Neutrino Physics

Lecture 2

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Outline

- Neutrino oscillations – experimental aspects
- Reactor neutrinos
- Accelerator neutrinos
- Future experiments

Oscillations - experimental aspects

$$P(\nu_\alpha \rightarrow \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i<j} \Re(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \cdot \sin^2 \Phi_{ij} \pm 2 \sum_{i<j} \Im(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \cdot \sin^2 \Phi_{ij}$$

$$\Phi_{ij} = \Delta m^2_{ij} \frac{L}{4E_\nu} = 1.27 \cdot \Delta m^2_{ij}[eV^2] \cdot \frac{L[km]}{E_\nu[GeV]}$$

- In the 3-neutrino case - transition probabilities $P(\nu_\alpha \rightarrow \nu_\beta)$ depend on:
  - Mixing angles: θ_{23}, θ_{13}, θ_{12}
  - Complex phase: δ_{CP}
  - Independent mass splittings: Δm^2_{32} , Δm^2_{12}

  } Pontercorvo-Maki-Nakagawa-Sakata (PMNS) model parameters

  - Detector-source distance (L), neutrino energy (E) – chosen experimentally

- Formulas above are valid for vacuum oscillations → Matter effects related to the interactions of electron neutrinos with matter modify the mixing angles and mass splittings giving effective angles and splittings (not discussed here).

Oscillations - experimental aspects

- Neutrino oscillation experiments measure:
  - Appearance probability: $P(\nu_\alpha \rightarrow \nu_\beta) = ?$
  - Disappearance (survival) probability: $P(\nu_\alpha \rightarrow \nu_\alpha) = ?$

- Number of observed (detected) neutrino interactions is proportional to:
  - neutrino-target (eg. neutrino-nucleus) cross section σ,
  - neutrino flux Φ
  - number of interacting targets (eg. number of target nuclei) T

$$N_{Obs} \approx \sigma * \Phi * T$$

Neutrino oscillation experiments

$$\sin^2(\theta_{12}) = 0.307 \pm 0.013$$
$$\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5}\ \mathrm{eV}^2$$
$$\sin^2(\theta_{23}) = 0.547 \pm 0.021 \quad \text{(Inverted order)}$$
$$\sin^2(\theta_{23}) = 0.545 \pm 0.021 \quad \text{(Normal order)}$$
$$\Delta m^2_{32} = (-2.546^{+0.034}_{-0.040}) \times 10^{-3}\ \mathrm{eV}^2 \quad \text{(Inverted order)}$$
$$\Delta m^2_{32} = (2.453 \pm 0.034) \times 10^{-3}\ \mathrm{eV}^2 \quad \text{(Normal order)}$$

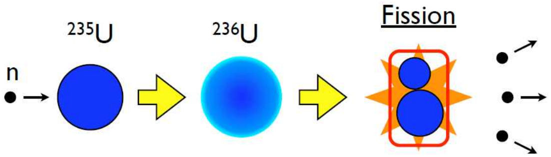
$$\sin^2(\theta_{13}) = (2.18 \pm 0.07) \times 10^{-2}$$
$$\delta,\ CP \text{ violating phase} = 1.36 \pm 0.17\ \pi \text{ rad}$$

- Major experiments that contributed to these results:

Experiment	Dominant	Important
Solar Experiments	θ_{12}	Δm^2_{21} , θ_{13}
Reactor LBL (KamLAND)	Δm^2_{21}	θ_{12} , θ_{13}
Reactor MBL (Daya-Bay, Reno, D-Chooz)	θ_{13}, $\lvert\Delta m^2_{31,32}\rvert$	
Atmospheric Experiments (SK, IC-DC)		θ_{23},$\lvert\Delta m^2_{31,32}\rvert$, θ_{13},δ_{CP}
Accel LBL ν_μ,$\bar{\nu}_\mu$, Disapp (K2K, MINOS, T2K, NOνA)	$\lvert\Delta m^2_{31,32}\rvert$, θ_{23}	
Accel LBL ν_e,$\bar{\nu}_e$ App (MINOS, T2K, NOνA)	δ_{CP}	θ_{13} , θ_{23}

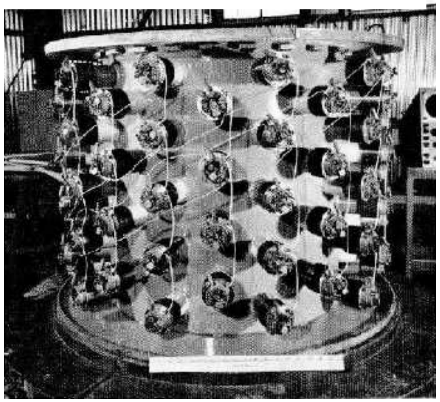
Reactor neutrinos

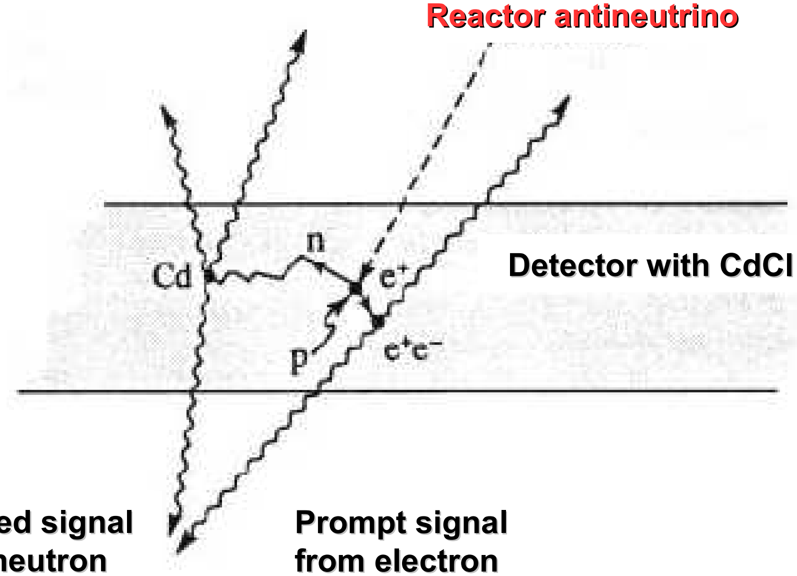
- In the nuclear reactors electron antineutrinos are produced as a result of the nuclear fission of heavy isotopes ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu



- 6 antineutrinos are produced per one fission reaction
- Typical nuclear powerplant (1 GW reactor) produces 2×10^{20} antineutrinos per second
- Number of detected antineutrinos is proportional to the reactor power
- There's a long tradition of using reactor antineutrinos to study neutrino properties. It started in 1953 by Reines & Cowan (detector located next to the Savannah River powerplant)

Reines & Cowan detector





Frederick Reines & Clyde Cowan

Nobel prize for Reines in 1995

Reactor neutrinos

- Reactor experiments are measuring the probability of disappearance of electron antineutrinos from the reactor.

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = ?$$

- A precise prediction of the antineutrino flux from the nuclear reactor is crucial because we need to compare the measured neutrino spectrum with the predicted one.
- Detailed calculation of the antineutrino flux from the nuclear reactor is challenging (summing up the spectra of beta decays)
  - Fission processes of four main isotopes involves thousands(!) of beta decay branches → The main problem of reactor neutrino experiments is the neutrino flux calculation
  - Many improvements in the reactor neutrino flux calculations recently.
- Currently operating reactor neutrino experiments:

Name	Reactor power (GW_{th})	Baseline (km)	Detector mass (t)	Year
KamLAND	various	180 (ave.)	1,000	2001–
Double Chooz	4.25×2	1.05	8.3	2011–2018
Daya Bay	2.9×6	1.65	20×4	2011–
RENO	2.8×6	1.38	16	2011–
JUNO	26.6 (total)	53	20,000	

Reactor neutrinos – observed spectrum

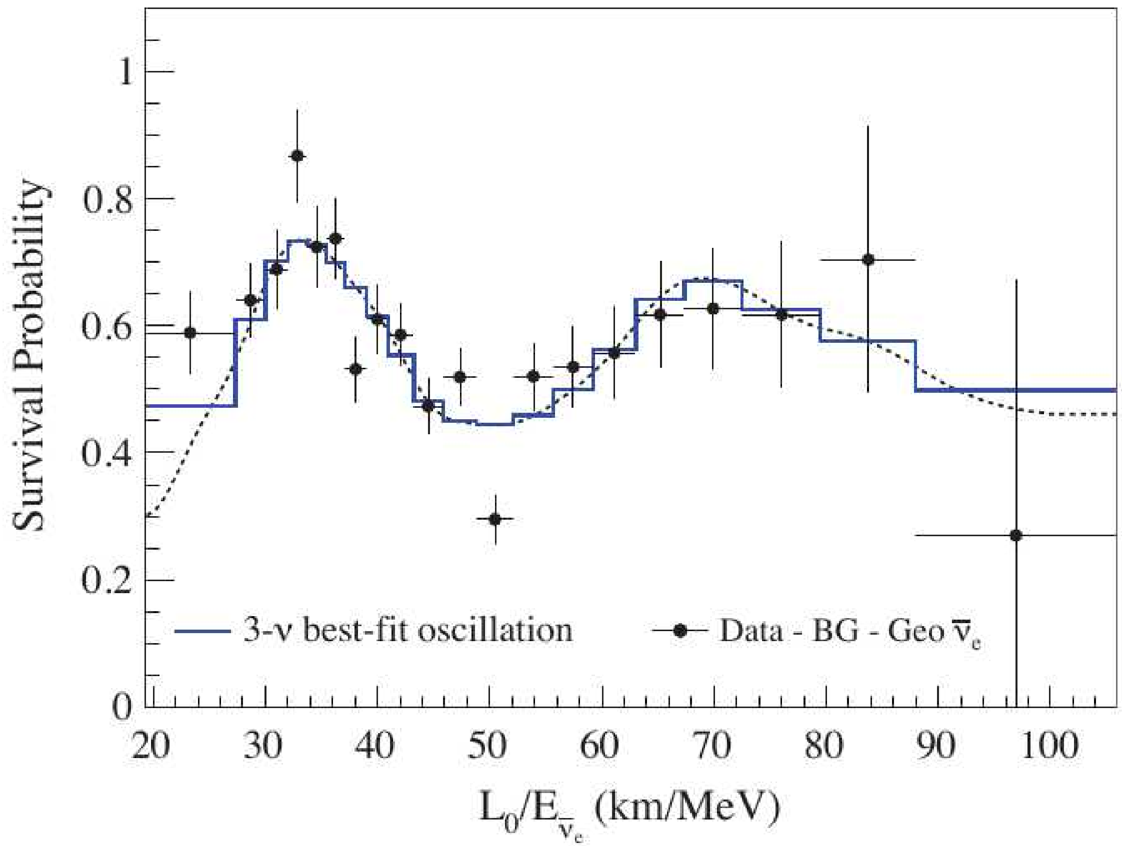
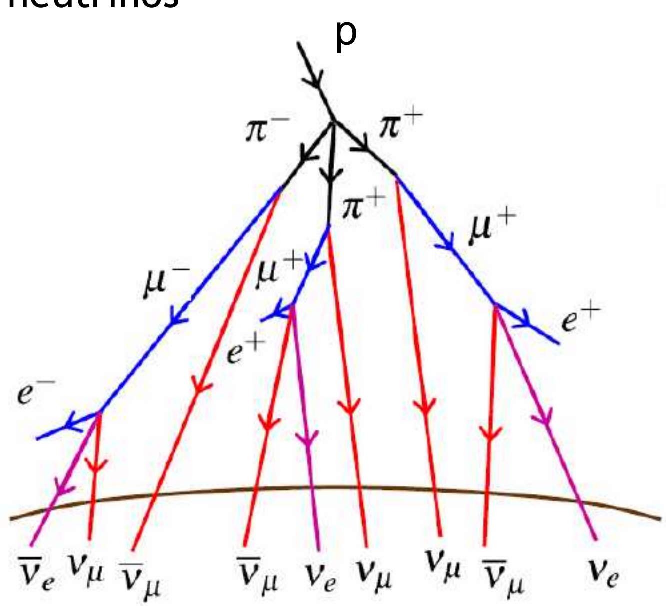


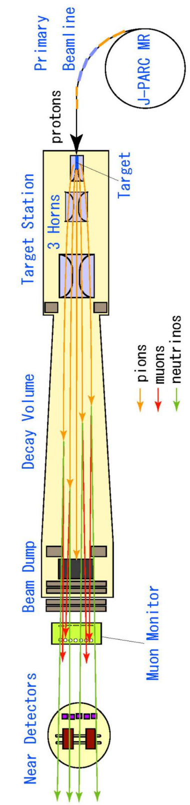
Figure 14.7: Ratio of the observed $\bar{\nu}_e$ spectrum to the expectation for no-oscillation versus L_0/E for the KamLAND data. $L_0 = 180$ km is the flux-weighted average reactor baseline. The 3-ν histogram is the best-fit survival probability curve from the three-flavour unbinned maximum-likelihood analysis using only the KamLAND data. This figure is taken from [150].

Accelerator neutrinos - basic idea

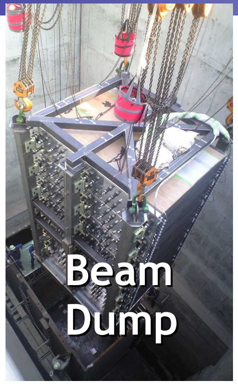
- The main principle behind the production accelerator neutrinos is an analogy to atmospheric neutrino production mechanism
  - Accelerate protons to high energies with the accelerator
  - Collide protons with the target (eg. graphite) and produce secondary particles, mainly pions
  - Let the pions decay and produce neutrinos

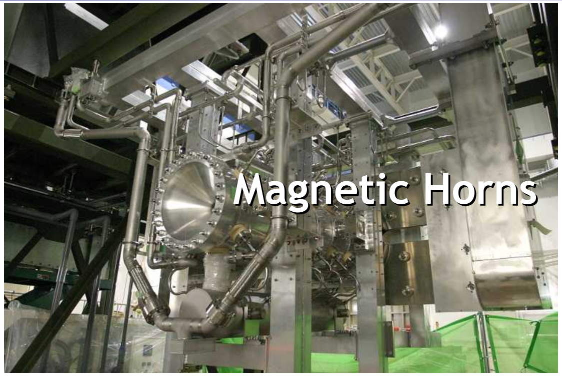


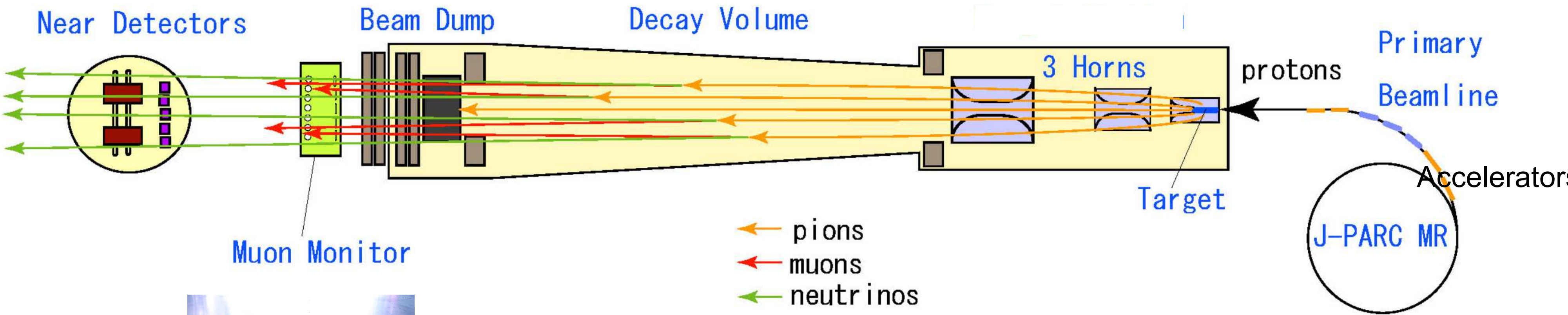
- Some extra ideas in accelerator neutrino production:
  - Focus charged pions with the same sign (and deflect pions with opposite sign) with magnetic horns (toroidal magnetic field).
    - Ultimately able to get either neutrino (positive pions are focused) or antineutrino (negative pions are focused) beam.
    - Can change the polarity of the horns → one experiment can operate in two modes: neutrino or antineutrino mode
  - Stop muons produced in the charged pion decay using a block of graphite and iron → beam dump.

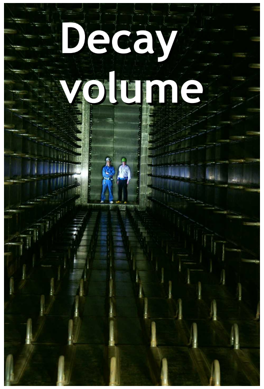


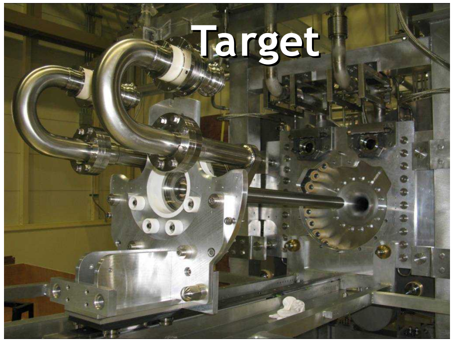
Accelerator neutrinos



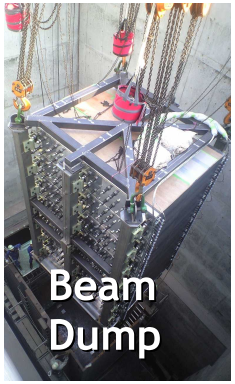


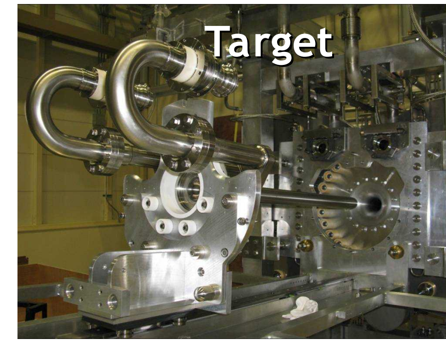


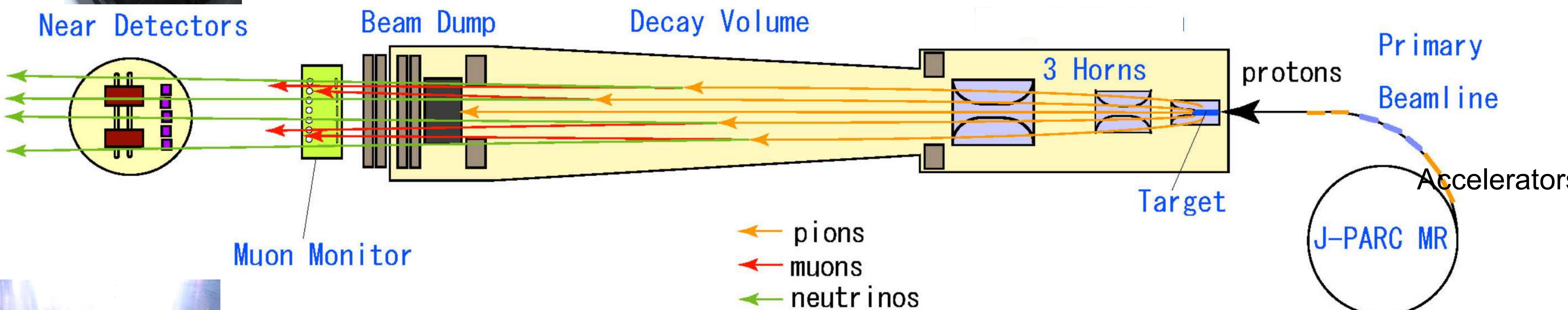


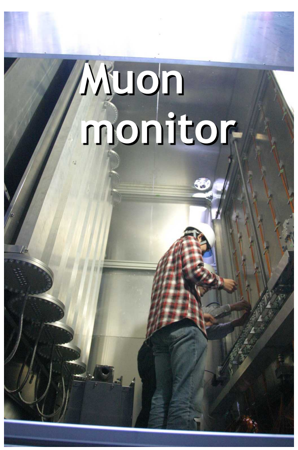


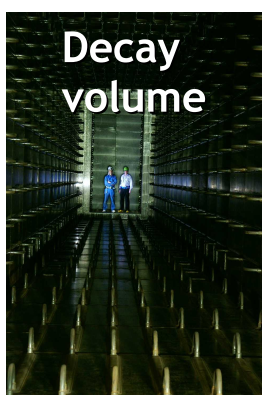
Accelerator neutrinos

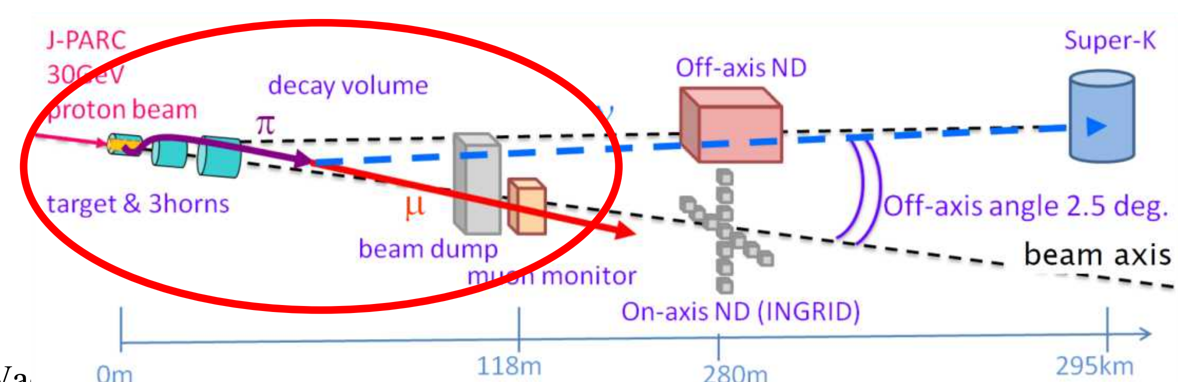




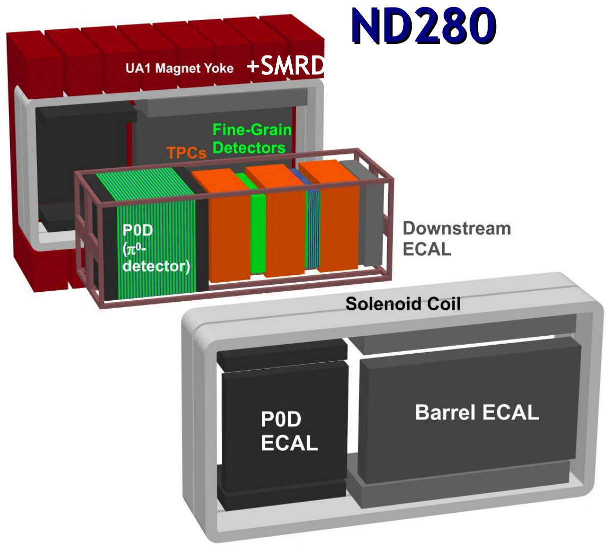


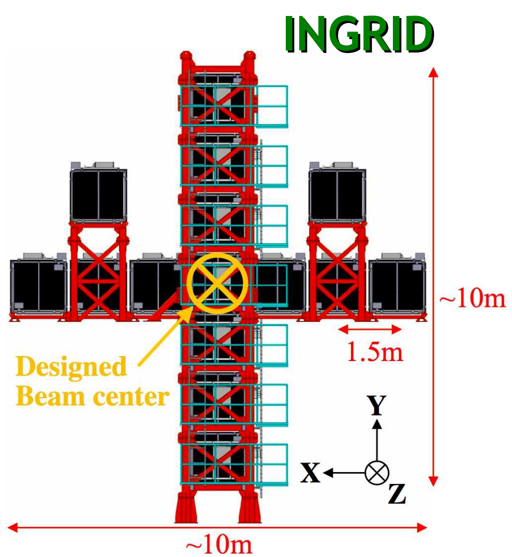




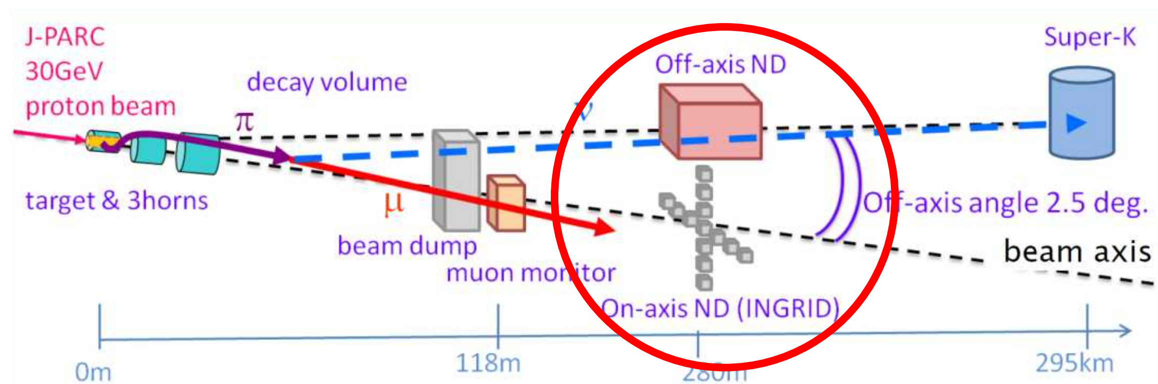


Near detector example (T2K)

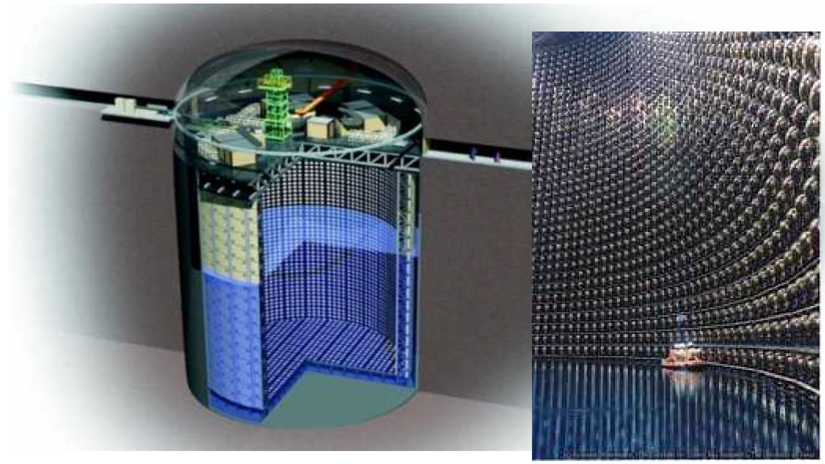


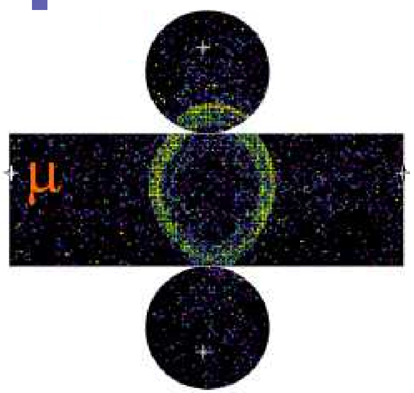


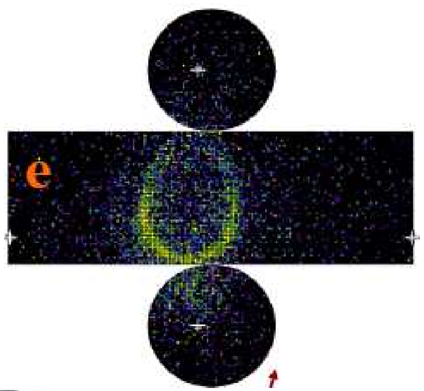
- Off-axis detector:
  - Several sub-detectors in 0.2T magnetic field:
    - Tracker (TPC + FGD), pizero detector (P0D), electromagnetic calorimenter (ECAL), muon ranger (SMRD)
  - Measures the neutrino flux before the oscillations occur
  - Measures intrinsic ν_e contamination
  - Measures neutrino interaction cross sections
- On-axis detector (INGRID):
  - 16 iron-scintillator modules form the cross
  - Monitoring flux, direction and stability of the neutrino beam
  - Neutrino cross section measurements

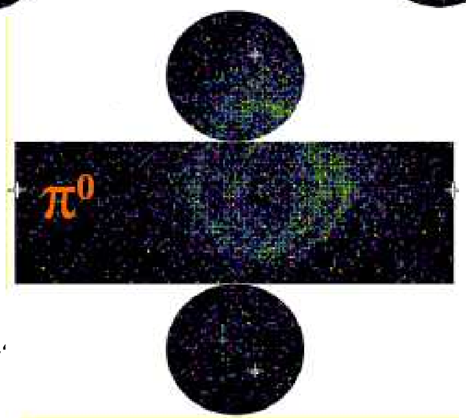


Far detector (T2K)

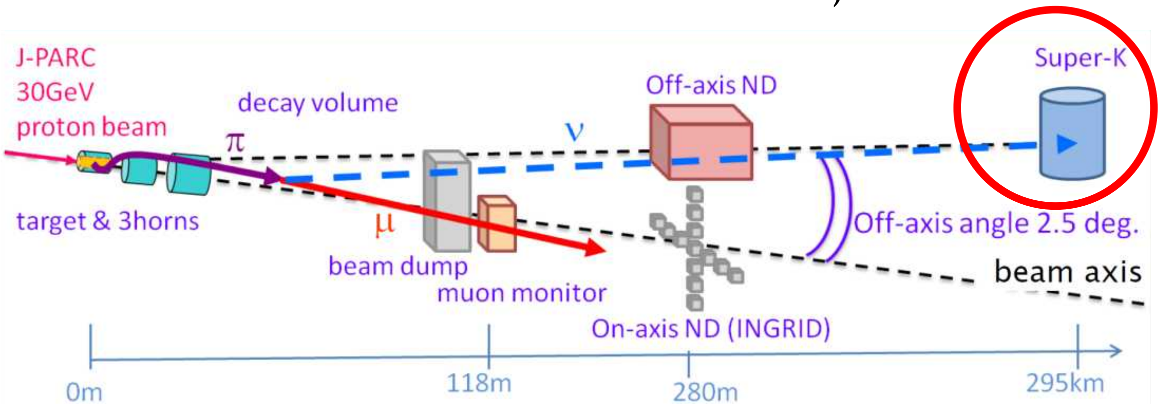




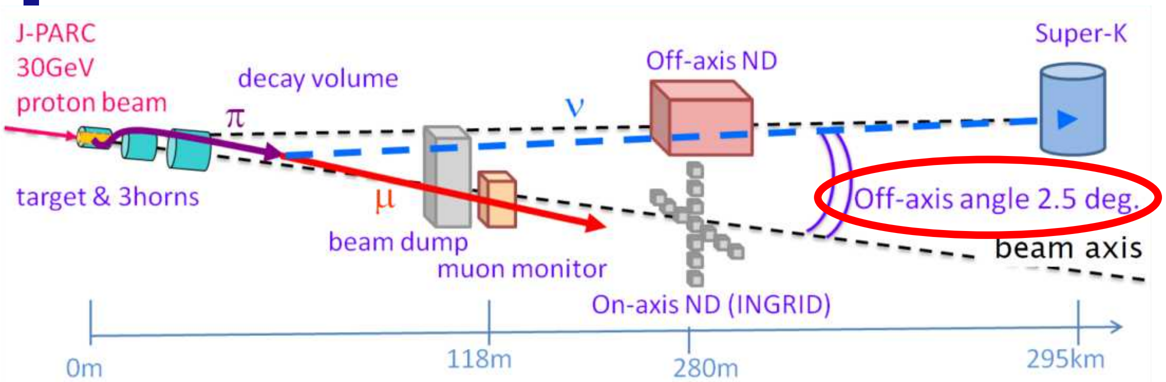


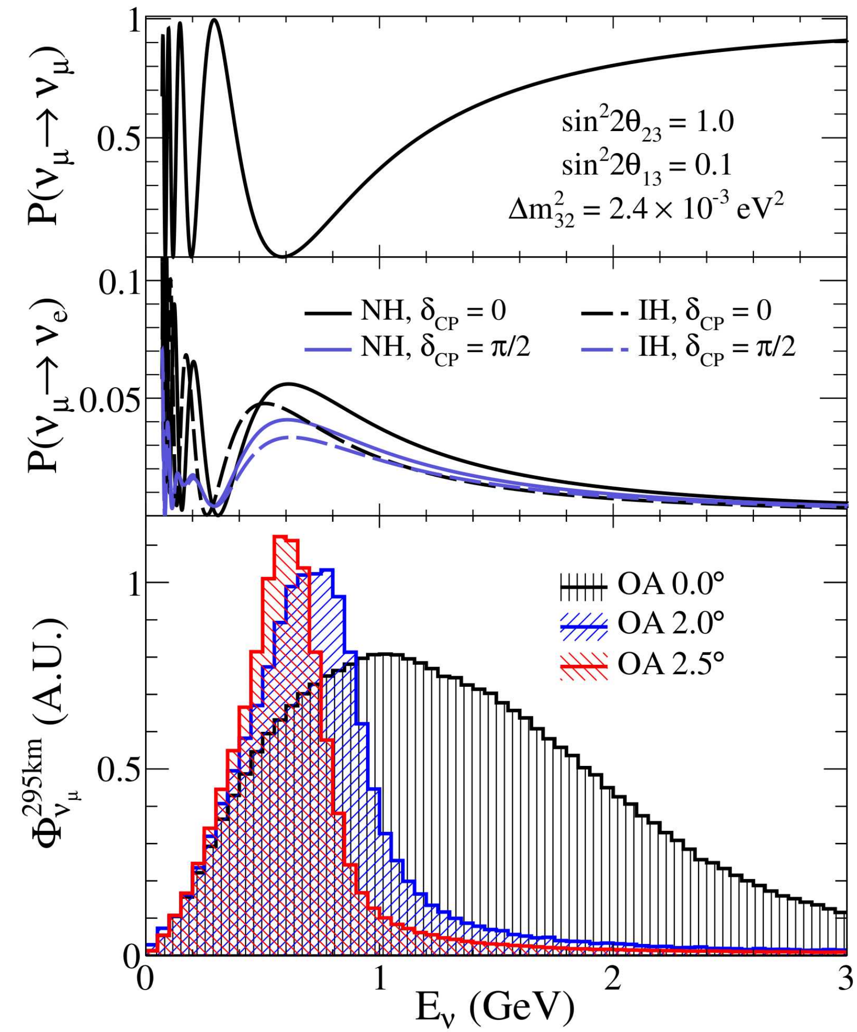


- Super-Kamiokande (operating since 1996):
  - Water Cherenkov (50 kt, 22.5 kt fiducial volume).
  - 11 000 (inner) + 2000 (outer) photomultipliers
  - Neutrino energy resolution ~10%
  - Particle identification:
    - Good electron-muon discrimination (<1% muons identified as electrons)
    - Neutral pion detection (rejecting background from neutrino interactions with π^0).



Off-axis beam concept



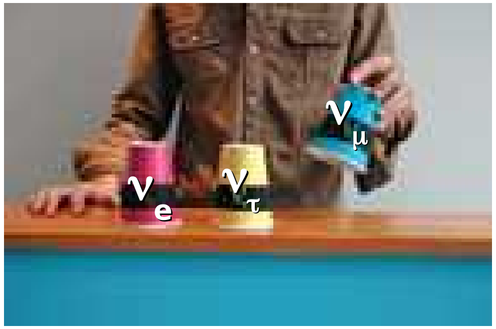


- Currently two world leading accelerator experiments (T2K, NOvA) use 'off-axis' beam idea:
  - Pion decay kinematic effect
  - Thin energy spectrum with the mean energy tuned to the neutrino oscillation probability
  - Lower background from high energy interactions that are difficult to reconstruct

Accelerator neutrino oscillations

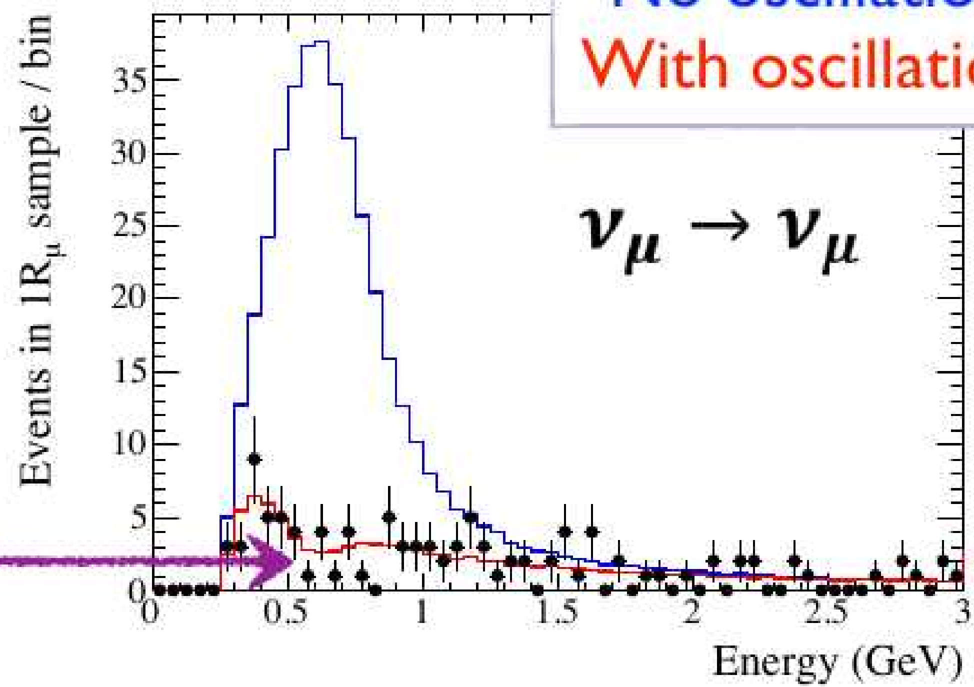
Disappearance of muon neutrinos/antineutrinos from the beam

(ν_μ/anti-ν_μ disappearance)



$$P(\overset{(-)}{\nu_\mu} \rightarrow \overset{(-)}{\nu_\mu}) \simeq 1 - 4\cos^2\theta_{13}\sin^2\theta_{23} \times [1 - \cos^2\theta_{13}\sin^2\theta_{23}]\sin^2\frac{\Delta m^2_{32} L}{4E} + (\text{solar, matter effect terms})$$

No oscillation
With oscillation



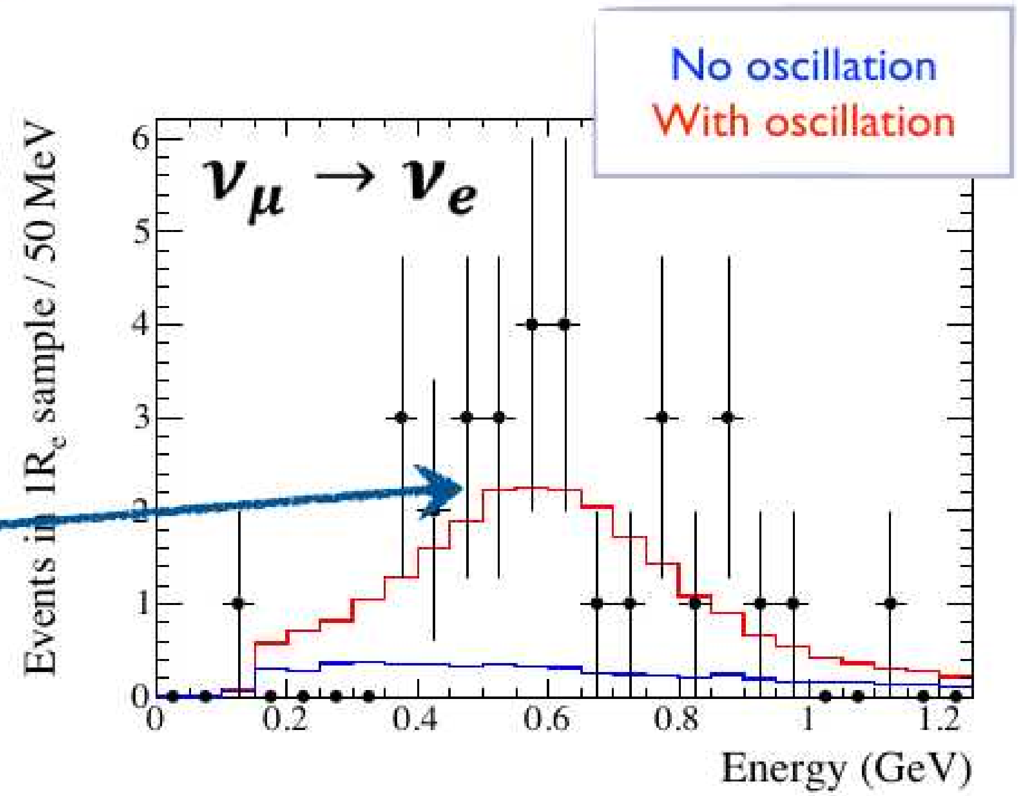
Location of min: Δm^2_{32}
Depth of min: $\sin^2 2\theta_{23}$

Accelerator neutrino oscillations

Electron neutrino/antineutrino appearance in the muon neutrino/antineutrino beam (ν_e/anti-ν_e appearance)

$$P(\overset{(-)}{\nu_\mu} \to \overset{(-)}{\nu_e}) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{32}L}{4E}$$
$$(+)-\left[\sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13}\cos\theta_{13}\right.$$
$$\left.\times\sin\frac{\Delta m^2_{21}L}{4E}\sin^2\frac{\Delta m^2_{32}L}{4E}\sin\delta_{CP}\right]$$
$$+\ (\text{CP-even, solar, matter effect terms})$$

Magnitude of the peak
$\sin^2\theta_{23}$, $\sin^2 2\theta_{13}$, δ_{CP}



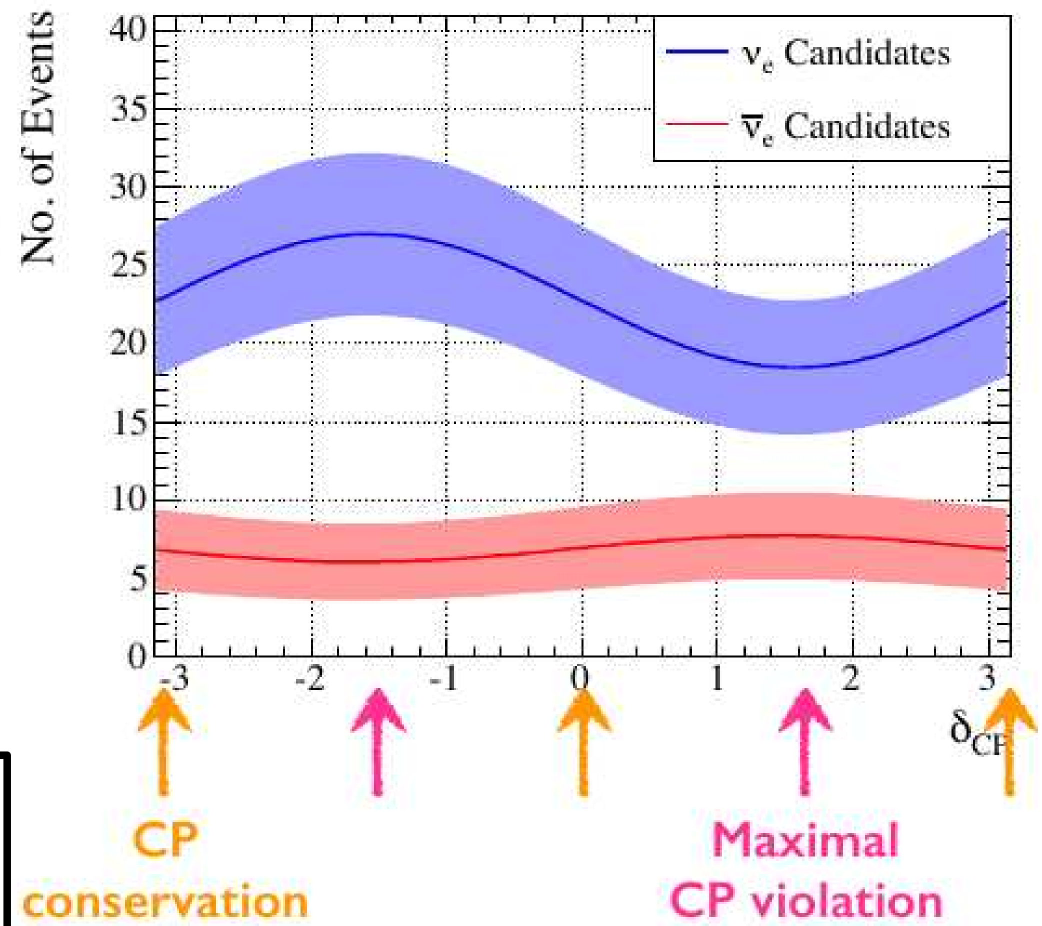
CP violation in neutrino sector?

Use accelerator neutrinos and measure:

$$CPV: \quad P(\nu_\mu \rightarrow \nu_e) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$$

$$P(\nu_\mu \rightarrow \nu_e) \simeq \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{32} L}{4E}$$
$$(+)-\left[\sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \cos\theta_{13} \times \sin\frac{\Delta m^2_{21} L}{4E} \sin^2 \frac{\Delta m^2_{32} L}{4E} \sin\delta_{CP} \right]$$
$$+ \text{(CP-even, solar, matter effect terms)}$$

$\sin\delta_{CP}$ occurs in ν_e and $\bar{\nu}_e$ appearance probability with opposite sign



Complicated measurement because the sensitivity to measure δ_{CP} depends on:

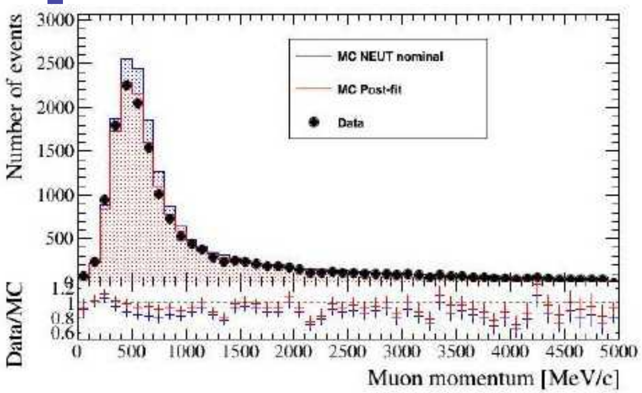
δ_{CP} true value, θ_{23} true value, mass ordering

Need to have control over all systematic effects → precision measurements in neutrino oscillations

Accelerator neutrino oscillation analysis

Neutrino flux model:
Monte Carlo simulations + external data from other experiments (eg. NA61)

Neutrino interaction models and their uncertainties:
Monte Carlo simulations + external data (MINERvA, MiniBooNE experiments)

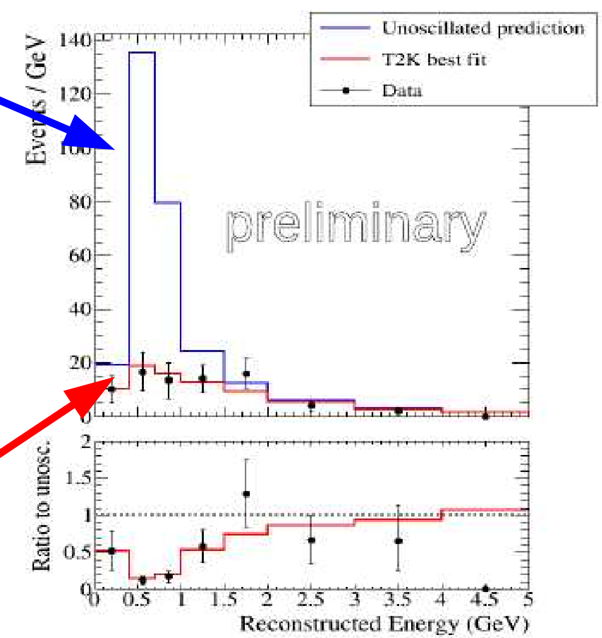


Fit to the data from the near detector

From near detector fit:
Flux model parameters,
Neutrino interaction model parameters,
Backgrounds in far detector

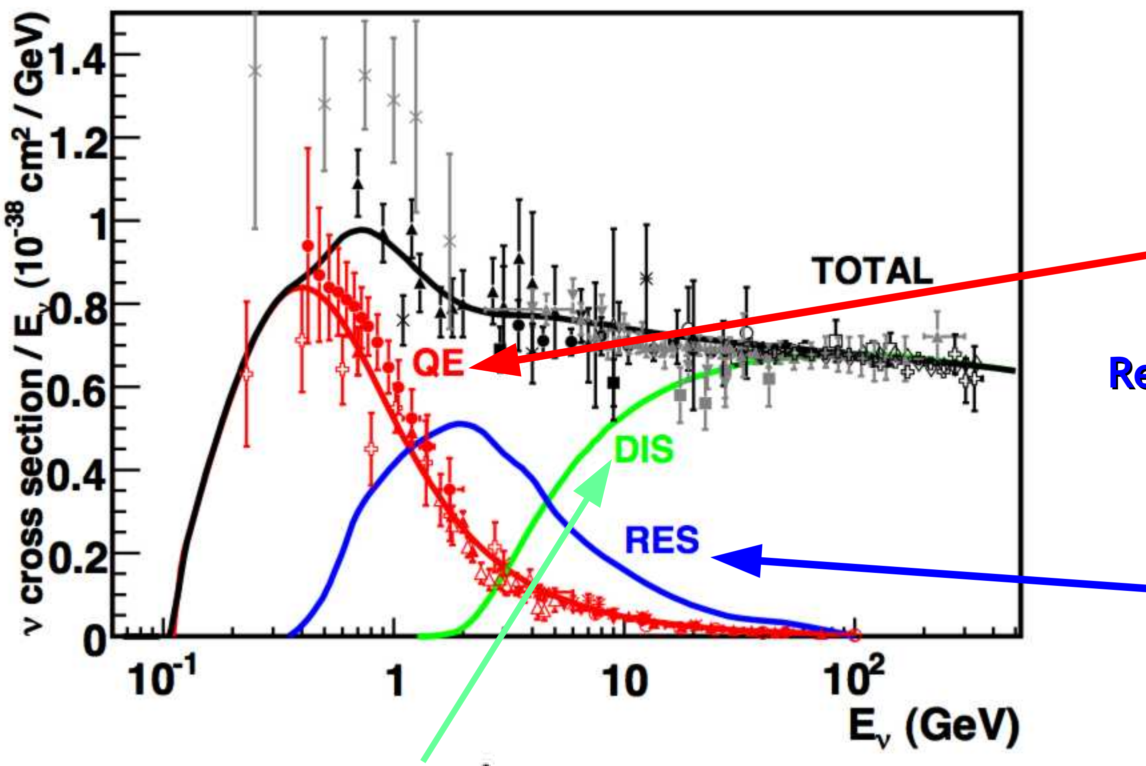
Expected neutrino spectrum
In far detector

Fit to the data from far detector (with PMNS model)

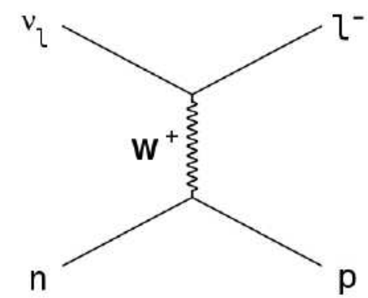


Neutrino interactions (accelerator neutrinos)

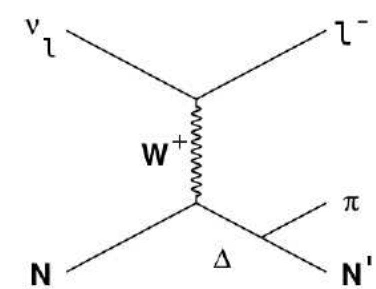
Charged-current interactions

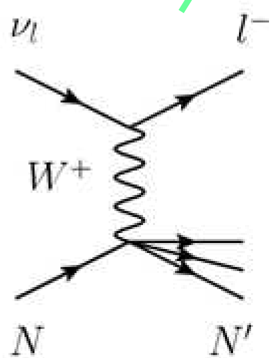


Quasi-elastic scattering - CCQE (dominant in T2K)



Resonance pion production - RES (dominant in NOvA)





Deep Inelastic Scattering (DIS) (NOvA)

+ additional complications:

- Nuclear 'initial-state' models
- Nuclear re-interactions models (Final State Interactions)
- ...

Accelerator neutrino experiments

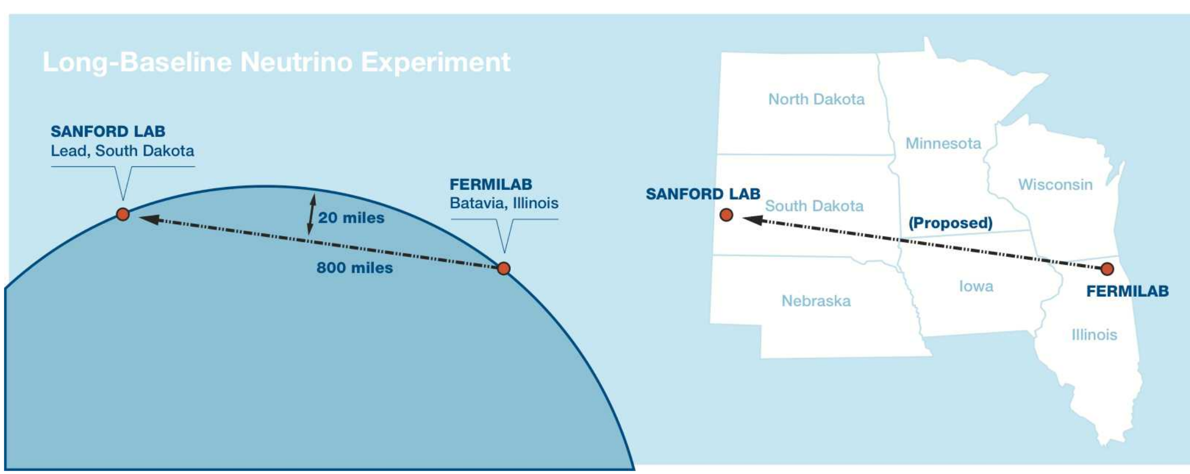
Name	Beamline	Far Detector	L (km)	E_ν (GeV)	Year
K2K	KEK-PS	Water Cherenkov	250	1.3	1999–2004
MINOS	NuMI	Iron-scintillator	735	3	2005–2013
MINOS+	NuMI	Iron-scintillator	735	7	2013–2016
OPERA	CNGS	Emulsion	730	17	2008–2012
ICARUS	CNGS	Liquid argon TPC	730	17	2010–2012
T2K	J-PARC	Water Cherenkov	295	0.6	2010–
NOvA	NuMI	Liquid scint. tracking calorimeter	810	2	2014–

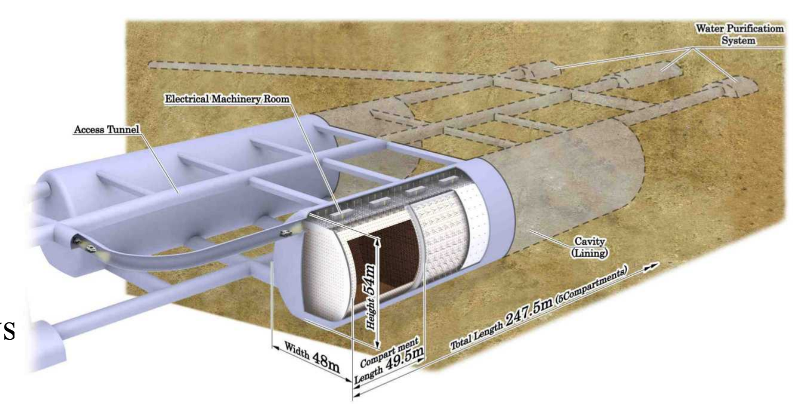
- History of accelerator neutrino studies and major results:
  - K2K (Japan): confirmed atmospheric neutrino oscillations discovered by Super-Kamiokande
  - MINOS, MINOS+ (USA): measured atmospheric neutrino oscillations Δm^2_{32}, θ_{23}
  - OPERA (Italy): confirmed $\nu_\mu \rightarrow \nu_\tau$ oscillations
  - ICARUS (Italy): first neutrino detector using liquid argon Time Projection Chambers technique
  - T2K (Japan): θ_{13} angle measurement, Δm^2_{32} measurement, first measurement of δ_{CP} phase
  - NOvA (USA): θ_{13} angle measurement, δ_{CP} phase measurement, mass ordering

Future accelerator neutrino experiments

- DUNE (USA)
  - USA flagship accelerator neutrino project.
  - Neutrino beam produced in Fermilab (1.2 MW and 2.4 MW power after upgrade)
  - 10 kton or larger liquid argon detector in South Dakota (1300 km from Fermilab) 1.5 km underground.
  - Two prototype far detectors are at the European research center CERN. The first started taking data in September 2018 and the second is under construction.
  - Should be able to measure δ_{CP} ~ 20 degree accuracy (~10 degrees after beam upgrade).
  - Start ~2028

- Hyper-Kamiokande (Japan)
  - T2K experiment extension with larger far detector.
  - High-intensity neutrino beam (1.7 MW) from J-PARC complex
  - Far detector – 0.5 kton water Cherenkov 300 km from J-PARC.
  - Measuring δ_{CP} with accuracy of 18 degrees but depends on mass ordering measurements.
  - Start ~2027





Summary & prospects

- Today covered:
  - ✓ Artificial neutrino sources: reactor, accelerator
  - ✓ Neutrino Oscillations
- To remember:
  - → How are reactor neutrinos produced and measured?
  - → Accelerator neutrinos: production, oscillations, CP violation
- There are many other interesting topics such as: sterile neutrinos, neutrino masses, absolute neutrino mass measurements, neutrinoless double-beta decay, neutrino interactions – unfortunately no time to cover...