Measuring the NC single π^0 background to $\nu_\mu \rightarrow \nu_e$ oscillation, using the Near Detector of T2K

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Outline

- Description of the T2K experiment
- NC π^0 measurement at the Near Detector; importance for the oscillation analysis
- π^0 reconstruction using the ECals

Motivation for measuring neutrino oscillation

- Neutrino oscillation given by PMNS matrix, mixing mass and flavour eigenstates

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & C_{23} & S_{23}\\ 0 & -S_{23} & C_{23}\end{pmatrix}\begin{pmatrix}C_{13}^{*} & 0 & S_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -S_{13}e^{-i\delta} & 0 & C_{13}\end{pmatrix}\begin{pmatrix}C_{12} & S_{12} & 0\\ -S_{12} & C_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

- ν_μ disappearance: $P(\nu_\mu \rightarrow \nu_x) \approx \underline{\sin^2 2\theta_{23}} \sin^2(\underline{\Delta m^2_{23}} L/4E)$

(Probability for muon neutrino of energy E to oscillate to another flavour after distance L)

~1
Is it maximal?

$\sim 2.4\times10^{-3}$ eV^2

- ν_e appearance: $P(\nu_\mu \rightarrow \nu_e) \approx \underline{\sin^2 2\theta_{13}} \sin^2 \theta_{23} \sin^2(\Delta m^2_{23} L/4E)$

< 0.1
Is it nonzero?

(Probability for muon neutrino of energy E to oscillate to electron neutrino after distance L)

* $C_{13} = \cos\theta_{13}$, etc.

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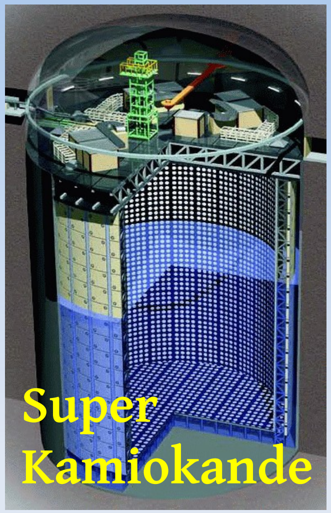
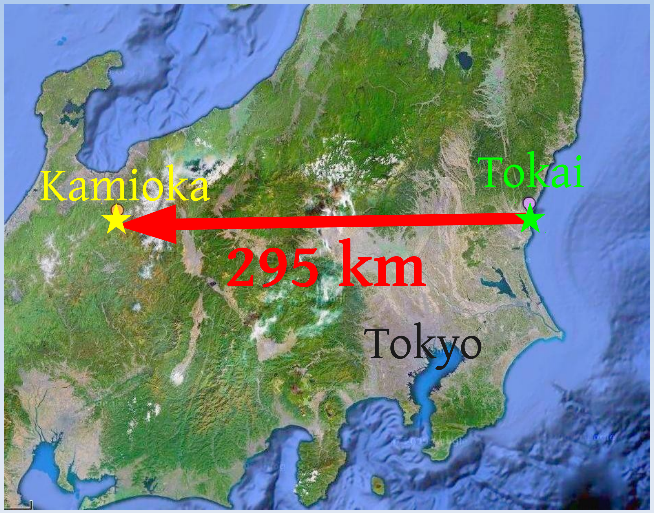
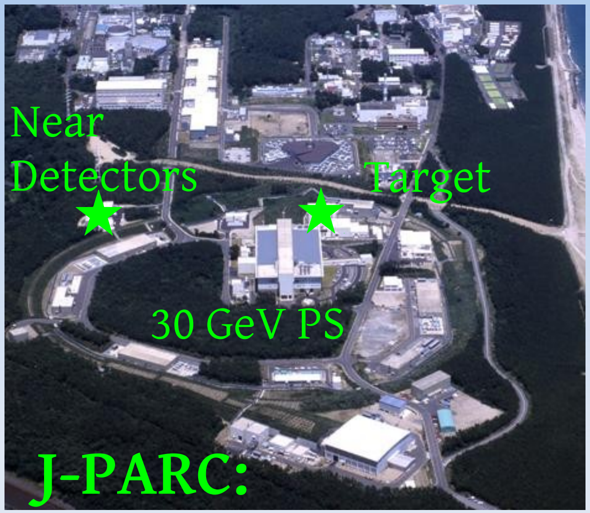
The T2K Experiment





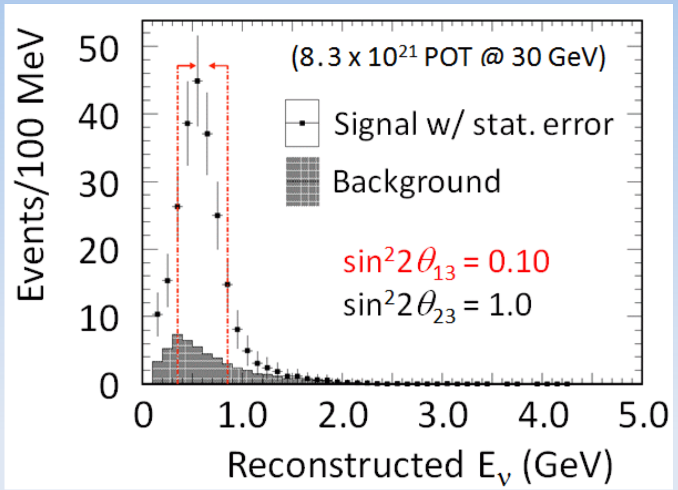


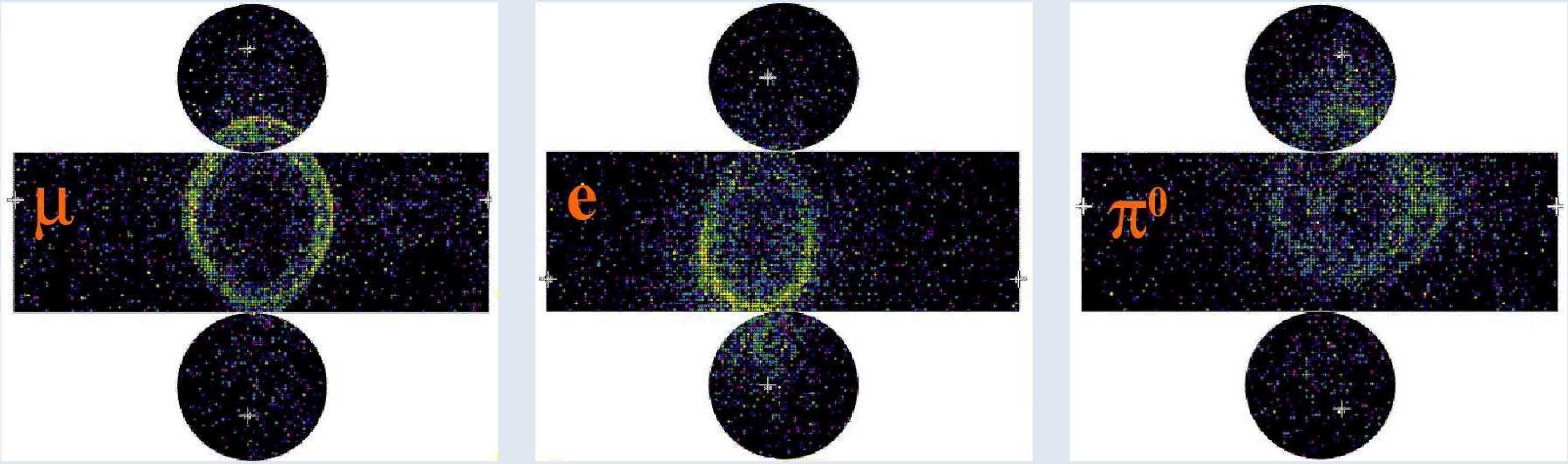
Japan Proton Accelerator Research Complex

- At J-PARC, the world's most intense neutrino beam is created
- 280m from the production target, beam passes through set of near detectors, used to characterise the beam before oscillation
  - Beam direction & composition monitoring, cross section measurements
- 295km downstream, the beam passes through Super-Kamiokande
  - 50kt water Cerenkov detector, ν_μ disappearance & ν_e appearance measurement

π^0 background to ν_e appearance

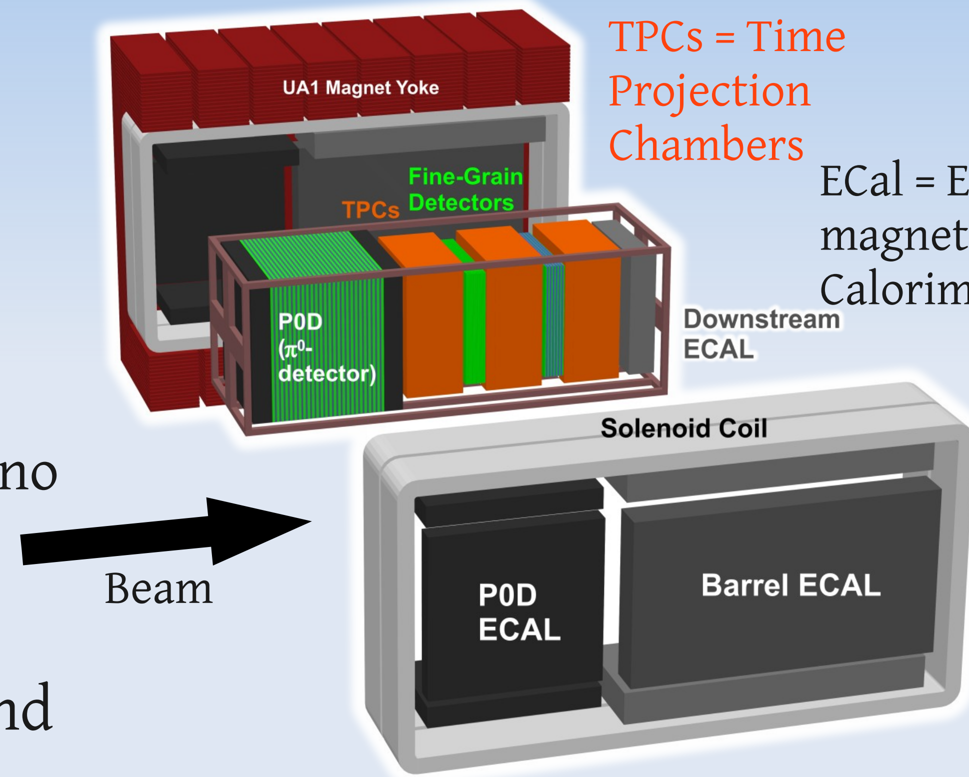
- ν_e signal: 1 e-like ring
- Main backgrounds:
  - ν_e contamination in the beam (~60%)
  - NC π^0 where photon rings misreconstruct as single e-like ring (~40%)





The Off-Axis Near Detector (ND280)

- P0D makes high-statistics measurement of inclusive π^0 production
- Tracker region (TPCs + FGDs) allows for charge, PID determination of tracks
  - FGDs act as targets for neutrino interactions in the region



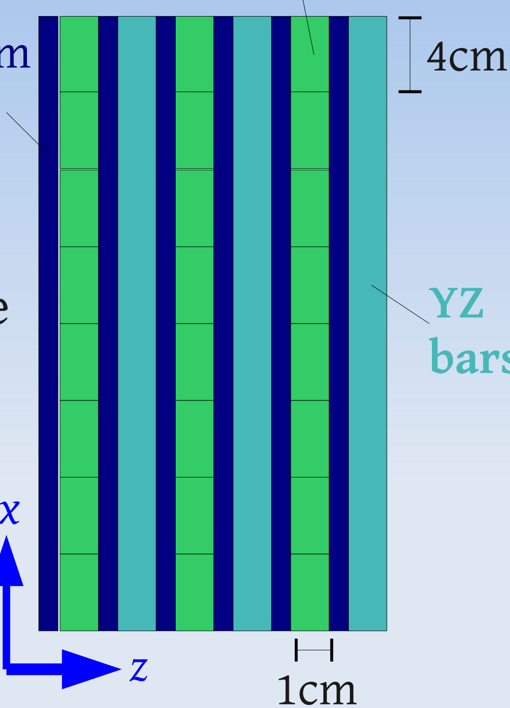
TPCs = Time Projection Chambers

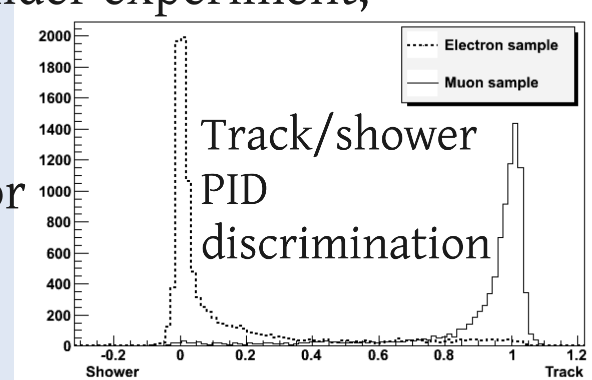
ECal = Electro-magnetic Calorimeter

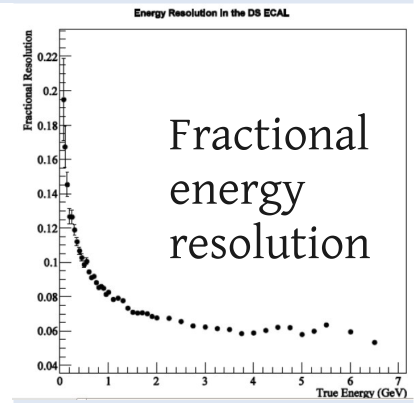
- ECals perform additional PID, make energy measurement, and convert photons
  - This allows for another π^0 analysis using the tracker, to perform a complementary measurement to the P0D. Lower statistics (lower target mass) but higher purity

The ECal modules

- The tracker region is surrounded by 7 ECal modules
- Each is formed of layers of lead and scintillator bars; lead to provide dense material for showering, and scintillator as the active material
- Energy resolution of EM showers: 7%/√E(GeV)
- Modules are used for particle ID
- An important function for π^0 analysis is to provide directional information – this is not a collider experiment, vertex position is unknown
- However, photons from π^0 decays have energies approaching lower thresholds for detection

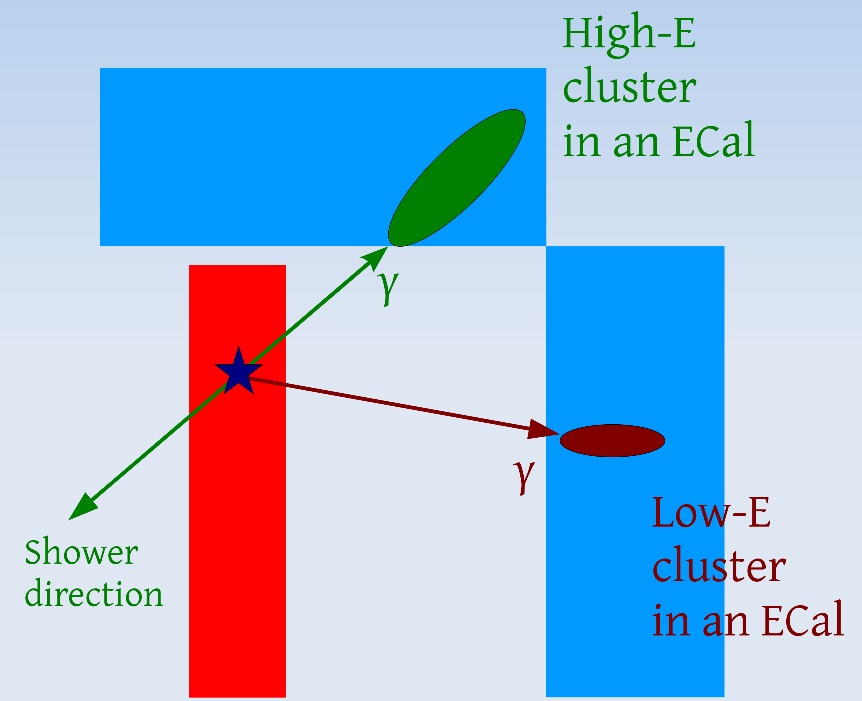






π^0 vertex reconstruction

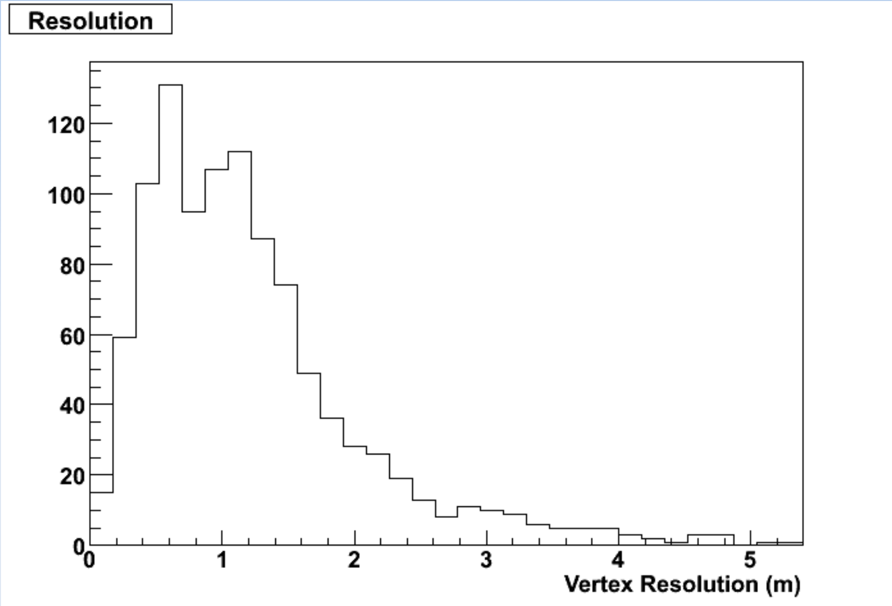
- Given an event with two clusters in the ECals, take the pointing direction of the higher energy cluster, and extrapolate until it intersects an FGD
- Place vertex at the midpoint of this intersection
- Use this vertex as a candidate for a π^0 decay, and assume photons come from this position
- Reconstruct the π^0 mass and momentum, using the energies and directions of the photons

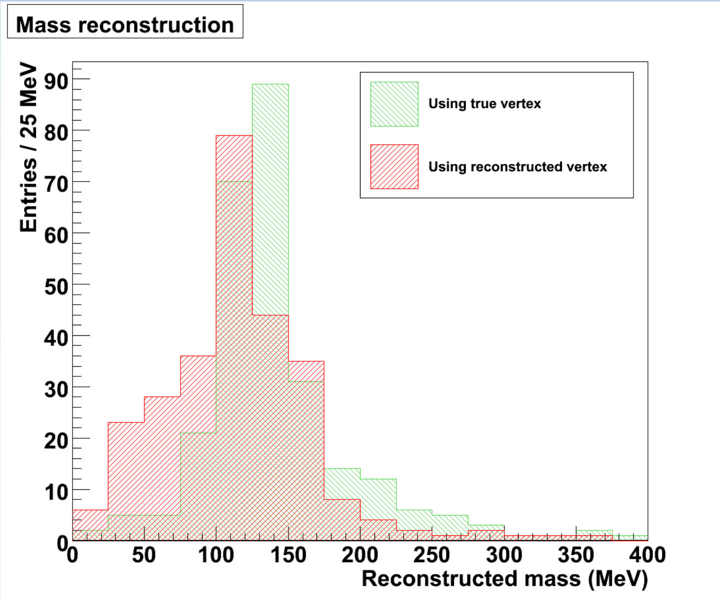


Analysis cuts

- An activity cut in the FGDs
  - NC interactions should produce less hits in the FGDs
- Remove clusters matched with charged tracks in TPCs
  - Currently using truth, as reconstruction is in development
- Time difference cut when matching two views of a single cluster
  - < 10 ns between cluster views
- Maximum energy cut on a single cluster
  - Should remove clusters produced by neutrino interactions in the ECal modules themselves; cut at 600 MeV
- Time difference cut when matching two clusters to a single π^0 candidate
  - < 10 ns between two clusters

Reconstruction performance





- Vertex resolution (recon – true position difference)

- Reconstructed mass. Shown is the mass if the true vertex is used (i.e. only energy resolution effects), and when the reconstructed vertex is used
- Underlines importance of good vertex resolution

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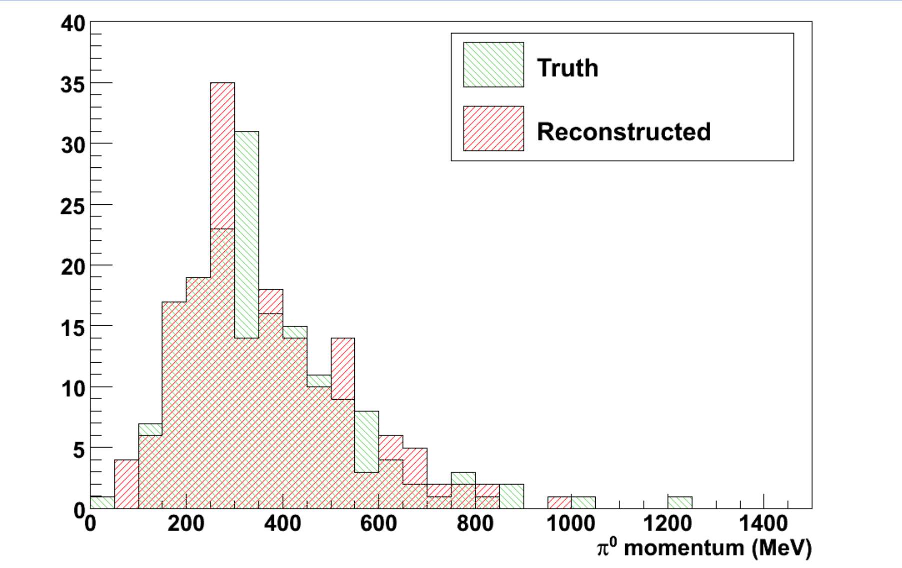
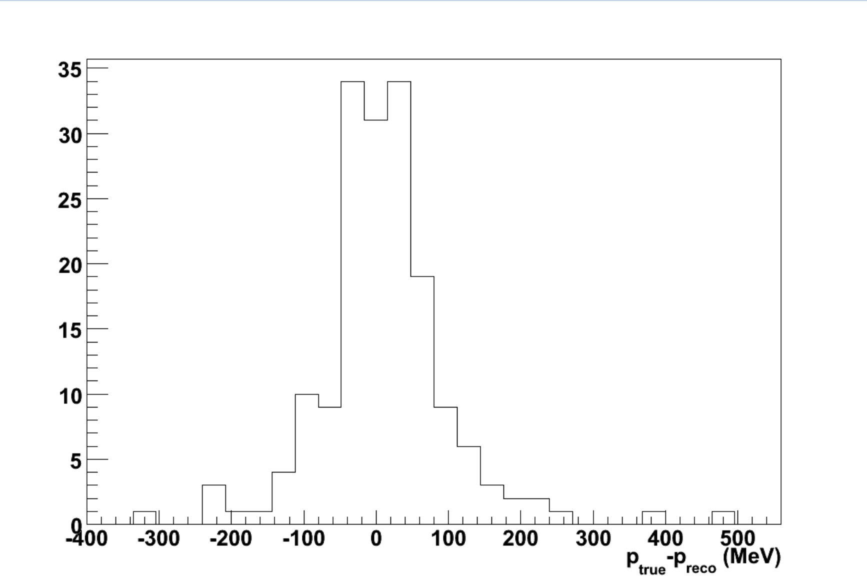
Momentum resolution



- True & reconstructed momentum



- Momentum resolution
- σ ~ 60 MeV

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Improvements to the reconstruction

- Have already begun upgrading the reconstruction
  - Removal of constraint that the vertex has to be in an FGD; now use the intersection of both photon directions
  - Including photon directional resolutions into the vertex resolution
  - Incorporate directional information, i.e. discriminating between particles coming in to the ECal modules from the tracker region, or from the magnet

Summary

- A Neutral Current π^0 analysis in the Tracker region of ND280, using the ECal modules, provides an independent and complementary measurement to the P0D analysis, with different systematics, statistics and efficiencies
- Currently the analysis has an efficiency of ~10% for reconstructing π^0's produced in the FGDs, with no other charged particles produced in the interaction
- ~120/yr reconstructed events expected
- Reconstruction is still in development, and these numbers will hopefully improve

Backup

Photon shower pointing

- An important requirement of the ECal modules is to provide directional information for photon showers
  - This isn't a collider experiment – the vertex position is not localised
- Take the shower origin as mean hit position in the innermost layer
- Adapting a “thrust” algorithm (used in other HEP experiments, e.g. BaBar), the direction is taken as the axis **a** which maximises the quantity t (thrust) given by:

$$t = \frac{\sum |a \cdot P|}{\sum \sqrt{P \cdot P}}$$

- Here, **P** is the position vector of each hit relative to the shower origin