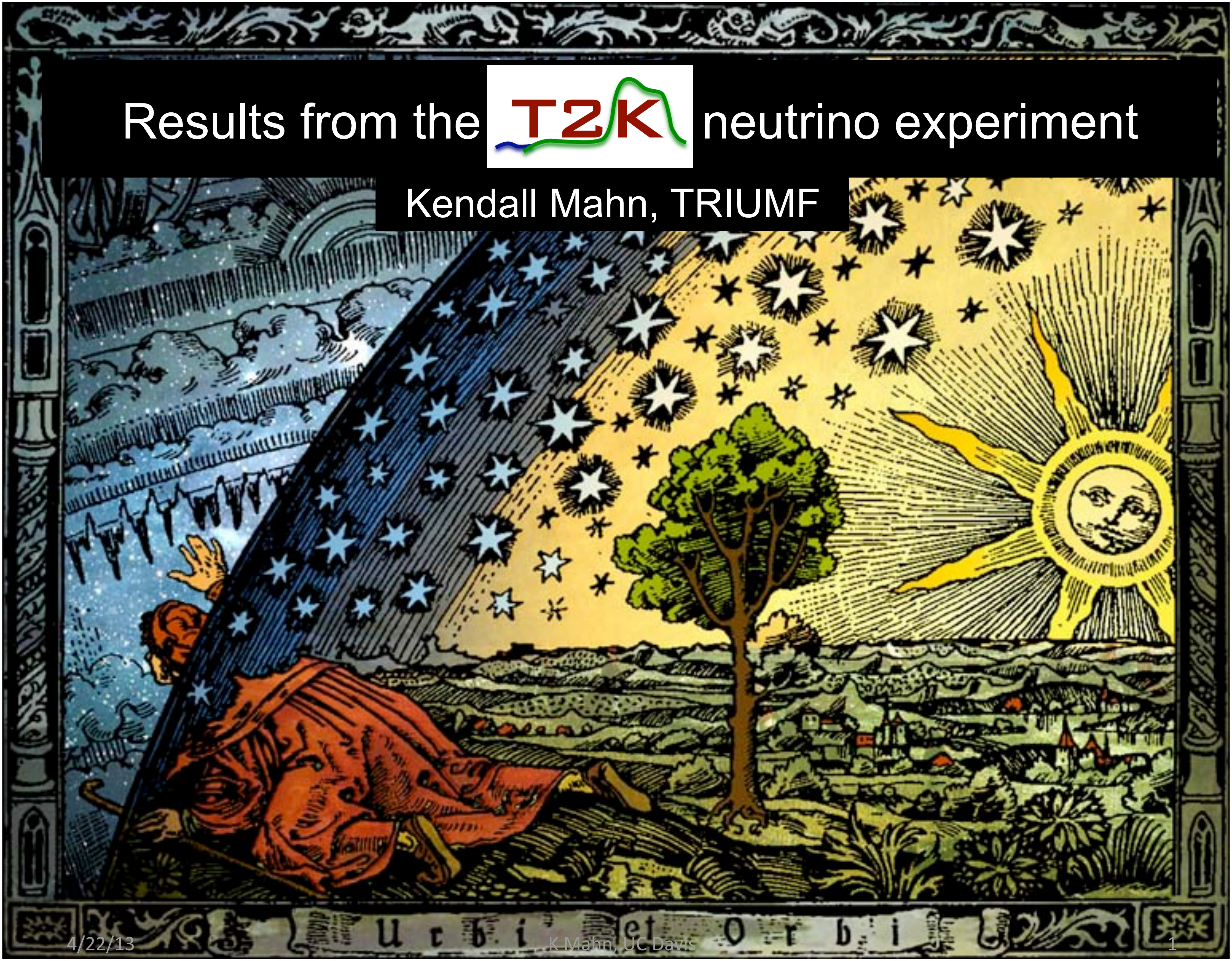
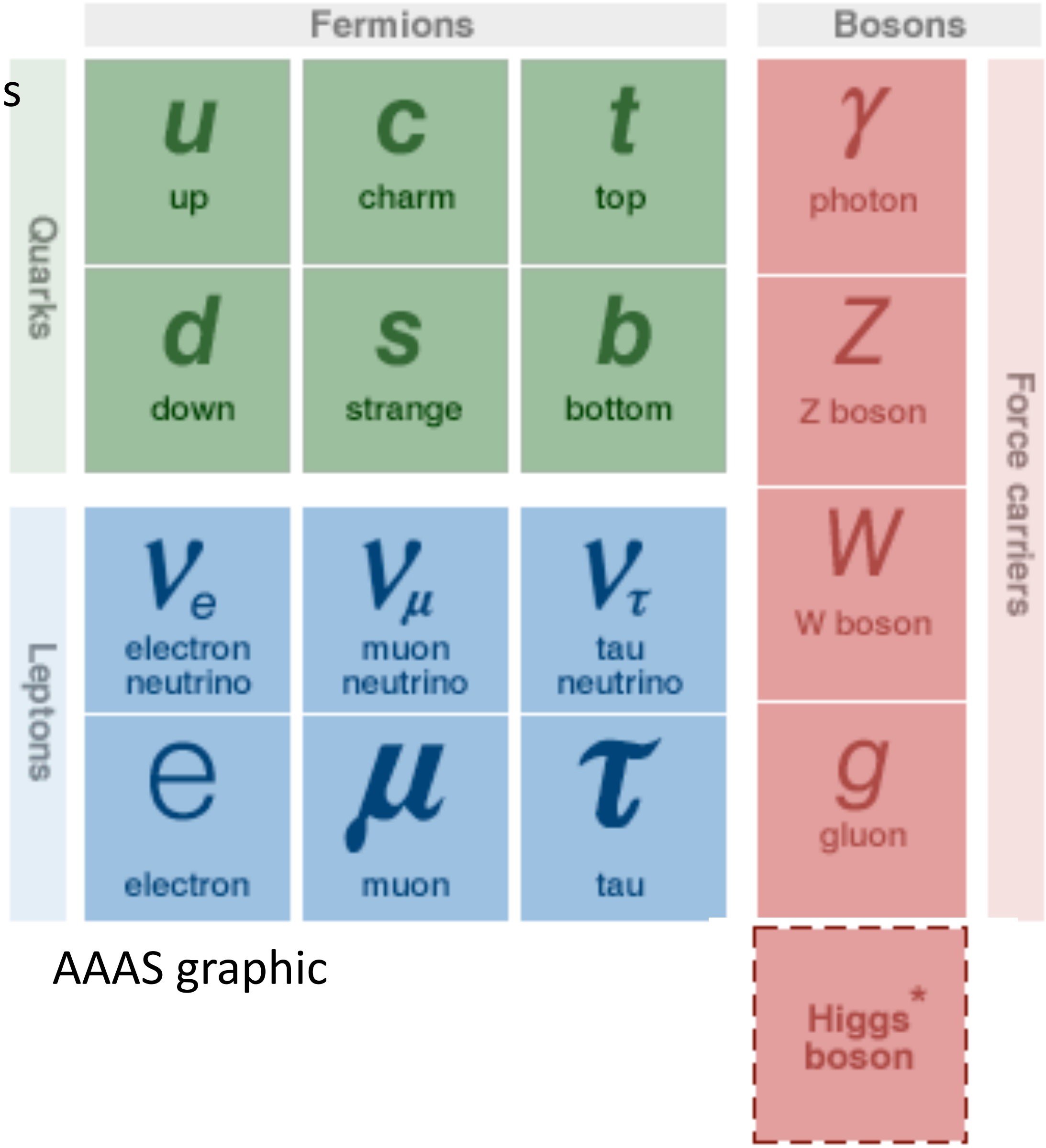
Results from the T2K neutrino experiment

Kendall Mahn, TRIUMF



The Standard Model



Protons, neutrons

Photons

Electrons

Protons, neutrons

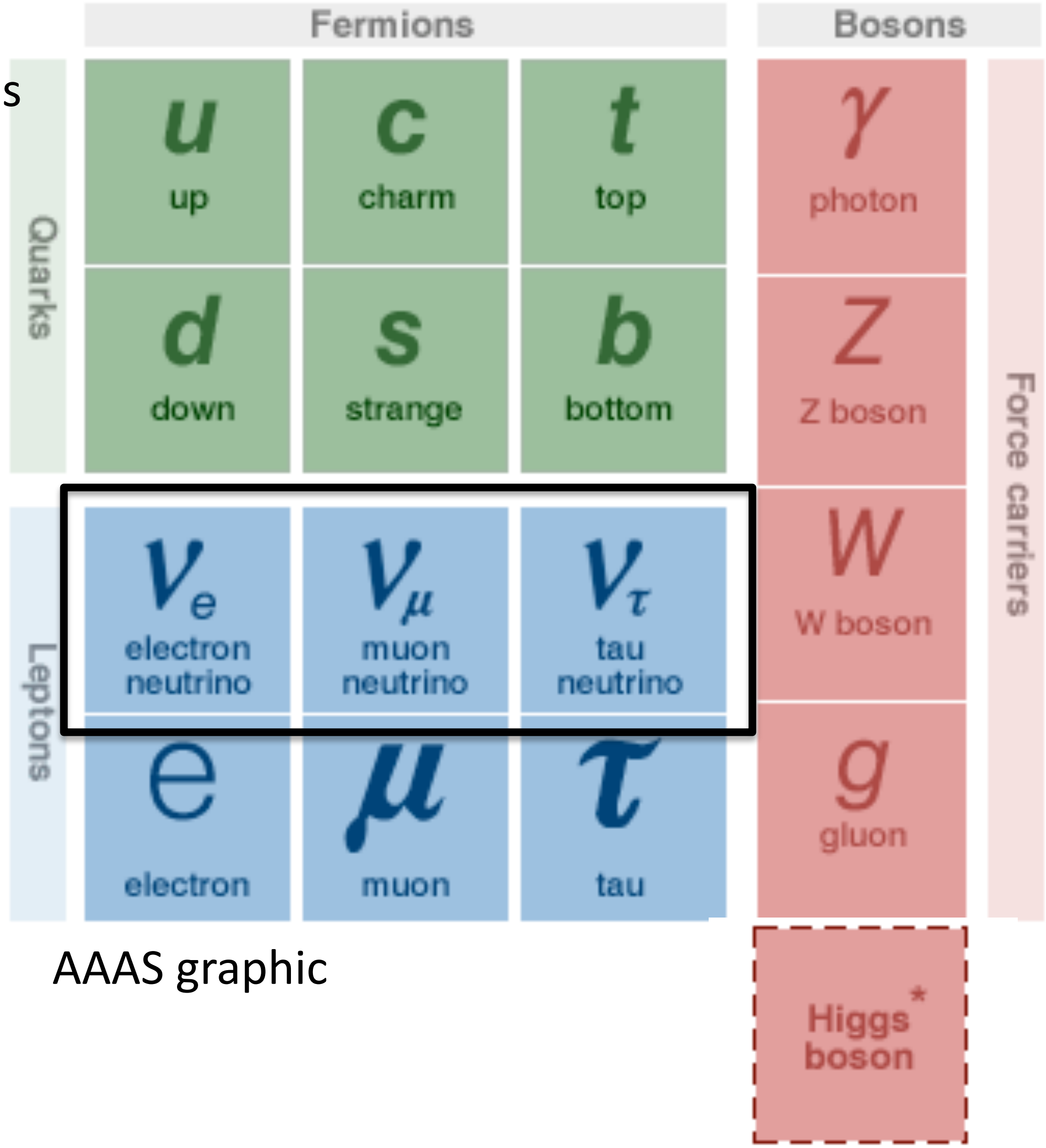
AAAS graphic

The Standard Model

Protons, neutrons

Neutrinos!

Electrons



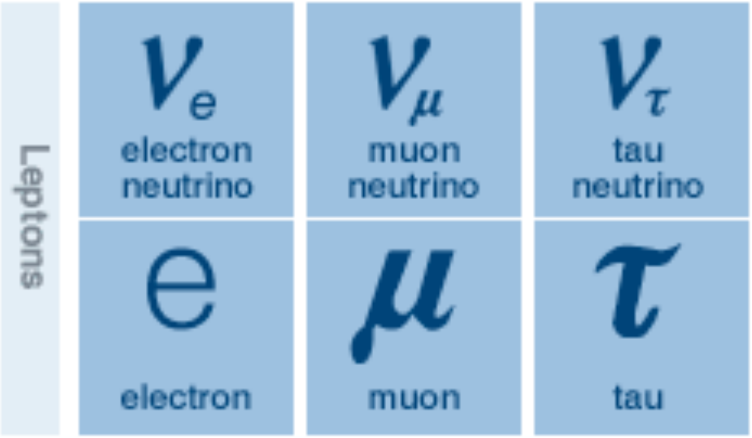
Photons

Protons, neutrons

AAAS graphic

What we now know about neutrinos

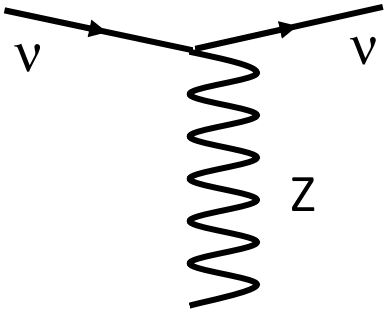
- Three flavors: ν_e, ν_μ , ν_τ



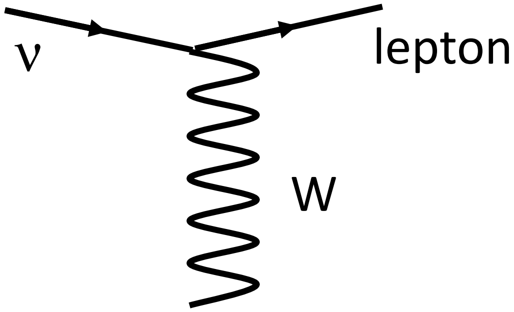
What we now know about neutrinos

- Three flavors: ν_e, ν_μ, ν_τ
- Neutral
- Interact via the weak force

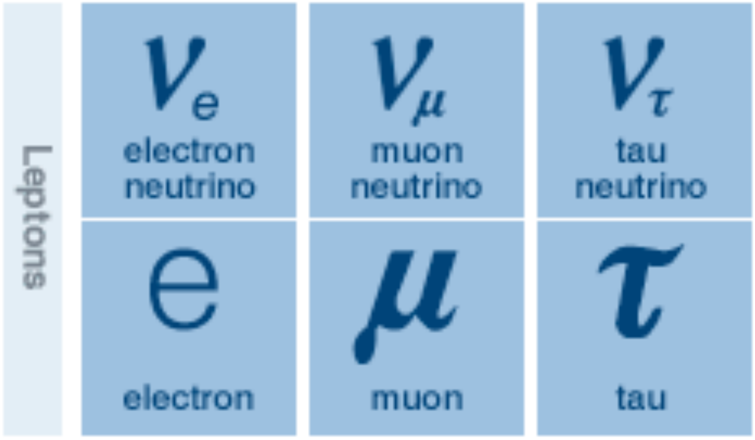
Neutral Current (NC)



Charged Current (CC)



$$\nu_e \longrightarrow e$$
$$\nu_\mu \longrightarrow \mu$$
$$\nu_\tau \longrightarrow \tau$$



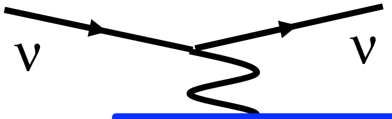
Leptons			
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino
	e electron	μ muon	τ tau

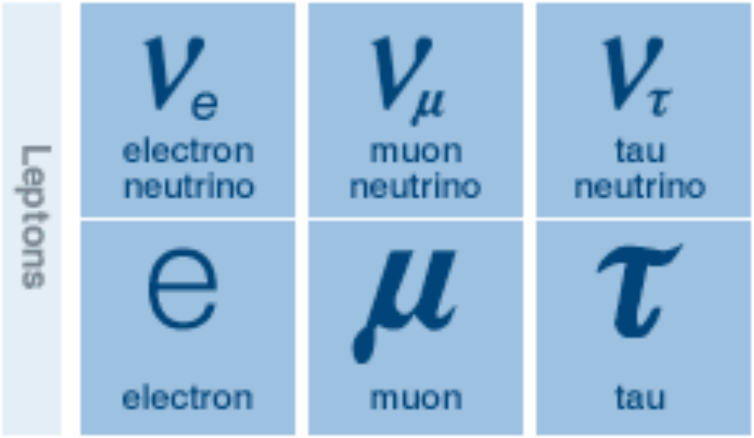
	Force carriers
Z Z boson	
W W boson	

What we now know about neutrinos

- Three flavors: ν_e, ν_μ, ν_τ
- Neutral
- Interact via the weak force

Neutral Current (NC)

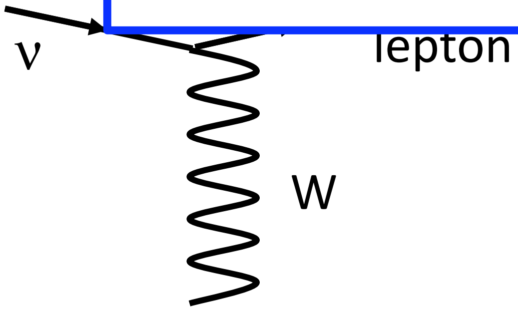




At neutrino energy (E_ν) ~1 GeV, σ_{CC} ~ 10^{-38} cm^2

Mean free path through lead is 1 light year

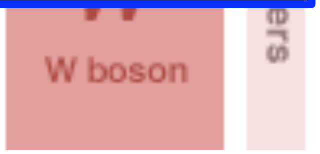
Charg



$$\nu_e \longrightarrow e$$

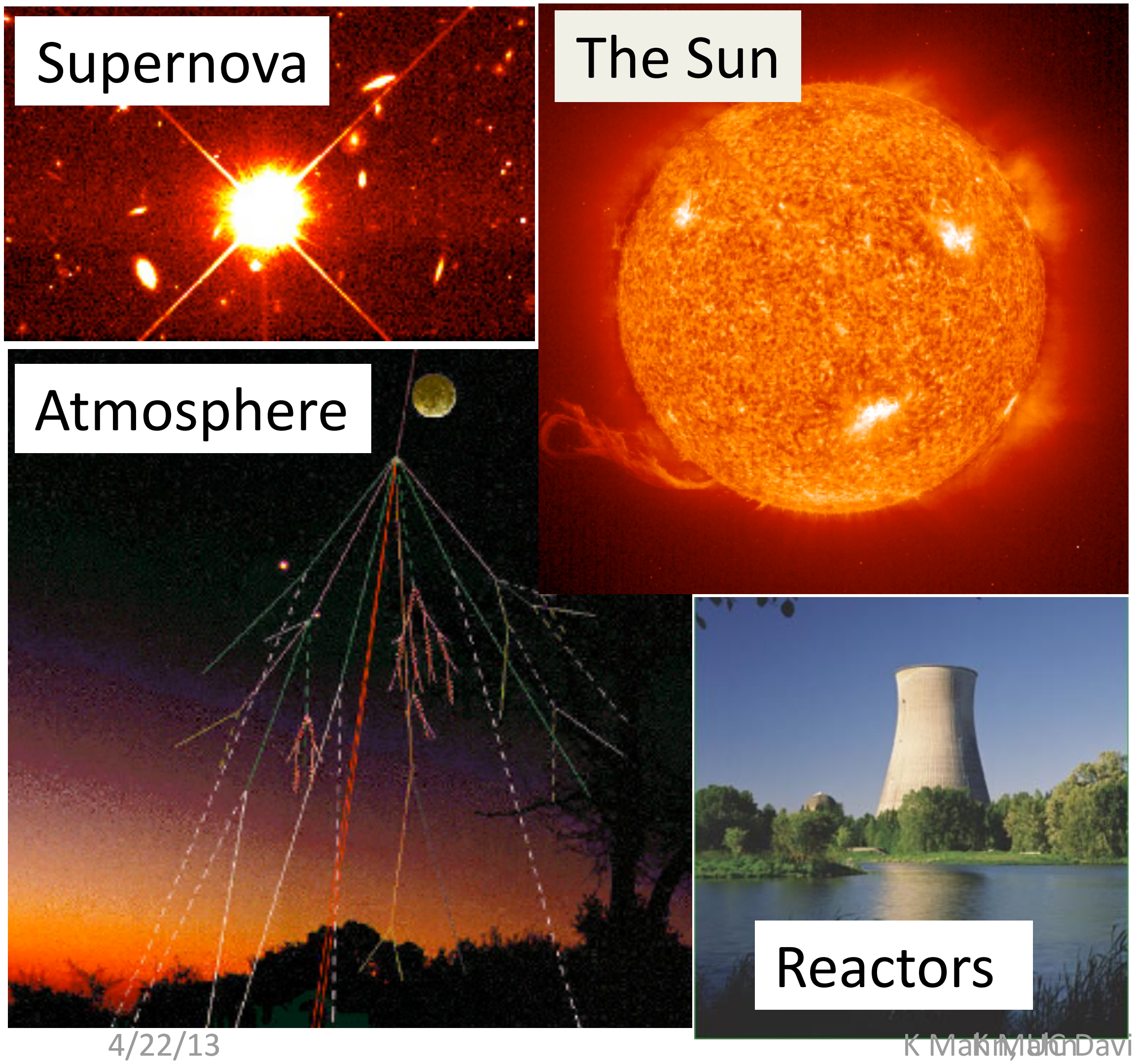
$$\nu_\mu \longrightarrow \mu$$

$$\nu_\tau \longrightarrow \tau$$



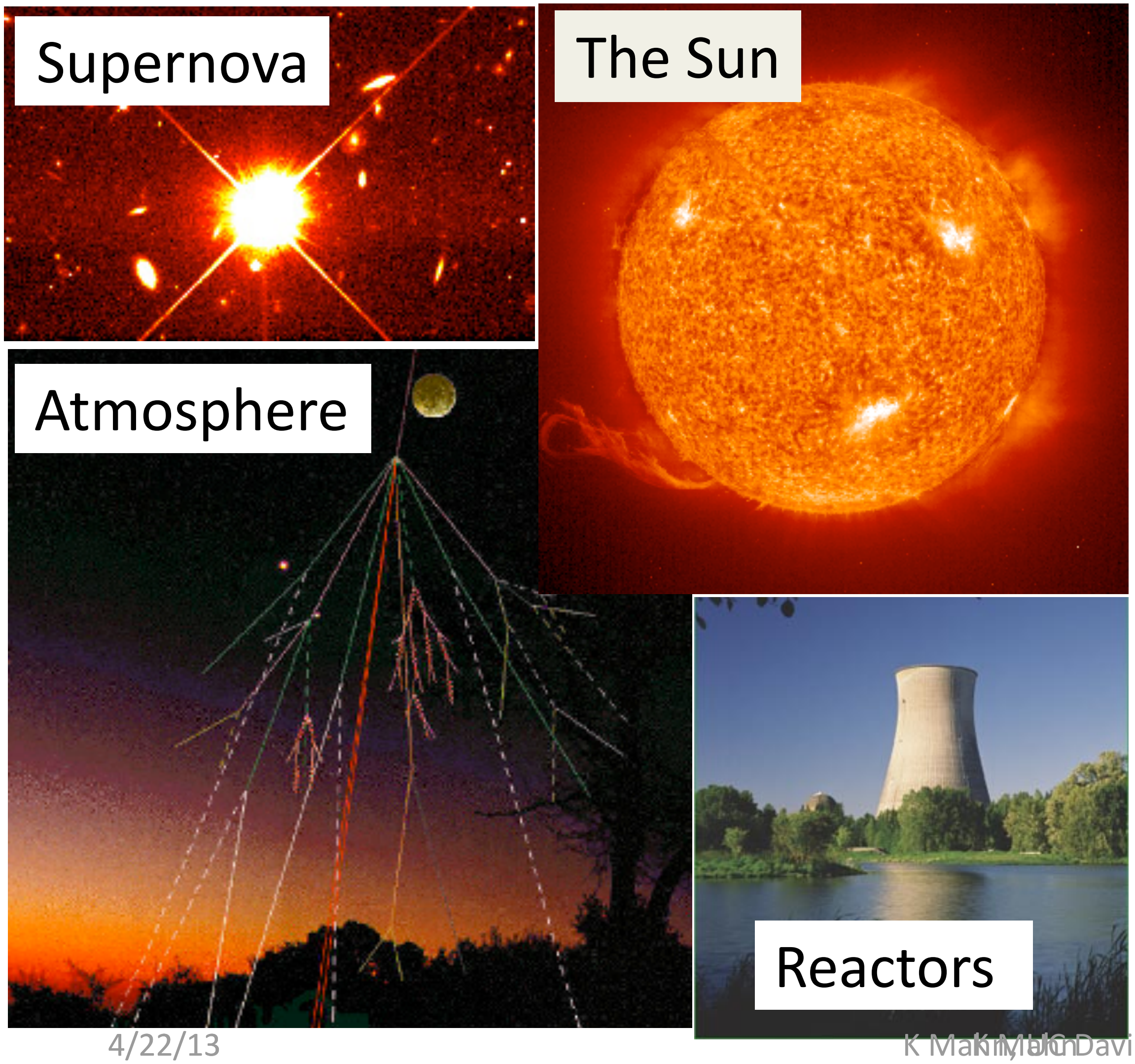
What we now know about neutrinos

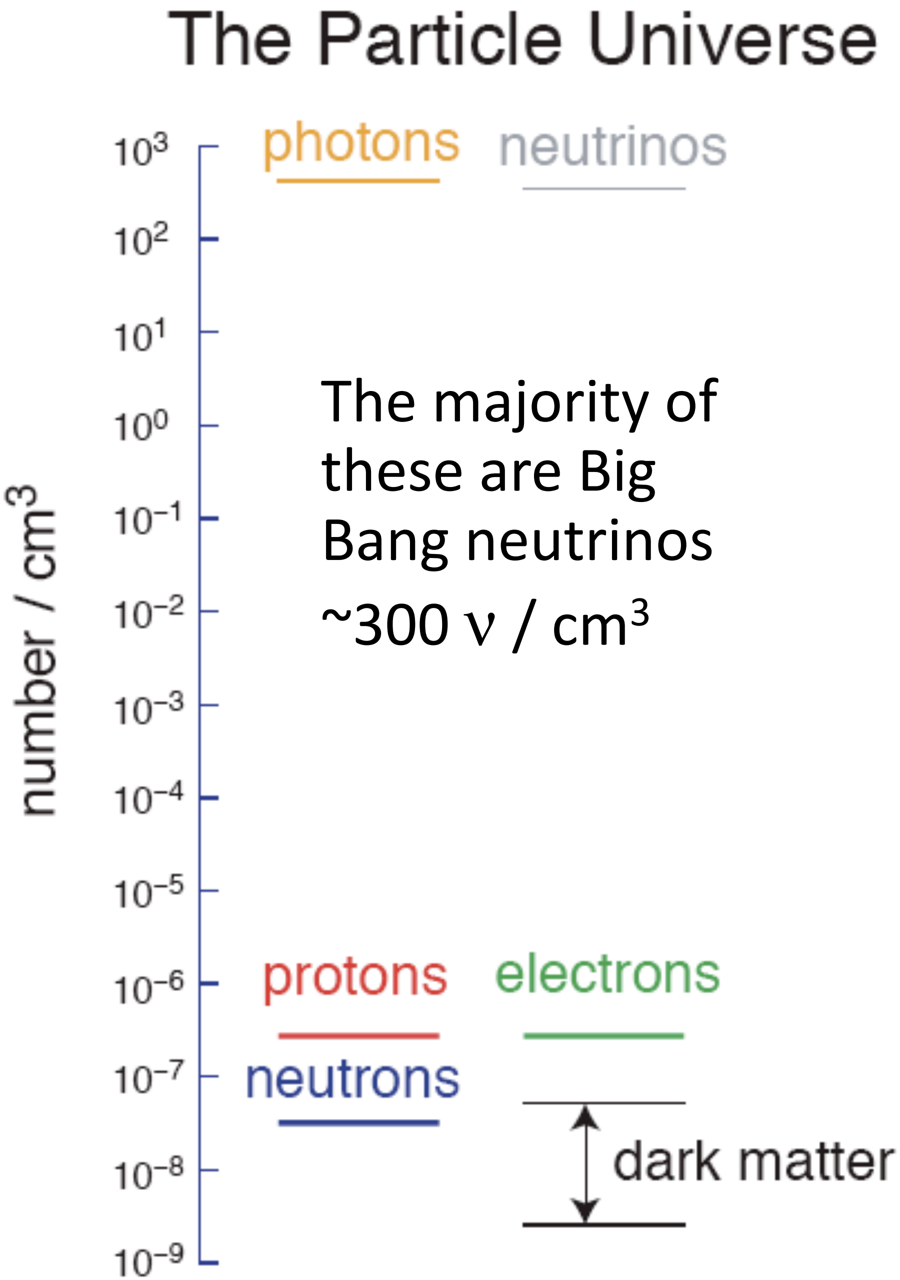
- Three flavors: ν_e, ν_μ, ν_τ
- Neutral
- Interact via the weak force
- Abundant



What we now know about neutrinos

- Three flavors: ν_e, ν_μ, ν_τ
- Neutral
- Interact via the weak force
- Abundant





The majority of these are Big Bang neutrinos

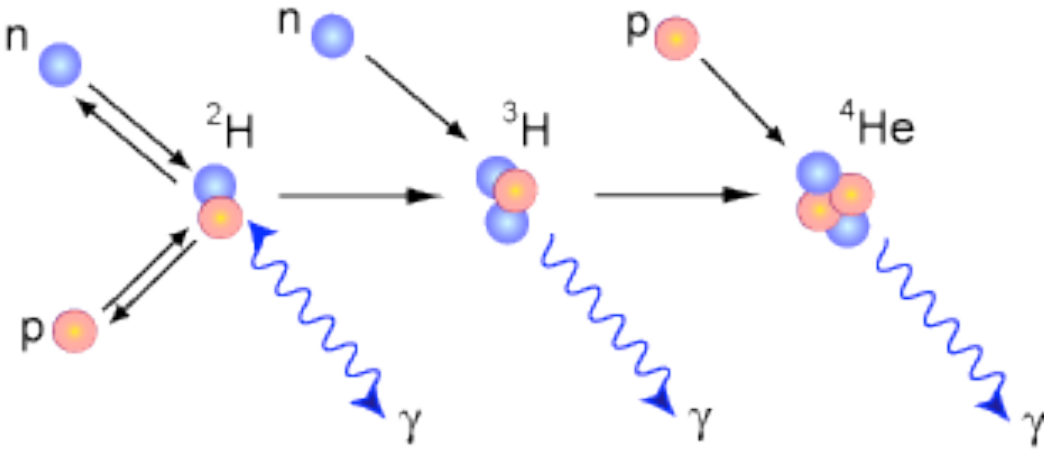
~300 ν / cm^3

H. Murayama graphic

What we now know about neutrinos

- Three flavors: ν_e, ν_μ, ν_τ
- Neutral
- Interact via the weak force
- Abundant

The amount of neutrinos and antineutrinos affects the formation of elements in the early universe:



CSIRO graphic

$$\nu_e + n \to e^- + p$$

$$\overline{\nu}_e + n \to e^+ + n$$

What we now know about neutrinos

- Three flavors: ν_e, ν_μ, ν_τ
- Neutral
- Interact via the weak force
- Abundant
- Massive

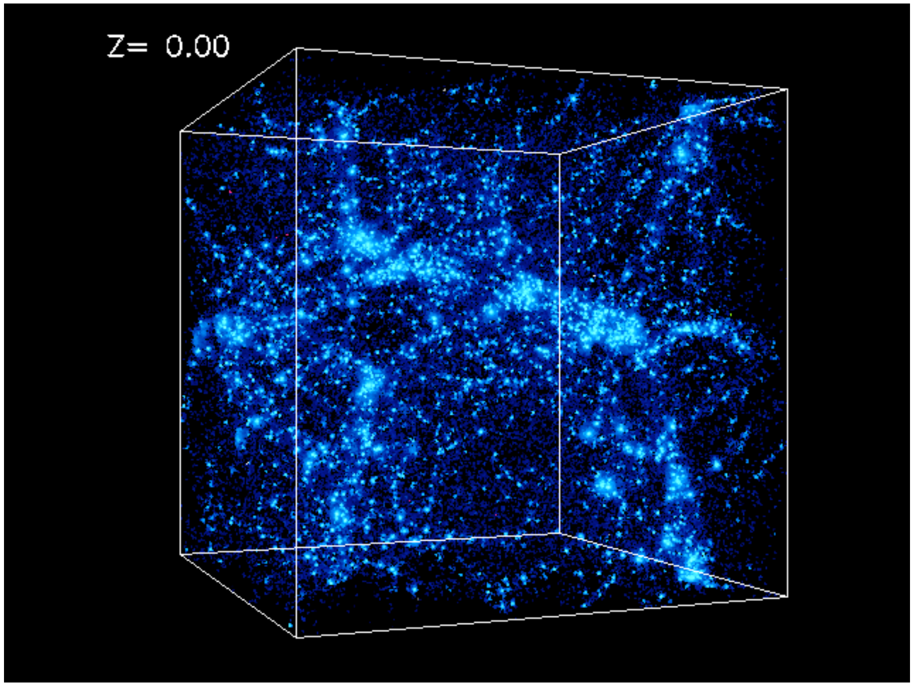
The mass of the neutrino is small but it has a big impact in the early universe

At early times, neutrinos behave like radiation

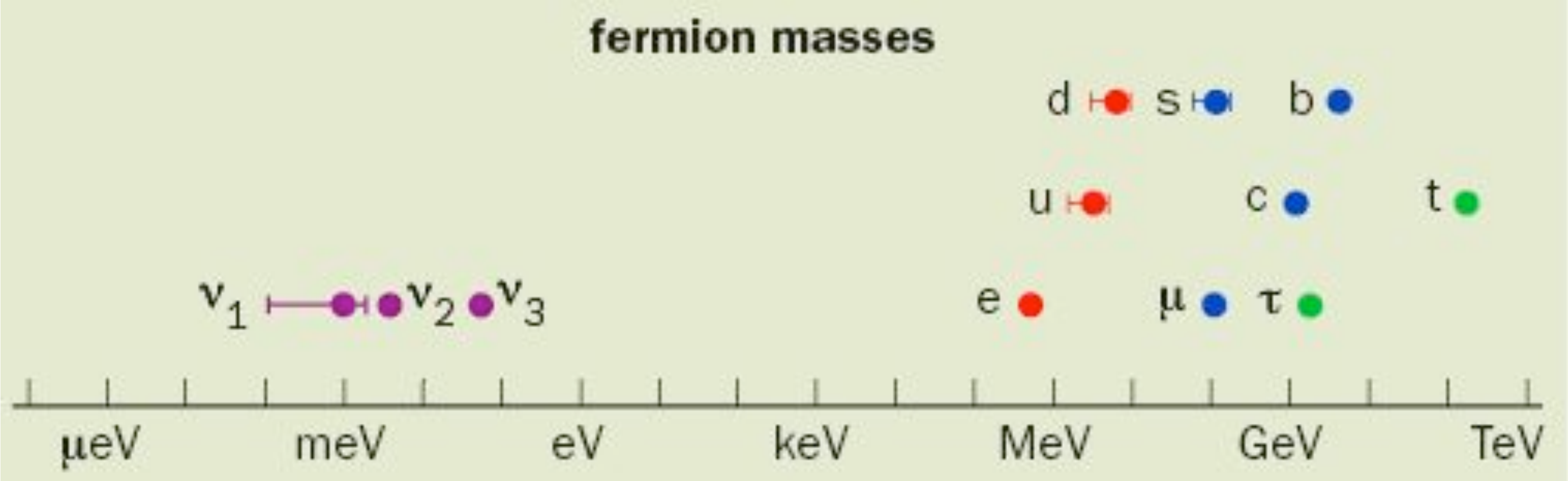
At late times, neutrinos behave like matter

Affects large scale structure formation

Center for Cosmological Physics graphic



Neutrino mass is SMALL



H. Murayama graphic

While we know neutrinos have mass, we don't know the origin of neutrino mass

- Neutrinos are unlike other particles in the Standard Model because they are neutral and only interact with the weak force (and gravity)

Why is neutrino mass non-zero?

Why is it so much smaller than the other particles?

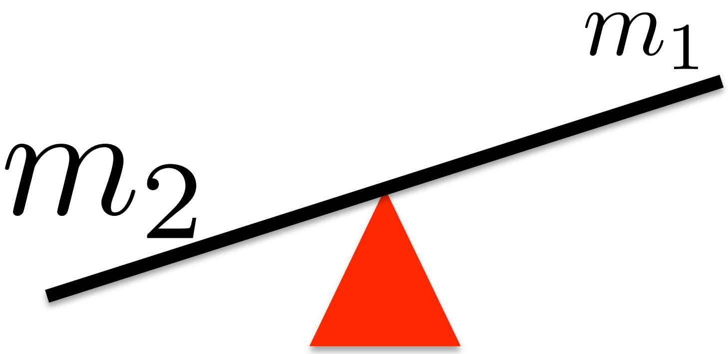
Neutrino mass

The “see saw mechanism” explains the lightness of the neutrino mass by adding a (very heavy) neutrino which doesn’t interact

If we have one neutrino which interacts in the Standard Model (m_D) and a heavy partner (m_R) then:

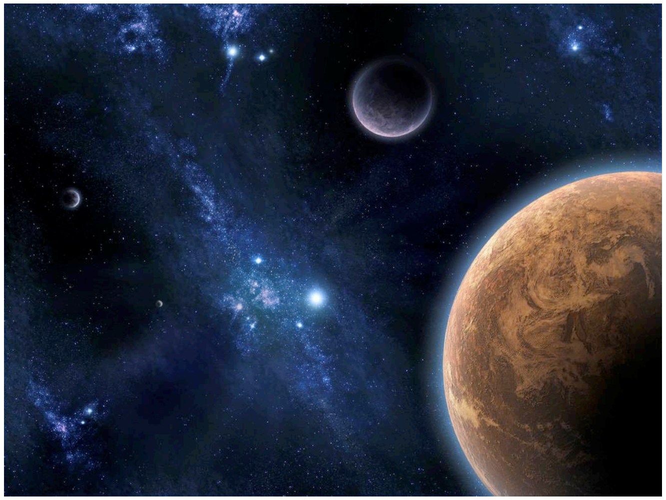
$$m_1 \simeq \frac{(m_{\rm D})^2}{m_R} \ll m_{\rm D}\,,$$

$$m_2 \simeq m_R\,,$$



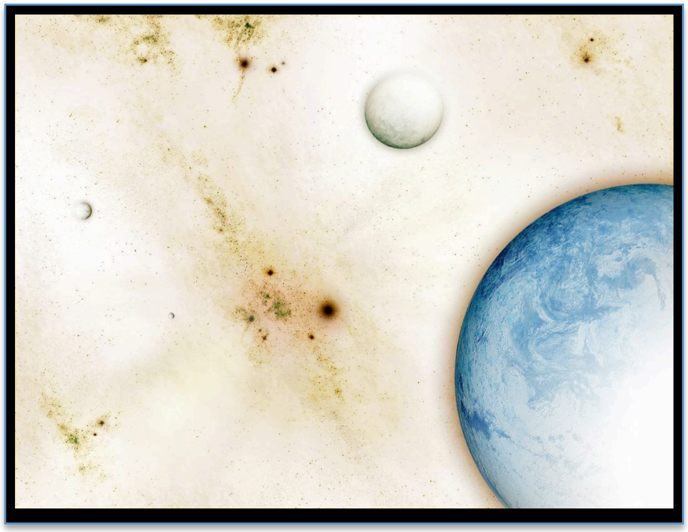
To get the observed neutrino mass, then m_2~m_R is very heavy (10^{15} GeV)

Neutrinos and the matter-antimatter asymmetry



?

≠

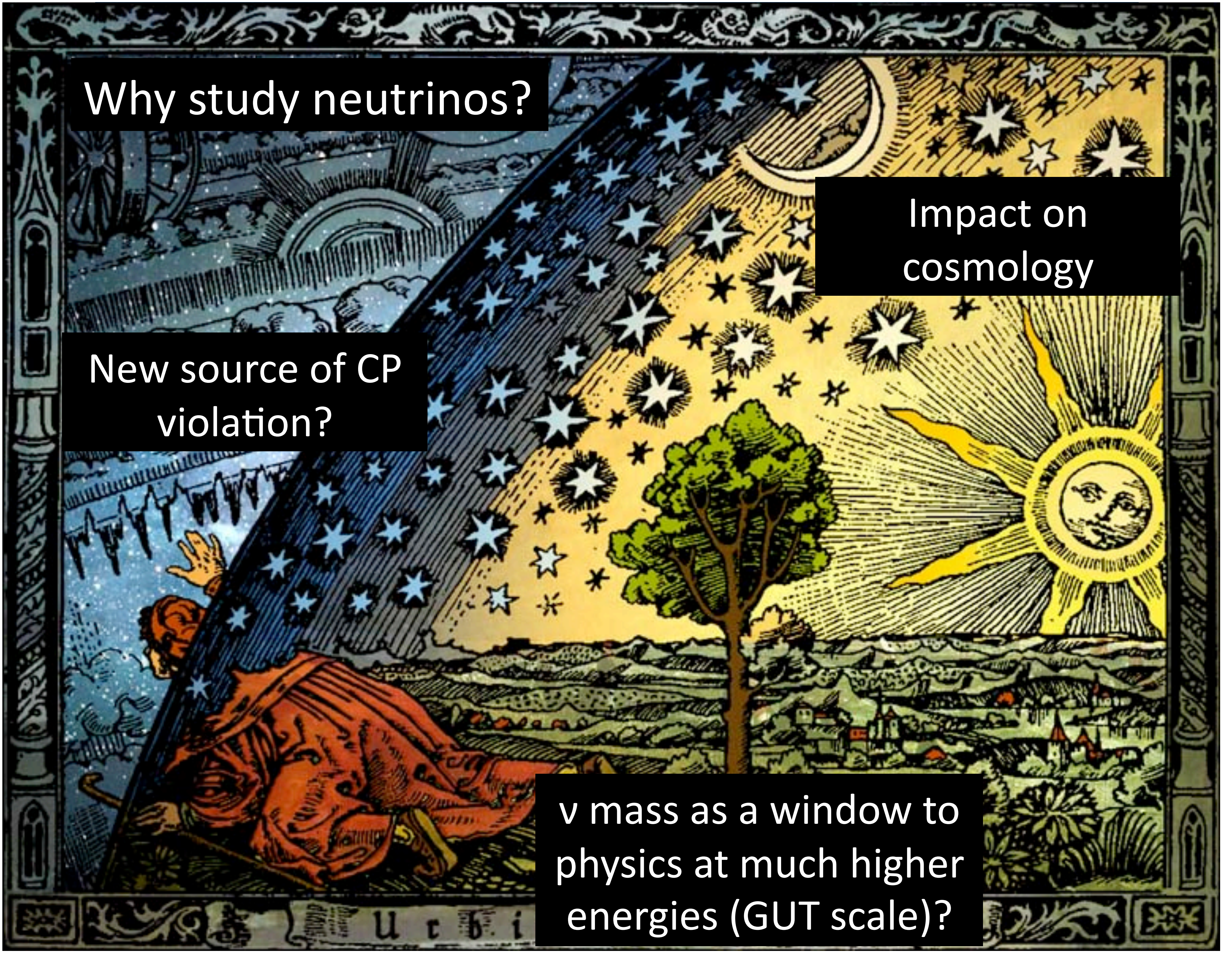


How do we explain the observed matter-antimatter asymmetry in the universe?

- To create this asymmetry, we need: non-thermal equilibrium, CP violation and baryon number violation
- So far, there is no sufficient source of CP violation in the Standard Model

If there is CP violation with neutrinos, CP violating decays of the heavy neutrino can create the baryon number violation

Searching for CP violation with neutrinos may lead to insights about this mechanism



Why study neutrinos?

Impact on cosmology

New source of CP violation?

ν mass as a window to physics at much higher energies (GUT scale)?

What is neutrino oscillation?

We know neutrinos have mass because of we observe neutrino “oscillation”: the interference between the flavor and mass eigenstates of the neutrino

If we start with two neutrino flavor (ν_e, ν_μ) and two mass states (ν_1, ν_2) then:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\,\theta & \sin\,\theta \\ \text{-}\sin\,\theta & \cos\,\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

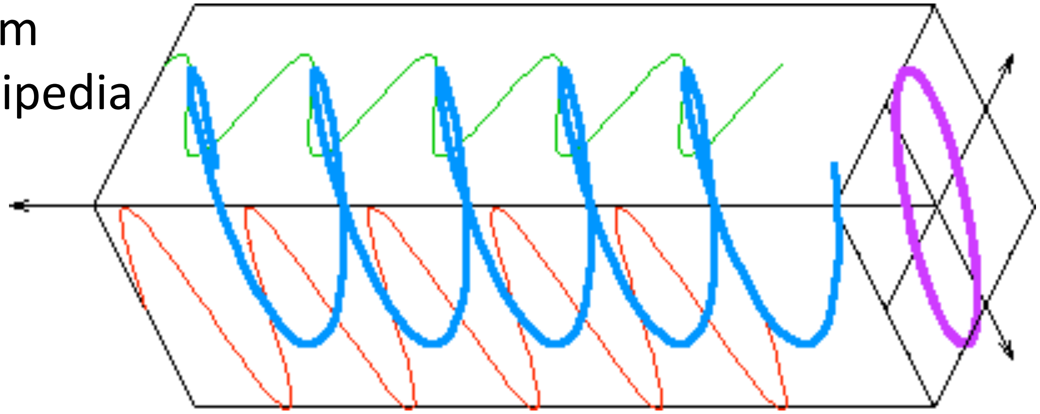
The flavor state evolution in time is like an elliptically polarized wave:

$$|\nu_e(t)\rangle = \cos\,\theta\; e^{-iE_1 t}\,|\nu_1\rangle - \sin\,\theta\; e^{-iE_2 t}\,|\nu_2\rangle$$

What is neutrino oscillation?

The flavor state evolution in time is like an elliptically polarized wave:

$$|\nu_e(t)\rangle = \cos\theta\ e^{-iE_1t}\,|\nu_1\rangle - \sin\theta\ e^{-iE_2t}\,|\nu_2\rangle$$



From wikipedia

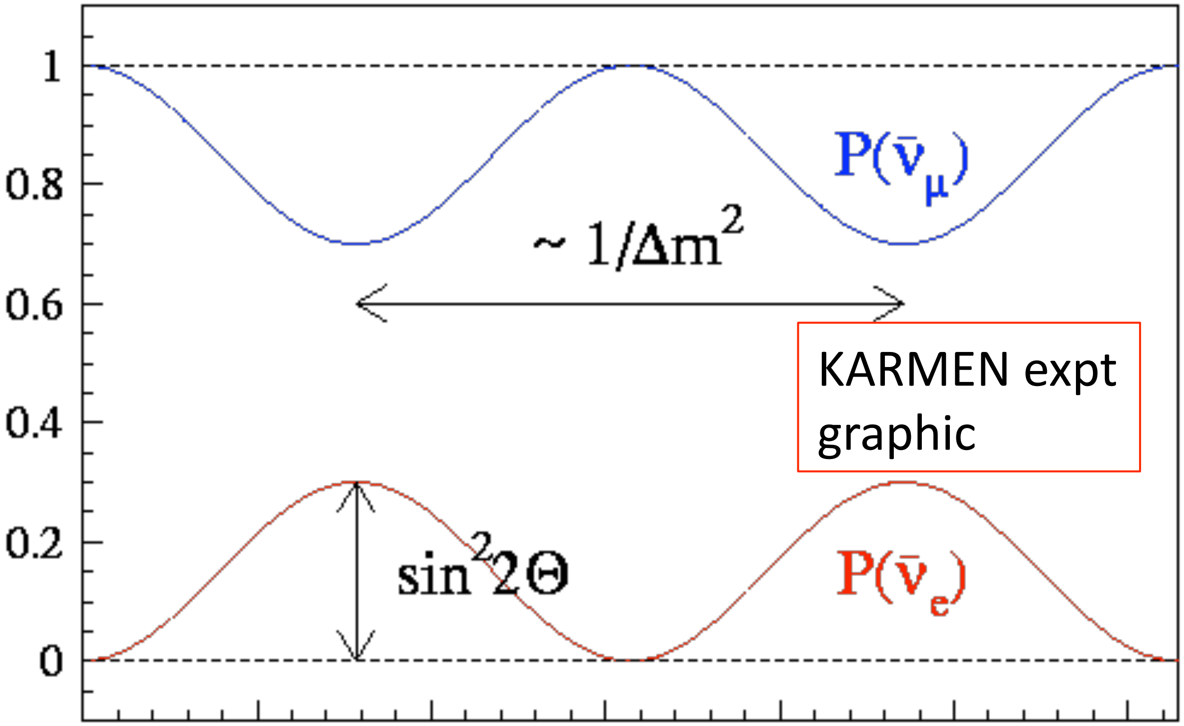
Starting polarized along the x-axis (like starting in ν_μ state) then:

- Some time later polarization is along y-axis (ν_e)
- Or back to the x-axis (ν_μ)

No mass, no oscillation

Neutrino oscillation

$$P_{\mu e} = \sin^2 2\theta \sin^2\left(\frac{1.27\boxed{\Delta m_{ij}^2}\boxed{L}}{\boxed{E}}\right)$$



KARMEN expt graphic

Probability to observe ν_μ after starting in flavor state ν_e depends on:

- θ: Mixing angle
- L (km): Distance the neutrino has travelled
- E (GeV): Energy of the neutrino
- Δm^2 (eV^2): mass splitting

  Difference of the square of the mass eigenvalues

$$\boxed{\Delta m_{ij}^2 = m_i^2 - m_j^2}$$

If neutrinos have no mass, or degenerate masses, no interference is possible

Open questions about neutrino mixing

Flavor eigenstates
(coupling to the W)

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

Mass eigenstates
(definite mass)

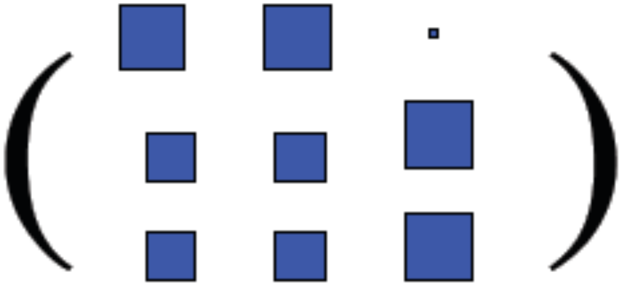
Unitary PMNS mixing matrix

Three observed flavors of neutrinos (ν_e, ν_μ, ν_τ) means U is represented by three independent mixing angles (θ_{12}, θ_{23}, θ_{13}) and a CP violating phase δ

$$\theta_{12} = 33.6° \pm 1.0°$$

$$\theta_{23} = 45° \pm 6° \quad (90\%\mathrm{CL})$$

$$\theta_{13} = 9.1° \pm 0.6°$$



Is θ_{23} mixing maximal (45°?)

Open questions about neutrino mixing

Flavor eigenstates (coupling to the W)

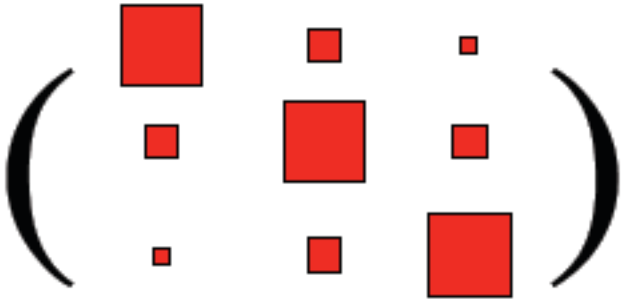
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Mass eigenstates (definite mass)

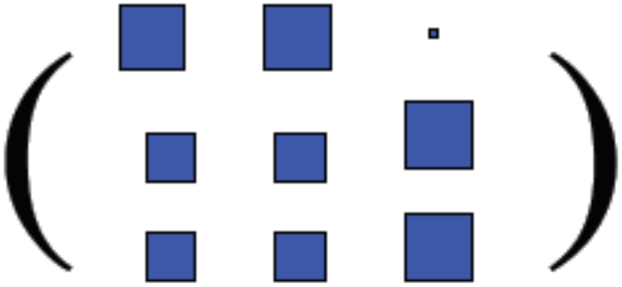
Unitary PMNS mixing matrix

Three observed flavors of neutrinos (ν_e, ν_μ, ν_τ) means U is represented by three independent mixing angles (θ_{12}, θ_{23}, θ_{13}) and a CP violating phase δ

Quark mixing angles are small:



Neutrino mixing angles are large:



Why are quark and lepton mixing so different?

Open questions about neutrino mixing

Flavor eigenstates (coupling to the W)

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

Mass eigenstates (definite mass)

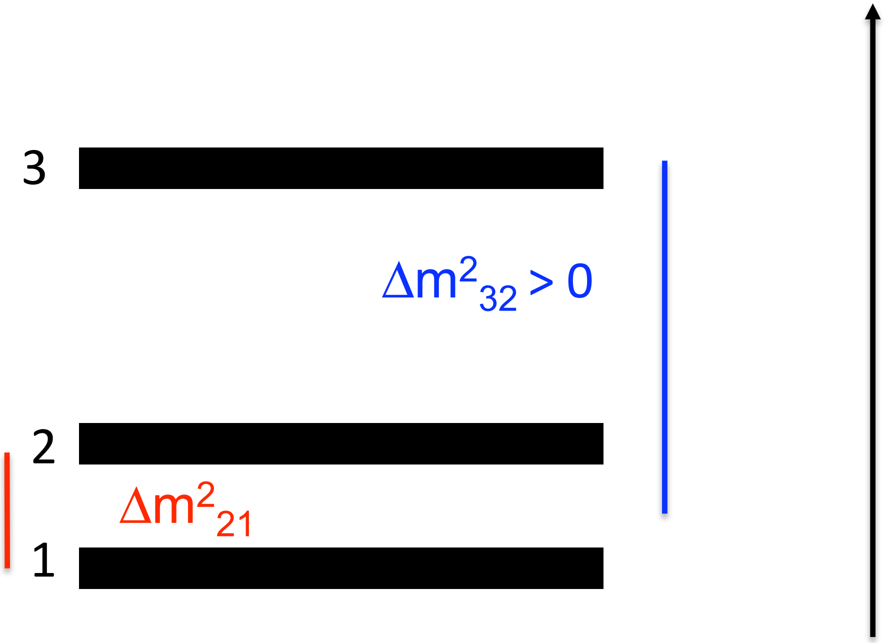
Unitary PMNS mixing matrix

Three observed flavors of neutrinos (ν_e, ν_μ, ν_τ) means U is represented by three independent mixing angles (θ_{12}, θ_{23}, θ_{13}) and a CP violating phase δ

$$\delta_{CP} = ??$$

Is there CP violation in the neutrino sector?
Is it large?

Neutrino mass differences



Neutrino mass squared (m_i^2)

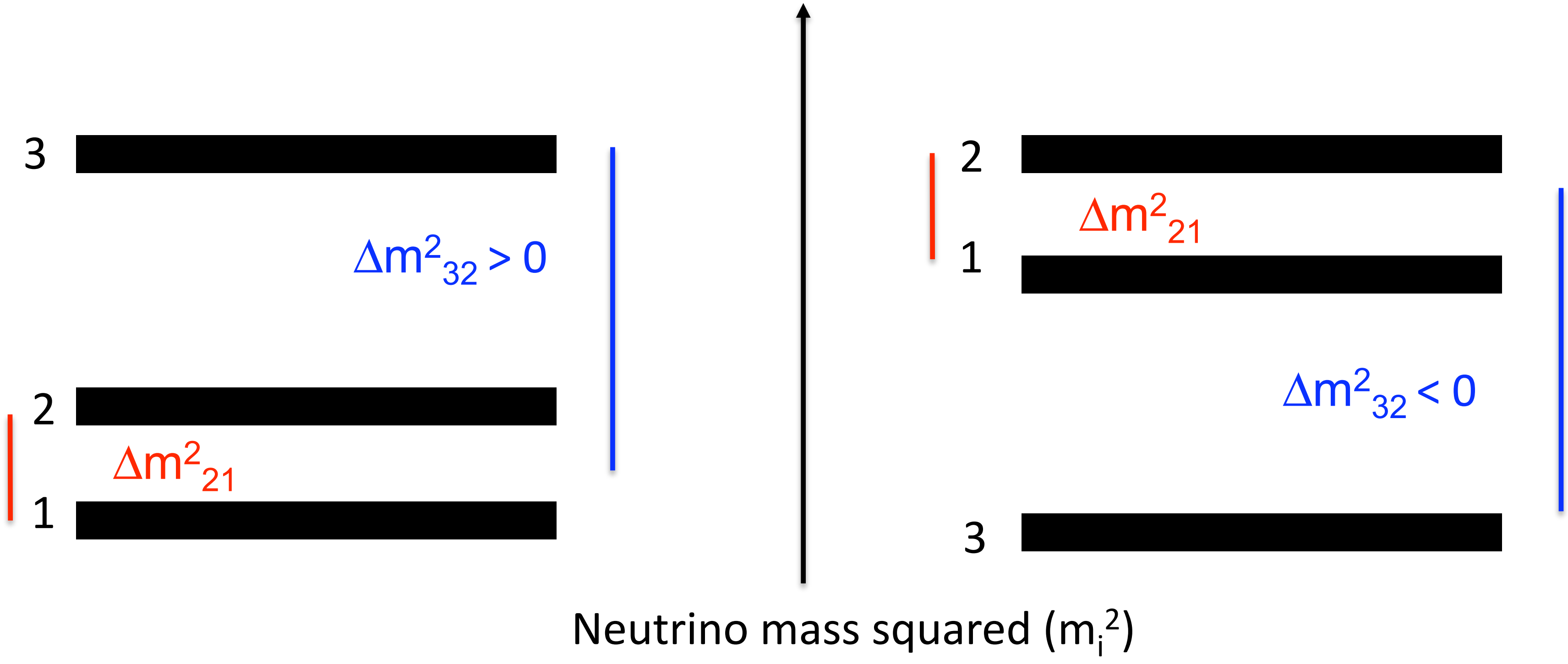
$$\boxed{\Delta m^2_{ij} = m^2_i - m^2_j}$$

Three neutrino mass eigenstates mean two independent mass differences

Two observed mass “splittings”, determined from atmospheric and solar neutrino experiments, respectively

- Δm^2(atmospheric) = $|\Delta m^2_{32}| \sim 2.4 \times 10^{-3}$ eV^2
- Δm^2(solar) = $\Delta m^2_{21} \sim 7.6 \times 10^{-5}$ eV^2

Open questions about neutrino mixing



The sign of Δm^2_{32}, or the “mass hierarchy” is still unknown

- Normal “hierarchy” is like quarks (m_1 is lightest, $\Delta m^2_{32} > 0$)
- Inverted hierarchy has m_3 lightest ($\Delta m^2_{32} < 0$)

Neutrino oscillation, revisited

$\Delta m^2_{32} >> \Delta m^2_{21}$, producing high frequency and low frequency oscillation terms

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\sum_{i>j}\mathrm{Re}\left[U_{\beta i}U^*_{\alpha i}U^*_{\beta j}U_{\alpha j}\right]\sin^2\left(\frac{\boxed{\Delta m^2_{ij}}\boxed{L}}{4\boxed{E}}\right) + 2\sum_{i>j}\mathrm{Im}\left[U_{\beta i}U^*_{\alpha i}U^*_{\beta j}U_{\alpha j}\right]\sin\left(\frac{\boxed{\Delta m^2_{ij}}\boxed{L}}{2\boxed{E}}\right)$$

If choose L, E, such that $\sin^2(\Delta m^2_{32}L/E)$ is of order 1, then Δm^2_{21} terms will be small. Then...

ν_μ "disappear" into ν_e, ν_τ

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

A small fraction of ν_e will "appear"

$\Delta m^2_{31} \sim \Delta m^2_{32}$

Only leading order term shown

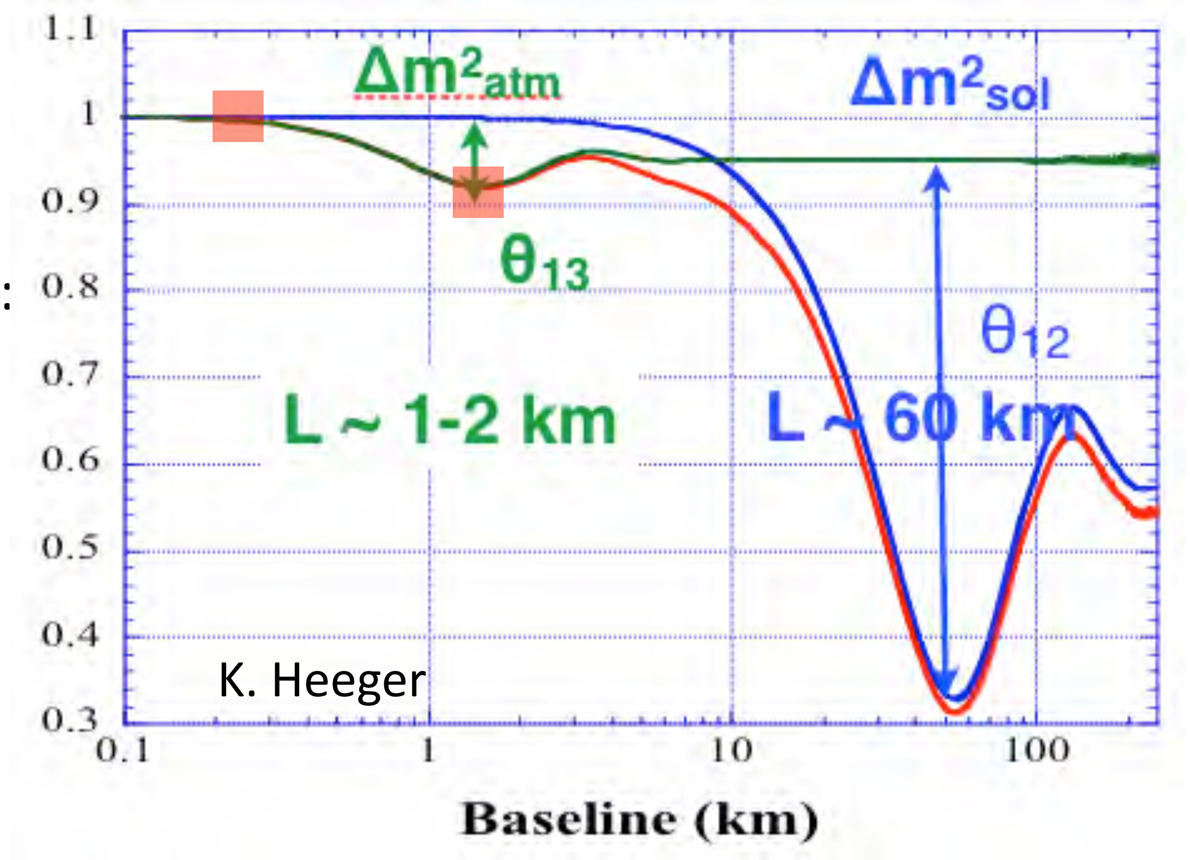
$$\boxed{P(\nu_\mu \rightarrow \nu_e) \cong \sin^2 2\theta_{13}\sin^2\theta_{23}\sin^2\left(\frac{\Delta m^2_{31}L}{4E}\right)}$$

Disappearance measurements: reactors

Antineutrino disappearance from (a group of) reactors

Measure rate with inverse beta decay:

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



K. Heeger

Determine θ_{13} from difference between near and far detectors from the reactor complex

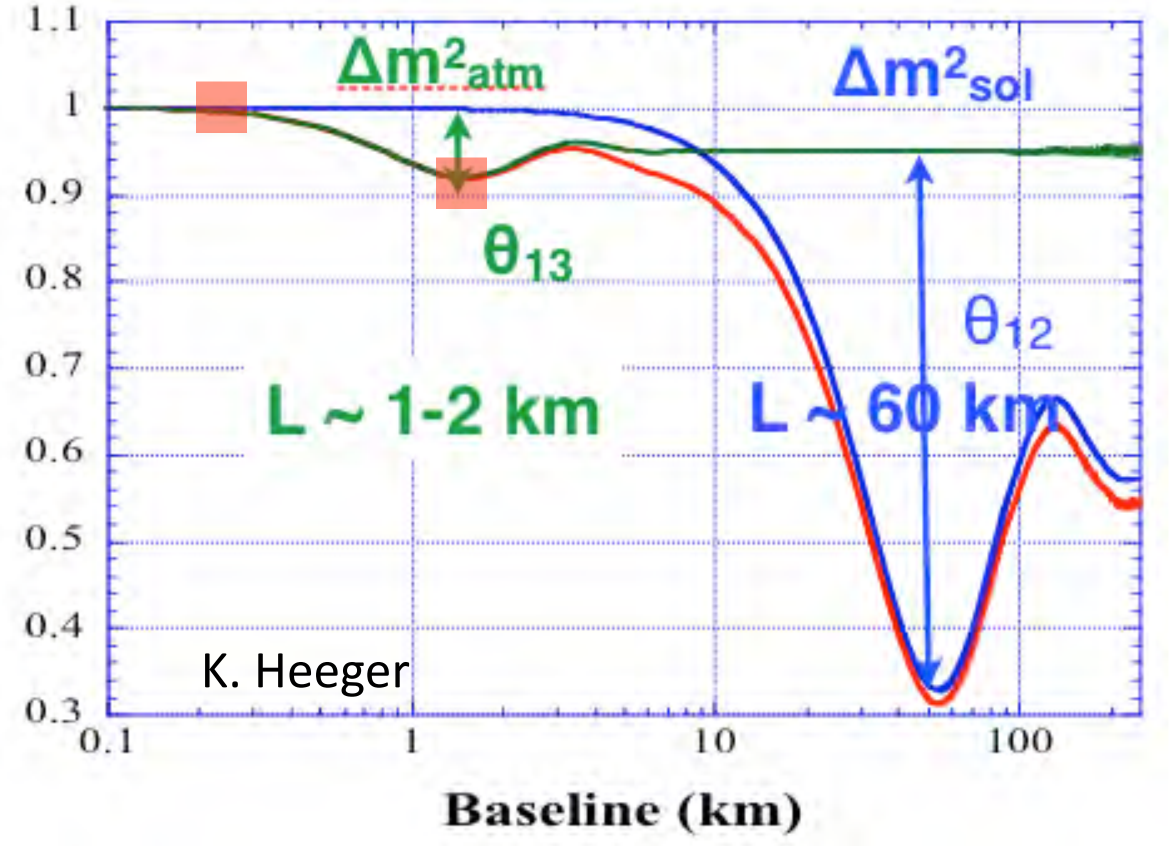
$$P(\nu_e \rightarrow \nu_{x \neq e}) \approx \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$

Disappearance measurements: reactors

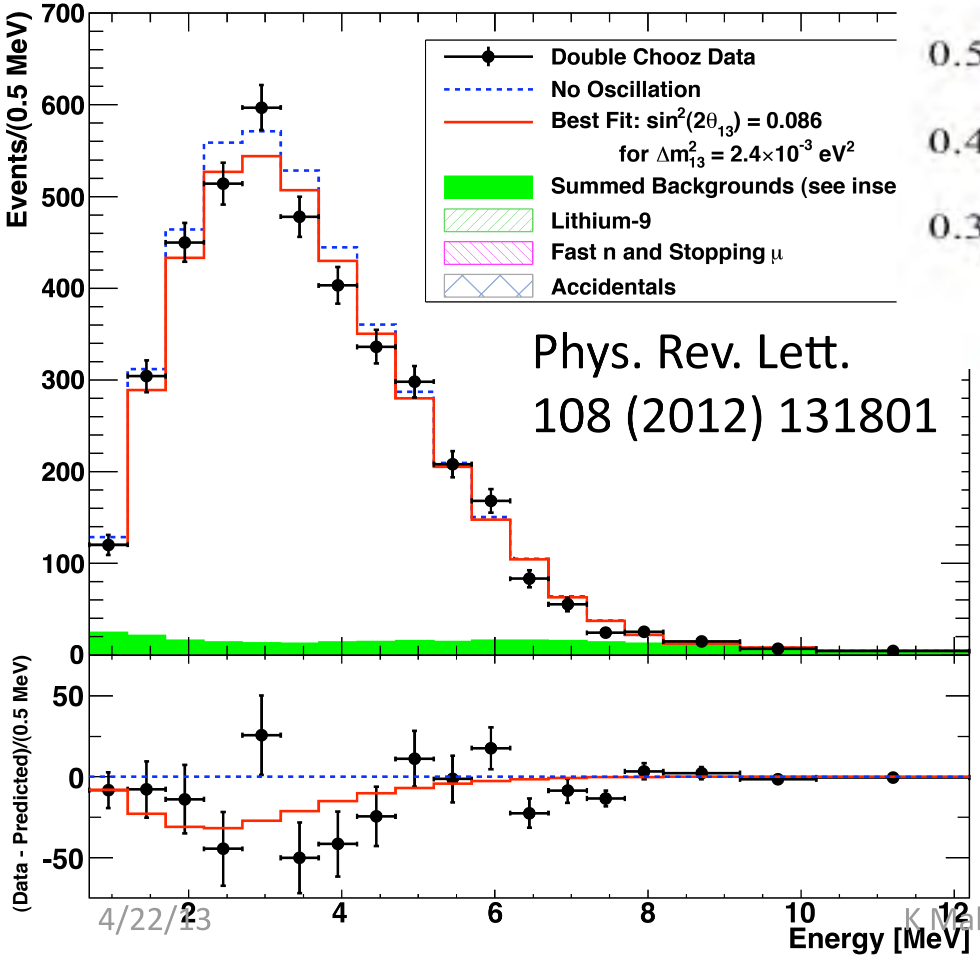
Antineutrino disappearance from (a group of) reactors

Measure rate with inverse beta decay:

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



K. Heeger



Phys. Rev. Lett. 108 (2012) 131801

Determine θ_{13} from difference between near and far detectors from the reactor complex

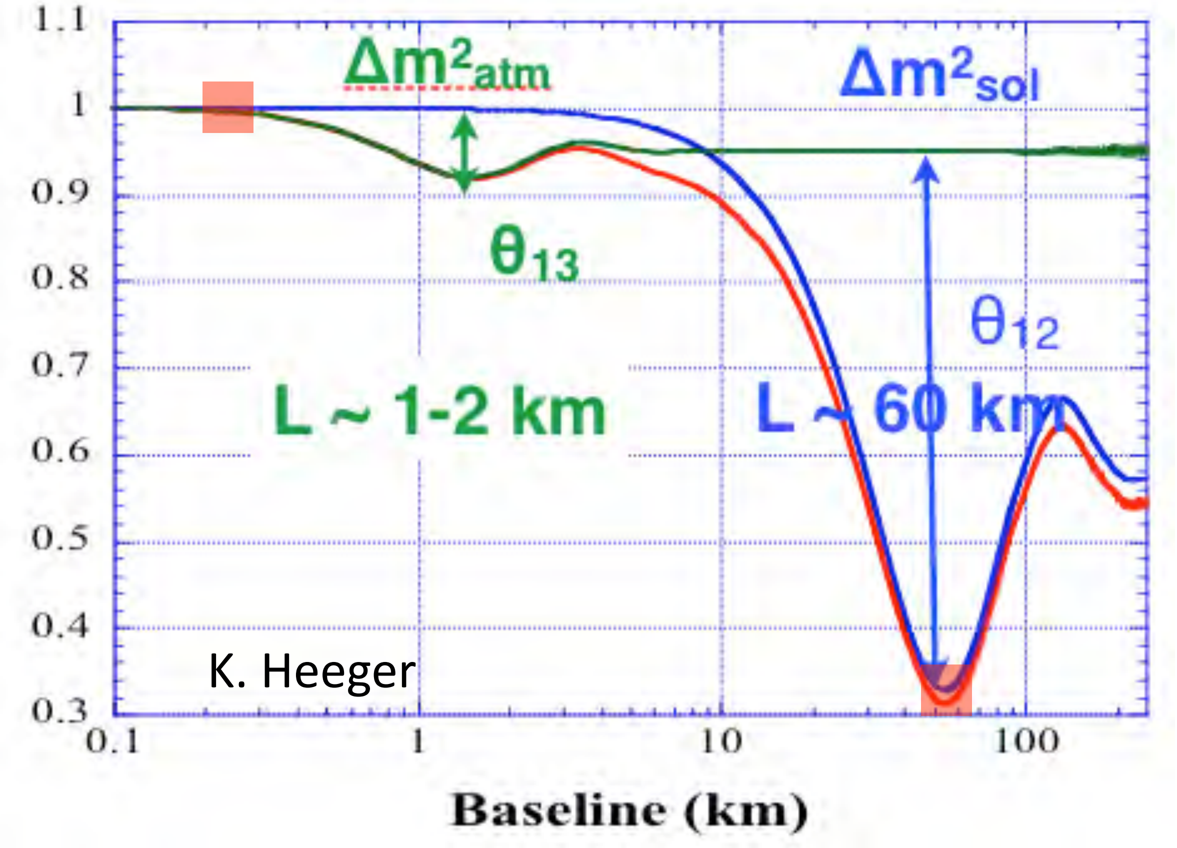
$$\theta_{13} = 9.1^\circ \pm 0.6^\circ$$ PDG2012

Daya Bay, RENO, Double Chooz collaborations

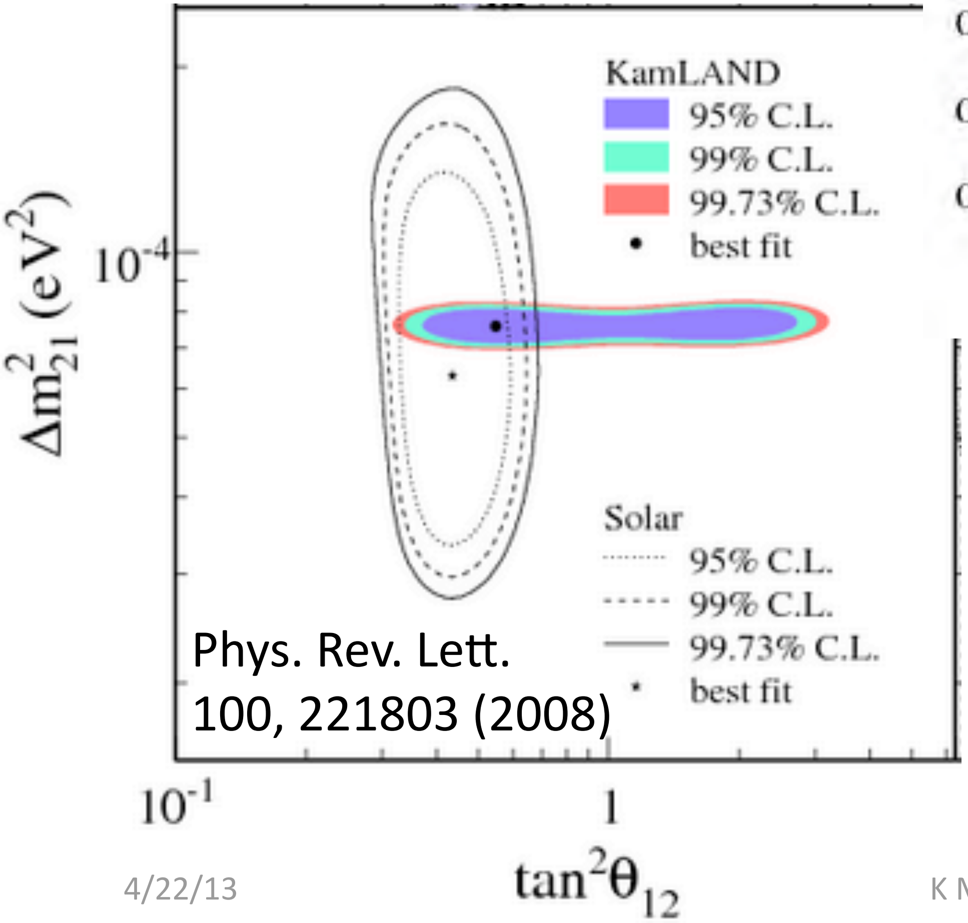
Disappearance measurements

Can also use reactor sources to measure solar mixing parameter (KamLAND)

Complementary to solar neutrino experiments (e.g. SNO)



K. Heeger



Phys. Rev. Lett. 100, 221803 (2008)

Determine Δm^2_{21} , θ_{12} from the distorted energy spectrum

$$\Delta m^2_{21} = 7.6 \times 10^{-5} eV^2$$

$$\theta_{12} = 33.6° \pm 1.0°$$

PDG2012

Disappearance with atmospheric sources

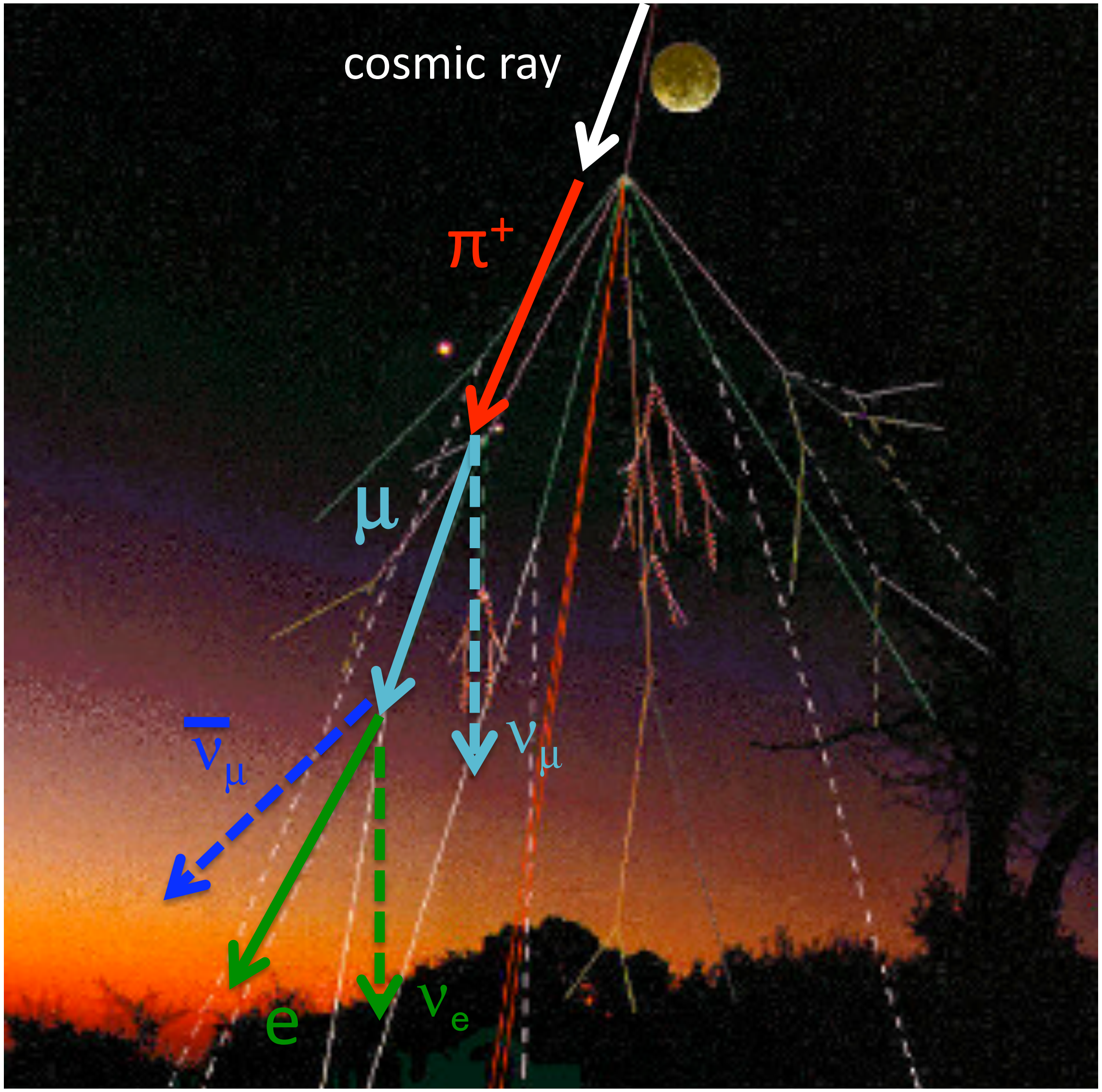
Muon neutrino disappearance from atmospheric neutrinos

Cosmic rays (protons, He, etc) hit nuclei in atmosphere:

- Produces muon neutrinos, muon antineutrinos and electron neutrinos

Need a large detector and time:

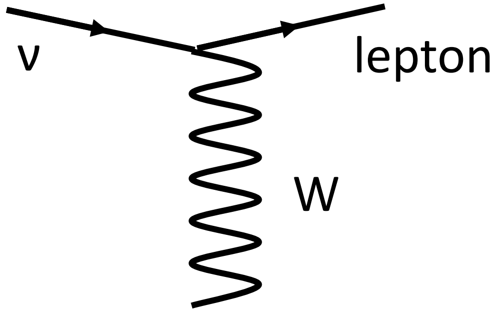
- MINOS
- IceCube
- Super-Kamiokande



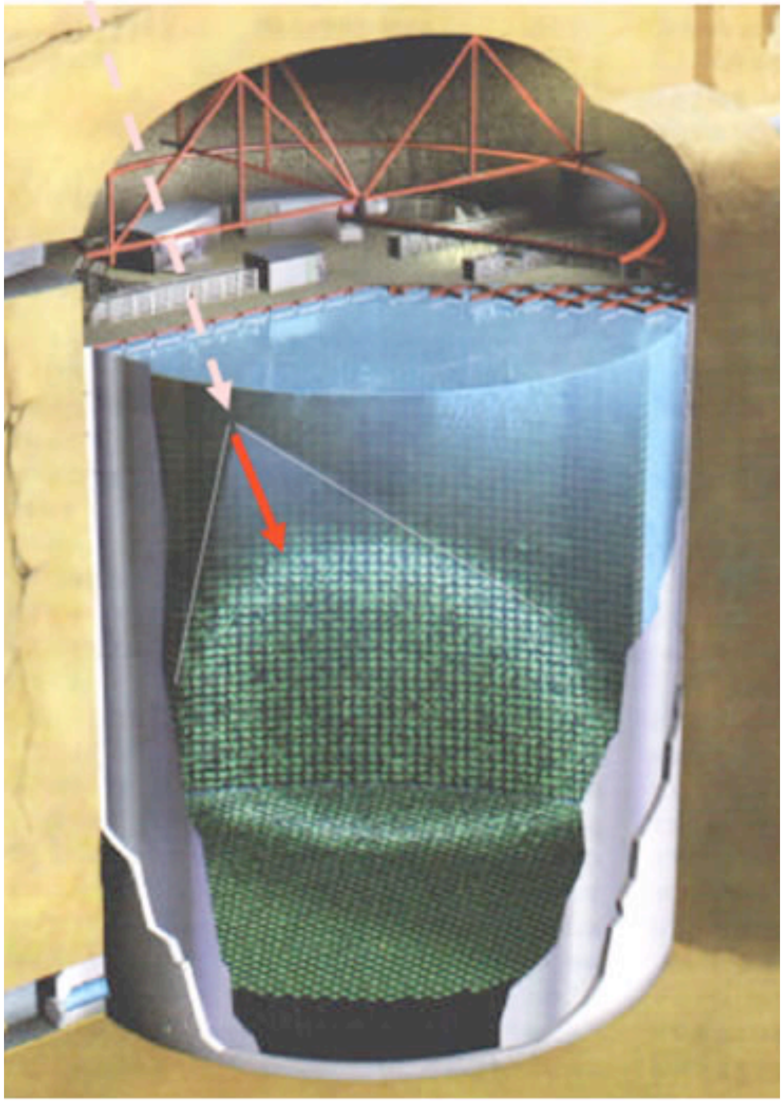
Detecting atmospheric neutrinos

Detect neutrino interactions with charged current interactions

Charged Current (CC)



$$\nu_e \longrightarrow e$$
$$\nu_\mu \longrightarrow \mu$$
$$\nu_\tau \longrightarrow \tau$$



Super-Kamiokande: 22.5kton fiducial volume water Cherenkov detector

Charged particles emit Cherenkov light

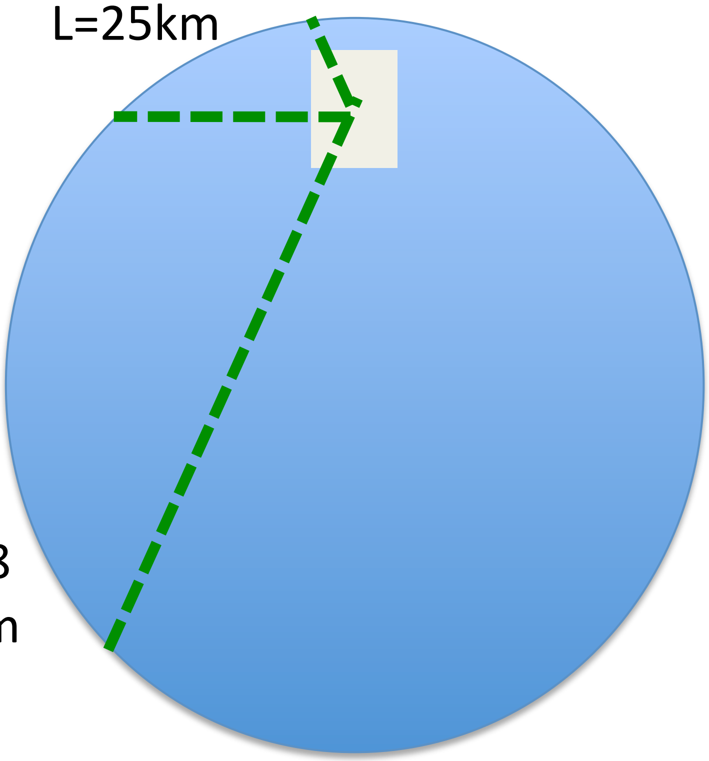
- Ring is imaged by 11,129 PMTs; ring is used used to determine the lepton direction and momentum
- Entering (non-neutrino) events are rejected by outer veto region
- Select ν_e or ν_μ events from ring shape and topology

Disappearance measurements: atmospheric nu

Oscillation probability changes with L:

- Distance from production to detector
- As a function of angle from the zenith cos(θ)

$$P(\nu_\mu \to \nu_\mu) \cong 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{1.27\Delta m_{32}^2 L}{E}\right)$$

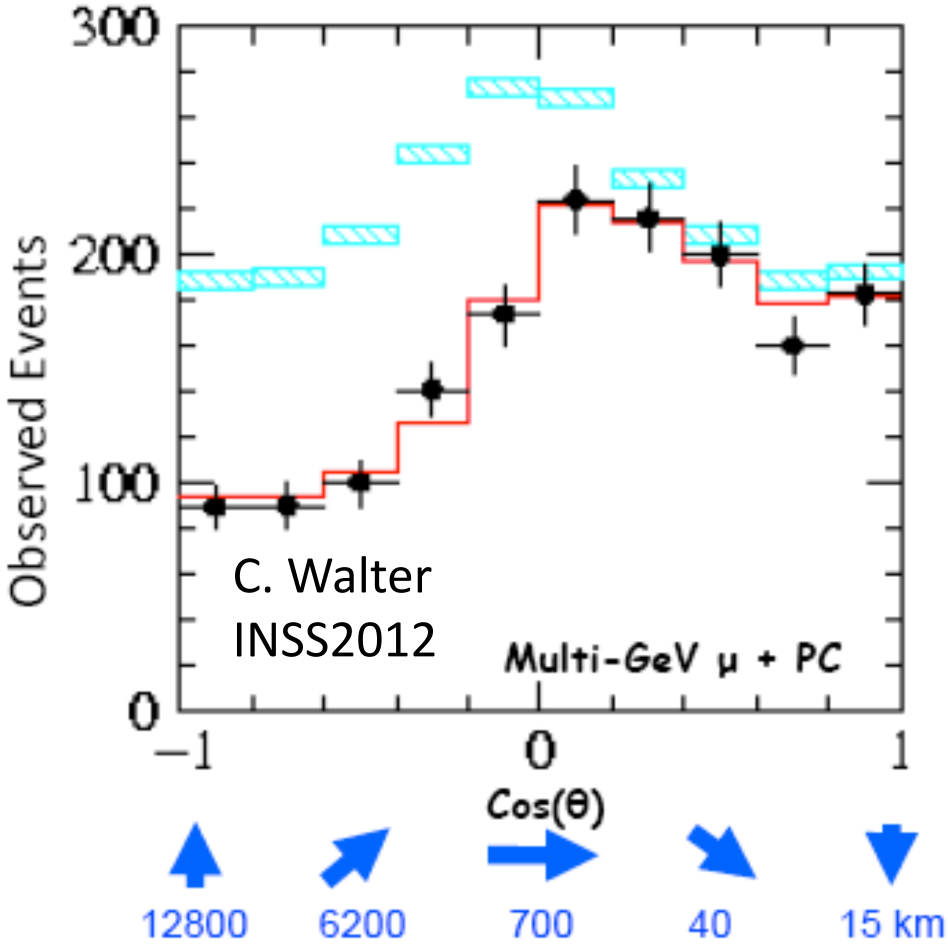


Disappearance with atmospheric sources

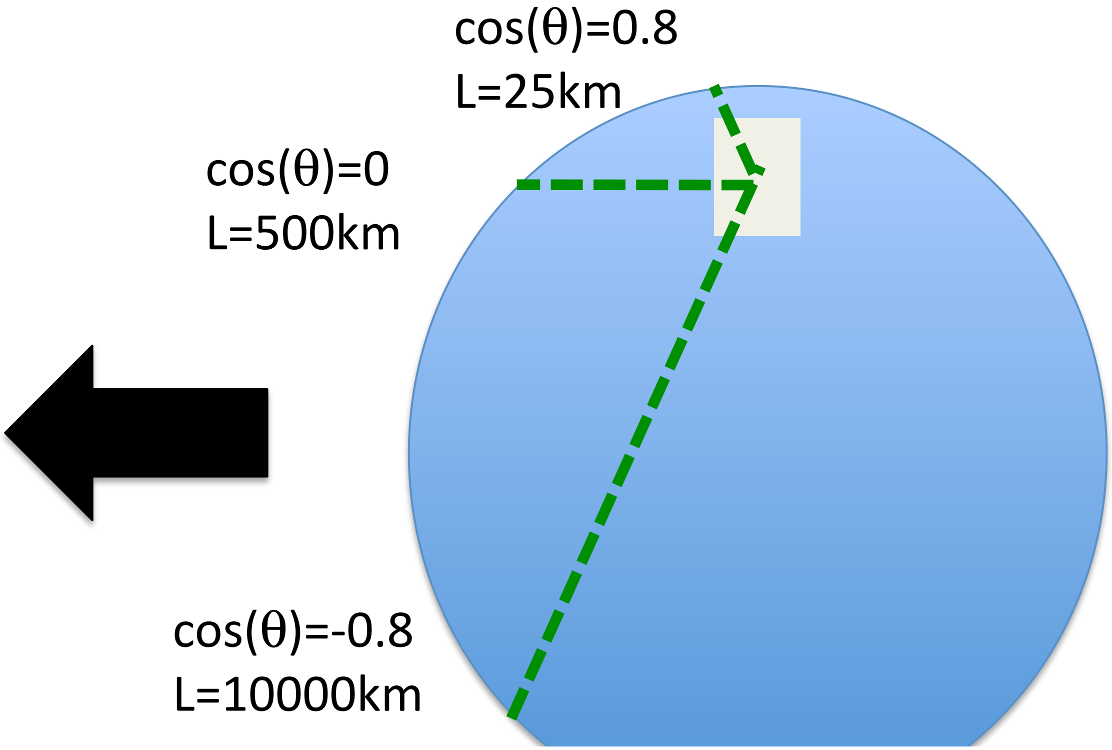
Oscillation probability changes with L:

- Distance from production to detector
- As a function of angle from the zenith cos(θ)

$$P(\nu_\mu \to \nu_\mu) \cong 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{1.27\Delta m^2_{32} L}{E}\right)$$



C. Walter
INSS2012



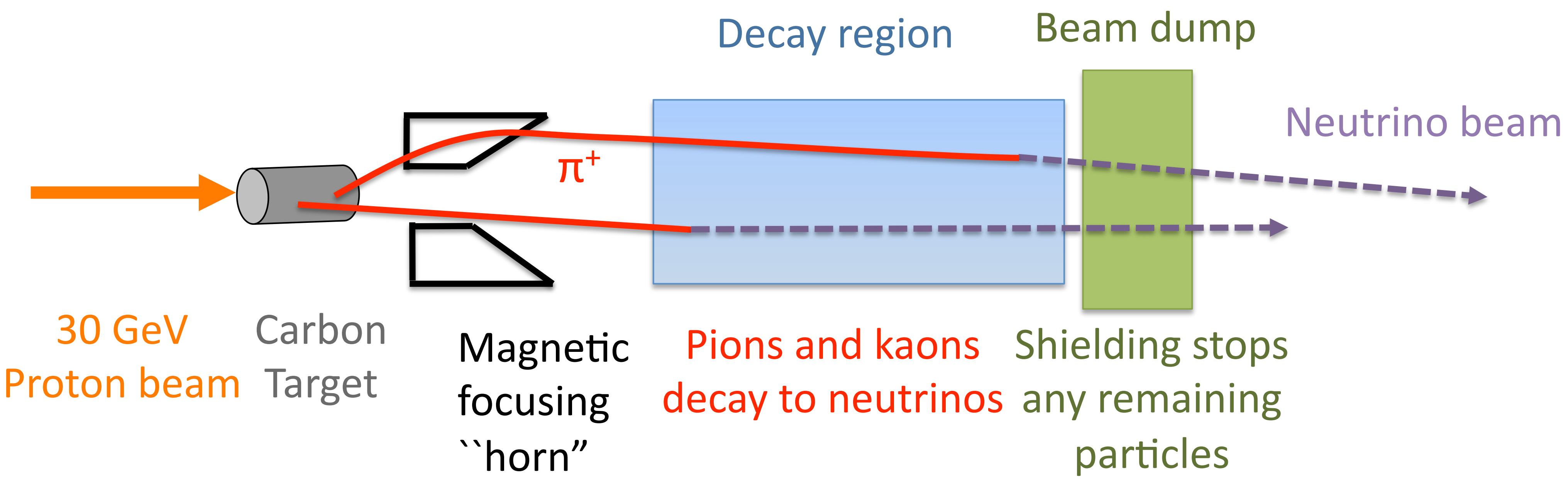
Determine $|\Delta m^2_{32}|$, θ_{23} from atmospheric and accelerator neutrinos:

$$\Delta m^2_{32} = 2.35 \times 10^{-3} eV^2$$

$$\theta_{23} = 45^\circ \pm 6^\circ$$

PDG2012

Accelerator-based neutrino sources

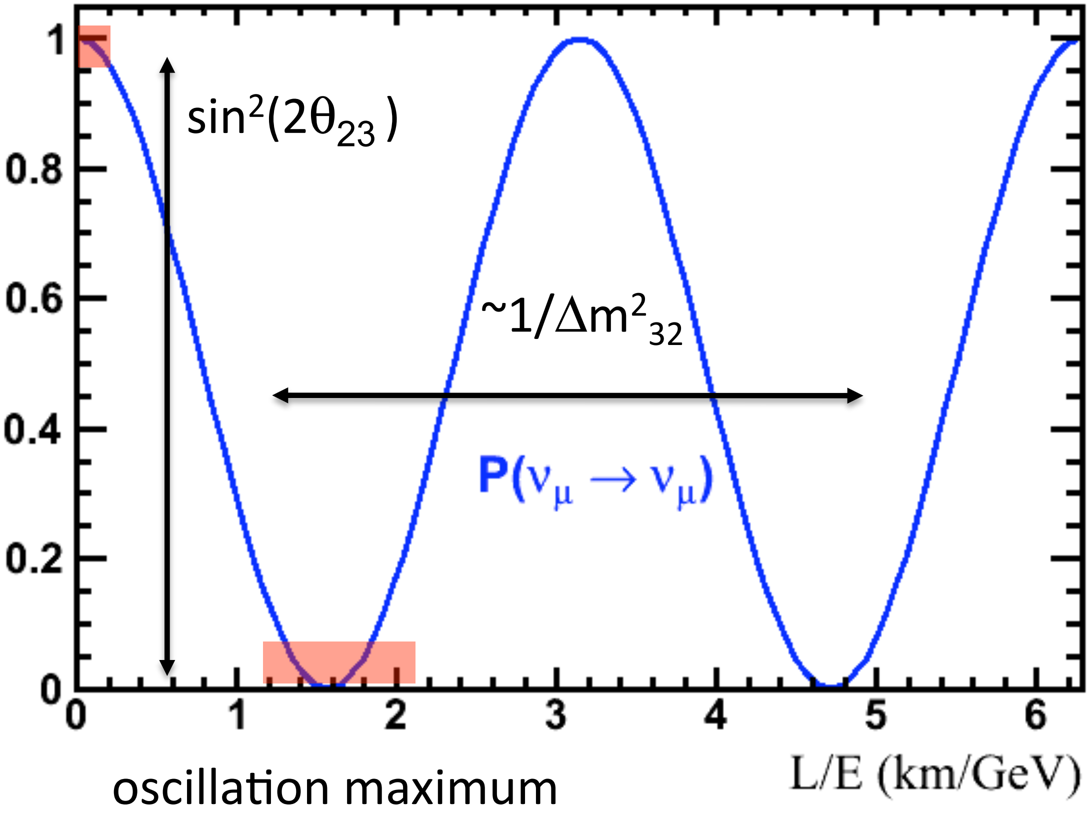


Advantages of an accelerator-based neutrino source:

1. >99% muon neutrino flavor, small ν_e component from muon, kaon decay
2. Intensity of proton beam increases neutrino rate
3. Switch magnetic horn polarization to focus π^- and produce an antineutrino beam
4. Tunable neutrino energy spectrum optimized for oscillation

Disappearance with accelerator sources

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

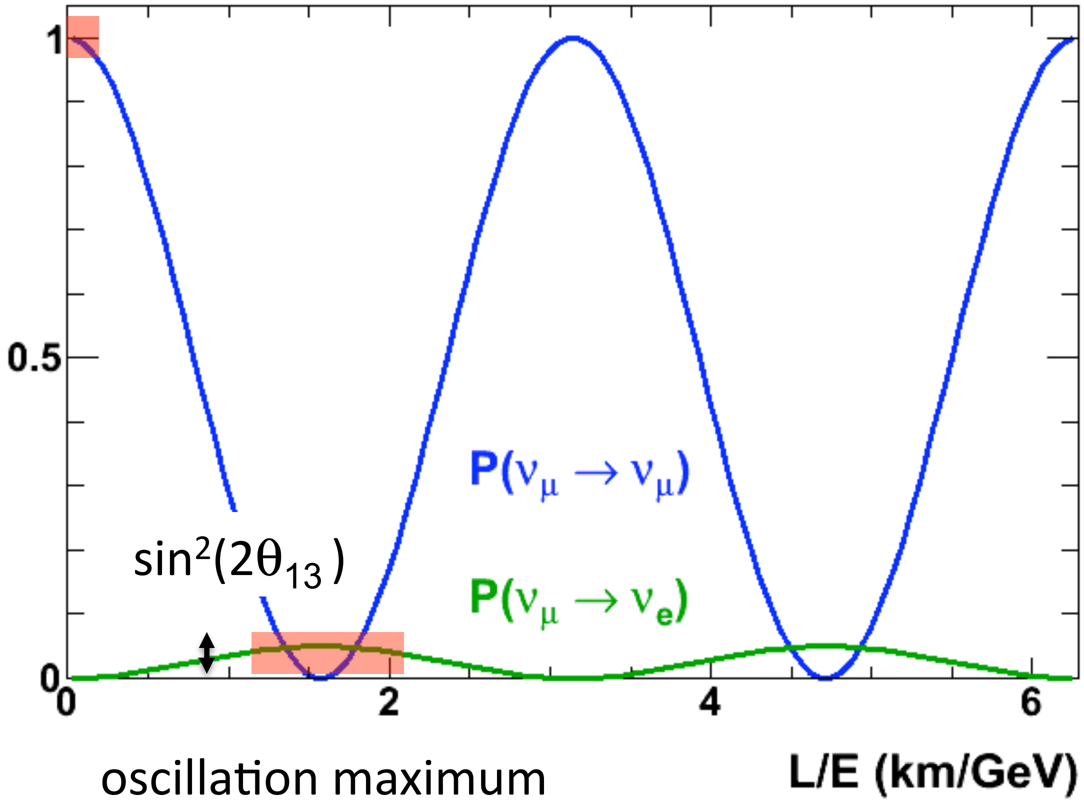


Typical experimental setup:

- Measure ν_μ rate at L=0
- Measure ν_μ rate at L~oscillation maximum
- Infer oscillation parameters from rate change (θ_{23}) and distortion of spectrum (Δm^2_{32})

Appearance with accelerator sources

$$P(\nu_\mu \rightarrow \nu_e) \cong \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$



Typical experimental setup:

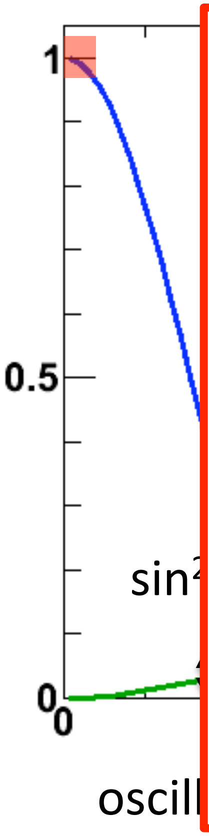
- Measure ν_μ rate* at L=0

*In practice also measure any ν_e background rates at L=0

- Measure ν_e rate at L~oscillation maximum
- Infer oscillation parameters from rate change (θ_{13})

Appearance with accelerator sources

$$P(\nu_\mu \rightarrow \nu_e) \cong \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$



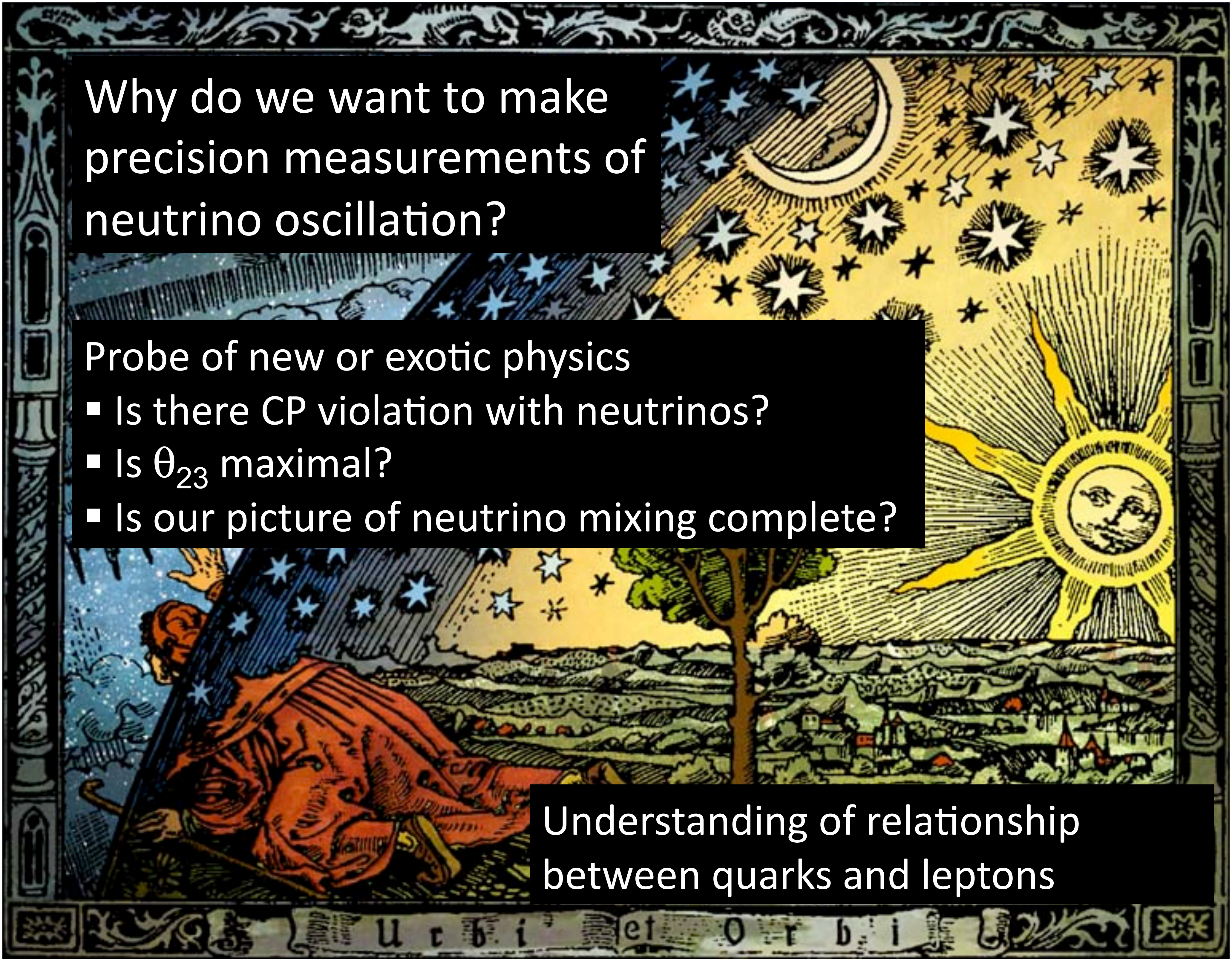
Subleading terms of ν_μ to ν_e appearance depend on δ_{CP}, mass hierarchy

Requires precision measurements of:
Δm^2_{32}, θ_{23} , Δm^2_{21}, θ_{12} and θ_{13}

rs

Measurements of ν_μ to ν_e appearance are sensitive to new or exotic physics

Why do we want to make precision measurements of neutrino oscillation?



Probe of new or exotic physics

- Is there CP violation with neutrinos?
- Is θ_{23} maximal?
- Is our picture of neutrino mixing complete?

Understanding of relationship between quarks and leptons

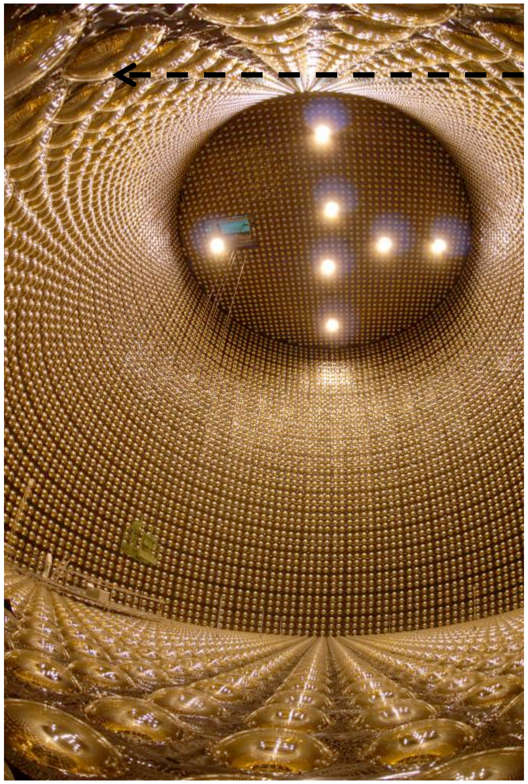
The Tokai-to-Kamioka (T2K) experiment

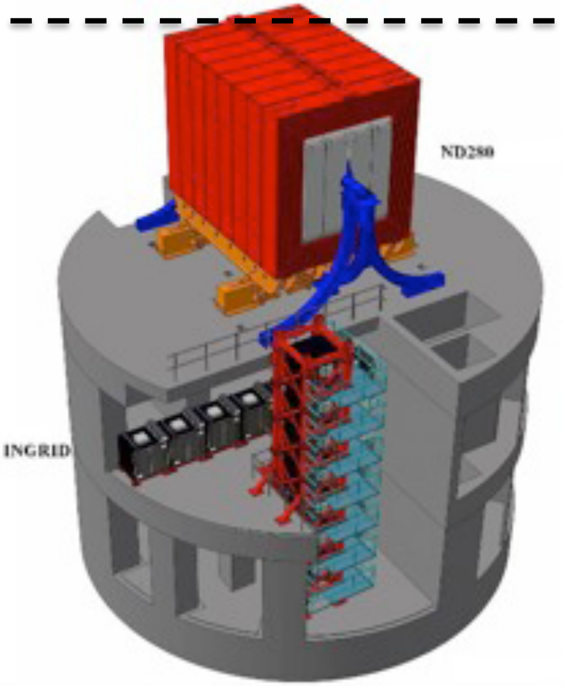
``Long baseline” (L~ 295km) neutrino experiment designed to measure ν_e appearance (θ_{13}) and ν_μ disappearance ($\Delta m^2_{32,}$ θ_{23})

Far detector
Super-Kamiokande

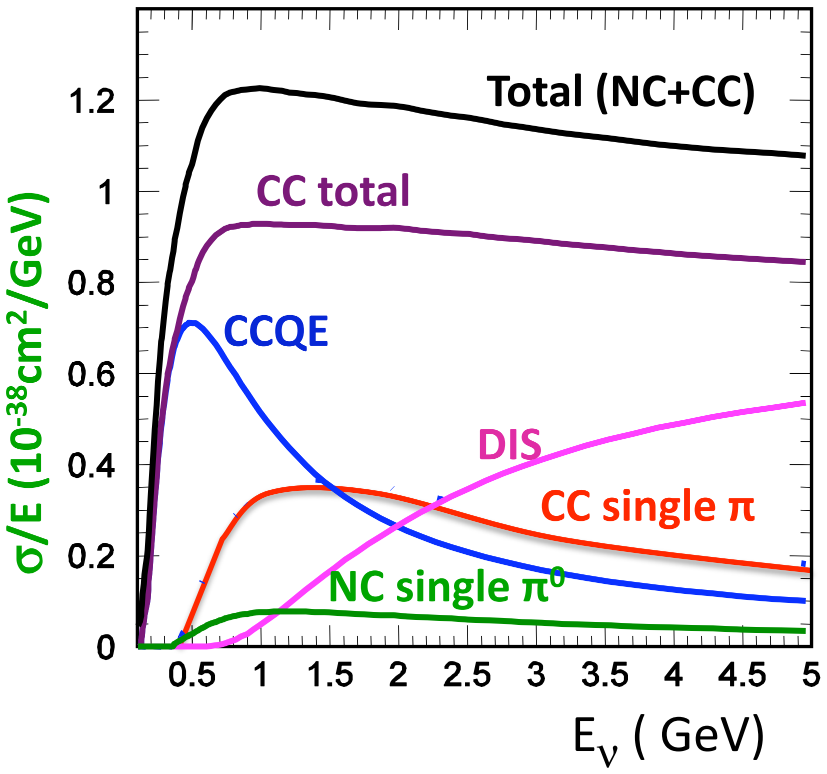
Near detectors
ND280

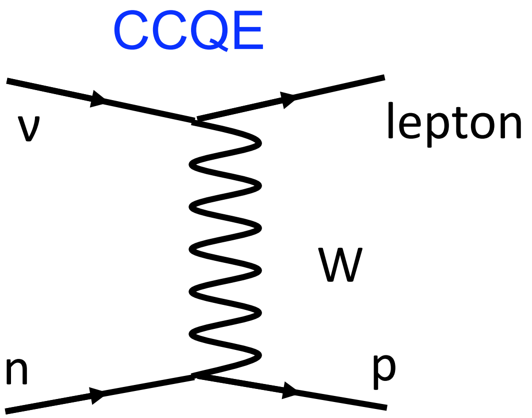
Neutrino beam
Peak E_ν~0.6 GeV





Neutrino interactions at T2K





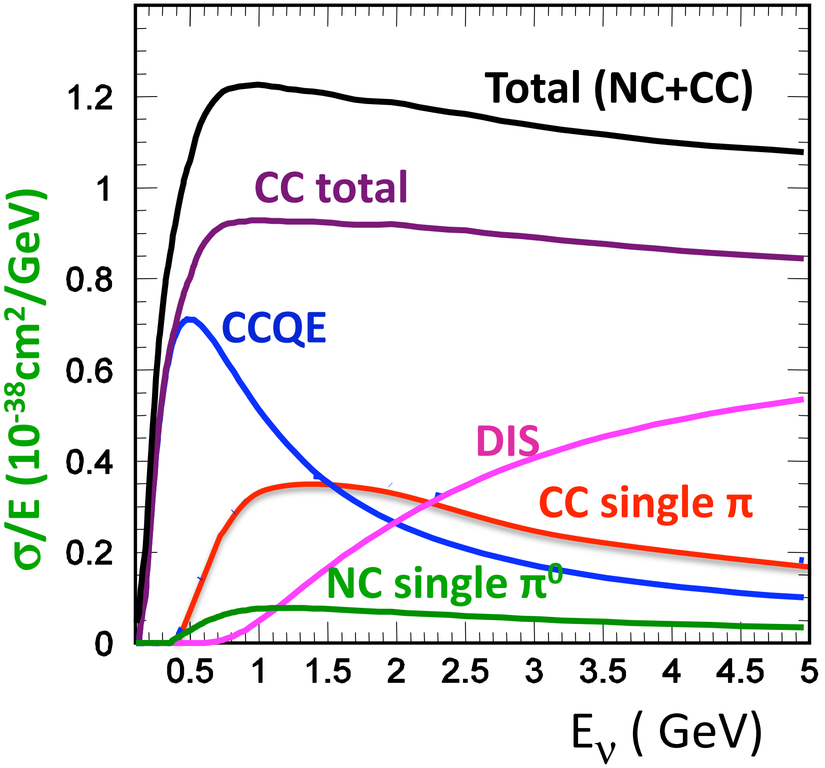
$$\nu_e \longrightarrow e$$

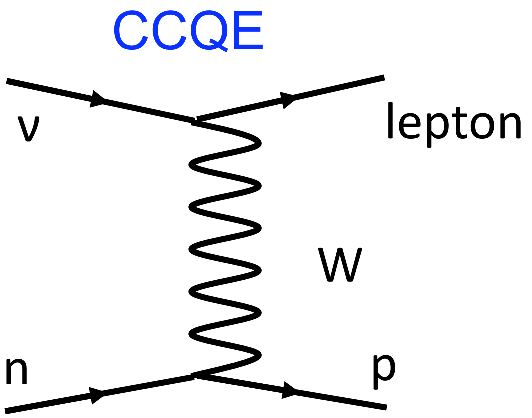
$$\nu_\mu \longrightarrow \mu$$

At E_ν~0.6 GeV, most neutrino interactions are Charged Current Quasi Elastic (CCQE)

- Neutrino flavor determined from flavor of outgoing lepton

Neutrino interactions at T2K





$$\nu_e \longrightarrow e$$
$$\nu_\mu \longrightarrow \mu$$

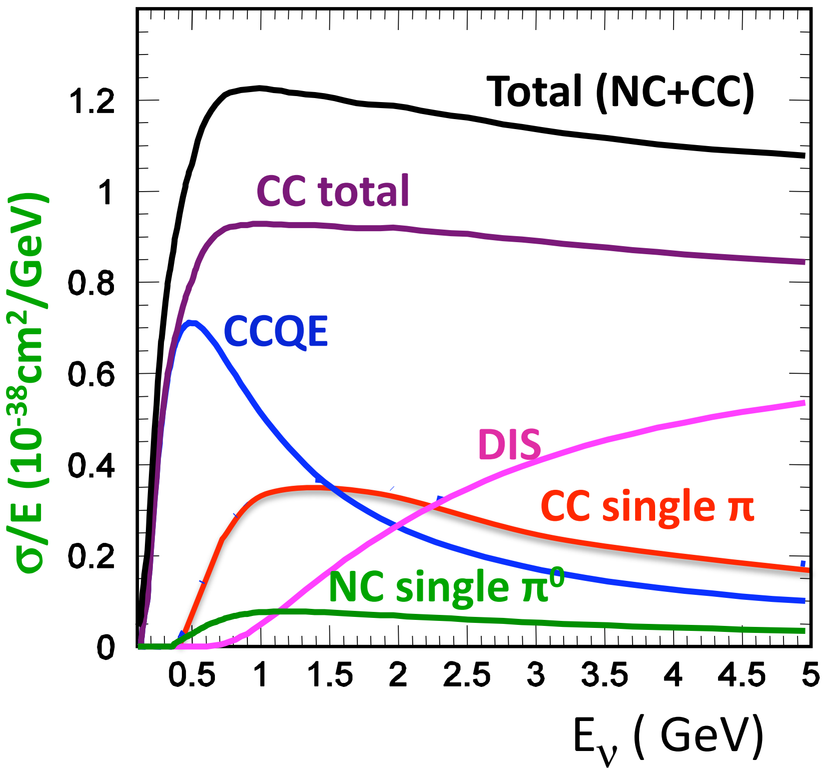
At E_ν~0.6 GeV, most neutrino interactions are Charged Current Quasi Elastic (CCQE)

- Neutrino flavor determined from flavor of outgoing lepton
- Infer neutrino properties from the muon (or electron) momentum and angle:

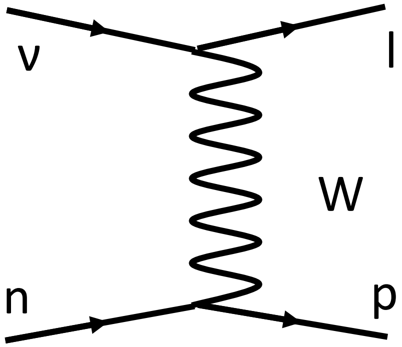
$$E_\nu^{QE} = \frac{m_p^2 - {m'}_n^2 - m_\mu^2 + 2{m'}_n E_\mu}{2({m'}_n - E_\mu + p_\mu \cos\theta_\mu)}$$

2 body kinematics
Assumes the target
nucleon is at rest

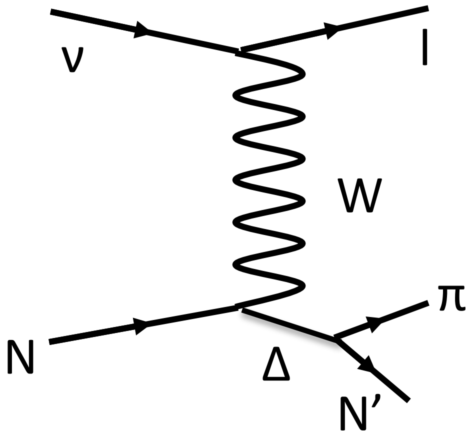
Neutrino interactions at T2K



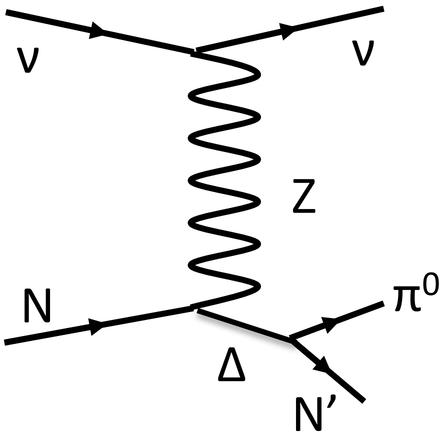
CCQE



CCπ



NCπ



Other interactions important for T2K analysis:

- Charged current single pion production (CCπ)
  - Lepton and pion (charged or neutral) produced
- Neutral current single pion production (NCπ^0)
  - No lepton in final state (happens for all flavors)
  - Only neutral pion (π^0) produced in detector
  - Can mimic ν_e signal at Super-Kamiokande

ν_e appearance analysis

$$N(\nu_e) = \Phi(E_\nu)\ \sigma(E_\nu)\ \epsilon\ P(\nu_\mu \to \nu_e)$$

Fit the observed rate to determine $\sin^2 2\theta_{13}$ Also depends on:

Neutrino flux prediction

Neutrino cross section model

Far detector selection, efficiency

ν_e appearance analysis

$$N(\nu_e) = \Phi(E_\nu)\ \sigma(E_\nu)\ \epsilon\ P(\nu_\mu \rightarrow \nu_e)$$

Fit the observed rate to determine $\sin^2 2\theta_{13}$ Also depends on:

Neutrino flux prediction

Neutrino cross section model

Far detector selection, efficiency

We reduce the error on the rate of ν_e with the near detector:

$$N(\nu_\mu) = \Phi(E_\nu)\ \sigma(E_\nu)\ \epsilon$$

Neutrino flux prediction

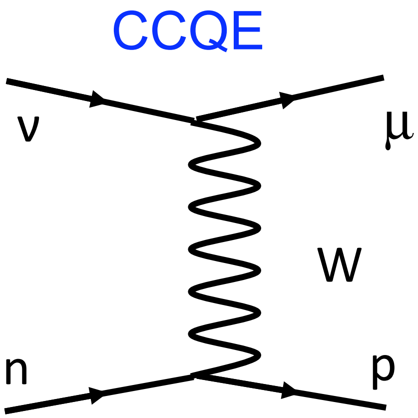
Neutrino cross section model

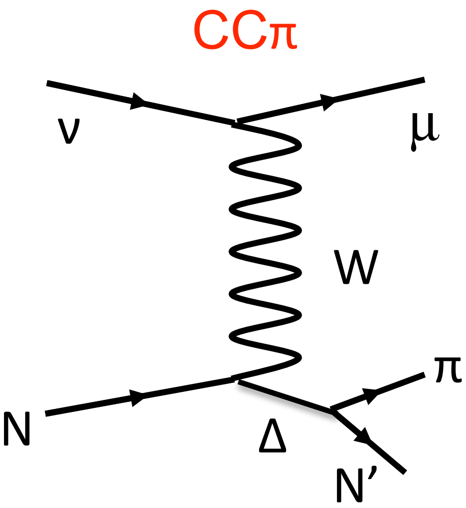
Near detector selection, efficiency

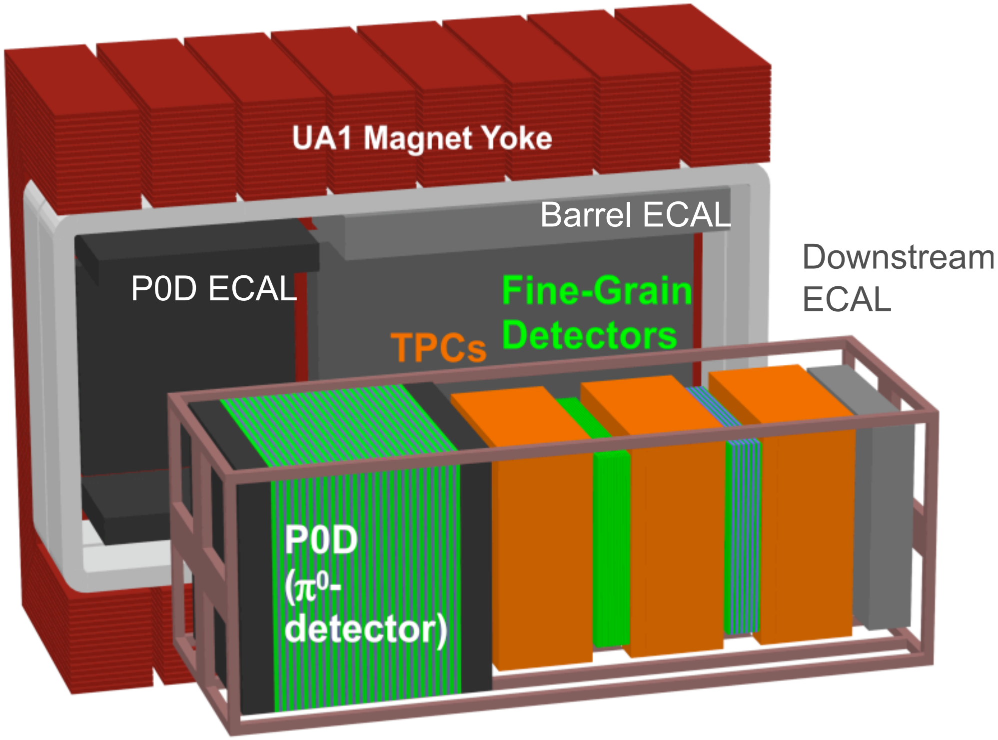
Challenge as osc analysis co-convener:
correlate the physics, coordinate the students, convince the physicists

Near detectors (ND280)

Measure unoscillated ν_μ(CC) rate:
Select nothing coming in (neutrino)
and muons coming out (ν_μ)







T2K experiment
NIM A 624, 591 (2010)

Analysis this year relies on "Tracker", constructed at TRIUMF

- 2 scintillator based tracking detectors (FGDs)
- 3 time projection chambers (TPCs)
- Placed inside the UA1 magnet

Additional detectors include:

- P0D (π^0 detector)
- Electromagnetic calorimeters
- Muon range detectors

Selecting CC ν_μ interactions

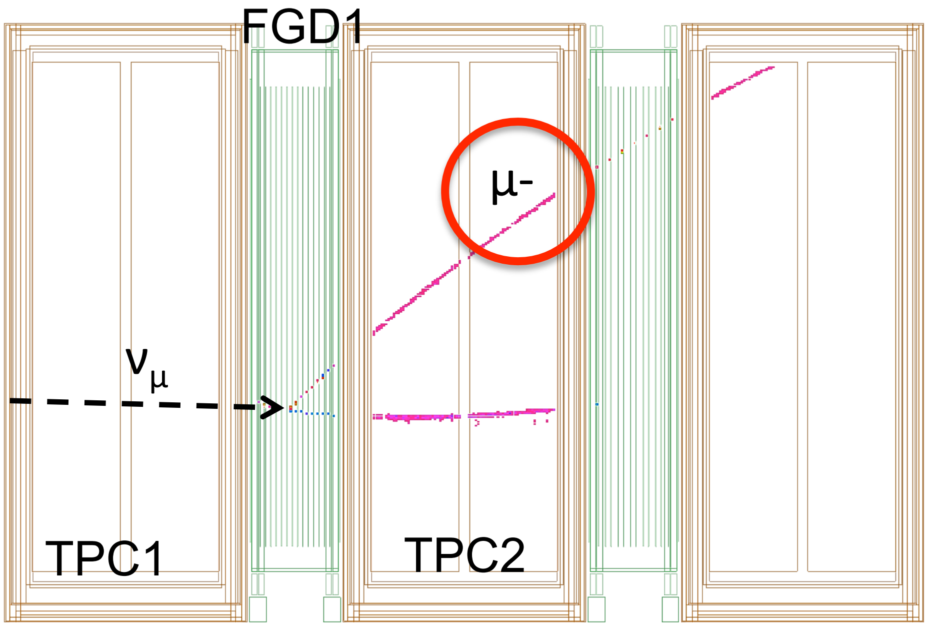
Measure unoscillated ν_μ(CC) rate

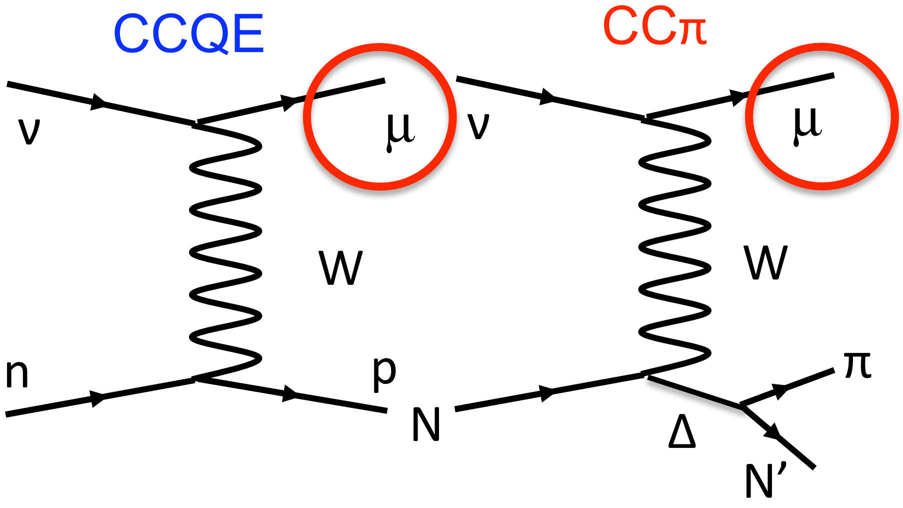
1. Neutrino interaction in FGD1

- Veto events with TPC1 tracks
- Events within FGD1 fiducial volume

2. Select highest momentum, negative curvature track as μ^- candidate

- Energy loss of the track in TPC also consistent with muon hypothesis



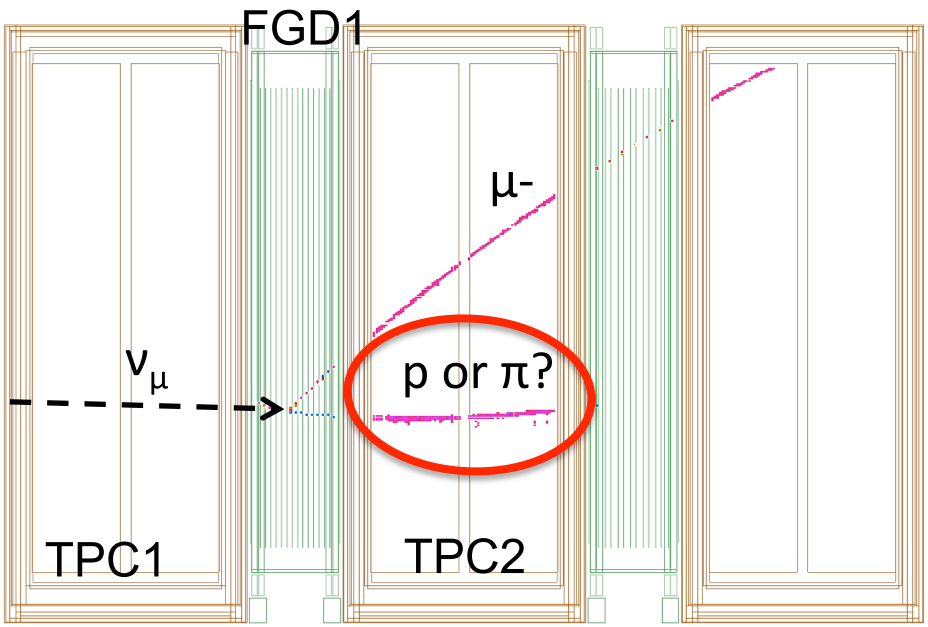


Selecting CC ν_μ interactions

Measure unoscillated ν_μ(CC) rate

1. Neutrino interaction in FGD1
   - Veto events with TPC1 tracks
   - Events within FGD1 fiducial volume

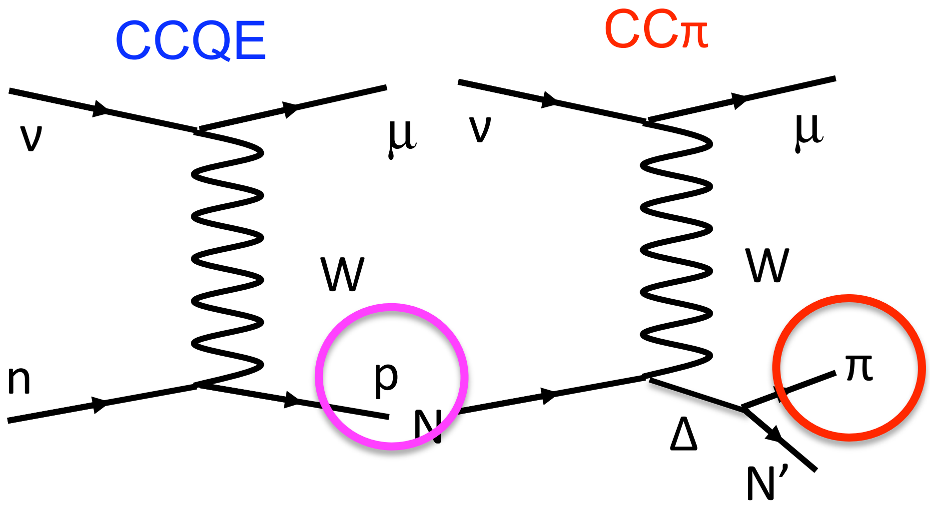
2. Select highest momentum, negative curvature track as μ^- candidate
   - Energy loss of the track in TPC also consistent with muon hypothesis



Further separate sample into two categories to increase sensitivity to cross section:

CCQE enhanced:
- 1 TPC-FGD matched track
- no decay electron in FGD1

CCnonQE enhanced:
- all other CC interactions



Near detector rate constraint

Tune flux, cross section models with a likelihood fit

- p-θ distribution is sensitive to rate (Φ x σ)

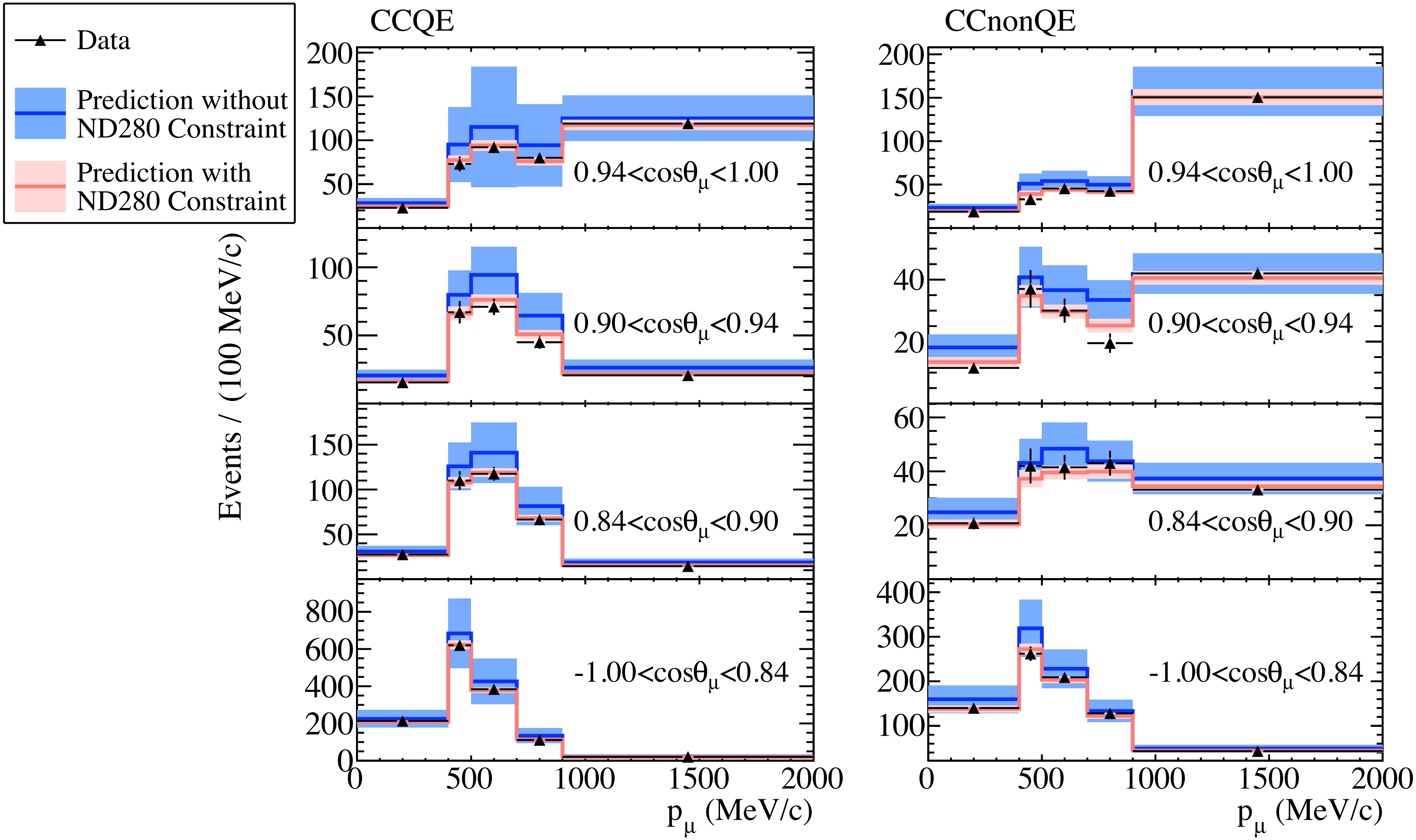
$$\boxed{E_\nu^{QE} = \frac{m_p^2 - {m'}_n^2 - m_\mu^2 + 2{m'}_n E_\mu}{2({m'}_n - E_\mu + p_\mu \cos\theta_\mu)}}$$

- Fit includes information on flux, cross sections from external measurements (e.g. beam monitors, neutrino cross section measurements)
- Shared flux, similar CC cross section composition of near and far detector selections

$$N(\nu_e) = \boxed{\Phi(E_\nu)}\,\boxed{\sigma(E_\nu)}\,\epsilon\, P(\nu_\mu \rightarrow \nu_e)$$

$$N(\nu_\mu) = \boxed{\Phi(E_\nu)}\,\boxed{\sigma(E_\nu)}\,\epsilon$$

Results of near detector rate fit



- Rate changed by no more than 10% across all energies
- CC cross sections, ν_μ flux uncertainties reduced substantially
- $\Delta\chi^2 = 29.1$, p=0.925

Expected number of ν_e candidates

After ND280 tuning, expect ~11 events with ν_μ to ν_e oscillation, 3 without

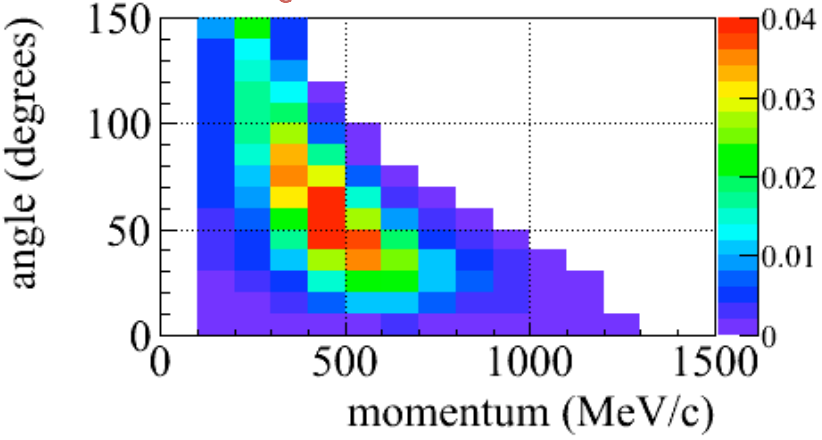
- Rate, p-θ kinematics of events distinguishes signal from background

Signal (ν_μ to ν_e osc)	**# events**
@$\sin^2 2\theta_{13}=0.1, \delta cp=0$	8.2

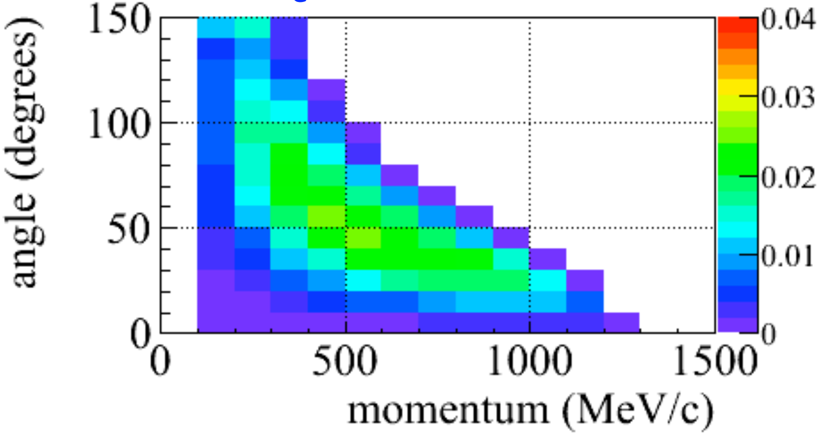
ν_e signal@Δm^2_{32} =2.4 x 10^{-3} eV^2, $\sin^2 2\theta_{23}=1.0$

Background	**# events**
beam $\nu_e + \overline{\nu}_e$	1.8
$\nu_\mu + \overline{\nu}_\mu$ (mainly NC) background	1.3
osc through θ_{12}	0.2
total:	3.3±0.4(sys)

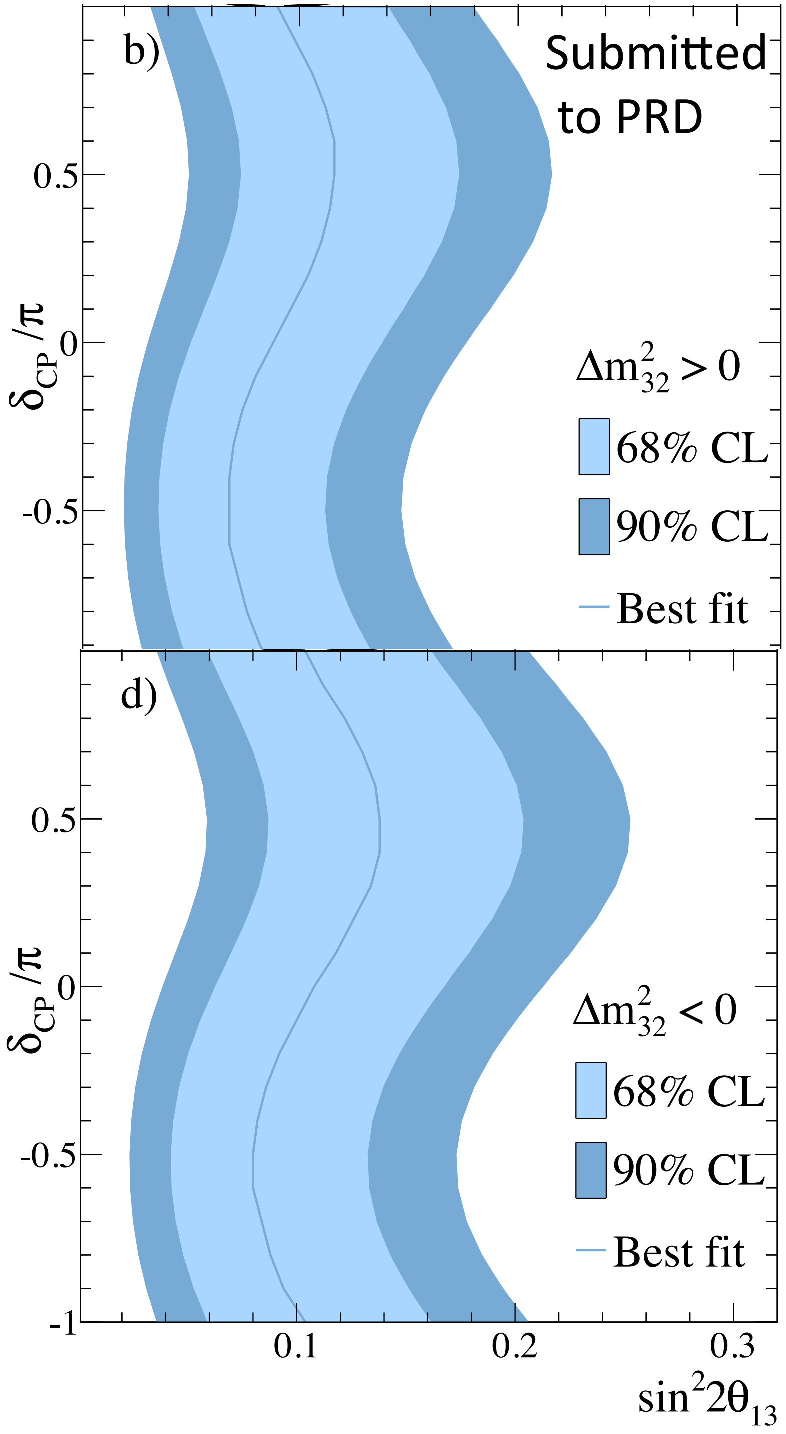
CC ν_e signal



CC ν_e background

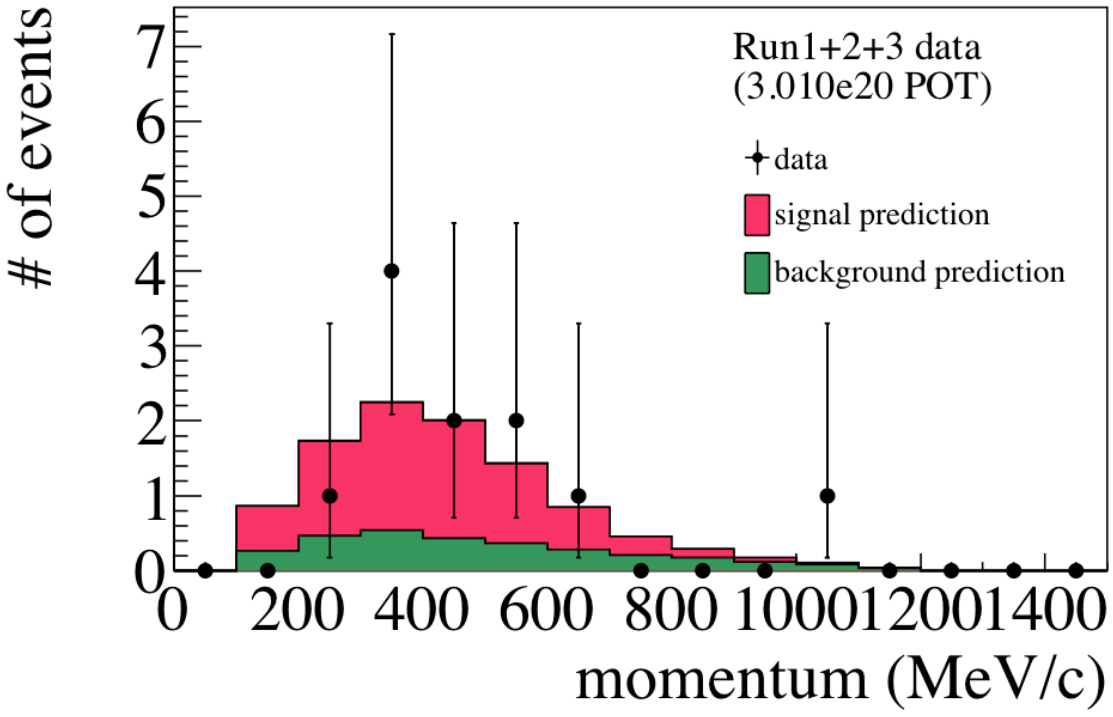


ν_e appearance results

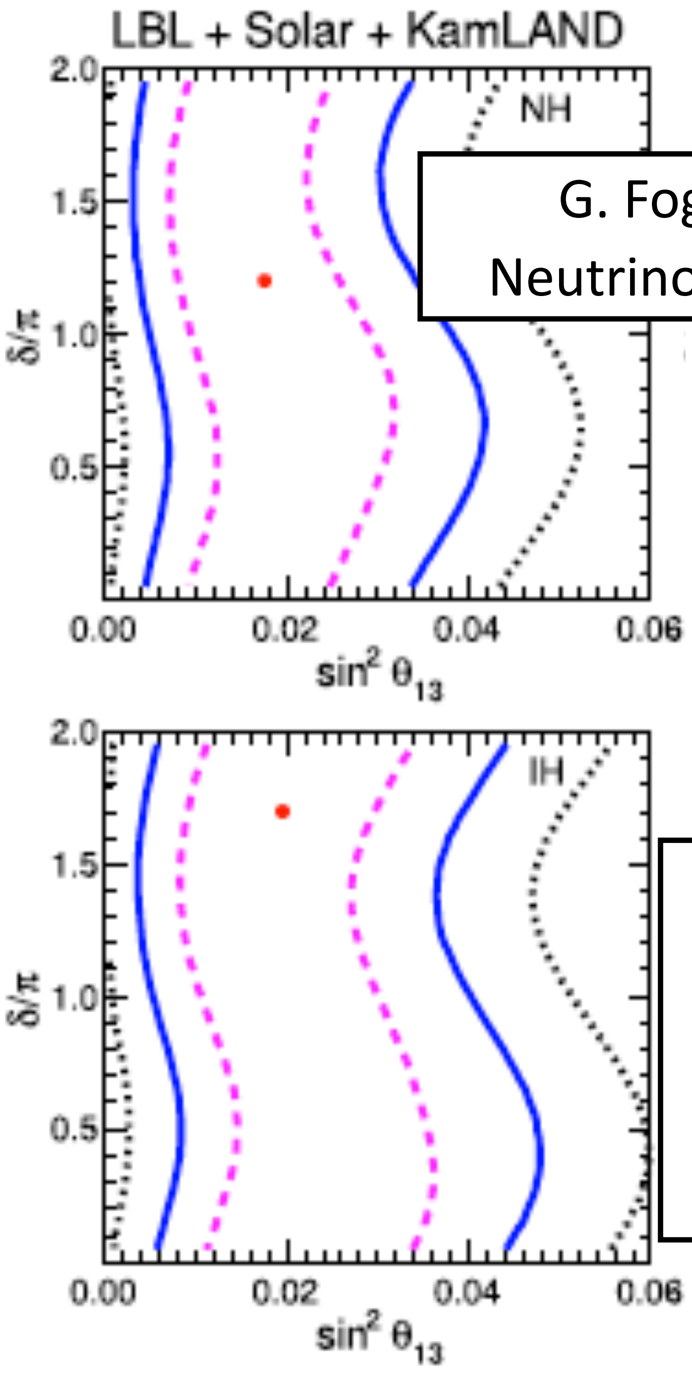


- 11 candidate events observed for background of 3.3±0.4
- Probability to see 11 events or more for $\sin^2 2\theta_{13}=0$ is 0.0009 (3.1σ equivalent)
- Fit assumes $|\Delta m^2_{32}|=2.4 \times 10^{-3}$ eV^2 and $\sin^2 2\theta_{23} = 1$
- For normal hierarchy, best fit:

  $\sin^2 2\theta_{13}= 0.088 +0.049 -0.039$

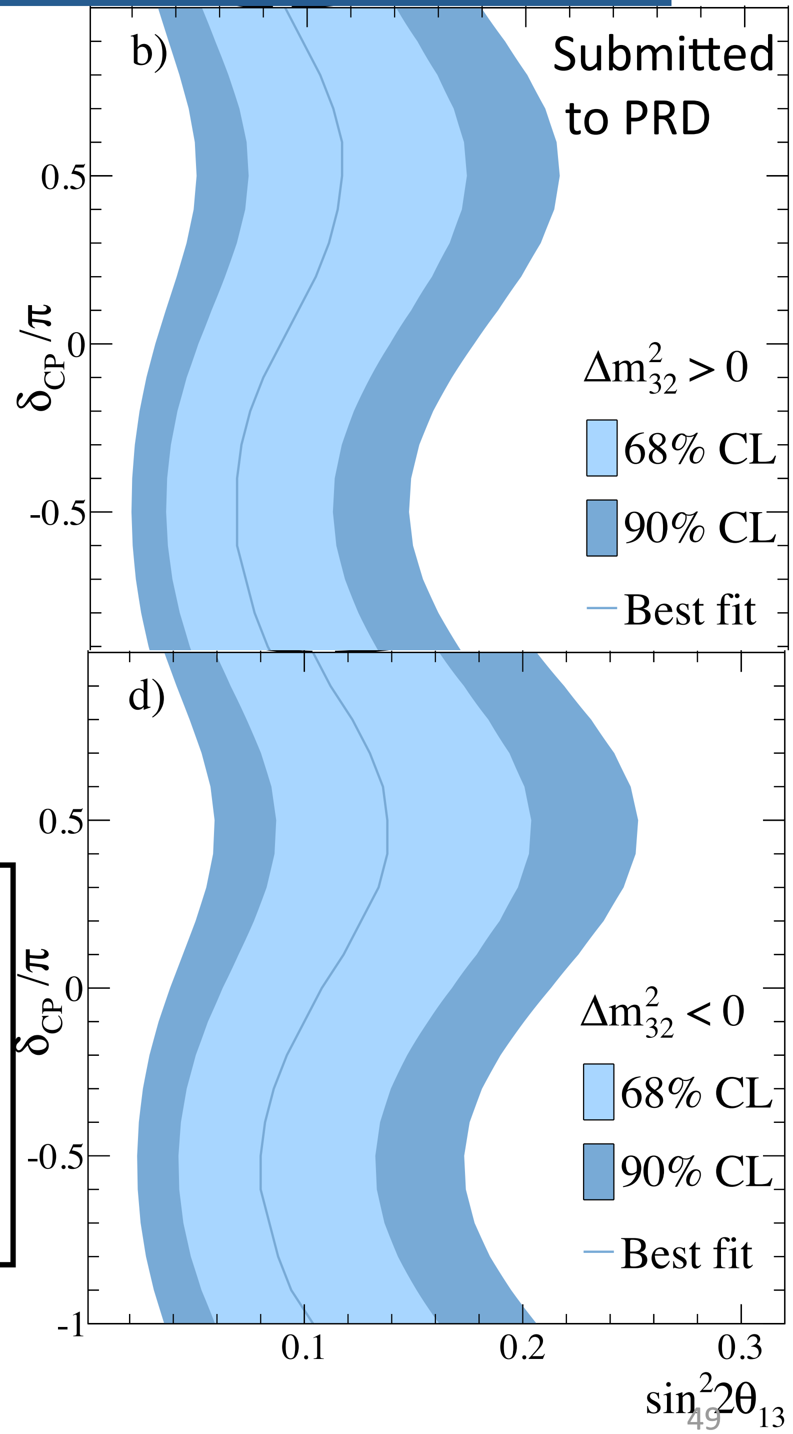


Implications of a large θ_{13}



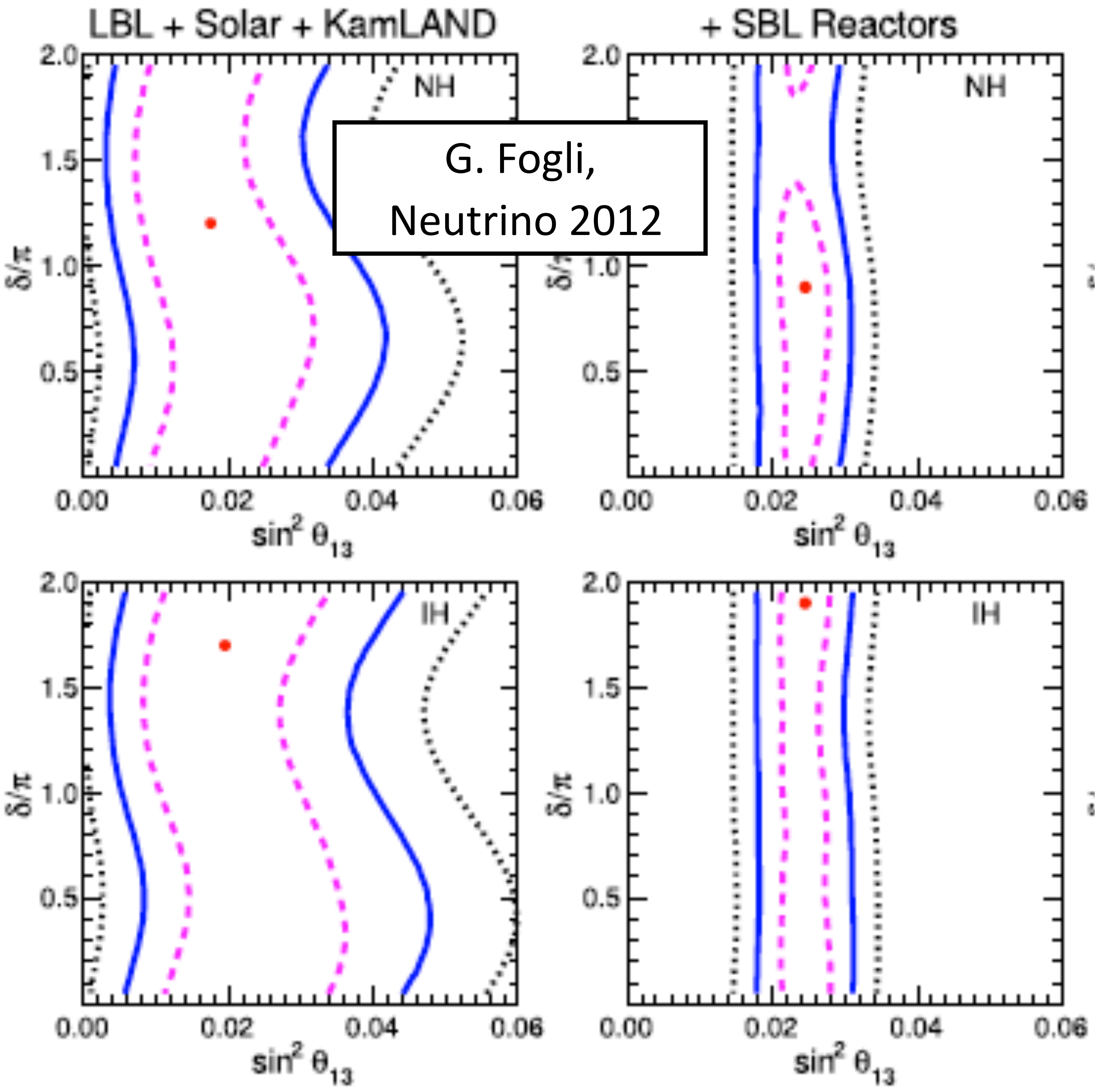
G. Fogli, Neutrino 2012

Long baseline (LBL) appearance depends on all the mixing parameters, including δ_{CP}, θ_{13}



Submitted to PRD

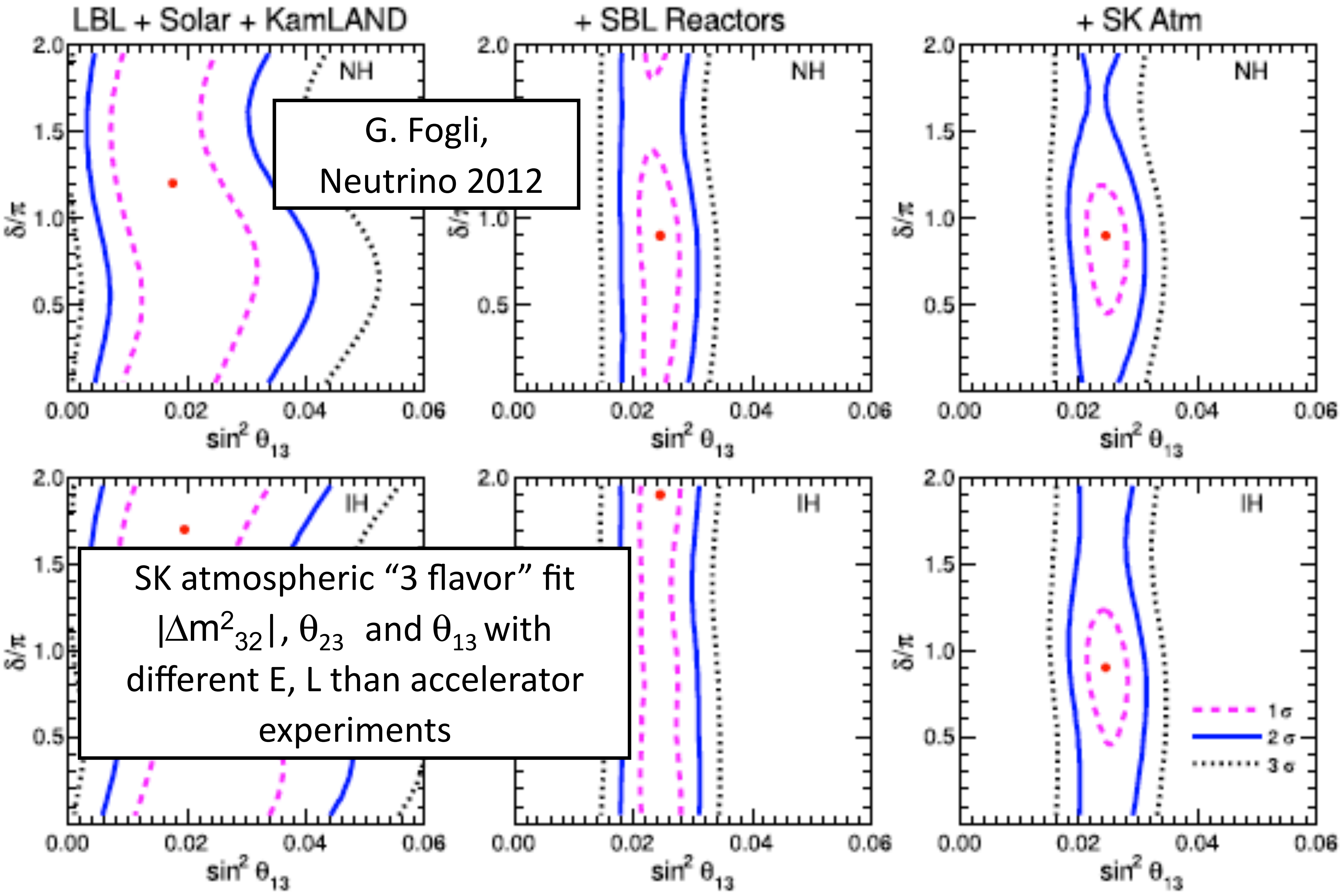
Implications of a large θ_{13}



G. Fogli,
Neutrino 2012

Reactor experiments are a pure measurement of θ_{13}

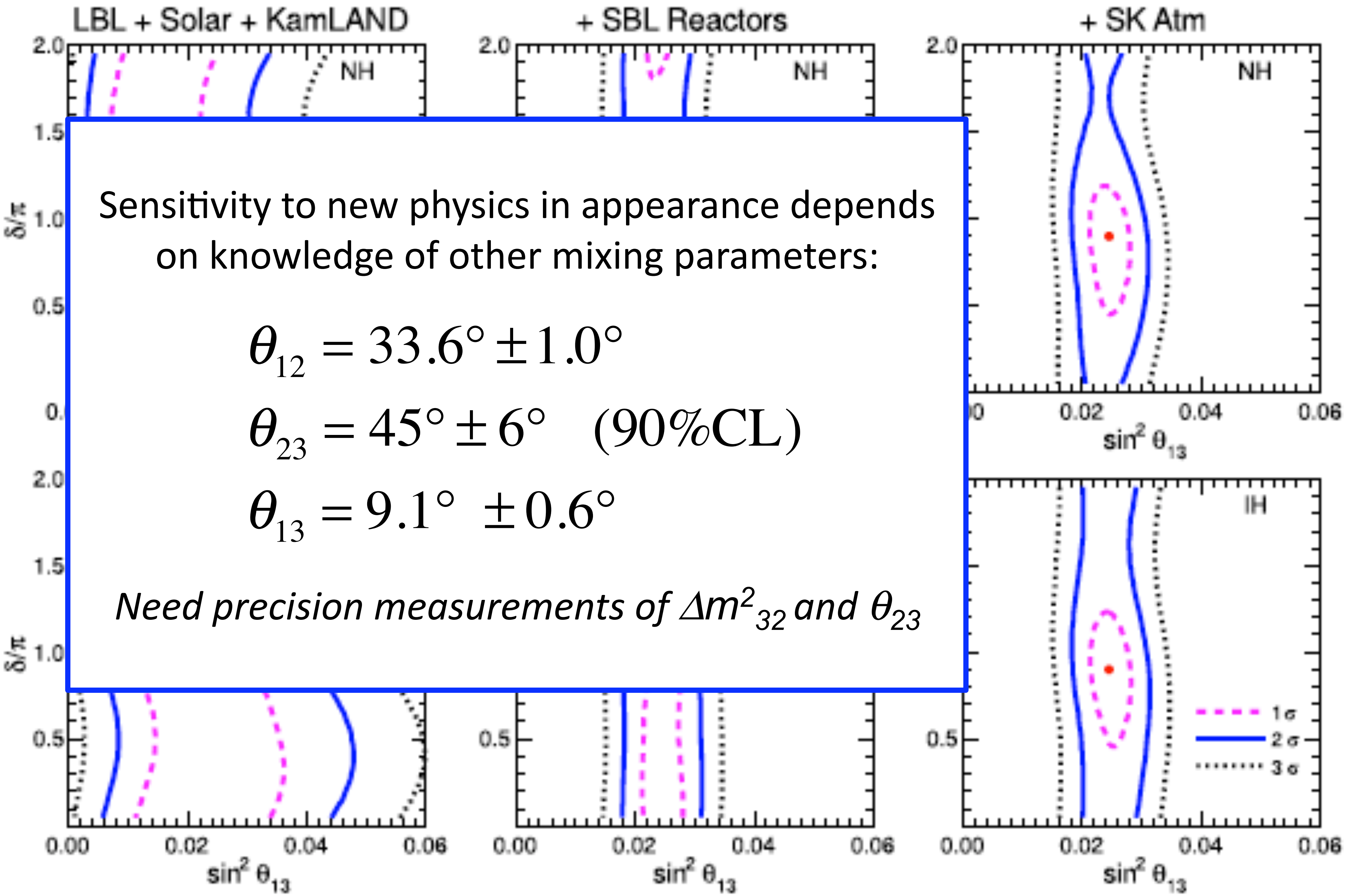
Implications of a large θ_{13}



G. Fogli, Neutrino 2012

SK atmospheric "3 flavor" fit $|\Delta m^2_{32}|$, θ_{23} and θ_{13} with different E, L than accelerator experiments

Implications of a large θ_{13}



Sensitivity to new physics in appearance depends on knowledge of other mixing parameters:

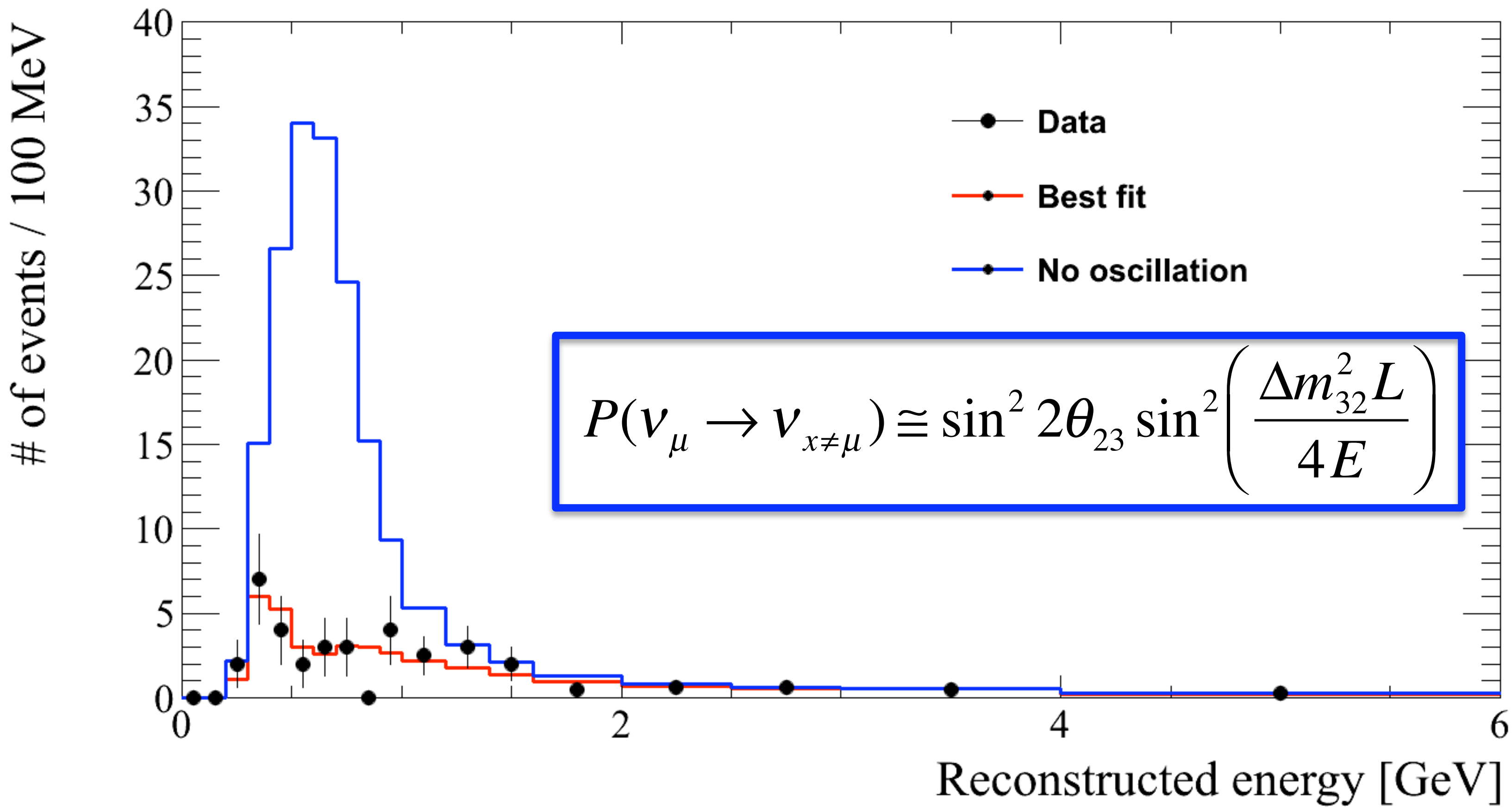
$$\theta_{12} = 33.6° \pm 1.0°$$

$$\theta_{23} = 45° \pm 6° \quad (90\%\mathrm{CL})$$

$$\theta_{13} = 9.1° \ \pm 0.6°$$

Need precision measurements of Δm^2_{32} and θ_{23}

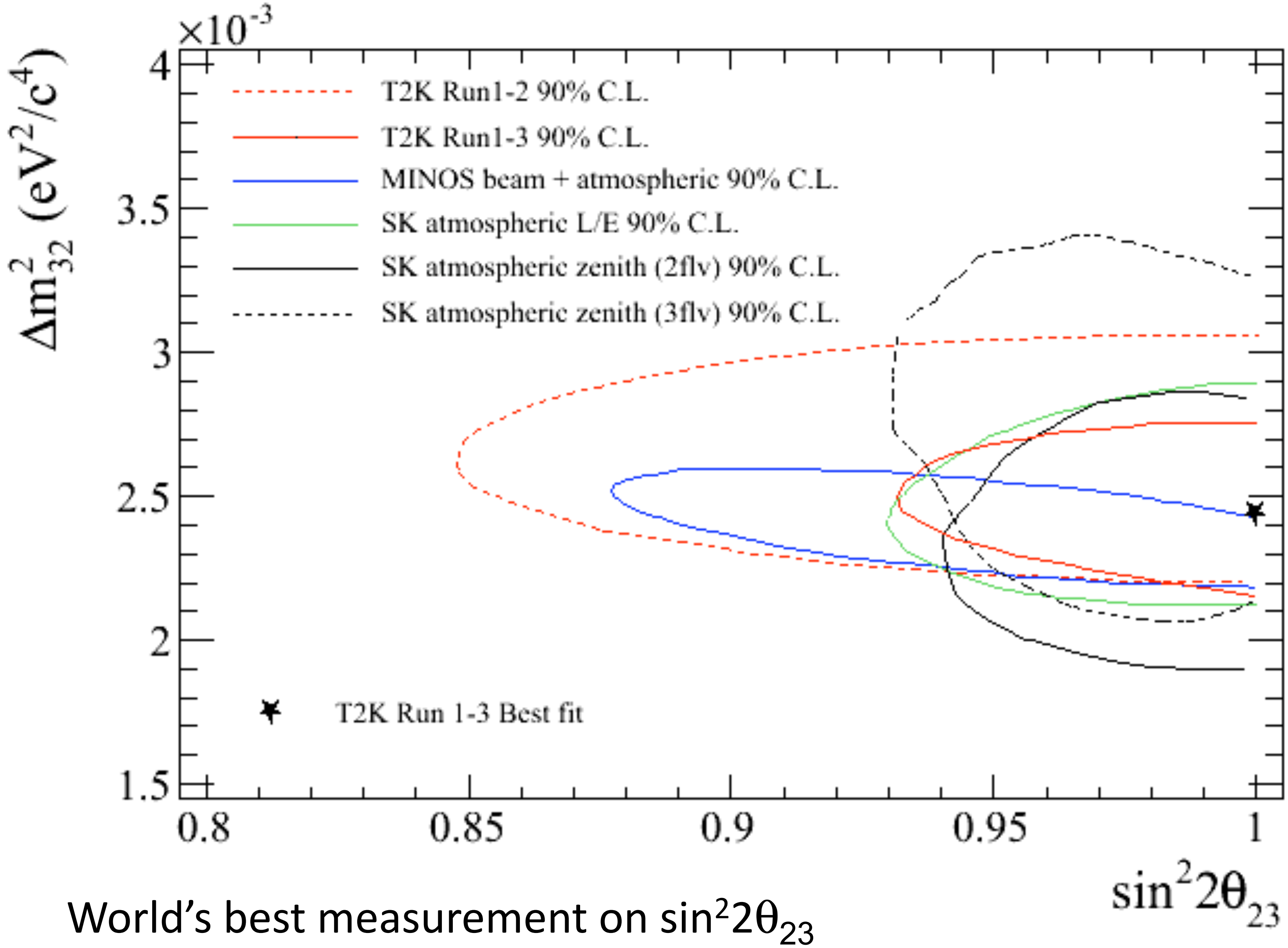
T2K ν_μ disappearance



Disappearance distorts energy spectrum and rate of ν_μ candidates

- Select CCQE ν_μ candidates at SK
- Reconstruct neutrino energy from muon kinematics
- Apply same near detector tuning as for ν_e appearance

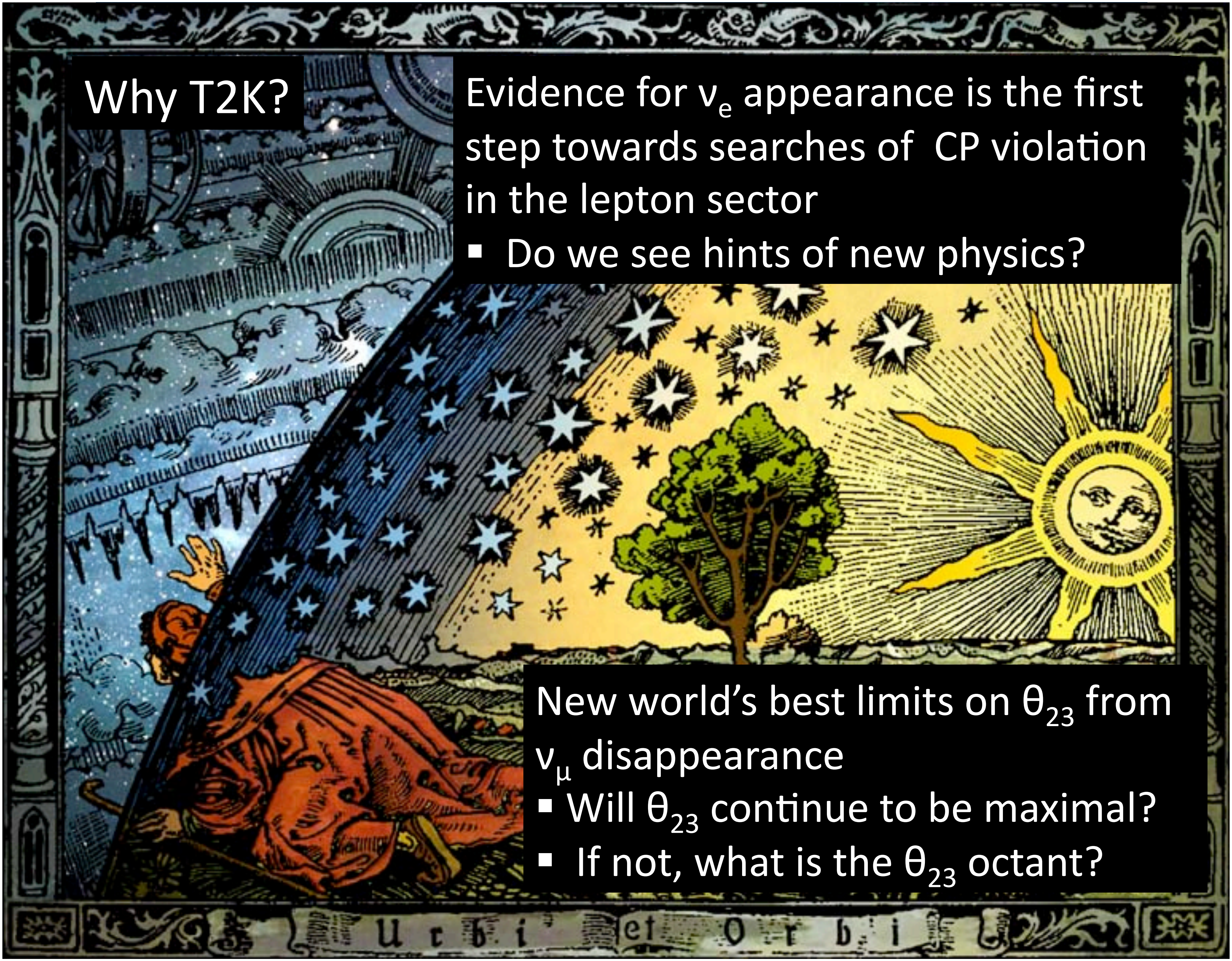
ν_μ disappearance results



World's best measurement on $\sin^2 2\theta_{23}$

- Best fit is consistent with maximal mixing (θ_{23} =45°)
- Expect to ~double statistics with this year's data set ending in July

Why T2K?



Evidence for ν_e appearance is the first step towards searches of CP violation in the lepton sector

- Do we see hints of new physics?

New world's best limits on θ_{23} from ν_μ disappearance

- Will θ_{23} continue to be maximal?
- If not, what is the θ_{23} octant?

What is needed to measure δ_{CP}?

Compare ν_e appearance to $\overline{\nu}_e$ appearance to determine an asymmetry:

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

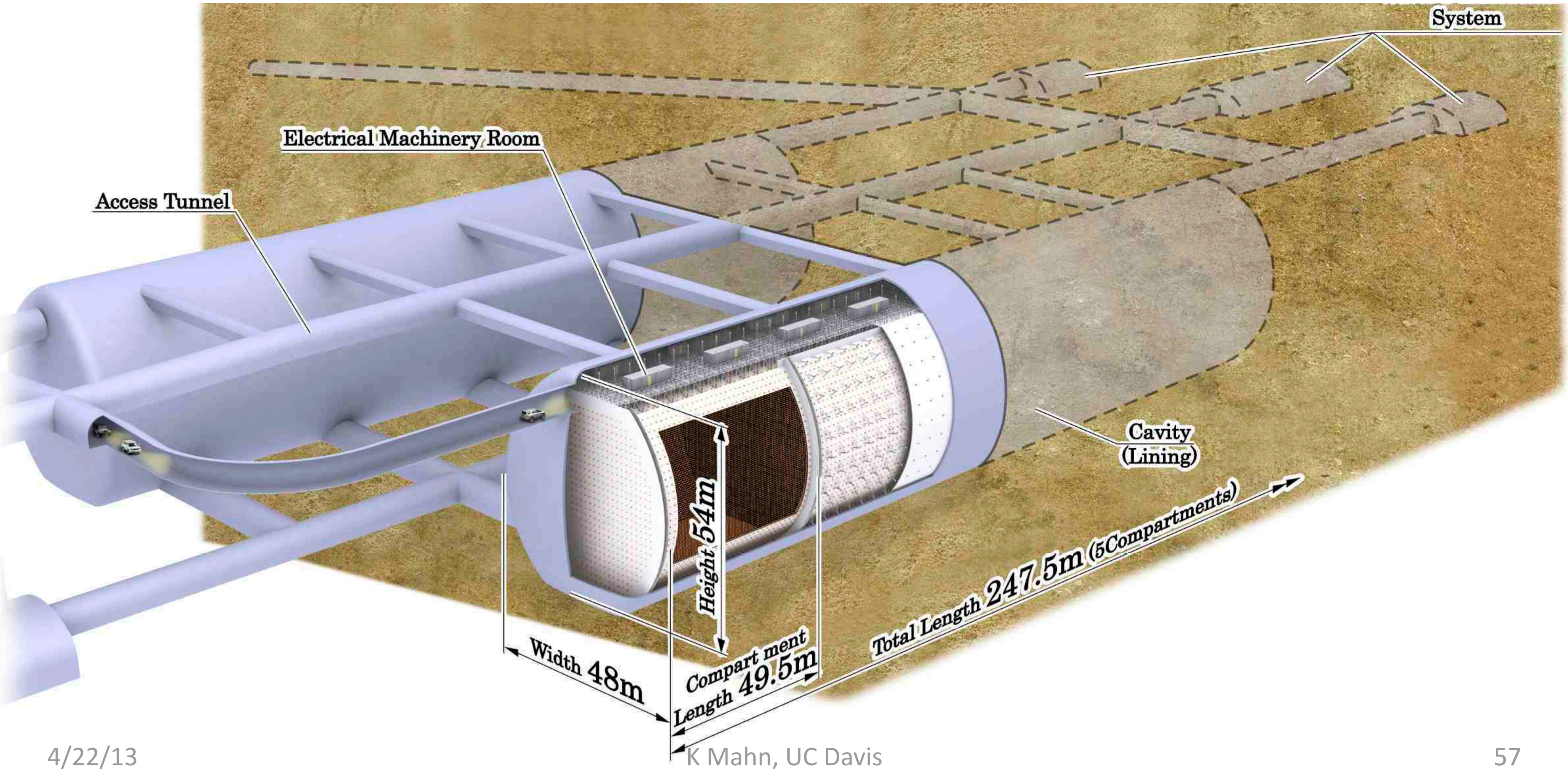
With θ_{13} "large", then A_{CP} is small (~20-30%), so the measurement of δ_{CP} need systematic uncertainties of <5% or better

- T2K's current statistics: 11 events (ν_e appearance probability)
- Need more raw event rate, with a larger detector

Hyper-Kamiokande

~1Mton detector, approximately 25x Super-Kamiokande

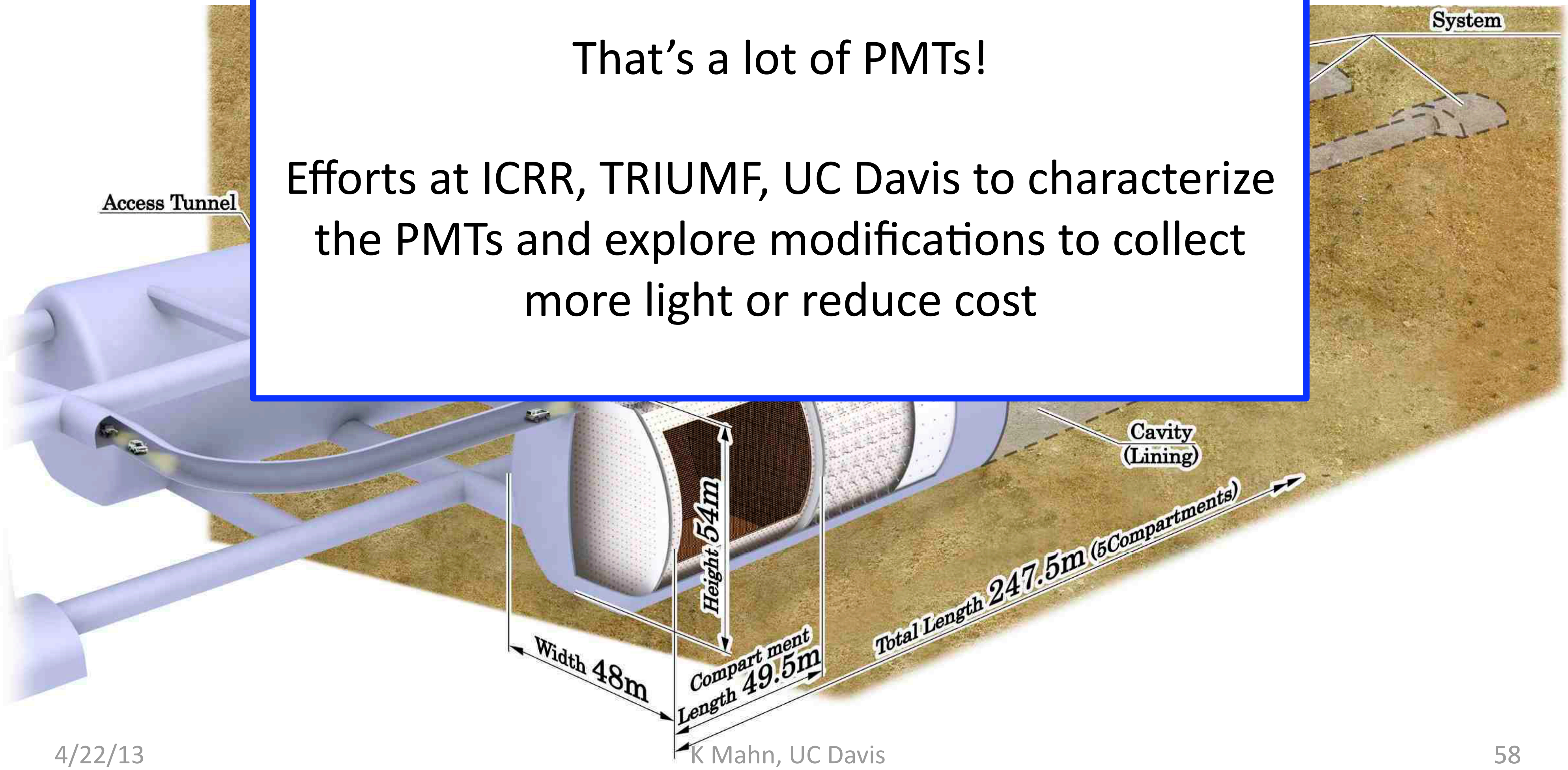
- 99,000 inner PMTs, 25,000 veto region PMTs (10 compartments)
- Same neutrino beamline as T2K, different cavern
- Other physics reach: solar neutrinos, atmospheric neutrinos, astrophysical neutrinos (supernova), geo-neutrinos and proton decay



Hyper-Kamiokande

~1Mton detector, approximately 25x Super-Kamiokande

- 99,000 inner PMTs, 25,000 veto region PMTs (10 compartments)
- Same neutrino beamline as T2K, different cavern
- Other physics reach: solar neutrinos, atmospheric neutrinos, astrophysical neutrinos (supernova), geo-neutrinos and proton decay



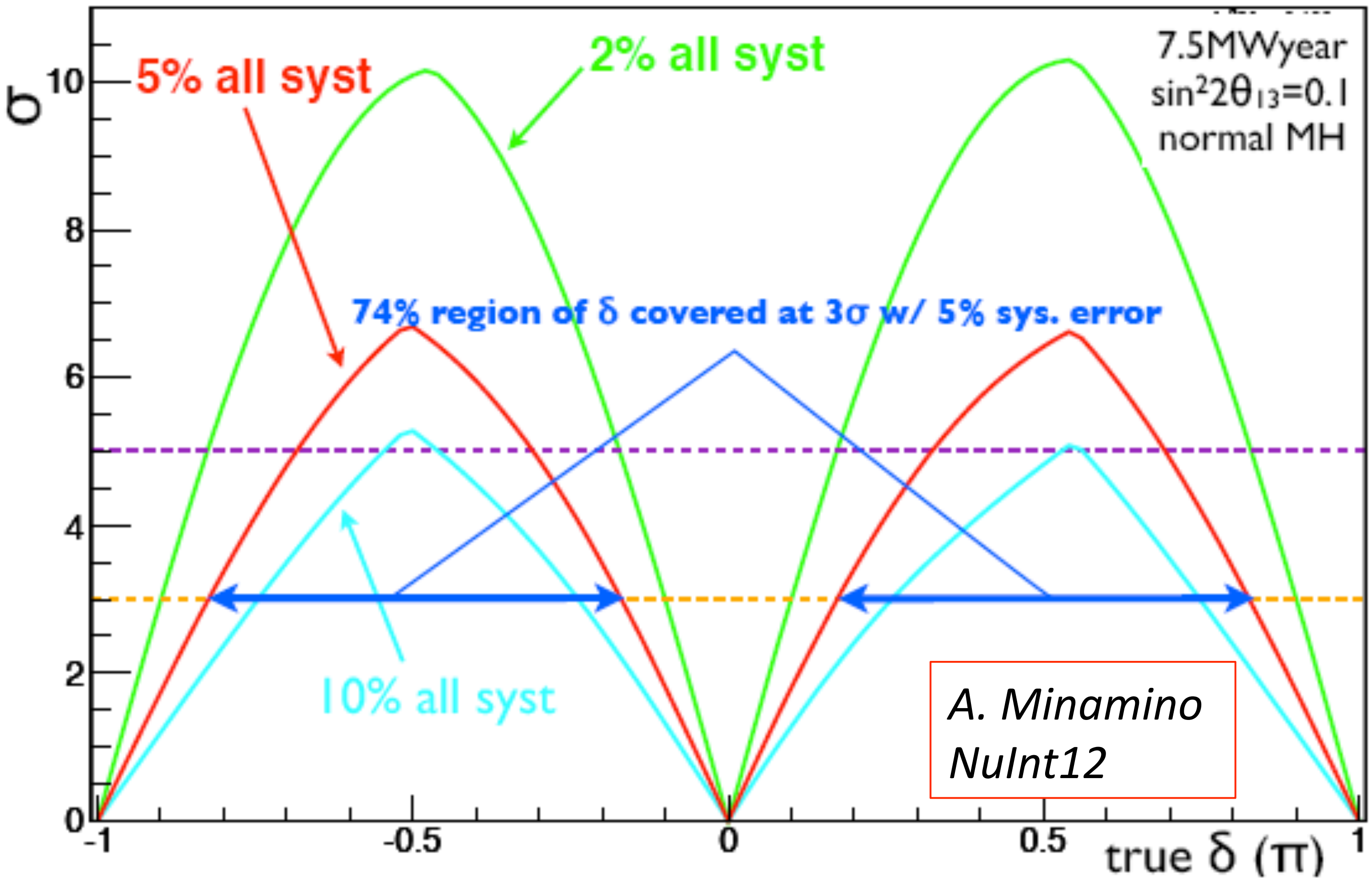
That’s a lot of PMTs!

Efforts at ICRR, TRIUMF, UC Davis to characterize the PMTs and explore modifications to collect more light or reduce cost

δ_{CP} discovery sensitivity

HK LOI: hep-ex 1109.3262

	ν run	**ν run**
Signal ν_{e}, ν_e	3560	1959
NC	649	678
CC ν_e ν_e	880	878
Other	81	403



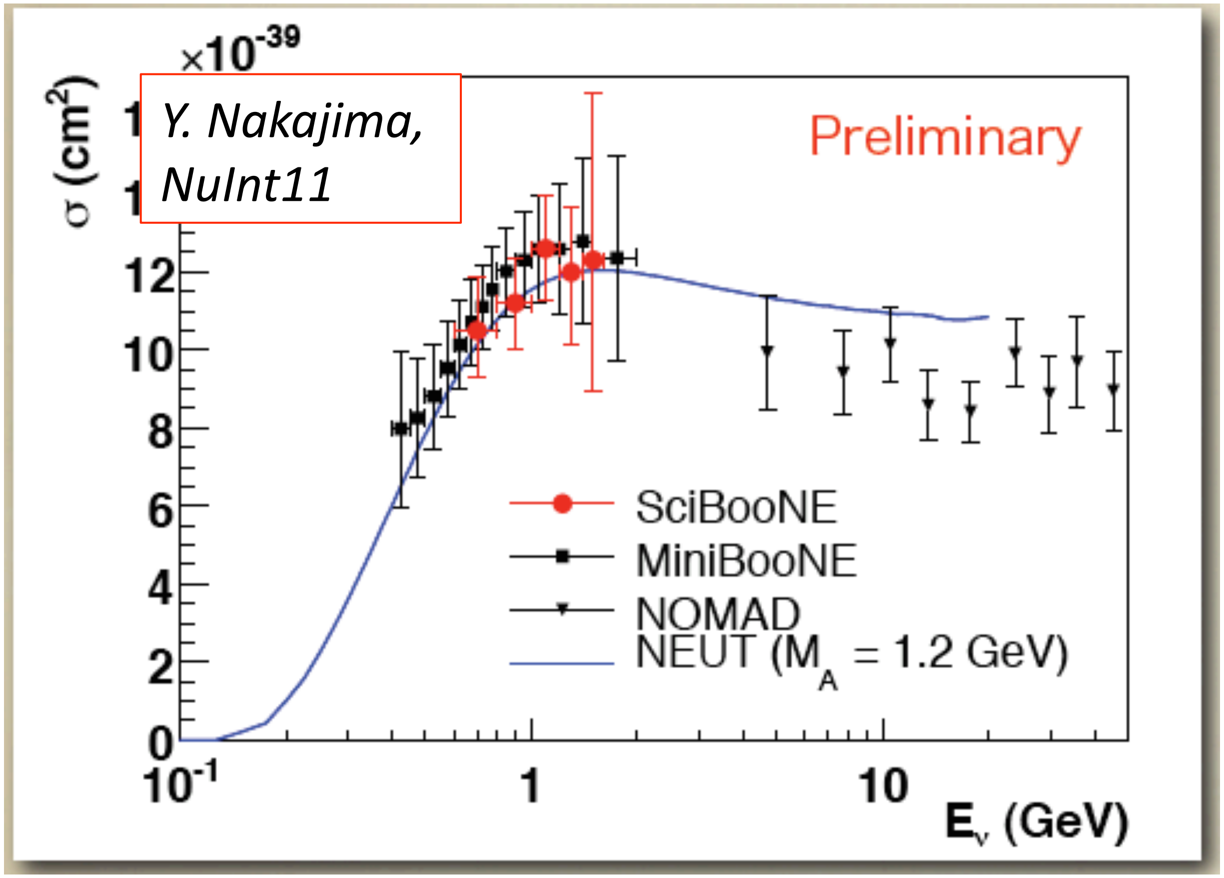
A. Minamino NuInt12

With <5% overall systematic uncertainty, HK could observe evidence of nonzero δ_{CP}

- Statistical uncertainty ~2%
- Improved control of systematic uncertainties corresponds to increased physics impact

How do we achieve <5% systematics?

Uncertainties	ν_e sig+bkrd
ν flux+xsec (constrained by ND280)	±5.7%
ν xsec (unconstrained by ND280)	±7.5%
Far detector	±3.9%
Total	±10.3%



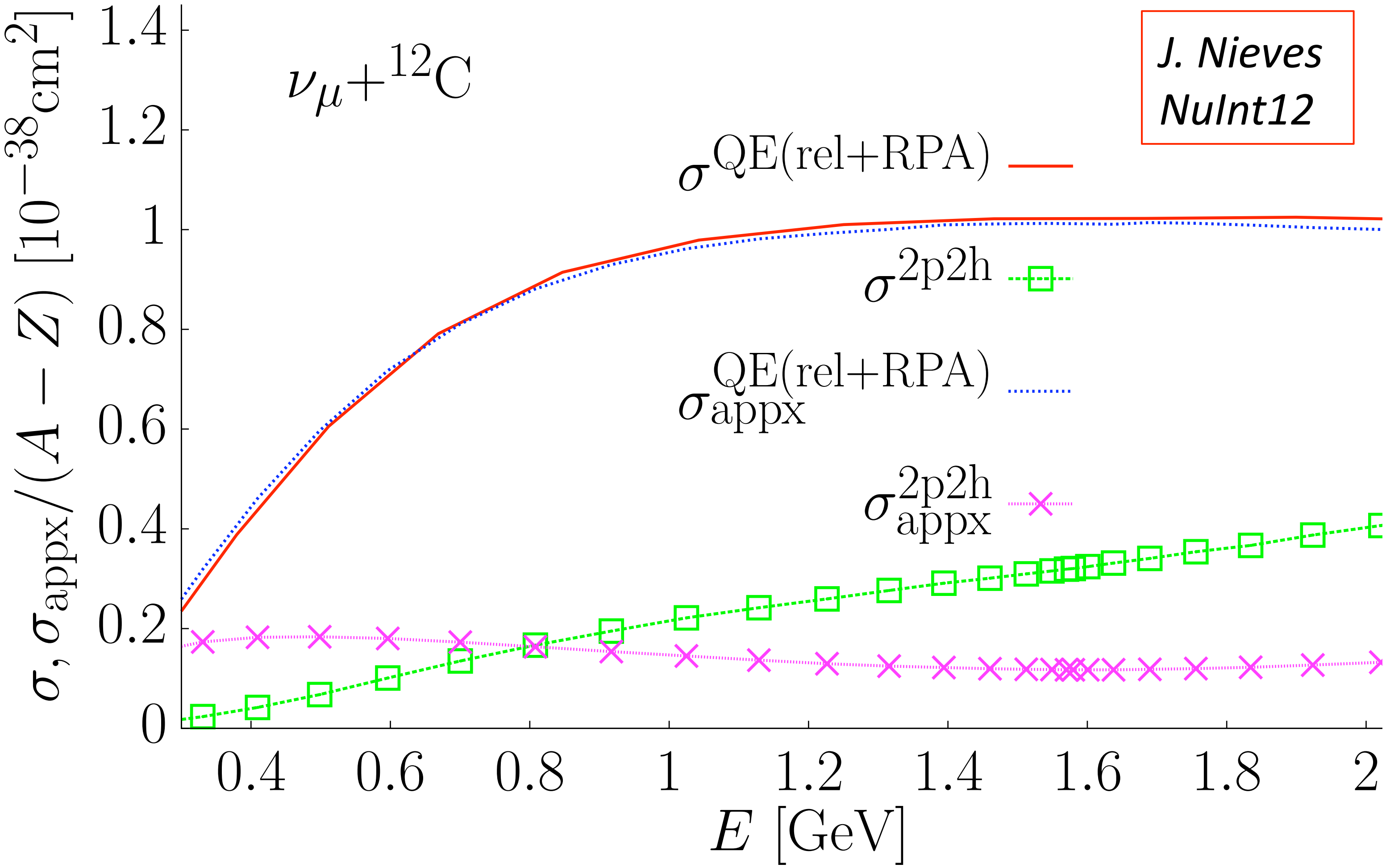
Y. Nakajima, NuInt11

The largest systematic uncertainties currently on the T2K ν_e appearance analysis are neutrino interaction model uncertainties

- Disagreements between data and neutrino interaction model with other neutrino experiments (e.g. MiniBooNE, SciBooNE)
- Differences between alternate interaction models than those currently used by T2K

Also challenges faced by LBNE, LBNO, other proposed long baseline neutrino experiments

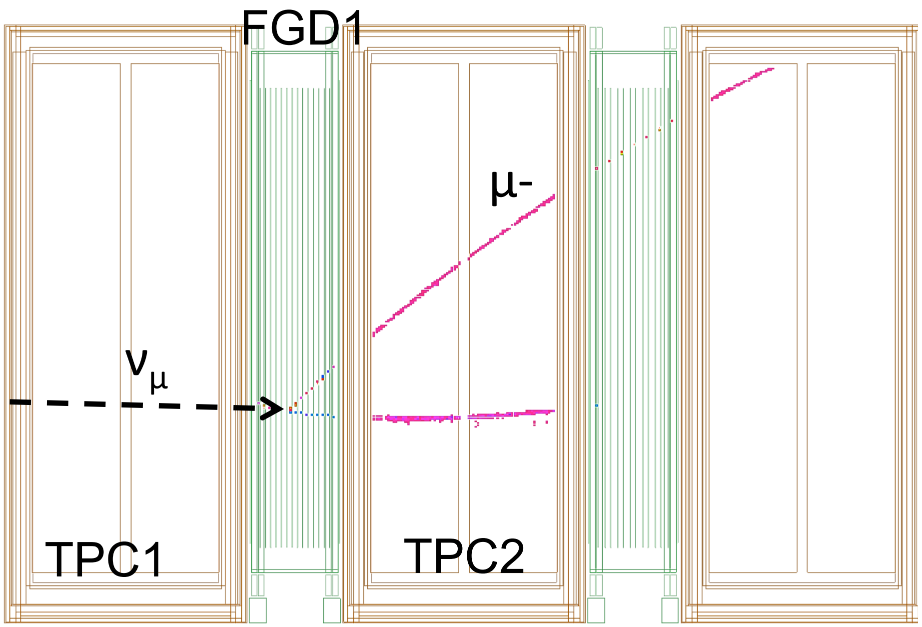
T2K’s efforts to reduce cross section uncertainties

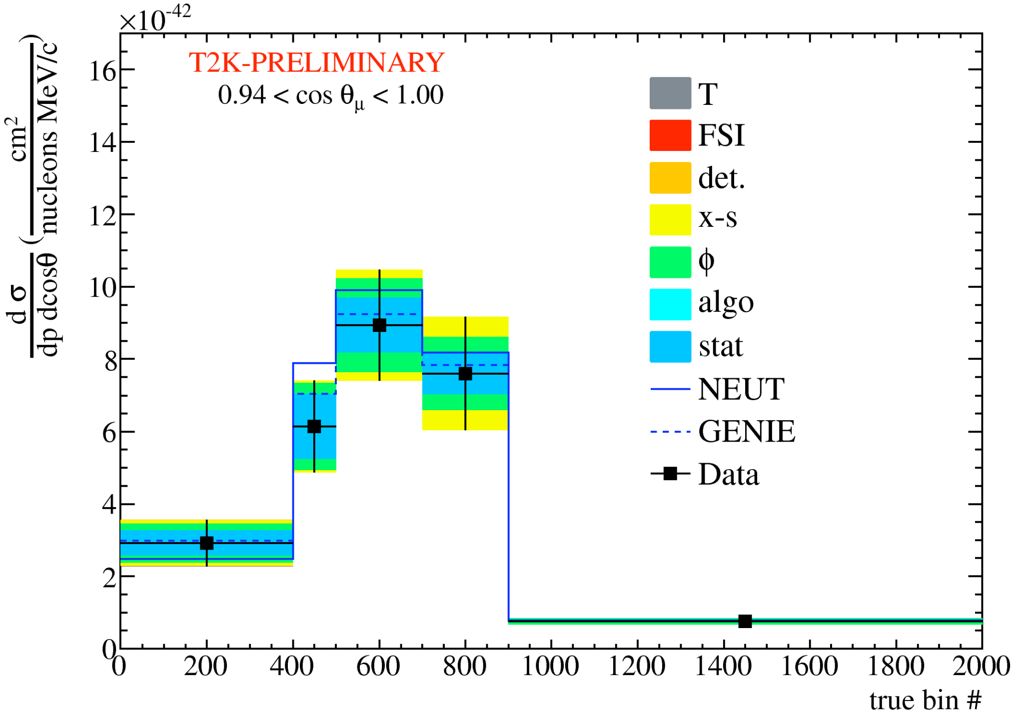


1) Incorporate alternate or updated neutrino interaction models into our simulations

- Validate existing models with electron, pion scattering data
- Add new models which help resolve disagreements with neutrino data to MC

T2K's efforts to reduce cross section uncertainties





2) Test the agreement of new models with ND280, as ND280-XSEC co-convener:

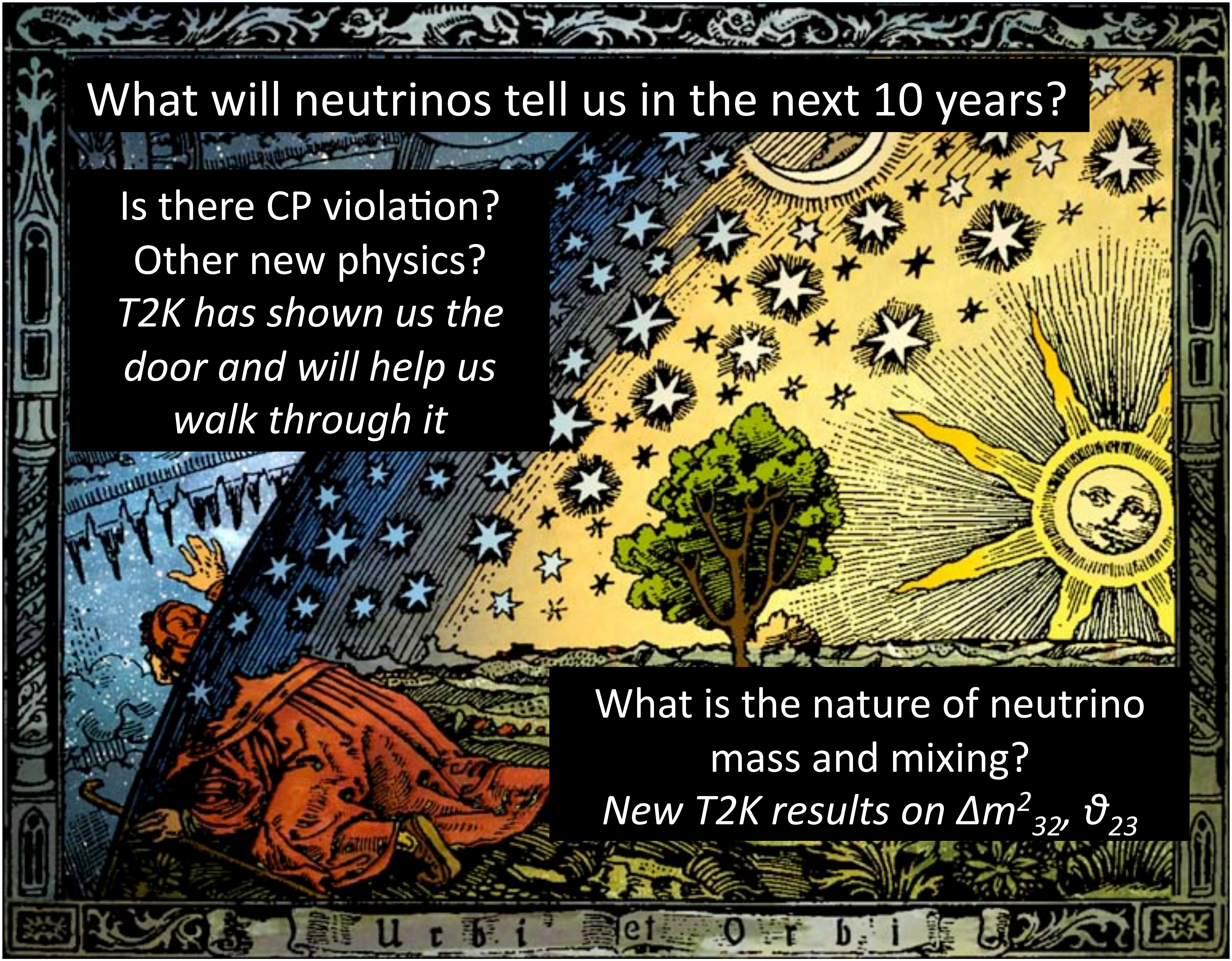
- Detailed information (particle type, kinematics) out of the interaction
- Provide cross section measurements for community to further develop models

    Produced T2K's first cross section measurement (CC inclusive)

    Accepted for publication in PRD

- ND280 performance, limitations important to determine what is needed for a HK near detector program

What will neutrinos tell us in the next 10 years?



Is there CP violation?
Other new physics?
T2K has shown us the door and will help us walk through it

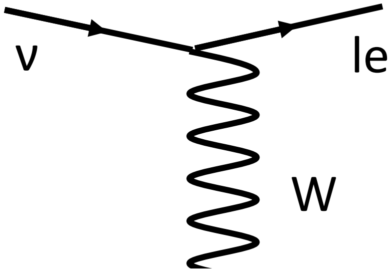
What is the nature of neutrino mass and mixing?
New T2K results on Δm^2_{32}, ϑ_{23}

Backup slides

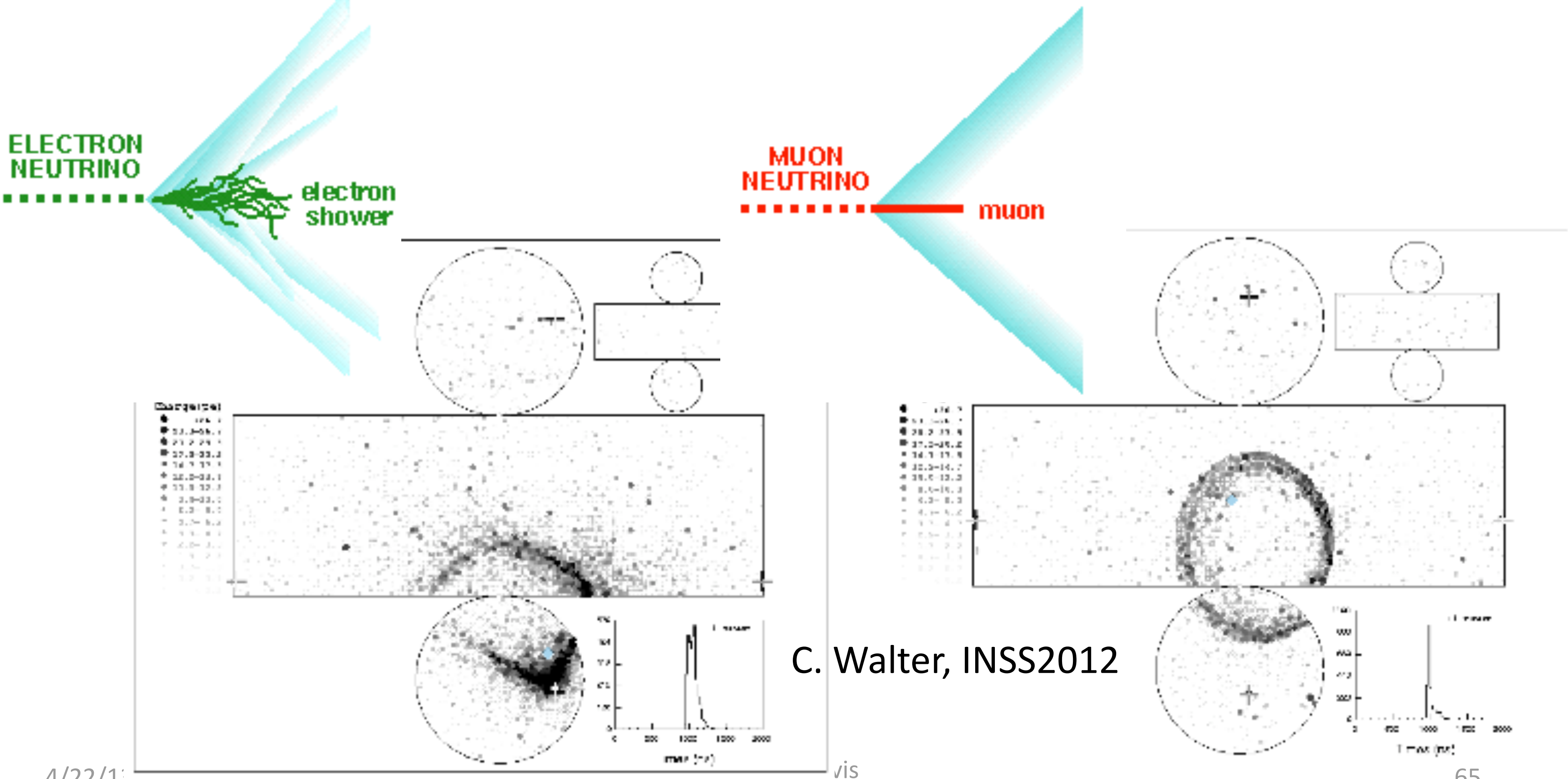
Detecting atmospheric neutrinos

Select ν_e or ν_μ events from ring shape and topology

Charged Current (CC)



$$\nu_e \longrightarrow e$$
$$\nu_\mu \longrightarrow \mu$$
$$\nu_\tau \longrightarrow \tau$$



C. Walter, INSS2012

Selecting CC ν_e interactions

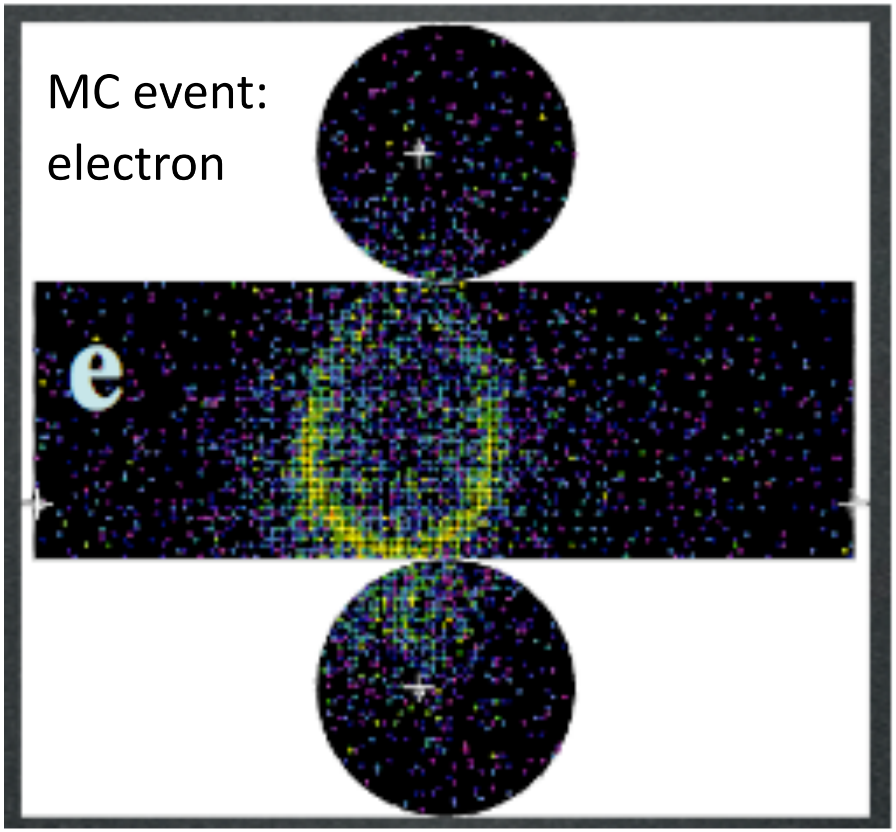
Signal: CC ν_e from ν_μ to ν_e oscillation

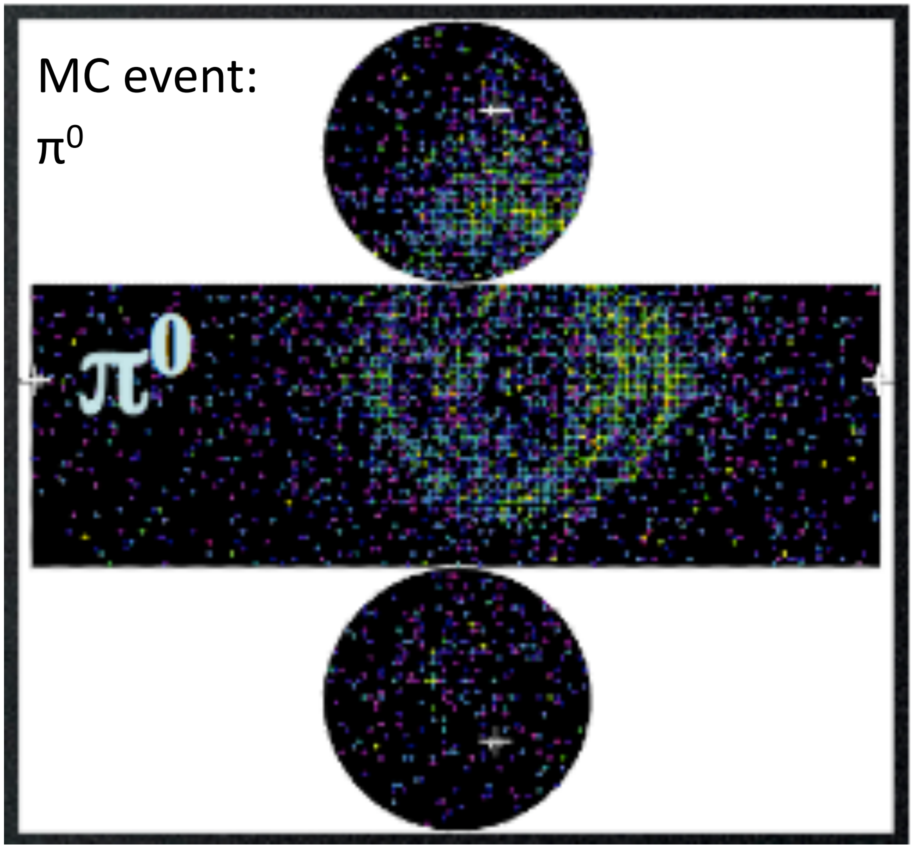
Background: CC ν_e
Irreducible beam ν_e

Background: NCπ^0 ν_μ
Mimics CC ν_e

A π^0 from a NC interaction will decay to two photons (two electron-like rings)

- Search for 2nd ring
- Calculate invariant mass
- Reject events consistent with π^0 invariant mass

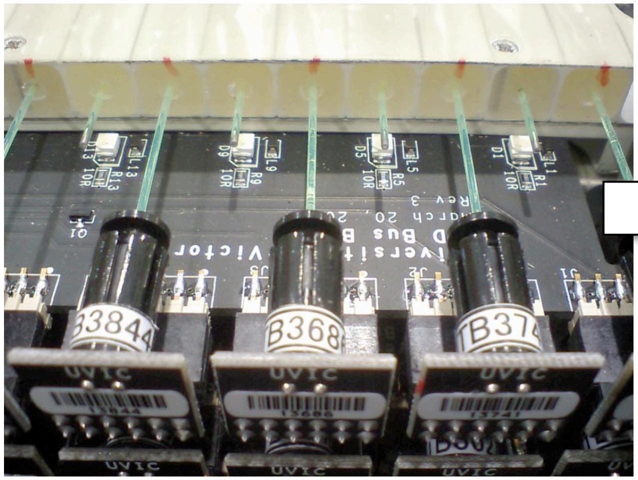


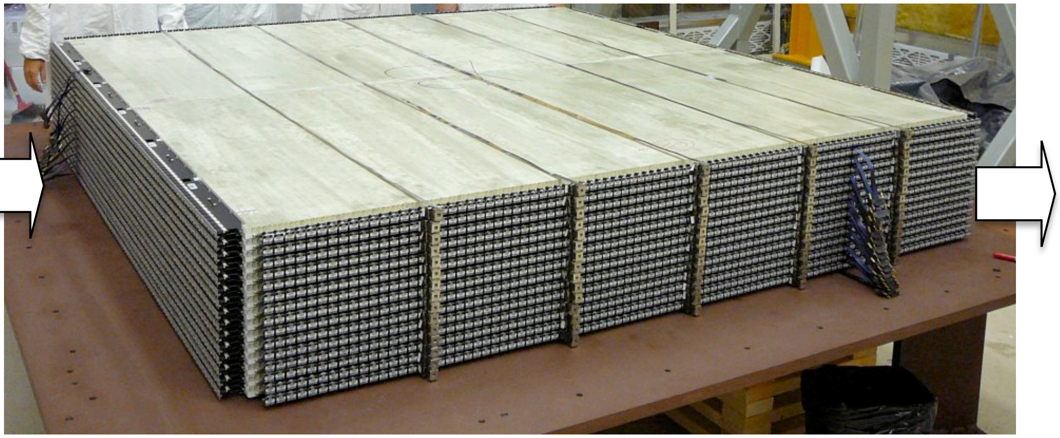


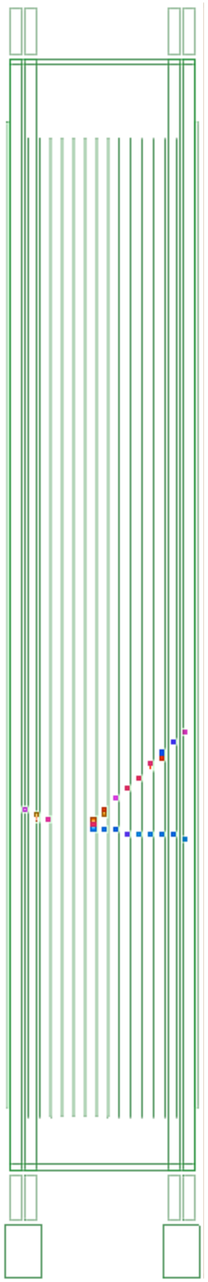
Fine Grained Detectors (FGDs)

Scintillation light (from charged particles) is sent down a wavelength shifting fibre connected to a multi-pixel-photon-counter (MPPC)

- MPPCs function in a magnetic field
- First large scale use







X and Y scintillator layers can be used for 3D tracking

1cm^2 bar size provides detailed vertex information

P.-A. Amaudruz et al,
“The T2K fine-grained detectors”,
NIM A (2012) 10.1016/j.nima.2012.08.020

Time projection chambers (TPCs)

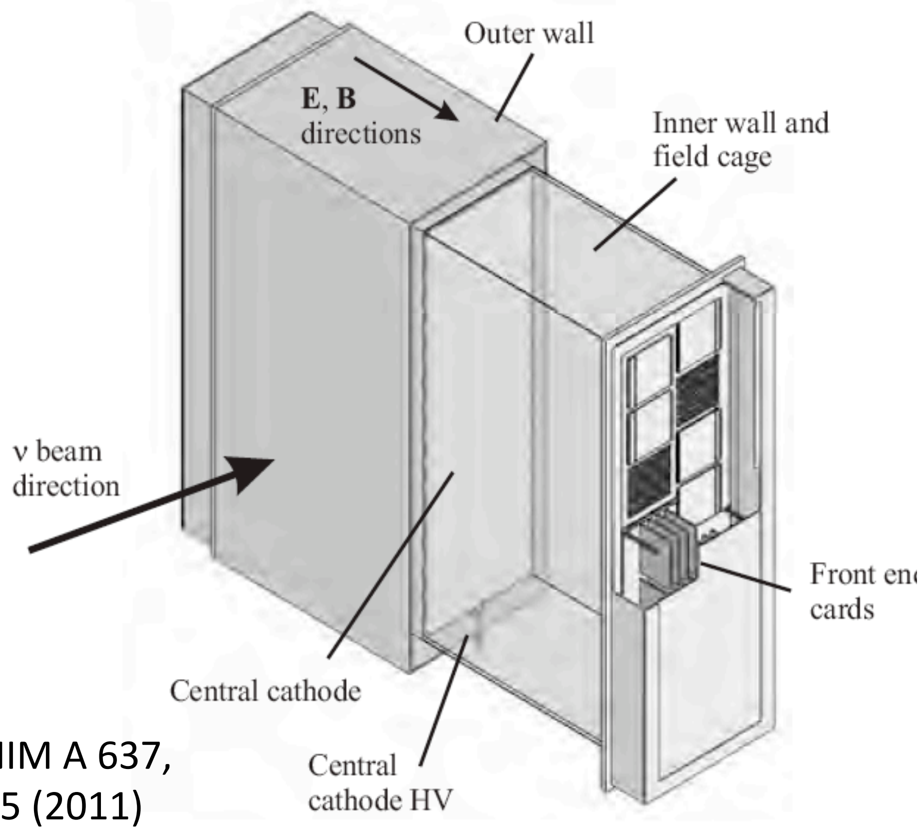
Charged particle ionizes gas; electrons drift to readout plane (E~25kV)
``Wireless” TPC: Use of bulk micromegas detectors in readout

3D tracks are reconstructed provided drift velocity in the gas and timing of entry from other subdetectors

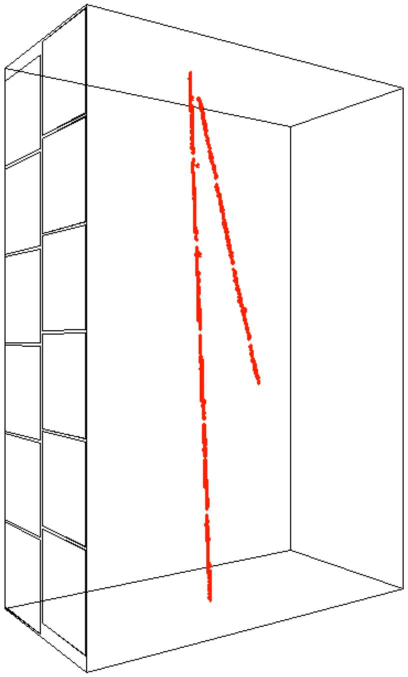
Momentum of the particle can be determined from curvature

- 0.2T B field; p_μ ~ 1 GeV/c has <10% momentum resolution

Built DQ system, alignment convener



NIM A 637, 25 (2011)



Overall systematic uncertainty

After ND tuning, systematic uncertainties reduced to ~10% on signal+ background

- Overall uncertainty halved with use of the near detector data

Signal (ν_μ to ν_e osc)	**# events**
@$\sin^2 2\theta_{13}=0.1, \delta cp=0$	7.81

Background	**# events**
beam $\nu_e + \overline{\nu}_e$	1.73
$\nu_\mu + \overline{\nu}_\mu$ (mainly NC) background	1.31
osc through θ_{12}	0.18
total:	3.22 ±0.43(sys)

ν_e signal@$\Delta m^2_{32}=2.4 \times 10^{-3}$ eV^2, $\sin^2 2\theta_{23}=1.0$

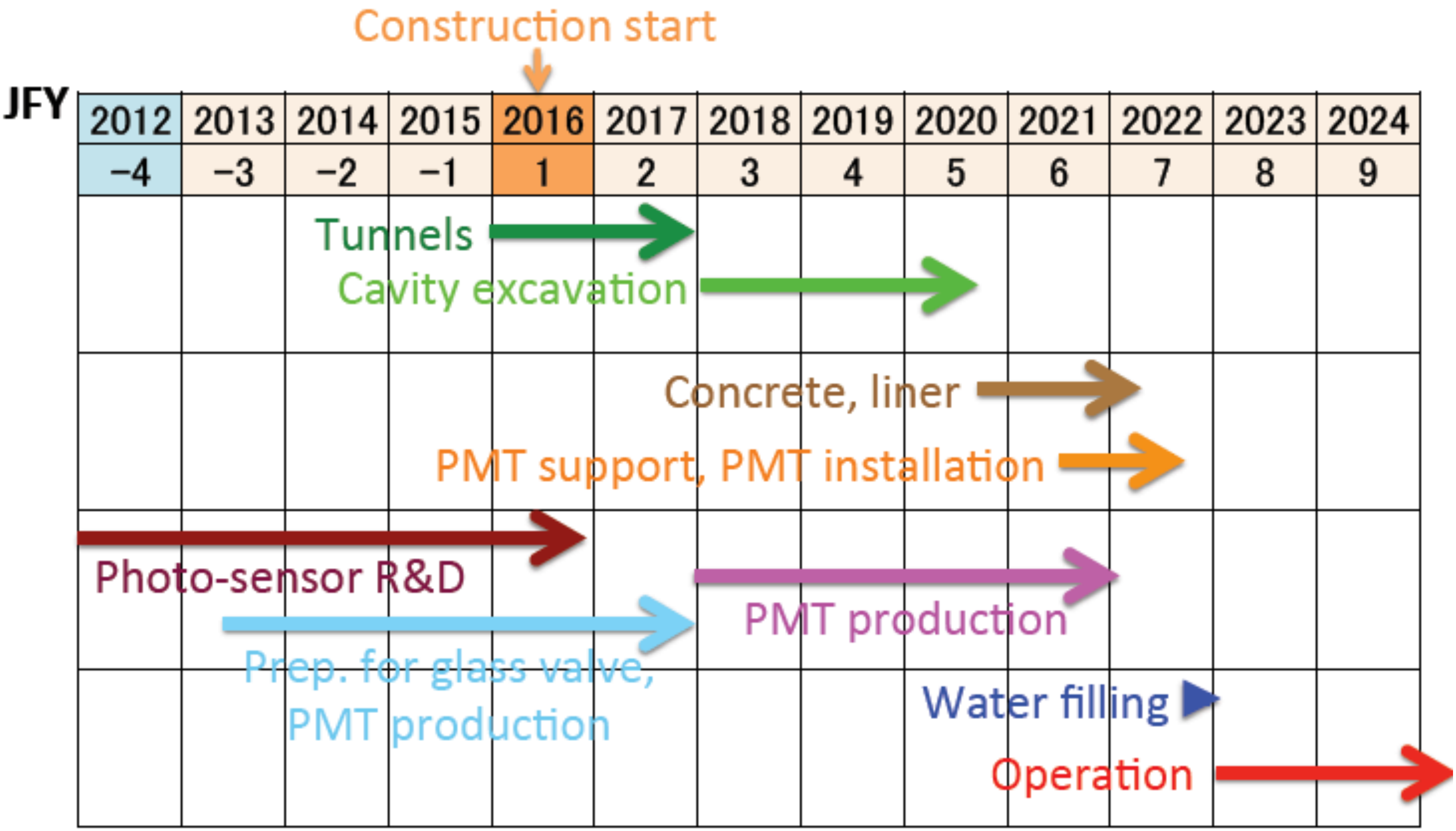
Uncertainties	**ν_e bkrd**	**ν_e sig+bkrd**
ν flux+xsec (constrained by ND280)	±8.7%	±5.7%
ν xsec (unconstrained by ND280)	±5.9%	±7.5%
Far detector	±7.7%	±3.9%
Total	±13.4%	±10.3%
No ND measurement	**26%**	**22%**

Hyper-K timeline

A. Minamino
NuInt12

Schedule

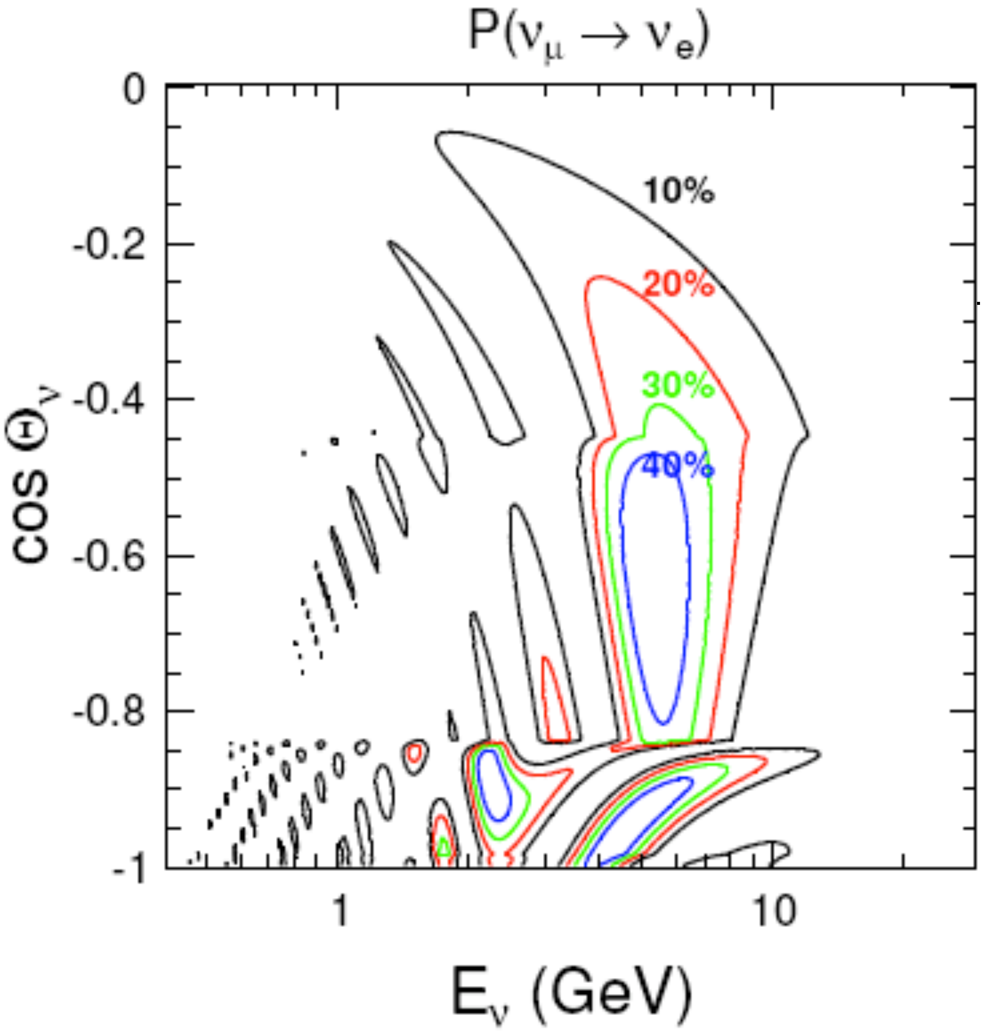
assuming budget being approved from JPY2016



Appearance measurements: atmospheric nu

Electron neutrino rate is altered by ν_μ to ν_e appearance and survival probability of ν_e

- Contours of equal probability as a function of E_ν and $\cos(\theta)$

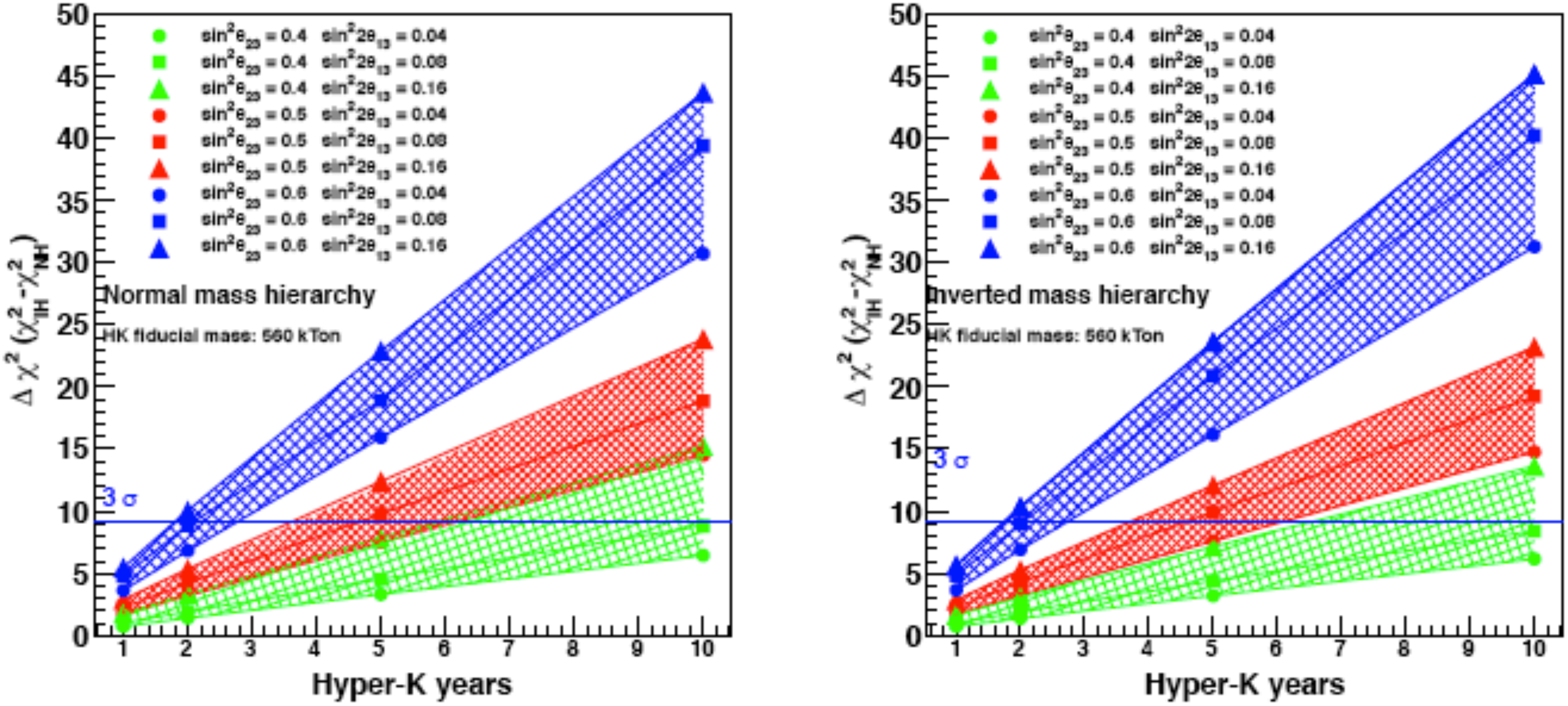


Appearance probability depends on all mixing parameters, including δ_{CP}, θ_{13}

- θ_{23}<45 degrees amplifies lower energy ν_e rate through the Earth's core
- normal hierarchy ($\Delta m^2_{32} > 0$) increases higher energy ν_e rate through Earth's core

Super-Kamiokande collaboration
Phys Rev D81 092004,2010

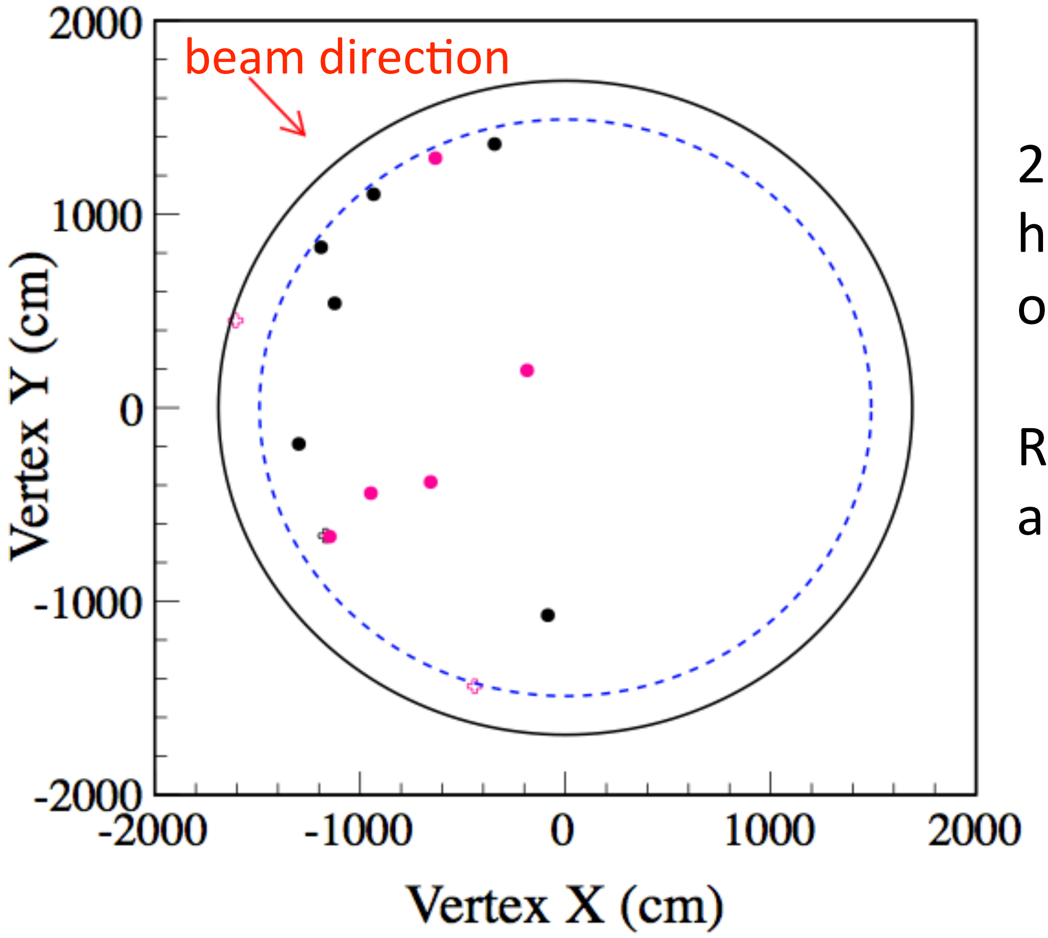
Hyper-K and mass hierarchy



Delta Chi2 for the true normal hierarchy (left) and inverted (right)
for HK (atmospheric nu alone, ~3sigma across most of par space, better with T2HK)

- Nova resolves mass hierarchy at ~2 sigma for 40% of all values of delta
- Proposed Daya Bay II reactor experiments can be sensitive to MH
- PINGU 20: 3-11 sigma, depending on par space, systematics after 5 yrs
- Cosmology, or neutrinoless double beta decay may also provide indications

Vertex distribution of ν_e candidates

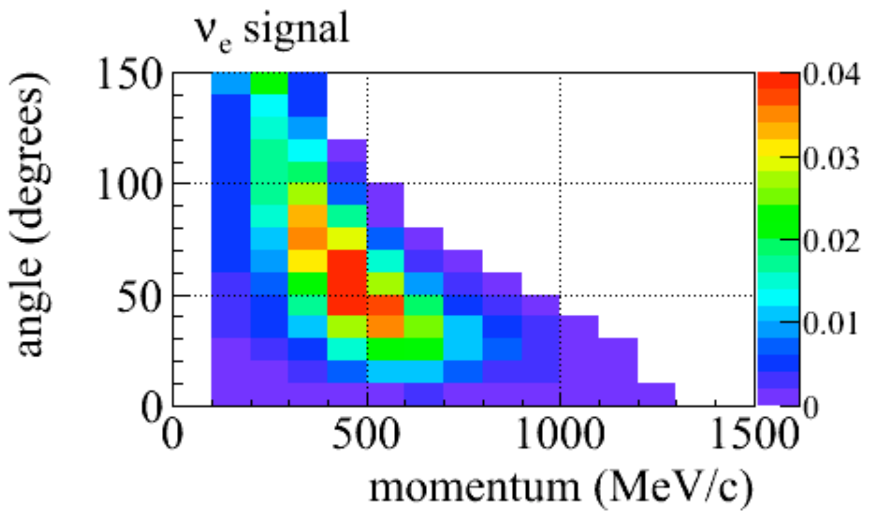


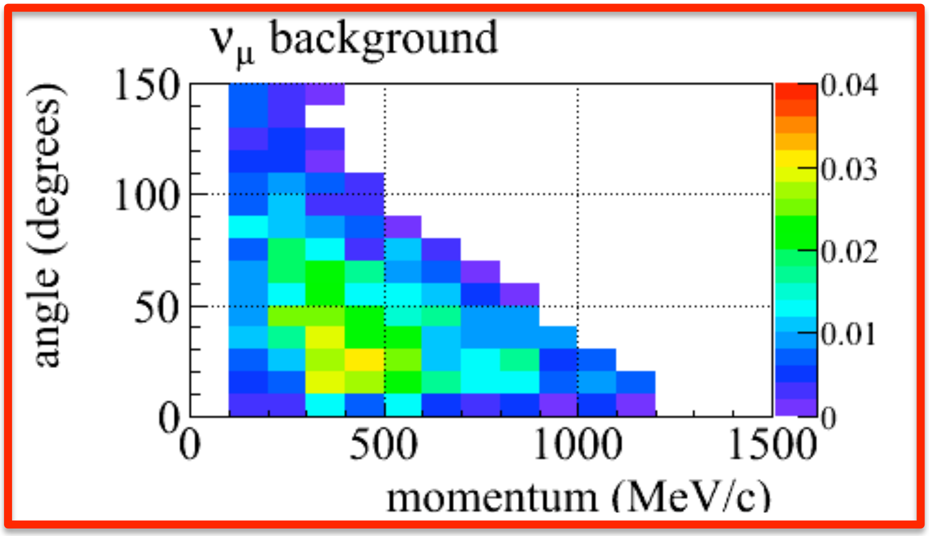
2011 analysis (Run 1+2, black points) had a discrepancy in radial distribution of event candidates

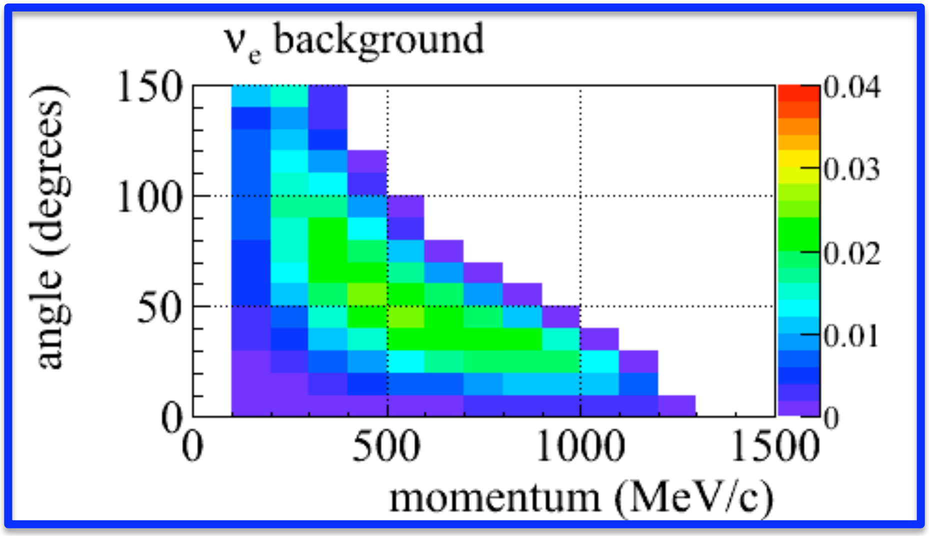
Radial distribution of new data (Run 3, pink) appears normal

KS test of radial distribution
Run 1+2: 10%
Run 3: 74.6%

Separating signal and background





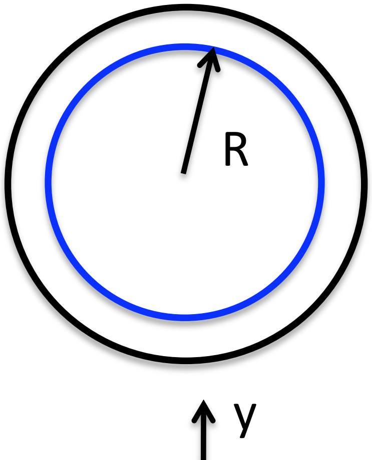


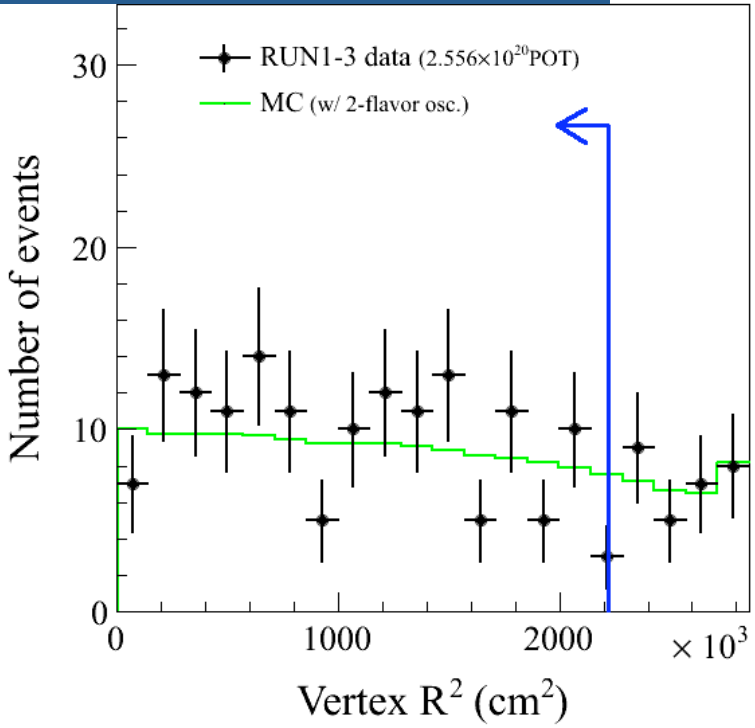
Additional separation of signal, background events with CC ν_e candidate kinematics

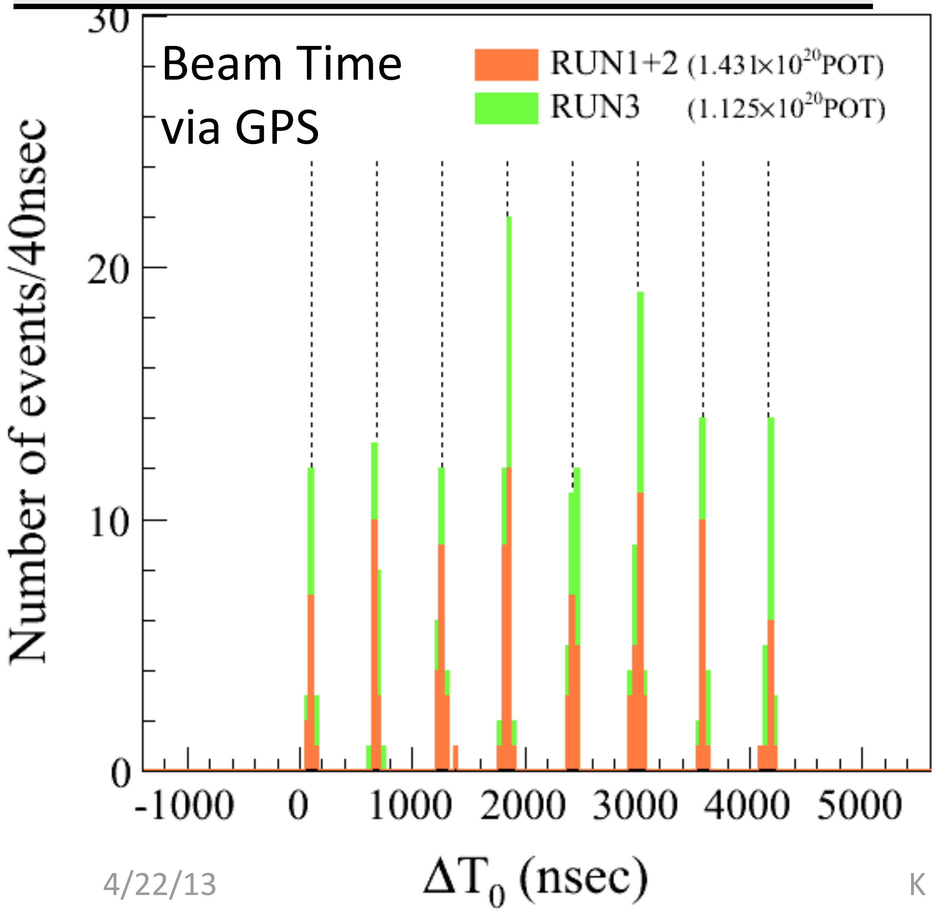
- CC ν_e backgrounds come from higher energy neutrinos and populate signal and higher momentum region
- NC backgrounds are due to misID'd photons that reconstruct as electrons at low momentum and low angle (as well as the signal region)

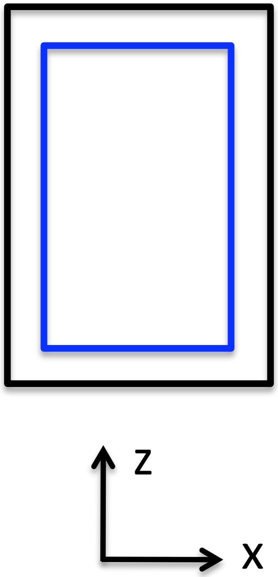
Basic neutrino event selection (Run 1+2)

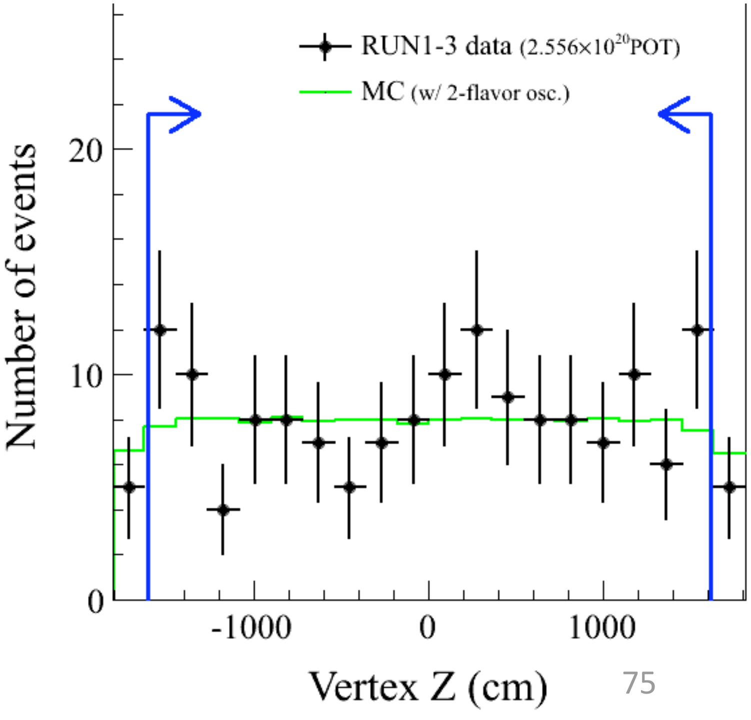
Basic neutrino selection (precuts)
Event time within beam window
No activity in the veto
Visible E > 30 MeV
Reconstructed vertex >2m from wall
Single reconstructed ring







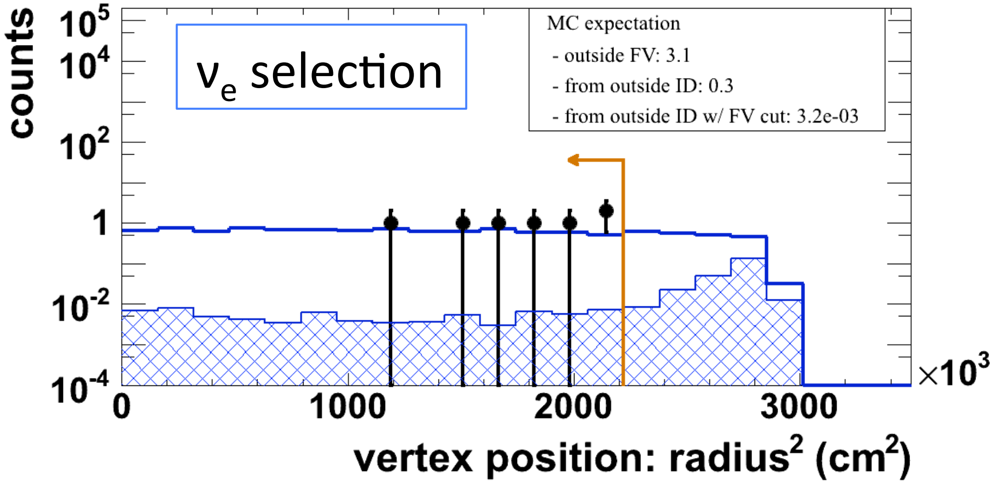




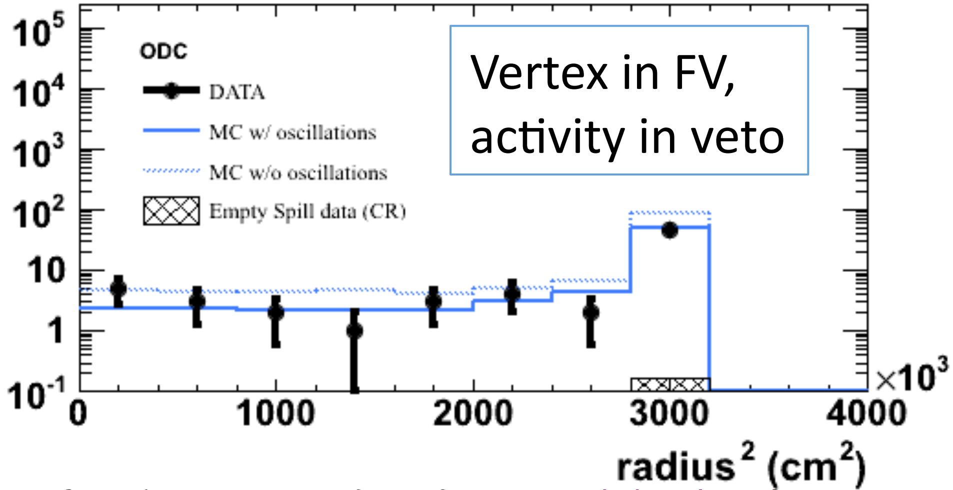
Beam backgrounds at high radius (Run 1+2)

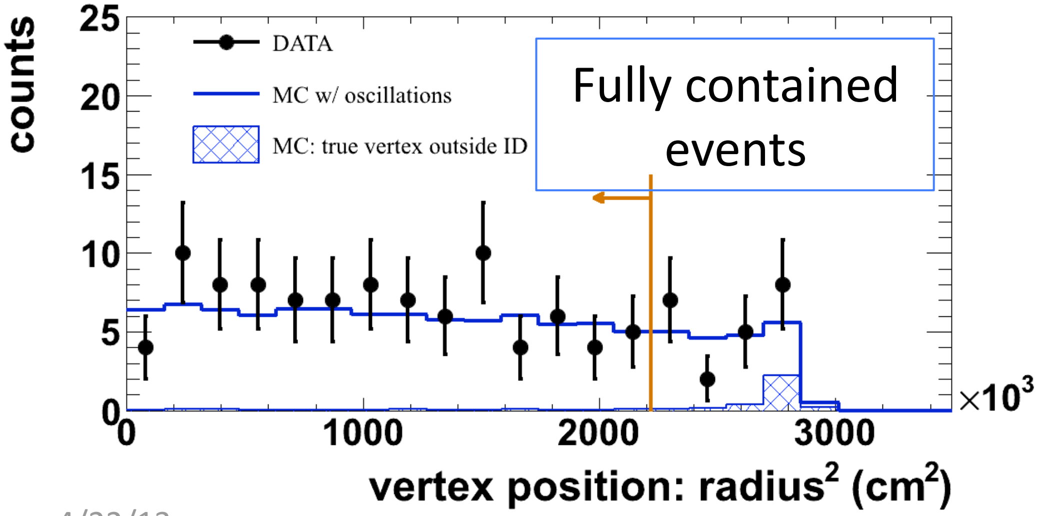
MC simulates neutrino interactions upstream of the detector (e.g. π^0 production)

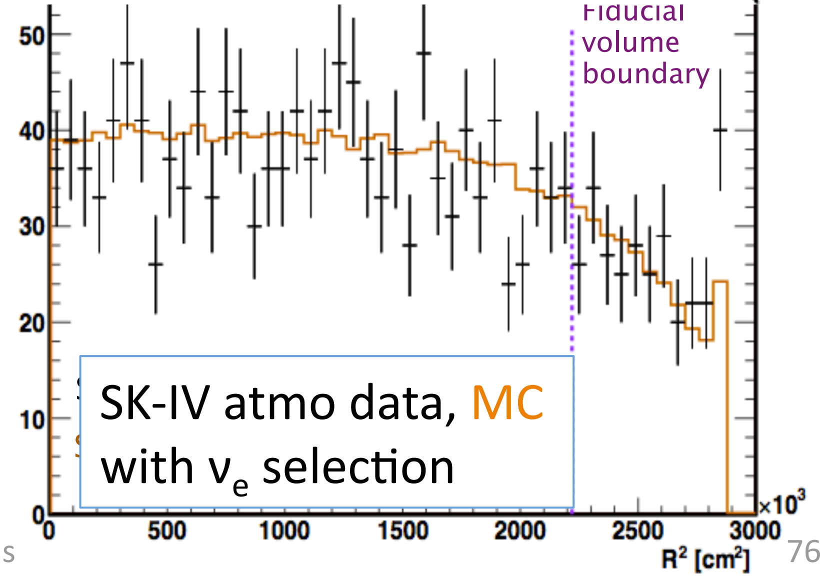
- Only 1 ν_e event cut by FV selection (no excess of ν_e events outside FV)
- Dedicated sample of events entering tank (with activity in veto) agree
- No bias to radial distribution of atmospheric sample under T2K ν_e selection


ν_e selection

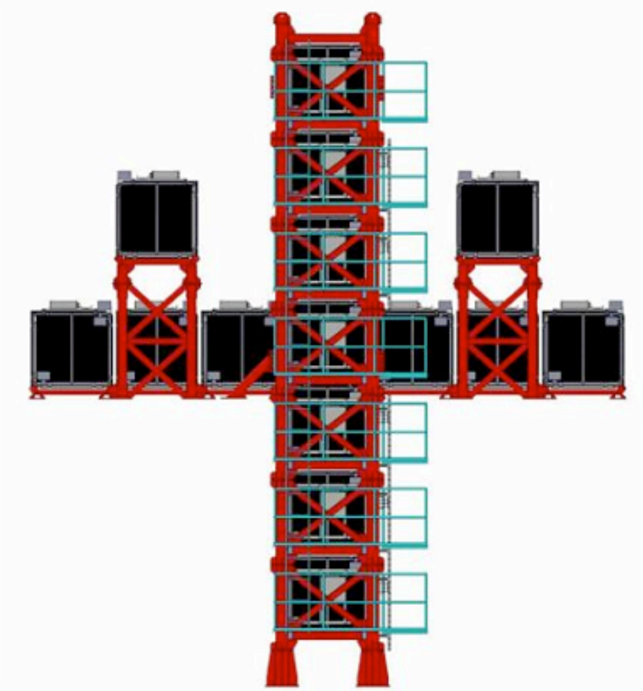
MC expectation
- outside FV: 3.1
- from outside ID: 0.3
- from outside ID w/ FV cut: 3.2e-03


Vertex in FV, activity in veto


Fully contained events


SK-IV atmo data, MC with ν_e selection

On-axis Interactive Neutrino GRID (INGRID)



16 modules arranged in a cross

- X-Y iron-scintillator layers, 7.1 tons each

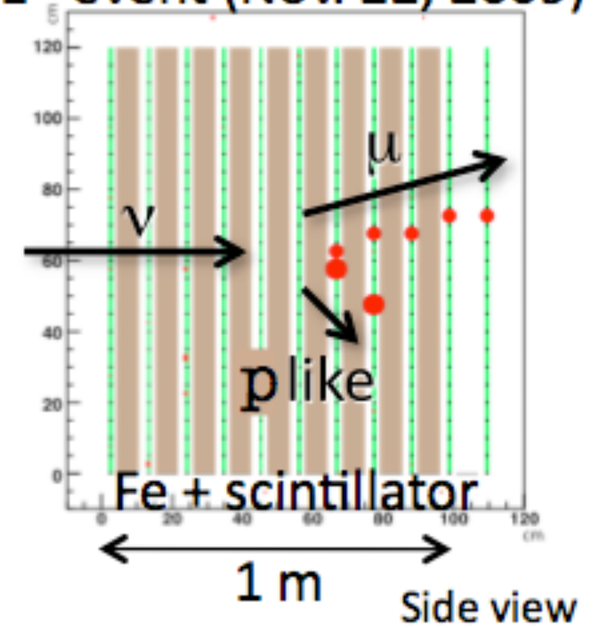
Count neutrino interactions in each module to determine neutrino rate vs. position

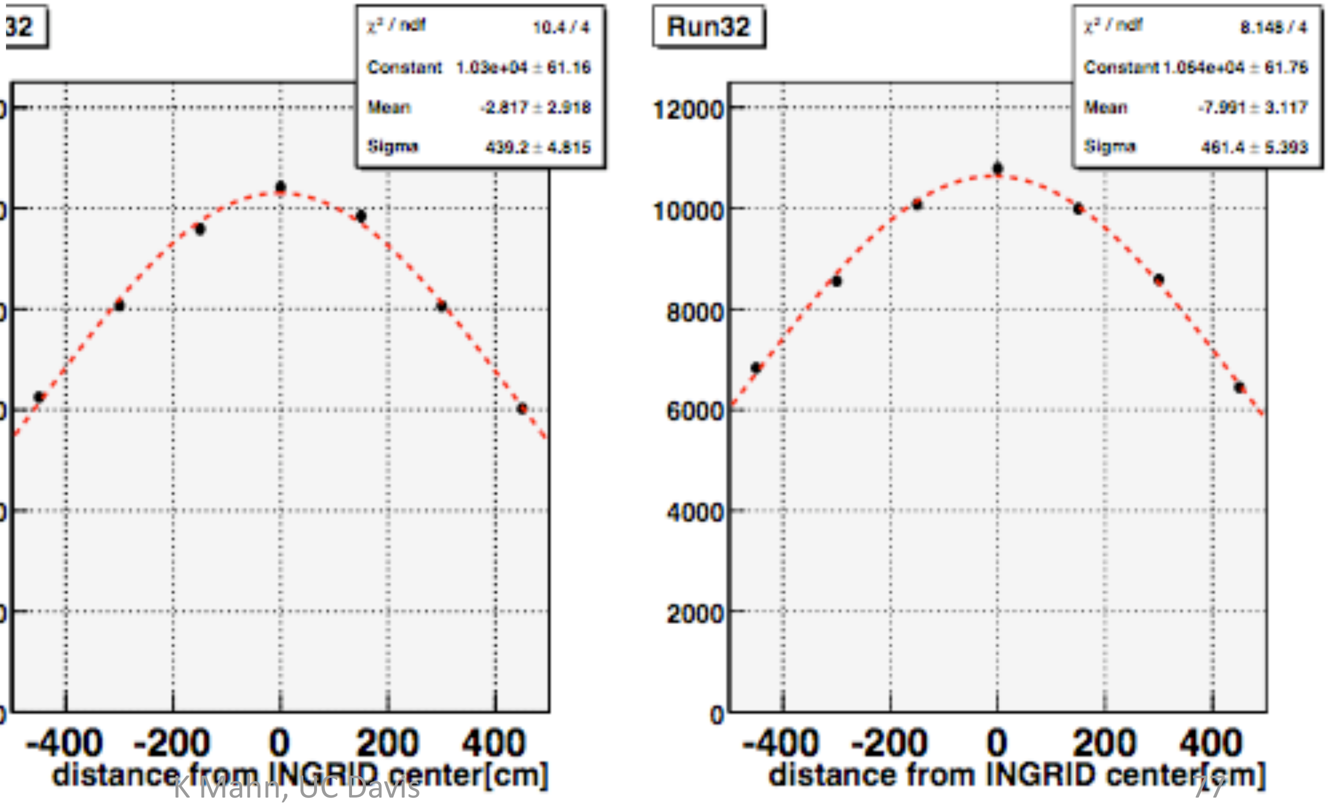
Extract beam direction better than 0.5 mrad

Monitor of neutrino beam vs. time

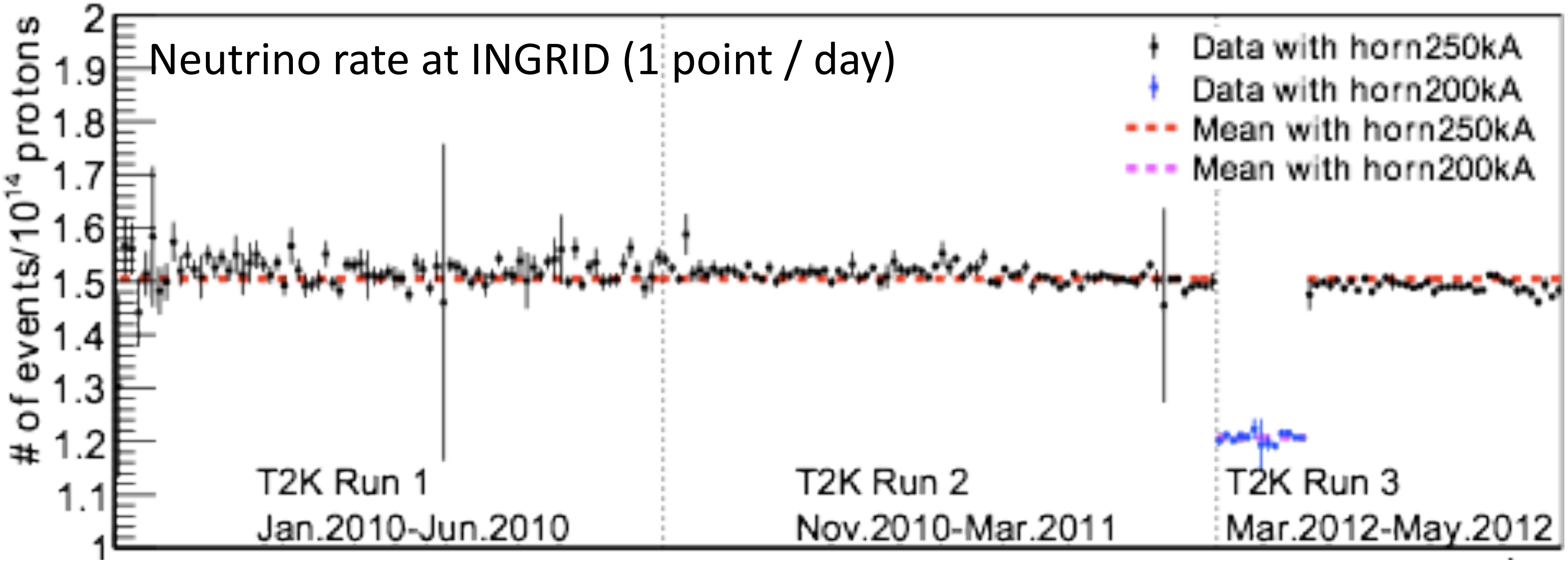
- ~1.5 ν / 10^{14} protons on target
- ~10,000 events / day

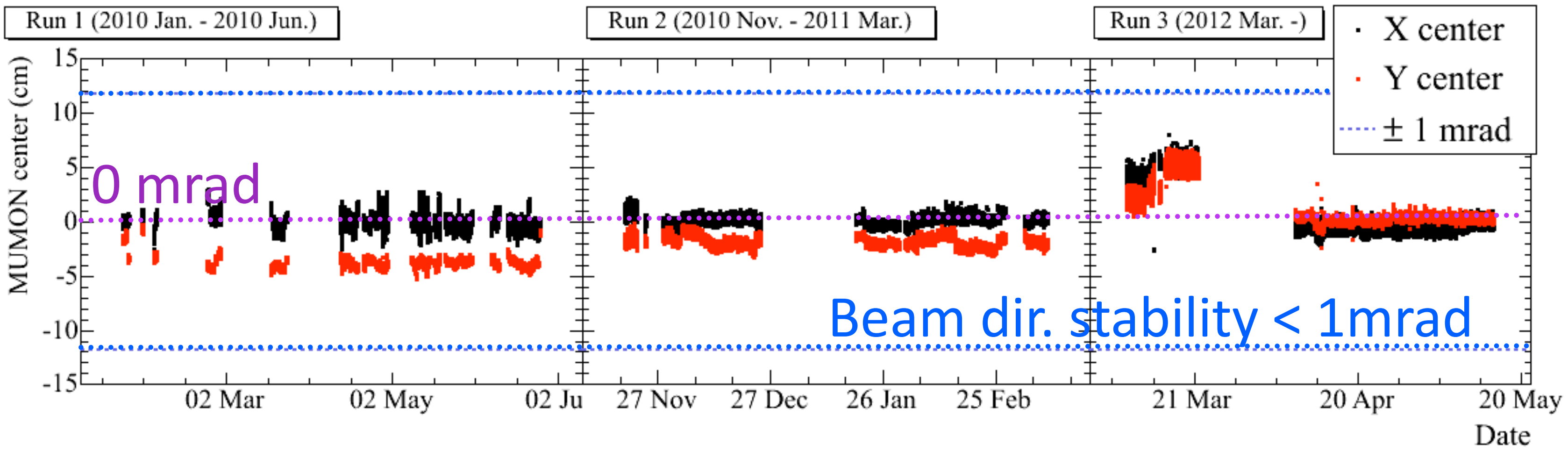
1st event (Nov. 22, 2009)





Neutrino beam stability

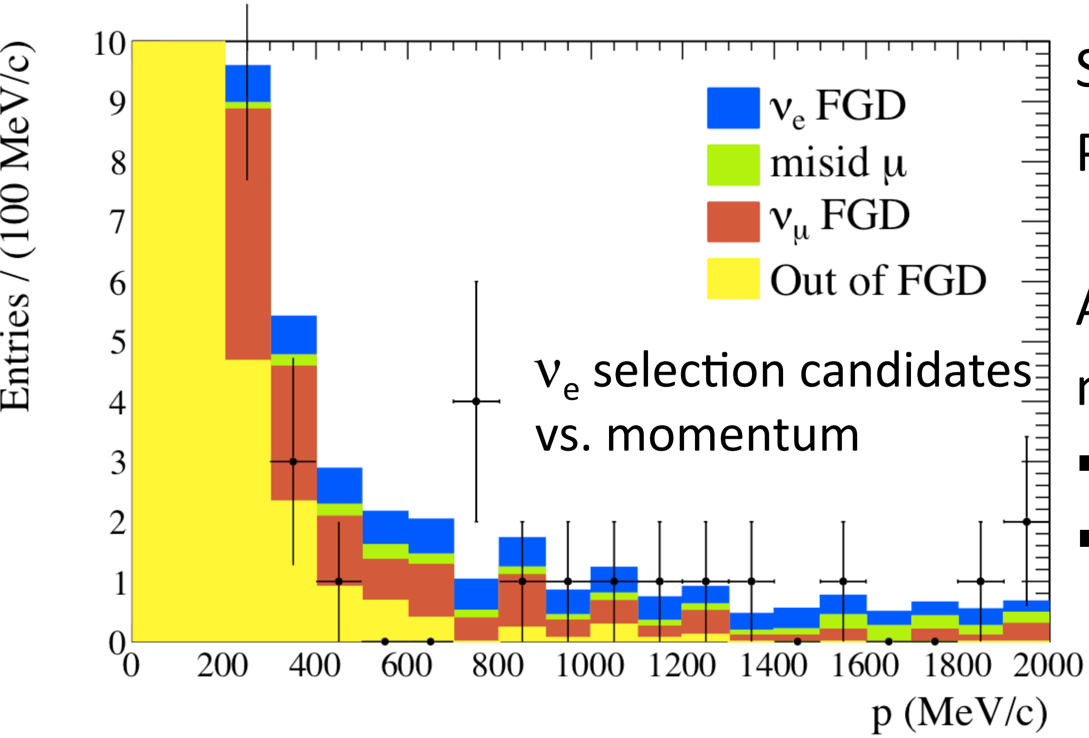

Neutrino rate at INGRID (1 point / day)


0 mrad

Beam dir. stability < 1mrad

Beam direction (x and y)
with the muon monitor
Stable to <1 mrad

ND280 beam ν_e rate cross-check (I)



ν_e selection candidates vs. momentum

Select ν_e candidates at ND280 with TPC PID to check rate of intrinsic beam ν_e

Additional backgrounds to ν_e selection, measured via control samples

- μ misidentified as e
- e from photon conversion (photons emitted in ν_μ interactions in FGD and other subdetectors)

Ratio of observed ν_e / ν_μ events is consistent with untuned prediction

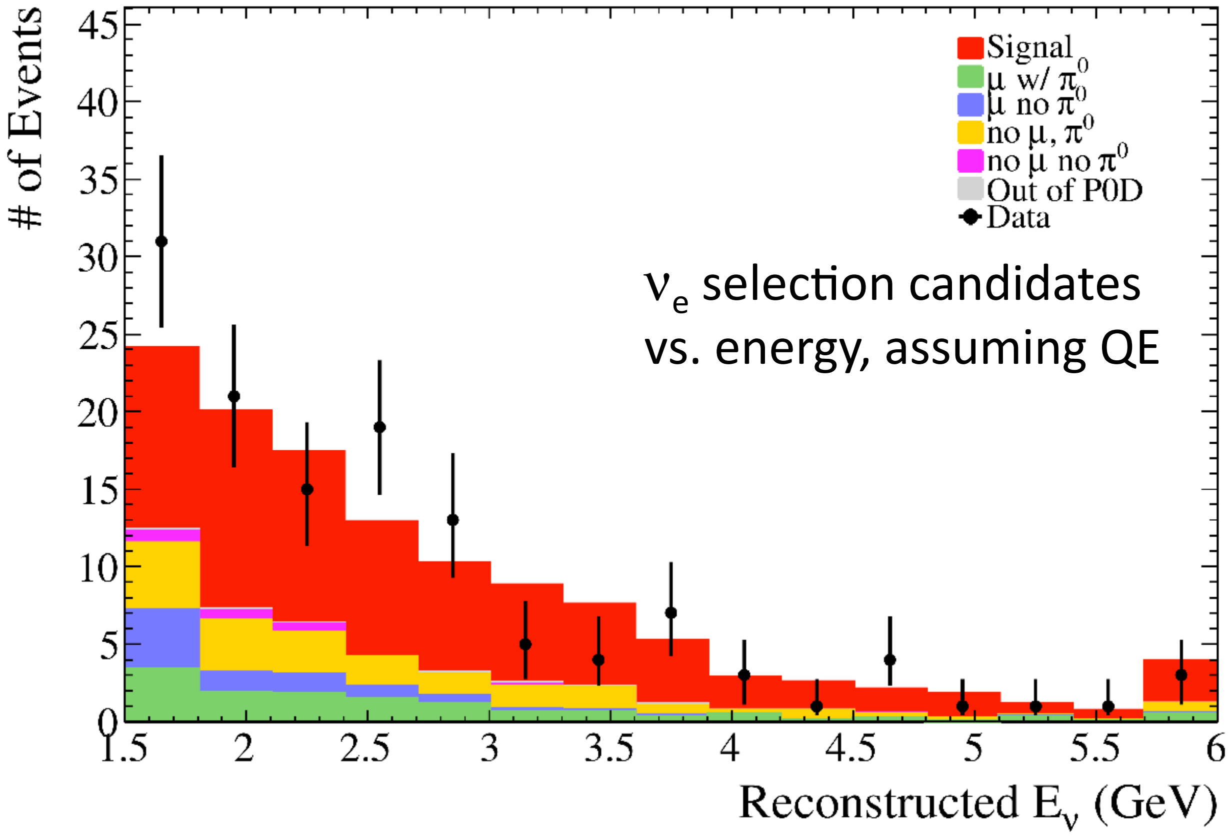
$N(\nu_e)/ N(\nu_\mu) = R(e:\mu) = 1.0\% \pm 0.7\%$ (statistics) $\pm 0.3\%$ (systematics)

$R(e:\mu, \text{data}) / R(e:\mu, \text{MC}) = 0.6 \pm 0.4$ (statistics) ± 0.2 (systematics)

Improvements to the analysis:

- Improved rejection of backgrounds with ECals
- More data: 2.88×10^{19} POT shown here

ND280 beam ν_e rate cross-check (II)



ν_e selection candidates vs. energy, assuming QE

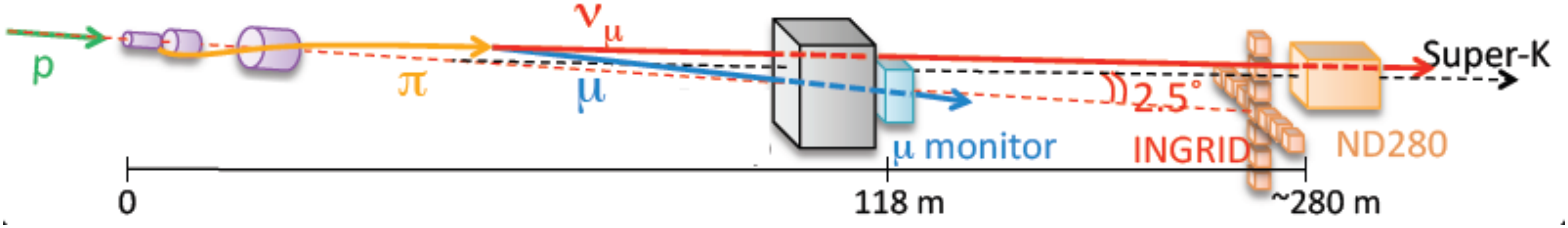
Select high energy CC ν_e candidates within the P0D:

- Reconstructed track matched in x,y with vertex in FV consistent with an single EM shower (reject π^0 mutiple photon showers and muons)
- Primary backgrounds are HE π^0 events

Consistent with current untuned MC:

data-bkrd(MC)/sig(MC)= R = 1.19 ± 0.15(statistics) ± 0.26 (systematics)

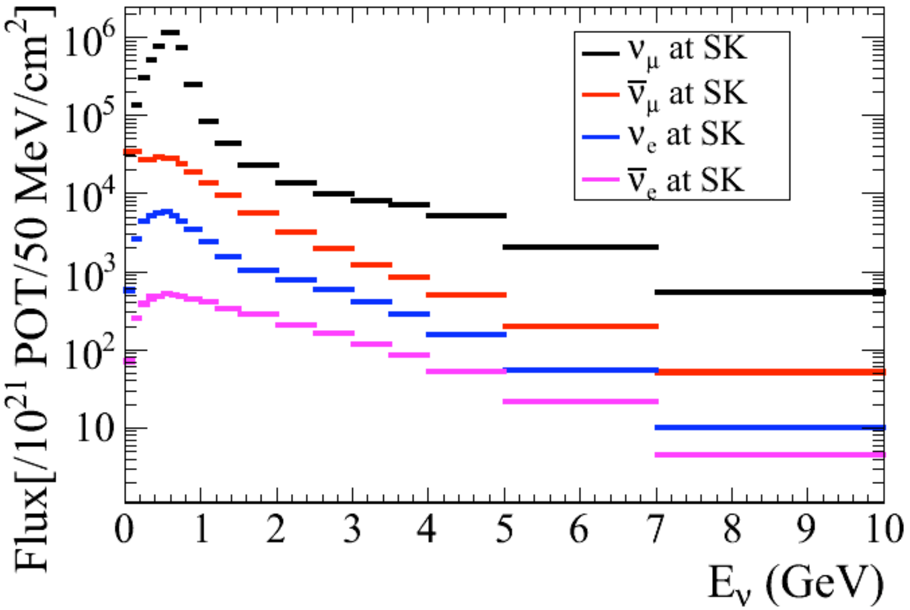
Neutrino flux prediction



FLUKA/Geant3 beam simulation

Unoscillated flux at SK:

- ν_μ from π^+, K decay
- ~1% ν_e from μ, K decay



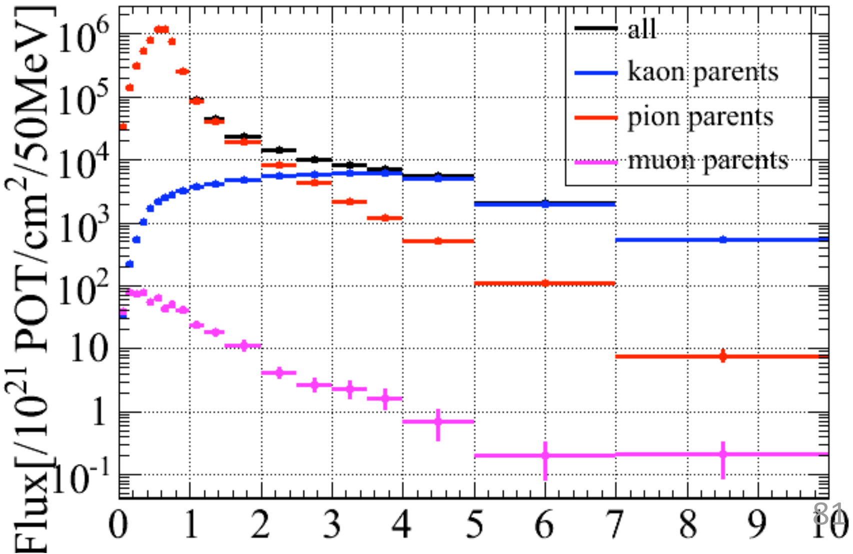
Prediction and uncertainties determined by external or in-situ measurements of:

- proton beam
- π, K production from NA61 experiment

Phys.Rev.C 84, 034604 (2011)

Phys.Rev.C 85, 035210 (2012)

- alignment and off-axis angle

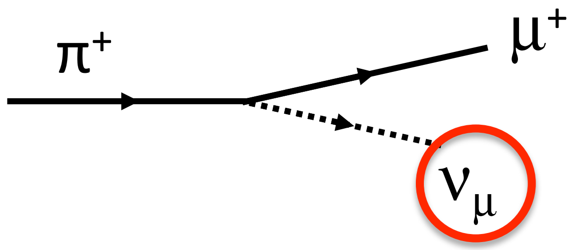


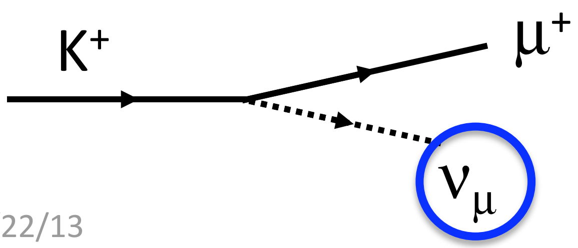
Neutrino flux at ND and SK

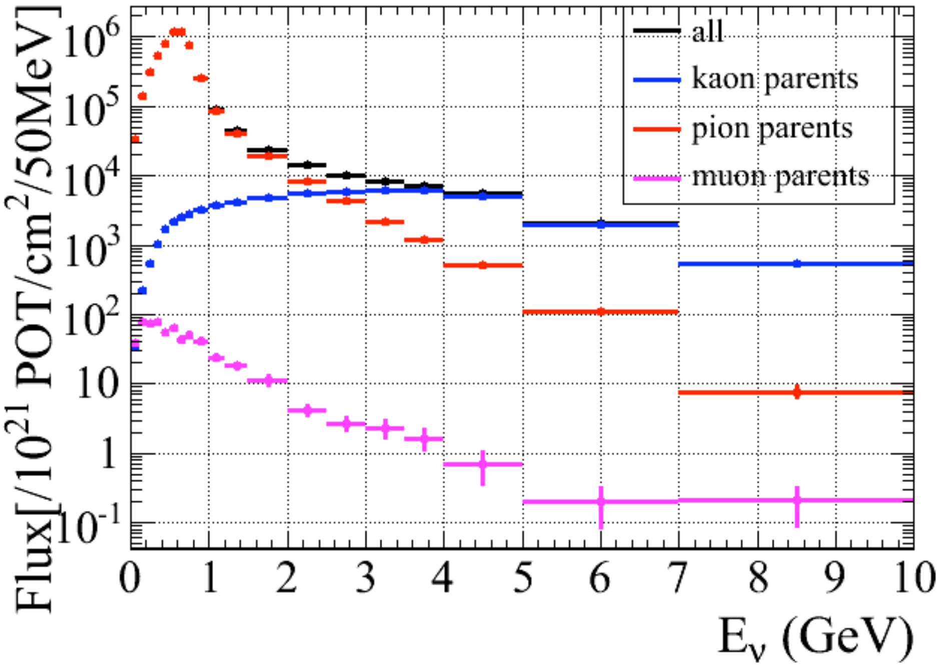
Neutrino Mode	Trkr. ν_μ CCQE	Trkr. ν_μ CCnQE	SK ν_e Sig.	SK ν_e CC intrinsic Bgnd.	SK ν_e NC Bgnd.
$\pi^+ \to \nu_\mu + \mu^+$	82.2%	45.8%	99.3%	1.1%	70.3%
$\mu^+ \to \nu_e + e^+ + \bar{\nu_\mu}$	<1%	<1%	<0.1%	66.0%	<0.1%
$K^{+,0} \to \nu_e + X$	<1%	<1%	<0.1%	33.0%	<0.1%
$K^{+,0} \to \nu_\mu + X$	17.4%	53.4%	0.7%	–	29.7%

ND samples represent ν_μ flux

- ν_μ from π decay: CCQE, CCnQE samples
- ν_μ from K decay: CCnQE sample



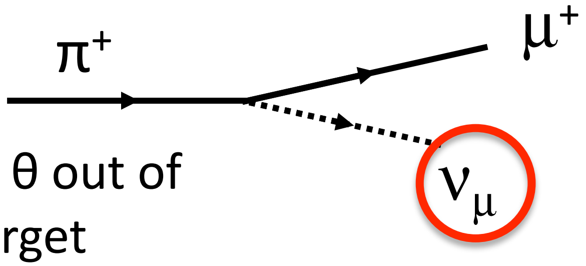




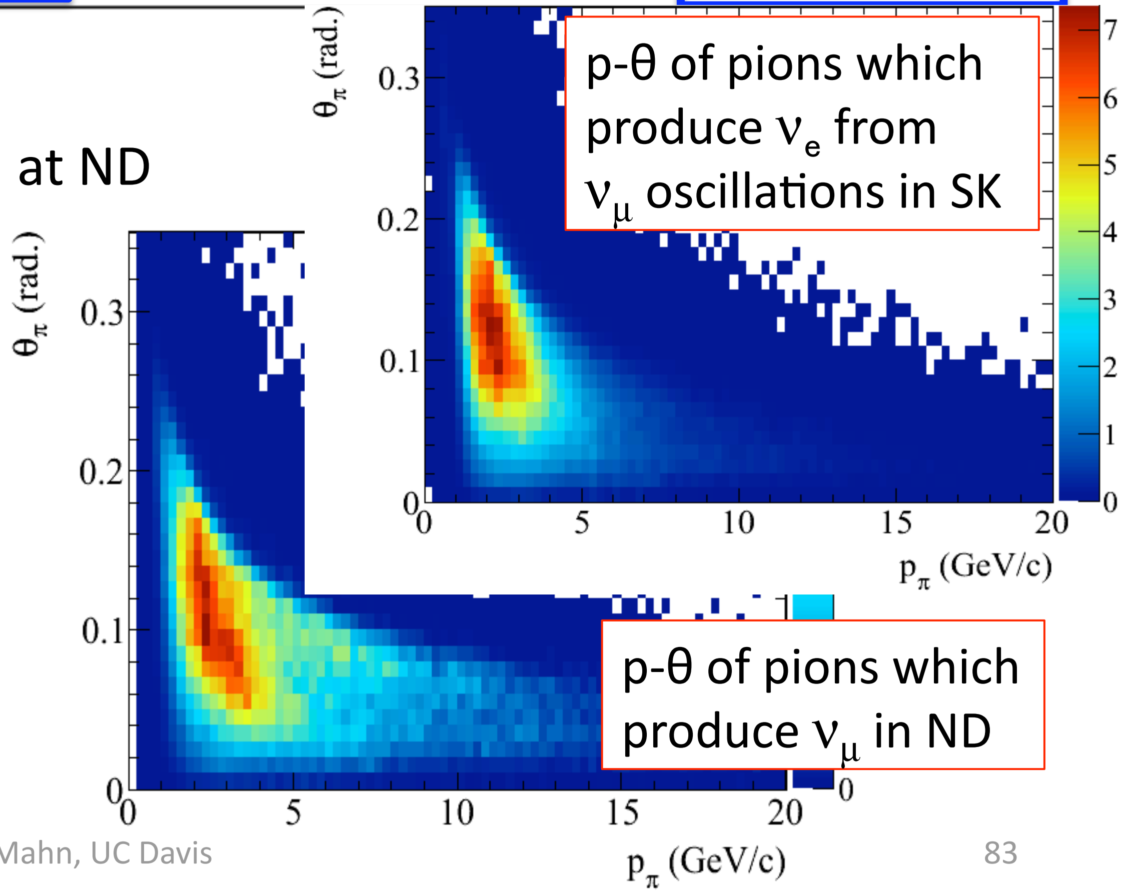
Neutrino flux at ND and SK

Neutrino Mode	Trkr. ν_μ CCQE	Trkr. ν_μ CCnQE	SK ν_e Sig.	SK ν_e CC intrinsic Bgnd.	SK ν_e NC Bgnd.
$\pi^+ \rightarrow \nu_\mu + \mu^+$	82.2%	45.8%	99.3%	1.1%	70.3%
$\mu^+ \rightarrow \nu_e + e^+ + \bar{\nu_\mu}$	<1%	<1%	<0.1%	66.0%	<0.1%
$K^{+,0} \rightarrow \nu_e + X$	<1%	<1%	<0.1%	33.0%	<0.1%
$K^{+,0} \rightarrow \nu_\mu + X$	17.4%	53.4%	0.7%	–	29.7%

SK signal and NC background events come from ν_μ flux directly measured at ND



p, θ out of target



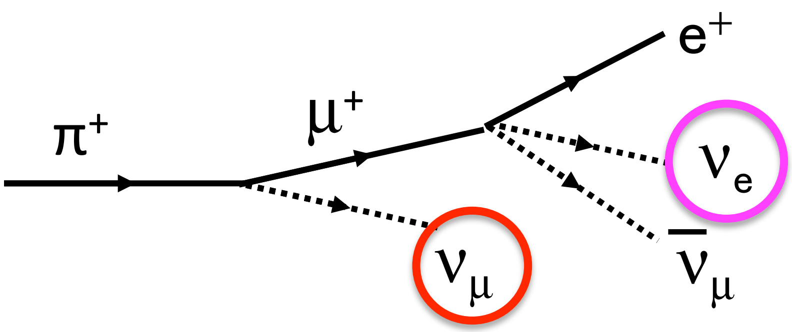
p-θ of pions which produce ν_e from ν_μ oscillations in SK

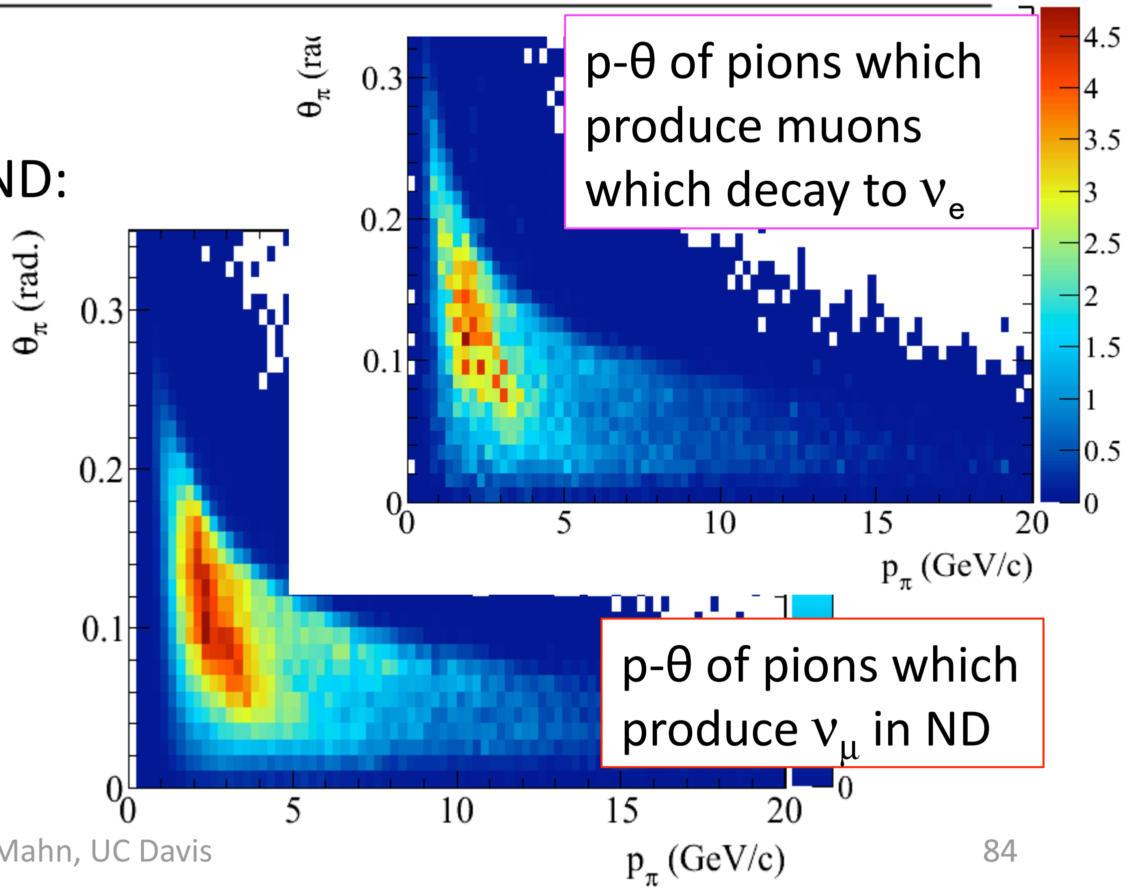
p-θ of pions which produce ν_μ in ND

Neutrino flux at ND and SK

Neutrino Mode	Trkr. ν_μ CCQE	Trkr. ν_μ CCnQE	SK ν_e Sig.	SK ν_e CC intrinsic Bgnd.	SK ν_e NC Bgnd.
$\pi^+ \rightarrow \nu_\mu + \mu^+$	82.2%	45.8%	99.3%	1.1%	70.3%
$\mu^+ \rightarrow \nu_e + e^+ + \bar{\nu_\mu}$	<1%	<1%	<0.1%	66.0%	<0.1%
$K^{+,0} \rightarrow \nu_e + X$	<1%	<1%	<0.1%	33.0%	<0.1%
$K^{+,0} \rightarrow \nu_\mu + X$	17.4%	53.4%	0.7%	–	29.7%

CC background from beam ν_e is strongly correlated with ν_μ flux at ND:

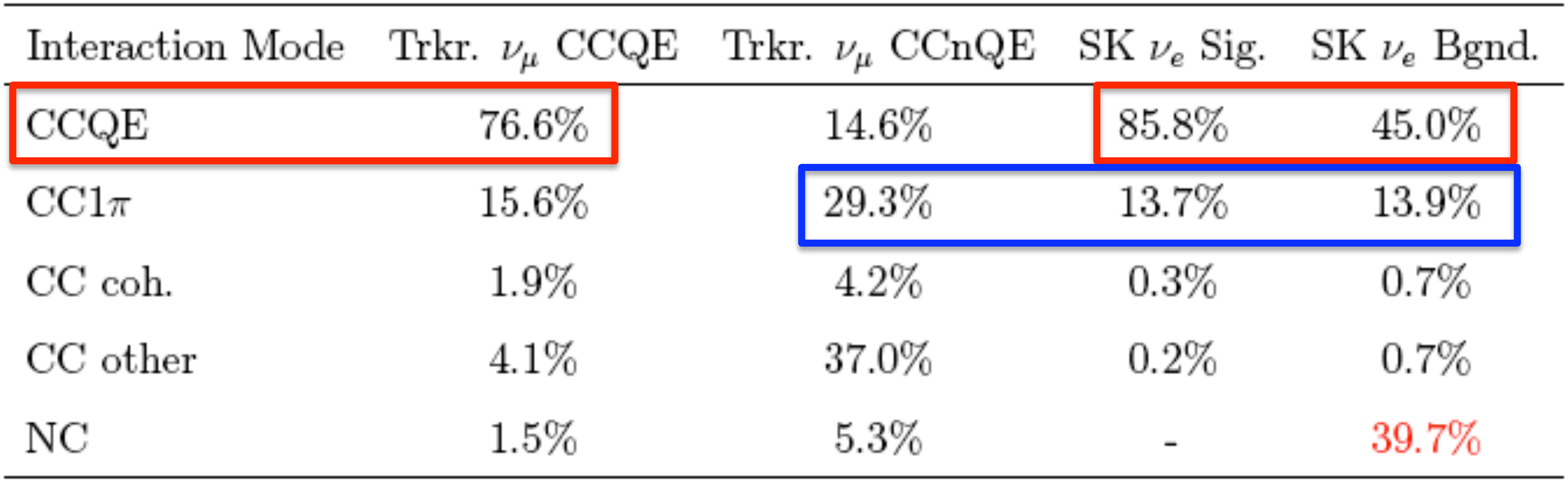




p-θ of pions which produce muons which decay to ν_e

p-θ of pions which produce ν_μ in ND

Neutrino interactions at ND and SK



Interaction Mode	Trkr. ν_μ CCQE	Trkr. ν_μ CCnQE	SK ν_e Sig.	SK ν_e Bgnd.
CCQE	76.6%	14.6%	85.8%	45.0%
CC1π	15.6%	29.3%	13.7%	13.9%
CC coh.	1.9%	4.2%	0.3%	0.7%
CC other	4.1%	37.0%	0.2%	0.7%
NC	1.5%	5.3%	-	39.7%

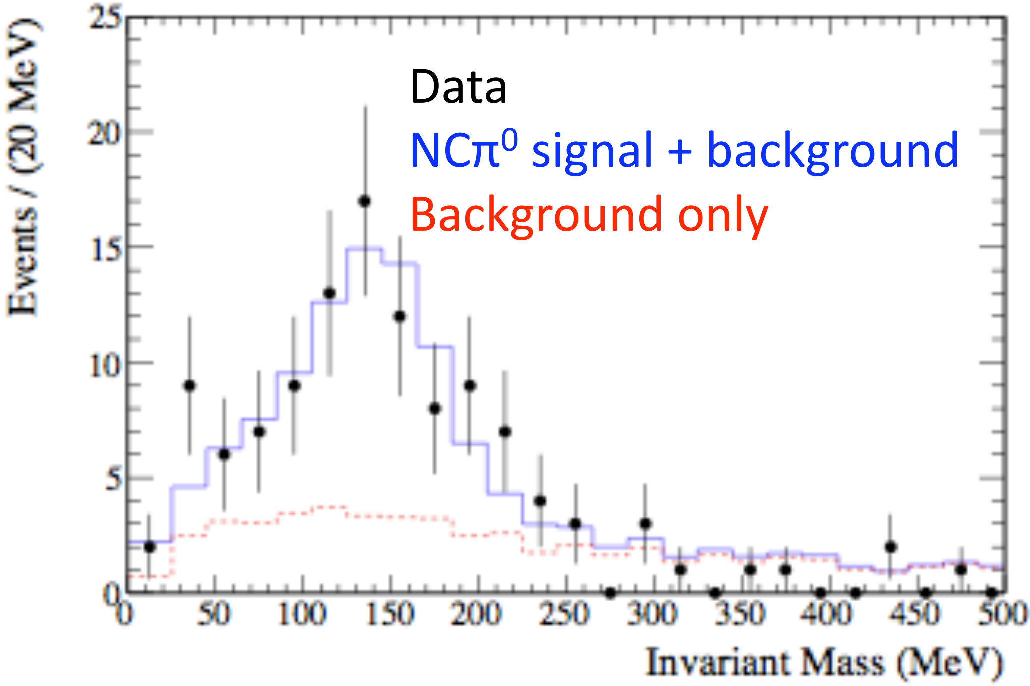
CCQE and CC1π are the largest interaction mode in ND, SK samples

- Separation of CCQE and CCnQE ND samples gives additional power for fit to constrain cross section models
- Need to account for acceptance difference between ND (forward going selection) and SK (4π selection) for identical changes to cross section to correlate the two samples

From experience with SciBooNE/MiniBooNE joint analysis, developed machinery to alter the cross section for each simulated event

Neutrino interactions at ND and SK

Interaction Mode	Trkr. ν_μ CCQE	Trkr. ν_μ CCnQE	SK ν_e Sig.	SK ν_e Bgnd.
CCQE	76.6%	14.6%	85.8%	45.0%
CC1π	15.6%	29.3%	13.7%	13.9%
CC coh.	1.9%	4.2%	0.3%	0.7%
CC other	4.1%	37.0%	0.2%	0.7%
NC	1.5%	5.3%	-	39.7%

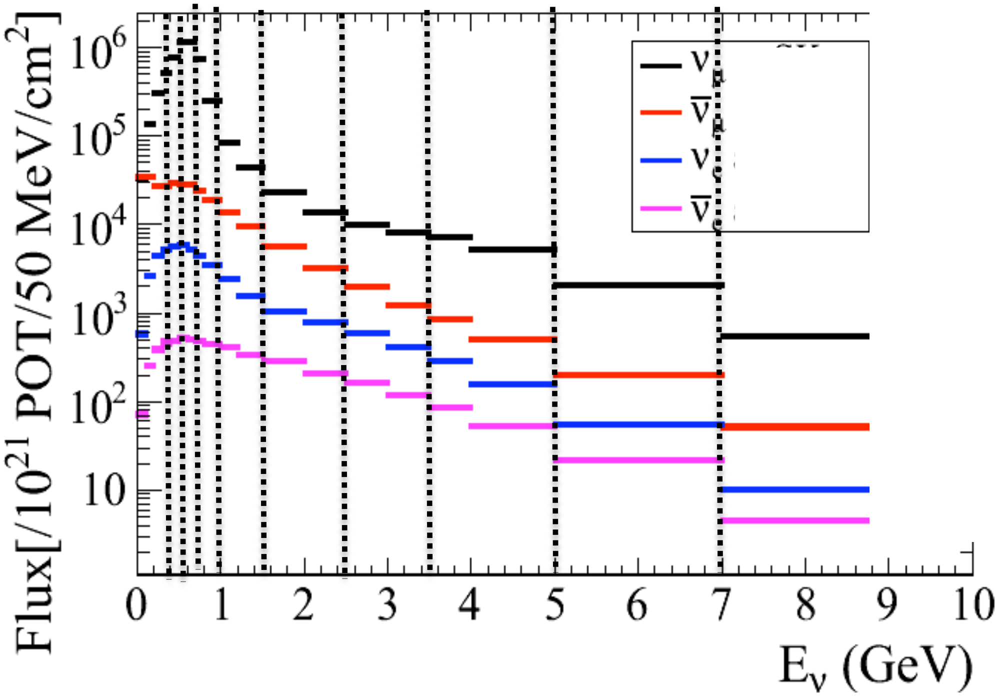


- Indirect constraint on NC ($1\pi^0$) through CC1π in ND measurement
- Additional ND selection of NCπ^0 with P0D detector to cross check rate prediction

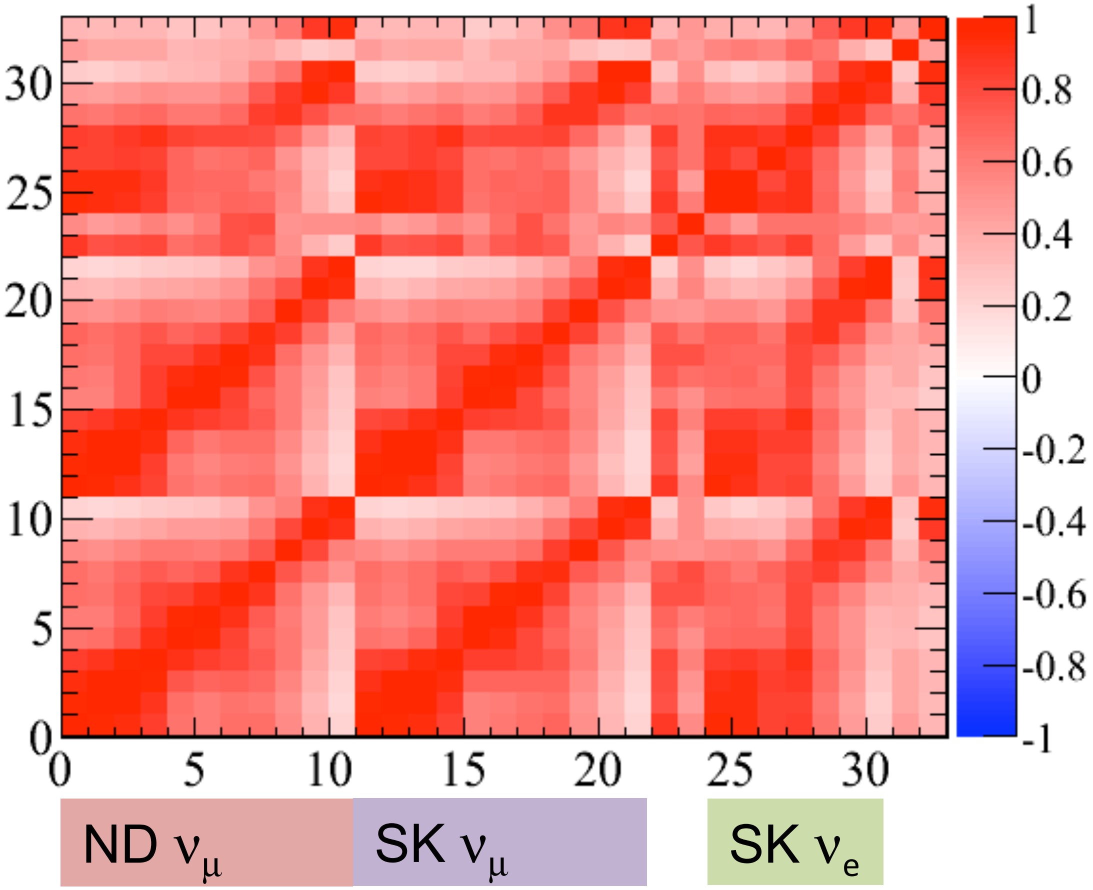
Flux parameterization

Neutrino flux prediction

Flux parameterization: f_i
Normalization on E_ν bin i for SK and ND samples



Correlations between flux bins

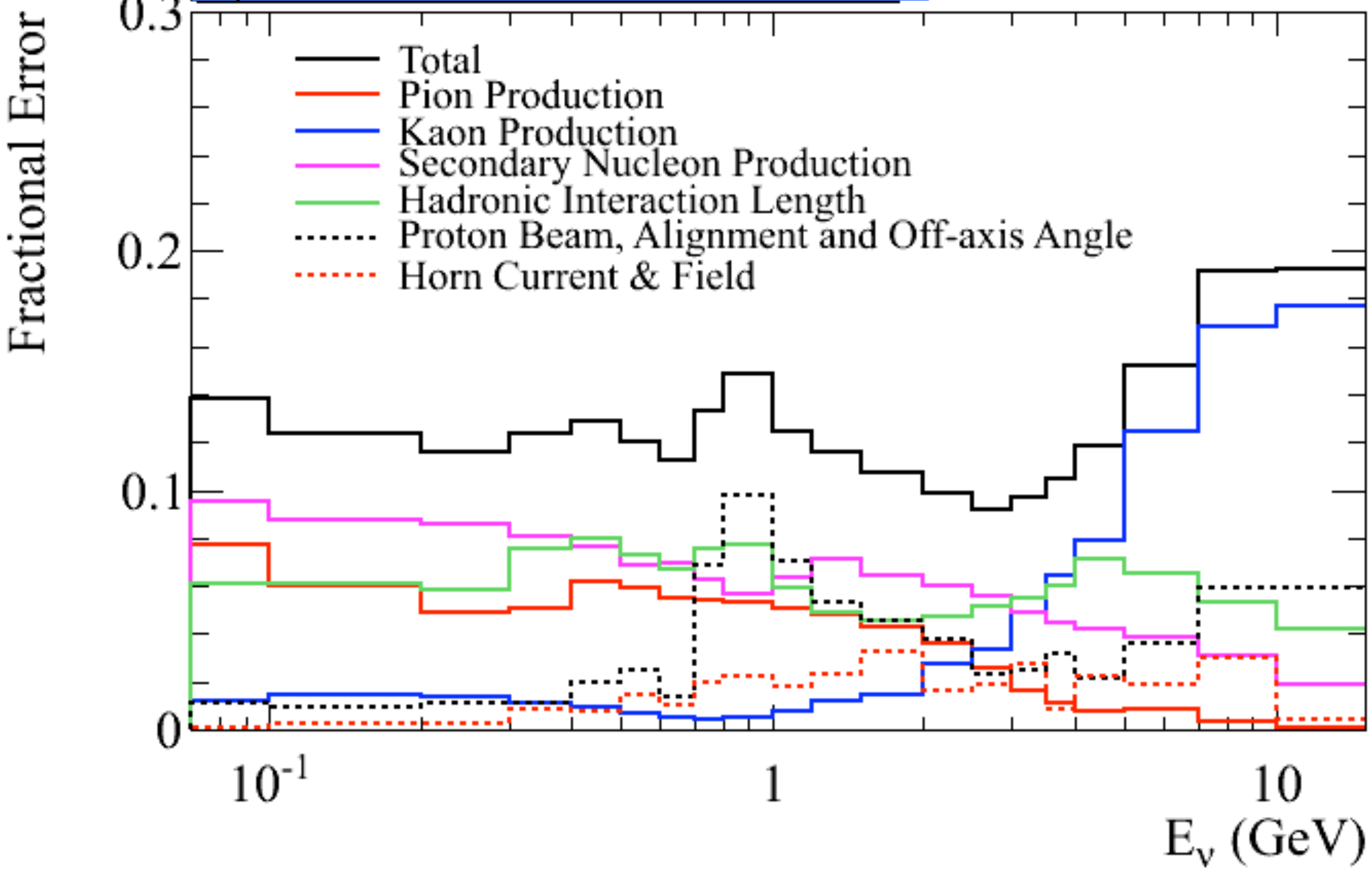


Correlations in flux covariance are shared hadron production uncertainties

Flux covariance built from measurements of beam or external data (e.g. NA61)

T2K neutrino flux uncertainties

ν_μ flux fractional uncertainties



Cross section parameterization

Cross section parameterization: x_k

Model parameters:

- MAQE and MARES (modify Q^2 distribution of QE and resonant 1pi cross sections)
- Fermi momentum (pF) provides low Q2 handle, and is target dependant (C vs. O)
- Spectral function – RFG model-model difference is also target dependant

Normalizations provide overall scaling independent of Q^2 on a particular interaction

Apply cross section to observables at ND, SK using reweighting techniques

M_A^{QE} (GeV)	1.21 ± 0.45	1.19 ± 0.19
M_A^{RES} (GeV)	1.162 ± 0.110	1.137 ± 0.095
CCQE Norm. 0-1.5 GeV	1.000 ± 0.110	0.941 ± 0.087
CCQE Norm. 1.5-3.5 GeV	1.00 ± 0.30	0.92 ± 0.23
CCQE Norm. >3.5 GeV	1.00 ± 0.30	1.18 ± 0.25
CC1π Norm. 0-2.5 GeV	1.63 ± 0.43	1.67 ± 0.28
CC1π Norm. >2.5 GeV	1.00 ± 0.40	1.10 ± 0.30
NC1π^0 Norm.	1.19 ± 0.43	1.22 ± 0.40
Fermi Momentum (MeV/c)	217 ± 30	224 ± 24
Spectral Function	0(off) ± 1(on)	0.04 ± 0.21
CC Other Shape (GeV)	0.00 ± 0.40	-0.05 ± 0.35

Parameter value, uncertainty is determined from MiniBooNE single pion samples

Parameter value, uncertainty is extrapolated to SK sample

ND280 likelihood

$$-2lnL = \boxed{2\sum_{i}^{p,\theta\ bins} N_i^{pred}(\vec{f},\vec{x},\vec{d}) - N_i^{data} + N_i^{data} ln[N_i^{data}/N_i^{pred}(\vec{f},\vec{x},\vec{d})]}$$

Likelihood function, with Poisson statistics

$$+\sum_{j}^{E_\nu\ bins}\sum_{k}^{E_\nu\ bins}(1-f_j)(V_f^{-1})_{j,k}(1-f_k)$$

$$+\sum_{l}^{xsec\ pars}\sum_{m}^{xsec\ pars}(x_{nom}-x_l)(V_x^{-1})_{l,m}(x_{nom}-x_m)$$

$$+\sum_{i}^{p,\theta\ bins}\sum_{n}^{p,\theta\ bins}(1-d_i)(V_d^{-1})_{i,n}(1-d_n)$$

$$+ ln(\frac{|V_d(\vec{f},\vec{x})|}{|V_d^{nom}|})$$

Fit CCQE, CCnQE p_μ-θ_μ distribution (20x2 bins)

Sensitive to to rate (Φ x σ) changes:

$$E_\nu^{QE} = \frac{m_p^2 - {m'}_n^2 - m_\mu^2 + 2m'_n E_\mu}{2(m'_n - E_\mu + p_\mu \cos\theta_\mu)}$$

ND280 likelihood

$$-2lnL = 2\sum_{i}^{p,\theta\ bins} N_i^{pred}(\vec{f},\vec{x},\vec{d}) - N_i^{data} + N_i^{data} ln[N_i^{data}/N_i^{pred}(\vec{f},\vec{x},\vec{d})]$$

$$\boxed{+\sum_{j}^{E_\nu\ bins}\sum_{k}^{E_\nu\ bins}(1-f_j)(V_f^{-1})_{j,k}(1-f_k)} \quad \boxed{ln\ L_{flux}(\vec{f}\ )}$$

$$\boxed{+\sum_{l}^{xsec\ pars}\sum_{m}^{xsec\ pars}(x_{nom}-x_l)(V_x^{-1})_{l,m}(x_{nom}-x_m)} \quad \boxed{ln\ L_{xsec}(\vec{x}\ )}$$

$$+\sum_{i}^{p,\theta\ bins}\sum_{n}^{p,\theta\ bins}(1-d_i)(V_d^{-1})_{i,n}(1-d_n)$$

$$+\ ln(\frac{|V_d(\vec{f},\vec{x})|}{|V_d^{nom}|})$$

Prior constraint terms for flux, cross section parameters

- V_f and V_x are covariance matricies
- Determined using in-situ and external datasets: beam monitors, NA61, MiniBooNE

ND280 likelihood

$$-2lnL = 2\sum_{i}^{p,\theta\ bins} N_i^{pred}(\vec{f},\vec{x},\vec{d}) - N_i^{data} + N_i^{data} ln[N_i^{data}/N_i^{pred}(\vec{f},\vec{x},\vec{d})]$$

$$+\sum_{j}^{E_\nu\ bins}\sum_{k}^{E_\nu\ bins}(1-f_j)(V_f^{-1})_{j,k}(1-f_k)$$

$$+\sum_{l}^{xsec\ pars}\sum_{m}^{xsec\ pars}(x_{nom}-x_l)(V_x^{-1})_{l,m}(x_{nom}-x_m)$$

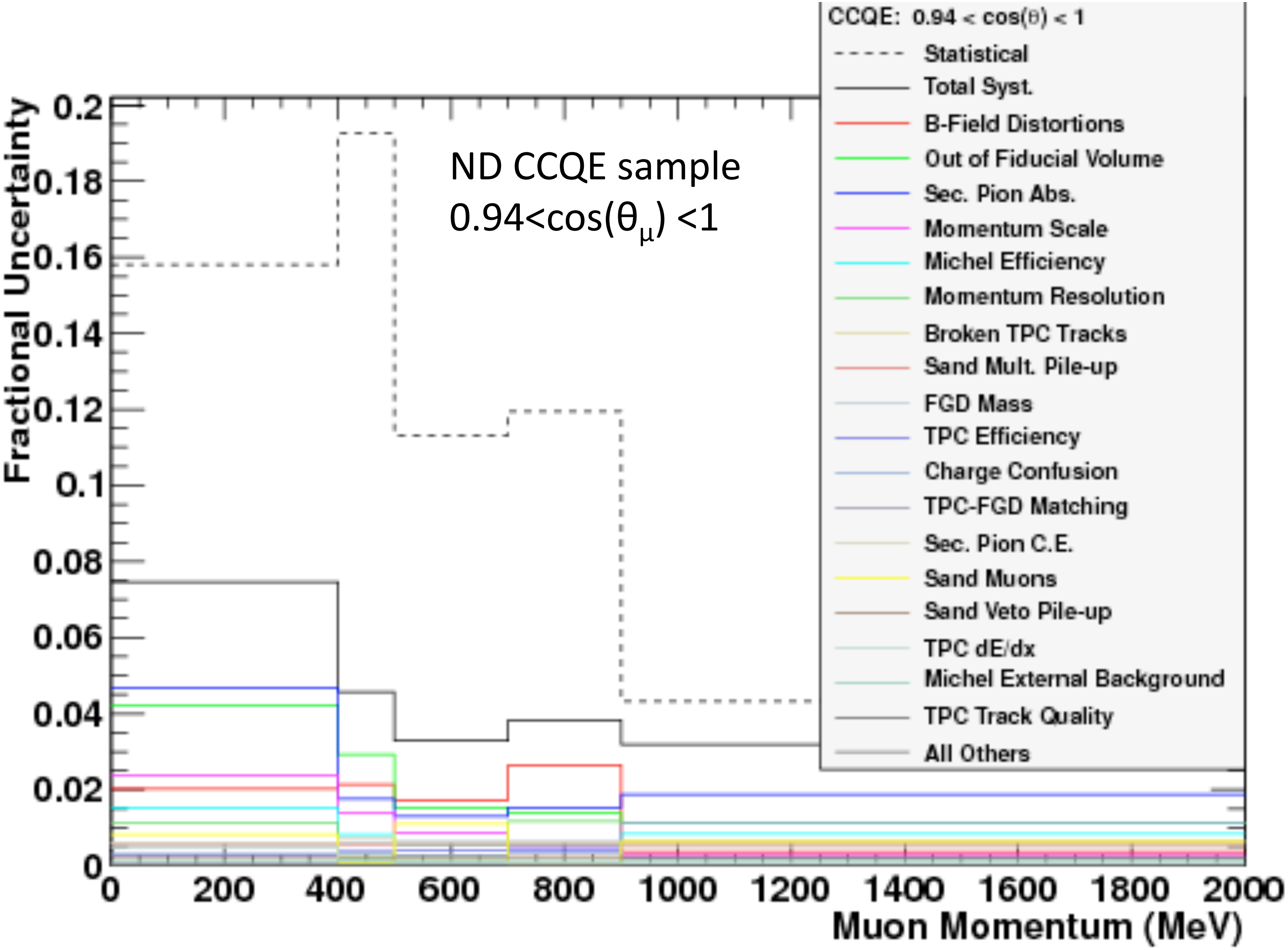
$$\boxed{+\sum_{i}^{p,\theta\ bins}\sum_{n}^{p,\theta\ bins}(1-d_i)(V_d^{-1})_{i,n}(1-d_n)}$$

$$\boxed{+\,ln\left(\frac{|V_d(\vec{f},\vec{x})|}{|V_d^{nom}|}\right)}$$

Prior constraint likelihood terms for detector systematic errors

- Also includes uncertainties (e.g. FSI) which could not be otherwise easily parameterized
- Determined from control samples, calibration data, and external pion scattering data

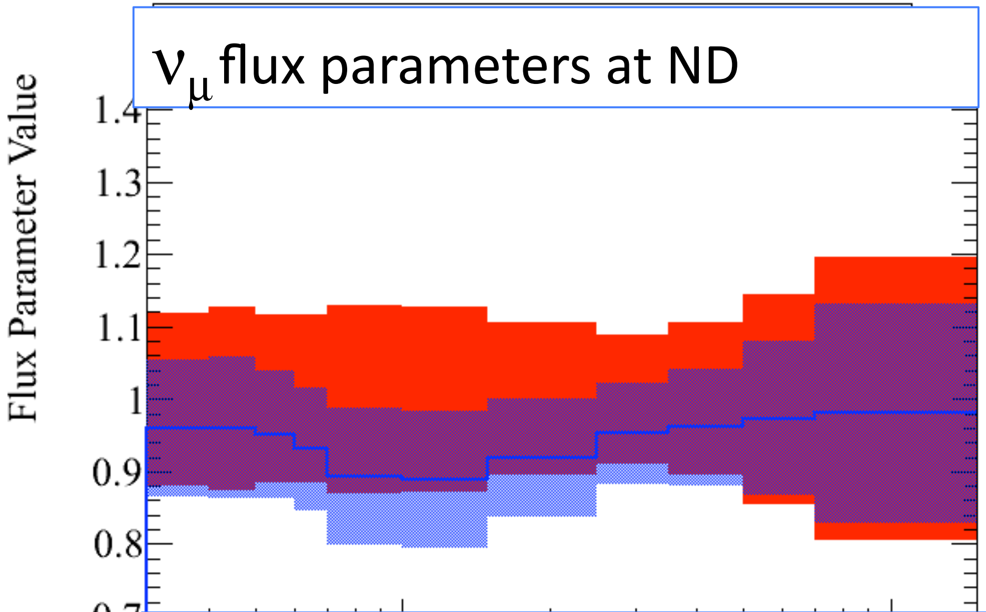
Detector systematic errors



ND CCQE sample
$0.94<\cos(\theta_\mu)<1$

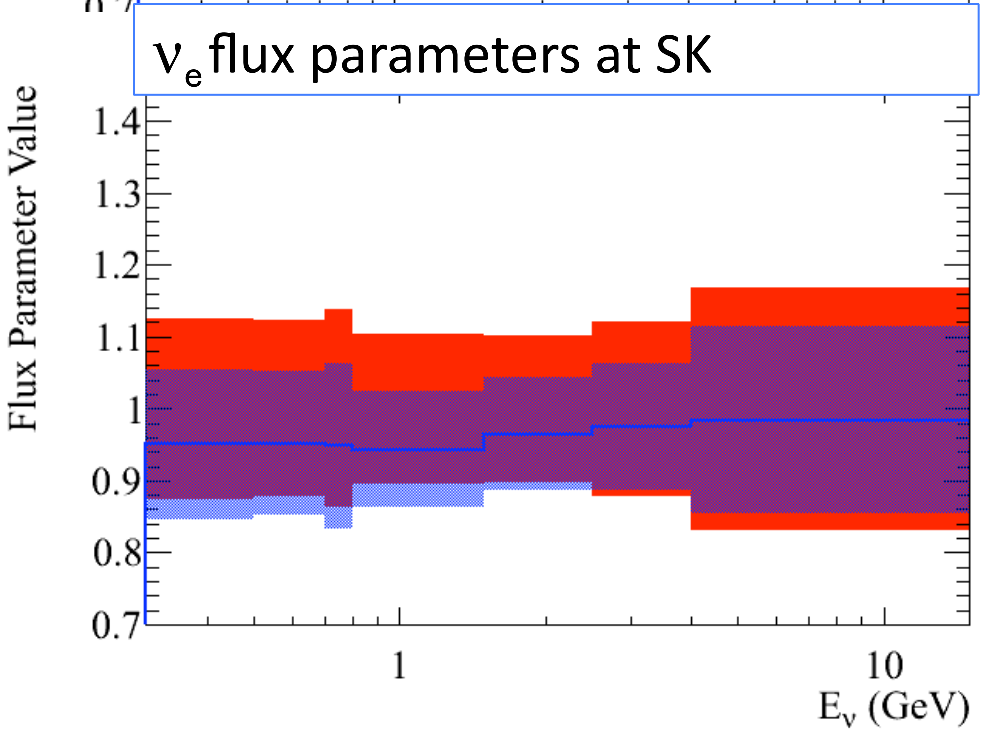
Fractional systematic uncertainty for vs. momentum

Flux parameters change after ND measurement

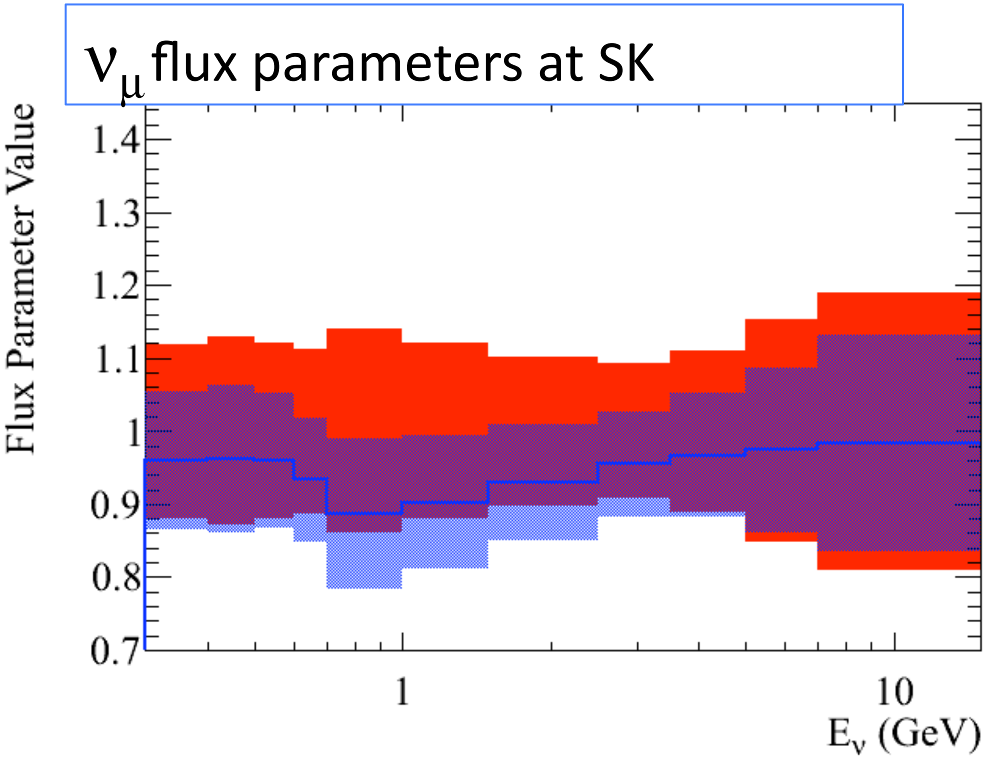


ν_μ flux parameters at ND

- Flux parameters
  without ND measurement and
  with ND measurement



ν_e flux parameters at SK



ν_μ flux parameters at SK

Effect of ND measurement on ν_e signal, background

- Rate of ν_e signal and backgrounds without ND measurement and with ND measurement
- Uncertainty envelope from constrained flux, cross section parameters
- Includes correlation between flux and cross section at ND, SK