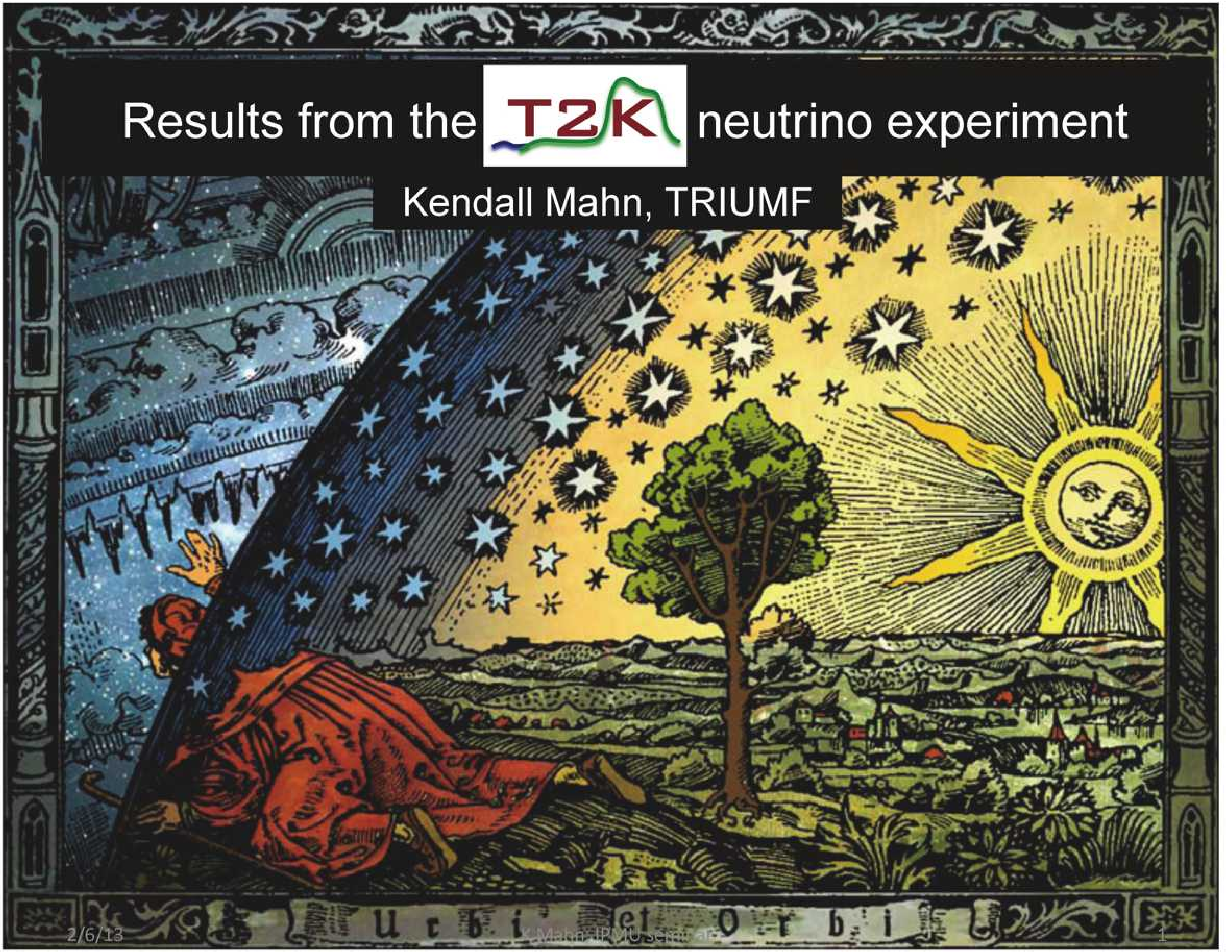
Results from the T2K neutrino experiment

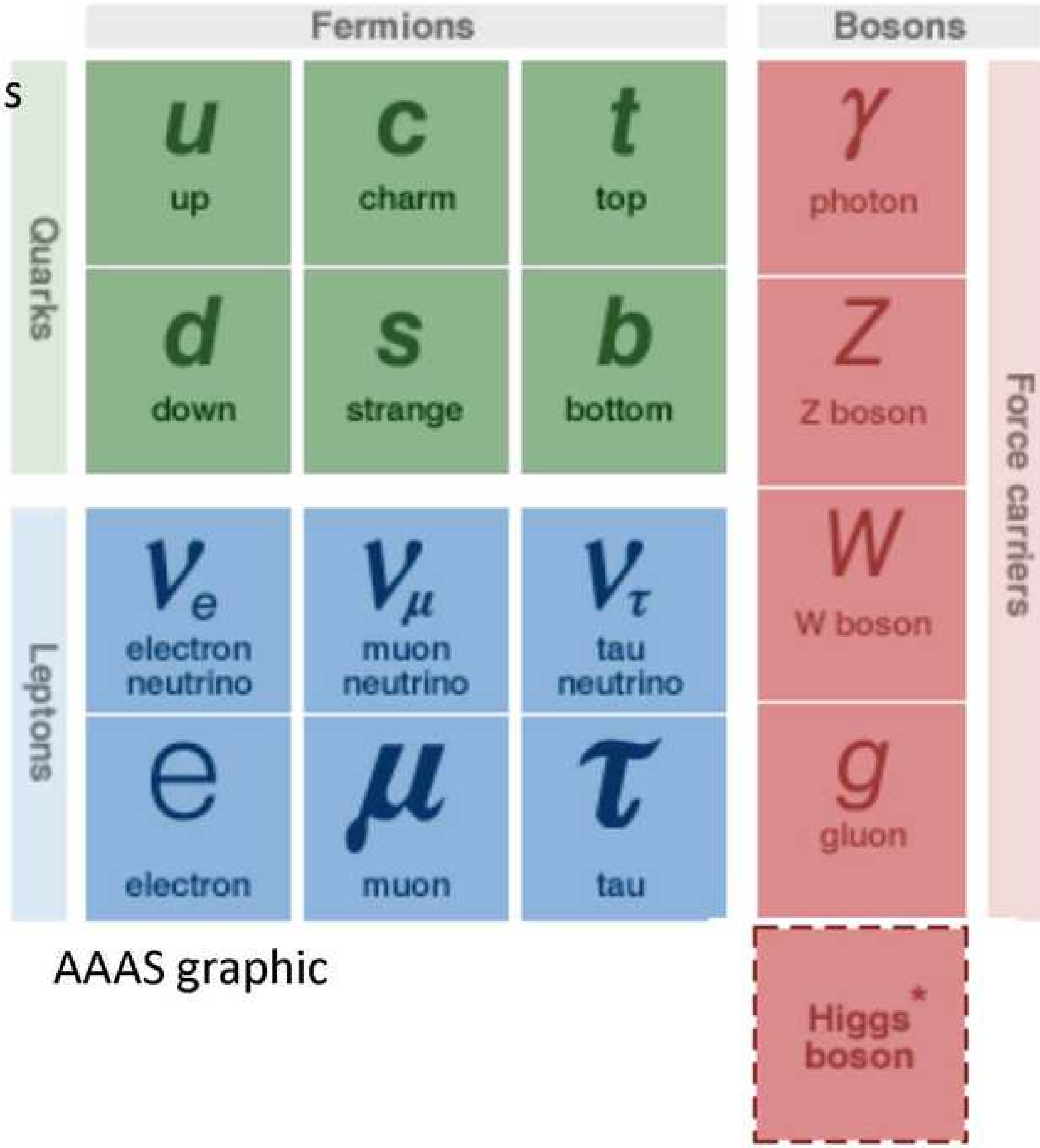
Kendall Mahn, TRIUMF



The Standard Model

Protons, neutrons

Photons



Electrons

Protons, neutrons

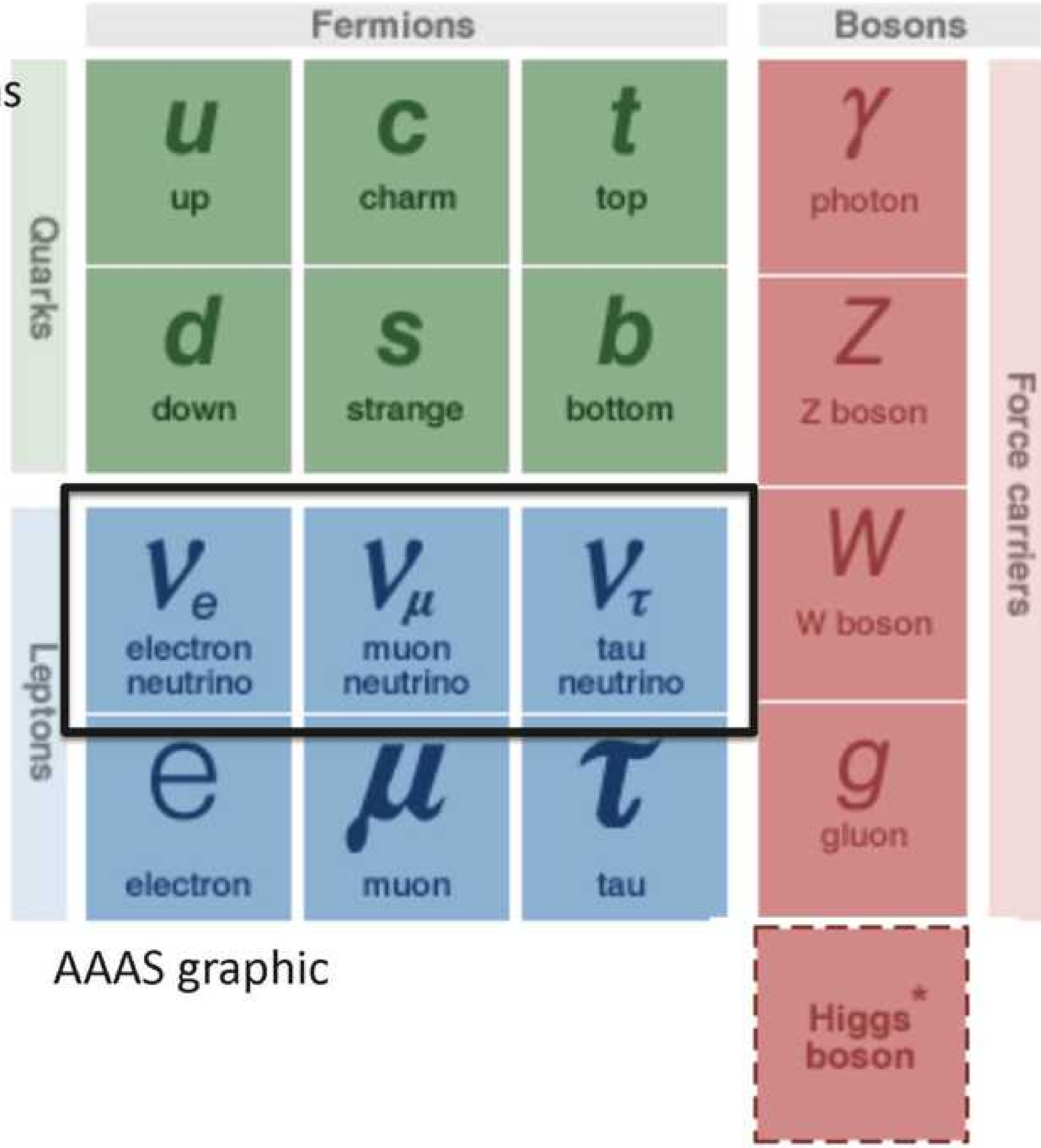
AAAS graphic

The Standard Model

Protons, neutrons

Neutrinos!

Electrons



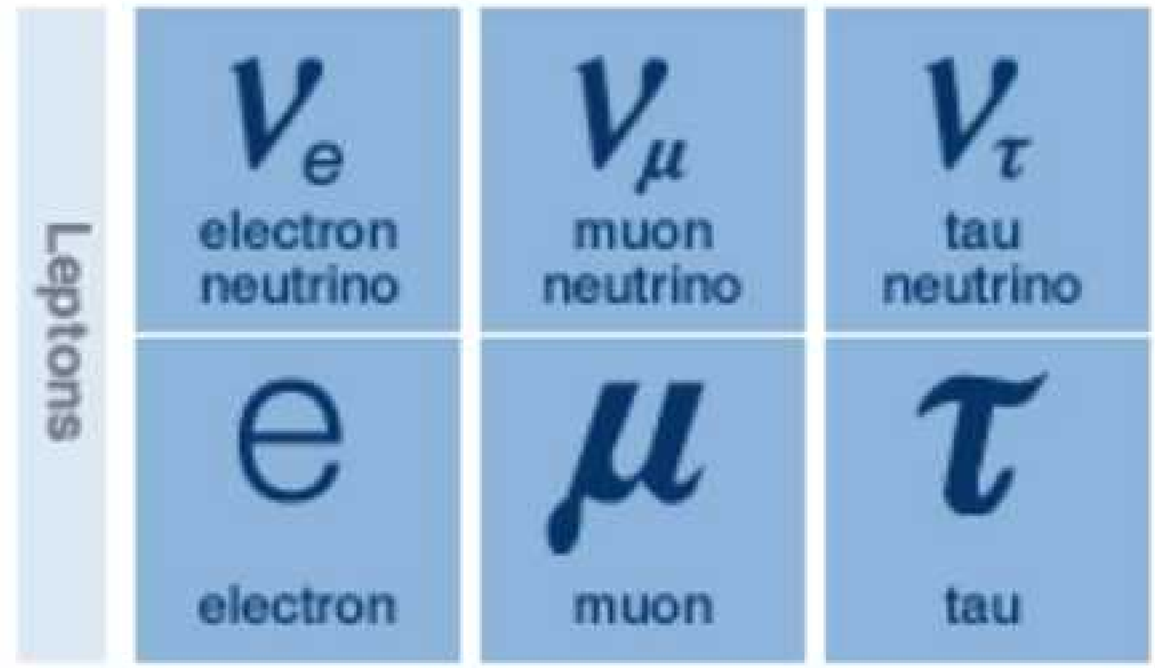
Photons

Protons, neutrons

AAAS graphic

What we now know about neutrinos

- Three flavors: ν_e, ν_μ, ν_τ



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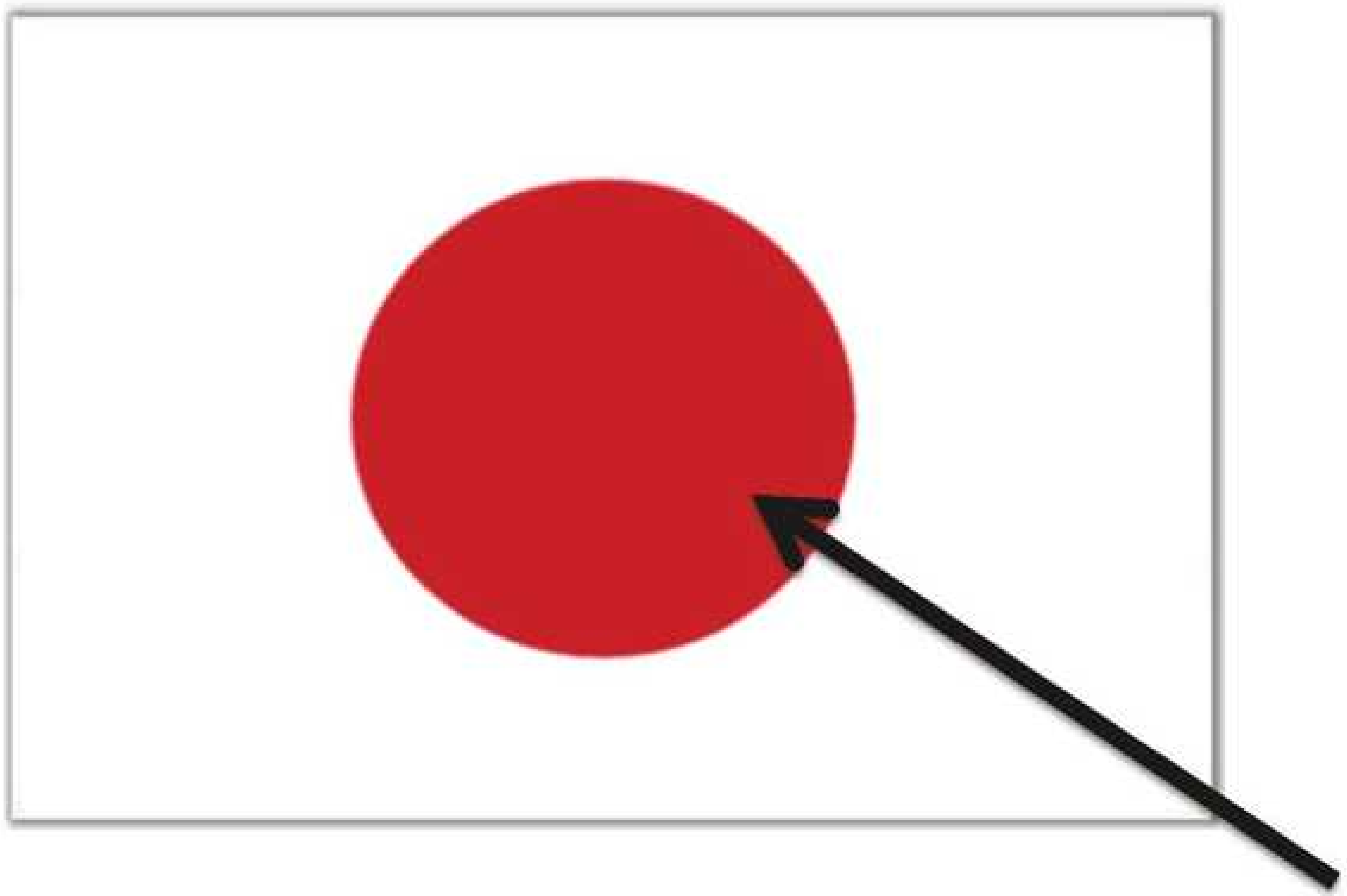
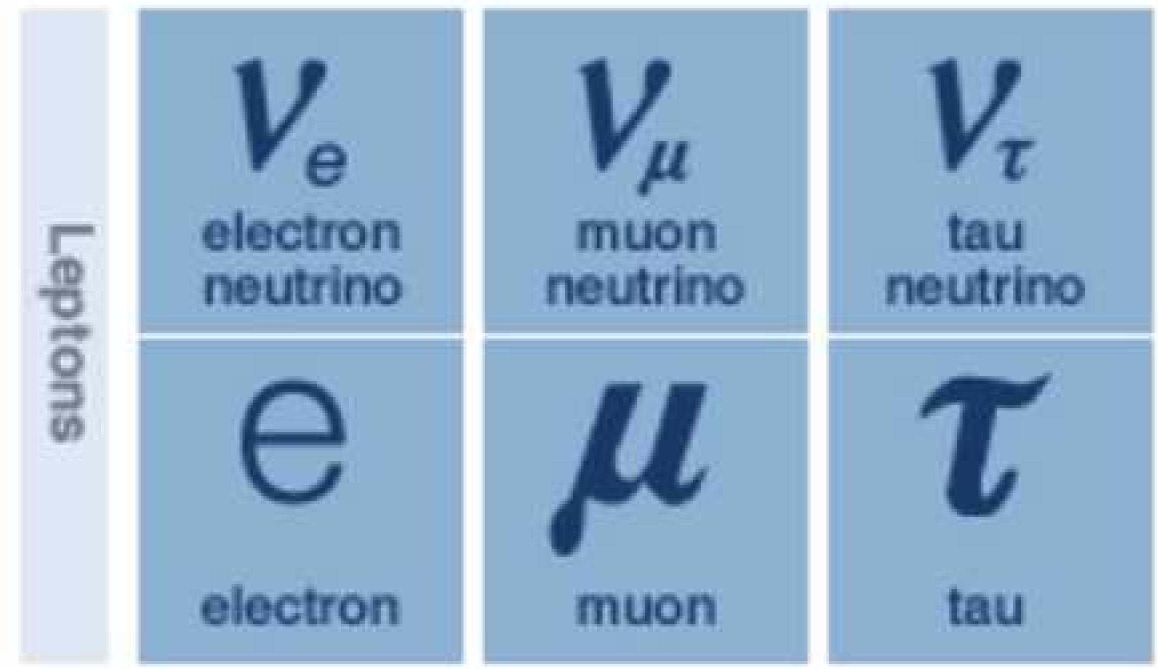
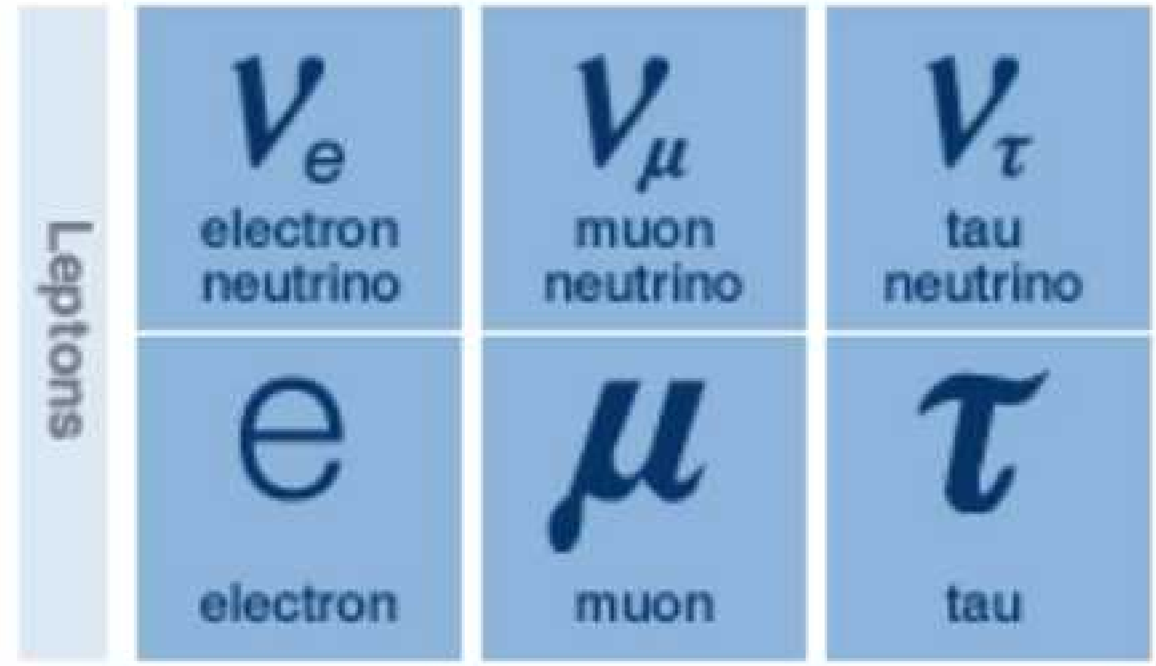




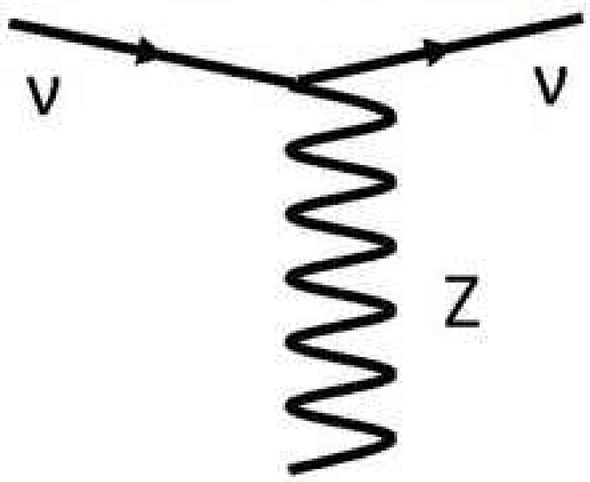
This is an electron neutrino

What we now know about neutrinos

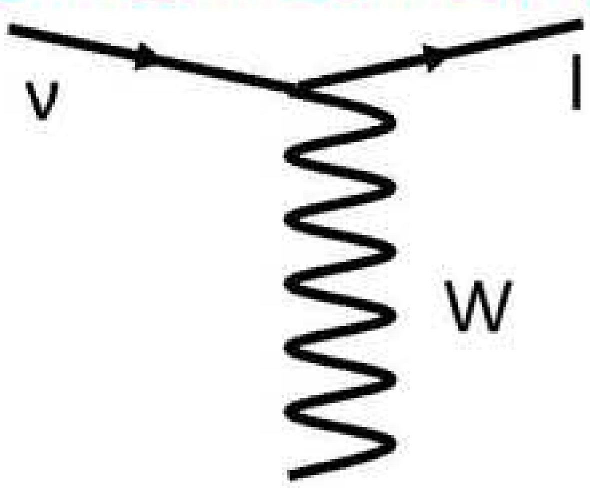
- Three flavors: ν_e, ν_μ, ν_τ
- Neutral
- Interact via the weak force



Neutral Current (NC)



Charged Current (CC)



$$\nu_e \rightarrow e$$
$$\nu_\mu \rightarrow \mu$$
$$\nu_\tau \rightarrow \tau$$

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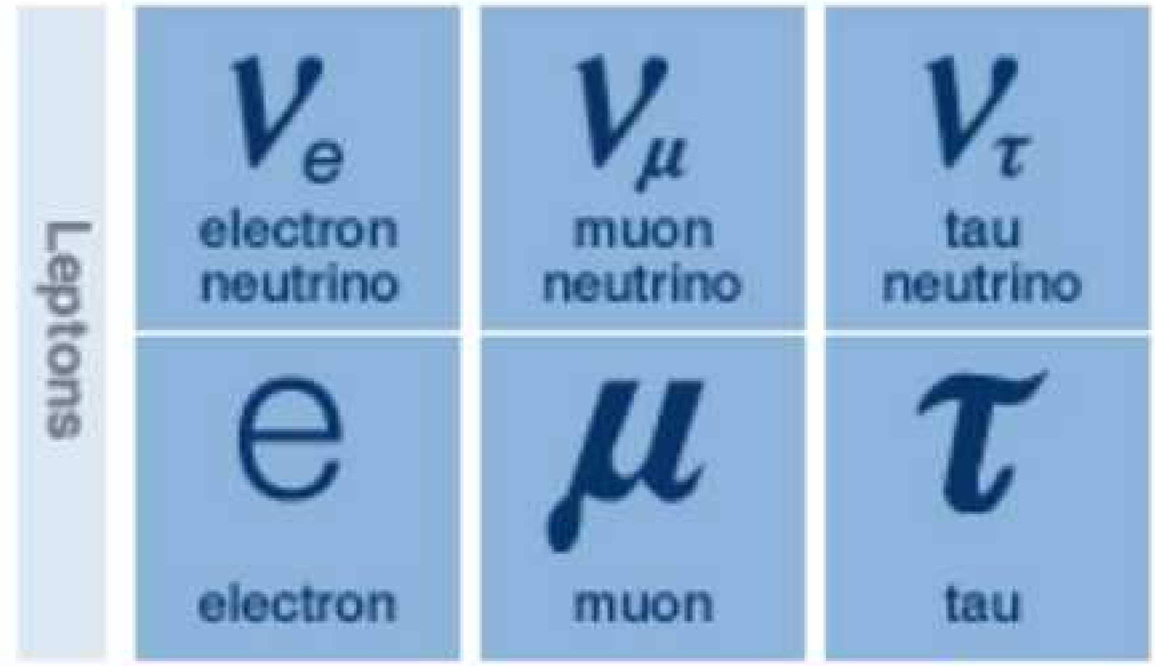
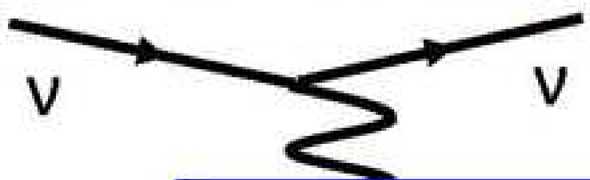


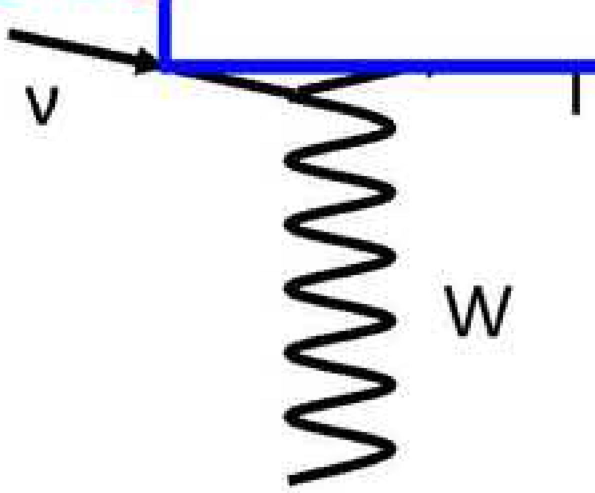
Neutral Current (NC)



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

Mean free path through lead is 1 light year

Charg



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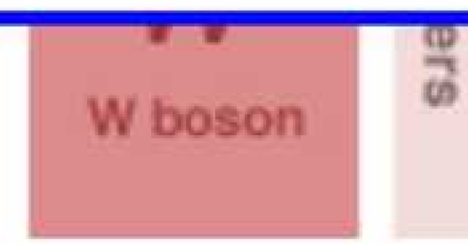

What we now know about neutrinos

- Three flavors: ν_e, ν_μ, ν_τ
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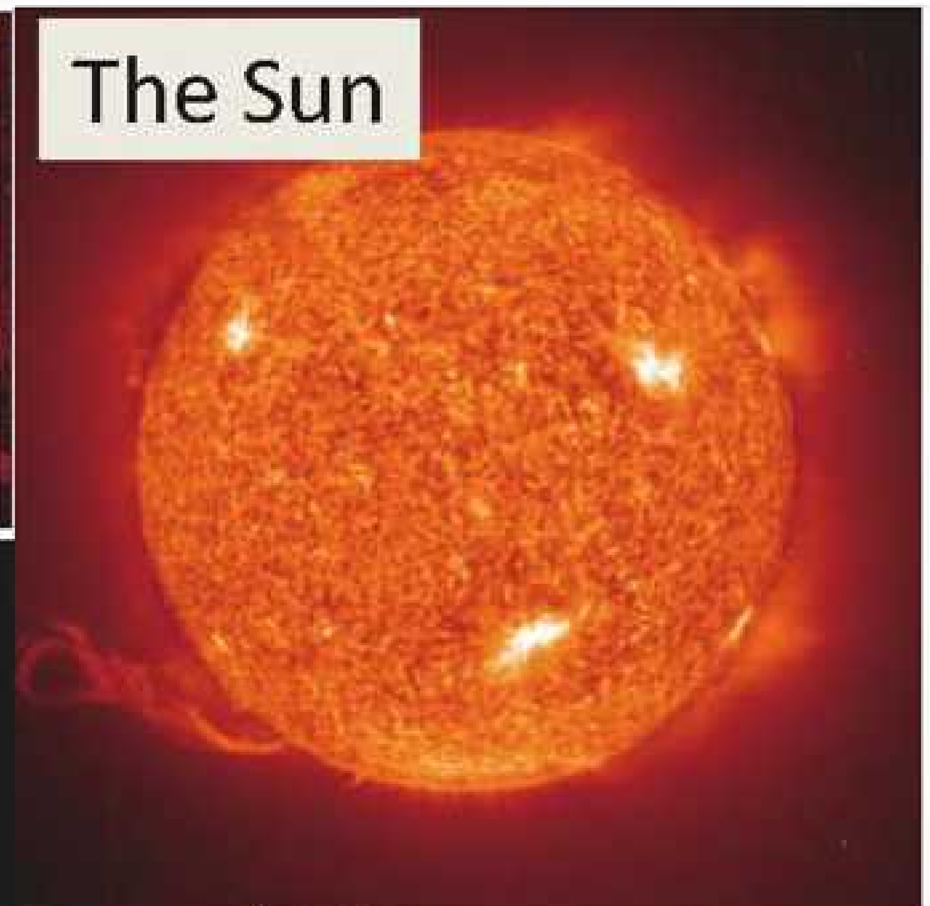

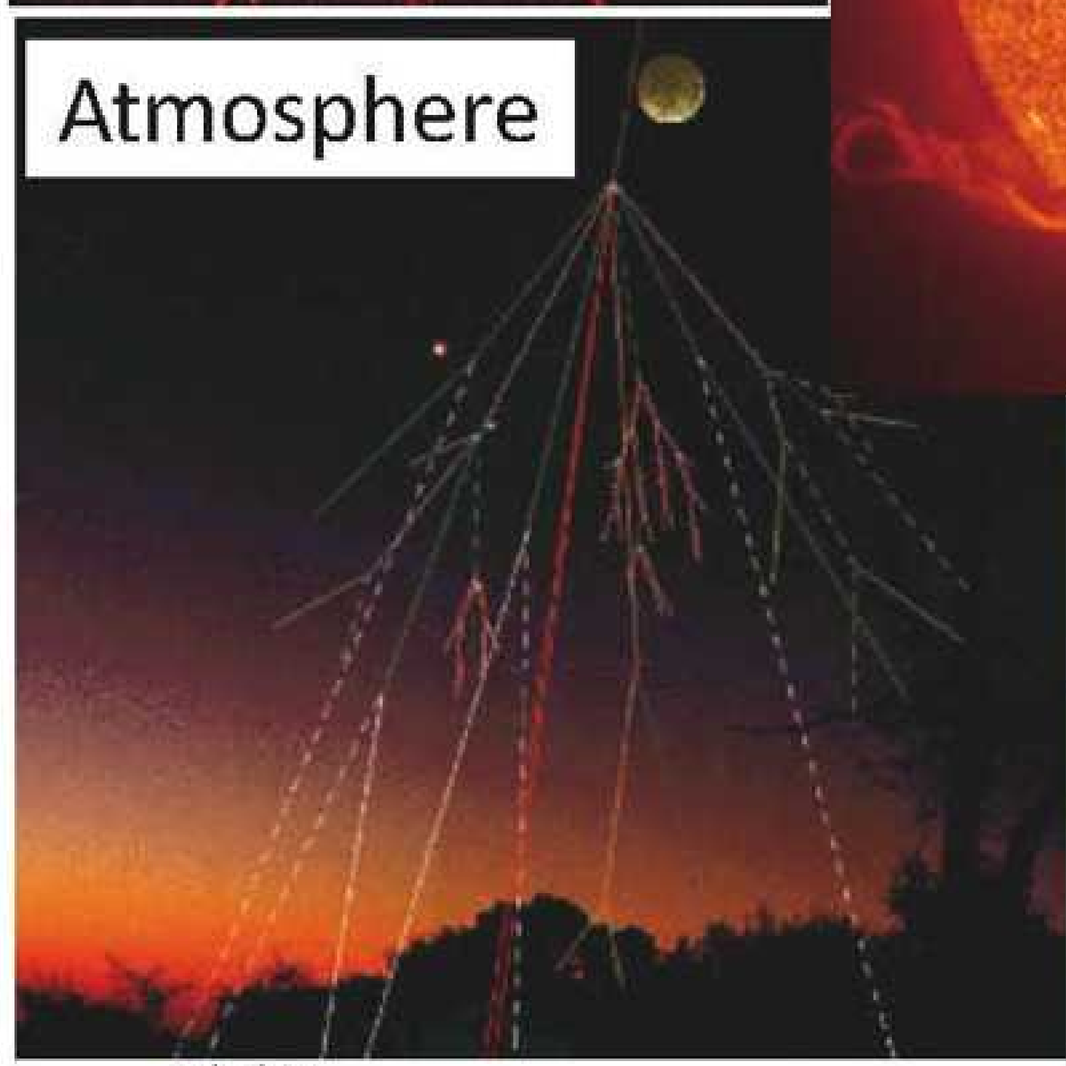

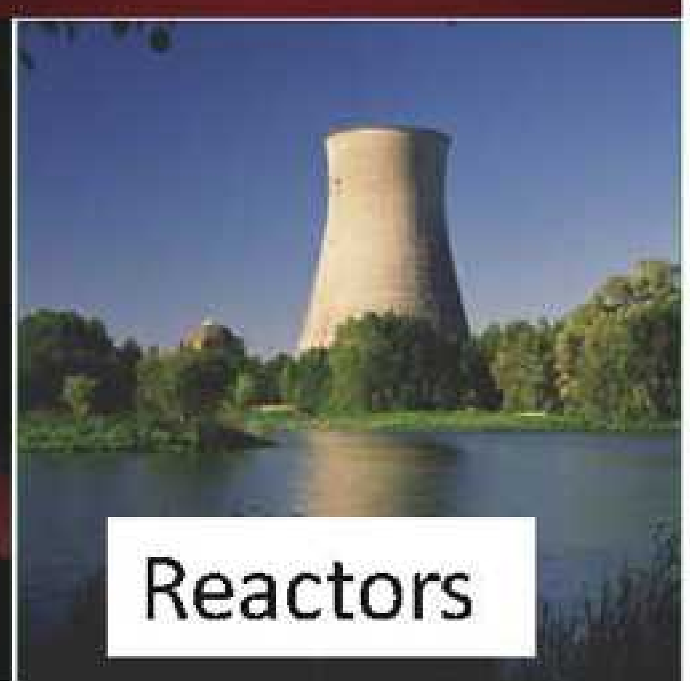

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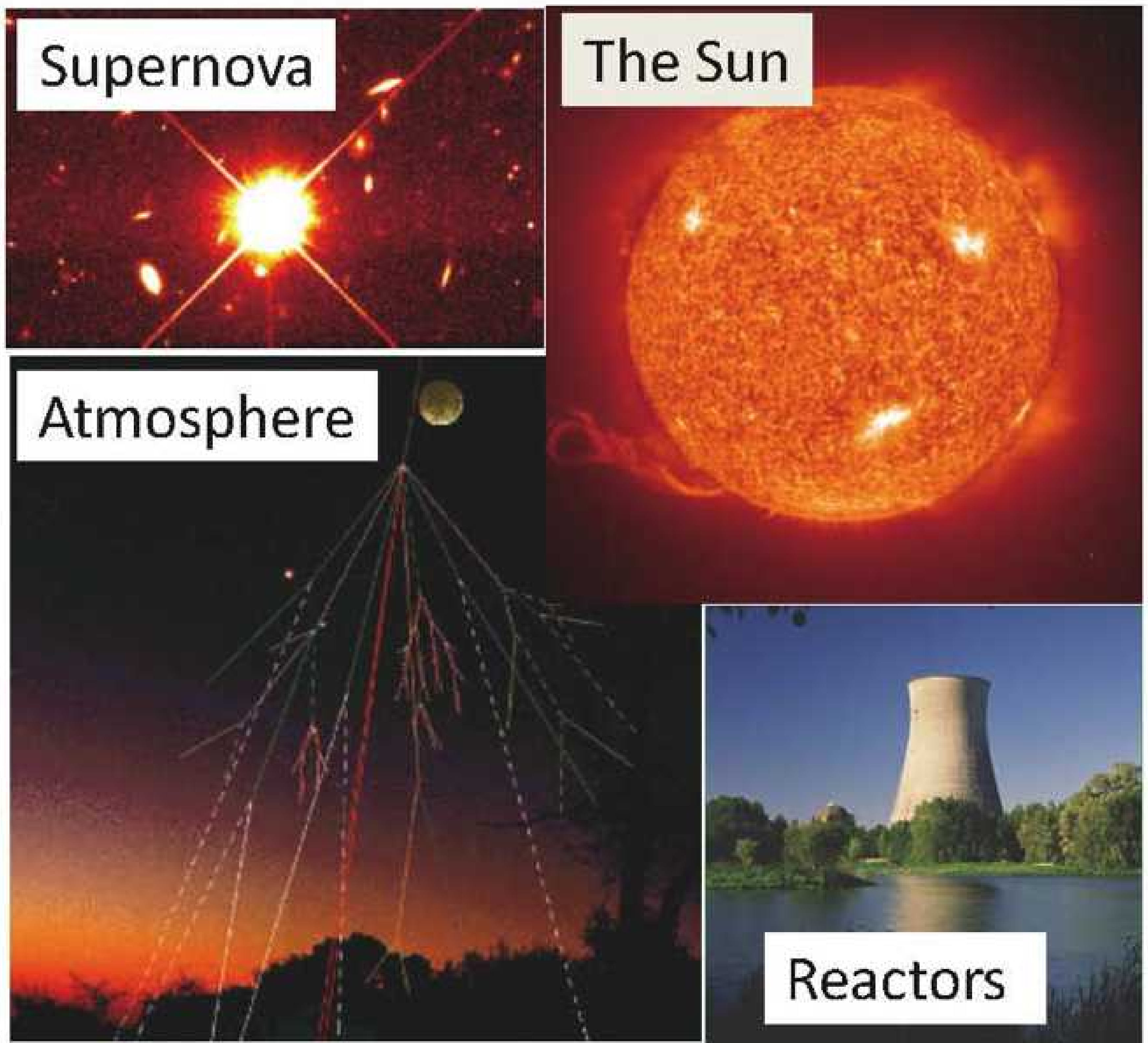
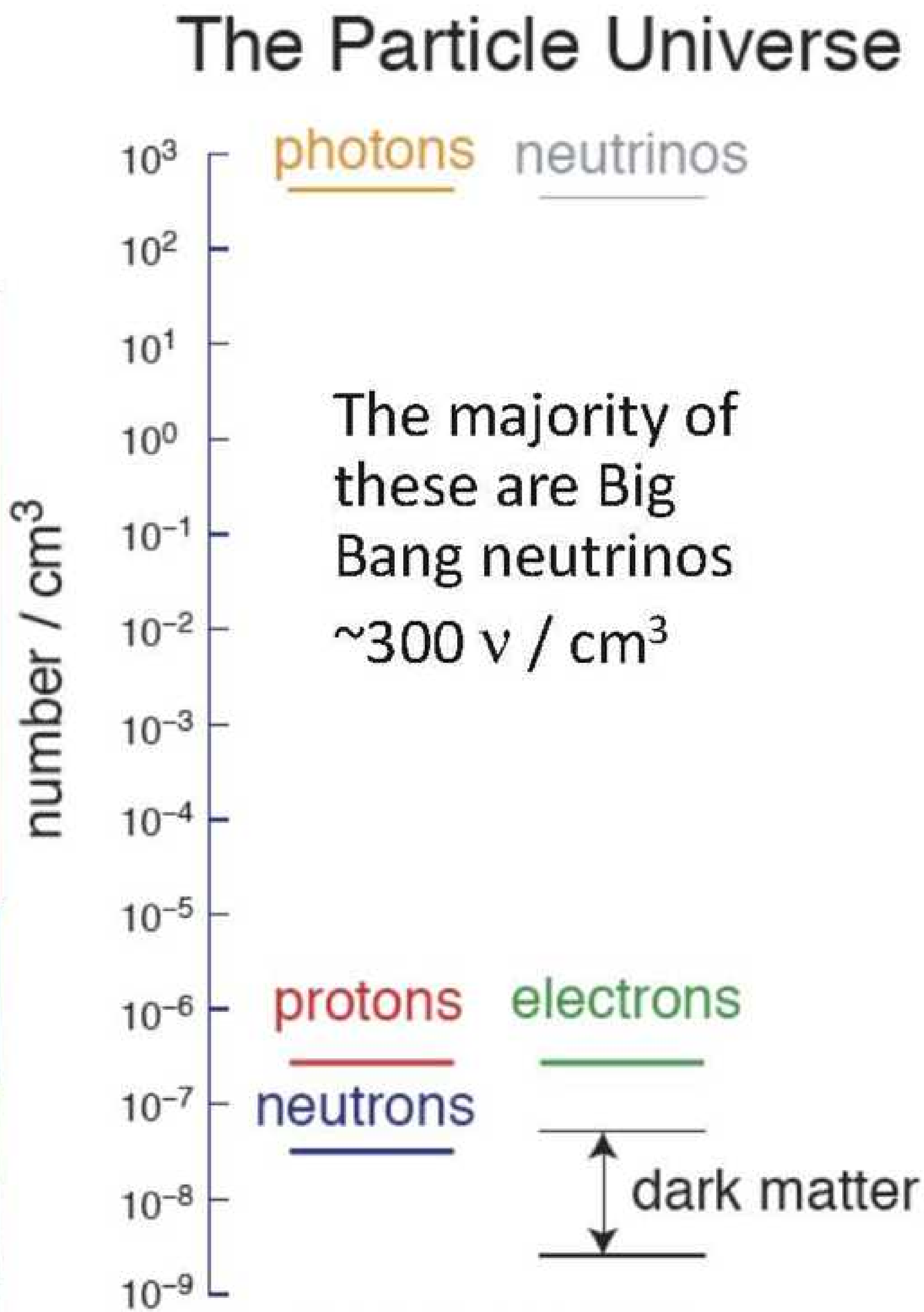




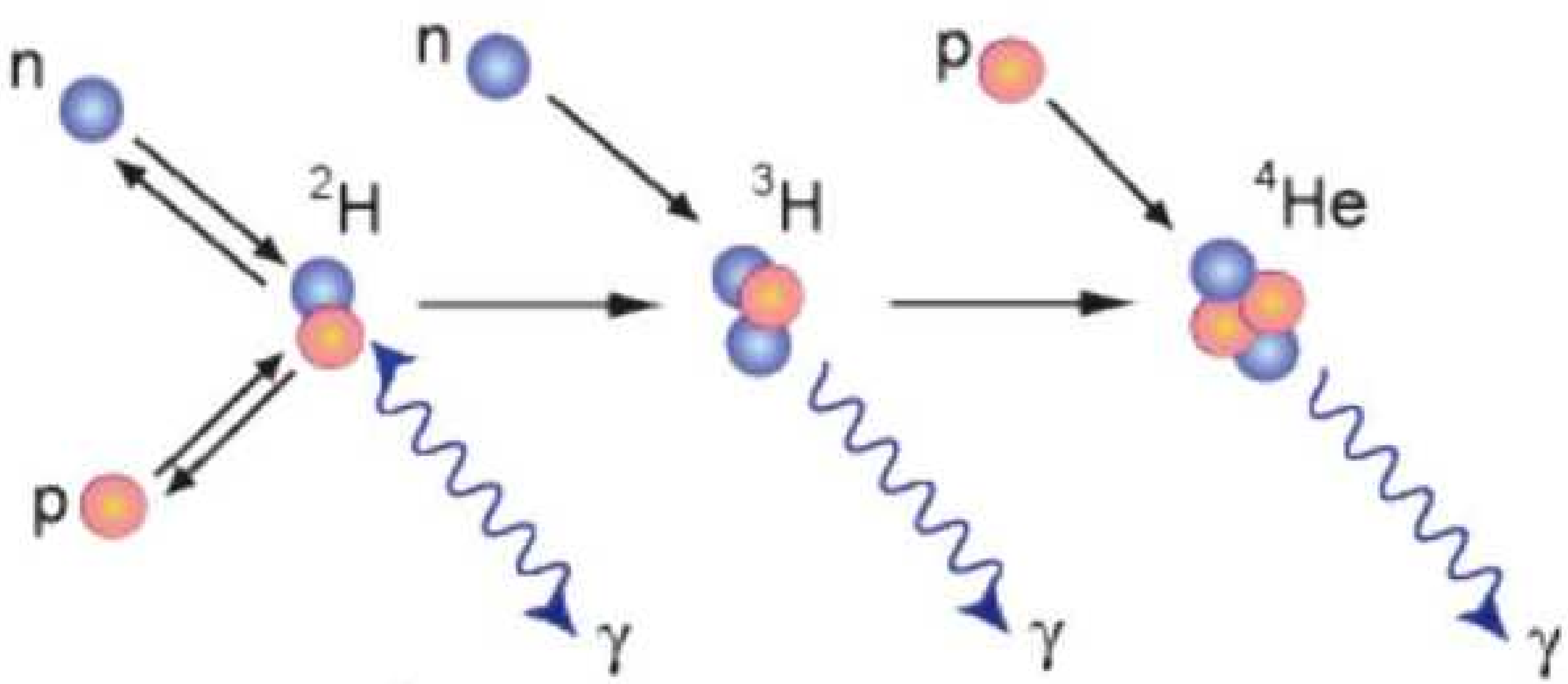
H. Murayama graphic

What we now know about neutrinos

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

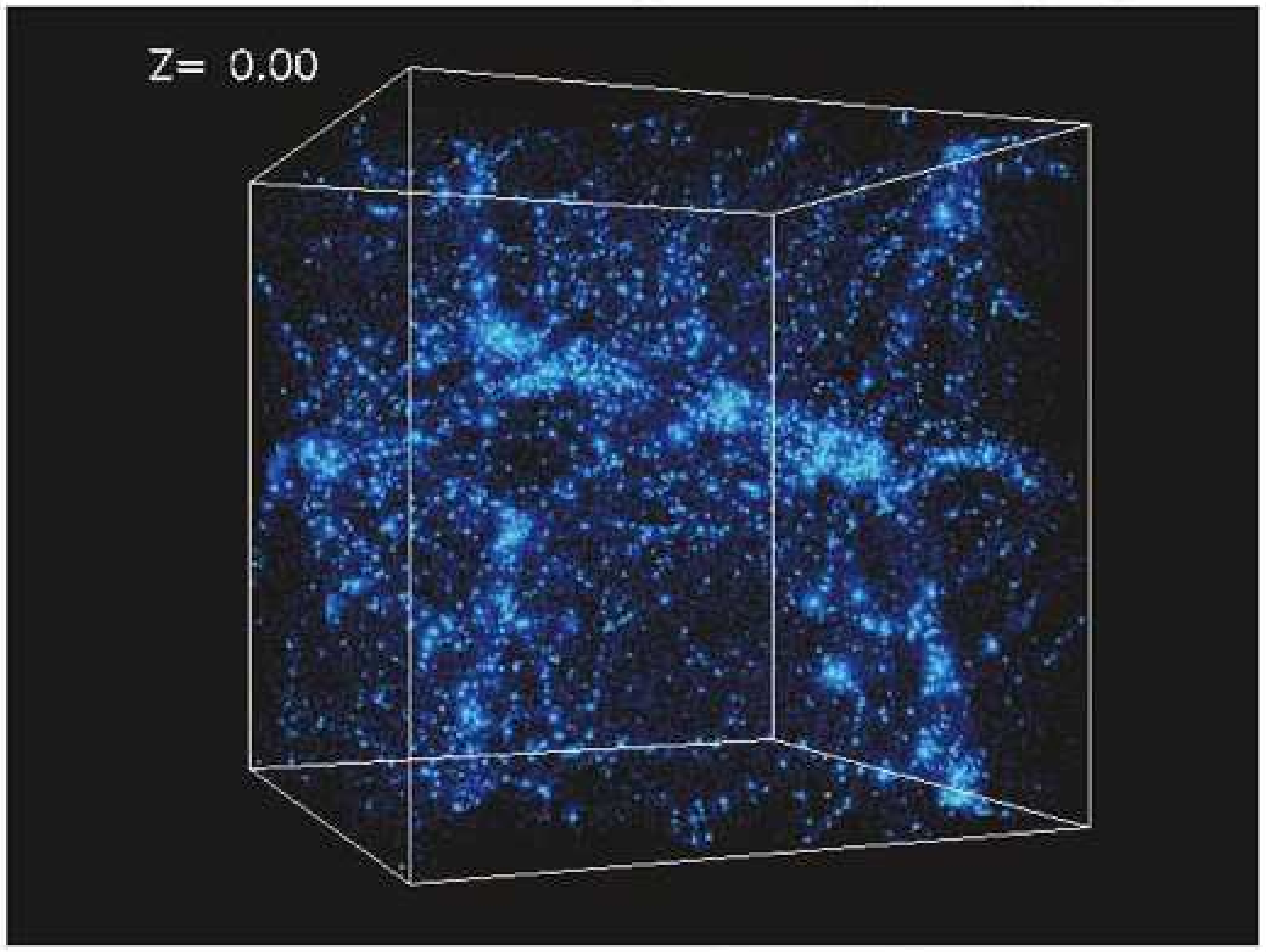
The mass of the neutrino is small but it has a big impact in the early universe

At early times, neutrinos behave like radiation
Impacts Big Bang nucleosynthesis



CSIRO graphic

Center for Cosmological Physics graphic



At late times, neutrinos behave like matter
Affects large scale structure formation

Neutrino mass

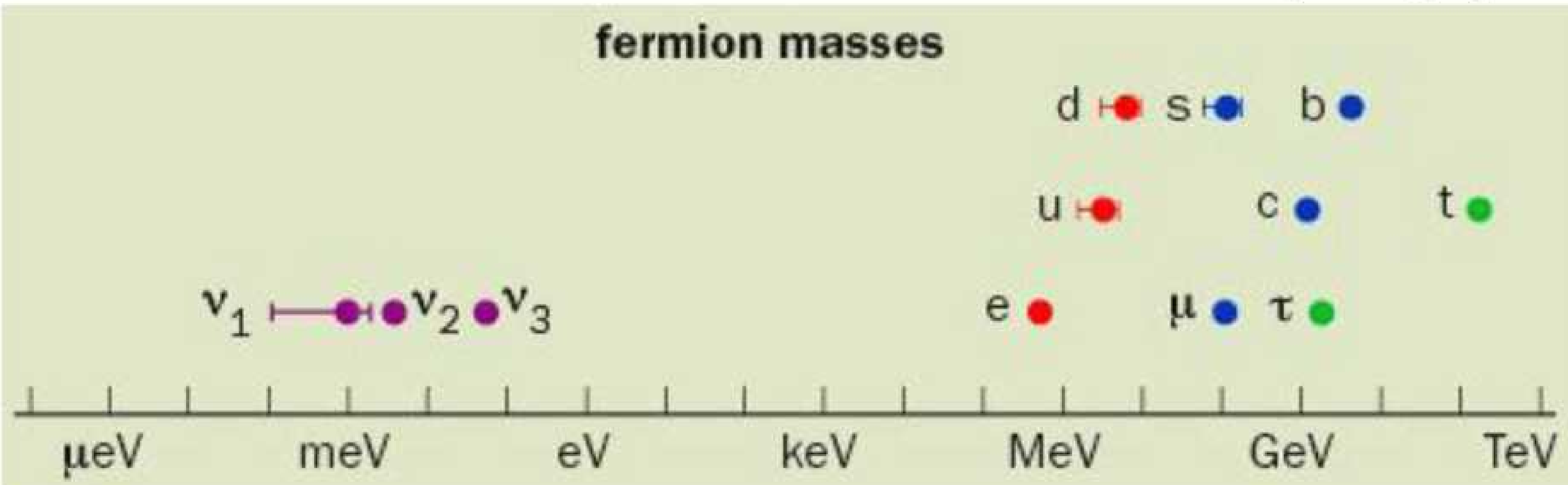
In the SM Lagrangian, charged leptons have Dirac mass terms which couple left and right chiral components:

$$-m_D(\overline{\nu}_L\nu_R + \overline{\nu}_R\nu_L)$$

However, neutrinos are massless in the SM

Neutrinos only interact with the ``left handed'' weak force

H. Murayama graphic



Why is neutrino mass non-zero?

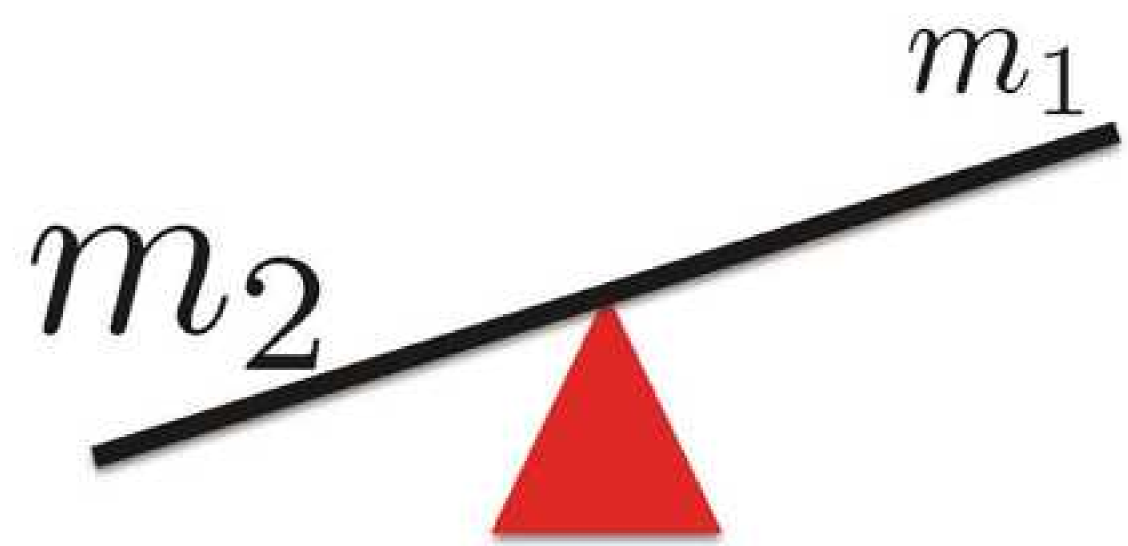
Why is it so much smaller than the other particles?

Neutrino mass

The "see saw mechanism" explains the lightness of the neutrino mass by adding a (very heavy) right-handed neutrino

If there is one left-handed neutrino, and a right-handed partner, and assuming neutrinos are Majorana particles (with a Majorana mass term) then we get:

$$m_1 \simeq \frac{(m_D)^2}{m_R} \ll m_D ,$$
$$m_2 \simeq m_R ,$$

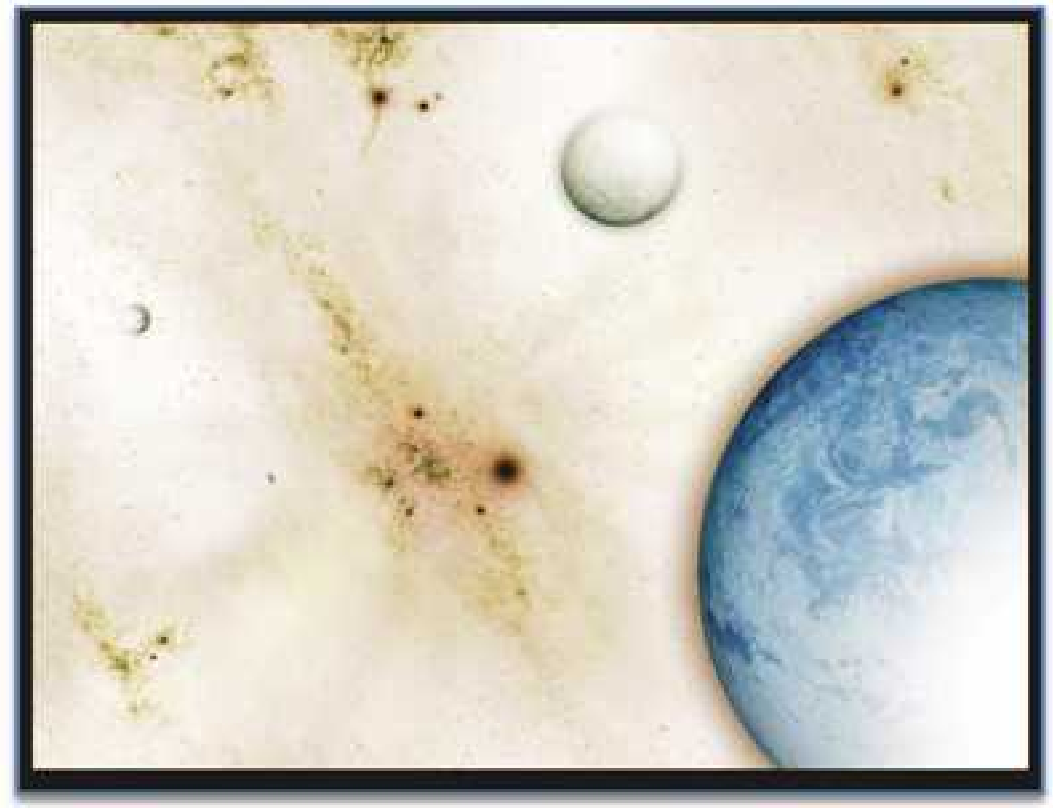


If $m_D \sim m_{top} \sim 100$ GeV, and $m_1 \sim m_\nu < 0.01$eV, then $m_2 \sim m_R \sim 10^{15}$ GeV

Neutrino mass may be related to a higher energy scale than we can otherwise study

Neutrinos and the matter-antimatter asymmetry

? ≠

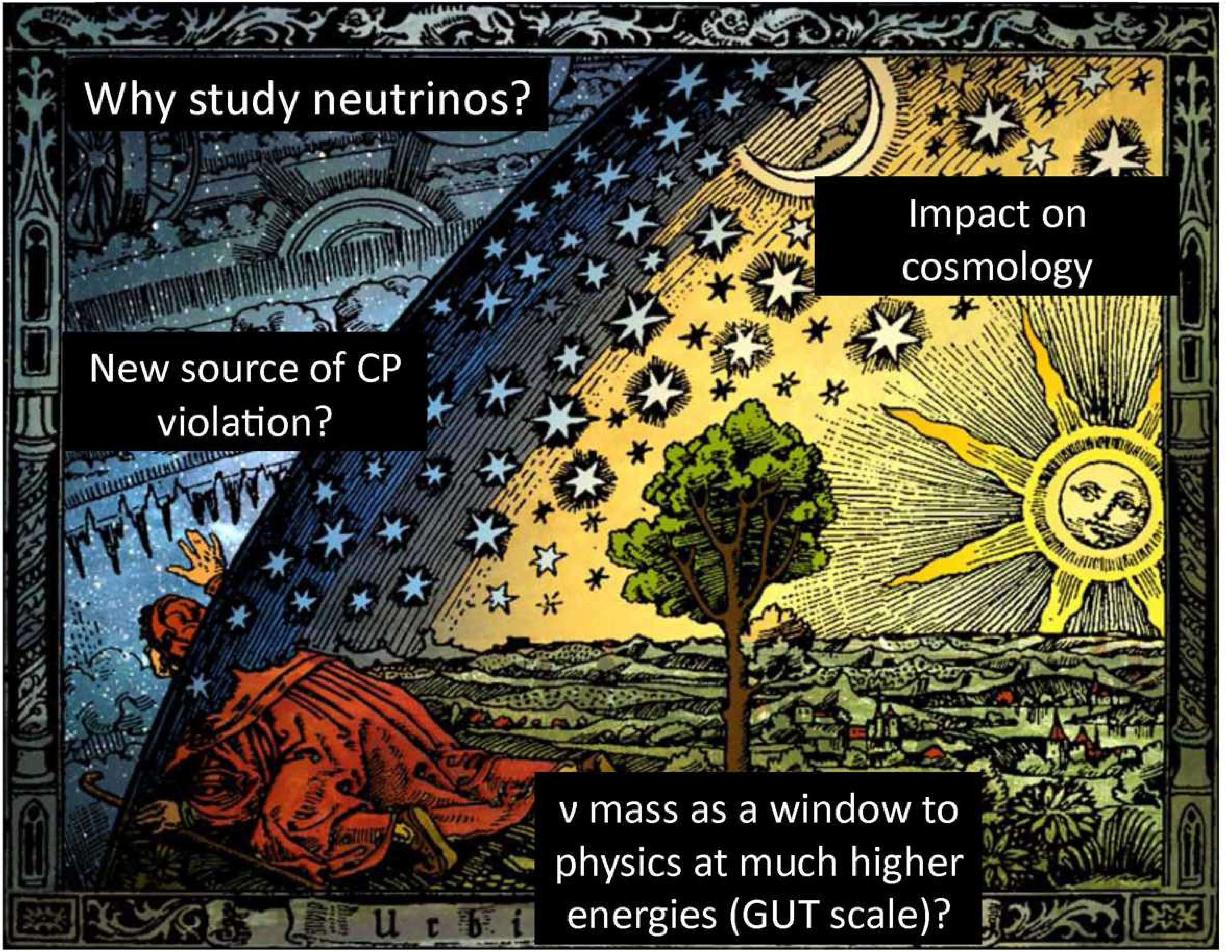


Neutrinos have mass, which is suggestive of a heavy, right handed neutrino, N_R

``Leptogenesis'': CP violation in the decay of N_R can create a lepton number asymmetry which can be converted to a baryon number asymmetry
M. Fukugita and T. Yanagida, Phys. Lett. B 174, 45 (1986)

For the matter-antimatter asymmetry to be generated, we require: non-thermal equilibrium, CP violation and baryon number violation
A.D. Sakharov, Pis'ma Zh. Eksp. Teor. Fiz. 5, 32 (1967) [JETP Lett. 5, 24 (1967)]

Studying CP violation with light neutrinos may lead to insights about CP violation of N_R


Why study neutrinos?
Impact on cosmology
New source of CP violation?
ν mass as a window to physics at much higher energies (GUT scale)?
Urbi

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

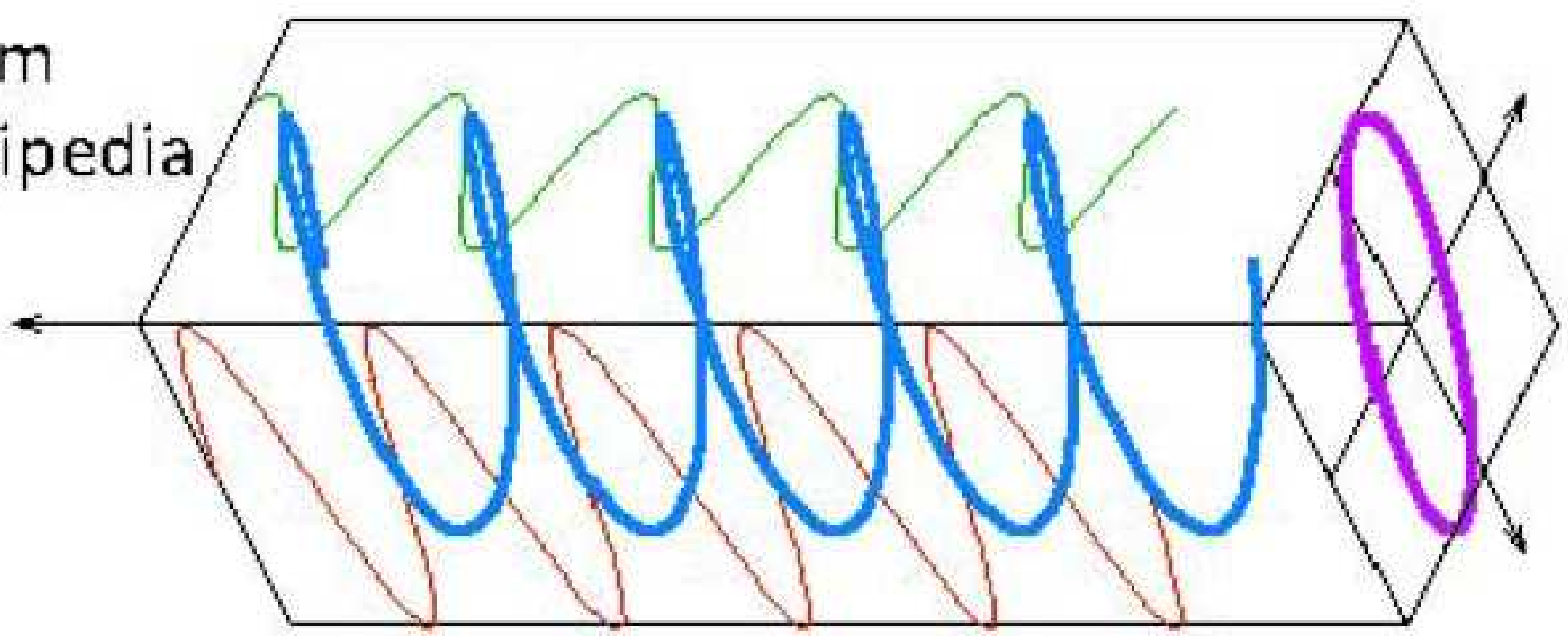
If we start with two neutrino flavor (ν_e, ν_μ) and two mass states (ν_1, ν_2) then:

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

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

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

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 mixing matrix

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

$c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$

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

$$\times\, diag(e^{\frac{i\alpha_1}{2}}, e^{\frac{i\alpha_2}{2}}, 1)$$

Potential Majorana phases do not contribute to neutrino oscillation probabilities

Neutrino oscillation

As the neutrinos propagate, the mass states interfere:

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

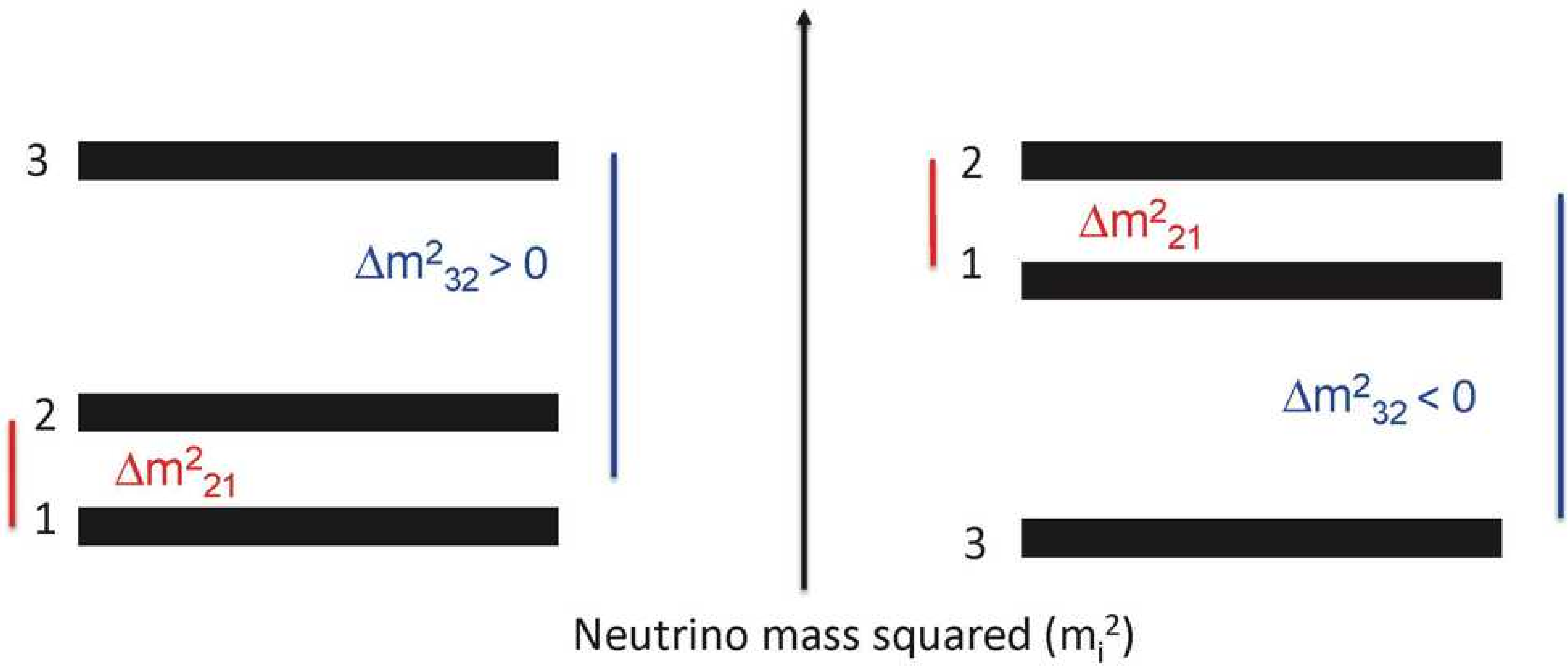
Probability to observe ν_β after starting in flavor state ν_α depends on:

- Mixing matrix $U_{\alpha i}$ (and mixing angles)
- 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

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

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

Current state of neutrino mixing



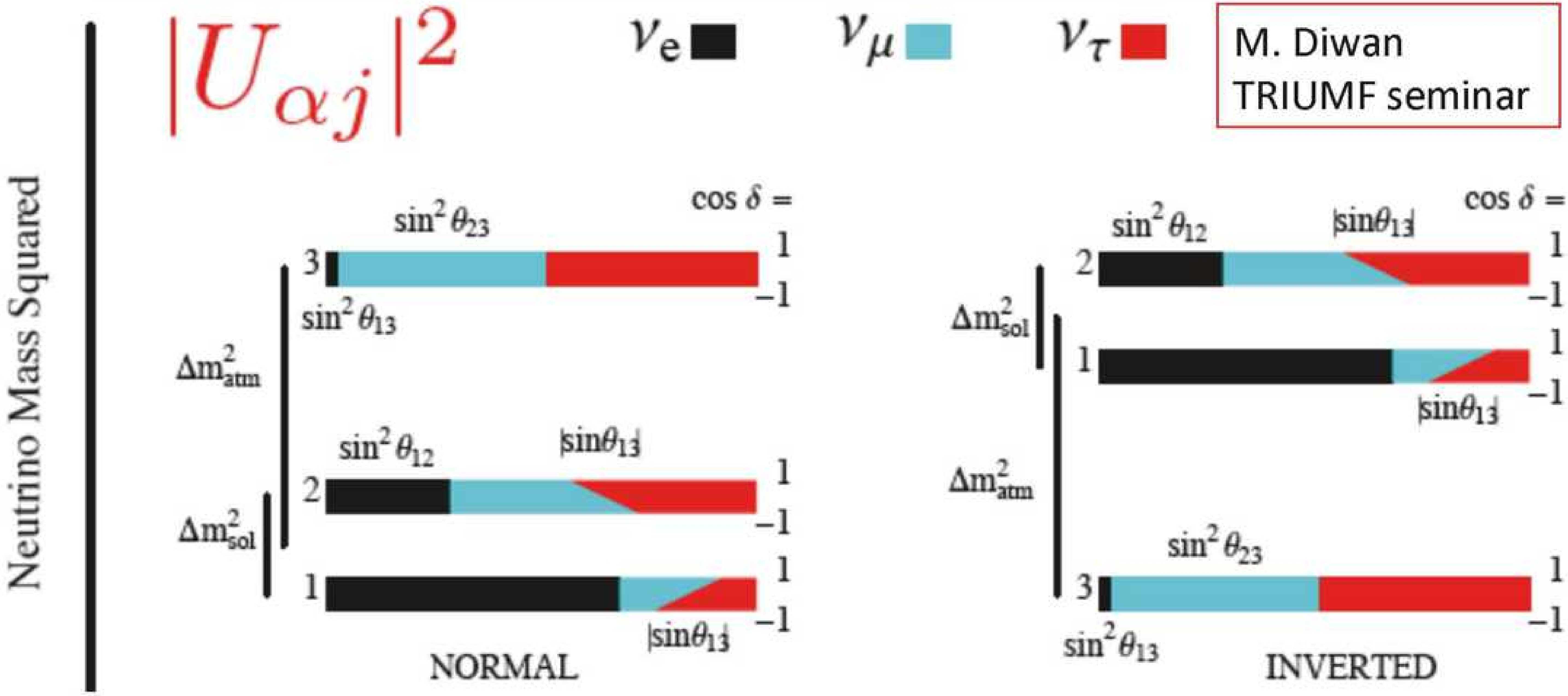
Two observed mass splittings, determined from atmospheric and solar neutrino experiments, respectively

- 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

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 ($\Delta m^2_{32} < 0$)

Current state of neutrino mixing



M. Diwan
TRIUMF seminar

U has three mixing angles and one phase:

- "Atmospheric" θ_{23} ~37°-53°
- "Solar" θ_{12} ~34°
- θ_{13} ~9°
- δ(CP) = ?

Why are quark and lepton mixing so different?

θ^{CKM}_{12}~13.0°, θ^{CKM}_{23}~2.3°, θ^{CKM}_{13}~0.2°

Is there CP violation in the neutrino sector?

Neutrino oscillation, revisited

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

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

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

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

A small fraction of ν_e will "appear"

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

Only leading order term shown

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

Appearance and disappearance

ν_μ "disappear" into ν_e, ν_τ

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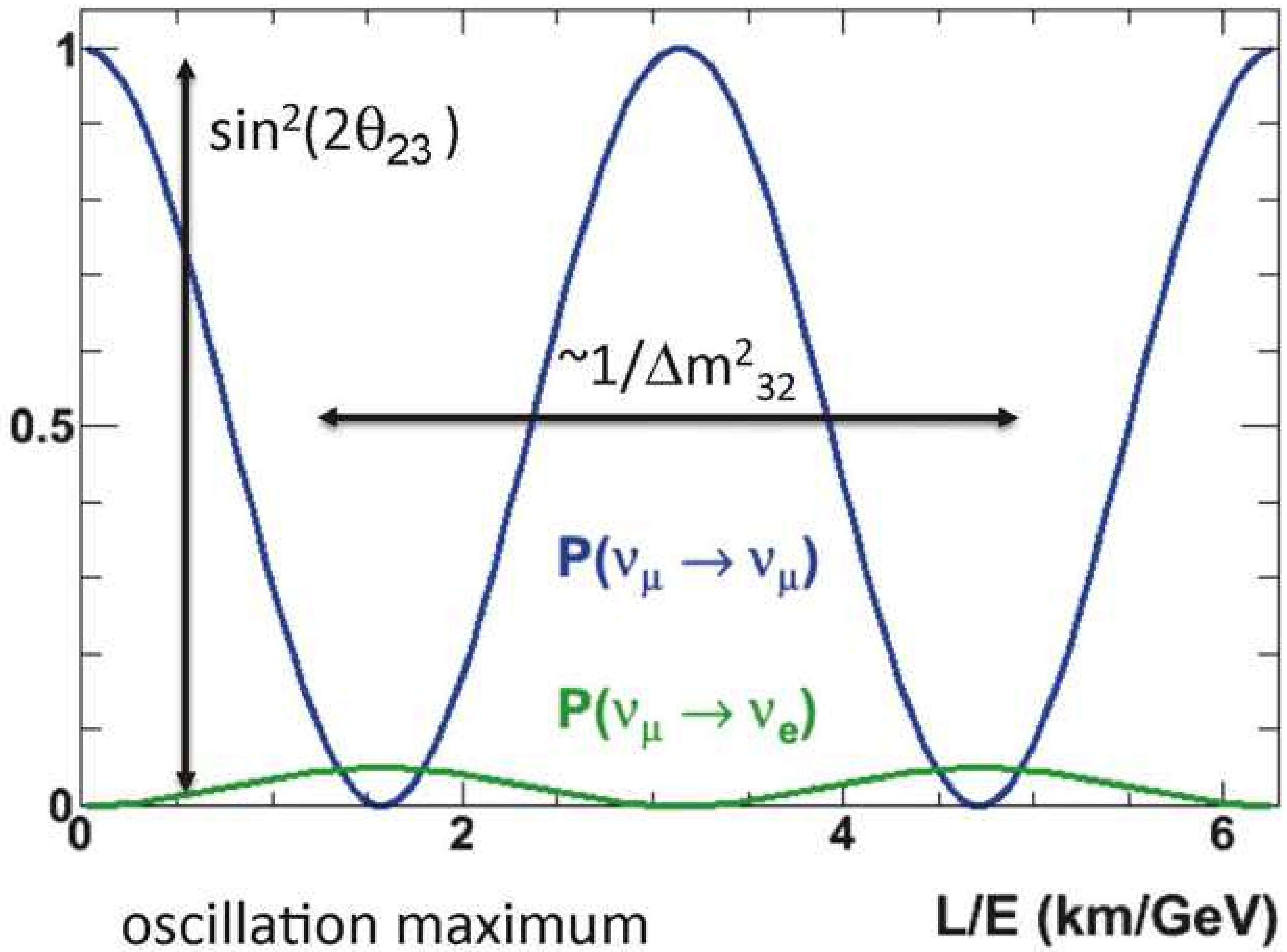


Oscillatory behavior, hence, neutrino oscillations

Electron neutrino appearance

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) \;=\; & 4C_{13}^2 S_{13}^2 S_{23}^2 \cdot \sin^2 \Delta_{31} \quad \text{Leading term} \\
& +8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21} \\
\text{CP violating term} \; & -8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \cdot \sin\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21} \\
& +4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta) \cdot \sin^2 \Delta_{21} \quad \text{solar} \\
& -8C_{13}^2 S_{12}^2 S_{23}^2 \cdot \frac{aL}{4E_\nu} (1 - 2S_{13}^2) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \quad \text{matter effects} \\
& +8C_{13}^2 S_{13}^2 S_{23}^2 \frac{a}{\Delta m_{13}^2} (1 - 2S_{13}^2) \sin^2 \Delta_{31}
\end{aligned}
$$

Measurements of ν_μ to ν_e appearance are sensitive to:

- CP violation
- ``θ_{23} octant'': if θ_{23} is non maximal, is it more or less than 45 deg?
- Sign of Δm^2_{32} through ``matter effects''; difference in ν_μ, ν_τ and ν_e interactions as they travel through matter
- New or exotic physics

Requires precision measurements of Δm^2_{32}, θ_{23} (ν_μ disappearance)

How to do an oscillation experiment

Search for deficit of ν_μ (disappearance)

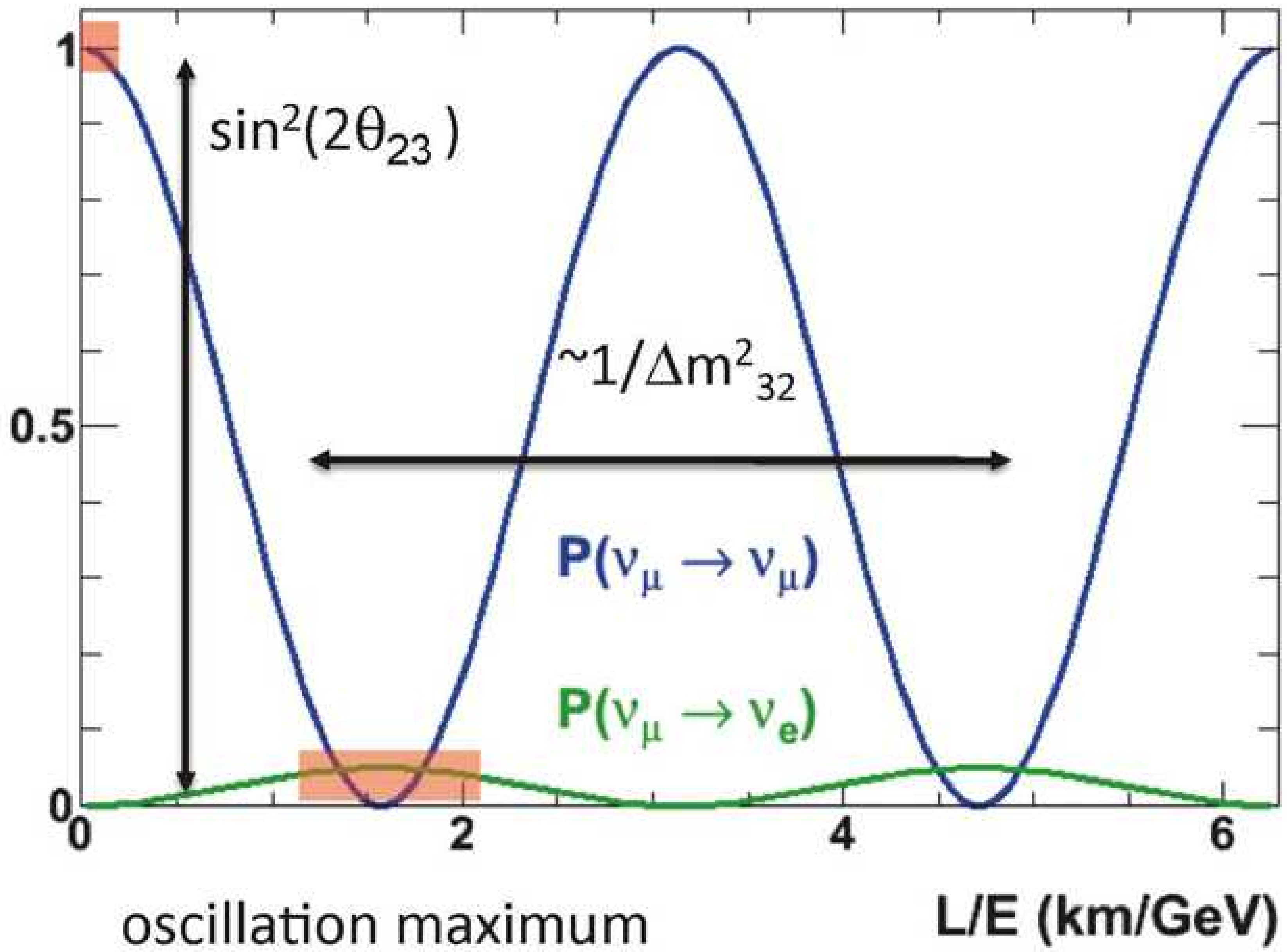
$$P(\nu_\mu \to \nu_\mu) \cong 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$$

Search for excess of ν_e (appearance)

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

Only leading order term shown

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



oscillation maximum

Typical experimental setup:

- Source of neutrino energy E
- Measure ν_μ rate* at L=0
- Measure ν_μ, ν_e rate at L~oscillation maximum
- Infer oscillation parameters from rate change and distortion of spectrum

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

The Tokai-to-Kamioka (T2K) experiment

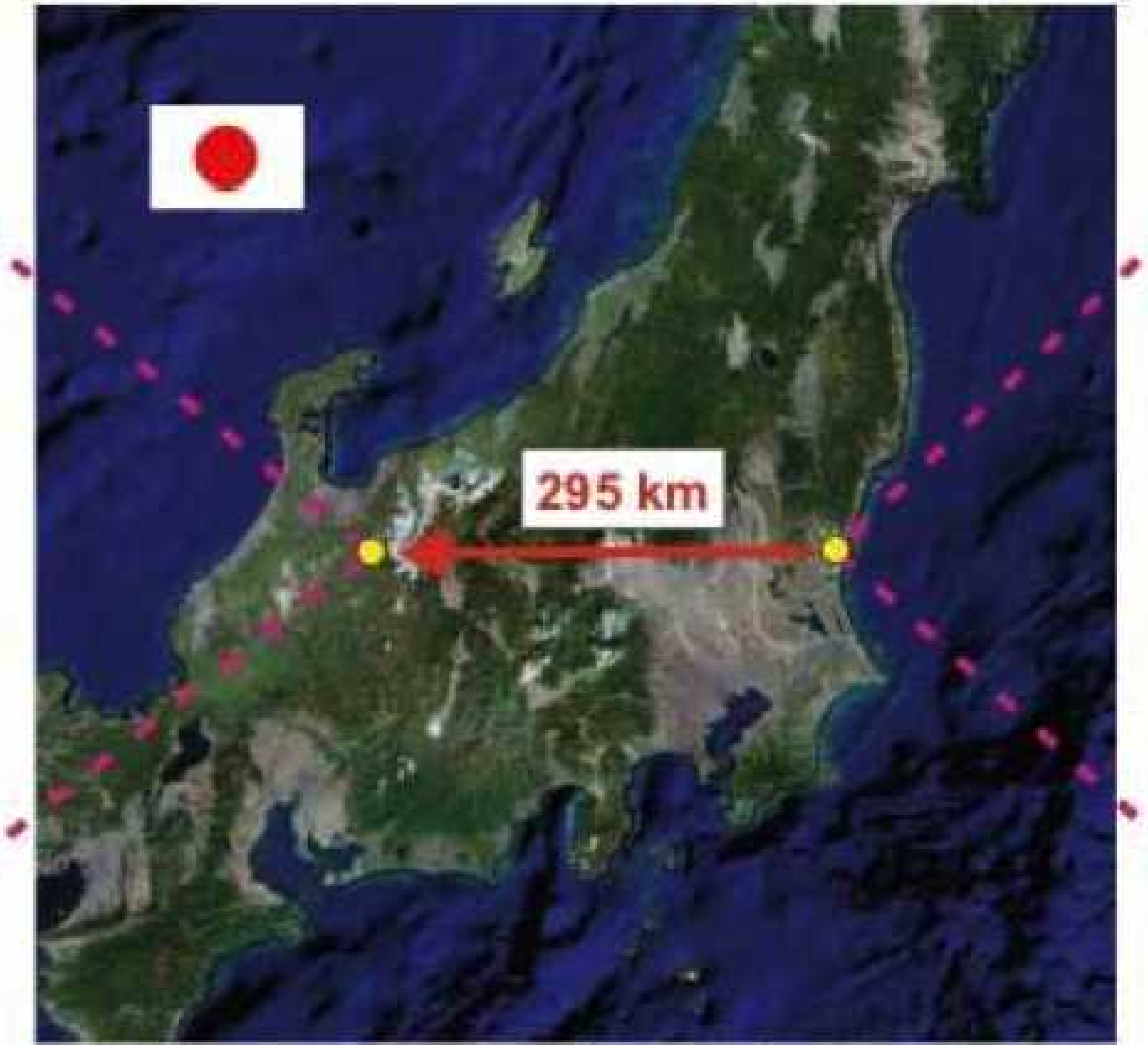
``Long baseline" (L~ 295km) neutrino experiment designed to measure:

ν_e appearance (θ_{13}) and ν_μ disappearance (Δm^2_{32}, θ_{23})

Three necessary pieces:

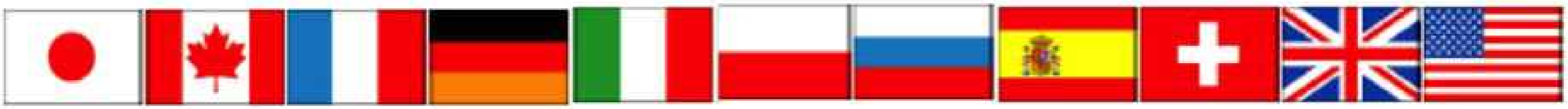
1) Intense neutrino source
2) Measurement of unoscillated ν_μ rate at L~0
3) Immense detector of ν_μ, ν_e at L~ oscillation maximum

Far detector:
Super-Kamiokande
located near Kamioka



Beam source and near detectors:
J-PARC accelerator complex
located in Tokai-mura

The T2K Collaboration



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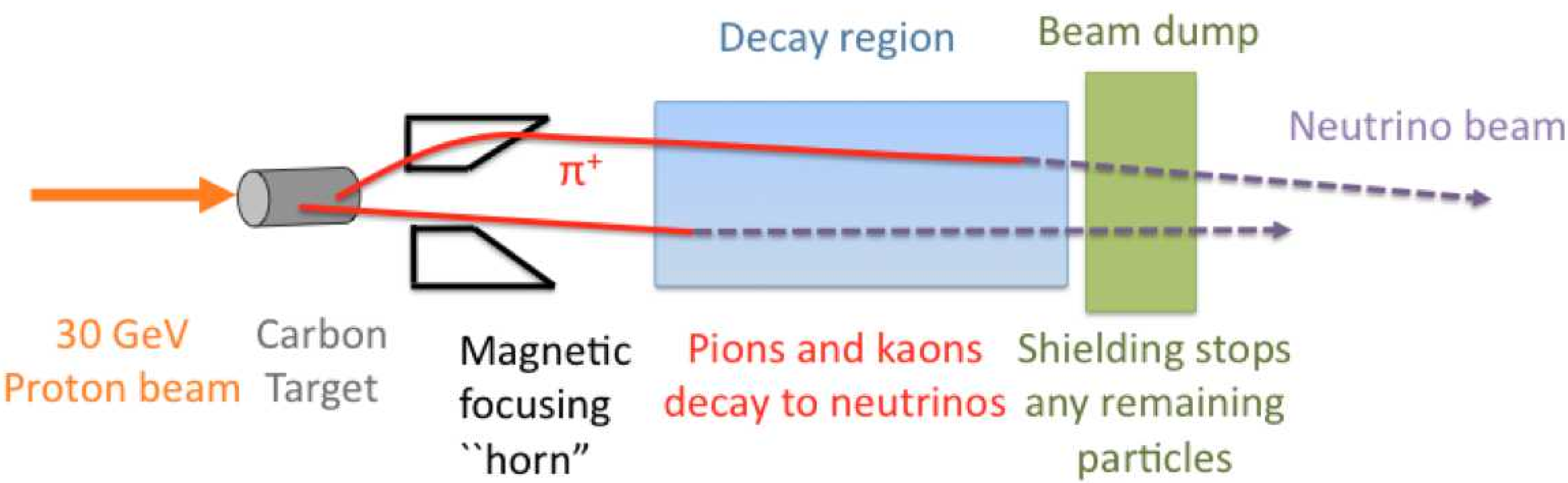
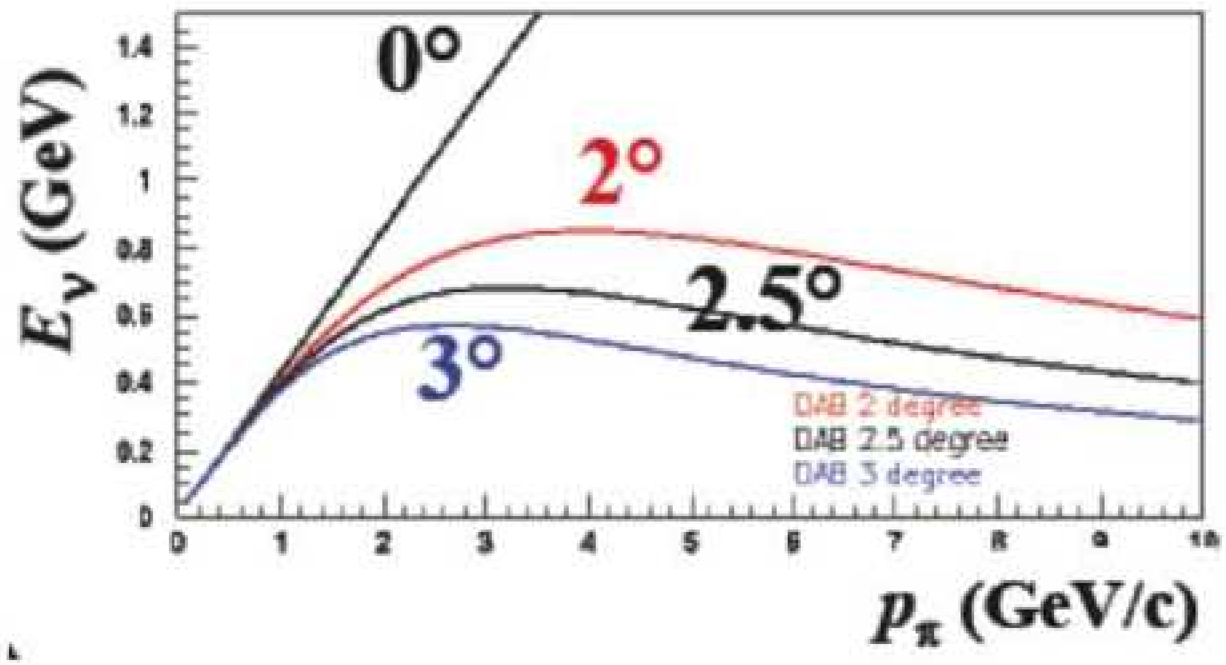
Conventional neutrino beam



Advantages of an accelerator based neutrino source:

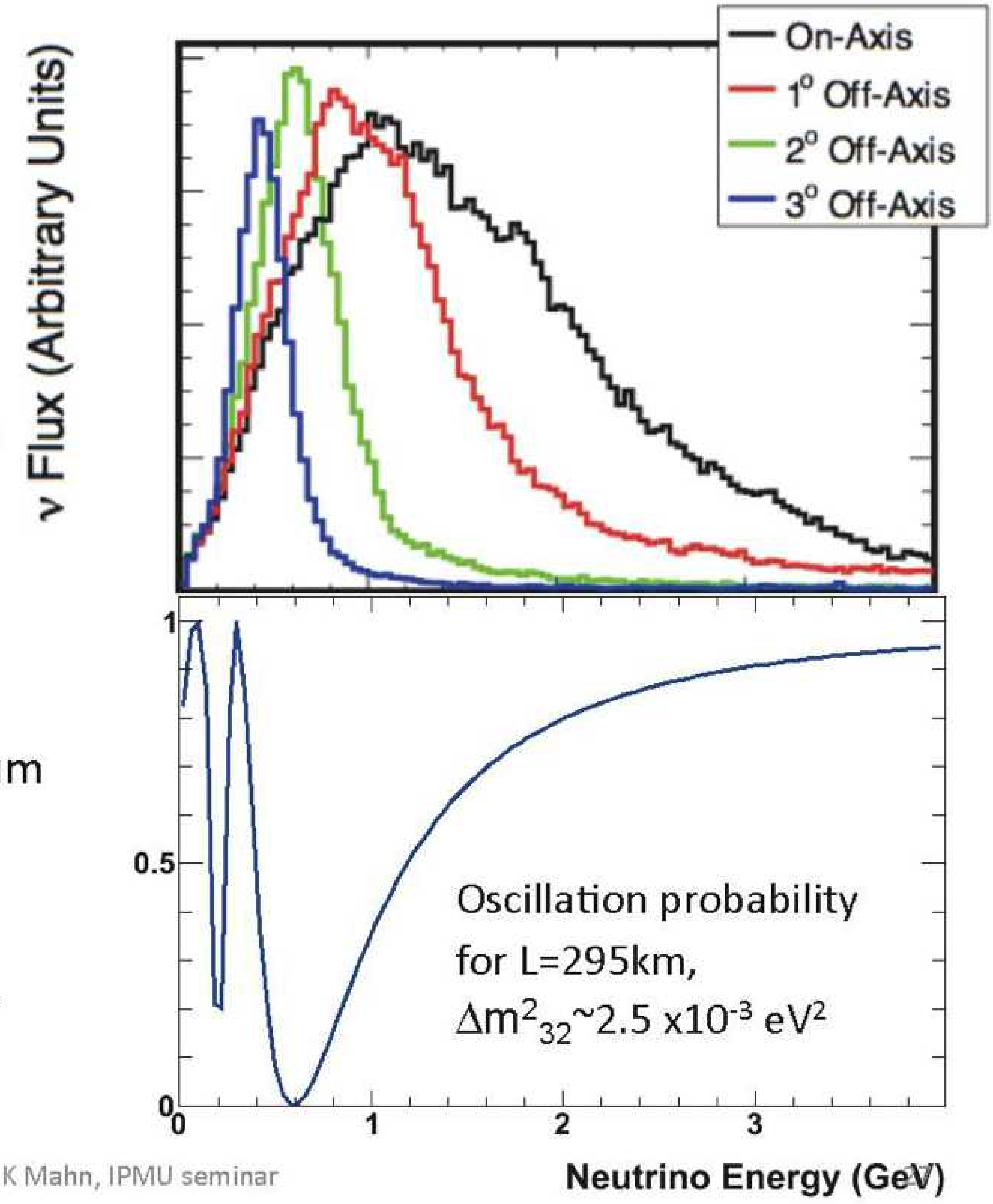
1. >99% muon neutrino flavor, small ν_e component from muon, kaon decay
2. Intensity of proton beam increases neutrino rate
3. Switch magnetic horn polarization to focus π^- and produce an antineutrino beam
4. Tunable neutrino energy spectrum optimized for oscillation

The off-axis advantage



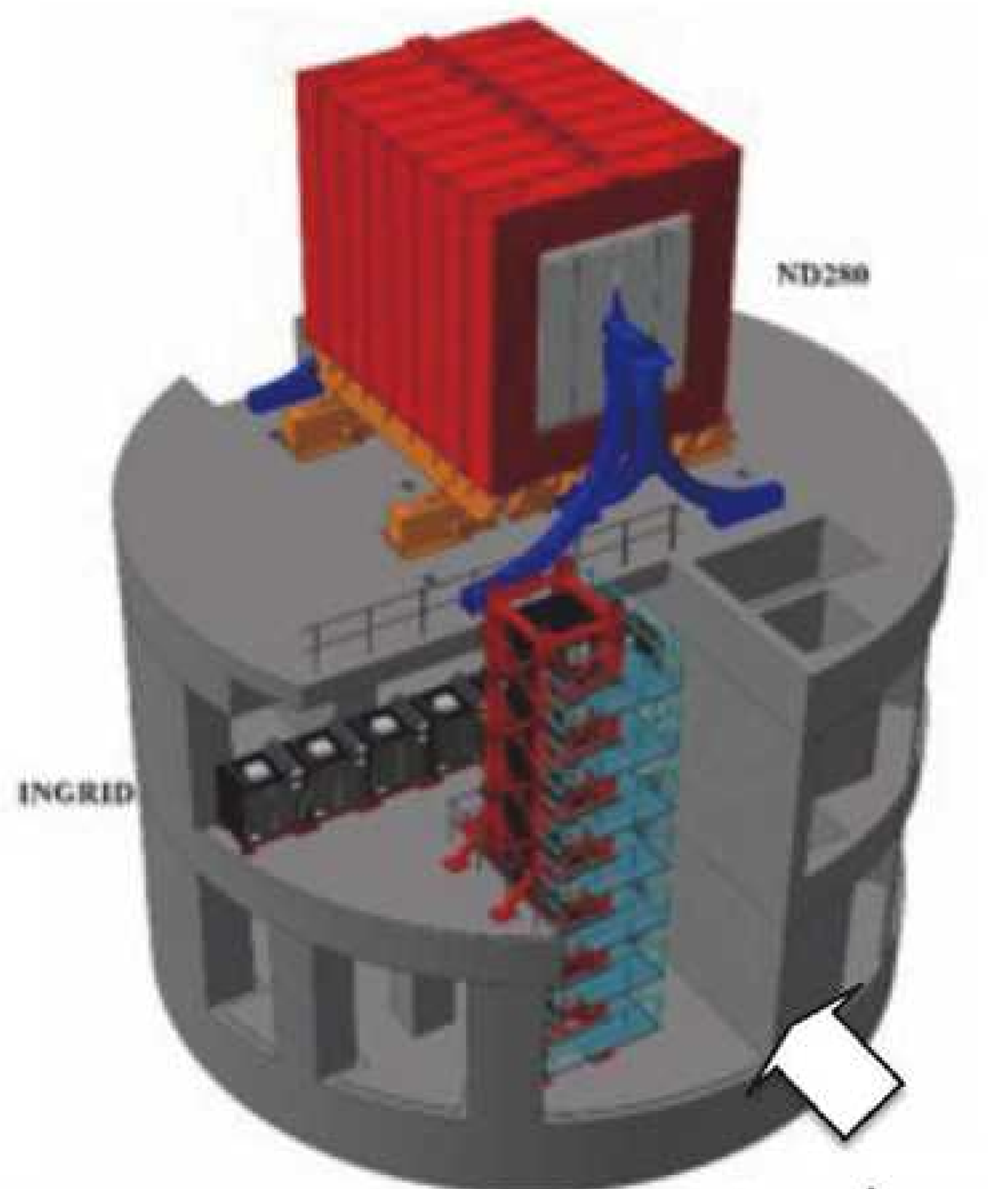
T2K uses a novel 'off-axis' technique
Developed at TRIUMF for a long baseline neutrino experiment (BNL889)

- Narrower neutrino energy spectrum from pion decay kinematics
- Peak can be set to ~oscillation maximum
- Reduces backgrounds from higher energy neutrino interactions



Neutrino detectors of T2K

<u>Off-axis ND280 detectors</u>



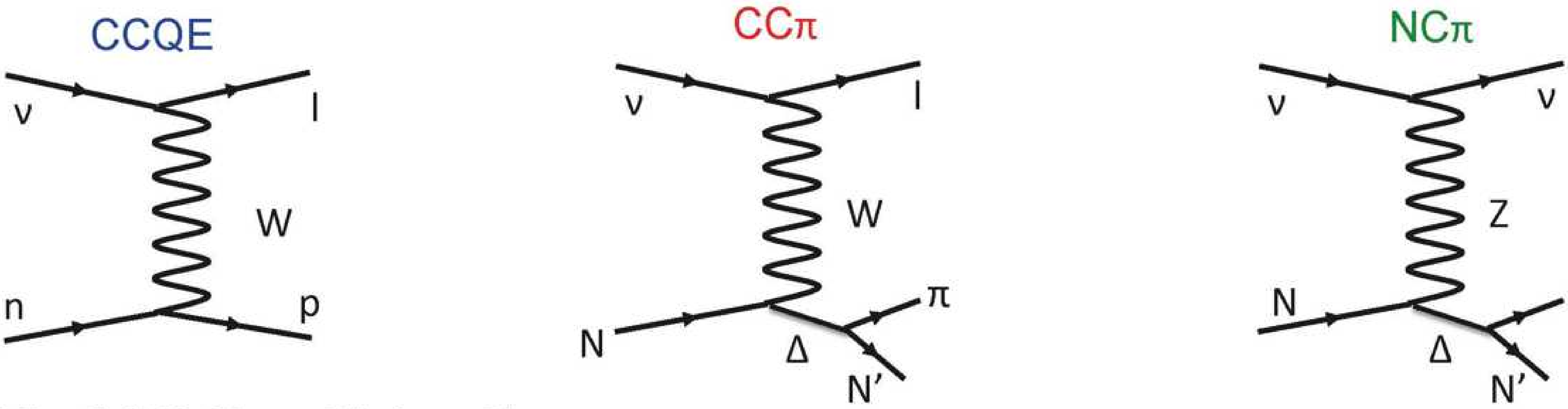
proton beam
direction

<u>On-axis INGRID detector:</u>

Measure beam direction, stability with high statistics ν event sample

<u>Off-axis Super-Kamiokande detector</u>

Neutrino interactions at T2K



At Eν~0.6 GeV most interactions are

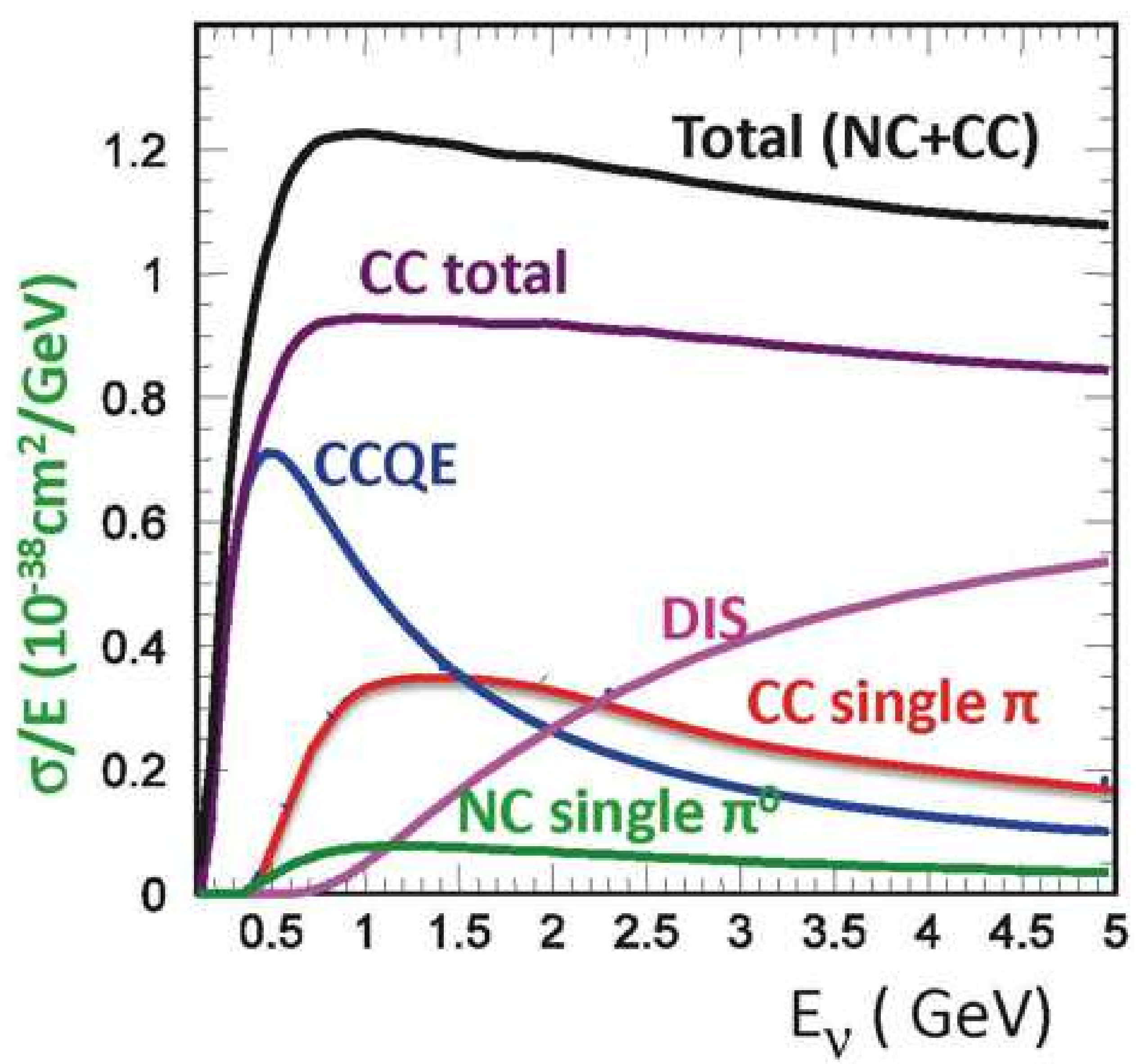
Charged Current Quasi Elastic

- Neutrino flavor determined from flavor of outgoing lepton i.e. e for ν_e, μ for ν_μ
- Infer neutrino properties from the lepton momentum and angle:

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

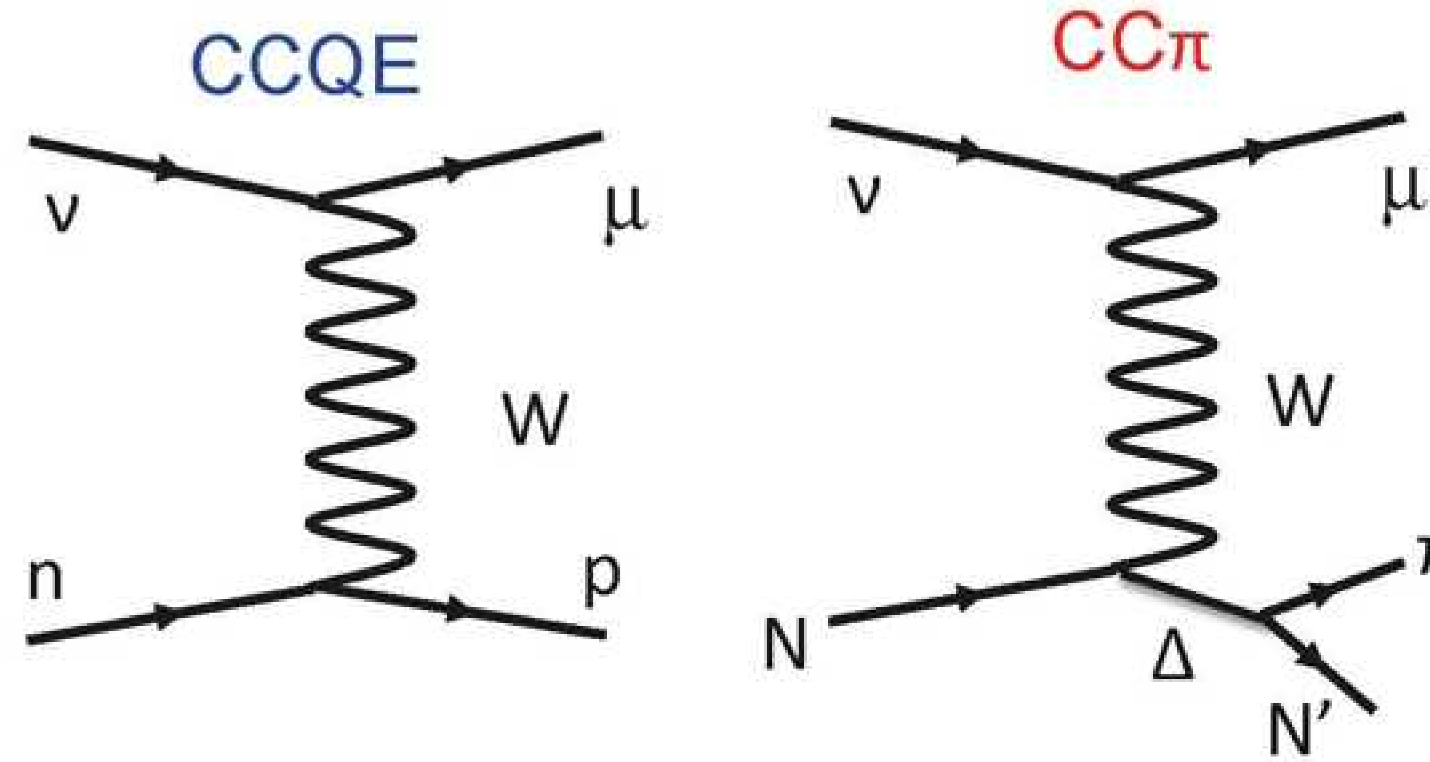
Single pion production is also important:

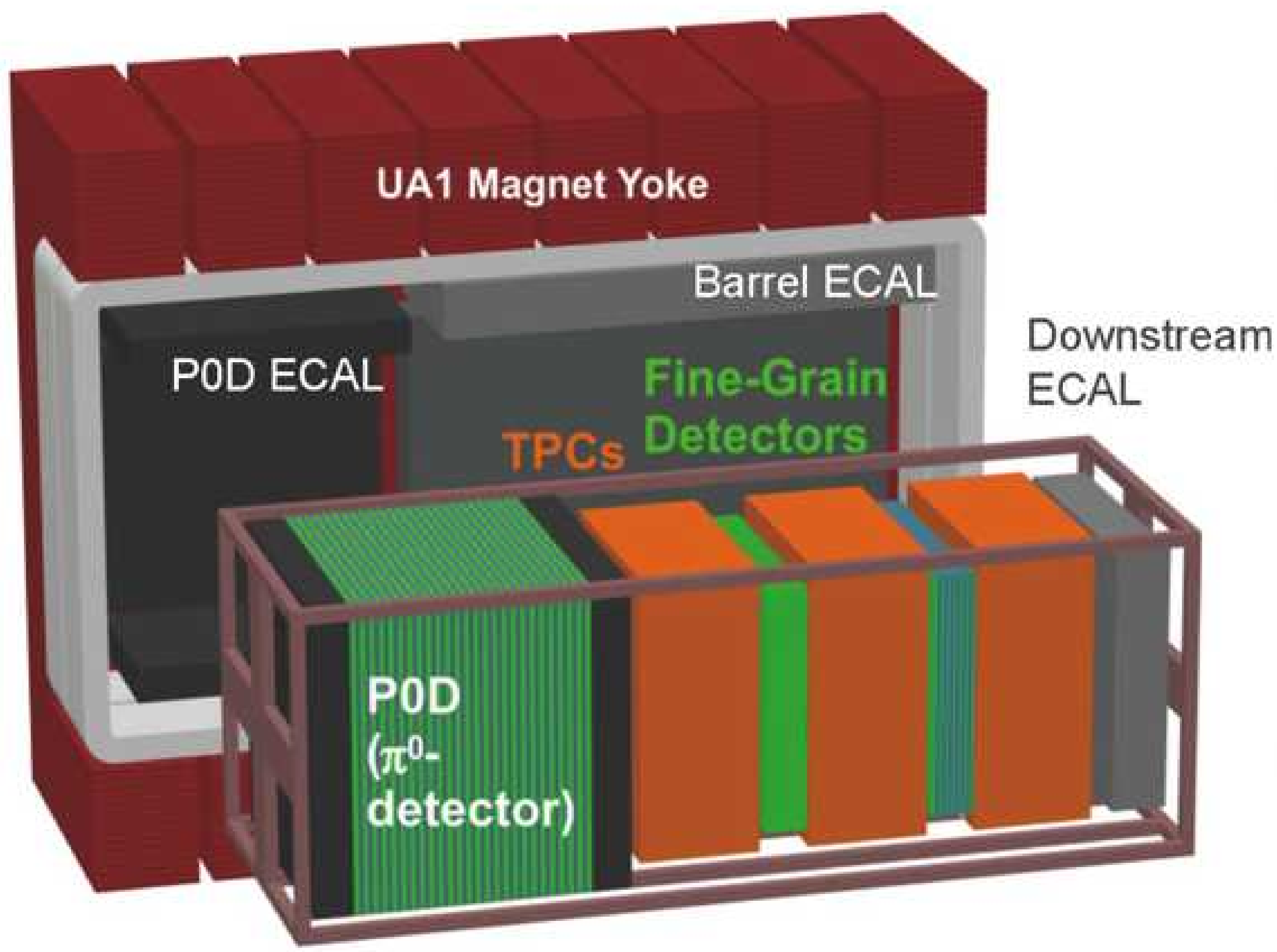
CCπ and NCπ



Near detectors (ND)

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

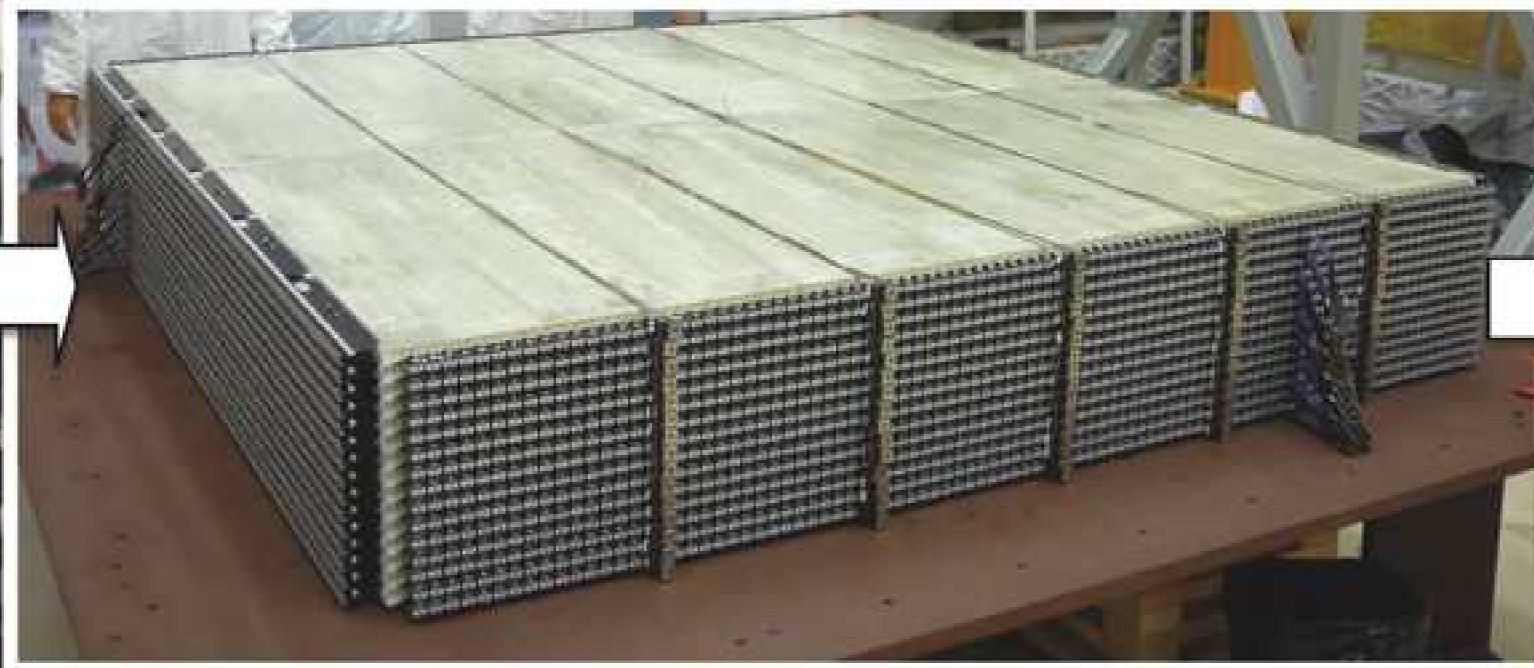
Additional detectors include:

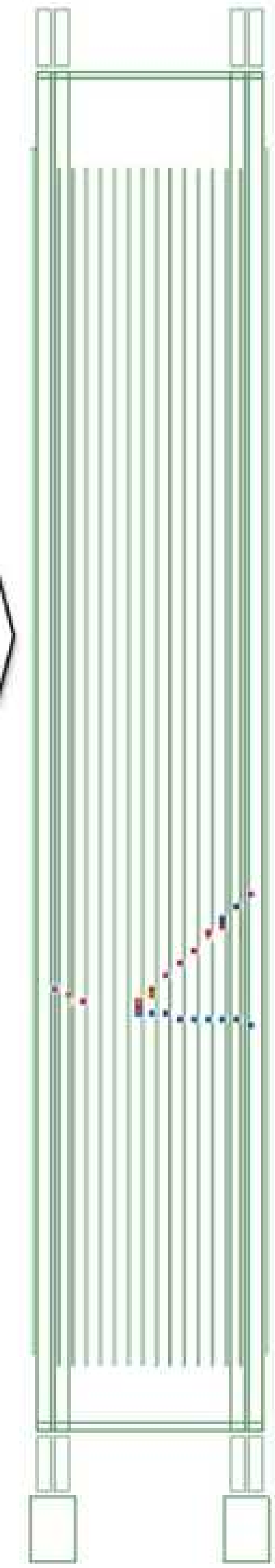
- P0D (π^0 detector)
- Electromagnetic calorimeters
- Muon range detectors

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)

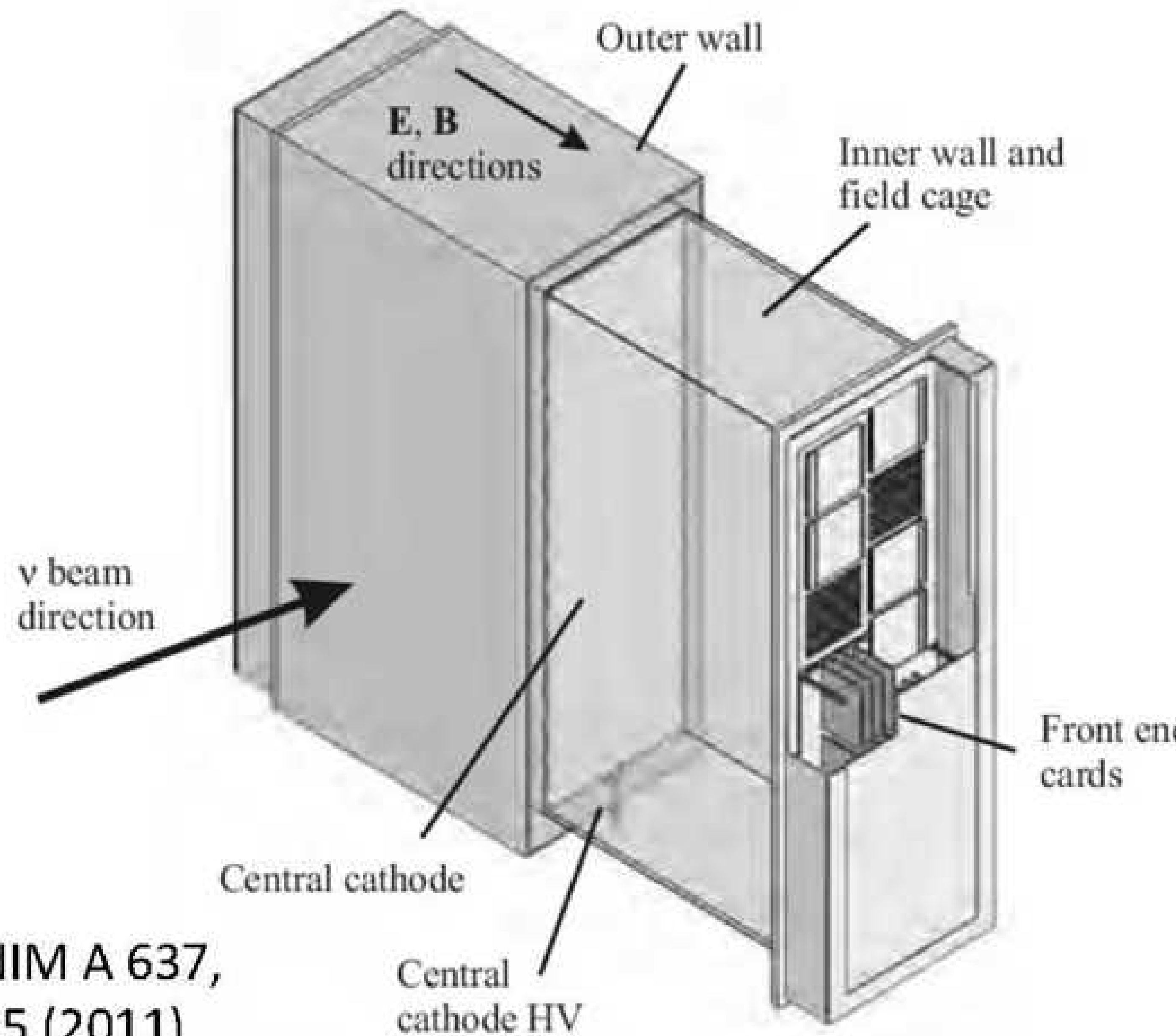
Charged particle ionizes gas; electrons drift to readout plane (E~25kV)
``Wireless" TPC: Use of bulk micromegas detectors in readout

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

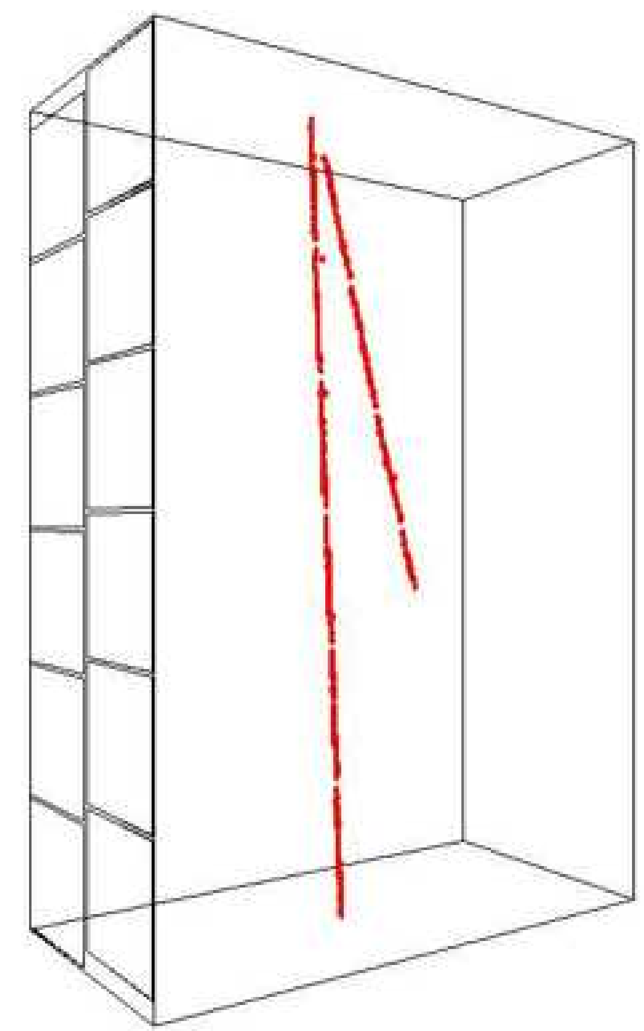
Momentum of the particle can be determined from curvature

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

Built DQ system, alignment convener



NIM A 637, 25 (2011)



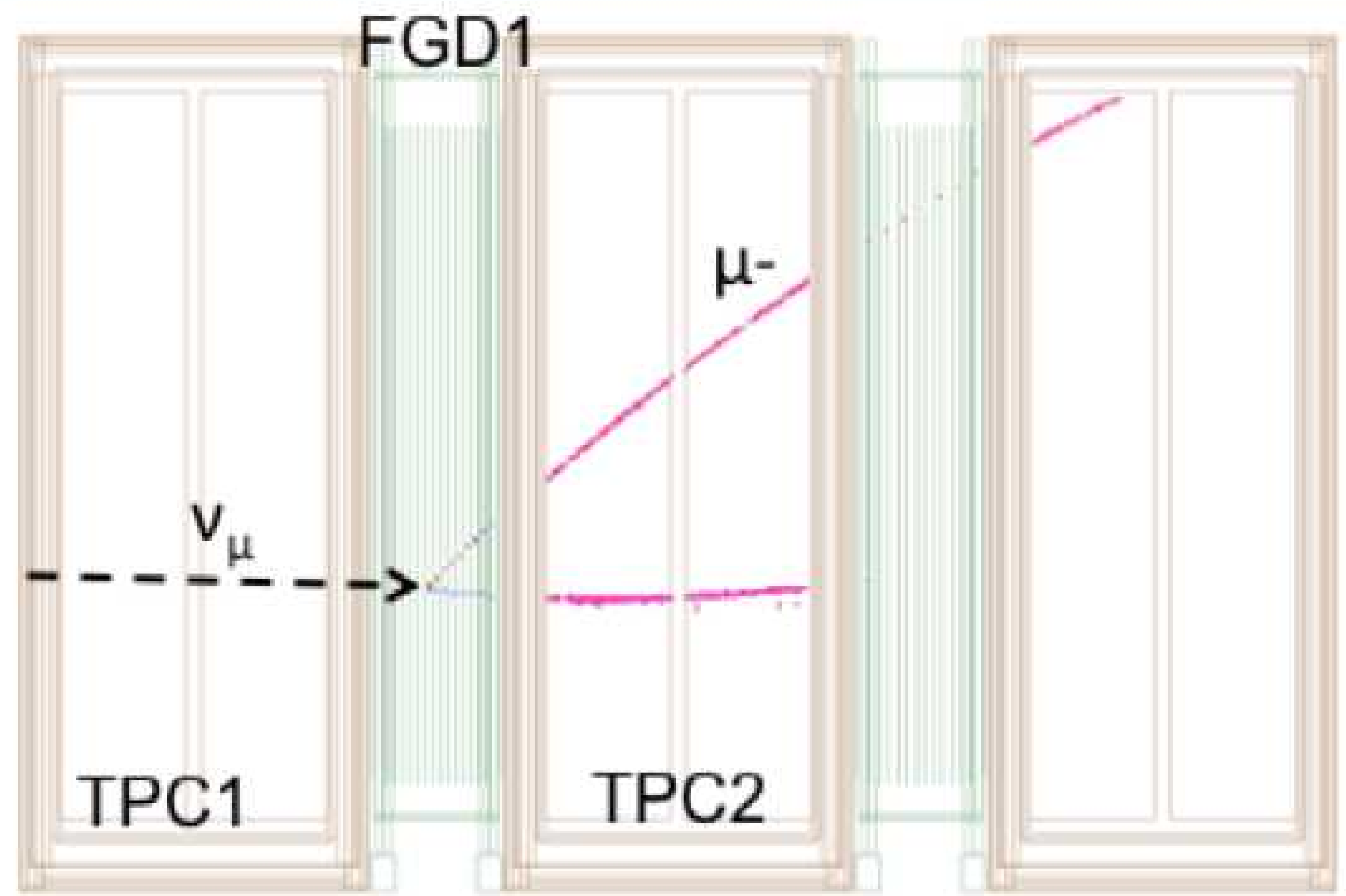
Selecting CC ν_μ interactions

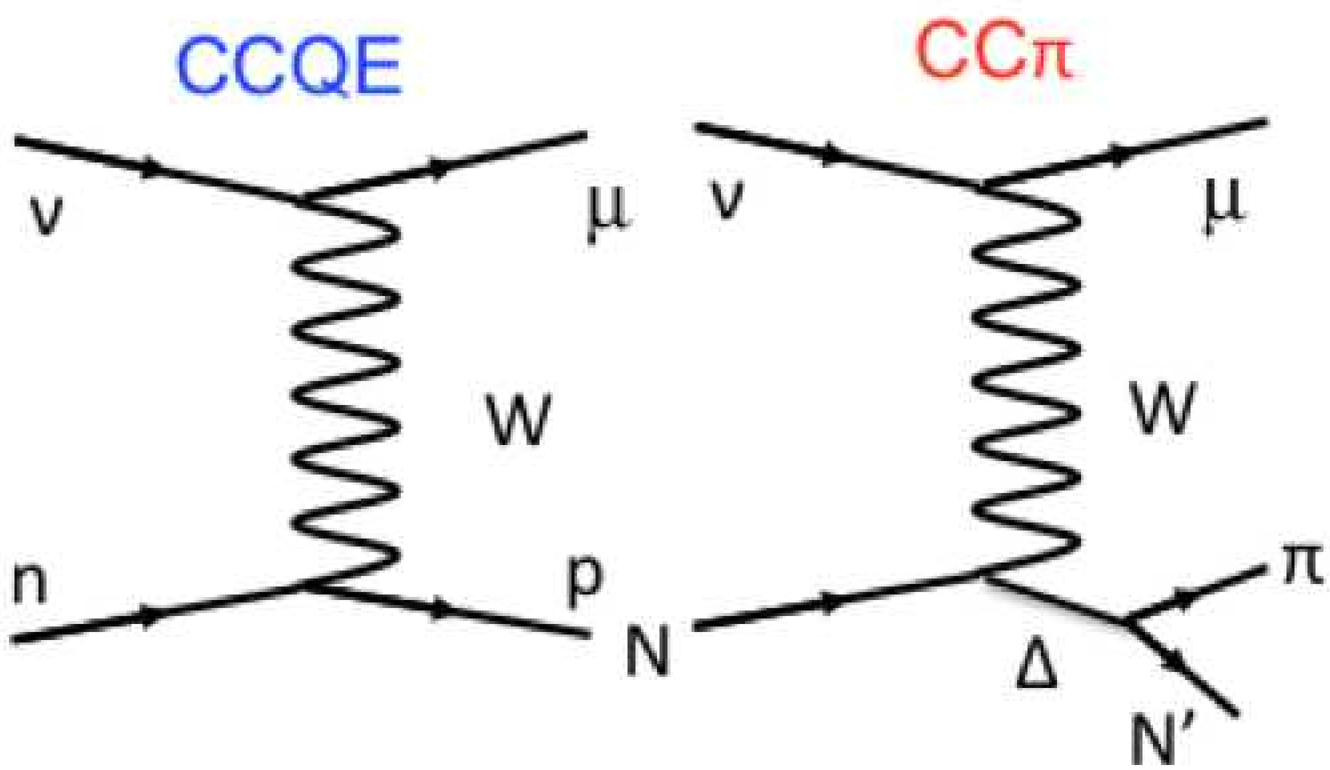
Measure unoscillated ν_μ(CC) rate

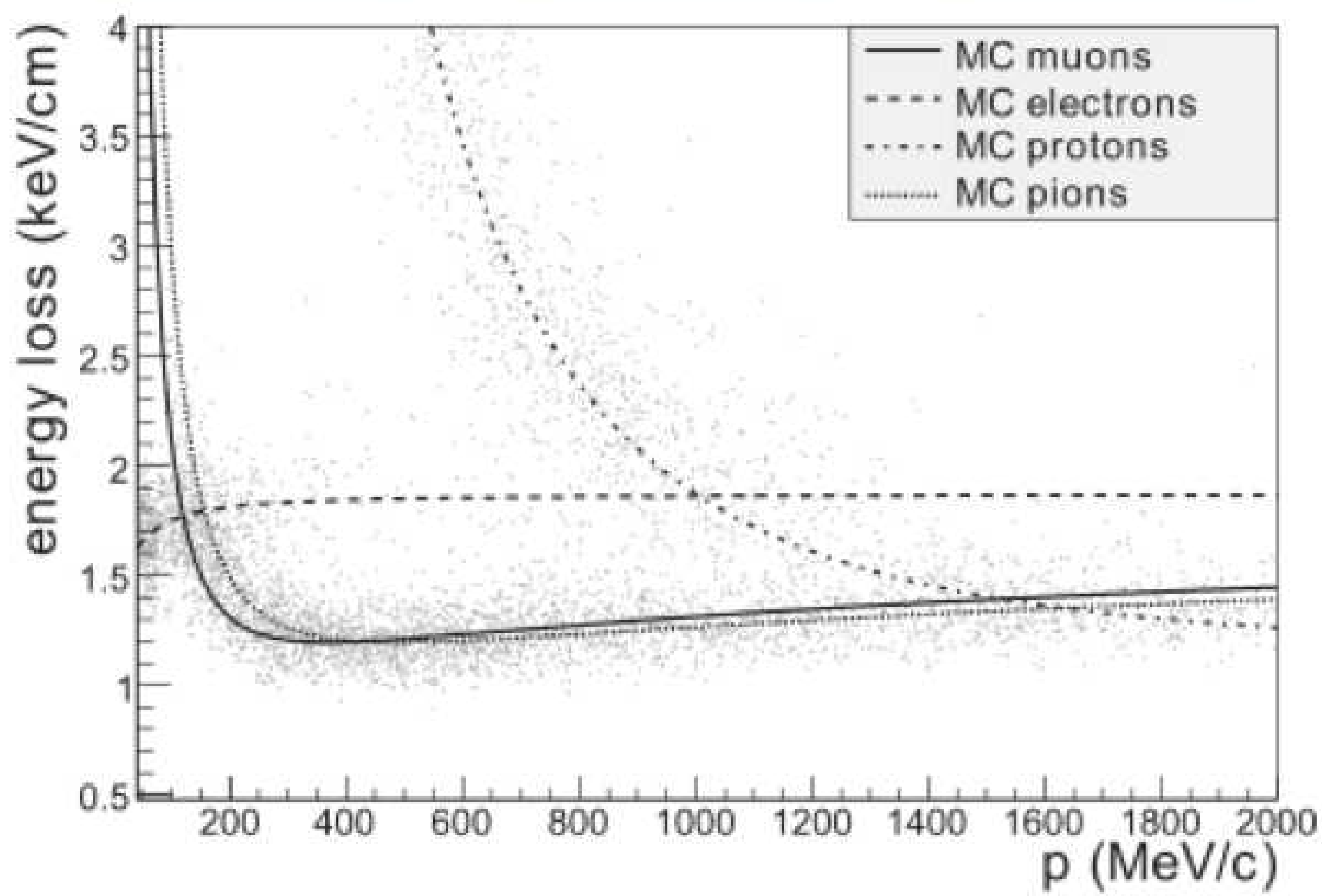
1. Neutrino interaction in FGD1
   - Veto events with TPC1 tracks
   - Events within FGD1 fiducial volume

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

3. Check muon candidate is consistent with muon energy loss in TPC







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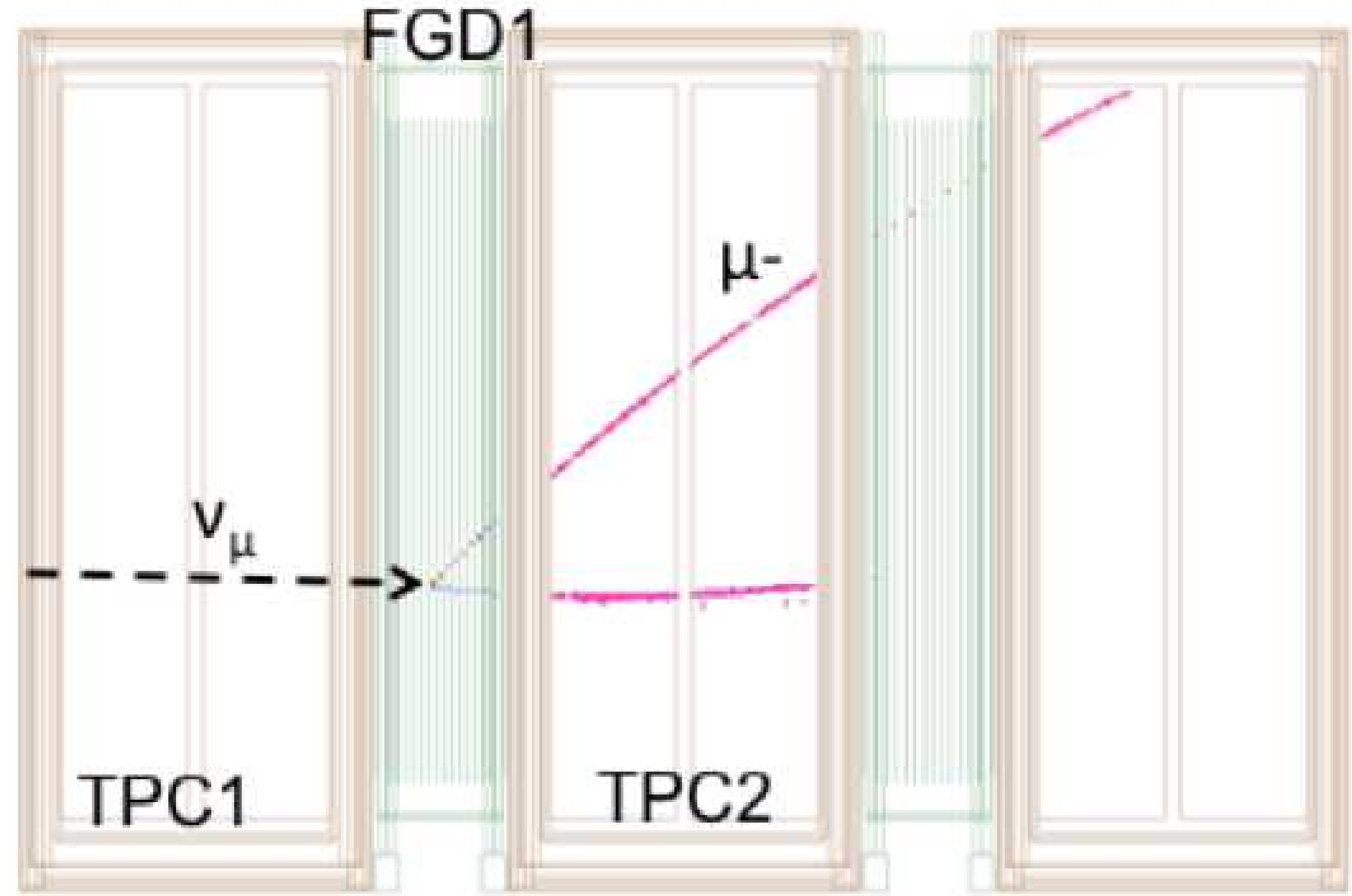
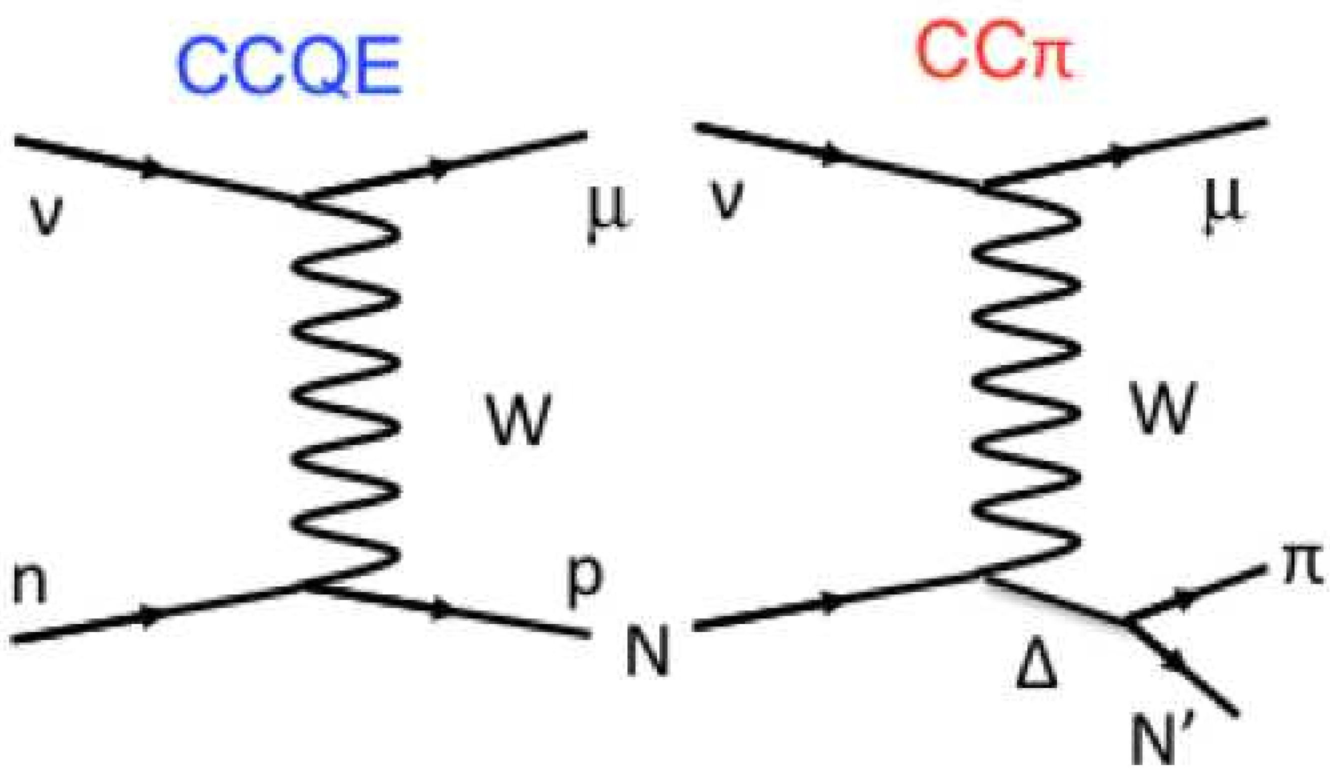




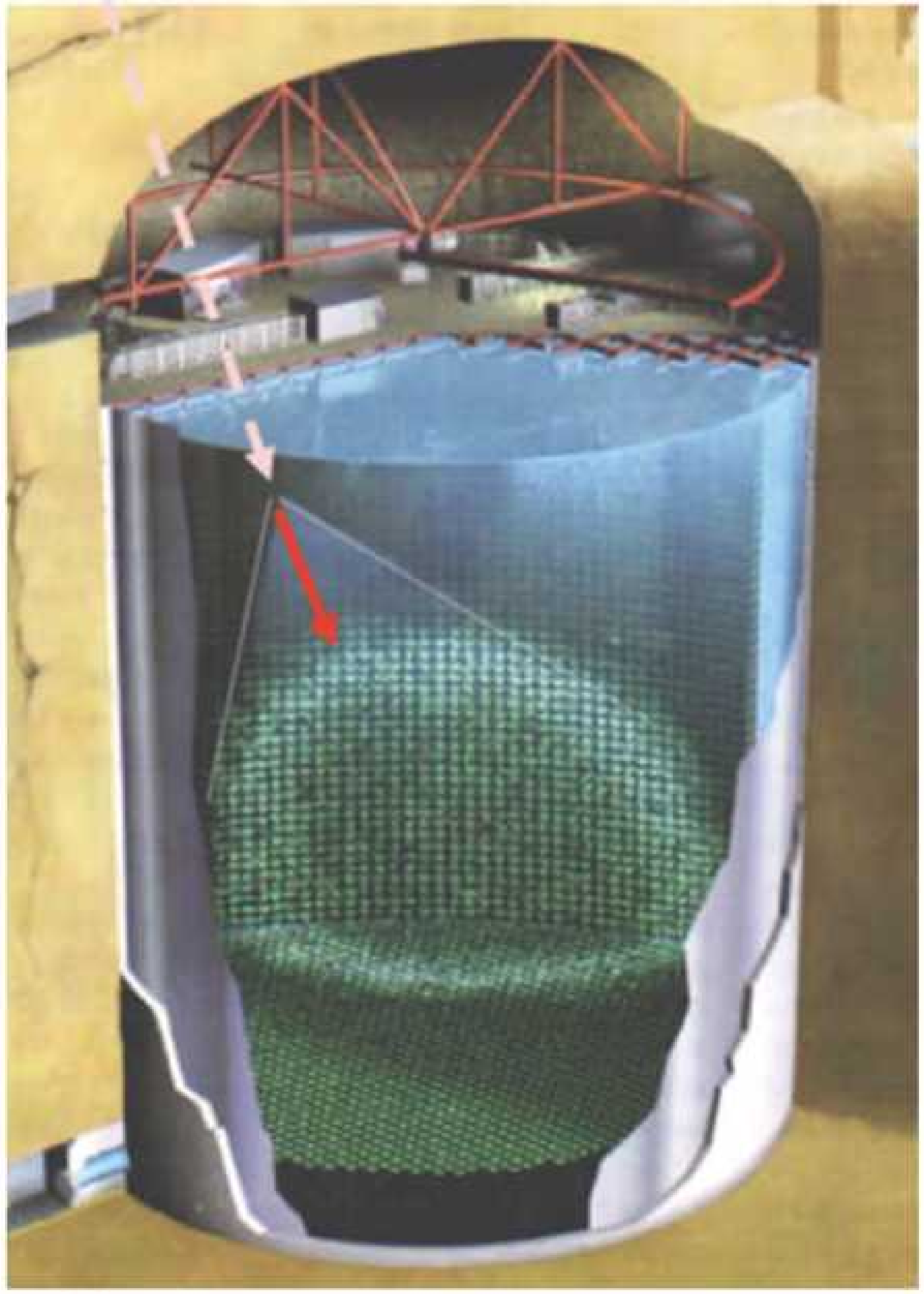
Further separate sample into two categories:

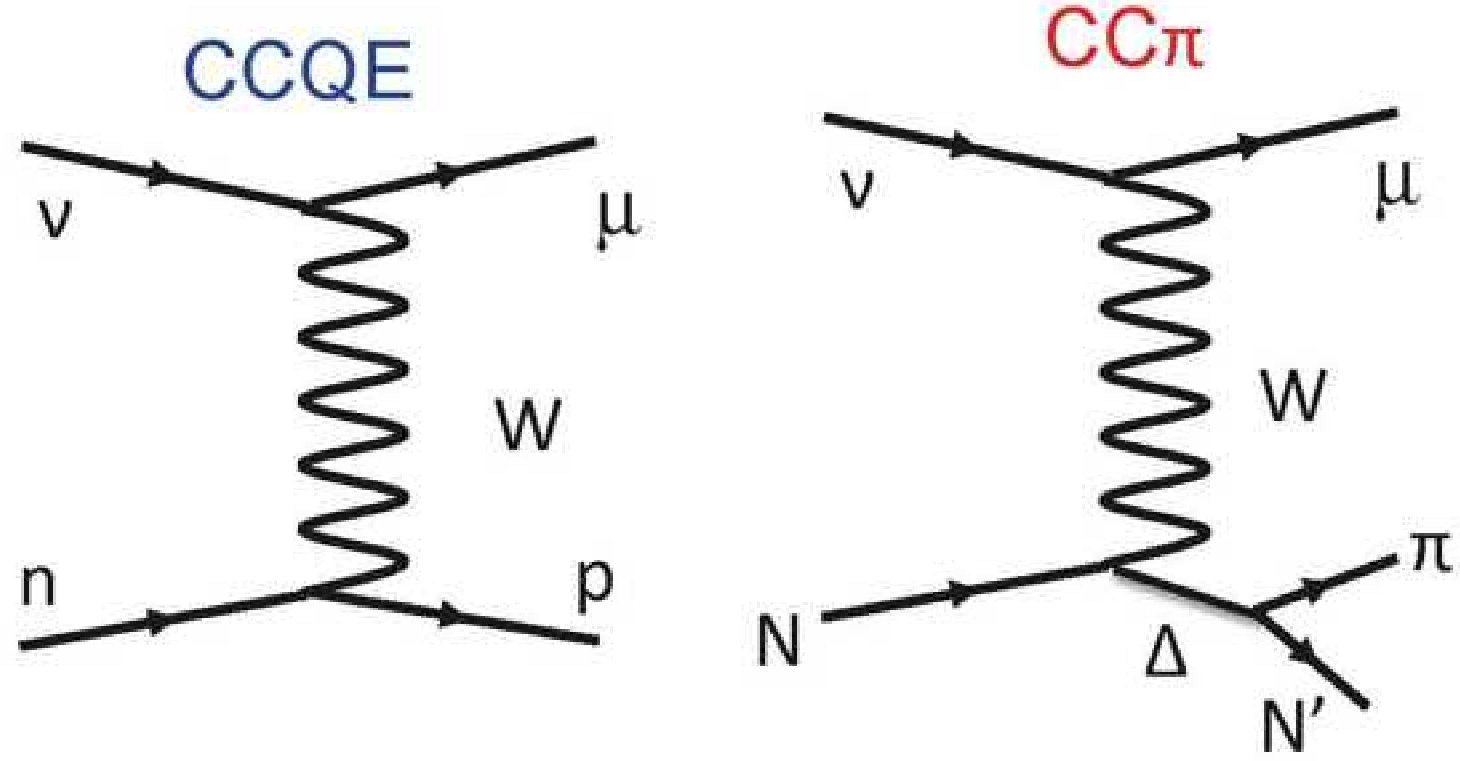
CCQE enhanced:
- 1 TPC-FGD matched track
- no decay electron in FGD1

CCnonQE enhanced:
- all other CC inclusive

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 lepton 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

Selecting CC ν_e interactions

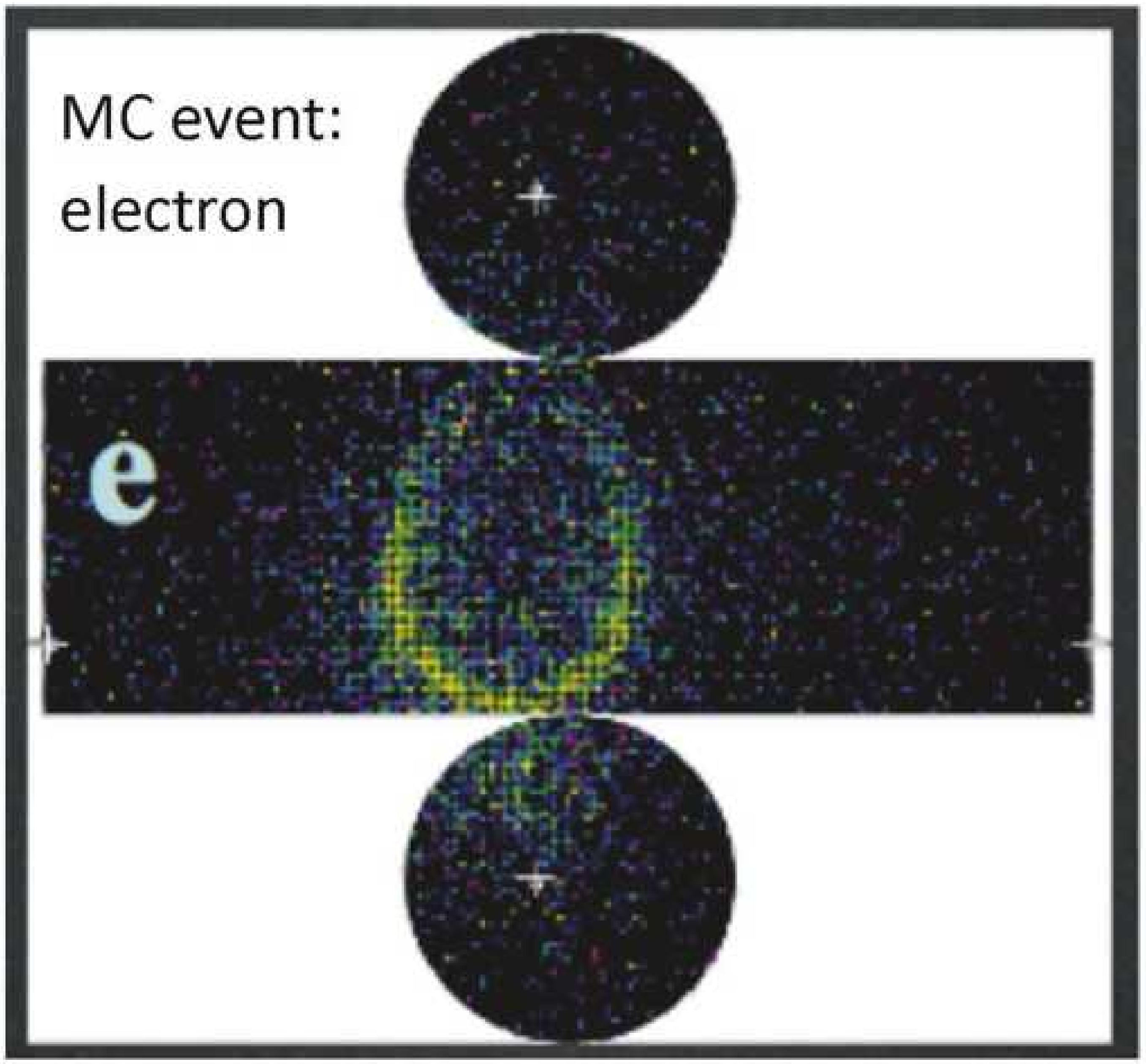
Signal: CC ν_e from ν_μ to ν_e oscillation

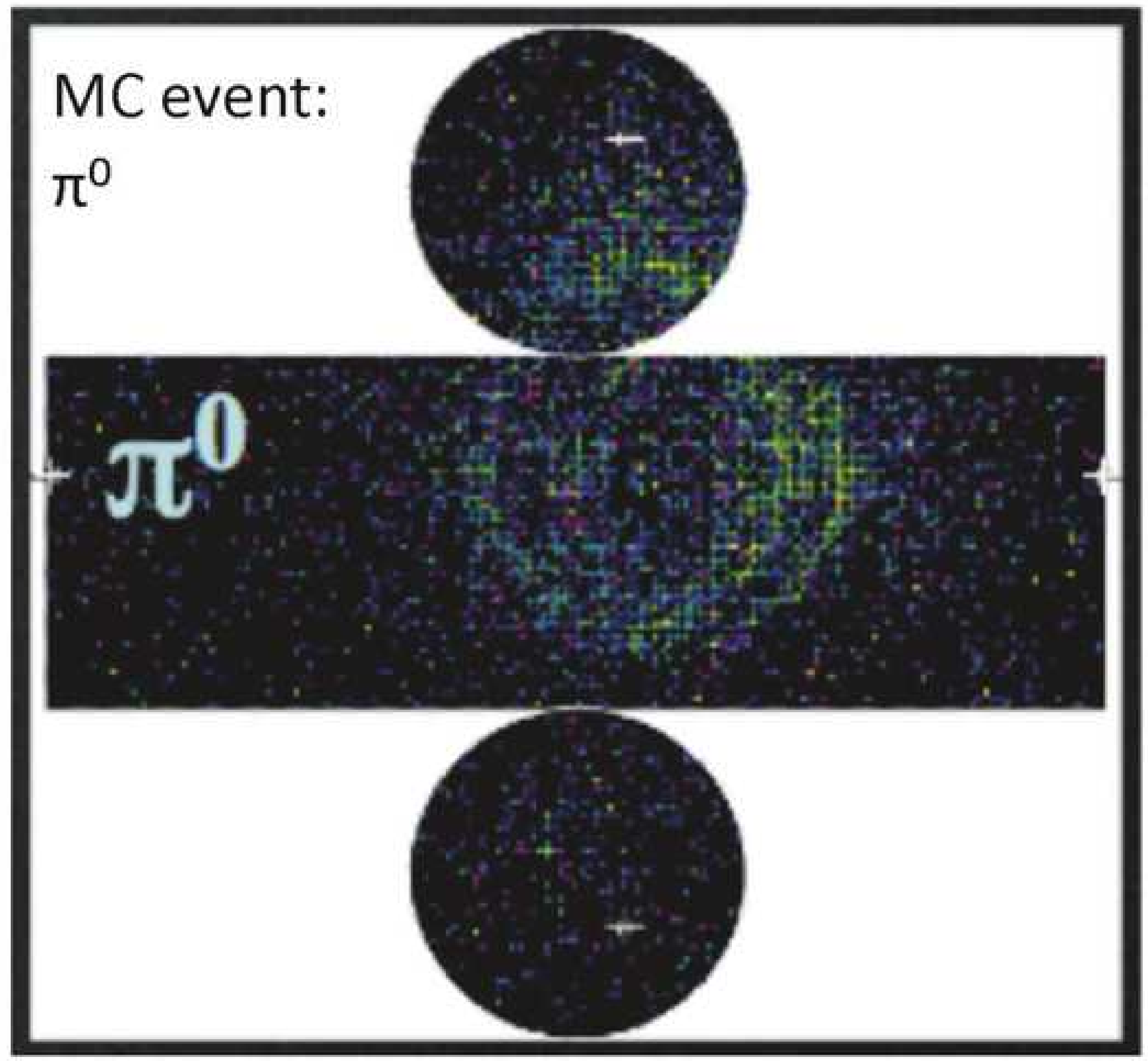
Background: CC ν_e
Irreducible beam ν_e

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





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

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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

Neutrino interactions at ND and SK

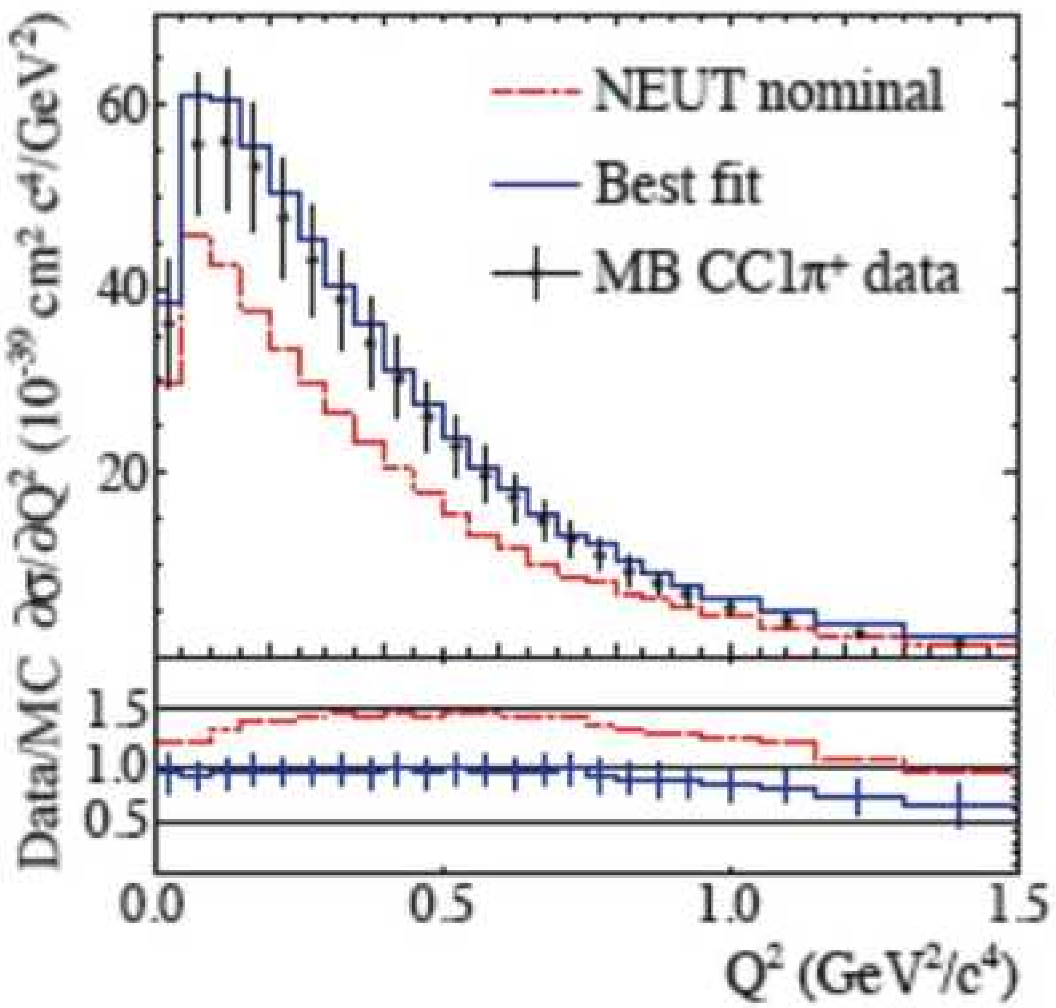
Interaction Mode	Trkr. ν_μ CCQE	Trkr. ν_μ CCnQE	SK ν_e Sig.	SK ν_e Bgnd.
CCQE	76.6%	14.6%	85.8%	45.0%
CC1π	15.6%	29.3%	13.7%	13.9%
CC coh.	1.9%	4.2%	0.3%	0.7%
CC other	4.1%	37.0%	0.2%	0.7%
NC	1.5%	5.3%	-	39.7%

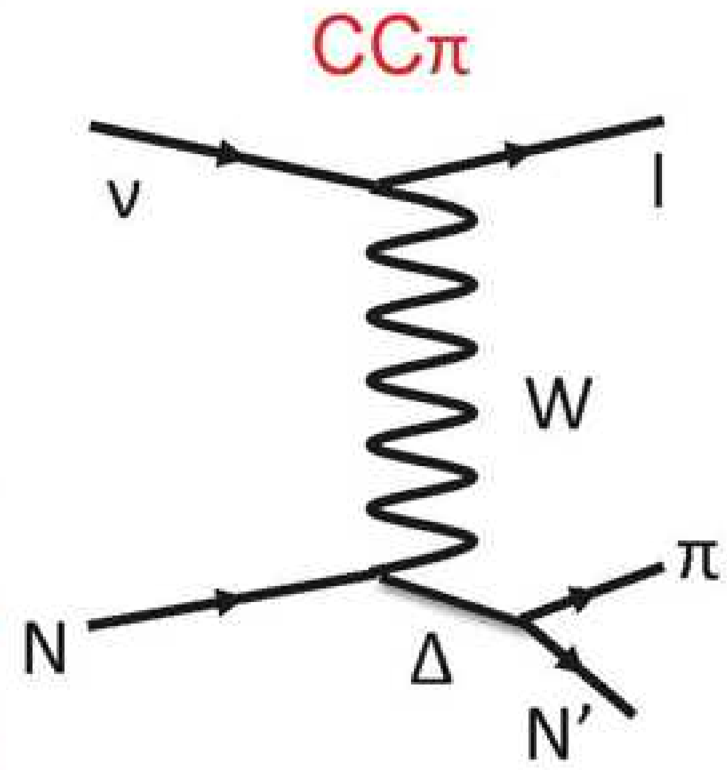
CCQE and CC1π are the largest interaction mode in ND, SK samples

- 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 "reweighting" code to alter the cross section for each simulated event

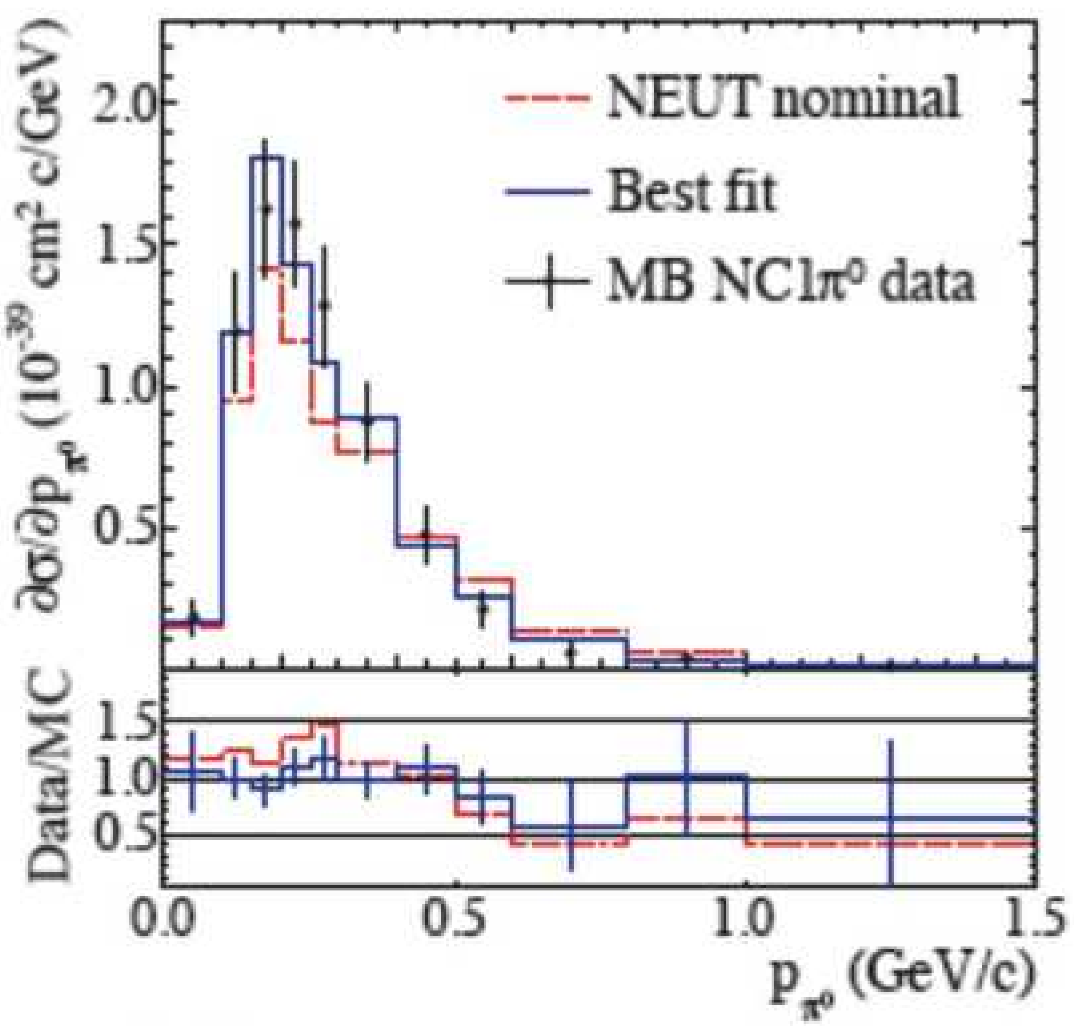
Neutrino interaction uncertainties

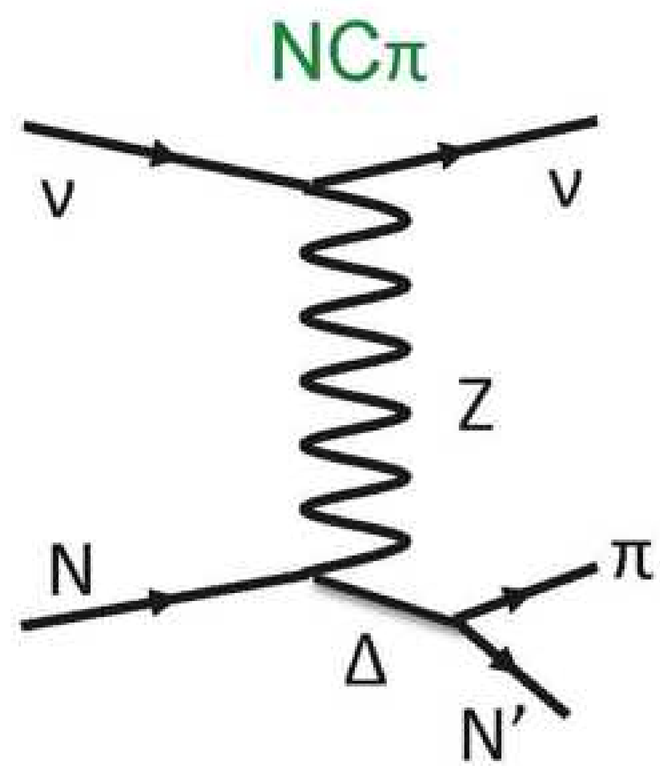




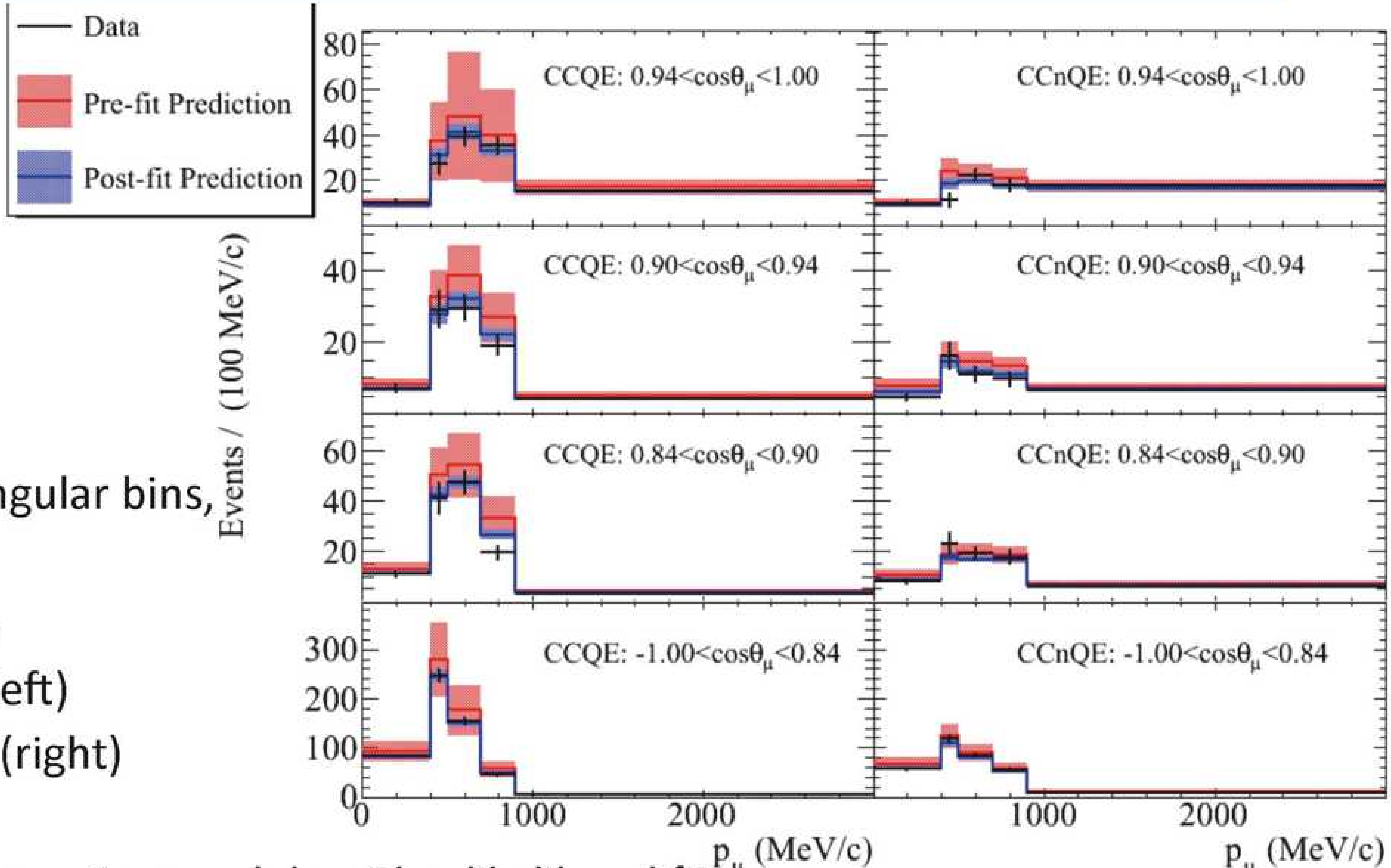
Started a program to compare cross section model (NEUT) to external neutrino-nucleon data to set uncertainties

- Possible with reweighting code
- Single pion (CC and NC) interaction MiniBooNE datasets fit simultaneously
- SciBooNE, K2K datasets used as cross check





Fit of ND280 data to constrain rate



Event rate in angular bins, vs momentum for ND280 data
CCQE sample (left)
CCnQE sample (right)

Tune flux, cross section models with a likelihood fit

- p-θ distribution is sensitive to rate (Φ x σ)
- CC cross sections, ν_μ flux uncertainties reduced substantially; $\Delta\chi^2 = 29.1$, p=0.925

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

Expected number of ν_e candidates

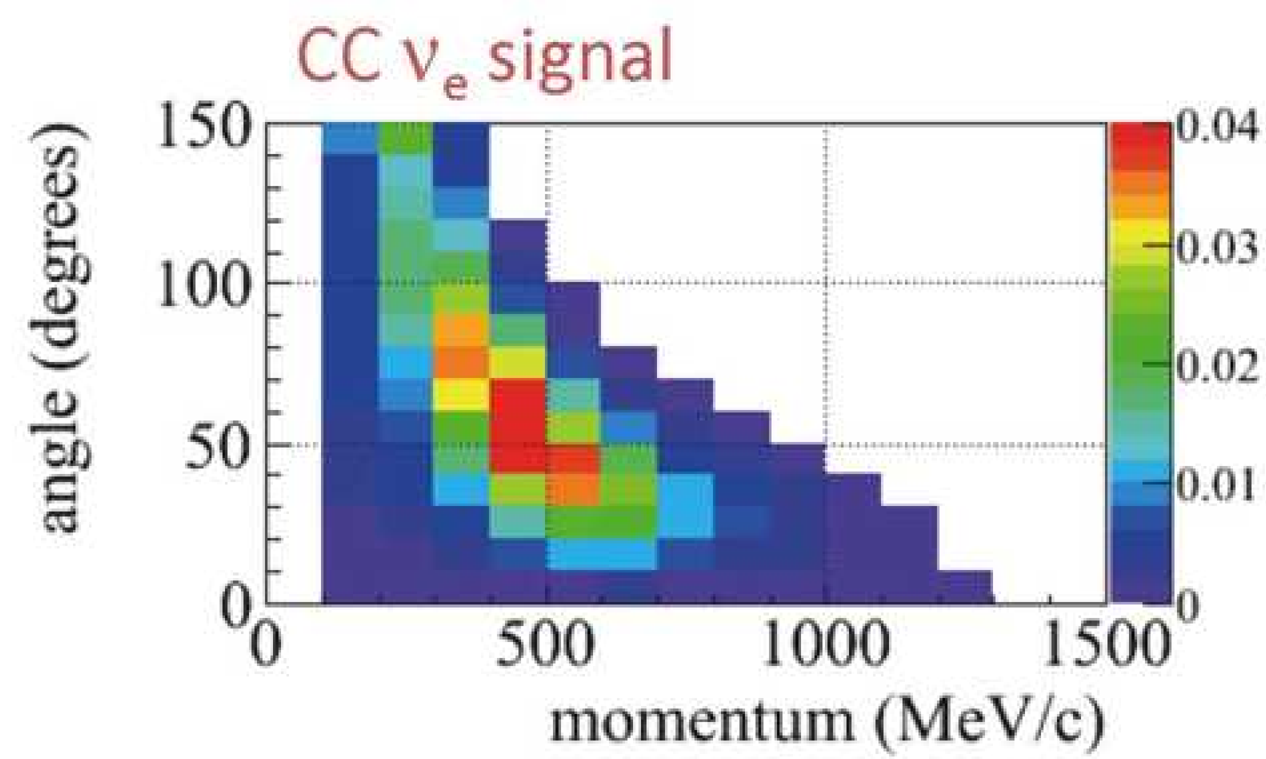
After ND tuning, expect ~11 events with ν_μ to ν_e oscillation, 3 without

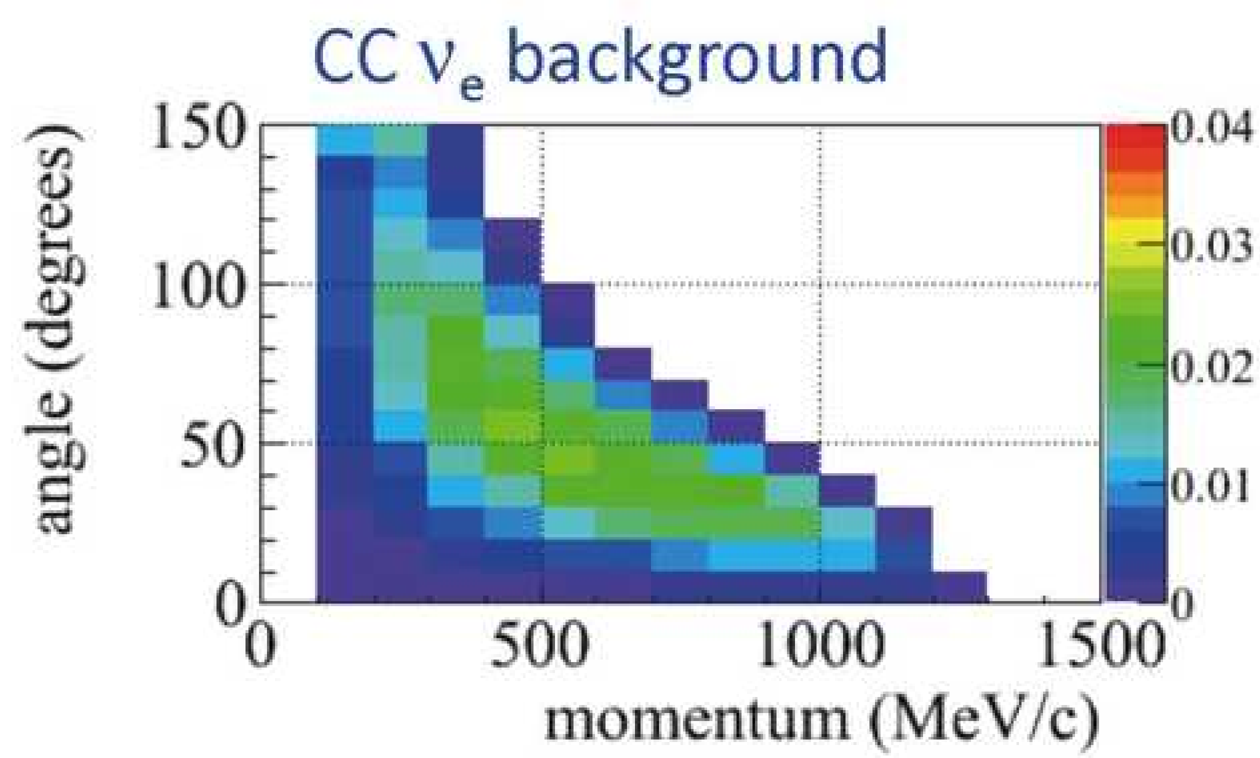
- Rate, p-θ kinematics of events distinguishes signal from background

Signal (ν_μ to ν_e osc)	# events
@$\sin^2 2\theta_{13}$=0.1,δcp=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@Δm^2_{32}=2.4 x 10^{-3} eV^2, $\sin^2 2\theta_{23}$=1.0





Overall systematic uncertainty

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

- Overall uncertainty halved with use of the near detector data

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$\nu_e$signal@Δm^2_{32} =2.4 x 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%**

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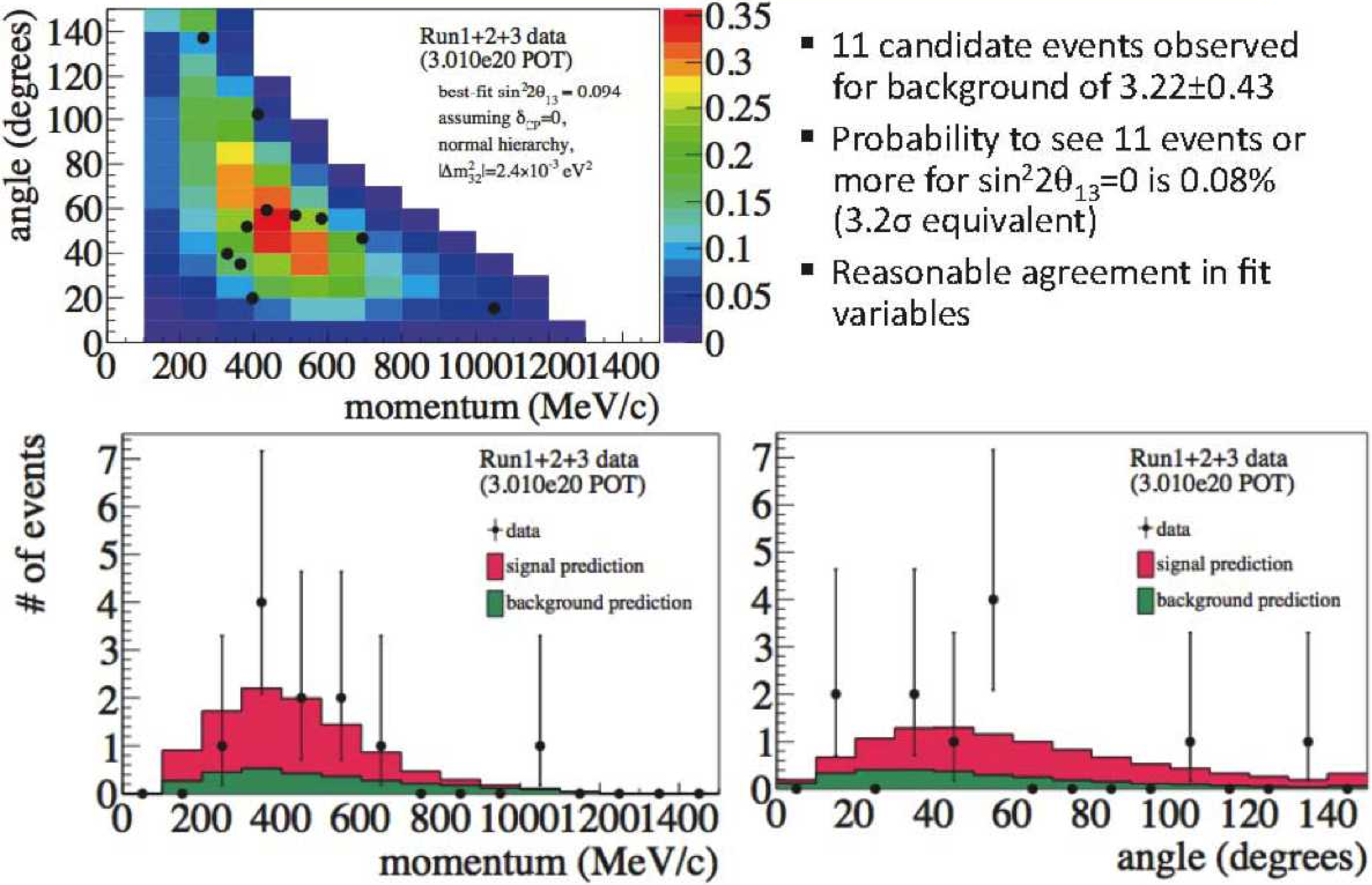
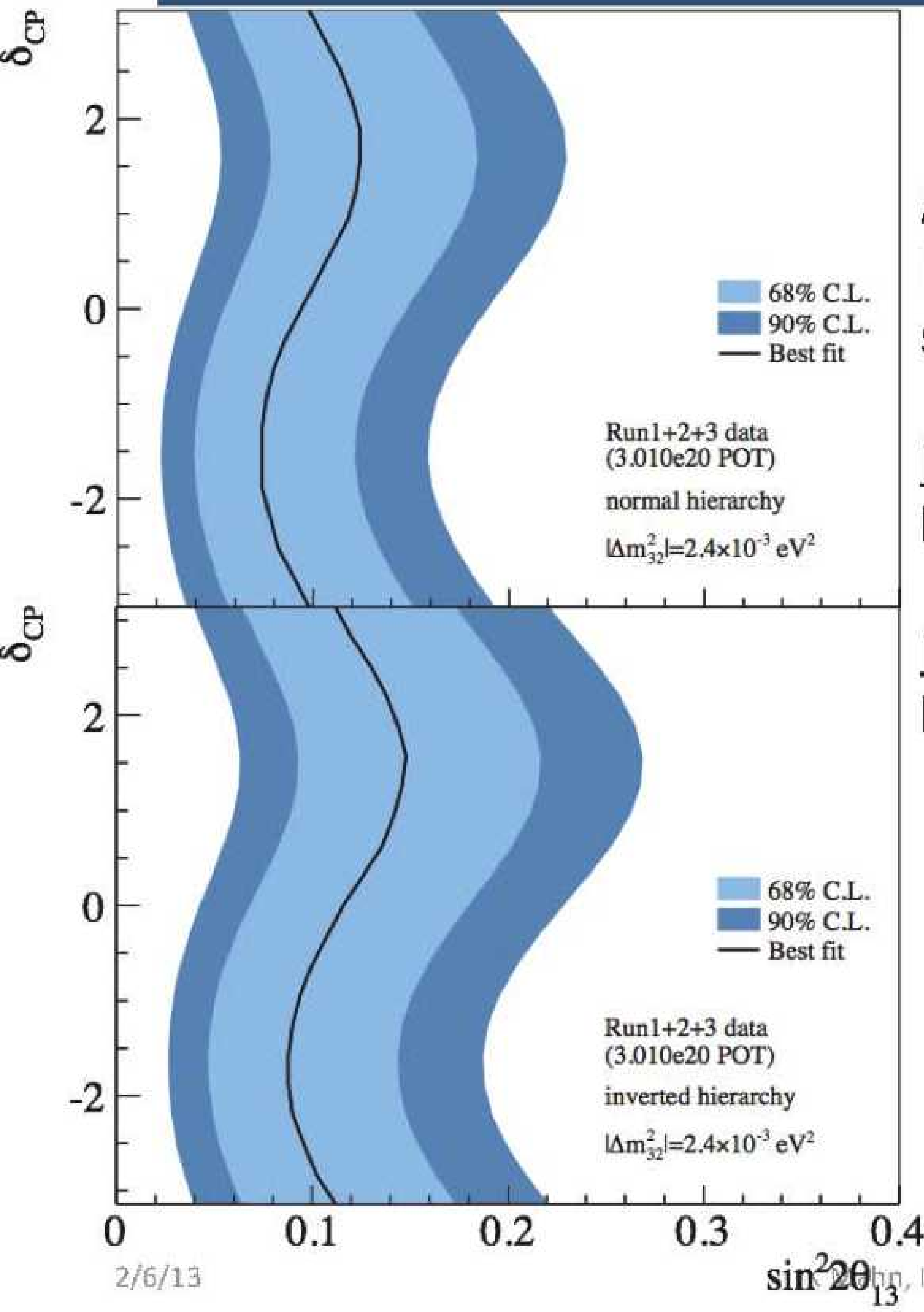
What do we see in data?

Distributions of ν_e candidates



- 11 candidate events observed for background of 3.22±0.43
- Probability to see 11 events or more for $\sin^2 2\theta_{13}=0$ is 0.08% (3.2σ equivalent)
- Reasonable agreement in fit variables

ν_e appearance results



Assuming:

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

$\sin^2 2\theta_{23} = 1$

Normal hierarchy ($\Delta m^2 > 0$), $\delta_{CP}=0$ (top)

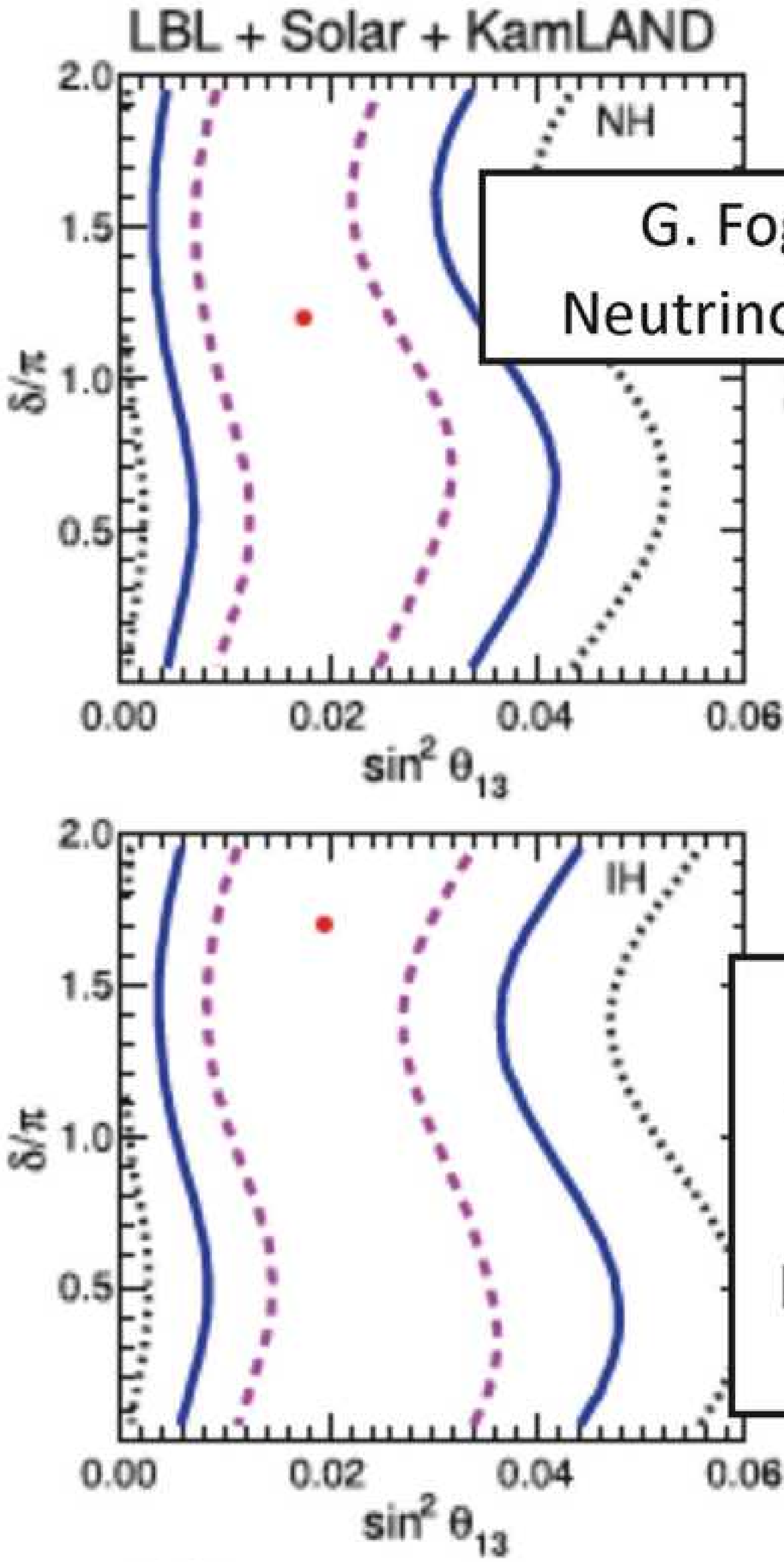
best fit $\sin^2 2\theta_{13} = 0.094\ {+0.053}\ {-0.040}$

Inverted hierarchy ($\Delta m^2 < 0$), $\delta_{CP}=0$ (bottom)

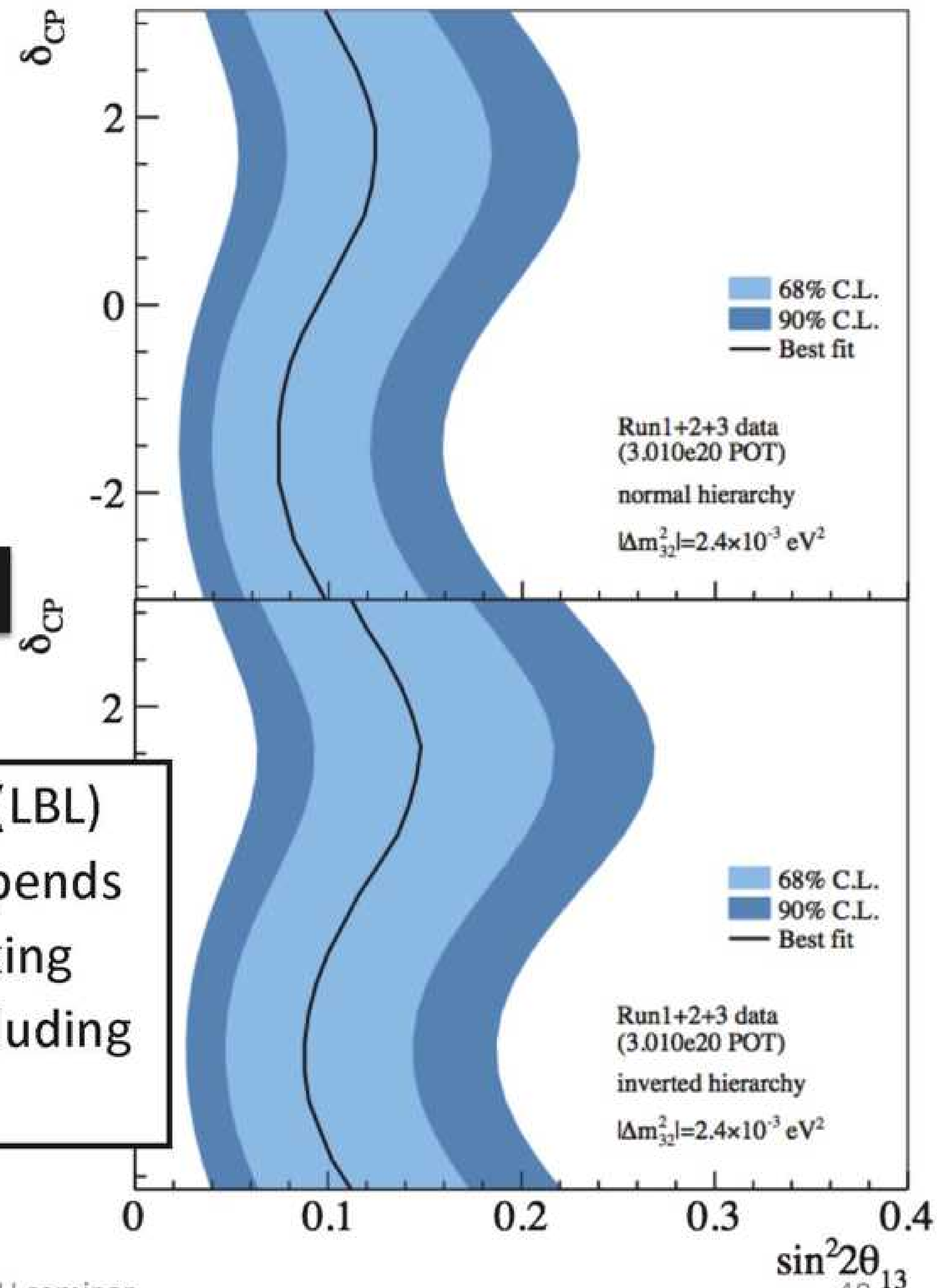
best fit $\sin^2 2\theta_{13} = 0.116\ {+0.063}\ {-0.049}$

- Rate+shape fit (p-θ) consistent with rate-only fit, and to reconstructed energy fit

Implications of a large θ_{13}

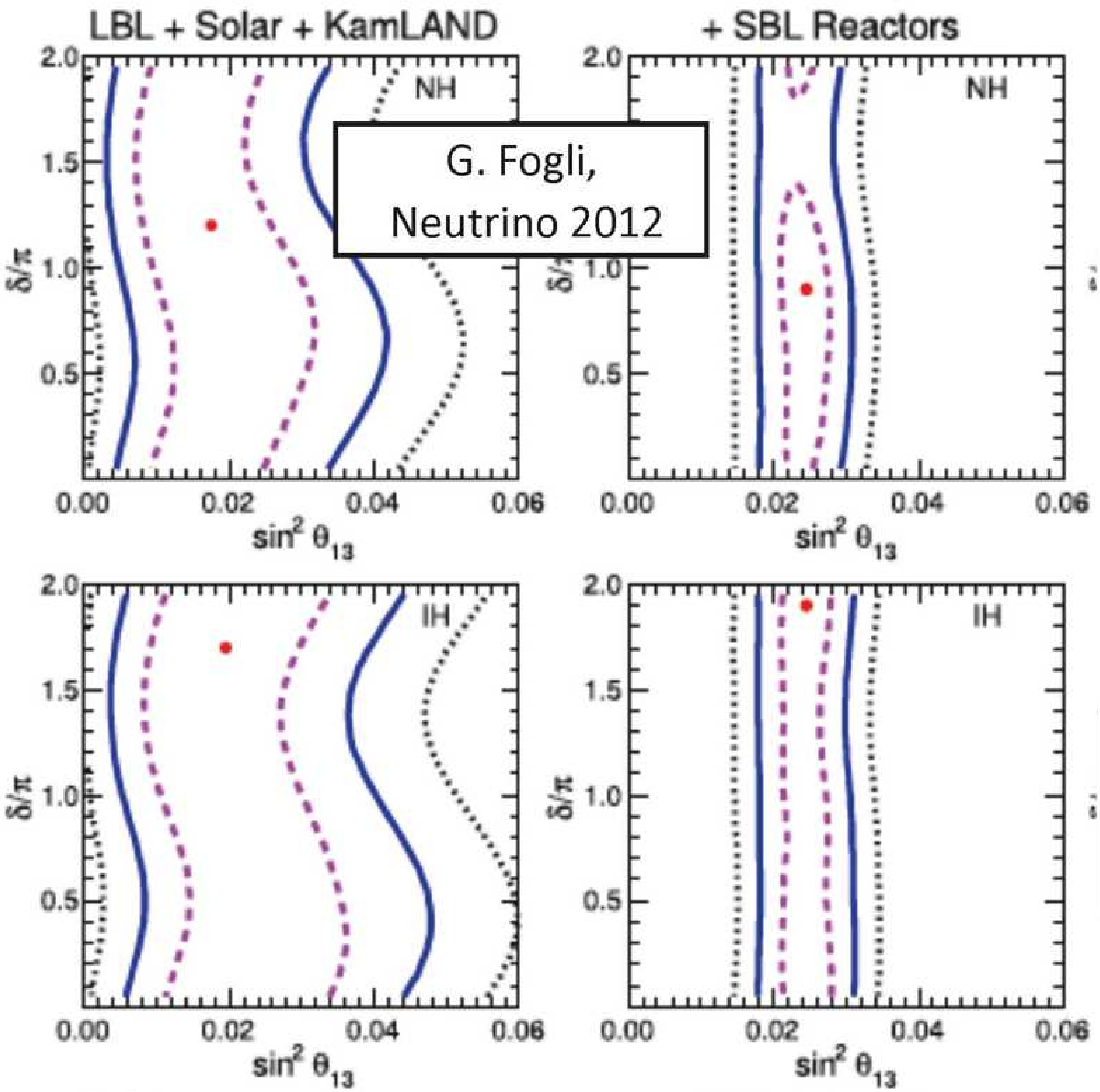


G. Fogli, Neutrino 2012



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

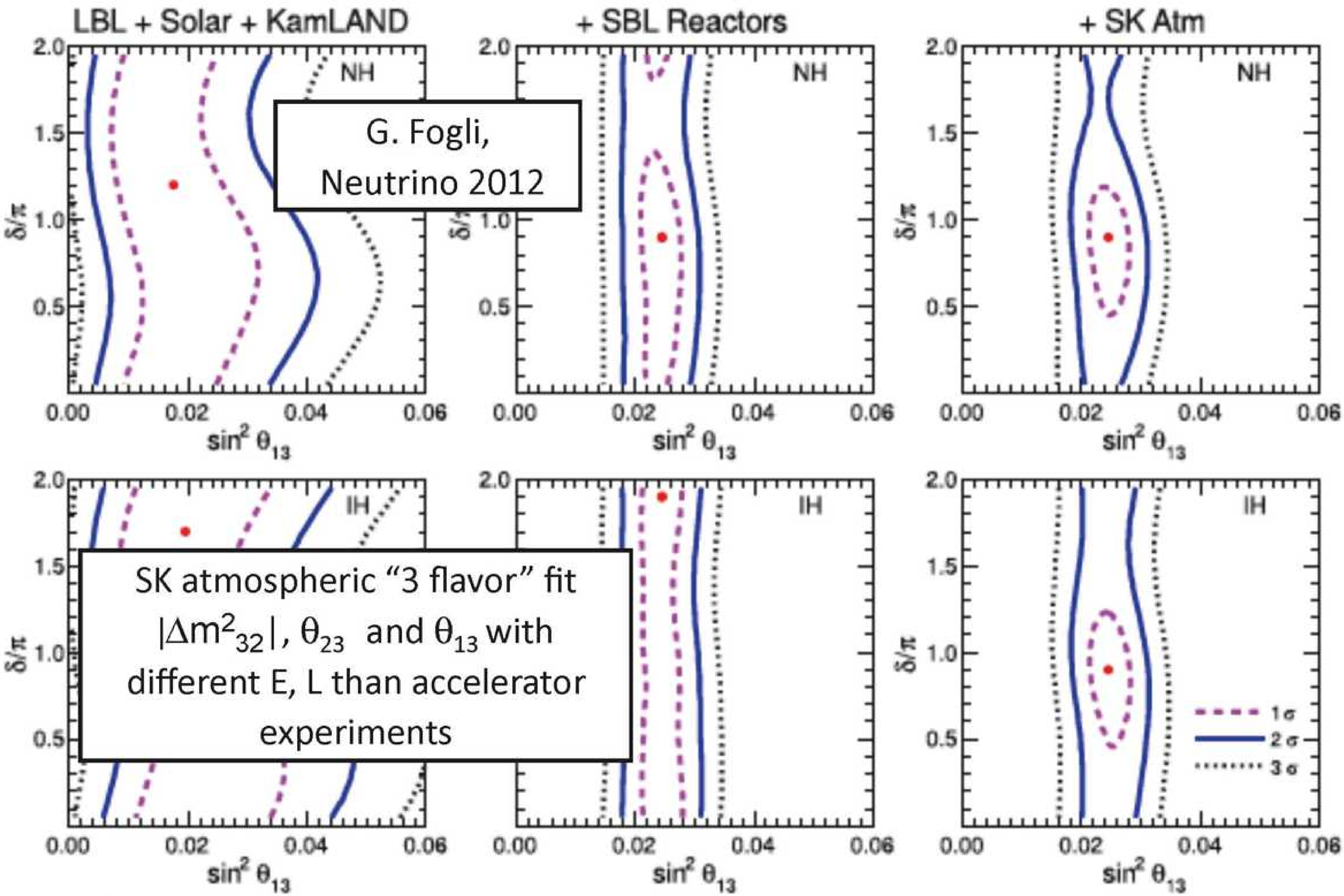
Implications of a large θ_{13}



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

Electron neutrino appearance

$$
\begin{aligned}
P(\nu_\mu \rightarrow \nu_e) \;=\;& 4C_{13}^2 S_{13}^2 S_{23}^2 \cdot \sin^2 \Delta_{31} \quad \text{Leading term} \\
& +8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21} \\
\text{CP violating term} \quad & -8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \cdot \sin\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21} \\
& +4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta) \cdot \sin^2 \Delta_{21} \quad \text{solar} \\
& -8C_{13}^2 S_{12}^2 S_{23}^2 \cdot \frac{aL}{4E_\nu} (1 - 2S_{13}^2) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \quad \text{matter effects} \\
& +8C_{13}^2 S_{13}^2 S_{23}^2 \frac{a}{\Delta m_{13}^2} (1 - 2S_{13}^2) \sin^2 \Delta_{31}
\end{aligned}
$$

Appearance measurements are sensitive to all parameters in neutrino mixing

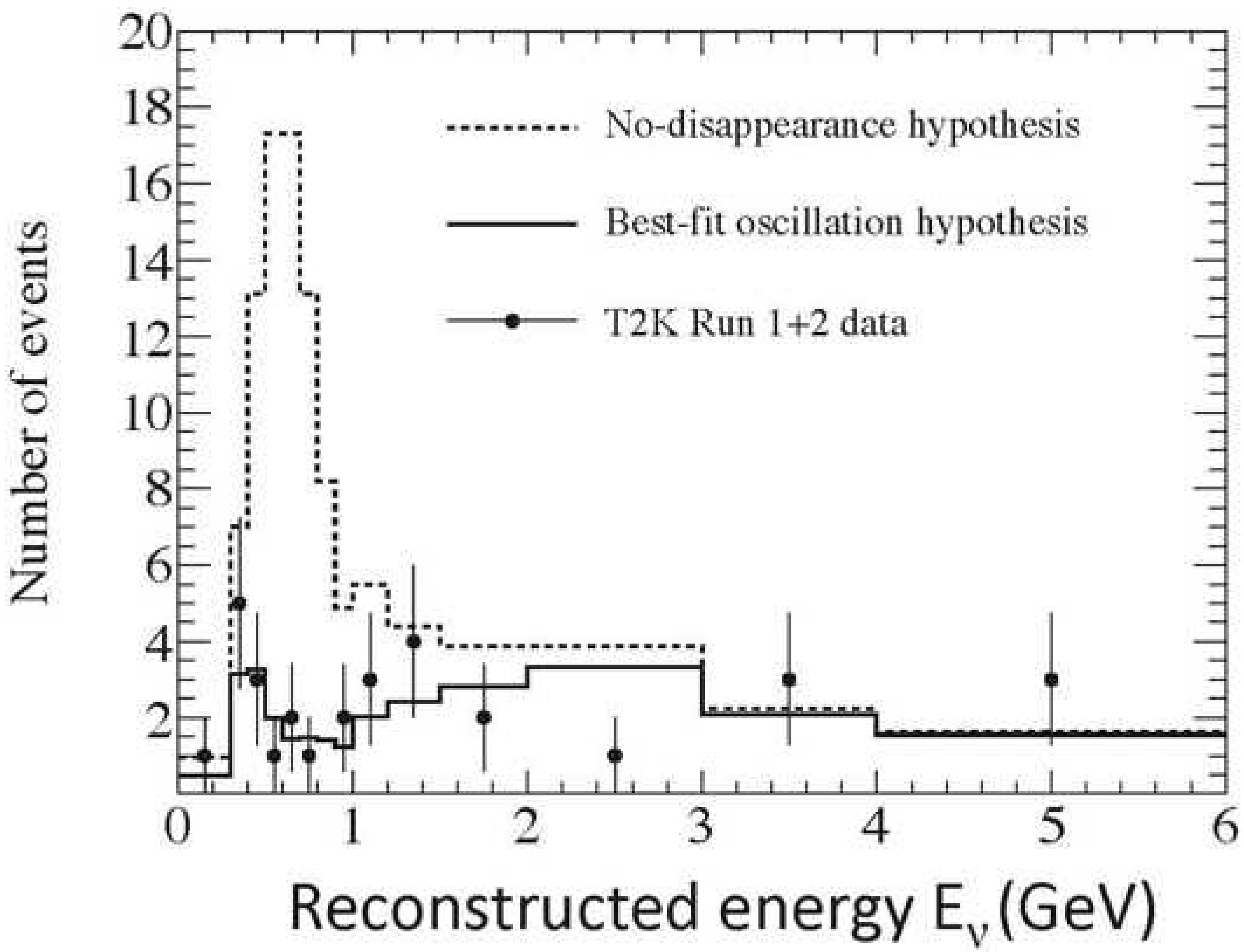
$$\theta_{12} = 33.6° \pm 1.0°$$

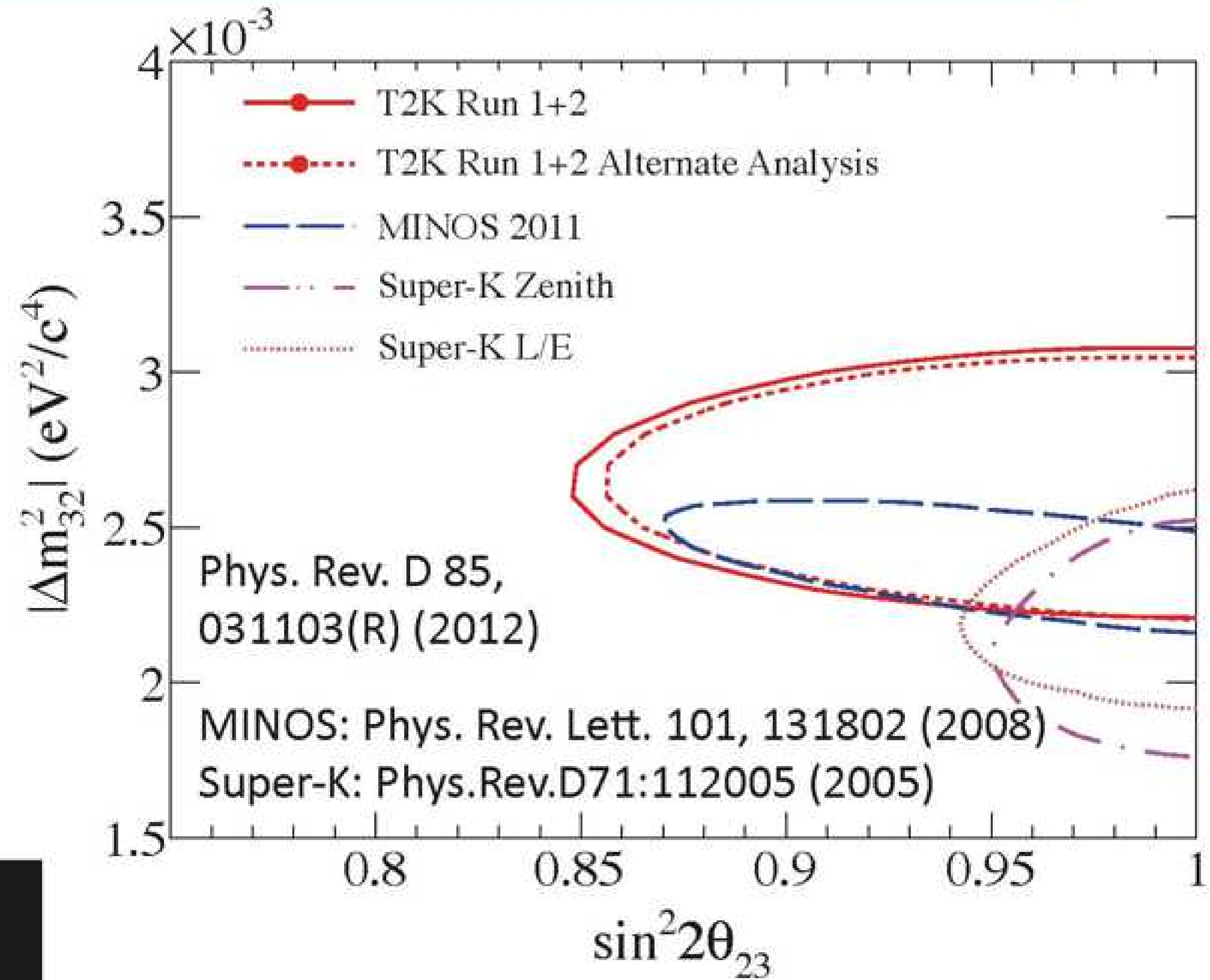
$$\theta_{23} = 45° \pm 6° \quad (90\%\text{CL})$$

$$\theta_{13} = 9.1° \pm 0.6° !$$

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

T2K first ν_μ disappearance results



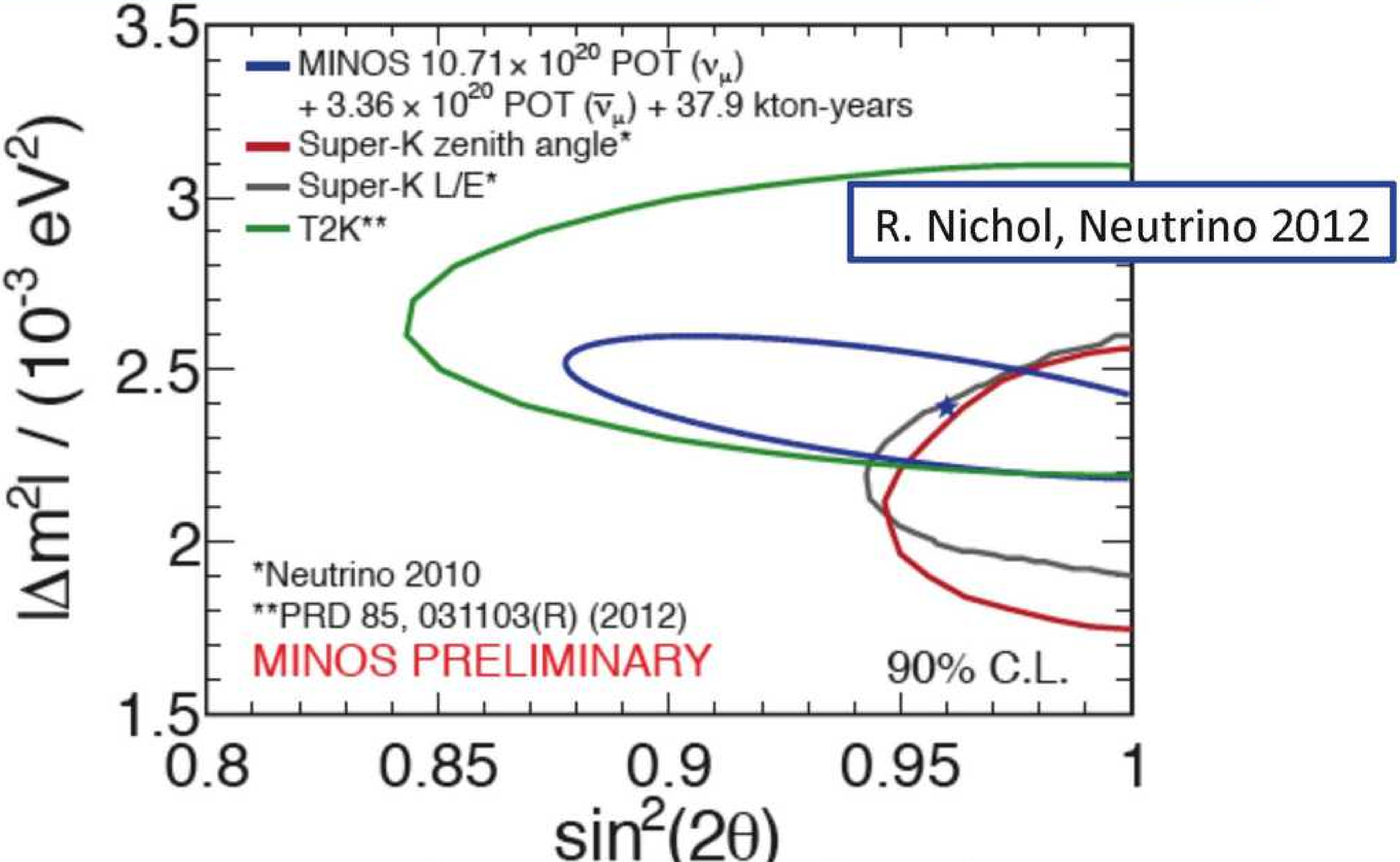


Summary of uncertainties	ν_μ signal Δm^2_{32}=2.4 x 10^{-3} eV^2 $\sin^2 2\theta_{23}$=1.0
ν flux	±4.8%
ν interactions	+8.3 -8.1%
Near detector	+6.2 -5.9%
Far detector	±10.3%
Total	+15.4 -15.1%

- Disappearance distorts energy spectrum and rate of ν_μ candidates
- 31 events pass ν_μ selection with $103.6^{+13.8}_{-13.4}$ expected for no oscillation

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

ν_μ disappearance status



New MINOS atmospheric + accelerator best fit moved away from maximal mixing

T2K new results for Lake Louise

- Sensitivity to maximal mixing of $\sin^2 2\theta_{23}$ >0.91 (90%CL)
- With this coming year's data set, $\sin^2 2\theta_{23}$ >0.95 (90%CL)

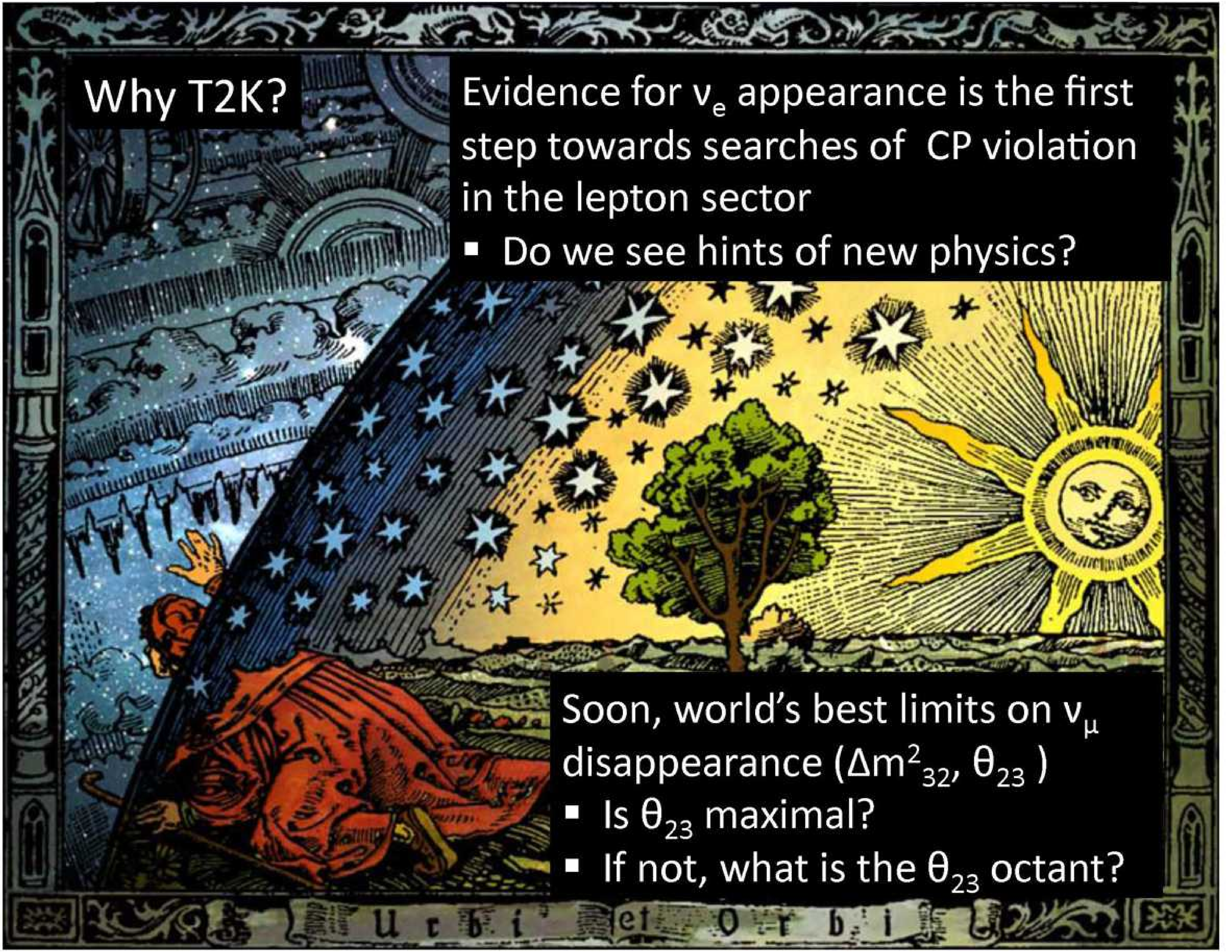
Why T2K?

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?

Soon, world's best limits on ν_μ disappearance (Δm^2_{32}, θ_{23})

- Is θ_{23} 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:

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

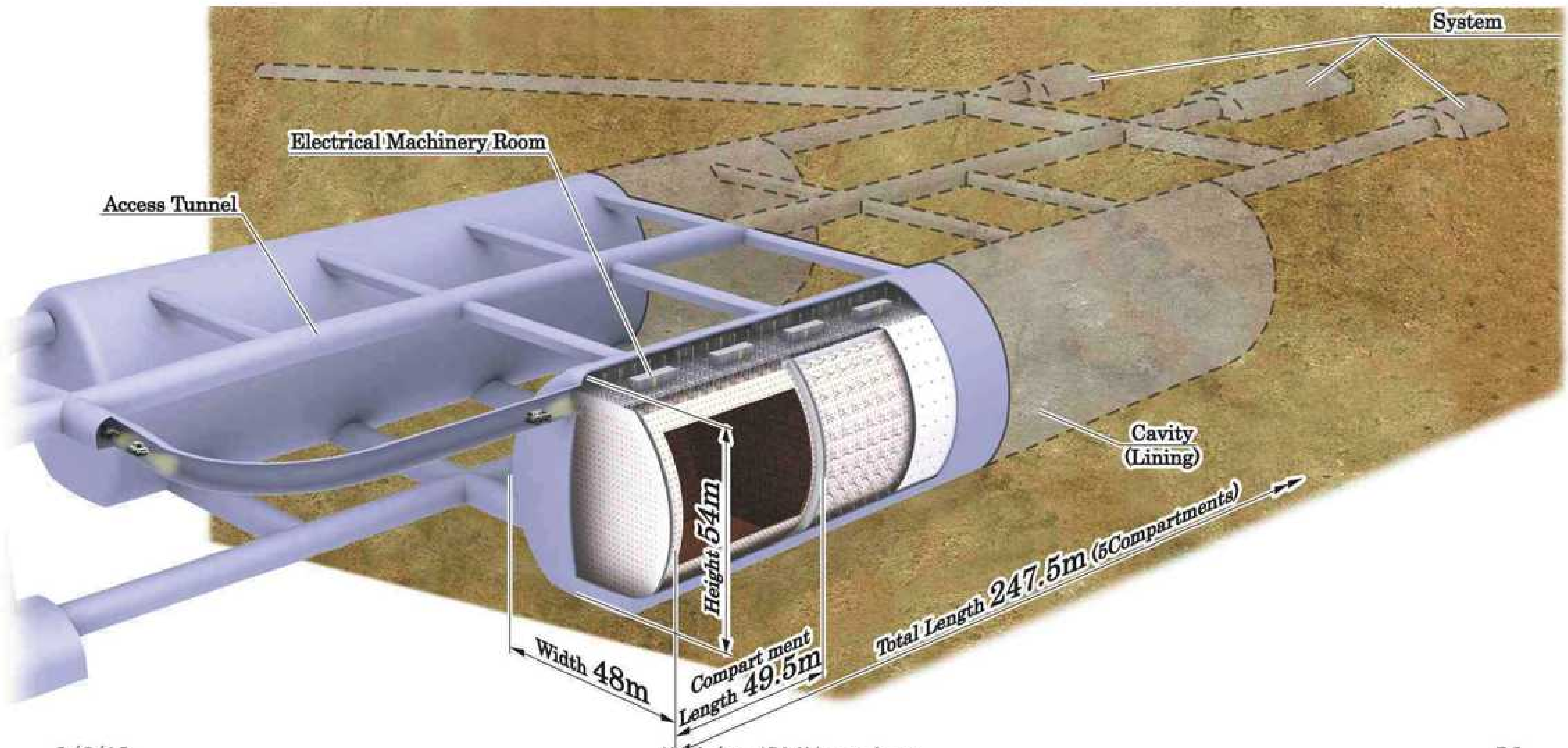
With θ_{13} “large”, then A_{CP} is small (~20-30%), so the measurement of δ_{CP} need systematic uncertainties of <5% or better

- T2K’s current statistics: 11 events
- 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, off-axis angle as T2K, different cavern
- Other physics reach: solar neutrinos, atmospheric neutrinos, astrophysical neutrinos (supernova), geo-neutrinos and proton decay



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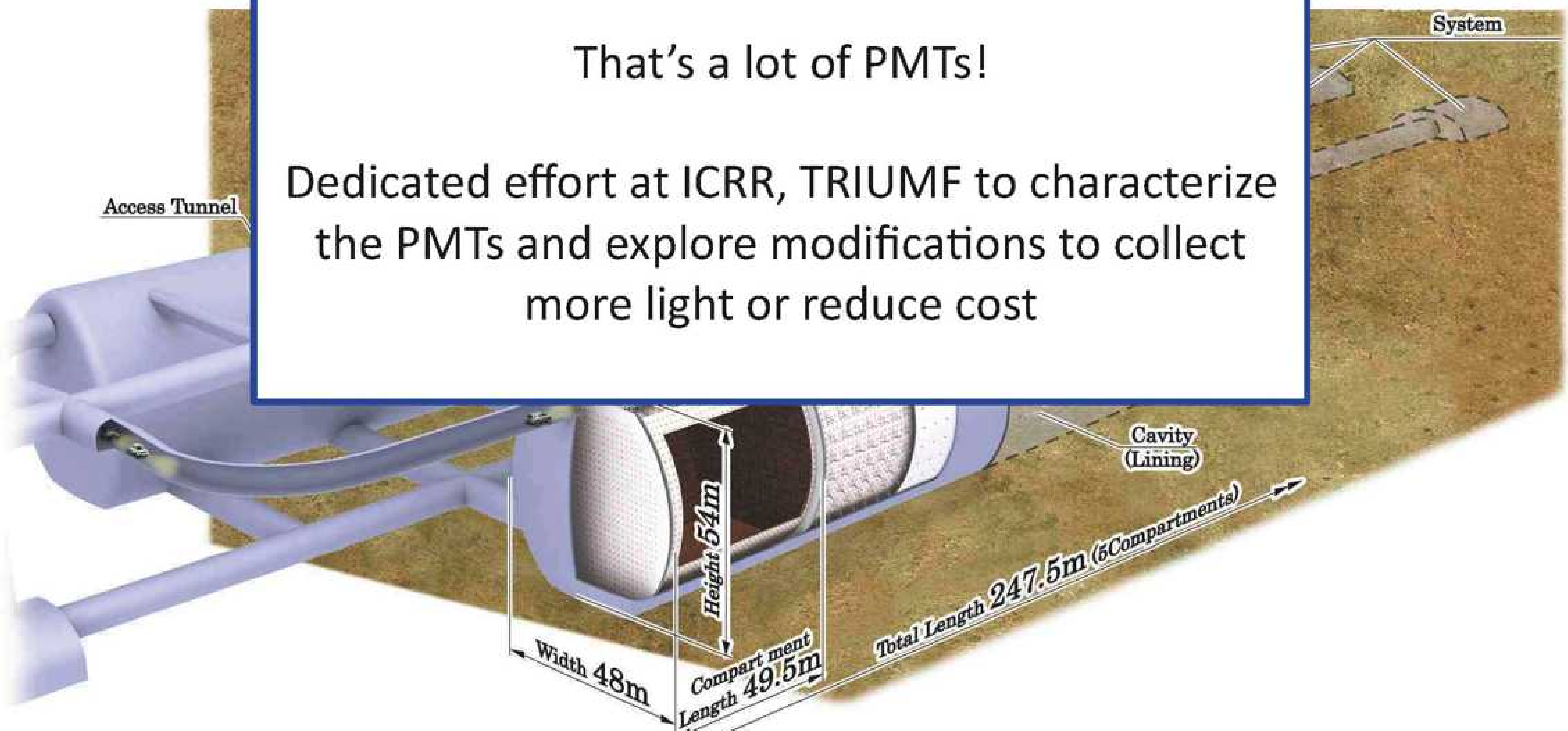
- 99,000 inner PMTs, 25,000 veto region PMTs (10 compartments)
- Same neutrino beamline, off-axis angle as T2K, different cavern
- Other physics reach: solar neutrinos, atmospheric neutrinos, astrophysical neutrinos (supernova), geo-neutrinos and proton decay



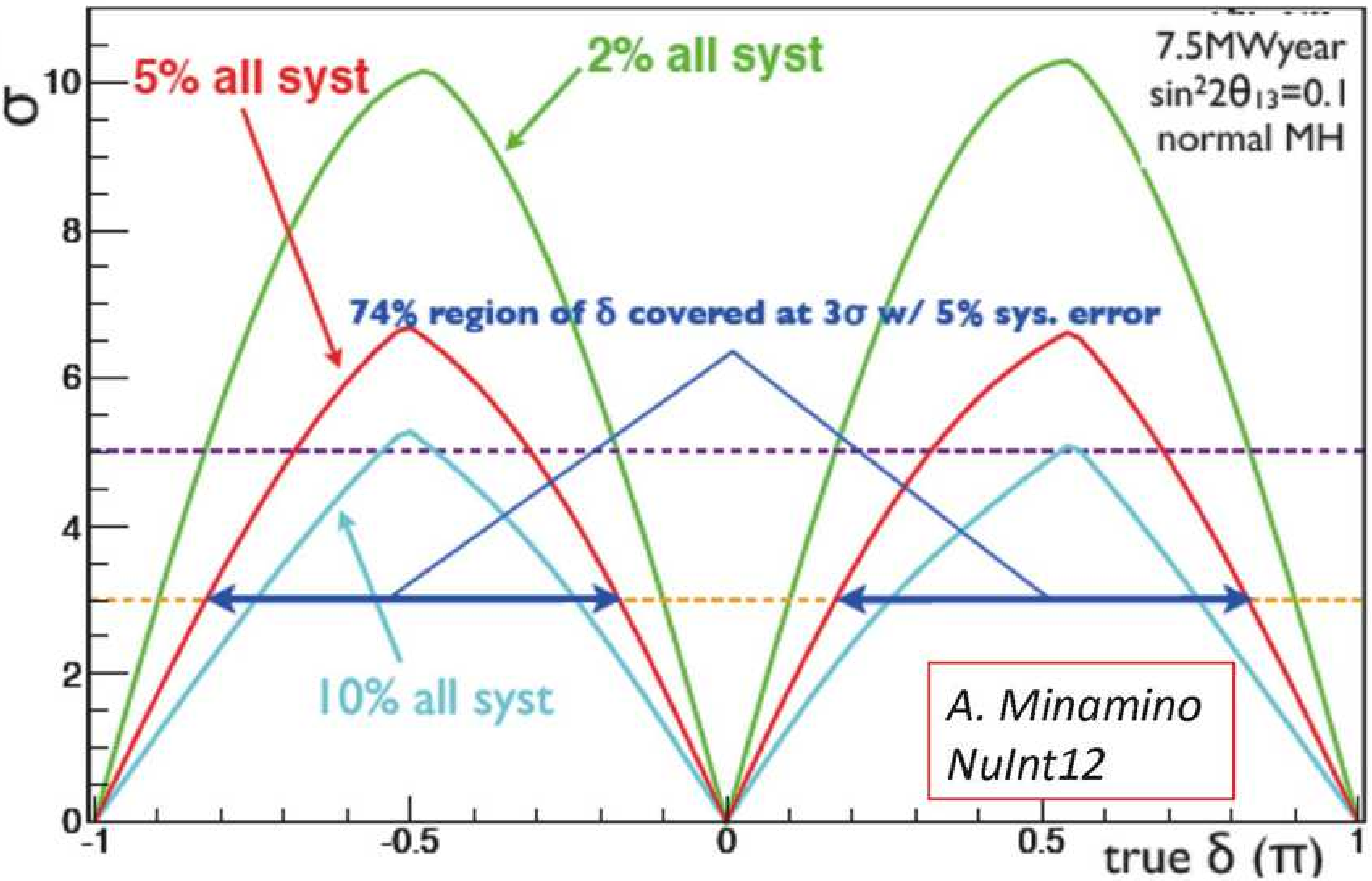
That's a lot of PMTs!

Dedicated effort at ICRR, TRIUMF 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

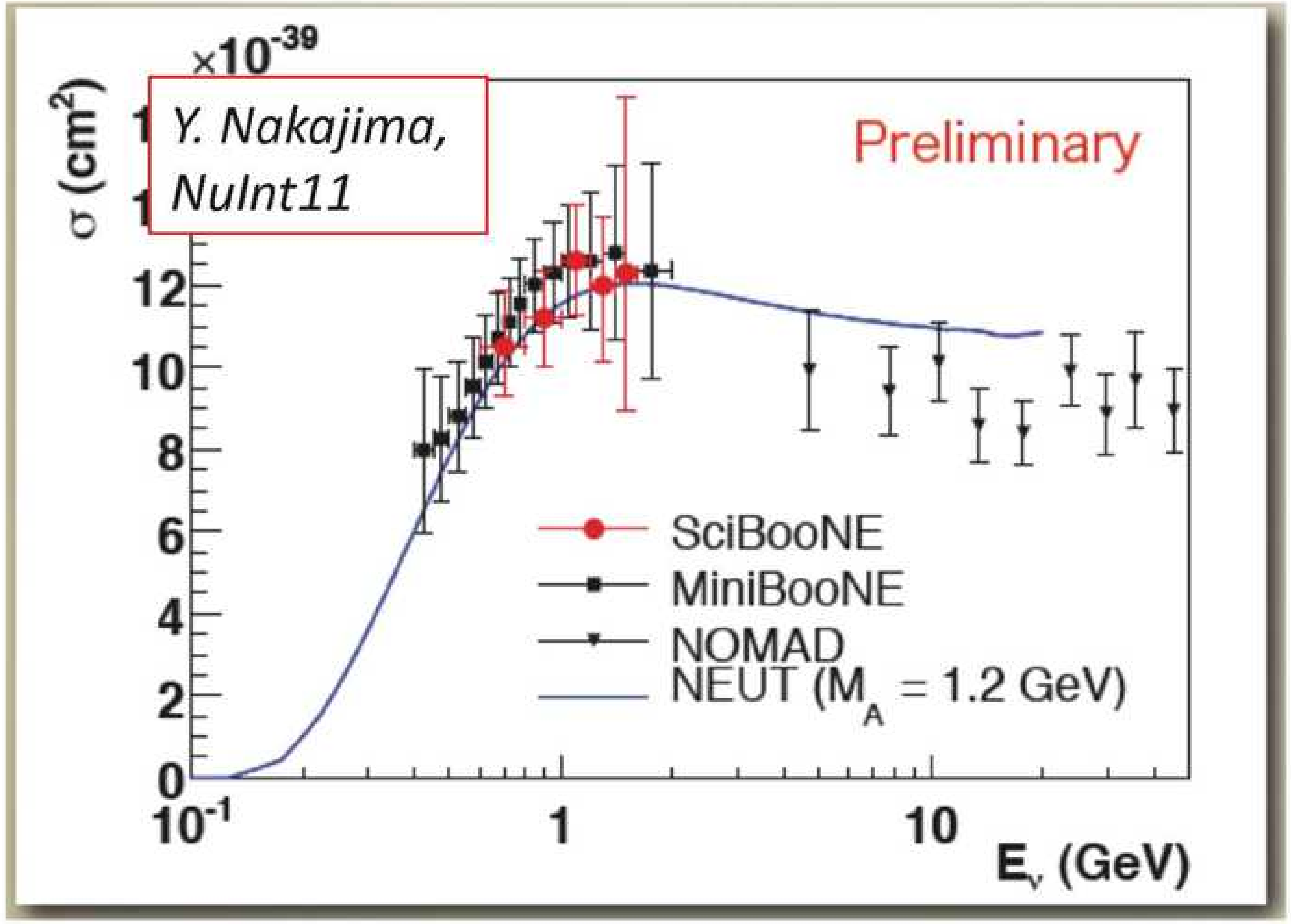


With <5% overall systematic uncertainty, HK could observe evidence of nonzero δ_{CP}

- 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%

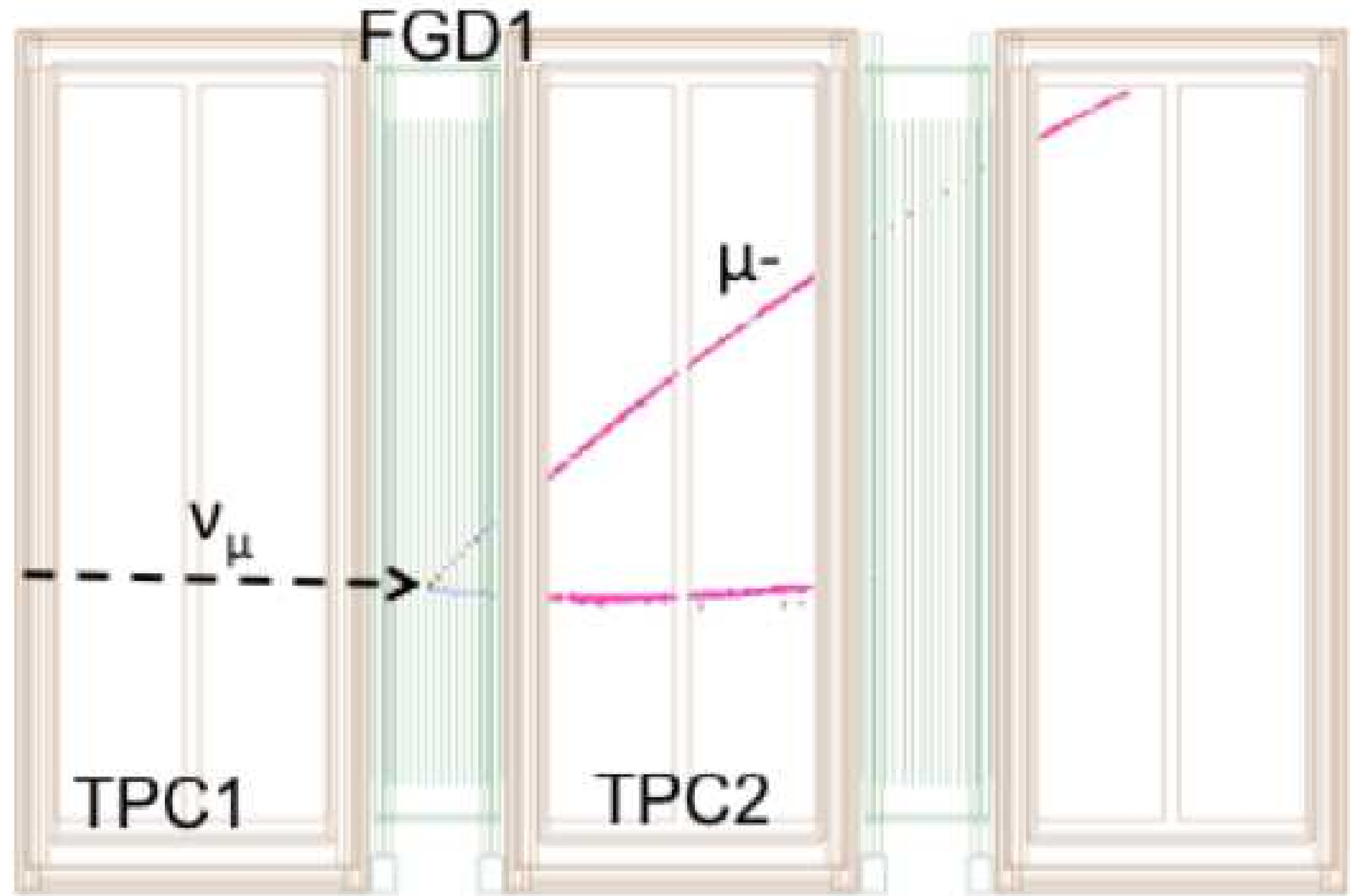


The largest systematic uncertainties currently on the T2K ν_e appearance analysis are neutrino interaction model uncertainties

- 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

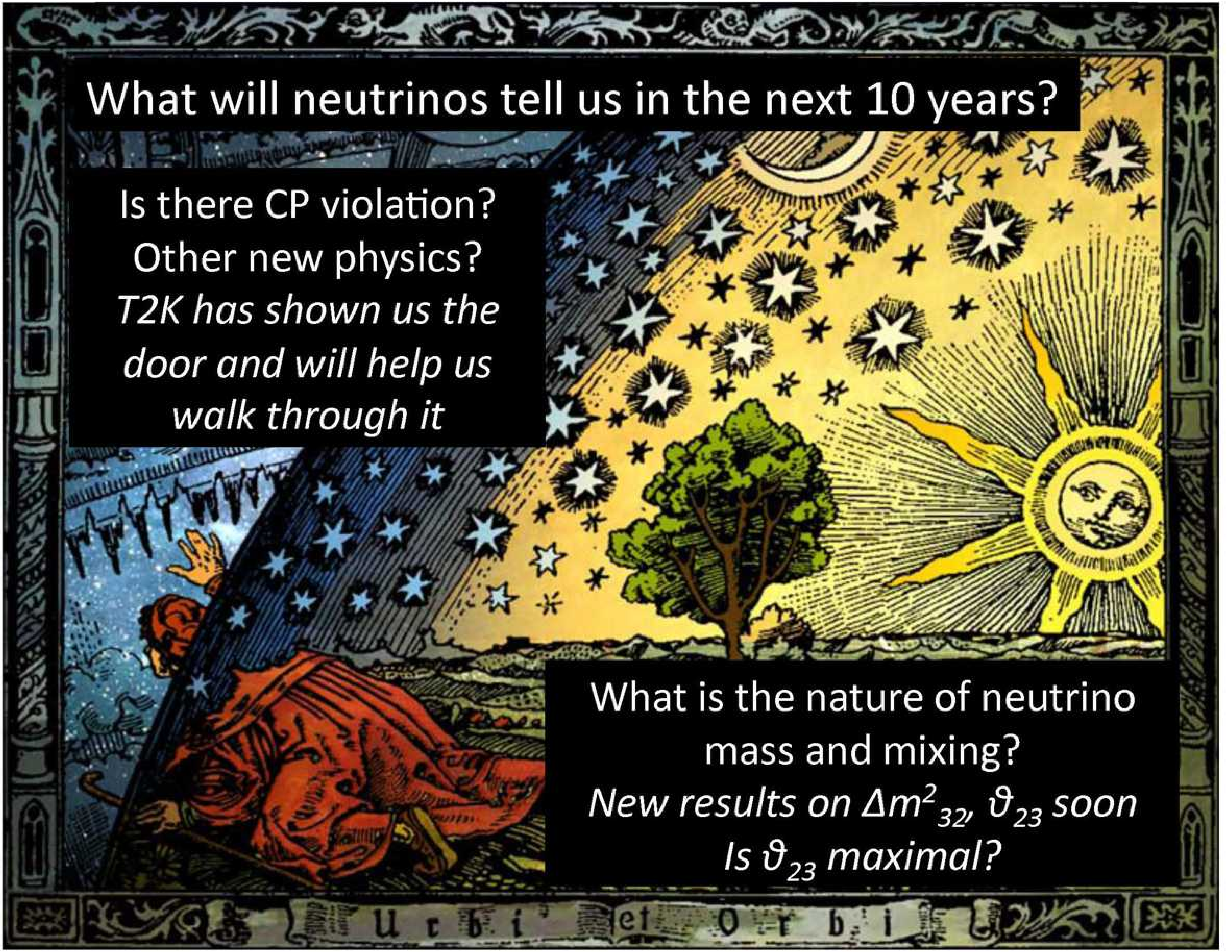
T2K's efforts to reduce cross section uncertainties

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%



Incorporate alternate or updated neutrino interaction models into our simulations
- Combination of experimental data (ν, e, π) and theory

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) this summer
- ND280 performance, limitations important to determine what is needed for a HK near detector program
- Investigate what is achievable on T2K for antineutrino, ν_e cross sections


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 results on Δm^2_{32}, ϑ_{23} soon
Is ϑ_{23} maximal?
Urbi et Orbi

Backup slides

Disentangling ν_e appearance

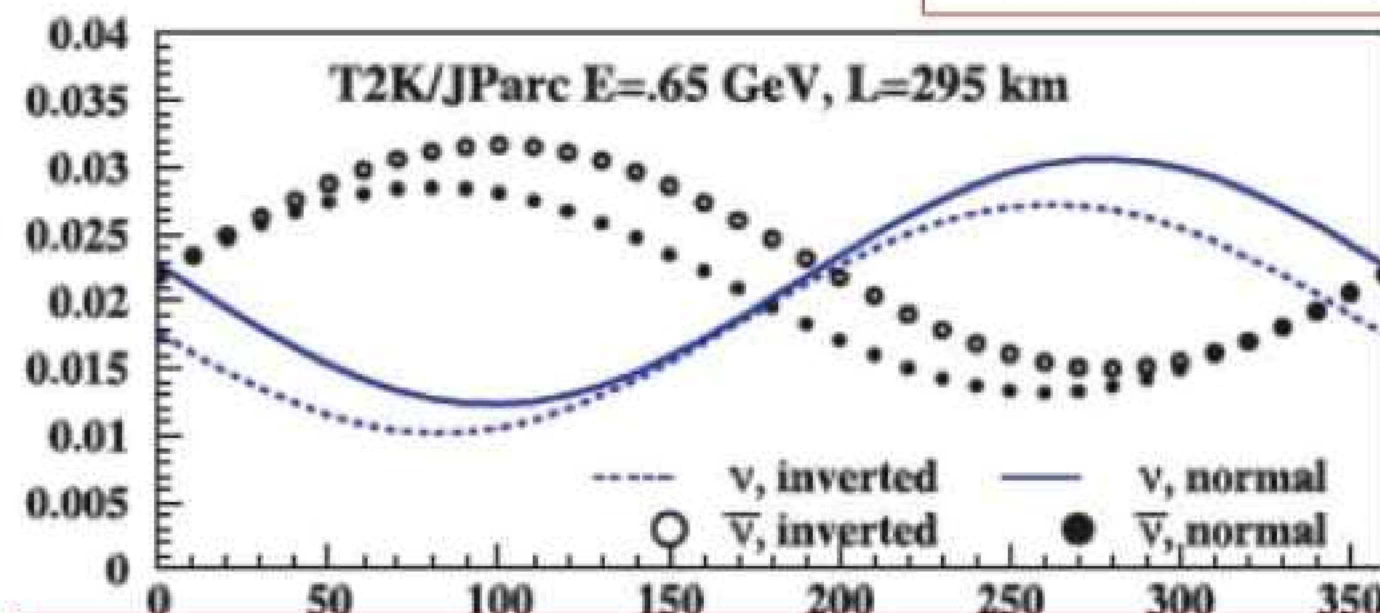
$$
\begin{aligned}
P(\nu_\mu \to \nu_e) \;=\;& 4C_{13}^2 S_{13}^2 S_{23}^2 \cdot \sin^2 \Delta_{31} \quad \text{Leading term} \\
&+8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21} \\
\text{CP violating term} \quad & -8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \cdot \sin\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21} \\
&+4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta) \cdot \sin^2\Delta_{21} \quad \text{solar} \\
&-8C_{13}^2 S_{12}^2 S_{23}^2 \cdot \frac{aL}{4E_\nu} (1 - 2S_{13}^2) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \\
&+8C_{13}^2 S_{13}^2 S_{23}^2 \frac{a}{\Delta m_{13}^2} (1 - 2S_{13}^2) \sin^2\Delta_{31} \quad \text{matter effects}
\end{aligned}
$$

T. Nakaya, Neutrino2012

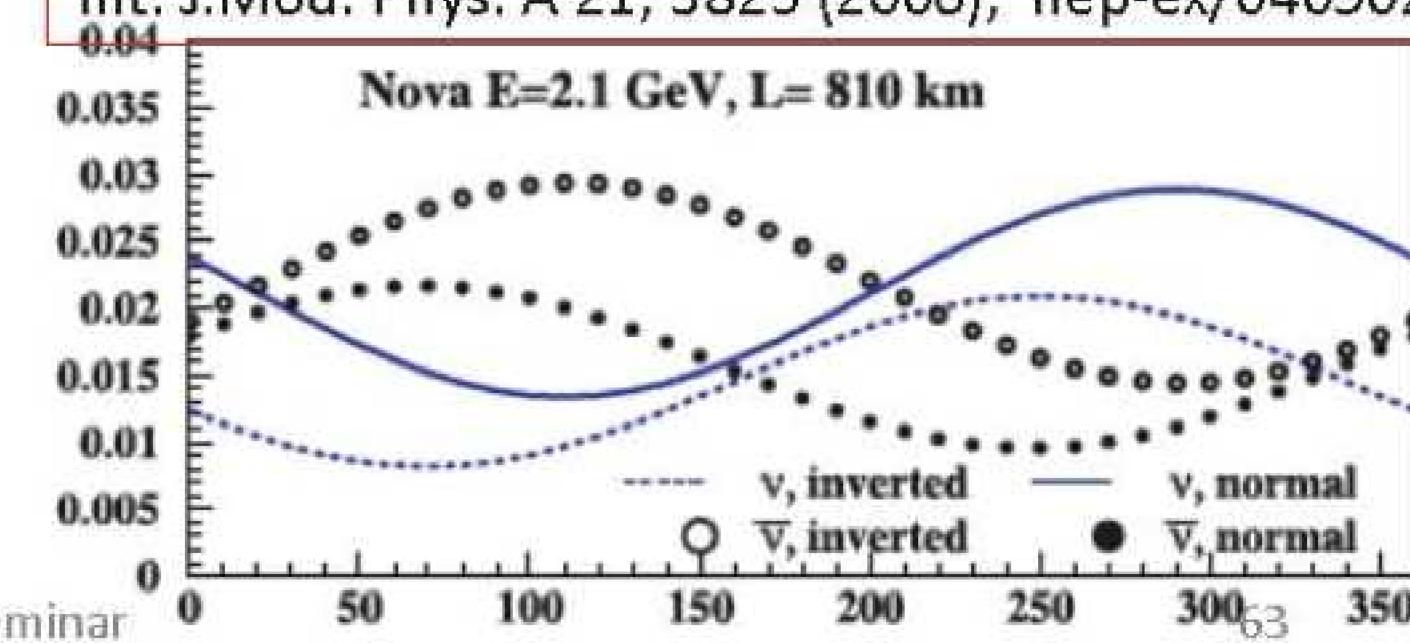
Plot of this oscillation probability for T2K and for Nova vs. δcp:

For fixed δcp:

1) The probability is different for neutrinos and antineutrinos (blue vs. black)
2) The probability is different depending on the hierarchy (solid vs. dashed)
3) Matter effects (and mass hierarchy) dependence is important for higher beam energy and longer baseline



Int. J.Mod. Phys. A 21, 3825 (2006), hep-ex/0409028



Disentangling ν_e appearance

The following is a common way to understand the physics sensitivity of a given experiment (or combinations of experiments)

Examples taken from R. Patterson at Neutrino 2012 for Nova

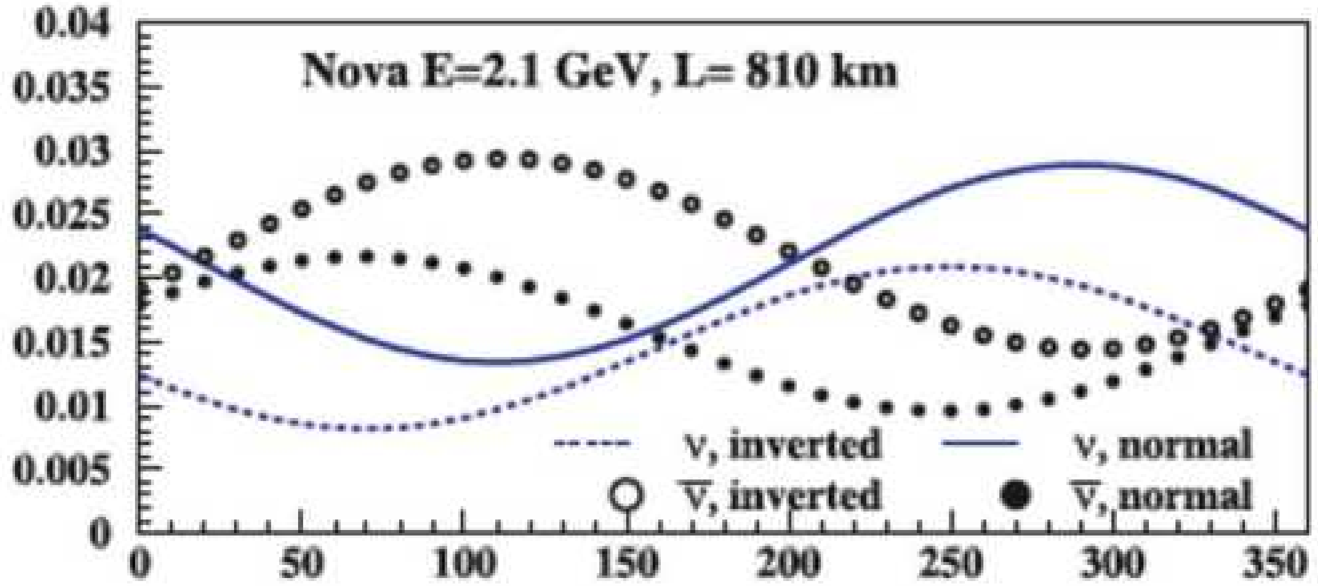
Please stop me if it stops making sense!

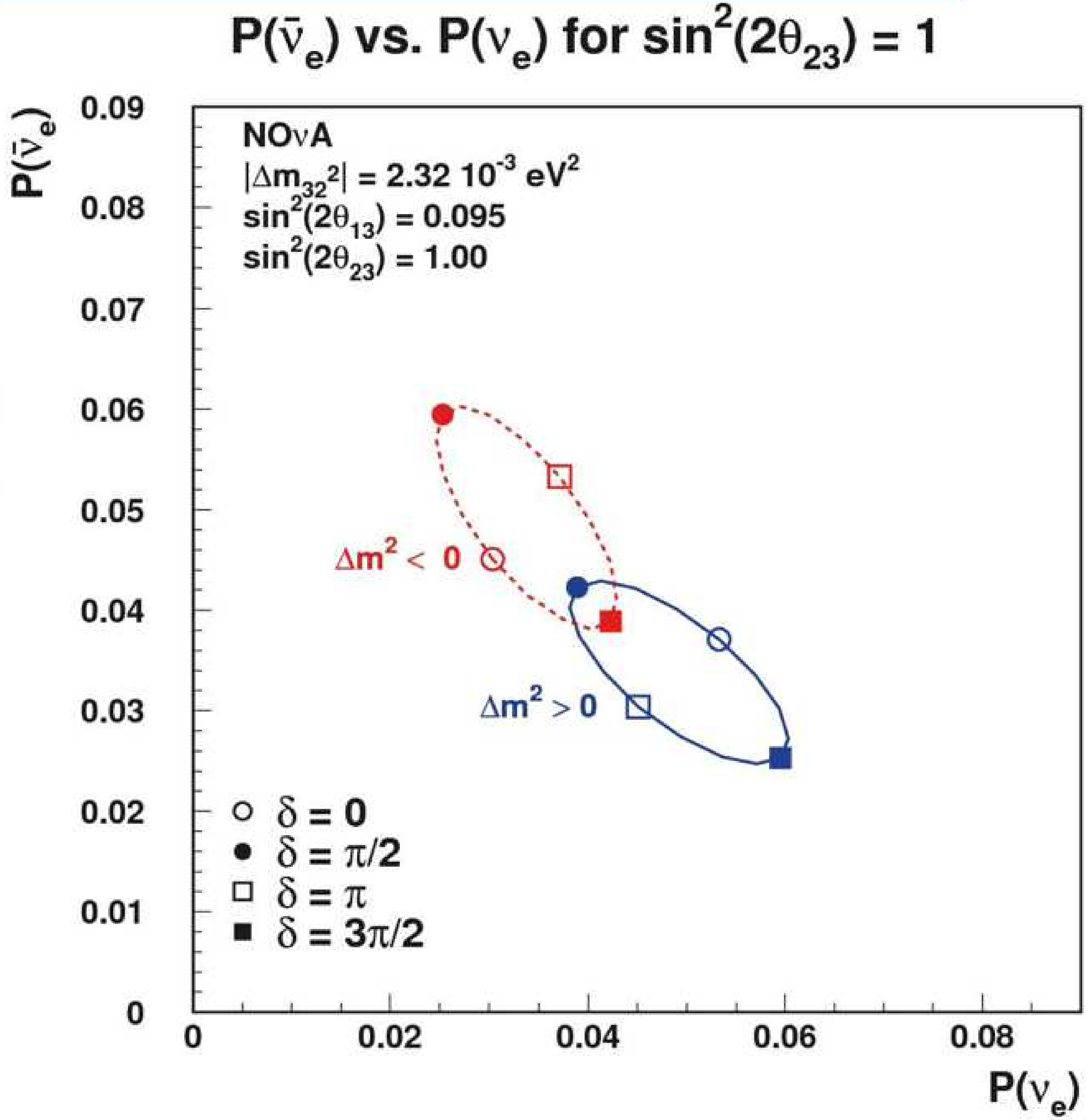
Determining the mass hierarchy

$P(\overline{\nu}_e)$ vs. $P(\nu_e)$

Sine wave becomes an ellipse

Ellipse shifts based on hierarchy





Determining the mass hierarchy

$P(\overline{\nu}_e)$ vs. $P(\nu_e)$

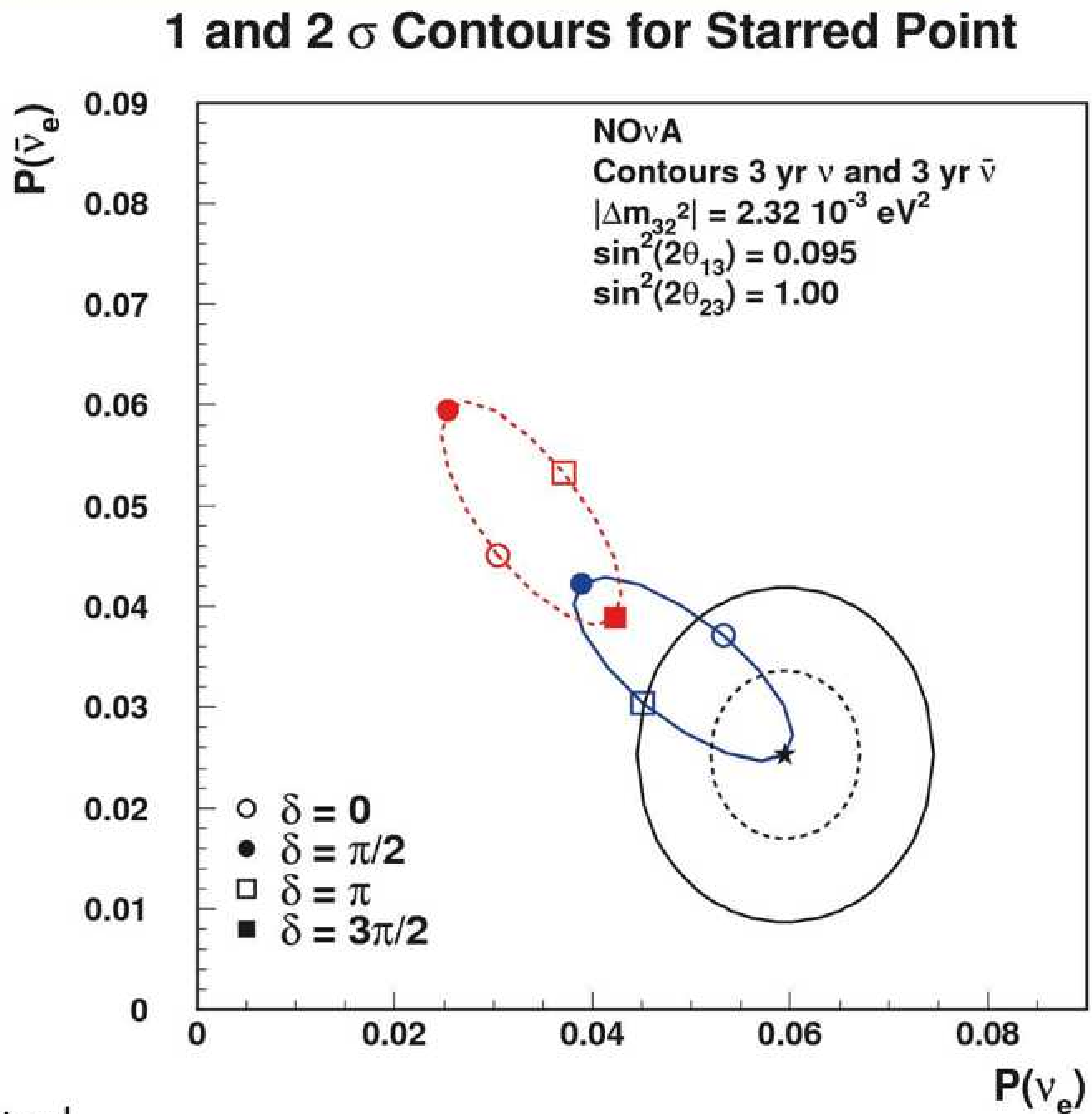
Sine wave becomes an ellipse

Ellipse shifts based on hierarchy

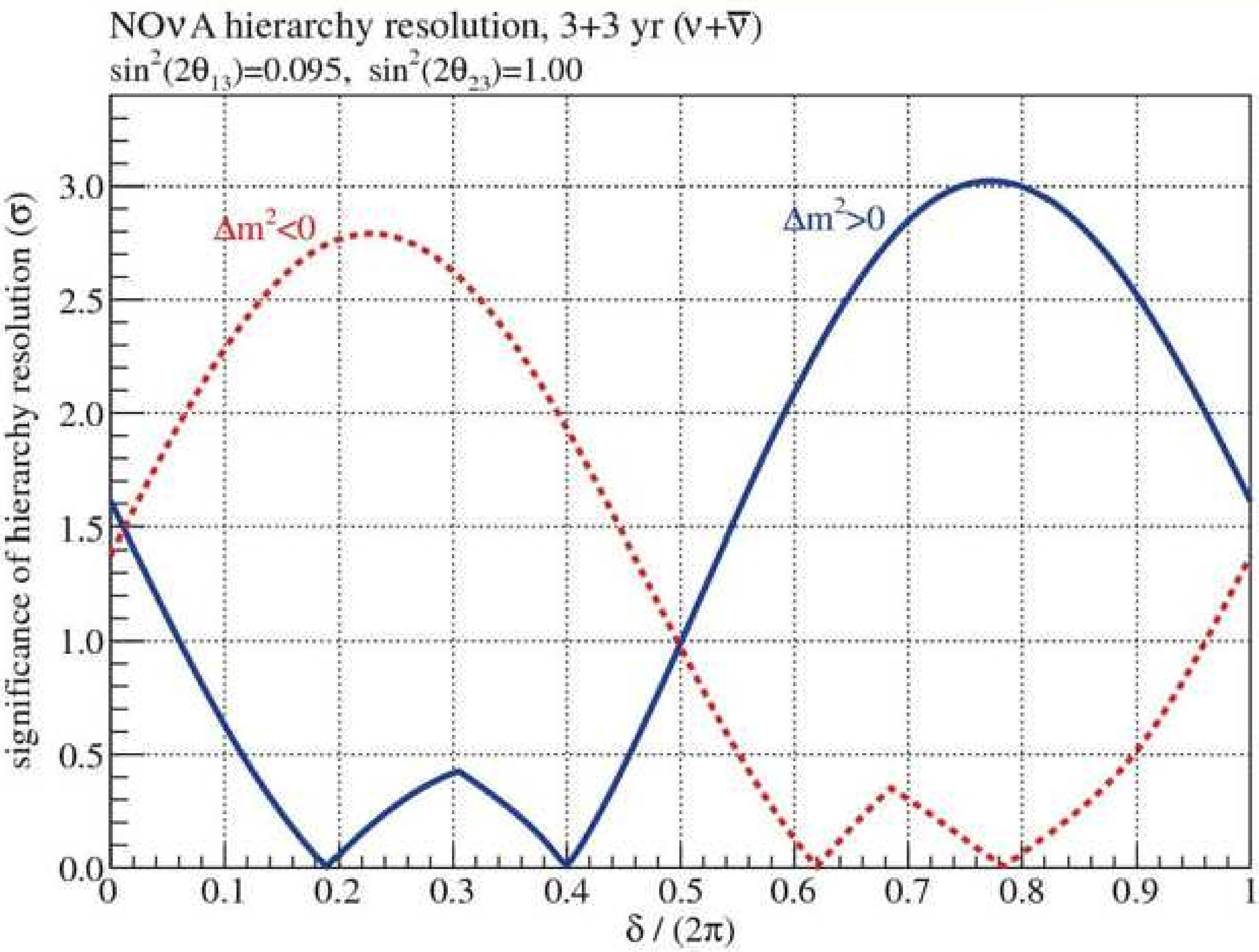
Nova runs for 3 years with a neutrino beam, 3 years with antineutrinos

Given a measured $P(\nu_e)$ and $P(\overline{\nu}_e)$, will select one point on the ellipse (black)

This particular point excludes all inverted hierarchy scenarios at >2σ

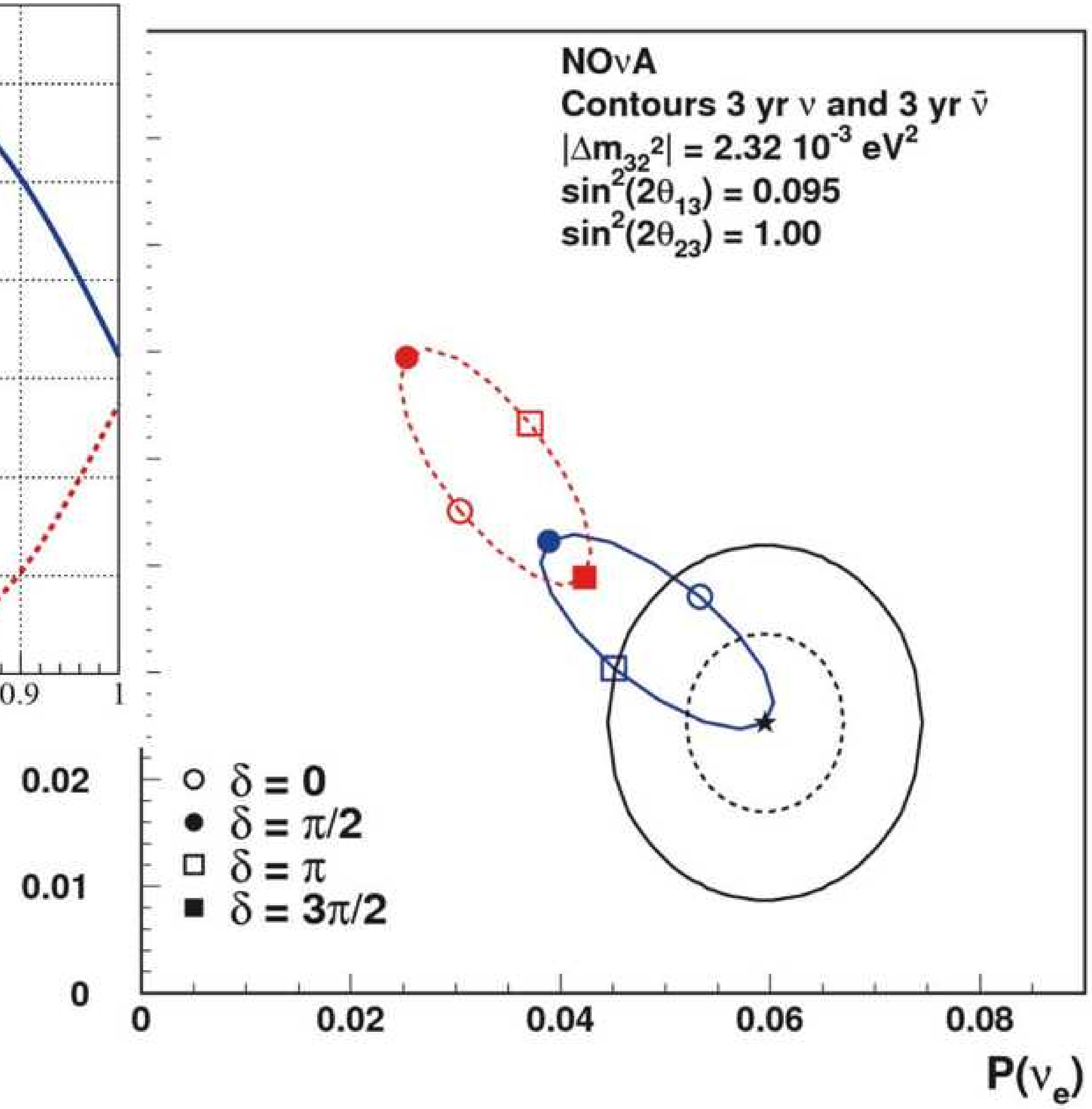


Determining the mass hierarchy

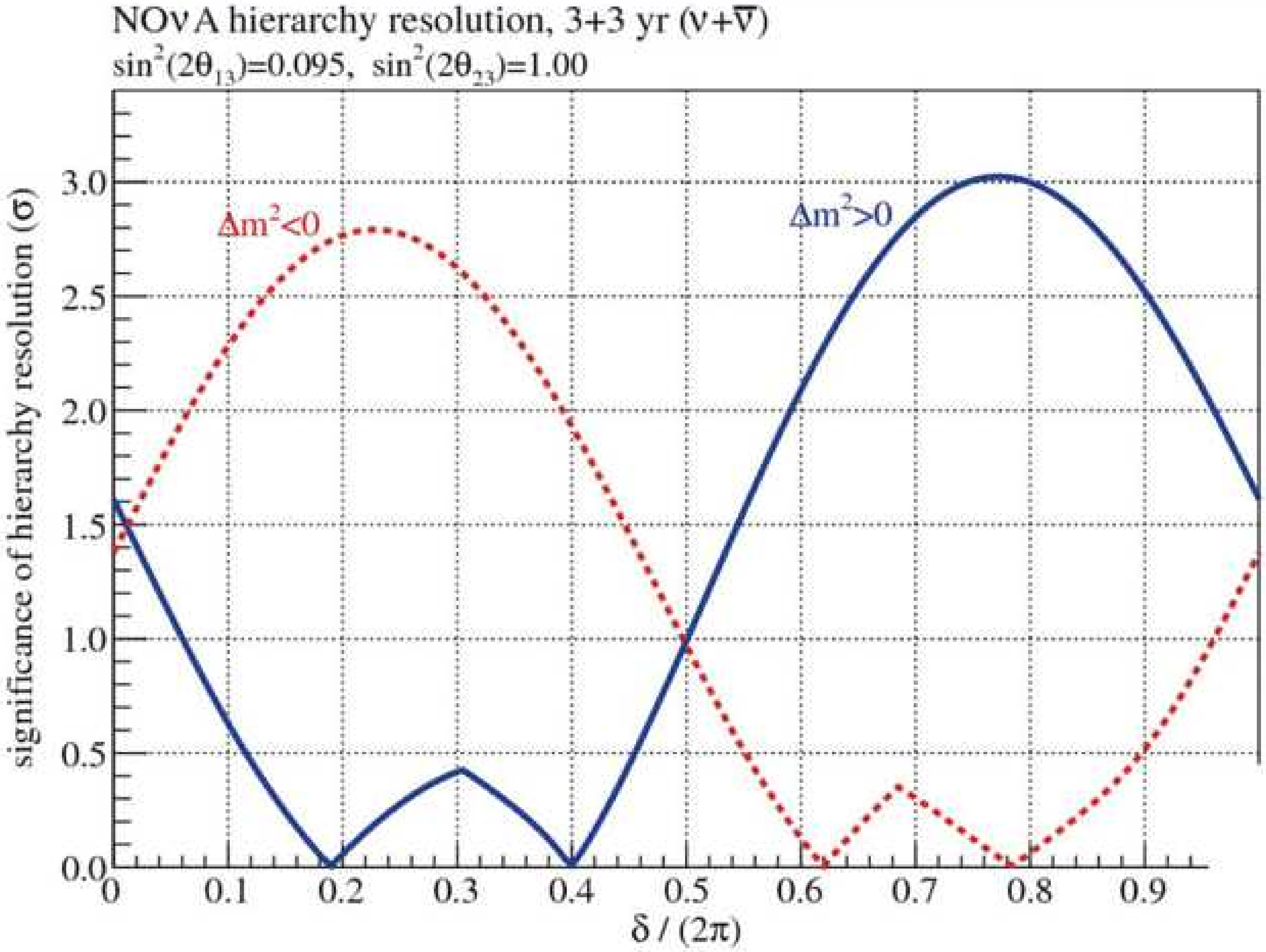


Now plot significance with which we determine the mass hierarchy (vs. δcp)

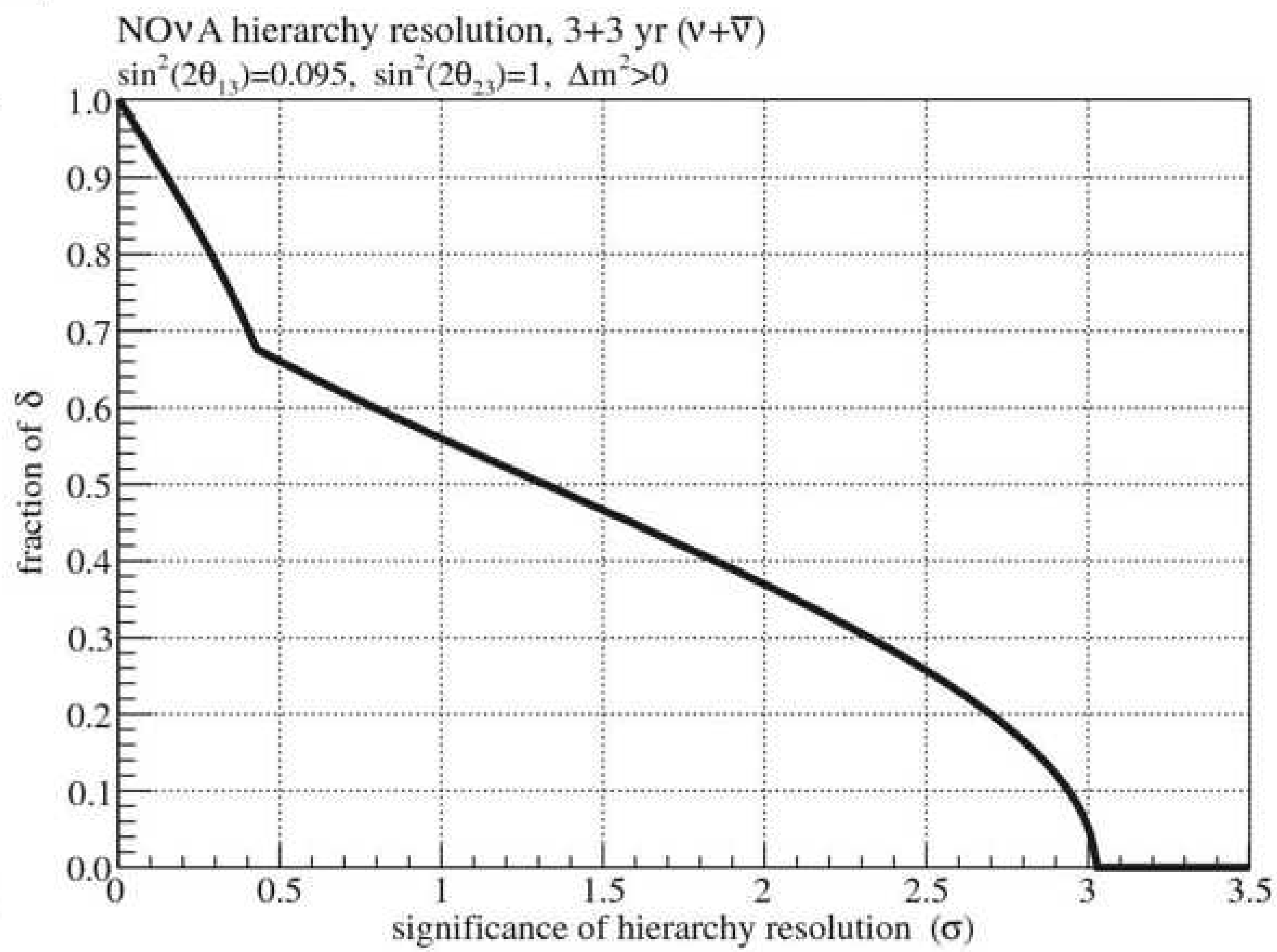
and 2 σ Contours for Starred Point



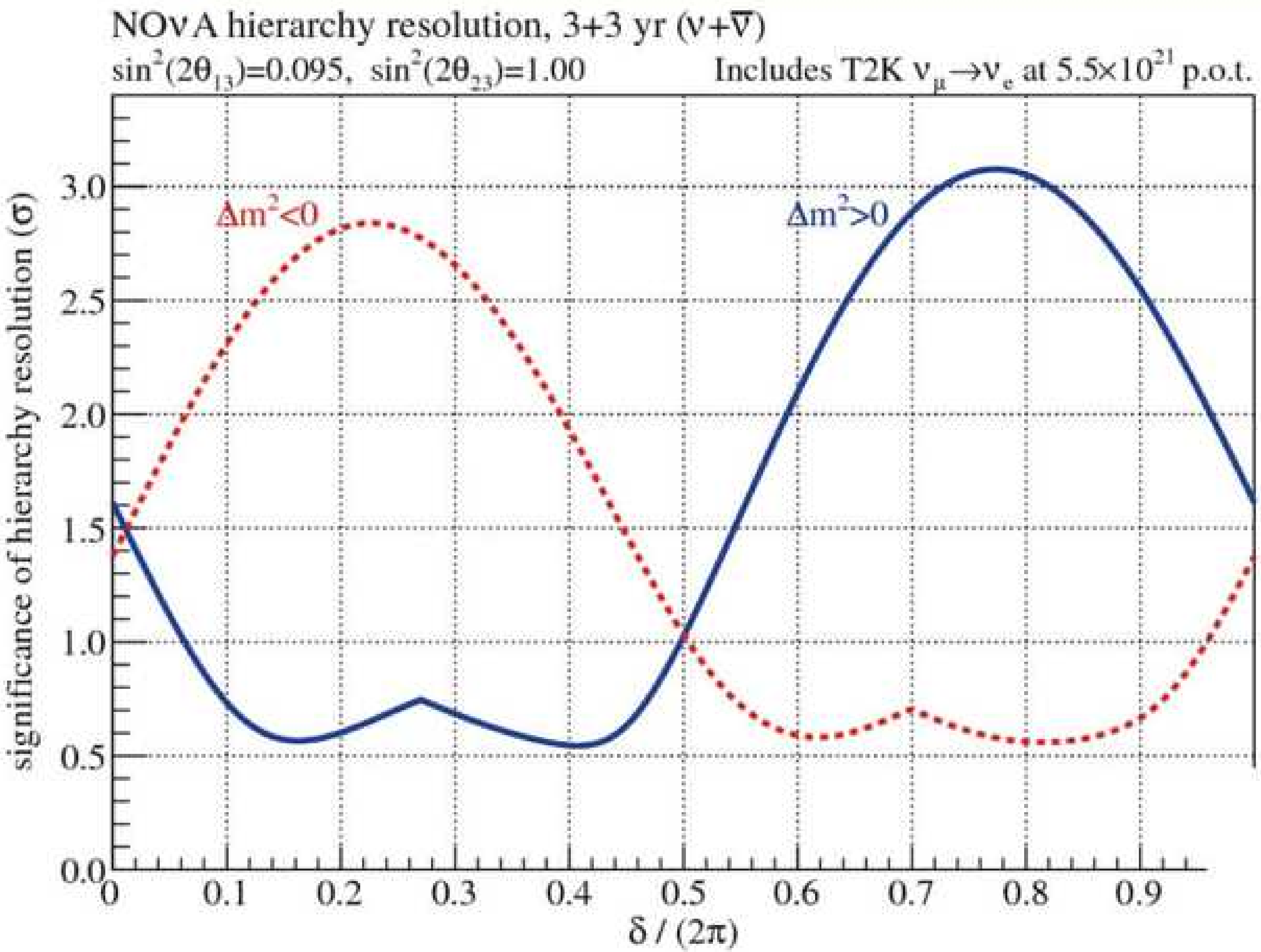
Determining the mass hierarchy



For how many δcp points (what fraction of all δcp space) do we resolve the mass hierarchy at >1σ? >2σ? ~*40%*

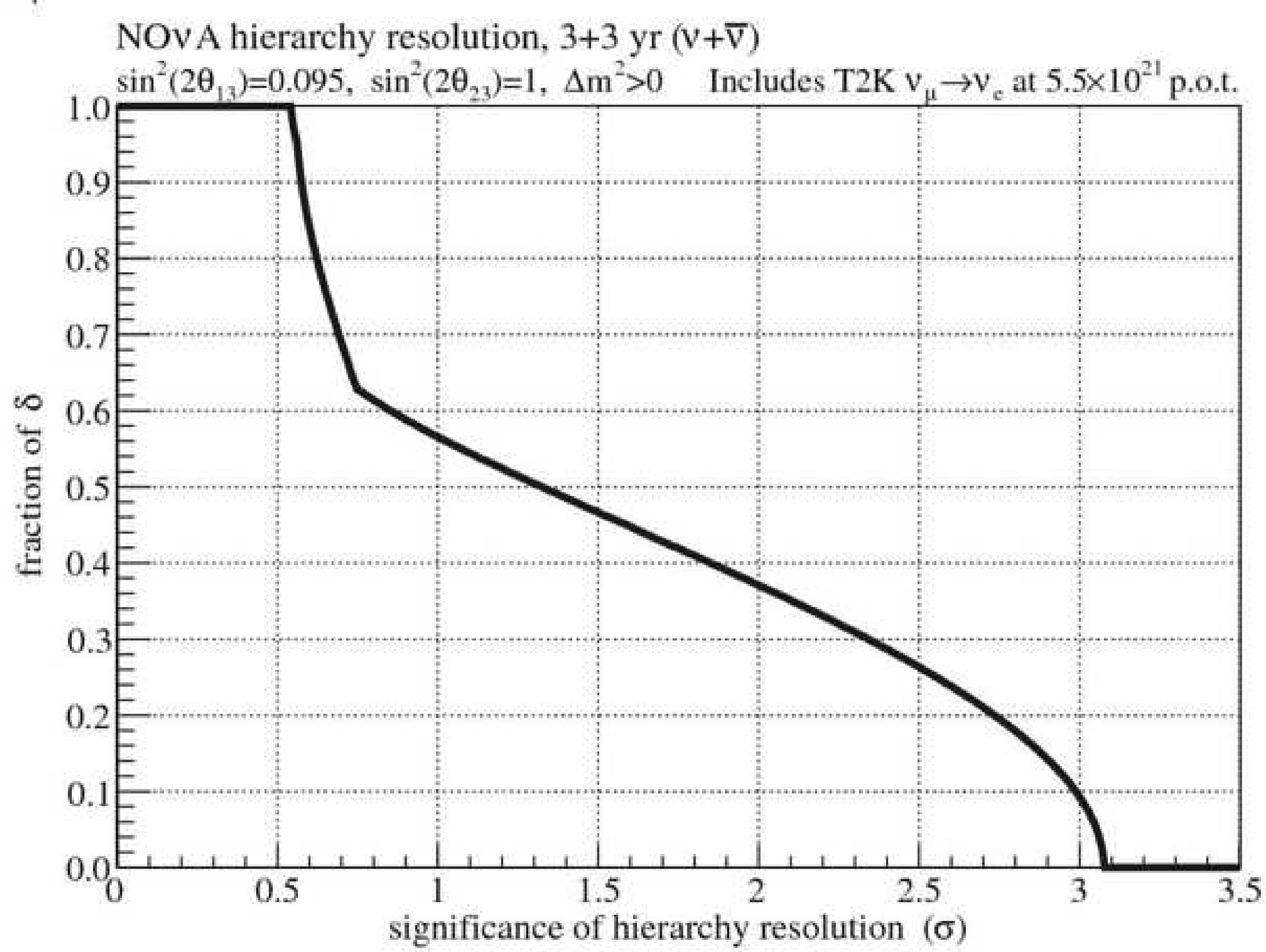


Determining the mass hierarchy

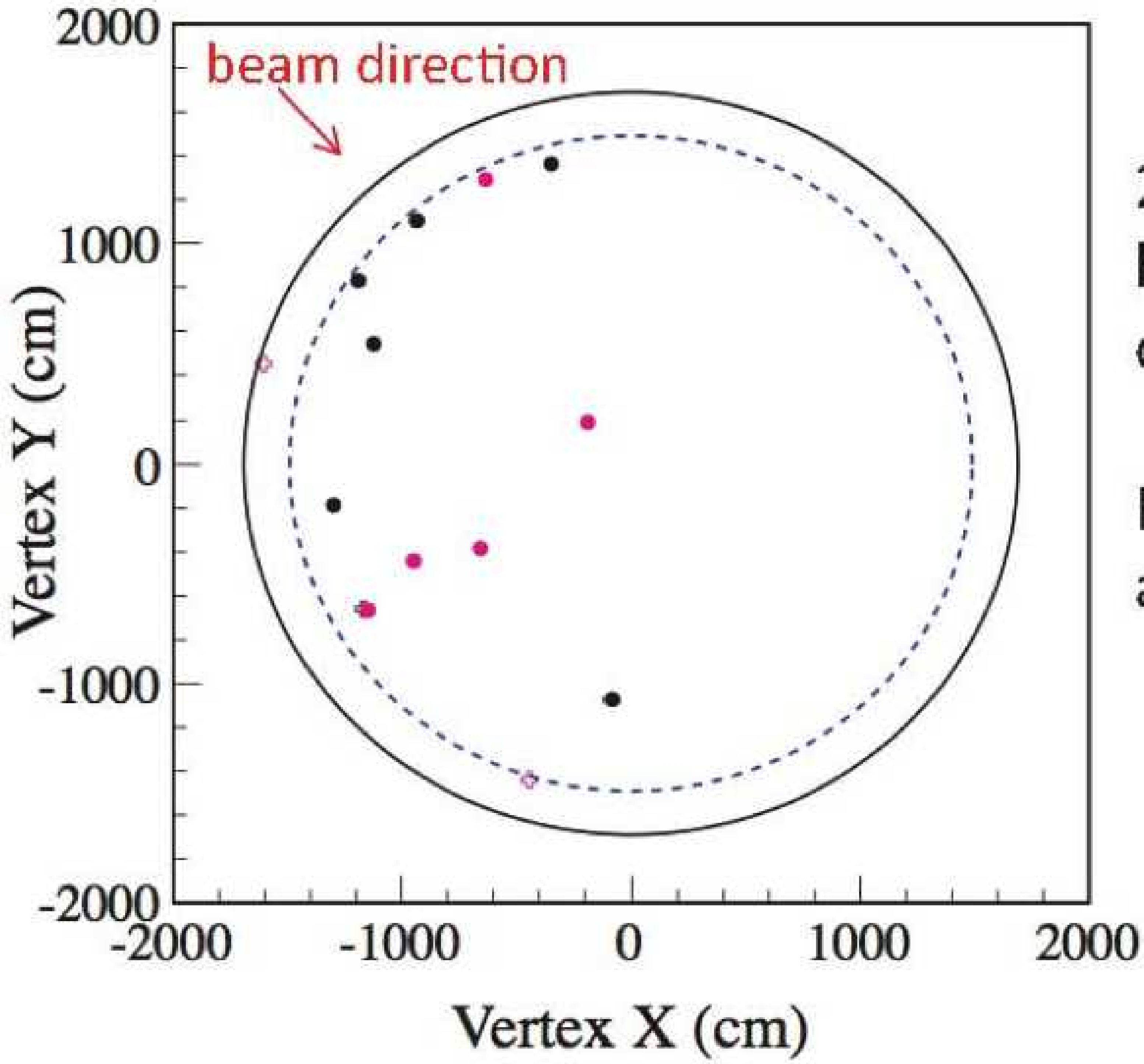


Recall: T2K measures $P(\nu_e)$ with a different (minimal) dependence on the mass hierarchy

Combining both results improves the global extraction of the mass hierarchy (and other parameters)



Vertex distribution of ν_e candidates

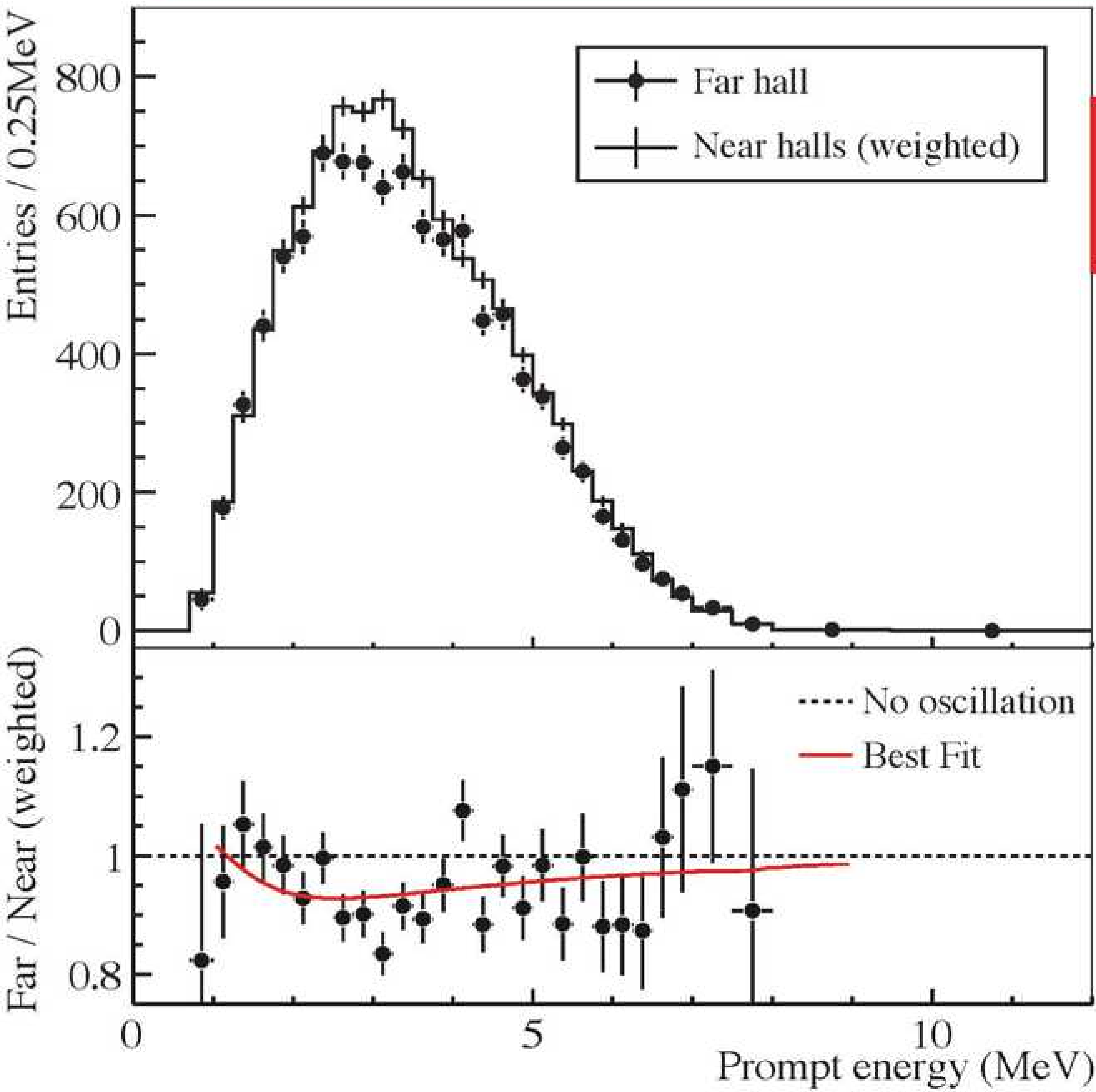


2011 analysis (Run 1+2, black points) had a discrepancy in radial distribution of event candidates

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

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

Results from reactor experiments



arXiv:1203.1669v1, submitted to PRL

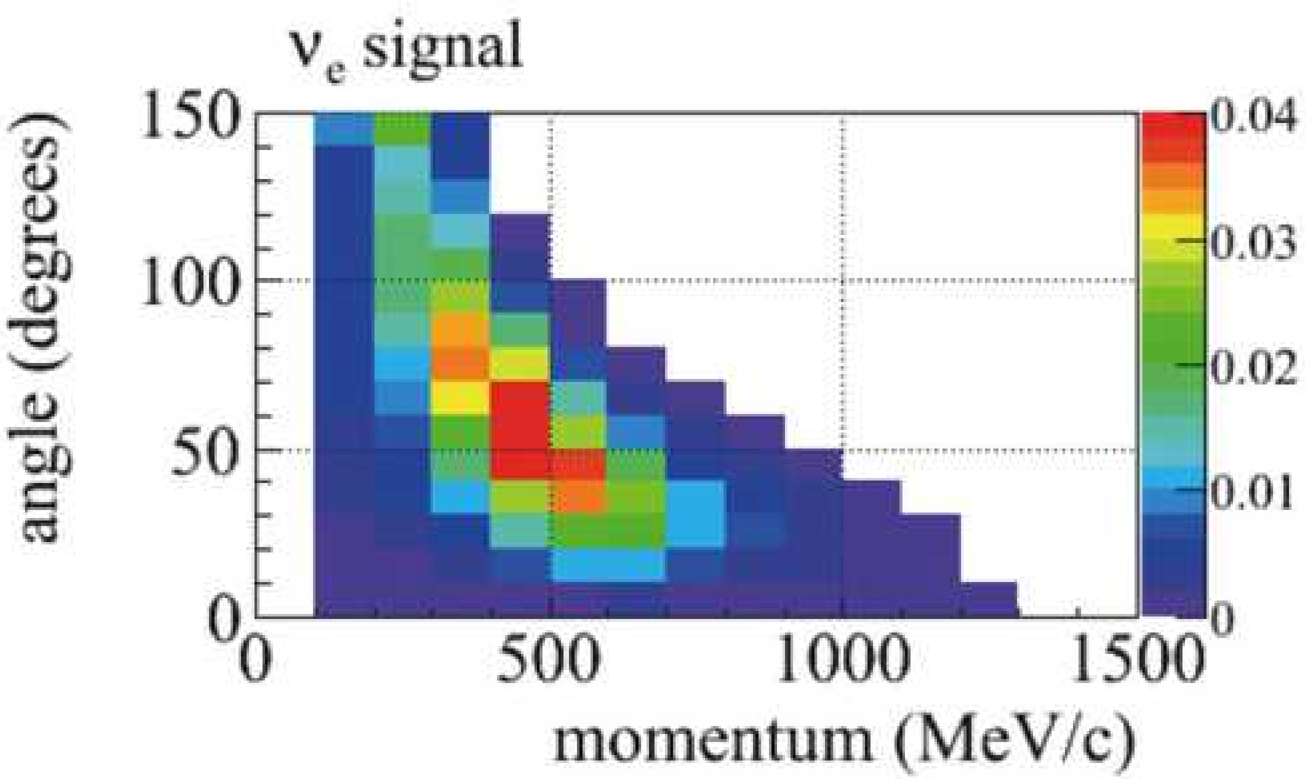
$$\overline{\nu}_e + p \rightarrow e^+ + n$$

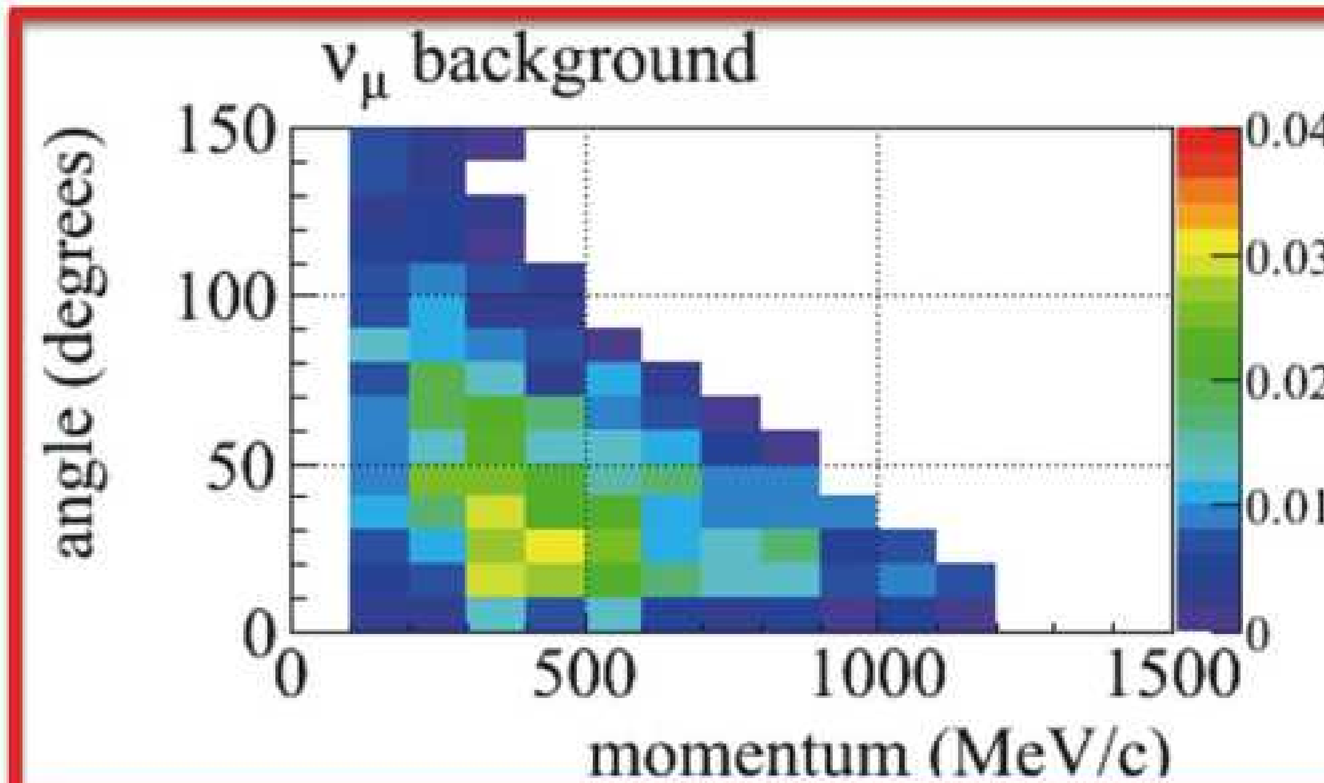
$\overline{\nu}_e$ disappearance:

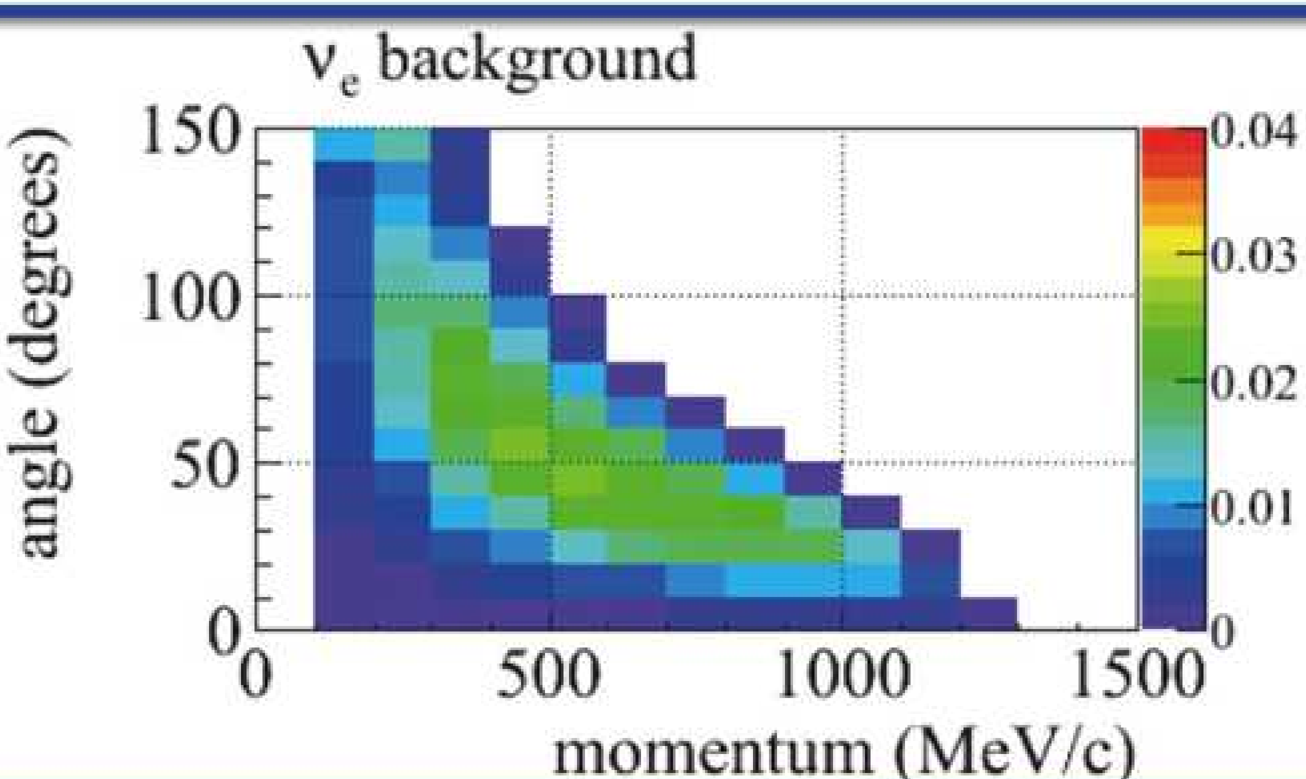
$$P(\nu_e \rightarrow \nu_{x \neq e}) \approx \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$

- Double Chooz:
  Dec 2011, arXiv:1112.6353
  $0.017 < \sin^2 2\theta_{13} < 0.16$ at 90% C.L.
- Daya Bay (right)
  Mar 2012, arXiv:1203.1669v1
  $\sin^2 2\theta_{13} = 0.092$
  ± 0.016(stat)± 0.005(syst)
- RENO:
  April 2012
  $\sin^2 2\theta_{13} = 0.103$
  ± 0.013(stat)± 0.011 (syst)

Separating signal and background





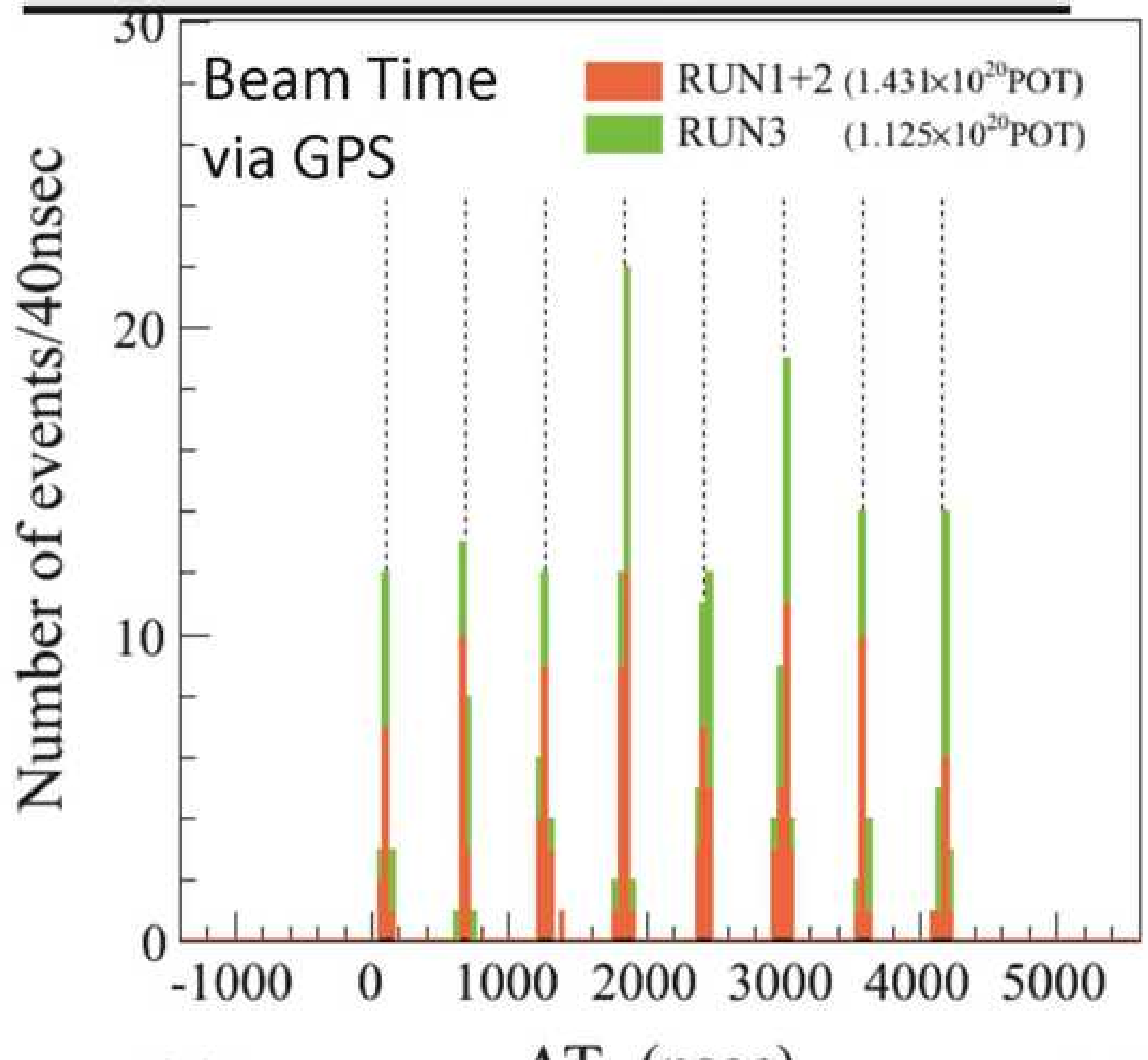


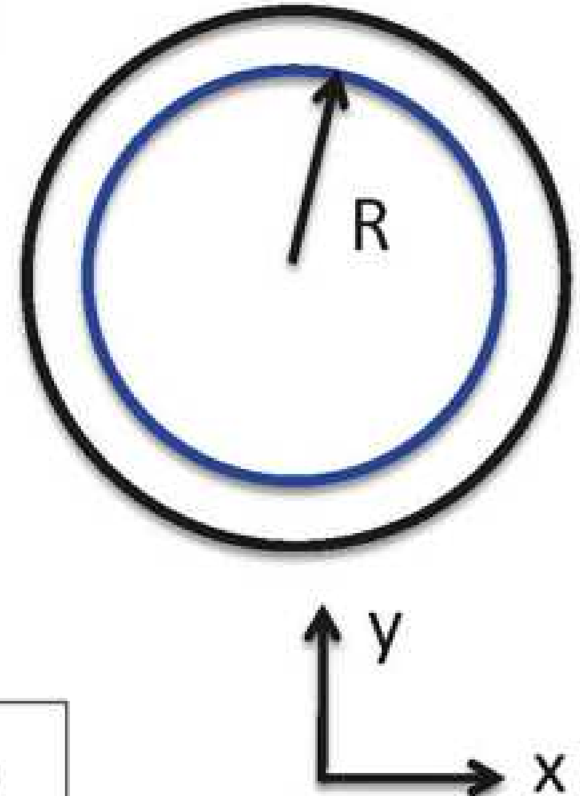
Additional separation of signal, background events with CC ν_e candidate kinematics

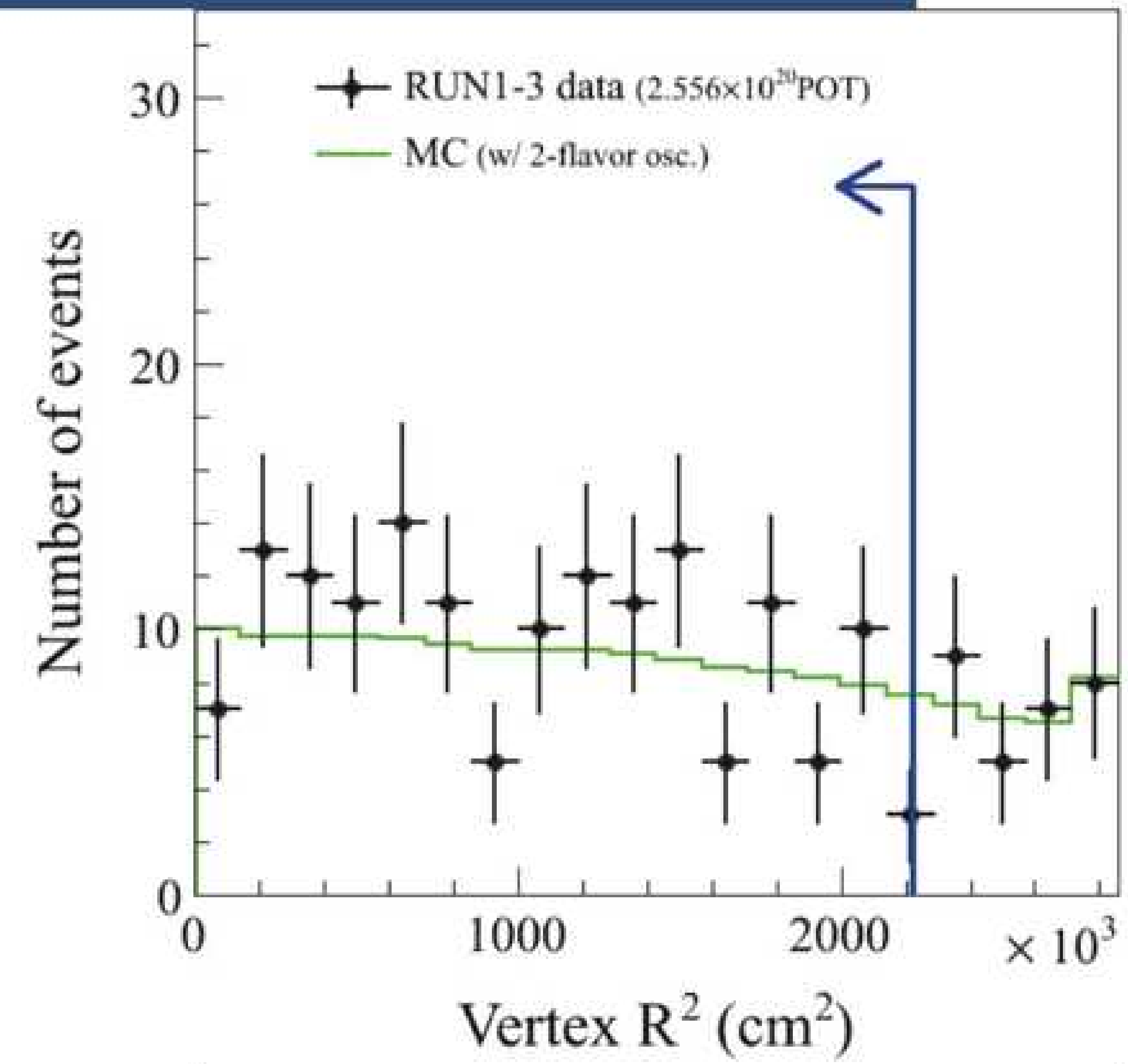
- CC ν_e backgrounds come from higher energy neutrinos and populate signal and higher momentum region
- NC backgrounds are due to misID'd photons that reconstruct as electrons at low momentum and low angle (as well as the signal region)

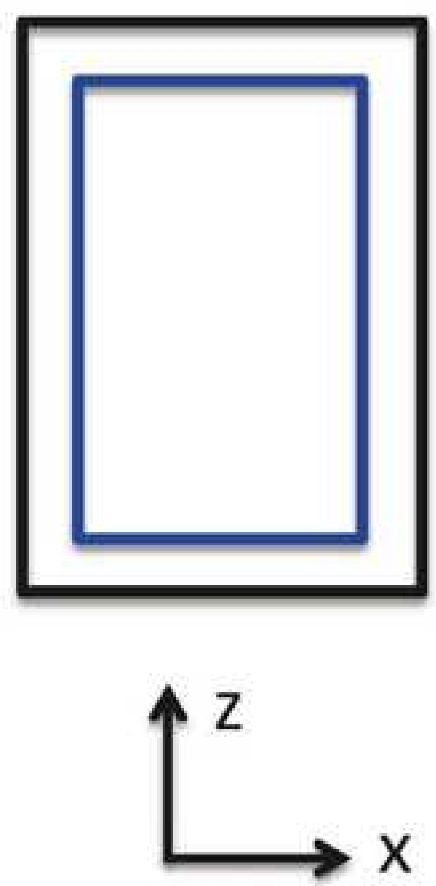
Basic neutrino event selection (Run 1+2)

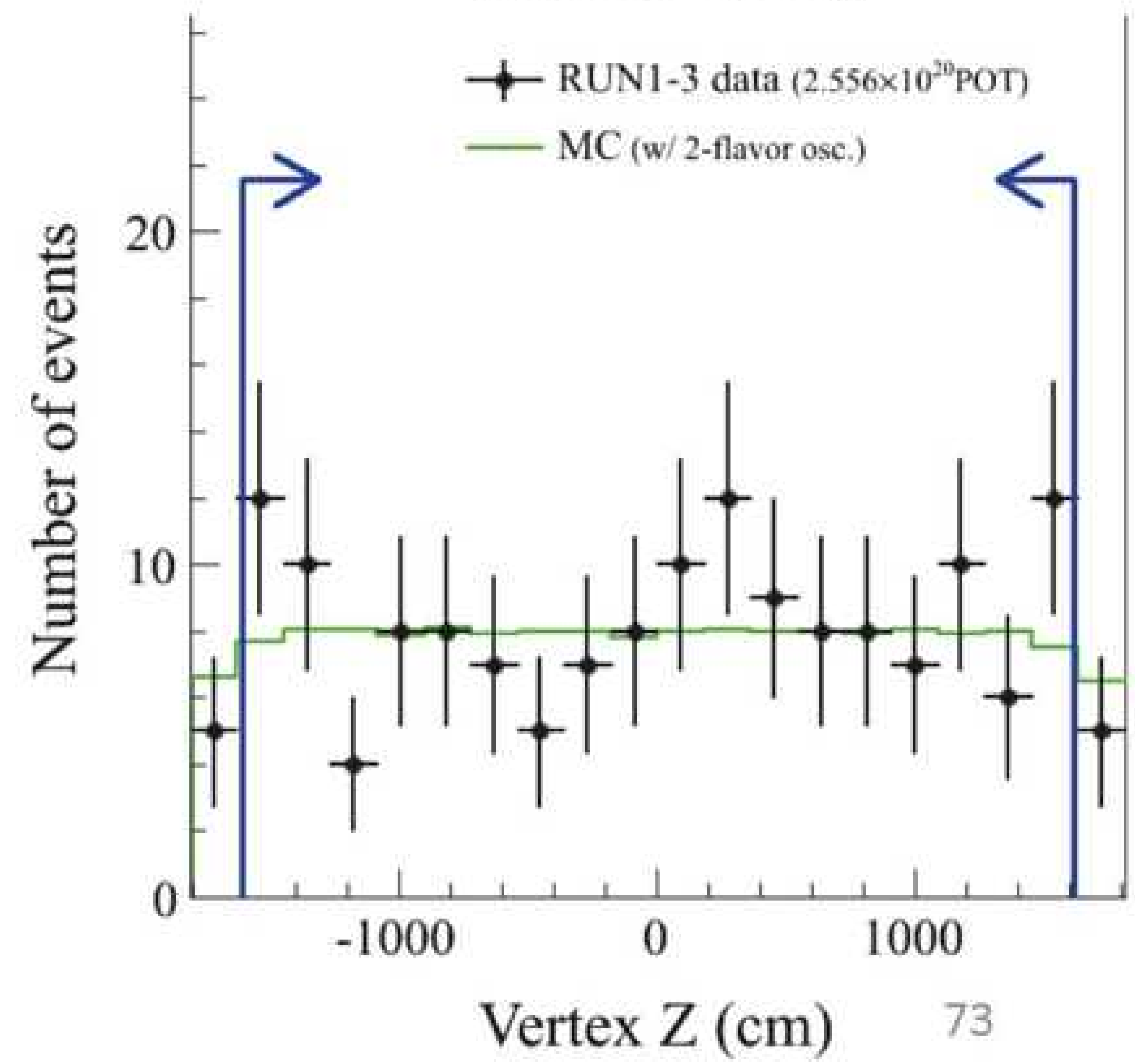
Basic neutrino selection (precuts)
Event time within beam window
No activity in the veto
Visible E > 30 MeV
Reconstructed vertex >2m from wall
Single reconstructed ring







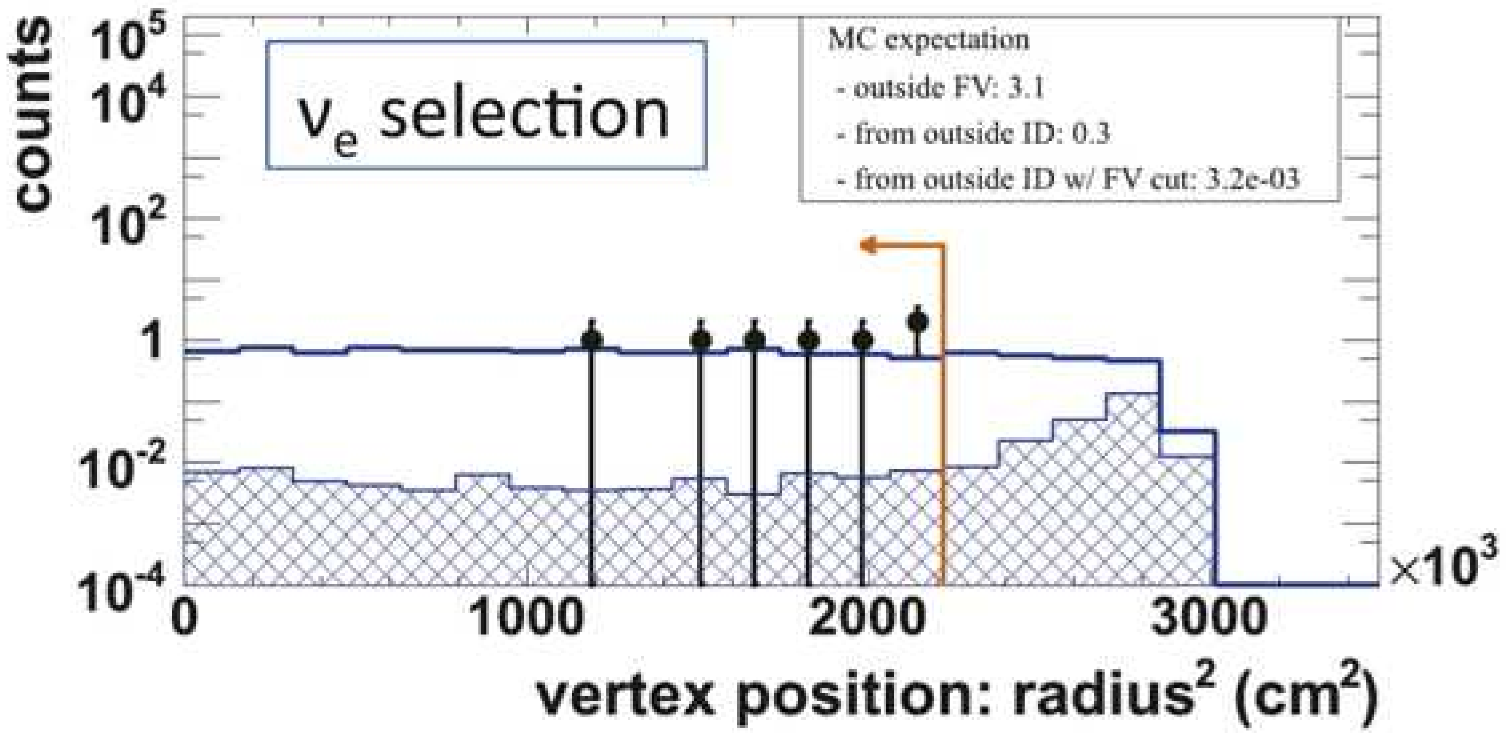


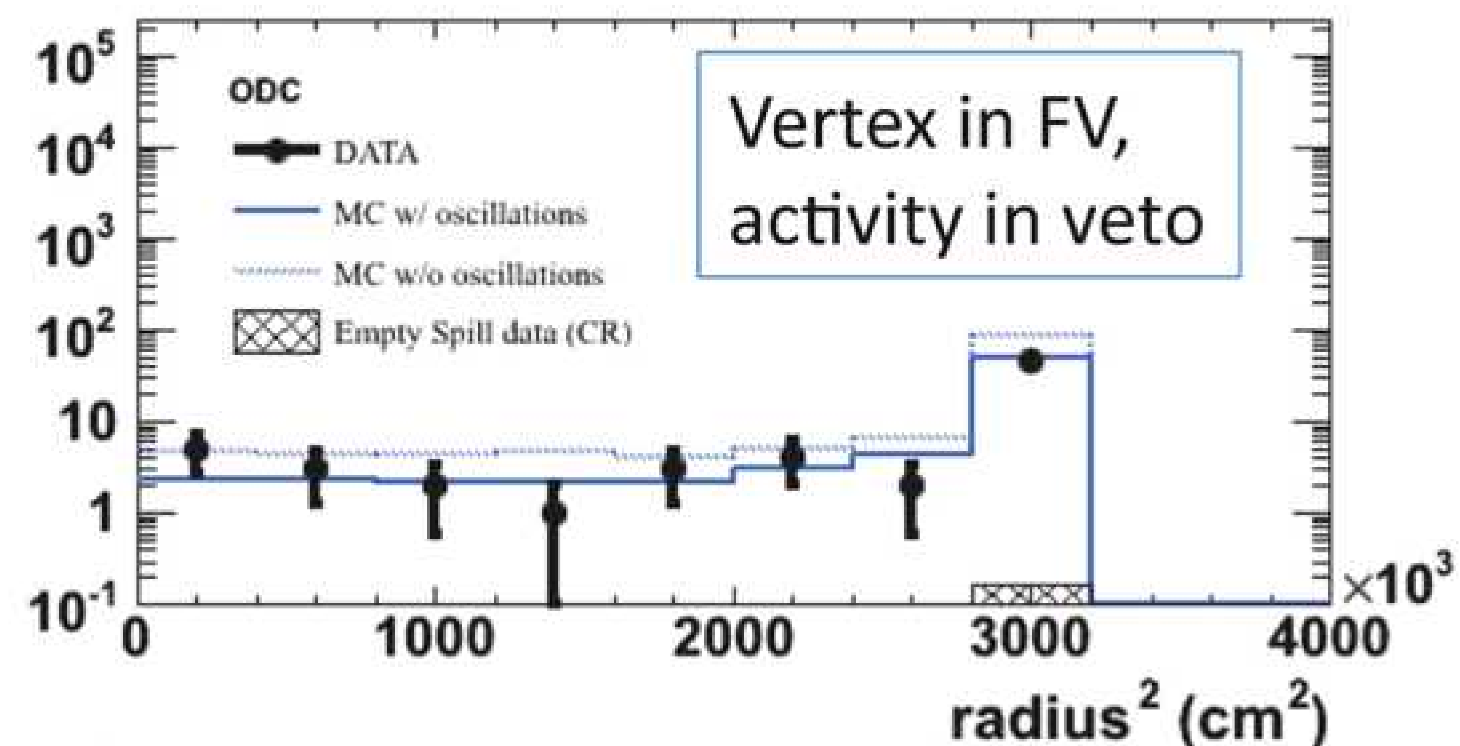


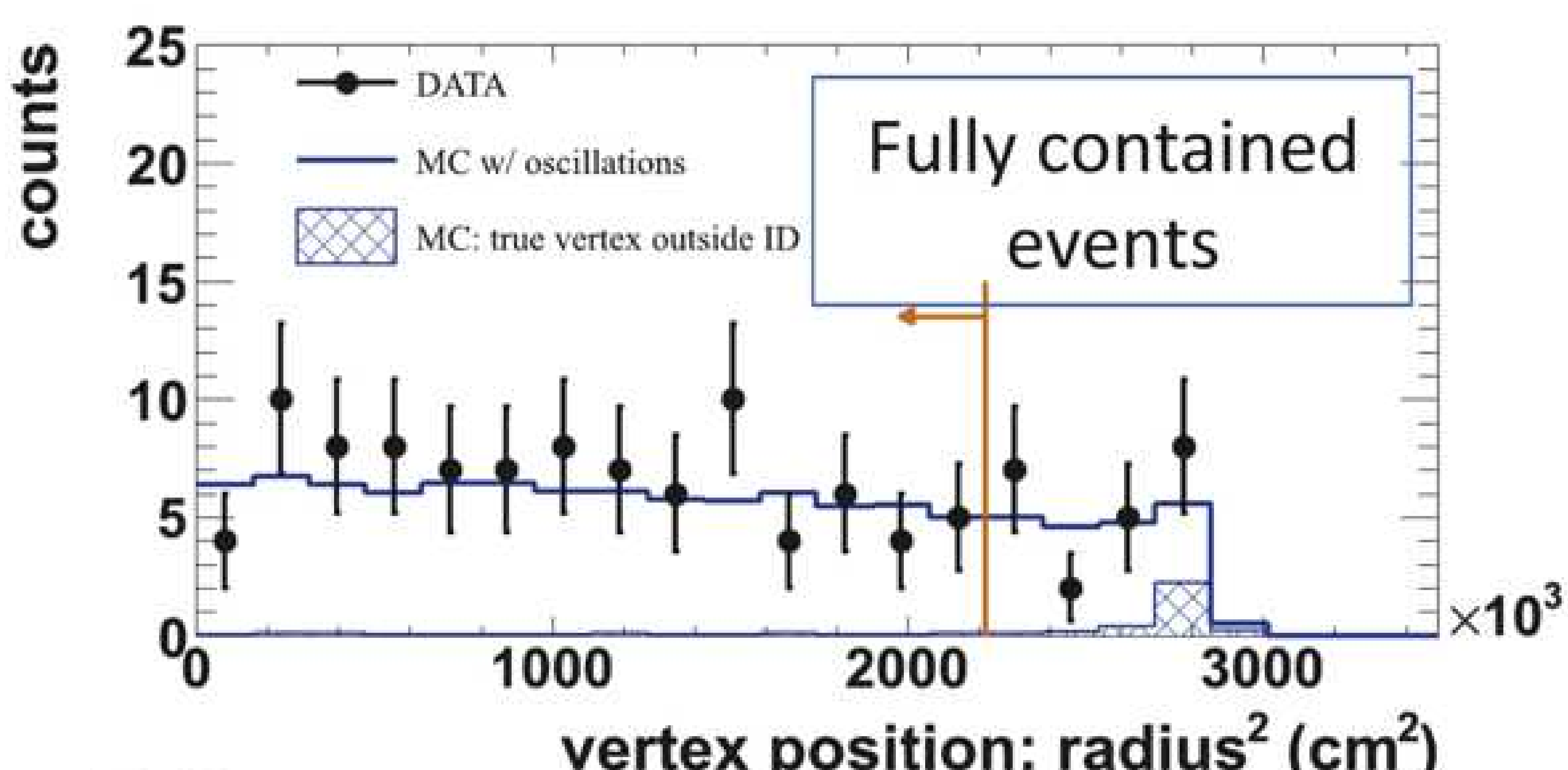
Beam backgrounds at high radius (Run 1+2)

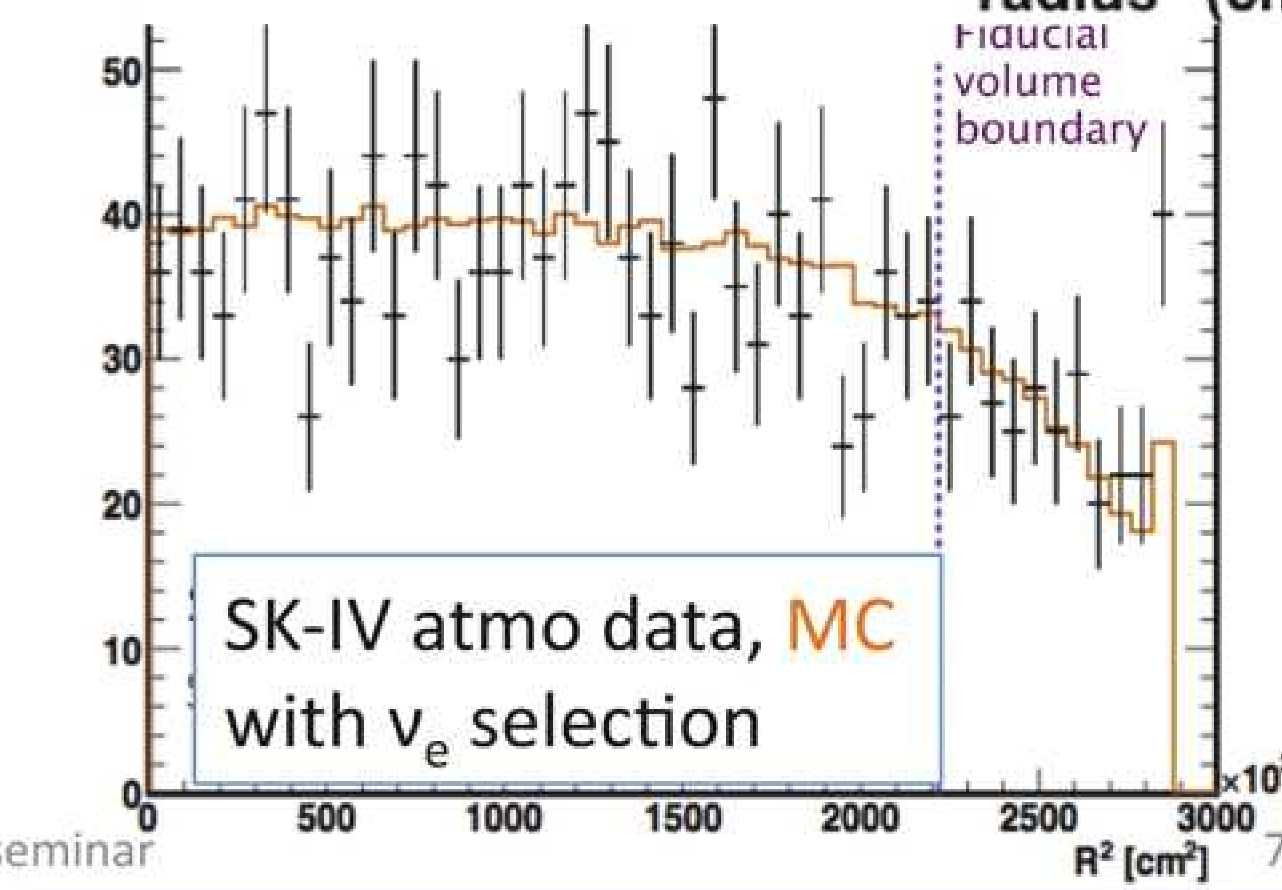
MC simulates neutrino interactions upstream of the detector (e.g. π^0 production)

- 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

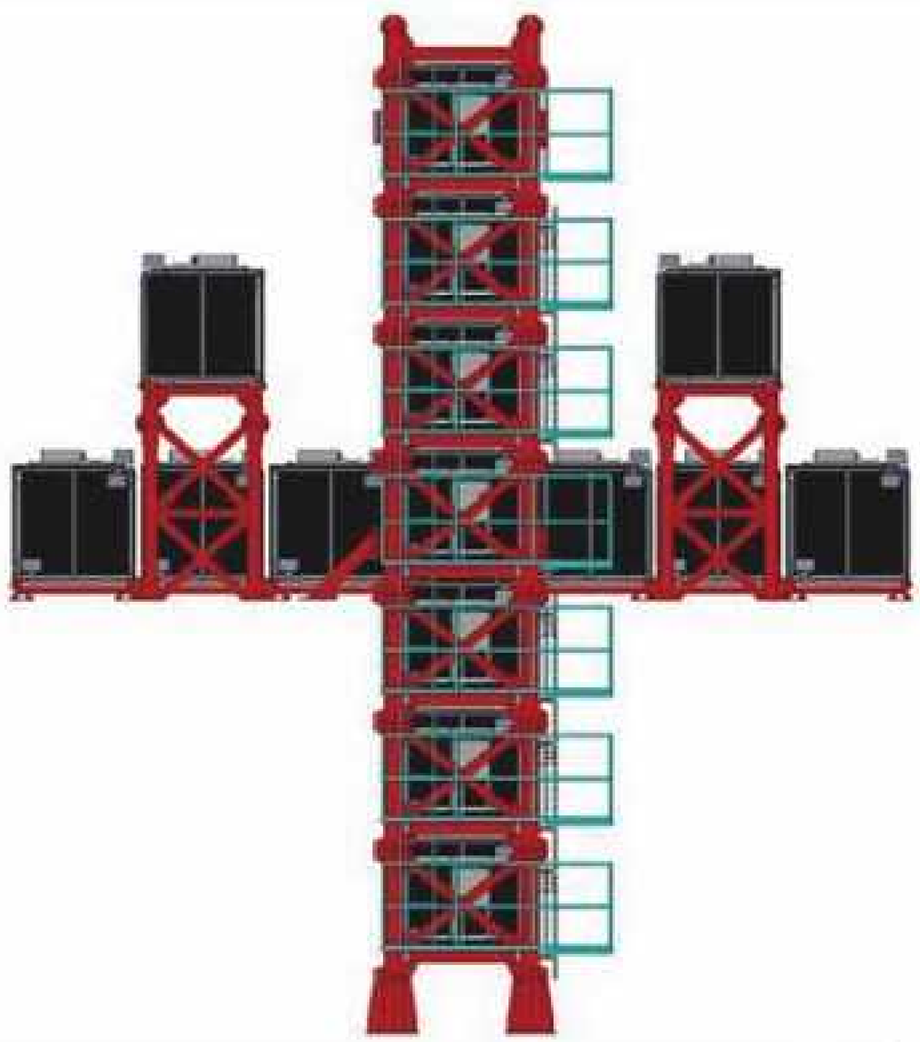








On-axis Interactive Neutrino GRID (INGRID)



16 modules arranged in a cross

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

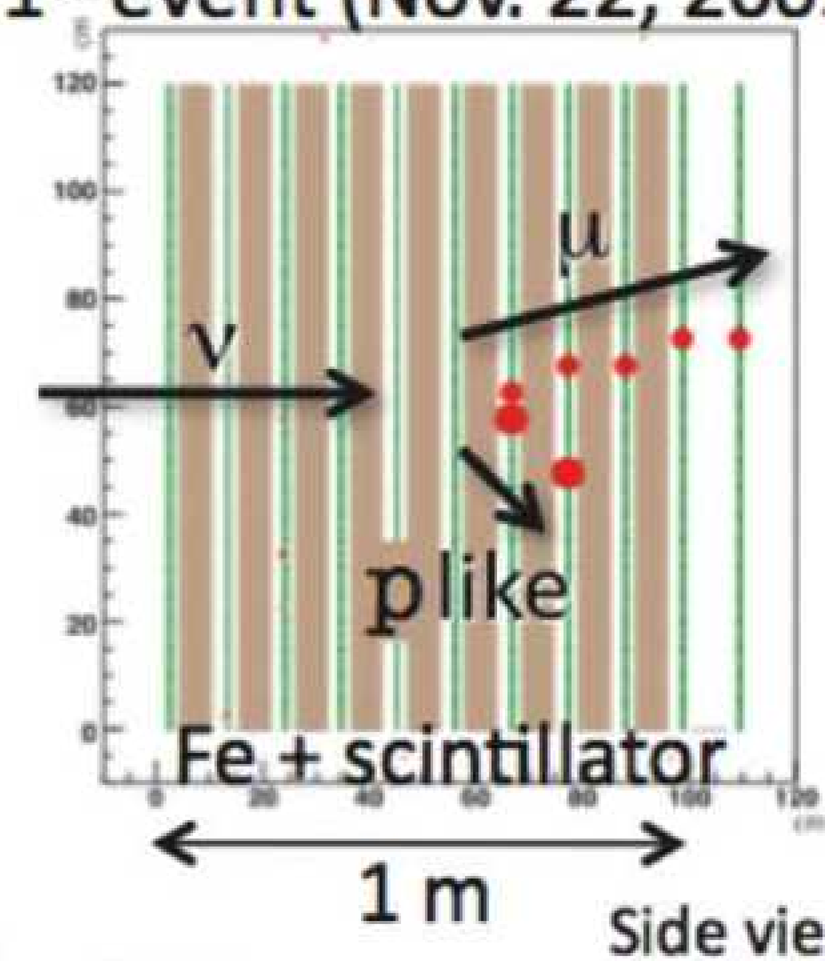
Count neutrino interactions in each module to determine neutrino rate vs. position

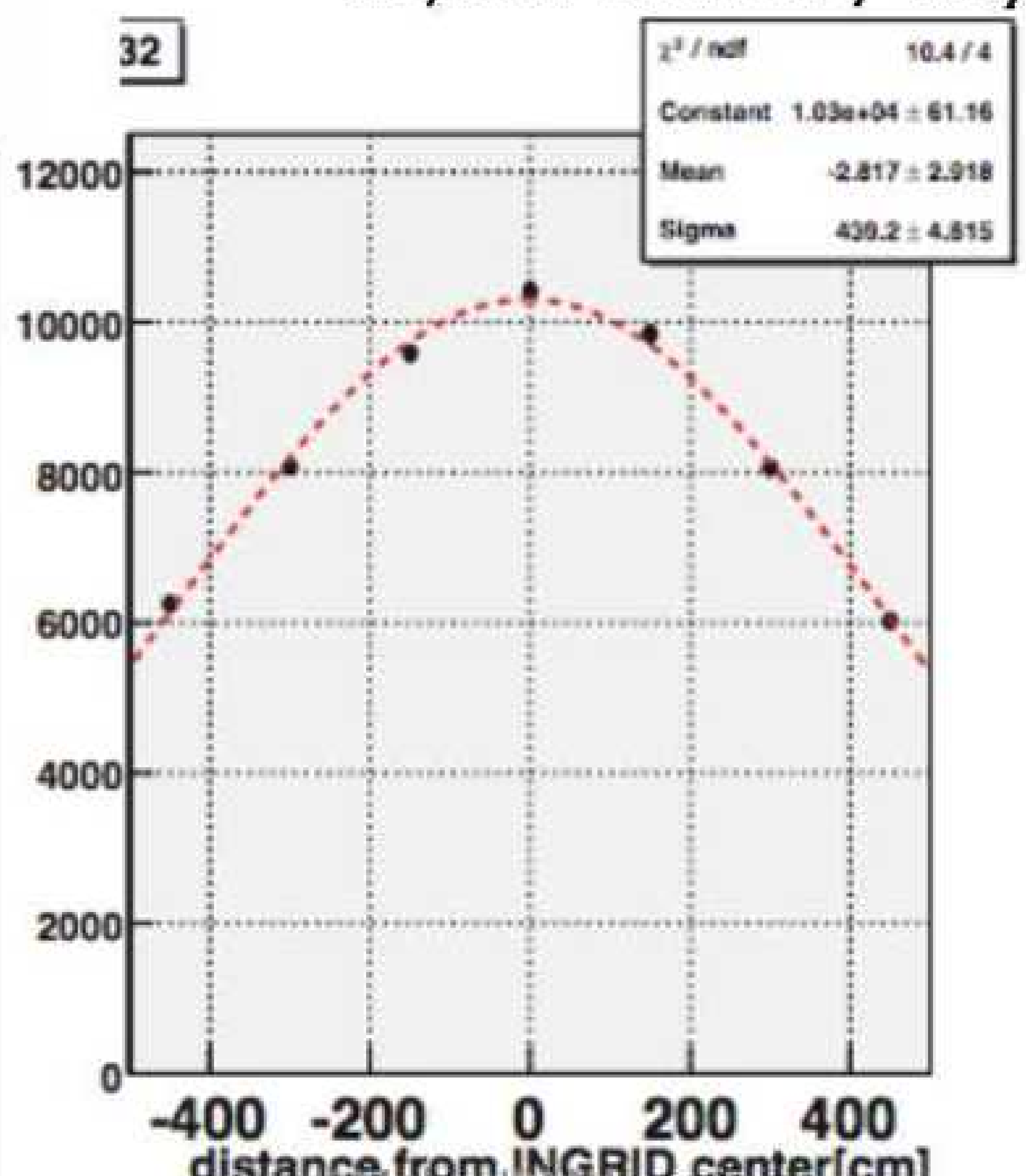
Extract beam direction better than 0.5 mrad

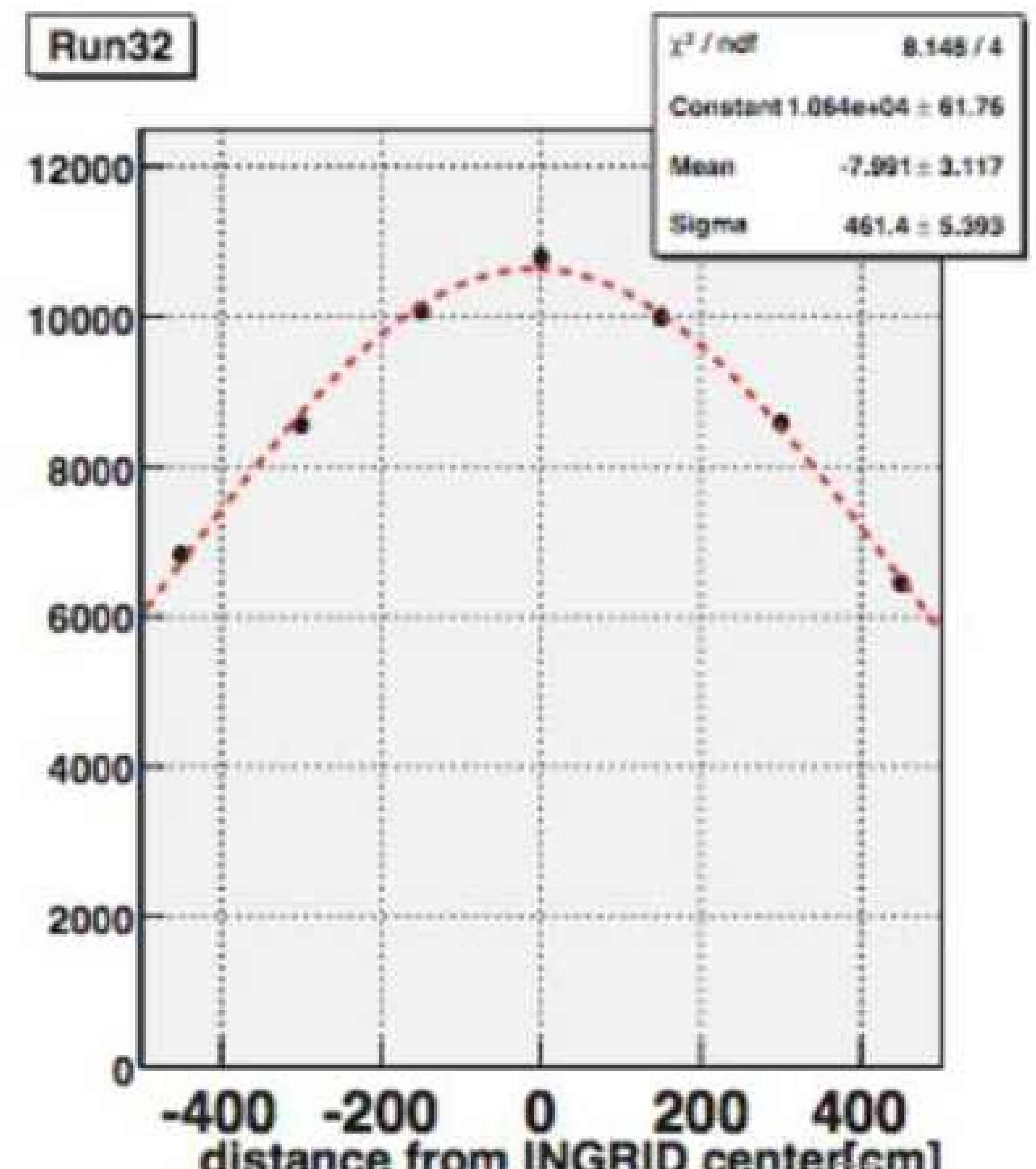
Monitor of neutrino beam vs. time

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

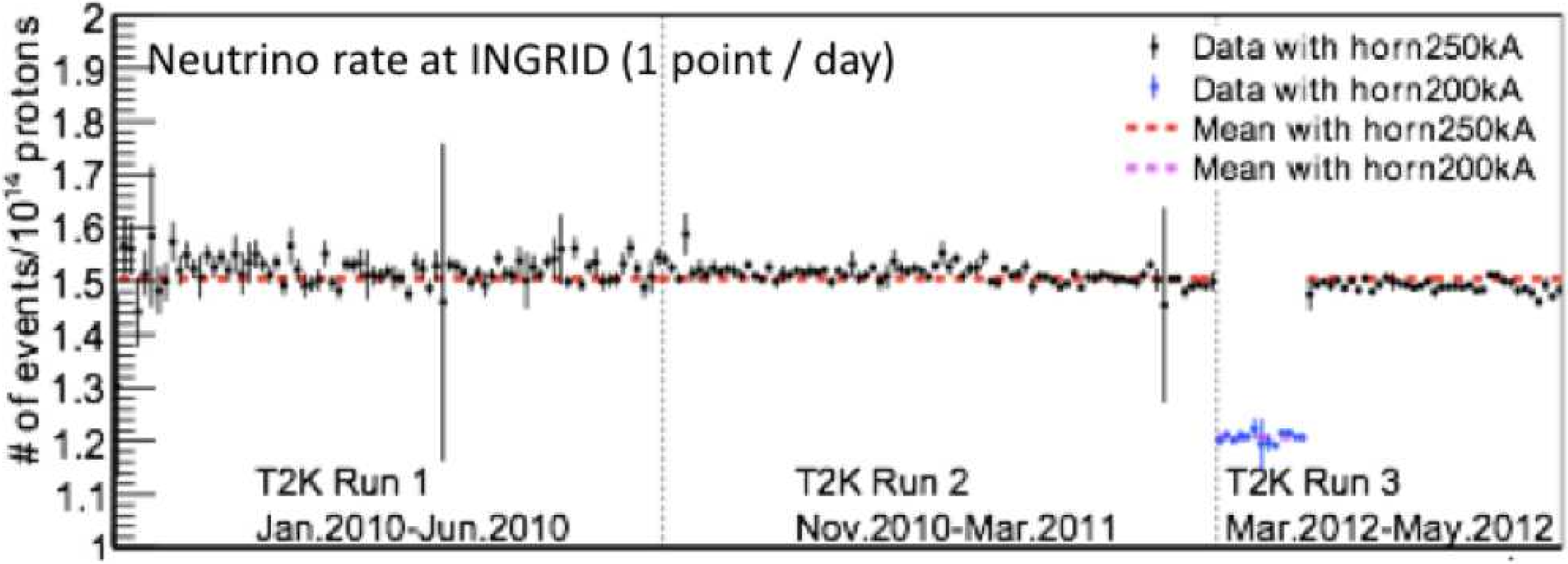
1st event (Nov. 22, 2009)

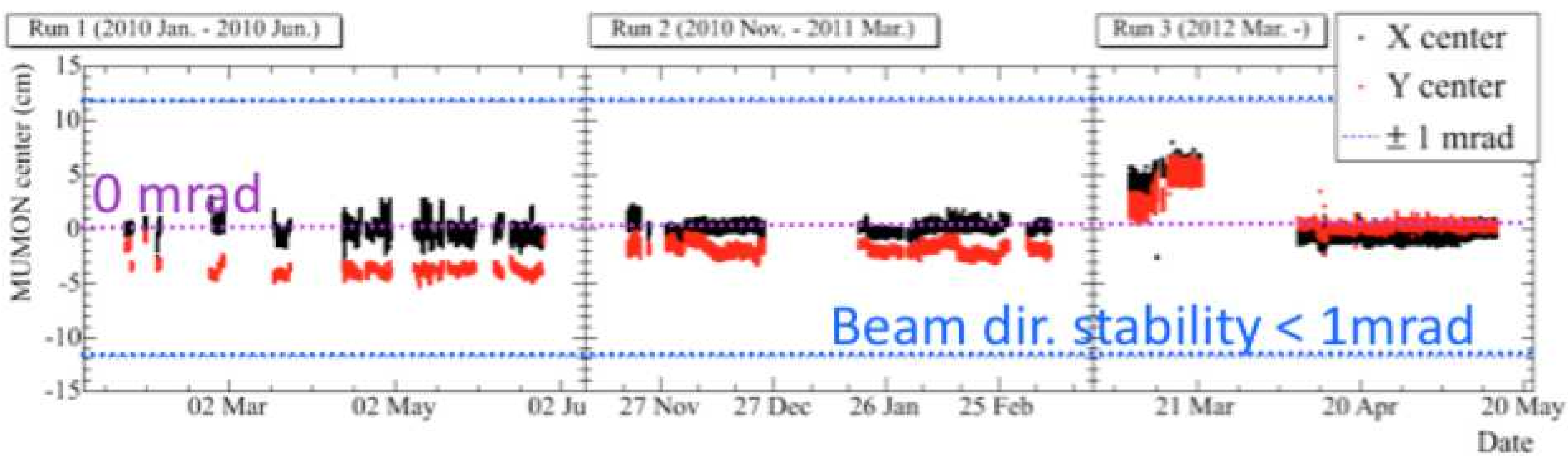






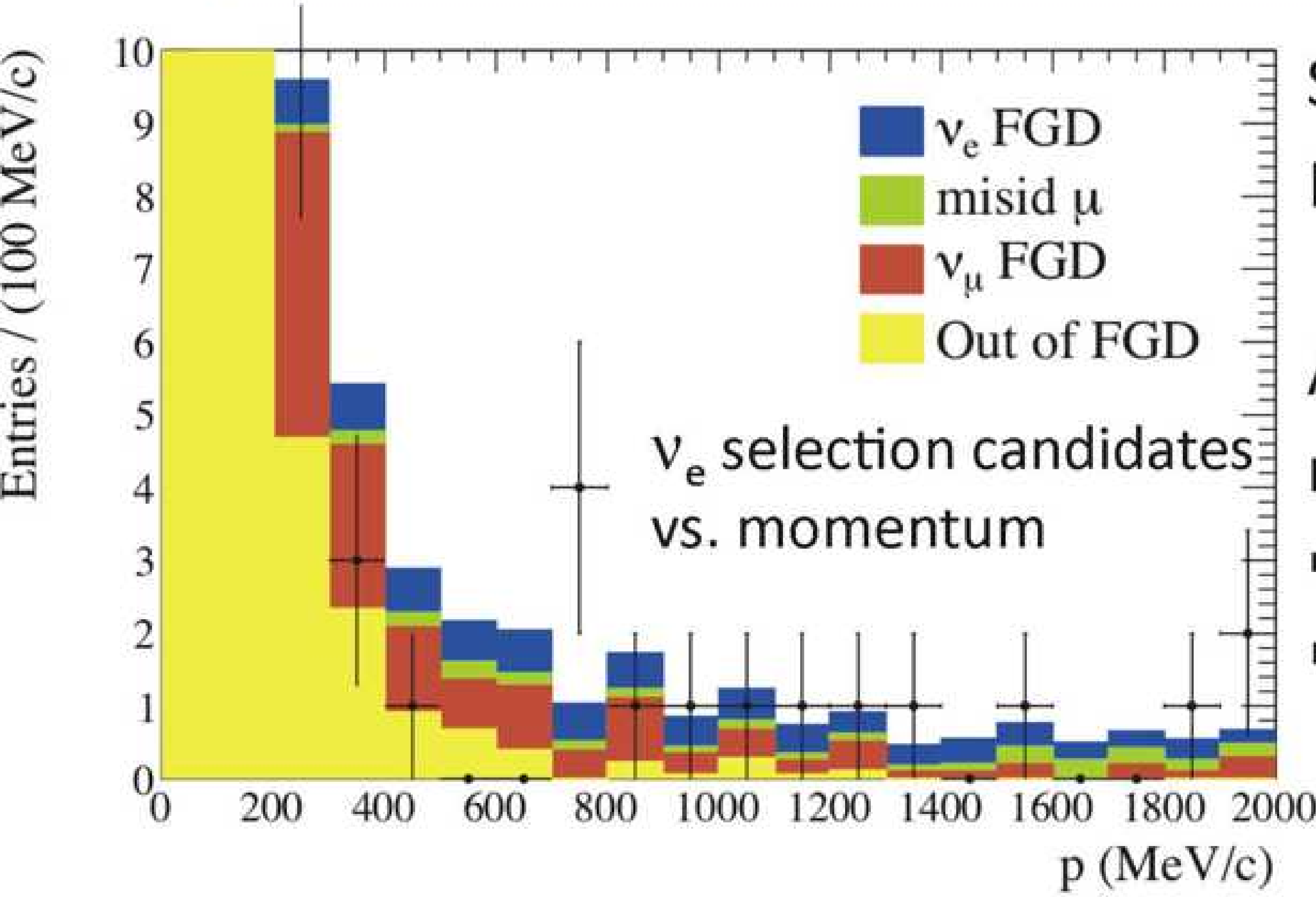
Neutrino beam stability





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

ND280 beam ν_e rate cross-check (I)



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

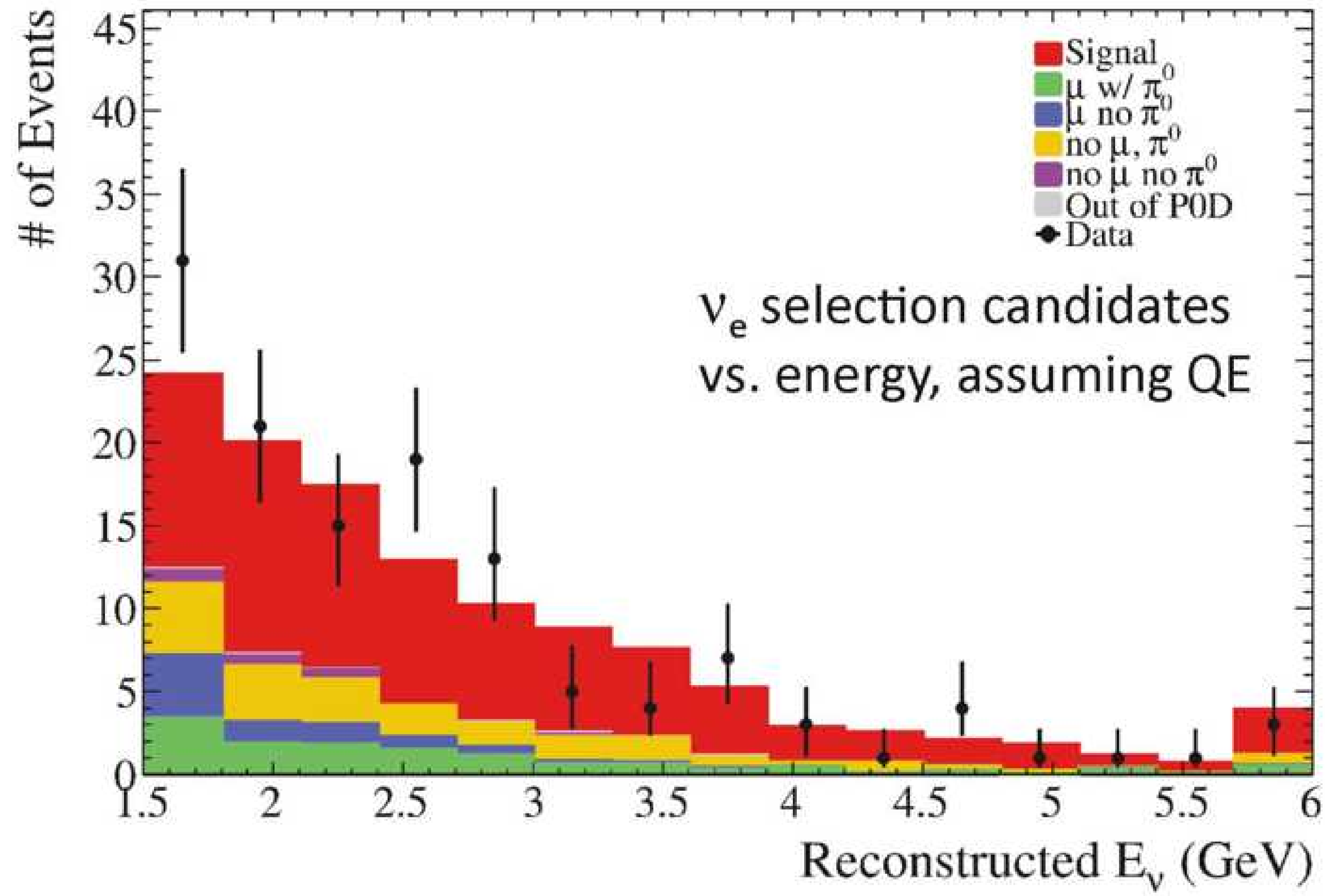
$N(\nu_e)/N(\nu_\mu) = R(e:\mu) = 1.0\% \pm 0.7\%$ (statistics) $\pm 0.3\%$ (systematics)

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



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

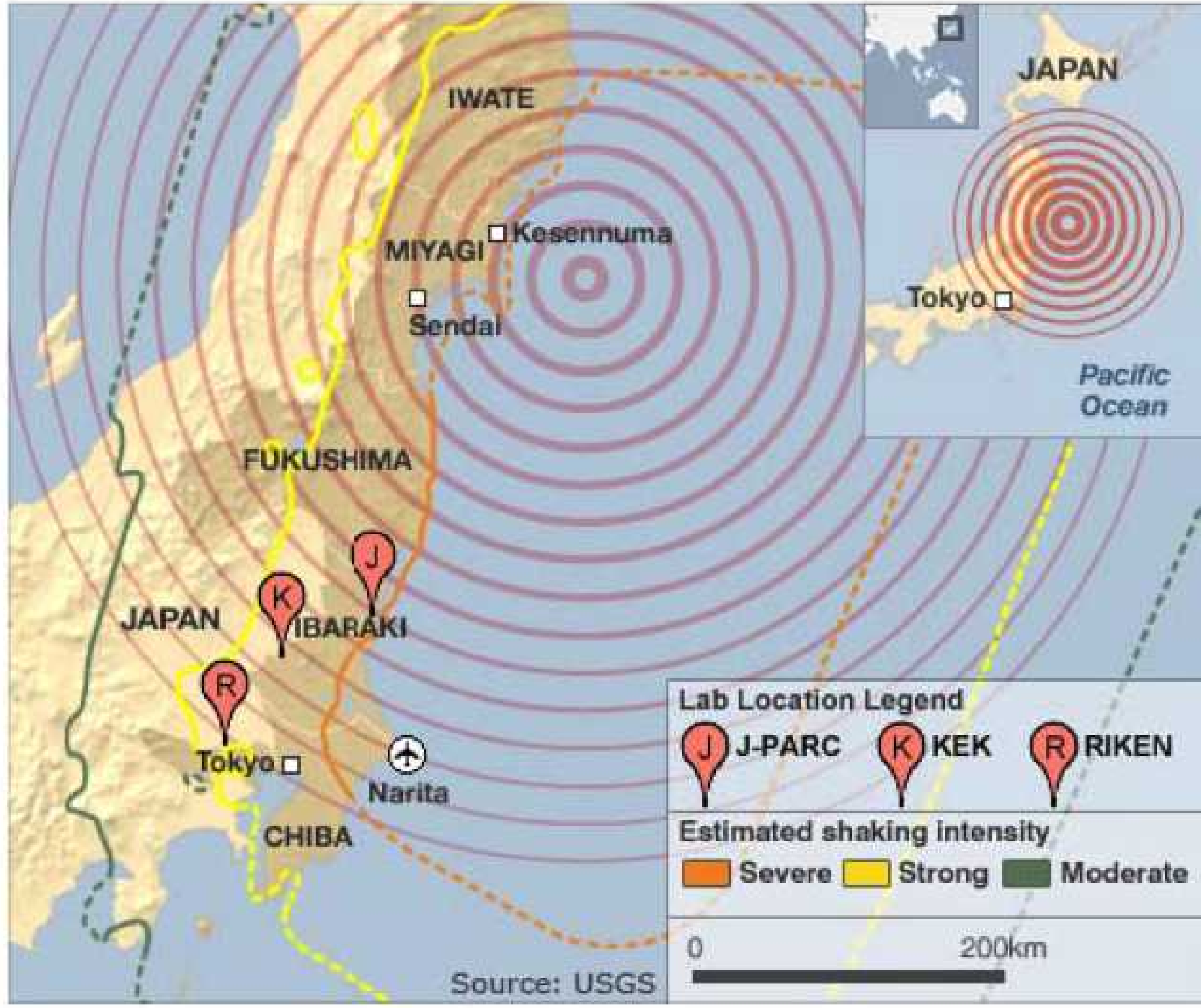
Consistent with current untuned MC:

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

Earthquake and T2K

On March 11th, 2011, Japan experienced a severe earthquake followed by a tsunami

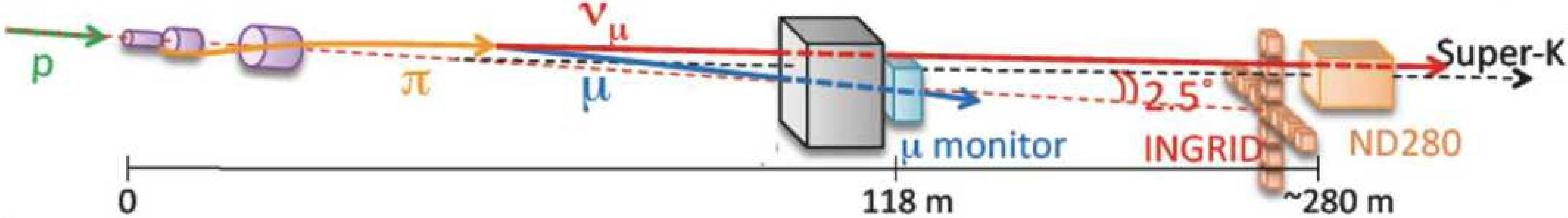
- Magnitude 9 earthquake on Richter scale, magnitude 6+ at J-PARC
- The tsunami did not reach J-PARC
- Accelerator was not operating (maintenance day)
- No reported injuries to T2K collaborators or J-PARC employees



T2K experiment status:

- Repairs made to infrastructure and accelerator
- Minor repairs and recommissioning of J-PARC near detectors successful
- First beam in late Dec 2011
- T2K run scheduled for ~4 months prior to summer 2012 shutdown

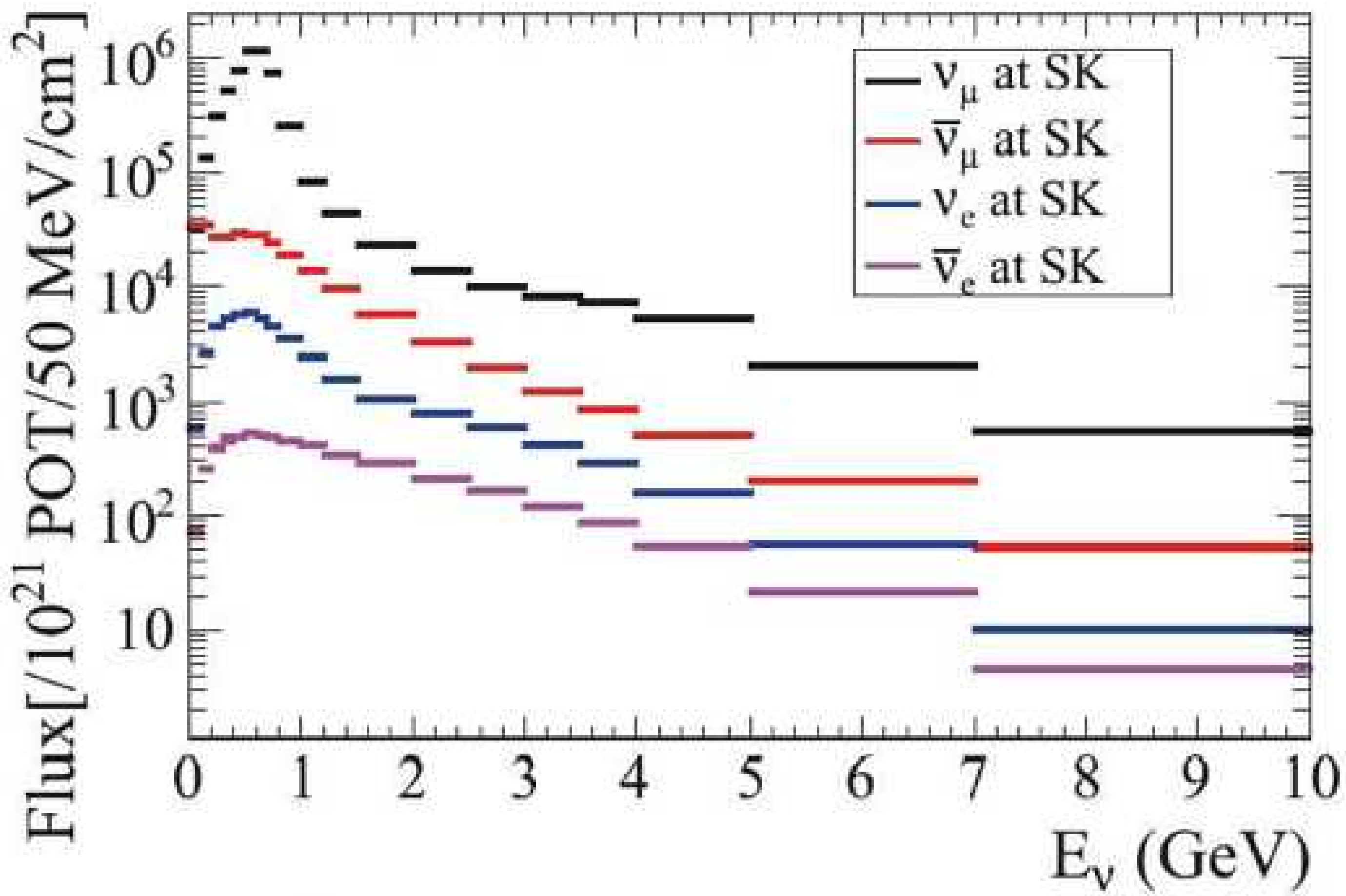
Neutrino flux prediction



FLUKA/Geant3 beam simulation

Unoscillated flux at SK:

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



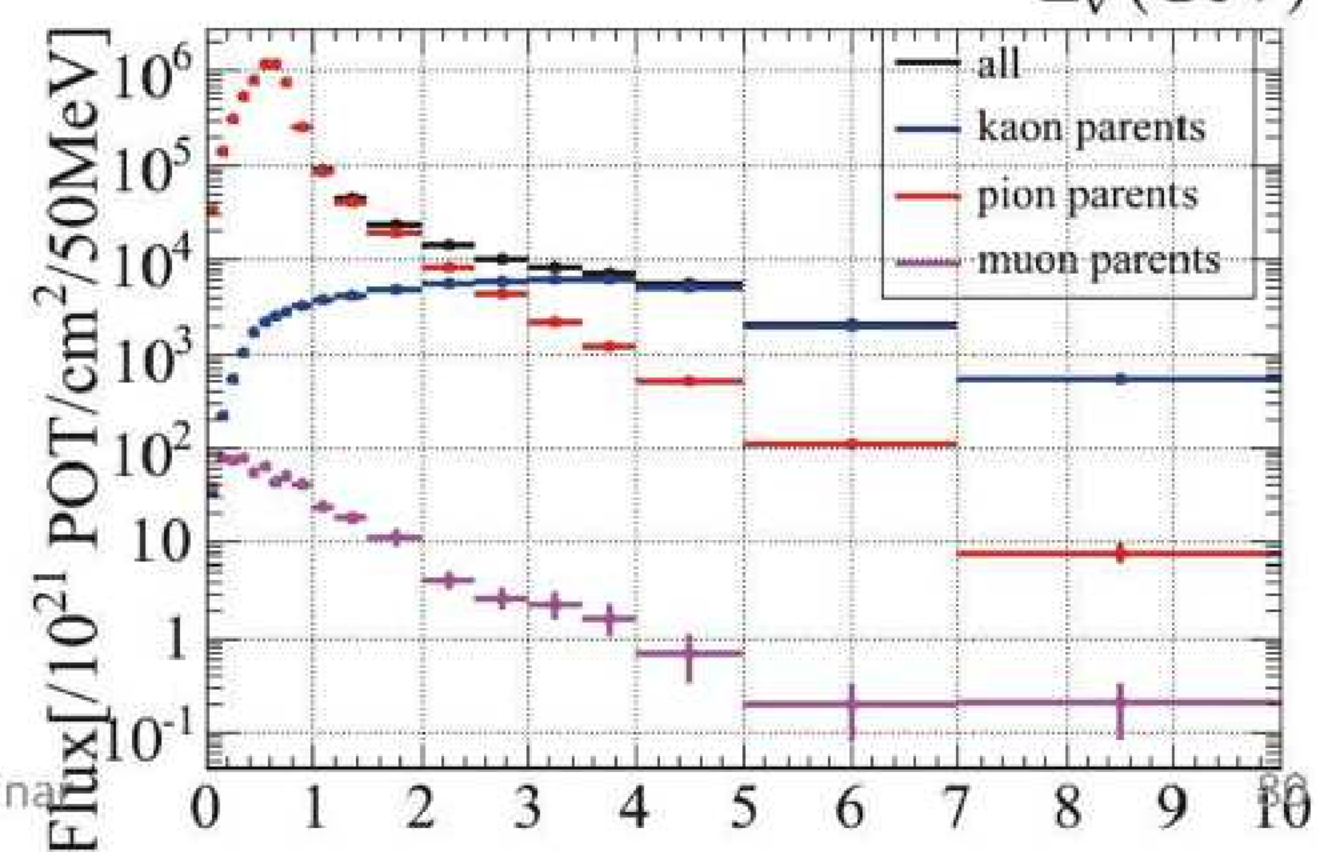
Prediction and uncertainties determined by external or in-situ measurements of:

- 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

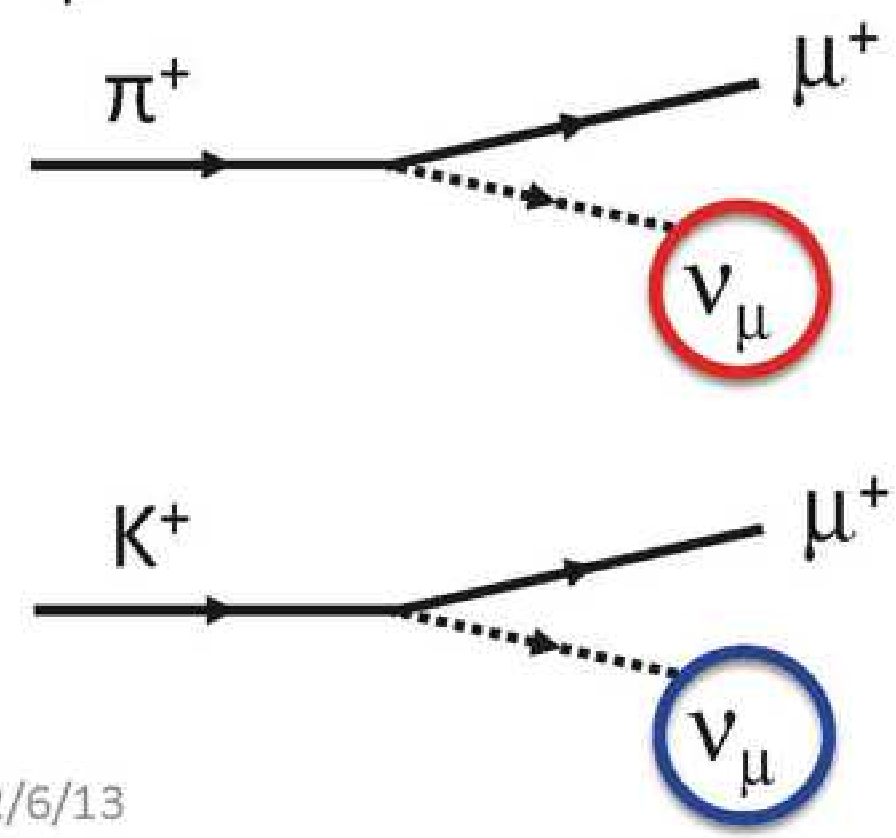


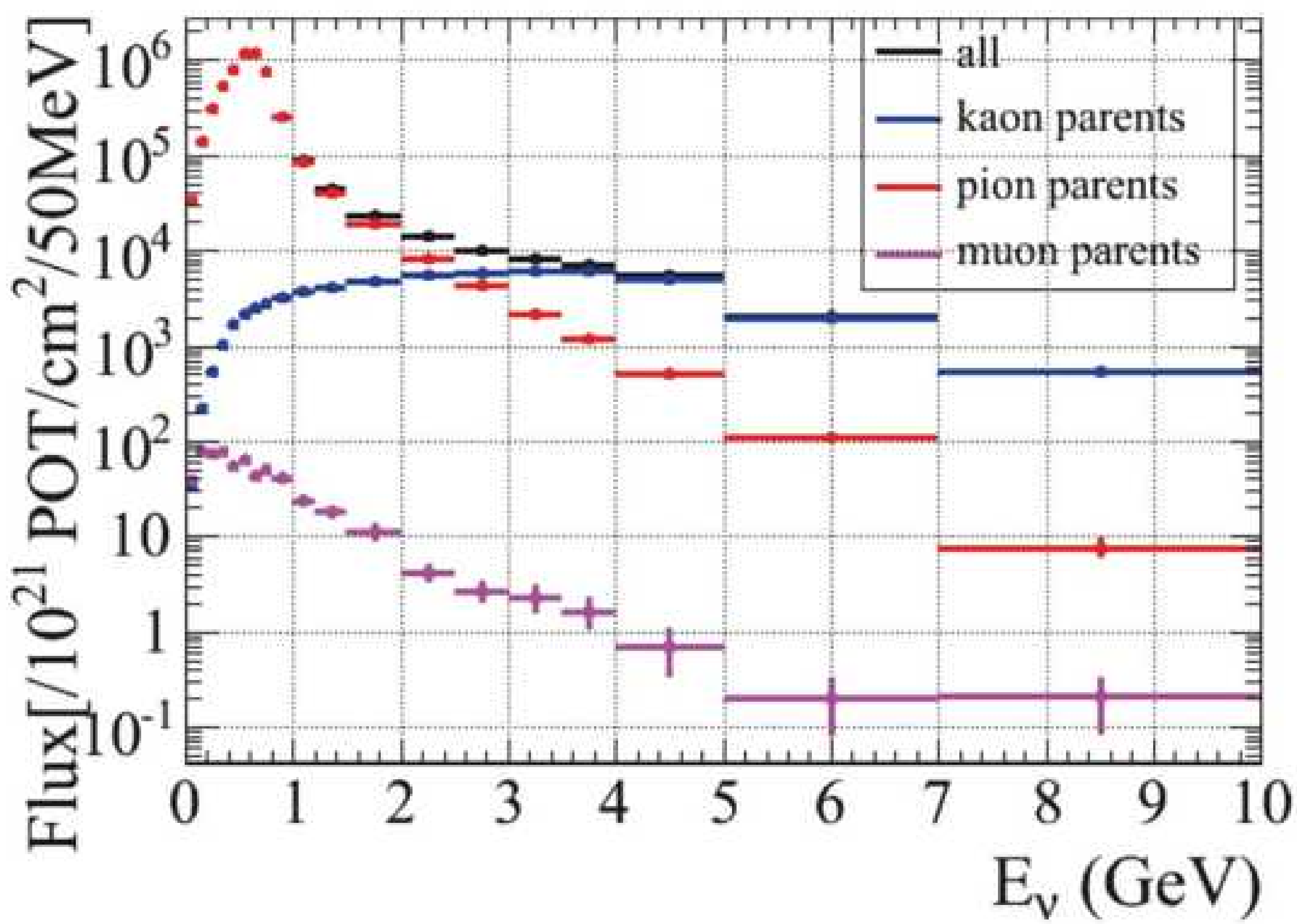
Neutrino flux at ND and SK

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.
$\pi^+ \rightarrow \nu_\mu + \mu^+$	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%

ND samples represent ν_μ flux

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

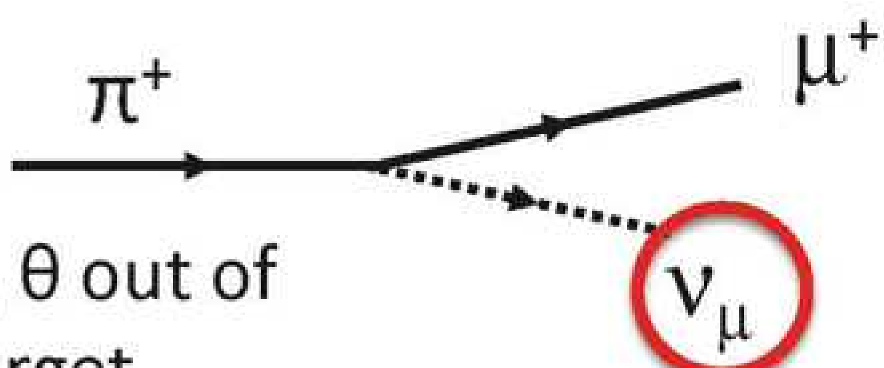




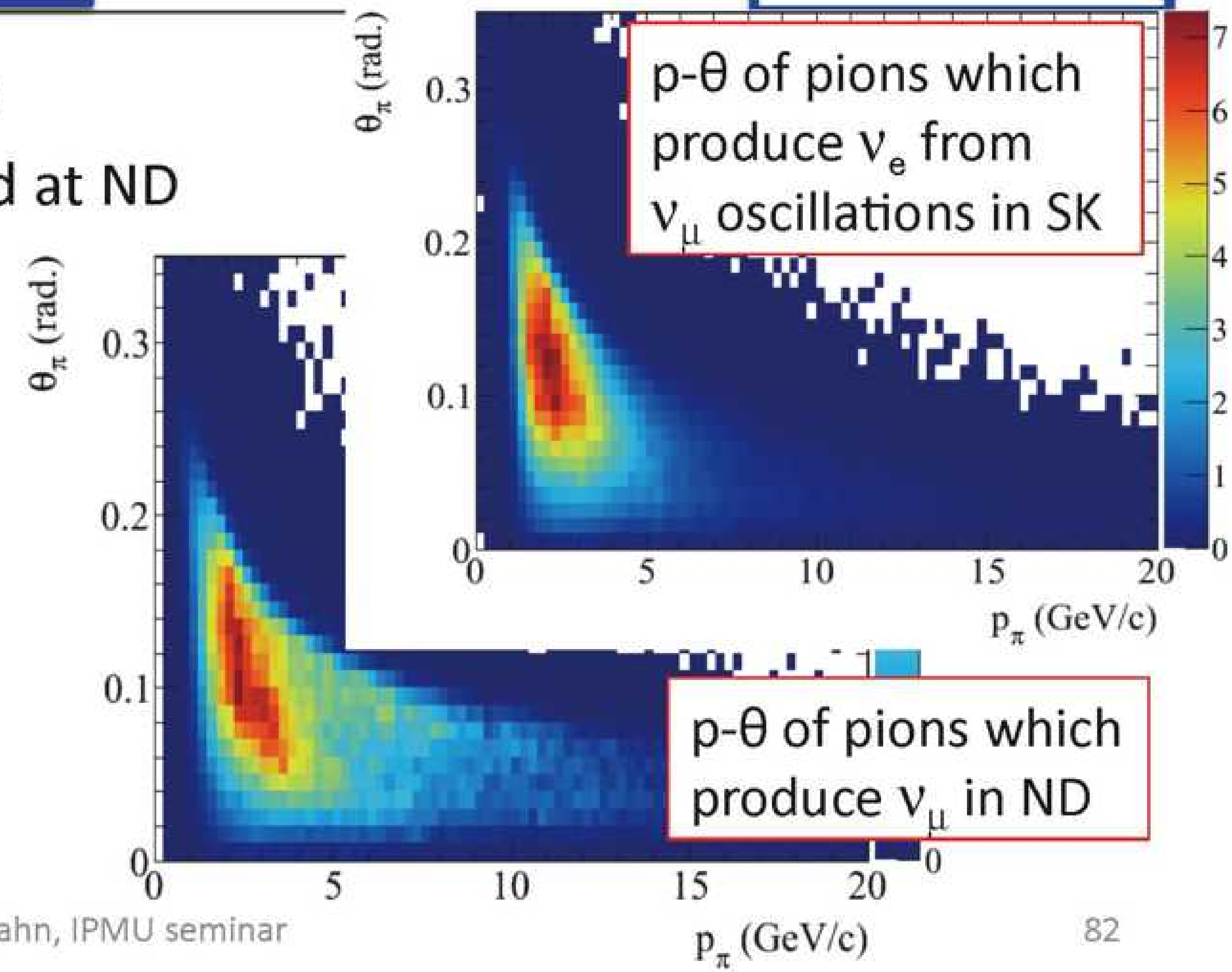
Neutrino flux at ND and SK

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



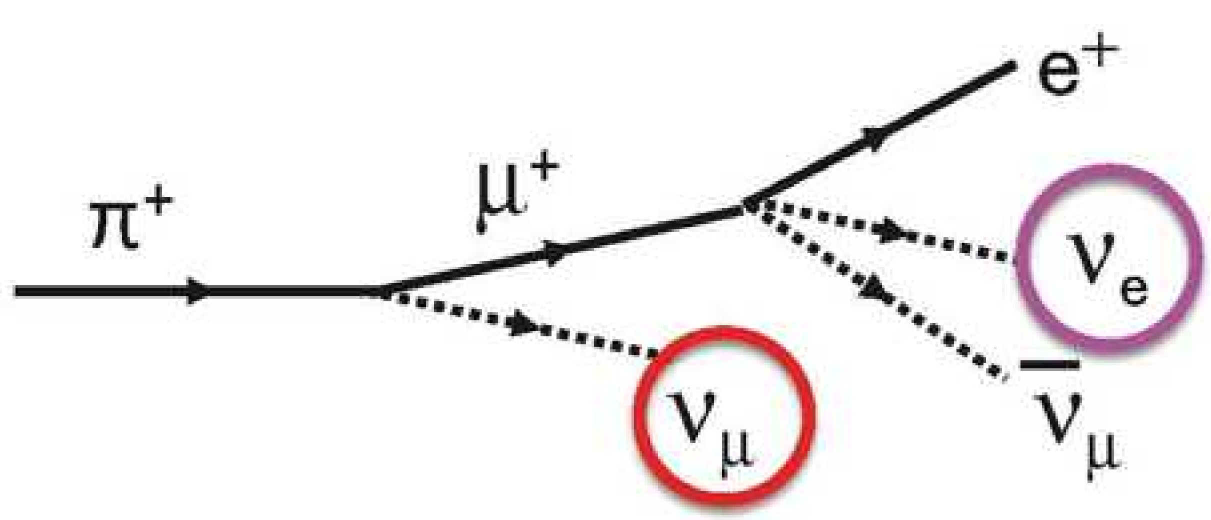
p, θ out of target

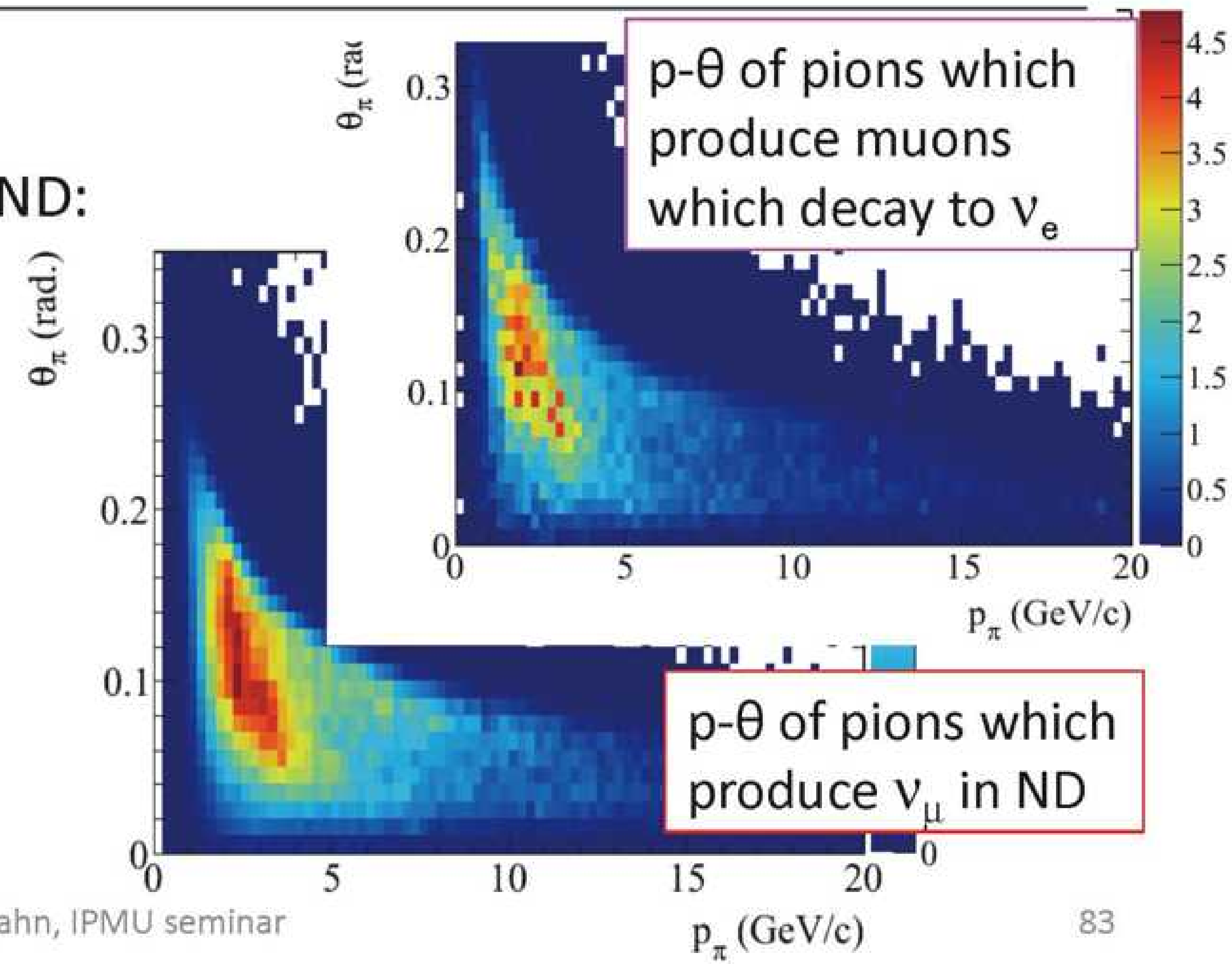


Neutrino flux at ND and SK

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%

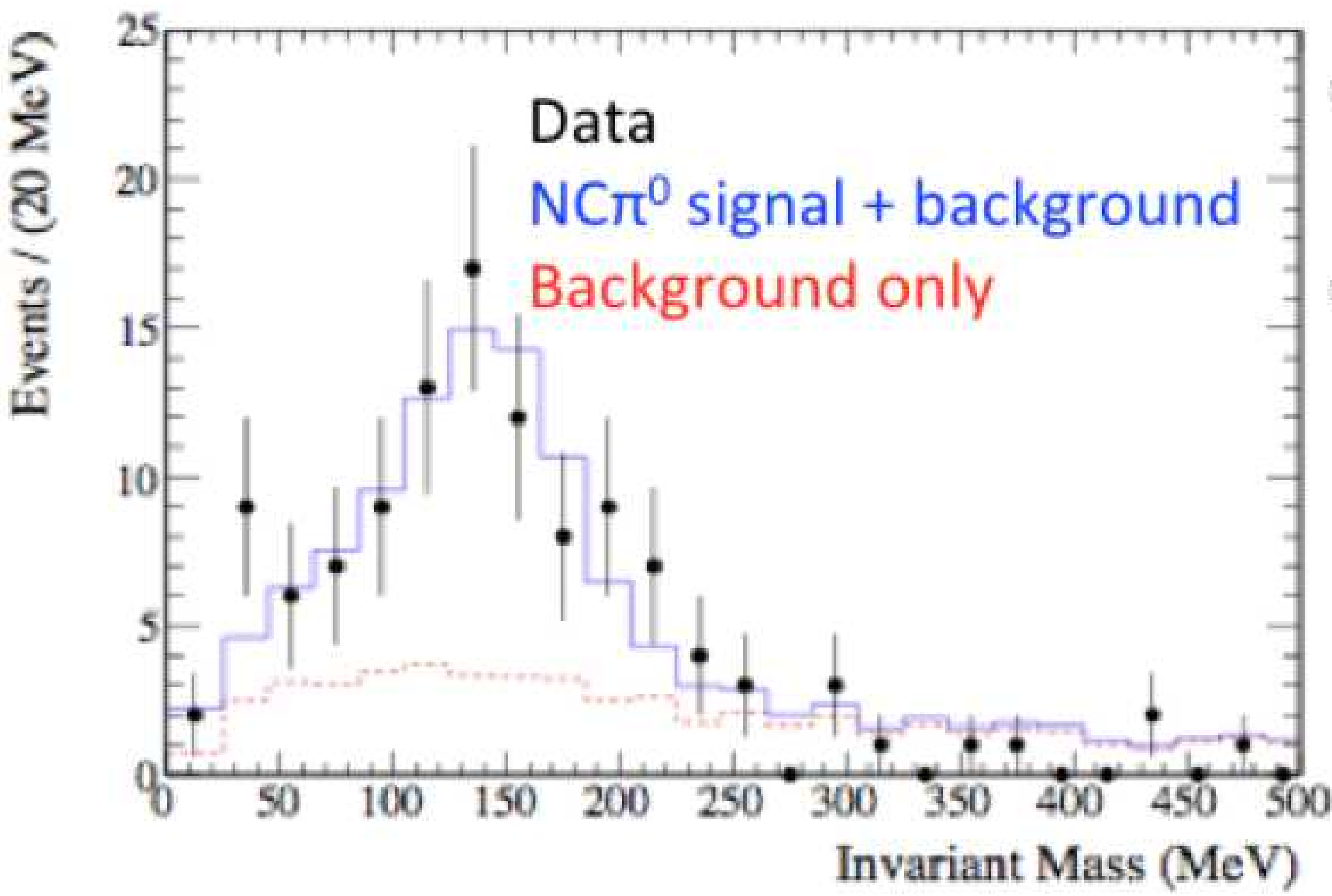
CC background from beam ν_e is strongly correlated with ν_μ flux at ND:





Neutrino interactions at ND and SK

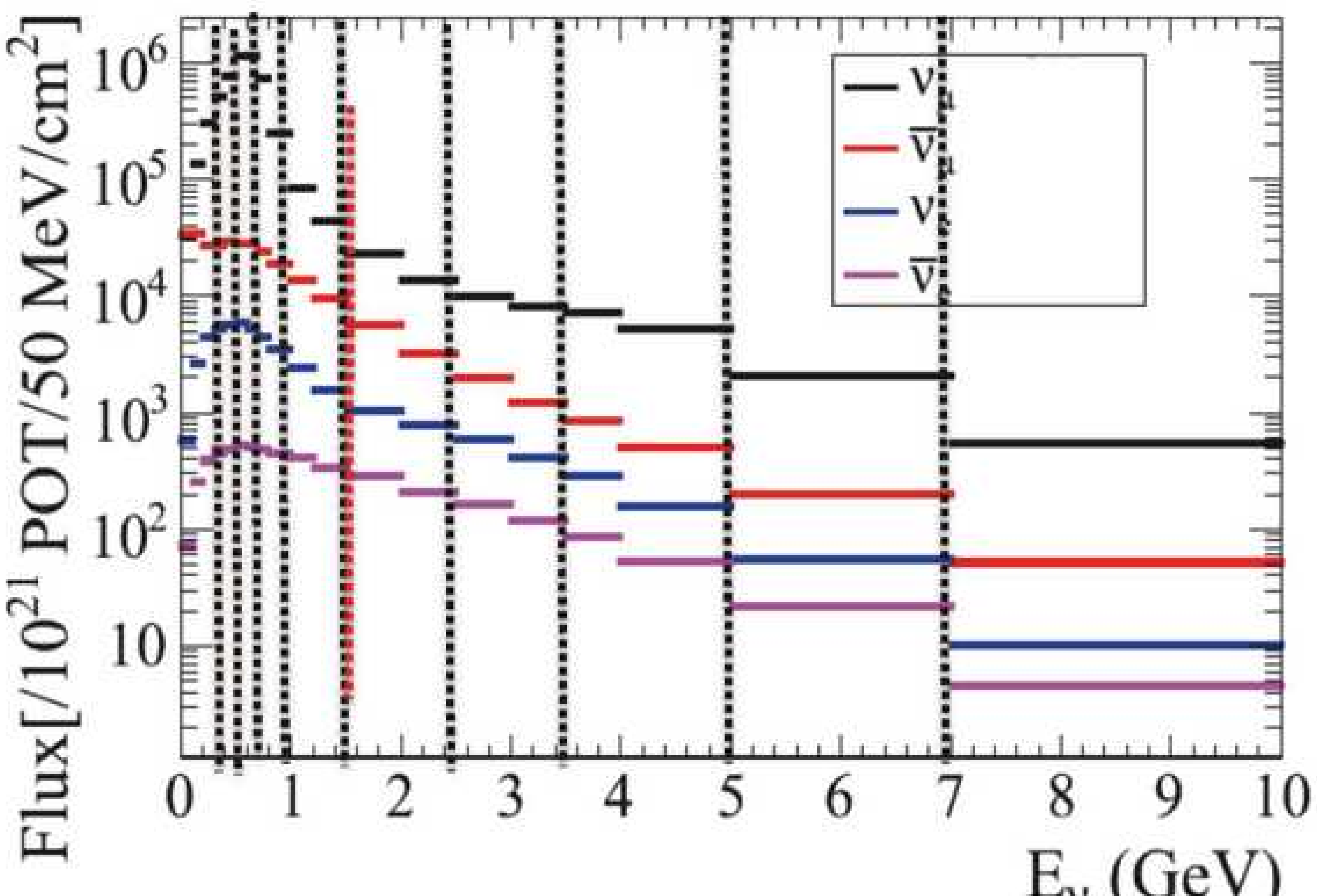
Interaction Mode	Trkr. ν_μ CCQE	Trkr. ν_μ CCnQE	SK ν_e Sig.	SK ν_e Bgnd.
CCQE	76.6%	14.6%	85.8%	45.0%
CC1π	15.6%	29.3%	13.7%	13.9%
CC coh.	1.9%	4.2%	0.3%	0.7%
CC other	4.1%	37.0%	0.2%	0.7%
NC	1.5%	5.3%	-	39.7%

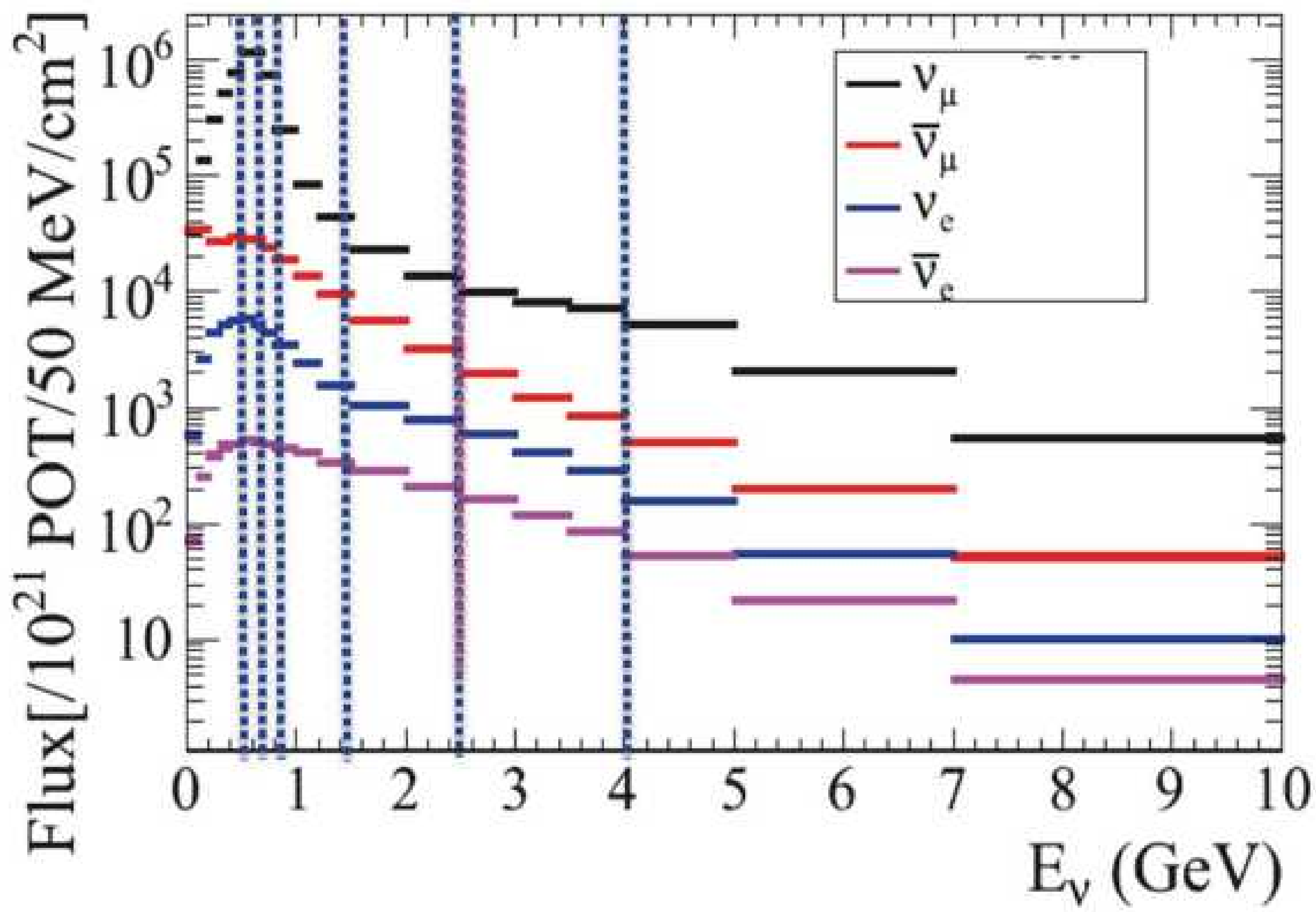


- Indirect constraint on NC ($1\pi^0$) through CC1π in ND measurement
- Additional ND selection of NCπ^0 with P0D detector to cross check rate prediction

Core of analysis: Flux parameterization

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





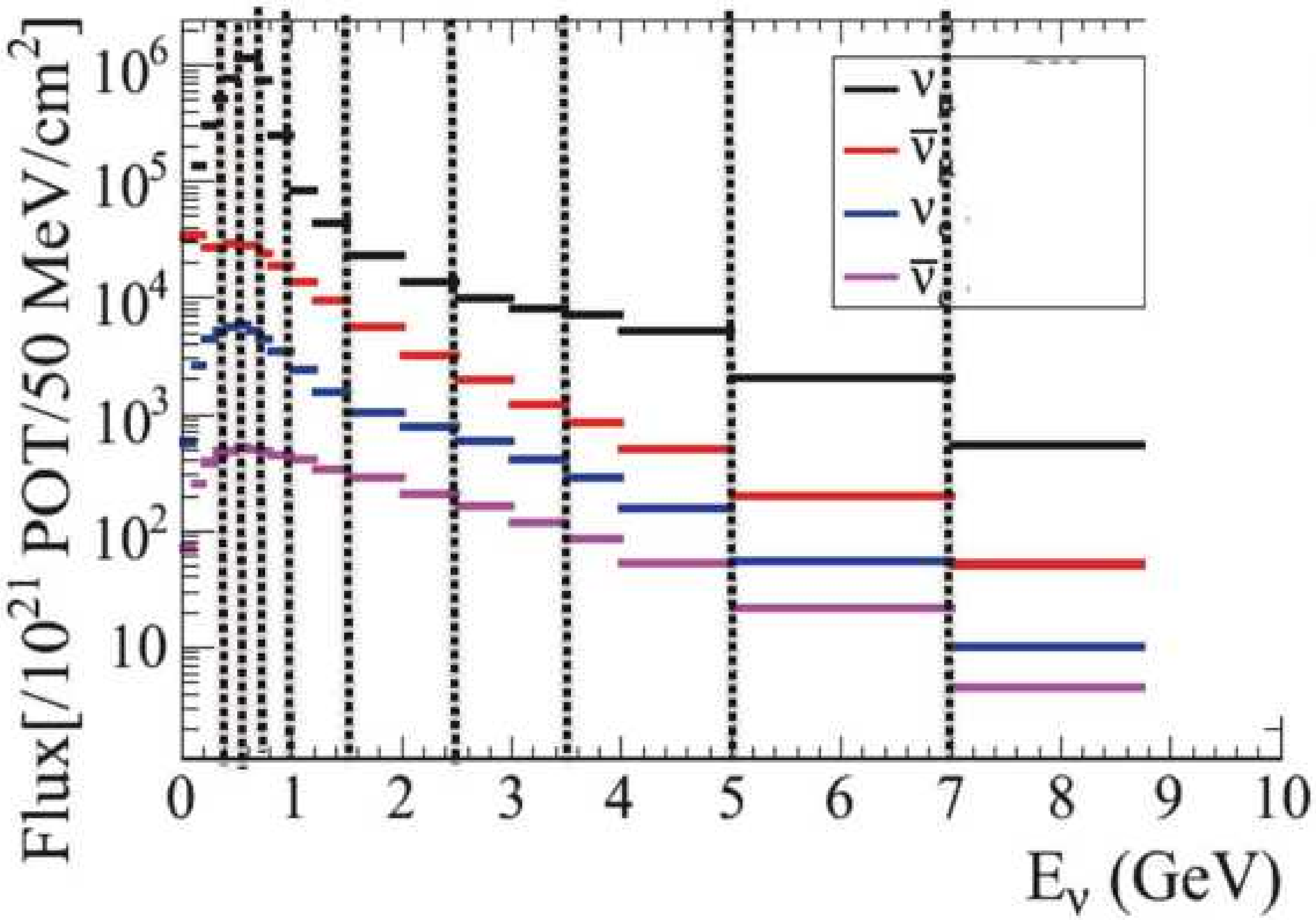
Current binning for T2K flux:

- ν_μ: 0.0-0.4, 0.4-0.5, 0.5-0.6, 0.6-0.7, 0.7-1.0, 1.0-1.5,1.5-2.5, 2.5-3.5, 3.5-5.0, 5.0-7.0, 7.0-30.0 GeV *(11 bins each ND and SK samples, index 0-10 and 11-21)*
- $\bar{\nu}_\mu$: 0.0-1.5, 1.5-30.0 GeV *(2 bins, SK sample, index 22-23)*
- ν_e : 0.0-0.5, 0.5-0.7, 0.7-0.8, 0.8-1.5, 1.5-2.5, 2.5-4.0, 4.0-30.0 GeV *(7 bins, index 24-30)*
- $\bar{\nu}_e$: 0.0-2.5, 2.5-30.0 GeV *(2 bins, SK sample, index 31-32)*

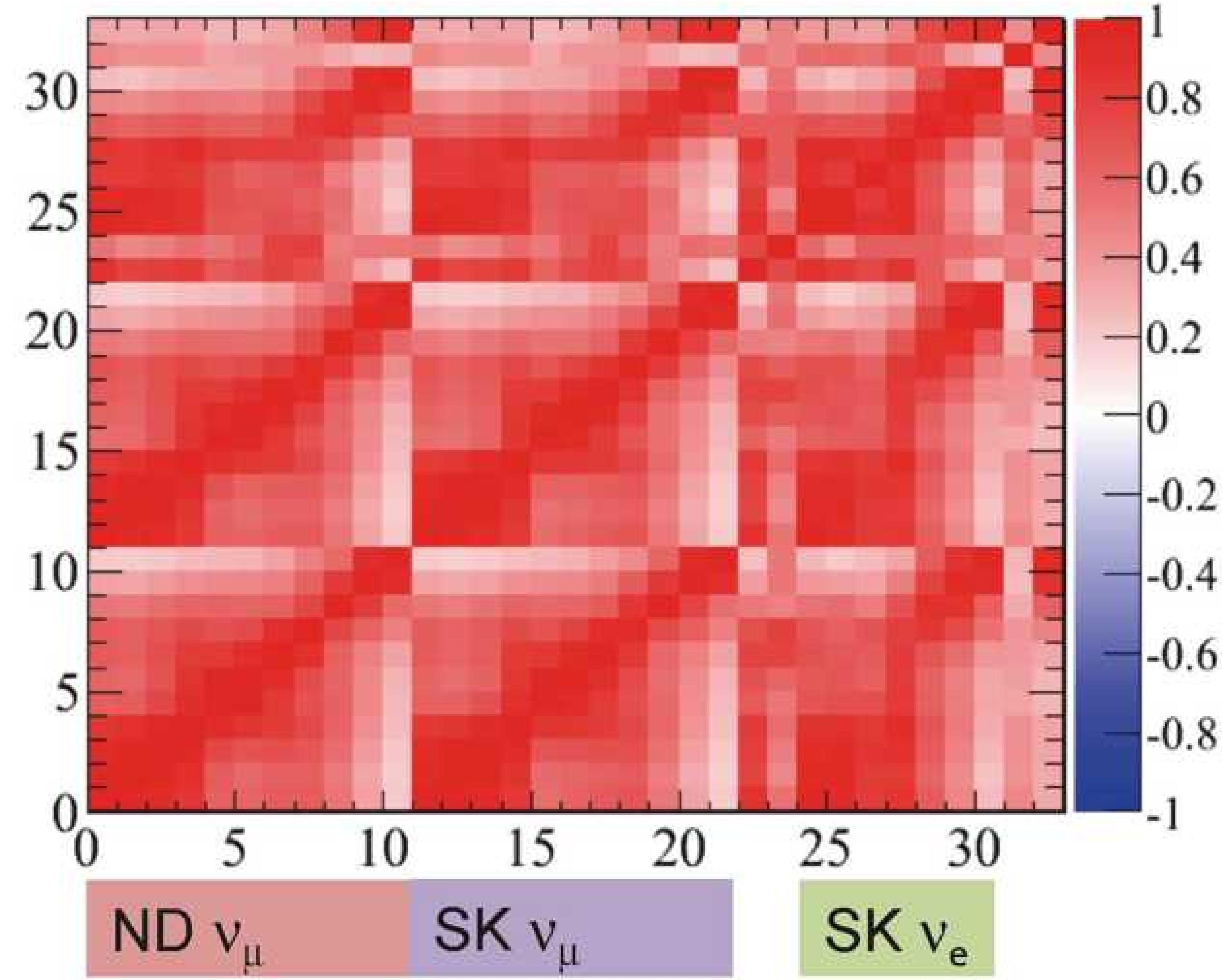
Flux parameterization

Neutrino flux prediction

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



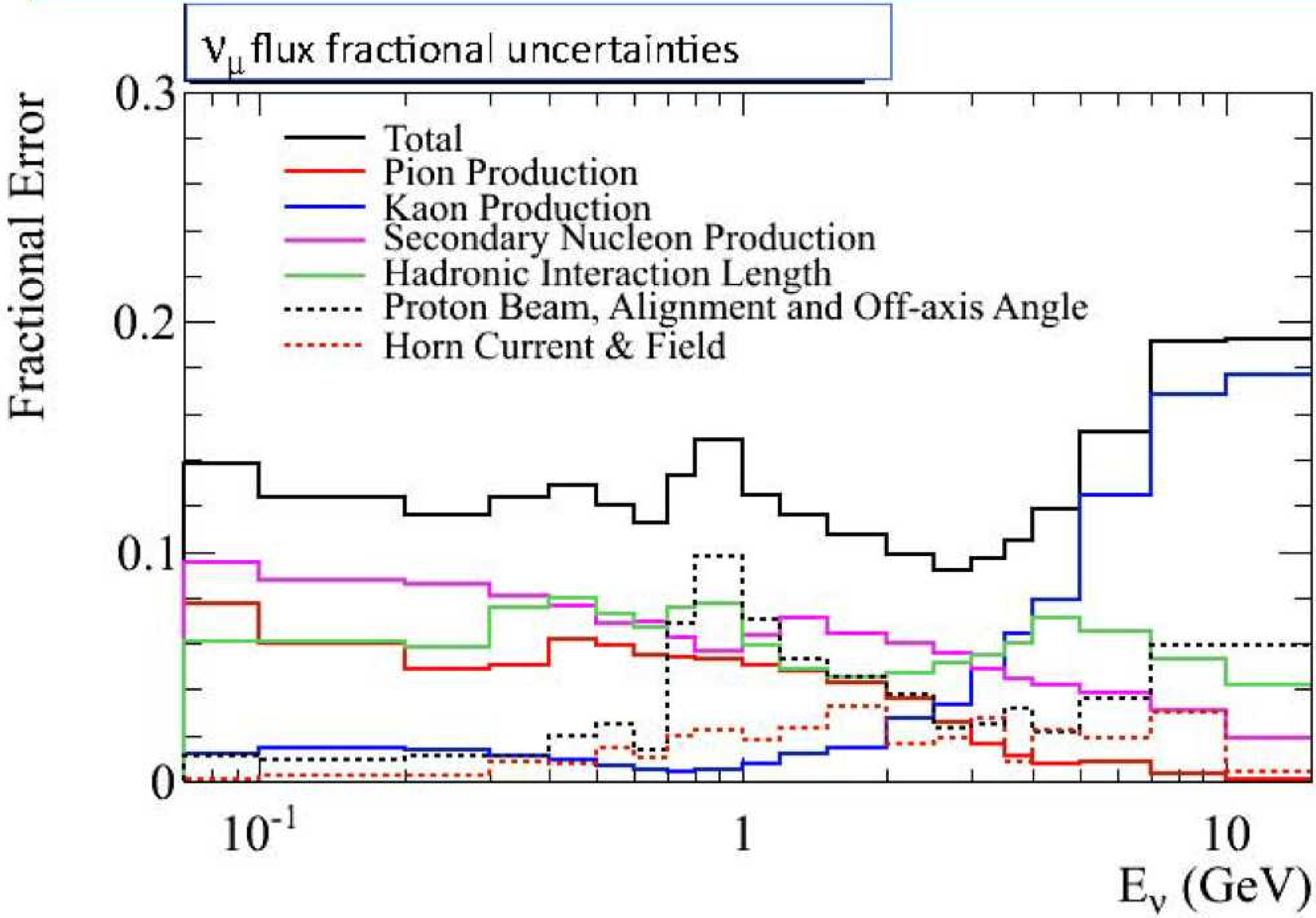
Correlations between flux bins



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



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

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

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

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

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

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

ND280 constraint
$ln\ L_{ND280}(\vec{f},\vec{x},\vec{d})$

+

Neutrino flux term
$ln\ L_{flux}(\vec{f})$

+

Neutrino xsec term
$ln\ L_{xsec}(\vec{x})$

ND280 likelihood

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

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

$ln\ L_{flux}(\vec{f}\ )$

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

$ln\ L_{xsec}(\vec{x}\ )$

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

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

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

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

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

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

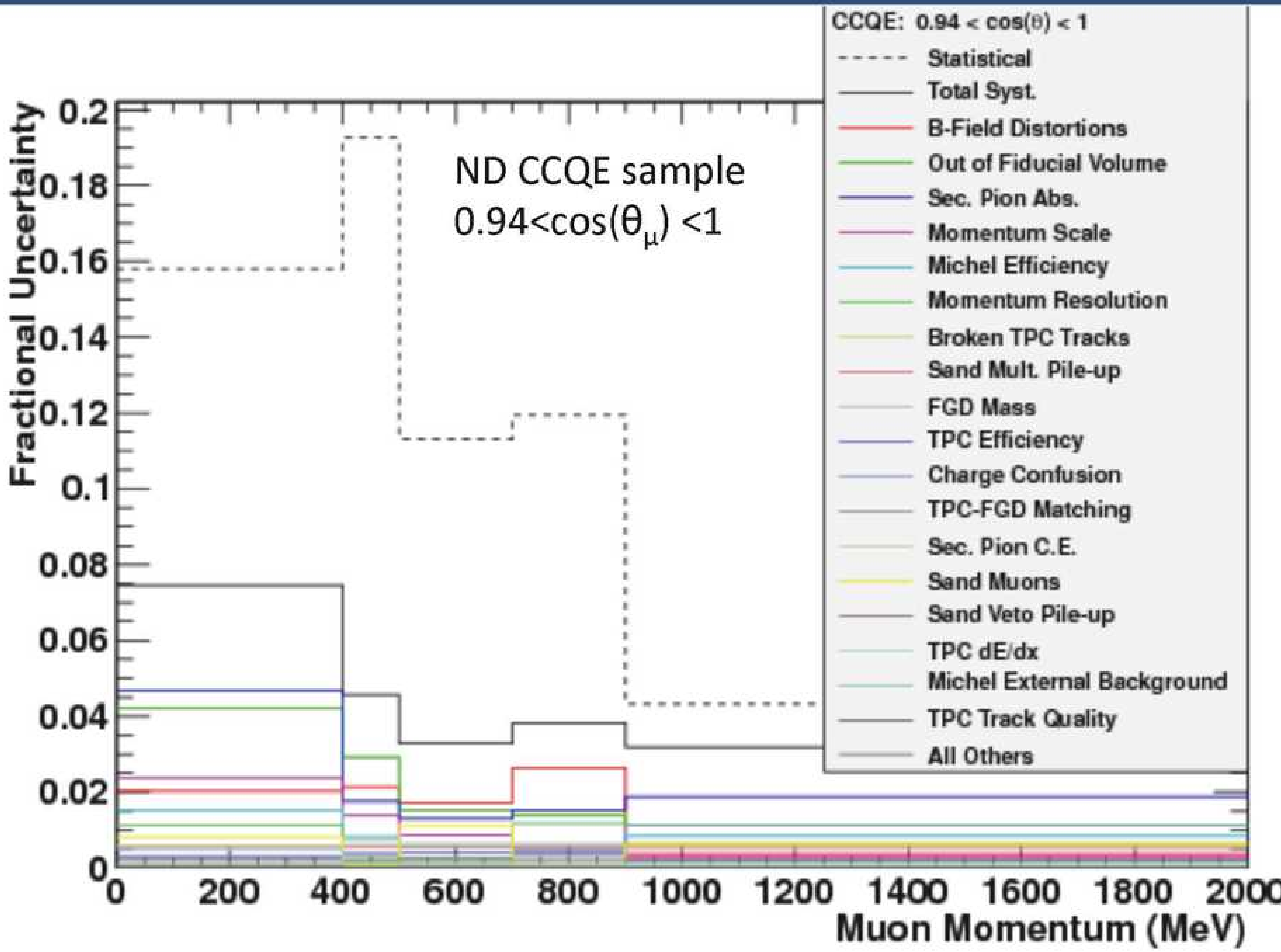
$$+ \sum_{i}^{p,\theta\ bins}\sum_{n}^{p,\theta\ bins}(1-d_i)(V_d^{-1})_{i,n}(1-d_n)$$

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

Prior constraint likelihood terms for detector systematic errors

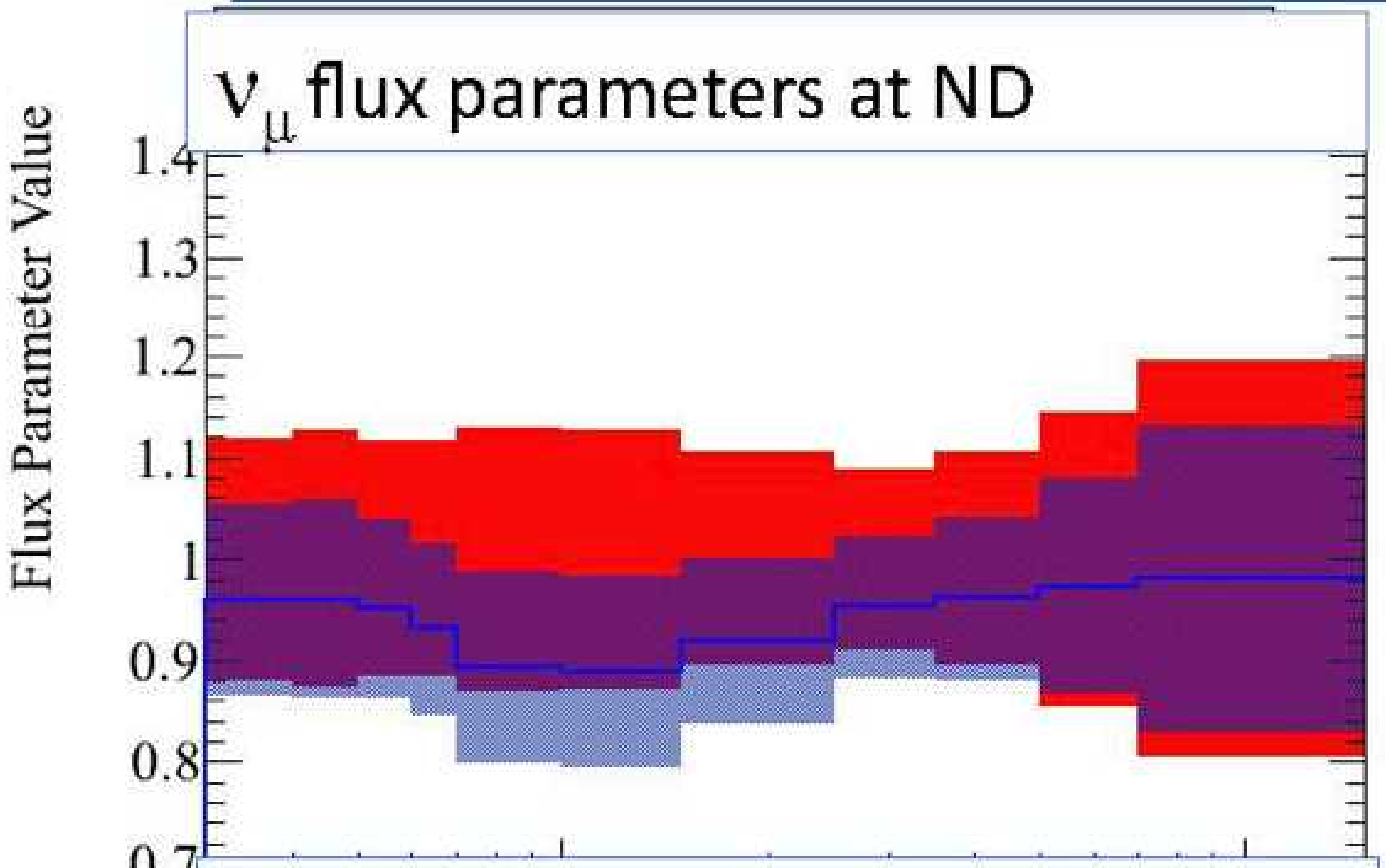
- Also includes uncertainties (e.g. FSI) which could not be otherwise easily parameterized
- Determined from control samples, calibration data, and external pion scattering data

Detector systematic errors

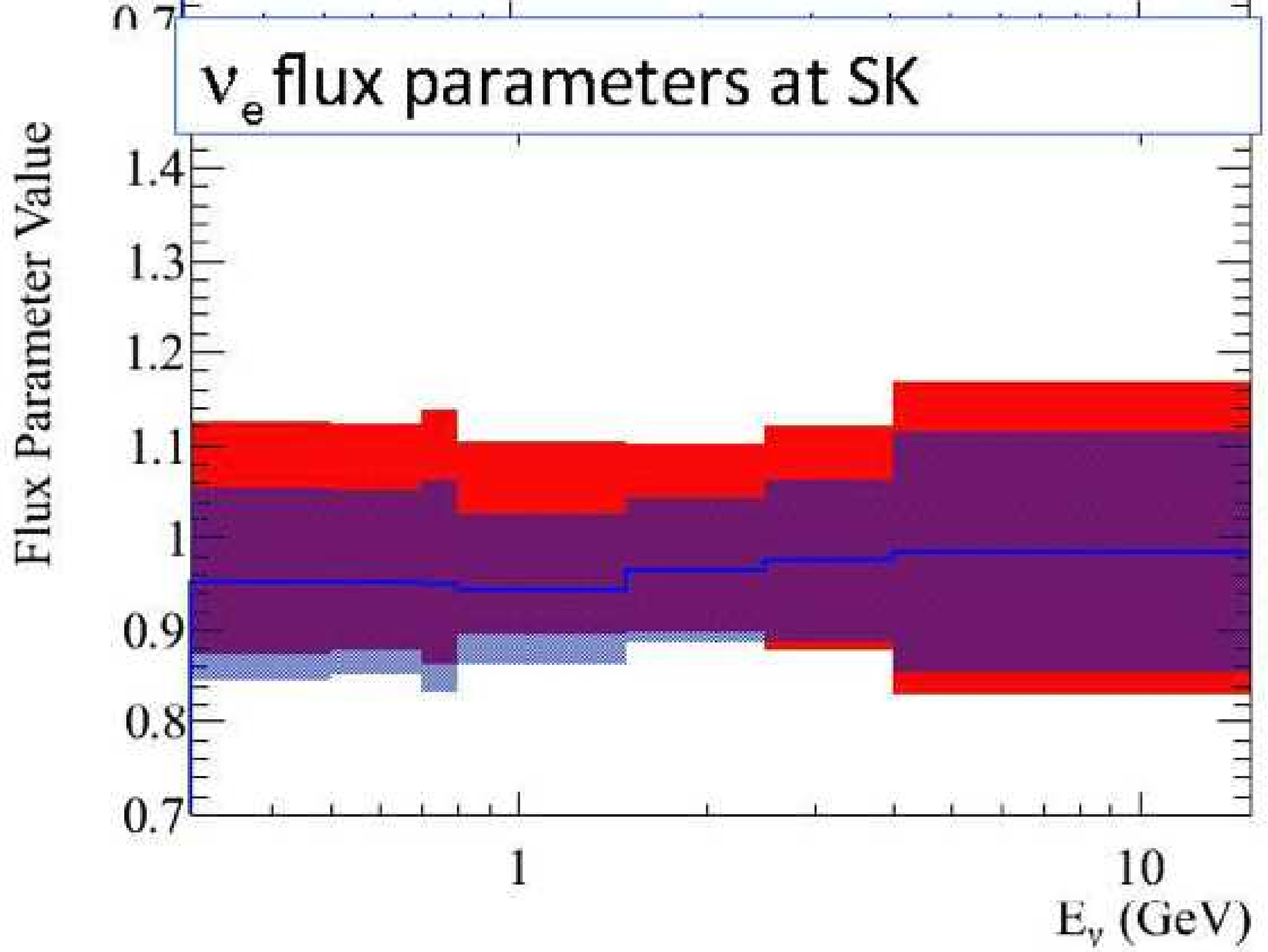


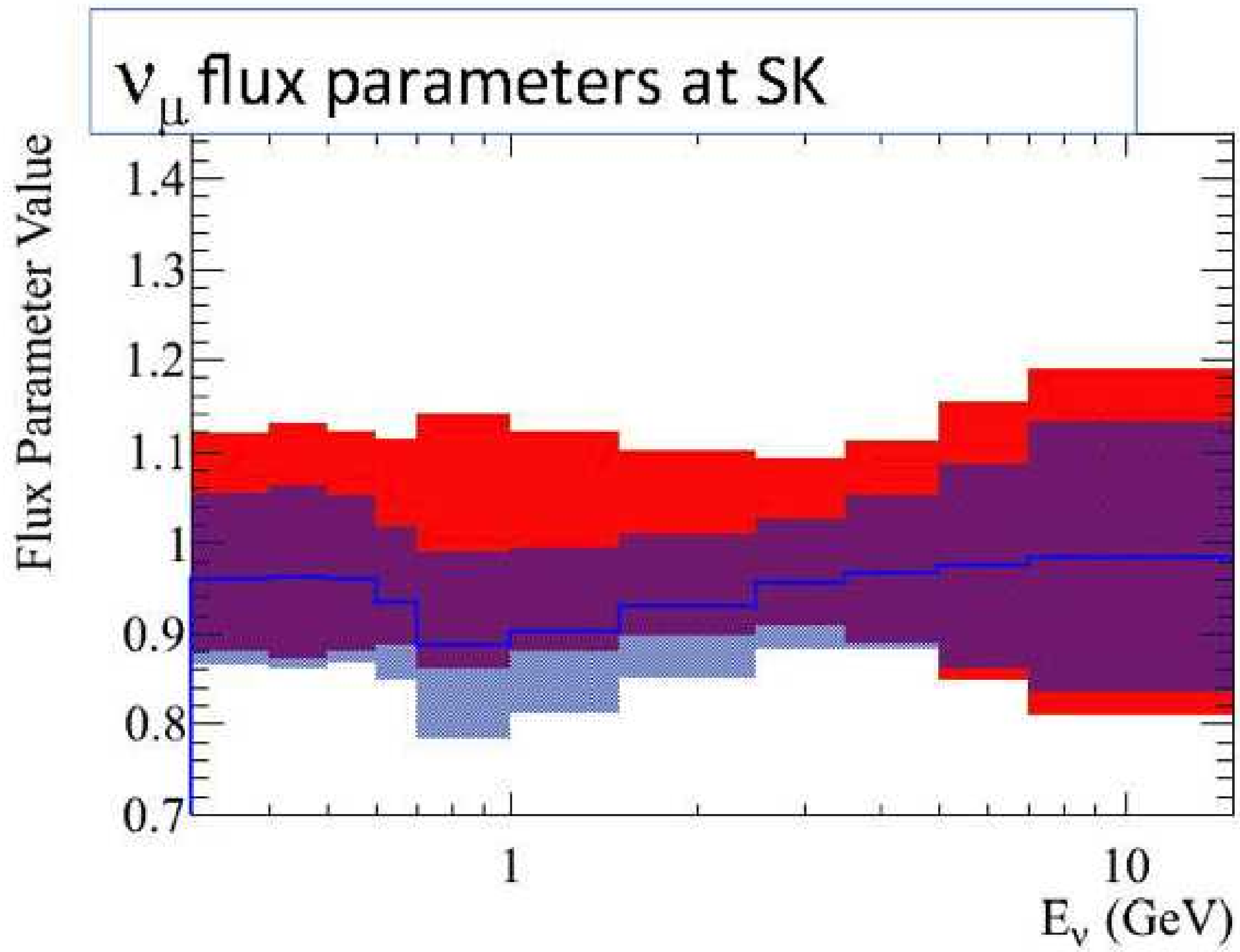
Fractional systematic uncertainty for vs. momentum

Flux parameters change after ND measurement



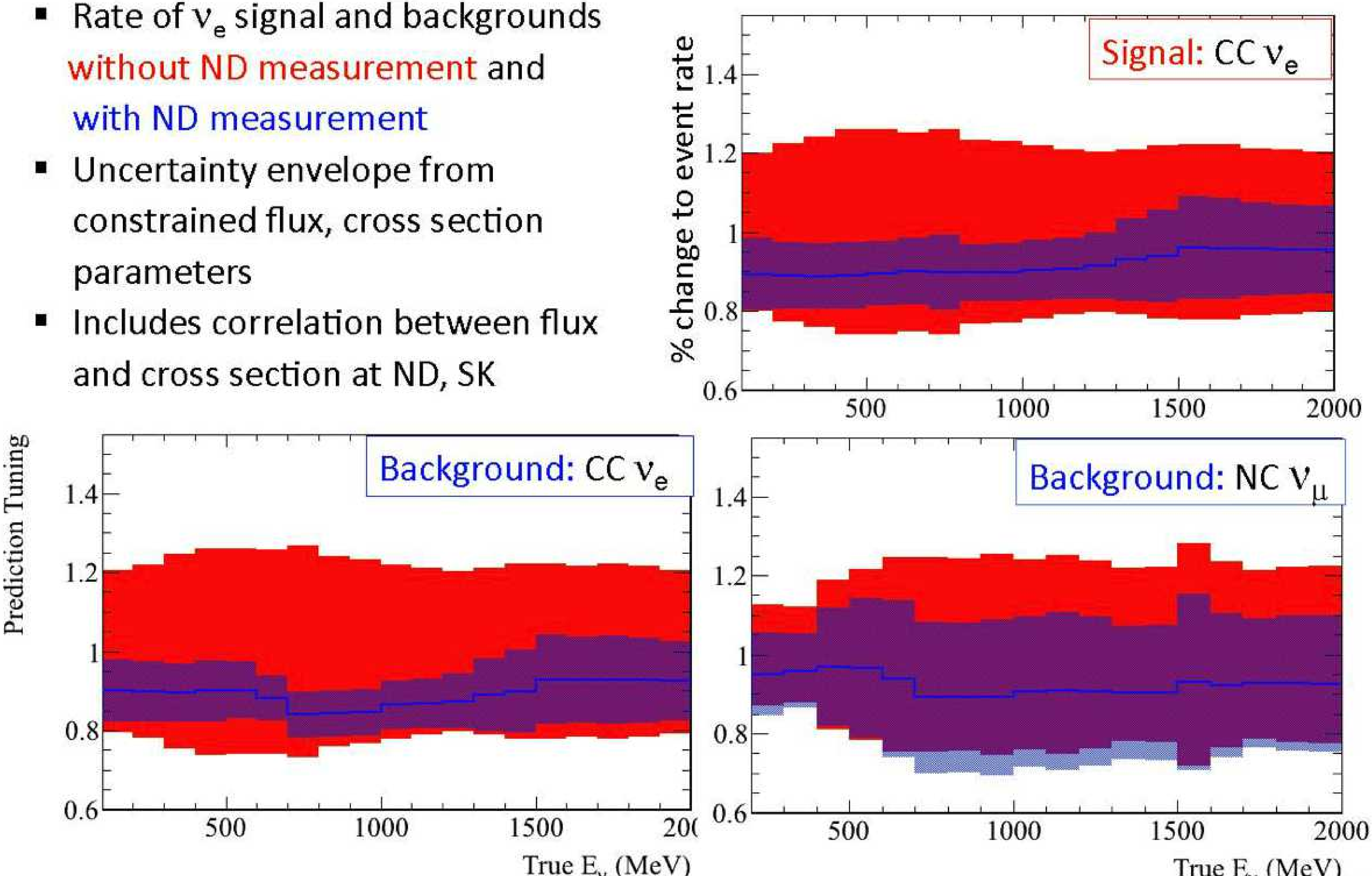
- Flux parameters without ND measurement and with ND measurement





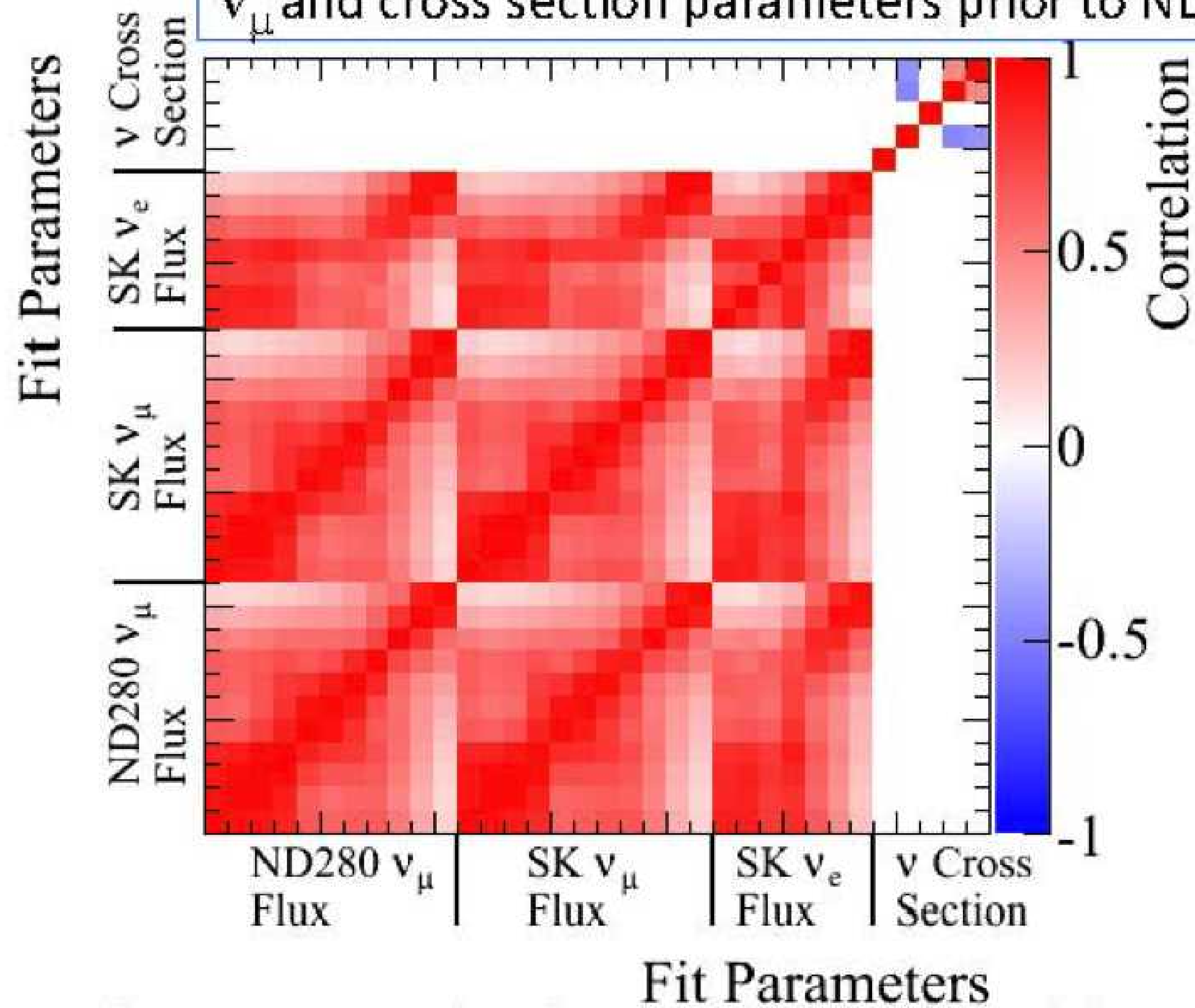
Effect of ND measurement on ν_e signal, background

- 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



Covariance

ν_μ and cross section parameters prior to ND measurement

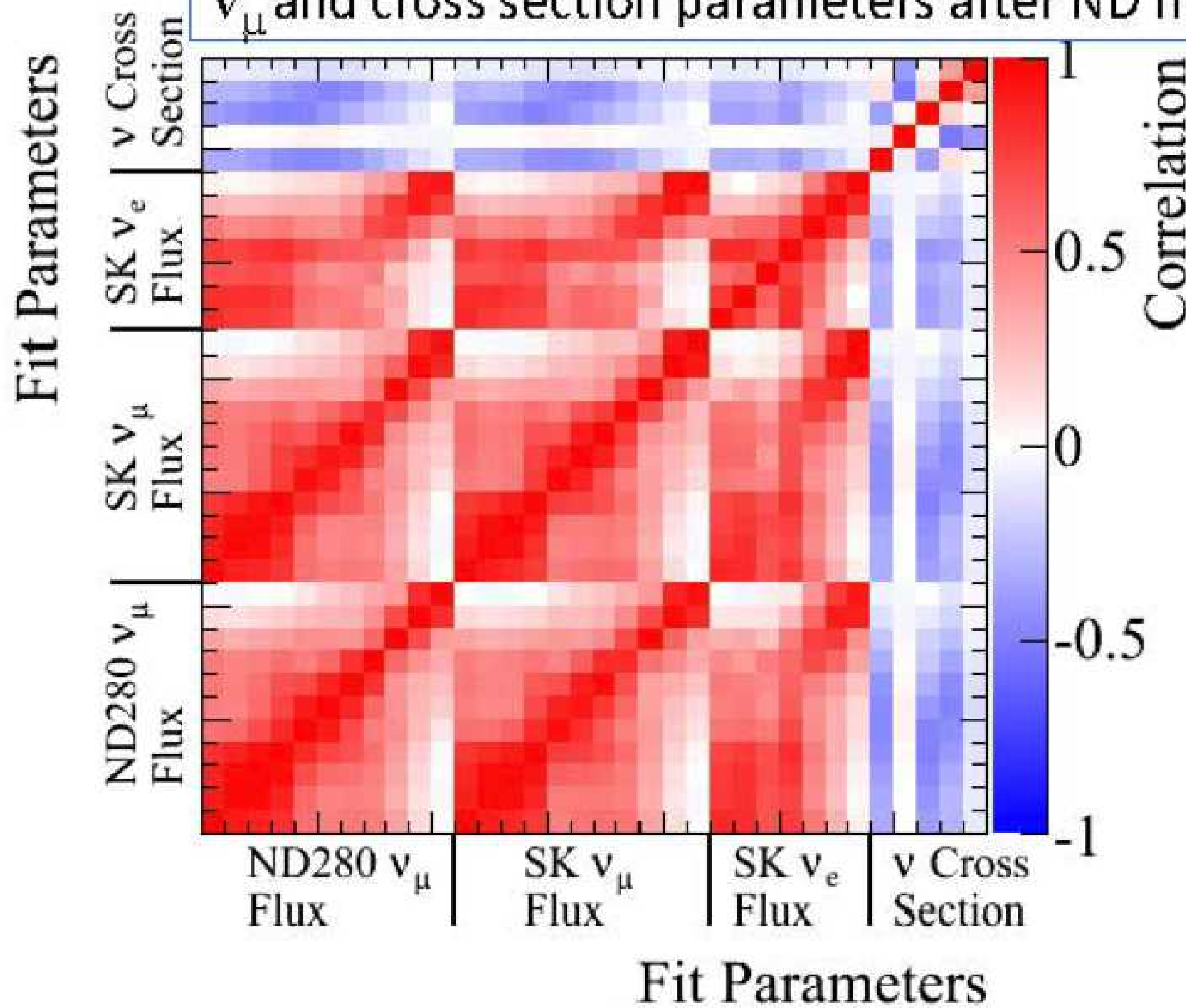


ν_μ, ν_e fluxes are correlated according to external data and how flux at ND, SK is shared

Correlations between ND, SK shared cross section parameters determined from external data fits

Covariance post-ND measurement

ν_μ and cross section parameters after ND measurement



Flux and shared cross section become correlated

Hyper-K timeline

Schedule

assuming budget being approved from JPY2016

A. Minamino
NuInt12