T2K and The Electromagnetic Calorimeter

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Birmingham University Seminar, 24th Feb 2010

Queen Mary University of London

Outline

- Neutrino oscillations in a nutshell.
- An overview of T2K.
- The physics goals of T2K.
- The experimental apparatus of T2K and its readiness for data taking.
- A closer look at the downstream electromagnetic calorimeter of T2K's near detector.
- Calibrating the downstream ECal - cosmic muon analysis, attenuation, MC–data comparison and testbeam.
- Conclusions.

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Neutrino Oscillations

- Puzzles explained as neutrino oscillations among flavours (Pontecorvo, 1957; Maki-Nakagawa-Sakata, 1962).
- Oscillations due to mis-match between flavour and mass eigenstates -> **Neutrinos have mass!**
- Mixing parameters: 3 mixing angles (θ_{12}, θ_{13}, θ_{23}) and 1 phase(δ).
- 2x2 matrices have first been measured by solar and atmospheric and reactor neutrino experiments whilst now we are trying to measure them using man made beams (at T2K we will be measuring the atmospheric parameters).

Pontecorvo, 1969

$\cos\theta_{12}$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \Leftrightarrow U = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{i\delta} \end{pmatrix}$$

Fields which interact via the weak interaction

Fields which propagate with definite mass

Almost standard 3D rotation matrix
Pontecorvo-Maki-Nakagawa-Sakata (PMNS) Matrix

Neutrino Oscillations

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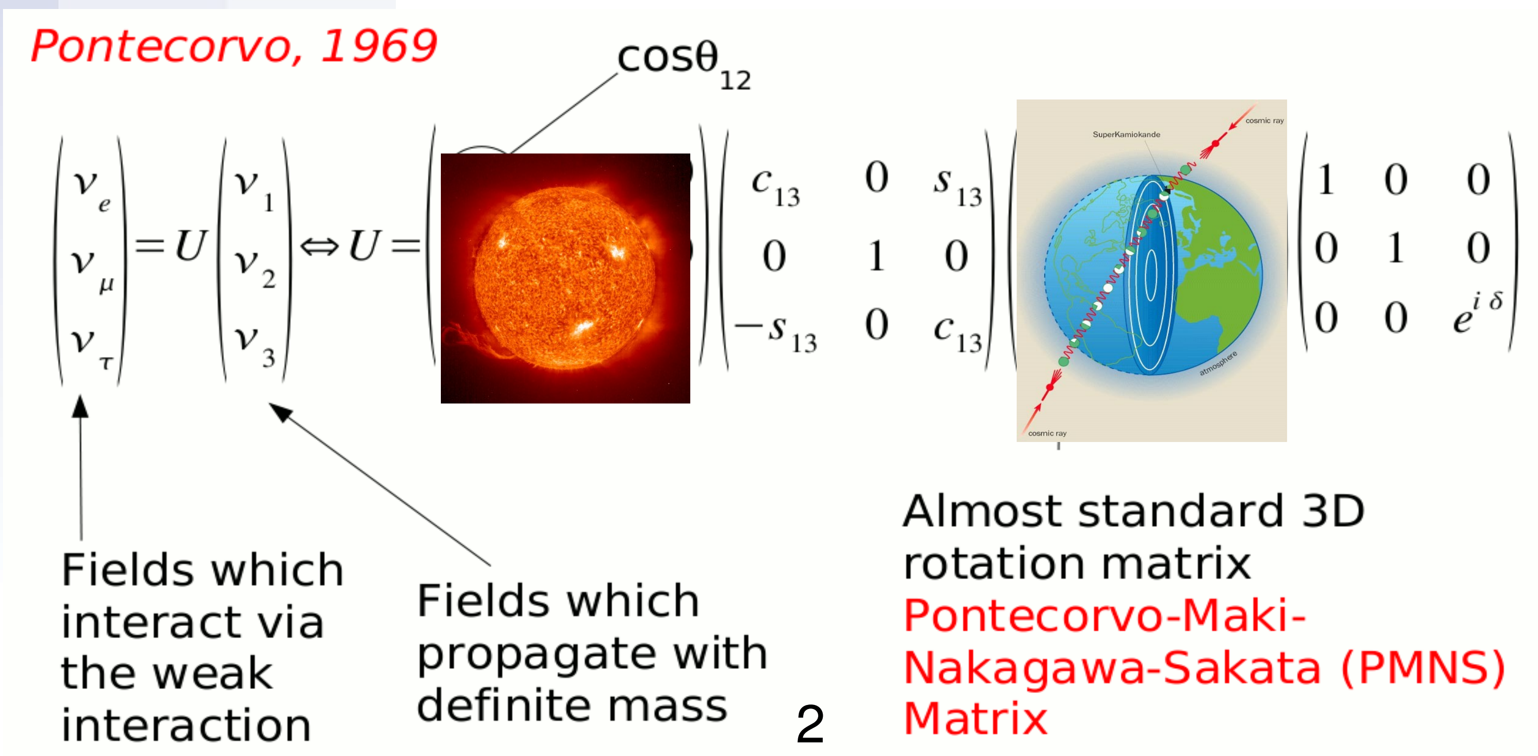


Neutrino Oscillations - T2K Goals

Search for the ν_e appearance: $\nu_\mu \rightarrow \nu_e$

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2\left(1.27\, \Delta m^2_{23}\, L/E\right) + \ldots$$

-Examine if θ_{13} is non-zero or not

→ First step of the ~~CP~~ search in lepton sector

$$\begin{pmatrix}1 & 0 & 0\\ 0 & \cos\vartheta_{23} & \sin\vartheta_{23}\\ 0 & -\sin\vartheta_{23} & \cos\vartheta_{23}\end{pmatrix}\cdot\begin{pmatrix}\cos\vartheta_{13} & 0 & \sin\vartheta_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -\sin\vartheta_{13}e^{i\delta_{CP}} & 0 & \cos\vartheta_{13}\end{pmatrix}\cdot\begin{pmatrix}\cos\vartheta_{12} & \sin\vartheta_{12} & 0\\ -\sin\vartheta_{12} & \cos\vartheta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}$$

Precise measurement of the ν_μ disappearance:

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2\left(1.27\, \Delta m^2_{23}\, L/E\right)$$

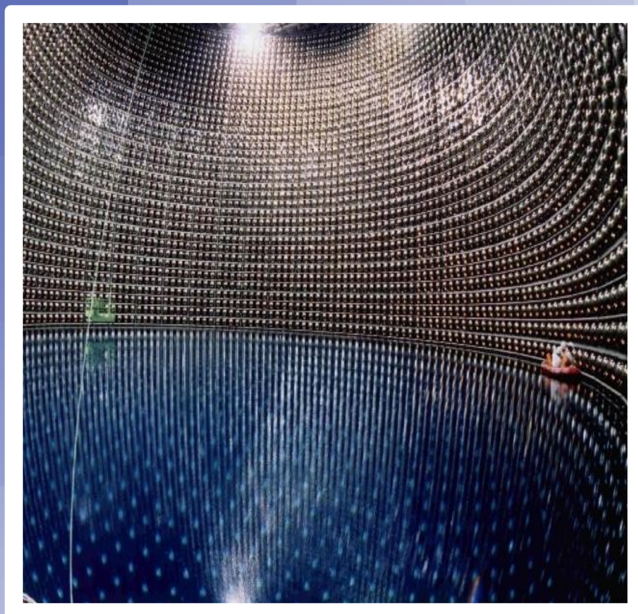
- Examine if θ_{23} give maximal mixing

ΔM^2 in eV^2, L in Km and E in GeV

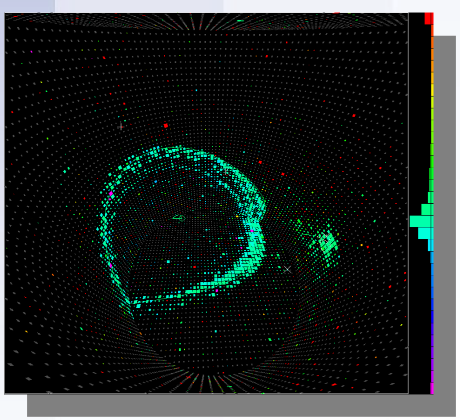
Hence we can see that the disappearance of ν_μ leads to the determination of θ_{23} and Δm^2_{23} while the appearance measurement can be used to measure θ_{13}.

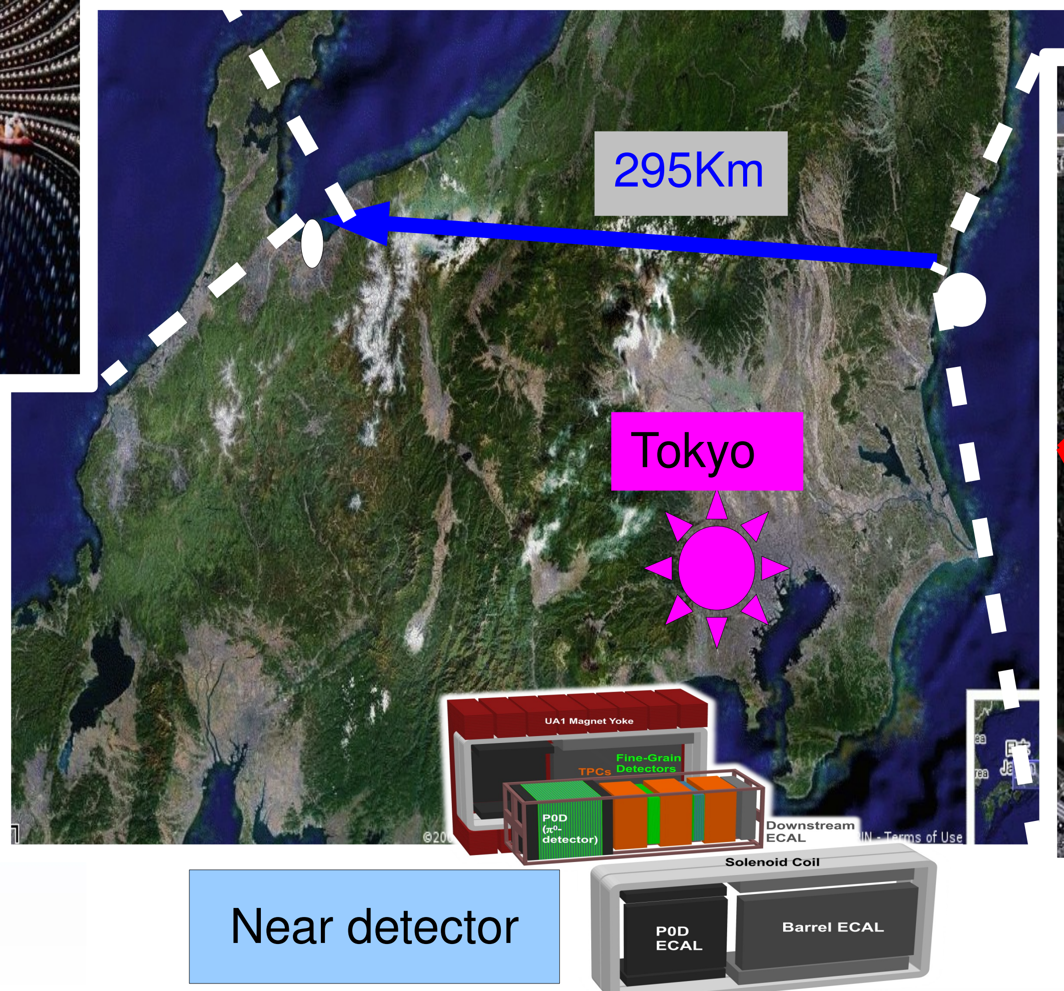
If $\delta \neq 0$ we have CP violation

T2K



Far detector





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Near detector

T2K Collaborators

478 Collaborators from 62 Institutions worldwide

- Canada
- France
- Germany
- Italy
- Japan
- Korea
- Poland
- Russia
- Spain
- Switzerland
- UK
- USA

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The Physics of T2K

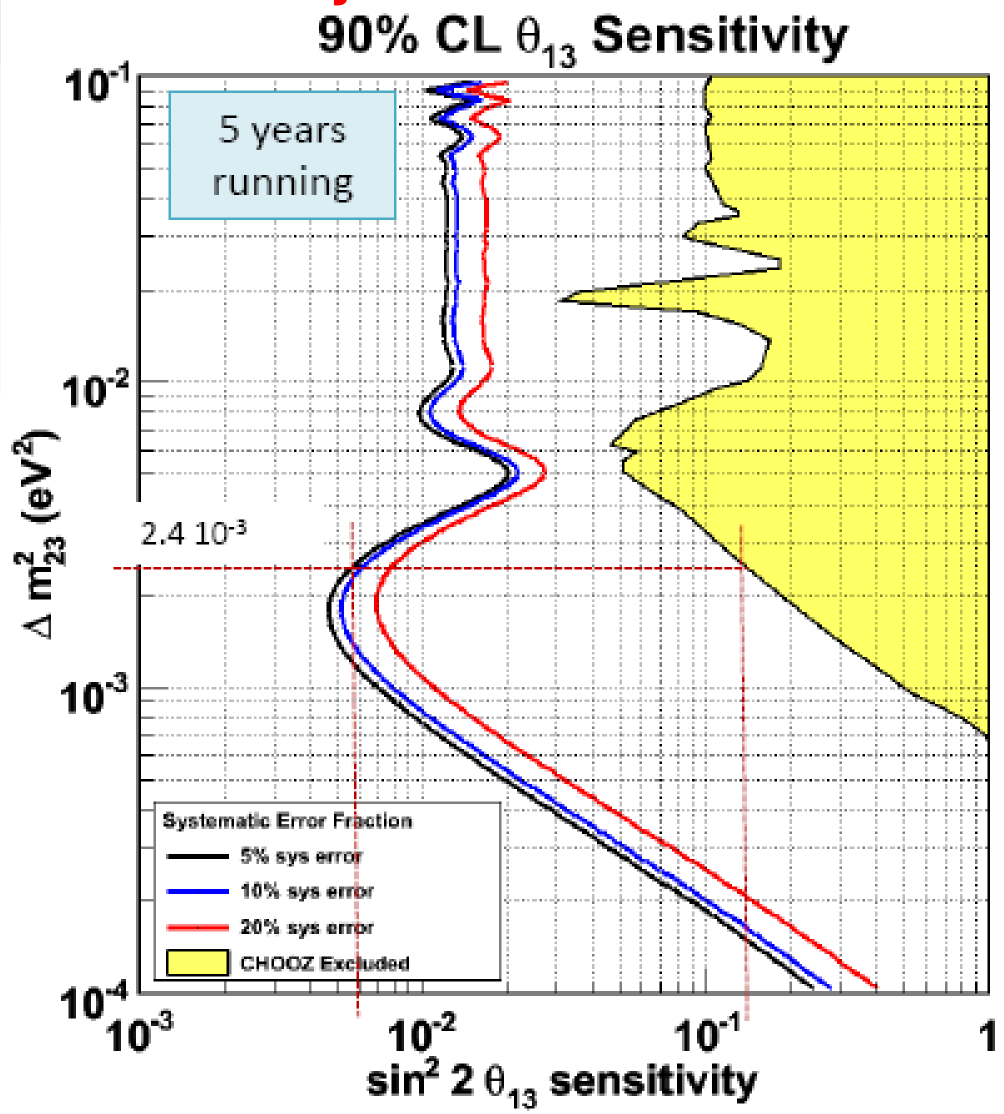
Primary Physics Goals

1) Improve sensitivity to θ_{13} by an order of magnitude.

2) Find whether θ_{23} is maximal,
   - crucial to constrain neutrino mass models

3) If $\theta_{13} \neq 0$ investigate CP violation in neutrino oscillations

Sensitivity



ν_e Appearance Measurement at T2K

- T2K has discovery potential for ν_e appearance.
- ~100 ν_e appearance events expected after $8x10^{21}$ POT at 30GeV. (Assuming $\sin^2 2\theta_{13} = 0.1$)
- ~20% total background.
- ~10% background from $NC\pi^0$.

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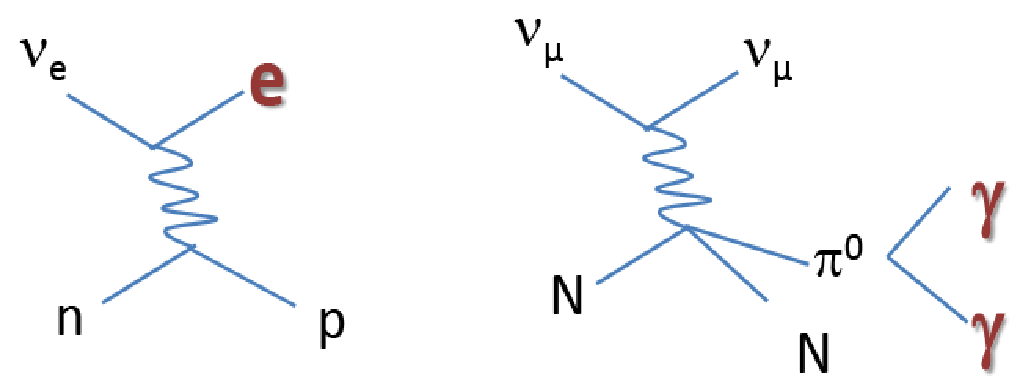
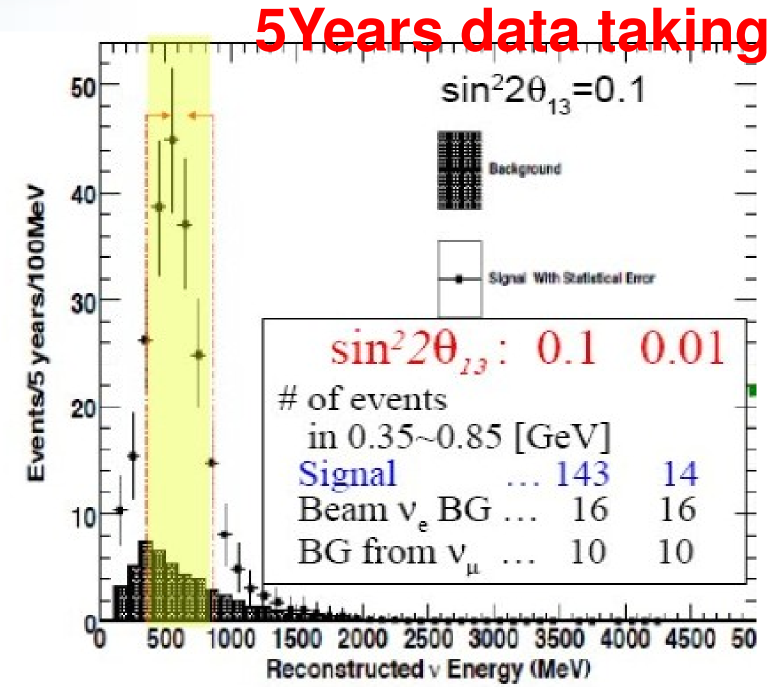
T2K - The Physics In Earnest

1)Pin down θ_{13} through $\nu_\mu \rightarrow \nu_e$ appearance

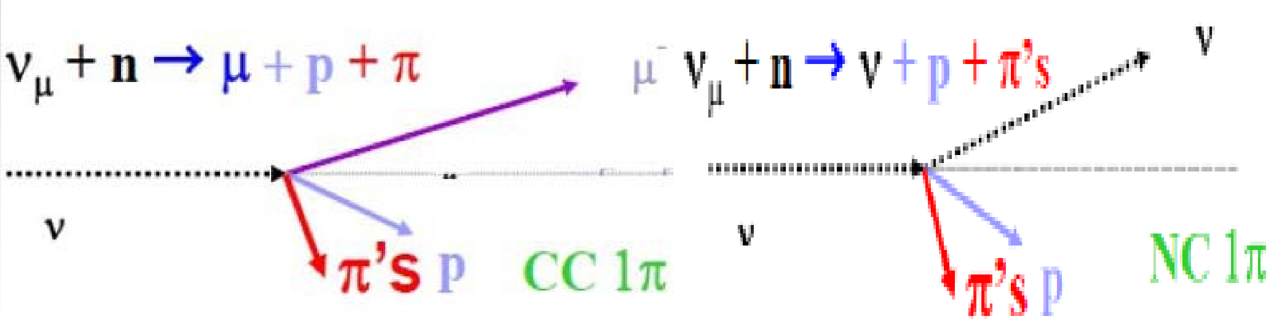
Backgrounds: ν_e beam contamination, NC-1π^0

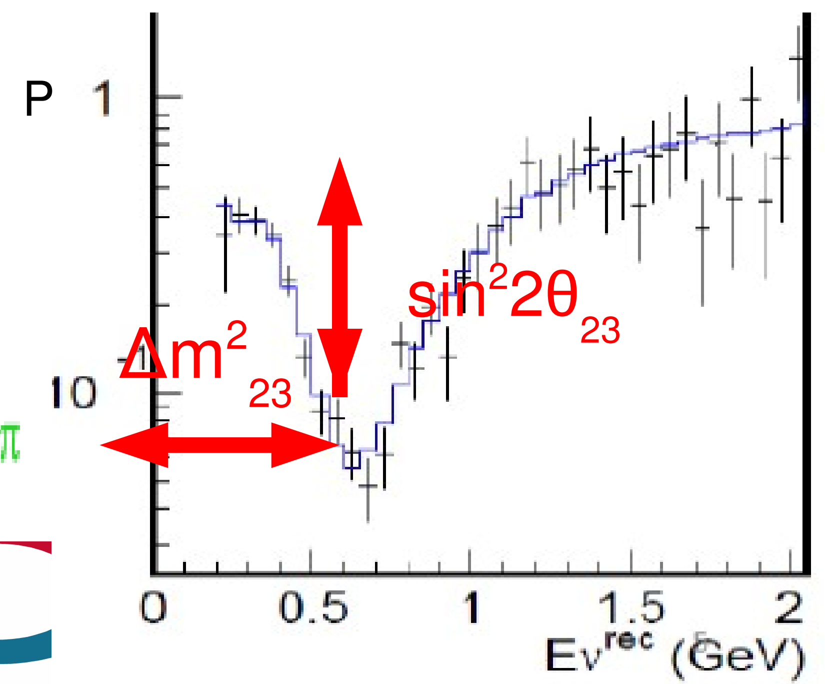




2)Determine whether θ_{23} is maximal and advance Δm^2_{23} through ν_μ disappearance

Background: single pion production

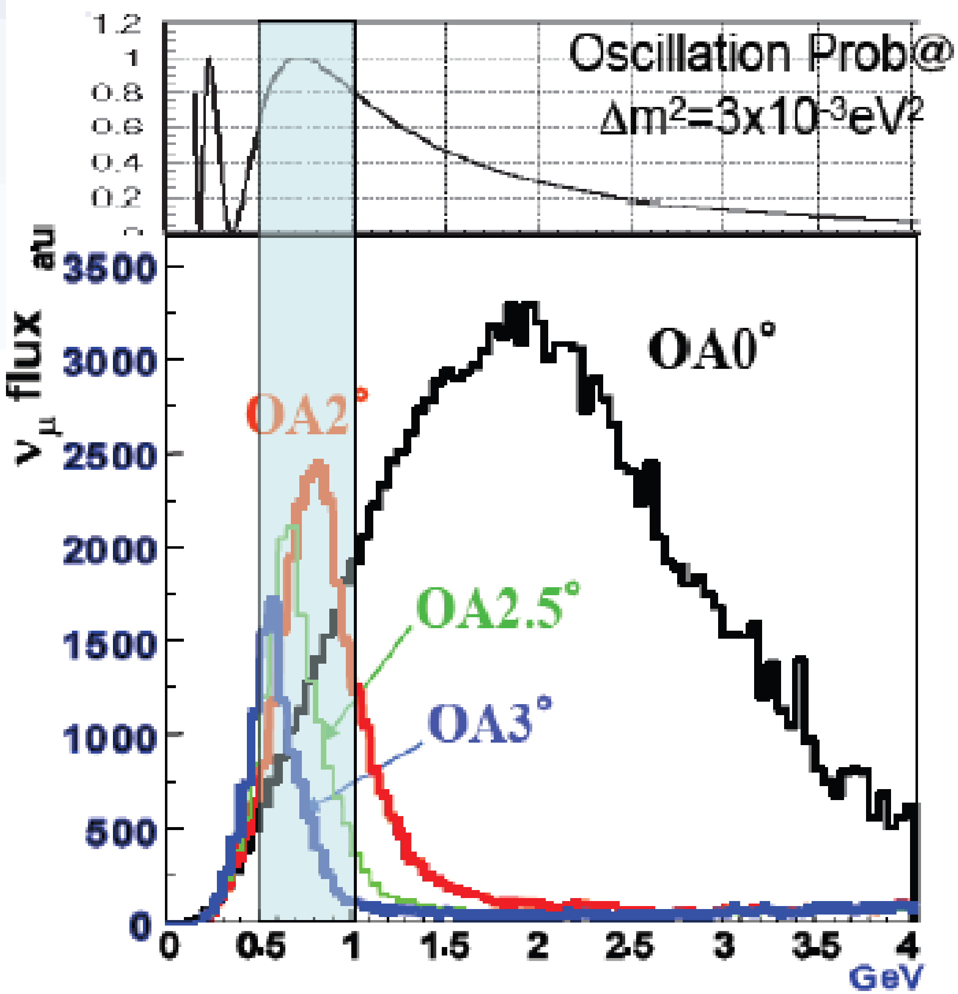




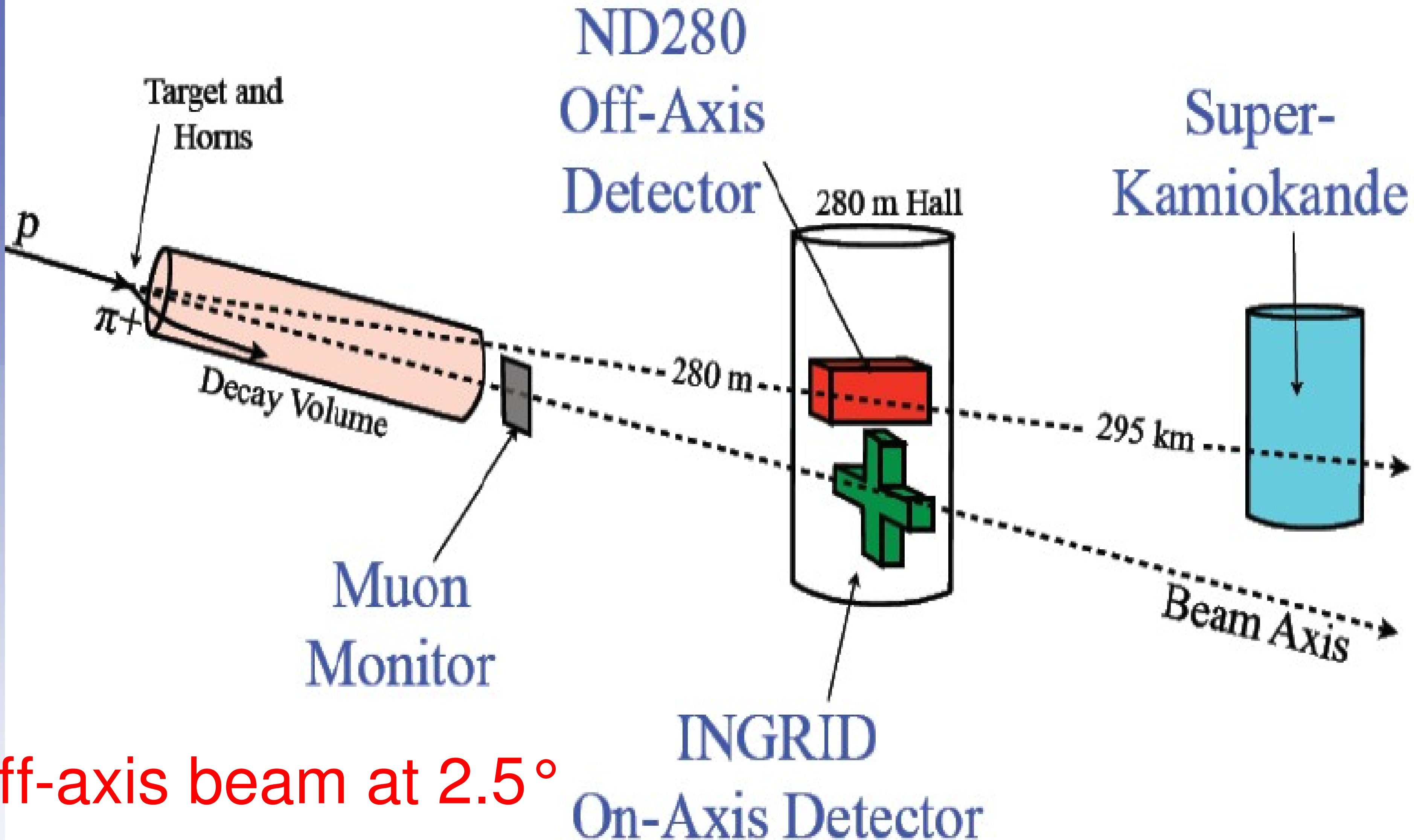
The Beam

- We want to see maximum oscillation with minimum background.
- Off-axis geometry provides (quasi) mono-energetic beam tuned to first oscillation maximum.
- Increases flux at maximum.
- Drastically cuts high energy tail responsible for inelastic interactions that are background to the CCQE event
- Minimises ν_e contamination of the beam in the peak region.
- T2K beam composition:

95% ν_μ, 4% anti-ν_μ, <1% ν_e

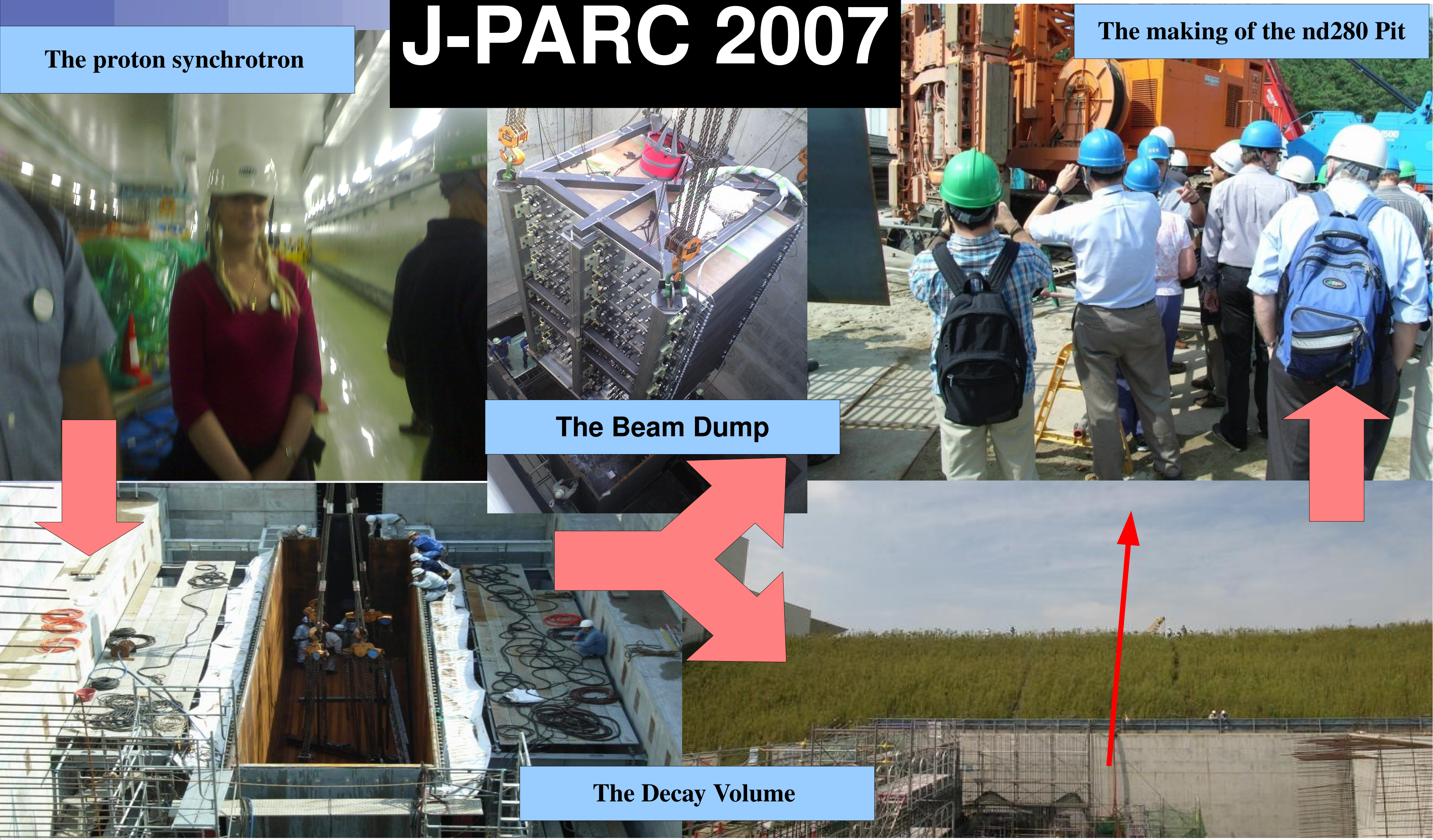


T2K - The Particulars

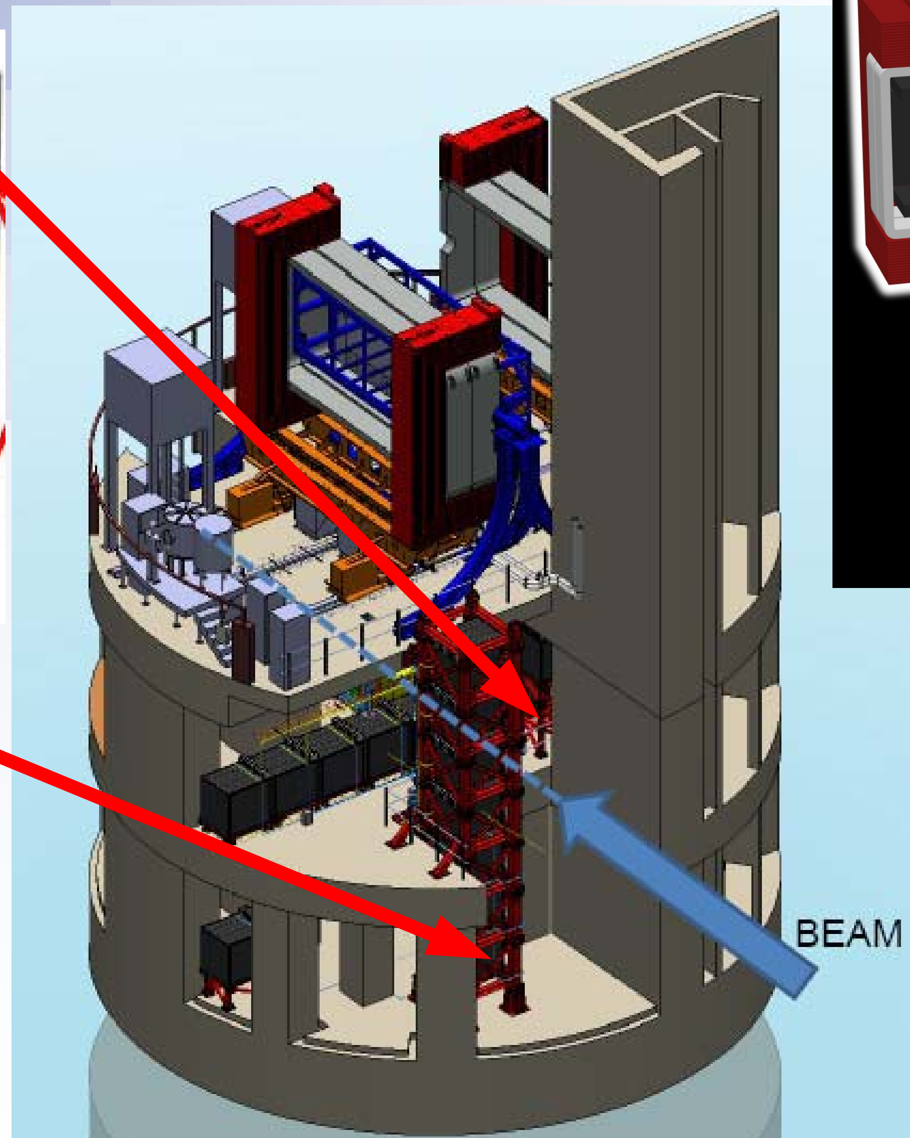


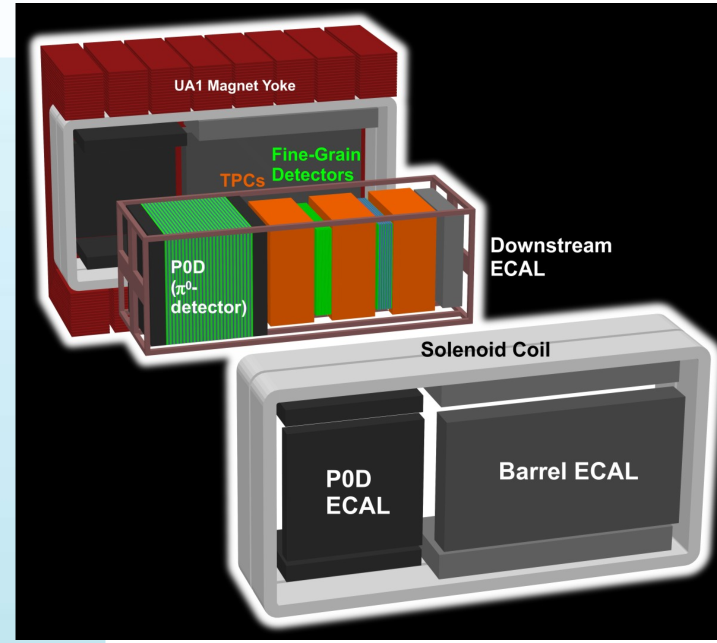
Off-axis beam at 2.5°

J-PARC 2007


The proton synchrotron
The Beam Dump
The making of the nd280 Pit
The Decay Volume

Near Detector – ND280 at 280m

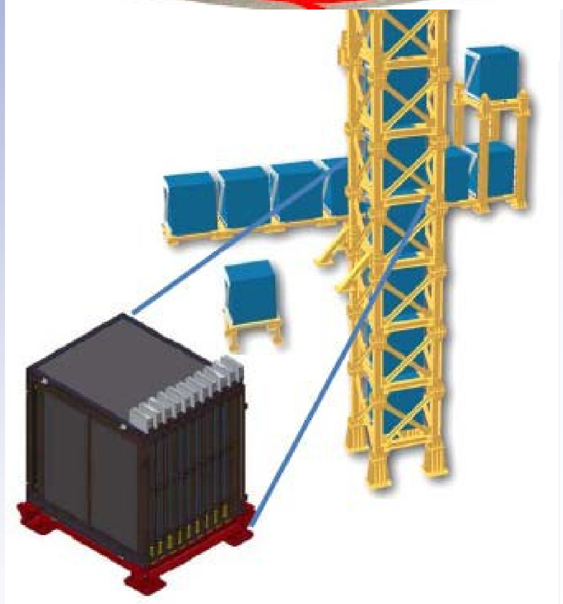




INGRID Interactive Neutrino Grid on axis neutrino monitor, Detects the exact beam position

ND280 off axis detector, characterises the neutrino beam and minimises the backgrounds to the oscillation measurement

Why We Need this Suite of Near Detectors



INGRID and beam monitors

- P-beam monitors in beamline, optical transition radiation monitor at target, muon monitors in the beam dump. Off-axis angle must be monitored to <1mrad (i.e. 2% shift in the ν peak energy).
- Direction of horn-focused ν-beam monitored by INGRID

  -16 modules

  -11 layers scintillator interleaved with Fe

  -sufficient statistics for a daily measurement
- Complete INGRID system was installed this Summer.

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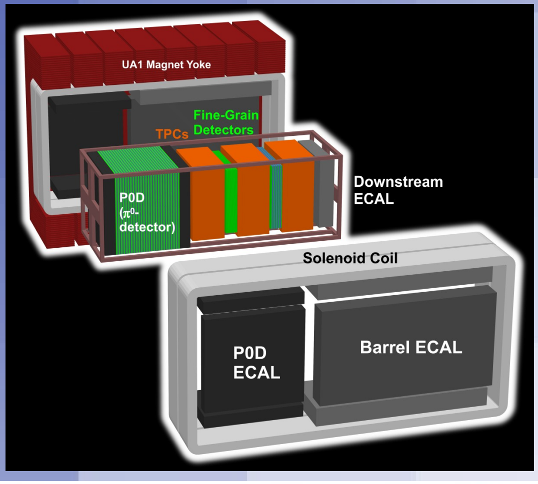
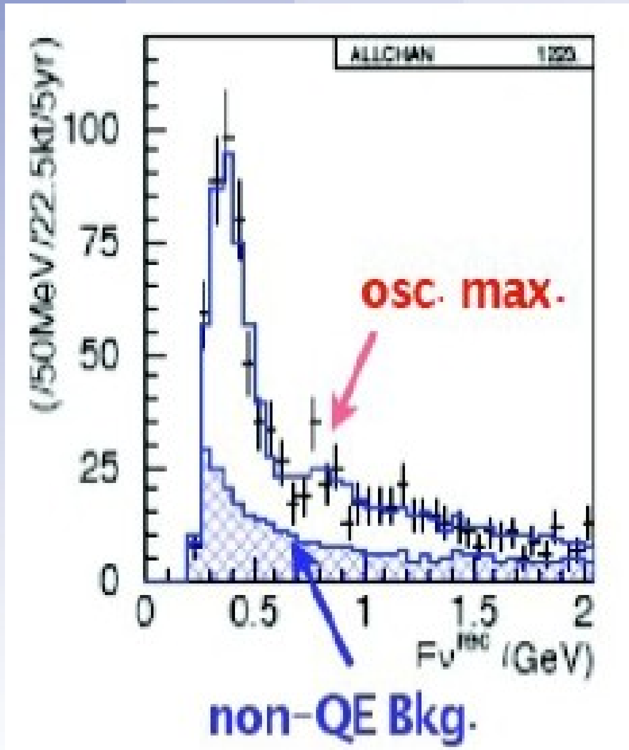
Why We Need this Suite of Near Detectors





ND280 Off-Axis detector

- Cross section measurements in ND280 needed to measure backgrounds at Super-K i.e.

  -NC-1π, CC-1π for ν_μ disappearance

  -NC-1π^0 for ν_e appearance

- **To achieve design precision on θ_{23}, and Δm_{23} demands: non-QE/QE ratio known to <10%** e.g. 5 yrs running (5x10^{21}POT) expect following No.s of NC-1π^0 events in P0D: C/Pb/brass=20k, water=8k ($\varepsilon(\pi^0)$=55%,purity=60%)

- ND280 will provide the most extensive measurements of sub-GeV neutrino cross-sections on oxygen to date, as we will see later.

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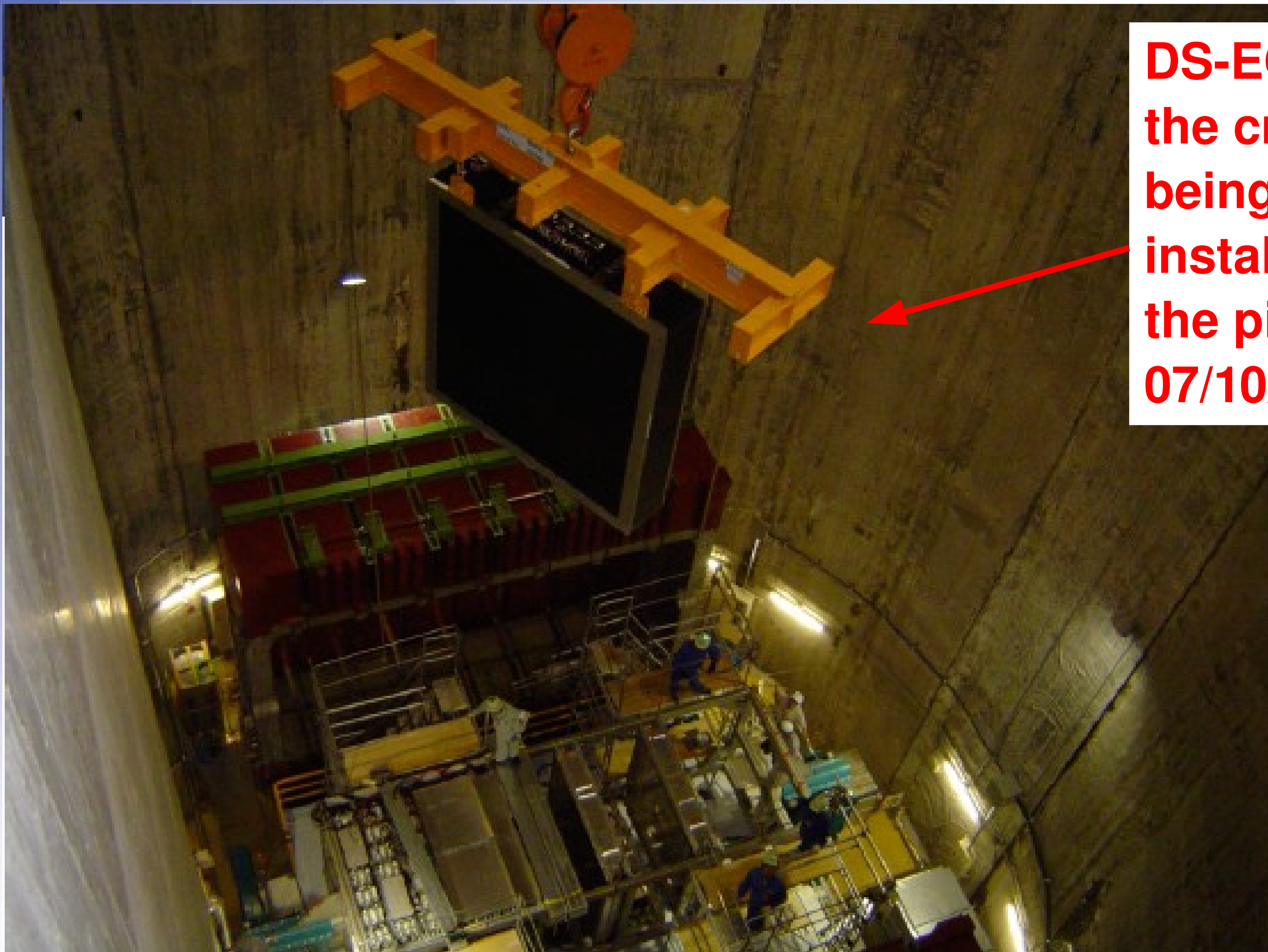
ND280 Installation in The Pit



DS-ECal on the crane being installed in the pit 07/10/09

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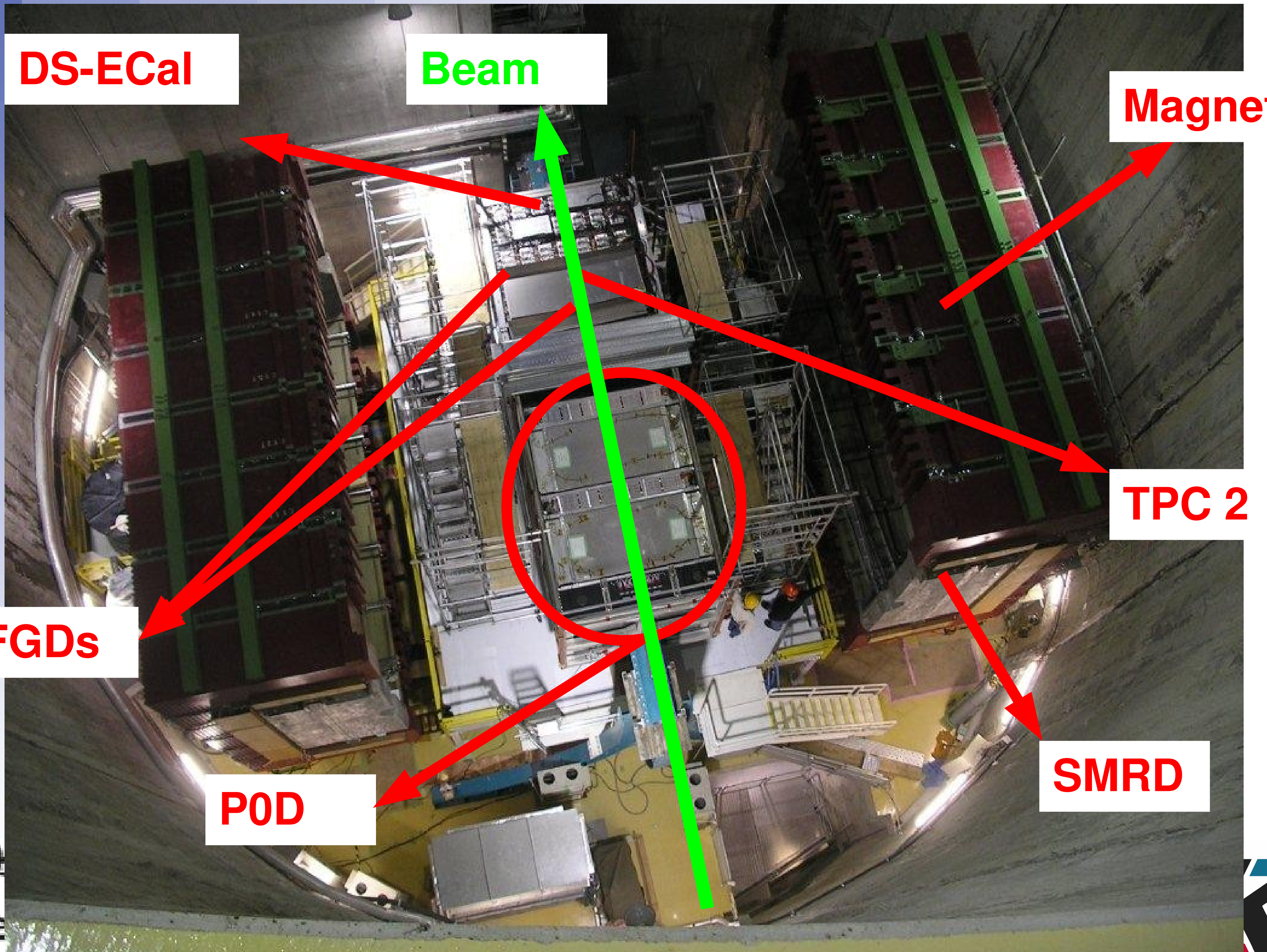
ND280 Installation in The Pit



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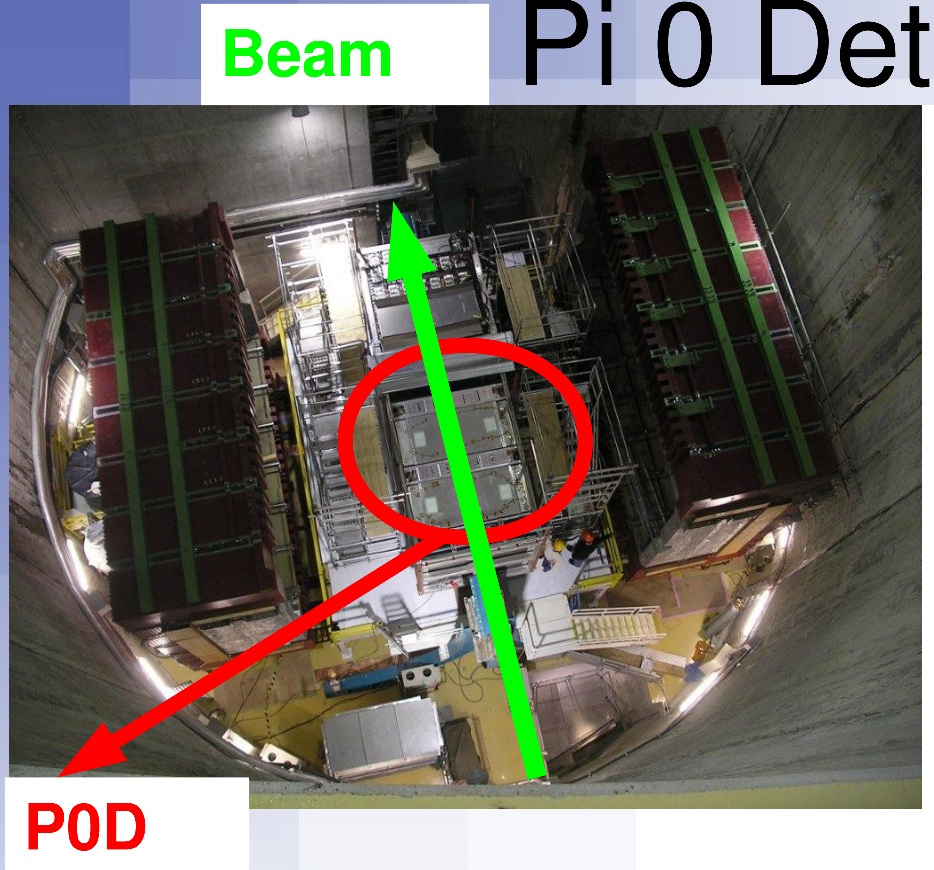
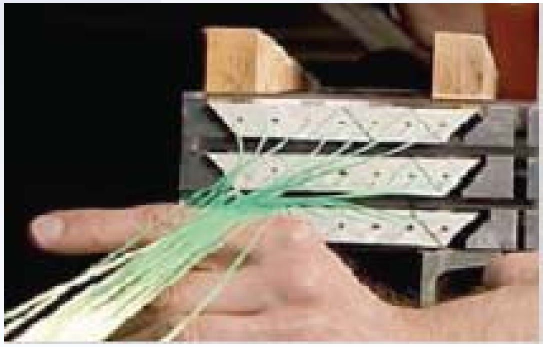
Pi 0 Detector - P0D





- 40 x-y brass+scintillator tracking planes interspersed with water volumes (Carbon:Oxygen 1.8ton:0.9ton)
- 5.7 X_0 upstream/downstream γ-stops
- WLS wavelength shifting fibre readout.
- All 4 P0D modules now installed, utilities installation and commissioned
- Surrounded by a coarse Pb scintillator calorimeter P0DECAL (5 X_0 thick) to collect escaping γ/mip's

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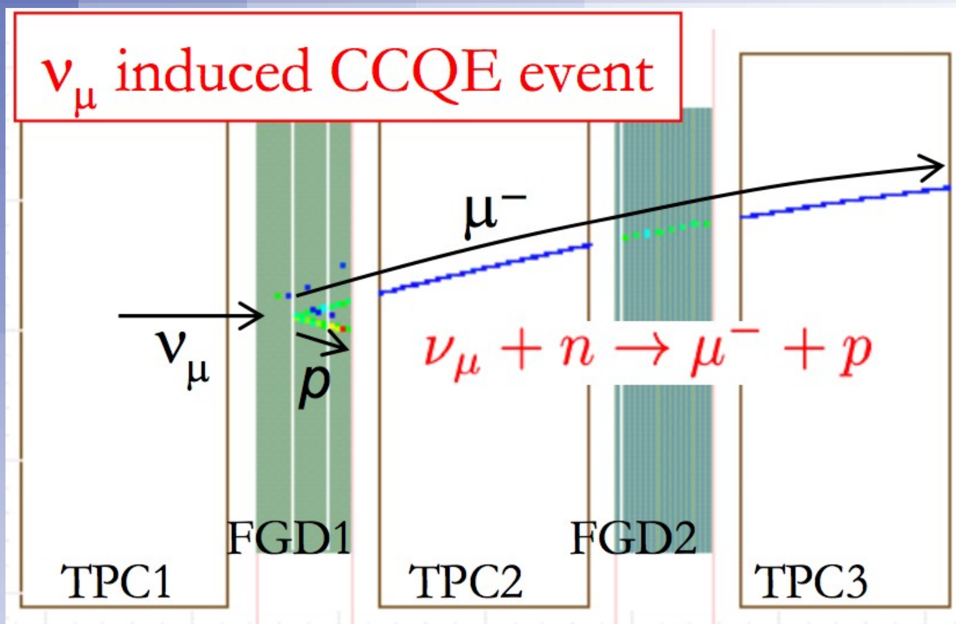
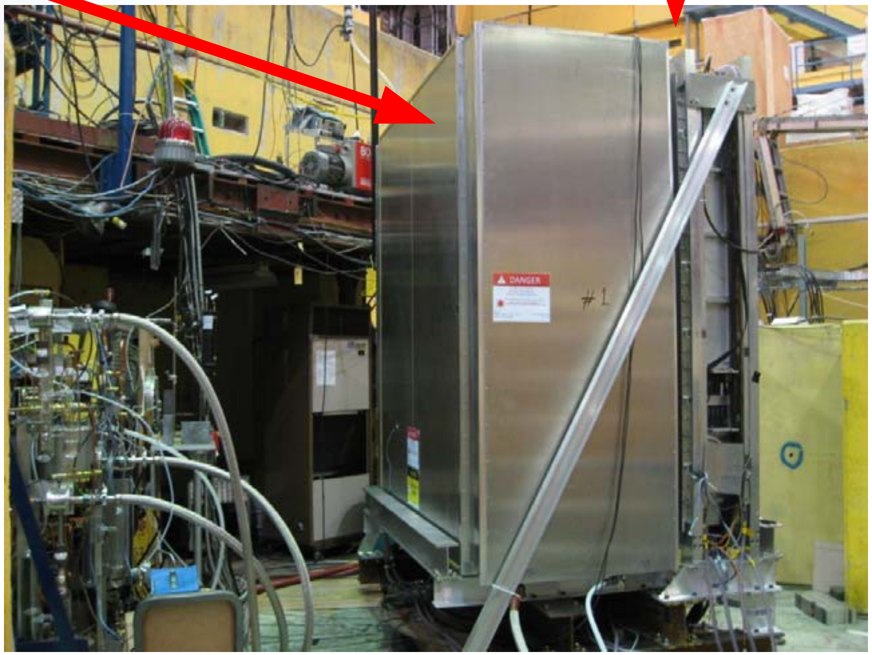
Tracker (TPCs+FGDs)

Time projection Chamber TPC & Fine Grain Detector FGD

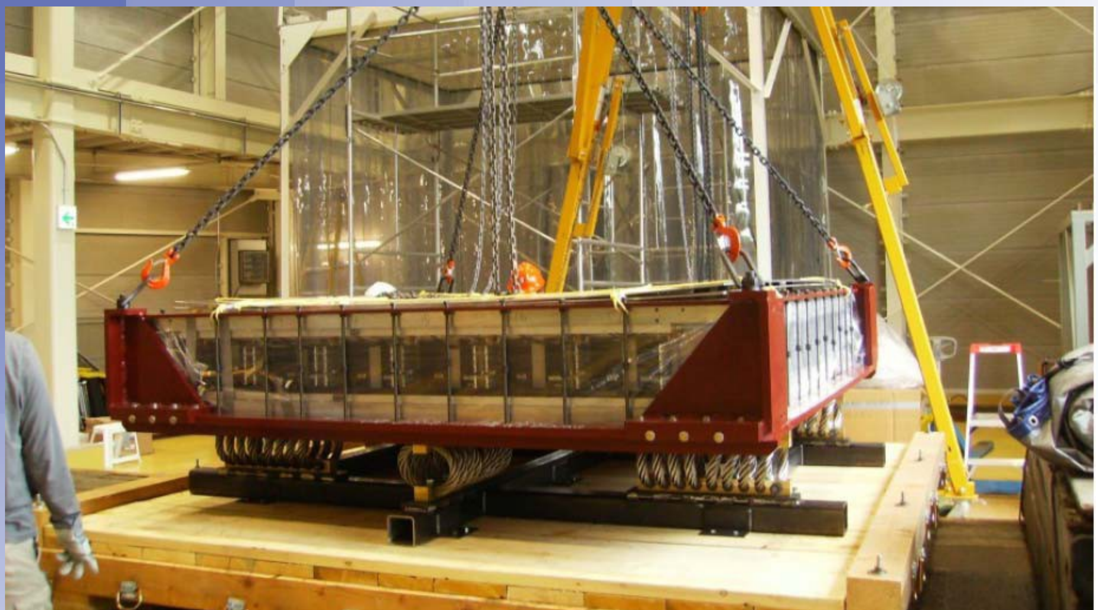




In testbeam at TRIUMF

Optimised to measure momenta and to provide PID (particle identification) of charged particles especially muons and pions.

Fine Grain Detectors - FGDs



Tested with cosmics and testbeam at TRIUMF

Installed in the ND280 pit at J-PARC in October

- target mass of tracker (1.3T/module)
- alternating x-y scintillator bars ($1cm^2$) fine enough to measure recoil γ
- 2^{nd} module contains scintillator + water (for cross section measurements at Super-K)

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Time Projection Chamber - TPC

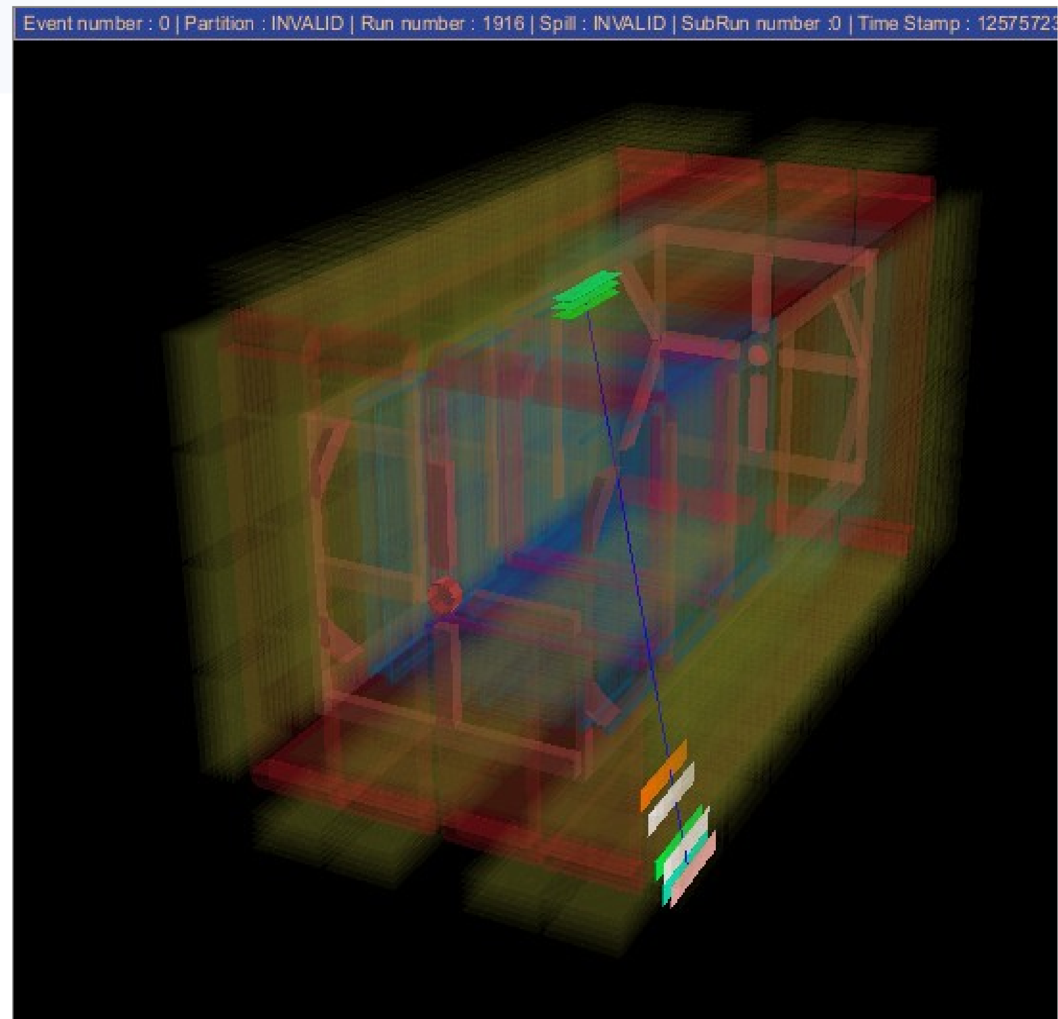
- high resolution tracking
- charge/momentum measurement: σ_p/p~10%
- 5σ e/μ discrimination
- First large-scale implementation of bulk micromegas (32 modules, 124K channels)

Tested with cosmics and testbeam at TRIUMF

Installed in the nd280 pit at J-PARC in October

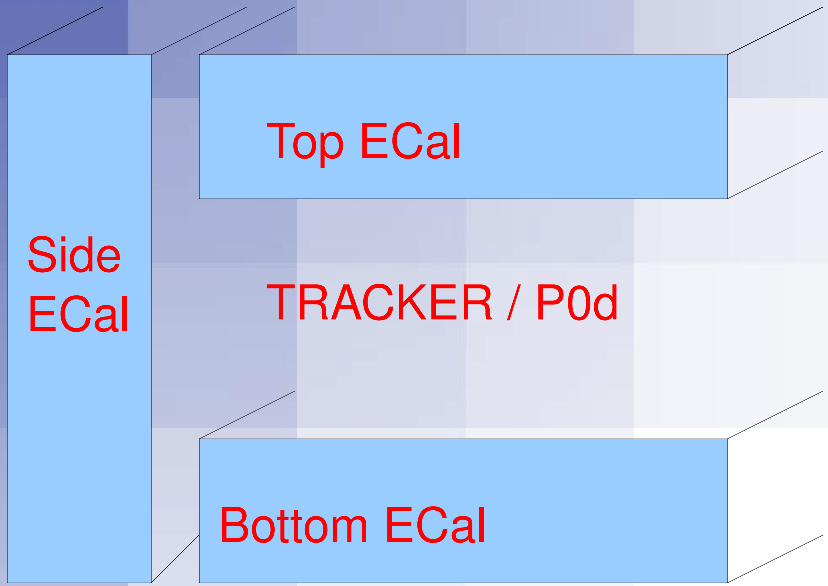
Side Muon Range Detector - SMRD

- Scintillator planes in UA1 hadronic calorimeter gaps in yoke



- All installed and commissioned

Electromagnetic Calorimeters - ECals



- 13 modules
- Left and right top, bottom and side ECals and P0d ECals surrounding the P0d and tracker and DS-ECal as an endcap.
- DS-ECal installed, commissioned and taking data.
- Top tracker modules installed early Jan.
- Commissioning underway.

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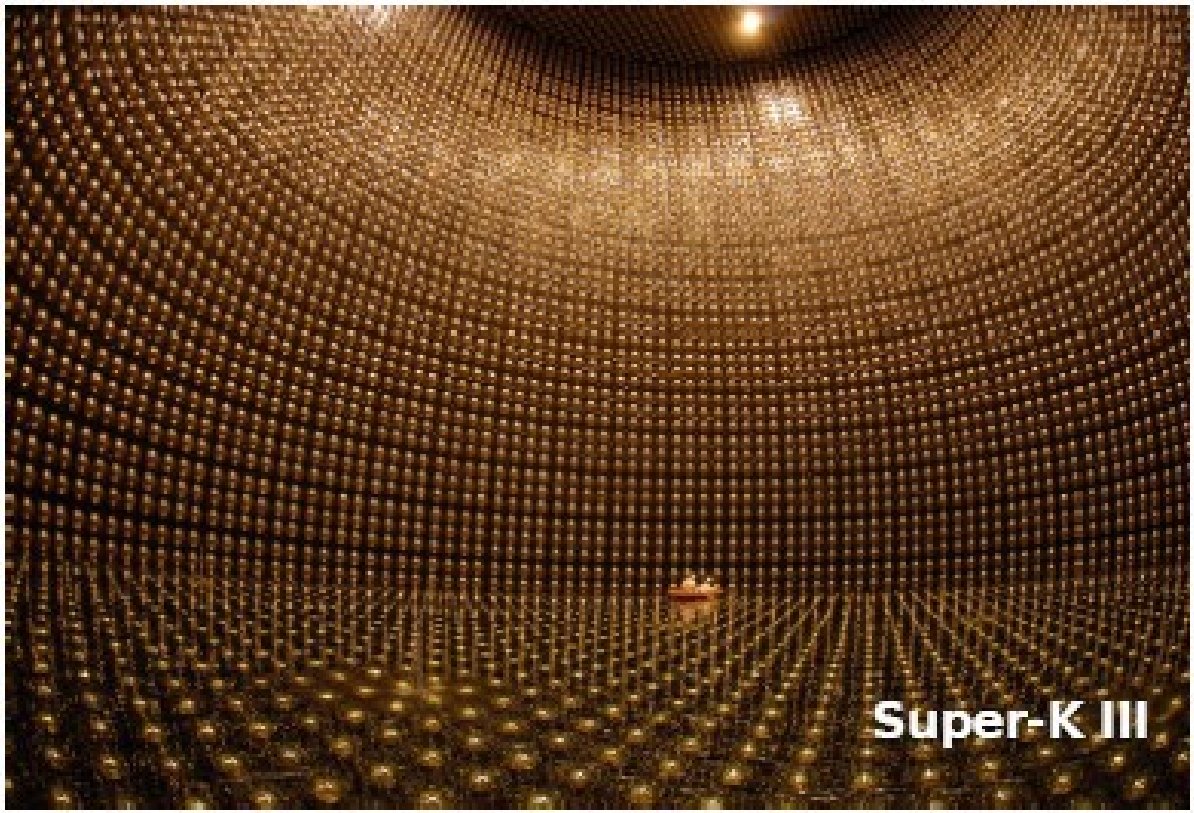
Far Detector - Super Kamiokande



- 50kTon Water Cherenkov detector
- 20” PMT x <11,129
- +Anti counter/outer detector/ veto detector 8” PMT x 1,885

- **New electronics installed in summer of 2008. (SK-IV)**
- **Stable and deadtime-less DAQ for improvement of decay-e tagging efficiency**
- **Ready for T2K experiment**

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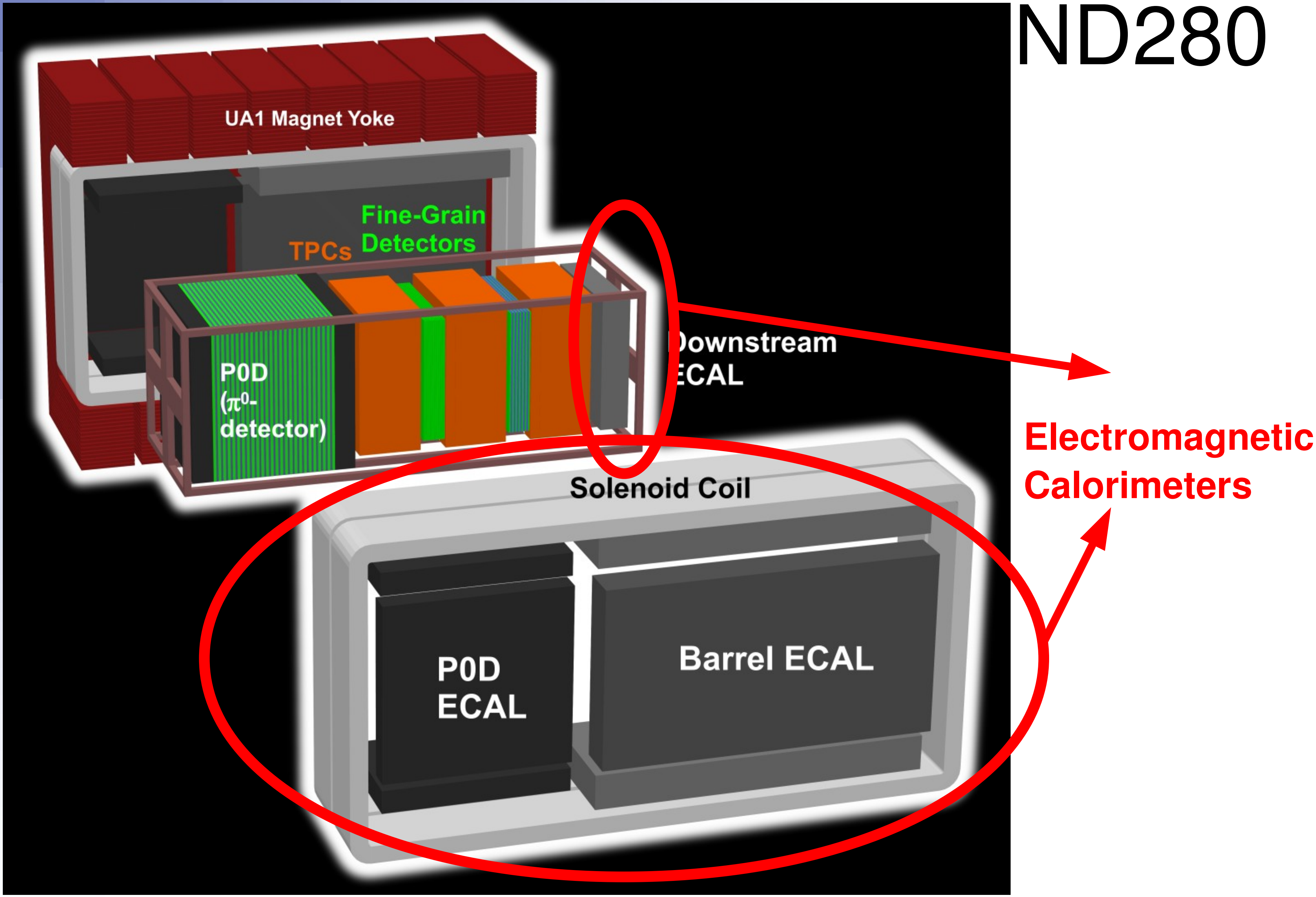
ND280



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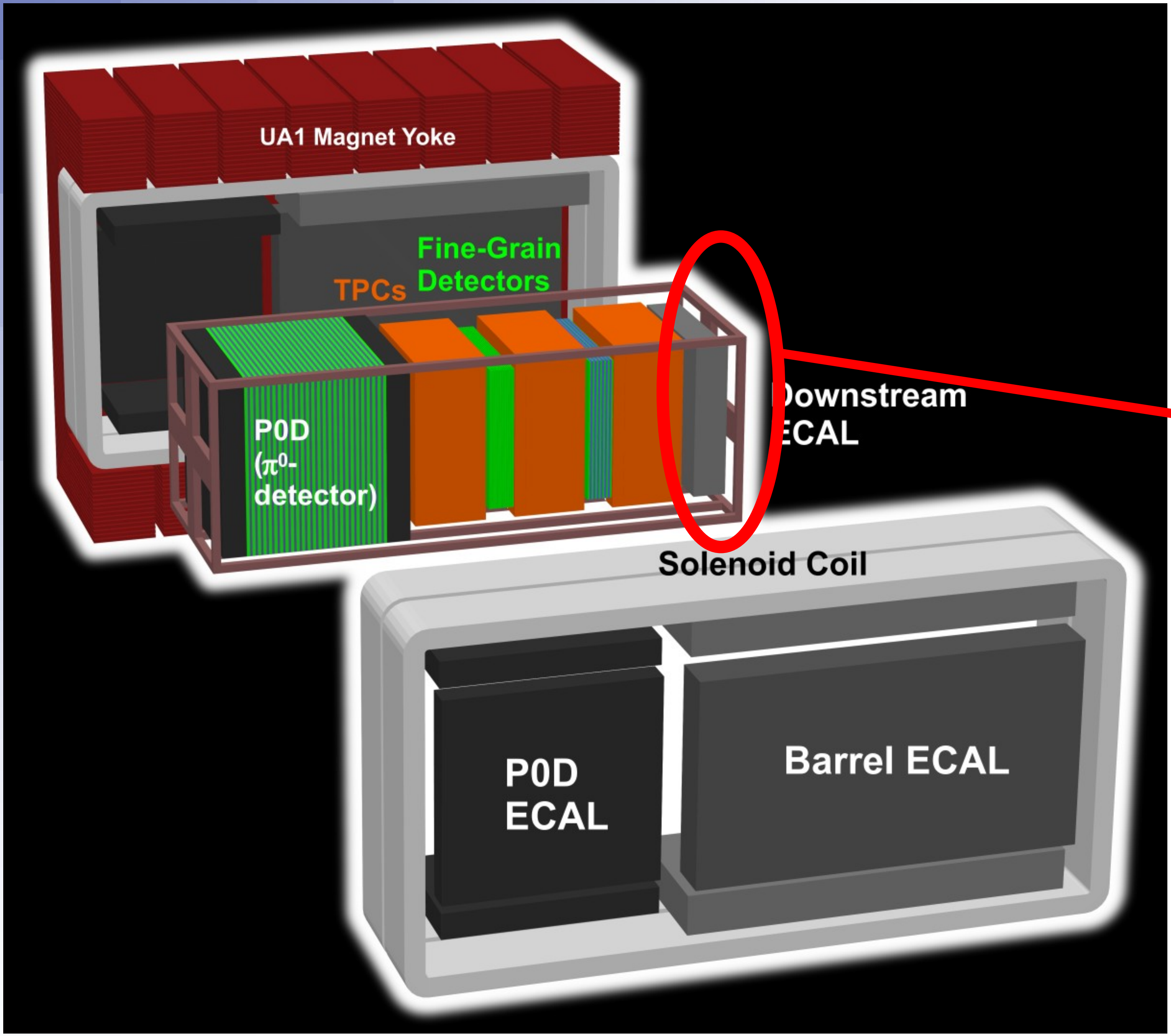
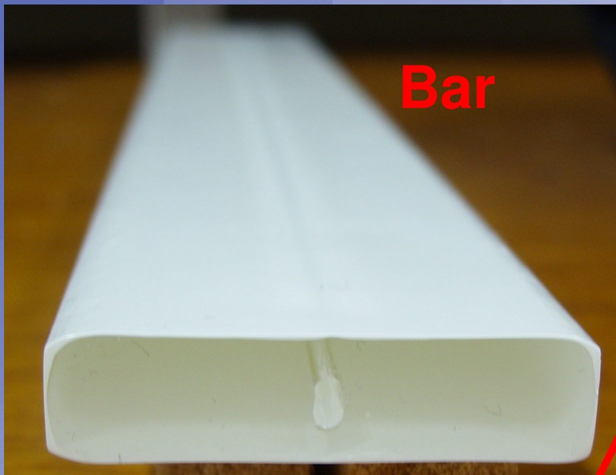
ND280



Downstream Electromagnetic Calorimeter

Built in Lancaster UK

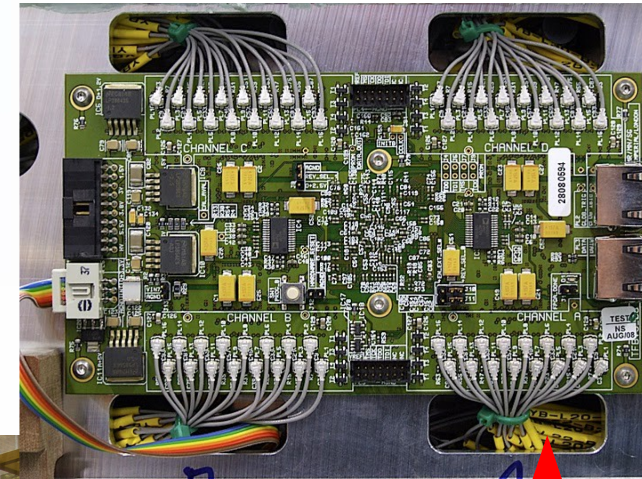
The DS-ECal



Bar

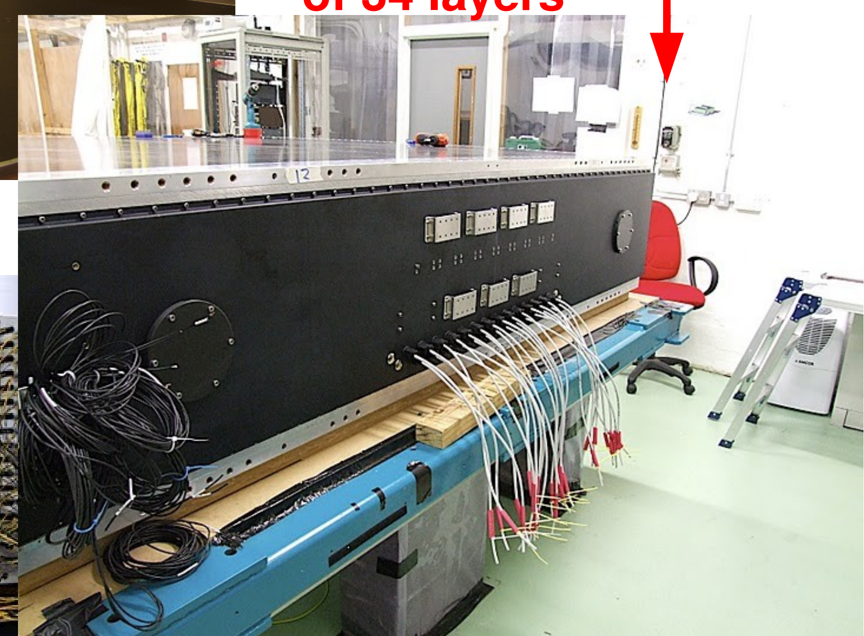
A layer of 50 bars being glued together

The finished layer

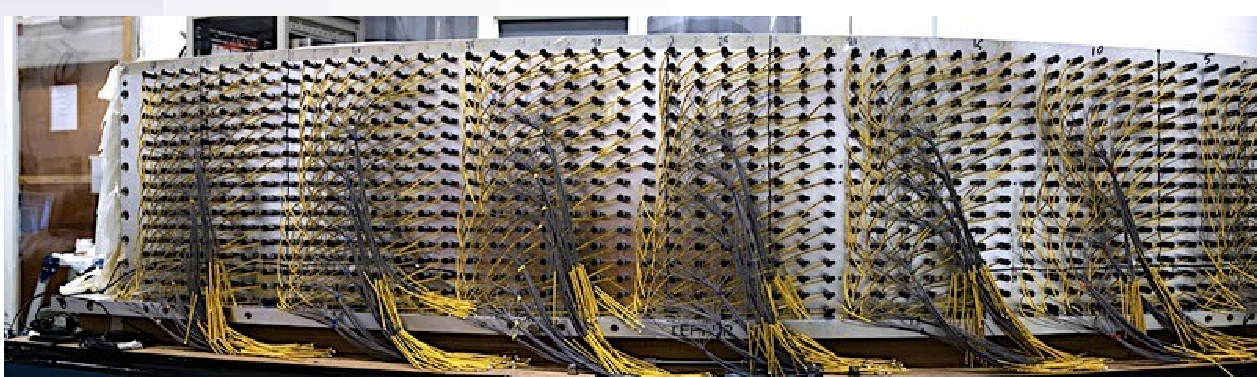


The electronics readout for the photosensors (MPPC's).

The finished DS-ECal of 34 layers

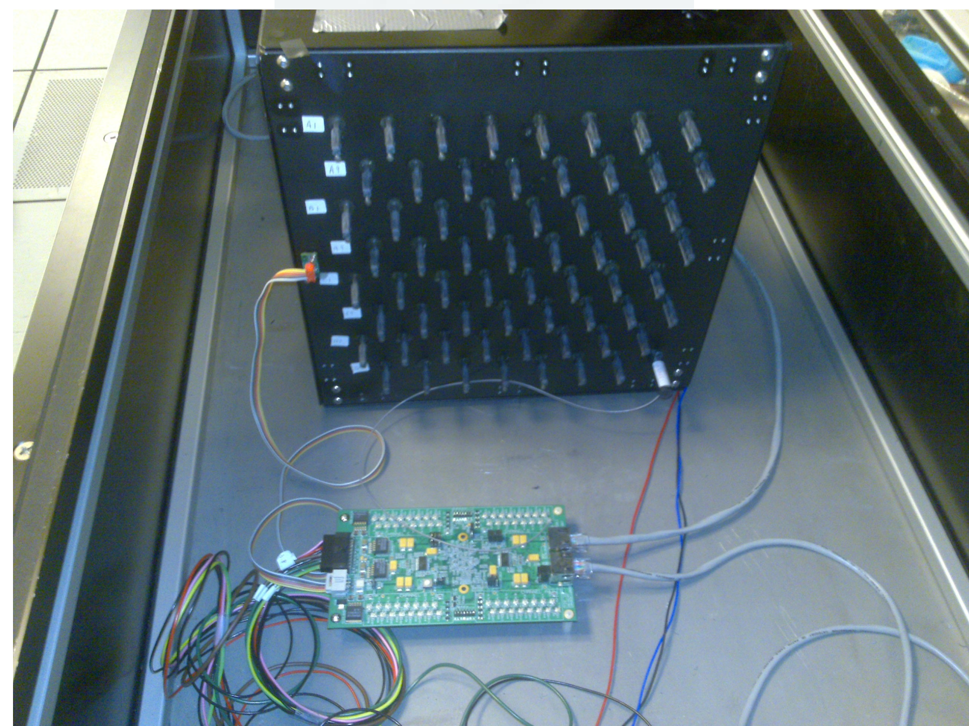


MPPC cables



Multi Pixel Photon Counter (MPPC) Construction and QA

- All detectors (except TPC's) use WLS fibres coupled to MPPC's as photosensors
- Pixel counters in Geiger mode
- Small, cheap and operate in B-fields
- Superb single p.e. Discrimination

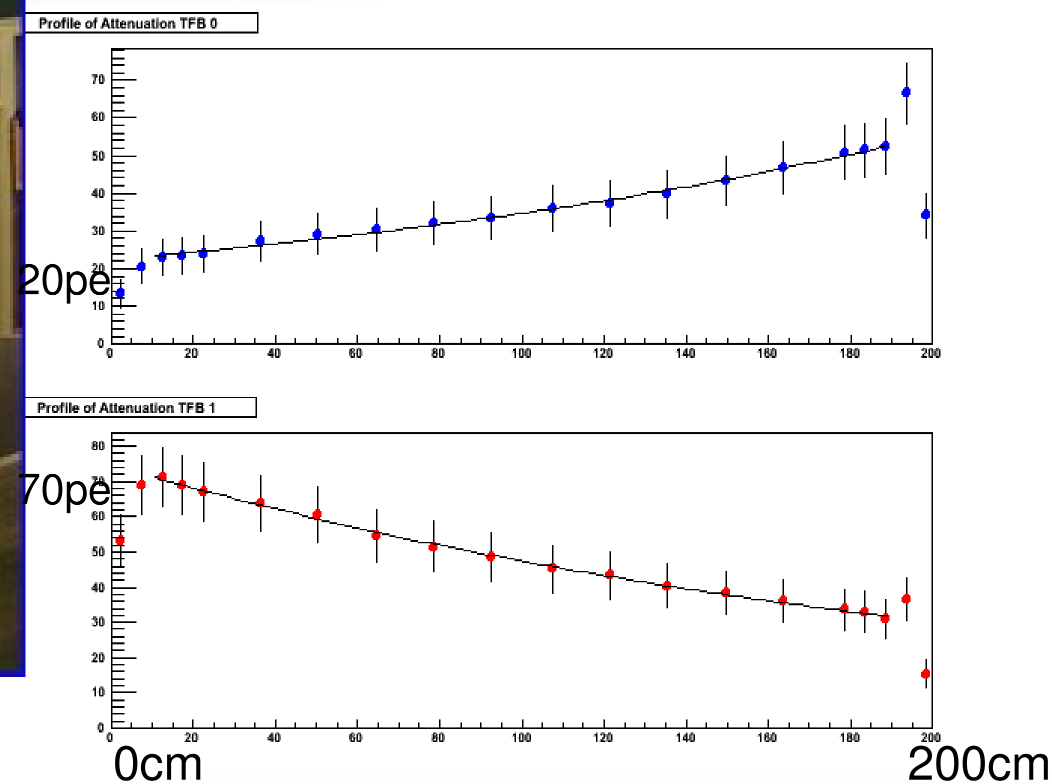


The Scanner To Test DS-ECal et al

The scanners to scan and test by layer, the scintillator bars of all ECal modules, were designed and built at Queen Mary University of London

Attenuation Plot with distance on x and light yield on y, for layer 15 bar 1 using scan data

The scanner in action



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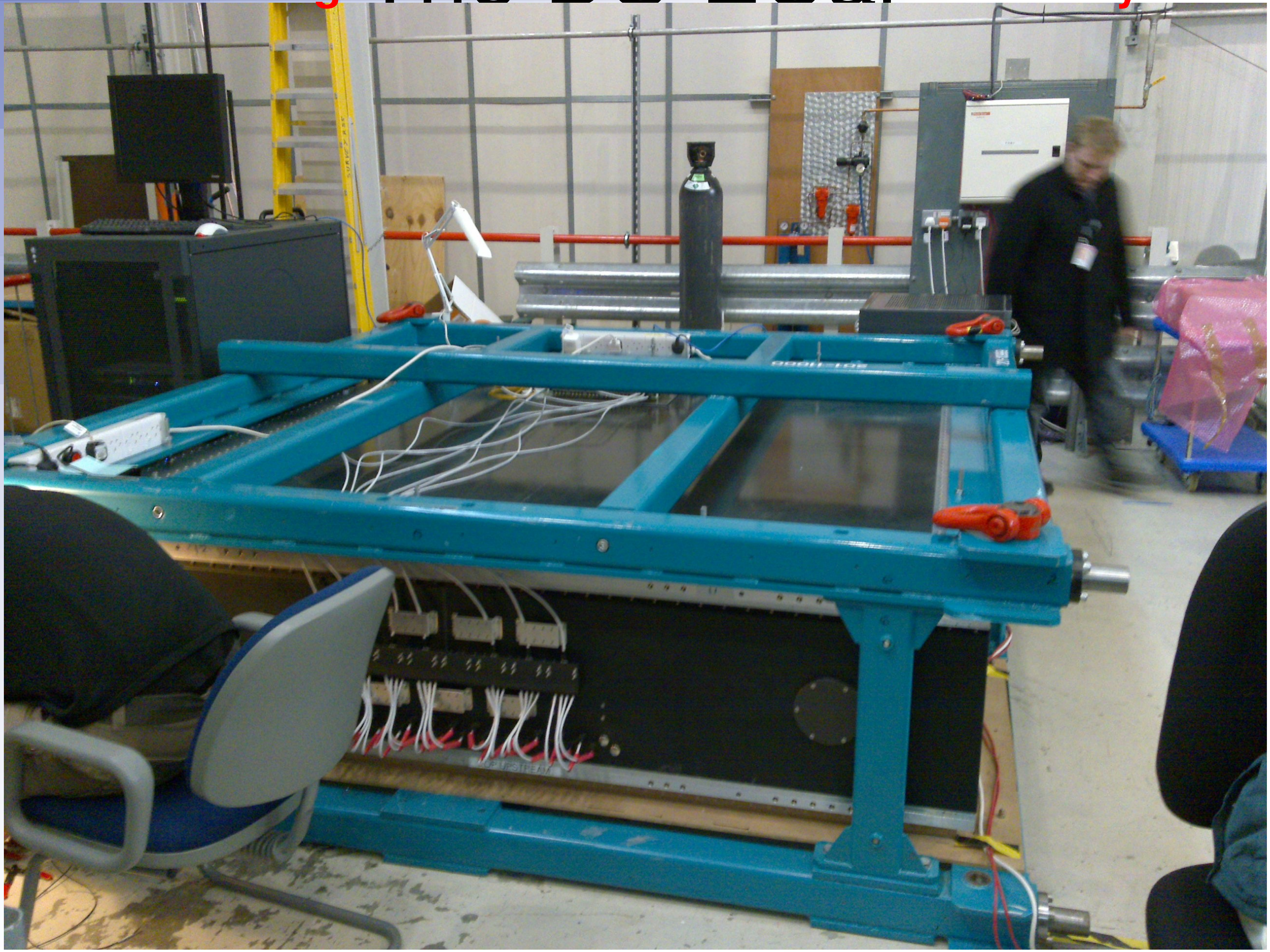
Initial Commissioning

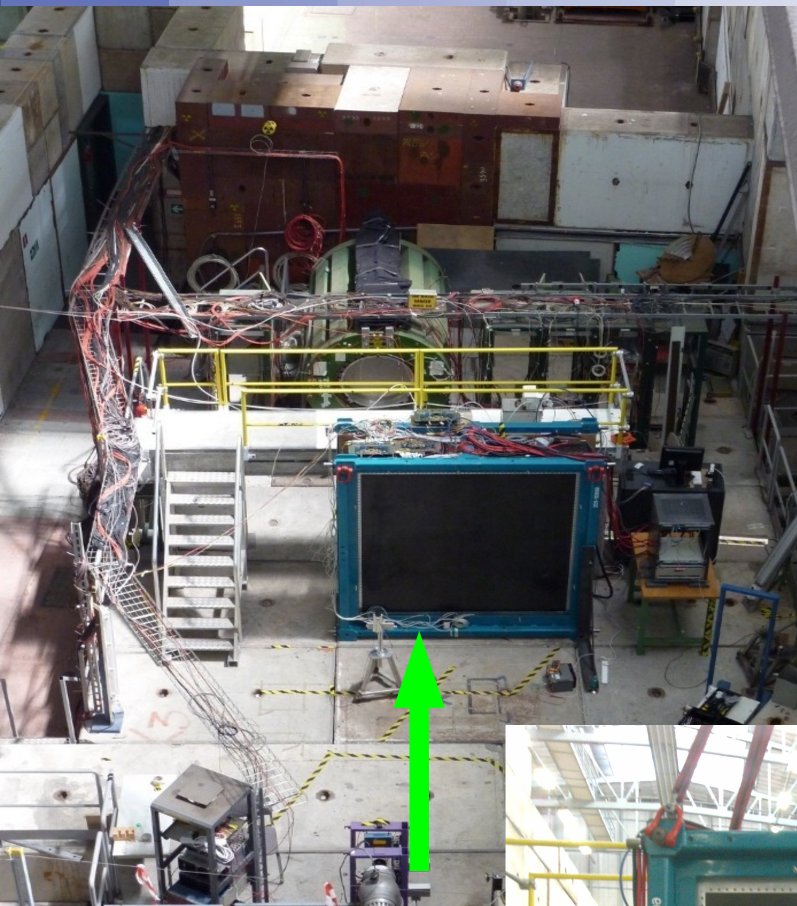
The DS-ECal

RAL May 09



The DS-ECal

Test beam at CERN



- Over 1M events taken
- Beam = e, p and π
- Full study of the data is underway.

Last tests before installation

At the Linac in J-PARC

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Last tests before installation

At the Linac in J-PARC

Me

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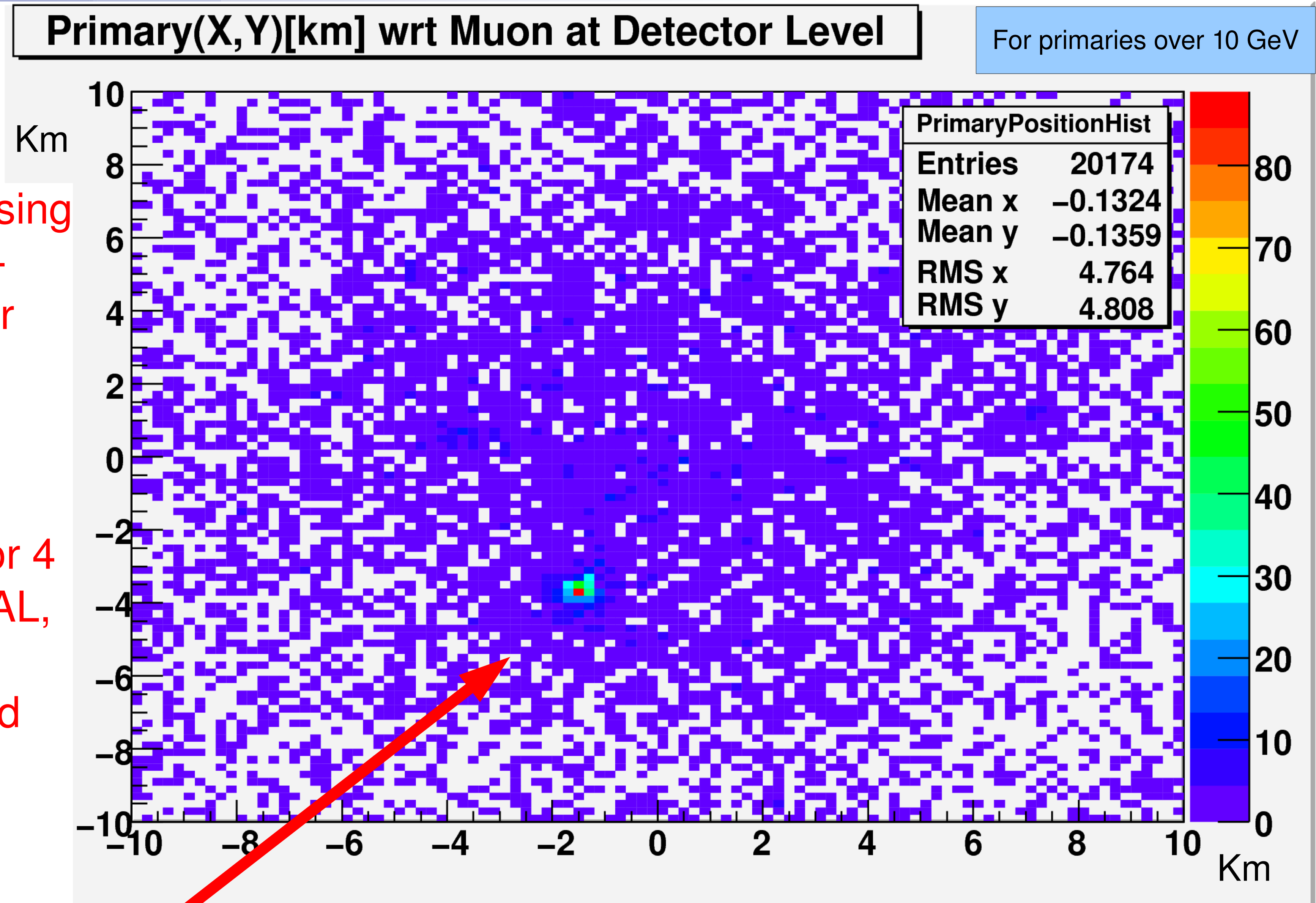
Calibrating The DS-ECal

- Essential to understand well the detector and its performance.
- The DS-ECal will be the only one of the 13 modules to be tested in a testbeam due to funding constraints.
- Commission and calibrate using testbeam data from CERN with positive (0.4-2.2GeV) and negative (0.4-4GeV) beams of electrons, protons and pions.
- Cosmic muon tests taken at RAL, CERN and J-PARC
- Many things to consider including DAQ understanding, PID, attenuation, alignment, gain, pedestals, MC-data comparison, stopping muons and Michel electrons and timing information.

Cosmic Flux Production and MC

- Produced using CORSIKA – extensive air shower simulation package.
- Produced for 4 locations RAL, CERN, TRIUMF and J-PARC.



For primaries over 10 GeV

Effect of magnetic field visible by off centre distribution

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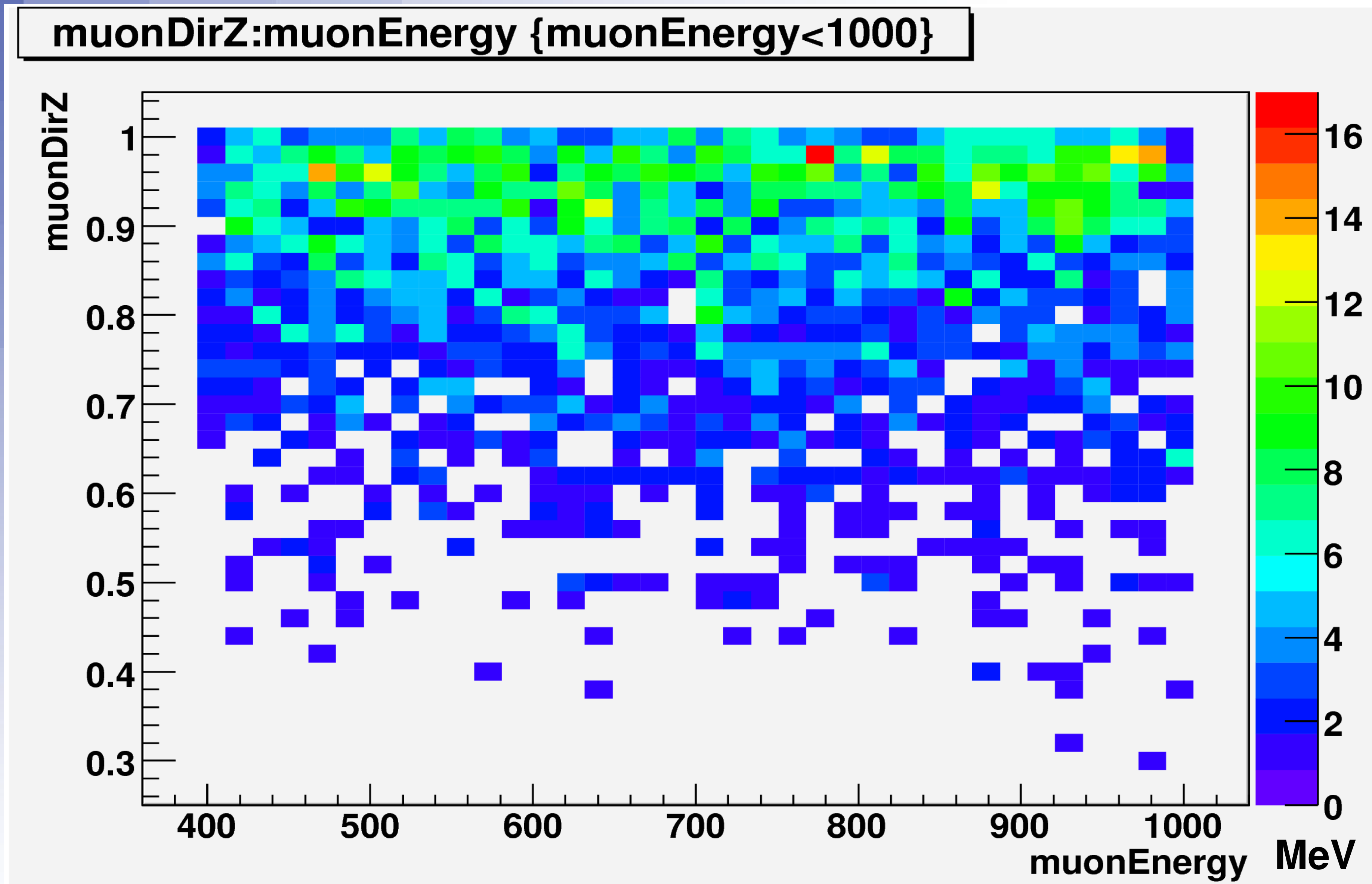
Cosmic Flux Production and MC



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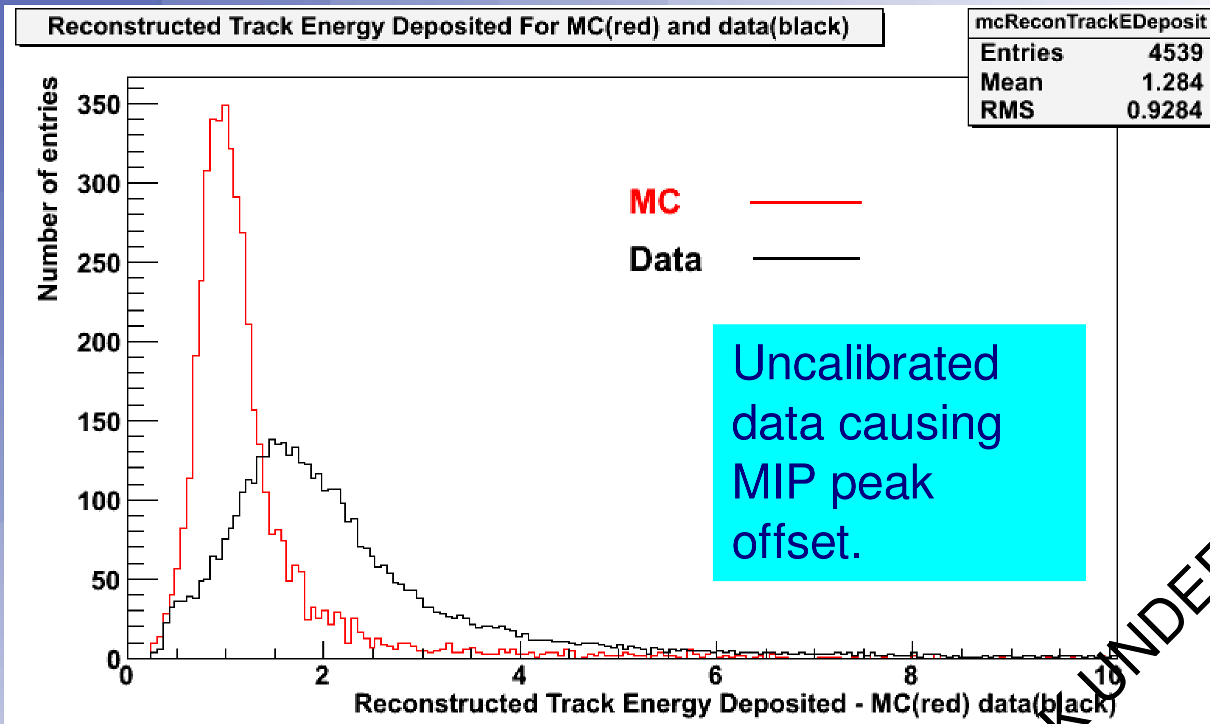
Cosmics MC Data Comparison DS-ECal

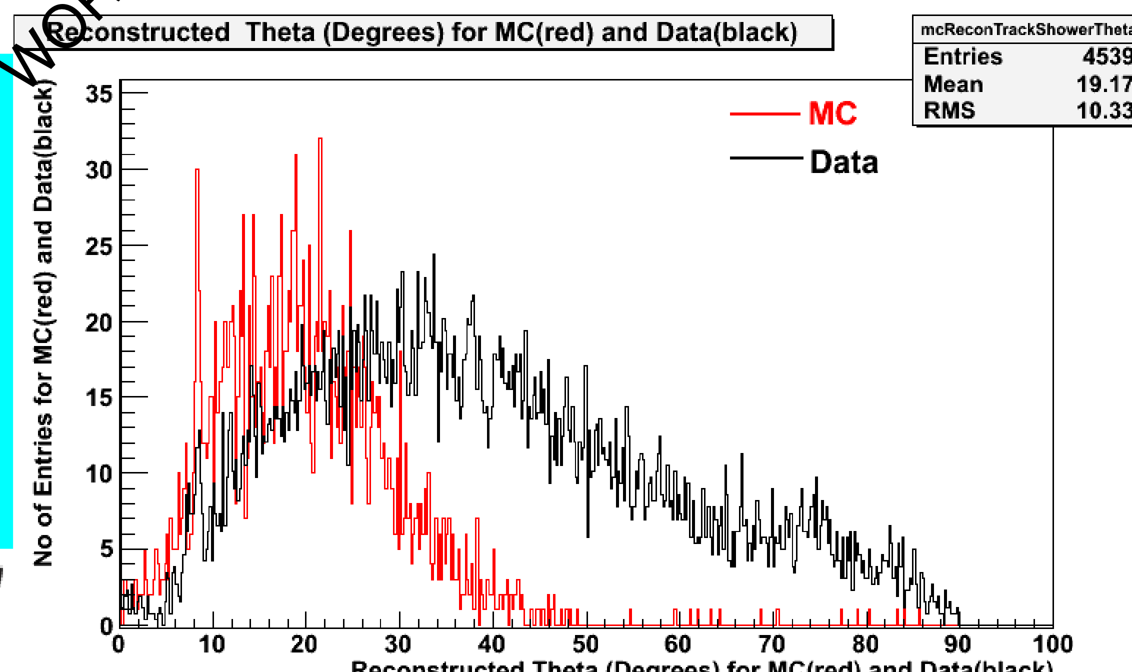


Uncalibrated data causing MIP peak offset.

Energy Comparison in MIPs

WORK UNDERWAY - PRELIMINARY

Direction Comparison in θ_{xz} where z is the vertical



Normalised data.
MC hasn't been run over the trigger which will cause some offset.
Also lower stats on MC mean that high angle tail is reduced.

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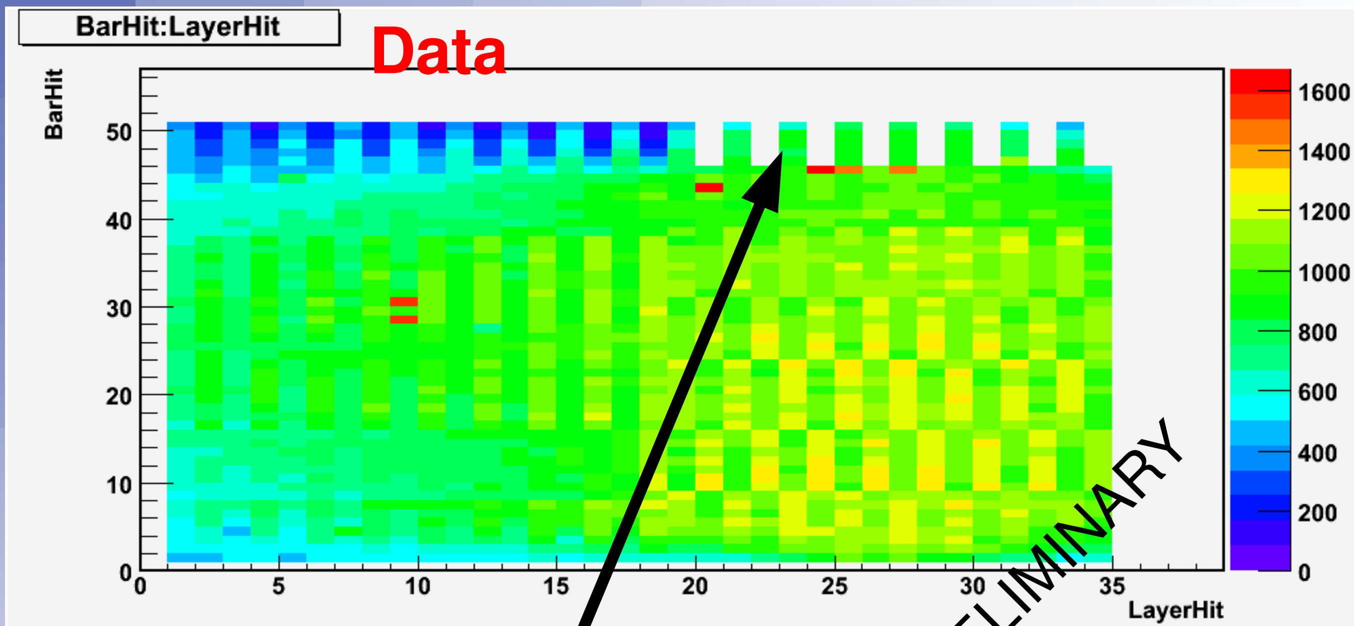
Cosmics MC Data Comparison DS-ECal

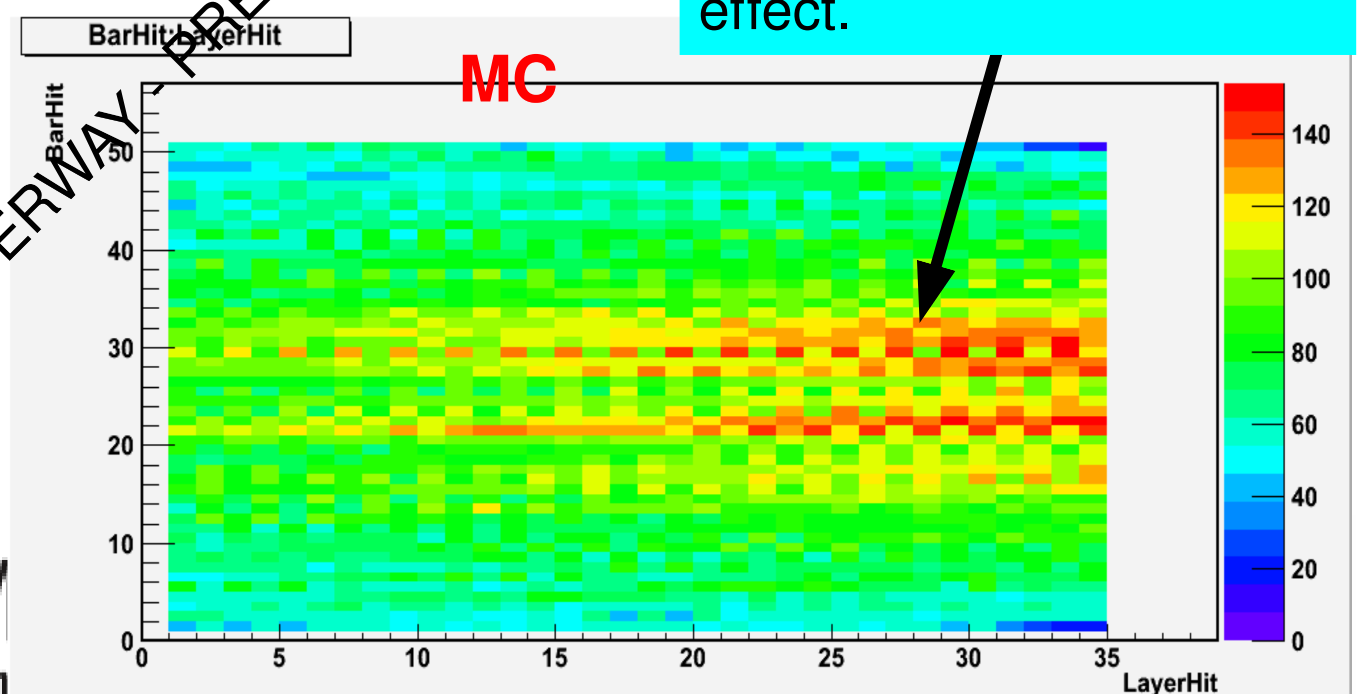
Detector Occupancy



Central region of increased hit density is due to the area of MC used being too small. MC covering increased area in production and will be finished soon. This should remove this effect.

Missing areas at the top left due to 2 dead TFB's (80 MPPC's) which have now been fixed.

WORK UNDERWAY - PRELIMINARY



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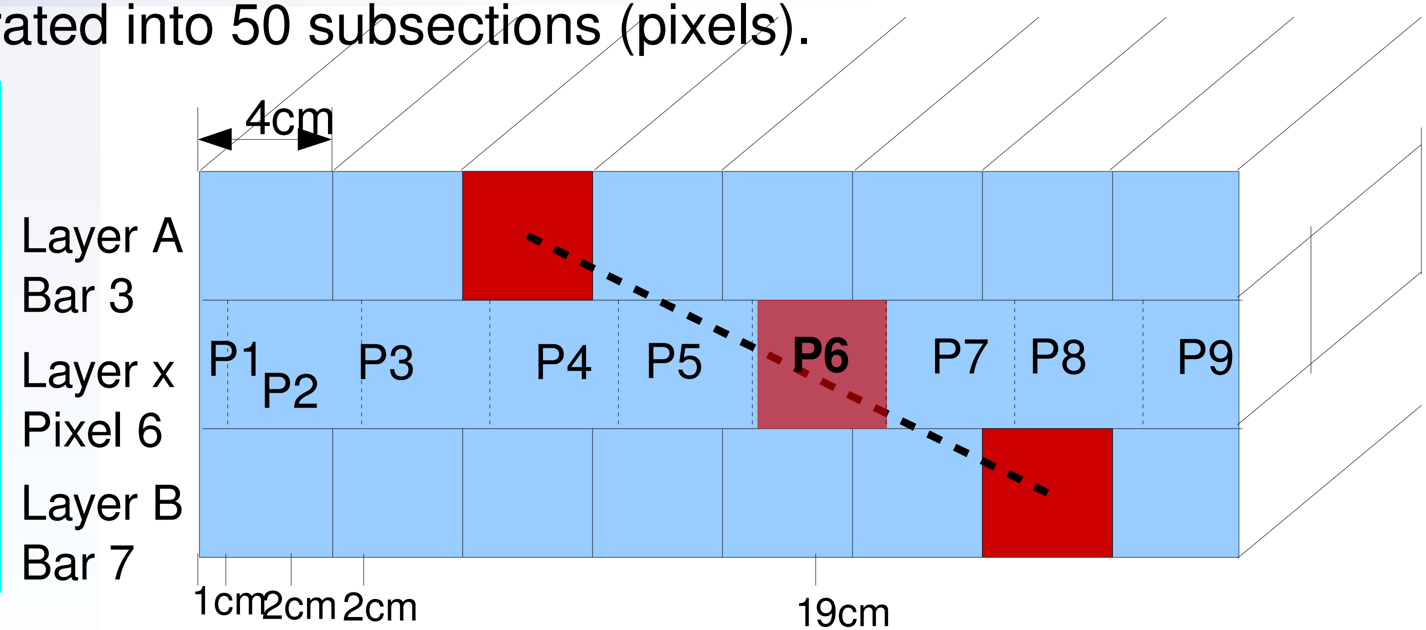
Attenuation Of DS-ECal Bars

- Find scintillator bar by bar attenuation calibration constants for the DS-ECal using cosmic ray data.
- Select tracks from muon hits without passing through reconstruction.
- Consider: charge layer and bar info and the MPPC that received the signal (since DS-ECal bars have double ended readout).
- Each Bar separated into 50 subsections (pixels).

•Hit position determined by taking average of bar # with max charge from layer above and below added together – except L1 and L34 which just use the one consecutive layer and extrapolation.



- Light yield per pixel of all track hits plotted for each MPPC: 50*3400 histograms and fit with a convoluted Landau-Gaussian.

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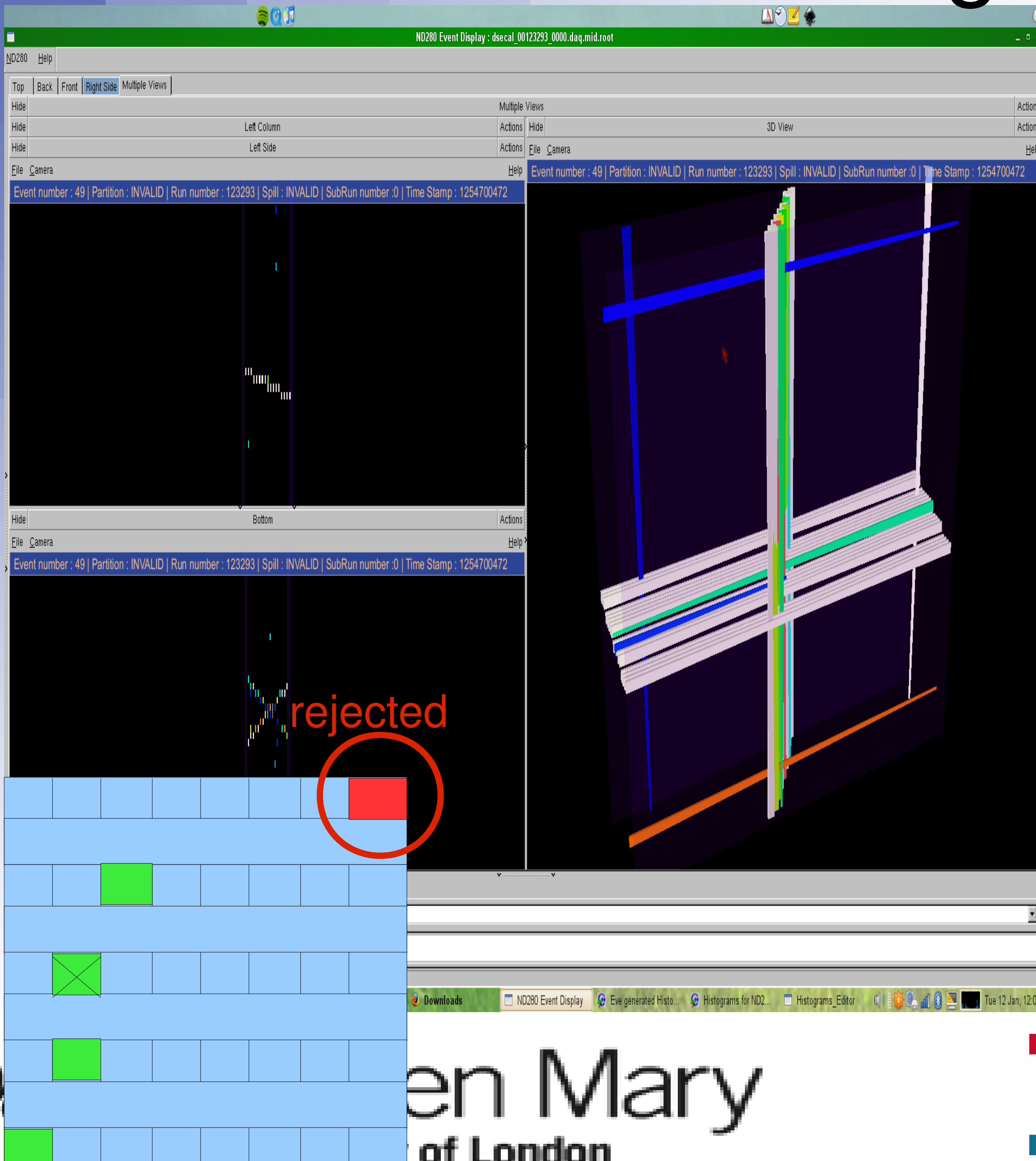
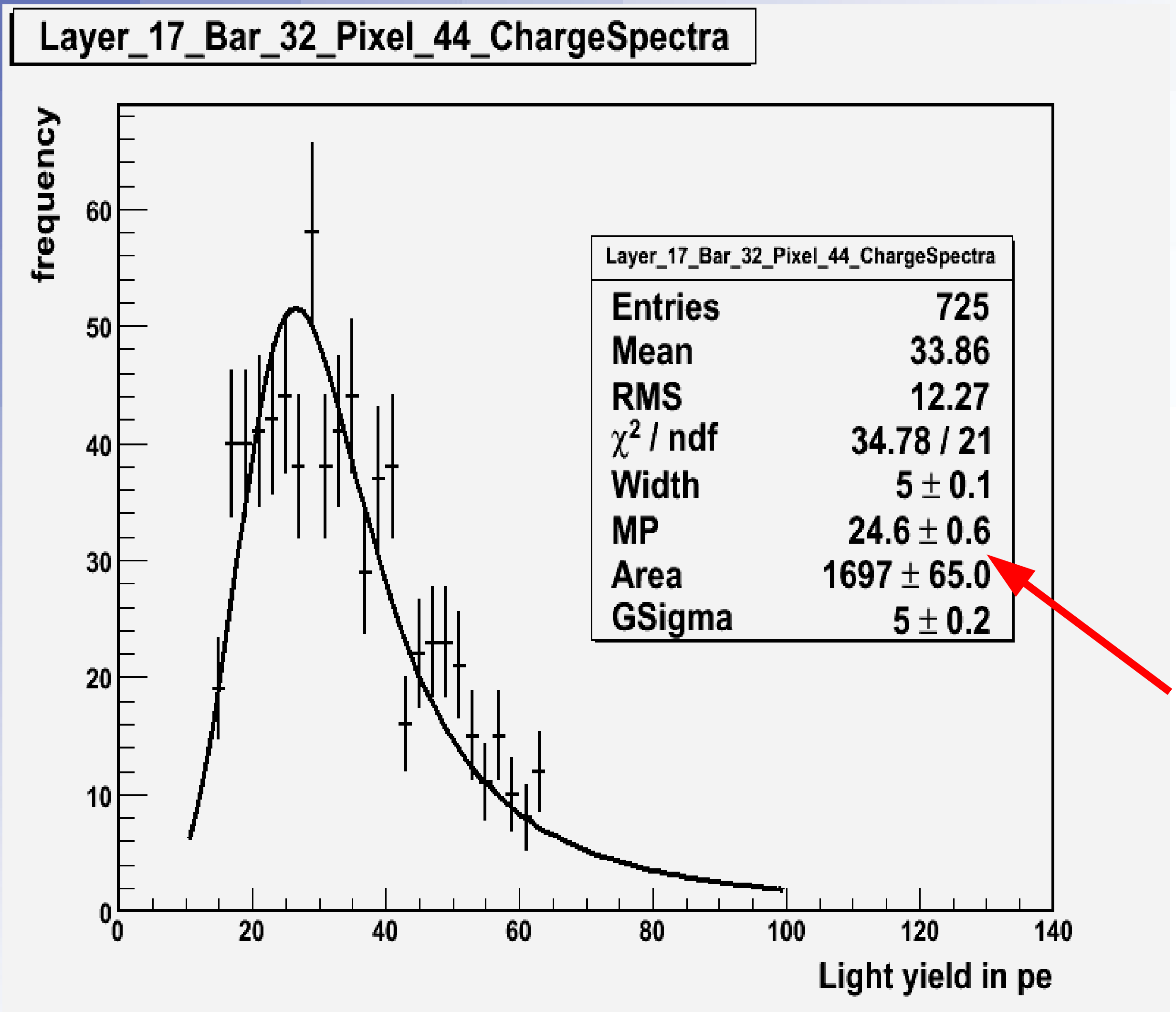
Track Finding Validation



Event Number in ev loop: 49
dsecal_12393_0000.daq.mid
Pixel: 18 L1 B 29
Pixel: 28 L2 B 18
Pixel: 18 L3 B 28
Pixel: 28 L4 B 18
Pixel: 18 L5 B 28
Pixel: 27 L6 B 18
Pixel: 18 L7 B 27
Pixel: 27 L8 B 18
Pixel: 18 L9 B 27
Pixel: 26 L10 B 19
Pixel: 19 L11 B 26
Pixel: 26 L12 B 19
Pixel: 19 L13 B 26
Pixel: 25 L14 B 19
Pixel: 19 L15 B 25
Pixel: 25 L16 B 19
Pixel: 19 L17 B 25
Pixel: 24 L18 B 19

Proof of Principle - Charge Spectra



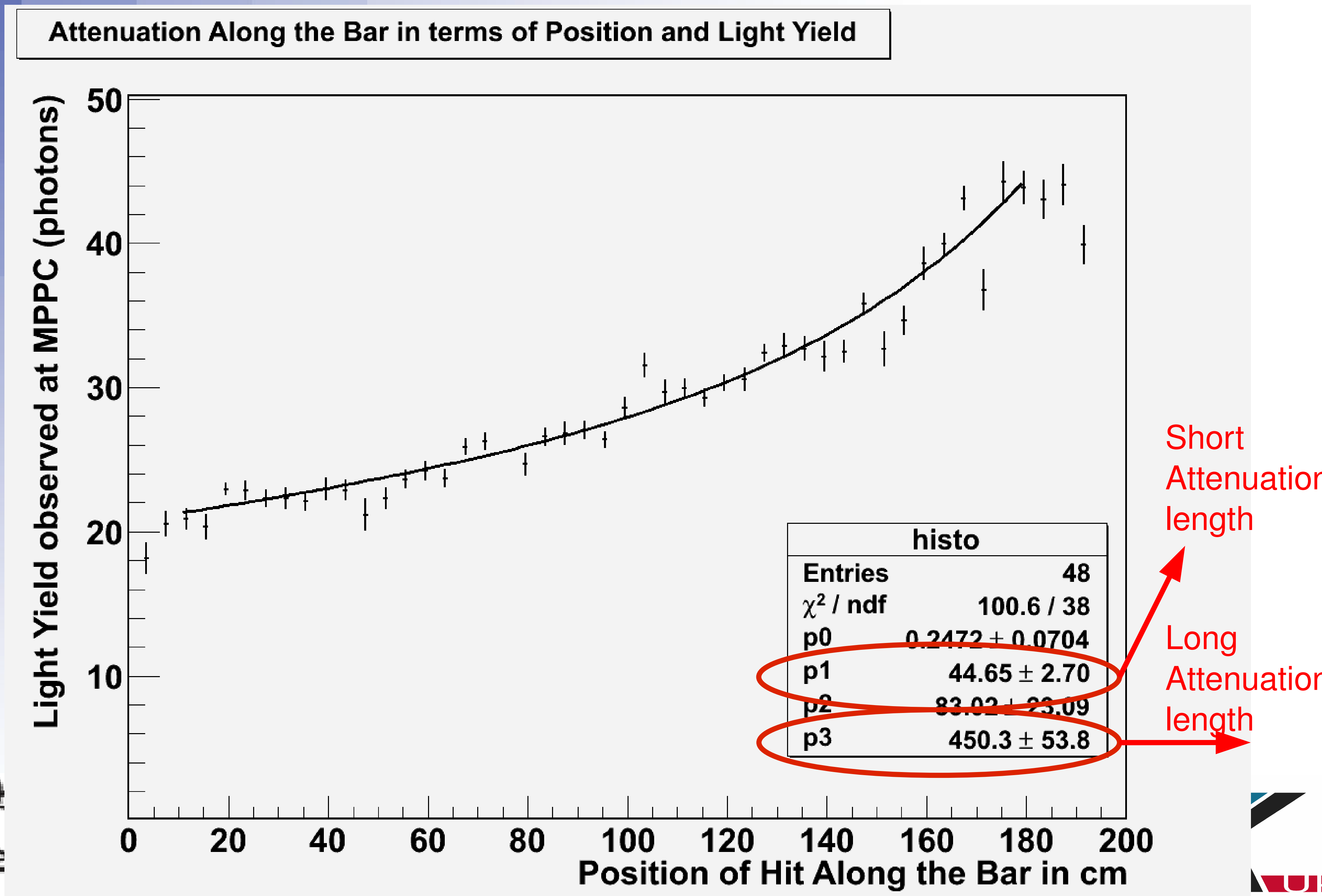
Light yield in photons calibrated from electronic readout counts.

This is pixel 44 of bar 32, layer 17

Convoluted Landau-Gaussian fit: Most Probable Value of light yield = **24.5 ± 0.6 photo electrons**

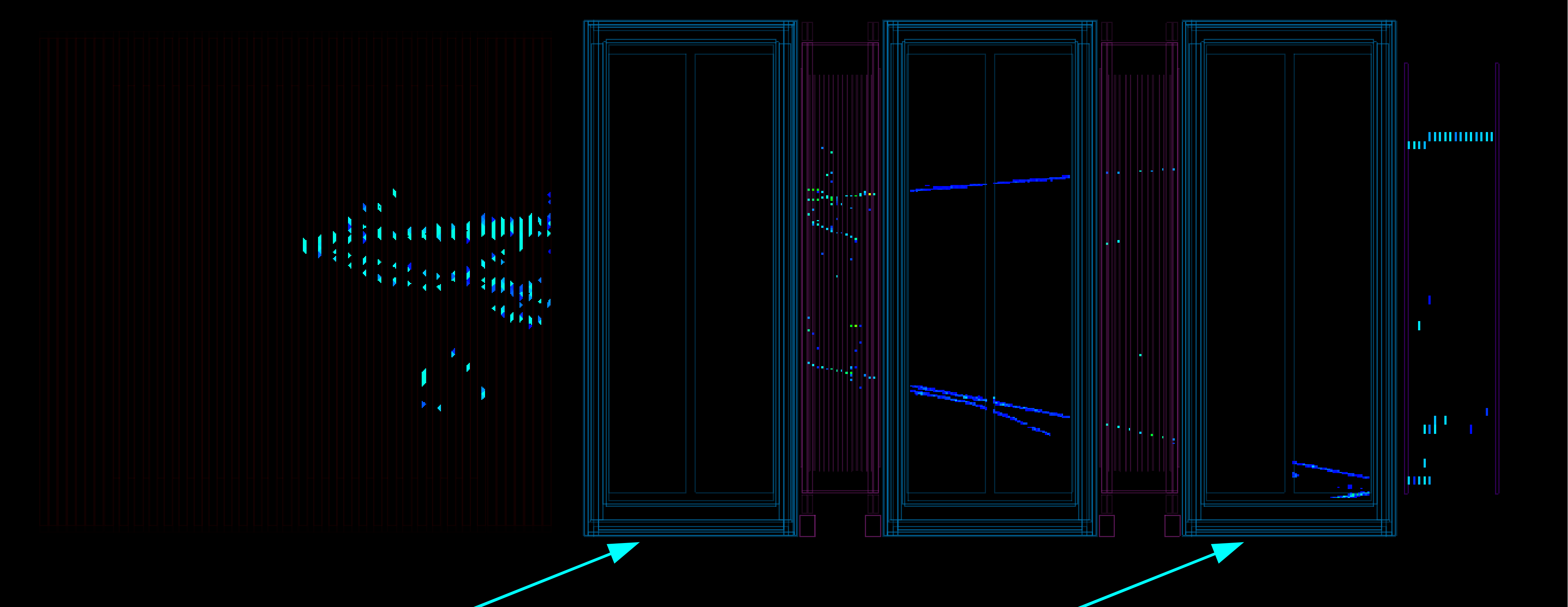
The MPV is plotted against position for each pixel of a bar to give the attenuation profile of the bar.

Double Exponential Fit ([0]*(exp(x/[1])+[2]*exp(x/[3])))



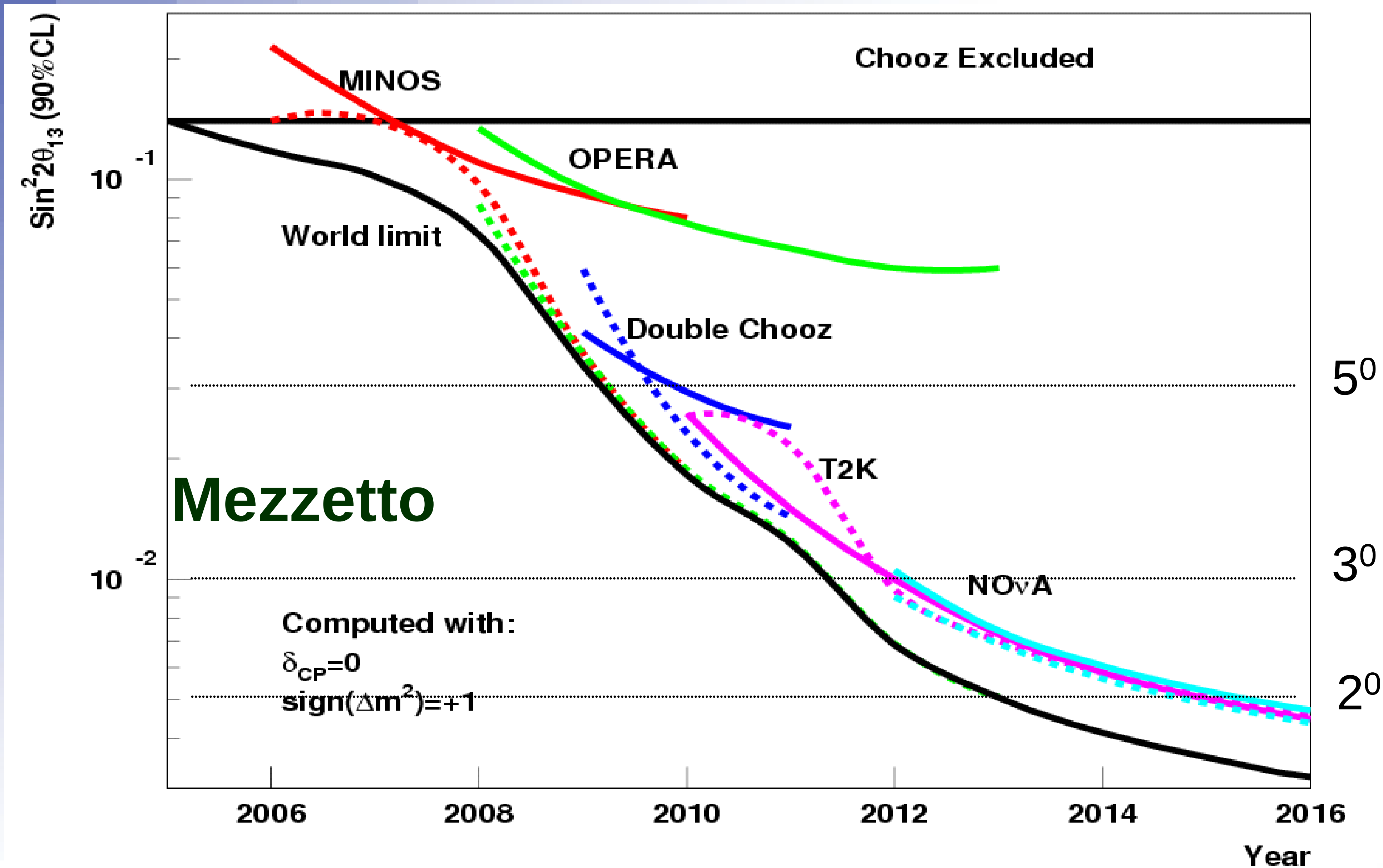
First Data – Exciting Times

- First beam Dec 09 during commissioning.
- Our first neutrino candidates have been seen by all sub-detectors of nd280!



TPC1 not yet installed TPC2 under commissioning

T2K - The Next 5 Years



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Conclusions

- T2K is a long-baseline neutrino oscillation experiment which aims to answer 3 of the biggest outstanding questions in neutrino oscillations
  - the value of θ_{13}
  - whether θ_{23} is maximal
  - Whether neutrino oscillations are CP violating.
- The near detector suite is at J-PARC and consists of INGRID to detect the beam position and the off-axis ND280 to characterise the beam and minimise backgrounds to the oscillation measurement.
- The T2K far detector is Super-K a 50kTon water Cherenkov detector.
- The ECals of ND280 are essential to the near detector and their calibration is therefore also essential
  - attenuation, mc-data comparison, cosmic muons and testbeam.
- T2K is being commissioned and will be ready for physics studies soon.

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Questions?

Backup Slides

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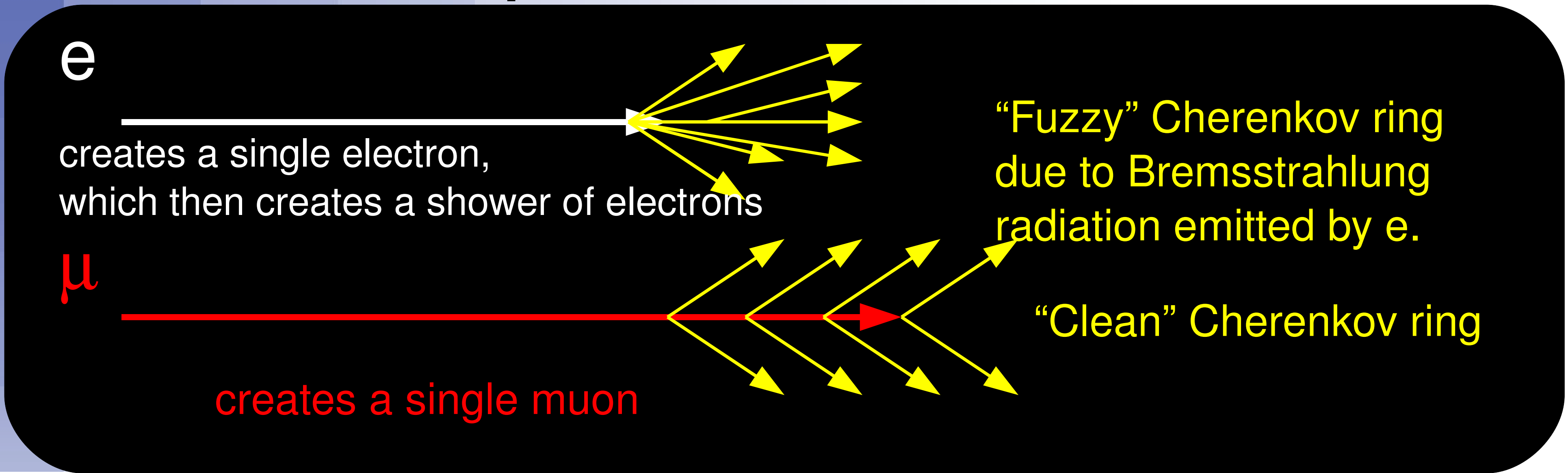
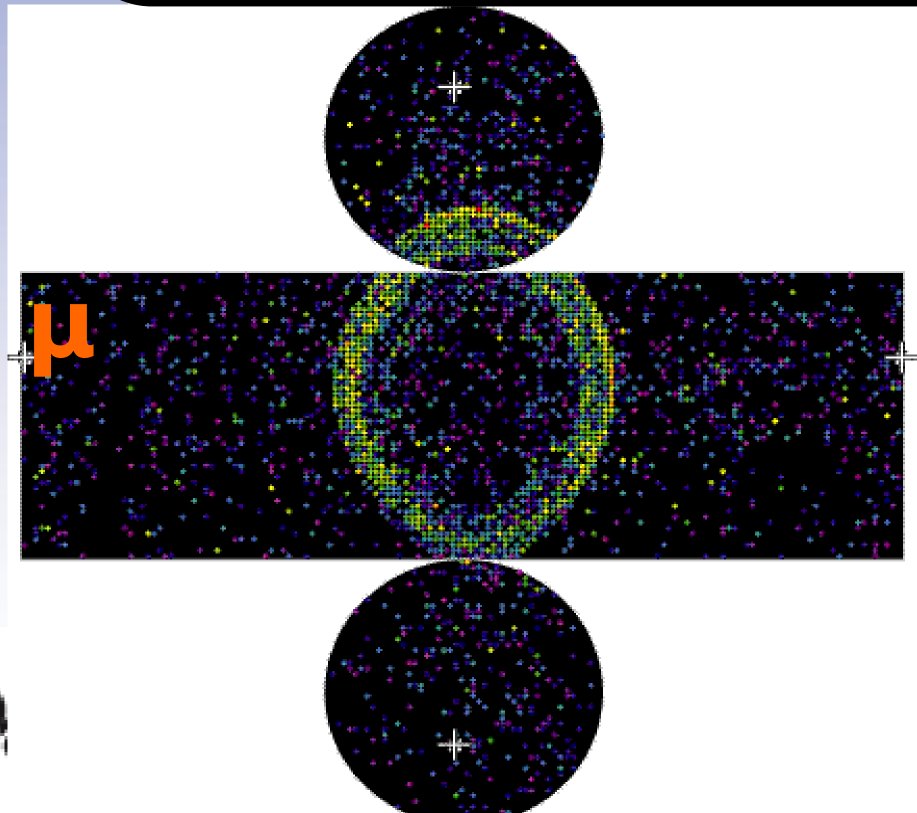
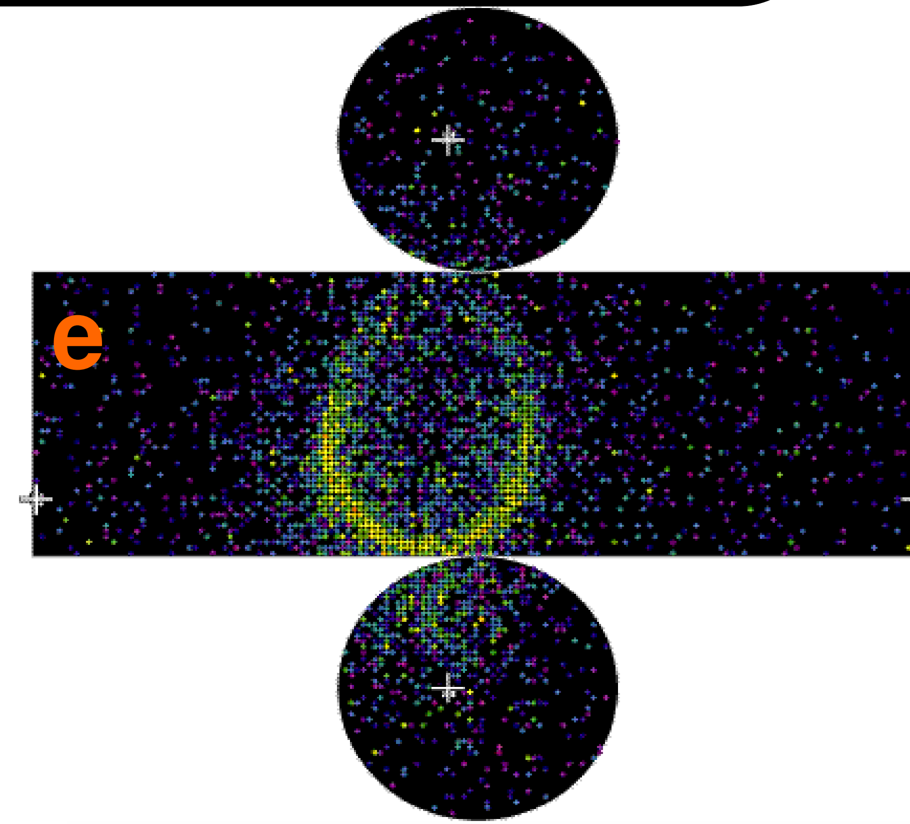
Super Kamiokande







The Future For T2K

- If $\sin^2 2\theta_{13}$ is measured at T2K and is found large (> ~0.01), ν CP-violation study is possible
- Oscillation prob. is different between neutrino and anti-neutrino
- CP violation can be studied by measuring 1st and 2nd max of oscillation w/ different E/L and/or both ν_μ and anti ν_μ beams.

$$P(\nu_e \rightarrow \nu_\mu) \approx \sin^2 2\theta_{13} T_1 + \alpha \sin 2\theta_{13}(T_2 + T_3) + \alpha^2 T_4$$

$$T_1 = \sin^2 \theta_{23} \frac{\sin^2[(1-A)\Delta]}{(1-A)^2}$$

$$T_2 = \sin \delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \sin \Delta \frac{\sin(A\Delta)}{A} \frac{\sin[(1-A)\Delta]}{(1-A)}$$

$$T_3 = \cos \delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \cos \Delta \frac{\sin(A\Delta)}{A} \frac{\sin[(1-A)\Delta]}{(1-A)}$$

$$T_4 = \cos^2 \theta_{23} \sin^2 2\theta_{12} \frac{\sin^2[A\Delta]}{A^2}$$

$$\alpha \equiv \frac{\Delta m^2_{21}}{\Delta m^2_{31}} \approx \pm 0.03 \qquad \Delta \equiv \frac{\Delta m^2_{31} L}{4E} \qquad A \equiv \frac{2\sqrt{2} G_F n_e E}{\Delta m^2_{31}}$$