Neutrino Physics

IHEP-JINR Neutrino Detector

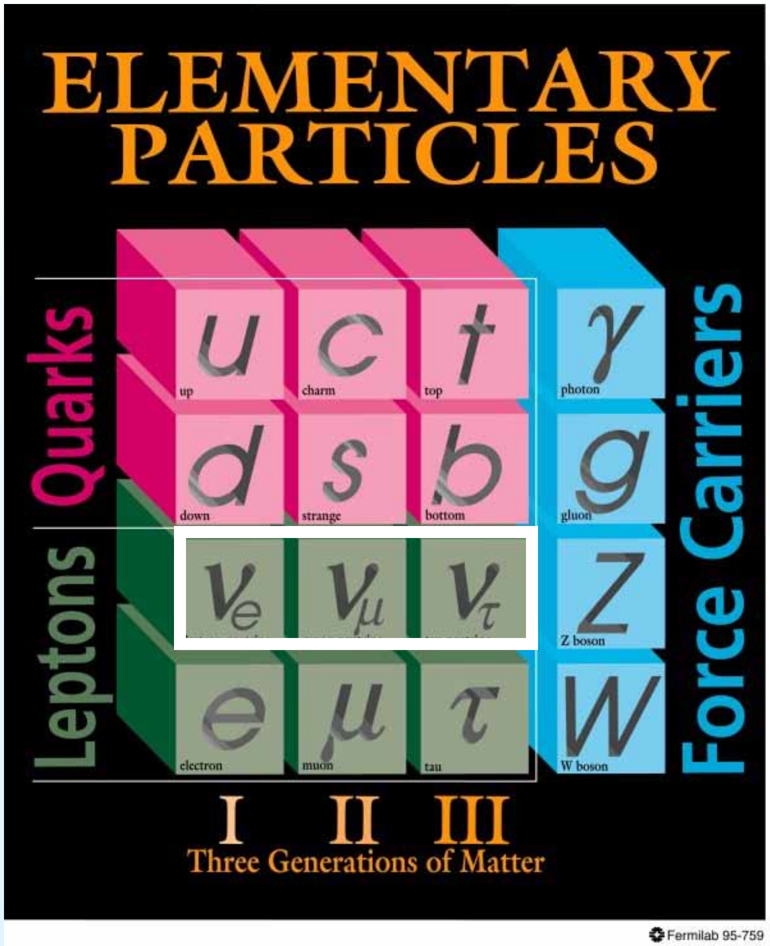
T2K experiment

Vladimir Kravtsov

Colorado State University

Particles of the "Standard Model"

Within the SM there are 3 different families of particles.
Each lepton has a neutrino associated with it.



Neutrinos are one of the fundamental particles and have only ***week interaction***.

Neutrino has a ***zero mass***, a ***zero charge*** and a ***spin 1/2***.

*Direct measurement of the **neutrino mass** by kinematical analysis of weak decays*

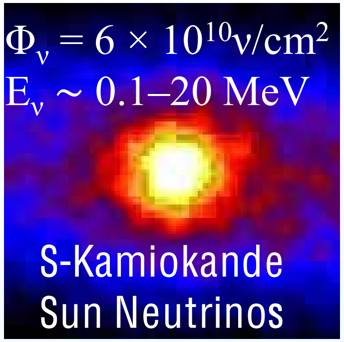
$$m_{e} < 2.3 eV$$

$$m < 170 keV$$

$$m < 18.2 MeV$$

The sources of neutrinos

Natural sources

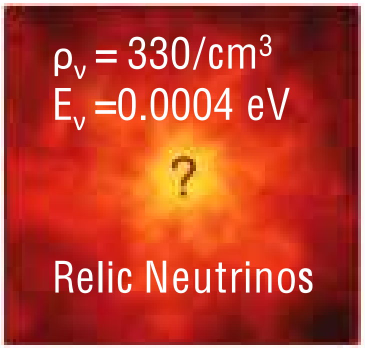


Solar

Atmospheric

Earth (Geo ν)

Supernovae



BigBang

Artificial sources

Accelerators

Reactors

A Brief History of the Neutrino

1914 The β-decay energy conservation crisis.
1930 Pauli proposes a new neutral particle is emitted in β-decay.
1932 Fermi names the new particle “neutrino” and introduces four-fermion interaction.
1956 The first observation of ***electron anti-neutrinos*** by Reines and Cowan.
1957 Bruno Pontecorvo proposes neutrino-antineutrino ***oscillations***.
1962 Ziro Maki, Masami Nakagawa and Sakata introduce neutrino flavor mixing and flavor oscillations (***MNSP matrix***).
1962 The ***muon neutrino*** is observed at BNL.
1973 Discovery of neutral currents at CERN.
1998 Super-Kamiokande announced the evidence of atmospheric neutrino oscillations
2000 First direct evidence for the ***tau neutrino***

Neutron β decay

Measured β spectra were continuous instead of discrete for 2-body decay

1914

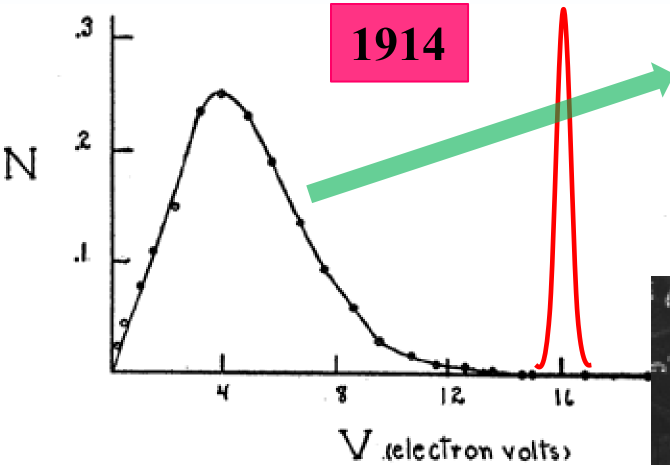
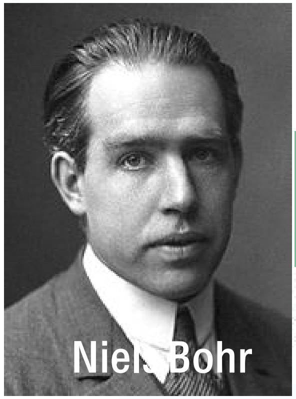
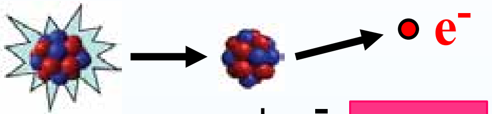


FIG. 5. Energy distribution curve of the be



Niels Bohr even suggested that perhaps energy conservation did not hold inside the nucleus.

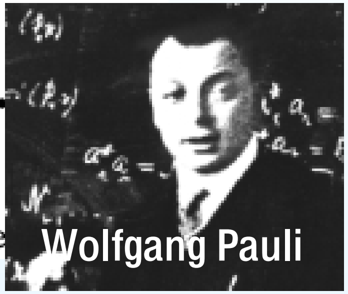
"At the present stage of atomic theory, however, we may say that we have no argument, either empirical or theoretical, for upholding the energy principle in the case of β-ray disintegrations".



$$n \rightarrow p + e^-$$

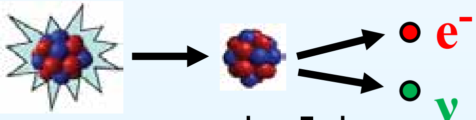
$$M_n c^2 \quad E_p + E_e$$

1930



Pauli proposed that a neutral particle shared the energy of beta decay with the emitted electron.

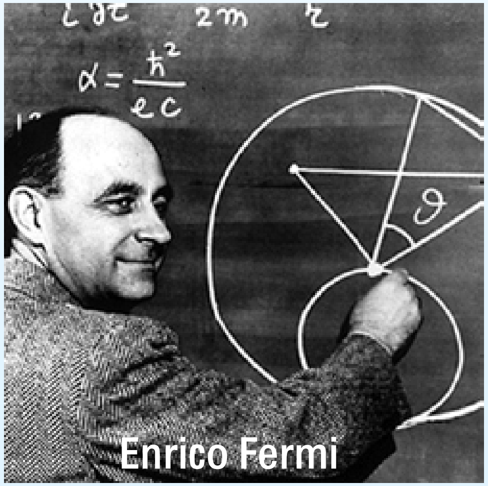
«I have done a terrible thing. I have postulated a particle that cannot be detected.» (1930)



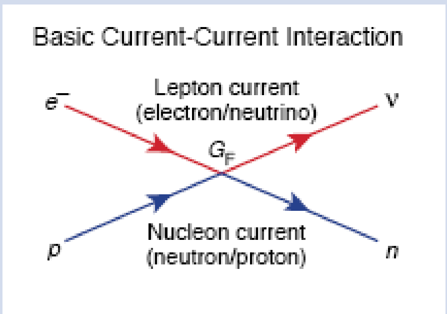
$$n \rightarrow p + e^- + \nu$$

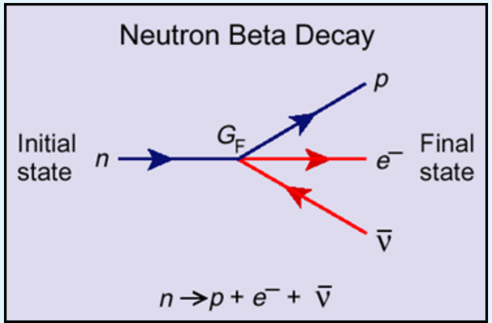
$$M_n c^2 = E_p + E_e + E$$

1934



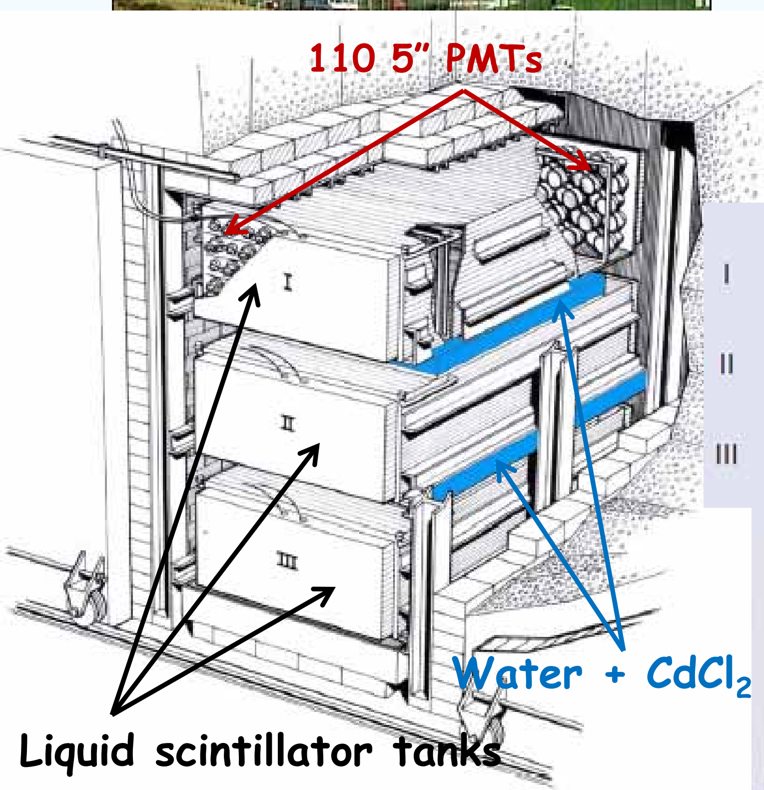
Fermi builds a new theory of to explain β-decay based on the current-current interaction and named a new particle "neutrino".



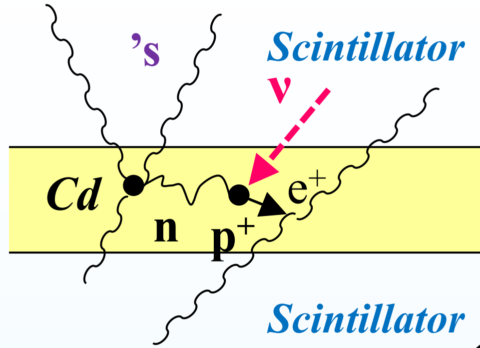


Discovery of Electron Neutrino (1956)

The fist experimental detection came from the high flux of neutrinos created in Savannah River reactor.



The inverse β decay produces two signals in tanks



$\bar{\nu}_e + p \rightarrow n + e^+$

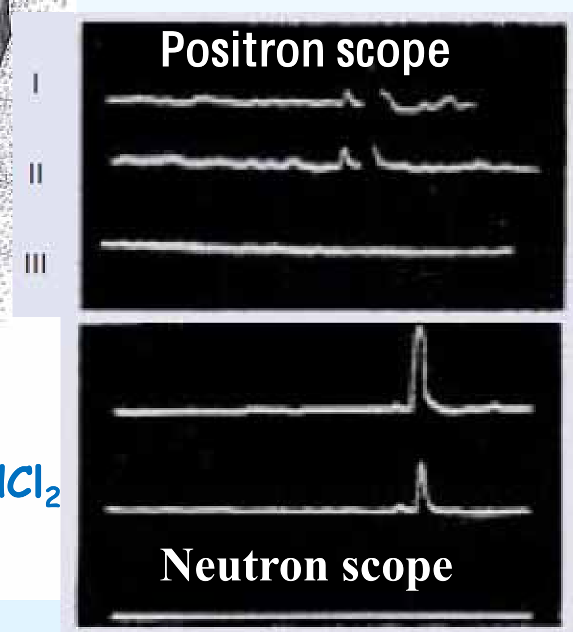
$e^+ + e^- \rightarrow \gamma + \gamma$

Prompt signal producing two 0.511 MeV γ's

$n + {}^{108}Cd \rightarrow {}^{109}Cd^* \rightarrow {}^{108}Cd + \gamma's$

Delayed signal from **n** capture on cadmium producing 9 MeV in γ's

A few μs later



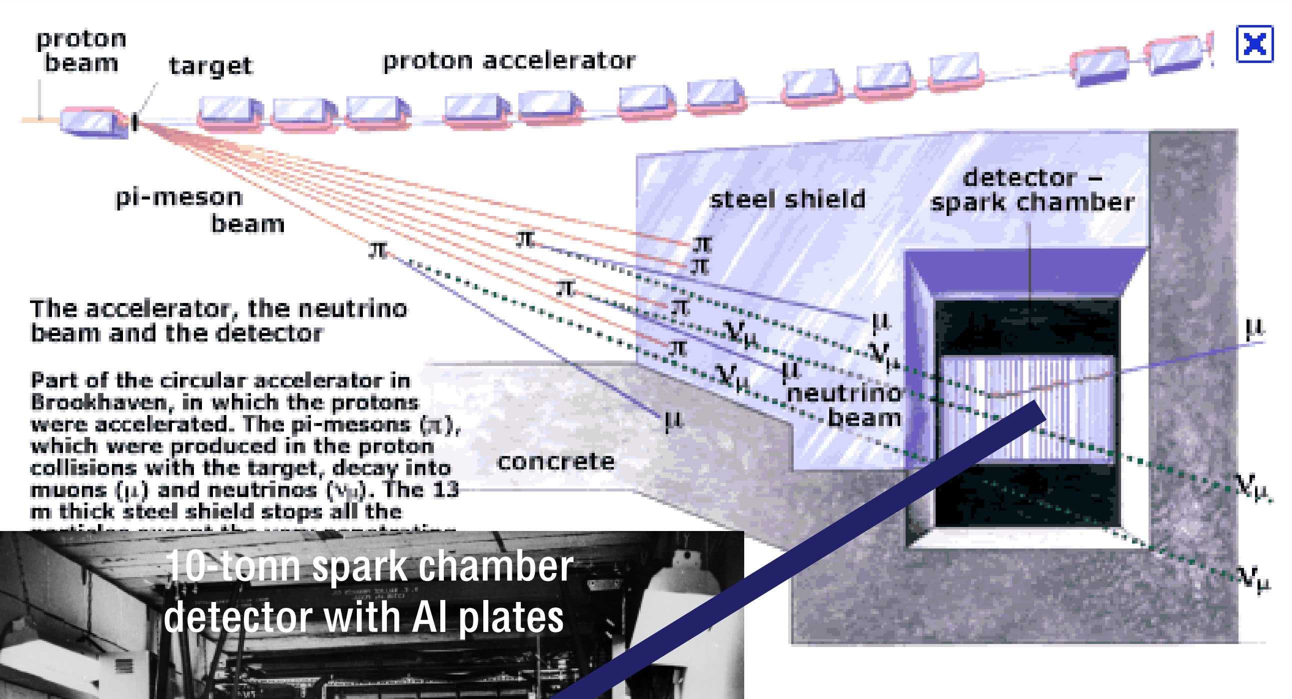
$\sigma = (1.1 \pm 0.3) \times 10^{-43} cm^2$

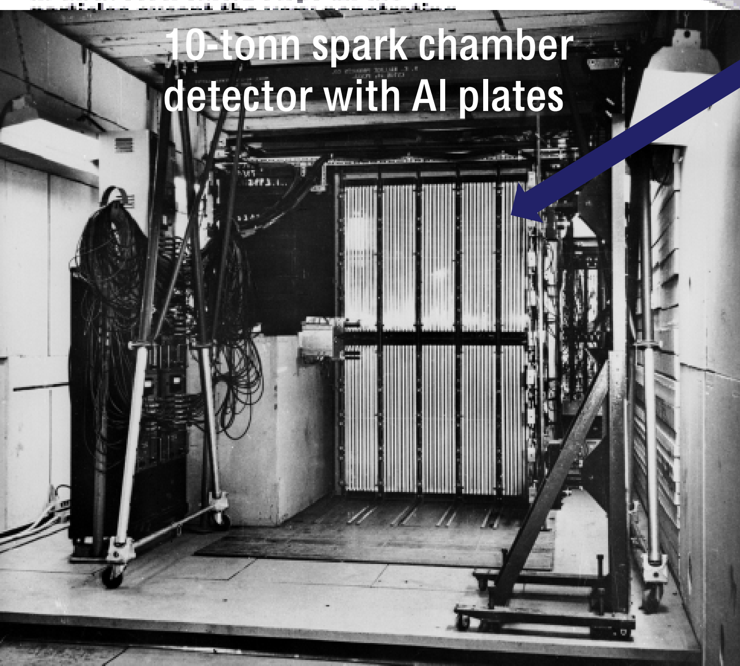
Science 124 (1956) 103;
Phys. Rev. 113 (1959) 273

The Nobel Prize in Physics 1995 was awarded to Frederick Reines *"for the detection of the neutrino"*

Discovery of Muon Neutrino (1962)

In 1962, Schwartz, Steinberger and Lederman built the very first neutrino beam and presented evidence for the muon neutrino





Neutrino beam

Main sources

$^+$ $^+ +$

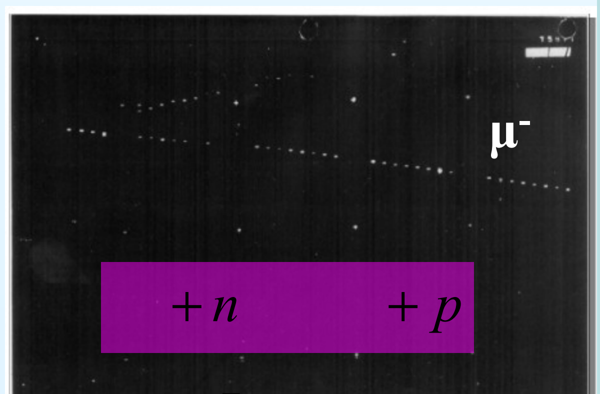
K^+ $^+ +$

Secondary sources

K^+ $^0 +$ $^+ +$

K^+ $^0 + e^+ +$ $_e$

$^+$ $e^+ +$ $_e +$

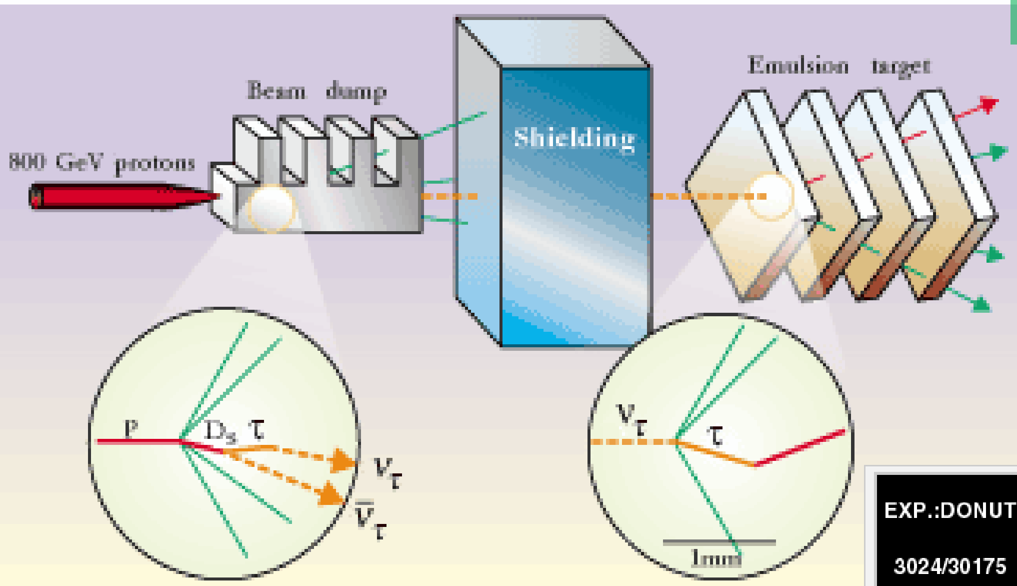


29 ν_μ interactions were registered

The Nobel Prize 1998 was awarded to Leon Lederman, Melvin Schwartz and Jack Steinberger *"for the neutrino beam method and the demonstration of the doublet structure of the leptons through the discovery of the muon neutrino "*

Discovery of Tau Neutrino (2000)

800 GeV protons from TeVatron (FNAL) on Tungsten target produce **Ds** mesons

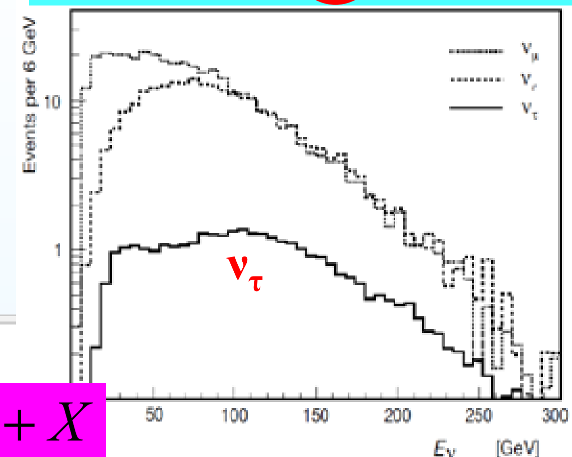


Decay of D_s meson and next τ lepton decay give ν_τ

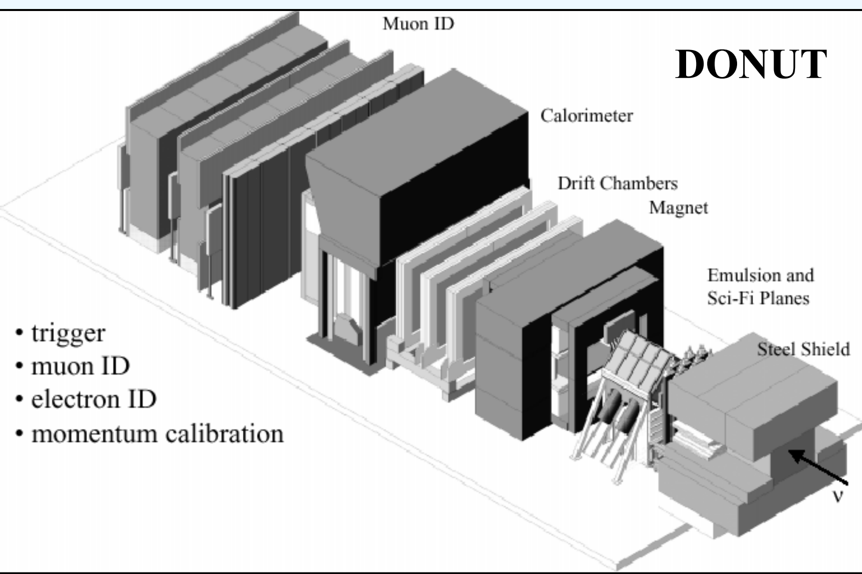
$D_s \quad +$

$l + \quad _l + \quad ^{-}, \quad l = e,$

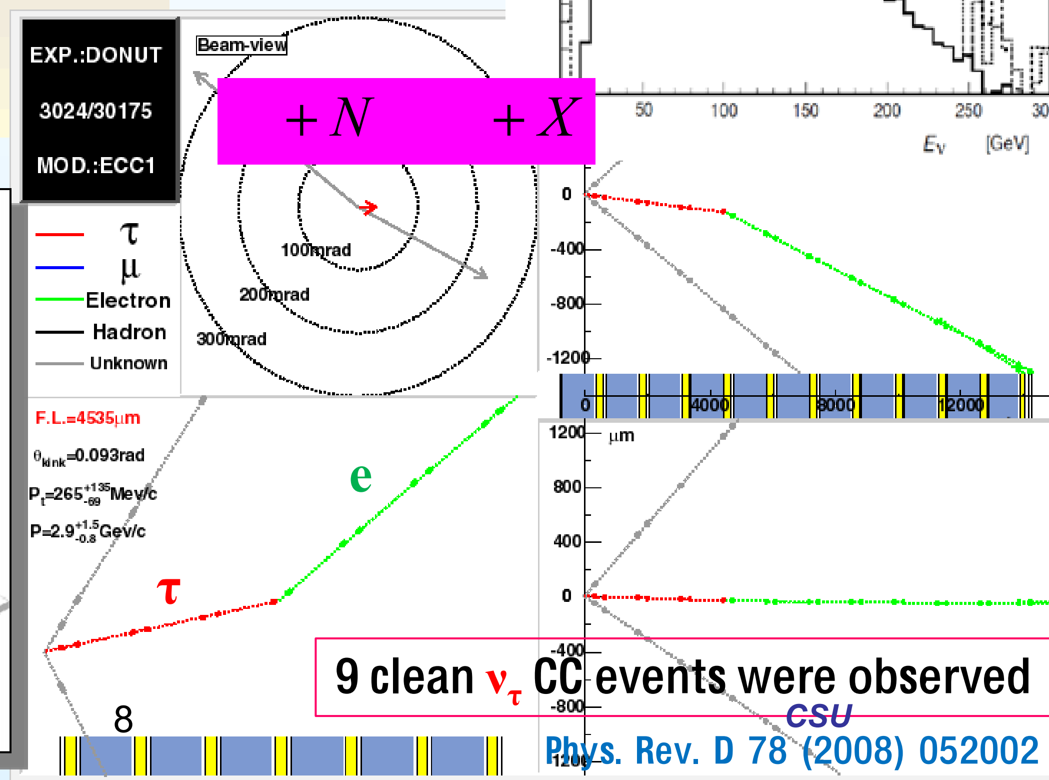
τ_τ=2.9x10^{-13}



$+N \quad +X$



- trigger
- muon ID
- electron ID
- momentum calibration

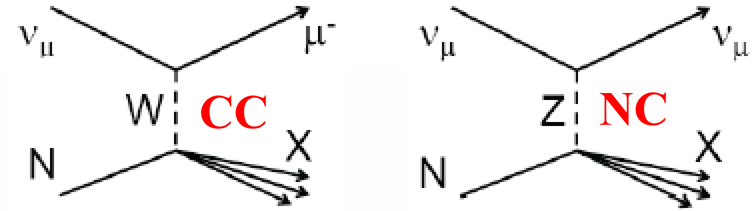


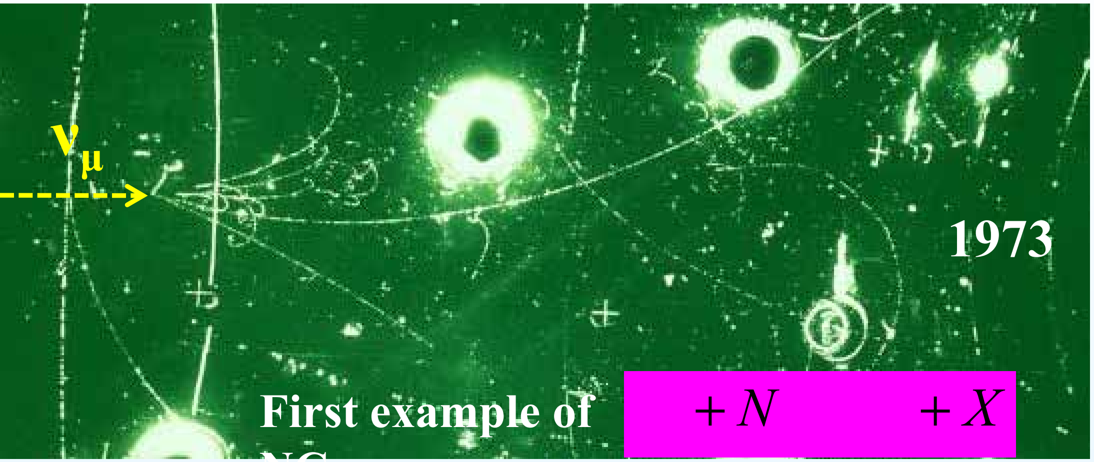
9 clean ν_τ CC events were observed

Phys. Rev. D 78 (2008) 052002

Neutral currents: triumph of the electro-weak unification (1973)

Weinberg and Salam develop a theory of electroweak interactions, but it requires a "neutral" weak current. The model introduces two types of weak interaction: Charged current (**CC**) and Neutral current (**NC**).





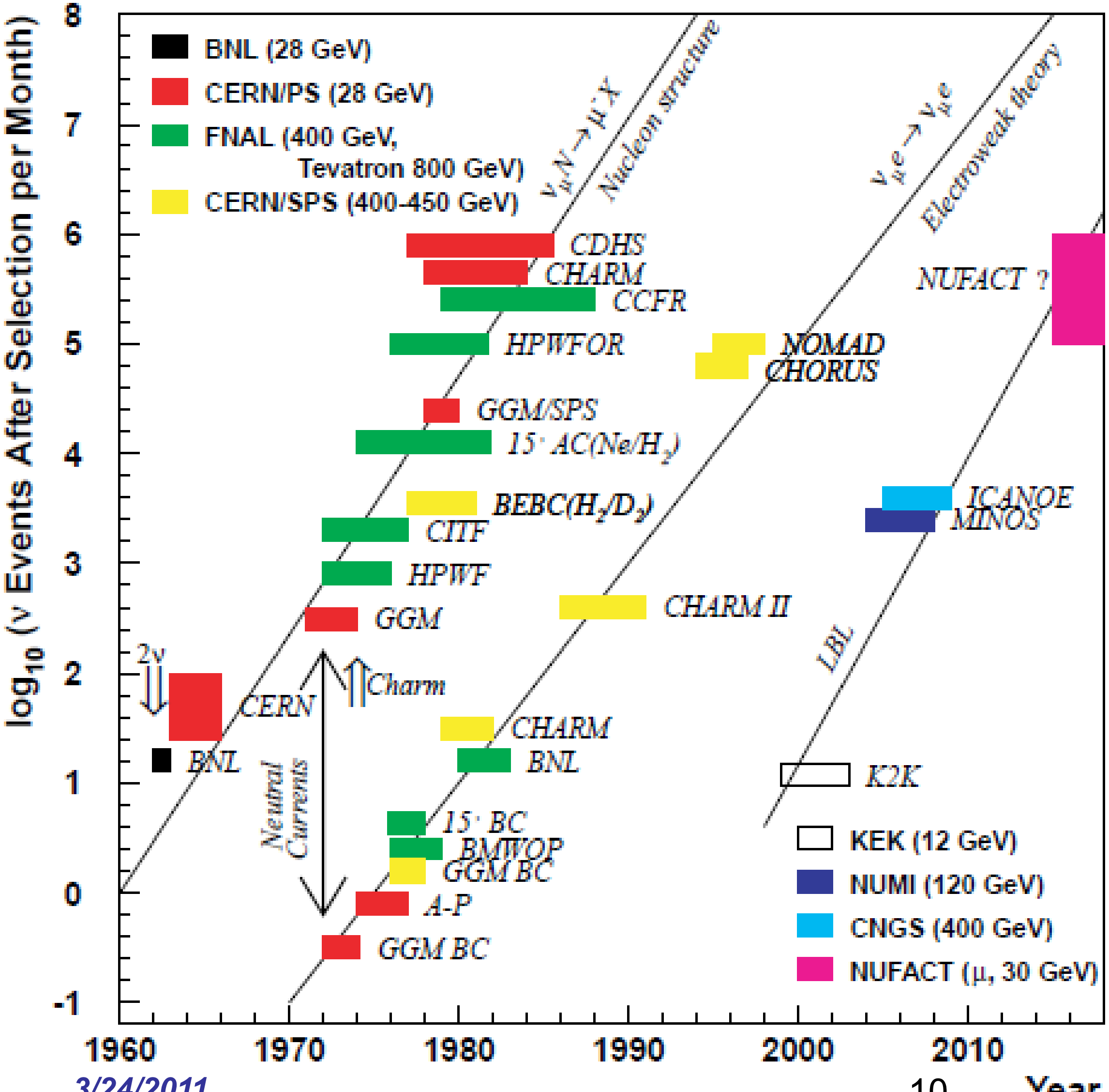
First example of NC

Gargamelle bubble chamber filled with freon (CF_3Br)

Big **E**uropean **B**ubble **C**hamber

Large neutrino calorimeter type detectors

A large sampling calorimeters can measure large statistics CC and NC data



Neutrino cross section is very low

$$\sigma^{\nu p} \sim 10^{-38} \mathrm{cm}^2 \frac{E_\nu}{\mathrm{GeV}}$$

FNAL (700 GeV)
CITF, HPWF, CCFR/NuTeV

BNL (28 GeV)
E-776, E-816

CERN (400 GeV)
Aachen-Padova, CDHS, CHARM

IHEP (70 GeV)
IHEP-ITEP, IHEP-JINR

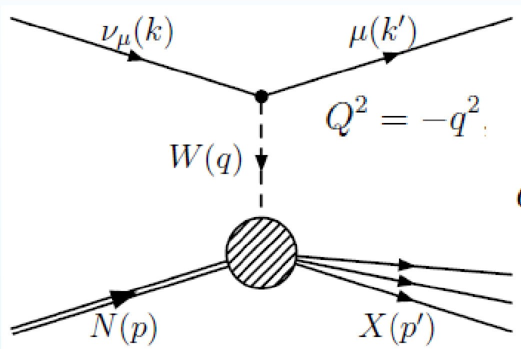
Large neutrino calorimeter type detectors goals

1. *Cross section measurements*

$+N \quad\quad +X$	- CC DIS	$+N \quad\quad +X$	- NC DIS	$+e \quad\quad +e$	- νe-scattering
$+n \quad\quad +p$	- CC QE	$+p \quad\quad +p$	- NC Elastic	$+e \quad\quad +\ {}_e$	- Inverse μ-decay

2. *Nucleon structure functions measurements*

$$\frac{1}{E_\nu}\frac{\mathrm{d}^2\sigma^{\nu(\bar\nu)}}{\mathrm{d}x\,\mathrm{d}y} = \frac{G_F^2 M_N}{\pi}\left[\frac{1}{2}y^2\cdot 2xF_1 + \left(1 - y - \frac{M_N x y}{2E_\nu}\right)F_2 \pm \left(y - \frac{1}{2}y^2\right)xF_3\right]$$



$$x = \frac{Q^2}{2\nu M_N} \qquad y = \frac{\nu}{\nu + E_\mu}$$

Bjorken scaling variables in the laboratory system

$\nu = E_\nu - E_\mu = E_{\rm had}$ - Energy transferred to nucleon

$Q^2 = 2E_\nu(E_\mu - p_\mu\cos\theta_\mu) - m_\mu^2 \simeq 4E_\nu p_\mu \sin^2\frac{1}{2}\theta_\mu$ - 4-momentum transfer

In terms of the quark distribution functions

$$2xF_1^\nu = F_2^\nu = 2x(d + \bar u + s + \bar c) \qquad xF_3^\nu = 2x(d - \bar u + s - \bar c)$$

$$2xF_1^{\bar\nu} = F_2^{\bar\nu} = 2x(\bar d + u + \bar s + c) \qquad xF_3^{\bar\nu} = 2x(-\bar d + u - \bar s + c)$$

3. *Measurement of $\sin^2\theta_W$ SM parameters*

$$R^\nu \equiv \frac{\sigma(\nu_\mu N \to \nu_\mu X)}{\sigma(\nu_\mu N \to \mu^- X)} = \frac{1}{2} - \sin^2\theta_W + \frac{5}{9}(1+r)\sin^4\theta_W \qquad r = \sigma_{CC}^{\bar\nu}/\sigma_{CC}^{\nu}$$

NuTeV →
$$R^- = \frac{\sigma_{NC}^\nu - \sigma_{NC}^{\bar\nu}}{\sigma_{CC}^\nu - \sigma_{CC}^{\bar\nu}} = \frac{R^\nu - rR^{\bar\nu}}{1-r} = \frac{1}{2} - \sin^2\theta_W$$

- Paschos–Wolfenstein relation removes the effects of sea quark scattering and is much less sensitive to heavy quark production

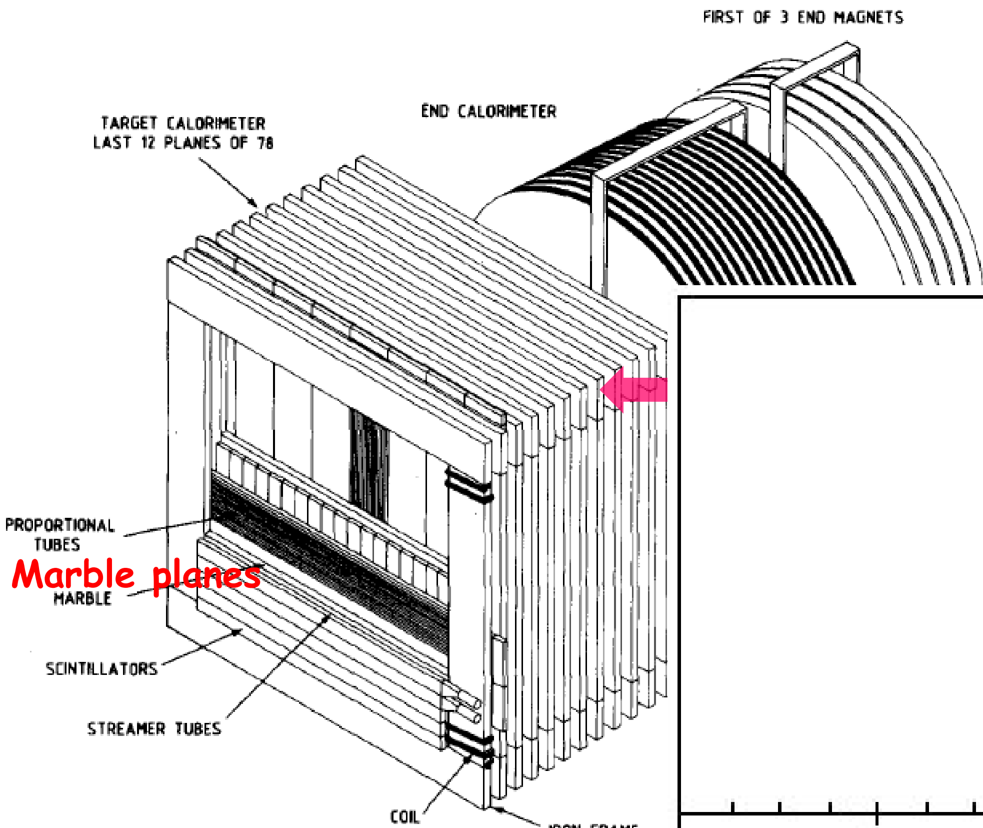
4. *Beam-dump experiments*

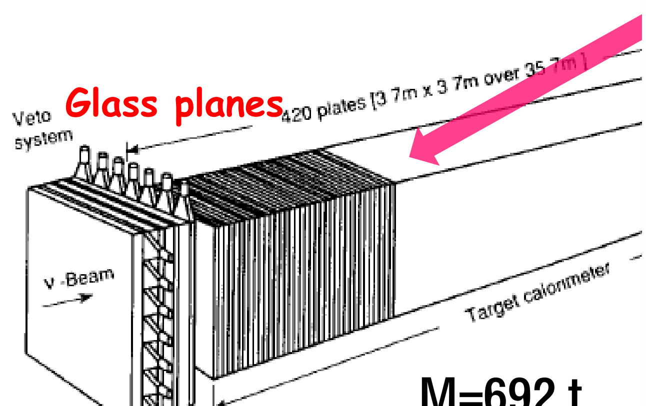
Search prompt neutrinos from charm particles production, Higgs, axion, heavy neutrino, …

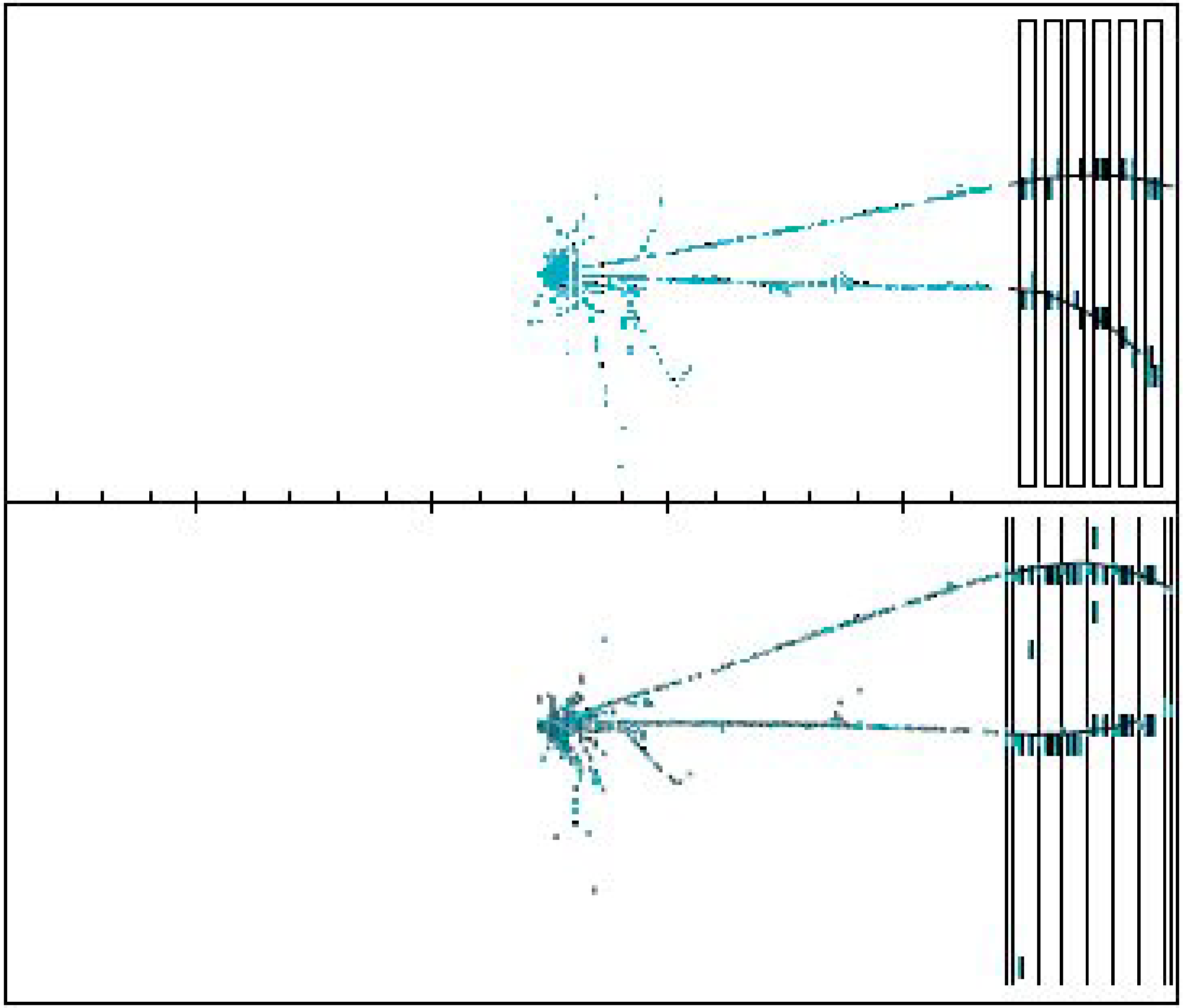
5. *Neutrino oscillations*

CERN: CHARM and CHARM-II (1986-1991) experiments

CHARM has a fine grained calorimeter with low Z target planes for good identification of electron from elastic νe-scattering







CERN: CDHS (1977-1983) experiment

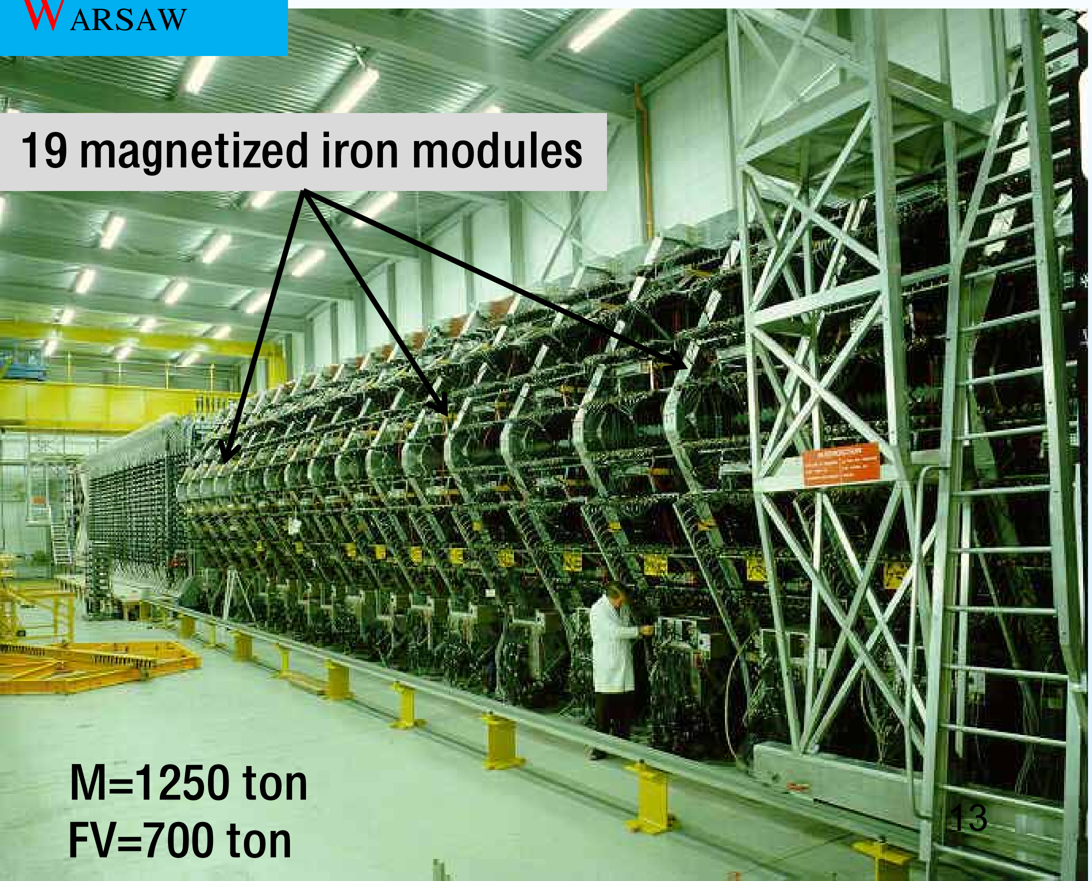
CDHS experiment was designed to study CC DIS and NC DIS neutrino interactions.
Detector combined the functions of a muon spectrometer and hadron calorimeter.

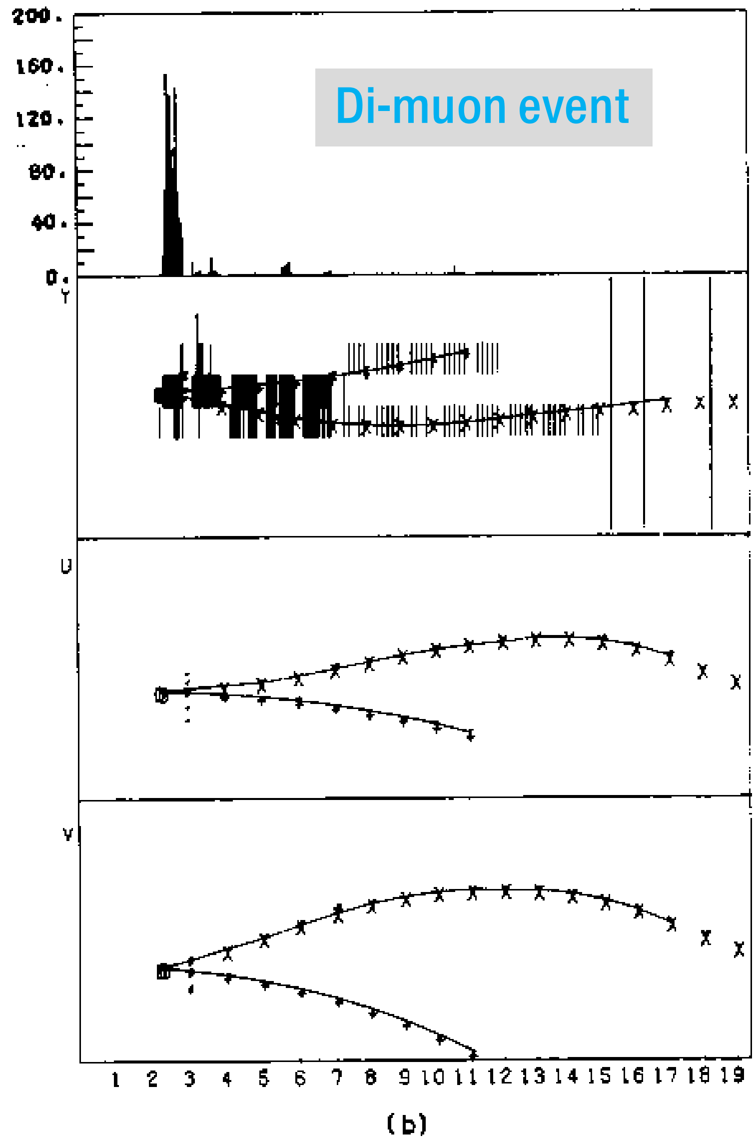
CERN
DORTMUND
HEIDELBERG
SACLAY
WARSAW

$+N \quad +X$ | $+N \quad +X$

$/E_e = 0.23/\sqrt{E_e(GeV)}$ - *electrons*

$/E \ = 0.56/\sqrt{E \ (GeV)}$ - *hadrons*

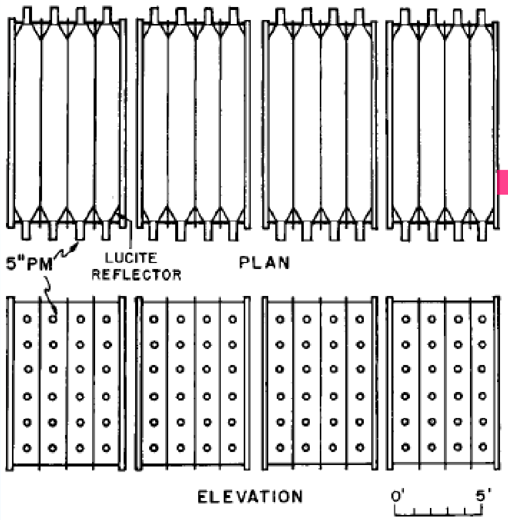




FNAL: HPWF and NuTeV experiments

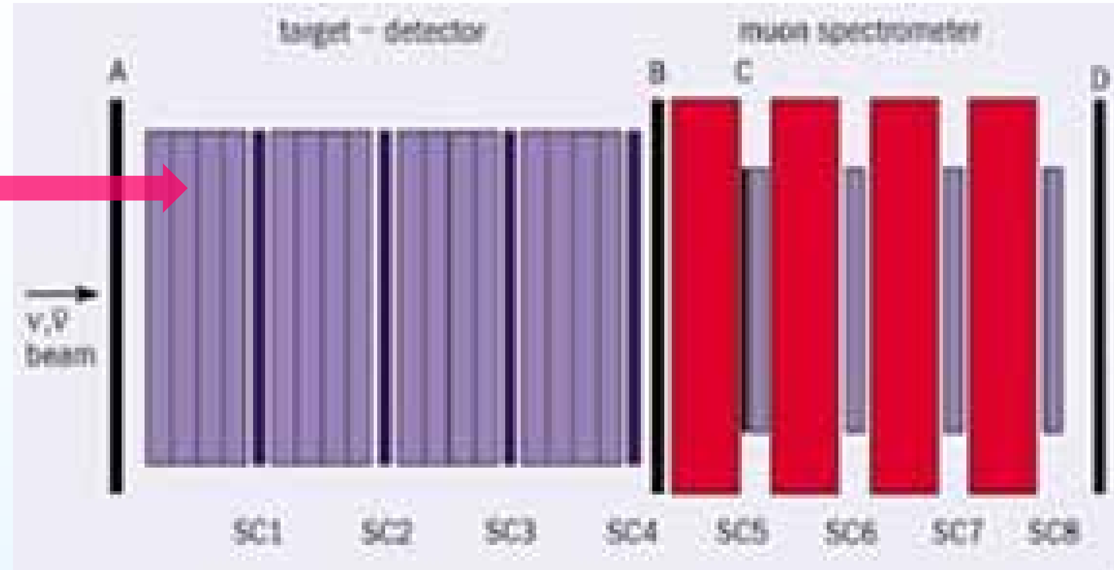
Calorimeter

$/E = 10 \quad 12\%, 10 \quad 150\, GeV$



HPWF

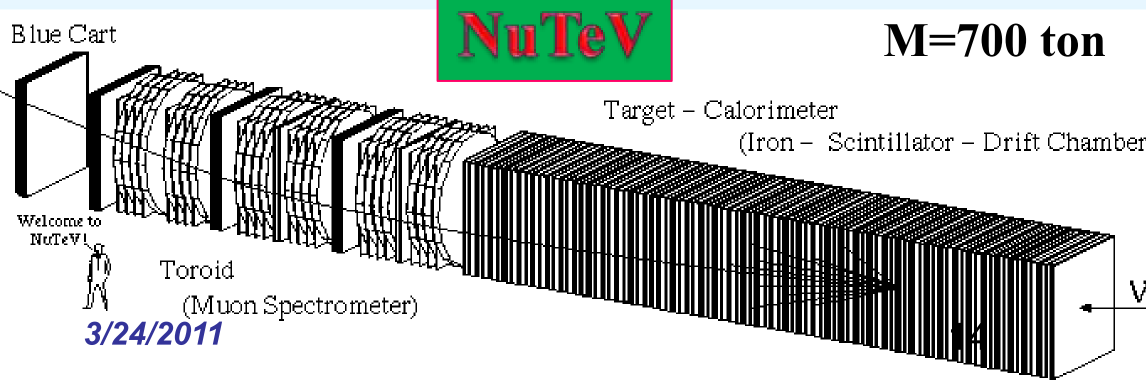
Neutrino target: liquid scintillator
Active detector: spark chamber and scintillator planes

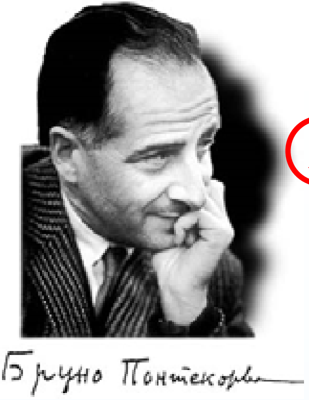


Neutrino target: iron planes
Active detector: drift chamber and scintillator planes

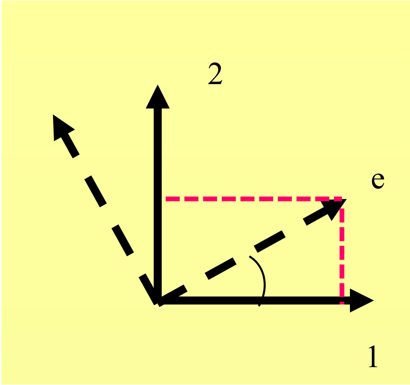
NuTeV

M=700 ton





Neutrino Oscillations



1. At t=0 we have a flavor eigenstates $_e$ and which are both mixtures of mass eigenstates $_1$ and $_2$:

$$|\ _e(0)\rangle = \ \cos\ |\ _1\rangle + \sin\ |\ _2\rangle$$
$$|\ (0)\rangle = \ \sin\ |\ _1\rangle + \cos\ |\ _2\rangle$$

2. According to Schrödinger equation the mass eigenstates $_1$ and $_2$ with energy E_1 and E_2 evolve in time as plane waves:

$$|\ _e(t)\rangle = |\ _1\rangle e^{\ iE_1t}\cos\ + |\ _2\rangle e^{\ iE_2t}\sin$$
$$|\ (t)\rangle = |\ _1\rangle e^{\ iE_1t}\sin\ + |\ _2\rangle e^{\ iE_2t}\cos$$

For relativistic neutrinos (E >> m)

$$E = \sqrt{p^2 + m^2} = p + \frac{m^2}{2E}$$

3. Assuming the same energy for both neutrino components we can write:

$$|\nu_\mu(t)\rangle = e^{\ i(p+m_1^2/2E_\nu)t}|\nu_1\rangle\sin\theta + |\nu_2\rangle e^{-it\ \ m^2/E_\nu}\sin\theta$$

4. The transition probability is, then, given by

$$P(\qquad _e) = |\langle\ _e|\ \ (t)\rangle|^2 = \left|\sin\ \ \cos\ \ (1\ \ e^{\ it\ \ m^2/2E}\ )\right|^2$$

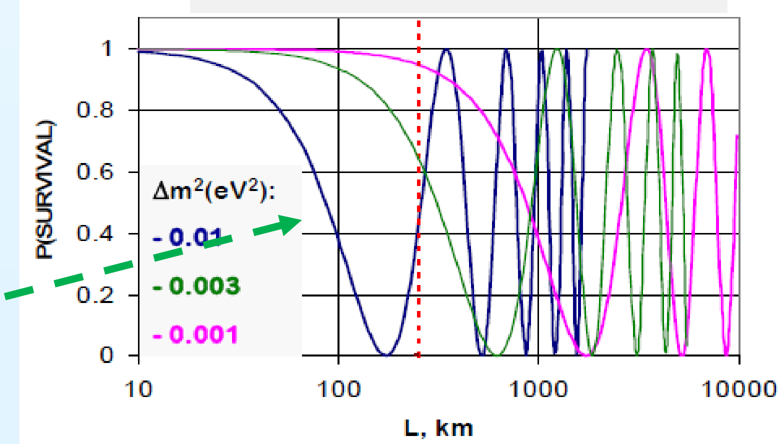
with $m^2 = m_1^2\ \ m_2^2$

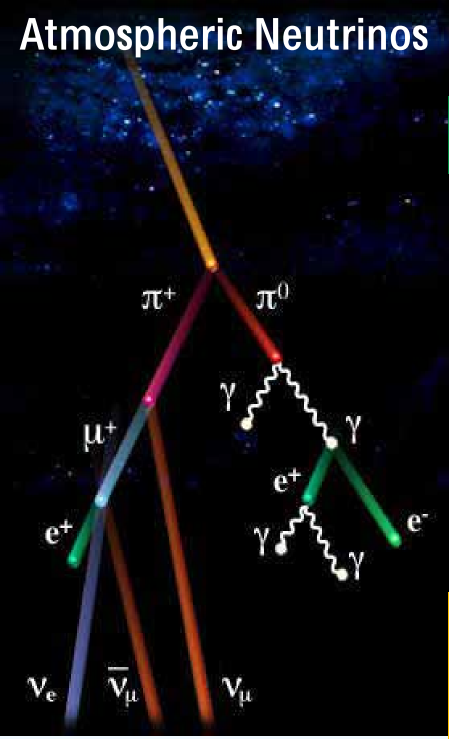
5. If we measure **Δm²** in eV², **L** in km, and **E** in GeV we can write the above as:

$$P(\qquad _e) = \sin^2 2\ \ \sin^2(\frac{1.27\ \ m^2 L}{E})$$

$$P(\qquad) = 1\ \ \sin^2 2\ \ \sin^2(\frac{1.27\ \ m^2 L}{E})$$

Fraction of remaining neutrinos





Neutrino Oscillations Discovery (1998)

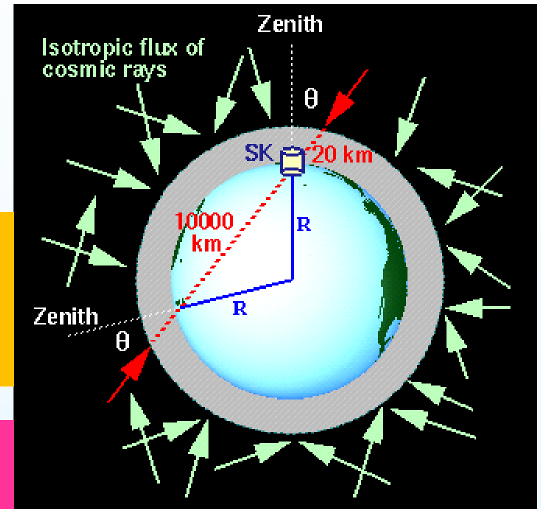
Neutrinos are produced by cosmic ray interactions in Earth's atmosphere

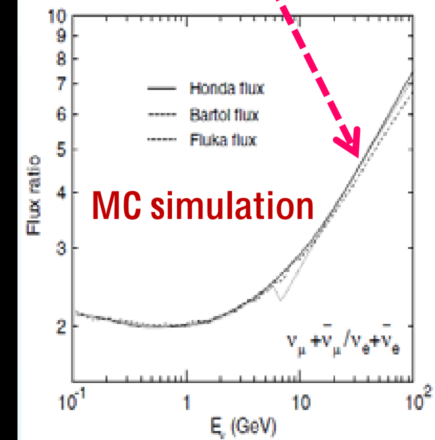
$^{+}$ $^{+}$ + $_{\mu}$ $^{+}$ e^{+} + ‾ + $_{e}$

+ ‾ e + $_{e}$ + ‾

Expectation → $\dfrac{(\;\;+\;\overline{\;\;}\;)}{(\;_{e}+\overline{\;\;}_{e})}$ 2

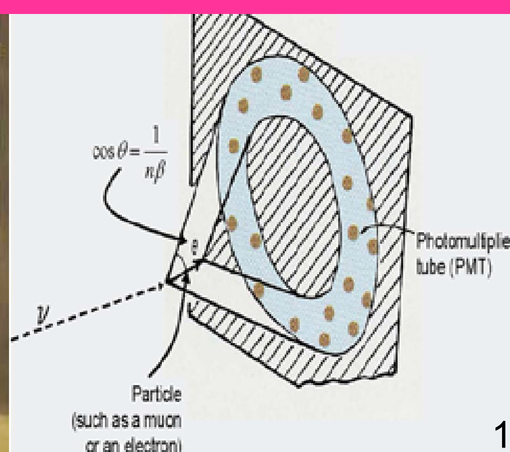
SK was measured the number of ν_μ and ν_e interactions as a function of zenith angle

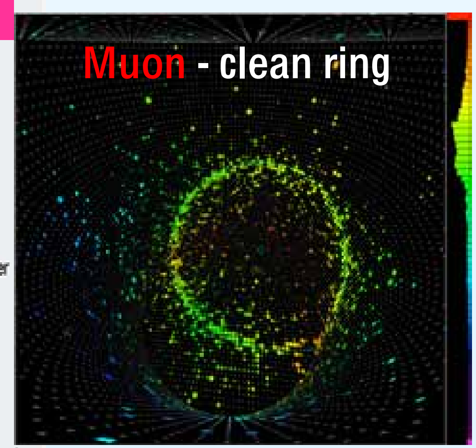




41.4m x 39.3m (Diameter)
50 ktons of pure water tank
with ≈11,000 20" PMTs

Particle identification is based on the pattern recognition of Cherenkov rings arising in water





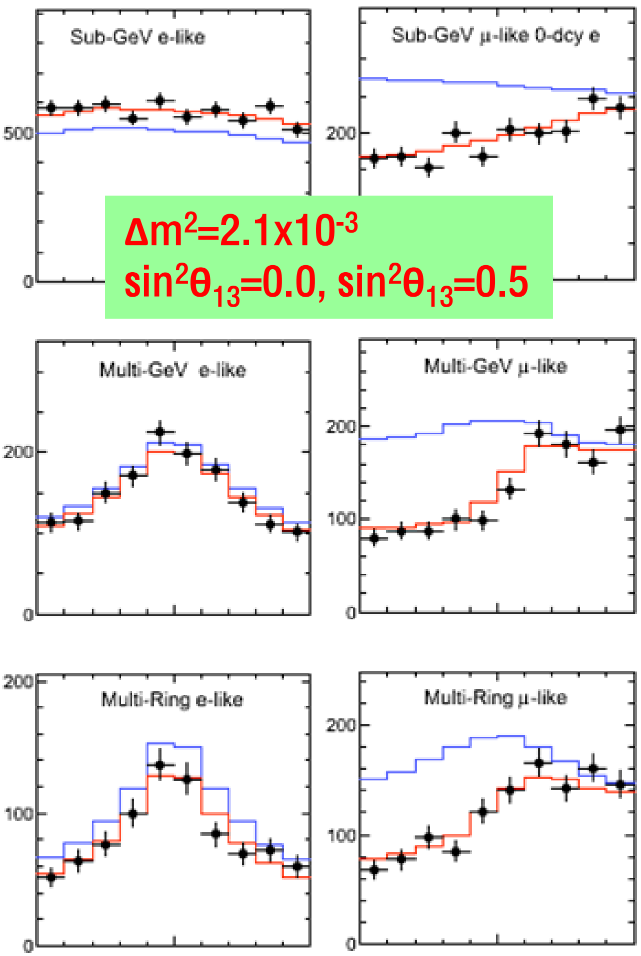
Neutrino Oscillations Discovery (1998)

$$R = \frac{(\;/e)_{Data}}{(\;/e)_{MC}}$$

R=1 if no oscillation

The registration efficiency for muons and electrons is very different

Takeuchi, Neutrino 2010



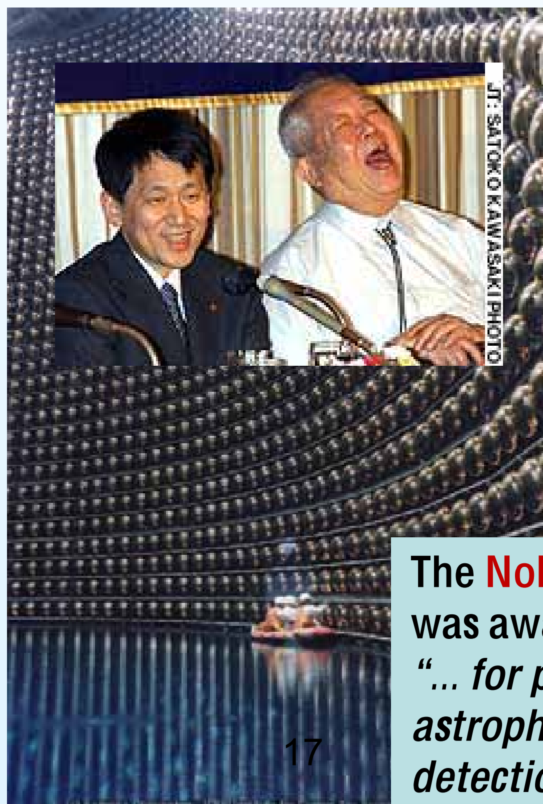
$\nu_\mu - \nu_\tau$ oscillation (best fit)

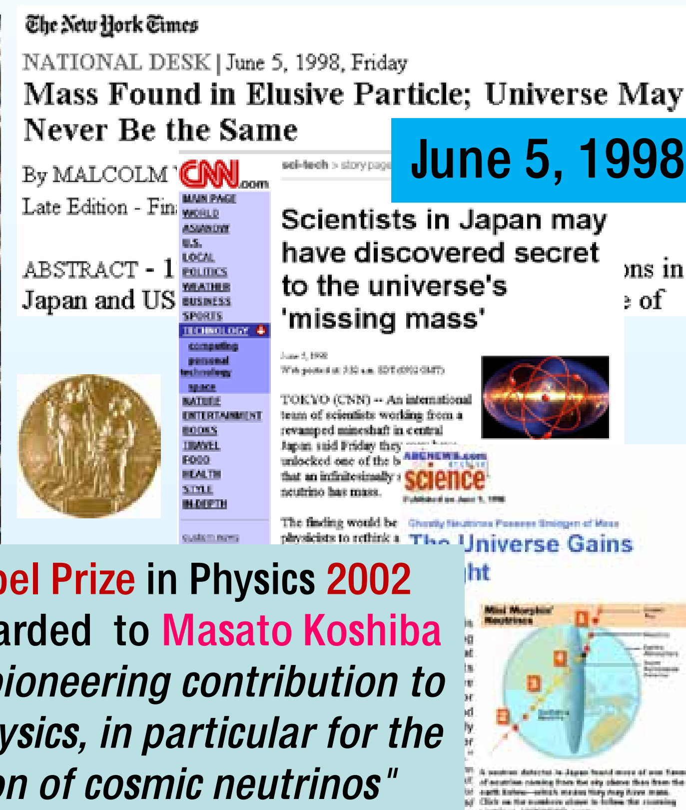
no oscillation

At the Neutrino 98 conference, SK experiment presented new data on the deficit in muon neutrinos produced in the Earth's atmosphere. This deficit depends on the distance the neutrinos travel - an indication that neutrinos oscillate and have mass.

$R = 0.63 \pm 0.03 \pm 0.05$ (sub-GeV)

$R = 0.65 \pm 0.05 \pm 0.08$ (multi-GeV)





June 5, 1998

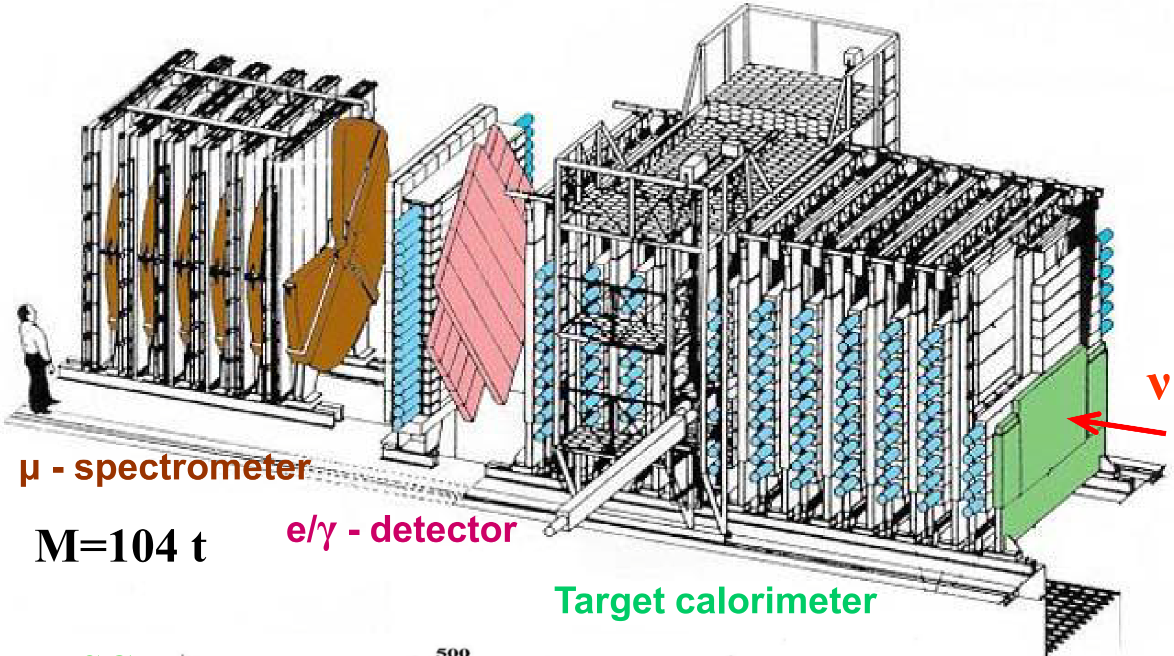
The Nobel Prize in Physics 2002 was awarded to Masato Koshiba *"... for pioneering contribution to astrophysics, in particular for the detection of cosmic neutrinos"*

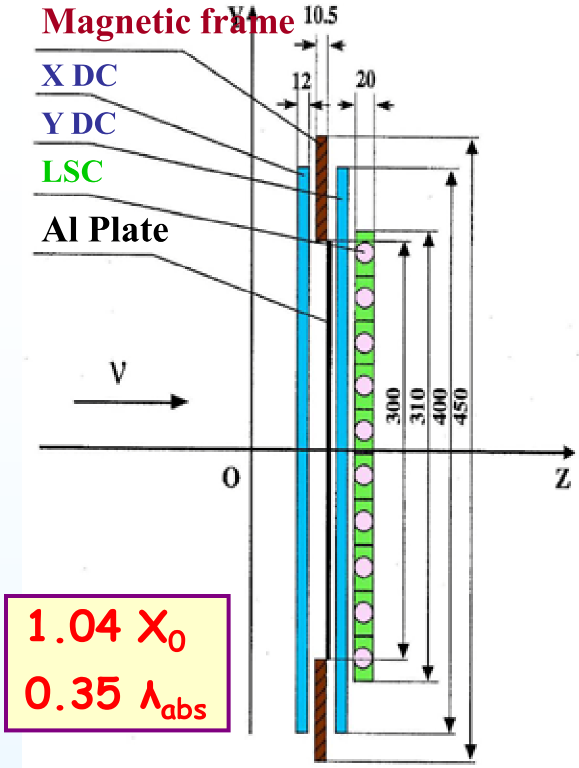
IHEP-JINR Neutrino Detector

Member of the IHEP-JINR Neutrino Detector Collaboration from 1979 to 2000

- *Neutrino Detector*
- *Beam dump Experiment*
  - Search of the light Higgs bosons and Axion
  - Limit on the charm production cross section
- *Oscillation Experiment*
- *Total cross section measurement*

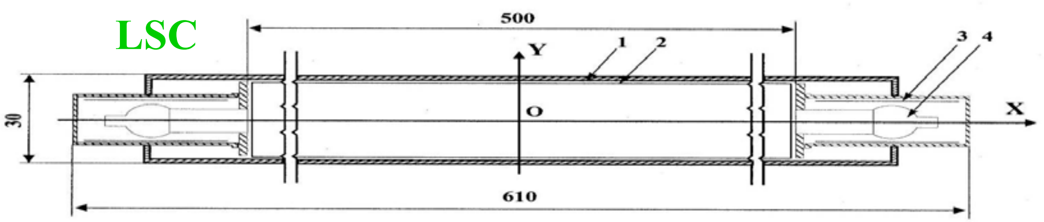
IHEP-JINR Neutrino Detector





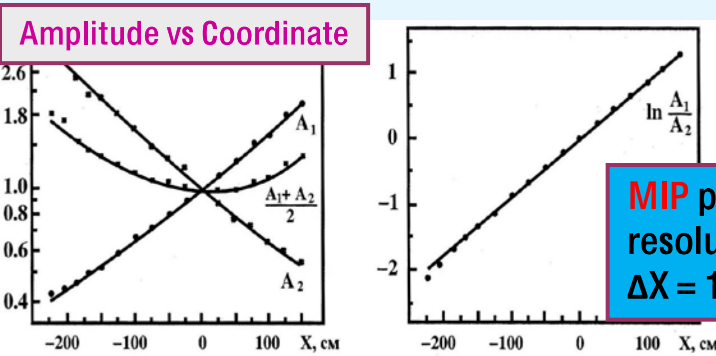
1.04 X_0

0.35 λ_{abs}

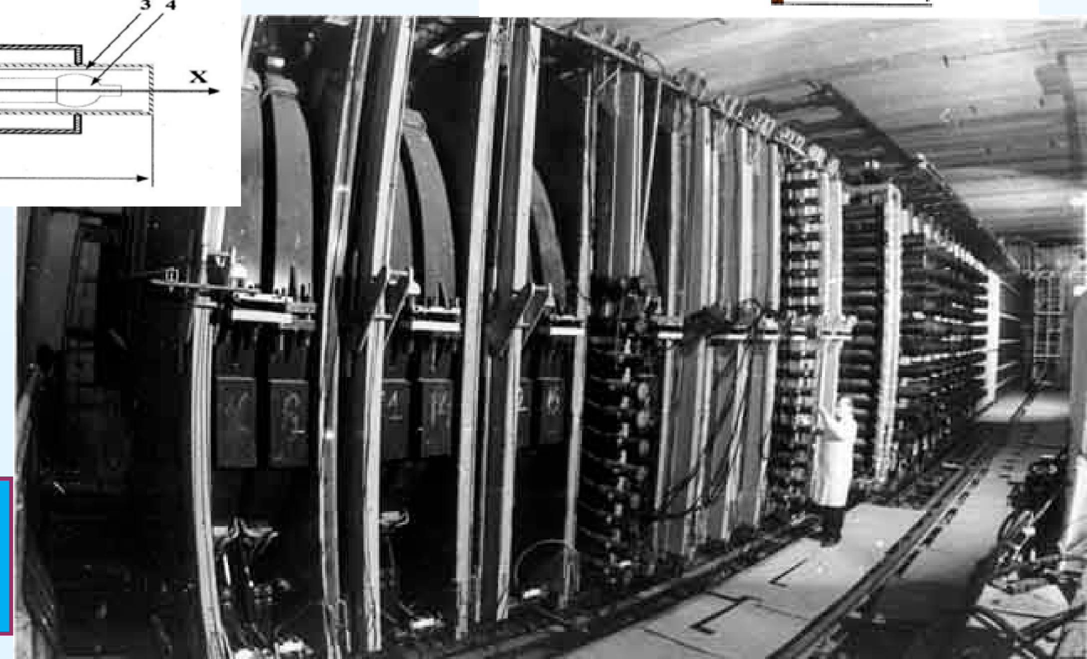


The 70 mkm Mylar container with liquid scintillator is inserted into 3mm Al box.

Amplitude vs Coordinate

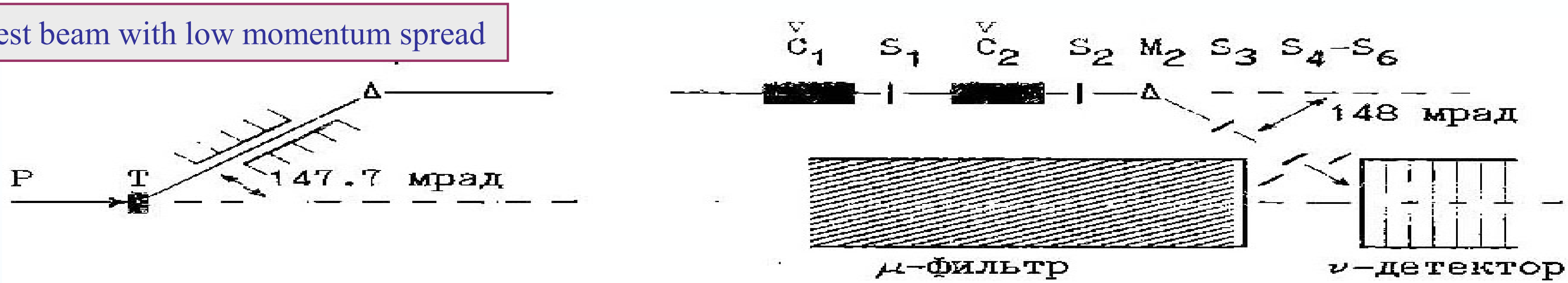


MIP position resolution
ΔX = 16 cm

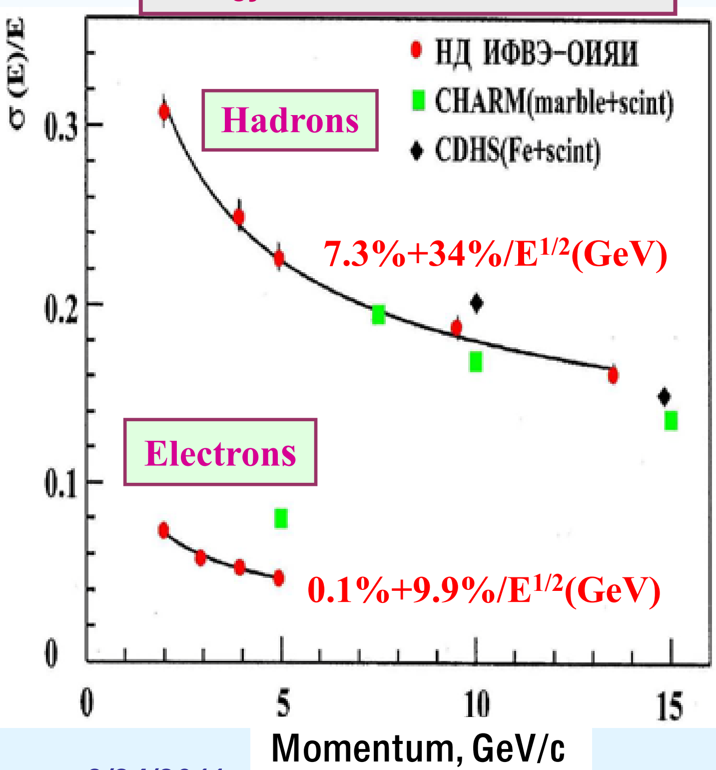


Neutrino Detector Calibration

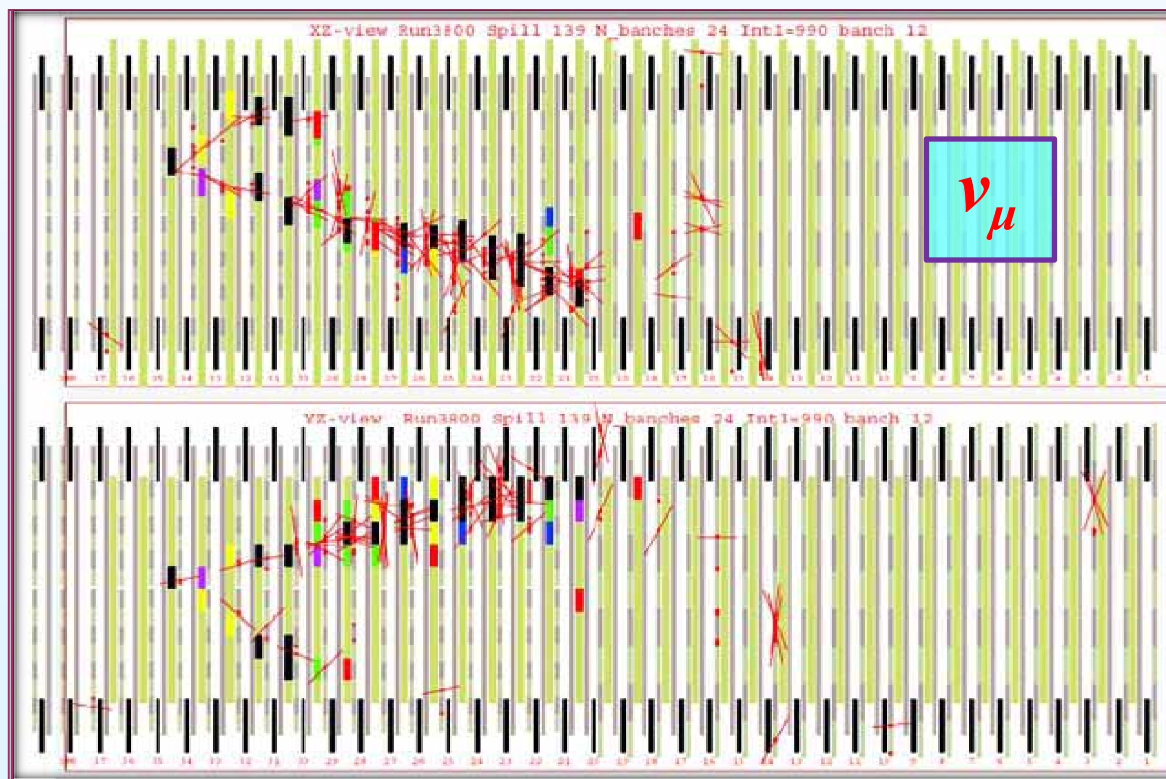
Test beam with low momentum spread



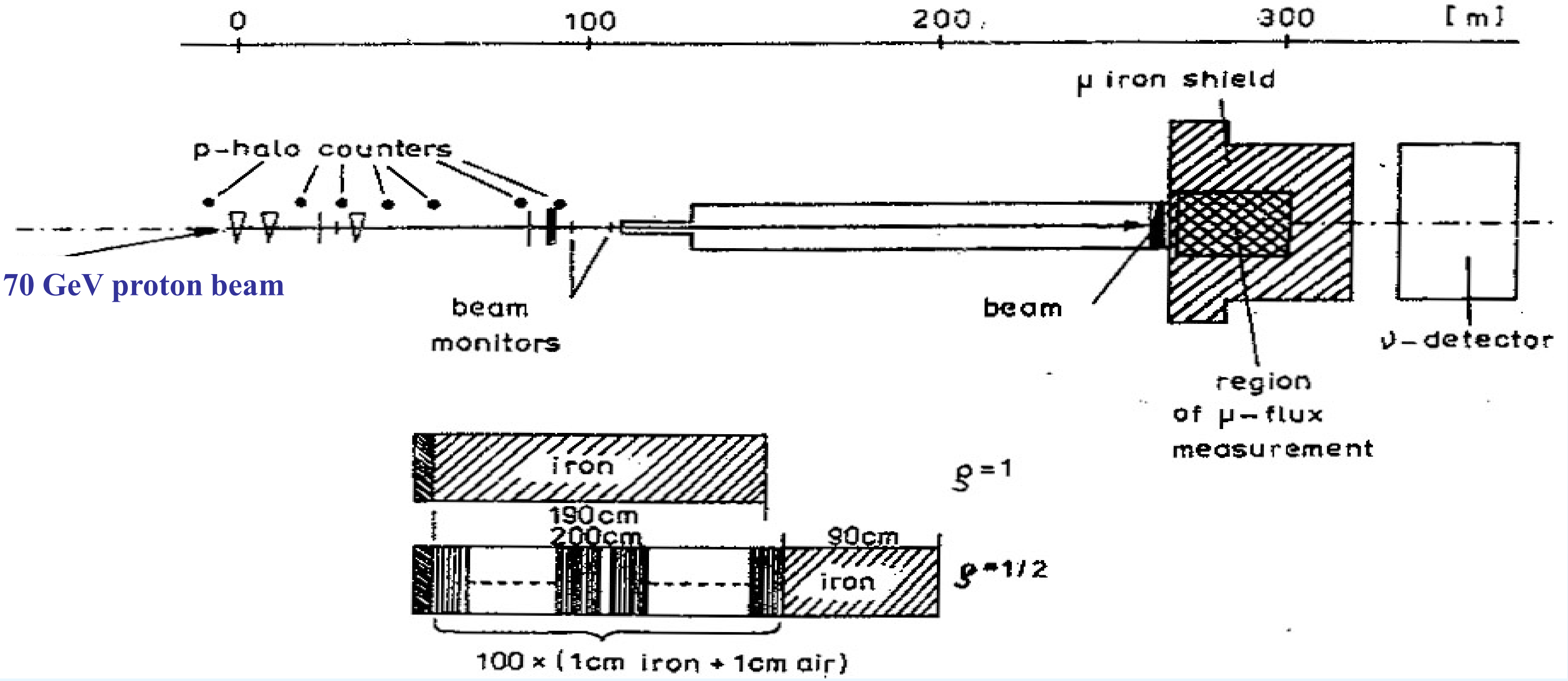
Energy resolution vs momentum



The examples of events from pion, electron, muon and neutrino interactions.



Beam dump Experiment



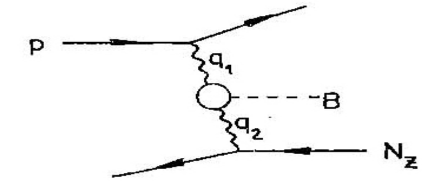
The 70 GeV proton beam with 1.21×10^{13} average proton intensity per accelerator pulse.
Iron beam dump target was located in front of the 54 m long iron muon shield.
The neutrino detector followed at a distance of 64 m downstream of the beam dump.

In two runs 1.1×10^{18} and 0.6×10^{18} protons on target were collected with relative target densities of $\rho = 1$ and $\rho = ½$

Beam dump: Search of Light Higgs and Axion

MSSM Two Higgs doublets with 3 neutral Higgs. Two from these particles (one scalar H and one pseudoscalar A) can be light.

Four possible processes of production



1. Coherent proton nucleus interaction

The couplings of (pseudo)scalar to fermions

$$g_{Hf} = i(\sqrt{2}G_F)^{1/2} m_f s_f$$

s_f, p_f – model dependent coupling constants

$$g_{Af} = i(\sqrt{2}G_F)^{1/2} m_f p_f$$

MSSM

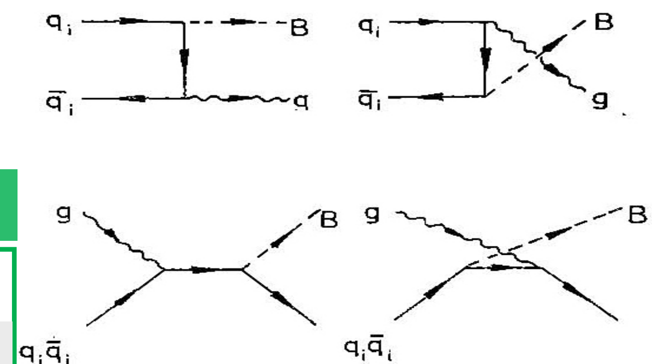
$s_f = \cos\alpha/\sin\beta$, $p_f = \cot\beta = 1/x$ for $f = u, c, t$

$s_f = -\sin\alpha/\cos\beta$, $p_f = \tan\beta = x$ for $f = d, s, b, e, \mu, \tau$

$x = \upsilon 2/\upsilon 1$ – ratio of vacuum expectations of Higgs doublets

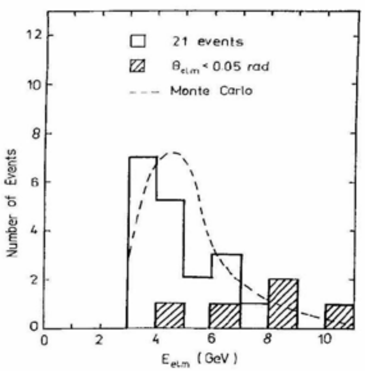
SM $s_f = 1$, $p_f = 0$

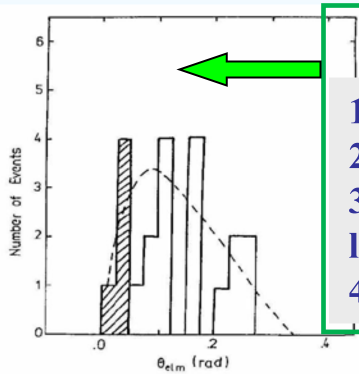
PQ axion p_f is the same as in MSSM



2. Parton parton interaction

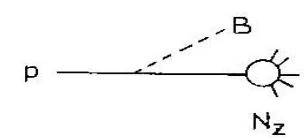
The search was performed for decays into $\gamma\gamma$-, e^+e^-- and $\mu^+\mu^-$- pairs



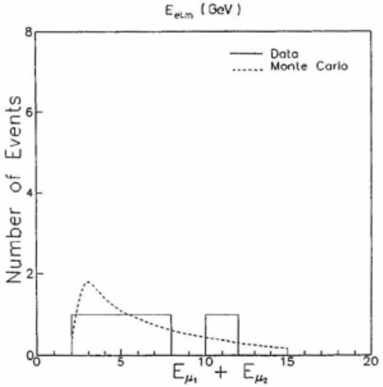


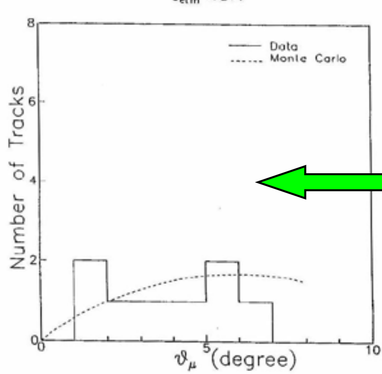
Cuts for $\gamma\gamma$- and e^+e^-

1. $E_{elm} > 3$ GeV
2. No track at primary vertex
3. $E_{had} < 1.5$ GeV – resolution limit of reconstruction program
4. $\theta_{elm} < 0.05$ rad



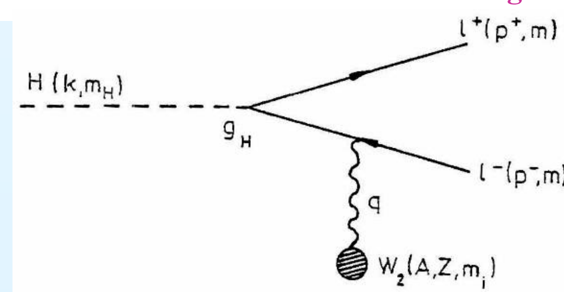
3. Initial state bremsstrahlung





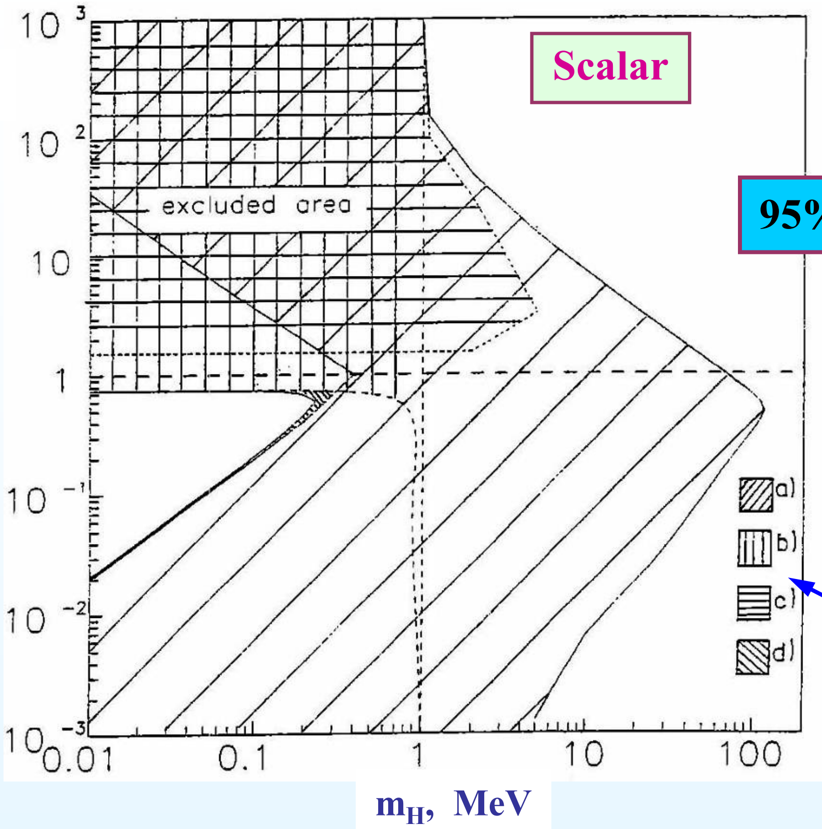
Cuts for $\mu^+\mu^-$-pairs

1. Two long tracks (muons)
2. $P_\mu > 3$ GeV
2. $\Delta P_\mu/P_\mu < 30\%$
3. $|E_{dep} - E_{mip}| < 0.5$ GeV
4. $\cos\theta_{max} > 0.99$

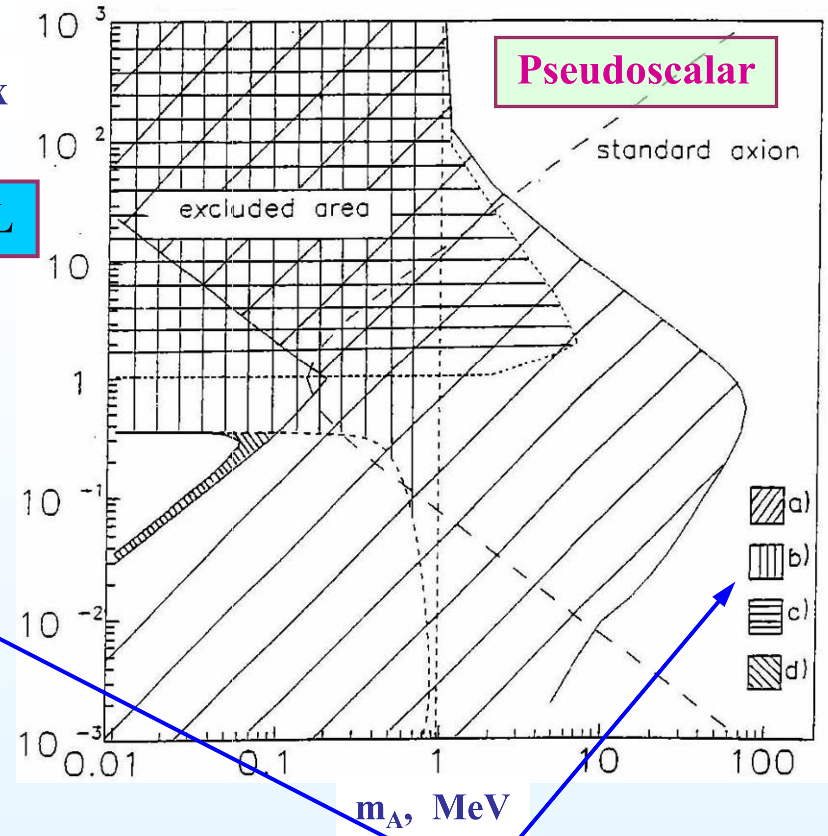


4. Bethe-Heitler process

Beam dump: Search of Light Higgs and Axion, end



95% CL



Higgs boson of SM was excluded for $m_H < 80$ MeV

a) Excluded by e^+e^- and $\gamma\gamma$ decays
b) Excluded by the e^+e^- Bethe-Heitler process
c) Excluded by the $\mu^+\mu^-$ Bethe-Heitler process
d) Excluded by a combined fit using a) and b)

95% CL

<u>Standard axion</u> was excluded in the range $0.008 < X < 32$ and for mass range
0.2 - 3.2 MeV for most $x > 1$
0.2 - 11 MeV for most $x < 1$

Particle Data Group, J. Phys. G 33, 1 (2006)

Beam dump: Charm Production Cross Section

Three types of interaction were studied for estimation of charm production cross section:

1. Prompt ν_e charged current interaction
2. Prompt ν_μ charged current interaction
3. “Equilibrium” or “rock” muons produced in neutrino interaction at the end of muon iron shield.

Cuts for ν_e events

1. $E_{elm} > 3$ GeV
3. $Y = E_{had}/(E_{elm}+E_{had}) < 0.4$

Cuts for ν_μ events

1. Track length in ND $\geq 3\ \lambda_{abs}$
2. Track length in magnetized steel ≥ 50 cm
3. $P_\mu \geq 3$ GeV
4. Start of track in the fist plane of ND (for muons from muon shield only)

Calculation of “prompt” events number

a) Extrapolation method

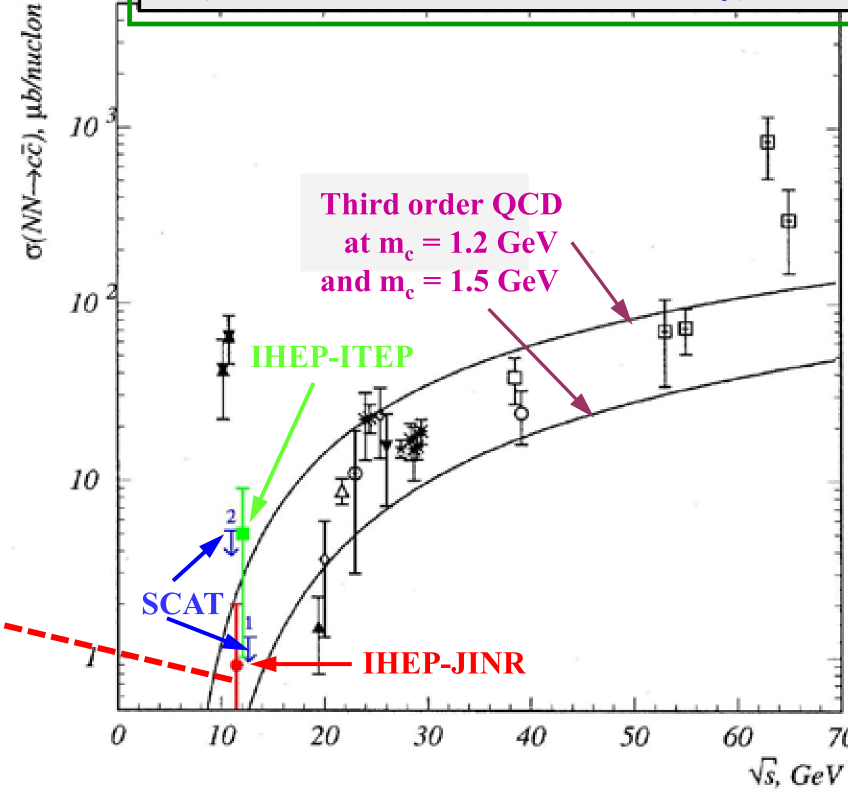
The charm production does not depend from target density. The production of conventional neutrinos is proportionally to the inverse target density.

$$N_{prompt} = 2N_{\rho=1} - N_{\rho=1/2} - \varepsilon(N_{\rho=1/2} - N_{\rho=1})$$

ε – correction for the leakage of hadrons shower

b) Subtraction method

Subtraction of calculated contribution of conventional neutrino interactions from the total number of measured events.

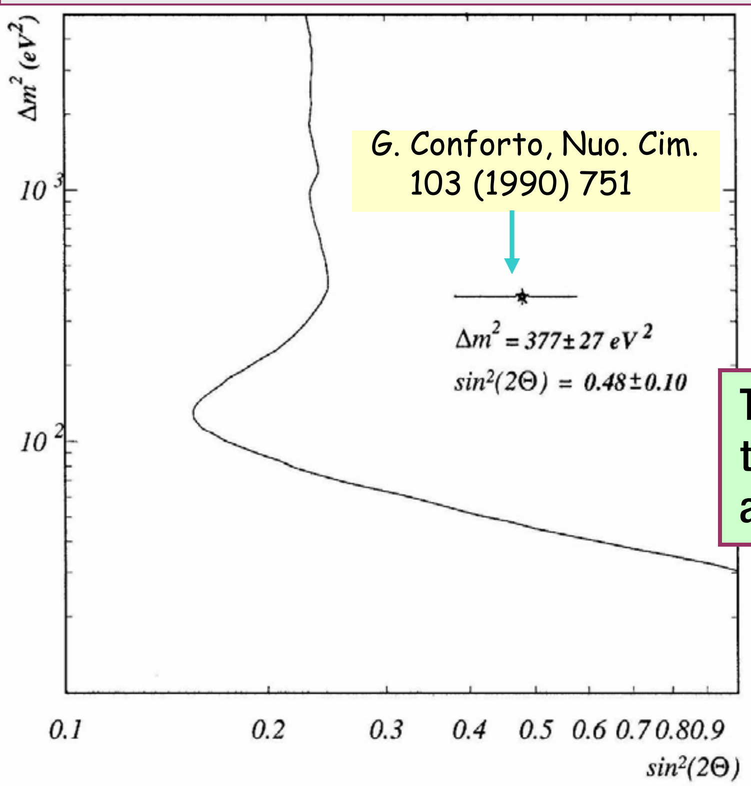


$\sigma_{charm} < 2.4$ μb/nucleon (90% CL) at $\sqrt{s} = 11.5$ GeV

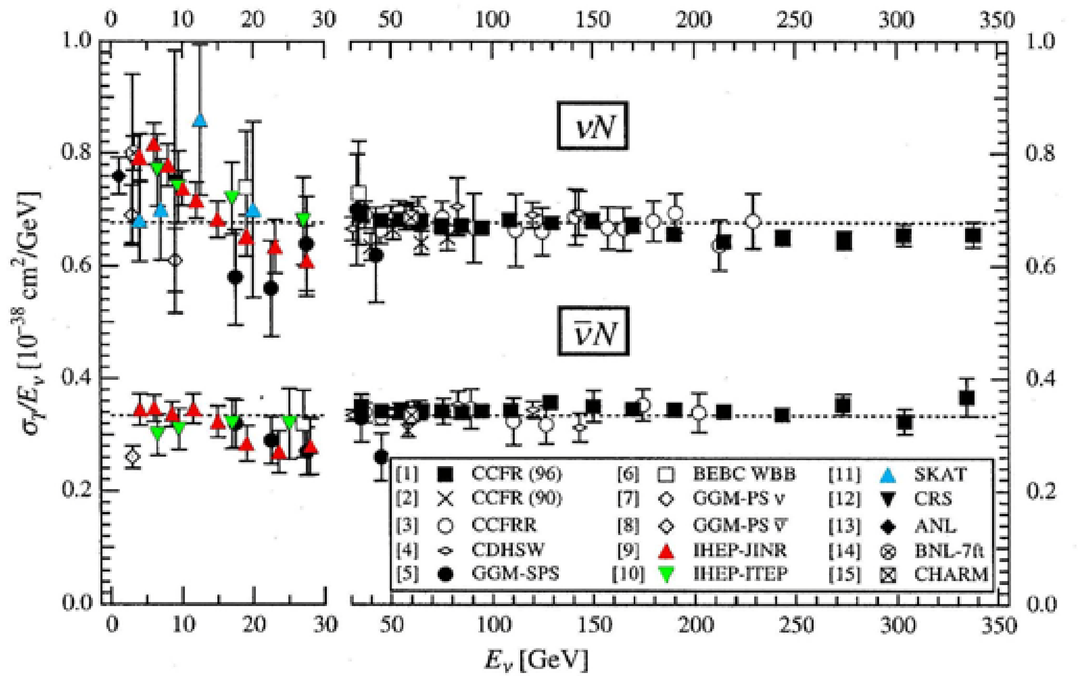
Oscillation Experiment

Osc. experiment was initiated by paper of Prof. Conforto from Italy. He studied the results of 3 CERN experiments and was seeing some indication for oscillations. These detectors where exposed at the same time but located at the different distance from target.

$$P(\ _e \quad _x) = \sin^2 2 \quad \sin^2 \ 1.27 \ m^2 \frac{L}{E}$$



Measurement of Neutrino Total Cross Section



Special neutrino beam with 12 m short decay length was developed. The fraction of ν_e for such beam was 3.25% which is much higher than for standard neutrino beams.

The length of the decay cavity *(L = 12 m)* is short when compared to the distance from decay point to the detector (72 m average) and to the length of the neutrino detector *(L = 25 m)* .

Give possibility to study L/E dependency

Minimization of $^2 = (1 \quad R)^2$ **with different L/E parameters**

$$R = \frac{N_{exp}(L/E) \quad N_{bgd}(L/E)}{N_{MC}(L/E)}$$

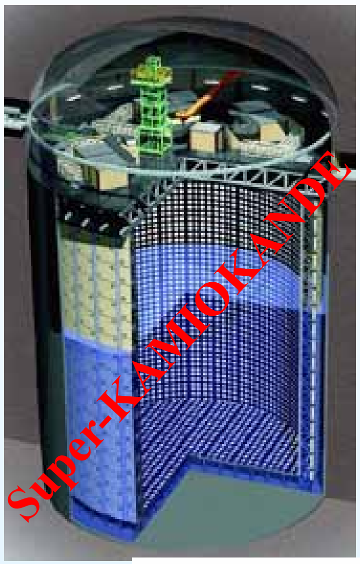
T2K experiment

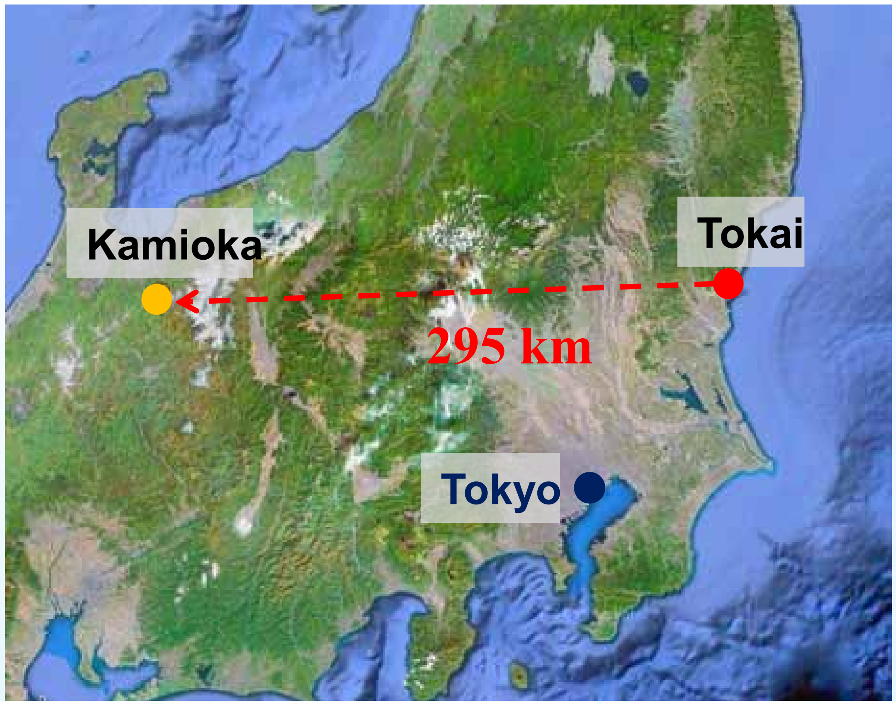
- ***T2K*** experiment
- ***ND280*** detector
- ***P0D*** calibration with ***'rock' muons***
- **CC QE** events in ***P0D***
- First preliminary results of ***T2K*** experiment

T2K (Tokai to Kamioka) experiment

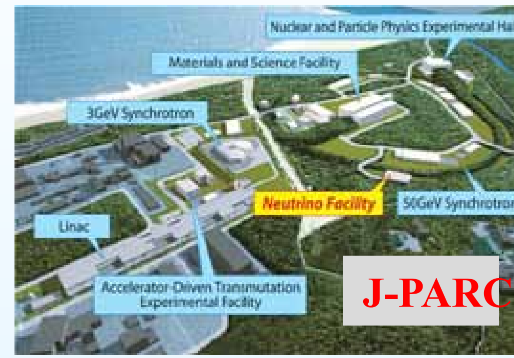
First off-axis long baseline oscillation neutrino experiment with high power 30 GeV proton beam of J-PARC Main Ring

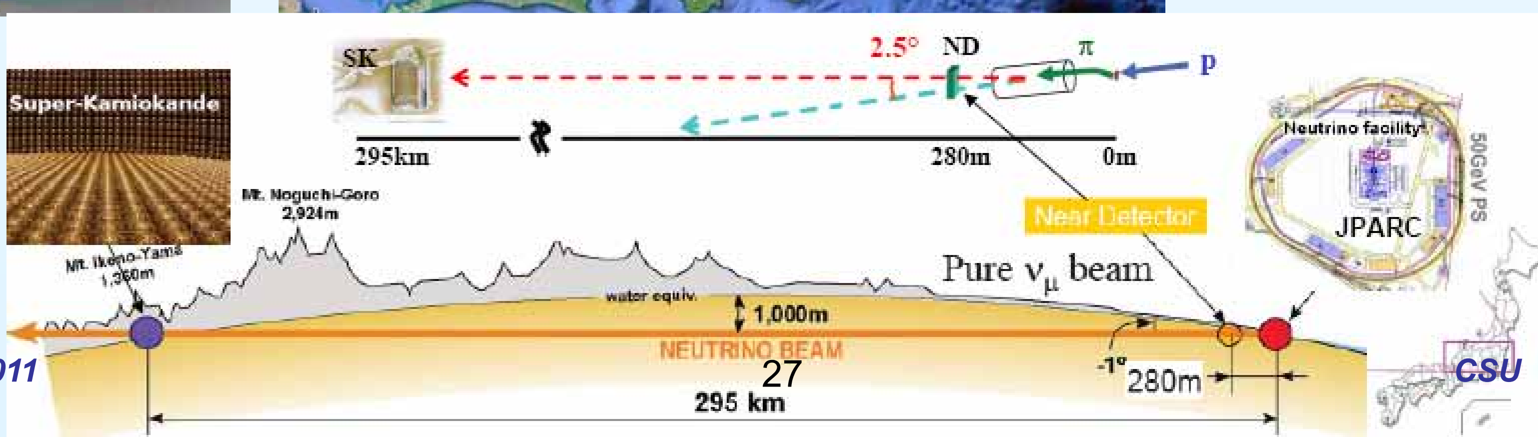
50-kT water Cherenkov detector





Japan
Proton Accelerator
Research Complex





Main Physics Goals

The Maki–Nakagawa–Sakata–Pontecorvo (MNSP) lepton mixing matrix relates the **mass eigenstates** (ν_1, ν_2, ν_3) to the **flavor eigenstates** (ν_e, ν_μ, ν_τ)

$$_e \quad = \begin{pmatrix} 1 & 0 & \\ 0 & \cos_{23} & \sin \\ 0 & \sin_{23} & \cos \end{pmatrix} \qquad U = \begin{pmatrix} \cos & \sin \\ \sin & \cos \end{pmatrix} \qquad \begin{pmatrix} _{12} & \sin_{12} & 0 \\ n_{12} & \cos_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{matrix} _1 \\ _2 \\ _3 \end{matrix}$$

atmospheric, beam | solar, reactor

SK atm, K2K, MINOS, T2K	CHOOZ, T2K	SNO, KamLAND
$_{23} = 45^0 \quad 8^0$	$\sin^2 2 \;_{13} < 0.14(90\%CL)$	$_{12} = 33.9^0 \quad 1.2^0$
$m^2_{23} \sim 2.5 \quad 10^{\;3} eV^2$		$m^2_{12} \sim 8 \quad 10^{\;5} eV^2$

Measurements

- **Measure the mixing parameter θ_{13} by search ν_e appearance**

$$P(\qquad _e) \quad \sin^2 2 \;_{13} \sin^2 \;_{23} \sin^2\left(1.27 \quad m^2_{13} L / E \right)$$

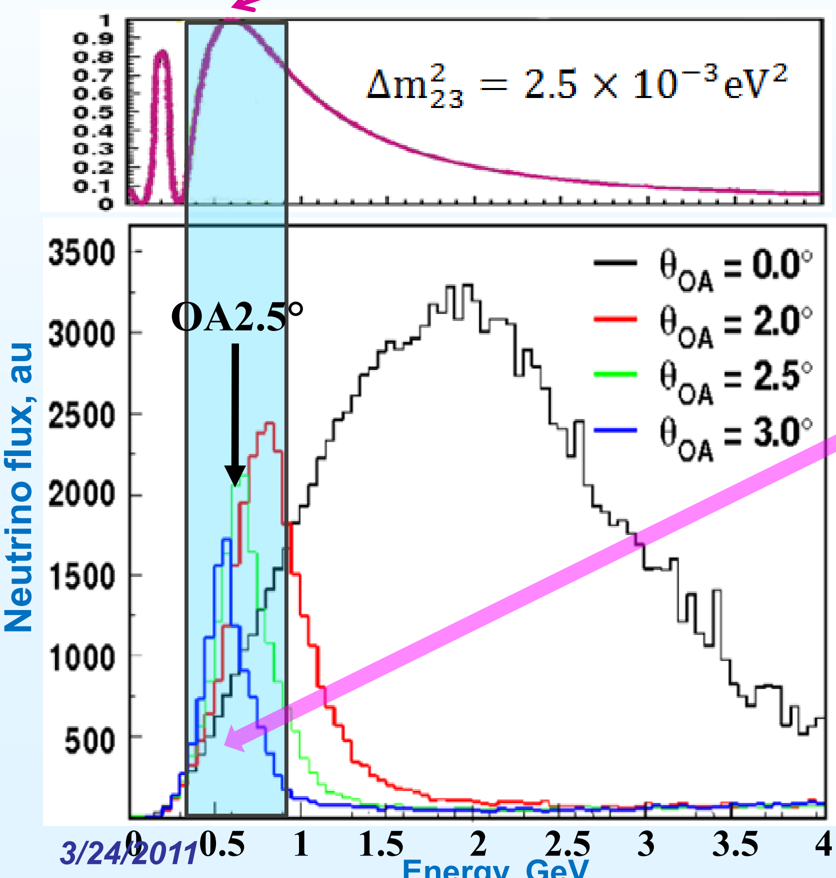
- **Precise measurement θ_{23}, $|\Delta m_{23}^2|$ by observing ν_μ disappearance**

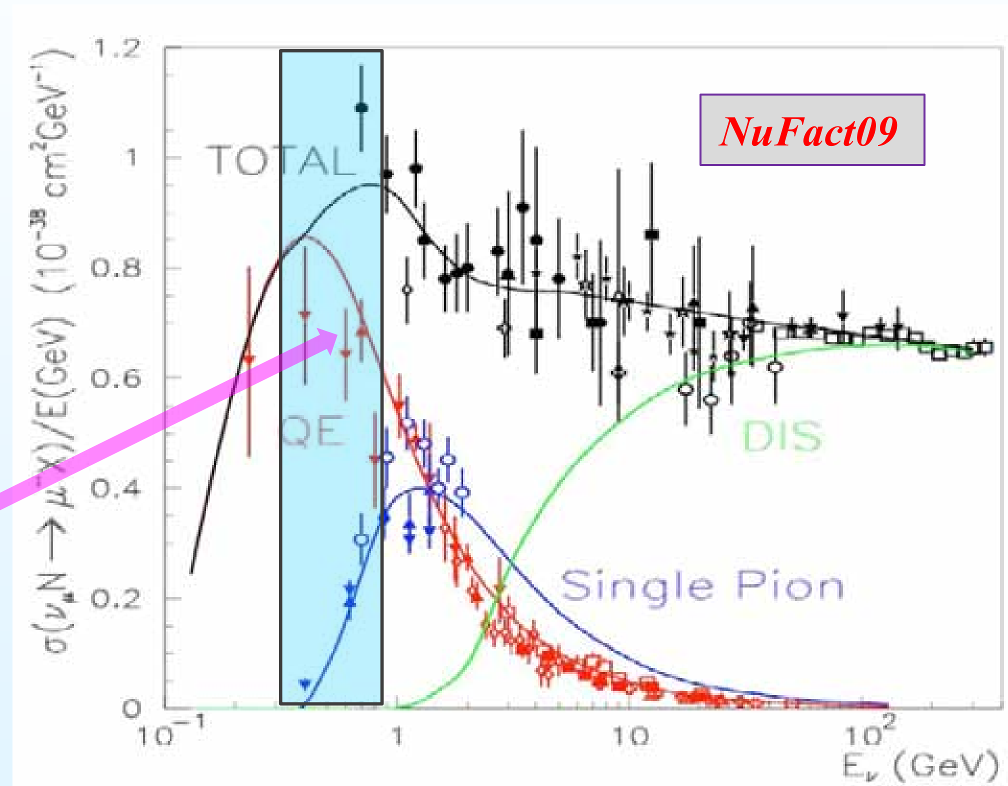
$$P(\qquad) \quad 1 \quad \sin^2 2 \;_{23} \sin\left(1.27 \quad m^2_{23} L / E \right)$$

Off-axis beam

- Neutrino energy depends on the angle relative to the beam axis
- Increasing of the angle gives narrower neutrino spectrum like monochromatic narrow beam
- Off-axis angle was set to 2.5° where peak of $\boldsymbol{Flux \times \sigma_\nu}$ has an oscillation maximum

- Narrow neutrino spectrum reduces the backgrounds in the electron neutrino measurement from DIS high energy interaction and the high energy ν_e beam contamination
- CC QE is dominant process in region of neutrino spectrum at 2.5°

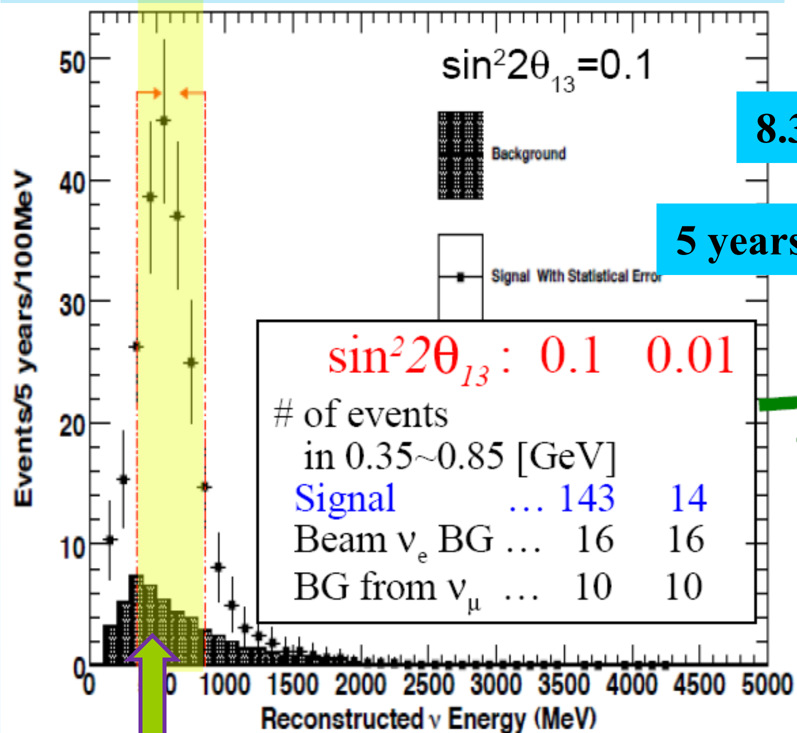




Sensitivity to θ_{13}

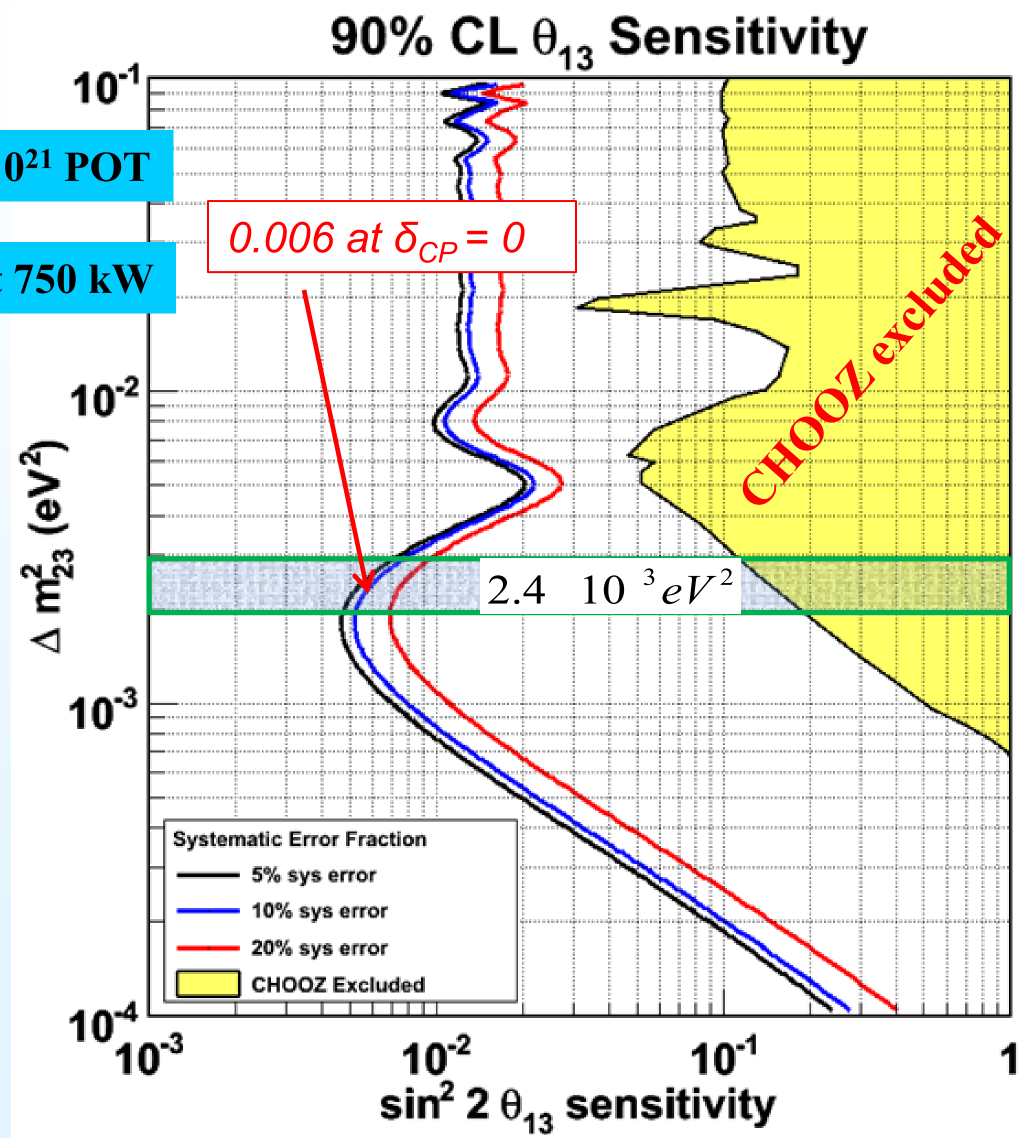
Detection of ν_e appearance: $\nu_\mu \rightarrow \nu_e$

Reconstructed E_ν in **CC QE** ν_e interaction



8.3x10^21 POT

5 years at 750 kW

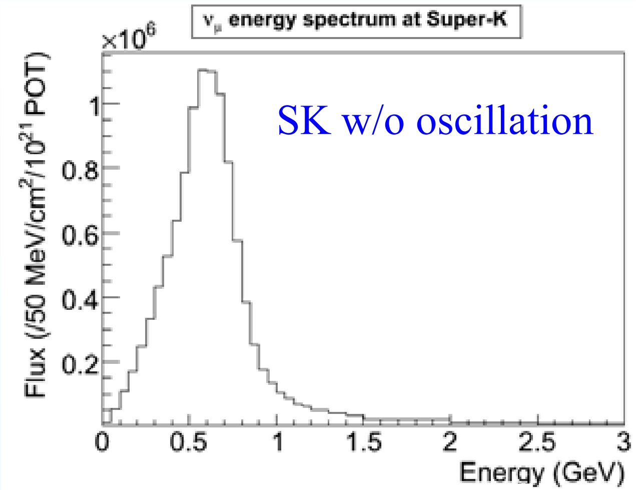


Main backgrounds

- beam ν_e contamination
  $\nu_e + n \rightarrow e^- + p$
- NC π^0 events
  $\nu_\mu + N \rightarrow \nu_\mu + p + \pi^0$
  $\hookrightarrow \gamma + \gamma$

Sensitivity to θ_{23} and Δm_{23}^2

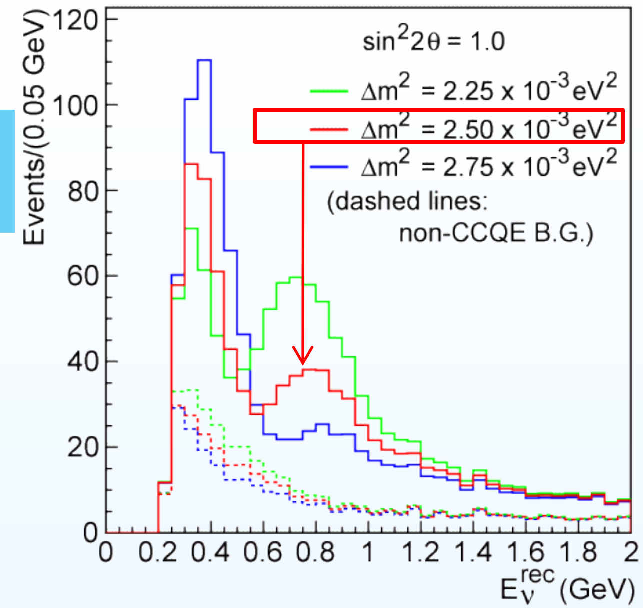
Detection of ν_μ disappearance



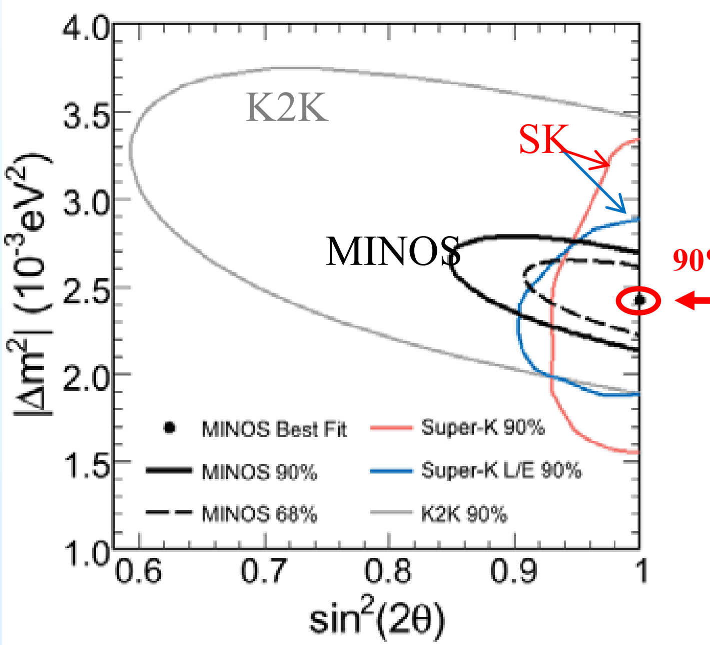
Oscillation changes a form of neutrino spectrum

$P(\nu_\mu \to \nu_\mu)$

SK with oscillation



Present limits



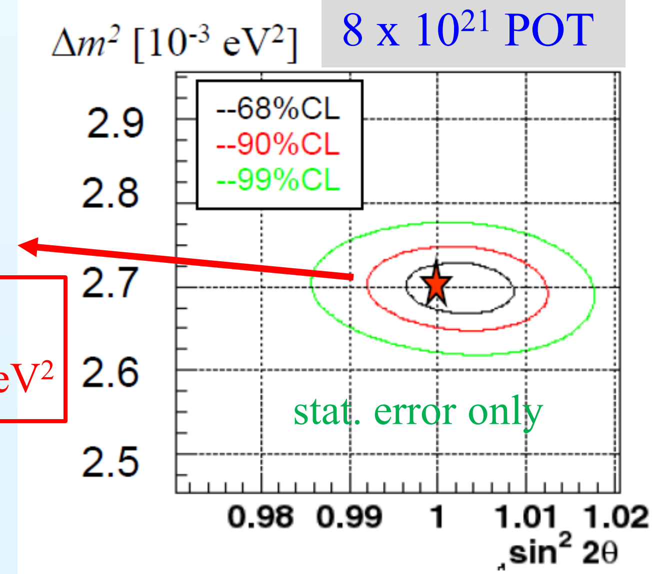
90% CL

T2K sensitivity

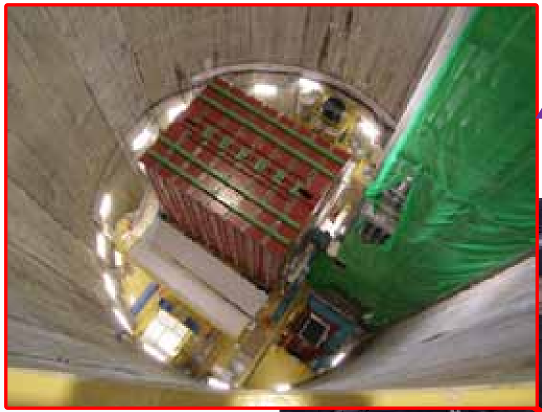
$\delta(\sin^2 2\theta_{23}) < 0.01$

$\delta(\Delta m_{23}^2) < 1 \times 10^{-4}$ eV²

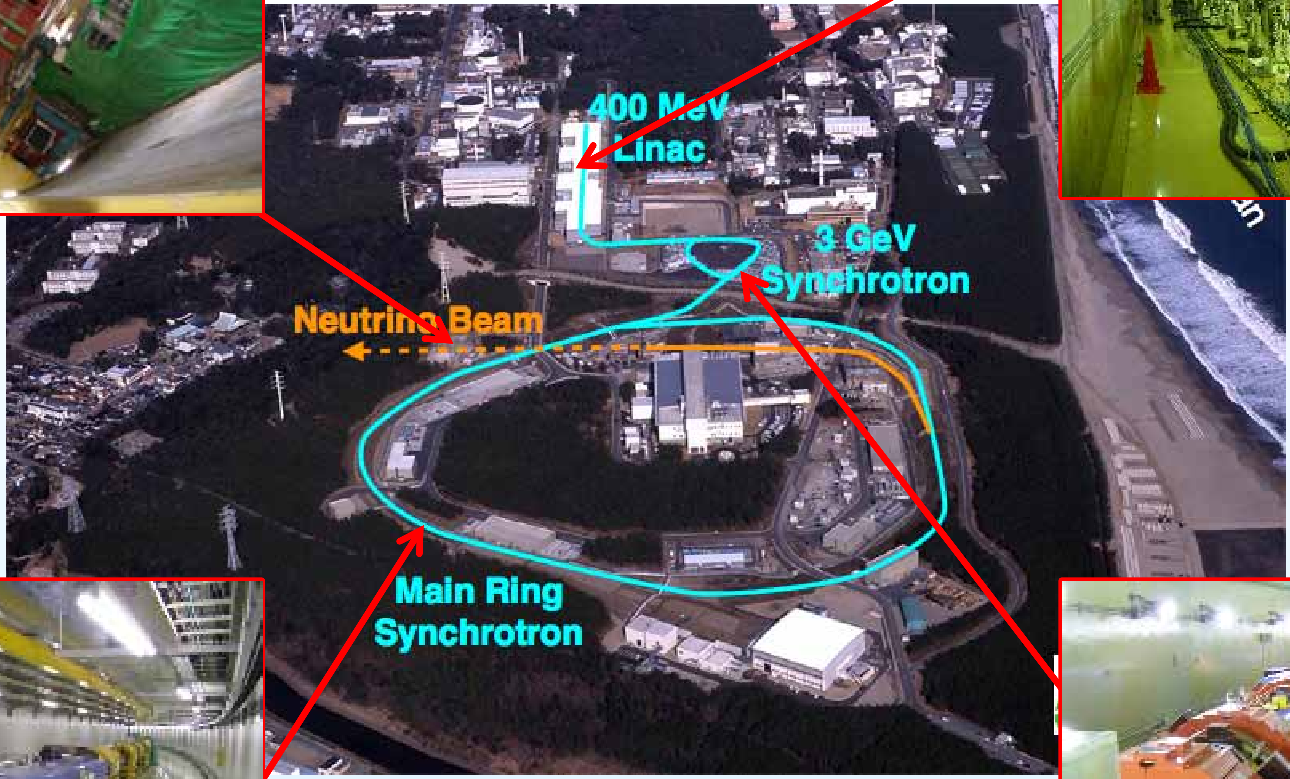
8 x 10²¹ POT



J-PARC accelerator facility

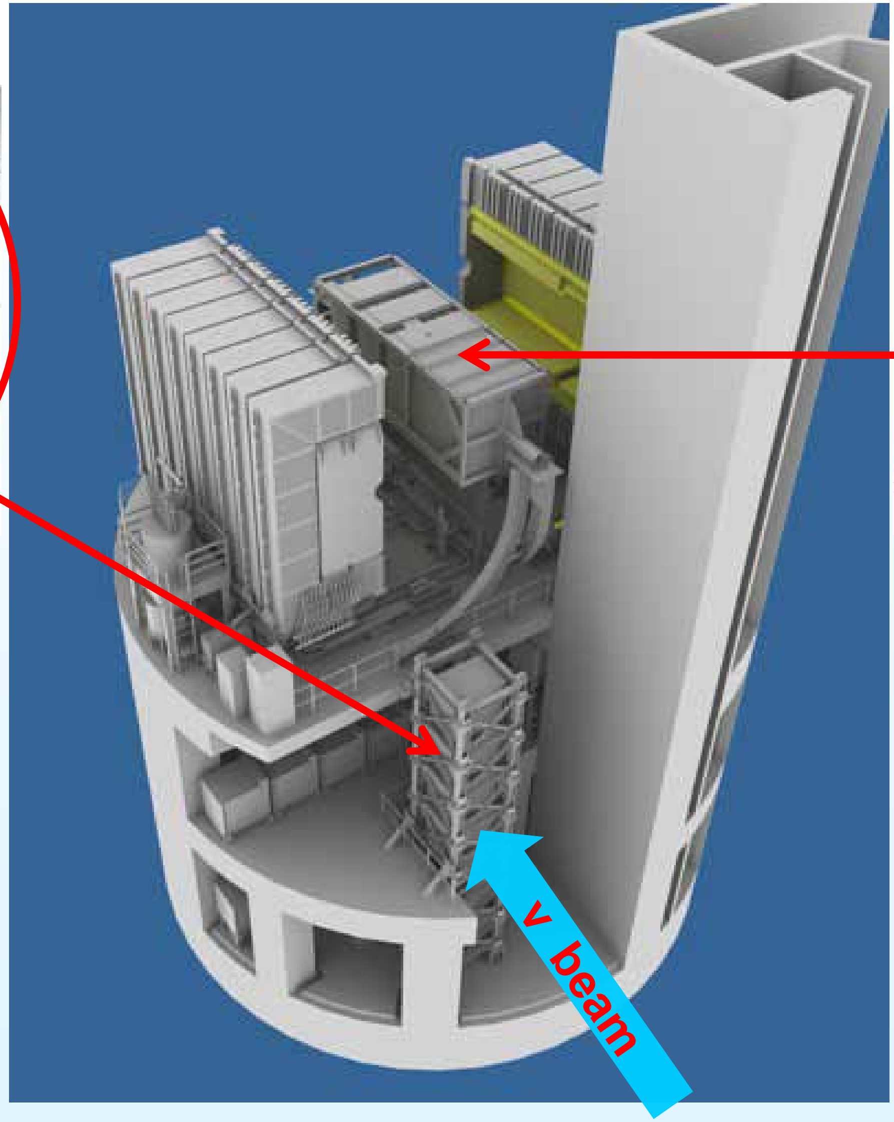


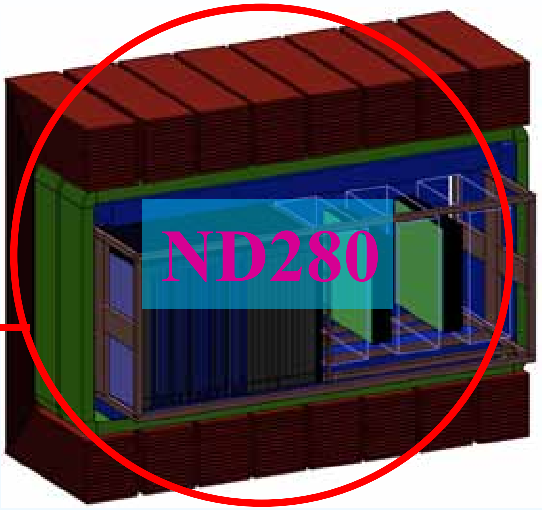
Near detectors



30 GeV proton accelerator

Near detectors





On-axis
Neutrino Beam Monitor

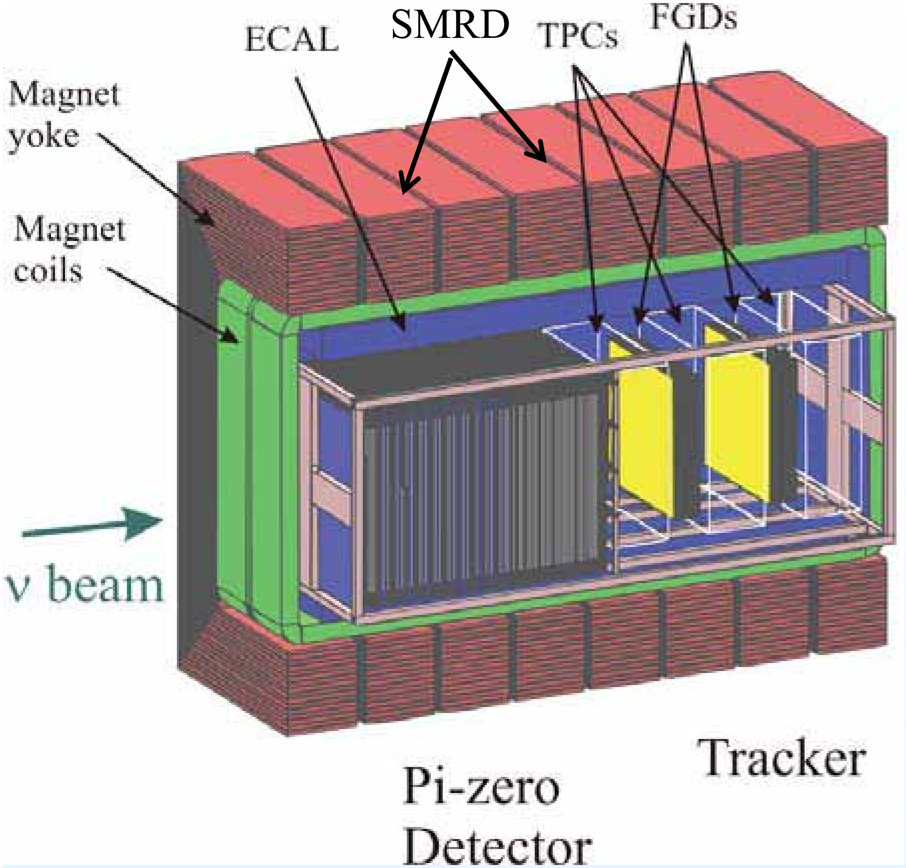
Off-axis
Neutrino Detector

ND280 off-axis detector

ND280 detector consists of 5 subdetectors:

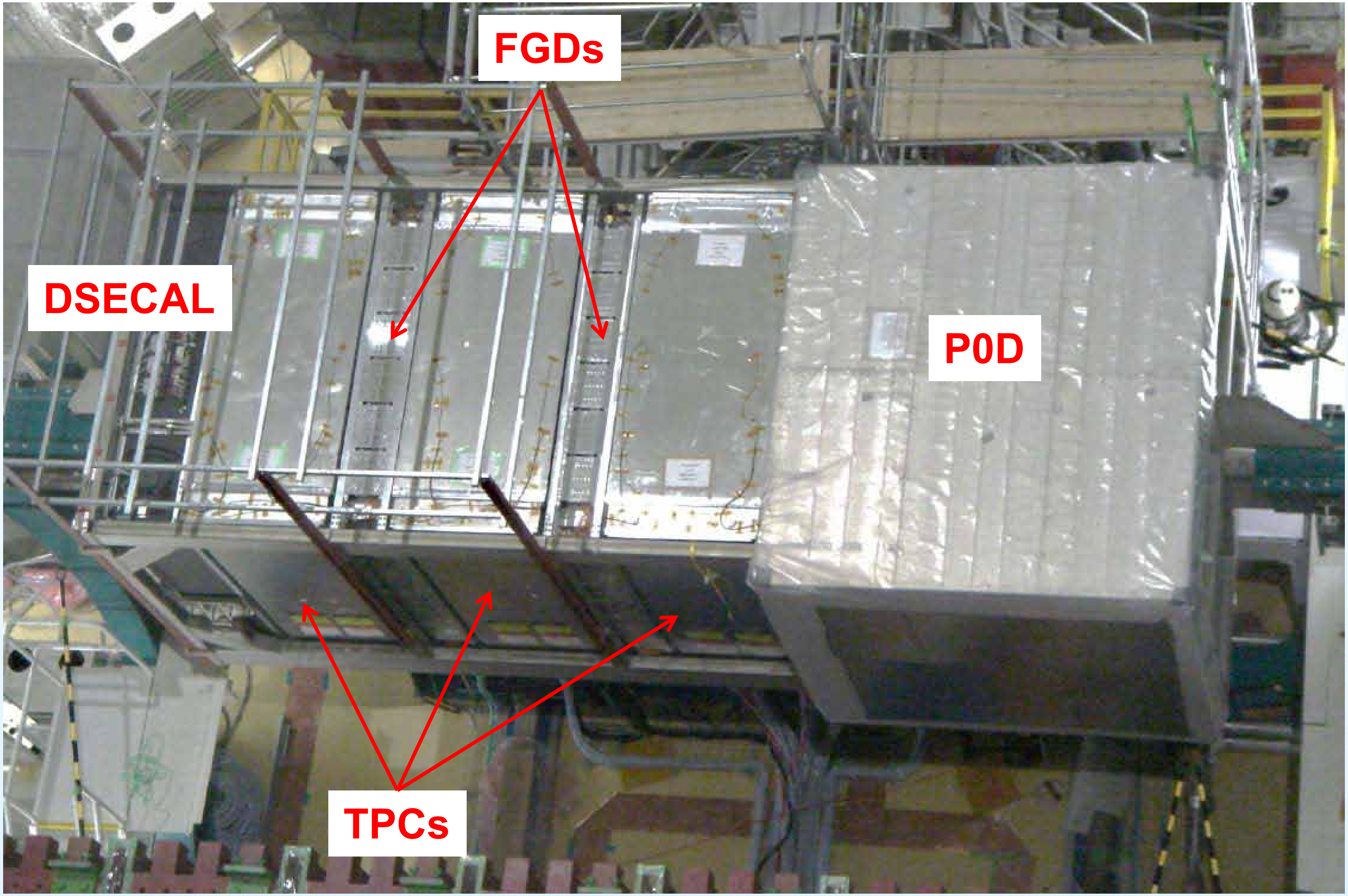
- π^0 detector (PØD)
  - Optimized for CC π^0 and NC π^0 measurements
  - Measures ν_e contamination
- Tracker: fine-grained detector (FGD) and time projection chambers (TPC) measures CC QE, CC 1π and NC 1π interactions
- Electromagnetic calorimeter (ECAL) detects EM activities coming from PØD/Tracker
- Side muon range detector (SMRD) identification of side-going muons

All detectors housed in UA1/NOMAD magnet with field 0.2 T



Detector was commissioned in March 2010 and now taking the data during 1 year

Top view of ND280 detector

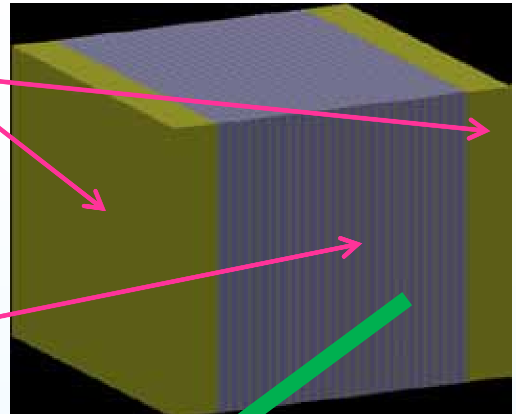


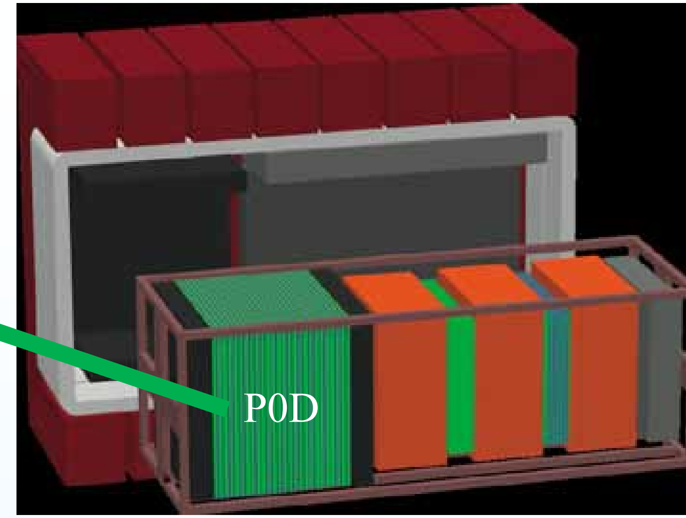
π^0 detector (P0D)

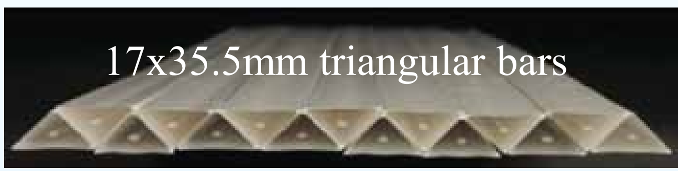
4 supermodules (p0dules)

Upstream and Central
Ecal γ-catchers
Lead/Scint sandwich

Upstream and Central
Water Target Ecals
Water/Scint sandwich

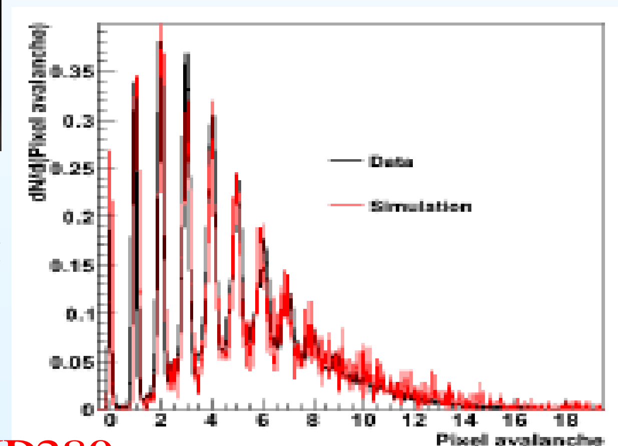


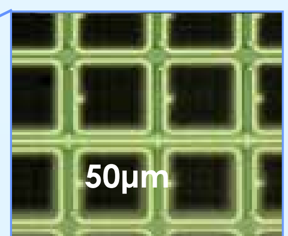




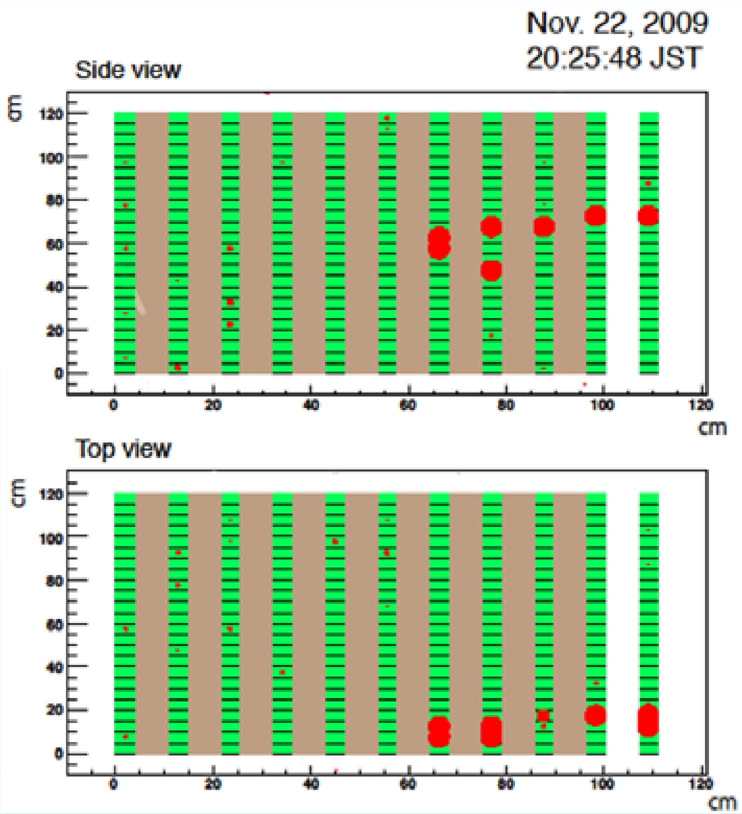
Scintillator detectors read out via **WLS** fiber coupled to Si **MPPC**: 667 pixel avalanche photodiode, area of 1.3x 1.3mm^2

First large-scale use in HEP experiments: ~50,000 MPPCs for ND280

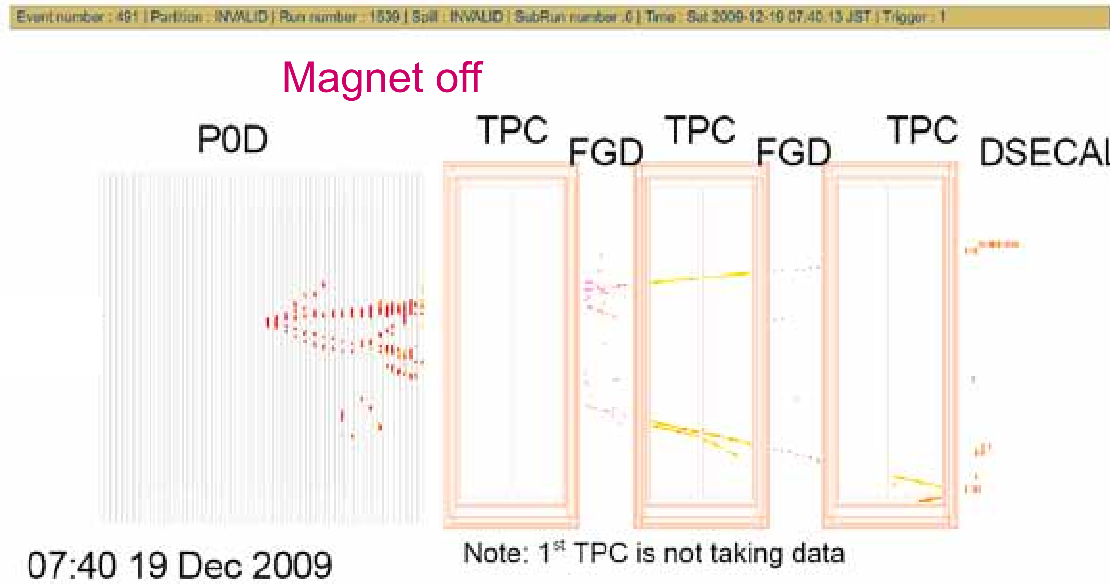




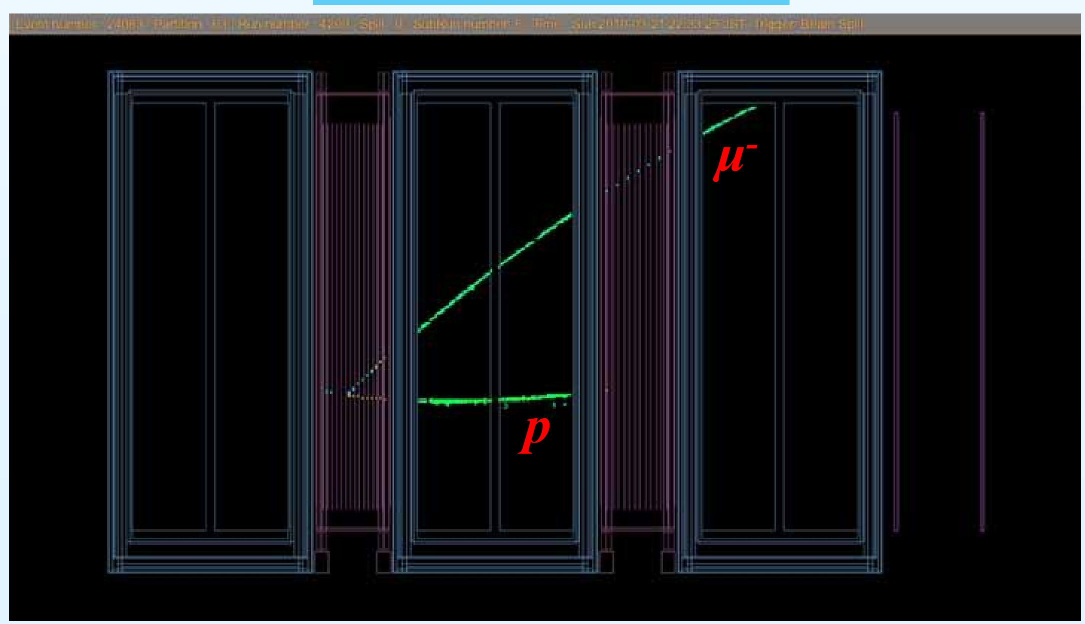
First neutrino event (INGRID)



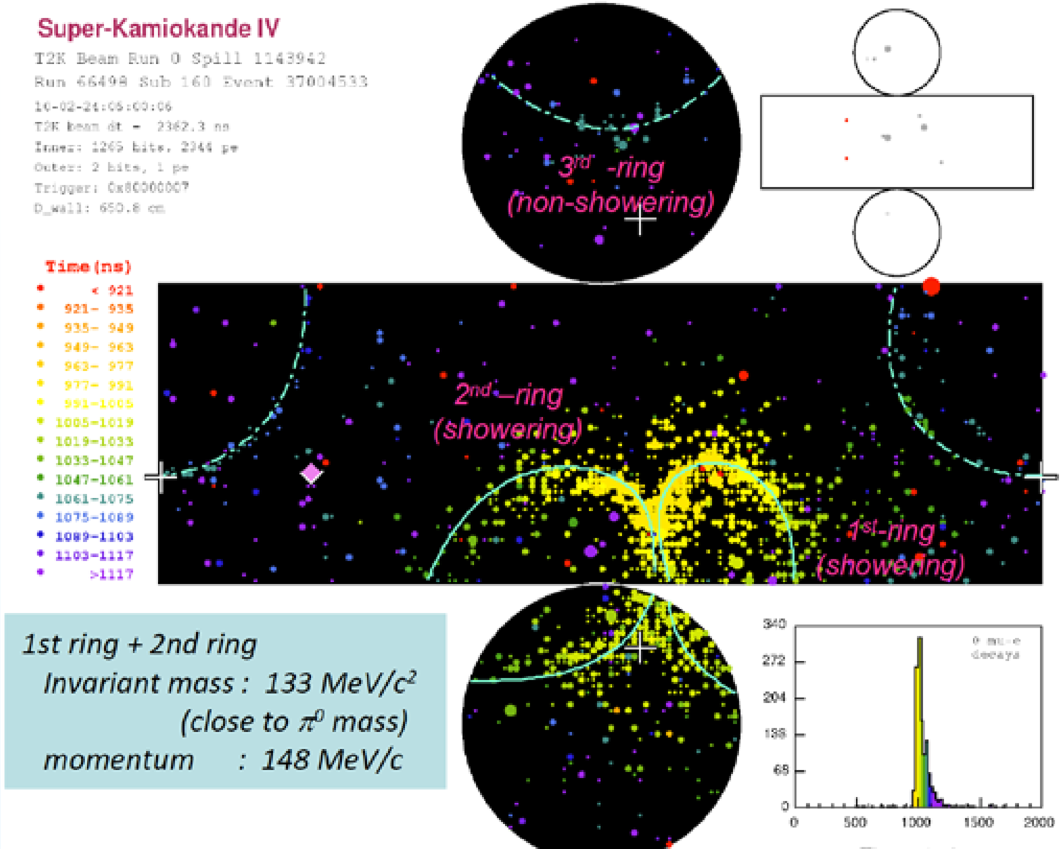
First neutrino event at ND280



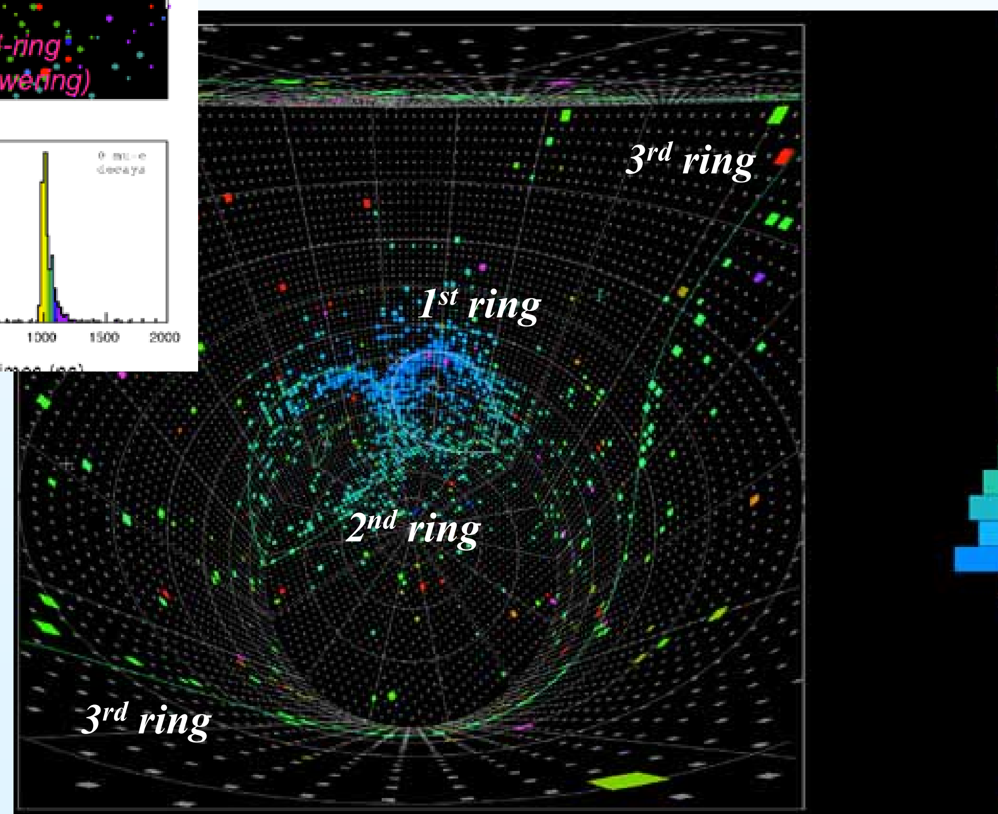
CCQE event at Tracker



First neutrino event at SK



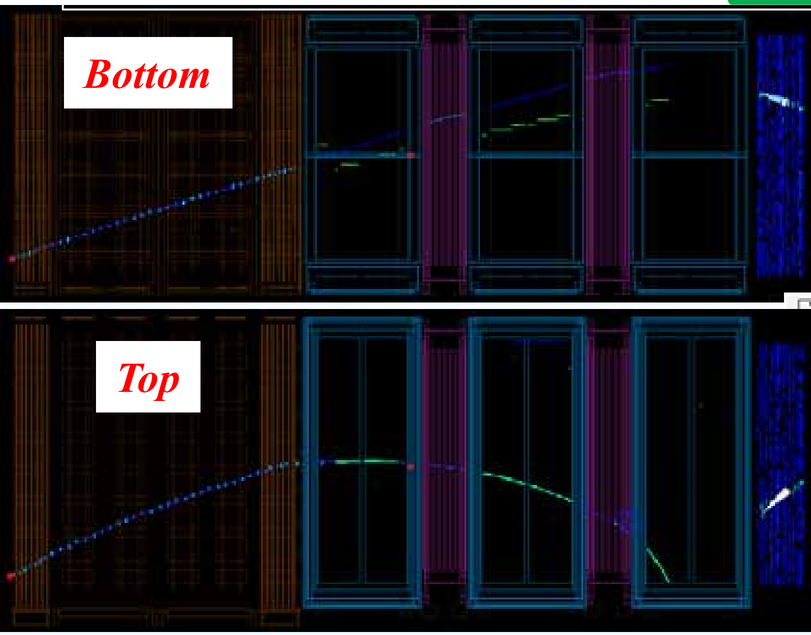
1st ring + 2nd ring
Invariant mass : 133 MeV/c^2
(close to π^0 mass)
momentum : 148 MeV/c

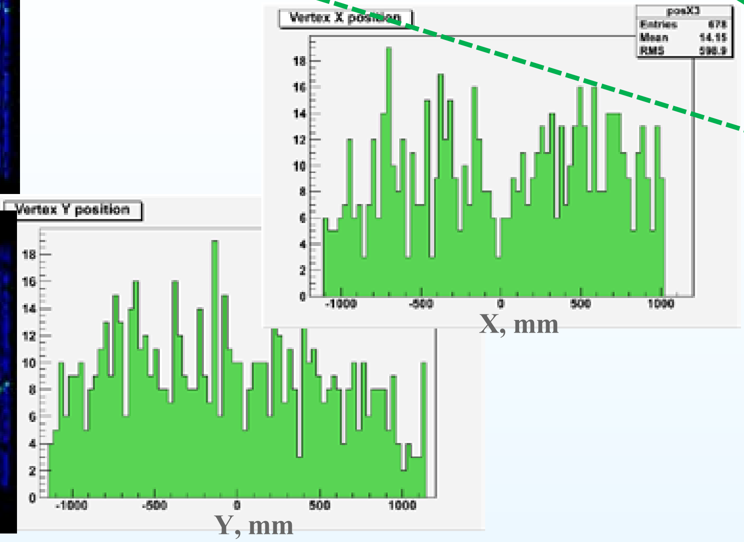


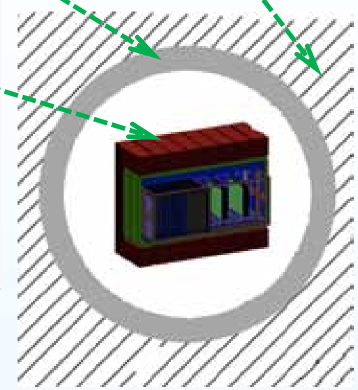
2010/2/24 6:00:06

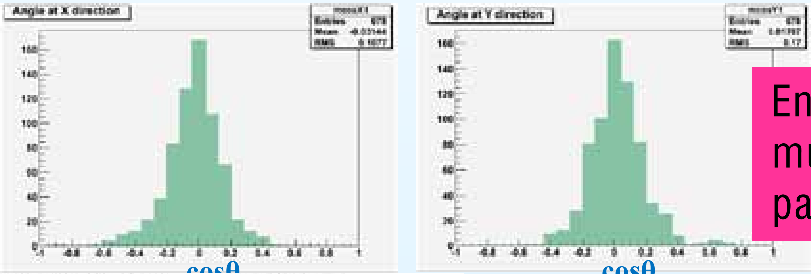
P0D calibration with ‘rock’ muons

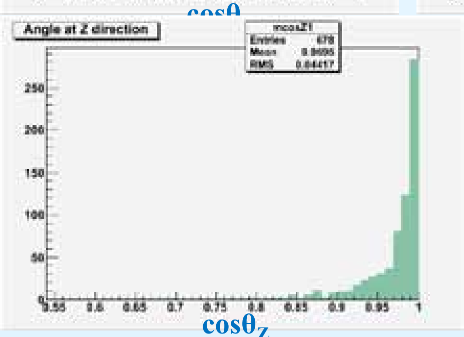
‘Rock’ muons are going outside to P0D muons produced at neutrino interaction on the outer matter that is mainly ***magnet steel***, pit construction ***concrete*** and ***rock ground***.



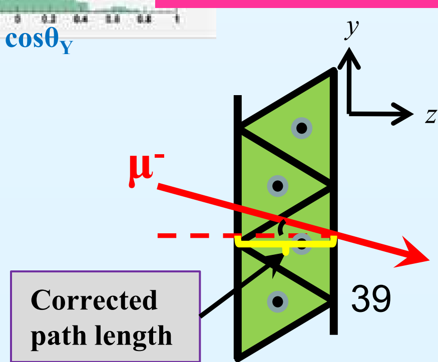


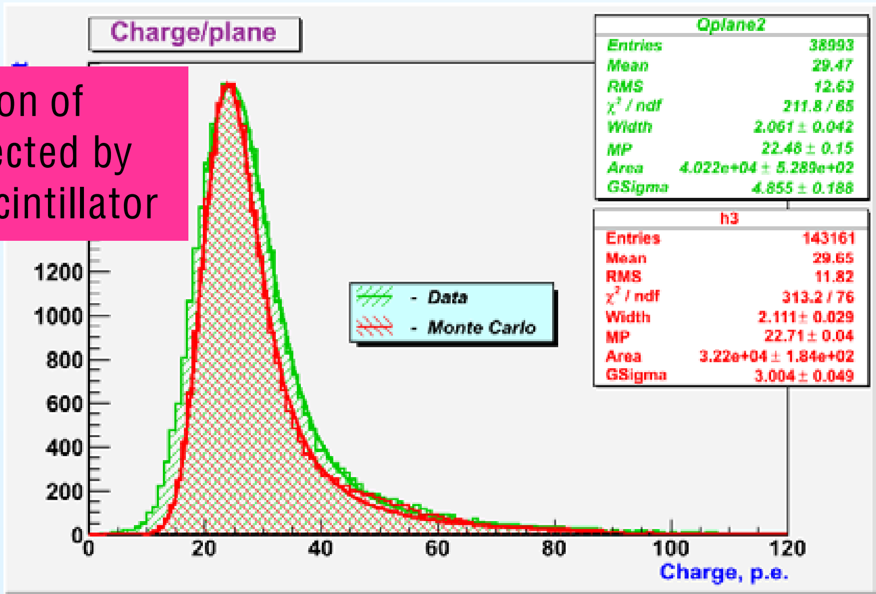




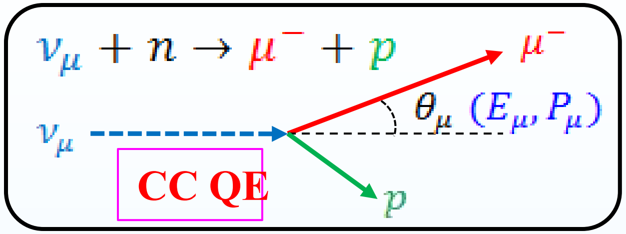


Energy deposition of muon was corrected by path length in scintillator

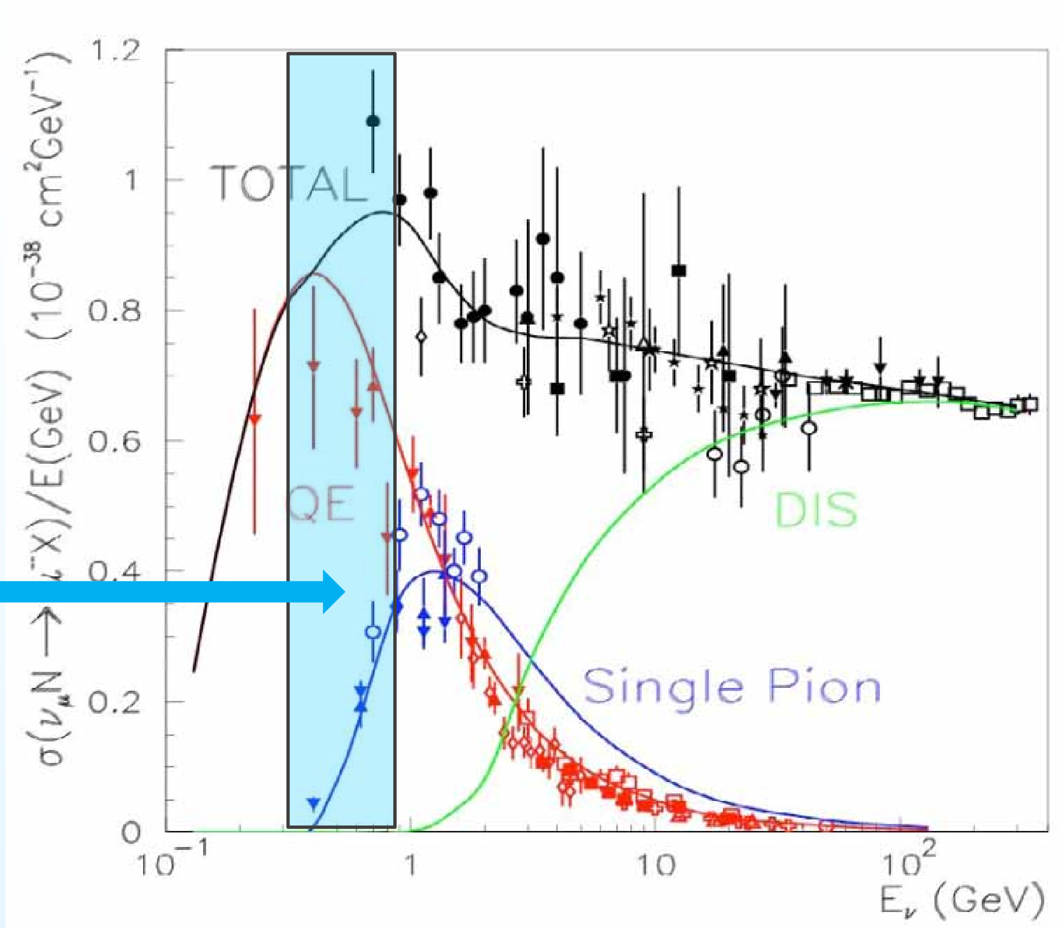




Charged current quasielastic neutrino interaction (CCQE) in P0D



CC QE is dominant process in the region of T2K off-axis neutrino spectra at 2.5° and has simple 2-body kinematics



In the simplest case of invisible proton E_ν can be calculated from measured momentum and angle of μ^-

$$E_\nu^{rec} = \frac{m_N E_\mu - m_\mu^2/2}{m_N - E_\mu + p_\mu \cos\theta_\mu}$$

CCQE: POT's, requirements, cuts, …

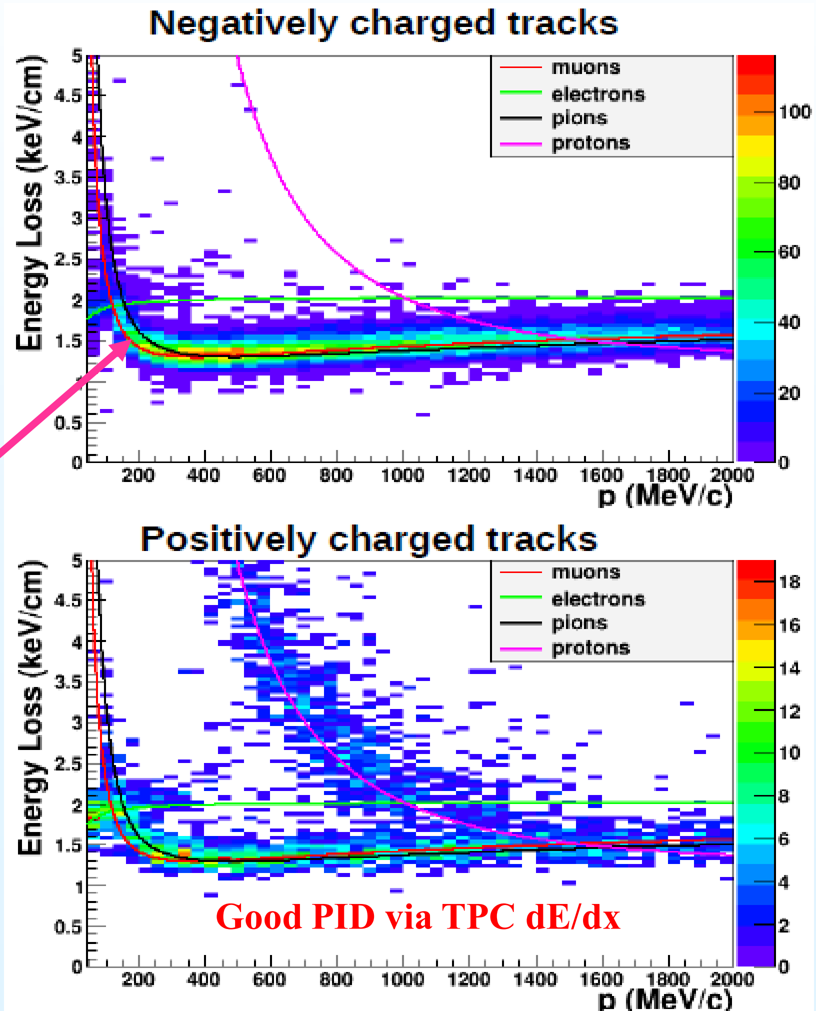
- NEUT MC for study of backgrounds, reconstruction efficiency and purity of 1-track and 2-track CCQE events
- The total data PoT's number is 2.84×10^{19}
- The total PoT's number of ***NEUT*** MC is 1.3×10^{20}
- MC distributions were normalized to the total number of data PoT's

Fiducial Volumes

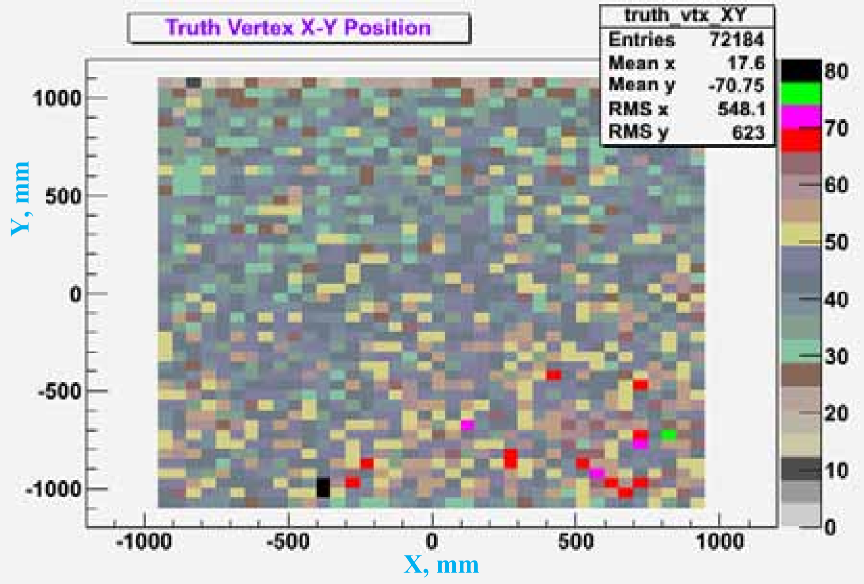
1. ***Full P0D*** -3224 < Z < -1016 mm
   First 3 and last 1 P0Dules were excluded
2. ***Water Target*** -1236 < Z < -1348 mm
   24 internal P0Dules
3. ***Central Ecal*** -3224 < Z < -1016 mm
   5 internal P0Dules

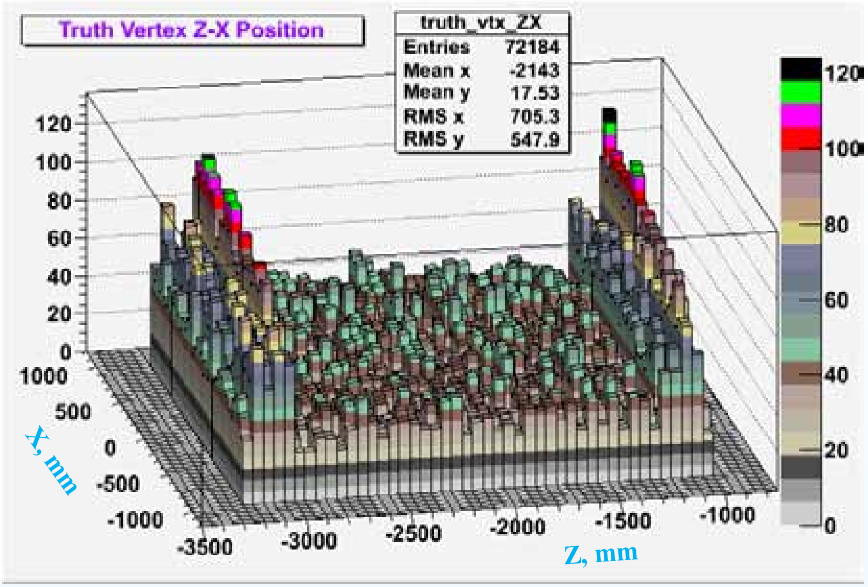
Requirements and cuts

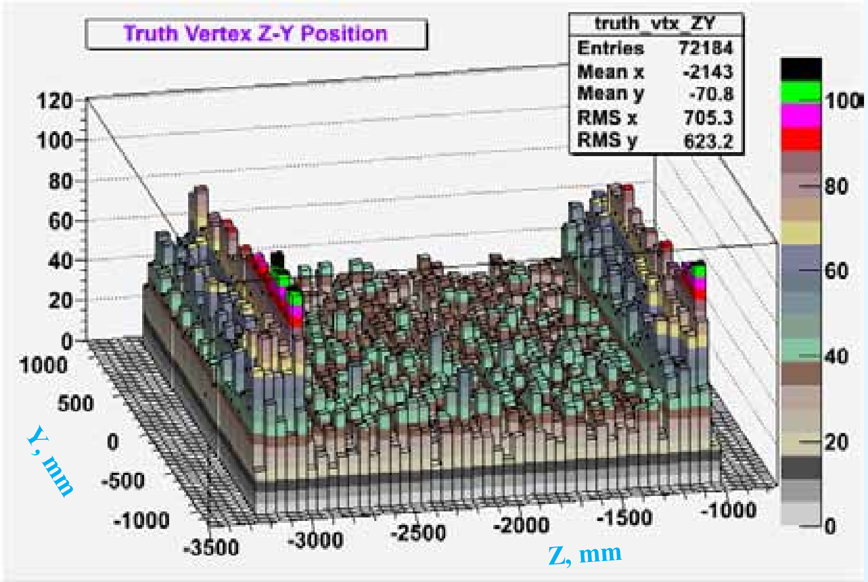
1. 1 or 2 track segments in TPC
2. Vertex should be at P0D Fiducial Volume
3. Long track should be negative
4. TPC PID corresponds to muon

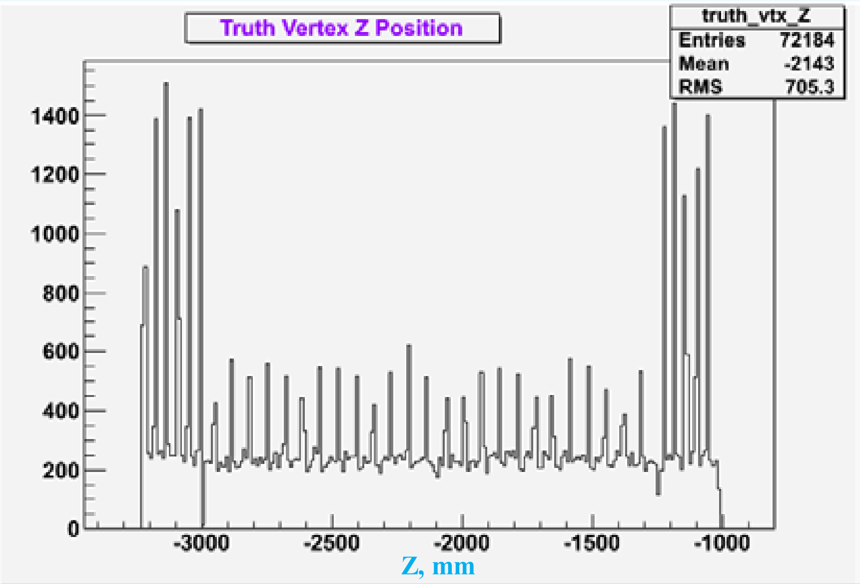


CCQE: Full P0D True Vertex position

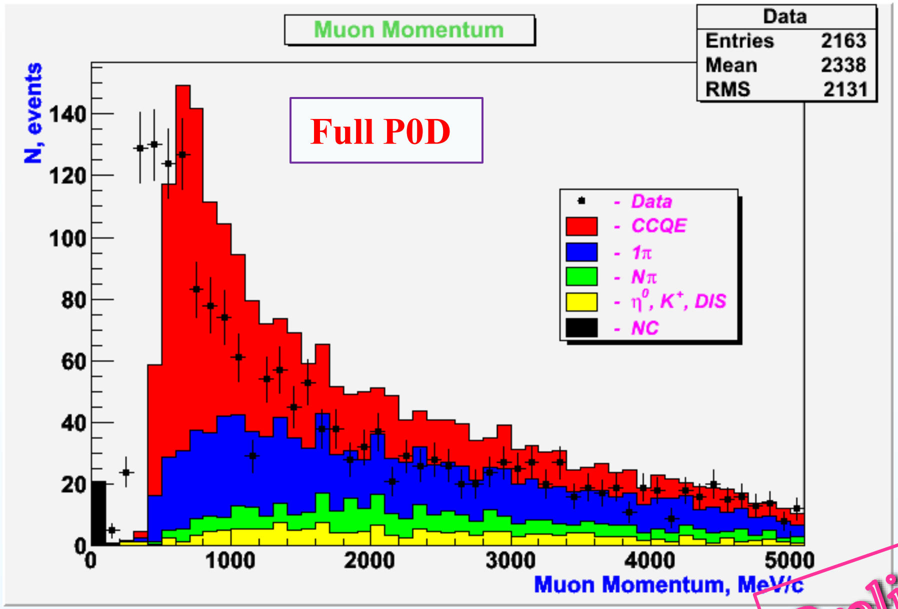


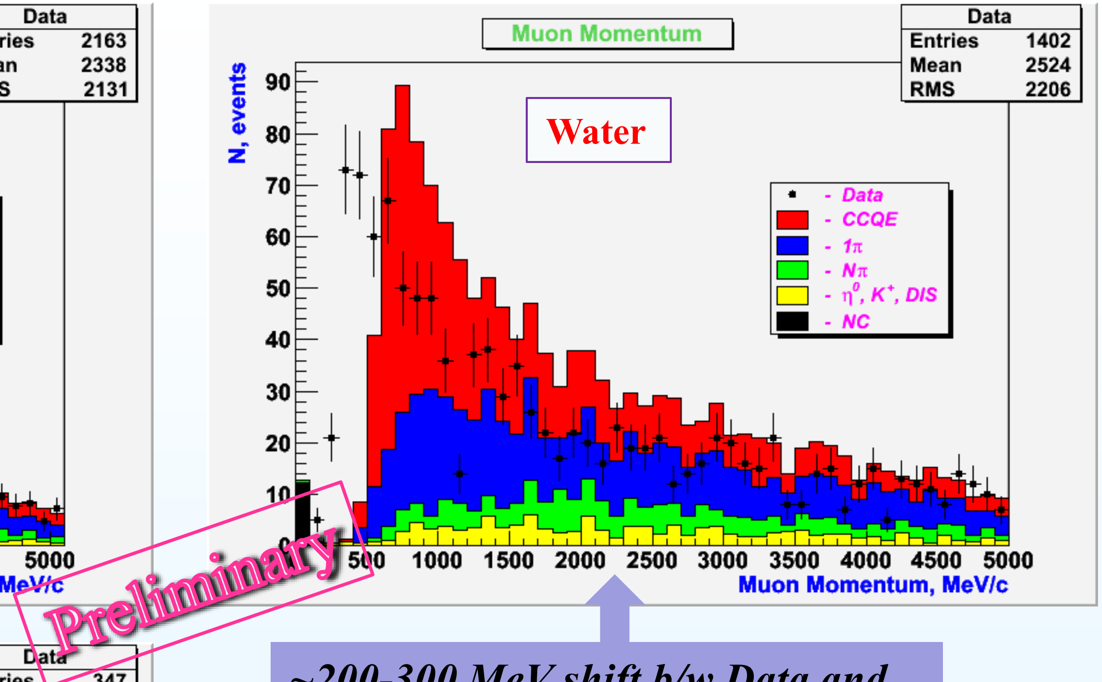


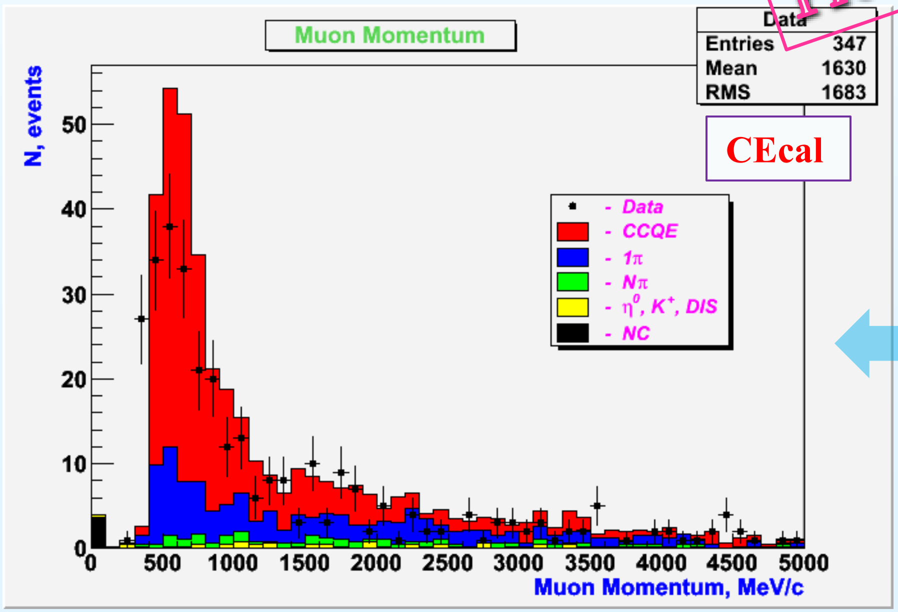




CCQE: 1-track CCQE and backgrounds for selected events





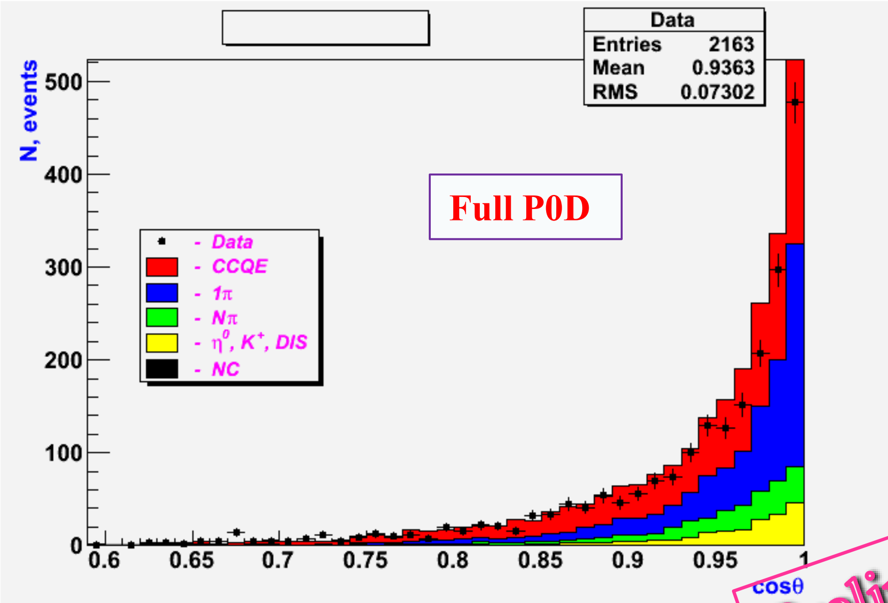


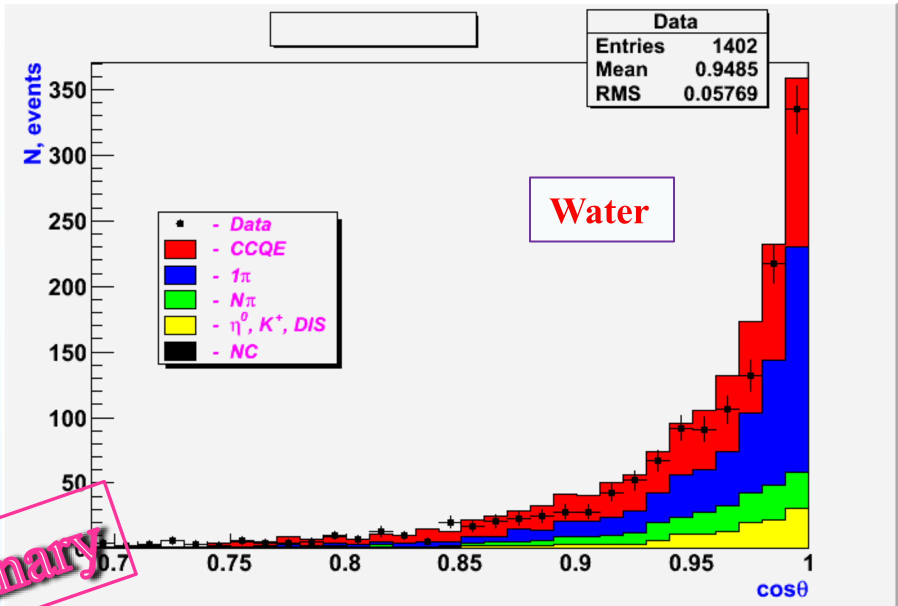
~200-300 MeV shift b/w Data and MC due to the Global reconstructed momentum is not corrected for track energy loss in P0D

Small ~50-100 MeV shift b/w Data and MC for Cecal due to the short track length in P0D

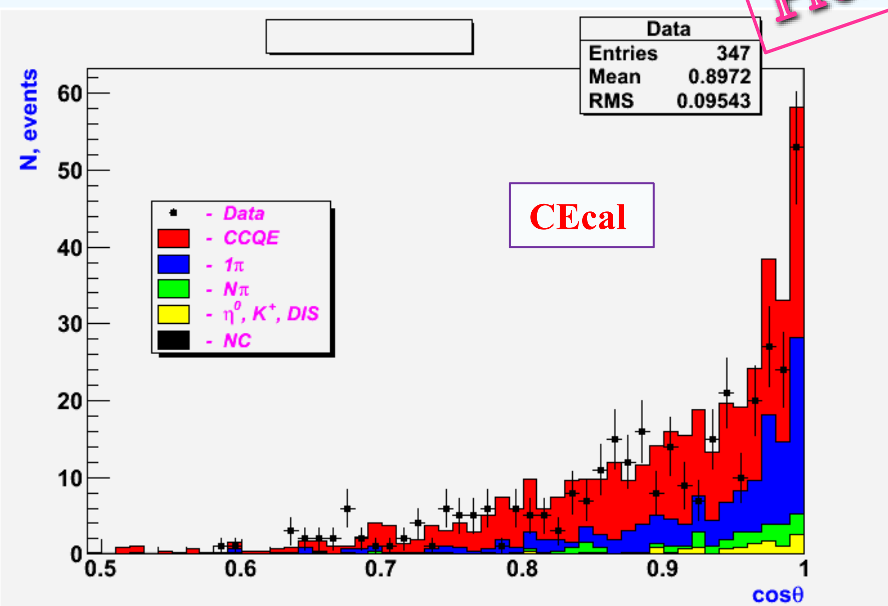
The shift will be corrected in upcoming version of nd280 software

CCQE: 1-track CCQE and backgrounds angles for selected events





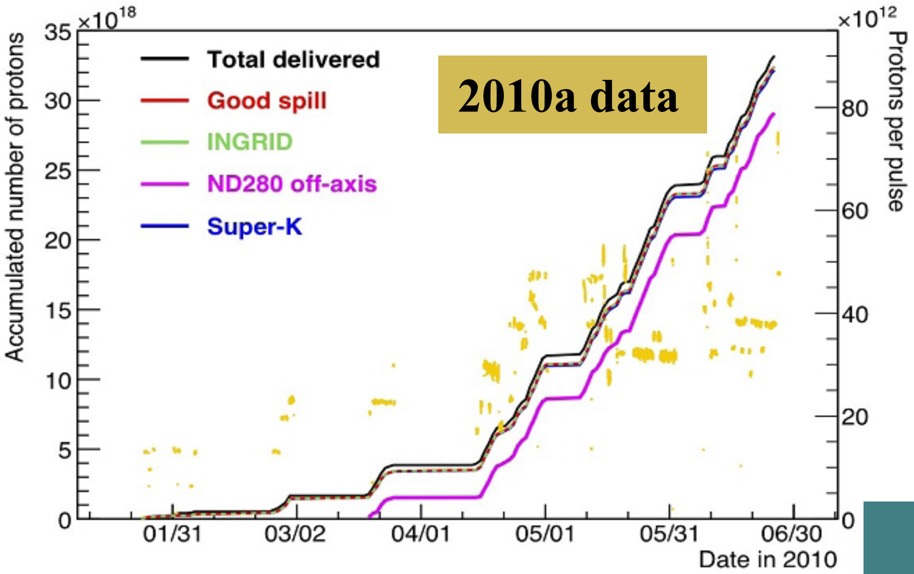
Preliminary



Nice agreement between Data and MC

First T2K preliminary results

2010a data were collected during Jan – June 2010.



- Total SK data: 3.23×10^{19} PoT (15.5 kW x 10^7s)
- Stable running at 3.8×10^{13} PoT/spill (≈54 kW) shots up to 100 kW

SK event pre-selection was based on FV cuts, ring counting and PID.

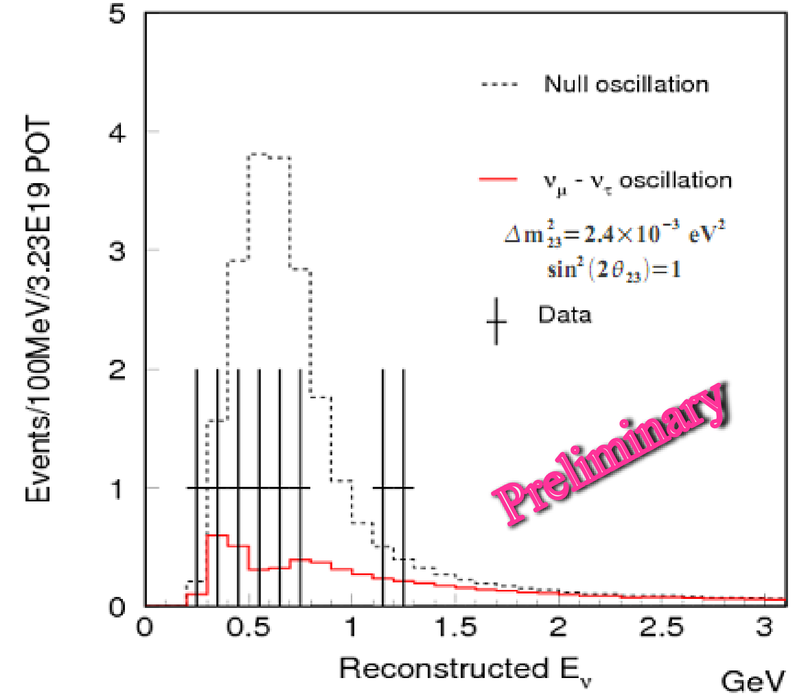
8 ν_μ and 2 ν_e candidates were selected for next analysis

Preliminary

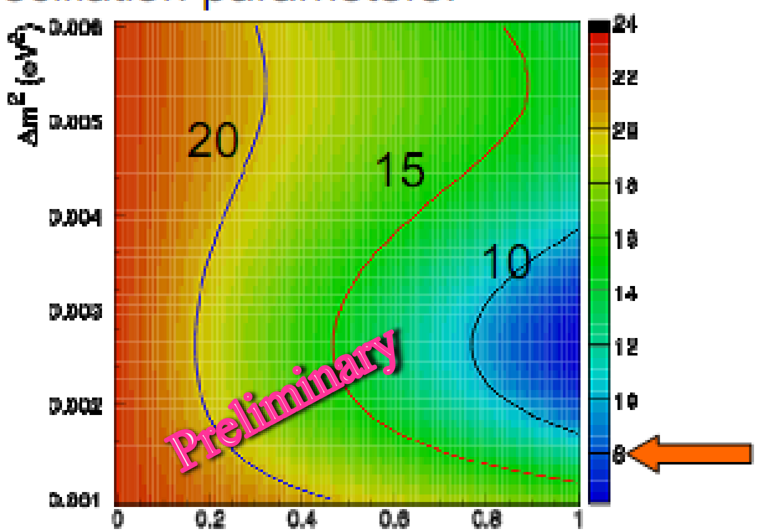
	Data	MC: No oscillation	MC: Oscillation $\Delta m^2 = 2.4\times10^{-3}$ (eV^2) $\sin^2 2\theta_{23} = 1.0$
Fully-Contained	33	54.5	24.6
Fiducial Volume, $E_{vis} > 30$MeV	23	36.8	16.7
Single-ring μ-like (P_μ>200MeV/c)	8	24.5 ±3.9	7.1 ±1.3
Single-ring e-like (P_e>100MeV/c)	2	1.5 ±0.7	1.3 ±0.6
Multi-ring	13	10.2	8.0

ν_μ disappearance analysis

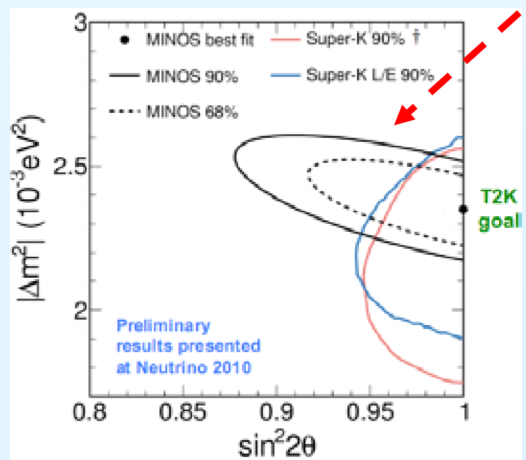
Preliminary	Data	MC	
		No oscillation	Oscillation $\Delta m^2 = 2.4 \times 10^{-3}$ (eV^2) $\sin^2 2\theta_{23} = 1.0$
Fully-Contained	**33**	54.5	24.6
Fiducial Volume, $E_{vis} > 30$MeV	**23**	36.8	16.7
Single-ring μ-like (P_μ>200MeV/c)	**8**	24.5 ±3.9	7.1 ±1.3
N(decay e) < 2 (E_{rec} < 10 GeV)	**8**	22.8 ±3.2	6.3 ±1.0



Expected # of events as a function of Oscillation parameters.



Number of events consistent with oscillation parameters measured by MINOS/SK/K2K



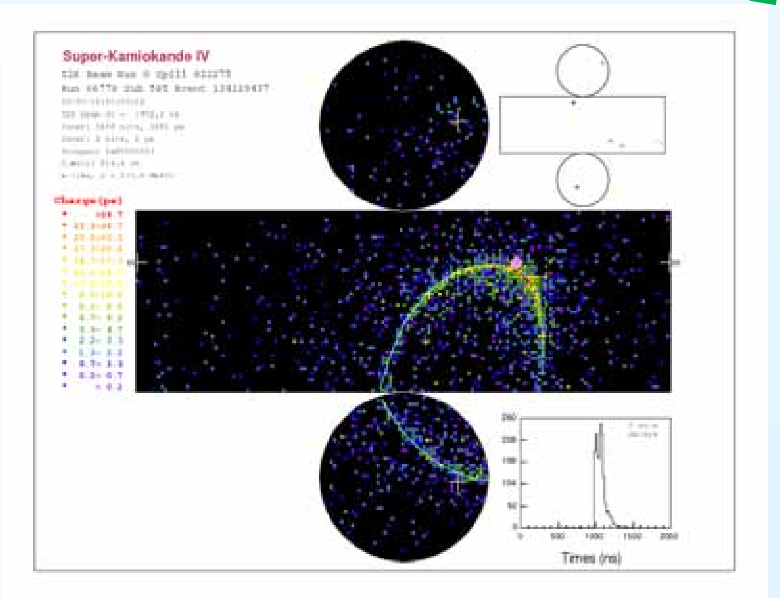
Final ν_e event selection

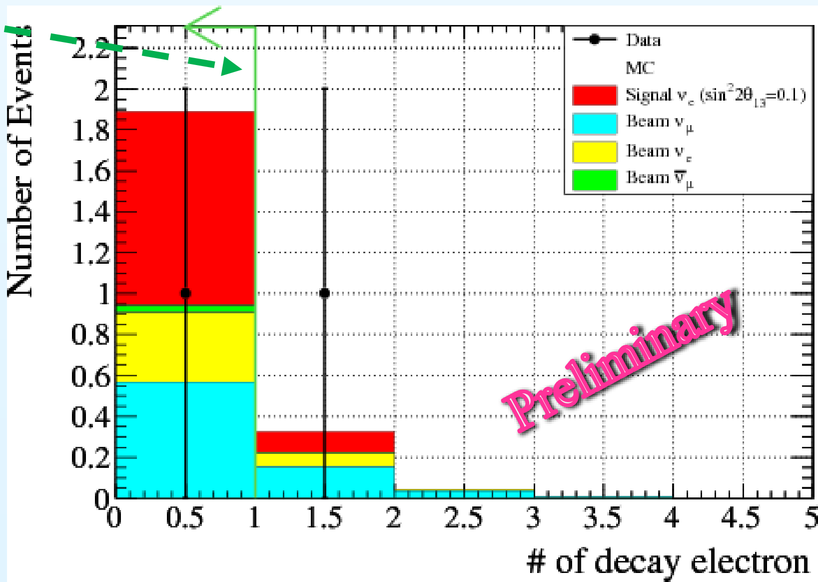
Preliminary	Data	MC	
		No oscillation	Oscillation $\Delta m^2 = 2.4 \times 10^{-3}$ (eV^2) $\sin^2 2\theta_{23} = 1.0$ $\theta_{13}=0$
Fully-Contained	**33**	54.5	24.6
Fiducial Volume, E_{vis} > 30MeV	**23**	36.8	16.7
Single-ring e-like (P_e>100MeV/c)	**2**	1.5 ±0.7	1.3 ±0.6

Additional background rejection

- no decay electron
- $m_{\gamma\gamma}$ < *105 MeV assuming second* ring exist
- reconstructed E_ν < 1250 MeV

When # of decay electron cut was applied only 1 candidate of ν_e event remains





ν_e appearance analysis

Upper bound of θ_{13} are evaluated by 2 independent methods:

A: Feldman-Cousins

B: Classical one-sided limit

Systematic uncertainties are took into account for both analysis.

90% CL upper limit at m^2_{23}=2.4 10^{-3}eV^2, $_{CP}$ = 0

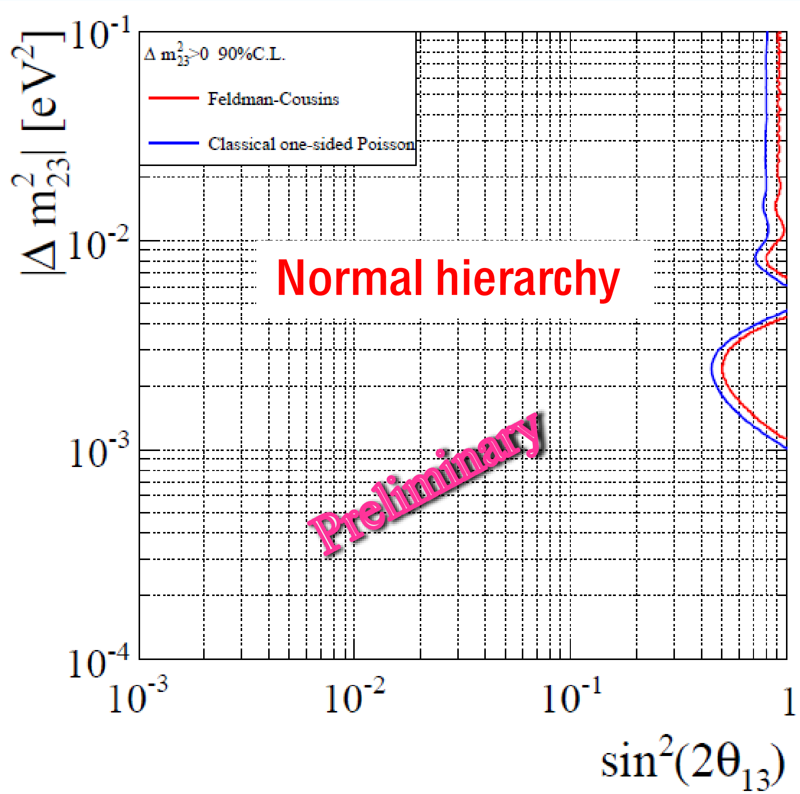
A

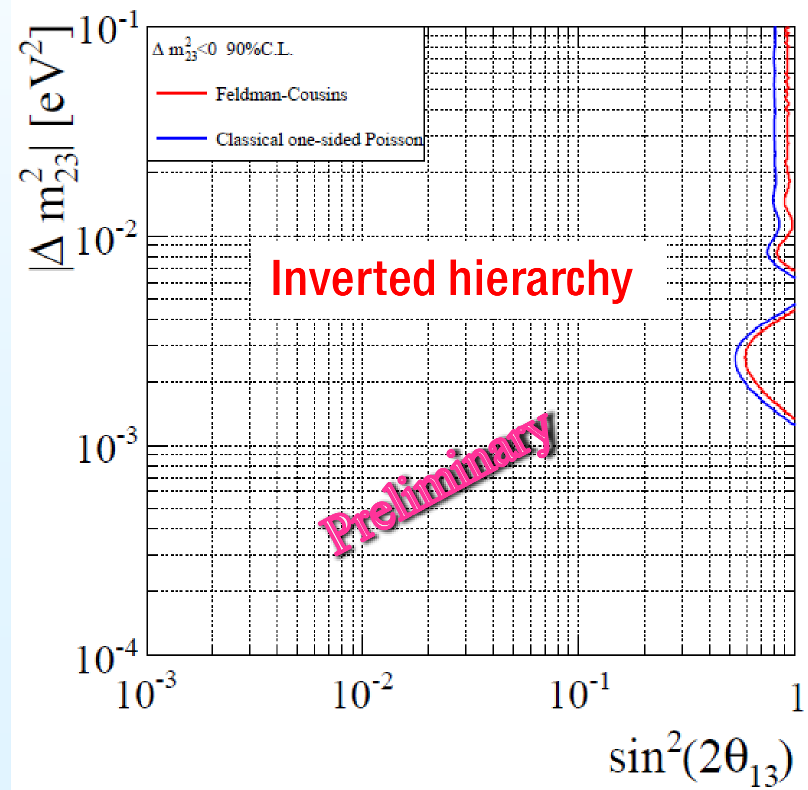
Hierarchy	Upper Limit	Sensitivity
Normal ($\Delta m^2_{23} > 0$)	0.50	0.35
Inverted ($\Delta m^2_{23} < 0$)	0.59	0.42

Preliminary

B

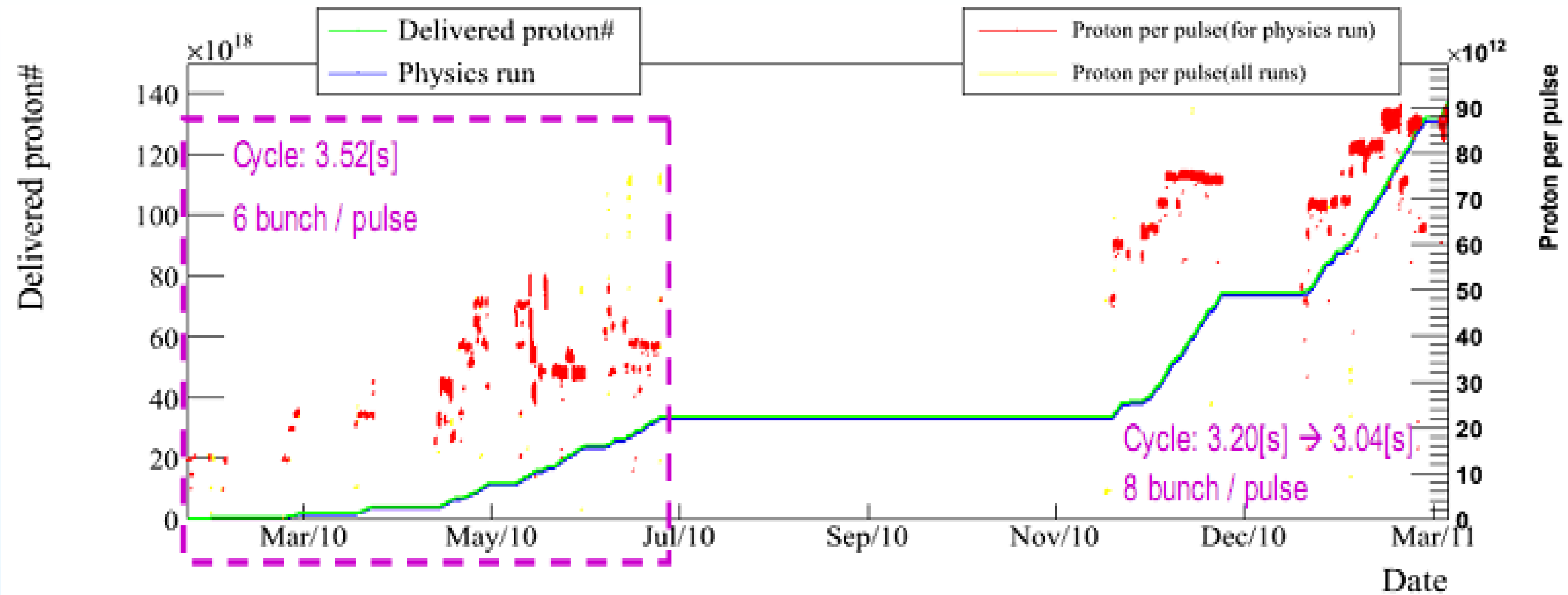
Hierarchy	Upper Limit	Sensitivity
Normal ($\Delta m^2_{23} > 0$)	0.44	0.32
Inverted ($\Delta m^2_{23} < 0$)	0.53	0.39





Backup slides

Future prospects



Run 2010b (from Nov 2010 – March 2011)

- 9.3×10^{13} p/spill (8 bunches/spill/3.04s)
- Max beam power: ~145 kW
- Total data collected up to Mar 11: 1.45×10^{20} PoT (including run 2010a)