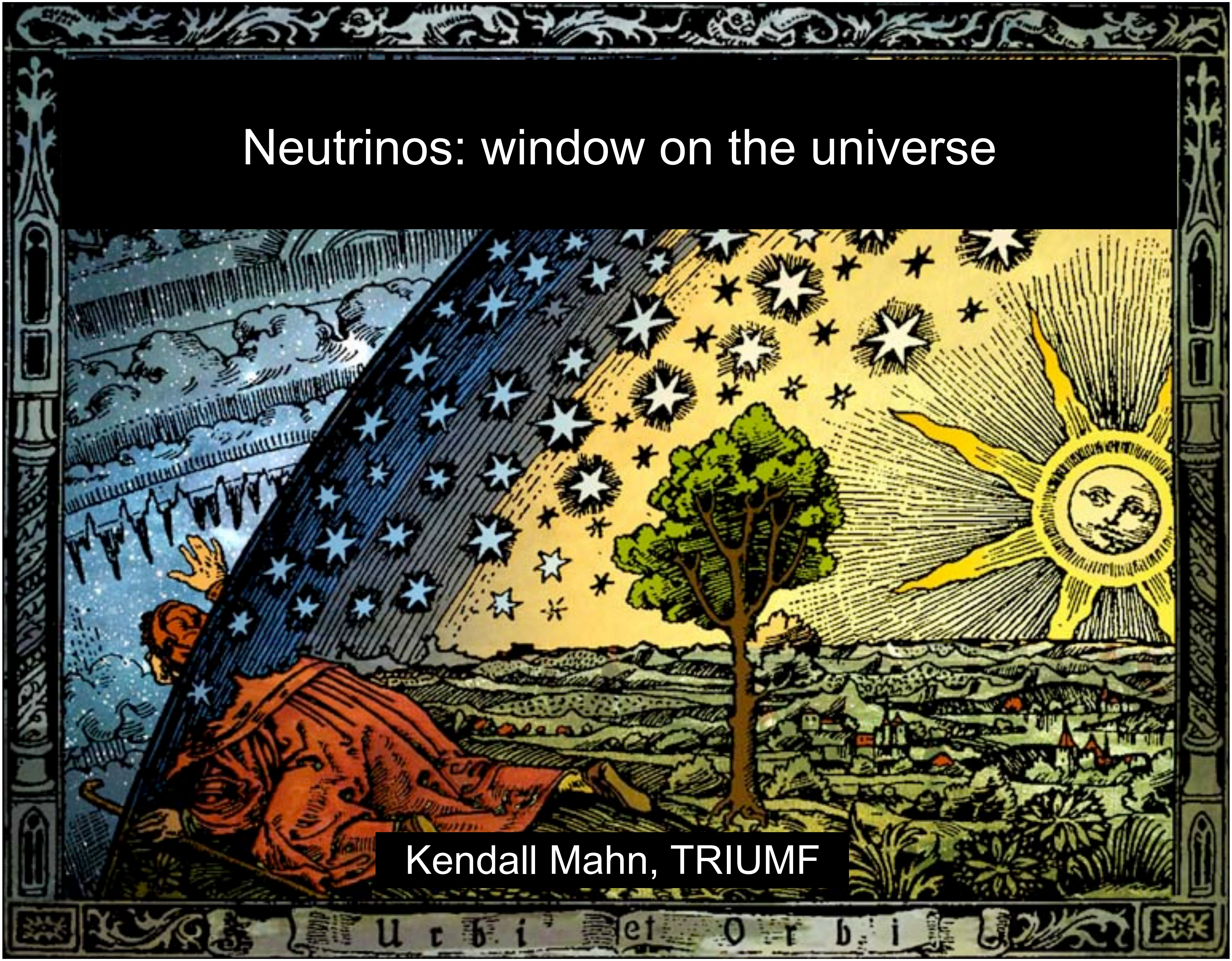
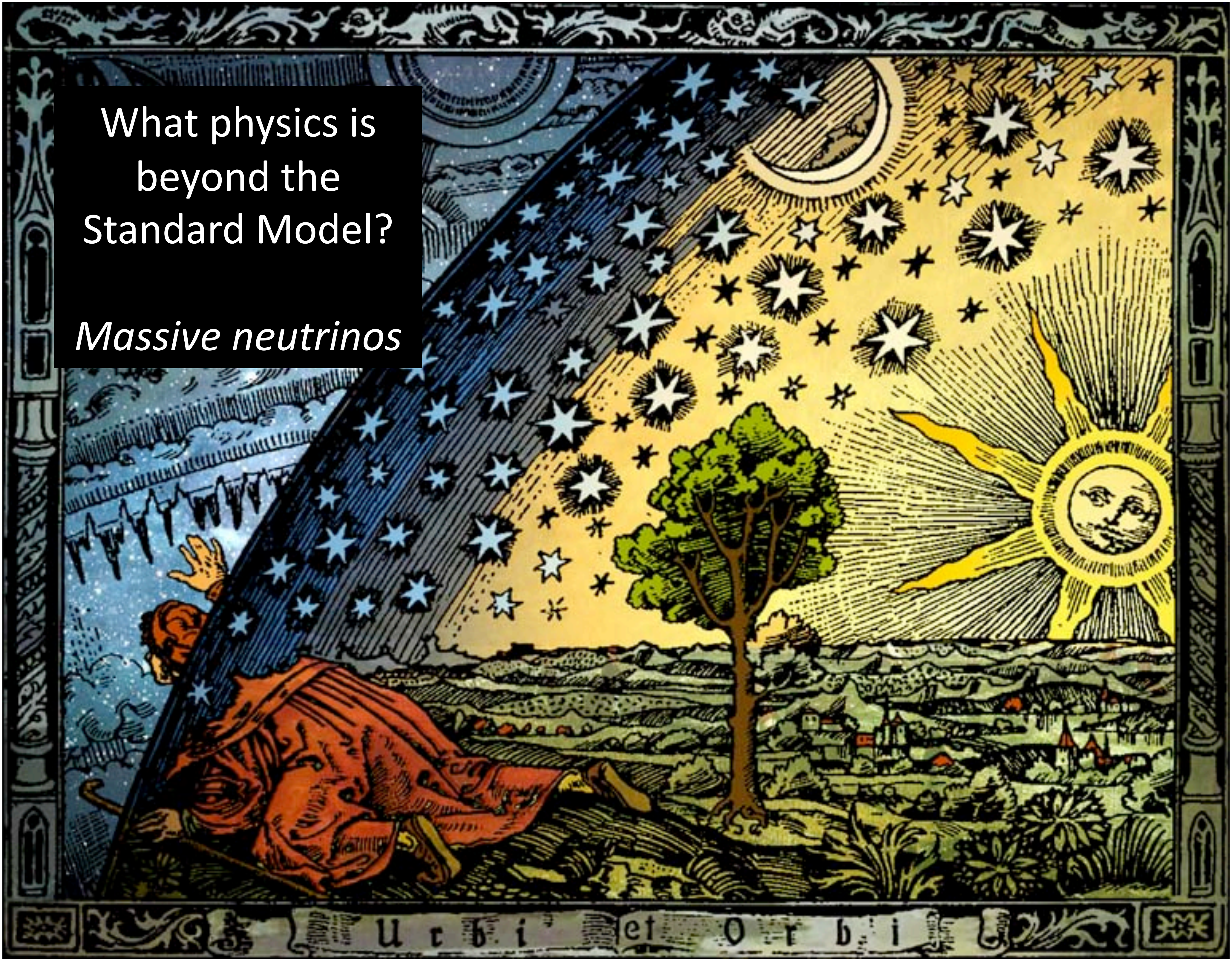
Neutrinos: window on the universe



Kendall Mahn, TRIUMF

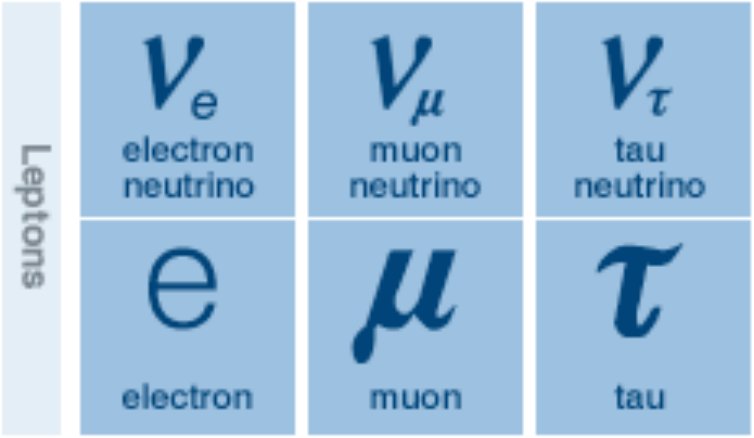


What physics is beyond the Standard Model?

Massive neutrinos

What we now know about neutrinos

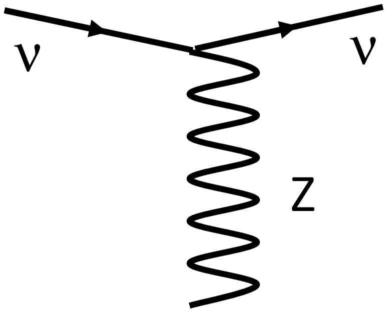
- Three flavors: ν_e, ν_μ , ν_τ

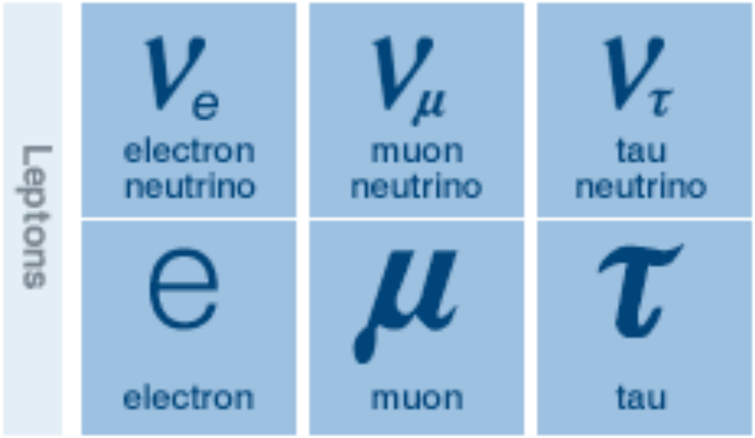


What we now know about neutrinos

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

Neutral Current (NC)

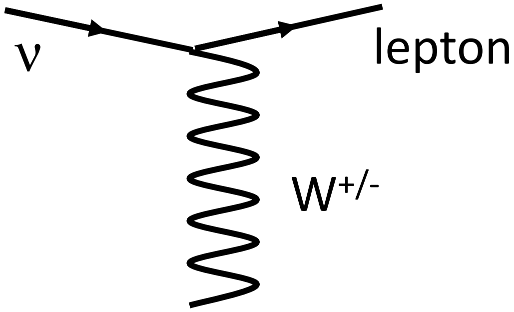




Leptons

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

Charged Current (CC)



$$\nu_e \longrightarrow e$$

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

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

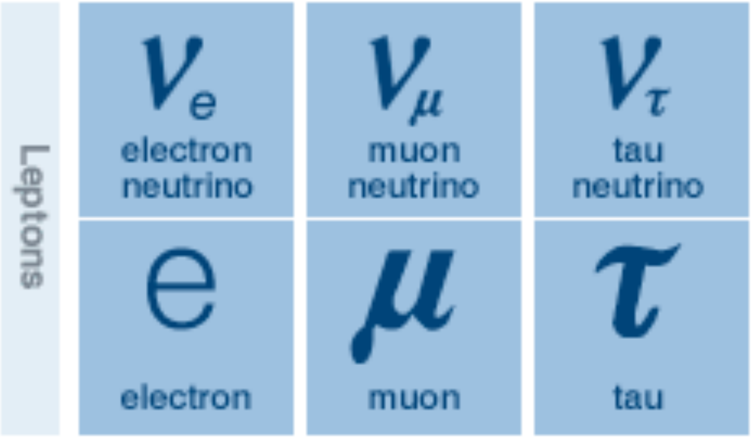
Z
Z boson

W
W boson

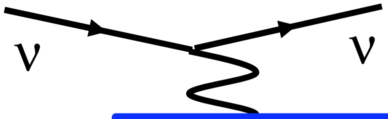
Force carriers

What we now know about neutrinos

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



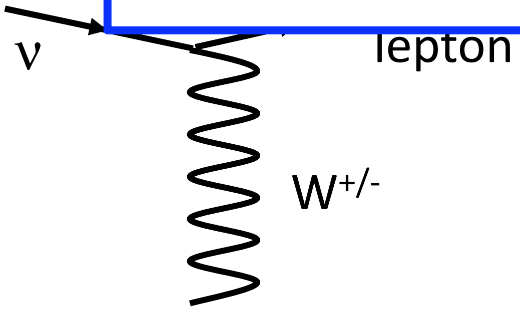
Neutral Current (NC)



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

Mean free path through lead is 1 light year

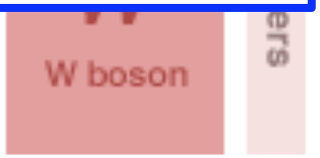
Charg



$$\nu_e \longrightarrow e$$

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

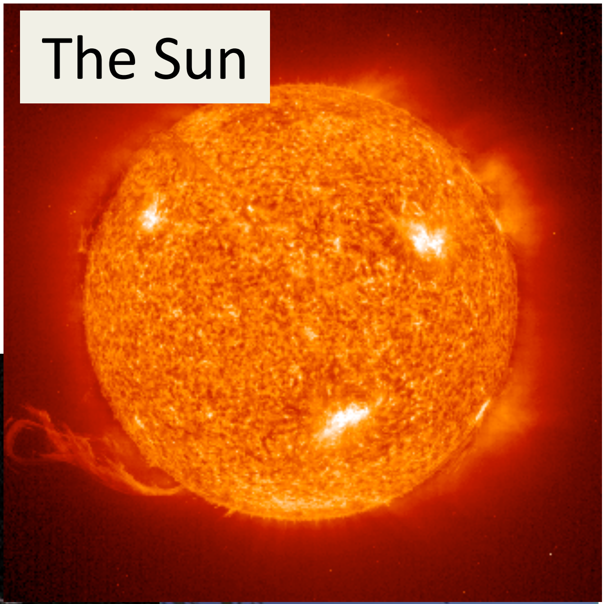
$$\nu_\tau \longrightarrow \tau$$



What we now know about neutrinos

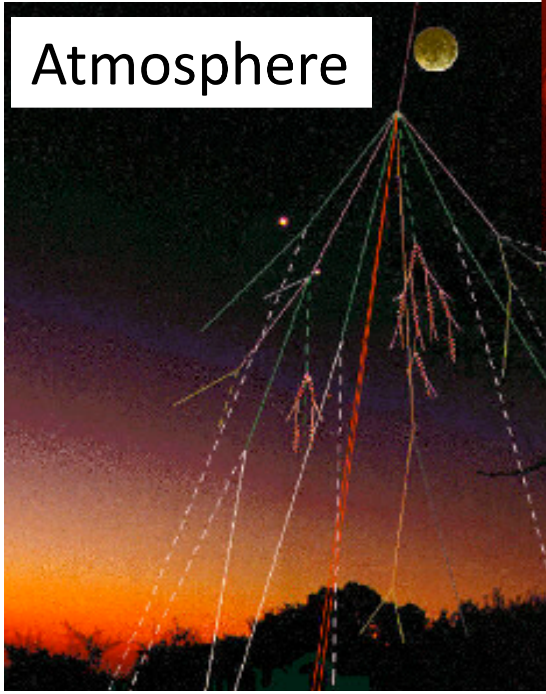
- Three flavors: ν_e, ν_μ, ν_τ
- Neutral
- Interact via the weak force
- Abundant

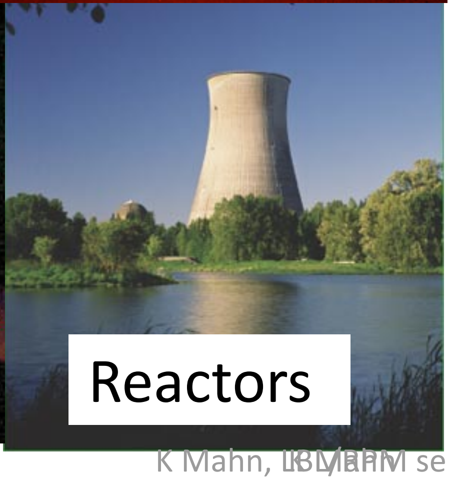

Supernova

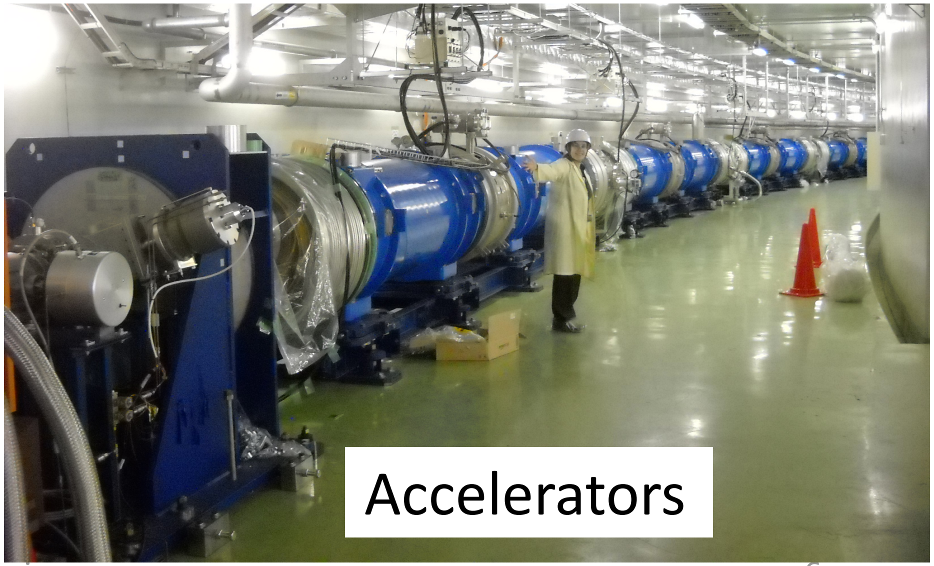

The Sun


The Earth


Bananas


Atmosphere


Reactors


Accelerators

What we now know about neutrinos

- Three flavors: ν_e, ν_μ, ν_τ
- Neutral
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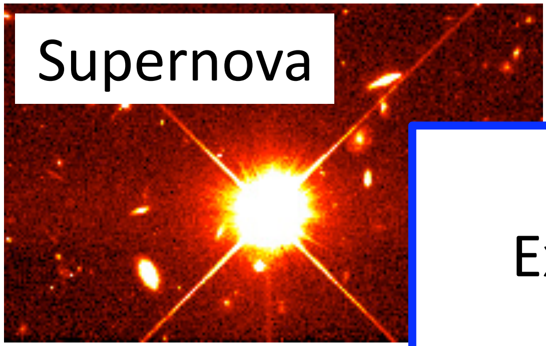
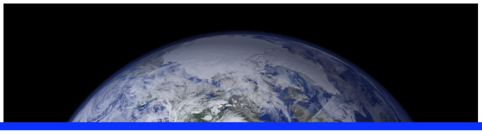
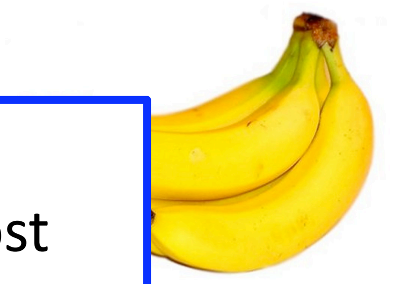

Supernova


The Sun

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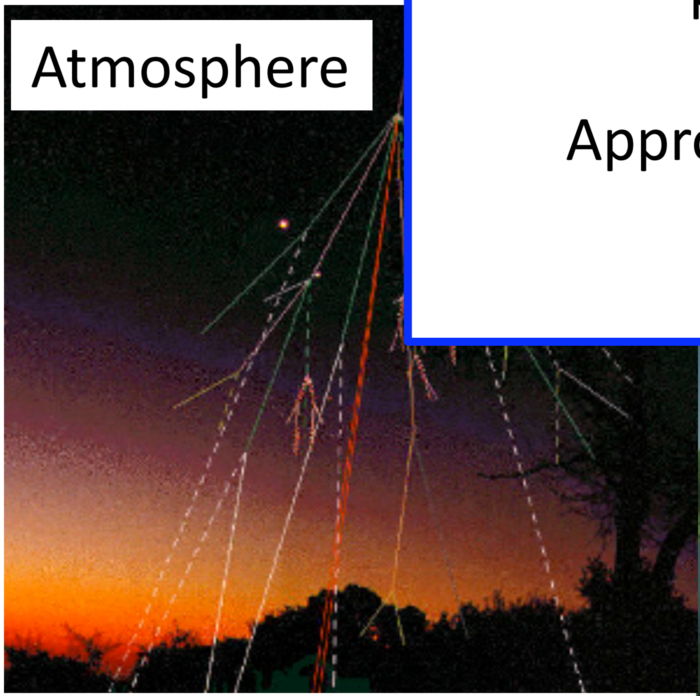

Atmosphere


Reactors


Accelerators

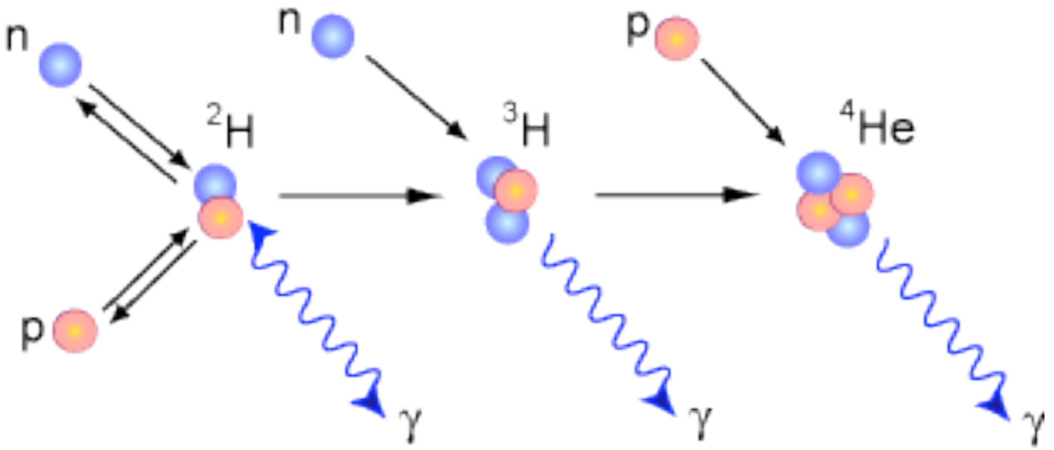
Except for the photon, neutrinos are the most plentiful particle in the universe

Approximately 10,000 Big Bang neutrinos fit in your hand

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

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

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

What we now know about neutrinos

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

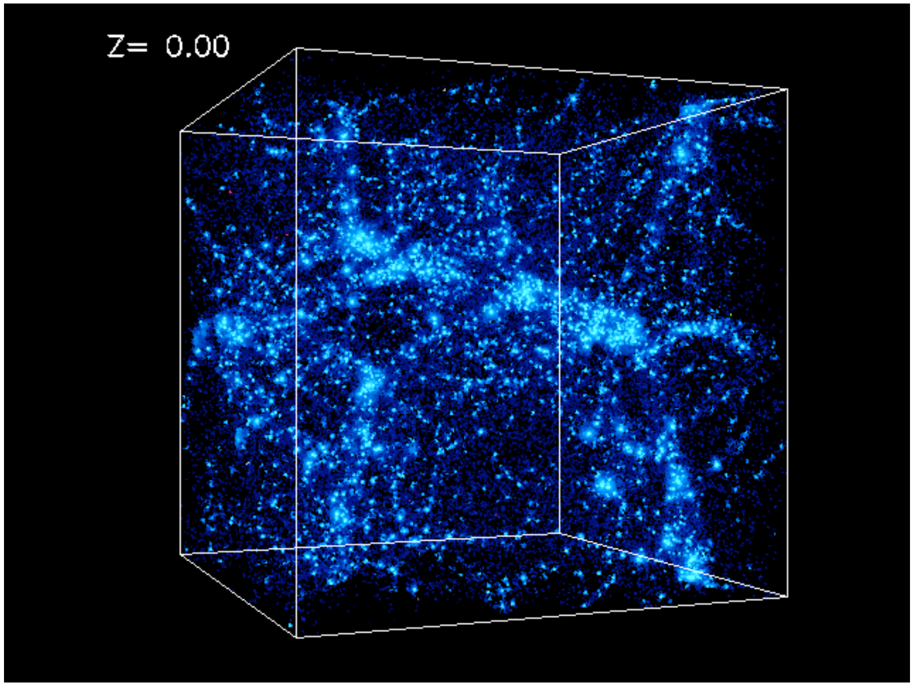
Just because a mass is small doesn't mean it is not important...

The total mass of the neutrinos in the universe is about the same as the total mass of the stars

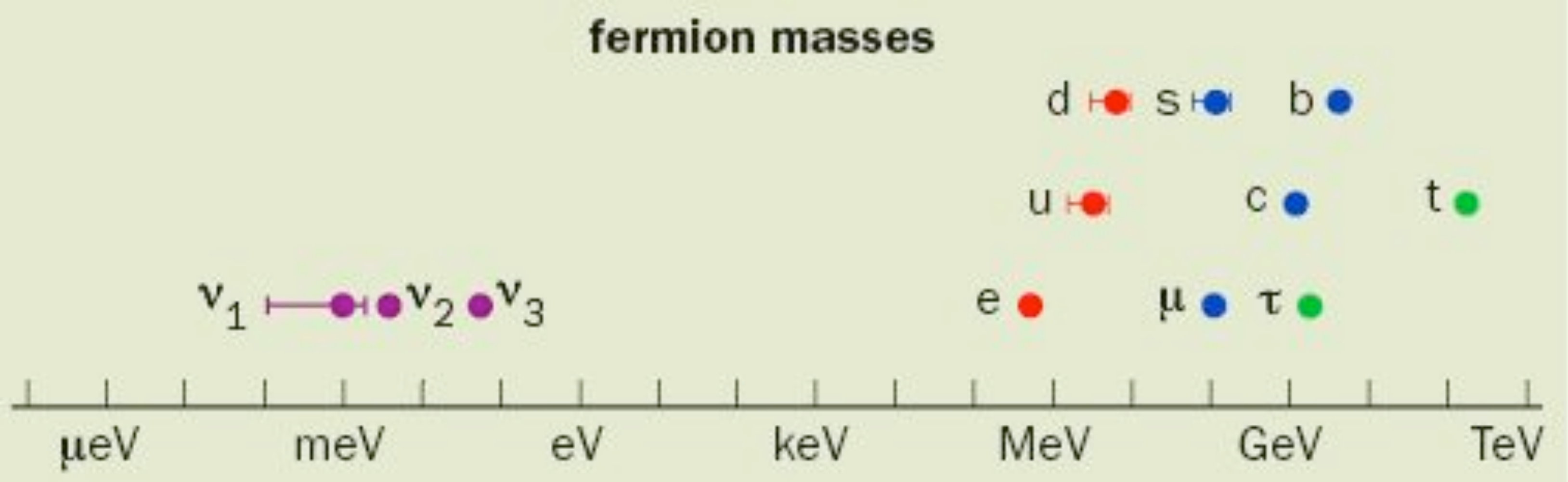
Neutrino mass affects large scale structure formation

- At early times, neutrinos behave like radiation
- At late times, neutrinos behave like matter

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?

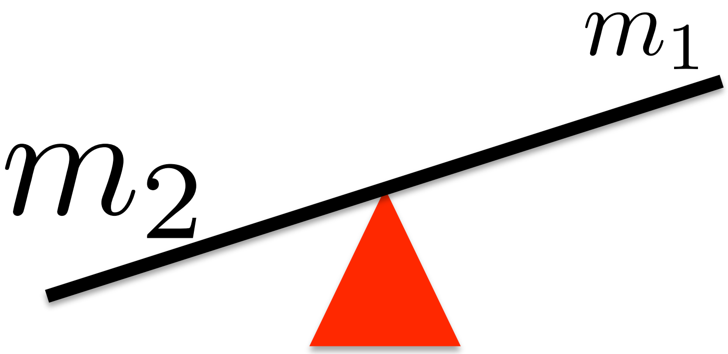
Neutrino mass

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:

$$m_1 \simeq \frac{(m_D)^2}{m_R} \ll m_D \,,$$

$$m_2 \simeq m_R \,,$$



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

Neutrinos and the matter-antimatter asymmetry

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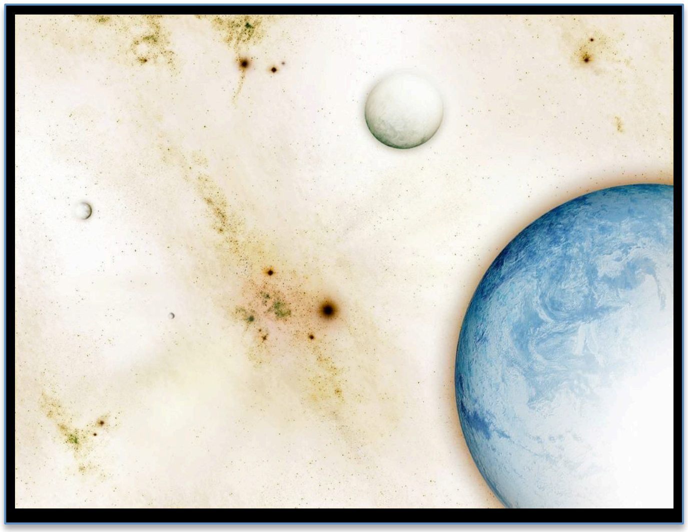


How do we explain the observed matter-antimatter asymmetry in the universe?

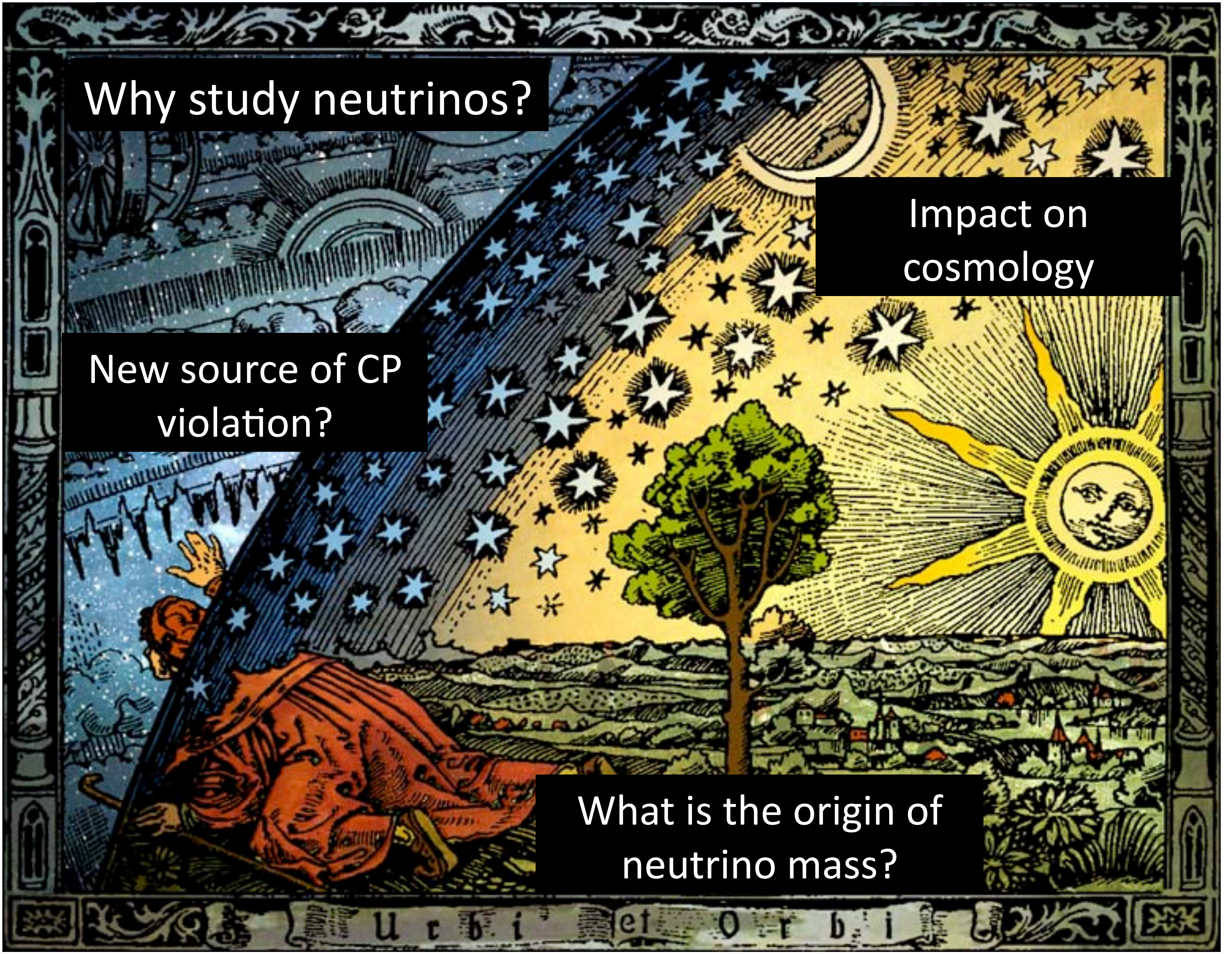
- To create this asymmetry, we need: non-thermal equilibrium, CP violation and baryon number violation
- So far, there is no sufficient source of CP violation in the Standard Model

CP violating decays of the heavy neutrino could create the baryon number violation

- If a decay violates CP, then the rates for neutrinos (matter) and antineutrinos (antimatter) are different

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

Why study neutrinos?



Impact on cosmology

New source of CP violation?

What is the origin of neutrino mass?

What is neutrino oscillation?

We know neutrinos have mass because of we observe neutrino “oscillation”

This is a purely quantum mechanical effect where the mass eigenstates (ν_1, ν_2, ν_3) are superpositions of the flavor eigenstates (ν_e , ν_μ, ν_τ)

fnal.gov graphic

If I reached in a jar of ν_2 without looking, I would have about a 1/3 chance to eat:

a green jelly bean (ν_e / lime)

or a yellow jelly bean (ν_μ / lemon)

or a blue jelly bean (ν_τ / berry)

Example with just 2 neutrinos

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

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

The two states are related via a matrix which depends on a mixing angle, θ, exactly like a coordinate system changes under a rotation matrix:

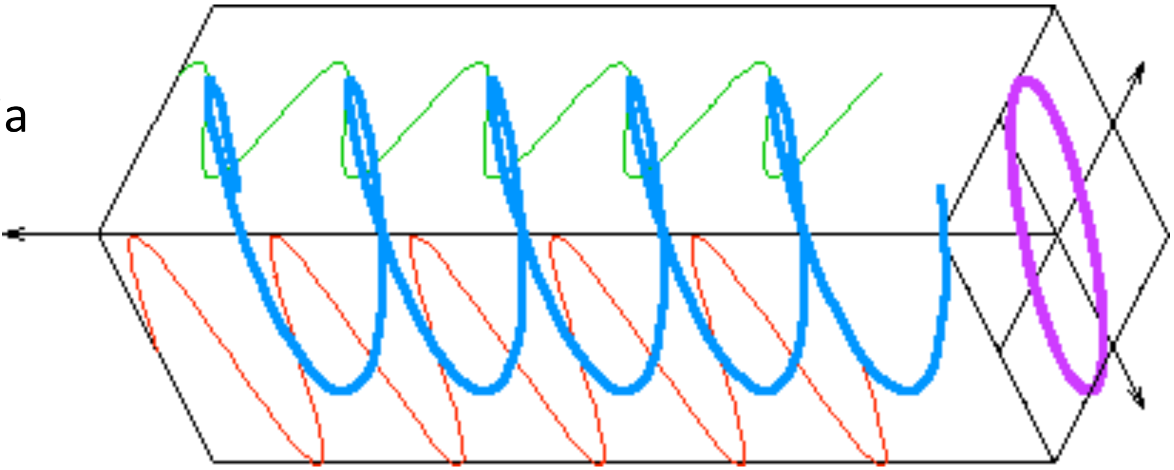
If we want to see how the flavor state changes with time, we evolve the individual mass eigenstates with a phase which depends on their energy

$$|\nu_\mu(t)\rangle = -\sin\,\theta\; e^{-i\boxed{E_1}t}\,|\nu_1\rangle + \cos\,\theta\; e^{-i\boxed{E_2}t}\,|\nu_2\rangle$$

Example with 2 neutrinos

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

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



From wikipedia

Starting polarized along the x-axis is like starting in the ν_μ state:

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

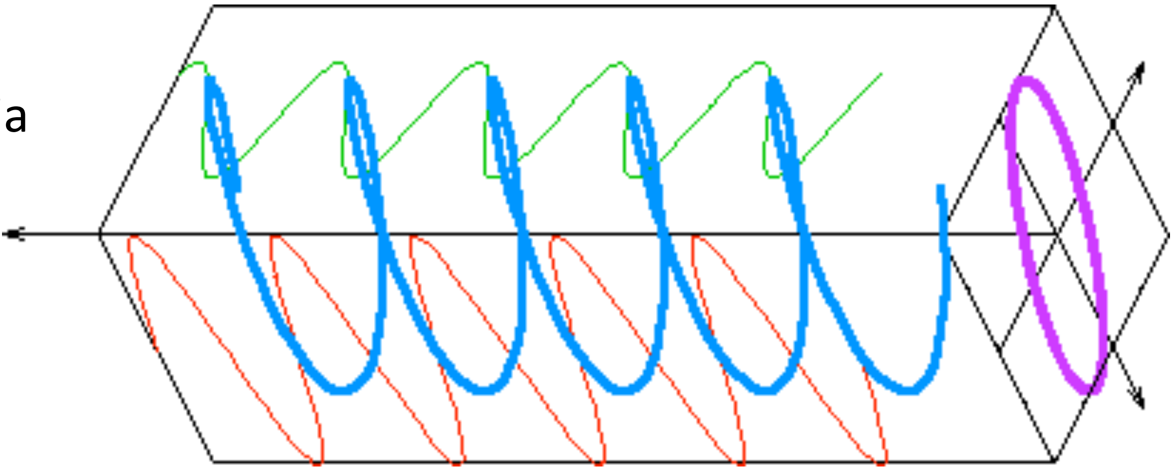
No mass, no oscillation!

Example with 2 neutrinos

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

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

From wikipedia



The probability of observing a ν_e state, starting from a ν_μ state is:

$$P_{\mu e} = \langle \nu_e\,|\nu_\mu(t)\rangle = \sin^2(2\theta)\;\sin^2(1.27\Delta m^2_{21} L/E)$$

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

Neutrino oscillation

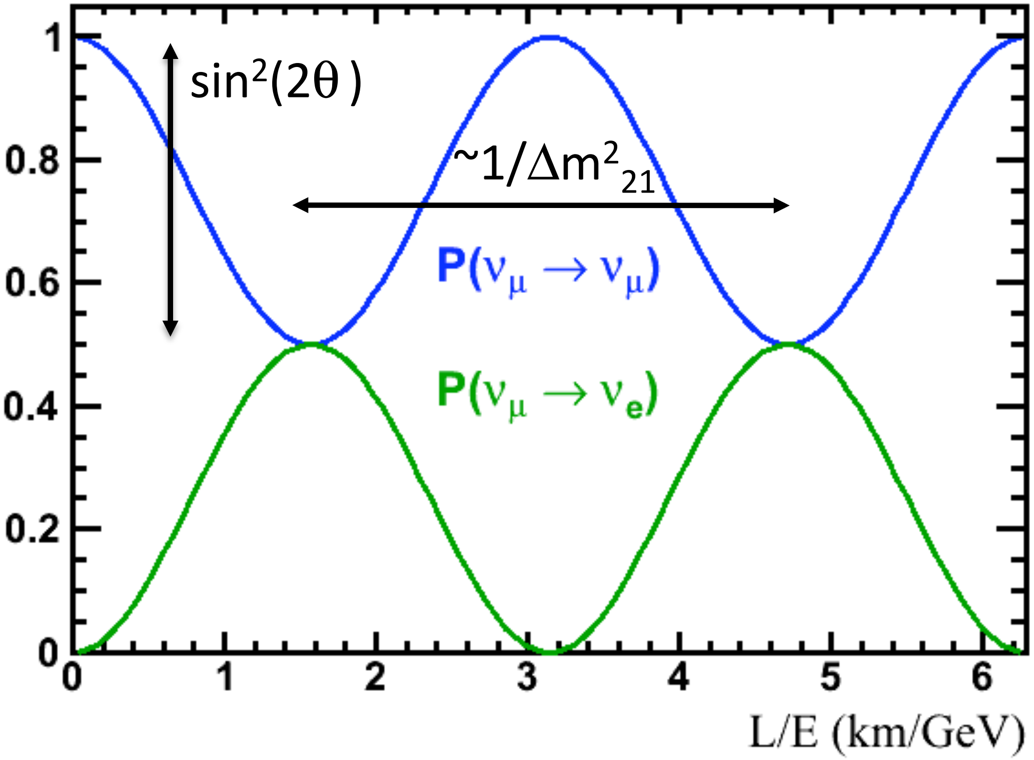
$$P_{\mu e} = \sin^2(2\theta)\ \sin^2(1.27\Delta m^2_{21} L/E)$$

Probability to observe ν_e after starting in flavor state ν_μ 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

$$\boxed{\Delta m^2_{21} = m^2_2 - m^2_1}$$



Neutrino oscillation

$$P_{\mu e} = \sin^2(2\theta)\ \sin^2(1.27\Delta m^2_{21} L/E)$$

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

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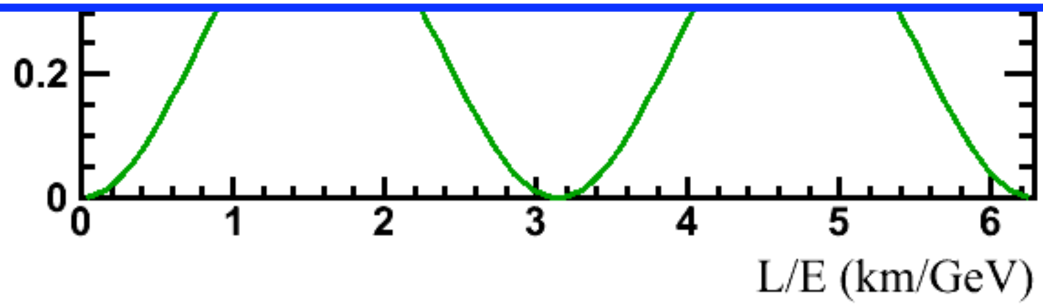
  Difference of the square of the mass eigenvalues

$$\boxed{\Delta m^2_{21} = m^2_2 - m^2_1}$$

Typically, an experiment has L and E determined from the neutrino source and detector setup

and measures Δm^2, θ



Open questions about neutrino mixing

Flavor eigenstates (coupling to the weak force)

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

Mass eigenstates (definite mass)

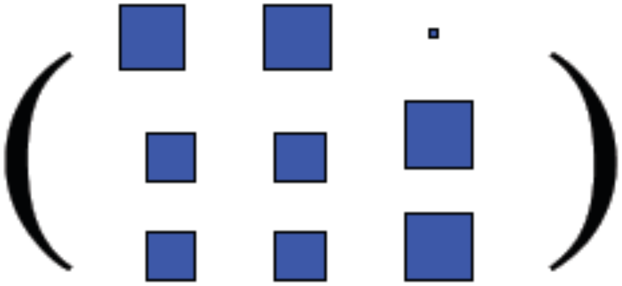
Unitary PMNS mixing matrix

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

$$\theta_{12} = 33.6^\circ \pm 1.0^\circ$$

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

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



Is θ_{23} mixing maximal (45°?)

Open questions about neutrino mixing

Flavor eigenstates (coupling to the weak force)

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

Mass eigenstates (definite mass)

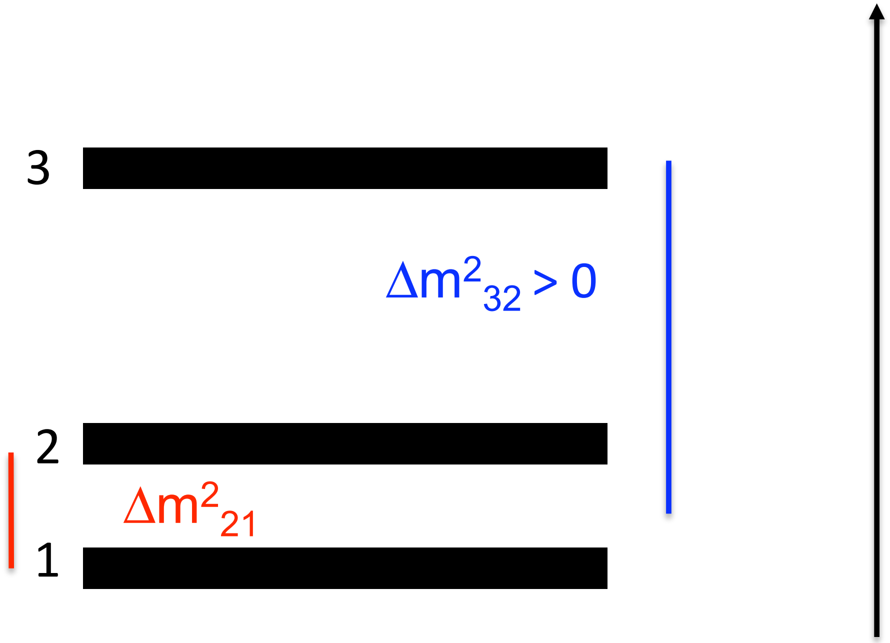
Unitary PMNS mixing matrix

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



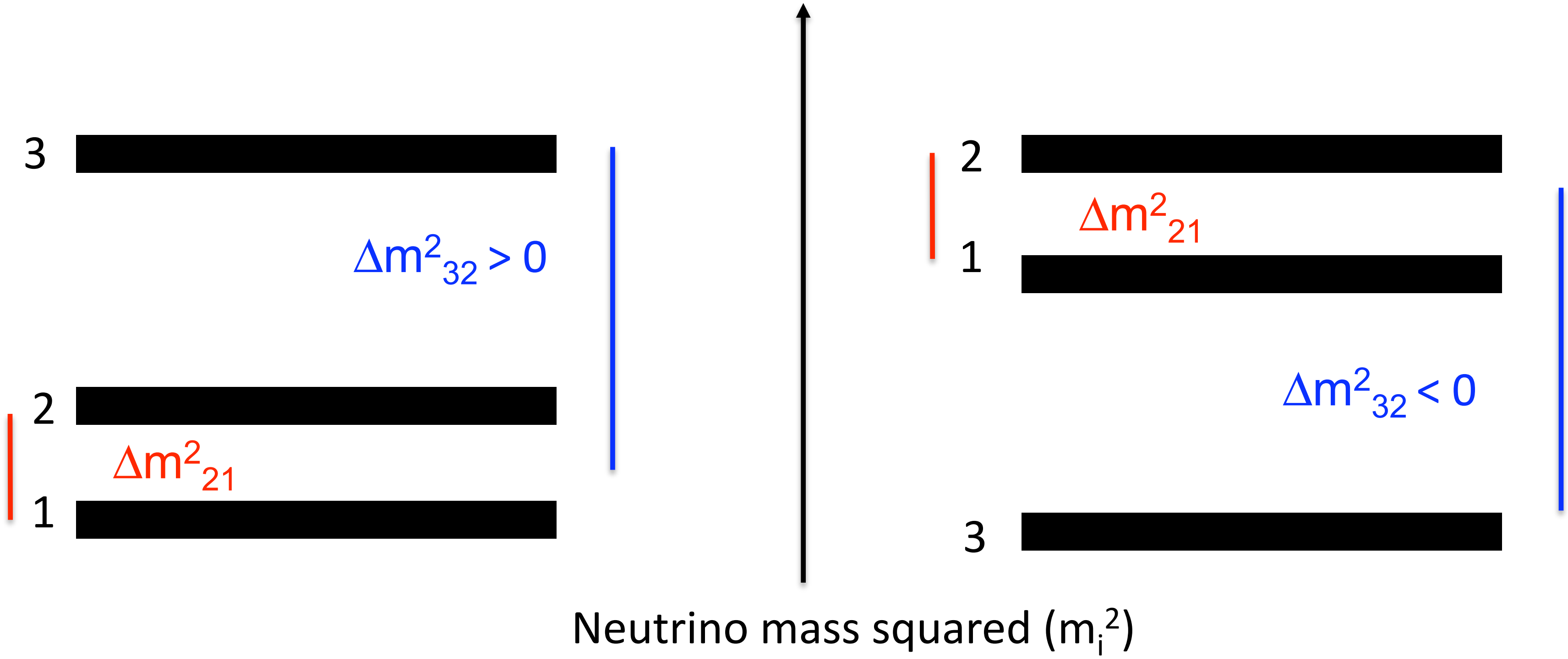
$$\boxed{\Delta m^2_{ij} = m^2_i - m^2_j}$$

Three neutrino mass eigenstates mean two independent mass differences

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

- Δm^2(atmospheric) = $|\Delta m^2_{32}|$ ~ 2.4×10^{-3} eV^2
- Δm^2(solar) = Δm^2_{21} ~ 7.6×10^{-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 ($\Delta m^2_{32} < 0$)

What is the mass hierarchy?

Neutrino oscillation, revisited

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

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\sum_{i>j}\mathrm{Re}\left[U_{\beta i}U^*_{\alpha i}U^*_{\beta j}U_{\alpha j}\right]\sin^2\left(\frac{1.27\Delta m^2_{ij}L}{E}\right) + 2\sum_{i>j}\mathrm{Im}\left[U_{\beta i}U^*_{\alpha i}U^*_{\beta j}U_{\alpha j}\right]\sin\left(\frac{2.54\Delta m^2_{ij}L}{E}\right)$$

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

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

Only leading order terms shown

A small amount of ν_e will "appear"

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

$$\boxed{P(\nu_\mu \rightarrow \nu_e) \cong \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2\left(\frac{1.27\Delta m^2_{31}L}{E}\right)}$$

Neutrino oscillation, revisited

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

$$P_{\alpha\beta} = \delta_{\alpha\beta} \quad \left(\frac{1.27\Delta m^2_{ij} L}{} \right) \quad \left(\frac{2.54\Delta m^2_{ij} L}{E} \right)$$

If choose … small.
Then...

ν_μ "disap

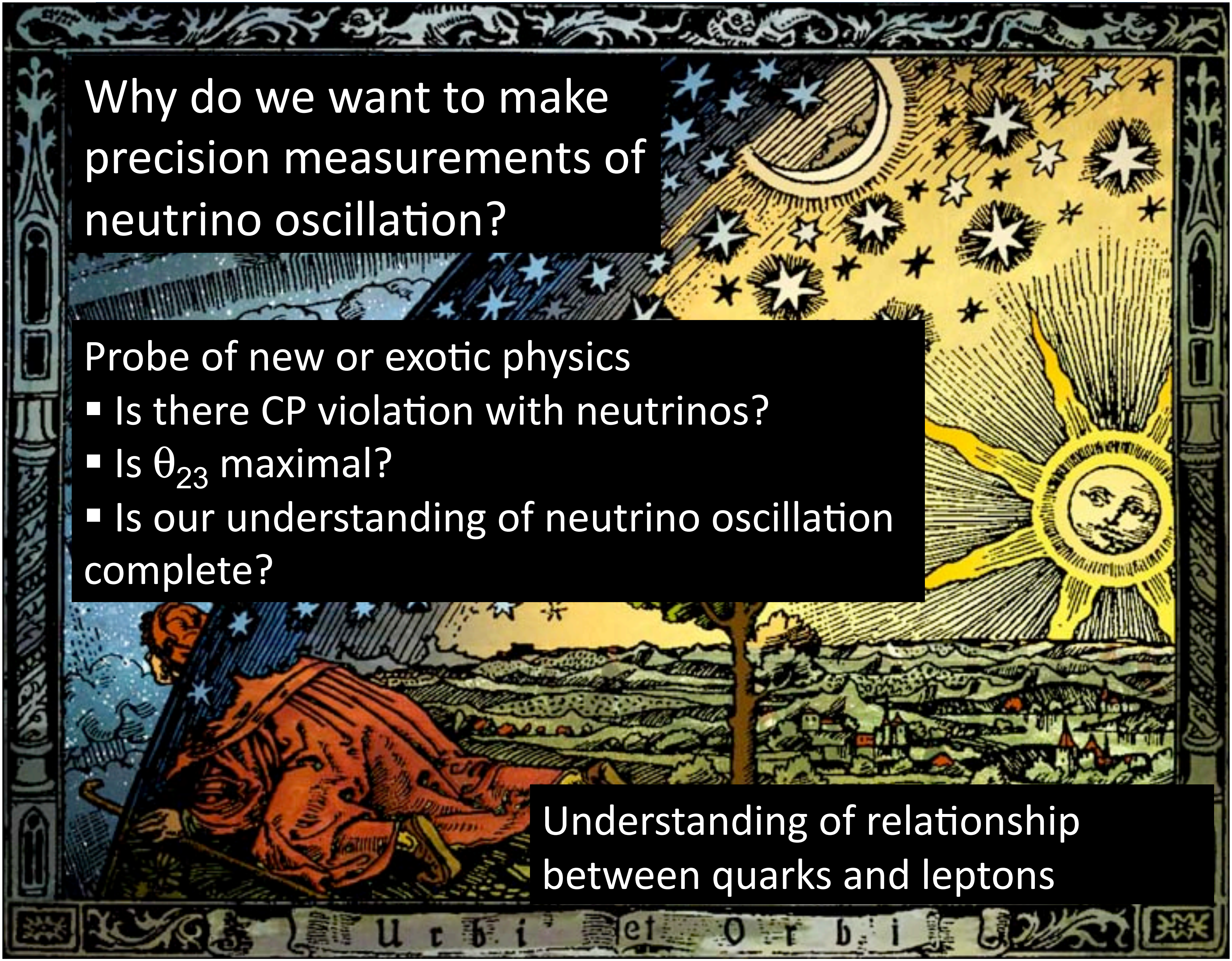
A small an
$\Delta m^2_{31} \sim \Delta$

Subleading terms of ν_μ disappearance allow for a determination of $\sin^2\theta_{23}$

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}

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

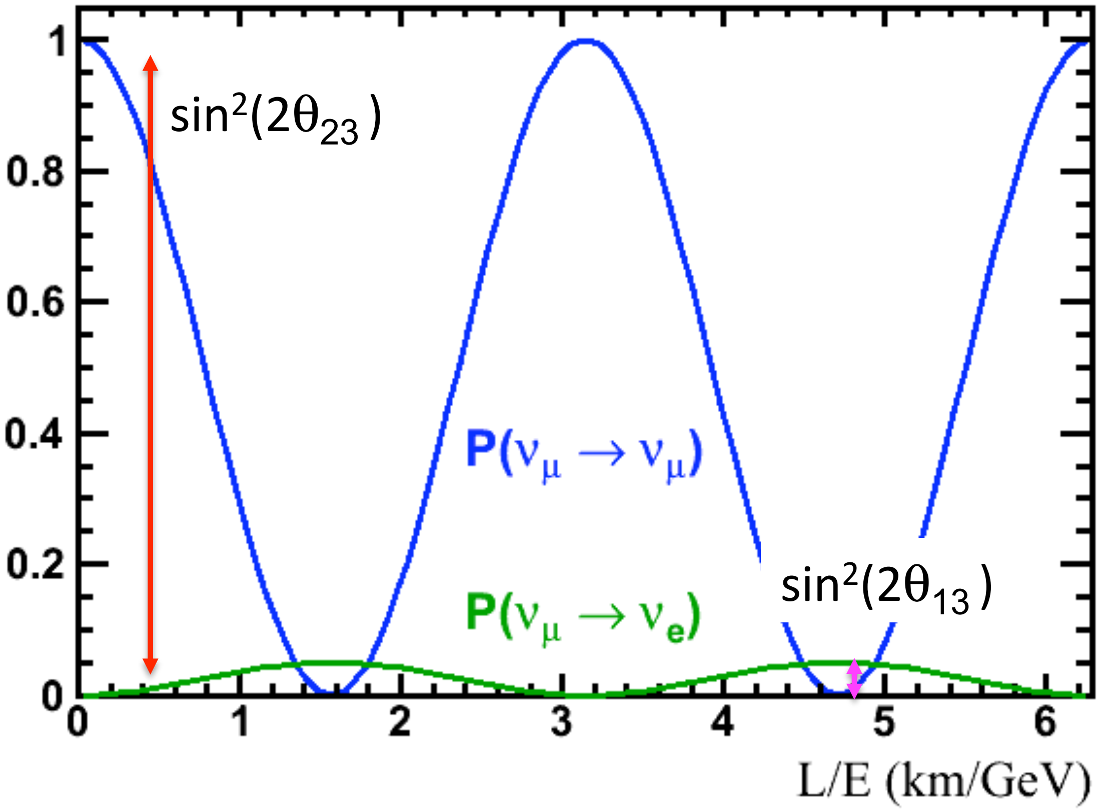
- Is there CP violation with neutrinos?
- Is θ_{23} maximal?
- Is our understanding of neutrino oscillation complete?

Understanding of relationship between quarks and leptons

Oscillation experiments

We infer the values of oscillation parameters from:

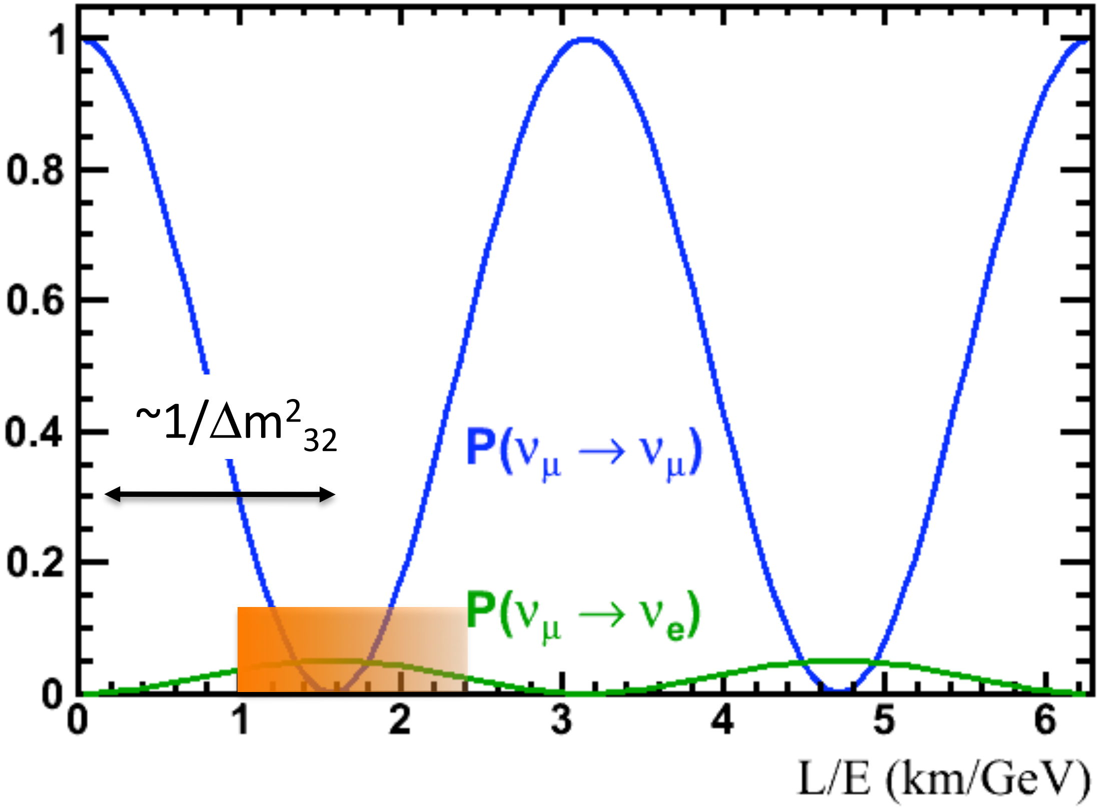
- the decreased event rate in ν_μ disappearance (θ_{23})
- the increased event rate in ν_e appearance (θ_{13} etc)



Oscillation experiments

We infer the values of oscillation parameters from:

- the decreased event rate in ν_μ disappearance (θ_{23})
- the increased event rate in ν_e appearance (θ_{13} etc)
- and the distortion to the neutrino spectrum (Δm^2_{32})



Oscillation experiments

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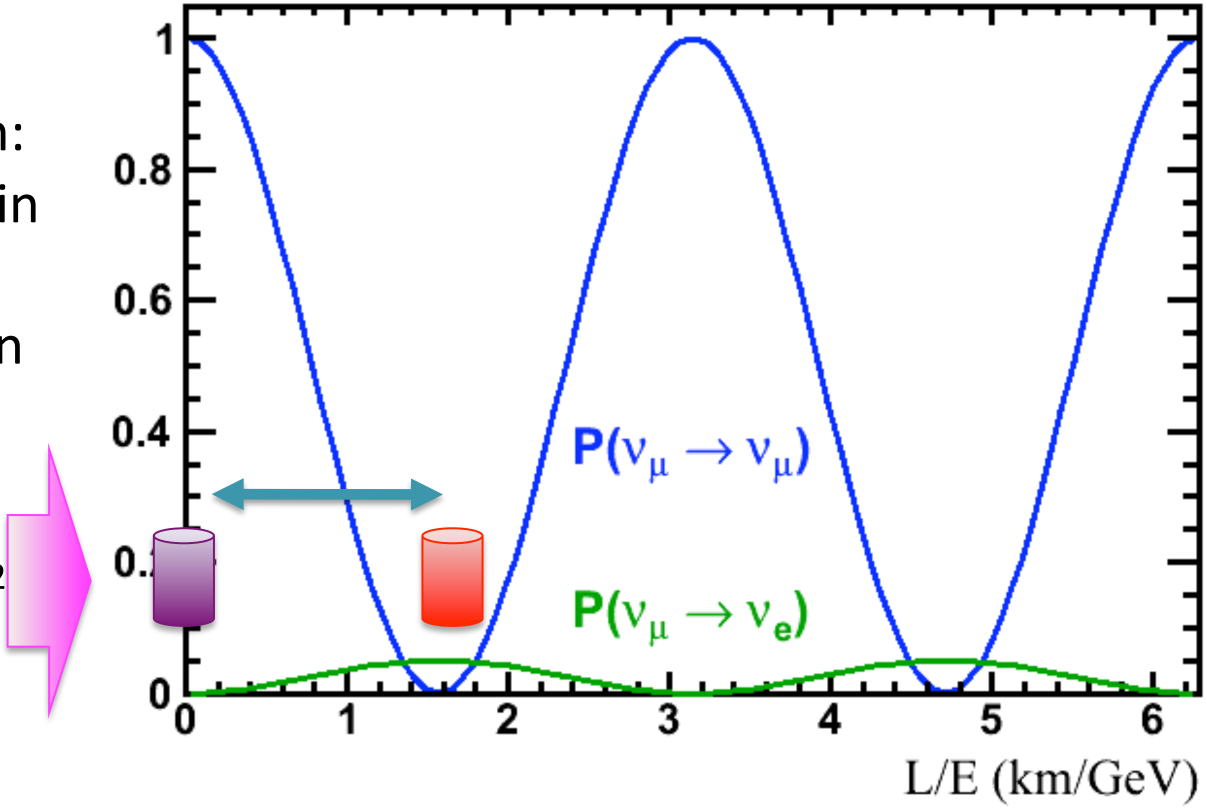


To search for neutrino oscillation, we need:

1) An intense neutrino source of muon neutrinos
2) A sufficient distance for oscillation to occur
3) A measurement of unoscillated ν_μ (and ν_e background) rate at L~0
4) A measurement of ν_μ, ν_e at L~ oscillation maximum

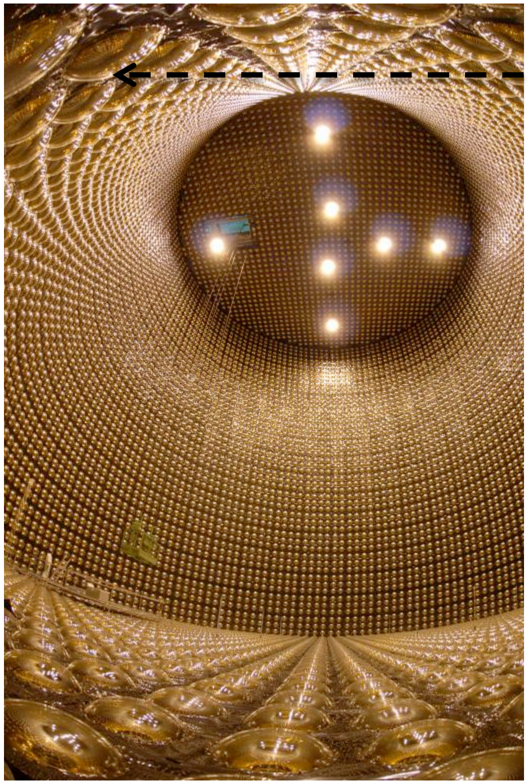
The Tokai-to-Kamioka (T2K) experiment

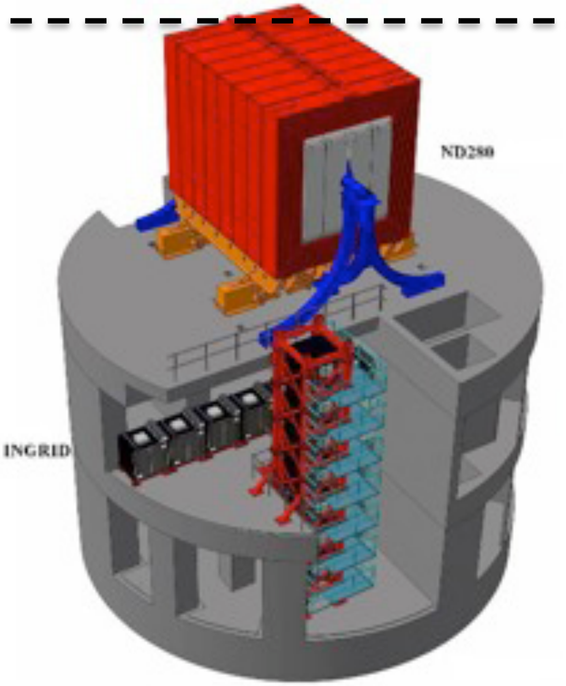
``Long baseline” (L~ 295km) neutrino experiment designed to measure ν_e appearance (θ_{13} and more) and ν_μ disappearance (Δm^2_{32}, θ_{23})

Far detector
Super-Kamiokande

Near detectors
ND280

Neutrino beam
Peak E_ν~0.6 GeV





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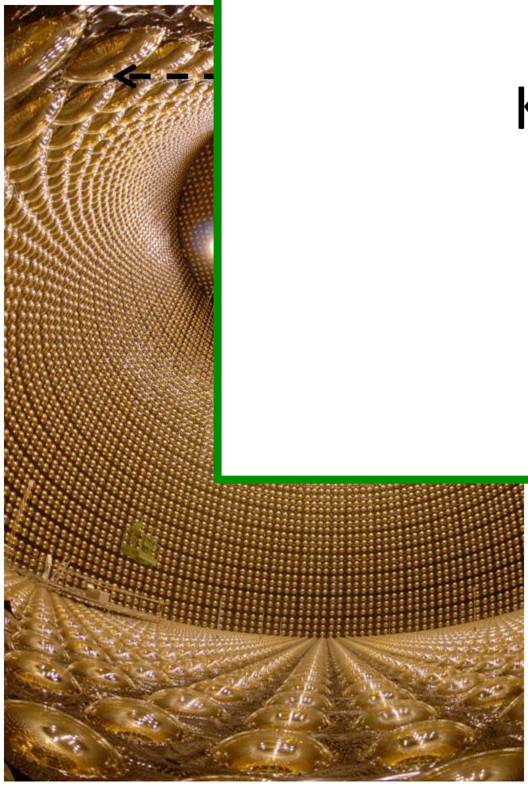
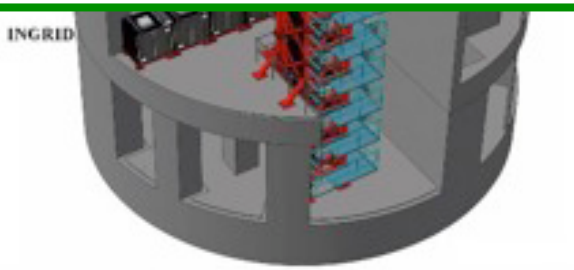
``Long baseline" (L~ 295km) neutrino experiment designed to measure ν_e appearance (θ_{13} and more) and ν_μ disappearance ($\Delta m^2_{32}, \theta_{23}$)

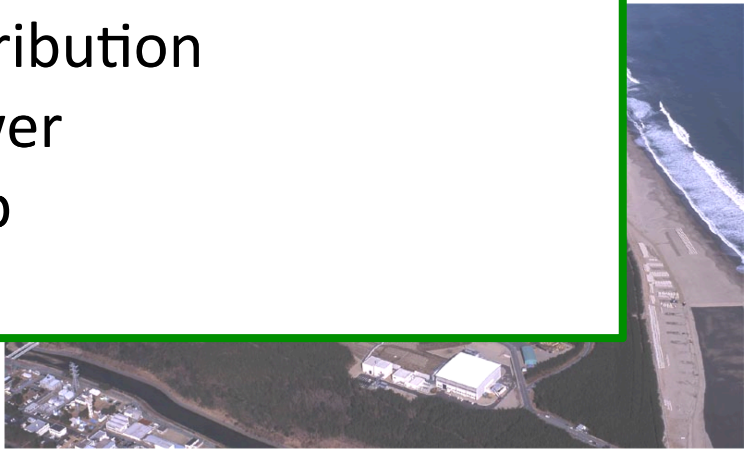
Far detector
Super-Ka

~500 collaborators from
59 institutions
11 countries

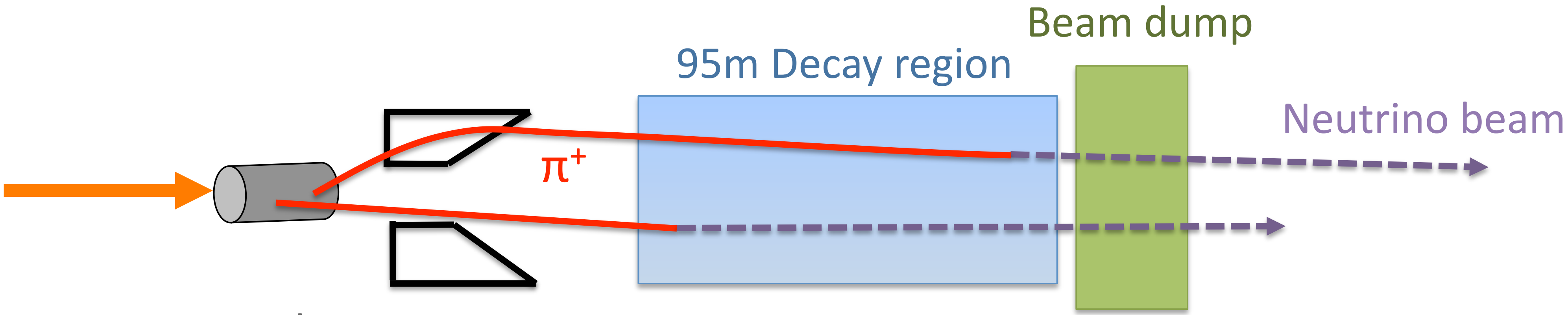
KM contributions marked as follows:
IC: Intellectual contribution
MP: Mahnpower
L: Leadership







Conventional neutrino beam



30 GeV Proton beam

Carbon Target

3 Magnetic focusing ``horns”

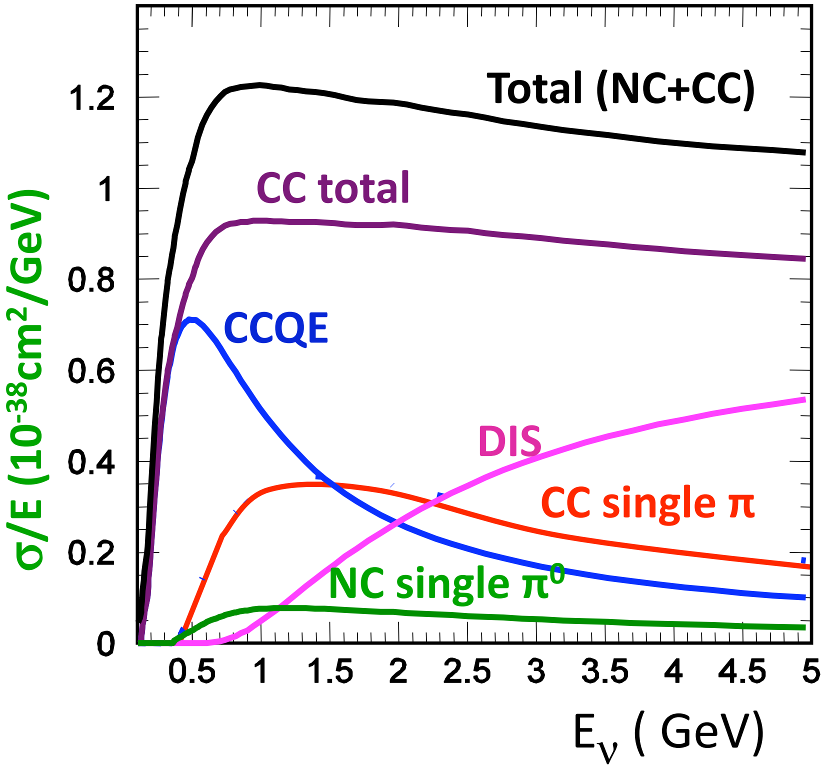
Pions and kaons decay to neutrinos

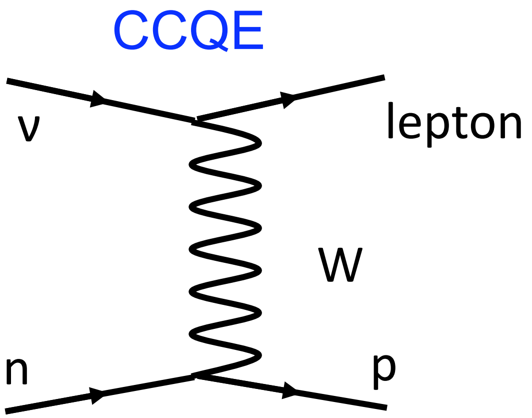
Shielding stops any remaining particles

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
    1. Determined by proton beam energy and position of the detector relative to the proton beam direction

Neutrino interactions at T2K



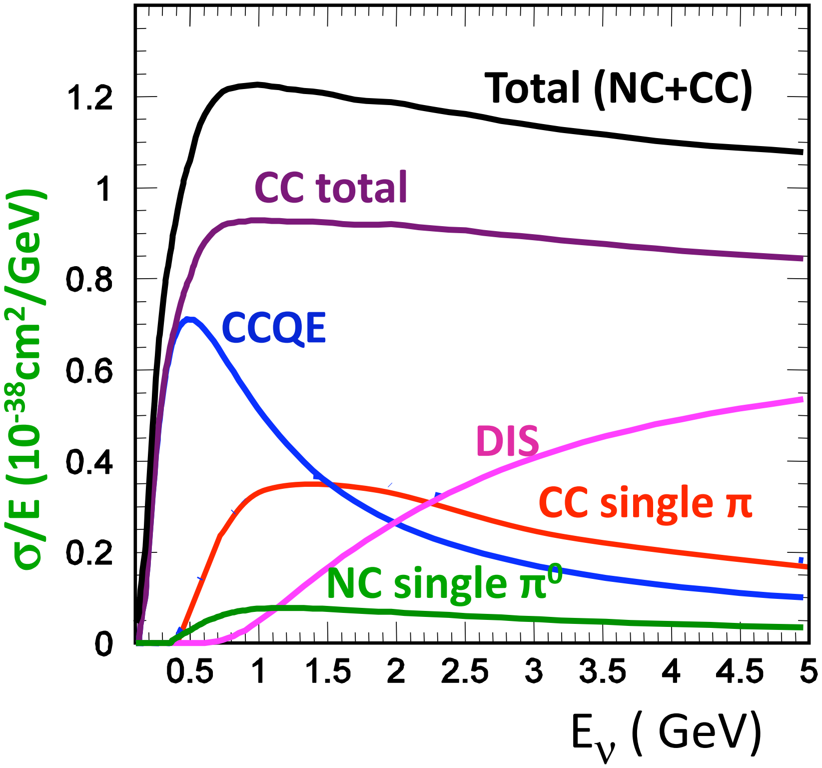


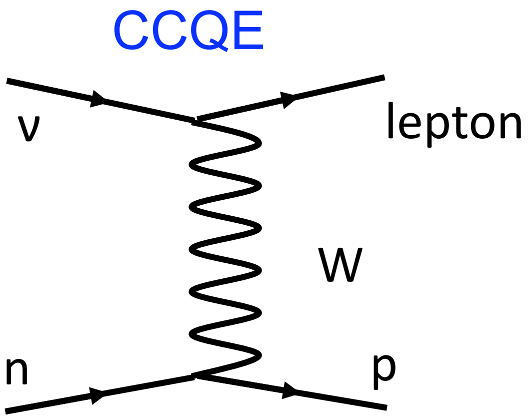
$$\nu_e \longrightarrow e$$
$$\nu_\mu \longrightarrow \mu$$

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





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

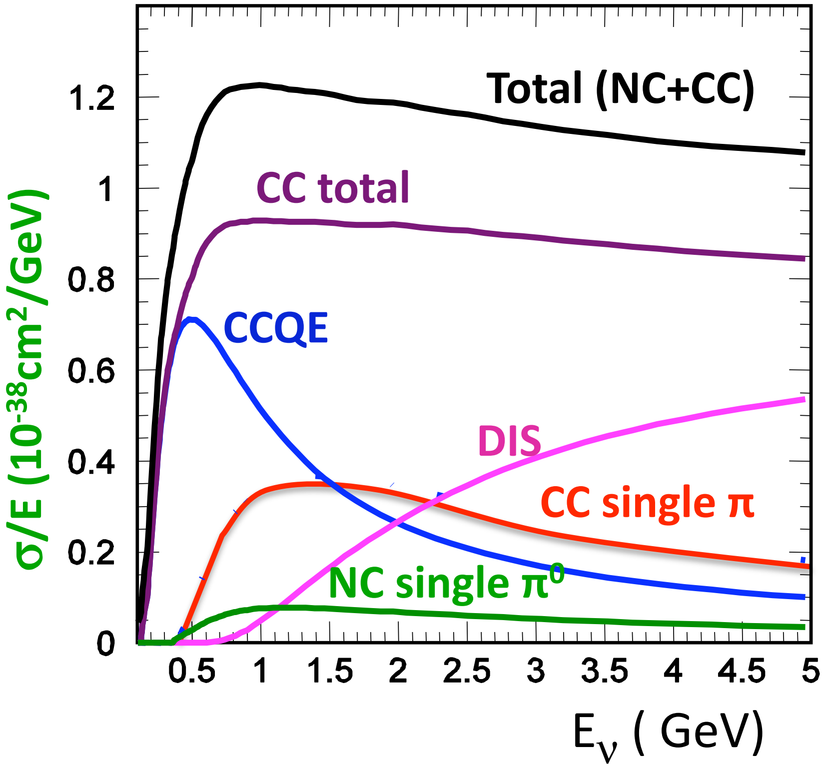
At E_ν~0.6 GeV, most neutrino interactions are Charged Current Quasi Elastic (CCQE)

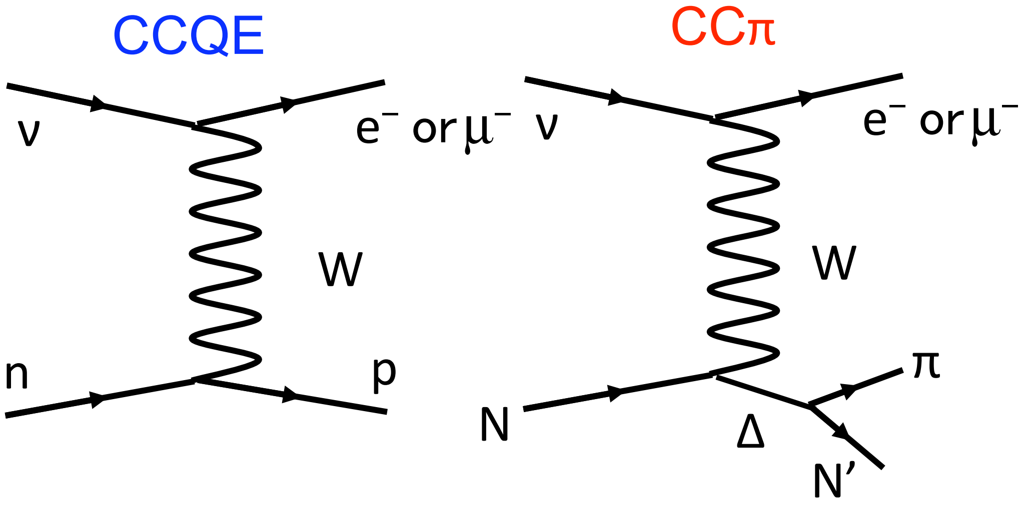
- Neutrino flavor determined from flavor of outgoing lepton
- Infer neutrino properties from the muon (or electron) momentum and angle:

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

2 body kinematics
Assumes the target nucleon is at rest

Neutrino interactions at T2K



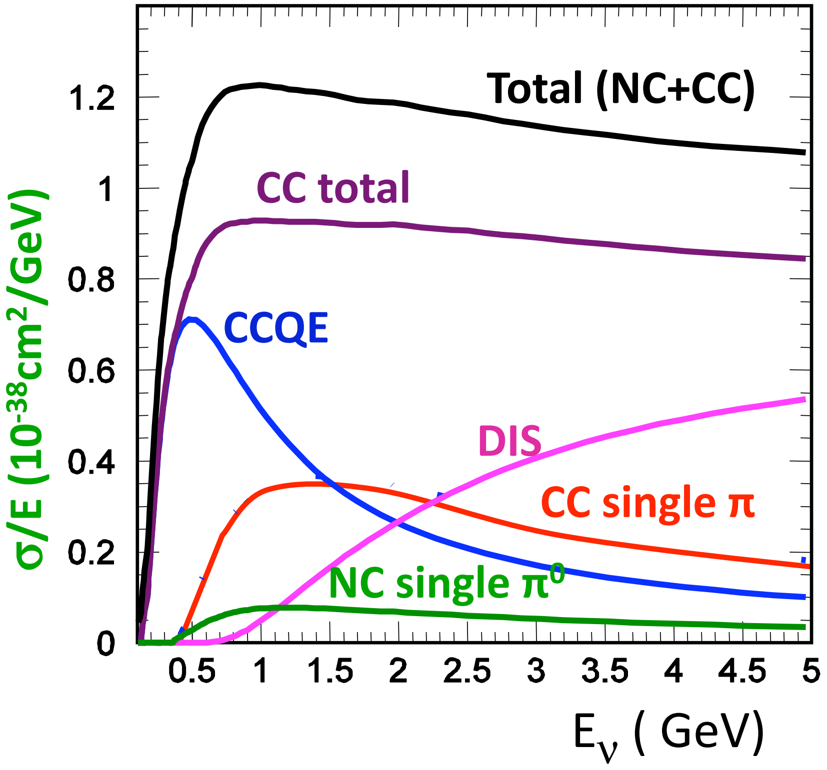


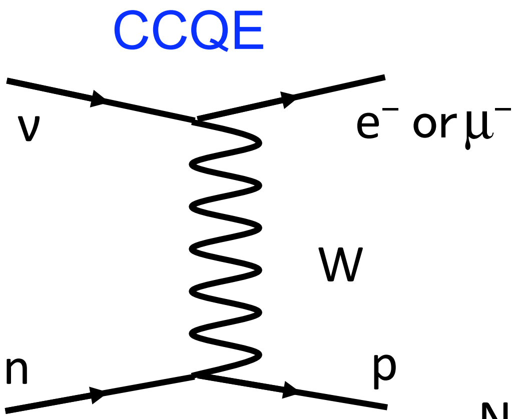
Other interactions important for T2K analysis:

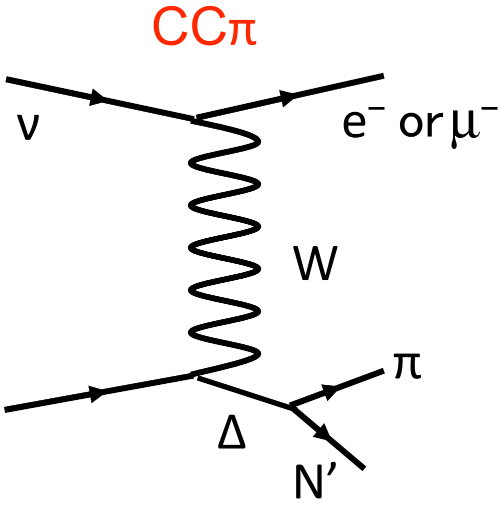
- Charged current single pion production (CCπ)
  - Lepton and pion (charged or neutral) produced
  - Oscillation signal (and background if pion is not identified)

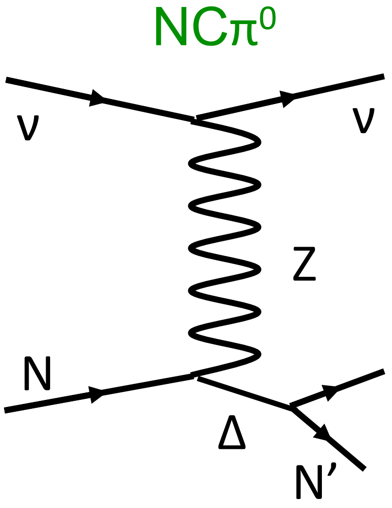
$$E_\nu^{QE} = \frac{m_p^2 - {m'}_n^2 - m_\mu^2 + 2{m'}_n E_\mu}{2({m'}_n - E_\mu + p_\mu \cos\theta_\mu)}$$

Neutrino interactions at T2K









Other interactions important for T2K analysis:

- 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

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

Fit the observed rate to determine the oscillation probability, P. 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 the oscillation probability, P. 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:

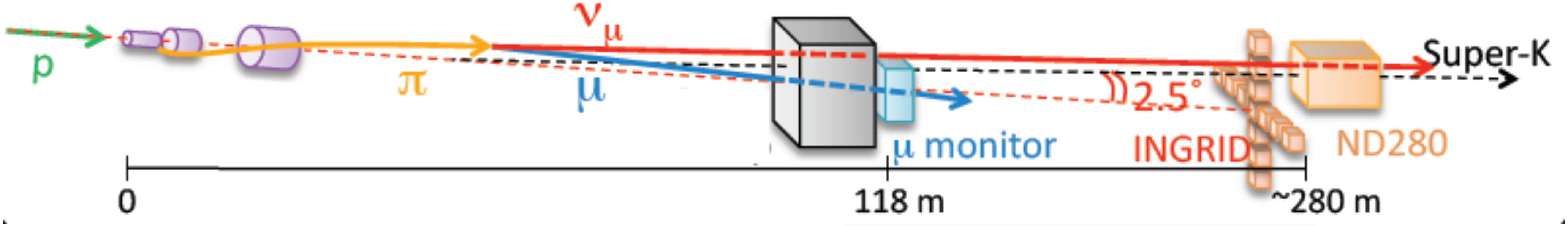
$$N(\nu_\mu) = \Phi(E_\nu)\ \sigma(E_\nu)\ \epsilon$$

Neutrino flux prediction

Neutrino cross section model

Near detector selection, efficiency

T2K Neutrino flux prediction



FLUKA/Geant3 beam simulation

Phys. Rev. D 87, 012001 (2013)

- 3 horn focusing system
- 280m from target:
  - INGRID on-axis ND280 off-axis
- ν_μ from π^+, K decay

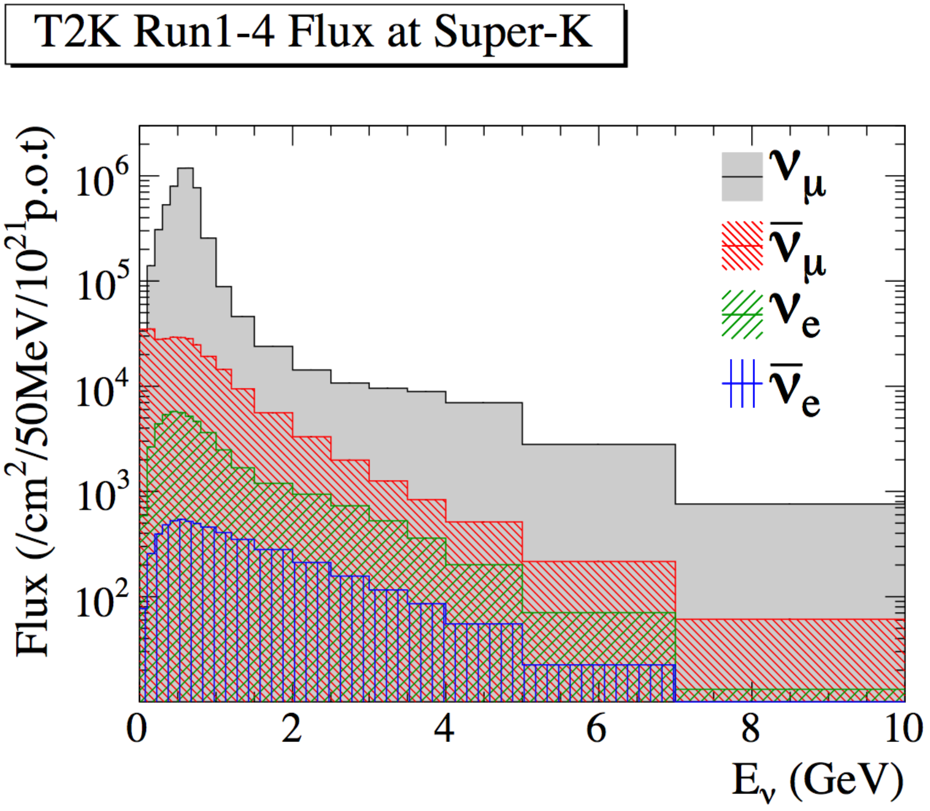
Prediction and uncertainties determined by external or in-situ measurements of:

- proton beam (30 GeV)
- π, K production from NA61 experiment

Phys.Rev.C 84, 034604 (2011)

Phys.Rev.C 85, 035210 (2012)

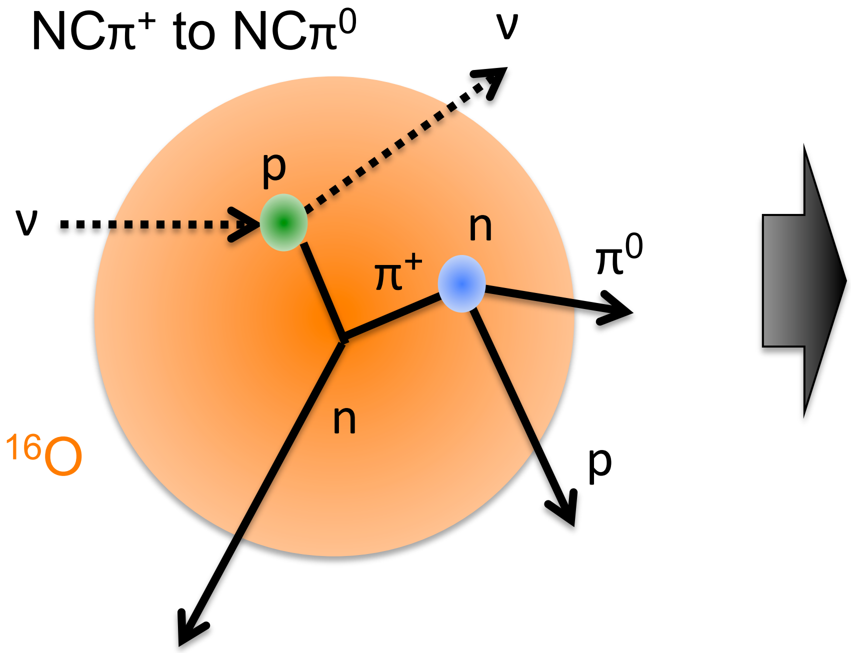
- alignment and off-axis angle

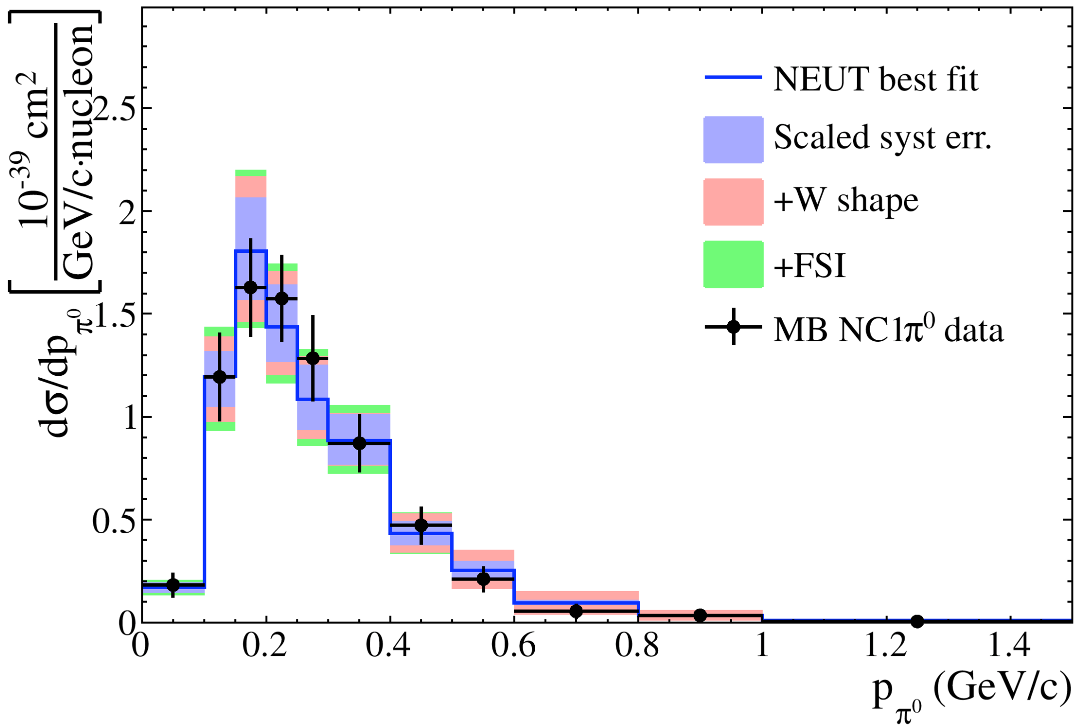


Neutrino interaction uncertainties

Cross section model (NEUT, GENIE) relates lepton kinematics to neutrino energy:

- Initial interaction of neutrino with nucleon
- Final state interaction model (FSI) of outgoing particles, especially pions



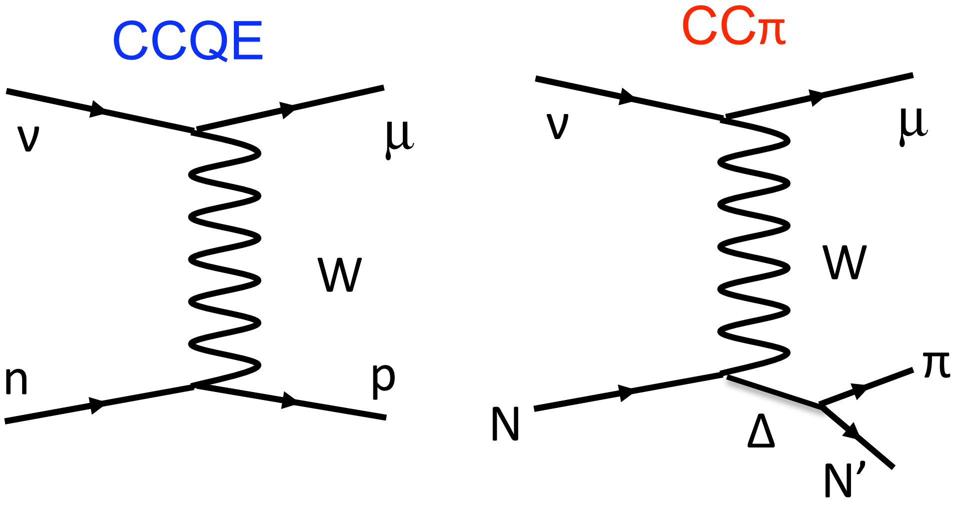


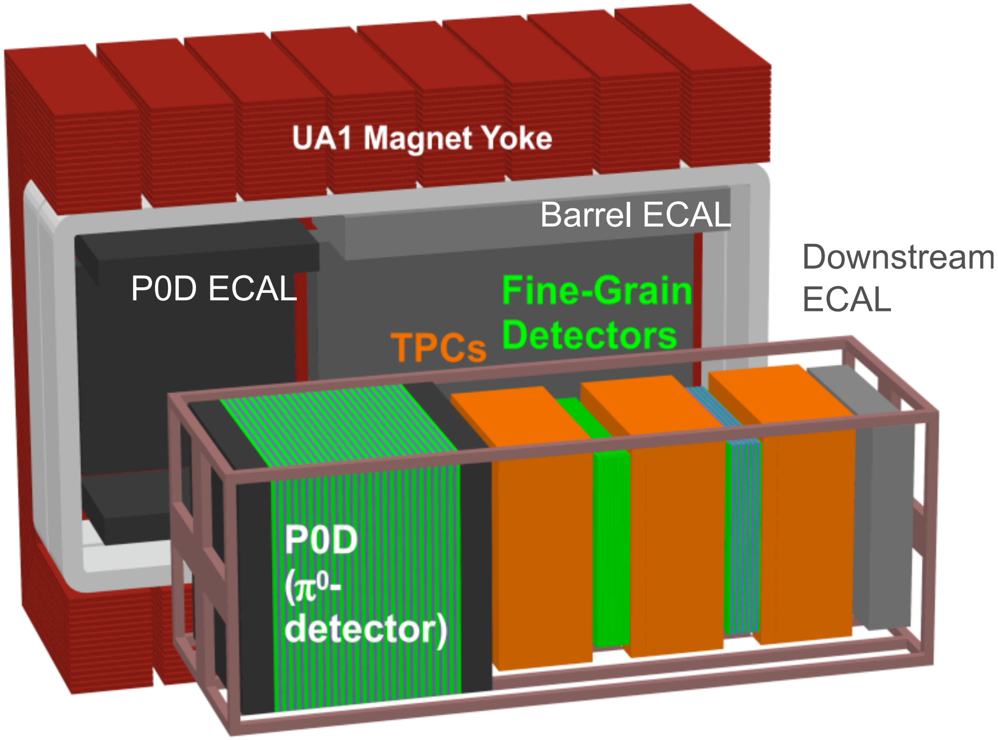
IC: Cross section model uncertainties set from fits to MiniBooNE data (E_ν ~ 1 GeV) for signal and background (CCQE, CC1π and NCπ^0) interactions

- Single pion (CC and NC) interaction datasets fit simultaneously
- SciBooNE, K2K datasets used as cross check
- **IC**, **MP**: Development of software to weight cross section in MC in both near and far detectors simultaneously

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)

Center of ND280 is the "Tracker":

- 2 scintillator based tracking detectors (FGDs)
- 3 time projection chambers (TPCs)
- Placed inside the UA1 (B=0.2T) magnet

Additional detectors include:

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

Selecting CC ν_μ interactions

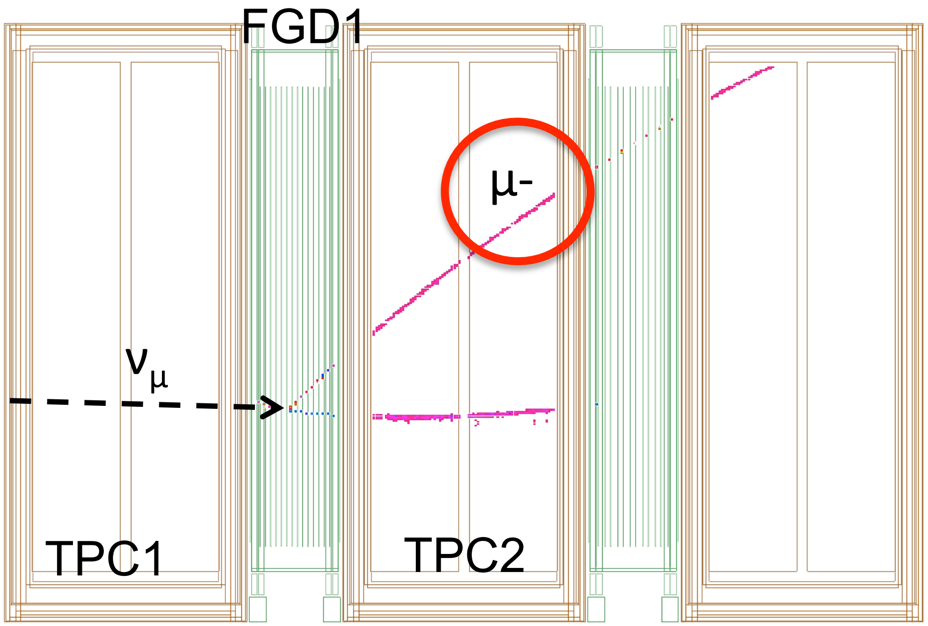
Measure unoscillated ν_μ(CC) rate

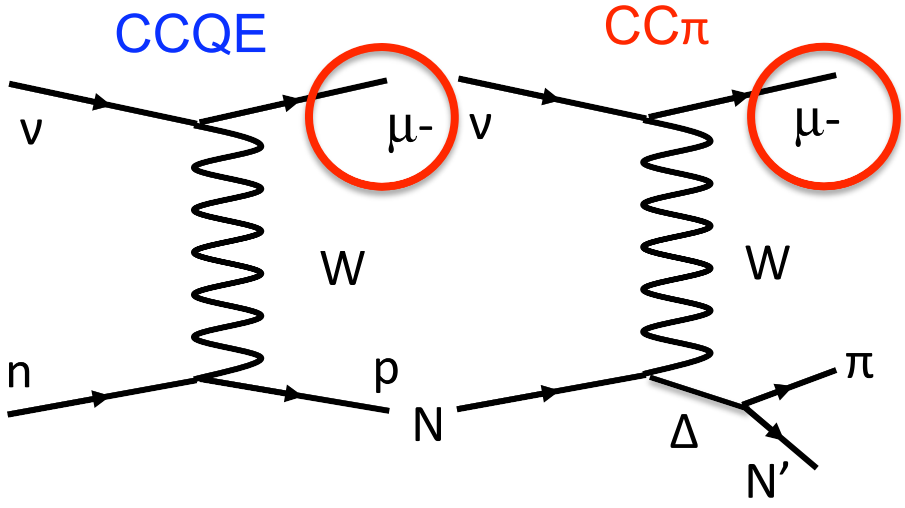
1. Neutrino interaction in FGD1

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

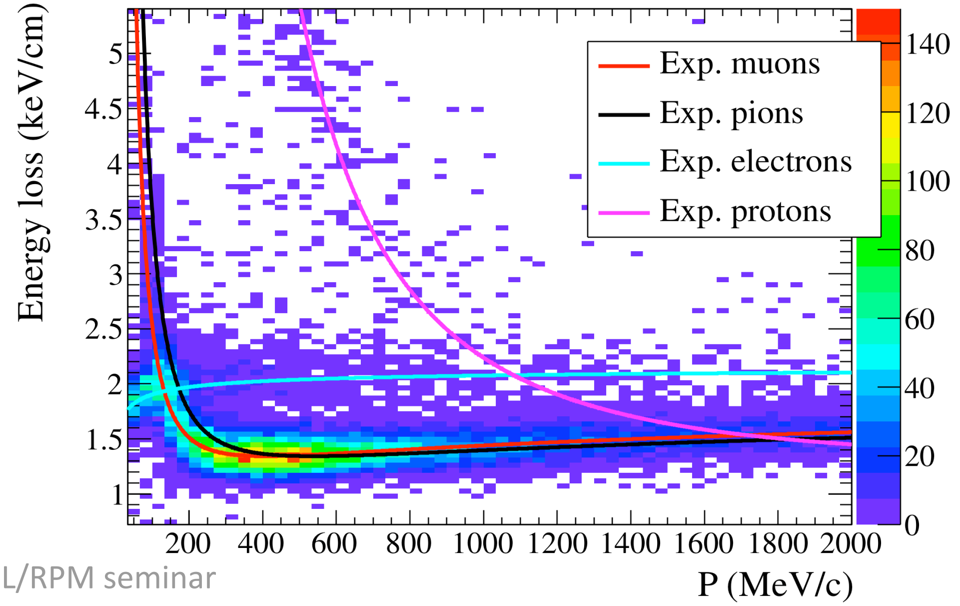
2. Select highest momentum, negative curvature track as μ^- candidate

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





MP: *TPC commissioning, data quality system and alignment*



Selecting CC ν_μ interactions

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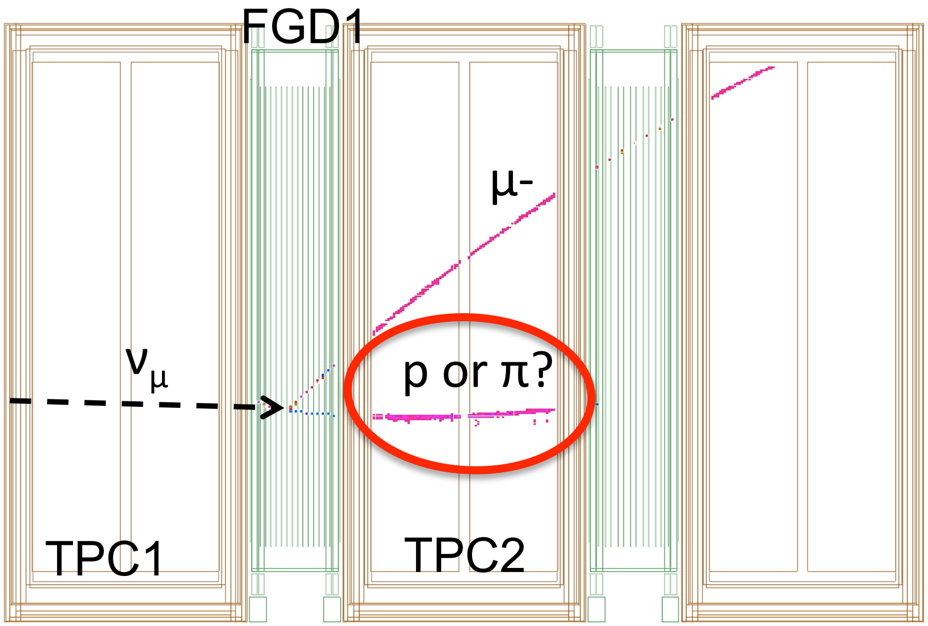
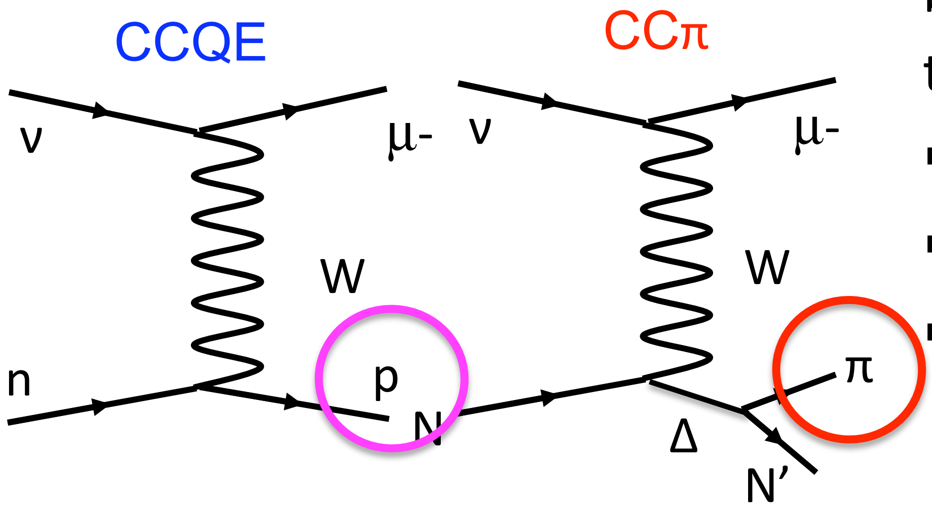


Further separate sample into three categories based on final state: CC0π / CC1π / CC other to increase sensitivity to cross section:
- FGD track: decay electron / π-p dE/dx
- TPC-FGD matched track: π-p dE/dx
- Electrons identify π^0 (often from DIS events)



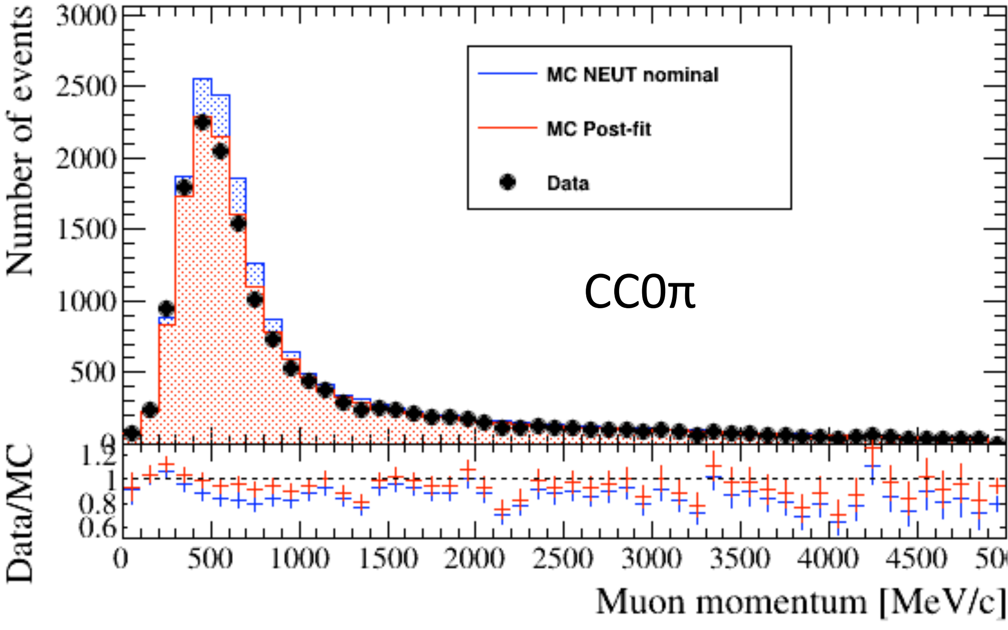
Near detector rate constraint

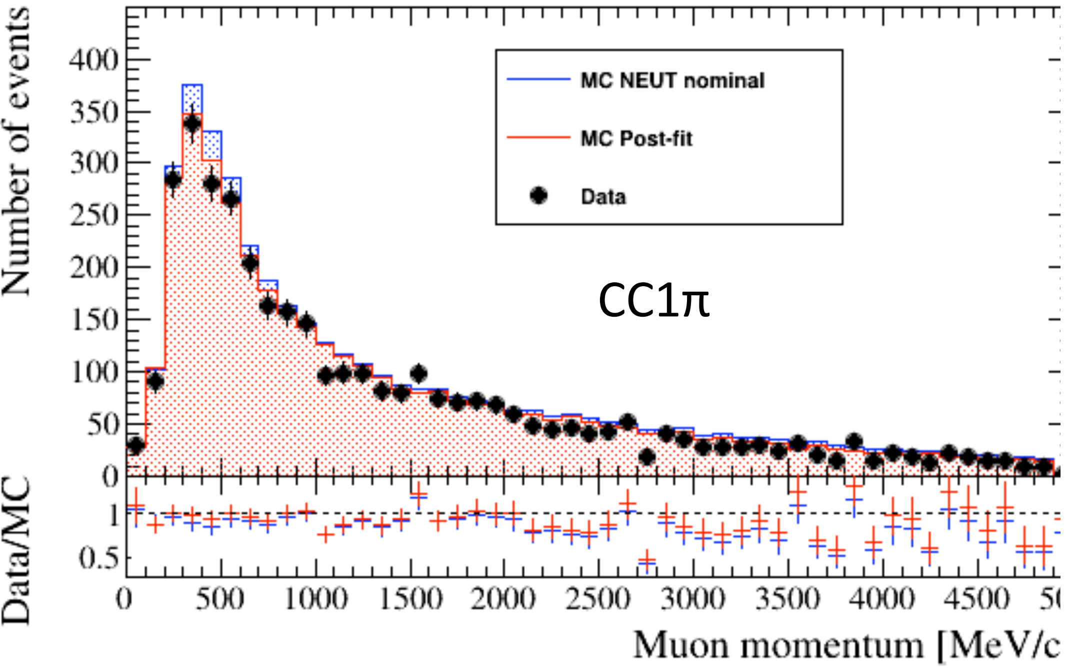
IC: Tune flux, cross section models with a likelihood fit

- 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)





Results of near detector rate fit

- Shared flux, similar CC cross section composition of near and far detector selections result in substantial reduction to CC cross sections, ν_μ flux uncertainties

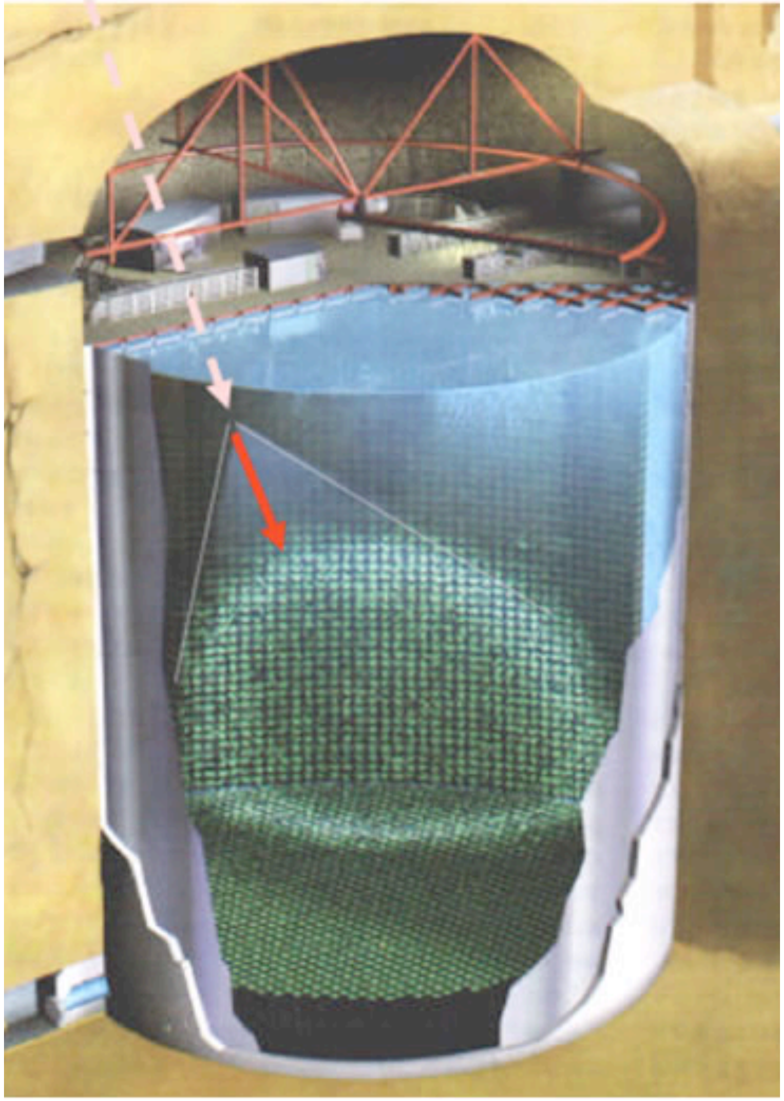
Uncertainties	**ν_e sig+bkrd**	**ν_e background**
ν flux+xsec (before) after ND280 constraint	(25.9%) ±2.9%	(21.7%) ±4.8%
ν xsec (unconstrained by ND280)	±7.5%	±6.8%
Far detector	±3.5%	±7.3%
Total	±8.8%	±11.1%

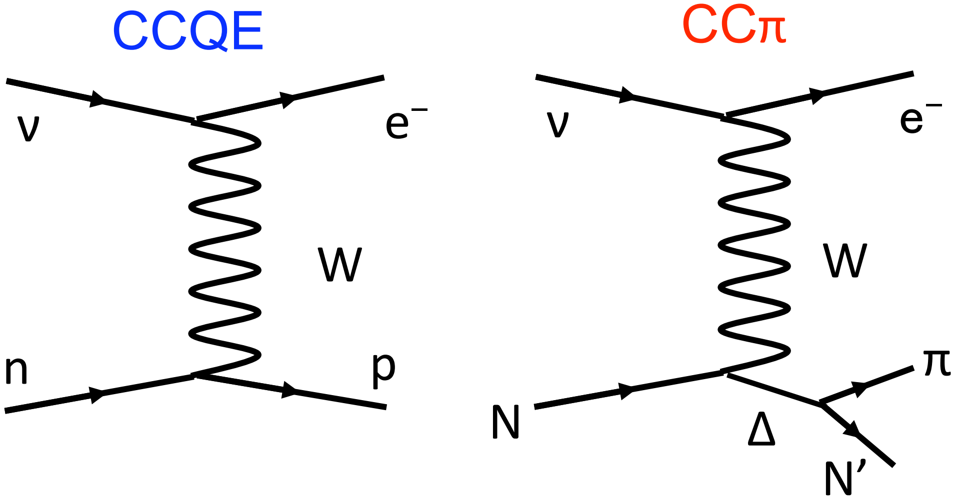
$$N(\nu_e) = \boxed{\Phi(E_\nu)}\,\boxed{\sigma(E_\nu)}\;\epsilon\;P(\nu_\mu \rightarrow \nu_e)$$

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

Far detector

Measure ν_e(CC) rate from ν_μ oscillation
Select nothing coming in (neutrino)
and an electron coming out (ν_e)





Super-Kamiokande: 22.5kton fiducial volume water Cherenkov detector

Charged leptons emit Cherenkov light

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

Expected number of ν_e candidates

After ND280 tuning, expect 21.6 events with expected ν_μ to ν_e oscillation

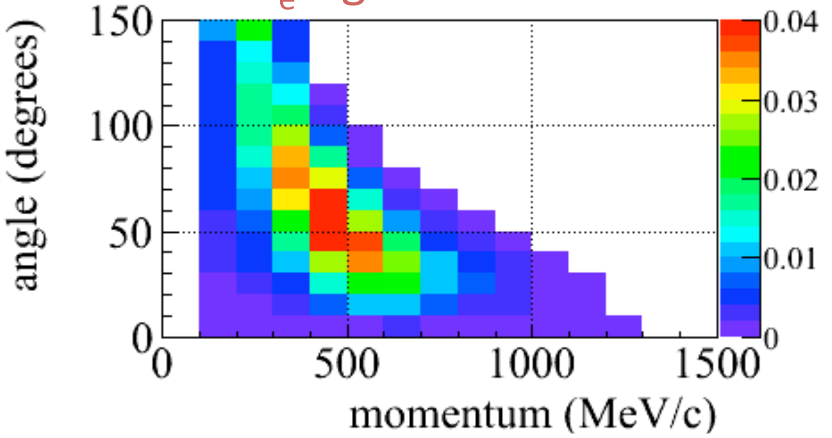
- Rate, p-θ kinematics of events distinguishes signal from background

Signal (ν_μ to ν_e osc)	**# events**
@$\sin^2 2\theta_{13}$=0.1,δcp=0	16.7

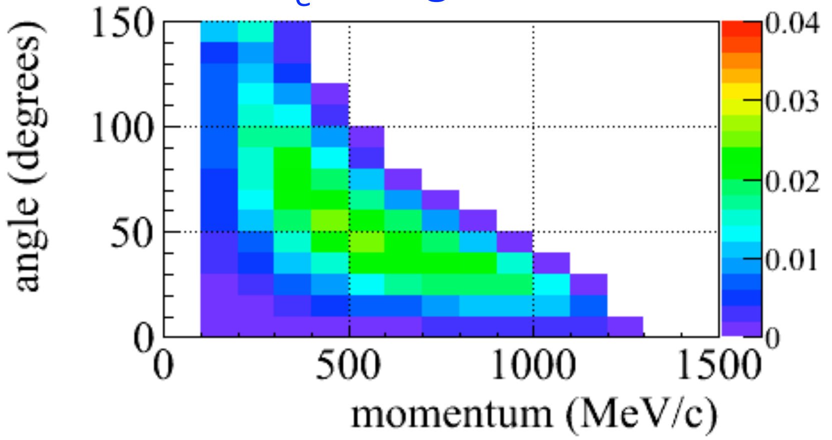
ν_e signal@Δm^2_{32} =2.4 x 10^{-3} eV^2, $\sin^2 2\theta_{23}$=1.0
Excludes θ_{12} component

Background	**# events**
beam ν_e	3.2
ν_μ (mainly NC) background	1.1
osc through θ_{12}	0.6
total assuming $\sin^2 2\theta_{13}$=0	4.92±0.55

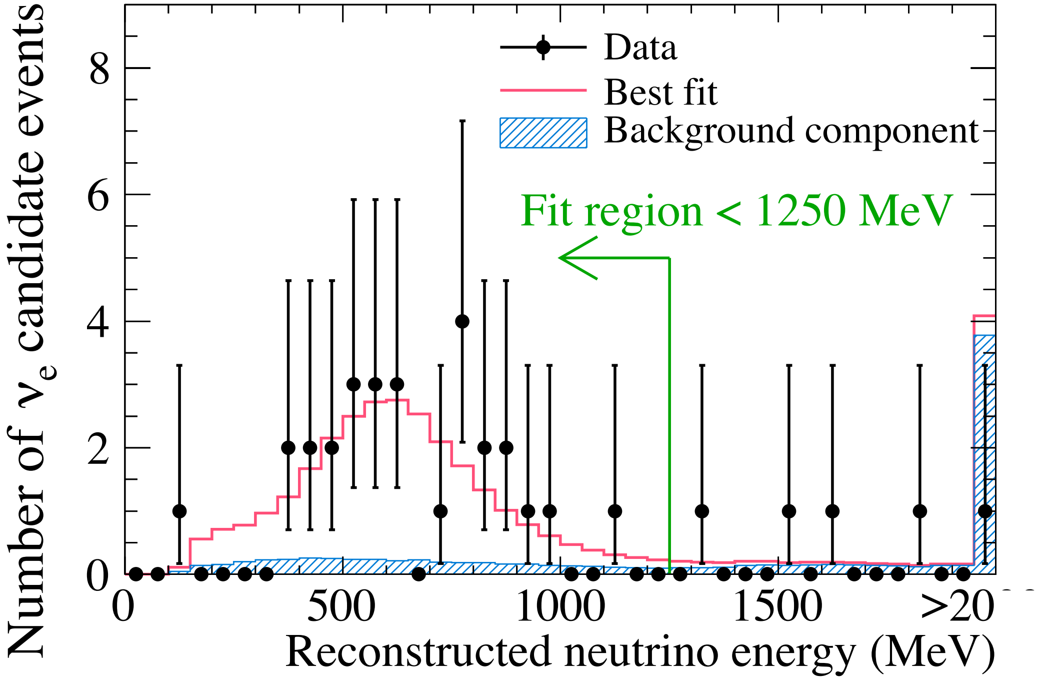
CC ν_e signal



CC ν_e background



Discovery of ν_e appearance!



First observation of CC ν_e appearance:

- 28 candidate events observed

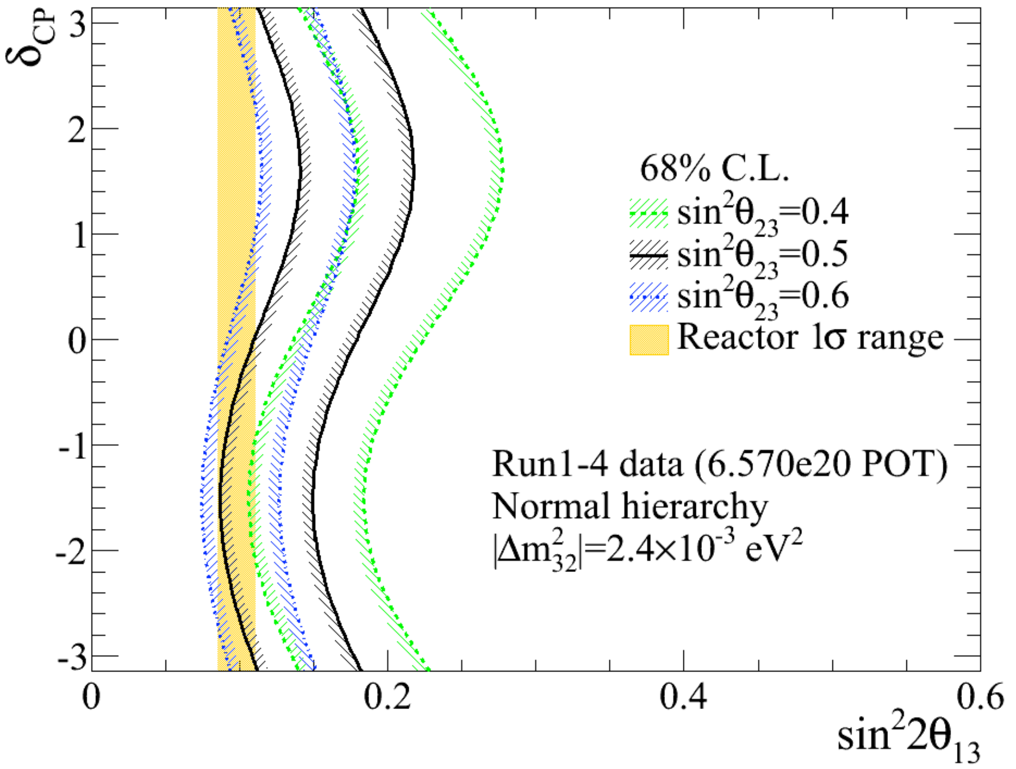
(expected 21.6 with $\sin^2 2\theta_{13}=0.1$)

- 7.3σ significance for non-zero θ_{13}
- Phys. Rev. Lett. 112, 061802 (2014)

Appearance probability depends on δ_{CP} and all other oscillation parameters, including:

- Δm^2_{21}, θ_{12} and θ_{13} from solar, reactor experiments
- Δm^2_{32}, θ_{23} from atmospheric, accelerator-based experiments

1D scan vs. δ_{CP}



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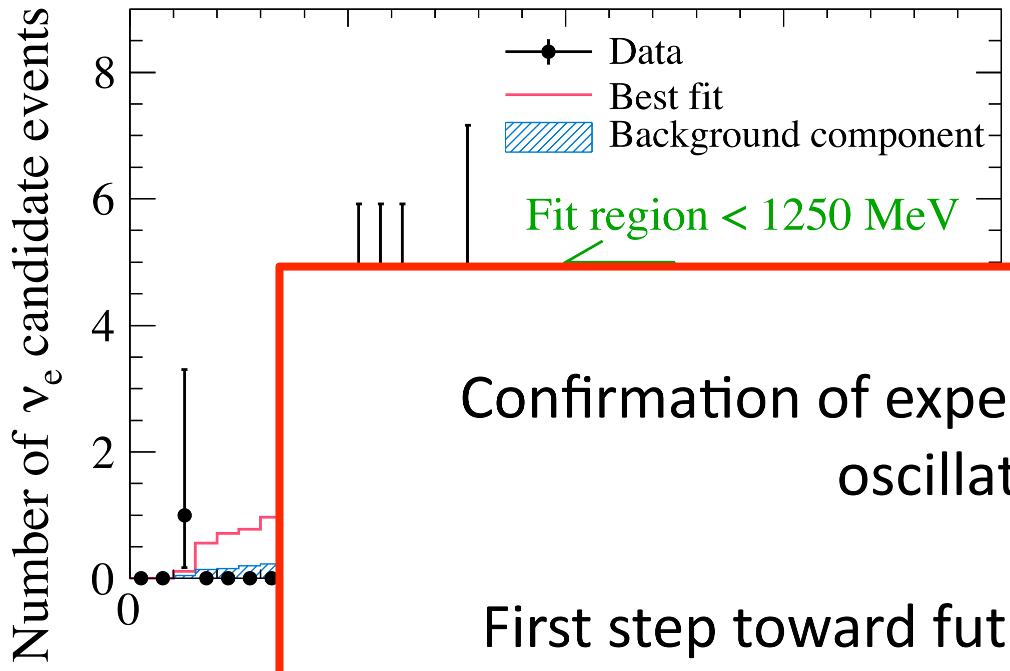


First observation of CC ν_e appearance:

- 28 candidate events observed

(expected 21.6 with $\sin^2 2\theta_{13}=0.1$)

θ_{13}

014)

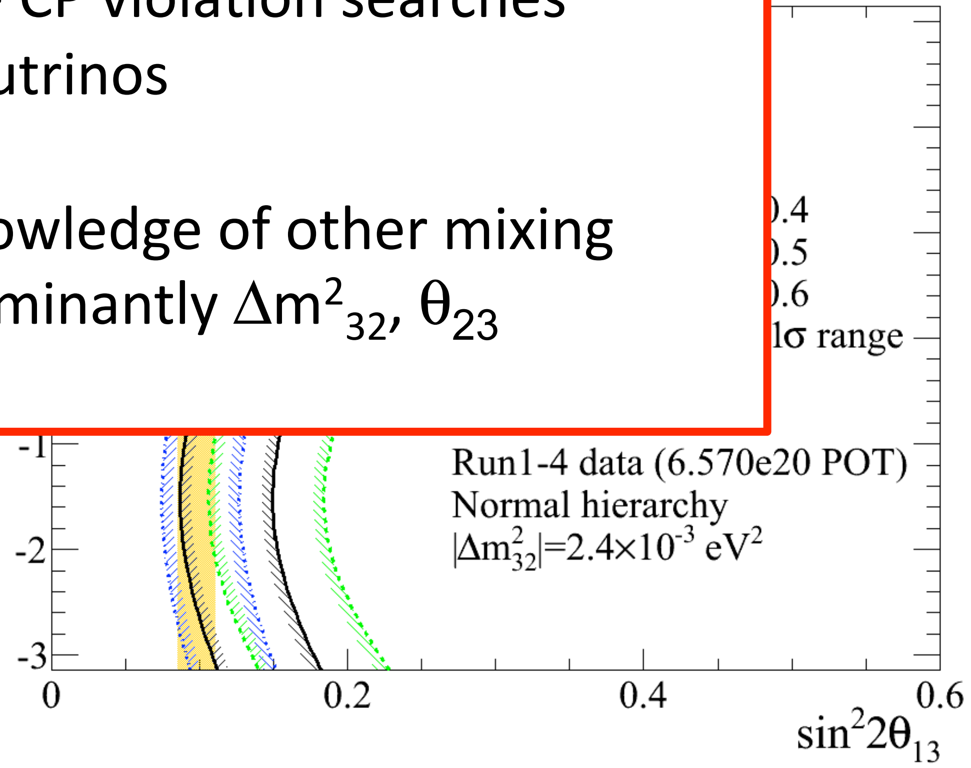
Confirmation of expected three flavor neutrino oscillation physics

First step toward future CP violation searches with neutrinos

Depends on precision knowledge of other mixing parameters, predominantly Δm^2_{32}, θ_{23}

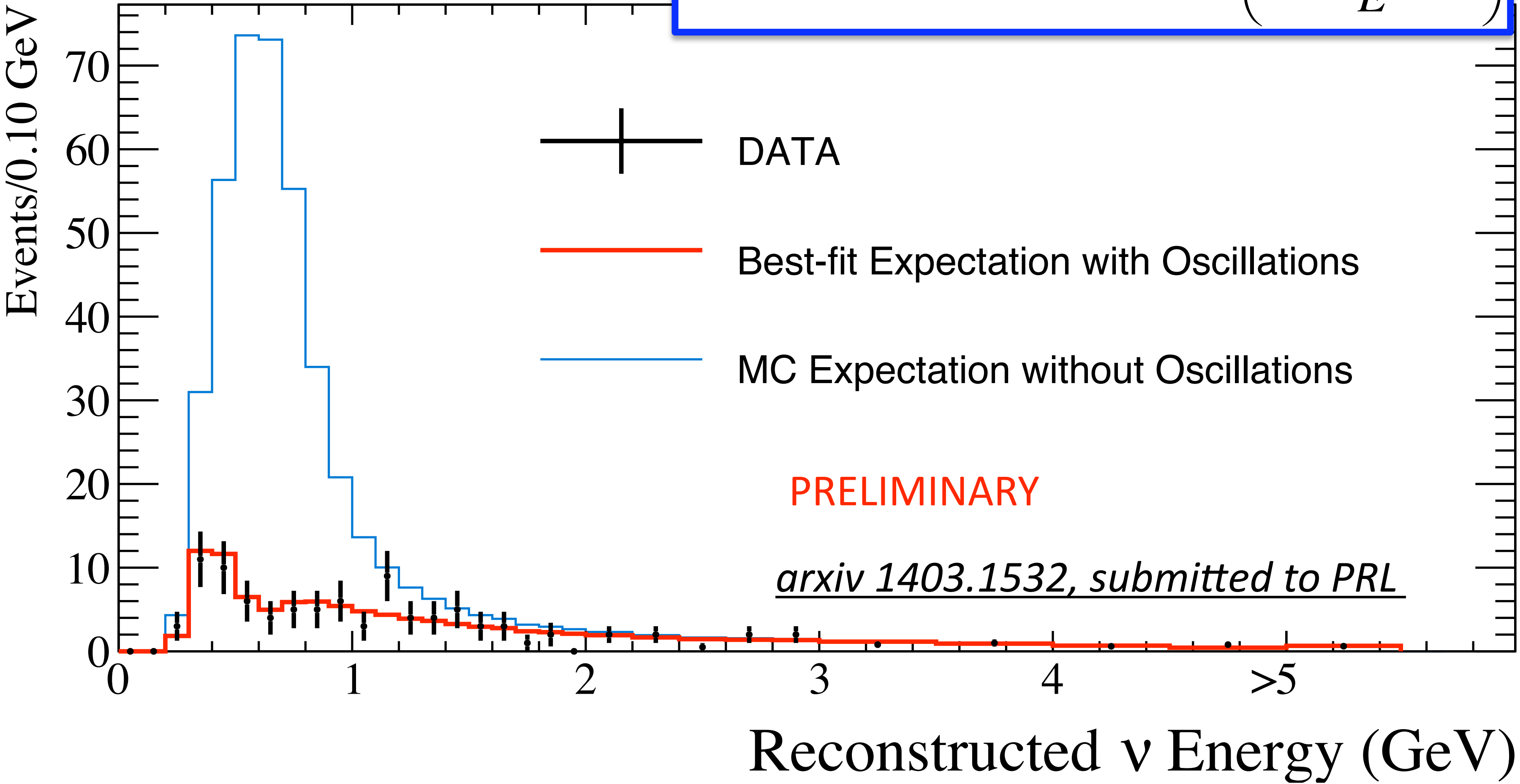
Appearar
and all
includi

- Δm^2_{21},
experiments
- Δm^2_{32}, θ_{23} from atmospheric, accelerator-based experiments



NEW: T2K ν_μ disappearance

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



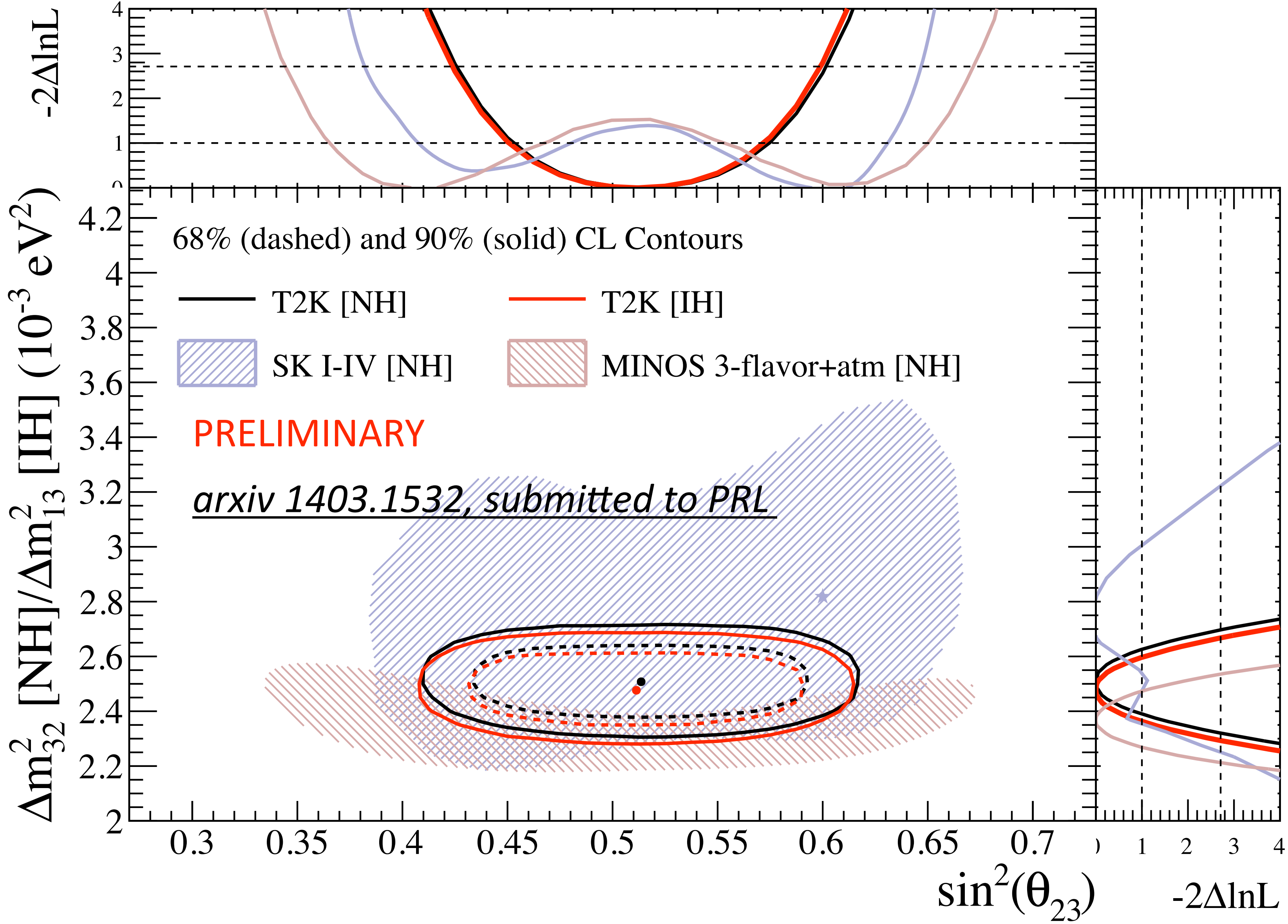
PRELIMINARY

arxiv 1403.1532, submitted to PRL

Disappearance distorts energy spectrum and rate of ν_μ candidates

- Select CCQE ν_μ candidates at SK with ring info, decay electron tag
- Reconstruct neutrino energy from muon kinematics
- Apply same near detector tuning as for ν_e appearance

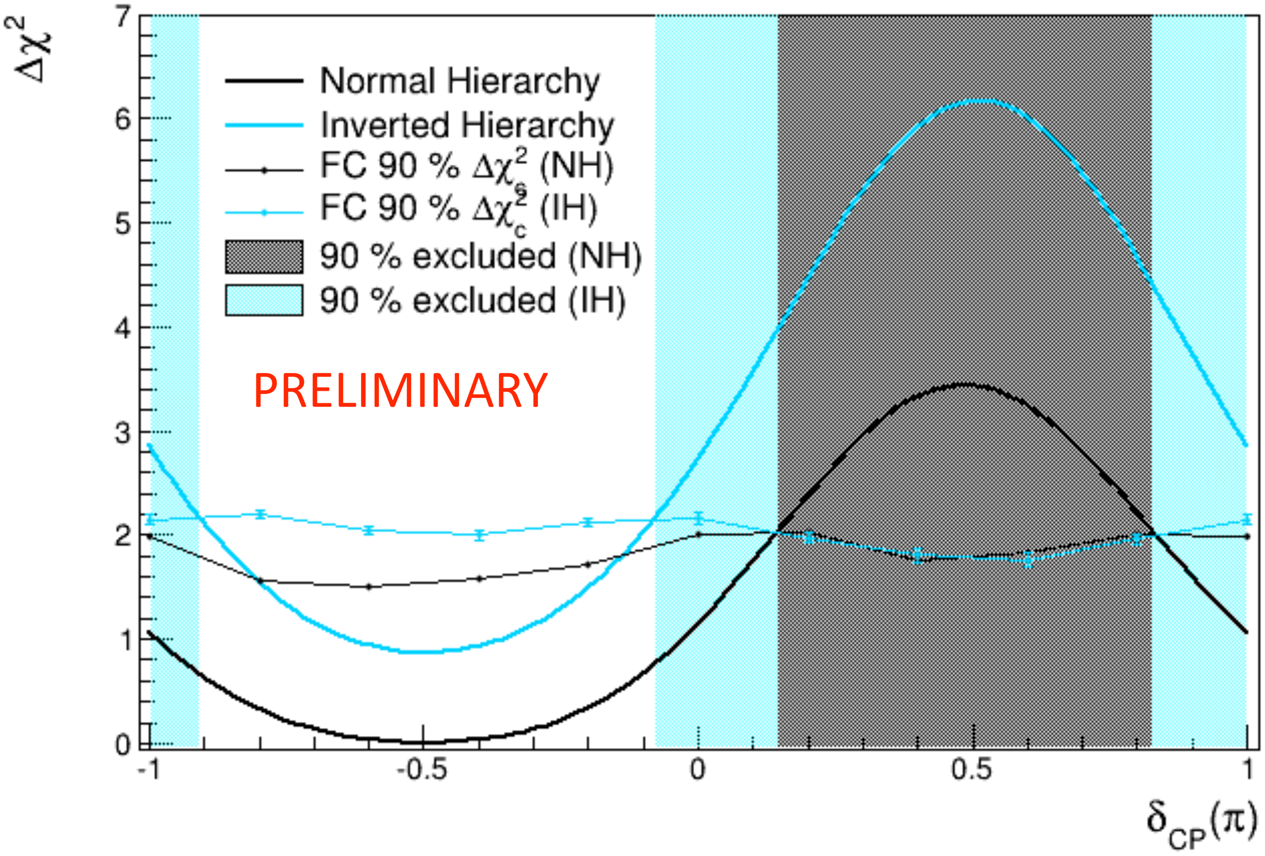
NEW: ν_μ disappearance results



Sensitivity to the octant through sub-leading terms (θ_{23} >45°? <45°?)

- Best constraint on θ_{23}, still consistent with maximal (45°) mixing

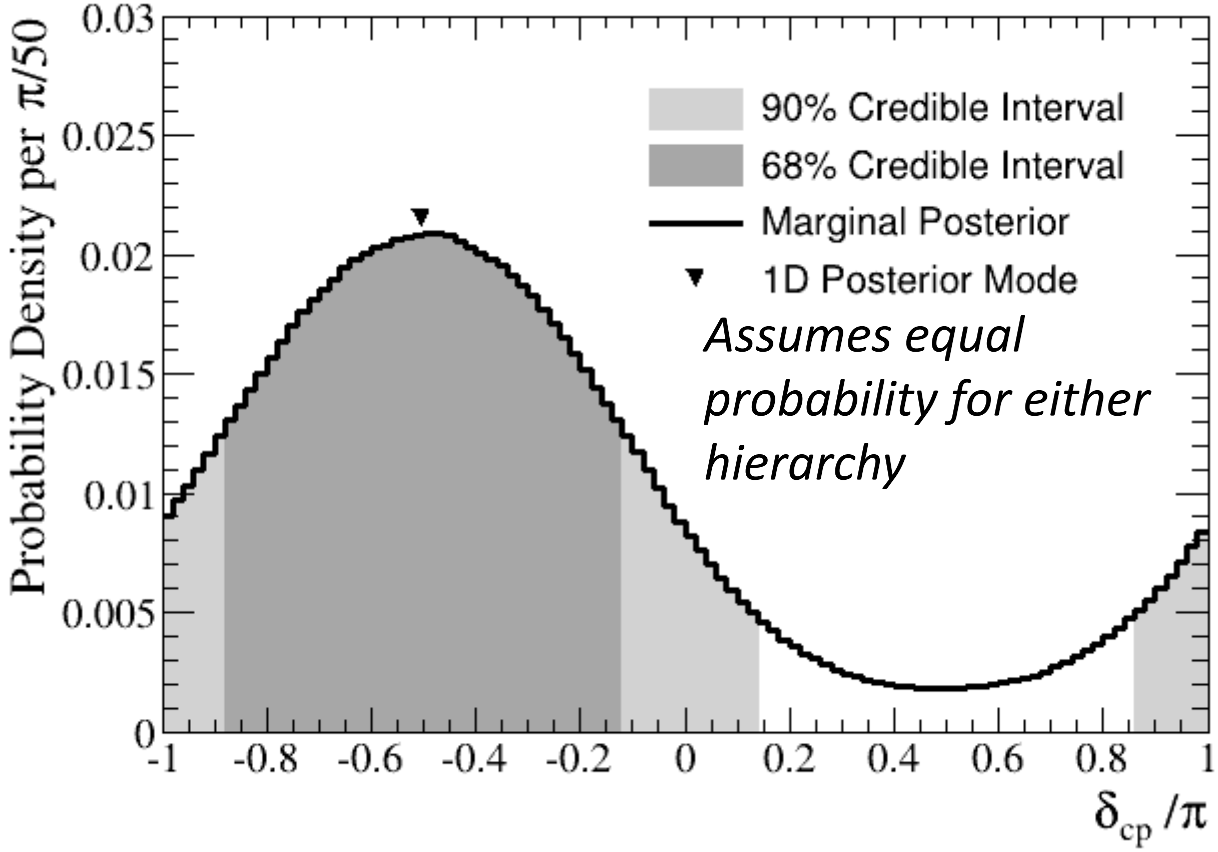
NEW: joint ν_μ – ν_e analysis results



90%CL exclusion of δ_{CP} values (~$\pi/2$) when constraints on Δm^2_{32}, θ_{23} , Δm^2_{21}, θ_{12} and θ_{13} are included

- Fit includes T2K ν_μ, ν_e samples and correlations
- $\sin^2\theta_{13} = 0.095\pm0.010$
- PDG2013 based on reactor experiments

NEW: joint ν_μ – ν_e analysis results



Assumes equal probability for either hierarchy

90%CL exclusion of δ_{CP} values (~π/2) when constraints on Δm^2_{32}, θ_{23} , Δm^2_{21}, θ_{12} and θ_{13} are included

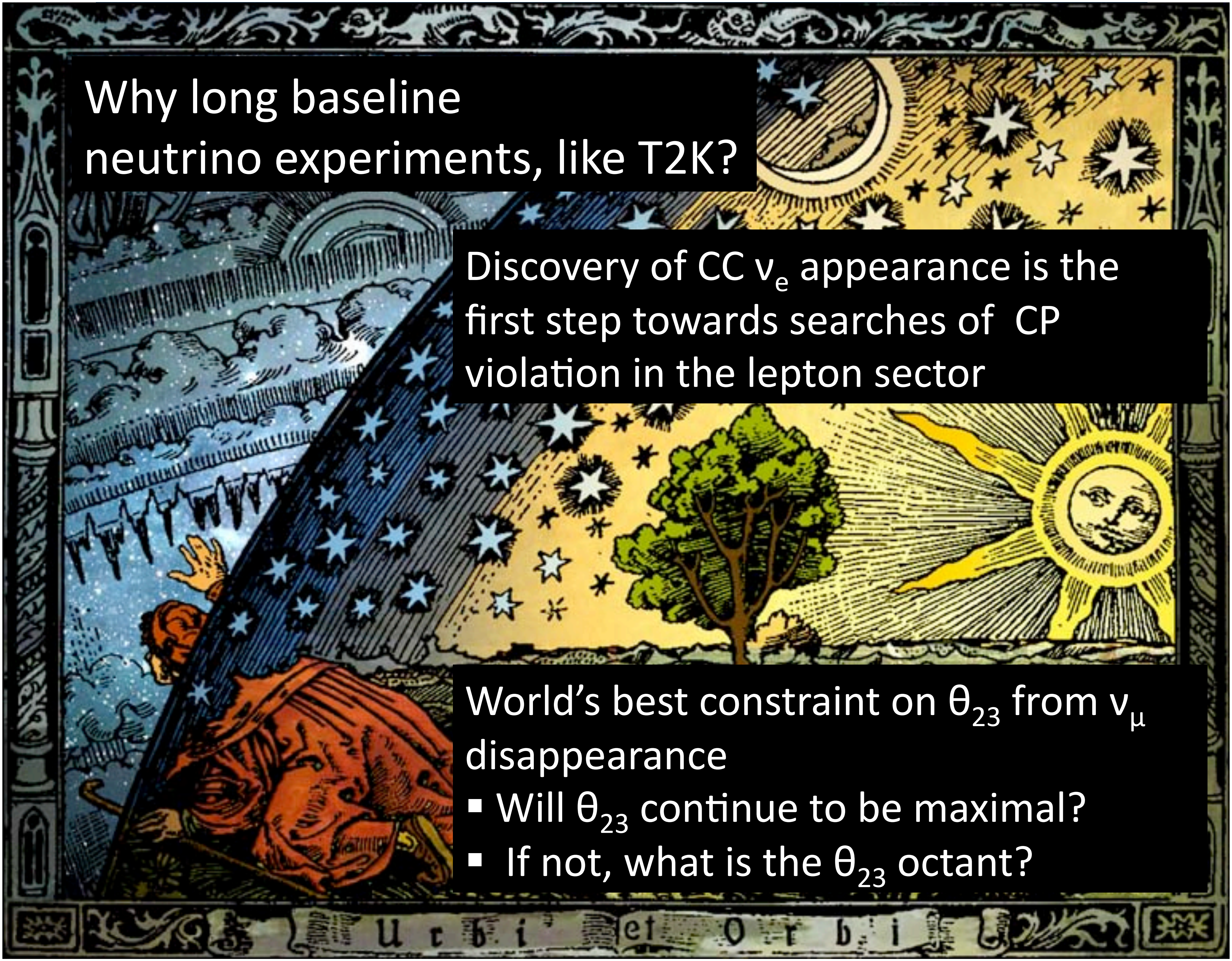
- Fit includes T2K ν_μ, ν_e samples and correlations
- $\sin^2\theta_{13} = 0.095 \pm 0.010$
- PDG2013 based on reactor experiments

Complementary Baysian joint analysis is a Markov Chain Monte Carlo approach

- Simultaneous fit of ND280, SK samples
- Can compare probabilities for each combination of octant, mass hierarchy

Probability	$\Delta m^2_{32}>0$	$\Delta m^2_{32}<0$	Sum
$\sin^2\theta_{23} \leq 0.5$	18%	8%	26%
$\sin^2\theta_{23} > 0.5$	50%	24%	74%
Sum	68%	32%	

Why long baseline neutrino experiments, like T2K?

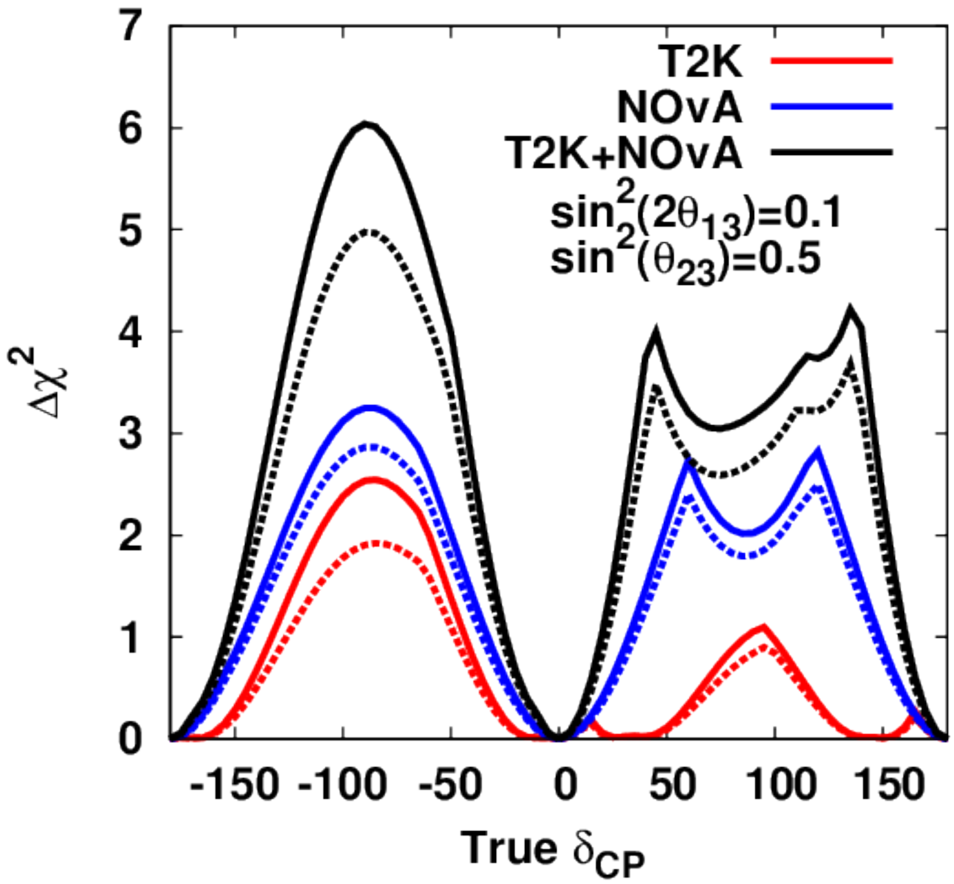


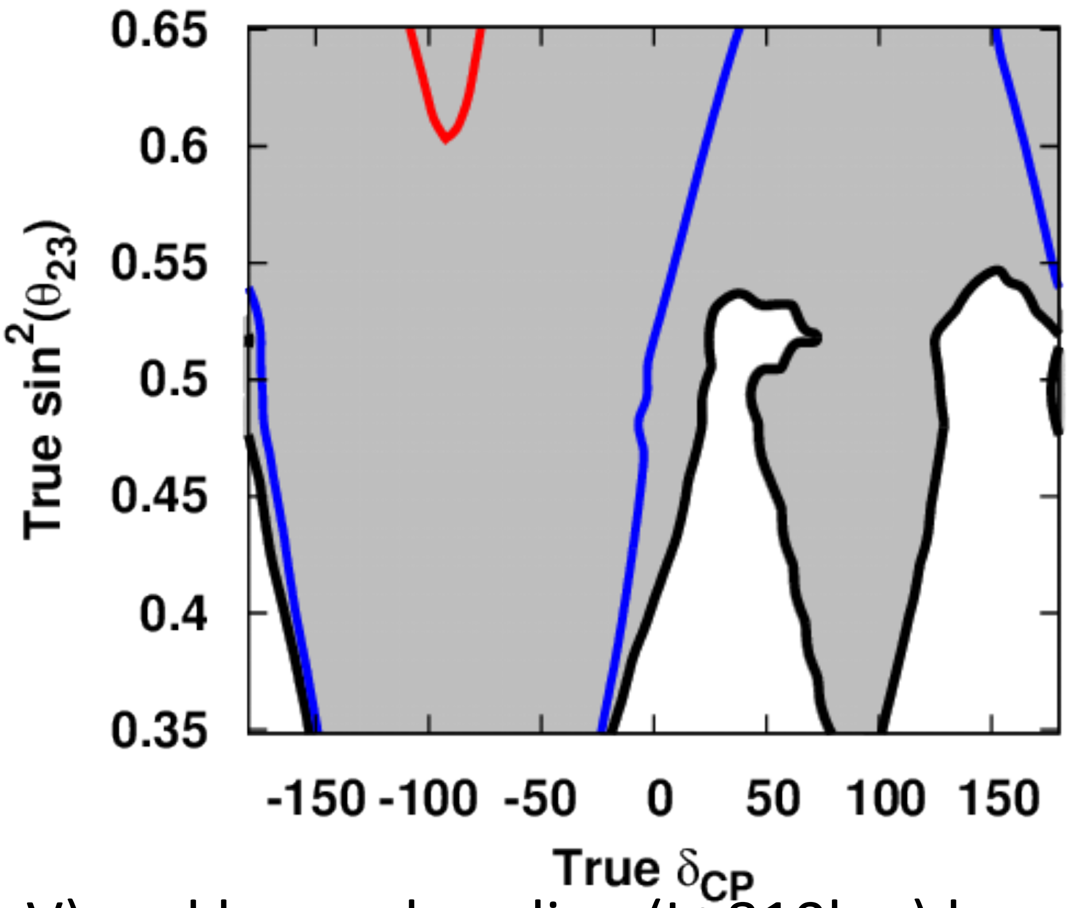
Discovery of CC ν_e appearance is the first step towards searches of CP violation in the lepton sector

World's best constraint on θ_{23} from ν_μ disappearance

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

What will we learn from T2K/NOvA?





NOvA's higher energy (peak E_ν~2 GeV) and longer baseline (L~810km) has a different dependence on mass hierarchy than T2K through the matter effect

- Left: Increased sensitivity to value of δ_{CP}, with for fixed values of θ_{13}, θ_{23} and with (dashed) and without (solid) systematic uncertainties applied
- Right: Gray regions are where the mass hierarchy can be determined to 90% CL for T2K(red), NOvA (blue), and T2K+NOvA (black)

What is needed to measure δ_{CP}?

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

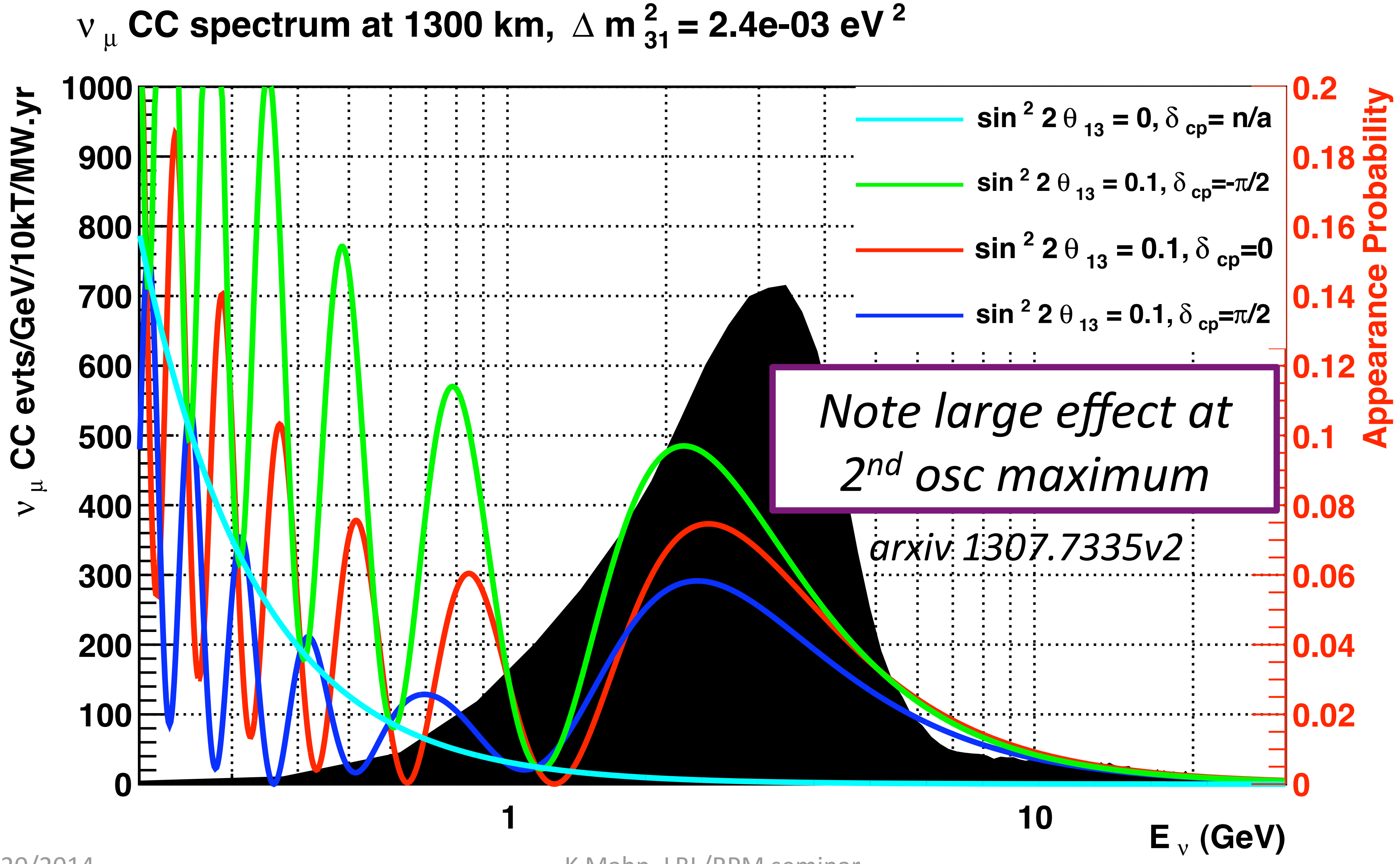
$$A_{CP} = \frac{P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}{P(\nu_\mu \rightarrow \nu_e) + P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)} \simeq \frac{\Delta m^2_{12} L}{4E_\nu} \cdot \frac{\sin 2\theta_{12}}{\sin\theta_{13}} \cdot \sin\delta$$

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

- T2K's current statistics: 28 events (ν_e appearance probability)
- Need more raw event rate, with a larger detector and/or intense beam

Long Baseline Neutrino Experiment

- Wide band (on-axis) beam can be used to see energy dependence of oscillation
- 1300km distance (Fermilab to South Dakota) for mass hierarchy, δ_{CP} physics
- Goal: 1% signal uncertainties / 5% background uncertainties
- Other LBL experiments, like Hyper-Kamiokande, assume similar uncertainties

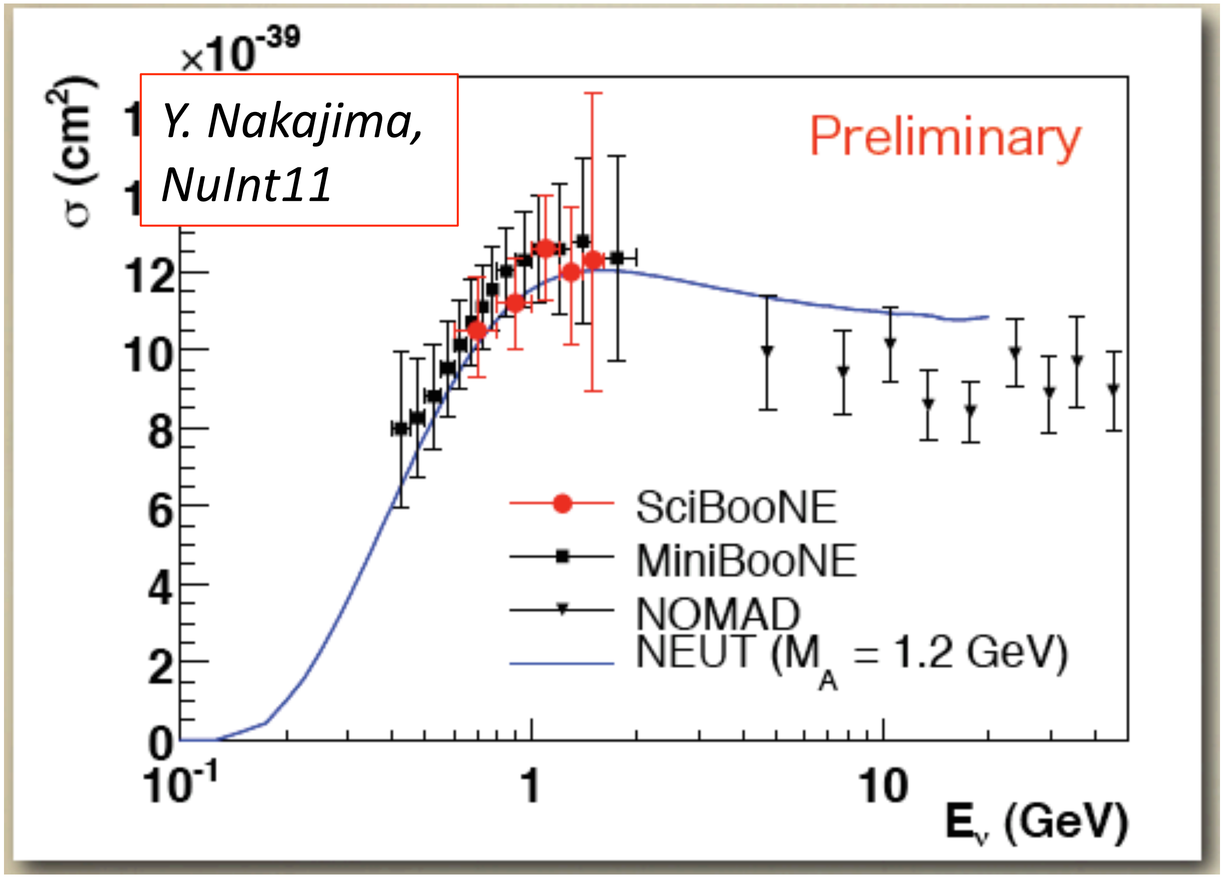


Note large effect at 2^{nd} osc maximum

arxiv 1307.7335v2

How do we achieve <5% systematics?

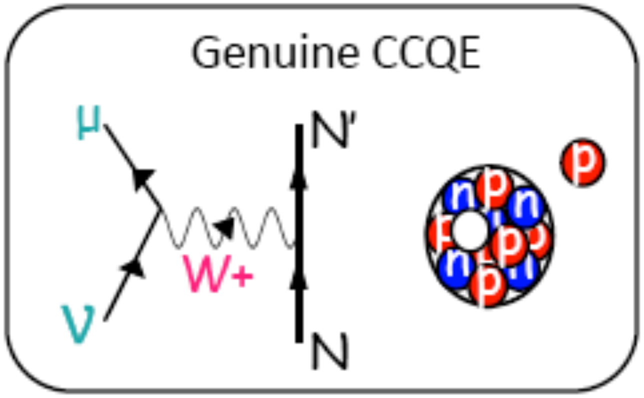
Uncertainties	ν_e sig+bkrd
ν flux+xsec (constrained by ND280)	±3.0%
ν xsec (unconstrained by ND280)	±7.5%
Far detector	±3.5%
Total	±8.8%

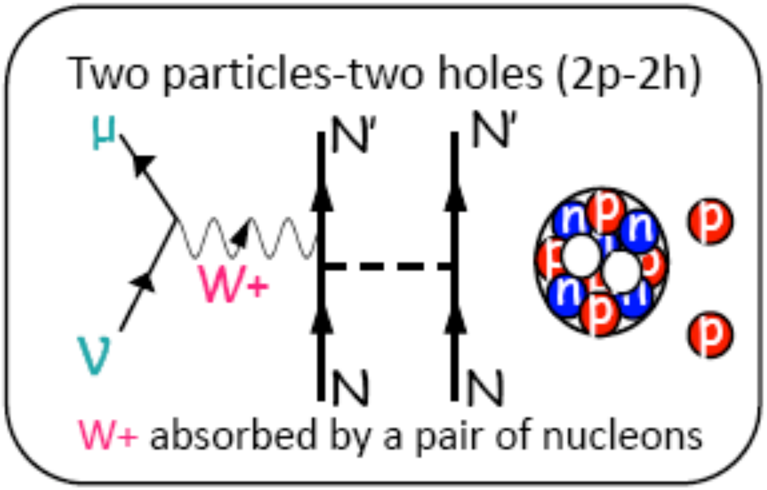

Y. Nakajima, NuInt11

The largest systematic uncertainties currently on the T2K oscillation analyses are from uncertainties on the CCQE, CC1π neutrino interaction models

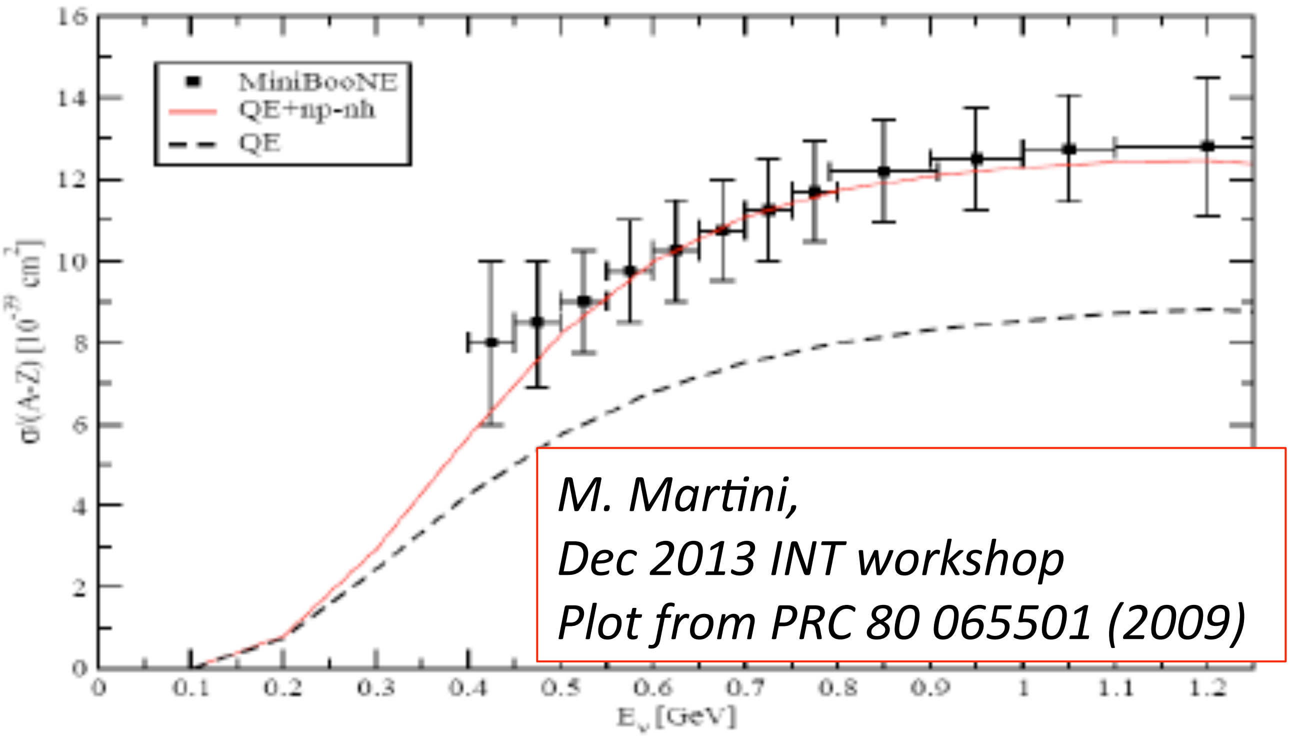
- Disagreements between models and existing neutrino experiment data (e.g. MiniBooNE, SciBooNE)
- Differences between new theoretical models and those currently used by T2K

CCQE and multinucleon interactions


Genuine CCQE


Two particles-two holes (2p-2h)

W+ absorbed by a pair of nucleons

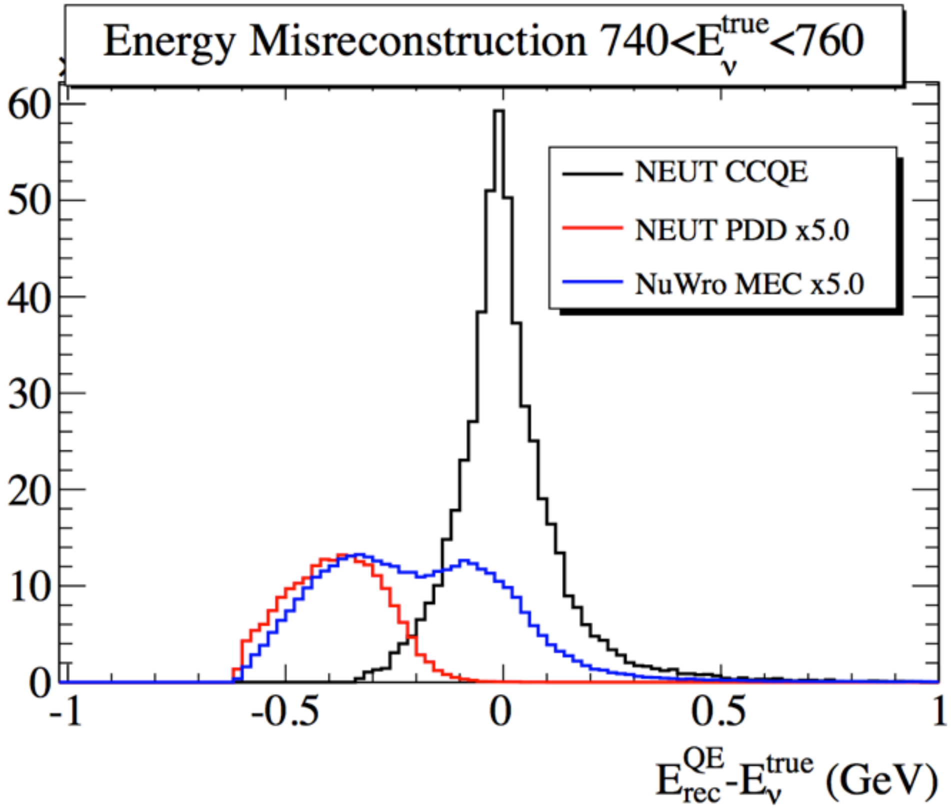


M. Martini,
Dec 2013 INT workshop
Plot from PRC 80 065501 (2009)

"Multinucleon" processes may explain the enhanced CCQE cross section observed by MiniBooNE, SciBooNE experiments

- Effort to include multinucleon models into neutrino generators used by T2K (NEUT)
  - Currently working with Nieves et al model (PRC 70, 055503 (2004)) combined with Sobczyk multinucleon ejection model (PRC 86, 015504 (2012))
  - Further details at recent Dec 2013 INT workshop: http://www.int.washington.edu/talks/WorkShops/int_13_54W/

Multinucleon processes and T2K



Toy samples generated at Δm^2_{32} =2.46 x 10^{-3} eV^2, $\sin^2\theta_{23}$=0.514 (maximal)

Par	Bias	RMS	Run 1-3 data fit errors
$\sin^2\theta_{23}$	0.0012 (0.3%)	0.016 (3.6%)	±0.082
Δm^2_{32} (x10^{-3} eV^2)	-0.005 (-0.2%)	0.014 (0.6%)	+0.17-0.15

IC: Understand the potential effect of multinucleon processes on the osc analysis

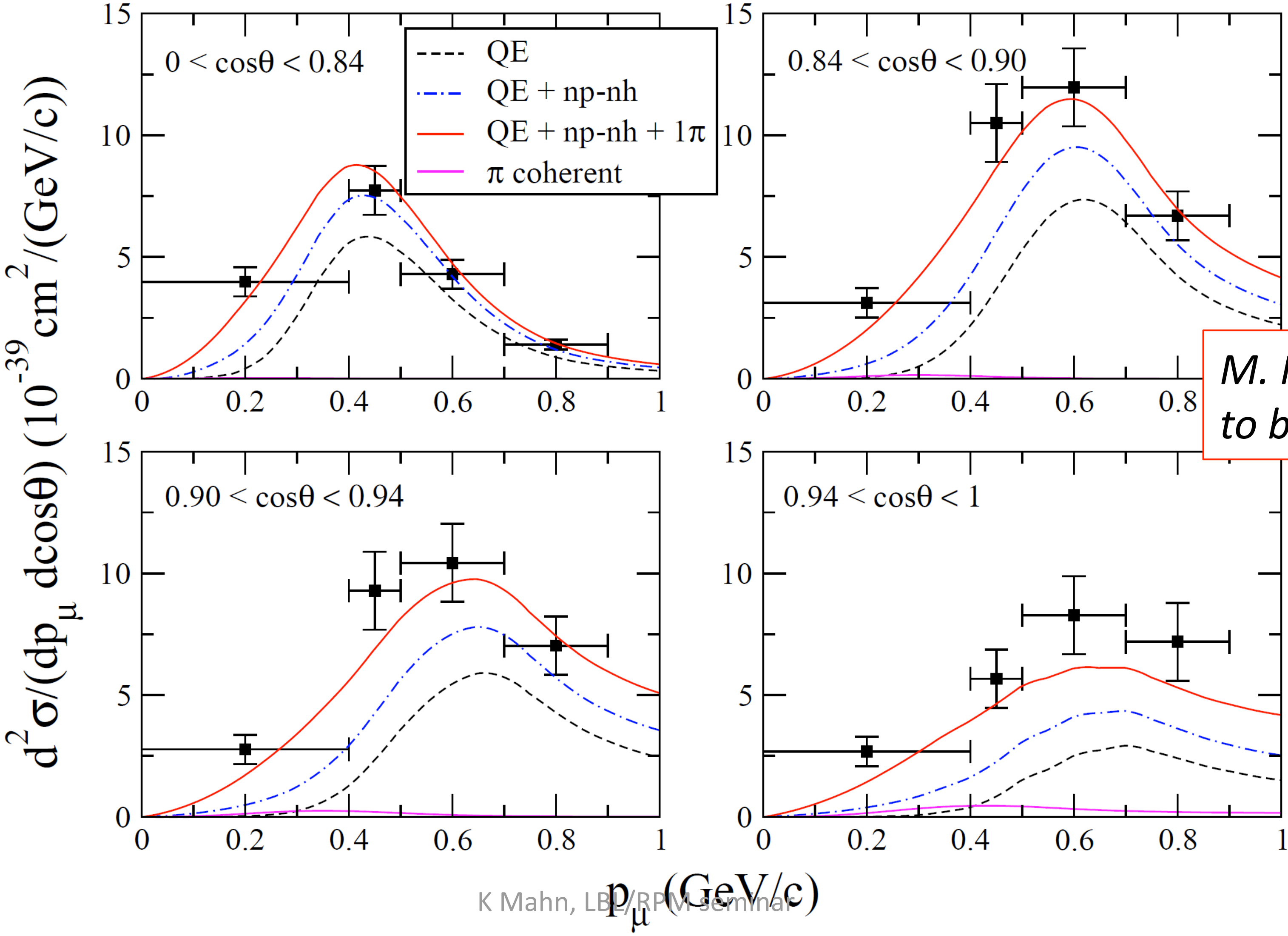
- Multinucleon processes create a shift between true and reconstructed E_ν, similar to CC1π, especially (already simulated) pionless delta decay ("PDD")
  - PDD is a dominant uncertainty (6.2%) on the overall CCQE ν_μ event rate at SK
- Uses simulated events at near detector and full near to far extrapolation machinery and oscillation fit.
  - Includes ND280 rate constraint and different true/reconstructed Enu association
  - Still limited (only 1 model, proton FSI not simulated at SK, etc)

T2K efforts to understand neutrino interactions

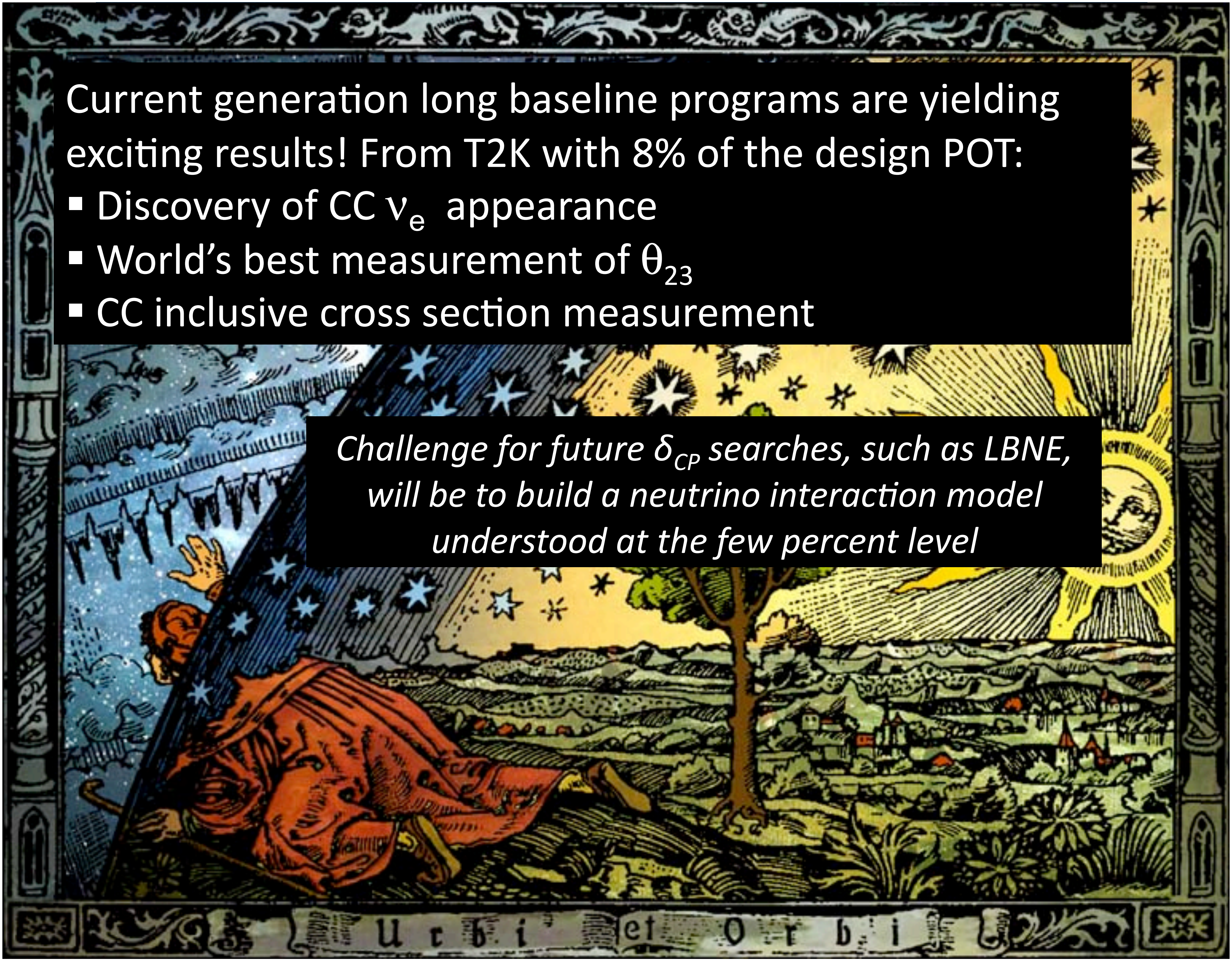
IC, L: Test the agreement of new models with ND280, as ND280-XSEC co-convener:

- Provide measurements of inclusive, exclusive CC cross sections
- Direct (final state) and indirect (below) information about multinucleon processes

Produced T2K's first xsec measurement:
CC inclusive double differential cross section [PRD 87, 092003 (2013)]



M. Martini,
to be submitted



Current generation long baseline programs are yielding exciting results! From T2K with 8% of the design POT:

- Discovery of CC ν_e appearance
- World's best measurement of θ_{23}
- CC inclusive cross section measurement

Challenge for future δ_{CP} searches, such as LBNE, will be to build a neutrino interaction model understood at the few percent level