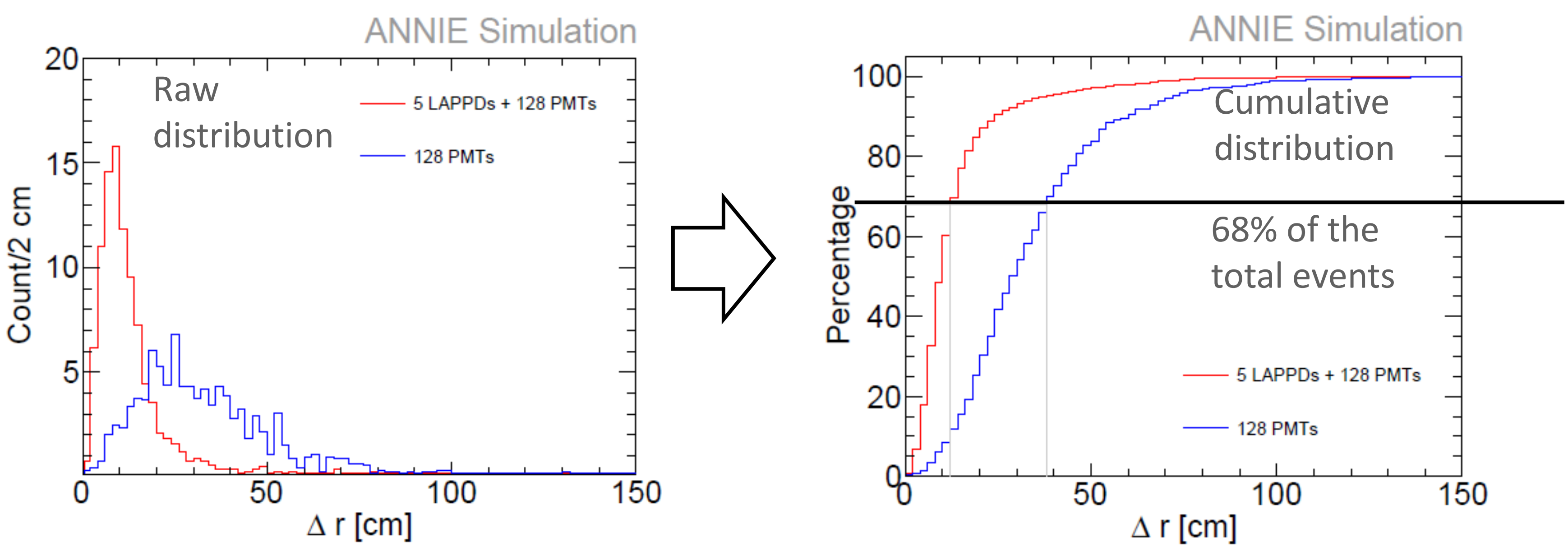




Vertex Displacement: Δr

Idealized reconstruction: take the true vertex and track direction as the seed for the track fit

- Muons that are produced within a fiducial volume and stop inside the MRD are selected
- LAPPDs show significant improvement on the vertex resolution
- 128 PMT-only (20% coverage) : 38 cm
- 5 LAPPDs + 128 PMTs : 12 cm (more than a factor of 3!)

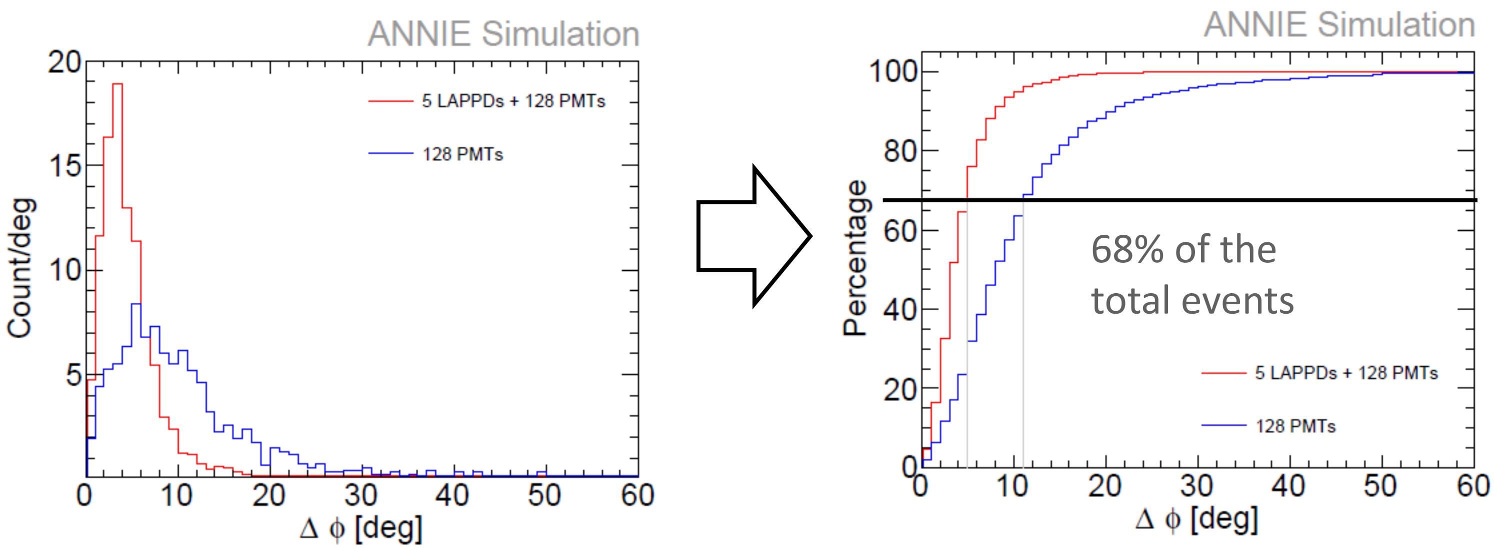


Distance between the true and the reconstructed vertices

Track Angular Displacement: Δφ

Idealized reconstruction: take the true vertex and track direction as the seed for the track fit

- 128 PMT-only (20% coverage) : 10 degree track angle resolution
- 5 LAPPDs + 128 PMTs: 5 degree track angle resolution (a factor of two improvement!)

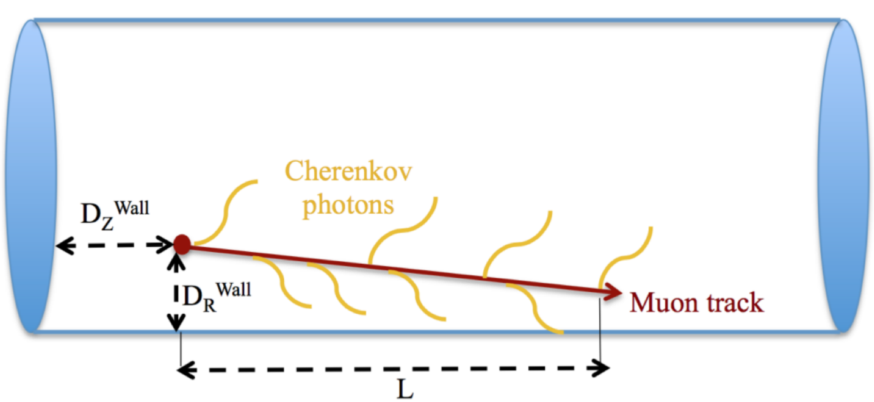


Angle between the true and the reconstructed muon tracks

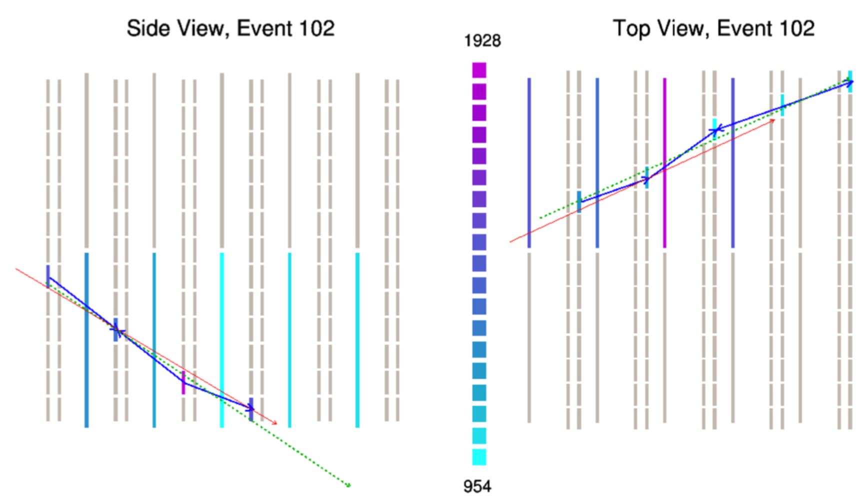
Track length reconstruction

- Muon energy is measured as the sum of energy deposit in water and MRD
- Track length in the water tank is calculated using a **Deep Learning Neural Network** (from Tensorflow package).
- Tracks in MRD are reconstructed in two 2D views and then matched into a 3D view
- MRD reconstruction is done in a separate framework. For the present studies, the track length is calculated as the distance between the true entry and stop points of the muon (neglect scattering)

Track in water



Track in MRD

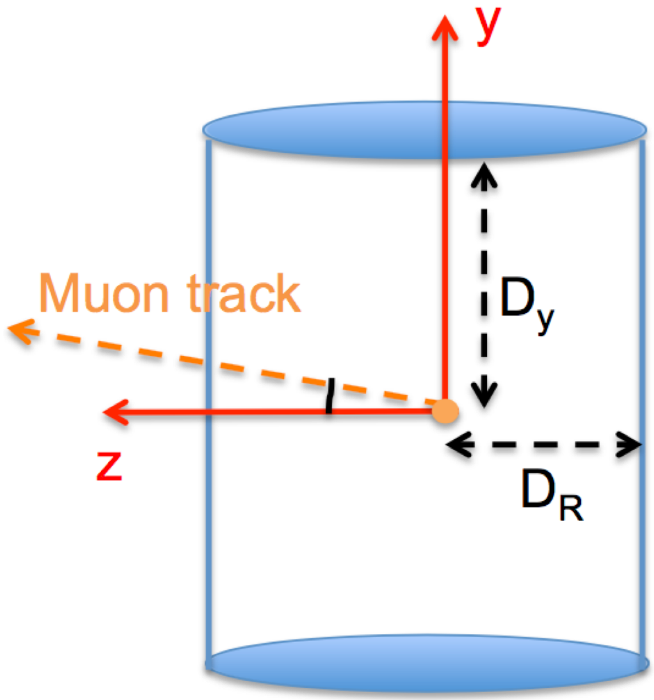


Energy reconstruction

- **Boosted Decision Trees (BDT)** machine learning algorithm was used
- Select CCQE events with E_ν< 2GeV
- Select events with muon stopped within the MRD
- The algorithm is trained with multiple input parameters

Input Variables:

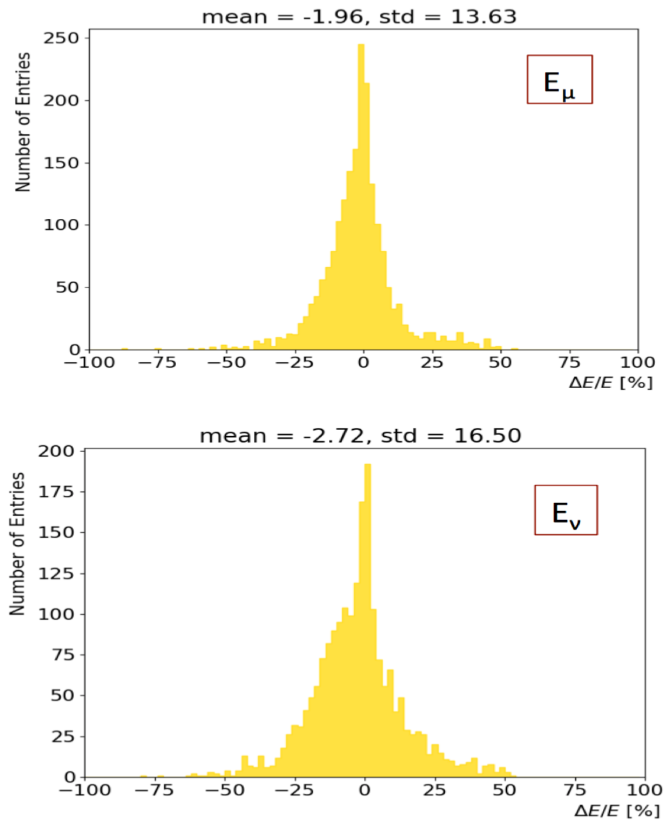
- Track length in water and MRD
- Angle difference between the reconstructed track direction and the beam direction
- The total number of hits in PMTs and LAPPDs
- The reconstructed vertex coordinates
- The distances of the reconstructed vertex from the detector walls (D_R, D_y)

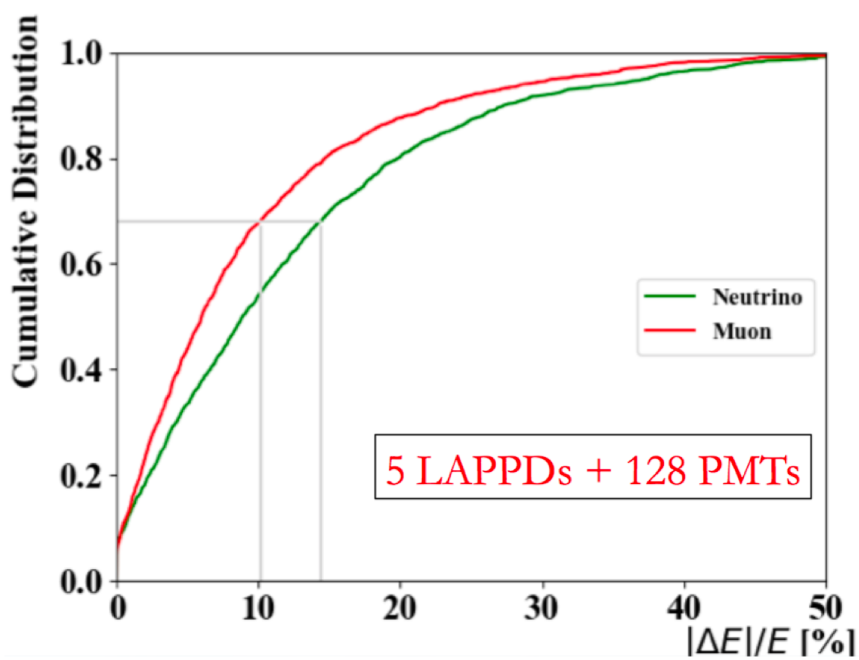


E. Drakopoulou , arXiv:1710.05668v3

Energy Reconstruction

- Figure of merit: $\Delta E/E = 100 * (E_{true} – E_{reco}) / E_{true}$
- The muon (neutrino) energy resolution achieved at the 68th percentile of all reconstructed events from the sample is 10% (14%).

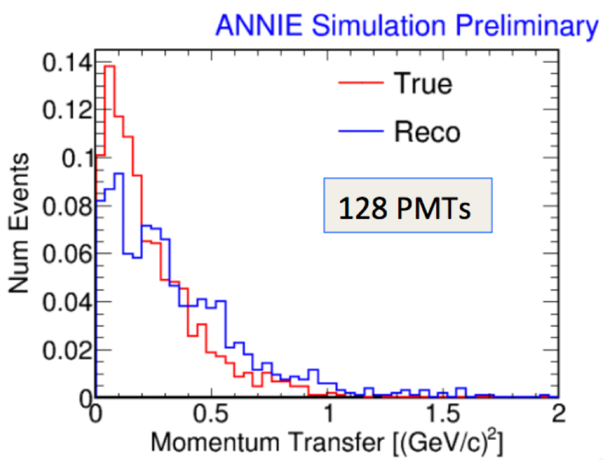


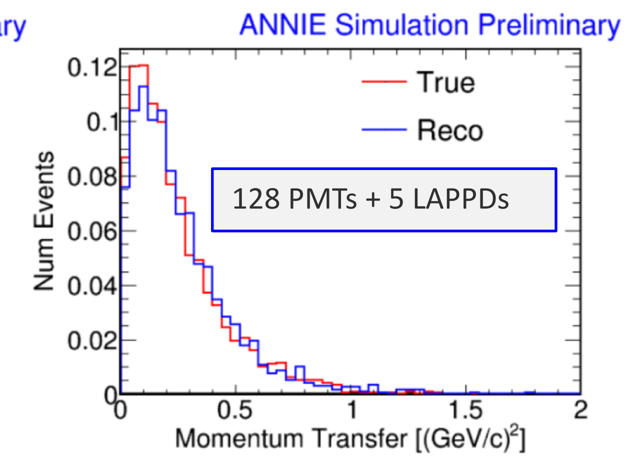


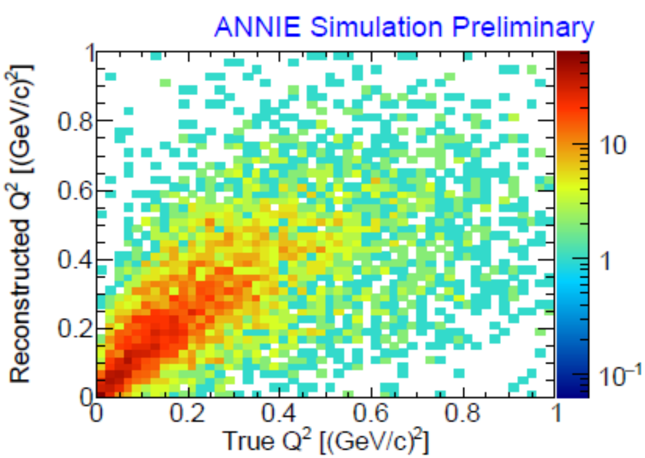
arXiv:1803.10624

Momentum transfer reconstruction

- Assuming CCQE interaction, the reconstructed muon and neutrino energies, together with the muon angle are used to calculate the momentum transferred.
- Stopped muon events are selected for which the muon energy is measurable as the sum of energy deposited in the water tank and the MRD.



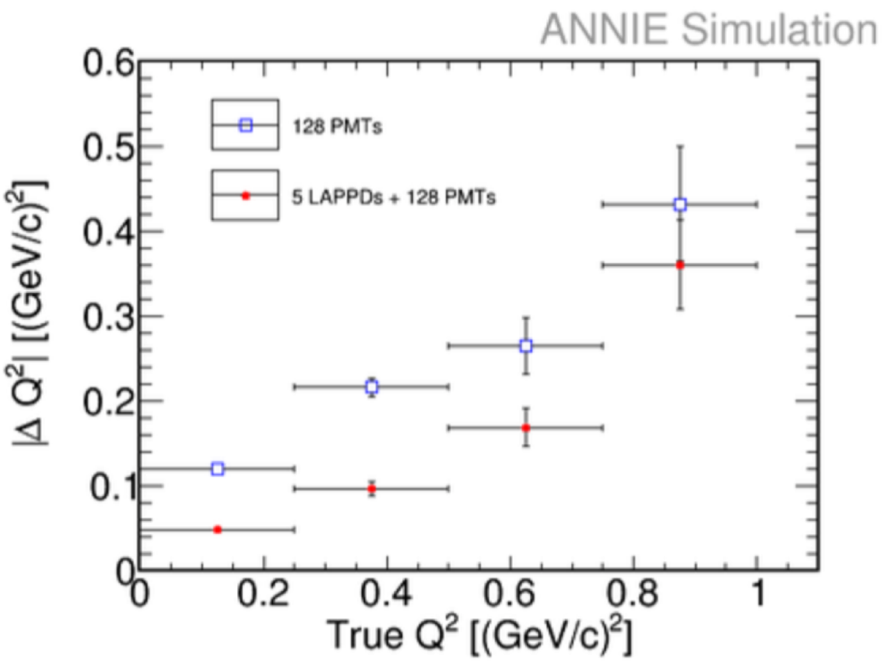




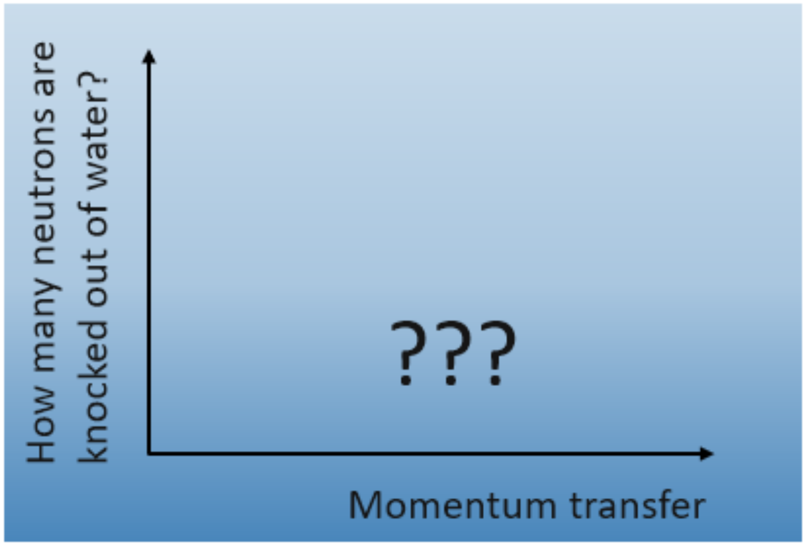
Marcus O'Flaherty (University of Sheffield)

Momentum transfer reconstruction

- $\Delta Q^2 = Q^2_{reco} - Q^2_{true}$, reconstructed by the ANNIE detector with 128 PMTs only and 5 LAPPDs + 128 PMTs
- The 1-sigma Q^2 resolution is extracted from the ΔQ^2 distribution for 4 bins in true Q^2.
- The addition of 5 LAPPDs improves the Q^2 resolution.



ANNIE delivery



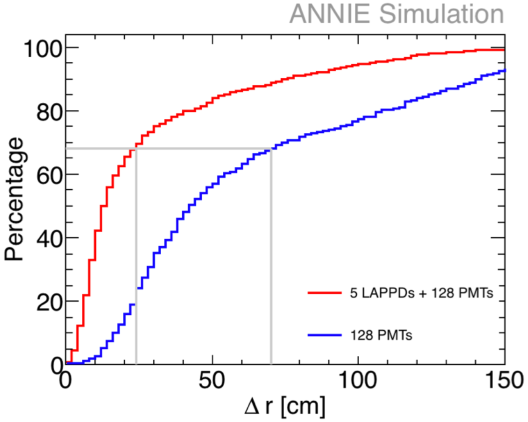
ANNIE Proposal: arXiv:1707.08222 [physics.ins-det]

Work ongoing

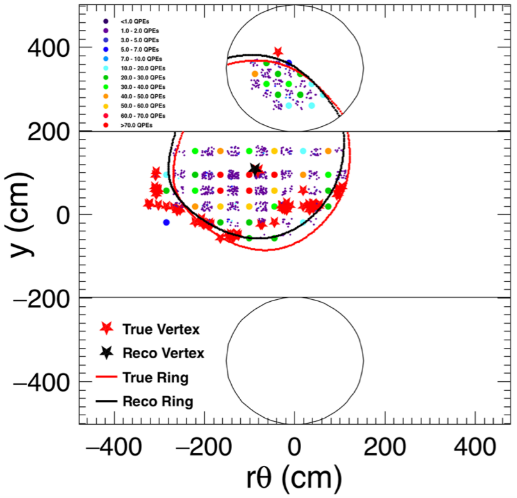
- Improve algorithms to do a more realistic reconstruction
  - Seed finding
  - Maximum likelihood function
- Investigate Hough transform for ring counting
  - Doesn’t work with ANNIE Cherenkov disk
  - Need edge detection
- Extend single-track fitter to double-track fitter
- Develop a likelihood fitter for Particle identification

More information in backup slides

Realistic reconstruction



Hough transform with edge detection



Summary

- In Phase I, ANNIE demonstrated neutron background is low enough.
- The key technological component of Phase II, LAPPDs, are now being produced by Incom Inc. ANNIE will deploy 5 LAPPDs for Phase II physics measurement.
- Simulation and Reconstruction tools for ANNIE Phase II are in place and show good performance.
  - Vertex & track reconstruction with PMT + LAPPD configuration
  - Machine learning tools are being developed for energy reconstruction
  - Q^2 improves with additional 5 LAPPDs
- ANNIE Phase II data taking is foreseen in late 2018.

Thanks for your attention!
Qestions?

Backup

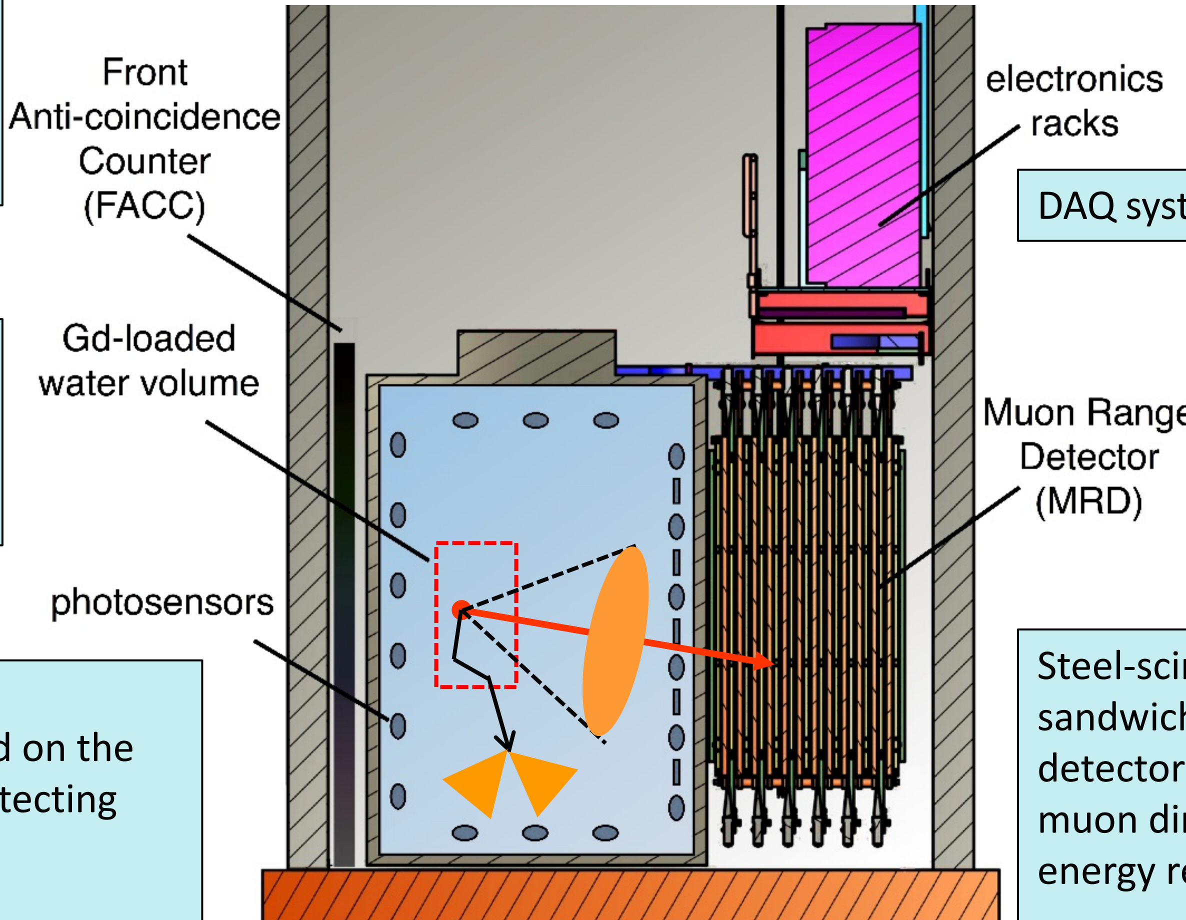
ANNIE detector

Scintillator paddles to **veto muons** not originating from the tank

3 m x 4 m tank filled with 26-ton Gd-loaded water

Inside the tank:
>100 PMTs installed on the inner surface for detecting neutron capture

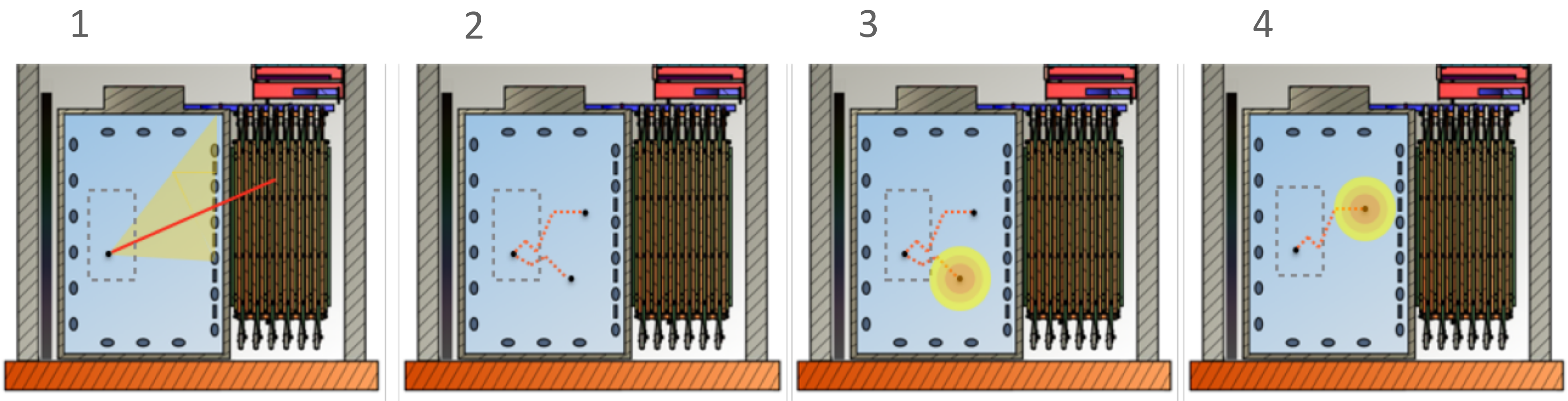
LAPPDs with < 100 ps time resolution for improved track reconstruction of muons.



DAQ system

Steel-scintillator sandwich detector capable of muon direction and energy reconstruction

How does ANNIE work?



- 1 – **Charge Current neutrino interaction** in the fiducial volume
- 1 – Neutrino vertex and muon direction reconstructed using **LAPPDs**
- 1 - Muon momentum reconstructed by the MRD
- 2 - Final state neutrons are getting thermalized in the water volume
- 3 - Neutron capture on Gd emitting 8 MeV gammas
- 4 - Gamma rays are detected by PMTs

Vertex and track reconstruction

Step1: “Simple vertex” fit

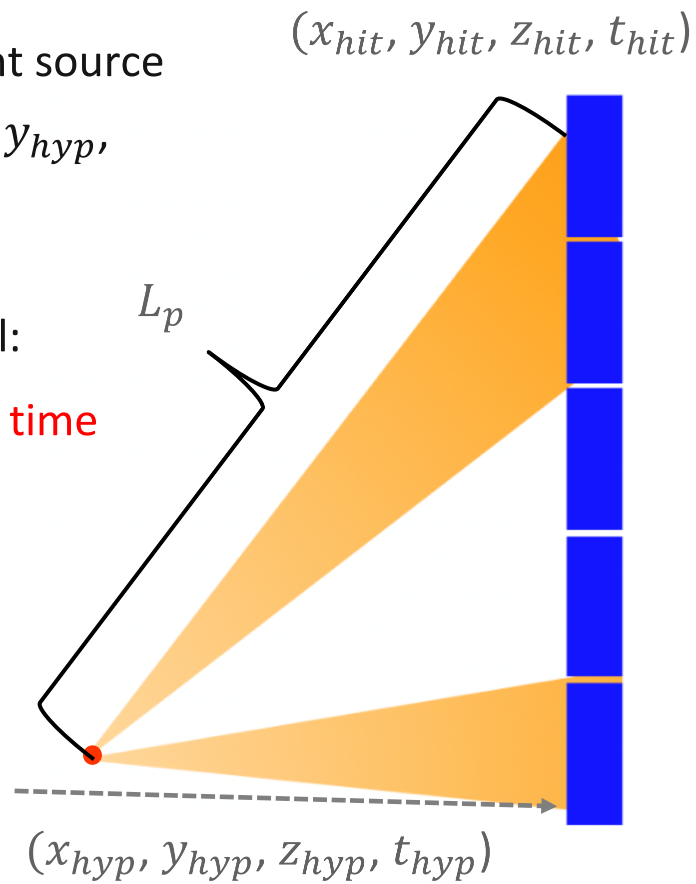
four parameter fit: (x, y, z, t)

- Conceptualize Cherenkov light as coming from a point source
- Assume a hypothesized point-source location ($x_{hyp}, y_{hyp}, z_{hyp}, t_{hyp}$)
- For each photon hit, calculate the point time residual:

$$\Delta t = t_{hit} - \frac{L_p}{c/n}$$

Photon travel time

- **For all the hits, calculate the timing-based Figure-of-Merit (timing likelihood)**
- **Adjust four parameters** to maximize time FOM. FOM takes the maximum value when the width of the time residual distribution is minimized

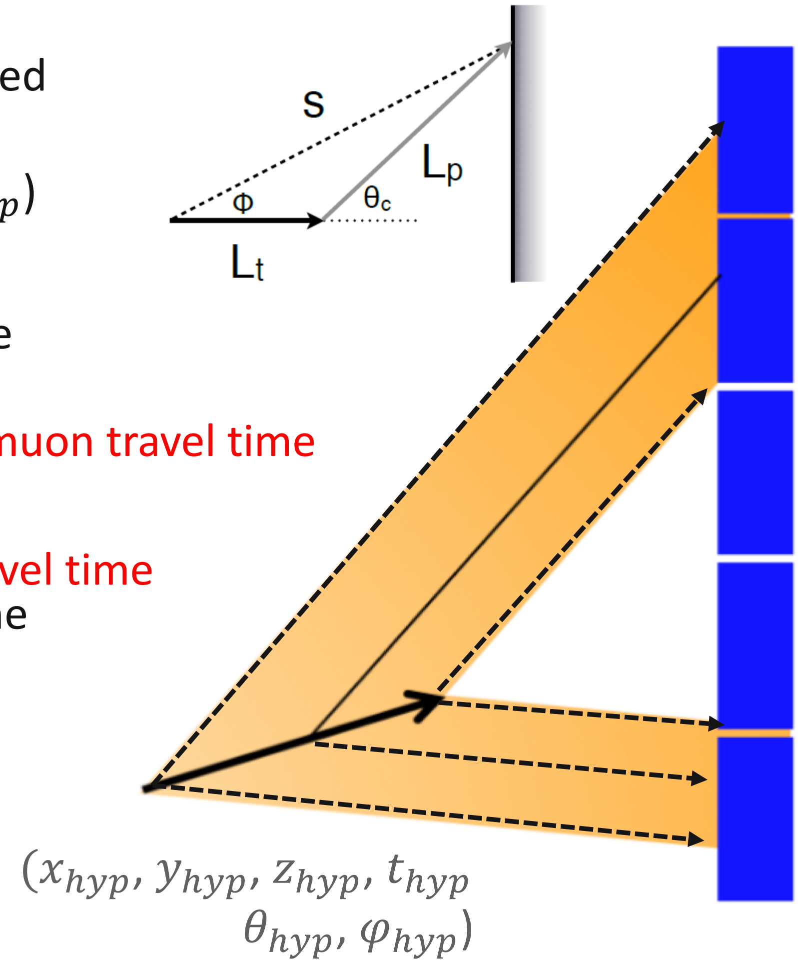


Vertex and track reconstruction

Step2: "Extended vertex" fit

six parameter fit: $(x, y, z, t, \theta, \varphi)$

- Starting from the "simple vertex" obtained from step1, assume a hypothesized track $(x_{hyp}, y_{hyp}, z_{hyp}, t_{hyp}, \theta_{hyp}, \varphi_{hyp})$



- For each hit, calculate the extended time residual:

$$\Delta t = t_{hit} - \frac{L_p}{\frac{c}{n}} - \frac{L_t}{c}$$

muon travel time

Photon travel time

- For each hit, compare the measured cone edge to the simulated one.

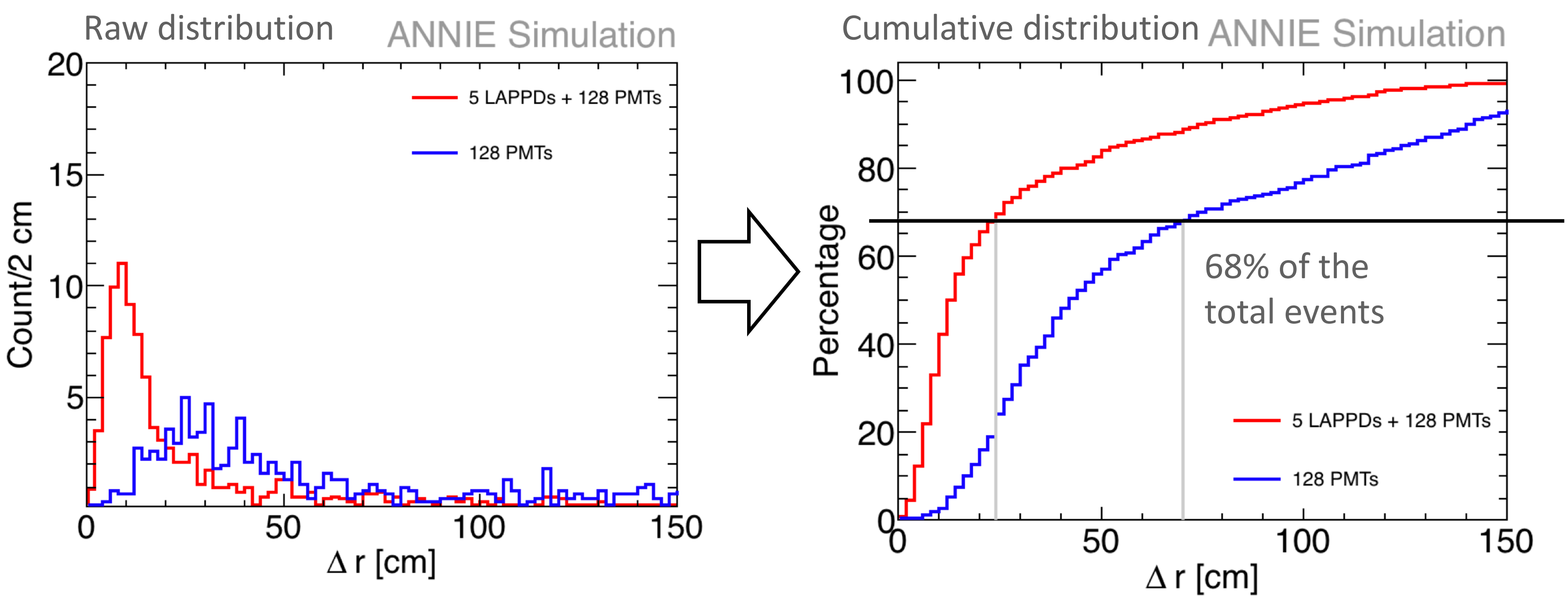
- For all hits, calculated the overall FOM **(FOM$_{time}$ + FOM$_{cone}$)**

- **Adjust six parameters** to maximize the FOM

Realistic reco: vertex resolution

- Find the seeds with 4-hit combinations
- 128 PMT-only (20% coverage) : 70 cm (40 cm in idealized reco)
- 5 LAPPDs + 128 PMTs : 23 cm (15 cm in idealized reco)

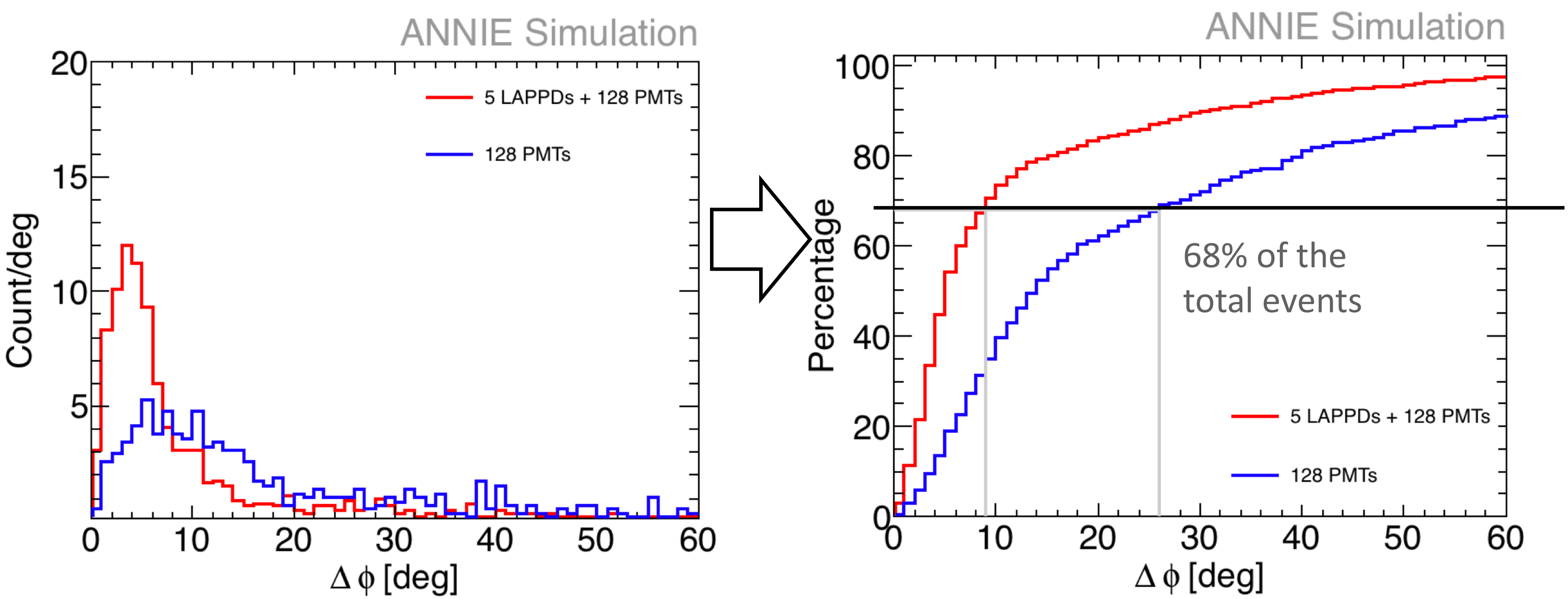
Distance between the true and the reconstructed vertices



Realistic reco: track angular resolution

- 128 PMT-only (20% coverage) : 27 deg (13 deg in idealized reco)
- 5 LAPPDs + 128 PMTs: 9 deg (5 deg in idealized reco)

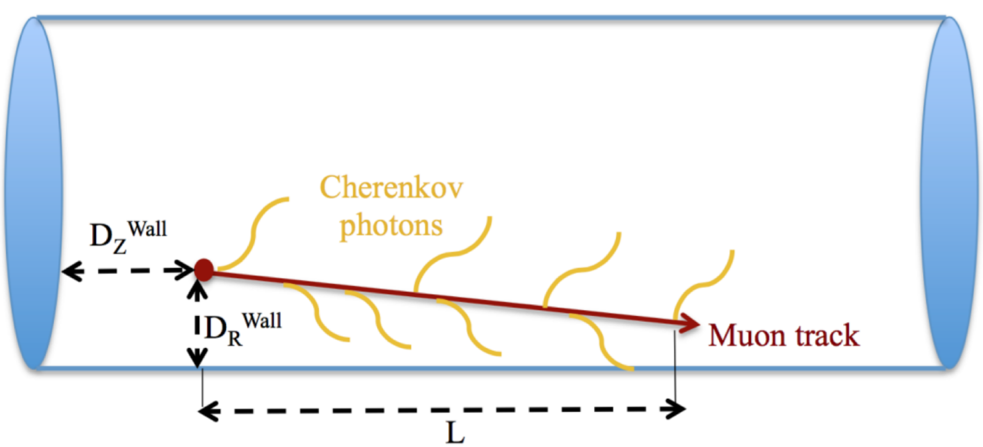
Angle between the true and the reconstructed muon tracks

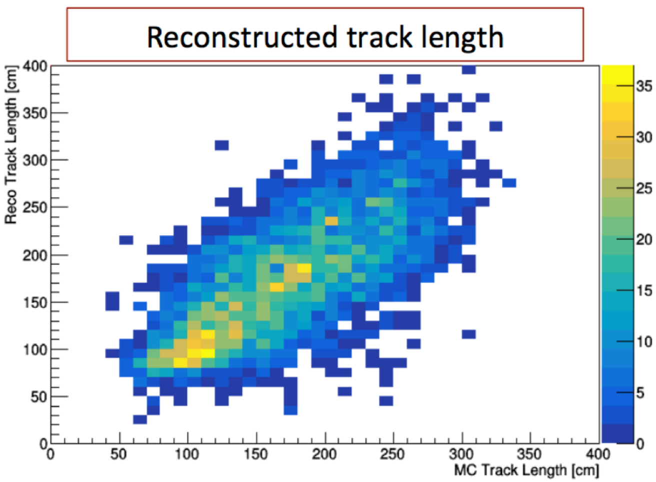


Track length in water

- The track in water was initially reconstructed as the distance between the first and last Cherenkov photon emission point along the track (L).
- In order to improve the reconstructed track length in the water tank a **Deep Learning Neural Network** (from Tensorflow package) was used.

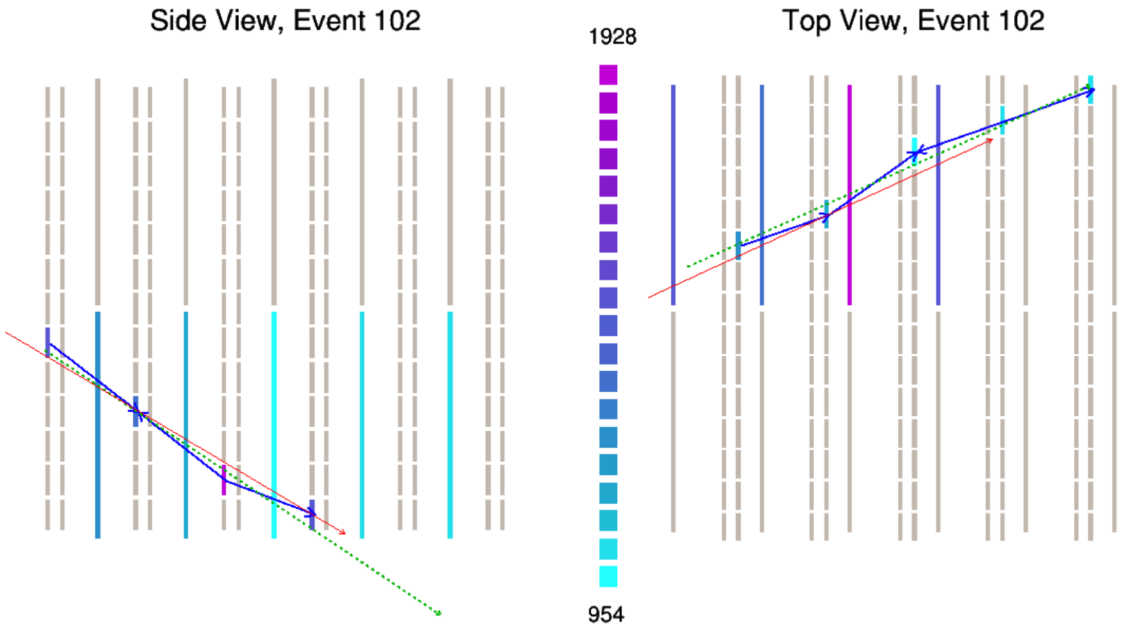
- **The algorithm is trained on multiple input variables:**
  - – • All Cherenkov photons emission points
  - – • Hit times
  - – • The previously estimated track length, L
  - – • The total number of hits in PMTs and LAPPDs





Track length in MRD

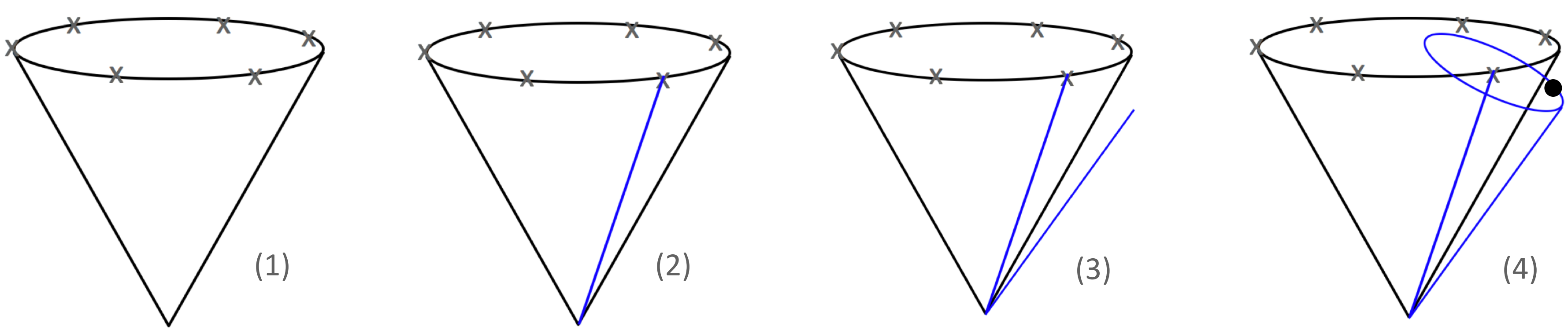
- To estimate the MRD track length a track is fit to the recorded hits in all layers
- Tracks are reconstructed in two 2D views and then matched into a 3D view
- MRD reconstruction is done in a separate framework and will be merged to the main software.
- For present studies, the track length is calculated as the distance between the true entry and exit points of the muon (neglect scattering)



Red: True track
Blue: Reconstructed cells
Green: Fit to cells

Hough transform works in 3D

1) Code works in 3D. We find the most overlapping direction, not radius
2) Draw a line from the vertex to the hit
3) Rotate the line out of the page around the vertex by the Cherenkov cone angle
4) Rotate this line around the original line
5) Each point on the circumference is defined by (ϕ, θ) relative to z direction
6) Add a count at (ϕ, θ) for all hits at this cone angle
7) If angle is unknown, then need to change the angle and repeat the steps
8) Each peak in the (ϕ, θ) distribution is a ring center



Edge detection + Hough transform

1) Convert (x, y, z) to (ϕ, θ)
2) Run filtering algorithm (use a simple ROOT::Smooth() function for now)
3) Set a threshold and convert the raw distribution to binary
4) Calculate gradients at both direction and get the magnitude
5) The pixels/bins with non-zero gradient are at the cone edge
6) Loop over the hits and only keep the hits close to the edge
7) Run Hough transform