Measuring θ_{13}:

T2K & Double Chooz

Federico Sánchez

IFAE

III Jornadas CPAN

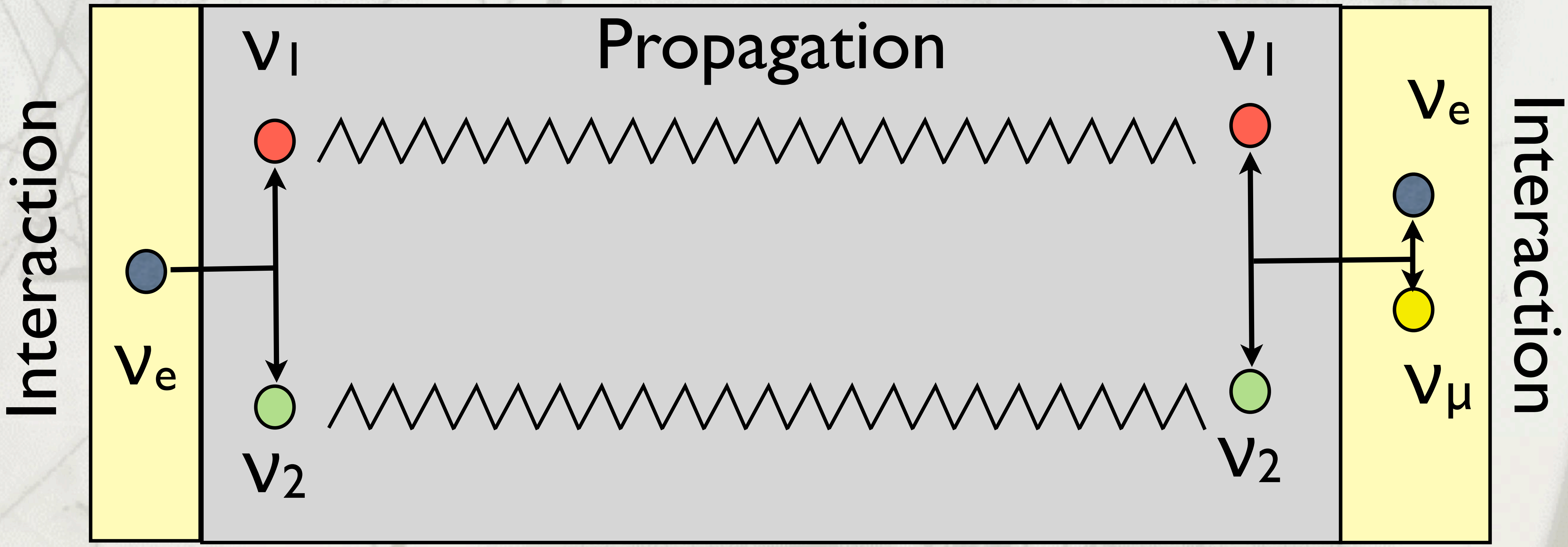
Barcelona, del 2 al 4 de noviembre de 2011

Outlook

- Oscillation in a “nutshell” .
- Long base line vs reactor experiments
- Spanish contribution to neutrino oscillations:
    - T2K
    - Double-Chooz
- Conclusions and final remarks

Neutrino oscillation

- Neutrinos are produced always as a flavor neutrino but they propagate in vacuum as mass eigenstates.
- Mass eigenstates != flavour eigenstates.



- If neutrinos 1 & 2 propagate at different speeds (mass) keeping the quantum coherence at the interaction point the proportions between 1 & 2 states changes and it might appear other neutrino flavor.

Oscillations with 3 ν's

Mass eigenstates != flavour eigenstates

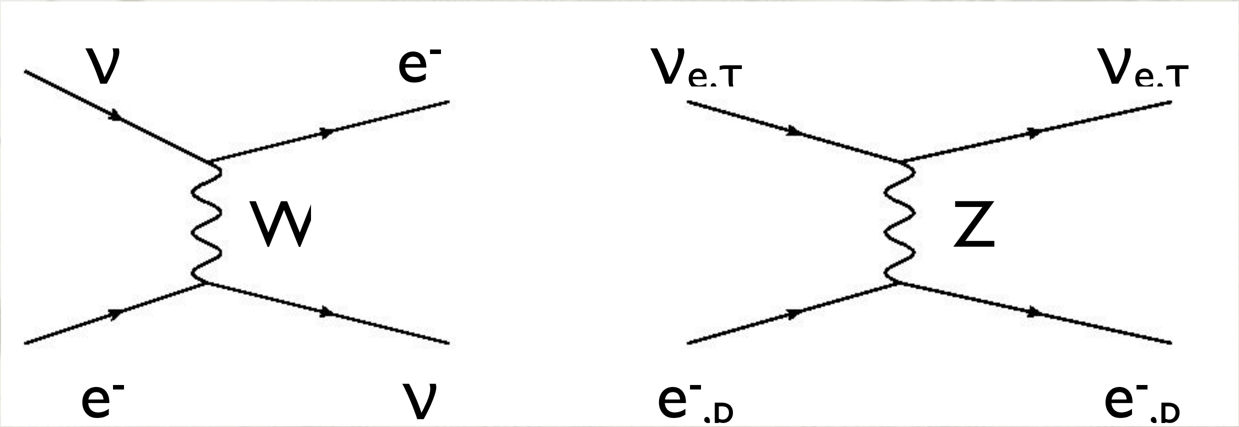
$$U_{PNMS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta_{CP}} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$\begin{pmatrix} \nu_e & \nu_\mu & \nu_\tau \end{pmatrix} = U_{PNMS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- With 3ν, there are 3 angles and 1 imaginary phase (δ).
- The phase allows for CP violation similar to the quark sector.
- There are also 2 values of Δm^2, traditionally Δm^2_{12} & Δm^2_{31} with their signs.
- Oscillations are not sensitive to absolute mass.

Neutrinos in matter

- Neutrino oscillations are altered by interaction with matter.
- This is actually the model for solar neutrino oscillation model.
- Neutrinos can have two types of interaction with matter:
  - Incoherent inelastic: $\sigma \sim 10^{-43}$ (E/MeV)^2
  - Coherent. The medium is unchanged and the scattered and un-scattered waves interfere enhancing the effect.
  - It introduces a phase in the propagation, that can be invisible except for the fact that matter is made of electrons. The matter effects introduce a relative phase between electrons and other flavours.



Measurements

$\theta_{12}, \Delta m^2_{12}$

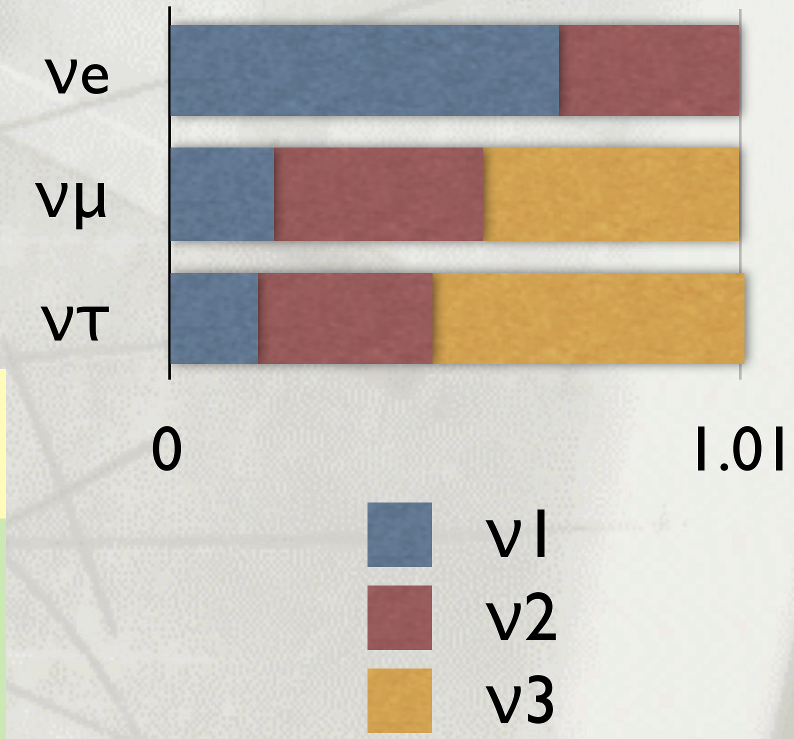
- Natural sources (neutrinos from the sun) : SNO, SuperKamiokande, Borexino, Gallex, GNO, SAGE, Homestake.
- Man-made sources (nuclear reactors): Kamland.

$\theta_{32}, \Delta m^2_{32}$

- Natural sources (atmospheric neutrinos): SuperKamiokande.
- Man-made sources(accelerators): K2K, Minos.

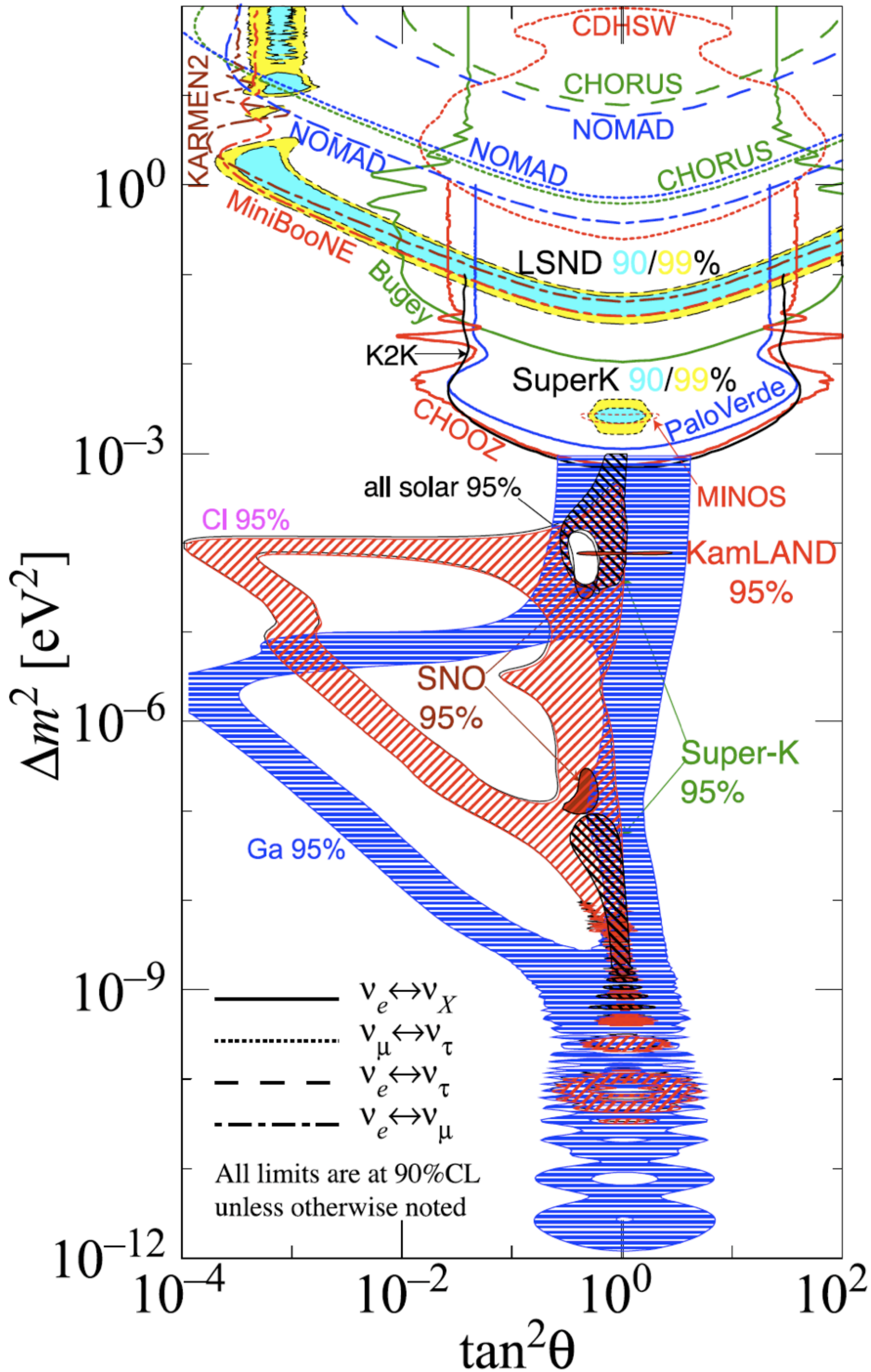
The usual "we know"

$$\Delta m^2_{21} = 7.67^{+0.22}_{-0.21} \times 10^{-5} eV^2$$
$$|\Delta m^2_{31}| = 2.46 \pm 0.15 \times 10^{-3} eV^2$$
$$\theta_{12} = 34.5^o \pm 1.4$$
$$\theta_{23} = 42.3^o \pm +5.1 - 3.3$$ Maximal?
$$\theta_{13} < 10.1^o (90\% C.L.)$$
$$\delta_{CP} \in [0^o, 360^o]$$



- Still a long way to go!. But, it might be closer that we think!.
- Most urgent: values of δ_{CP}, θ_{13}, absolute mass scale.

Angles and masses



Particle data group review

θ_{13}: accelerators vs reactors

Accelerator T2K

- Appearance experiment.
- Oscillation depends on θ_{13}, θ_{23}, sign Δm^2, δ_{CP} and matter effects:
  - degeneracies.
  - possible sign Δm^2 & δ_{CP}
- Multipurpose: several oscillation (θ_{23}, steriles) and non-oscillation physics.
- Experimental challenges:
  - beam intensity, flavor composition and flux extrapolation.
  - ν N interaction cross-sections.

Reactor Double Chooz

- Disappearance experiment.
- Oscillation depends on θ_{13}.
  - No degeneracies except for θ_{23} obtained from accelerators.
- No access to sign Δm^2 & δ_{CP}
- Experimental challenges:
  - backgrounds
  - systematic uncertainties.

Reactors

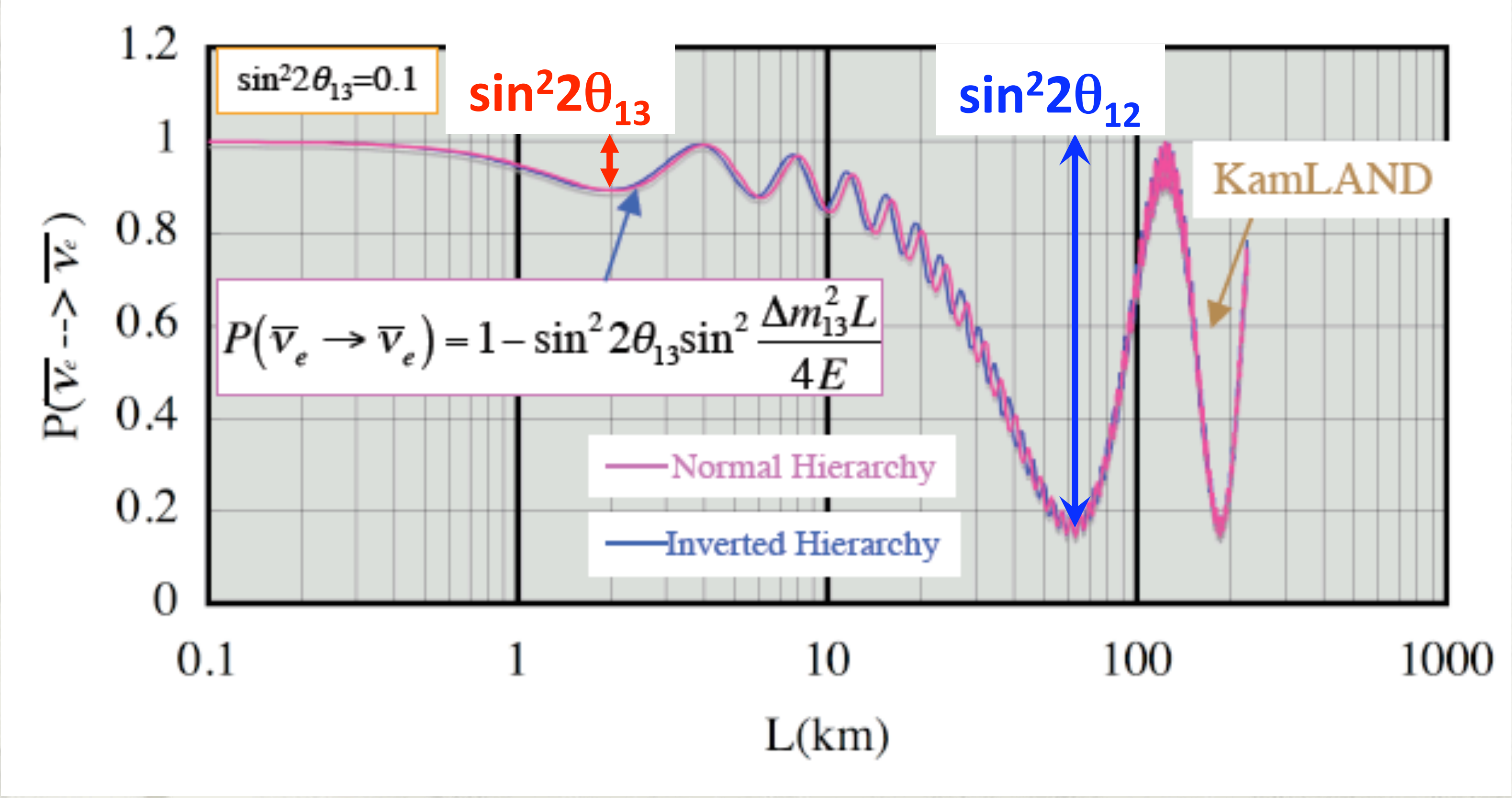
3 senior staff, 2 postdocs, 2 phD, 3 engineers, 2 technical staff.

(PI: I.Gil Botella)

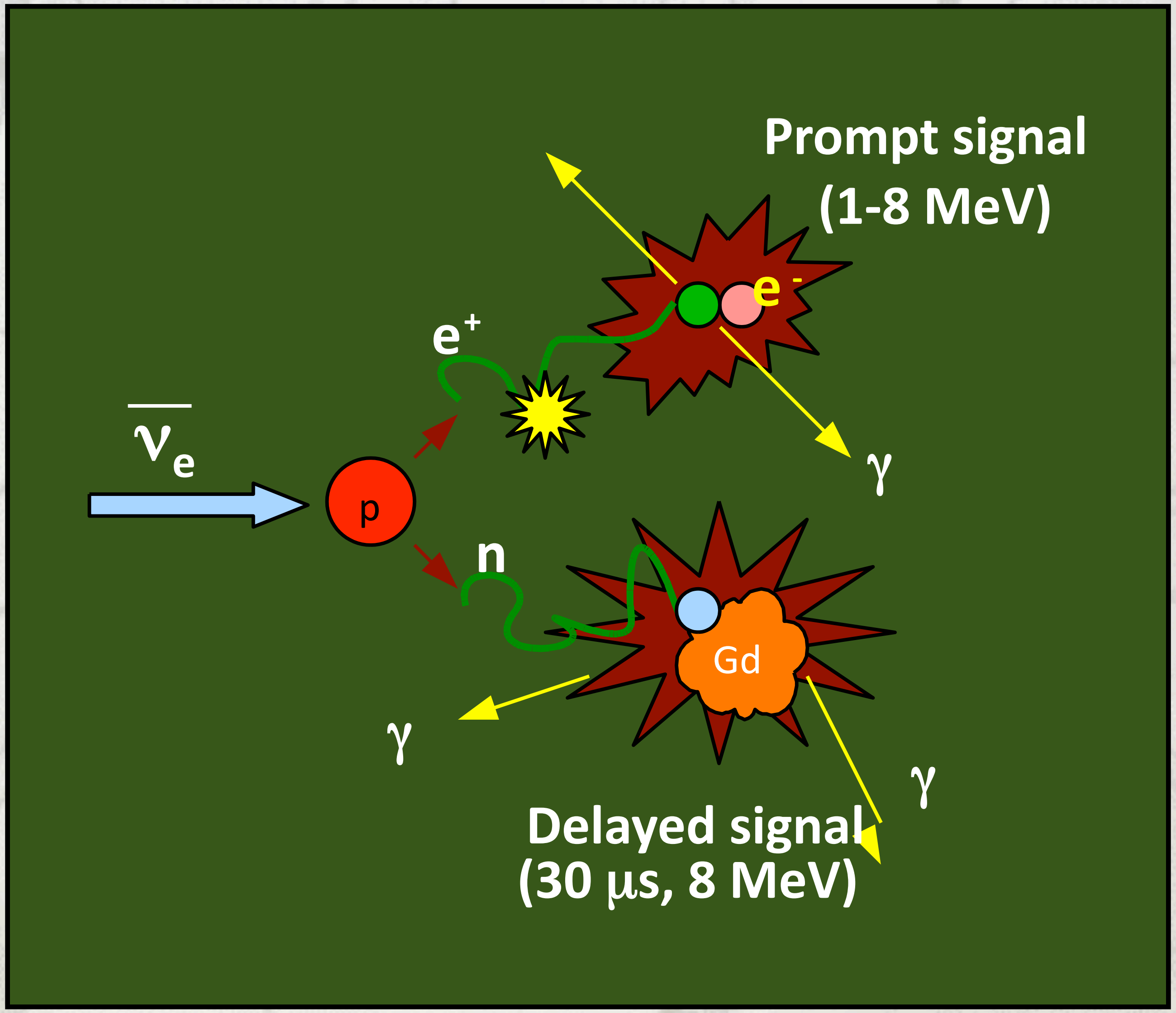
Reactor principle.

Clean measurement

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{13}^2 L}{4E_\nu}\right) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\left(\frac{\Delta m_{21}^2 L}{4E_\nu}\right)$$



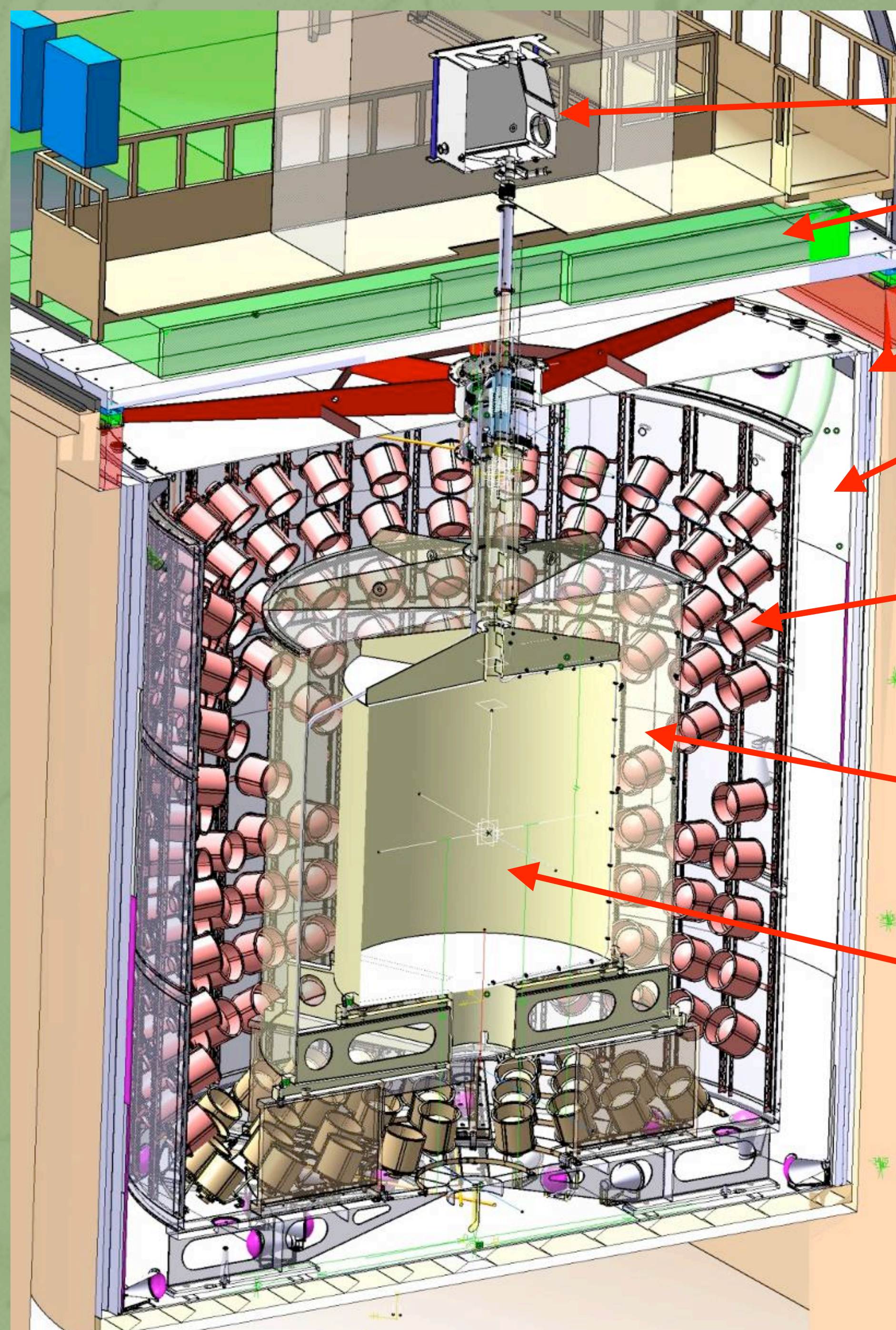
Reactor principle



- Prompt photons from **e⁺** annihilation:
  - $E_{VIS} \sim \mathbf{E}_{\nu} - (M_n - M_p) + m_e$
- Delayed photons from **n** capture:
  - on H : t ~200 s, E~2 MeV
  - on Gd: t ~30 s, E ~8 MeV

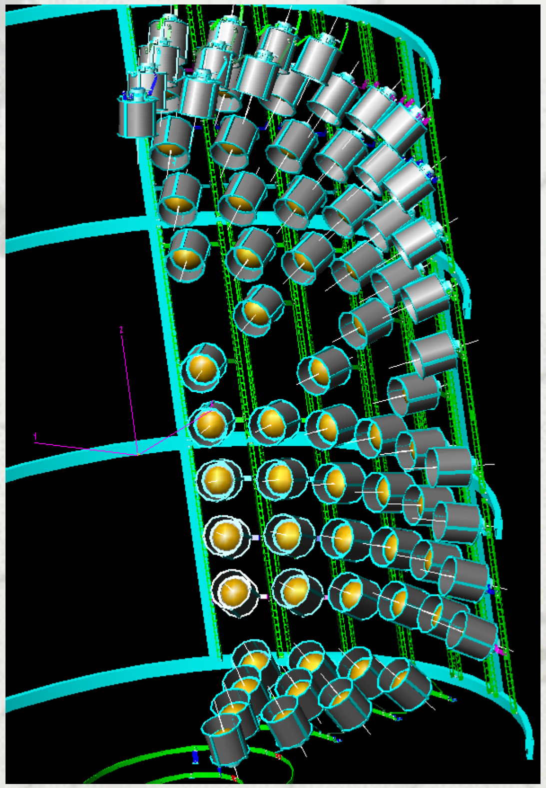
Double Chooz

Detector design



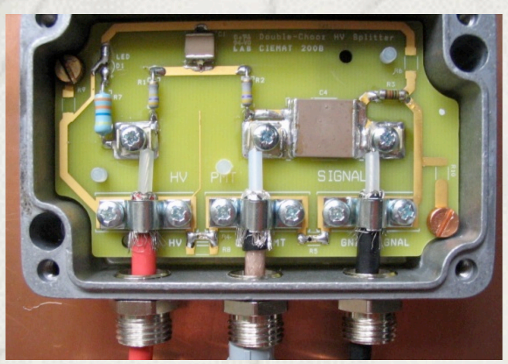
- **Calibration glove box**
- **Outer veto**: plastic scintillator strips
- **Shielding**: 15 cm steel
- **Inner veto**:
  - 90 m^3 of liquid scintillator & 78 8” PMTs
- **Buffer**:
  - 110 m^3 of non scintillating mineral oil & 390 10” PMTs
- **Gamma-catcher**:
  - 22.3 m^3 of liquid scintillator
- **Target**:
  - 10.3 m^3 of liquid scintillator doped with 1 g/L of Gd

Double Chooz



DETECTOR MECHANICS
- Design and construction of special tools for acrylics installation
- Design, construction and assembly of PMT mechanical supports
- Installation of PMTs in the detectors

PHOTODETECTION SYSTEM
- PMT functionality tests
- PMT characterization under magnetic field
- Design, tests, production and assembly of PMT magnetic shields



COMMON FUND
- Filling system
- Buffer and veto liquids
- Safety systems
- Running costs

ELECTRONICS
- Design, tests, production and installation of PMT HV splitters

ONLINE SYSTEM
- DAQ Event Builder development

SIMULATION, DATA RECONSTRUCTION AND PHYSICS ANALYSIS
- Detector simulation software
- Data reconstruction algorithms
- Background simulation
- Analysis tools for sys. and sens. estimation
- Coordination of the European cluster

GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA E INNOVACIÓN

Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

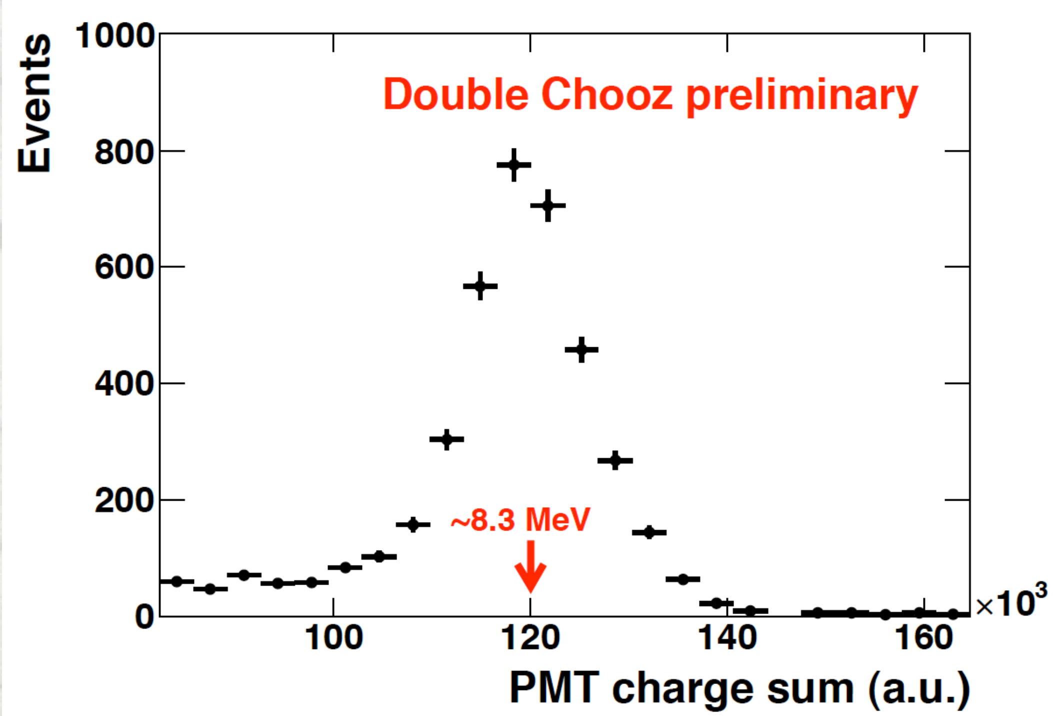
Double Chooz

GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA E INNOVACIÓN

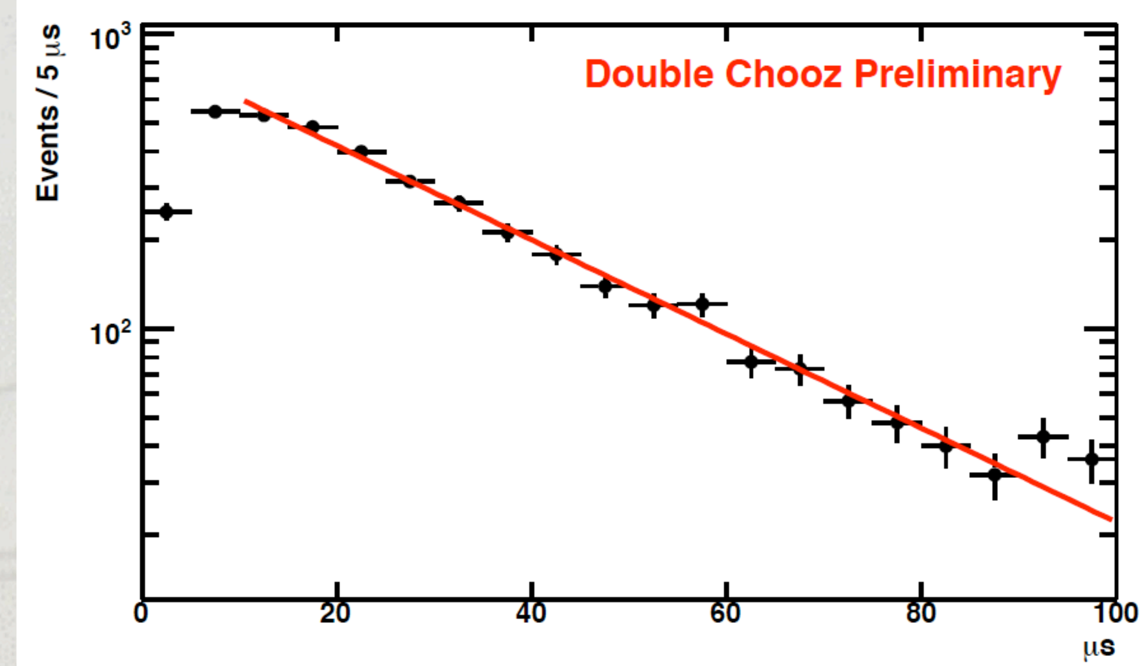
Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

Neutrino detection

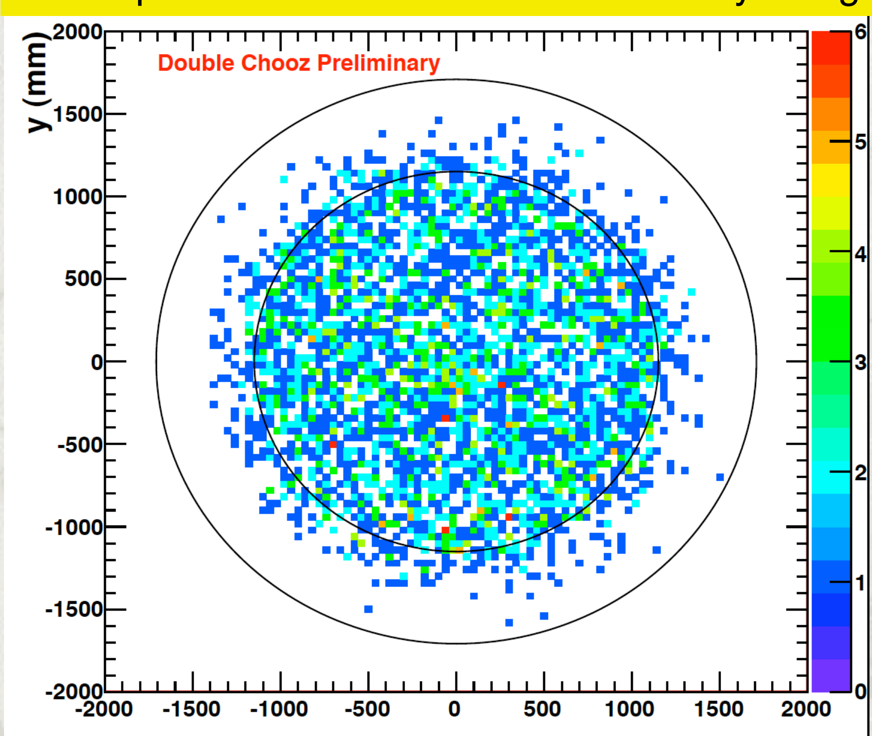
Energy spectrum in the delayed Gd-energy window (6 – 12 MeV)



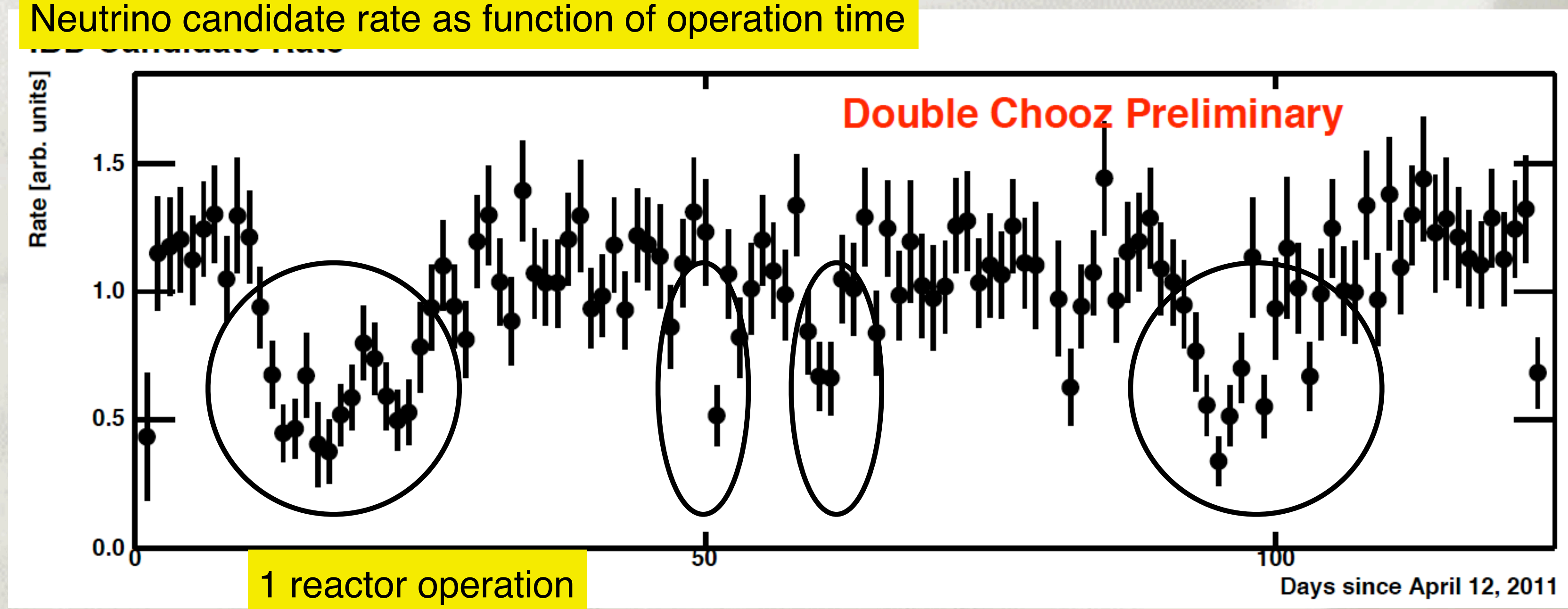
Timing distribution between prompt and delayed signal
n-capture on Gd ~ 30 μs



Vertex position reconstruction of the delayed signal



Neutrino candidate rate as function of operation time

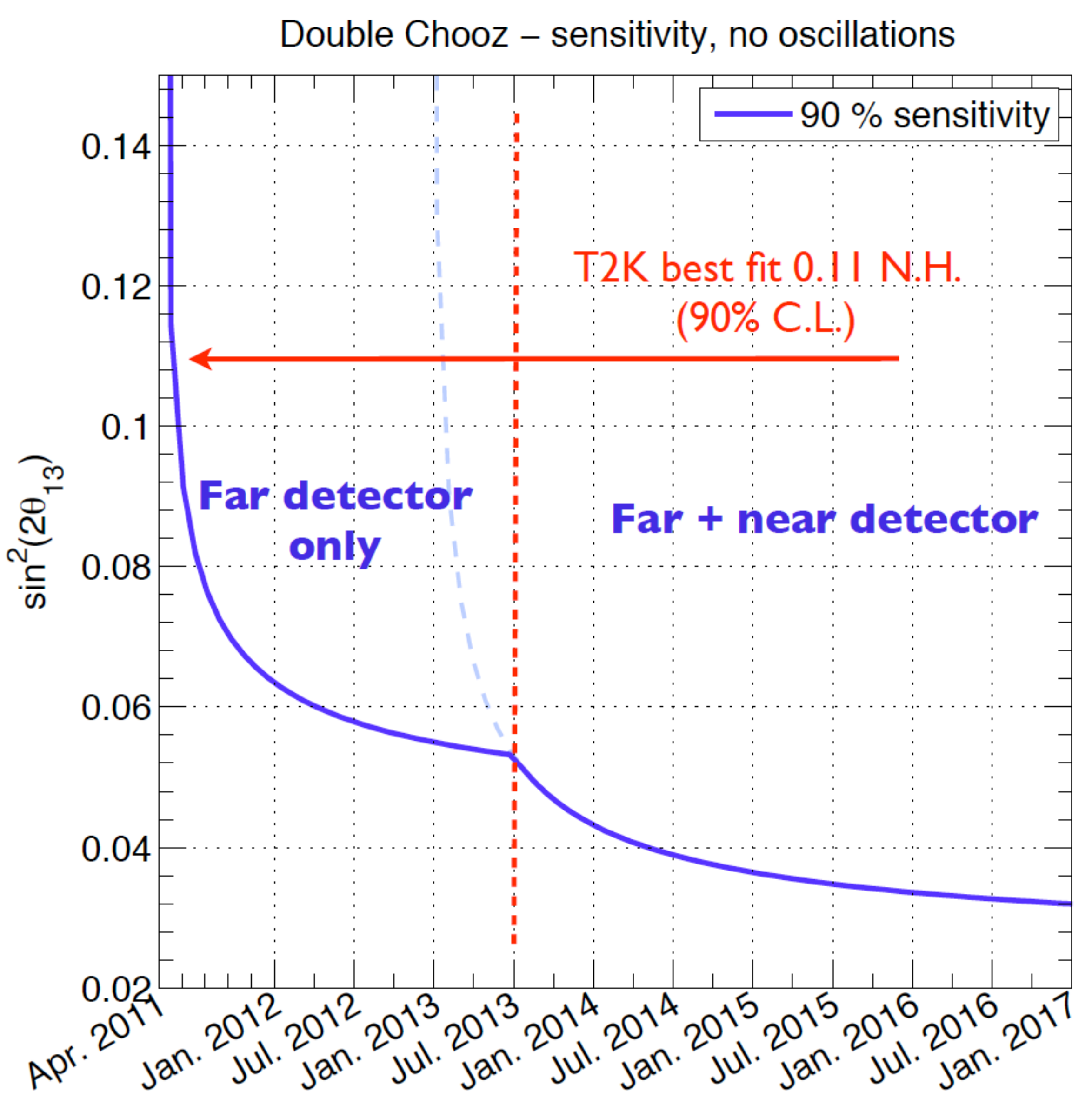


1 reactor operation

Double Chooz

- T2K best fit can be addressed with 2011 statistics.

Results are expected very soon.



Accelerators

T2K

IFAE 1 senior staff, 2 postdocs, 2 phD, 1 engineer (P.I.: F.Sanchez)

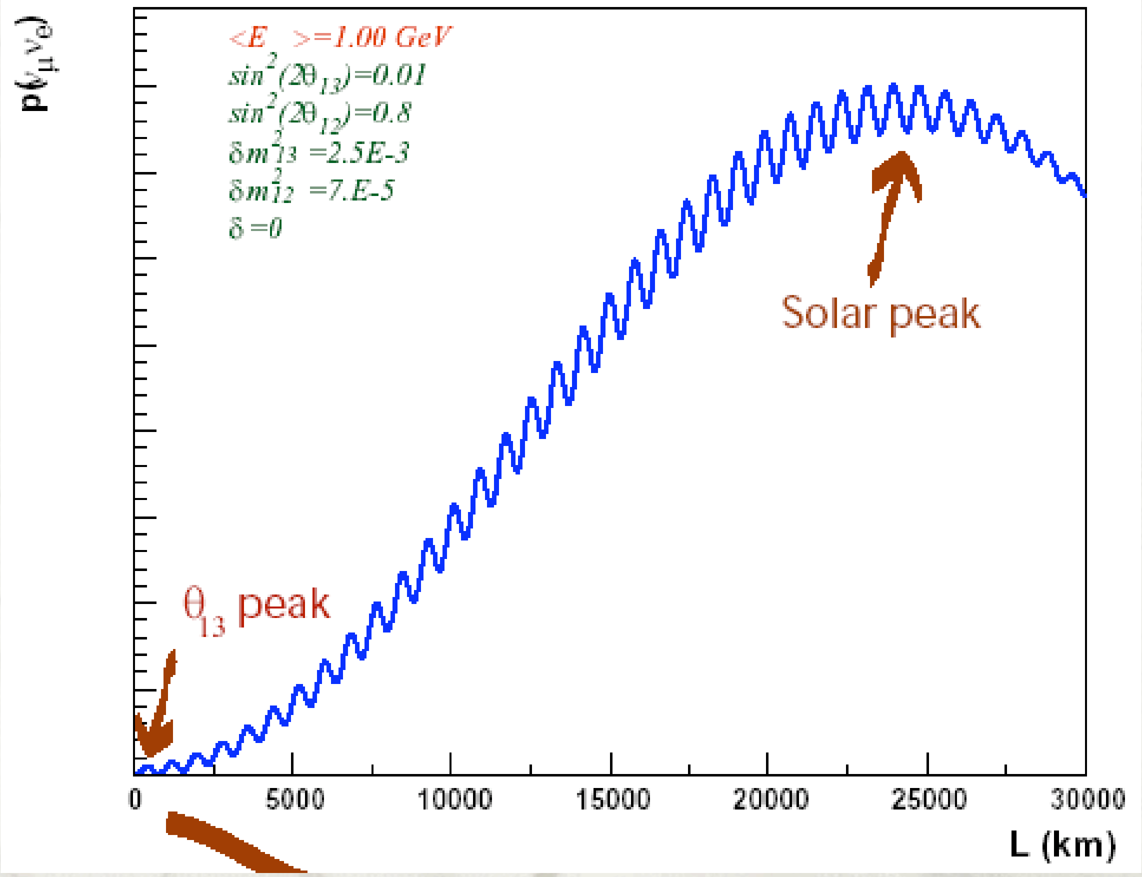
IFIC 1 senior staff, 1 postdocs, 2 phD (P.I.: A.Cervera)

Measuring θ 13

$$
\begin{aligned}
P_{\nu_\mu,\nu_e} = \; & \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{31}L}{4E} \\
& + \cos^2\theta_{23}\cos^2\theta_{13}\sin^2\theta_{12}\sin^2\frac{\Delta m^2_{21}L}{4E} \\
& + 8\cos^2\theta_{13}\sin\theta_{13}\sin\theta_{23}\cos\theta_{23}\sin\theta_{12}\cos\theta_{12}\sin\frac{\Delta m^2_{31}L}{4E}\sin\frac{\Delta m^2_{12}L}{4E}\cos(\frac{\Delta m^2_{32}L}{4E}\delta_{CP}) \\
& - 2\sin^2\theta_{12}\sin^2\theta_{23}\sin^2 2\theta_{13}\sin\frac{\Delta m^2_{21}L}{4E}\sin\frac{\Delta m^2_{31}L}{4E}\cos\frac{\Delta m^2_{32}L}{4E} \\
& + 4\cos^2\theta_{13}\sin^2\theta_{12}\sin\theta_{13}\sin\theta_{23}(\sin\theta_{23}\sin\theta_{13}\sin\theta_{12} - 2\cos\theta_{12}\cos\theta_{23}\cos\delta_{CP})\sin^2\frac{\Delta m^2_{21}L}{4E}
\end{aligned}
$$

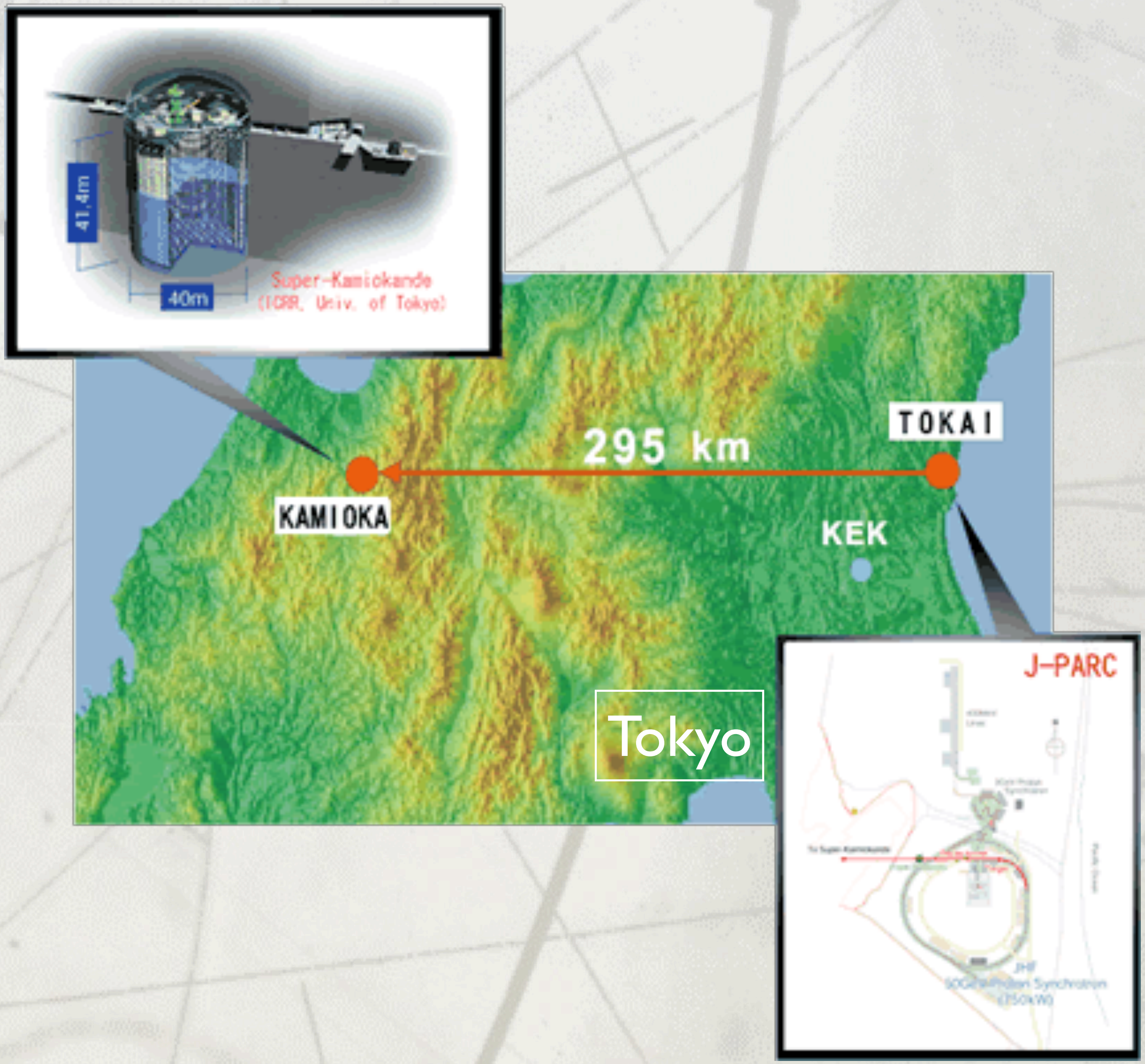
θ 13 peak

Solar peak



- $\nu_\mu \rightarrow \nu_e$ compites with the solar oscillation.
- decoupled only from the L/E value similar to reactor neutrinos.

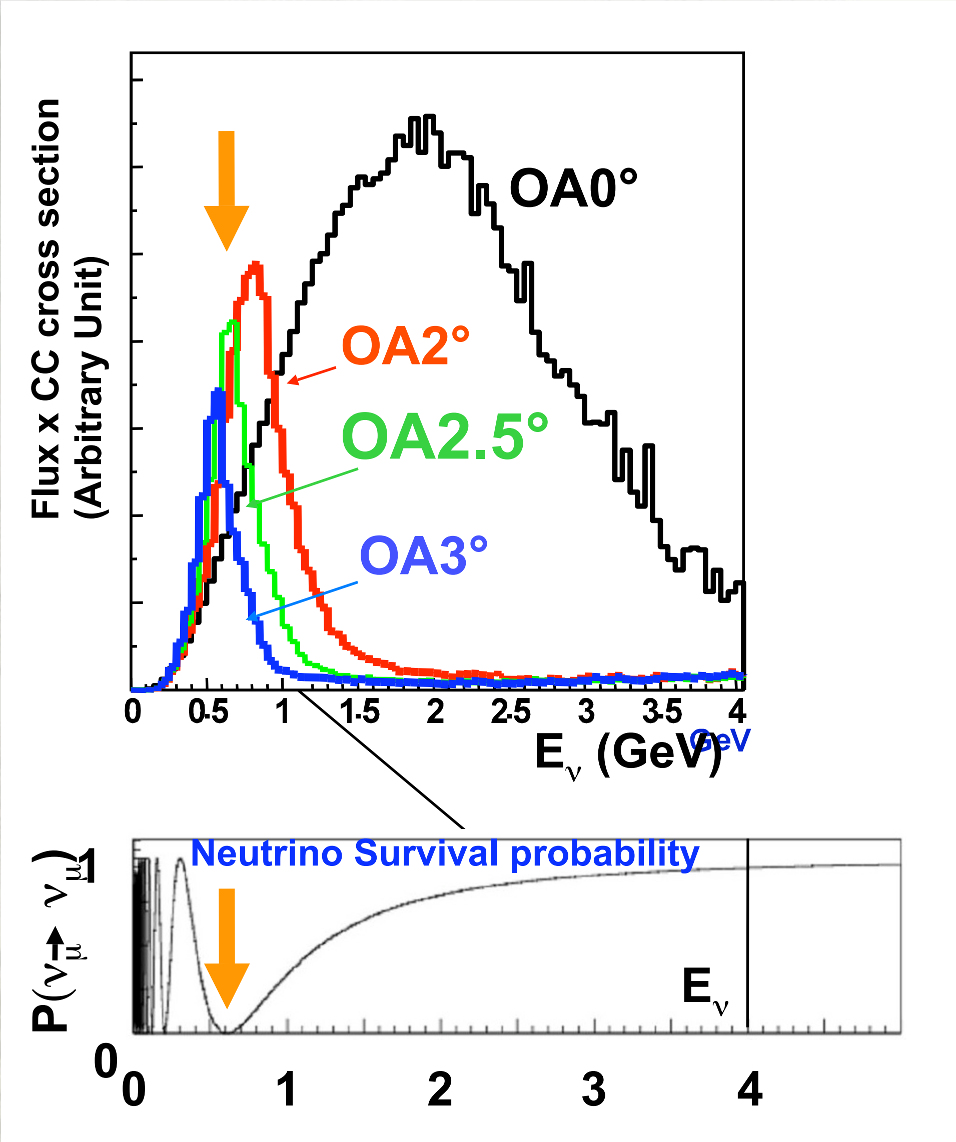
T2K

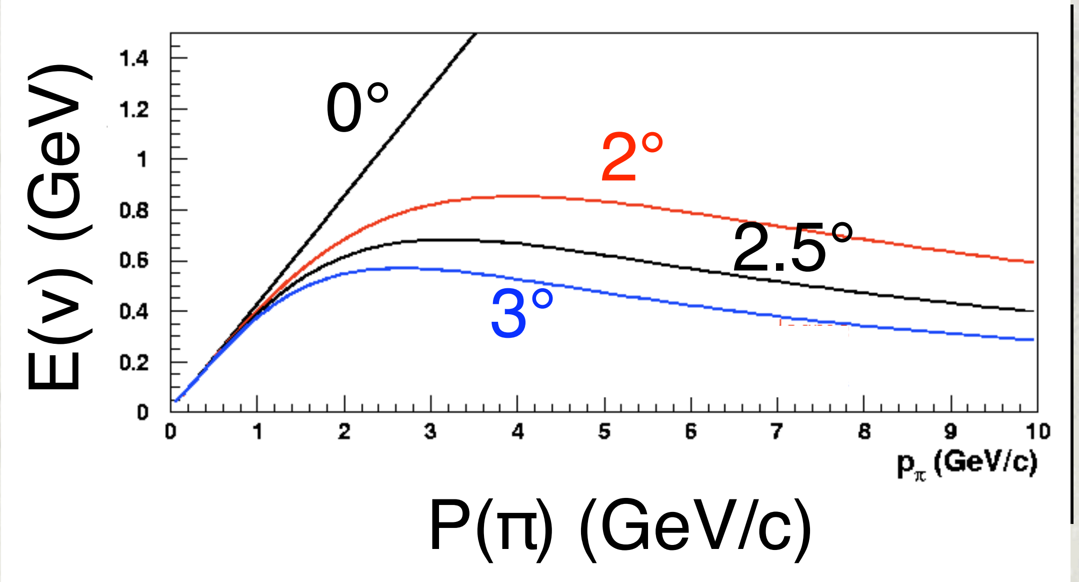


- $\nu_\mu \rightarrow \nu_e$ & $\nu_\mu \rightarrow \nu_\mu$ from high intensity accelerator.
- E_ν ~ 600 MeV.
- Oscillation distance: 295km.
- Off-axis technique → narrow energy spectrum.

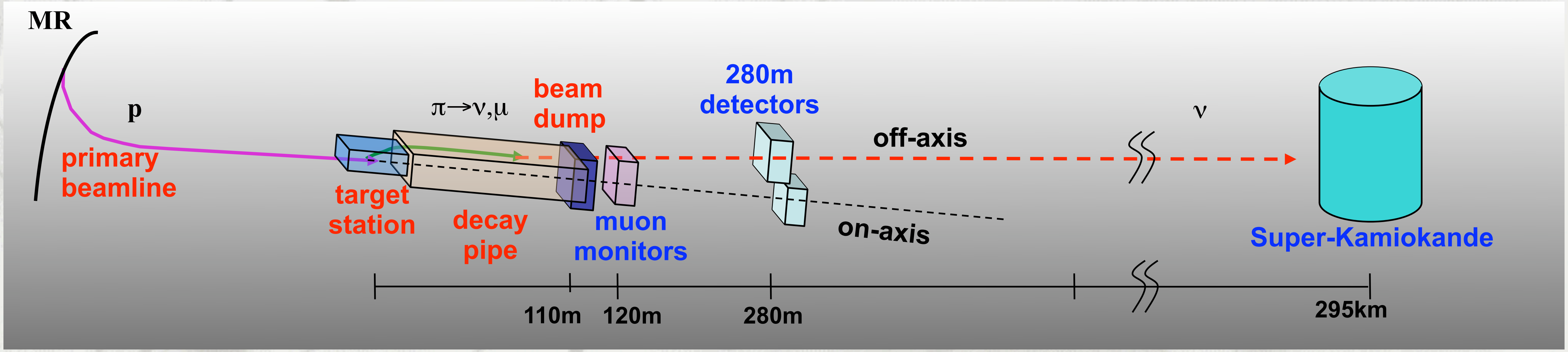
T2K: off-axis

- T2K is the first long baseline experiment using off-axis technique
- Reduced dependence of E_ν from E_π
  - Intense beam where the oscillation effect is maximum (~0.6 GeV)
  - Enhance the CCQE sample, reducing the high energy tails of the beam → reduce the backgrounds to oscillation signal





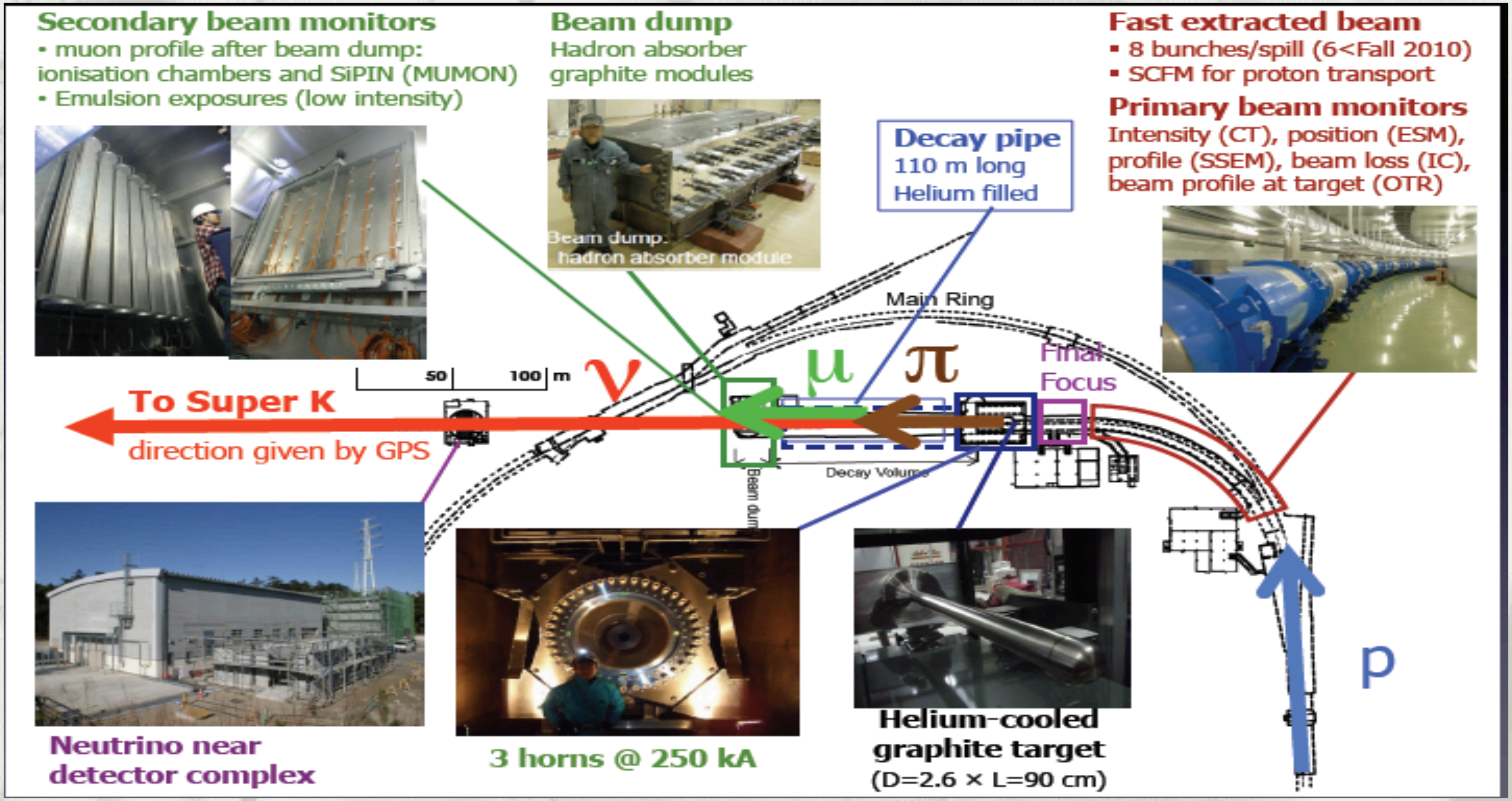
T2K concept



- Beamline:
  - Produce a narrow band neutrino beam (peak energy ~600 MeV) using Off-axis beam technique: center of the beam ~2.5° off from SK direction
  - Design beam power 750 kW (50 kW in 2010, stable 145 kW in 2011)
- Detectors:
  - Proton beam profile, position and intensity monitored in several detectors along the beamline
  - 2 detectors monitor neutrino beam stability and direction: Muon Monitor and INGRID
  - Off-axis Near Detector (ND280): measure ν interaction rates and flavors before the oscillation
  - Off-axis Far Detector (SK): measure ν interaction rates and flavors after the oscillation

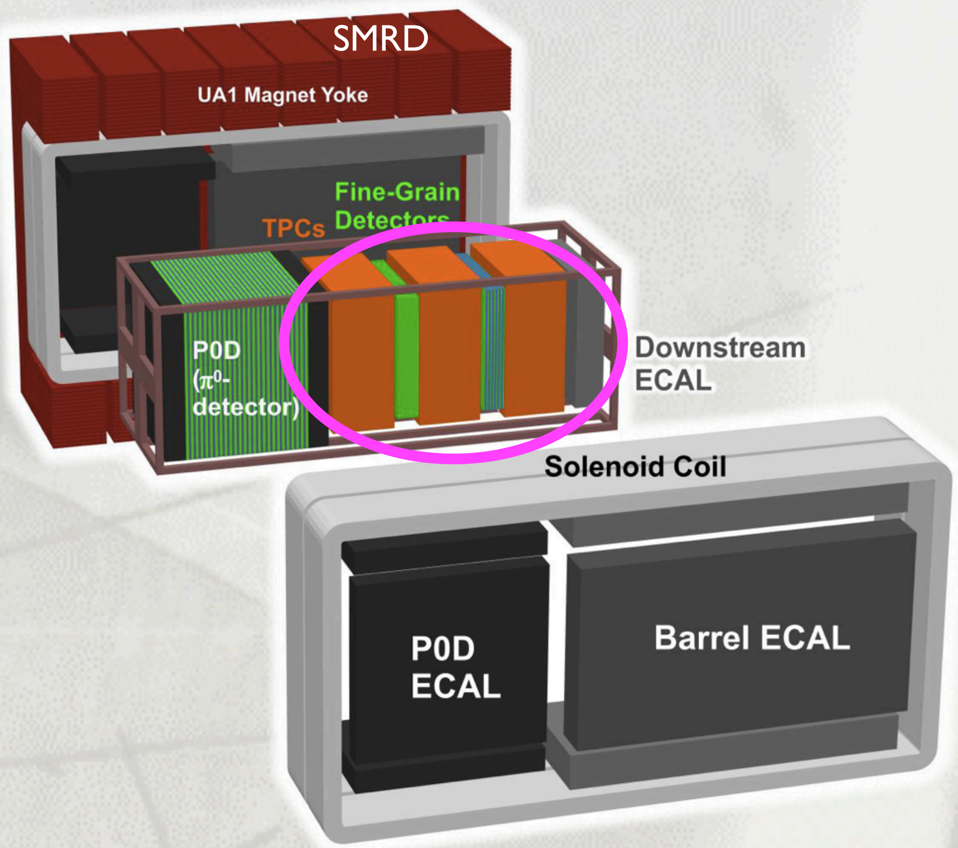
T2K:beam

- 30 GeV proton accelerator
- Single turn extraction of the protons from the MR to target station (8 bunches)
- Graphite target + 3 Horns: hadrons (π, K) are produced and charge selected
- Decay tunnel (110 m): $\pi \rightarrow \mu + \nu_{\mu}$ (+ other decays from kaons and muons that produce other neutrino species).
- The majority of muons and survived hadrons are stopped by the beam dump



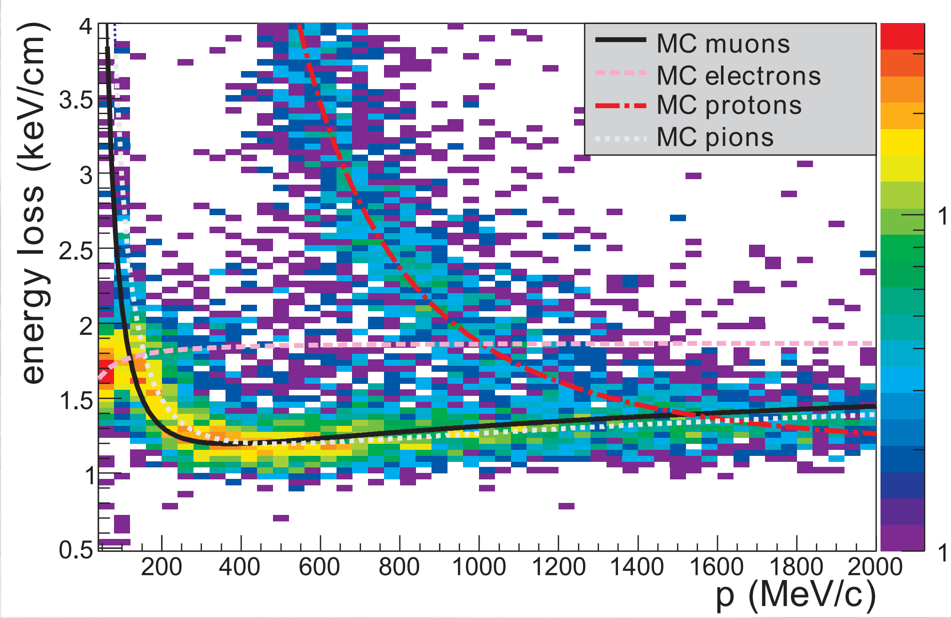
T2K: Off-axis ND280

- Set of detector installed inside the ex-UA1/NOMAD magnet providing a 0.2 T magnetic field.
- Measure ν_μ and ν_e spectra before the oscillation
- Measure cross-sections for backgrounds to oscillation
- Dedicated π^0 detector (P0D), EM calorimeter to identify e/ γ (ECAL), side muon range detector for high angle μ (SMRD)



- The Tracker:
  - 2 fine grained detectors (FGD)
    - Active target for neutrino interactions (carbon and water)
    - 1.6 ton of Fiducial Volume
  - 3 time projection chambers (TPC)*
    - Instrumented with MicroMEGAS detectors
    - Reconstruct momentum and charge of the particles produced in ν interactions
    - PID capabilities measuring dE/dx in the gas

TPC dE/dx vs P for Positive tracks
<8% resolution for MIPs



*NIM, A **637** (2011) pp. 25-46

T2K

ND280 · IFAE · IFIC – Institut de Física Corpuscular

TPC

- MicroMegas production quality assessment at CERN.
- Data Acquisition.
- Electronics for readout.
- TestBeam installation and data analysis.
- Contributed to MicroMegas (30%) and HV purchase (~20%).
- TPC calibration and distortions.

Magnet

- Water cooling piping.
- Slow control.
- Shipping and refurbishing.

Software

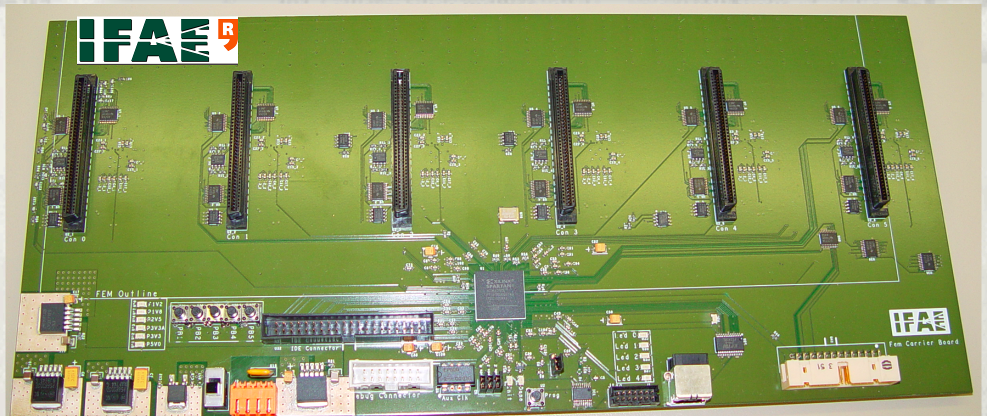
- Near detector reconstruction:
- kalman filter.
- TPC reconstruction.
- Analysis tools.
- Calibration framework.

Analysis

- muon neutrino CC inclusive for oscillations.
- electron neutrino CC inclusive for oscillations.
- Neutrino cross-secitons: CCQE, NCE, CC-Coh, CC-Nπ

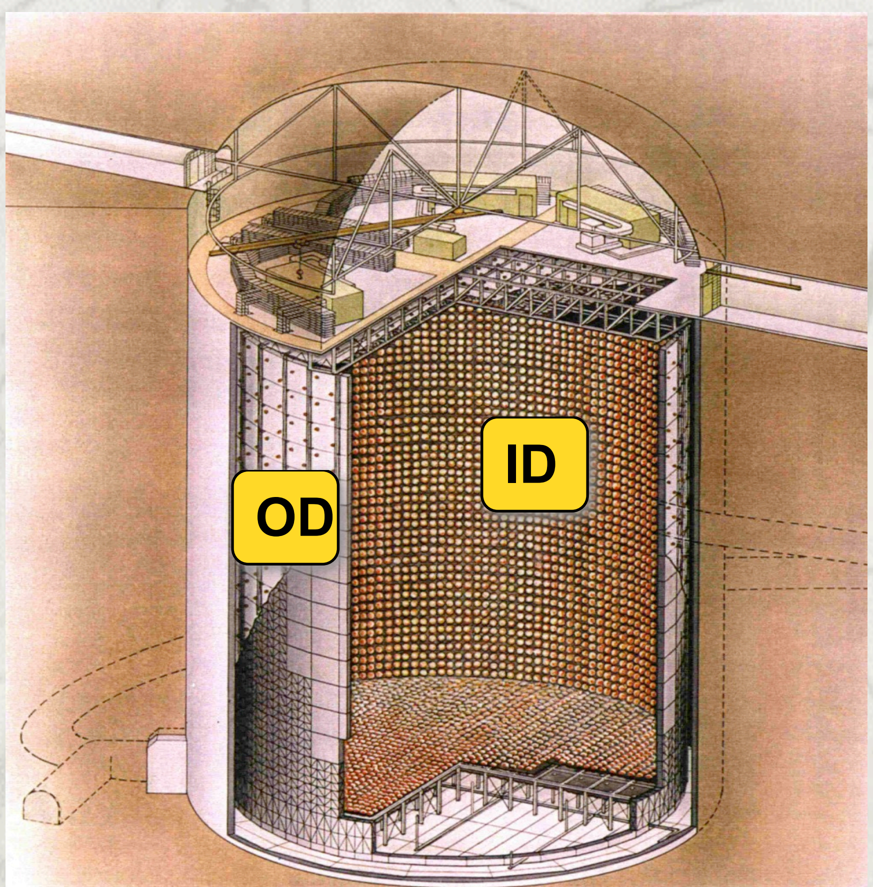
Managment

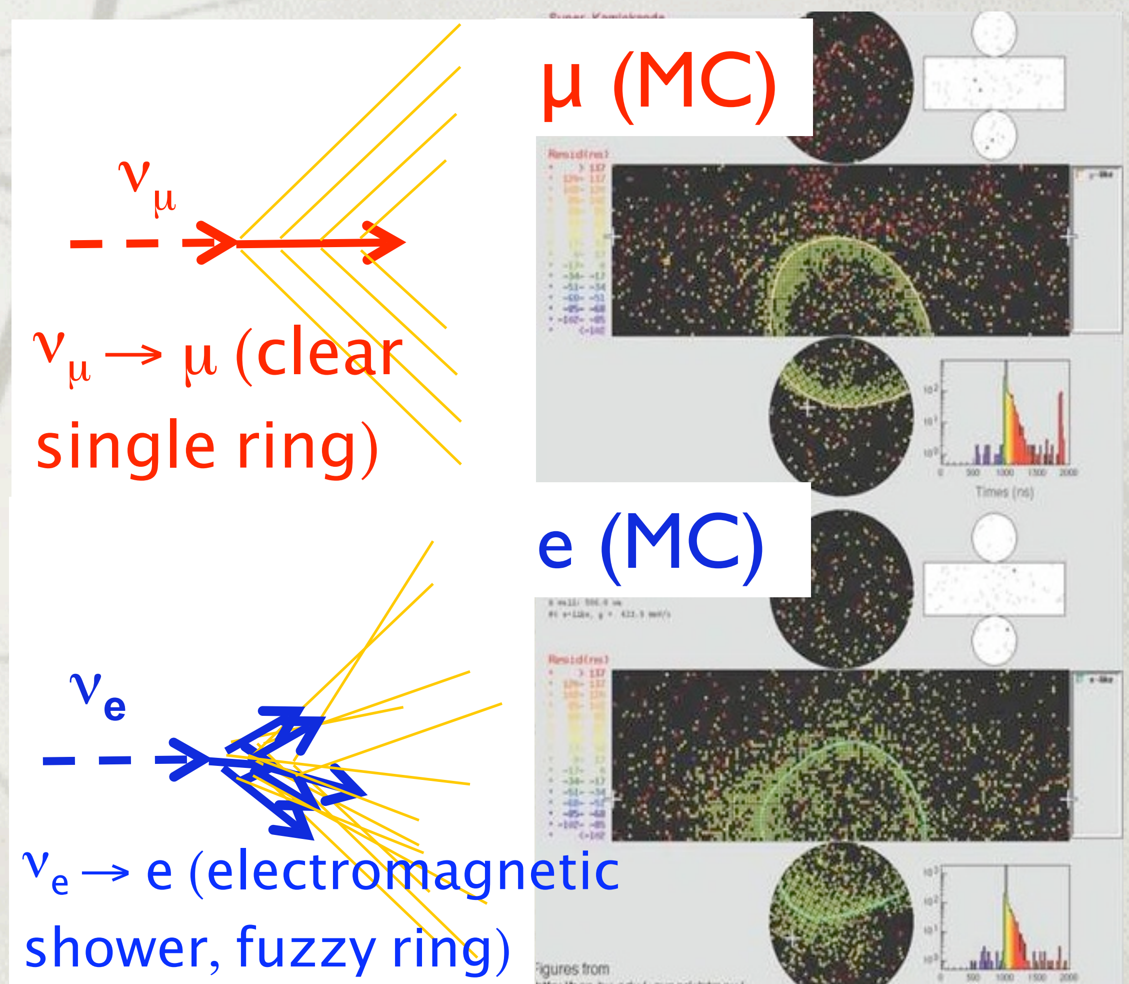
- Reconstruction convener
- Calibration convener
- numu analysis convener
- European convener for detector design

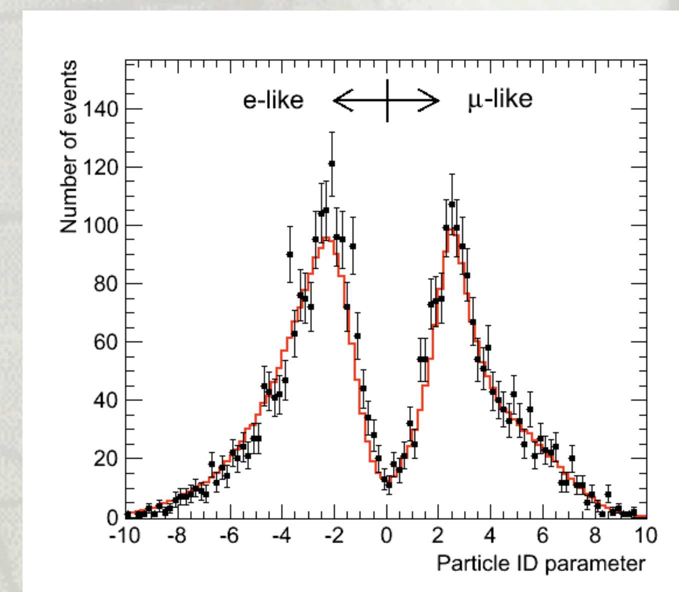


T2K far Detector: Super-Kamiokande

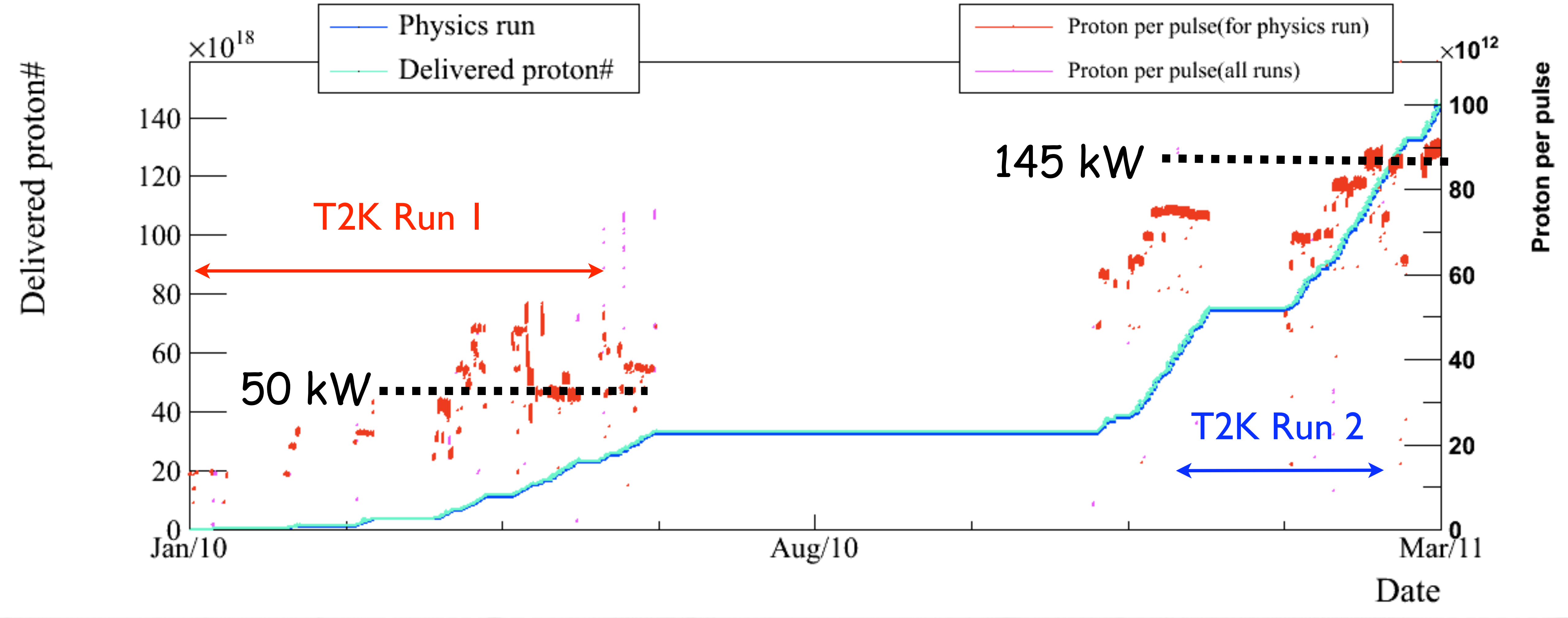
- 50 kton water Cherenkov detector (22.5 kton Fiducial Volume)
- Optically divided between an inner detector (ID) and an outer detector (OD)
  - 11129 20-inch Hamamatsu PMTs for the inner detector
- 1000 meters underground in the Kamioka mine (295 km from JPARC)
- Very good PID capabilities: probability of a muon reconstructed as an electron of 1%







Run1+Run2 data set

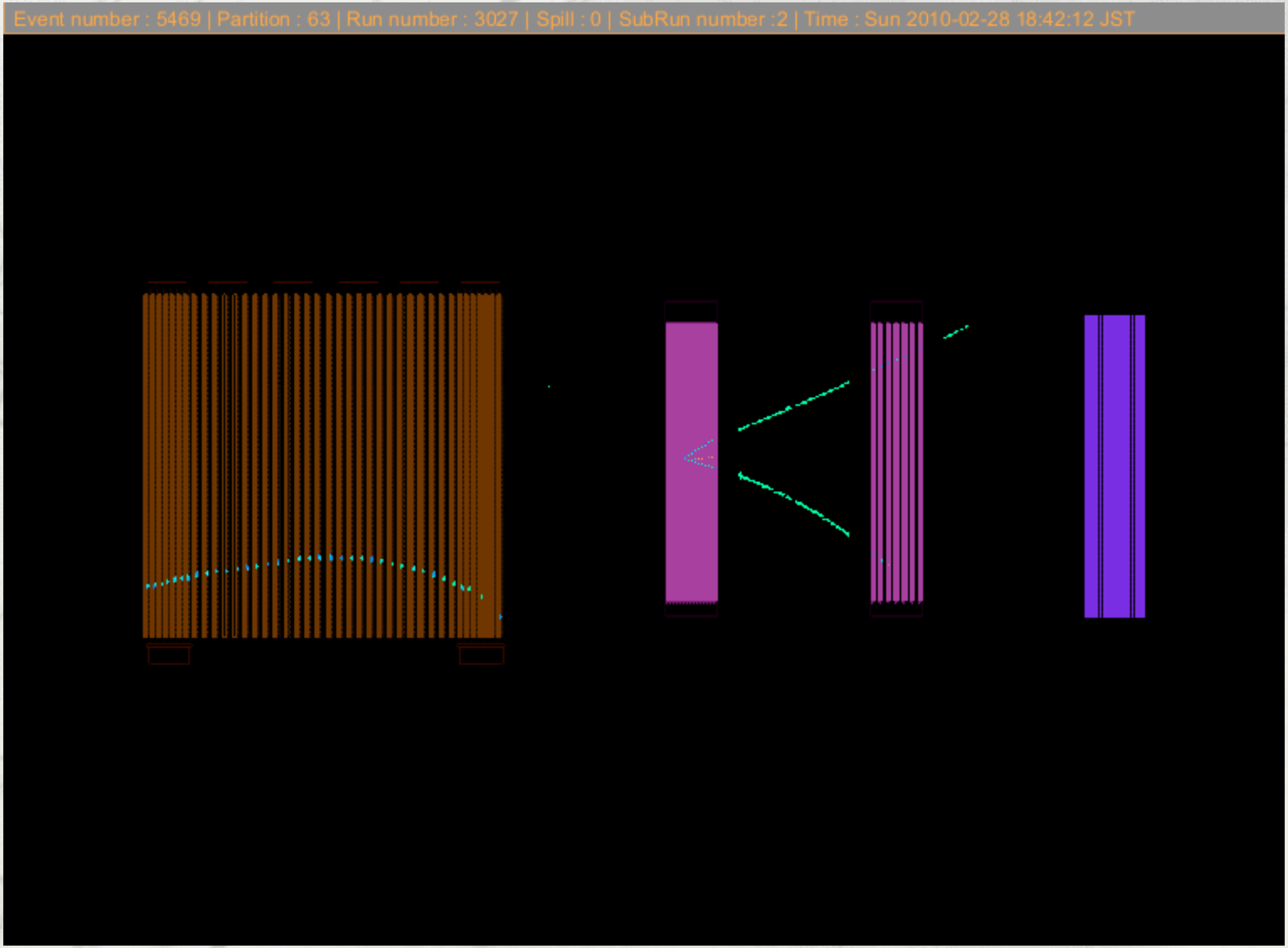


Run 1 (Jan-Jun 2010)
3.23×10^{19} p.o.t for analysis
50 kW stable beam operation

Run 2 (Nov 2010 - Mar 2011)
11.08×10^{19} p.o.t for analysis
145 kW stable beam operation

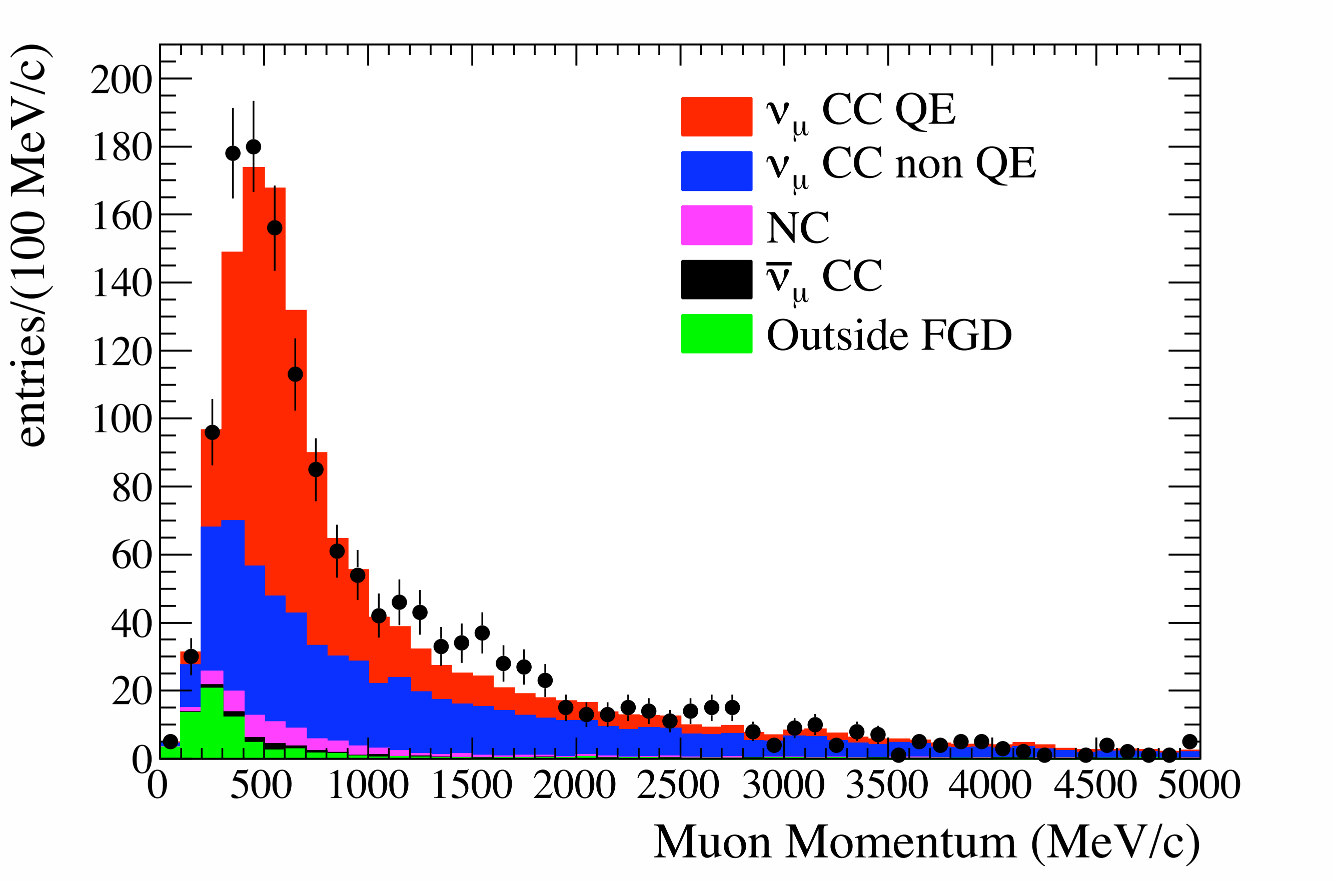
The total number of protons used for this analysis is 1.43×10^{20} p.o.t → 2% of the T2K final physics goal.

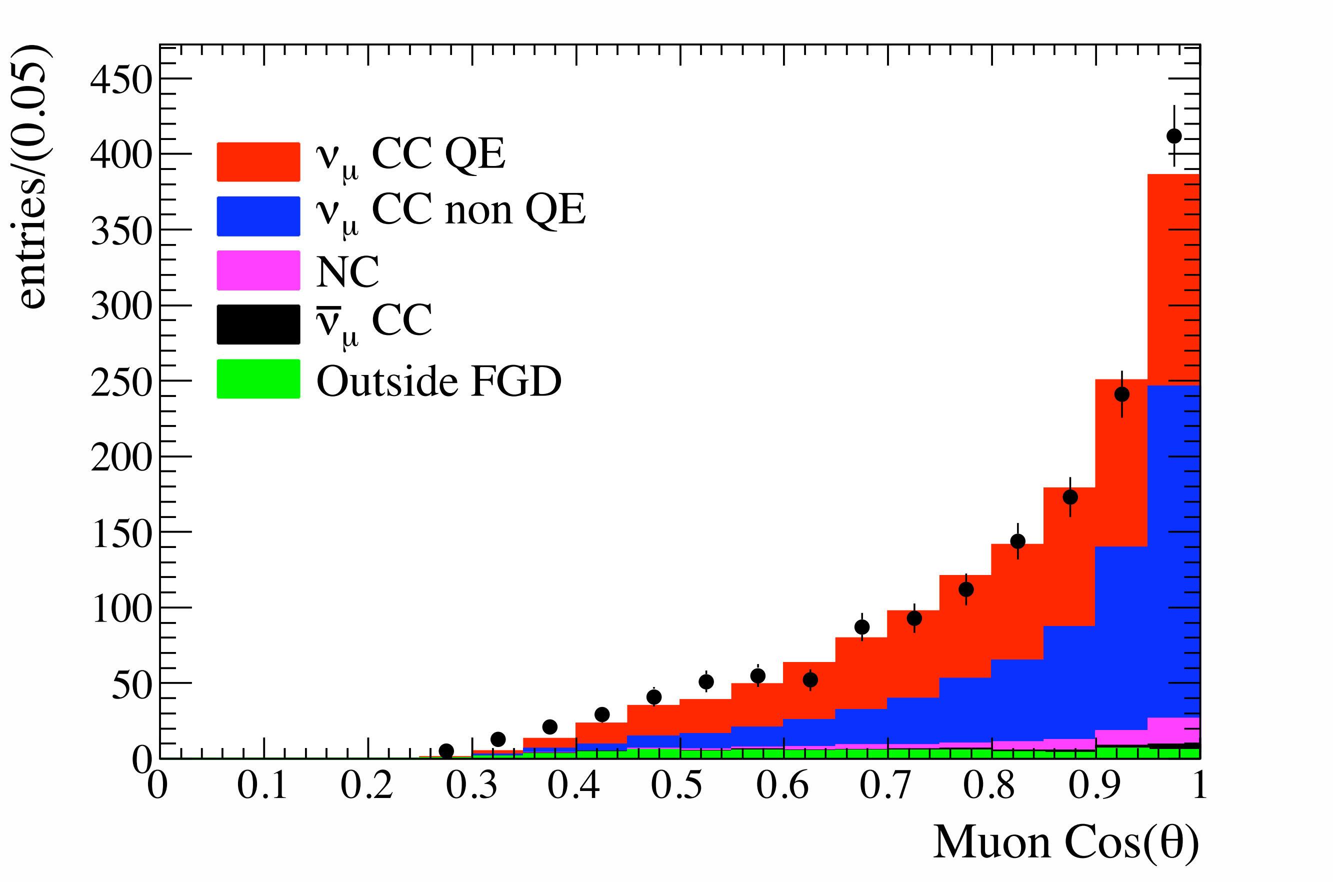
Neutrino event



Inclusive CC ν_μ analysis

- Selection of μ-like tracks requiring dE/dx in the TPC compatible with muons
- Good agreement between data and MC.



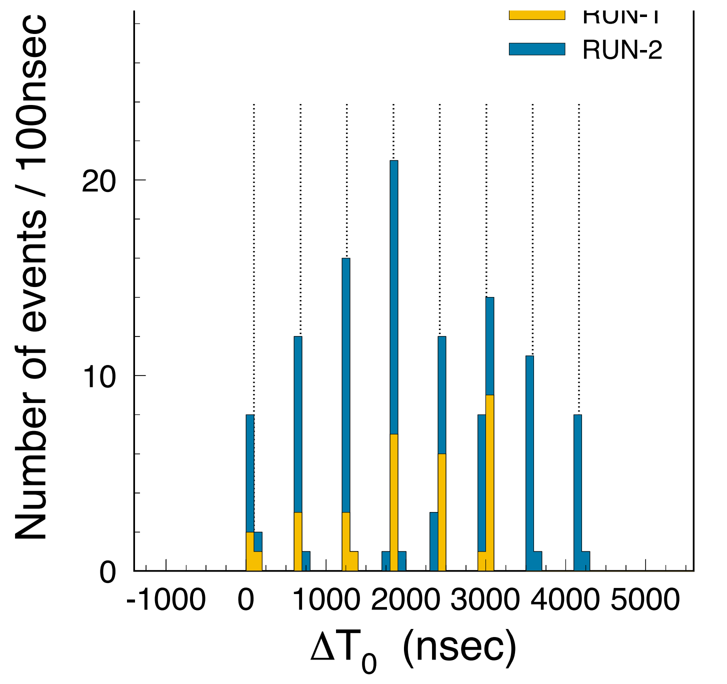


$$R(data/MC) = 1.036 \pm 0.028(stat)^{+0.044}_{-0.037}(det.\ syst) \pm 0.038(phys.\ model)$$

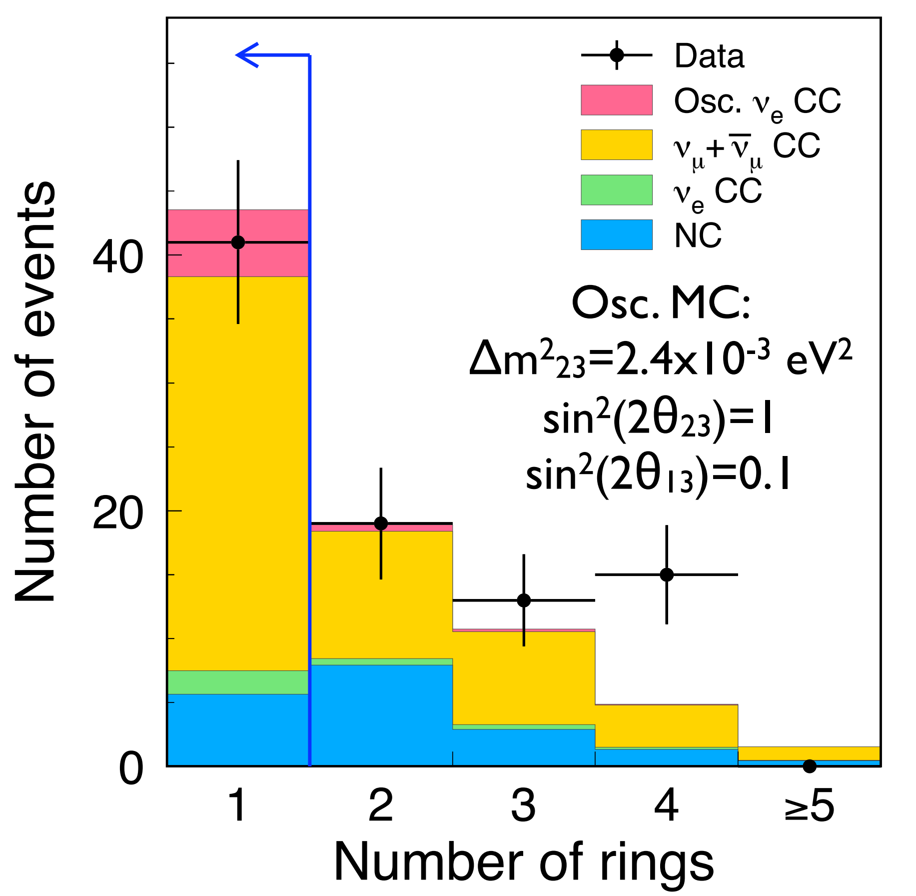
Super-Kamiokande event selection

- Predefined event selection for ν_μ and ν_e
- First steps that are common:
  - SK synchronized to beam timing using GPS
  - Fully contained events in the Inner Detector, minimal activity in the Outer Detector
  - Starting in the FV (FCFV)
  - Number of rings = 1
  - PID algorithm to distinguish e-like and μ-like events

121 FC events (8 bunches)

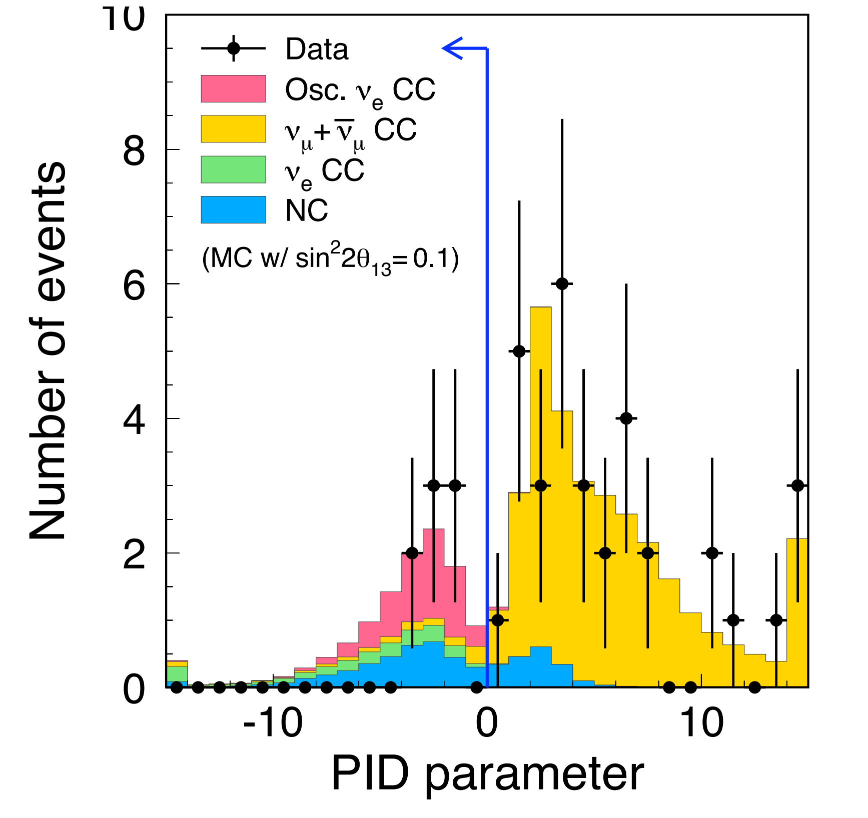


41 single ring



8 e-like events

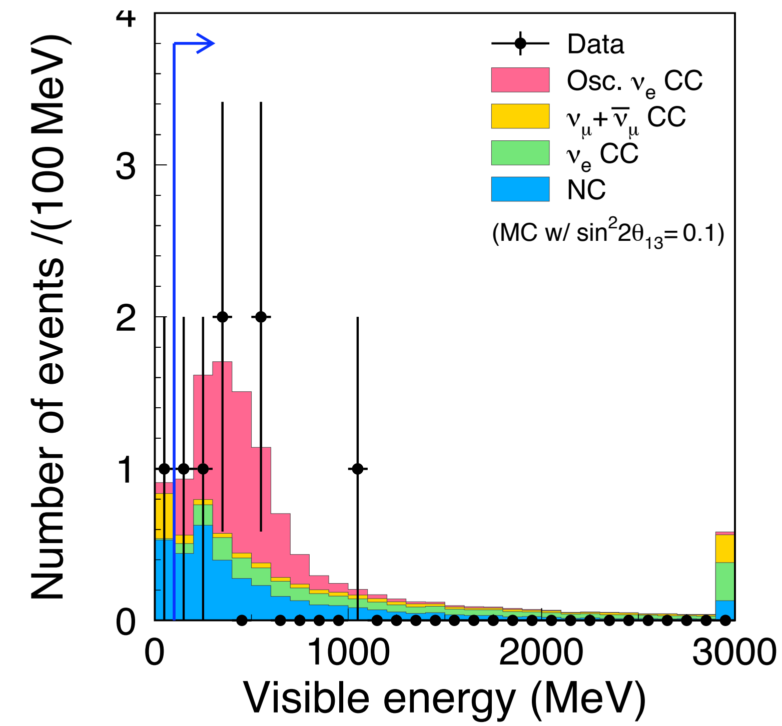
33 μ-like events



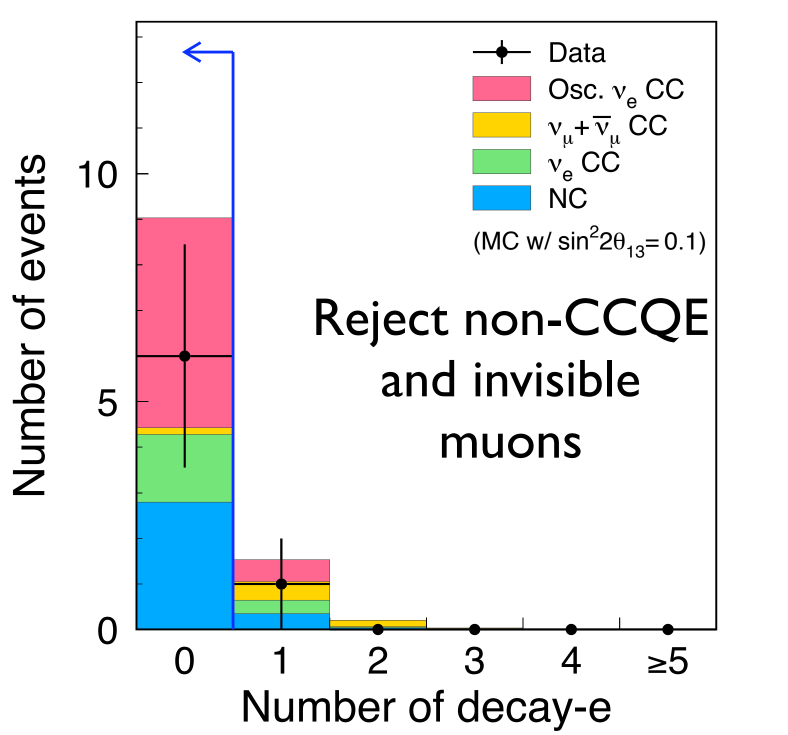
ν_e event reduction

- After ring counting 8 single ring e-like events are selected
- SK "tight" cuts are applied to further reject the background:
    - 6 events are selected over a predicted background of 1.5 (mainly electron neutrinos in the beam).

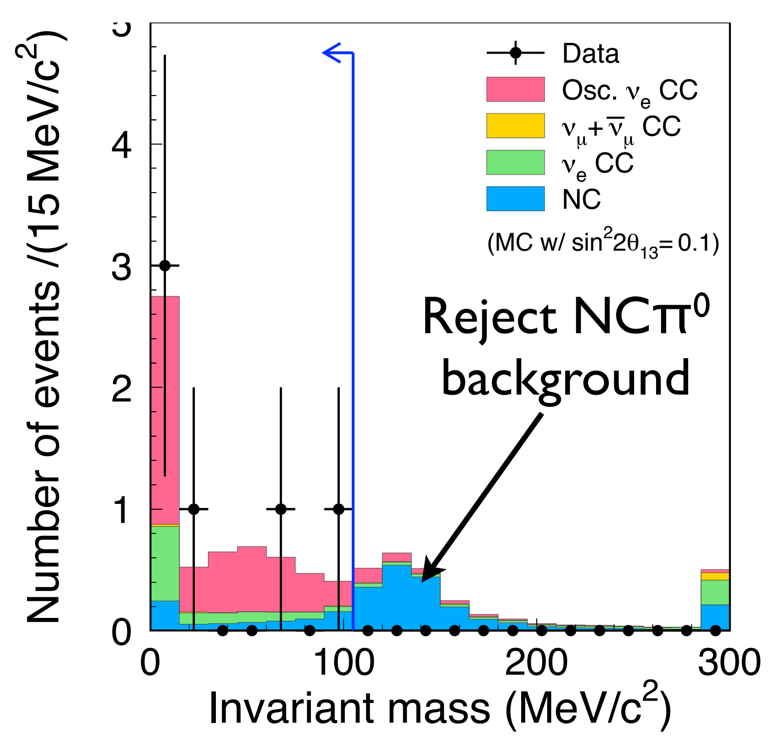
1) E(vis)>100 MeV → N=7



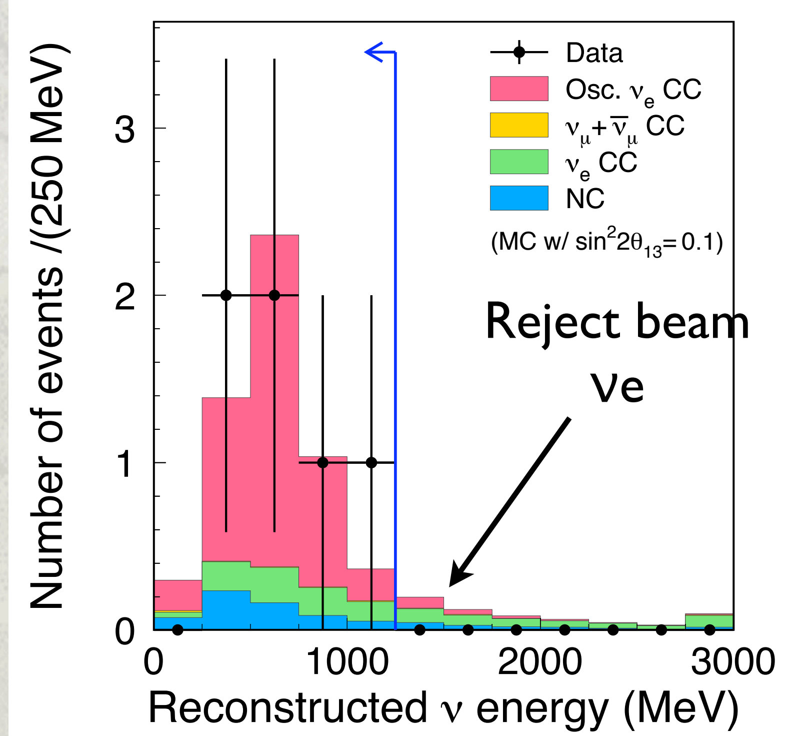
2) No decay electrons → N=6



3) M_{inv} with forced 2nd ring <105 MeV → N=6



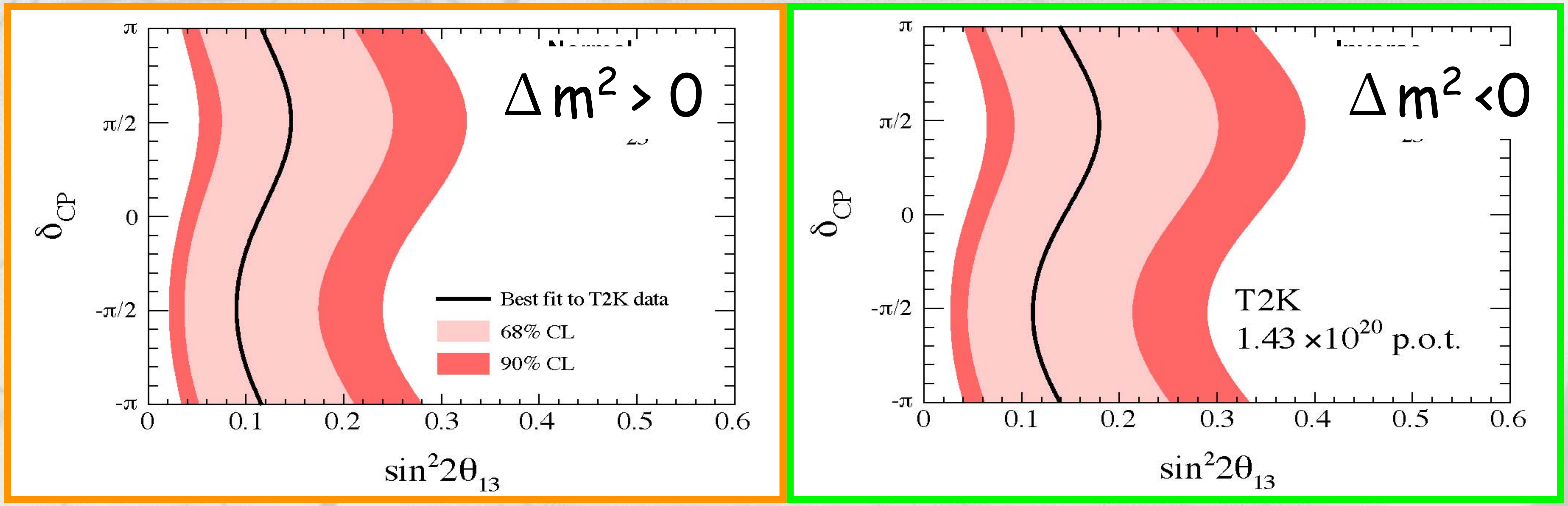
4) Rec neutrino energy <1250 MeV → N=6



ν_e appearance analysis

- Probability of observing 6 events if $\sin^2(2\theta_{13})=0 \rightarrow 0.7\%$ (2.5 σ significance)
- For $\sin^2(2\theta_{23})=1$ and $\Delta m^2_{23}=2.4\times10^{-3}$ eV^2:
  - Normal hierarchy, $\delta=0$:
    - Best fit $\rightarrow \sin^2(2\theta_{13})=0.11$ and $0.03<\sin^2(2\theta_{13})<0.28$ at 90% C.L.
  - Inverted hierarchy, $\delta=0$:
    - Best fit $\rightarrow \sin^2(2\theta_{13})=0.14$ and $0.04<\sin^2(2\theta_{13})<0.34$ at 90% C.L.

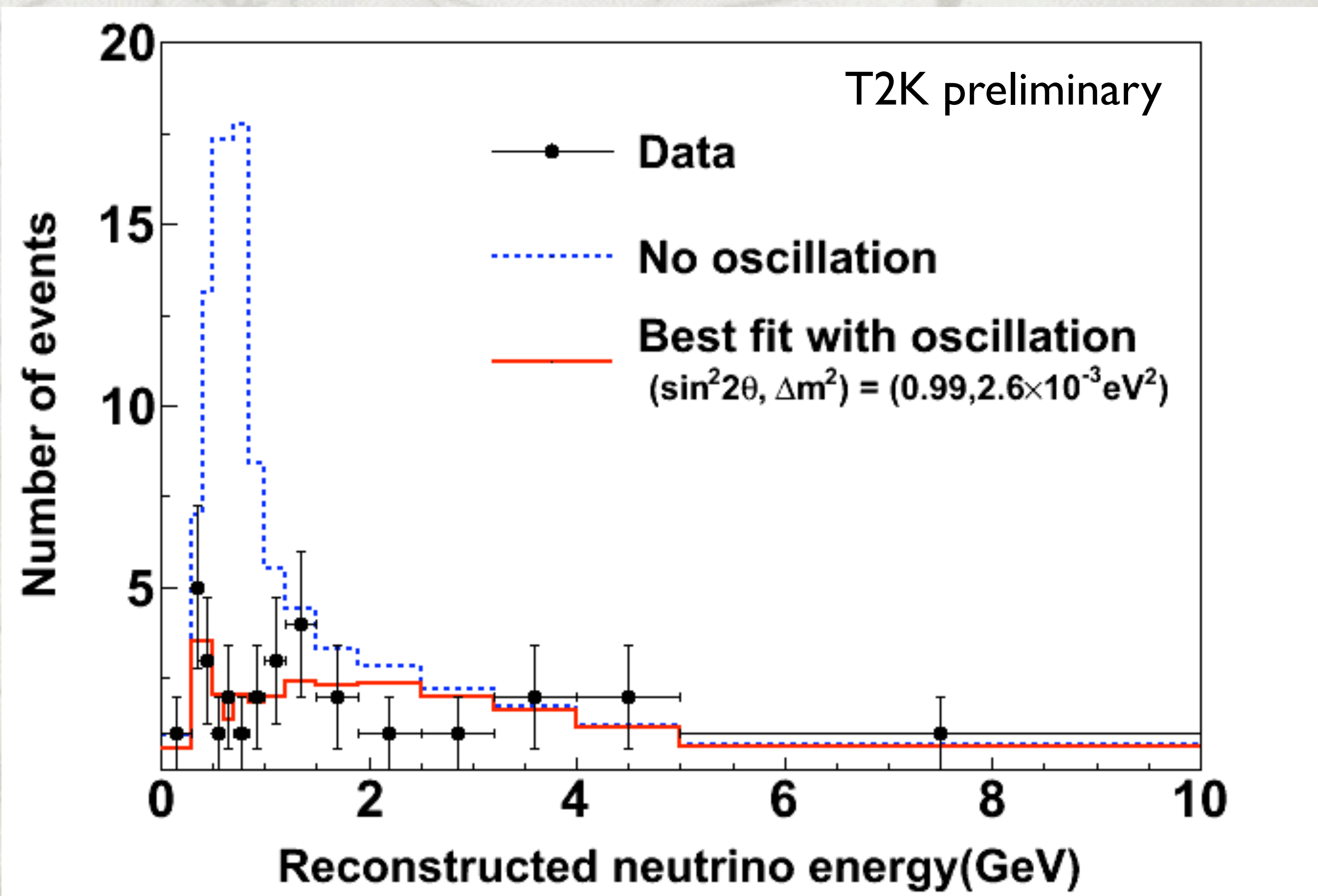
Published in Phys. Rev. Lett. 107, 041801 (2011)



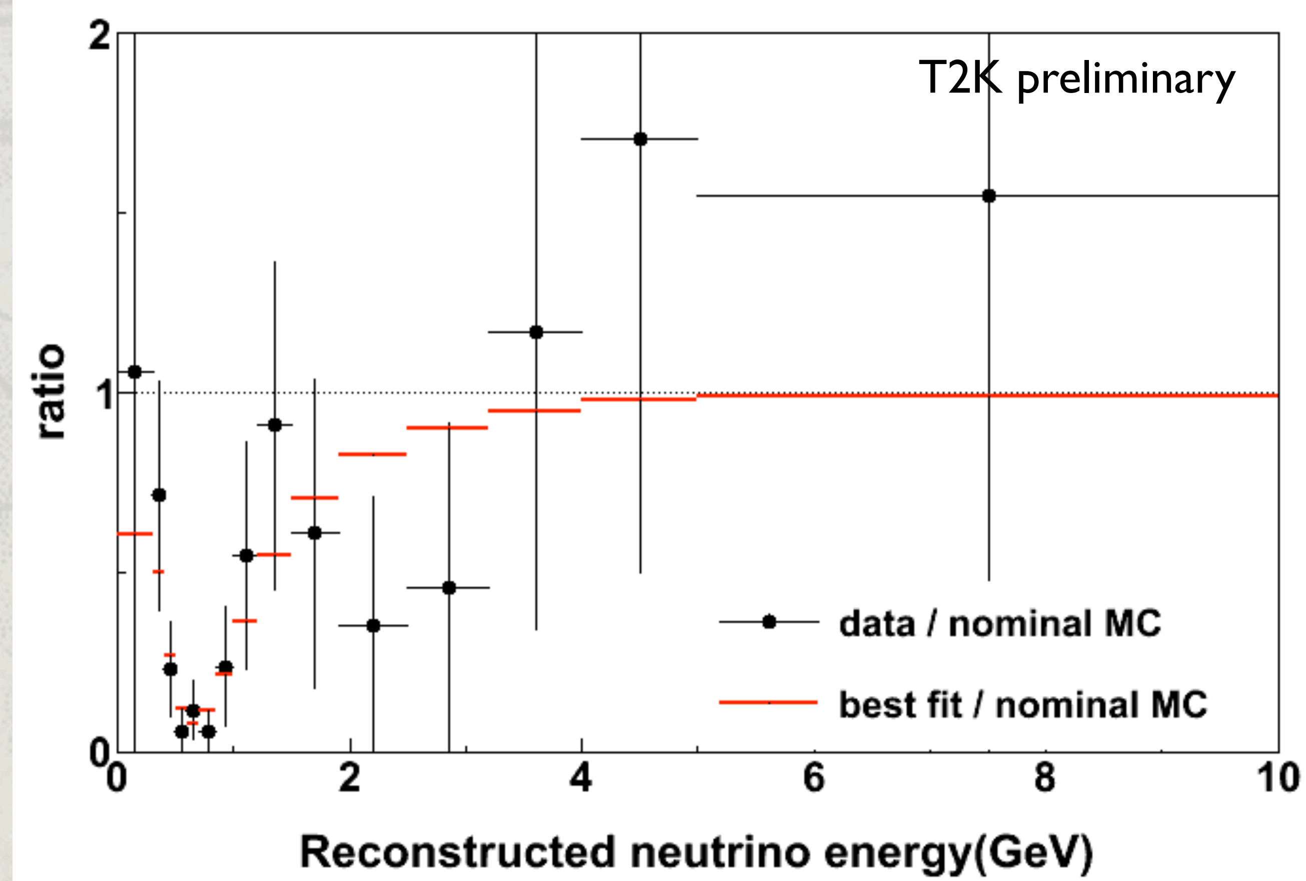
CP phase degeneracy & Δm^2 sign clearly visible

ν_μ disappearance

- Single muon event in SuperKamiokande fiducial volume.
- Observed events at SK satisfying ν_μ disappearance criteria: 31
- Oscillation parameters extracted from an oscillation fit on $E(\nu)^{rec}$
- The oscillation pattern due to the disappearance of ν_μ is clearly visible in the reconstructed energy spectrum → advantage of using off-axis configuration

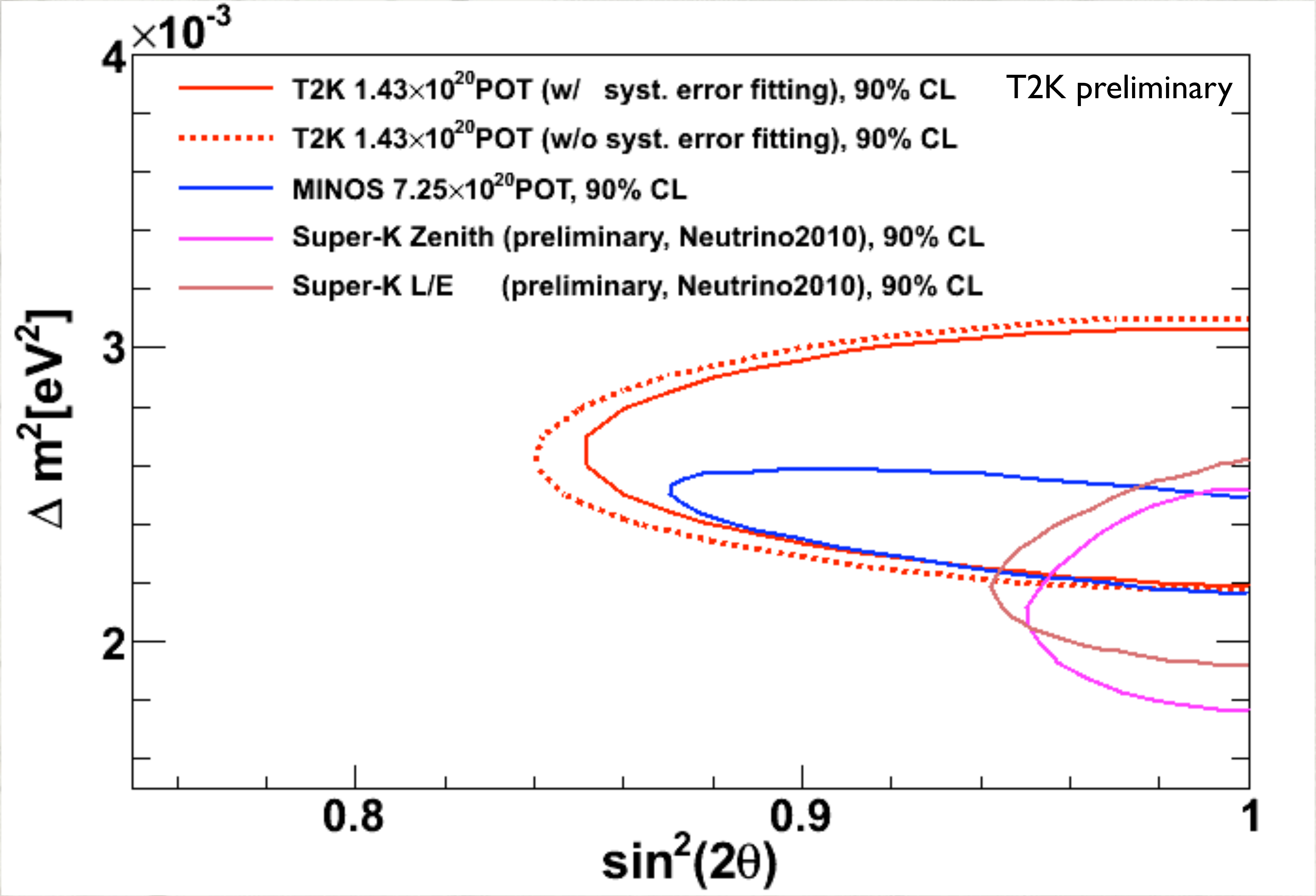


Ratio between data and MC without oscillation



ν_μ disappearance

- T2K results are in good agreement with previous results.
- It is not statistically significant but low statistics.
- The sensitivity to the mixing angle is larger than in Minos (off-axis)



Conclusions

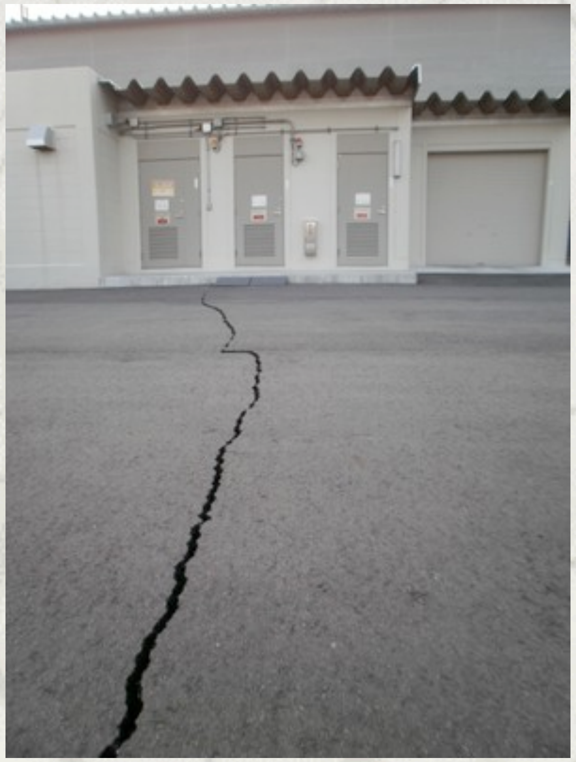
- Spanish groups have contributed to neutrinos oscillation efforts since 2002 for the first confirmation of oscillation in accelerators (K2K experiment).
- Current θ_{13} world leading experiment have strong Spanish contributions.
- Very exciting times: θ_{13} might be around the corner.
  - First indication by T2K this summer!. (138 citations in Spires in 4 months)
  - Double Chooz will deliver results soon.

Coming months will shape the future neutrino physics:
Strong Spanish contribution
Spanish expertise to play leading role in the future (CP)

Backup slides

Earthquake

- Ground level damages → rapidly repaired
- Equipments → no fatal damages
- LINAC floor, MR tunnel side pit, Near Detector bottom floor submerged under water
  - Fixed in few weeks
  - No serious damages on components
- Tunnel moved or bent of ~ several cm
  - Major alignment of many components need to be done
- We plan to resume JPARC beam operation in January 2011. Still on schedule.
- Two physics runs (~1 month each) for users before March 2012
- Future milestone:
  - 0.5 MW x 10^7 s (1×10^{21} p.o.t.) in Summer 2013
    - Conclude θ_{13} different from 0 (more than 5 σ at present T2K best fit)



Superluminal neutrinos & T2K

- Official statement by T2K :
  - Based on our initial assessment of our capability, at the moment T2K cannot make any definitive statement to verify the Opera measurement of the speed of neutrino (Opera Anomaly).
  - We will assess a possibility to improve our experimental sensitivity for a measurement to cross-check the OPERA anomaly in the future.Such a measurement with an improved system, however, could take a while to achieve.

- Time of flight in T2K :
- Baseline is shorter: 300 km vs 700 km
- Energy is lower: E_ν < 10 GeV vs E_ν > 20 GeV
- Actual GPS synchronization precission ~100 ns.

Measuring δ_{CP}

- To measure CP we need:
  - $\theta_{13} \neq 0$.
    - If 0, this is like a 2 neutrino mixing and the phase is cancelled.
  - Neutrino appearance:
    - If we look at disappearance only, this is like two neutrino oscillation and the phase cancelled out.
  - One of the following:
    - Compare ν and $\bar{\nu}$ transitions.
    - Compare disappearance (no CP effect) to appearance experiment (CP effect) so we can derive the phase.
    - Measure first and second oscillation maximum.

Measuring θ_{13}

- There are two possibilities explored now:
  - $\nu_\mu \longrightarrow \nu_e$ with atmospheric Δm^2 (long base line: T2K, Nova)

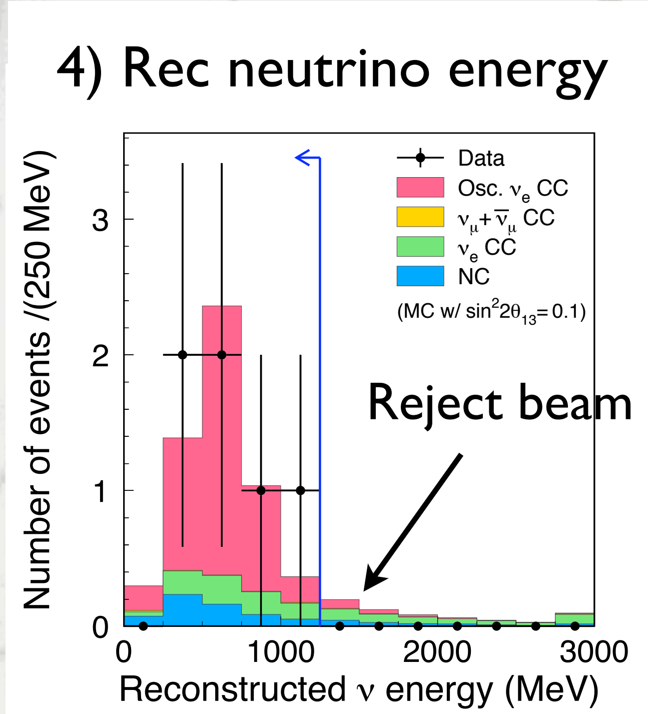
$$P_{\nu_\mu,\nu_e} = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{31}L}{4E}$$
$$+\cos^2\theta_{23}\cos^2\theta_{13}\sin^2\theta_{12}\sin^2\frac{\Delta m^2_{21}L}{4E}$$
$$+8\cos^2\theta_{13}\sin\theta_{13}\sin\theta_{23}\cos\theta_{23}\sin\theta_{12}\cos\theta_{12}\sin\frac{\Delta m^2_{31}L}{4E}\sin\frac{\Delta m^2_{12}L}{4E}\cos(\frac{\Delta m^2_{32}L}{4E}\delta_{CP})$$
$$-2\sin^2\theta_{12}\sin^2\theta_{23}\sin^2 2\theta_{13}\sin\frac{\Delta m^2_{21}L}{4E}\sin\frac{\Delta m^2_{31}L}{4E}\cos\frac{\Delta m^2_{32}L}{4E}$$
$$+4\cos^2\theta_{13}\sin^2\theta_{12}\sin\theta_{13}\sin\theta_{23}(\sin\theta_{23}\sin\theta_{13}\sin\theta_{12}-2\cos\theta_{12}\cos\theta_{23}\cos\delta_{CP})\sin^2\frac{\Delta m^2_{21}L}{4E}$$

    - Sensitive to CP and matter effects (not in the formula).
  - $\nu_e \longrightarrow \nu_e$ with “atmospheric” Δm^2 (reactor experiments)

$$P_{\nu_e,\nu_e} \approx 1 - \sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{31}L}{4E} - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\frac{\Delta m^2_{21}L}{4E}$$

    - Insensitive to CP phase.

Results



Source	Nexp
Beam ν_e	0.8
ν_μ Neutral Current	0.6
ν_μ Charged Current	0.1
Total	1.5±0.3

- We observed 6 ν_e candidates
- The expected number of events from un-oscillated neutrinos is 1.5

Syst for $\theta_{13}=0$ → Nexp = 1.5±0.3

error source	syst. error
ν flux	$\pm 8.5\%$
ν int. cross section	$\pm 14.0\%$
Near detector	$^{+5.6}_{-5.2}\%$
Far detector	$\pm 14.7\%$
Near det. statistics	$\pm 2.7\%$
Total	$^{+22.8}_{-22.7}\%$

Dominated by hadron production

Dominated by FSI and NCπ0 cross-section uncertainties

ND280 dominated by TPC tracking efficiency and ionization in the gas

SK dominated by ring counting, PID and π^0 mass systematics