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Neutral Current π^0 Interactions in the T2K Near Detector

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IoP Joint HEPP and APP Meeting

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Outline

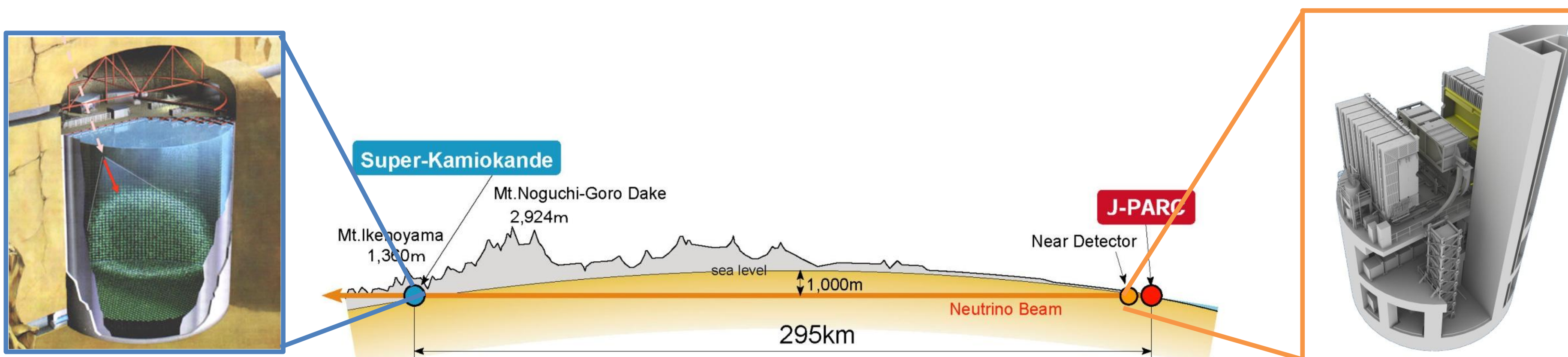
- An overview of the T2K experiment
- Neutral current (NC) π^0 interactions
  - Background to ν_e appearance analysis
  - Using the T2K near detector ND280
  - Motivation for selection: where do the photons go?
  - Definition of signal
  - Selecting protons
  - Selecting photons
- Time calibration of the ECAL

The T2K Experiment

The Tokai to Kamioka (T2K) experiment is a long baseline neutrino experiment in Japan.

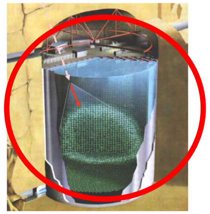
It was designed and built to answer two big questions in neutrino physics:

1. Is θ_{23} maximal?
2. What is the value of θ_{13}?
   Is it non-zero?



Super-Kamiokande

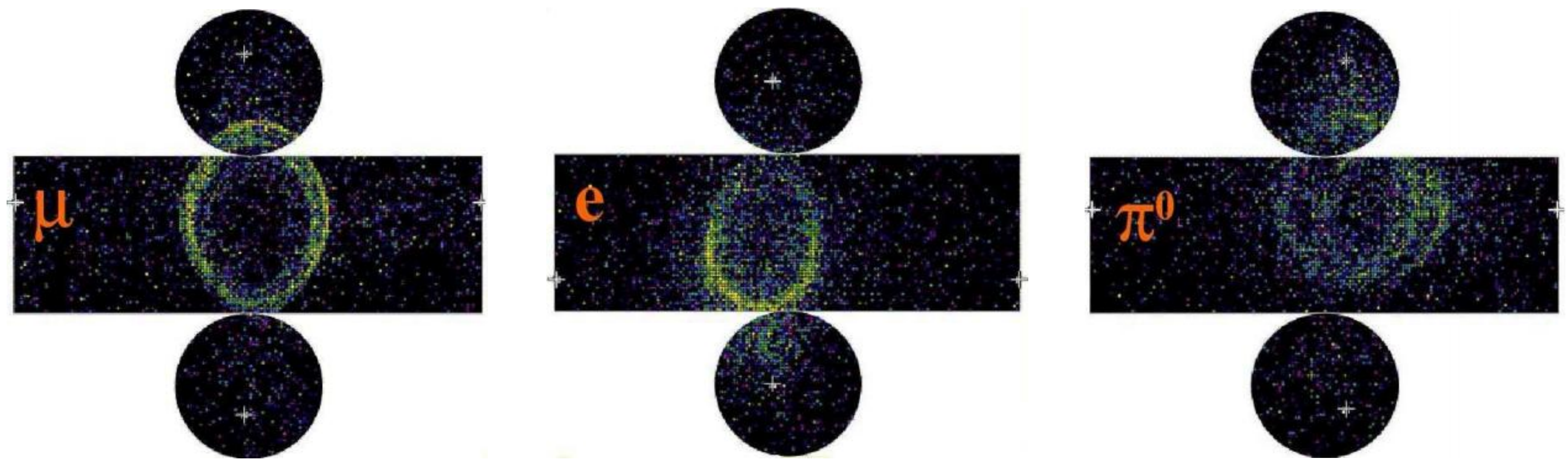
Near detector suite



Background to ν_e Appearance

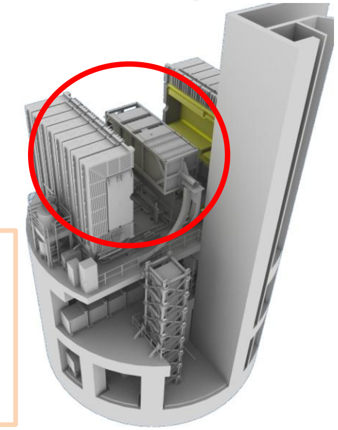
The main backgrounds to the current ν_e analysis are:

1. ν_e contamination of the beam (~60%)
2. $NC\pi^0$ events that are mis-reconstructed (~40%)



The ND280 Detector

– Characterises the beam before neutrinos oscillate.
– Measures neutrino cross-sections.

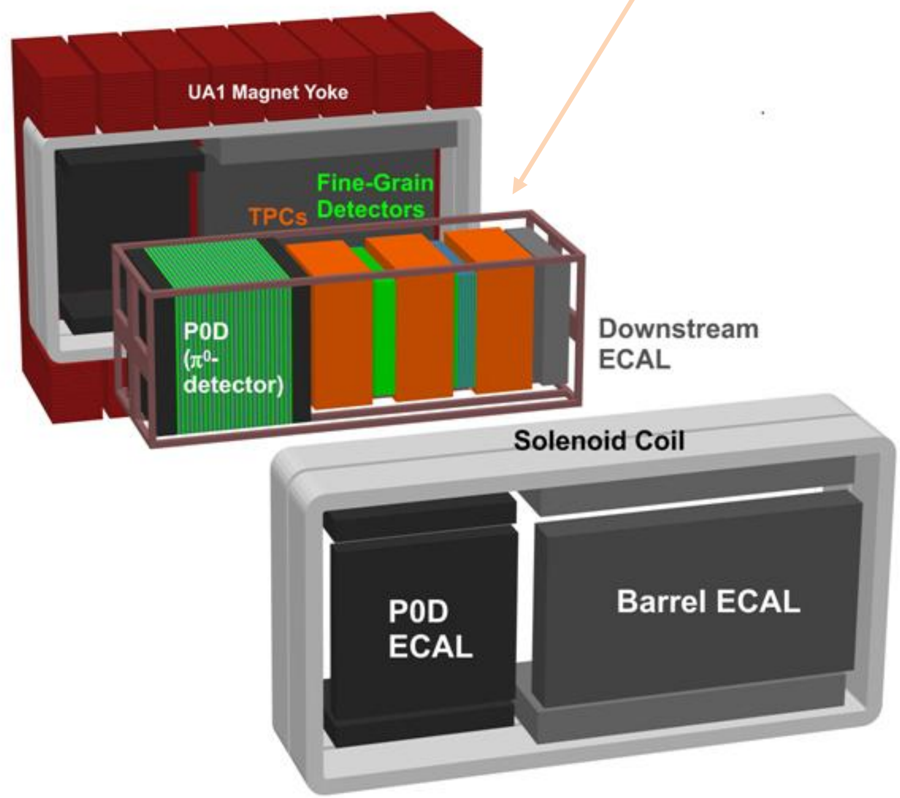


Magnetic Field: 0.2T

Tracker (FGDs + TPCs): optimised for measuring the momenta of charged particles (μ, e, p and $\pi^{\pm}$).

Electromagnetic Calorimeter:

- Consists of alternating layers of plastic scintillator and lead.
- Read out is done by Multi-Pixel Photon Counters (MPPCs).
- Used to detect electromagnetic energy (photons produced in π^0 decay).
- Aids in particle ID.

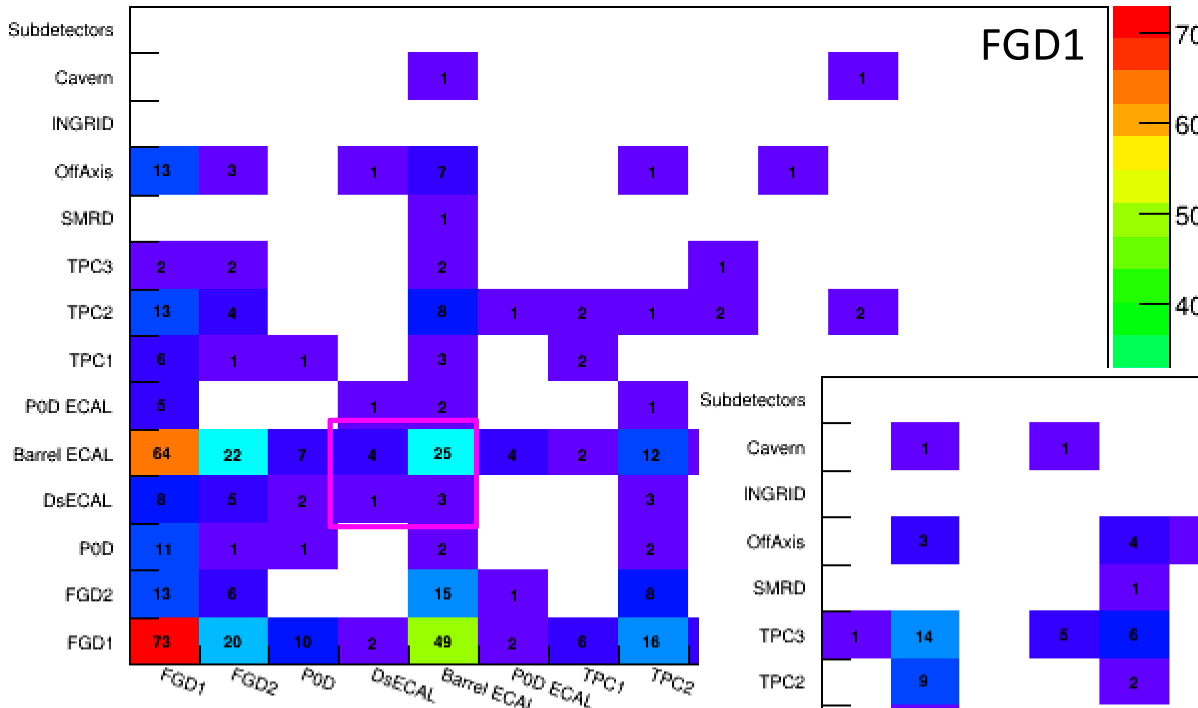


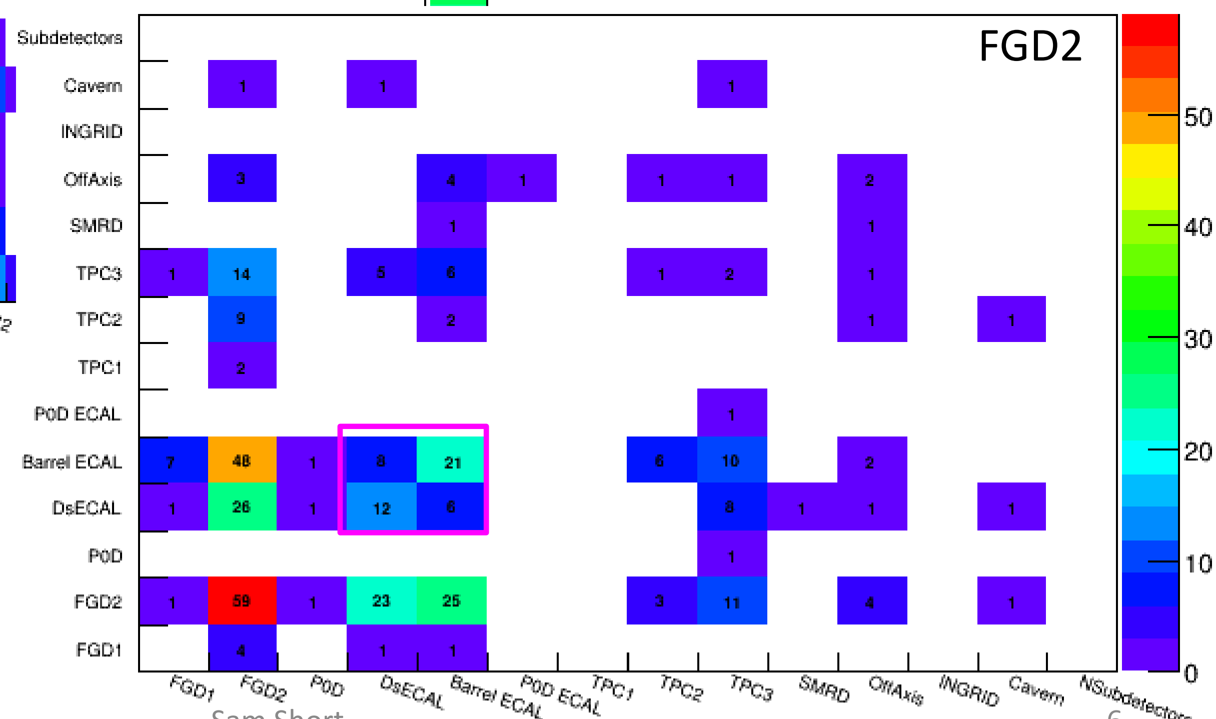
FGDs: provide active targets for neutrino interactions.

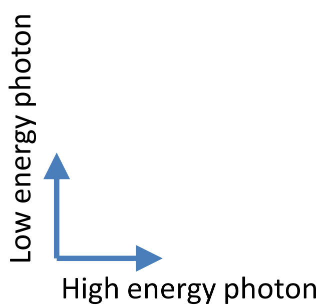
Time Projection Chambers: High resolution tracking chambers.

Motivation For Selection

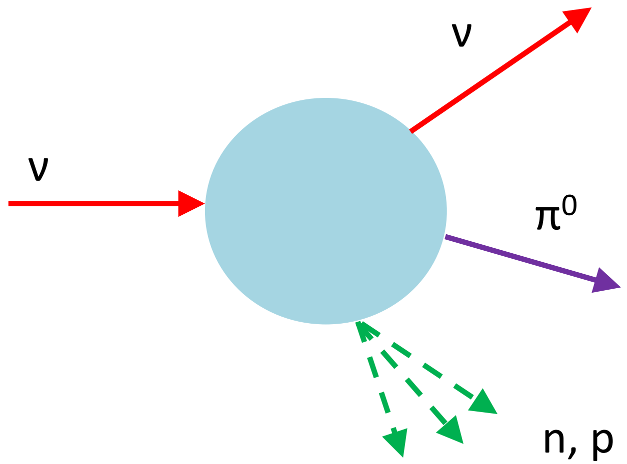
Where do the photons from NC π^0 interactions go?







Selecting NCπ^0 Interactions

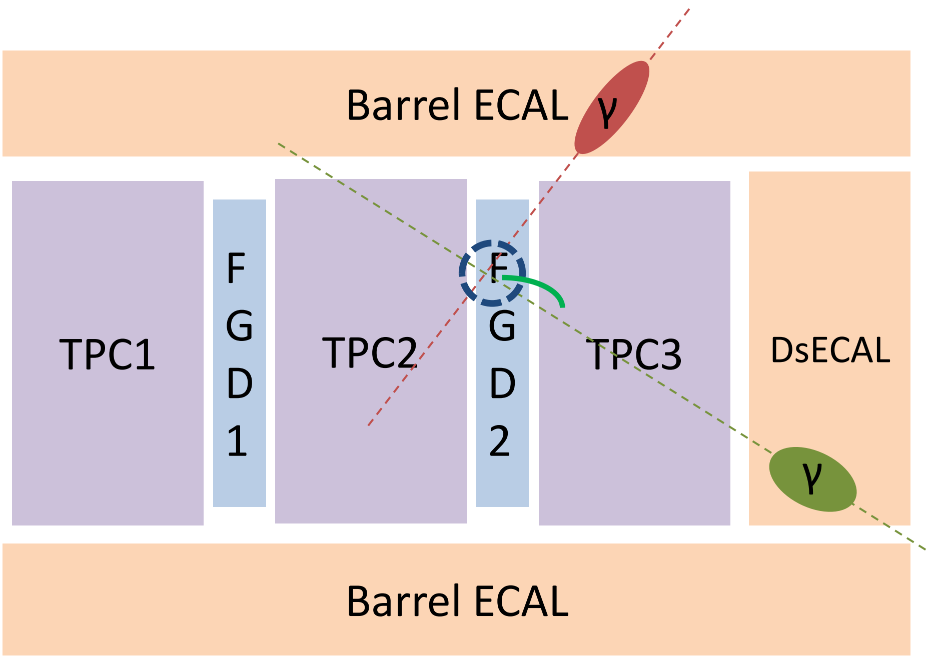


Definition of Signal:

- Interaction is neutral current
- Occurs in an FGD
- 1 π^0 in the final state
- Any number of nucleons
- No other final state particles

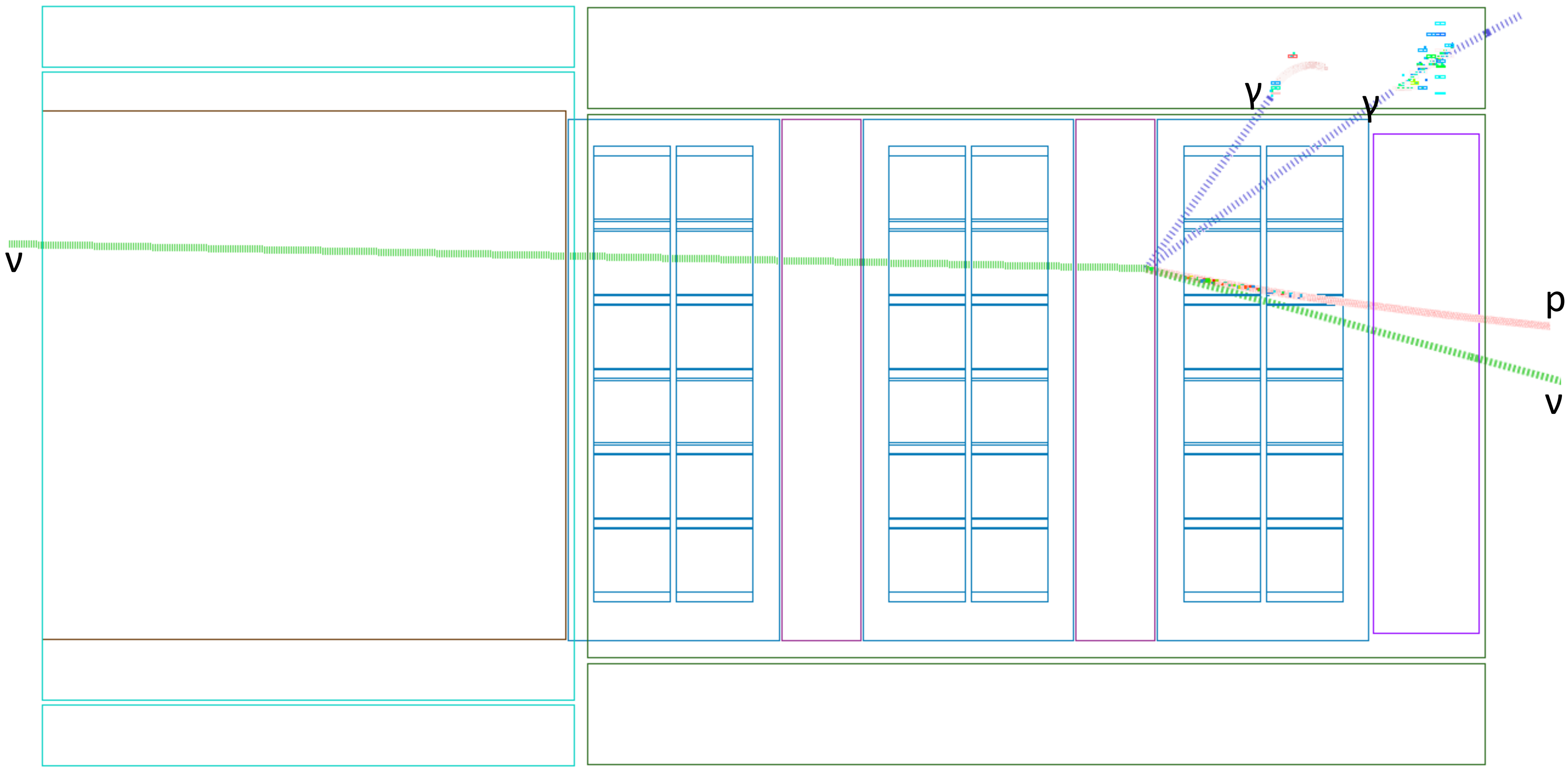
Looking for Signal in Detector:

- π^0 decays to 2 photons
- **Both** photons convert in the ECAL (barrel or downstream)
- Can use protons to help locate the vertex



Selecting NCπ^0 Interactions

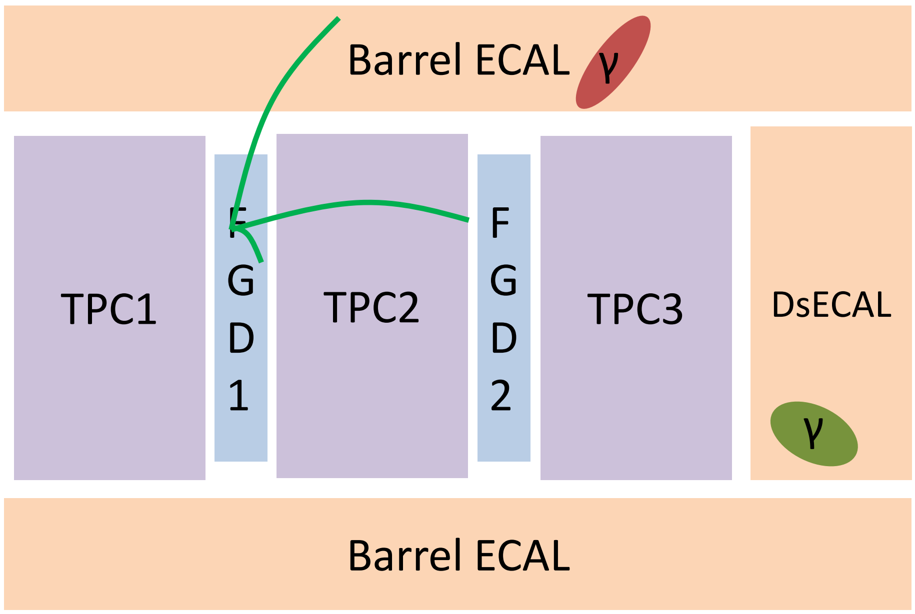
Example of a "golden" signal interaction



Selecting NCπ^0 Interactions

Require all tracks are proton-like

- Have **three** sources of information for selecting proton-like tracks:
  - **TPC**: pulls calculated using measured and expected dE/dx values
  - **FGD** : pulls calculated using measured and expected dE/dx values
  - **ECAL**: use charge per unit length of the track



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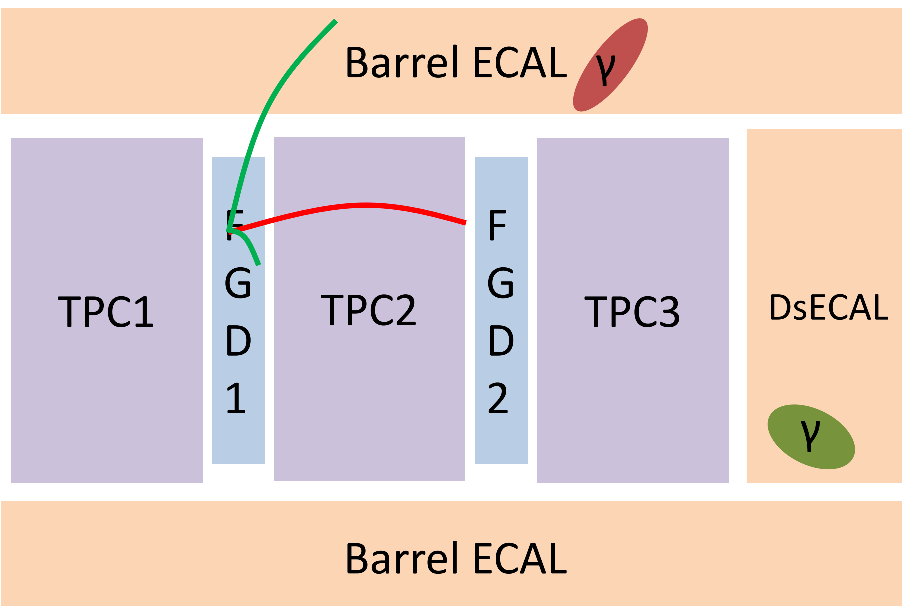
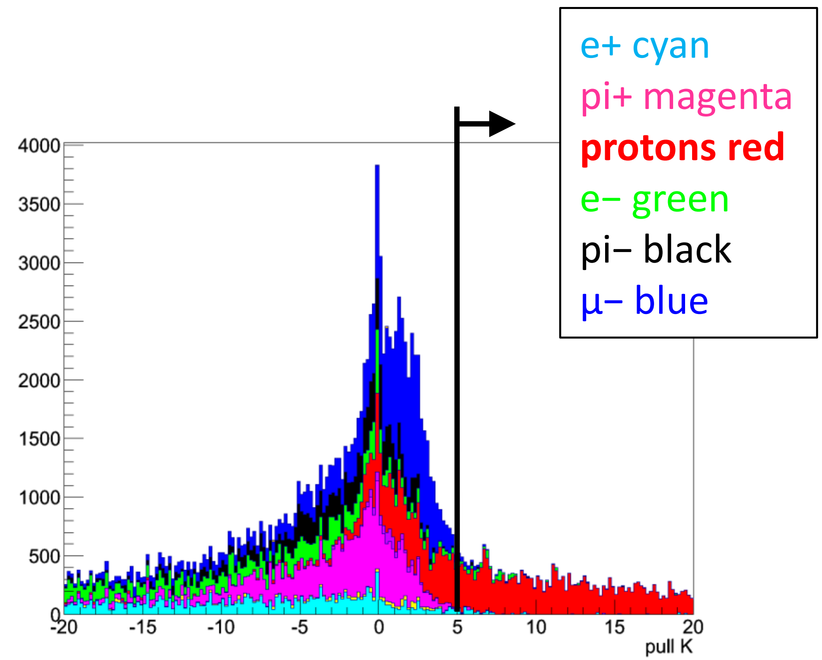
Selecting NCπ^0 Interactions

Require all tracks are proton-like

Use TPC pulls





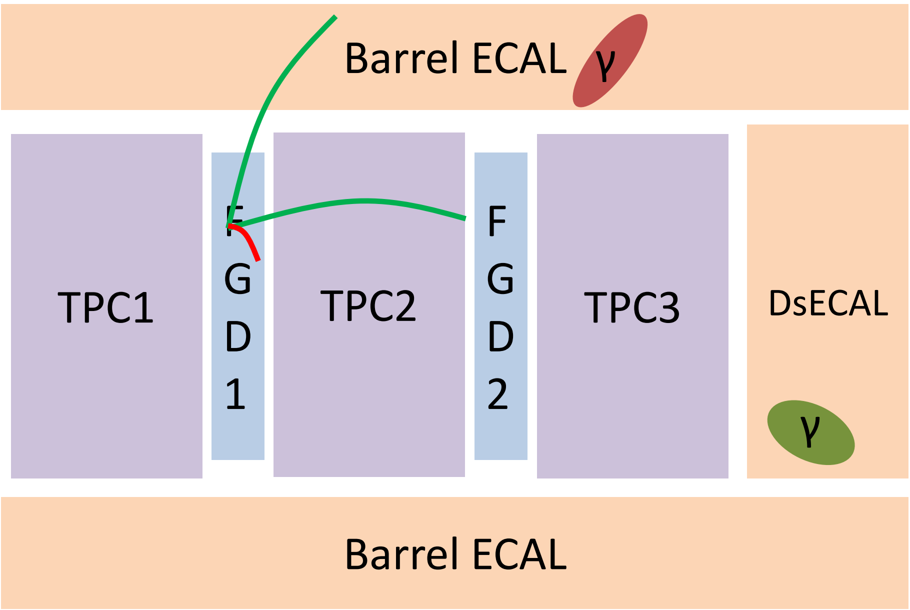
Efficiency = 34%

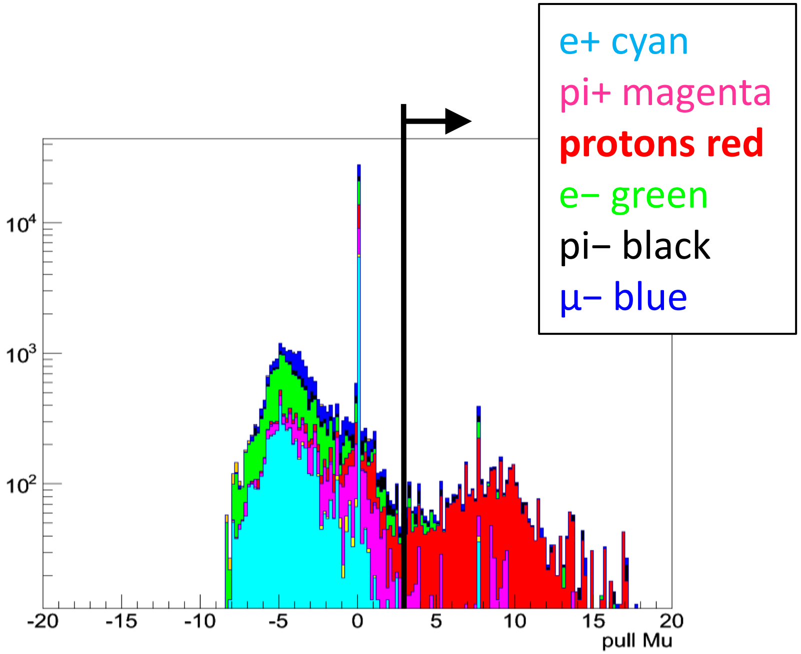
Purity = 86%

Selecting NCπ^0 Interactions

Require all tracks are proton-like

Use FGD pulls



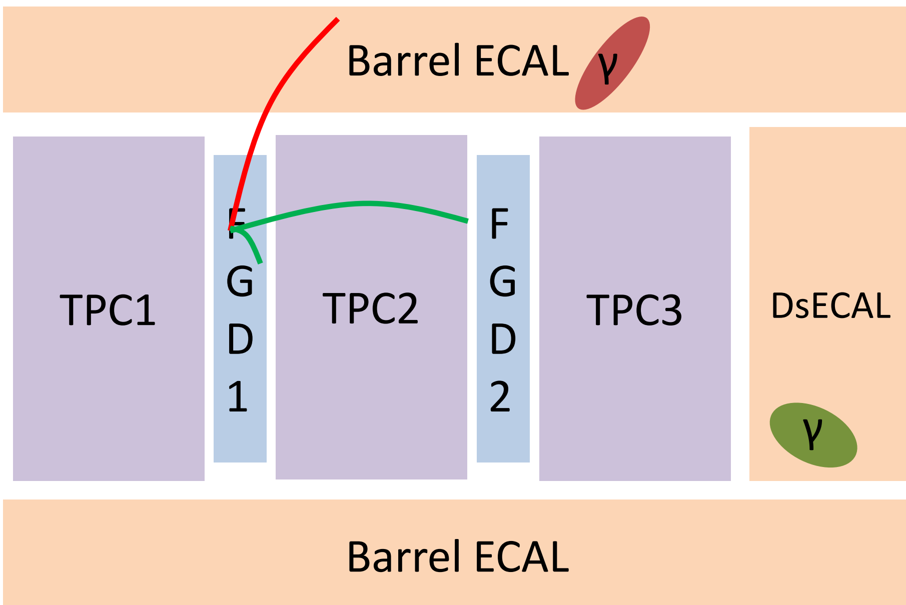


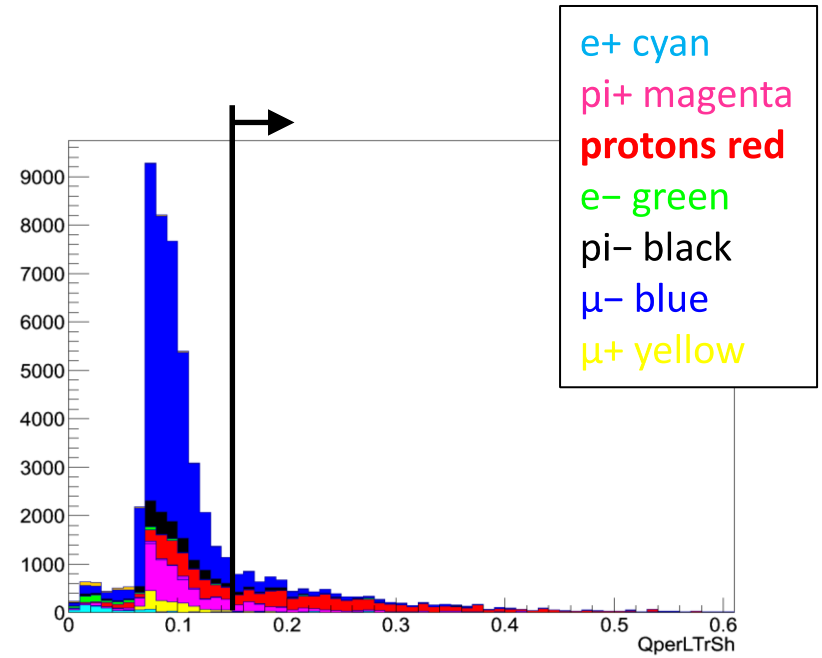
Efficiency = 33%
Purity = 65%

Selecting NCπ^0 Interactions

Require all tracks are proton-like

Use ECAL charge per unit length





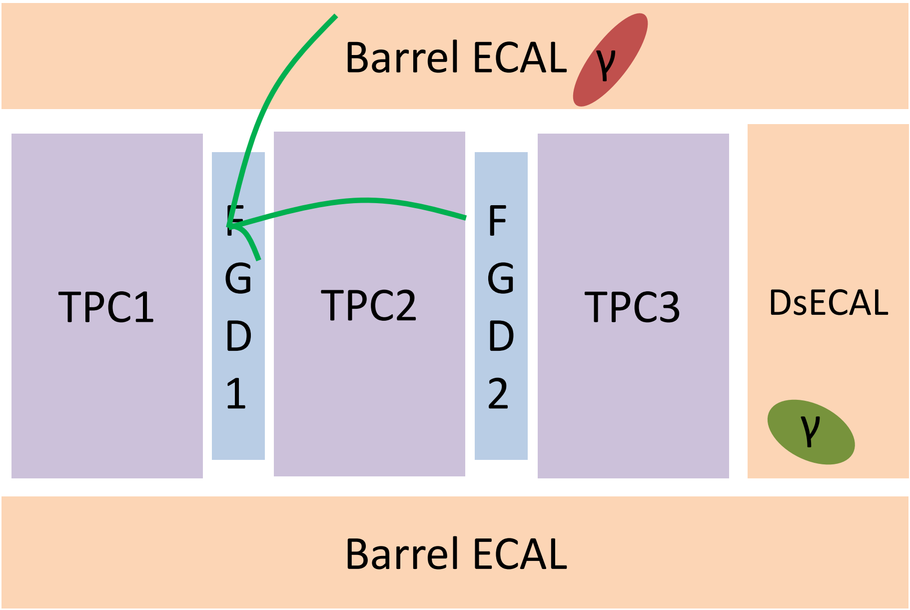
Efficiency = 32%
Purity = 64%

Selecting NCπ^0 Interactions

Require all tracks are proton-like

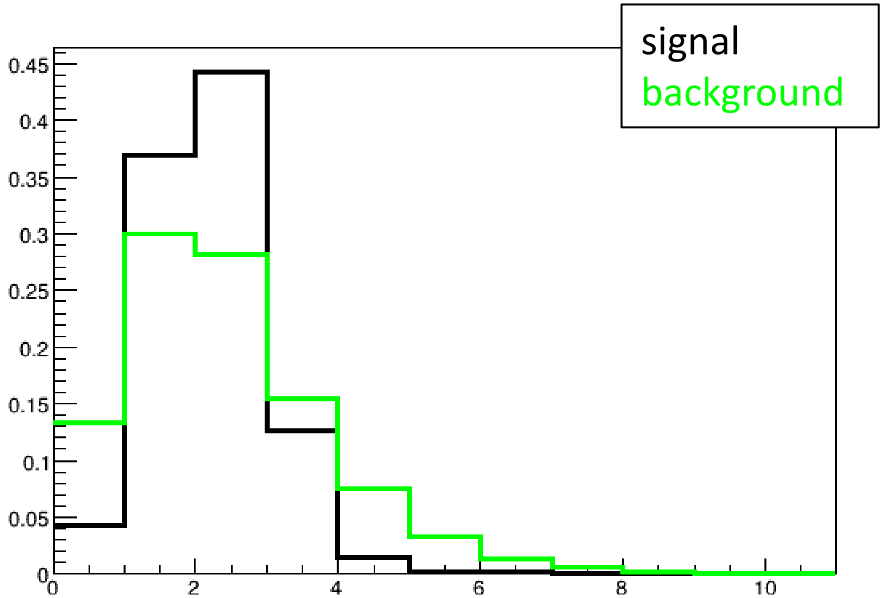
- Using the **three** sources of information have efficiency and purity for selecting proton-like tracks of:

Efficiency = 34%
Purity = 86%

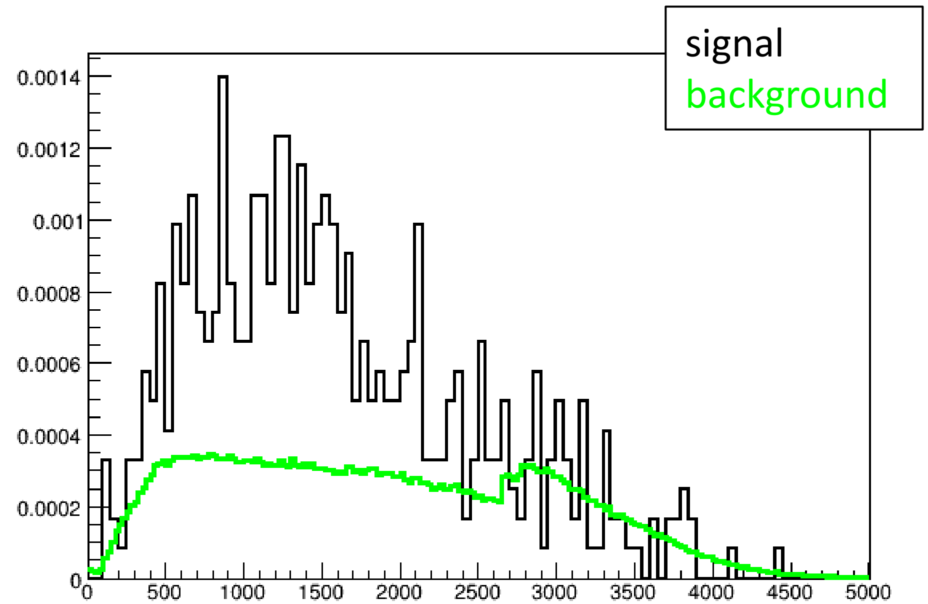


Selecting NCπ^0 Interactions

ECAL variables



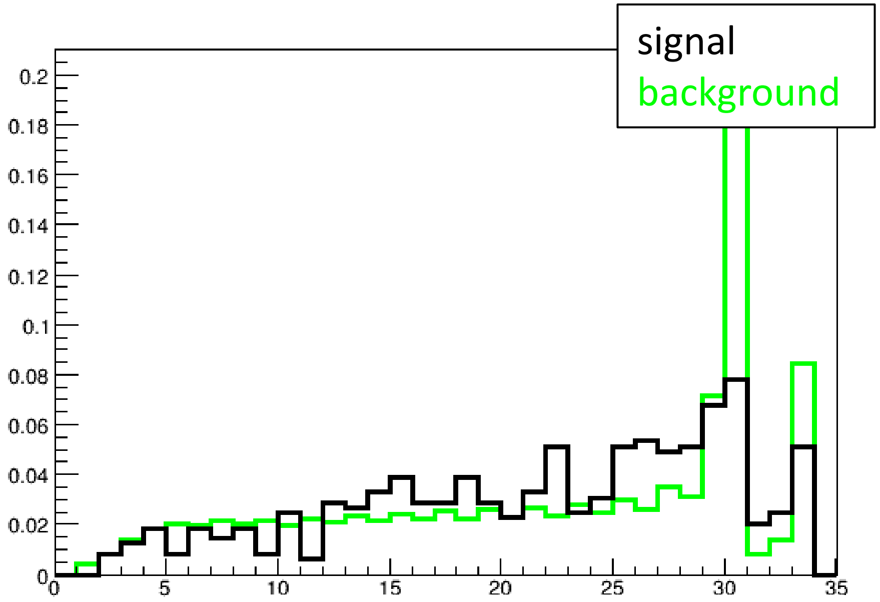
Number of reconstructed ECAL clusters



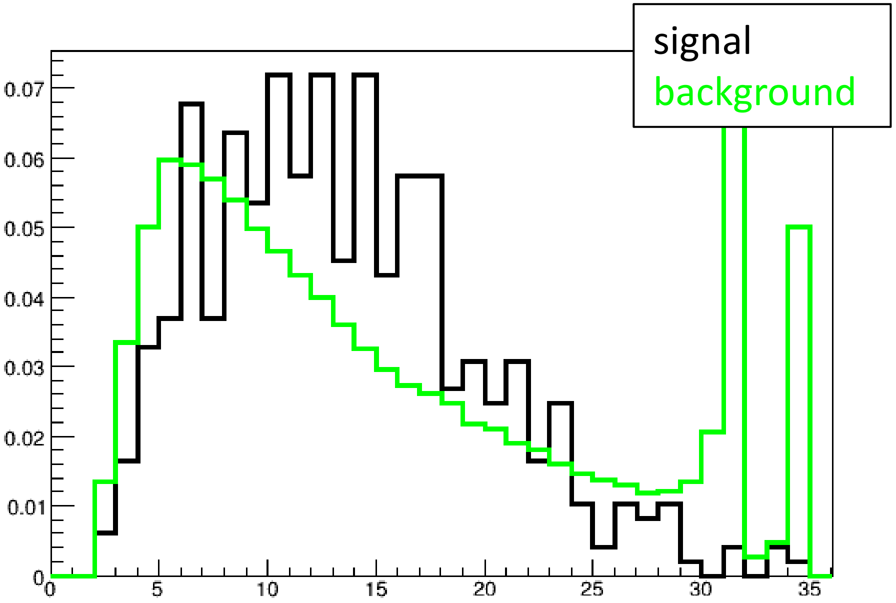
Distance between ECAL clusters (mm)

Selecting NCπ^0 Interactions

ECAL variables



Most outside ECAL layer hit

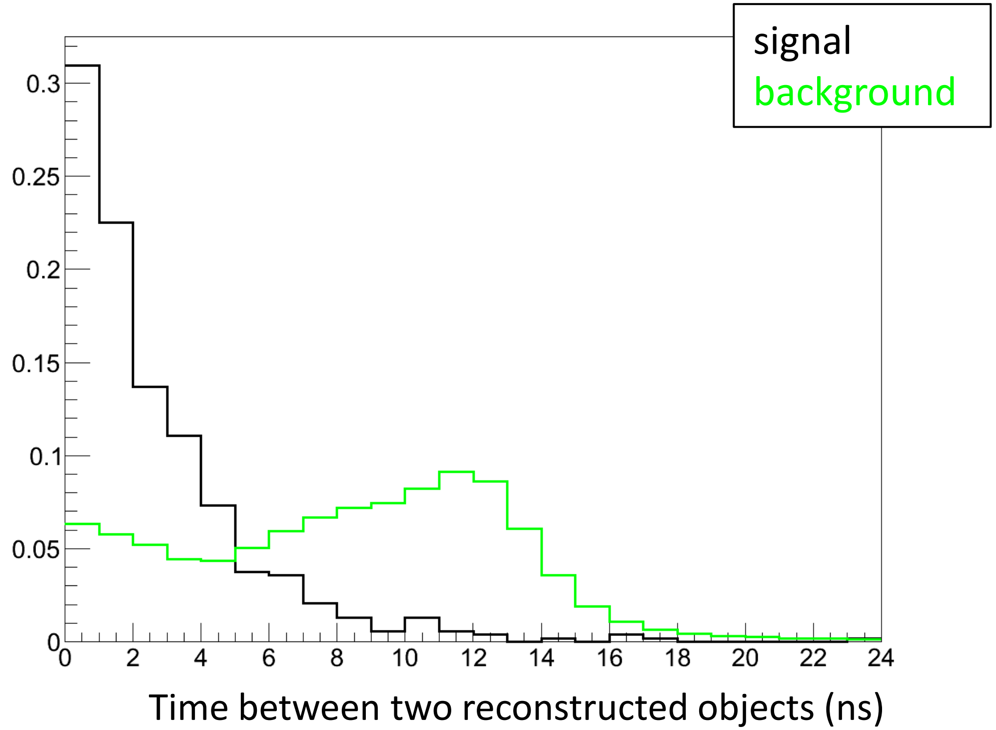


Number of layers hit

Selecting NCπ^0 Interactions

Time between ECAL clusters

- One of the cuts used to select the signal is the time between the photon candidates in the ECAL.



- Good ECAL time calibration is essential!

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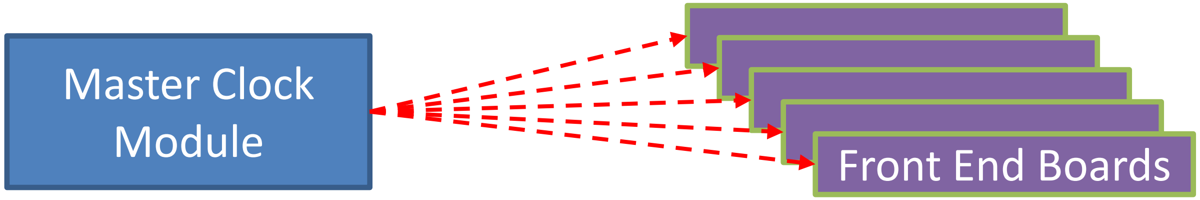
ECAL Time Calibration

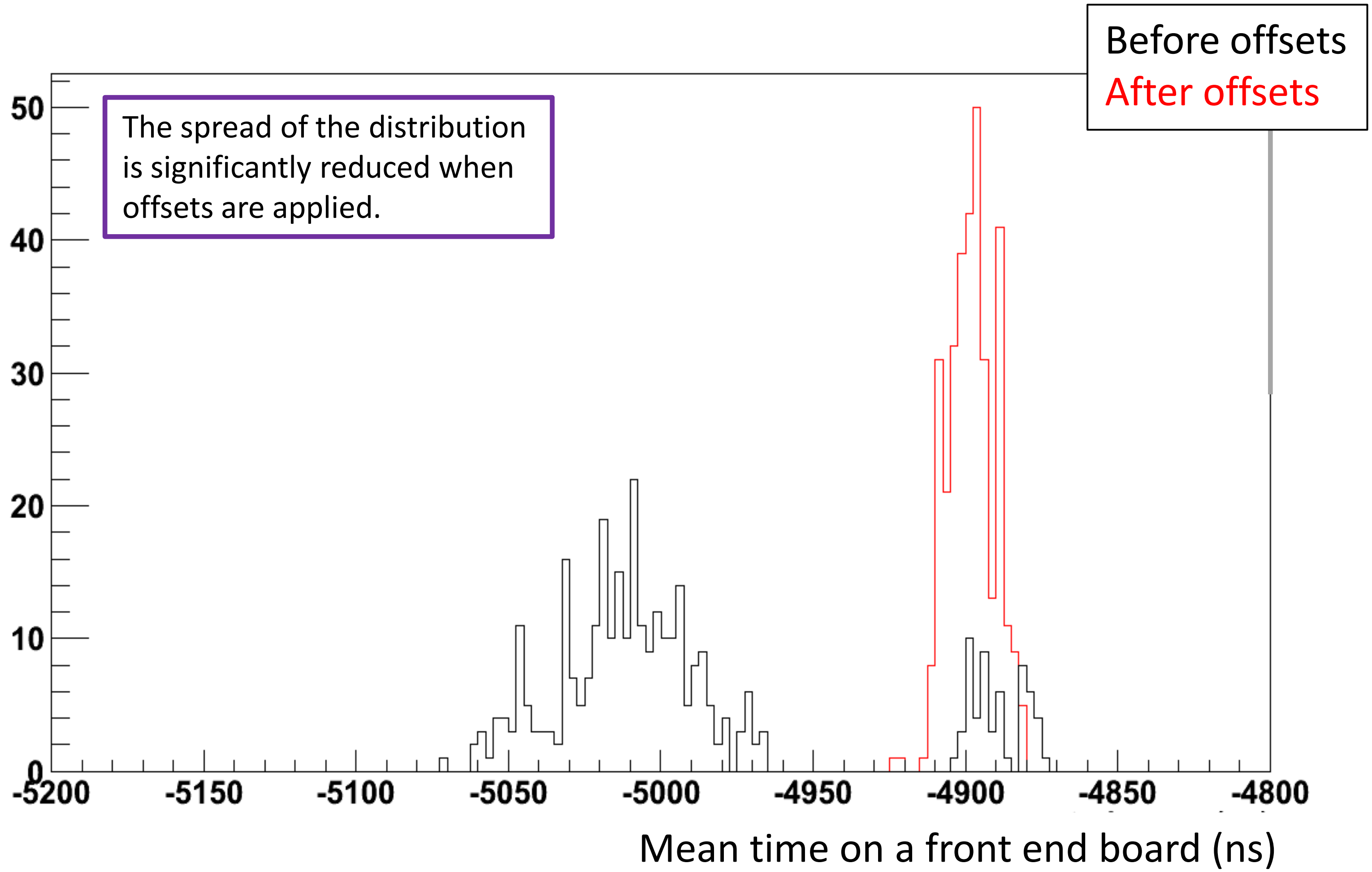
- Good time calibration is also important for:
  - Rejection of noise hits
  - Clustering of hits
  - Cross-subdetector track matching
  - Particle direction determination
- The cables connecting the electronics boards have different lengths → **time offsets**.



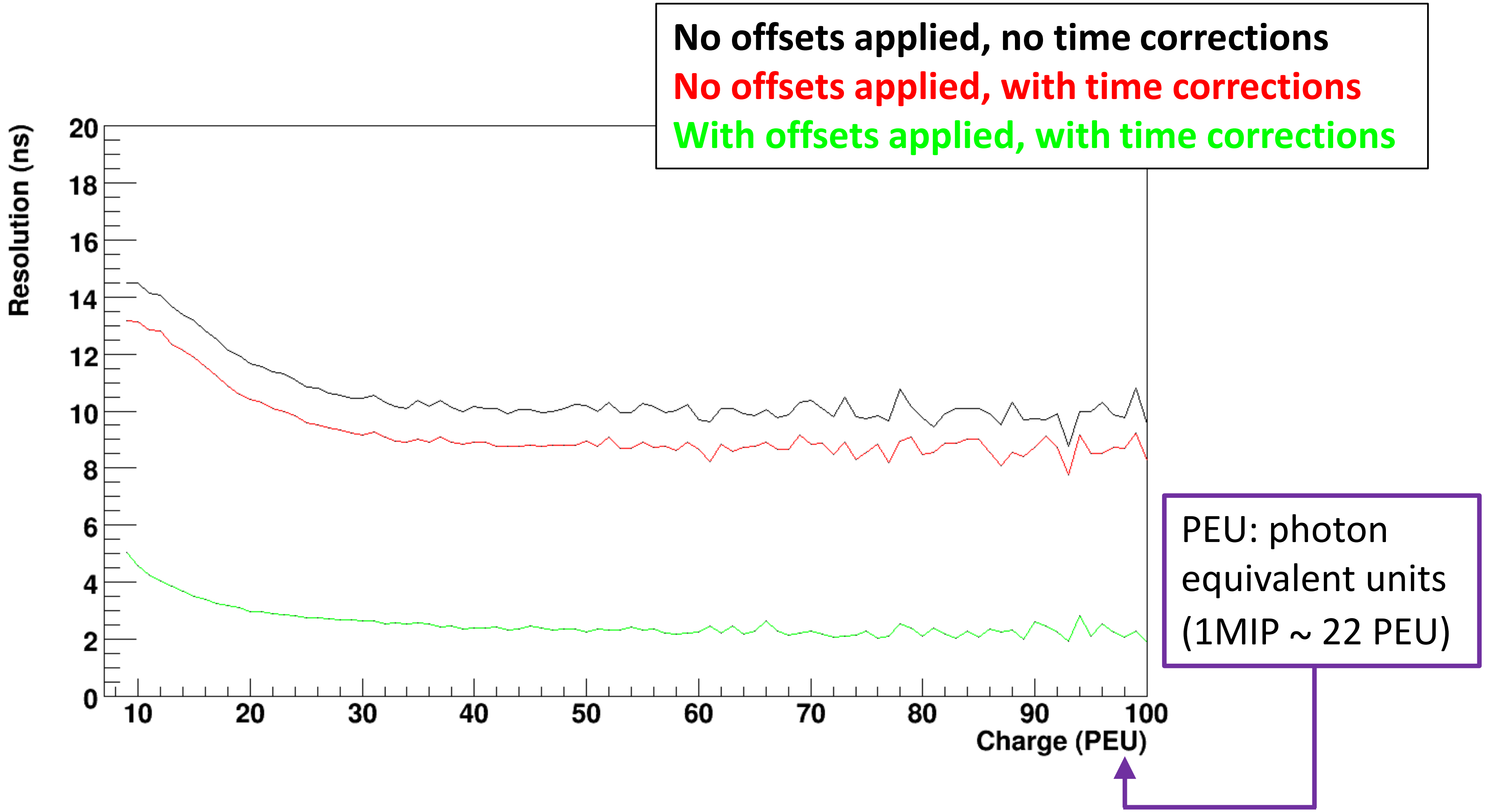
- Use an event by event method to align the time on each board.

ECAL Time Calibration

Mean time on a front end board before and after time offsets were applied.



ECAL Time Resolution



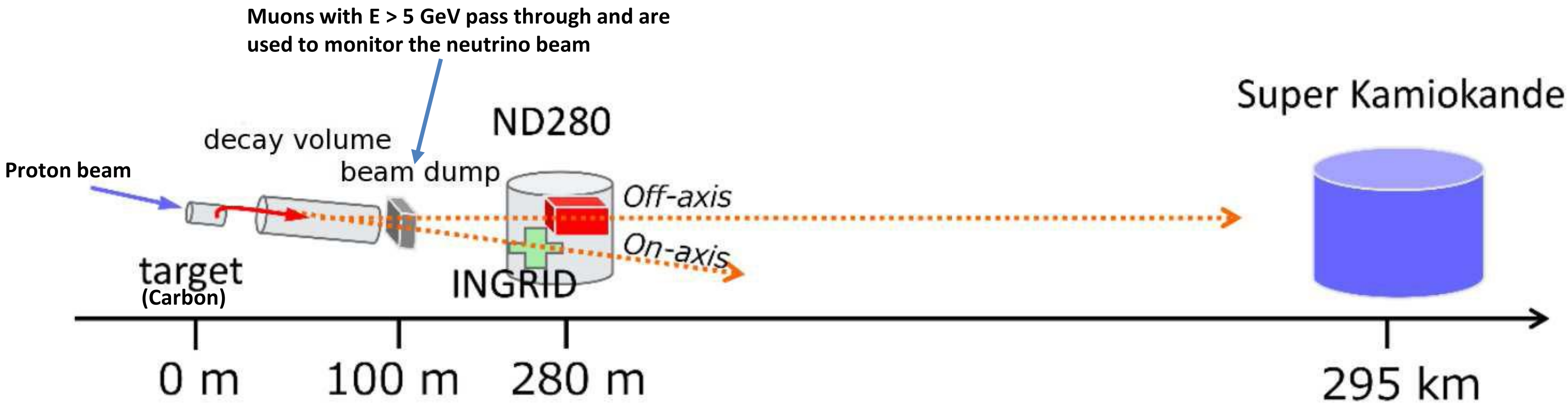
For high charge hits achieve a resolution of approximately 2.5ns, whereas for low charge hits this is around 5ns.

Summary

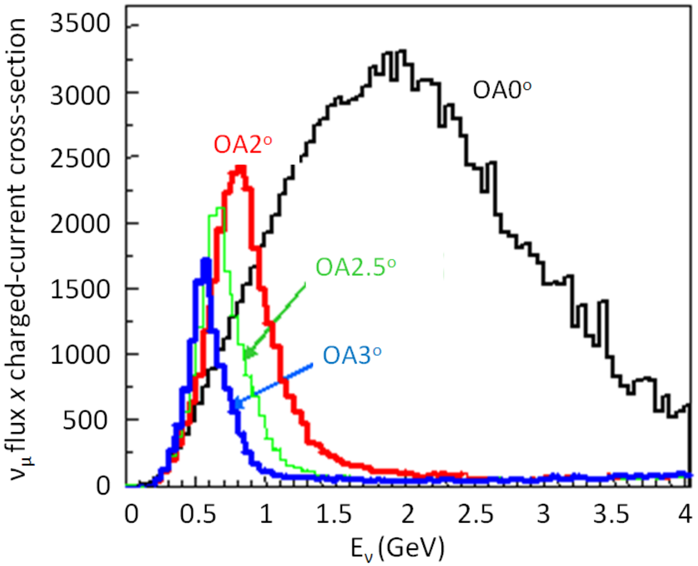
- π^0 from neutral current interactions are a major background to the ν_e appearance analysis
- We can select NC π^0 interactions by looking for:
  - Photons from π^0s that convert in the barrel and downstream ECAL
  - Protons in the tracker
- To remove background events:
  - Make a cut on the time between ECAL clusters (requires good time calibration)
  - Will use reconstructed π^0 invariant mass
  - Currently investigating other ECAL variables to use
  - Will look into using an MVA
- Achieved a resolution of 2.5ns for high charge hits in the ECAL

Supplementary Slides

Neutrino Beam



- Off-axis beam reduces the spread of muon neutrino energies.
- Chosen off-axis angle is 2.5° which corresponds to a peak beam energy of 0.7 GeV.



Three Flavour Neutrino Oscillations

- Flavour eigenstates are a linear combination of mass eigenstates ν_i where i = 1, 2, 3, given by:

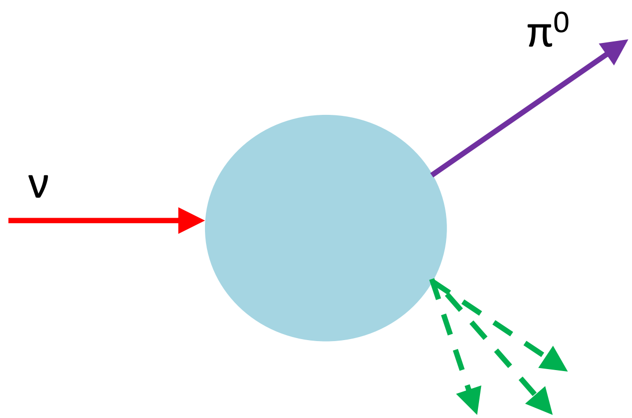
$$|\nu_\alpha\rangle = U_{\alpha i}|\nu_i\rangle$$

$$U \equiv \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- Neutrino produced in state $|\nu_\alpha\rangle$ at a time t later it will be in state $e^{-iE_i t}|\nu_\alpha\rangle$
- Oscillation probability:

$$P(\nu_\mu \to \nu_e; t) = \left|U_{ei} e^{-iE_i t} U^*_{\mu i}\right|^2 = \left|\langle \nu_e | \nu(t)\rangle\right|^2$$

Protons in NCπ^0 Interactions

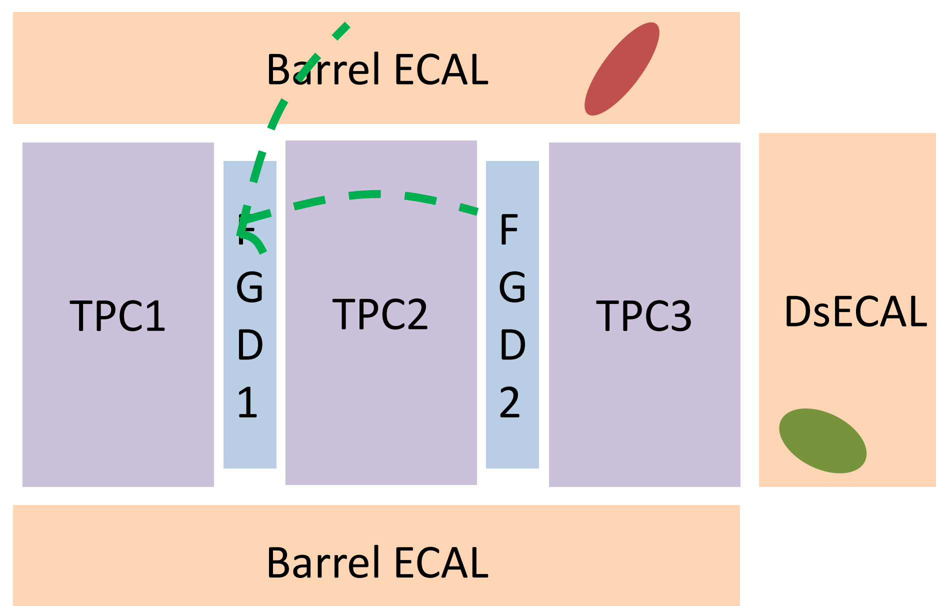


Where do they go?

Final Subdetector	% of Signal Events
FGD1	28.1
FGD2	37.44
P0D	0.06
DsECAL	13.88
Barrel ECAL	7.02
TPC1	0.11
TPC2	3.48
TPC3	5.48
SMRD	0.39
Off Axis	2.49
Cavern	1.55

How many are produced?

Number of FSI Protons	% Signal Events
0	14.57
1	53.46
2	15.82
3	7.83
4+	8.33



Reconstructing a Vertex

- Apply the proton cuts outline on previous slides.
  - Require all tracks in the event are proton-like.
- Then, have the following information available:

	Information Available	% of Candidate Events
1	Tracker tracks	8.64
1.1	1 track	8.03
1.2	2 tracks	0.55
1.3	3 tracks	0.05
1.4	4+ tracks	0.01
2	Unused FGD hits	91.36
3	No tracker information	0

Use the charge weighted hit position as the interaction vertex.
If there are two, choose the one with the largest total charge.

Take the start of the global track as the vertex.

TFB Offset Calculation

- Need a method to calculate TFB offsets for the barrel ECAL modules.
  - SMRD towers (used for triggering) have different cable lengths – this affects the time relative to trigger, as a latency is introduced.
    - Cannot compare hit times from different events, as they may have triggered on different towers.
  - Also, cosmics with different ECAL detector combinations have different times.
    - i.e. consider a track going through the top ECAL -> DsECAL – this will have late times in the DsECAL. However, a track going through the DsECAL -> bottom ECAL will have early times in the DsECAL.
- Use an event by event method to calculate the offsets.

TFB Offset Calculation

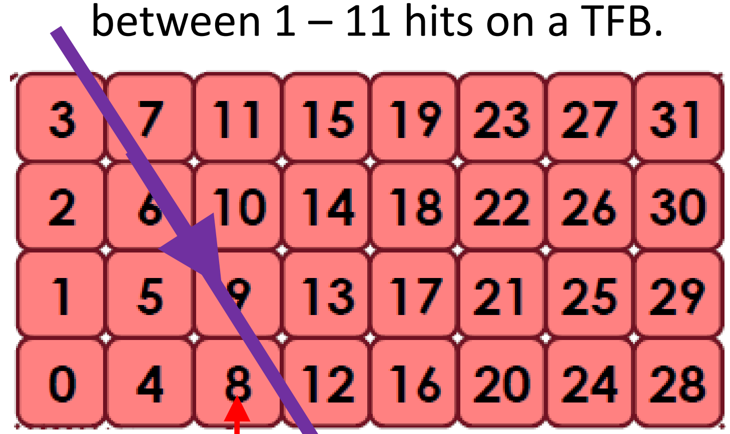
Outline of the event by event method.

- As there are no events with hits in every TFB need to correct e.g. TFBa back to TFBb in every event it occurs in.
  - Need a mapping of TFBs for all events, to determine which TFB combinations occur together most frequently.
  - Use Prim's algorithm.
- So, loop over all of the events and determine these combinations.
- For example, for RMM0 the combinations of TFBs occurring most frequently are:

0&2, 0&10, 0&6, 0&4, 0&3, 0&1, 4&5, 6&9, 6&7, 6&15, 7&8, 9&11, 10&25, 10&20, 10&14, 10&12, 10&19, 10&17, 11&23, 12&24, 12&21, 12&16, 12&13, 15&18, 20&22, 21&27, 25&26

(This is calculated every time the offsets are calculated, it is not hard coded.)

This event has hits in TFB 3, 7, 6, 9, 8, 12. Generally, there are between 1 – 11 hits on a TFB.

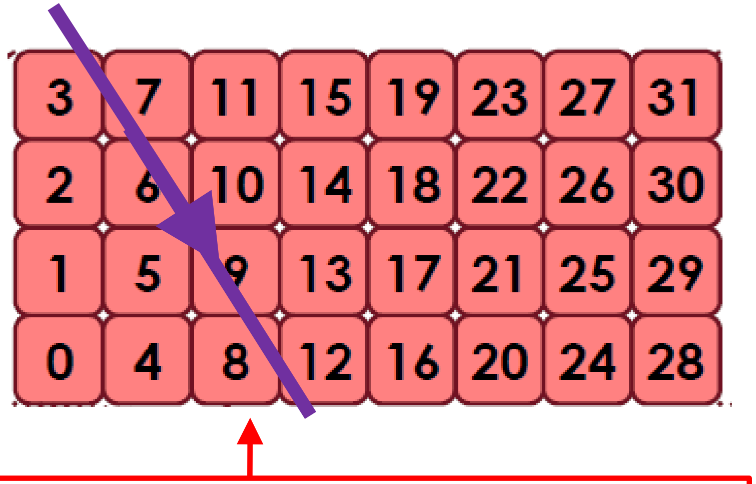


This is not the actual position of TFBs in an ECAL module.

TFB Offset Calculation

- For each event:
  - Correct for the time of flight and time taken for light to travel down the bar.
  - Iterate over the TFBs in that event to find “mapped pairs” outputted from Prim’s algorithm.
  - This example has three:
    - TFB6 & TFB9
    - TFB6 & TFB7
    - TFB7 & TFB8
  - Determine the mean hit time for these TFBs.
    - As there are many hits per TFB.
  - Save the difference in the mean:
    - i.e. meanTFB6 – meanTFB9
- Repeat this for every event.

This event has hits in TFB 3, 7, 6, 9, 8, 12.



This is not the actual position of TFBs in an ECAL module.

TFB Offset Calculation

- Finally, determine the offset for each TFB with respect to the first TFB on that RMM.

$$\text{If } O_i \text{ represents the local offset between TFB}_i \text{ and TFB}_{i+1}$$
$$\text{Global offset for } TFB_i = O_0 + O_1 + \ldots + O_{i-1}$$

- i.e. the offset for TFB 8 is calculated as follows:
  – (TFB0 – TFB6) + (TFB6 – TFB7) + (TFB7 – TFB8).
- Due to the nature of Prim’s algorithm, there is only one “route” to get the TFB offsets per TFB.

Prim's Algorithm

A greedy algorithm that finds a minimum spanning tree.

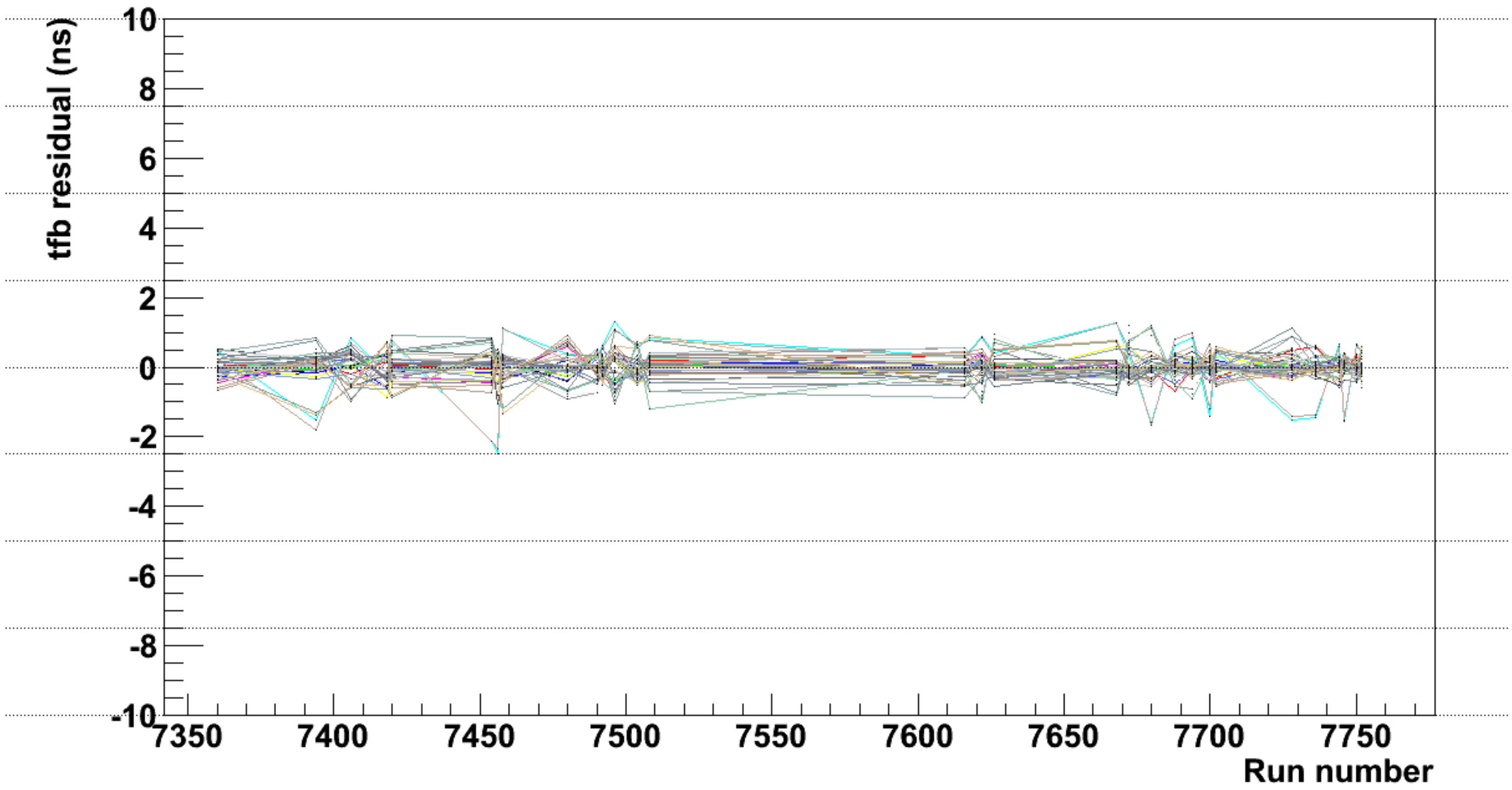
An example:

- Having looped over all the events in the file(s), obtain information regarding the multiplicity of hits for combinations of two TFBs.
- Start on TFB0 and consider all the combinations of 2 TFBs including TFB0:
  - TFB0 &TFB1 -----> n hits
  - TFB0 & TFB2 -----> n-7 hits
  - TFB0 & TFB3 -----> n+10 hits
  - TFB0 & TFB4 -----> n+23 hits
  - TFB0 & TFB6 -----> n-19 hits
  - TFB0 & TFB10 -----> n+1 hits
  - TFB0 & TFB 21 -----> n hits
- Pick the one with the largest number of hits e.g. TFB0 & TFB4. Save these TFB numbers.
- Now, look for the largest number of hits for TFB0 **or** TFB4.
  - TFB4 & TFB20 -----> n+1 hits
  - TFB4 & TFB9 -----> n-3 hits
- Now, would choose the combination TFB0 & TFB3. Add TFB3 to the list... TFB0 **or** TFB4 **or** TFB3
- And so on until you have used all the TFBs...

* Or see: http://en.wikipedia.org/wiki/Prim's_algorithm

Residual Offset vs Run Number

ECAL RMM 3



Resolution

- For each event, correct each hit for the time of flight and the time taken for the light to travel down the bar.
- For the files where offsets were applied, if everything was corrected for, all hits should now have the same time.
- So, to determine the resolution for each event choose the hit in that event with the highest charge (as know the resolution is best for high charge hits) and subtract the time of the other hits from this hit time.
- Plot this time difference as a function of charge.
- Then, take the rms of the distribution (as only the distributions with all corrections resemble a Gaussian, so chose not to do a fit) and say the resolution is the rms/sqrt(2).