NATIONAL ACCELERATOR LABORATORY

U.S. DEPARTMENT OF ENERGY

Office of Science

H. A. TANAKA

ACCELERATOR-BASED NEUTRINO EXPERIMENTS

RECALL: NEUTRINO ECONOMICS

- The ability to precisely study neutrino interactions depends heavily on statistics
  - i.e. how many neutrino interactions you observe

$$N(\nu_\alpha \rightarrow \nu_\beta) = \boxed{\varphi} \times \boxed{\sigma} \times \boxed{V \times n \times \varepsilon} \times \boxed{P(\nu_\alpha \rightarrow \nu_\beta)}$$

neutrino oscillations

- N = number of neutrino interactions
- φ = flux of neutrinos (neutrinos/cm^2)
- σ = neutrino interaction cross section on target (e.g. electron, nucleon, nucleus)
- V = volume of detector (cm^3)
- n = number of density of targets
- ε = detection efficiency

Lecture 1: how do we produce large number of neutrinos with accelerators

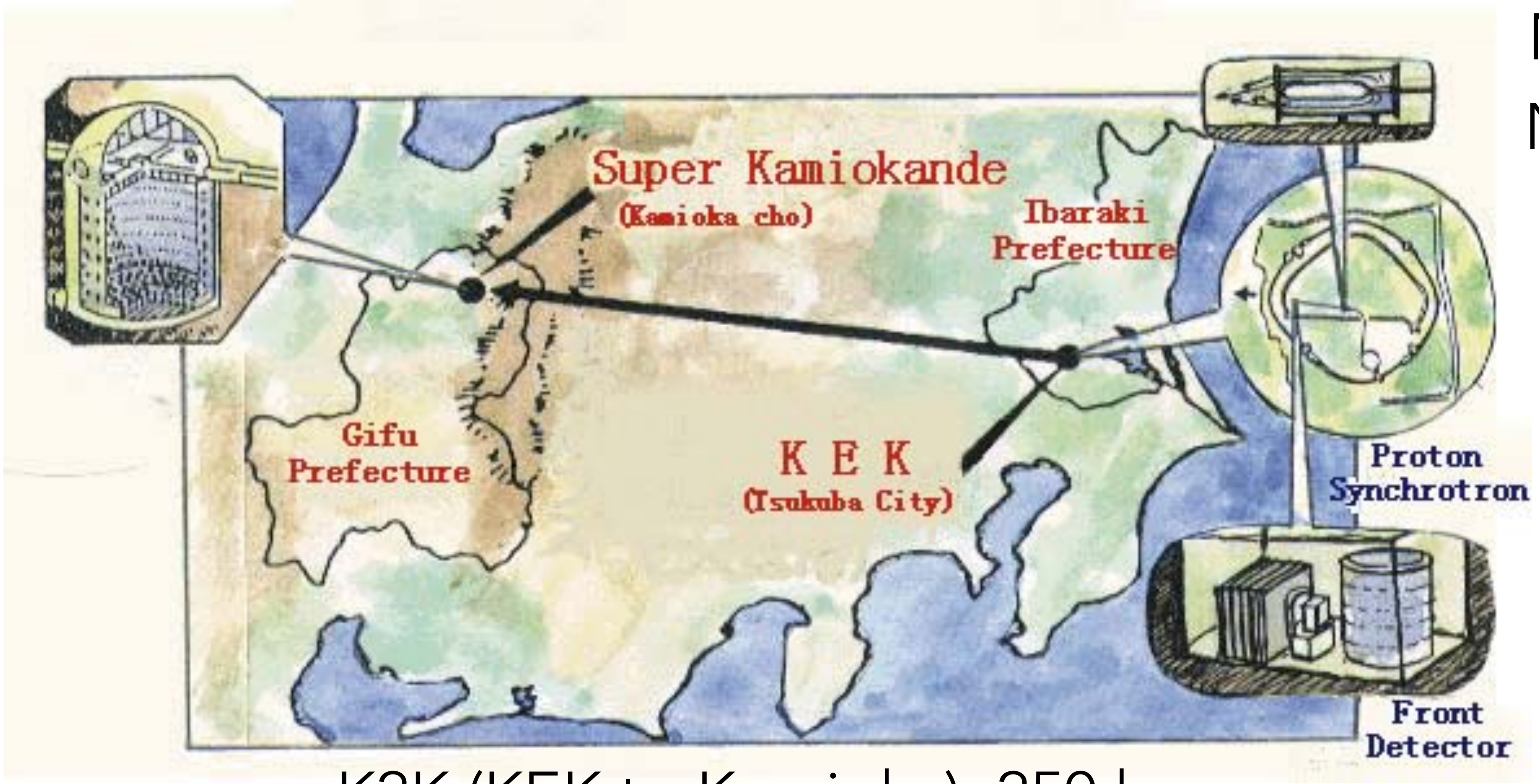
Thanks, Minerba!

Lecture 2: How do we make massive detectors that can efficiently detect neutrino interactions

Thanks, David!

LECTURE 3:
LONG-BASELINE EXPERIMENTS

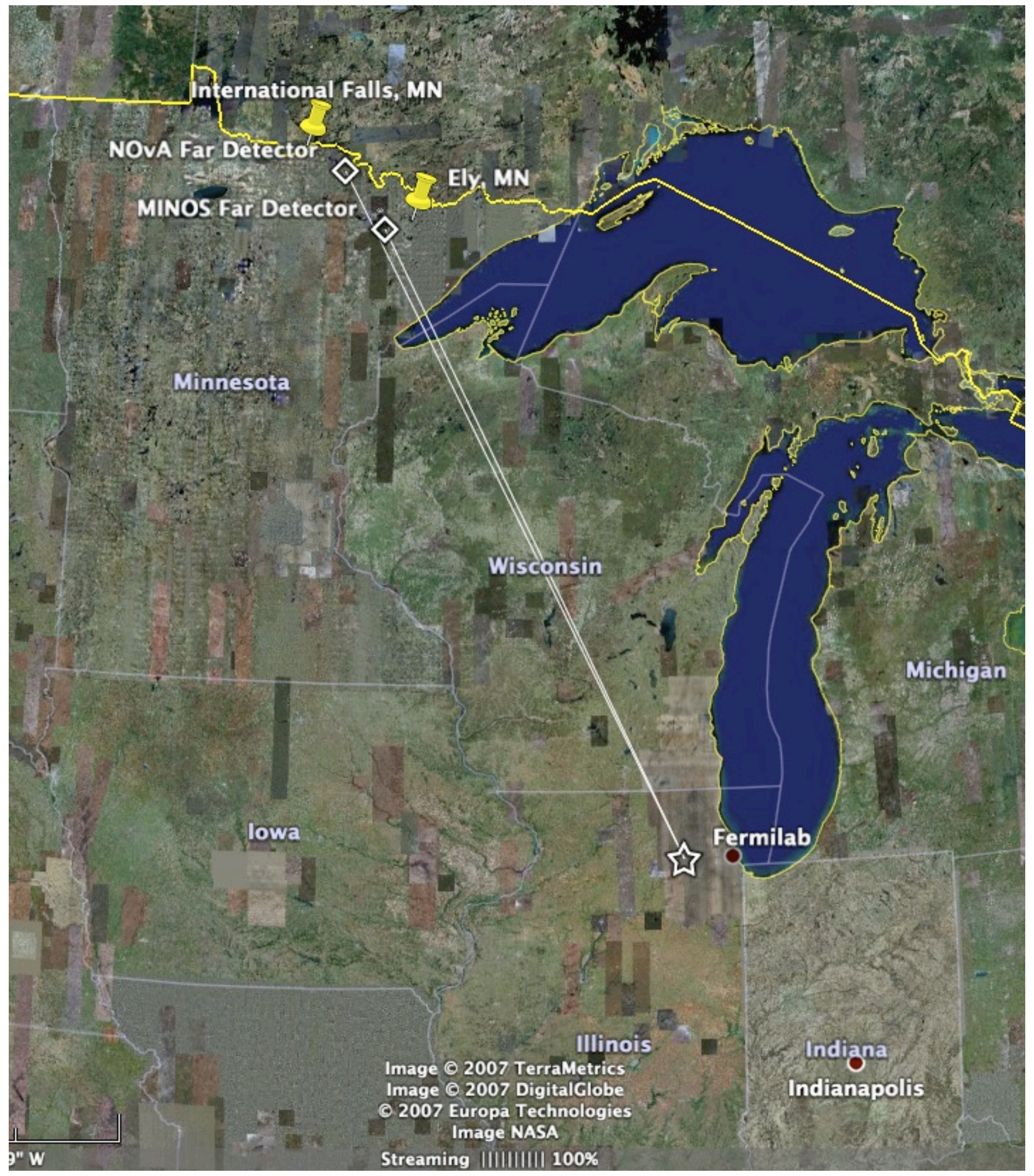
"LONG-BASELINE" EXPERIMENTS

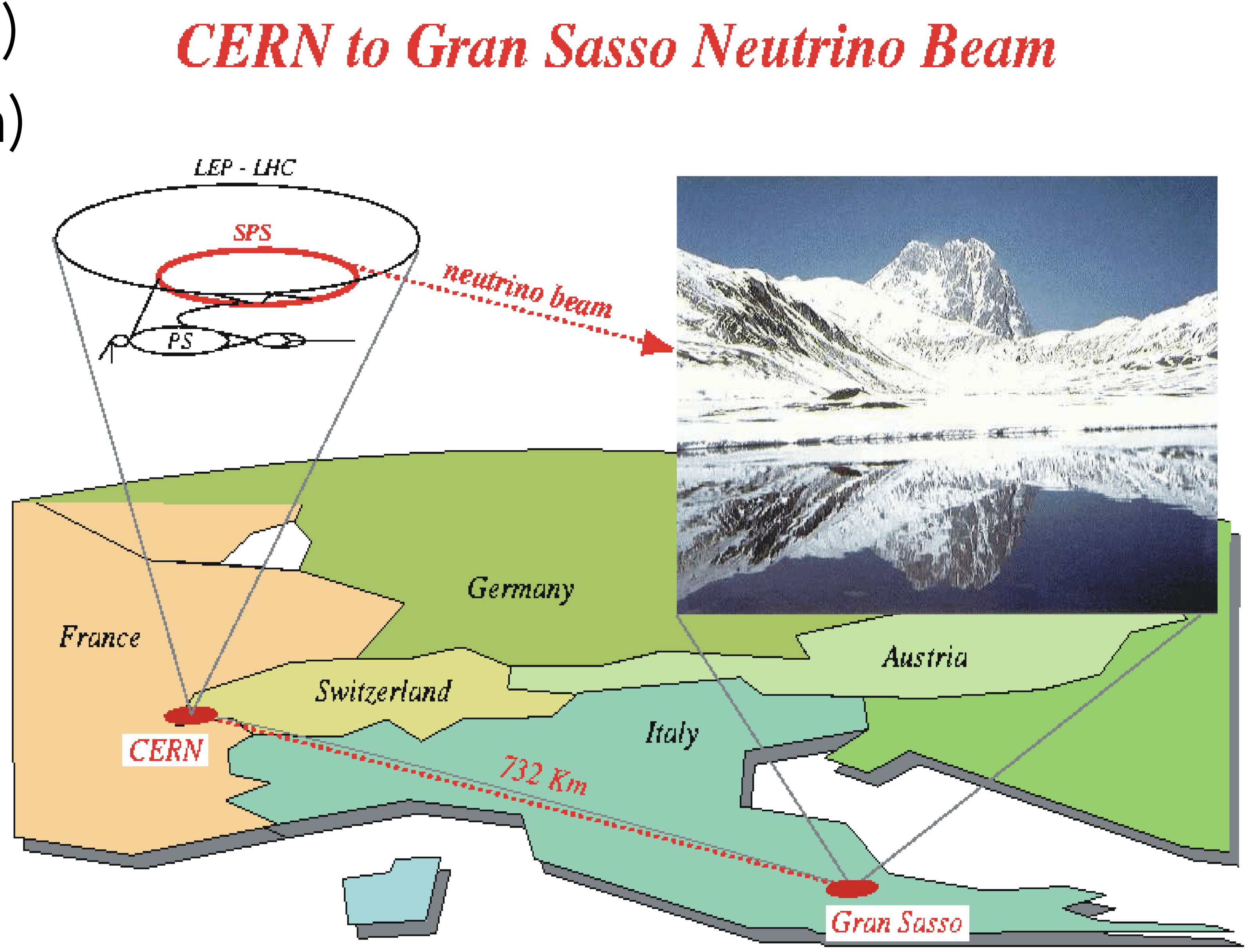


K2K (KEK to Kamioka): 250 km

MINOS: FNAL to Soudan (732 km)

NOvA: FNAL to Ash River (812 km)





OPERA: CERN to Gran Sasso (732 km)

T2K (Tokai to Kamioka): 295 km

- Accelerator-based neutrino beams have been sent to detectors hundreds of km away on three continents

RECALL:

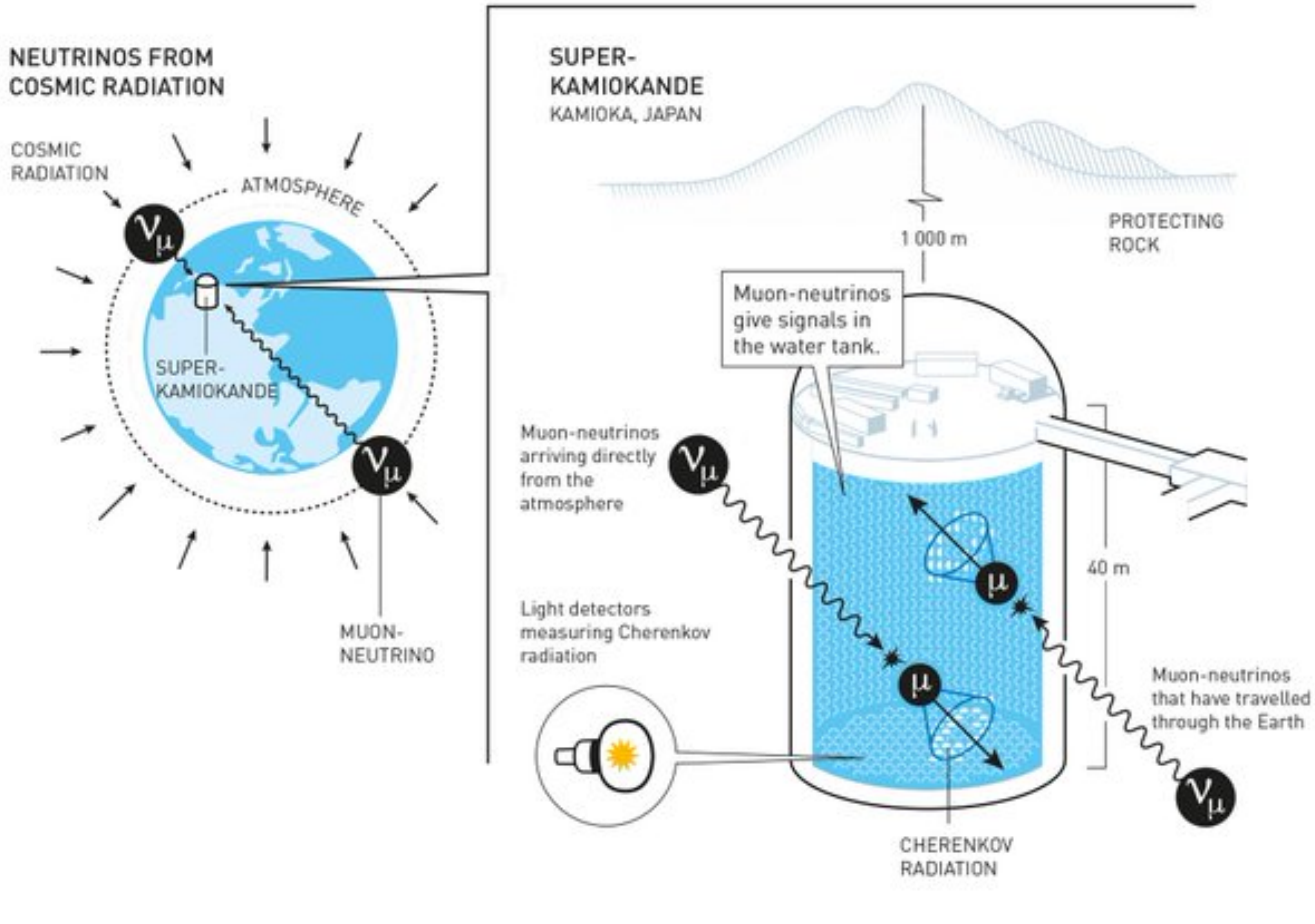
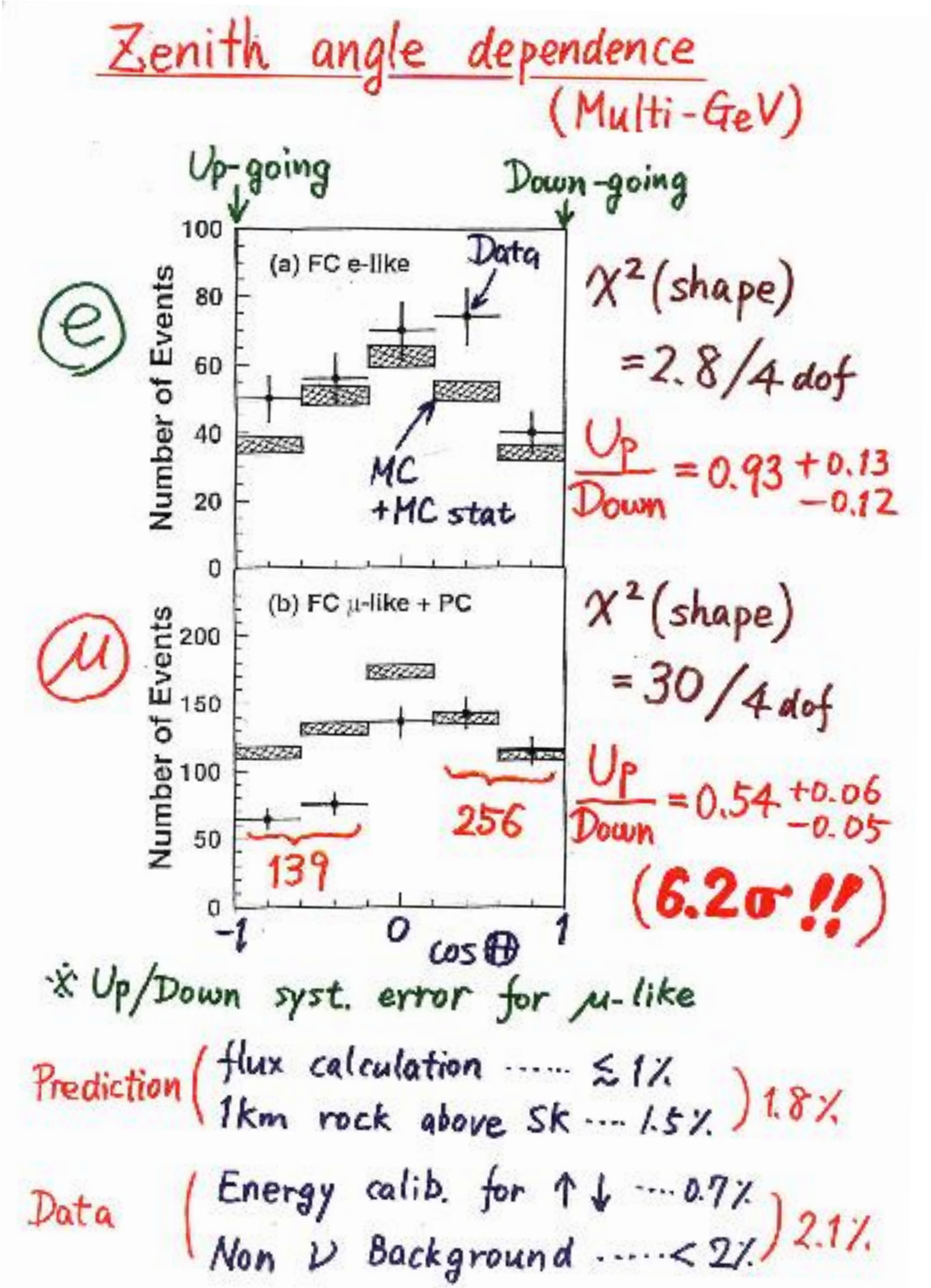
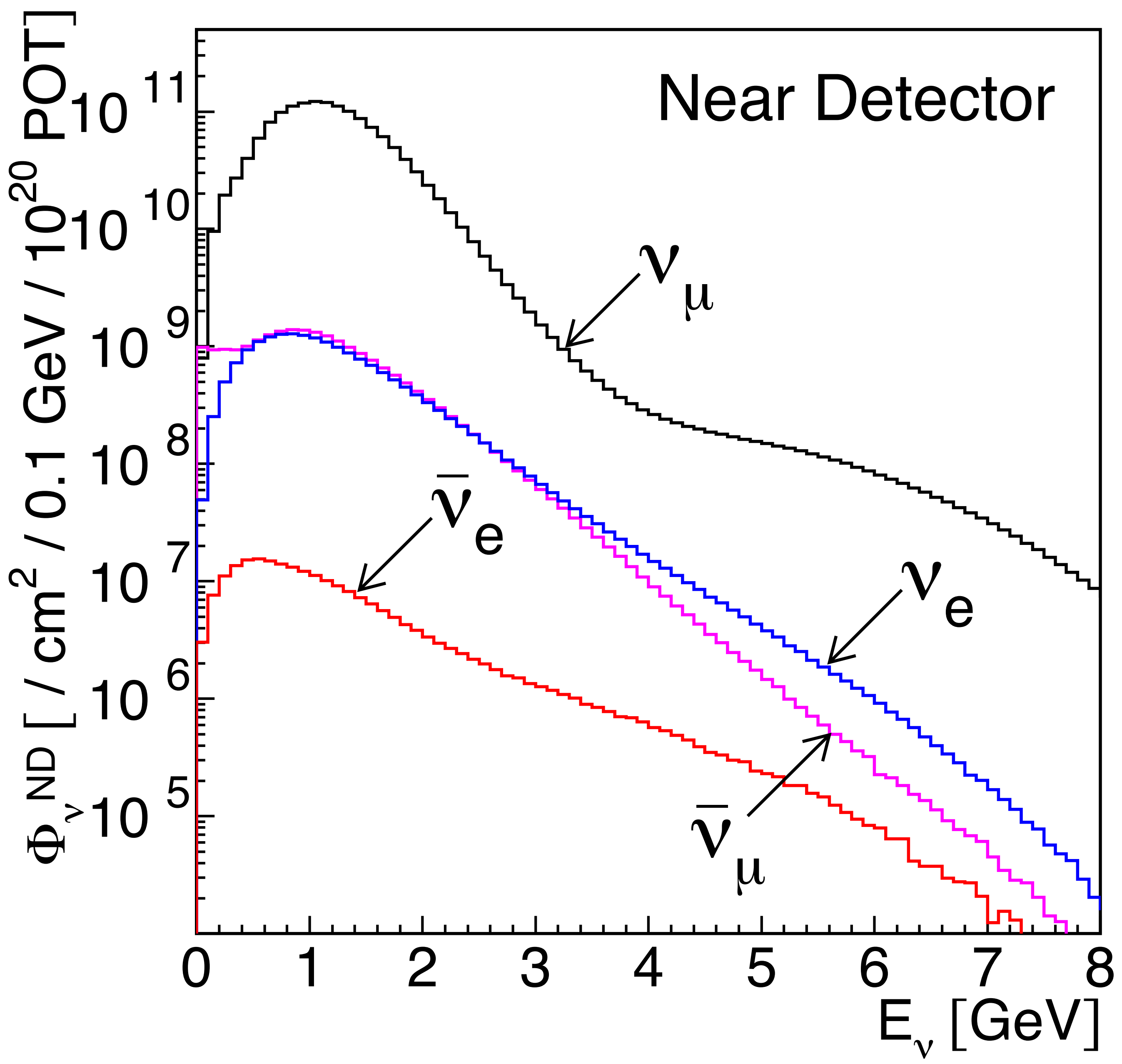


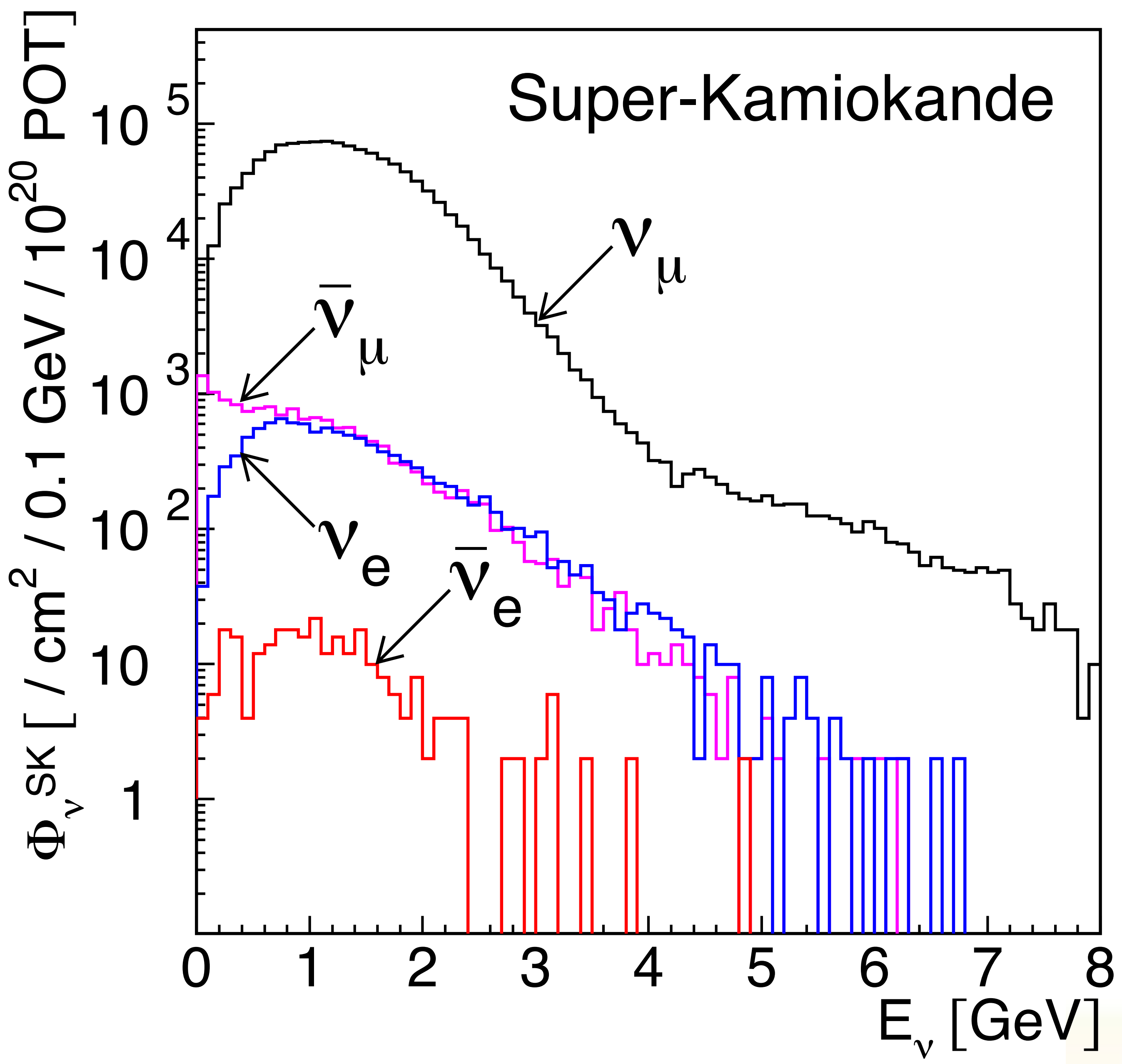
Illustration: © Johan Jarnestad/The Royal Swedish Academy of Sciences



- Can we study this with an accelerator-based neutrino beam?

K2K (KEK-TO-KAMIOKA)

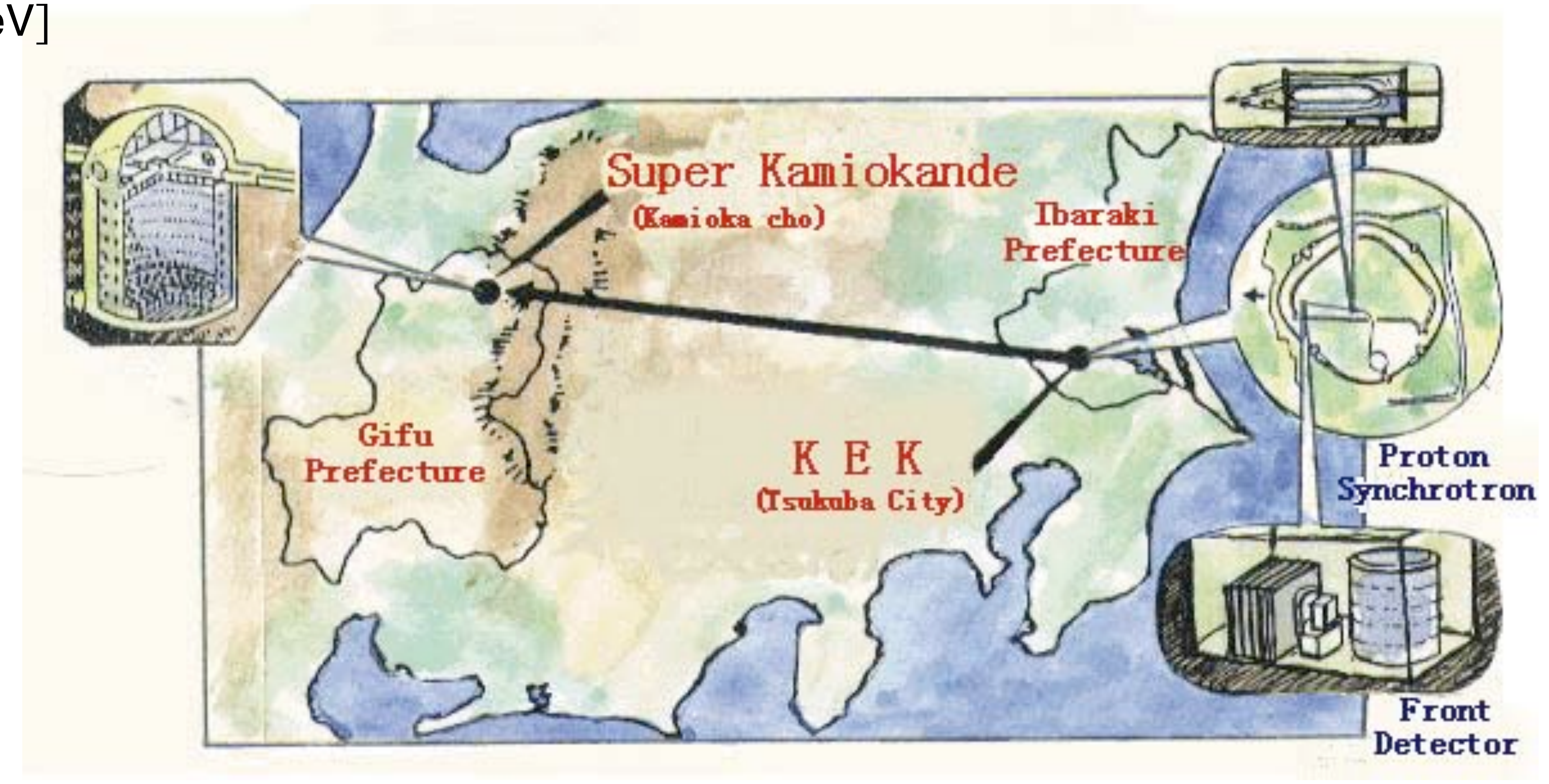




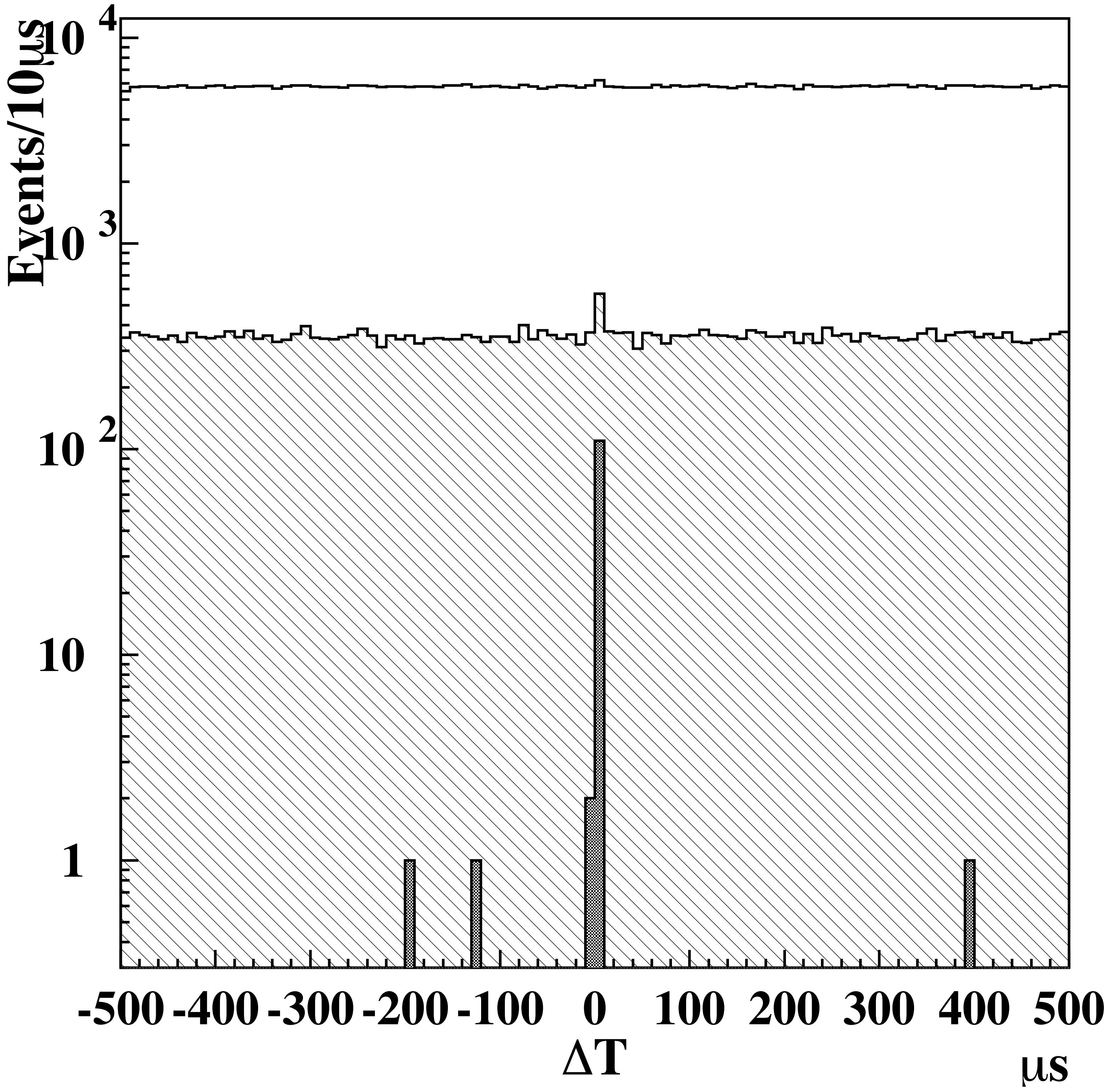
$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \times \sin^2 \left[1.27\Delta m^2 \frac{L(\text{km})}{E(\text{GeV})}\right]$$

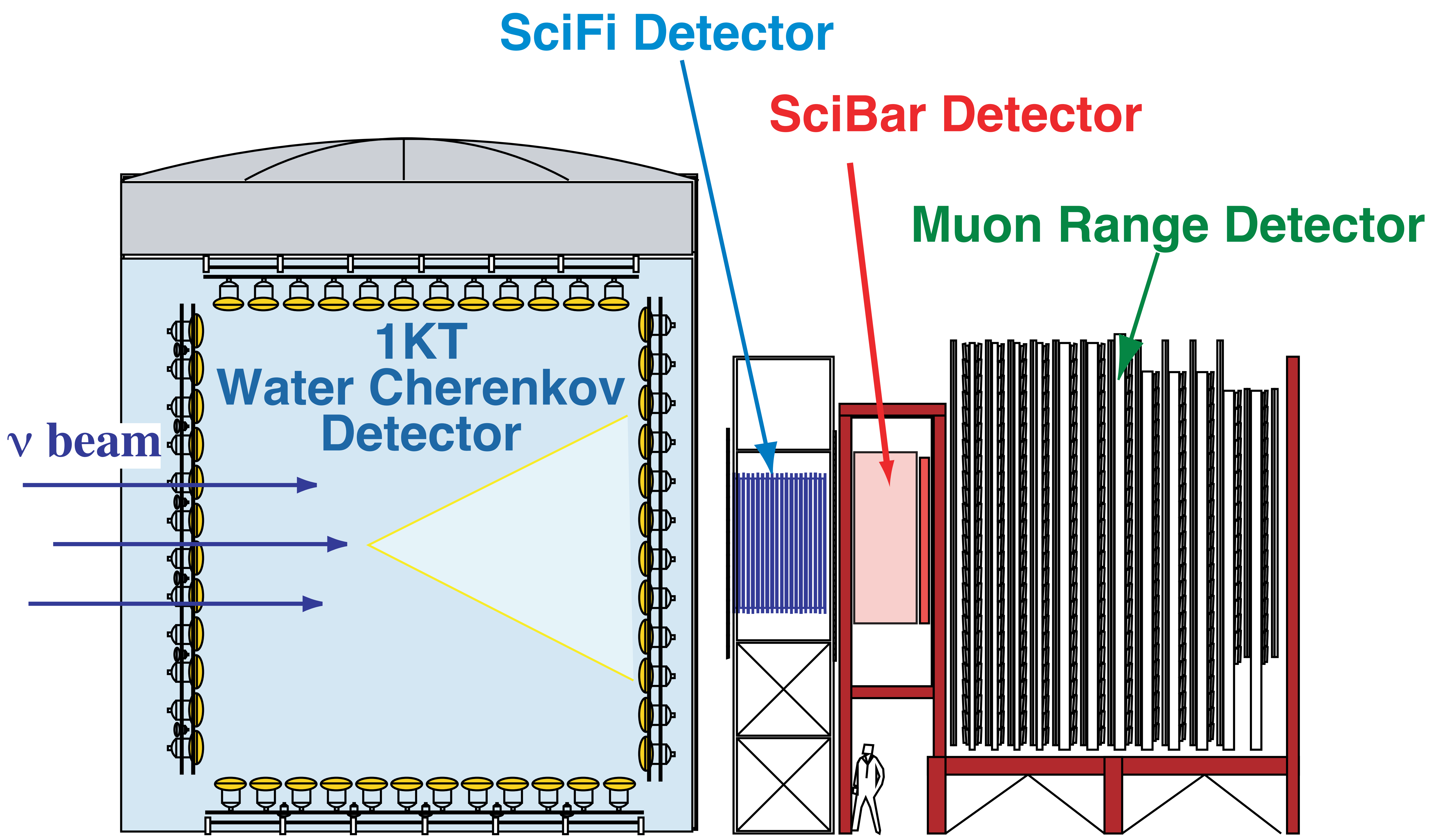
- Accelerator based beams usually produce neutrinos of O(1 GeV)
- If $\Delta m^2 \sim 2.5\text{x}10^{-3}$ eV^2:
- L (km) ~ (π/2) x E (GeV)/Δm^2 (eV)
- ~ 500 km for 1 GeV neutrinos

- Challenges
  - Making an intense enough neutrino beam for a detector 250 km away
  - Alignment of the neutrino beam
  - Timing between near and far detector



FEATURES:

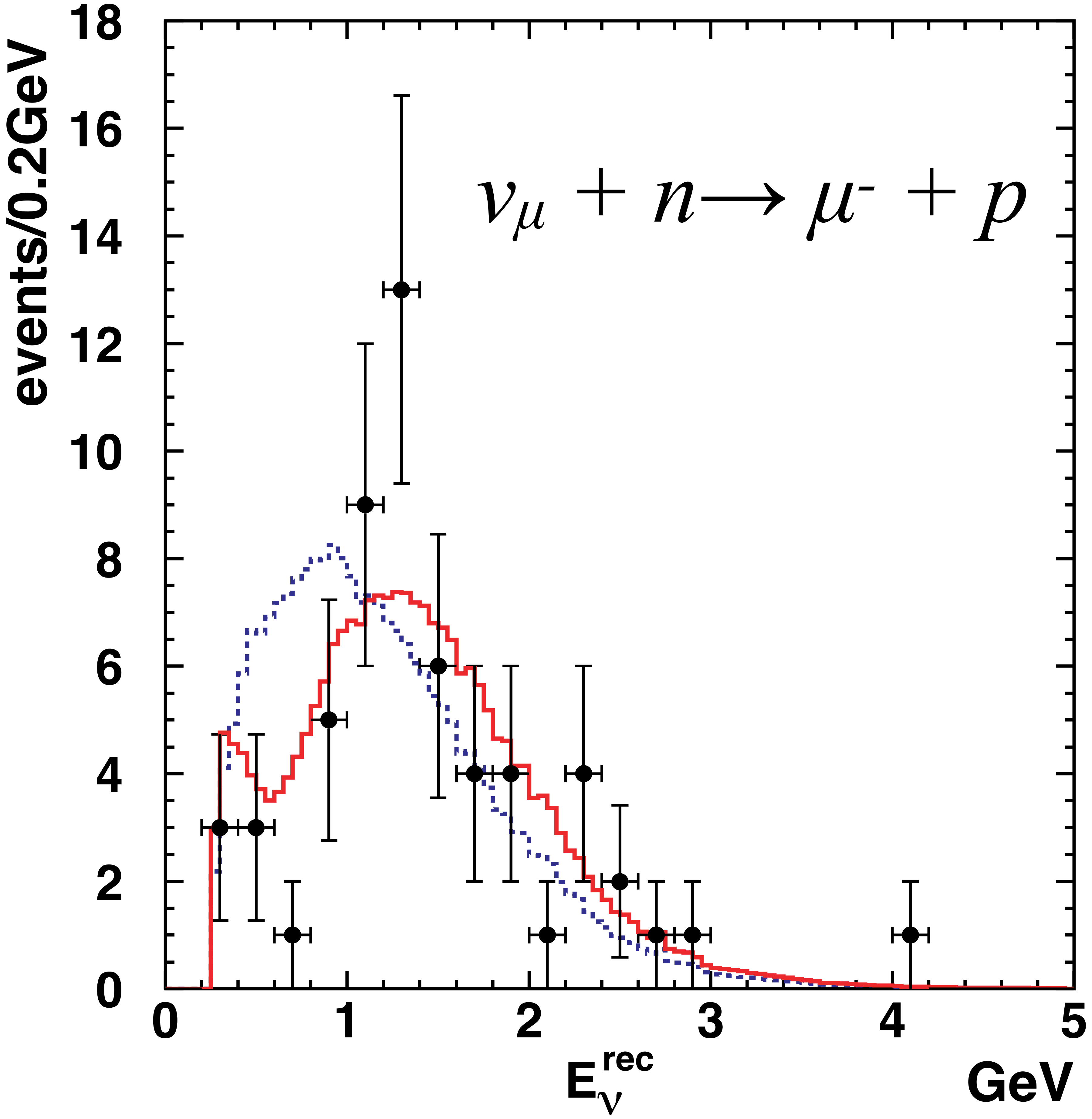


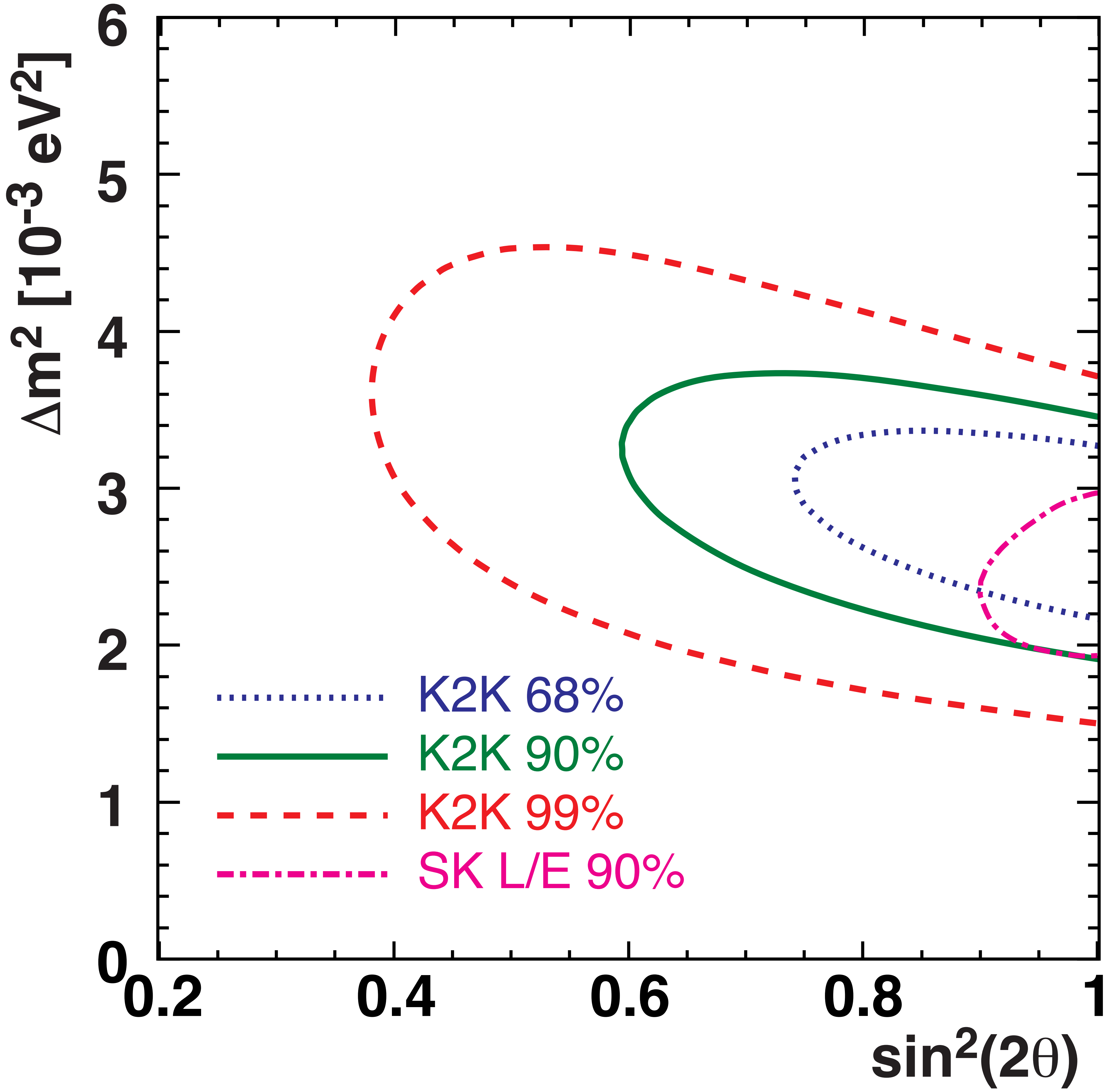


- **Timing:**
  - we know when the beam comes from the accelerator
  - typically, protons are delivered in O(μs) pulse every O(s)
  - neutrinos are produced with the same time structure

- **Near Detector**
  - place neutrino detectors at small L such that oscillation effects should be small (Δm^2 L/E ~ 0)
  - "control sample" of neutrinos without oscillation effects.
  - measure rates, backgrounds, etc.

K2K RESULTS

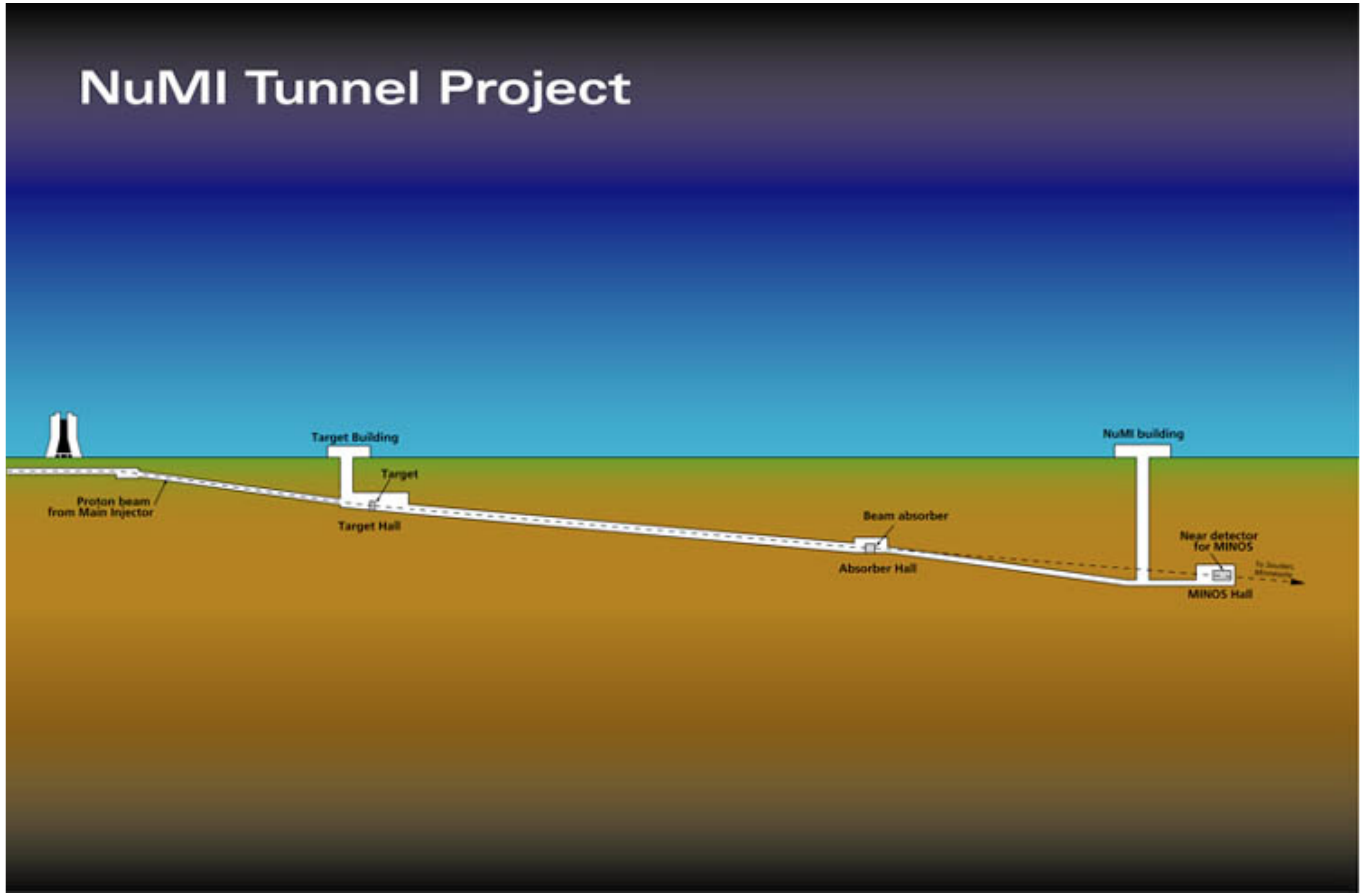




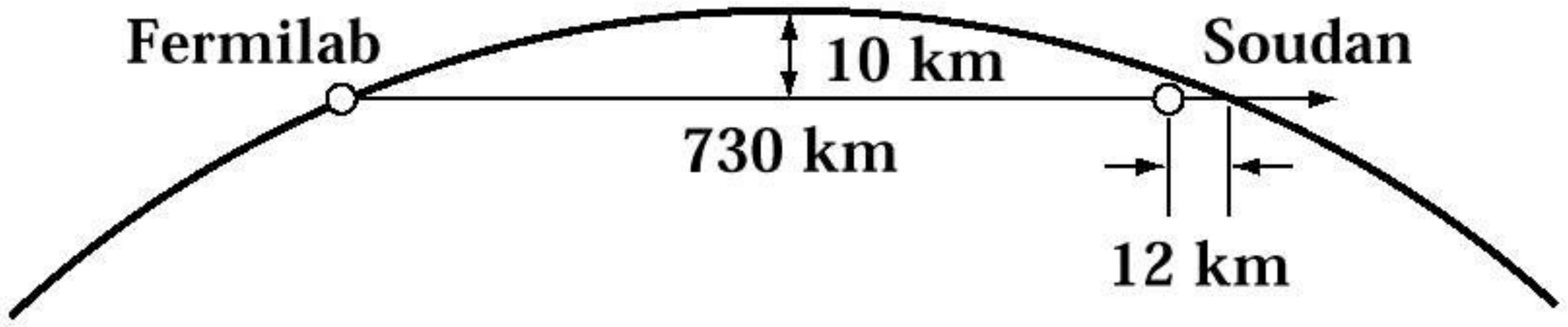
- Total observed interactions at SK in K2K beam: 112
- expected based: 158±9
- 58 single ring muon events used for spectrum analysis

- Confirmation of atmospheric muon neutrino deficit with accelerator-based beam at 4.3 σ

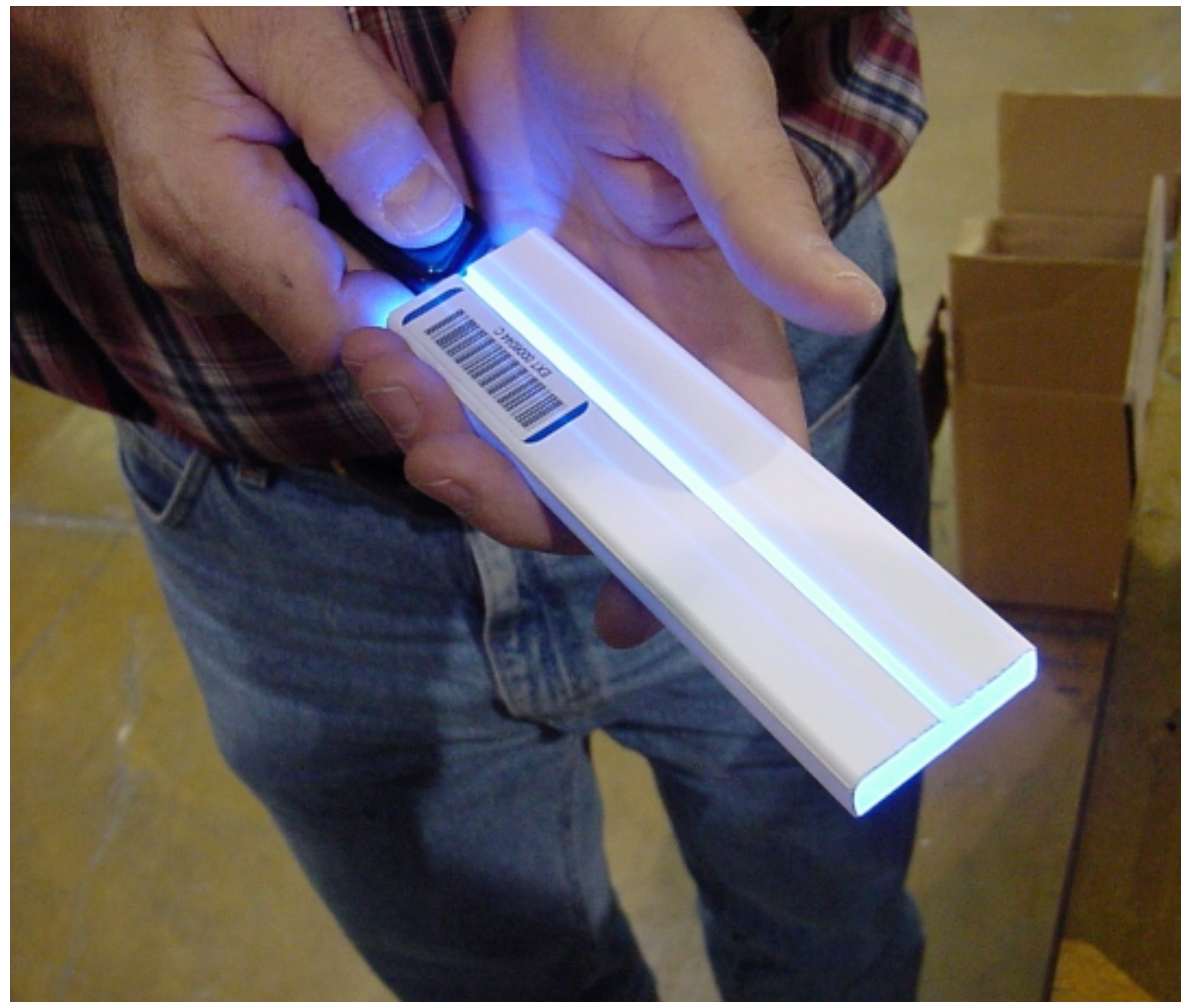
MINOS

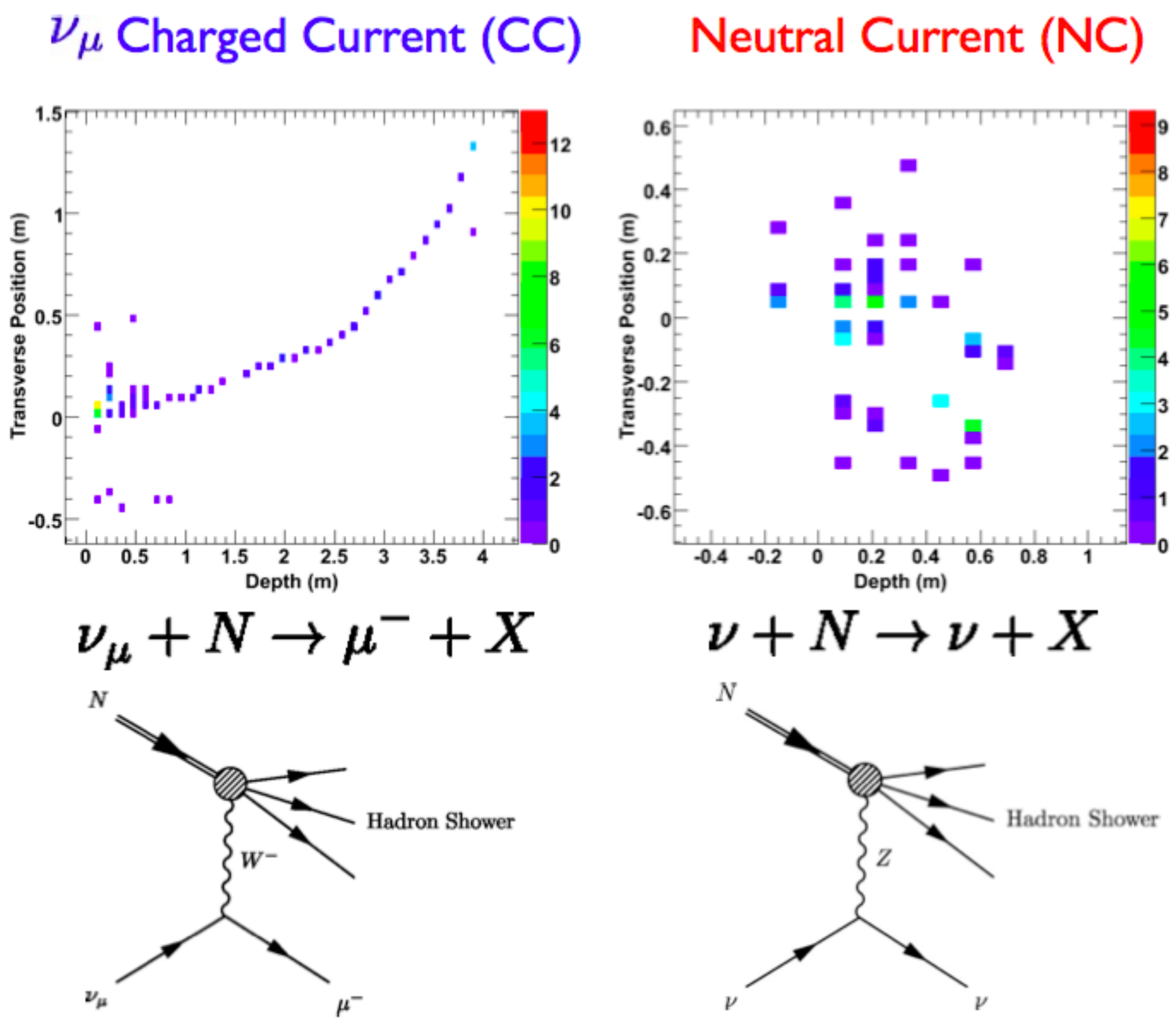


- Fermilab-based neutrino beam sent 730 km to Minnesota
- Neutrinos generated using 120 GeV FNAL Main Injector



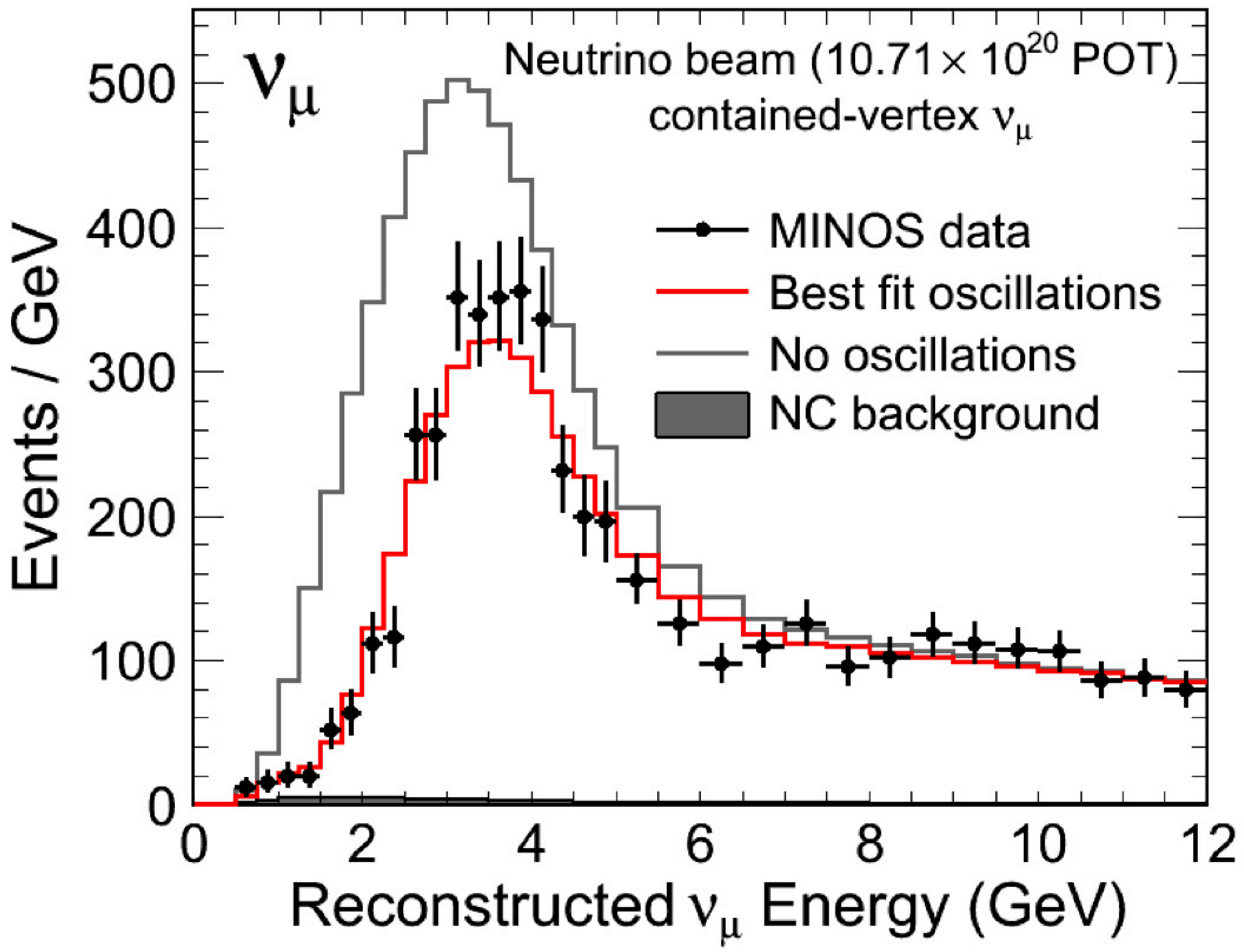
MINOS DETECTOR:

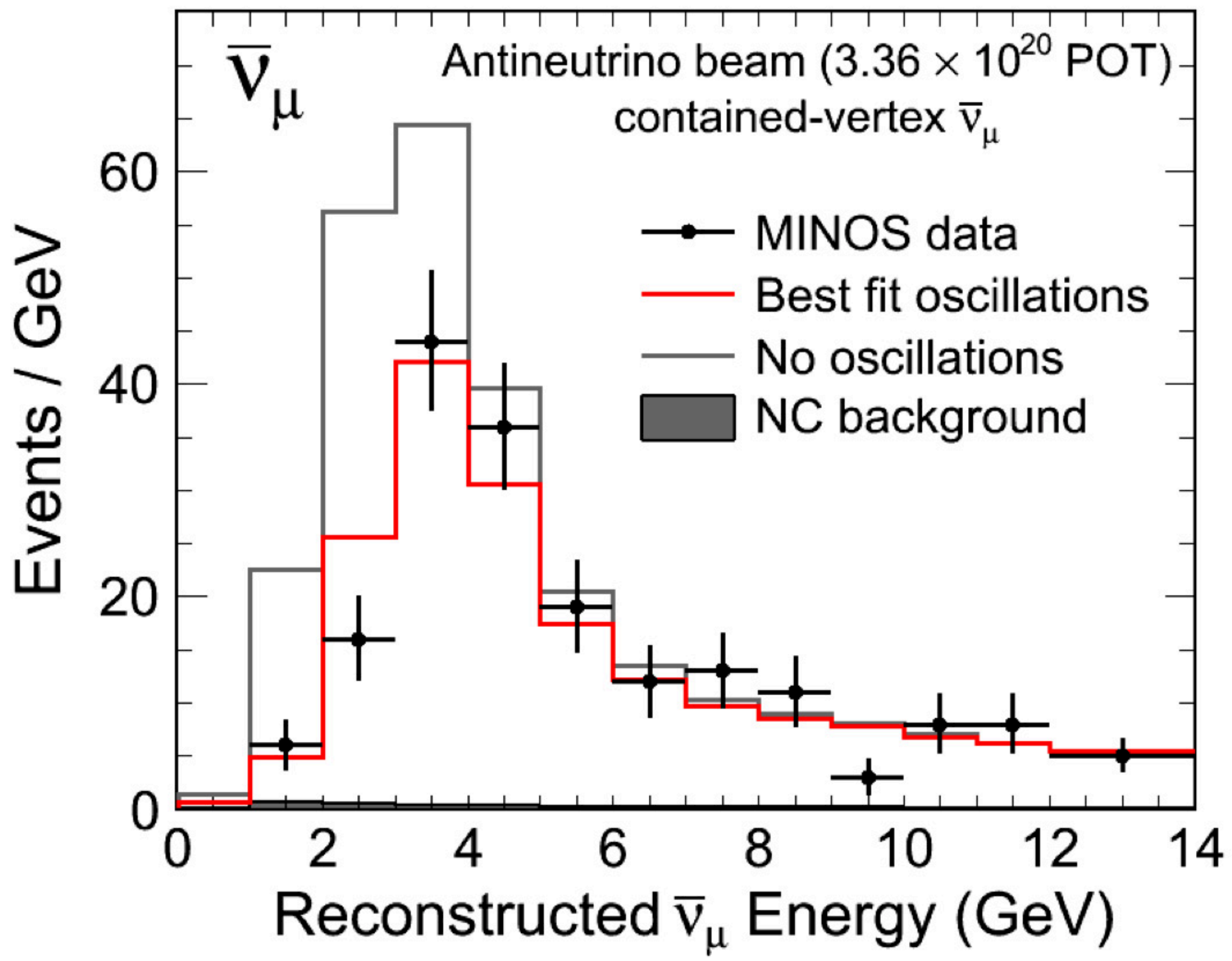


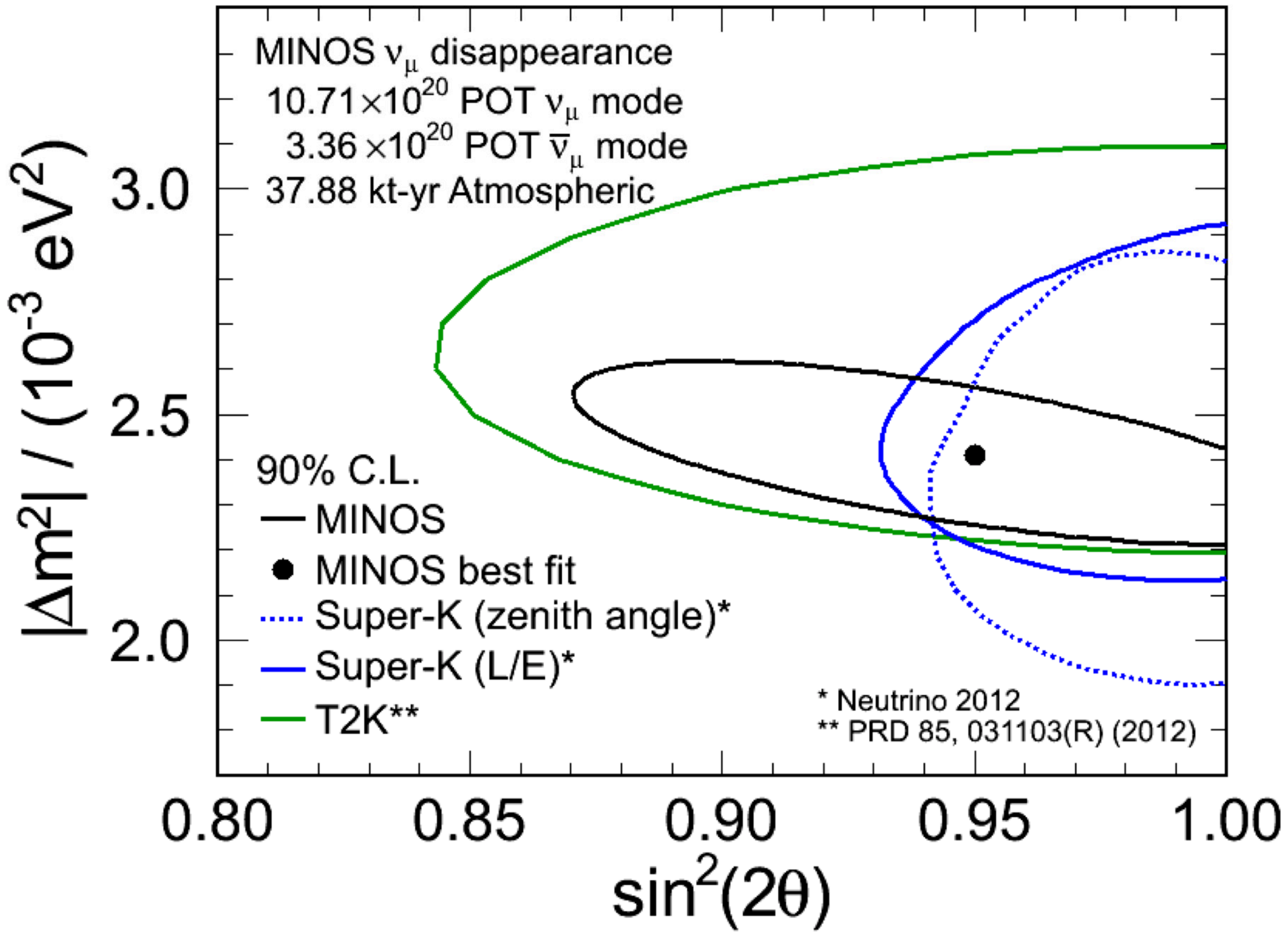


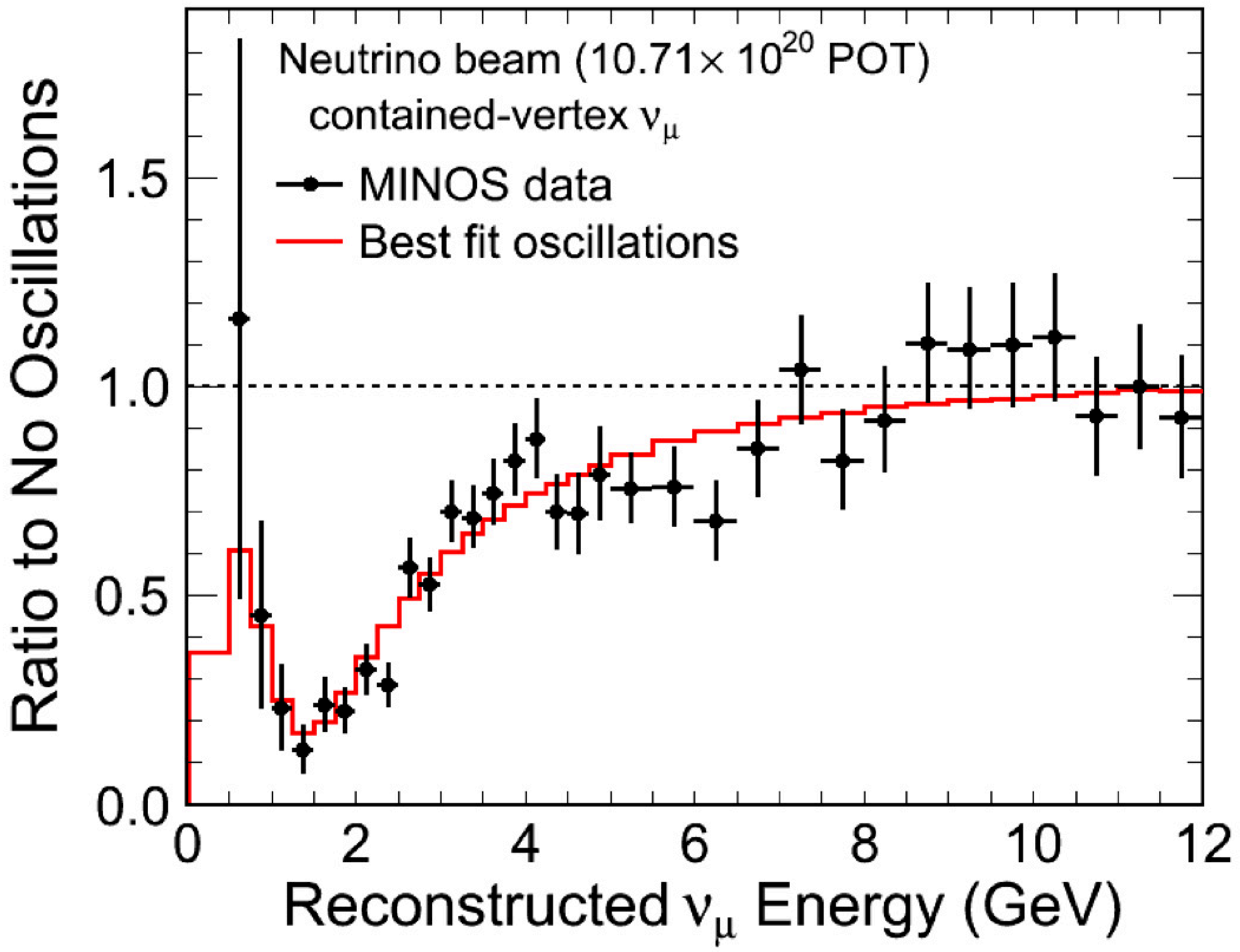
- Magnetized steel plates alternating with scintillator strips
  - 2.54 cm thick steel plates, 1 cm x 4.1 cm scintillator bars
- Functionally identical Near (0.98 ton) and Far (5.4 ton) detectors
- Very clean identification of muon neutrinos with sign of muon identified.

MINOS RESULTS



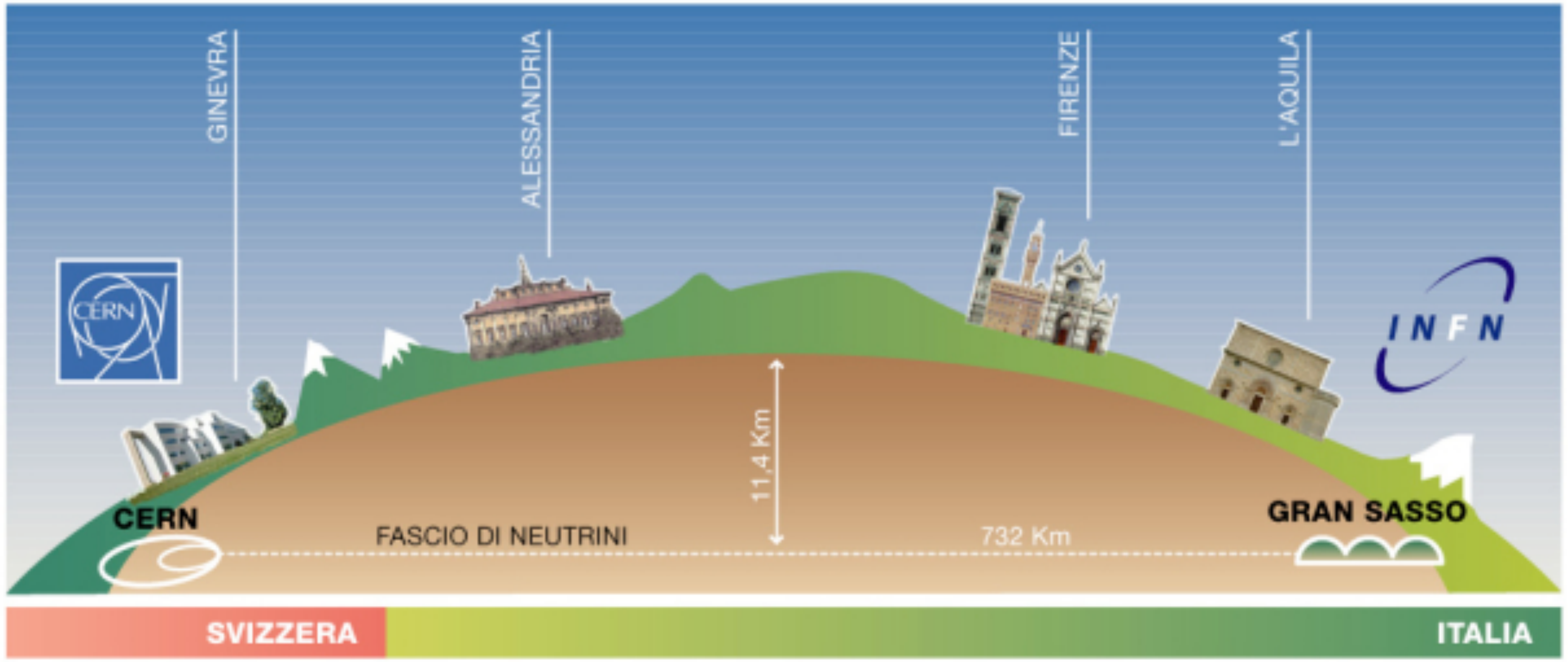


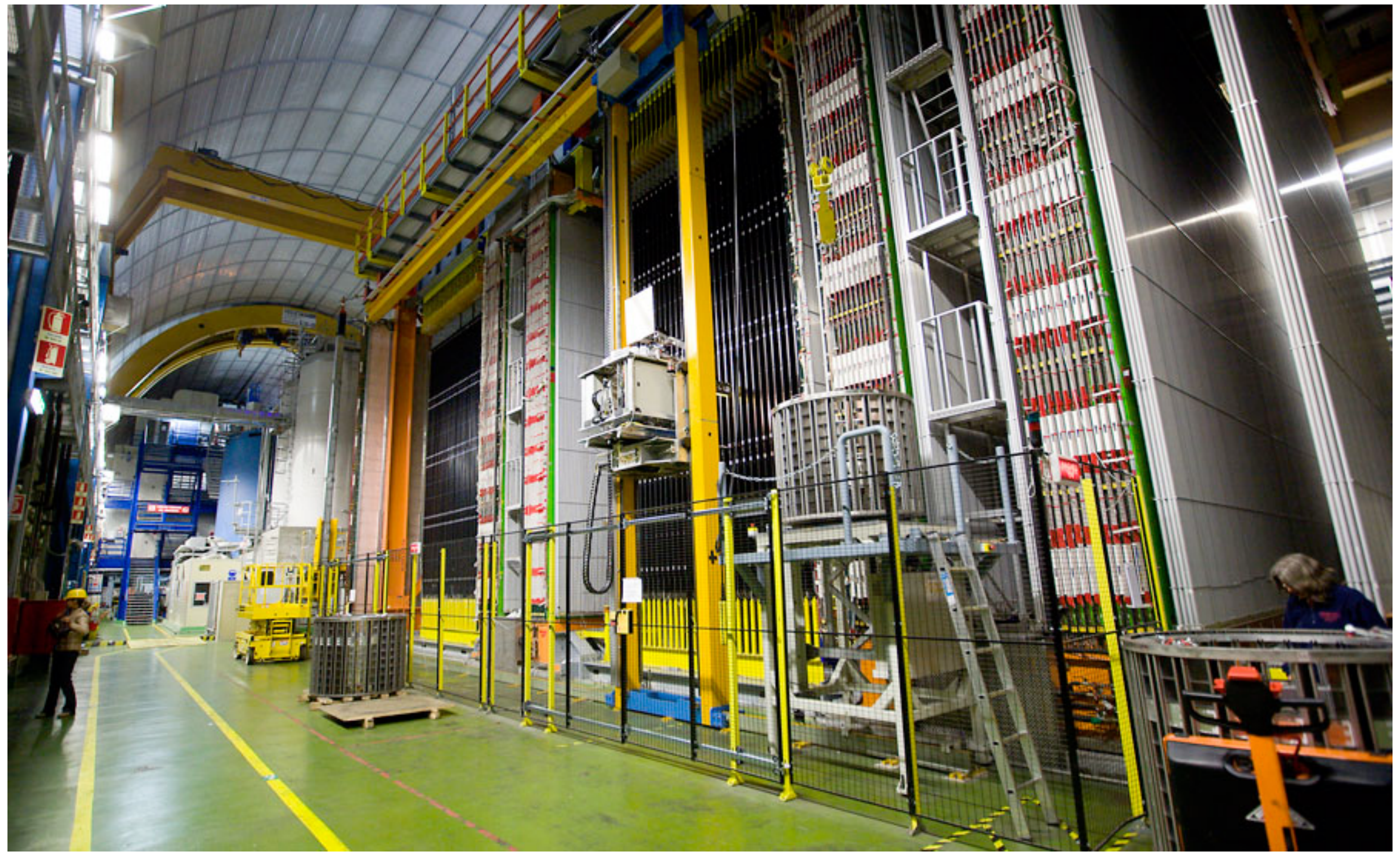


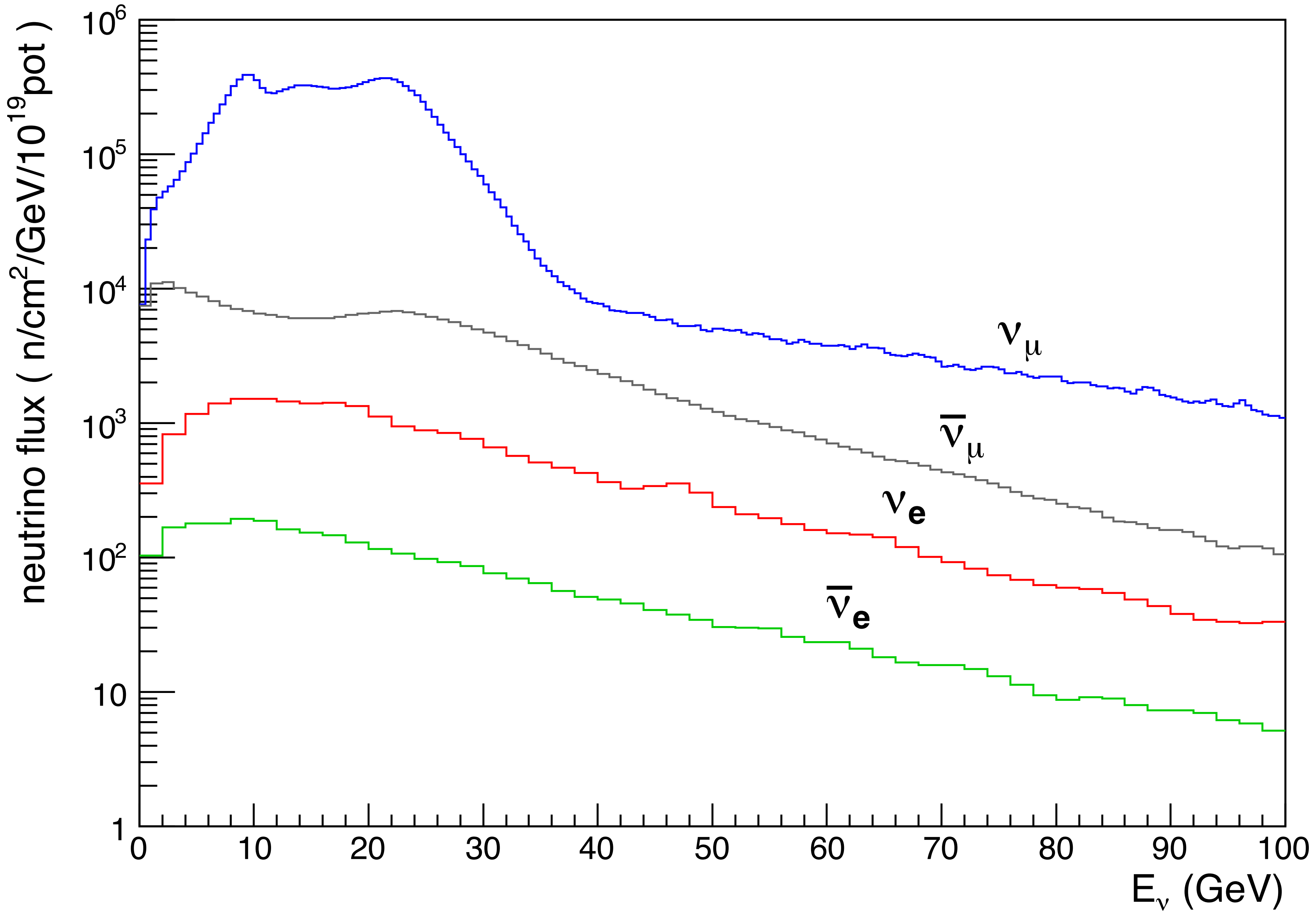


- Intense beam gives precise measurement of oscillation probability
- Confirm large ν_μ disappearance consistent with maximal mixing
- eventually many channels were studied:
  - $\bar{\nu}_\mu$ disappearance with antineutrino beam
  - atmospheric neutrinos
  - $\nu_e/\bar{\nu}_e$ events (more on this later)

OPERA



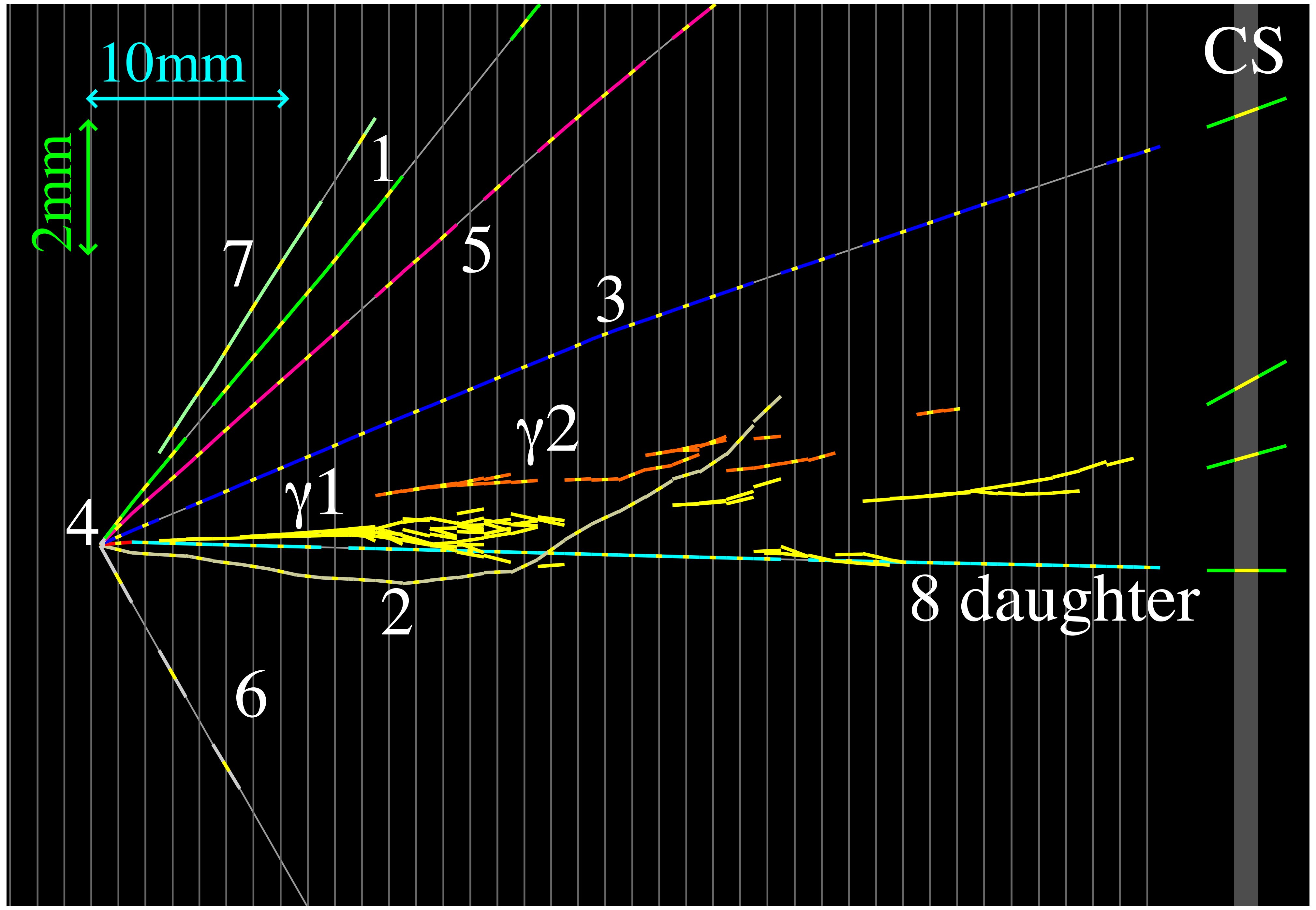


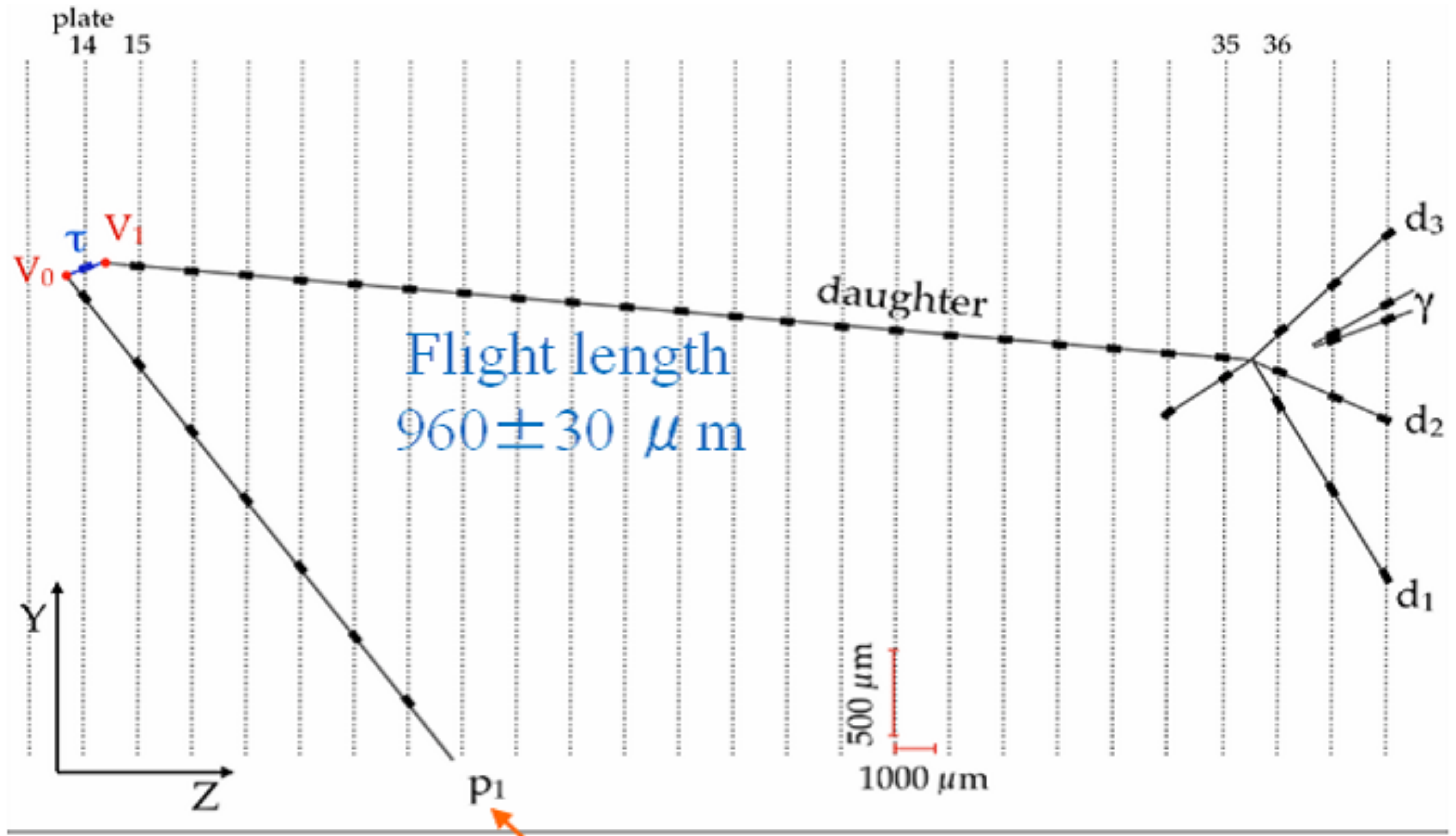


- Experiment to look explicitly for the "appearance" of ν_τ due to $\nu_\mu \rightarrow \nu_\tau$ oscillations
- 450 GeV CERN SPS protons used to produce a "wide-band" high energy muon neutrino beam
  - Significant flux above τ production threshold of ~3.5 GeV

ν_τ DETECTION

- Look for "kinks" arising from τ decay
- Typical τ decay modes
  - $\tau \rightarrow \nu_\tau + (e/\mu) + \nu_{e/\mu}$ (~17% each)
  - $\tau \rightarrow \nu_\tau + \pi^- + \pi^0$ (~25%)
  - $\tau \rightarrow \nu_\tau + \pi^-$ (~11%)
- $\tau = 2.9\text{x}10^{-13}$ sec → $c\tau \sim 10^{-2}$ cm
  - requires extremely precise tracking
  - extremely large emulsion-based tracker.
- 5 candidate events observed in 5 year run
  - Expected background in absence of oscillations: 0.25 events
    - charm particle production
    - hadronic interaction of pions
  - Significance: 5.1 σ
- **UPDATE: Final results with 10 observed events**
  - **2 background events expected, 6.1 σ significance**



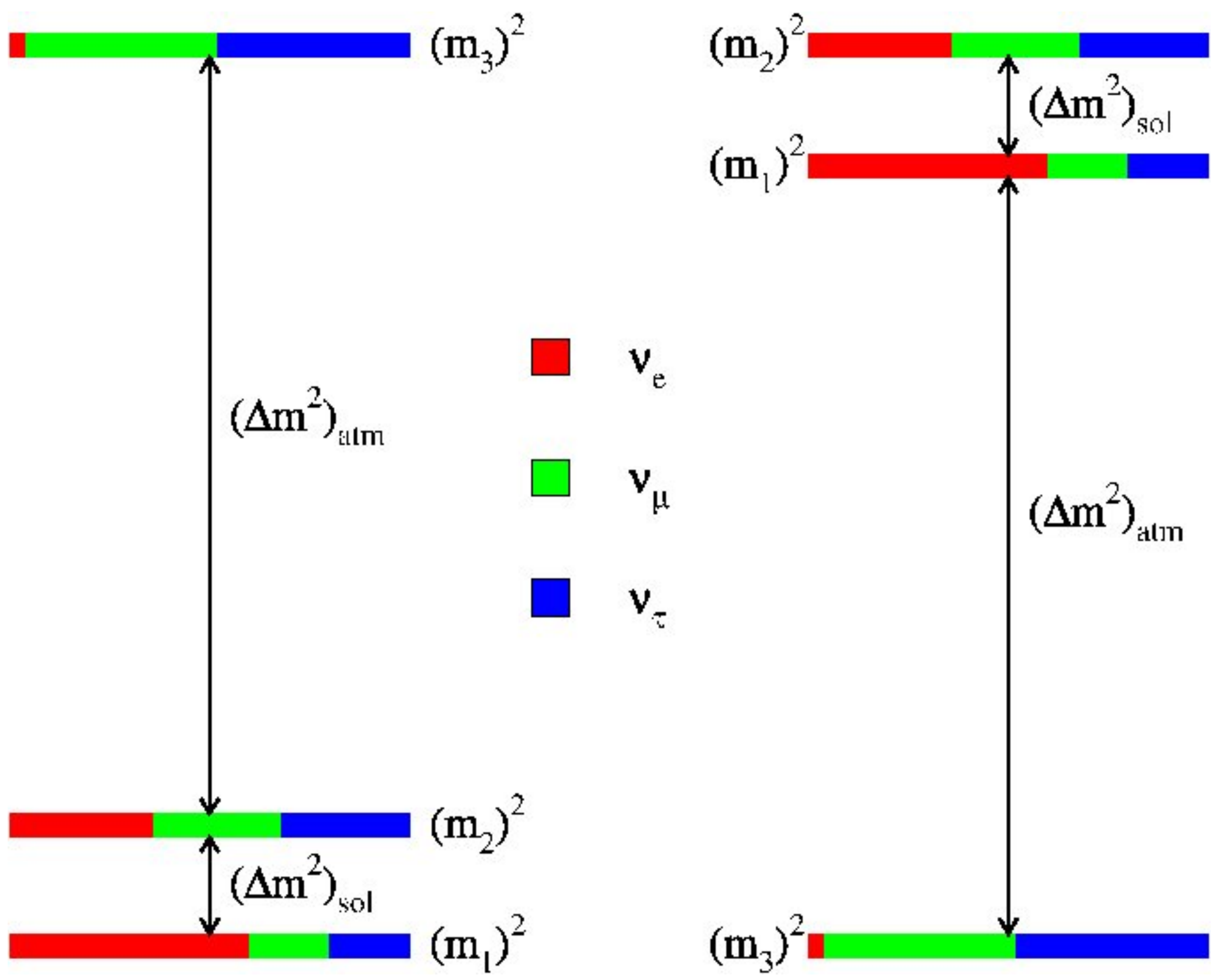


identified as a proton by dE/dx analysis [26]

NEUTRINO OSCILLATIONS C. 2010

Established

- ν_μ disappearance due to neutrino oscillations in both atmospheric and accelerator neutrinos
  - large, possibly maximal: $\theta_{23} \sim \pi/4$
  - mass splitting of $\Delta m^2 \sim 2.5 \times 10^{-3}$ eV^2
- These ν_μ are transitioning primarily to ν_τ
  - no ν_e excess in atmospheric data (or accelerator) where we observe ν_μ deficit
  - explicit observation of ν_τ appearance in SK and OPERA
- Next question for accelerator-based neutrinos
  - do some of these ν_μ oscillate to ν_e?
  - this would be evidence for $\theta_{13} \neq 0$



$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{+i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_1/2} & 0 \\ 0 & 0 & e^{i\alpha_2/2} \end{pmatrix}$$

FROM BORIS

$c_{ij} \equiv \cos\theta_{ij}$
$s_{ij} \equiv \sin\theta_{ij}$

The leptonic mixing matrix U is —

$$\begin{array}{cccc} & \nu_1 & \nu_2 & \nu_3 \\ U = & \multicolumn{3}{c}{\begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix}} \end{array}$$

$$\times \mathrm{diag}\Big(\underbrace{\mathrm{e}^{i\alpha_1/2}, \mathrm{e}^{i\alpha_2/2}}_{\text{Majorana phases}}, 1\Big)$$

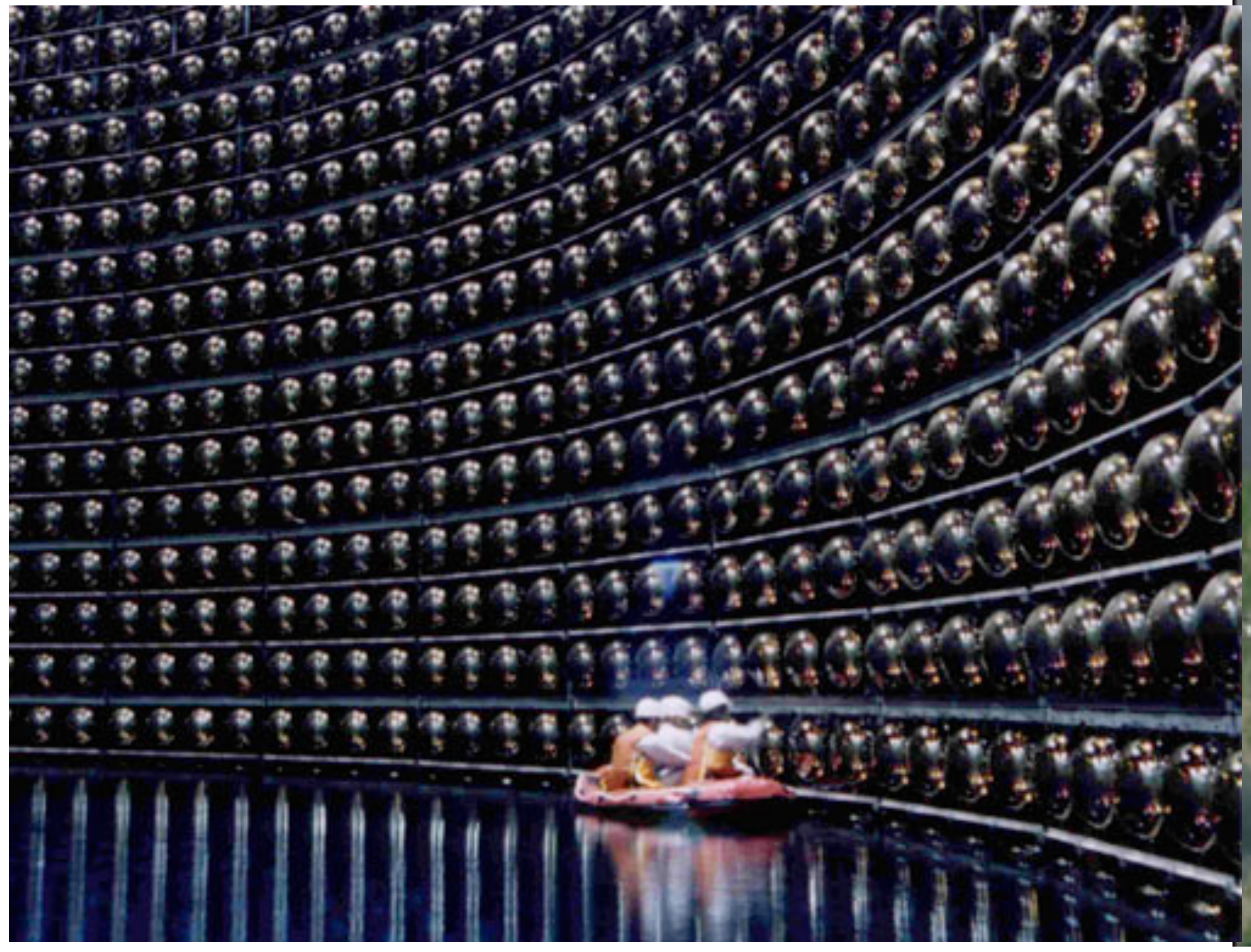
SANITY CHECK

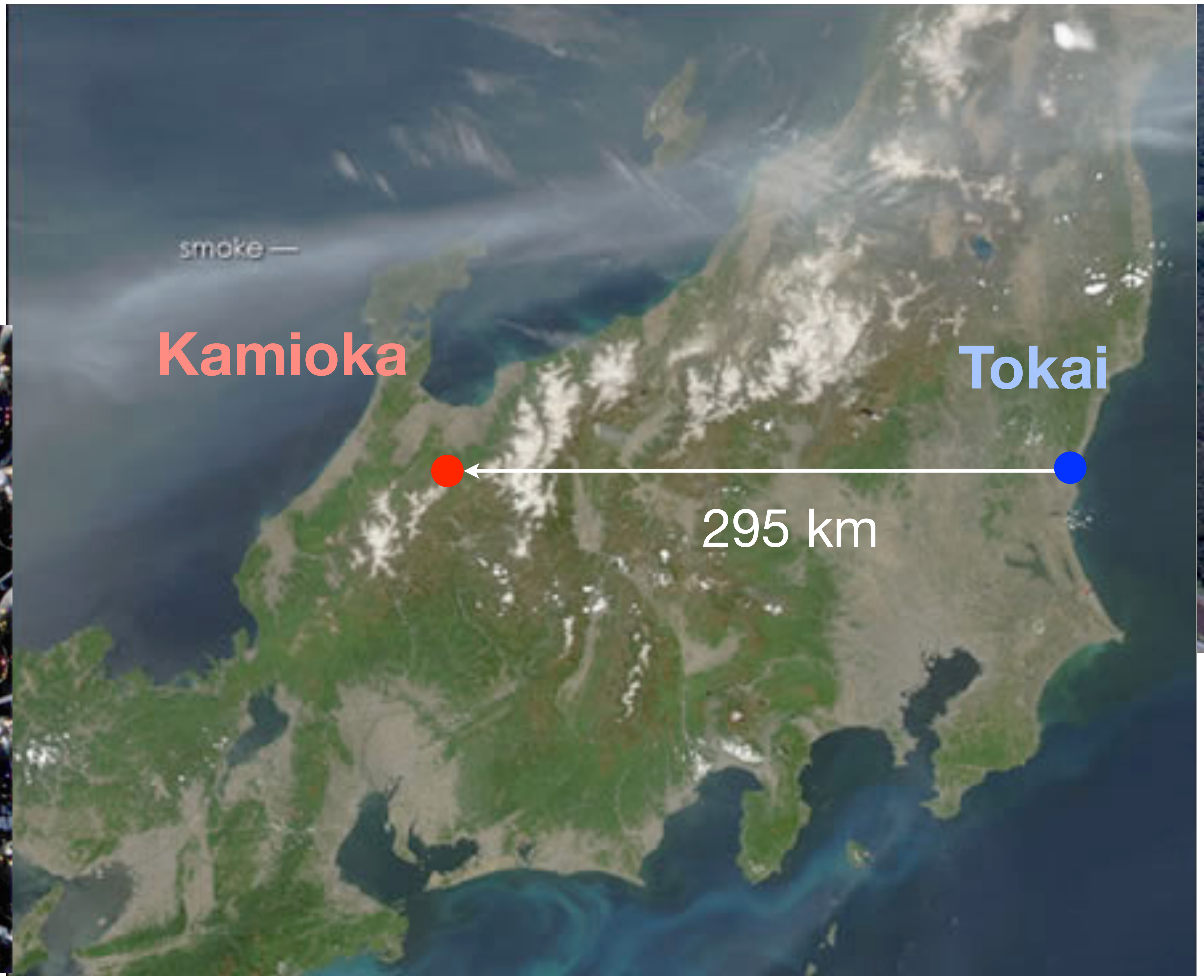
- Can $P(\nu_\mu \rightarrow \nu_e) \neq 0$ if $\theta_{13} = 0$
- How can we determine if $\theta_{13} \neq 0$

THE T2K EXPERIMENT

TOKAI-TO-KAMIOKA

Super Kamiokande
"far" detector



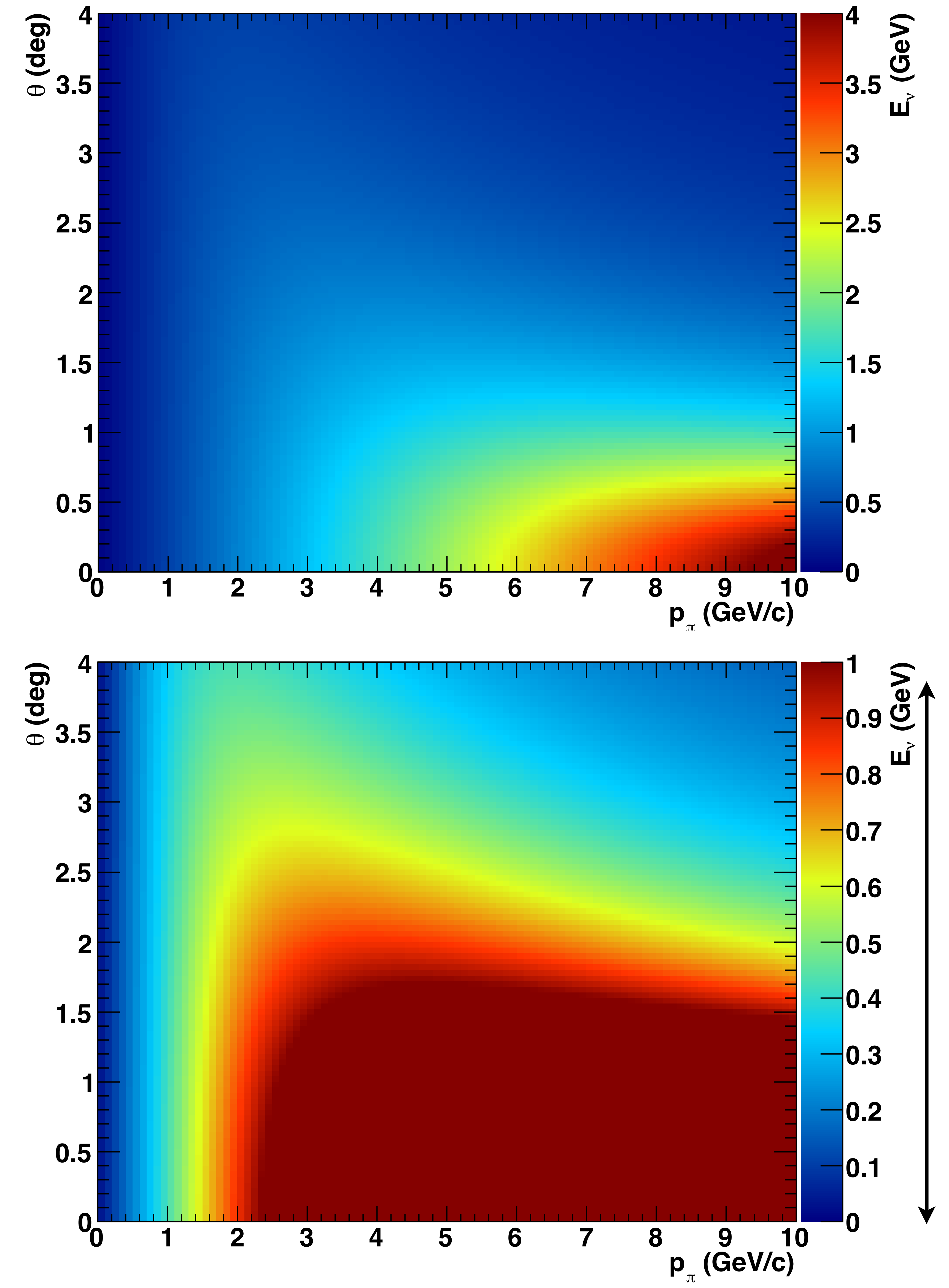


ND280
"near" detector

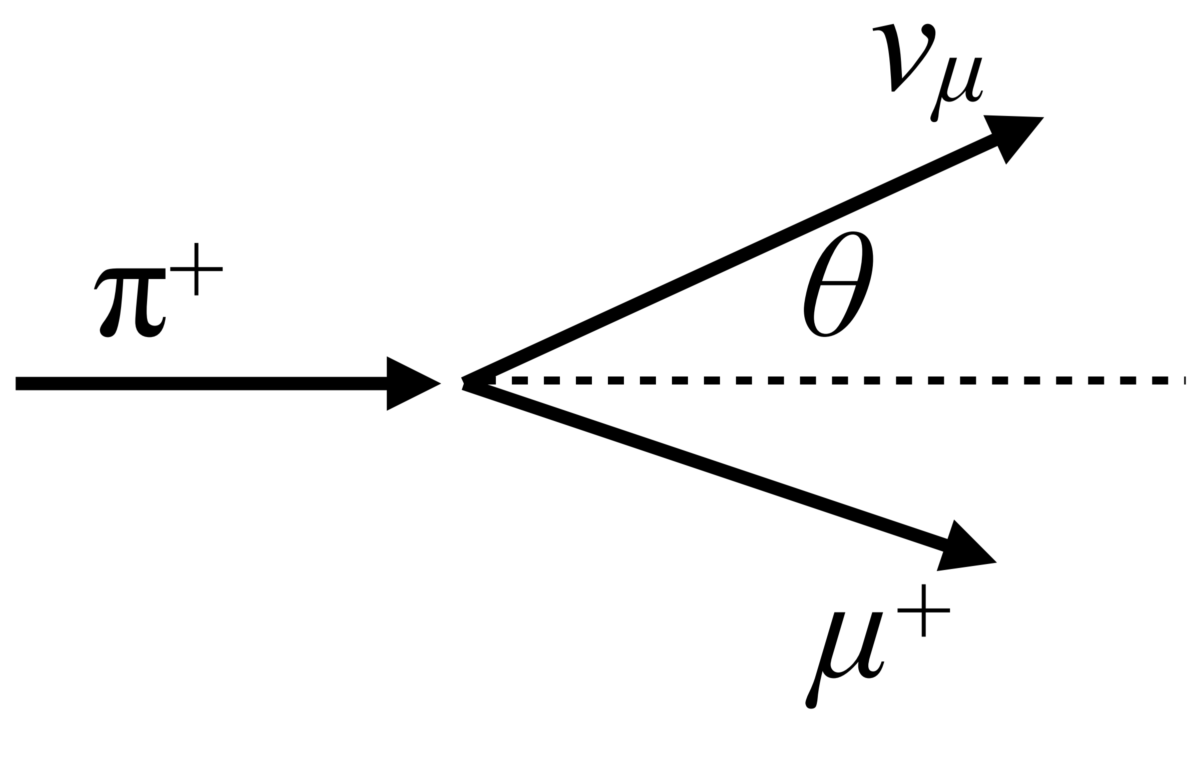
J-PARC

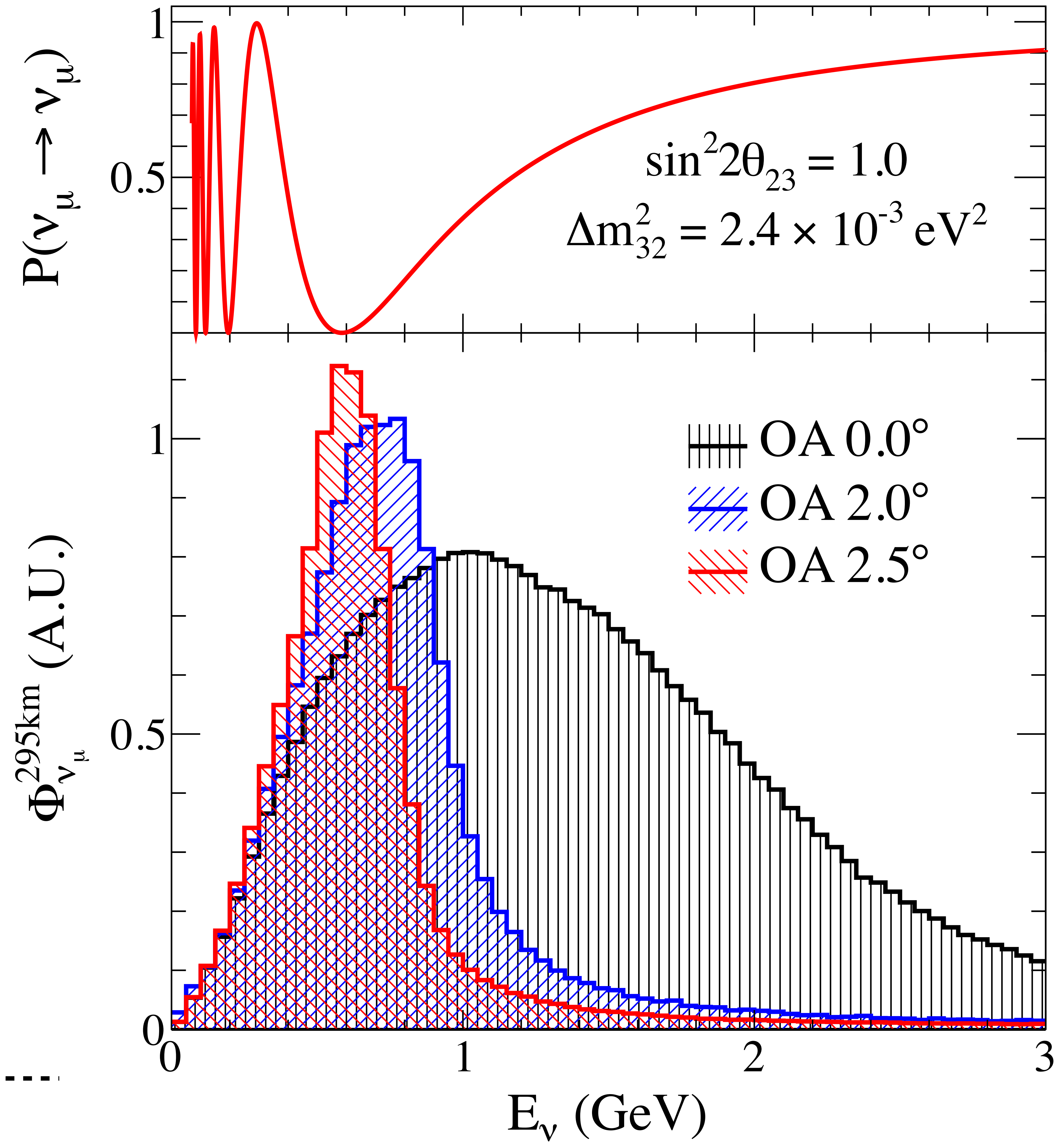
- Long baseline experiment
- accelerator-based neutrino beam using new J-PARC Main Ring
  - design power of 750 kW (50 times more intense than K2K)
- 295 km distance from J-PARC (in Tokai) to Kamioka

OFF-AXIS BEAM CONCEPT

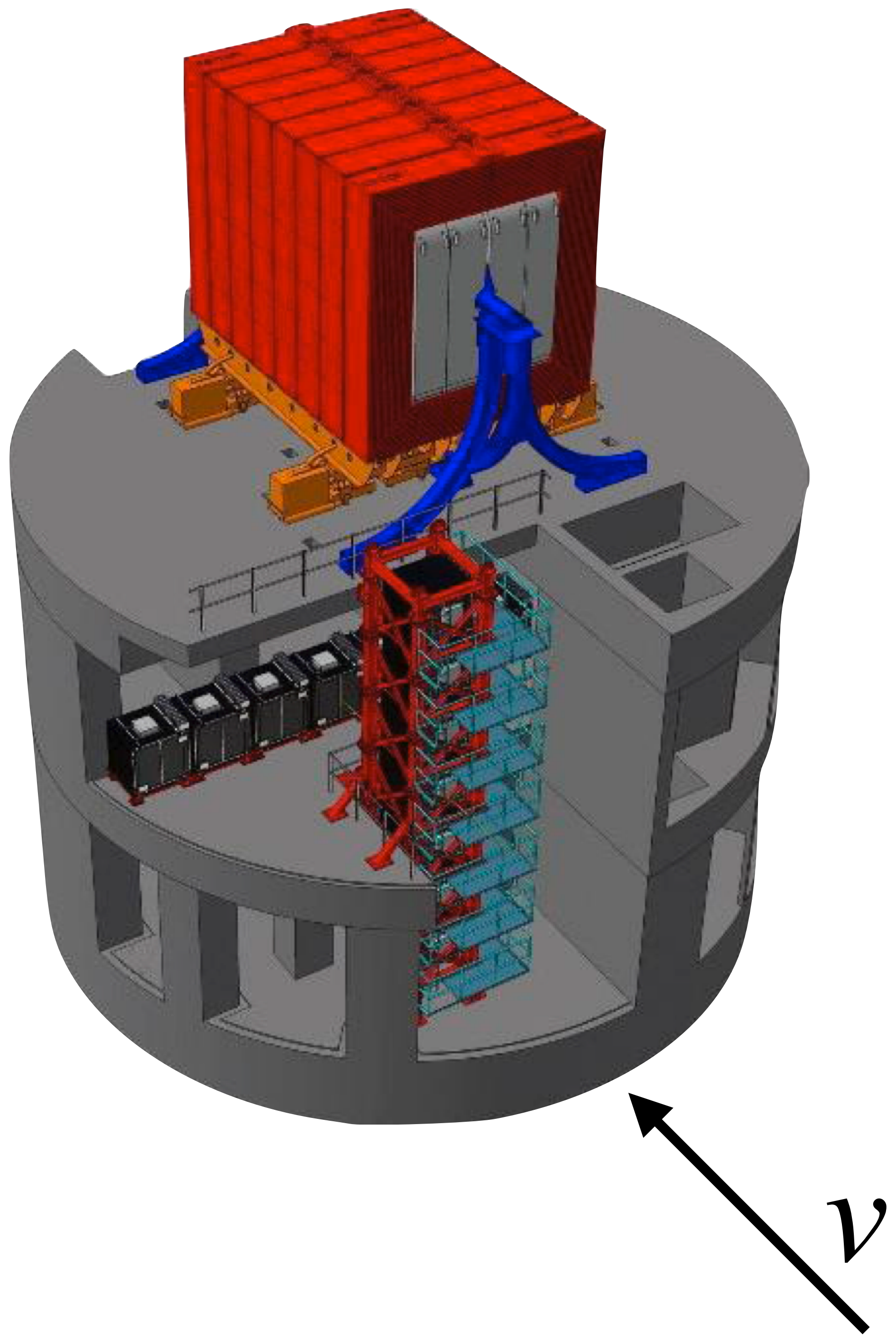


- Tune neutrino energy spectrum by pointing the beam away from your detector
- Also reduce “feeddown” backgrounds from higher energy



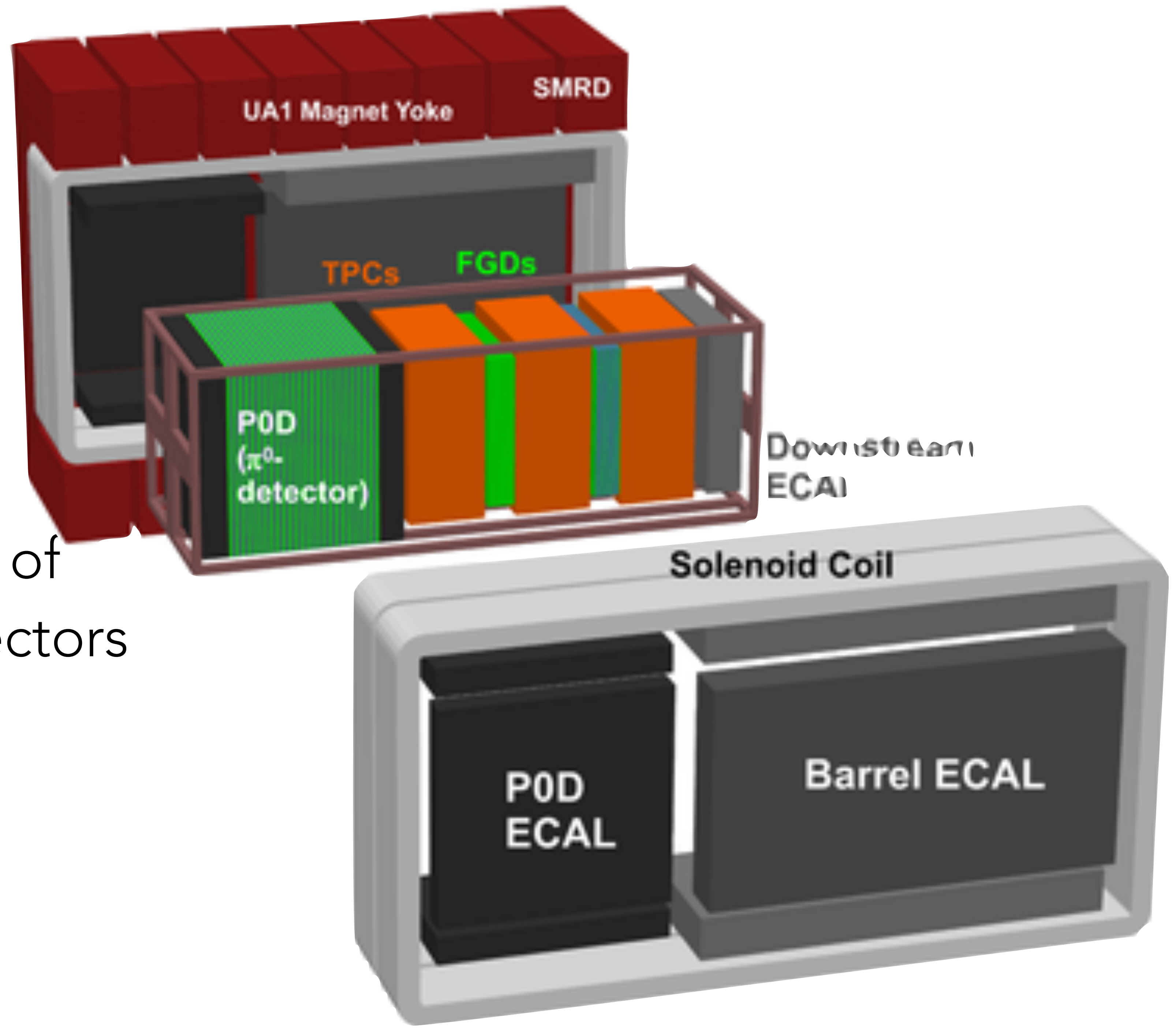


NEAR DETECTORS



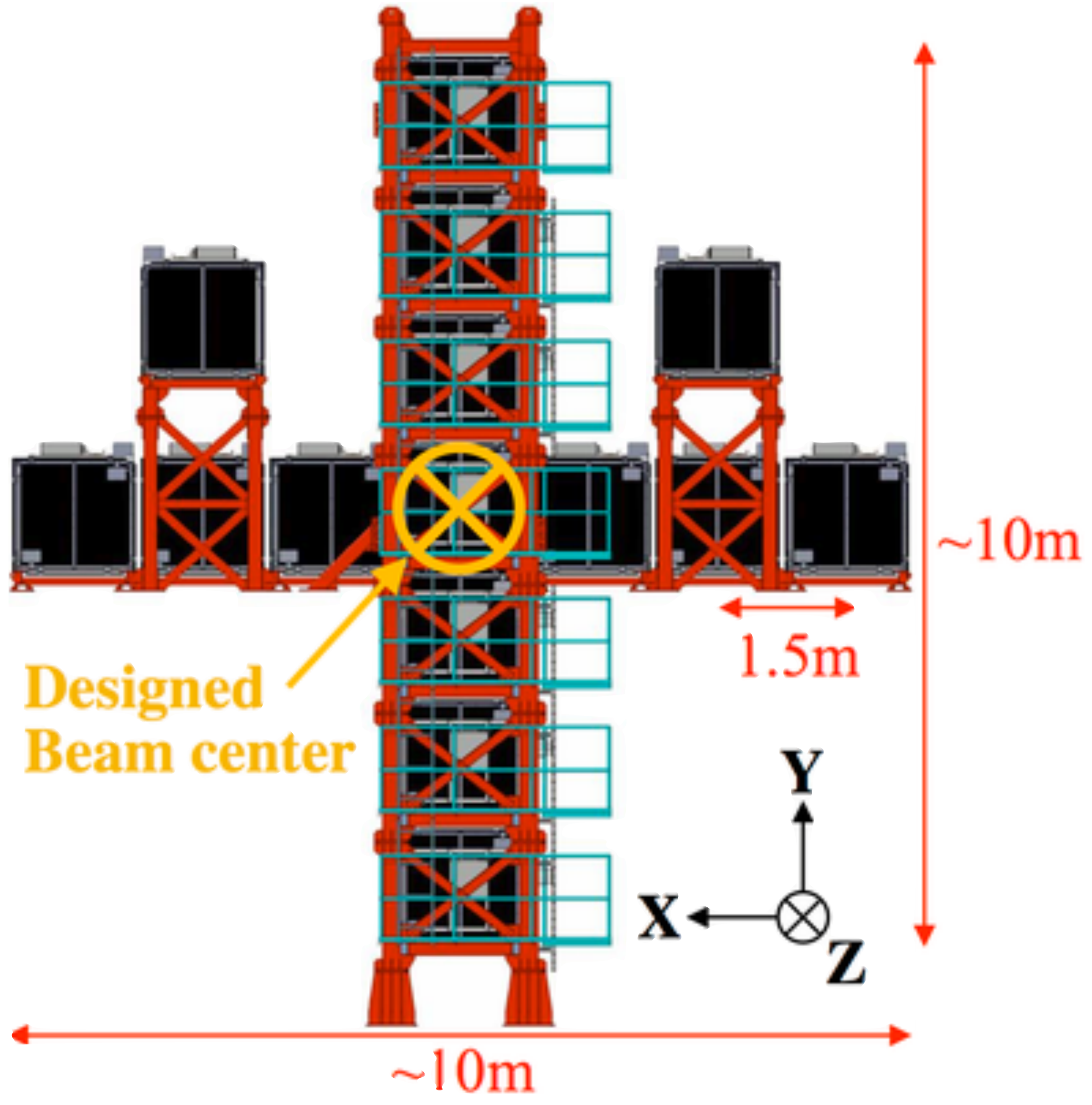
ND280:

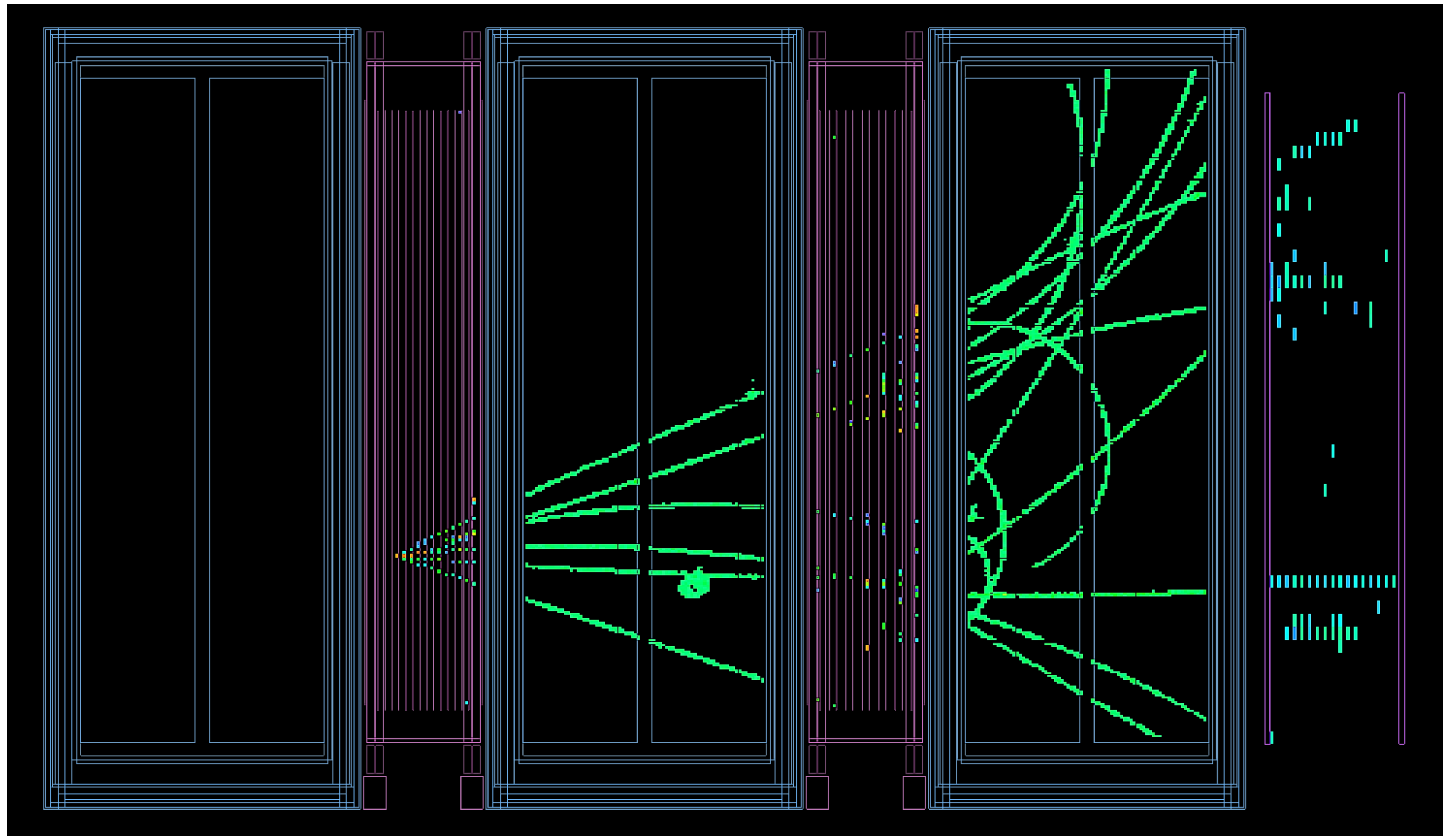
- off-axis detector systems comprised of tracking, calorimetry and muon detectors
- 0.20 T field from UA1 magnet
- scintillator and water targets



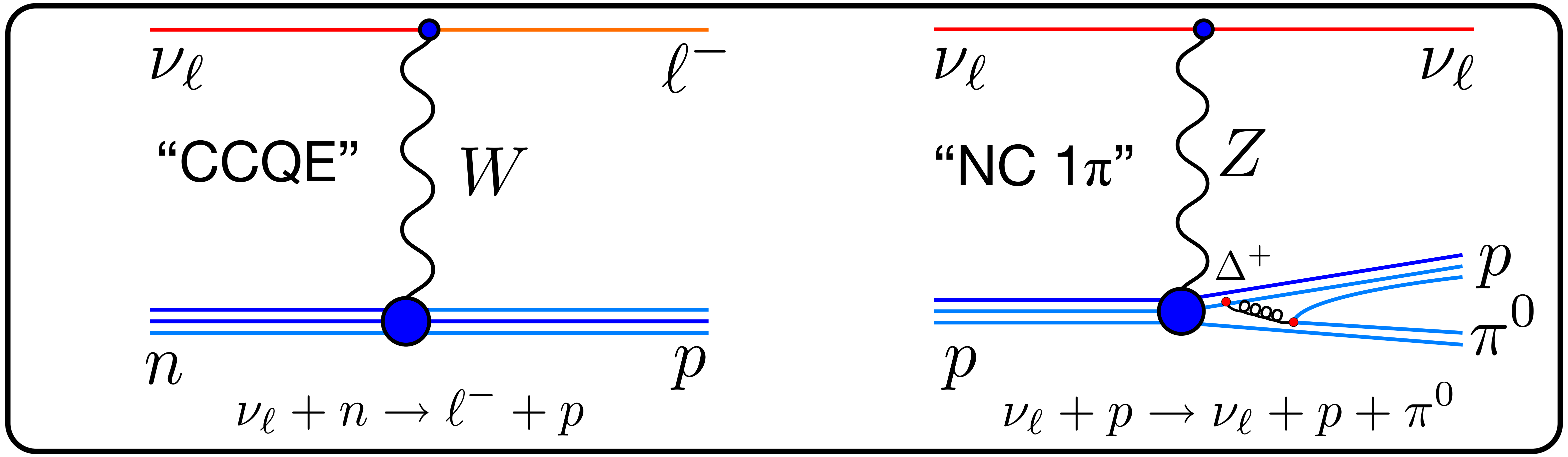
INGRID

- 7x7 grid of scintillator/Fe neutrino detectors spanning beam axis
- monitor beam direction and rate





NEUTRINO INTERACTIONS AT T2K



$\nu_\ell + n \rightarrow \ell^- + p$

Signal

- Single μ/e-like ring
- E_ν by energy/direction of lepton, 2-body kinematics

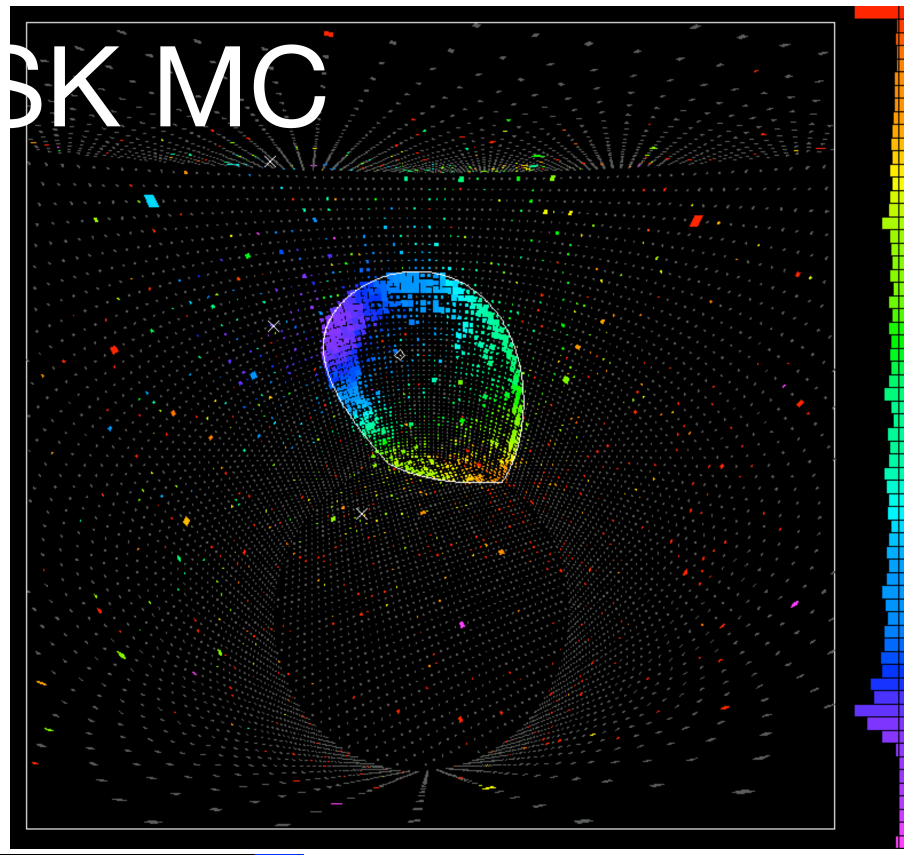
$\nu_\ell + (n/p) \rightarrow \nu_\ell + (n/p) + \pi^0$

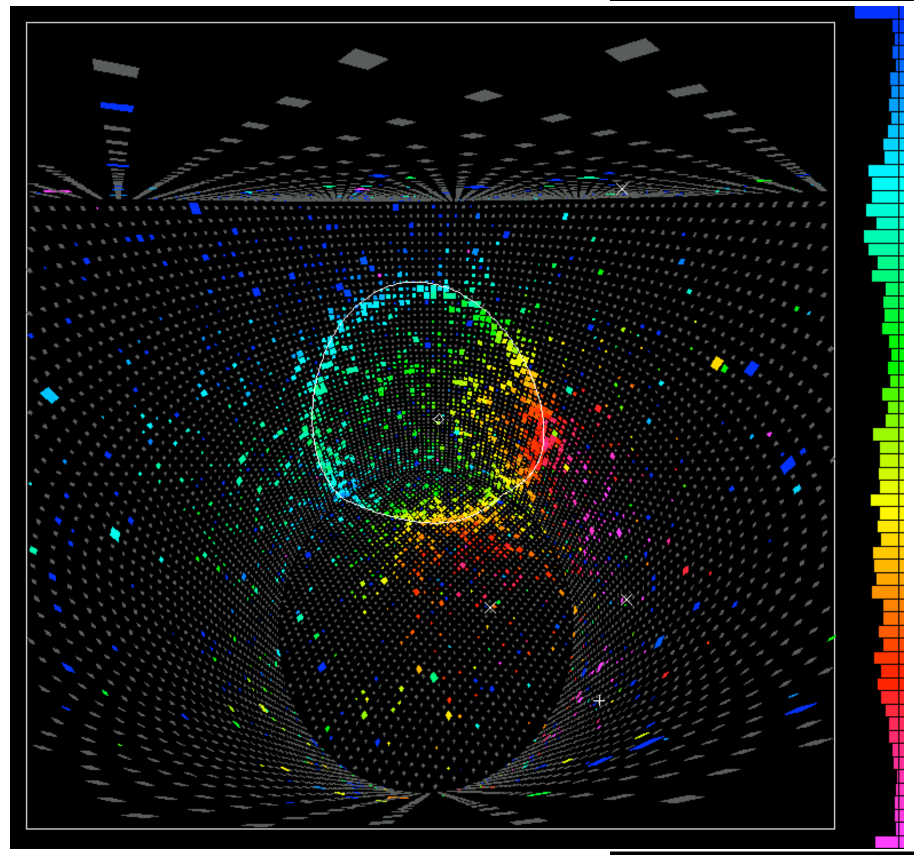
$\nu_\ell + (n/p) \rightarrow \ell^- + (n/p) + \pi$

Backgrounds

- $\pi^0 \rightarrow \gamma + \gamma$: ring counting, 2-ring reconstruction
  - γ misidentified as e from ν_e CCQE
  - powerful rejection capabilities reduce this by $O(10^2)$
- μ/π^+: ring counting, decay electron cut
- Pure ν_e samples (S/B~10) obtained with high efficiency

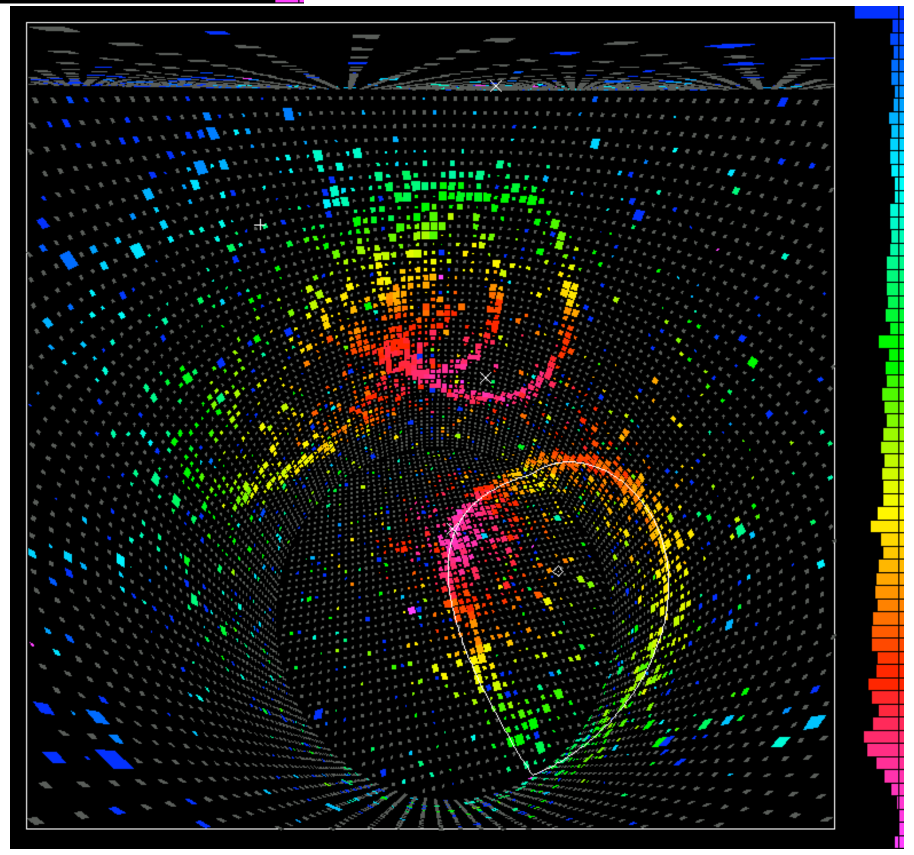
μ



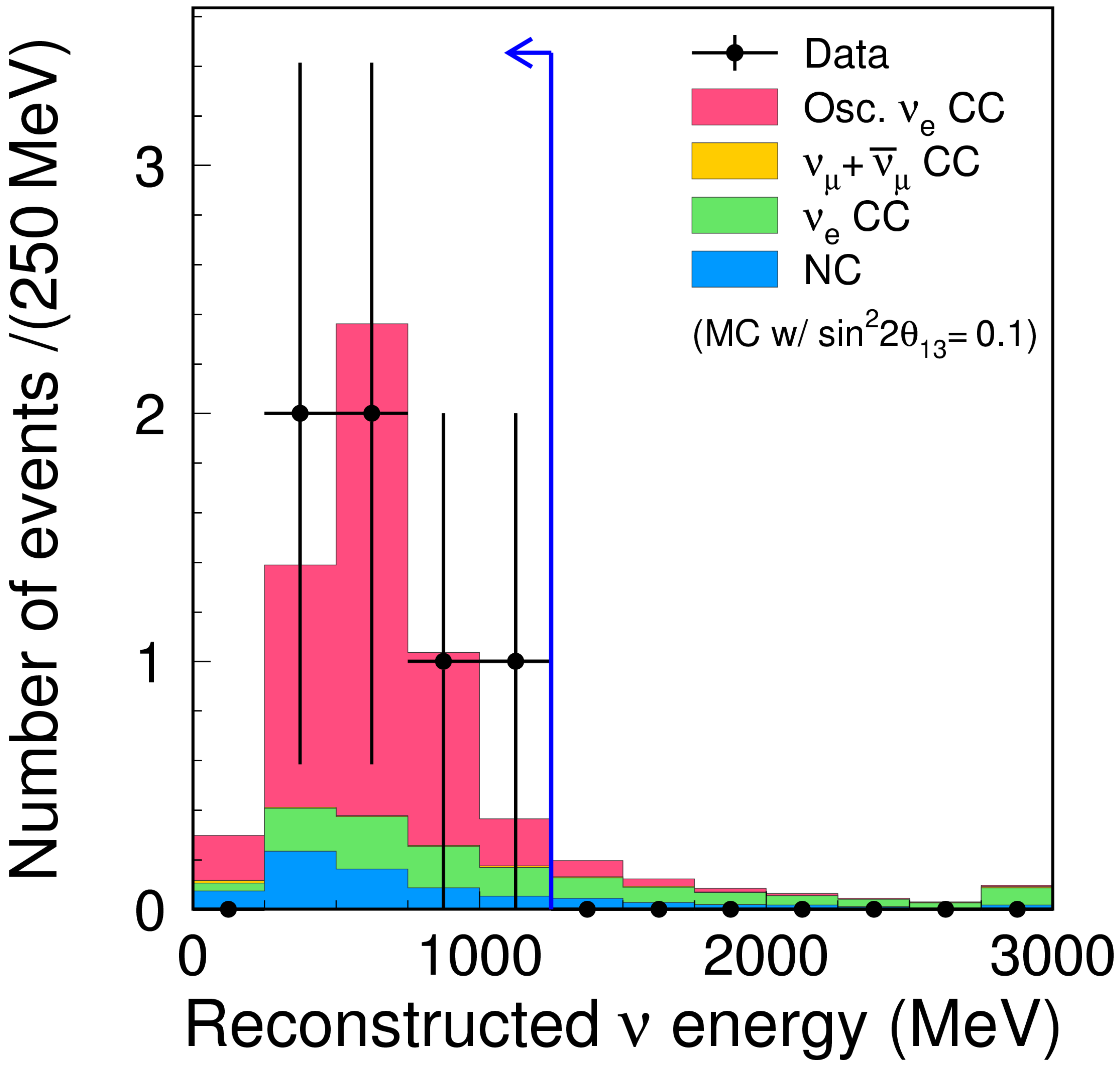


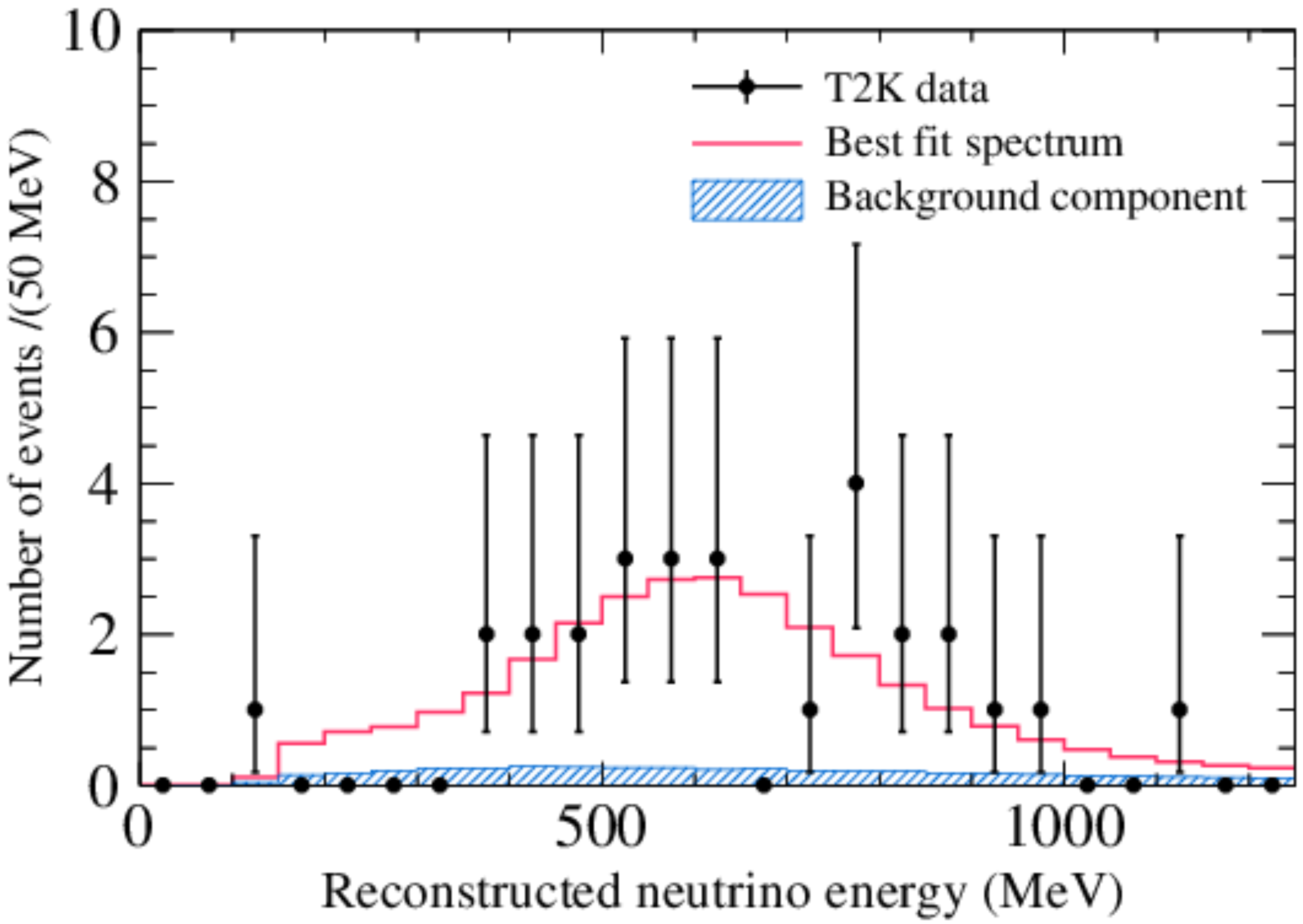
e/γ

multi ring



OBSERVATION OF ν_e APPEARANCE

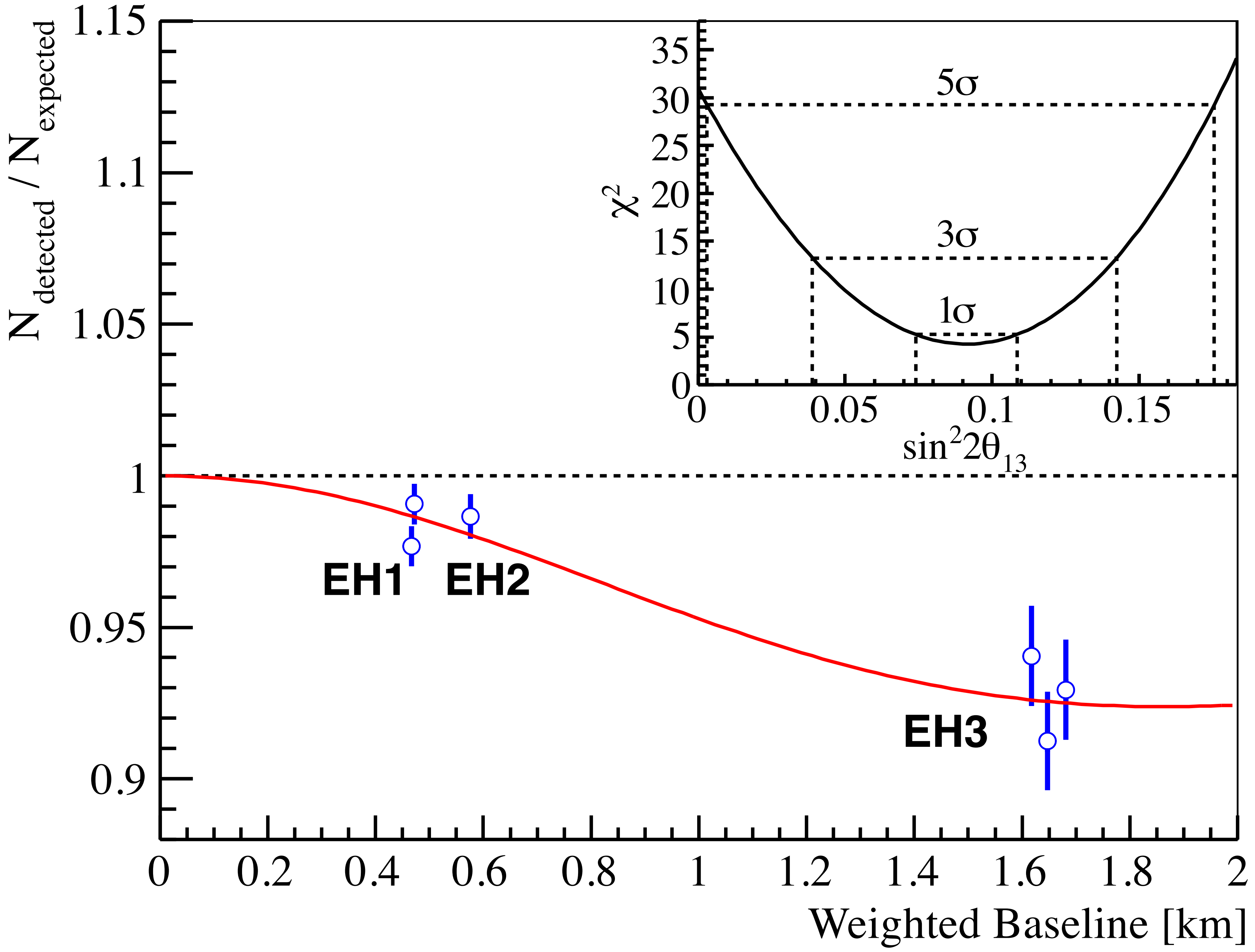


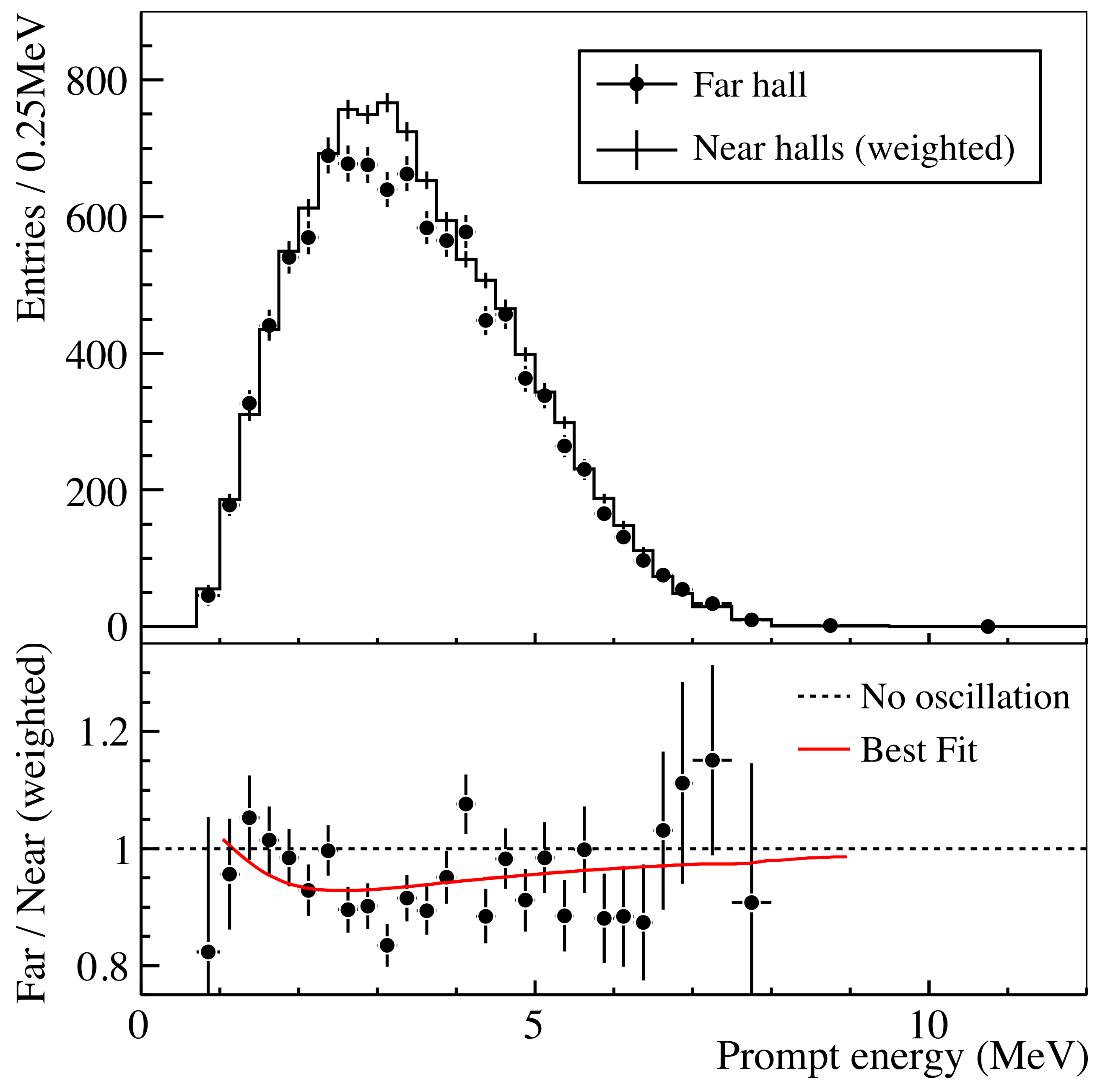


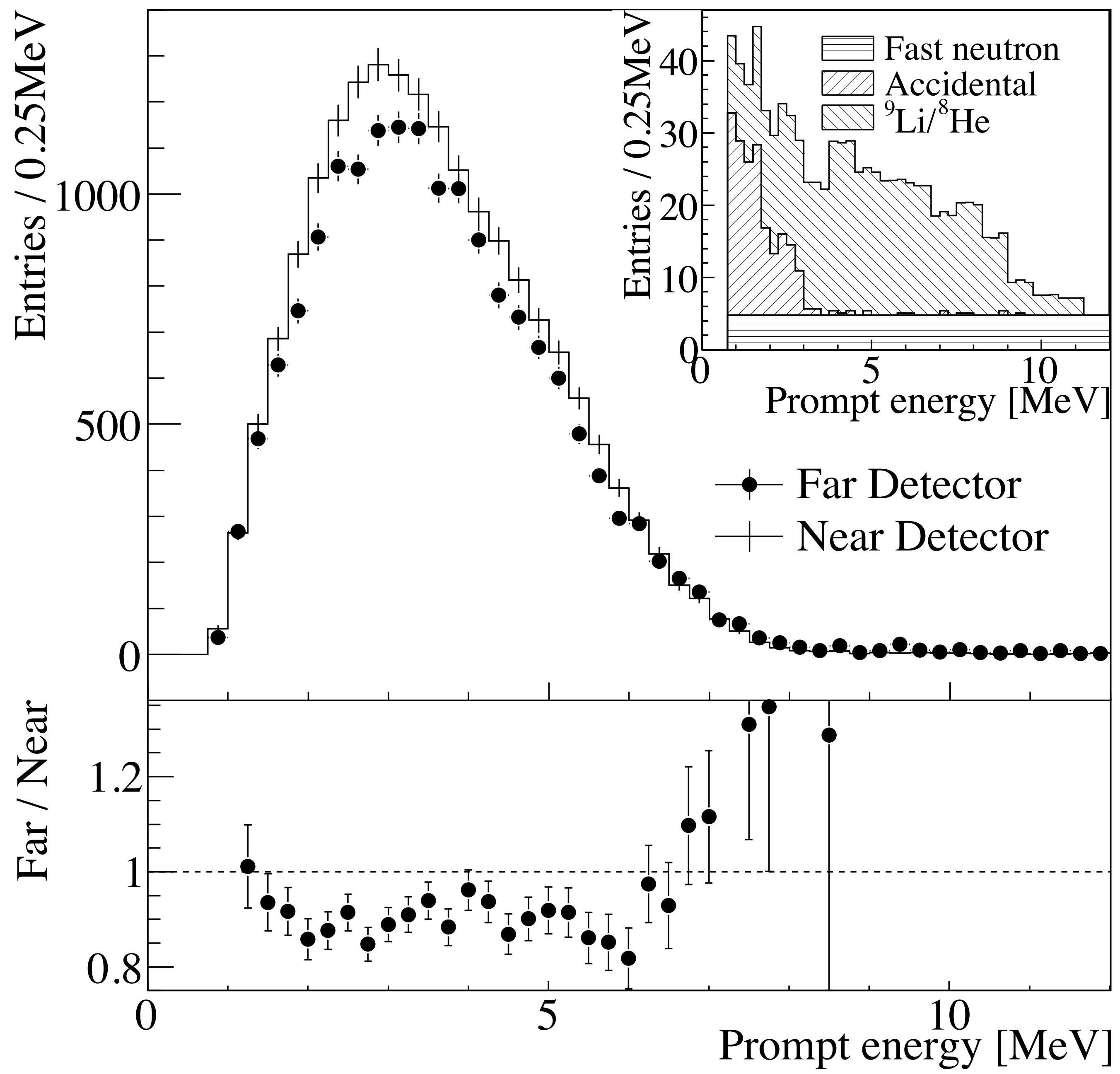
ν_e events observed at SK in T2K ν_μ beam

- 2011: 1.4 x 10^{20} protons-on-target
  - 6 events on background of 1.5 events (2.5 s)
- 2013: 6.6 x 10^{20} protons-on-target
  - 28 events on background of 5.0 events

REACTOR EXPERIMENTS







- 2012: Daya Bay and RENO definitively observed disappearance of reactor $\overline{\nu}_e$ on a baseline of ~1 km
- Patrick will discuss this in detail
  - reactor measurements allow determination of θ_{13} free of other oscillation parameters
  - precision on both θ_{13} and Δm^2 have increased steadily, and are among the most precisely measured parameters

$$\text{PDG2017: } \sin^2\theta_{13} = 0.0210 \pm 0.0011$$

DISENTANGLING THE MIXING MATRIX

$\nu_\mu \rightarrow \nu_e$ OSCILLATION PROBABILITY

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

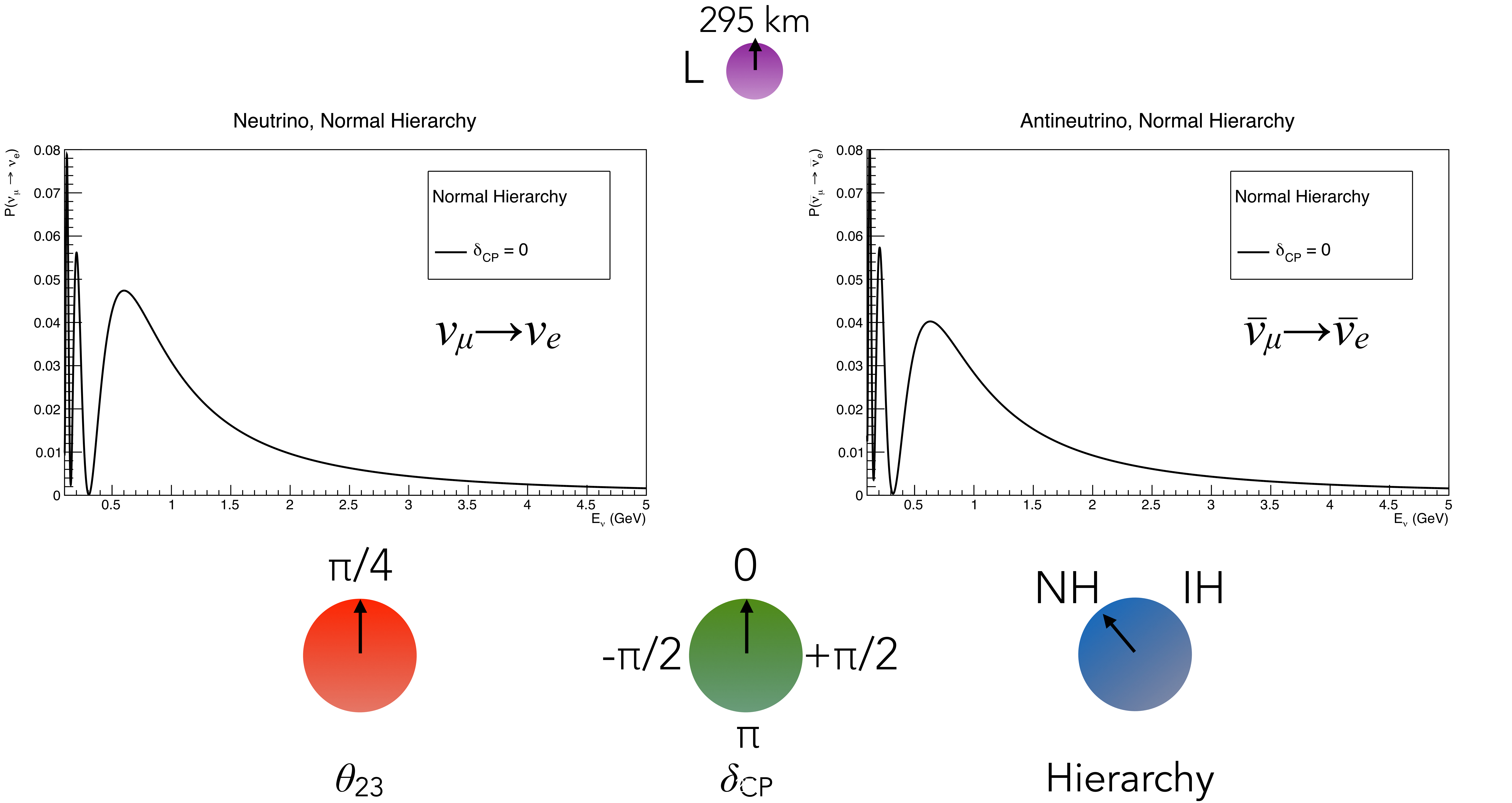
M. Freund, Phys.Rev. D64 (2001) 053003

$$\alpha = \left| \frac{\Delta m^2_{21}}{\Delta m^2_{31}} \right| \sim \frac{1}{30} \qquad \Delta \equiv \frac{\Delta m^2_{31} L}{4E} \qquad x \equiv \frac{2\sqrt{2} G_F N_e E}{\Delta m^2_{31}}$$

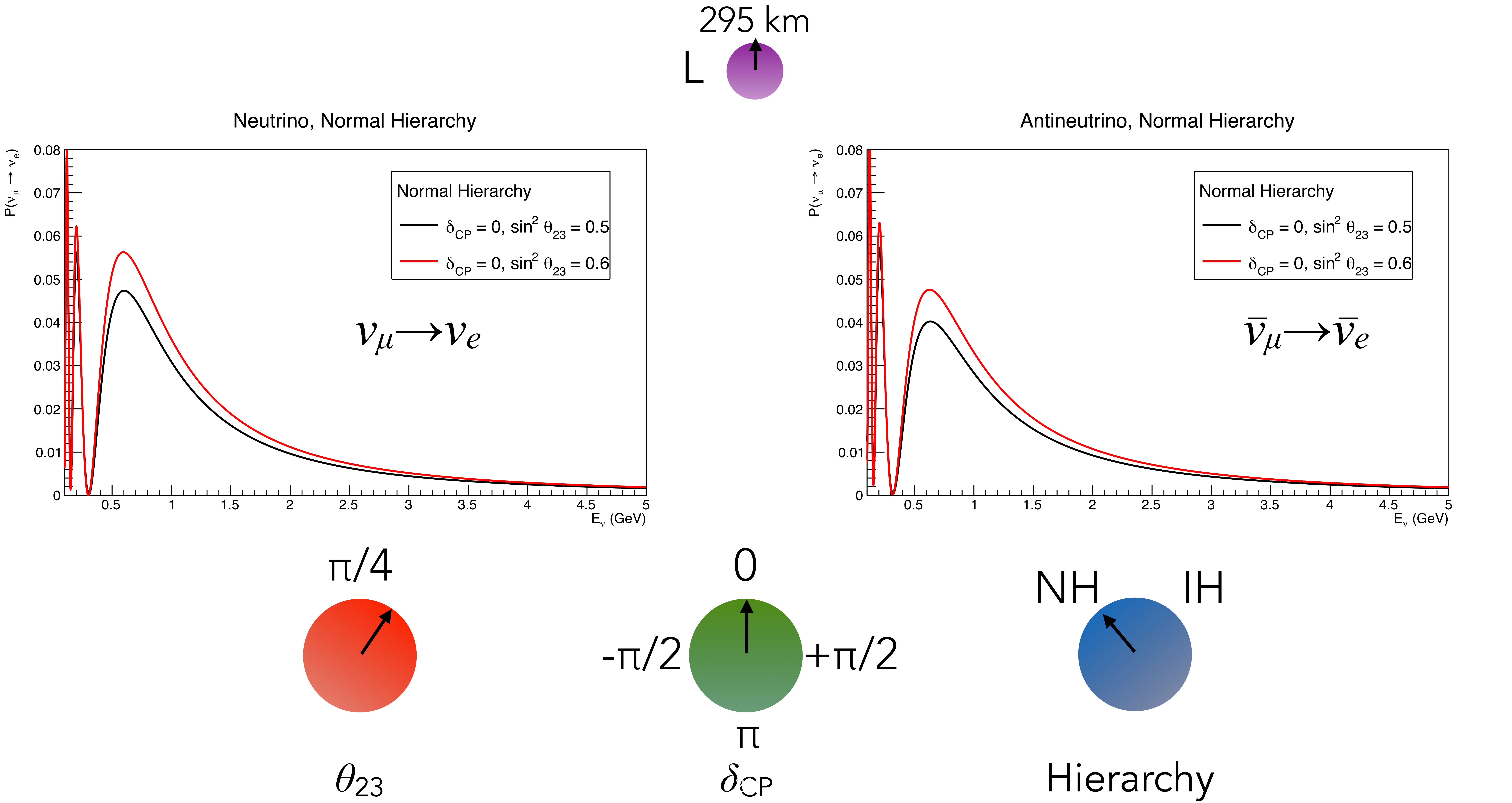
- CP odd phase δ can result in
  - asymmetry of oscillation probabilities P($\nu_\mu \rightarrow \nu_e$) ≠ P($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$)
  - distortion of $\nu_e/\bar{\nu}_e$ appearance spectrum
- θ_{23} (as opposed to $2\theta_{23}$) dependence allows “octant” resolution if $\theta_{23} \neq 45°$
- Mass hierarchy sensitivity through $\boldsymbol{x}$: $\nu_e/\bar{\nu}_e$ enhanced in normal/inverted hierarchy

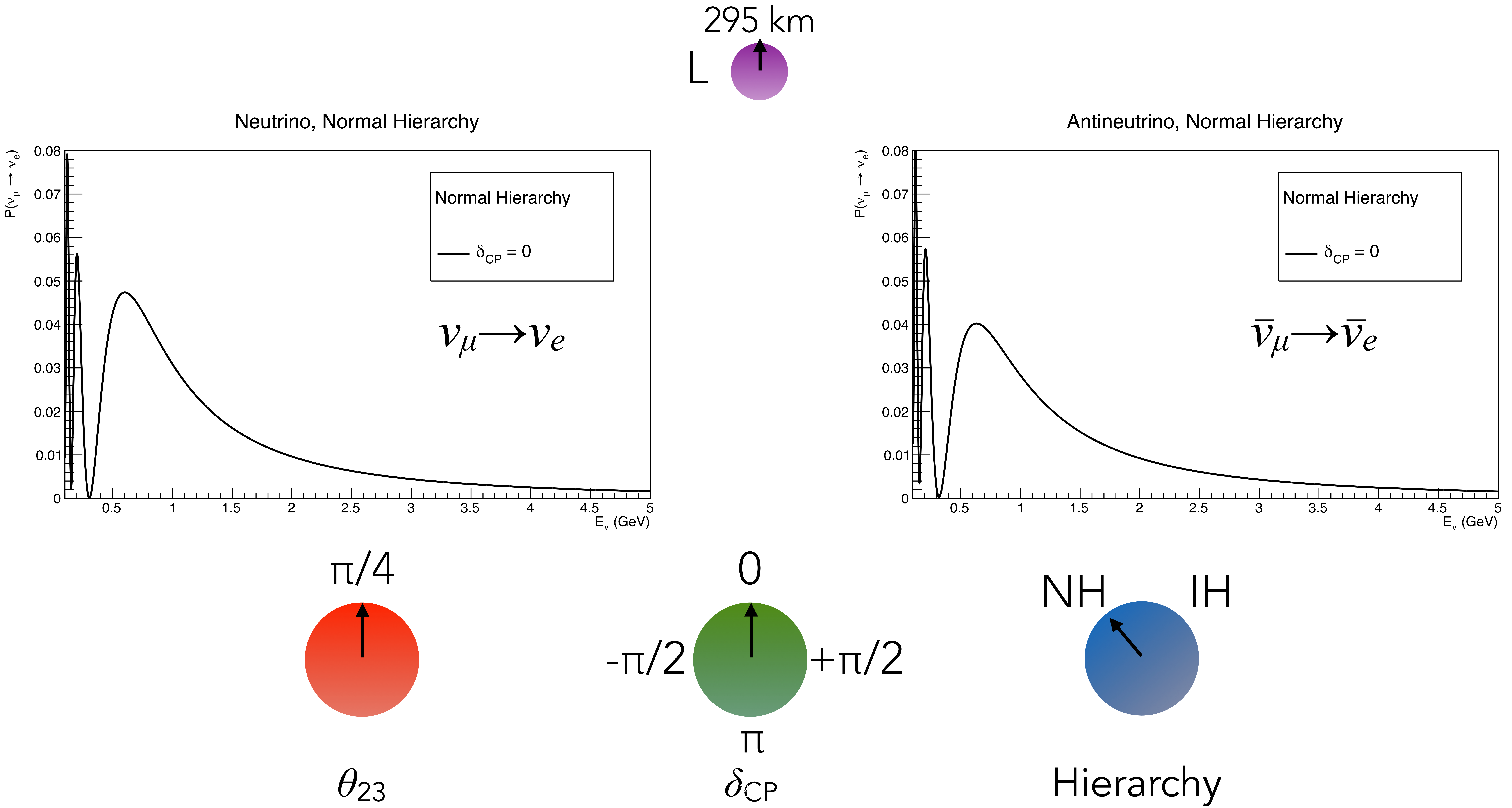
ASIDE:

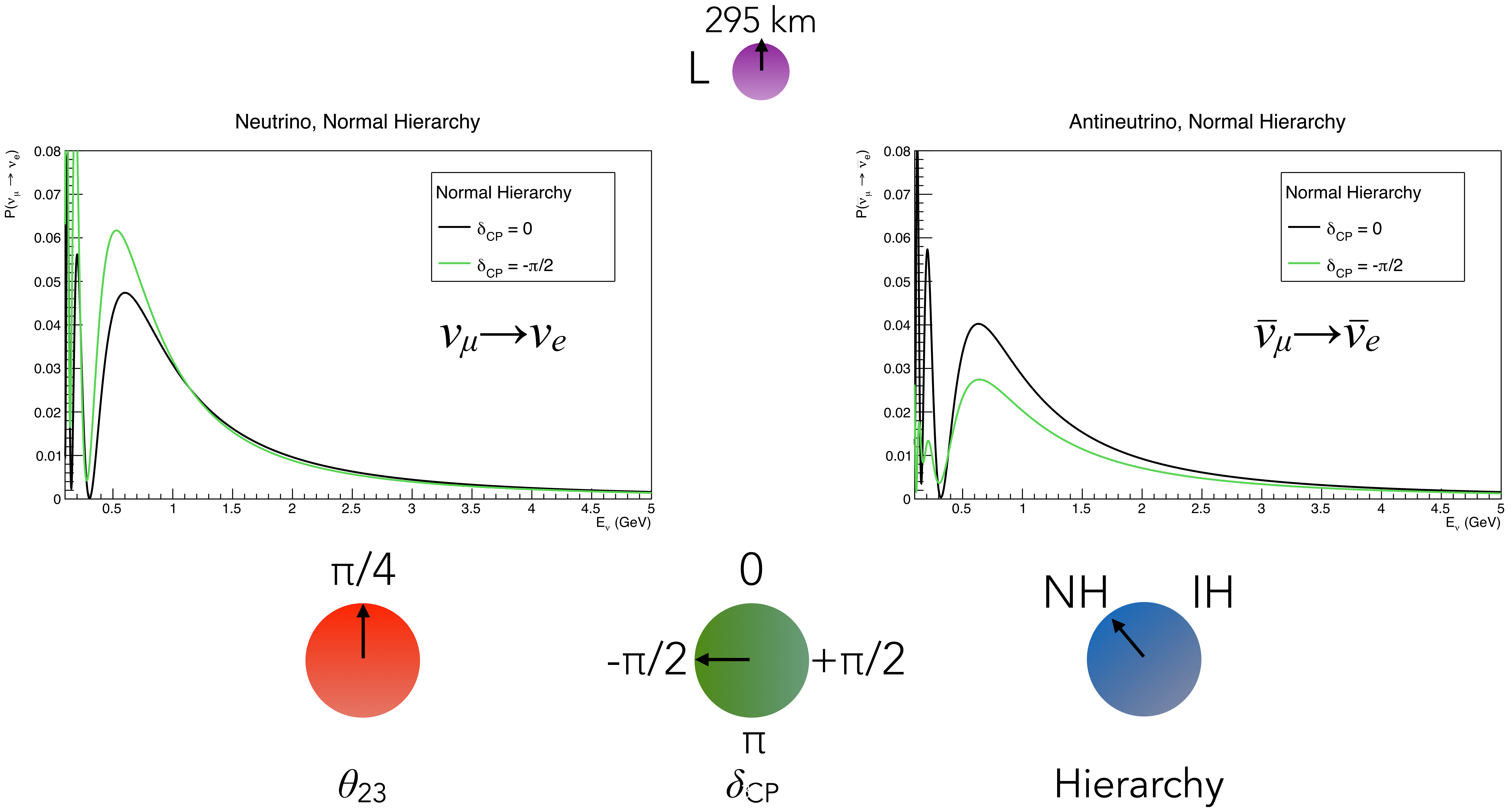
- Good news! $\nu_\mu \rightarrow \nu_e$ oscillation is sensitive to many neutrino oscillation parameters
  - including CP violation and mass ordering
- Bad news! $\nu_\mu \rightarrow \nu_e$ oscillation is sensitive to many neutrino oscillation parameters
  - needs a joint analysis of
    - ν_μ disappearance channels ($\sin^2 2\theta_{23}$, Δm^2)
    - neutrino and antineutrino oscillation modes ($\sin^2 \theta_{23}$, $\sin \theta_{13}$, δ_{CP}, mass ordering)
  - θ_{13} measured from reactors



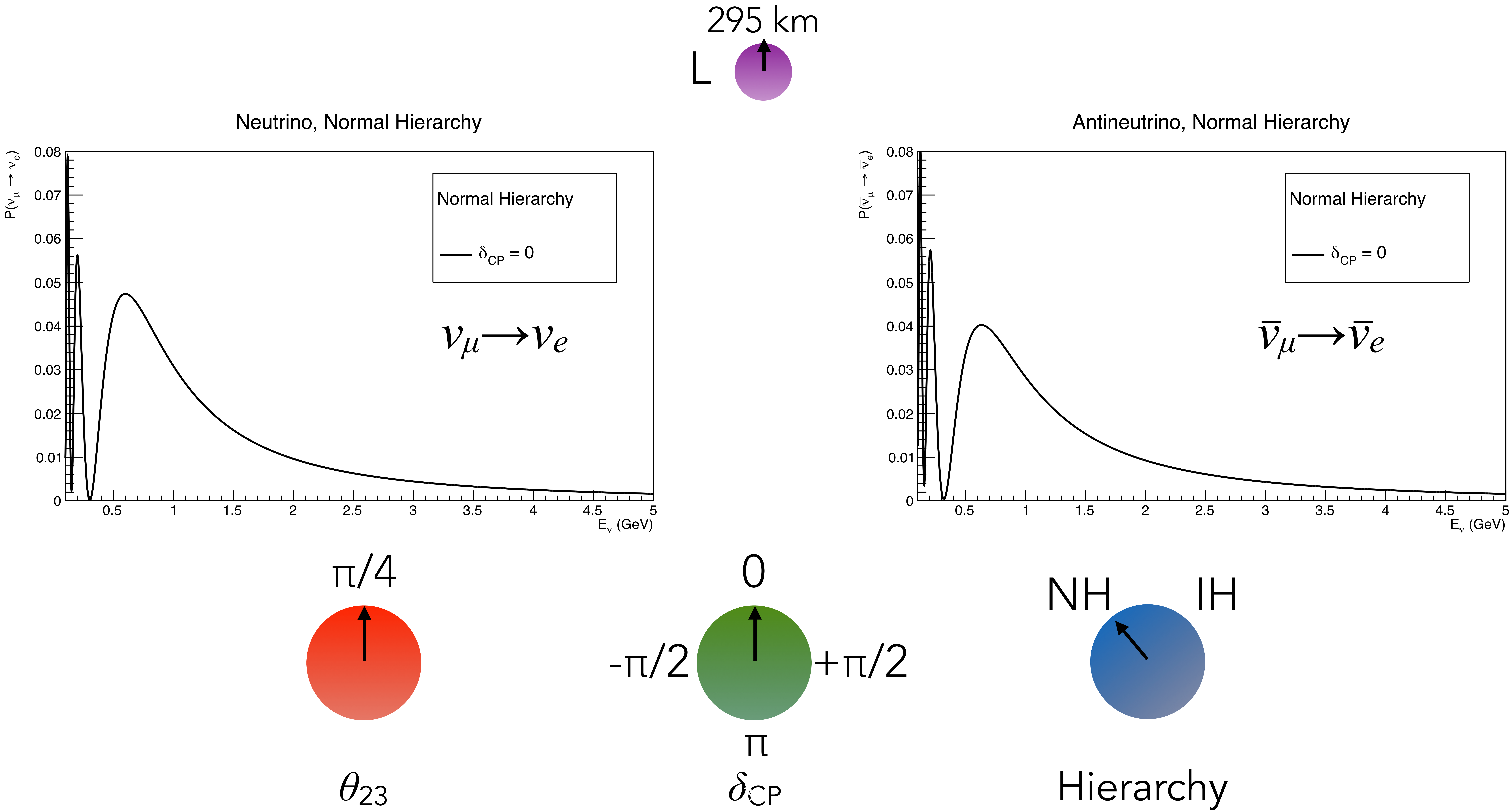
295 km
L
Neutrino, Normal Hierarchy
Normal Hierarchy
δCP = 0
νμ→νe
P(νμ → νe)
Eν (GeV)
Antineutrino, Normal Hierarchy
Normal Hierarchy
δCP = 0
ν̄μ→ν̄e
P(ν̄μ → ν̄e)
Eν (GeV)
π/4
θ23
0
-π/2
+π/2
π
δCP
NH
IH
Hierarchy


295 km
L
Neutrino, Normal Hierarchy
$P(\nu_\mu \to \nu_e)$
Normal Hierarchy
$\delta_{CP} = 0, \sin^2\theta_{23} = 0.5$
$\delta_{CP} = 0, \sin^2\theta_{23} = 0.6$
$\nu_\mu \to \nu_e$
E_ν (GeV)
Antineutrino, Normal Hierarchy
$P(\bar{\nu}_\mu \to \bar{\nu}_e)$
Normal Hierarchy
$\delta_{CP} = 0, \sin^2\theta_{23} = 0.5$
$\delta_{CP} = 0, \sin^2\theta_{23} = 0.6$
$\bar{\nu}_\mu \to \bar{\nu}_e$
E_ν (GeV)
π/4
θ_{23}
0
-π/2
+π/2
π
δ_{CP}
NH
IH
Hierarchy

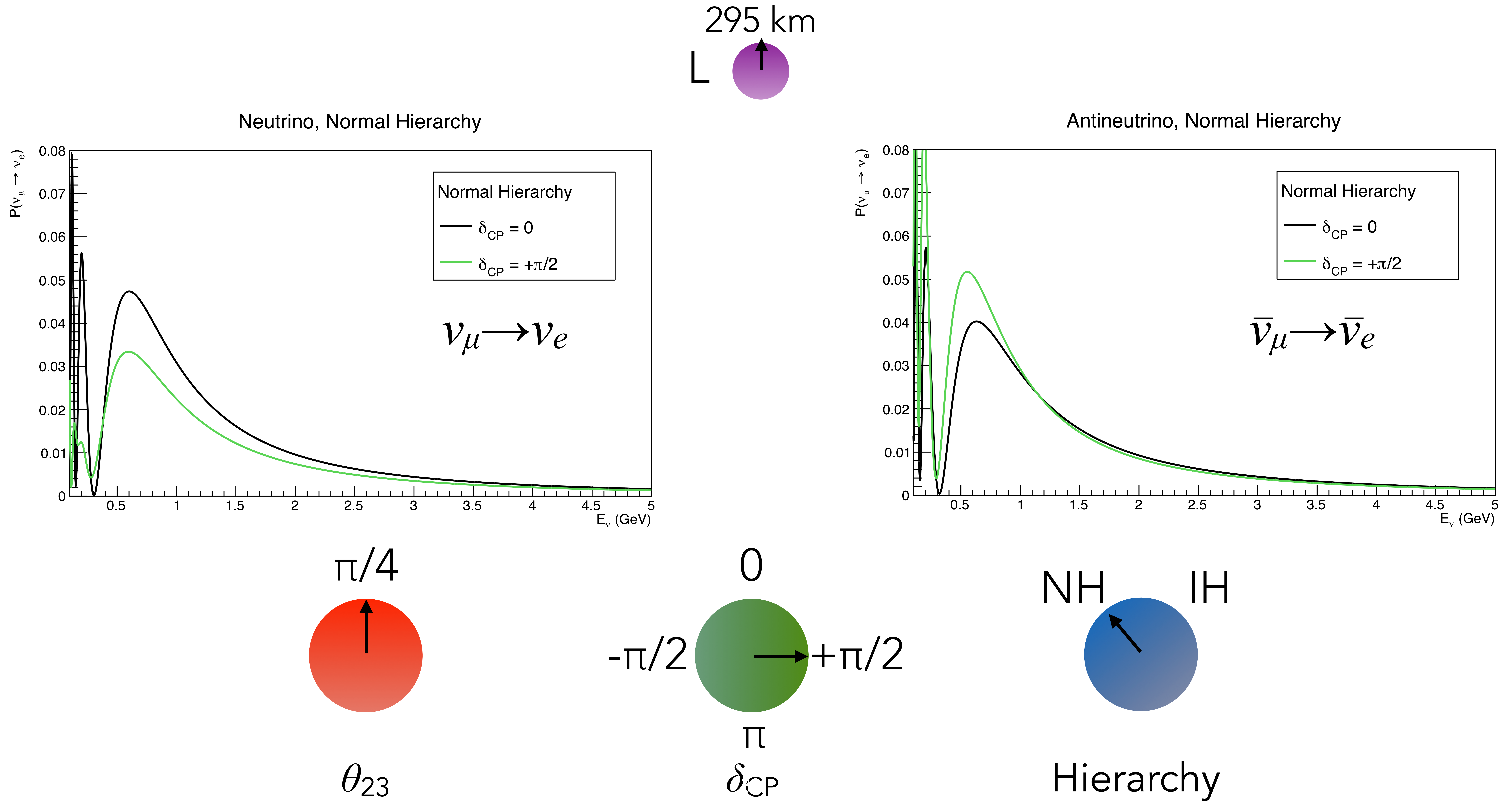

295 km
L
Neutrino, Normal Hierarchy
P(ν_μ → ν_e)
Normal Hierarchy
δ_CP = 0
ν_μ→ν_e
E_ν (GeV)
Antineutrino, Normal Hierarchy
P(ν̄_μ → ν̄_e)
Normal Hierarchy
δ_CP = 0
ν̄_μ→ν̄_e
E_ν (GeV)
π/4
θ23
0
-π/2
+π/2
π
δCP
NH
IH
Hierarchy

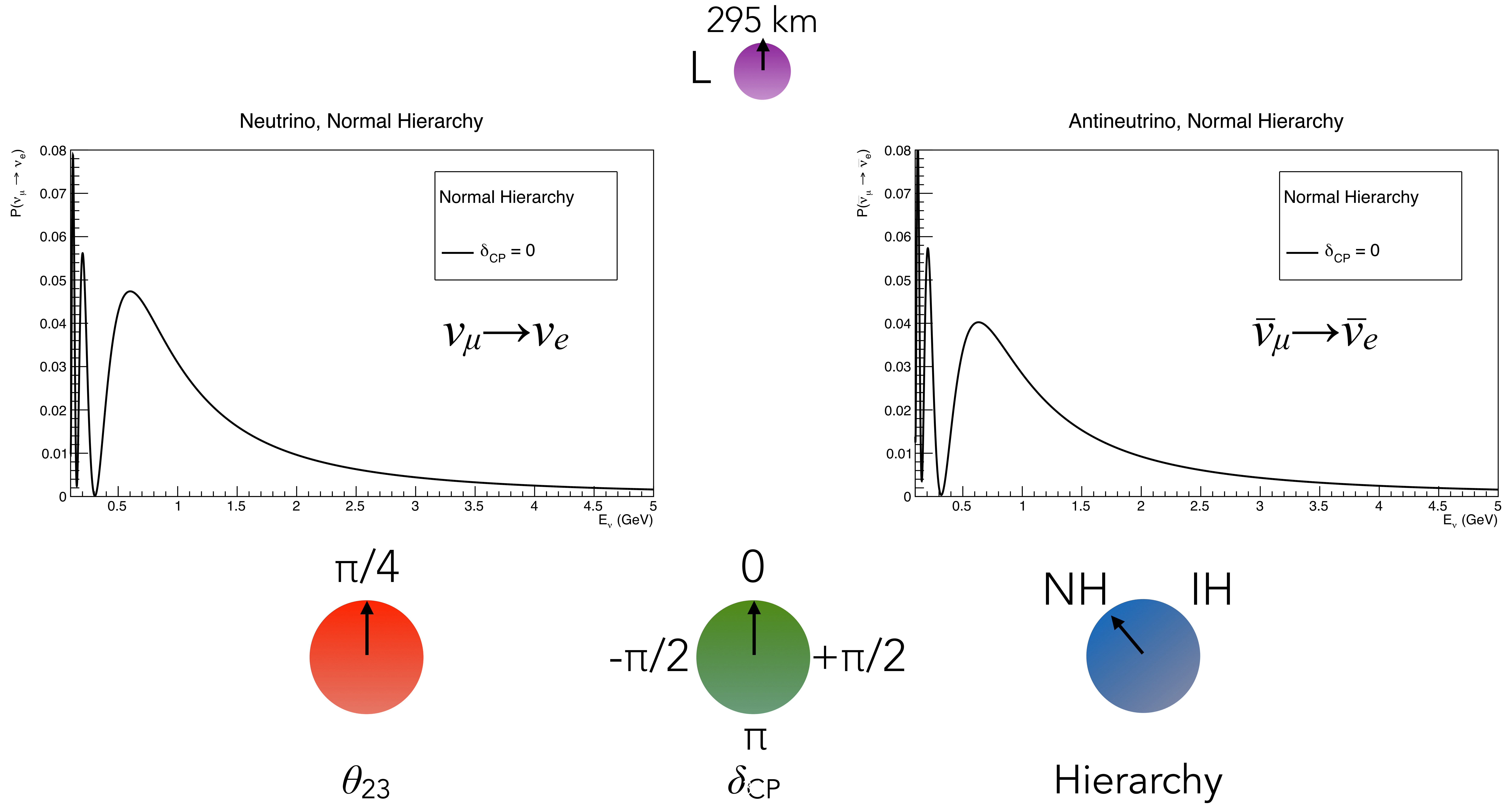


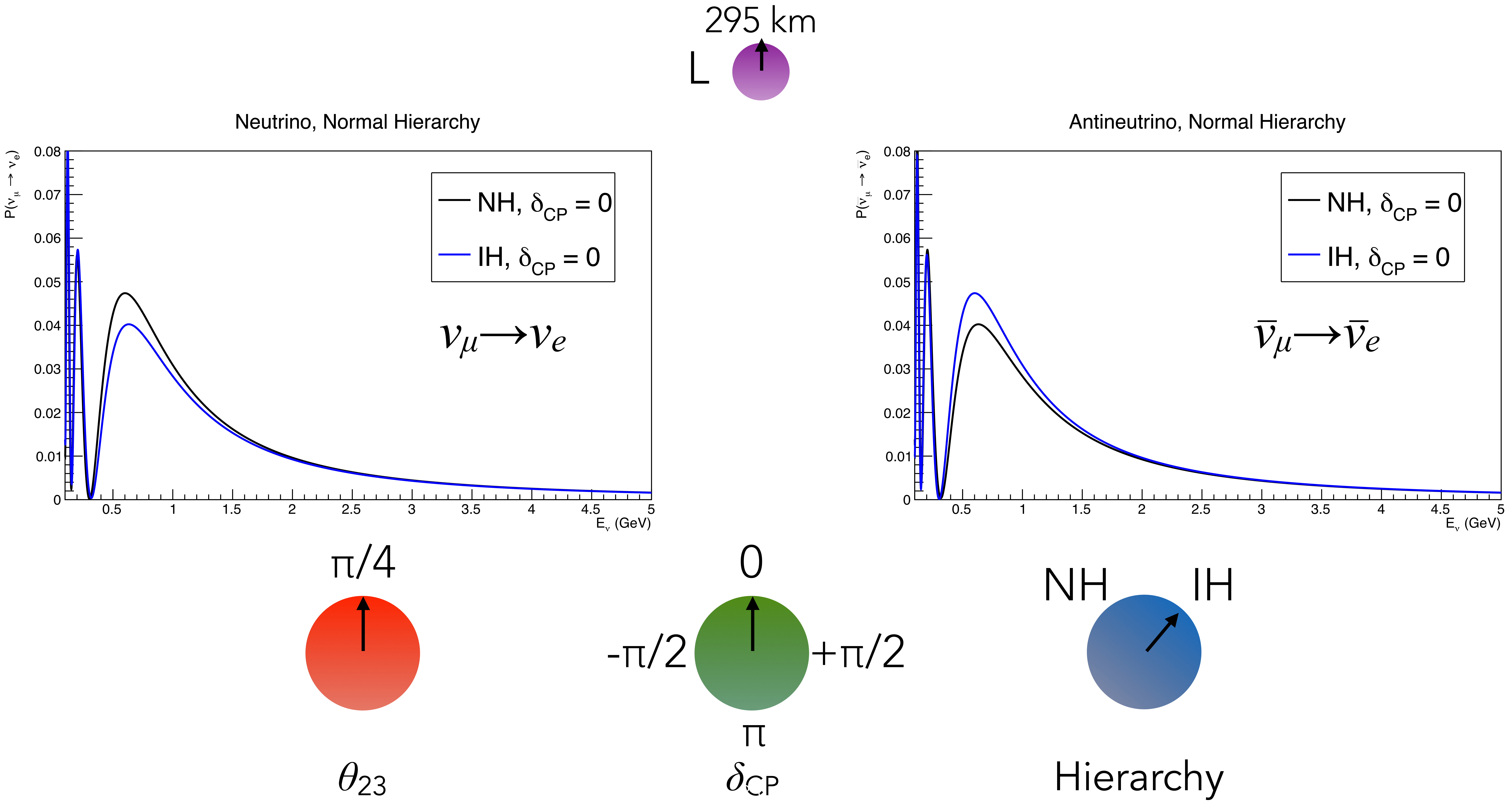
295 km
L
Neutrino, Normal Hierarchy
Antineutrino, Normal Hierarchy
$P(\nu_\mu \rightarrow \nu_e)$
$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
E_ν (GeV)
Normal Hierarchy
$\delta_{CP} = 0$
$\delta_{CP} = -\pi/2$
$\nu_\mu \rightarrow \nu_e$
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
π/4
θ_{23}
0
-π/2
+π/2
π
δ_{CP}
NH
IH
Hierarchy

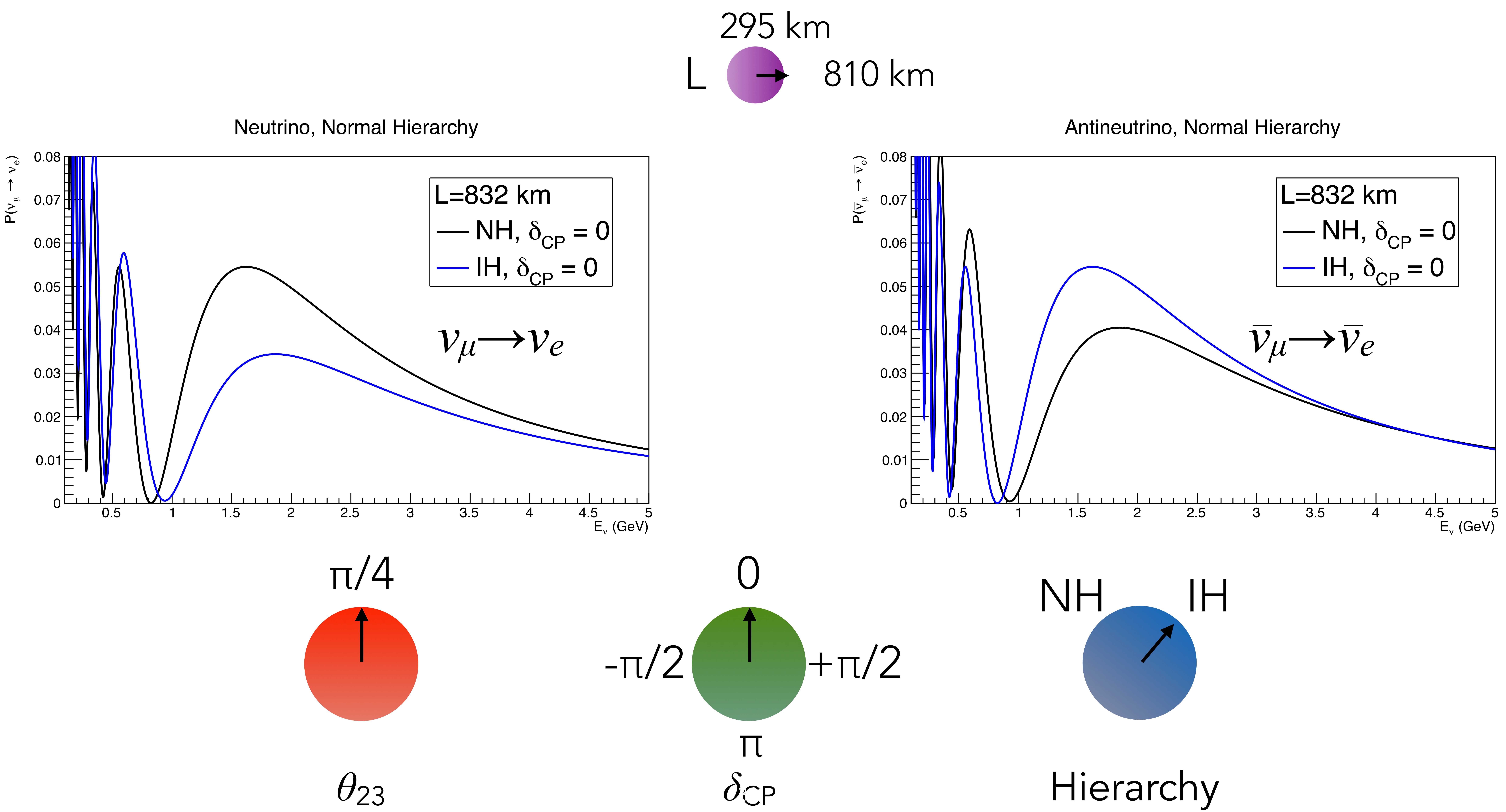

295 km
L
Neutrino, Normal Hierarchy
Normal Hierarchy
$\delta_{CP} = 0$
$\nu_\mu \rightarrow \nu_e$
$P(\nu_\mu \rightarrow \nu_e)$
E_ν (GeV)
Antineutrino, Normal Hierarchy
Normal Hierarchy
$\delta_{CP} = 0$
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$
E_ν (GeV)
π/4
θ_{23}
0
-π/2
+π/2
π
δ_{CP}
NH
IH
Hierarchy


295 km
L
Neutrino, Normal Hierarchy
$P(\nu_\mu \to \nu_e)$
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
E_ν (GeV)
Normal Hierarchy
$\delta_{CP} = 0$
$\delta_{CP} = \pi$
$\nu_\mu \rightarrow \nu_e$
Antineutrino, Normal Hierarchy
$P(\bar{\nu}_\mu \to \bar{\nu}_e)$
Normal Hierarchy
$\delta_{CP} = 0$
$\delta_{CP} = \pi$
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
$\pi/4$
θ_{23}
0
$-\pi/2$
$+\pi/2$
π
δ_{CP}
NH
IH
Hierarchy


295 km
L
Neutrino, Normal Hierarchy
P(ν_μ → ν_e)
Normal Hierarchy
δ_CP = 0
δ_CP = +π/2
ν_μ→ν_e
E_ν (GeV)
Antineutrino, Normal Hierarchy
P(ν̄_μ → ν̄_e)
Normal Hierarchy
δ_CP = 0
δ_CP = +π/2
ν̄_μ→ν̄_e
E_ν (GeV)
π/4
θ23
0
-π/2
+π/2
π
δCP
NH
IH
Hierarchy


295 km
L
Neutrino, Normal Hierarchy
Normal Hierarchy
$\delta_{CP} = 0$
$\nu_\mu \rightarrow \nu_e$
$P(\nu_\mu \rightarrow \nu_e)$
E_ν (GeV)
Antineutrino, Normal Hierarchy
Normal Hierarchy
$\delta_{CP} = 0$
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$
E_ν (GeV)
π/4
θ_{23}
0
-π/2
+π/2
π
δ_{CP}
NH
IH
Hierarchy


295 km
L
Neutrino, Normal Hierarchy
$P(\nu_\mu \to \nu_e)$
NH, δ_{CP} = 0
IH, δ_{CP} = 0
$\nu_\mu \to \nu_e$
E_ν (GeV)
Antineutrino, Normal Hierarchy
$P(\bar{\nu}_\mu \to \bar{\nu}_e)$
NH, δ_{CP} = 0
IH, δ_{CP} = 0
$\bar{\nu}_\mu \to \bar{\nu}_e$
E_ν (GeV)
π/4
θ_{23}
0
-π/2
+π/2
π
δ_{CP}
NH
IH
Hierarchy

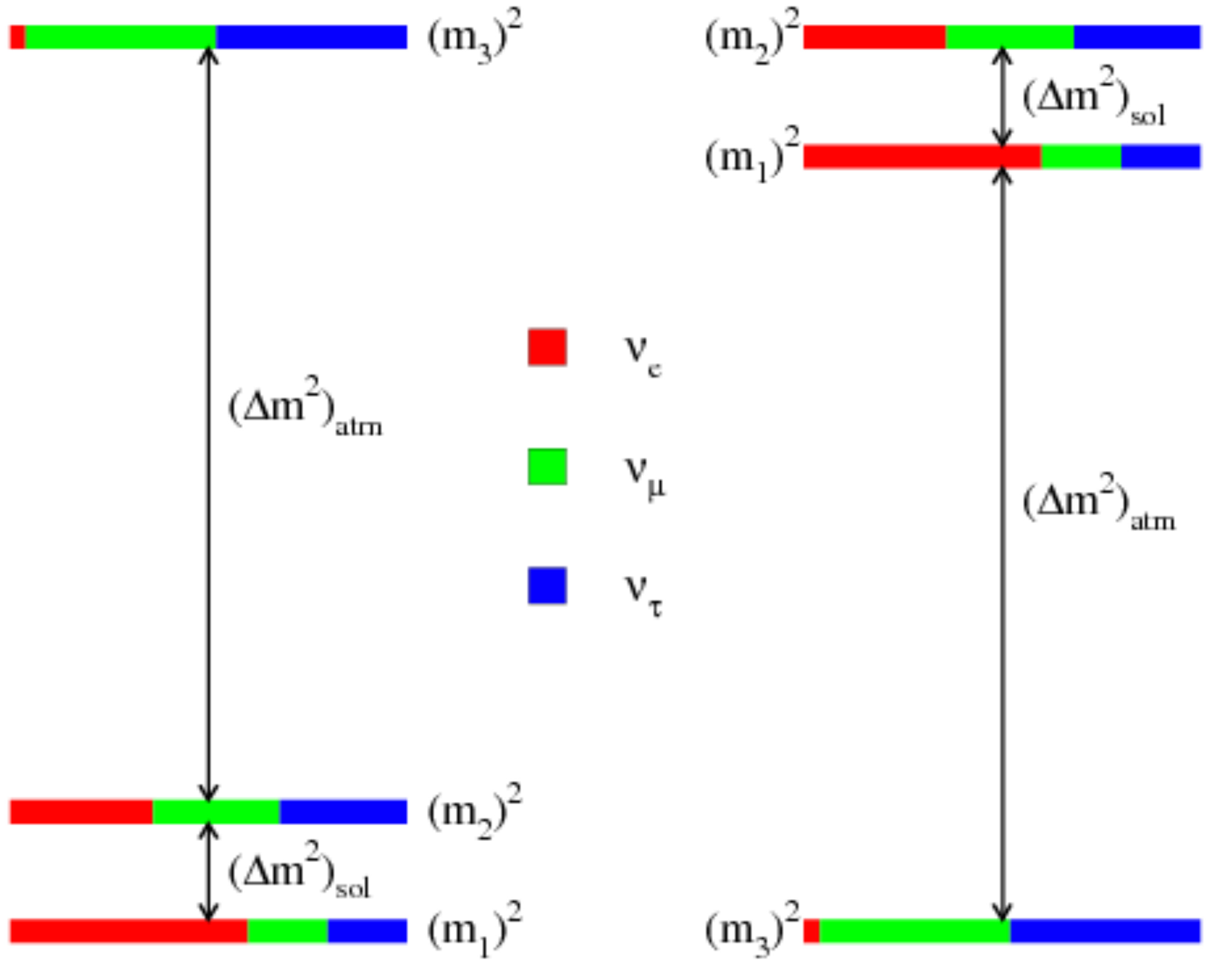


295 km
L
810 km
Neutrino, Normal Hierarchy
Antineutrino, Normal Hierarchy
L=832 km
NH, δ_{CP} = 0
IH, δ_{CP} = 0
$\nu_\mu \rightarrow \nu_e$
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
$P(\nu_\mu \rightarrow \nu_e)$
$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$
E_ν (GeV)
π/4
θ_{23}
0
-π/2
+π/2
π
δ_{CP}
NH
IH
Hierarchy

QUICK SUMMARY

- increase $\sin^2\theta_{23}$, $\sin^2 2\theta_{13}$
  - enhance both $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
- CP violating parameter δ
  - δ =0,π: no CP violation: vacuum oscillation probabilities equal
  - δ ~-π/2: enhance $\nu_\mu \rightarrow \nu_e$, suppress $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
  - δ ~+π/2: suppress $\nu_\mu \rightarrow \nu_e$, enhance $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

- "normal" hierarchy:
  - enhance $\nu_\mu \rightarrow \nu_e$
  - suppresses $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

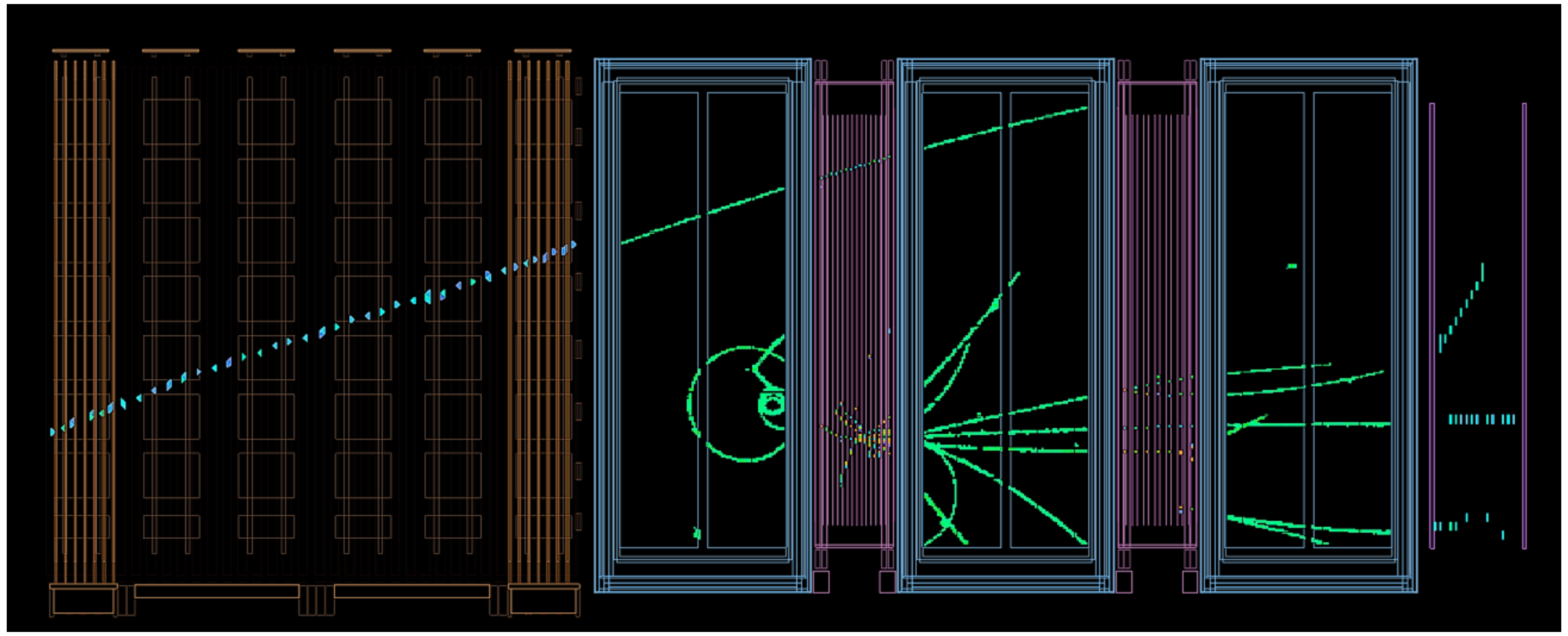


normal hierarchy inverted hierarchy

- "inverted" hierarchy:
  - suppress $\nu_\mu \rightarrow \nu_e$
  - enhance $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

ANALYSIS STRATEGY

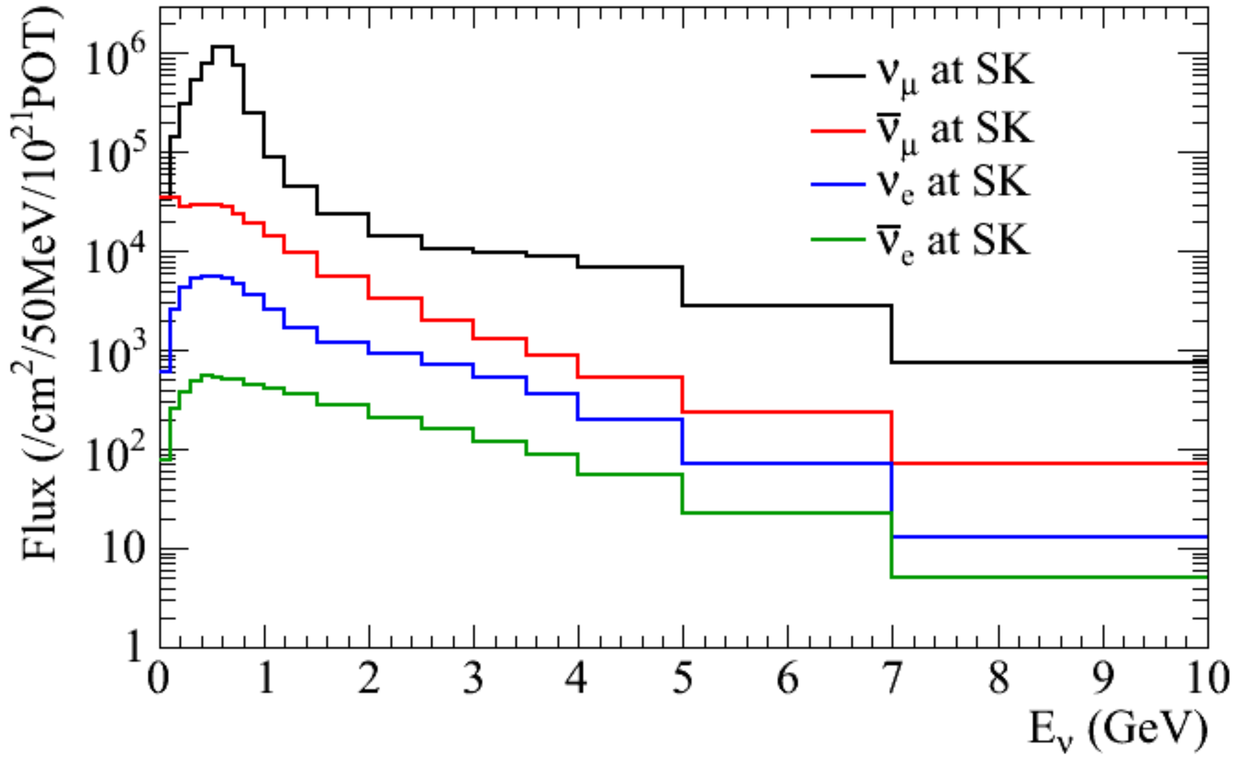
current analysis with 14.7 x 10^{20} POT ν-mode
7.6 x 10^{20} POT $\bar{\nu}$-mode



Near detectors observe the neutrinos prior to oscillations

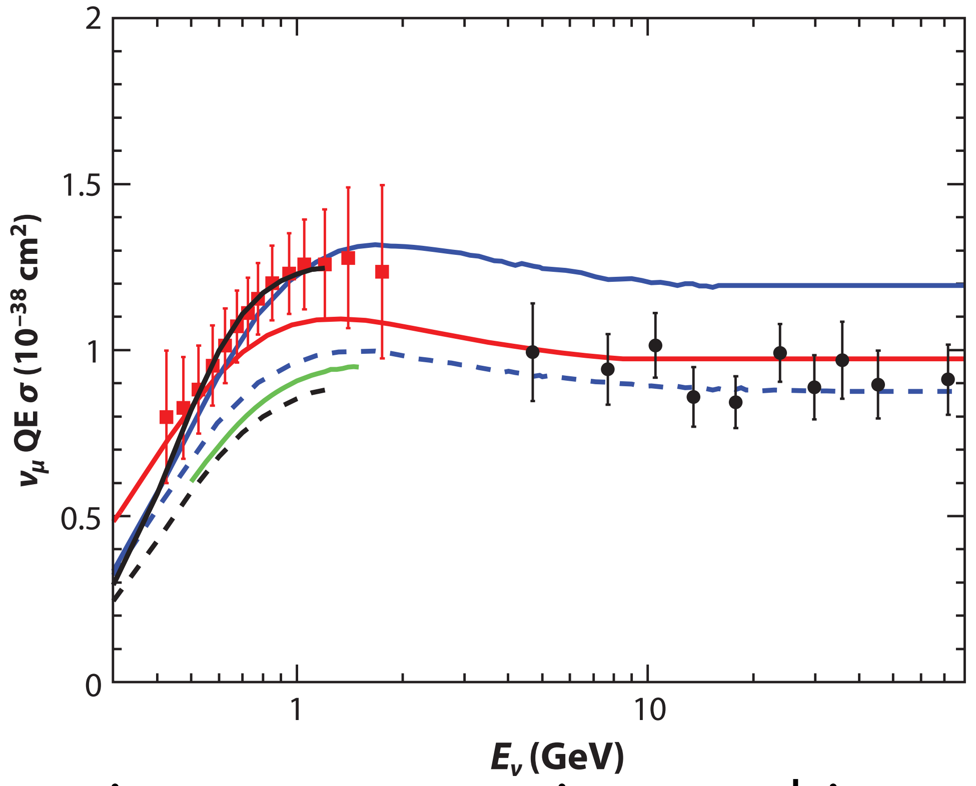
$\boxed{\varphi_\nu \cdot \sigma_\nu} \cdot \varepsilon_{NEAR}$

φ_ν



MC simulation of neutrino beam line tuned with external data + operational parameters

σ_ν

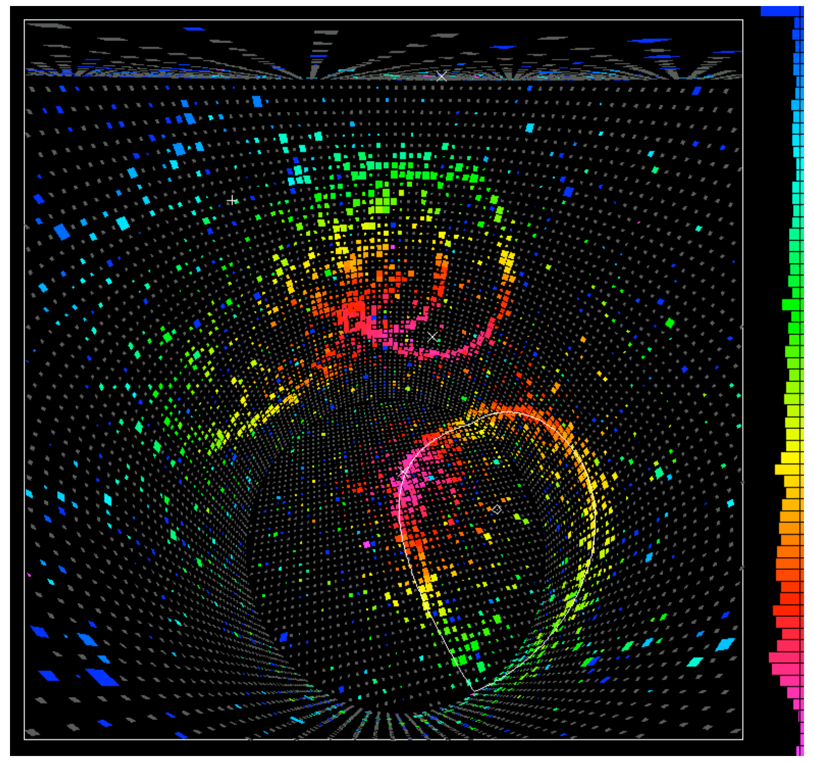


Neutrino cross section and interaction model tuned to external measurements

Far (L=295 km)
$\nu_\mu \rightarrow \nu_e$ (θ_{23} , θ_{13}, δ_{CP})
$\nu_\mu \rightarrow \nu_{\mu/\tau}$ ($2\theta_{23}$, Δm^2_{32})
ν_μ, ν_e backgrounds

$\rightarrow \boxed{\varphi_\nu \cdot \sigma_\nu} \cdot \varepsilon_{FAR} \cdot P_{osc}$

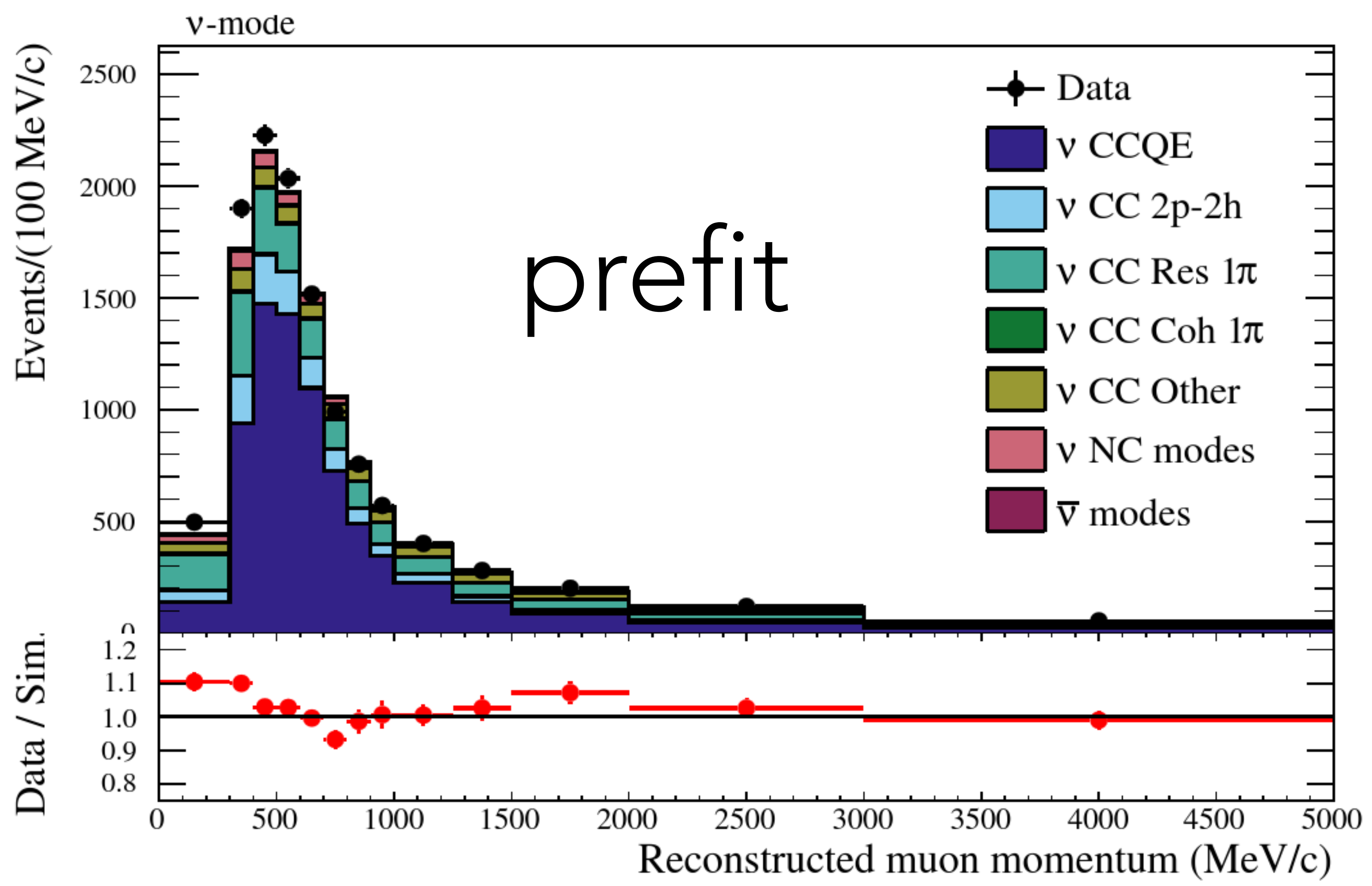
ε_{FAR}



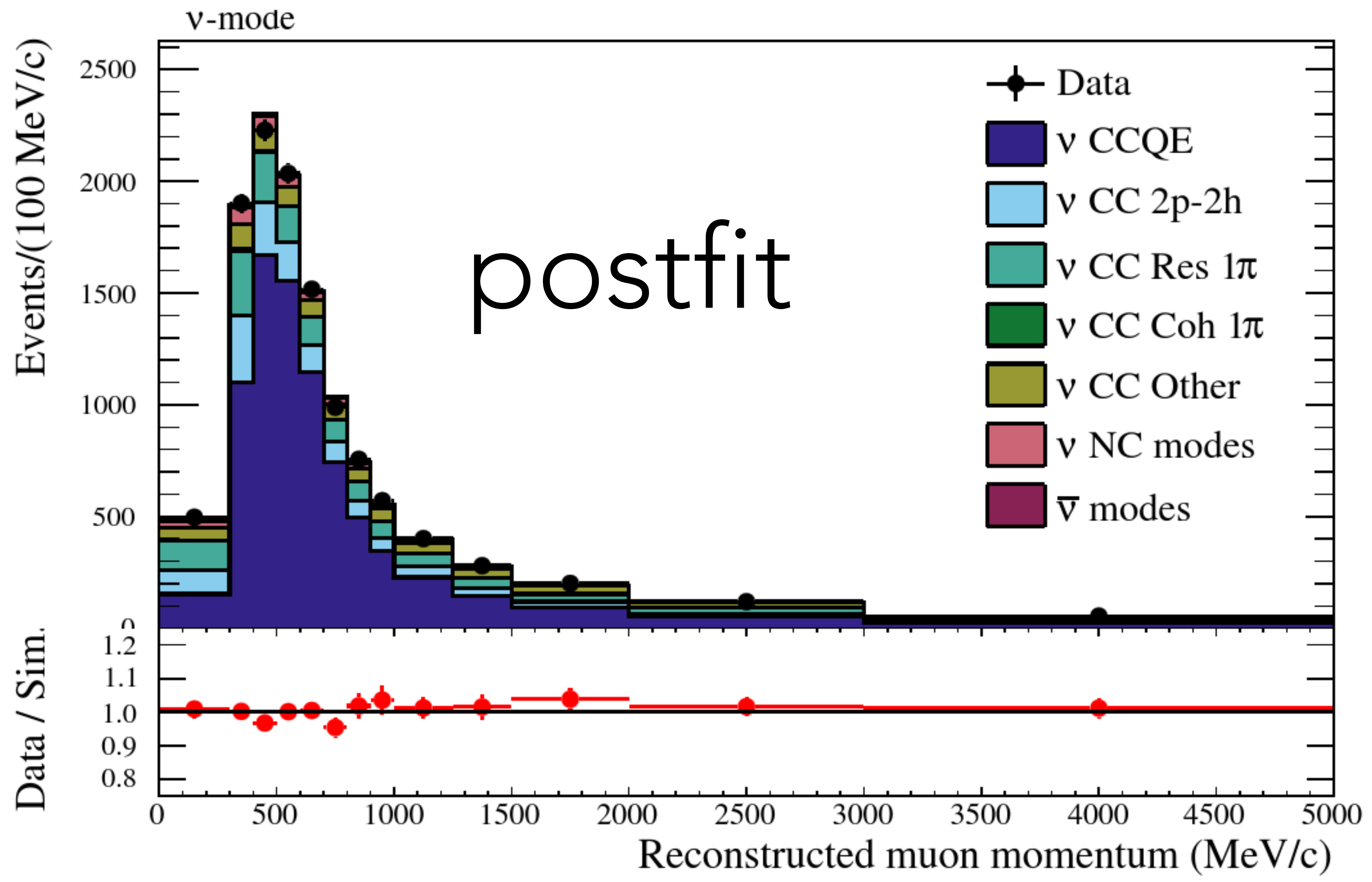
Detector simulation to determine efficiencies/ backgrounds

NEAR DETECTOR DATA

- Parameters govern the neutrino flux and cross section predictions
  - some of the relate to parameters within a model
    - e.g. parameters associated with form factors or nuclear model
  - some are "*ad hoc*"
    - flux of a particular neutrino at a particular energy
    - normalization of a particular neutrino interaction process
- Parameters have "input" uncertainties from a priori knowledge
  - some parameters have covariance
  - neutrino interaction/flux parameters typically do not have correlations
- Through the detector simulation, we predict what we should see in the near detector
  - parameters are adjusted to give a new "best fit" to the parameters and an updated covariance

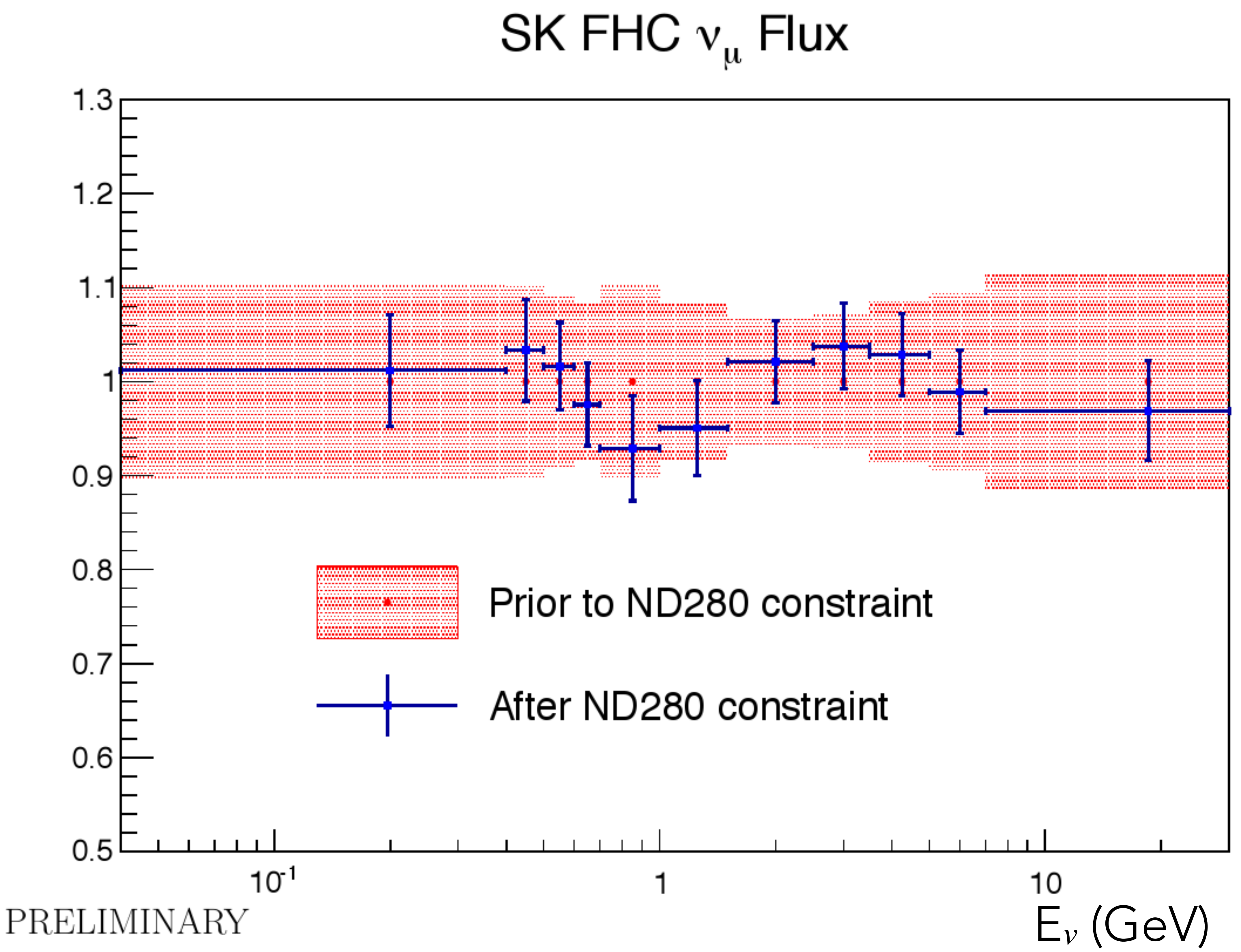


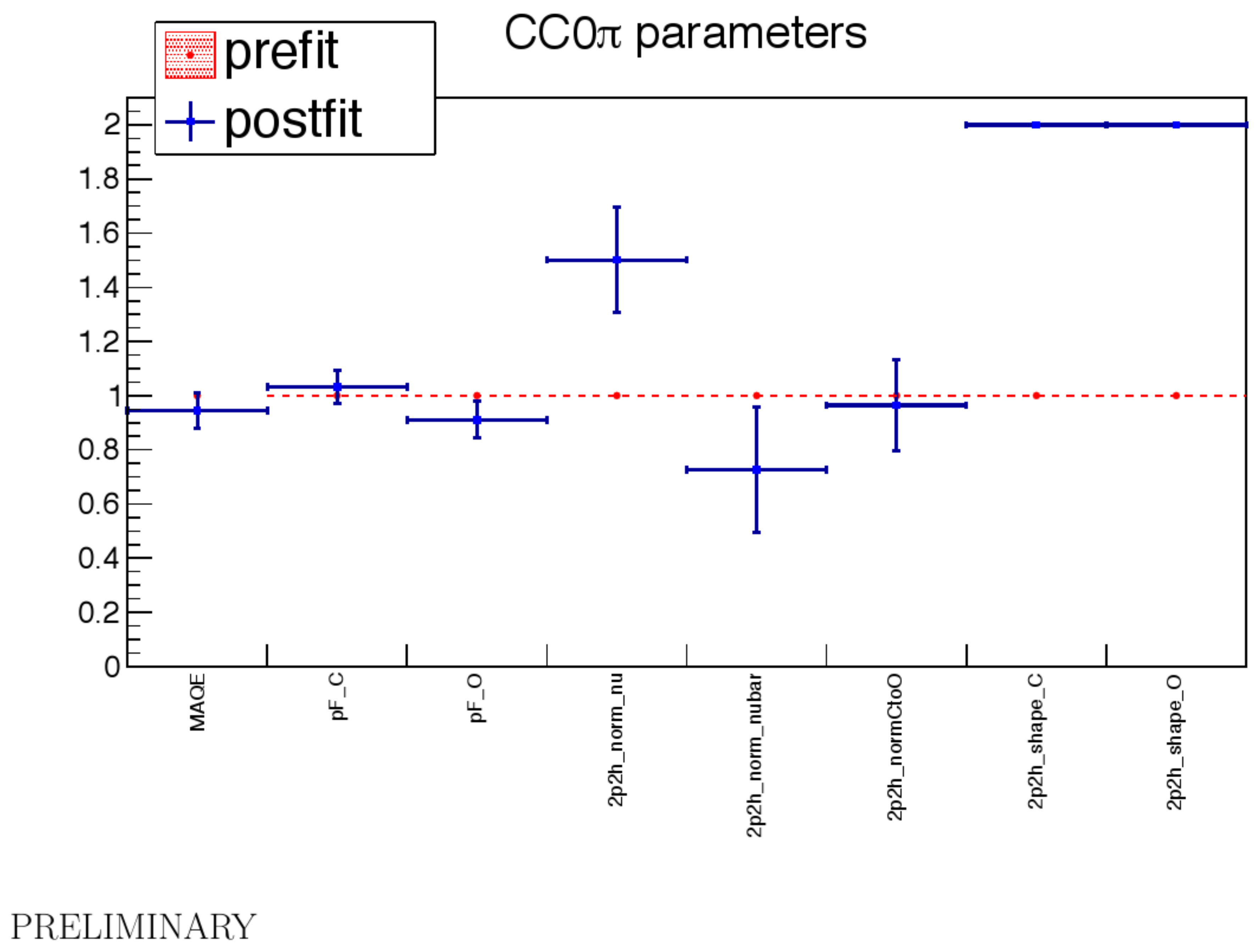
PRELIMINARY

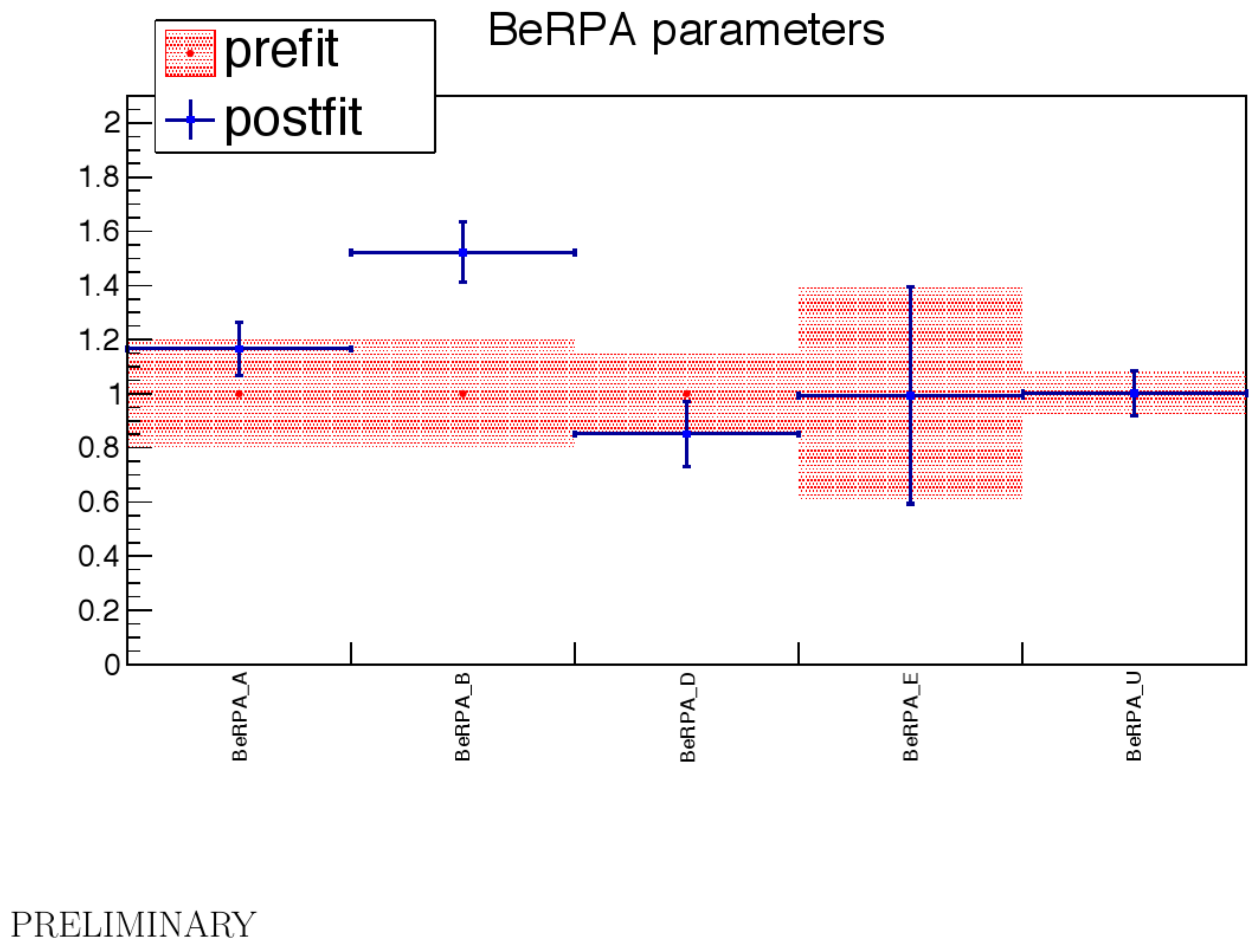


PRELIMINARY

IMPACT ON PARAMETERS

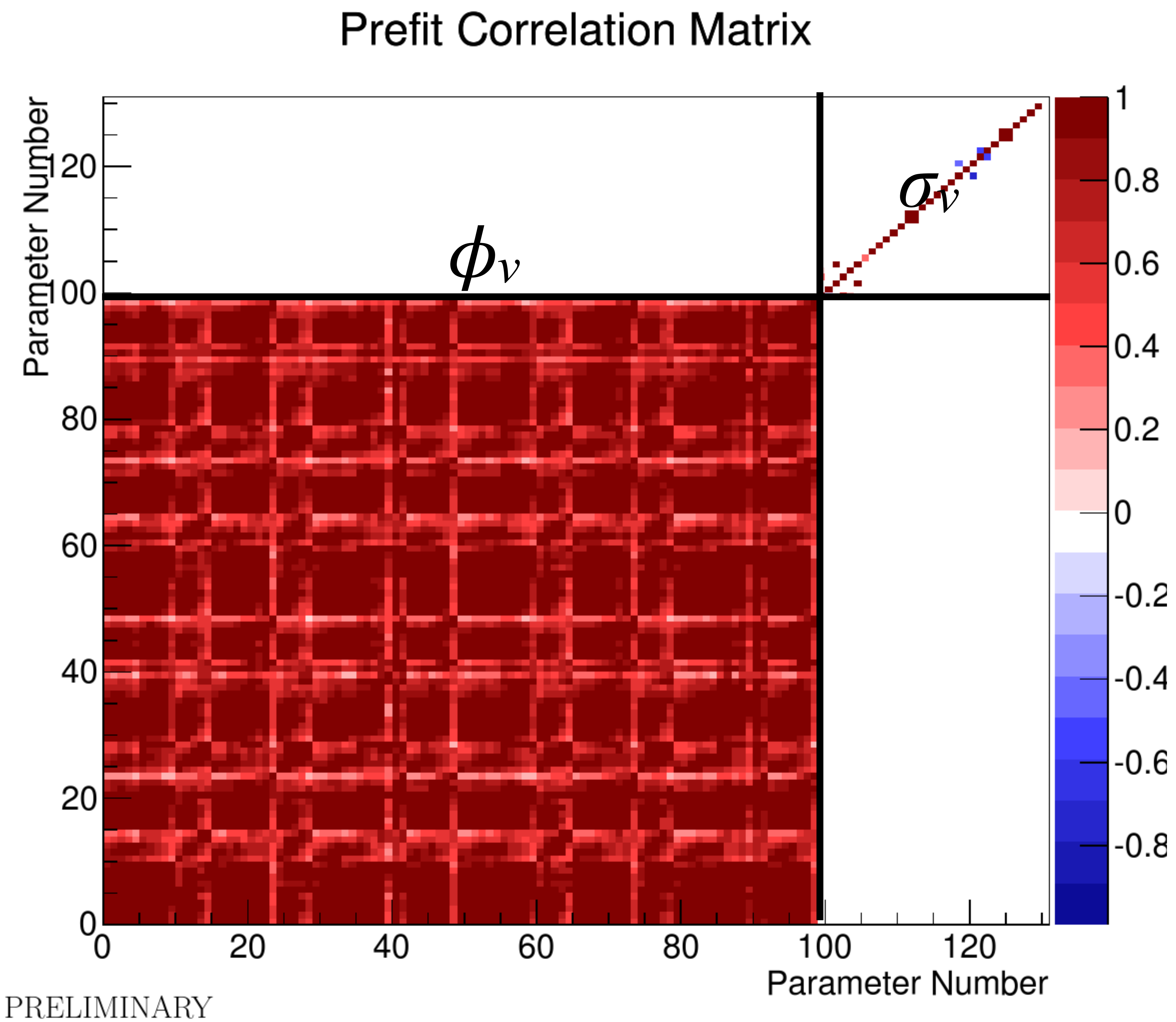




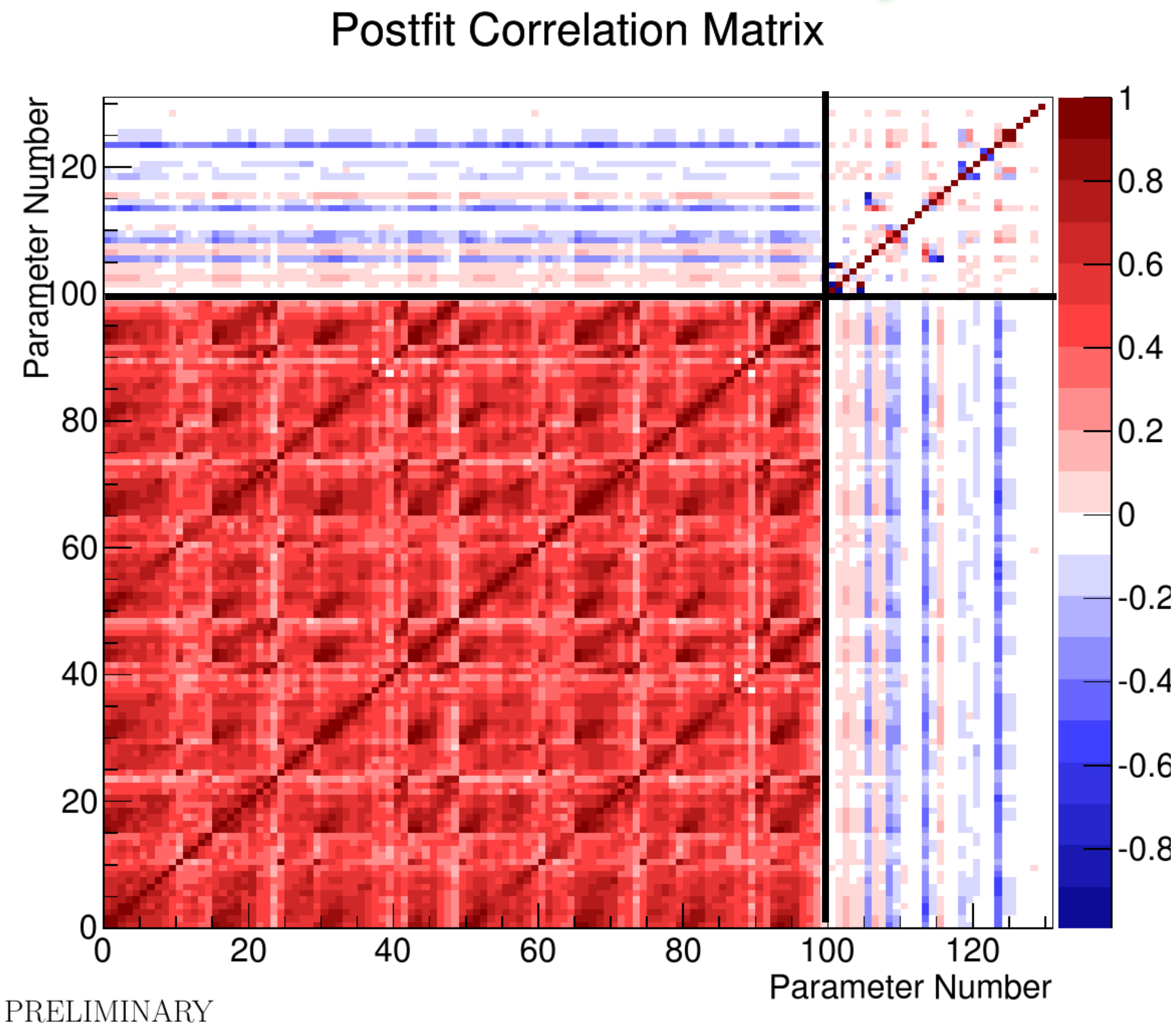


- Flux parameters generally have improved constraint
- Key "CCQE" parameters are fit with no constraints
- Additional ad hoc uncertainties where we consider the model variations to be insufficient to capture uncertainty

CORRELATION MATRIX



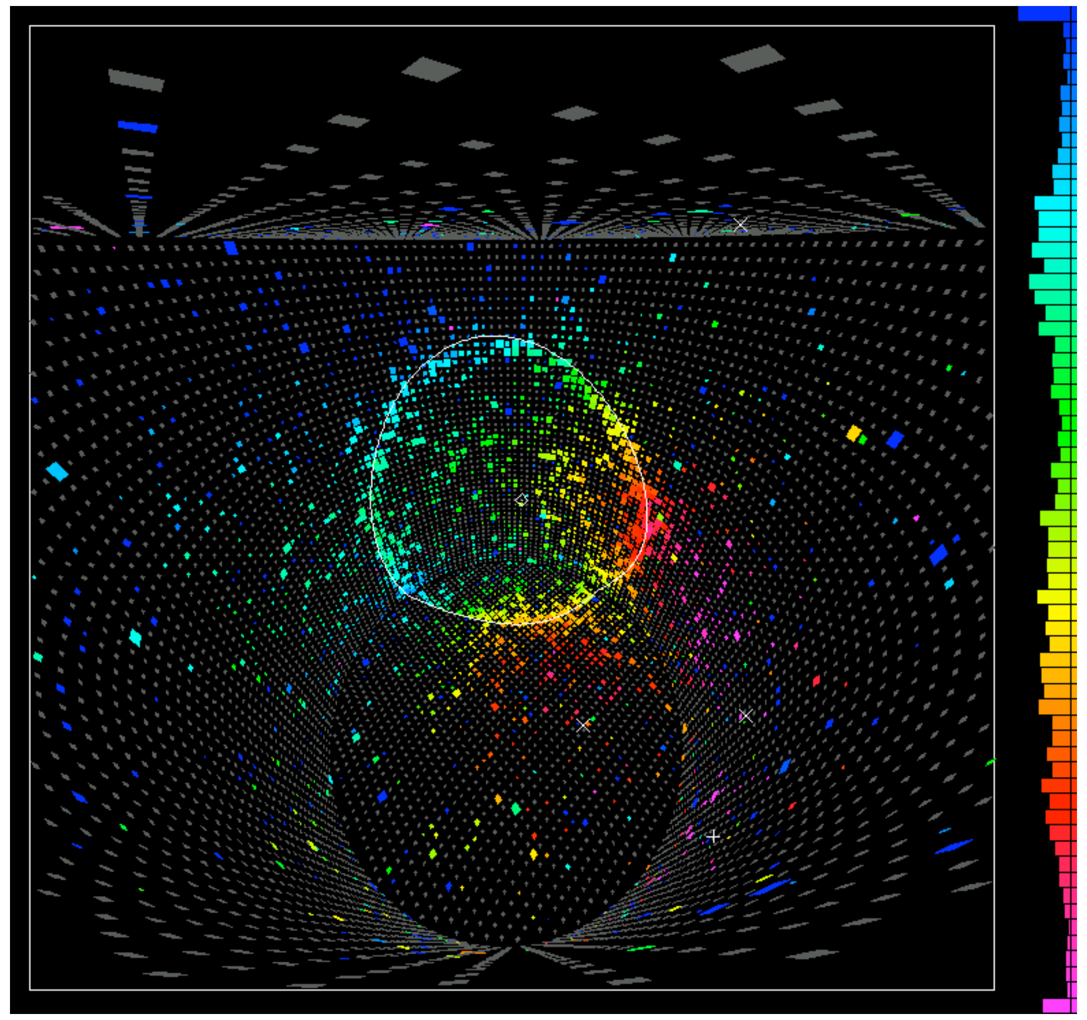
PRELIMINARY

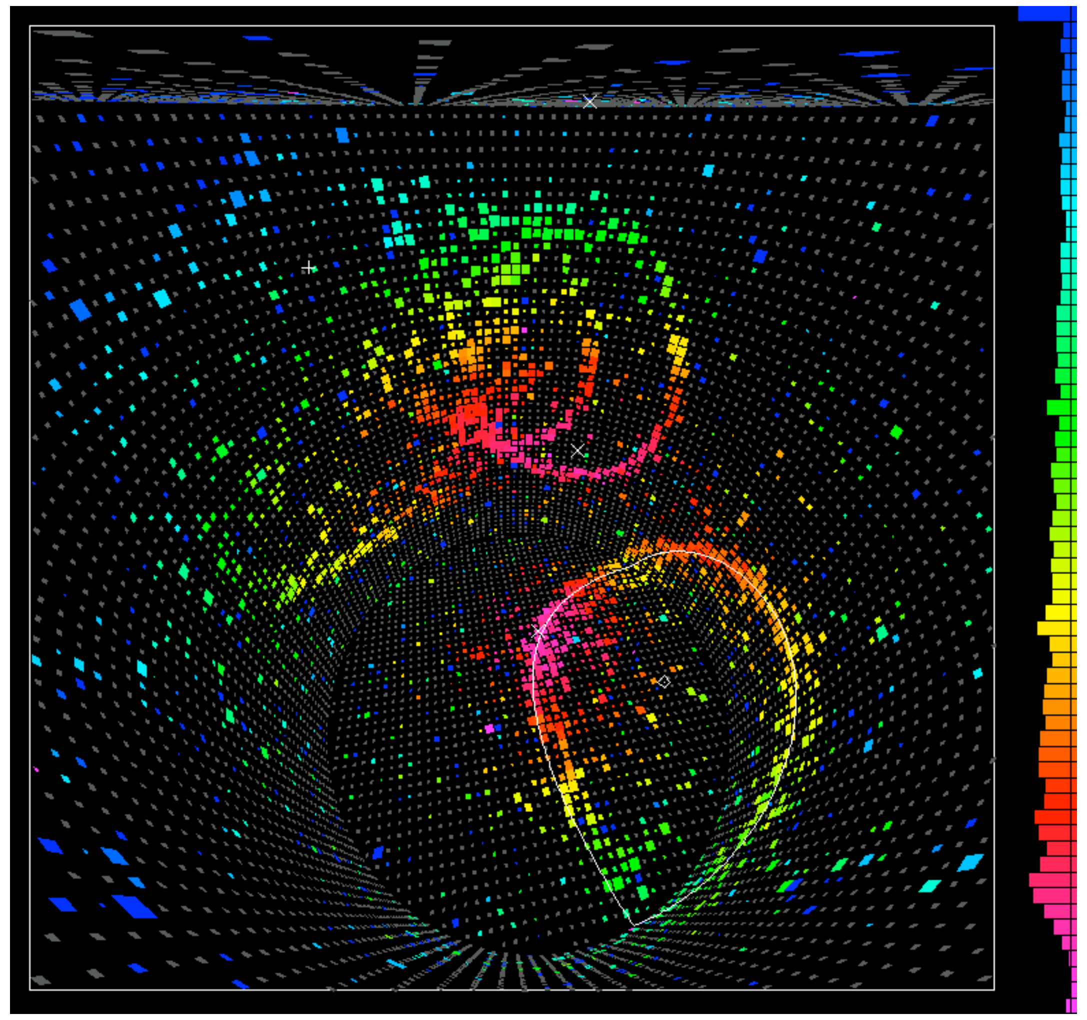


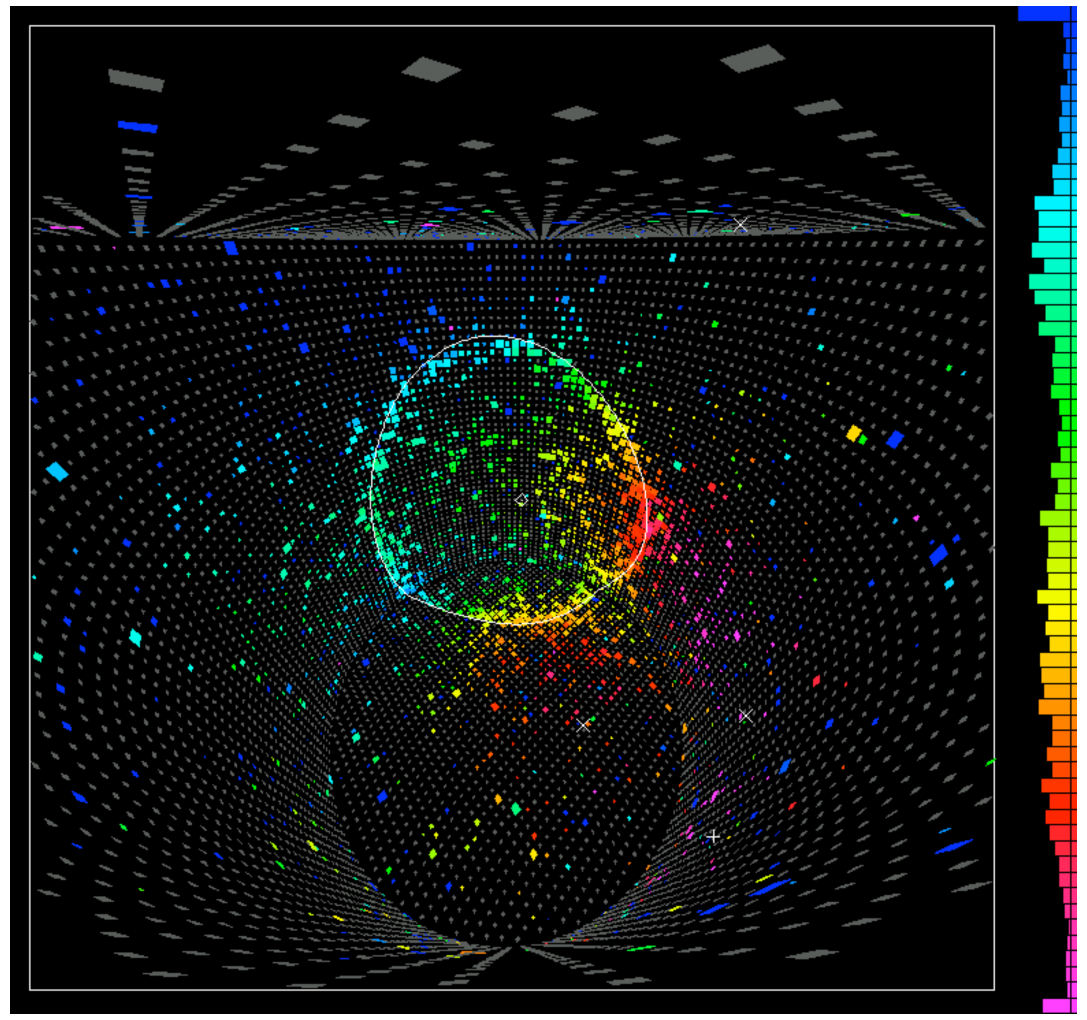
PRELIMINARY

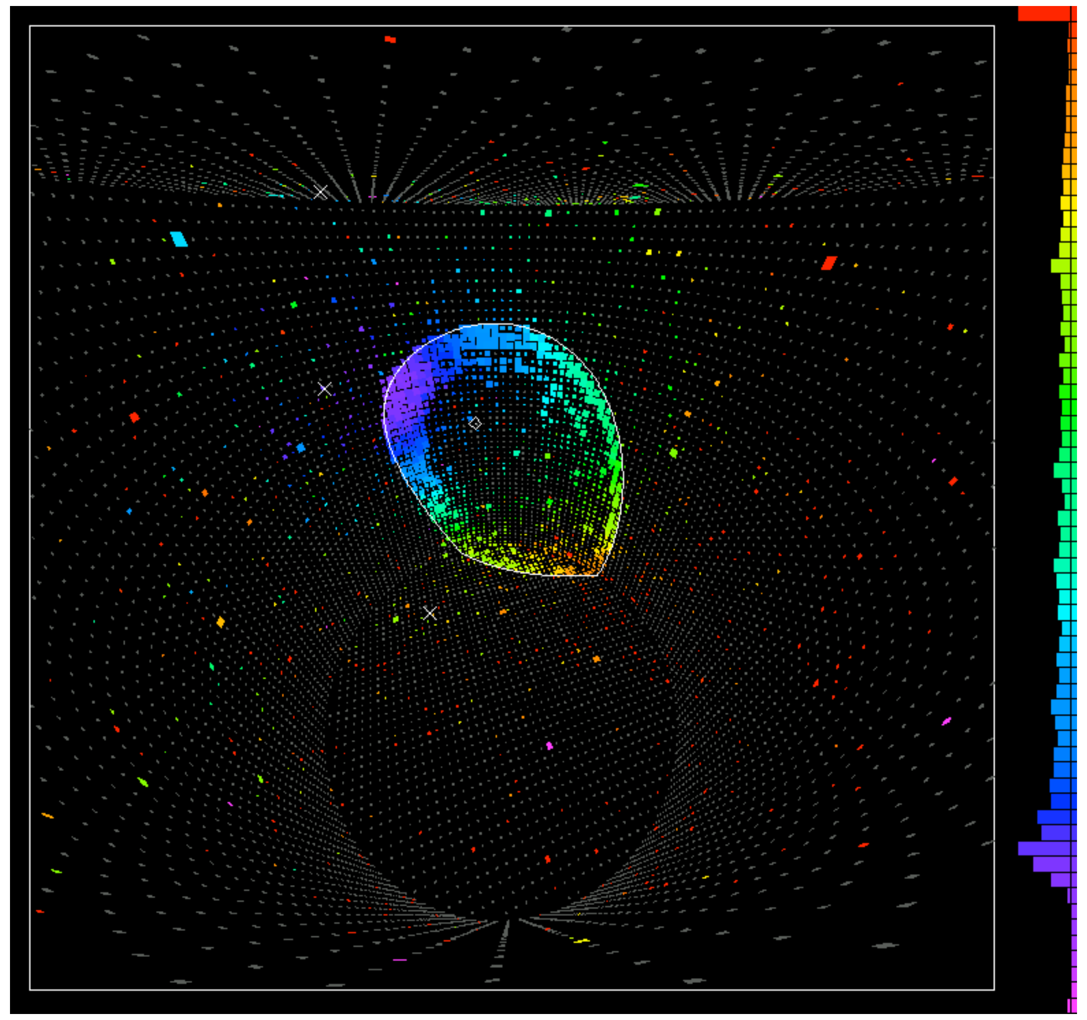
- Correlations introduced between flux and cross section parameters
- Generally anticorrelations → reduces variation in observed neutrino interactions

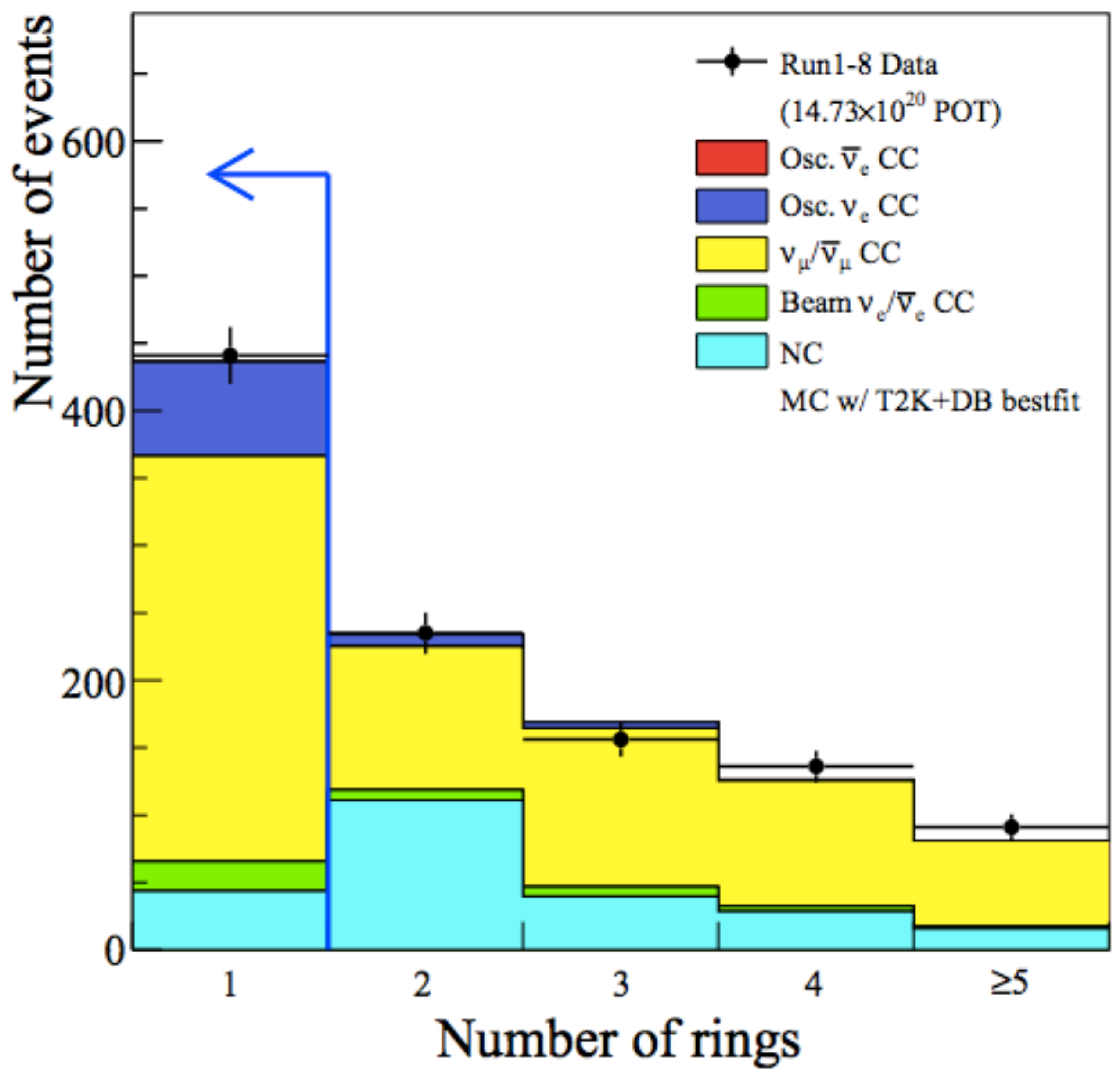
T2K SELECTION SCHEME (SIMPLIFIED)





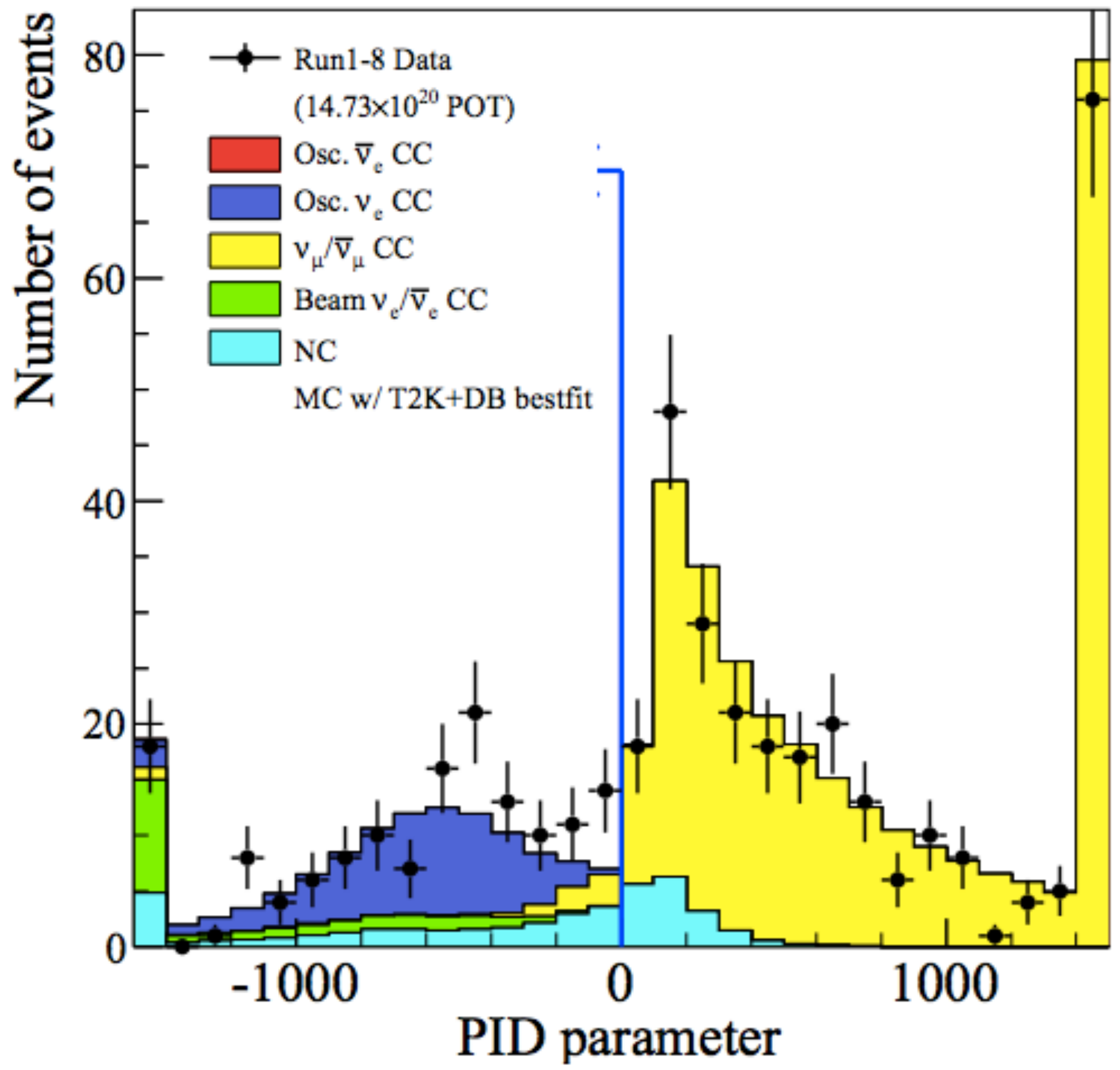




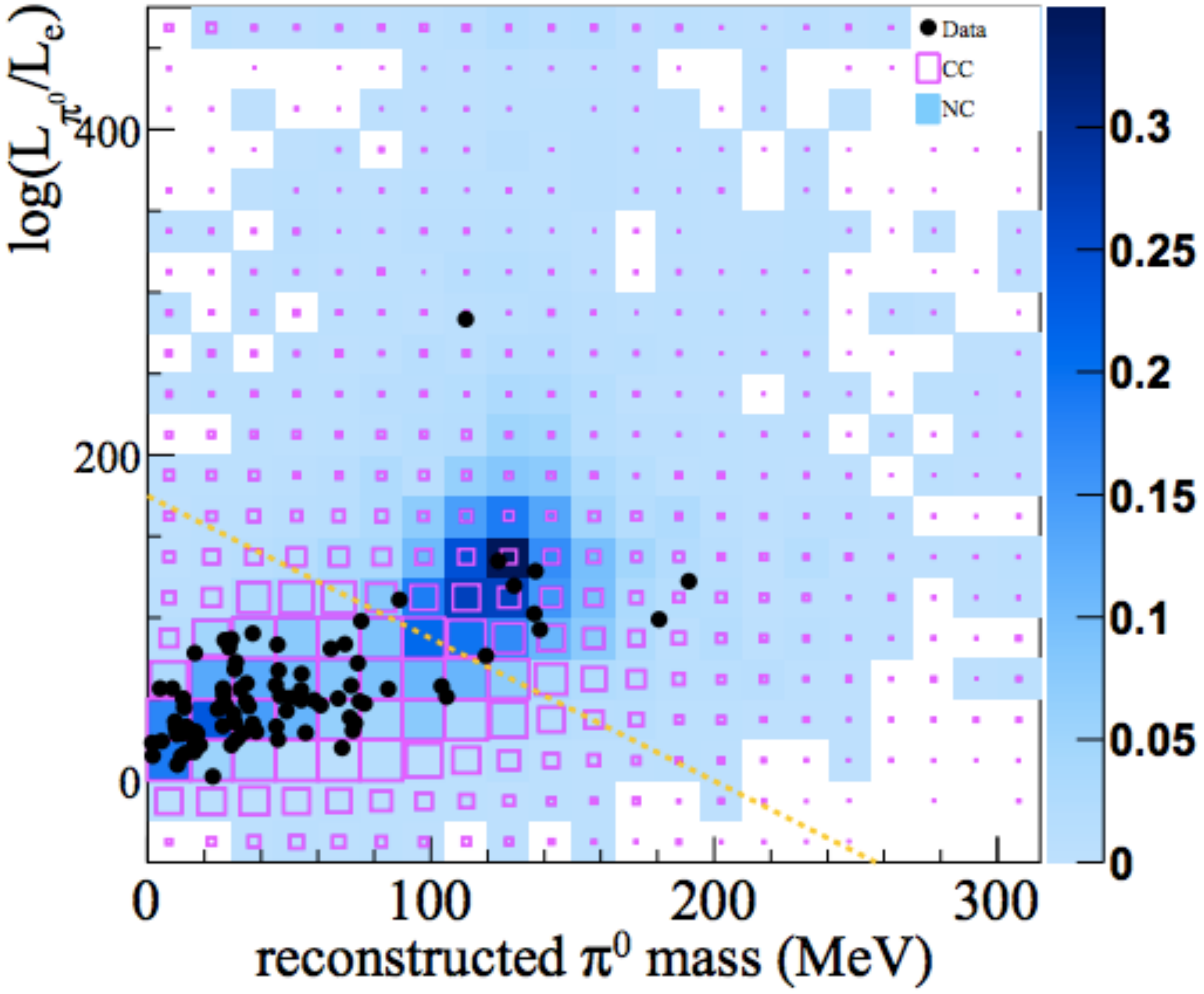


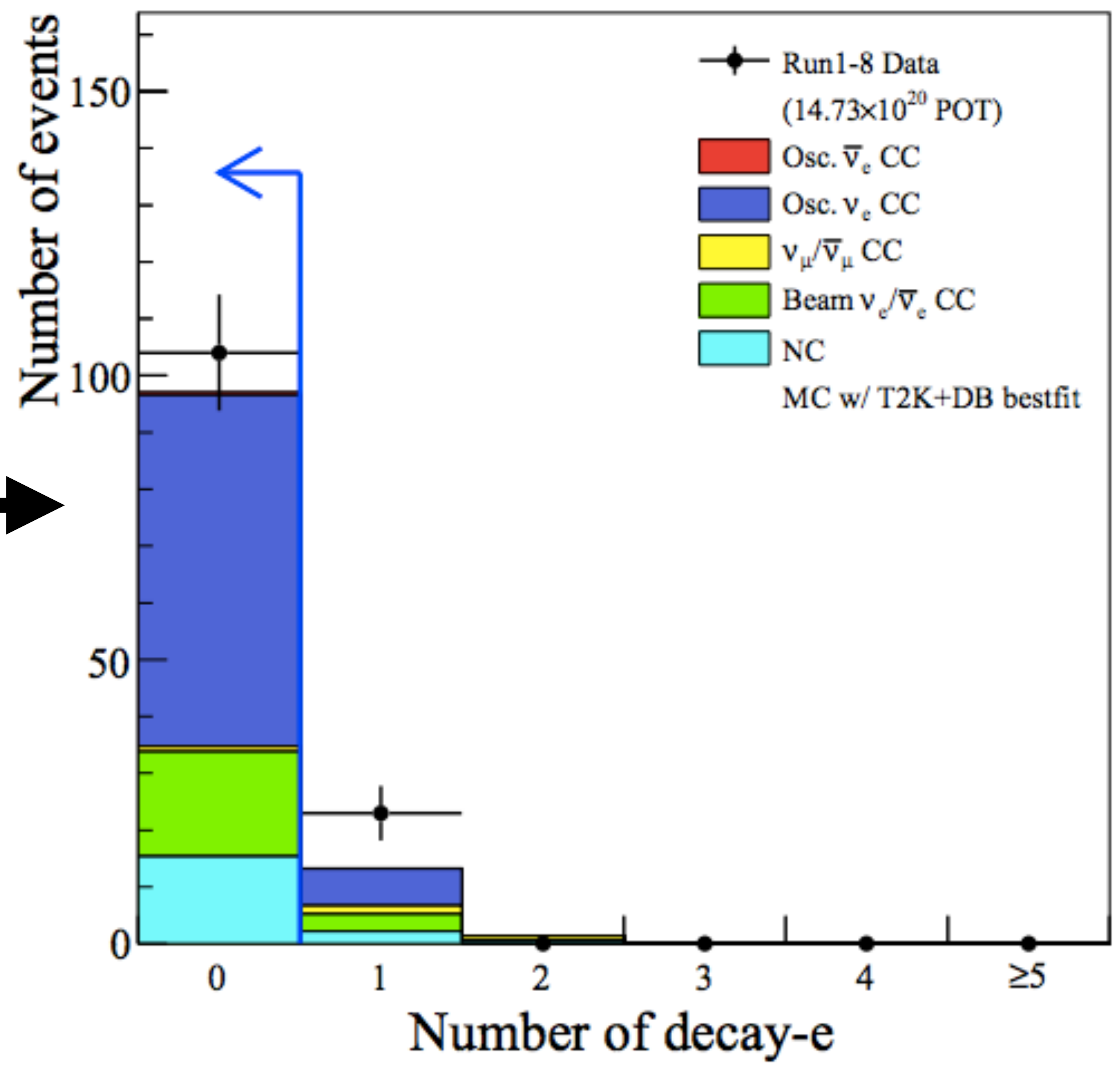
1 ring

e-like



T2K SELECTION SCHEME (CONTINUED





Additional π^0 rejection

- compare 2 ring to 1 ring assumption
- invariant mass of $\gamma\,\gamma$

Decay Electrons

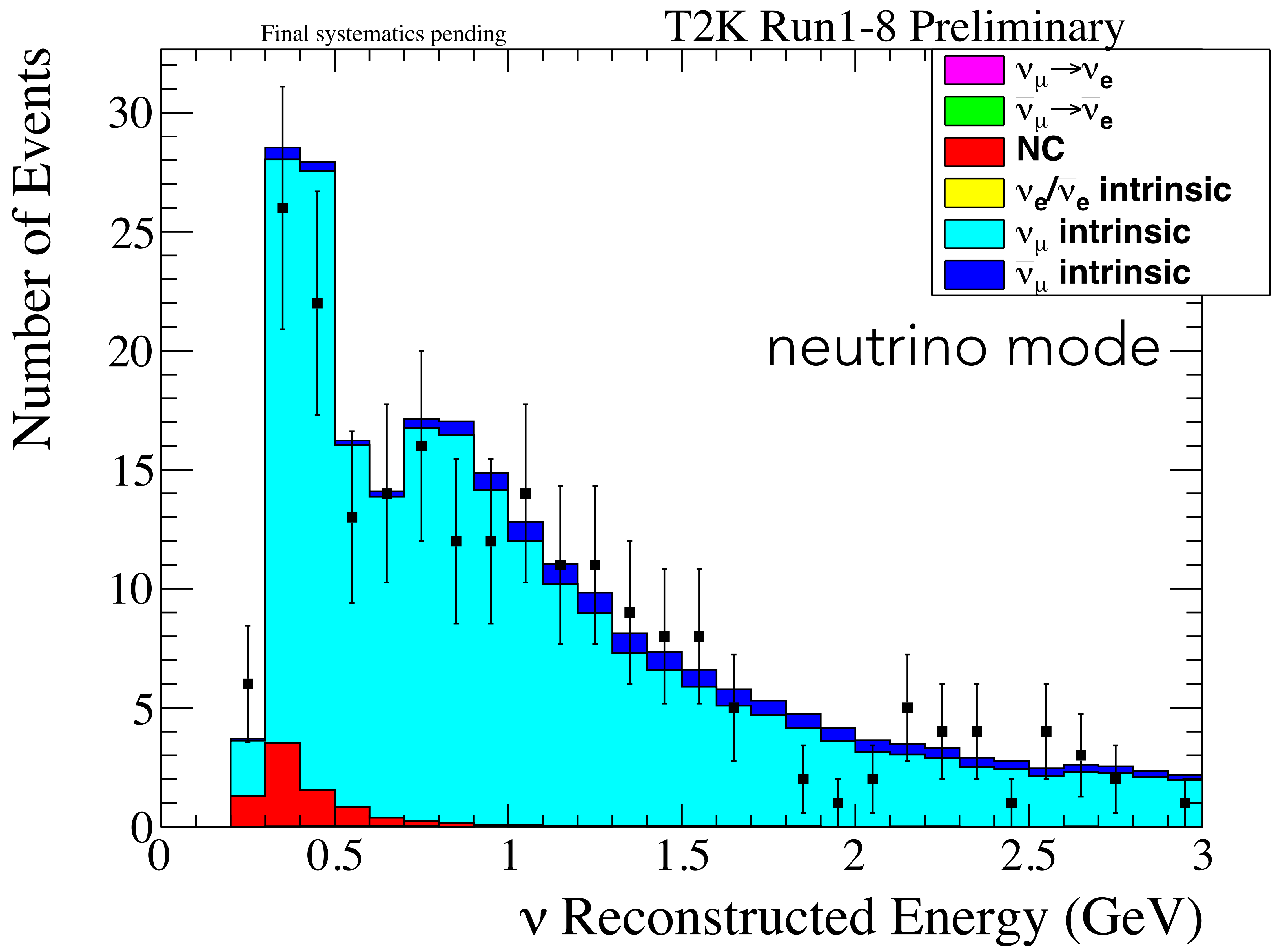
- ν-mode
  - Separate 0 and 1 decay electron ($\pi^+ \rightarrow \mu^+ \rightarrow e^+$)
- $\bar{\nu}$-mode
  - only 0 decay electron

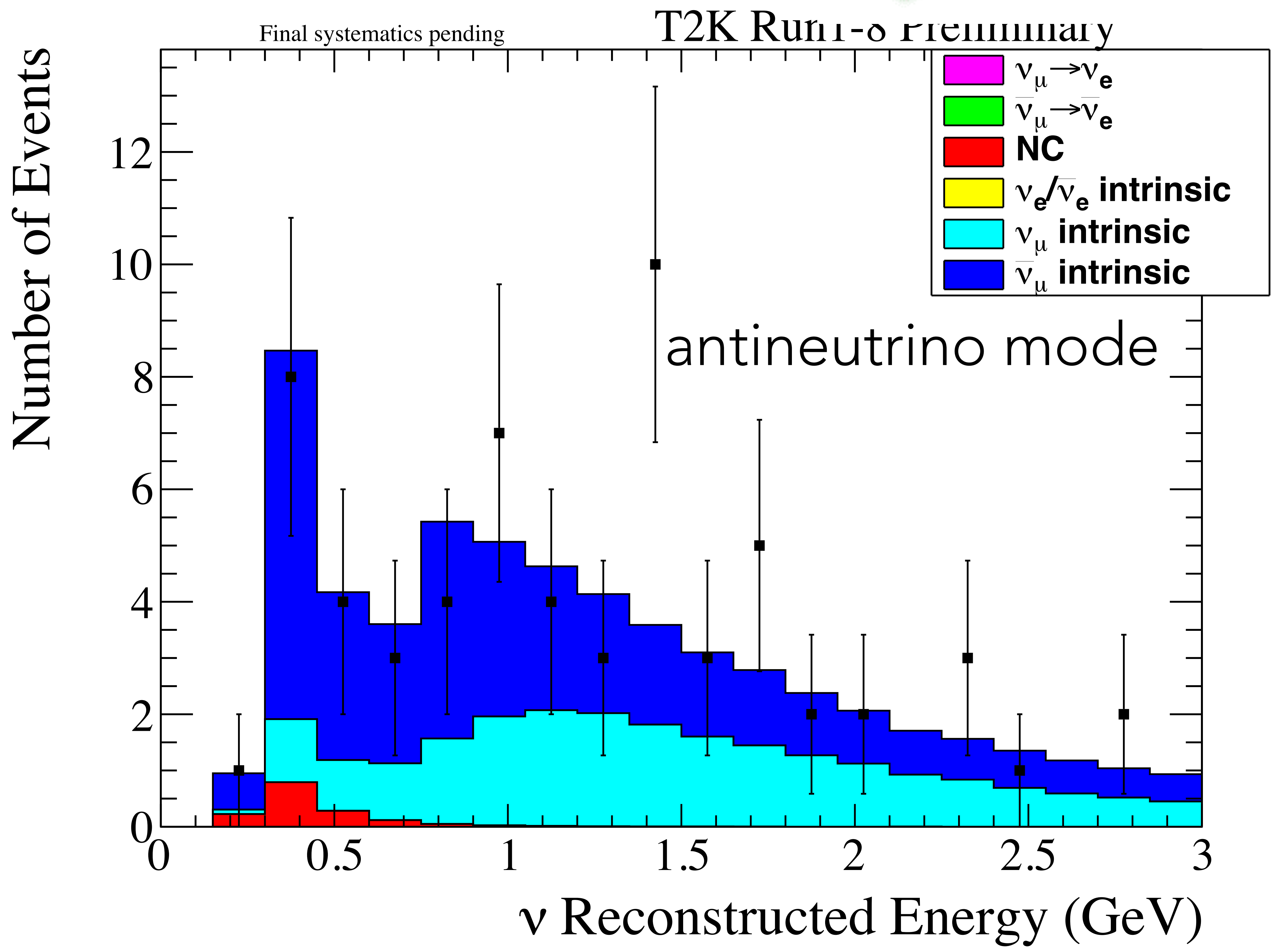
- Five samples:
  - ***ν*-mode**
    - 1Rμ (0,1 decay electron)
    - 1Re 0 decay electron
    - 1Re 1 decay electron
  - ***ν*-mode**
    - 1Rμ (0,1 decay electron)
    - 1Re 0 decay electron

$$\nu_\ell + n \rightarrow \ell + p$$

$$\nu_\ell + p \rightarrow \ell + p + \pi^+$$

T2K ν_μ EVENTS

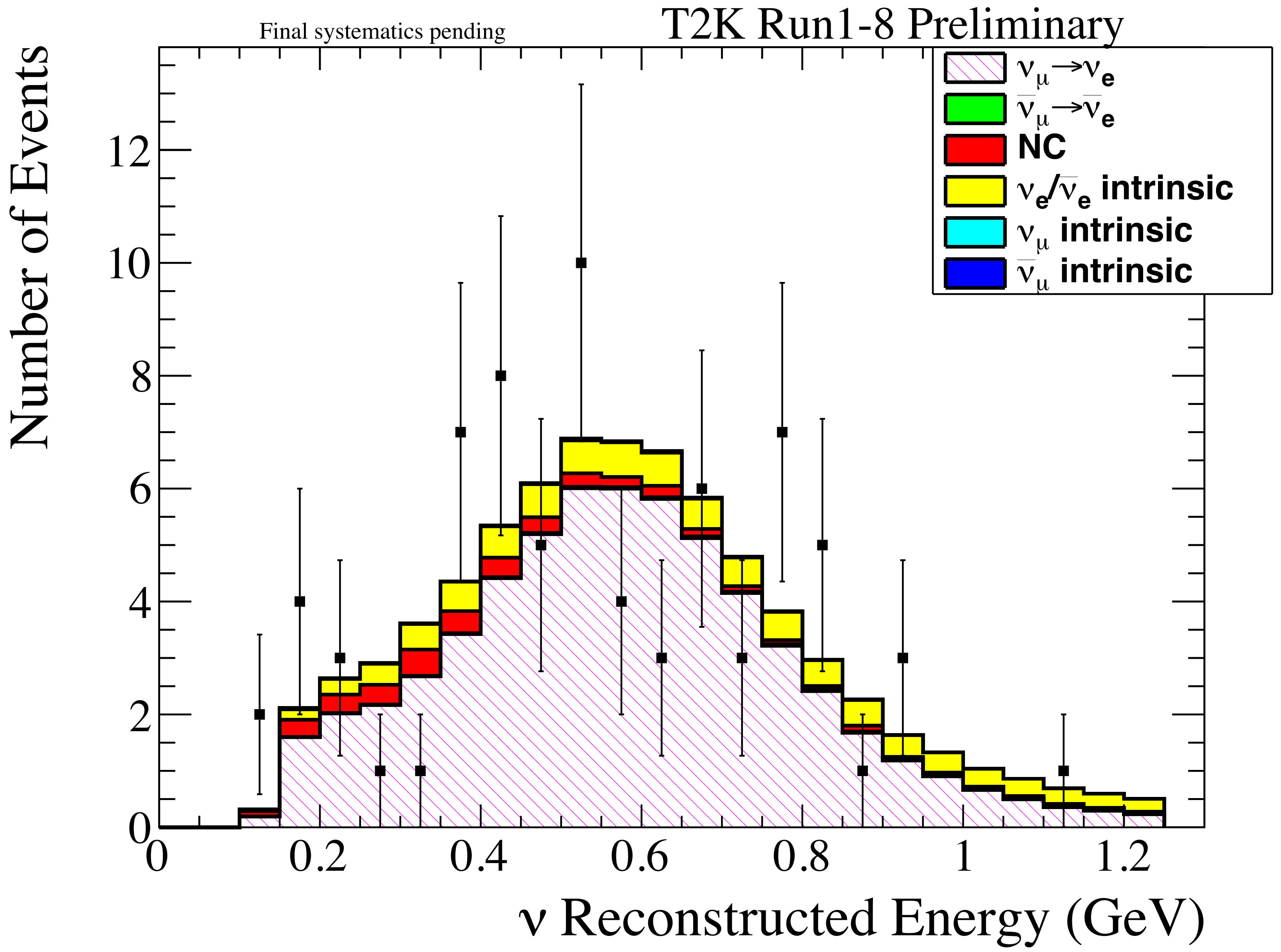




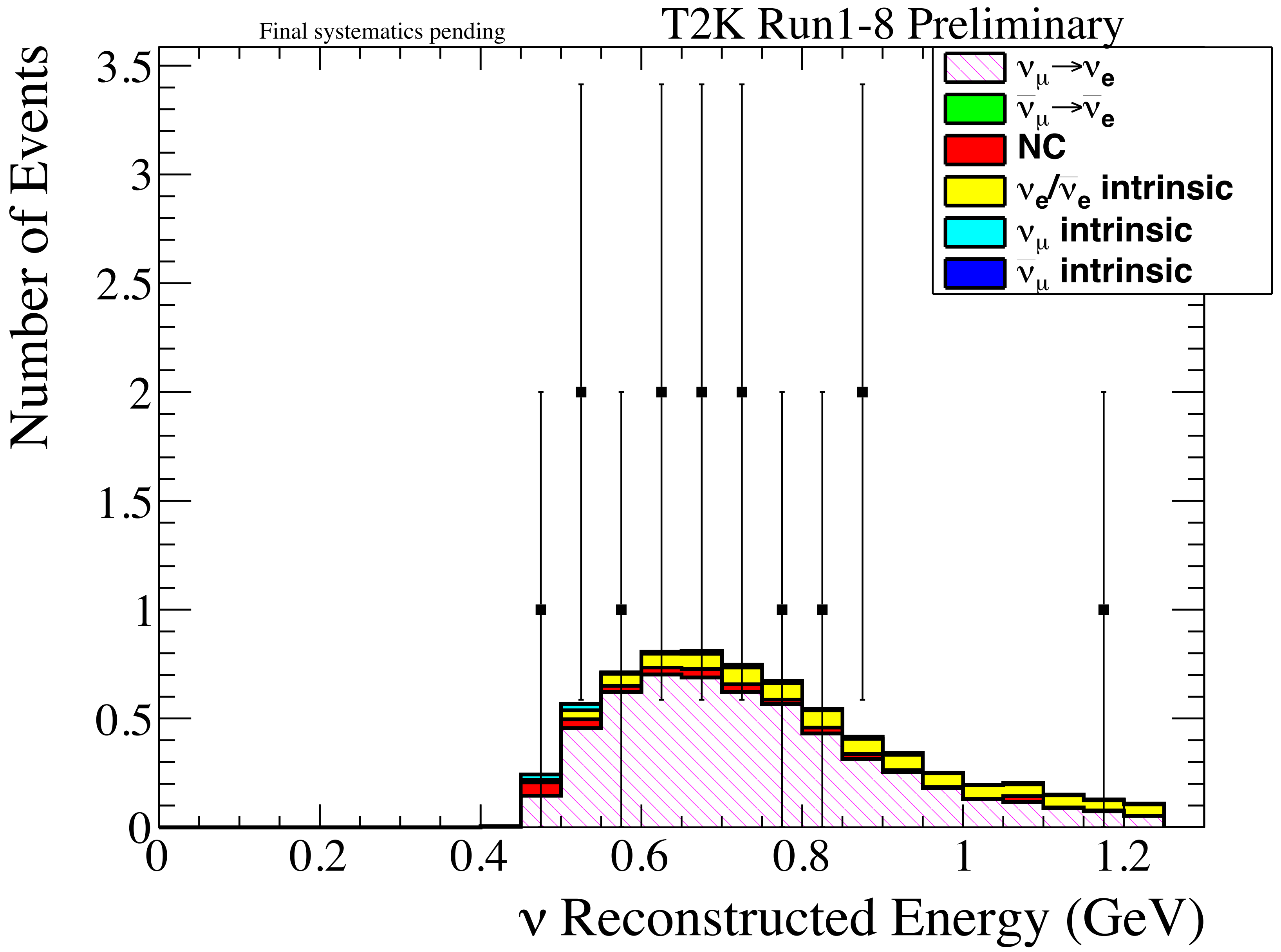
- 1Rμ ($\nu_\mu / \overline{\nu}_\mu$ candidates) observed in the SK detector

$$P(\nu_\mu \to \nu_\mu) \sim 1 - \left(\cos^4\theta_{13}\sin^2 2\theta_{23} + \sin^2 2\theta_{13}\sin^2\theta_{23}\right)\sin^2\Delta m^2_{31}\frac{L}{4E}$$

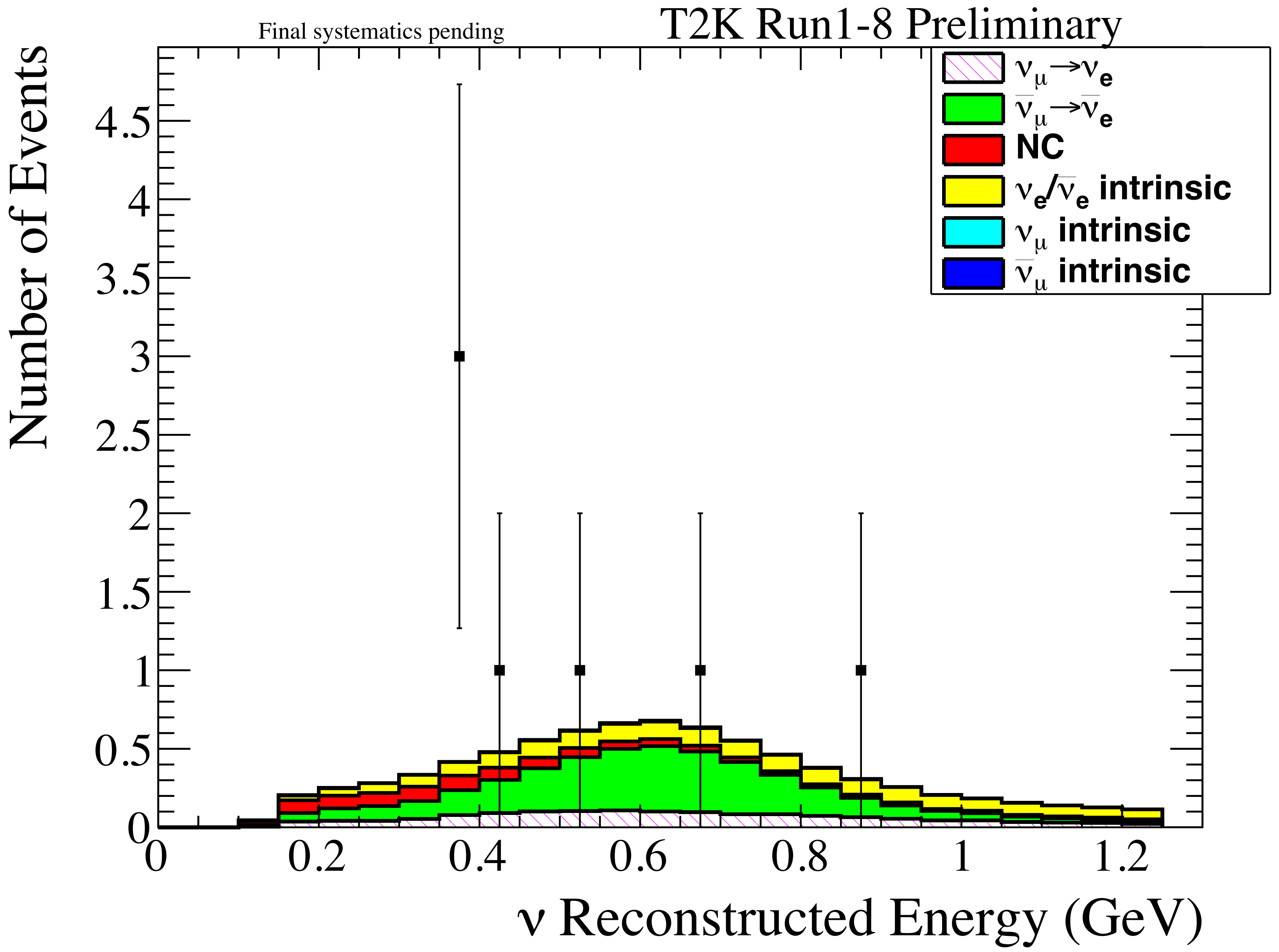
T2K ν_e EVENTS



ν-mode 1Re, 0 d.e.



ν-mode 1Re, 1 d.e.



$\bar{\nu}$-mode 1Re, 0 d.e.

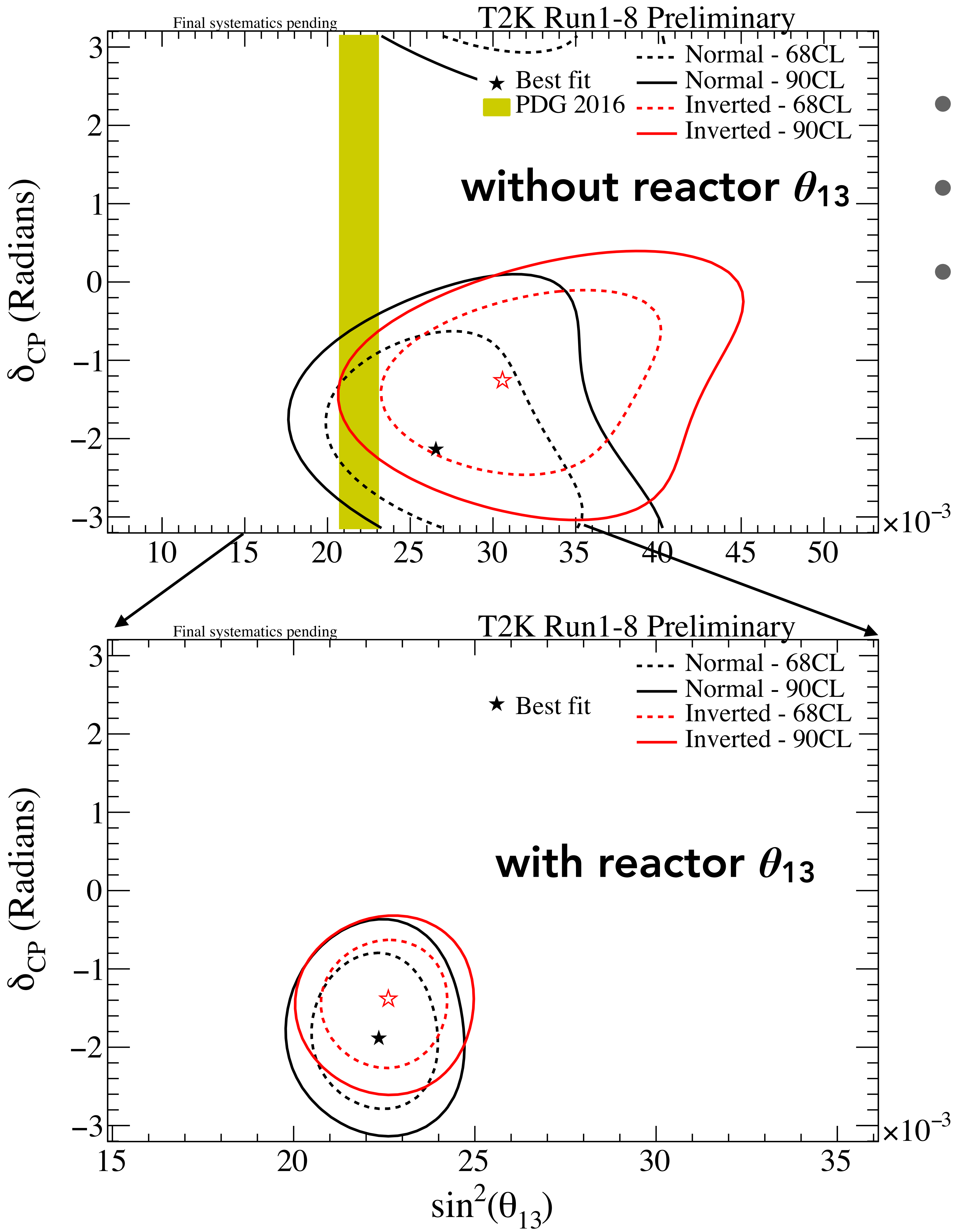
- 1Re (ν_e, $\bar{\nu}_e$) events observed in SK detector
  - 0 decay electron: targeting CCQE interactions
  - 1 decay electron: targeting CC1π^+ events where π^+ is below Cherenkov threshold

EVENT RATES

		$-\pi/2$	0	$+\pi/2$	π	OBS
ν mode	1Re 0 d.e.	**73.5**	61.4	49.9	61.9	**74**
	1Re 1 d.e.	**6.9**	6.0	4.9	5.8	**15**
$\bar{\nu}$ mode	1Re 0 d.e.	**7.9**	9.0	10.0	8.9	**7**
ν mode	1Rμ	**267.8**	267.4	267.7	268.2	**240**
$\bar{\nu}$ mode	1Rμ	**63.1**	62.9	63.1	63.1	**68**

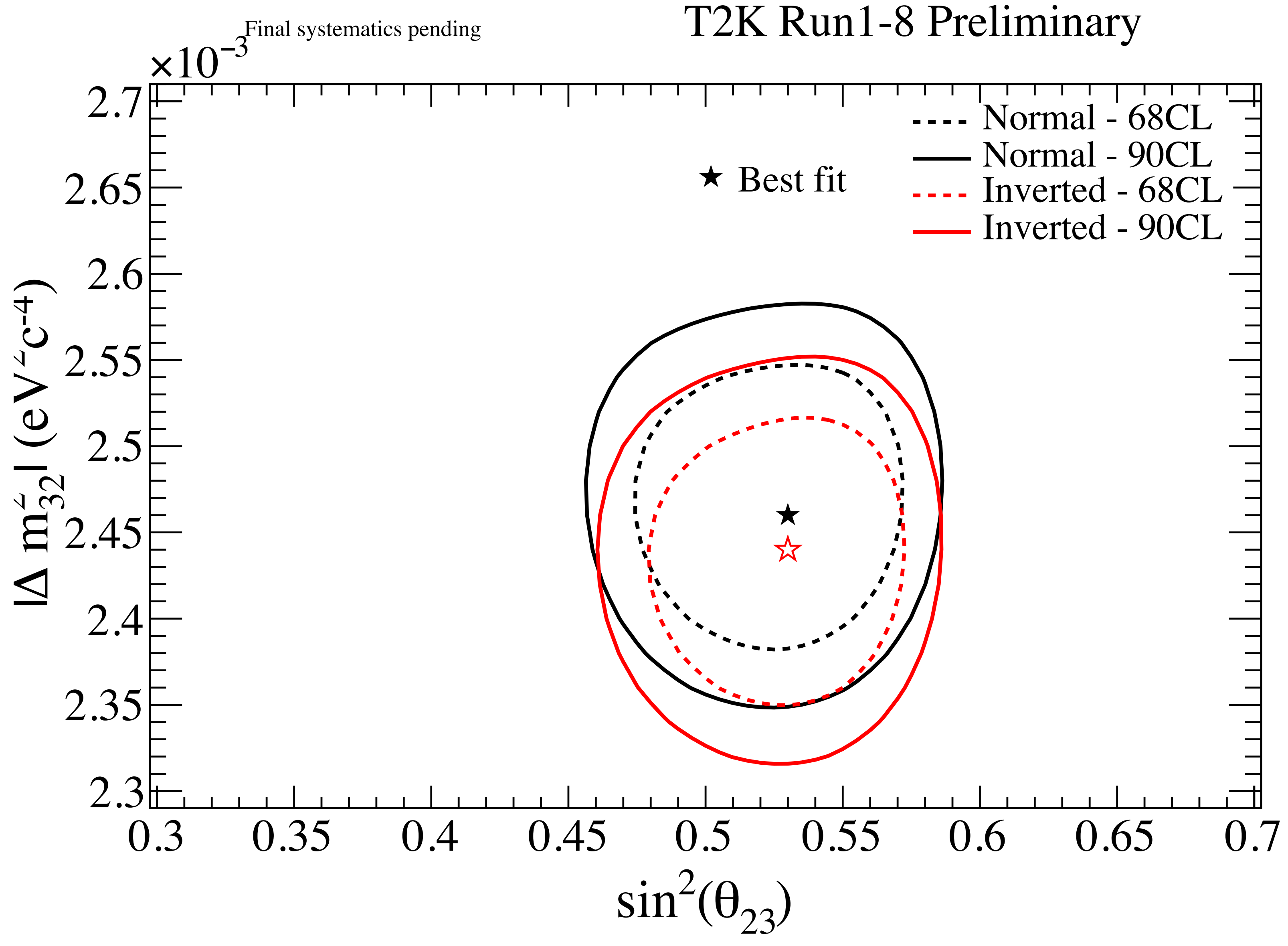
- ν_μ candidate prefer maximal disappearance
  - $\sin^2\theta_{23}$ ~0.5
- ν_e candidates favor large appearance in $\nu_\mu \rightarrow \nu_e$
  - normal hierarchy, δ_{CP} ~$-\pi/2$ ($+3\pi/2$)

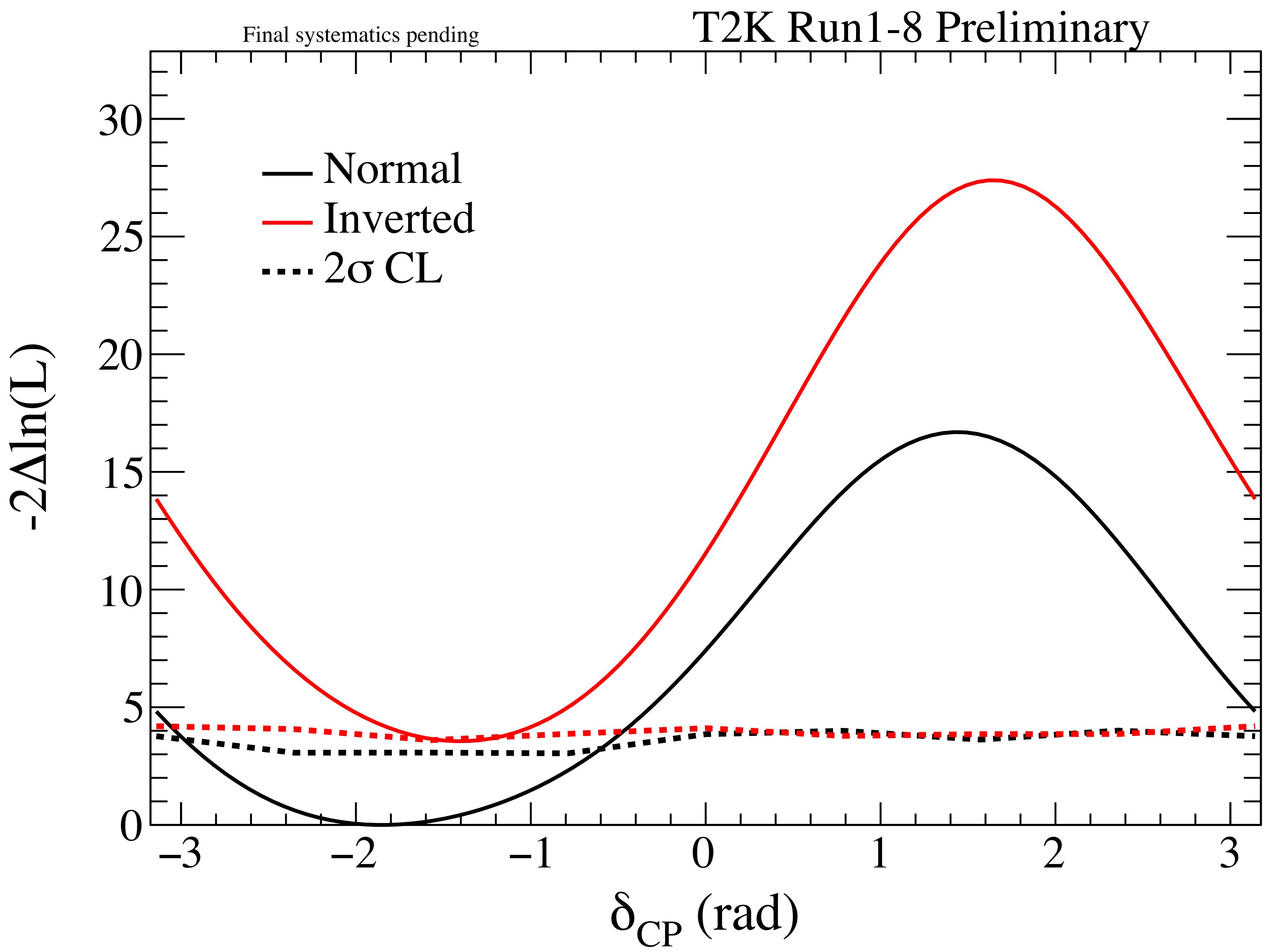
CONTOURS



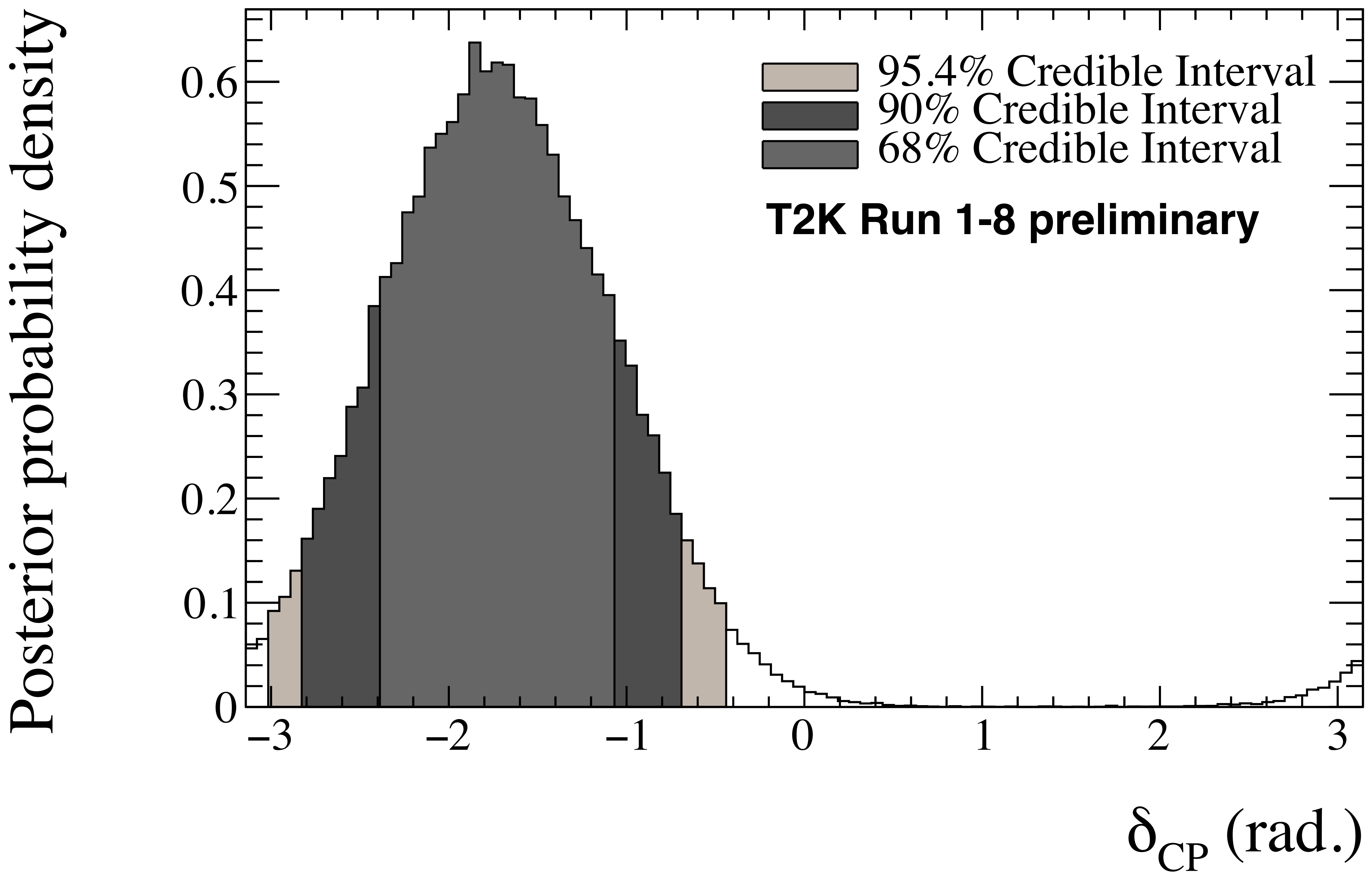
Fit procedure:

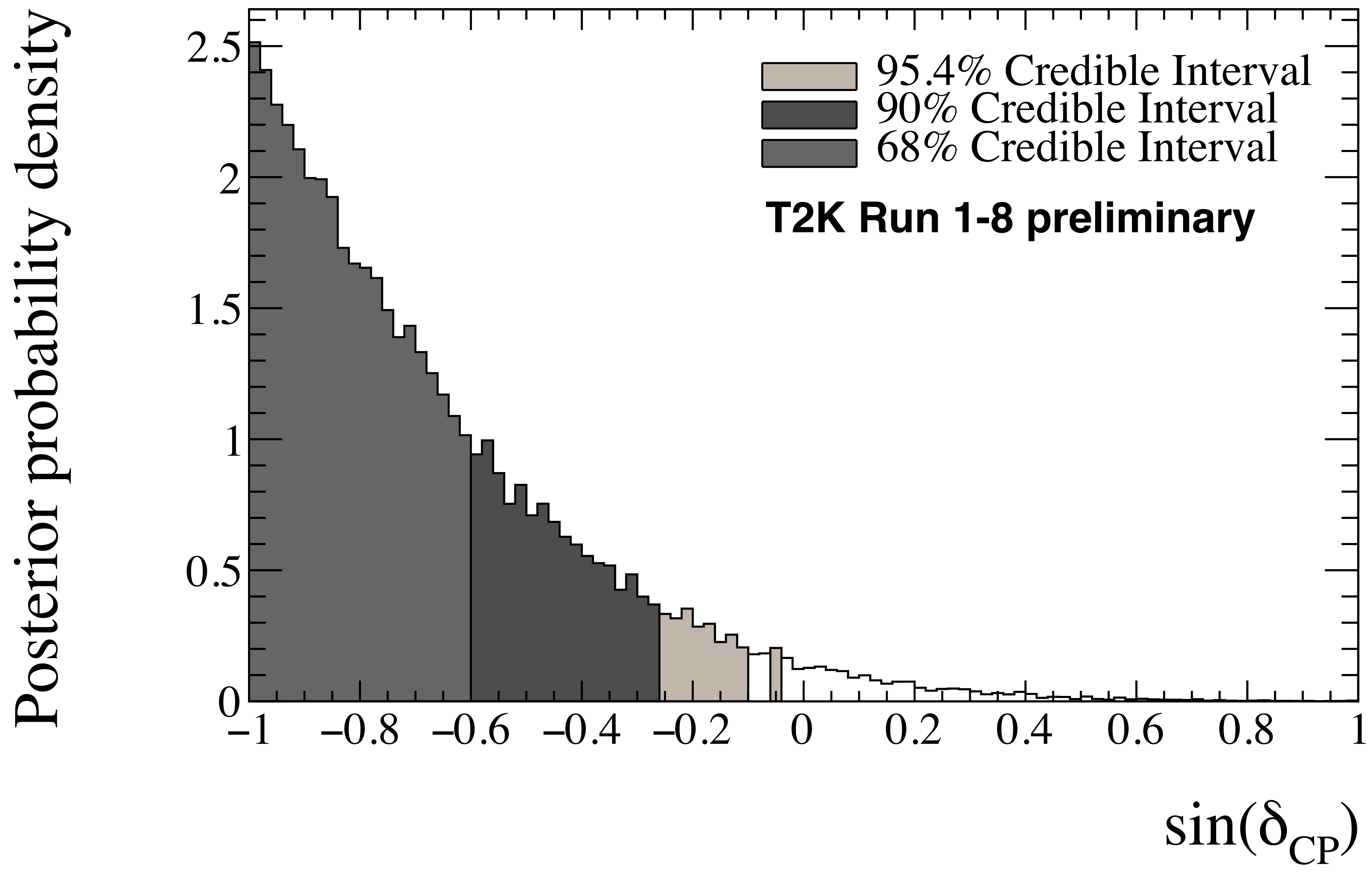
- Predict expected data distributions while varying oscillation parameters
- Calculate χ^2/likelihood between prediction and observed events
- Obtain best fit and allowed parameter space





T2K BAYESIAN ANALYSIS



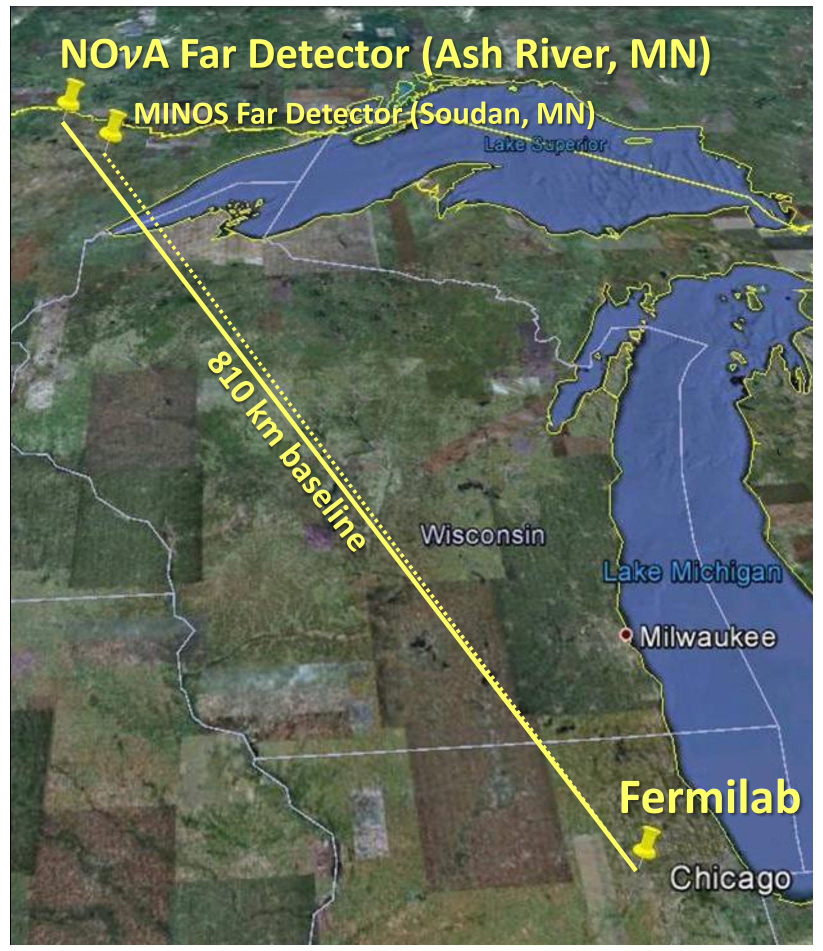


- Posterior probabilities based on Markov chain Monte Carlo
- δ_{CP}: two priors:
  - flat in δ_{CP}
  - flat in $\sin \delta_{CP}$ (amplitude of CP asymmetry)
- Weak preference for normal hierarchy, upper octant ($\sin^2\theta_{23} > 0.5$)

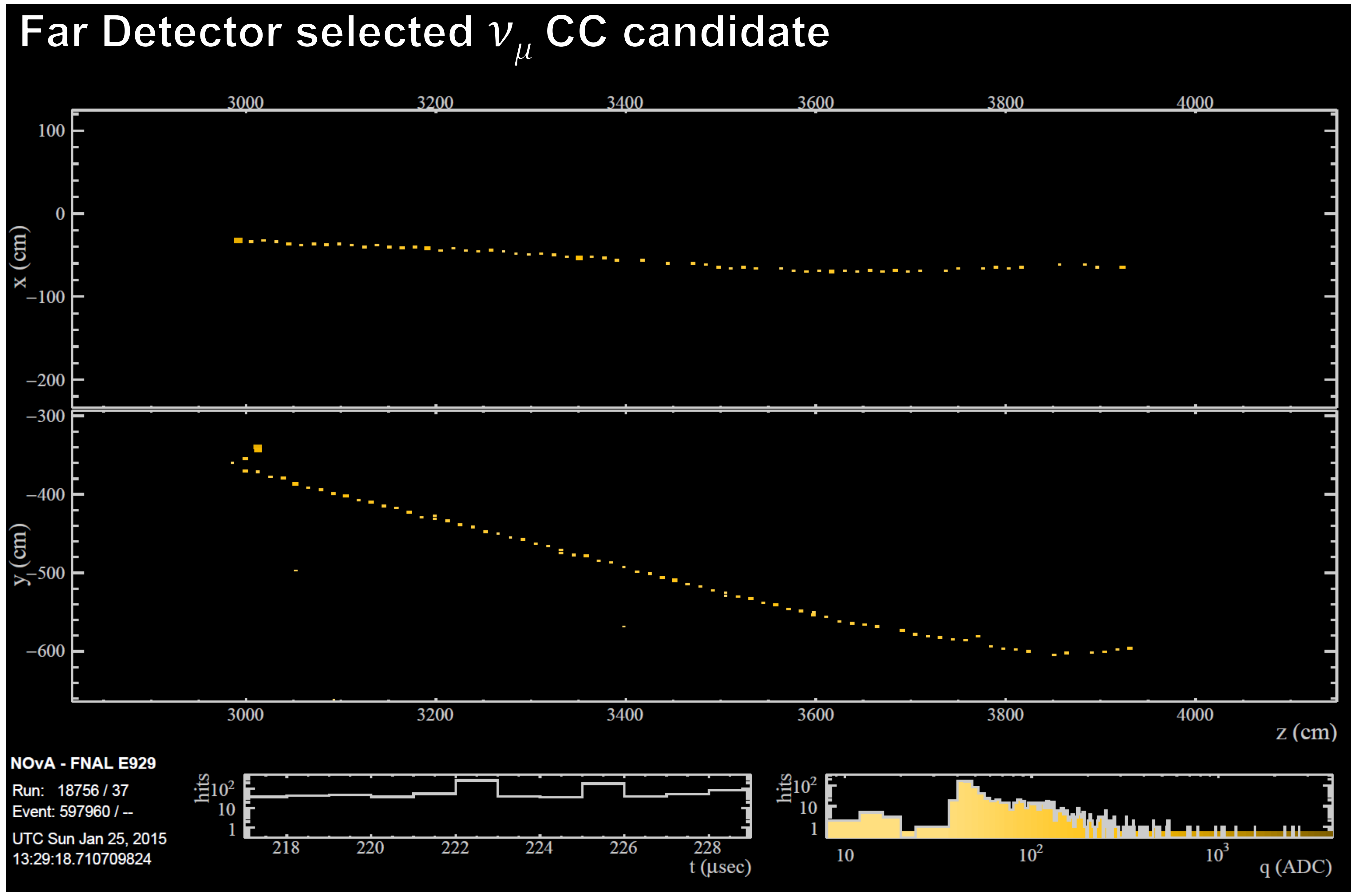
	NH	IH	SUM
$\sin^2\theta_{23} \leq 0.5$	0.214	0.022	0.236
$\sin^2\theta_{23} > 0.5$	0.668	0.096	0.764
SUM	0.882	0.118	1.000

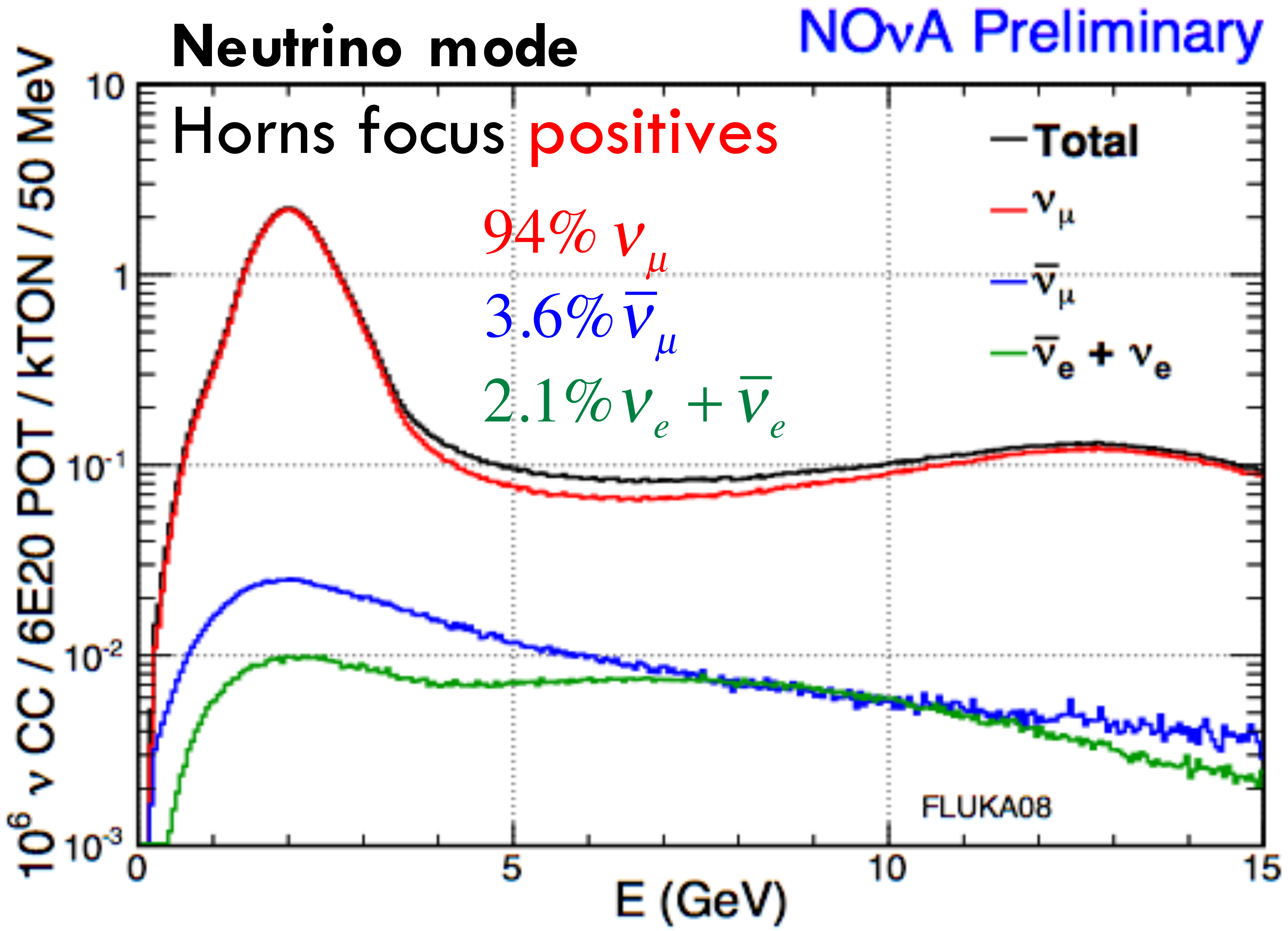
THE NOVA EXPERIMENT

NOvA:

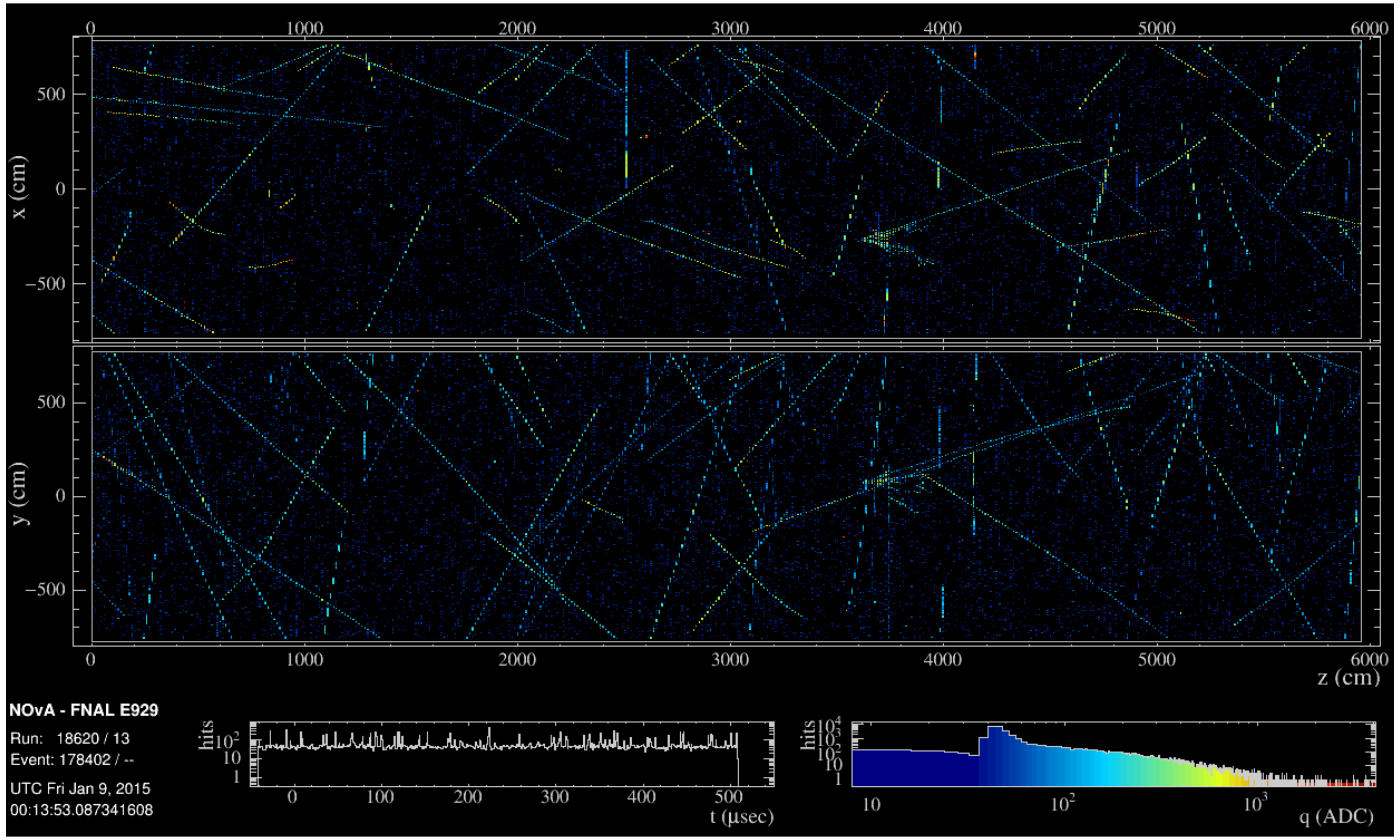


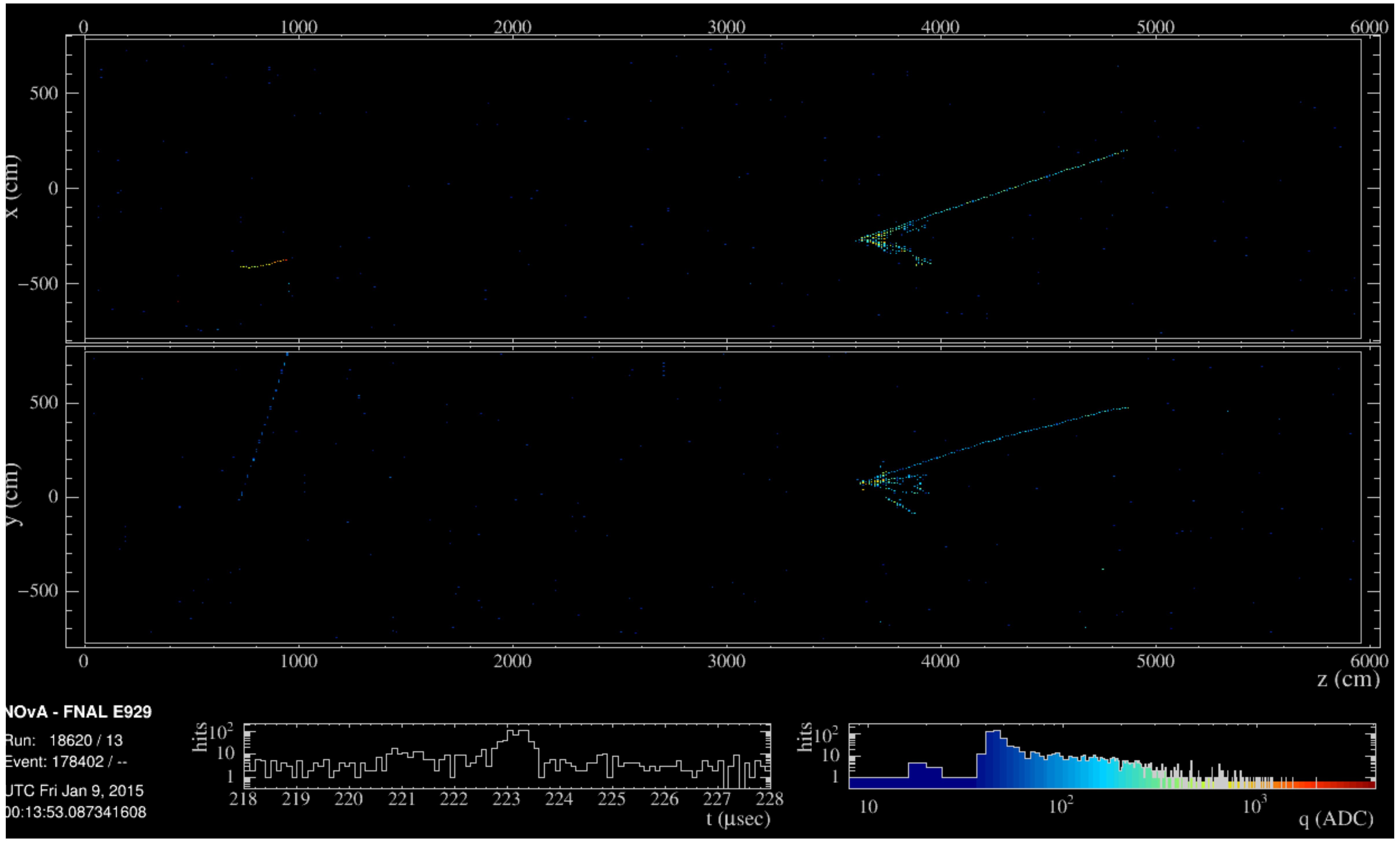
- Long baseline neutrino experiment from FNAL to Ash Hill with 810 km baseline
  - higher neutrino energy
  - larger matter effect, sensitivity to mass hierarchy
- 14kt fully active scintillating tracking detector





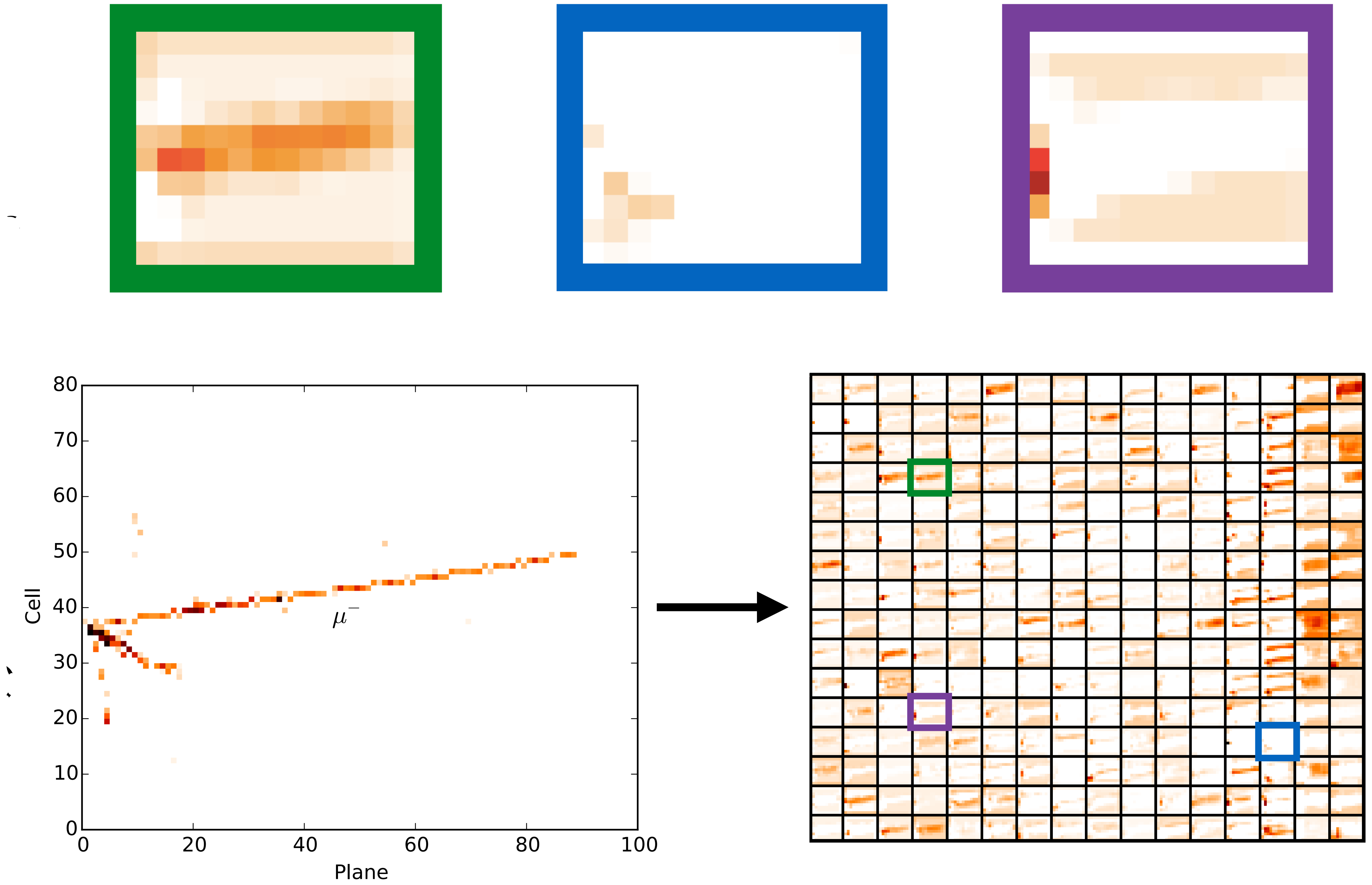
COSMIC BACKGROUND



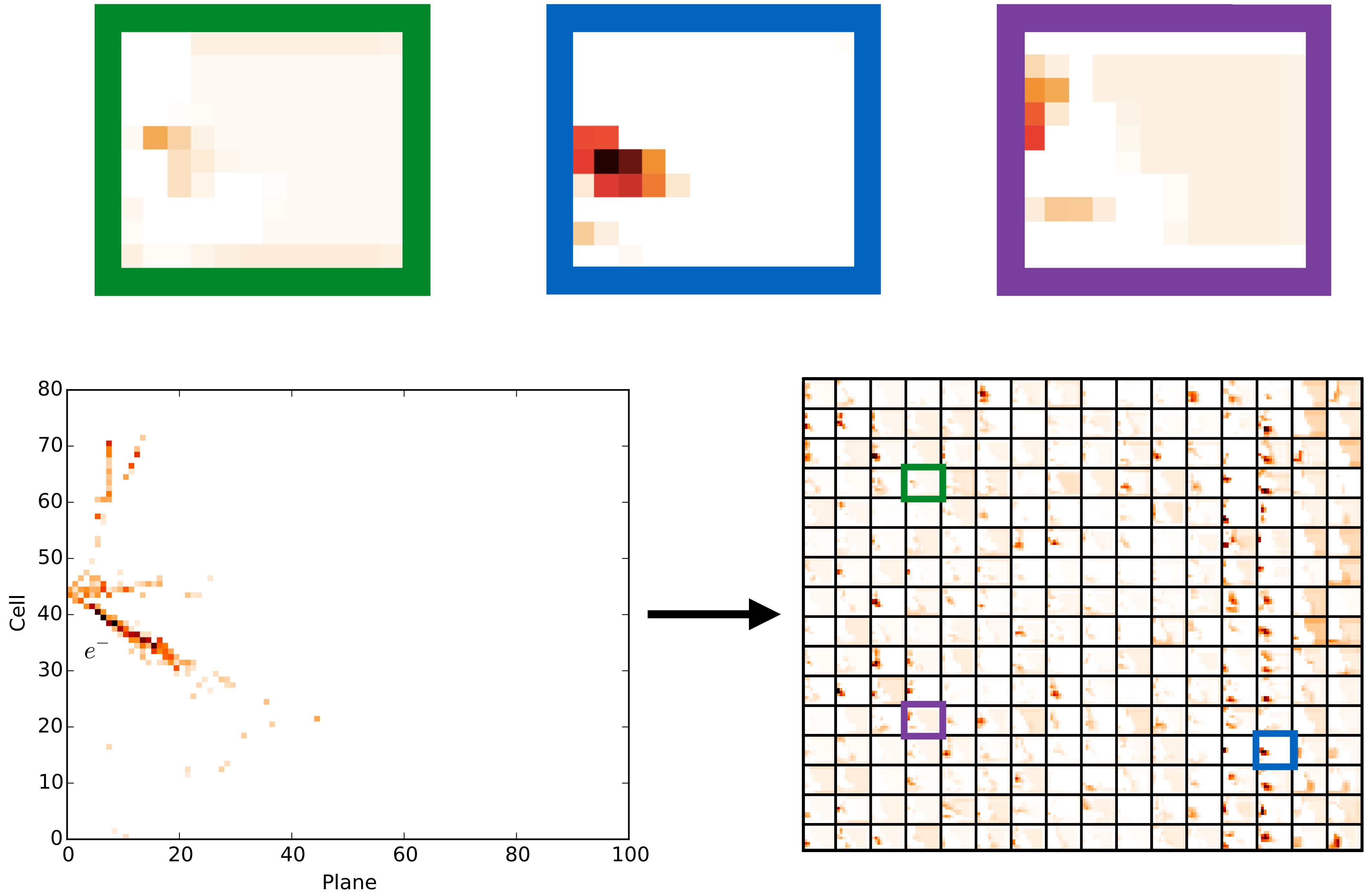


- Unlike Super-Kamiokande, the NOvA far detector is near the surface
    - large flux of cosmic rays passing through the detector
    - rejection of O($10^{7\text{-}8}$) is needed to bring reduce this background to manage level
        - a large part is achieved by the beam timing, but additional analysis is needed to achieve this
- Results with 8.85 x 10^{20} protons-on-target in neutrino mode
    - results with antineutrino mode data expected next week!

CONVOLUTIONAL NEURAL NETWORK

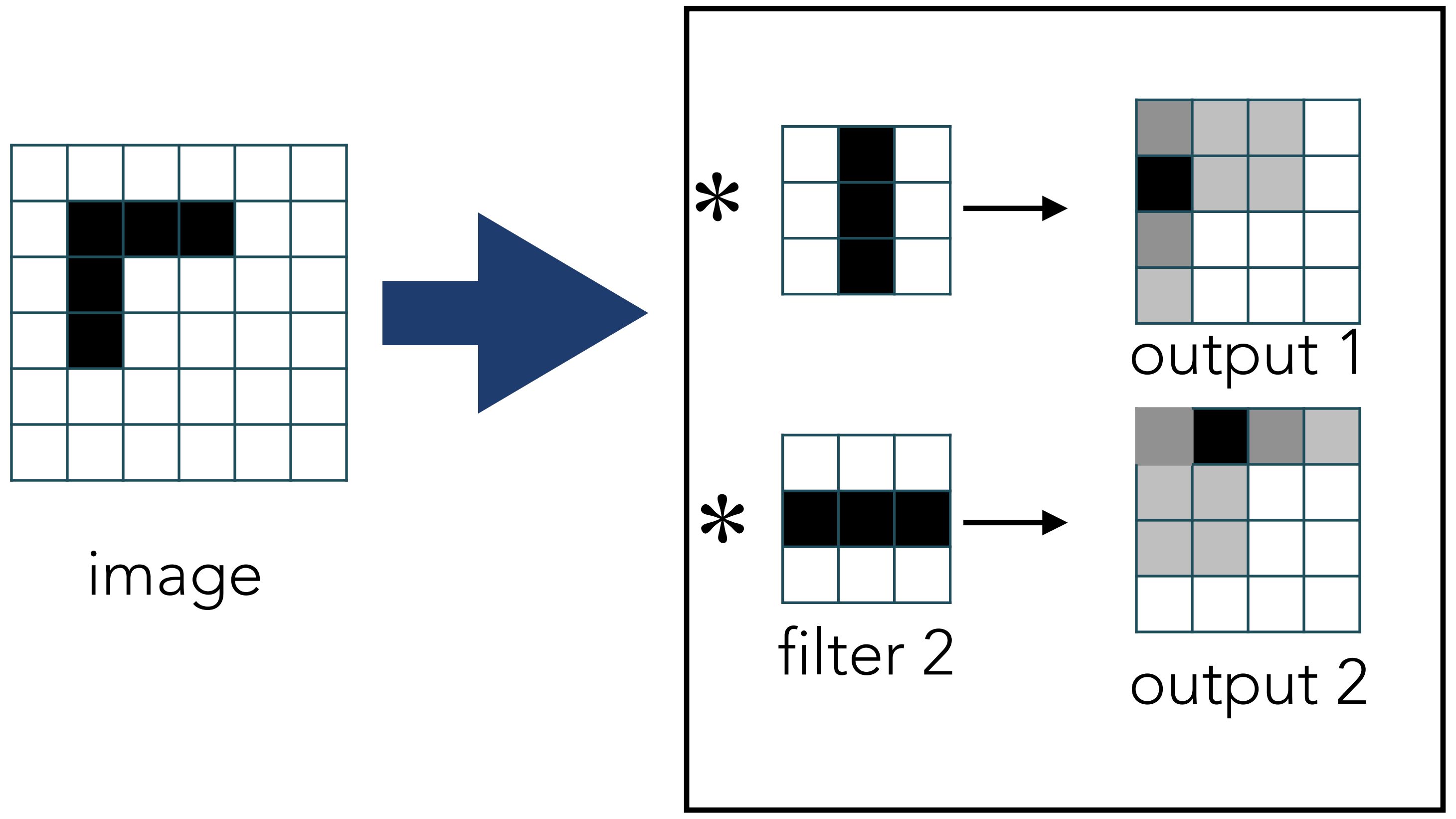


"A Convolutional Neural Network Neutrino Event Classifier"
A. Aurisano, A. Radovic, and D. Rocco et al
Journal of Instrumentation, Volume 11, September 2016



"A Convolutional Neural Network Neutrino Event Classifier"
A. Aurisano, A. Radovic, and D. Rocco et al
Journal of Instrumentation, Volume 11, September 2016

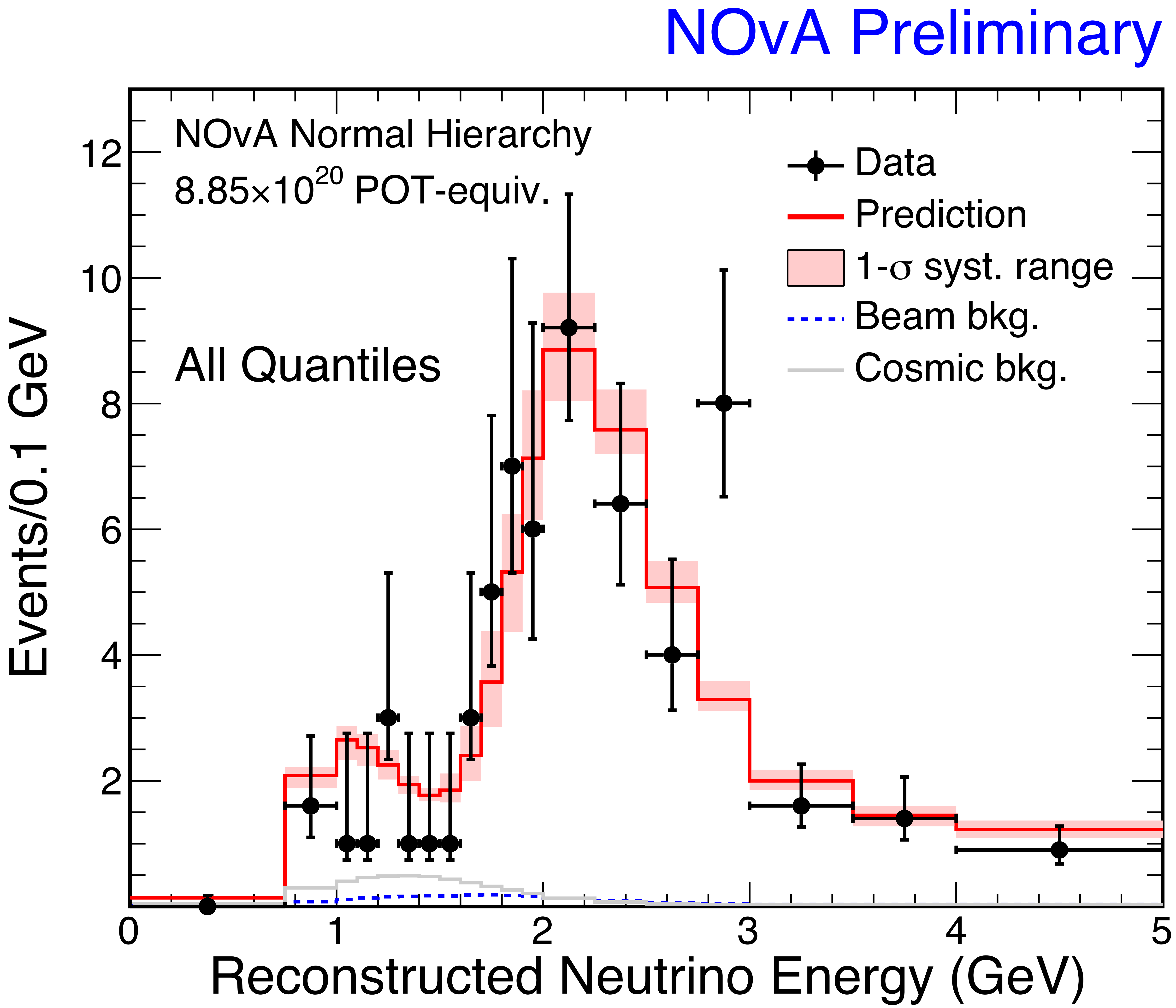
- Applications of modern visual recognition techniques:
    - convolution filter/kernel performs basic feature-finding functions
    - subsequent convolution layers can identify hierarchy of features
    - fully connected layers can then combine output generically to produce output.

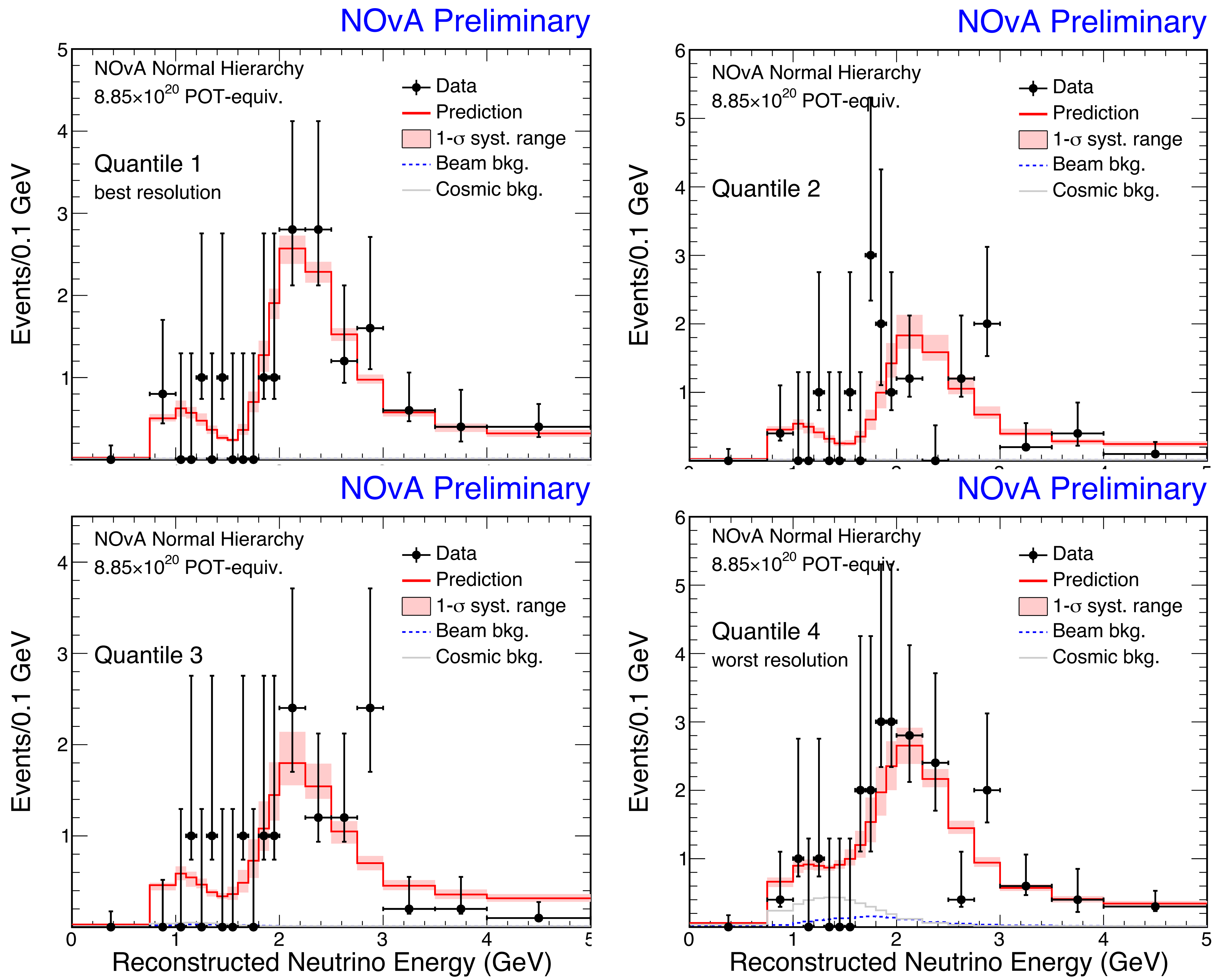


Input

first convolution layer

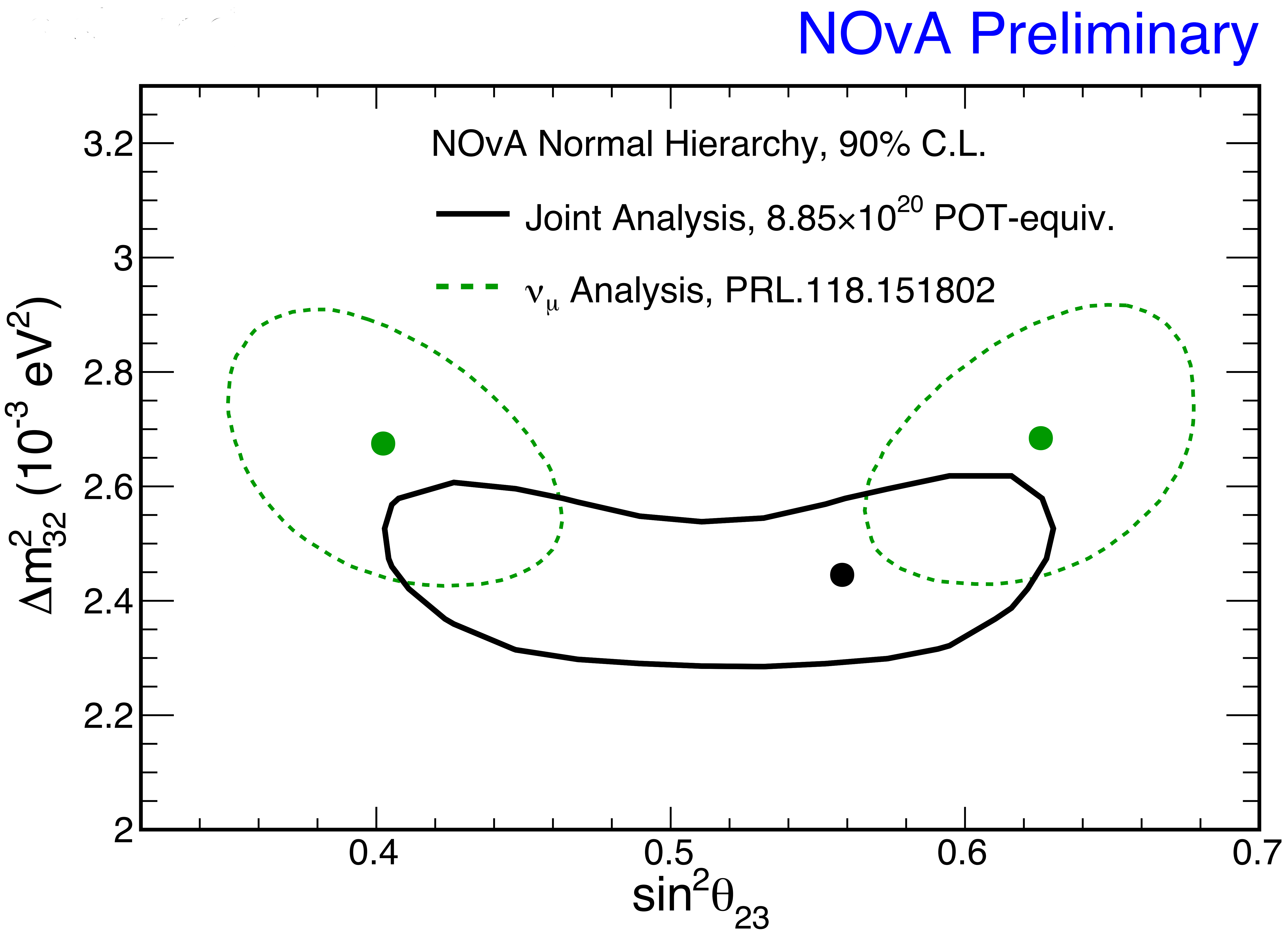
ν_μ INTERACTIONS



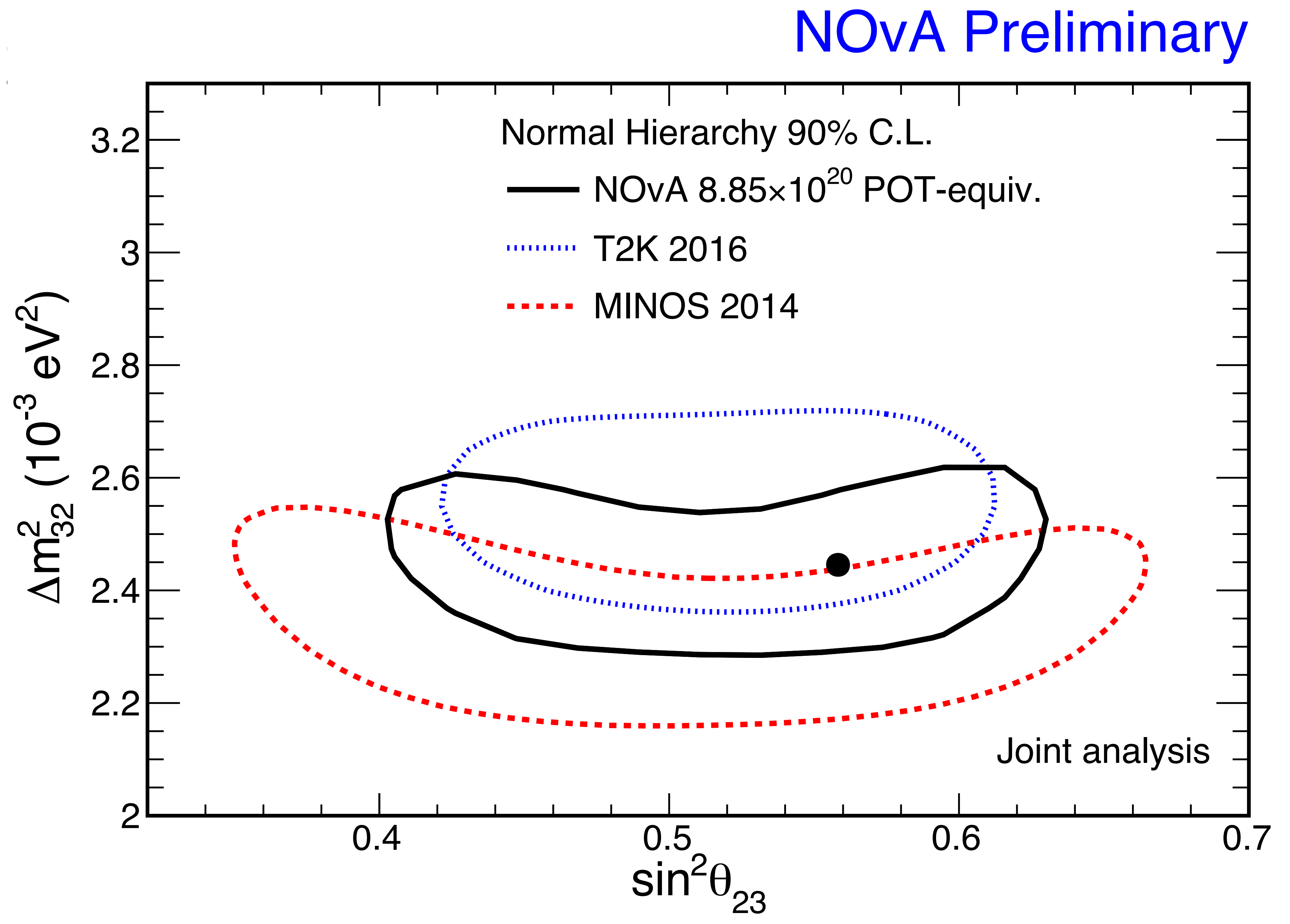


- Events are separated based on expected E_ν resolution
  - $E_\nu = f(E_\mu, E_{had})$
  - energy in the muon vs. hadron system

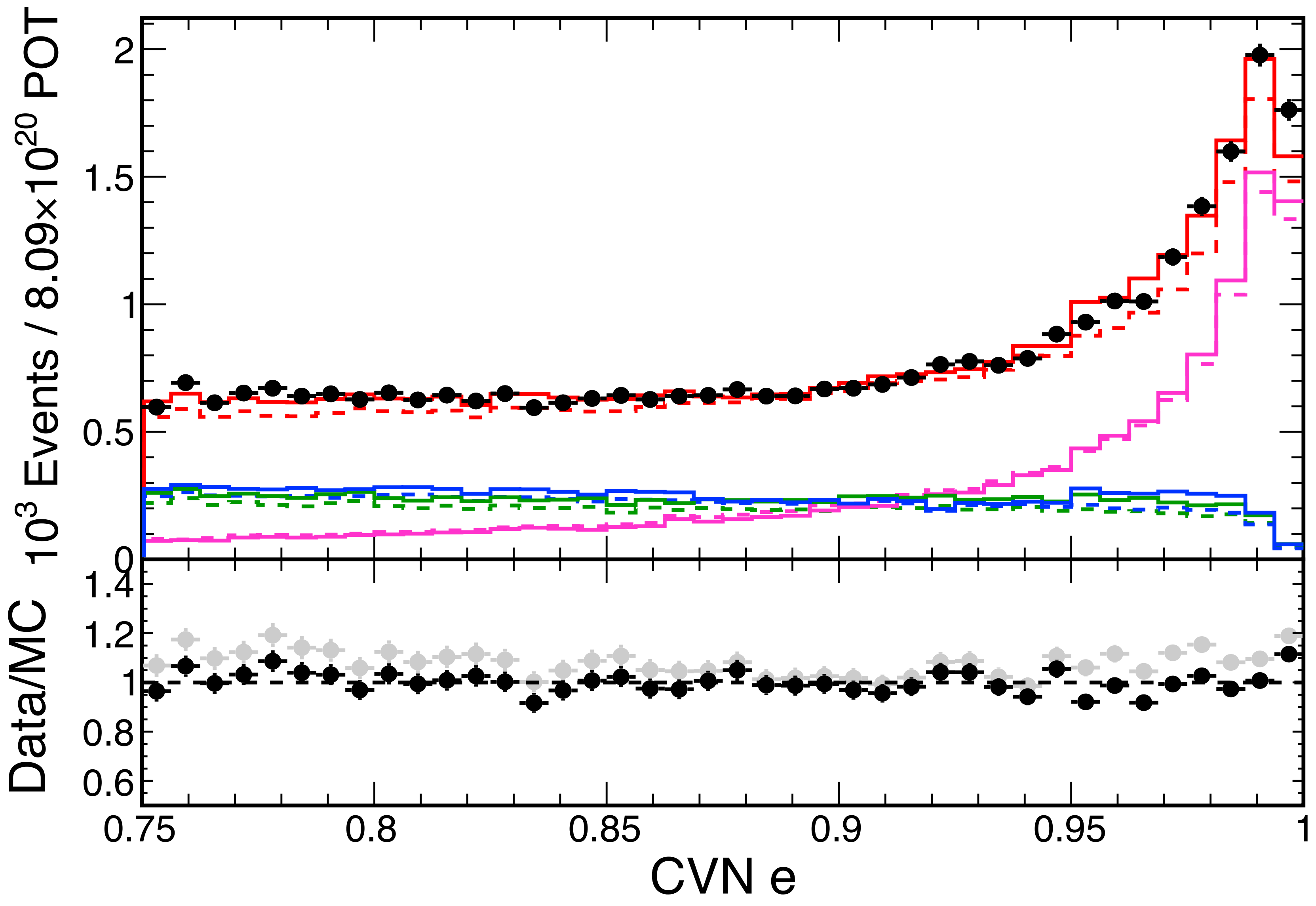
θ_{23} AND Δm^2 RESULT

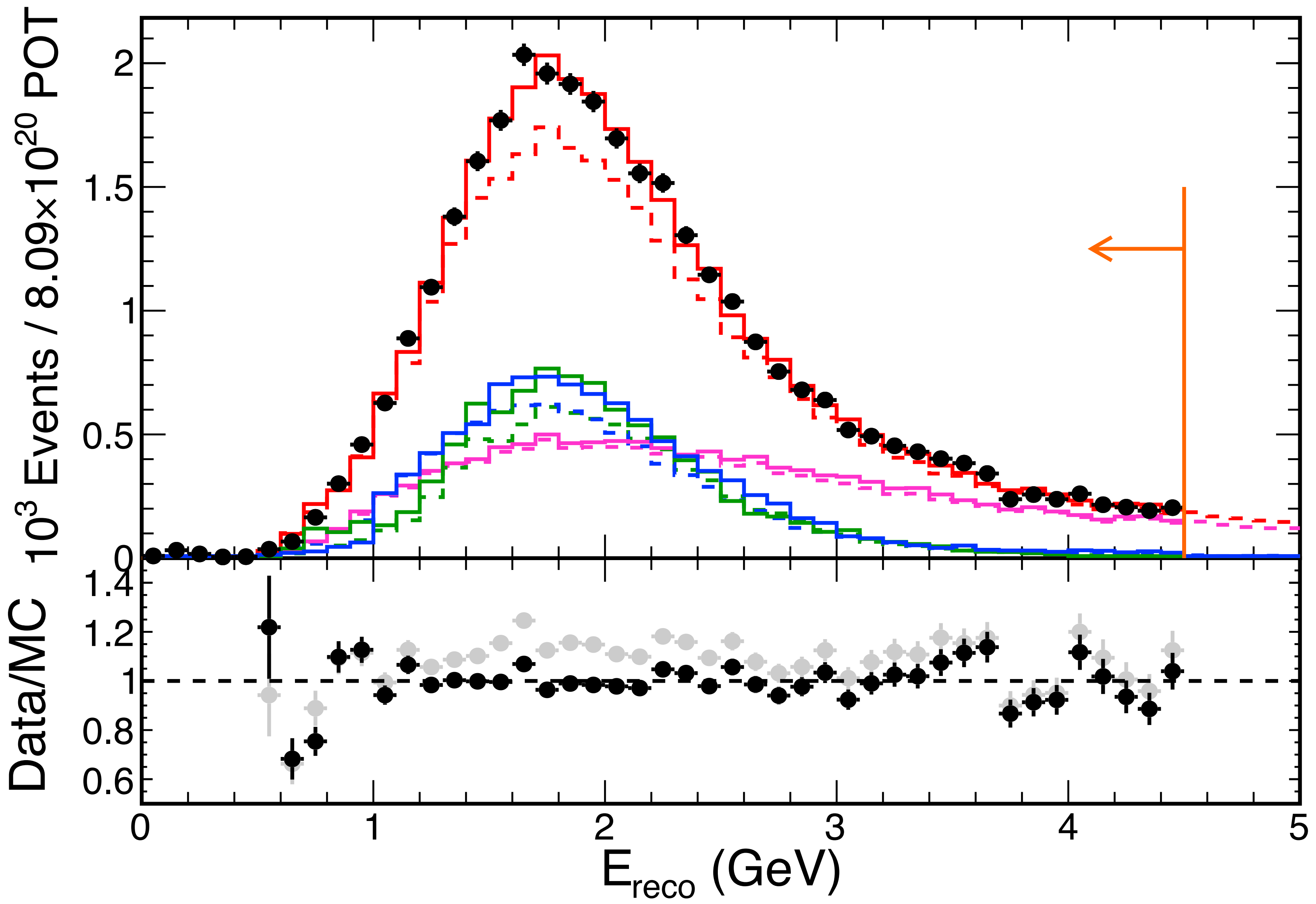


- Previous results with $6.05\text{x}10^{20}$ protons-on-target strongly disfavored non-maximal mixing
- New analysis includes:
  - improvements in detector modelling
  - improvements in neutrino interaction modelling (MEC/2p2h)
  - additional data

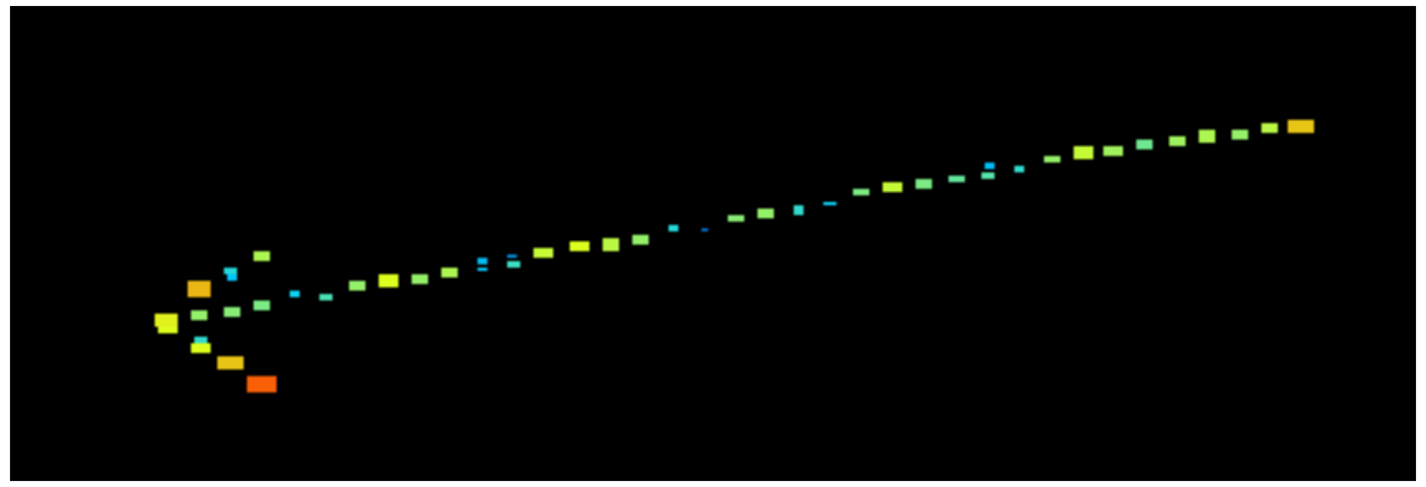


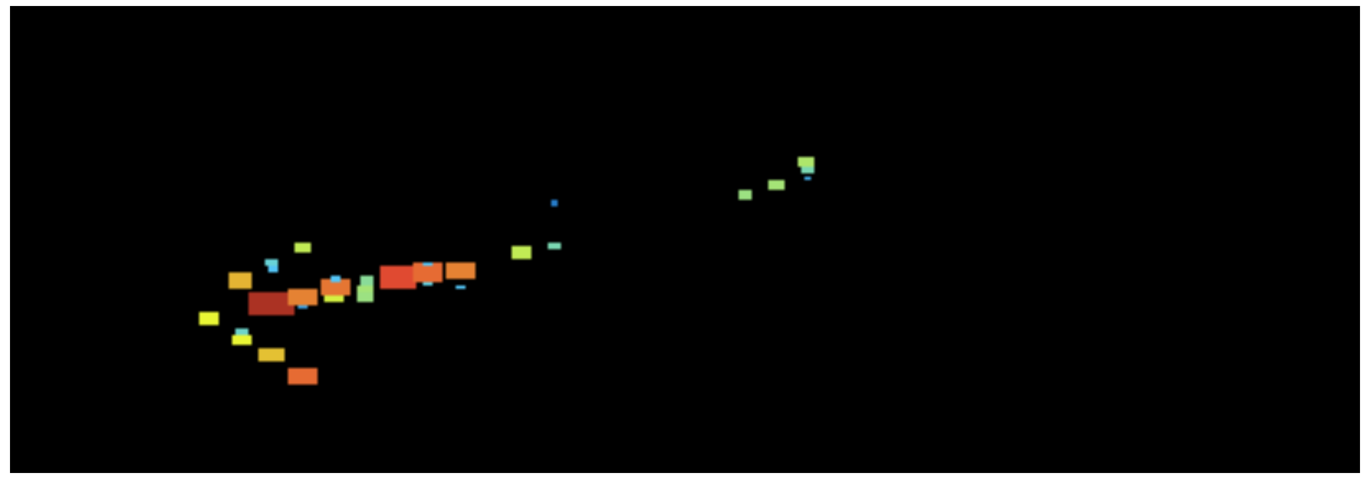
ν_e SELECTION





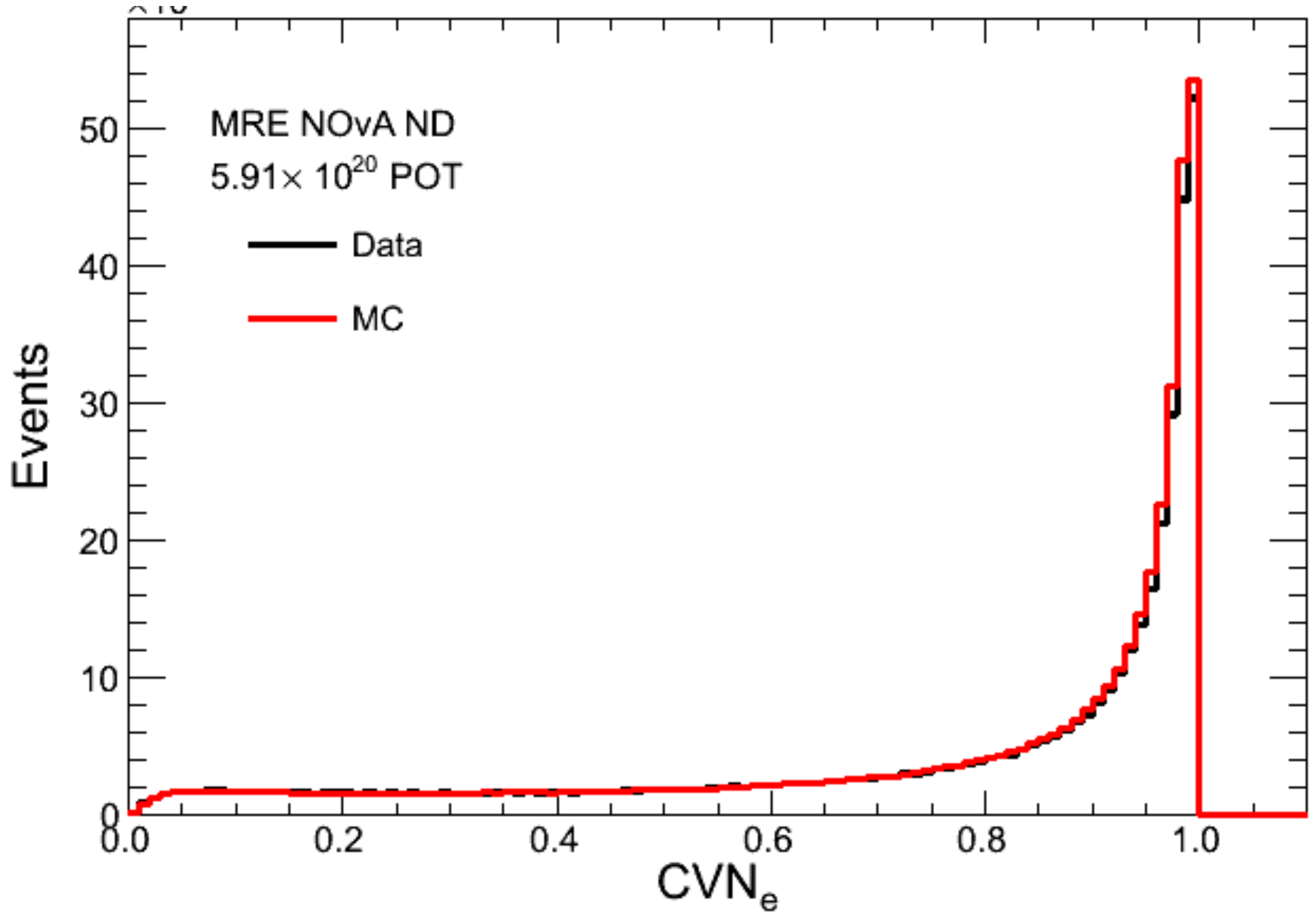
- CVN-based selection
- Power checks based on functionally identical near detector



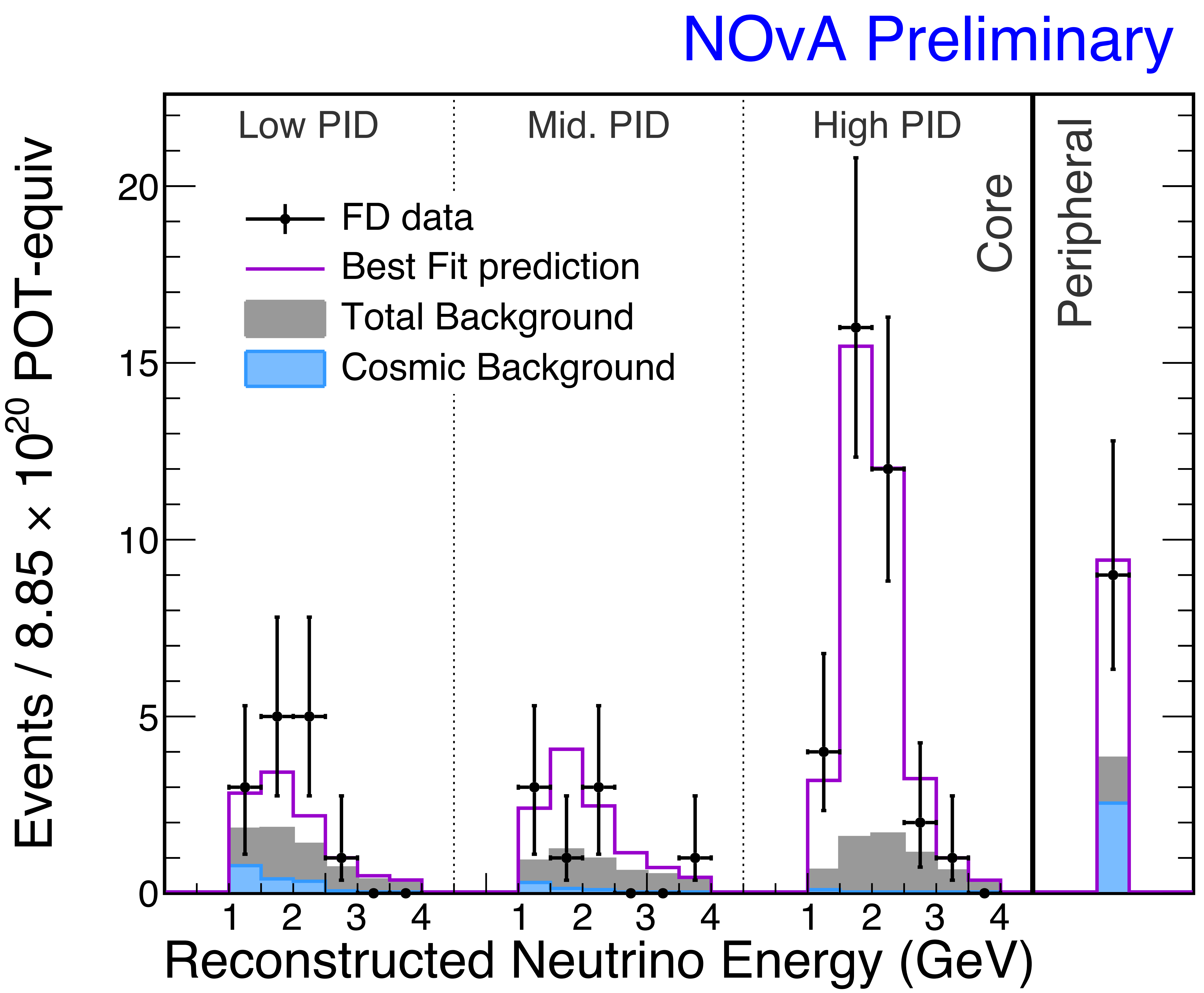


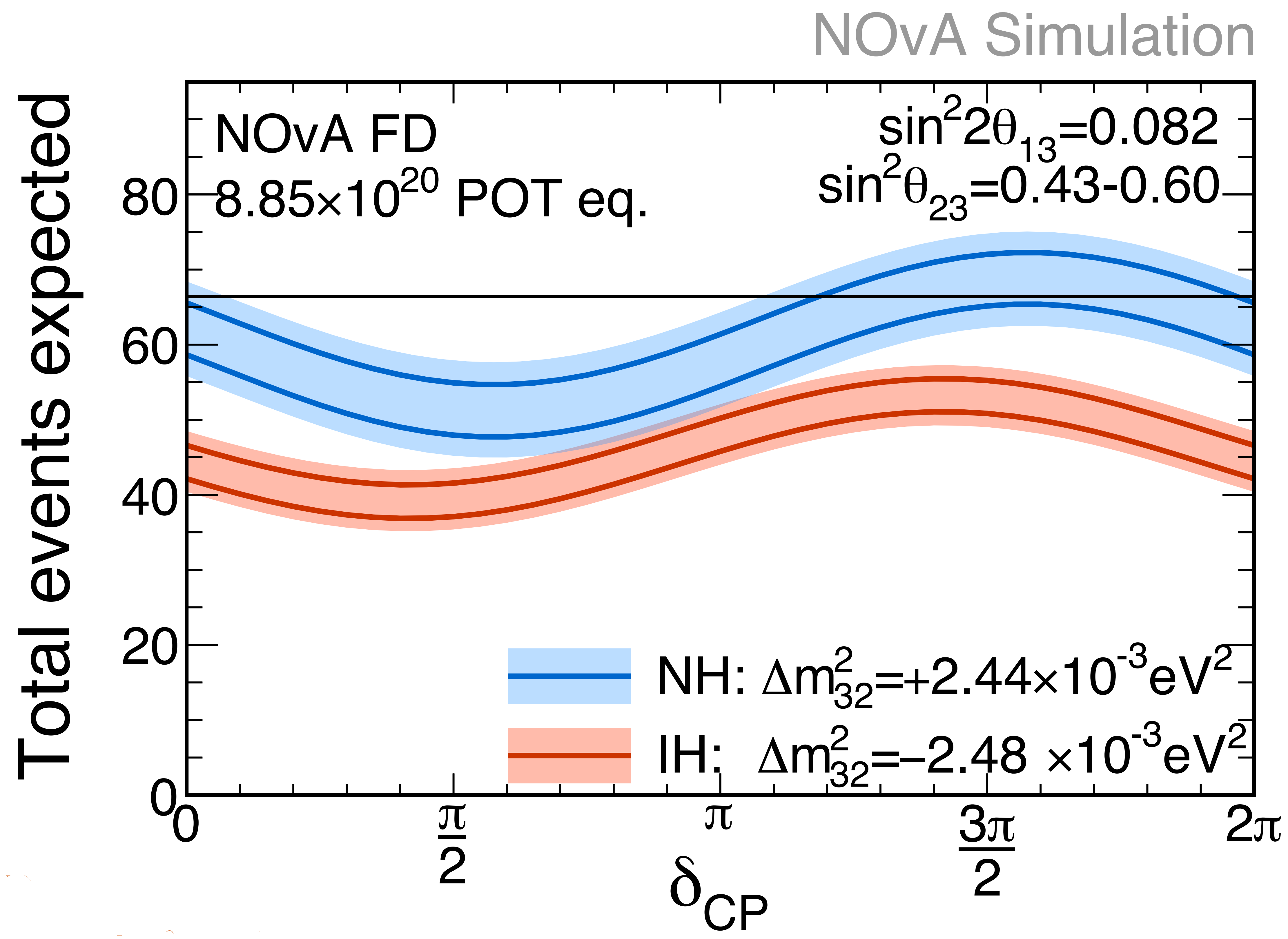
- Largest modelling uncertainty comes from hadronic system
  - clip muon from ν_μ CC interaction in data and MC
  - replace with an MC electron and reanalyze . . .

NOvA Preliminary



ν_e CANDIDATES IN FAR DETECTOR

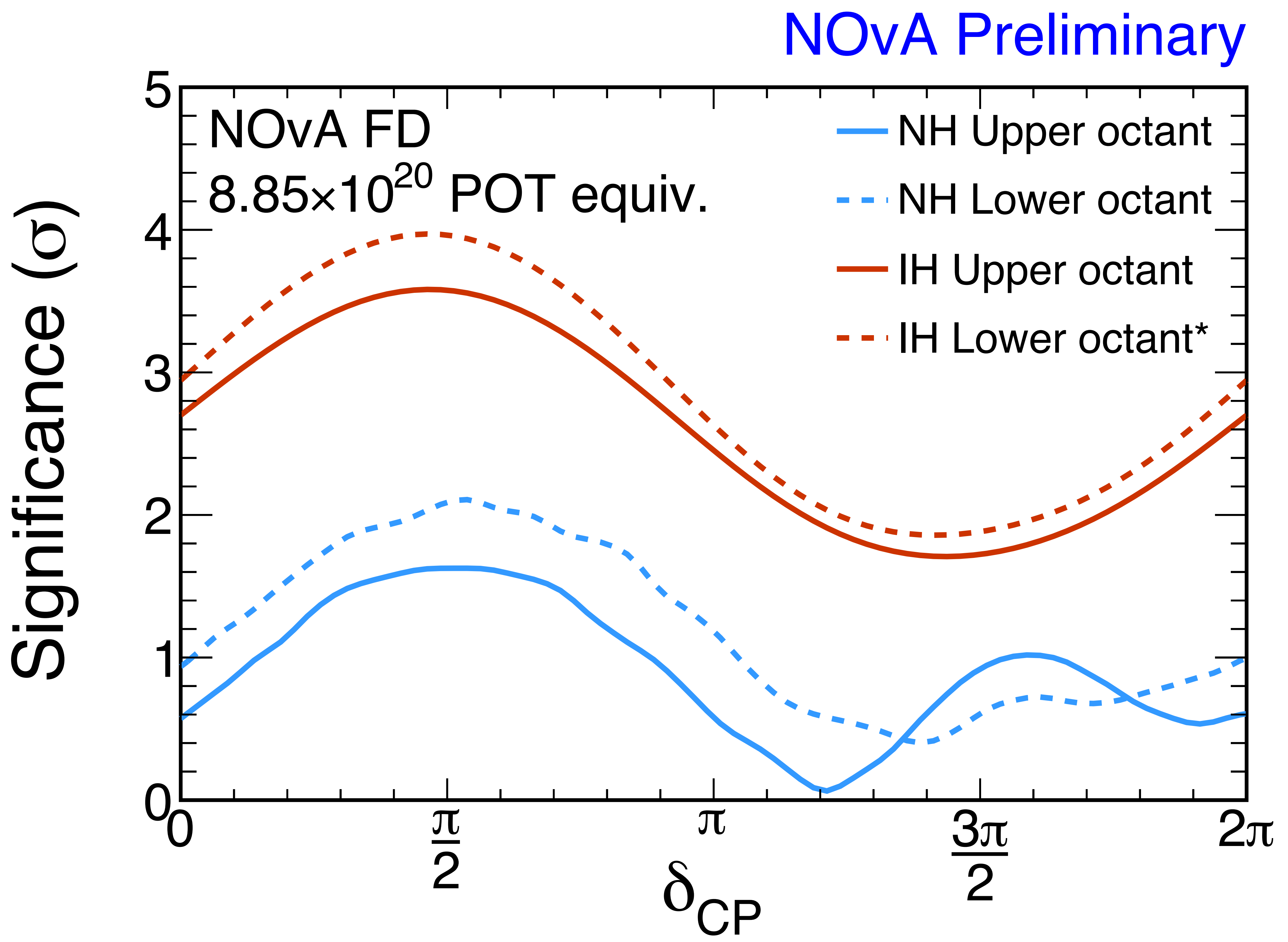


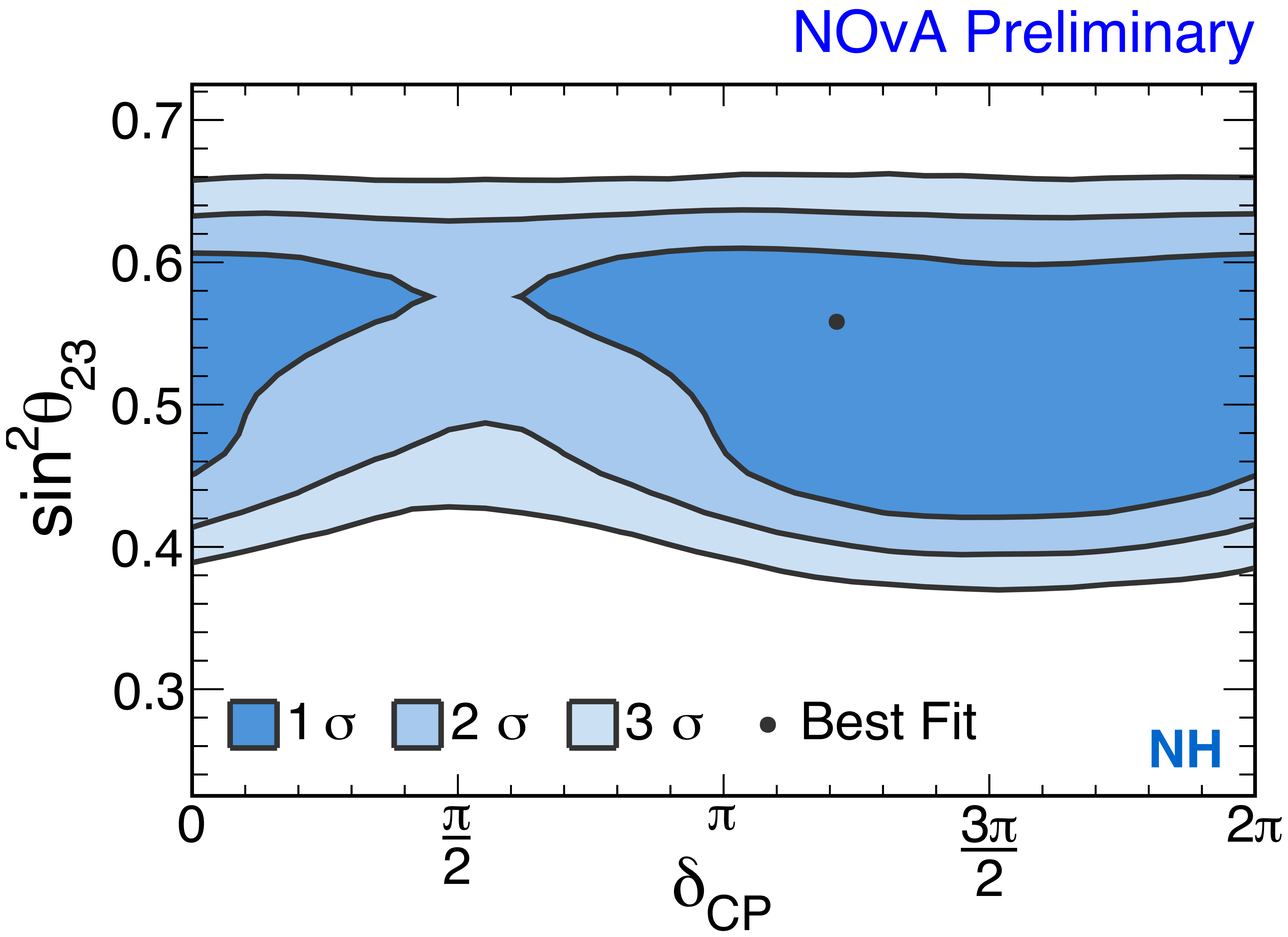


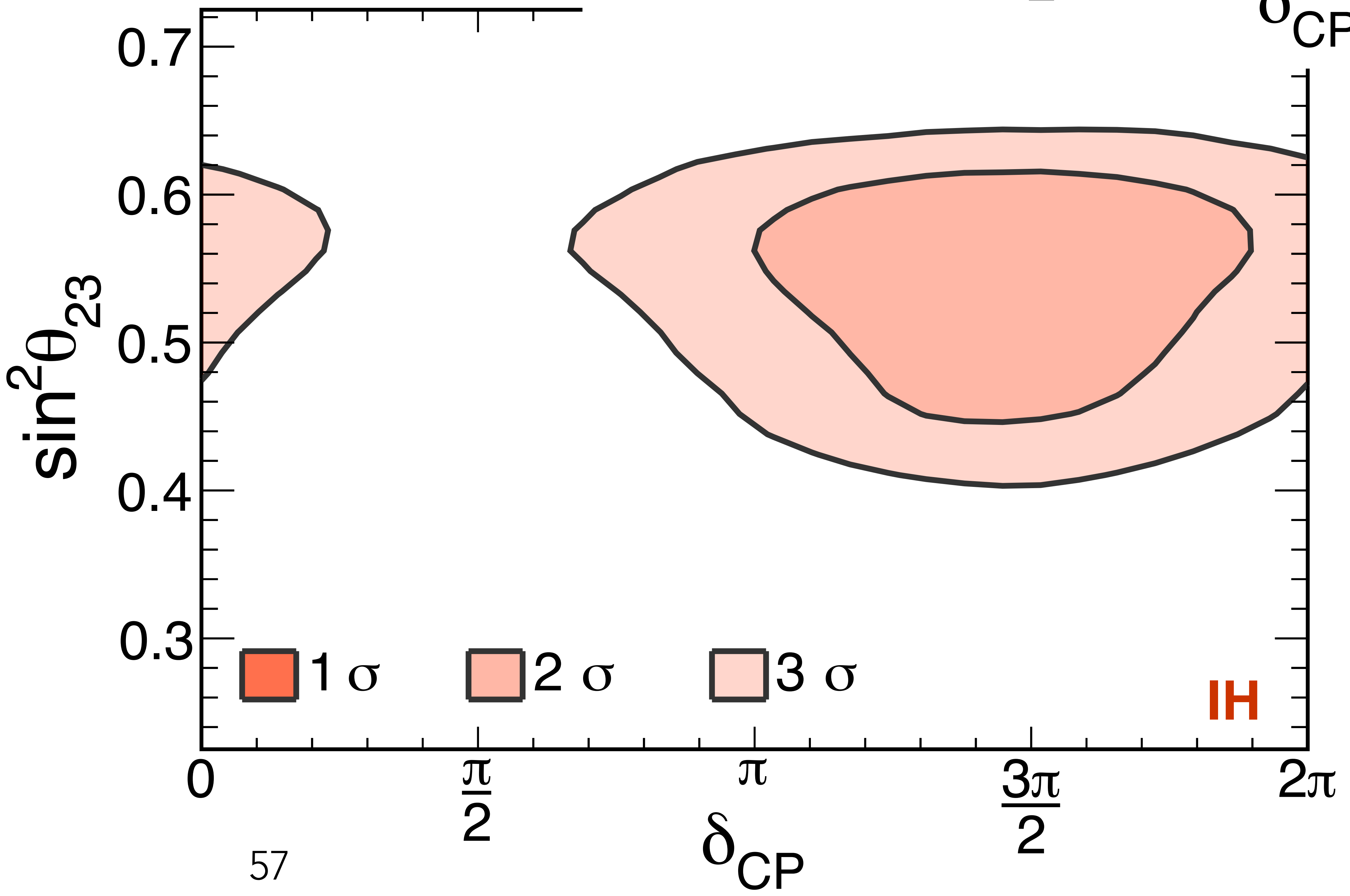
- ν_e candidates are binned according to the particle identification variable
- orthogonal sample rejected by cosmic samples also included ("peripheral)
- 66 candidates observed

CONTOURS

- As expected:
  - inverted hierarchy broadly disfavored
  - only $\delta_{CP} \sim 3\pi/2$ allowed at 2 σ level
  - in normal hierarchy, δ_{CP} around $\pi/2$ disfavored 2 σ level

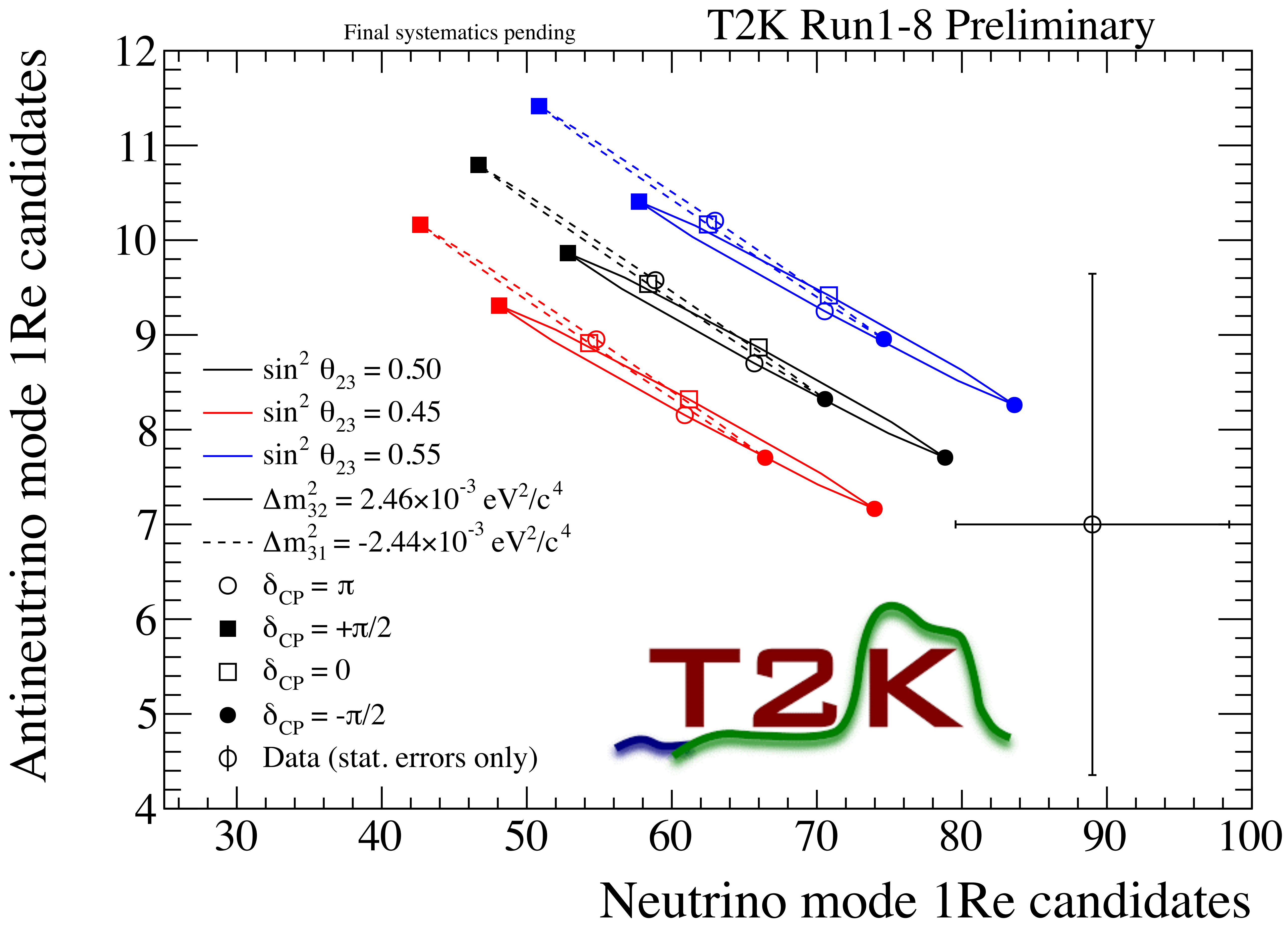


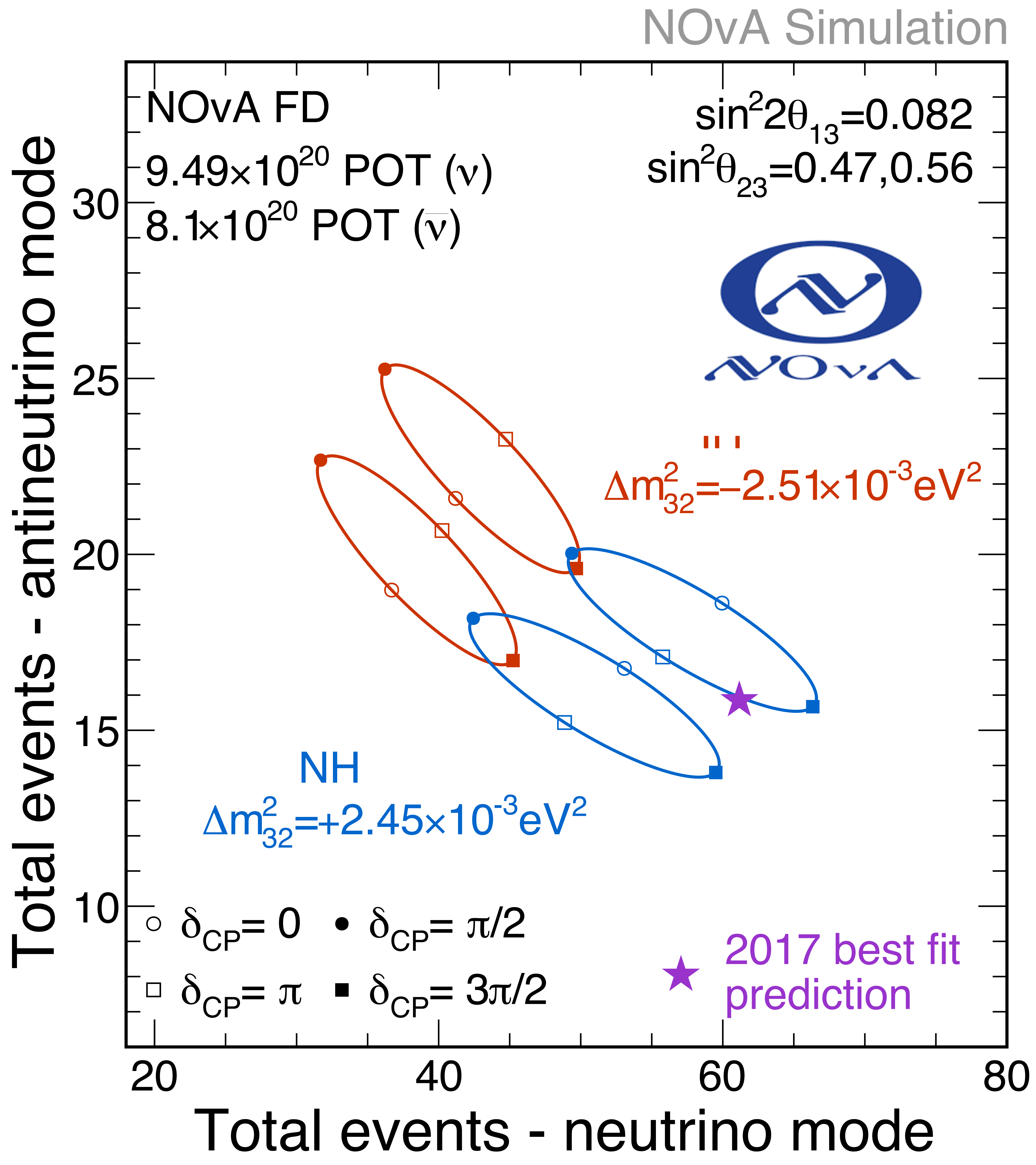




With constraint on θ_{13} from reactors

"BIPROBABILITY" PLOTS





- We may be in a "favorable" situation where CP violation and matter effects are constructively contributing
- Maybe not . . . .

CHALLENGES MOVING FORWARD

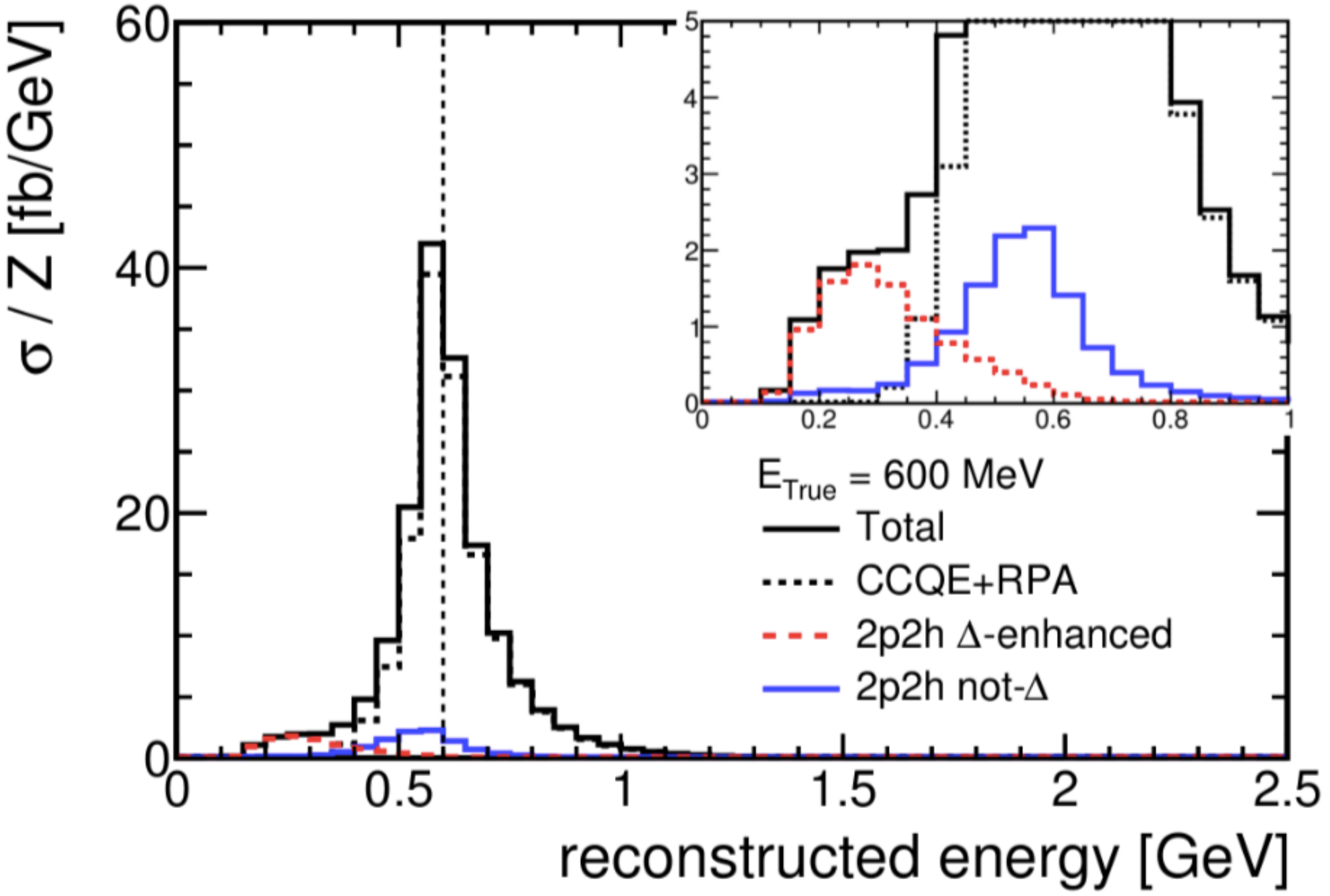
- Current analyses are still limited by statistical uncertainties
- However, we hope to accumulate much more data in the near future
  - T2K: ~3 x 10^{21} POT→ 7.8 x 10^{21} POT → 20 x 10^{21} POT
  - NOvA: ~9 x 10^{20} POT→ 36 x 10^{20} POT
- Systematics are difficult!
  - neutrino interaction modelling issue that we have been discussing
  - detector modelling
  - etc . . .
- Will require lots of hard work to reduce further

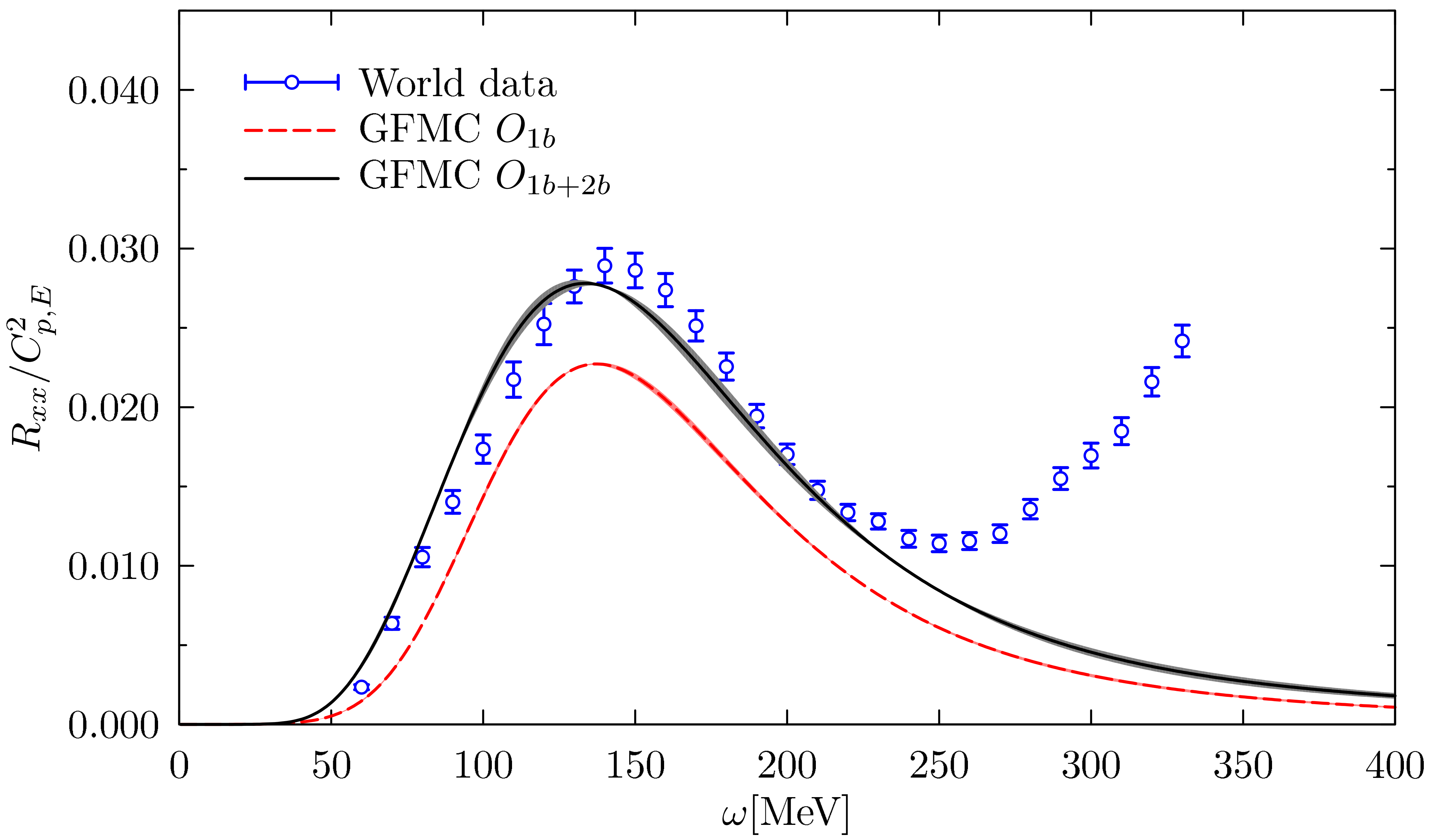
	1 RING μ		1 RING e			
SOURCE	ν mode	$\bar{\nu}$ mode	ν mode	$\bar{\nu}$ mode	ν mode 1 d.e.	$\nu/\bar{\nu}$
SK DETECTOR	1.9	1.5	3.0	4.2	16.7	1.6
SK FSI, HAD.	2.2	2.0	3.0	2.3	11.4	3.7
ND CONSTR. Φ, σ	3.2	2.7	3.2	2.9	4.1	2.4
$\sigma(\nu_e)/\sigma(\nu_\mu)$, $\sigma(\bar{\nu}_e)/\sigma(\bar{\nu}_\mu)$			2.6	1.5	2.6	3.1
NC 1γ			1.1	2.6	0.3	1.2
NC OTHER	0.3	0.3	0.1	0.3	1.0	0.1
TOTAL	**4.4**	**3.8**	**6.1**	**6.5**	20.9	4.8

current T2K systematics

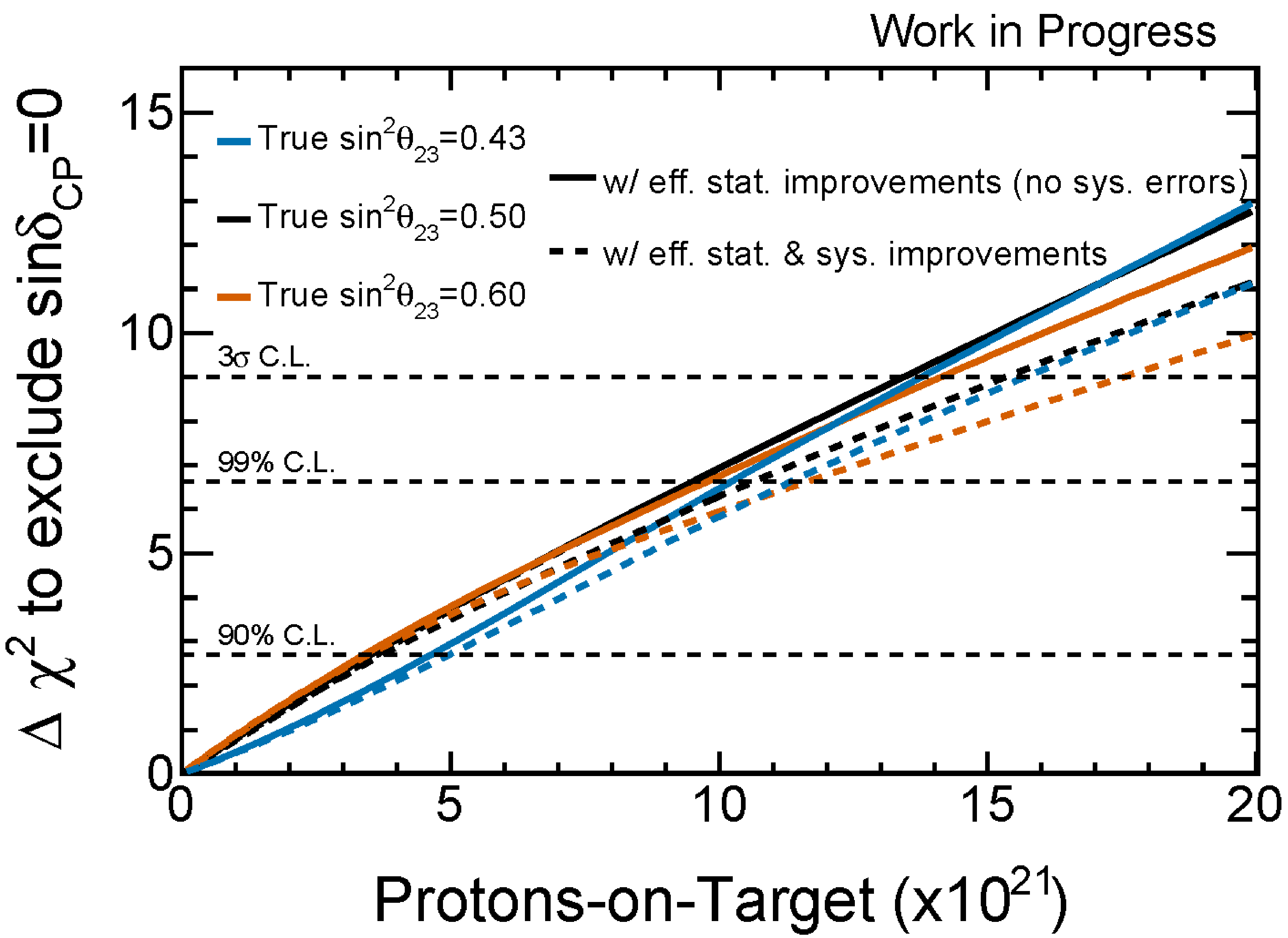
MULTINUCLEON MODELING ERROR

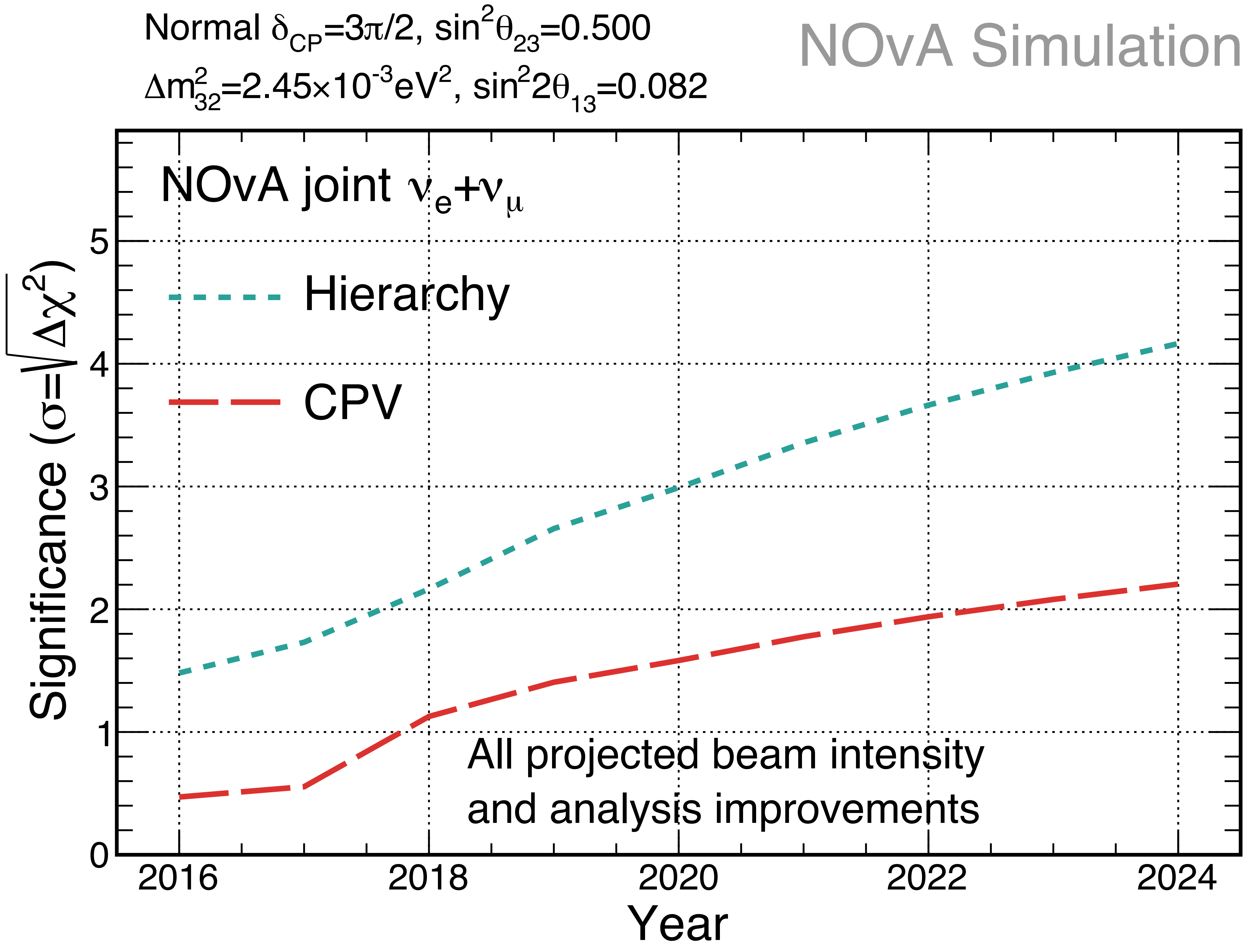
- The 2p-2h processes produce events with lower reconstructed energy
    - Energy mis-reconstruction largest in processes involving coupling to a **Δ resonance**
- Model the energy reconstruction error: allow strength of the 2p-2h cross-section to vary between all Δ-enhanced and all not-Δ-enhanced
- Also allow normalization for 2p-2h to vary separately for neutrinos and antineutrinos





WHAT'S "AROUND THE CORENR"





- If we believe the 3 flavour model and current preferred values, current significance is a statistical fluctuation
  - we would expect to "converge" back to expected significance
  - systematic errors will significantly impact results if not improved.

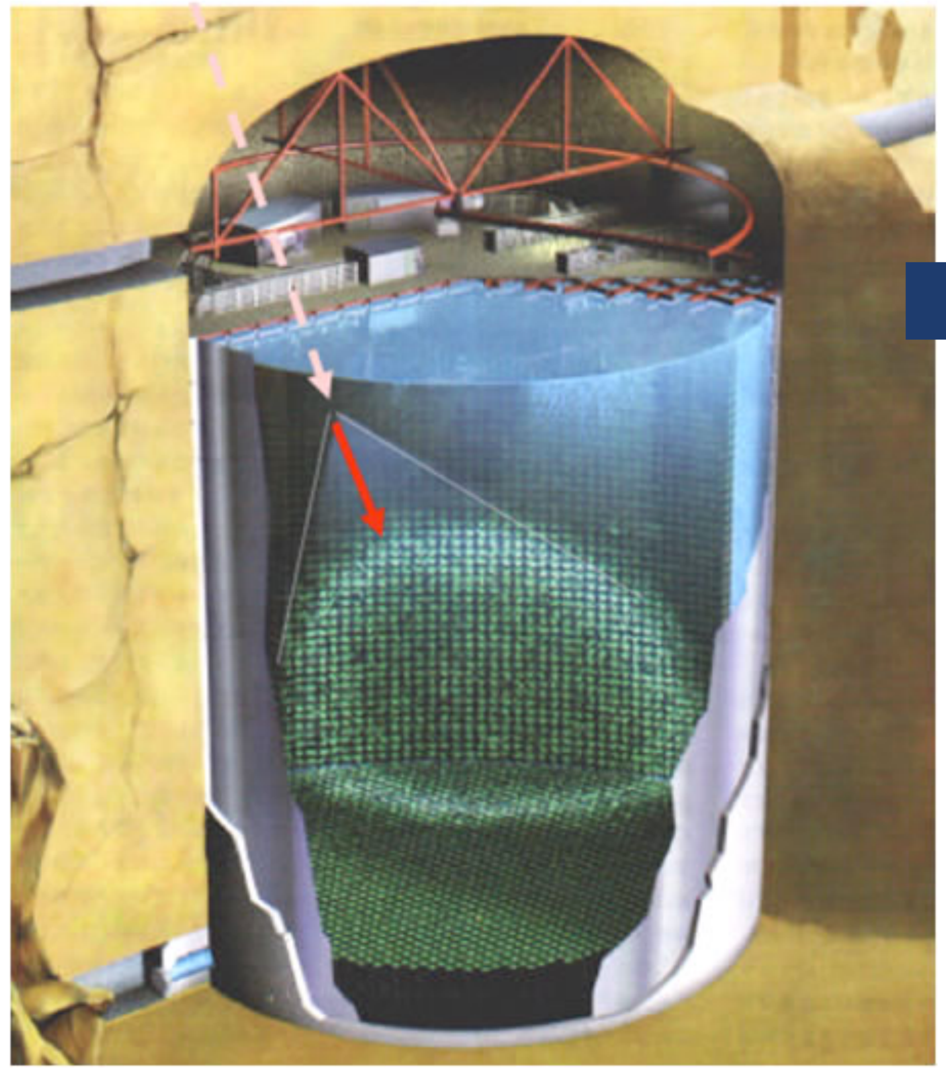
INTO THE FUTURE

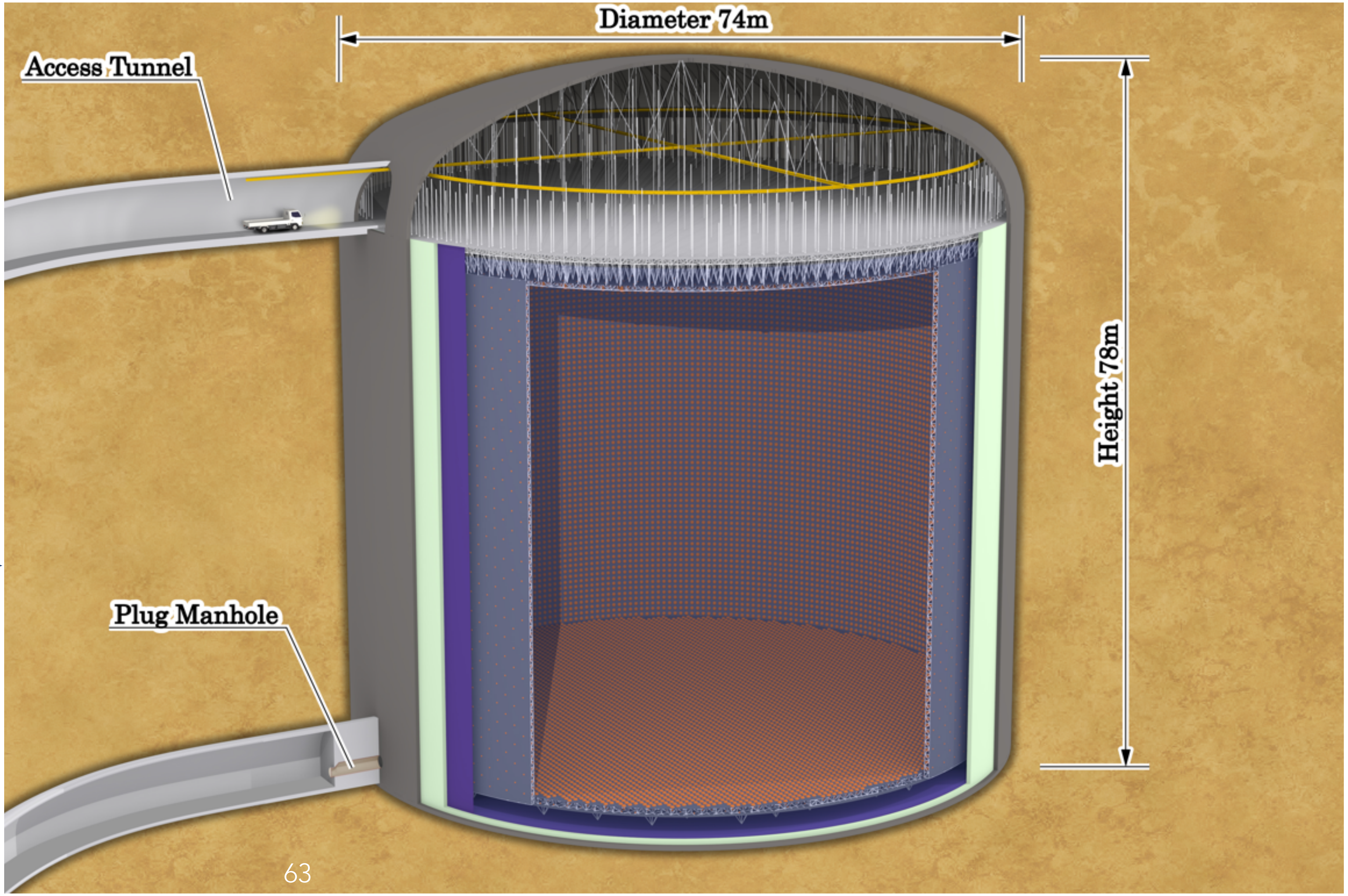
WHAT'S NEXT

$$N \propto \Phi_\nu \times \boxed{V \times \rho \times \epsilon} \times \sigma$$

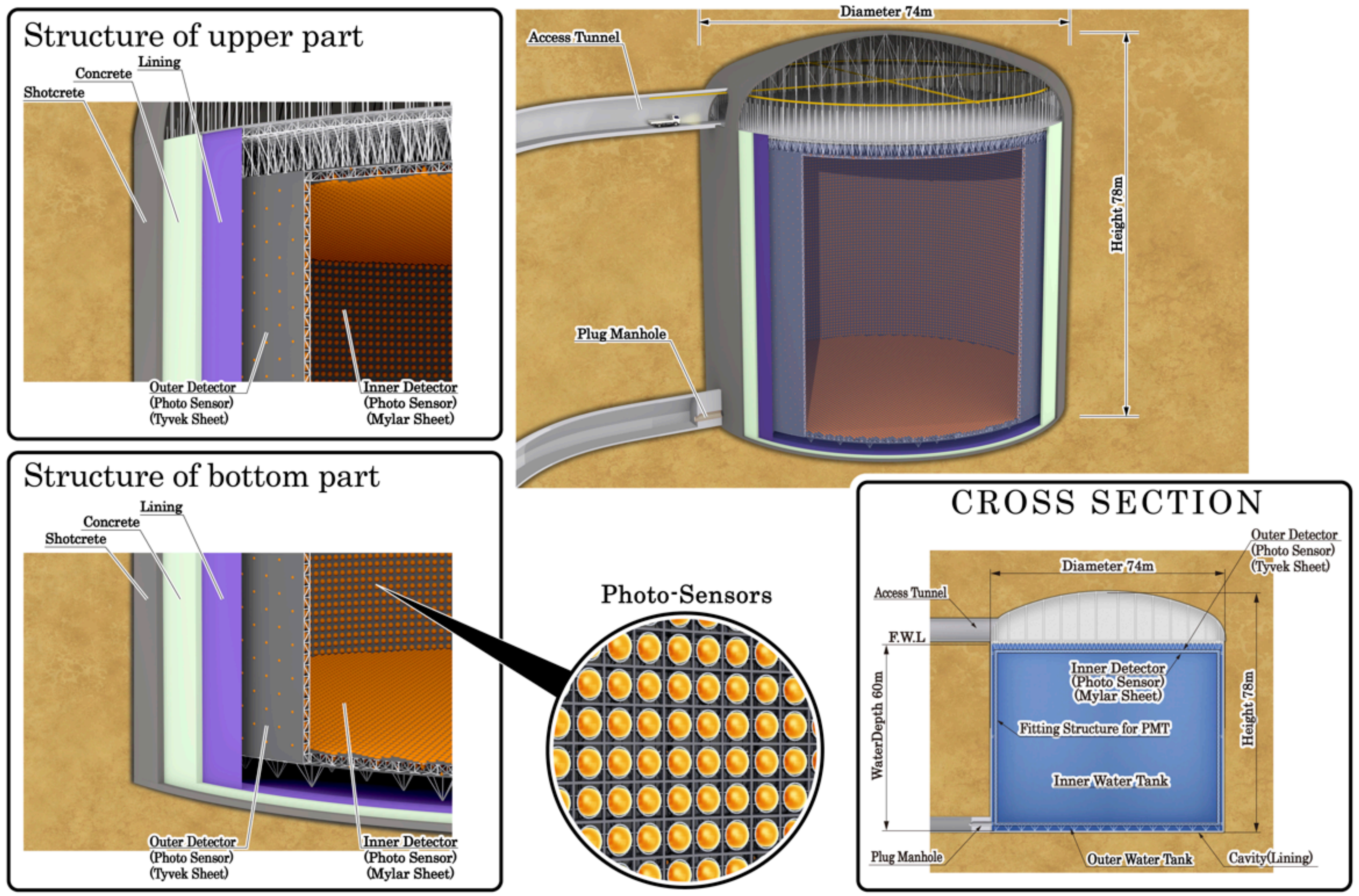
Detector upgrades

- Super-Kamiokande
  →Hyper-Kamiokande



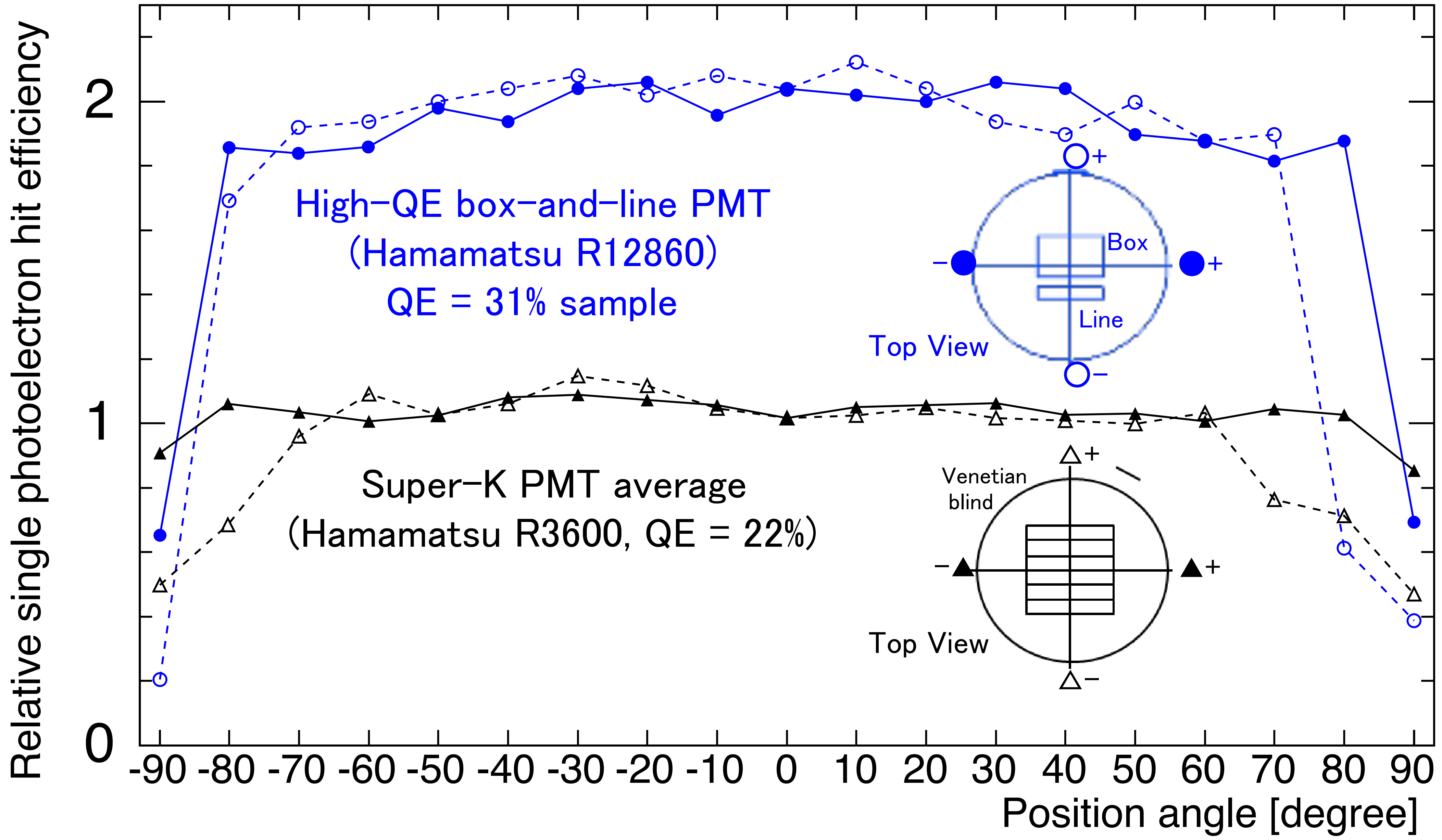


HYPER-KAMIOKANDE



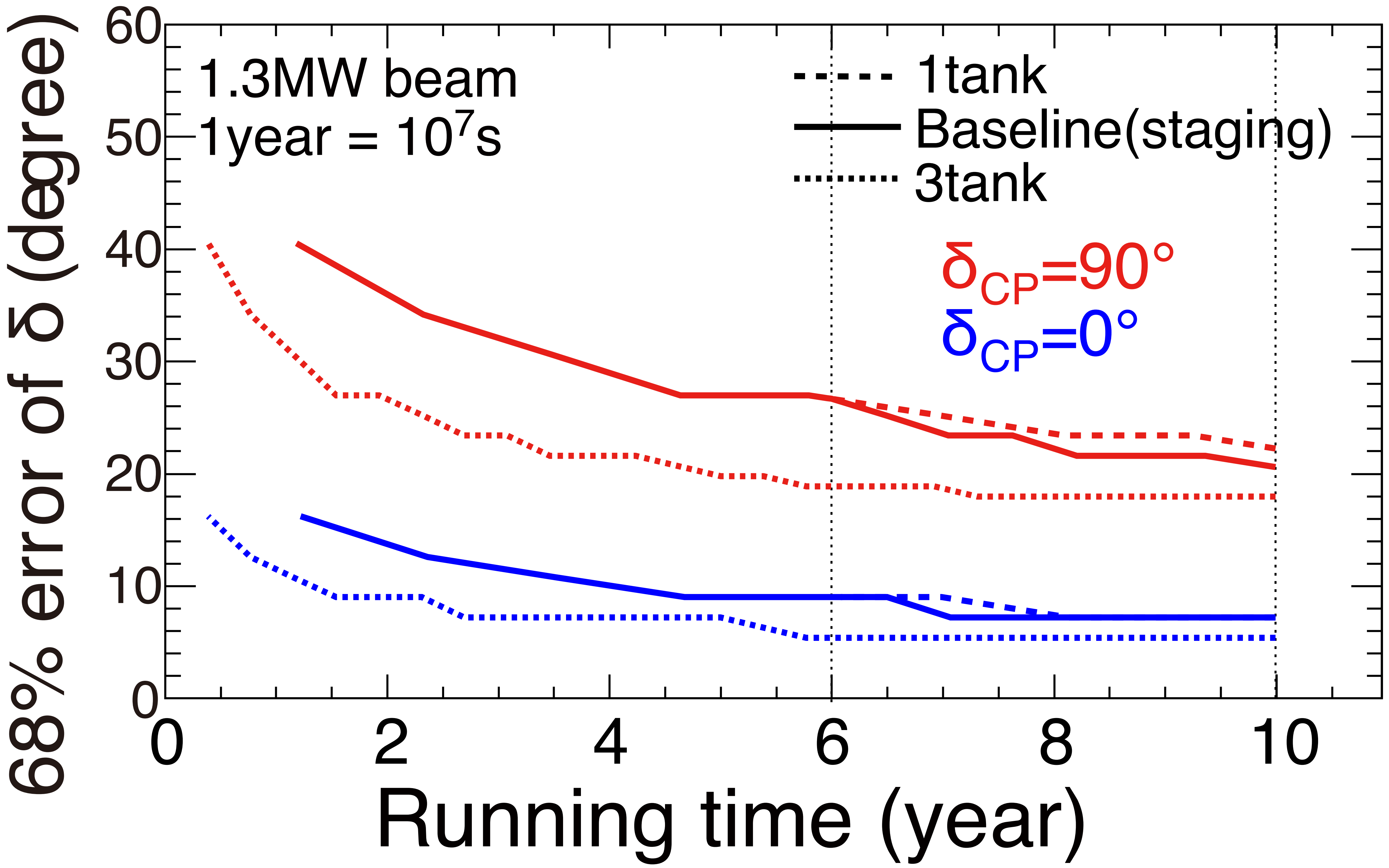
- Reconfigured design as two vertical cylindrical tanks with staged construction
  - 74 m diameter, 60 m height
  - 258 (187) kT tot. (fid.) volume
- Construction of 1st tank (2026) followed by 2nd tank several years later

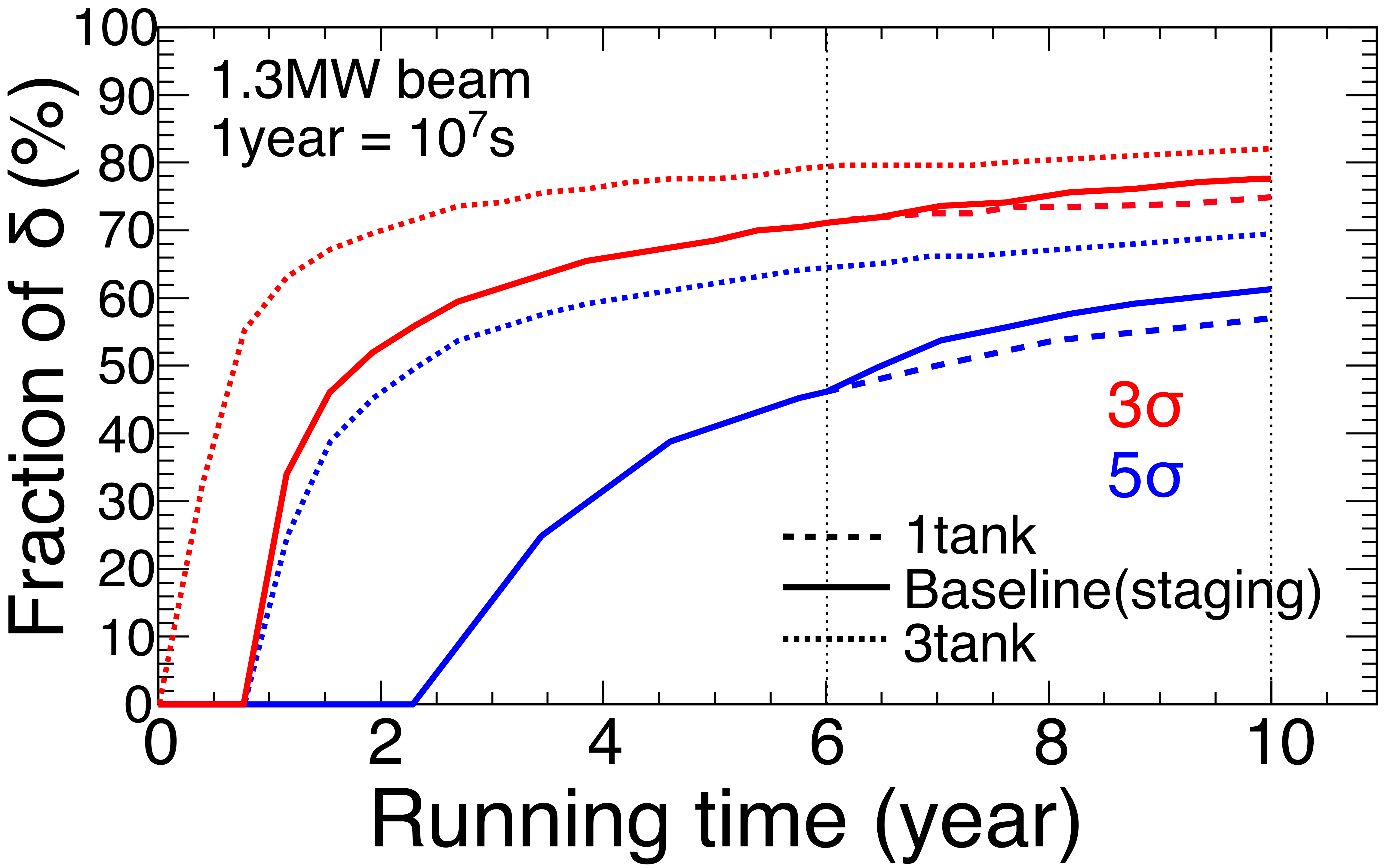
- "High Density" photosensor development:
  - same photocathode area as SK (40%)
  - large improvements in detection efficiency



NEUTRINO OSCILLATIONS AT HYPER-K

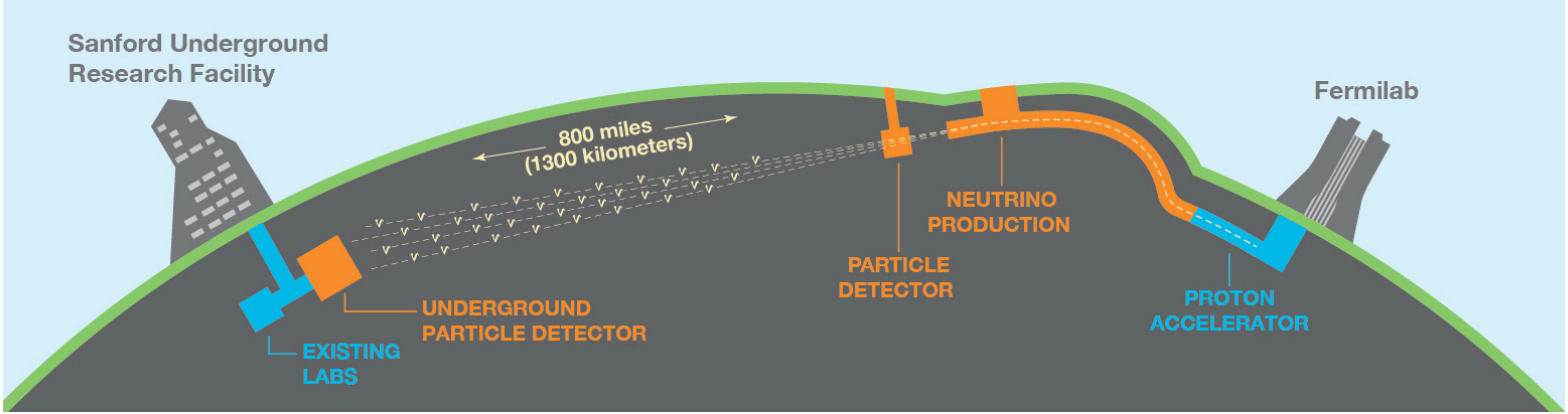
	δ_{CP}	TOTAL	SIGNAL $\nu_\mu \to \nu_e$	SIGNAL $\bar{\nu}_\mu \to \bar{\nu}_e$	BEAM ν_e	BEAM ν_μ	NC
ν MODE	0	2880	**2300**	21	362	10	188
$\bar{\nu}$ MODE	0	2669	289	**1656**	6	444	274

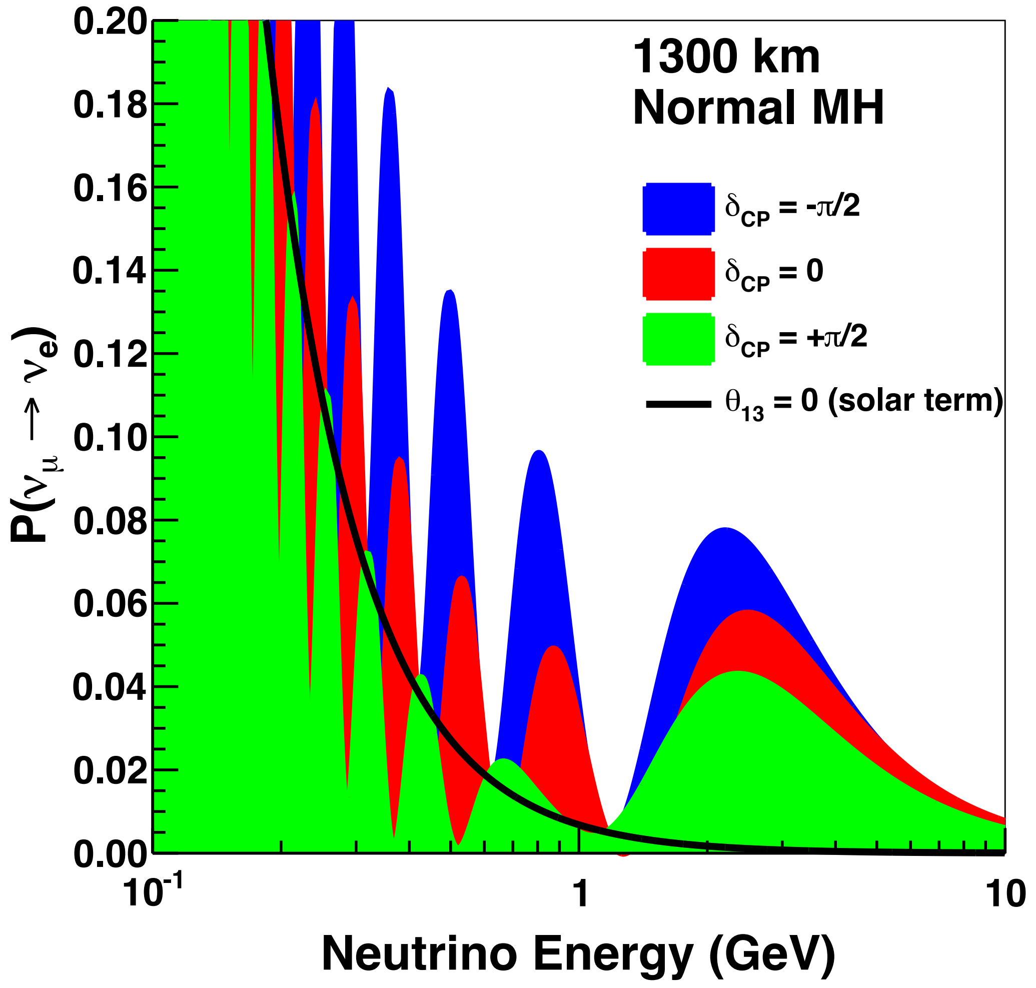


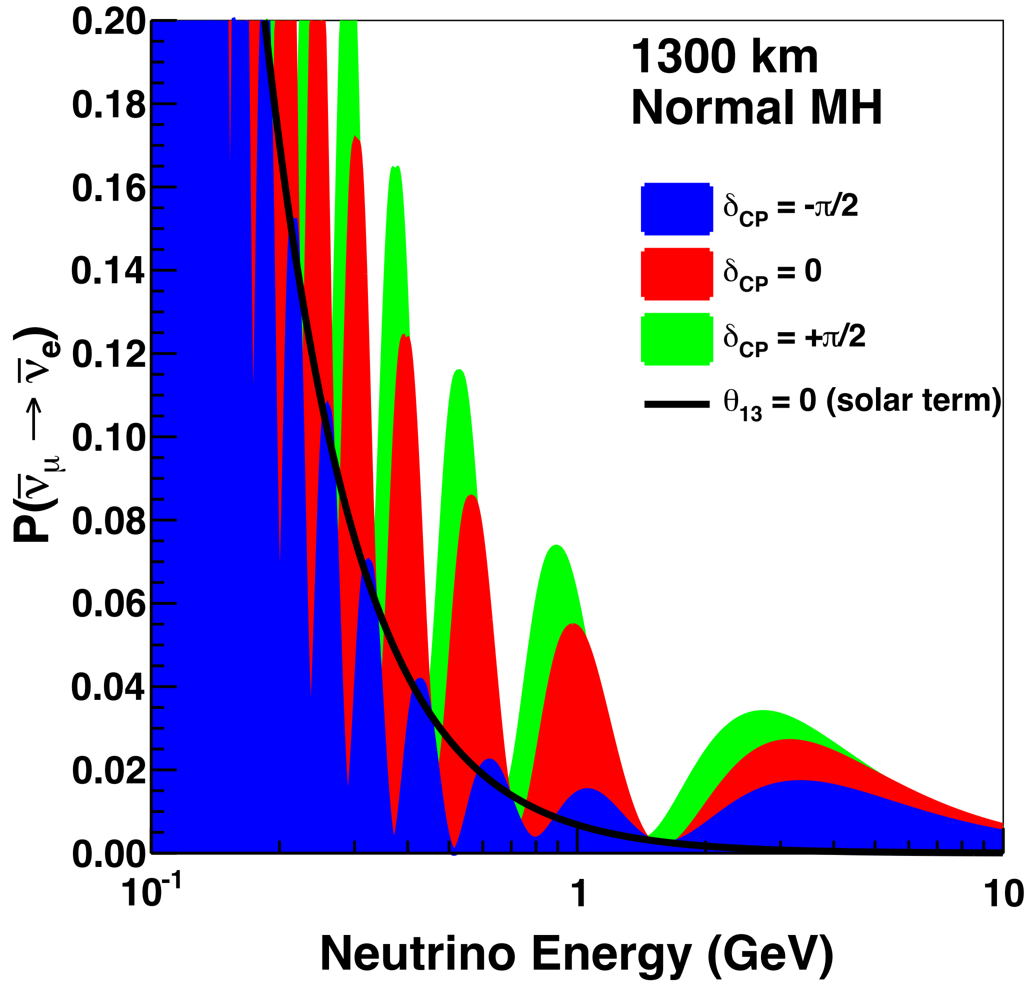


- Very high statistics due to enormous volume
- Like T2K, limited intrinsic sensitivity to mass ordering
  - sensitivity from atmospheric data
- Precision of ~7 degrees possible for δ_{CP} ~0, π
  - precision is significantly worse at δ_{CP} =±π/2

DUNE/LBNF

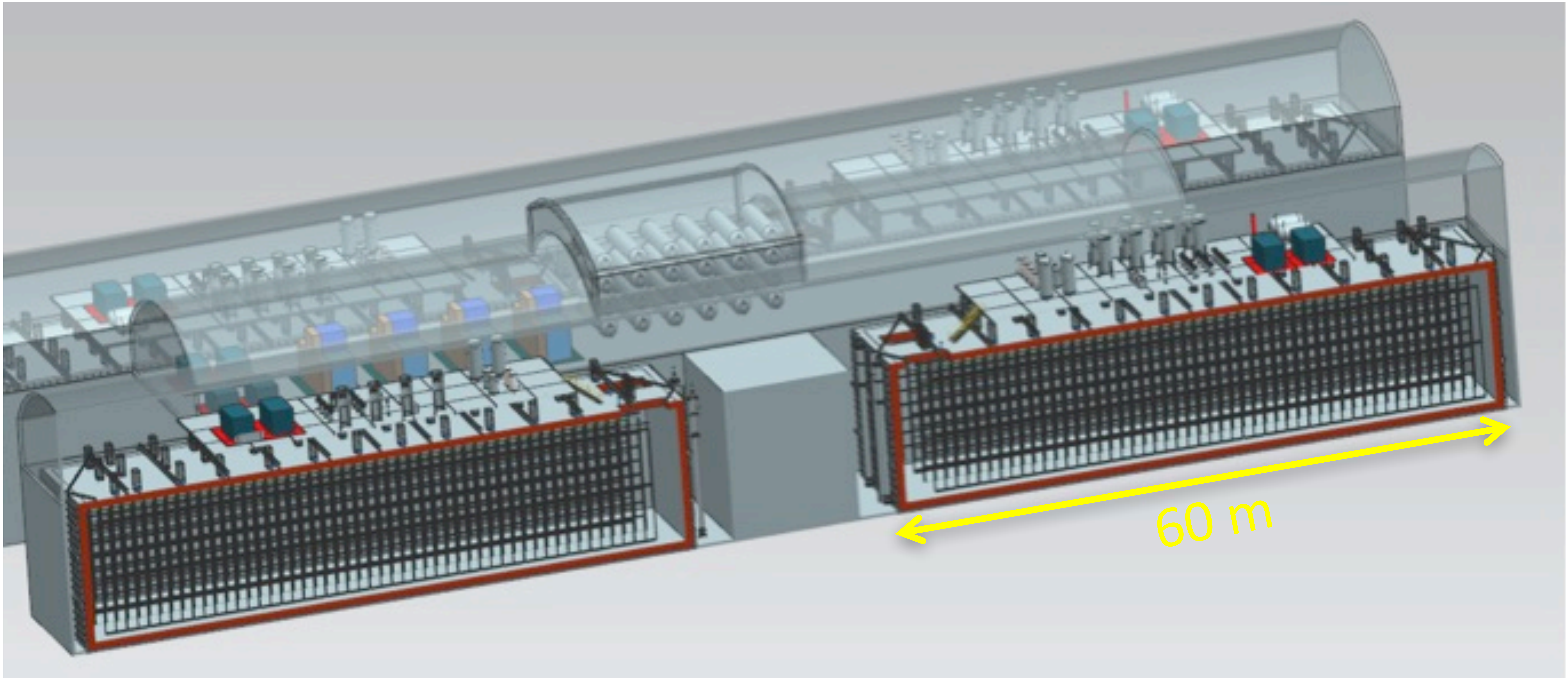






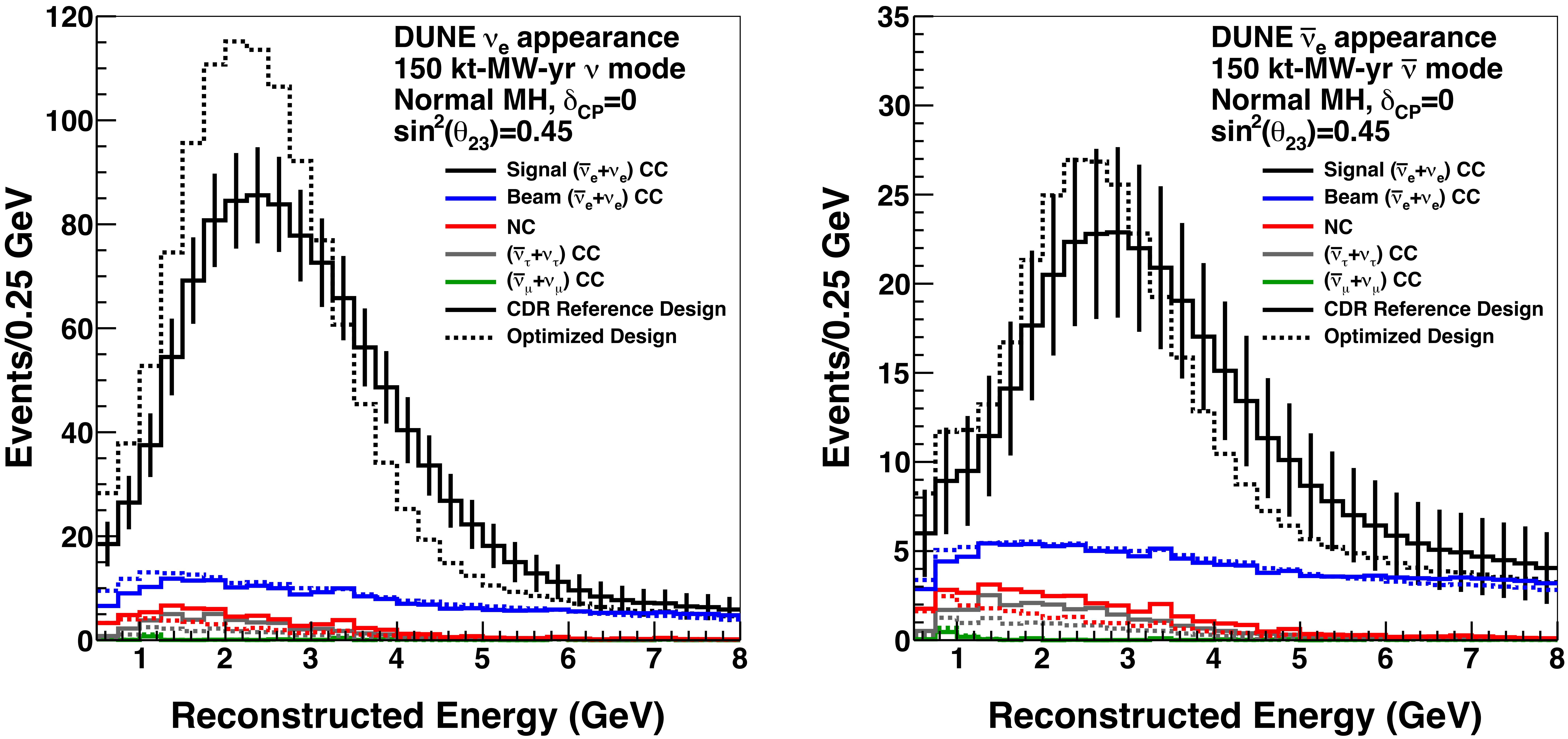
- MW on-axis beam from FNAL to SURF (1300 km)
- Higher energy: strong matter effects
  - very powerful capability to resolve mass ordering
  - Complementarity to Hyper-K from both underlying neutrino physics and LArTPC detector technology

FAR DETECTOR MODULES

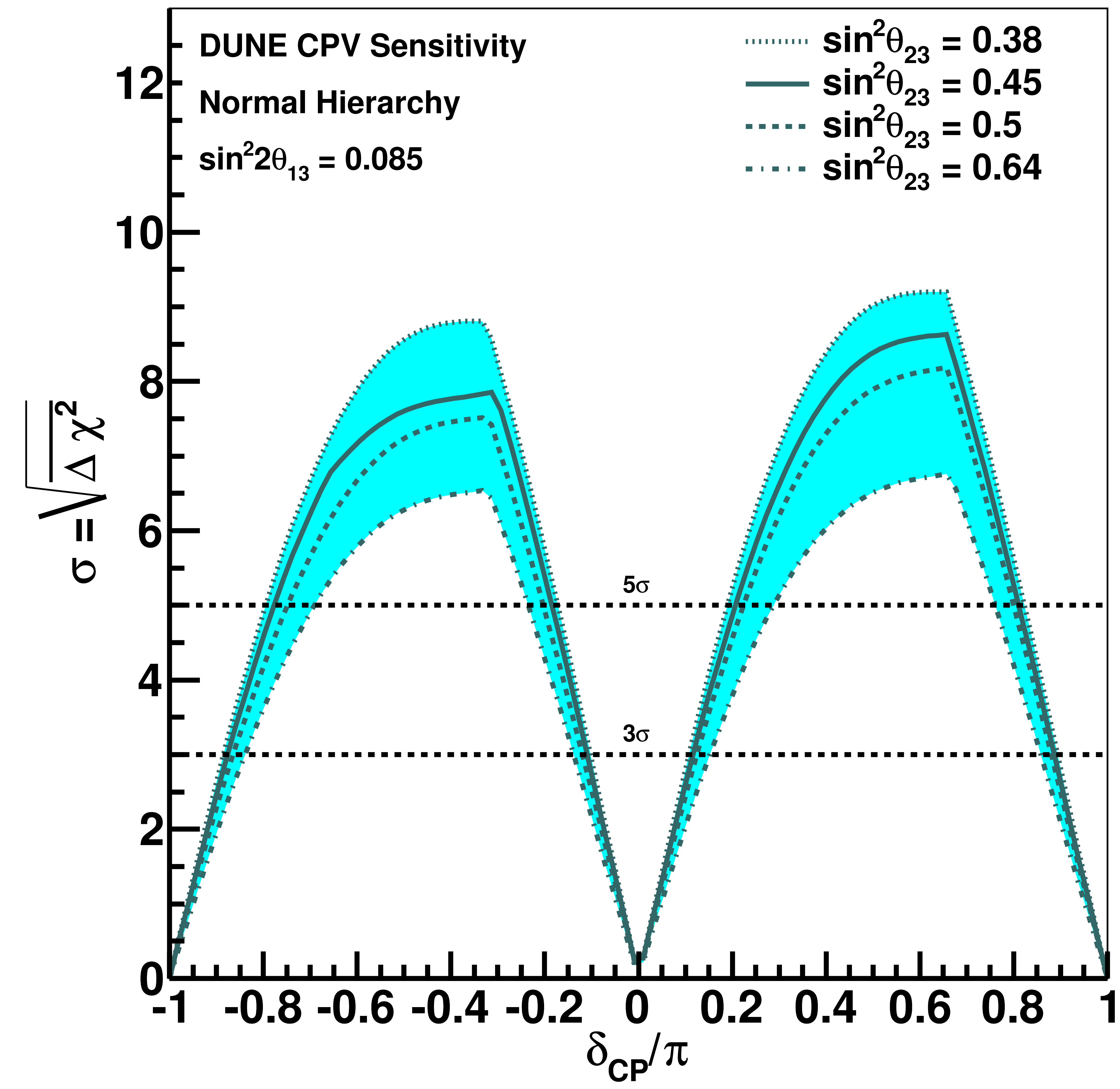


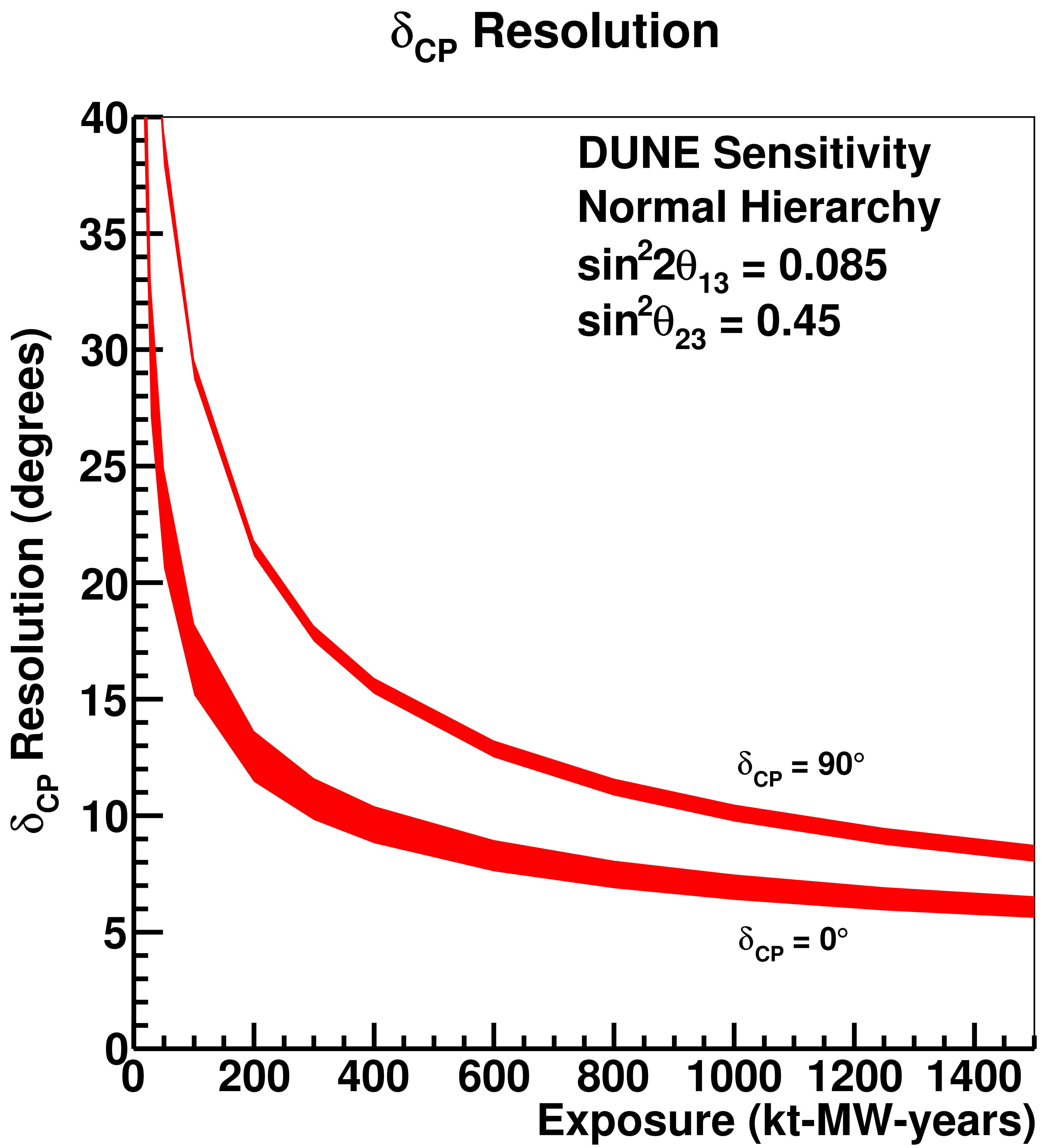
- Towards the largest LAr TPCs in existence (4 x 17 kT modules)

ν_e APPEARANCE AT DUNE:



SENSITIVITY:





SECOND OSCILLATION MAXIMUM

FROM BORIS

$$P(\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta) = \left| e^{-im_1^2 \frac{L}{2E}} \mathrm{Amp}^*(\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta) \right|^2$$

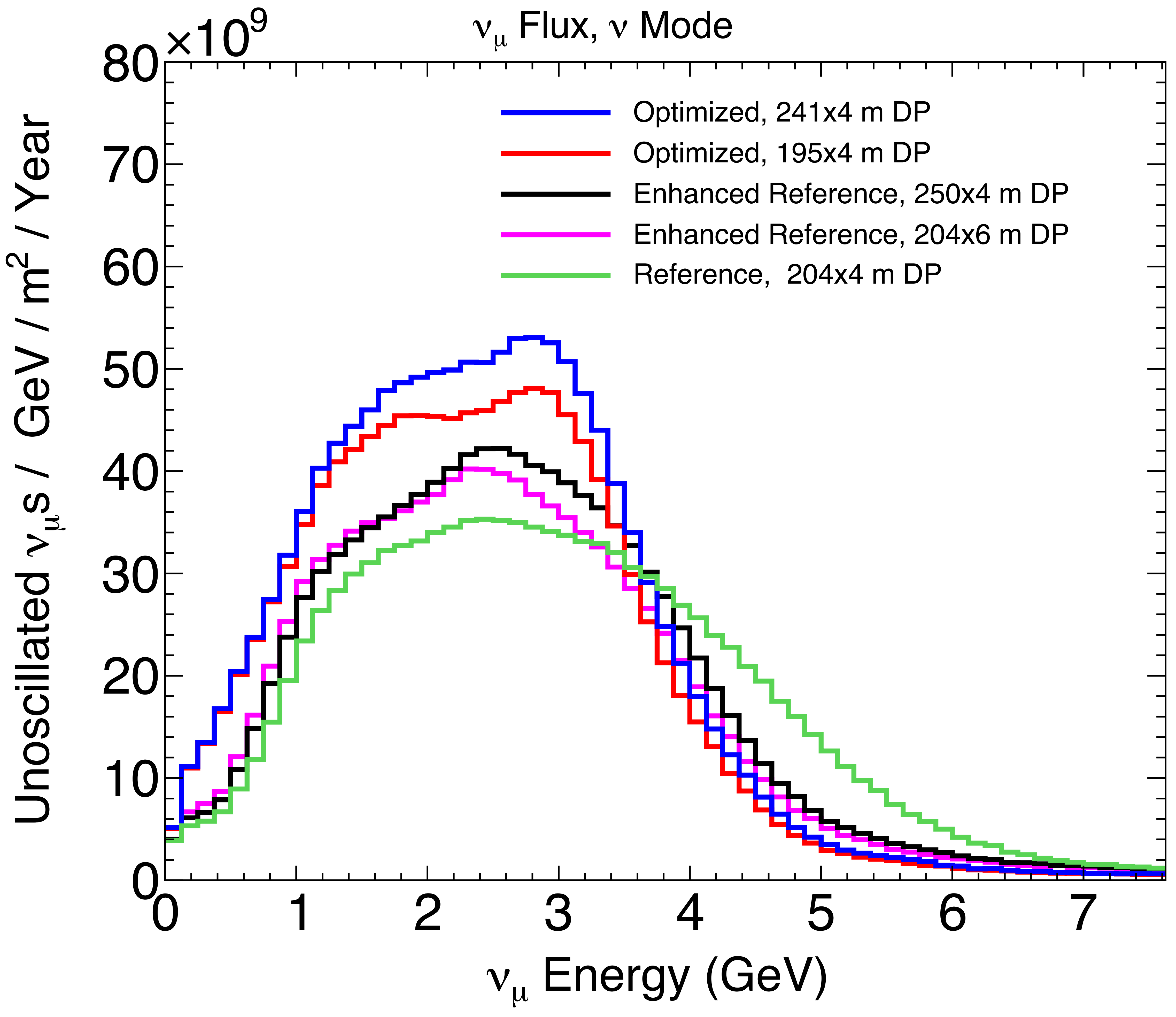
$$= 4[|U_{\alpha 3}U_{\beta 3}|^2 \sin^2 \Delta_{31} + |U_{\alpha 2}U_{\beta 2}|^2 \sin^2 \Delta_{21}$$

$$+2|U_{\alpha 3}U_{\beta 3}U_{\alpha 2}U_{\beta 2}| \sin \Delta_{31} \sin \Delta_{21} \cos(\Delta_{32} \underset{(-)}{+} \delta_{32})]$$

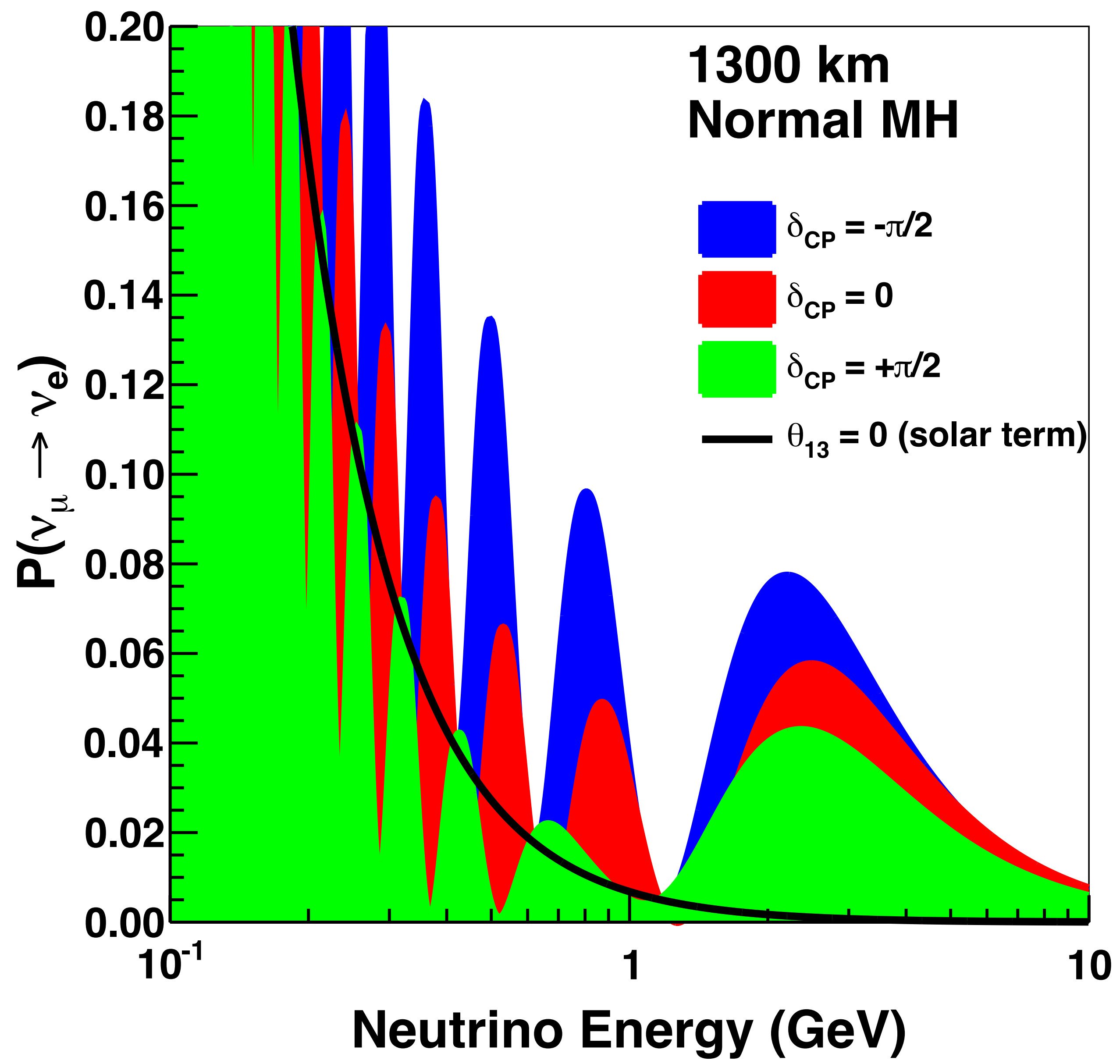
$$\text{Here } \delta_{32} \equiv \arg(U_{\alpha 3}U^*_{\beta 3}U^*_{\alpha 2}U_{\beta 2}) \,, \text{ a CP} - \text{violating phase.}$$

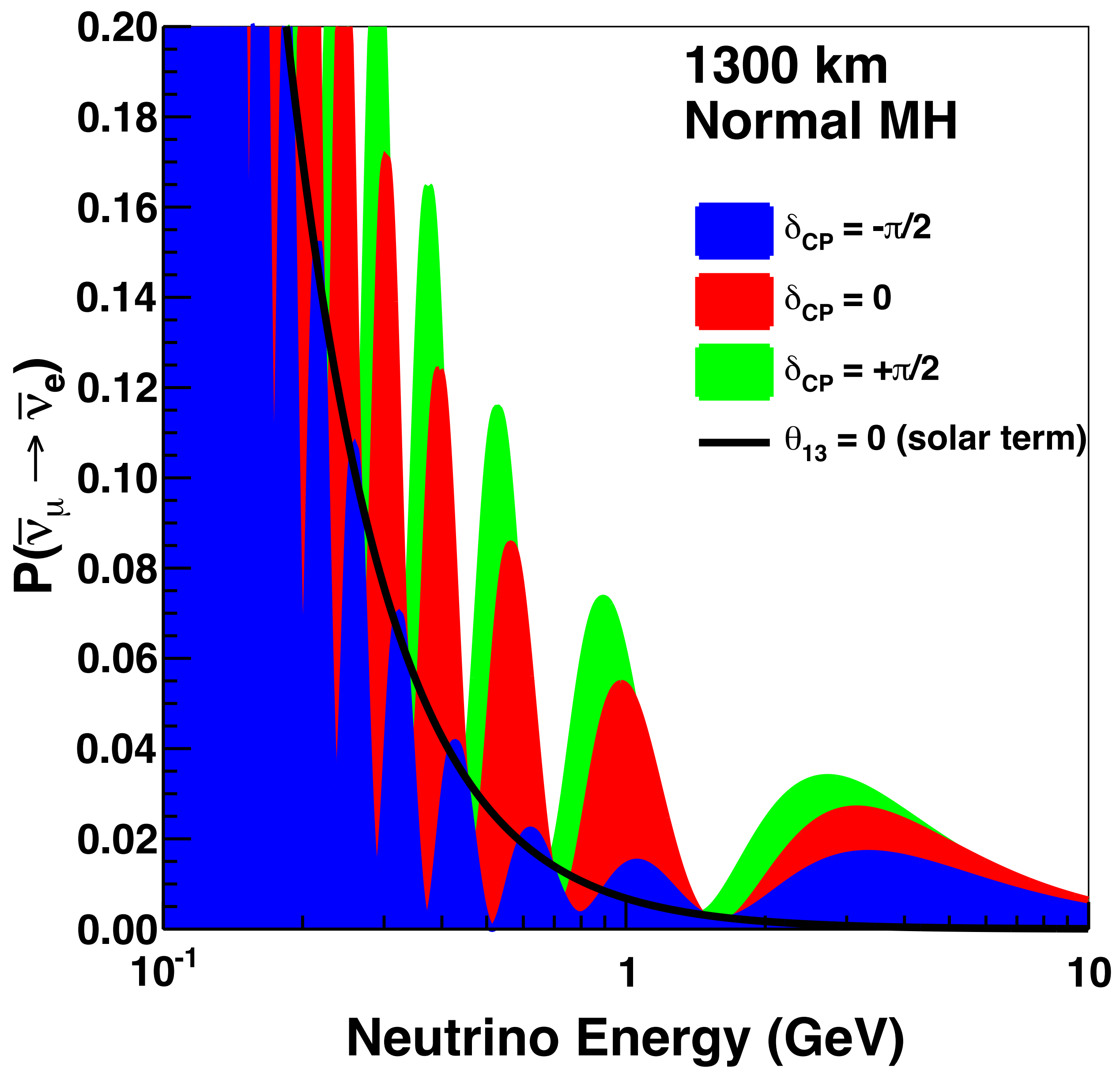
- We can expect a strong enhancement in CP violation effects at the second oscillation maximum.

OPTIMIZATION OF LBNF NEUTRINO BEAM



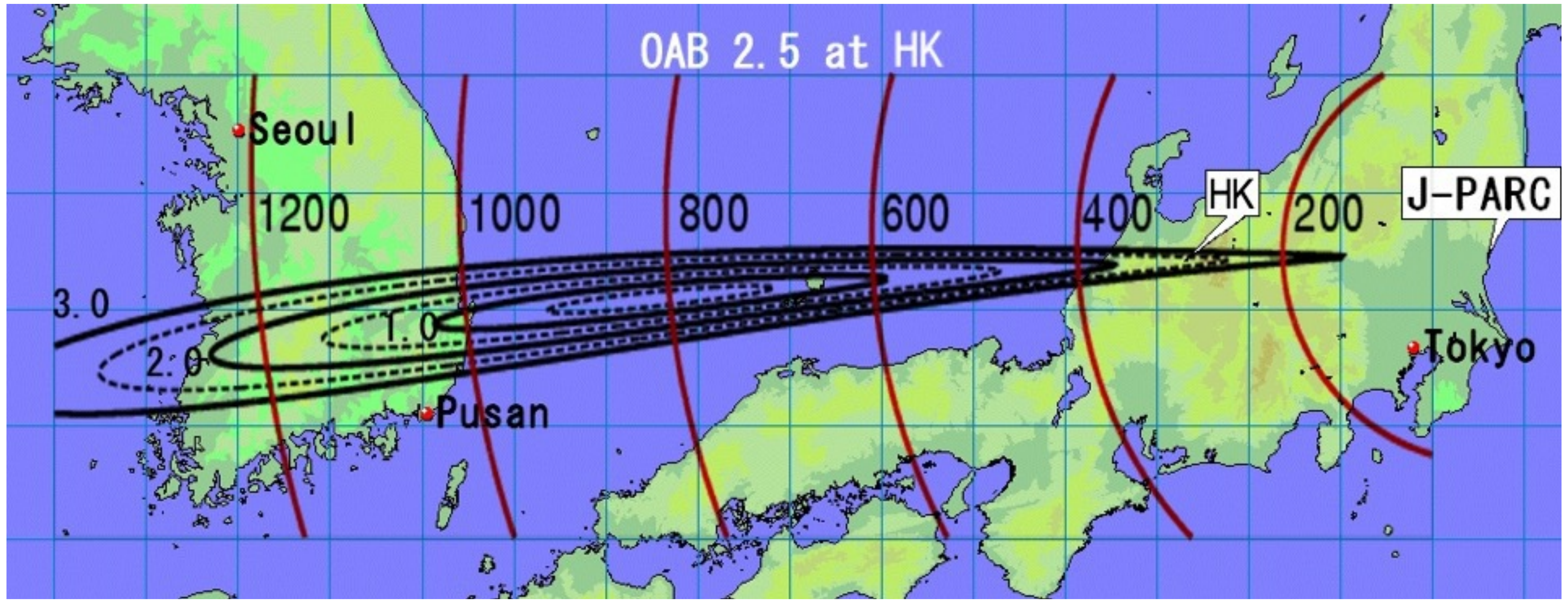
- Systematic study to optimize the beam line has resulted in a new design
  - second focussing horn is longer and further downstream
  - more flux at both the first and second oscillation maixmum
  - less wrong-sign background



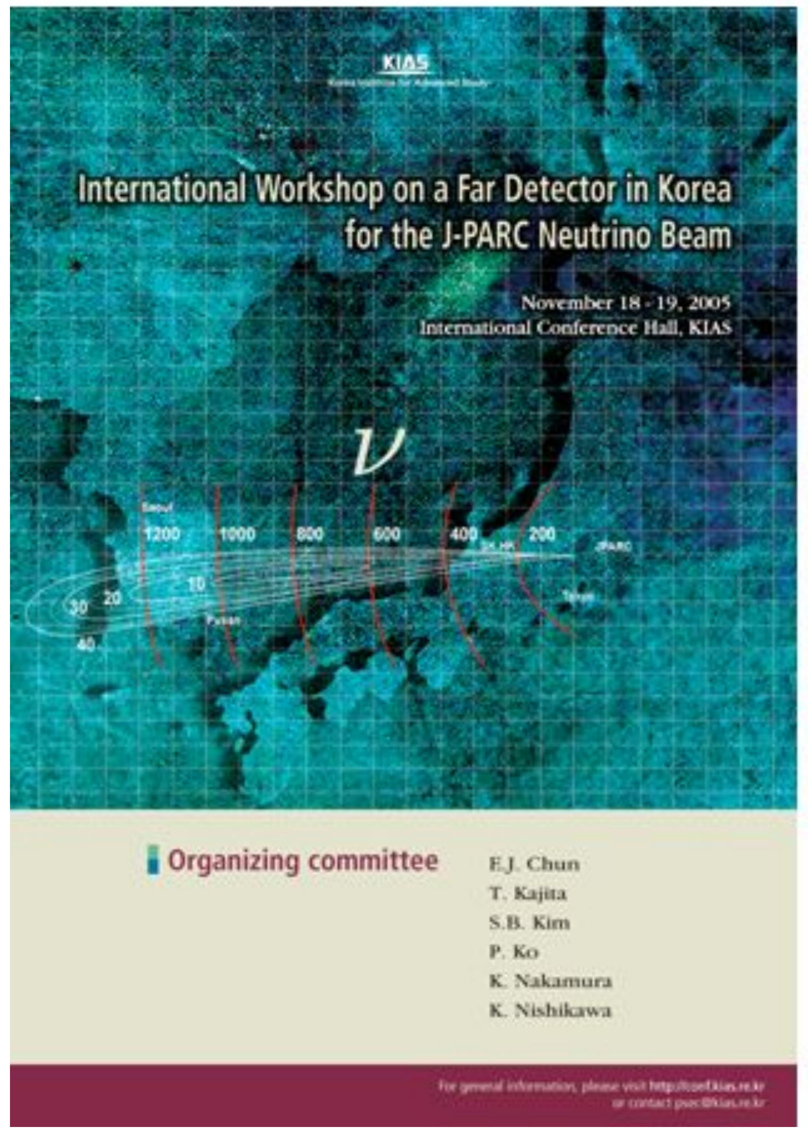


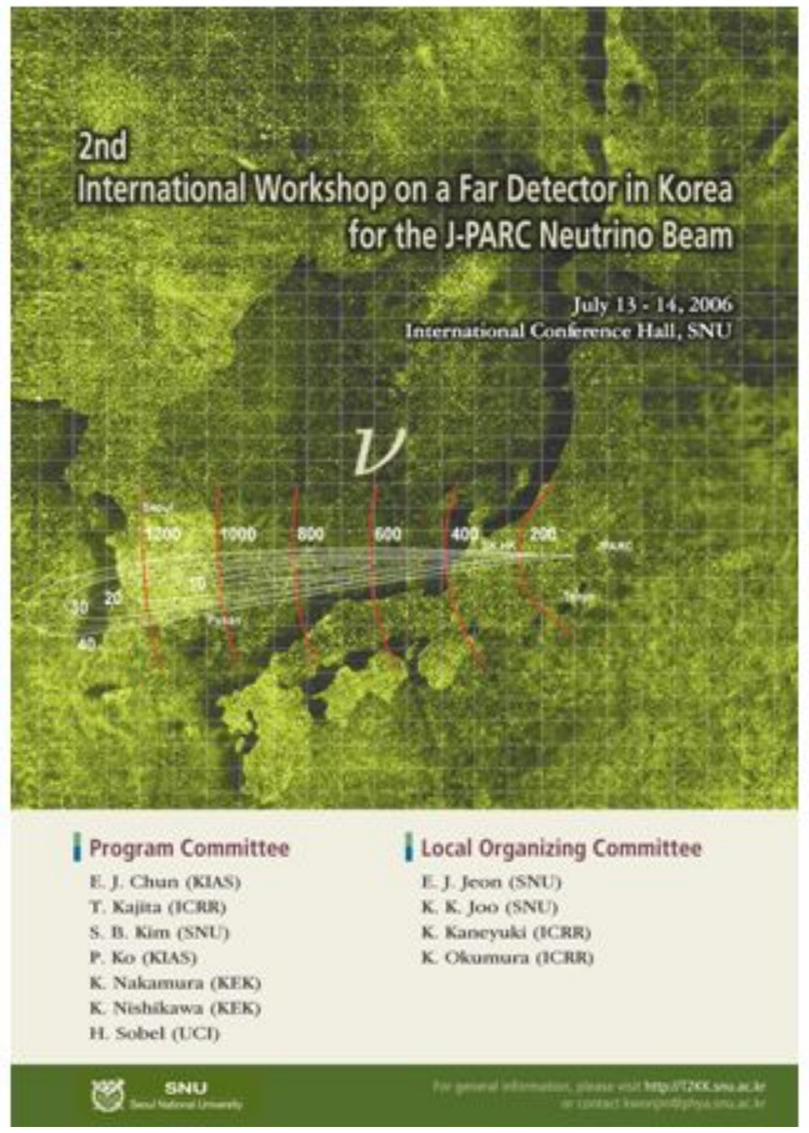
BEAM TO KOREA

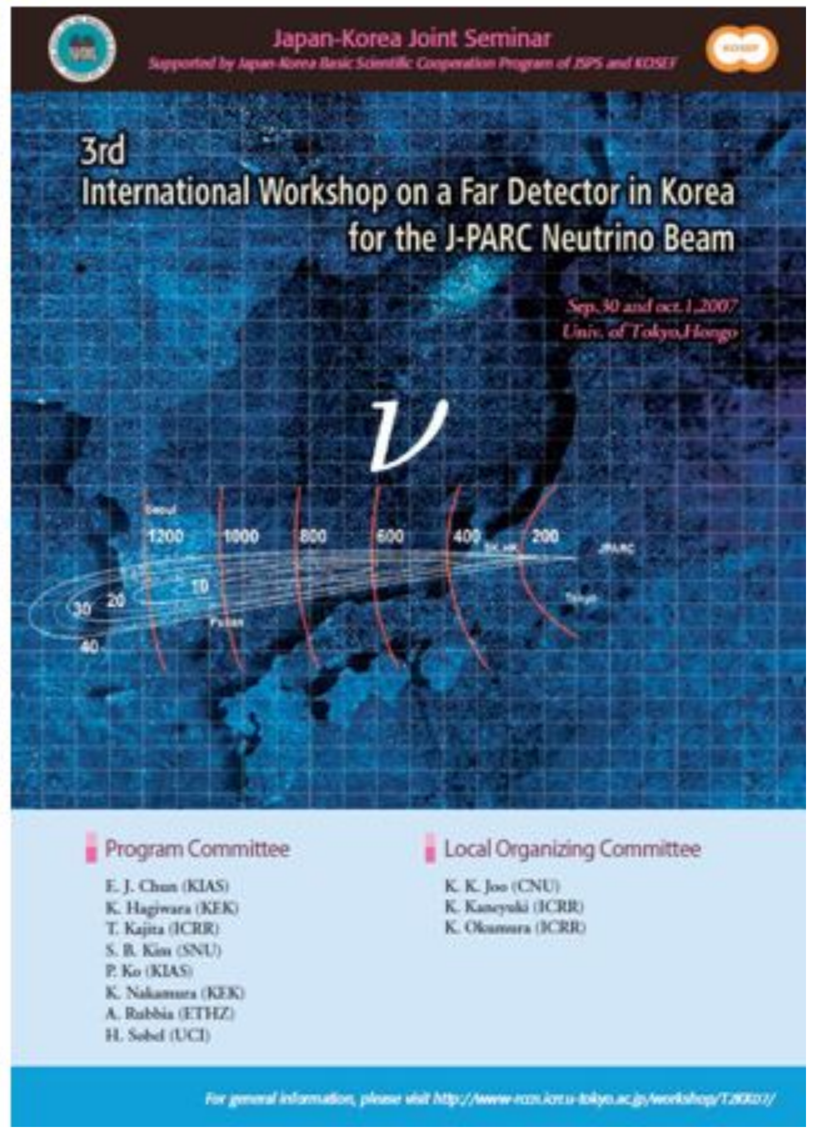
- Neutrino beams don't die . . . .
  - they can continue on to another detector
- The neutrino beam from J-PARC remerges out of the surface somewhere between Japan and South Korea
- Clips South Korea at an off-axis angle
  - various sites available for a detector between ~1 to ~3 degrees off axis
- Studies initiated over 10 years ago by T. Kajita (ICRR) and S.B. Kim (SNU)
  - focussed on having two detectors
    - one in Japan (Hyper-K)
    - one in Korea
    - with identical off-axis angles
  - θ_{13} not known at the time . . .



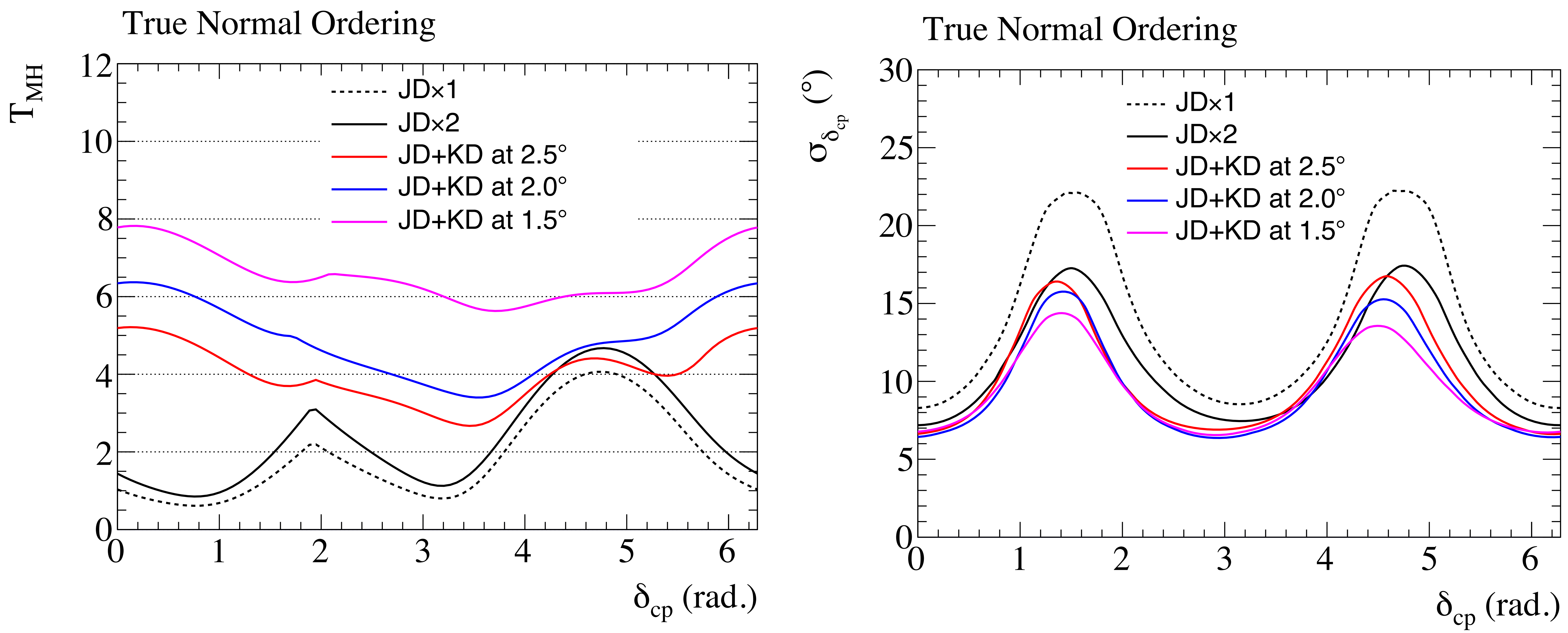
2005 KIAS | **2006 SNU** | **2007 U. Tokyo**

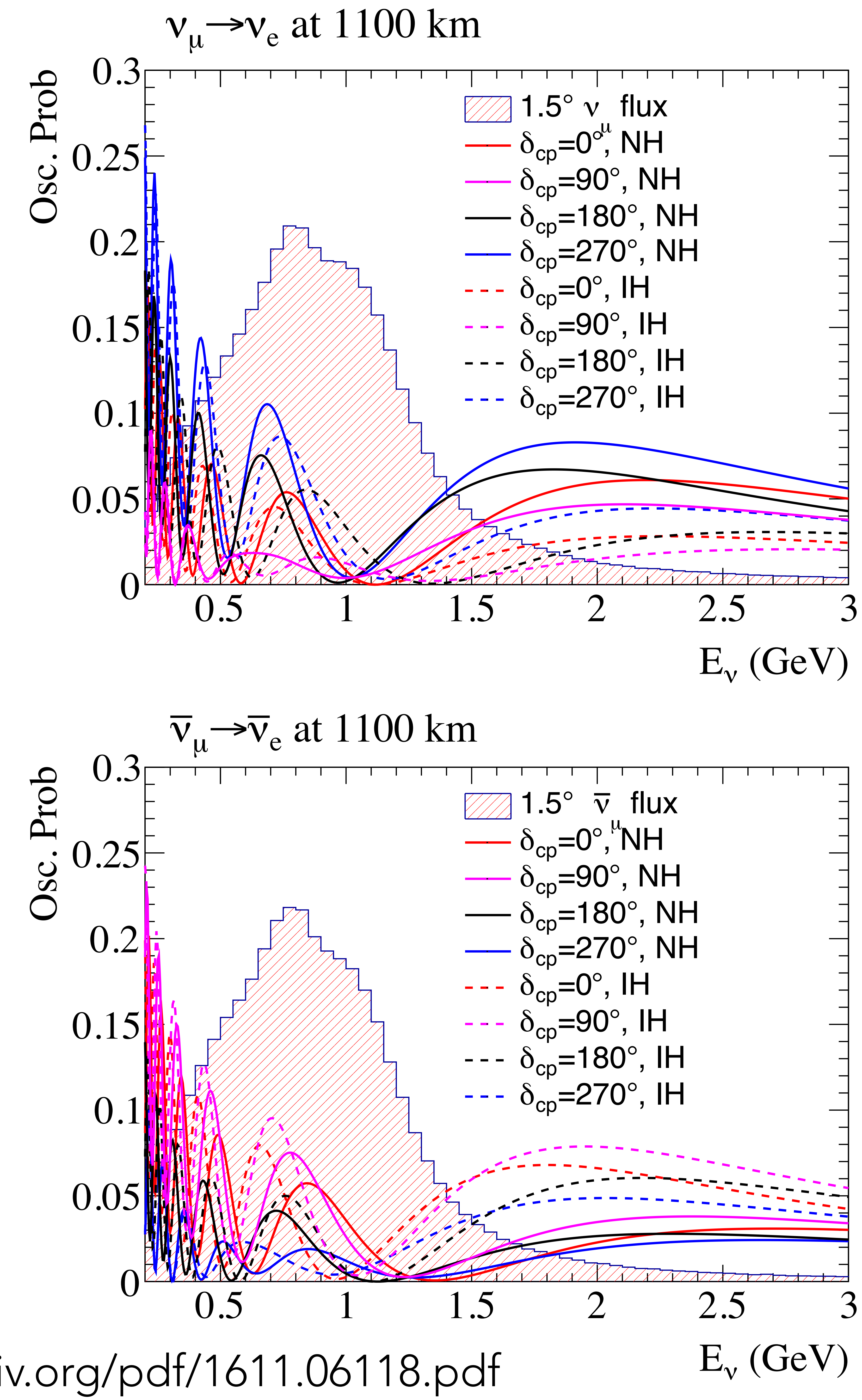






REVIVAL OF THE IDEA





- Reoptimization suggests that ~1.5deg off-axis angle is optimal
  - wider beam captures a bit of the first oscillation maximum
  - fully covers the second oscillation maximum
  - available site at ~1100 km and 1.3 deg off-axis
- Significantly improves relative to 1 (even 2) detectors at 295 km
  - mass ordering sensitivity
  - δ_{CP} precision in maximal cases of $\pm\pi/2$

http://arxiv.org/pdf/1611.06118.pdf

CONCLUSIONS

- It’s a golden age for (long-baseline) accelerator-based neutrino experiments
  - it’s been a “golden age” for neutrinos for a while . . . .
  - successive experiments over 15 years have made major milestones in studying neutrinos
- The future looks very bright:
  - continuation of highly successful ongoing experiments: T2K, NOvA
  - future program with DUNE/LBNF an Hyper-Kamiokande
  - Very rich in scientific opportunities
  - but with significant technical and scientific challenges (opportunities) for you!