H. A. TANAKA (UNIVERSITY OF TORONTO/IPP/TRIUMF)

NEUTRINO OSCILLATION EXPERIMENTS PART II

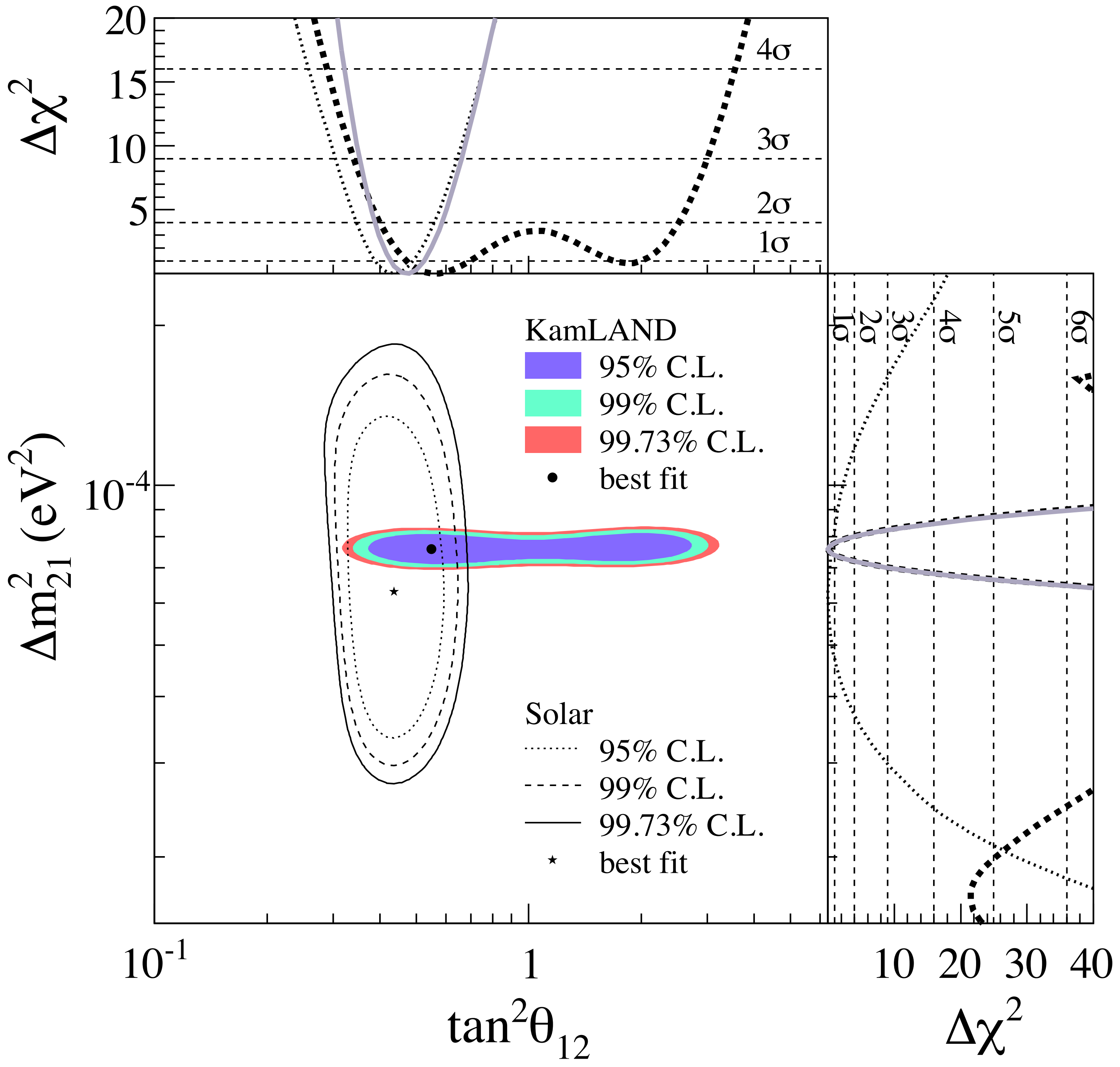
TRISEP 2016

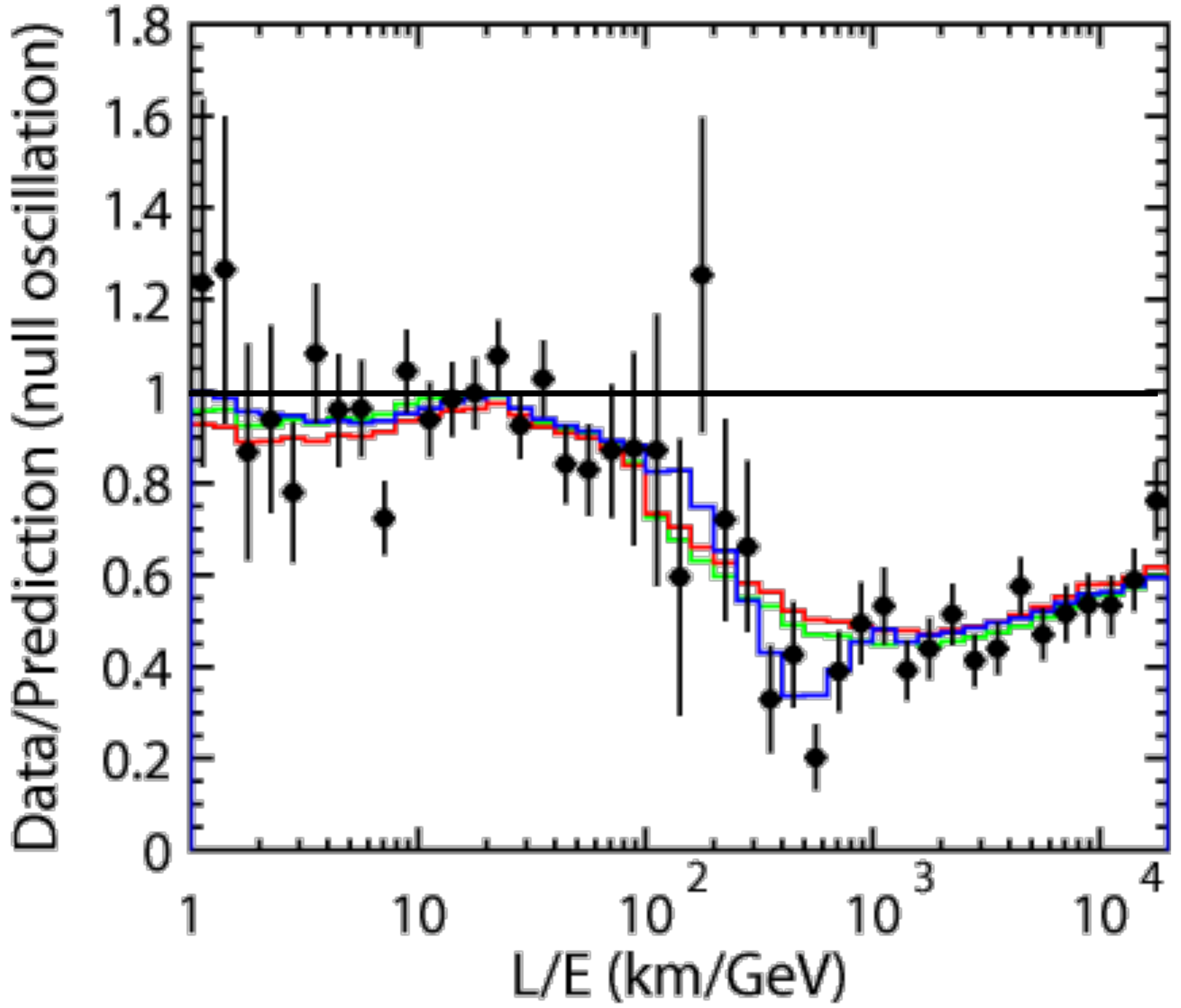
OVERVIEW

- Yesterday:
    - Challenges of studying neutrinos experimentally
    - Neutrino sources
    - Basic categorization of neutrino detectors
    - Quick review of neutrino oscillations
    - "Classical era" of neutrino oscillations
        - reactor and solar neutrino oscillations
        - atmospheric neutrino oscillations
- Today:
    - Verifying atmospheric neutrino oscillations
        - accelerator-based experiments
    - Three-flavour mixing
        - ν_e appearance, CP violation, θ_{23} octant, mass hierarchy . . .
    - Looking forward . . . .

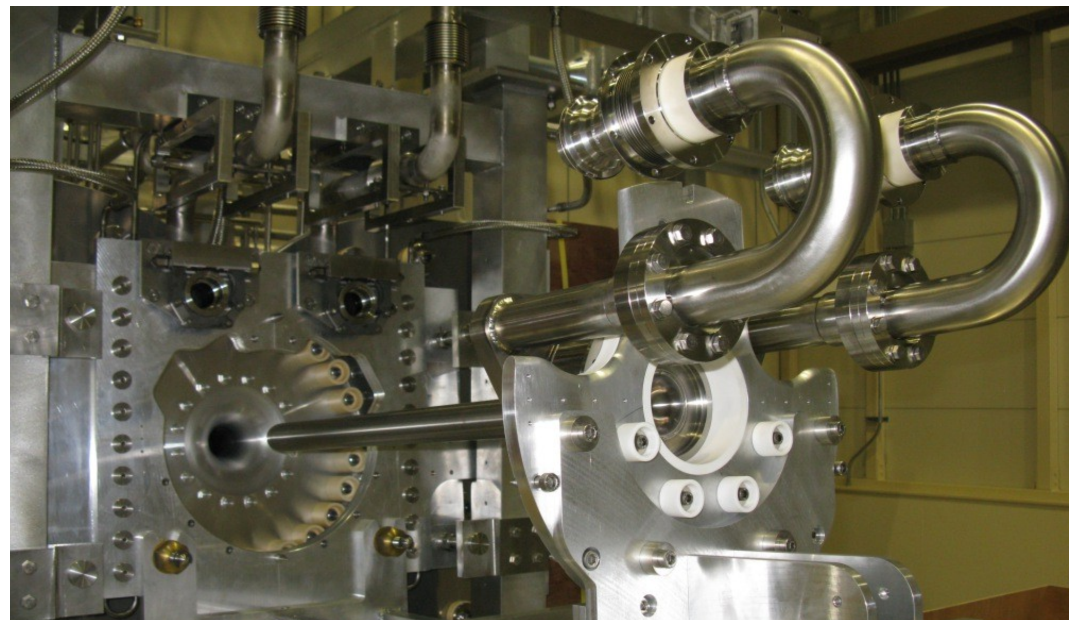
RECALL:

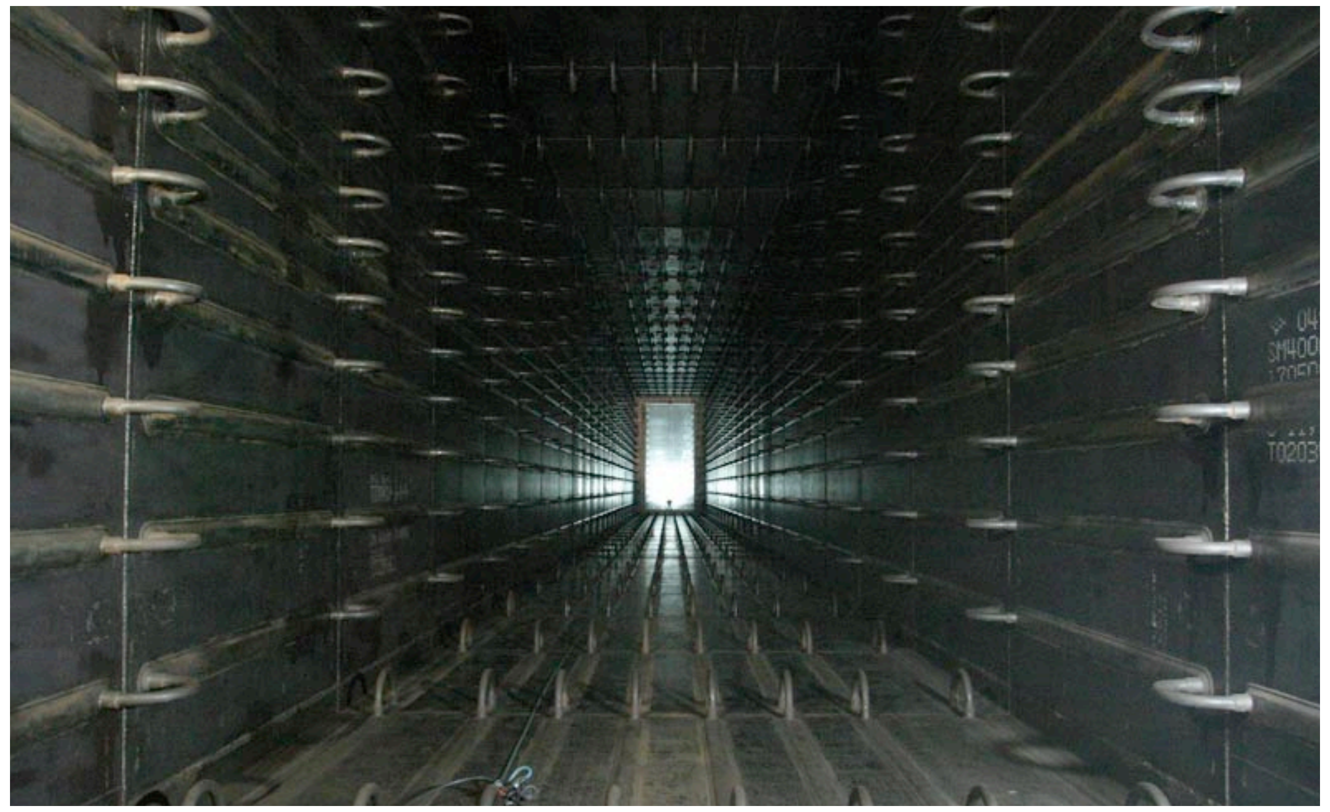
- A large deficit in ν_e from the sun explained by neutrino oscillations
  - SNO results show that ν_e are transitioning to other "active" flavours (ν_μ/ν_τ)
  - Absence of oscillatory behaviour in SK and SNO show the central role of matter effects
    - ν emerging from the sun are in an ~energy eigenstate
  - Confirmation of oscillatory signature at KAMLAND using reactor antineutrinos
  - Oscillation parameters:
    - $\sin^2 2\theta_{12}$ ~ 0.85, Δm^2_{21} ~ 7.5x10^{-5} eV^2
- A large deficit of ν_μ from atmospheric neutrinos observed at SK
  - zenith angle maps into baseline (L)
  - zenith angle dependence matches neutrino oscillations
    - $\sin^2 2\theta_{23}$ ~ 1, Δm^2_{32} ~ 2.5x10^{-3} eV^2
  - excess of ν_e not observed
    - infer that ν_μ are primarily oscillating to ν_τ
  - Can we confirm this with an person-made beam?

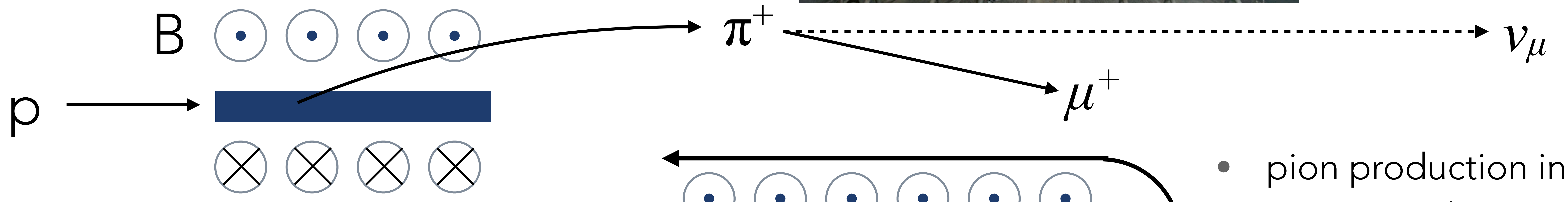


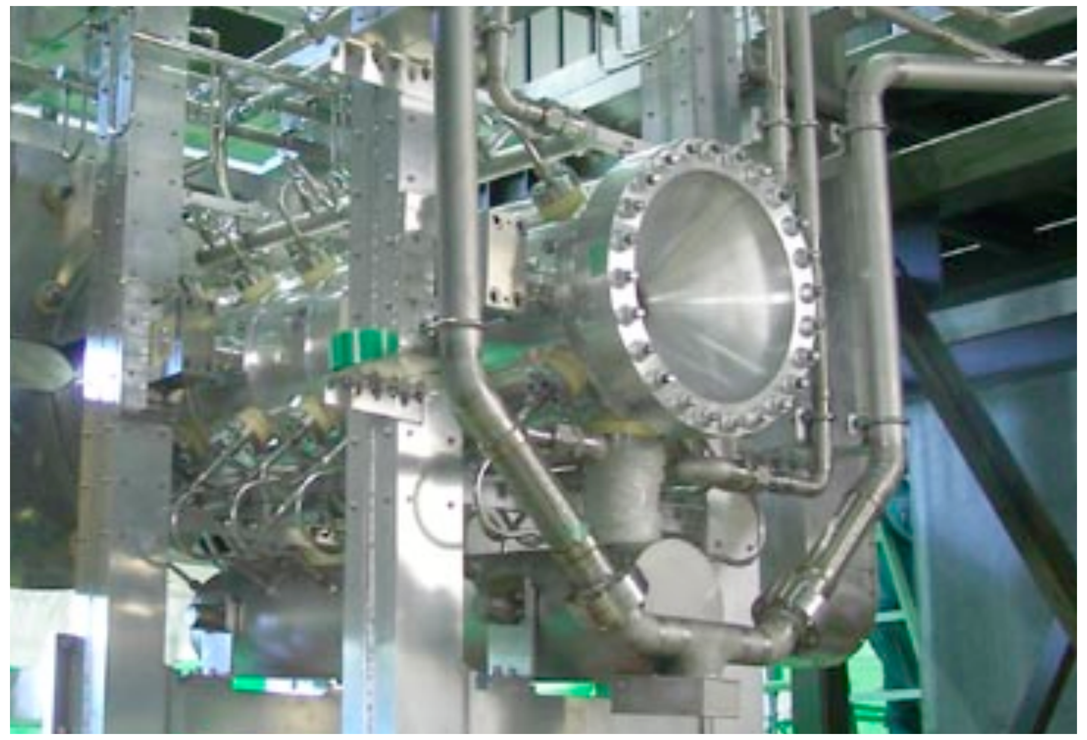


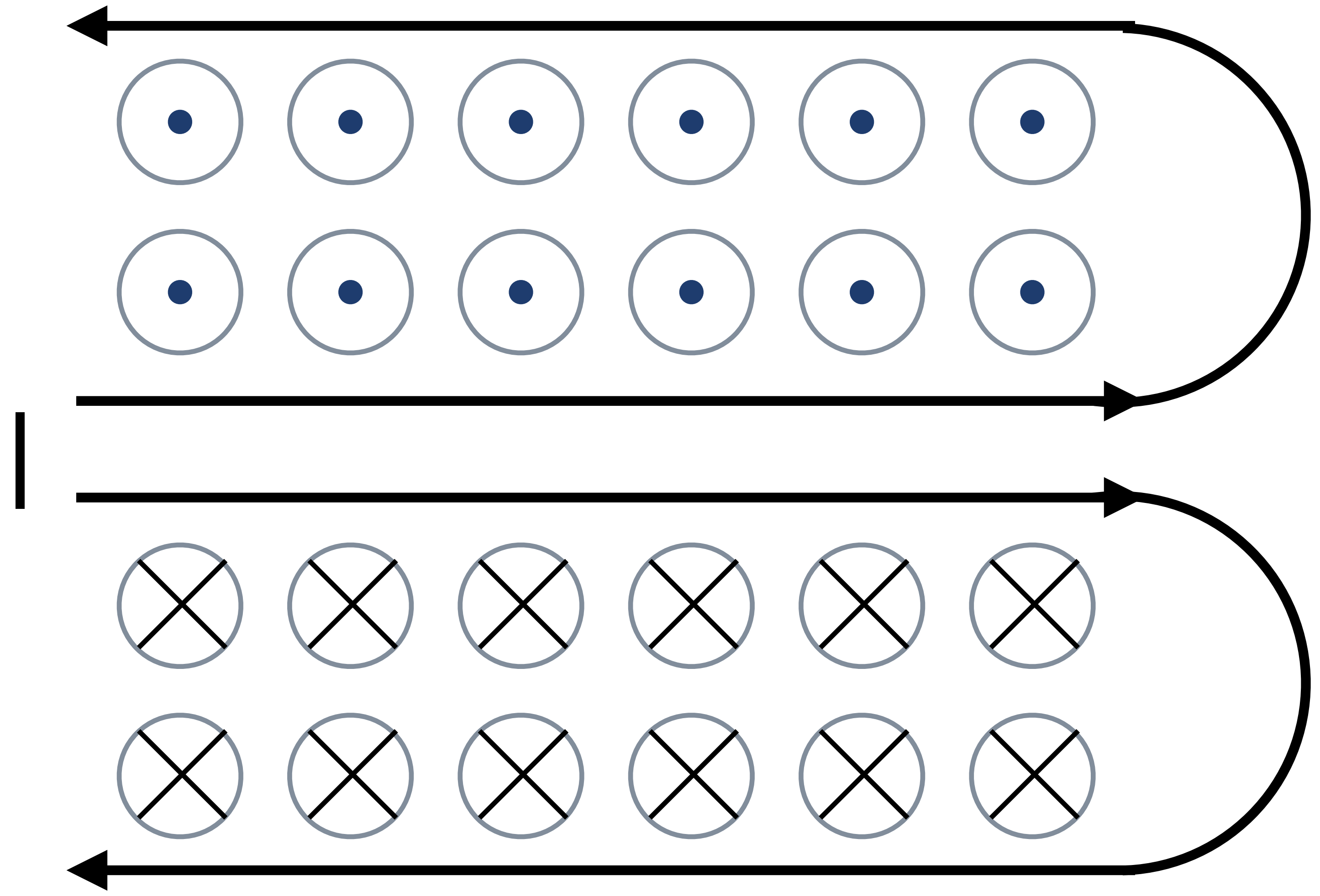
ACCELERATOR-BASED EXPERIMENTS









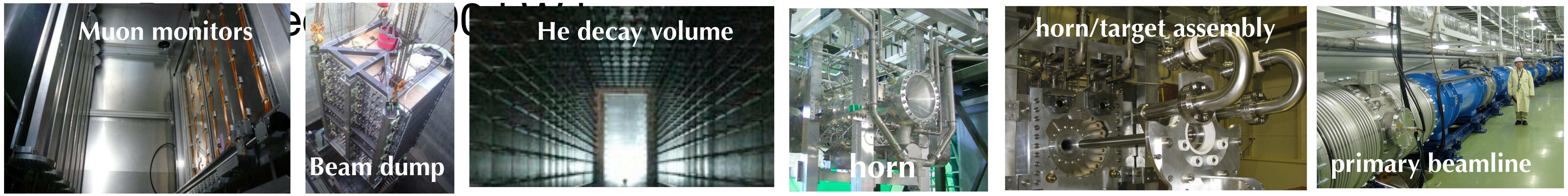


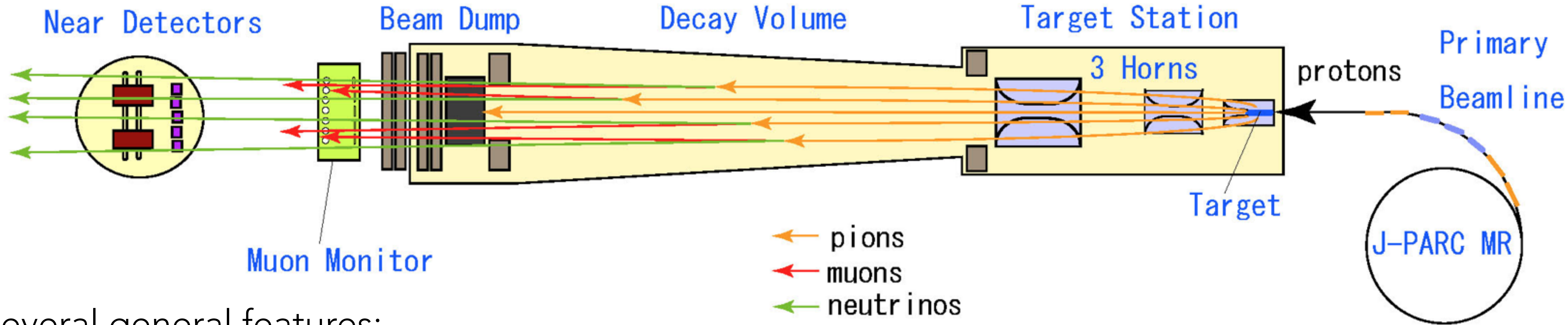
- pion production induced by proton-nucleus interactions
- one sign of pions focussed with electromagnet ("horn") into a long decay region where they decay to produce muon neutrinos
- "flip" the polarity to produce an muon antineutrino beam

1962

- Horn concept from Simon van der Meer (CERN, 1962)
- “Quiet Giant of Engineering and Physics”

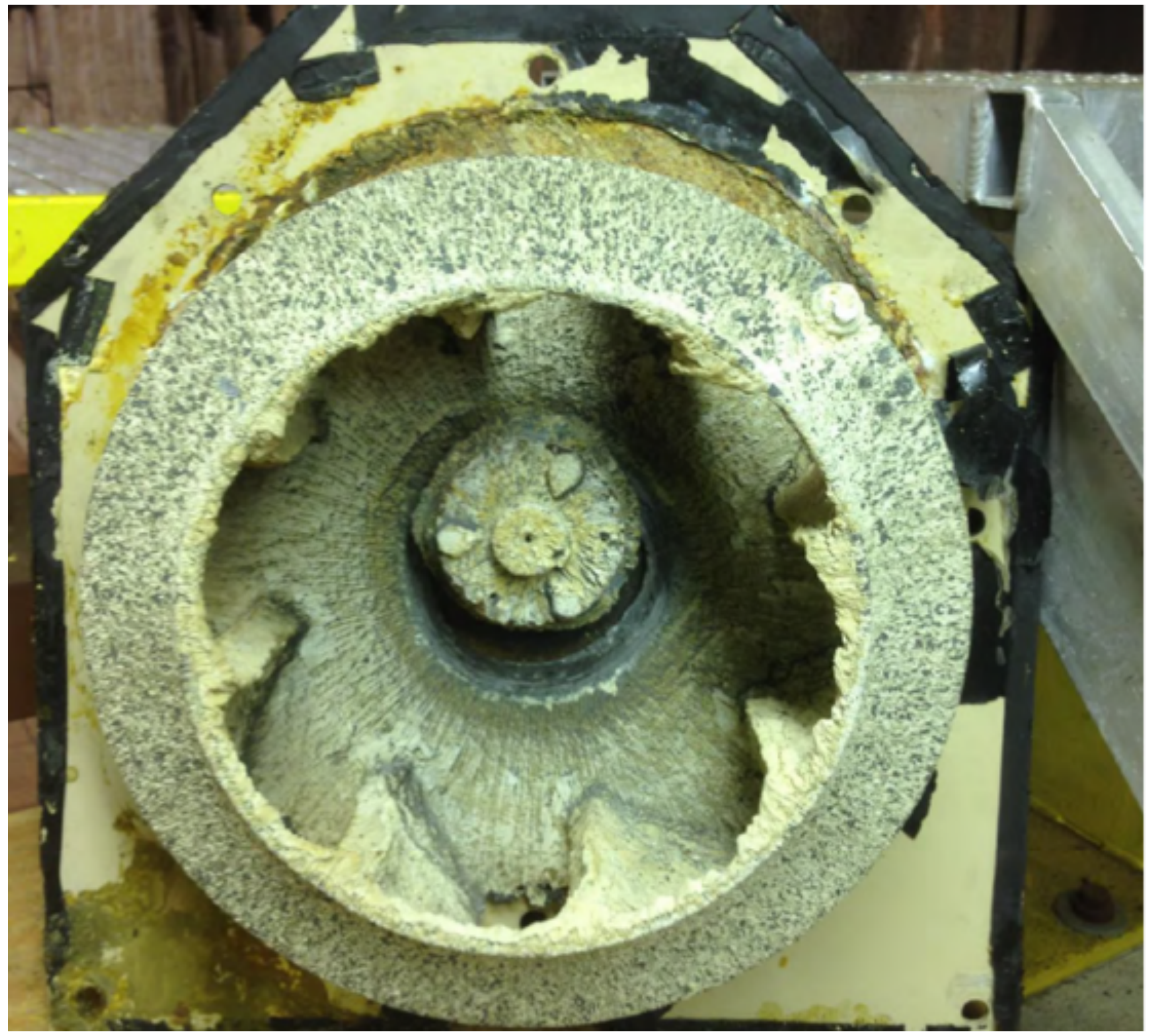
PRODUCING A NEUTRINO BEAM

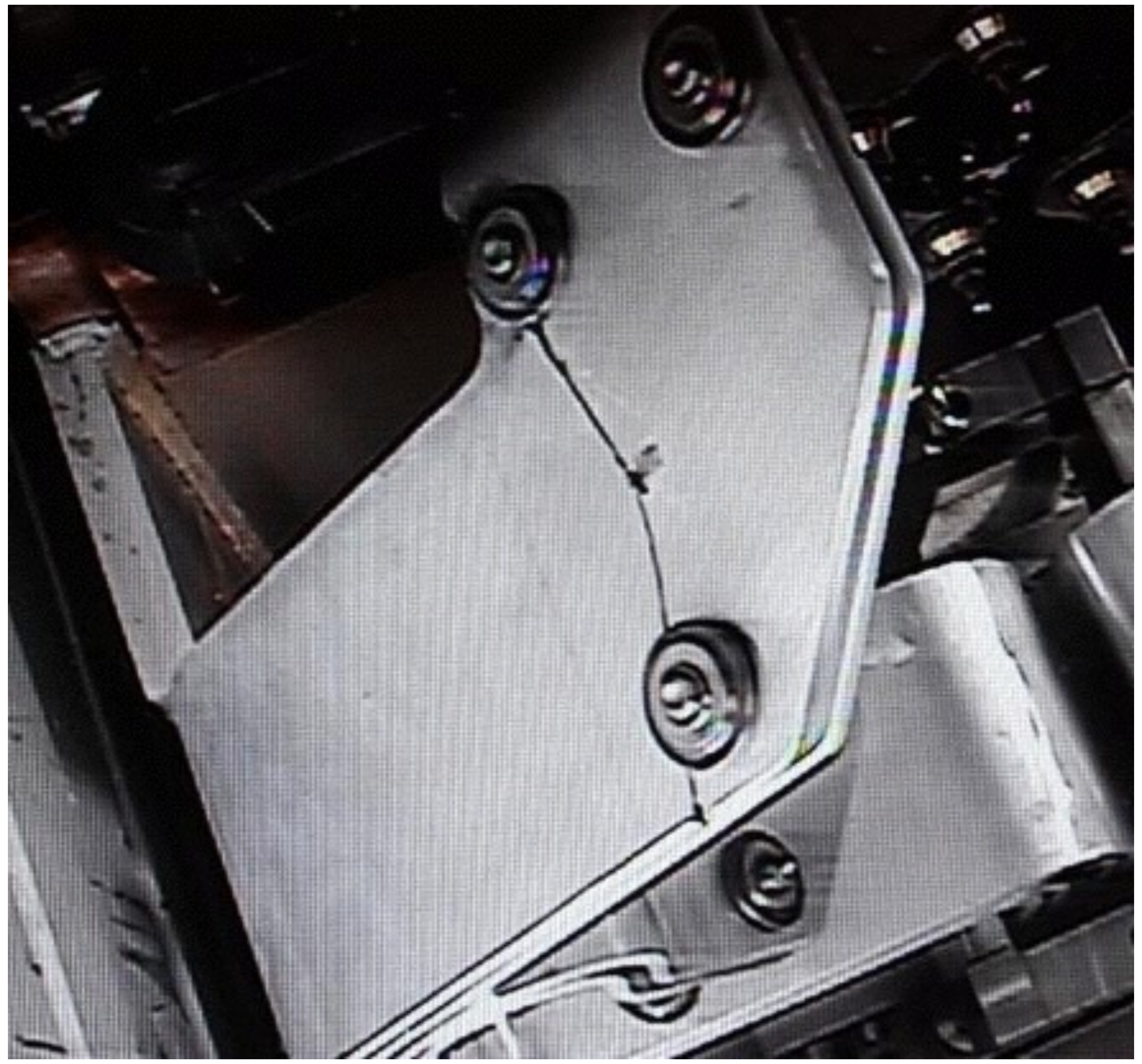


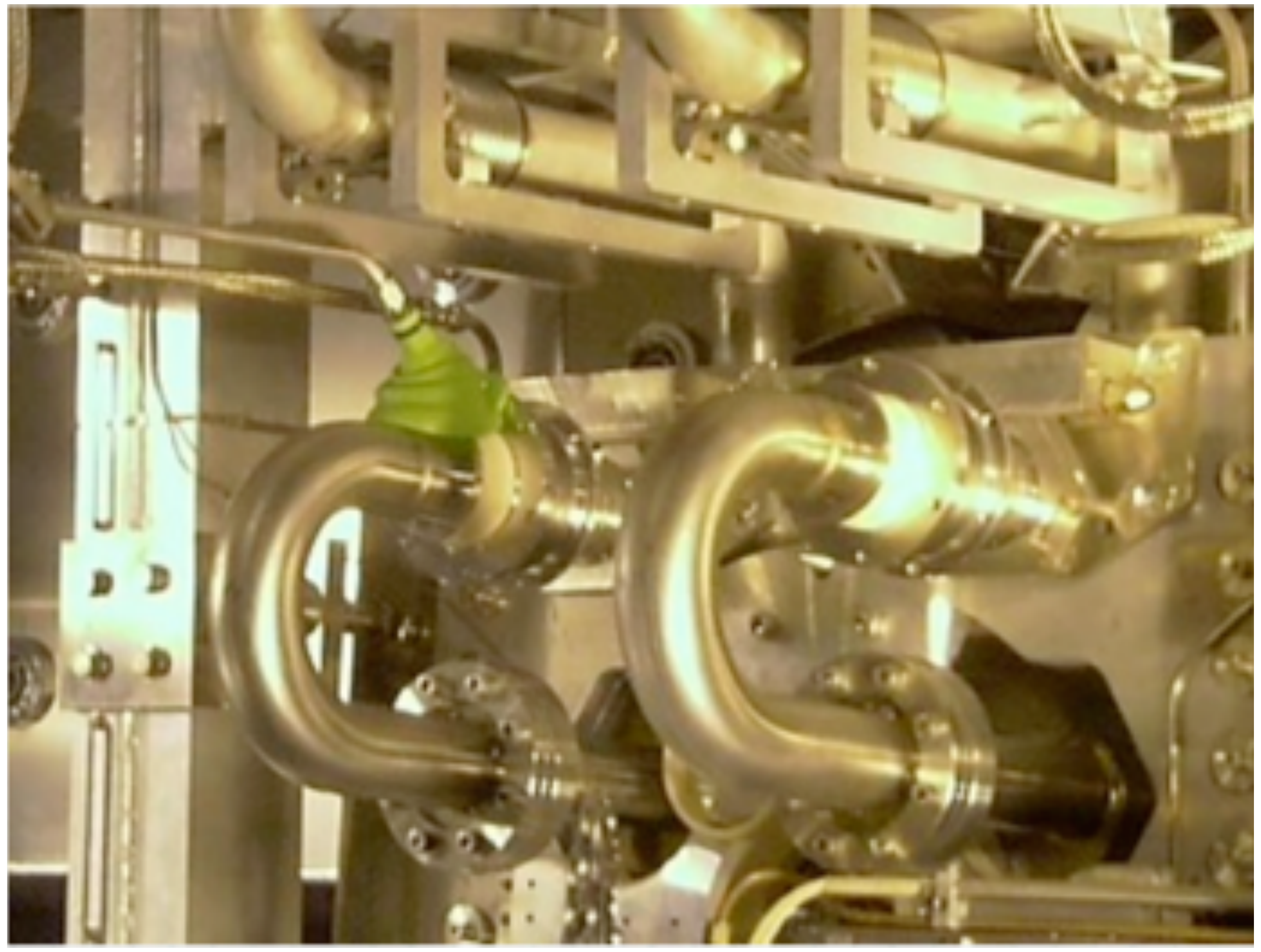


- Several general features:
  - upstream proton beam monitors
  - multiple horns
  - “Beam dump” or “beam absorber”: stop all particles except neutrinos (and muons)
  - muon monitors behind beam dump can measure stability of the beam
- **“Conventional Neutrino Beam”**

CHALLENGES



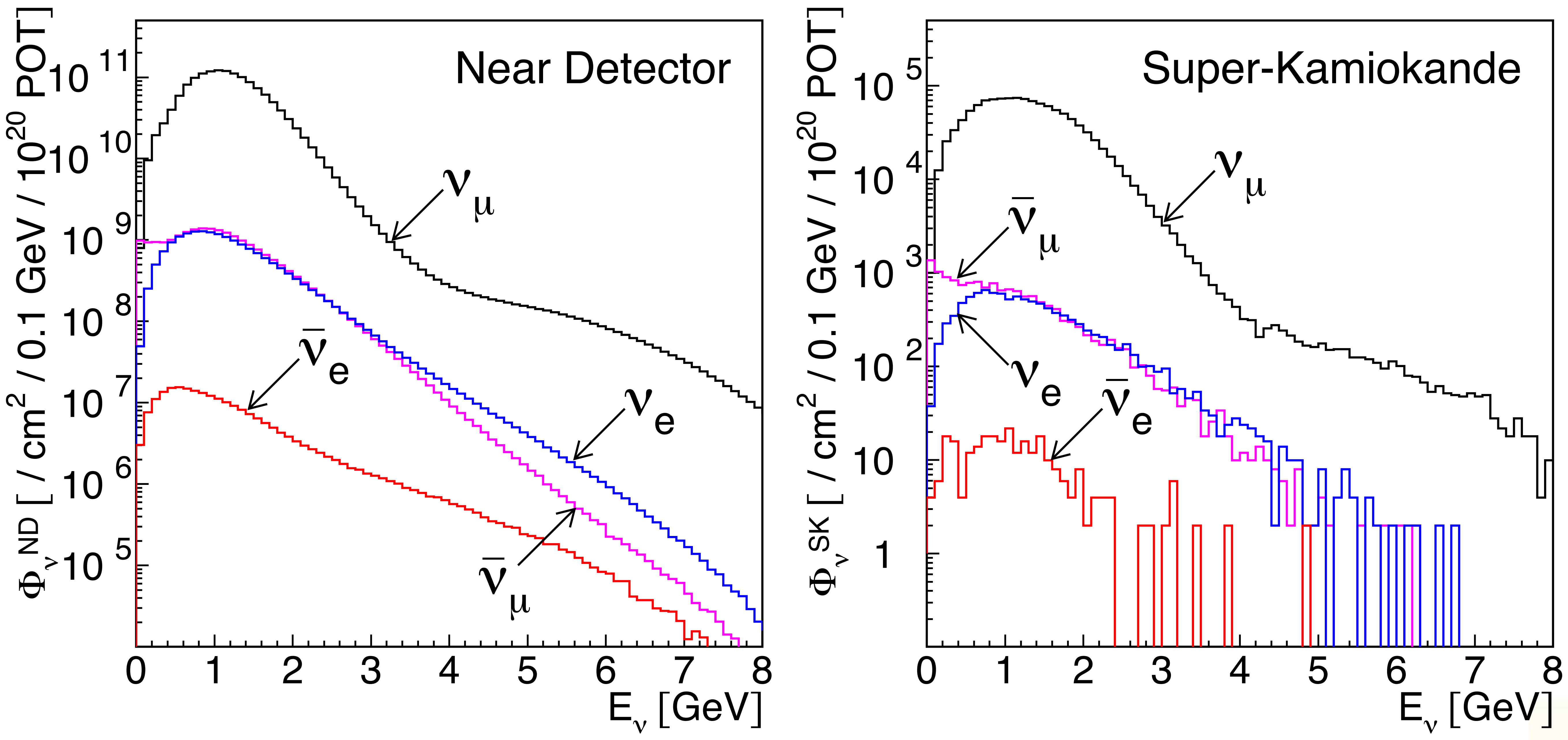




https://youtu.be/VWGXz5QHFH4

- High radiation
- enormous currents in horn
  - several hundred kA
- enormous mechanical shock/stress
- corrosion
- etc.

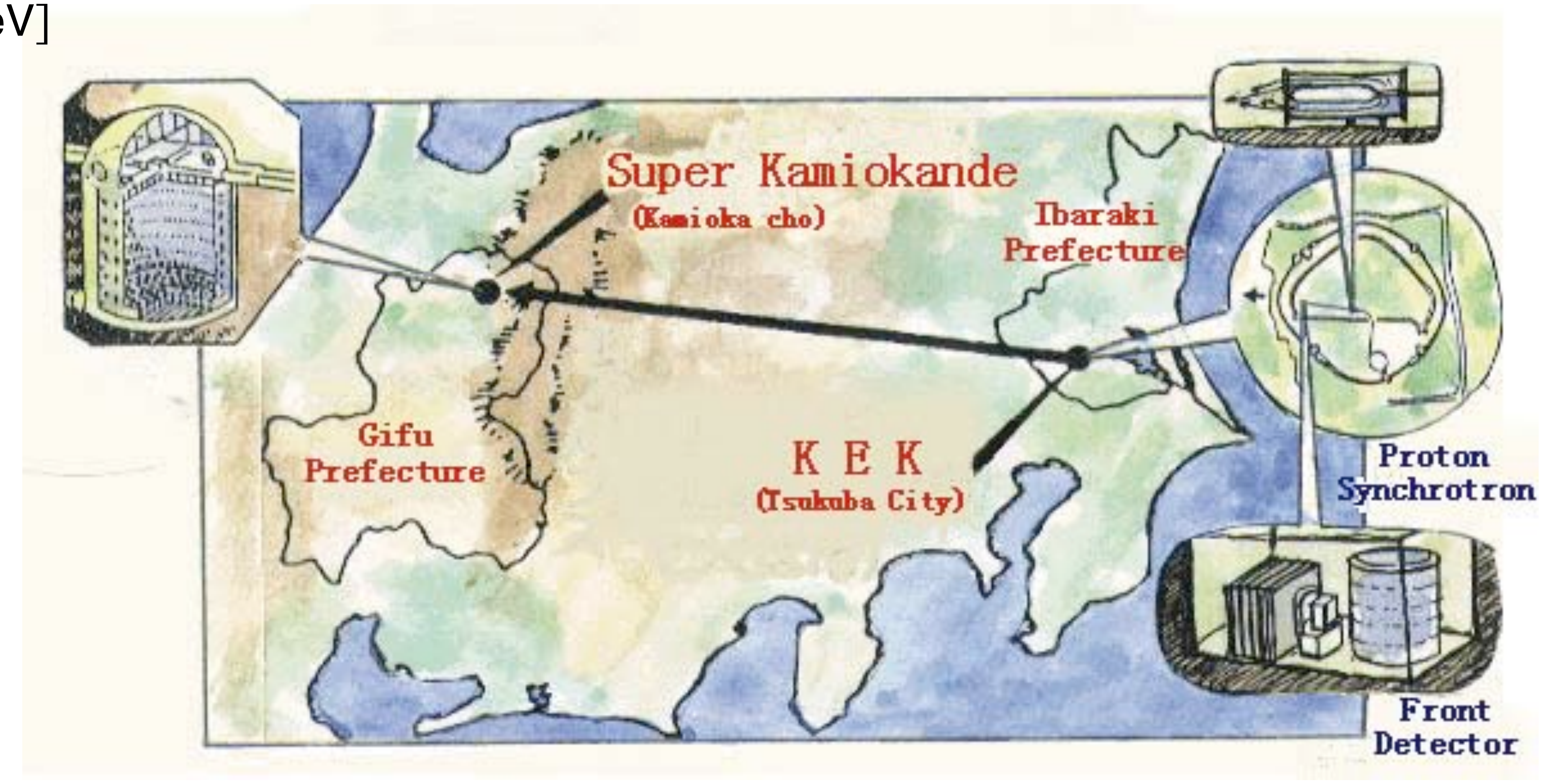
K2K (KEK-TO-KAMIOKA)



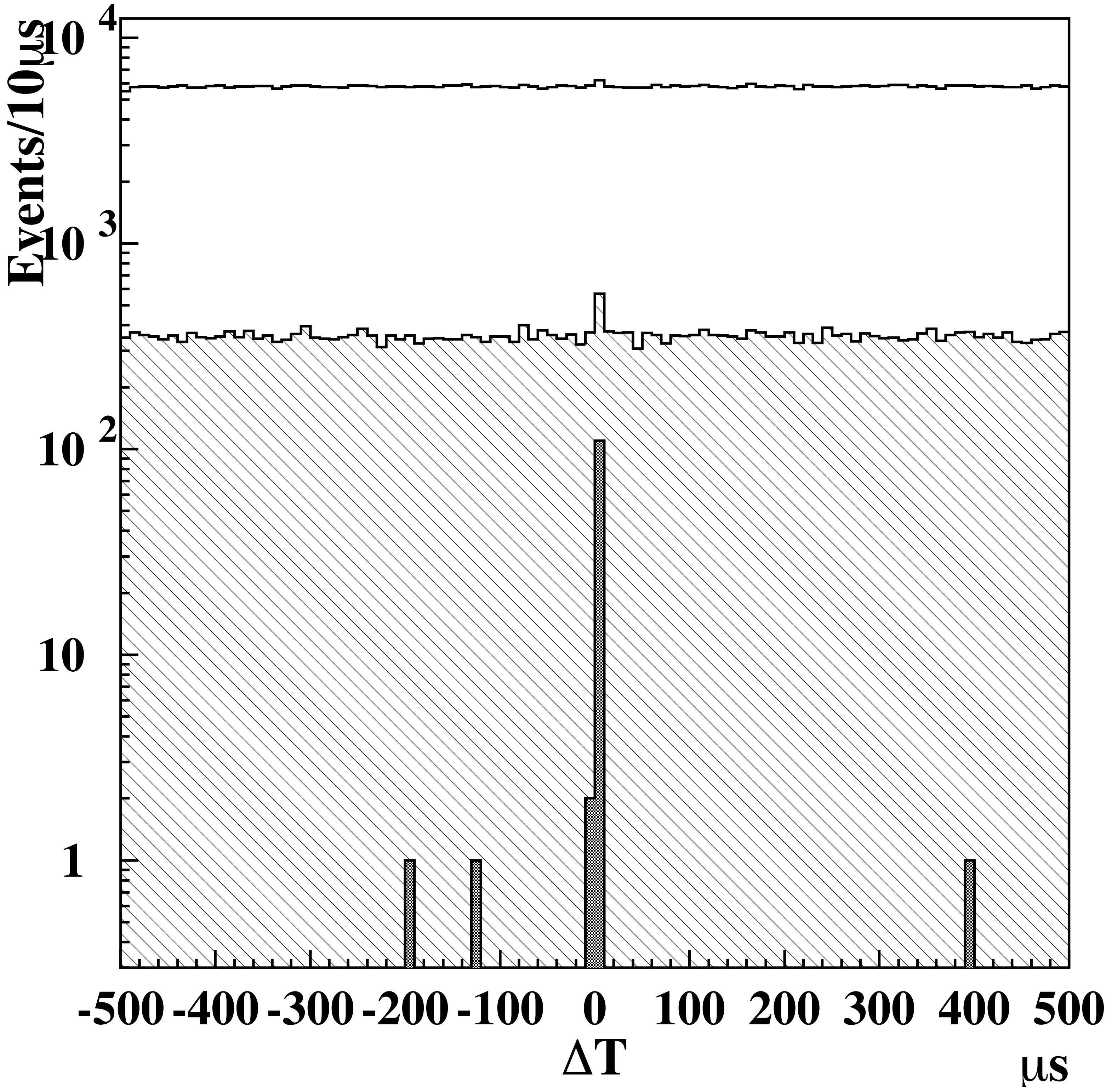
$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \times \sin^2 \left[1.27\Delta m^2 \frac{L(\mathrm{km})}{E(\mathrm{GeV})}\right]$$

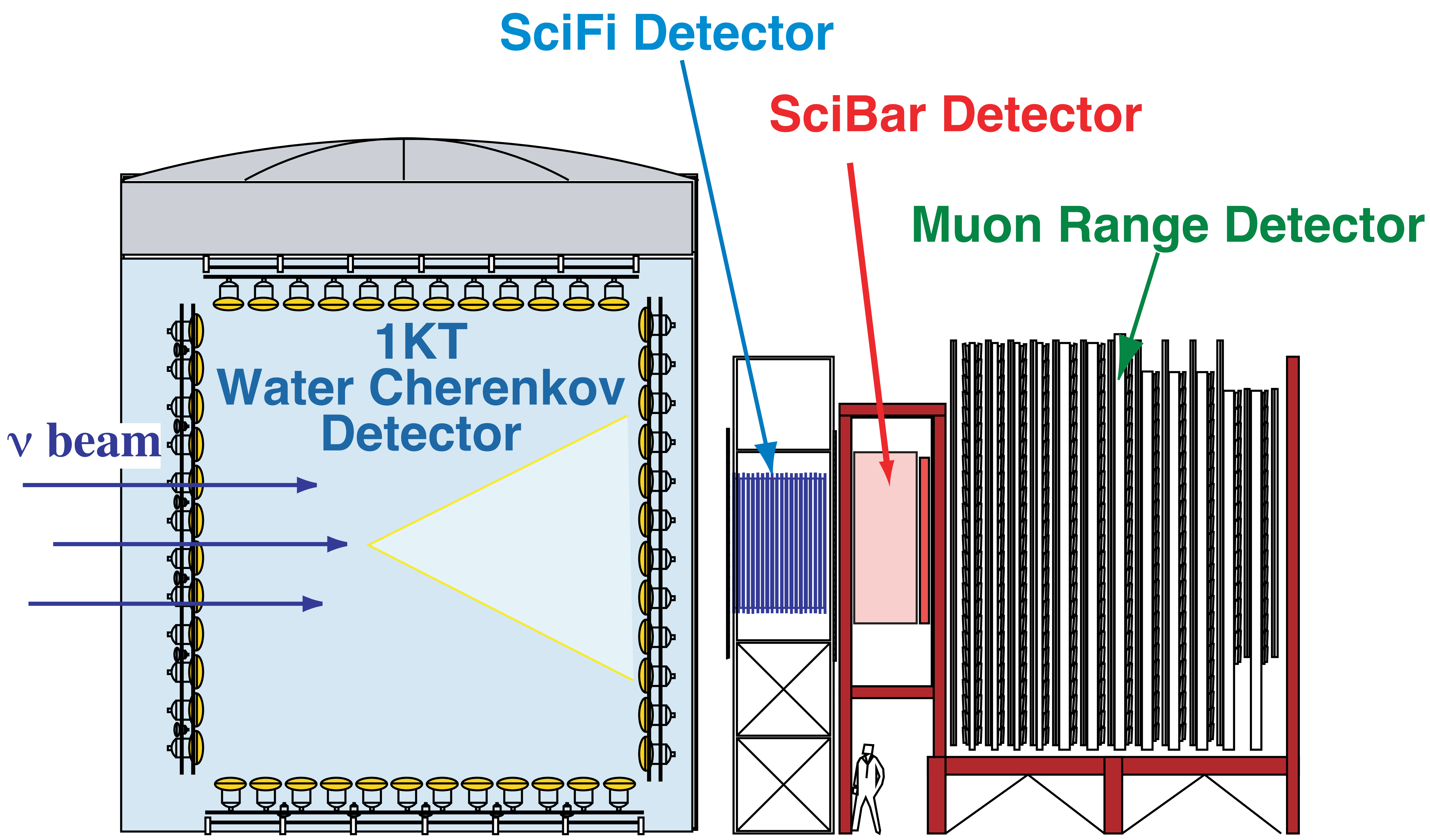
- Accelerator based beams usually produce neutrinos of O(1 GeV)
- If Δm^2 ~2.5x10^{-3} eV^2:
- L (km) ~ (π/2) x E (GeV)/Δm^2 (eV)
- ~ 500 km for 1 GeV neutrinos

- "Long Baseline" Neutrino Experiment
  - previously, accelerator-based experiments were typically carried out at (much) shorter distances
  - atmospheric neutrinos indicate that we need now to separate the accelerator and detector by O(10^2-10^3 km)
  - "K2K": first long baseline experiment sending neutrinos from KEK to Super-Kamiokande (250 km)



LONG BASELINE EXPERIMENTS

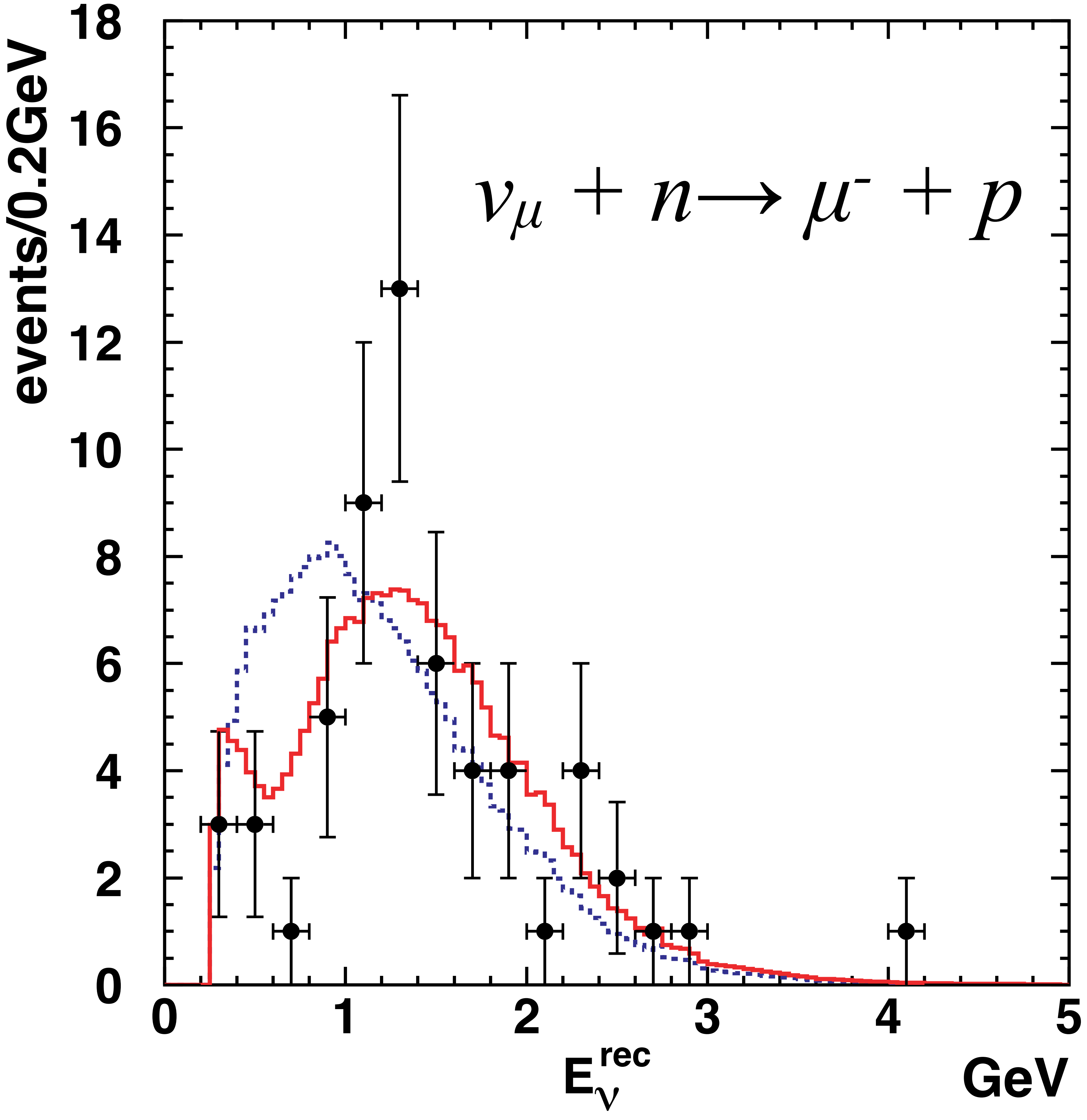


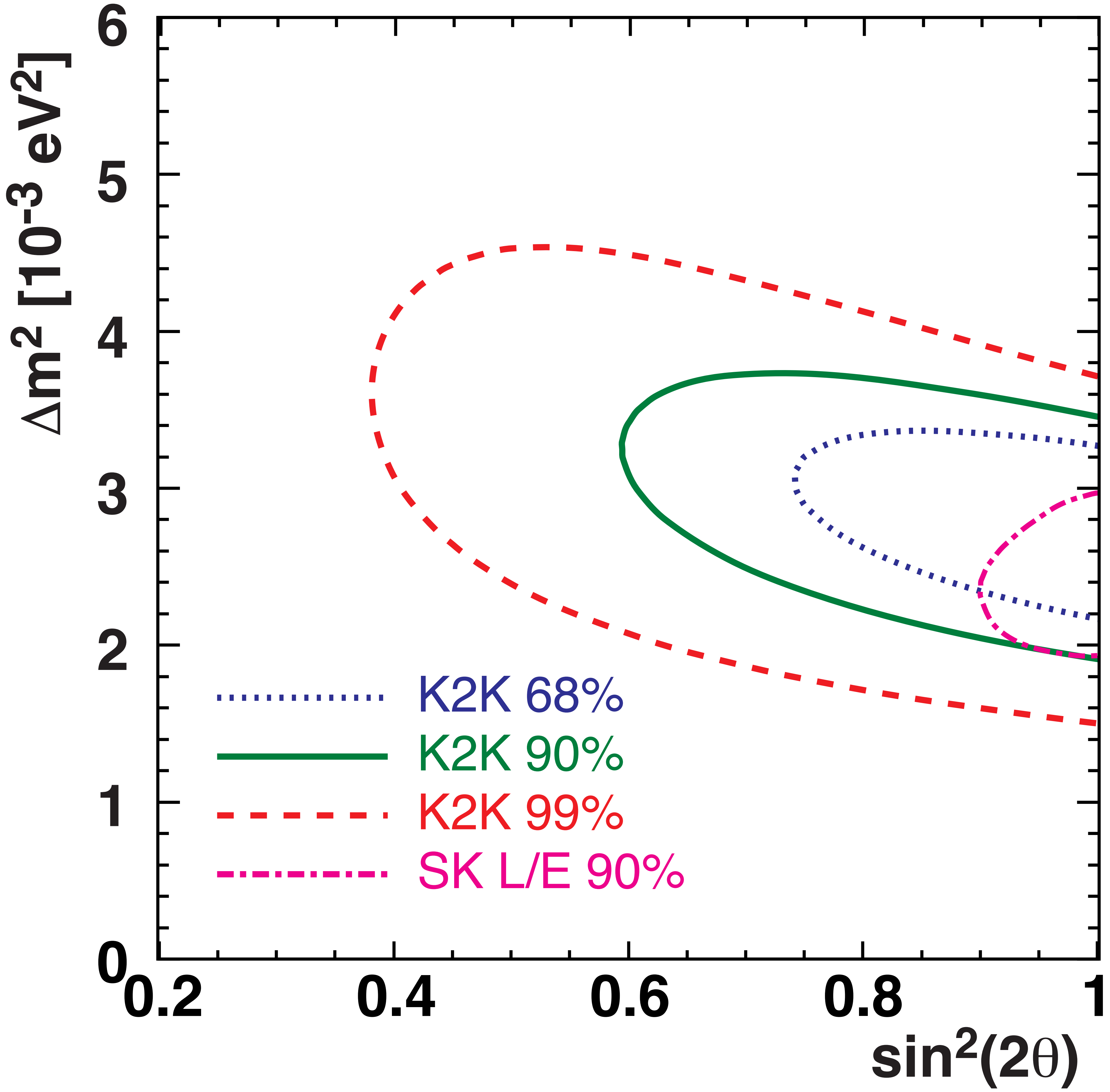


- Timing:
  - we know when the beam comes from the accelerator
  - typically, protons are delivered in O(μs) pulse every O(s)
  - neutrinos are produced with the same time structure
  - Typically, every spill is recorded

- 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

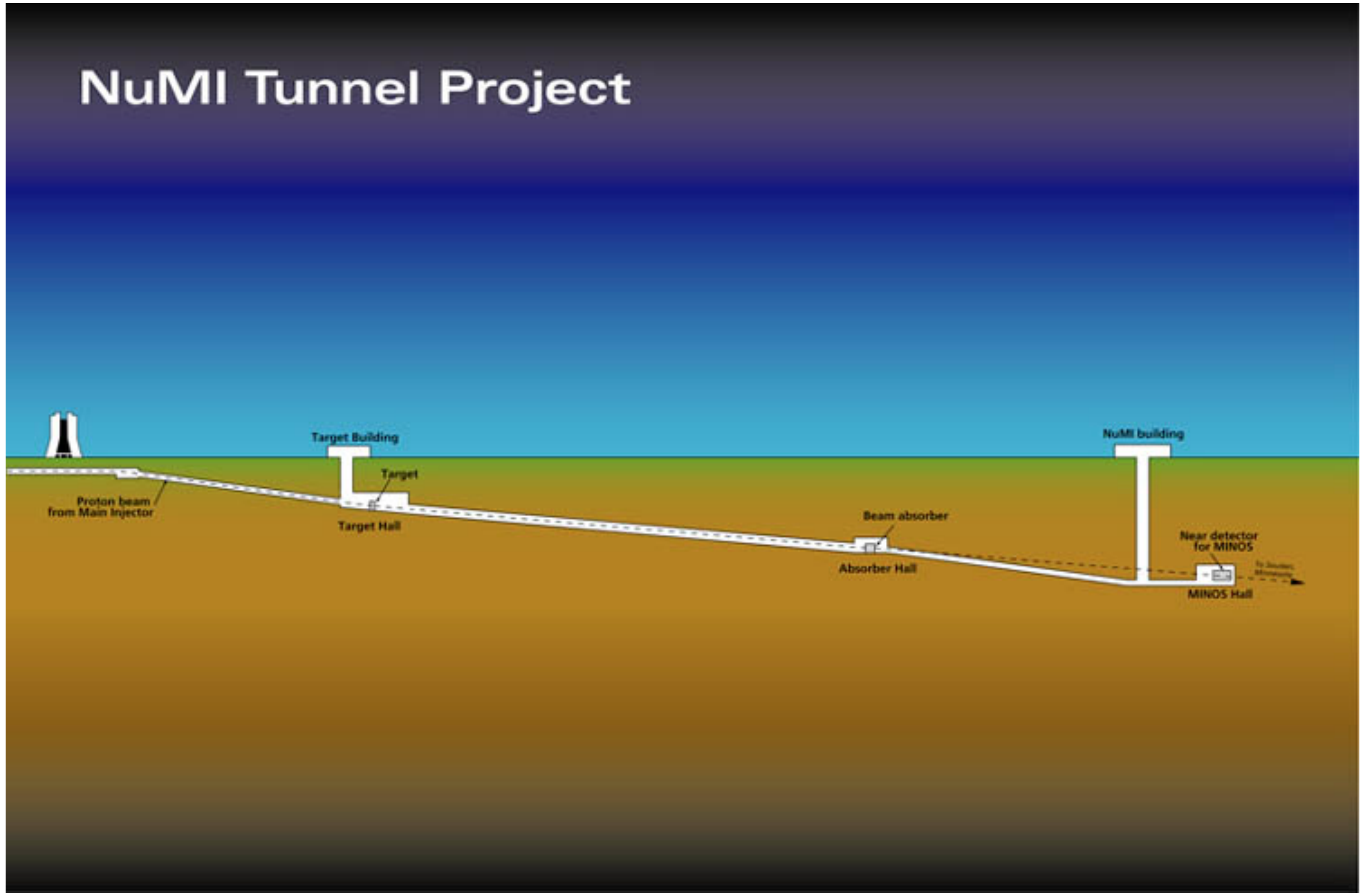




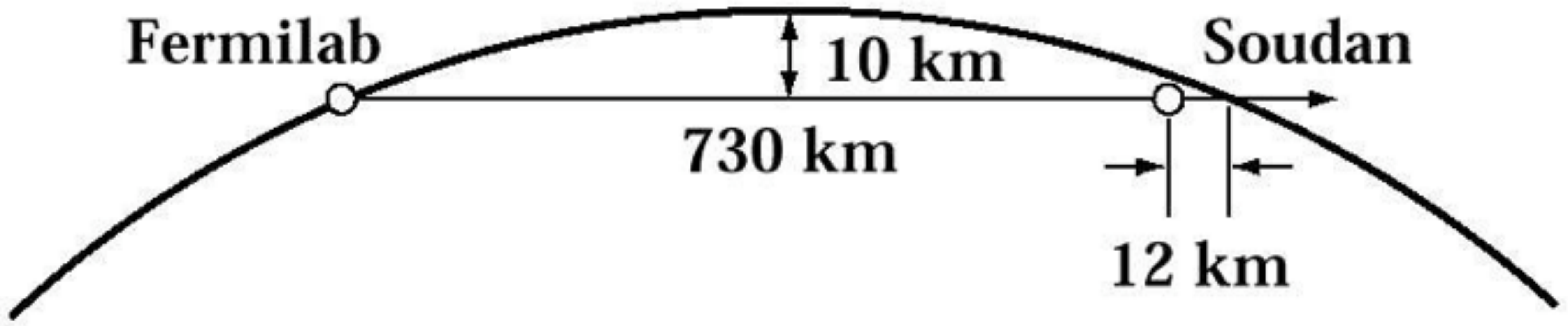
- Total observed interactions at SK in K2K beam: 112
- expected based on simulation and near detector data: 158±9
- 58 single ring muon events used for energy spectrum analysis

- Confirmation of atmospheric muon neutrino deficit with accelerator-based beam at 4.3 σ level
  - combined rate and shape information

MINOS

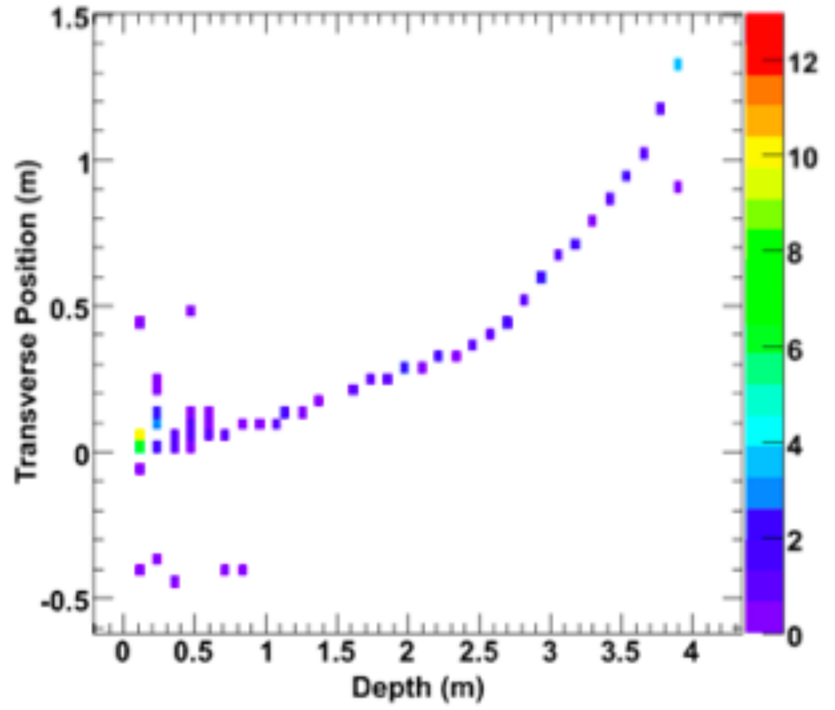


- Fermilab-based neutrino beam sent 730 km to Minnesota
- Neutrinos generated using 120 GeV FNAL Main Injector

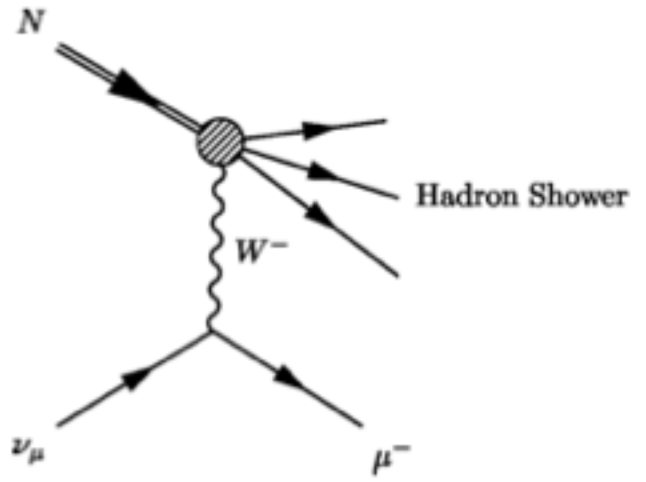


MINOS DETECTOR:

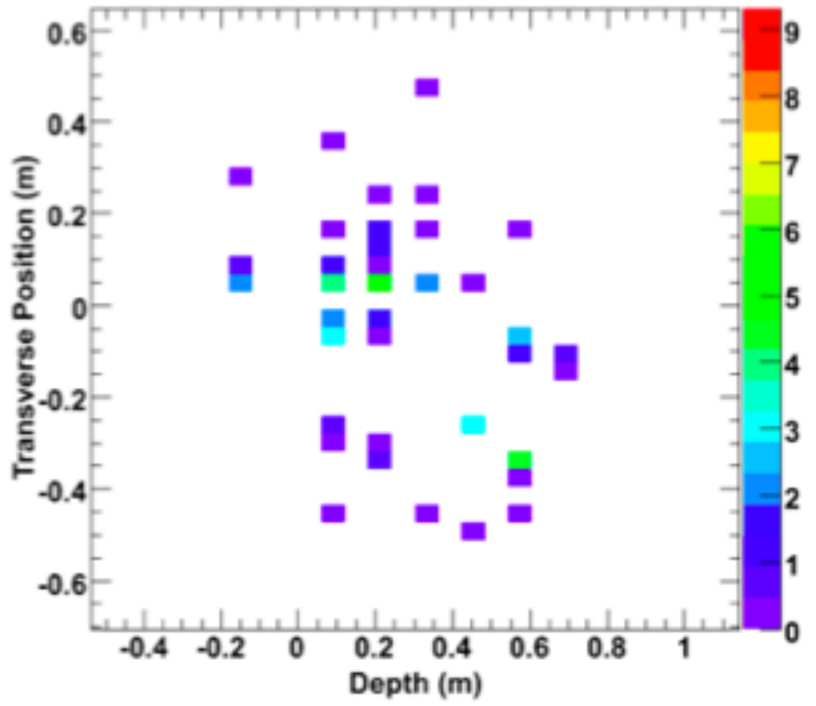
ν_μ Charged Current (CC)



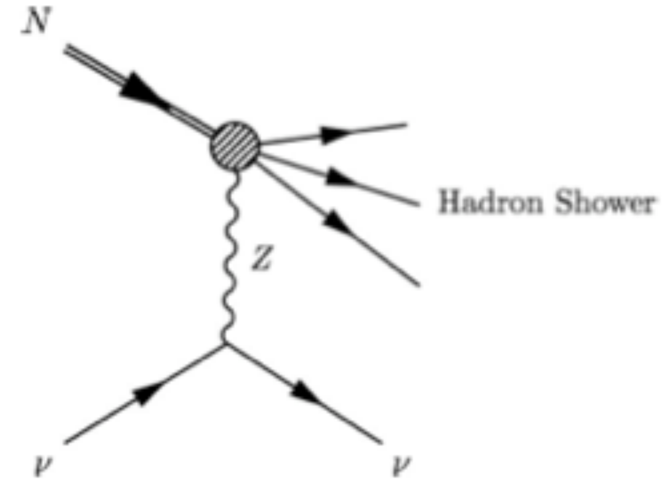
$$\nu_\mu + N \rightarrow \mu^- + X$$



Neutral Current (NC)

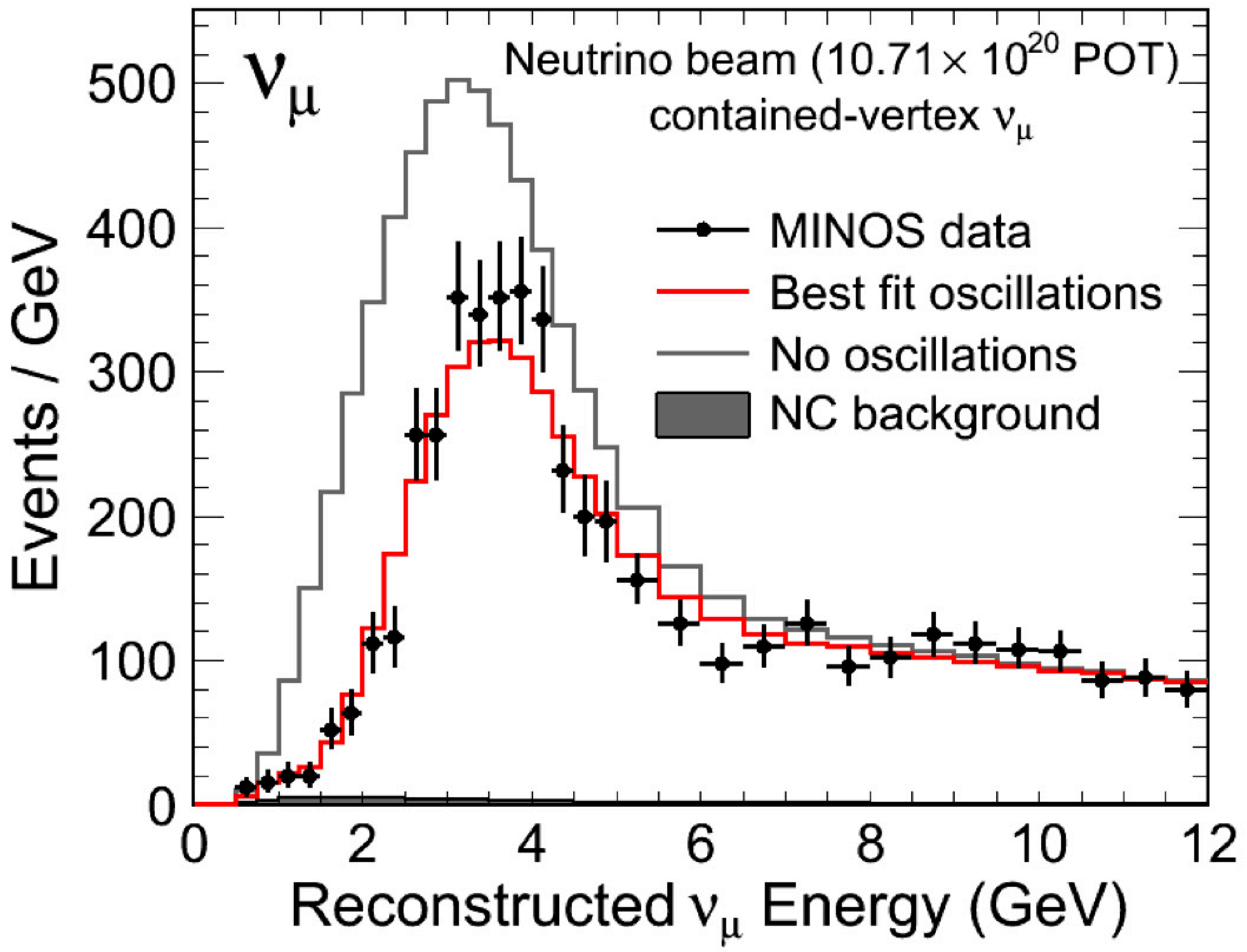


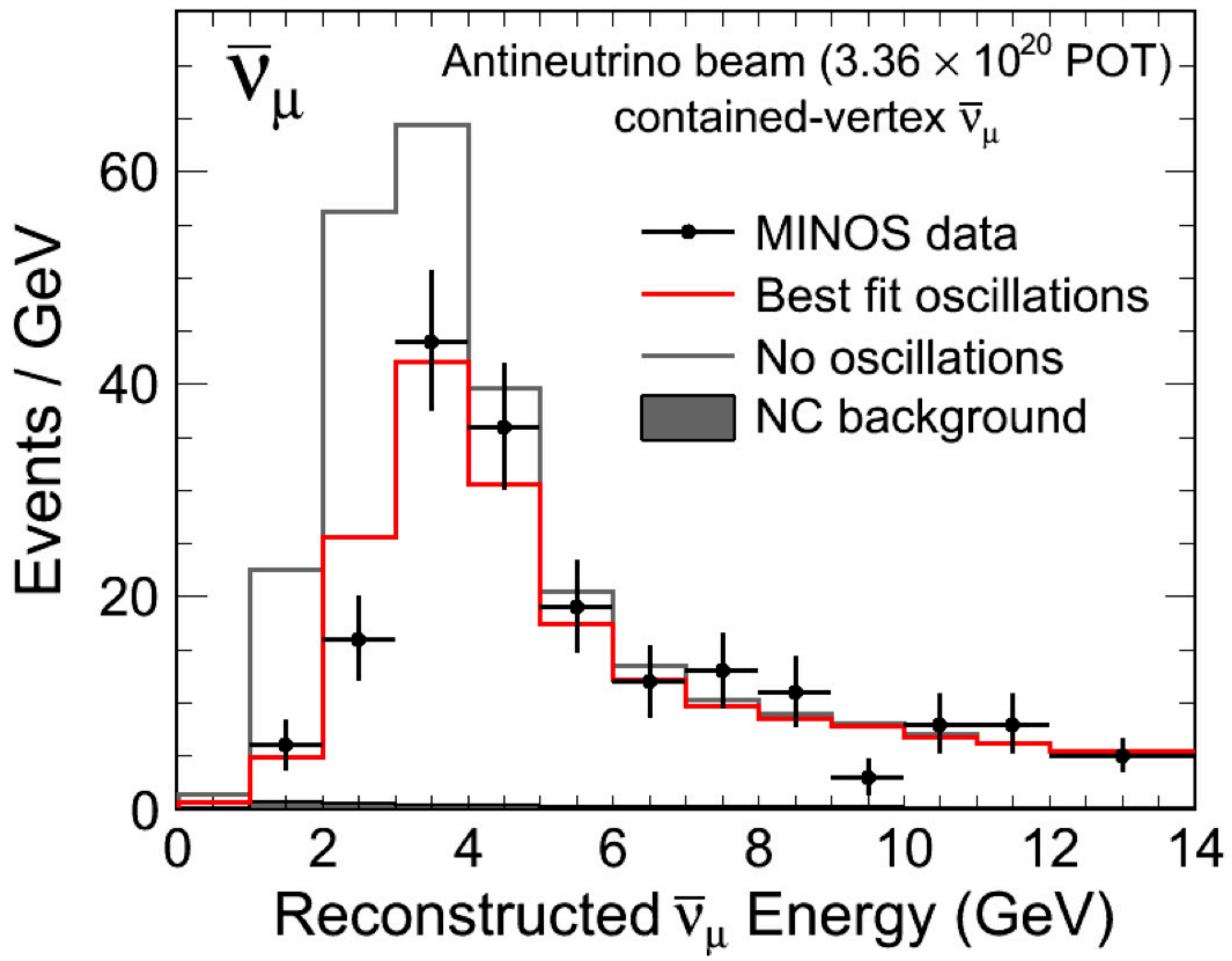
$$\nu + N \rightarrow \nu + X$$

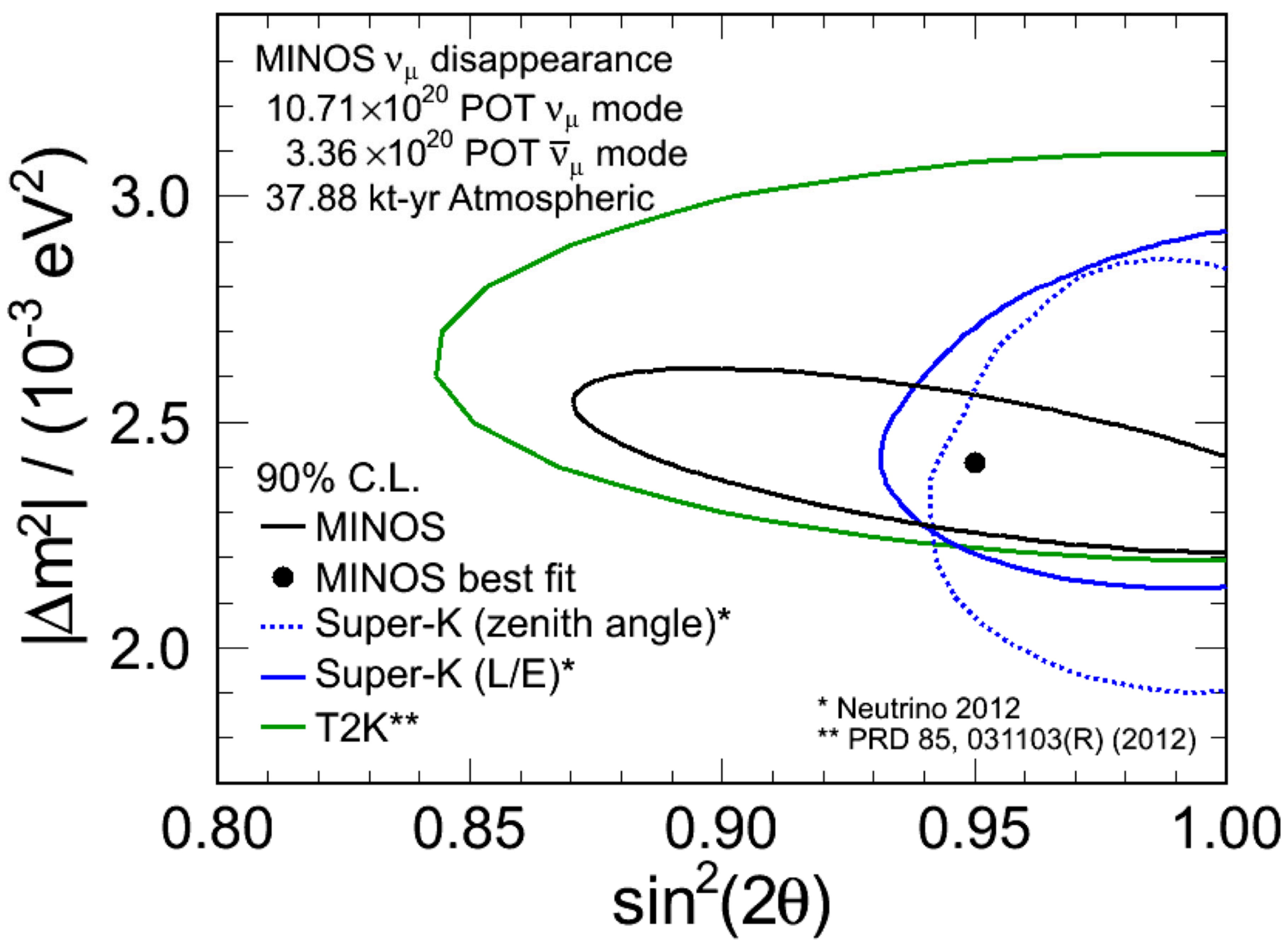


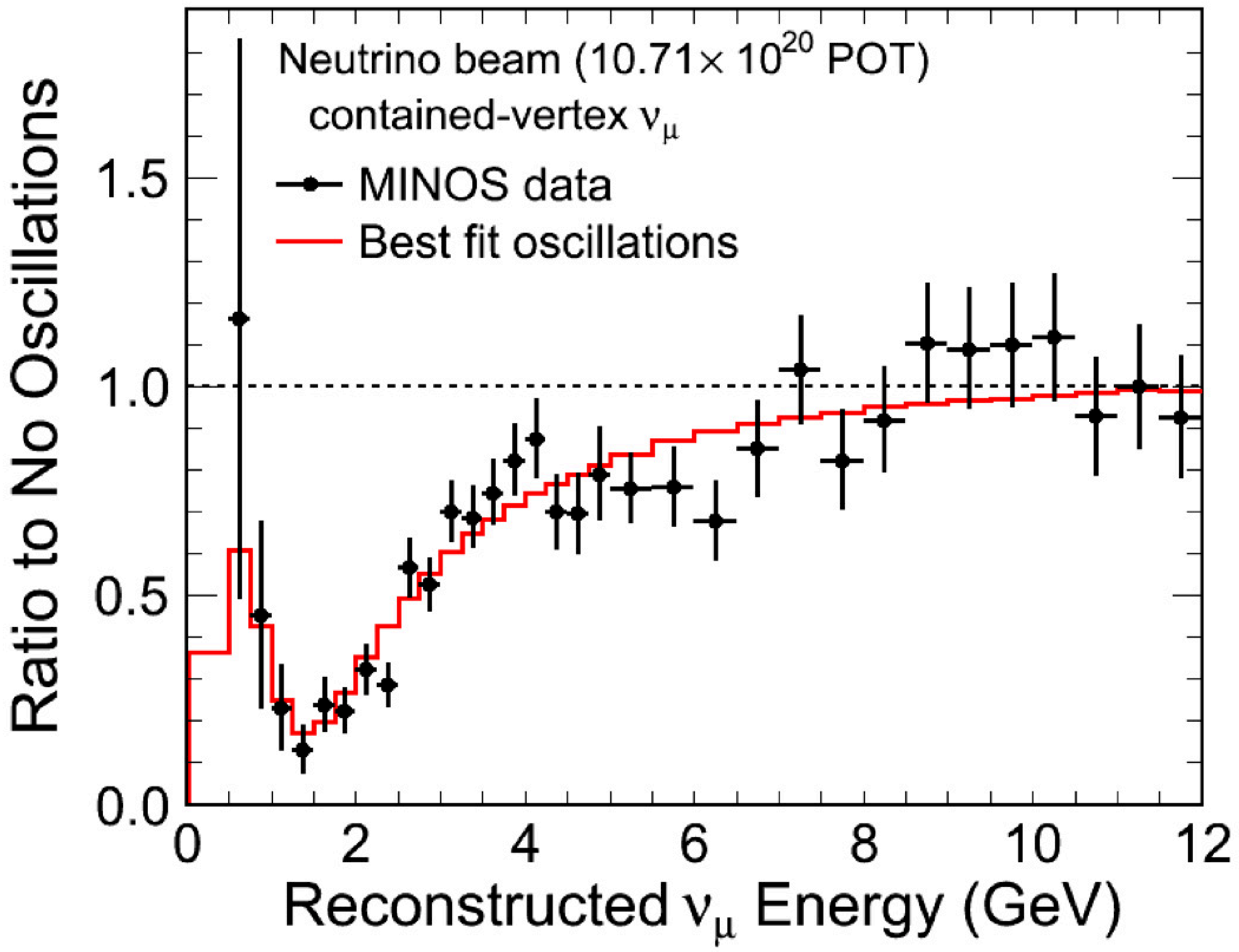
- Magnetized steel plates alternating with scintillator strips
  - 2.54 cm thick steel plates, 1 cm x 4.1 cm scintillator bars
- Functionally identical Near (0.98 ton) and Far (5.4 ton) detectors
- Very clean identification of muon neutrinos with sign of muon identified.

MINOS RESULTS



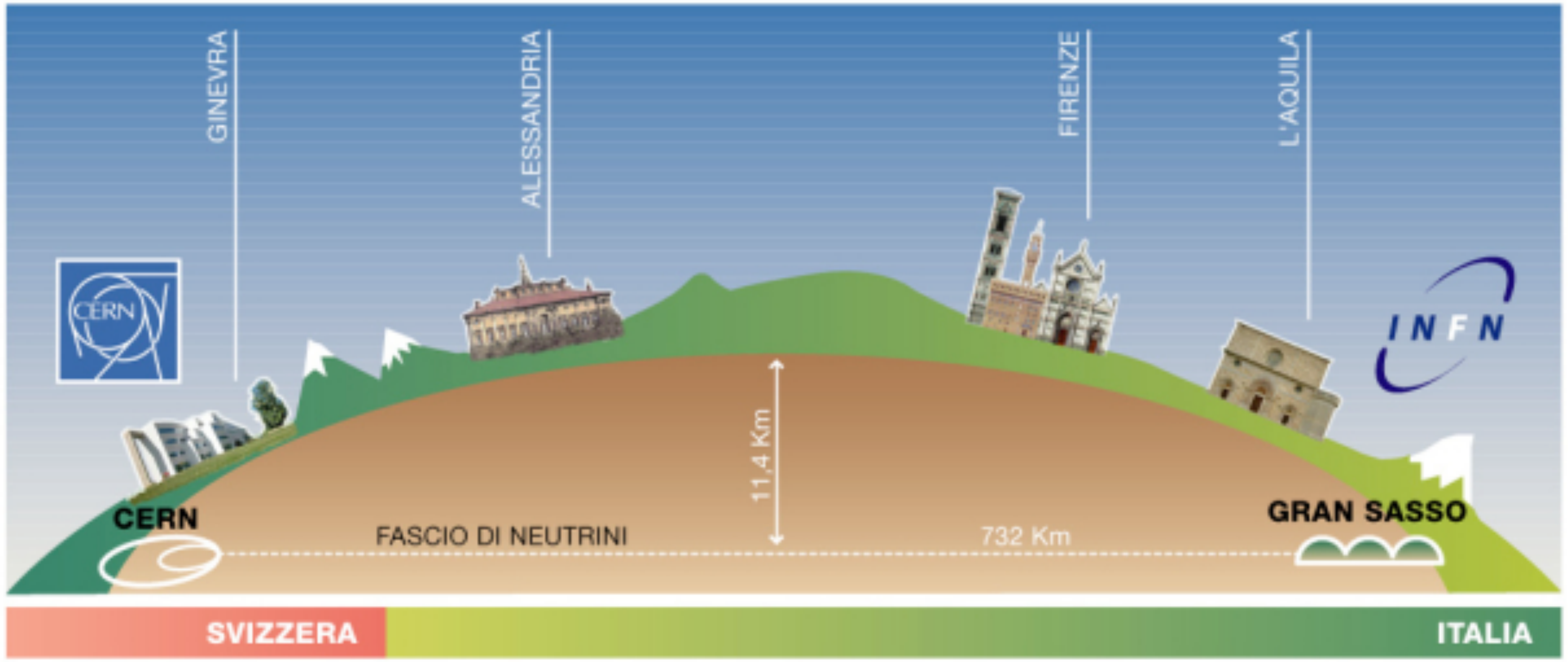


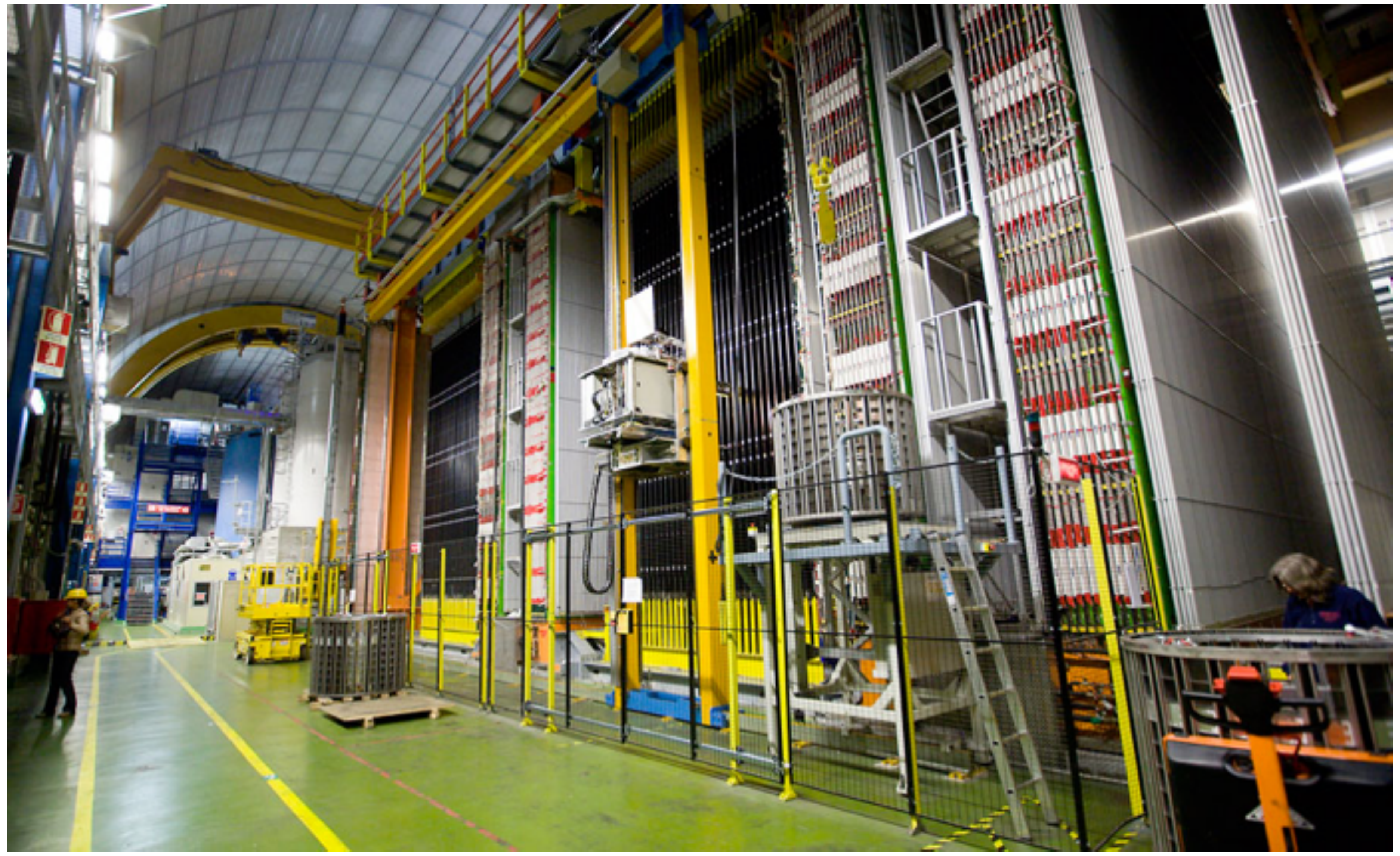


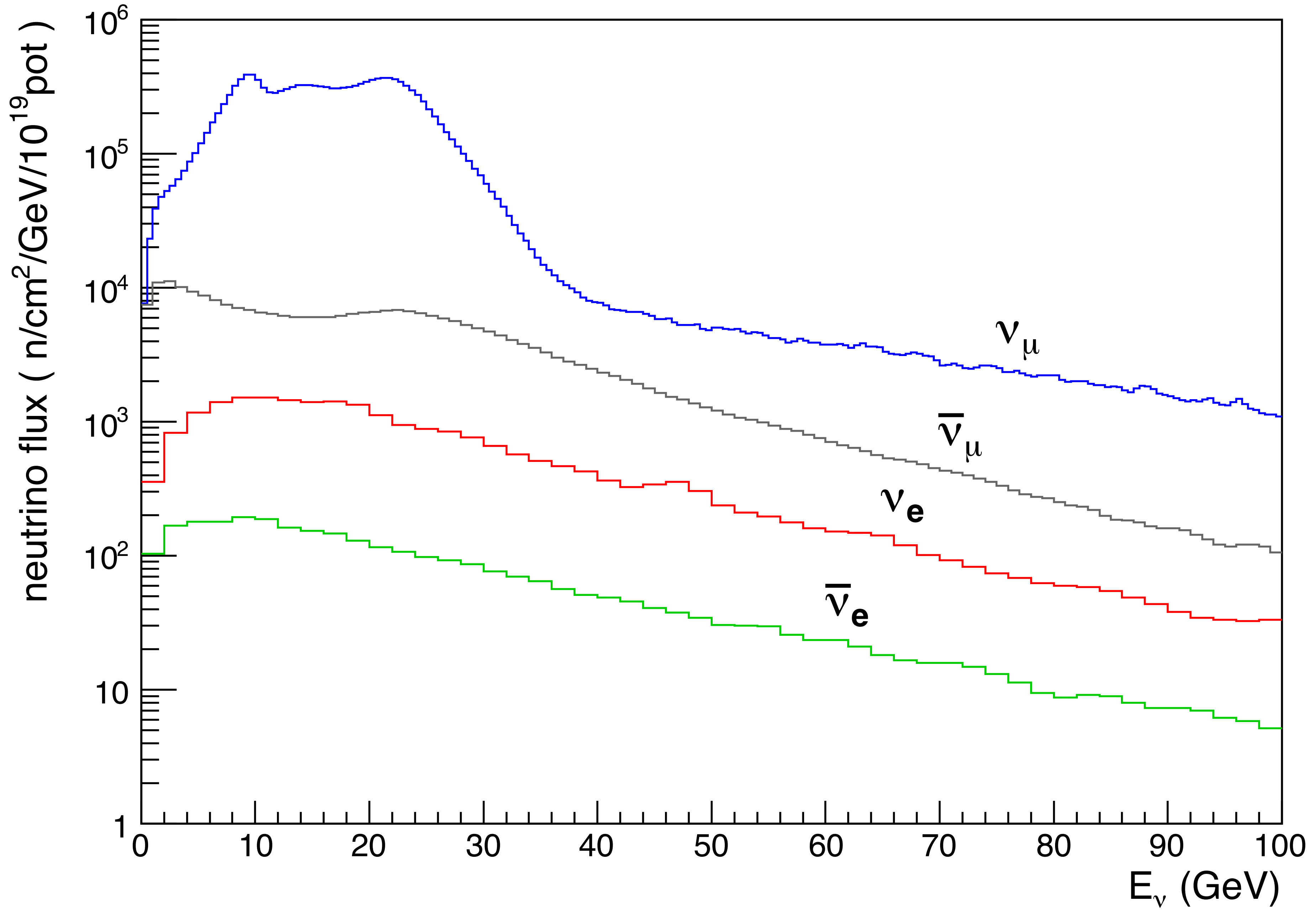


- Very intense beam gives precise measurement of oscillation probability
- Confirm large ν_μ disappearance consistent with maximal mixing
- eventually many channels were studied:
  - $\bar{\nu}_\mu$ disappearance with antineutrino beam
  - atmospheric neutrinos
  - $\nu_e/\bar{\nu}_e$ events (more on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

OPERA



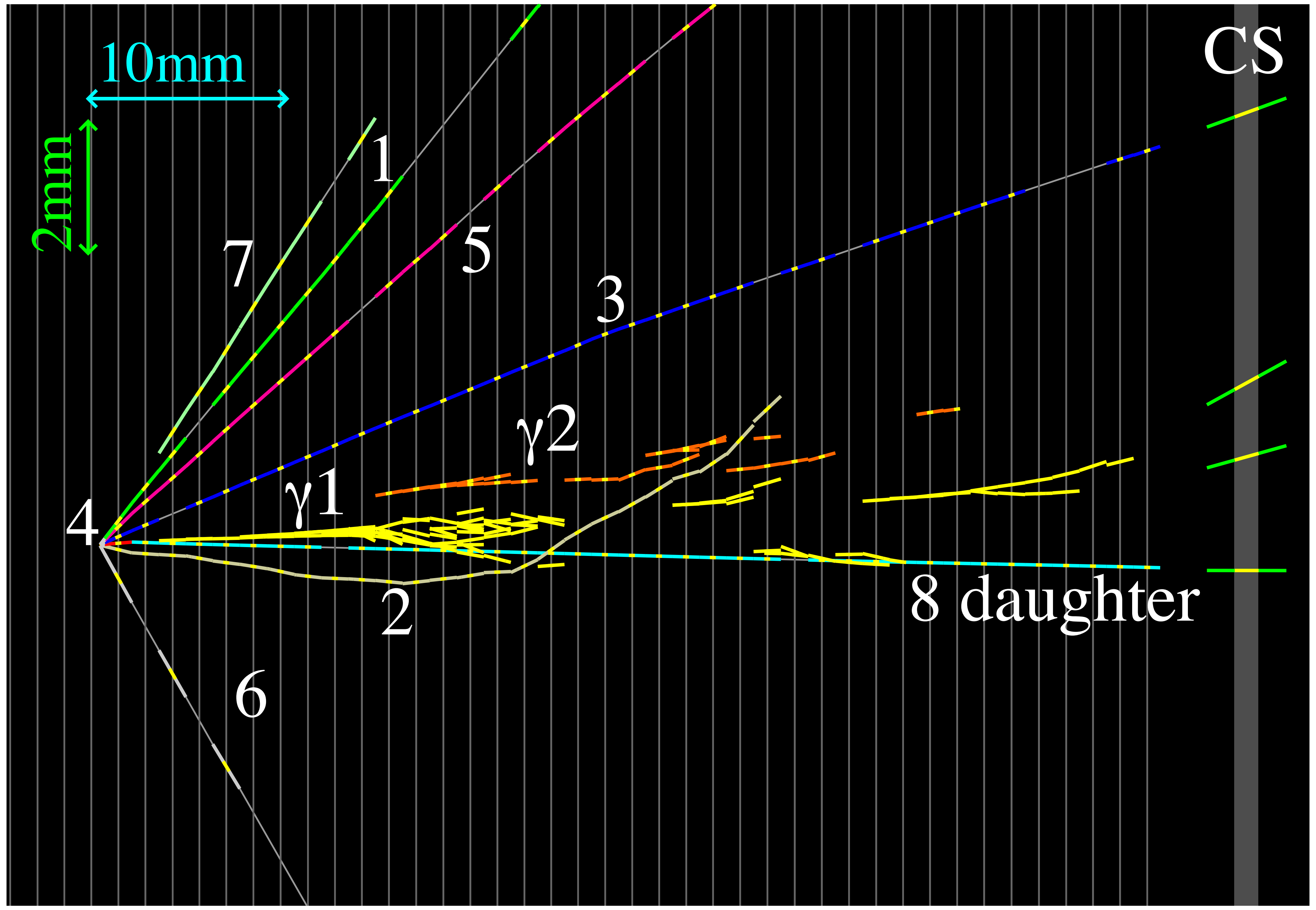


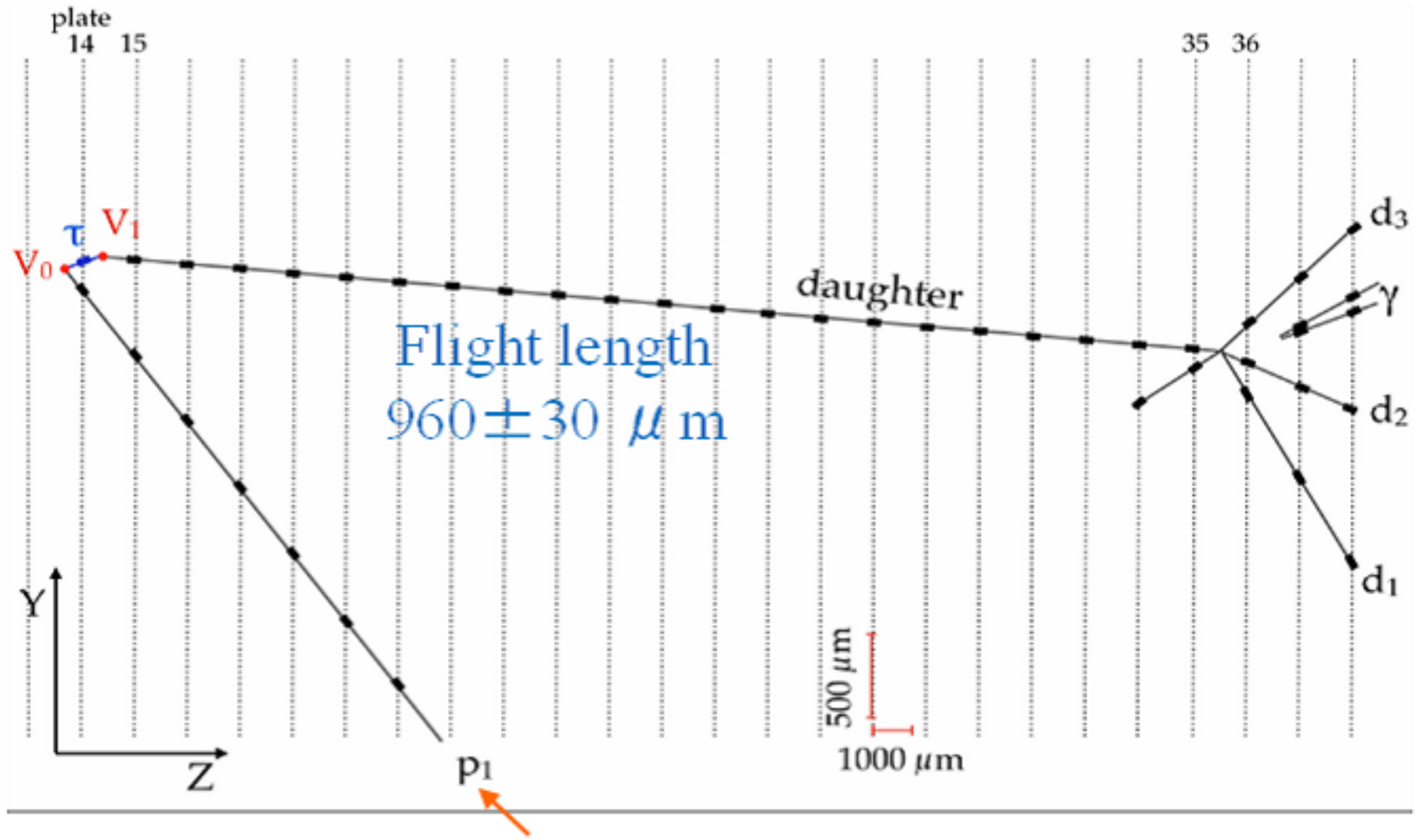


- Experiment to look explicitly for the "appearance" of nt due to $\nu_\mu \rightarrow \nu_\tau$ oscillations
- 450 GeV CERN SPS protons used to produce a "wide-band" high energy muon neutrino beam
  - Significant flux above τ production threshold of ~3.5 GeV

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 → $c\tau$ ~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

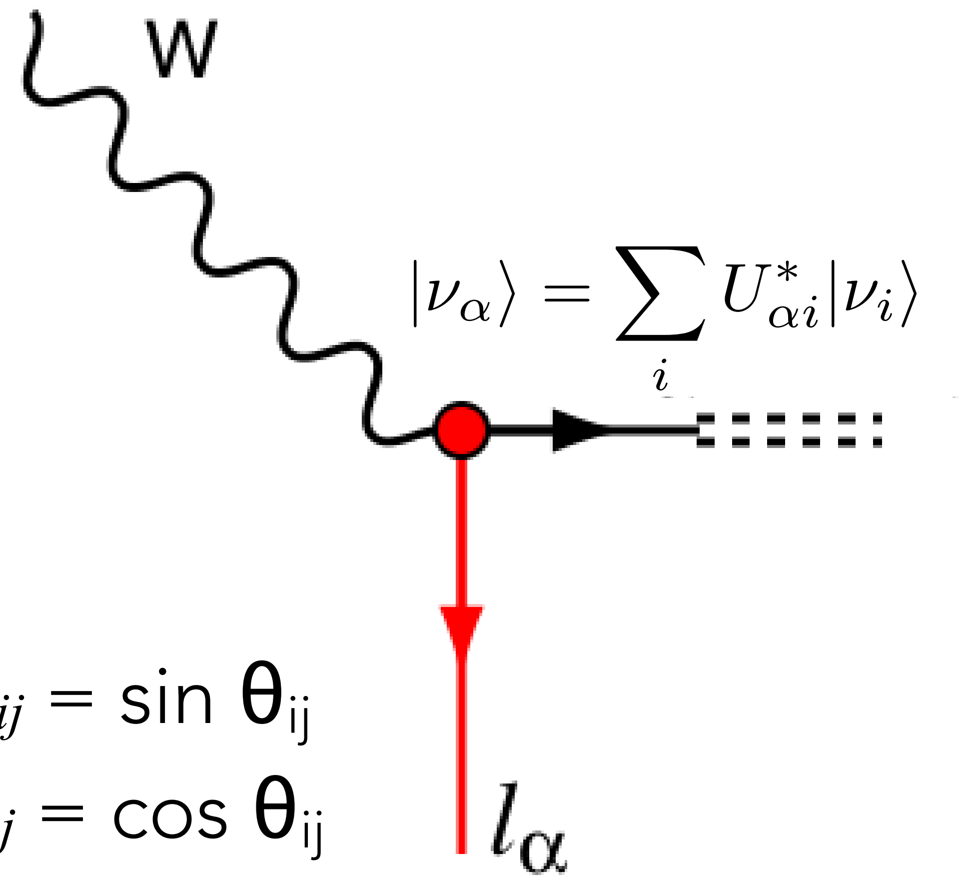




identified as a proton by dE/dx analysis [26]

COMPLETING THE PICTURE

TOWARDS 3-FLAVOR FRAMEWORK



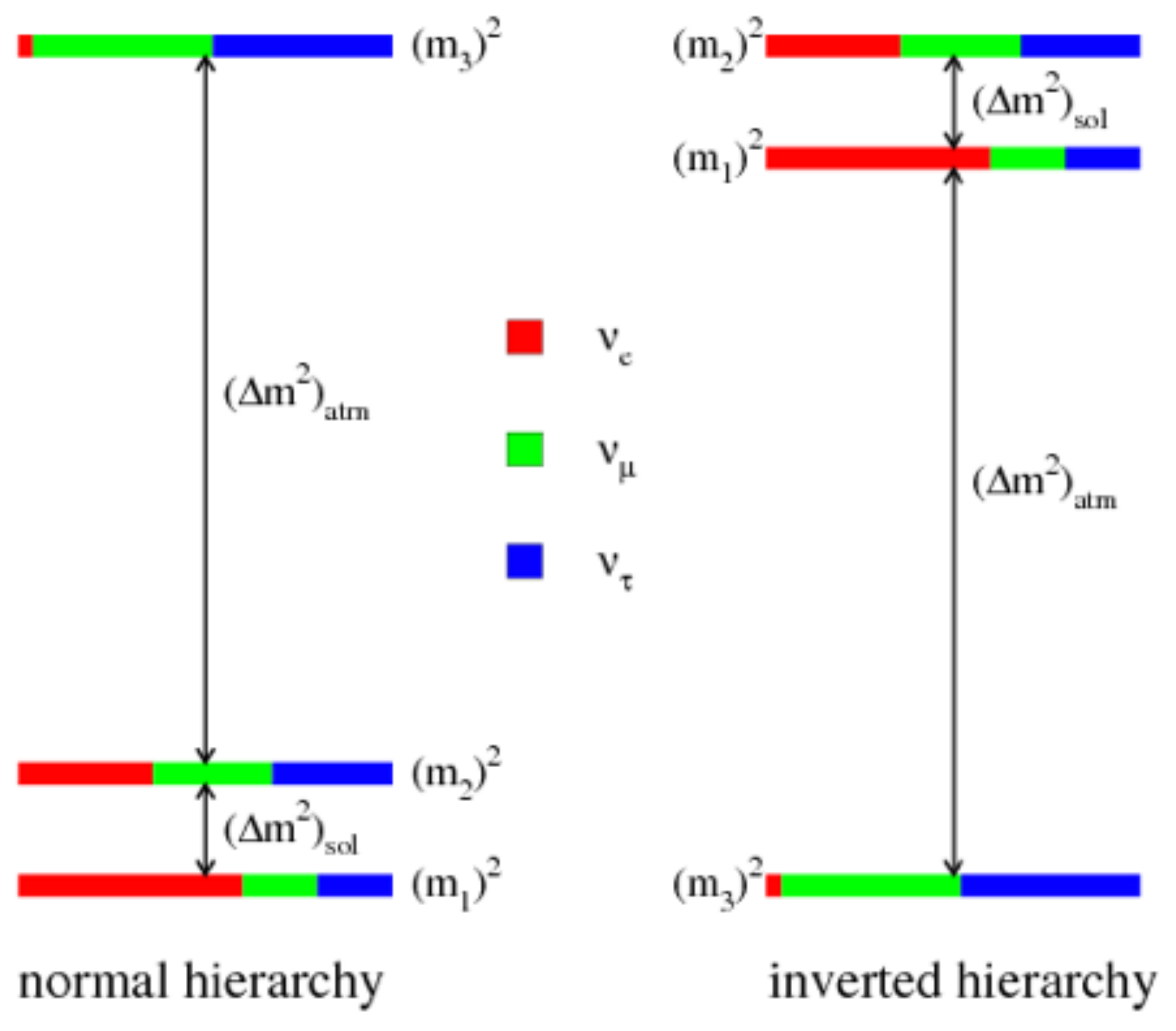
s_{ij} = sin θ$_{ij}$

c_{ij} = cos θ$_{ij}$

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

"standard" parametrization

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



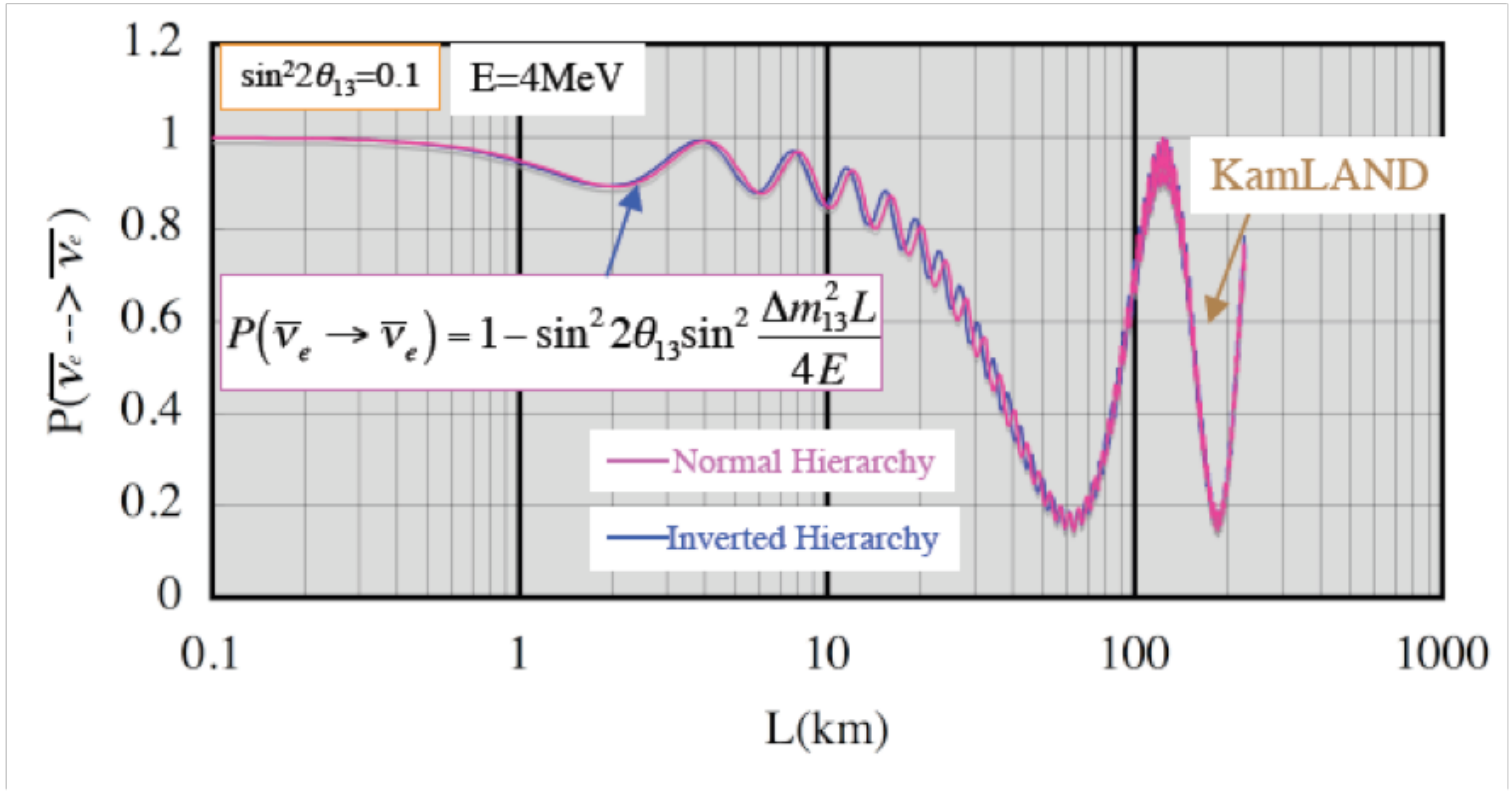
- Three rotation angles (θ_{12}, θ_{13}, θ_{23})
- One complex phase δ_{CP}
  - additional phases possible if neutrinos are "Majorana"
  - changes sign for antineutrino oscillations

- We've probed the θ$_{12}$/solar sector
- also θ$_{23}$ with atmospheric/accelerator experiments
- How do we probe θ$_{13}$?
- If we multiply out the above, we find that:
  - $|U_{e3}|^2 = \sin^2\theta_{13}$
  - "electron neutrino content of the third neutrino mass eigenstate"

ELECTRON NEUTRINO SURVIVAL

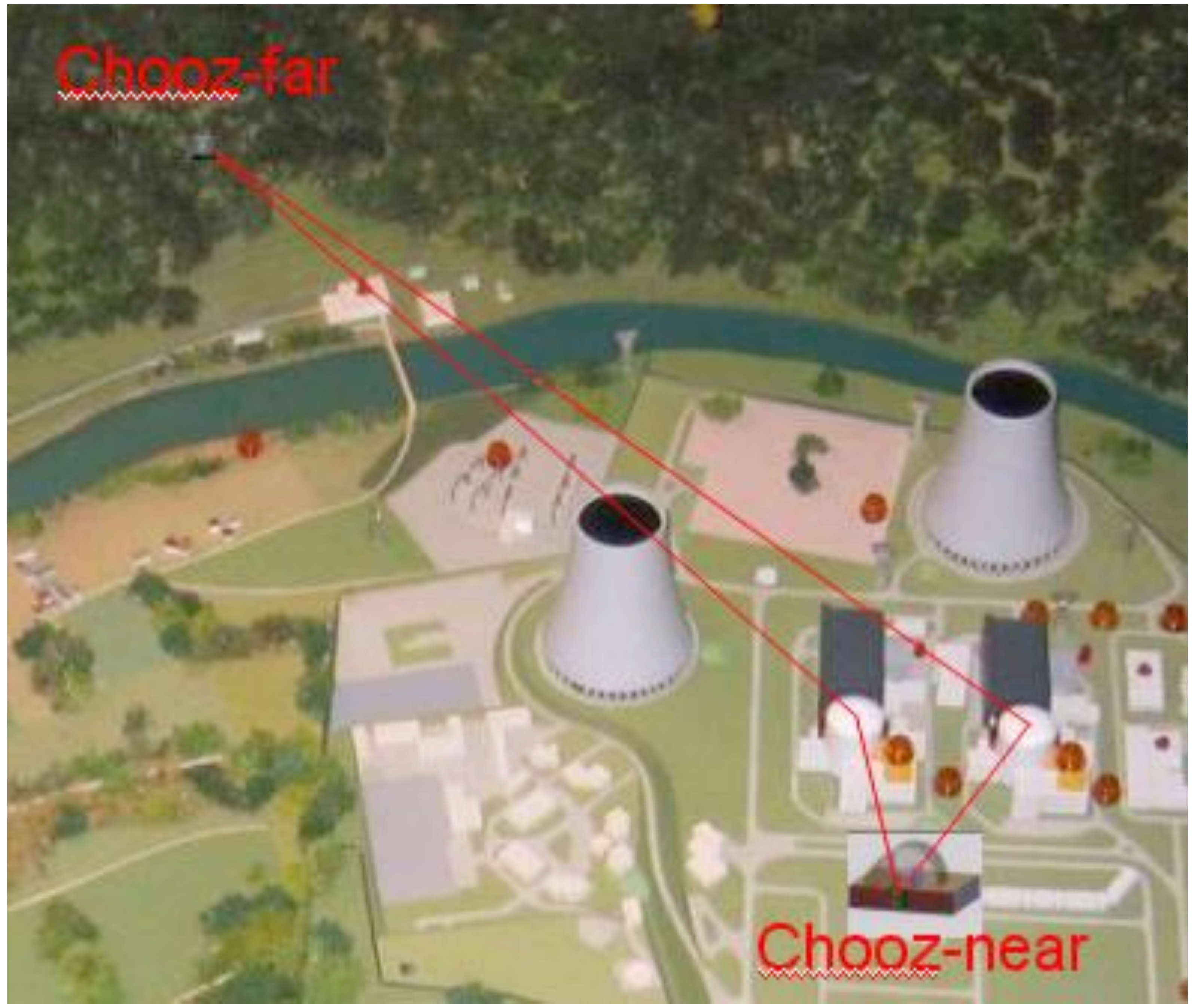
$$P(\nu_e \to \nu_e) \sim 1 - \sin^2 2\theta_{13} \sin^2(1.27\Delta m^2_{31} L/E) - \sin^2 2\theta_{12} \sin^2(1.27\Delta m^2_{21} L/E)$$

- Oscillation has two components
  - one oscillating with Δm^2_{31} ~ 2.5 x 10^{-3} eV^2
  - the other oscillating with Δm^2_{21} ~ 7.5 x 10^{-5} eV^2
  - the "wavelengths" are different by a factor of 30
- This means that the oscillation is maximum at:
  - L/E ~ 0.5 km/MeV for the Δm^2_{31} driven component
  - L/E ~ 15 km/MeV for the Δm^2_{21} driven component



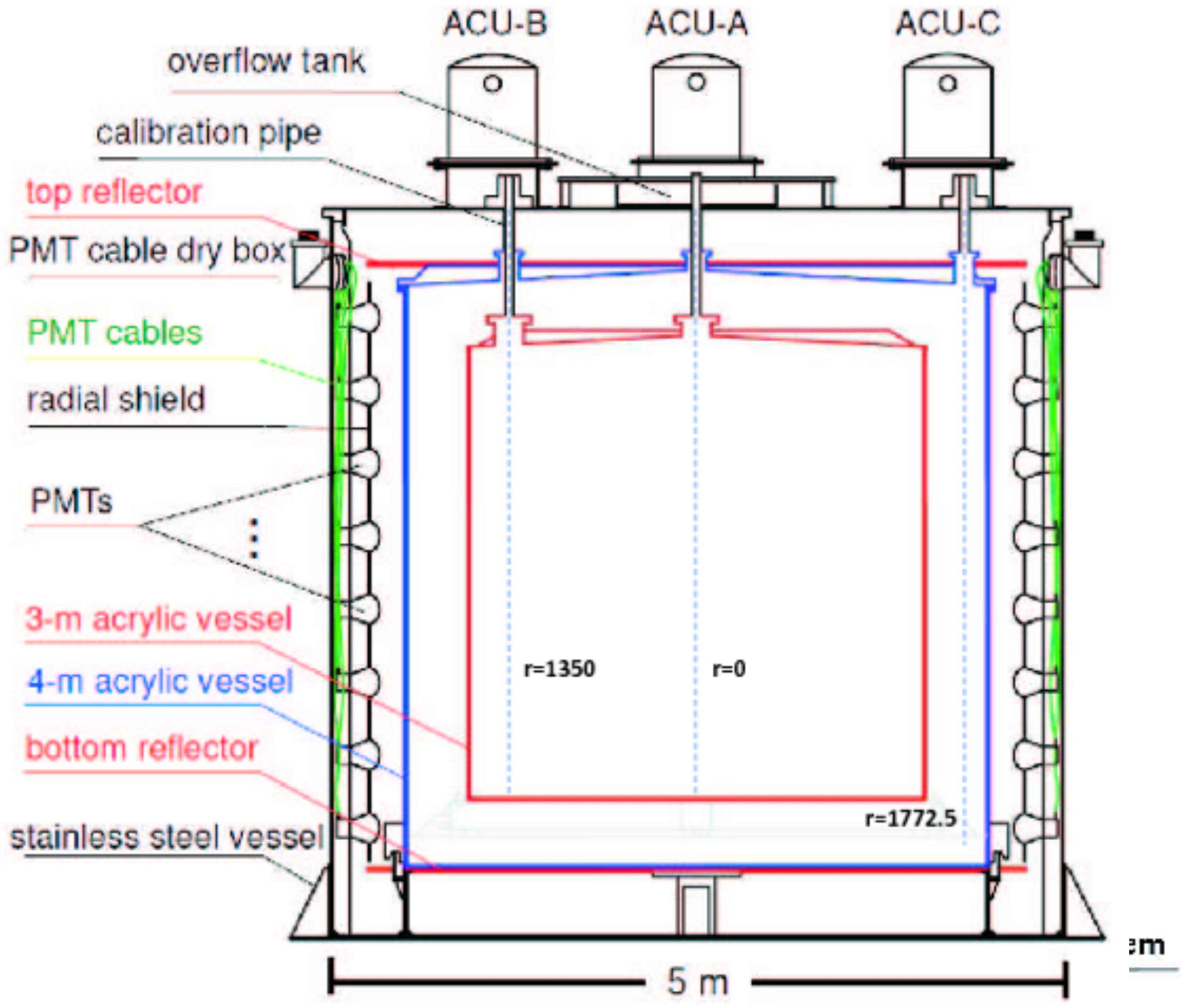
- Motivates measurement of reactor electron antineutrino disappearance at distance of ~1 km

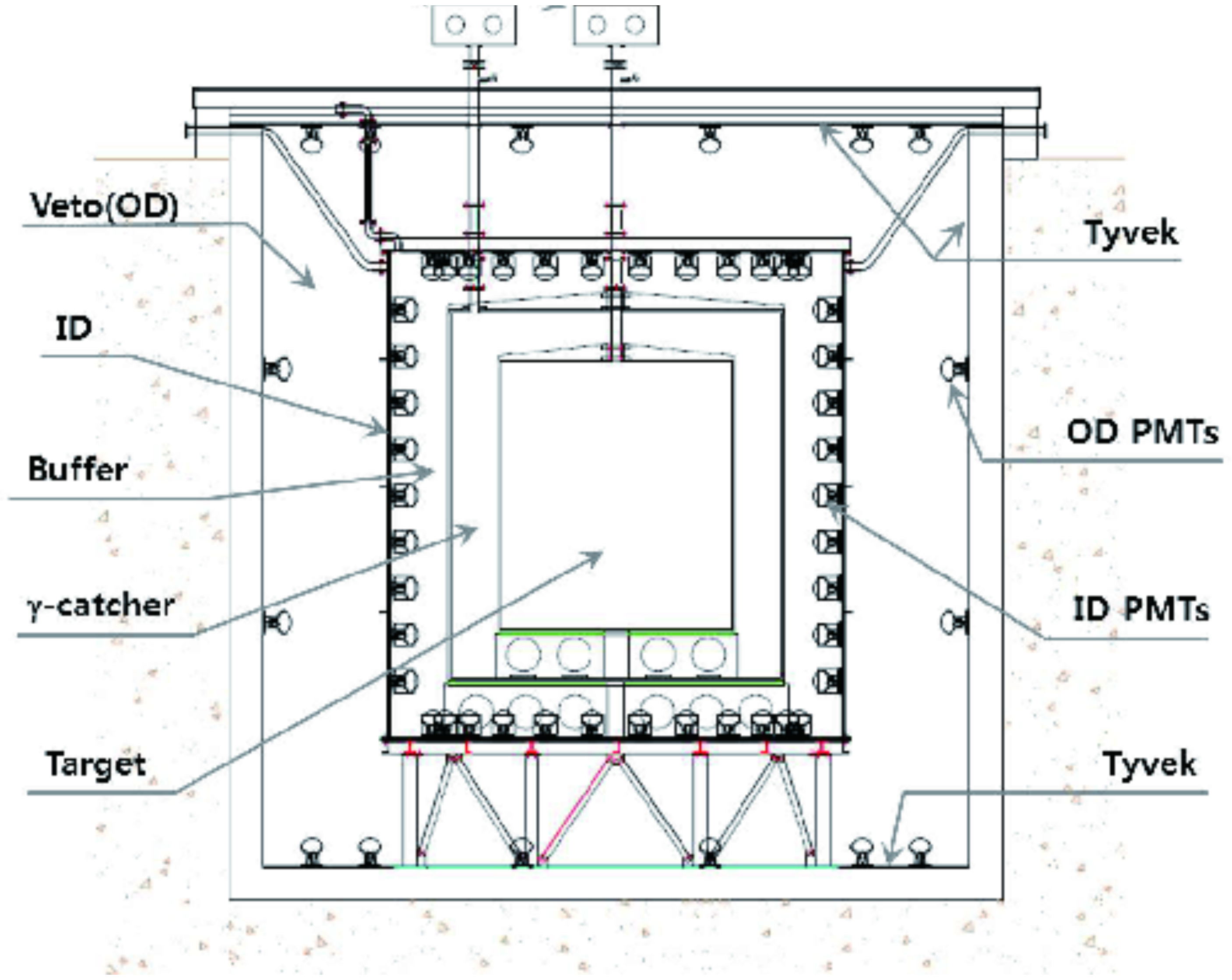
"SHORT BASELINE" REACTOR EXPERIMENTS

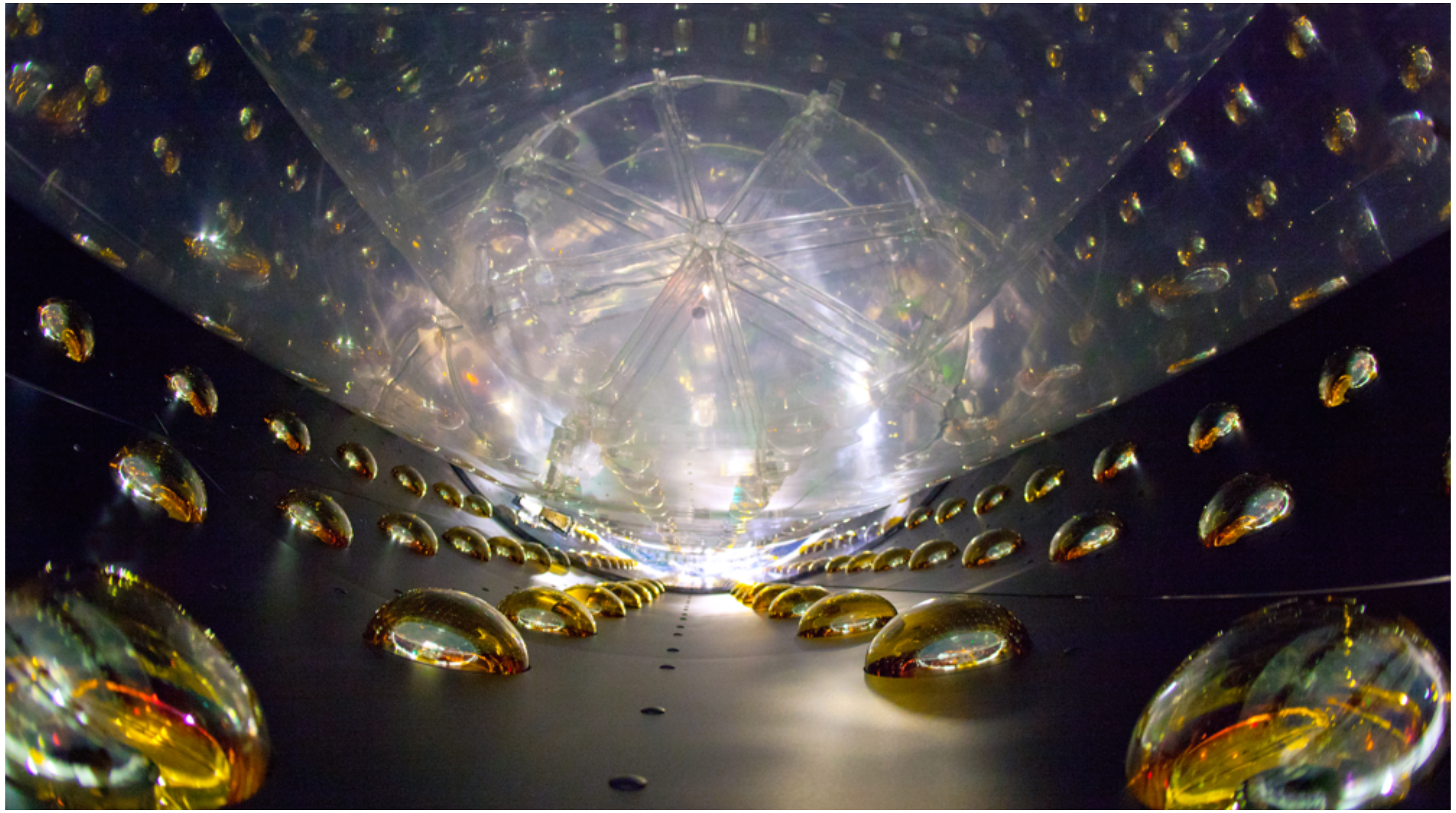


- **Daya Bay**
  - ~50 km from Hong Kong 17.4 GW of thermal power from two reactor complexes
  - multiple detectors at 3 sites
- **RENO**
  - west coast of South Korea
  - 16.5 GW thermal power from Yonggwang complex
  - near and far detector
- **Double Chooz**
  - Eastern France near Belgium
  - 2.9 GW from two reactor cores
  - near and far detector

DETECTORS





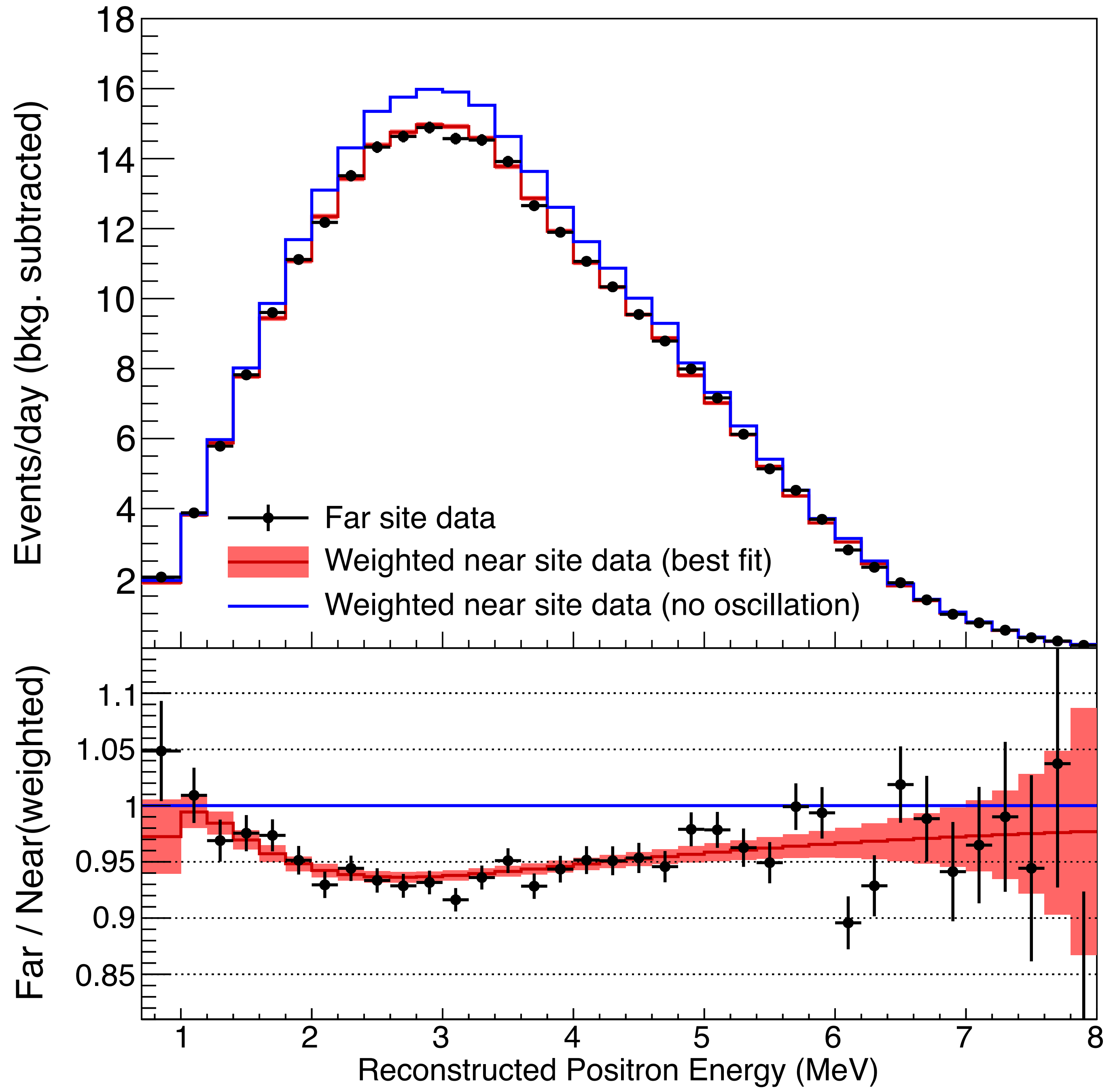


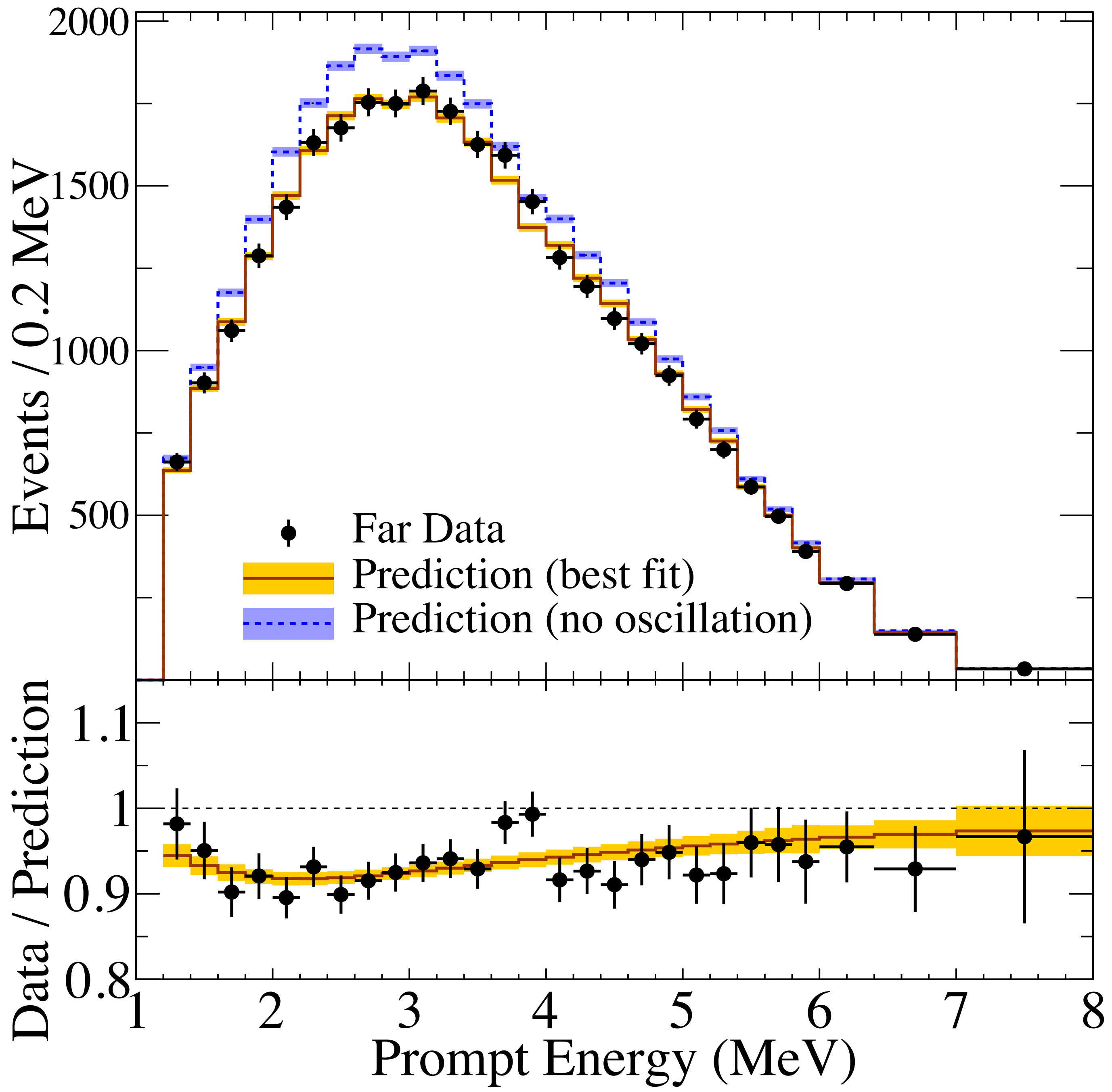
- Basic detection principle: inverse beta decay

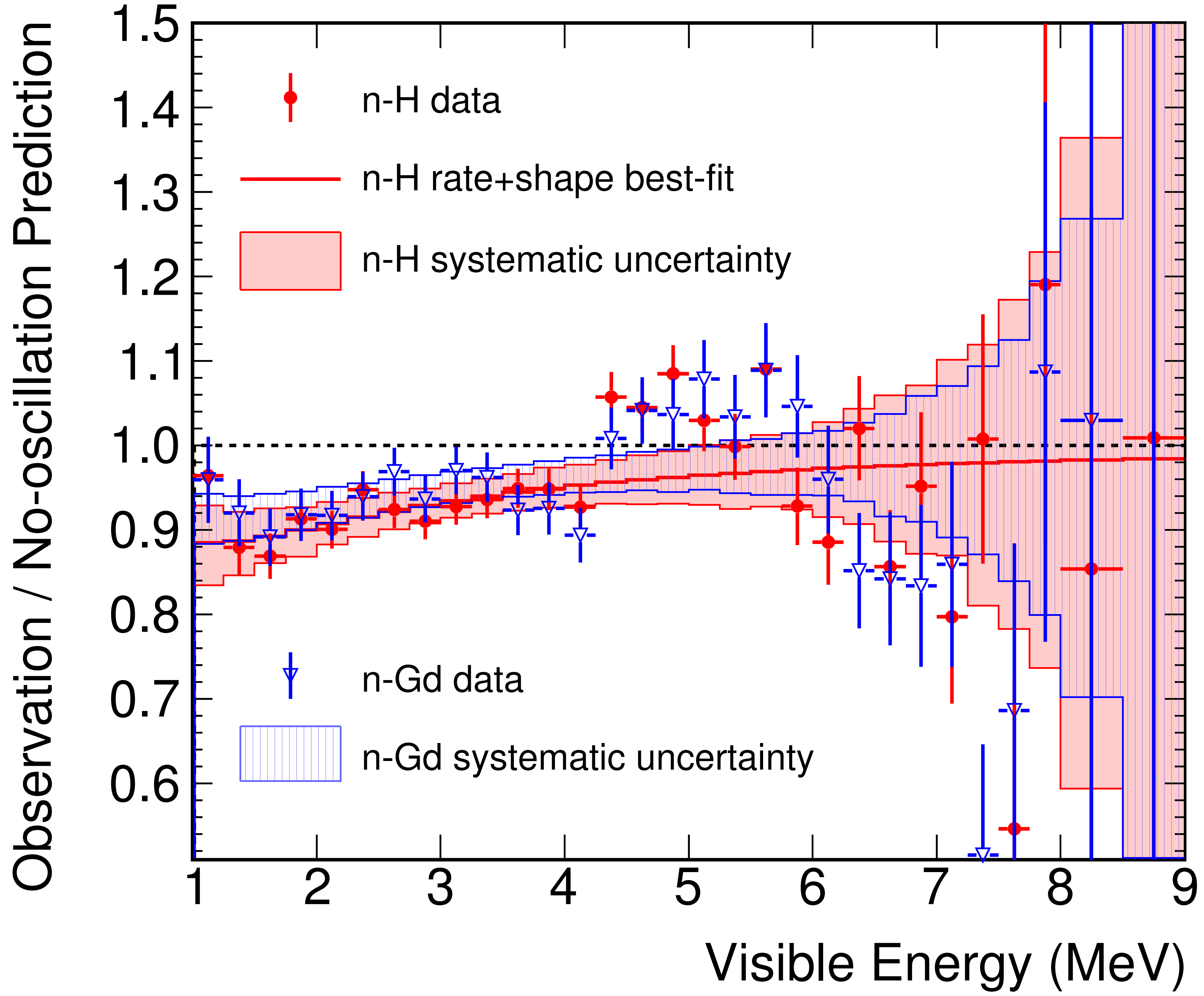
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

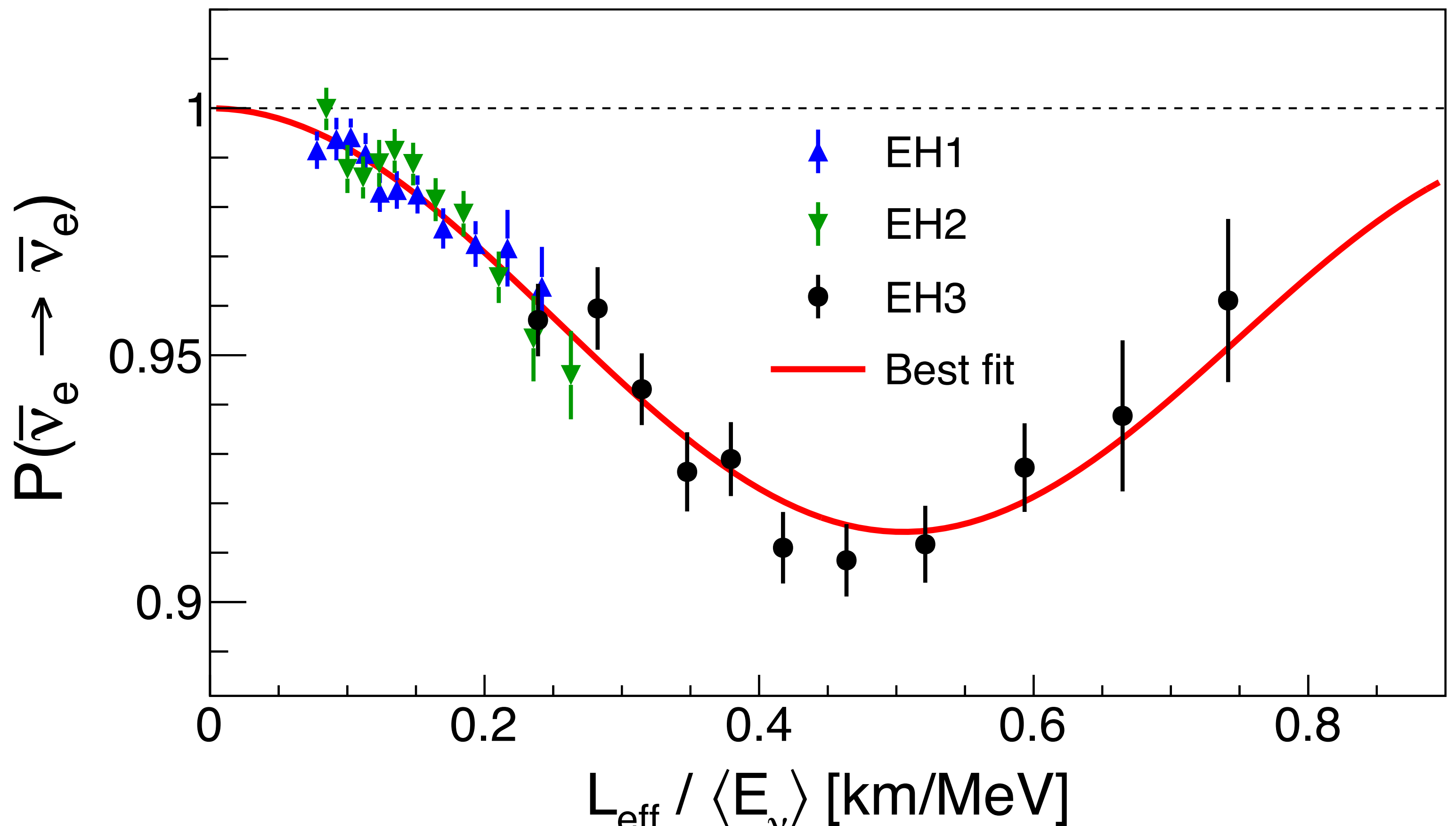
- Liquid scintillator detectors (primarily hydrocarbons)
    - provide free proton target
    - large light yield from scintillator
    - Gadolinium doping to aid neutron capture detection
    - "buffer" regions to isolate Gd-loaded region

RESULTS





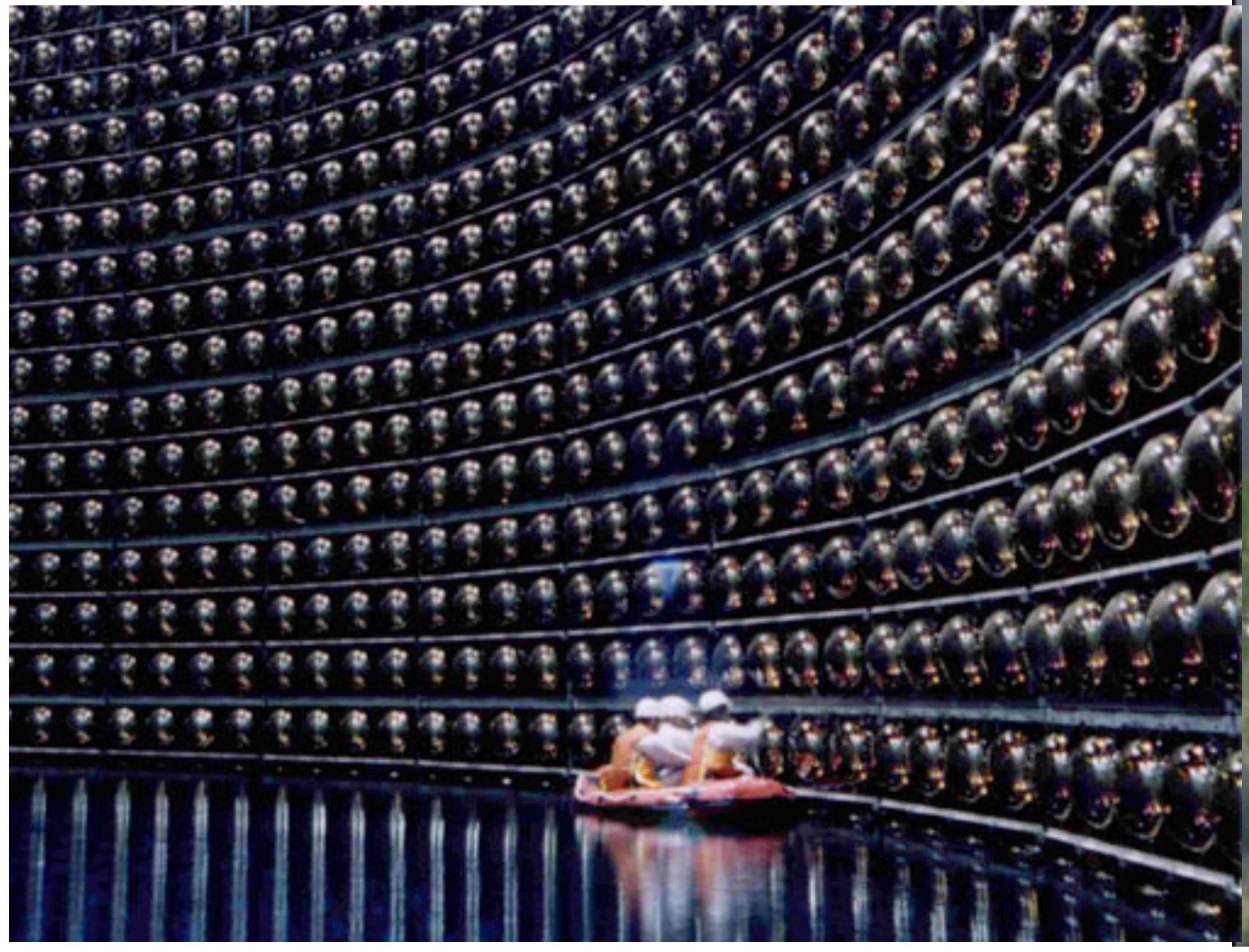


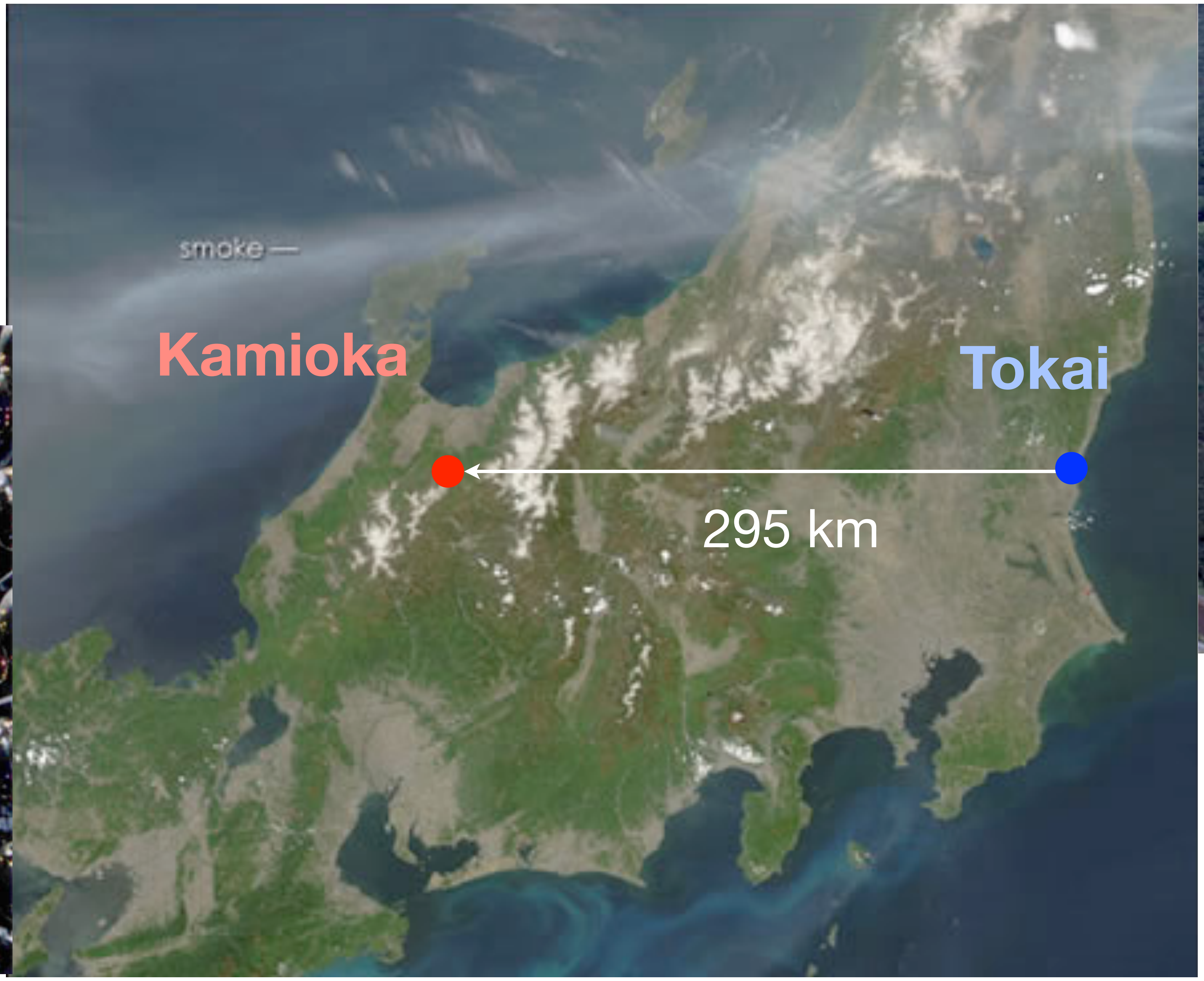


- $\sin^2 2\theta_{13} = 0.085 \pm 0.005$

BACK TO LONG BASELINE

Super Kamiokande
“far” detector



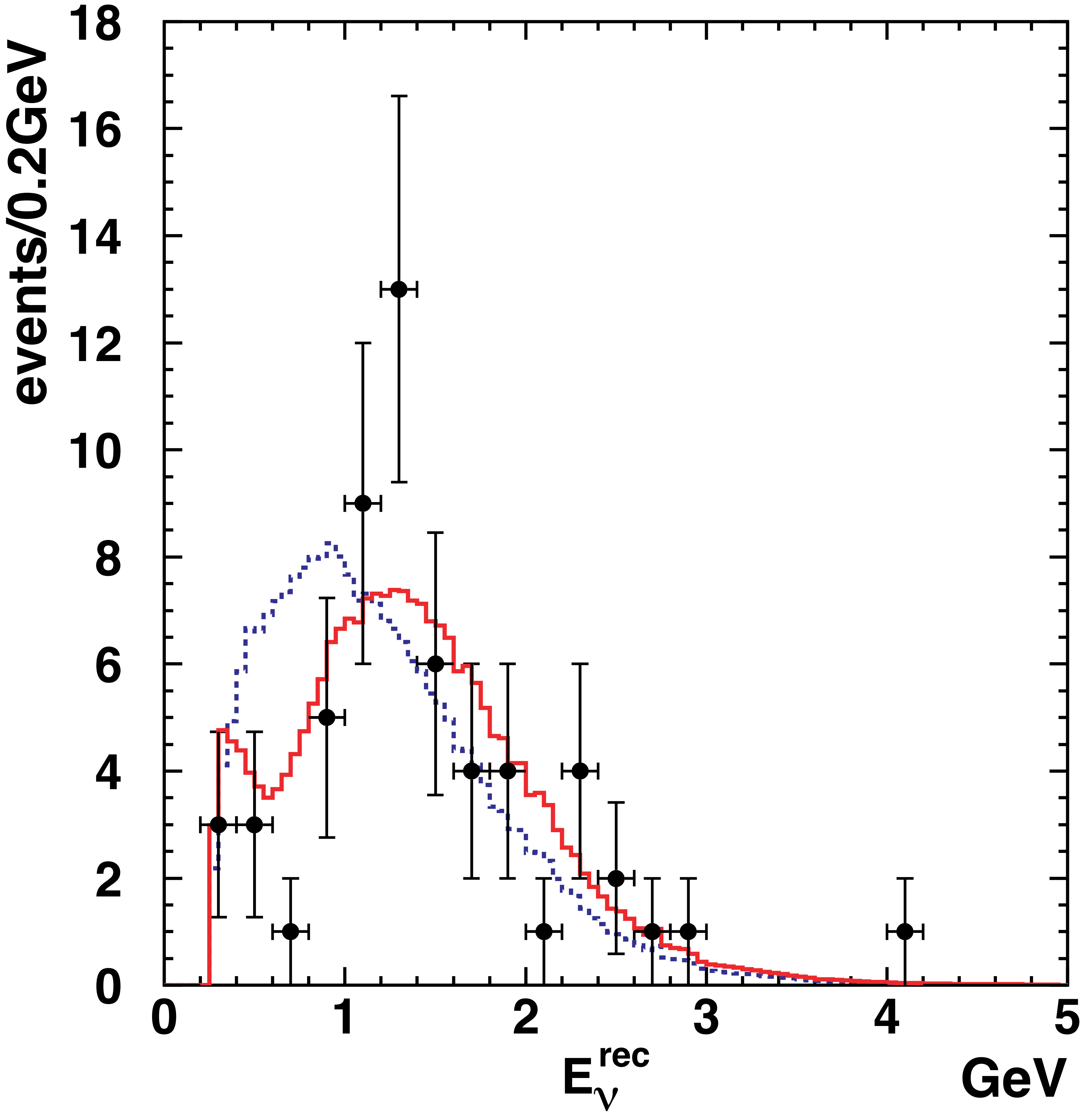


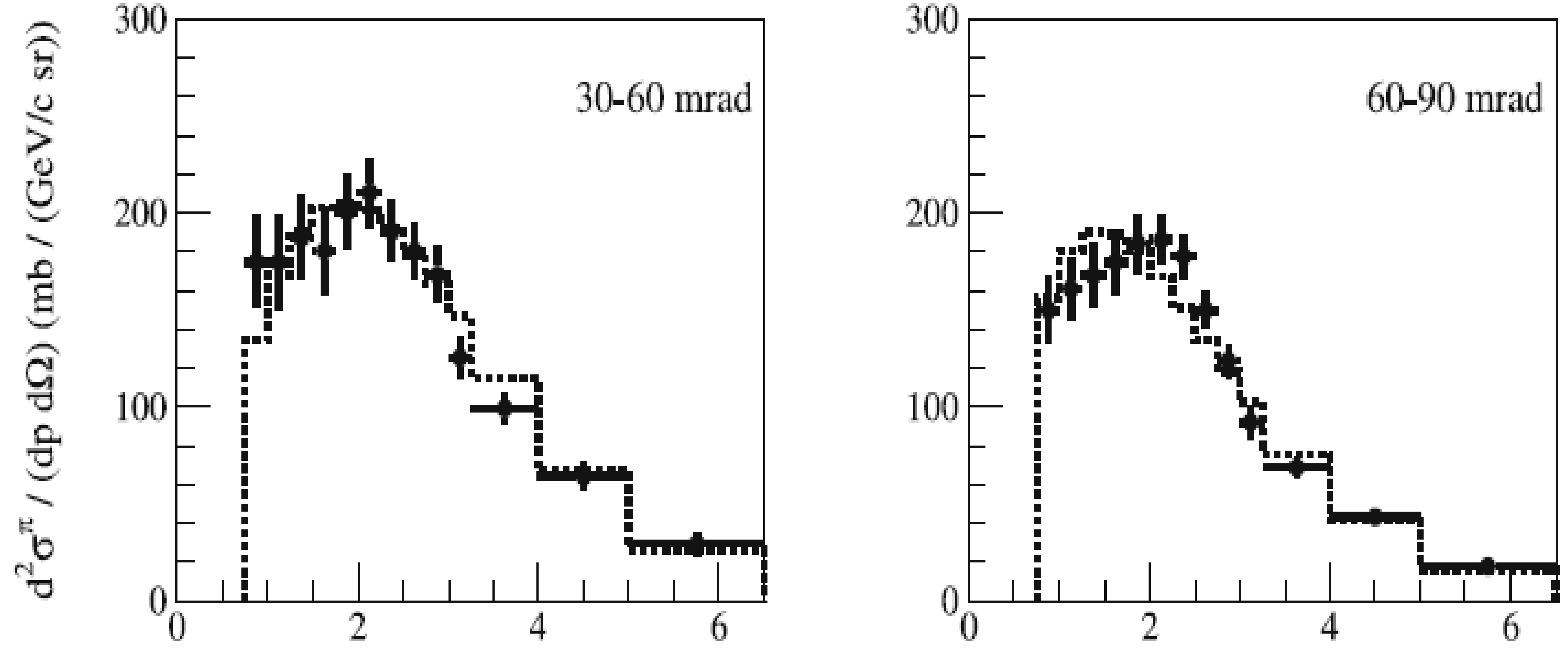
ND280
“near” detector

J-PARC

- New 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

IMPROVEMENT

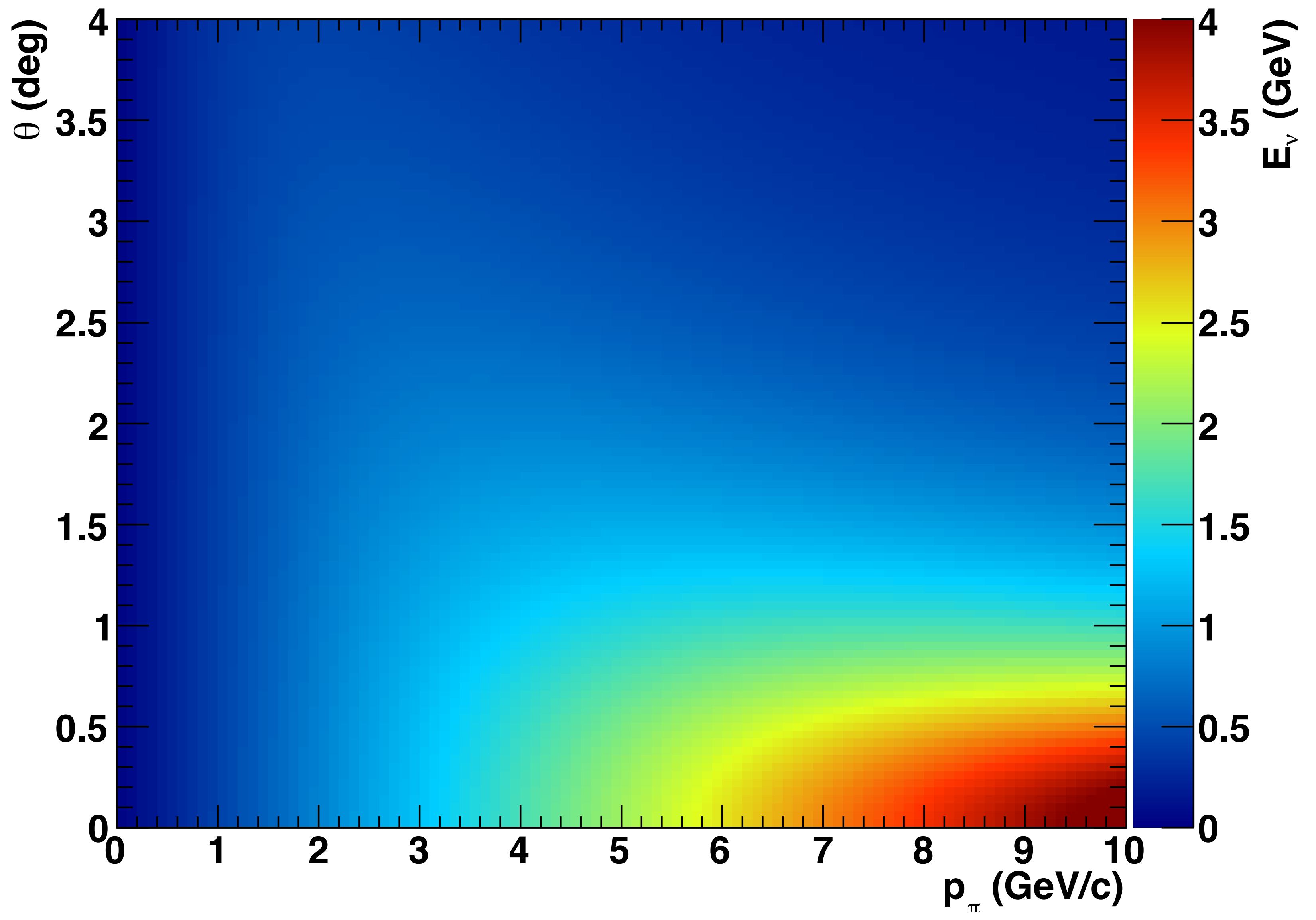


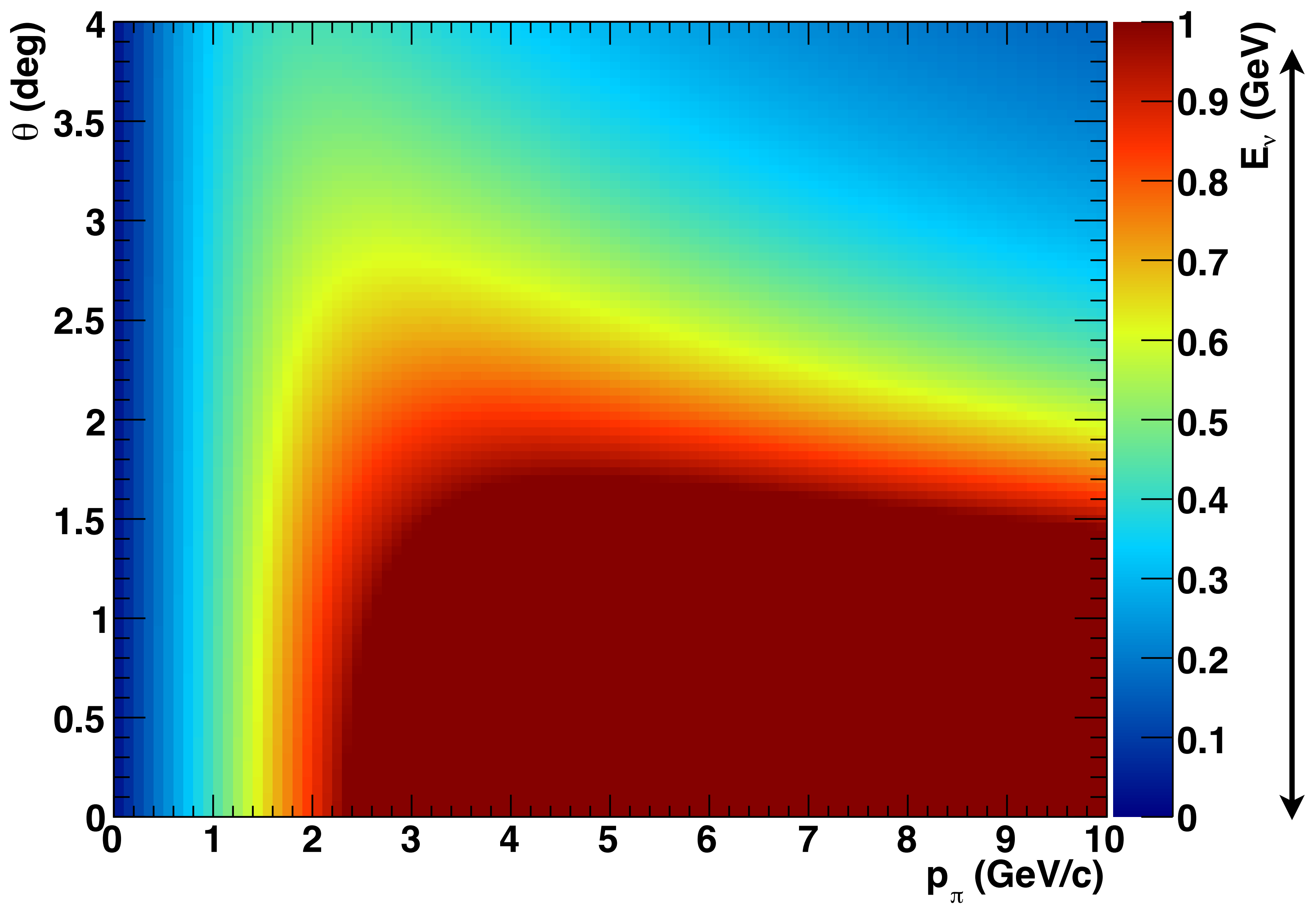


$$\pi^+ \longrightarrow \nu_\mu + \mu^+$$

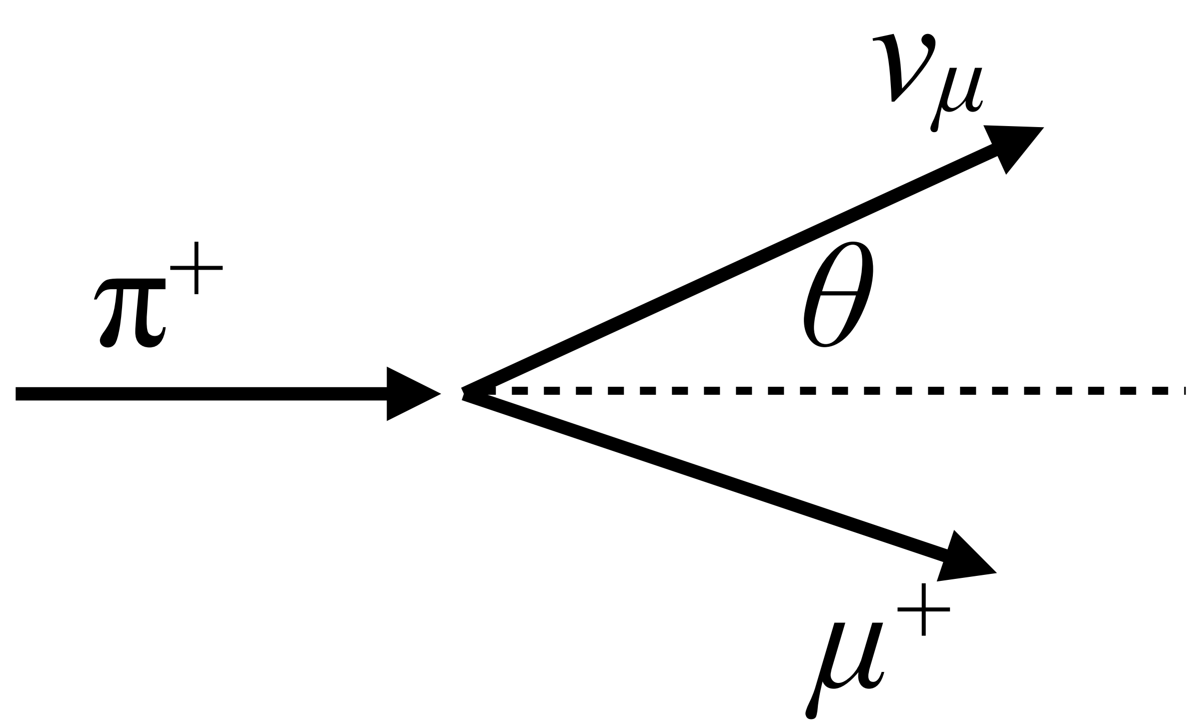
- For "forward' pion decays, neutrino energy is ~linear with pion energy
  - $E_\nu \sim 0.4 \times E_\pi$
- A neutrino beam aimed directly at a detector will have a broad energy spectrum that reflects the pion production spectrum

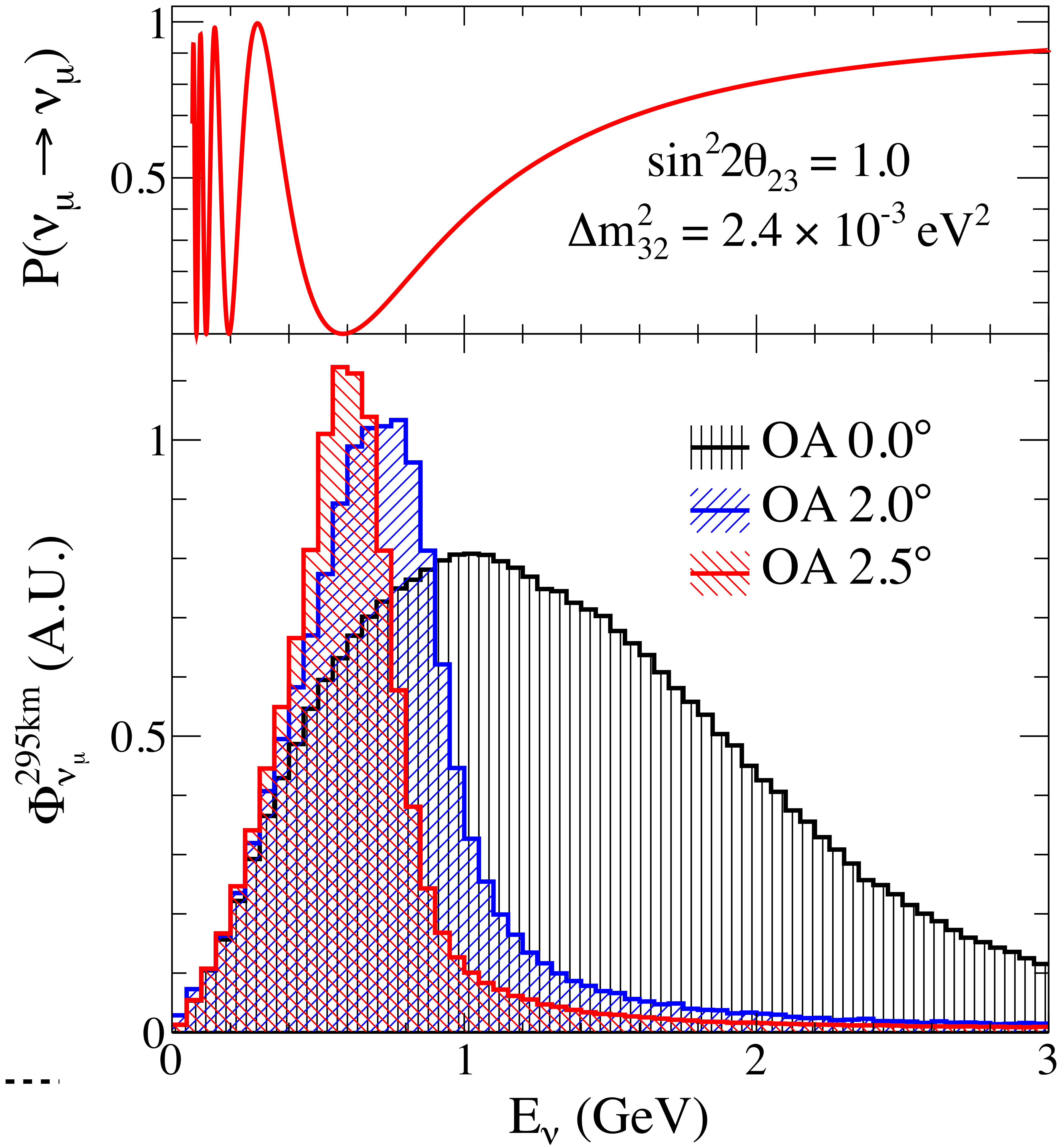
OFF-AXIS BEAM CONCEPT



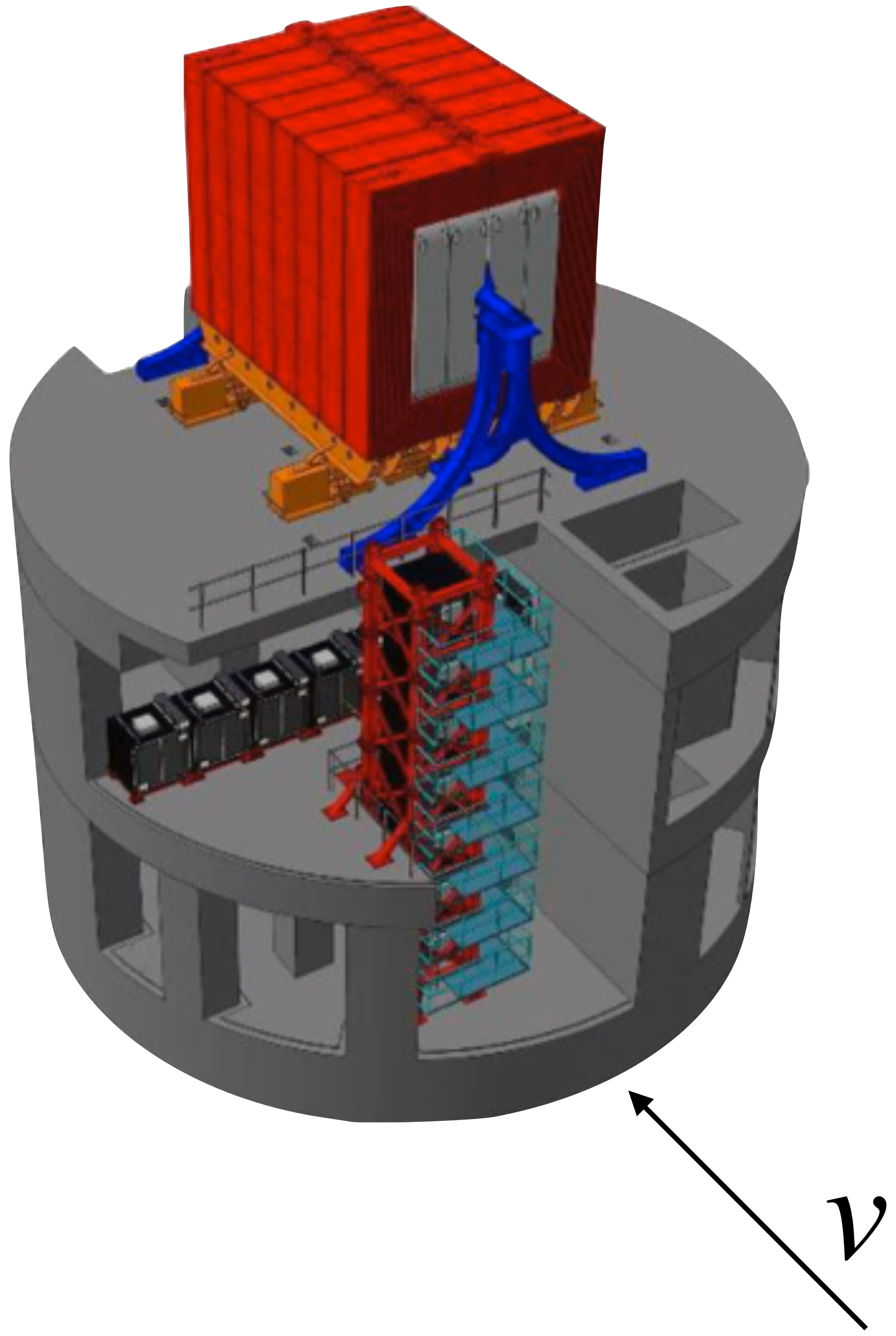


- Tune neutrino energy spectrum by pointing the beam away from your detector
- Also reduce "feeddown" backgrounds from higher energy





NEAR DETECTORS



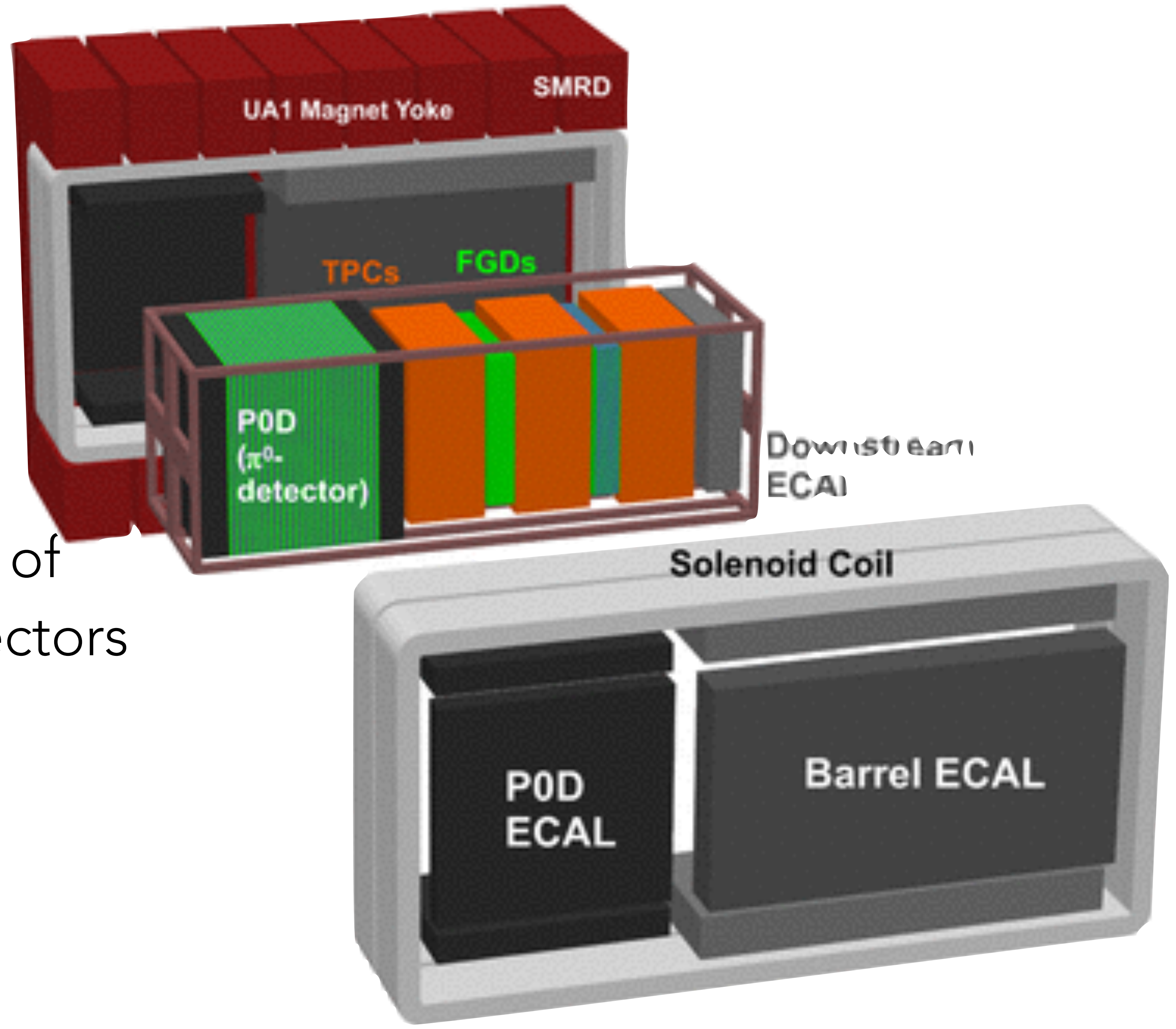
INGRID

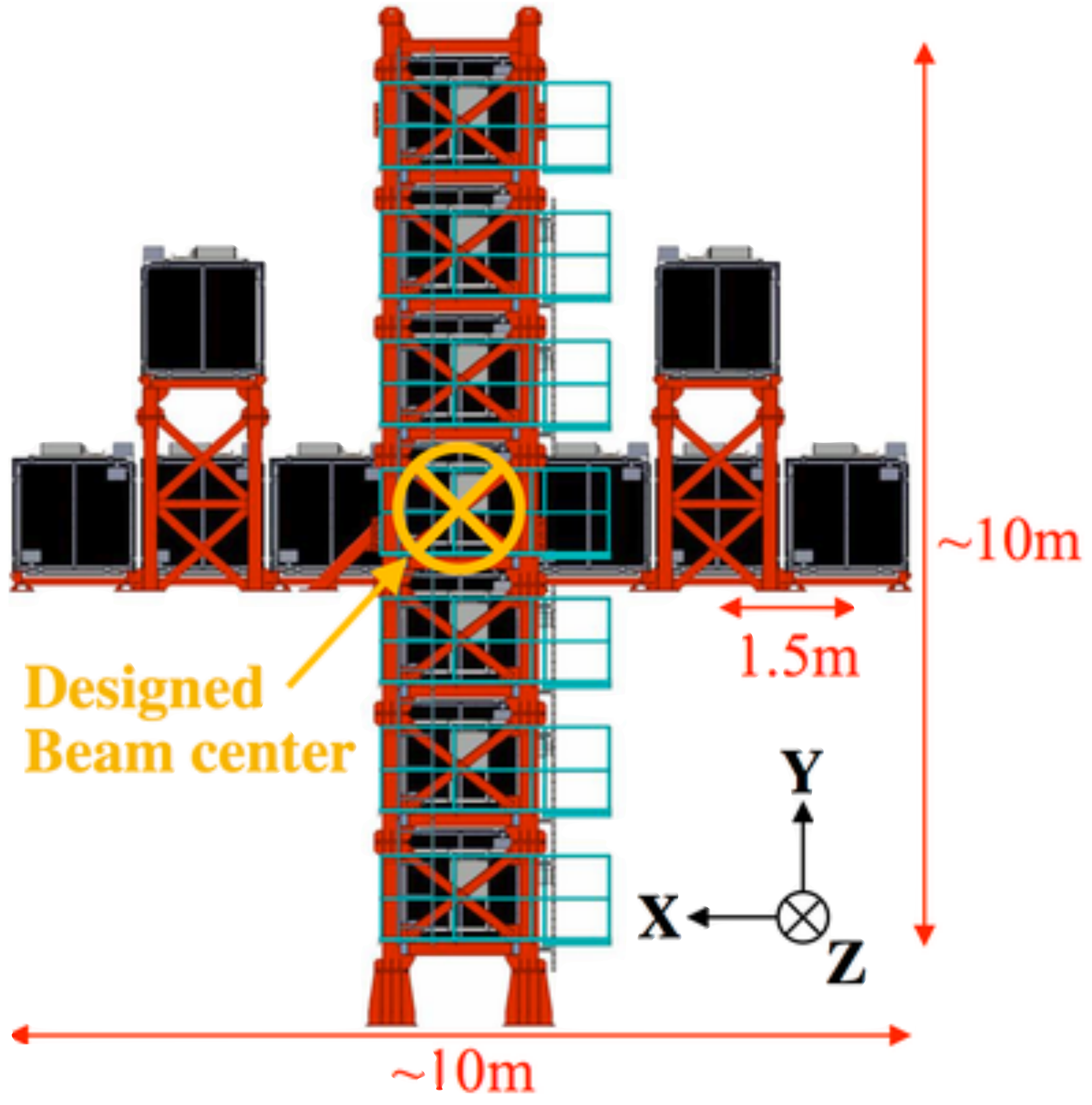
- 7x7 grid of scintillator/Fe neutrino detectors spanning beam axis
- monitor beam direction and rate

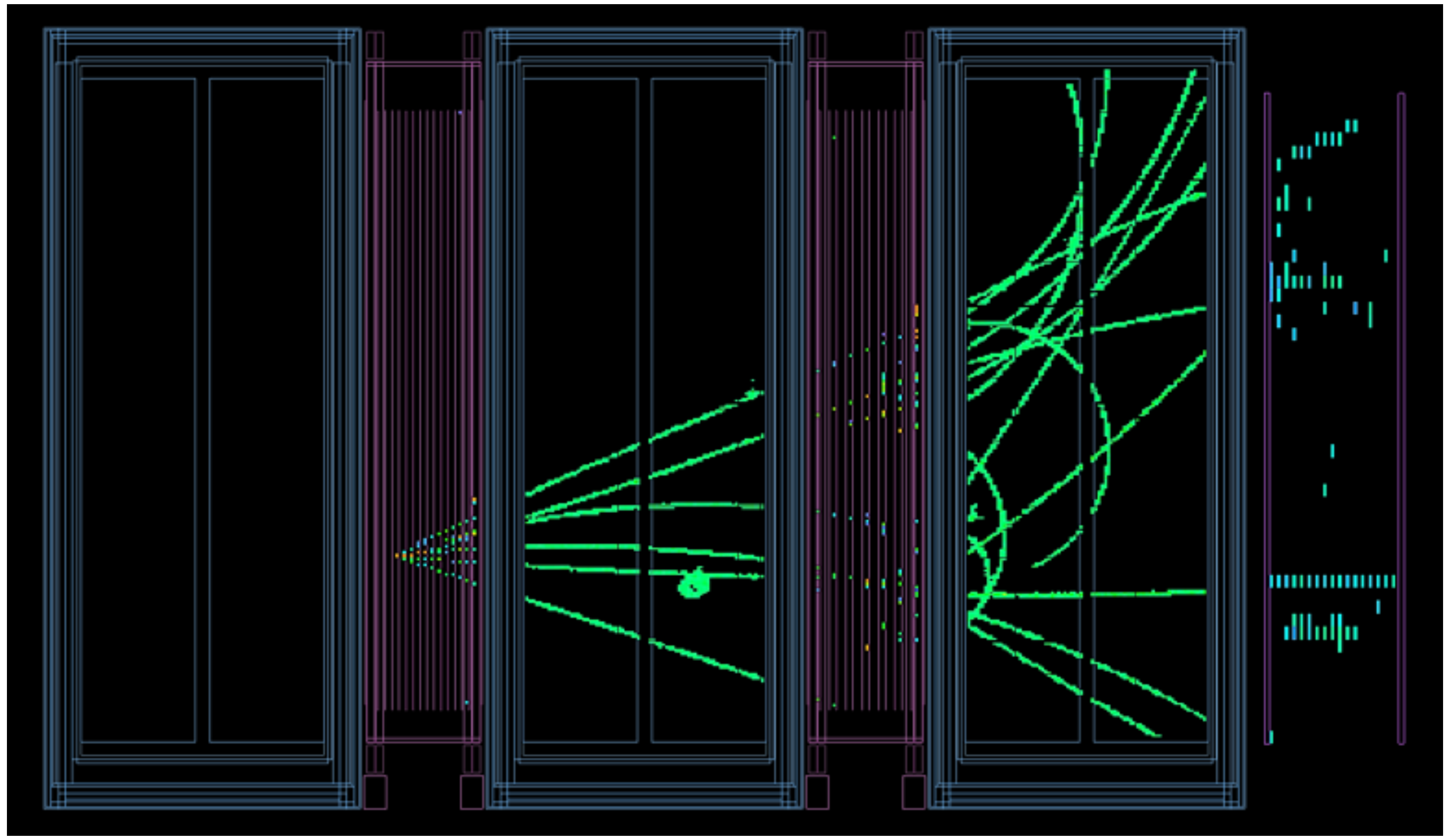
ν

ND280:

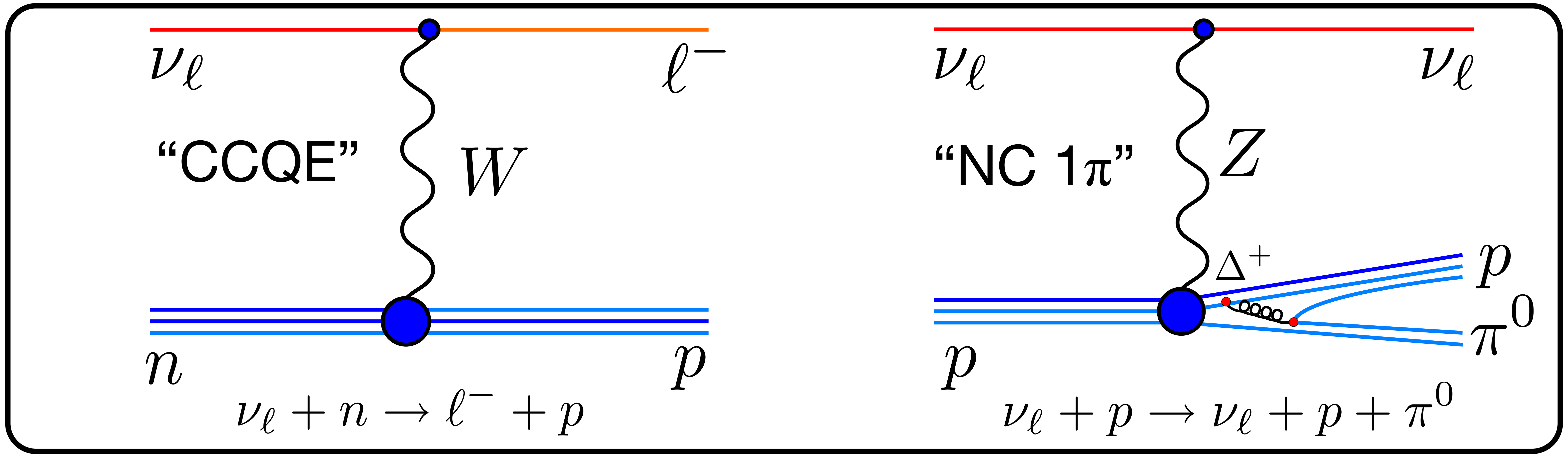
- off-axis detector systems comprised of tracking, calorimetry and muon detectors
- 0.20 T field from UA1 magnet
- scintillator and water targets







NEAR INTERACTIONS AT T2K



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

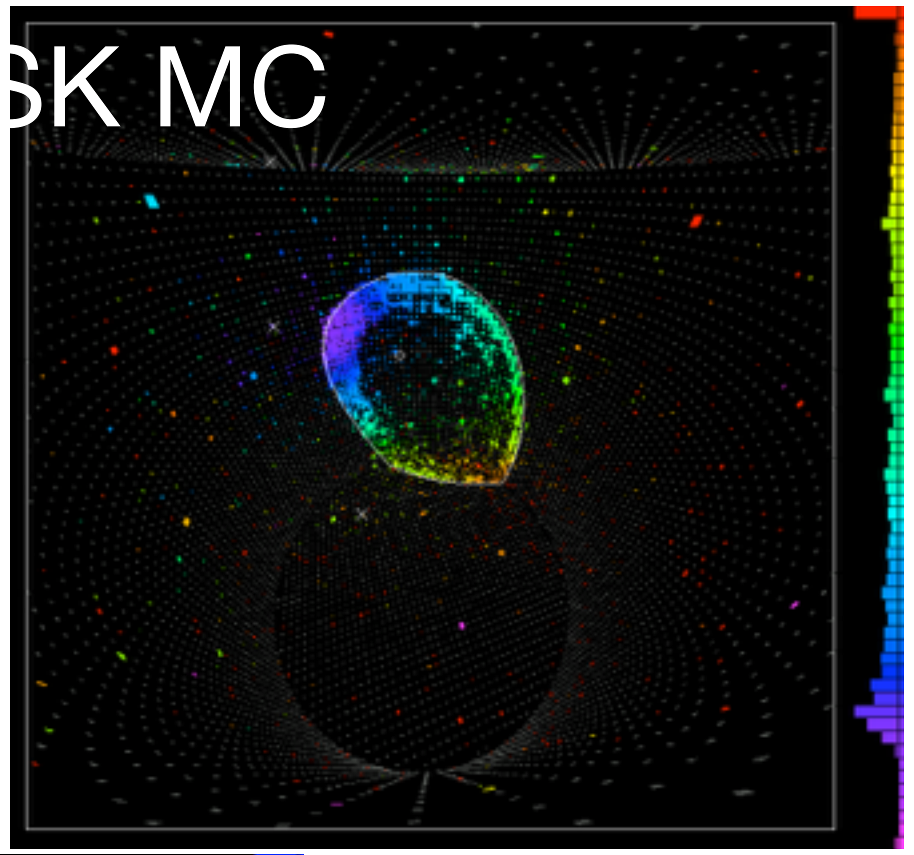
- Single μ/e-like ring
- E_ν by energy/direction of lepton, 2-body kinematics

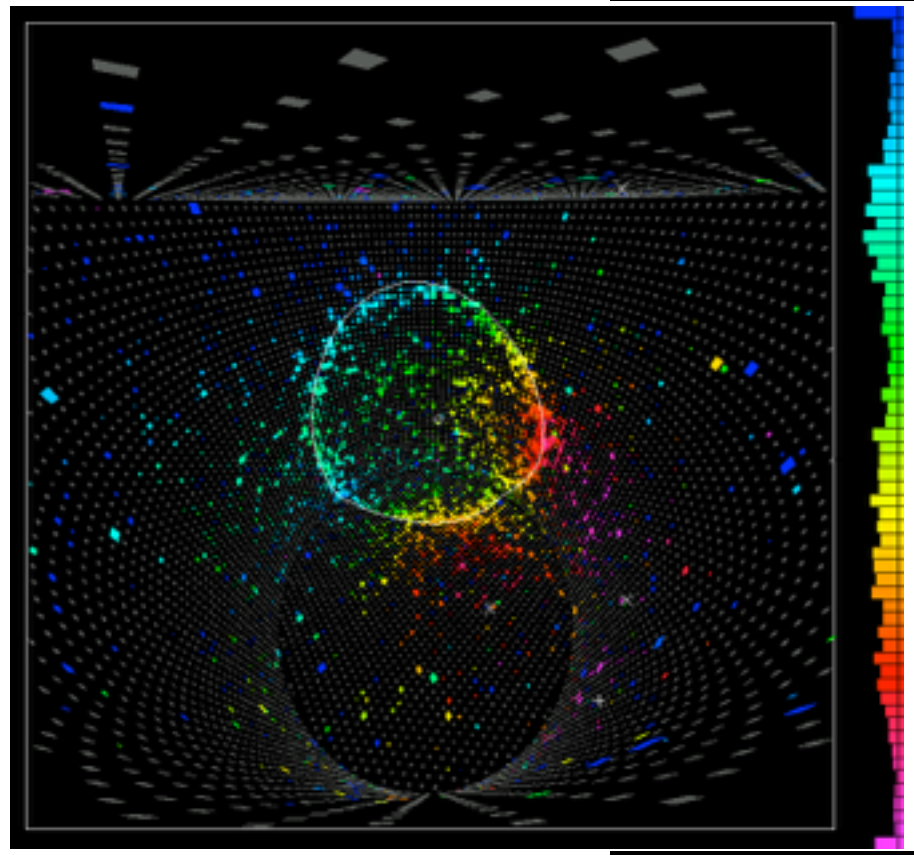
$\nu_\ell + (n/p) \rightarrow \nu_\ell + (n/p) + \pi^0$ **Backgrounds**

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

- $\pi^0 \rightarrow \gamma + \gamma$: 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

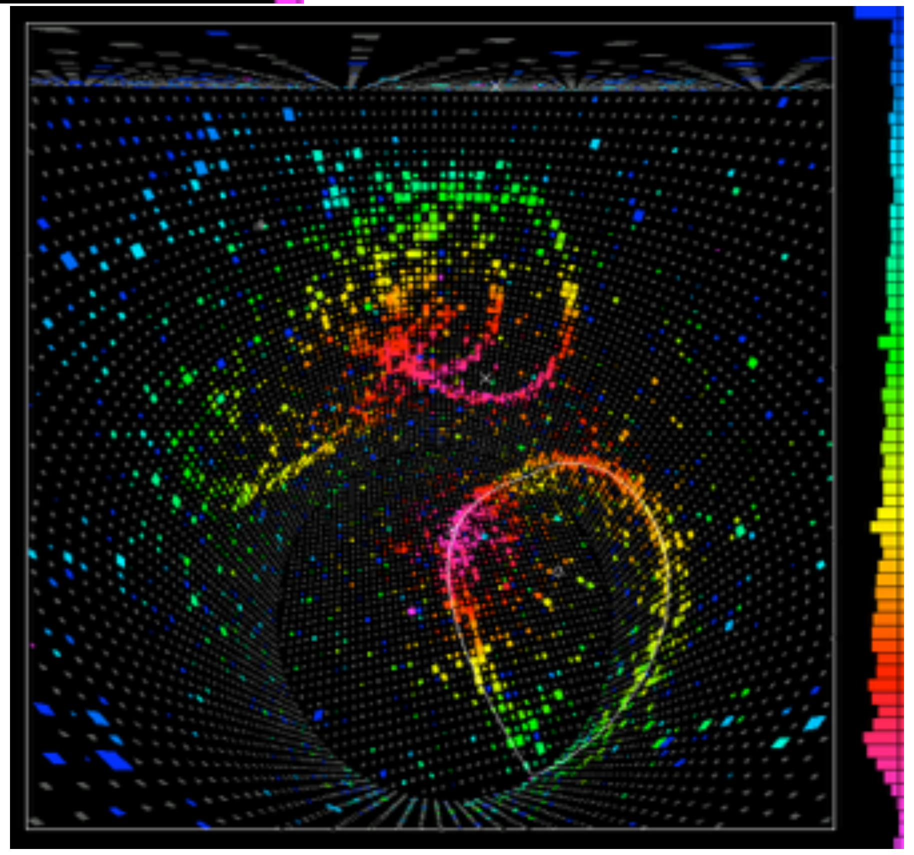
μ



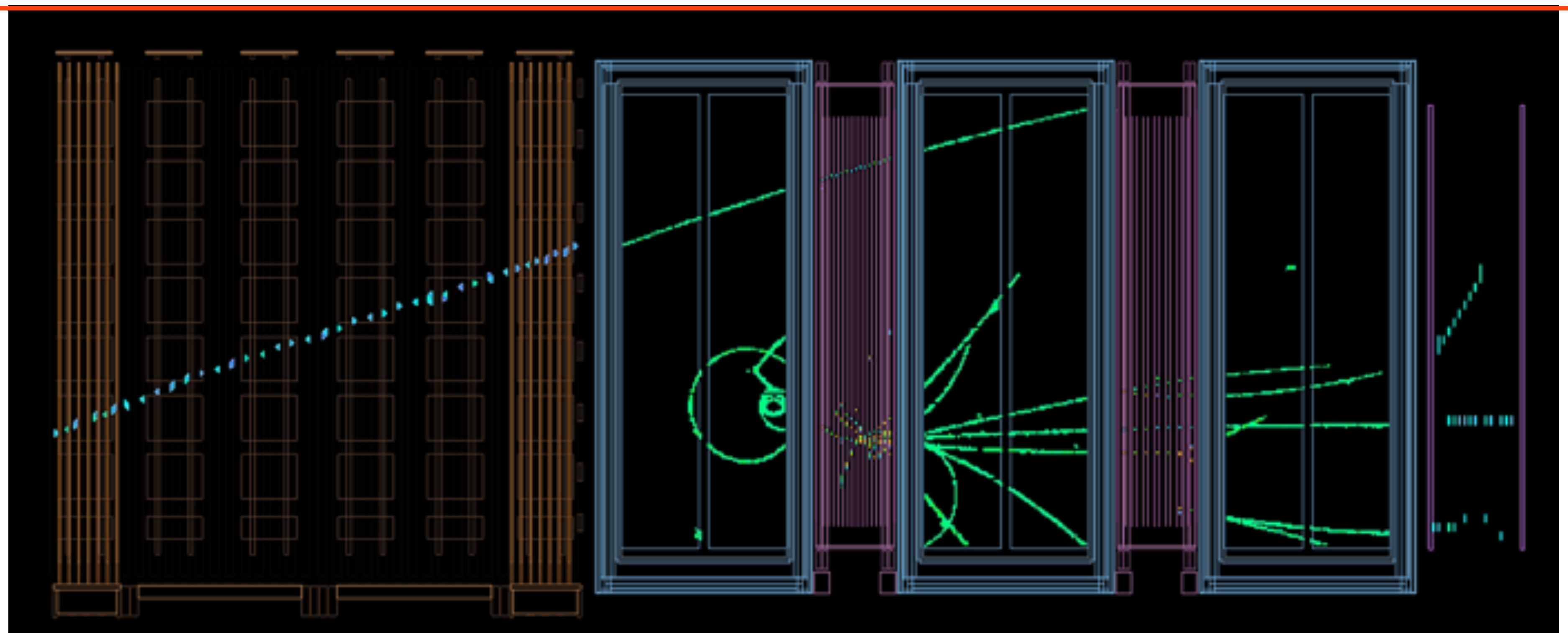


e/γ

multi ring

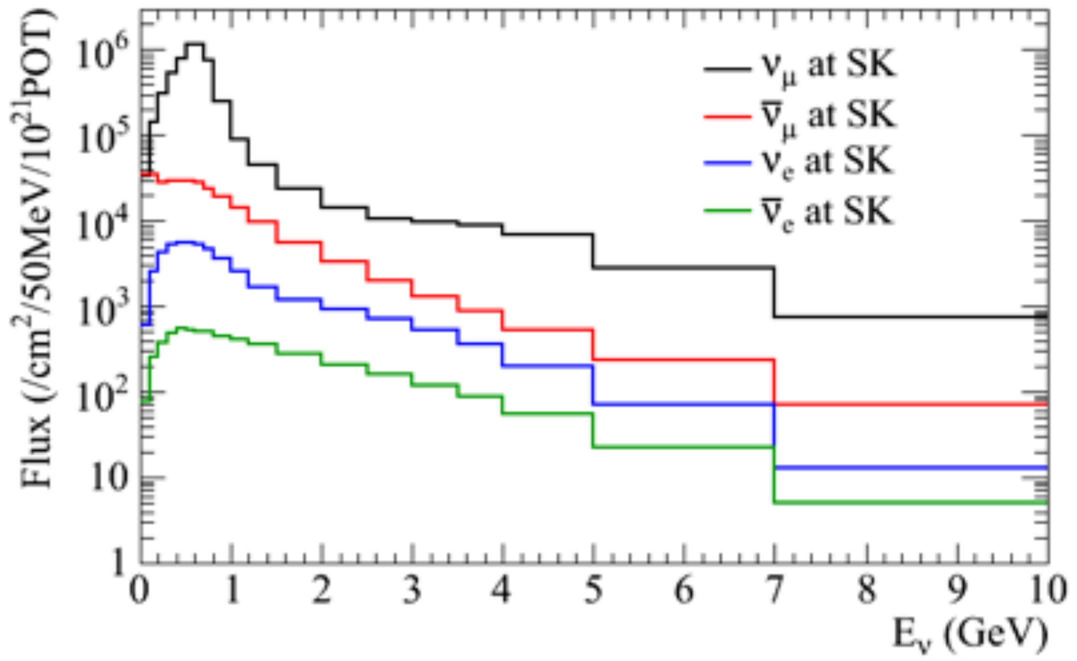


ANALYSIS STRATEGY

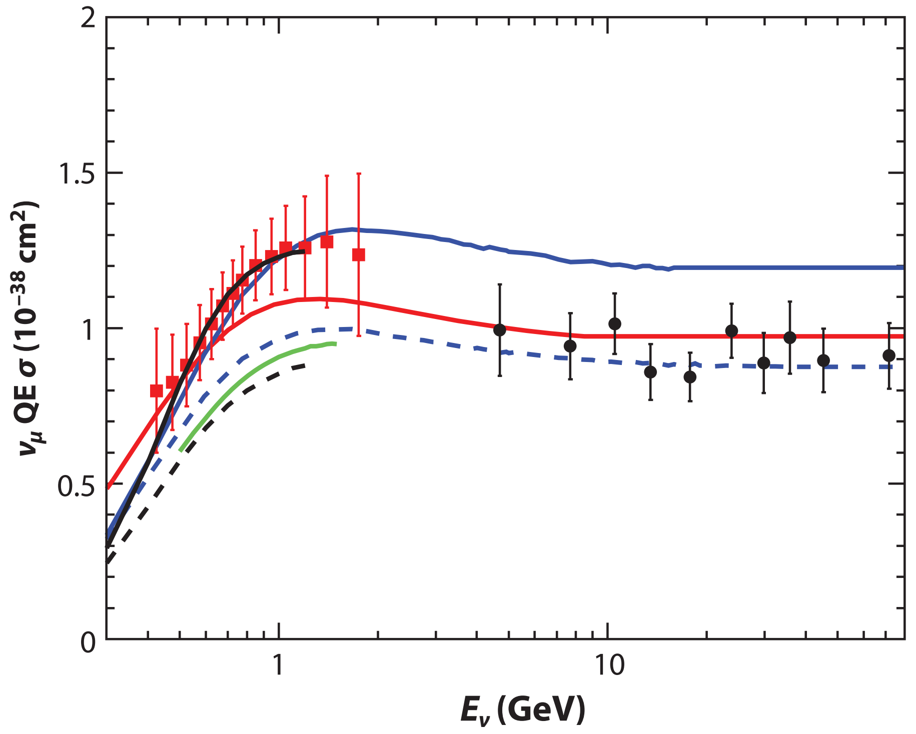


Near detectors observe the neutrinos prior to oscillations

φ_ν $\quad$ $\varphi_\nu \cdot \sigma_\nu \cdot \varepsilon_{NEAR}$ $\quad$ σ_ν



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



Neutrino cross section and interaction model tuned to external measurements

Far (L=295 km)

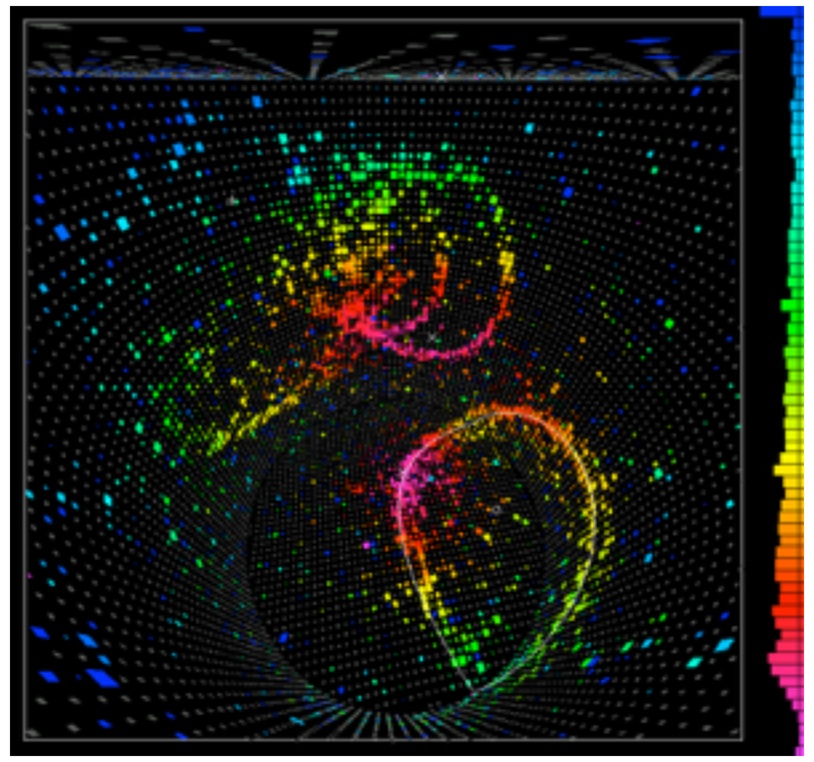
$\nu_\mu \rightarrow \nu_e$ (θ_{23}, θ_{13}, δ_{CP})

$\nu_\mu \rightarrow \nu_{\mu/\tau}$ ($2\theta_{23}$, Δm^2_{32})

ν_μ, ν_e backgrounds

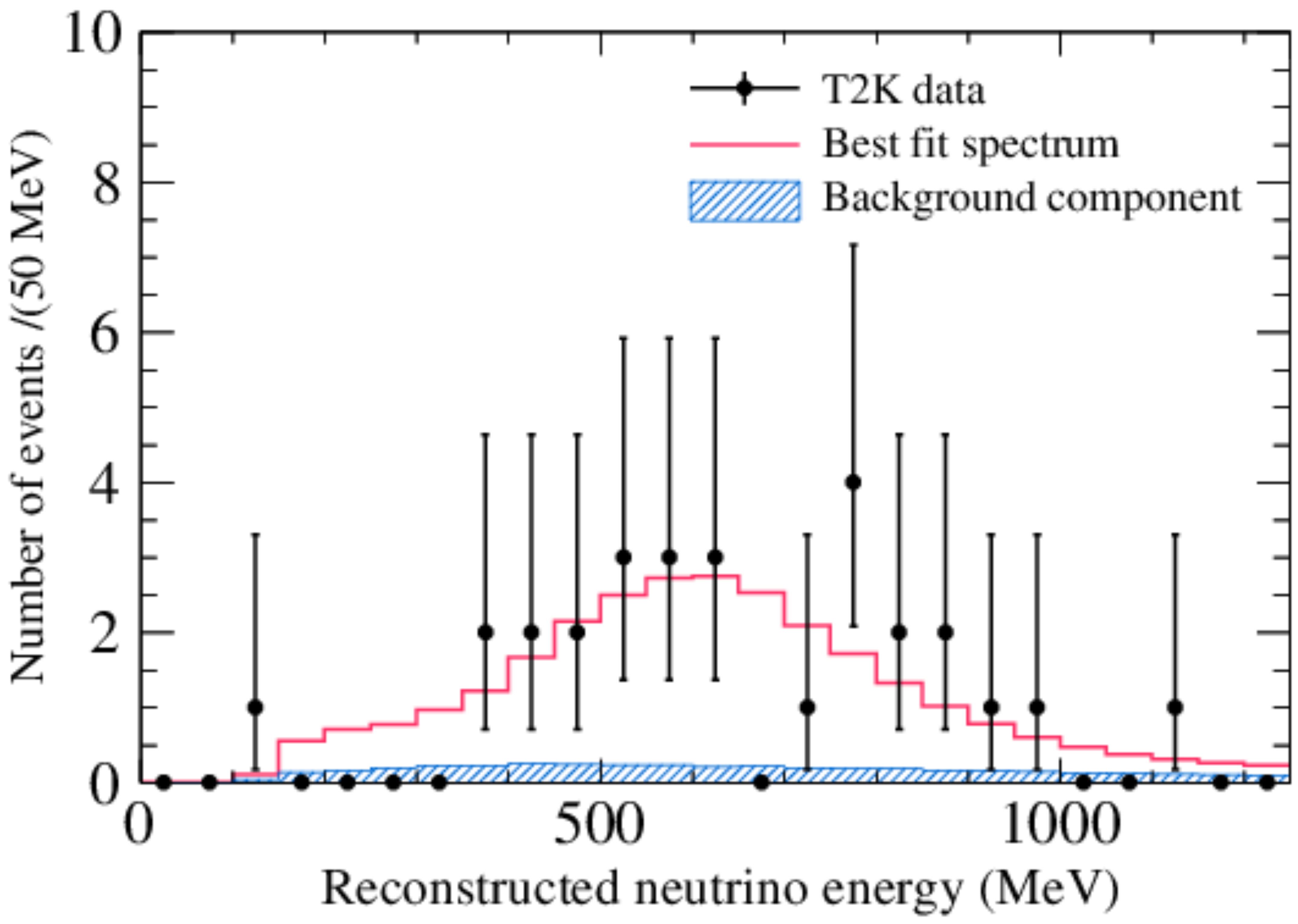
$\varphi_\nu \cdot \sigma_\nu \cdot \varepsilon_{FAR} \cdot P_{osc}$

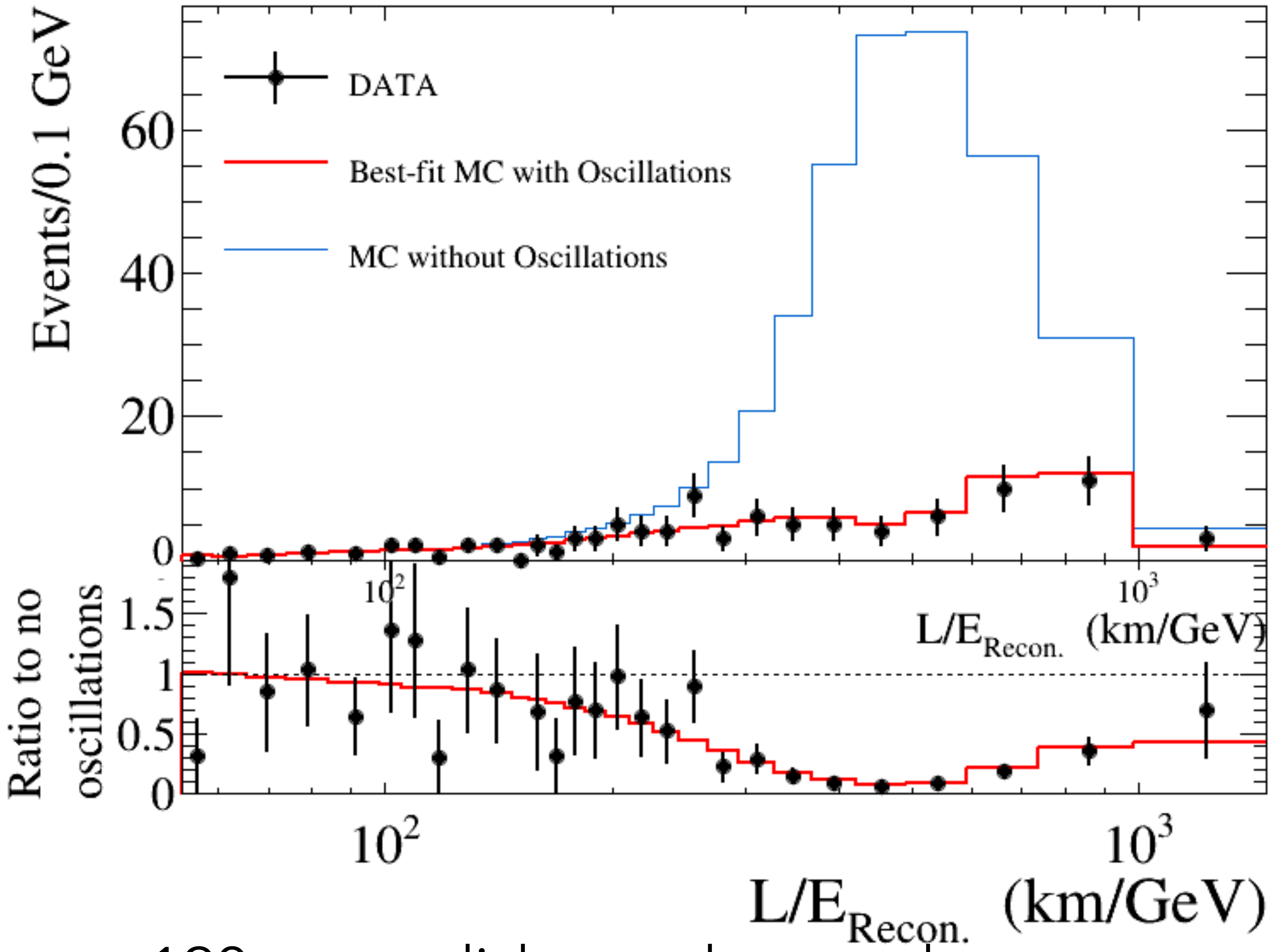
ε_{FAR}



Detector simulation to determine efficiencies/ backgrounds

OSCILLATION RESULTS





- 28 ν_e candidates
  - 5.0 expected in absence of oscillation effects
  - definitive observation of $\nu_\mu \rightarrow \nu_e$ oscillations

	Osc.	No osc.
ν_μ	0.9	1.4
$\bar{\nu}_\mu$	0.1	0.1
$\nu_e/\bar{\nu}_e$	3.3	3.5
$\nu_\mu \rightarrow \nu_e$	16.6	0.0
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	0.2	0.0
Total	21.1	5.0

expected number of ν_e candidates for $\delta_{CP} = 0$, $\sin^2\theta_{23} = 0.5$, NH

- 120 ν_μ candidates observed
  - 446 expected in absence of osc. effects
  - Most precise determination of ν_μ disappearance

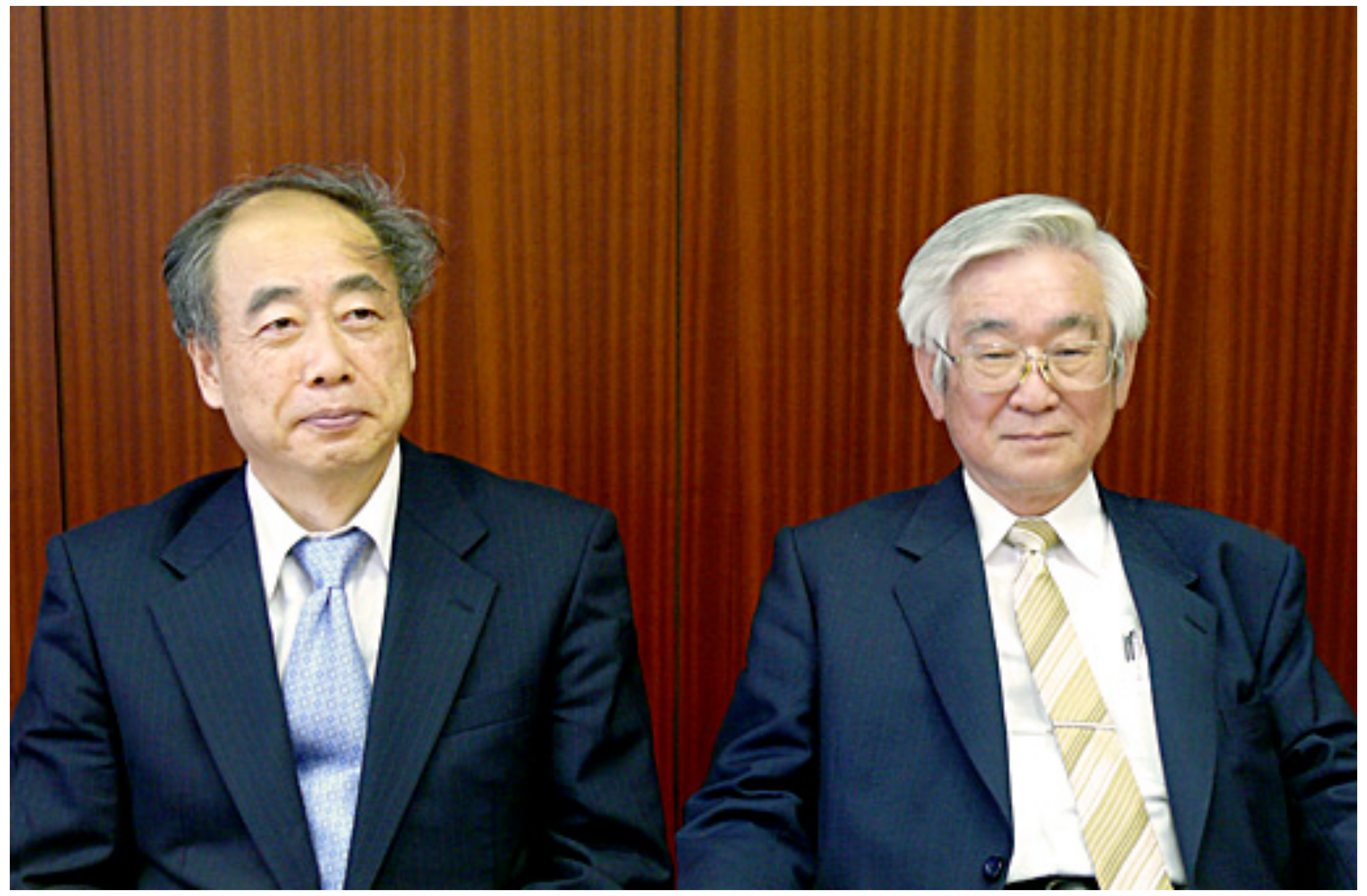
$$\sin^2\theta_{23} = 0.514^{+0.055}_{-0.056}$$
$$\Delta m^2_{32} = (2.51 \pm 0.51) \times 10^{-3}\ \mathrm{eV}^2/c^4$$

CONSEQUENCES

- Recall:

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

- $\theta_{13} \neq 0$:
  - ν_μ oscillating to ν_e at the "atmospheric" scale
  - ν_e disappearing at the "atmospheric" scale
- We now have full 3-flavor mixing
- The world of neutrino oscillations is a lot more complicated and richer now.



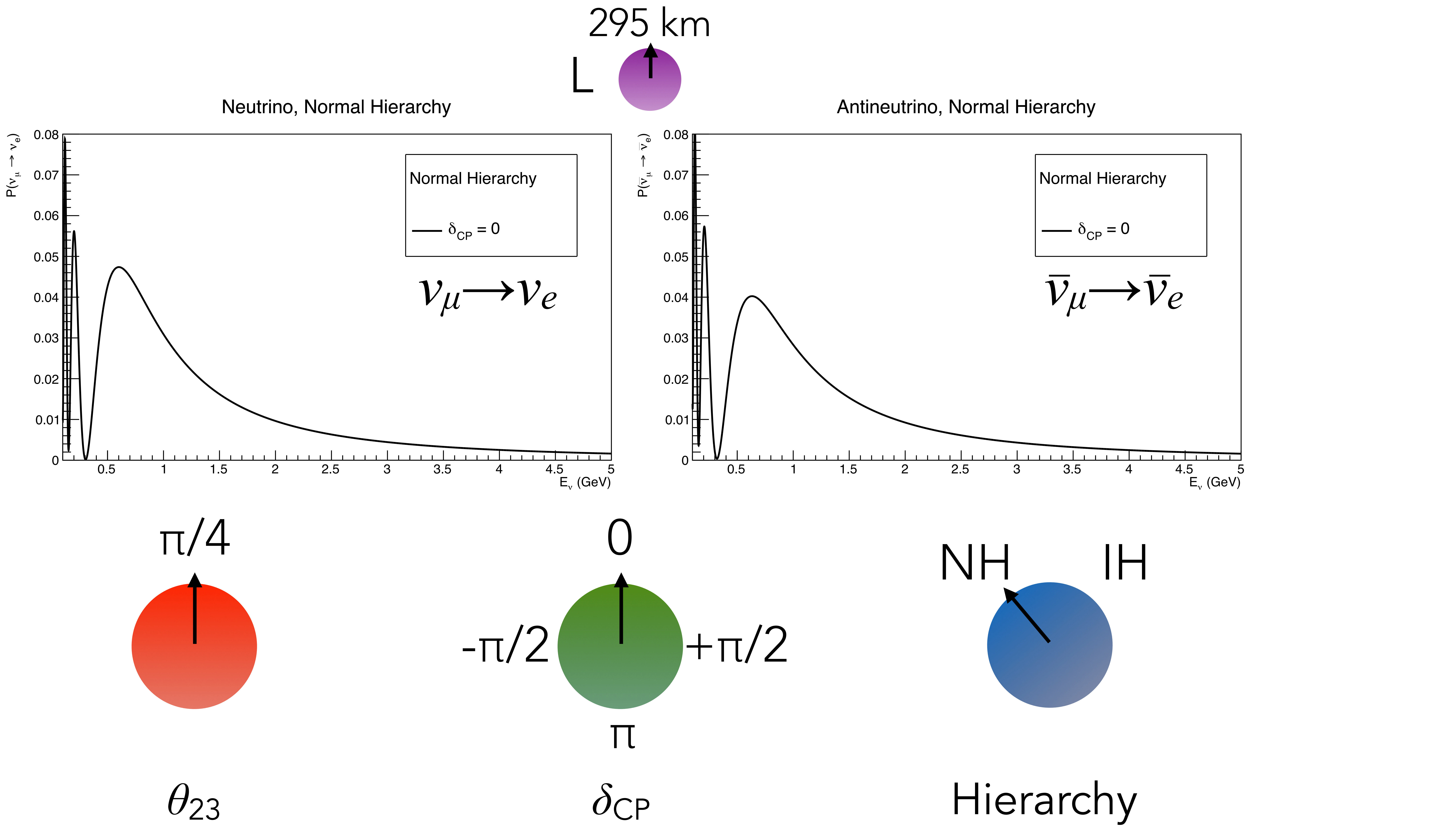
$\nu_\mu \rightarrow \nu_e$ OSCILLATION PROBABILITY

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

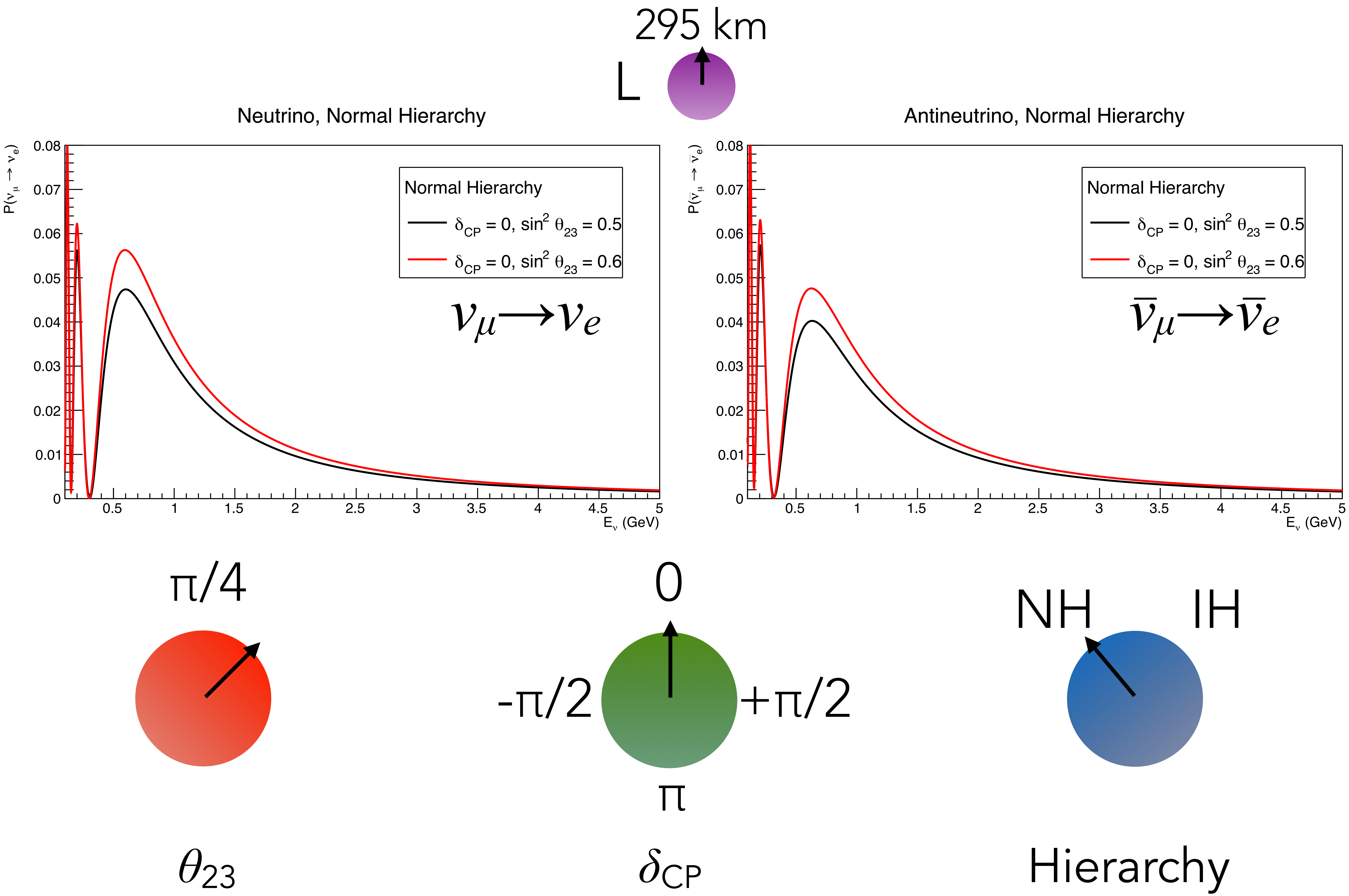
M. Freund, Phys.Rev. D64 (2001) 053003

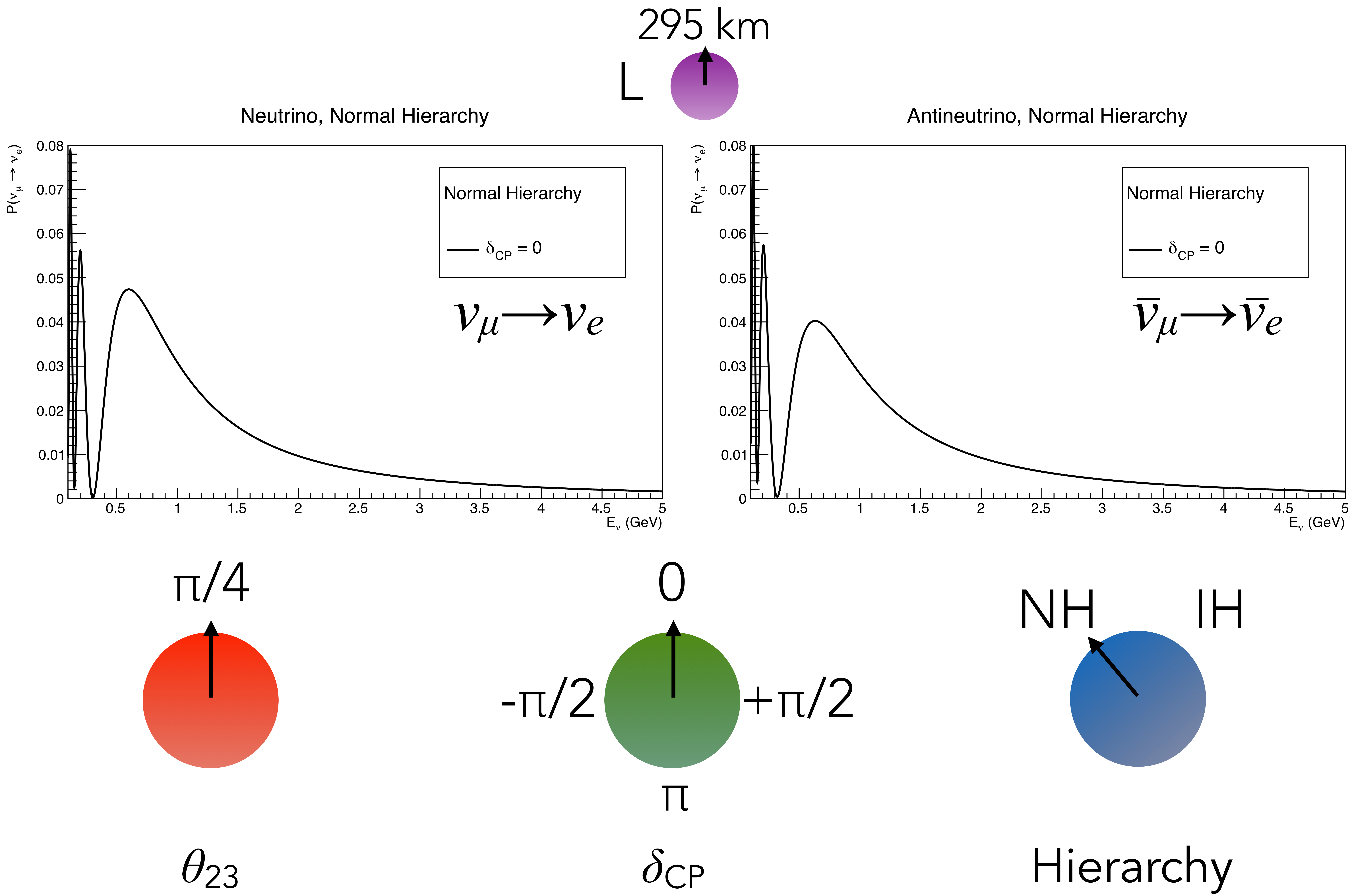
$$
\alpha = \left| \frac{\Delta m^2_{21}}{\Delta m^2_{31}} \right| \sim \frac{1}{30} \qquad \Delta \equiv \frac{\Delta m^2_{31} L}{4E} \qquad x \equiv \frac{2\sqrt{2} G_F N_e E}{\Delta m^2_{31}}
$$

- CP odd phase δ can result in
  - asymmetry of oscillation probabilities $P(\nu_\mu \rightarrow \nu_e) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$
  - 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

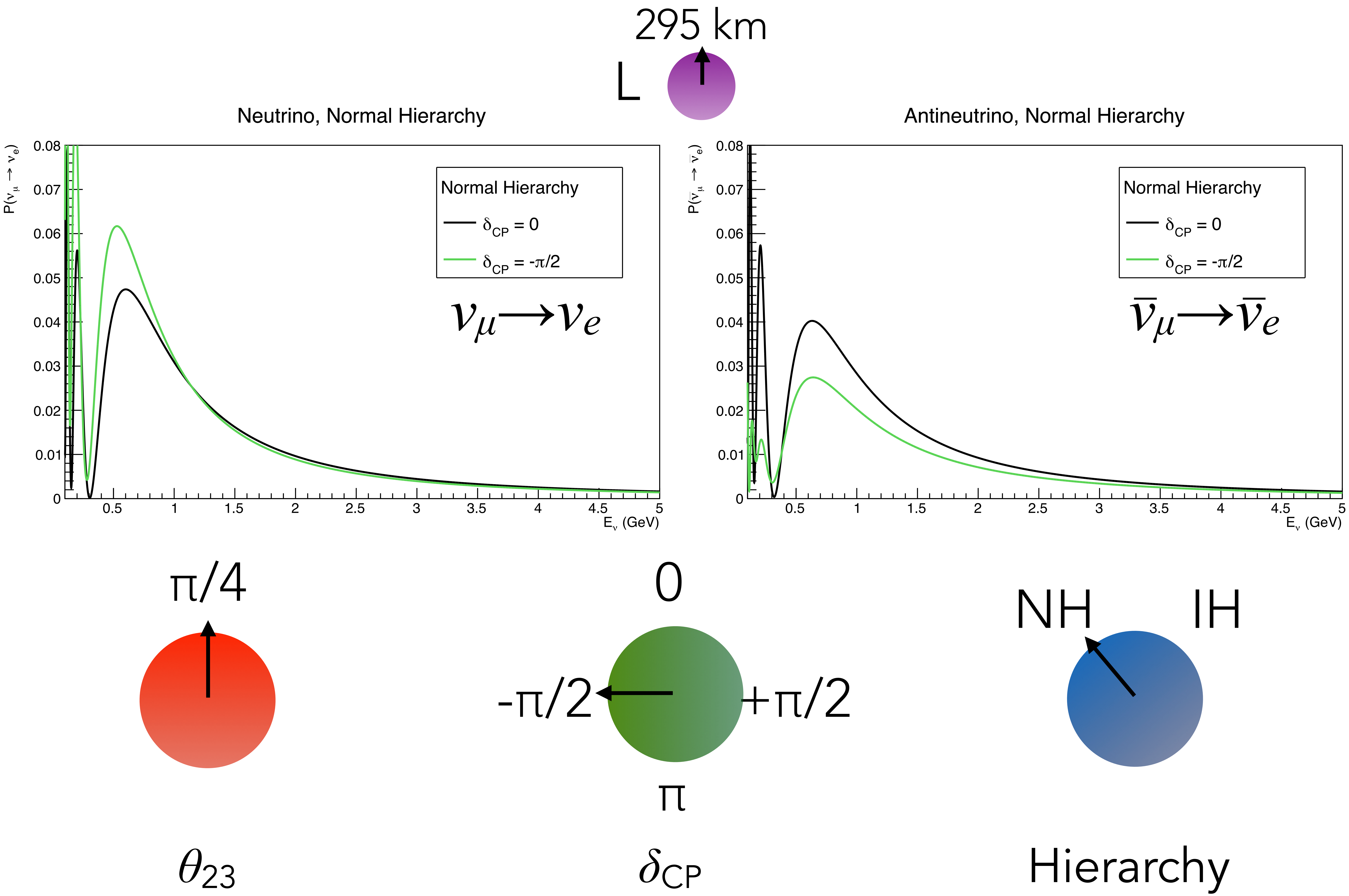


295 km
L
Neutrino, Normal Hierarchy
Antineutrino, Normal Hierarchy
Normal Hierarchy
δCP = 0
νμ→νe
ν̄μ→ν̄e
Eν (GeV)
π/4
0
-π/2
+π/2
π
NH
IH
θ23
δCP
Hierarchy

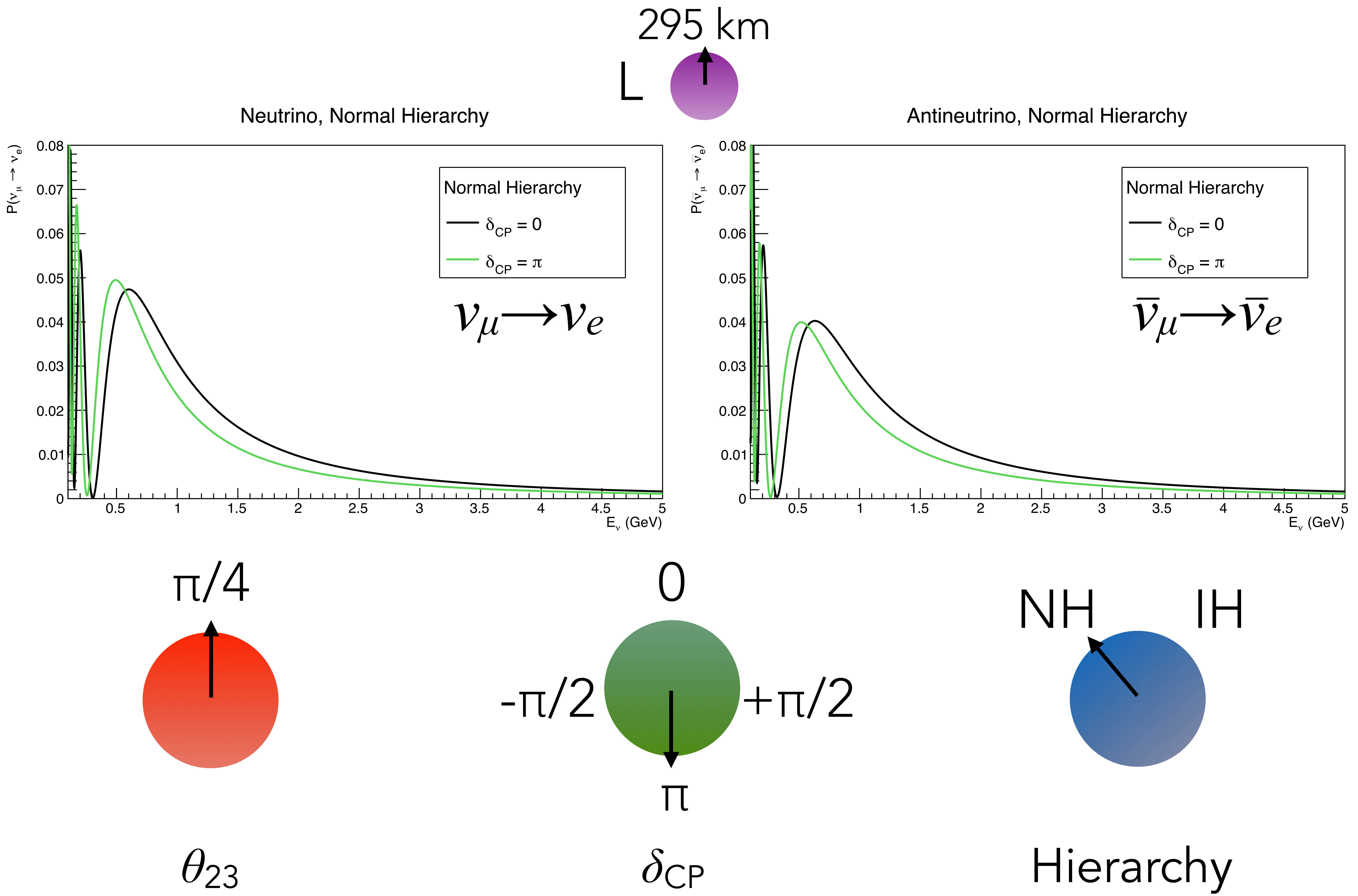

295 km
L
Neutrino, Normal Hierarchy
Antineutrino, Normal Hierarchy
Normal Hierarchy
δCP = 0, sin2 θ23 = 0.5
δCP = 0, sin2 θ23 = 0.6
νμ→νe
ν̄μ→ν̄e
Eν (GeV)
π/4
0
-π/2
+π/2
π
NH
IH
θ23
δCP
Hierarchy

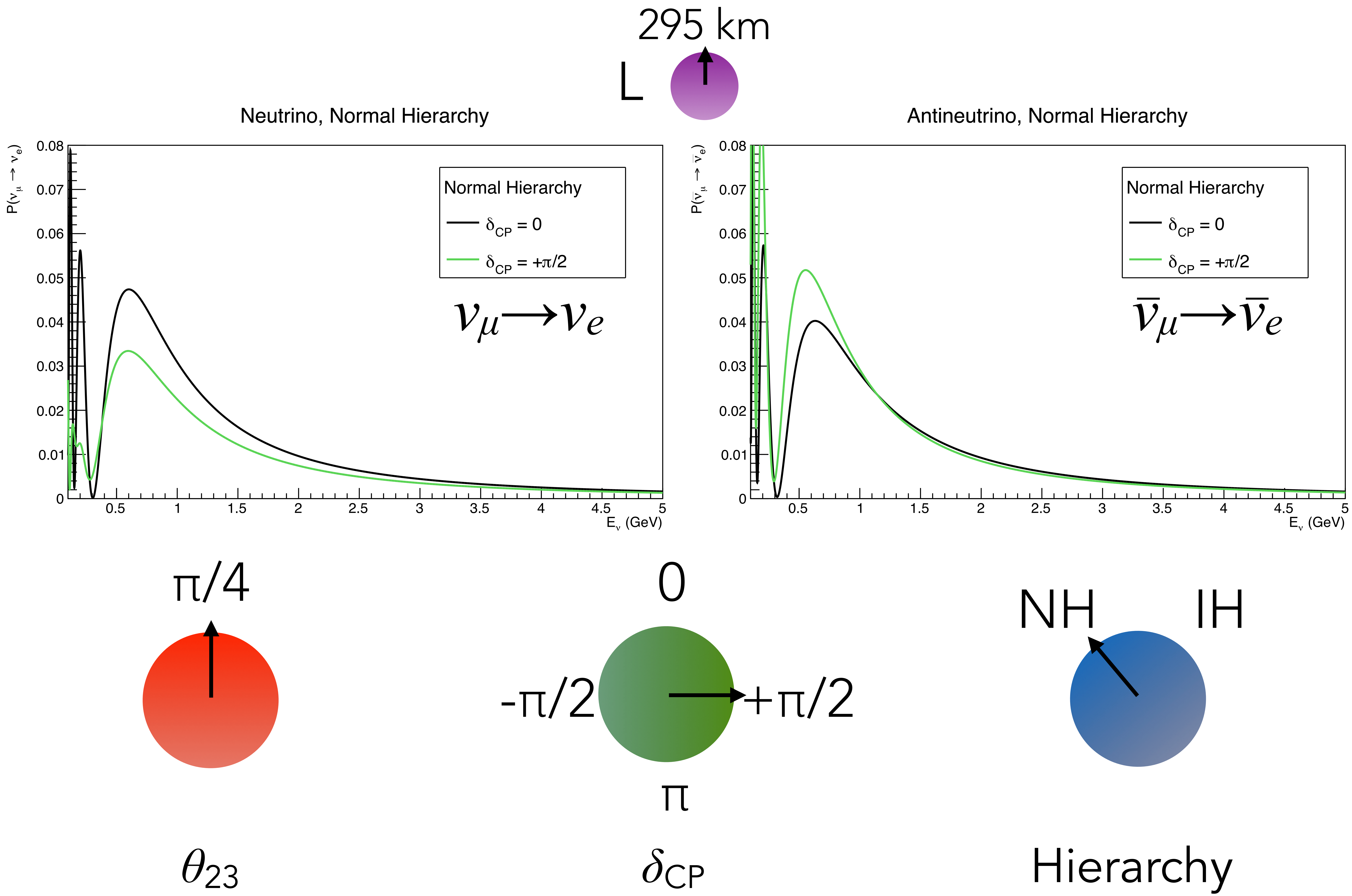


295 km
L
Neutrino, Normal Hierarchy
Antineutrino, Normal Hierarchy
P(ν_μ → ν_e)
P(ν̄_μ → ν̄_e)
Normal Hierarchy
δ_CP = 0
ν_μ→ν_e
ν̄_μ→ν̄_e
E_ν (GeV)
π/4
0
-π/2
+π/2
π
NH
IH
θ23
δCP
Hierarchy

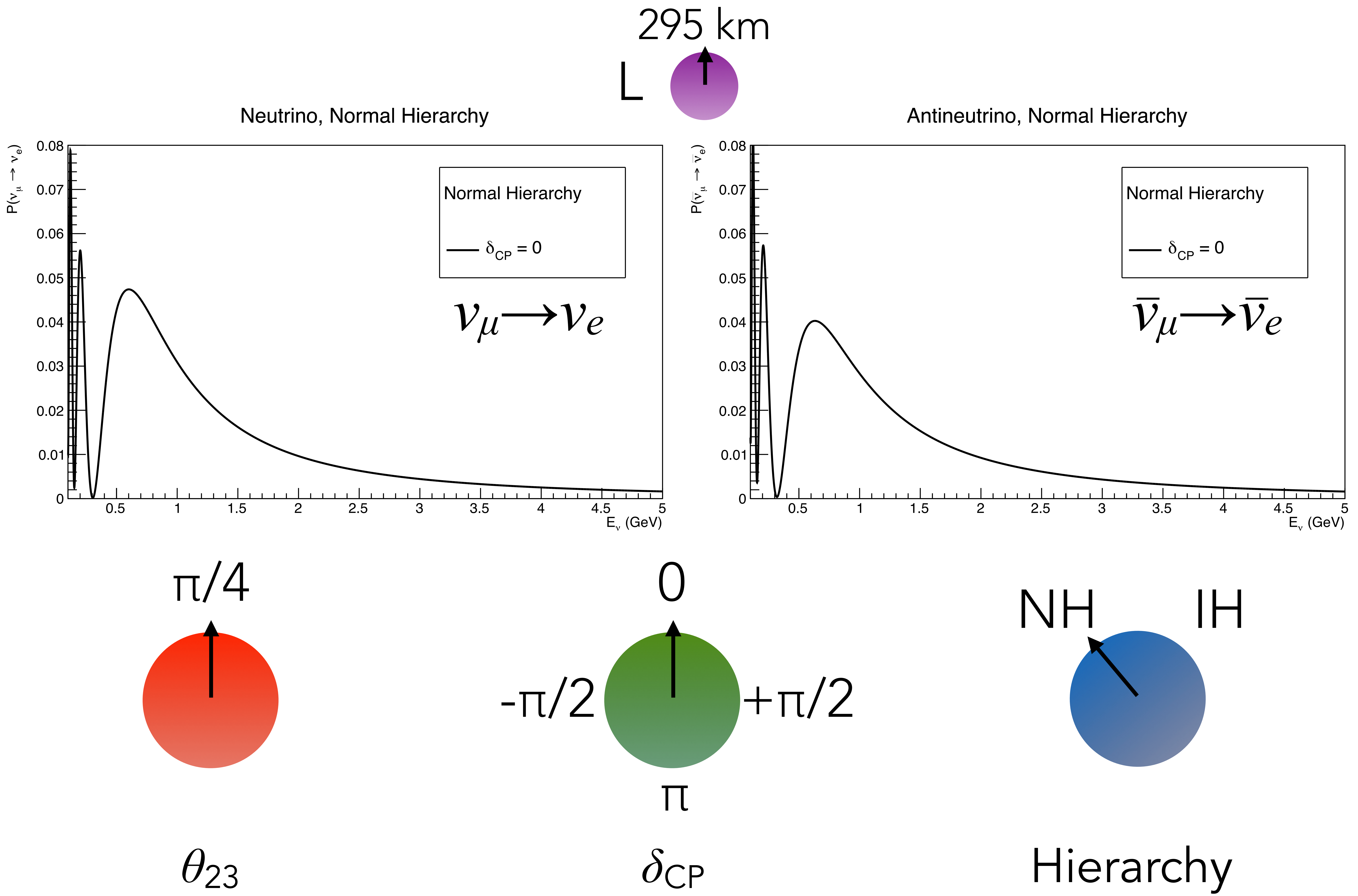


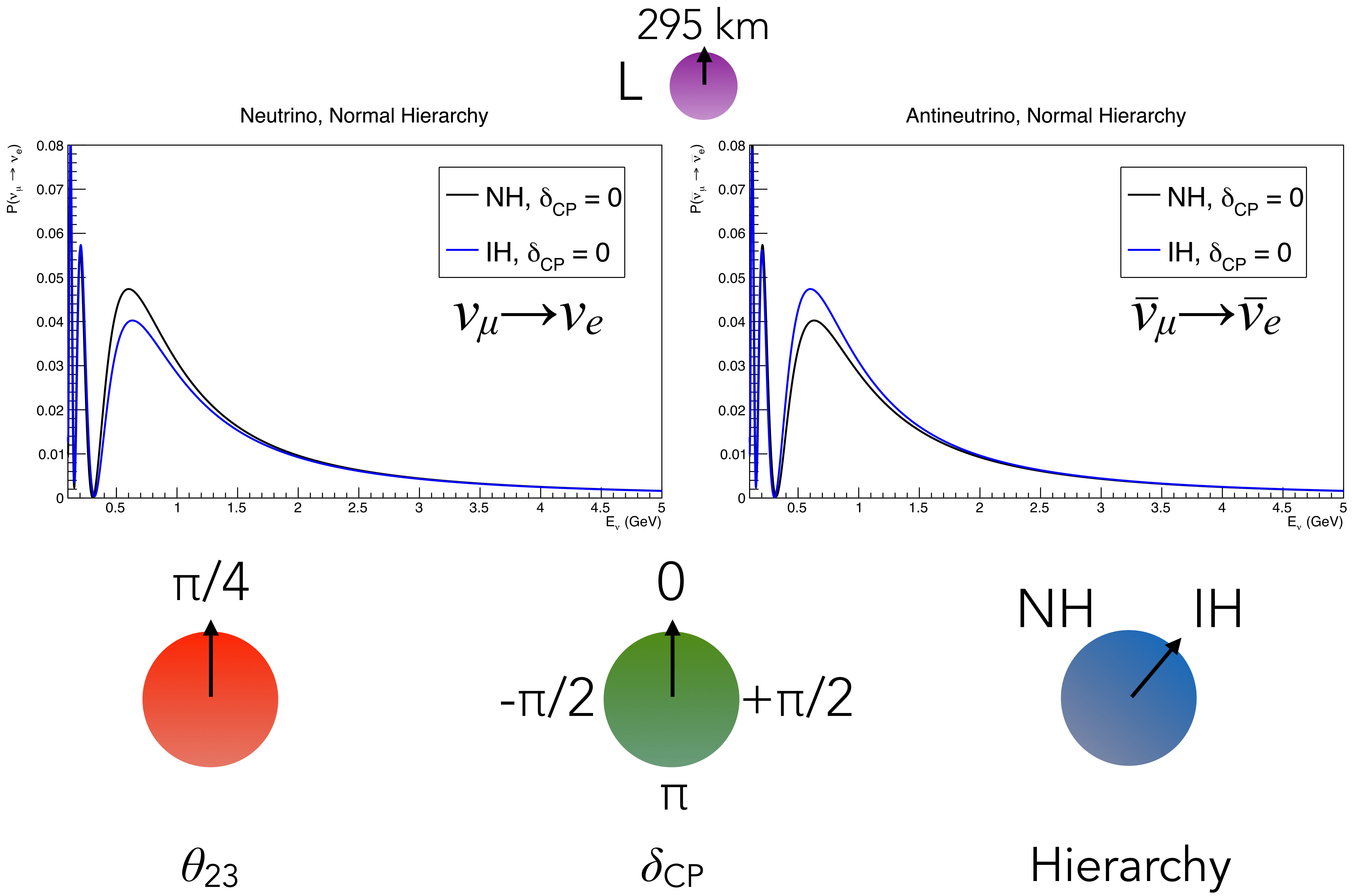
295 km
L
Neutrino, Normal Hierarchy
Antineutrino, Normal Hierarchy
Normal Hierarchy
δCP = 0
δCP = -π/2
νμ→νe
ν̄μ→ν̄e
Eν (GeV)
π/4
0
-π/2
+π/2
π
NH
IH
θ23
δCP
Hierarchy


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

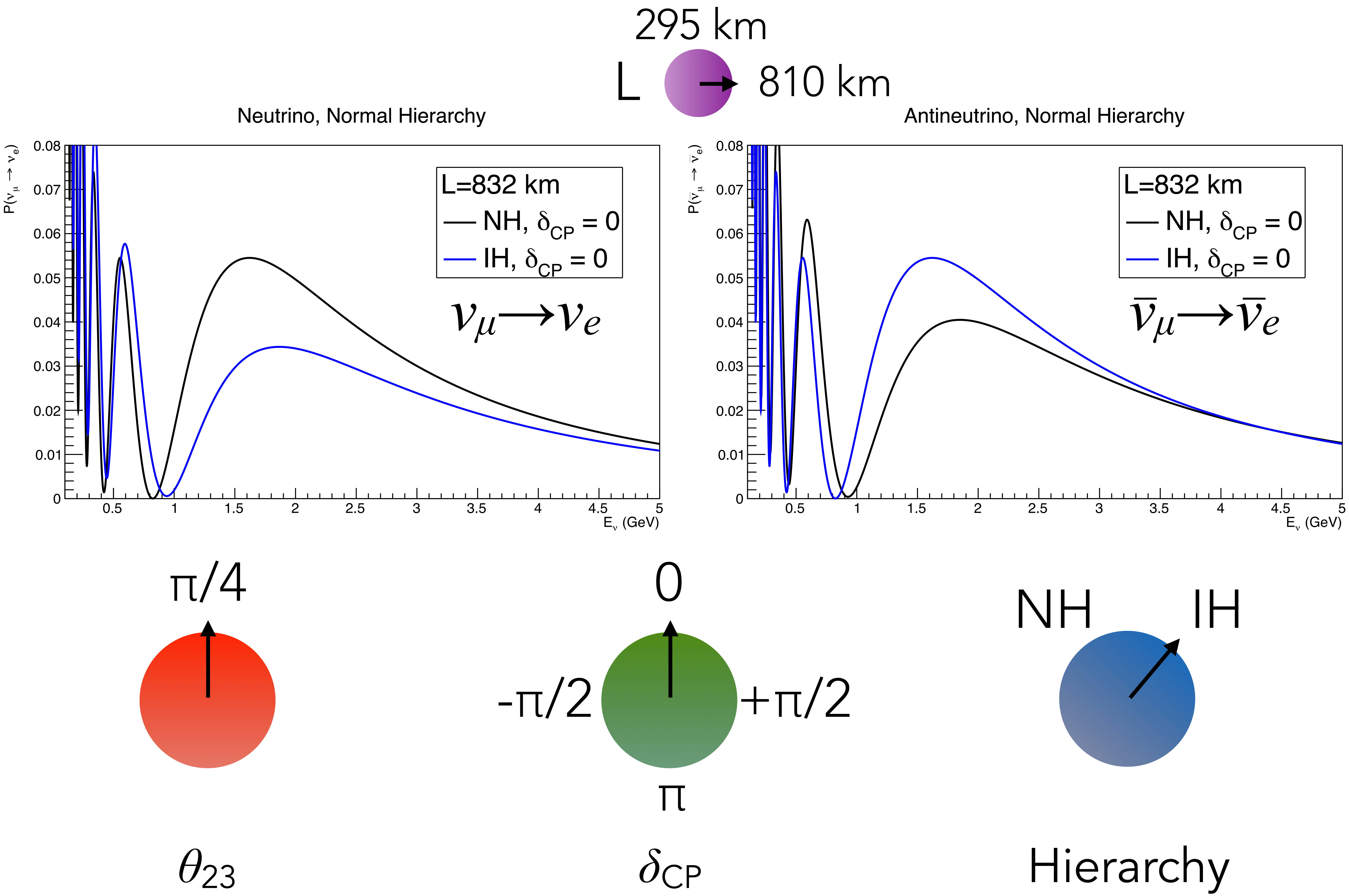


295 km
L
Neutrino, Normal Hierarchy
Antineutrino, Normal Hierarchy
Normal Hierarchy
δCP = 0
δCP = +π/2
νμ→νe
ν̄μ→ν̄e
Eν (GeV)
π/4
0
-π/2
+π/2
π
NH
IH
θ23
δCP
Hierarchy


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



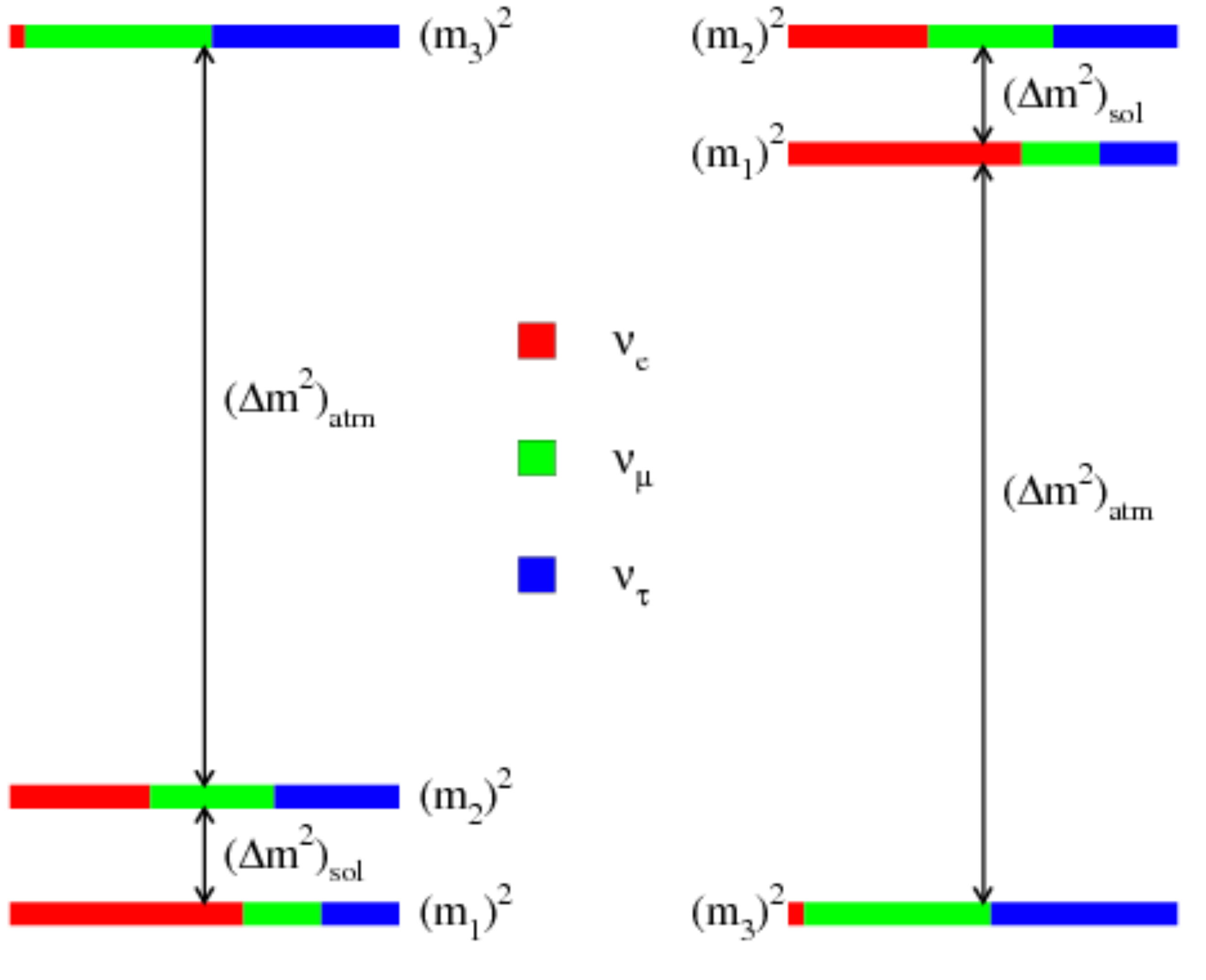
295 km
L
Neutrino, Normal Hierarchy
Antineutrino, Normal Hierarchy
NH, δCP = 0
IH, δCP = 0
νμ→νe
ν̄μ→ν̄e
Eν (GeV)
π/4
θ23
0
-π/2
+π/2
π
δCP
NH
IH
Hierarchy


295 km
L
810 km
Neutrino, Normal Hierarchy
Antineutrino, Normal Hierarchy
L=832 km
NH, δCP = 0
IH, δCP = 0
νμ→νe
L=832 km
NH, δCP = 0
IH, δCP = 0
ν̄μ→ν̄e
Eν (GeV)
Eν (GeV)
π/4
0
-π/2
+π/2
π
NH
IH
θ23
δCP
Hierarchy

QUICK SUMMARY

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

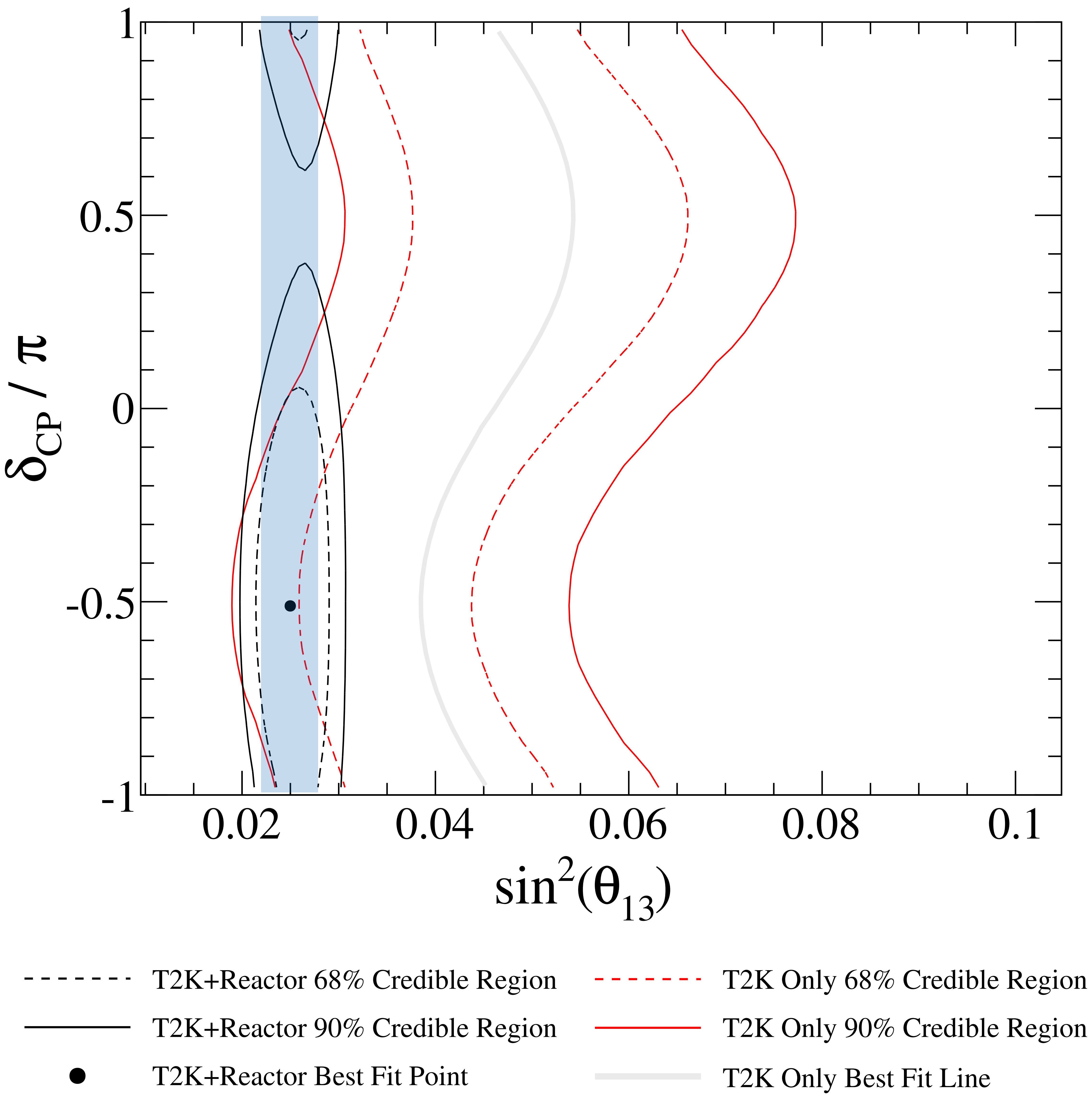
- "normal" hierarchy:
  - enhance $\nu_\mu \to \nu_e$
  - suppresses $\bar{\nu}_\mu \to \bar{\nu}_e$

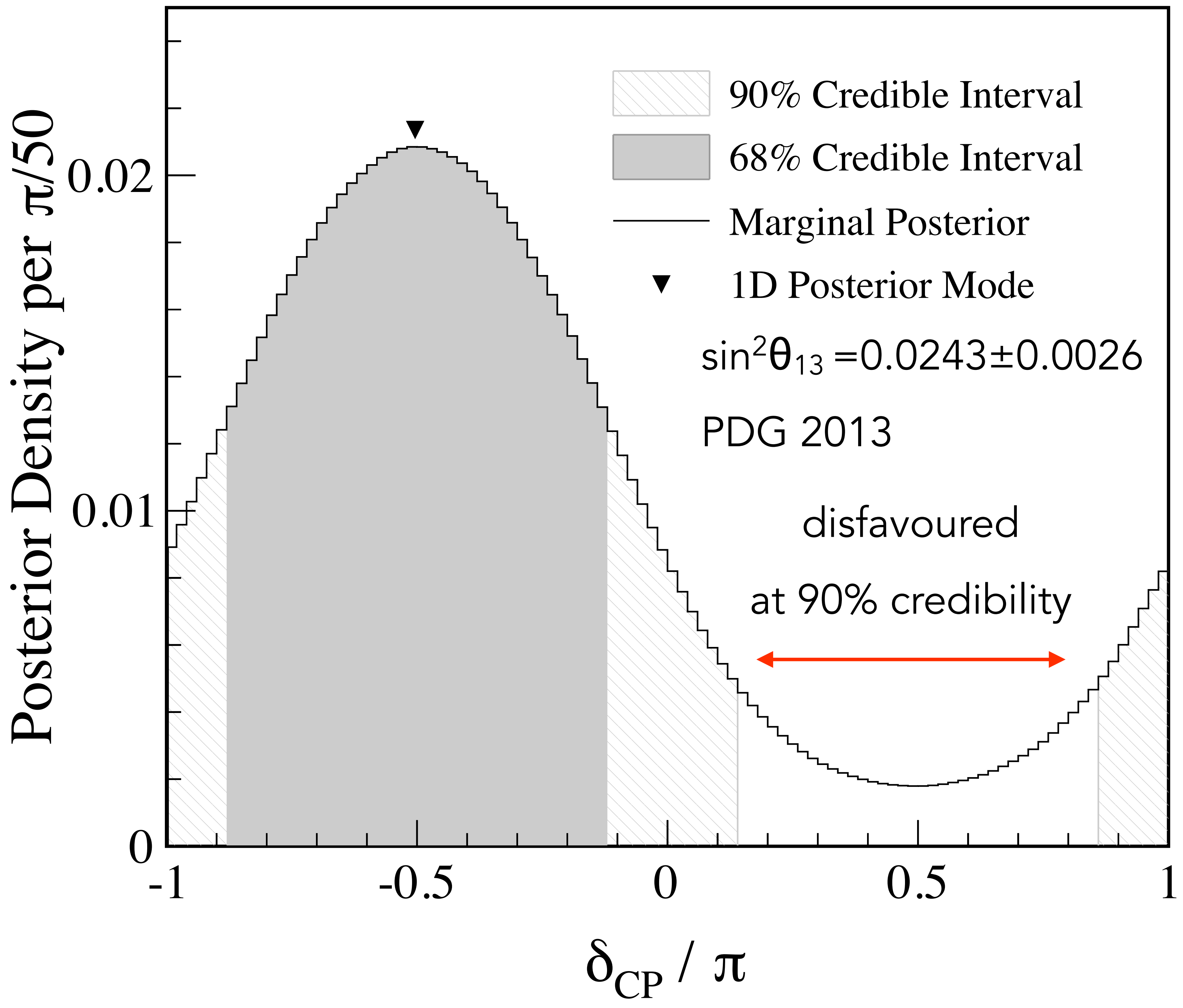


normal hierarchy   inverted hierarchy

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

T2K RESULTS

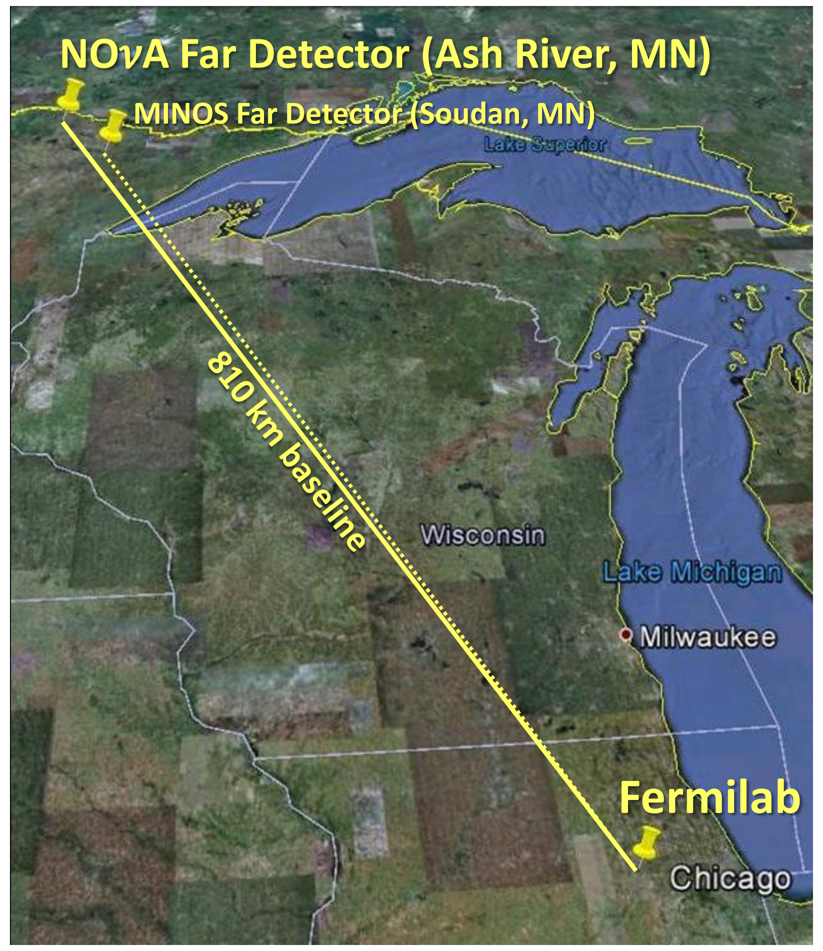




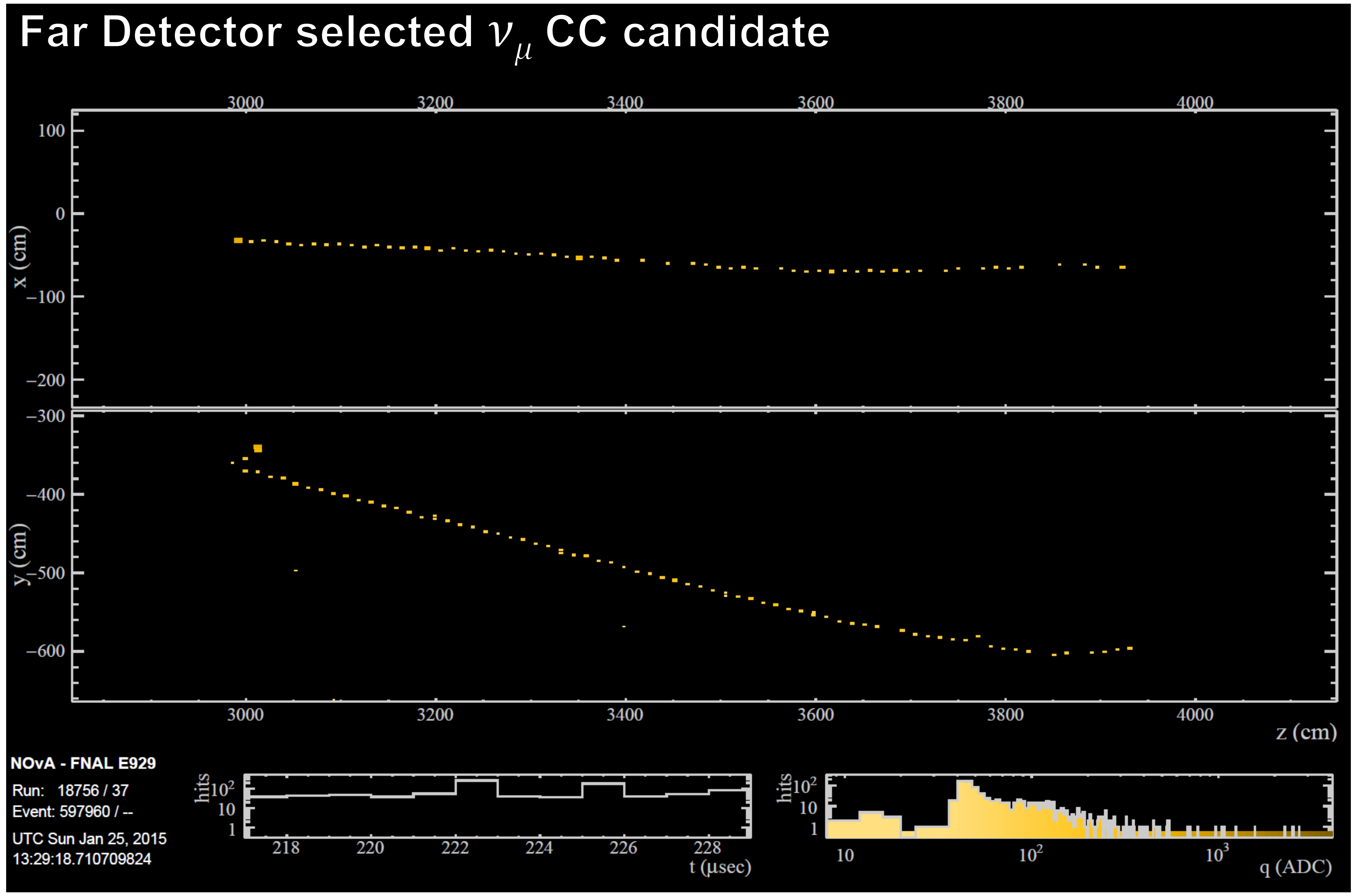
	NH	IH	SUM
$\sin^2\theta_{23} \leq 0.5$	0.179	0.078	0.257
$\sin^2\theta_{23} > 0.5$	0.505	0.238	0.743
SUM	0.684	0.316	1.000

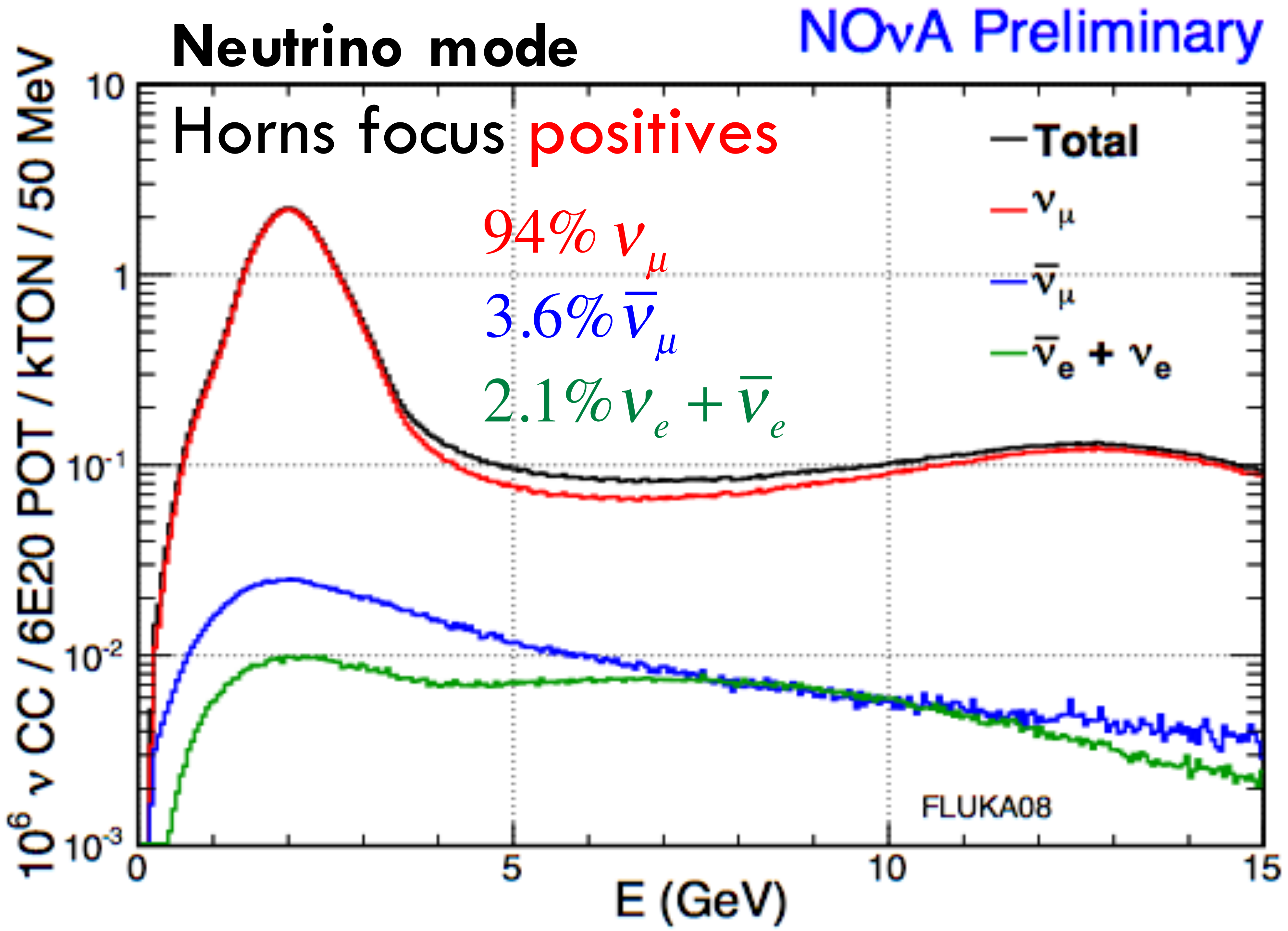
- With θ_{13} from reactor experiment, large ν_e appearance slightly prefers:
  - Normal Hierarchy, $\theta_{23} > \pi/4$, $\delta_{CP} \sim -\pi/2$

NOvA:

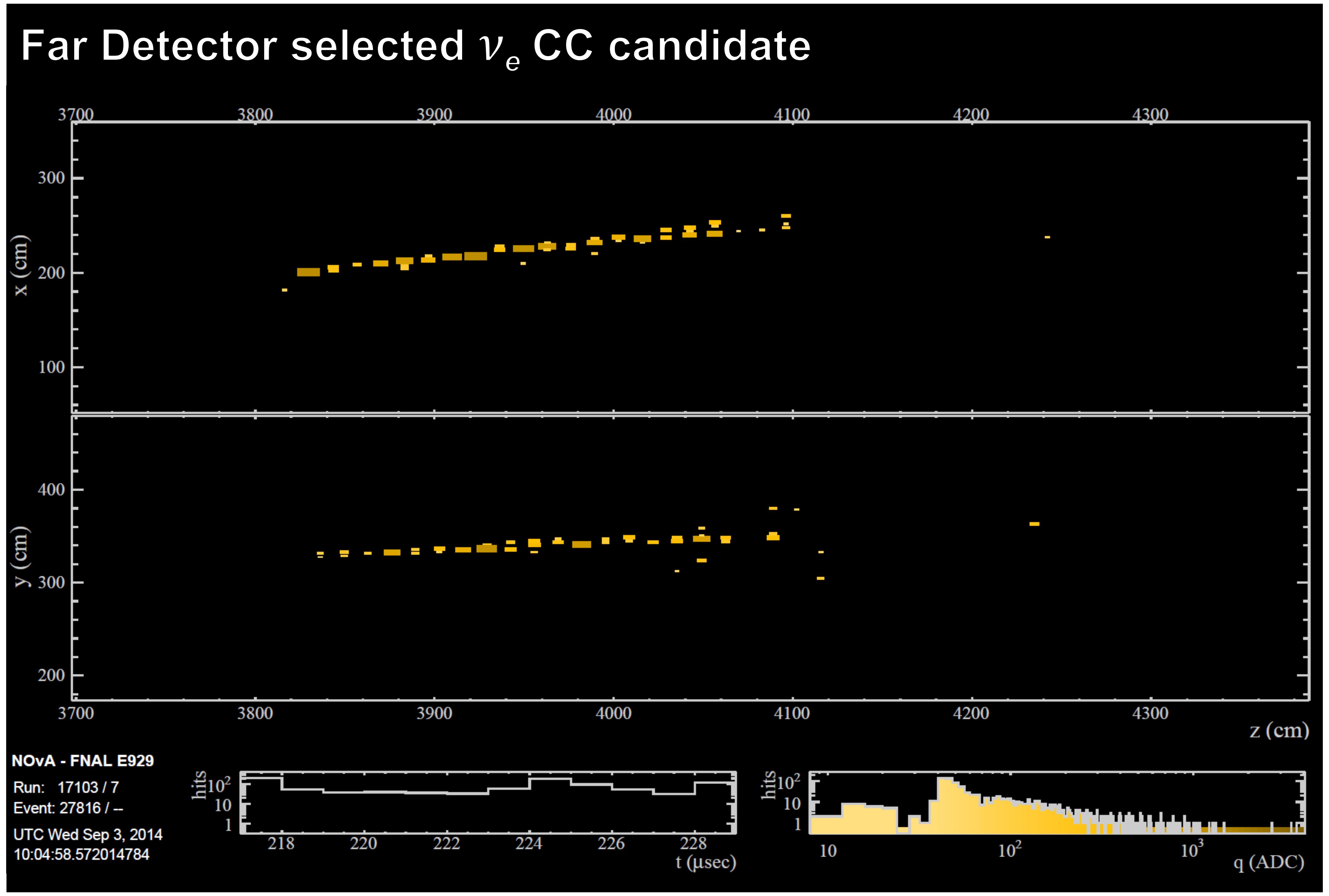


- Long baseline neutrino experiment from FNAL to Ash Hill with 810 km baseline
  - higher neutrino energy
  - larger matter effect and sensitivity to mass hierarchy
- 14kt fully active scintillating tracking detector

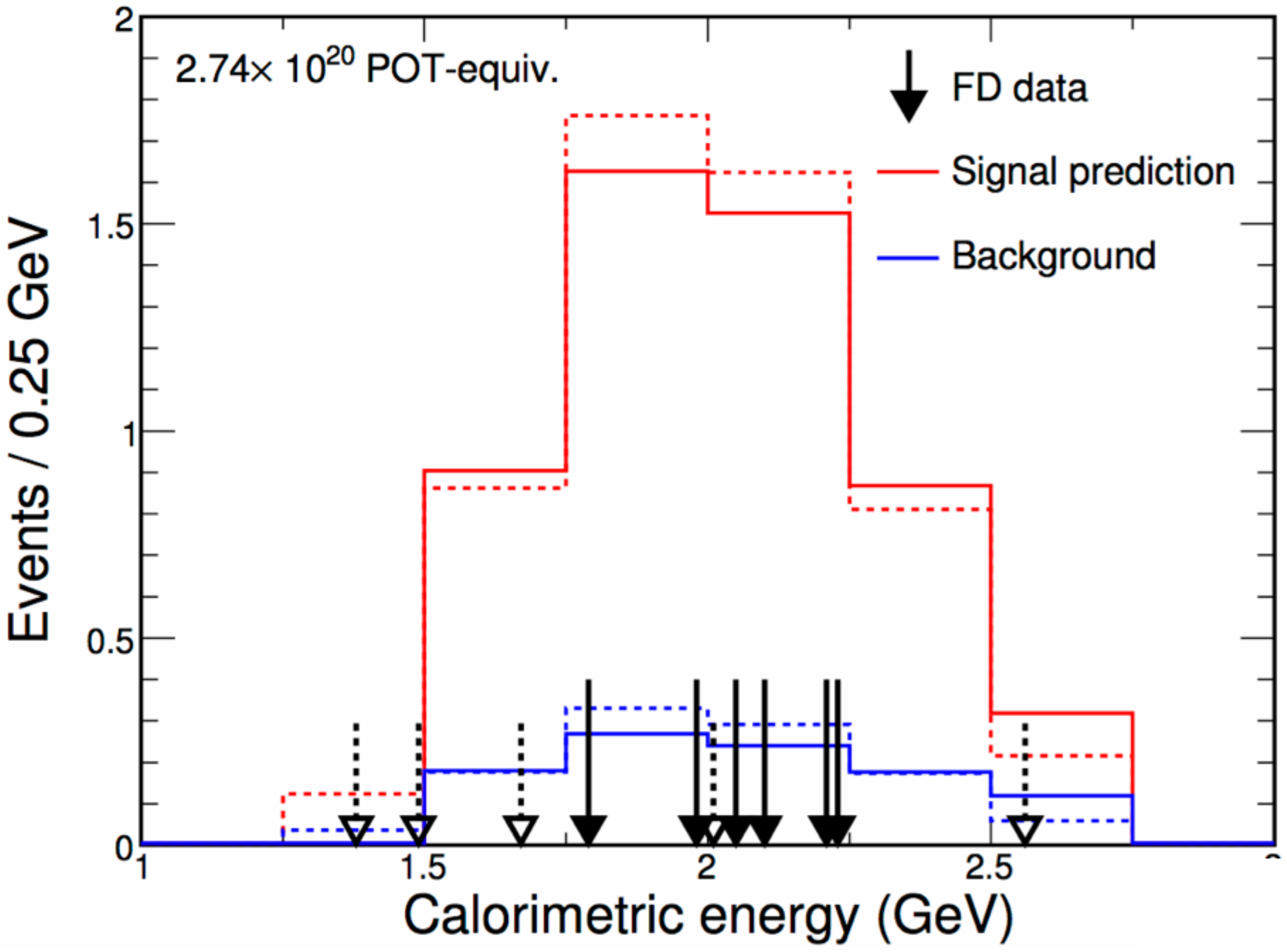




NOvA: ν_e EVENTS

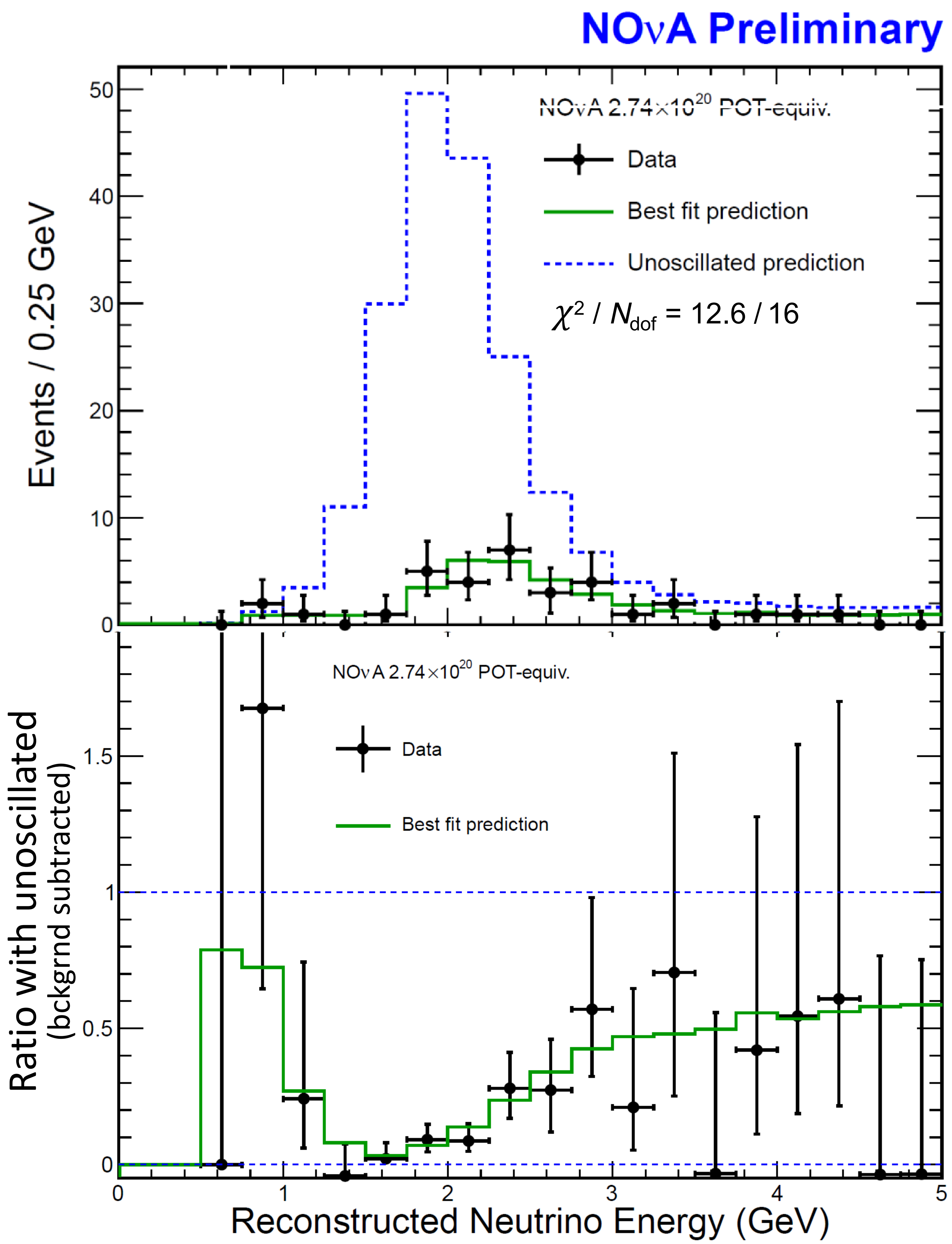


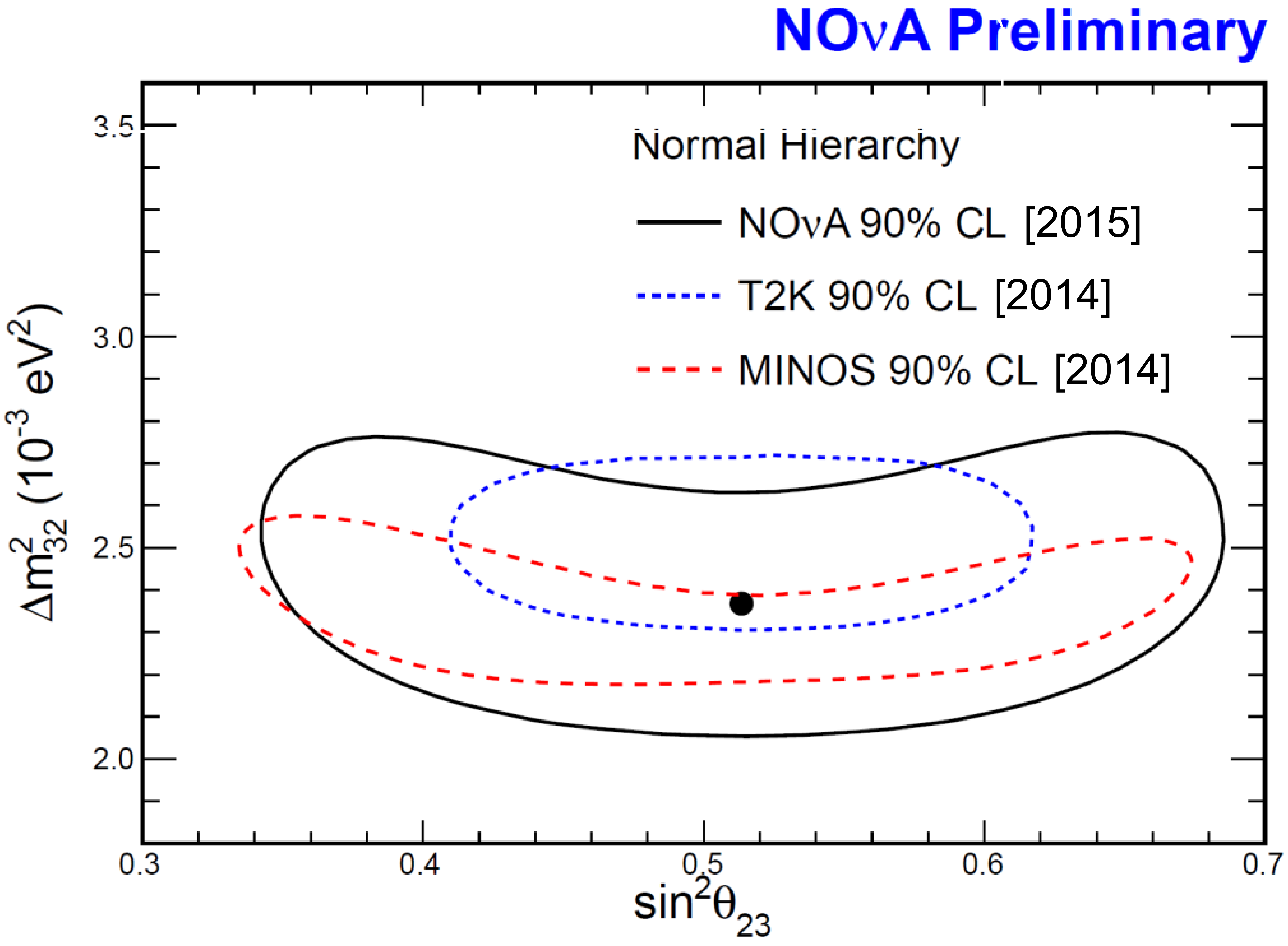
	NH $\delta_{cp}=-\pi/2$	IH $\delta_{CP}=+\pi/2$	EVENTS
LID	5.62±0.72	2.24±0.29	6
LEM	5.91±0.59	2.34±0.23	11



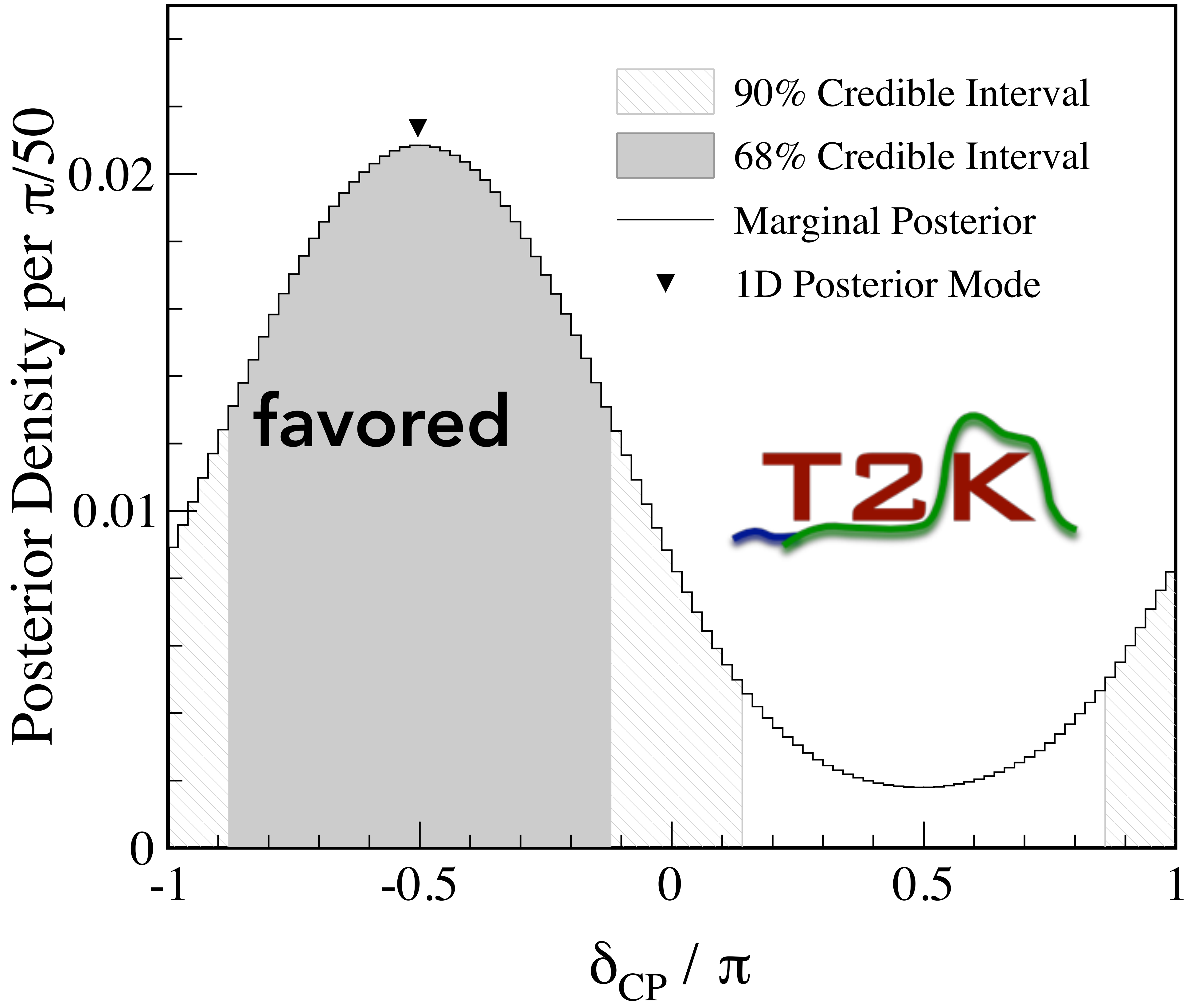
- "prefer normal hierarchy"
- "prefer δ_{CP} ~ -π/2"

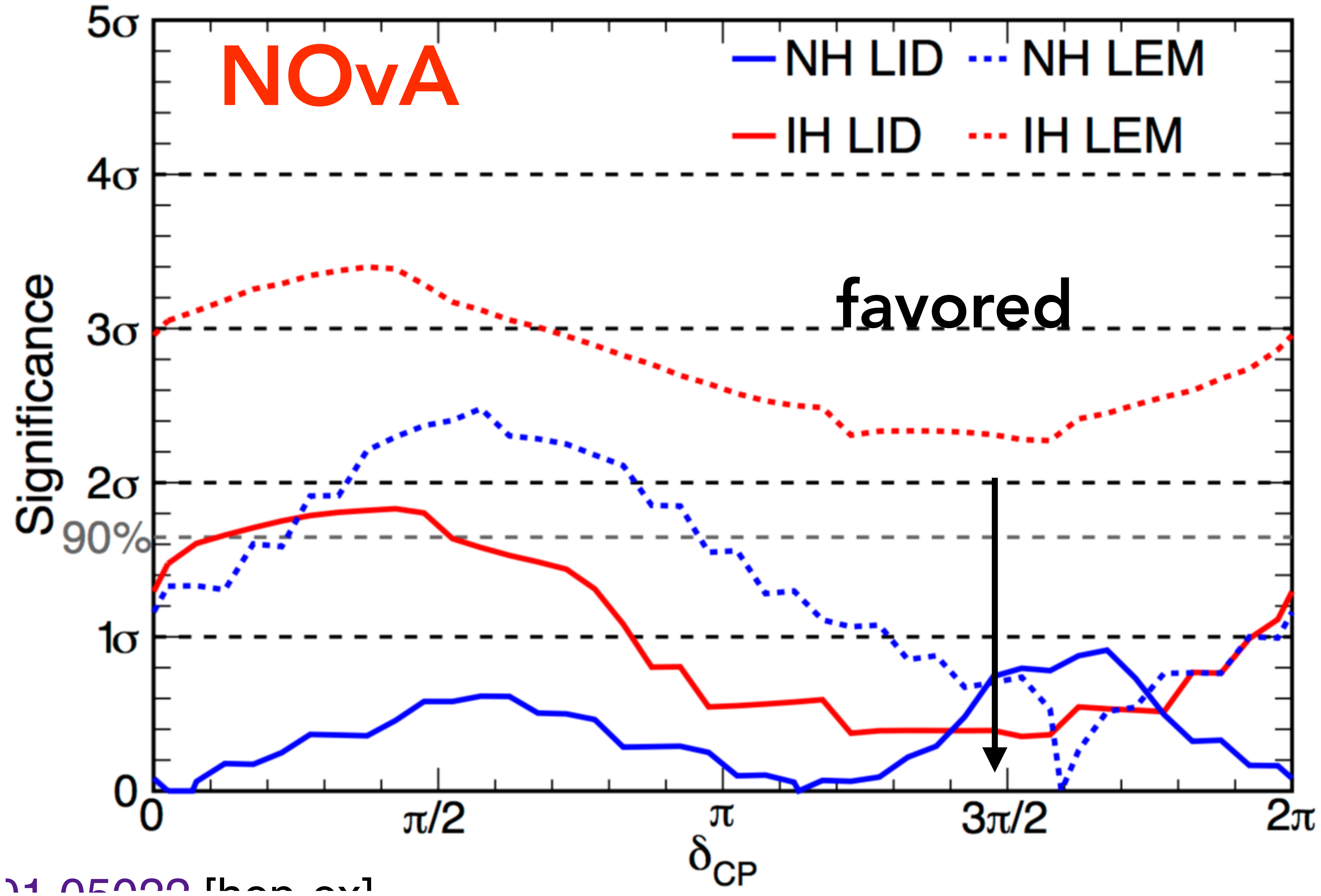
Θ$_{23}$: MAXIMAL?


NOνA Preliminary
NOνA 2.74×10^20 POT-equiv.
Data
Best fit prediction
Unoscillated prediction
χ^2 / N_dof = 12.6 / 16
Events / 0.25 GeV
NOνA 2.74×10^20 POT-equiv.
Data
Best fit prediction
Ratio with unoscillated (bckgrnd subtracted)
Reconstructed Neutrino Energy (GeV)

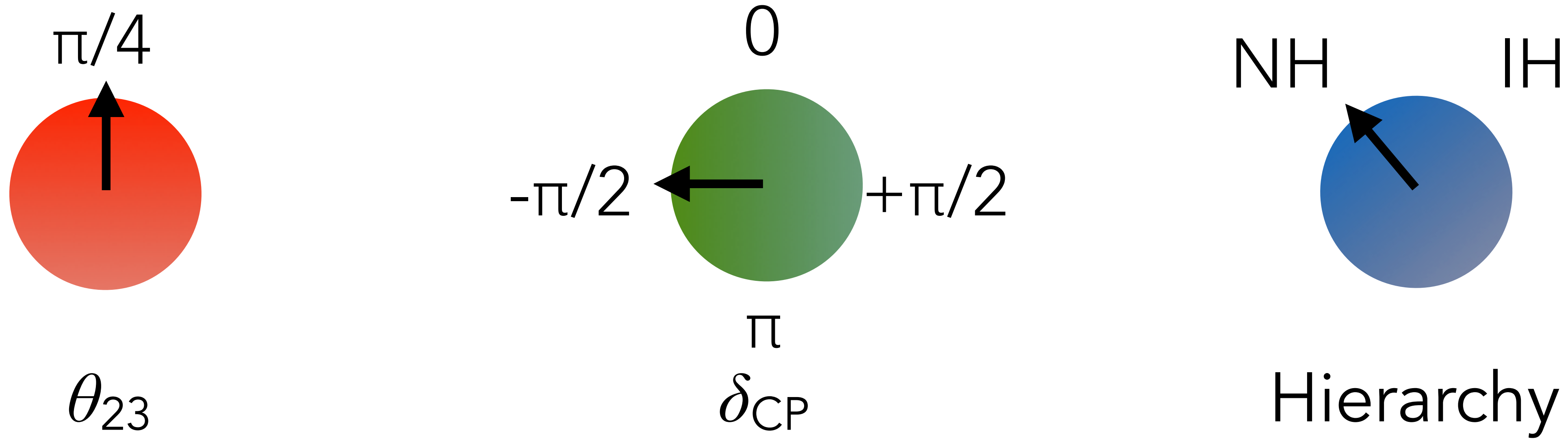

NOνA Preliminary
Normal Hierarchy
NOνA 90% CL [2015]
T2K 90% CL [2014]
MINOS 90% CL [2014]
Δm^2_32 (10^-3 eV^2)
sin^2θ_23

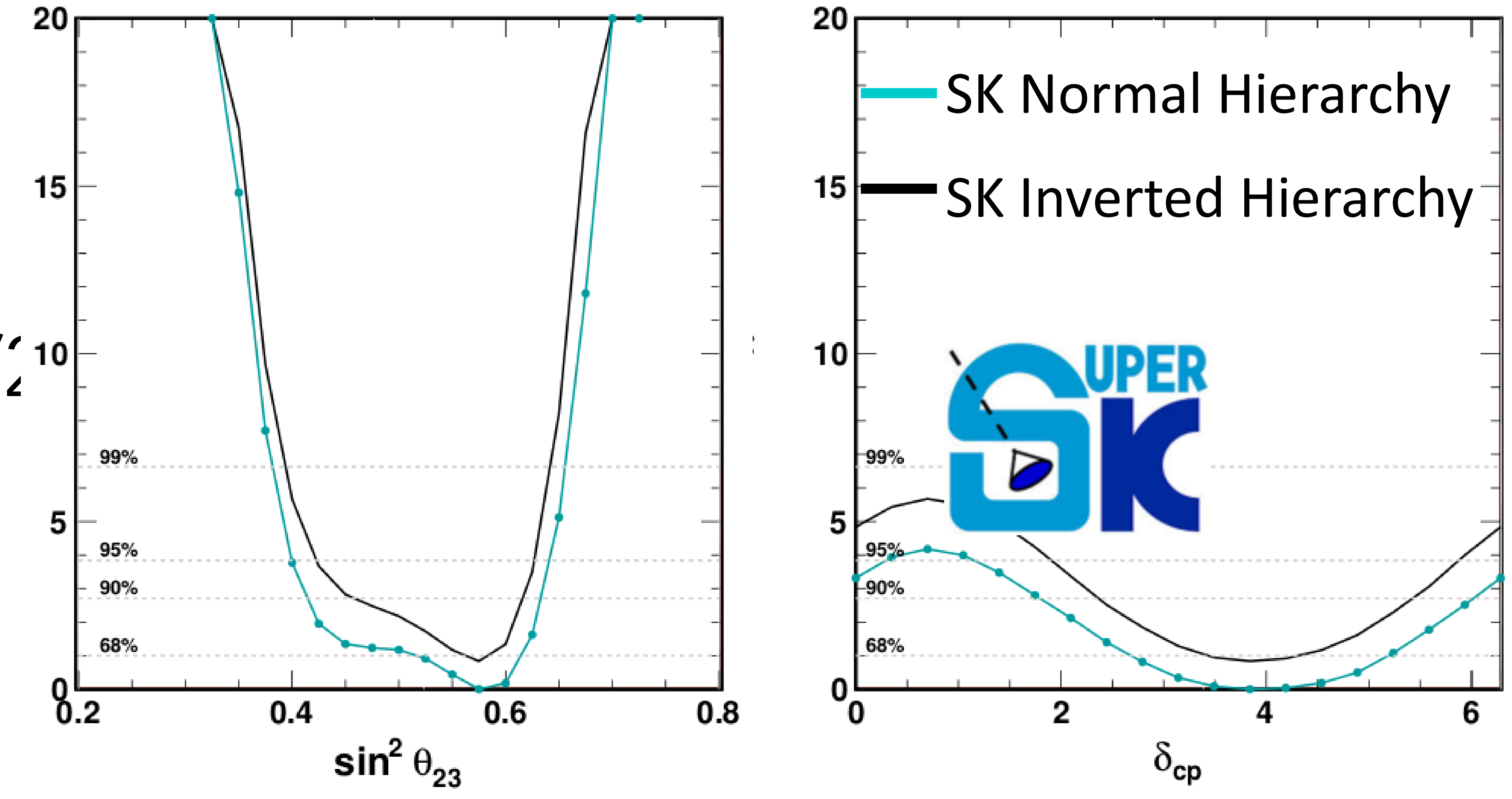
SUMMARY:



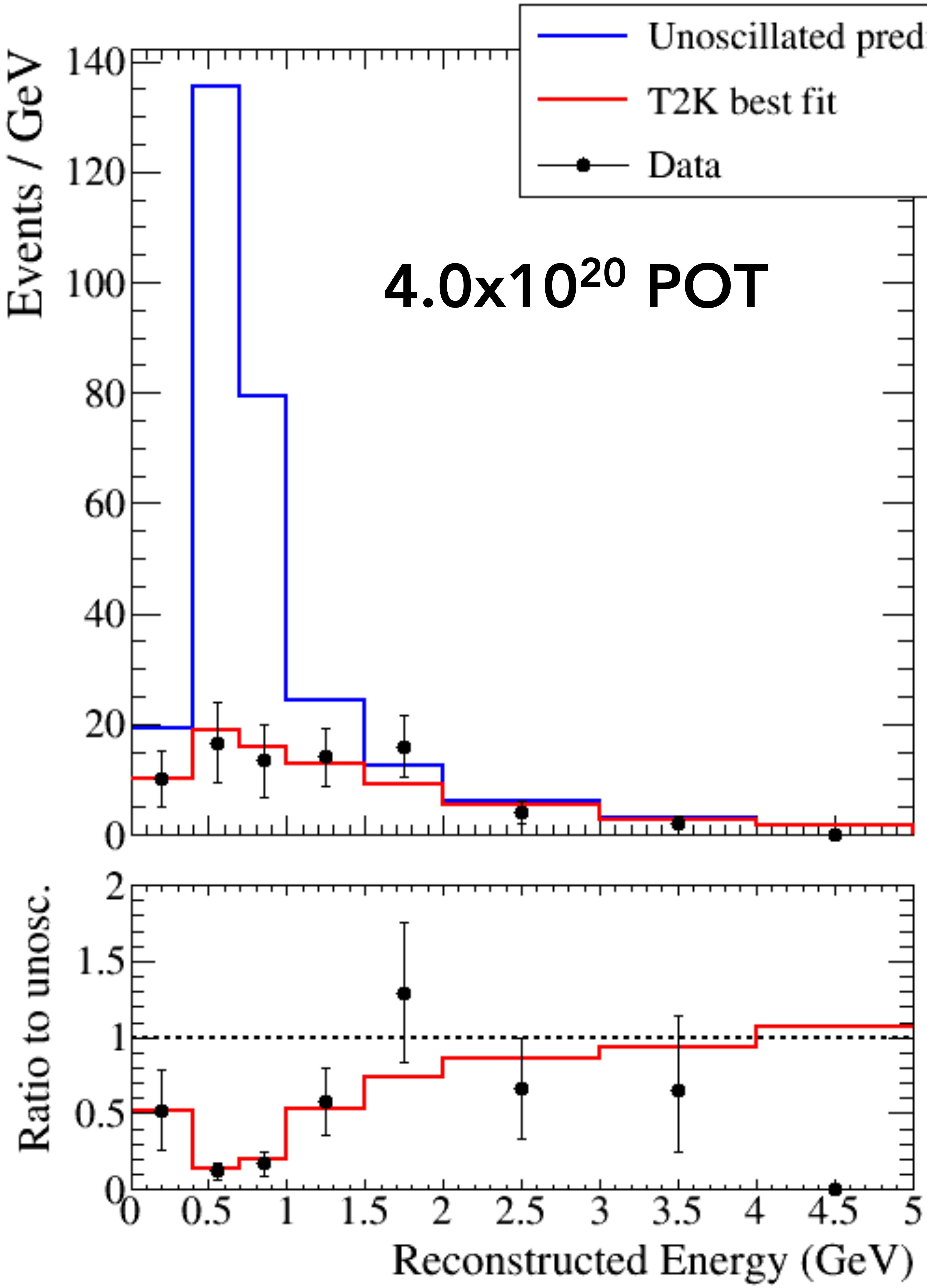


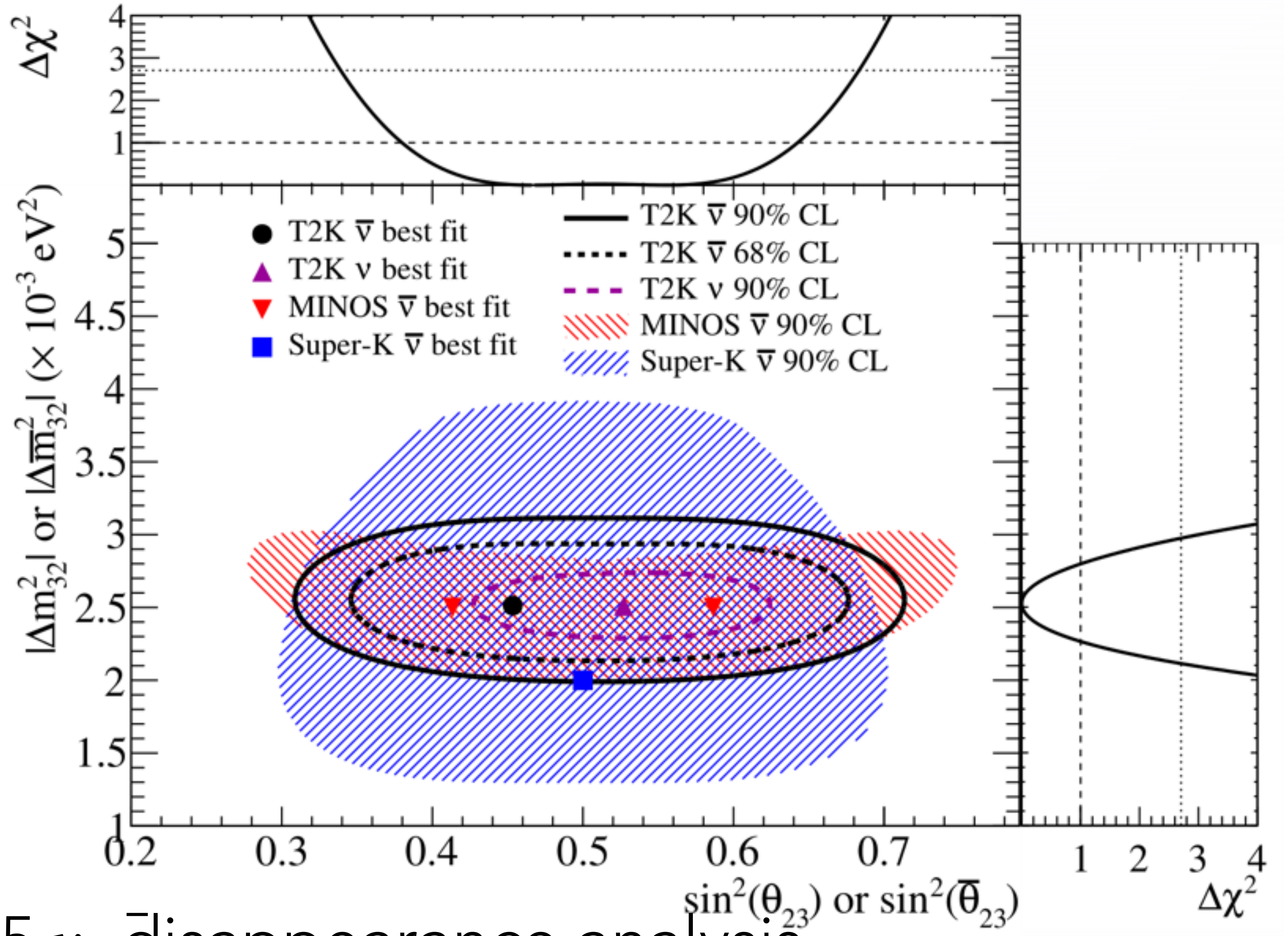
- T2K, SK, and NOvA see large $\nu_\mu \rightarrow \nu_e$ appearance that weakly favours NH, δ_{CP} = -π/2





FIRST ANTINEUTRINO RESULTS FROM T2K





- 2015 $\bar{\nu}_\mu$ disappearance analysis
  - Competitive measurement with 1 year of data.
- $\bar{\nu}_e$ appearance results
  - 3 events observed
  - 3.2 expected with current best-fit values (δ_{CP}~ -π/2)

WHAT'S NEXT

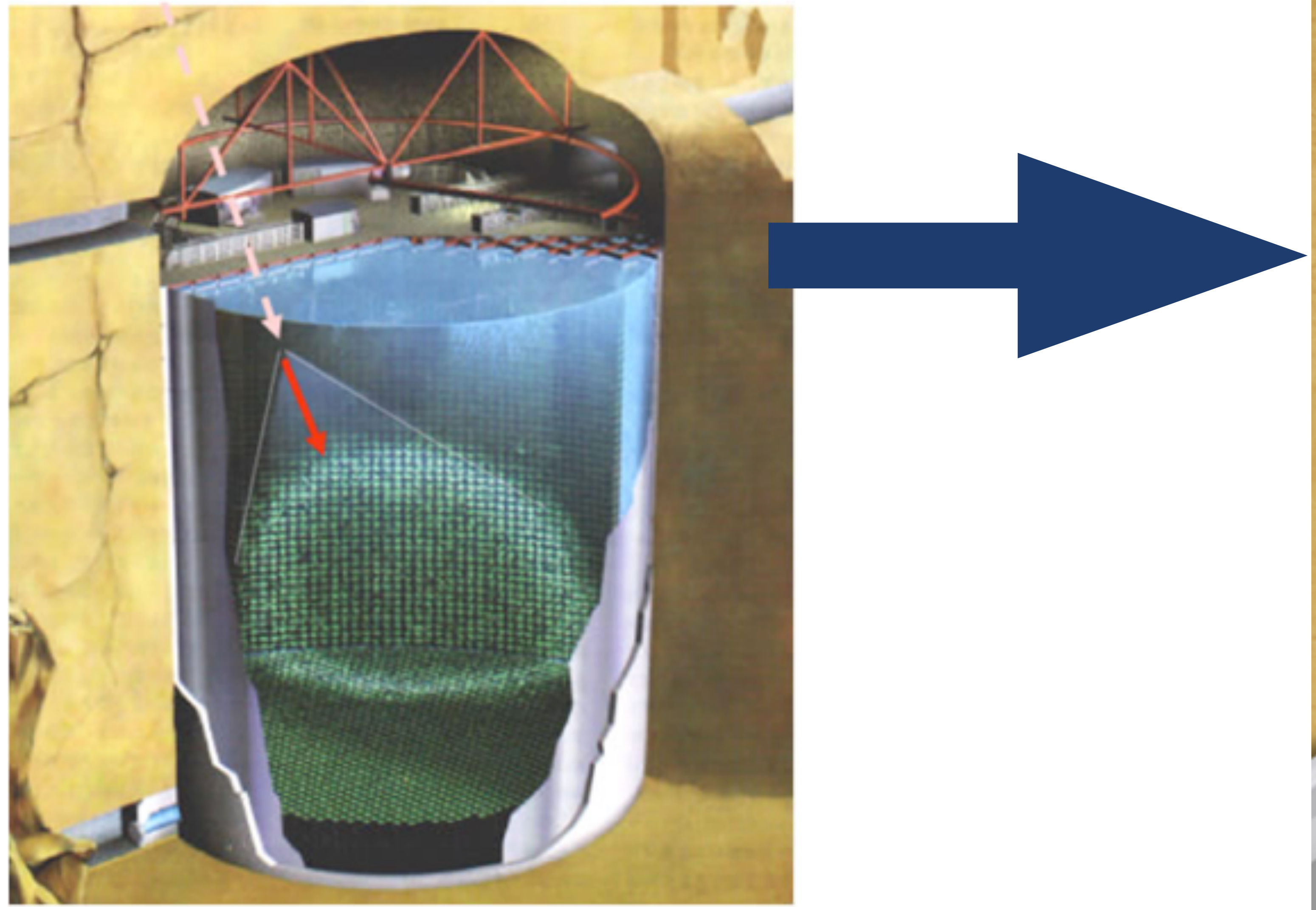
- Near term:
  - Continued T2K and NOvA running to study
    - mass hierarchy, CP violation
    - whether θ_{23} is in fact maximal (if not its "octant")
  - If we are lucky, we may get some indication of the situation with this current round of experiments
    - particularly if the parameters are near "maximal" values that produce the largest and unambiguous effects.
- It is very likely, however, that a new generation of experiments are needed to definitively resolve these questions.

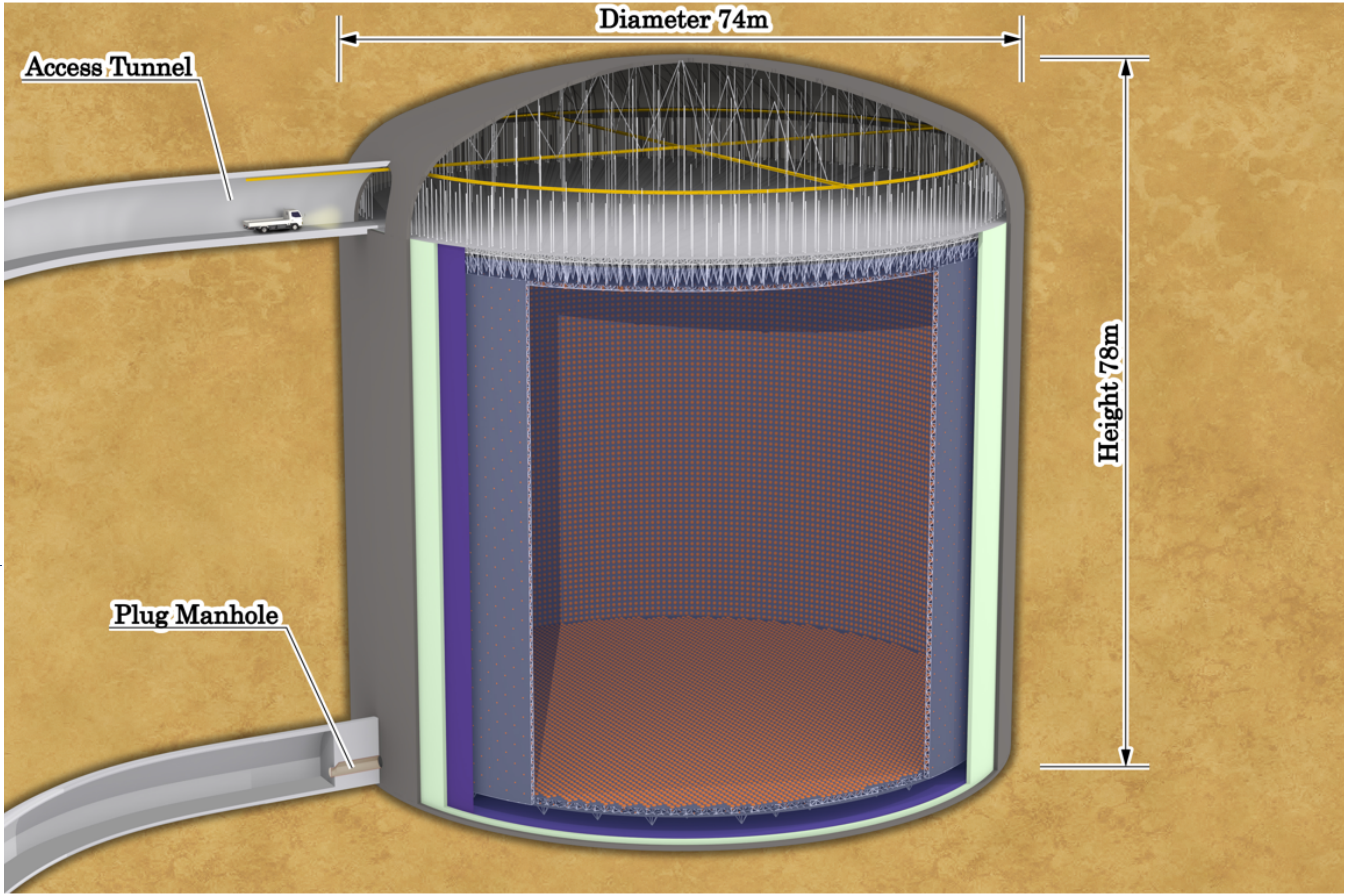
WHAT'S NEXT

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

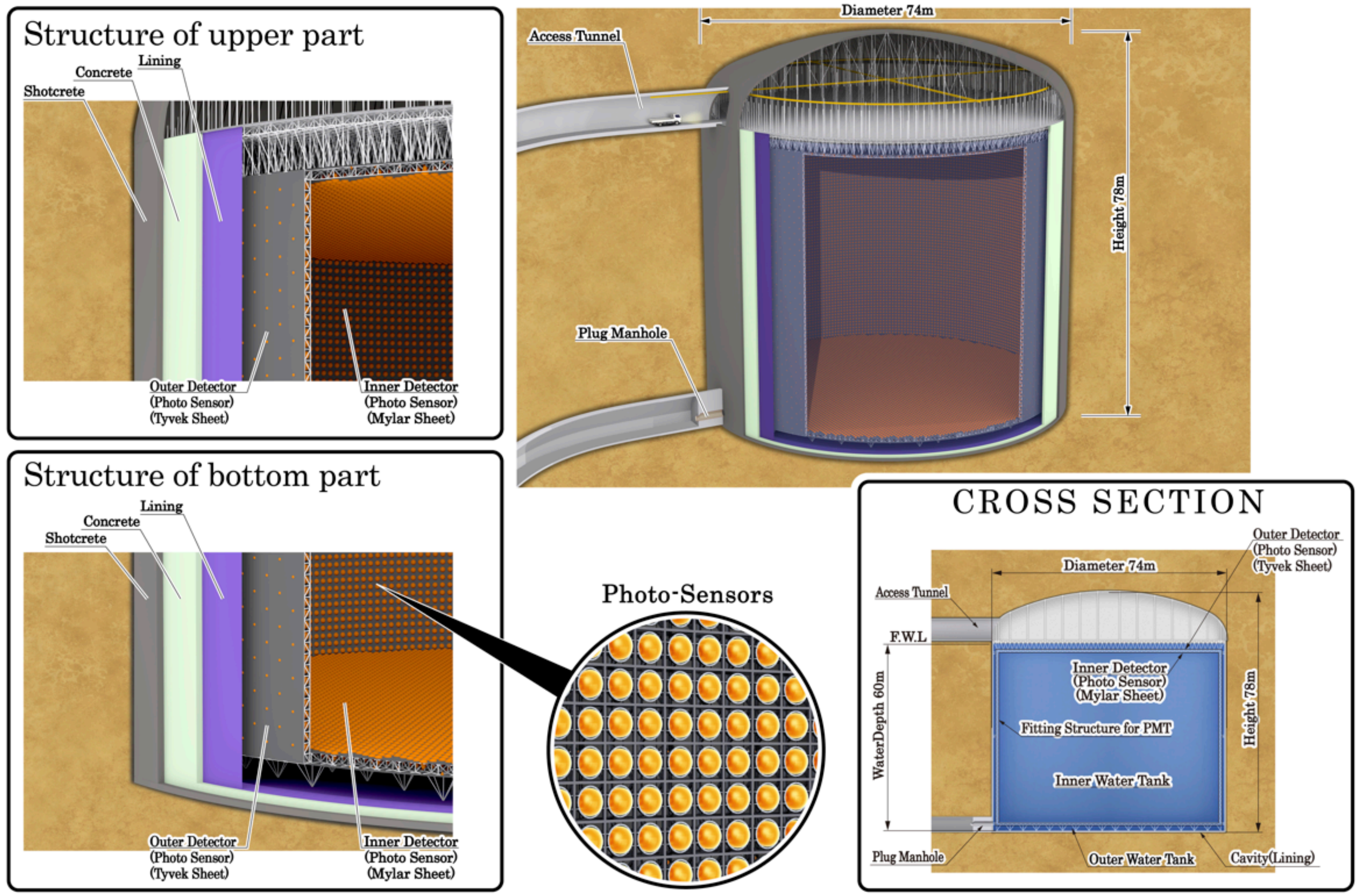
Detector upgrades

- Super-Kamiokande
  →Hyper-Kamiokande

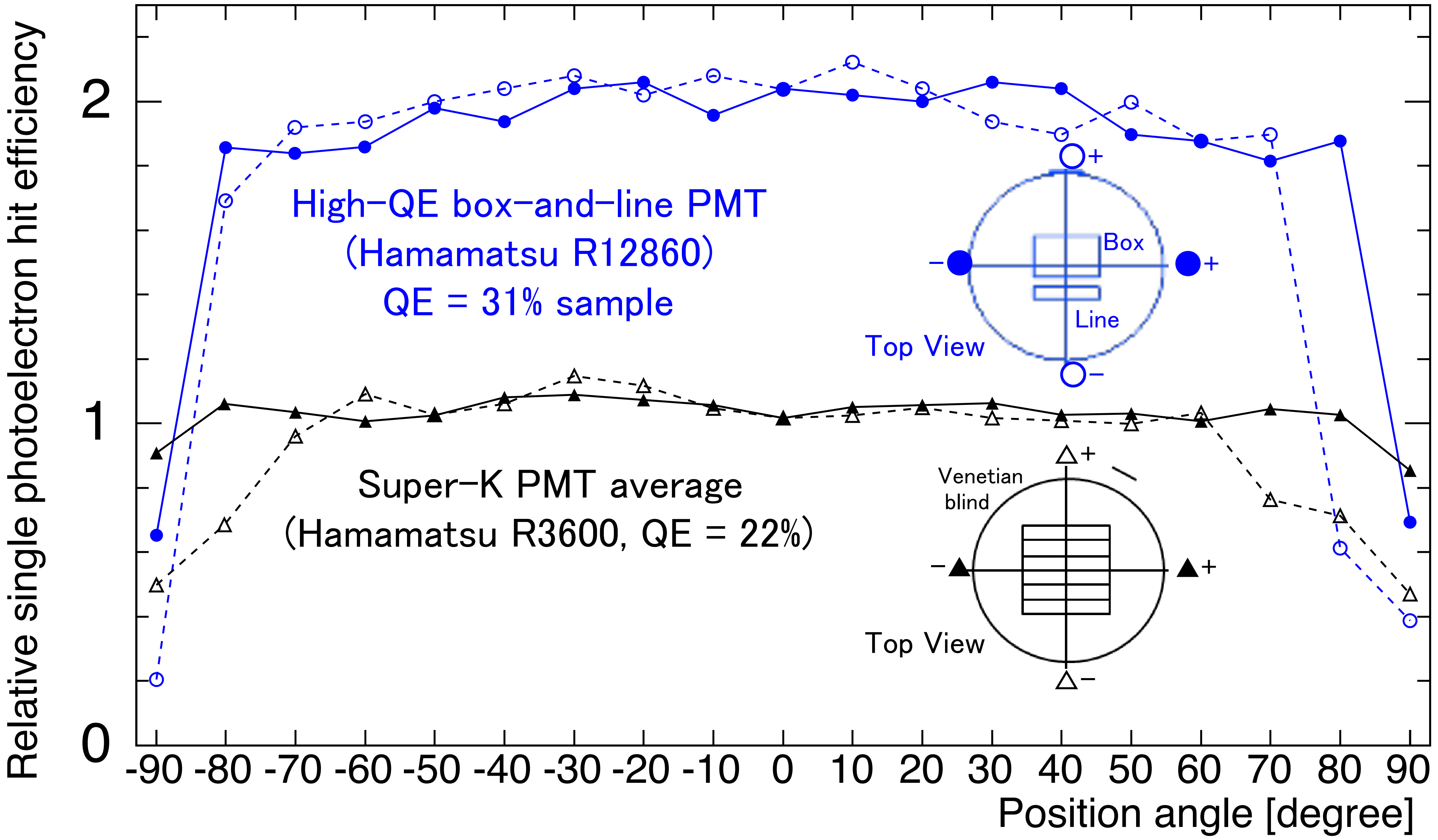




HYPER-KAMIOKANDE



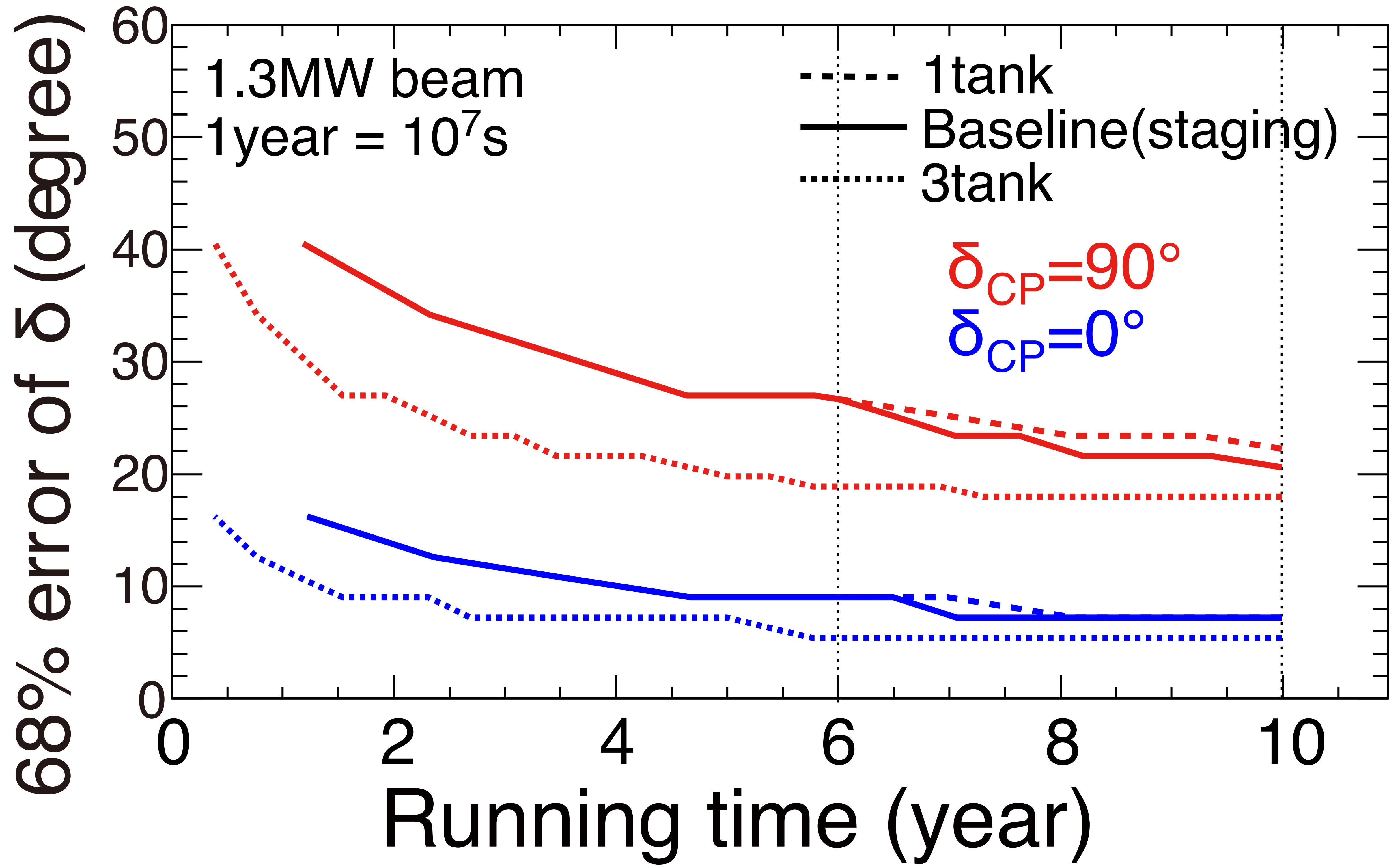
- Reconfigured design as two vertical cylindrical tanks with staged construction
  - 74 m diameter, 60 m height
  - 258 (187) kT tot. (fid.) volume
- Construction of 1st tank (2026) followed by 2nd tank several years later

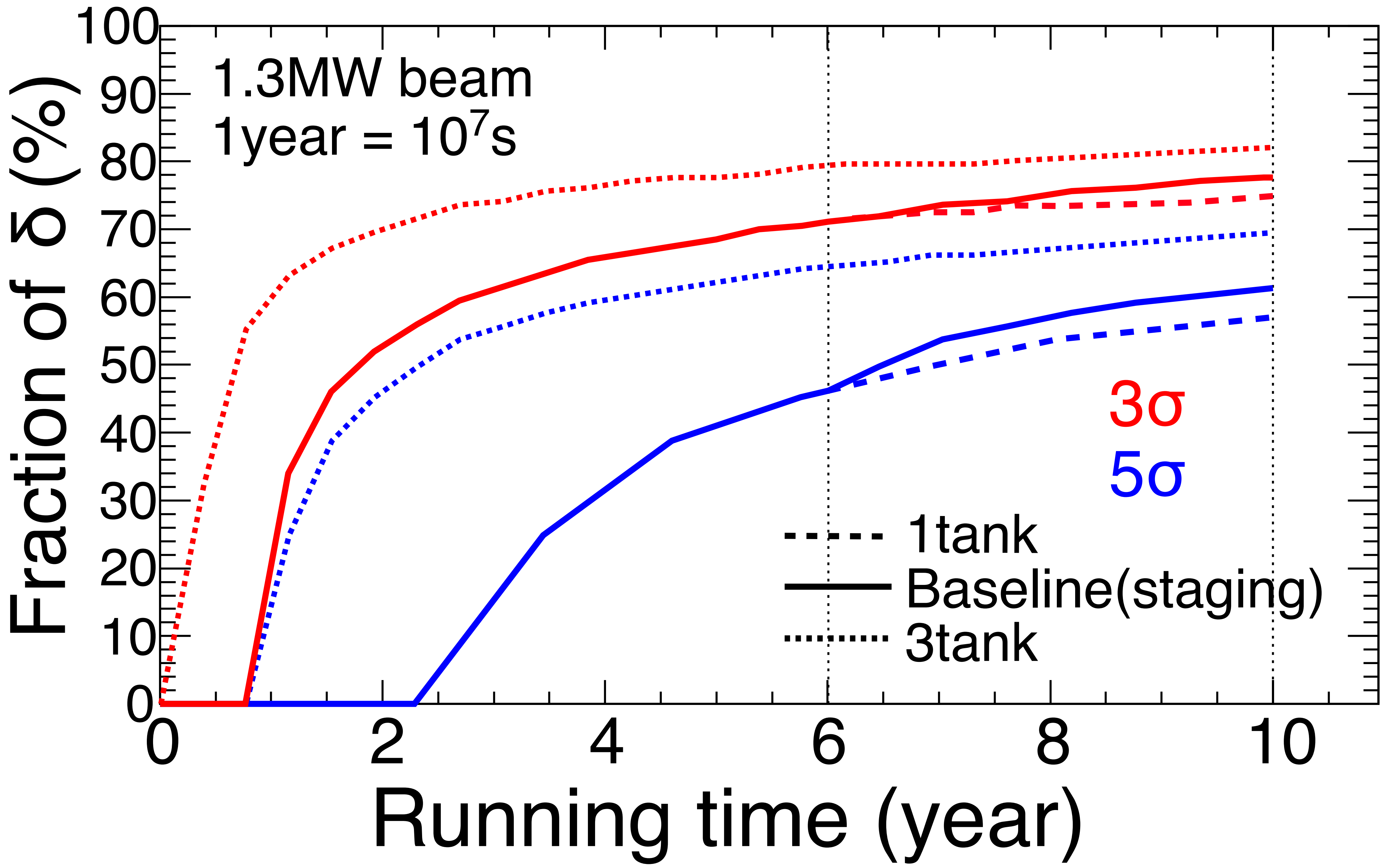


- “High Density” photosensor development:
  - same photocathode area as SK (40%)
  - large improvements in detection efficiency

NEUTRINO OSCILLATIONS AT HK

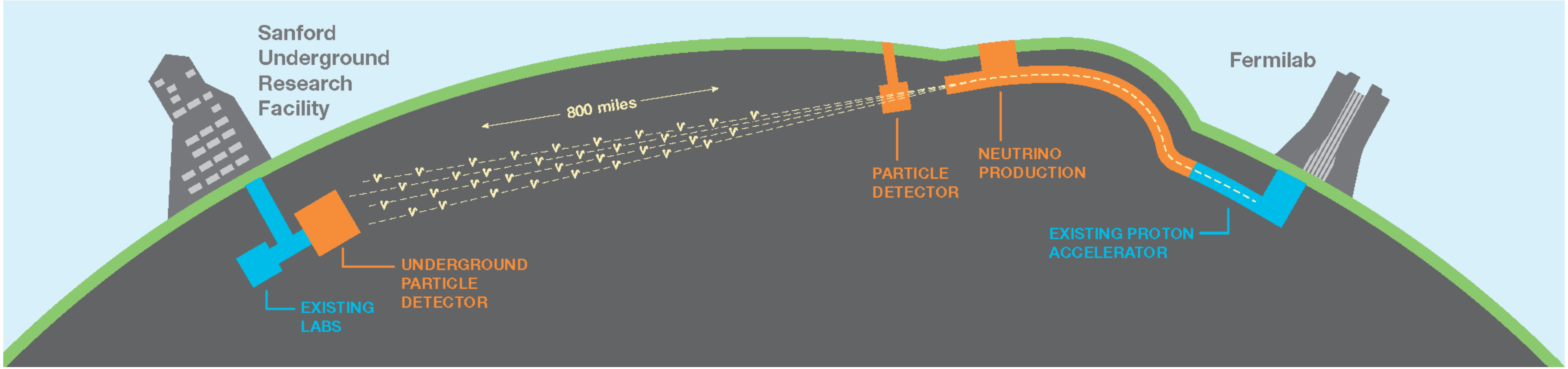
	δ_{CP}	TOTAL	SIGNAL $\nu_\mu \to \nu_e$	SIGNAL $\bar{\nu}_\mu \to \bar{\nu}_e$	BEAM ν_e	BEAM ν_μ	NC
ν MODE	0	2880	**2300**	21	362	10	188
$\bar{\nu}$ MODE	0	2669	289	**1656**	6	444	274



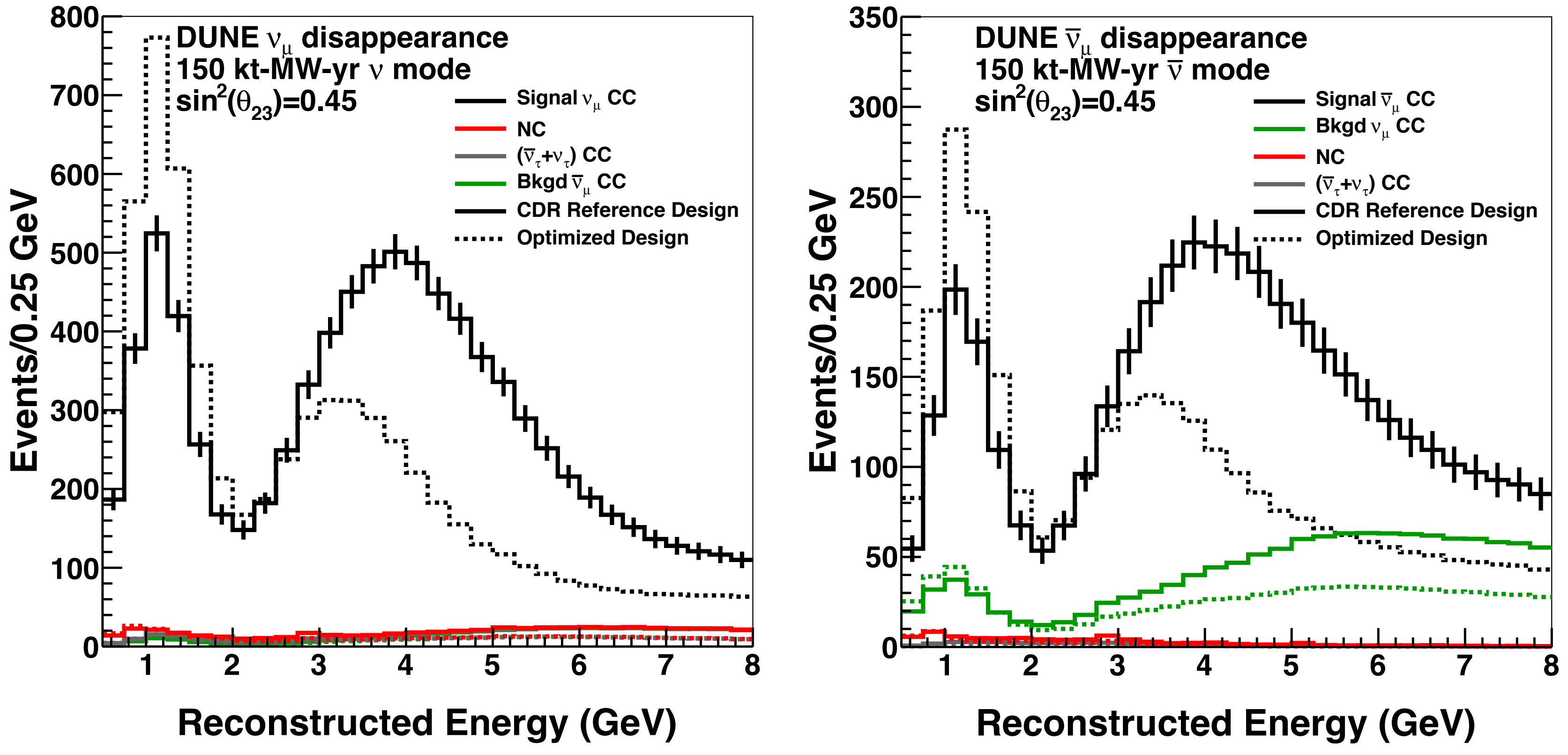


- Observation of CP violation for >76 (57)% of δ_{CP} values at > 3 (5) σ
- Measure δ_{CP} with up to ~7° precision

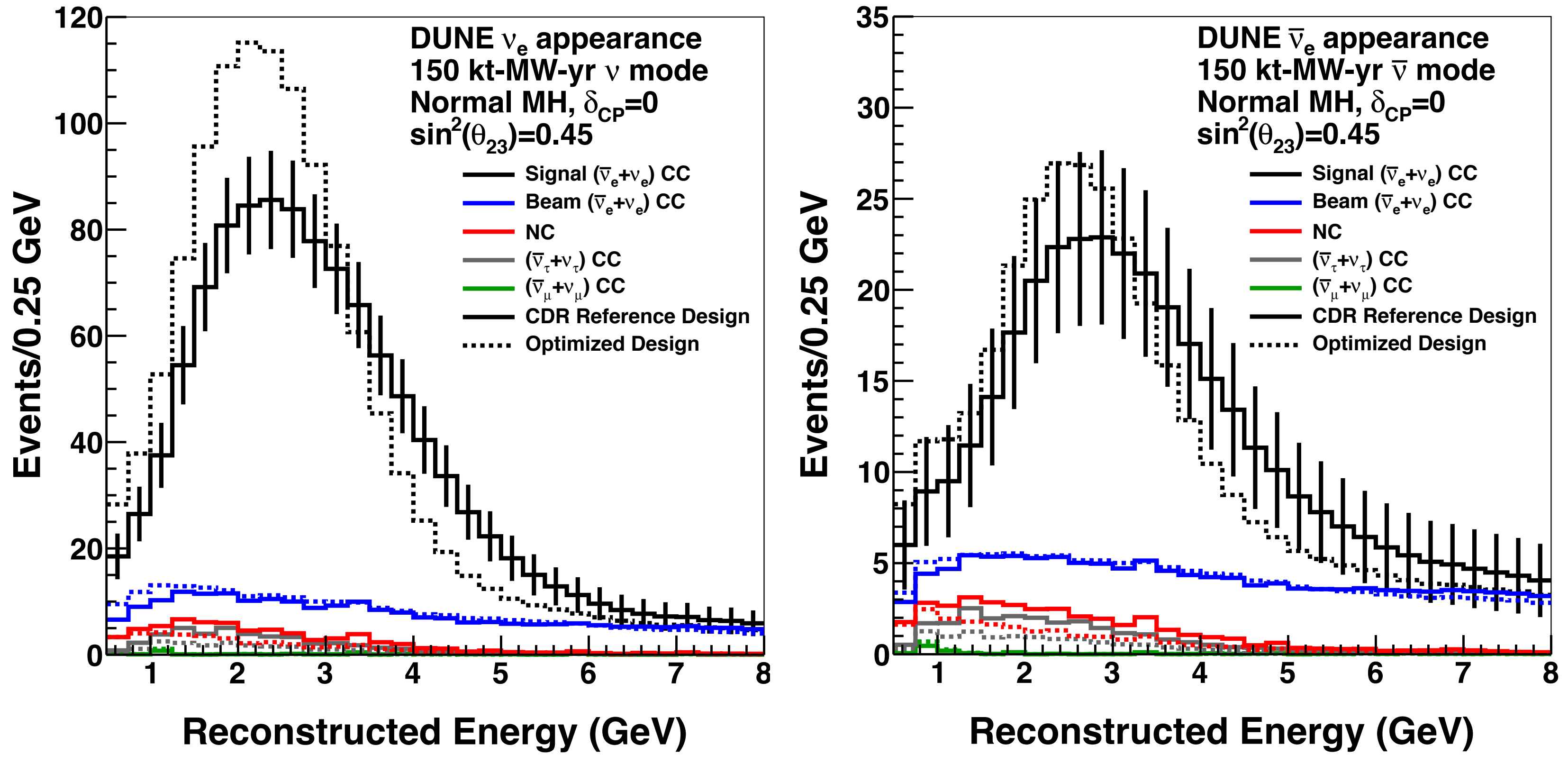
LBNF/DUNE



ν_μ disappearance

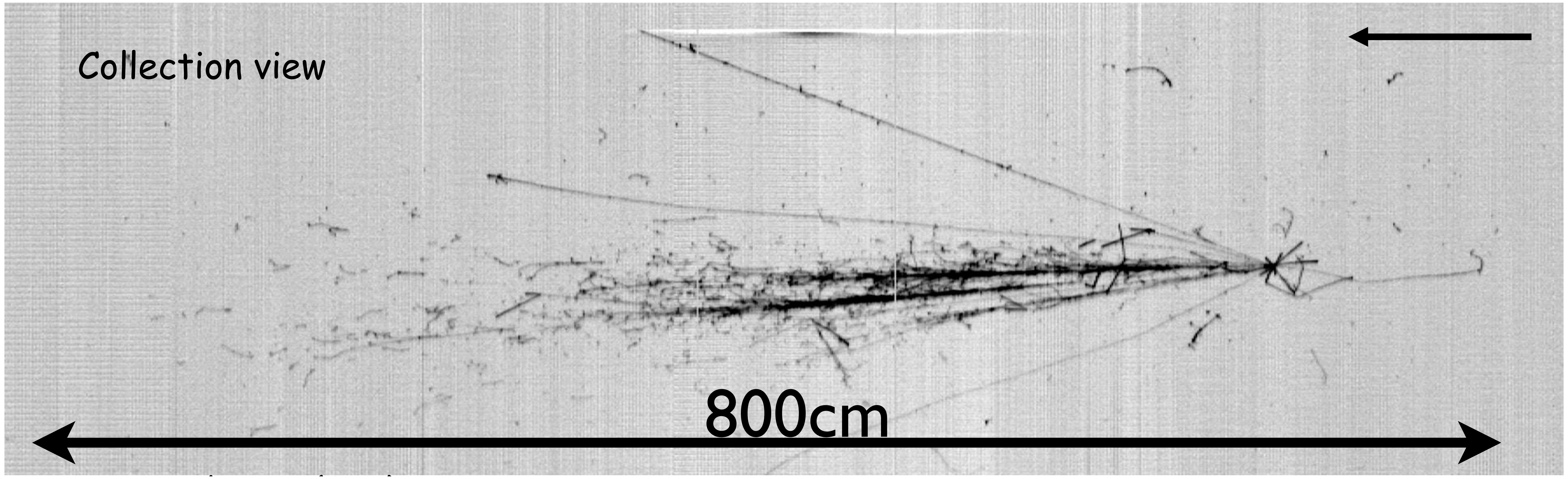


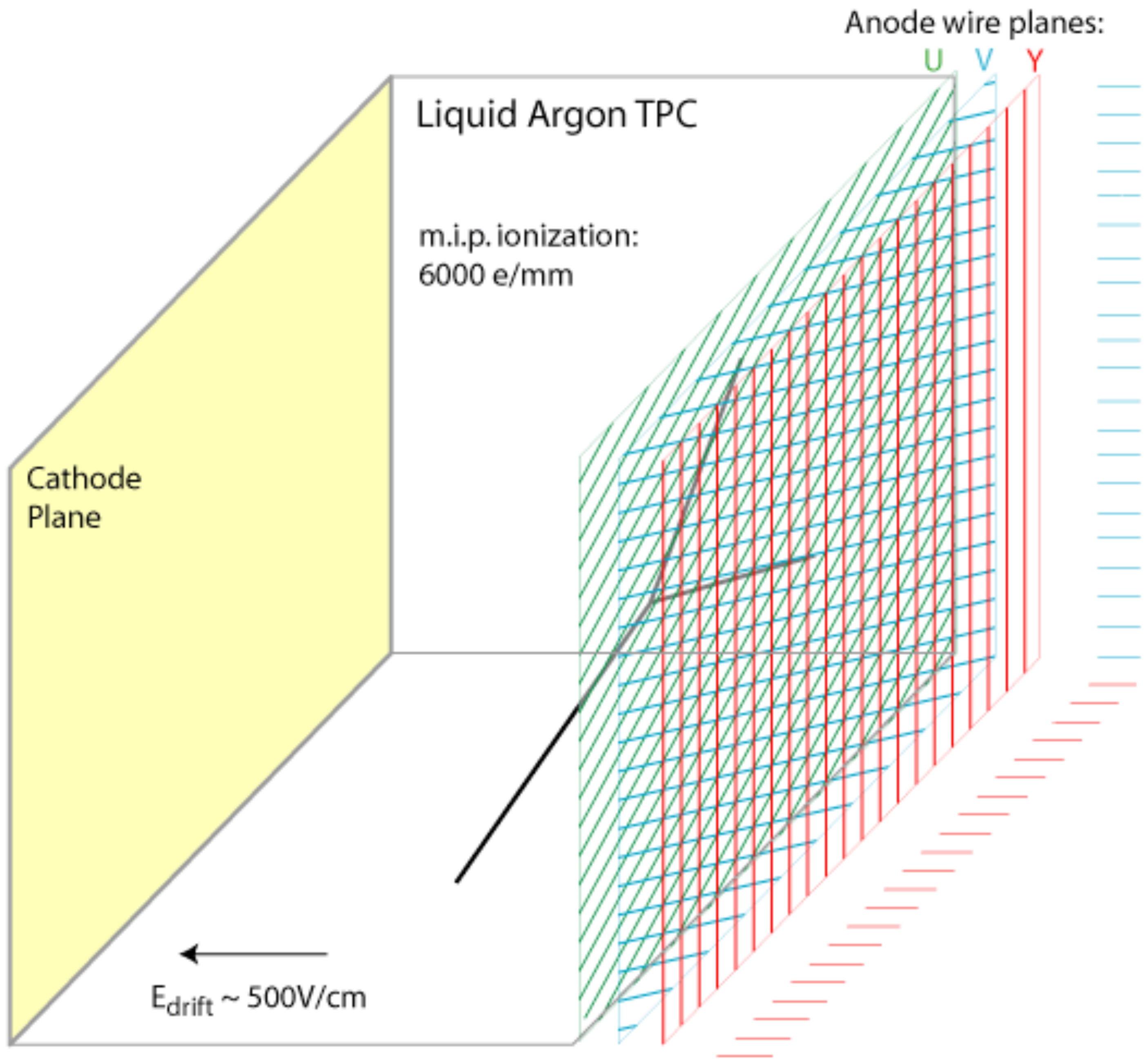
ν_e appearance

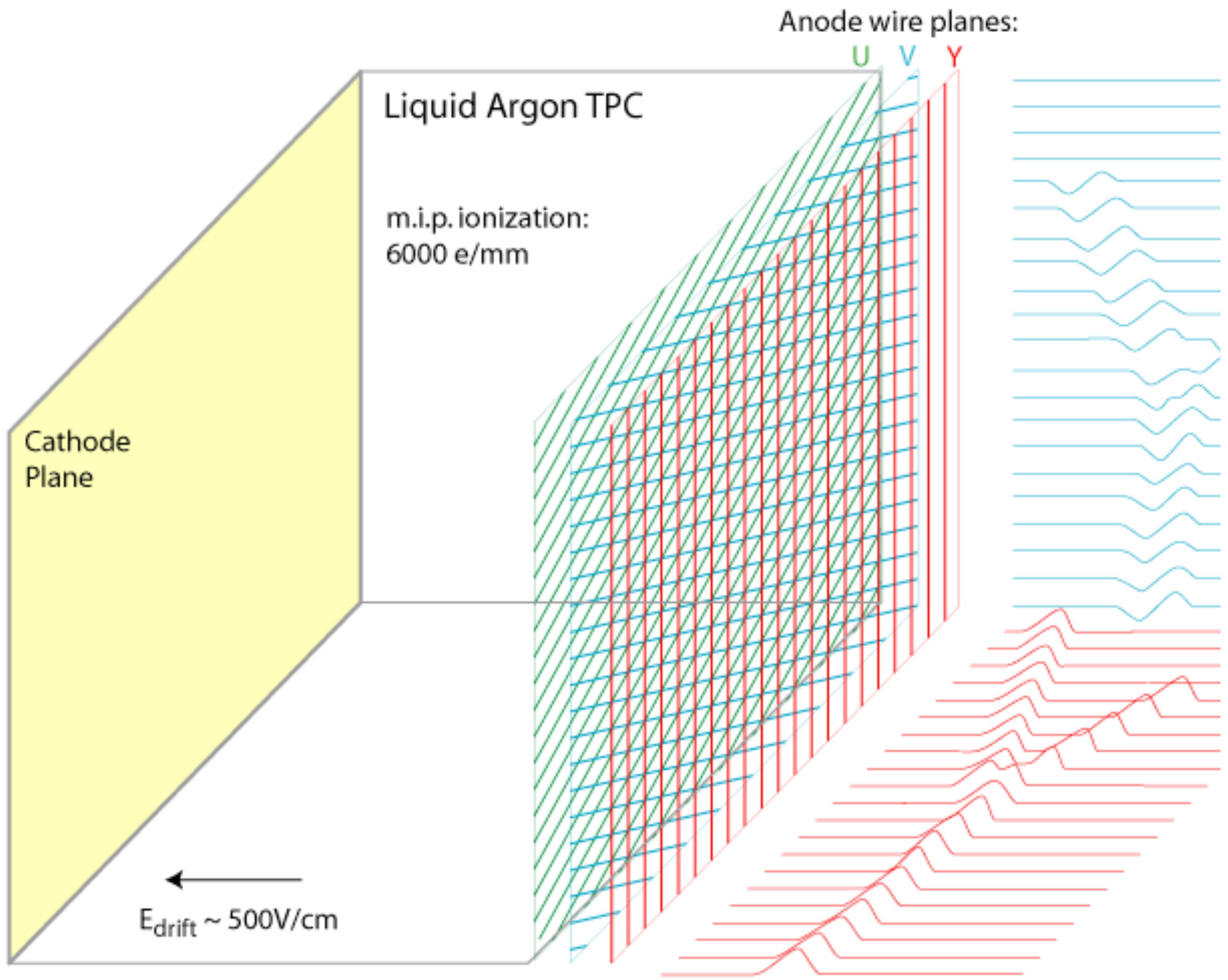


- Neutrino beam from Fermilab to Homestake (South Dakota) 1300 km away
- 4 x10 kT Liquid Argon Time Projection Chambers to detector neutrinos

LAR-TPC

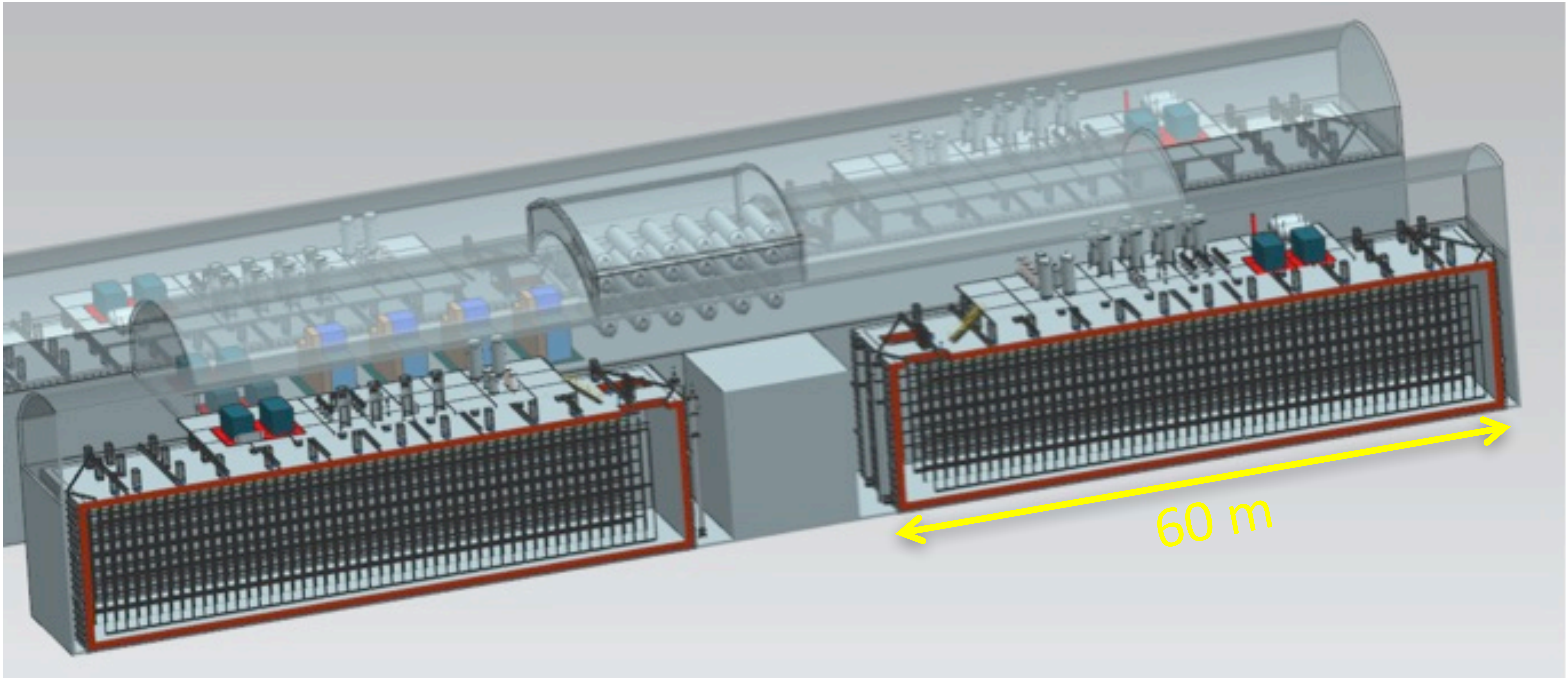






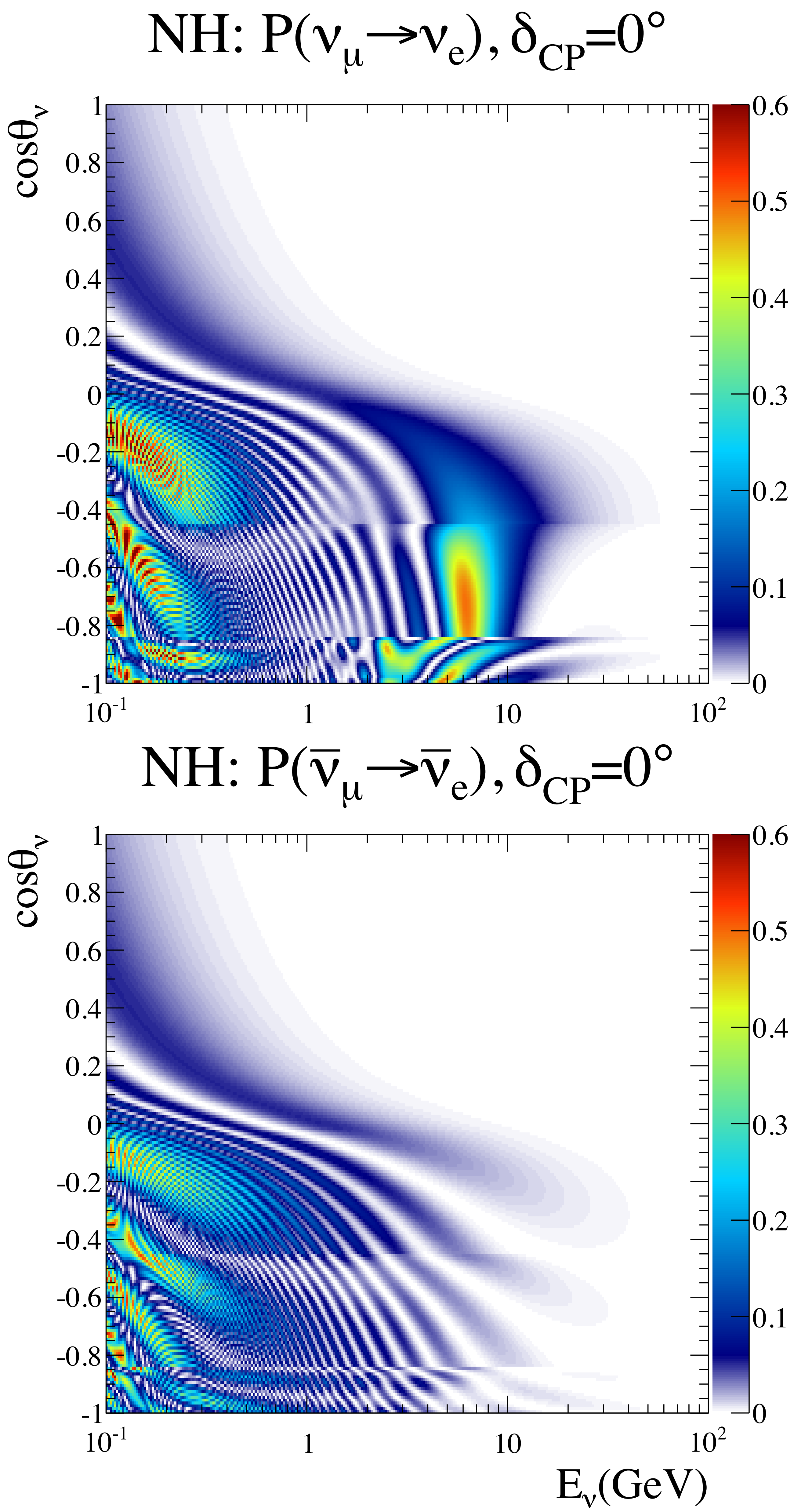
- Exquisite reconstruction of details of reconstruction
- Particularly well-suited for neutrino interactions at a few GeV

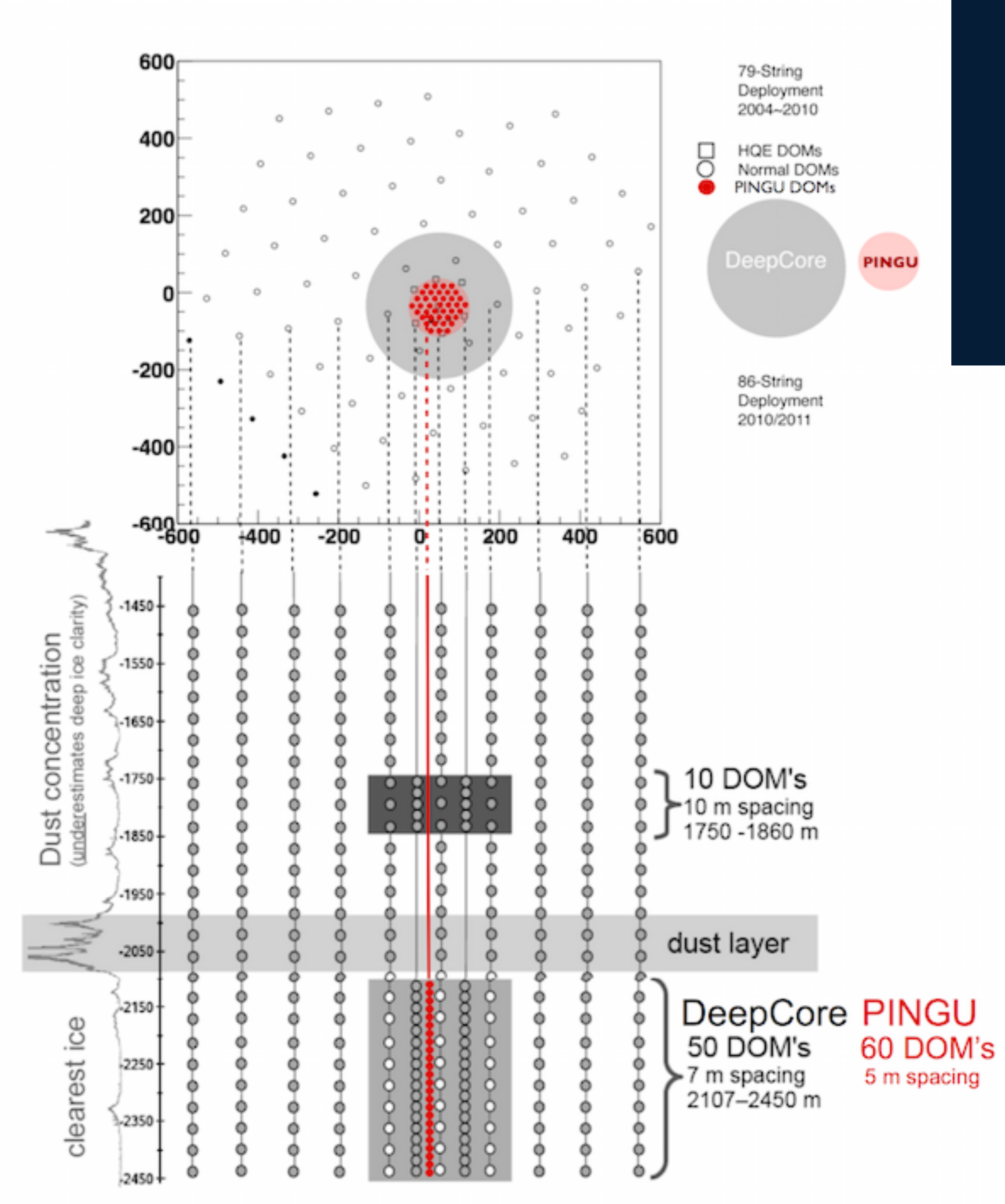
FAR DETECTOR MODULES

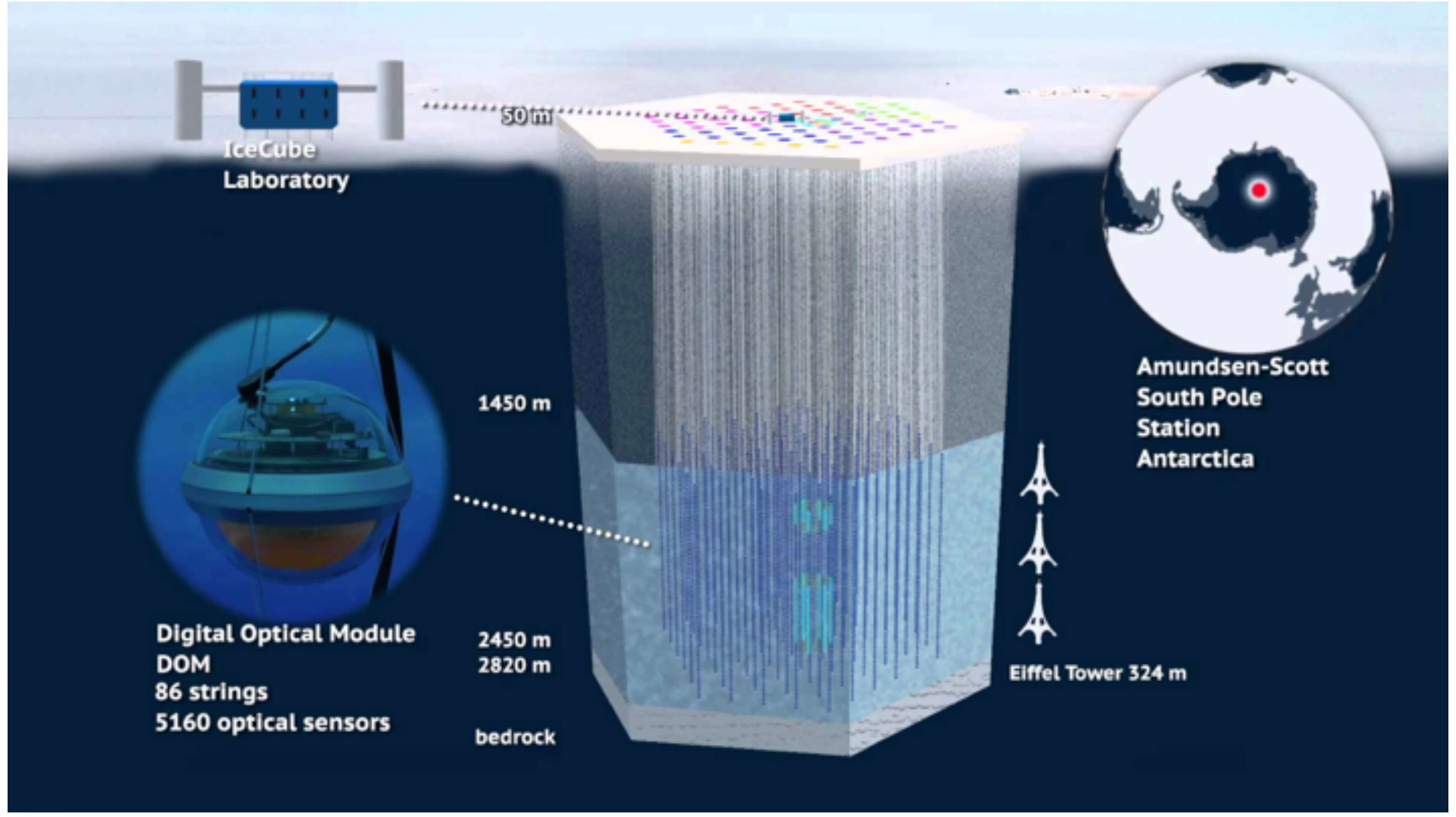


- Build the largest LAr TPCs in existence (4 x 10 kT modules)

PINGU AND ORCA



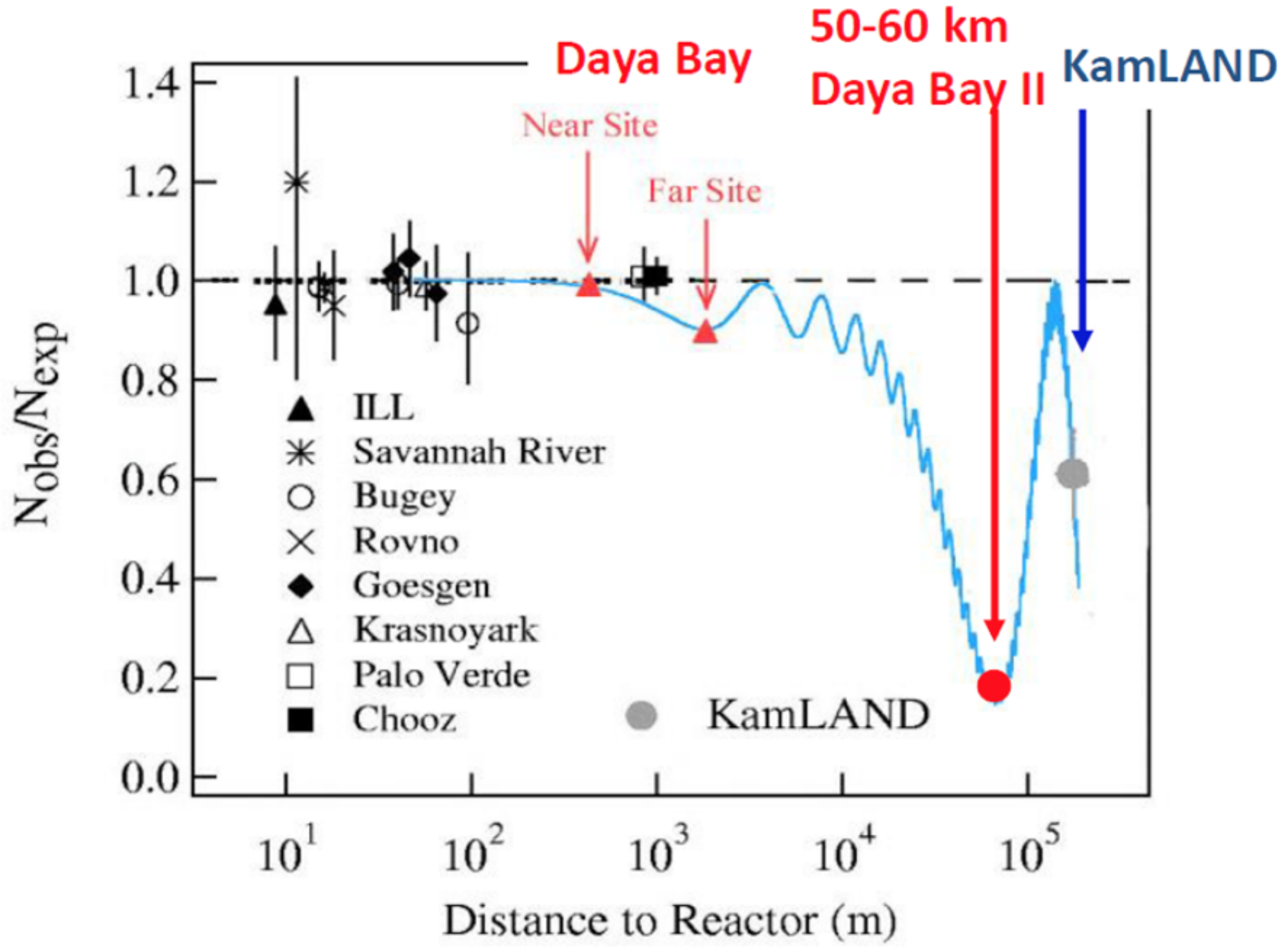


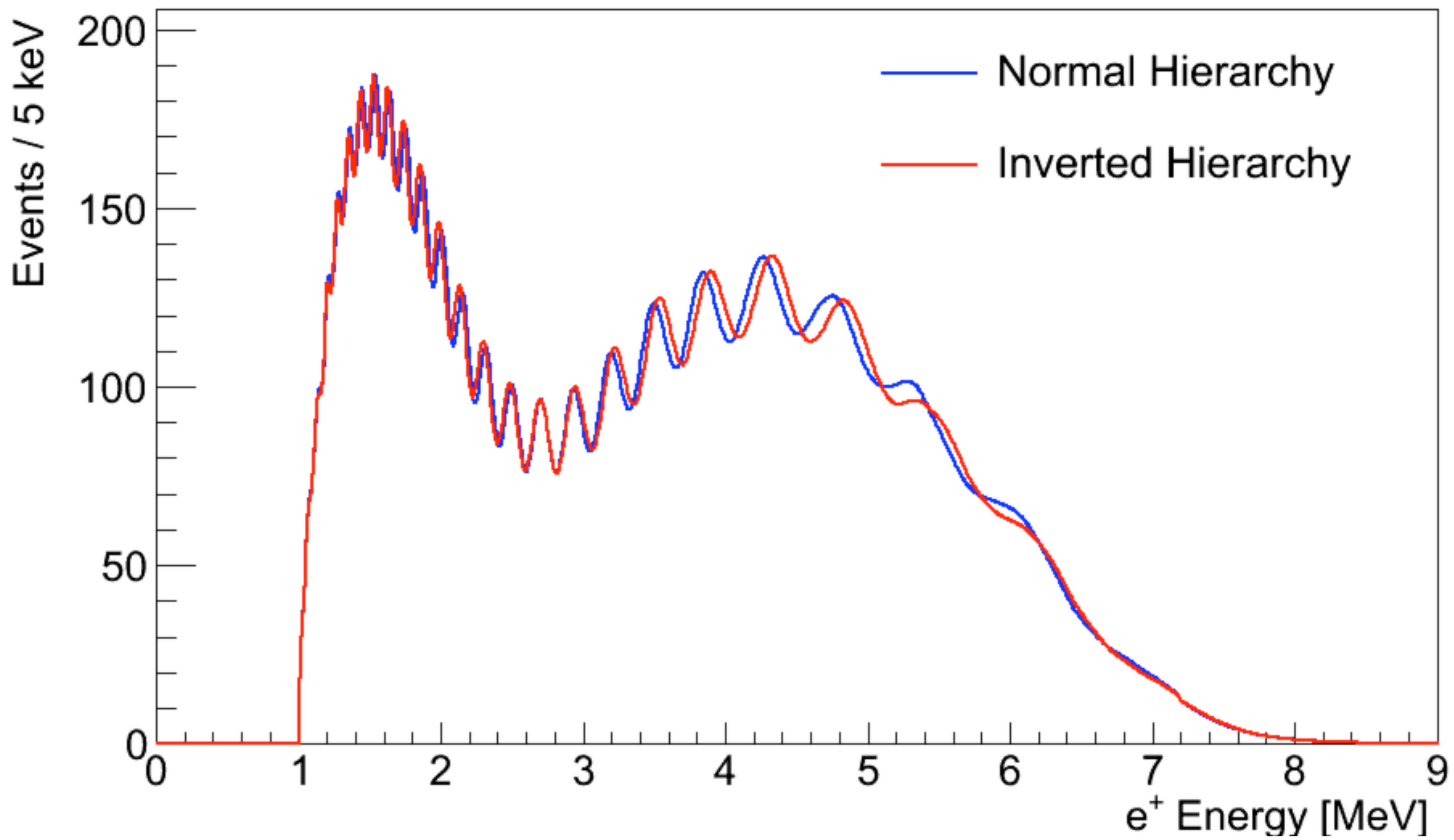


- PINGU: "in fill" of IceCube array in the South Pole
    - create "small region" of high photosensor density to reconstruct neutrino with energyies ~several GeV
    - use resonant matter effects of neutrinos passing through the core and mantle of the earth to resolve the hierarchy
- ORCA: similar effort in the Mediterranean Sea

JUNO

$$P(\nu_e \to \nu_e) \sim 1 - \sin^2 2\theta_{13} \sin^2(1.27\Delta m^2_{31} L/E) - \sin^2 2\theta_{12} \sin^2(1.27\Delta m^2_{21} L/E)$$

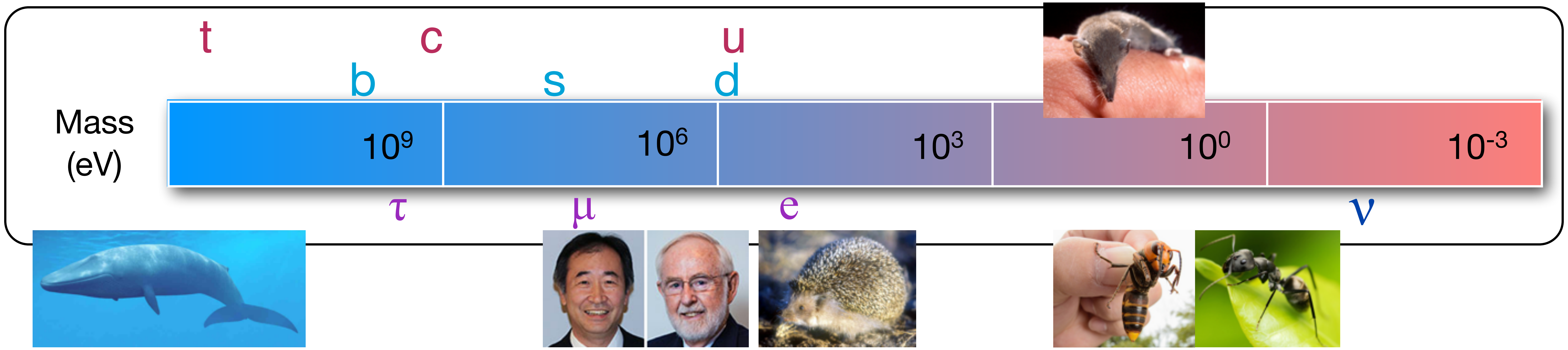


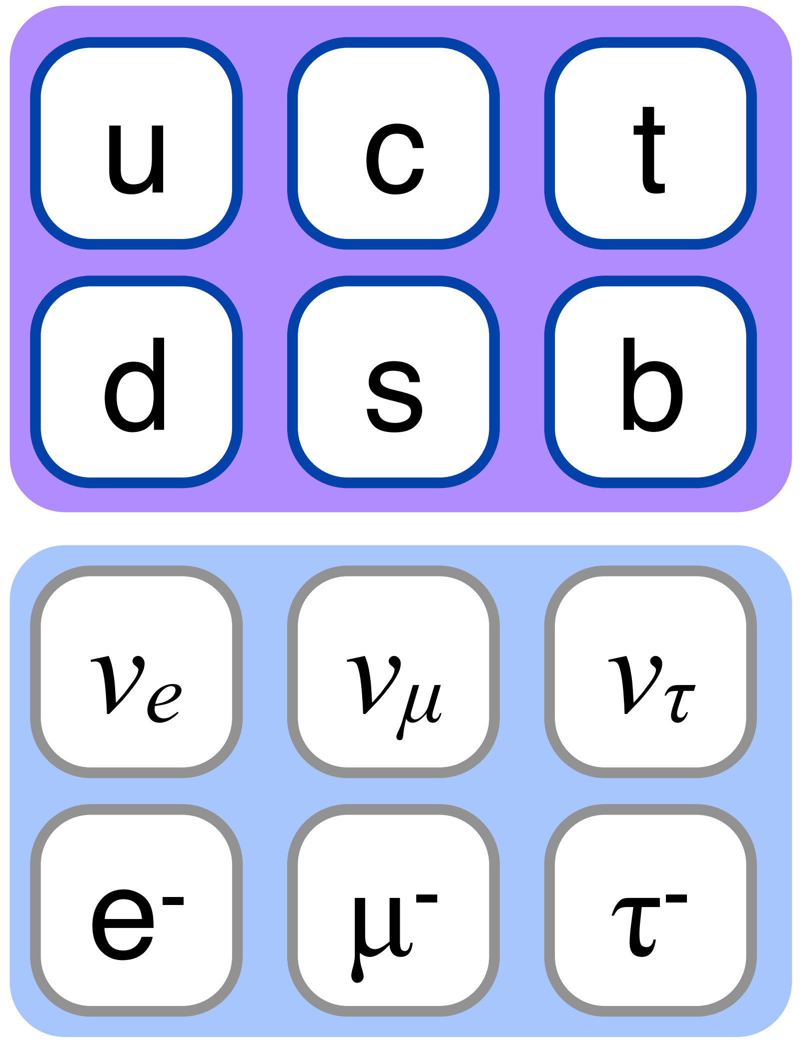


- If we have incredible energy resolution, we can detect a shift that arises from the mass hierarchy

ANSWERS OR MORE QUESTIONS

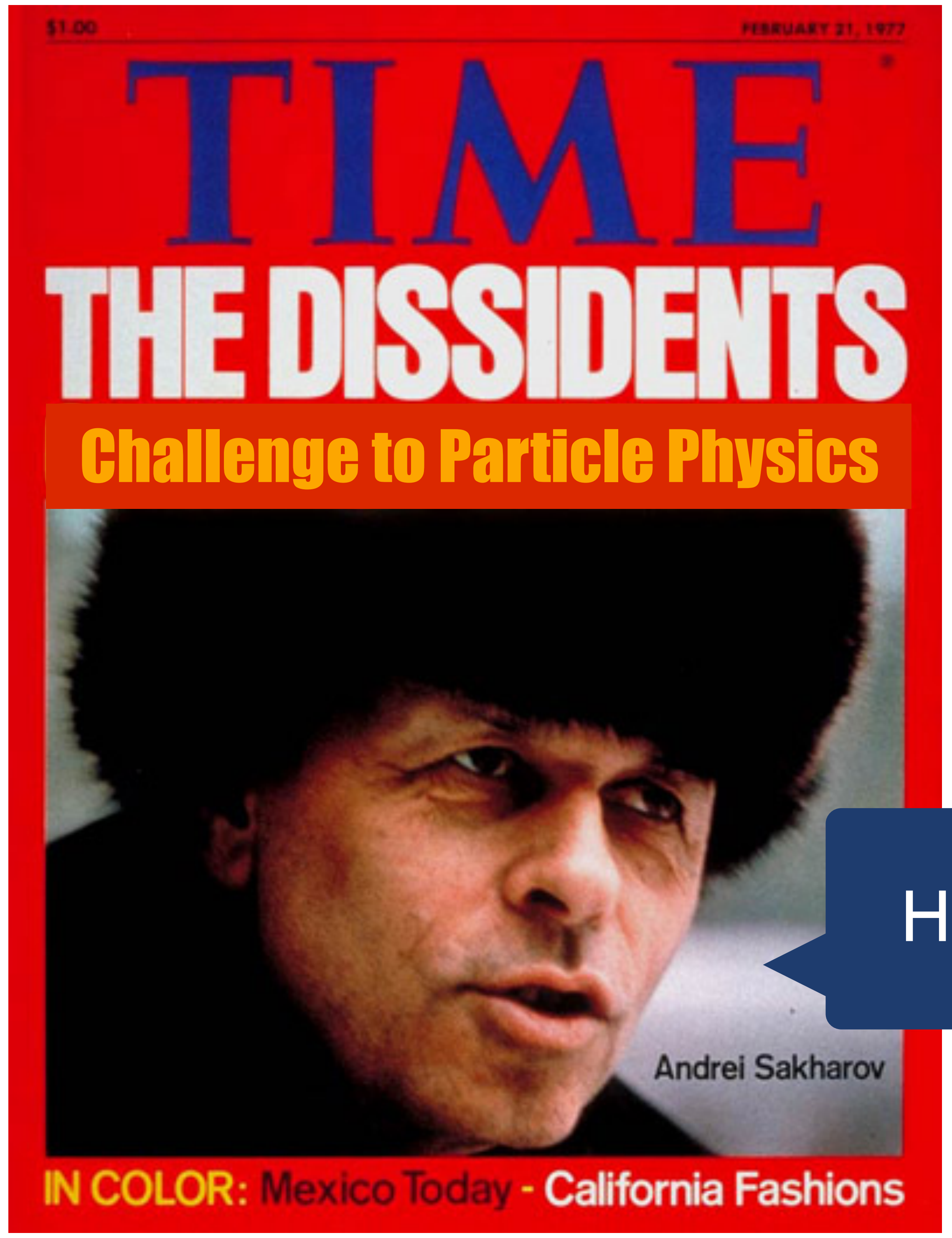
$$|U_{QUARK}| \sim \begin{pmatrix} 0.97428 & 0.2253 & 0.0034 \\ 0.2252 & 0.93745 & 0.0410 \\ 0.00862 & 0.0403 & 0.99915 \end{pmatrix} \qquad |U_{LEPTON}| \sim \begin{pmatrix} 0.8 & 0.5 & 0.15 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$





- Why are quark and lepton mixings so different?
  - is neutrino mixing "maximal"?
- Why are neutrino masses so tiny?
  - quarks/charged leptons masses from Higgs mechanism
  - do neutrinos get mass some other way?

THE MATTER DOMINATED UNIVERSE

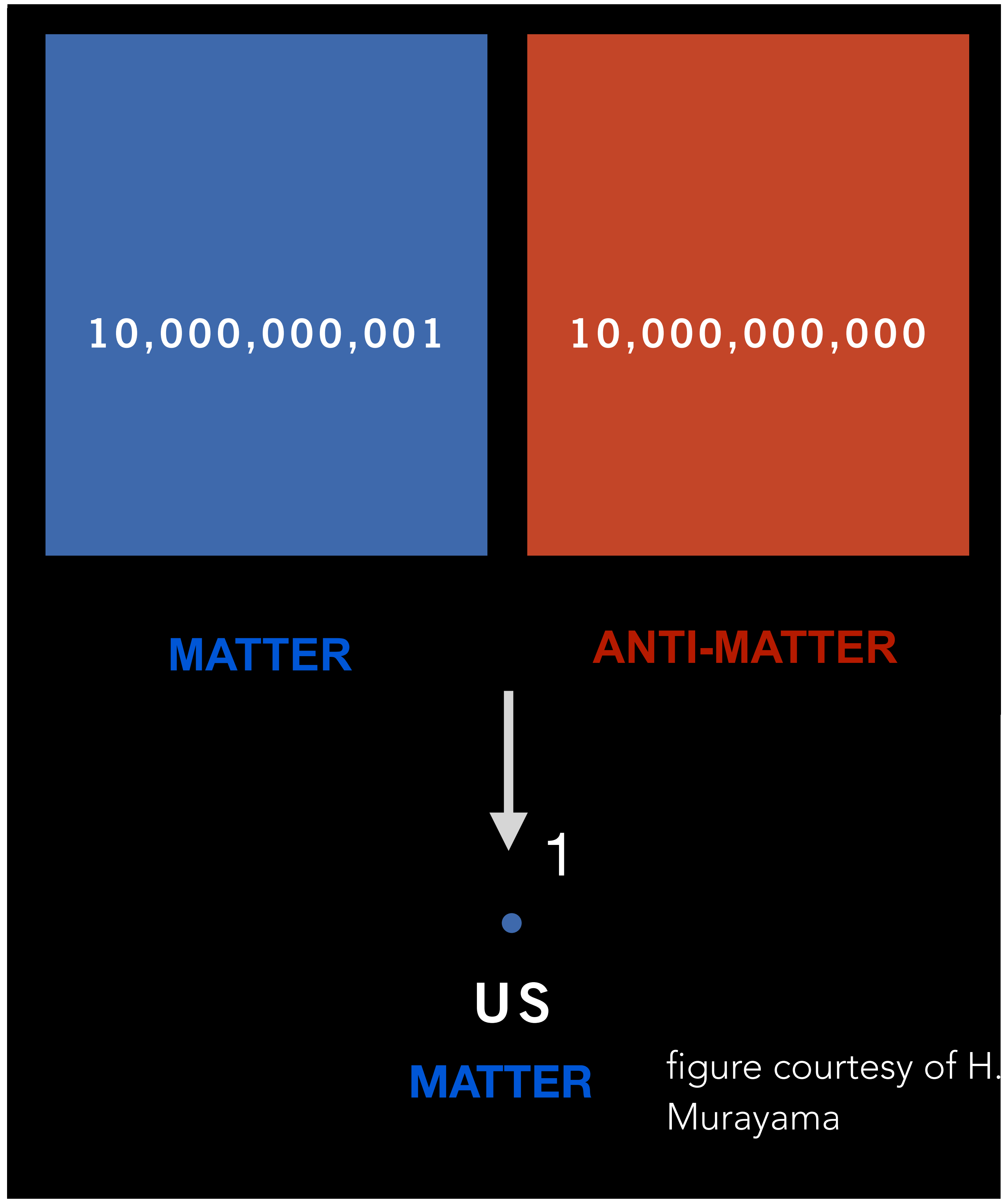


SAKHAROV CONDITIONS:

- BARYON NUMBER (B) VIOLATION
- VIOLATION OF C, CP SYMMETRY (CPV)
- DEPARTURE FROM THERMAL EQUILIBRIUM

HOW DID THIS HAPPEN?

$$\frac{\Delta B}{N_\gamma} \sim \mathcal{O}(10^{-10})$$



- Extremely small?
- Extremely large?
  - Known sources of CPV (quark CKM) cannot produce this asymmetry

Further **exploration** and **elucidation** of possible CPV sources is critical

ELUCIDATING CP VIOLATION

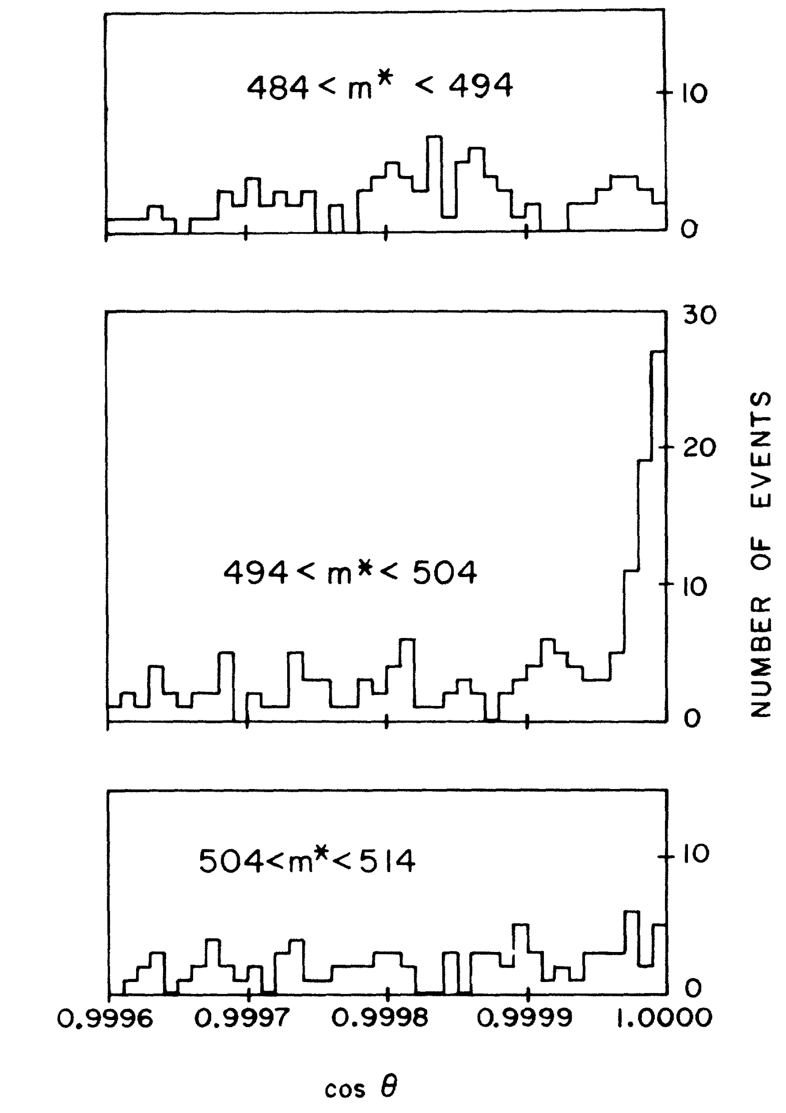


FIG. 3. Angular distribution in three mass ranges for events with cosθ > 0.9995.

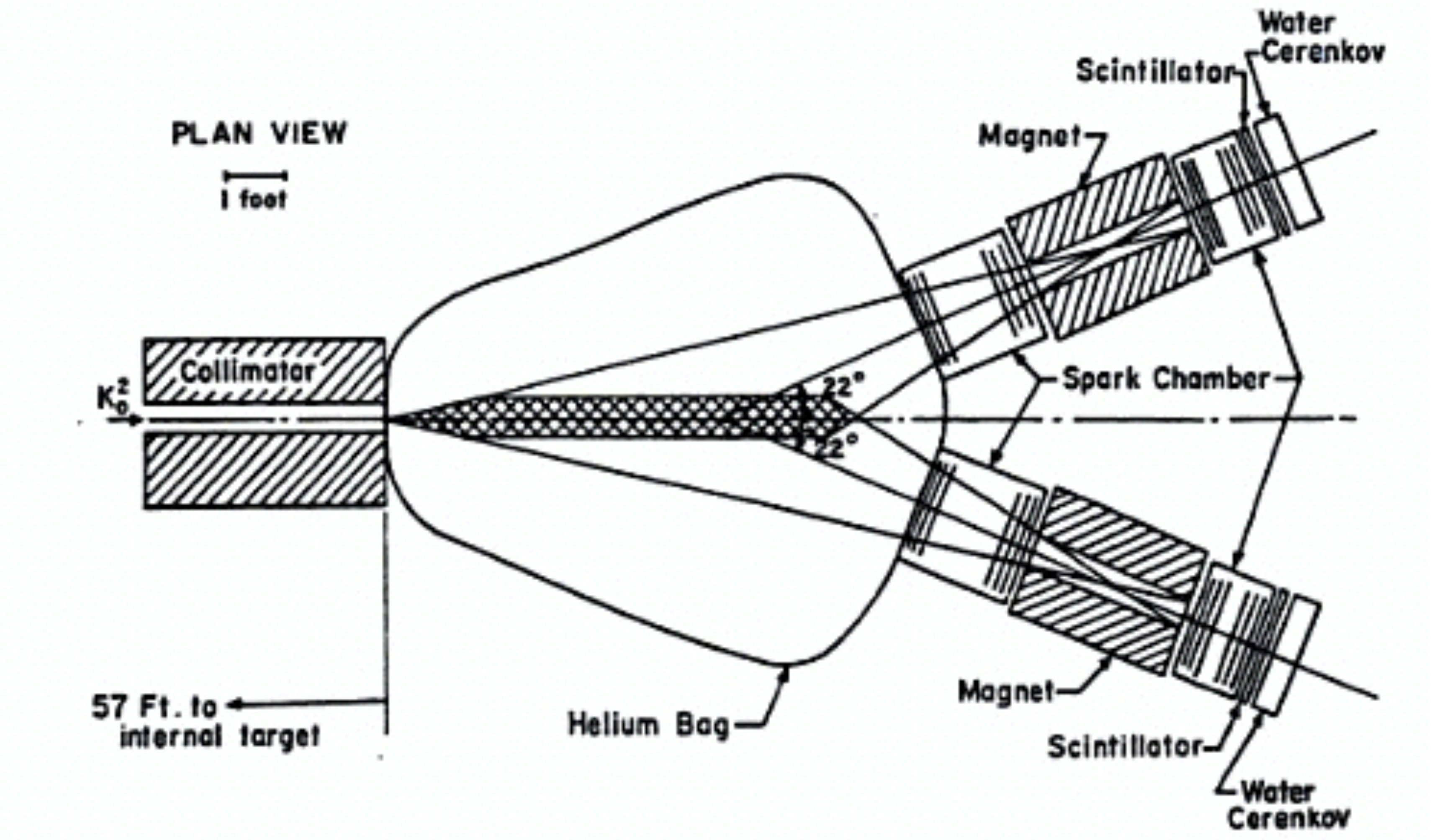
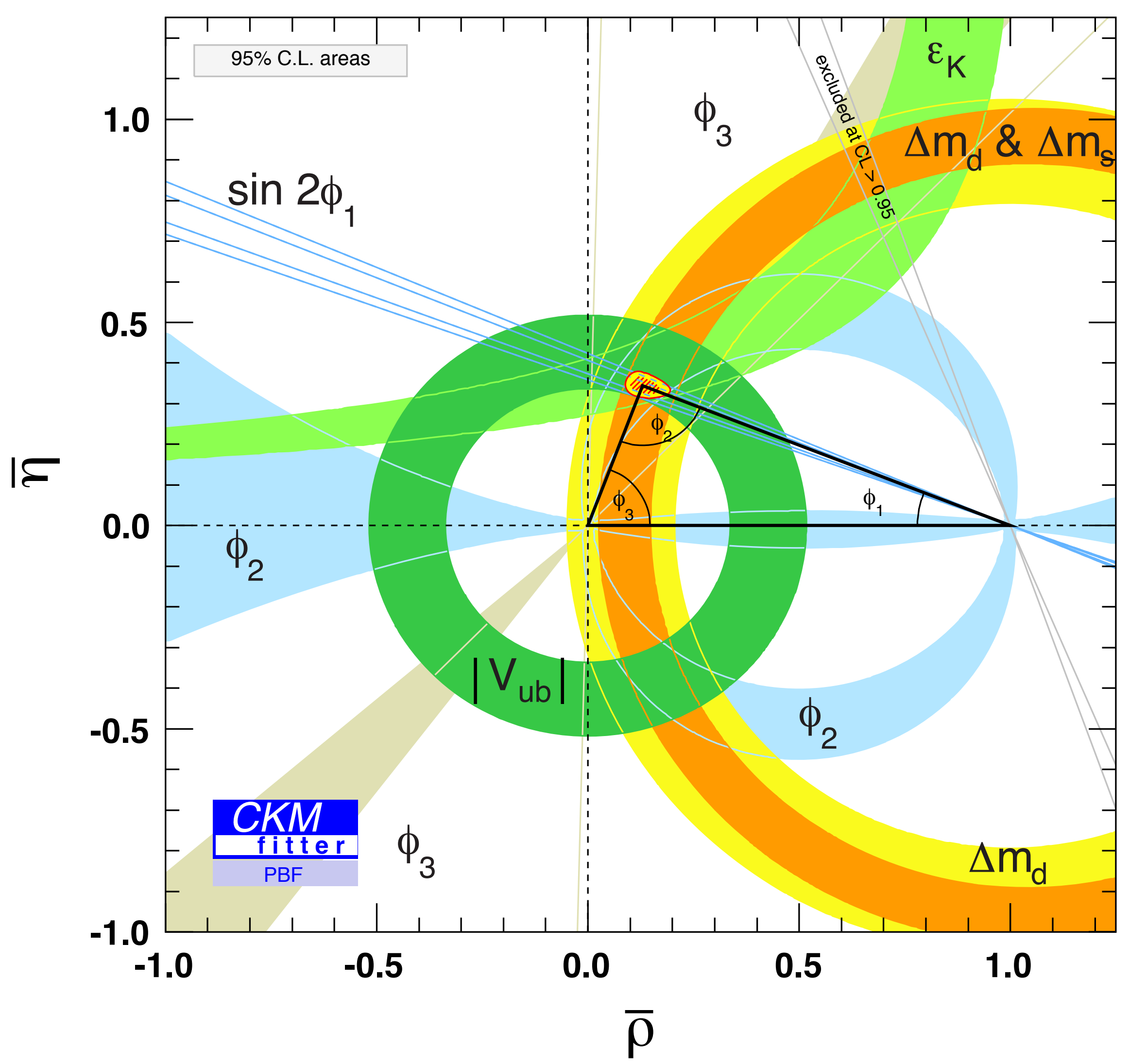
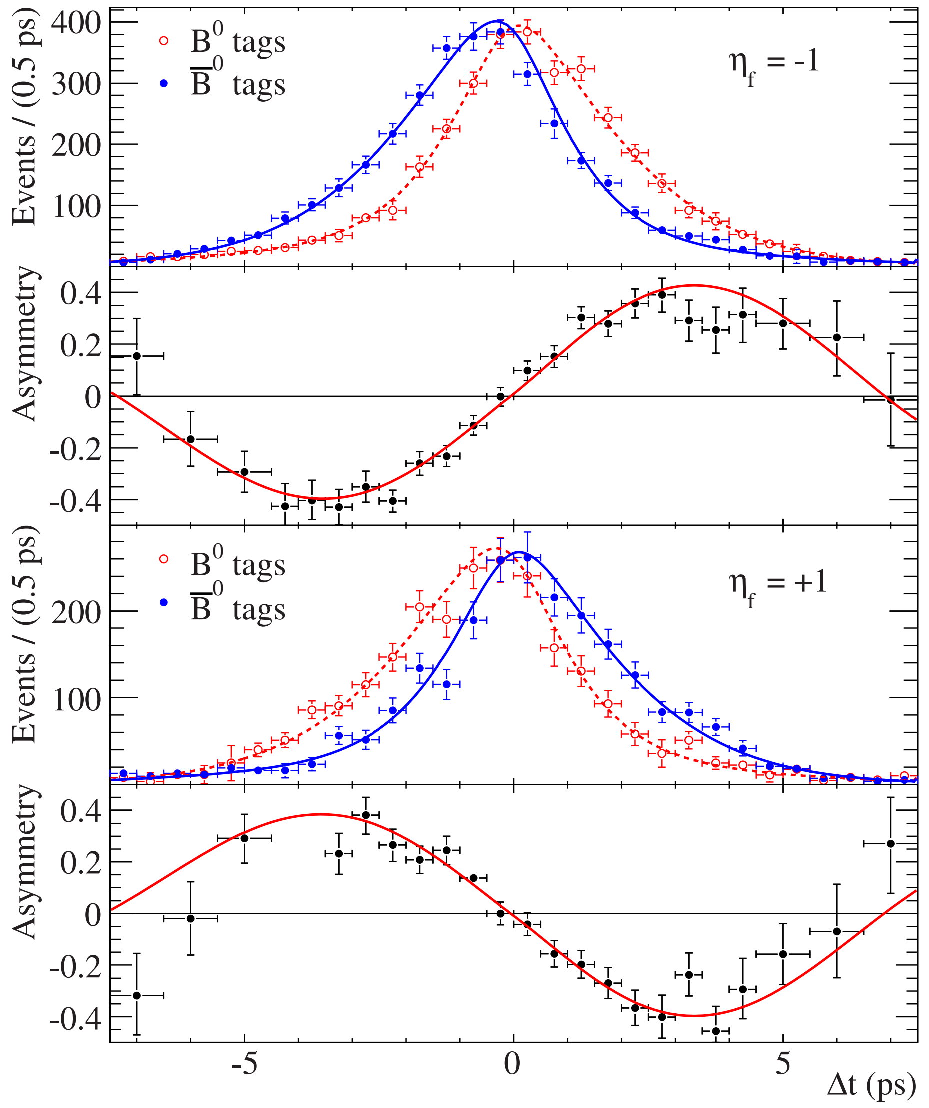
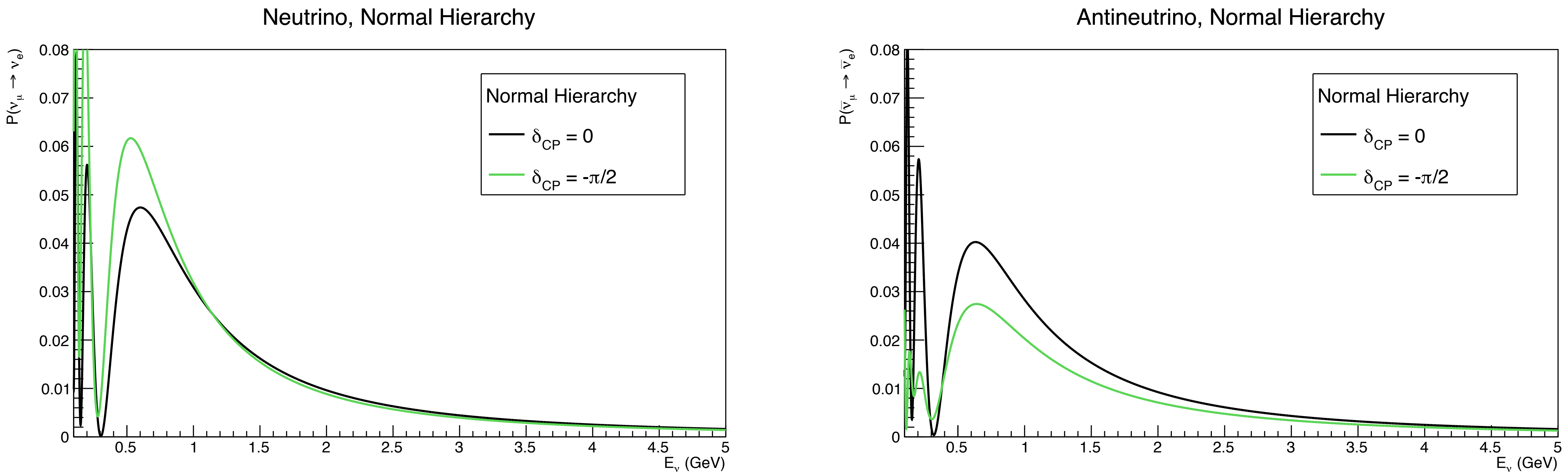


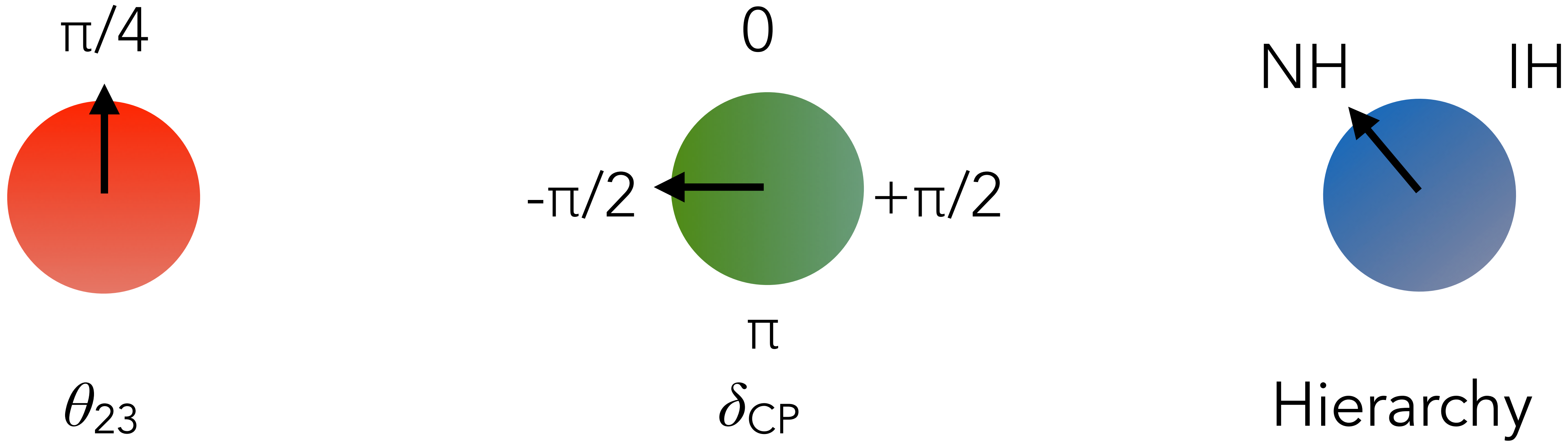
Fig. 9a. Set-up used to detect $K_2 \to \pi^+\pi^-$.





- 1964: Initial discovery of CP violation in $K_L \to \pi^+ + \pi^-$
- Nearly 50 years later, we know that this arises from a complex phase in quark mixing
- Observing CPV in neutrinos is the **beginning** of a program . . .





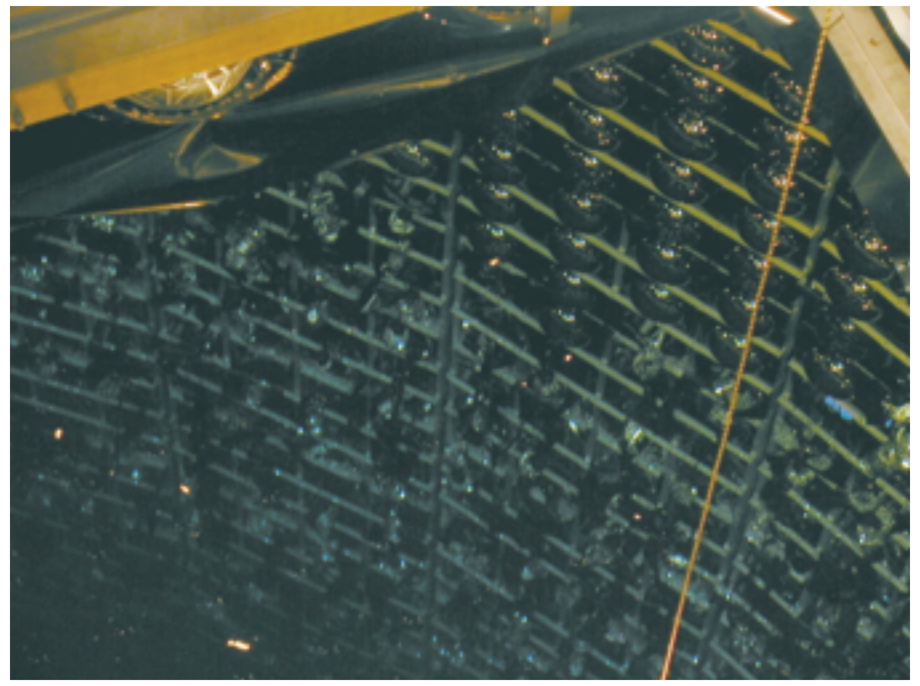
There is a most profound and beautiful question associated with the observed coupling constant. It is a simple number that has been experimentally determined to be close to 137.03597. It has been a mystery ever since it was discovered more than fifty years ago, and all good theoretical physicists put this number up on their wall and worry about it. Immediately you would like to know where this number for a coupling comes from: is it related to pi or perhaps to the base of natural logarithms? Nobody knows.

It's one of the greatest damn mysteries of physics: a magic number that comes to us with no understanding by man.

EPILOGUE OF RANDOM THOUGHTS

PMT IMPLOSION

courtesy: smartereveryday

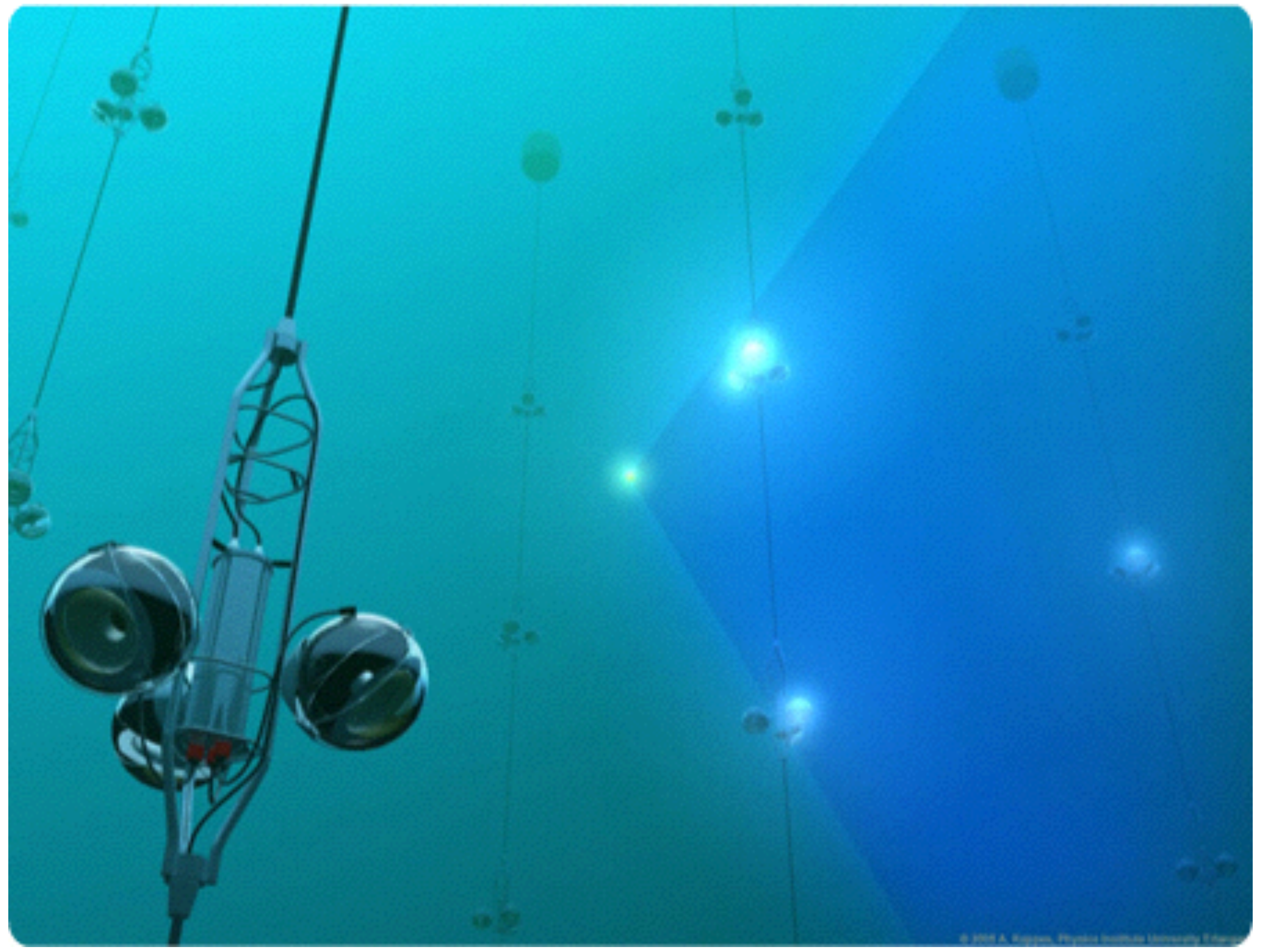


- "Prince Rupert's drop"
    - cooled molten glass is extraordinarily strong
    - enormous stresses are pent up from the cooling process
    - explosive release of stress if any part is broken
- Implosion of single PMT releases shockwave in water
    - induces implosion of adjacent PMTs
    - chain reaction destroys all PMTs in water

MODULES

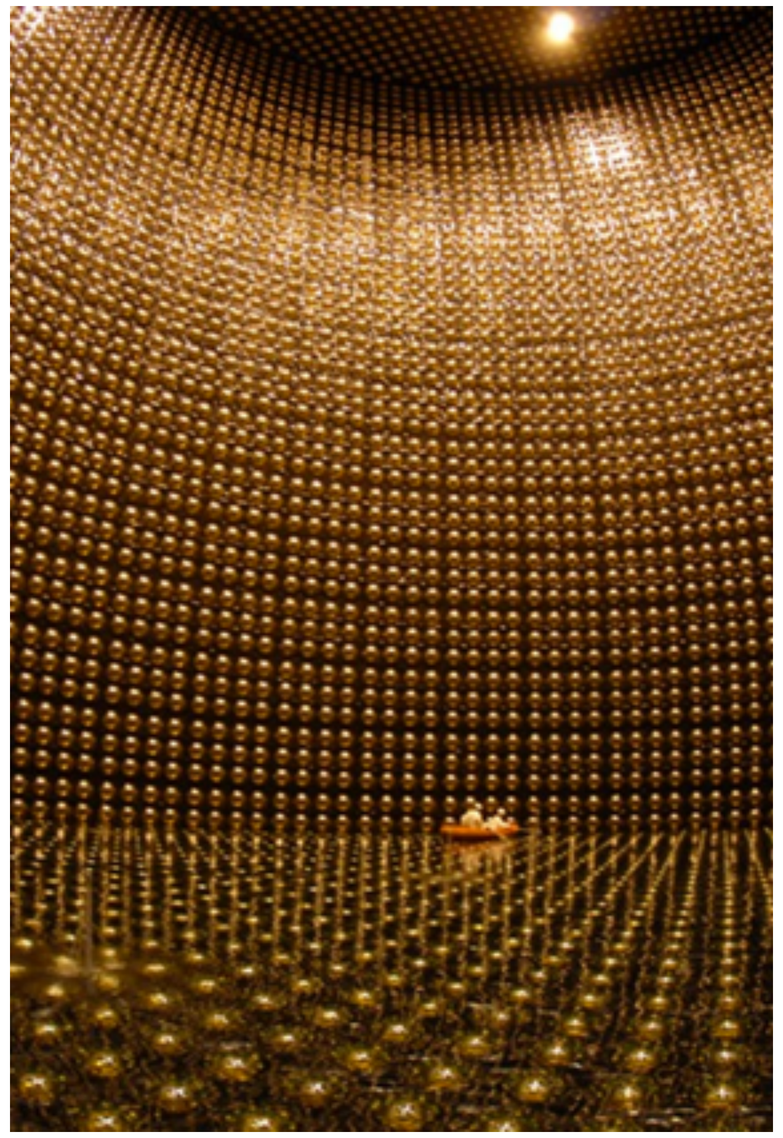
IceCube

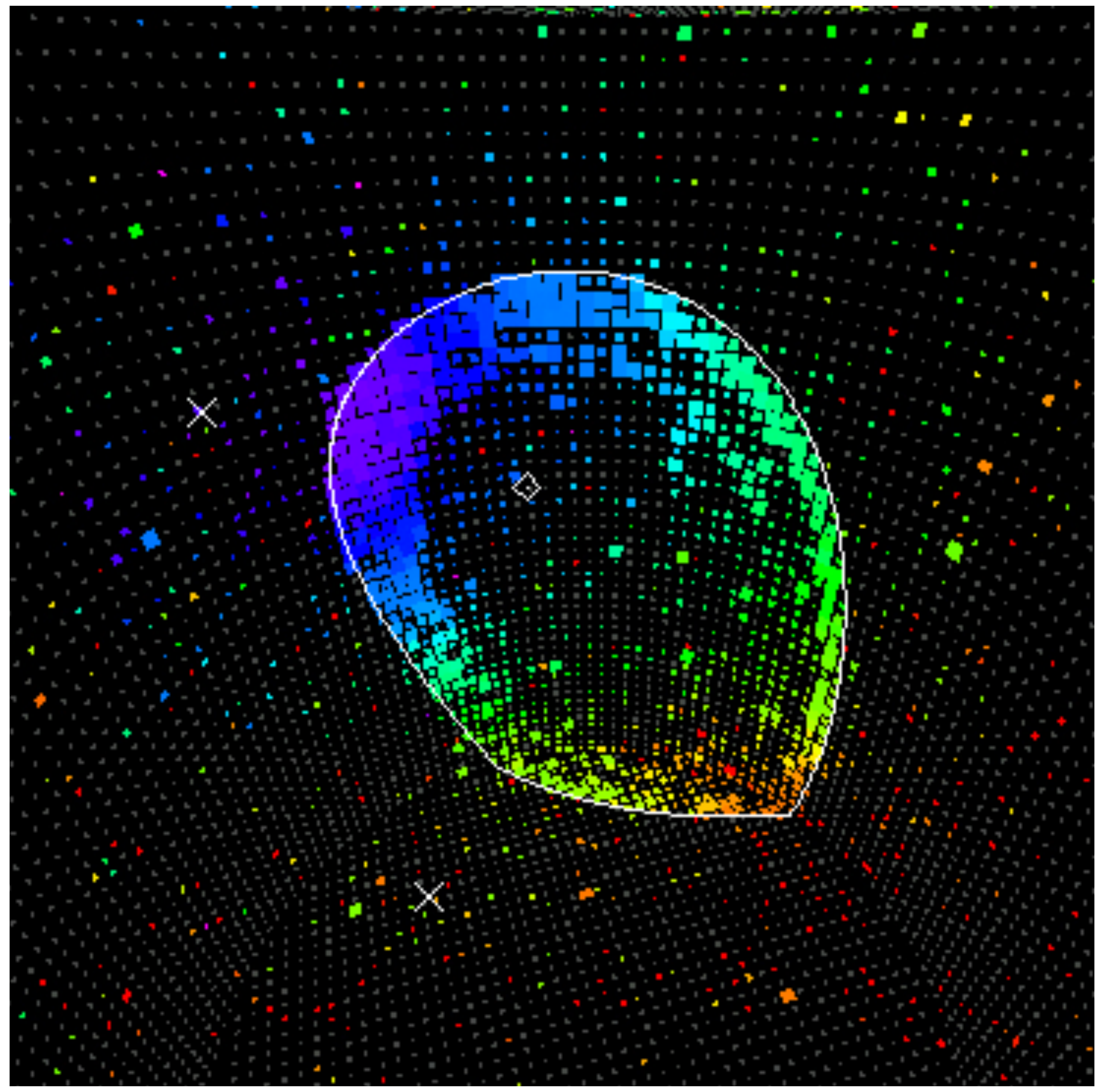
ANTARES

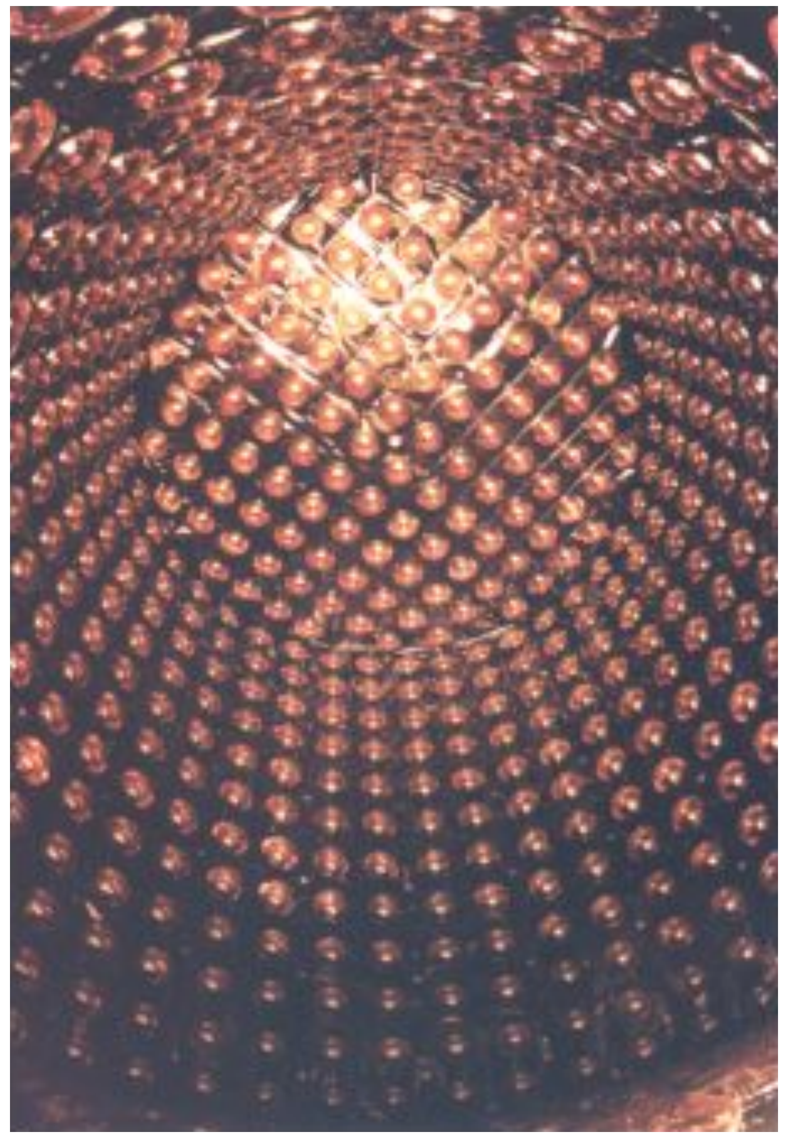


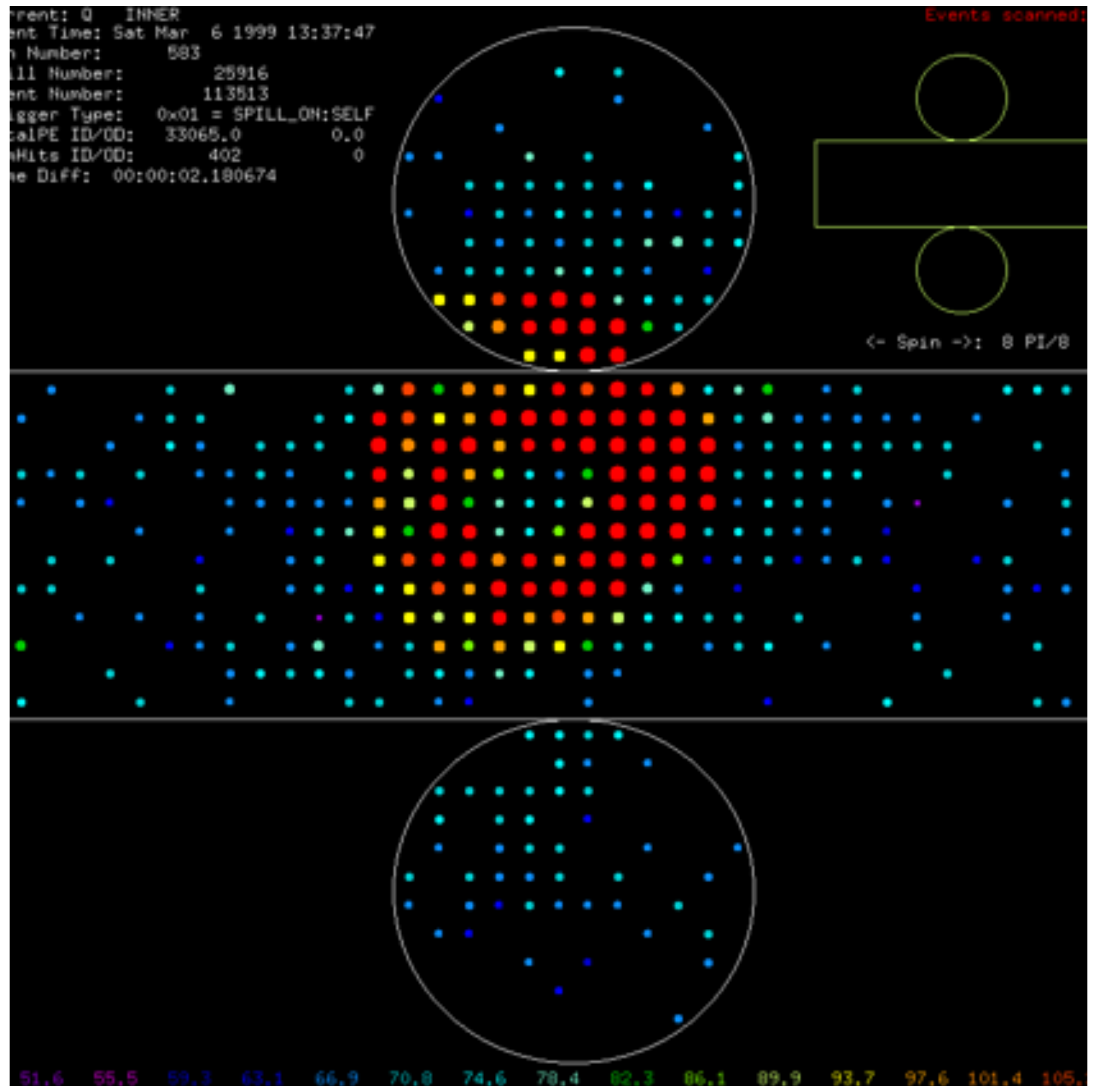
- "pDOM": PMT Digital Optical Module
- Vessel houses PMT, electronics, calibration, etc.
- Protection from:
  - pressures at ~1 km depth, (re-)freezing process
- Ready-made solution for very deep ice/water deployment of PMTs

GRANULARITY





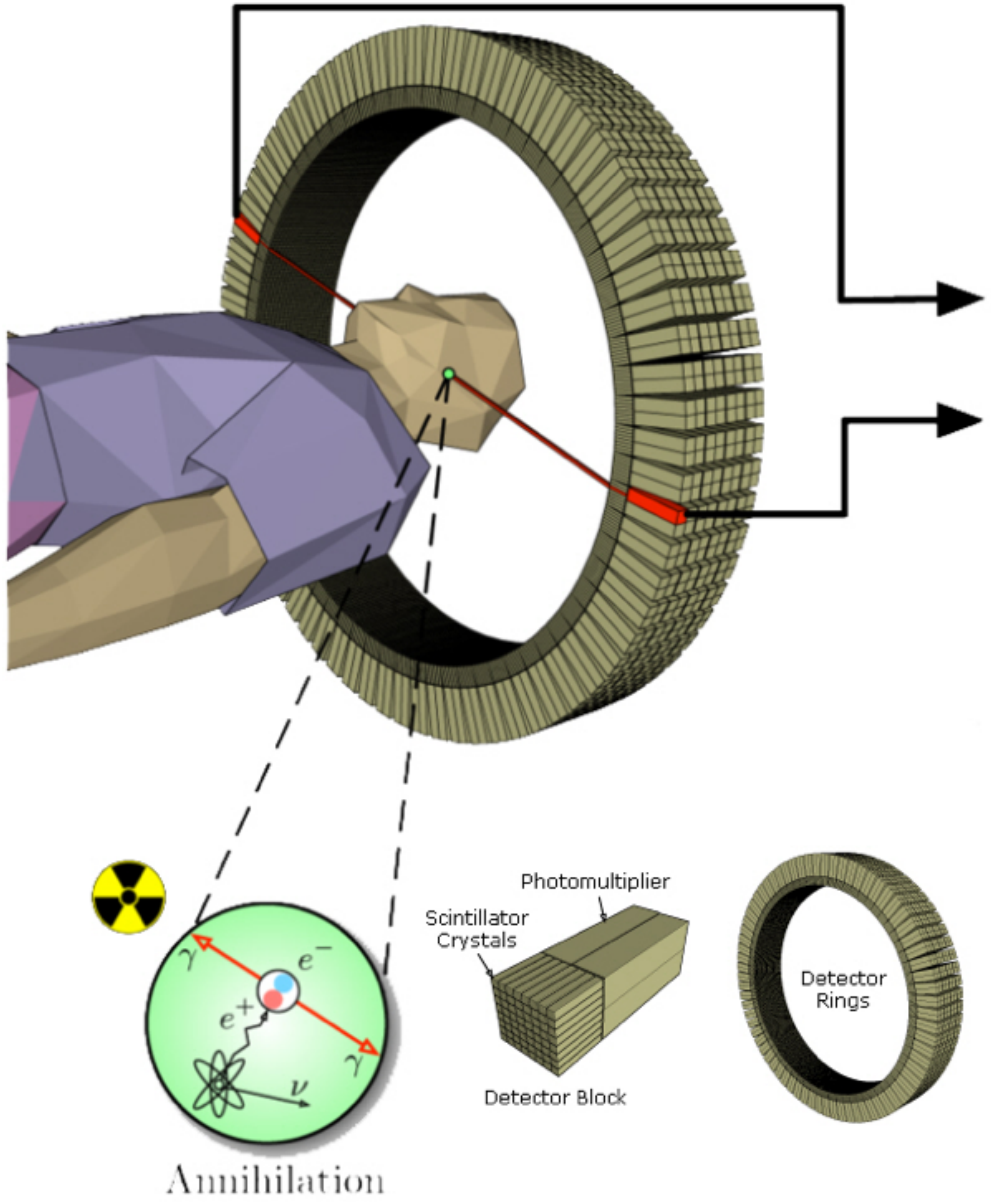




- K2K 1KT WČ detector
  - miniature version of SK
    - 1/50th size
    - R~ 5 m, H ~ 12 m
  - same 20" PMTs with 40% coverage

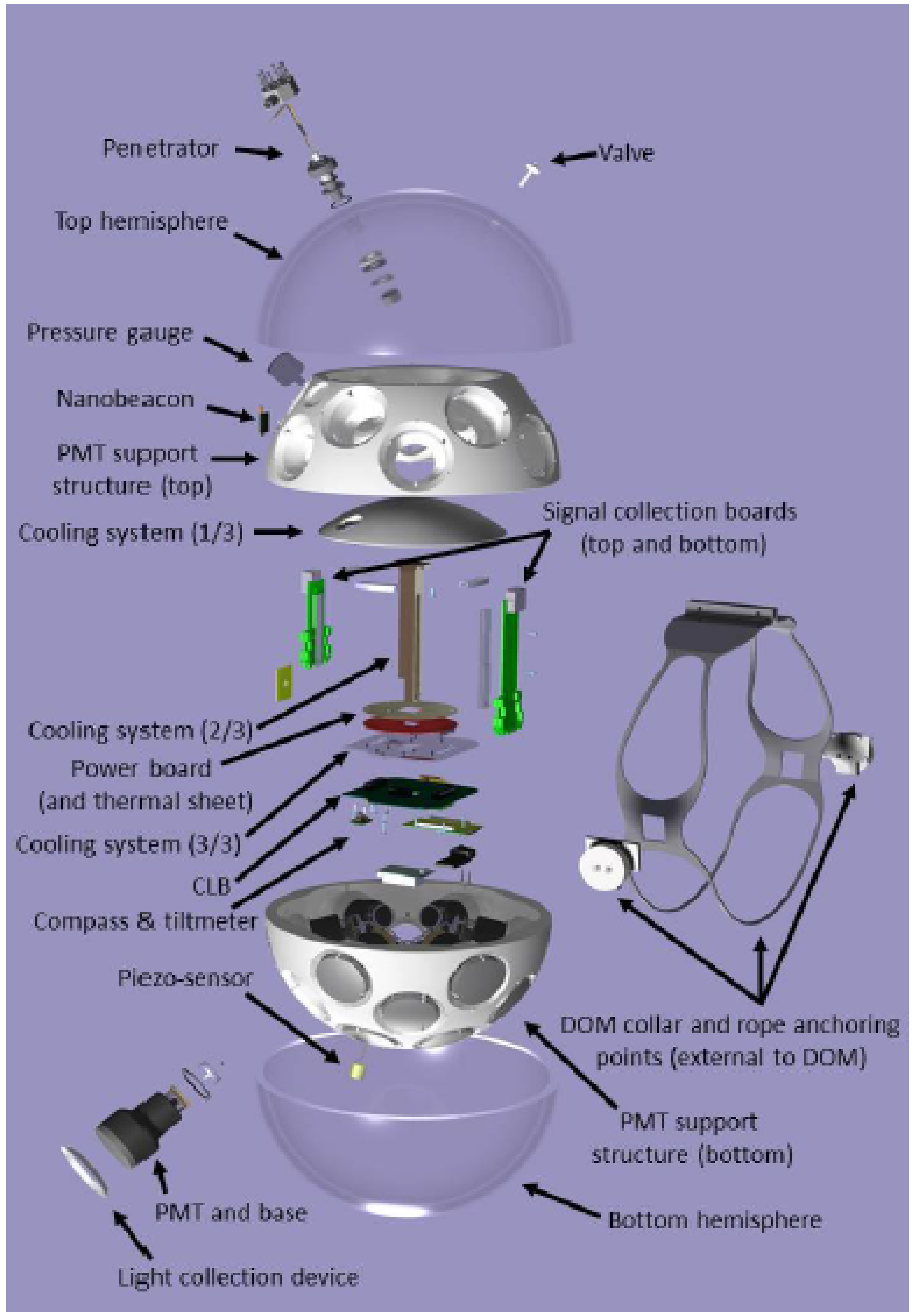
- Granularity/sampling near the wall suffers
  - SK: events must be > 2 m from the wall
    - Reduces "useable" volume
    - 33 kT → 22.5 kT
  - 1kT: "useable" volume similarly defined
    - only 50 tonnes!
- Finer granularity needed for events near the wall

ECONOMICS



- Large demand for small (~3″) PMTs for medical imaging industry (PET, etc.)
- Industrialization of production process
  - glass envelopes mass manufactured
  - some other assembly automated
- Multiple vendors
  - Hamamatsu, ETEL, HZC, etc.
- Comparable (lower?) cost/area with 20″ PMT

MERGING THE IDEAS



- "mPMT" concept from KM3NET:
  - incorporate 3" PMTs into "DOM" along with readout electronics, monitors, calibration devices, etc.
  - enhanced granularity with proven protection against deep sea deployment!