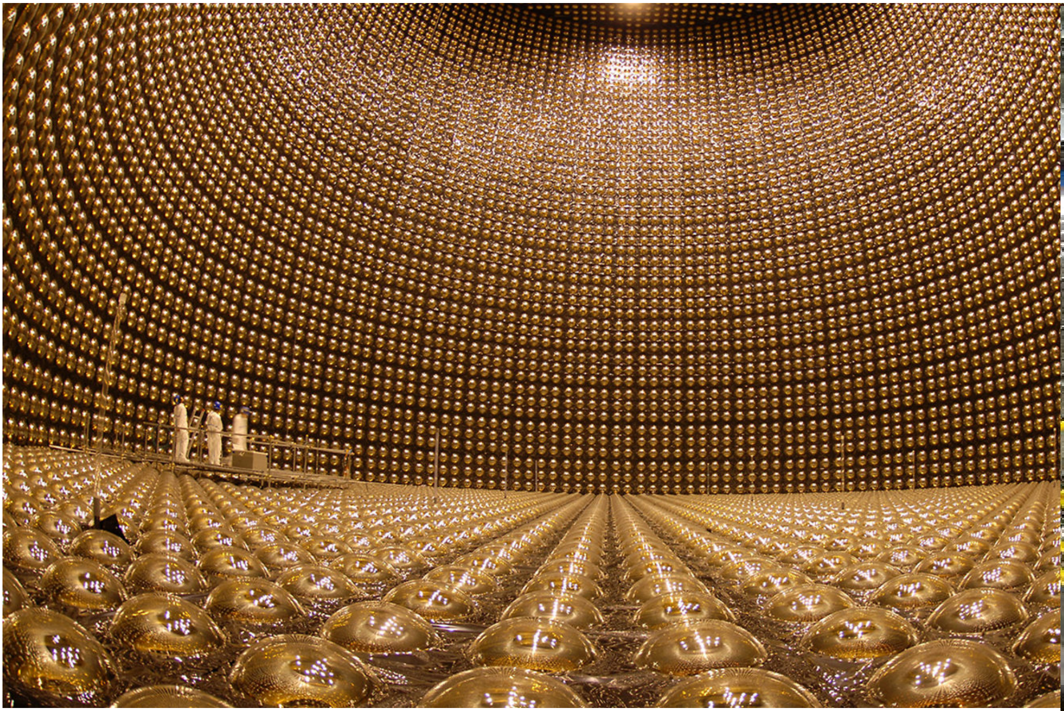
Current Long Baseline Neutrino Experiments



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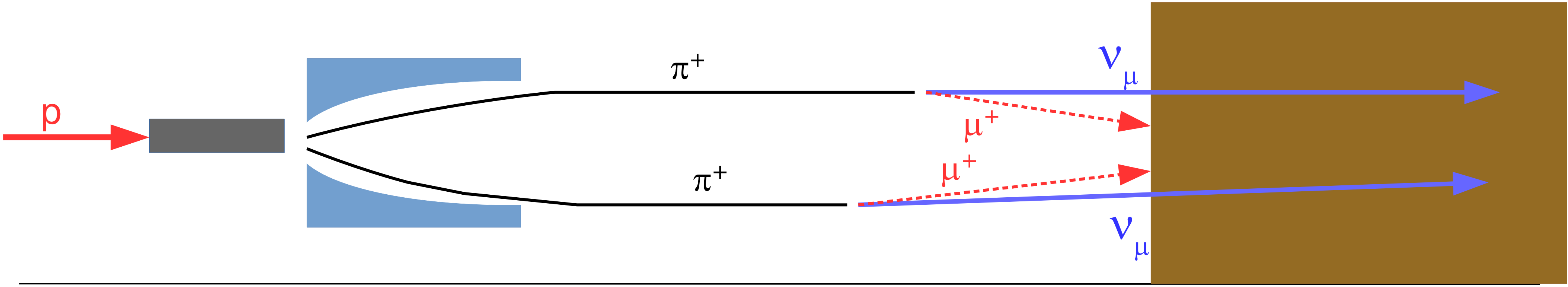


Scott Oser **(UBC/TRIUMF)**

TAUP 2017
July 26, 2017

The neutrino 3x3 mixing matrix

Different L/E values pick up different Δm² pairs, probing different parts of mixing matrix.

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

Atmospheric ν's:

$\theta_{23} \approx 46°$

Maximal mixing! (?)

Short baseline reactor ν's:

$\theta_{13} \approx 9°$

Small, quark-like mixing

Solar ν's:

$\theta_{12} \approx 33°$

Large, non-maximal mixing

Compare to identical parameterization of CKM matrix ...

$\theta_{23} \approx 2.4°$ $\theta_{13} \approx 0.2°$ $\theta_{12} \approx 13°$

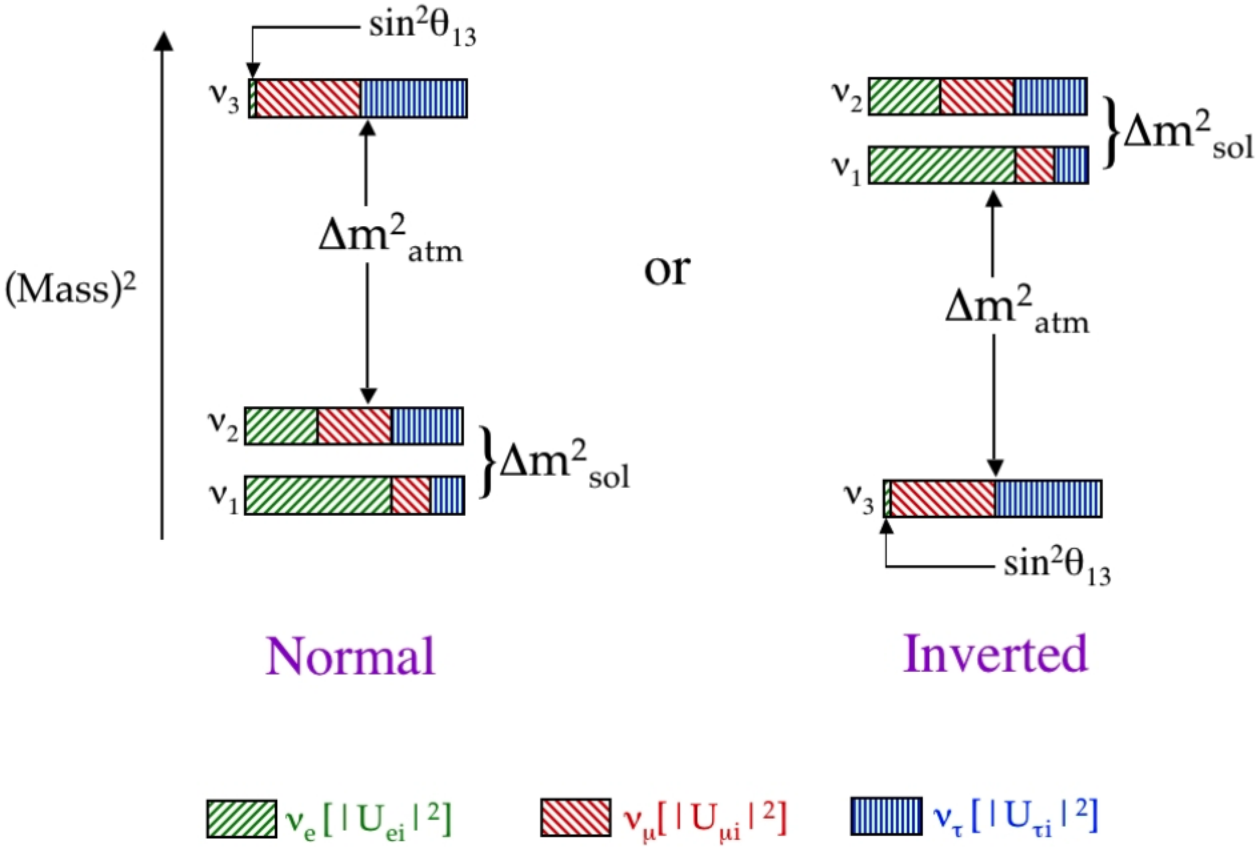
Mass Hierarchy

Currently unknown:

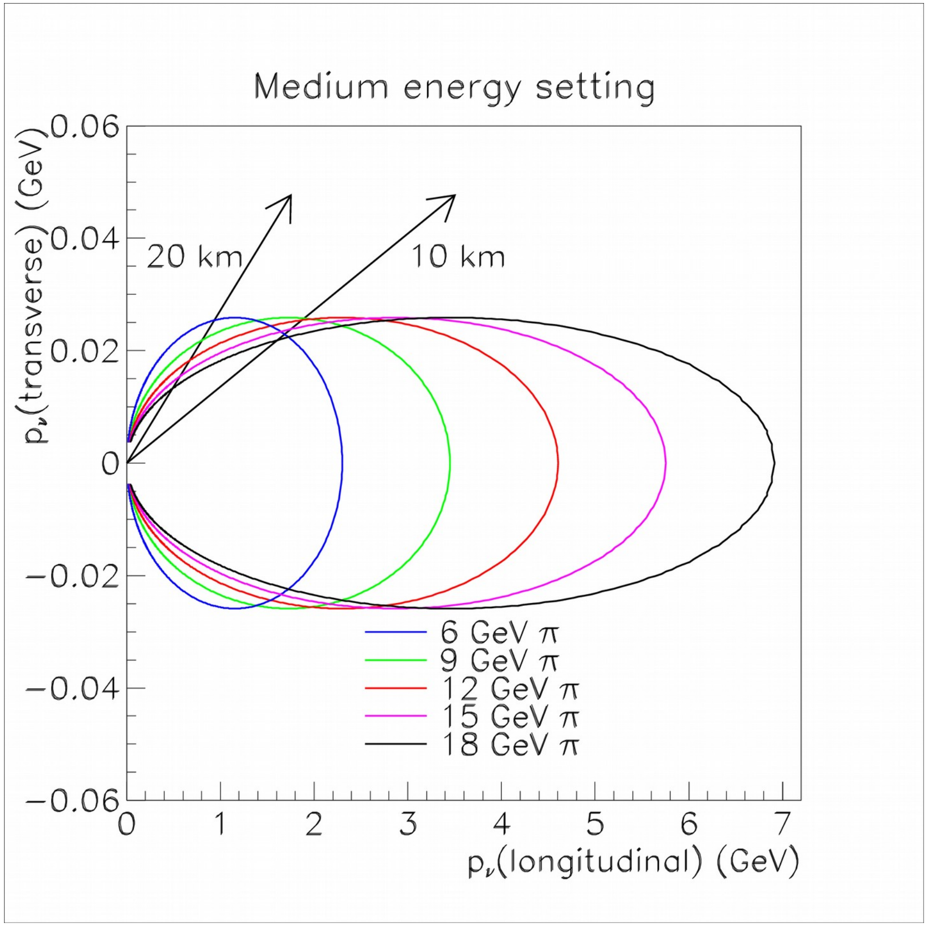
- value of δ_{CP}
- sign of the mass hierarchy

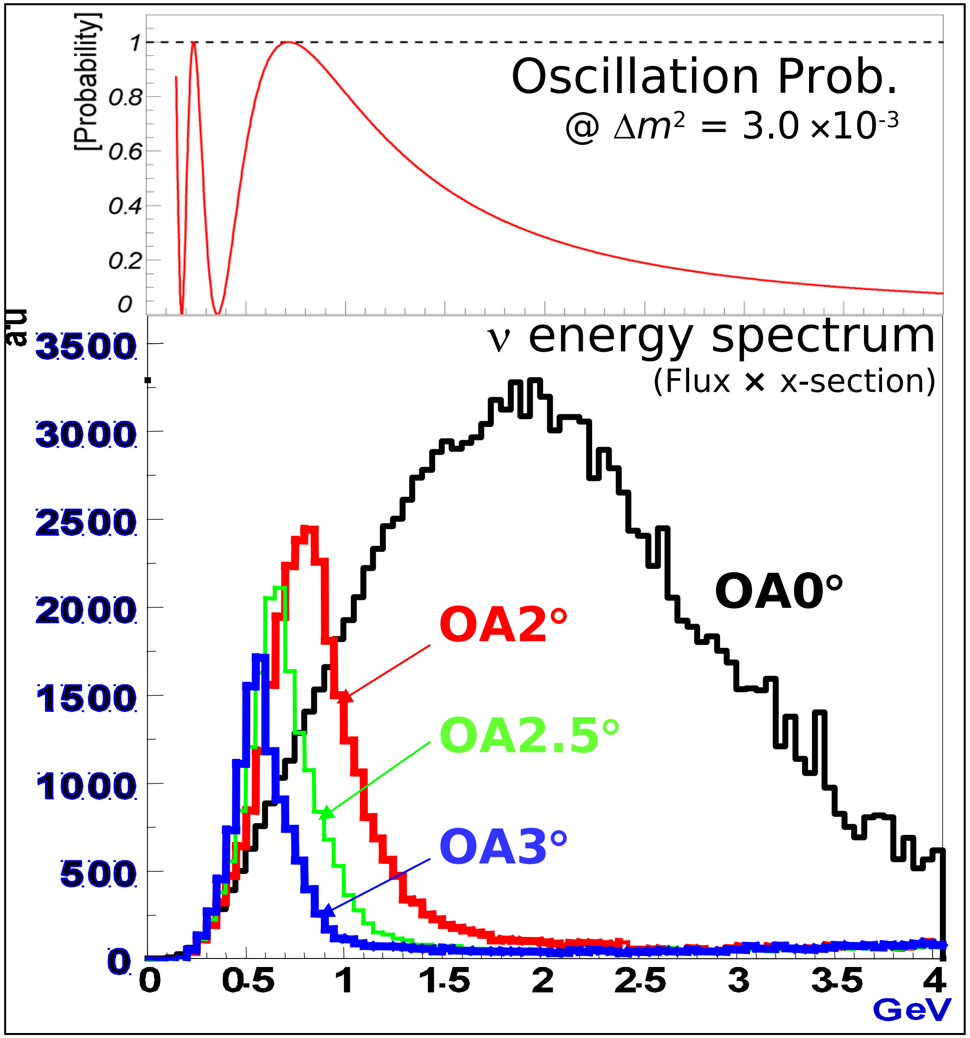
$|\Delta m^2_{32}| = 2.4 \times 10^{-3}\ \mathrm{eV}^2$

$\Delta m^2_{21} = 7.5 \times 10^{-5}\ \mathrm{eV}^2$



Off-Axis ν_μ Beam





Off-axis beam: more flux near peak oscillation energy, less flux at higher energies where ν_e backgrounds are produced.

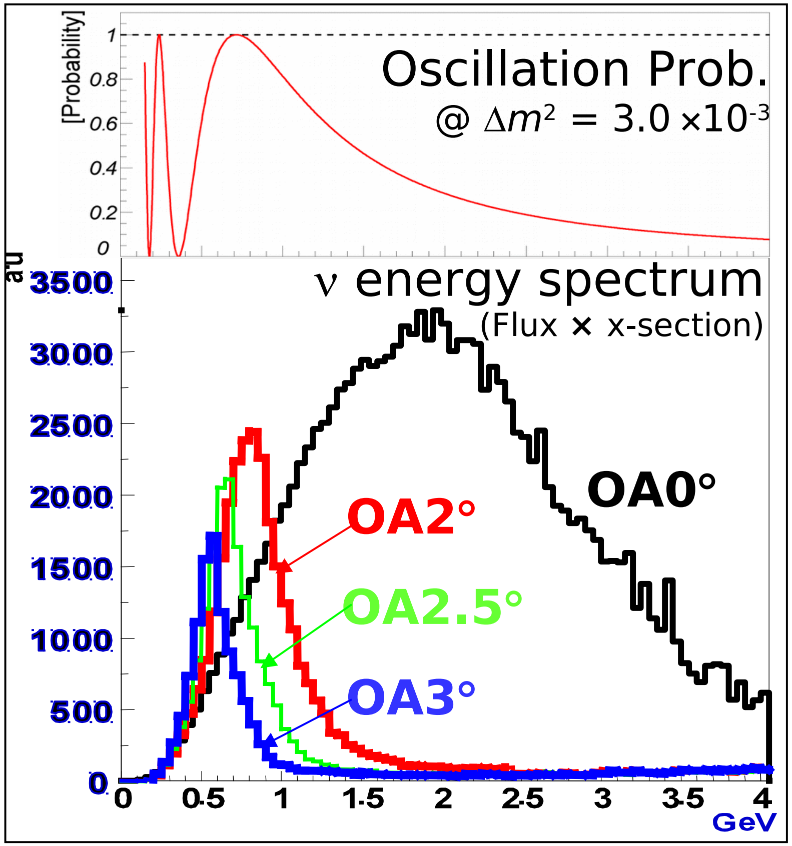
LBL signature #1: ν_μ disappearance

Starting from $P_{\nu_a \to \nu_b}(L, E) = \left| \sum_{j,k} U^*_{aj} U_{bj} U_{ak} U^*_{bk} e^{-i\frac{\Delta m^2_{jk} L}{2E}} \right|$

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \cos^4\theta_{13} \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$$

$$- \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$$

$$\approx 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$$



Sensitive to Δm^2_{32} and θ_{23}.

Same formula for neutrinos and for antineutrinos, if CPT holds.

LBL signature #2: ν_e appearance

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) \sim\ & \boxed{\sin^2 2\theta_{13} \times \sin^2 \theta_{23} \times \frac{\sin^2[(1-x)\Delta]}{(1-x)^2}} \\
& -\alpha \sin 2\theta_{13} \times \sin\delta \sin 2\theta_{12} \sin 2\theta_{23} \times \sin\Delta \frac{\sin[x\Delta]}{x} \frac{\sin[(1-x)\Delta]}{(1-x)} \\
& +\alpha \sin 2\theta_{13} \times \cos\delta \sin 2\theta_{12} \sin 2\theta_{23} \times \cos\Delta \frac{\sin[x\Delta]}{x} \frac{\sin[(1-x)\Delta]}{(1-x)} \\
& x \equiv 2\sqrt{2} G_F N_e \frac{E_\nu}{\Delta m^2_{31}} \qquad \Delta \equiv \frac{\Delta m^2_{31} L}{4E_\nu}
\end{aligned}
$$

Dominant term corresponds to a ~5% transition probability at the oscillation maximum

LBL signature #2: ν_e appearance

$$\begin{aligned} P(\nu_\mu \to \nu_e) \sim\; & \sin^2 2\theta_{13} \times \sin^2 \theta_{23} \times \frac{\sin^2[(1-x)\Delta]}{(1-x)^2} \\ & -\alpha \sin 2\theta_{13} \times \sin\delta \sin 2\theta_{12} \sin 2\theta_{23} \times \sin\Delta \frac{\sin[x\Delta]}{x} \frac{\sin[(1-x)\Delta]}{(1-x)} \\ & +\alpha \sin 2\theta_{13} \times \cos\delta \sin 2\theta_{12} \sin 2\theta_{23} \times \cos\Delta \frac{\sin[x\Delta]}{x} \frac{\sin[(1-x)\Delta]}{(1-x)} \end{aligned}$$

$$x \equiv 2\sqrt{2} G_F N_e \frac{E_\nu}{\Delta m^2_{31}} \qquad \Delta \equiv \frac{\Delta m^2_{31} L}{4E_\nu}$$

Terms containing δ are sensitive to CP phase. The δ's flip sign for antineutrinos.

The x parameter (matter effect) also flips sign for antineutrinos. The matter effect is subdominant at T2K due to low beam energy, but larger at NOνA.

CP, T, and CPT for neutrinos

$$P(\nu_a \to \nu_b) \xleftrightarrow{\text{CP}} P(\bar{\nu}_a \to \bar{\nu}_b)$$

$$P(\nu_a \to \nu_b) \xleftrightarrow{\text{T}} P(\nu_b \to \nu_a)$$

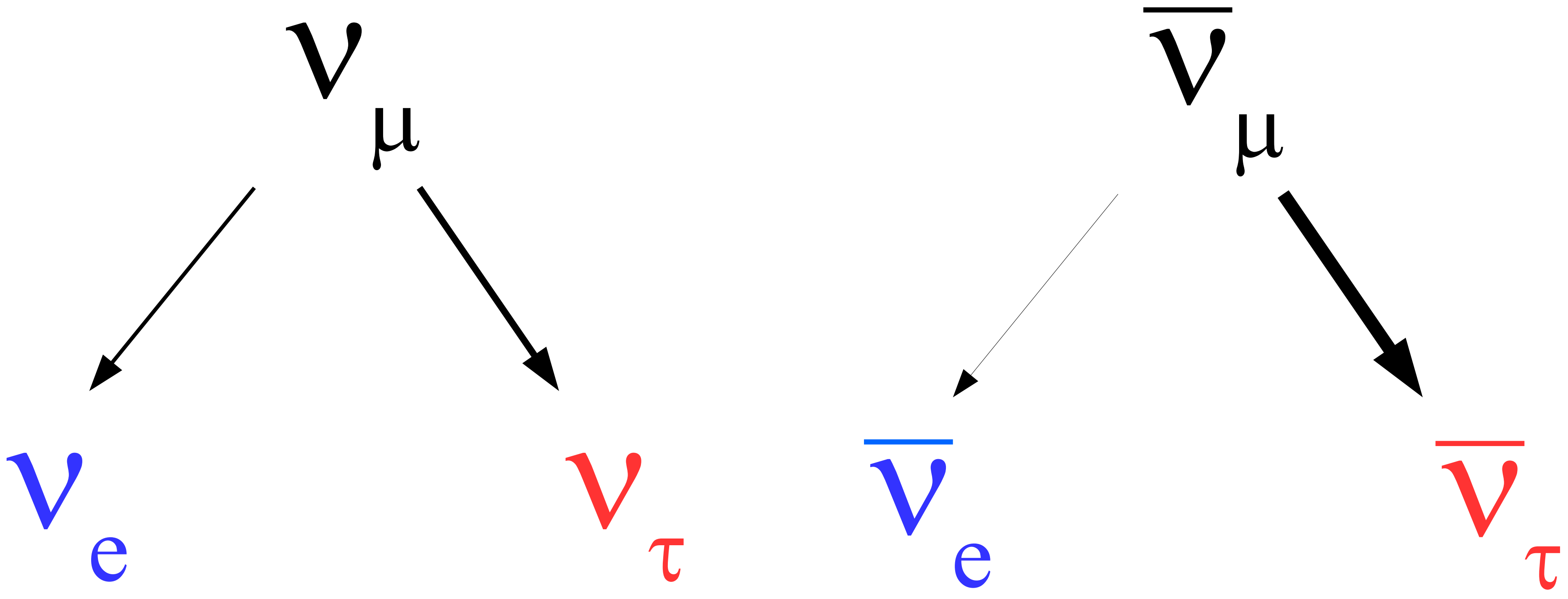
$$P(\nu_a \to \nu_b) \xleftrightarrow{\text{CPT}} P(\bar{\nu}_b \to \bar{\nu}_a)$$

$$P(\nu_a \to \nu_a) \xleftrightarrow{\text{CPT}} P(\bar{\nu}_a \to \bar{\nu}_a)$$

If CPT holds in neutrino sector, neutrino survival probability equals antineutrino survival probability.

As a result CP violation is observable only in appearance channels, in which the flavour of the appearing lepton is detected. This is why LBL neutrinos are interesting!

CP and three-flavour mixing



CP violation affects the mix of flavours that results from the oscillation

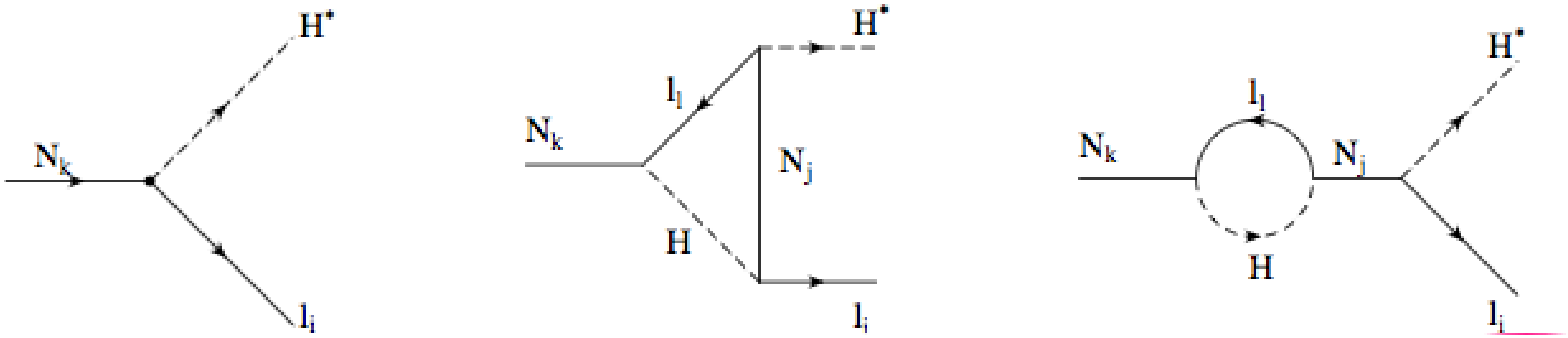
Leptogenesis

CP violation in quark sector not enough to explain observed matter-antimatter asymmetry in universe.

Neutrino mixing provides another possible source of CPV.

- Standard Leptogenesis: decays of RH neutrinos (CPV in decay)

  Quantum interference of tree diagram and one-loop diagram



Usual scenario: decay of heavy Majorana neutrinos Phys.Lett B 174, 45 (1986)
Many alternates, eg. leptogenesis with only Dirac ν's PRL 89:271601 (2002)

Relation of δ_{CP} to leptogenesis is model-dependent, but observation of leptonic CP violation is an important milestone.

Matter Effects and ν_e Appearance

Matter effects modify the oscillation formula. Because the Earth is made of electrons and not heavier leptons, the effective “index of refraction” for ν_e is different than that for ν_μ. At the oscillation maximum, the ν_e appearance probability changes to:

$$P(\nu_\mu \rightarrow \nu_e) \approx \left(1 + 2\frac{E}{E_R}\right) P_{vac}(\nu_\mu \rightarrow \nu_e)$$

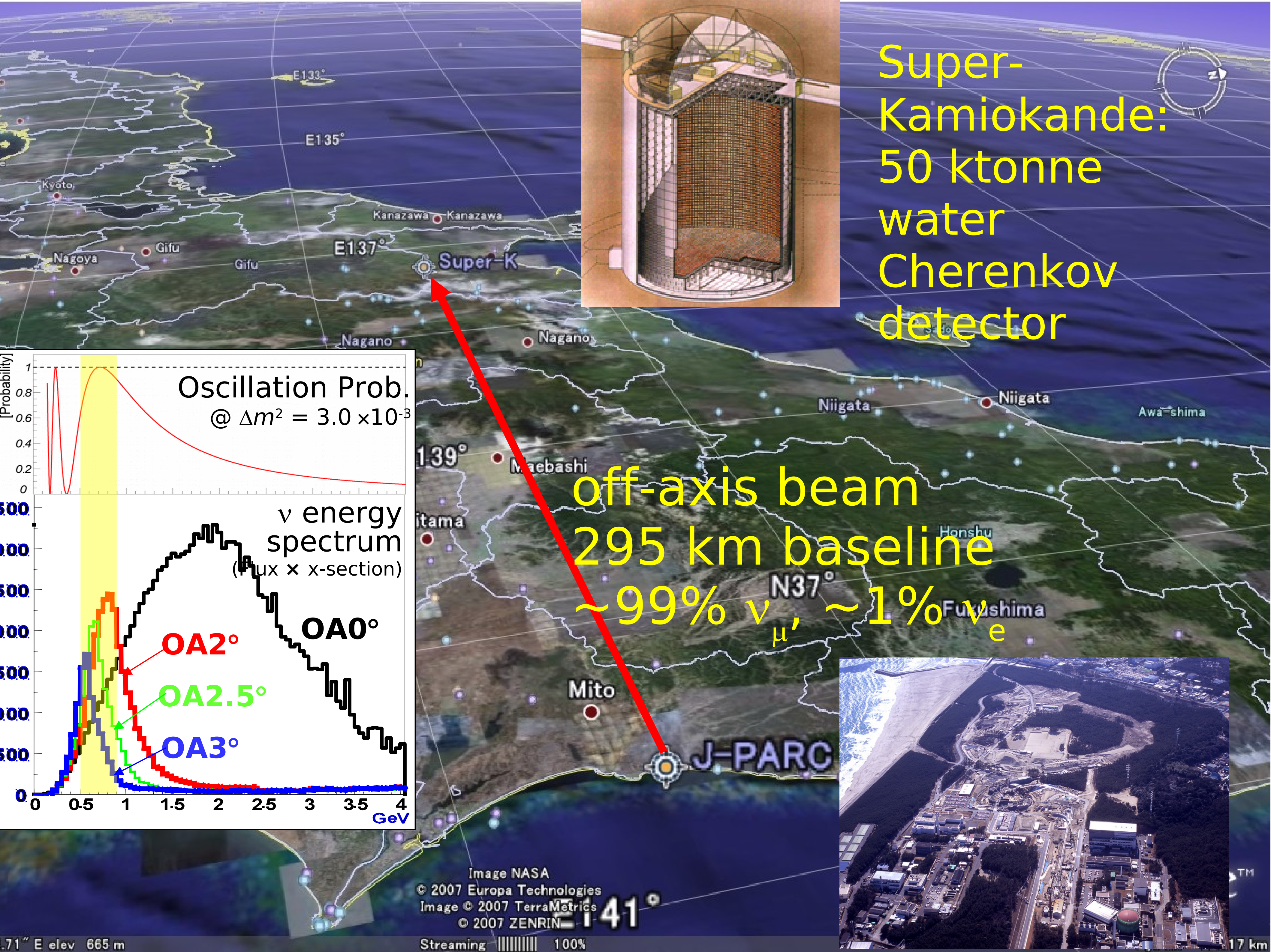
where

$$E_R = \frac{\Delta m^2_{32}}{2\sqrt{2}\,G_F N_e} = \pm 11\,GeV$$

The sign of the matter effect is opposite for neutrinos and anti-neutrinos, and depends on the sign of Δm^2 as well.

T2K

JAPAN PROTON ACCELERATOR RESEARCH COMPLEX (J-PARC):
Tokai, Japan
30 GeV proton synchrotron
design power: 0.75MW
(upgradable to >1MW)

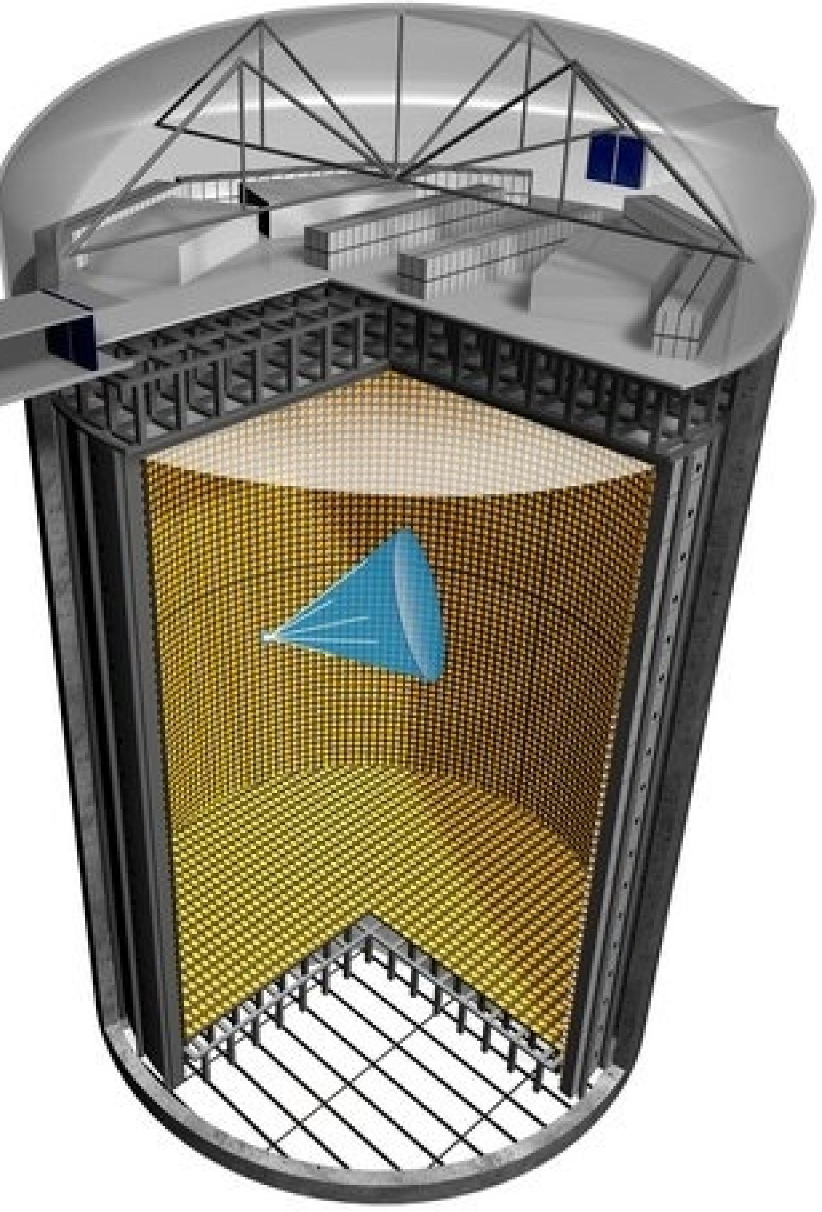


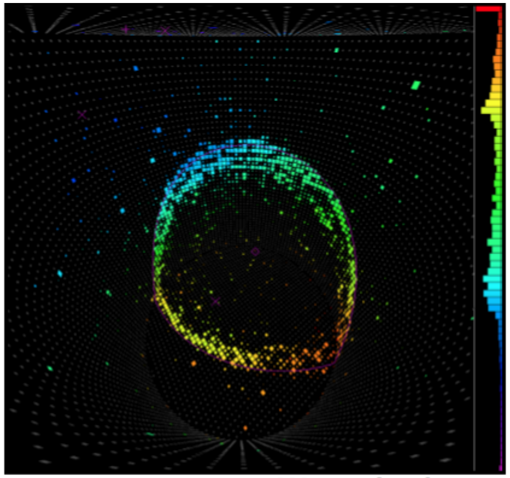
Super-Kamiokande: 50 ktonne water Cherenkov detector

off-axis beam
295 km baseline
~99% ν_μ, ~1% ν_e

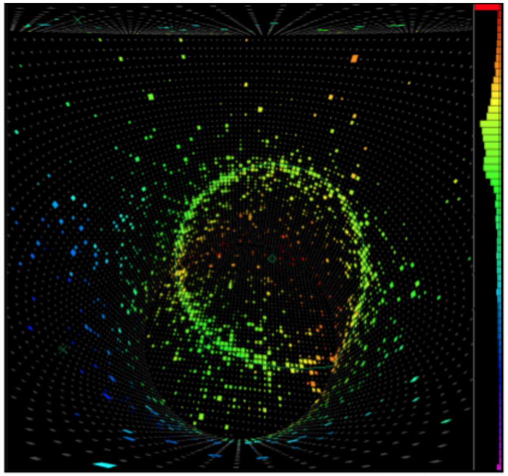
Sophisticated on-axis and off-axis near detectors 280m from proton target

Super-Kamiokande





muon-like (ν_μ)

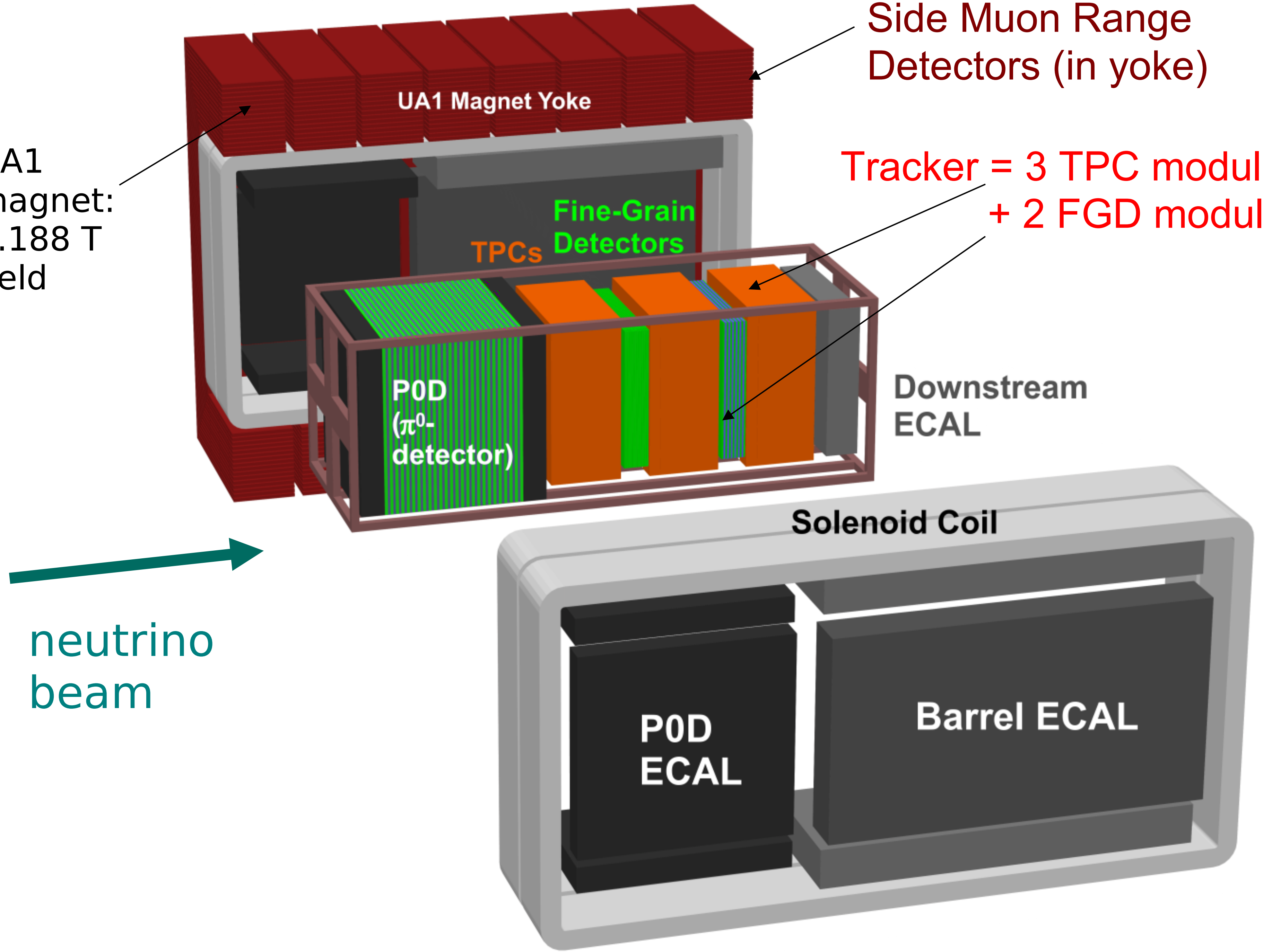


electron-like (ν_e)

Water Cherenkov detection.

Primary signal channel is CCQE single-ring events. Reconstruct ν energy in CCQE hypothesis from lepton kinematics.

Off Axis Near Detector



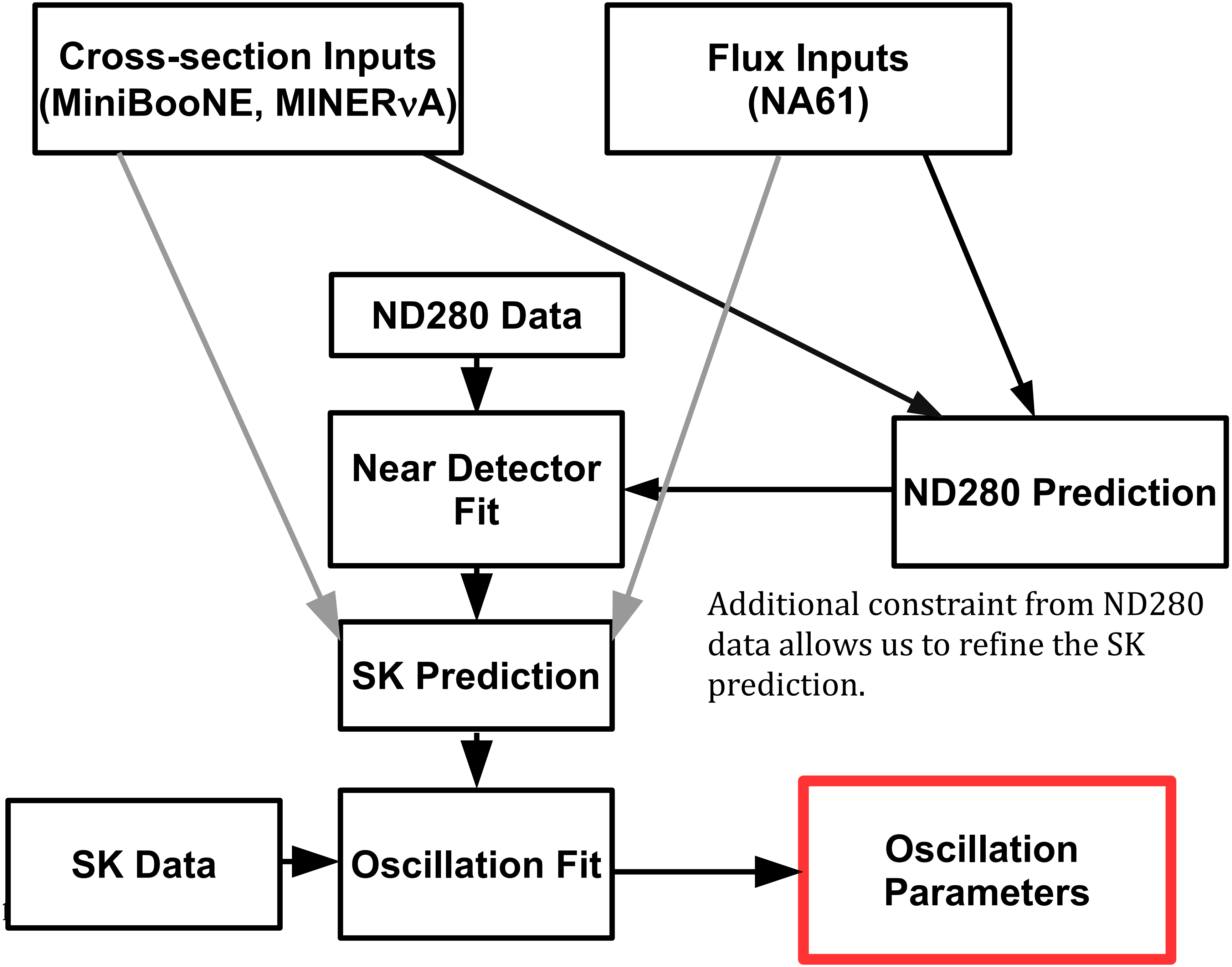
Side Muon Range Detectors (in yoke)

UA1 magnet: 0.188 T field

Tracker = 3 TPC modules + 2 FGD modules

neutrino beam

T2K Oscillation Analysis Structure



Cross-section Inputs (MiniBooNE, MINERνA)

Flux Inputs (NA61)

ND280 Data

Near Detector Fit

ND280 Prediction

SK Prediction

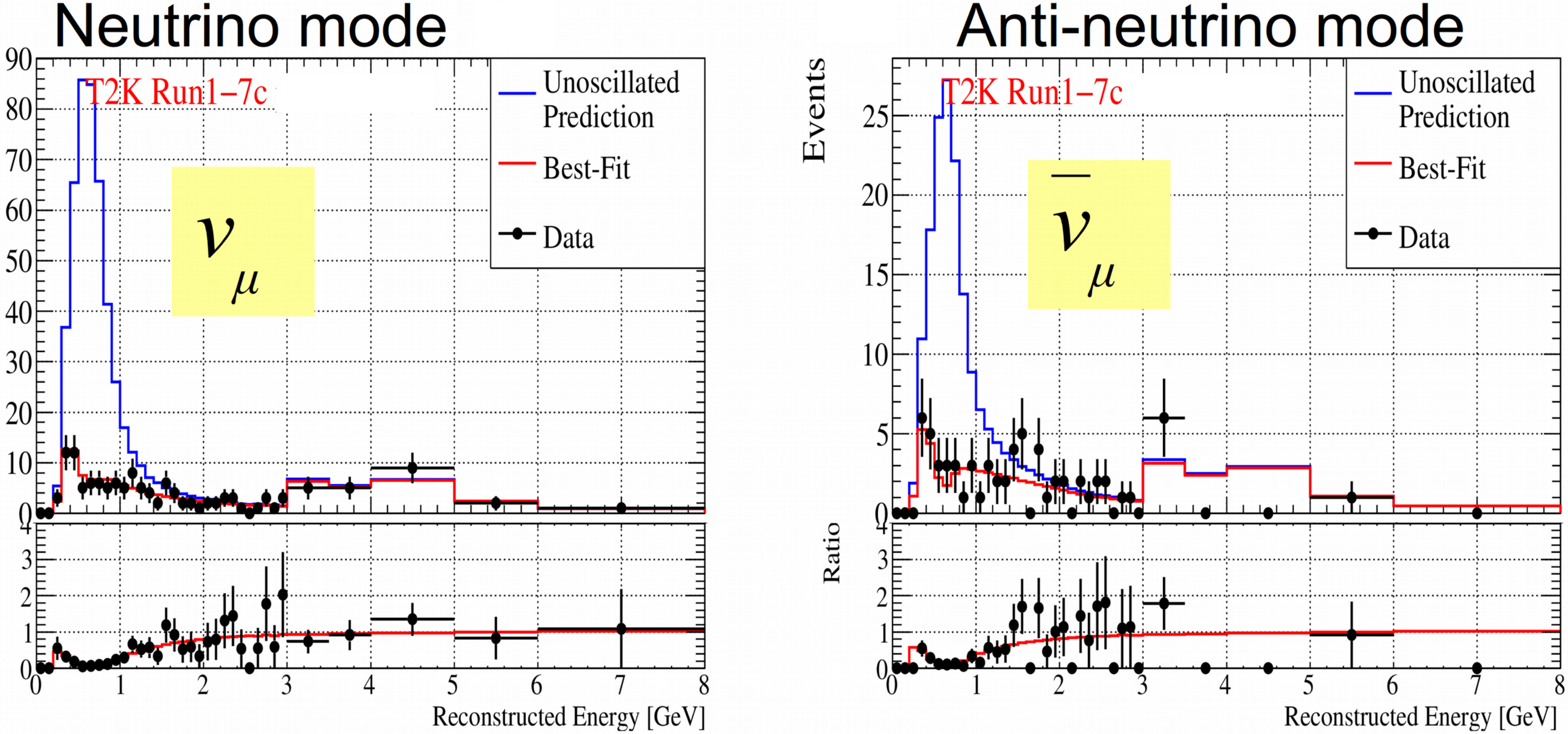
SK Data

Oscillation Fit

Oscillation Parameters

Additional constraint from ND280 data allows us to refine the SK prediction.

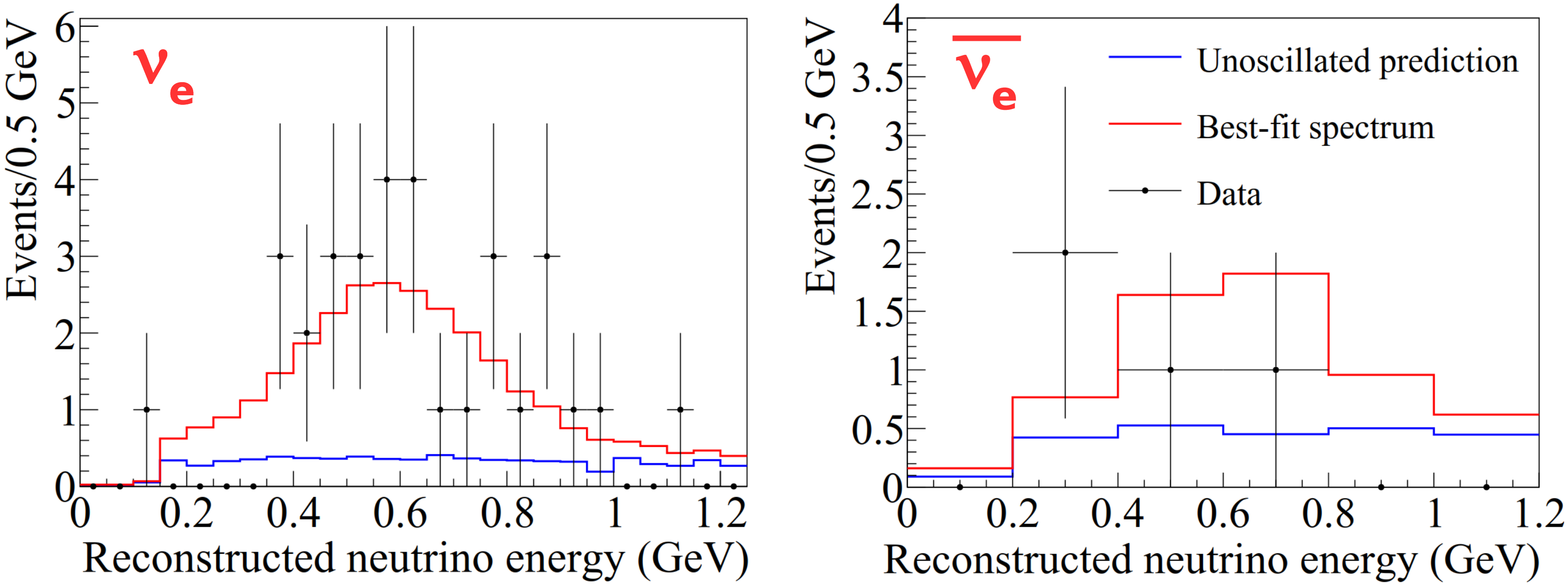
ν_μ disappearance results



Beam mode	Sample	Exp. Not Osc	Exp. $\delta_{CP} = 0$ (NH)	Observed
neutrino	μ-like	521.8	135.5	135
antineutrino	μ-like	184.8	64.1	66

7.5 x 10^{20} protons on target of ν data
+ 7.5 x 10^{20} protons on target of anti-ν data

ν_e appearance results

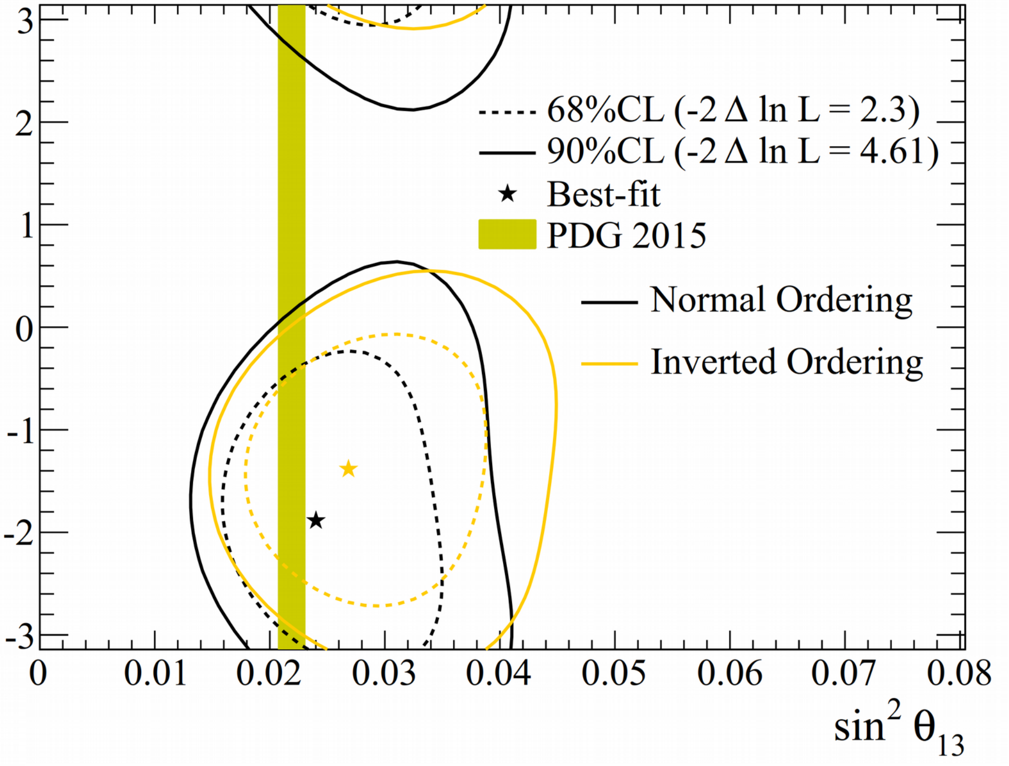


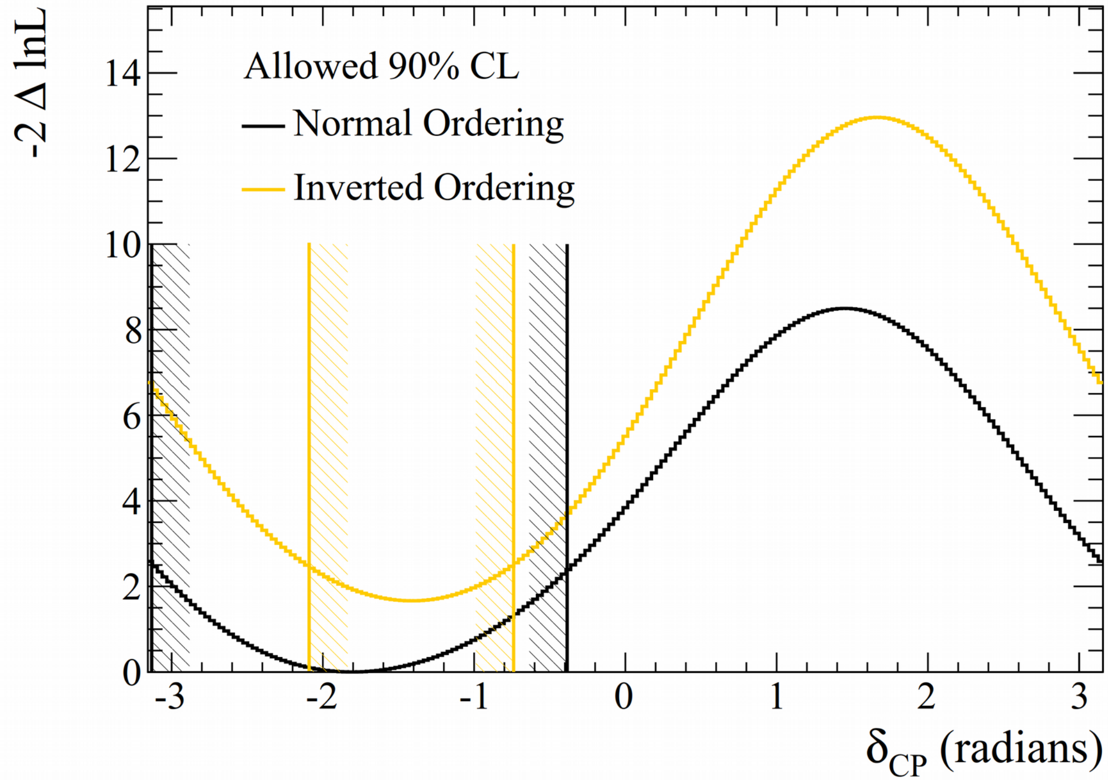
Normal	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = \pi/2$	$\delta_{CP} = \pi$	Observed
ν_e	28.7	24.2	19.6	24.1	32
$\overline{\nu}_e$	6.0	6.9	7.7	6.8	4

Inverted	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = \pi/2$	$\delta_{CP} = \pi$	Observed
ν_e	25.4	21.3	17.1	21.3	32
$\overline{\nu}_e$	6.5	7.4	8.4	7.4	4

δ_{CP} contours

The best-fit CP phase is close to -π/2: maximal CP effect. Formally speaking $\delta_{CP}=0$ is excluded at 90% CL.



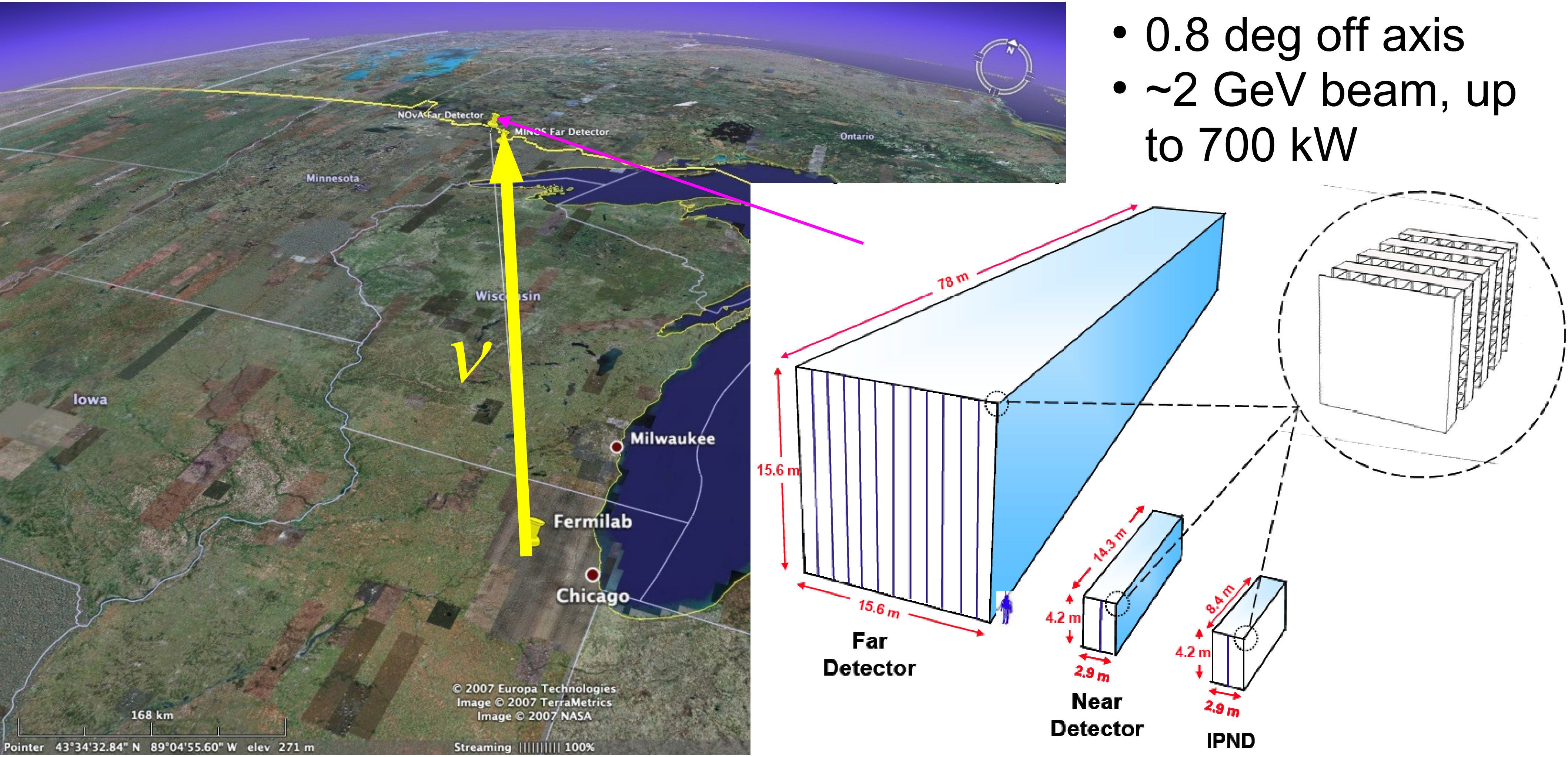


Caveat: the result is primarily driven by very high ν_e appearance rate at T2K, beyond expectations of model. In other words, limit is better than expected sensitivity.

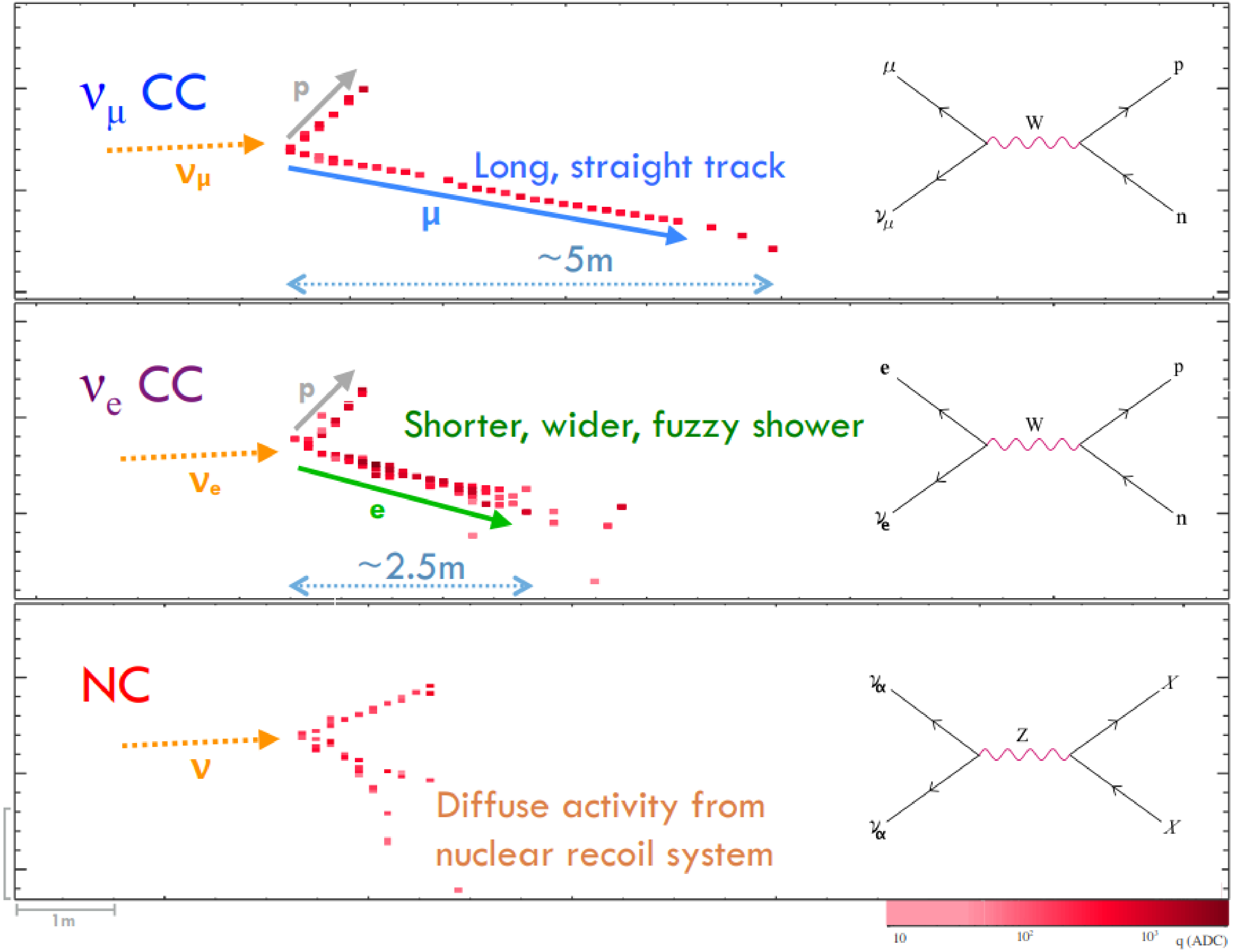
NOνA

FNAL to Ash River: 810km as the neutrino flies

- 14 kt liquid scintillator tracker
- 290t near detector
- 0.8 deg off axis
- ~2 GeV beam, up to 700 kW



NOνA vital characteristics

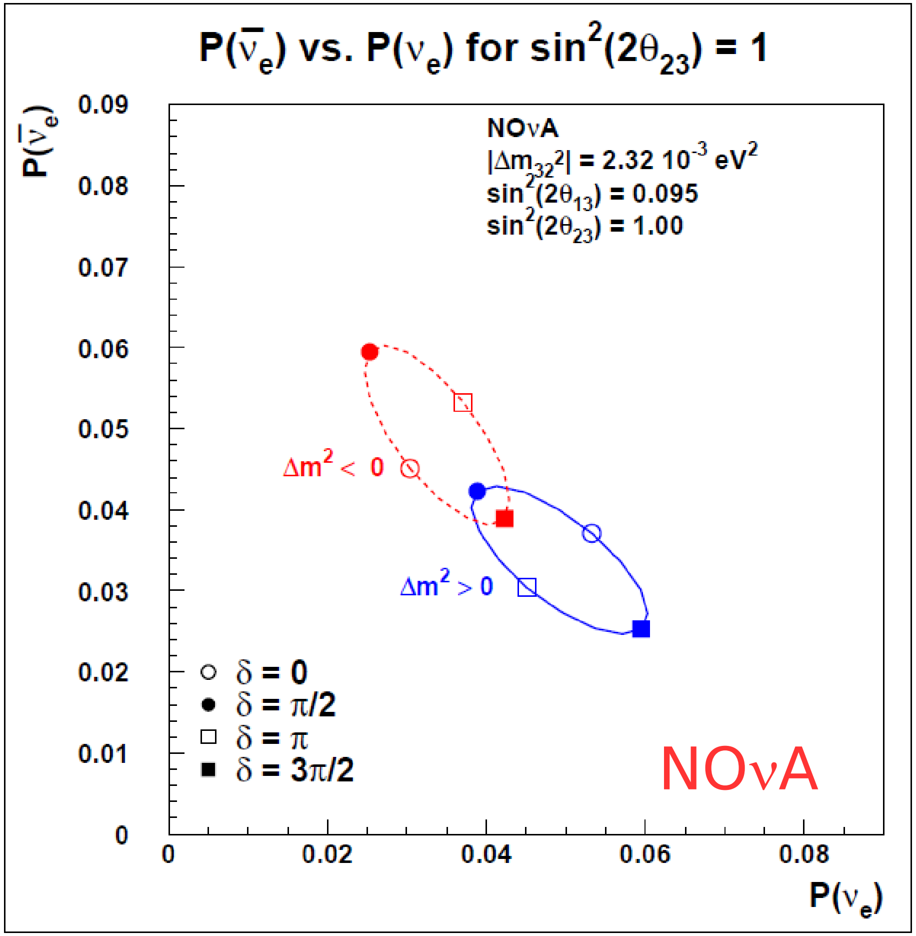


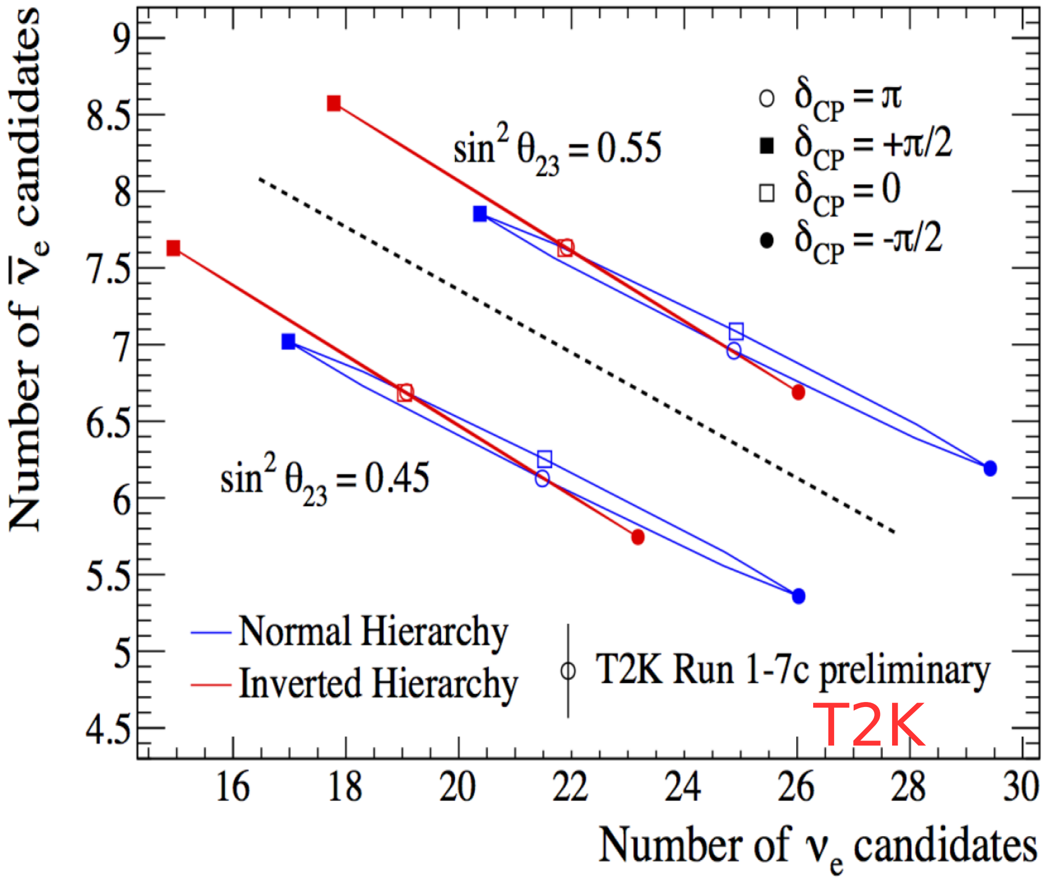
Flavour ID with NC sensitivity

Reconstruction informed by computer vision, machine learning

Beam energy of ~2GeV more sensitive than T2K to hadronic production. Energy estimation is more calorimetric than T2K, where hadrons usually are below detection threshold. (But hadrons are harder to model.)

NOνA matter effect sensitivity

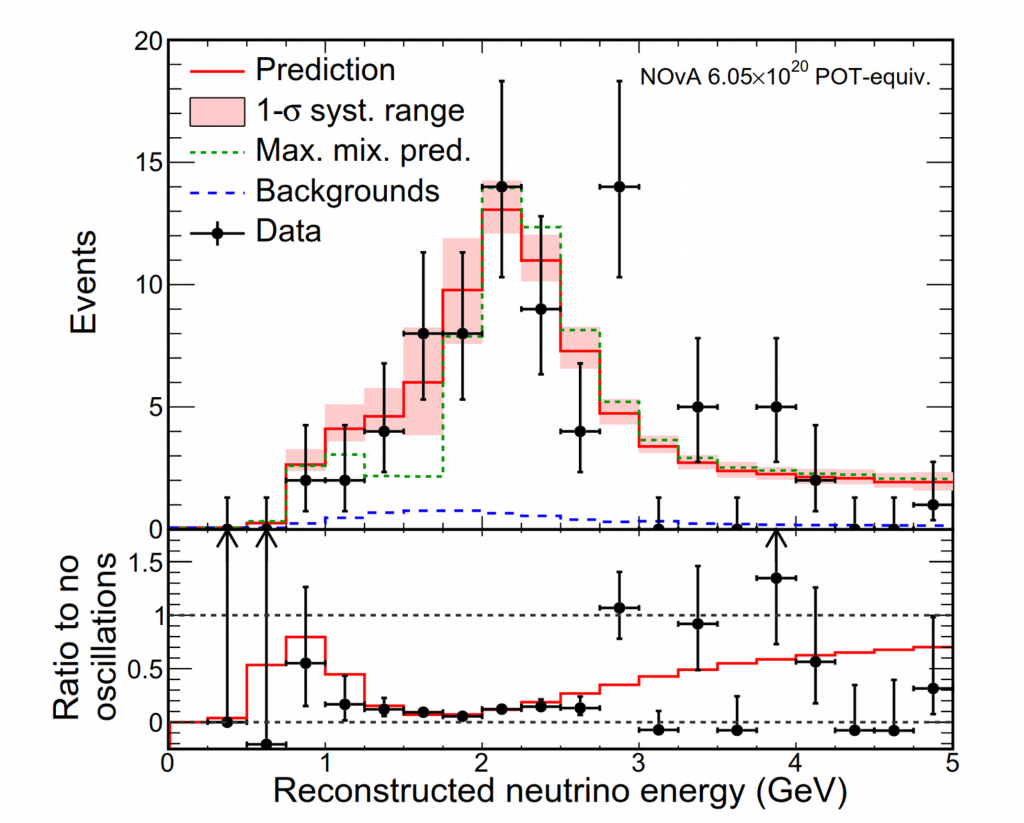


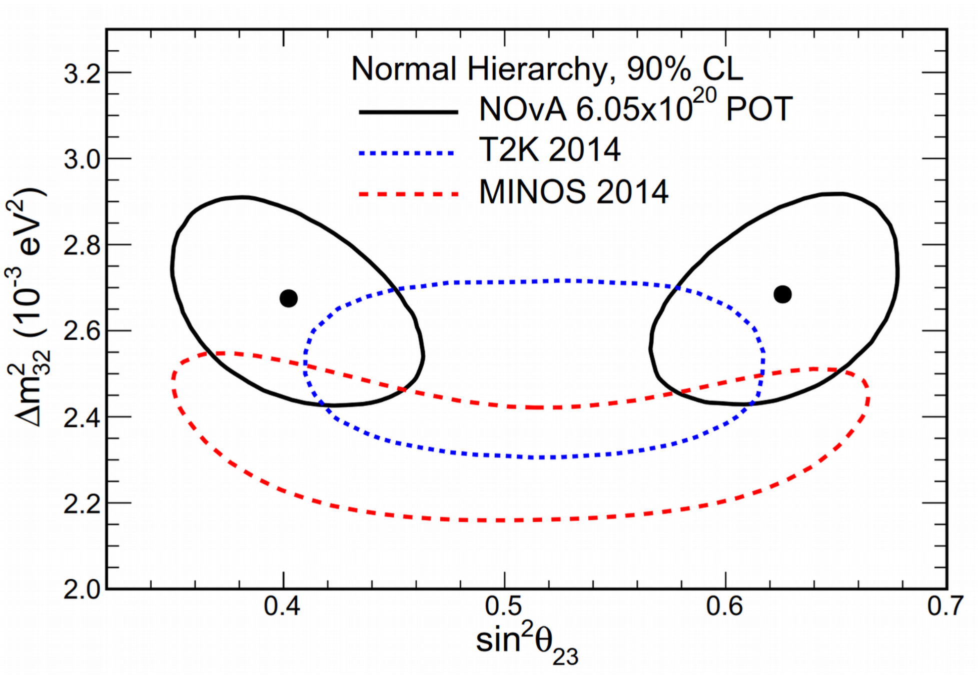


$$P(\nu_\mu \rightarrow \nu_e) \approx \left(1 + 2\frac{E}{E_R}\right) P_{vac}(\nu_\mu \rightarrow \nu_e)$$

Higher energy gives NOνA better sensitivity to matter effects than T2K

NOνA Oscillation Results





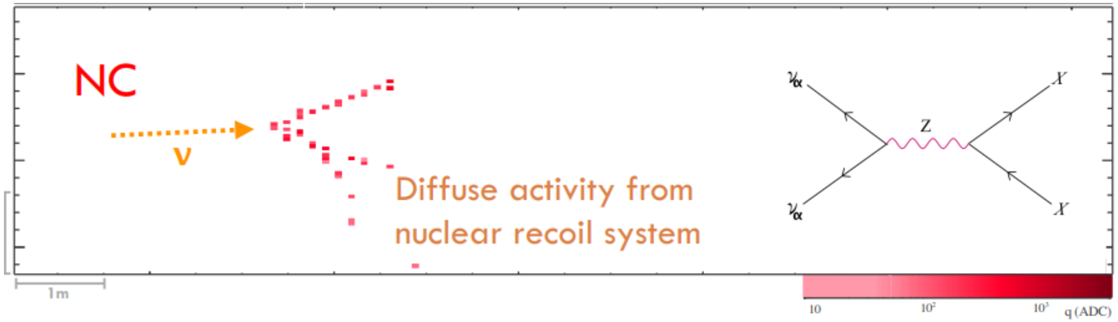
(6.05×10^{20} p.o.t. in neutrino mode)

33 ν_e events on background of 8.2±0.8

Maximal mixing disfavoured at 2.6σ

Phys. Rev. Lett. 118, 231801 (2017) arXiv: 1703.03328
Phys. Rev. Lett. 118, 151802 (2017), arXiv: 1701.05891

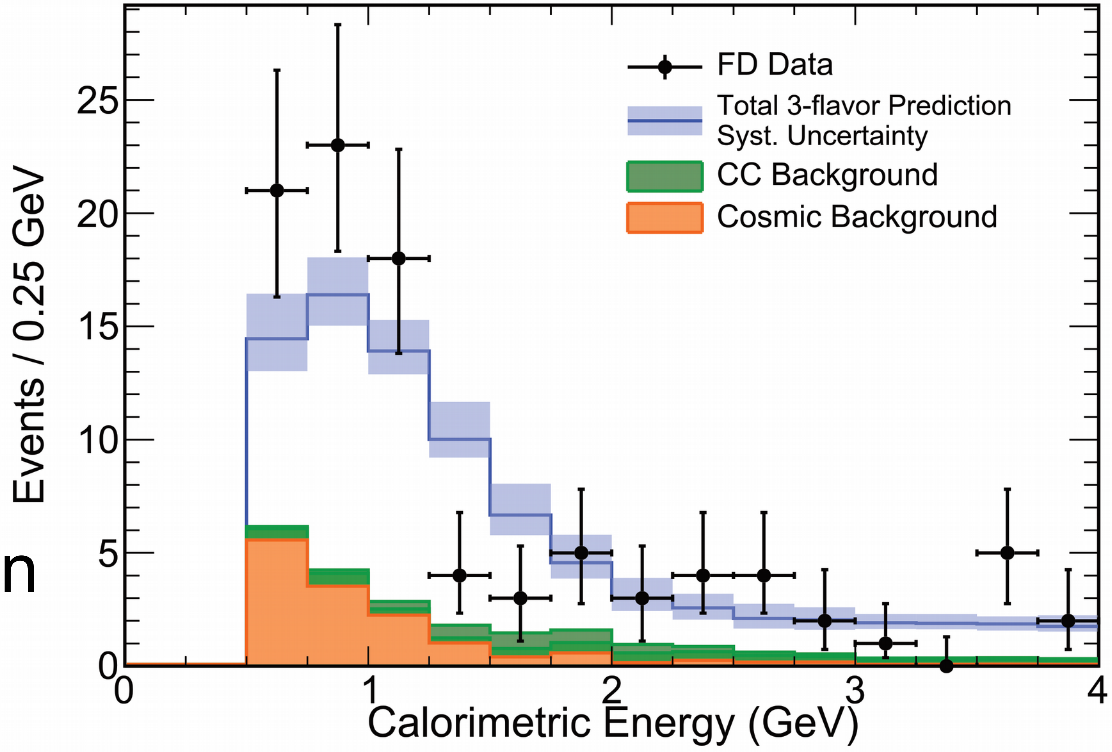
NOνA sterile neutrinos results



Neutral current sensitivity is unique capacity for NOνA. A convolutional neural network is used to distinguish events with no charged lepton.

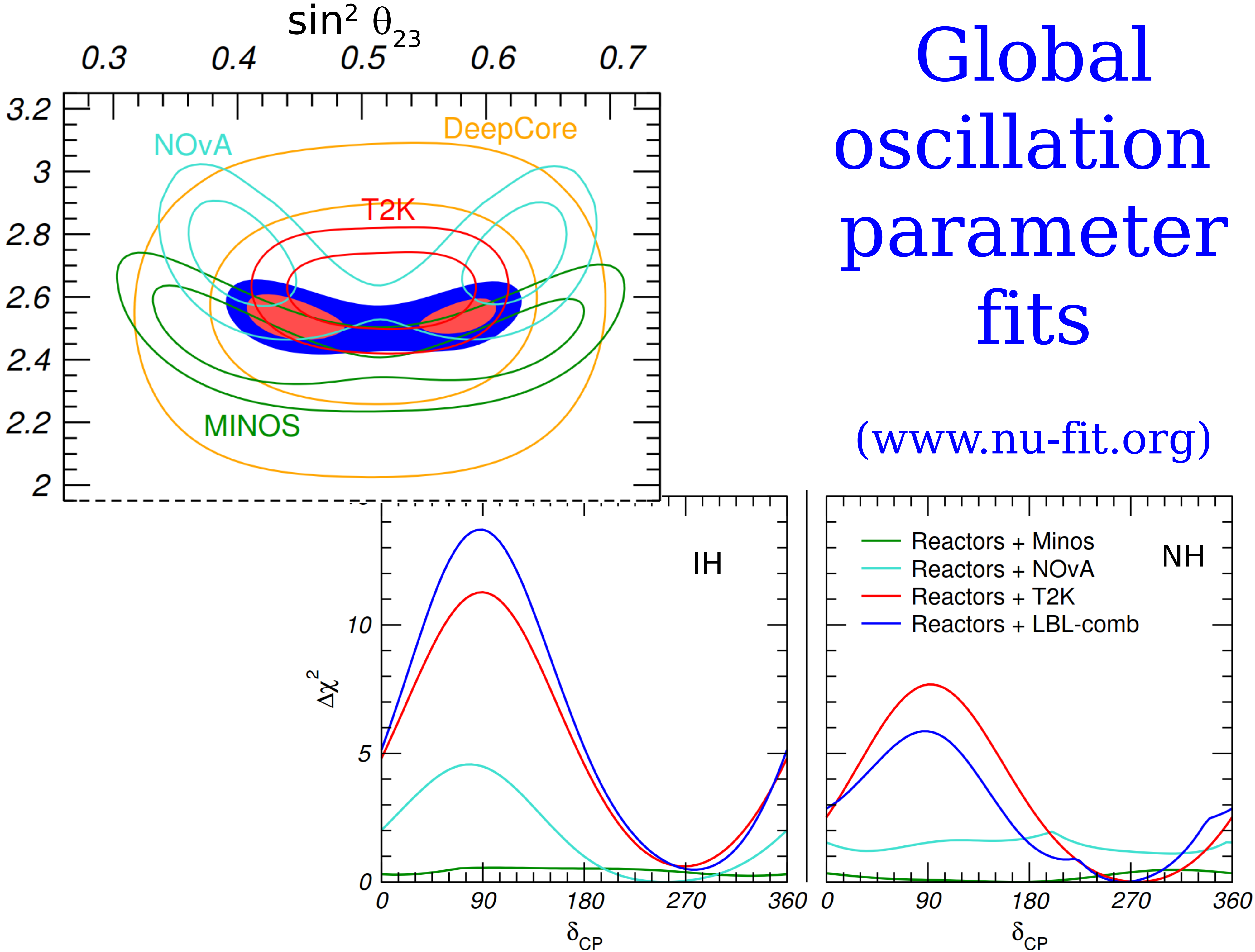
If neutrinos mix to a sterile state, then the NC rate may be less than expected.

Recent NOνA arXiv submission 1706.04592 saw 95 events where 83.5 ± 9.7(stat) ± 9.4(syst) were predicted assuming mixing only occurs between active neutrino species.

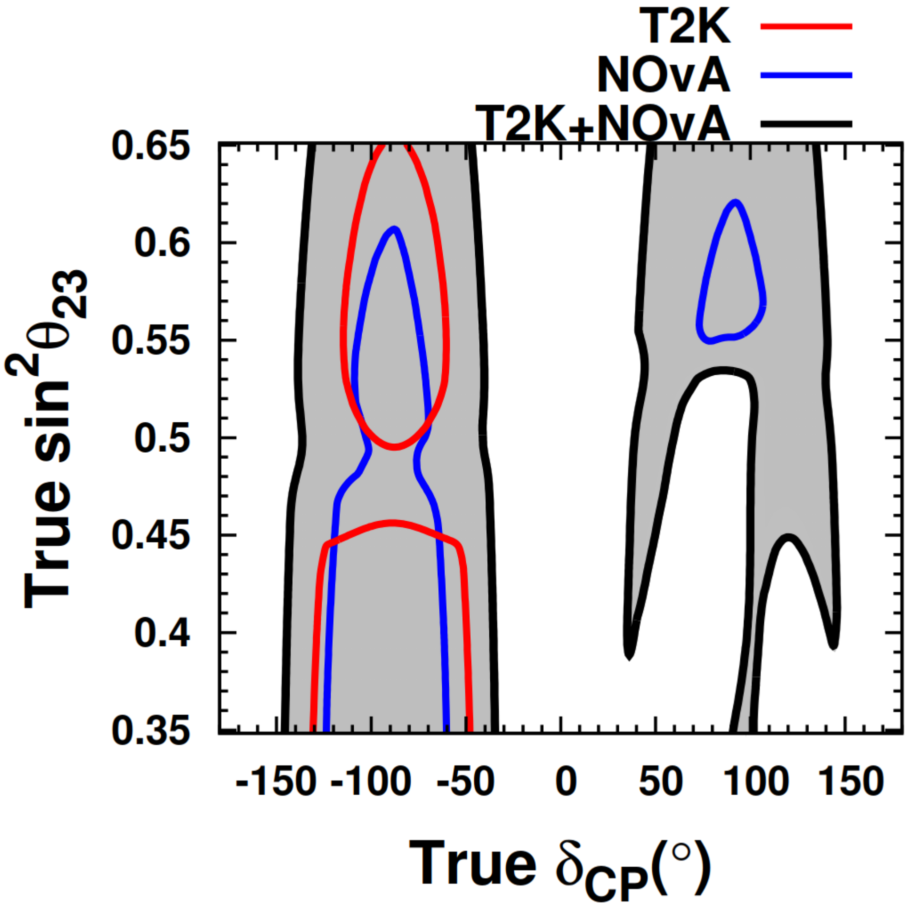


Global oscillation parameter fits

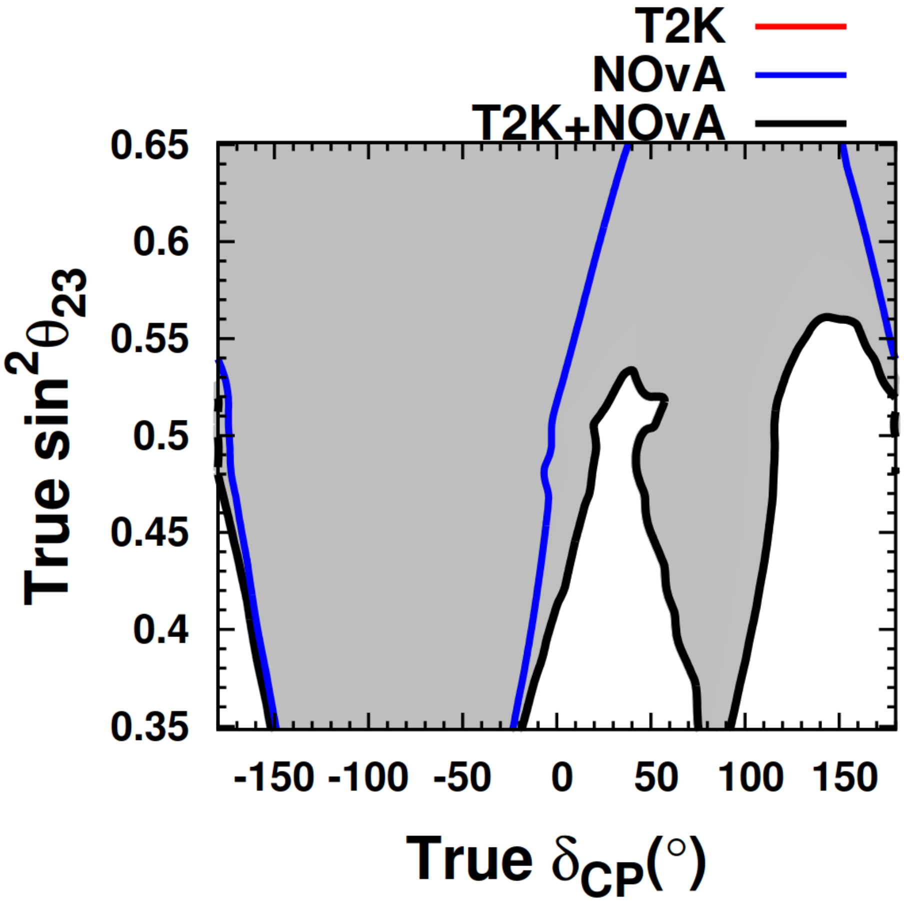
(www.nu-fit.org)



T2K+NOνA combined sensitivity



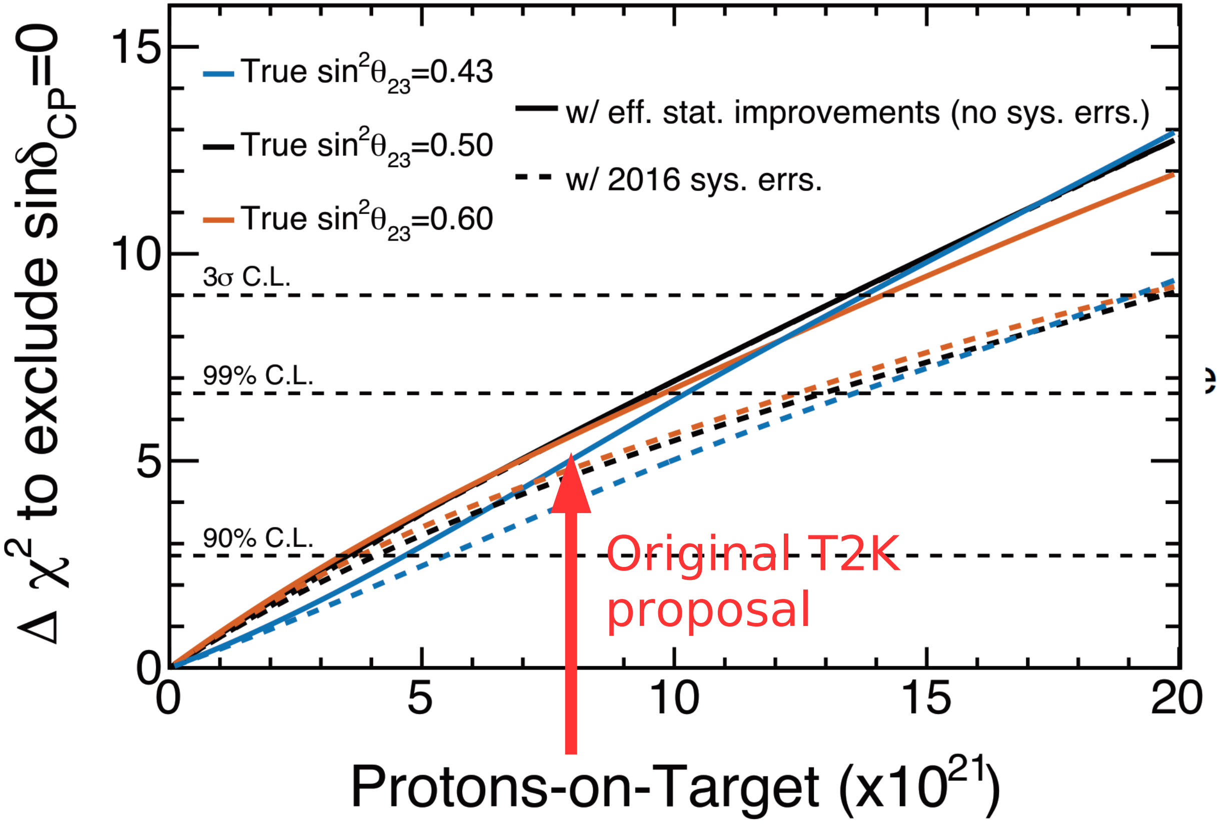
Regions for which δ_{CP}=0 is rejected at 90% CL (for normal hierarchy)

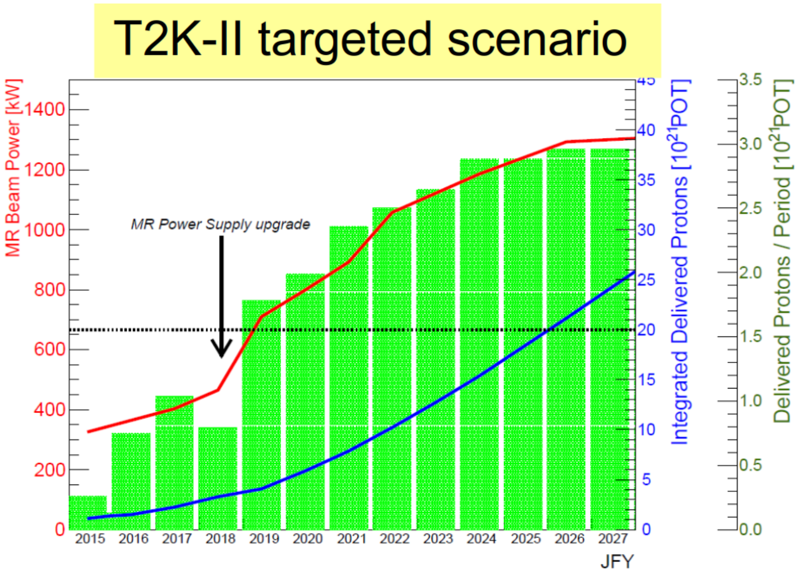


Regions for which the wrong mass hierarchy is rejected at 90% CL (for normal hierarchy)

Prog. Theor. Exp. Phys. (2015) 043C01

T2K-II





Proposal to continue running T2K until ~2025, with beam power and near detector upgrades, with an aim to achieve 3σ sensitivity to non-zero δ_{CP}.

arXiv: 1609.04111

Conclusions

Long baseline neutrino experiments with flavour sensitivity are the only window we have on CP violation in the neutrino sector.

T2K and NOνA results are consistent with each other and PMNS paradigm. First limits on CP violation, although still statistically weak, favour maximal CP effect.

LBL experiments dominate Δm^2_{32} and θ_{23} determination.

See parallel session talks by Mark Scott (T2K—Tuesday, 17:15, Neutrino 4), Nicoletta Mauri (OPERA—Tuesday, 17:00, Neutrino 4) and Kirk Bays (NOνA, Wednesday, 13:00, Neutrino 5) for details.

Backup Slides

CP Violation and ν_e Appearance

CP symmetry requires $P(\nu_\mu \rightarrow \nu_e) = P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$

For ν_e appearance at Δm^2_{32}:

$$A_{CP} = \frac{P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}{P(\nu_\mu \rightarrow \nu_e) + P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)} \simeq \frac{\Delta m^2_{12} L}{4 E_\nu} \frac{\sin 2\theta_{12}}{\sin \theta_{13}} \sin \delta_{CP}$$

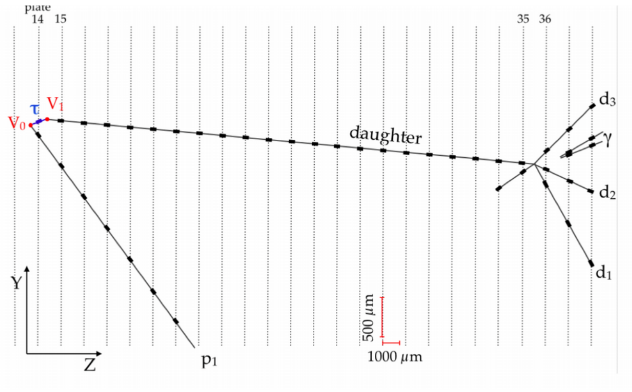
This may be a big asymmetry!

SO WHAT?

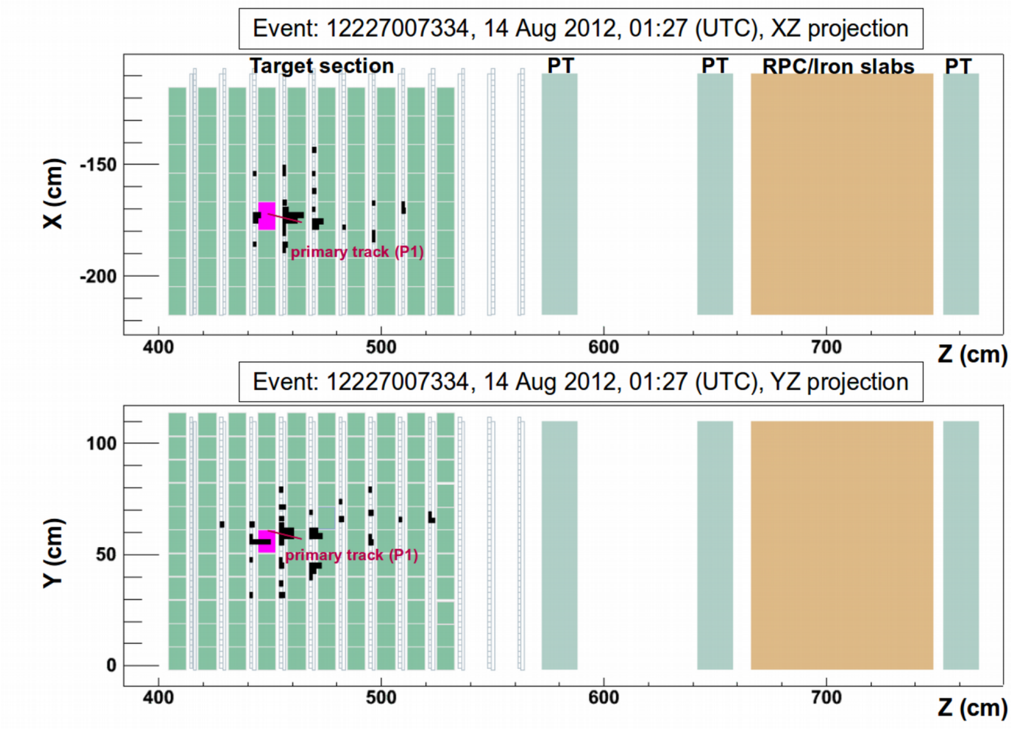
- Our universe is made of matter but not anti-matter.
- A cosmological asymmetry requires CP violation.
- Regular quark CP violation not enough---is this the missing piece?

OPERA

Beam from CERN to Gran Sasso, looking primarily for ν_τ appearance using emulsion technology.



Five ν_τ candidates seen on a background of 0.25 ± 0.05, & a claimed significance of 5.1σ.



Phys. Rev. Lett. 115, 121802 (2015)

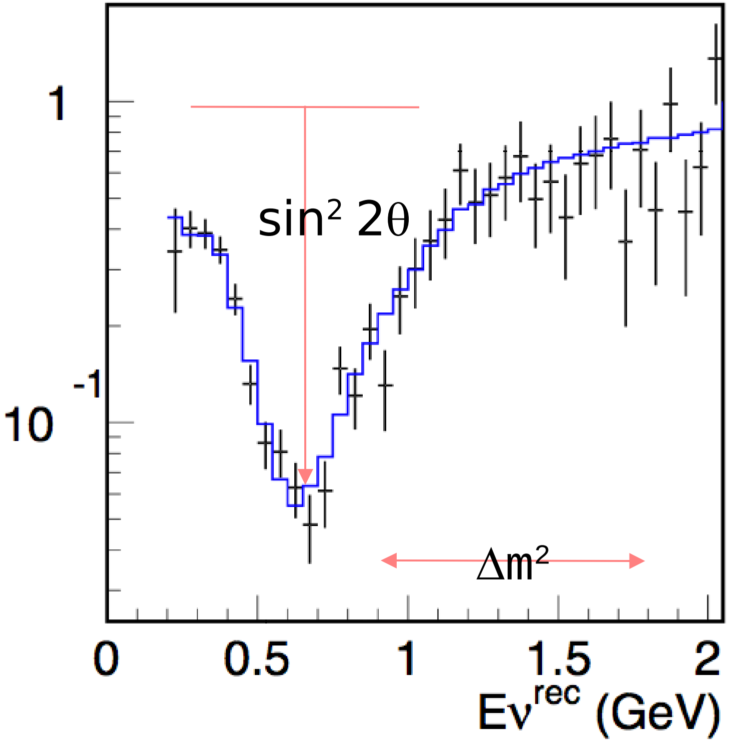
Flavour Oscillation

Because a flavour eigenstate produced by a weak interaction is a mix of mass eigenstates which, if $m_1 \neq m_1$, propagate with different kinematics, oscillation can occur.

$$|\nu(t=0)\rangle = |\nu_e\rangle = \cos\theta\,|\nu_1\rangle + \sin\theta\,|\nu_2\rangle$$

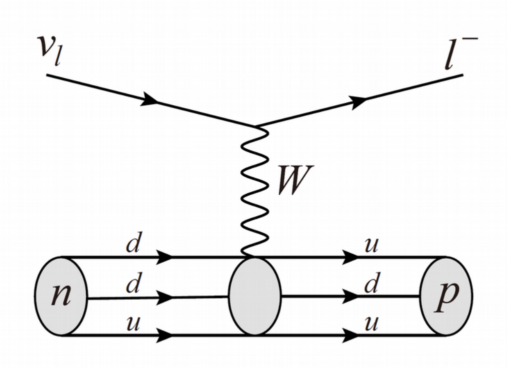
$$|\nu(t)\rangle = \begin{array}{l} e^{i\sqrt{p^2+m_1^2}\,t}\cos\theta\,|\nu_1\rangle \\ +e^{i\sqrt{p^2+m_2^2}\,t}\sin\theta\,|\nu_2\rangle \end{array}$$

$$Prob(\nu_e \to \nu_e) = 1 - \sin^2(2\theta)\sin^2\left(\frac{1.27\,\Delta m^2 L}{E}\right)$$

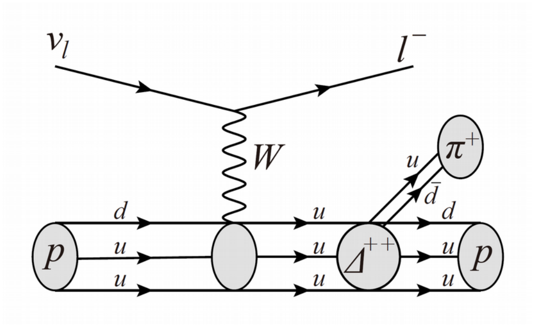


Units: [L] = km; [E] = GeV;
Δm^2 = [eV^2]

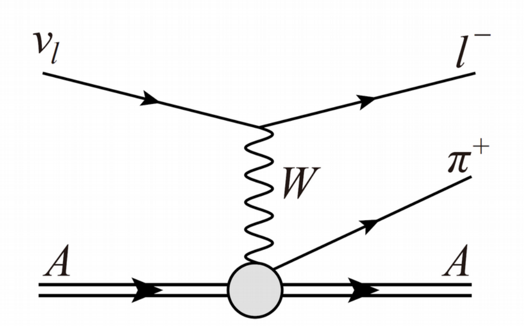
Neutrino interactions at ~1 GeV



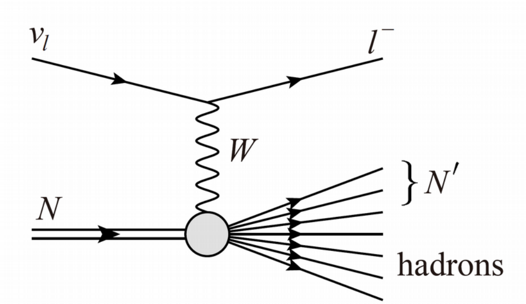
Charged-current quasielastic



Resonant Pion Production (CC 1π)



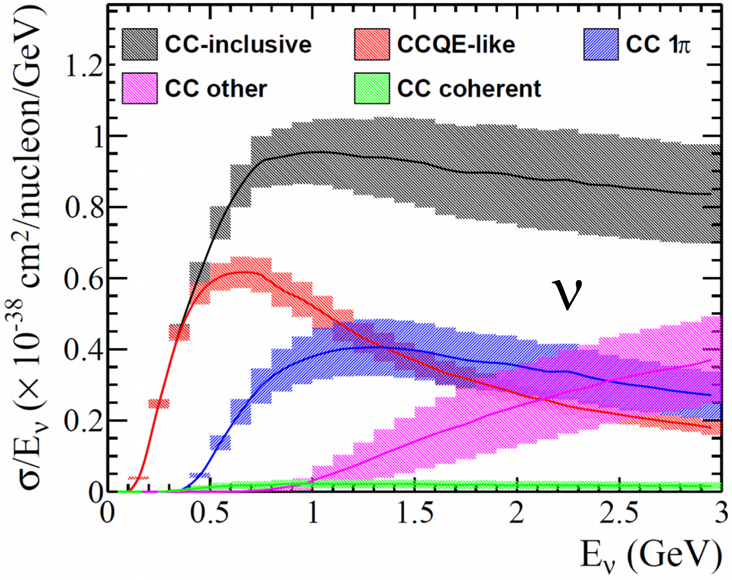
Coherent

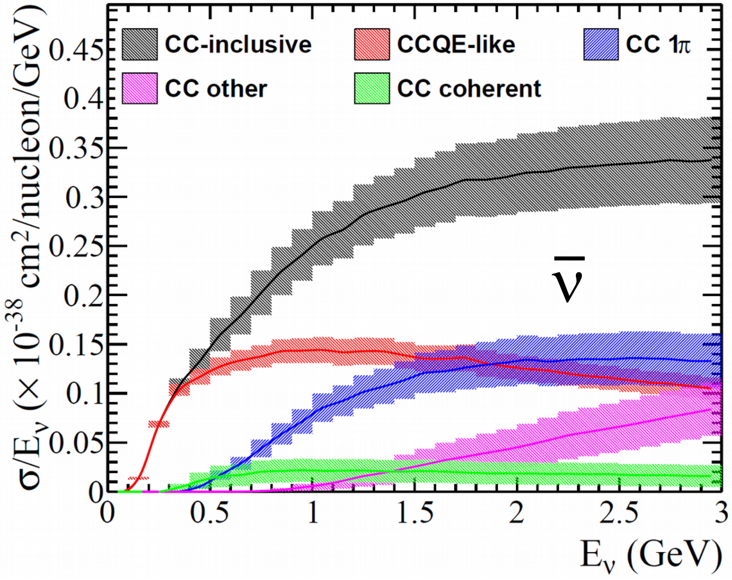


Deep Inelastic Scattering

T2K looks for final-state leptons from charged-current interactions

Cross-sections not well measured – need to use near detector to normalize.





Neutrino-Nucleon Interactions

The basic neutrino-nucleon interaction model is the dipole form factor model

- For CCQE interactions, this depends on a single physical parameter, the axial mass M_A.

CCQE interactions are particularly useful as the energy depends only on the outgoing lepton kinematics p_μ, θ_μ

- This is the main signal for T2K

$$E_{\text{reco}} = \frac{m_p^2 - (m_n - E_b)^2 - m_\mu^2 + 2(m_n - E_b)E_\mu}{2(m_n - E_b - E_\mu + p_\mu \cos\theta_\mu)}$$

Nuclear Effects

Dipole form factor model is sufficient for interactions with nucleons – not nuclear targets. In a nucleus there is binding energy, and Fermi motion of nucleons (no longer at rest). A simplistic nuclear model is used:

Relativistic Fermi Gas

Simple model of nuclear effects for CCQE interactions

- Nucleus is modeled as a Fermi gas of non-interacting neutrons and protons

Uses two nucleus-dependent parameters

- E_B : the nucleon binding energy
- p_F : the Fermi momentum
- Different for each nucleus

Random Phase Approximation

Correction to the RFG model

- Includes first-order nucleon-nucleon correlations not found in the RFG model

Models long range correlations between nucleons at low energies

- Not strongly nucleus dependent

Modelling CCQE interactions

Axial form factor for nucleon-neutrino interactions modelled by dipole parametrization:

$$F_A(Q^2) = g_A \left(1 + \frac{Q^2}{M_A^2}\right)^{-2}$$

Measurements of the axial mass from different experiments are all over the map!

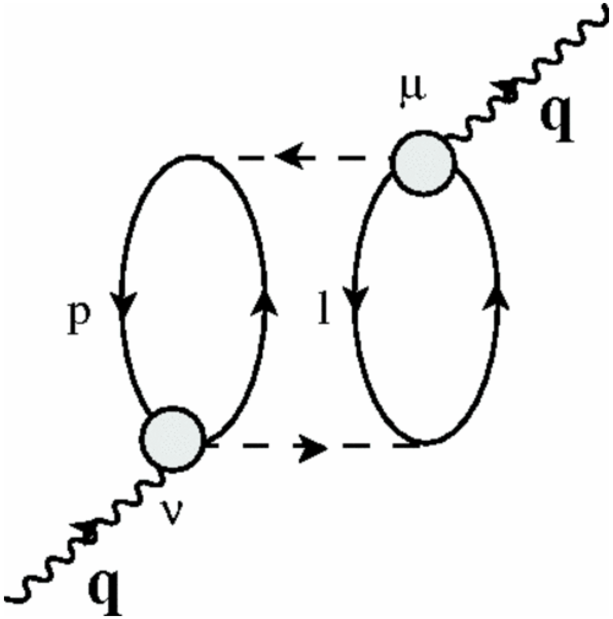
World average:	1.012 ± 0.031 ± 0.060 GeV
Deuterium experiments:	0.99 ± 0.04 GeV
MiniBooNE (carbon):	1.35 ± 0.17 GeV
K2K (carbon):	1.20 ± 0.12 GeV

It looks like other effects confound the free nucleon form factor.

Multi-nucleon effects

Other multinucleon correlations are not covered in the RFG + RPA model

- These interactions can produce multiple protons or neutrons in the final state – difficult to identify separately from CCQE
- Irreducible experimental background

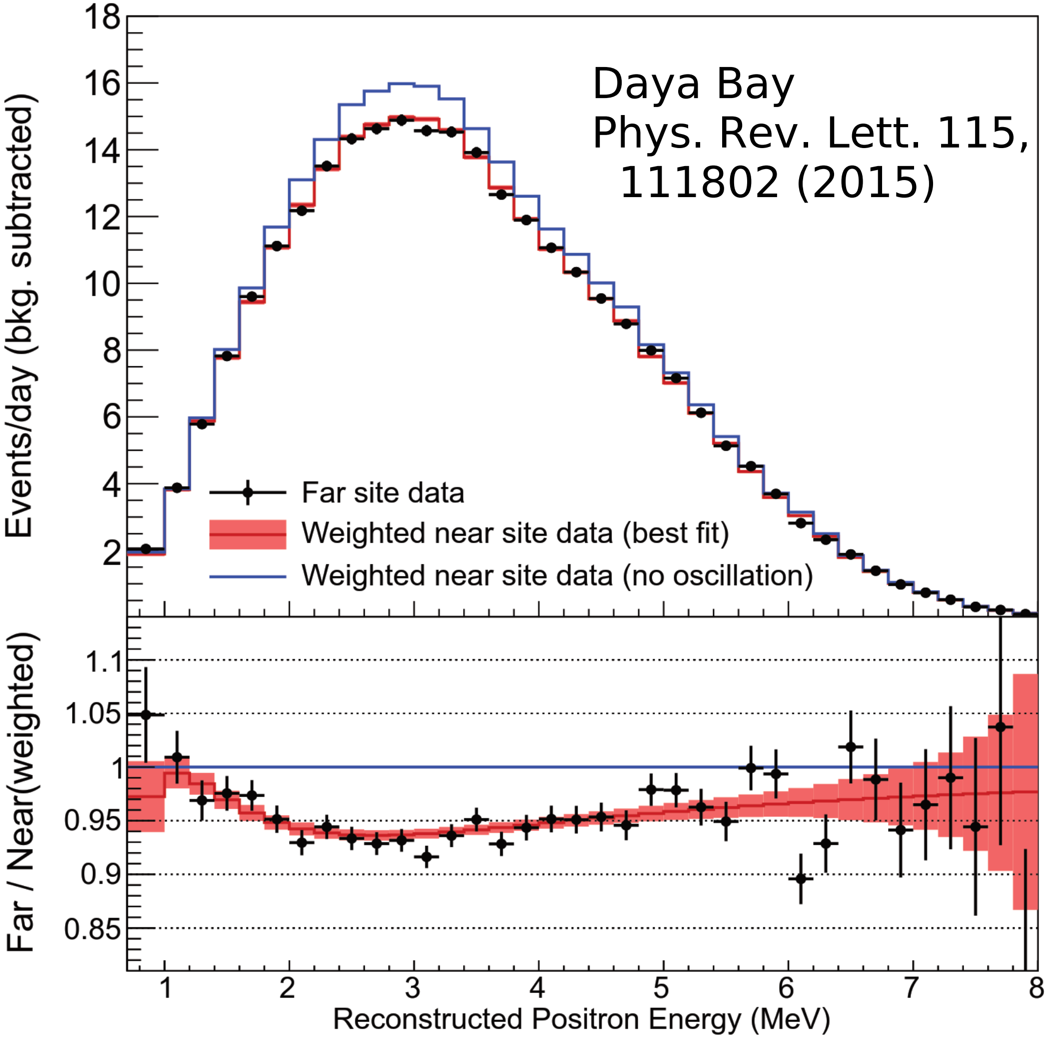


T2K models 2p-2h interactions, where two particle – hole pairs are propagated through the nucleus

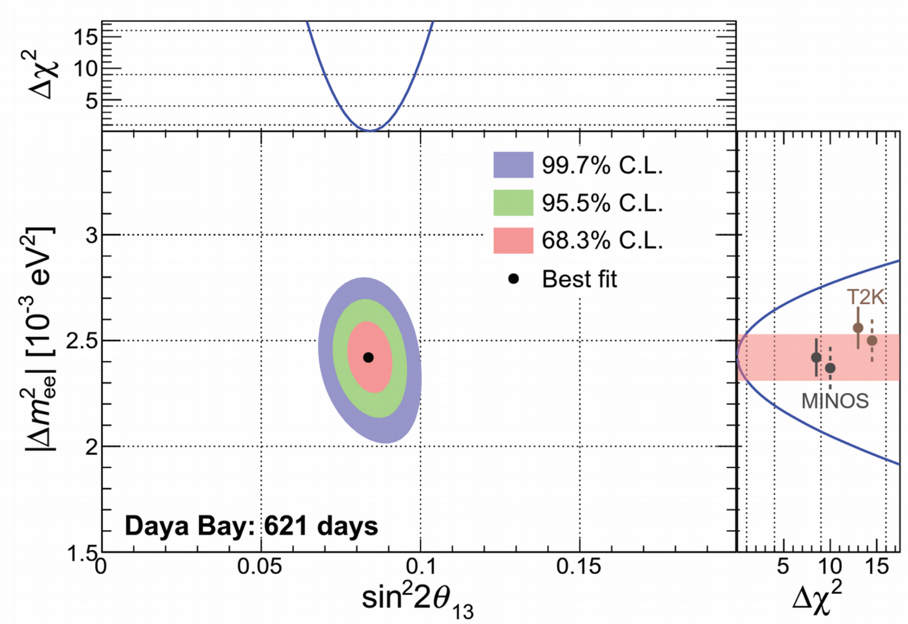
- Can produce two nucleons in the final state
- If not modeled, can have a significant effect on axial mass measurement: originally introduced to solve tensions between the axial mass measured with MiniBooNE and global averages
- T2K uses the Nieves 2p-2h model in the NEUT generator

Reactor neutrinos & θ_{13}

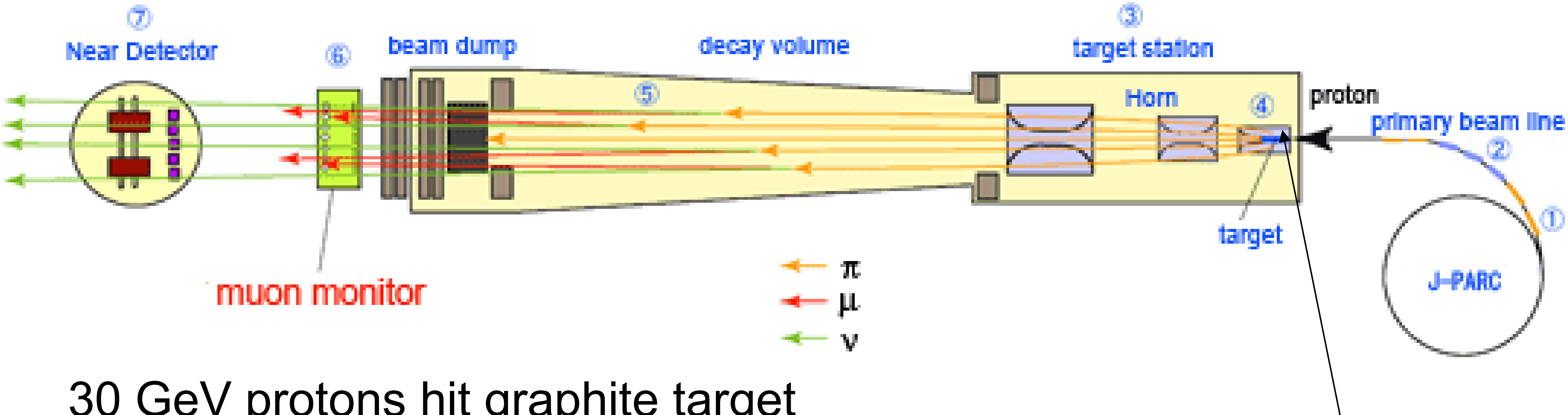
$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{1.27\,\Delta m^2_{31}\,L}{E}\right) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\left(\frac{1.27\,\Delta m^2_{21}\,L}{E}\right)$$



Daya Bay, RENO, Double CHOOZ look for disappearance of reactor neutrinos at ~1km baseline.



How To Make A Neutrino Beam



30 GeV protons hit graphite target

3 magnetic horns focus π^+, defocus π^-.

$\pi^+ \rightarrow \mu^+ + \nu_\mu$ in 110m long decay pipe

μ monitor at far end of beam dump:
fluence: 10^8 μ/cm^2/spill at full power

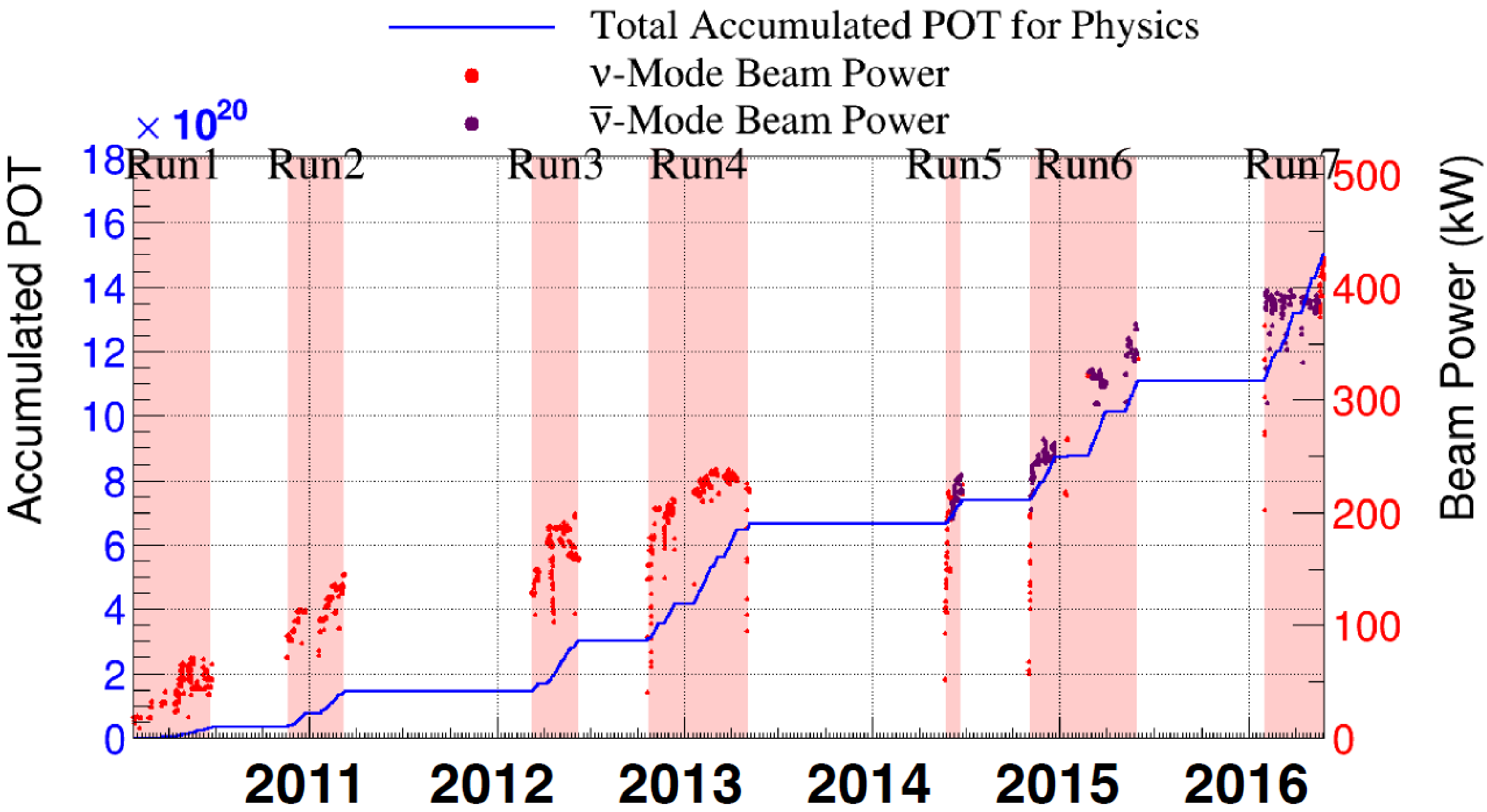
T2K's 90cm graphite target

↑

Inside the decay volume

← The 2nd focusing horn

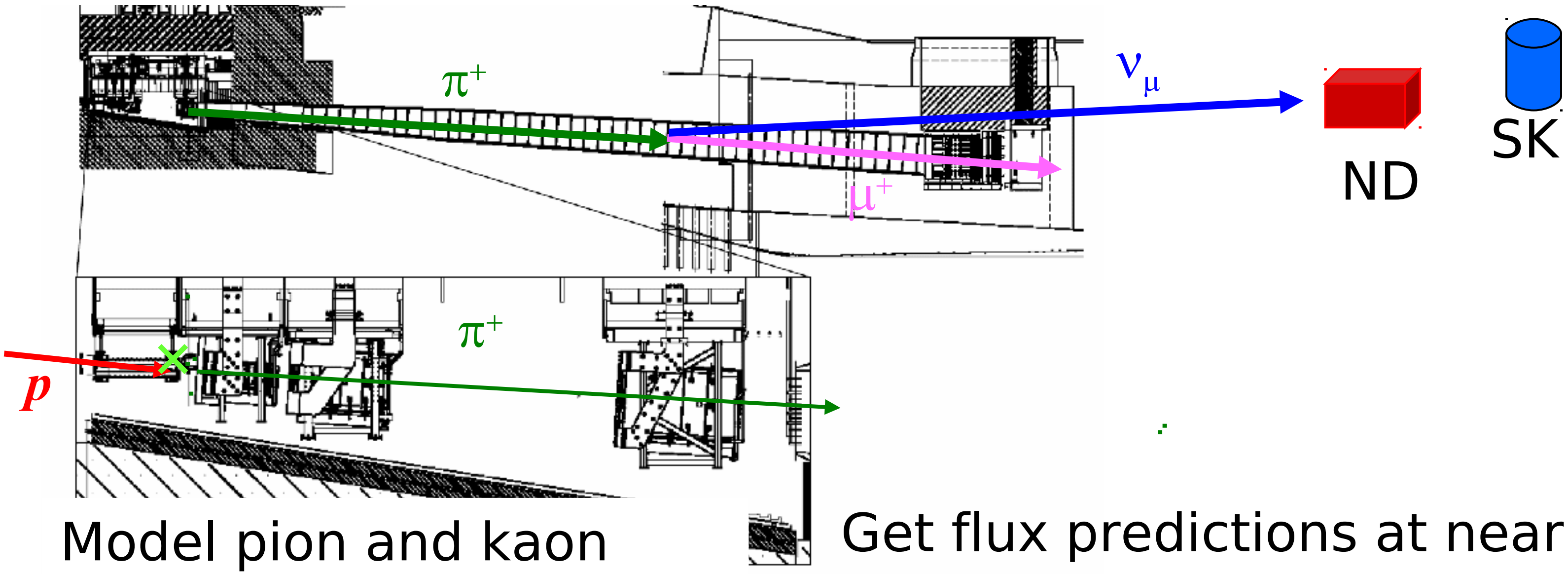
T2K data collection



27 May 2016
POT total: 1.510×10^{21}

ν-mode POT: 7.57×10^{20} (50.14%)
ν̄-mode POT: 7.53×10^{20} (49.86%)

T2K: Flux prediction (Beam MC)

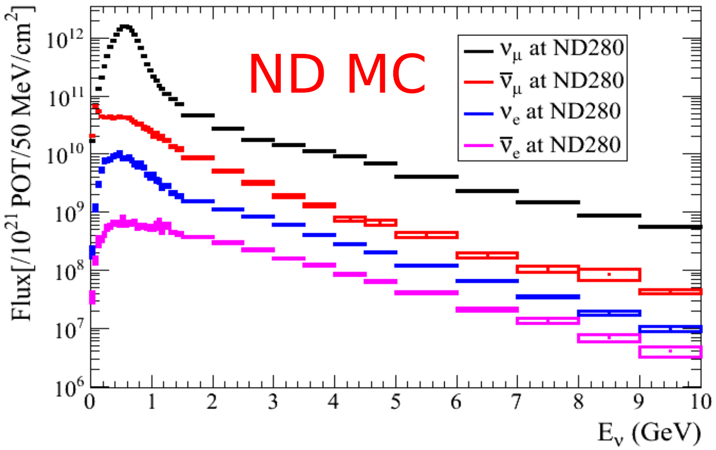


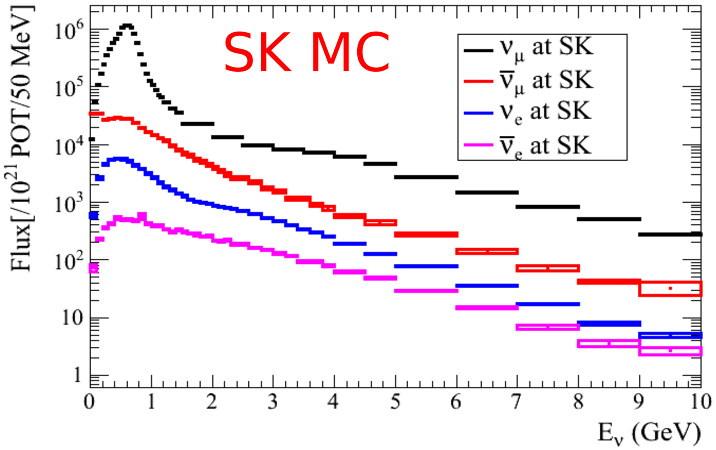
Simulate hadron production on target using FLUKA simulation

Model pion and kaon propagation and decay through horns and beamline

Get flux predictions at near detector and SK

Particle production cross sections tuned to external data from NA61 and others.





Backgrounds to ν_e Appearance

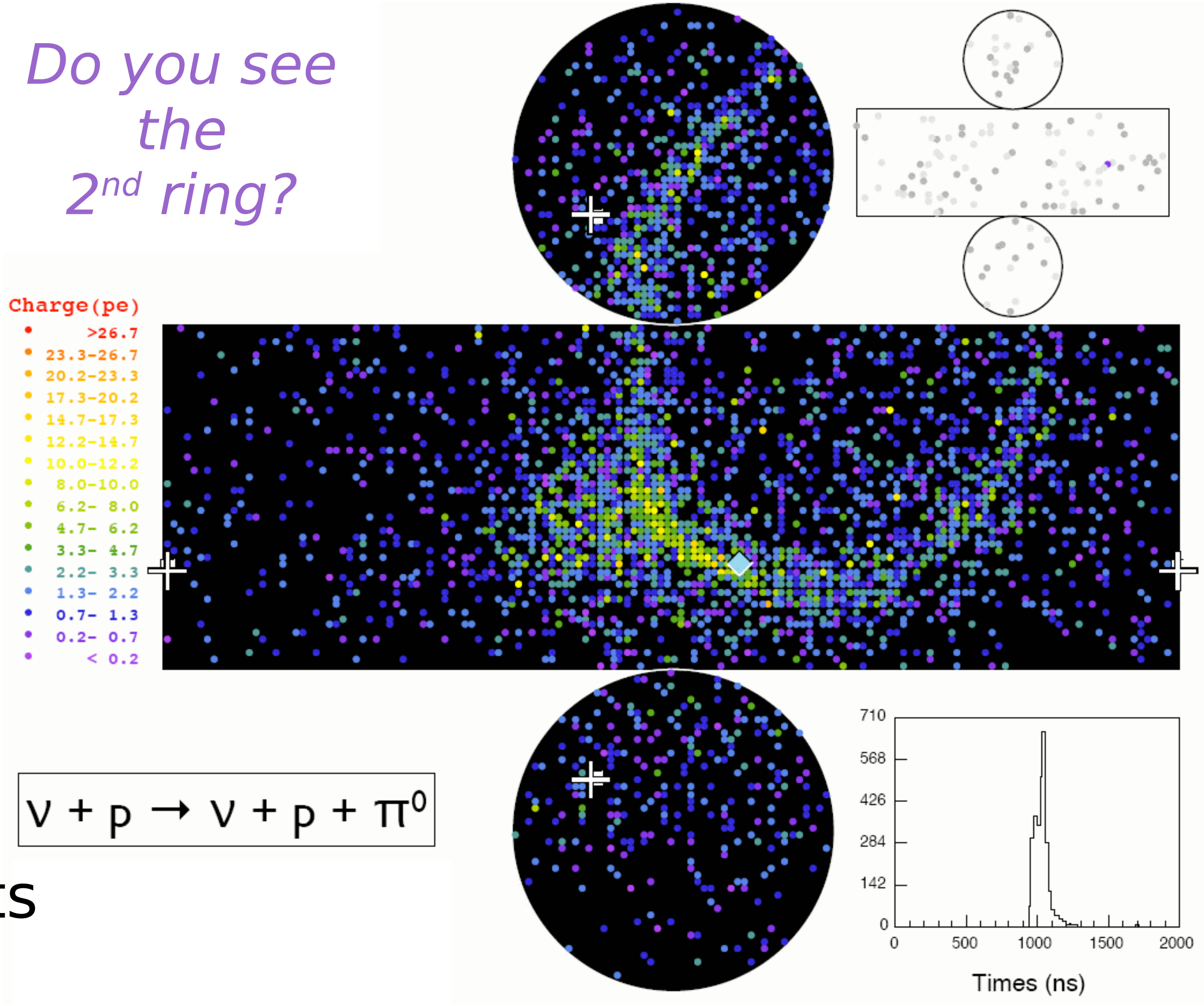
Intrinsic beam ν_e:

- reduce with E cut
- measure at ND

π^0 production, with one γ from event not detected at Super-K:

- better ID algorithms
- measure at ND
- measure π^0 in SK

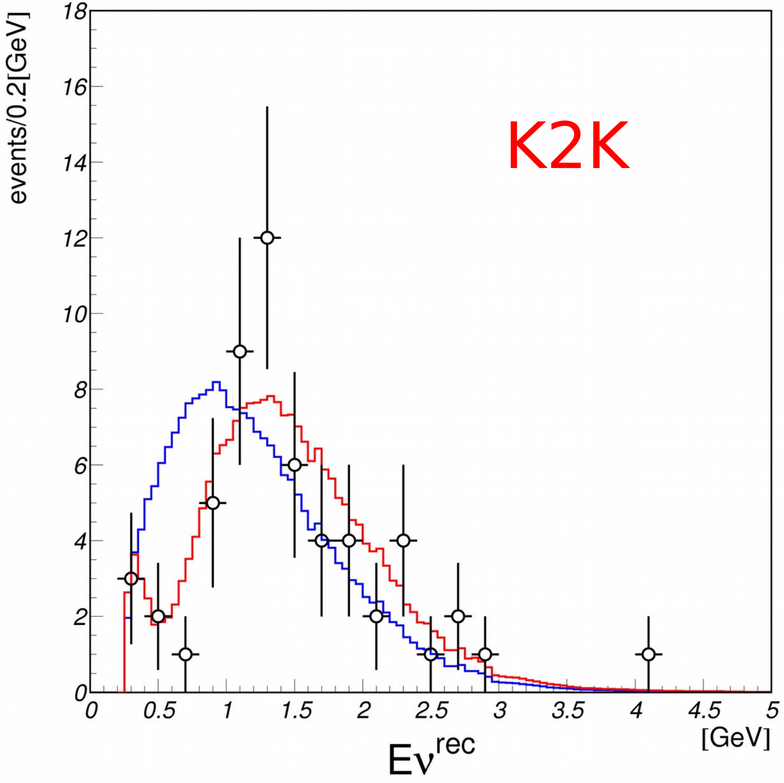
The intrinsic beam events are a more significant background.

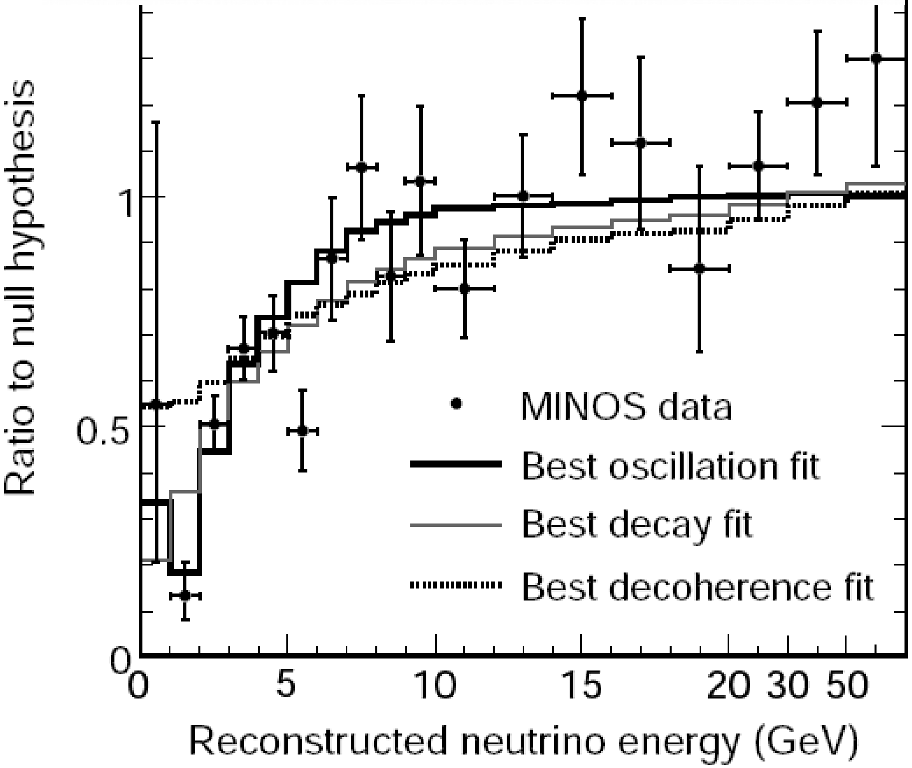


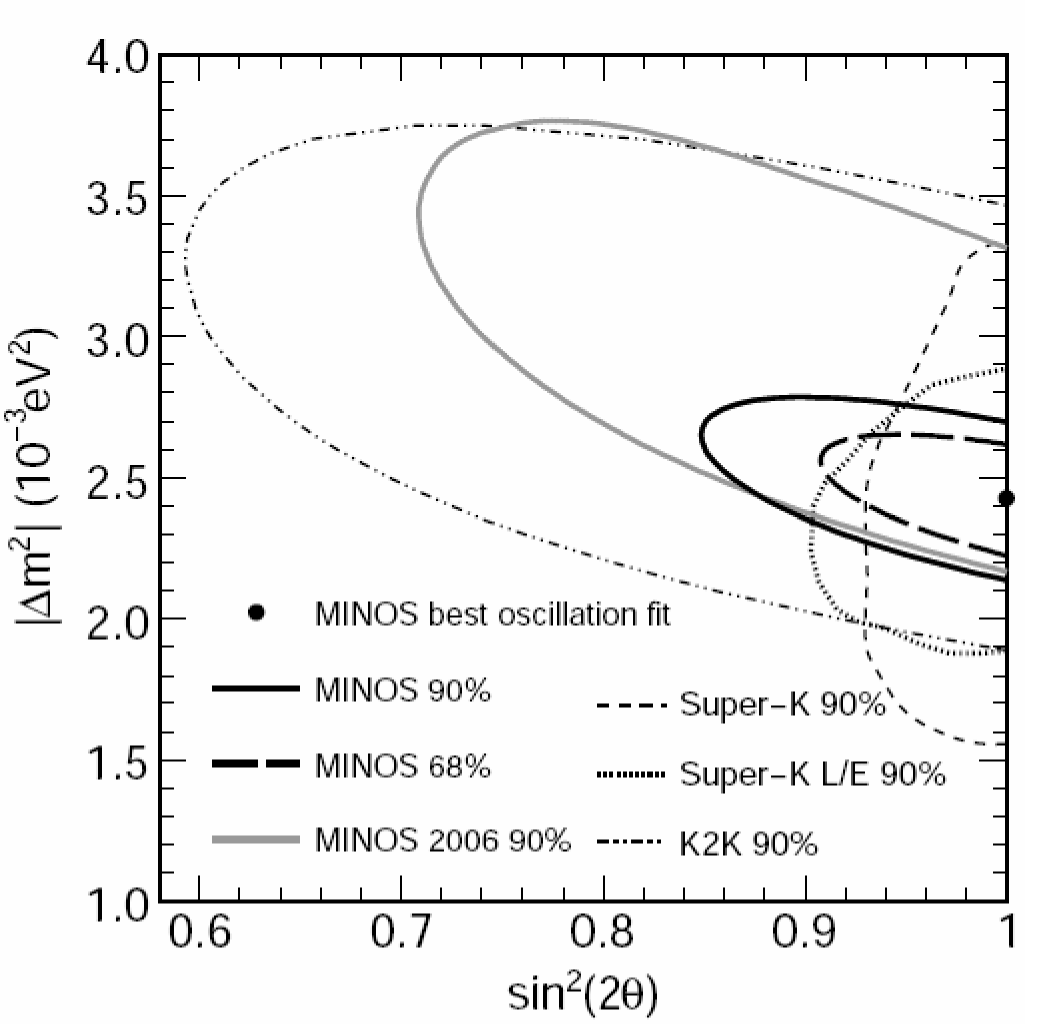
Do you see the 2^{nd} ring?

$\nu + p \rightarrow \nu + p + \pi^0$

K2K & MINOS

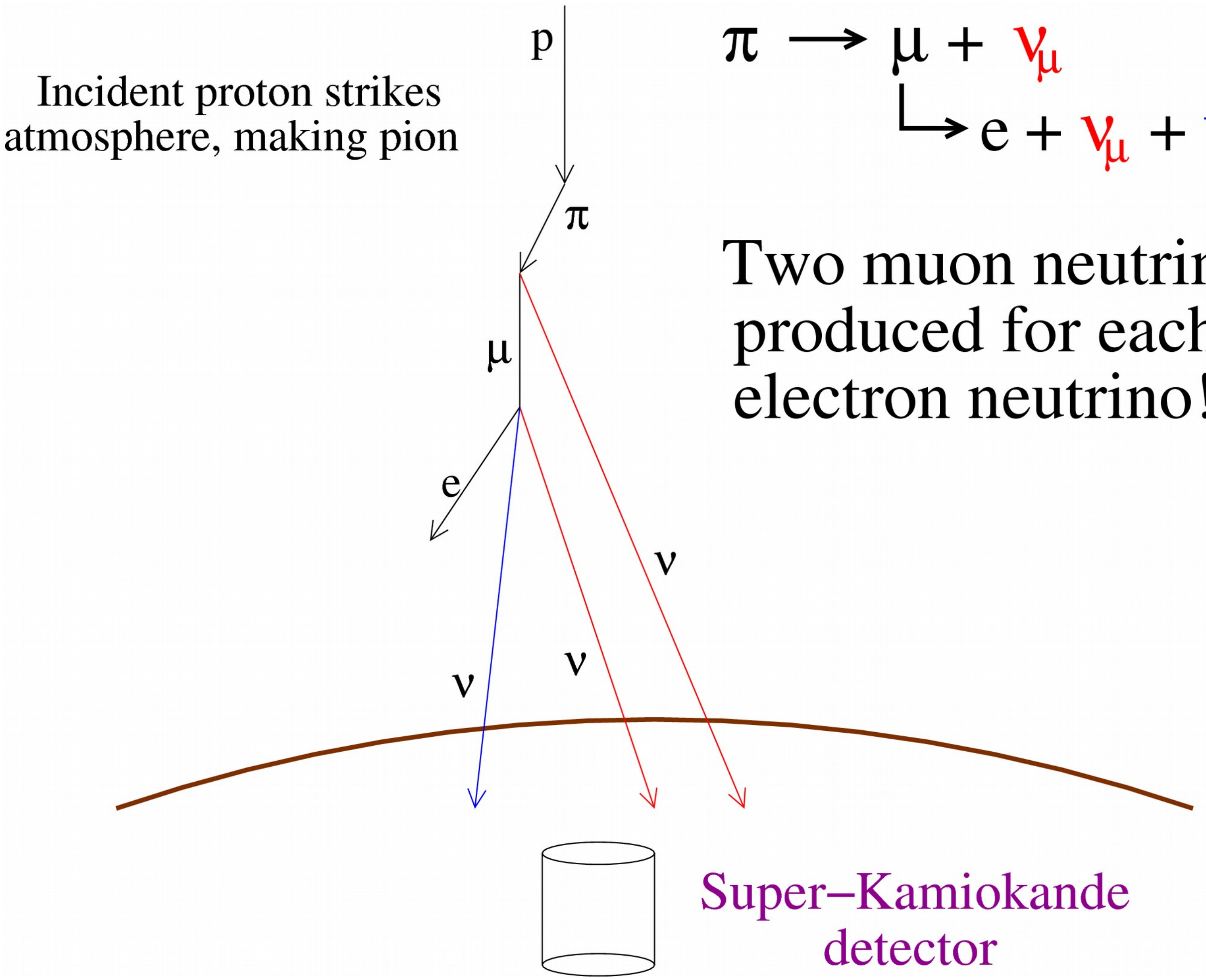






Consistency between atmospheric and long-baseline ν oscillation results.

Atmospheric Neutrinos



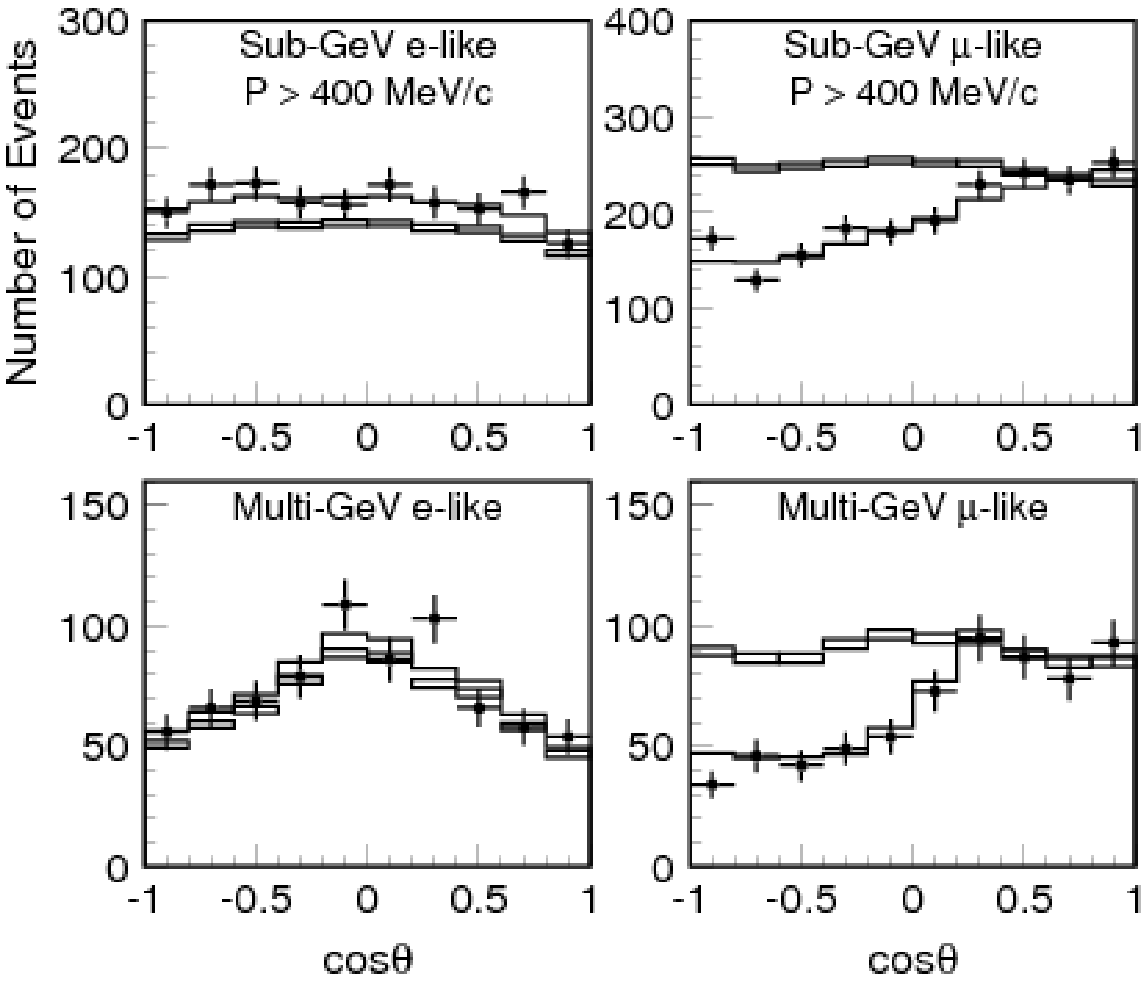
Incident proton strikes atmosphere, making pion

$$\pi \longrightarrow \mu + \nu_\mu$$
$$\hookrightarrow e + \nu_\mu + \nu_e$$

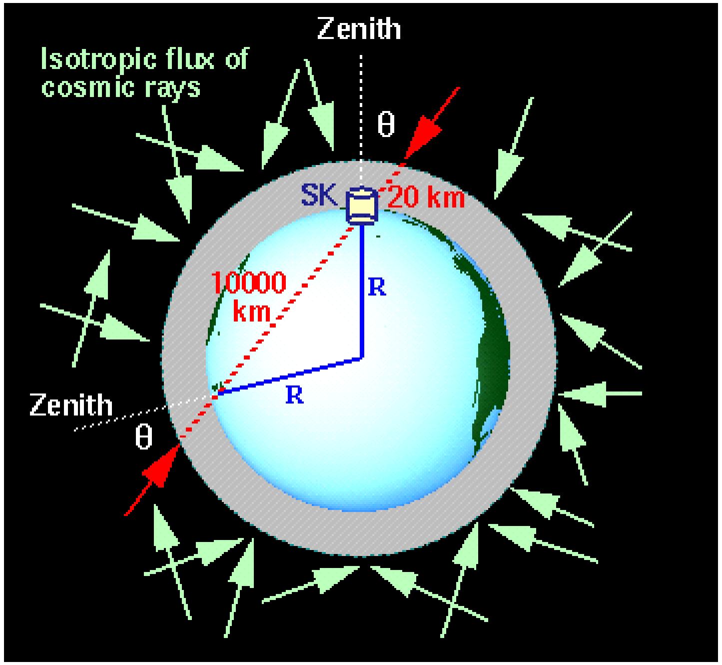
Two muon neutrinos produced for each electron neutrino!

Super–Kamiokande detector

Super-K atmospheric ν results



PRL 93:101801, 2004
PRD 71:112005, 2005

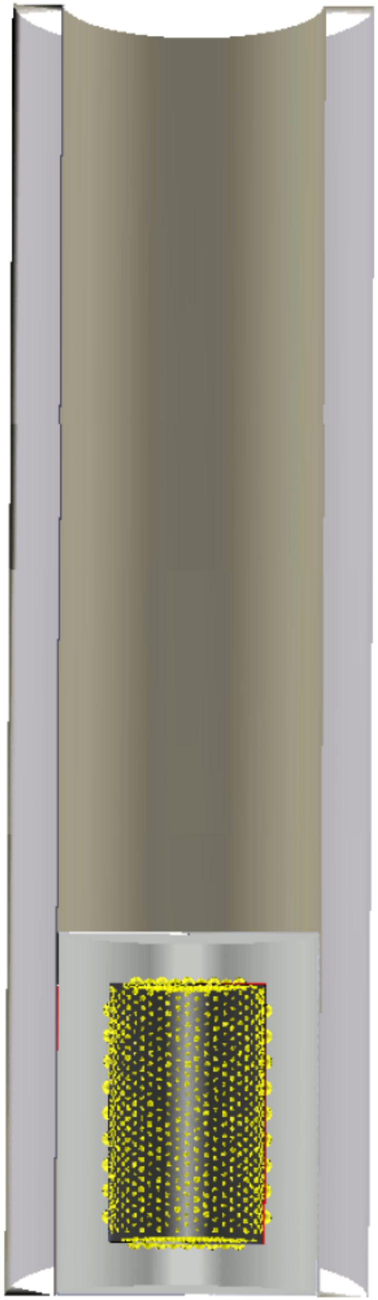


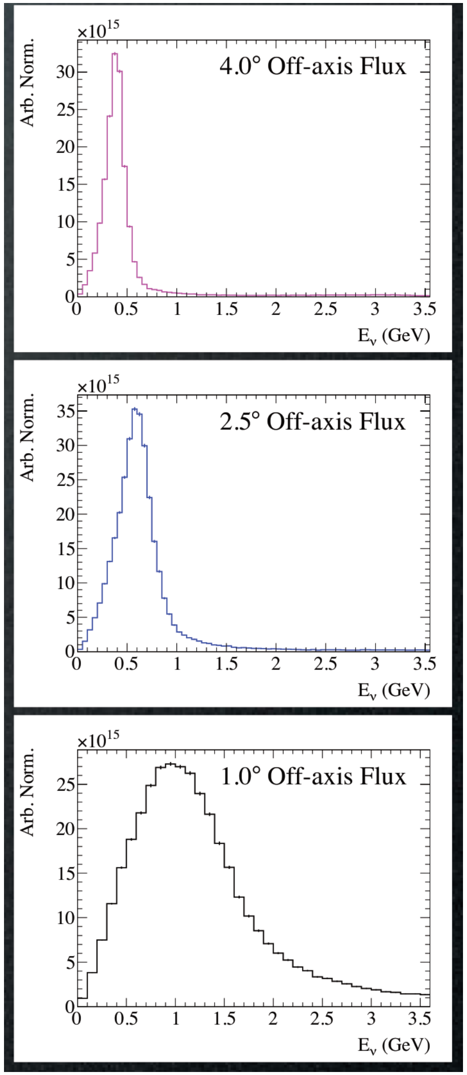
Deficit of upward-going ν_μ relative to downward-going.

No deficit for ν_e.

Seems like $\nu_\mu \rightarrow \nu_\tau$

NuPRISM concept





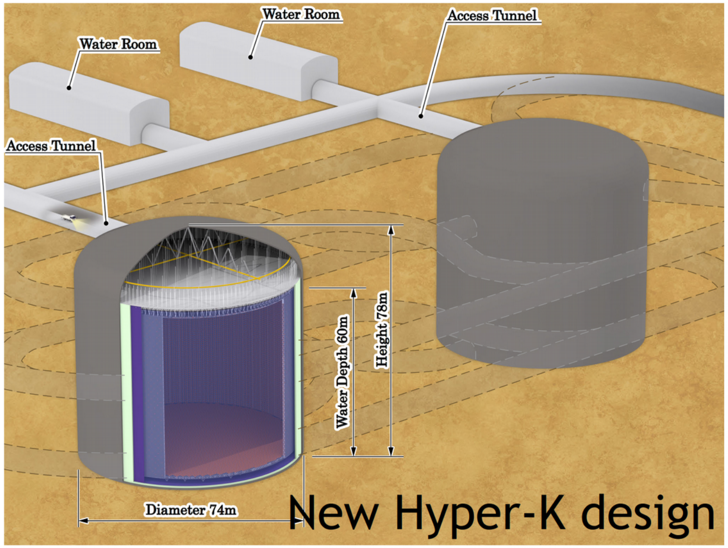
New concept to exploit the variation in neutrino energy with off-axis angle: tall water Cherenkov near detector spanning range of off-axis angles.

Data taken at different angles can directly predict neutrino interactions with arbitrary neutrino fluxes, including effects from oscillation.

Main proposal to Canadian government under review.

Hyper-K

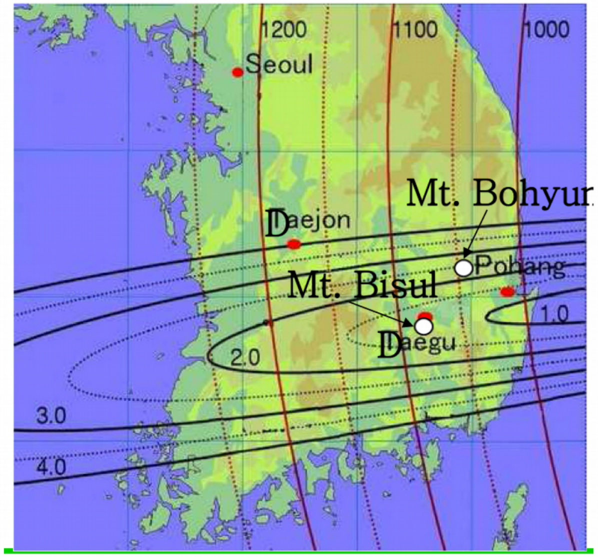
New technical design report: 187kton fiducial volume tank with enhanced photosensor coverage.



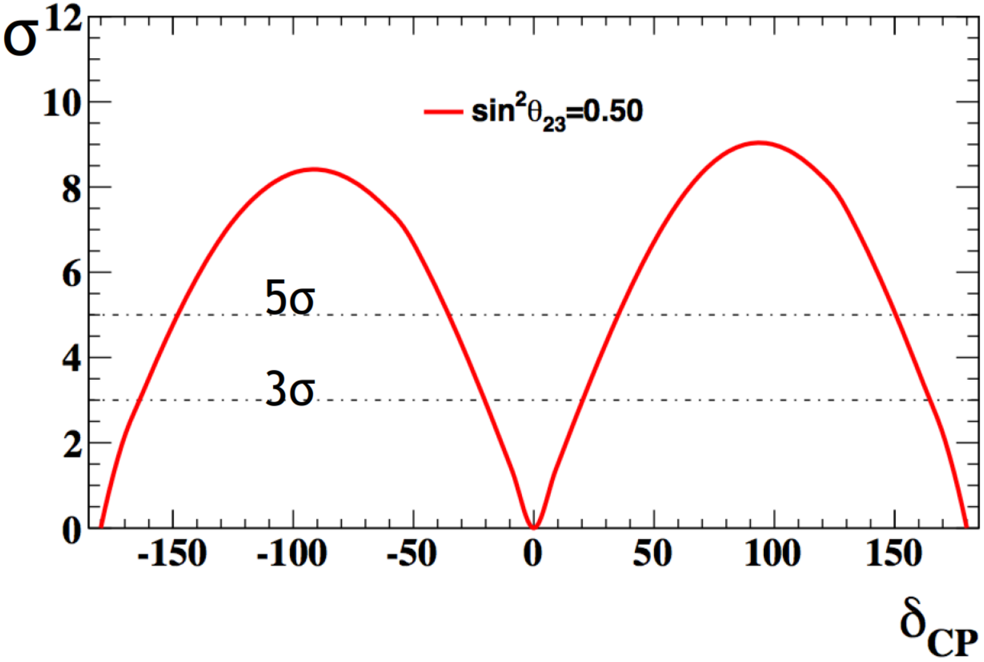
arXiv: 1502.05199

Proposal to locate a second detector in Korea at the second oscillation maximum.

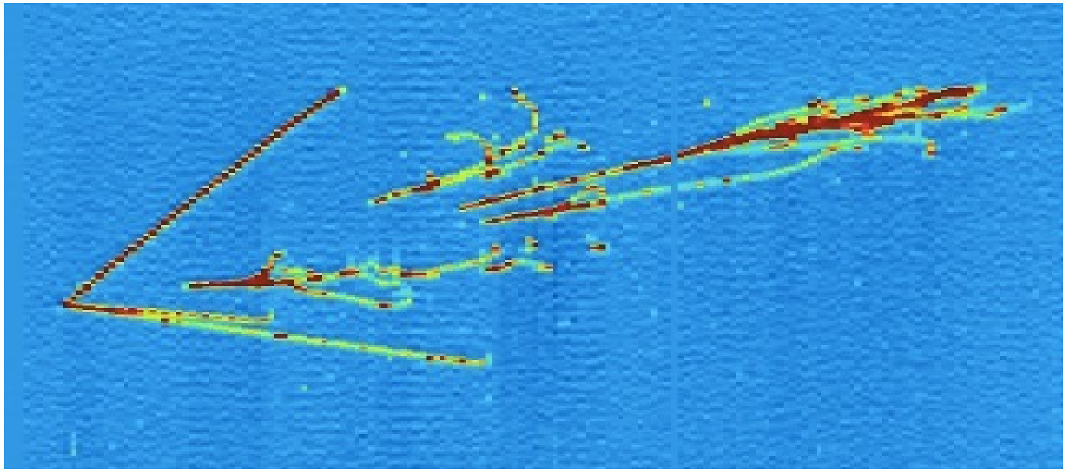
High sensitivity for δ_{CP}



arXiv: 1611.06118



DUNE



Very long baseline experiment aiming at CP violation using liquid argon TPCs as the detector technology.

Higher energy and baseline than Hyper-K.