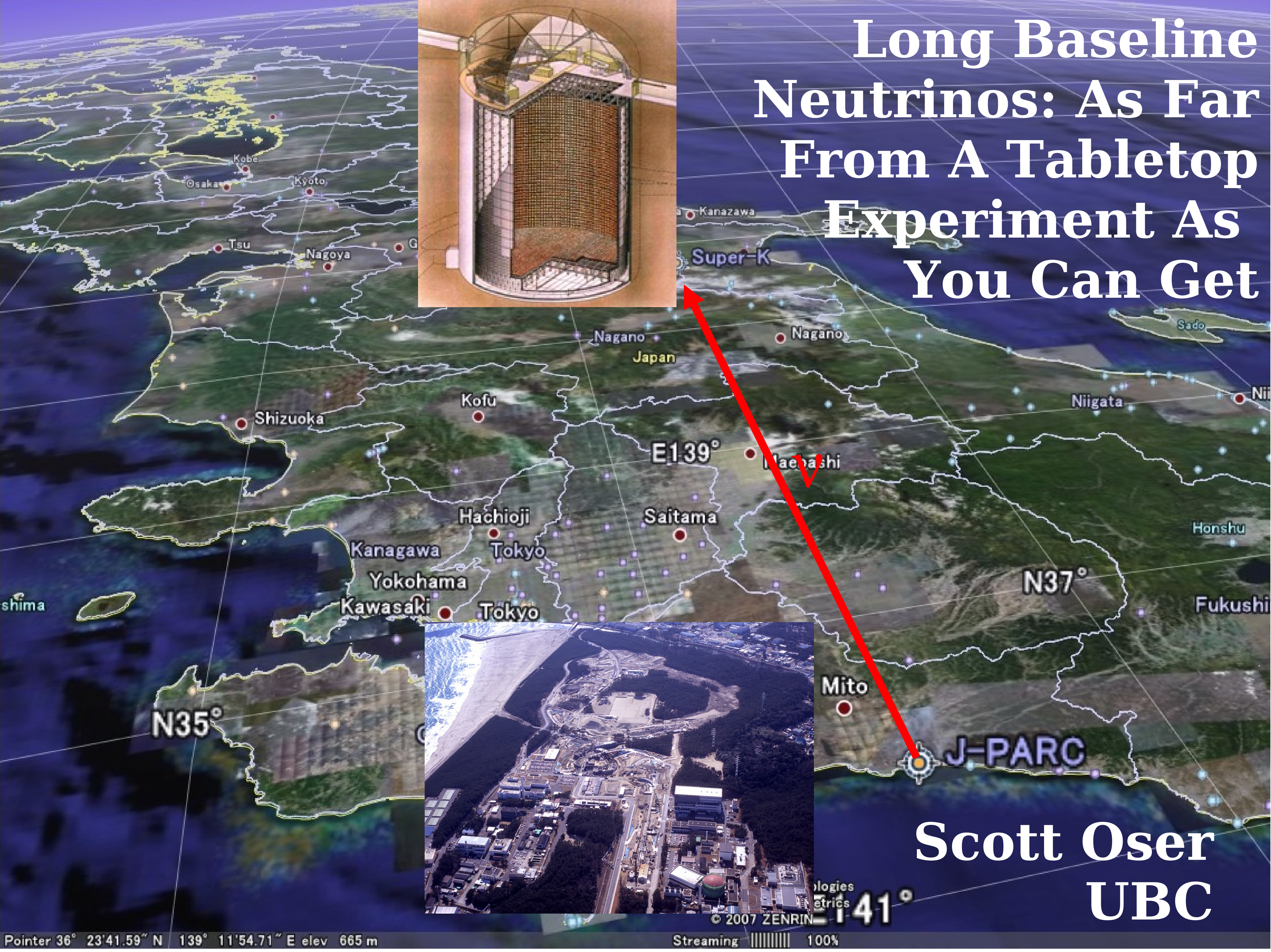
Long Baseline Neutrinos: As Far From A Tabletop Experiment As You Can Get

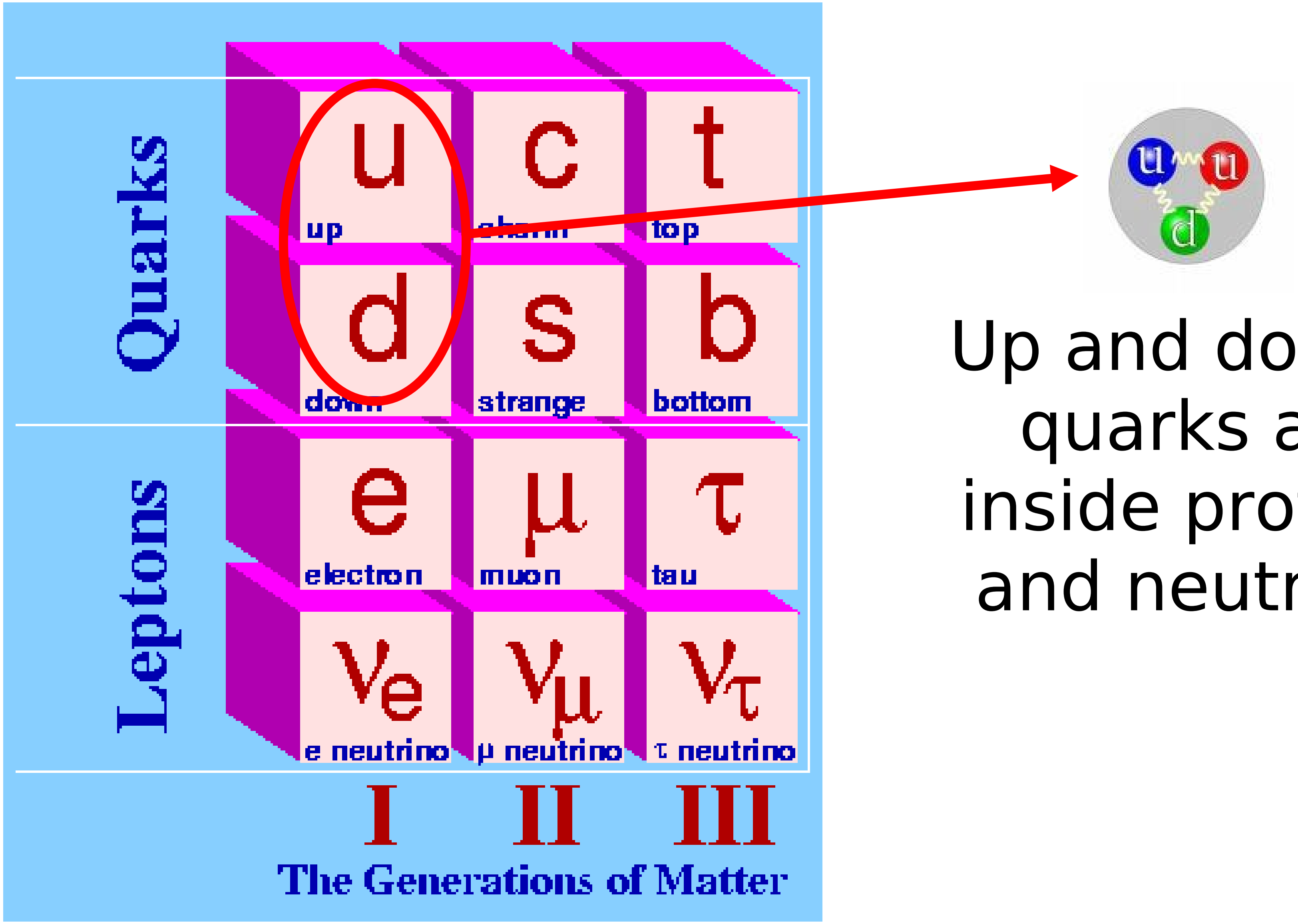


Scott Oser
UBC

Outline

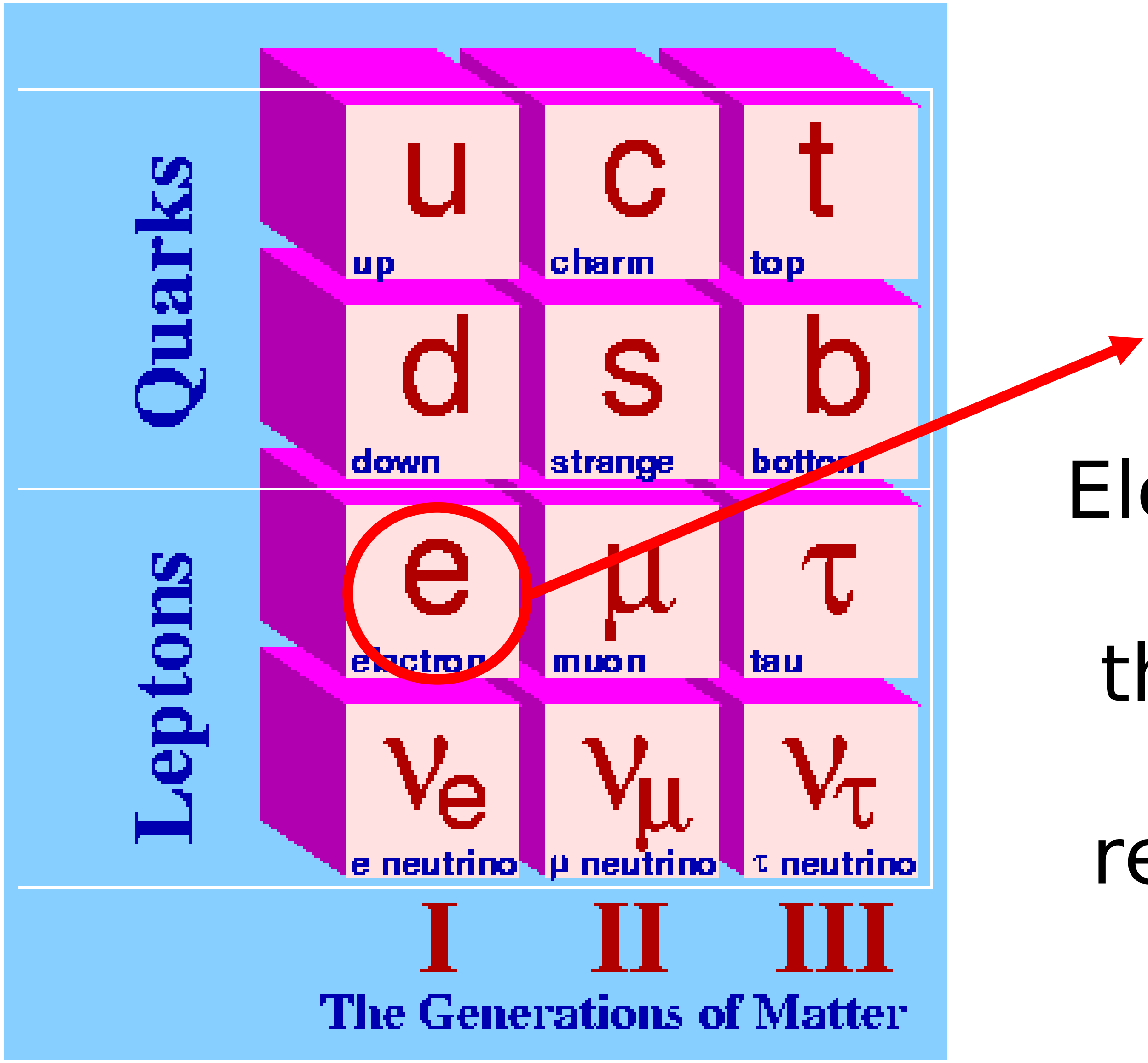
- Review of Neutrino Mixings & Oscillations
- The T2K Experiment
  - motivation
  - beamline
  - far detector
  - near detector
- Oscillation Results
- Present status and conclusions

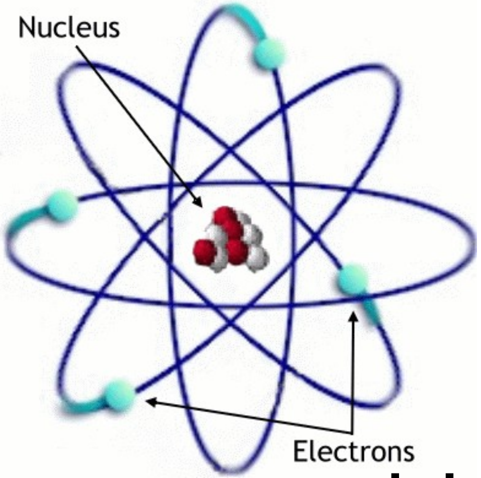
The Building Blocks of Matter



Up and down quarks are inside protons and neutrons

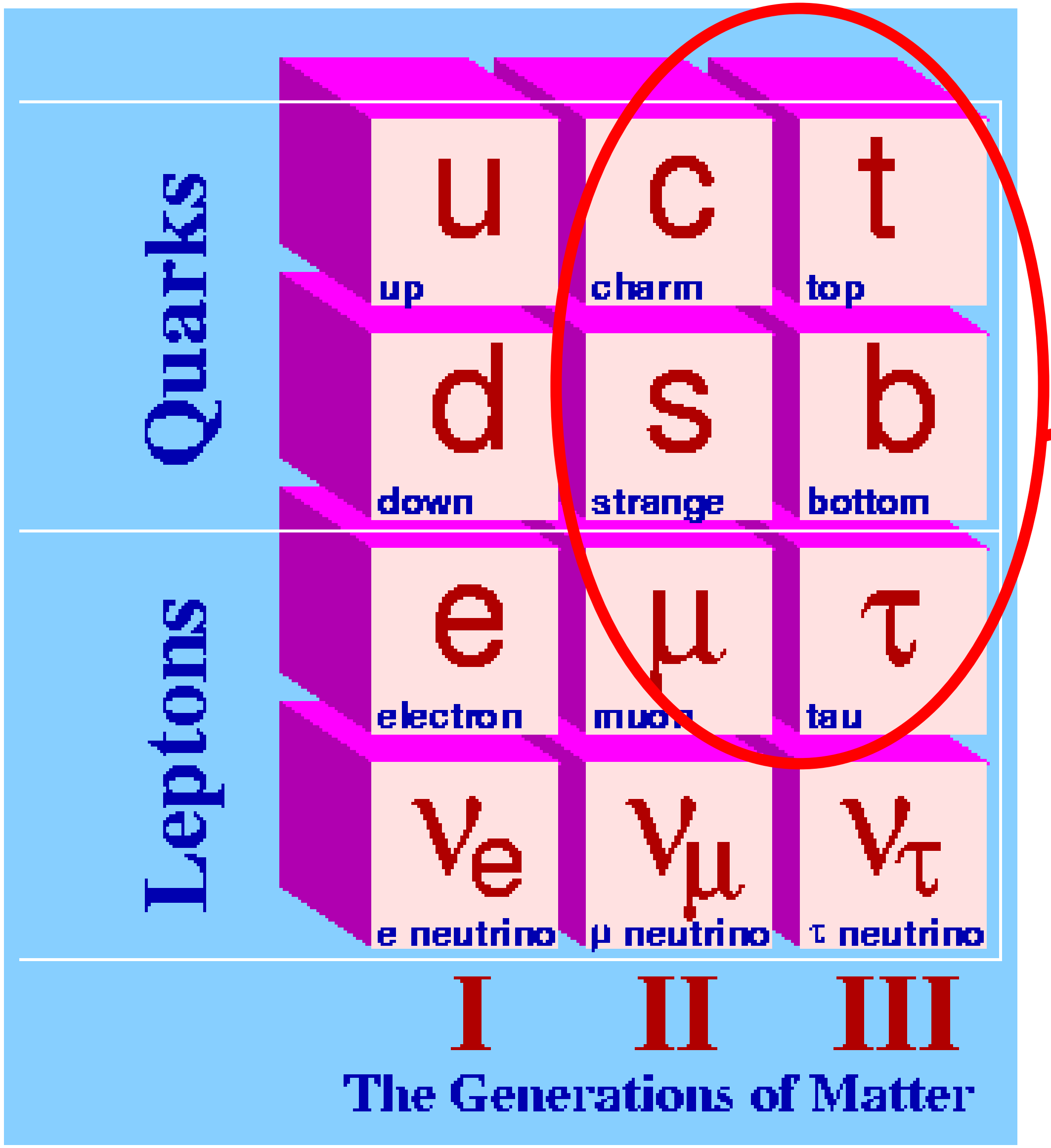
The Building Blocks of Matter





Electrons orbit atoms, flow through wires, and are responsible for chemistry

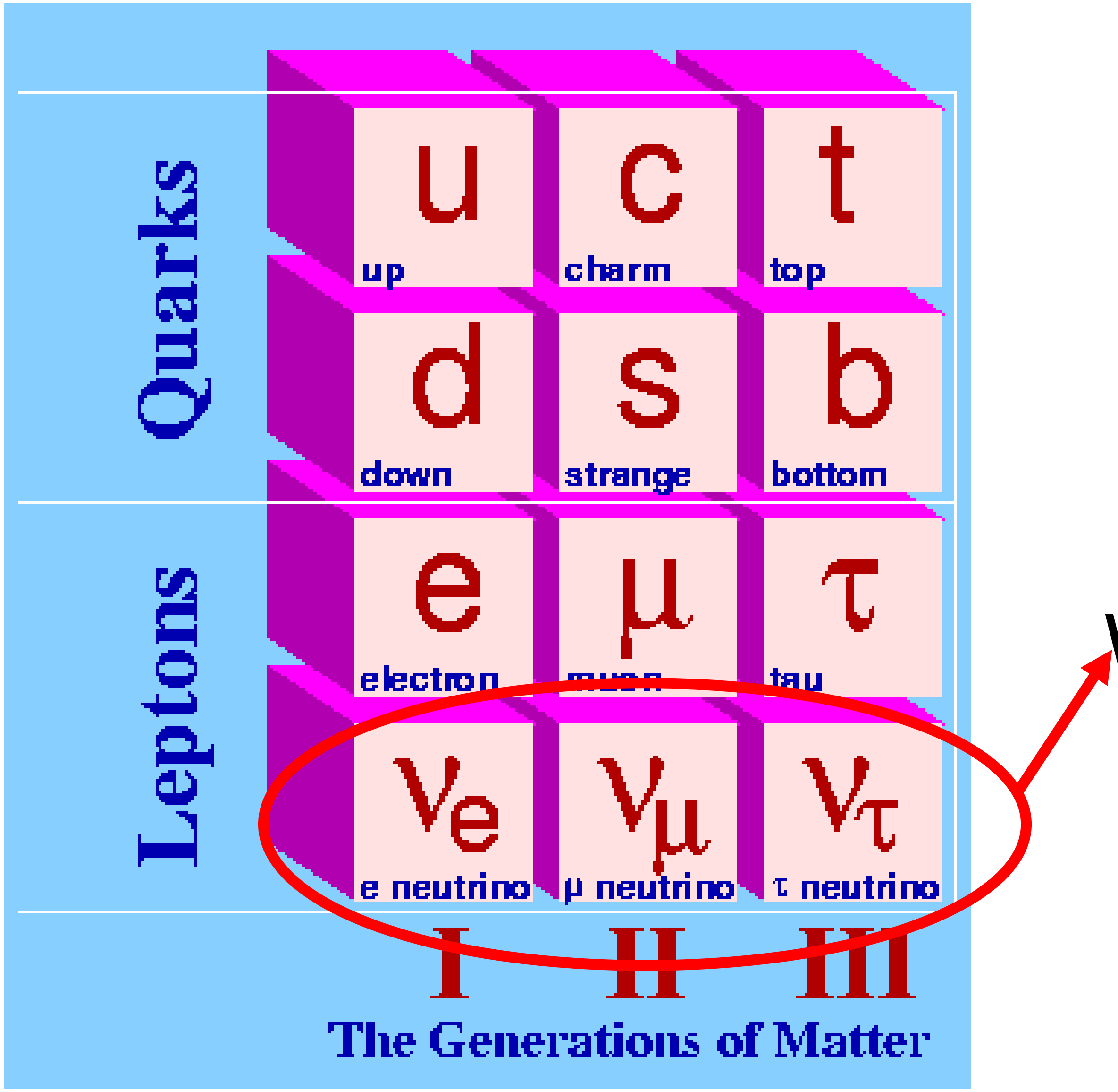
The Building Blocks of Matter



Heavier versions of quarks and electrons

This stuff is here because nature likes things to come in threes. I wish I knew why!

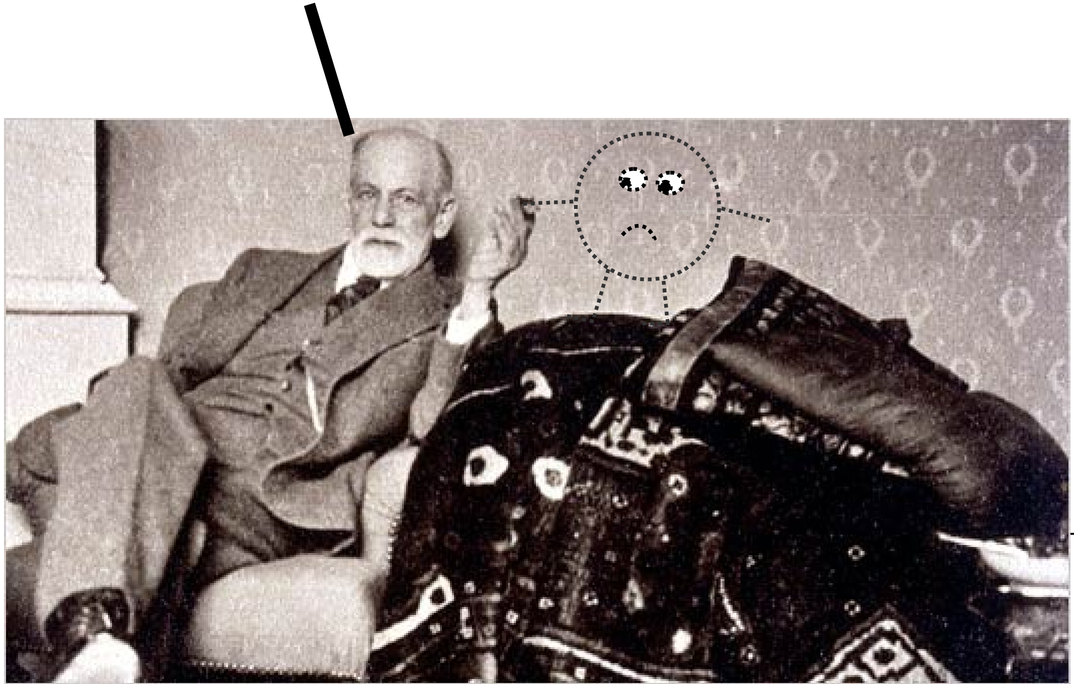
The Building Blocks of Matter



What's this?!?

What is a neutrino?

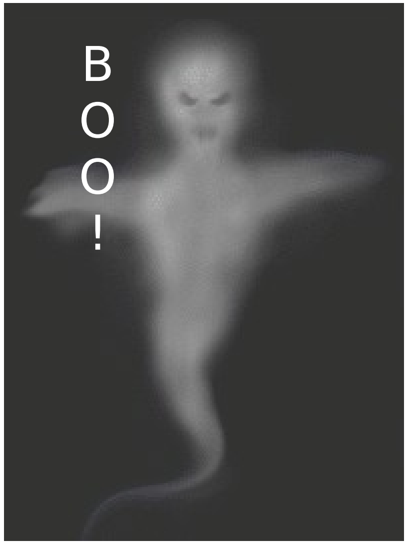
“You are experiencing a profound sense of loss from the removal of your charge and mass. Now, tell me about your mother.”



A particle with an identity crisis ...

In 1997 I might have told you that a neutrino is what's left after you remove an electron's charge and mass.

The particle that is barely there

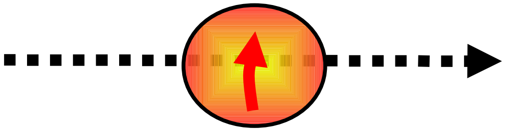


If you have no mass and no charge, what's left?
Very little it turns out ...

Neutrinos still have energy and carry momentum.

They carry angular momentum (spin) as well.

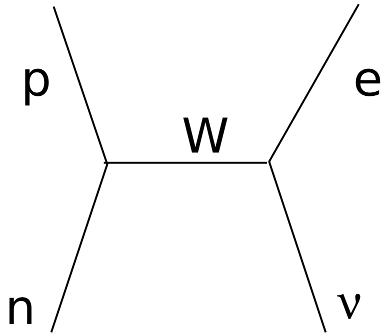
WEIRD fact: neutrinos always spin the same direction, which is different from other particles!



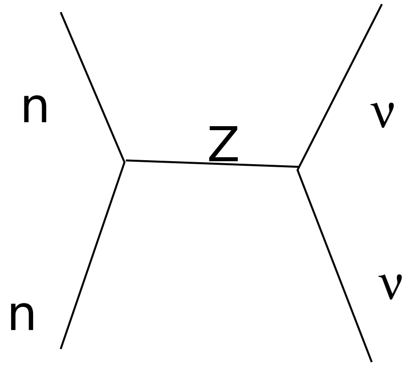
(spins clockwise when viewed head-on)

And they have interactions ...

Neutrino interactions: extremely weak!



“Charged current”: convert a neutrino into an electron, with a W particle carrying charge & momentum away

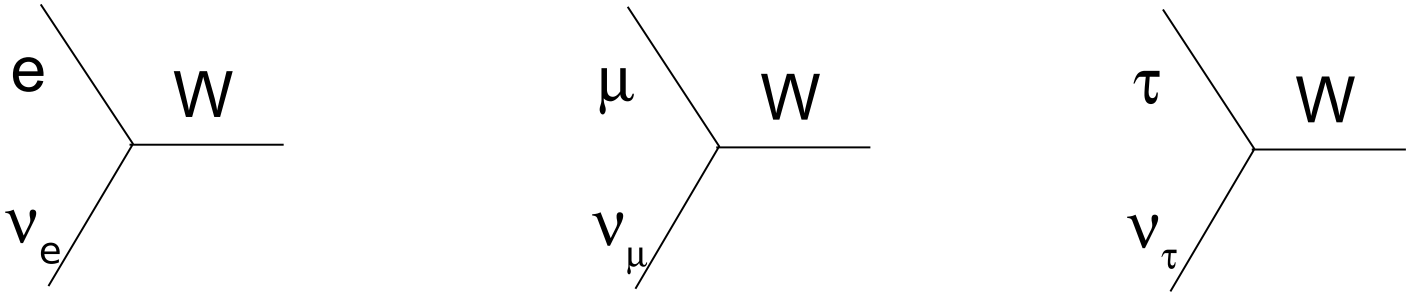


“Neutral current”: the neutrino survives, but some energy and momentum is transferred by a Z particle

Neutrinos can pass through 1000's of km of solid matter without stopping!

Three flavors of neutrinos

Like quarks and electrons, neutrinos come in 3's. The distinction is what kind of charged lepton they couple to:



The result is as if there's something like “electron-ness” or “mu-ness” or “tau-ness” that gets carried by the neutrino.

If for example a particle decays to make a μ and a ν_μ, then that neutrino later on should only ever be capable of making a μ. CONSERVATION OF FLAVOUR.

Neutrino Mixing

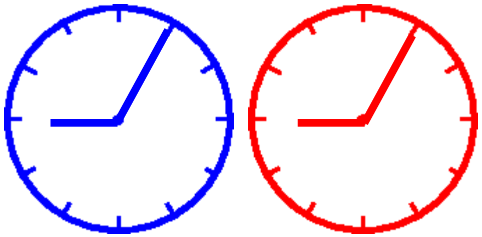
One way this picture could be modified is if flavour eigenstates are not identical to mass eigenstates. What if what we call ν_μ and ν_e are really just different combinations of two different states we'll call $|\nu_1\rangle$ and $|\nu_2\rangle$?

$$|\nu_e\rangle = \cos\theta\,|\nu_1\rangle + \sin\theta\,|\nu_2\rangle$$
$$|\nu_\mu\rangle = -\sin\theta\,|\nu_1\rangle + \cos\theta\,|\nu_2\rangle$$

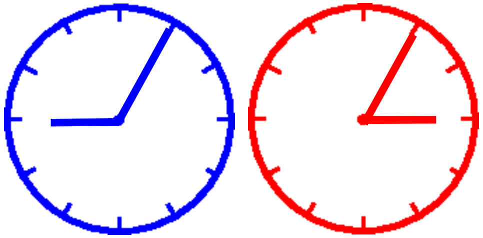
Think of $|\nu_1\rangle$ and $|\nu_2\rangle$ as the particle states with definite mass, while $|\nu_e\rangle$ and $|\nu_\mu\rangle$ are the states that couple to weak interactions.

A timely analogy

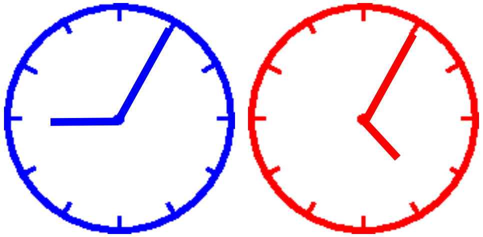
Imagine each neutrino as a pair of clocks



If both clocks read the same time, the neutrino acts like an electron neutrino.

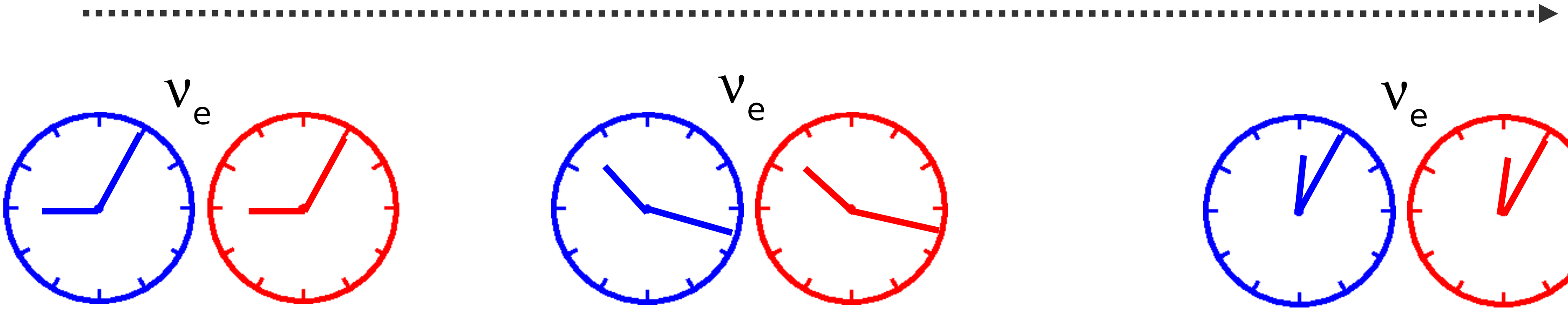


If the red clock is 6 hours ahead, the neutrino acts like an muon neutrino.



If the red clock is 4 hours ahead or four hours behind, then ⅔ of the time it acts like a ν_μ, and ⅓ of the time like a ν_e

Neutrinos are created as either ν_e or ν_μ

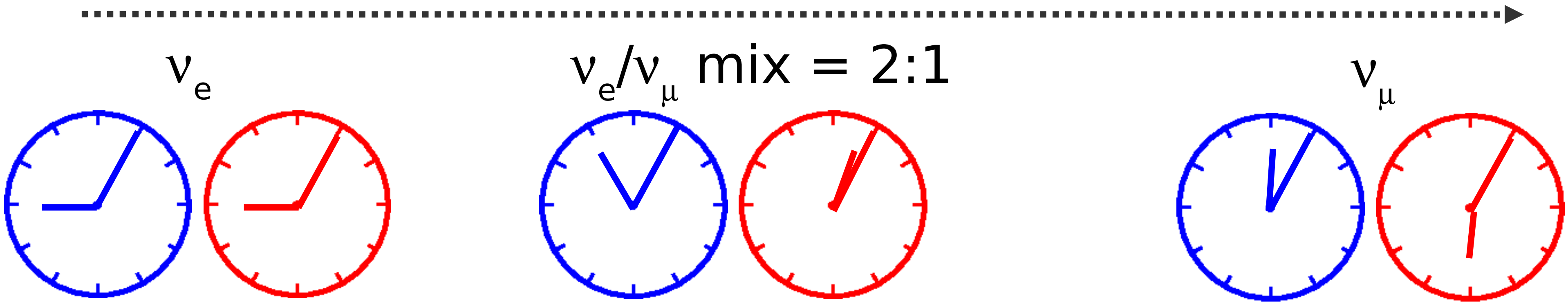


At the start, the clocks each read 9:05---in sync, so acts like electron neutrino

After a while, the clocks both read 10:17---still synchronized, still an electron neutrino

At a later time the situation is the same---clocks stay in sync!

What if the clocks get out of sync?



ν_e

ν_e/ν_μ mix = 2:1

ν_μ

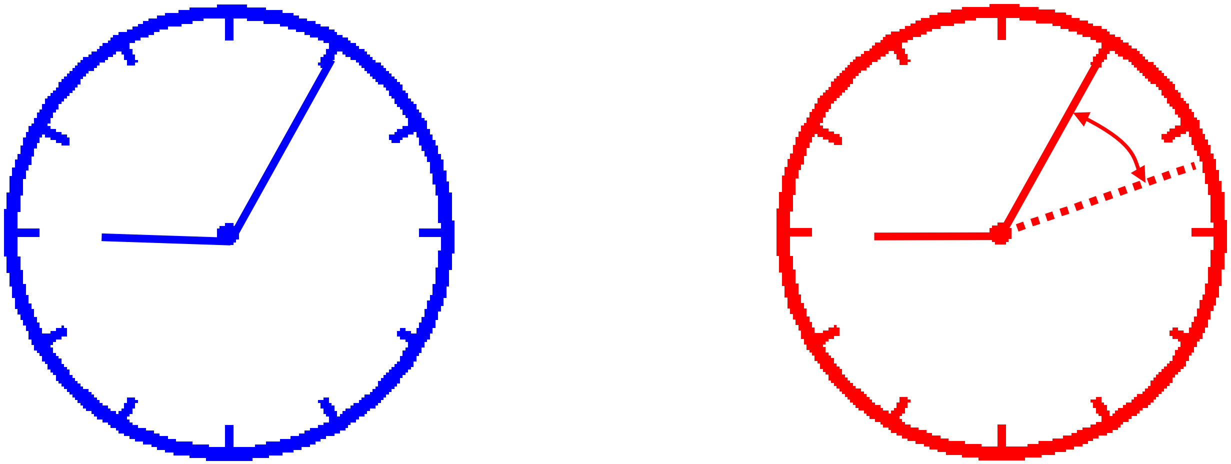
At the start, the clocks each read 9:05---in sync, so acts like electron neutrino

After a while, the red clock is 2 hours ahead: a mix of ν_e and ν_μ

Later still the clocks are the maximum of 6 hours apart---this neutrino acts like a ν_μ

What started out as an electron neutrino can then act like a muon neutrino!

What makes clocks get out of sync?



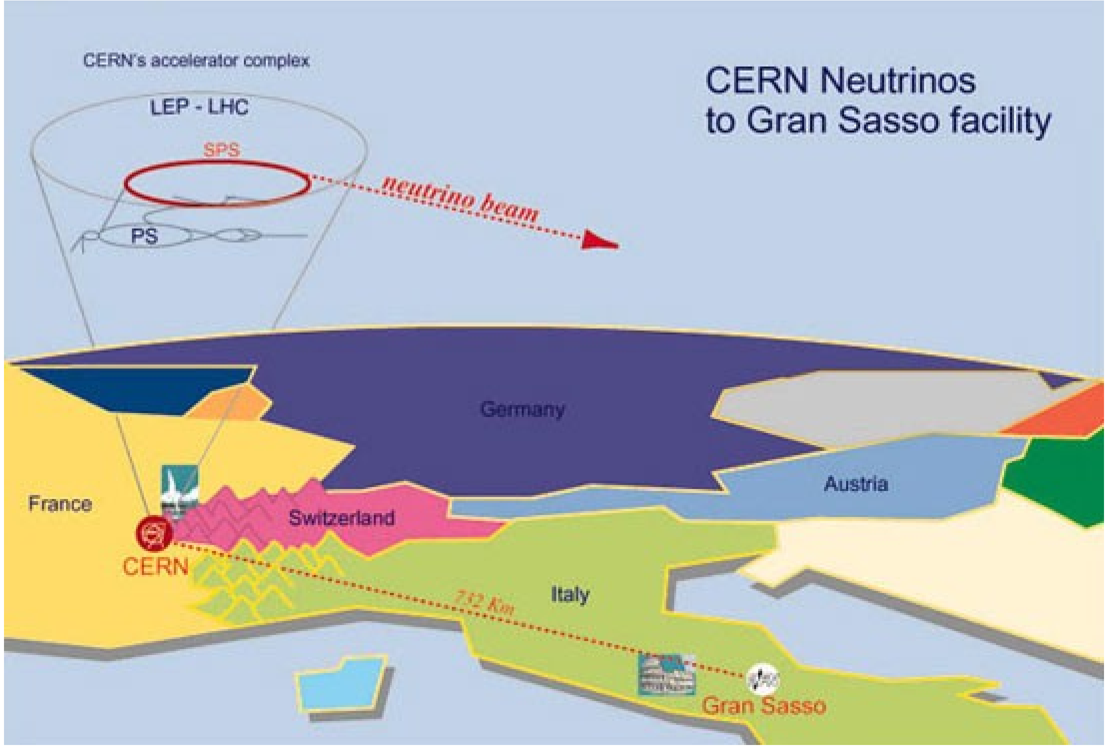
QM Phase: $e^{-i(Et-px)/\hbar} = e^{-i(\sqrt{p^2+m^2}x-px)\hbar}$

What controls the rates of the clocks are the masses and energies of the two mass eigenstates $|\nu_1\rangle$ and $|\nu_2\rangle$.

But if masses = 0, everything moves at *v*=*c*, and time dilation is infinite.

∴ Observable oscillation → non-zero mass.

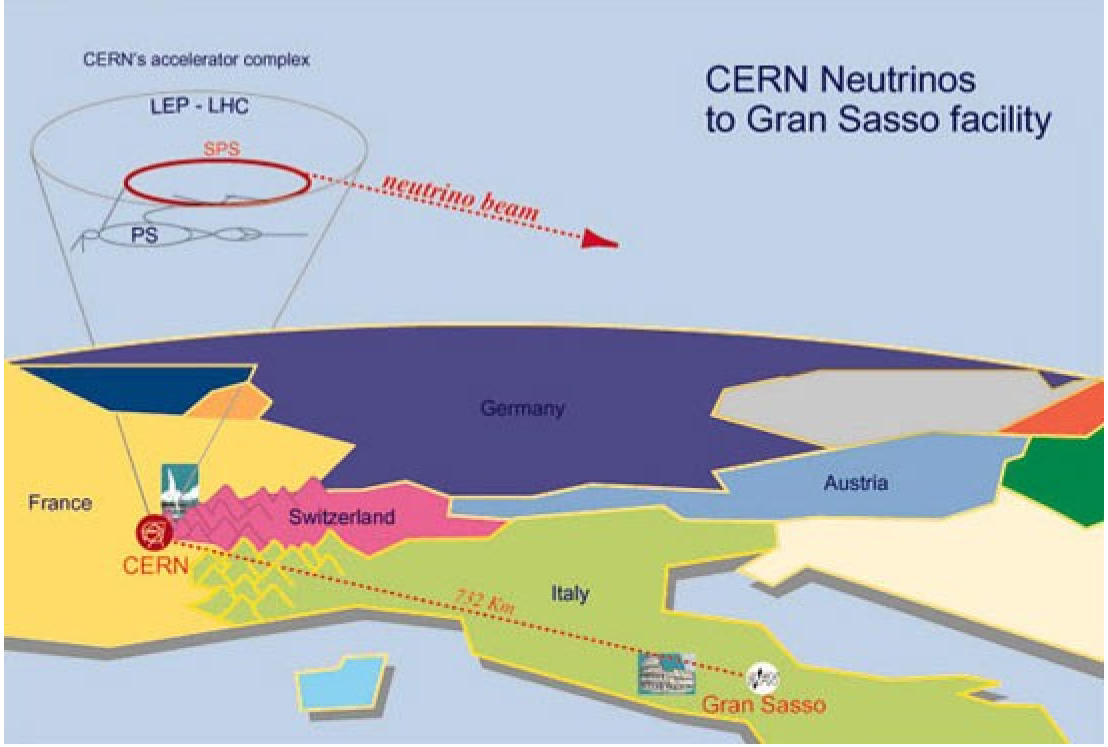
Aside: Can the clock run backwards?



OPERA experiment measured transit time of neutrinos from CERN to Gran Sasso. They report that the beam arrived 60ns faster than the speed of light.

Implies that $(v-c)/c = 2.5 \times 10^{-5}$

Aside: Can the clock run backwards?



T2K plans to upgrade its clocks and check this result within the next few years.

If we confirm the result, we will publish it yesterday.

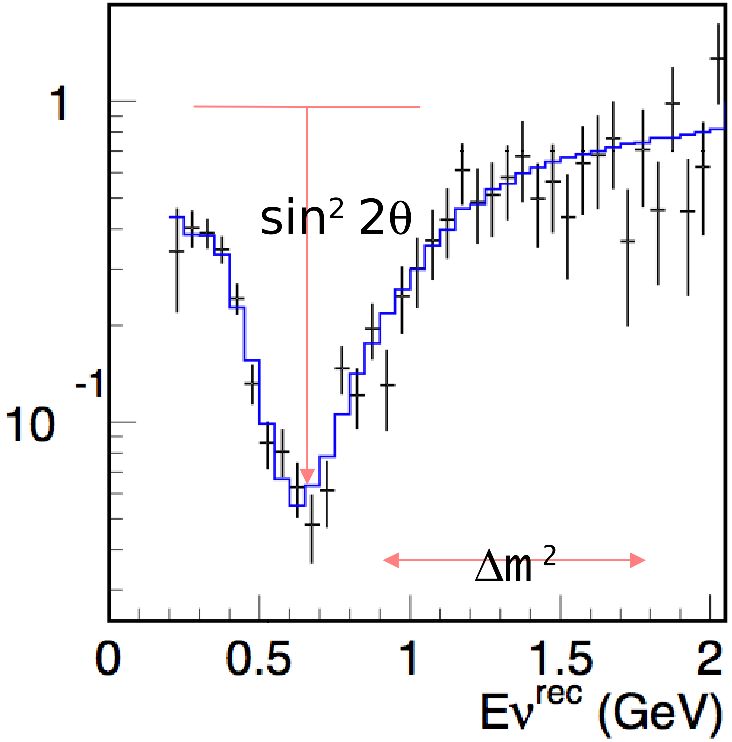
Flavour Oscillation

Because a flavour eigenstate produced by a weak interaction is a mix of mass eigenstates which, if $m_1 \neq m_2$, propagate with different kinematics, oscillation can occur.

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

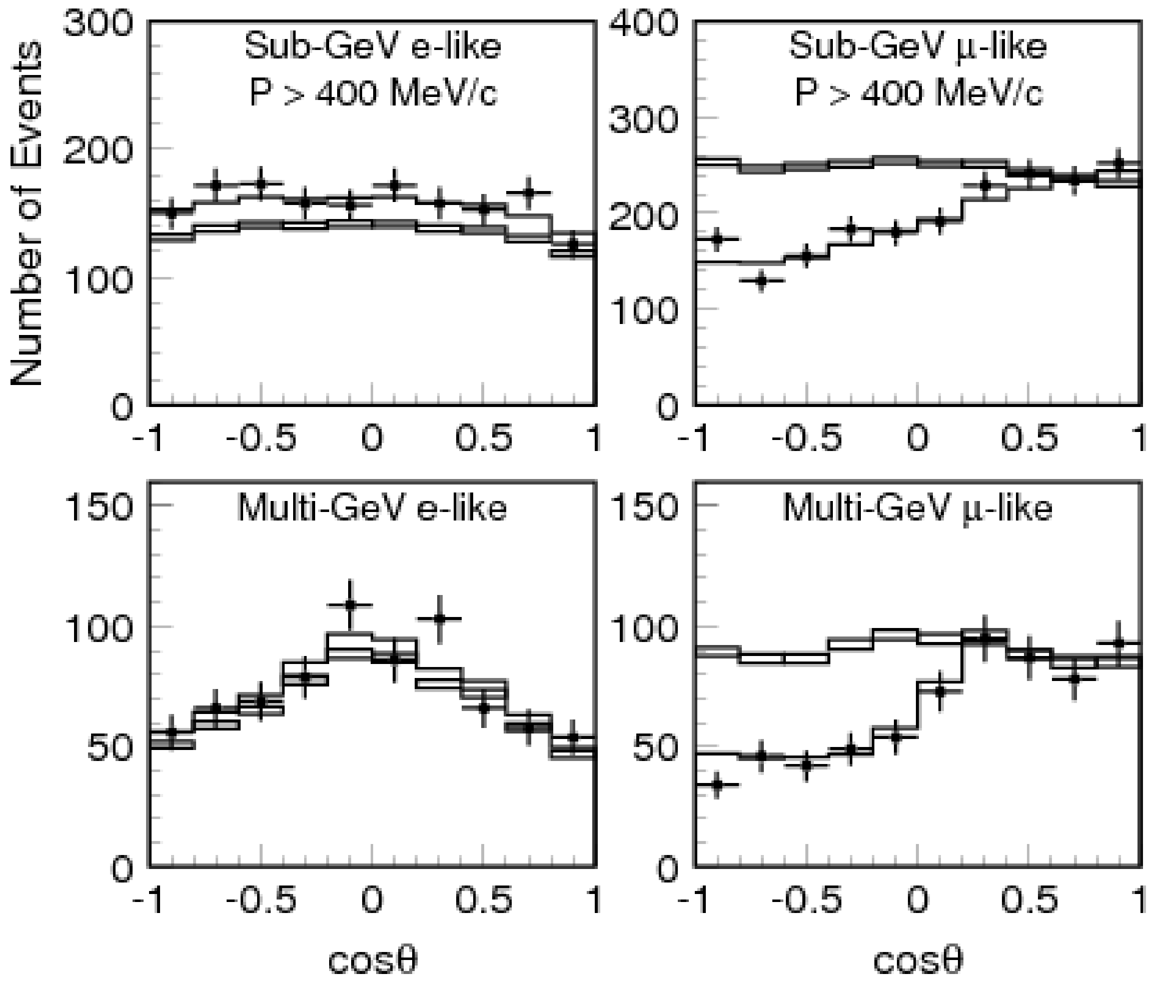
$$|\nu(t)\rangle = \begin{array}{l} e^{i\sqrt{p^2+m_1^2}\,t}\cos\theta|\nu_1\rangle \\ +e^{i\sqrt{p^2+m_2^2}\,t}\sin\theta|\nu_2\rangle \end{array}$$

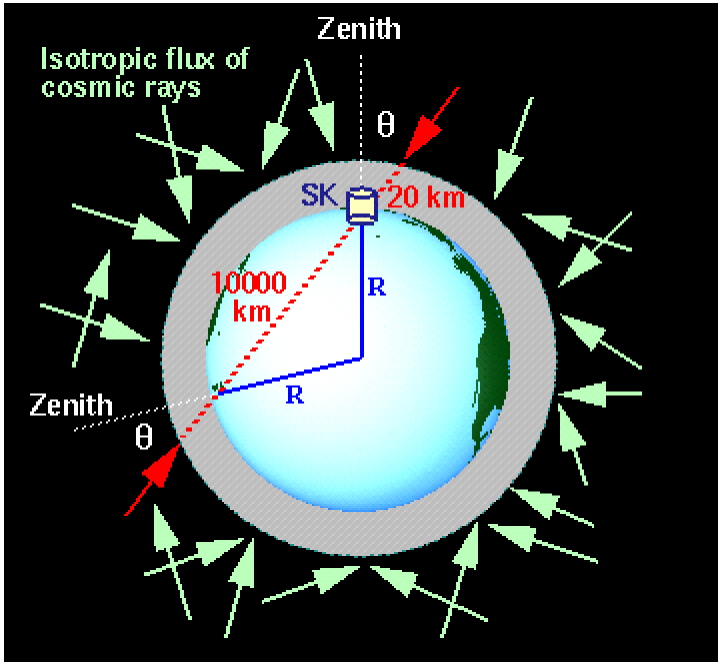
$$Prob(\nu_e \rightarrow \nu_e) = 1 - \sin^2(2\theta)\sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$



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

Super-K atmospheric ν results





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

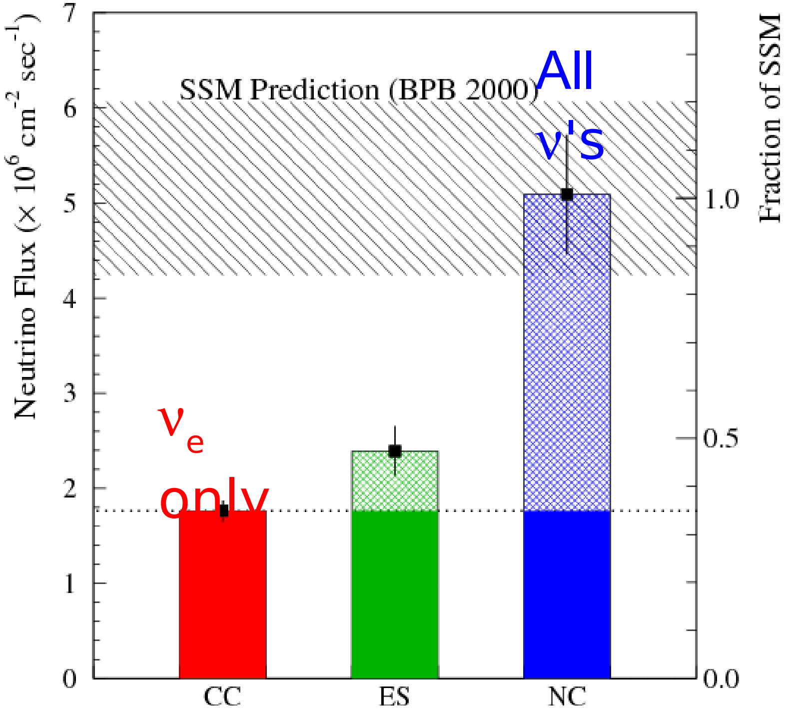
No deficit for ν_e.

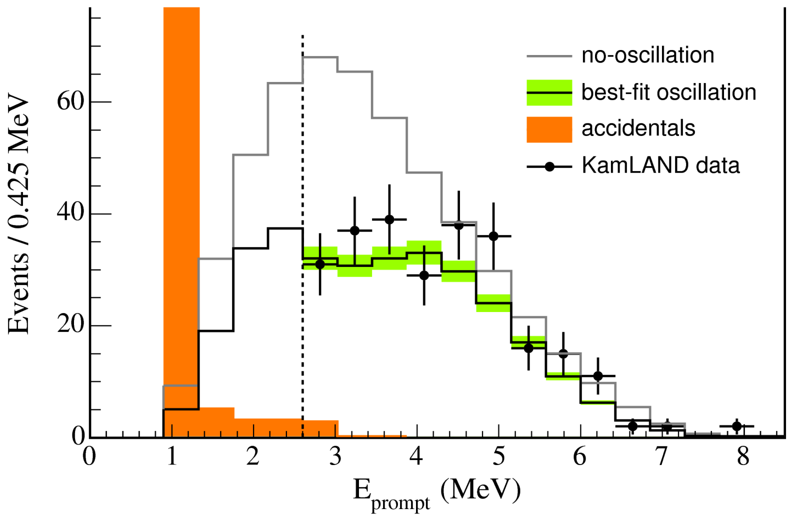
Seems like $\nu_\mu \to \nu_\tau$

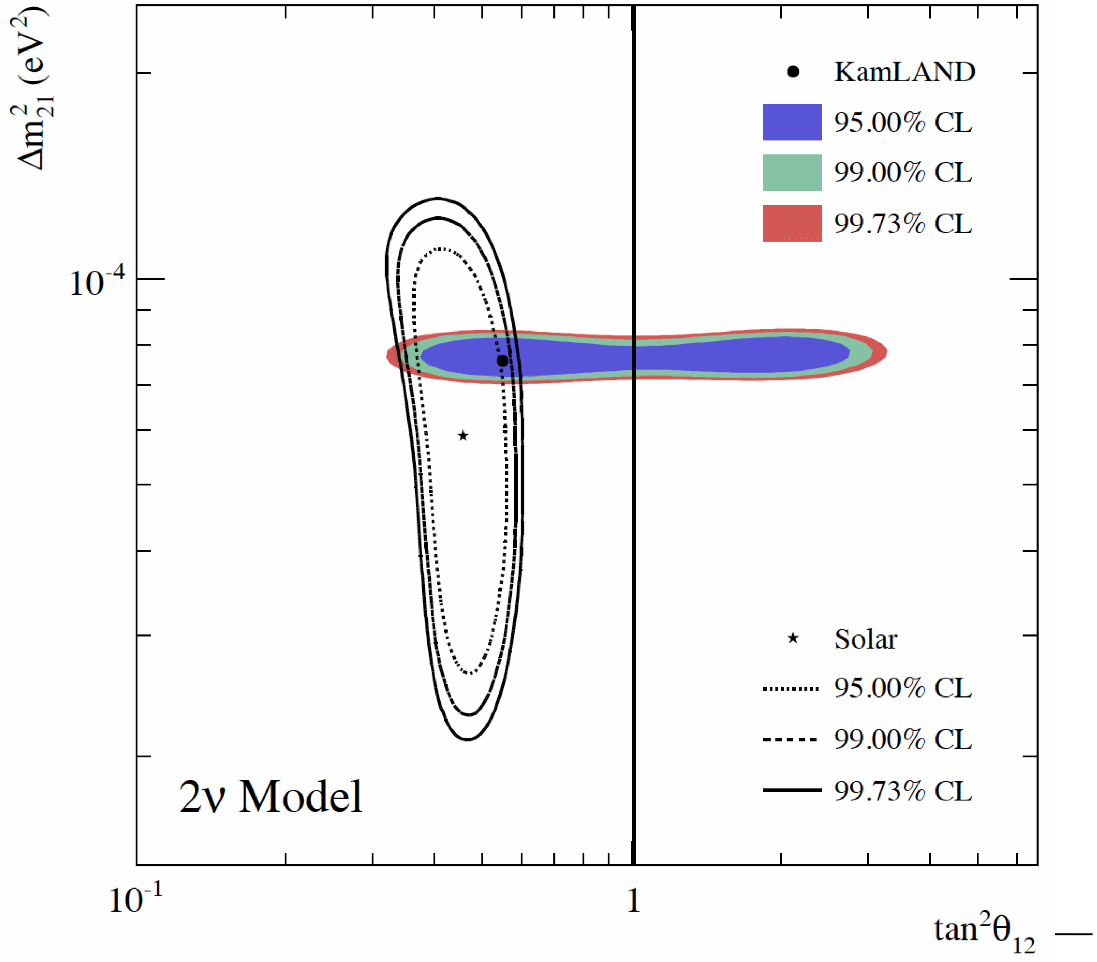
PRL 93:101801, 2004
PRD 71:112005, 2005

SNO & KamLAND

- Appearance of non-ν_e in solar ^{8}B flux
- Suppression and spectral distortion of reactor ν
- Consistent set of mixing parameters







The T2K Experiment

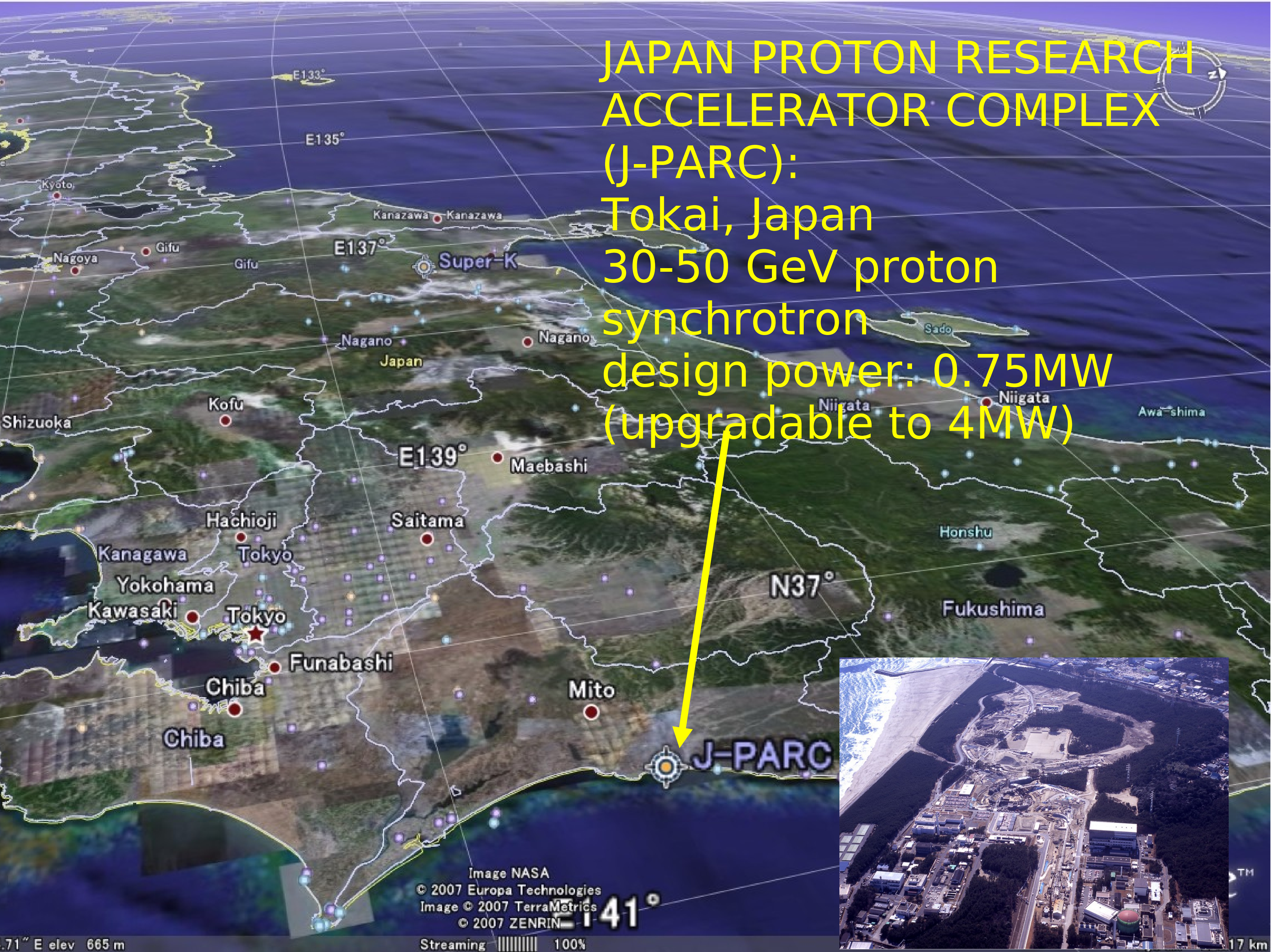
JAPAN PROTON RESEARCH ACCELERATOR COMPLEX (J-PARC):

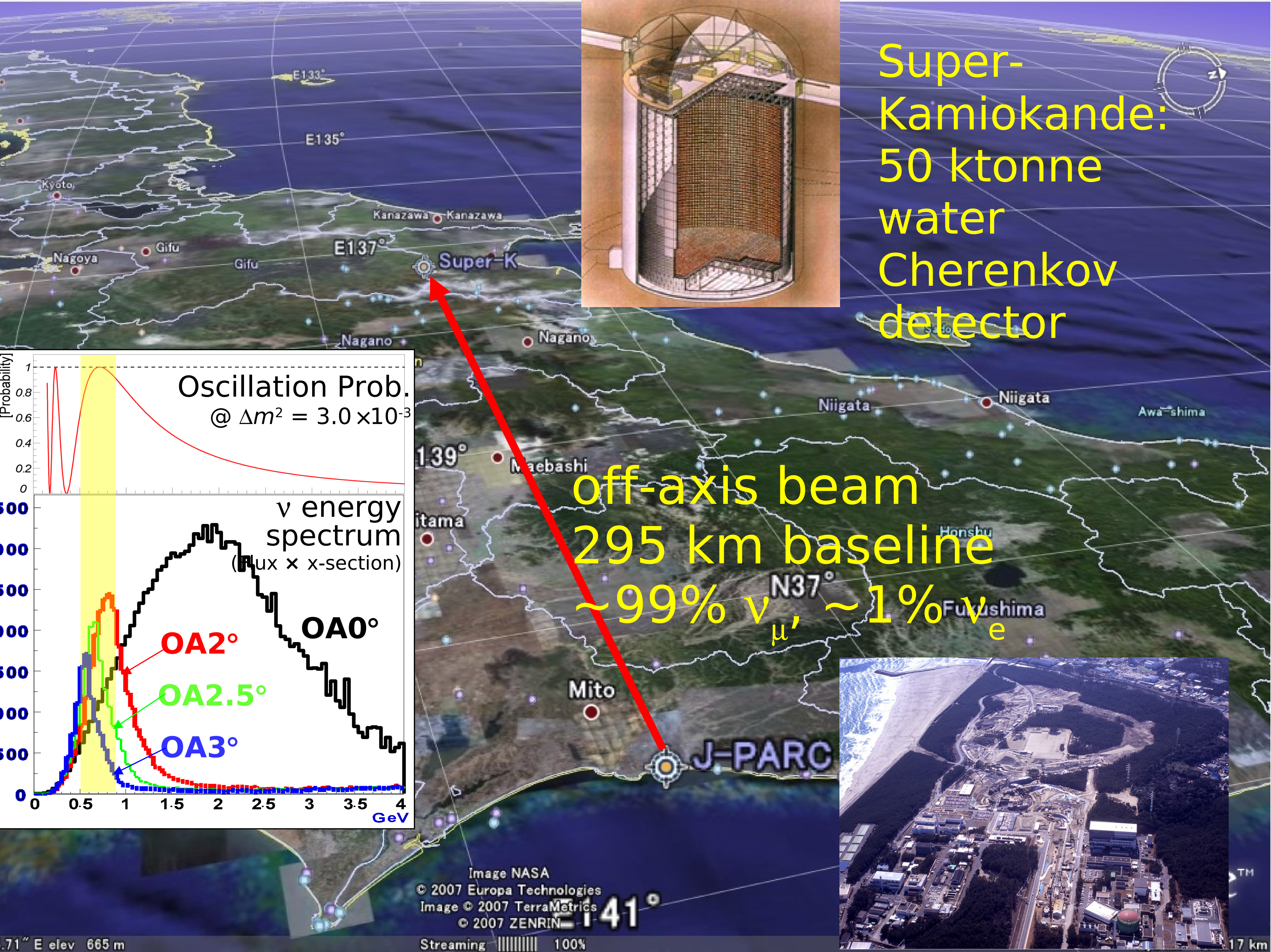
Tokai, Japan

30-50 GeV proton synchrotron

design power: 0.75MW

(upgradable to 4MW)

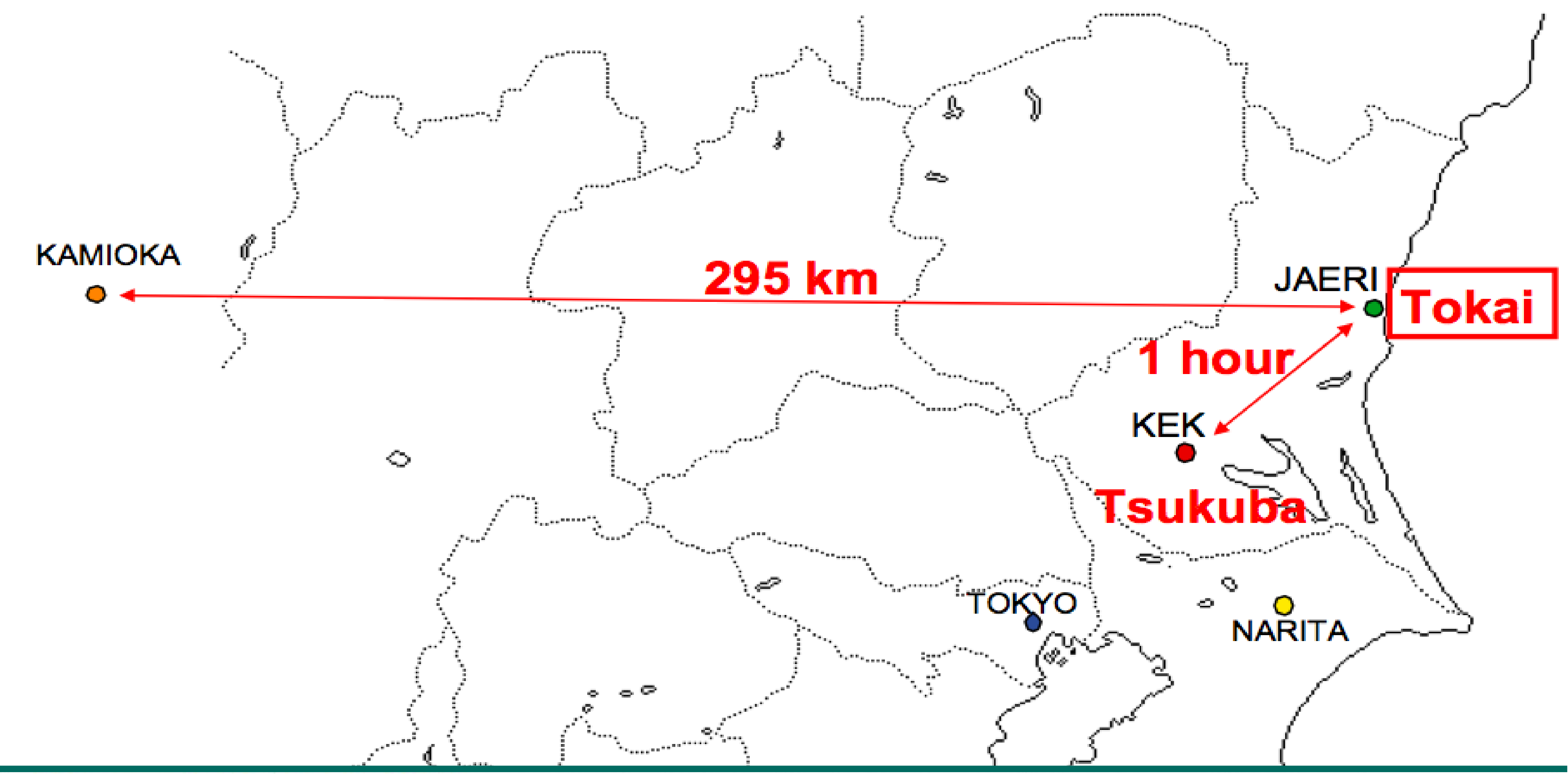


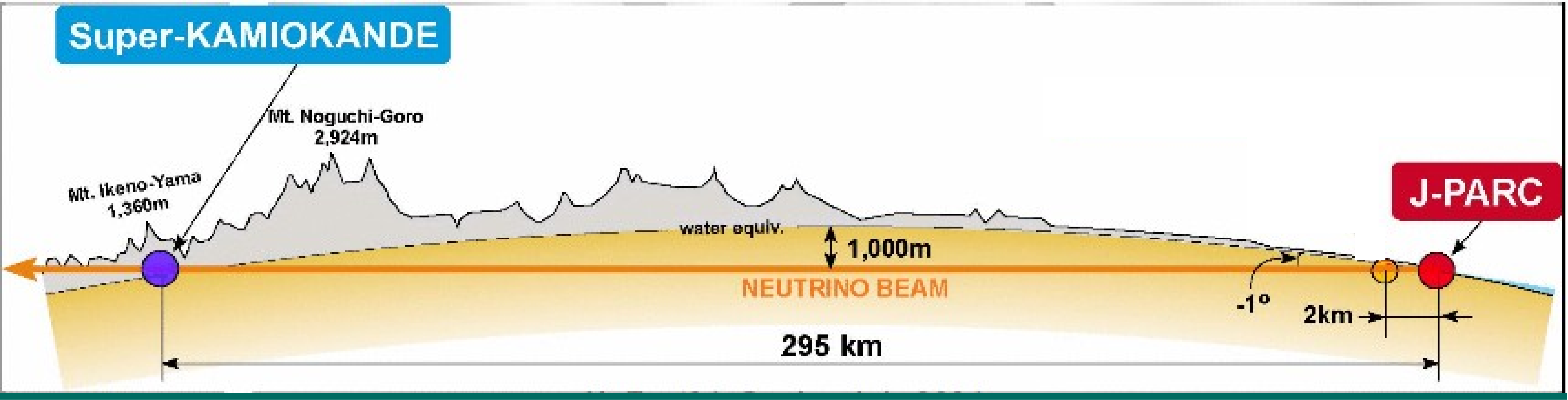


Super-Kamiokande: 50 ktonne water Cherenkov detector

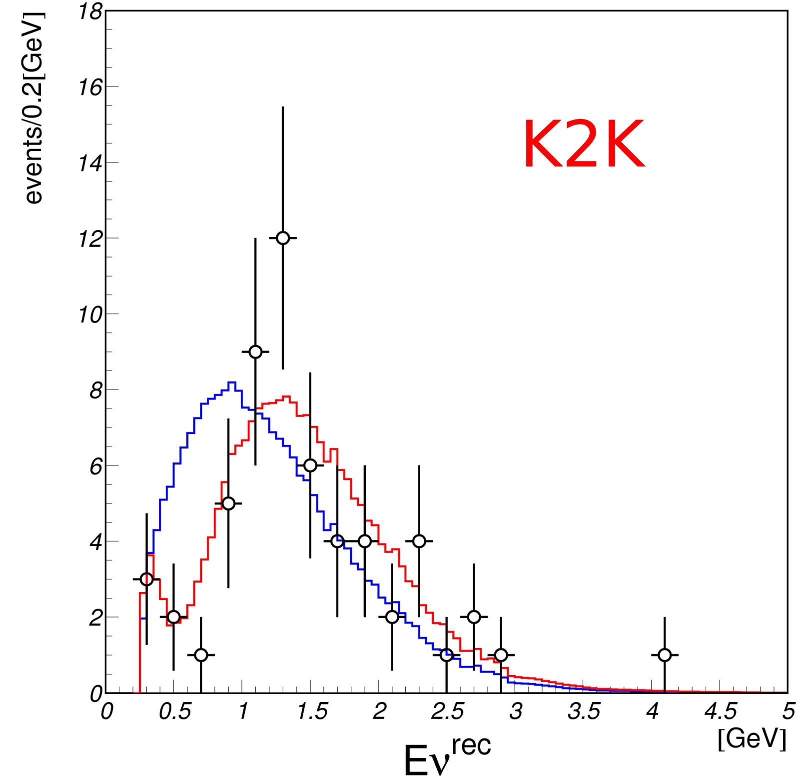
off-axis beam
295 km baseline
~99% ν_μ, ~1% ν_e

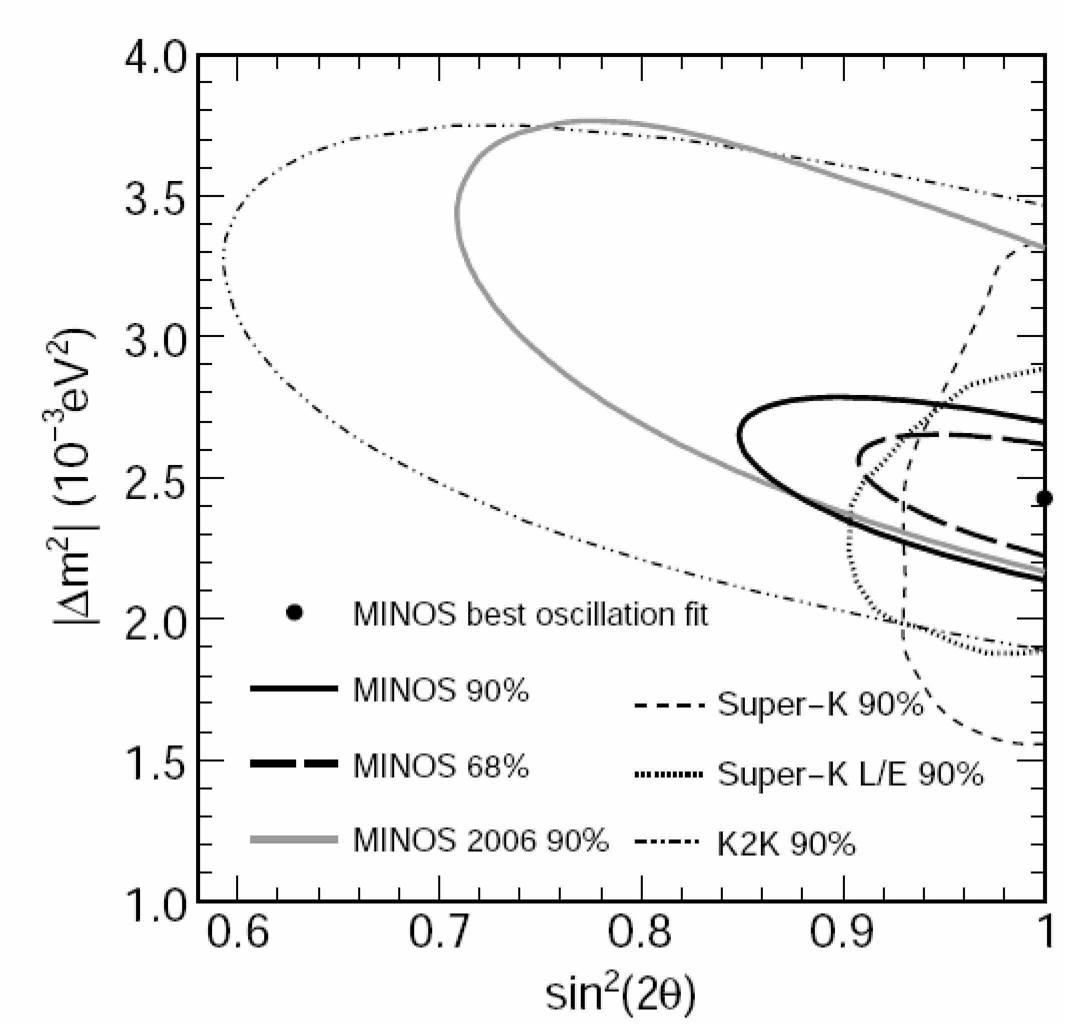
Sophisticated on-axis and off-axis near detectors 280m from proton target

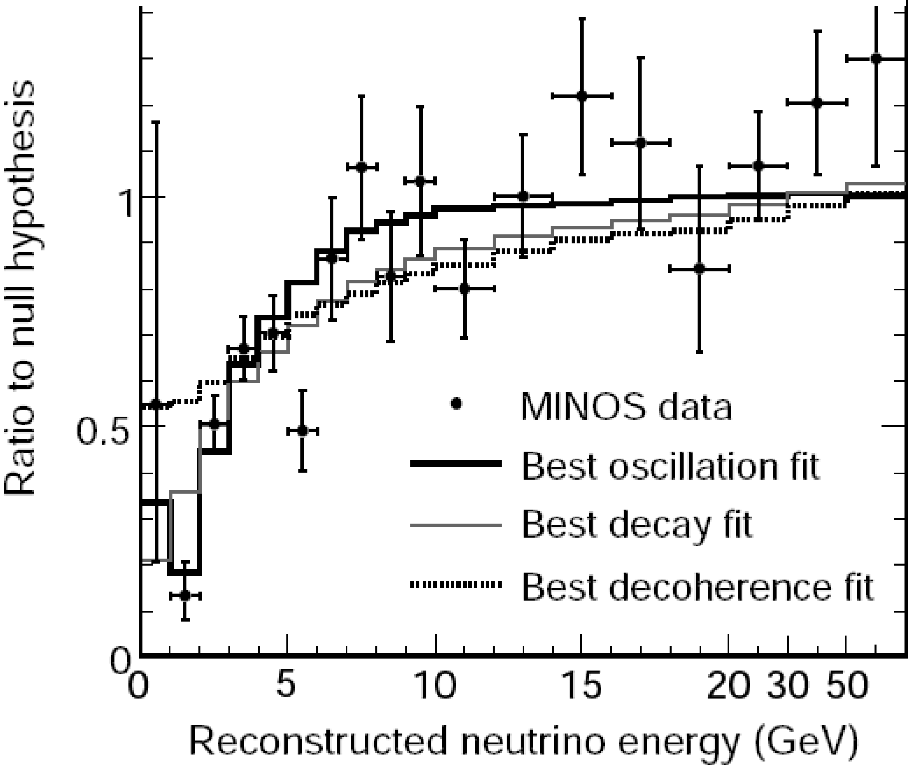

KAMIOKA
295 km
JAERI
Tokai
1 hour
KEK
Tsukuba
TOKYO
NARITA


Super-KAMIOKANDE
Mt. Noguchi-Goro
2,924m
Mt. Ikeno-Yama
1,360m
water equiv.
1,000m
NEUTRINO BEAM
J-PARC
-1°
2km
295 km

K2K & MINOS







Consistency between atmospheric and long-baseline ν oscillation results.

The full ν 3x3 mixing matrix

Different L/E values pick up different Δm^2 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:

$$\theta_{23} \approx \pi/4$$

Maximal mixing! (?)

Short baseline reactor ν's:

$$\theta_{13} < \pi/20$$

Small, quark-like mixing

Solar ν's:

$$\theta_{12} \approx \pi/6$$

Large, non-maximal mixing

Compare to identical parameterization of CKM matrix ...

$$\theta_{23} \approx \pi/76 \qquad \theta_{13} \approx \pi/870 \qquad \theta_{12} \approx \pi/14$$

θ_{13} and ν_e Appearance

The observed oscillations of atmospheric and long-baseline ν's seem to be $\nu_\mu \rightarrow \nu_\tau$. What about $\nu_\mu \rightarrow \nu_e$?

For oscillations involving ν_2 and ν_3 (atmospheric, long baseline), the limiting factor for $\nu_\mu \rightarrow \nu_e$ is how much ν_3 couples to electrons in CC weak interactions. To first order, in the absence of matter effects, at oscillation maximum this probability is:

$$\begin{aligned} P(\nu_\mu \rightarrow \nu_e) &= \sin^2 2\theta_{13} \sin^2 \theta_{23} \\ &\approx \frac{1}{2} \sin^2 2\theta_{13} \end{aligned}$$

This is the main goal of T2K.

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?

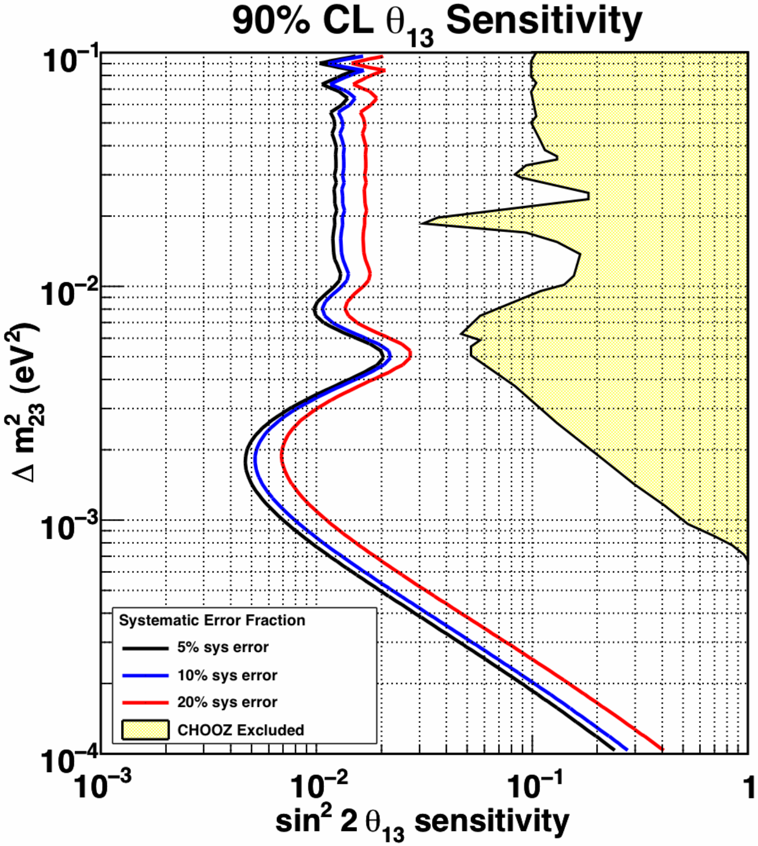
Our universe is made of matter but not anti-matter.
CP violation is a requirement for producing a cosmological asymmetry.
Regular quark CP violation not enough---is this the missing piece?

T2K ν_e Appearance

- Measure $\nu_\mu \rightarrow \nu_e$ appearance: will give θ_{13}.
- Based on observation of CCQE interactions at Super-K:

$$\nu_e + n \rightarrow e + p$$

- Flux of ν_e will be much smaller than ν_μ. Understanding and controlling all possible backgrounds is important T2K challenge.



90%CL Sensitivity
to ν_e appearance
(5 years at full 750kW power)

Factor of ~20 improvement in sensitivity over CHOOZ.

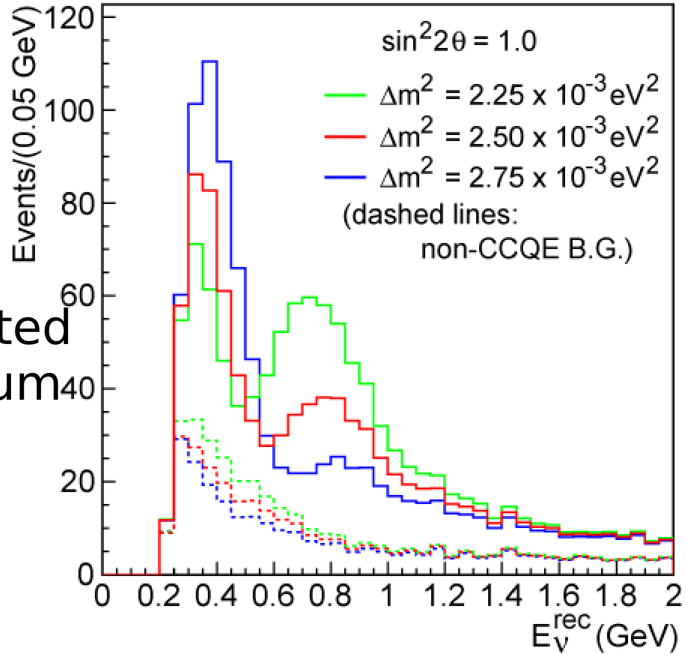
T2K ν_μ Disappearance

- Measure ν_μ disappearance: will give Δm^2_{32} and θ_{23}.
- Comparison of near/far spectra allows for extraction of ν_μ disappearance parameters.
- Use kinematically clean Charged-Current Quasi Elastic (CCQE) interaction to measure ν_μ flux and spectrum:

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

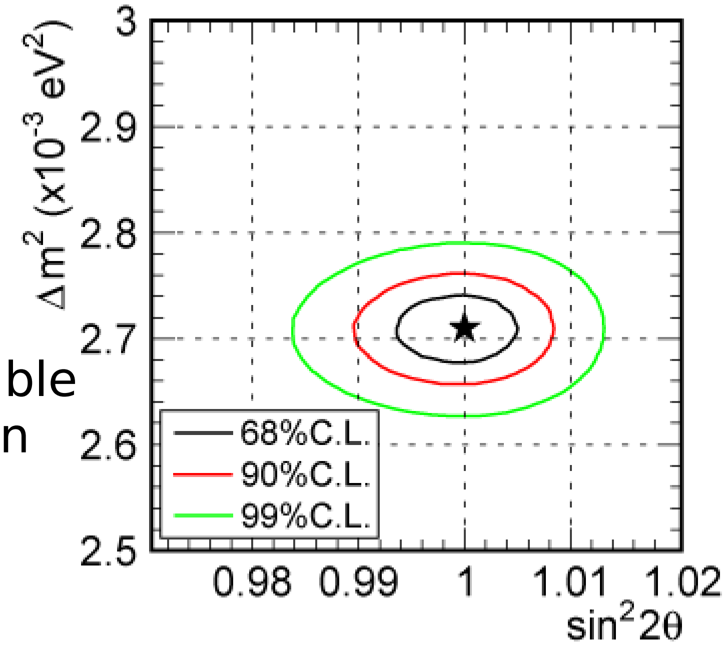
- High JPARC proton flux will allow for precise measurement.

Simulated Spectrum at SK



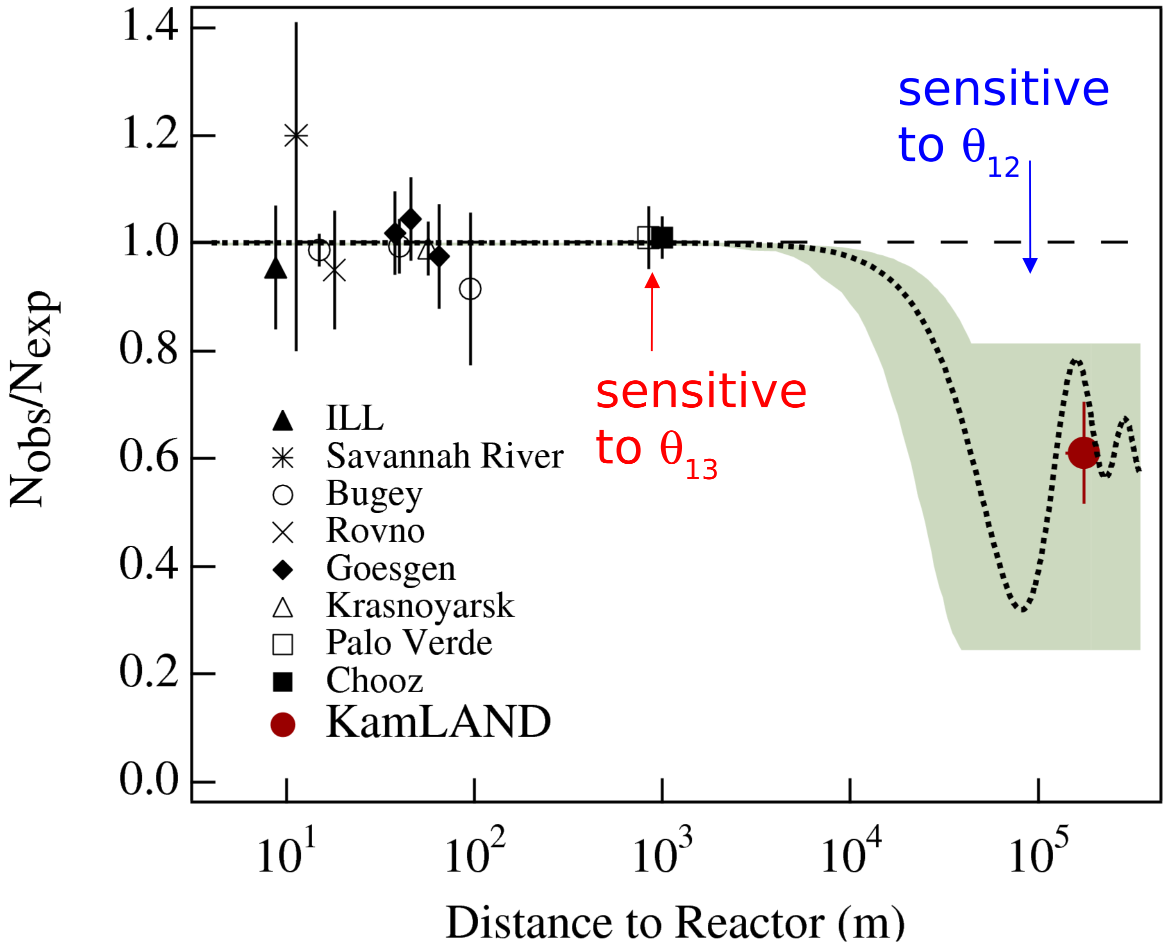
(5 years at full 750kW power)

Achievable Precision



θ_{13}: the CHOOZ limit

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



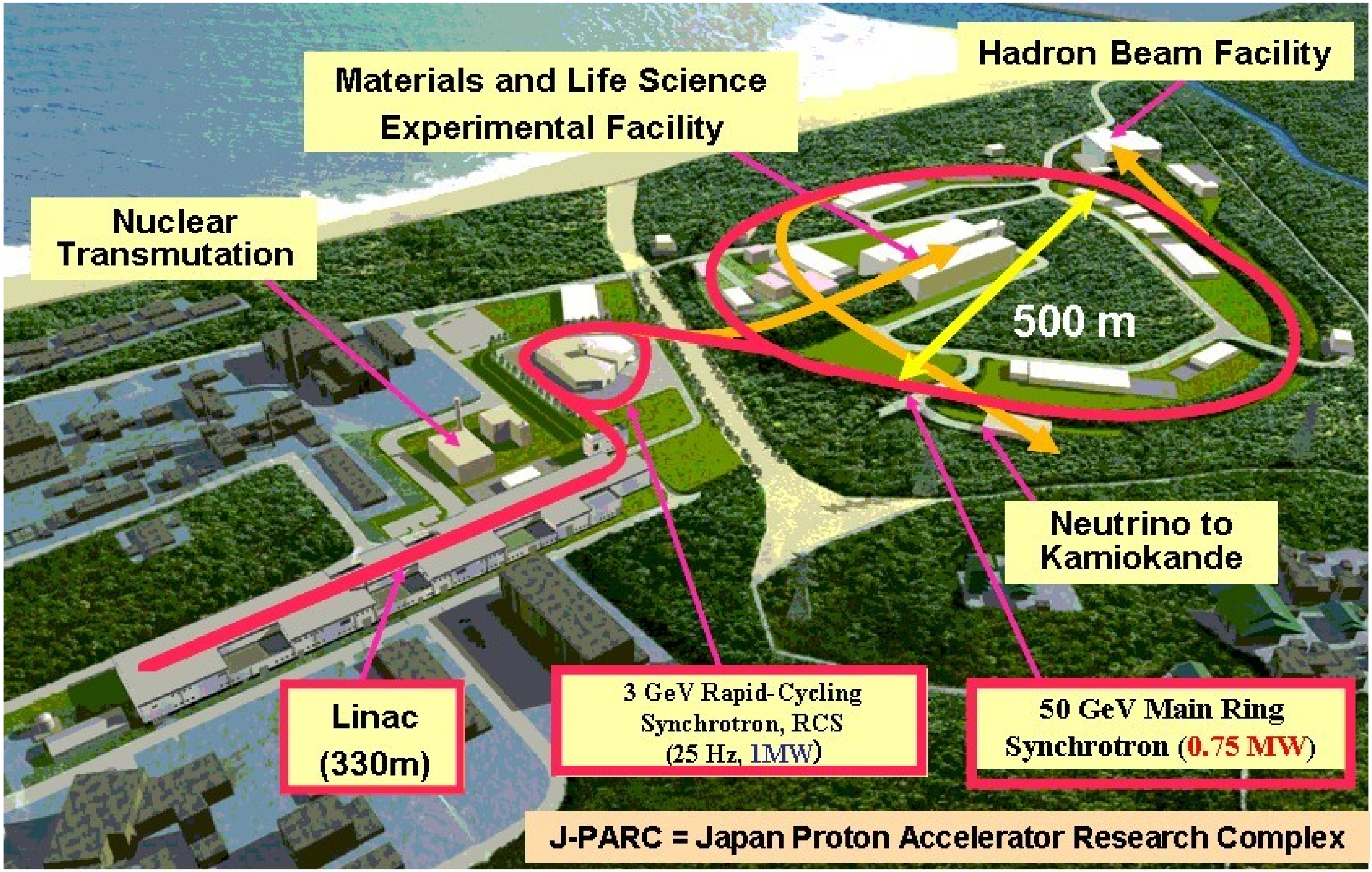
Reactor ν experiments at short baseline limits θ_{13}.

Best current limit from CHOOZ:

$\sin^2 2\theta_{13} < 0.15$ (90% C.L.)

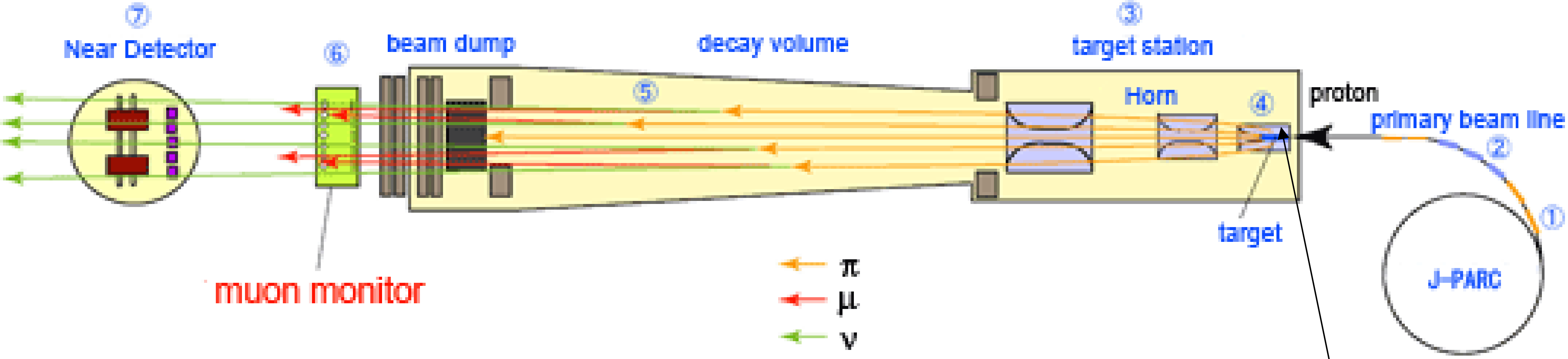
Reactor experiments sensitive to θ_{13} but not CP violation.

J-PARC



30 GeV proton beam in Tokai, Japan

How To Make A Neutrino Beam



30 GeV protons hit graphite target

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

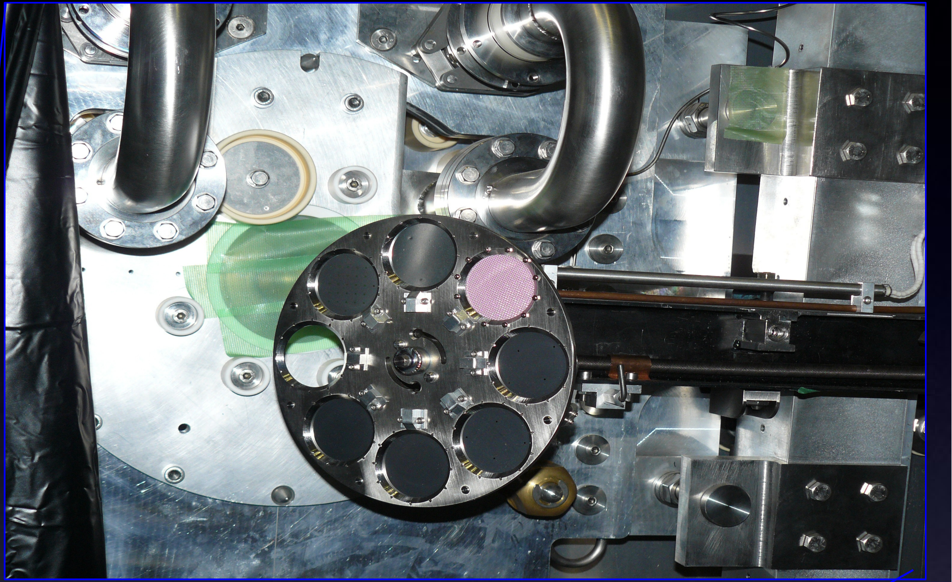
$\pi^+ \rightarrow \mu^+ + \nu_\mu$ in 110m long decay pipe

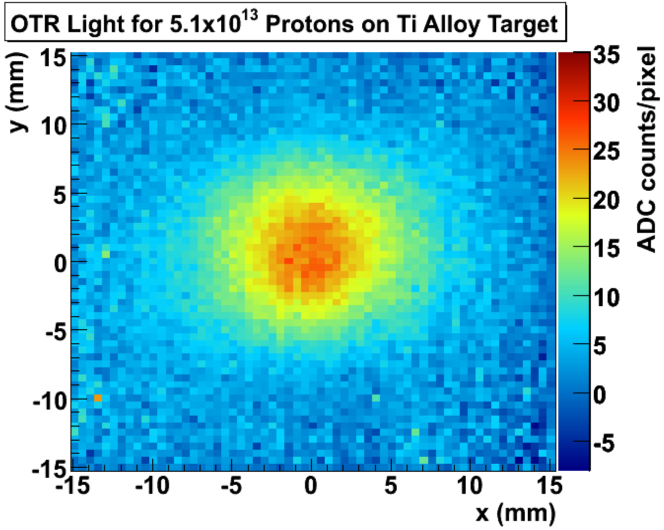
μ monitor at far end of beam dump:
fluence: $10^8\ \mu/\mathrm{cm}^2$/spill at full power

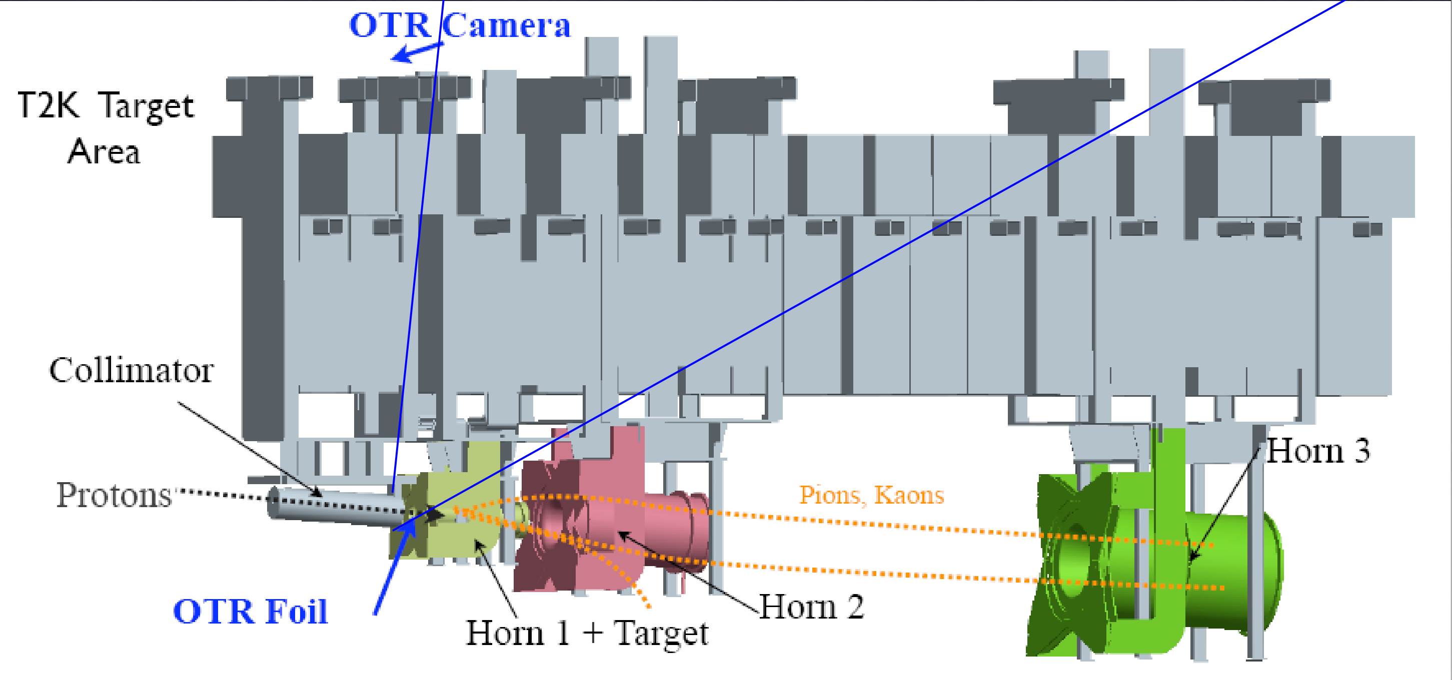
T2K's 90cm graphite target

Optical Transition Radiation Monitor (OTR): Toronto/York

- OTR detector is directly upstream of T2K target.
- Measures the proton beam width and position just before impact.
    - Cannot place conventional beam monitors in this position; wouldn't survive radiation.





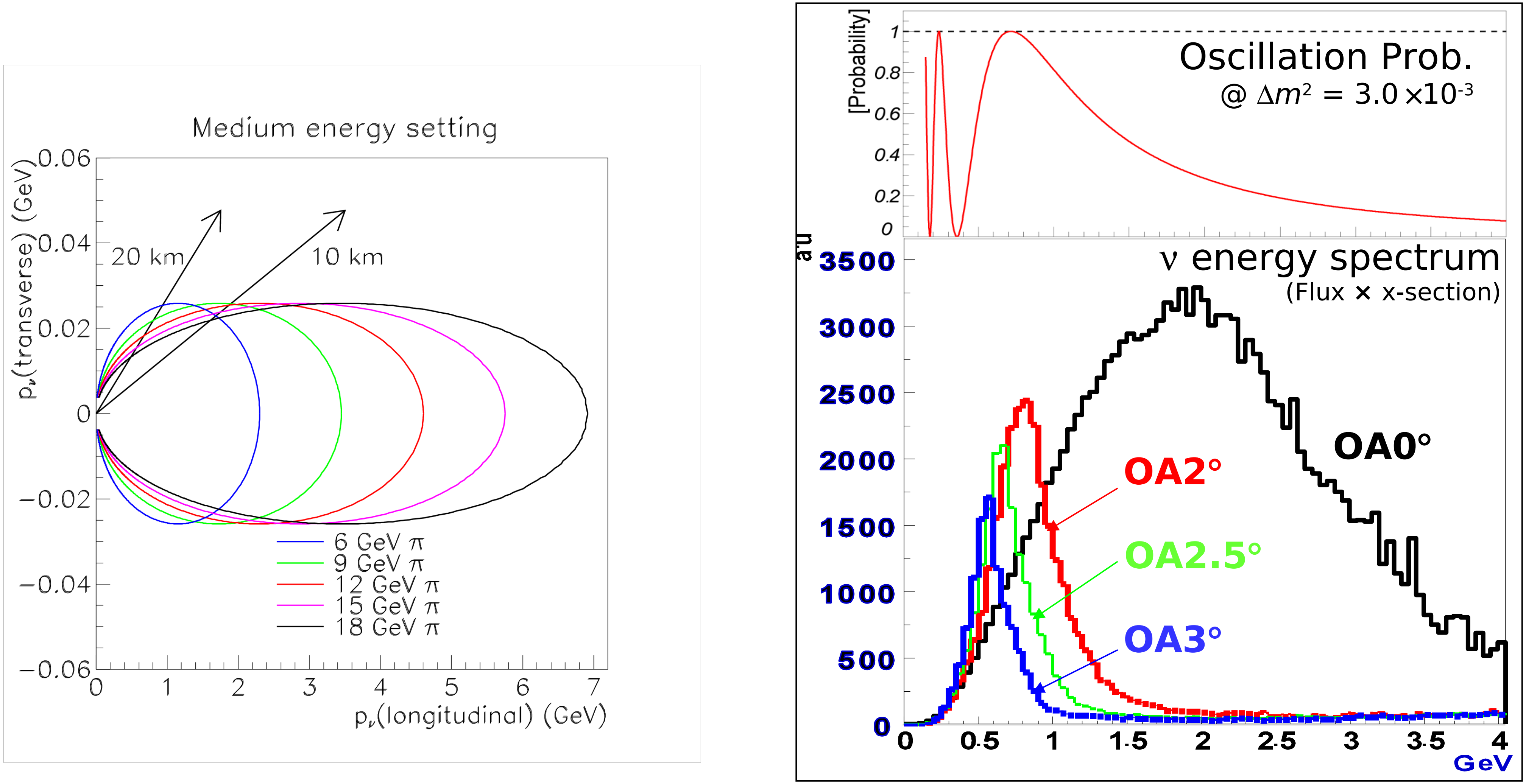


↑

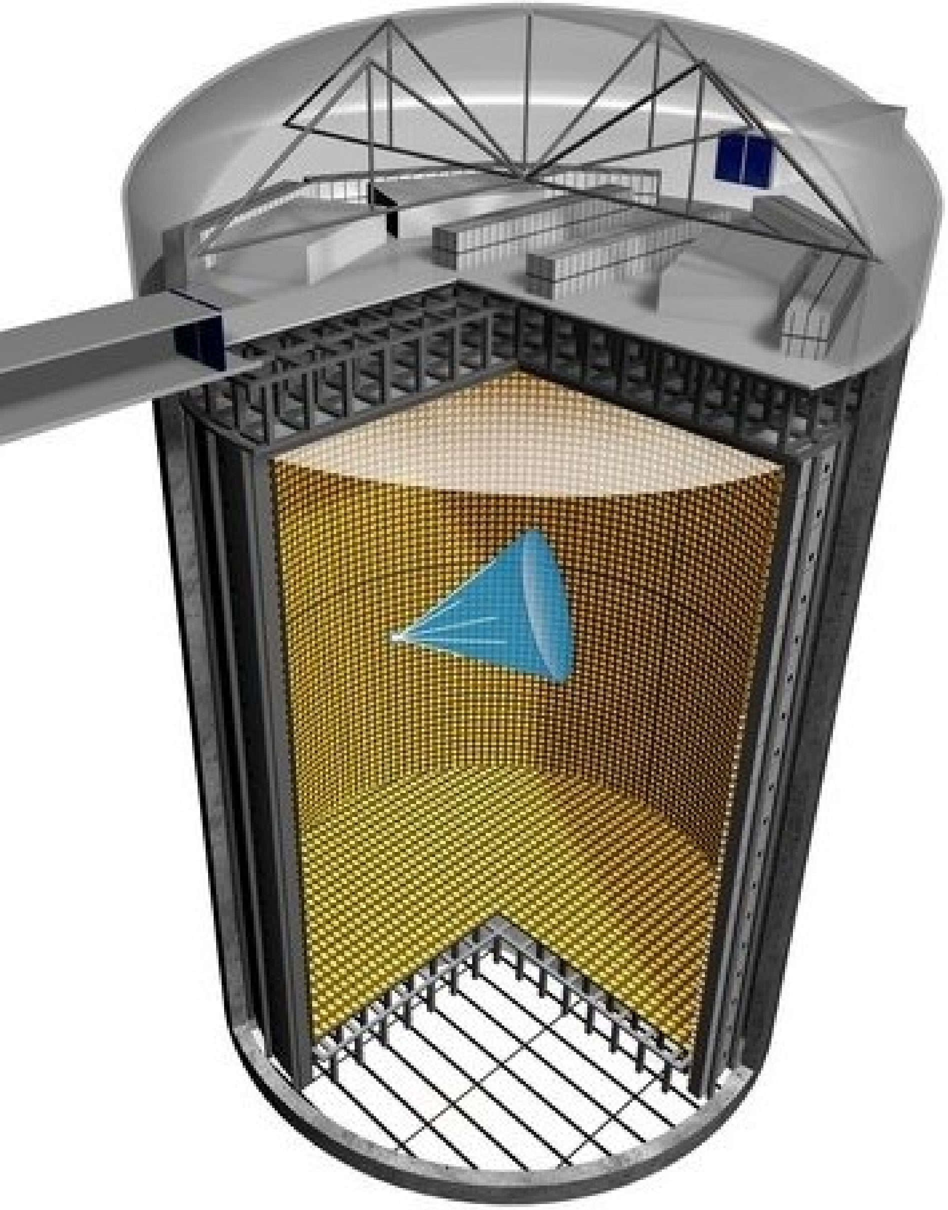
Inside the decay volume

← The 2nd focusing horn

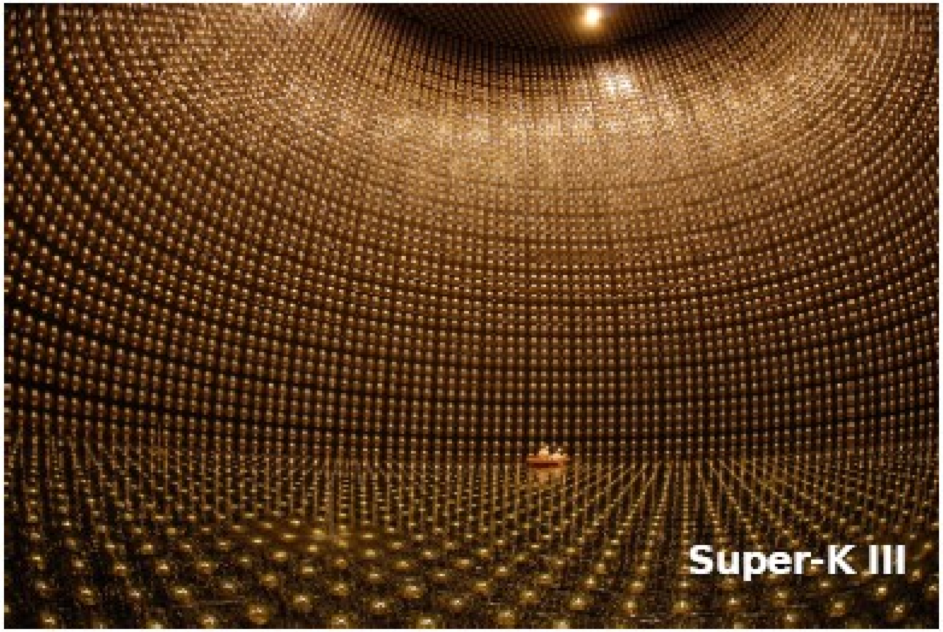
Off-Axis Beam Principle



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



Super-Kamiokande



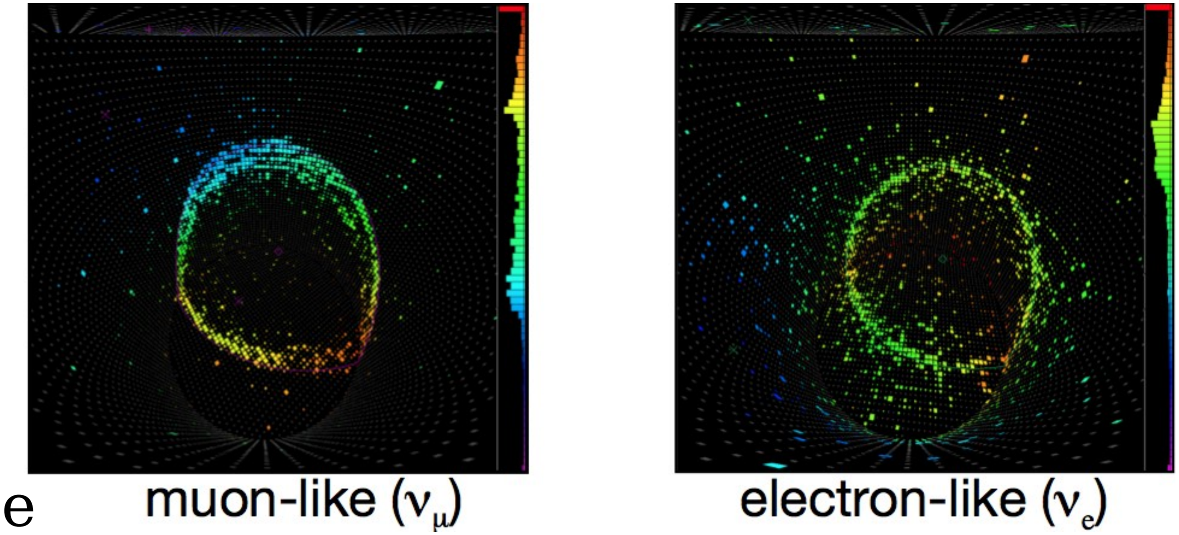
Large water Cherenkov detector

22.5ktonne water fiducial mass

~11,000 phototubes

Super-Kamiokande Event Selection

Super-K will measure CCQE ν_μ or ν_e events for key T2K measurements.


muon-like (ν_μ) electron-like (ν_e)

- Some challenges:
  - Understanding the irreducible background from beam
  - Understanding background ν_μ interactions that might mimic signal ν_μ or ν_e interactions, such as
    $\nu_\mu + n \to \mu + p + \pi^+$: CC1pi (ν_μ background)
    $\nu_\mu + n \to \nu_\mu + n + \pi^0$: NC1pi0 (ν_e background)

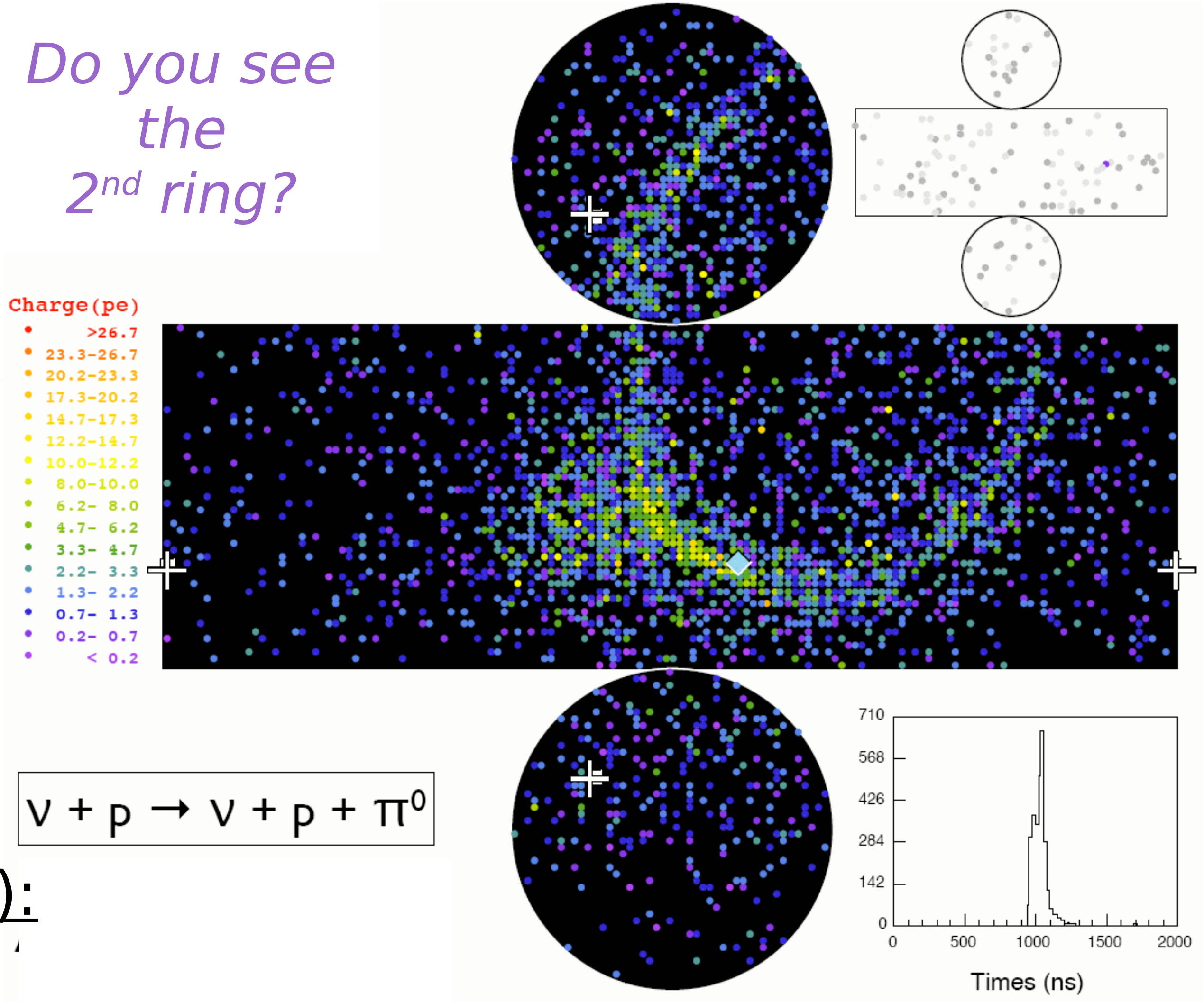
Backgrounds to ν_e Appearance

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



Do you see the 2^{nd} ring?

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

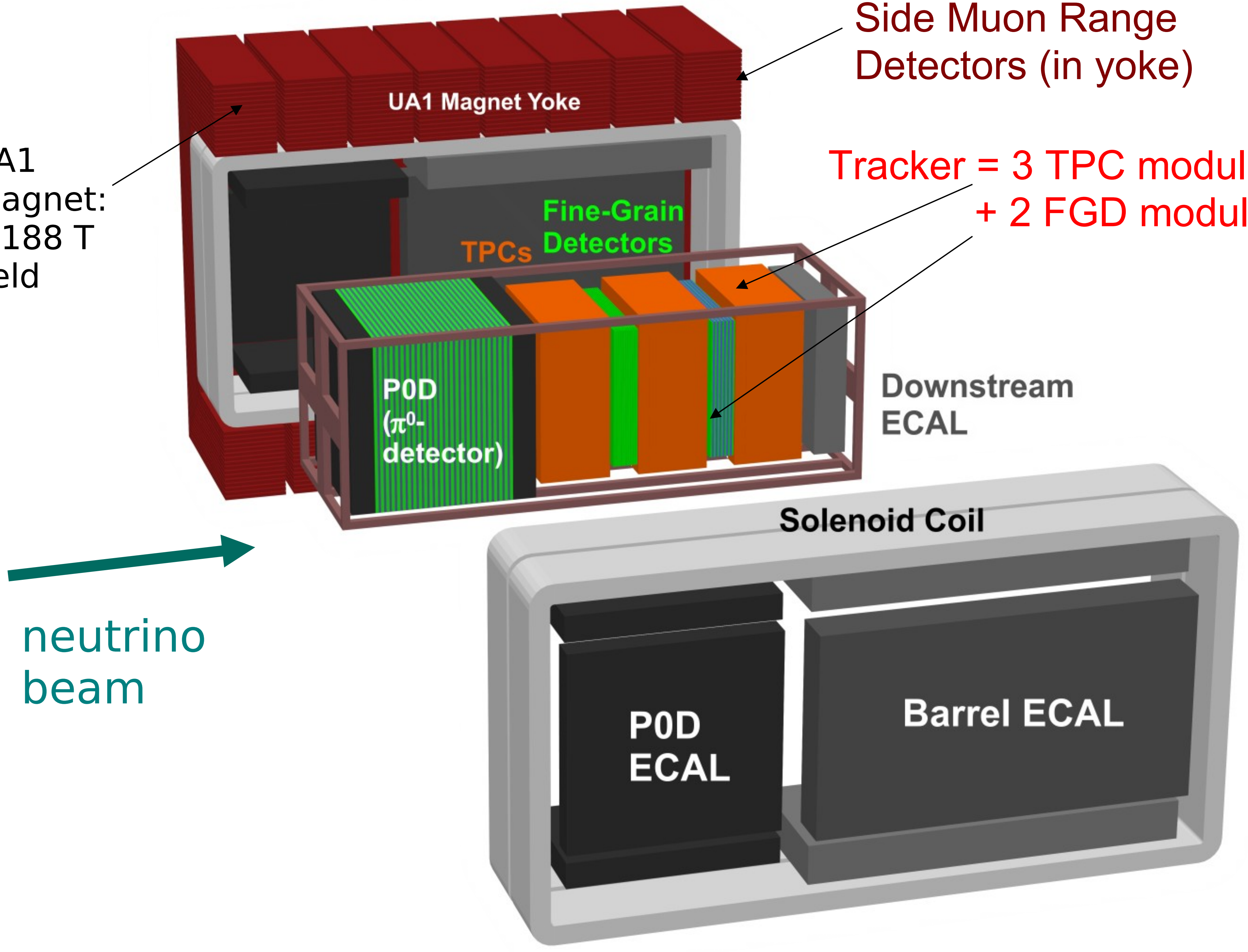
<u>Estimated bkgd (5 years):</u>

intrinsic ν_e: 17 events

π^0 production: 10 events

signal: 20 events for $\sin^2 2\theta_{13} = 0.01$

Off Axis Near Detector



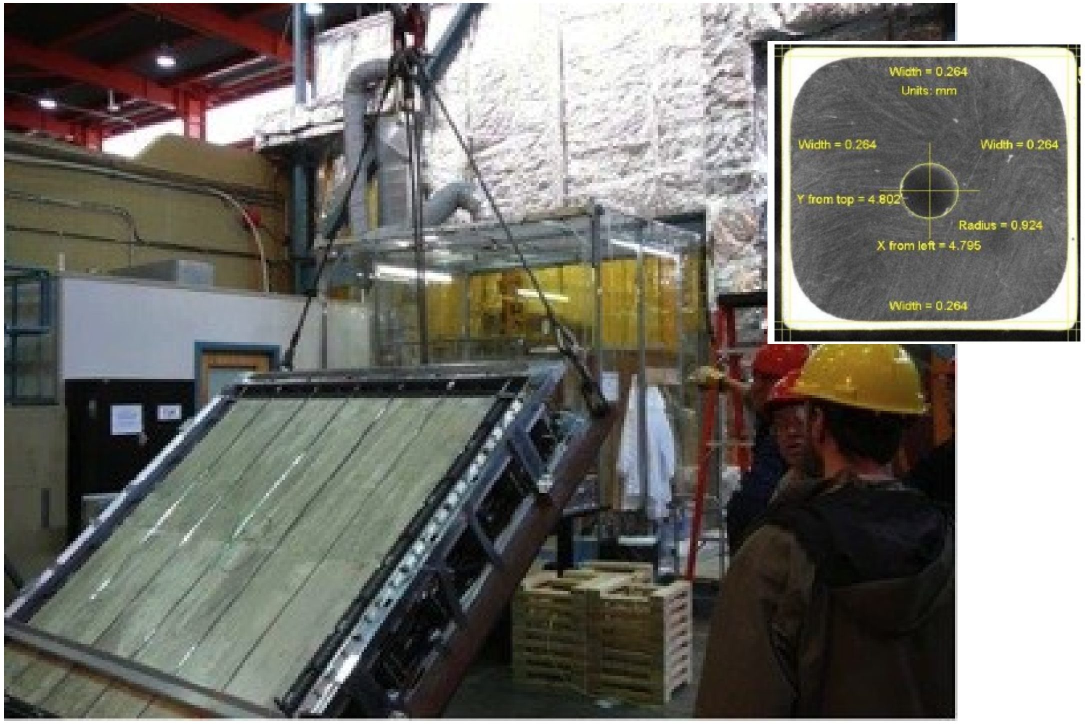
Side Muon Range Detectors (in yoke)

UA1 magnet: 0.188 T field

Tracker = 3 TPC modules + 2 FGD modules

neutrino beam

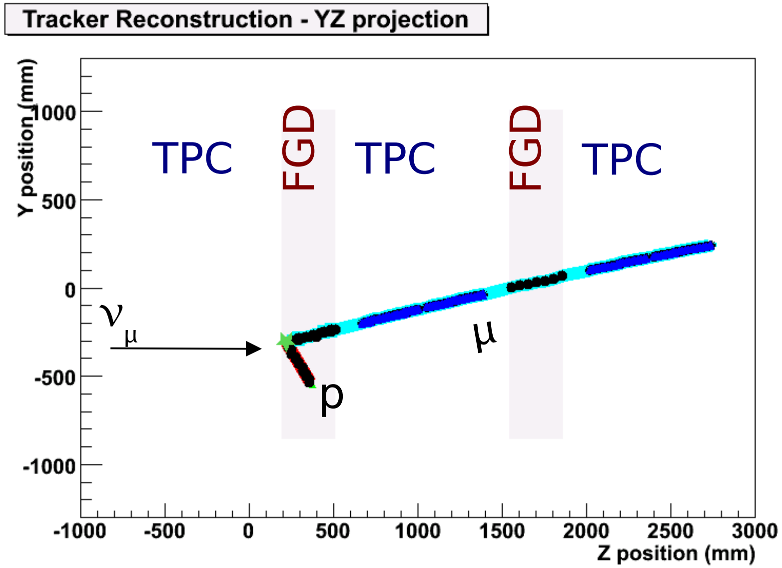
Near Detectors



↑ Fine-grained scintillator detector (long thin bars---active target mass)

← Large Time Projection Chamber (3D gas tracker)

Sample ND280 Measurements

- Charged-Current Quasi-Elastic:
  $\nu_\mu + n \rightarrow \mu + p$
- Super-K oscillation analysis uses this interaction mode; accurate/precise measurement before oscillation is essential.
- 

- Neutral-Current π^0:
  $\nu_\mu + N \rightarrow \nu_\mu + N + \pi^0$
- Interaction mode is an important background to Super-K ν_e appearance.
- P0D has large target mass and lead radiators; P0D + ECAL optimized for measurement of gammas from π^0.

Both P0D and FGD have water targets; allows for cleaner extrapolation to water-based Super-K.

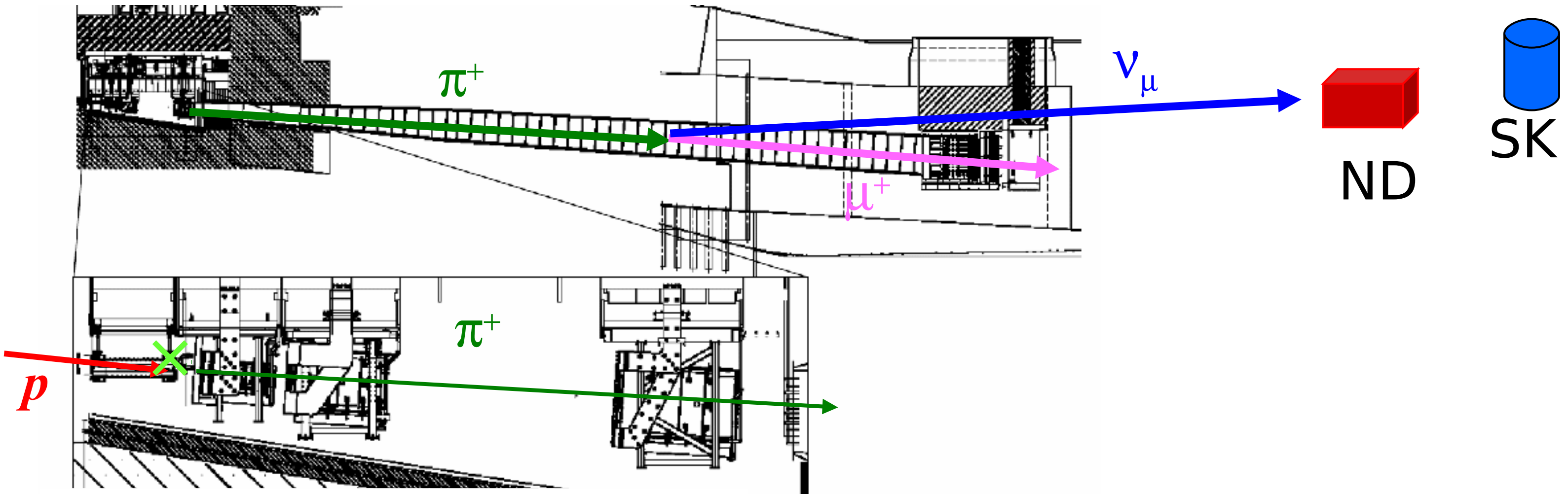
Oscillation Analysis

1. Predict number of neutrinos produced in beam
2. Verify & normalize prediction using near detector
3. Extrapolate to Super-K
4. Compare number of events seen at Super-K to number predicted

First results on ν_e appearance released in June:
- 1.43 x 10^{20} protons on target
- included all T2K data to date
- PRL 107, 041801, 2011

August: new results on ν_μ disappearance
- paper in preparation

T2K: Flux prediction (Beam MC)

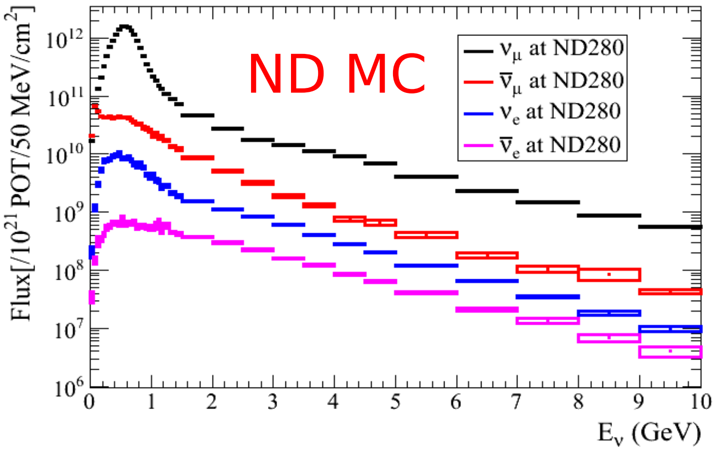


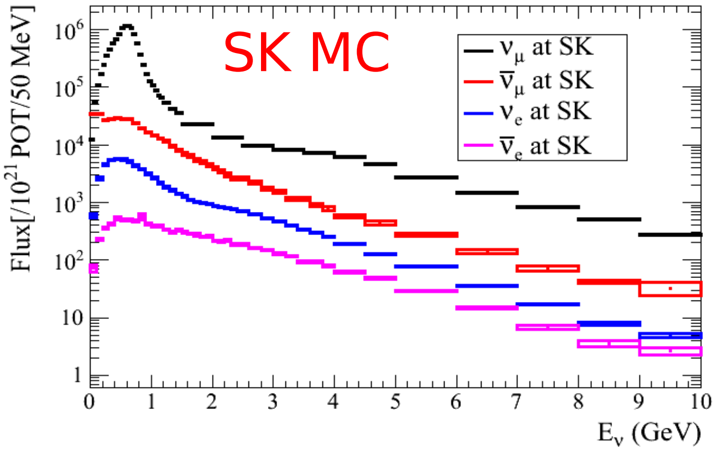
Simulate hadron production on target using FLUKA simulation

Model pion and kaon propagation and decay through horns and beamline

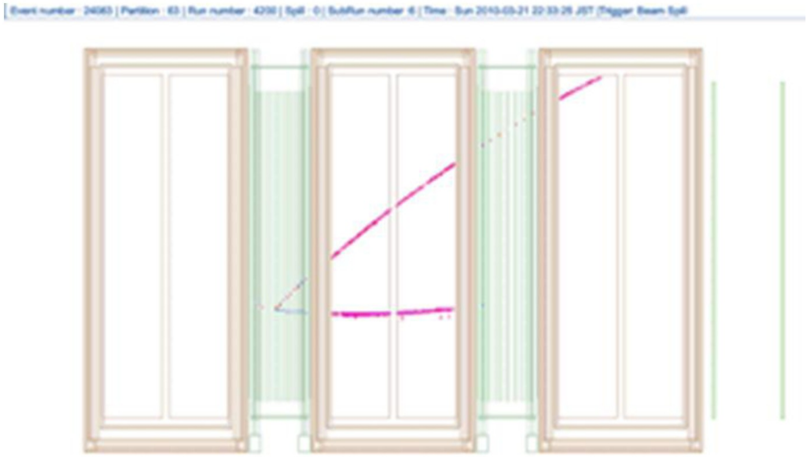
Get flux predictions at near detector and SK

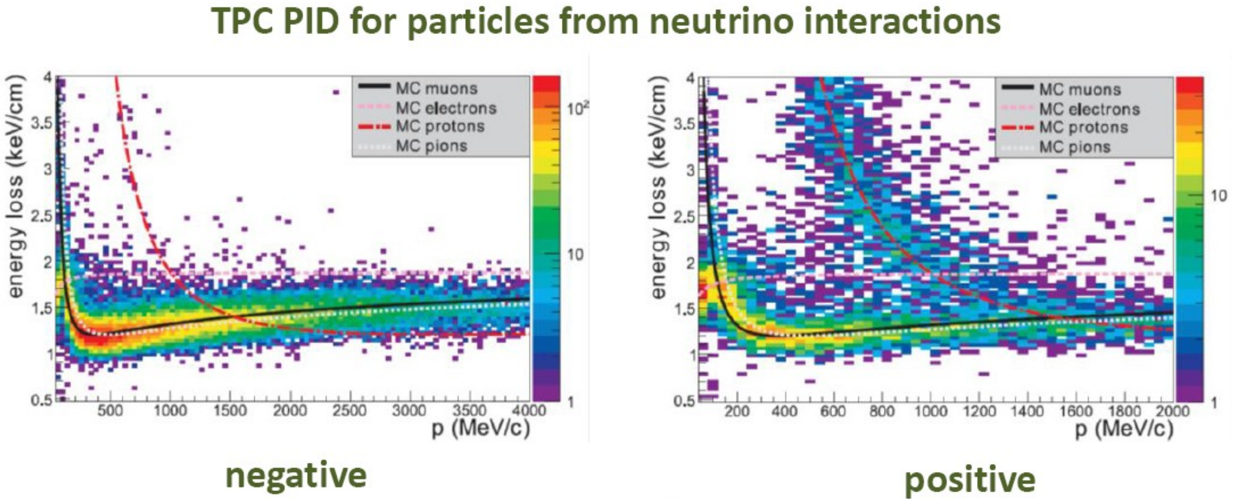
Particle production cross sections tuned to external data from NA61 and others.





$R_{DATA/MC}$:ND280: OFF axis detector





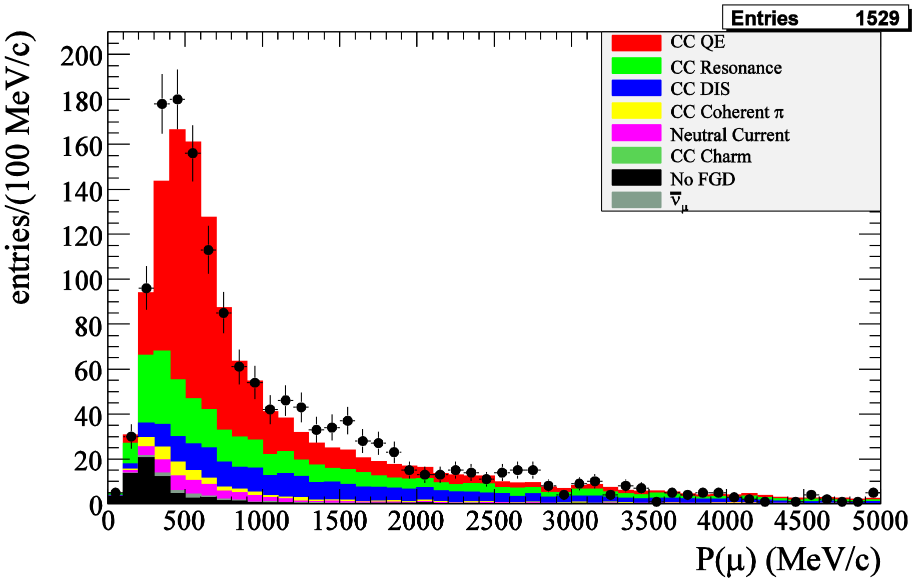
Inclusive CC ν_μ analysis:

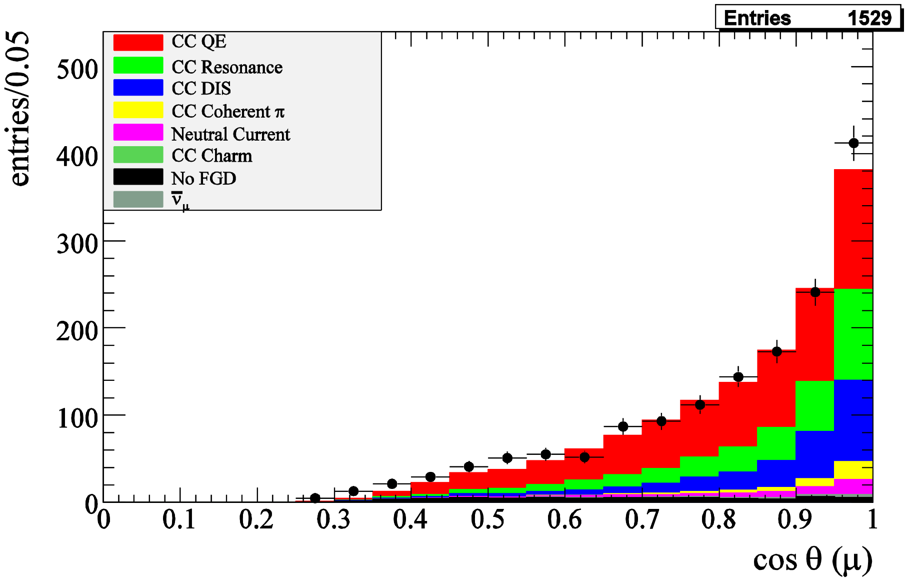
Select long negatively curving tracks in the ND280 tracker. These are candidate muons

Require that they have deposited ionization energy per path length consistent with being muons.

Estimate few percent background from other processes

ND280: Normalization DATA/MC





# of CC inclusive μ events:

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

$$N_{\mathrm{SK}}{}^{\mathrm{expected}} = (N_{\mathrm{ND}}{}^{\mathrm{DATA}} / N_{\mathrm{ND}}{}^{\mathrm{MC}}) \times (N_{\mathrm{SK}}{}^{\mathrm{MC}} + N_{\mathrm{bkg}}{}^{\mathrm{MC}})$$

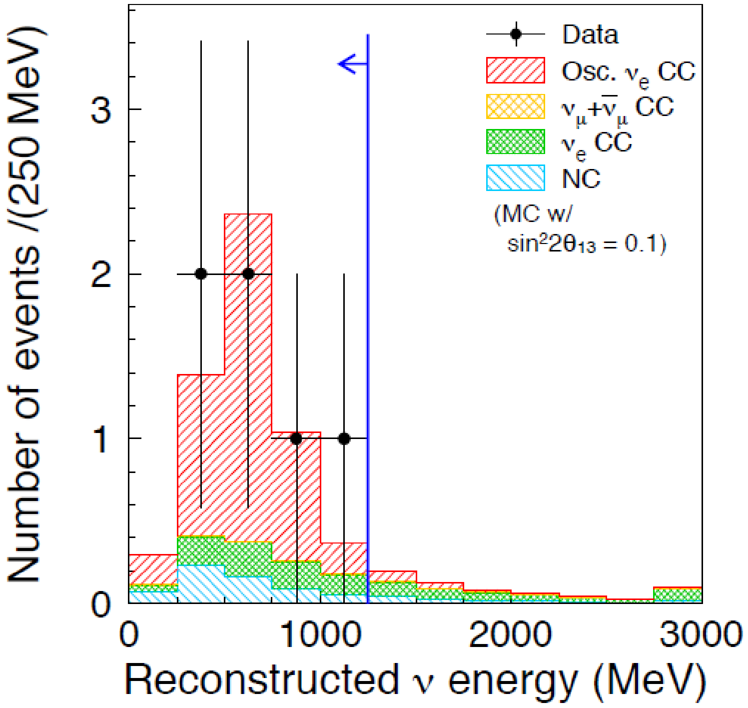
Total uncertainty for $N_{\mathrm{SK}}/N_{\mathrm{ND}}$: $\pm 2.7\% \oplus {}^{+5.6}_{-5.2}\ \%$ for background

Event Selection

Look for events with:

- A single electron-like ring
- No following decay electron
- Energy in expected range:

  $100 < E\nu < 1250$ MeV
- No evidence for 2nd ring with that could reconstruct to give π^0 mass



Signal Efficiency = 66%
Background Rejection:
  77% for beam νe
  99% for NC

6 candidate events seen

Selection criteria & cut values are fixed before analysis. Unbiased

Backgrounds

Three significant sources of background:

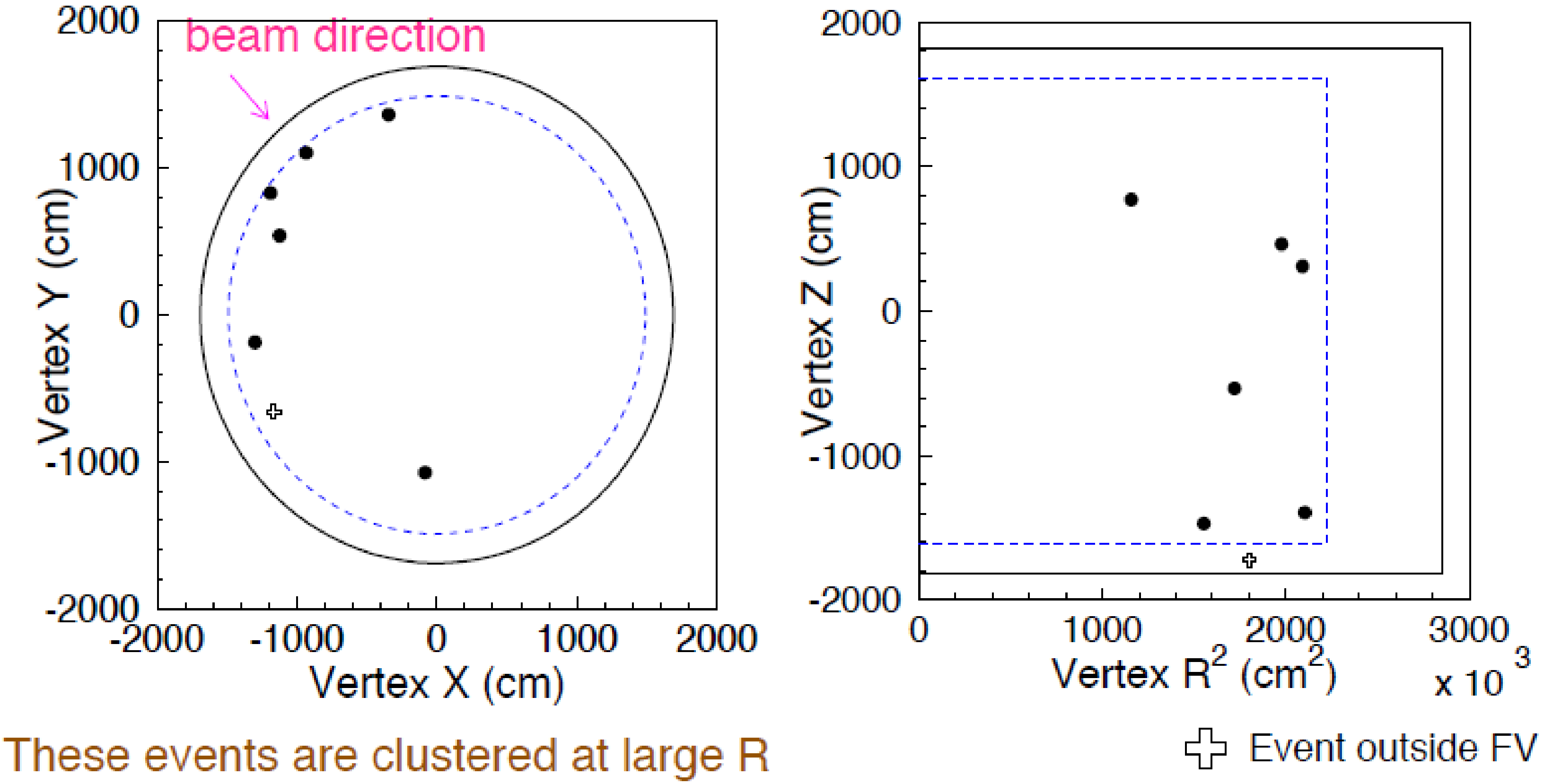
1. ν_e in beam	0.8
2. mis-reconstructed π^0	0.6
3. ν_μ-ν_e from subdominant θ_{12} effect	0.1
TOTAL:	**1.5±0.3**

If only known backgrounds produce ν_e in Super-K, the probability of seeing 6 or more candidate events is 0.7%.

Significance of excess: 2.5σ

Vertex distribution

Vertex distribution of ν_e candidate events

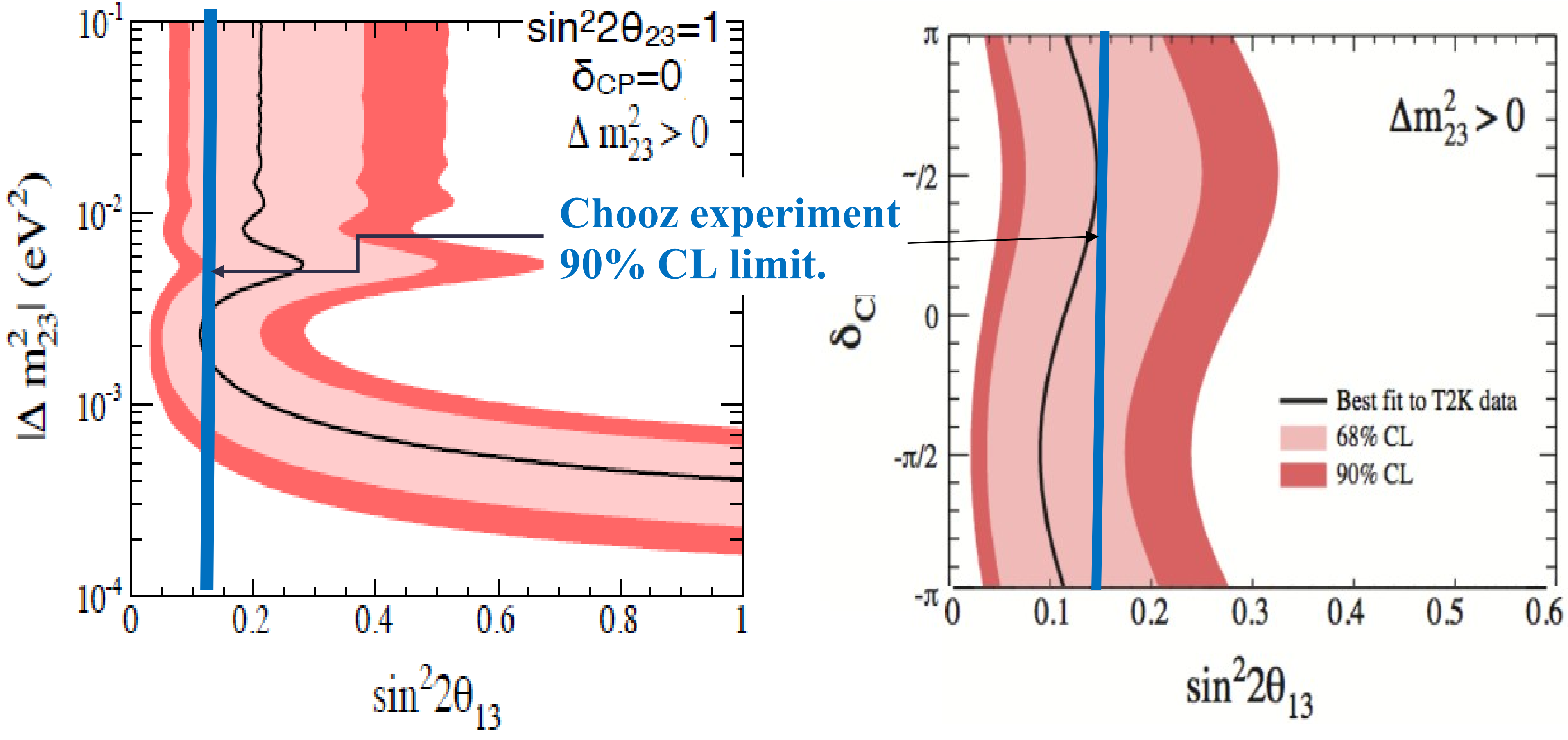


These events are clustered at large R

→ Perform several checks. for example

- * Check distribution of events outside FV → no indication of BG contamination
- * Check distribution of OD events → no indication of BG contamination
- * K.S. test on the R^2 distribution yields a p-value of 0.03

θ_{13} measurements



Chooz experiment 90% CL limit.

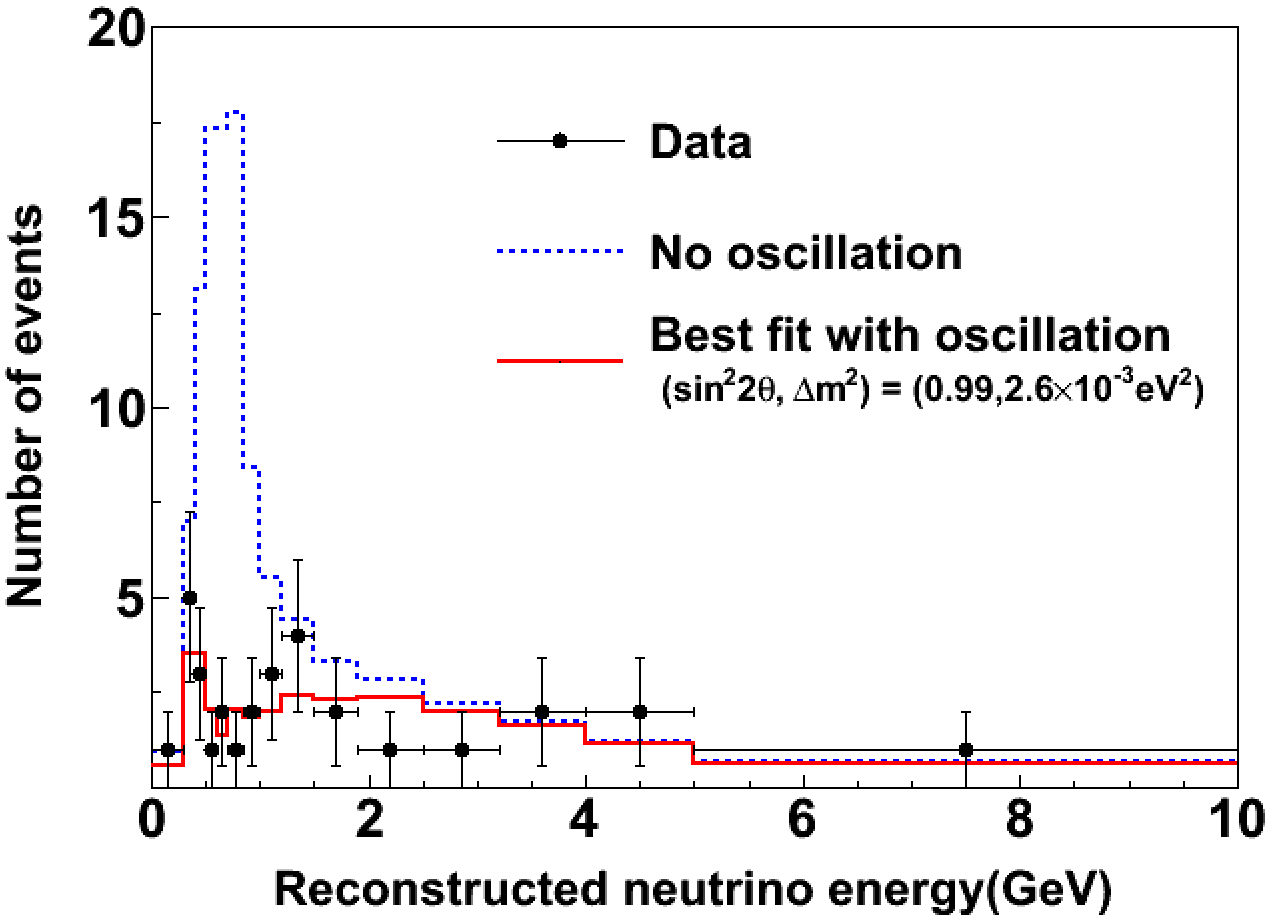
$(\Delta m_{23}{}^2>0)$		$(\Delta m_{23}{}^2<0)$
$0.03 < \sin^2 2\theta_{13} < 0.28$	**90%CL range**	$0.04 < \sin^2 2\theta_{13} < 0.34$
$\sin^2 2\theta_{13} = 0.11$	**Central value**	$\sin^2 2\theta_{13} = 0.14$

assuming $\Delta m^2_{23}=2.4 \times 10^{-3}$ eV^2, $\sin^2 2\theta_{23}=1$, $\delta_{CP}=0$

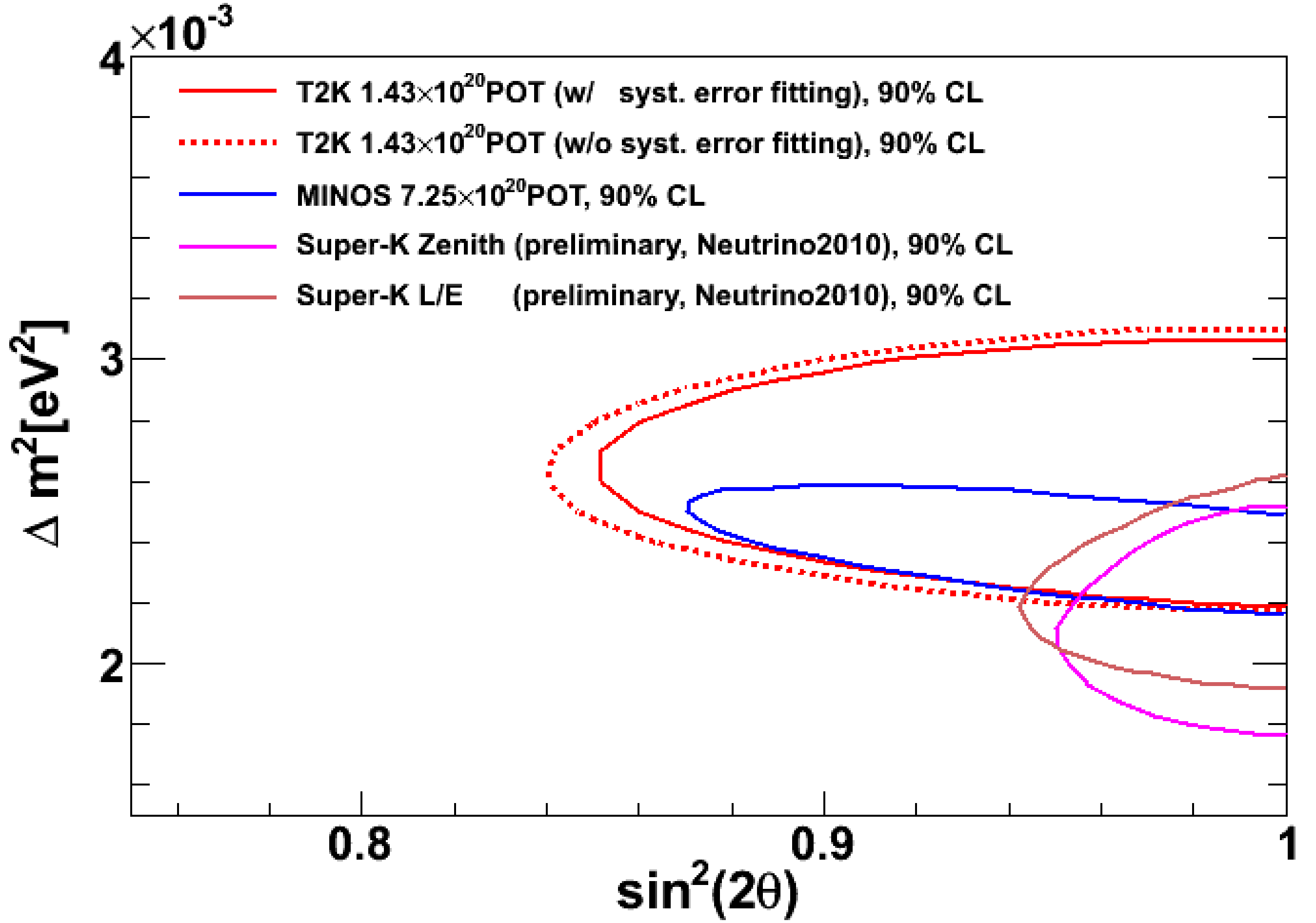
Muon neutrino disappearance

If neutrinos didn't oscillate, expect to see 103.7 ± 13.5 events at Super-K

Actual number seen: 31



Muon Neutrino Disappearance



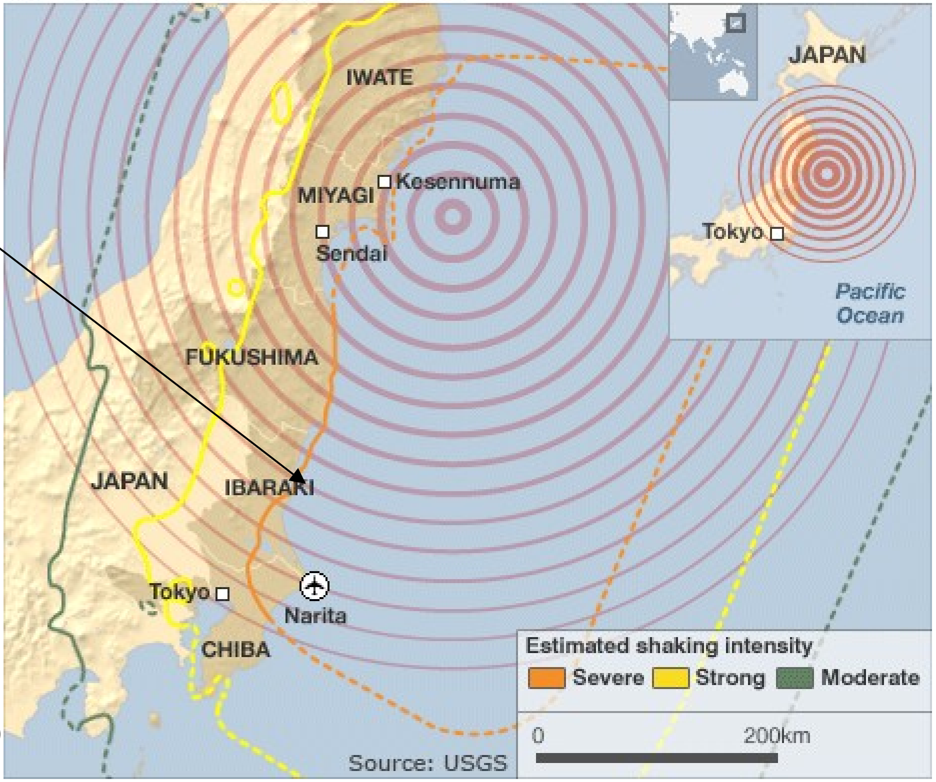
Oscillation contours already competitive
with only 2% of T2K's final data set!

March 11 Earthquake

Massive earthquake affected J-PARC directly.

- Tsunami did not reach lab!
- Most buildings sustained little damage
- Beam shut down automatically and normally
- T2K near detectors continued to read out data on battery backup

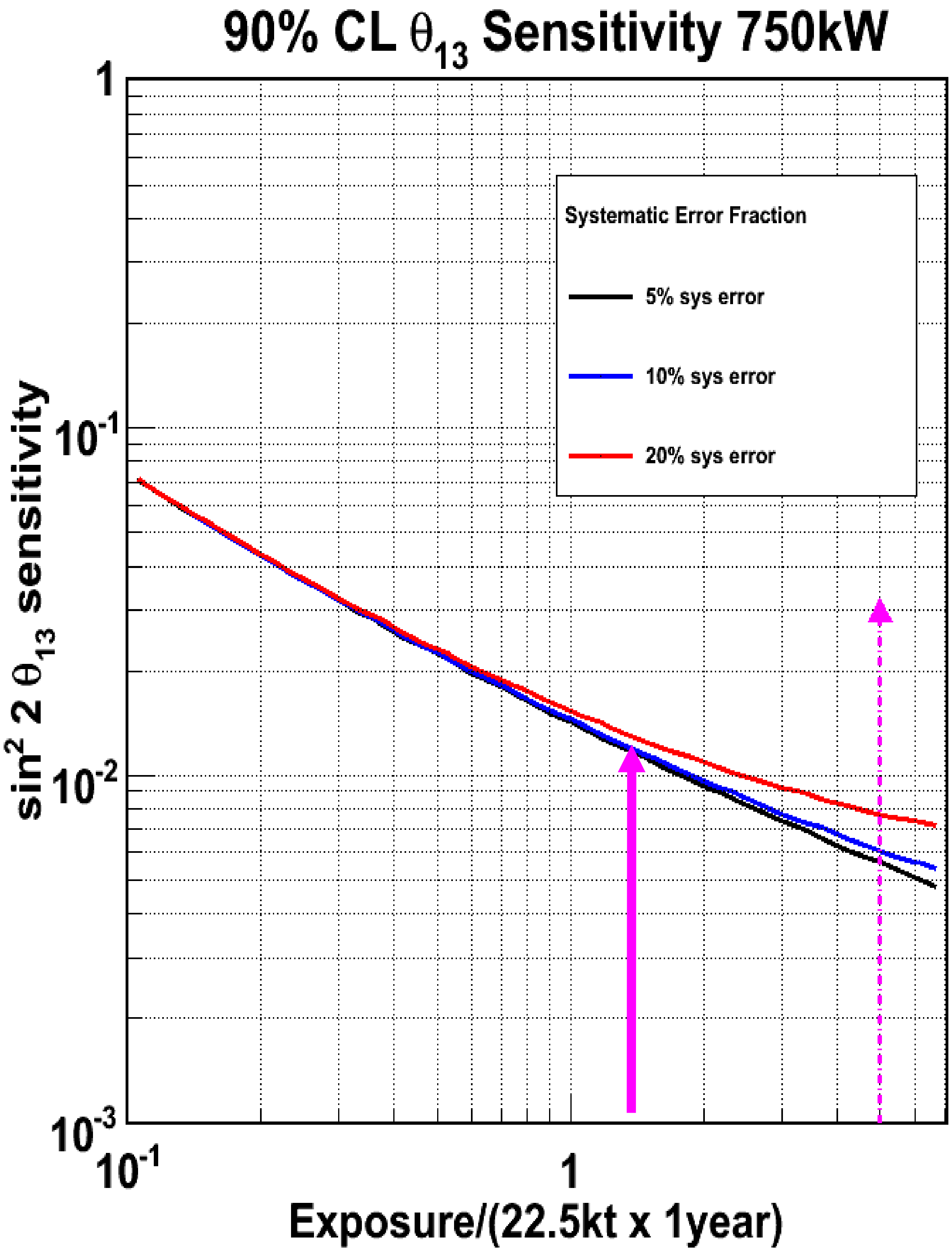
Areas affected by the quake



Source: USGS

Overall, minimal damage. Most work needed on realigning beam and reconnecting services severed by shifting ground.

Plan to restart accelerator in December.



Ultimate Sensitivity

Ultimately we aim for 750kW x 5×10^7 s, which should push down to $\sin^2 2\theta_{13} = .006$ (90% CL)

This would be 5 years of running at full power.

Intermediate target (2013?) is $\sin^2 2\theta_{13} = 0.013$

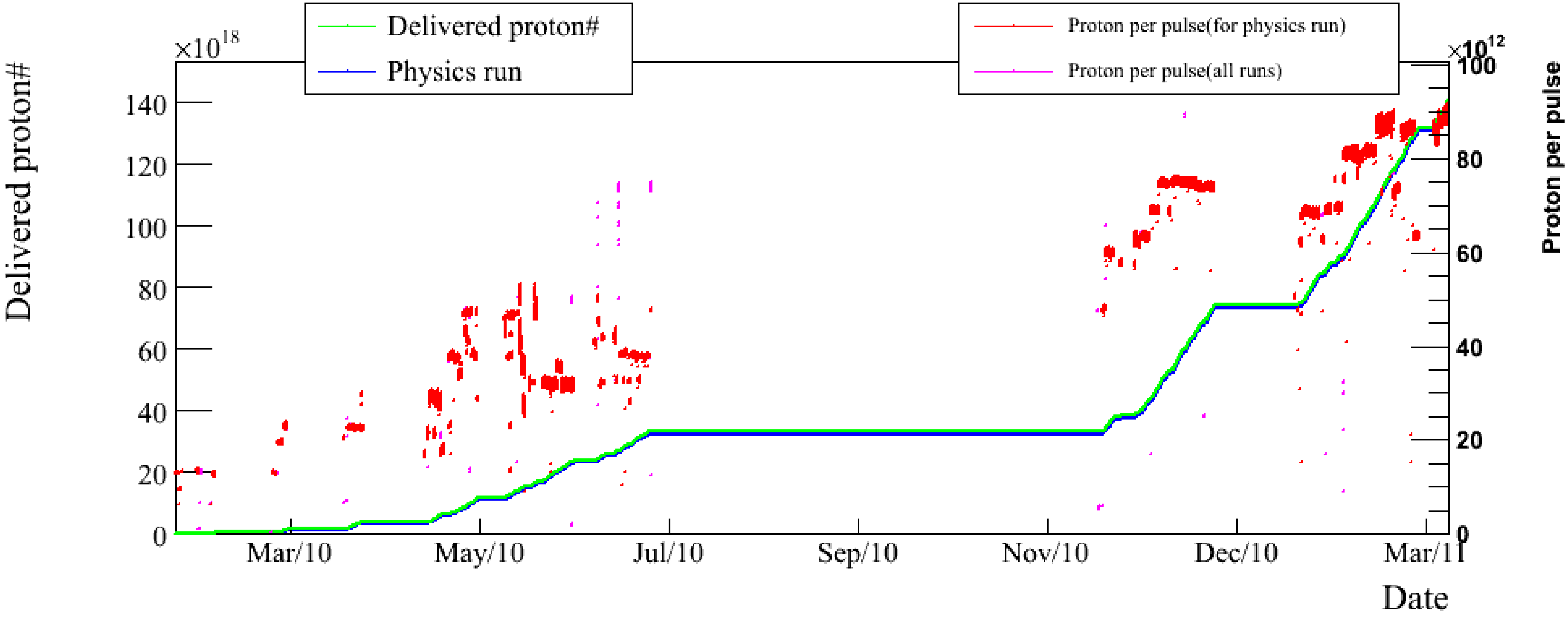
Beam power is very difficult to forecast at this stage ...

Conclusions and Outlook

- T2K has the seen first indication of $\nu_\mu \rightarrow \nu_e$ oscillations in long baseline beam
  - 2.5σ: Not yet statistically compelling, but exciting!
  - More data coming soon
- Muon neutrino disappearance compatible with previous measurements, already becoming competitive even with low statistics.
- The search for θ_{13} is on!

Backup slides

Oscillation Analysis



First results on ν_e appearance released in June:

- 1.43 x 10^{20} protons on target
- included all T2K data to date
- PRL 107, 041801, 2011

August: new results on ν_μ disappearance

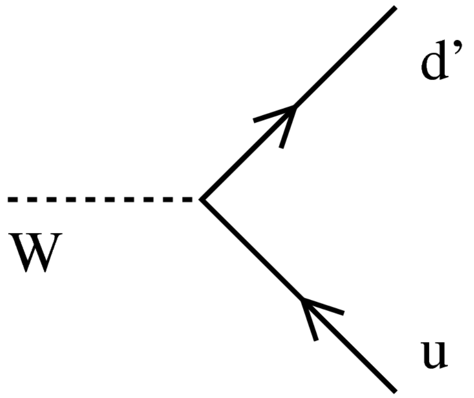
- paper in preparation

Outline of analysis ν_e appearance search

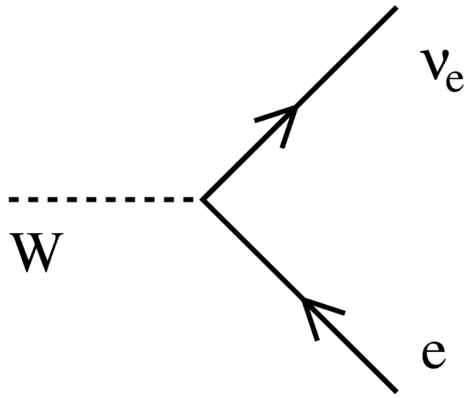
1. Calculate expected # of event as a function of oscillation parameters: θ_{13}, Δm^2_{13}
   - » $N_{\mathrm{SK}}^{\mathrm{MC}} = \int dE\, \Phi_{\mathrm{SK}}(\mathrm{E}) \times \sigma_{\mathrm{SK}}(\mathrm{E}) \times \varepsilon_{\mathrm{SK}}(\mathrm{E}) \times \mathrm{P}(\nu_\mu \rightarrow \nu_\varepsilon; \mathrm{E}; \theta_{13}, \Delta m^2_{13})$
     - $N_{\mathrm{bkg}}^{\mathrm{MC}}$ also should be estimated.
   - ND280 → $R_{DATA/MC} \equiv N_{\mathrm{ND}}^{\mathrm{DATA}}/N_{\mathrm{ND}}^{\mathrm{MC}}$

   → $N_{\mathrm{SK}}^{\mathrm{expected}} = R_{DATA/MC} \times (N_{\mathrm{SK}}^{\mathrm{MC}} + N_{\mathrm{bkg}}^{\mathrm{MC}})$
2. Select events ν_e candidate from data.
   - Select the “good beam spill”
   - T2K event selection
     - Select Fully Contained events in Fiducial Volume
     - Ring counting → Select CC-QE candidate
     - – PID : separate ν_e from ν_μ events
     - Background rejection cut → $N_{\mathrm{SK}}^{\mathrm{obs}}$
3. Estimate the oscillation parameter from $N_{\mathrm{SK}}^{\mathrm{expected}}$ and $N_{\mathrm{SK}}^{\mathrm{obs}}$.

Analogy of Neutrino and Quark Mixings



FOR EXPERTS



W couplings mix quark generations through a rotation between weak and strong flavour eigenstates.

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

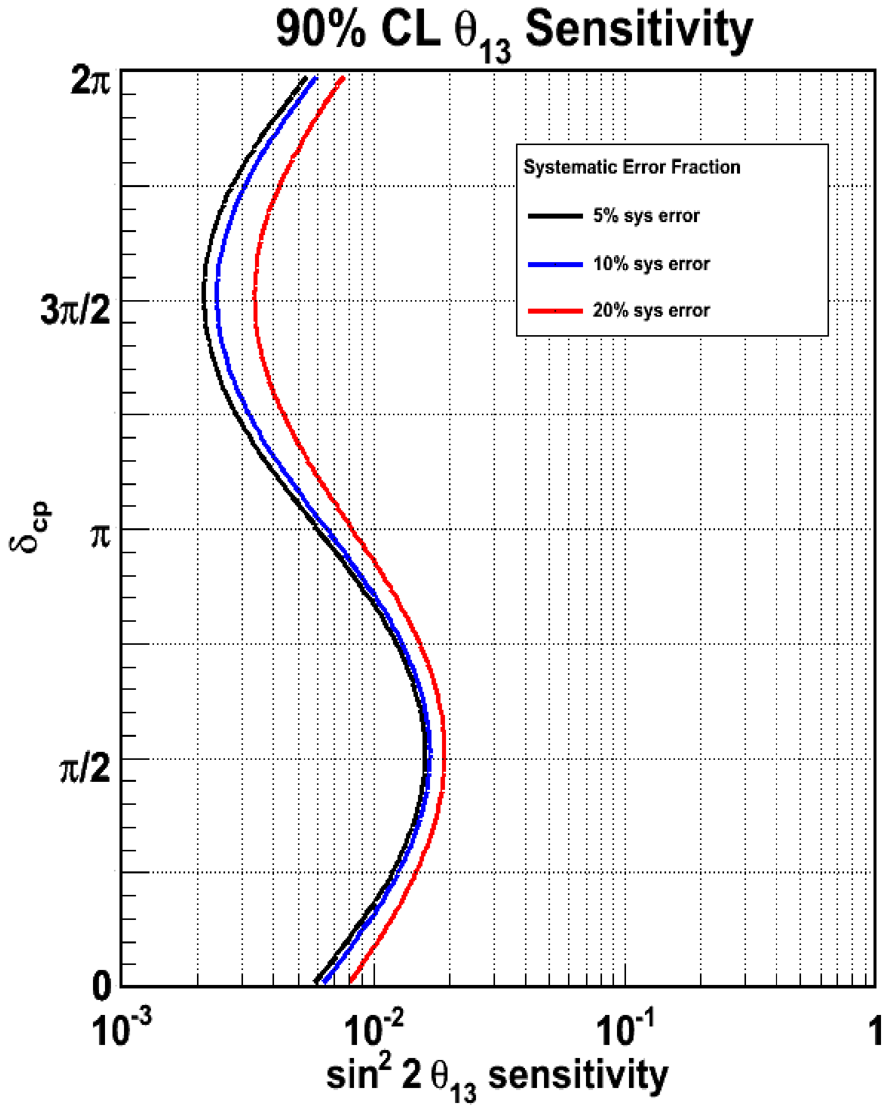
For neutrinos the rotation is between the weak flavour eigenstates and the mass eigenstates.

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Dependence on δ_{CP}

The electron appearance probability depends on the matter effect & CP-violating phase in addition to θ_{13}.

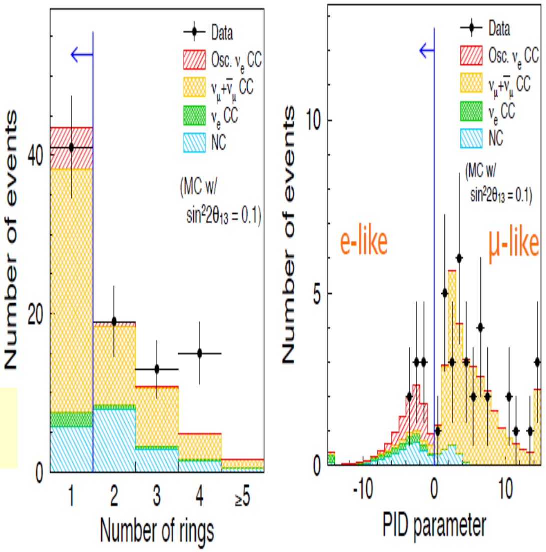
The community will need data from DoubleCHOOZ, Daya Bay, NOνA, or LBNE (FNAL→DUSEL) to disentangle.



Event selection

Single ring

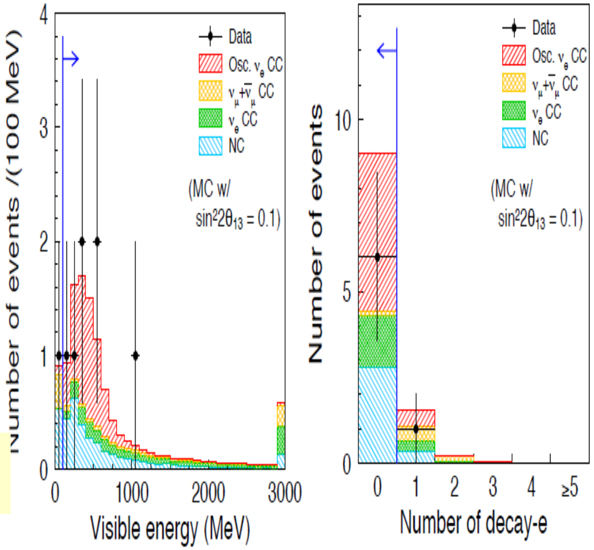
✦Enhance CCQE



41 events remained

Visible energy > 100 MeV

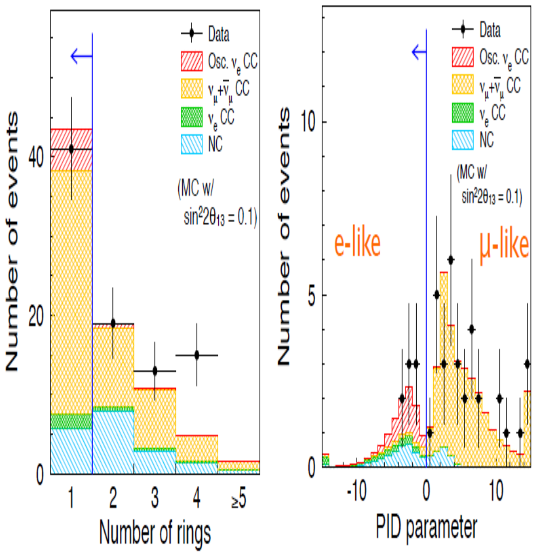
✦Suppress NC background and electrons from μ decay



7 events remained

PID is e-like

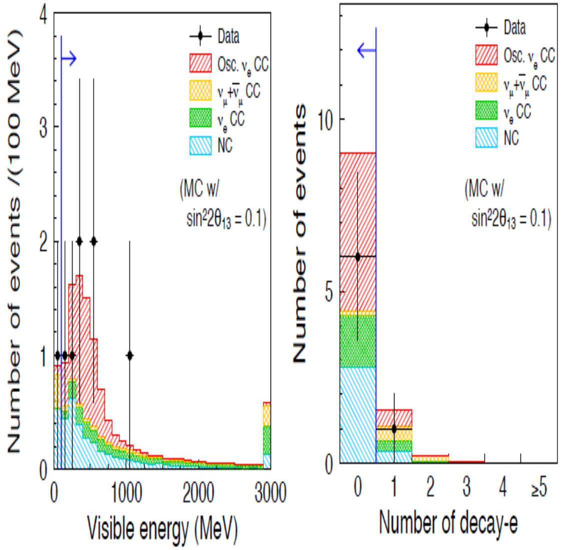
✦Enhance ν_e CC



8 events remained

No decay-e (delayed e)

✦Suppress invisible π or μ

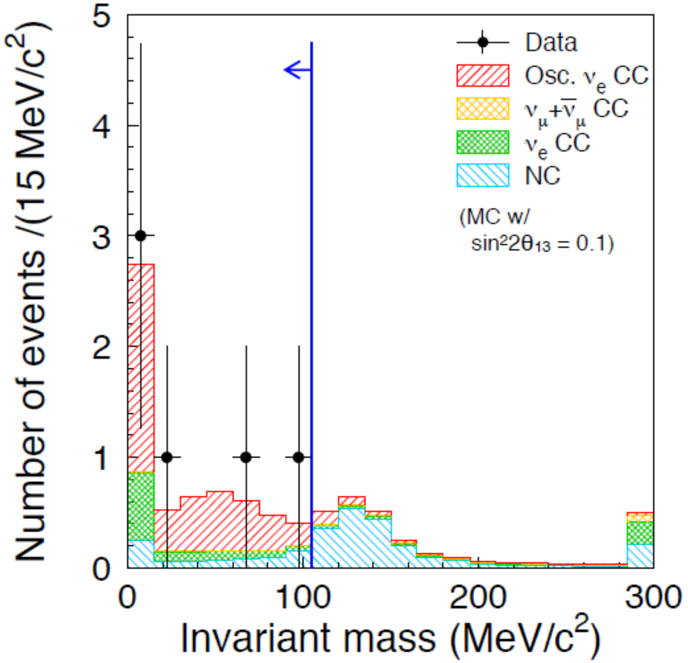


6 events remained

Event Selection

Invariant mass of already found 1 e-like ring + additional forced-reconstructed e-like ring Minv < 105MeV/c2

- Reject remaining π0 background



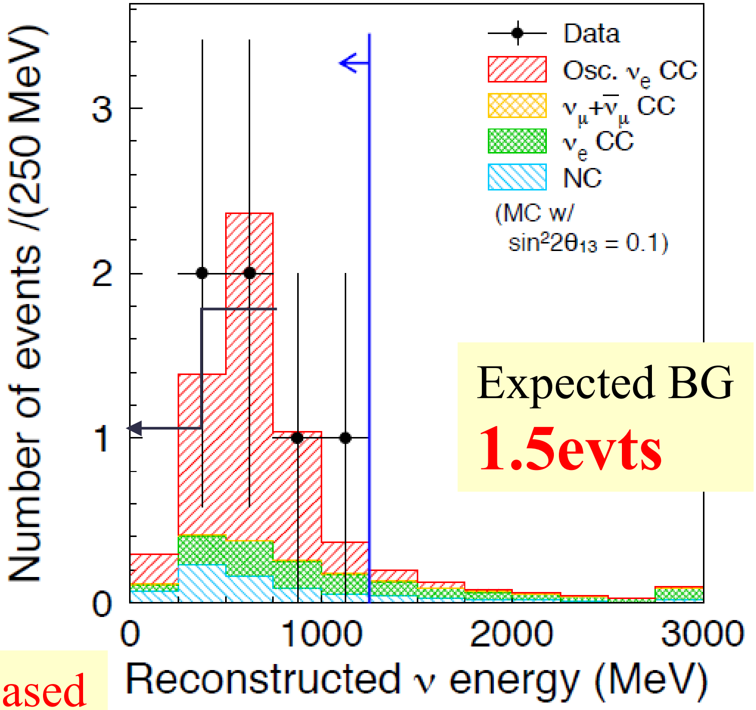
6 events remained

Reconstructed neutrino energy < 1250 MeV

- Reject higher energy intrinsic beam background from kaon decays

6 final candidate events remained!

Signal Efficiency = 66%
Background Rejection:
77% for beam νe
99% for NC

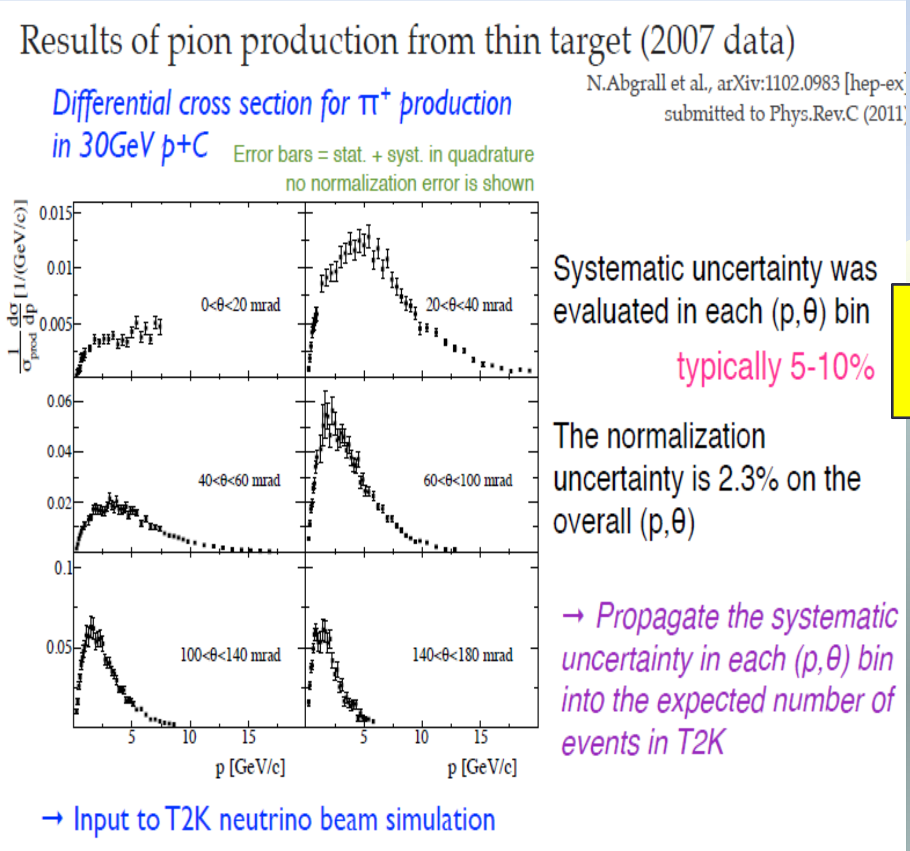


Expected BG
1.5evts

Selection criteria & cut values are fixed before analysis. Unbiased

Beam prediction w/ CERN/NA61 results

NA61 Results of pion production from 2007 thin (~2cm) target data



Results of pion production from thin target (2007 data)

N.Abgrall et al., arXiv:1102.0983 [hep-ex] submitted to Phys.Rev.C (2011)

Differential cross section for π^+ production in 30GeV p+C

Error bars = stat. + syst. in quadrature no normalization error is shown

Systematic uncertainty was evaluated in each (p,θ) bin

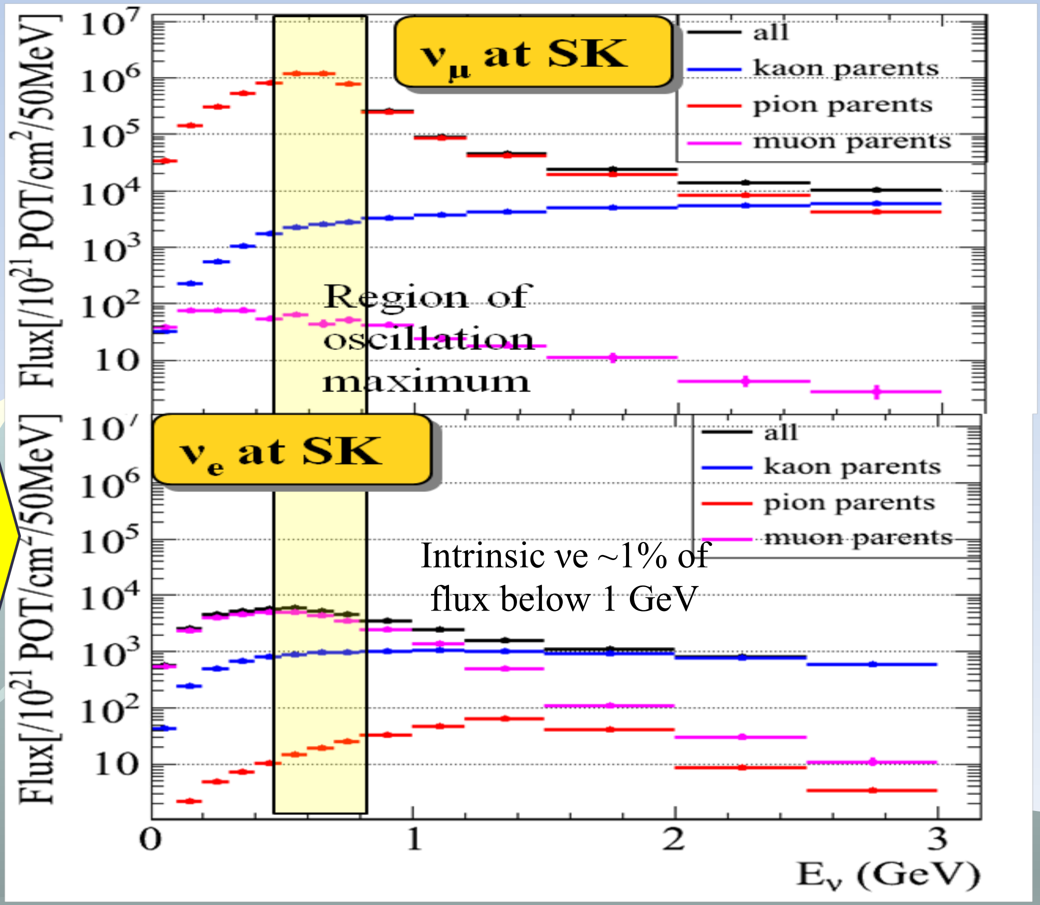
typically 5-10%

The normalization uncertainty is 2.3% on the overall (p,θ)

→ *Propagate the systematic uncertainty in each (p,θ) bin into the expected number of events in T2K*

→ Input to T2K neutrino beam simulation

N.Abgrall et al., arXiv:1102.0983[hep-ex]
Accepted for publication in Phys. Rev.C(2011)



Region of oscillation maximum

Intrinsic νe ~1% of flux below 1 GeV

Error from beam uncertainty

$$\delta N^{MC}_{ND} = 15.4\%$$

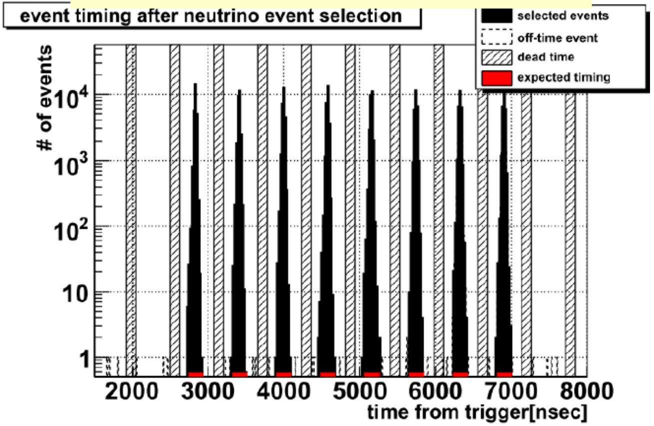
$$\delta N^{MC}_{SK} = 16.1\%$$

$$\delta\left(N^{MC}_{ND} \middle/ N^{MC}_{SK}\right) = 8.5\%$$

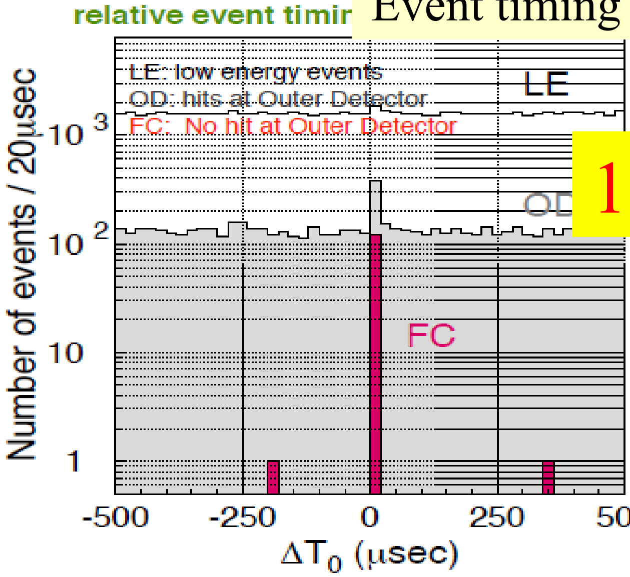
- Cancellation in ratio prediction thanks to near&far correlation

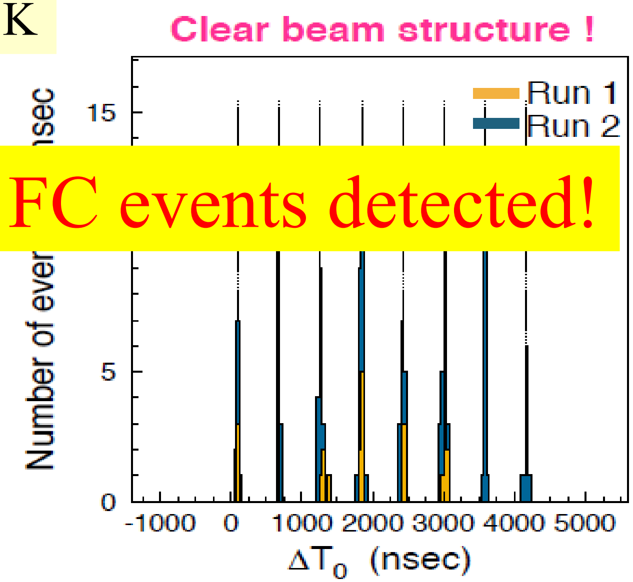
Event selection (1) timing

Near detector (INGRID)
Event timing distribution



Event timing @ SK



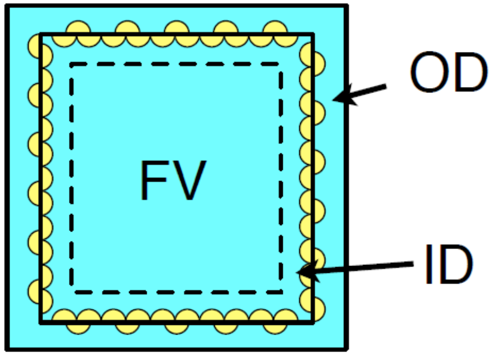


121 FC events detected!

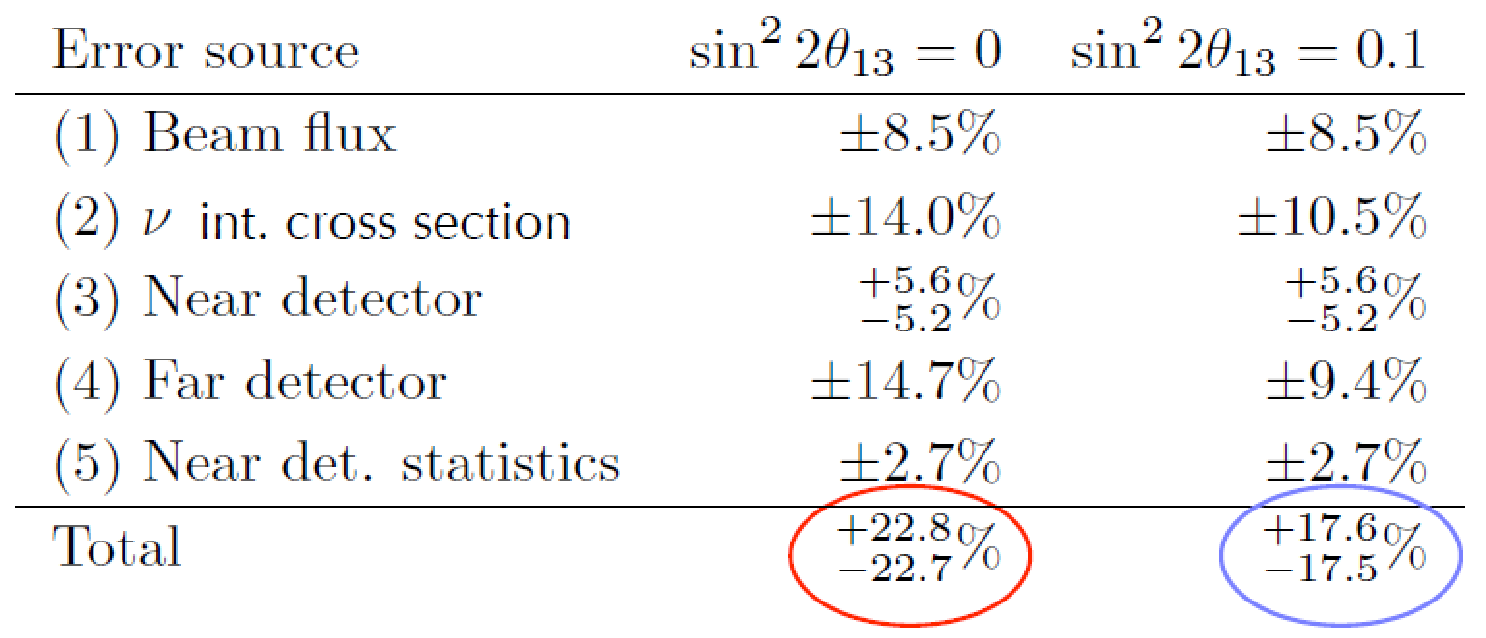
$\Delta T_0 = T_{GPS}@SK - T_{GPS}@J\text{-}PARC - TOF(\sim985\mu sec)$

$\Delta T_0 = T_{GPS}@SK - T_{GPS}@J\text{-}PARC - TOF(\sim985\mu sec)$

- Clear bunch timing structure of J-PARC!!
- **121 Fully Contained(FC) events detected (FC: hits in ID only, no OD hits)**



Systematic error



Error source	$\sin^2 2\theta_{13} = 0$	$\sin^2 2\theta_{13} = 0.1$
(1) Beam flux	$\pm 8.5\%$	$\pm 8.5\%$
(2) ν int. cross section	$\pm 14.0\%$	$\pm 10.5\%$
(3) Near detector	$^{+5.6}_{-5.2}\%$	$^{+5.6}_{-5.2}\%$
(4) Far detector	$\pm 14.7\%$	$\pm 9.4\%$
(5) Near det. statistics	$\pm 2.7\%$	$\pm 2.7\%$
Total	$^{+22.8}_{-22.7}\%$	$^{+17.6}_{-17.5}\%$

Further improvements are planned. Eg. Inclusion of NA61 Kaon results, etc

Smaller error for larger S/N

$$N^{exp}{}_{SK\ tot.} = 1.5 \pm 0.3 \text{ events}$$

for $\sin^2 2\theta_{13} = 0$ (w/ 1.43×10^{20} p.o.t.)

Number of events summary

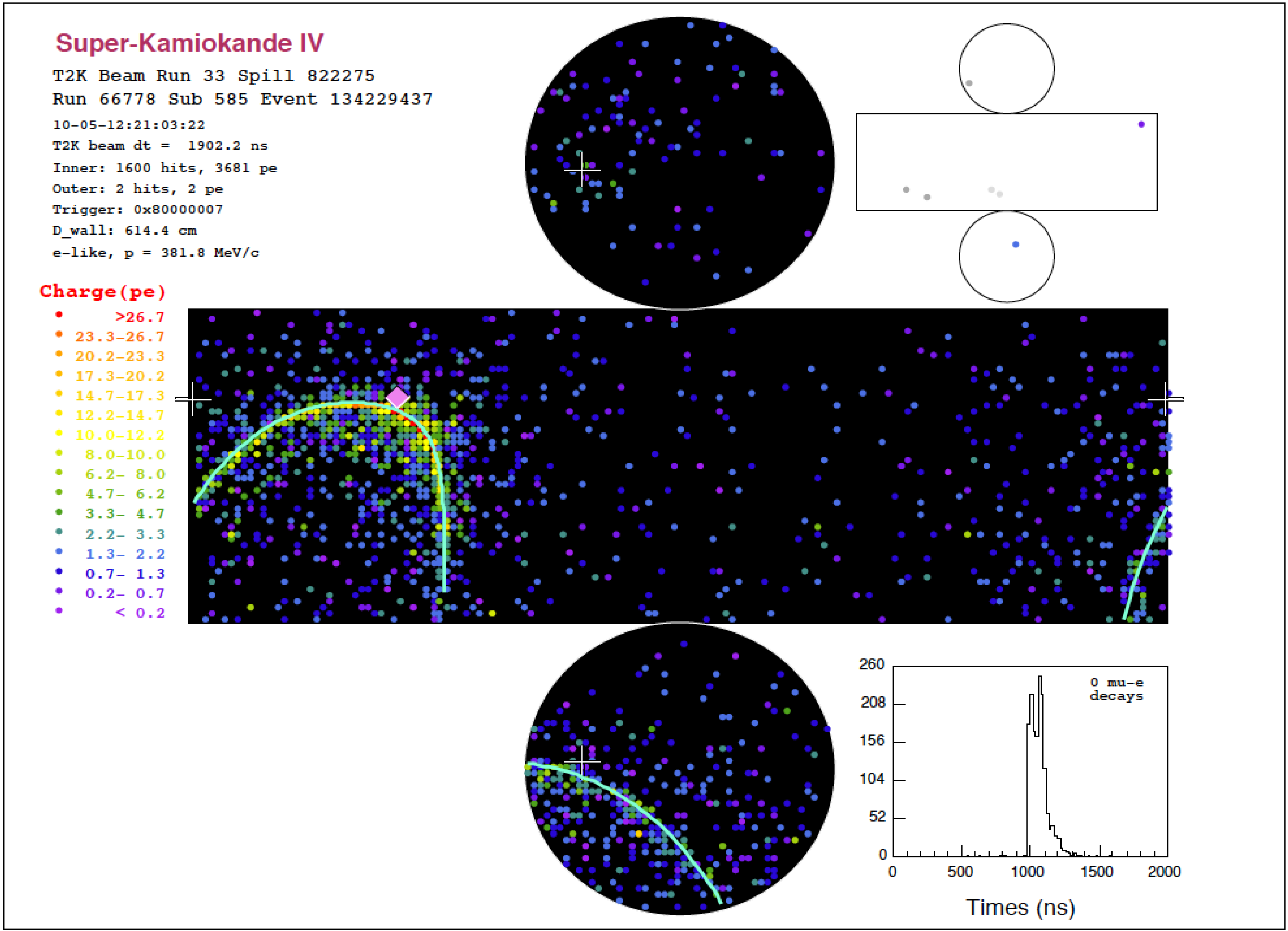
	Total	Beam νe	NC	νμ✳νe (sol term)
Expected BG $\sin^2 2\theta_{13} = 0$	1.5±0.3	0.8	0.6	0.1
Observed	6			

Probability to observe six or more events if $\theta_{13}=0$:

0.007

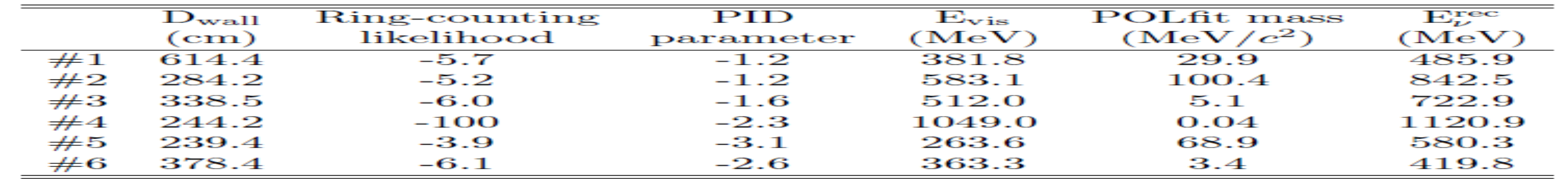
(**2.5 σ** significance)

A candidate



Super-Kamiokande IV

T2K Beam Run 33 Spill 822275
Run 66778 Sub 585 Event 134229437
10-05-12:21:03:22
T2K beam dt = 1902.2 ns
Inner: 1600 hits, 3681 pe
Outer: 2 hits, 2 pe
Trigger: 0x80000007
D_wall: 614.4 cm
e-like, p = 381.8 MeV/c

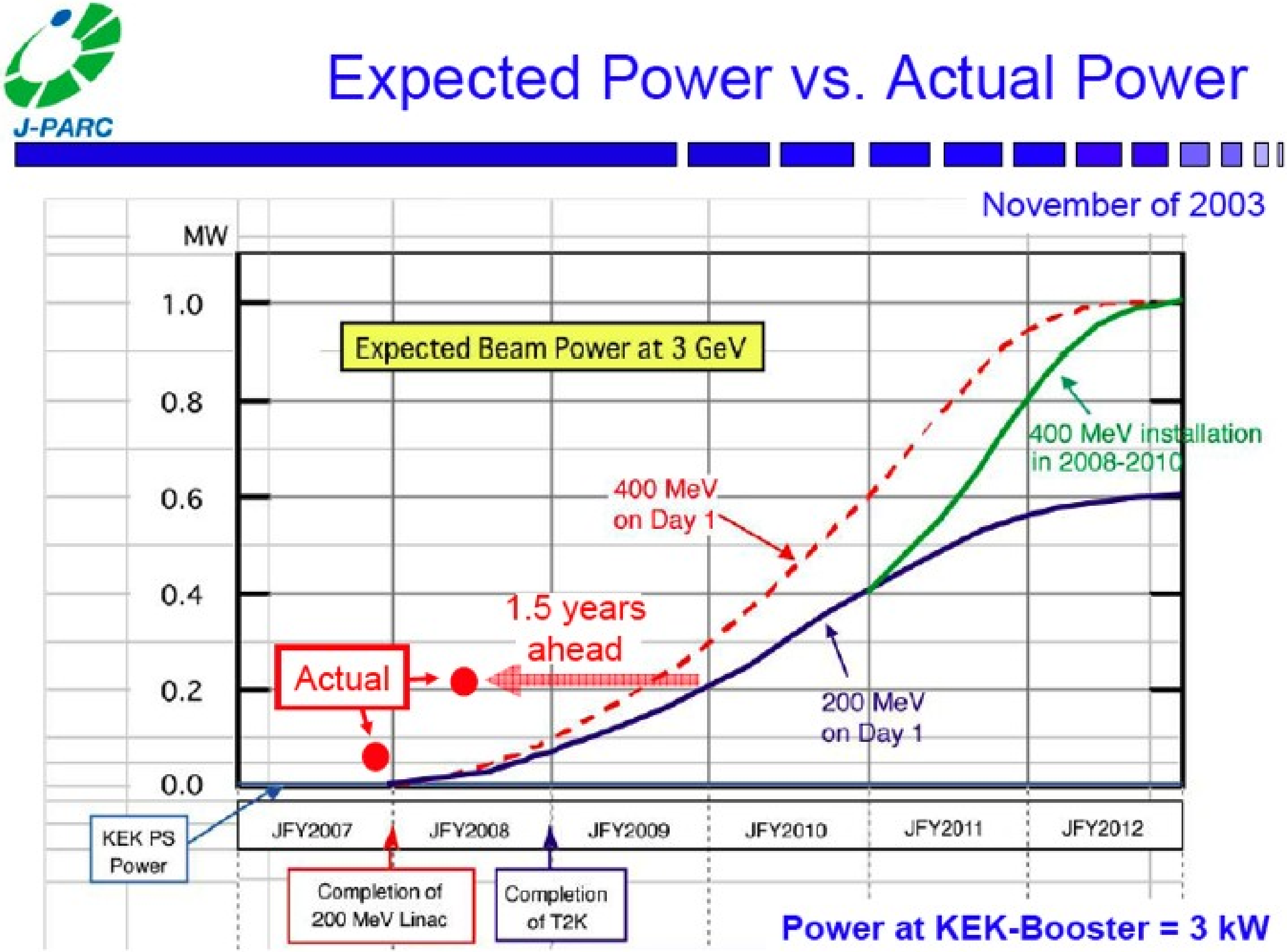


	D_{wall} (cm)	Ring-counting likelihood	PID parameter	E_{vis} (MeV)	POLfit mass (MeV/c^2)	E_ν^{rec} (MeV)
#1	614.4	-5.7	-1.2	381.8	29.9	485.9
#2	284.2	-5.2	-1.2	583.1	100.4	842.5
#3	338.5	-6.0	-1.6	512.0	5.1	722.9
#4	244.2	-100	-2.3	1049.0	0.04	1120.9
#5	239.4	-3.9	-3.1	263.6	68.9	580.3
#6	378.4	-6.1	-2.6	363.3	3.4	419.8

Table 6: Reconstructed information for the final ν_e candidate events.

JPARC Power Ramp-Up

- Plots shows RCS power.
- Main ring power is factor of 1.3-3 lower than RCS power (factor of 3 now, factor of 1.3 later).



Expected Power vs. Actual Power

November of 2003

Power at KEK-Booster = 3 kW

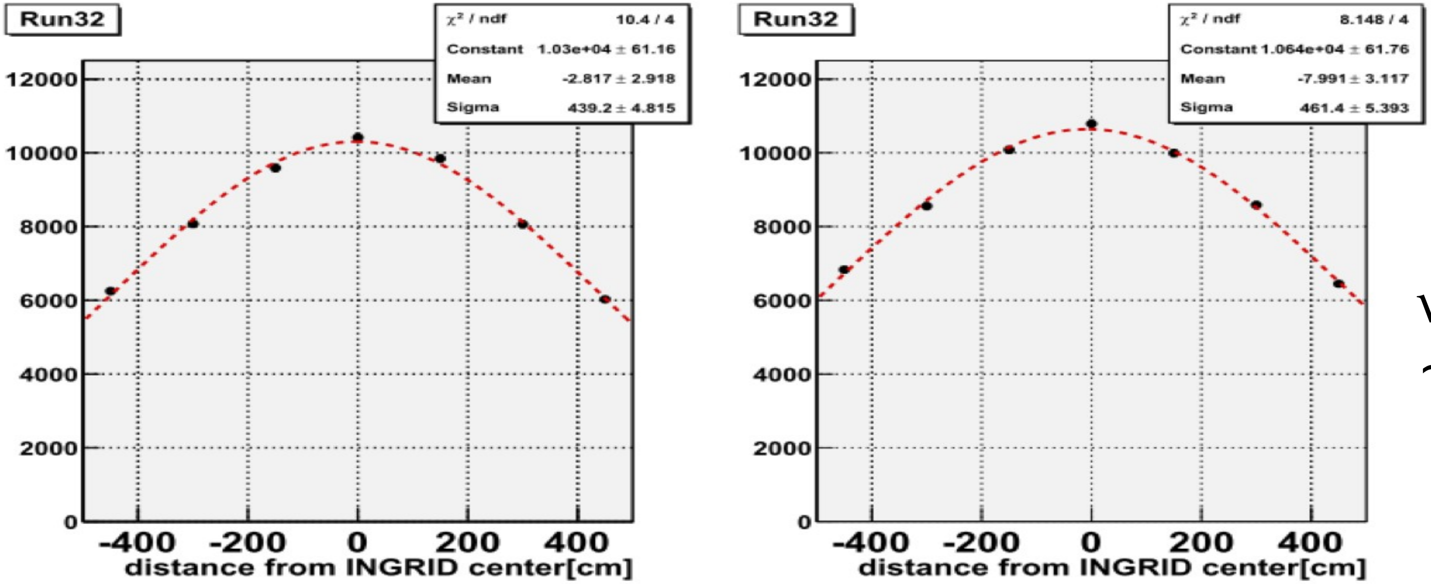
S. Nagamiya @ICFA seminar

Beam Pointing Check

An on-axis array of iron/scintillator neutrino detectors measures the beam profile and direction 280m from the production point.

Horizontal:+0.01±0.05(stat)±0.33(sys) mrad

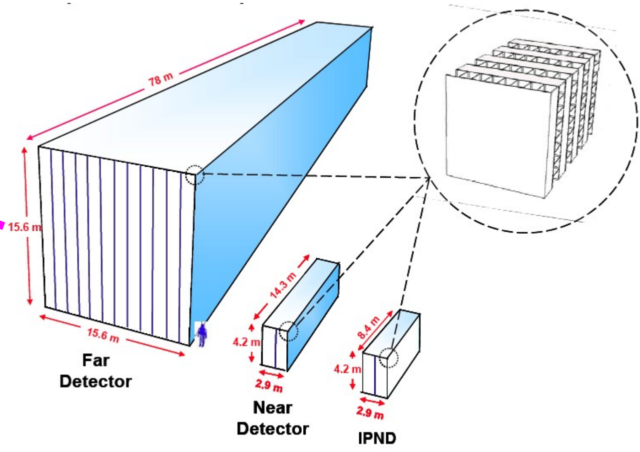
Vertical : -0.24±0.05(stat)±0.37(sys) mrad



ν beam width
~4.5m @ 280m

NOνA

15 kT liquid scintillator
0.8 deg off axis
Ready January 2014



upgrade NuMI from
400 kW to 700 kW

71

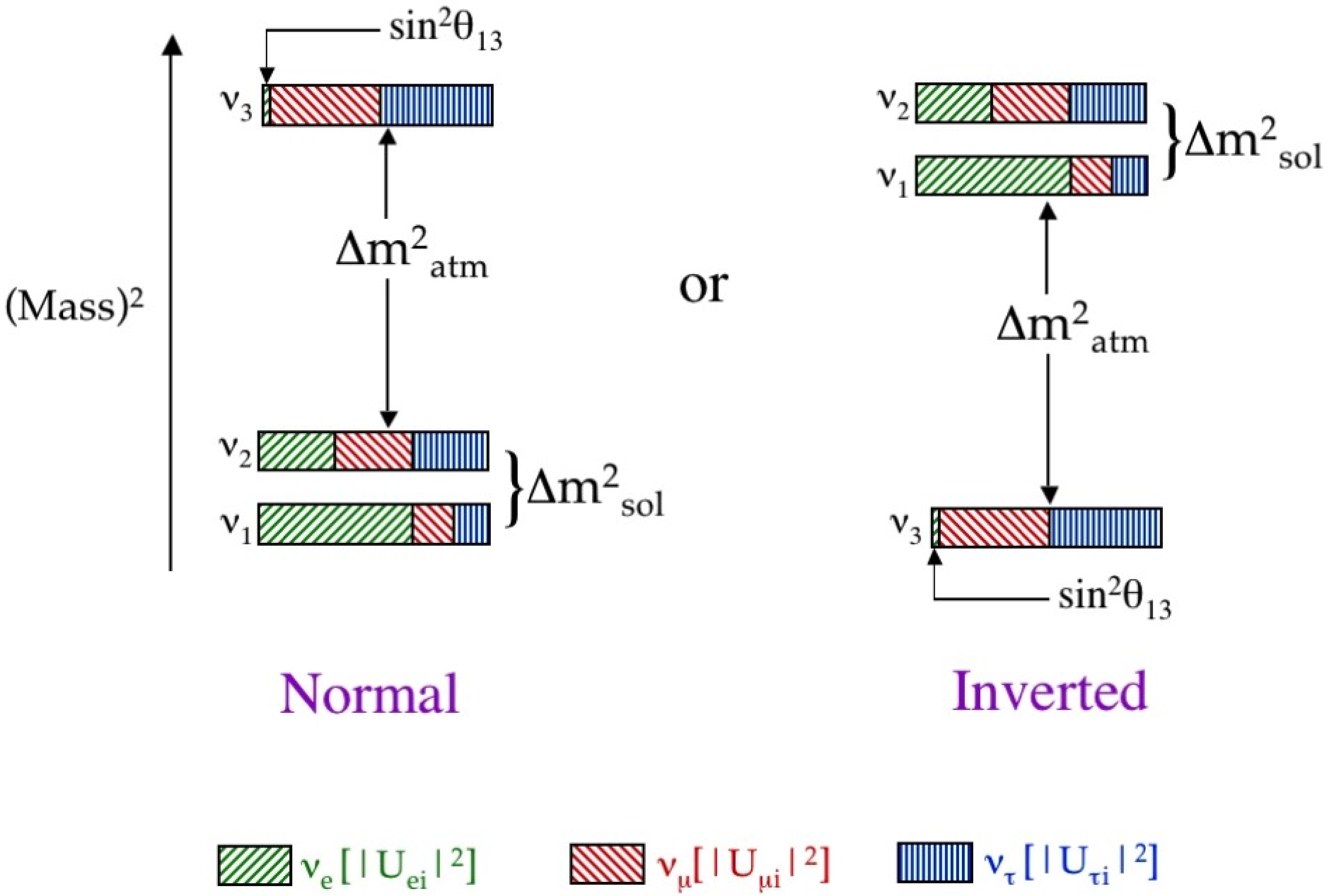
Mass Hierarchy

Currently unknown:

- θ_{13}
- δ_{CP}
- sign of the mass hierarchy

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

$\Delta m^2_{sol} = 7.6 \times 10^{-5}$ eV^2



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:

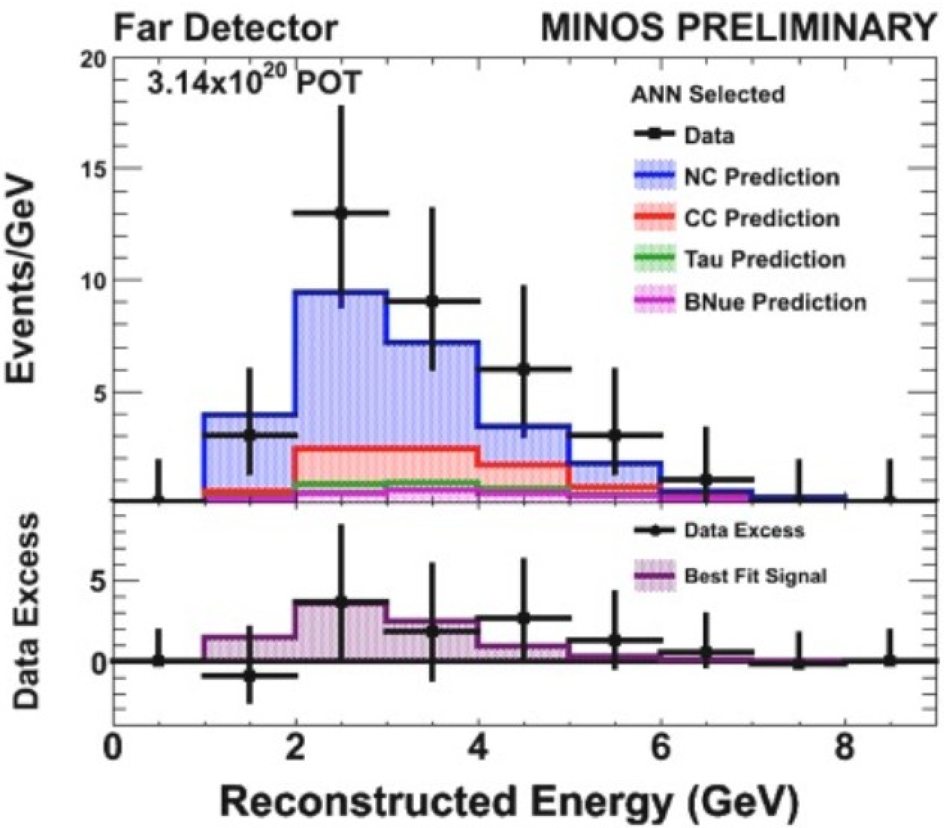
$$P(\nu_\mu \rightarrow \nu_e) \approx \left(1 + 2\frac{E}{E_R}\right) P_{vac}(\nu_\mu \rightarrow \nu_e)$$

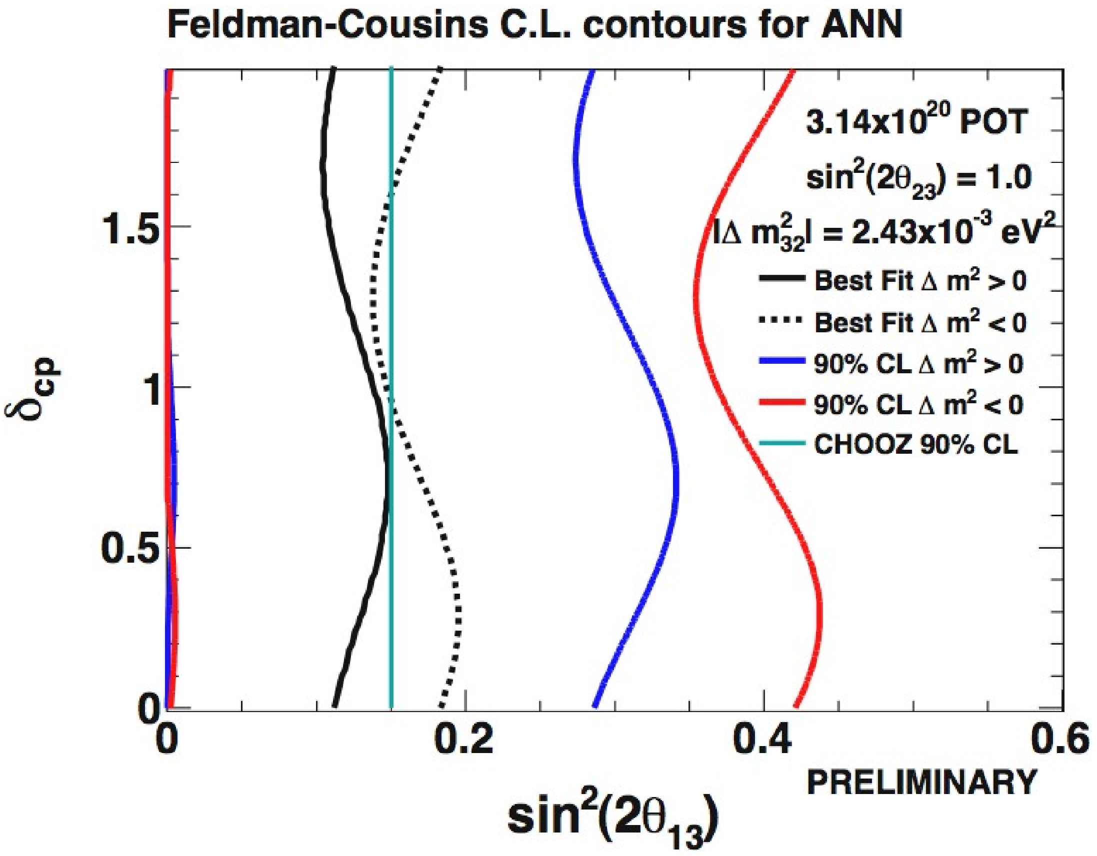
where

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

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

θ_{13}: MINOS & solar limits





MINOS $\nu_\mu \rightarrow \nu_e$: saw 35 events, expected background 27 ± 5 ± 2

$$\sin^2 2\theta_{13} = 0.078^{+0.079}_{-0.064}$$

Solar + KamLAND joint fit:

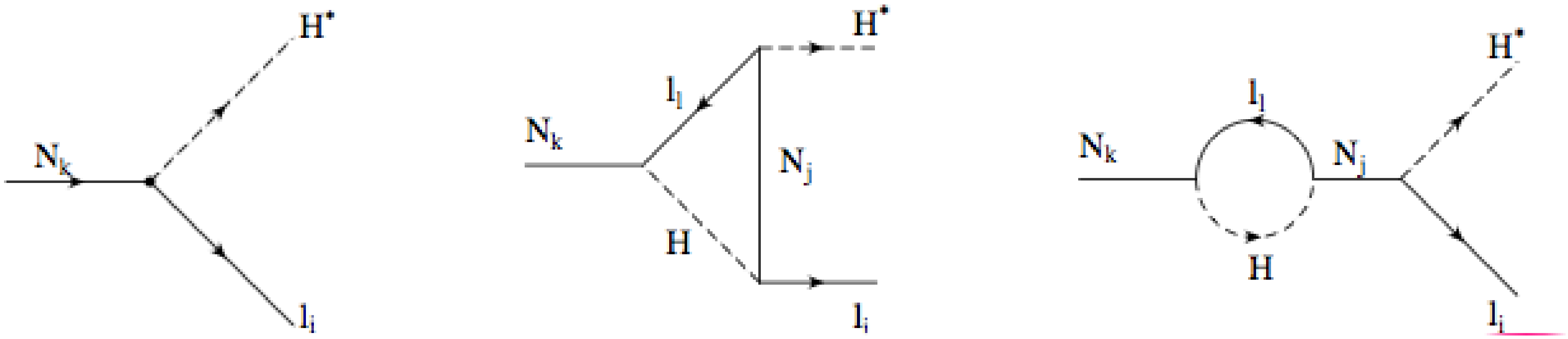
Leptogenesis

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

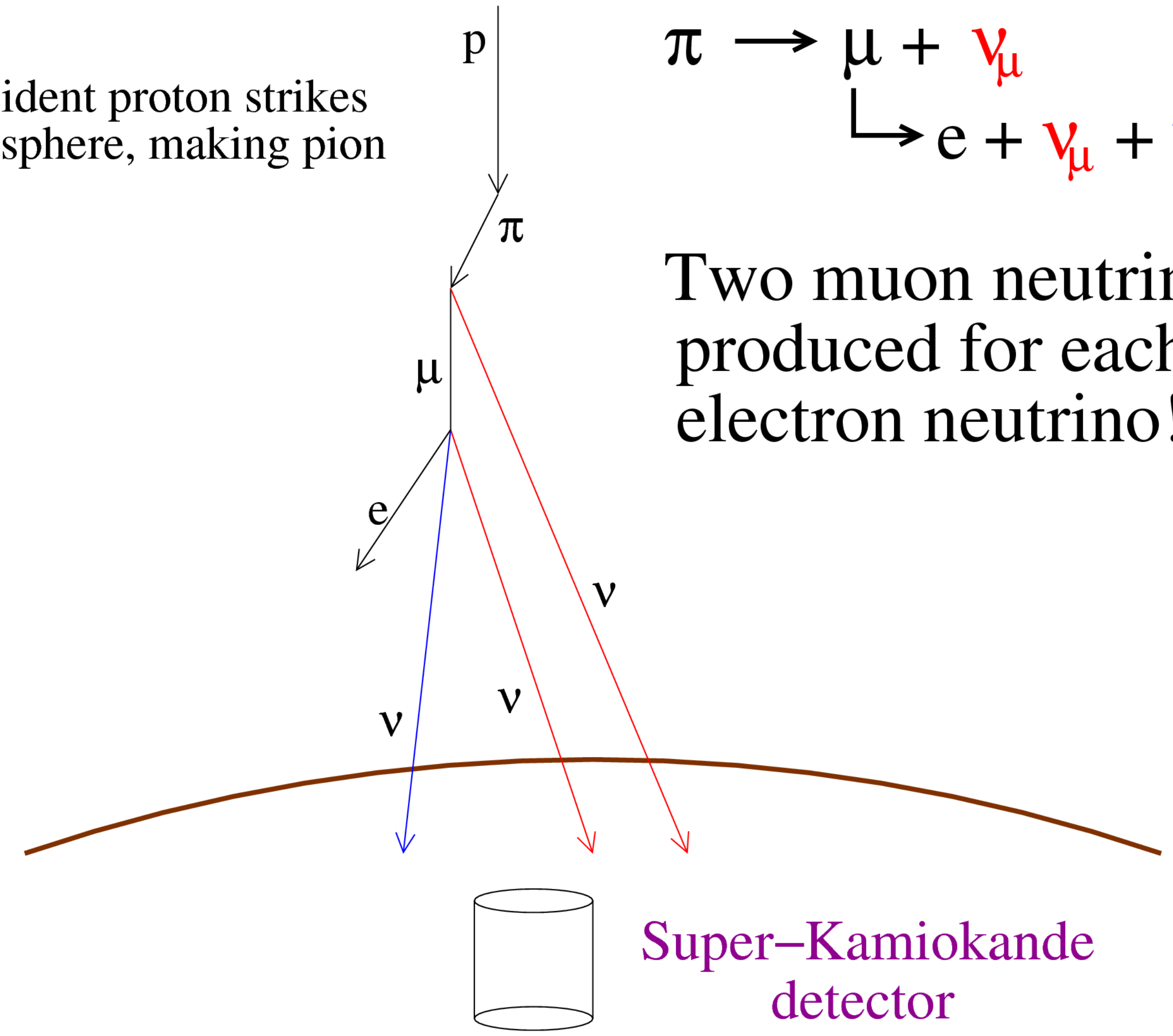


Usual scenario: decay of heavy Majorana neutrinos Phys.Lett B 174, 45 (1986)

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.

Atmospheric Neutrinos



Incident proton strikes
atmosphere, making pion

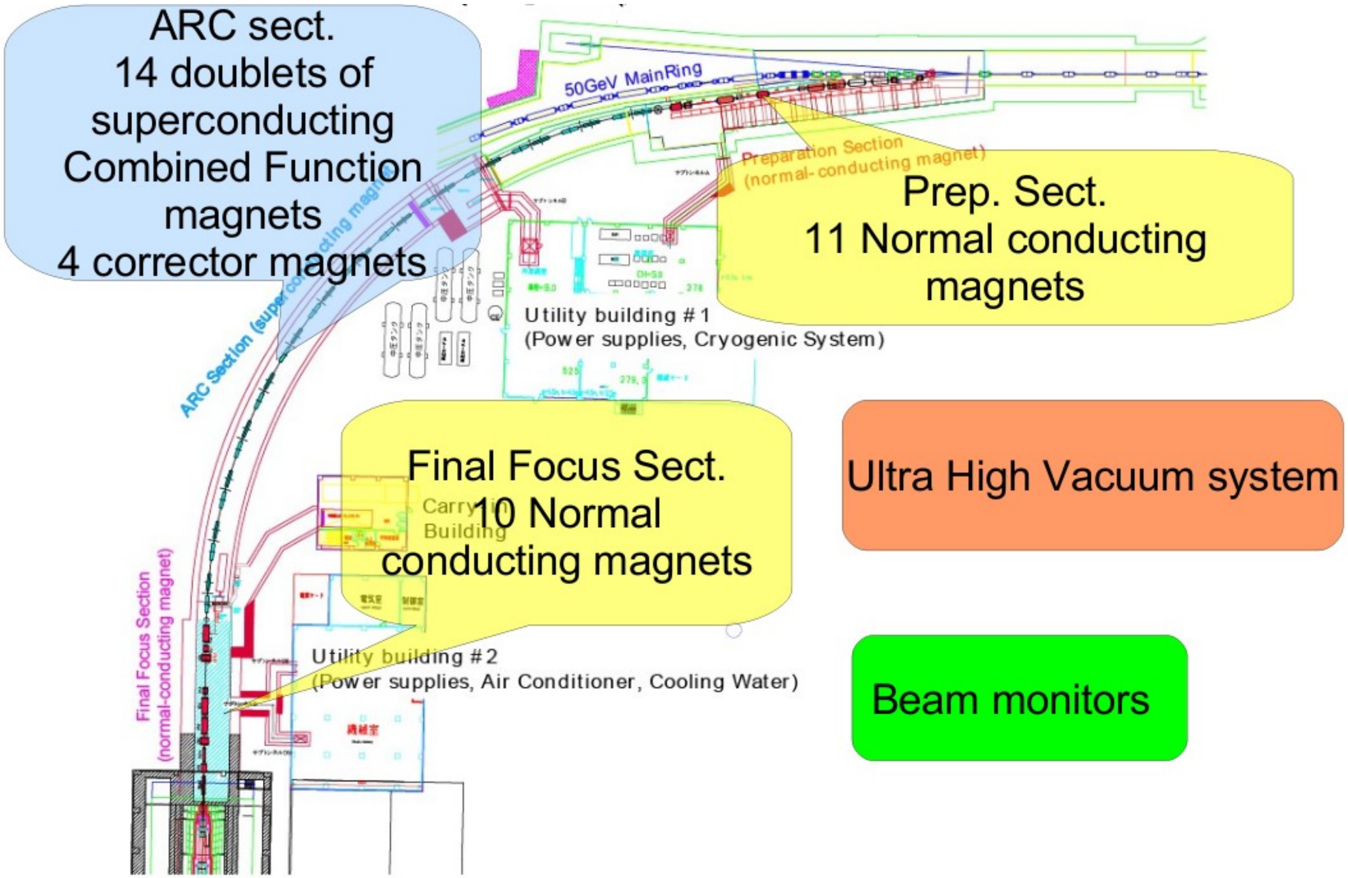
$$\pi \longrightarrow \mu + \nu_\mu$$
$$\hookrightarrow e + \nu_\mu + \nu_e$$

Two muon neutrinos
produced for each
electron neutrino!

Super–Kamiokande
detector

Neutrino Beamline

- T2K group responsible for construction of neutrino beamline at JPARC; huge amount of work.



ARC sect.
14 doublets of superconducting Combined Function magnets
4 corrector magnets

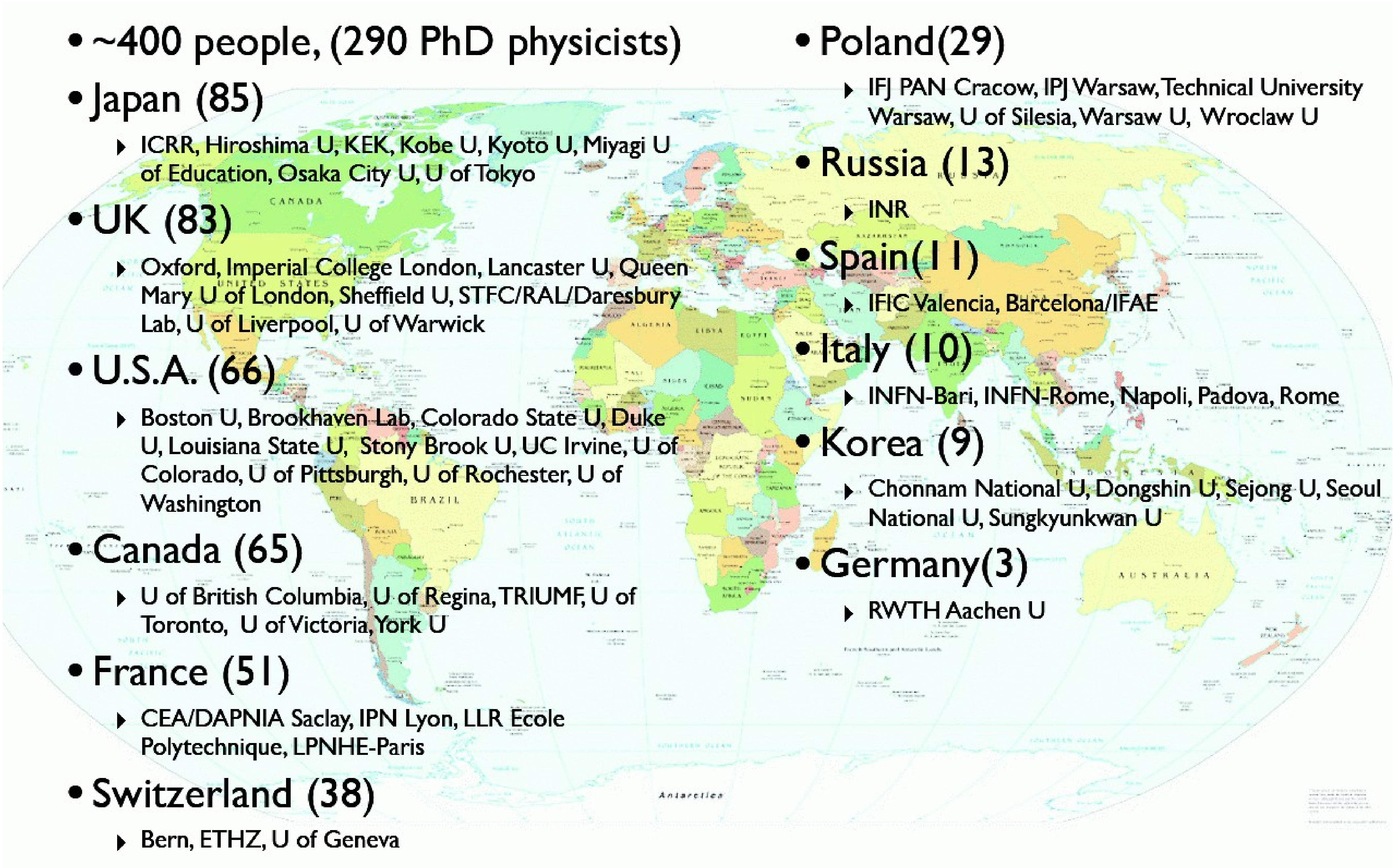
Prep. Sect.
11 Normal conducting magnets

Final Focus Sect.
10 Normal conducting magnets

Ultra High Vacuum system

Beam monitors

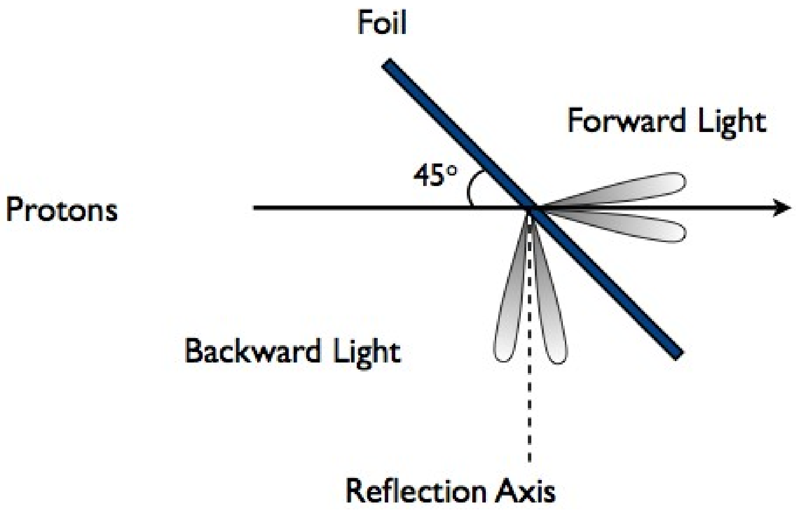
The T2K Collaboration

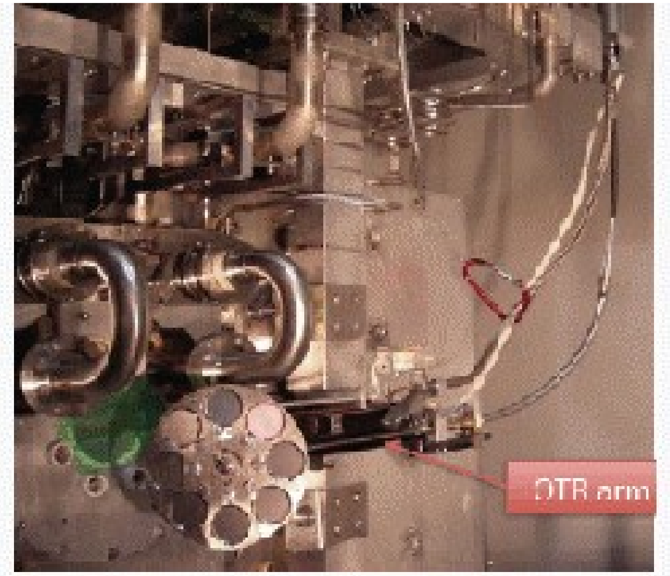


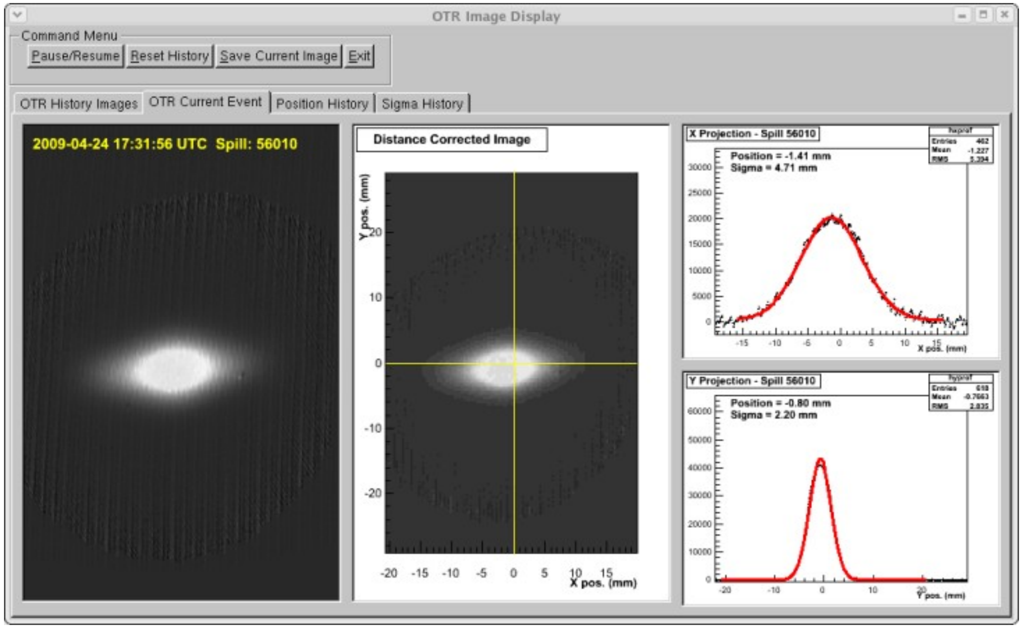
- ~400 people, (290 PhD physicists)
- Japan (85)
  - ICRR, Hiroshima U, KEK, Kobe U, Kyoto U, Miyagi U of Education, Osaka City U, U of Tokyo
- UK (83)
  - Oxford, Imperial College London, Lancaster U, Queen Mary U of London, Sheffield U, STFC/RAL/Daresbury Lab, U of Liverpool, U of Warwick
- U.S.A. (66)
  - Boston U, Brookhaven Lab, Colorado State U, Duke U, Louisiana State U, Stony Brook U, UC Irvine, U of Colorado, U of Pittsburgh, U of Rochester, U of Washington
- Canada (65)
  - U of British Columbia, U of Regina, TRIUMF, U of Toronto, U of Victoria, York U
- France (51)
  - CEA/DAPNIA Saclay, IPN Lyon, LLR Ecole Polytechnique, LPNHE-Paris
- Switzerland (38)
  - Bern, ETHZ, U of Geneva
- Poland(29)
  - IFJ PAN Cracow, IPJ Warsaw, Technical University Warsaw, U of Silesia, Warsaw U, Wroclaw U
- Russia (13)
  - INR
- Spain(11)
  - IFIC Valencia, Barcelona/IFAE
- Italy (10)
  - INFN-Bari, INFN-Rome, Napoli, Padova, Rome
- Korea (9)
  - Chonnam National U, Dongshin U, Sejong U, Seoul National U, Sungkyunkwan U
- Germany(3)
  - RWTH Aachen U

Monitoring the Beam Location

Optical Transition Radiation foil monitor just upstream of target





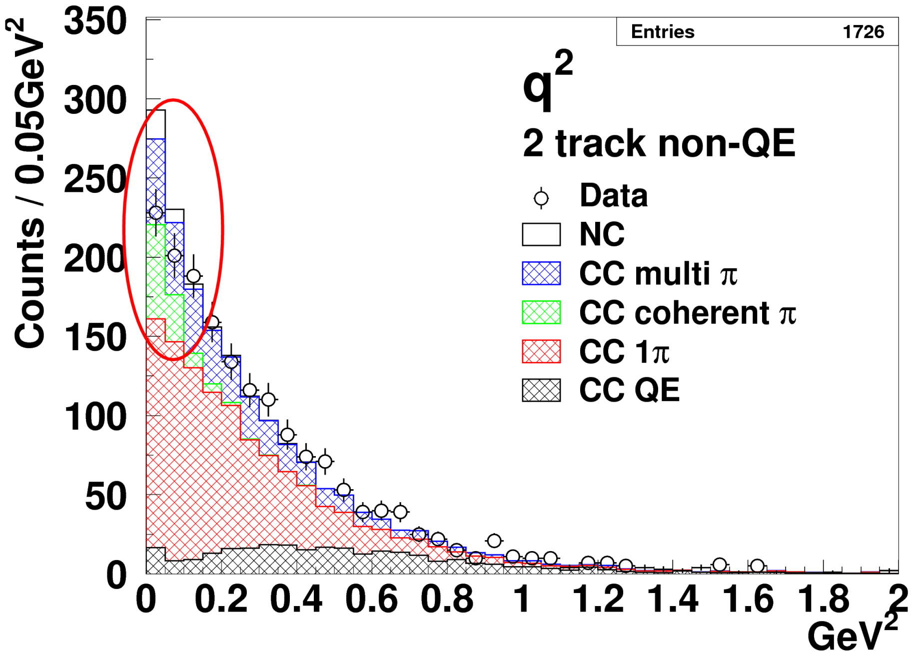


2009-04-24 17:31:56 UTC Spill: 56010

X Projection - Spill 56010
Position = -1.41 mm
Sigma = 4.71 mm

Y Projection - Spill 56010
Position = -0.80 mm
Sigma = 2.20 mm

Nuclear Effects



Data from K2K Scibar detector shows poor agreement in q^2 distribution for events selected as being not CCQE

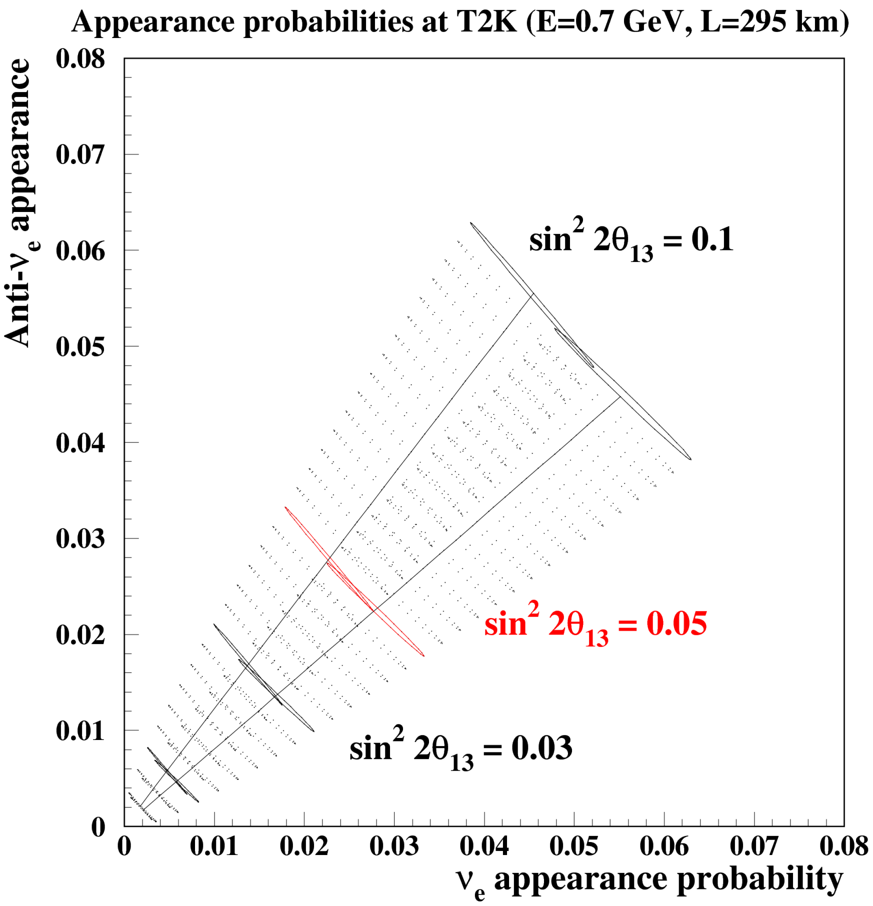
The neutrino world's version of a QCD background ... are there ain't no such thing as asymptotic freedom at these energies!

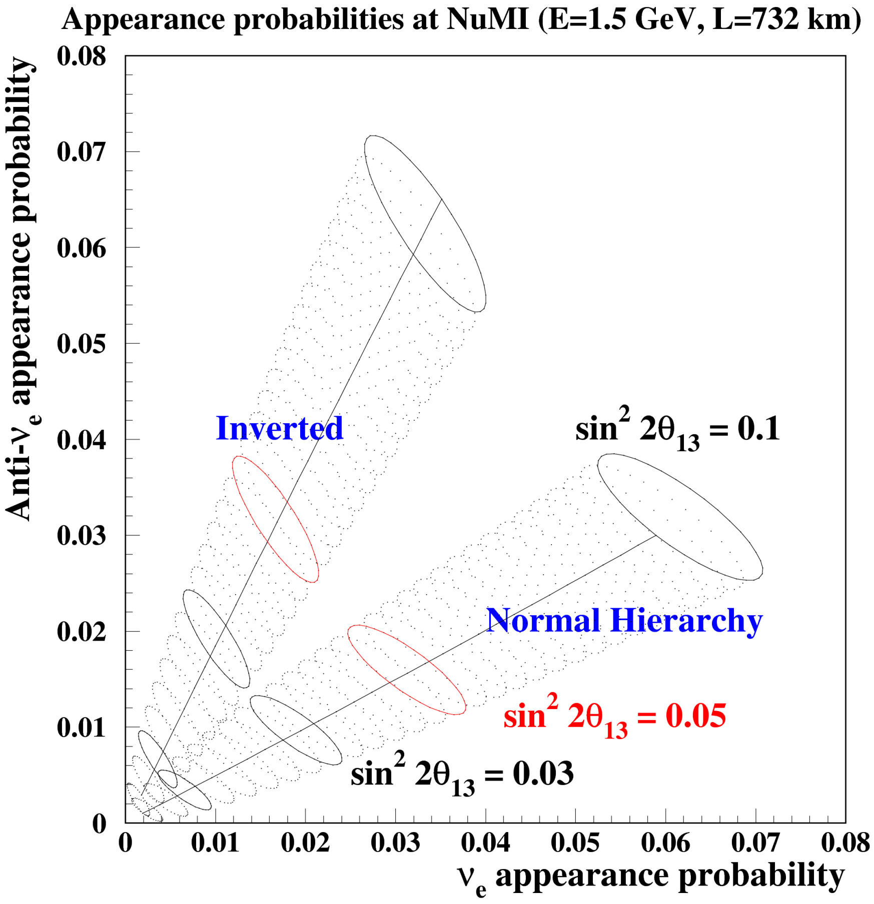
Nuclear effects quite important in modelling neutrino interactions: binding energy, Fermi motion, Pauli blocking, coherent scattering off of entire nucleus ...

Data anomalies abound!

May be different for different nuclei.

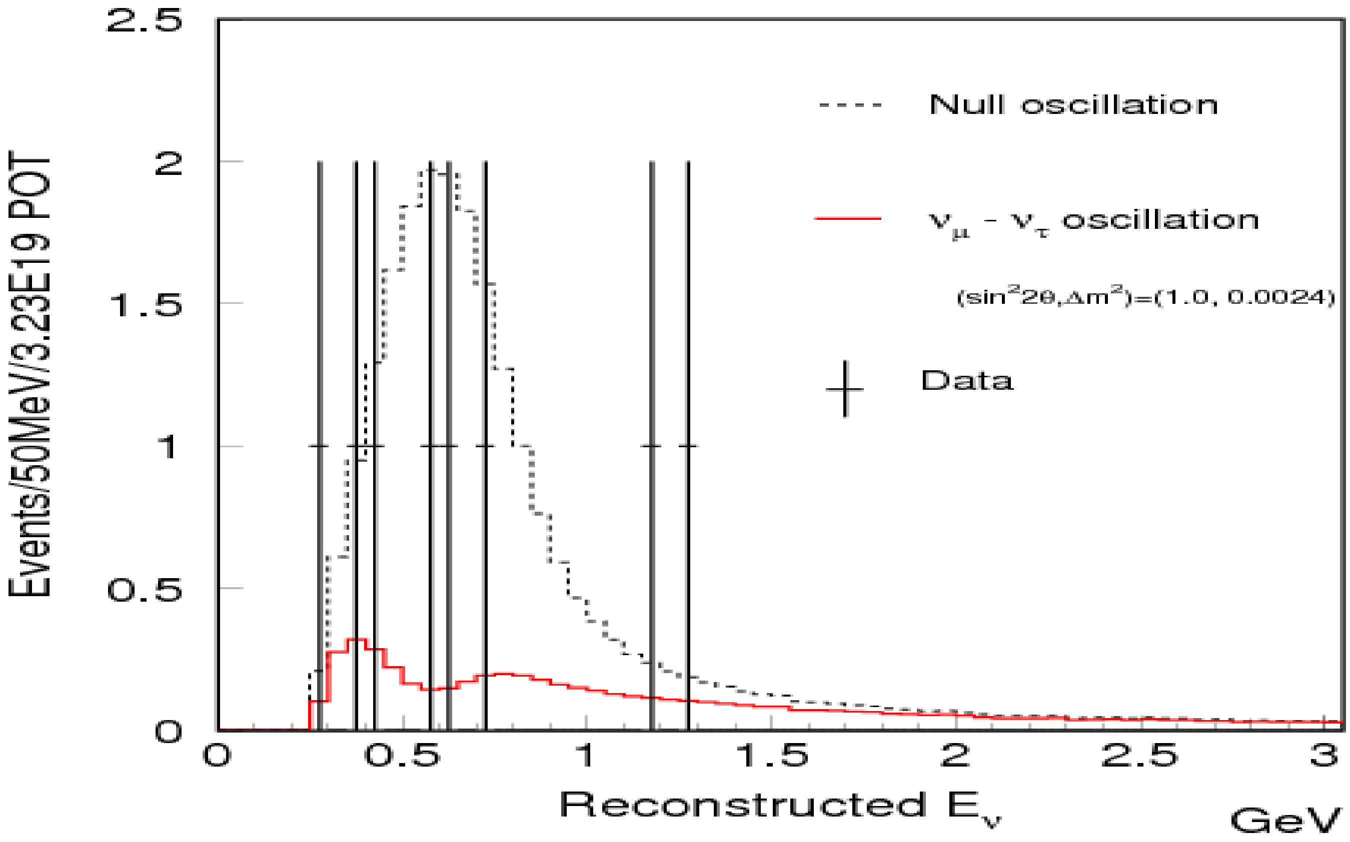
CP Violation and Matter Effects





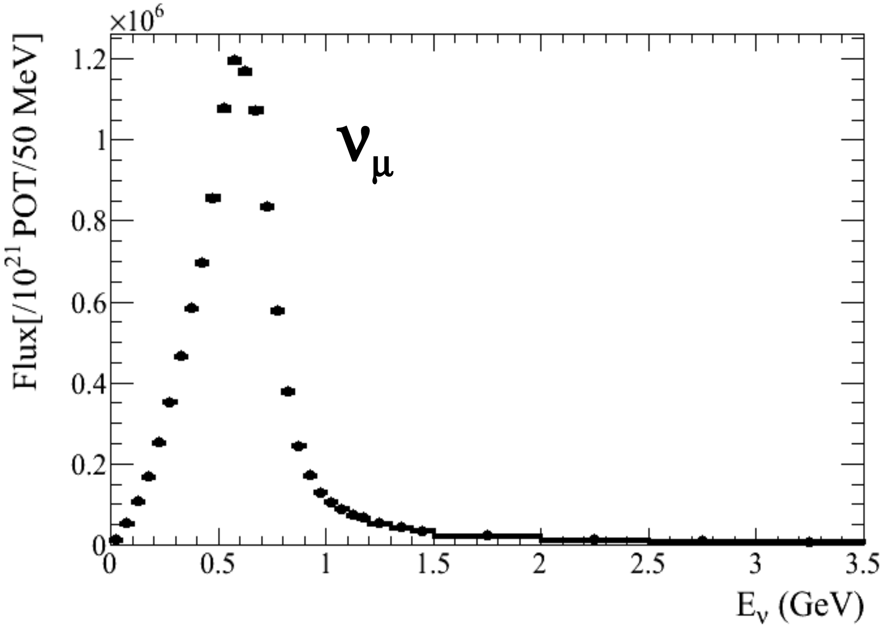
Significant parameter degeneracies will require multiple experiments to disentangle.

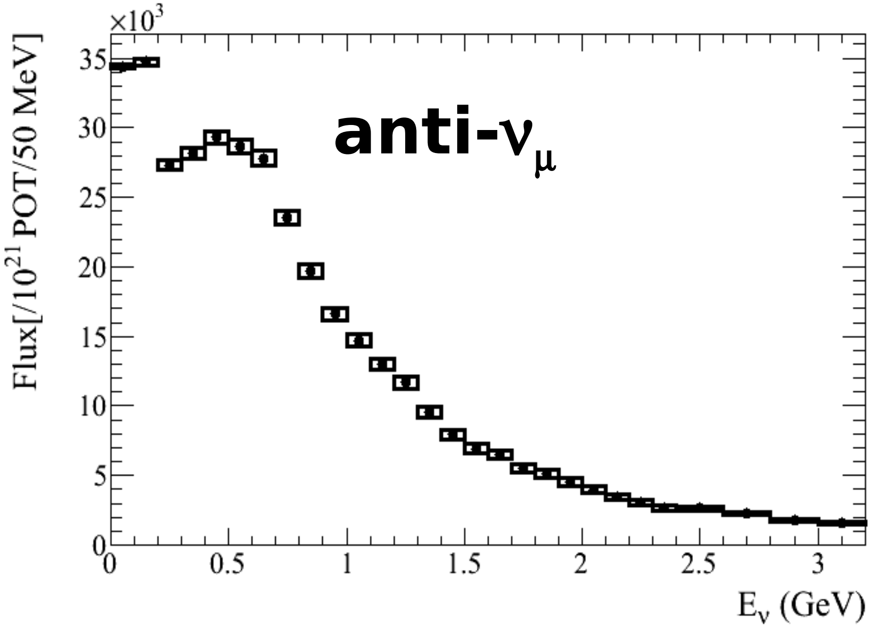
ν_μ disappearance analysis

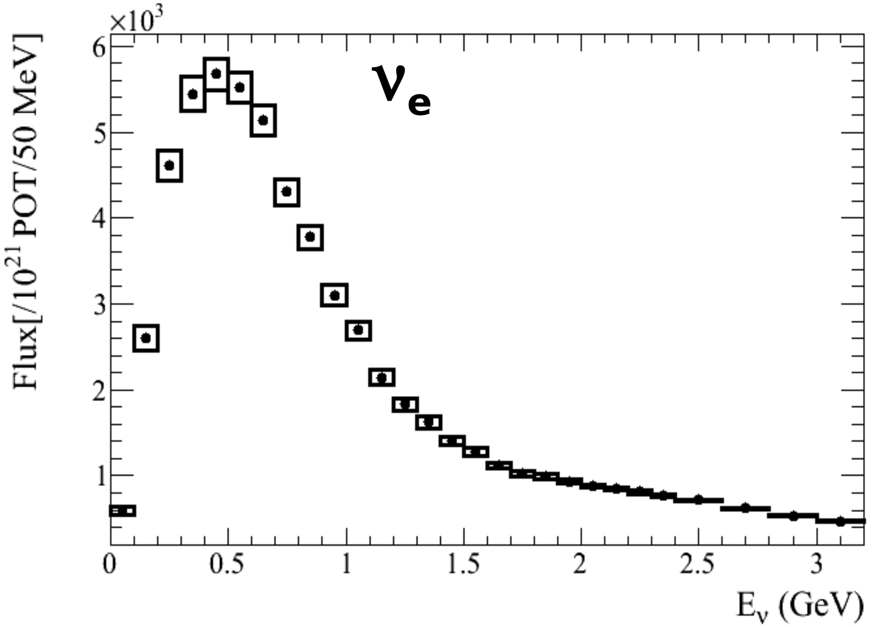


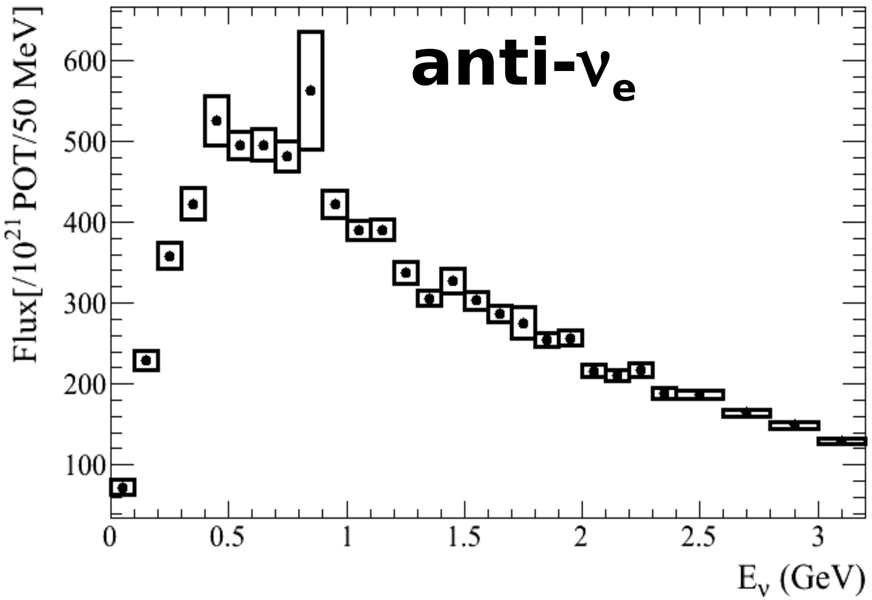
- 8 ν_μ events observed.
- # of events agree with MINOS / SK measurements.

flux at SK
(10d tuned flux)



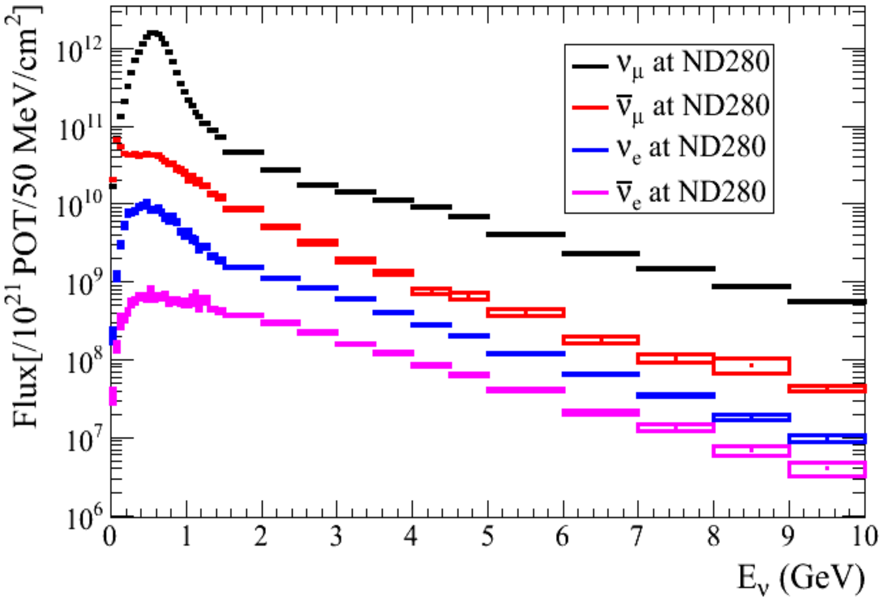




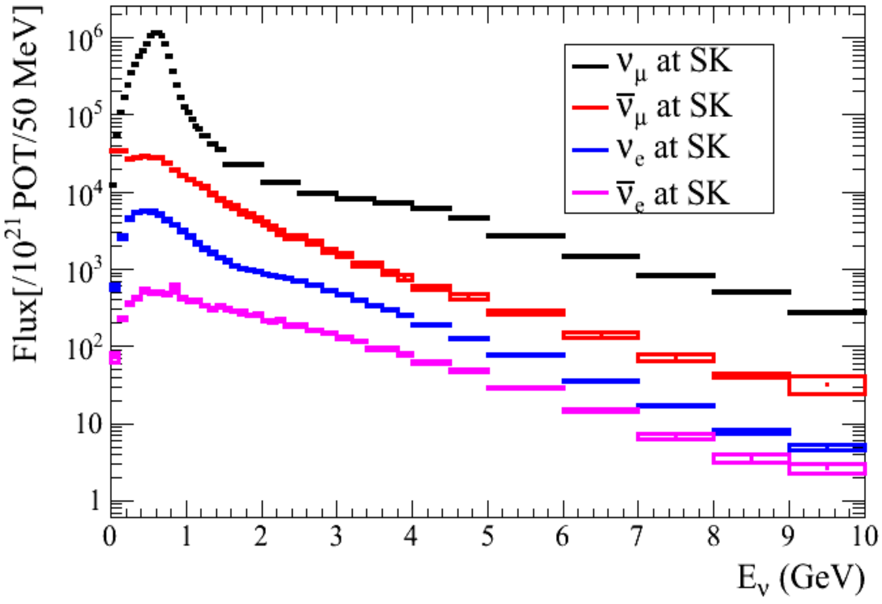


Flux predictions by flavor

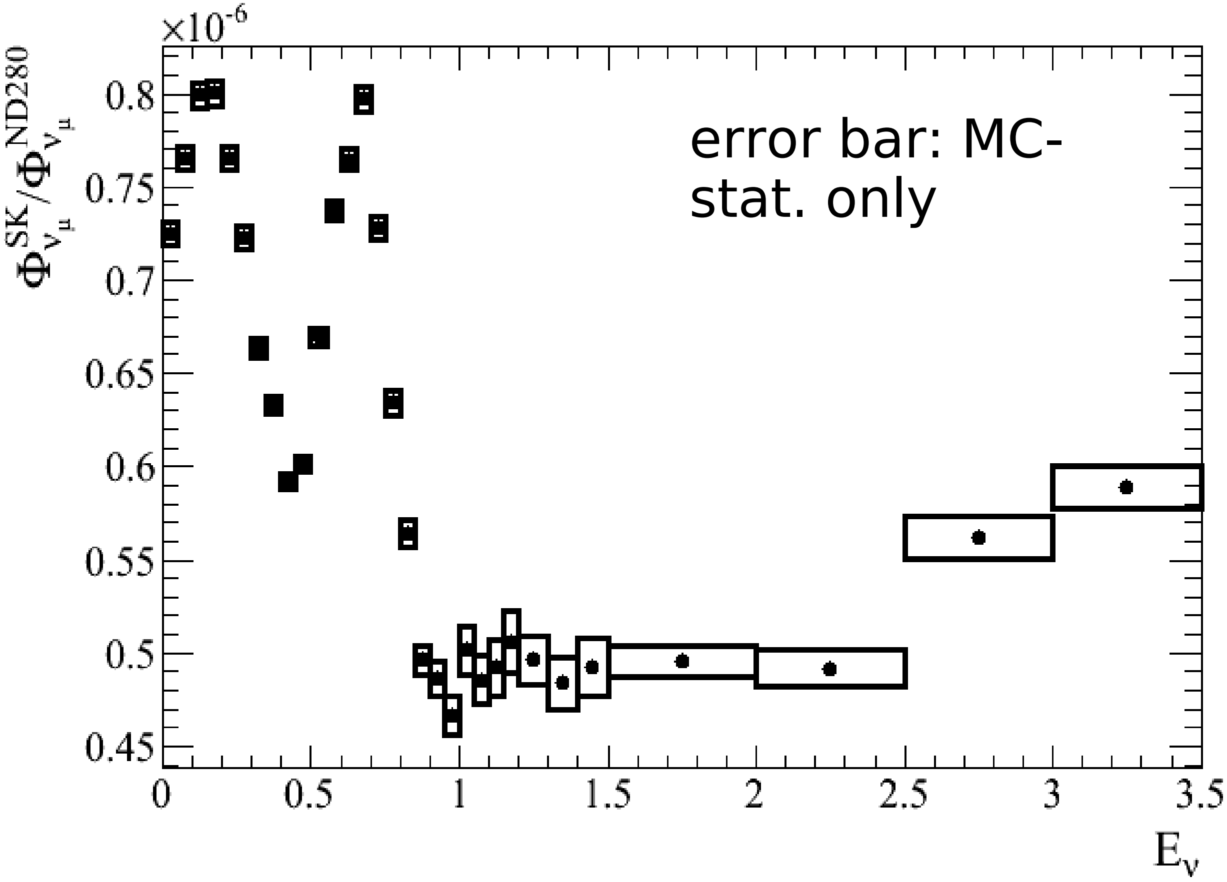
ND280



SK



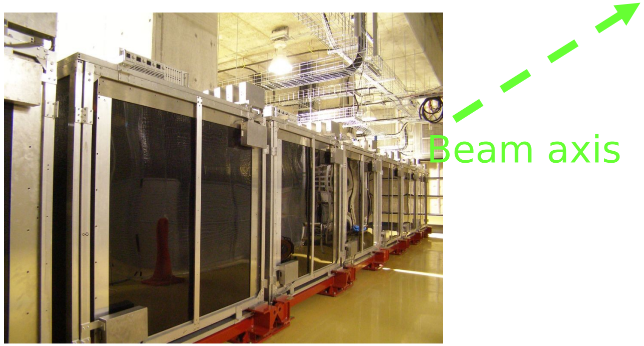
Far/Near ratio

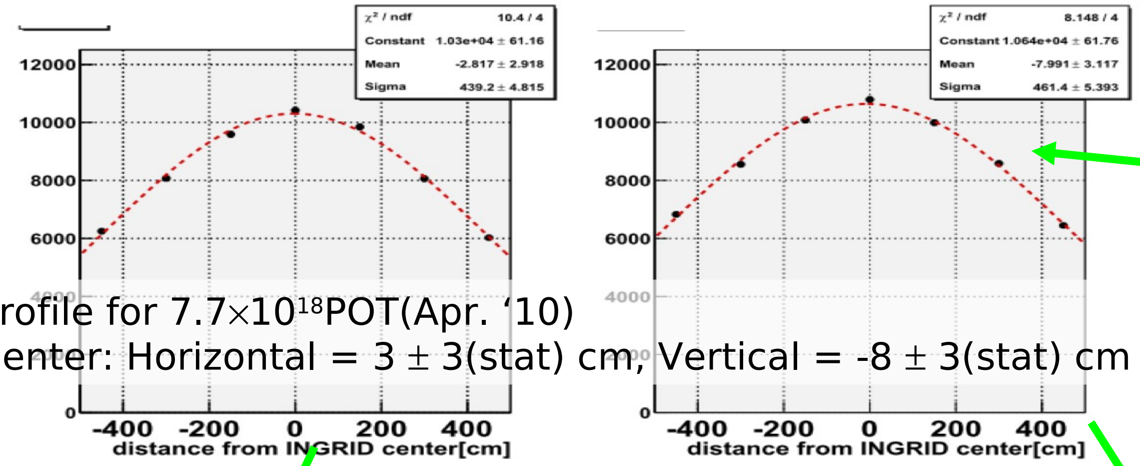


error bar: MC-stat. only

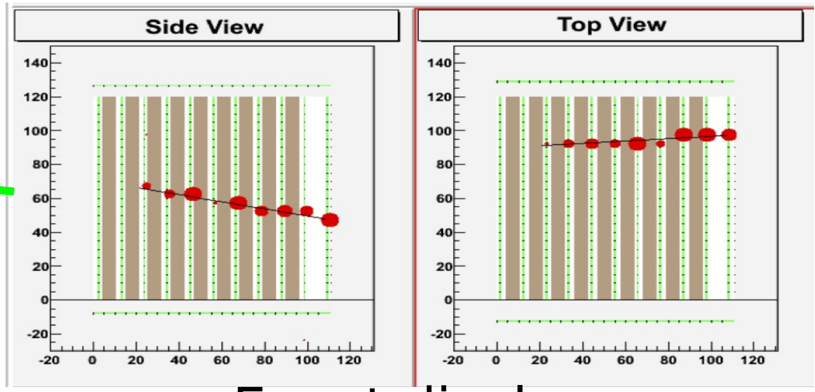
Beam direction: INGRID

- 7+7 array of the scintillator trackers with iron target.
- Distance from target = 279m (V) / 283m (H)
  → 10cm center shift ≡ 0.04mrad
- Beam direction from 2010 Jan. ~ Jun.
  - Horizontal:+0.01±0.05(stat.)±0.33(syst.) mrad
  - Vertical : -0.24±0.05(stat.)±0.37(syst.) mrad

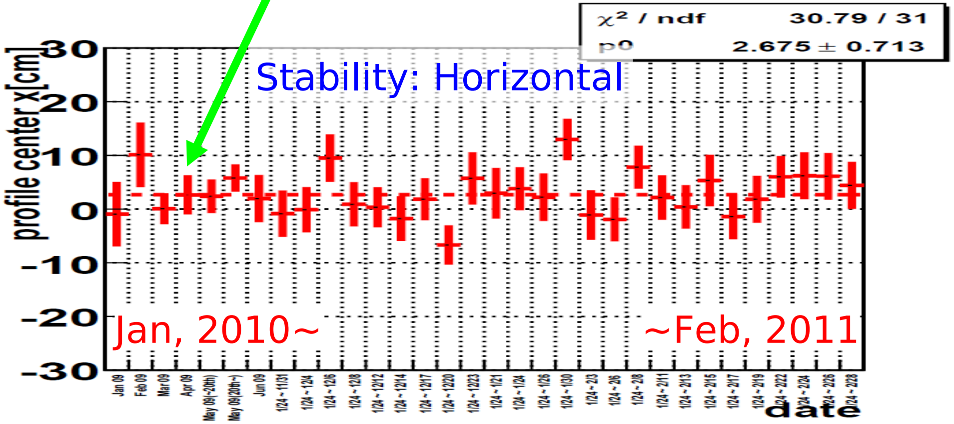




Profile for 7.7×10^{18}POT(Apr. '10)
Center: Horizontal = 3 ± 3(stat) cm, Vertical = -8 ± 3(stat) cm

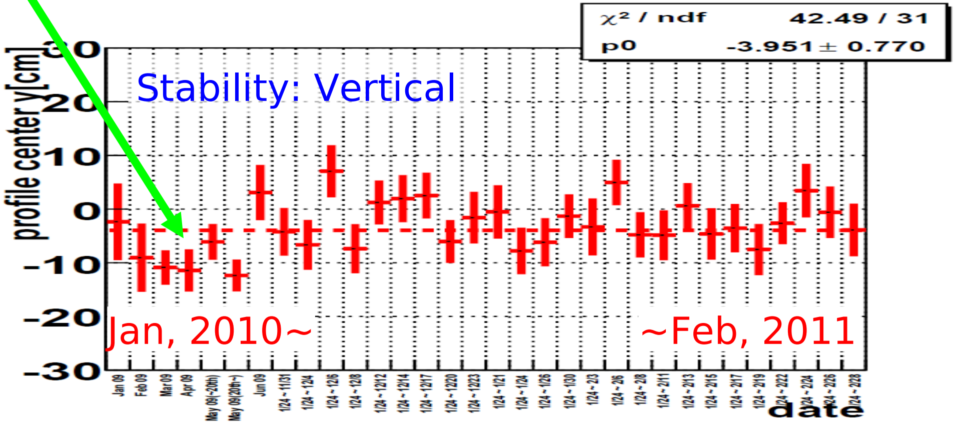


Event display



Stability: Horizontal

Jan, 2010~ ~Feb, 2011



Stability: Vertical

Jan, 2010~ ~Feb, 2011