Measurement of θ_{13} in Neutrino Oscillation Experiments

Stefan Roth, RWTH Aachen

Seminar, DESY, 21st/22nd January 2014

Deutsche Forschungsgemeinschaft

RWTH AACHEN UNIVERSITY

Overview

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

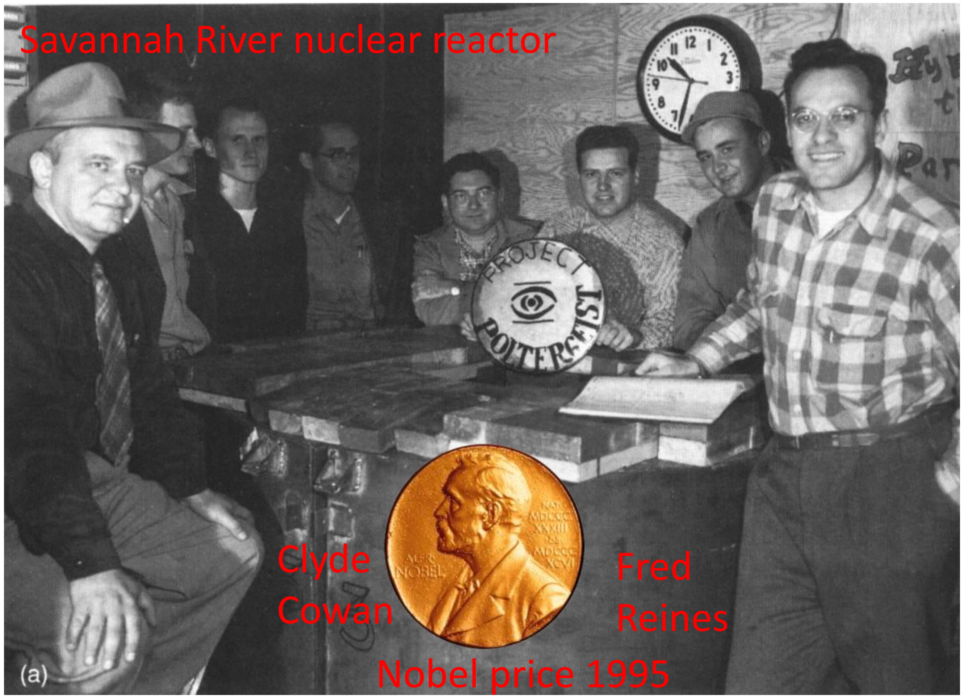
Two experiments with RWTH participation:

➢ 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

http://particlezoo.net

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



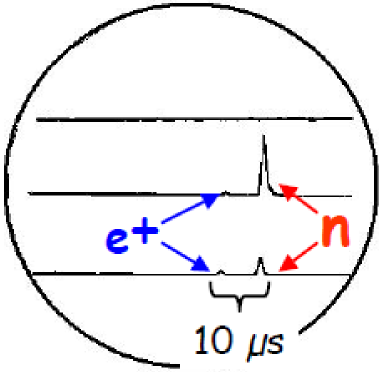
Nuclear reactors produce a large flux of anti-neutrinos $\bar{\nu}_e$

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

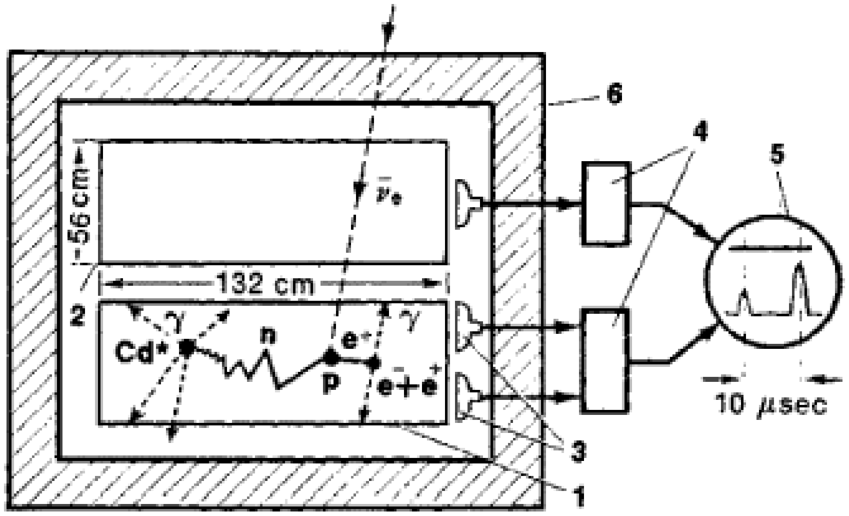
$$\bar{\nu}_e + p \rightarrow n + e^+$$

Inverse β-decay using delayed coincidences:

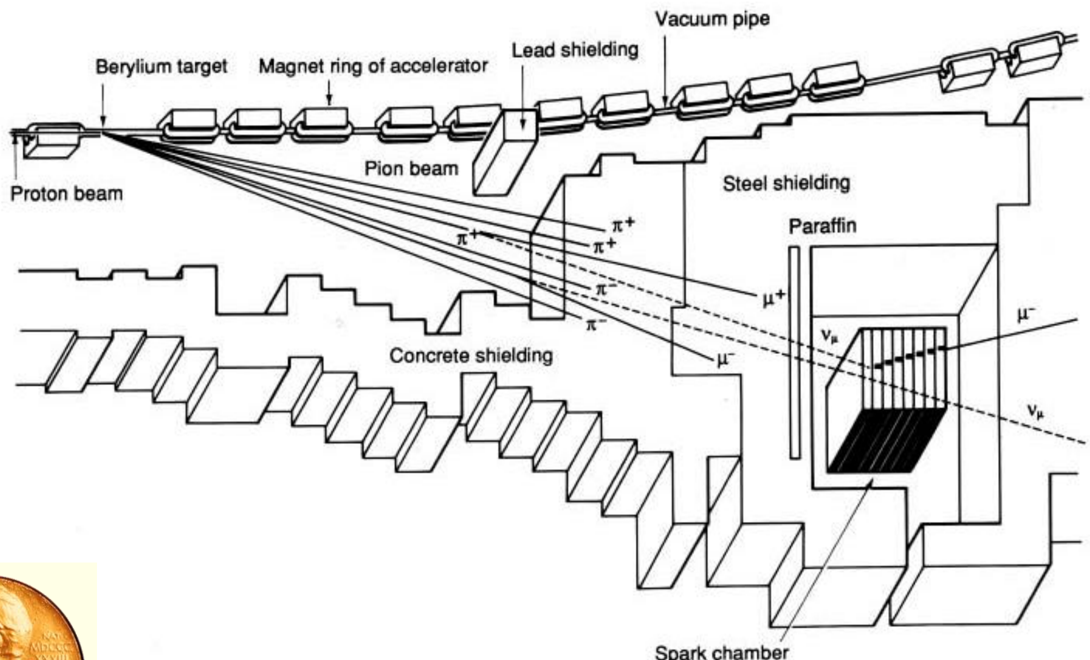
Prompt: positron annihilation



Delayed: neutron capture



Discovery of the Myon-Neutrino: Brookhaven (1960)



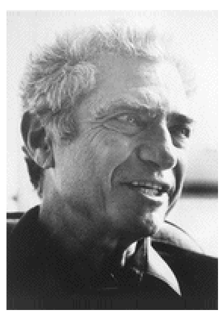
Pion beam produces ν_μ beam

$$\nu_\mu + n \rightarrow \mu^- + p$$

Nobel price 1988

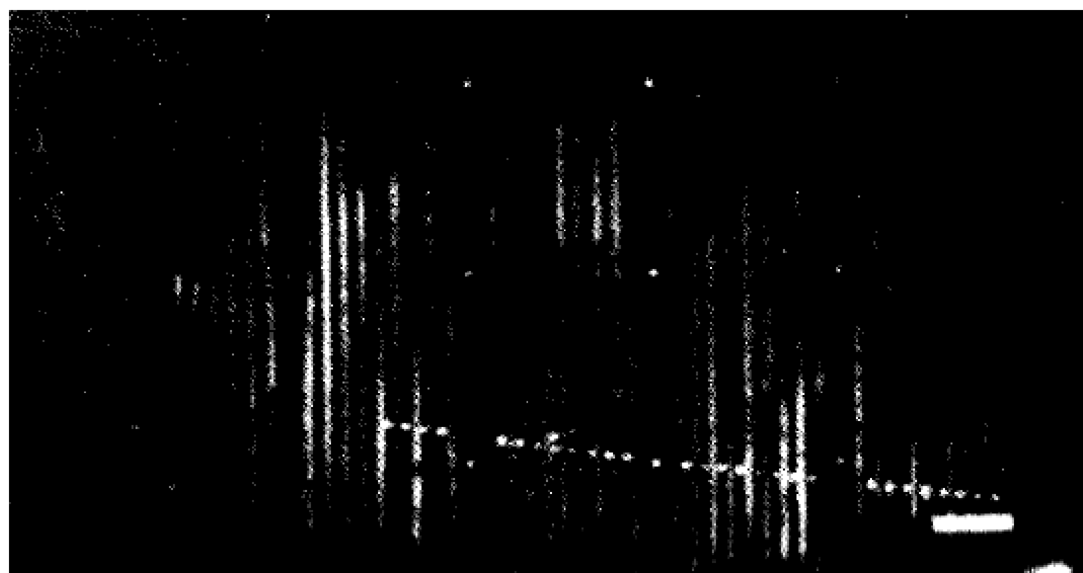
Leon Ledermann

Melvin Schwartz

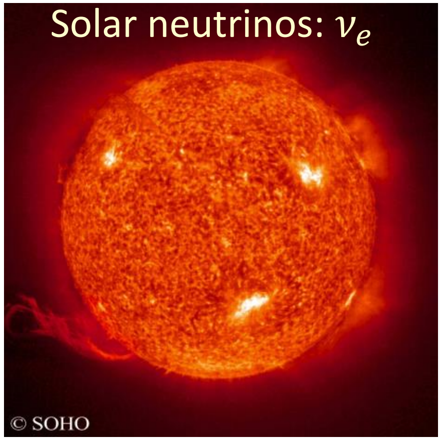


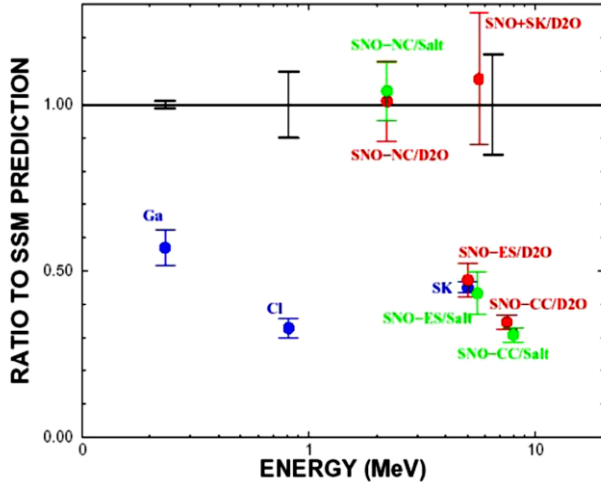
Jack Steinberger

Myon track starts within spark chamber



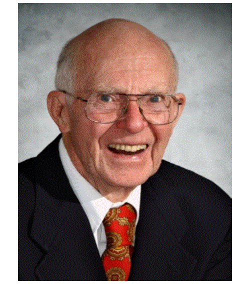
Discovery of Neutrino Oscillations





$\nu_e + \nu_\mu + \nu_\tau$

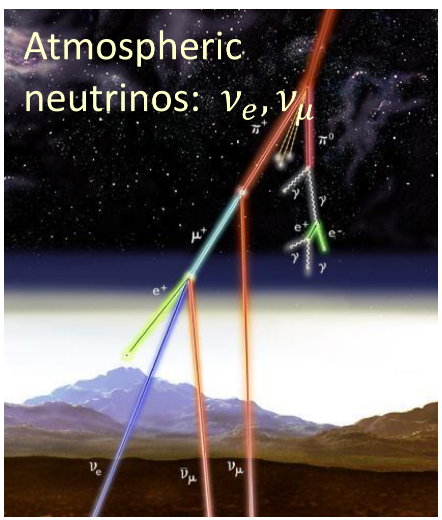
ν_e

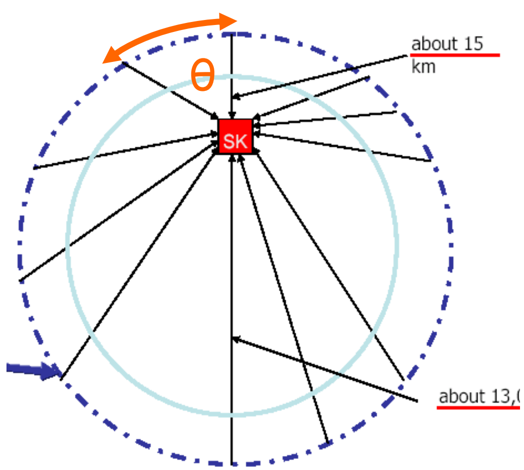


R. Davis

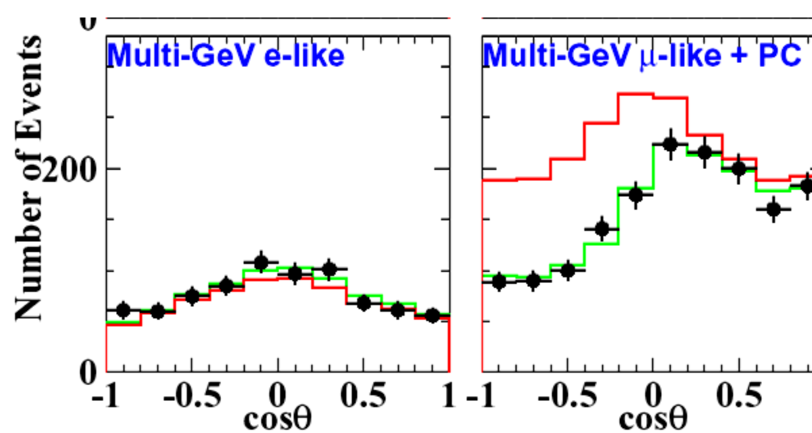
M. Koshiba

Nobel price 2002

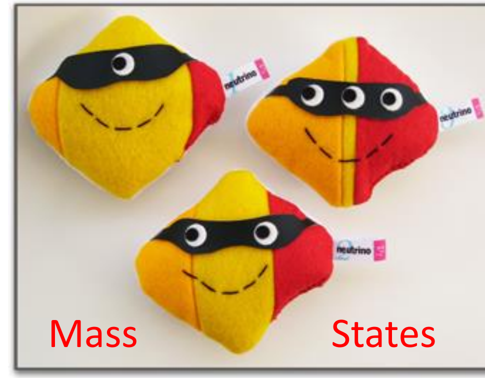




Measured
expected no oscillations
expected with oscillations



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: $c_{ij} = \cos\theta_{ij}\,,\ \ s_{ij} = \sin\theta_{ij}$

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

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

„Reactor“
$\theta_{13} \approx 10°$

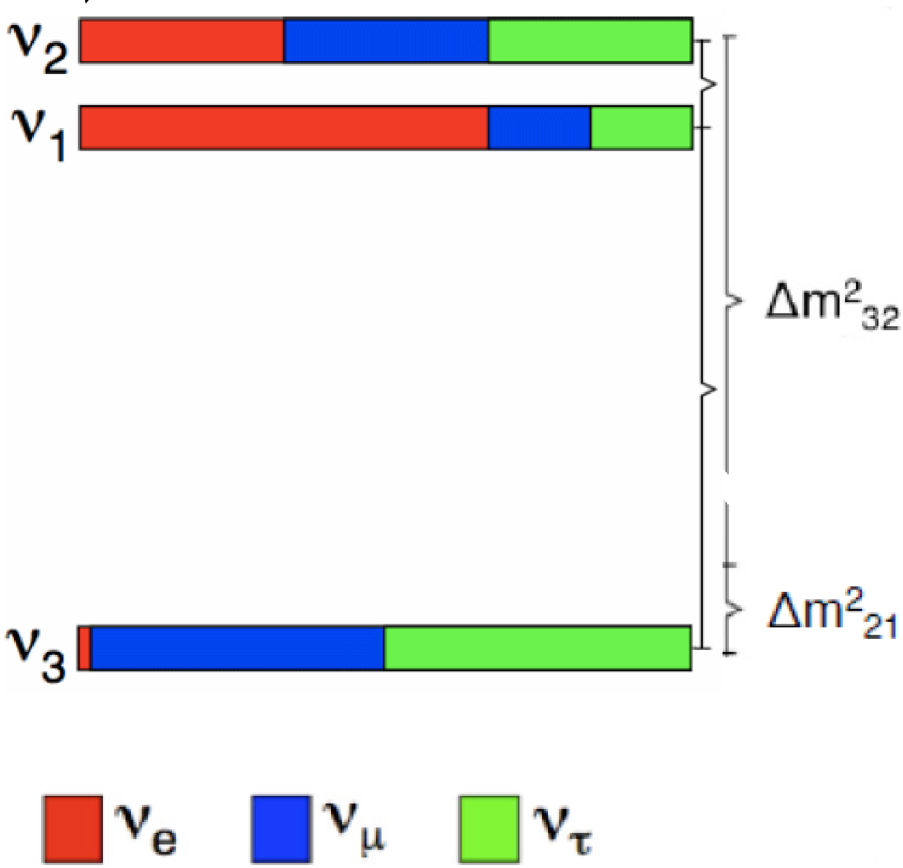
„Solar“
$\theta_{12} \approx 32°$

Majorana phases

Oscillation parameters

ν_e contribution to ν_3 is small!

How large are U_{e3} and θ_{13} ?



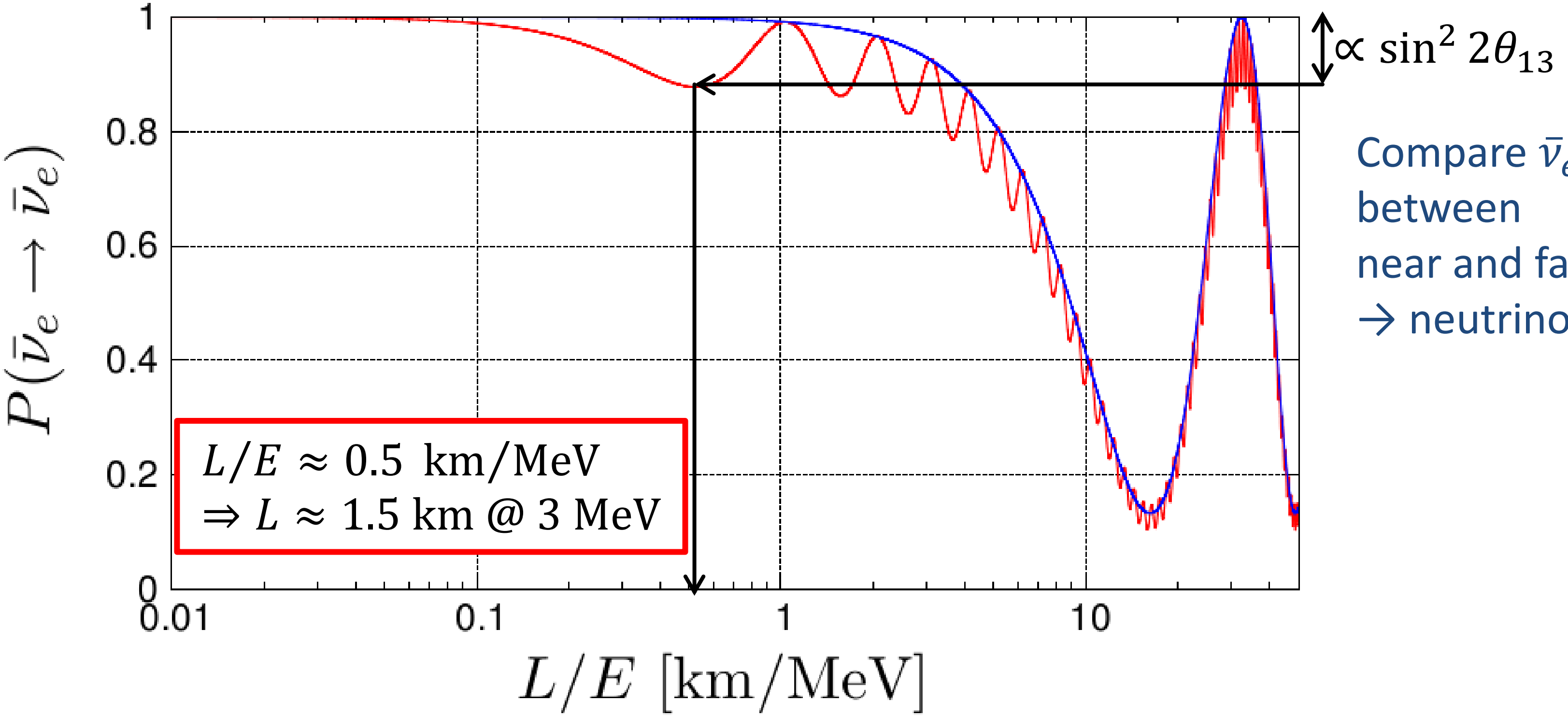
Atmospheric Neutrinos and K2K :
$\Delta m_{23} \approx 0.05$ eV
from $P(\nu_\mu \rightarrow \nu_\mu)$

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



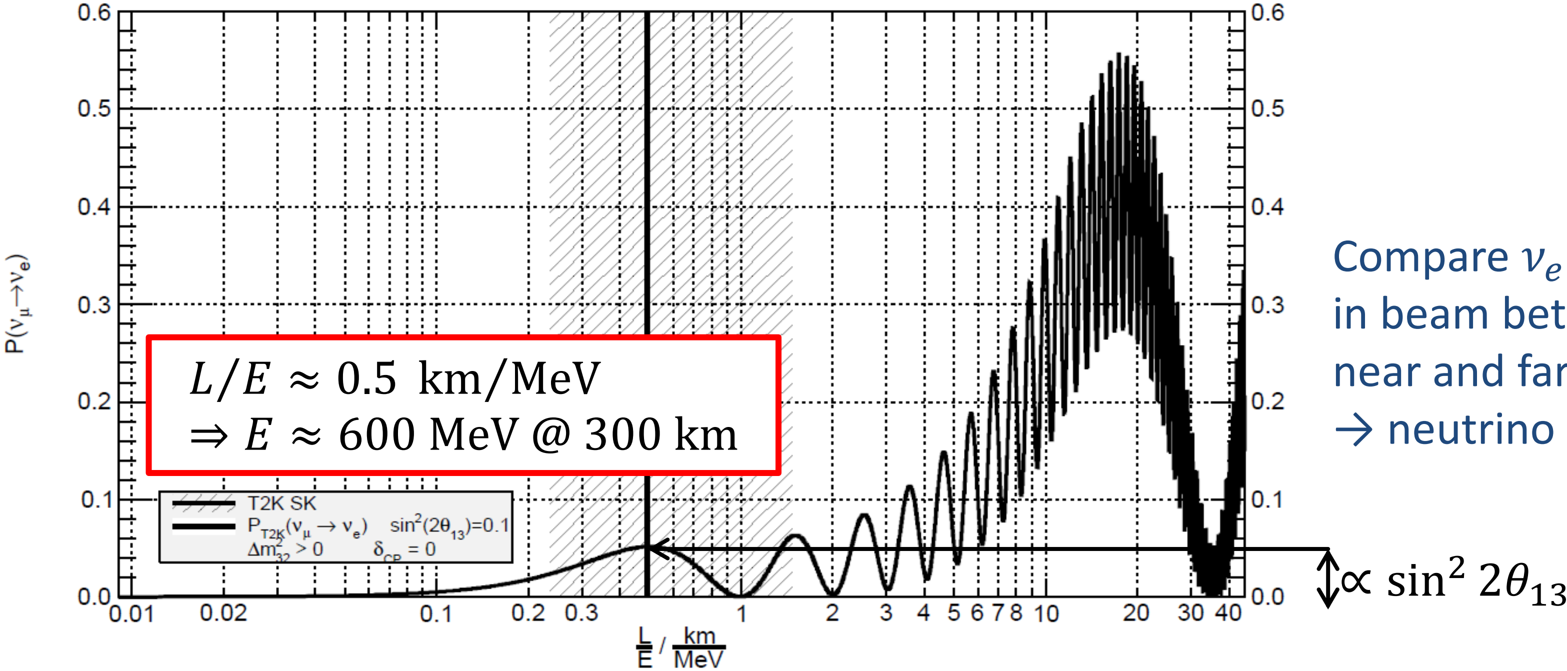
Compare $\bar{\nu}_e$ flux between near and far detector
→ neutrino deficit

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

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

Neutrino Oscillations (3 Masses)

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



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

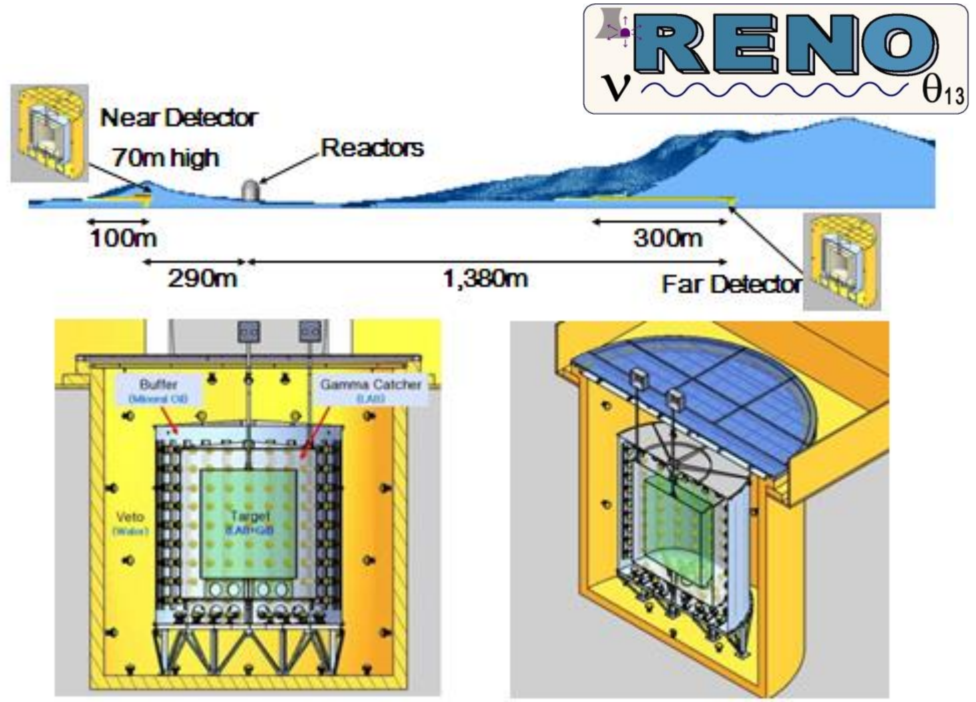
New Reactor Neutrino Experiments

DayaBay:

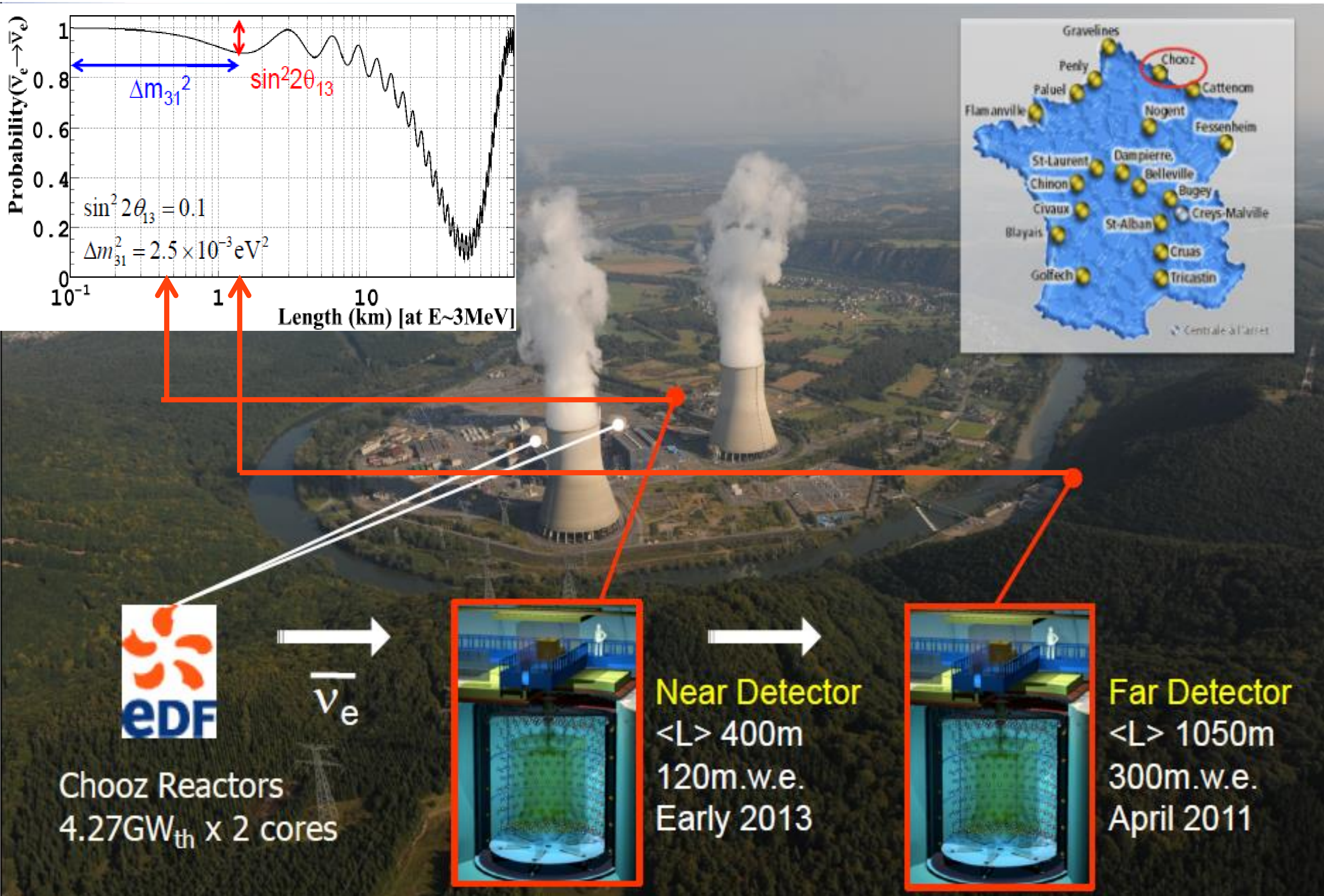
- Located at Daya Bay Nuclear Power Plant in China
- 6 x 2.9 GW_{th} nuclear reactors
- 6 neutrino detecors
  3 near (520 m from reactors)
  3 far (1650 m from reactors)

RENO:

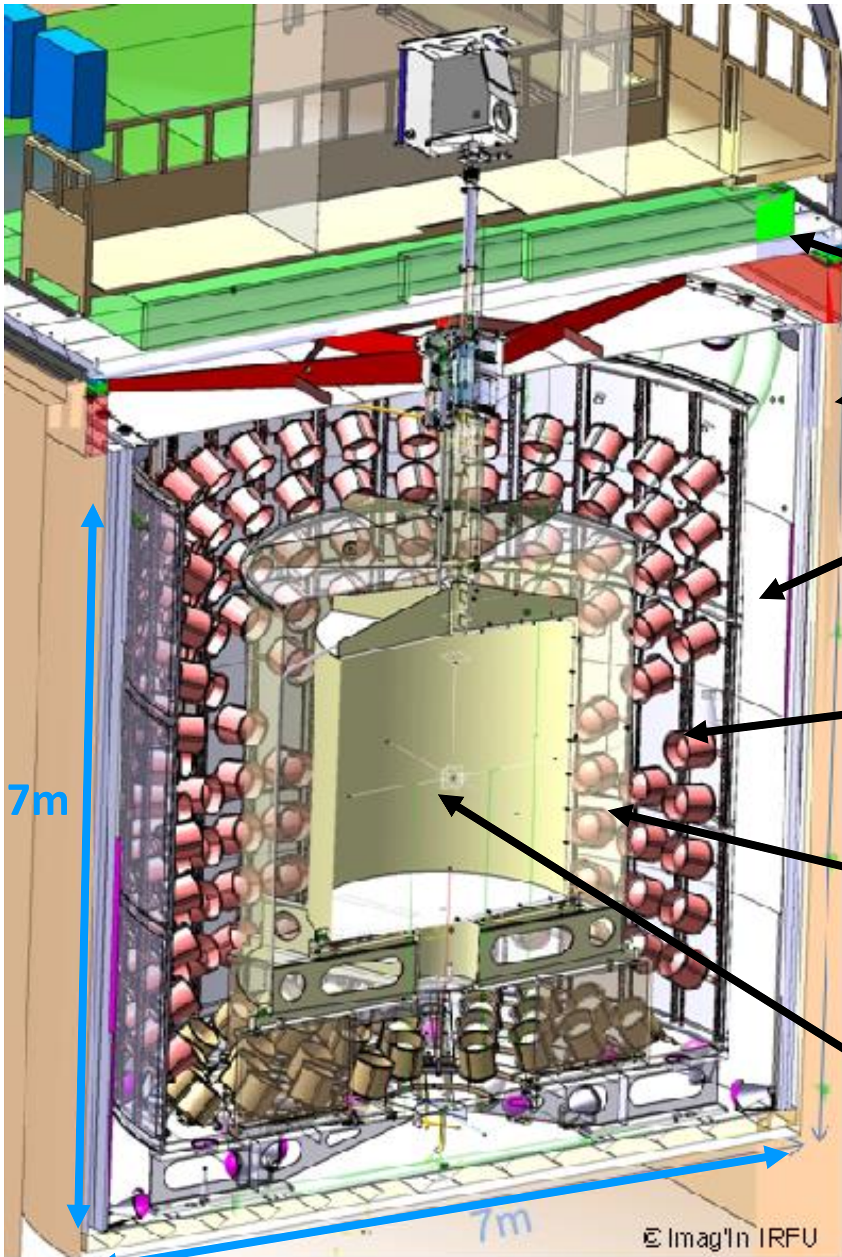
- Located at Yonggwang Nuclear Power Plant in Korea
- 6 x 2.8 GW_{th} nuclear reactors
- 2 neutrino detecors
  1 near (294 m from reactor)
  1 far (1383 m from reactor)



The Double Chooz Experiment



Design of the DoubleChooz Detectors



Onion like structure
to shield against backgrounds

Outer Veto:
Plastic scintillator

Steel Shielding (17 cm)

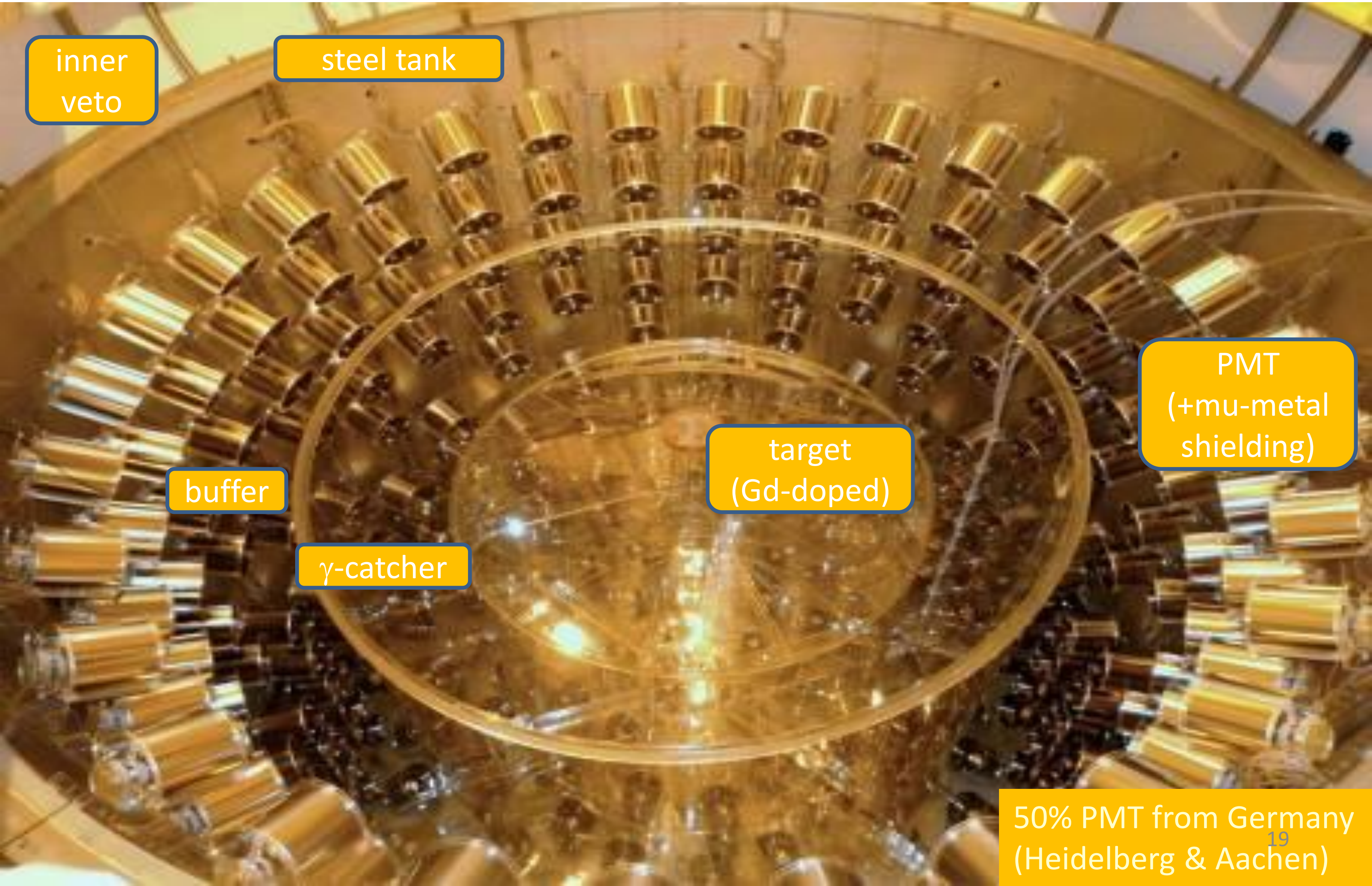
Inner Veto (steel vessel):
80 m^3 liquid scintillator, 80 PMT

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

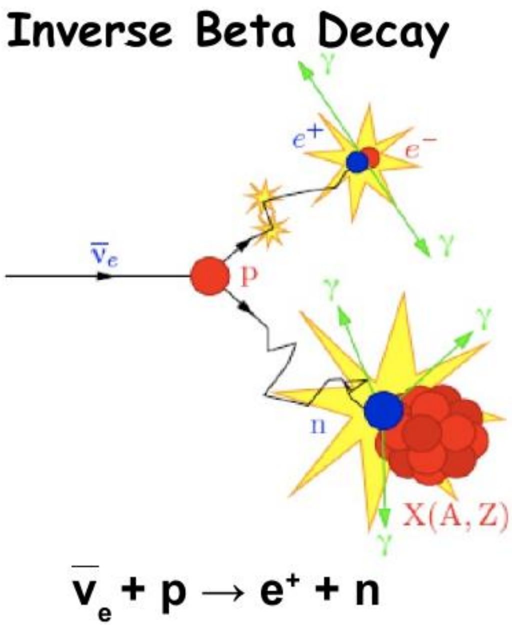
Target (acrylic vessel) :
10.3 m^3 liquid scintillator + 0.1% Gd

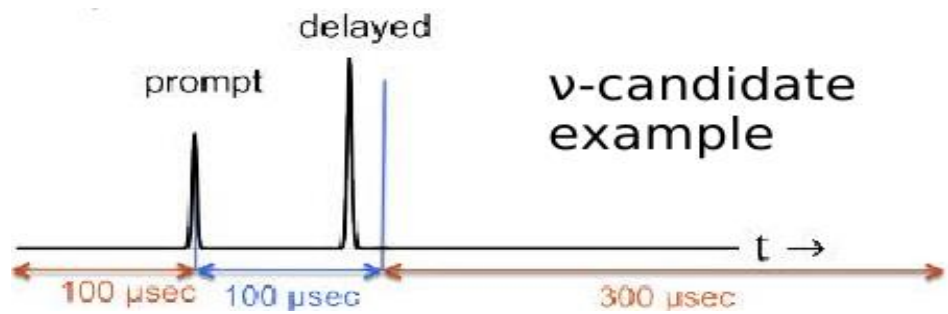
Detector Vessels before Closing

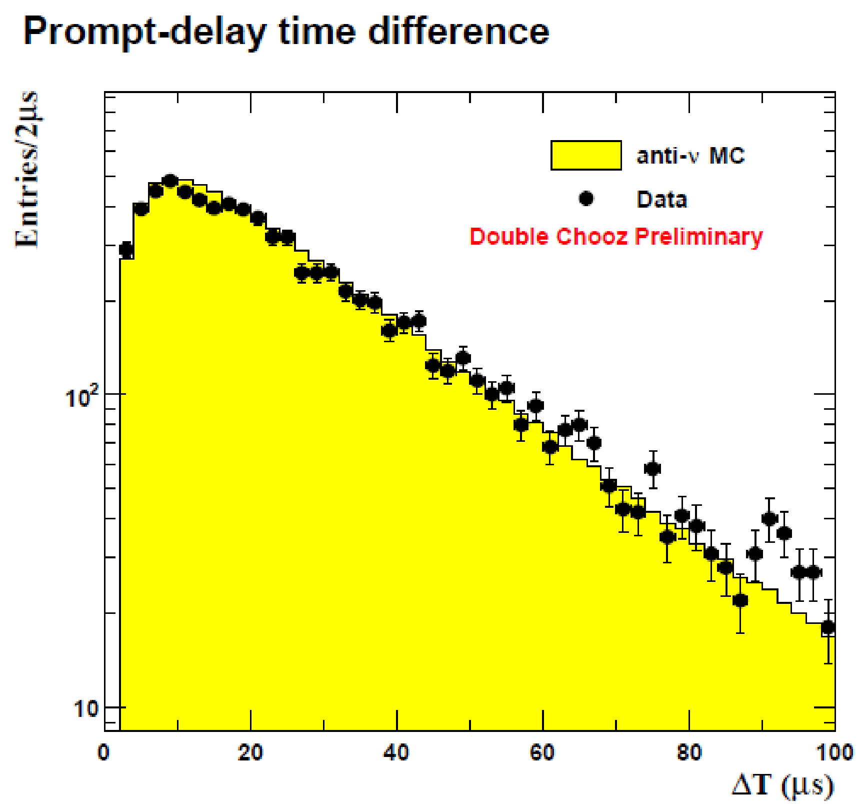


50% PMT from Germany (Heidelberg & Aachen)

Selection of Neutrino Candidates



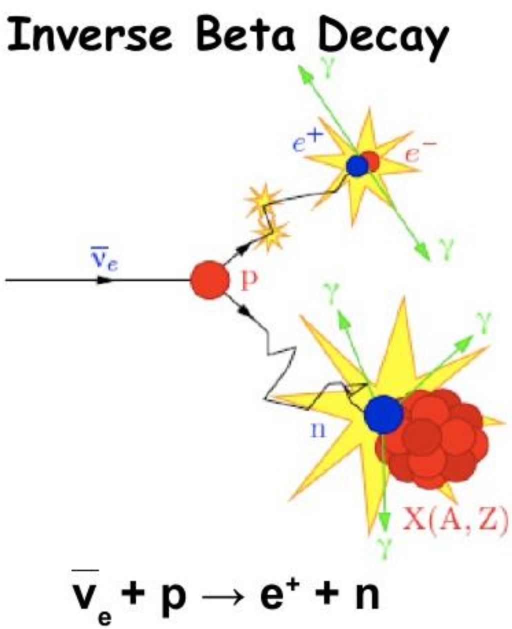


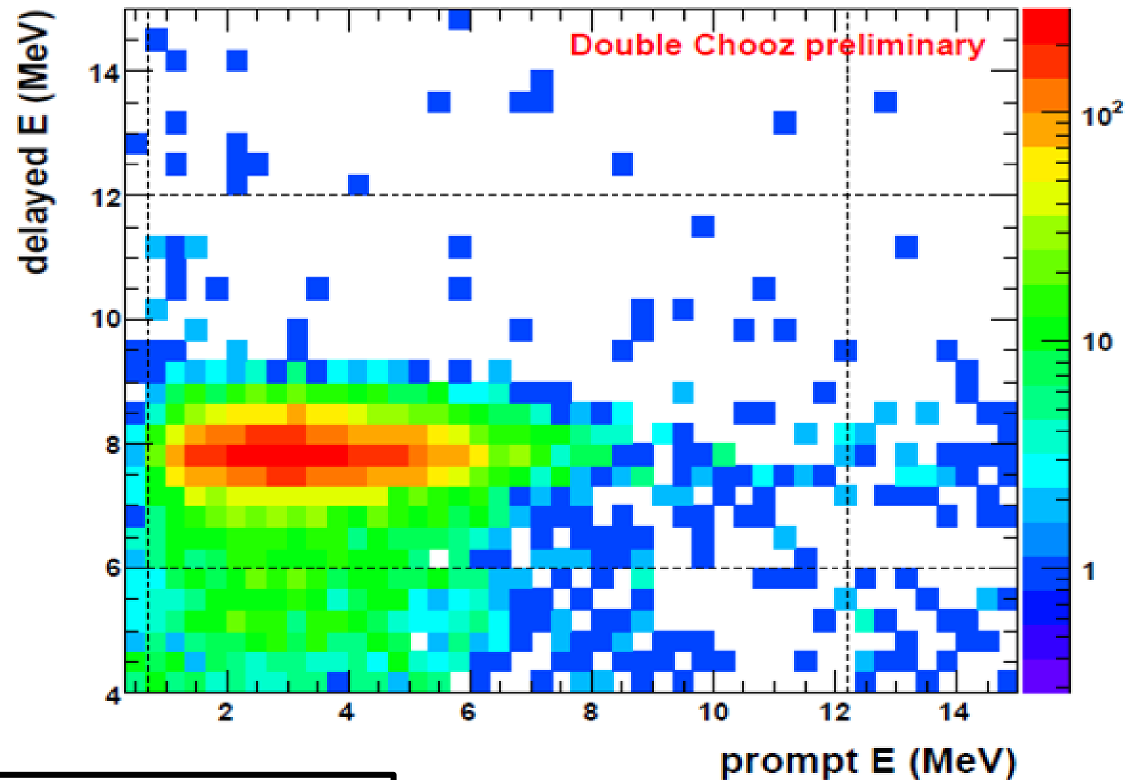


Coincidence Cut:

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

Selection of Neutrino Candidates





Energy Cut:

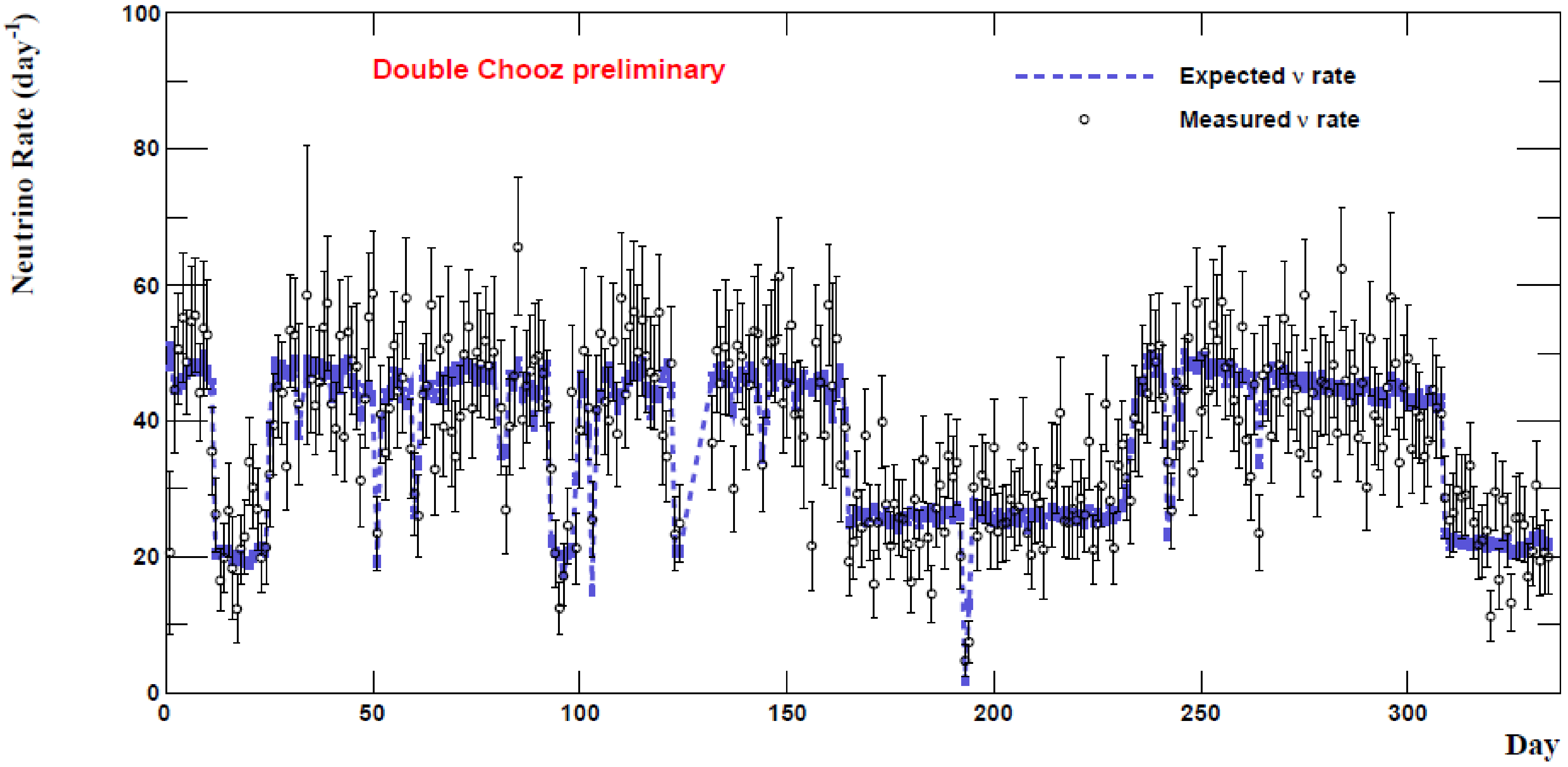
$$0.7\ \text{MeV} < E_{\text{prompt}} < 12.2\ \text{MeV}$$

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

Rate of Neutrino Candidates

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

Neutrino rate



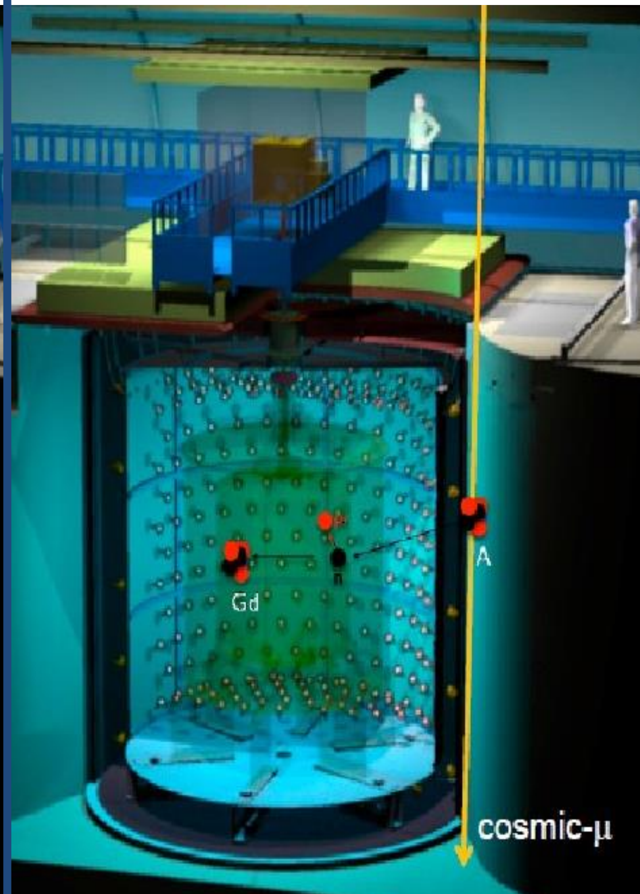
- In total 8249 candidates survive the cuts (no background subtraction)
- Good correspondence to reactor power history
- Indicates low background level in detector

Backgrounds

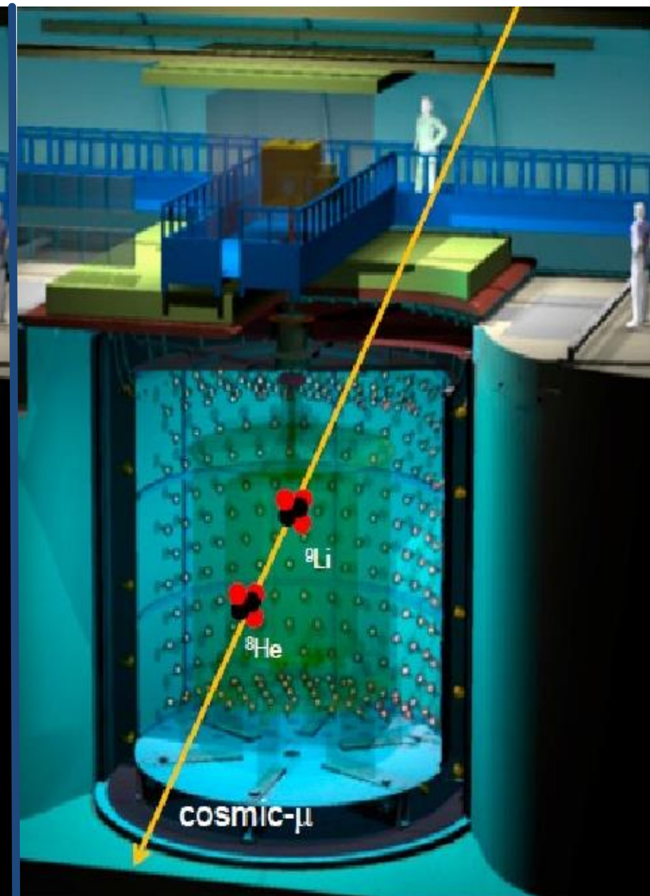
Accidental background

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

Correlated background

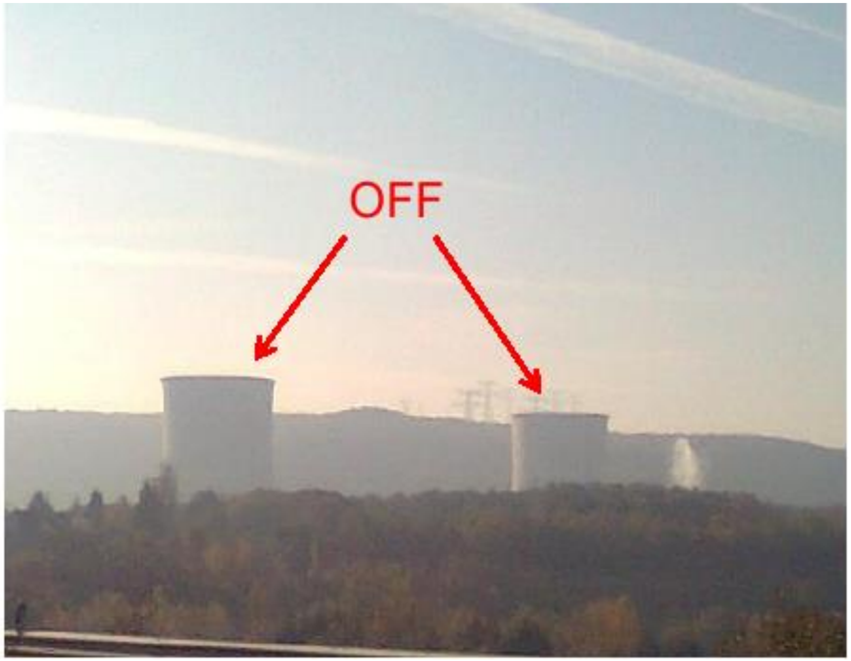


Prompt:
proton recoils from neutron
Delayed:
neutron capture on Gd



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

Background Estimation

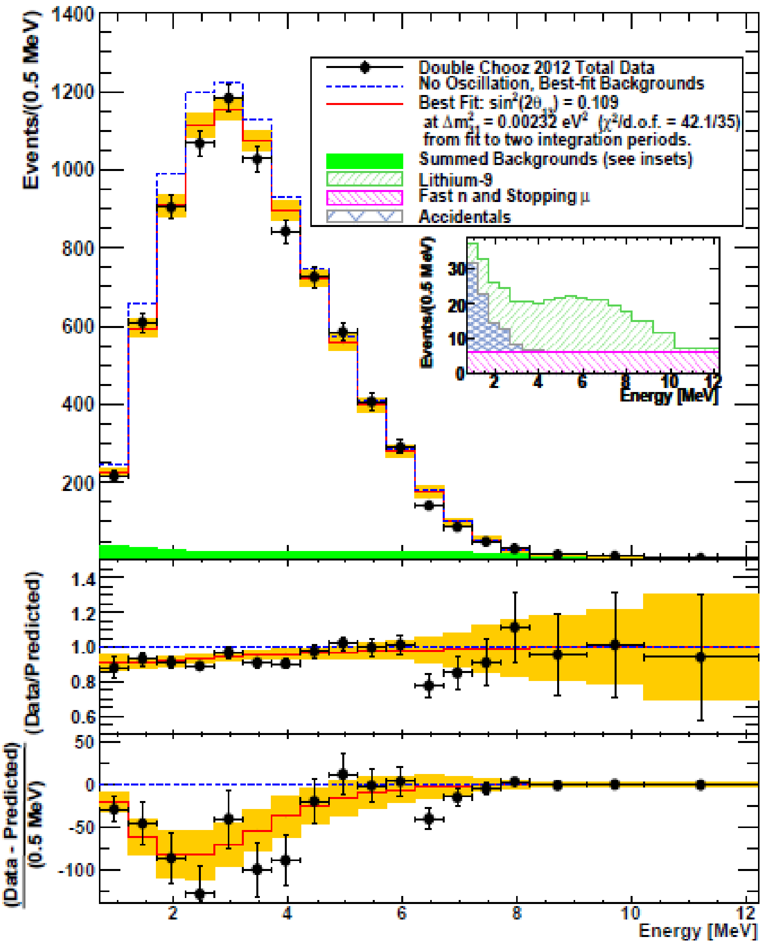


- Unique opportunity to measure backgrounds in-situ with both reactors off
  ~7,5 days of reactor OFF-OFF data

- 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:

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

- Rate & shape analysis yields

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

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

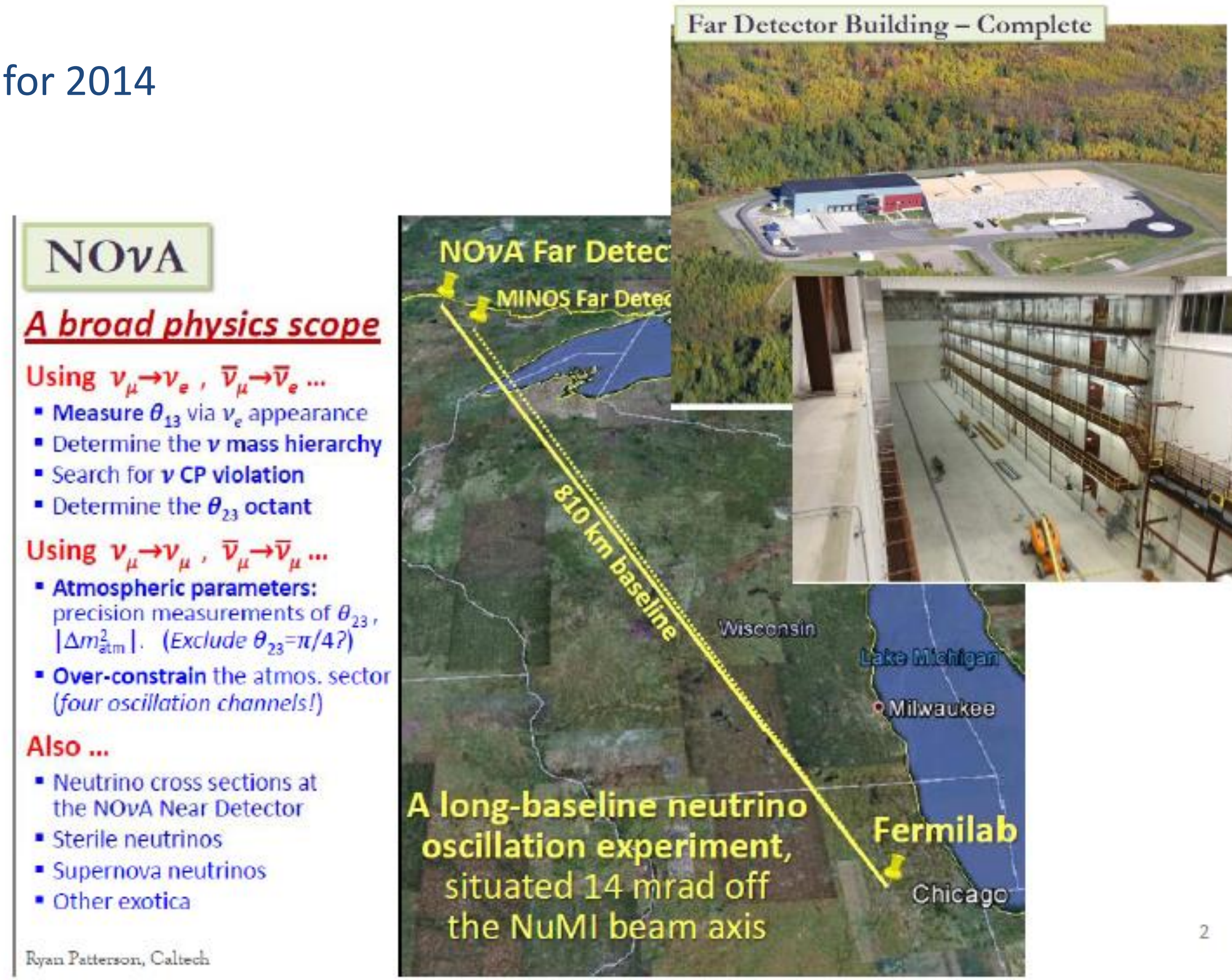
- Together with results from DayaBay and RENO:

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

New Accelerator Neutrino Experiments

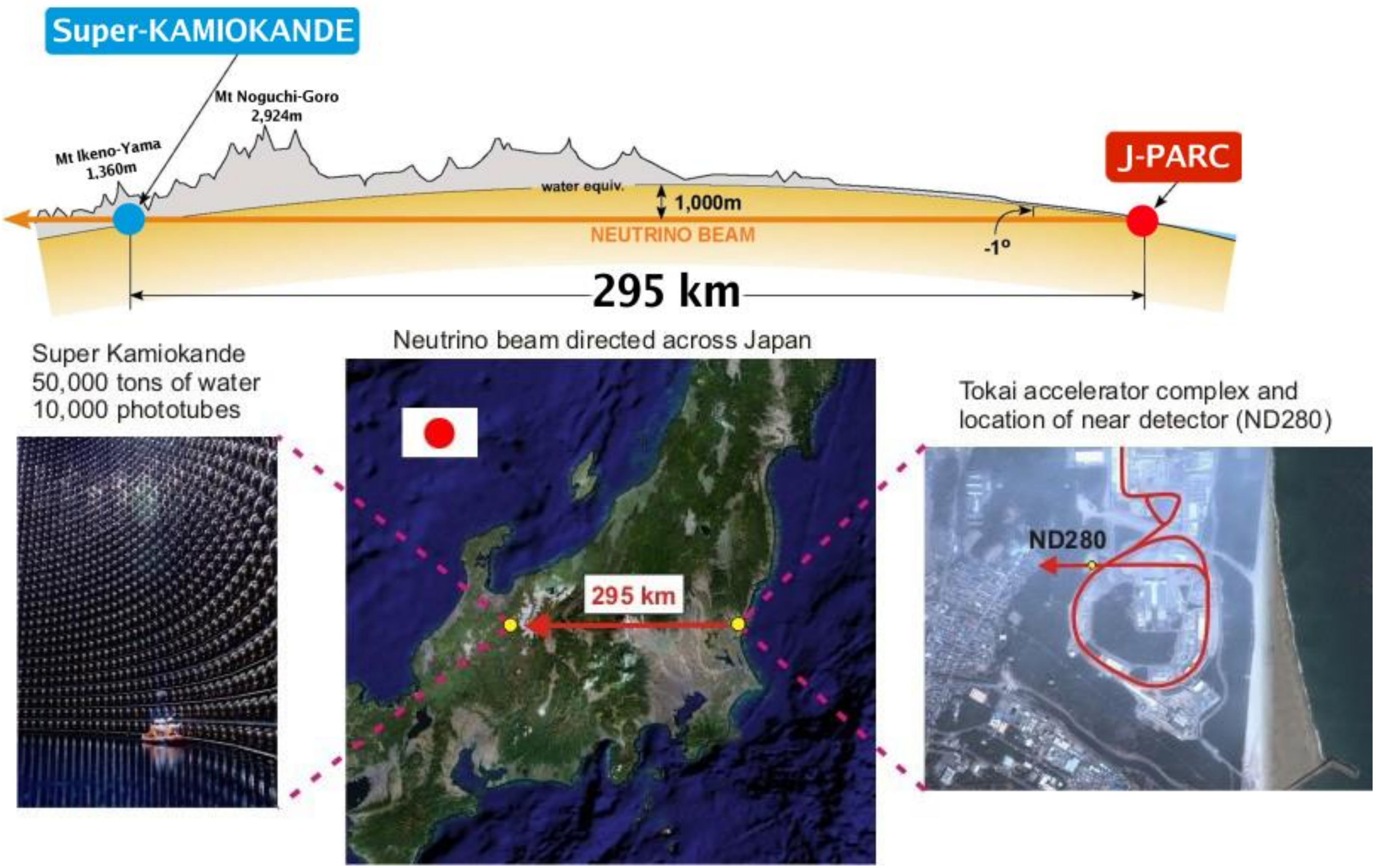
NOvA: Numi Off-Axis ν_e Appearance Experiment

Start planned for 2014

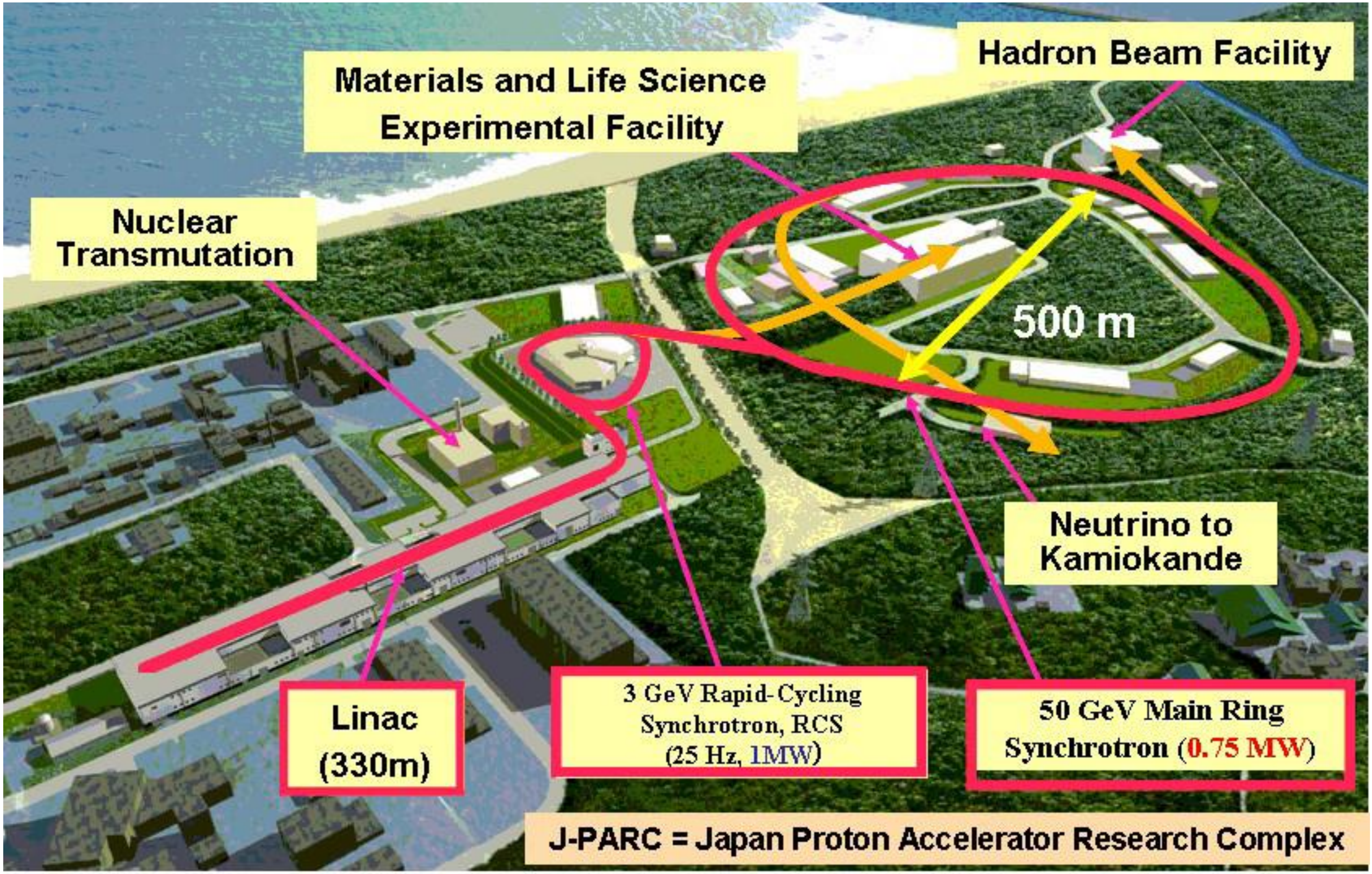


The T2K Experiment (Tokai To Kamioka)

Data taking since 2010



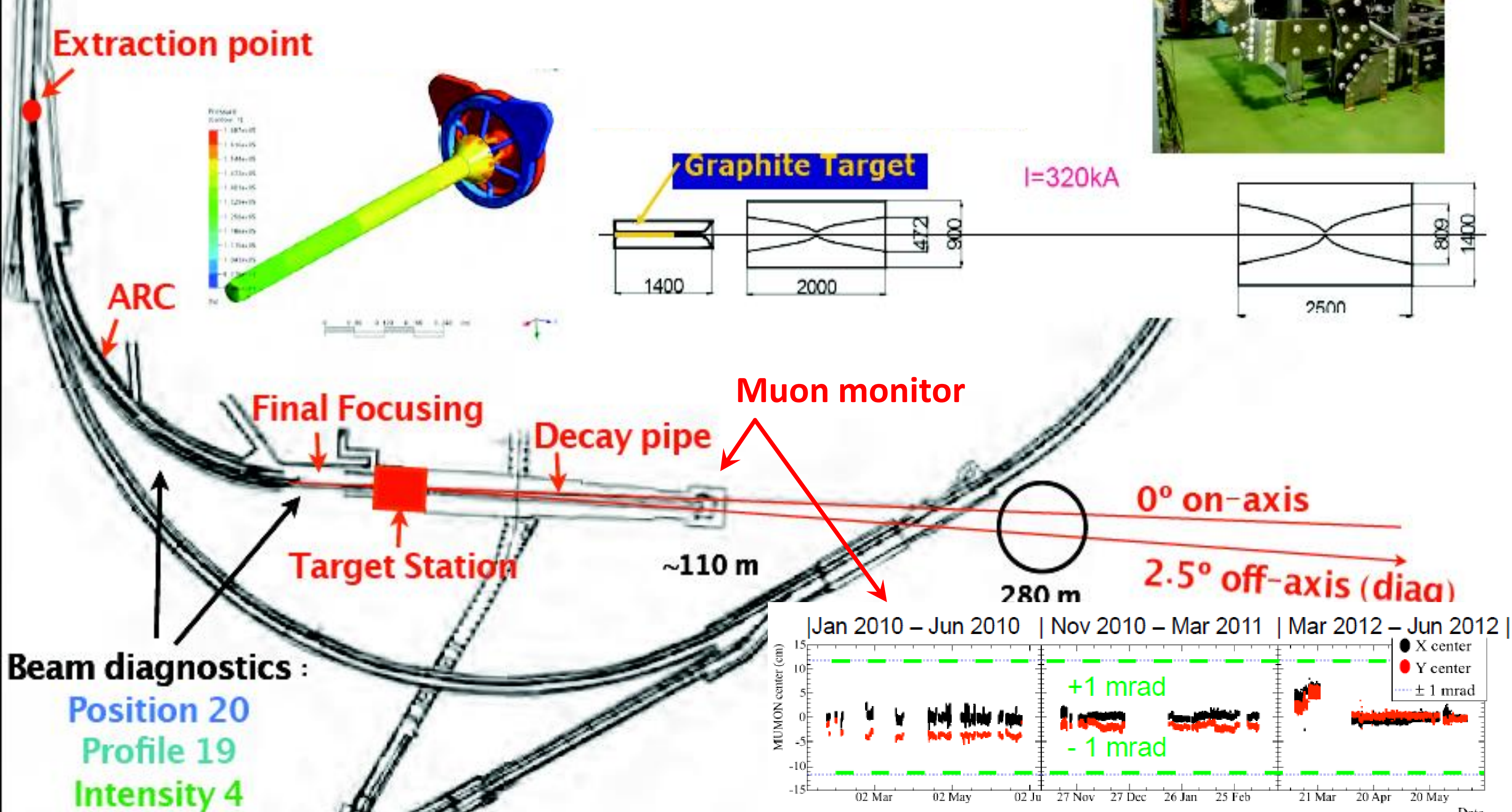
Japan Proton Accelerator Research Center J-PARC



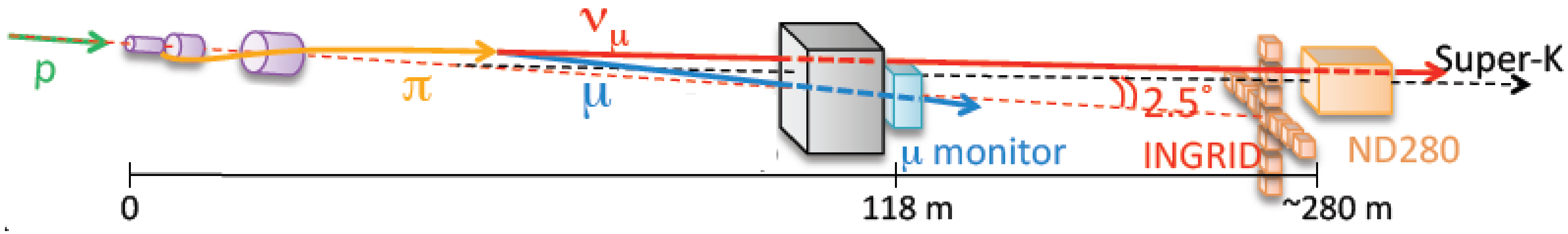
J-PARC: Joint project between KEK and JAEA

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

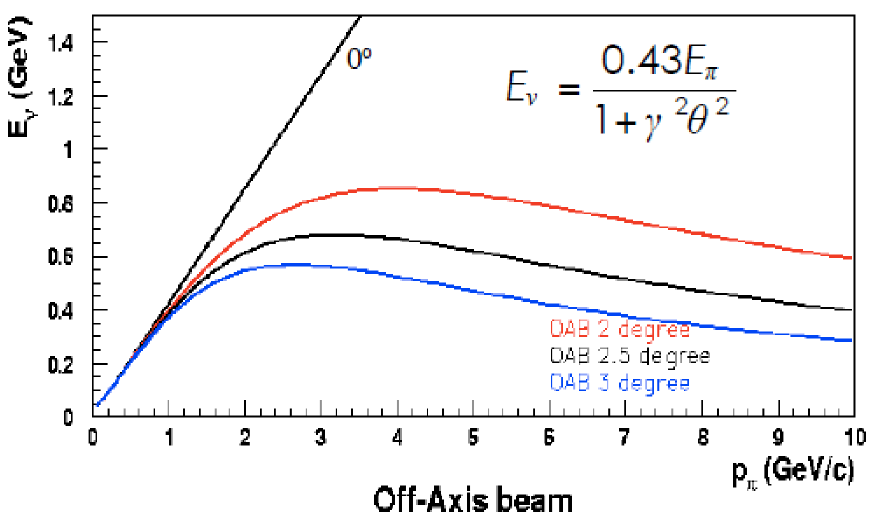


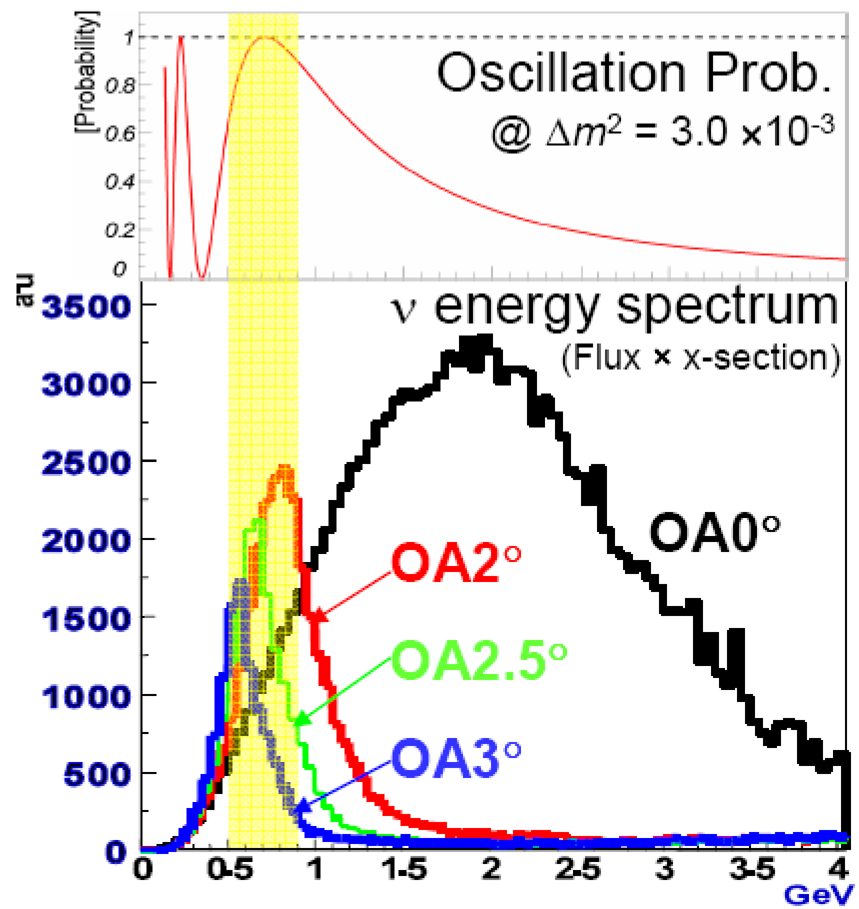
Off Axis Neutrino Beam



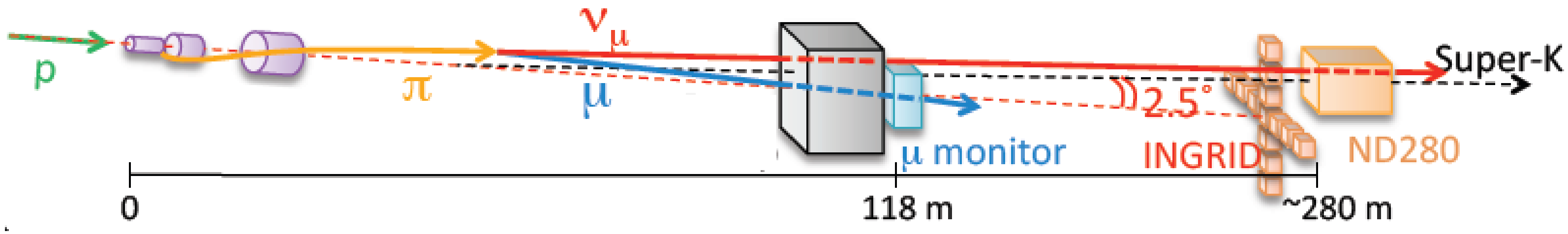
Neutrinos at 2.5° off-axis:

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





Off Axis Neutrino Beam

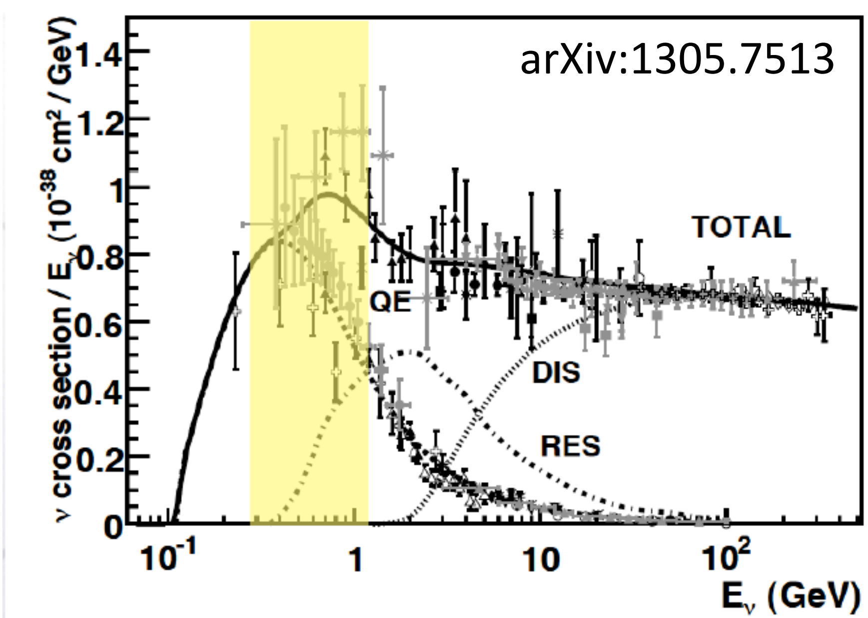


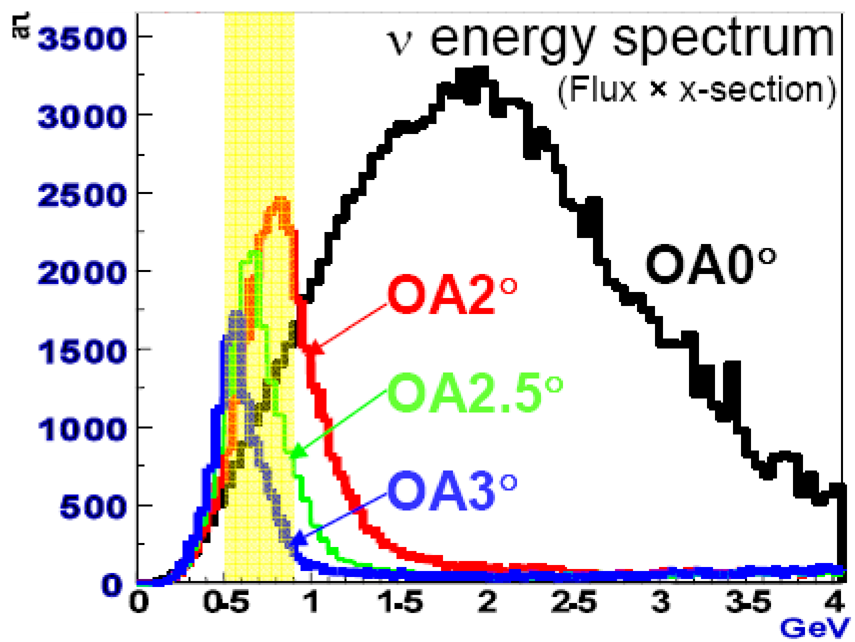
Charge Current (CC) processes:

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

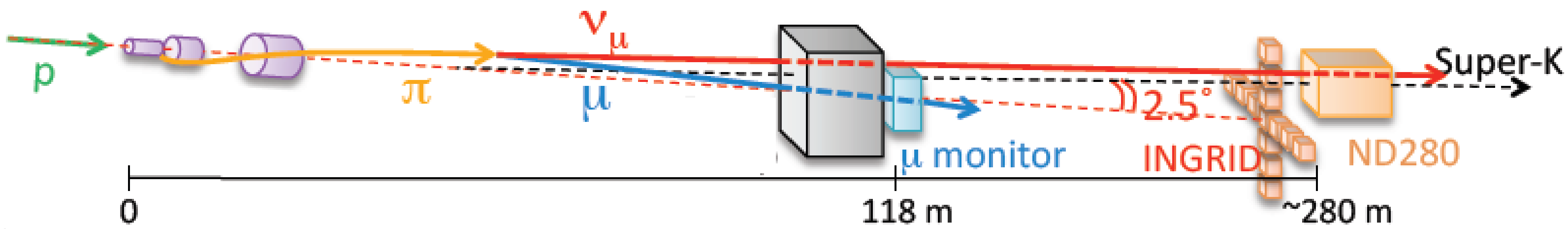
Neutrinos at 2.5° off-axis:

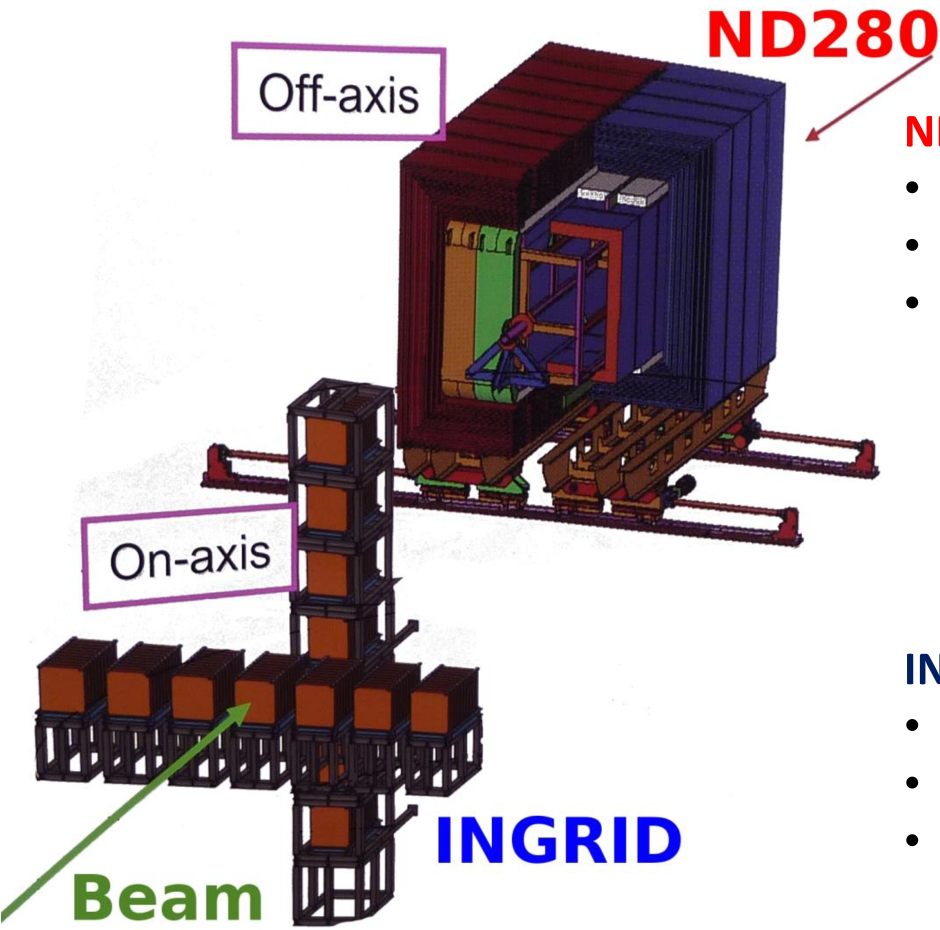
- Enhances CCQE fraction
- Reduces associated pion production





Neutrino Monitor





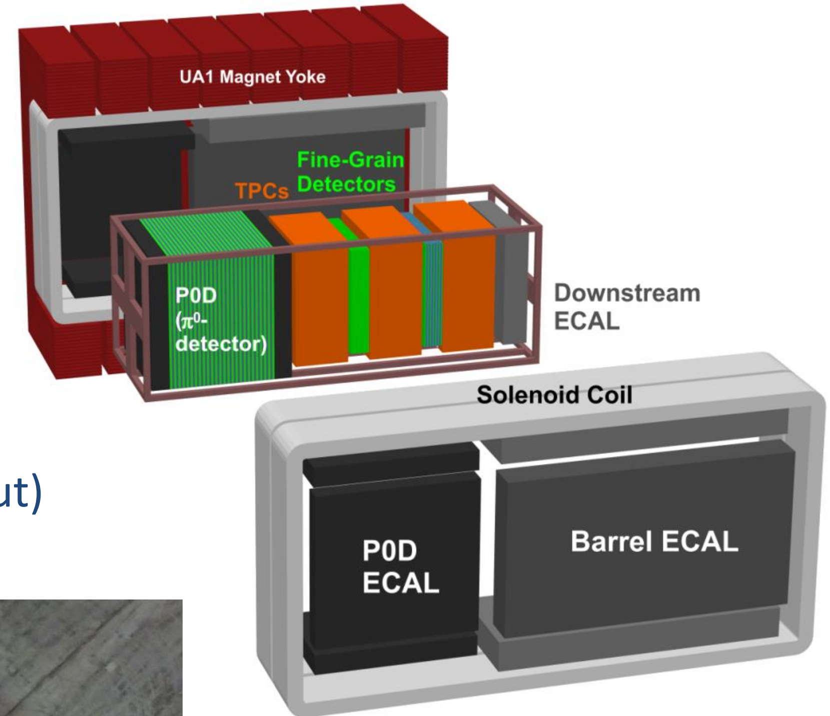
ND280:

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

INGRID:

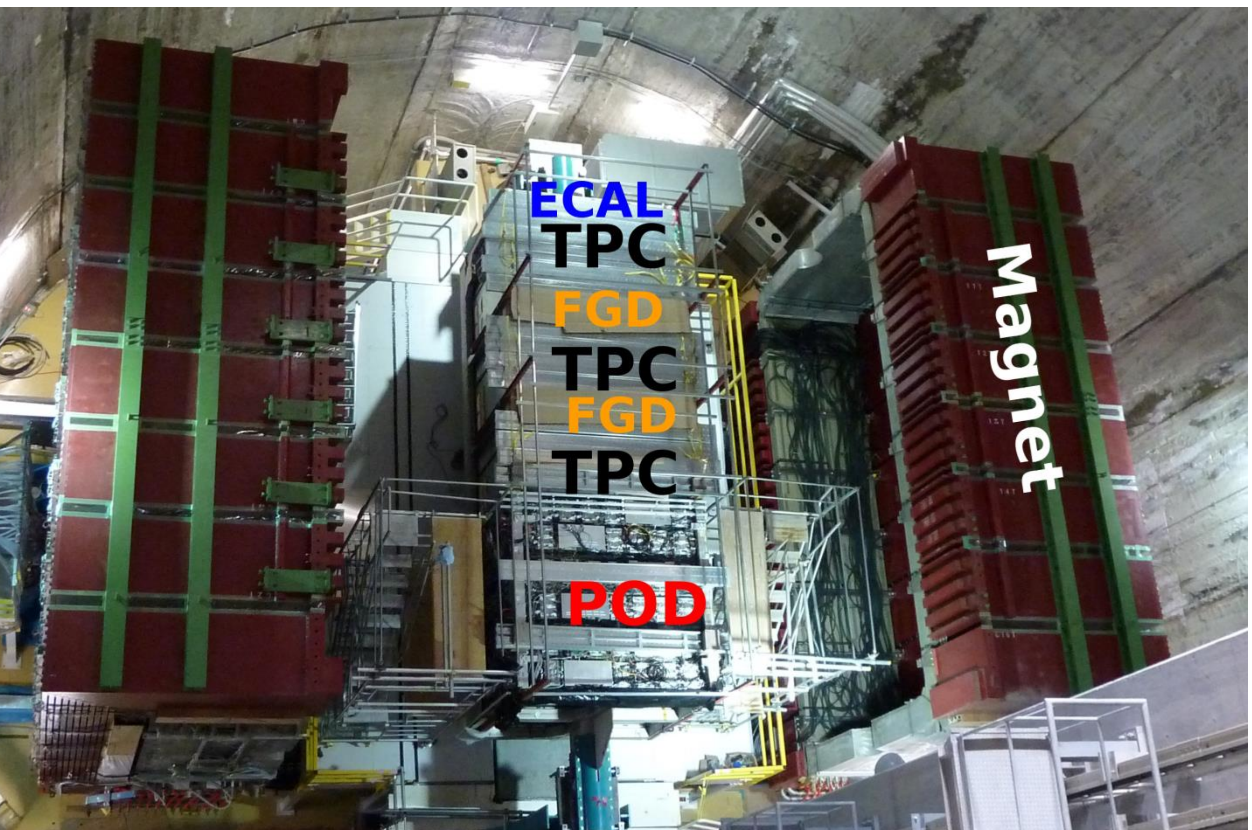
- Iron/Scintillator detector
- Beam profile
- Bunch timing

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)

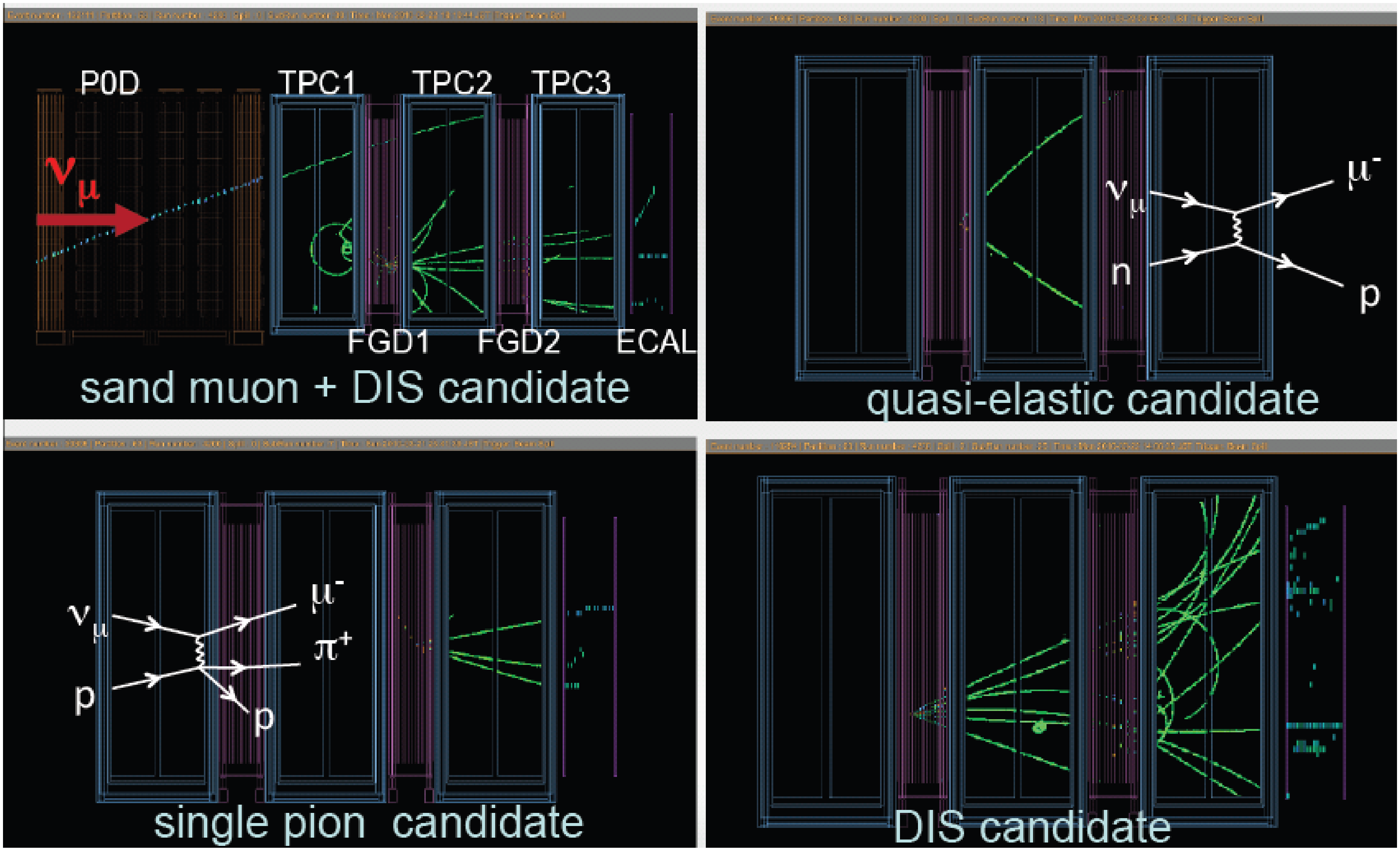


Magnet Moving System

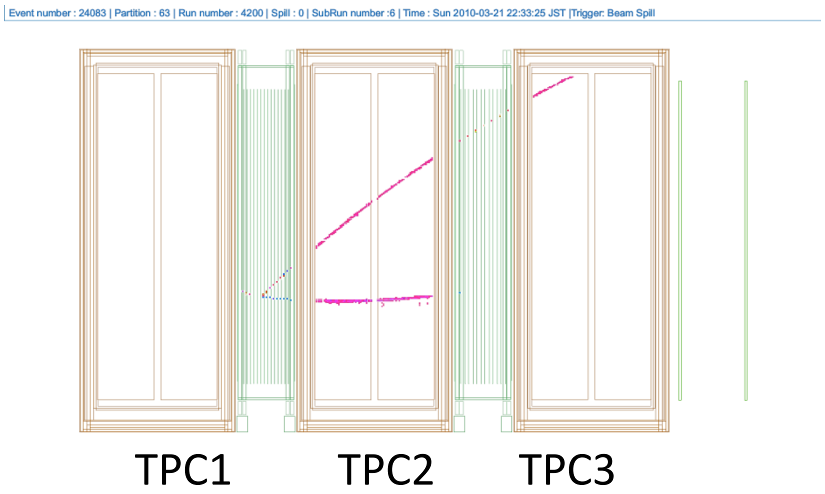
Opening and closing of 900 t UA1 magnet yokes
Adaption of HERA-B guide rollers to the UA1 magnet carriage
Re-use of ZEUS hydraulic movers

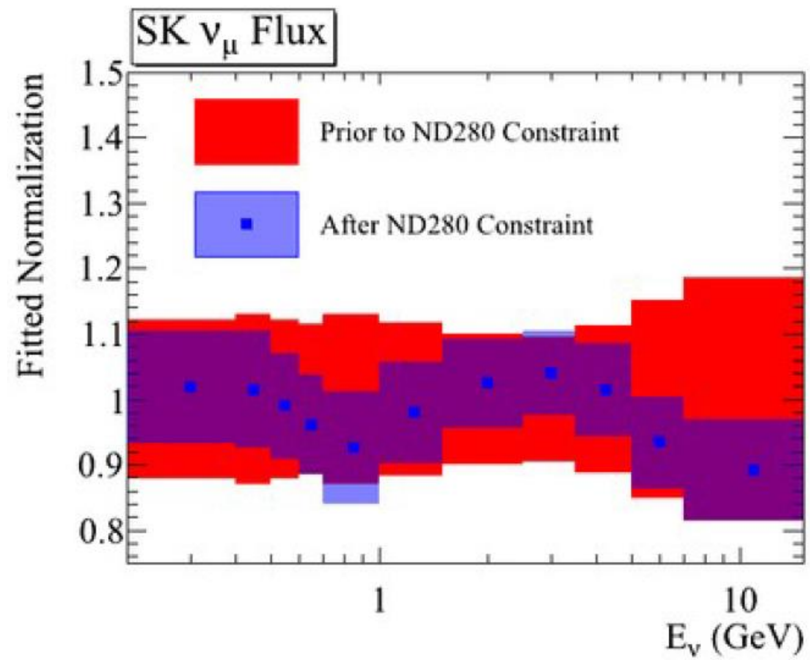
} Many thanks to DESY!

ND280 Event Gallery



Measurement of ν_μ flux at ND280





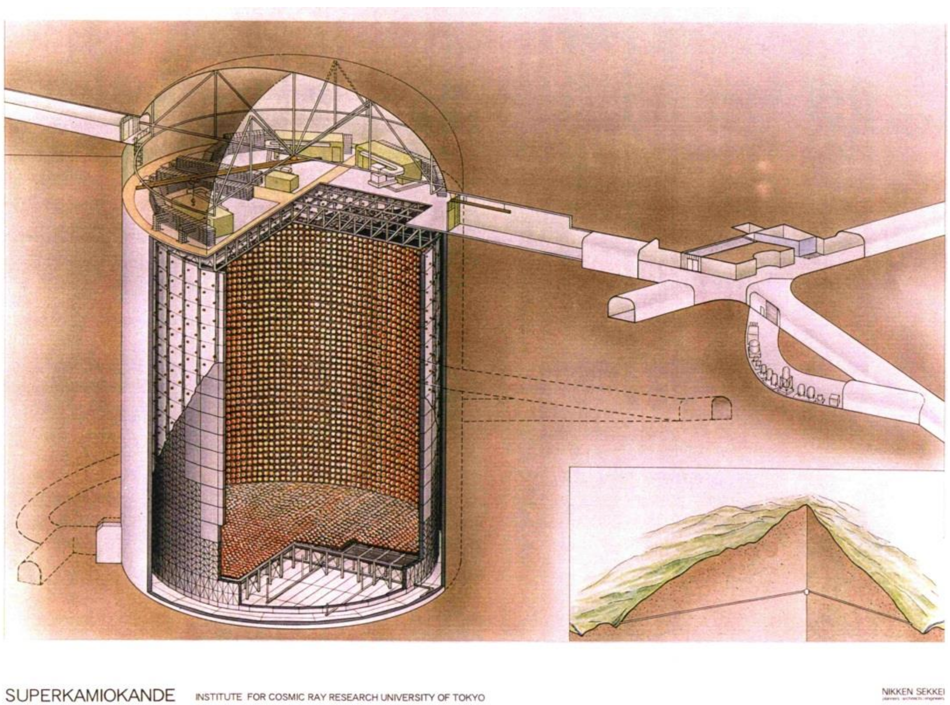
Basic CC event selection at ND280 for ν_μ:

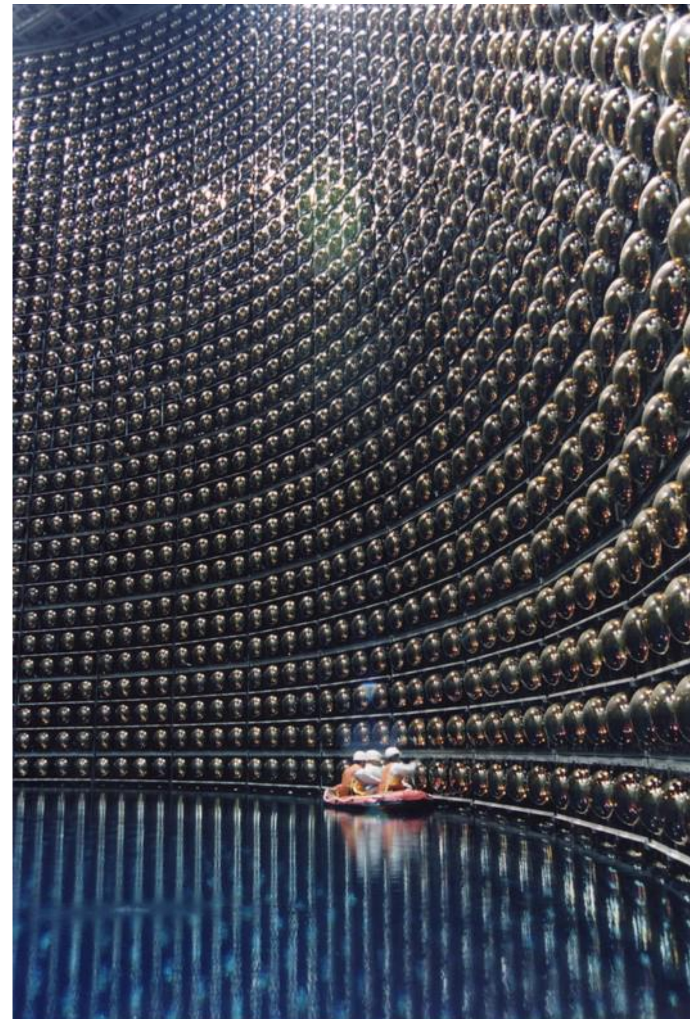
- Use the highest momentum, negative charged TPC track
- Select muon from TPC particle ID

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

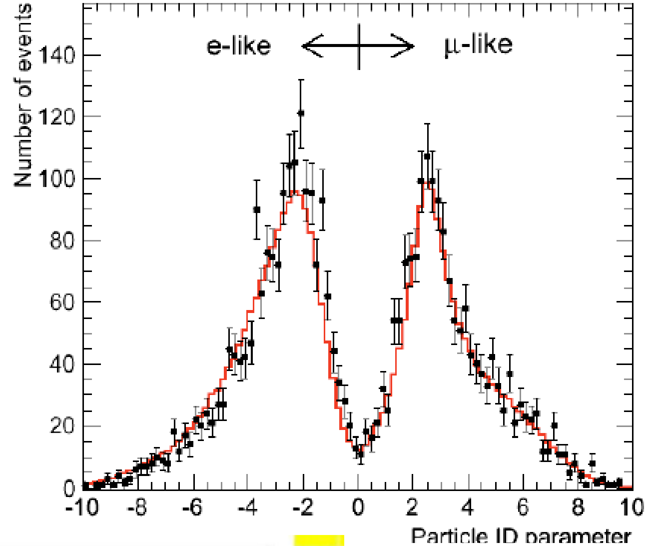
Super Kamiokande

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

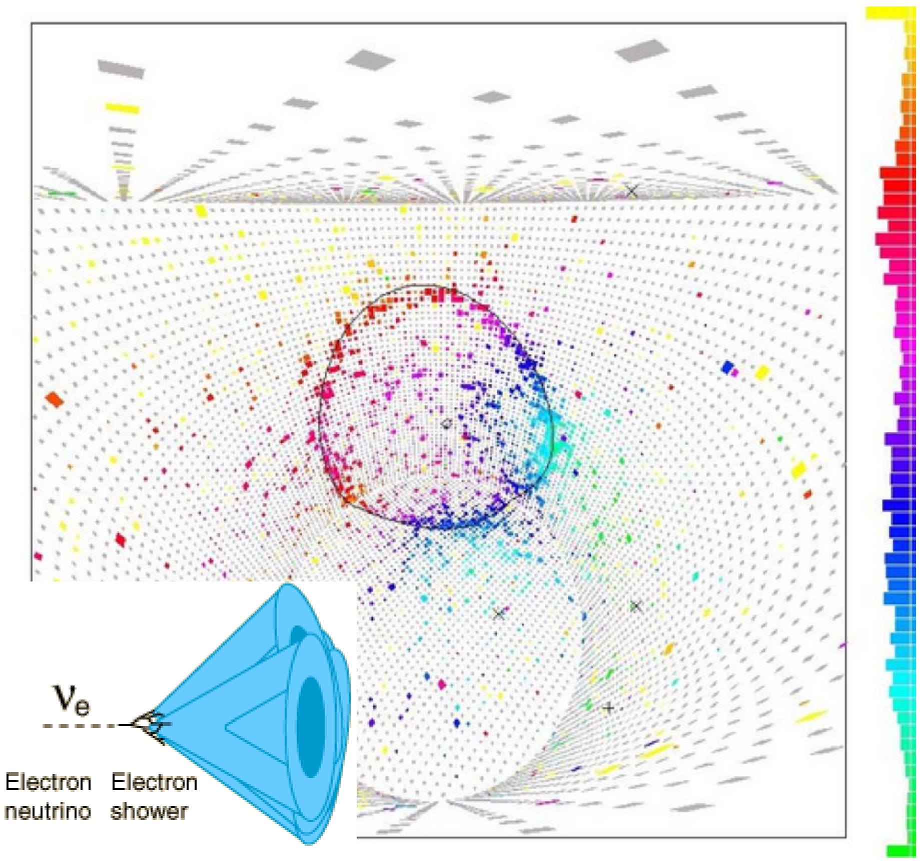




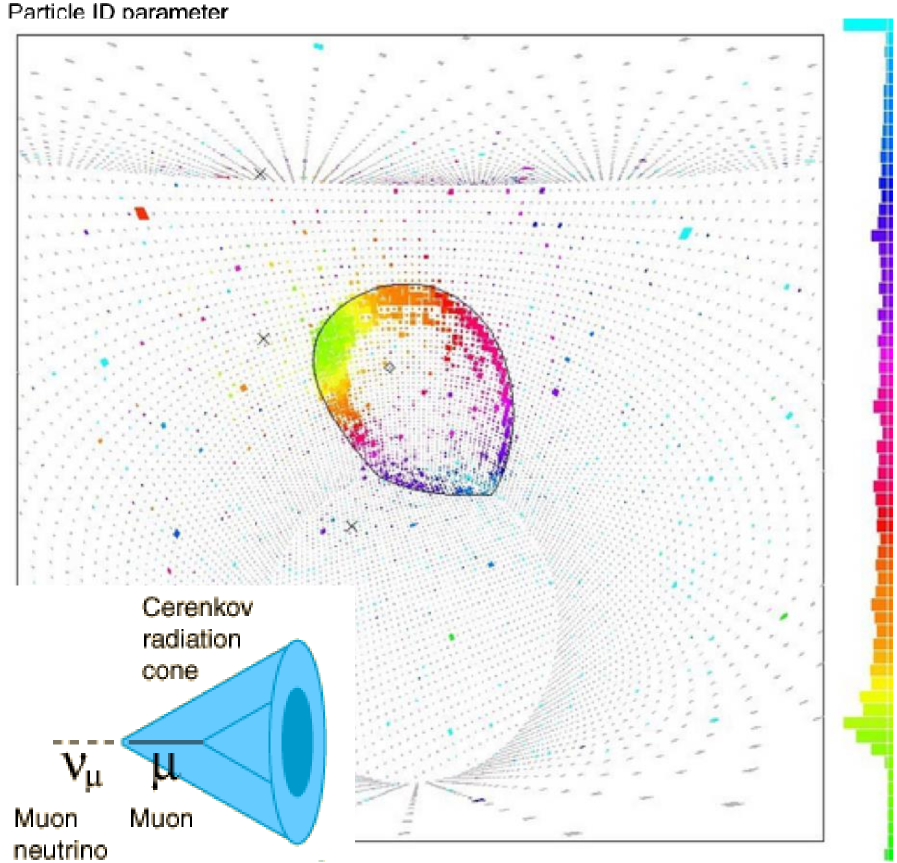
Events at Super K



Electron-like event



Muon-like event

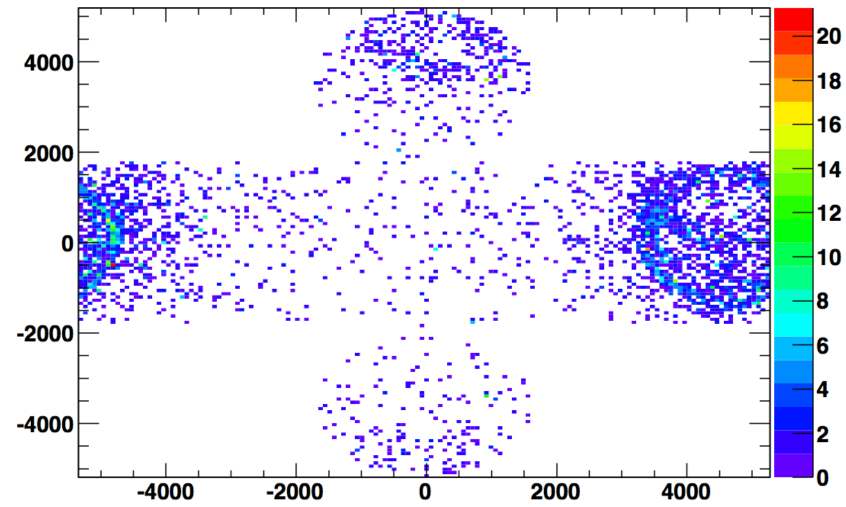


π^0 Background at Super-K

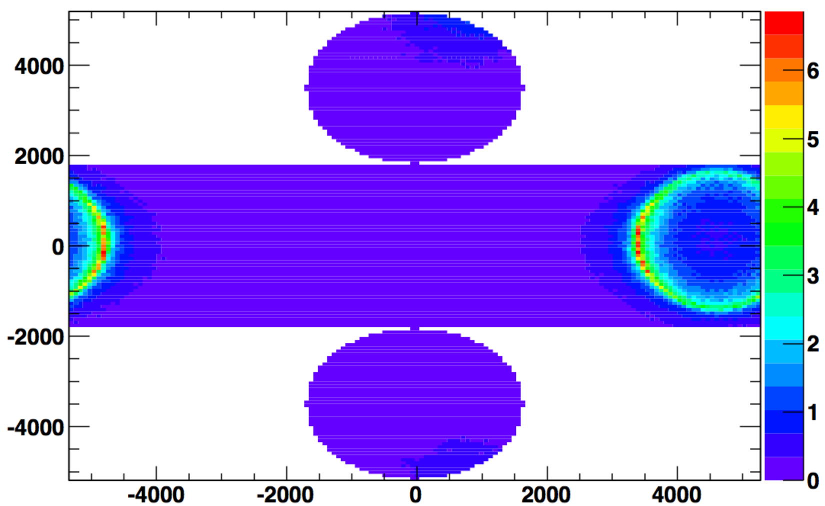
Important Background:

- 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

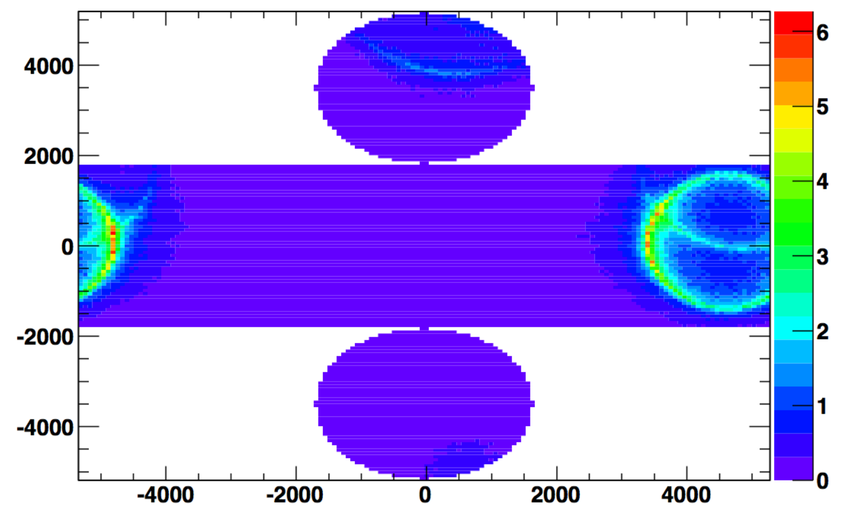
Measured charge



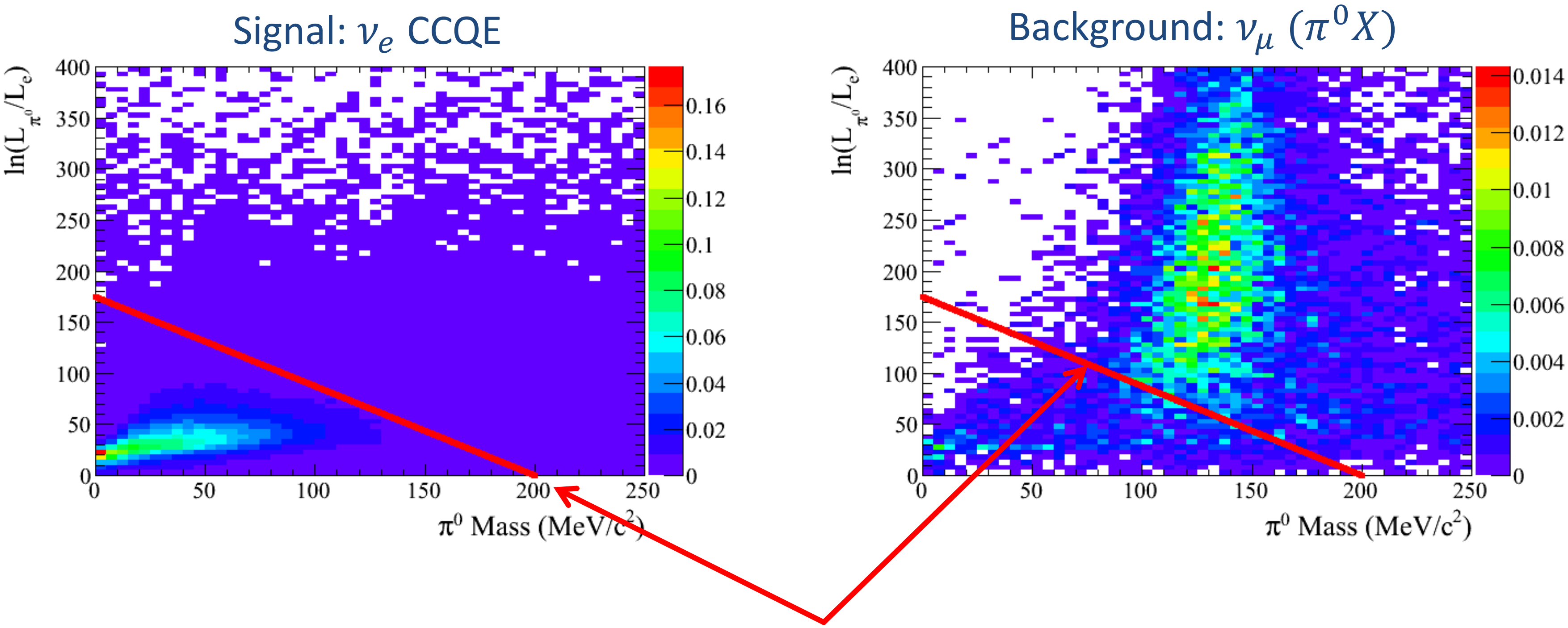
1-ring electron-like fit



2-ring π^0-like fit

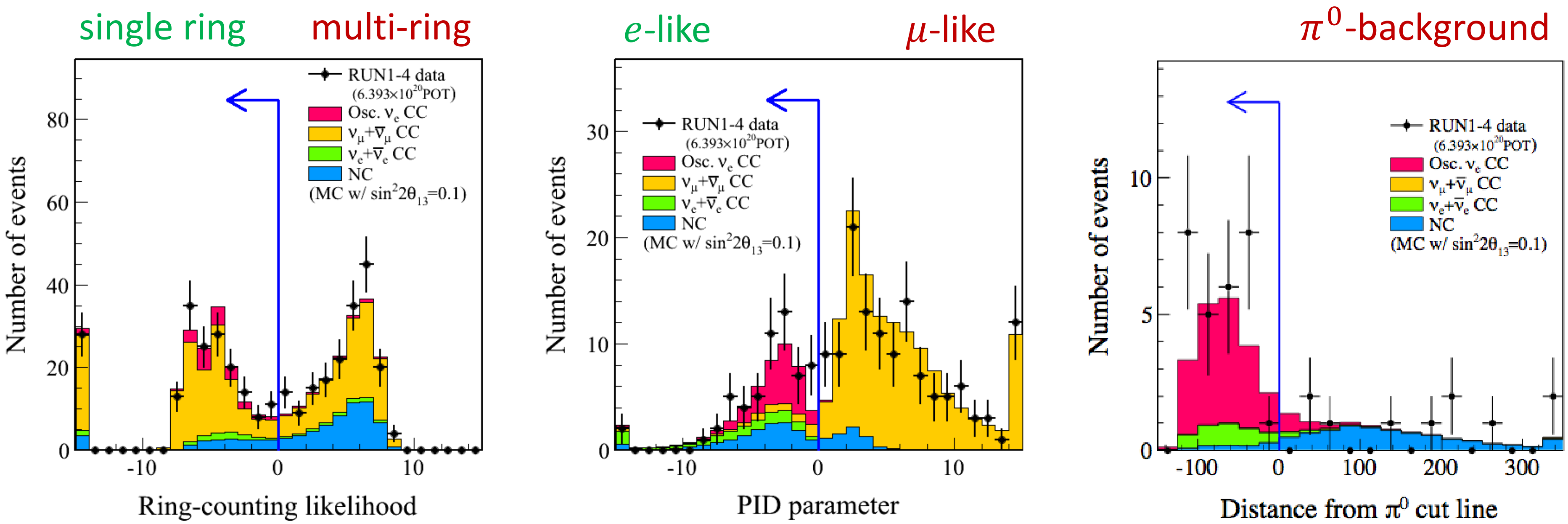


Likelihood ratio vs. π^0 mass



Cut line to seperate π^0 background

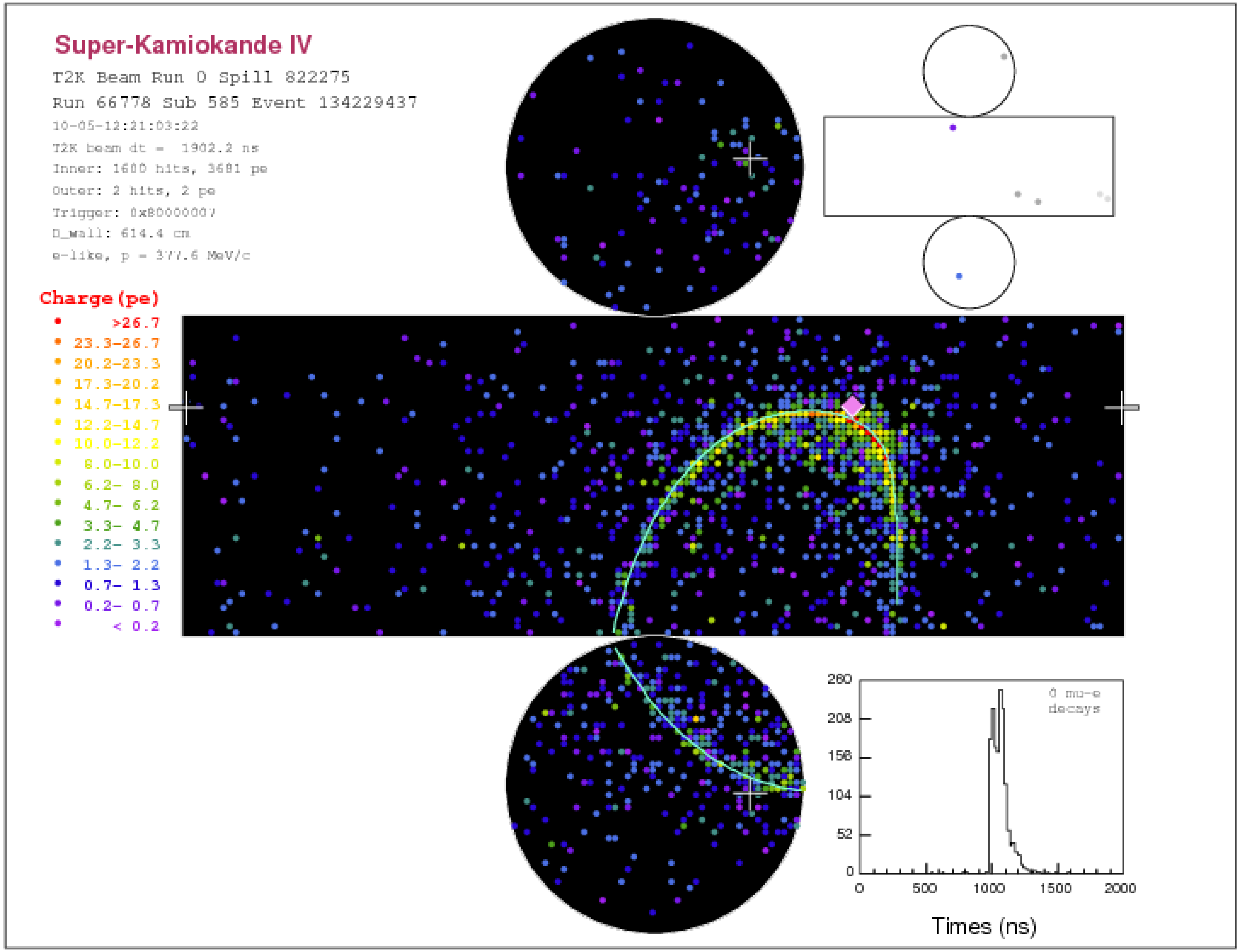
Selection of ν_e Appearance Candidates



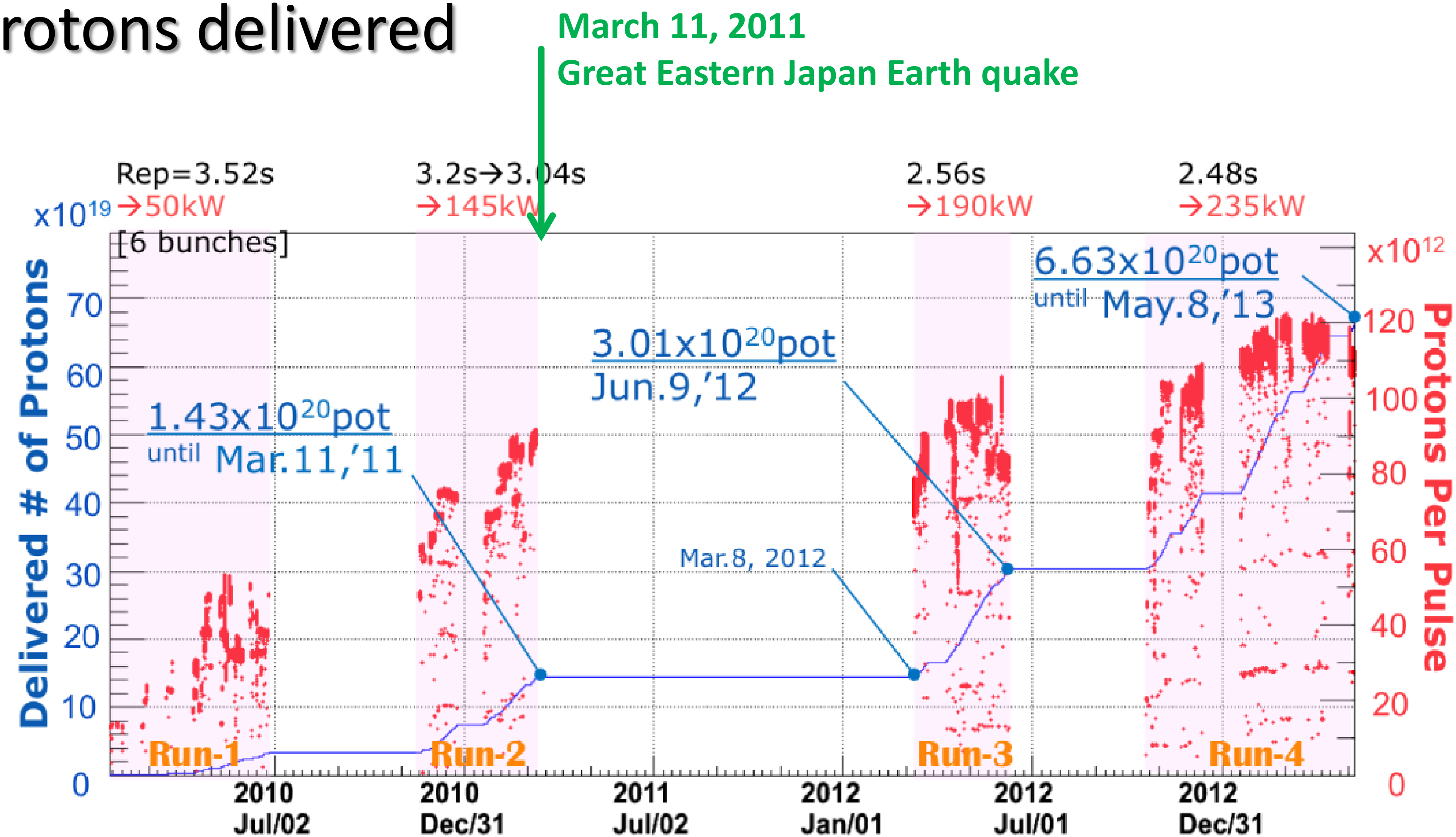
→ Observation of 28 ν_e candidates in $6.4 \cdot 10^{20}$ pot

Appearance of ν_e

First ν_e candidate observed (May 2010)

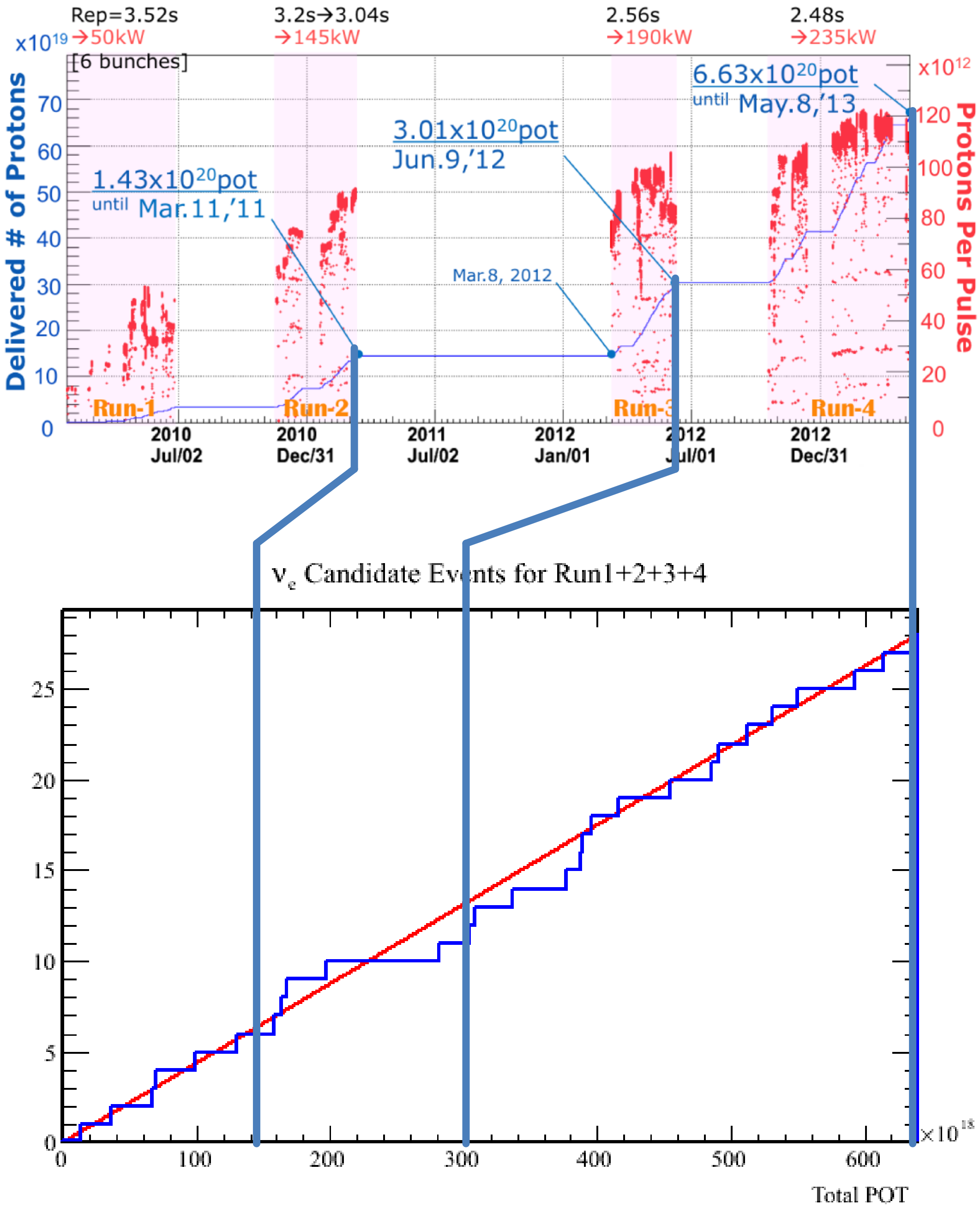


Protons delivered



Successful startup and running → Reached ~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)

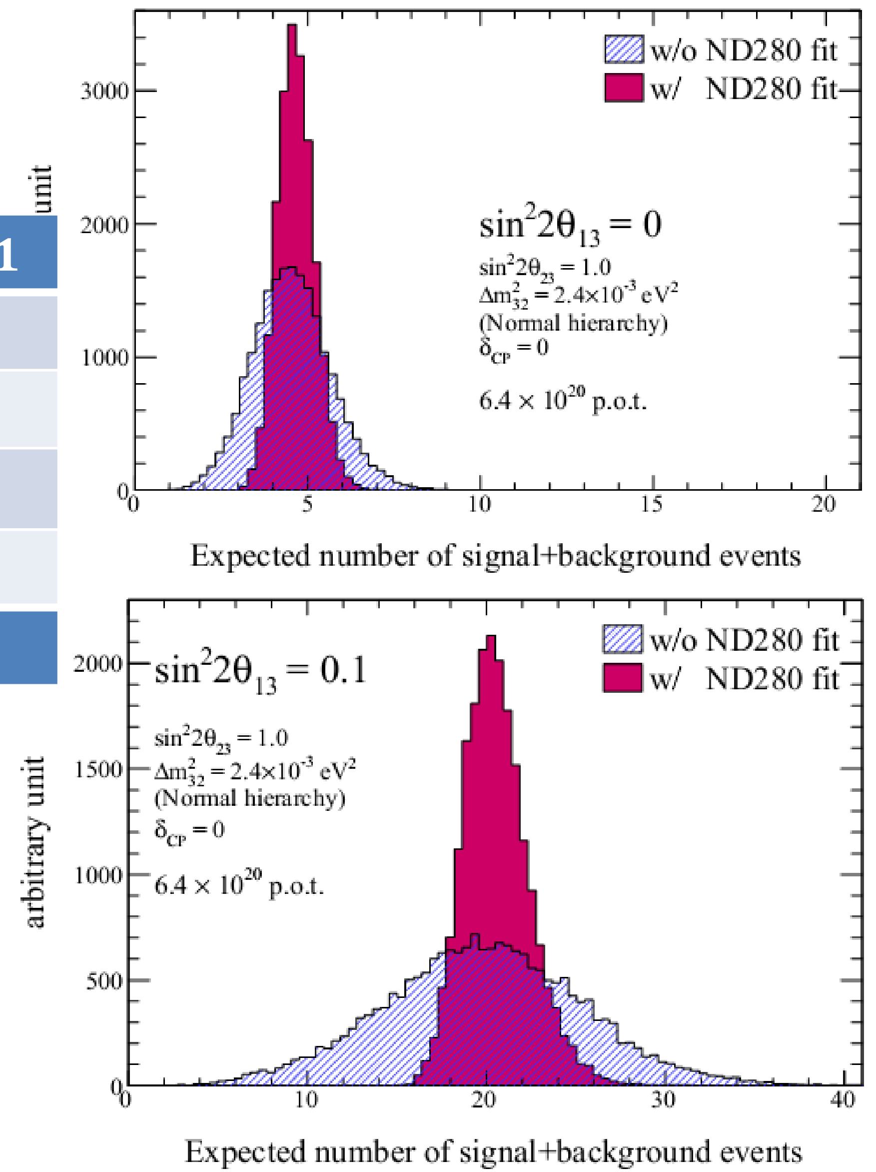
- Runs 1-4: $6.4 \cdot 10^{20}$ pot
  → Observation of ν_e appearance
  with 7.3σ (28 candidates)

Predicted Number of Events

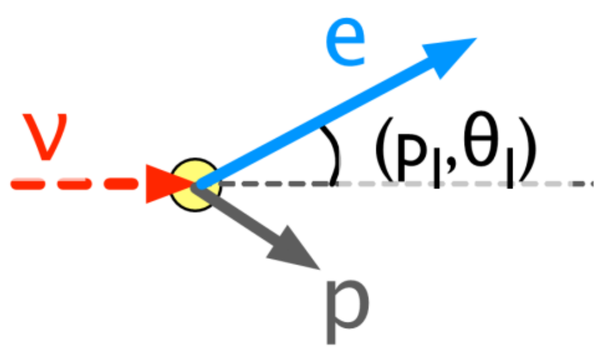
$6.4 \cdot 10^{20}$ pot

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!



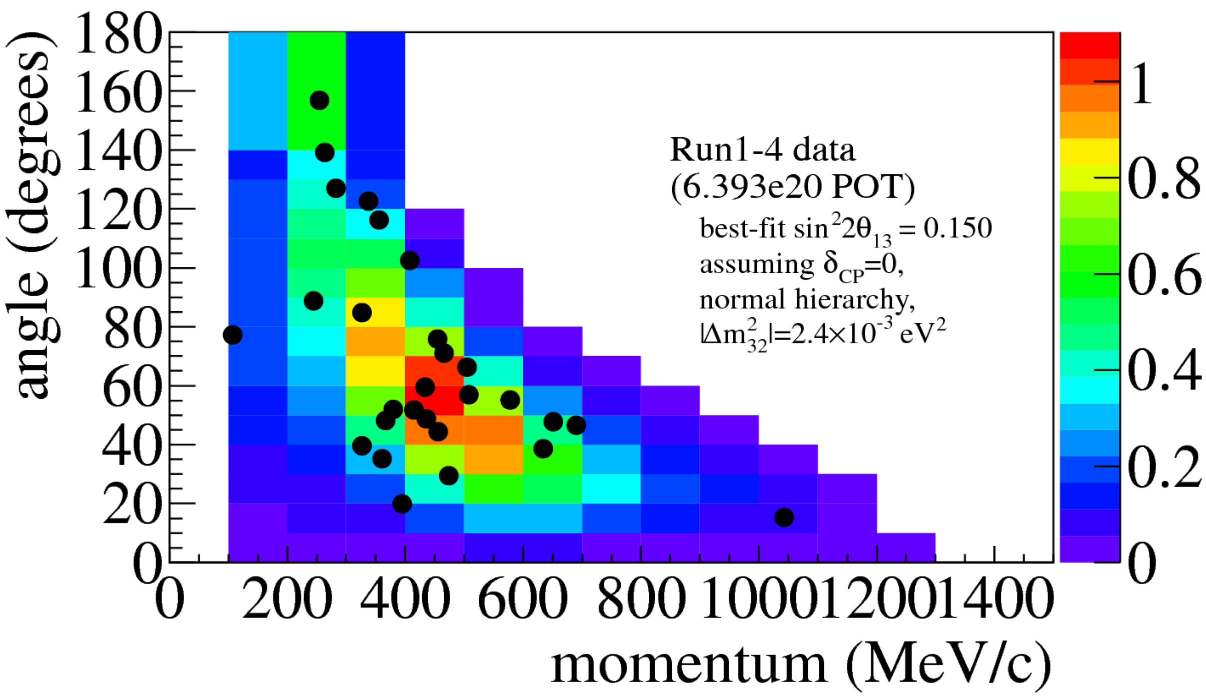
Fit to the Data



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

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



No oscillation hypothesis is excluded at 7.3 σ

Interpretation of ν_e data

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

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

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

for each value of δ_{CP}

→ Sensitivity to CP violating phase δ_{CP}:

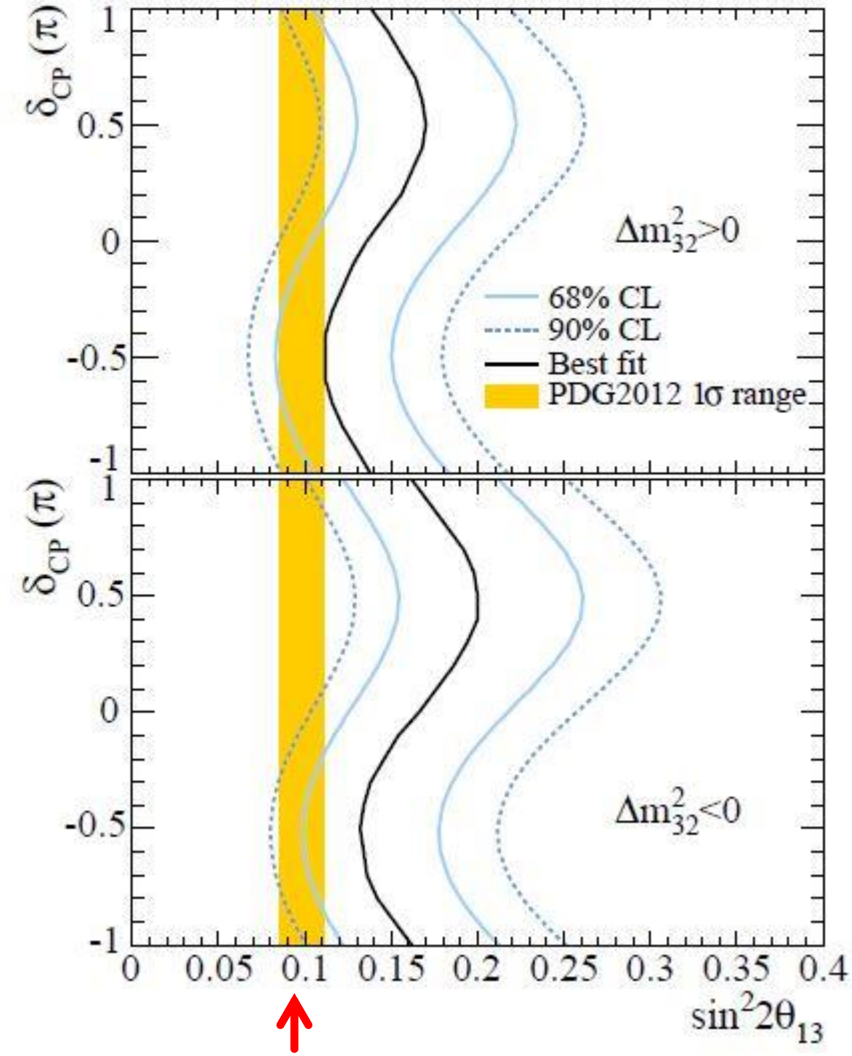
For normal mass hierarchy ($\Delta m^2_{32} > 0$)

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

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:

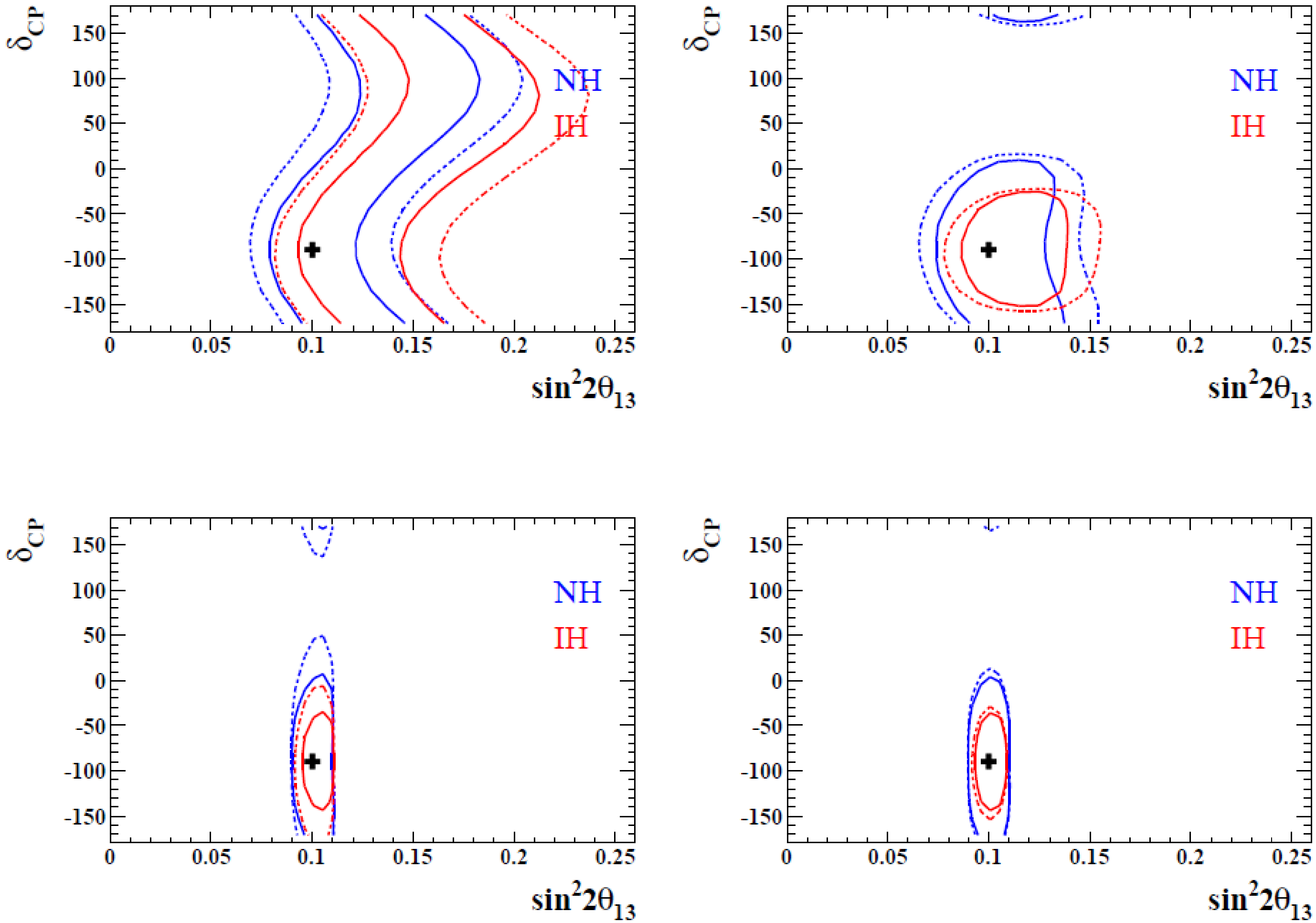
$\sin^2 2\theta_{13} = 0.098 \pm 0.013$ (PDG 2012)

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



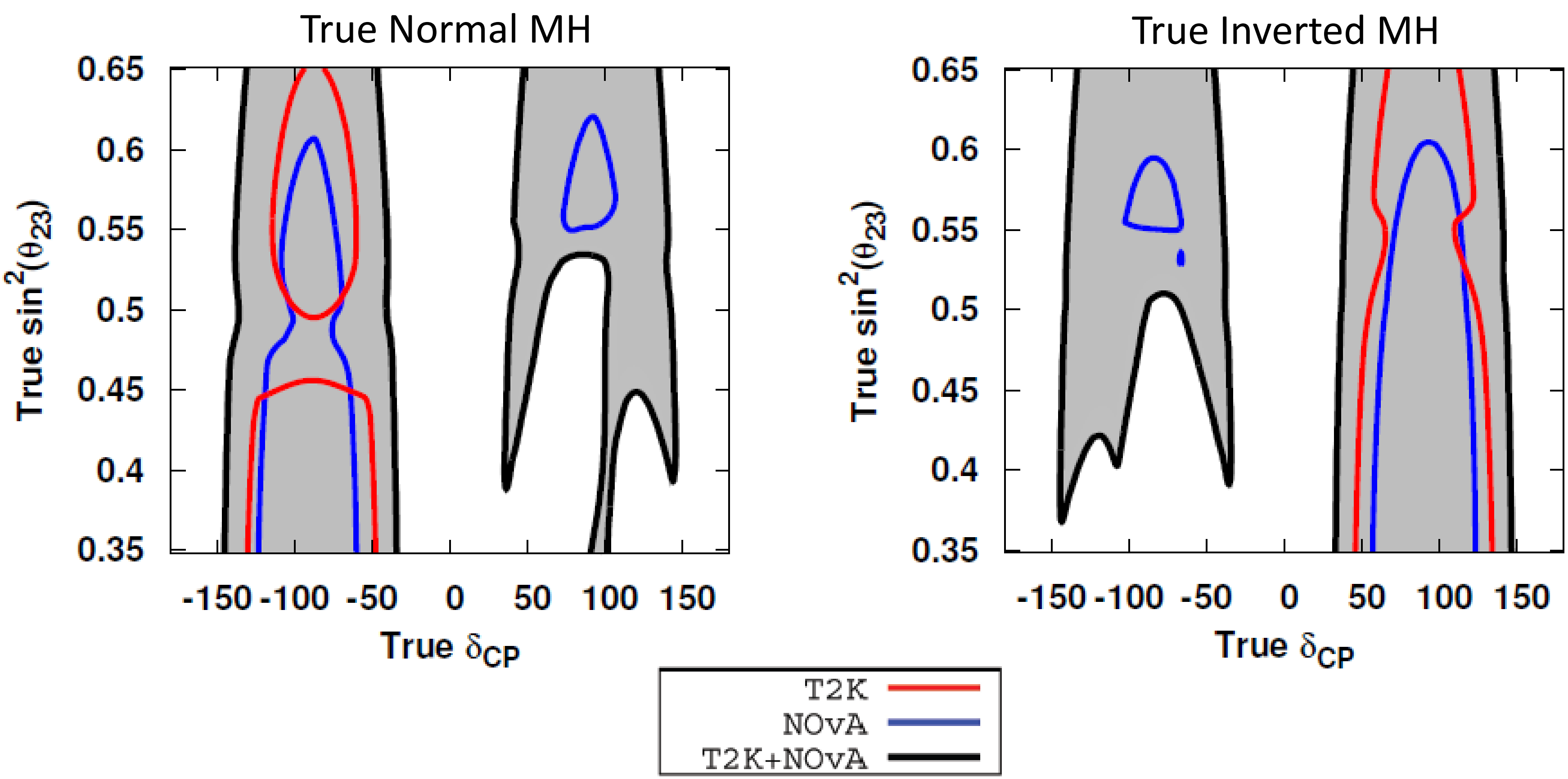
Without reactor constraint

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)**