UCDAVIS

Event Reconstruction Techniques for ANNIE Phase II

annie

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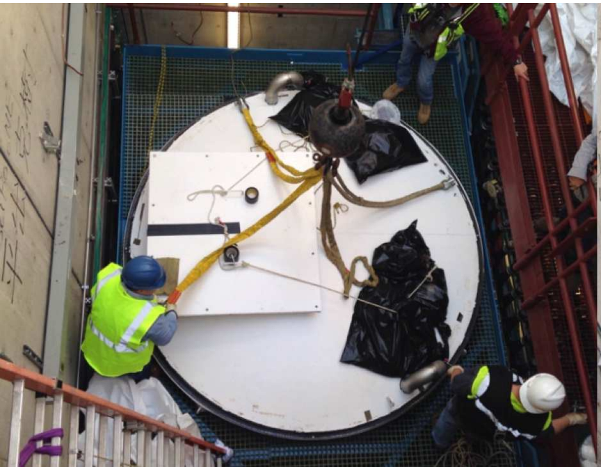
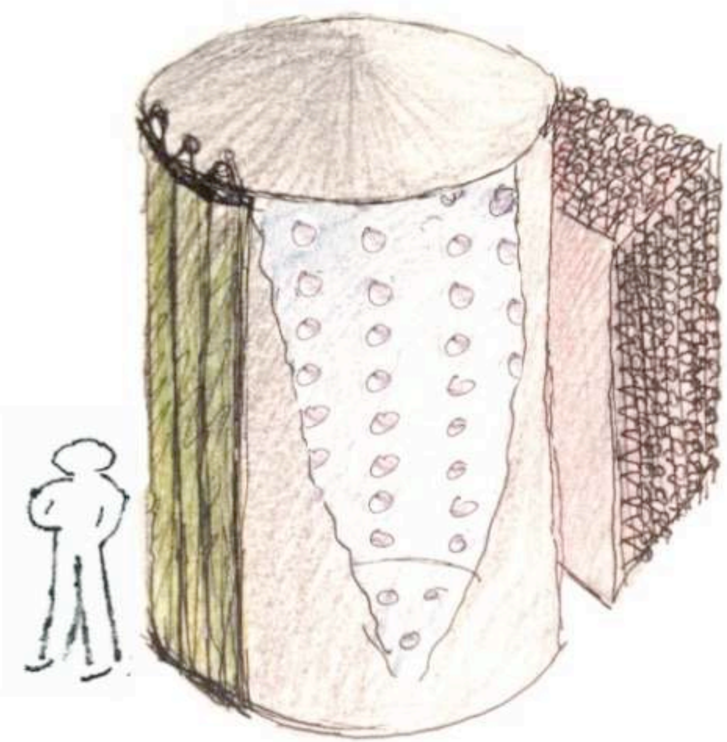
May 30, 2018, CIPANP, Palm Springs



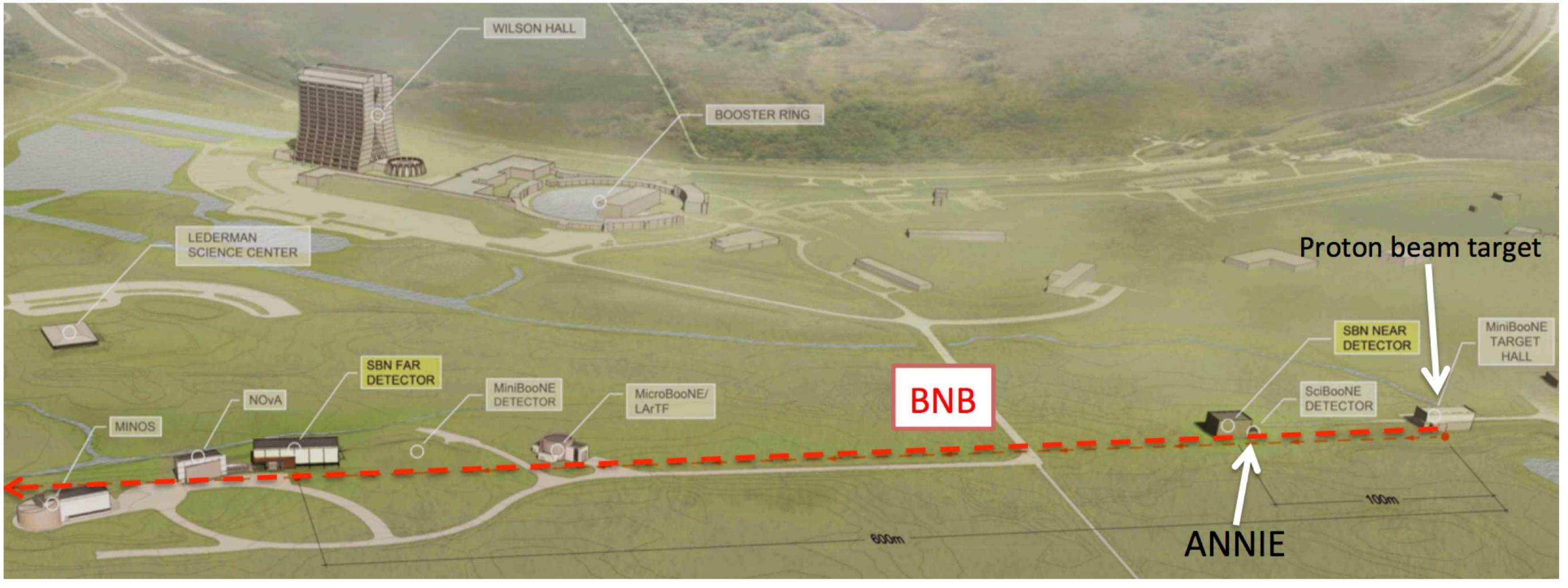
Outline

- Introduction on ANNIE
- Phase II simulation
- Phase II event reconstruction
  - Two detector configurations (w/o 5 LAPPDs)
  - Vertex and track reconstruction
  - Energy reconstruction
  - Momentum transfer
- Summary



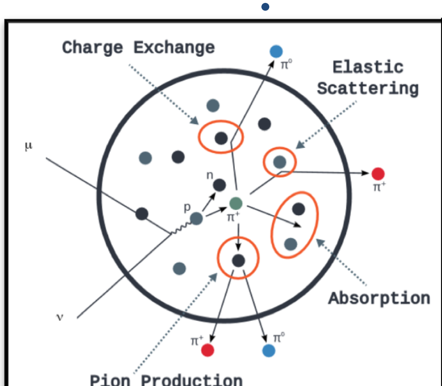
ANNIE

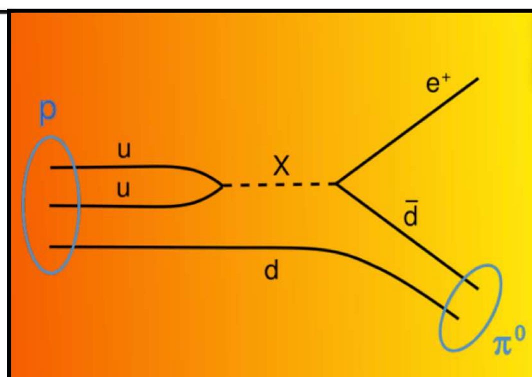
- **ANNIE: A**ccelerator **N**eutrino **N**eutron **I**nteraction **E**xperiment
- **26-ton Gd-loaded water Cherenkov detector** placed downstream of the Booster Neutrino Beam (BNB) at Fermilab
  - On-axis neutrino flux
  - Beam energy peaks around 700 MeV (relevant to atmospheric neutrinos)
  - 14×10^3 ν_μ of CC interactions per ton of water per year

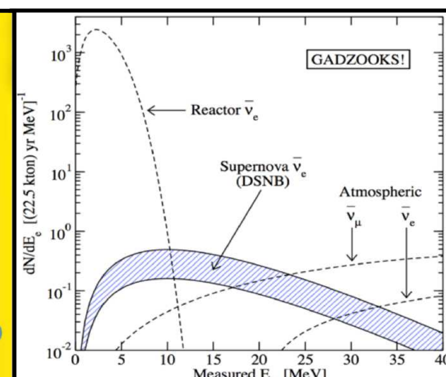


ANNIE Goals

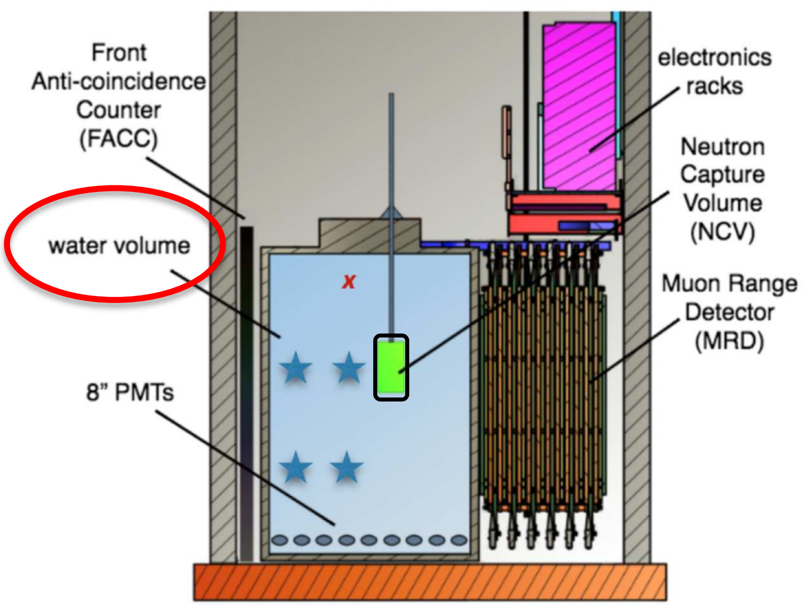
- **ANNIE primary physics goal:** Measure the **neutron multiplicity** from neutrino-nucleus interactions in water as a function of momentum transfer
  - Help to understand the uncertainties on energy reconstruction in long baseline oscillation measurement
  - Neutron yield is a possible handle for neutrino/antineutrino separation
  - Neutron tagging provides signal/background separation for proton decay measurements and supernova neutrino observations.
- **ANNIE technological goals:**
  - First application of **Gd-doped water** in a beam experiment: large capture cross section for final state neutrons.
  - First application of **Large-Area Picosecond Photodetectors (LAPPDs):** precision timing to localize interaction vertices in the small fiducial volume

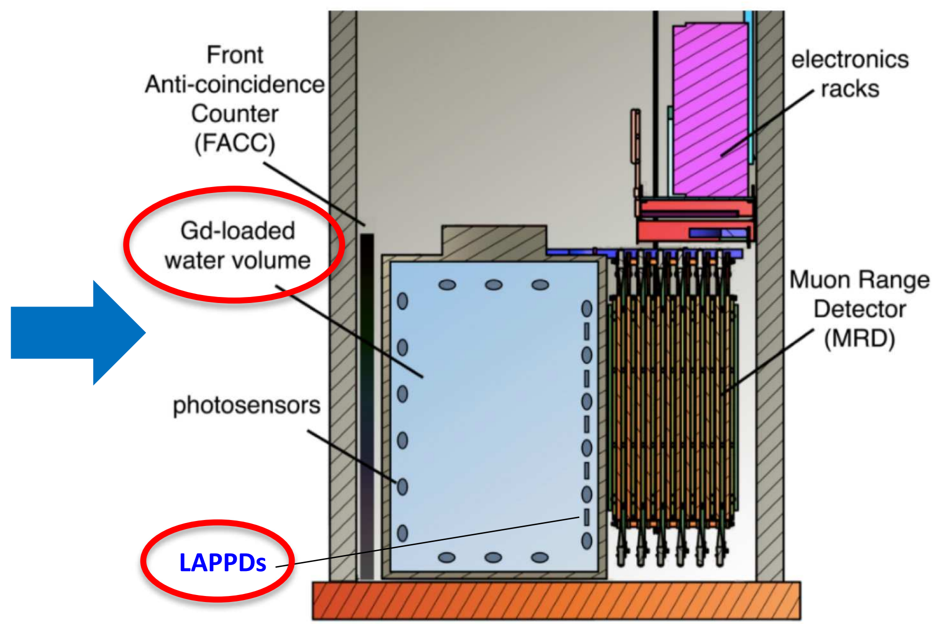






ANNIE Detector Overview

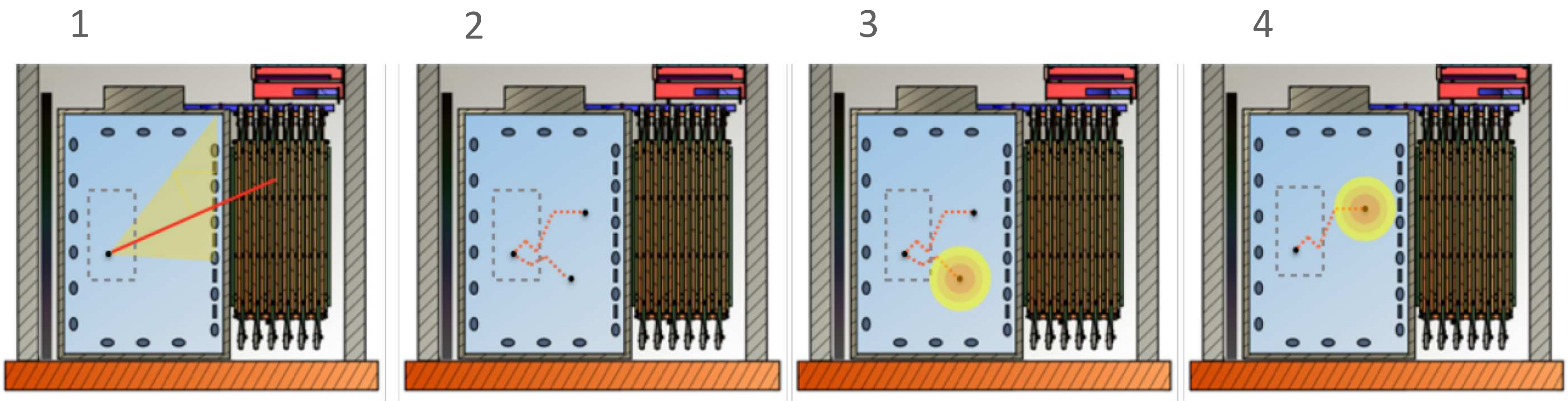




- **Ultra-pure water** in a 3m x 4m tank
- 2 layers of paddles in FACC and 2 layers in MRD.
- **Neutron capture vessel (NCV)** filled with 0.25% Gd-loaded liquid scintillator (EJ-335)
- 60 8 inch-PMTs act as a veto to the NCV.
- Data taking completed in September 2017.
- **Background is sufficiently low to proceed to Phase II**

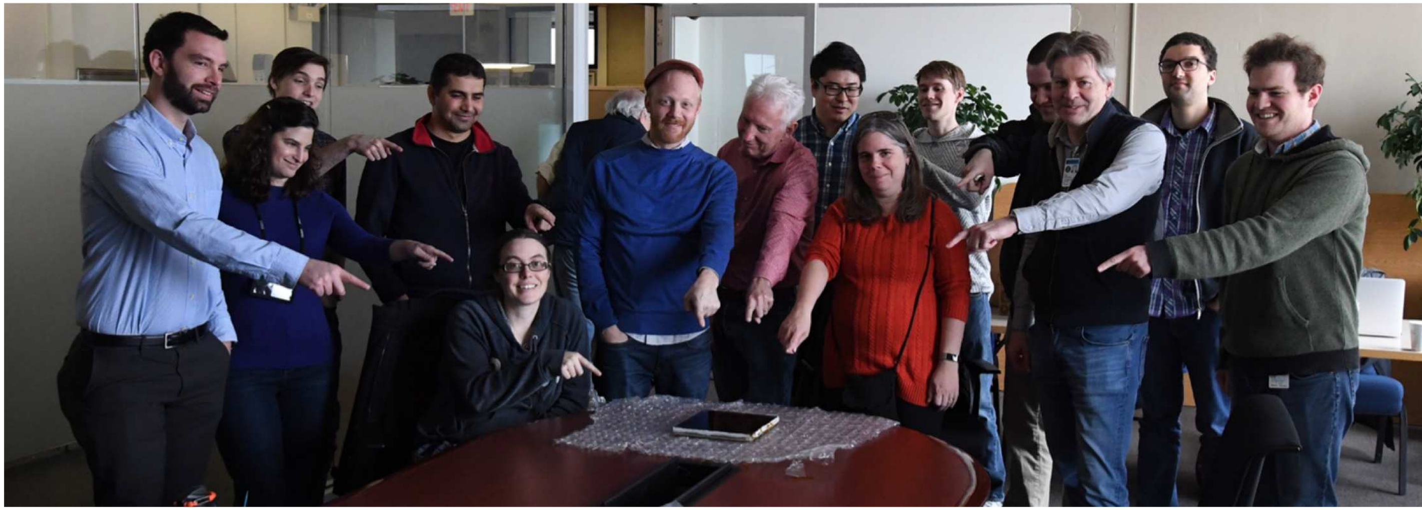
- **Gadolinium (0.2%) loaded water**
- Full MRD: 11 layers and 310 channels
- **125 PMTs + 5 LAPPDs**
- Calibration studies with AmBe source.
- It will be commissioned in the Fall 2018.
- **Phase II will be capable of making neutron final state neutrino cross-section measurements**

How does ANNIE work?



- 1 – **Charge Current neutrino interaction** in the fiducial volume
- 1 – Neutrino vertex and muon direction reconstructed using Cherenkov light detected by **fast-timing 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 an 8 MeV gamma cascade
- 4 - Gamma rays are detected by PMTs

LAPPDs in ANNIE



LAPPDs are MCP-based fast-timing photodetectors

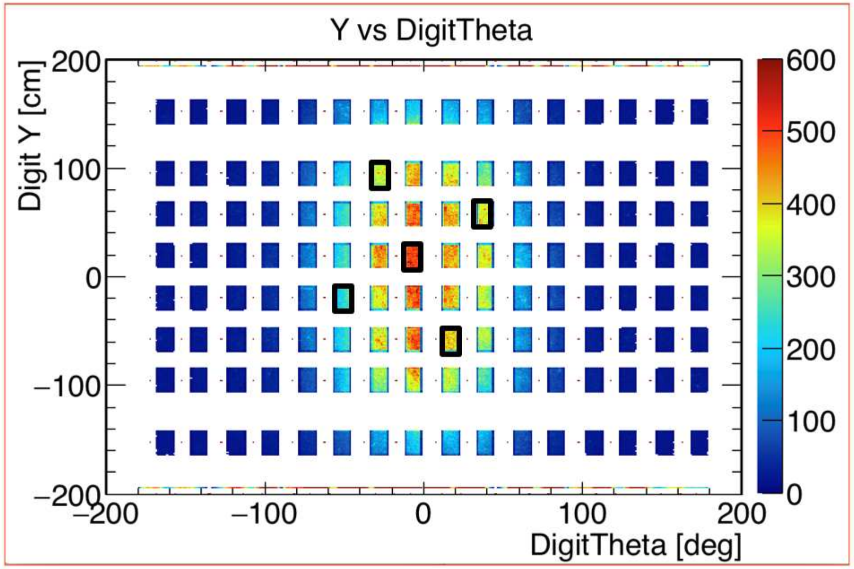
- Flat, Large-area: 20 cm × 20 cm
- Picosecond timing: <100 ps for SPE
- Quantum efficiency: >20%
- Position resolution: mm
- Lower Cost per Unit Area
- Atomic Layer Deposited Micro-channel Plate (MCP)

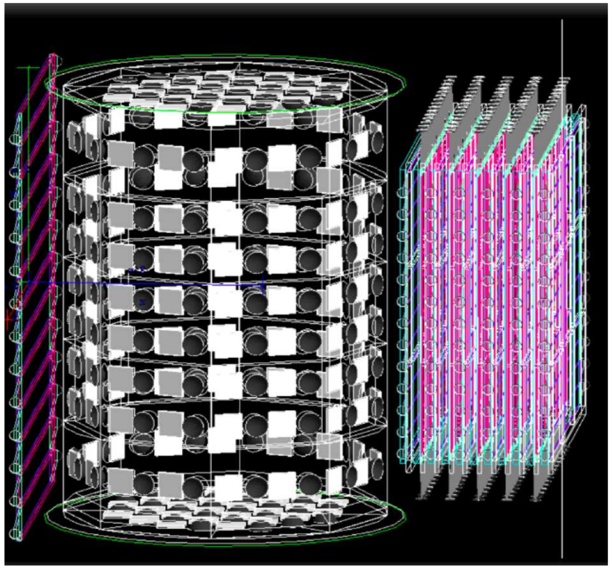
Next talk by V. Fischer

- **INCOM. Inc has commercialized the LAPPDs. The performance is quickly approaching the specifications needed by ANNIE**

Phase II Simulation

- ANNIE Phase II simulation in WCSim: 128 PMTs + 128 LAPPDs
- Dataset of ν_μ interactions provided by the GENIE generator
- 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 traditional PMTs and additional **5 LAPPDs** on the downstream wall of the tank.

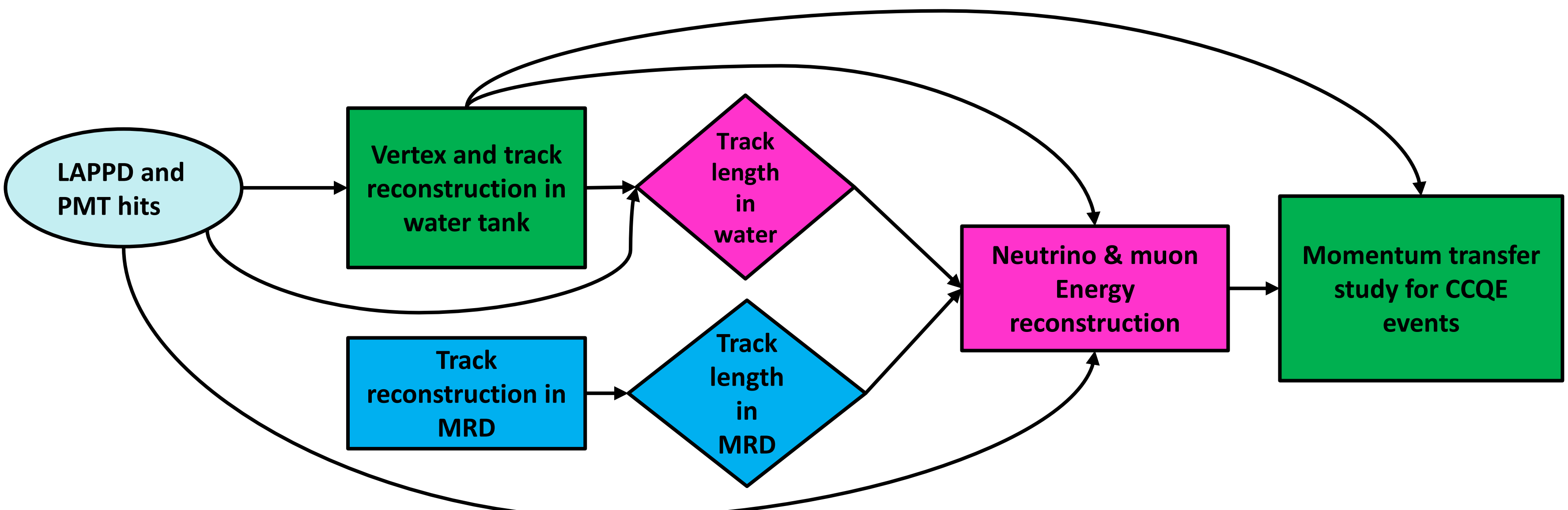




Phase II Reconstruction Strategy

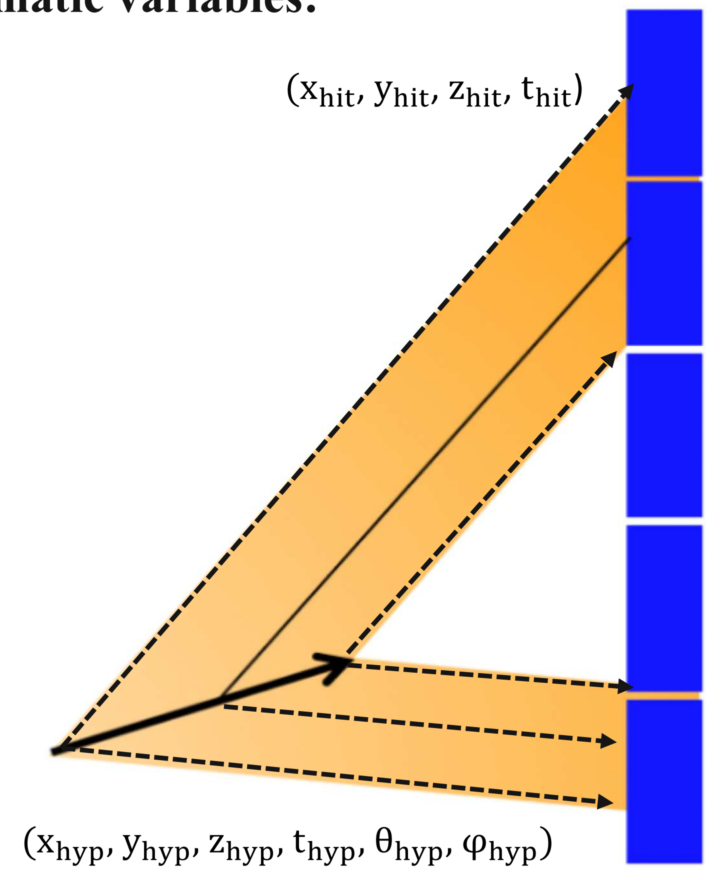
Reconstruction techniques

1) **Vertex and track** are reconstructed in water tank using maximum likelihood fit
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 interaction



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

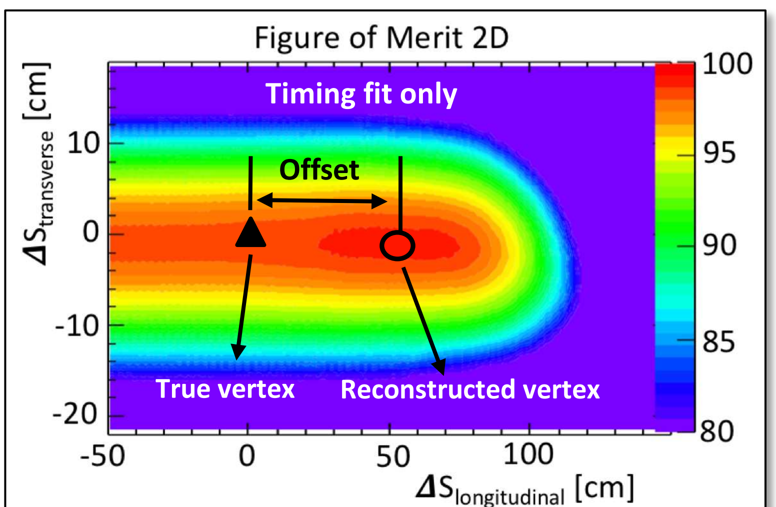


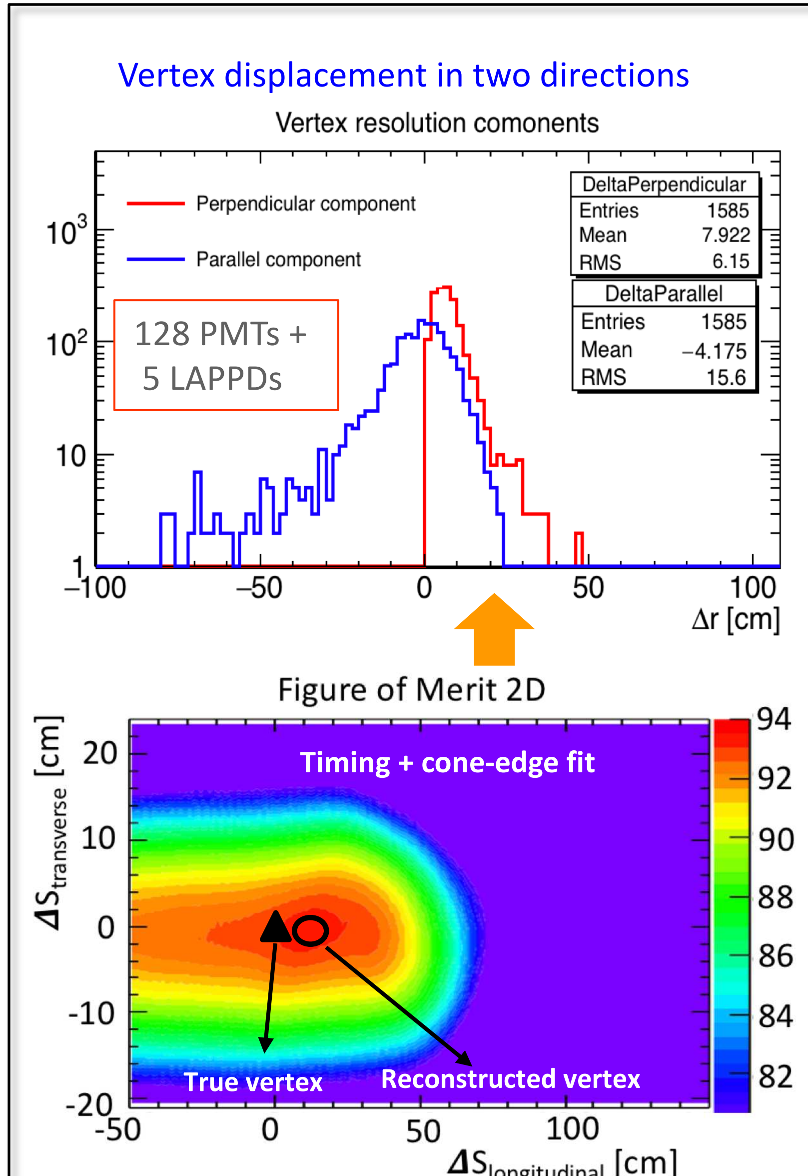
Basic strategy:

1) A timing-based likelihood (**$\mathbf{FOM_{time}}$**) function is used to fit the vertex position and time
2) A charge-based likelihood function (**$\mathbf{FOM_{cone}}$**) 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

Vertex constraints in two directions

- Timing places a weak constraint longitudinal to the muon direction due to the ambiguity issue of T_0
- Scattered light outside the cone helps a little, but not sufficiently.
- Cherenkov cone-edge offers better constraint to T_0, which significantly improves the vertex resolution along the muon track
- In ANNIE, the strong transverse constraint is provided by 5 downstream LAPPDs, and the longitudinal constraint is strengthened by the PMTs
- Overall constraint transverse to the muon direction is much stronger

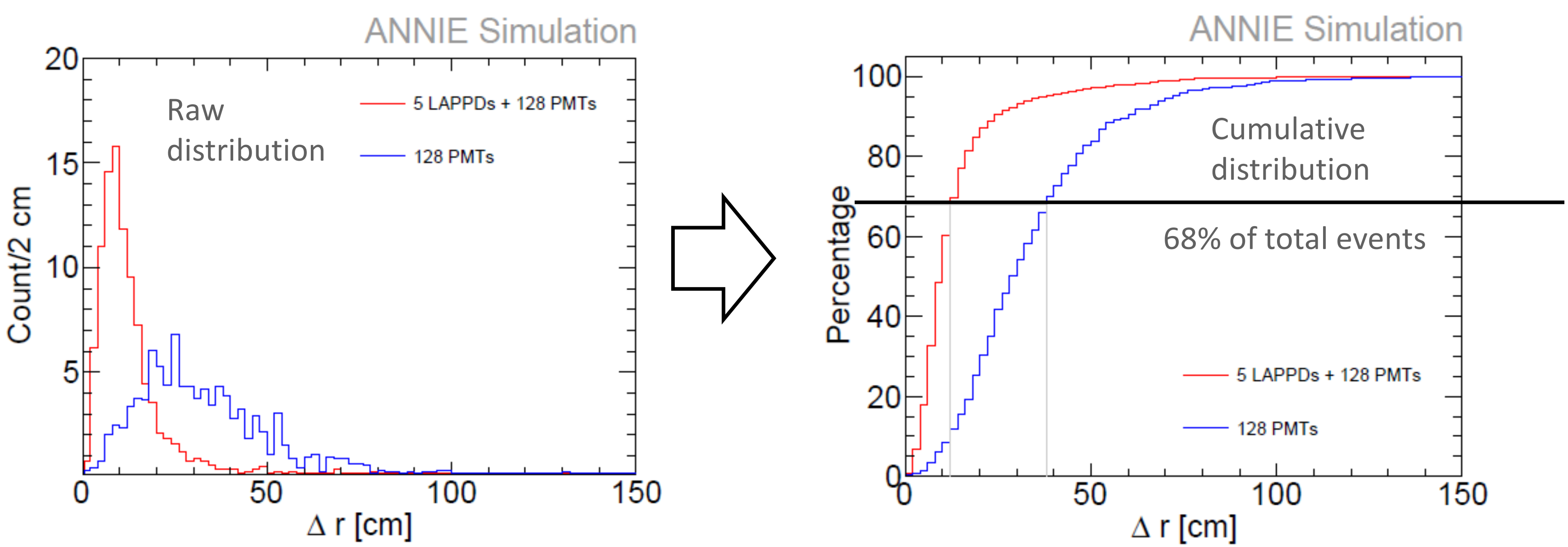




Vertex Displacement: Δr

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

- Only the 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

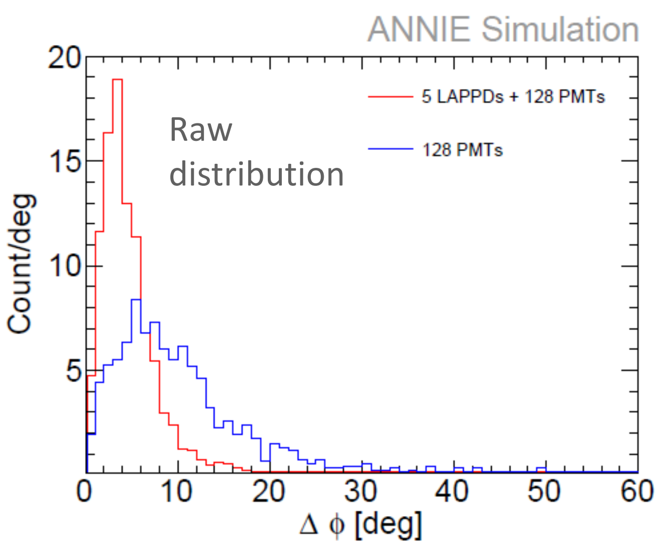


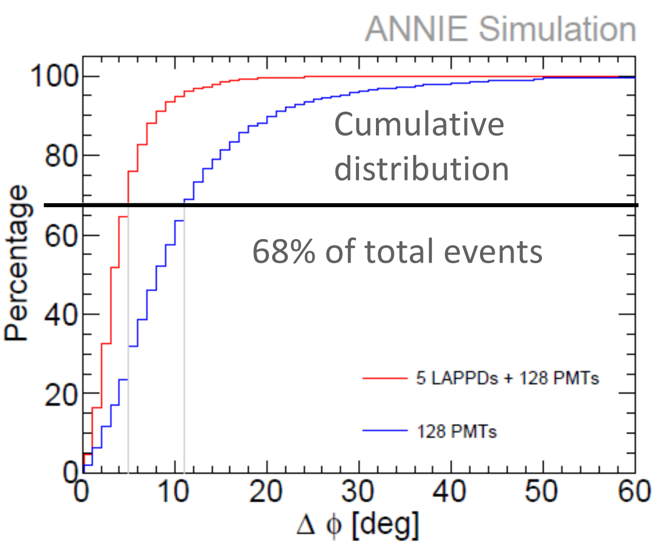
Distance between the true and the reconstructed vertices

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!)





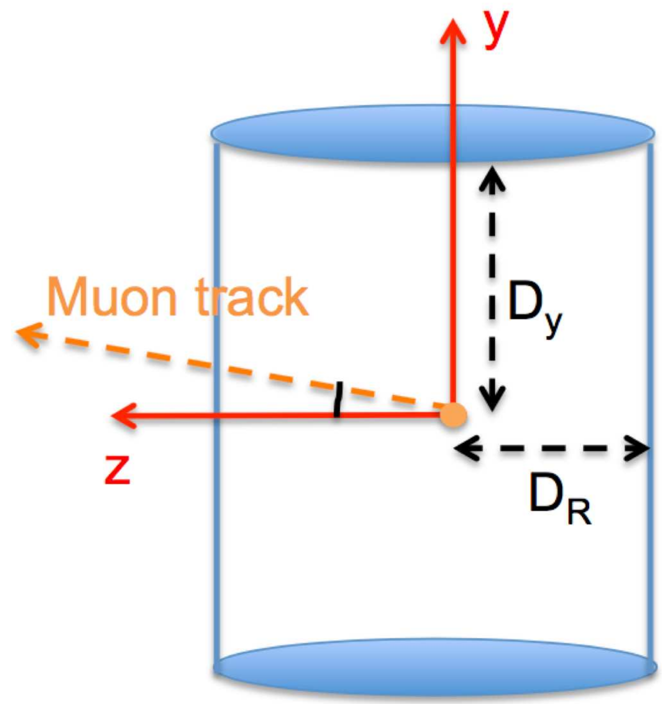
Angle between the true and the reconstructed muon tracks

Energy reconstruction

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

Input Variables:

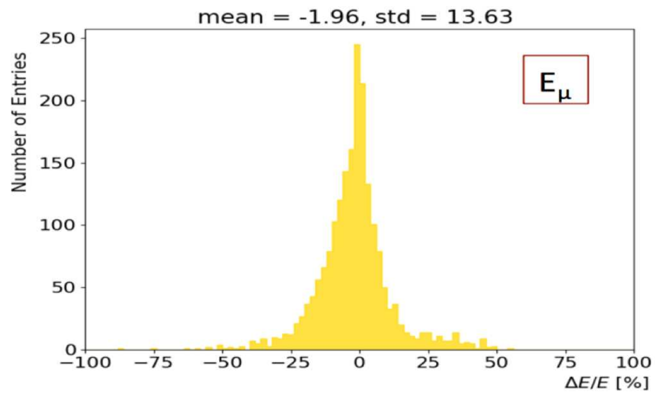
- **Track length in water** calculated by **D**eep **L**earning **N**eural **N**etwork
- **Track length in MRD** reconstructed using 10 layer of scintillator paddles
- Angle difference between the reconstructed track direction and the beam direction
- The total number of hits in PMTs and LAPPDs
- The reconstructed vertex coordinates
- The distances of the reconstructed vertex from the detector walls (D_R, D_y)

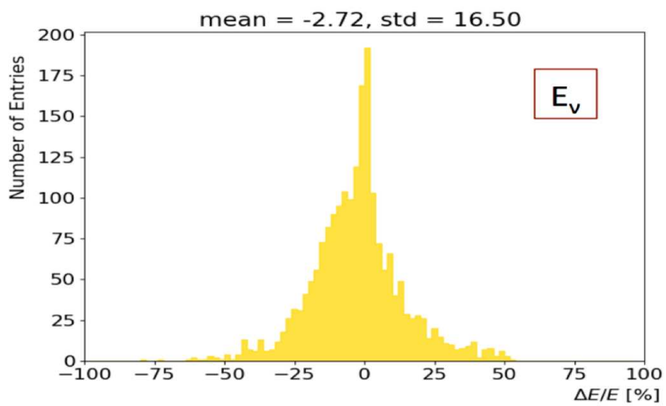


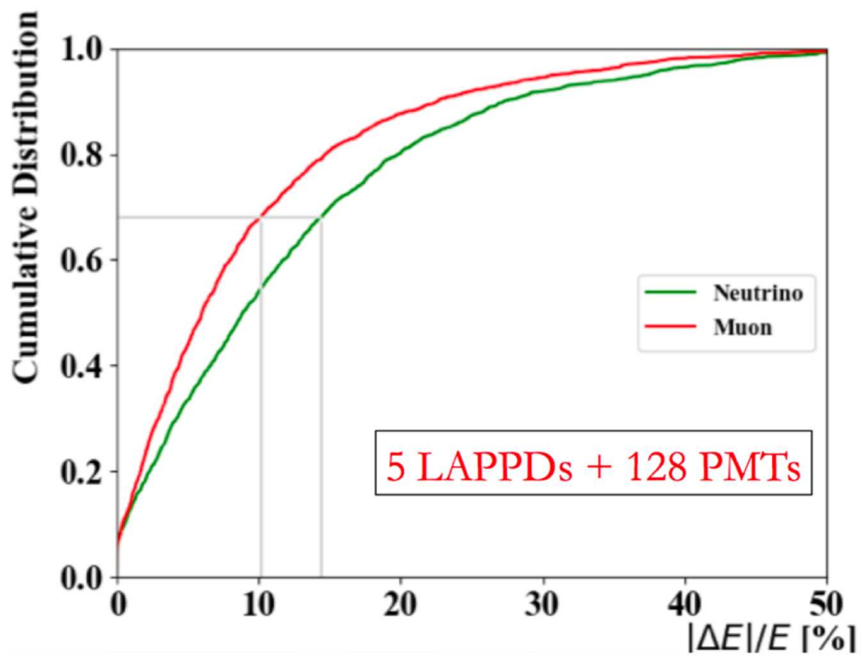
E. Drakopoulou , arXiv:1710.05668v3

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%).





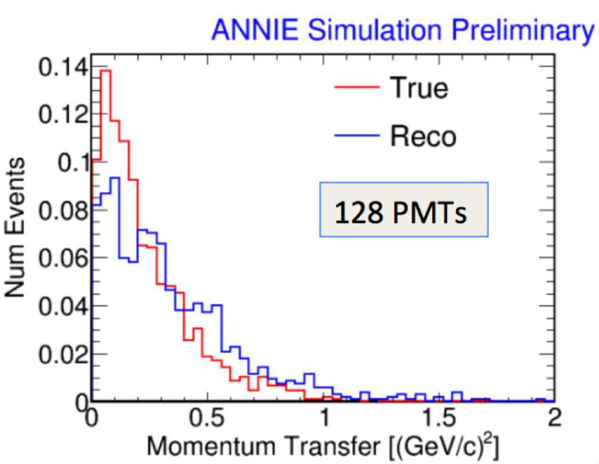


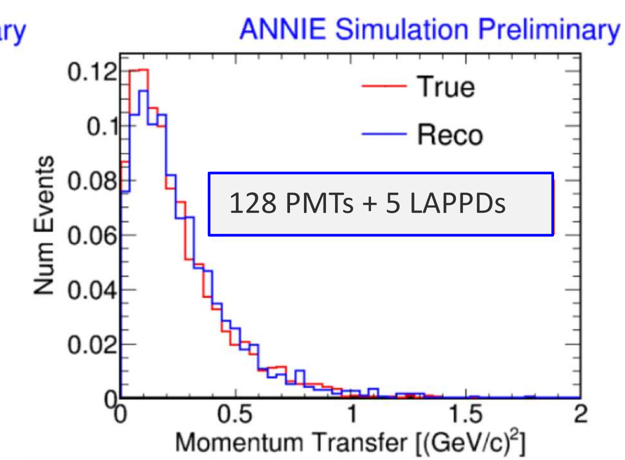
E. Drakopoulou , arXiv:1710.05668v3

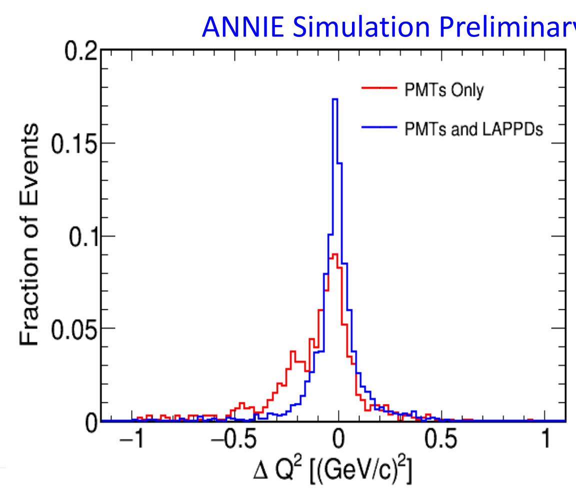
Momentum transfer reconstruction

- Stopped muon events are selected for which the muon energy is measured as the sum of energy deposited in the water tank and the MRD.

- Assuming CCQE interaction, the reconstructed muon and neutrino energies, together with the muon angle are used to calculate the momentum transferred.



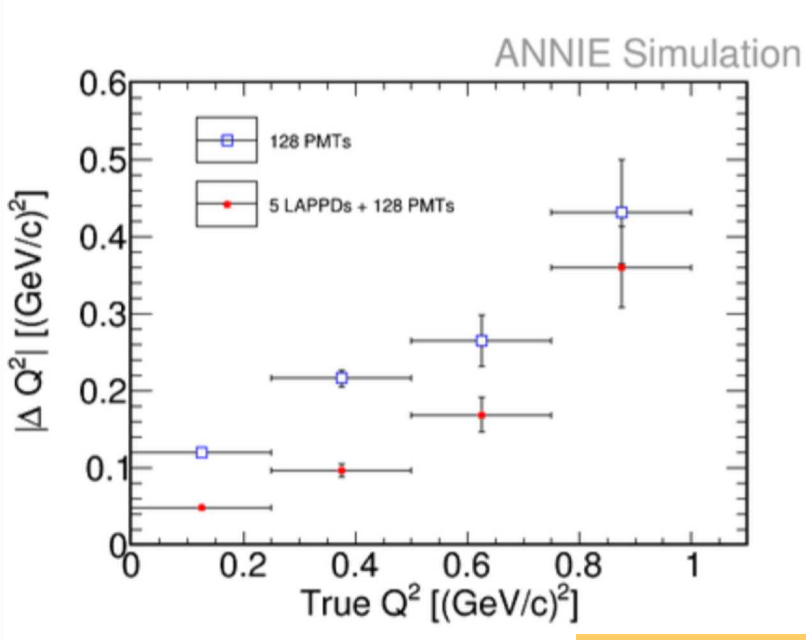




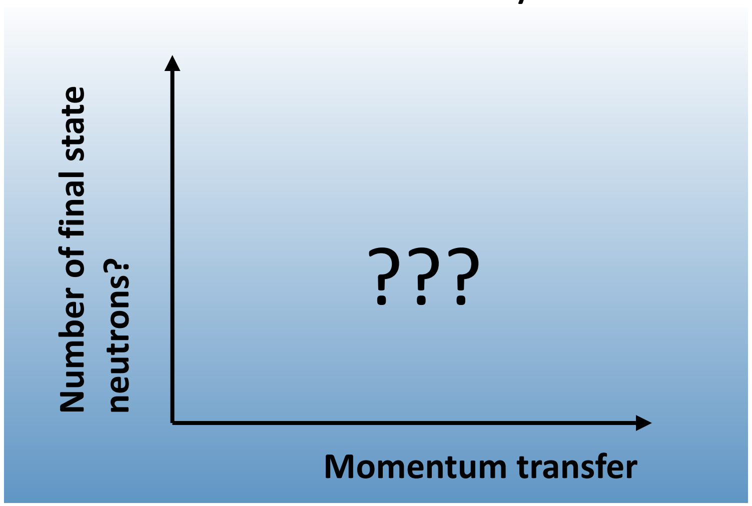
Marcus O'Flaherty (University of Sheffield)

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]

Summary

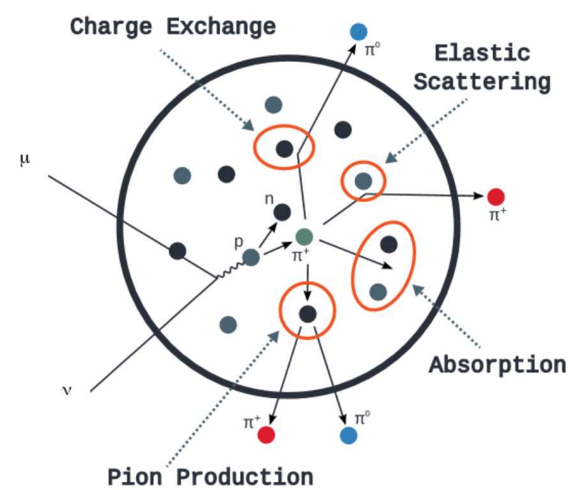
- ANNIE's physics goal is to measure the neutron multiplicity from neutrino interactions in water, as a function of momentum transfer
- ANNIE has finished Physics I background measurement and is moving to Phase II physics measurement (2018 fall).
- Simulation and Reconstruction tools for ANNIE Phase II are in place and show good performance.
  - Vertex & track reconstruction with PMT + LAPPD configuration
  - Machine learning tools are used for energy reconstruction
  - Momentum transfer reconstruction improves with 5 LAPPD
- Futhher development and improvement of the reconstruction techniques are ongoing

Thanks for your Attention! Questions?

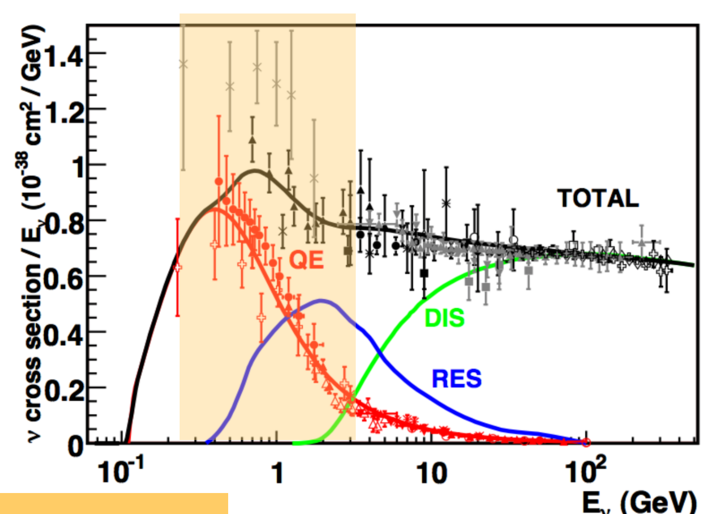
Backup

Long Baseline Oscillation Physics

- **In order to turn neutrino physics into a precision science, we need to understand the complex neutrino-nucleus interactions**
  - Dominant source of uncertainties on energy reconstruction
  - Neutrino-nucleus interaction is hard to model
  - Need comprehensive measurements of neutron/proton multiplicity for a variety of targets/Eν



- **ANNIE focuses on the CCQE-like events and measure final state neutrons in water from 0.5 – 3 GeV**
  - Better identification of pure CCQE interactions
  - Possible handle for neutrino/antineutrino separation
  - Complementarity with proton multiplicity measurements in liquid argon



Multiplicity and absence of neutrons is also a strong handle for signal-background separation in a number of physics analyses!

Proton Decay

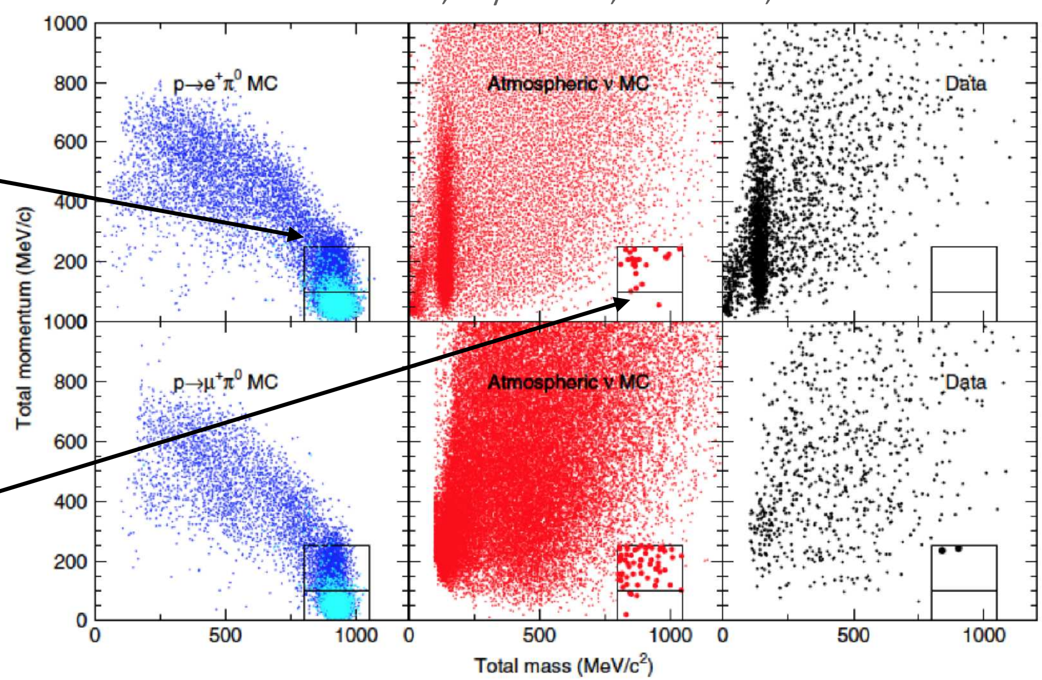
- Proton decay (PDK) remains one of the generic predications made by Grand Unification Theories (GUT)
- Main background from atmospheric neutrino interactions
- Backgound rejection using neutron tagging (n-Gd capture)
- Data is needed to implement the neutron yield in simulation of PDK backgrounds

$p \rightarrow e^{+} + \pi^{0}$

Proton decay events only rarely produce neutrons in the final state (<10% of the time)

Atmospheric neutrino interactions is likely to produce final state neutrons

K.Abe et al., Phys. Rev. D, 95:012004, 2017



Supernova Observation

Diffuse SuperNova Background (DSNB): continuous neutrinos flux from all past core-collapse supernovae =>difficult to detect

- Supernova neutrino is detected via the Inverse Beta Decay (IBD):

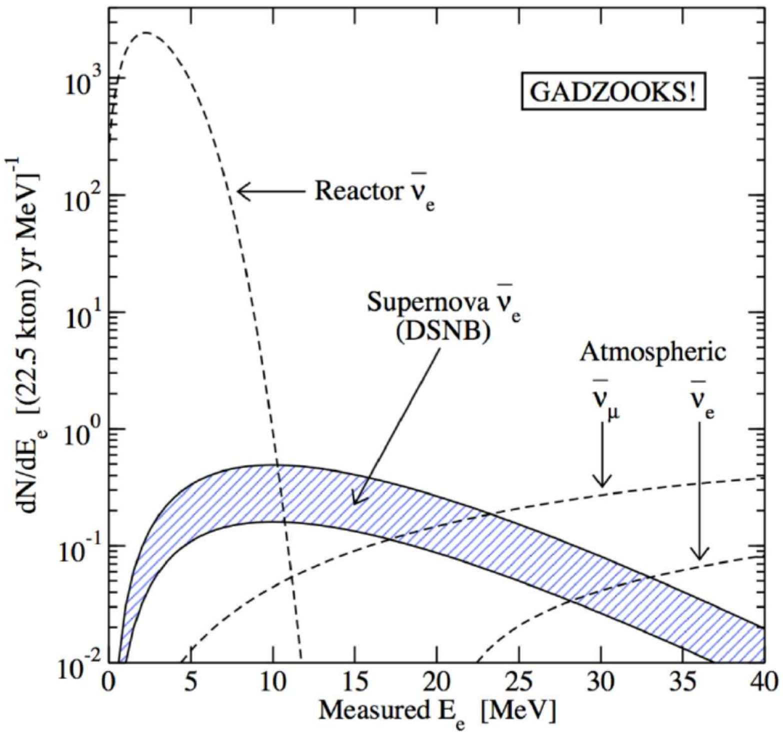
$$\overline{\nu_e} + p \rightarrow e^+ + n$$

- Main background (E>20 MeV): from decay of sub-Cherenkov muons produced by atmospheric neutrinos:

$$\mu^+ \rightarrow e^+ + \nu_e + \overline{\nu_\mu}$$
$$\mu^- \rightarrow e^- + \overline{\nu_e} + \mu$$

- **To discriminate signal and background, understanding of the atmospheric neutrino interactions is needed**

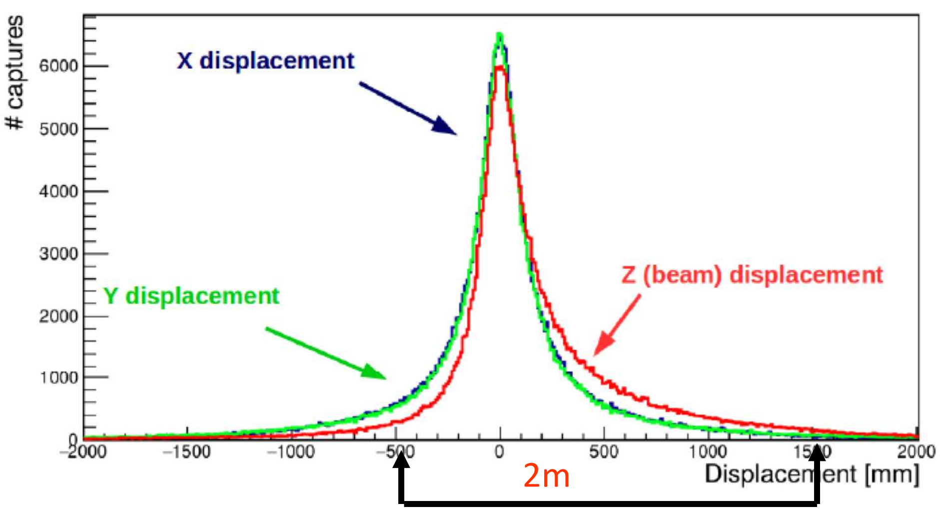
Beacom & Vagins, PRL, 93 (2004) 171101

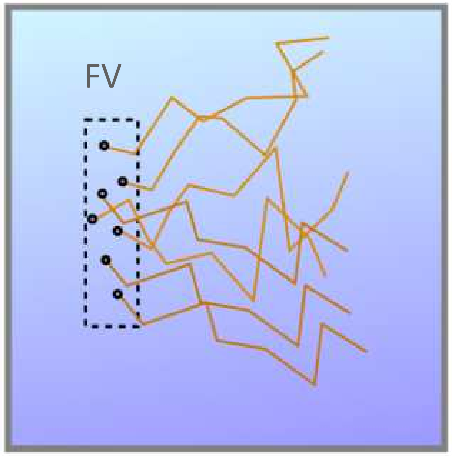


Why does ANNIE need LAPPDs?

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**



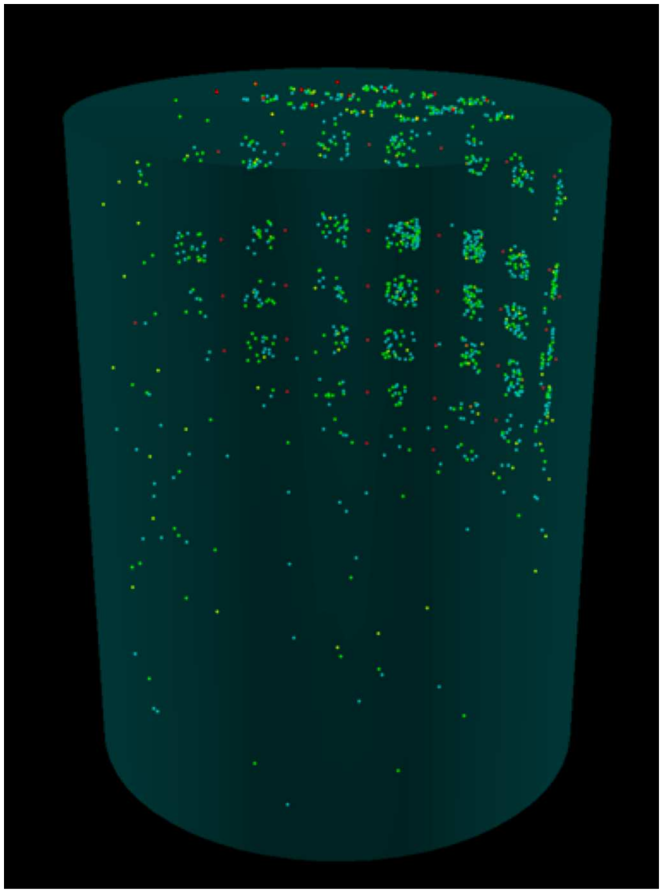


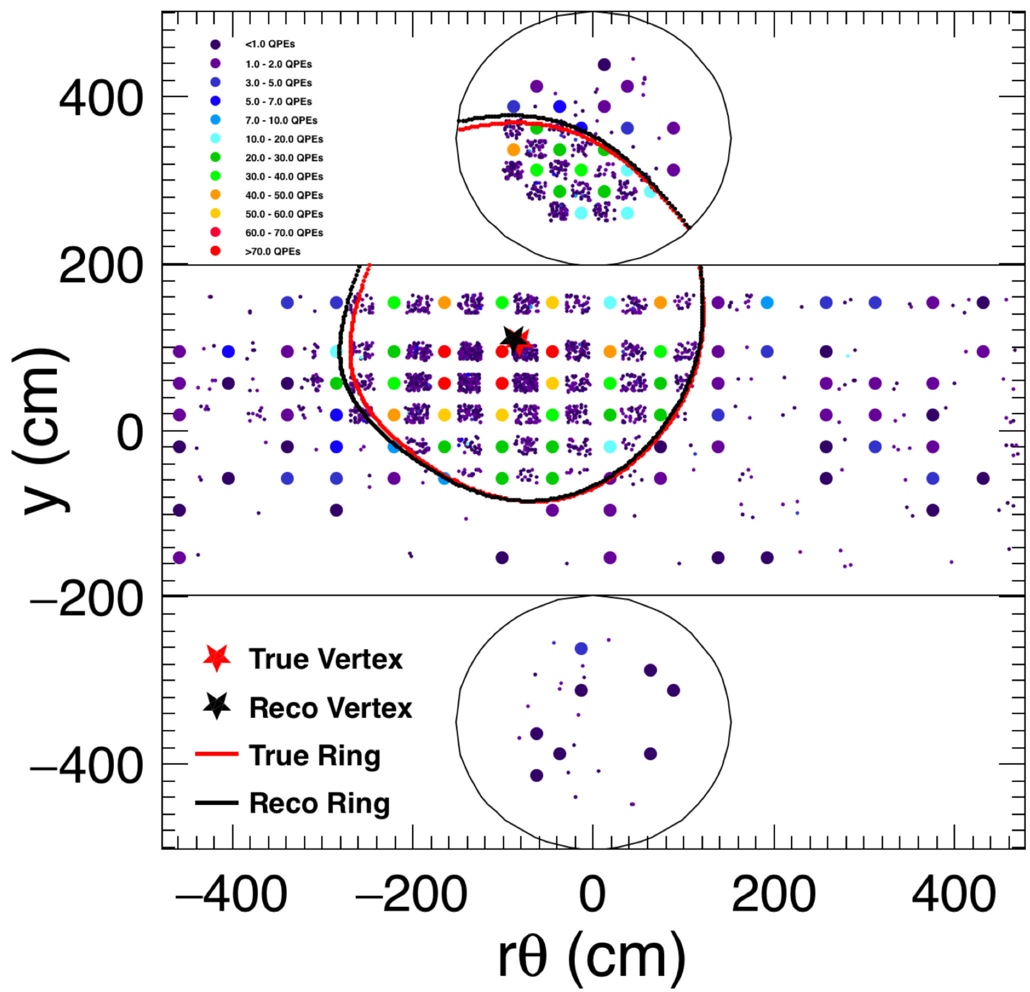
LAPPD commercialized by INCOM.

INCOM. http://www.incomusa.com/

A. Lyashenko, Incom LAPPD, Pico-Second Workshop, Kansas City Sept 15-18 2016

A Typical Event





Vertex and track reconstruction

Step1: "Simple vertex" fit

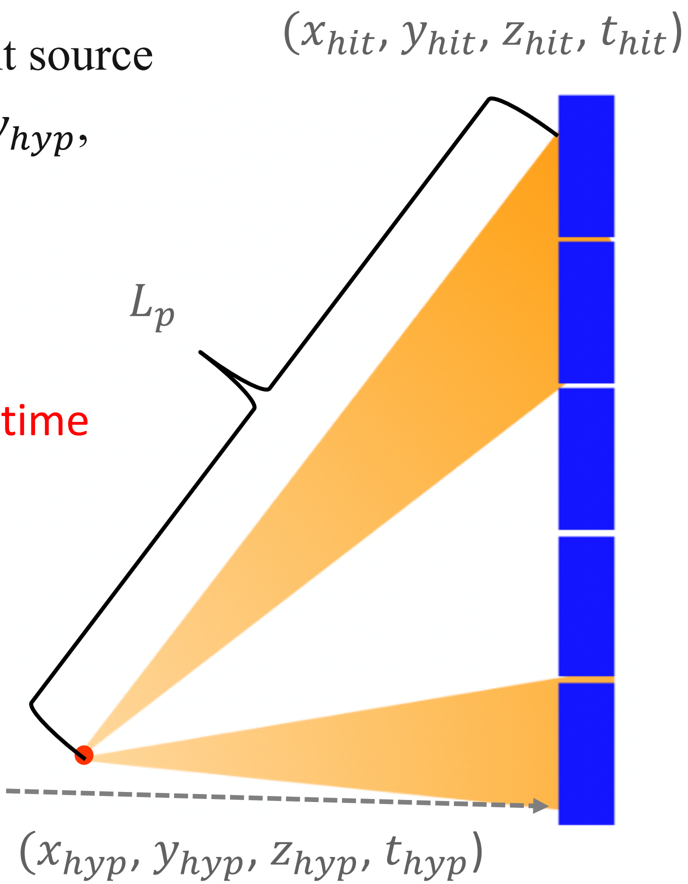
four parameter fit: (x, y, z, t)

- 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:

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

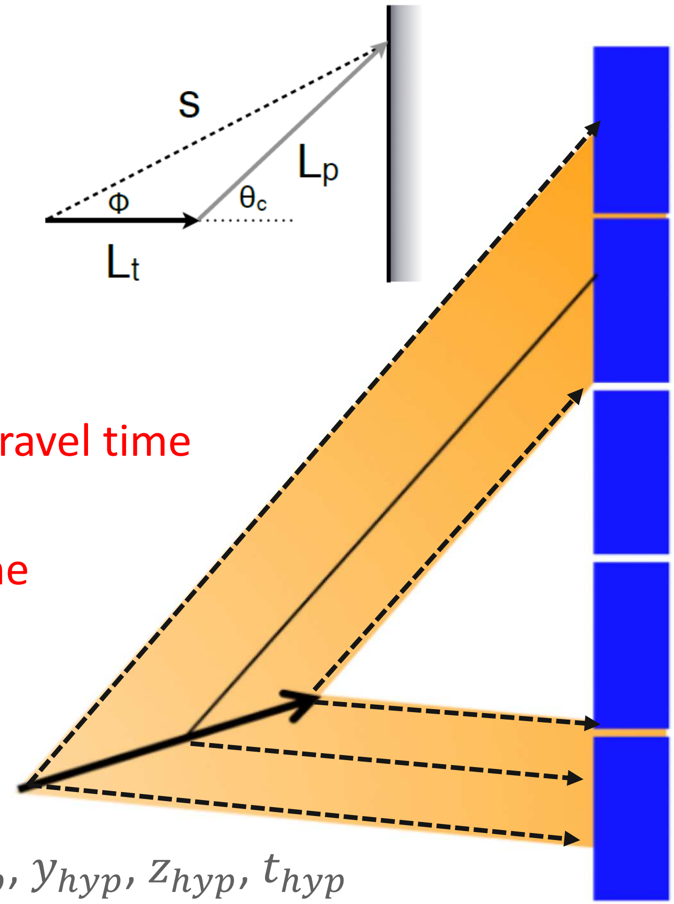
muon travel time

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

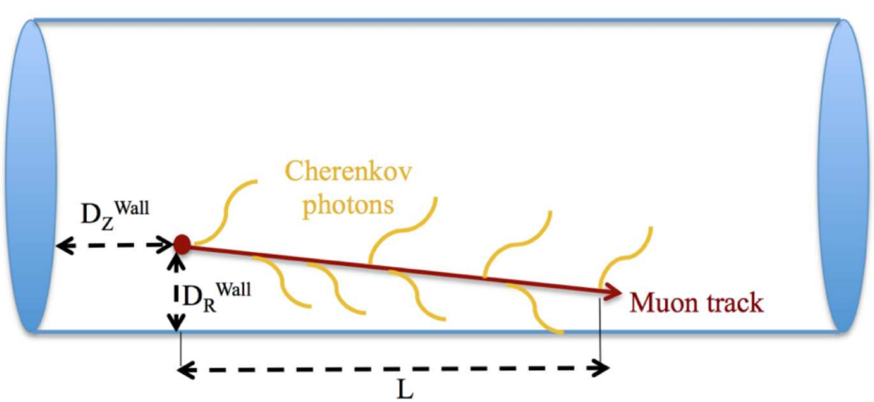


$(x_{hyp}, y_{hyp}, z_{hyp}, t_{hyp}$
$\theta_{hyp}, \varphi_{hyp})$

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