Measurement of θ_{13} in Neutrino Oscillation Experiments

Stefan Roth, RWTH Aachen

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DFG Deutsche Forschungsgemeinschaft

Overview

- Experiments with neutrinos
- Neutrino oscillations
- Reactor and accelerator neutrino experiments
- Current status and future sensitivities

Two experiments with RWTH participation:

- ➢ Reactor neutrino experiment Double Chooz
  Near and far detector
  at nuclear power plant
  Chooz (France)

- ➢ Accelerator neutrino experiment T2K
  Tokai to Kamioka
  long baseline neutrino
  experiment

ELECTRON-NEUTRINO ν_e

The **ELECTRON-NEUTRINO** wears a bandit's mask because he likes to steal away energy and is notoriously difficult to detect. Traveling close to the speed of light, he is the most pervasive form of matter in the universe. Trillions of neutrinos are passing through everything around us, including us, at every moment. The result of radioactive neutron decay, most neutrinos originate from the sun. Their mass is next to nothing.

Acrylic felt with poly fill for minimum mass.

$9.75 PLUS SHIPPING

●○○○○○○○○○○○ LIGHT HEAVY

MUON-NEUTRINO ν_μ

Like its first-generation sibling lepton the electron-neutrino, the **MUON-NEUTRINO** is extremely difficult to detect (hence the bandit's mask). Discovered in 1962, it is emitted in the decay of a muon. Its mass is about one-third of an electron.

Acrylic felt with poly fill for minimum mass.

$9.75 PLUS SHIPPING

●○○○○○○○○○○○ LIGHT HEAVY

TAU-NEUTRINO ν_τ

Like its sibling leptons the electron-neutrino and muon-neutrino, this cheeky little devil, the **TAU-NEUTRINO,** is extremely difficult to detect (hence the bandit's mask). Discovered in 2000, it is about 100 times heavier than a muon-neutrino.

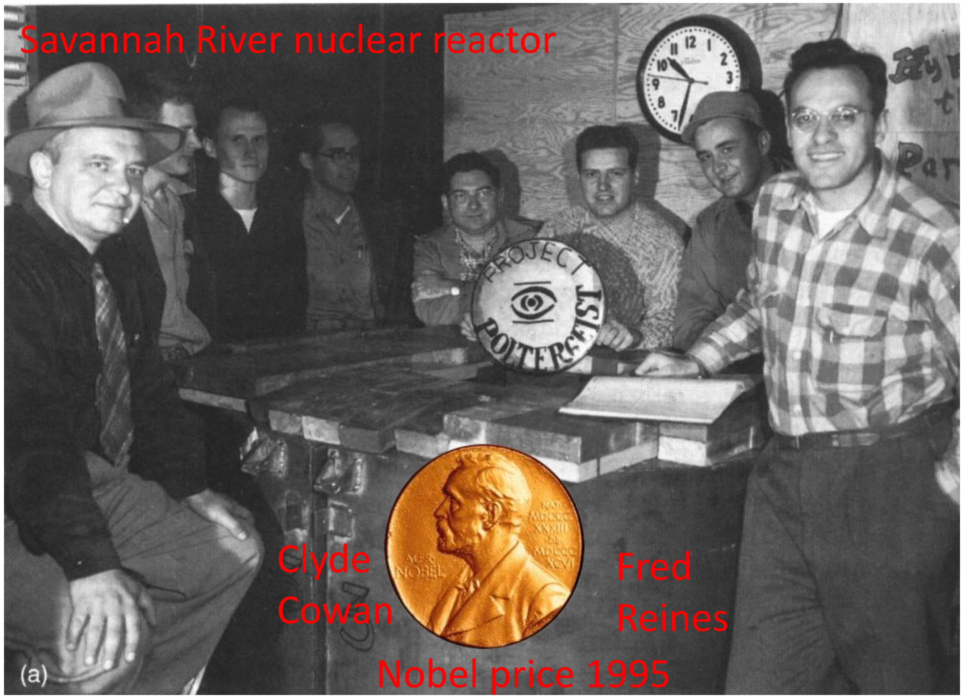
Wool felt with poly fill for minimum mass.

$9.75 PLUS SHIPPING

●●○○○○○○○○○○ LIGHT HEAVY

http://particlezoo.net

Discovery of the Neutrino: Project „Poltergeist“ (1956)



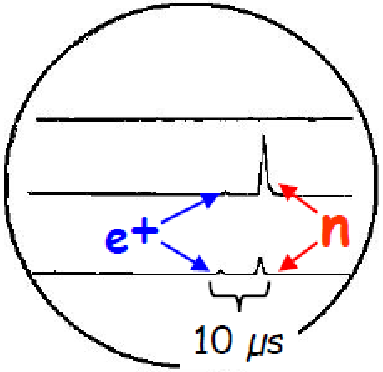
Nuclear reactors produce a large flux of anti-neutrinos $\bar{\nu}_e$

β-decays of the fission products of the isotopes ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu

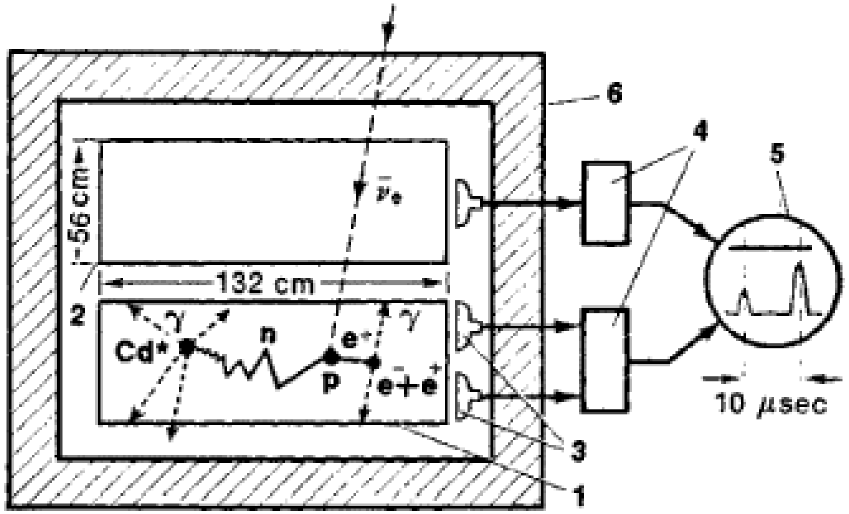
$$\boxed{\bar{\nu}_e + p \rightarrow n + e^+}$$

Inverse β-decay using delayed coincidences:

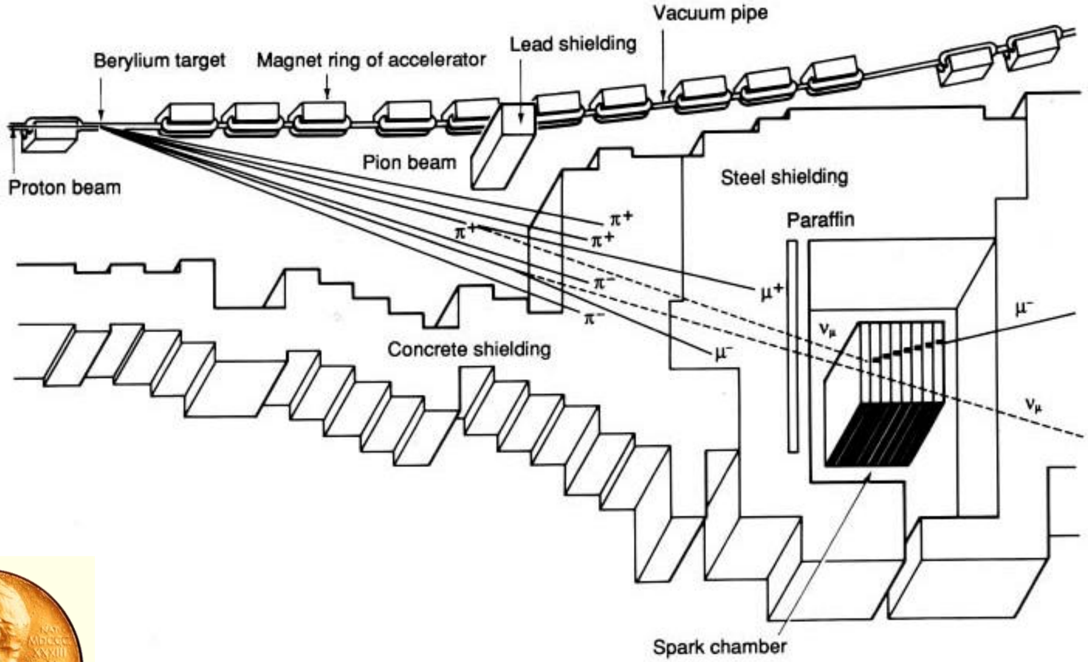
Prompt:
positron
annihilation



Delayed:
neutron
capture



Discovery of the Myon-Neutrino: Brookhaven (1960)



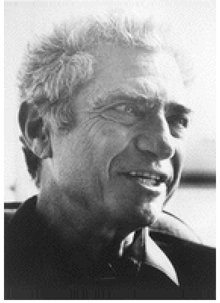
Pion beam
produces ν_μ beam

$$\boxed{\nu_\mu + n \rightarrow \mu^- + p}$$

Nobel price 1988

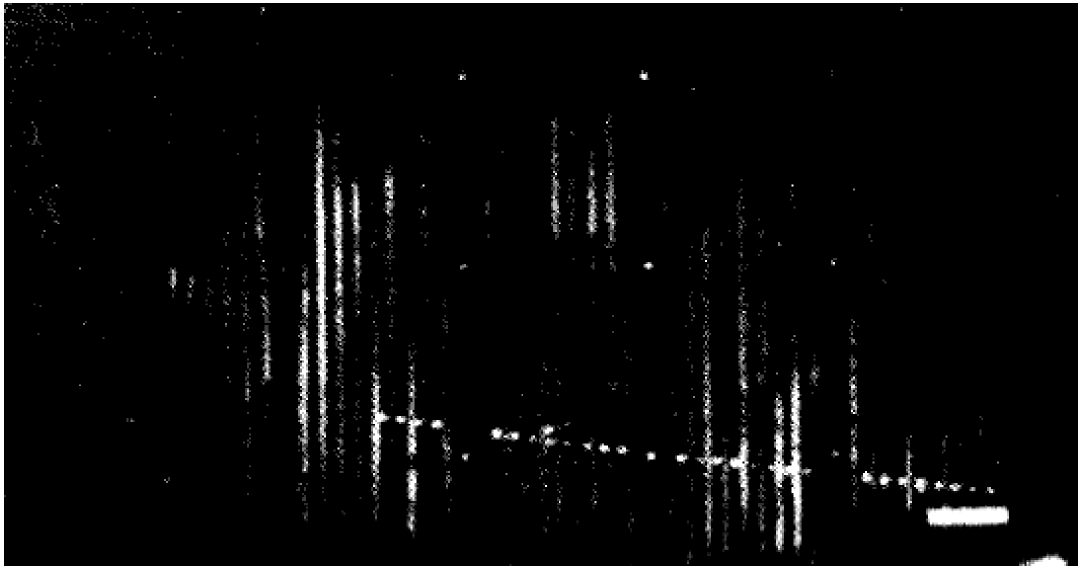
Leon
Ledermann

Melvin
Schwartz

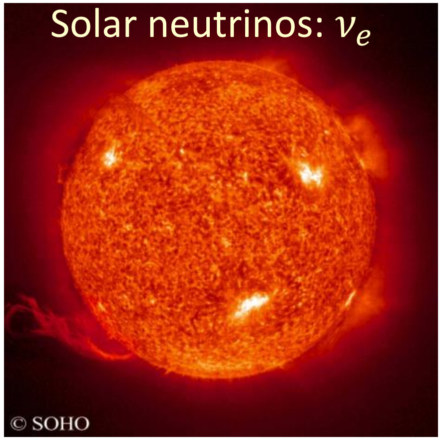


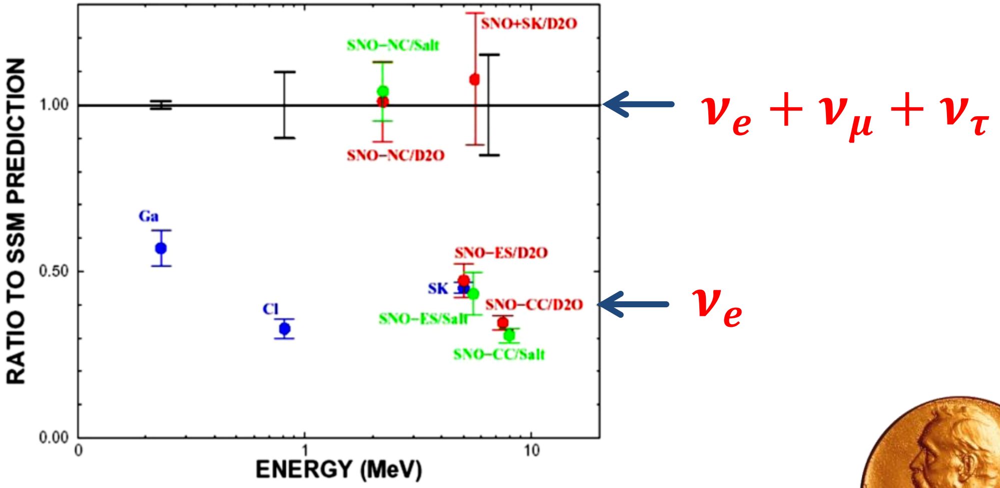
Jack
Steinberger

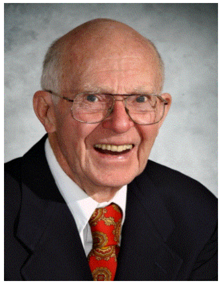
Myon track starts within spark chamber



Discovery of Neutrino Oscillations



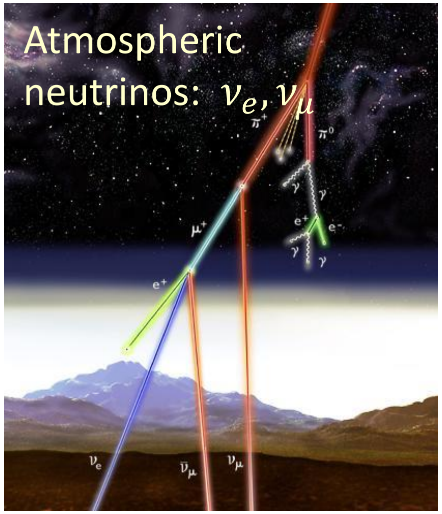


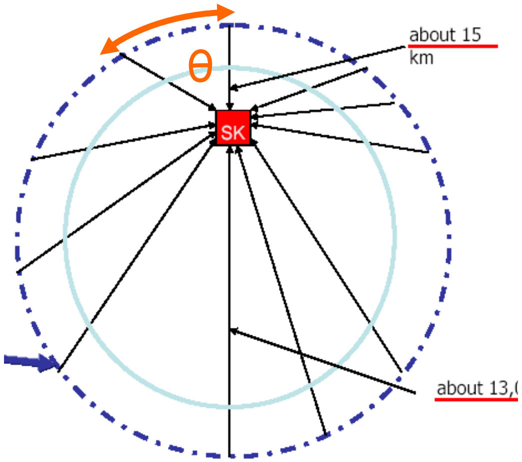


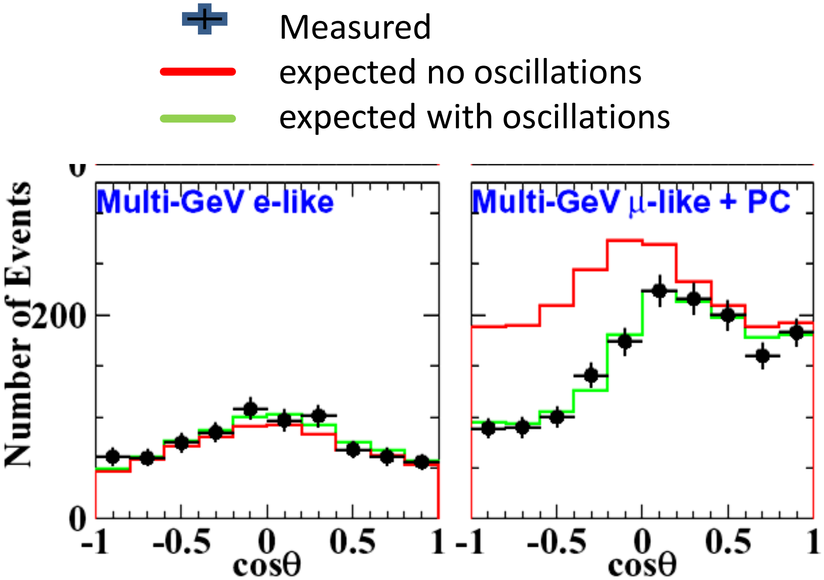
R. Davis

M. Koshiba

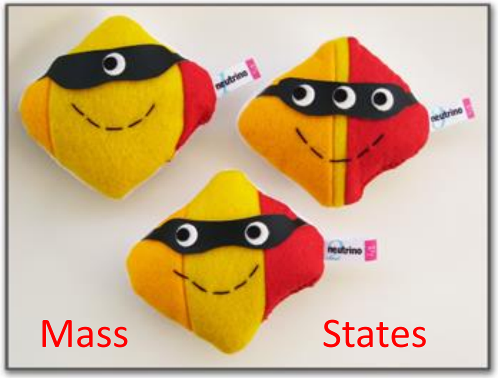
Nobel price 2002







Mixing of mass and flavor states



Production/detection:

$\boldsymbol{\nu_e, \nu_\mu, \nu_\tau}$

Propagation:

$\boldsymbol{\nu_1, \nu_2, \nu_3}$

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i} \; |\nu_i\rangle$$
$$\alpha = e, \mu, \tau$$
$$i = 1, 2, 3$$

Unitary rotation of states with
3 mixing angles: $\theta_{12}, \theta_{23}, \theta_{13}$
1 CP violating phase: δ_{CP}

Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix: $c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$

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

„Atmospheric“
$\theta_{23} \approx 45°$

„Reactor“
$\theta_{13} \approx 10°$

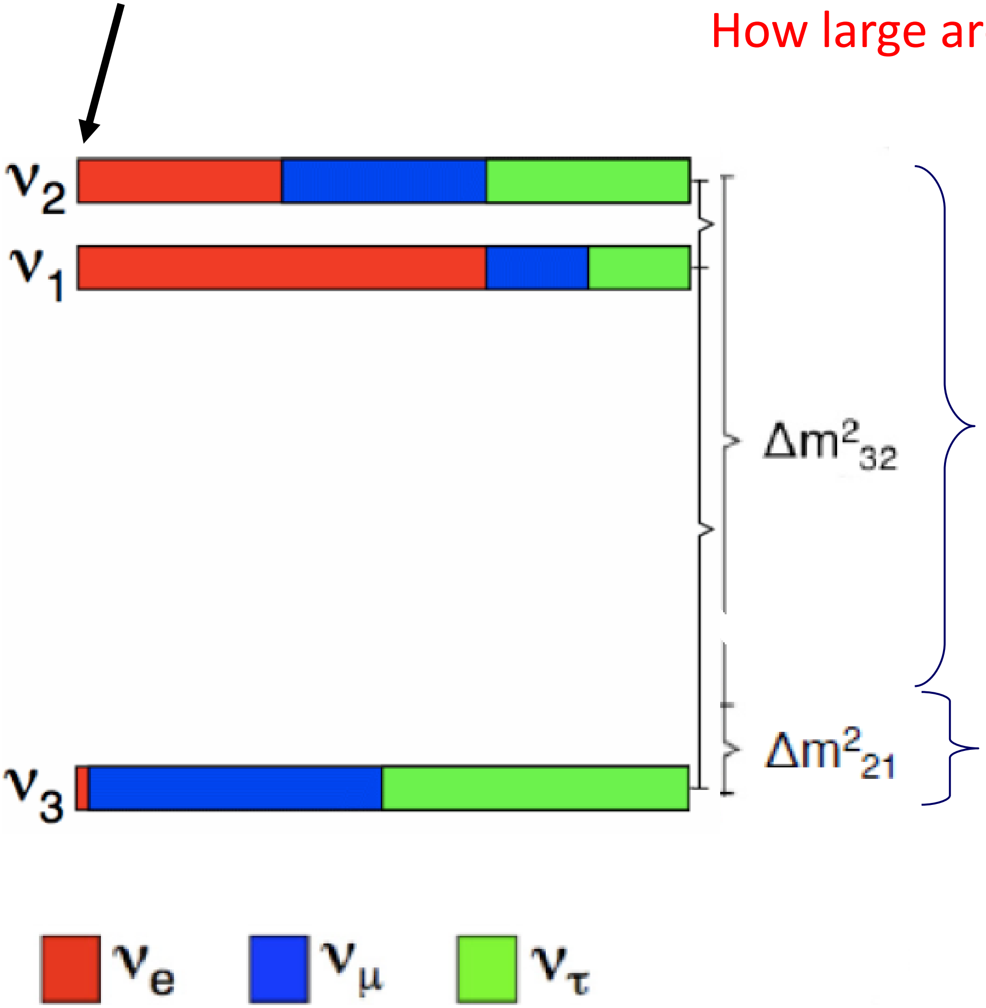
„Solar“
$\theta_{12} \approx 32°$

Majorana
phases

Oscillation parameters

ν_e contribution to ν_3 is small!

How large are U_{e3} and θ_{13} ?



Atmospheric Neutrinos and K2K :

$\Delta m_{23} \approx 0.05$ eV

from $P(\nu_\mu \rightarrow \nu_\mu)$

Solar Neutrinos and KamLAND :

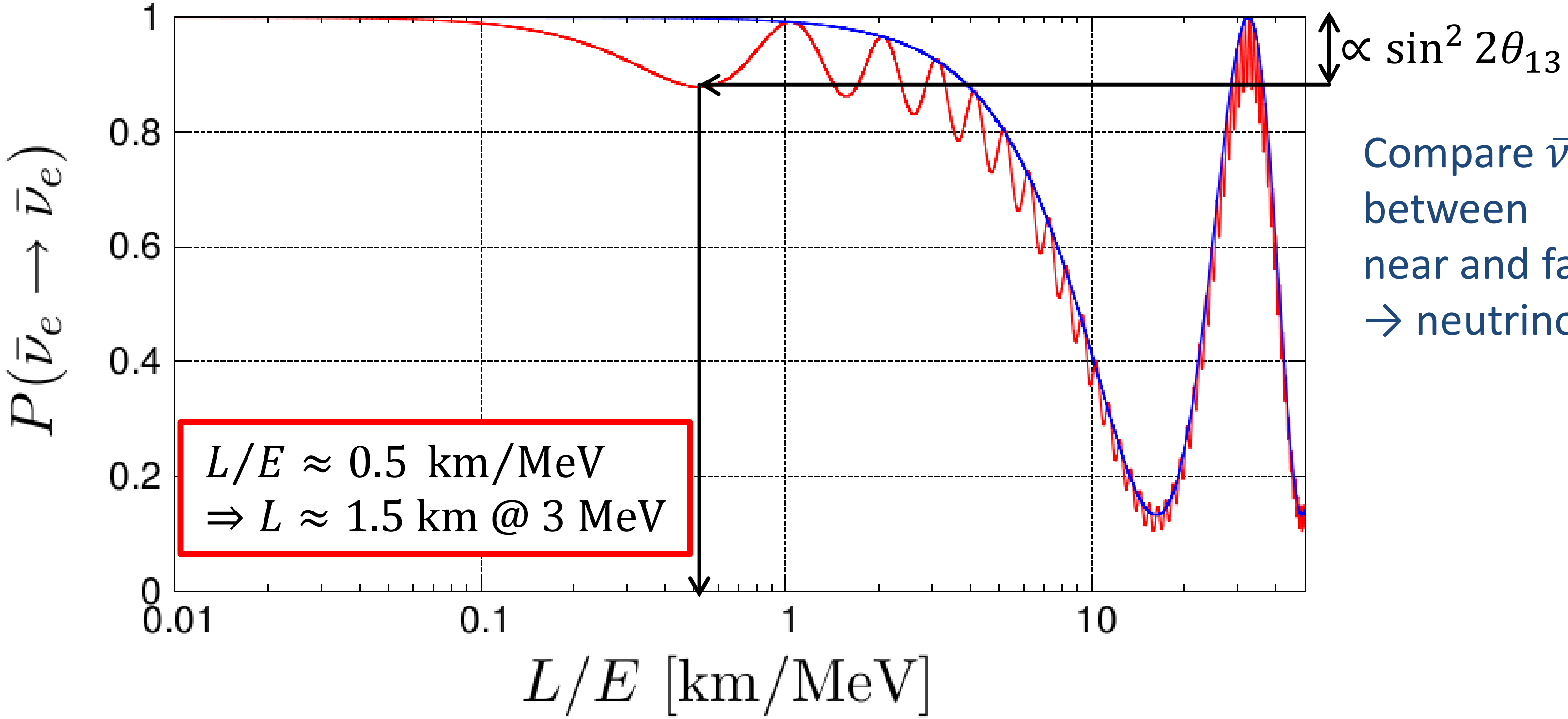
$\Delta m_{12} \approx 0.009$ eV

from $P(\nu_e \rightarrow \nu_e)$

(other possibility: inverted mass hierarchy)

Neutrino Oscillations (3 Masses)

Survival probability $P(\bar{\nu}_e \rightarrow \bar{\nu}_e)$:



$\propto \sin^2 2\theta_{13}$

$L/E \approx 0.5$ km/MeV
$\Rightarrow L \approx 1.5$ km @ 3 MeV

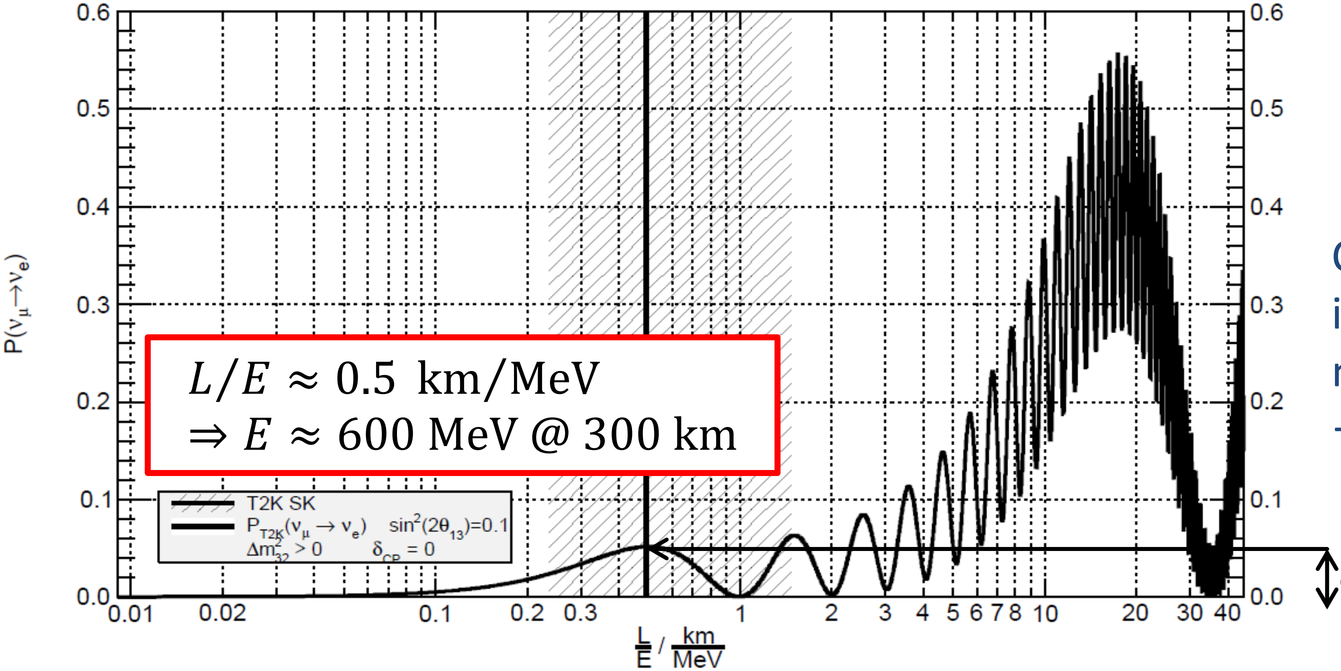
Compare $\bar{\nu}_e$ flux
between
near and far detector
→ neutrino deficit

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m_{31}^2 L}{4E} + f\left(\sin^2 \frac{\Delta m_{21}^2 L}{4E}\right)$$

$$\Delta \mathrm{m}_{31}^2 \approx \Delta m_{32}^2 = 2.3 \cdot 10^{-3}\ \mathrm{eV}^2 \gg \Delta m_{21}^2 = 7.5 \cdot 10^{-5}\ \mathrm{eV}^2$$

Neutrino Oscillations (3 Masses)

Appearance probability $P(\nu_\mu \rightarrow \nu_e)$:



$L/E \approx 0.5$ km/MeV
$\Rightarrow E \approx 600$ MeV @ 300 km

Compare ν_e content in beam between near and far detector
→ neutrino appearance

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \frac{\Delta m^2_{31} L}{4E} + f\left(\sin^2 \frac{\Delta m^2_{21} L}{4E}\right)$$

Here also neglected: Terms with δ_{CP}, Terms due to matter effects

New Reactor Neutrino Experiments

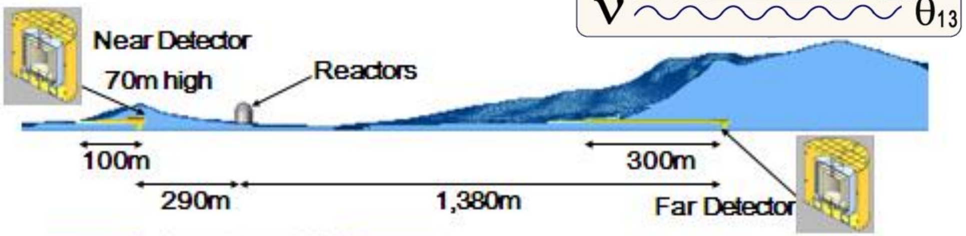
DayaBay:

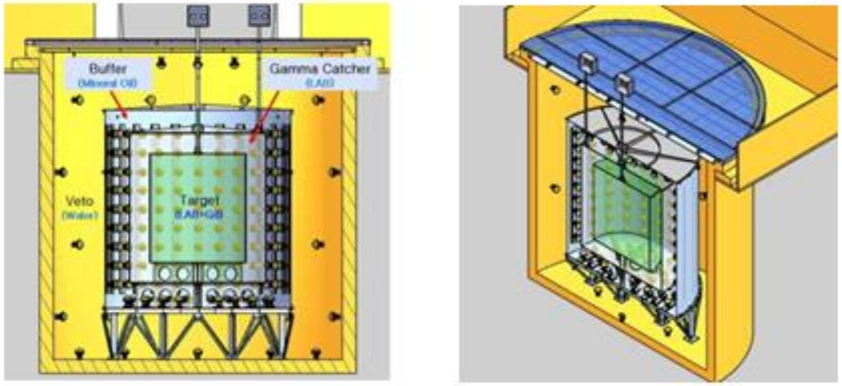
- Located at Daya Bay Nuclear Power Plant in China
- 6 x 2.9 GW_{th} nuclear reactors
- 6 neutrino detecors
  3 near (520 m from reactors)
  3 far (1650 m from reactors)

2011-12

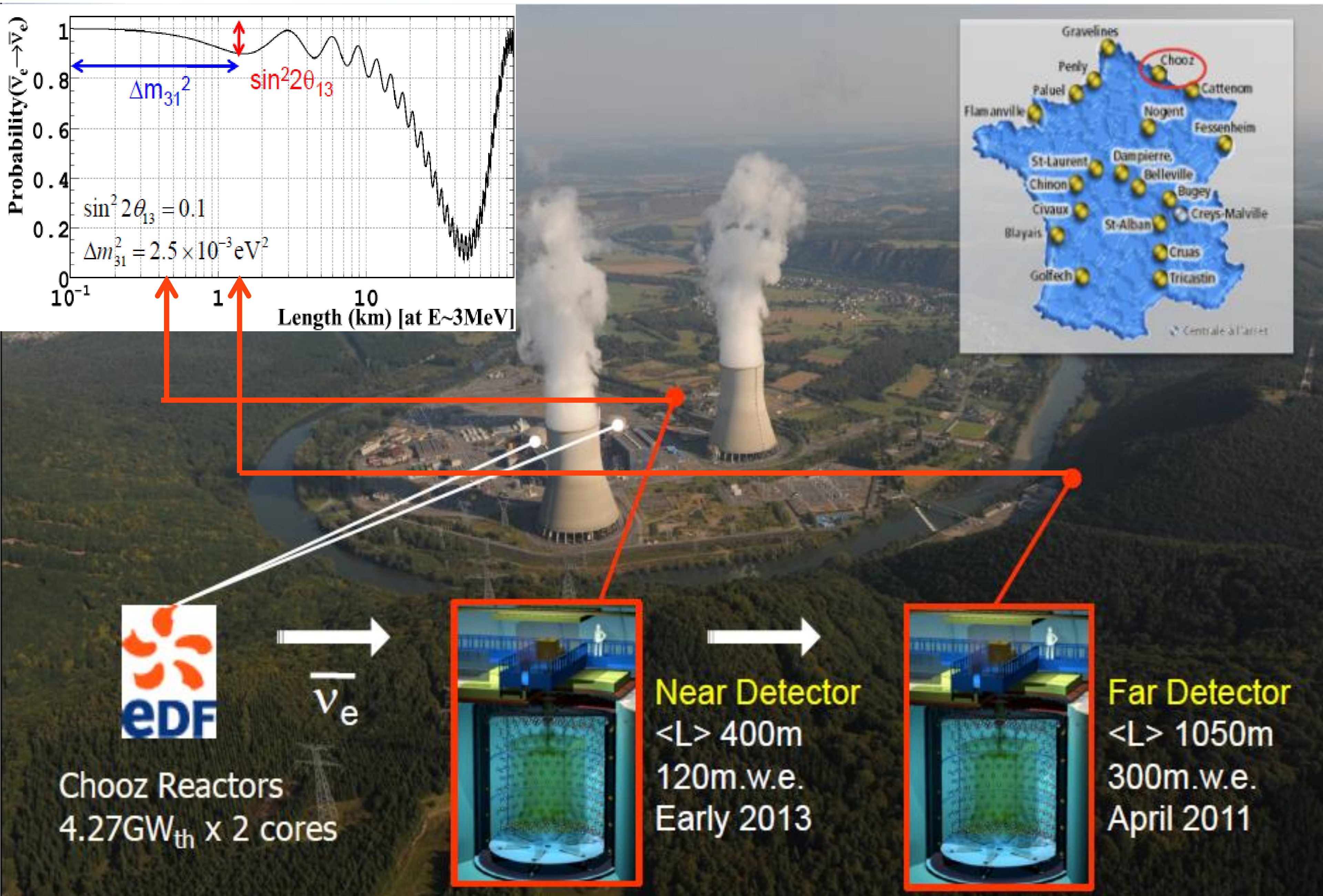
RENO:

- Located at Yonggwang Nuclear Power Plant in Korea
- 6 x 2.8 GW_{th} nuclear reactors
- 2 neutrino detecors
  1 near (294 m from reactor)
  1 far (1383 m from reactor)





The Double Chooz Experiment

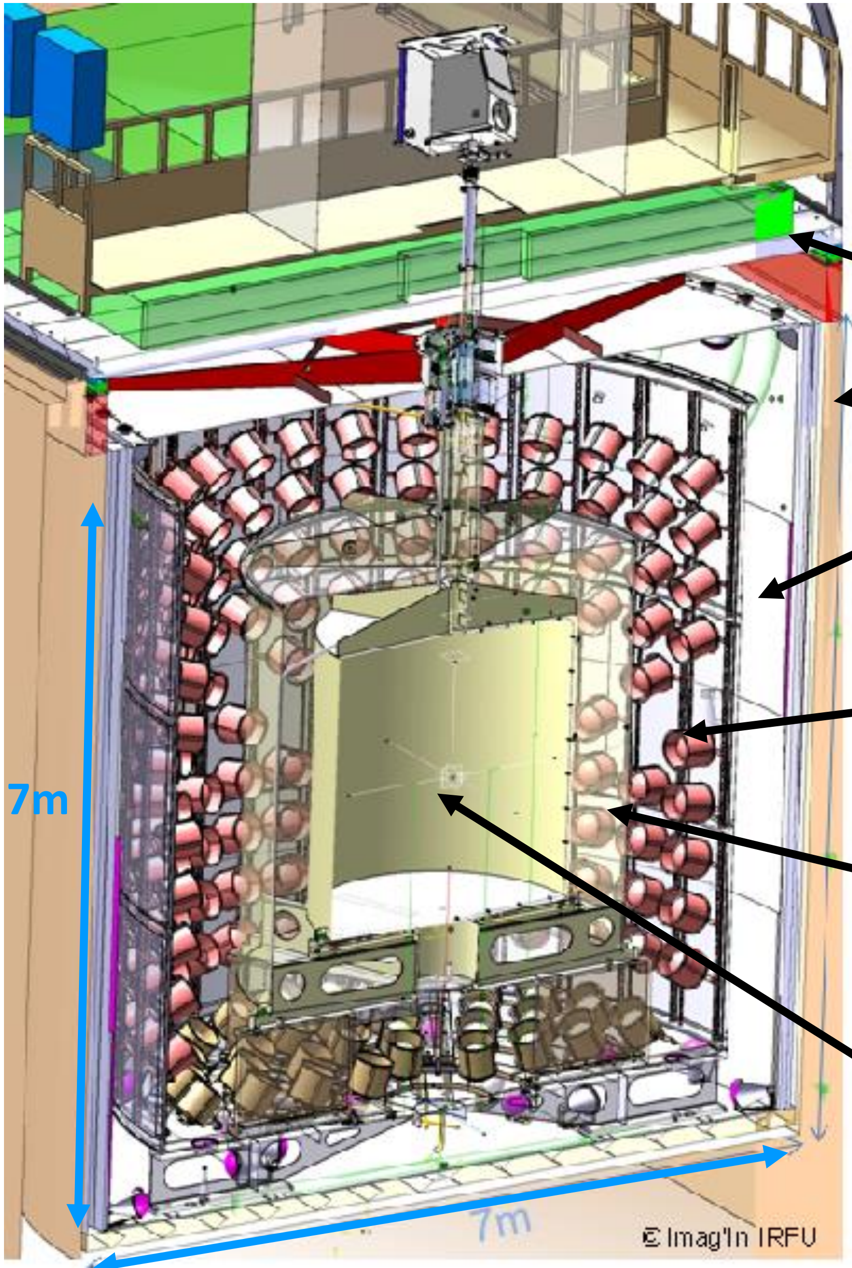


Chooz Reactors
$4.27\mathrm{GW}_{th}$ x 2 cores

Near Detector
<L> 400m
120m.w.e.
Early 2013

Far Detector
<L> 1050m
300m.w.e.
April 2011

Design of the DoubleChooz Detectors



Onion like structure
to shield against backgrounds

Outer Veto:
Plastic scintillator

Steel Shielding (17 cm)

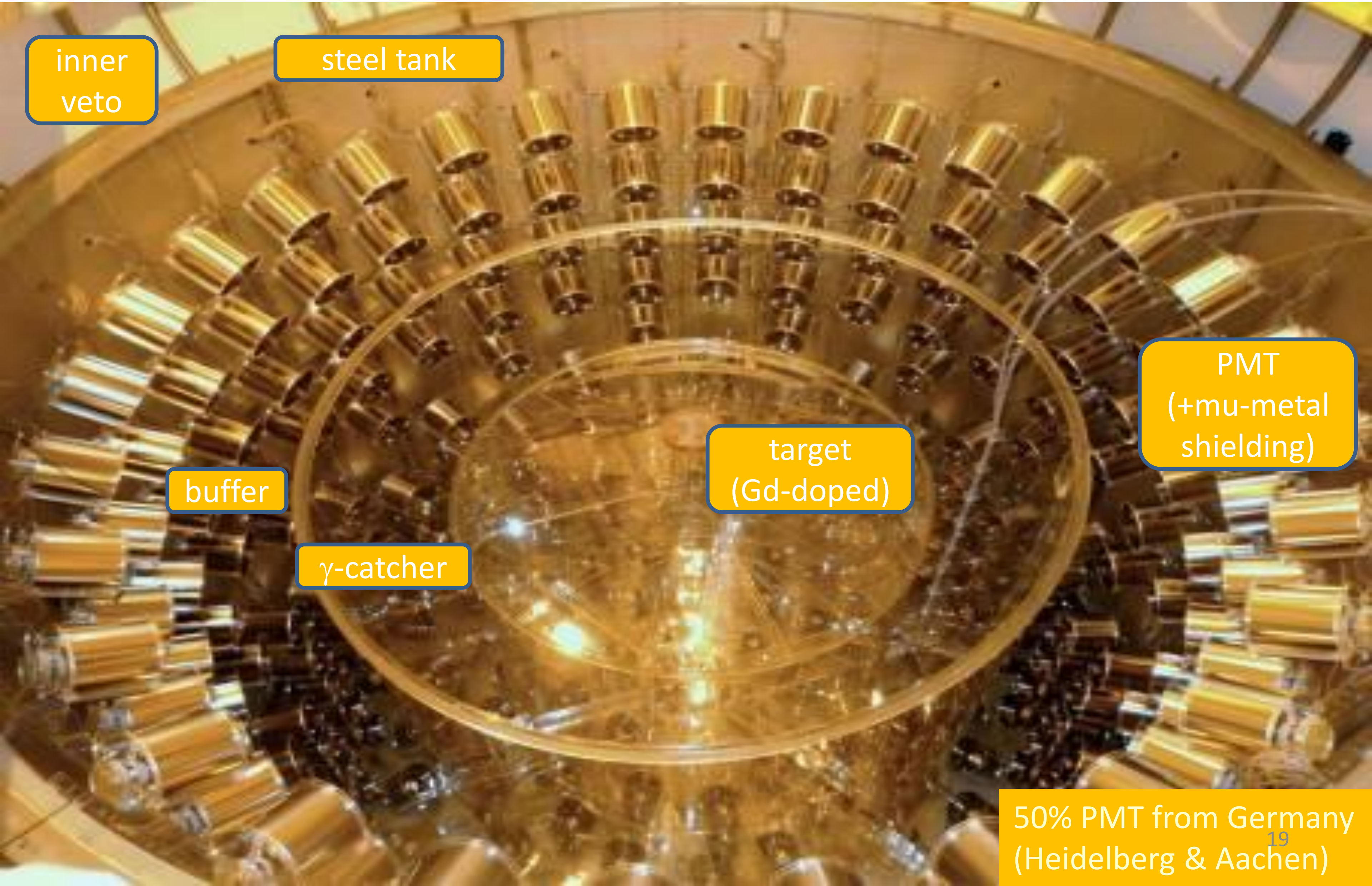
Inner Veto (steel vessel):
80 m^3 liquid scintillator, 80 PMT

Buffer (steel vessel): 100 m^3 oil
390 PMT (10 inch) observing the target

Gamma Catcher (acylic vessel):
22.6 m^3 liquid scintillator no Gd

Target (acrylic vessel) :
10.3 m^3 liquid scintillator + 0.1% Gd

Detector Vessels before Closing



inner veto

steel tank

PMT (+mu-metal shielding)

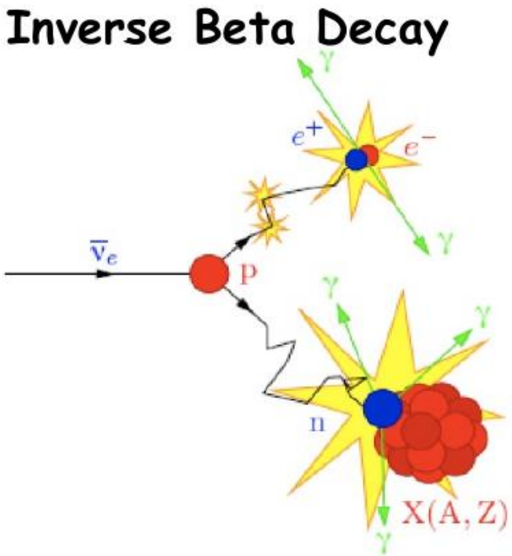
target (Gd-doped)

buffer

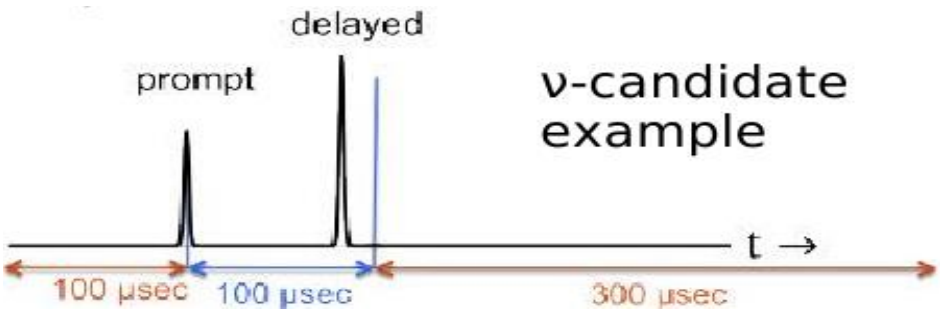
γ-catcher

50% PMT from Germany (Heidelberg & Aachen)

Selection of Neutrino Candidates



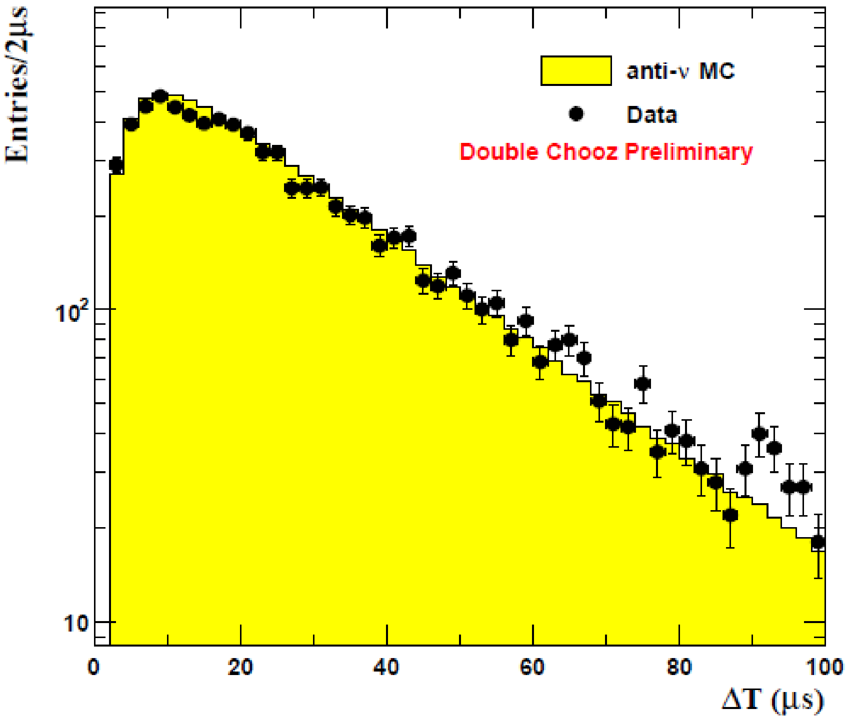
$\bar{\nu}_e + p \rightarrow e^+ + n$



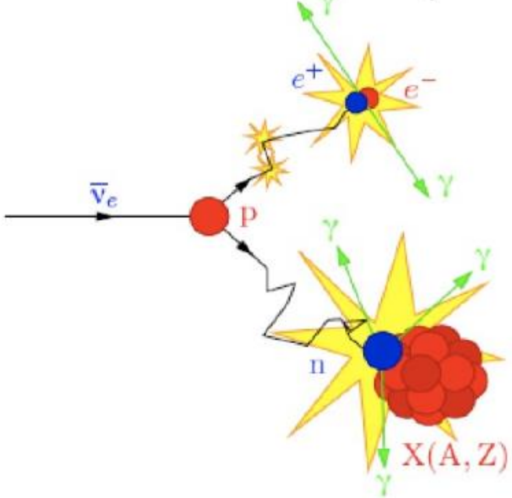
Coincidence Cut:

$2\ \mu s < \Delta T < 100\ \mu s$

Prompt-delay time difference

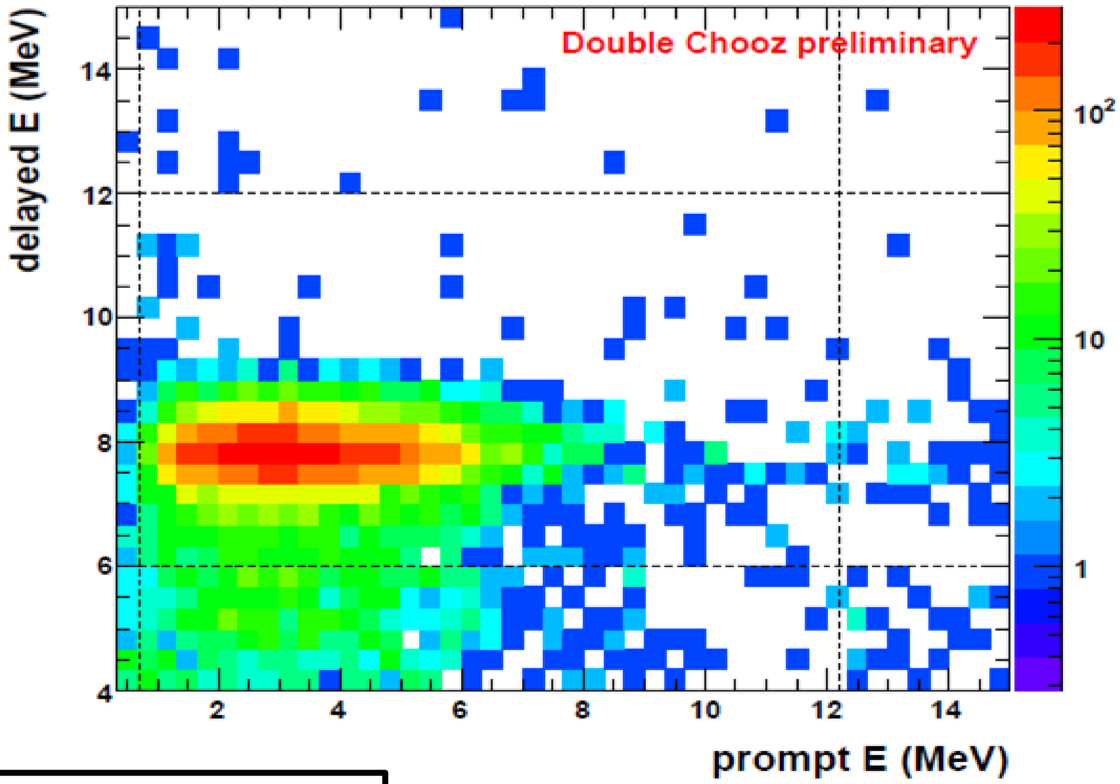


Selection of Neutrino Candidates



Inverse Beta Decay

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



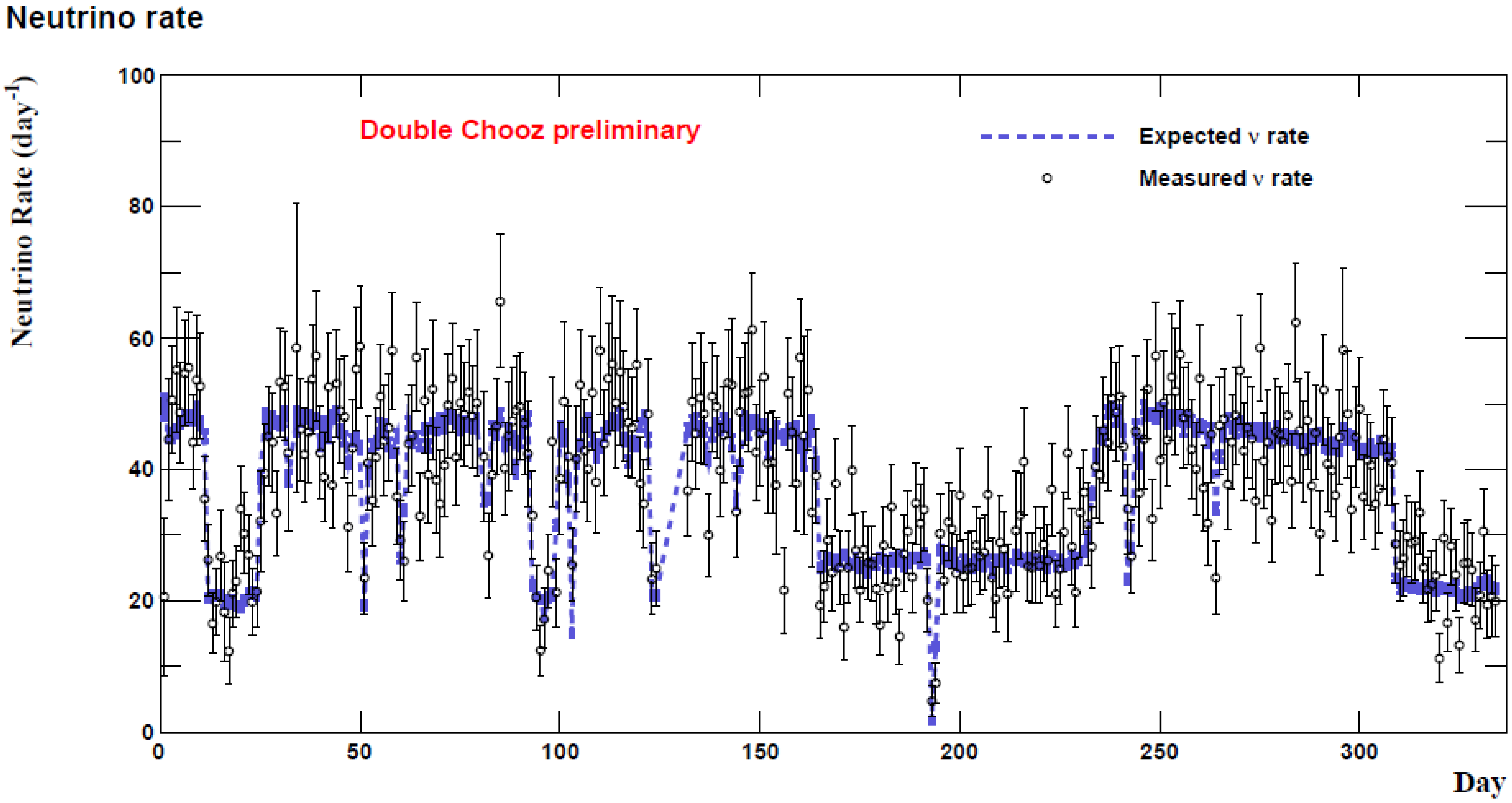
Energy Cut:

$0.7\ \text{MeV} < E_{\text{prompt}} < 12.2\ \text{MeV}$

$6.0\ \text{MeV} < E_{\text{delayed}} < 12.0\ \text{MeV}$

Rate of Neutrino Candidates

~36 neutrino candidates per day
~1 background event per day



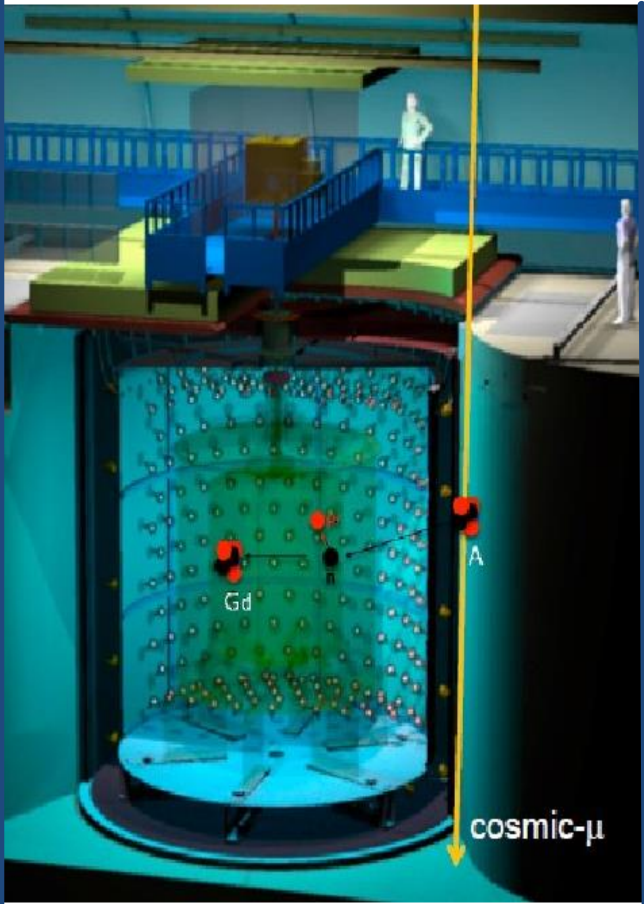
- In total 8249 candidates survive the cuts (no background subtraction)
- Good correspondence to reactor power history
- Indicates low background level in detector

Backgrounds

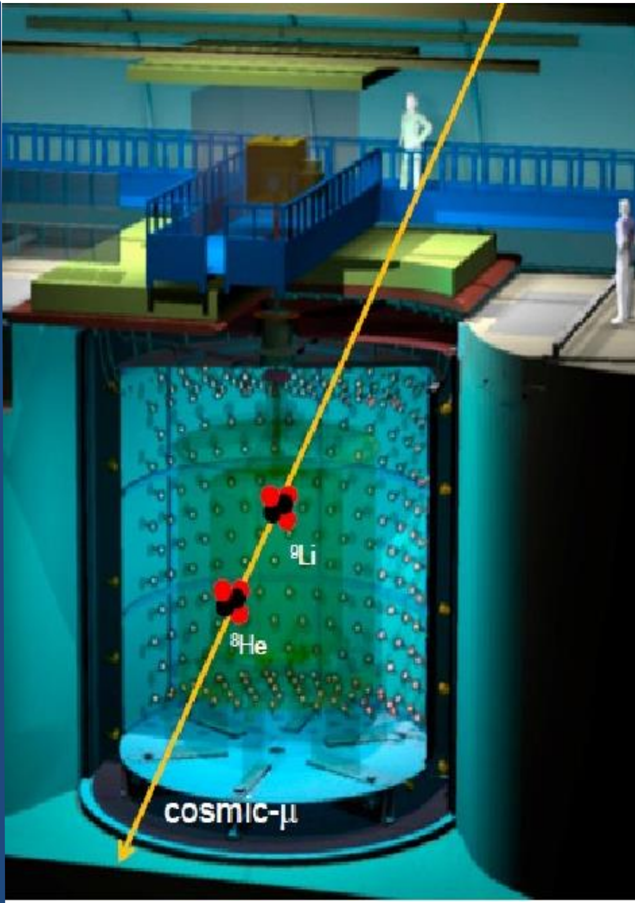
Accidental background

Prompt:
environmental gamma-ray
Delayed:
neutron induced by muon

Correlated background

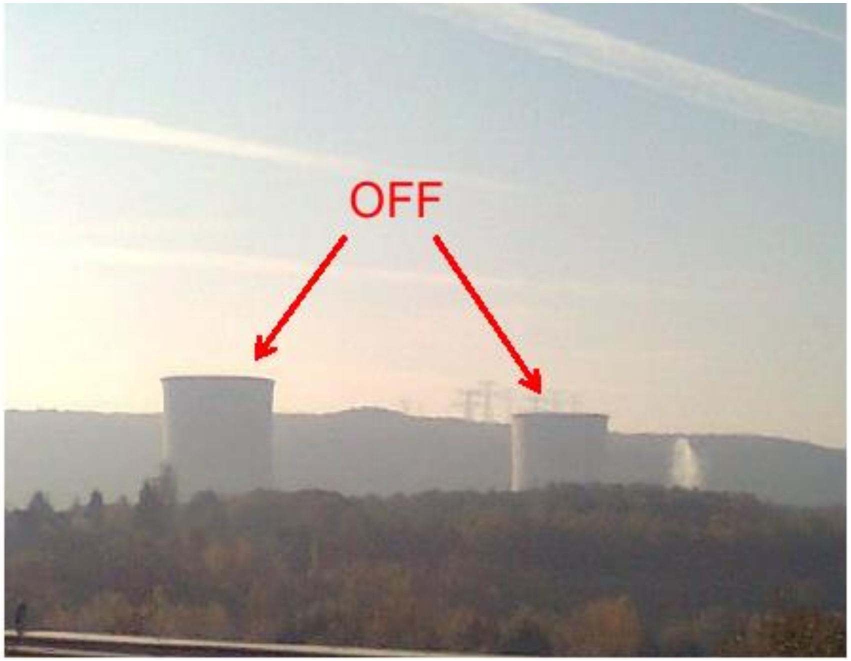


Prompt:
proton recoils from neutron
Delayed:
neutron capture on Gd



Cosmogenics: ^{9}Li/ ^{8}He
from μ-induced spallation
β – n emitters,
mimic the ν-signal

Background Estimation

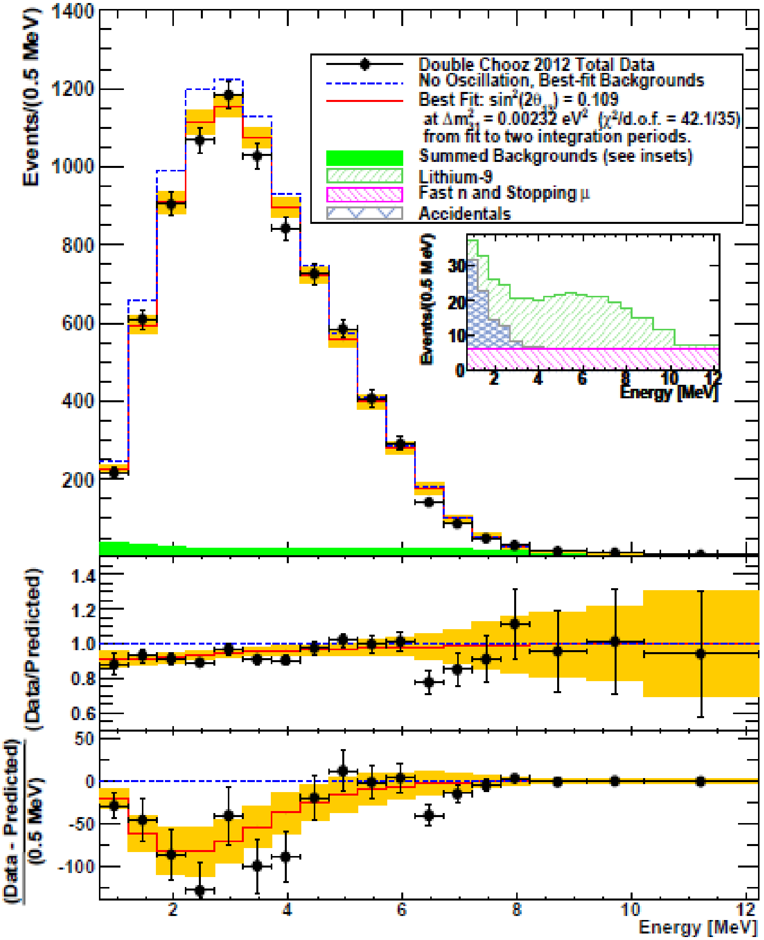


- Unique opportunity to measure backgrounds in-situ with both reactors off
  ~7,5 days of reactor OFF-OFF data

- background event rate are consistent with background calculation
  → waiting for more reactor OFF-OFF periods ...

Oscillation Analysis

Y. Abe et al. arXiv:1207.6632 (2012)



- Oscillation depends on neutrino energy:

$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{31} L}{4E}$$

- Rate & shape analysis yields

$$\sin^2 2\theta_{13} = 0.109 \pm 0.030\ (\mathrm{stat}) \pm 0.025\ (\mathrm{syst})$$

using $\Delta m^2_{31} \approx \Delta m^2_{32} = 2.32 \cdot 10^{-3} \mathrm{eV}^2$ (MINOS)

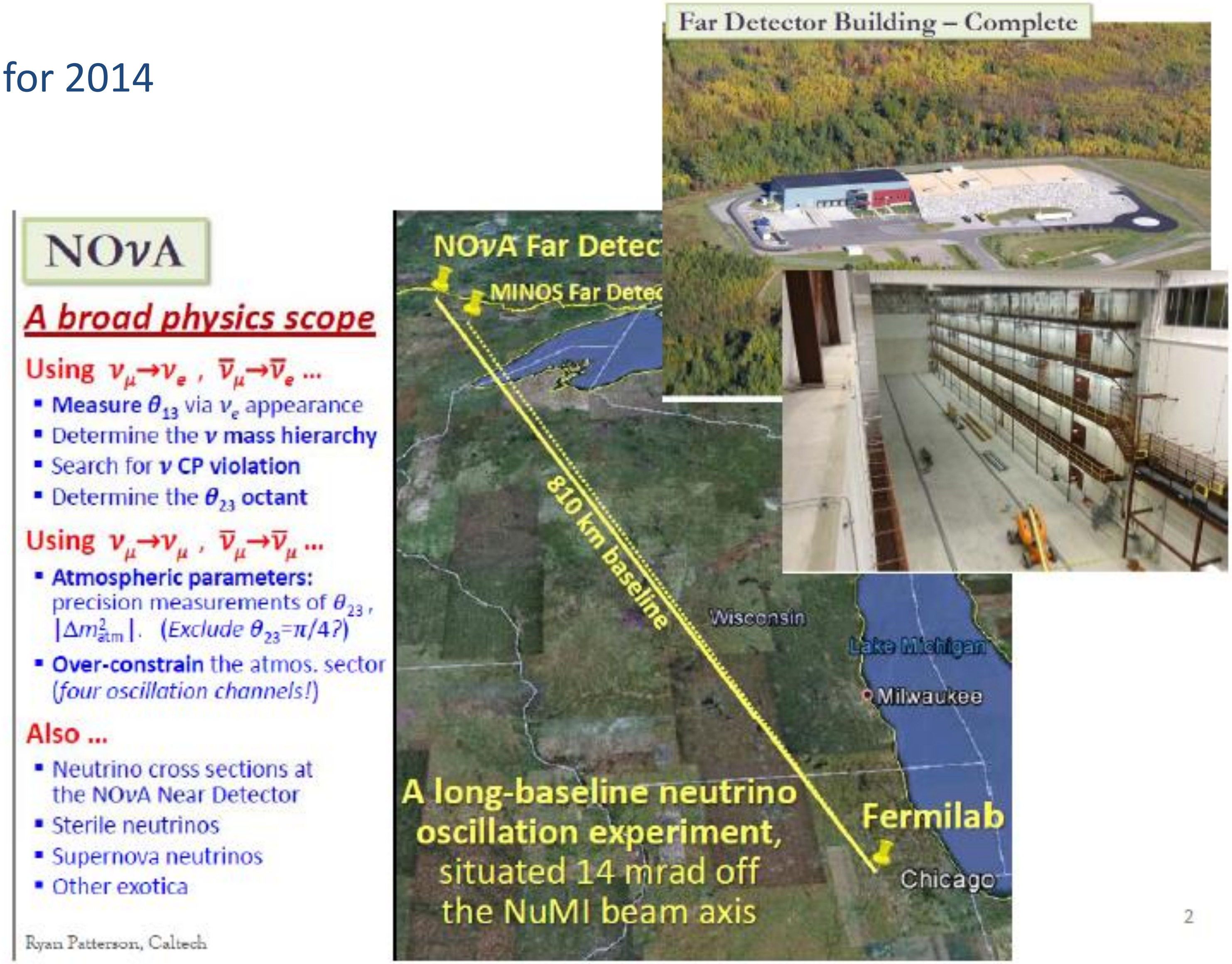
- Together with results from DayaBay and RENO:

$\boldsymbol{sin^2 2\theta_{13} = 0.095 \pm 0.010}$ (PDG 2014)

New Accelerator Neutrino Experiments

NOvA: Numi Off-Axis ν_e Appearance Experiment

Start planned for 2014



NOνA

A broad physics scope

Using $\nu_\mu \to \nu_e$, $\bar{\nu}_\mu \to \bar{\nu}_e$ ...

- **Measure θ_{13}** via ν_e appearance
- Determine the **ν mass hierarchy**
- Search for **ν CP violation**
- Determine the **θ_{23} octant**

Using $\nu_\mu \to \nu_\mu$, $\bar{\nu}_\mu \to \bar{\nu}_\mu$ ...

- **Atmospheric parameters:** precision measurements of θ_{23}, $|\Delta m^2_{\mathrm{atm}}|$. *(Exclude $\theta_{23}=\pi/4$?)*
- **Over-constrain** the atmos. sector *(four oscillation channels!)*

Also ...

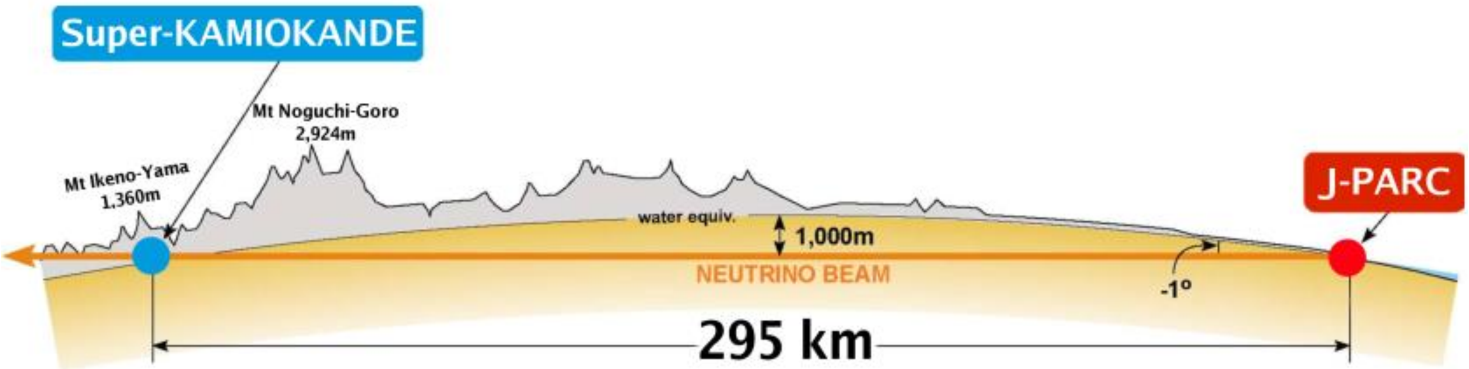
- Neutrino cross sections at the NOνA Near Detector
- Sterile neutrinos
- Supernova neutrinos
- Other exotica

Ryan Patterson, Caltech

A long-baseline neutrino oscillation experiment, situated 14 mrad off the NuMI beam axis

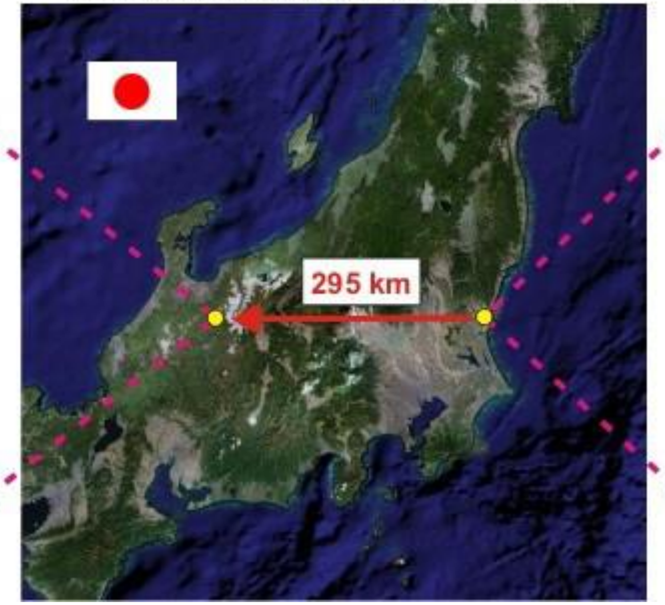
The T2K Experiment (Tokai To Kamioka)

Data taking since 2010



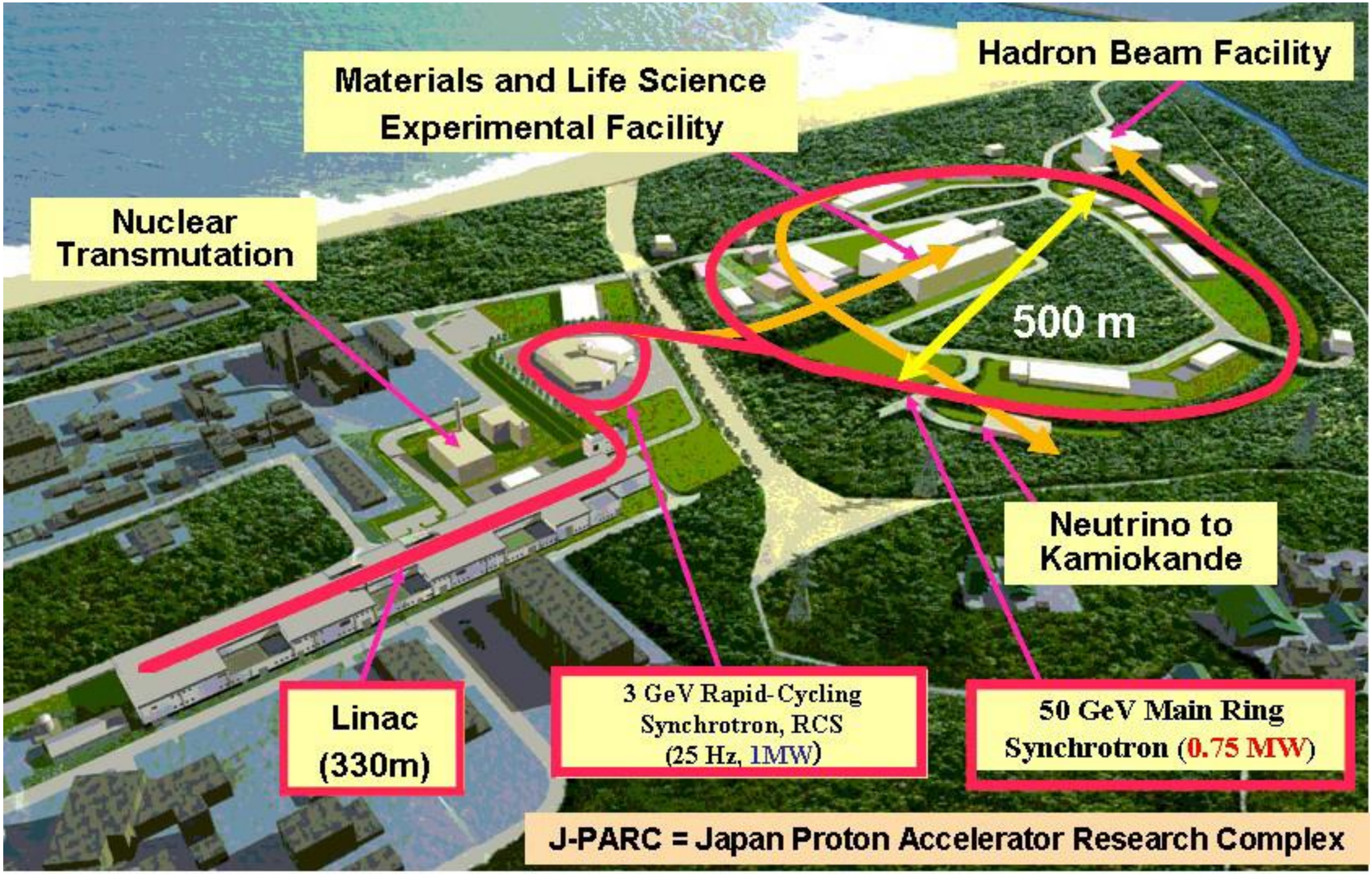
Super Kamiokande
50,000 tons of water
10,000 phototubes

Neutrino beam directed across Japan



Tokai accelerator complex and
location of near detector (ND280)

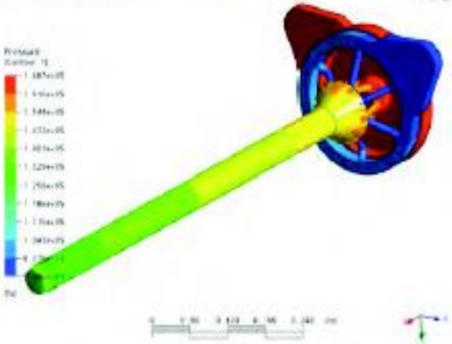
Japan Proton Accelerator Research Center J-PARC

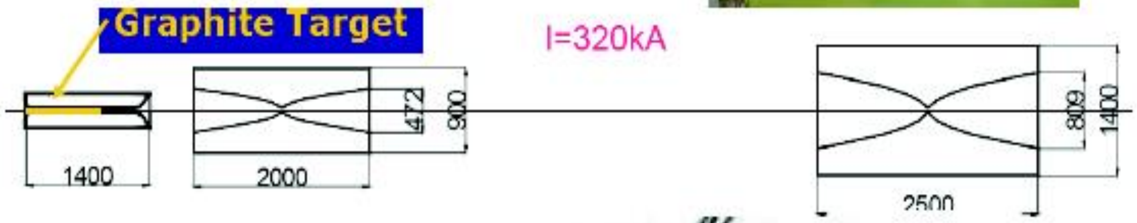


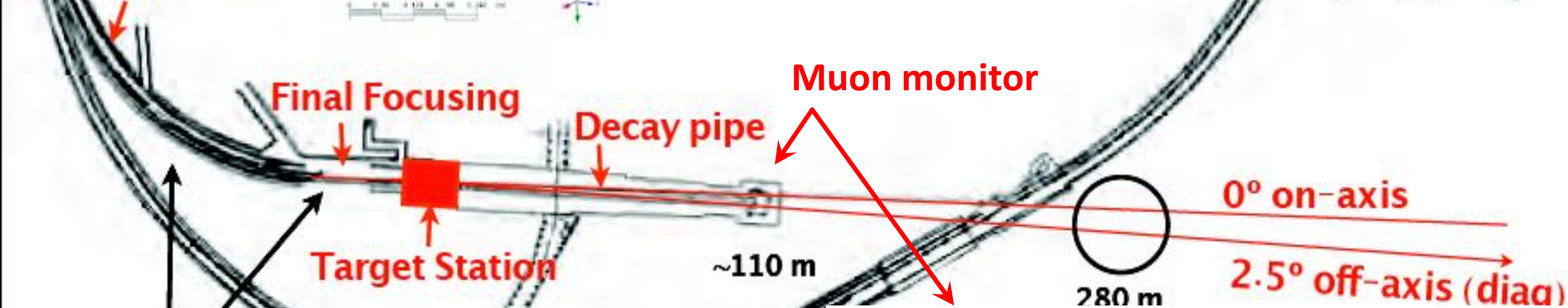
J-PARC: Joint project between KEK and JAEA

The Neutrino Beam

- 30 GeV proton beam on carbon target
- Beam intensity currently 220 kW, design value 700 kW
- Final goal is $8 \cdot 10^{21}$ protons on target (POT)
- Muon beam direction stable within 1 mrad





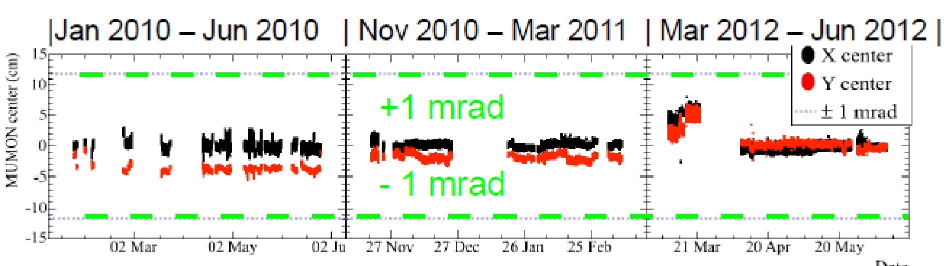


Beam diagnostics :

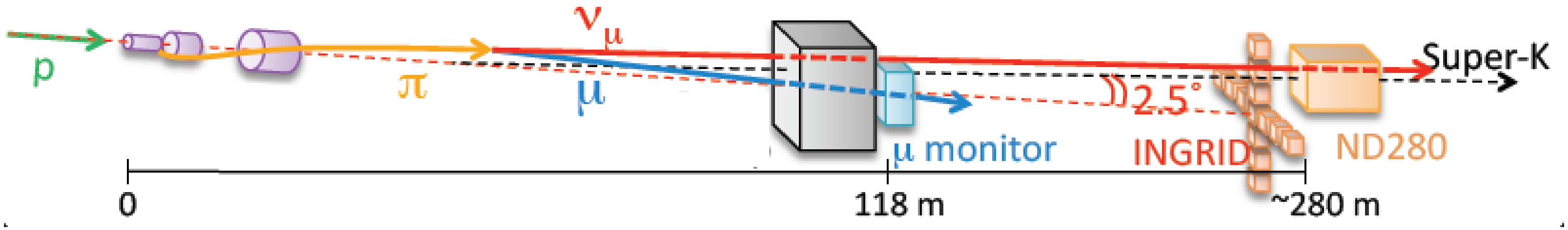
Position 20

Profile 19

Intensity 4

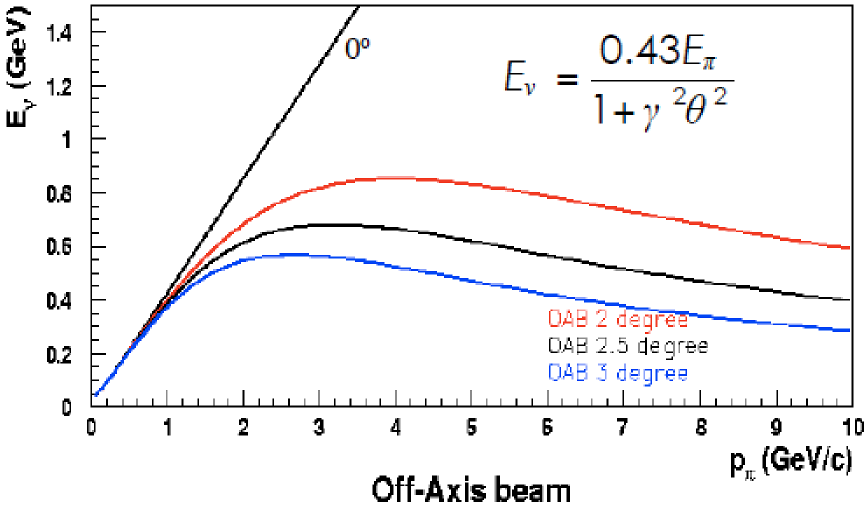


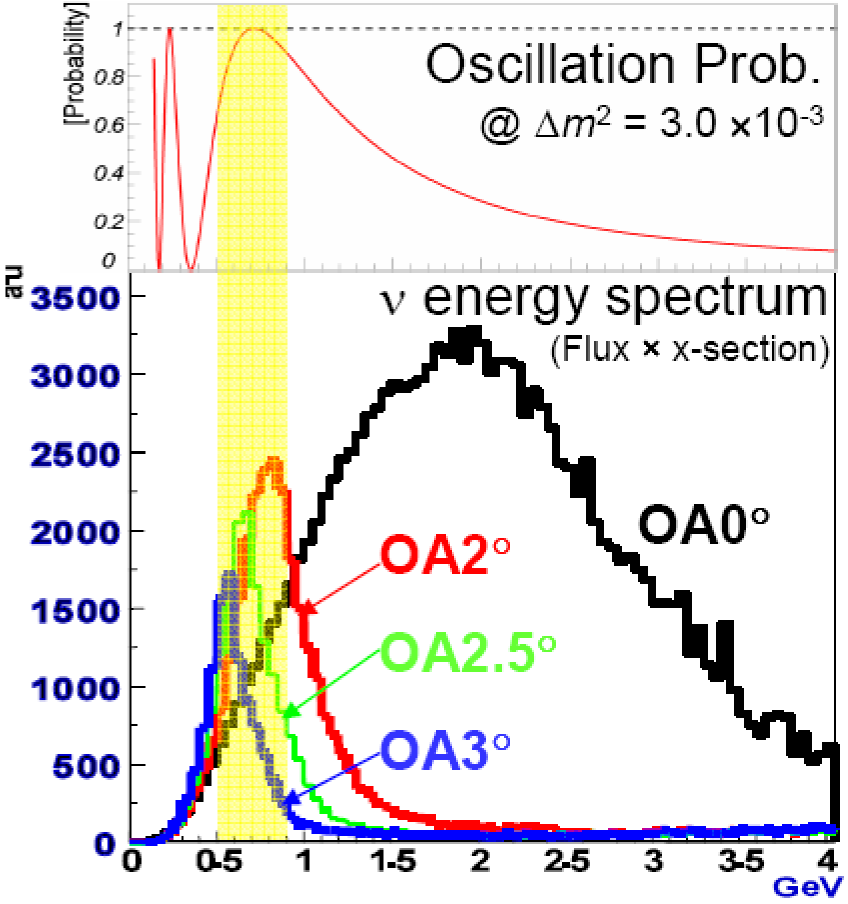
Off Axis Neutrino Beam



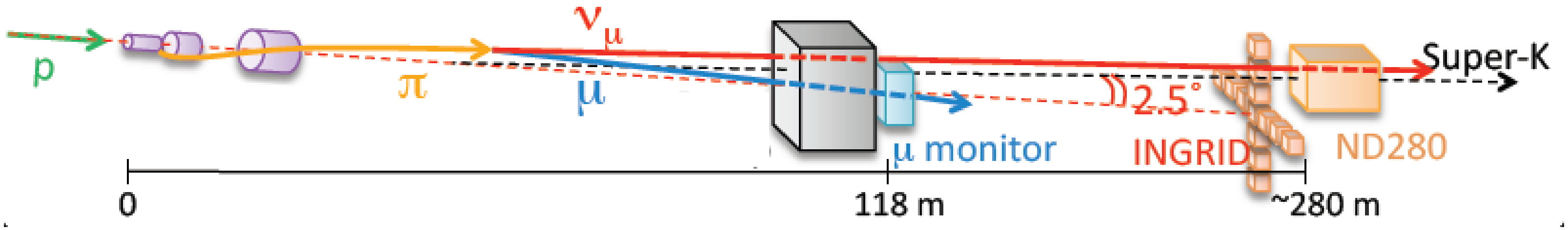
Neutrinos at 2.5° off-axis:

- Intense narrow energy band
- Energy maximum tuned to oscillation maximum at ~0.6 GeV





Off Axis Neutrino Beam

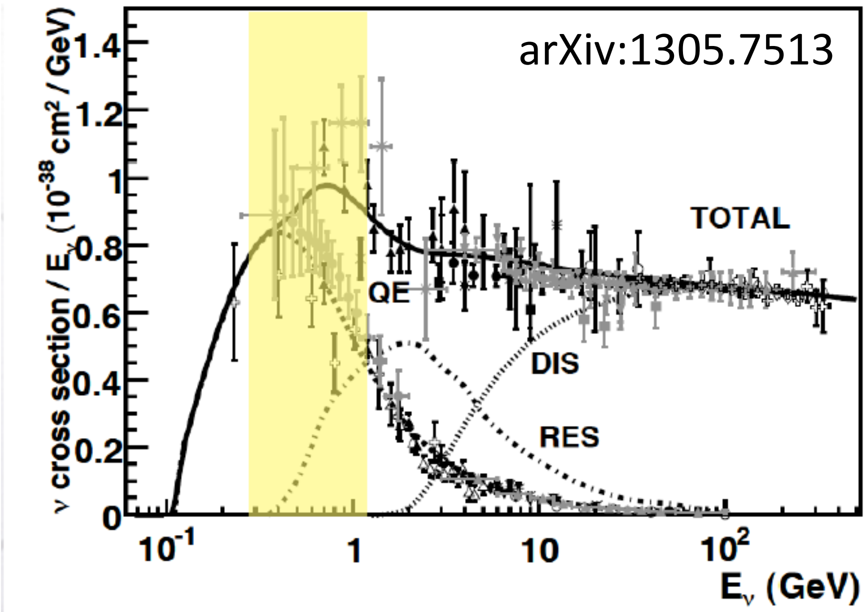


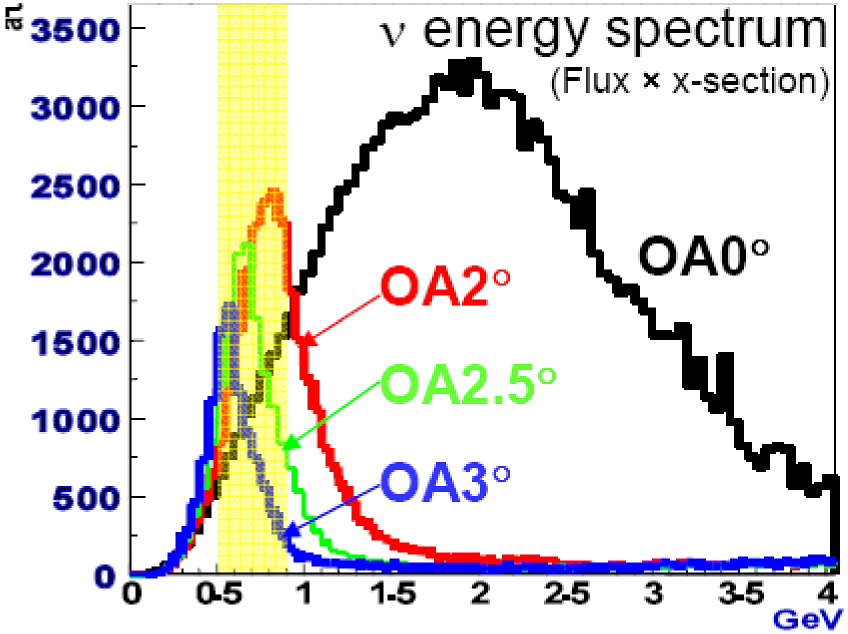
Charge Current (CC) processes:

- Quasi Elastic (QE): $\nu_\mu n \rightarrow \mu^- p$
- Resonant (RES): $\nu_\mu n \rightarrow \mu^- \pi^{+,0} N$
- Deep Inelastic (DIS): $\nu_\mu N \rightarrow \mu^- X$

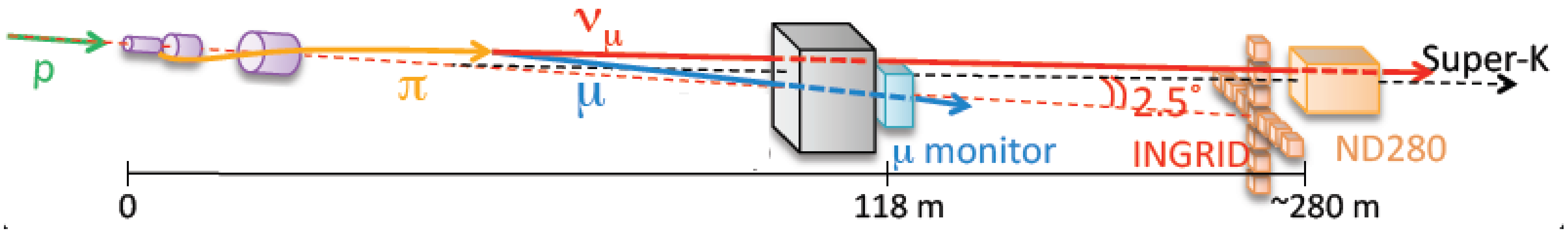
Neutrinos at 2.5° off-axis:

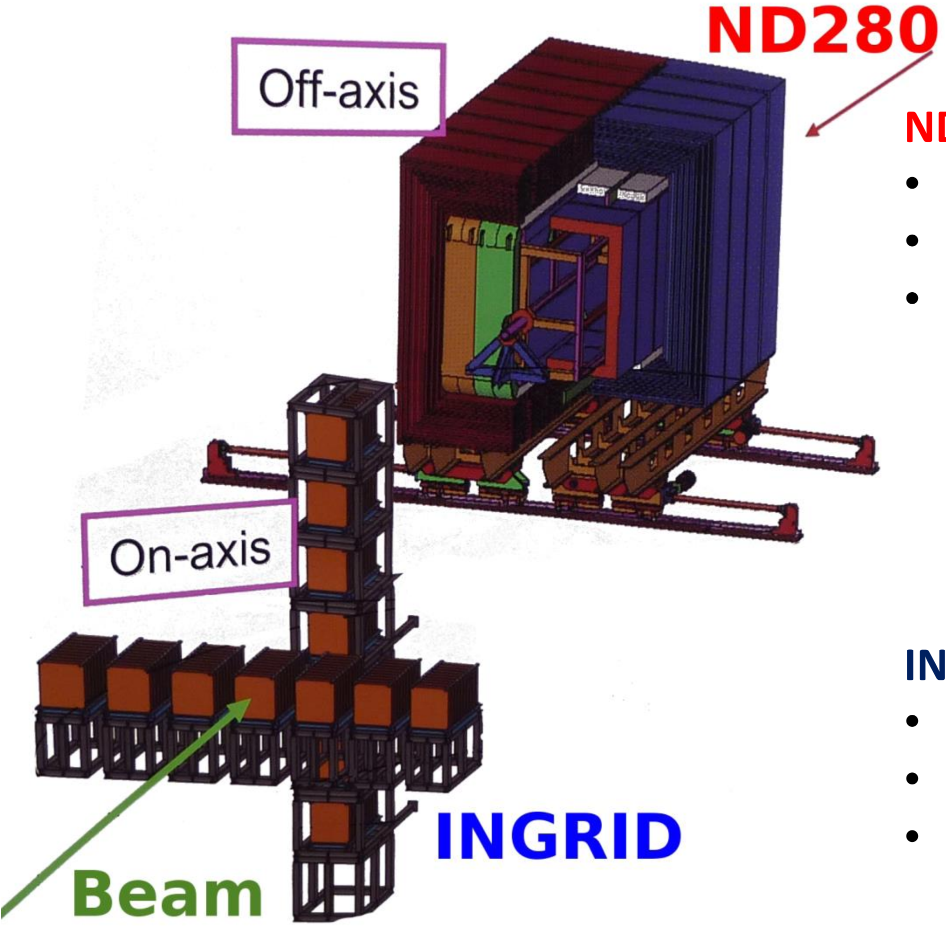
- Enhances CCQE fraction
- Reduces associated pion production





Neutrino Monitor





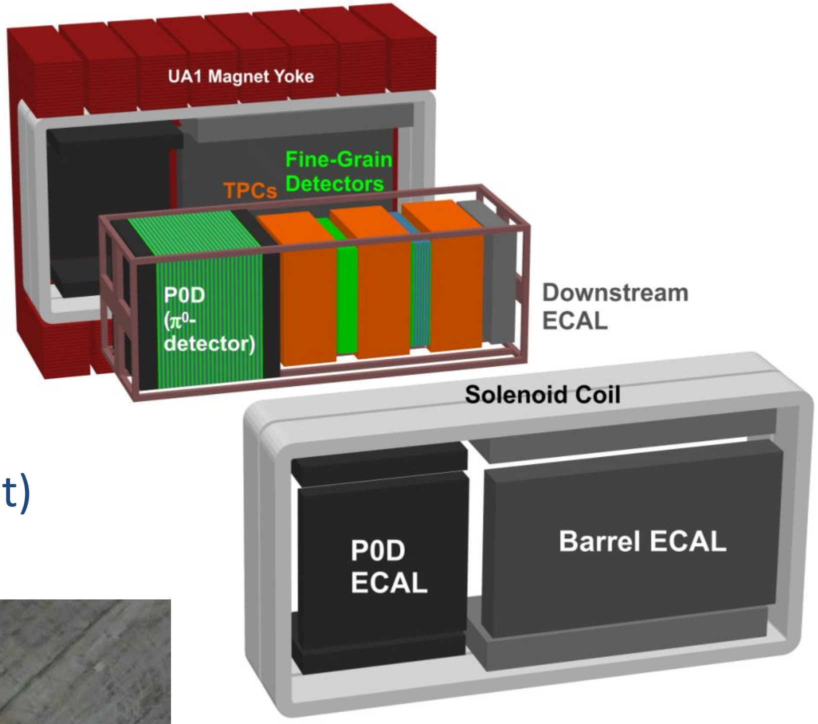
ND280:

- Tracker/Calorimeter in 0.2 T field
- Beam composition (ν_e background)
- neutrino flux and cross sections

INGRID:

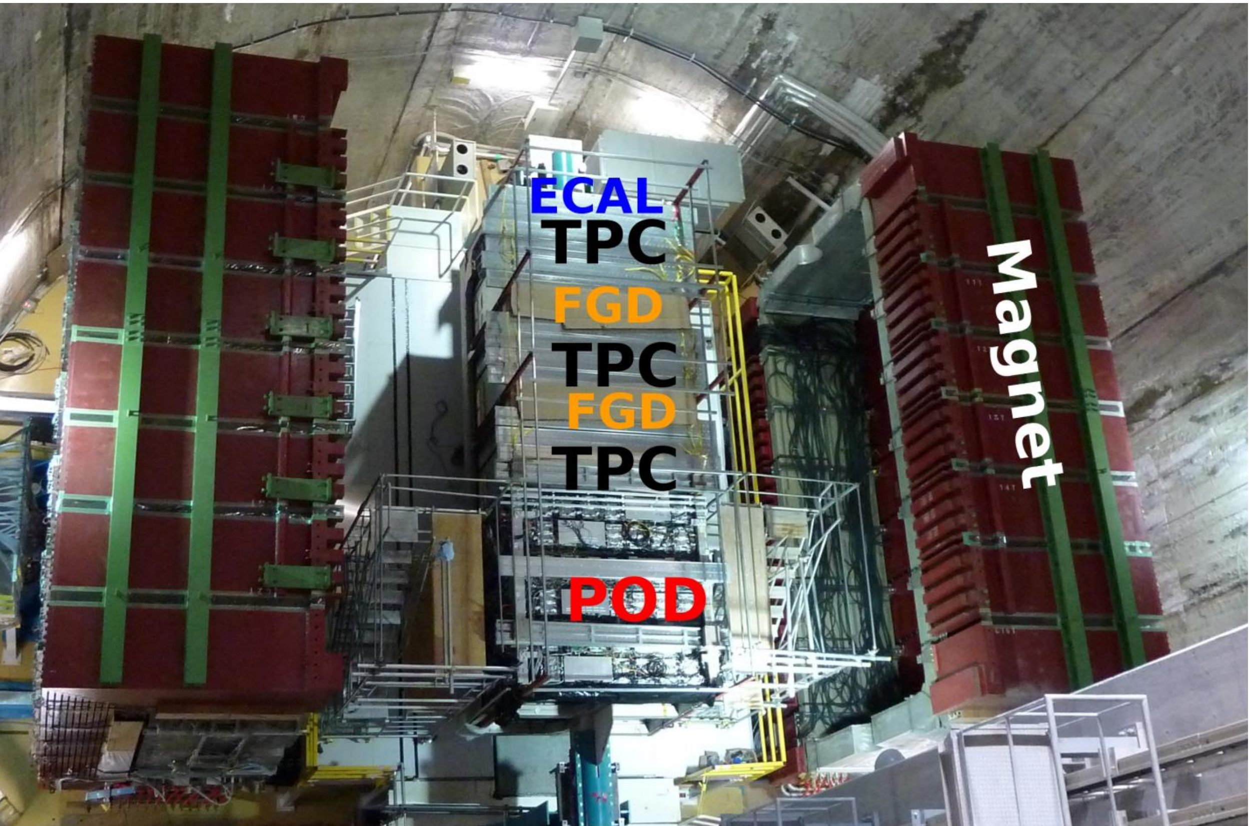
- Iron/Scintillator detector
- Beam profile
- Bunch timing

Near Detector 280m (ND280)



Inside 0.2 T UA1/NOMAD magnet:

- The π^0 detector P0D (lead/water/scintillators)
- Barrel and downstream ECAL
- Fine Grain Detectors FGD (water/scintillators)
- Time Projection Chambers TPC
  (large gas volume with micromegas readout)

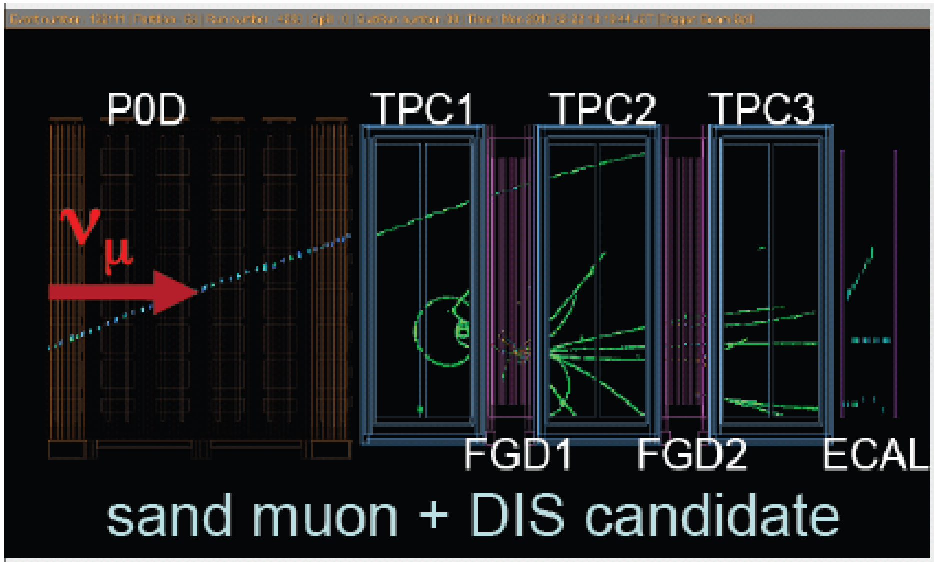


Magnet Moving System

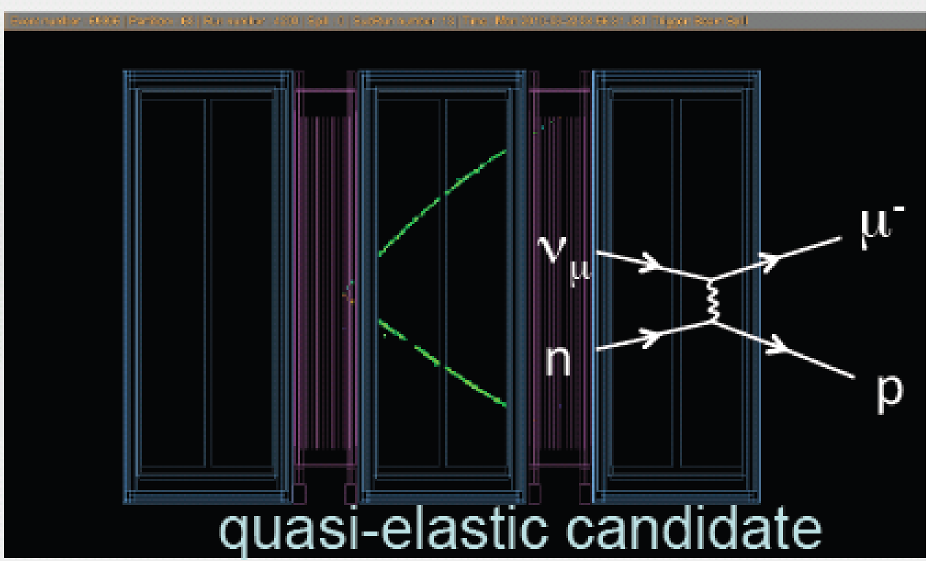
Opening and closing of 900 t UA1 magnet yokes
Adaption of HERA-B guide rollers to the UA1 magnet carriage
Re-use of ZEUS hydraulic movers

Many thanks to DESY!

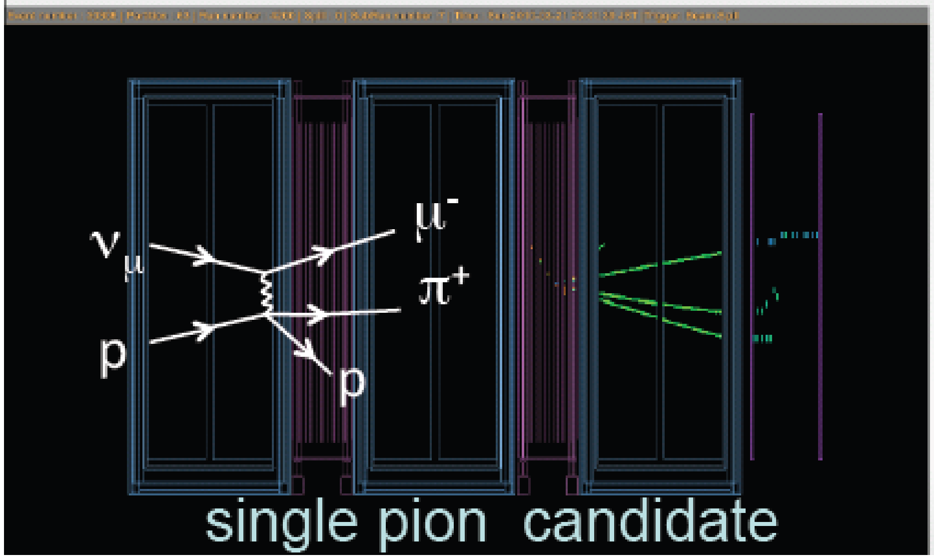
ND280 Event Gallery



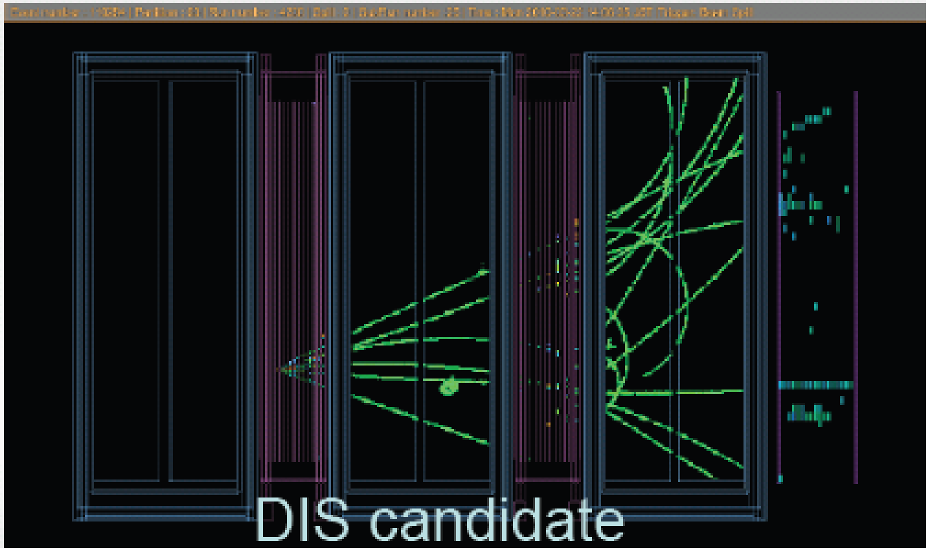
sand muon + DIS candidate



quasi-elastic candidate

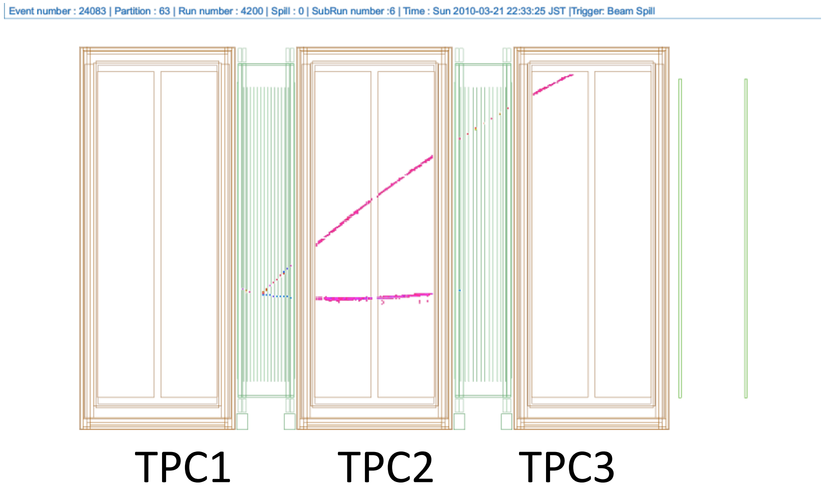


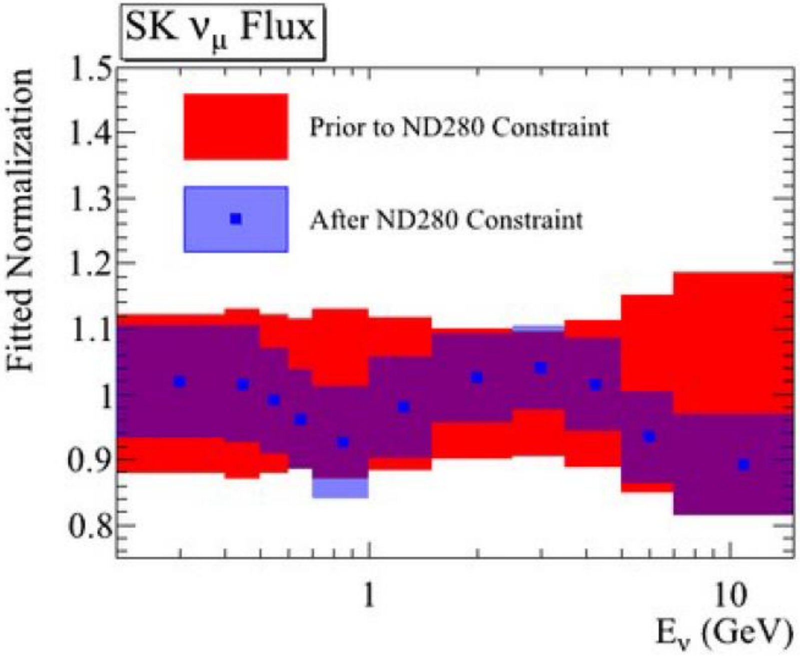
single pion candidate



DIS candidate

Measurement of ν_μ flux at ND280





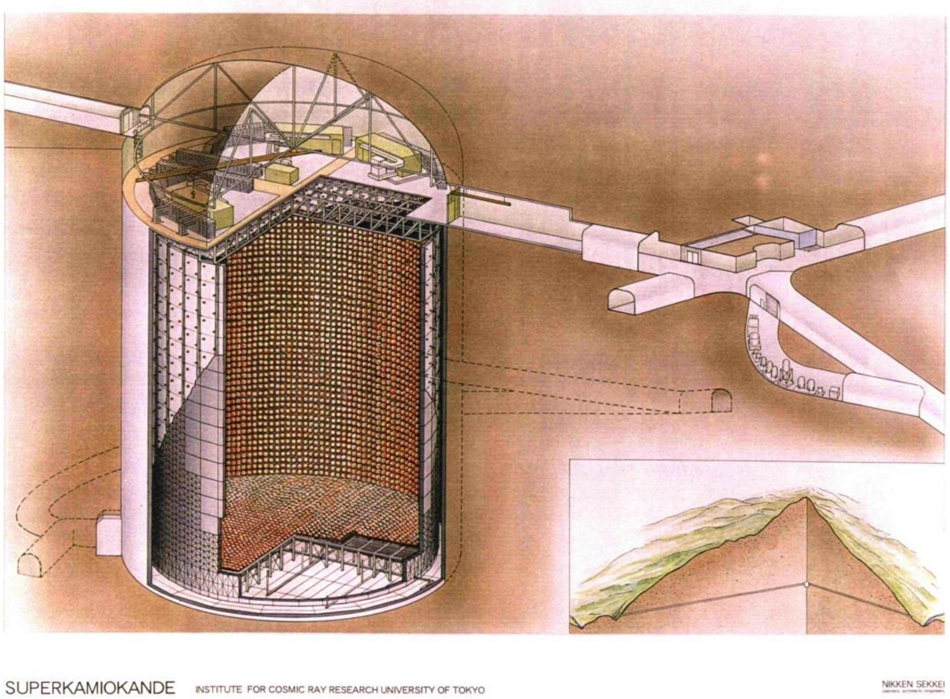
Basic CC event selection at ND280 for ν_μ:

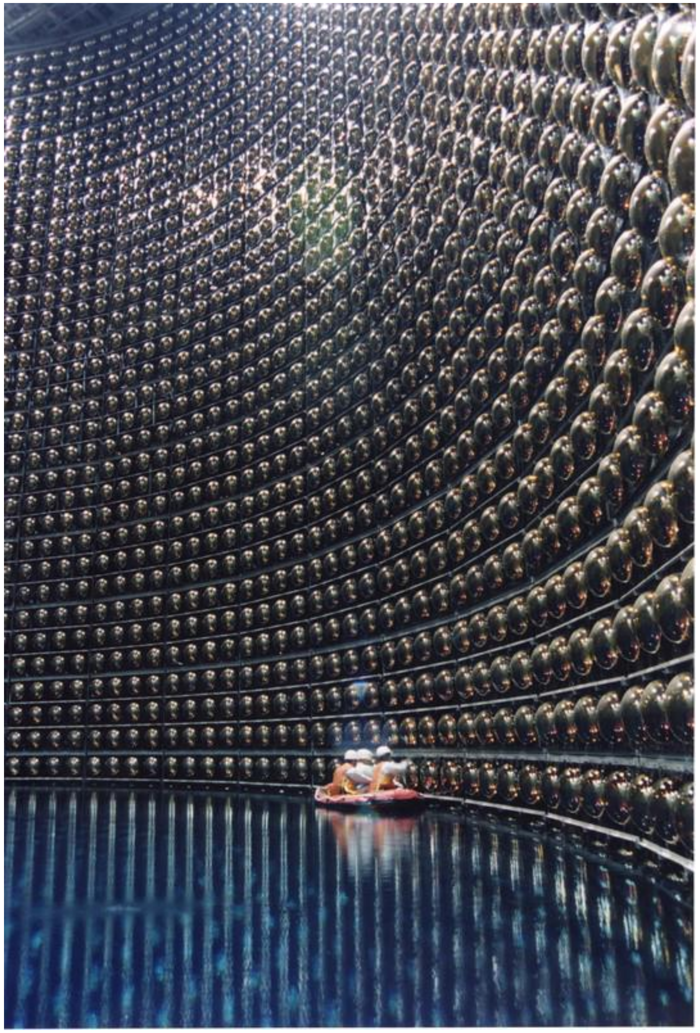
- Use the highest momentum, negative charged TPC track
- Select muon from TPC particle ID

Measurement of spectrum and flux of ν_μ neutrinos at ND280 yields prediction for ν_μ flux at SK

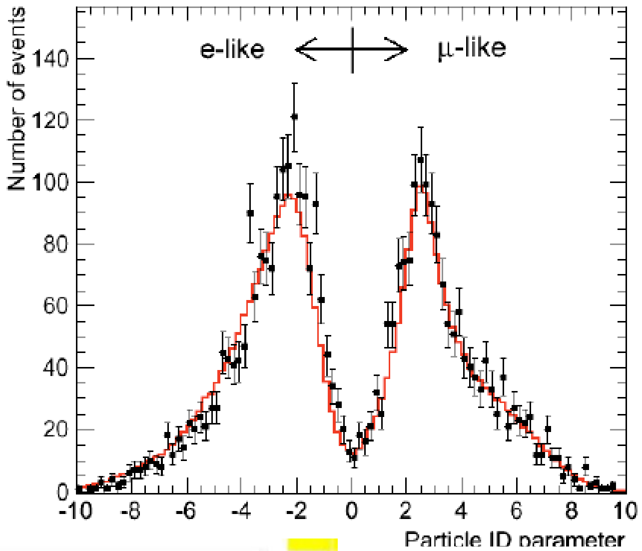
Super Kamiokande

Super-Kamiokande is a 50,000 ton water Cherenkov detector, with 11,000 photomultiplier tubes, which started observation in 1996 after 5 years of construction

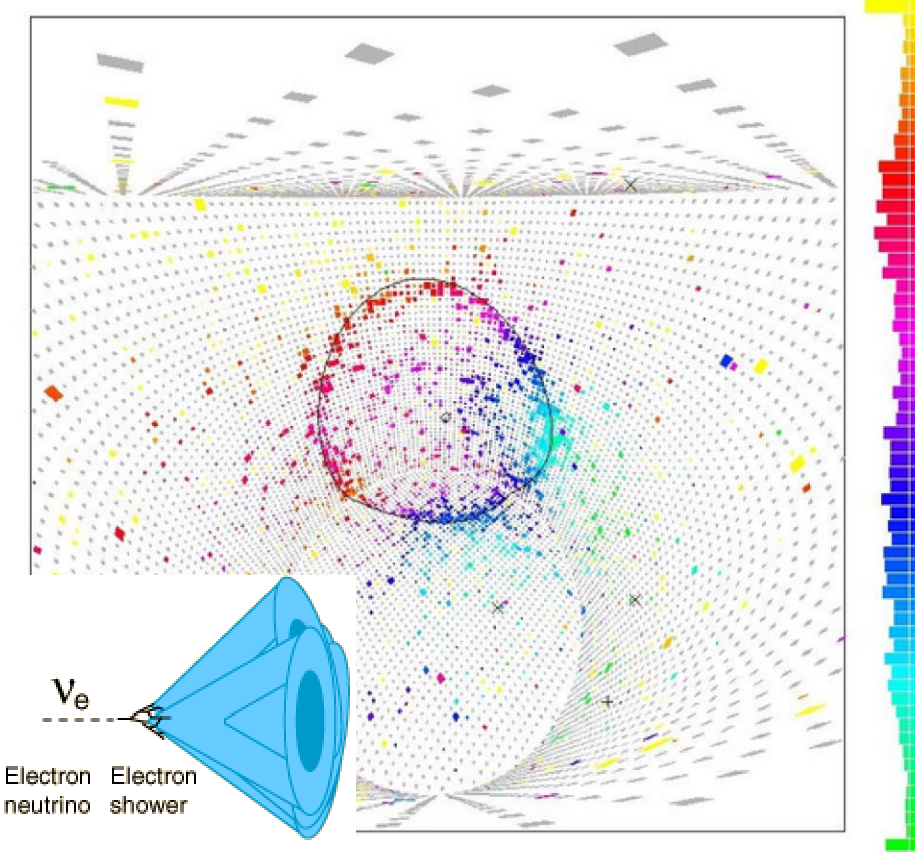




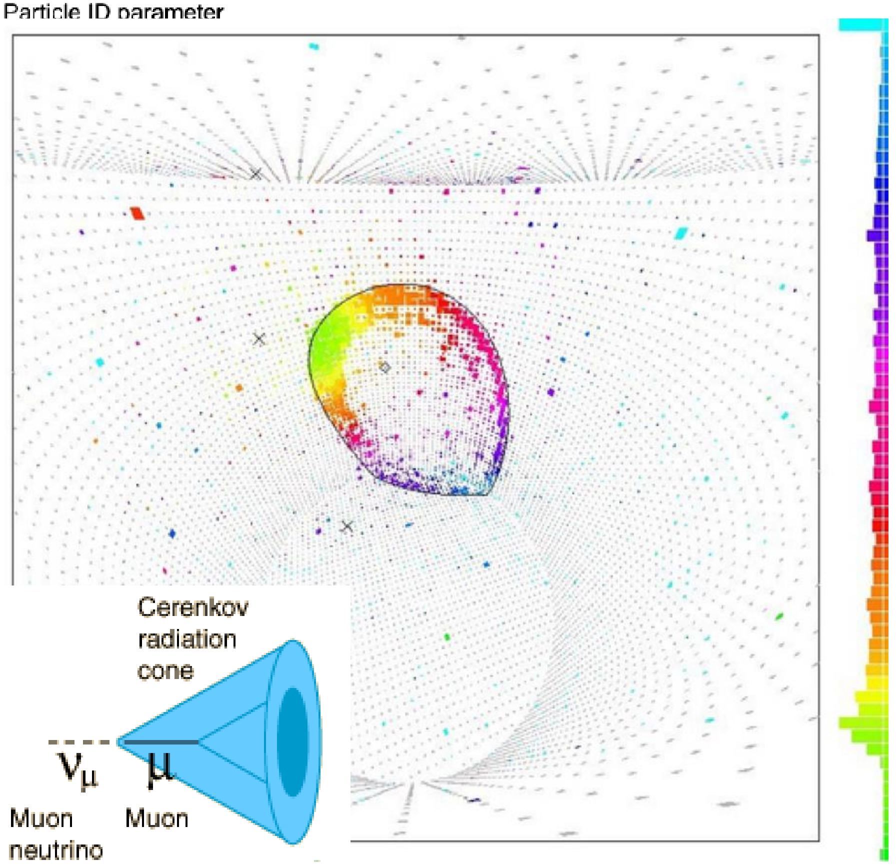
Events at Super K



Electron-like event



Muon-like event

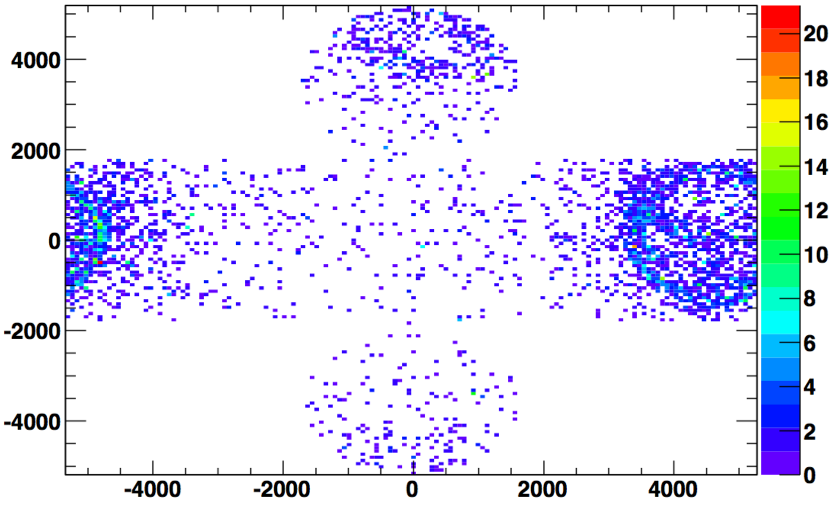


π^0 Background at Super-K

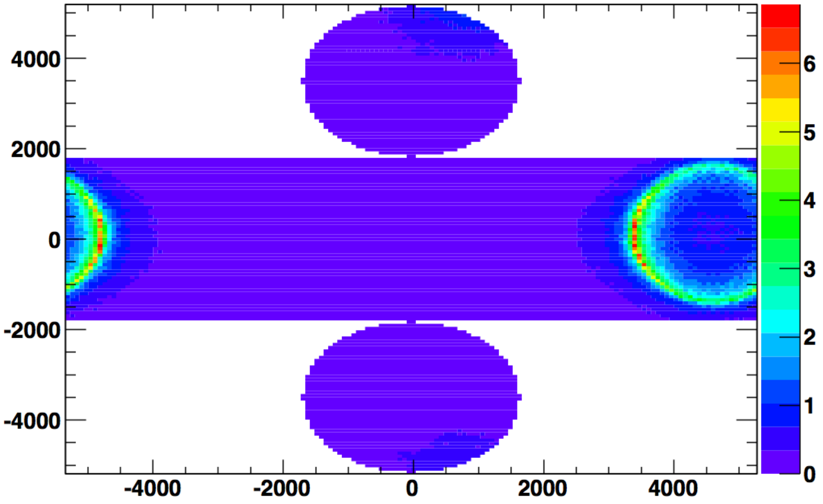
Important Background:

- Neutral Current process $\nu_\mu\, p \rightarrow \nu_\mu\, p\, \pi^0$
- Pion decay $\pi^0 \rightarrow \gamma\gamma$
- Photon conversion $\gamma \rightarrow e^+e^-$ with two overlapping electron-like rings
- Build likelihood ratio from two fits

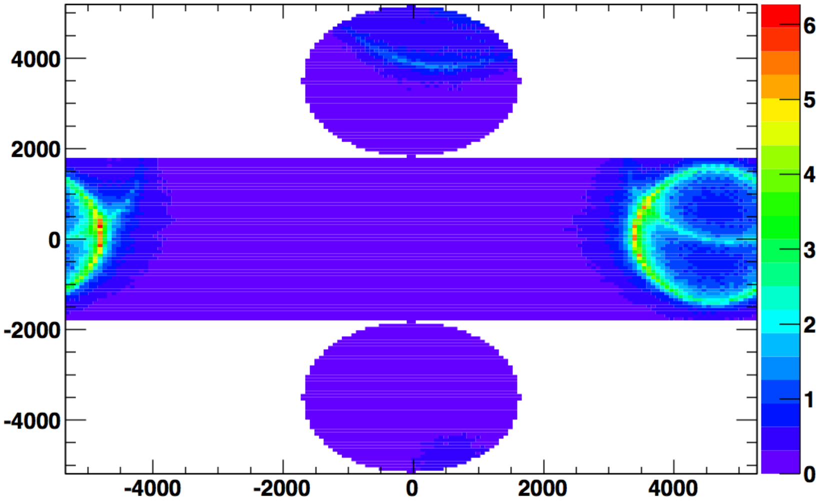
Measured charge



1-ring electron-like fit

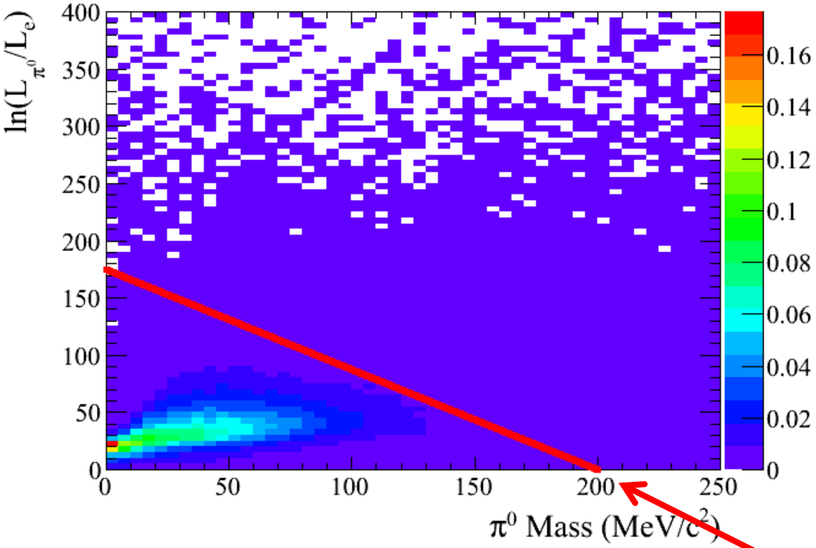


2-ring π^0-like fit

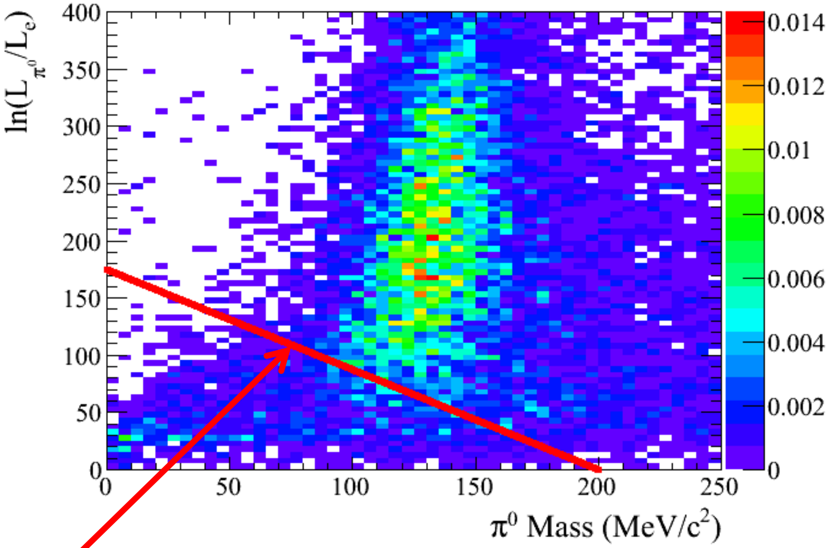


Likelihood ratio vs. π^0 mass

Signal: ν_e CCQE



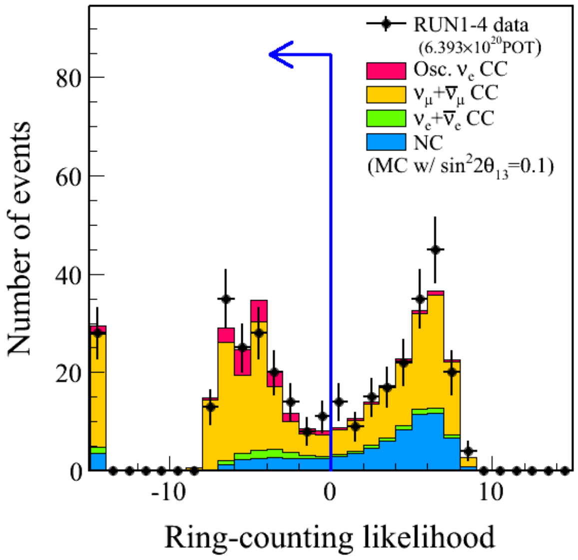
Background: $\nu_\mu\ (\pi^0 X)$



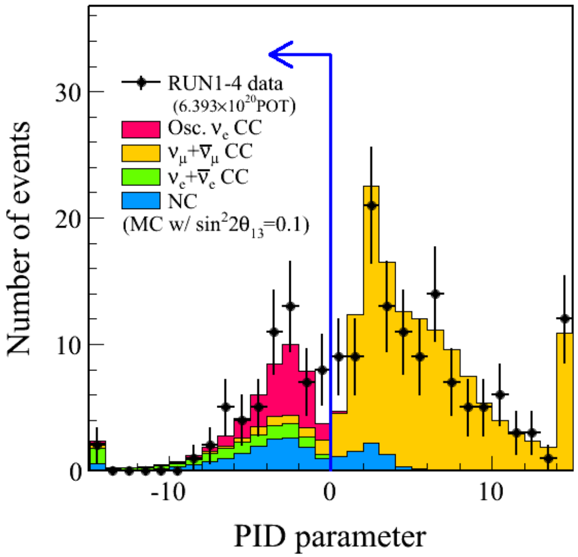
Cut line to seperate π^0 background

Selection of ν_e Appearance Candidates

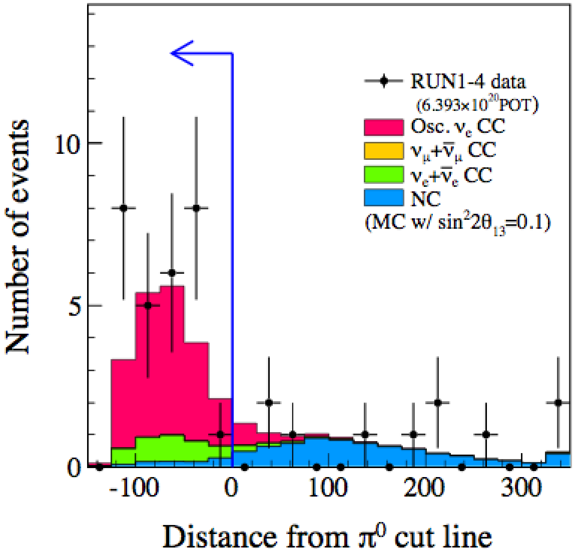
single ring multi-ring



e-like μ-like



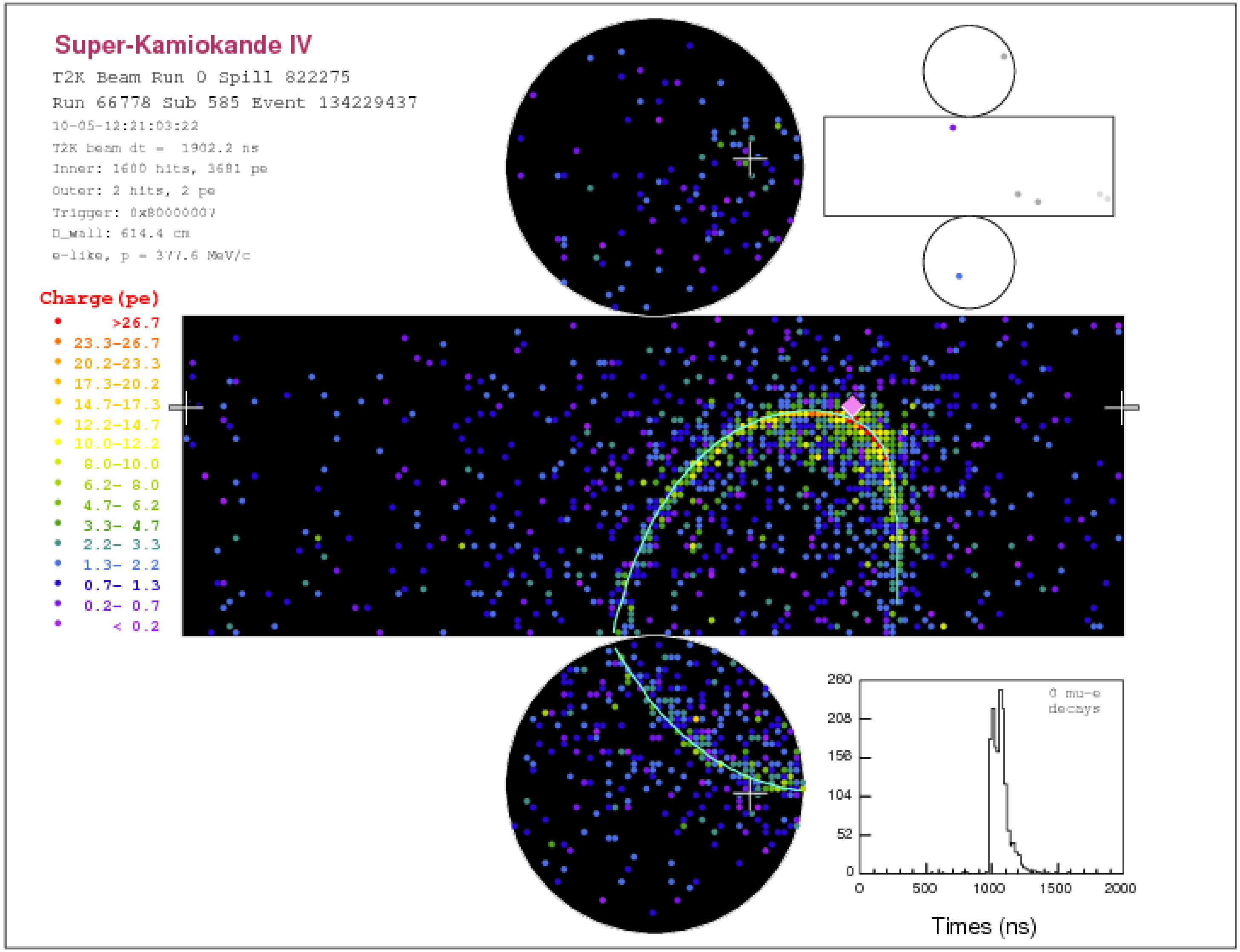
π^0-background



→ Observation of 28 ν_e candidates in $6.4\cdot10^{20}$ pot

Appearance of ν_e

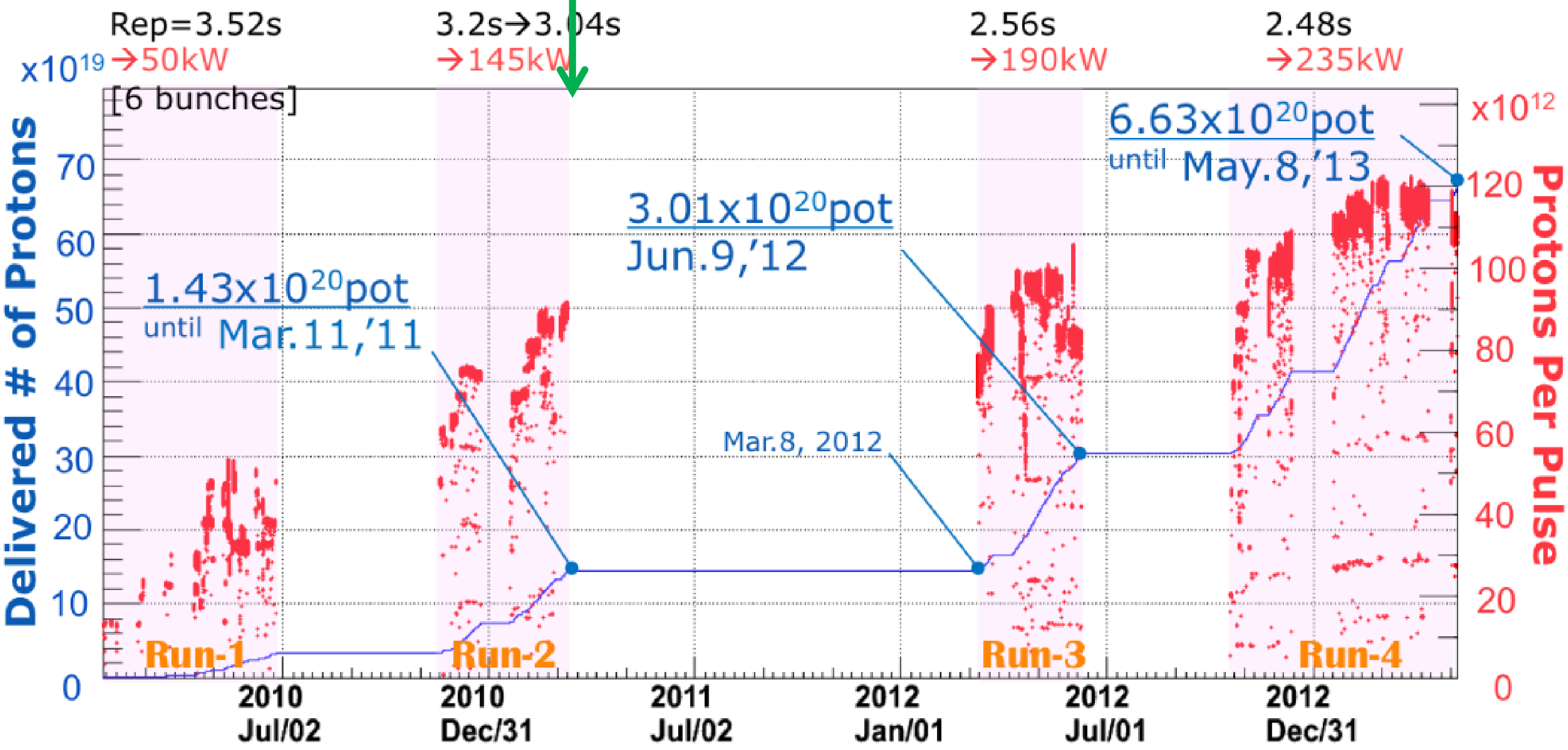
First ν_e candidate observed (May 2010)



```
Super-Kamiokande IV
T2K Beam Run 0 Spill 822275
Run 66778 Sub 585 Event 134229437
10-05-12:21:03:22
T2K beam dt =  1902.2 ns
Inner: 1600 hits, 3681 pe
Outer: 2 hits, 2 pe
Trigger: 0x80000007
D_wall: 614.4 cm
e-like, p = 377.6 MeV/c
```

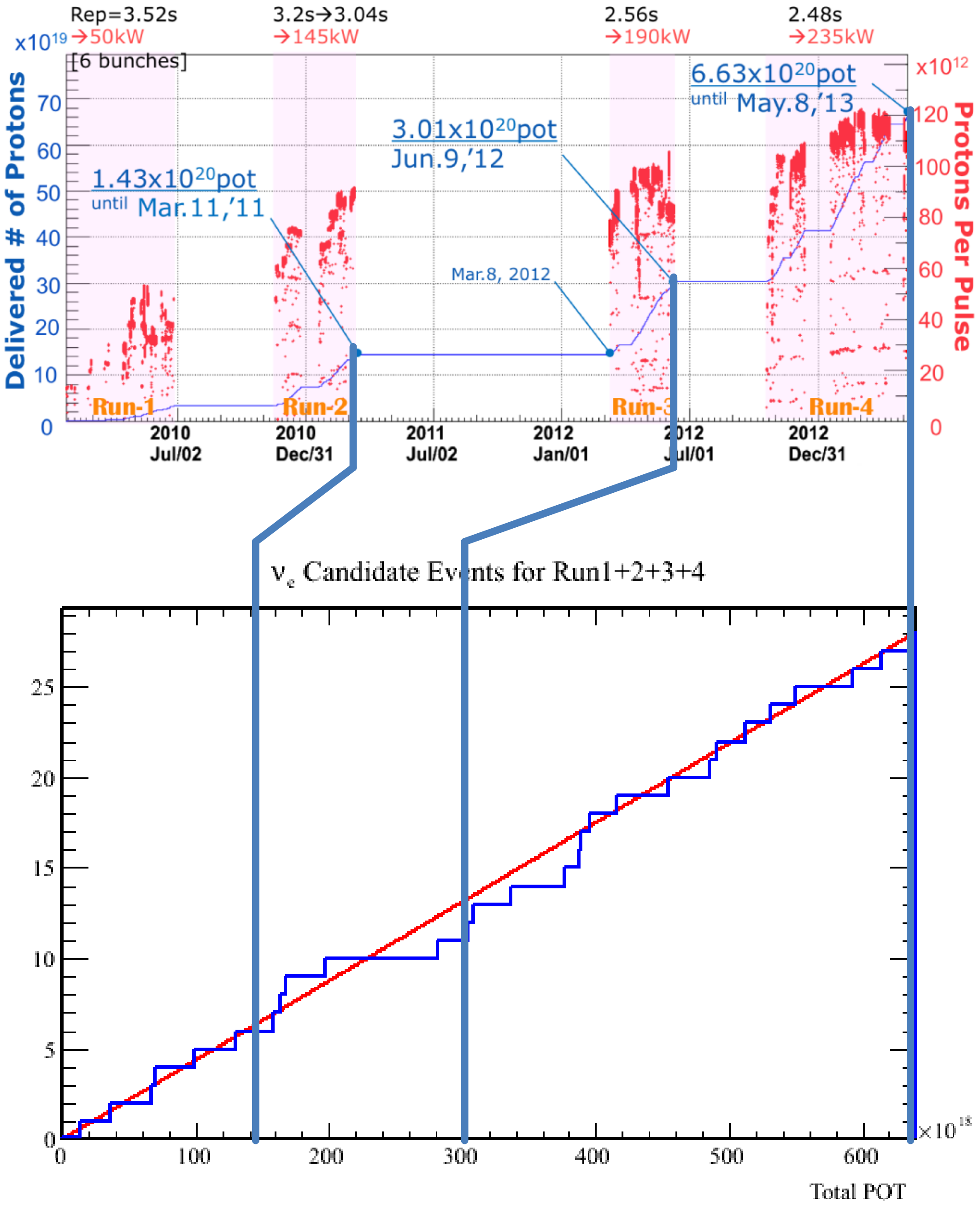
Protons delivered

March 11, 2011
Great Eastern Japan Earth quake



Successful startup and running → Reached $\sim 10\%$ of the final design goal of $8 \cdot 10^{21}$pot

Development of Data



- Runs 1-2: $1.4 \cdot 10^{20}$ pot

  → Indication of ν_e appearance

  with 2.5σ (6 candidates)

- Runs 1-3: $3.0 \cdot 10^{20}$ pot

  → Evidence of ν_e appearance

  with 3.1σ (11 candidates)

- Runs 1-4: $6.4 \cdot 10^{20}$ pot

  → Observation of ν_e appearance

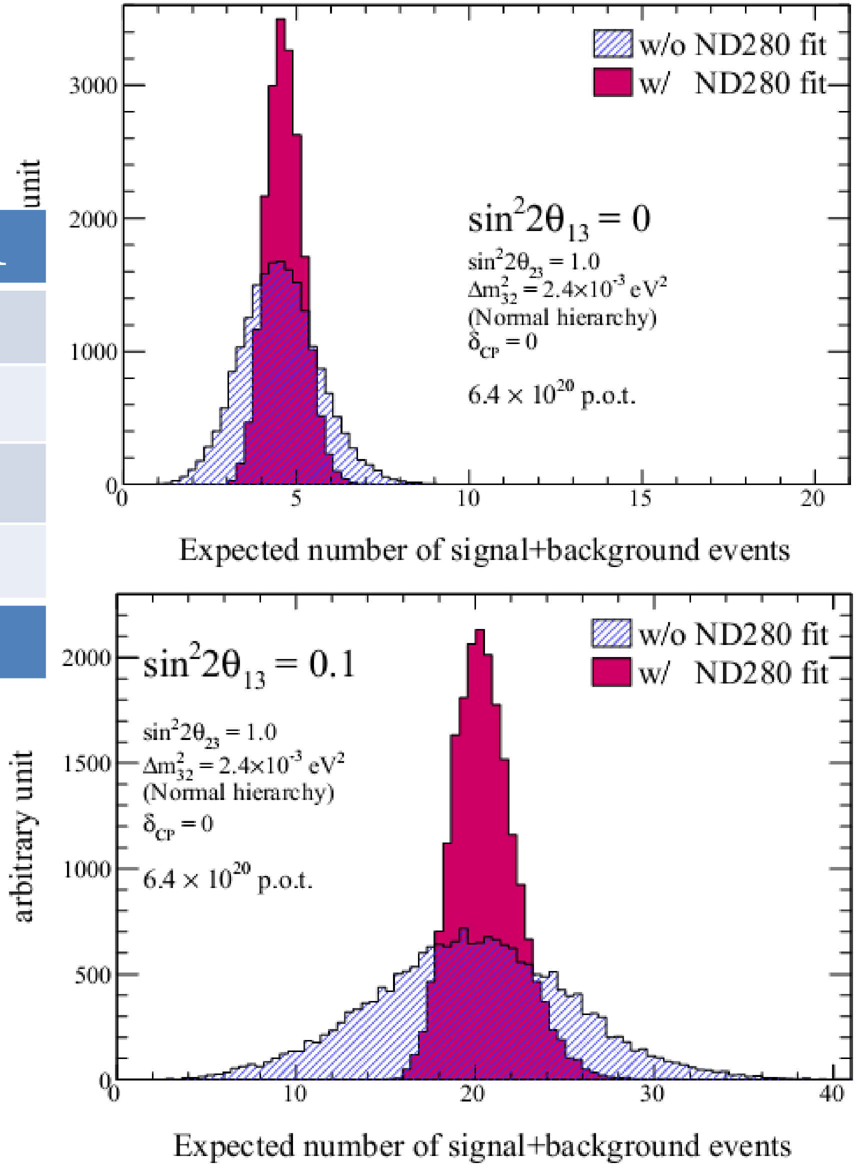
  with 7.3σ (28 candidates)

Predicted Number of Events

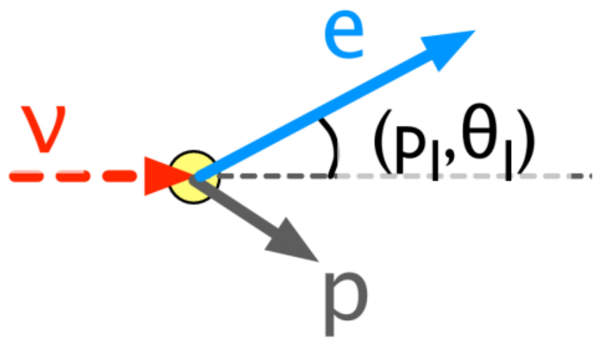
$6.4 \cdot 10^{20}$ pot

Event type	**$sin^2 2\theta_{13} = 0$**	**$sin^2 2\theta_{13} = 0.1$**
ν_e signal	0.4	16.4
ν_e backg.	3.2	2.9
ν_μ backg.	0.9	0.9
Other backg.	0.2	0.2
Total	**4.6**	**20.4**

Constraint from near detector very important!



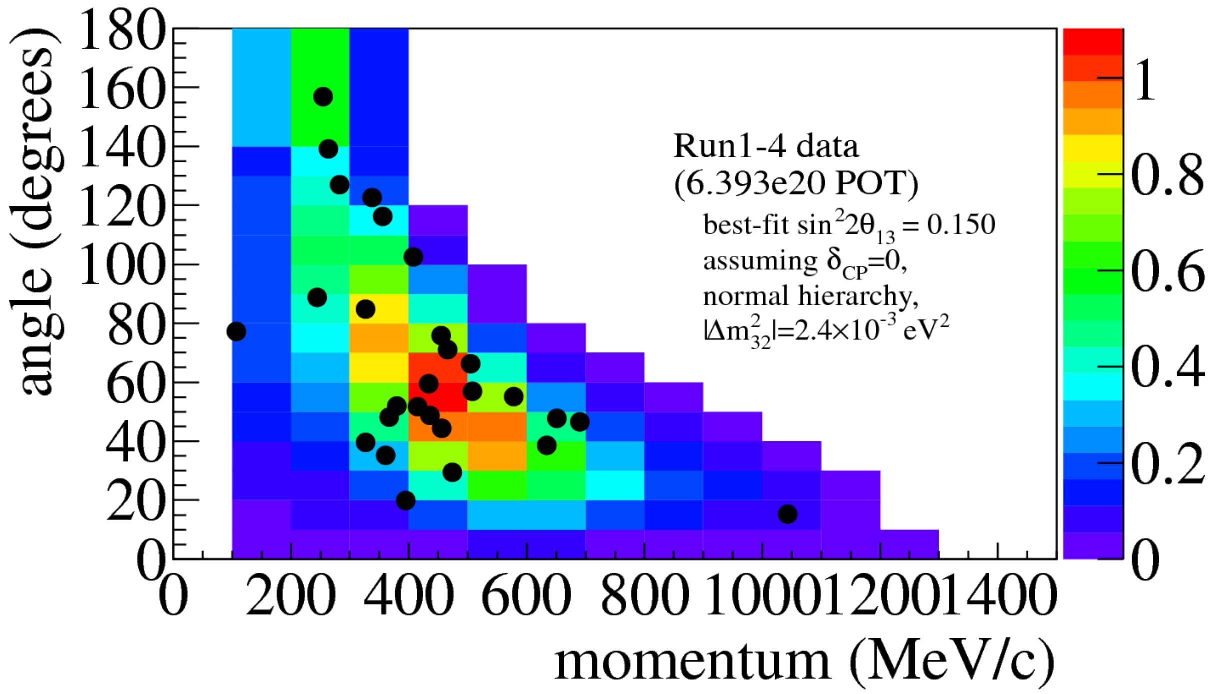
Fit to the Data



Likelihood is calculated by comparing the number of observed events (N_{obs}) and the electron momentum & angle (p-θ) distribution with MC.

Assuming $\delta_{CP} = 0$ and normal hierarchy

$$\Rightarrow \boldsymbol{\sin^2 2\theta_{13} = 0.140^{+0.038}_{-0.032}}$$



No oscillation hypothesis is excluded at 7.3 σ

Interpretation of ν_e data

With current $\sin^2 2\theta_{13}$ value:

$P(\nu_\mu \rightarrow \nu_e) \approx 0.051 - 0.014 \ \sin\delta_{CP}$

Allowed region of $\sin^2 2\theta_{13}$

for each value of δ_{CP}

→ Sensitivity to CP violating phase δ_{CP}:

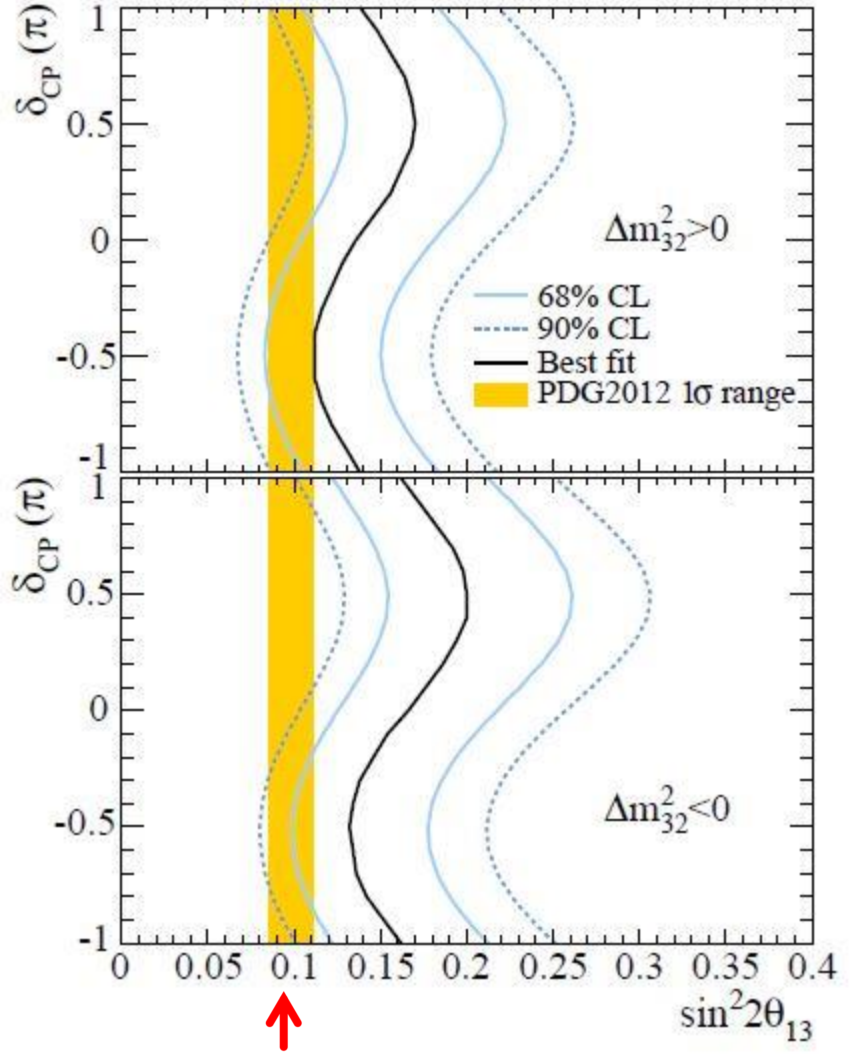
For normal mass hierarchy ($\Delta m^2_{32} > 0$)

$0.35\,\pi < \delta_{CP} < 0.63\,\pi$

for inverted mass hierarchy ($\Delta m^2_{32} < 0$)

$0.09\,\pi < \delta_{CP} < 0.90\,\pi$

are excluded at $90\%\ C.L.$



Constraint from reactor neutrinos:

$\sin^2 2\theta_{13} = 0.098 \pm 0.013$ (PDG 2012)

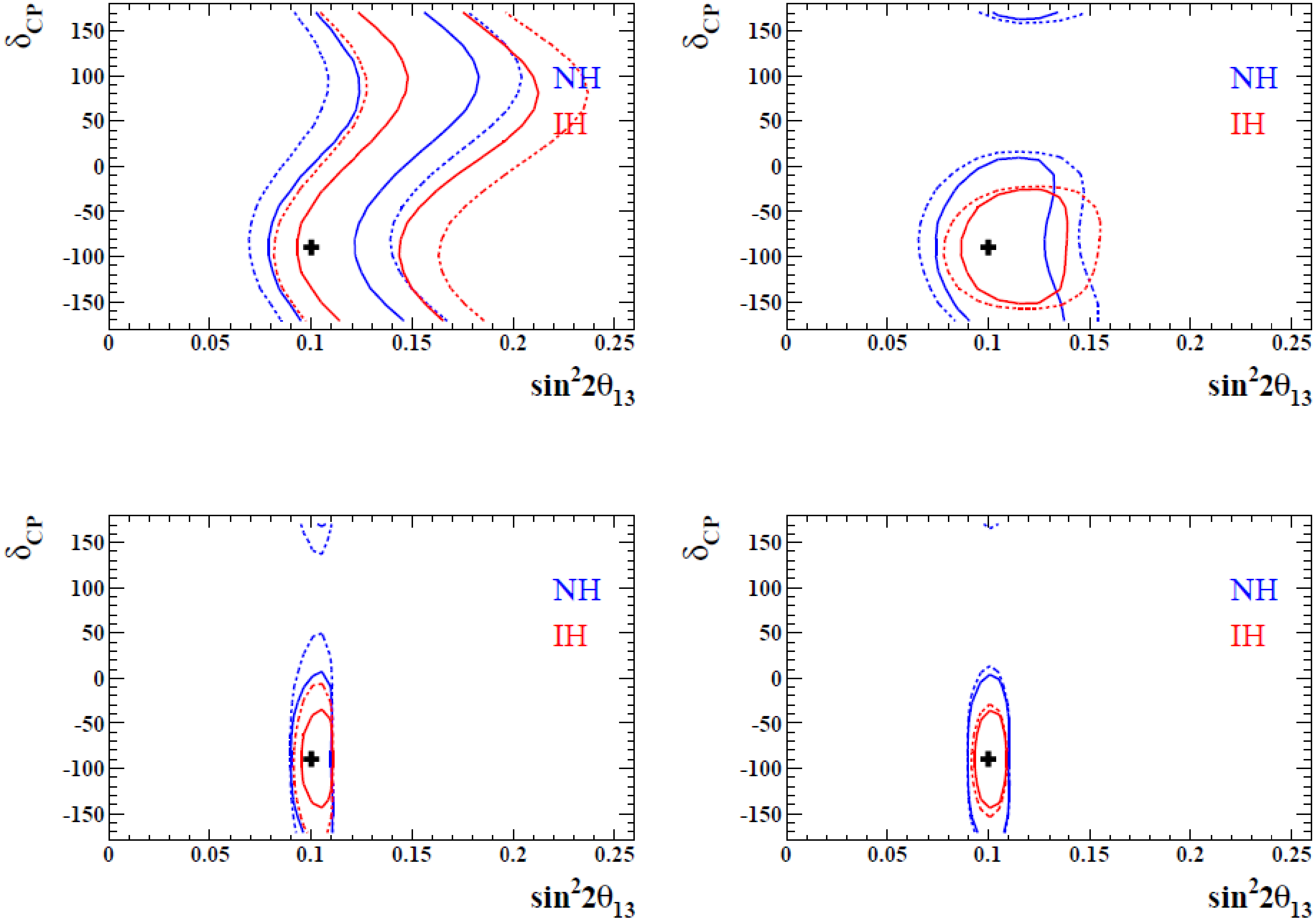
They measure $sin^2 2\theta_{13}$ independent from δ_{CP} and hierarchy

Future Prospects

T2K 90% C.L. regions for true $\delta_{CP} = -90°$, $\sin^2 2\theta_{13} = 0.1$, normal hierarchy

100% ν-running

50% ν-, 50% $\bar{\nu}$-running



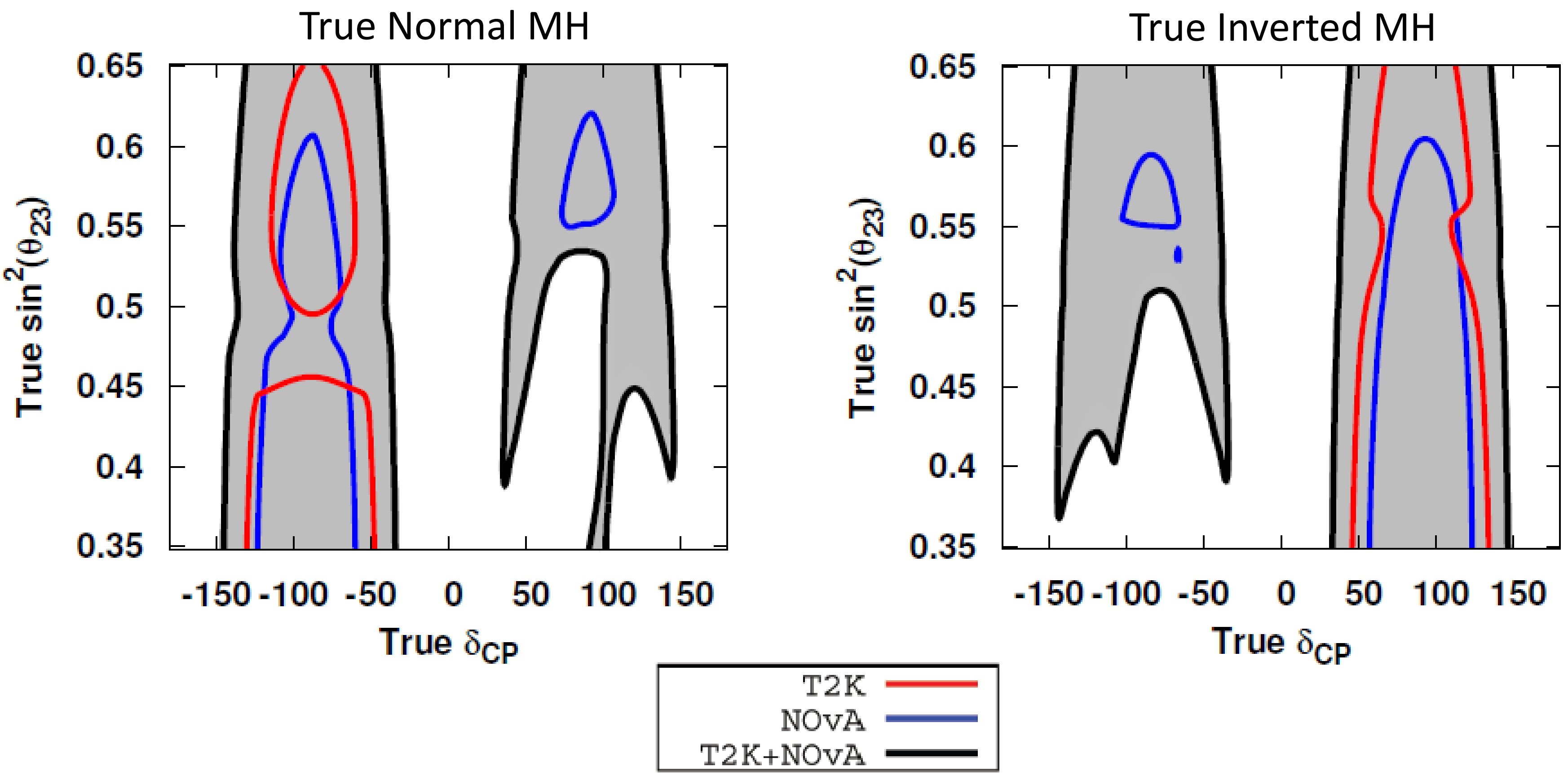
Without reactor constraint

With reactor constraint

→ Scheduled a pilot run with anti-neutrinos in 2014

Combination with NOvA

Region where evidence for CP violation can be found at the 90% C.L.



Conclusions

- **Physics of neutrino oscillations is a very active field**

- **Several new experiments have started (will start soon):**

  - **Reactor neutrino experiments DoubleChooz, Reno, DayaBay**

  - **Neutrino beam experiments T2K, Nova (2014)**

- **Measurement of θ_{13} has been established**

- **T2K has observed ν_e appearance, hence shows for the first time neutrino flavour transistion directly**

- **Combination of all neutrino experiments could resolve: CP-violation in leptonic sector (maybe mass hierarchy)**