

Status and Prospects of Neutrino Oscillation Experiments

Masaki Ishitsuka, Tokyo Institute of Technology

XVII International Workshop on Deep-Inelastic Scattering and Related Subjects DIS 2009

26-30 April 2009, Madrid

Neutrino oscillations

Flavor transition occurs as a consequence of (1) finite mass and (2) mixing of mass eigenstates and weak interaction eigenstates:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

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

θ_{23} :
 $P(\nu_\mu \rightarrow \nu_\mu)$ by
Atm. ν & $\bar{\nu}$ beam

θ_{13} :
 $P(\nu_e \rightarrow \nu_e)$ by Reactor ν
 $\theta_{13} & \delta$:
 $P(\nu_\mu \rightarrow \nu_e)$ by ν beam

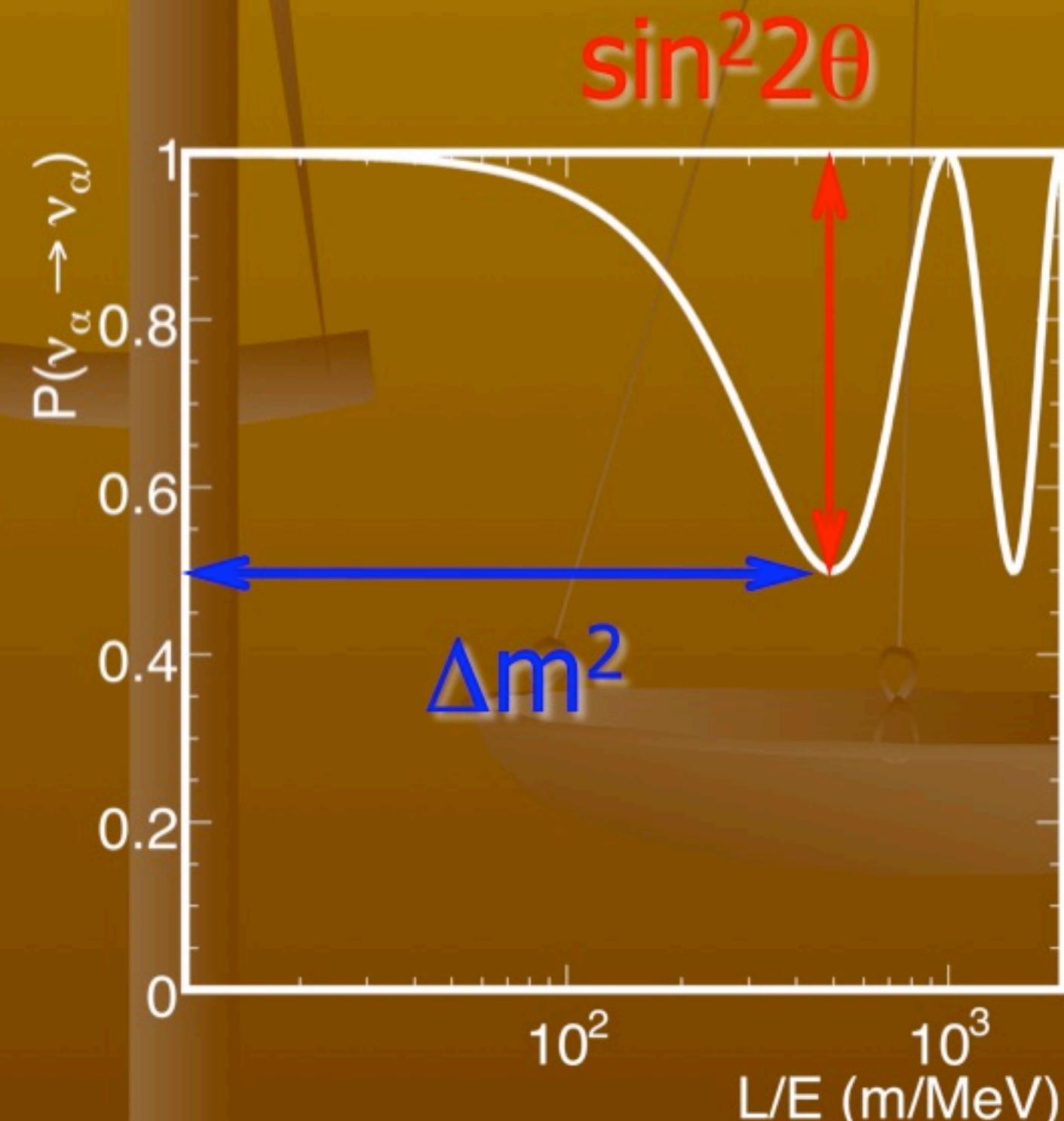
θ_{12} :
 $P(\nu_e \rightarrow \nu_x)$ by
Reactor ν & solar ν

Neutrino oscillation parameters:

MNS matrix: 3 mixing angles: $\theta_{12}, \theta_{23}, \theta_{13}$
1 phase: $\delta \Rightarrow$ CP-violation in ν -sector
Mass scales: 2 mass difference scales: $\Delta m_{12}^2, \Delta m_{23}^2$

In two flavor scheme:

$$P(\nu_\alpha \rightarrow \nu_\alpha) = 1 - \boxed{\sin^2 2\theta} \sin^2 \left(\frac{1.27 \times \boxed{\Delta m^2 [eV^2]} \times L [m]}{E [MeV]} \right)$$

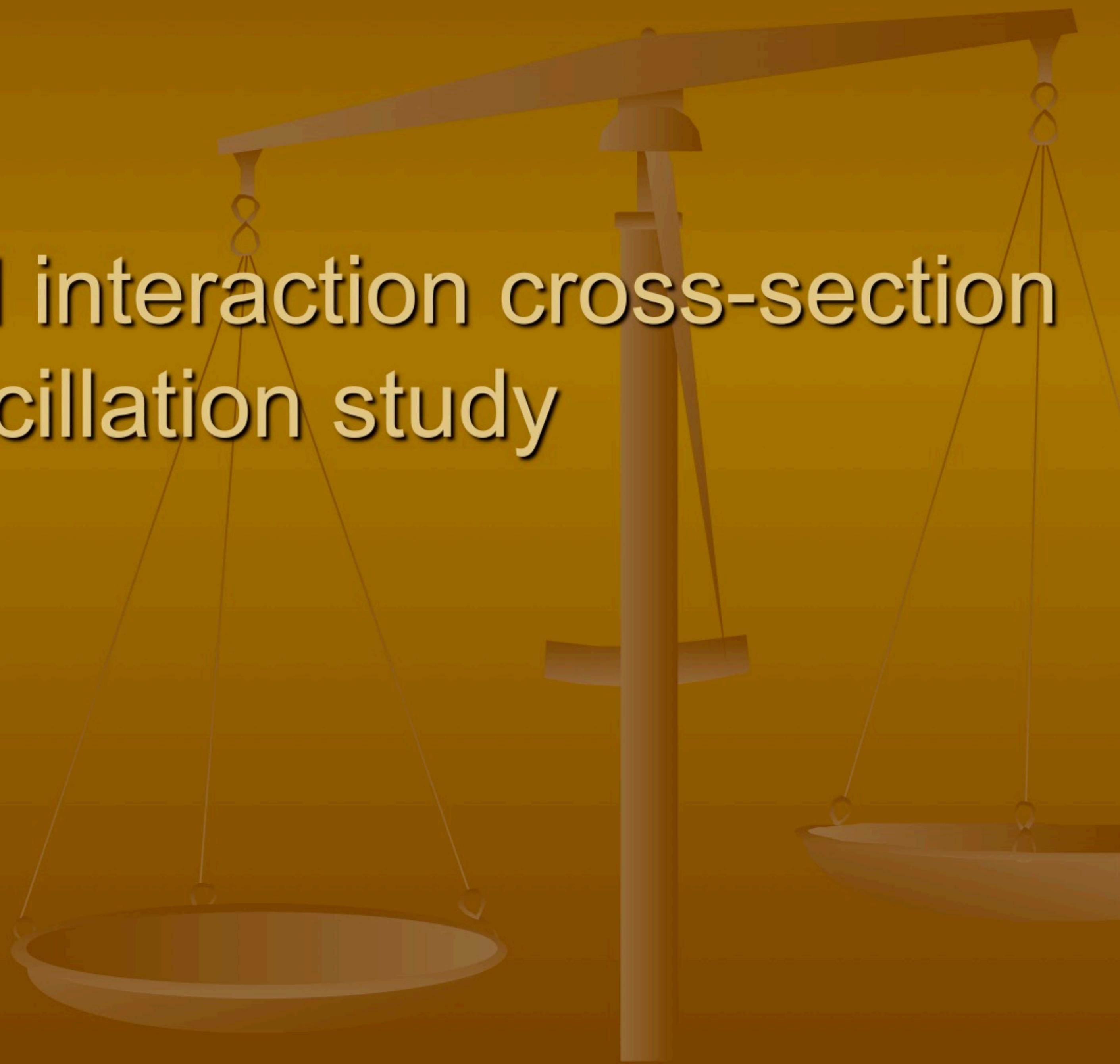


Overview of last decade

- ☒ 1960's - Solar neutrino problem - deficit of electron neutrinos
- ☒ 1980's - Atmospheric neutrino problem - deficit of muon neutrinos

- ☒ 1998 Discovery of neutrino oscillation (Super-Kamiokande)
- ☒ 2002 Flavor transition of solar neutrinos (SNO)
- ☒ 2003 Reactor neutrino disappearance (KamLAND)
- ☒ 2004 Evidence for oscillatory signature in atmospheric neutrinos (SK)
- ☒ 2005 Observation of oscillation in reactor neutrinos (KamLAND)
- ☒ 2005 Confirmation of muon neutrino oscillation by accelerator based neutrinos (K2K)
- ☒ 2007 No oscillation signal confirmed at $\Delta m^2 \sim 1\text{eV}^2$ scale (MiniBooNE)
- ☒ 2008 Deficit of ${}^7\text{Be}$ solar neutrinos by real time measurement (Borexino)
 - Precision measurement of neutrino oscillation parameters
 - "Atmospheric" neutrino oscillations at $\Delta m^2 \sim 3 \times 10^{-3}\text{eV}^2$ (SK+MINOS)
 - "Solar" neutrino oscillations at $\Delta m^2 \sim 8 \times 10^{-5}\text{eV}^2$ (KamLAND+solar exp's)

Neutrino flux and interaction cross-section in oscillation study



Oscillation study in wide energy range

■ Solar neutrinos (<20MeV)

Flux: Standard Solar Model (1~16% uncertainty)

Interaction: Elastic scattering $\nu_e + e^- \rightarrow \nu_e + e^-$ (~0.5%)

■ Reactor neutrinos (<10MeV)

Flux: Nuclear fission rate and $\bar{\nu}_e$ spectrum (~2%)

Interaction: Inverse β -decay $\bar{\nu}_e + p \rightarrow e^+ + n$ (~0.2%)

■ Atmospheric & beam ν (a few GeV)

Flux: Decay of secondary hadrons: $\pi \rightarrow \mu + \nu_\mu$

(10~20% mainly from hadron production spectra)

⇒ Up/down or FD/ND ratio cancels uncertainty.

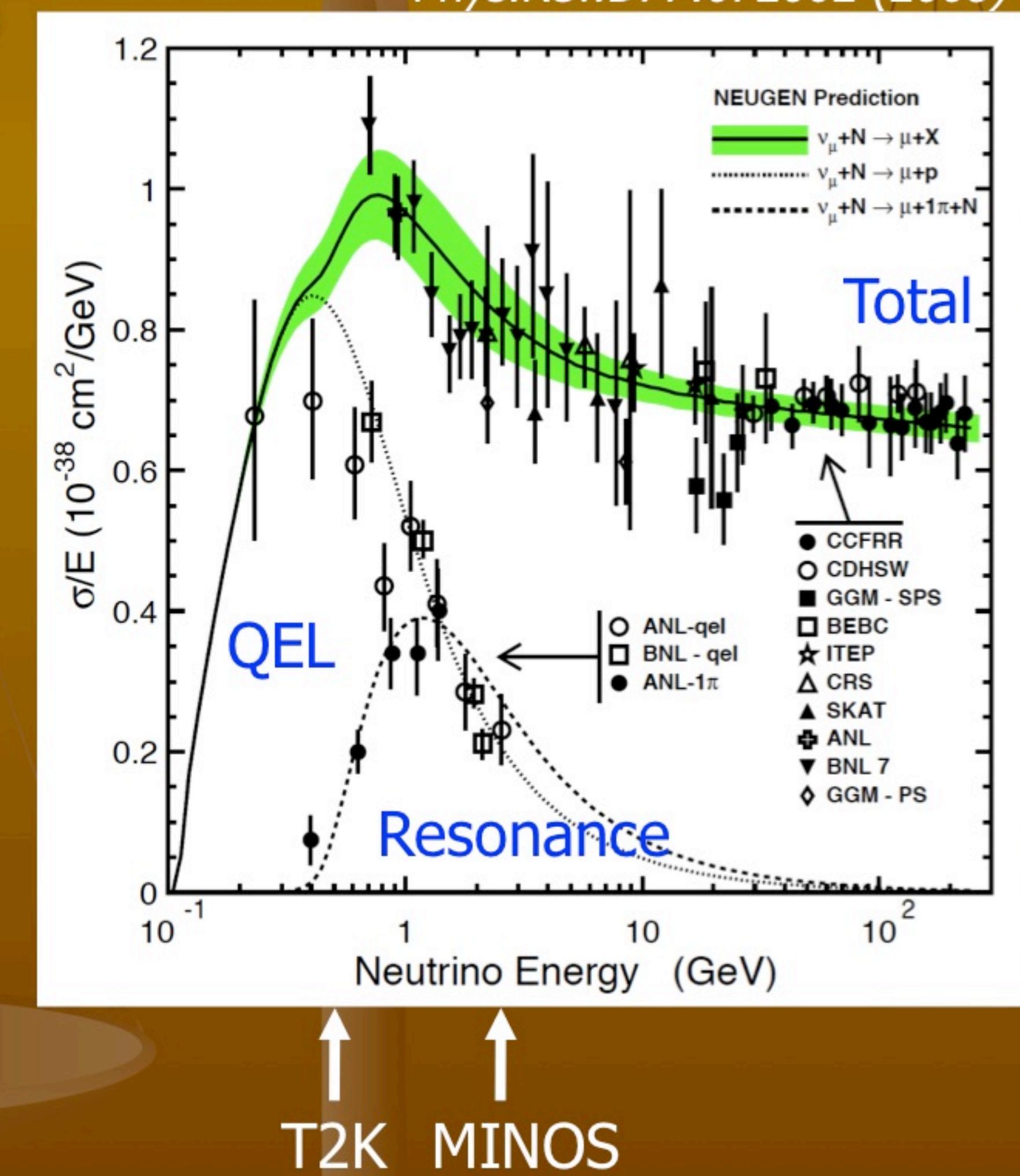
⇒ Measurement of hadron production cross-section by HARP, NA49, MIPP....

Interaction: $\nu + N$ by Quasi-Elastic/Resonance/DIS
(10~20% at a few GeV region)

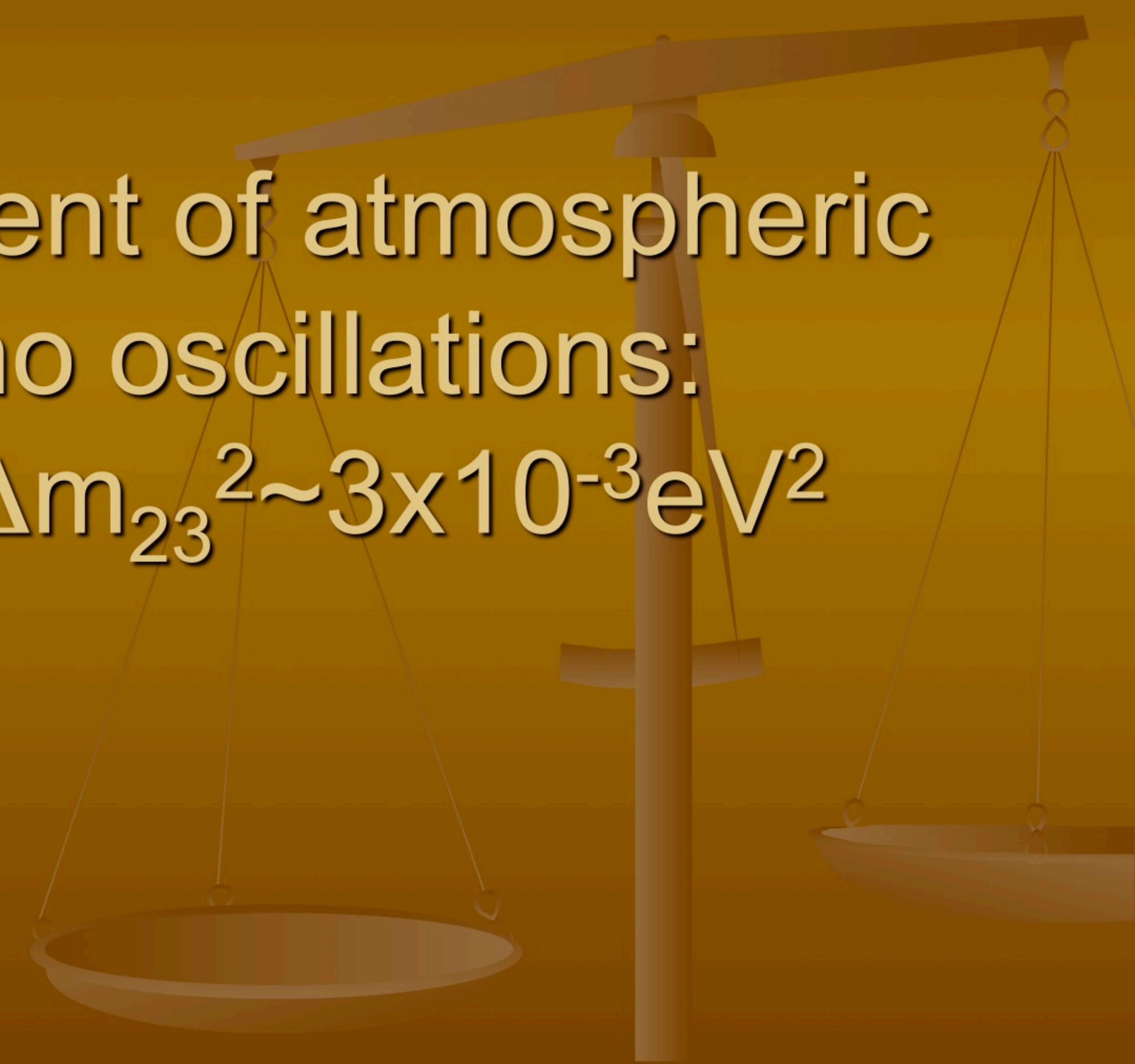
⇒ Up/down or FD/ND ratio cancels uncertainty.

⇒ Measurement of neutrino interaction by K2K ND,
SciBooNE, MINOS ND, MINERvA, T2K ND....

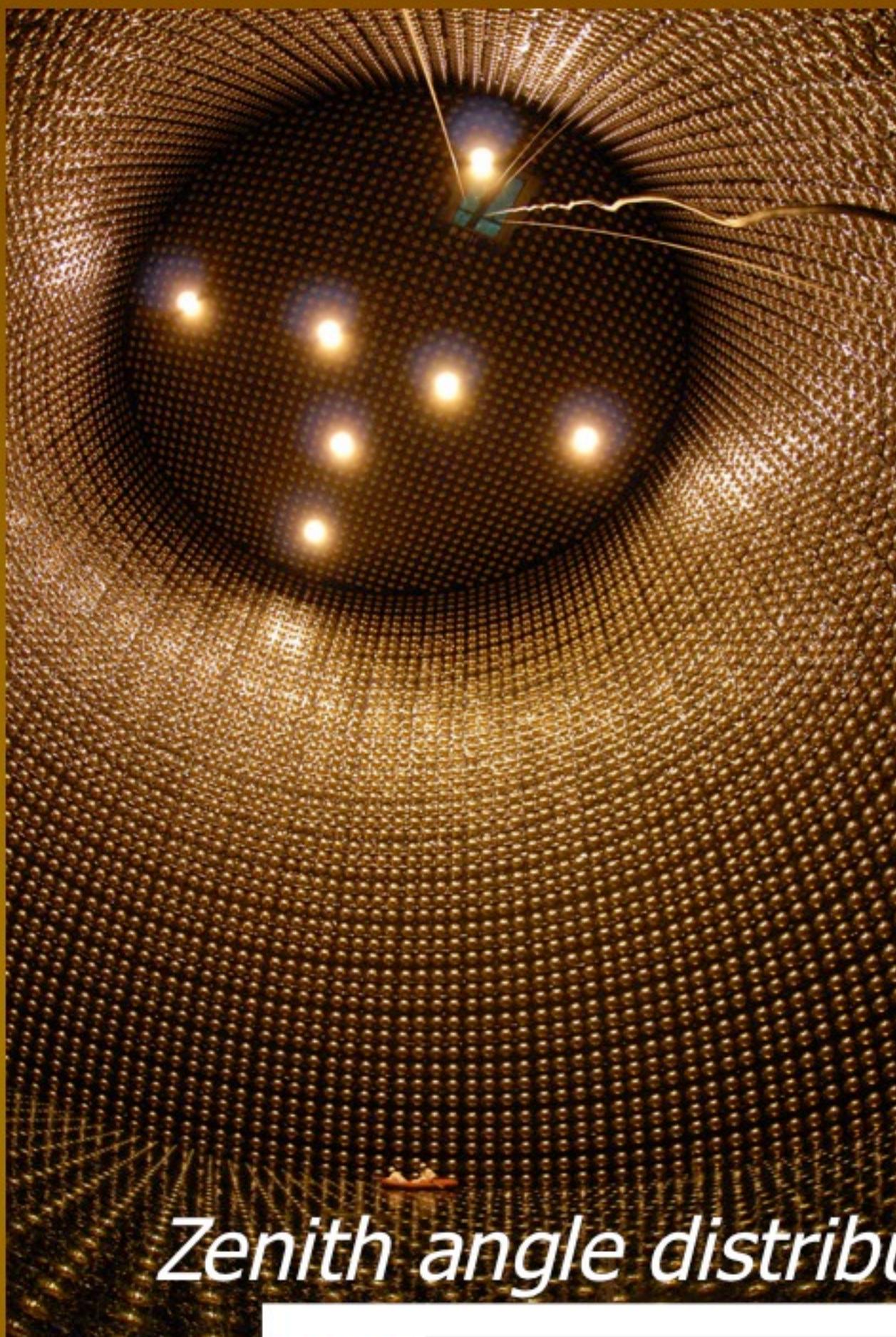
ν_μ CC cross-section in MINO MC
Phys.Rev.D77:072002 (2008)



Measurement of atmospheric neutrino oscillations: θ_{23} and $\Delta m_{23}^2 \sim 3 \times 10^{-3} \text{ eV}^2$



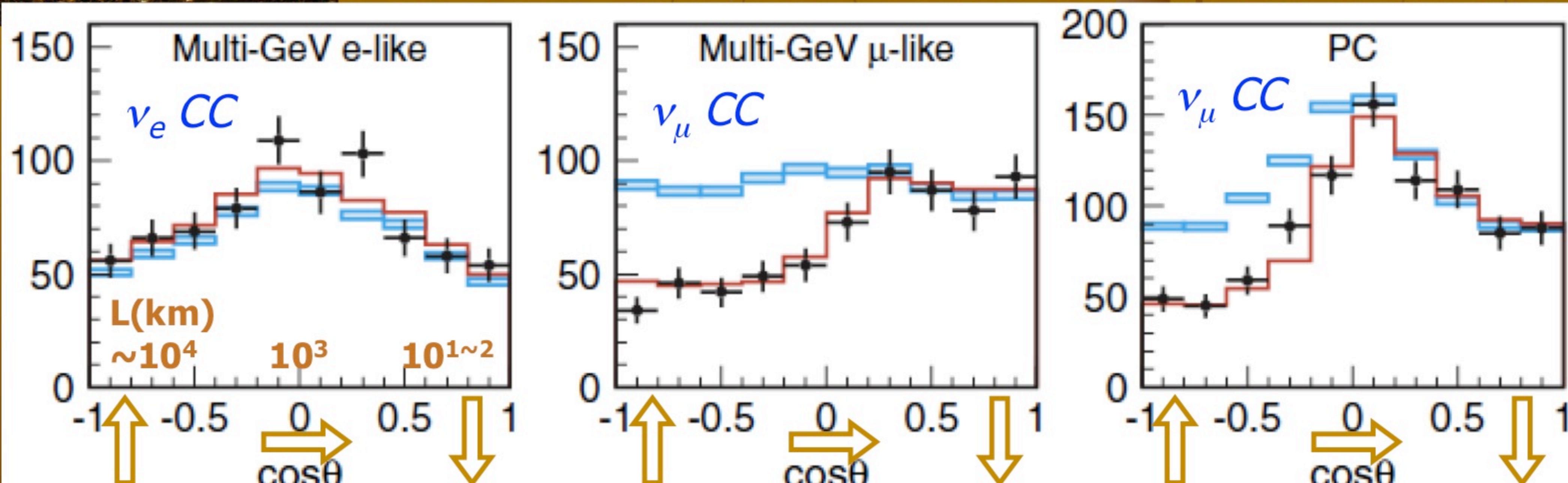
Discovery by Super-Kamiokande



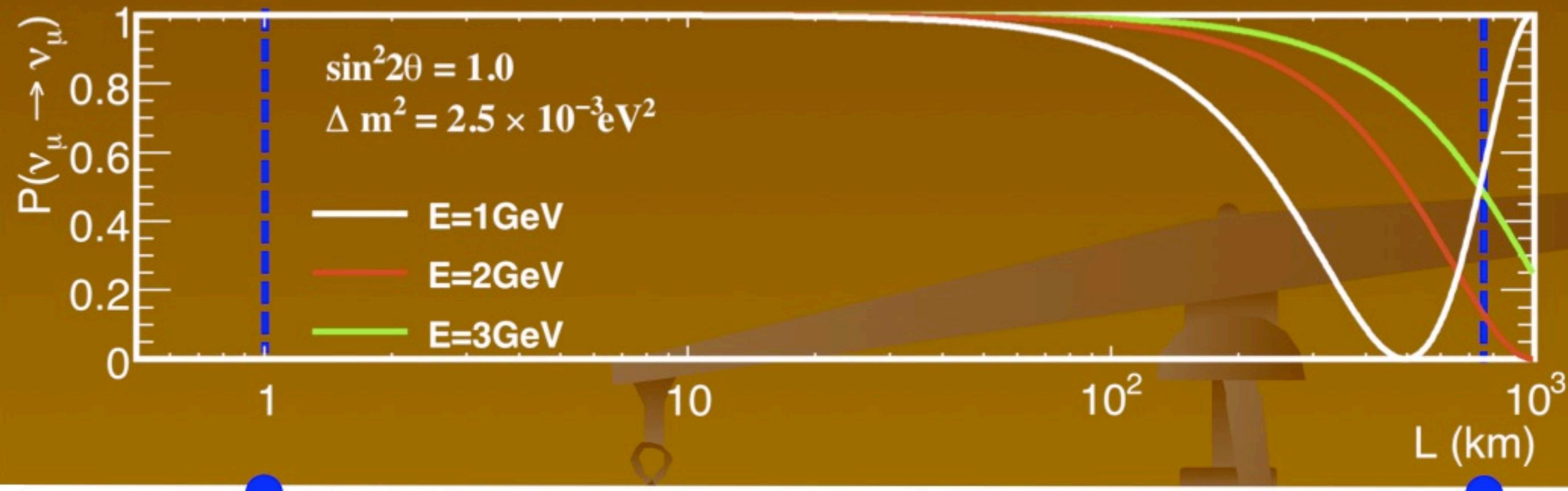
- 50kton water Cherenkov detector
- Located 2700m.w.e. underground to suppress cosmic μ background
- 20 inch PMT \times 11146 (40% coverage)
- μ/e PID ($>99\%$) by ring pattern
- Multi-purpose detector:
Atmospheric neutrinos, solar neutrinos, proton decay, supernova & relic neutrinos, far detector for K2K&T2K

Zenith angle distributions of SK-I atmospheric neutrino data

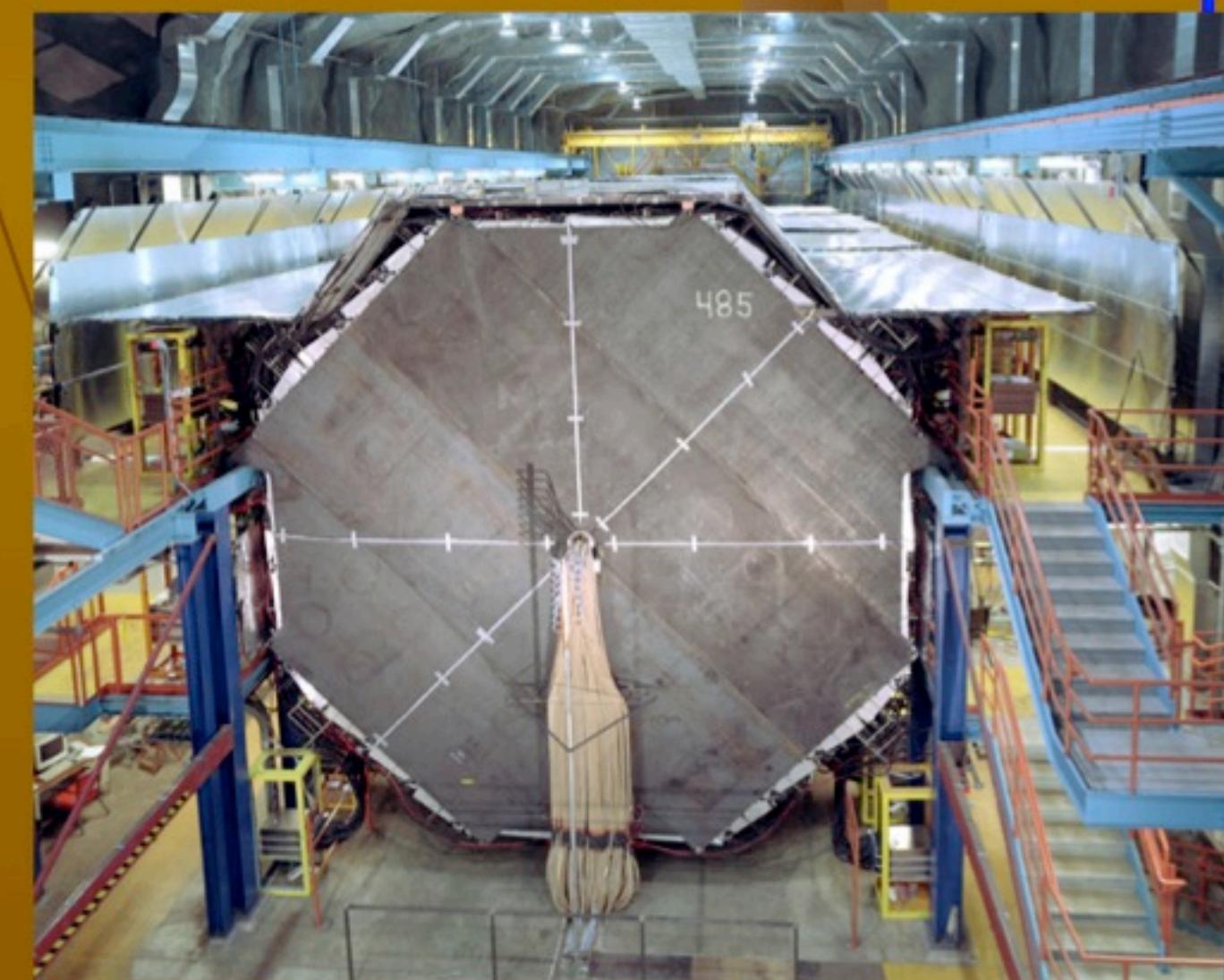
Phys.Rev.D71:112005 (2005)



Precise measurement by MINOS long-baseline experiment



- ✓ Intense muon neutrino beam from Fermilab Main Injector

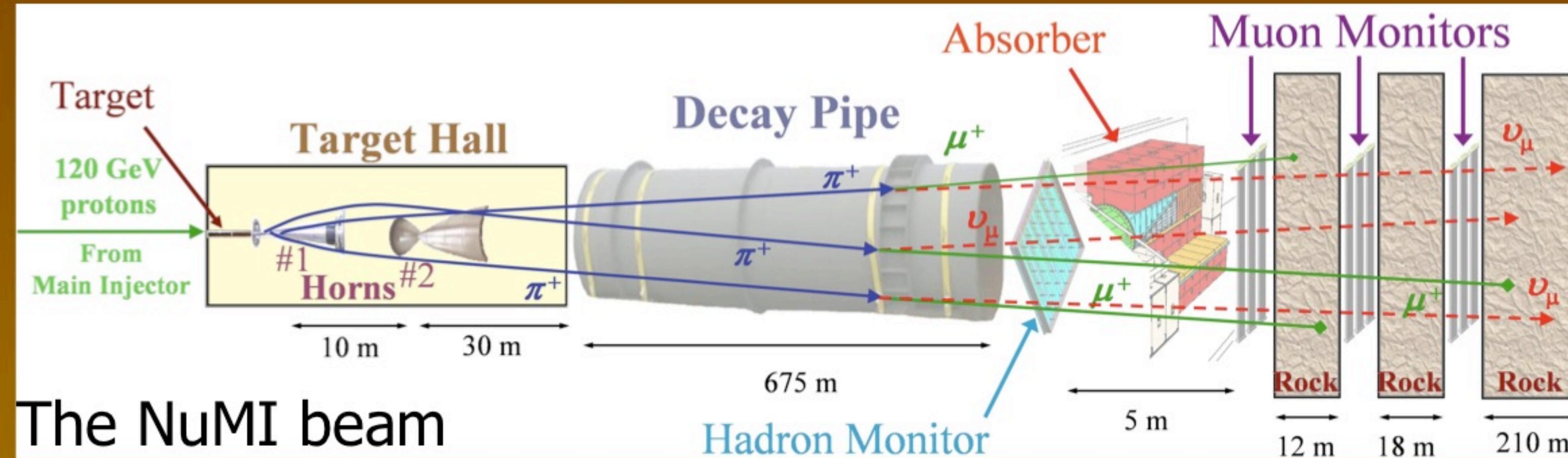


- ✓ Near detector at Fermilab to measure unoscillated energy spectrum

✓ Two detectors are based on the same target material and technology.
→ Systematic errors on neutrino flux, interaction cross-section and detector effects are strongly canceled by the comparison.

- ✓ Far detector measures neutrino energy spectrum after oscillation at Soudan mine

Creation of neutrino beam for MINOS



Making a pure muon neutrino beam

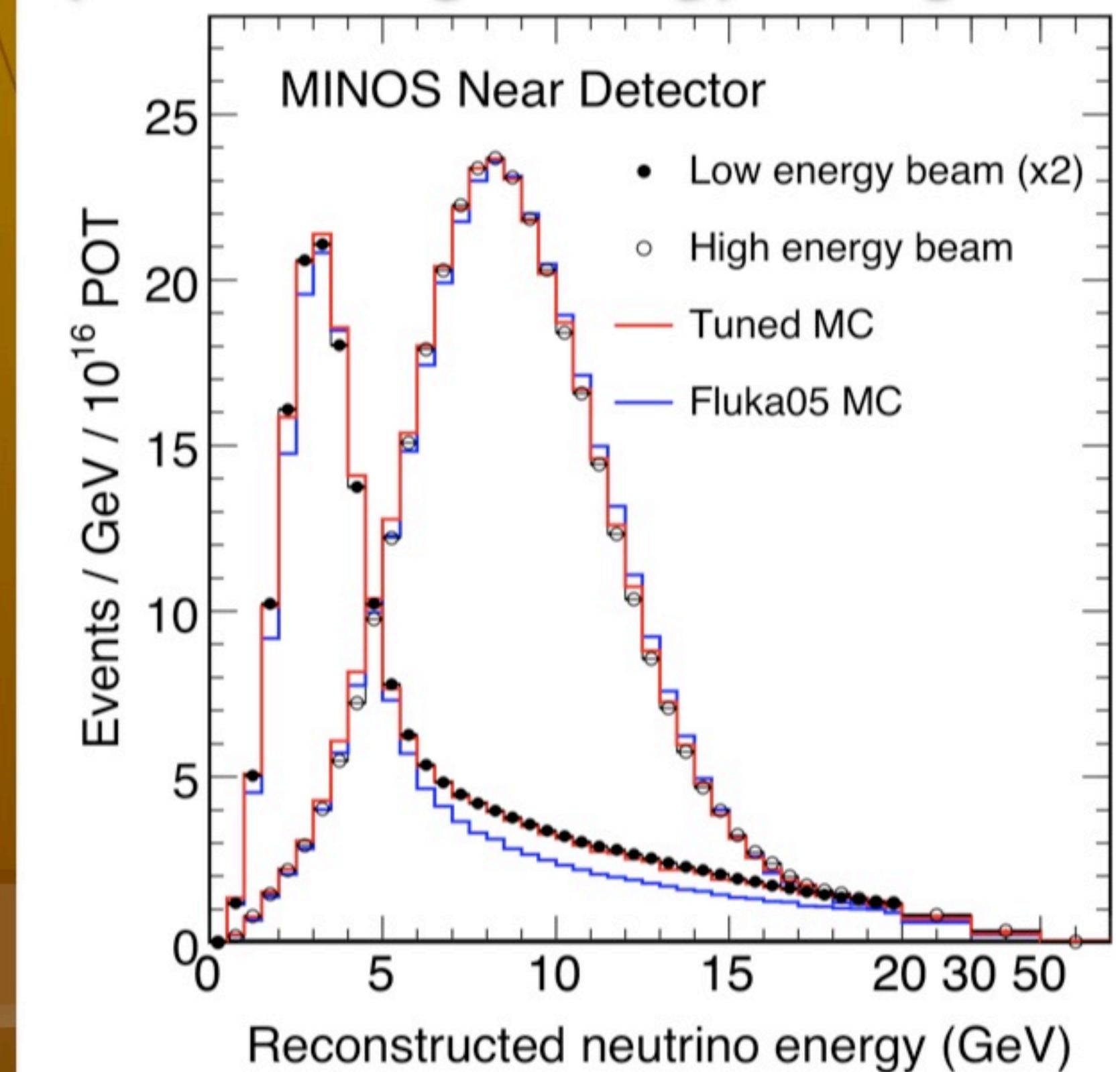
1. p+N interactions in target.
2. Focusing secondary π 's and K's.
3. Decay in evacuated pipe: $\pi \rightarrow \mu + \nu_\mu$.
4. Absorption of μ 's in downstream rock.
5. Muon neutrinos aim to far detector

- NuMI beam -

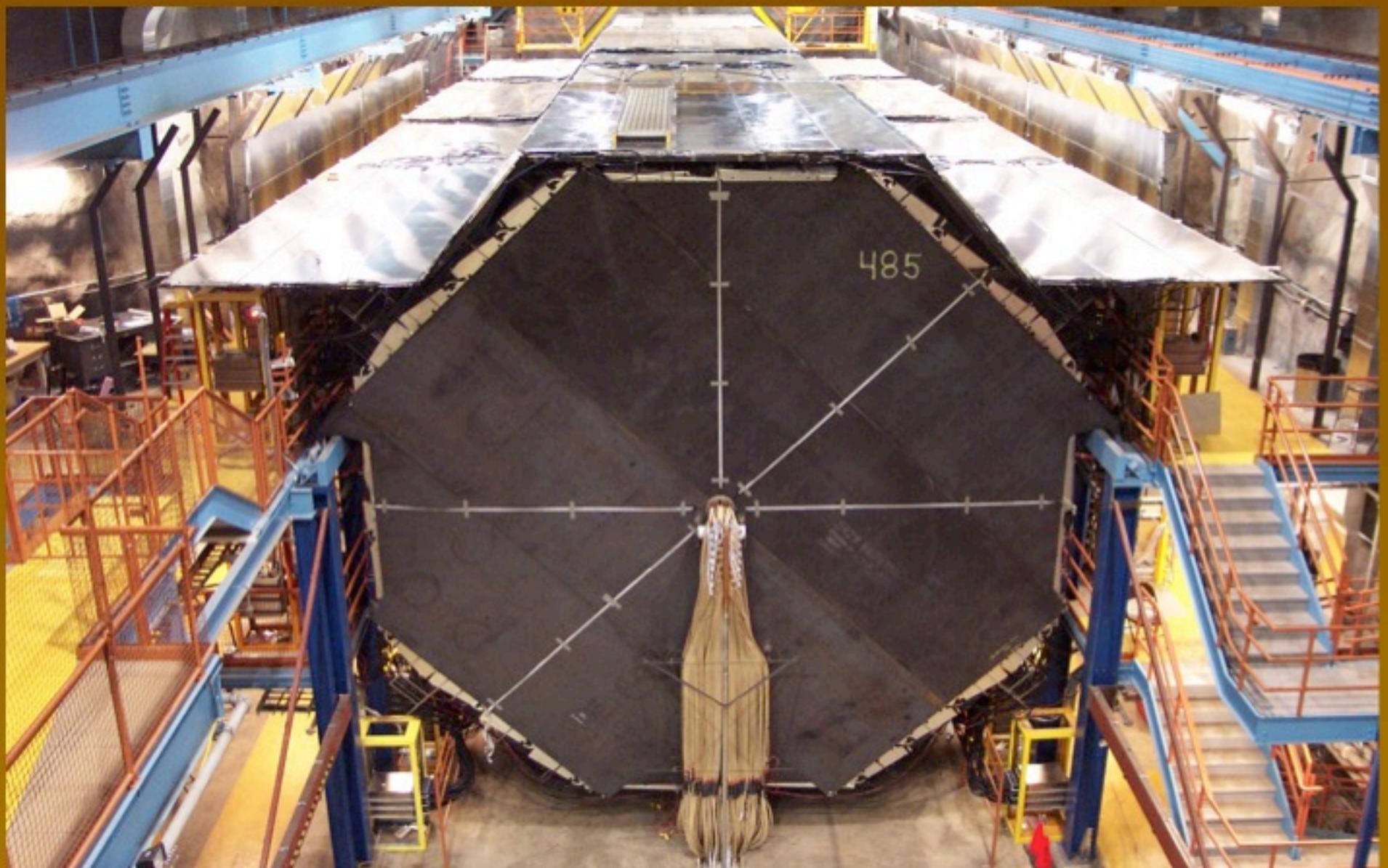
- 10 μ s spill of 120 GeV protons every 2.2 s.
- Intensity: 3×10^{13} POT/spill, 10^{18} POT/day.
- Relative target position to focusing horns determine the typical neutrino energy.
 ⇒ Tunable neutrino energy spectrum.
 ⇒ Hadron production tuning by ND data.

Phys.Rev.Lett.101:131802 (2008)

*Measured spectrum at near detector
(Low and high energy configurations)*



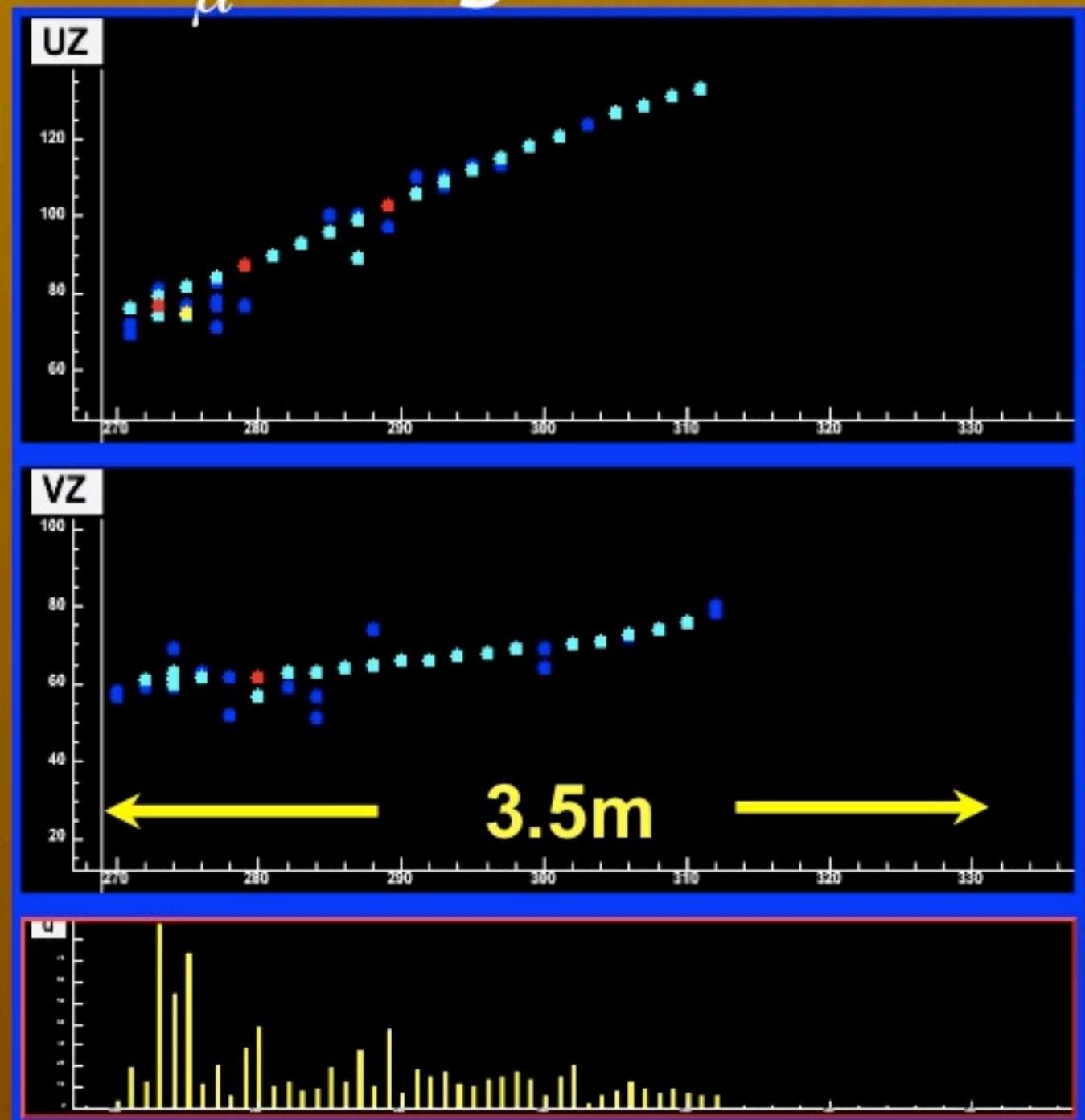
Neutrino interactions in MINOS detector



Iron and scintillator tracking calorimeter

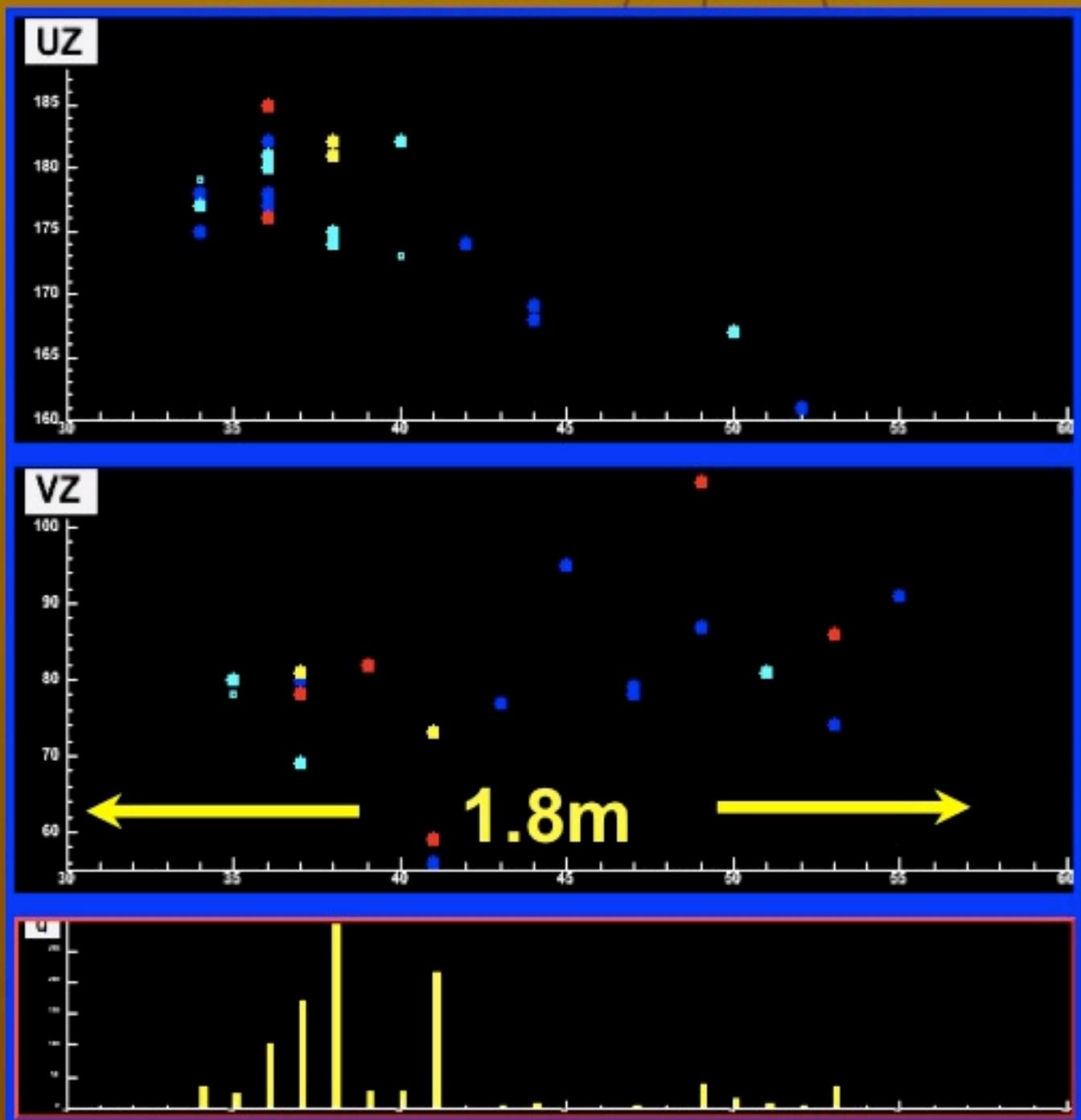
- 5.4kton (8x8x30m³) with 4.2kton fiducial vol.
- 484 steel/scintillator planes
- Magnetized steel planes: B~1.3T
- 1cmx4.1cm cross-section scintillator strips
- Readout by multi-anode PMT
- GPS time-stamping to synch FD/ND/Beam

ν_μ charged-current



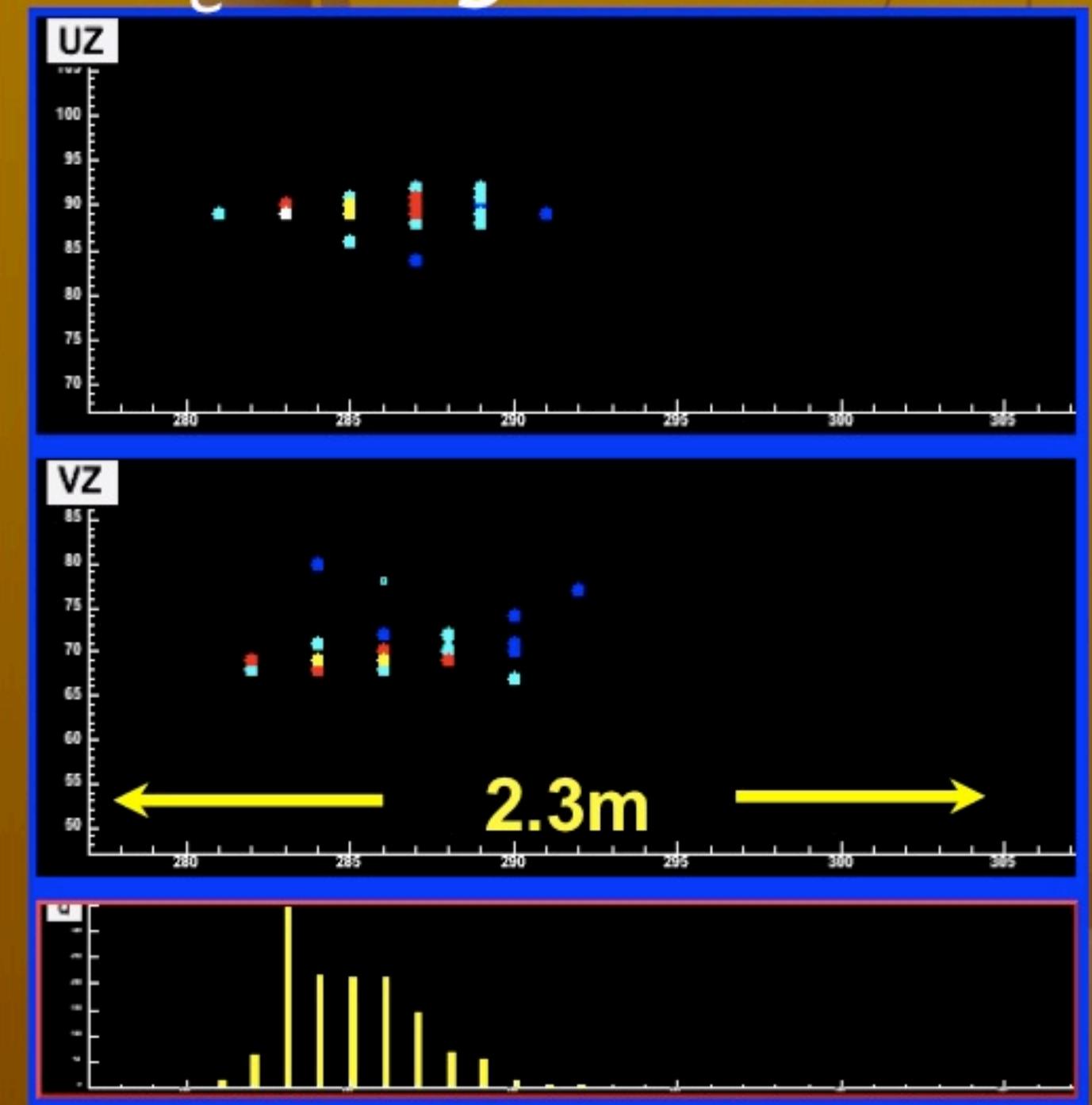
long μ track + hadronic activity at vertex

Neutral-current



short event, often diffuse

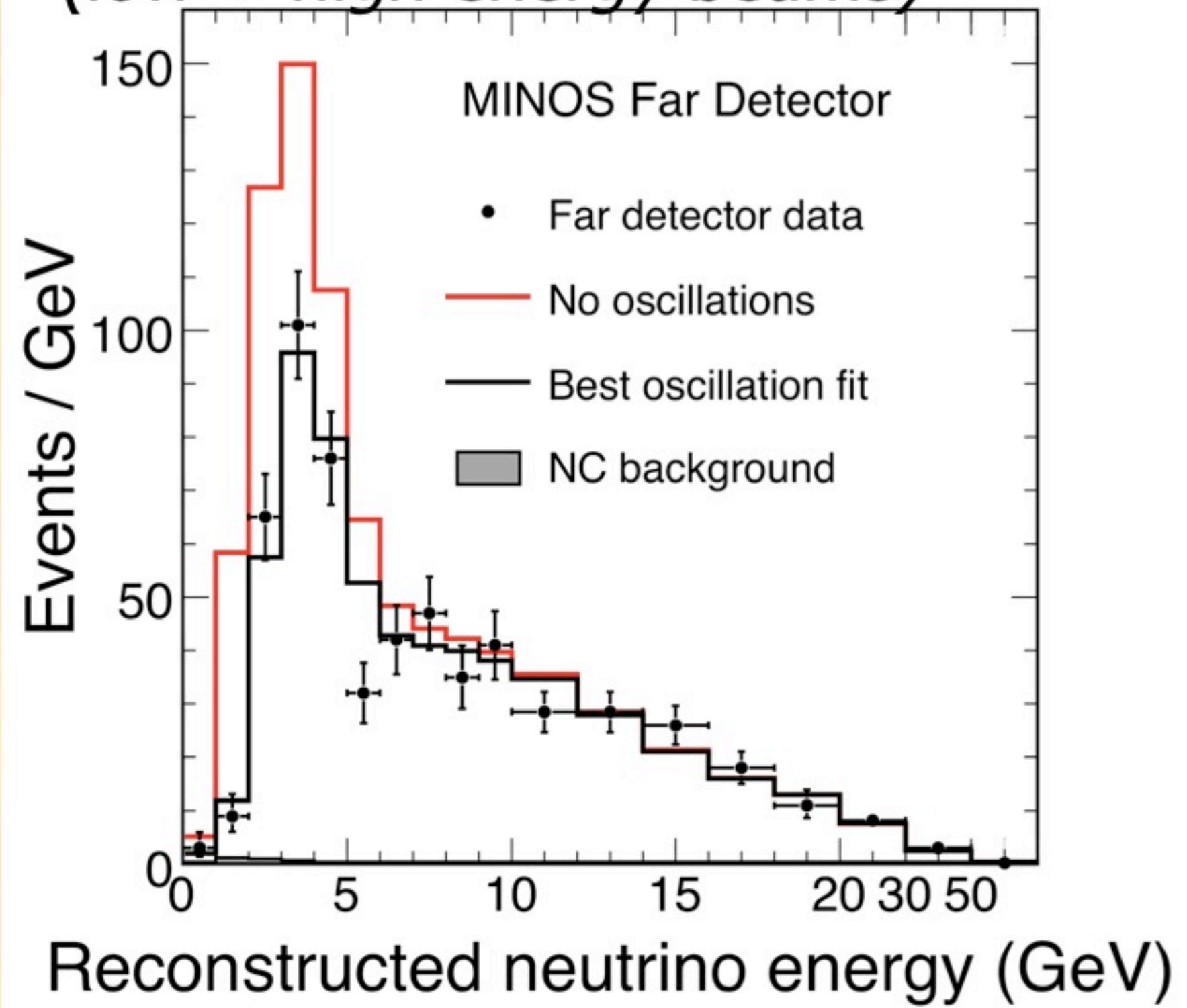
ν_e charged-current



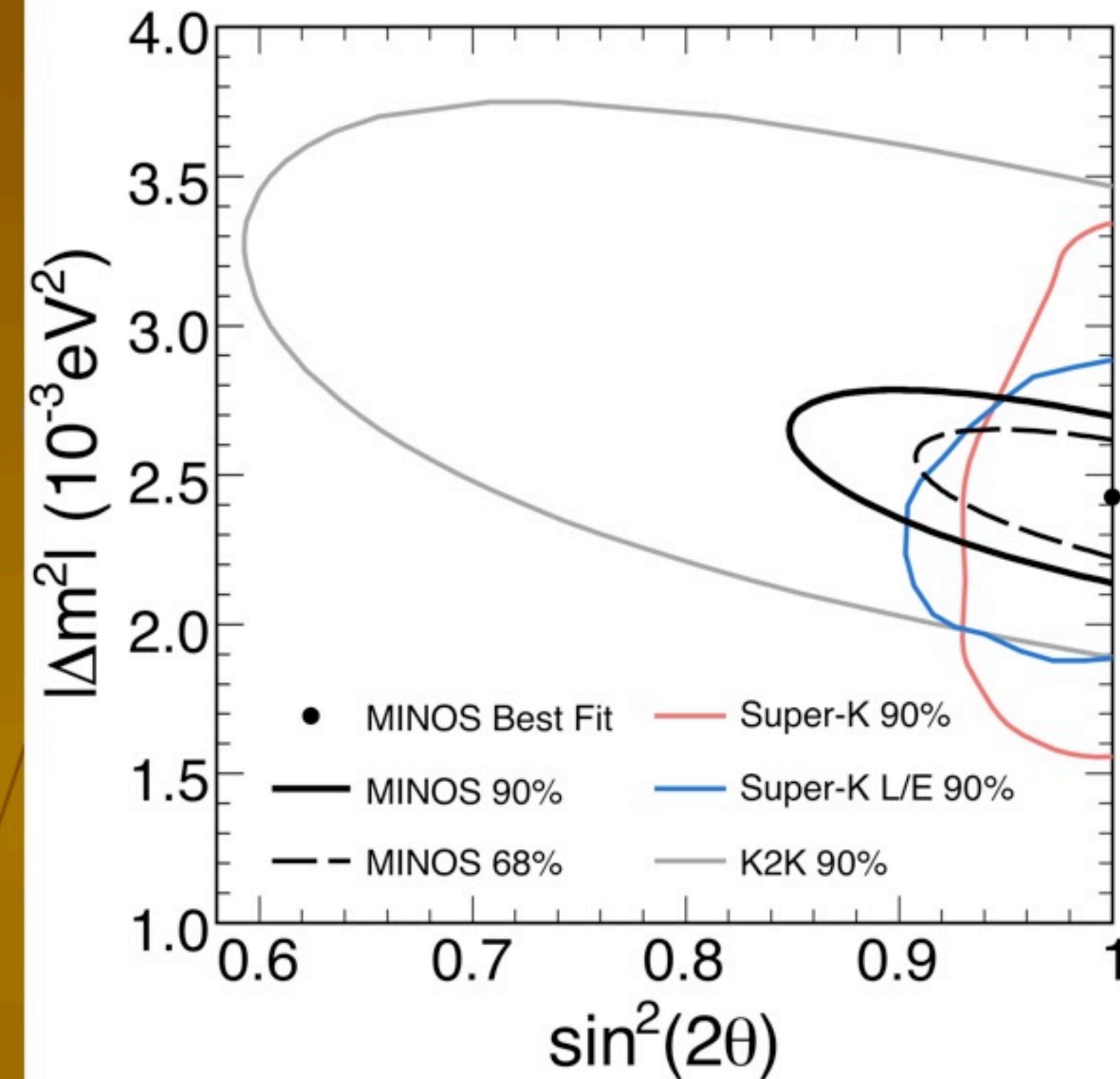
short, with typical EM shower profile

Results from MINOS ν_μ CC Analysis

*Measured energy spectrum at FD
(low + high energy beams)*



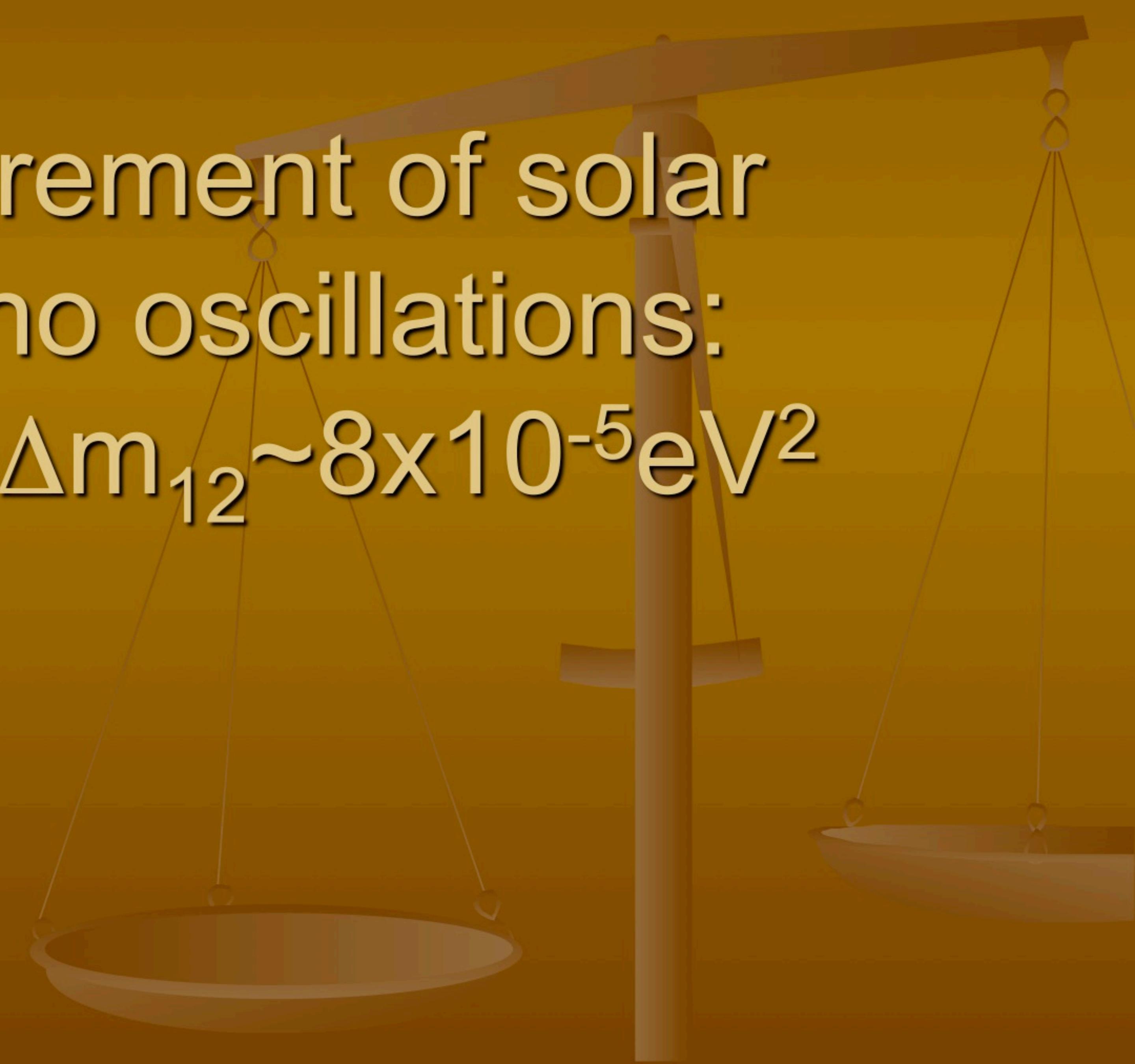
Allowed oscillation parameters region



- Significant deficit of ν_μ events: 848 events observed compare to 1065 ± 60 (syst.) expected without oscillation.
- Spectrum distortion was observed as predicted from neutrino oscillation.
- Data is consistent with $\nu_\mu \rightarrow \nu_\tau$ two flavor oscillation, and with SK and K2K.

$$|\Delta m_{23}^2| = (2.43 \pm 0.13) \times 10^{-3} \text{ eV}^2 \quad (68\% \text{ C.L.})$$

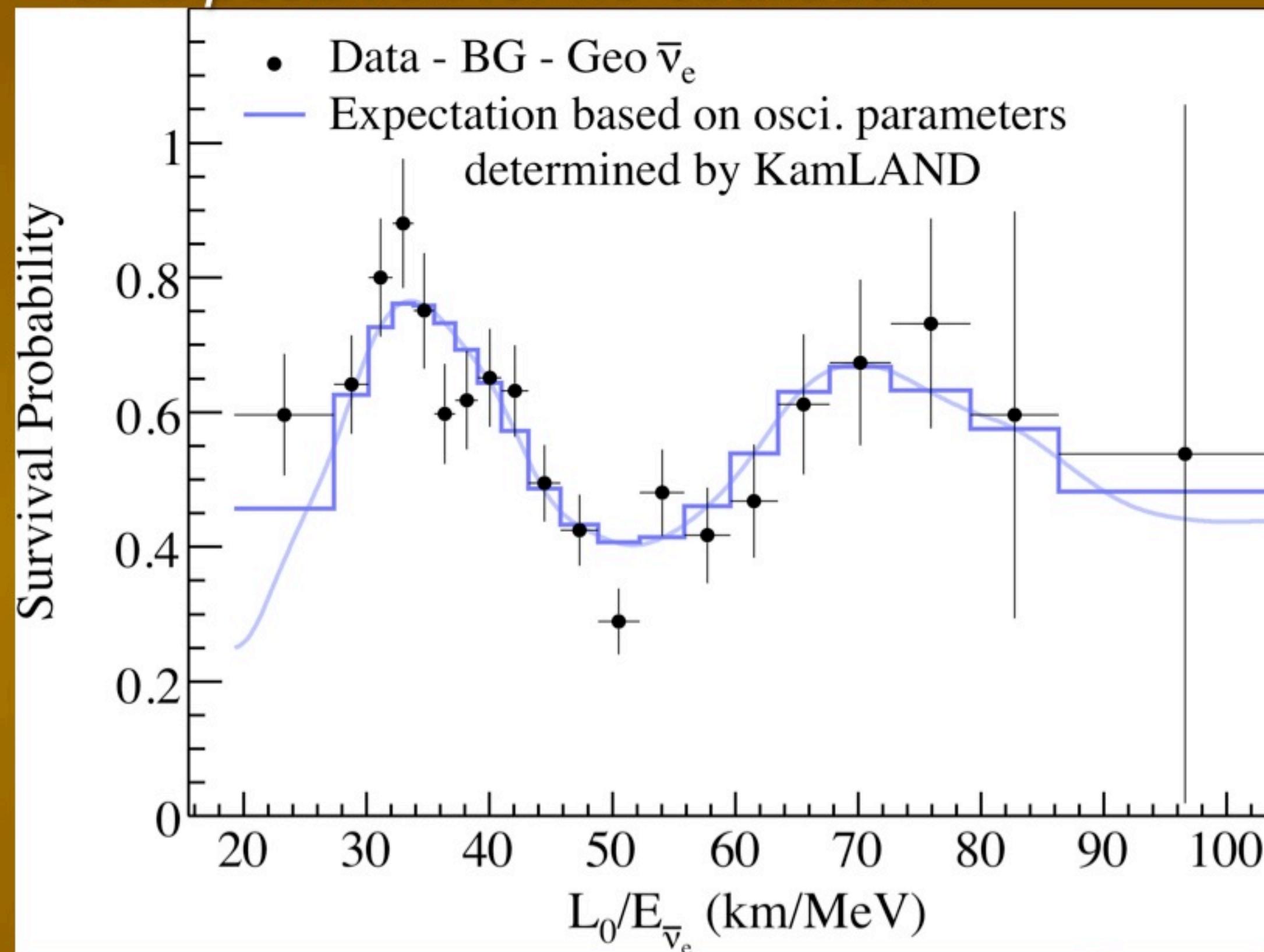
$$\sin^2 2\theta_{23} > 0.90 \quad (90\% \text{ C.L.})$$



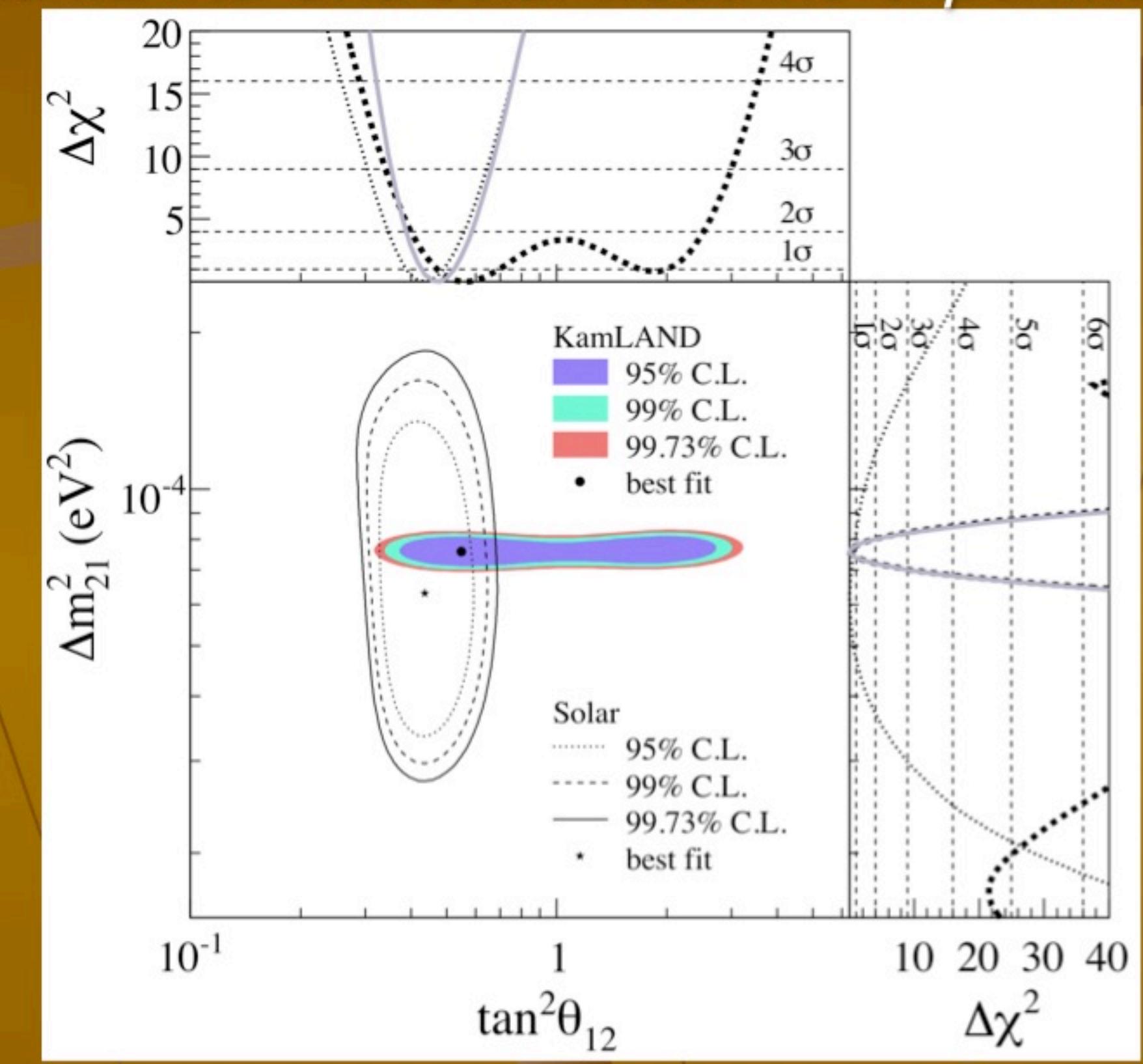
Measurement of solar neutrino oscillations: θ_{12} and $\Delta m_{12} \sim 8 \times 10^{-5} \text{ eV}^2$

Precise measurement by KamLAND and solar ν experiments

Ratio of measured anti-neutrino spectrum to expectation for no-oscillation



Allowed oscillation parameters region from KamLAND and solar neutrino experiments

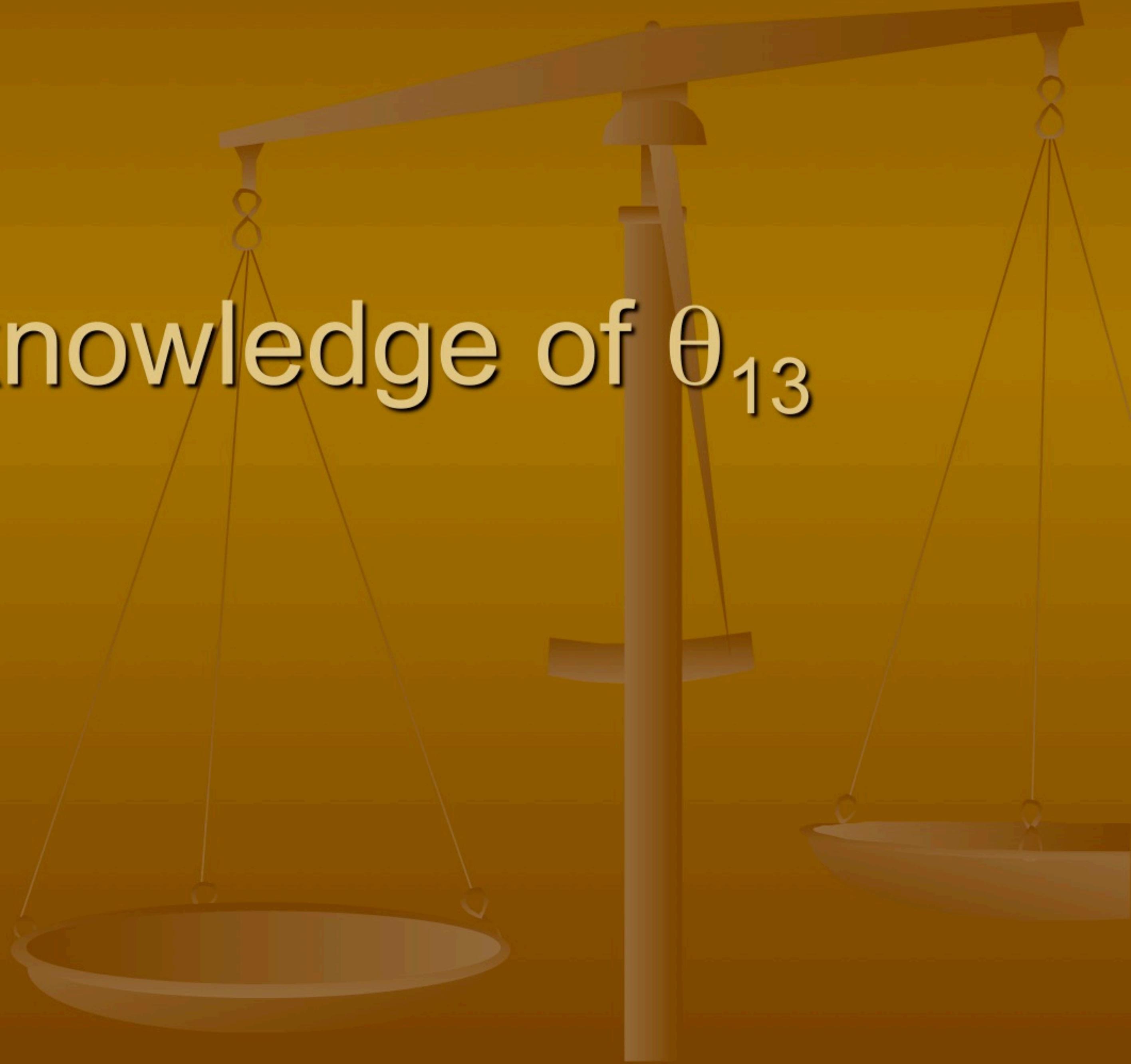


- Oscillation pattern observed in reactor neutrinos by KamLAND.
- Position of oscillation maximum provides precision measurement of Δm^2 .
- Global analysis of KamLAND and solar neutrino experiments:

$$\Delta m_{21}^2 = 7.59^{+0.21}_{-0.21} \times 10^{-5} \text{ eV}^2$$

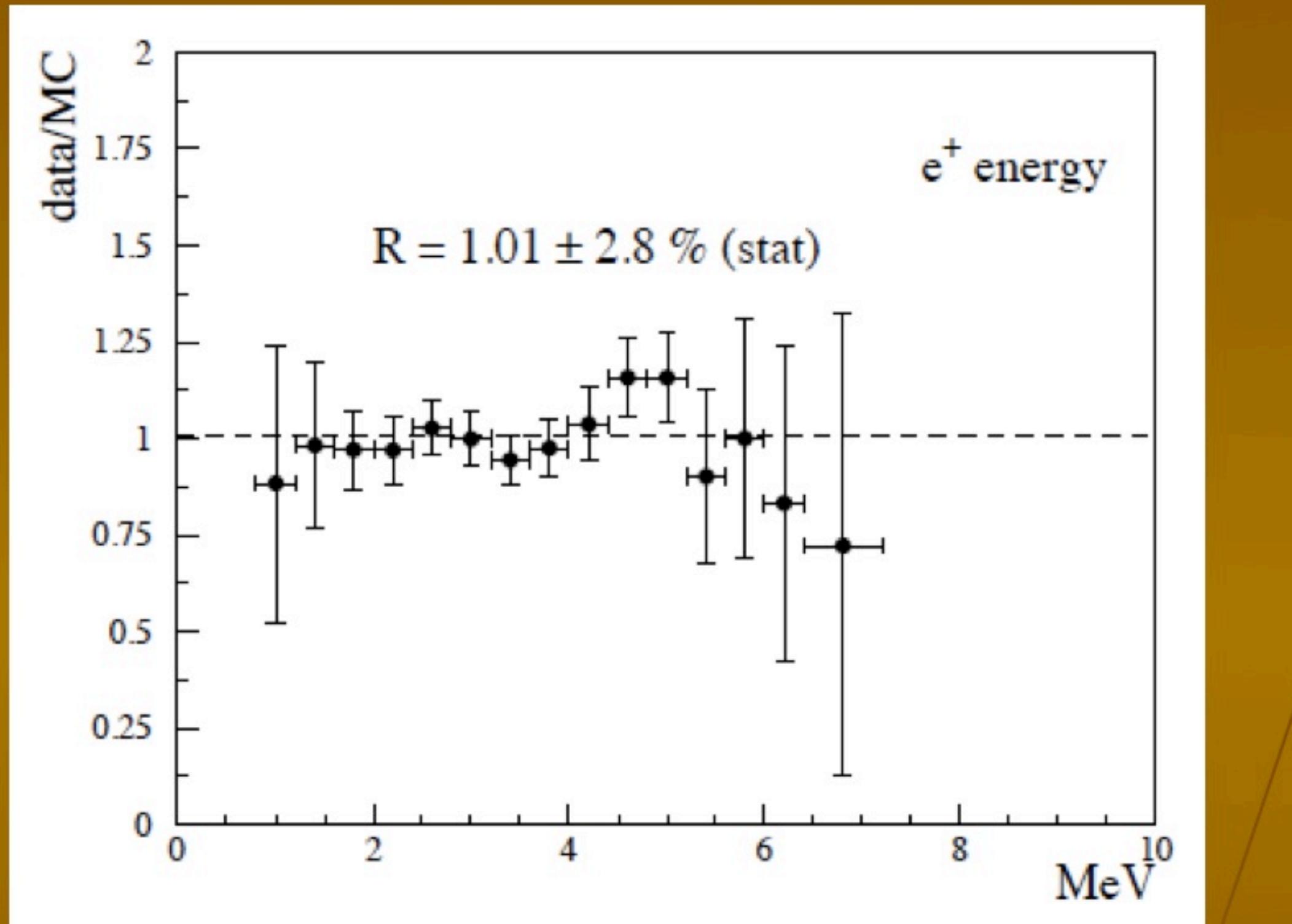
$$\tan^2 \theta_{12} = 0.47^{+0.06}_{-0.05}$$

Current knowledge of θ_{13}

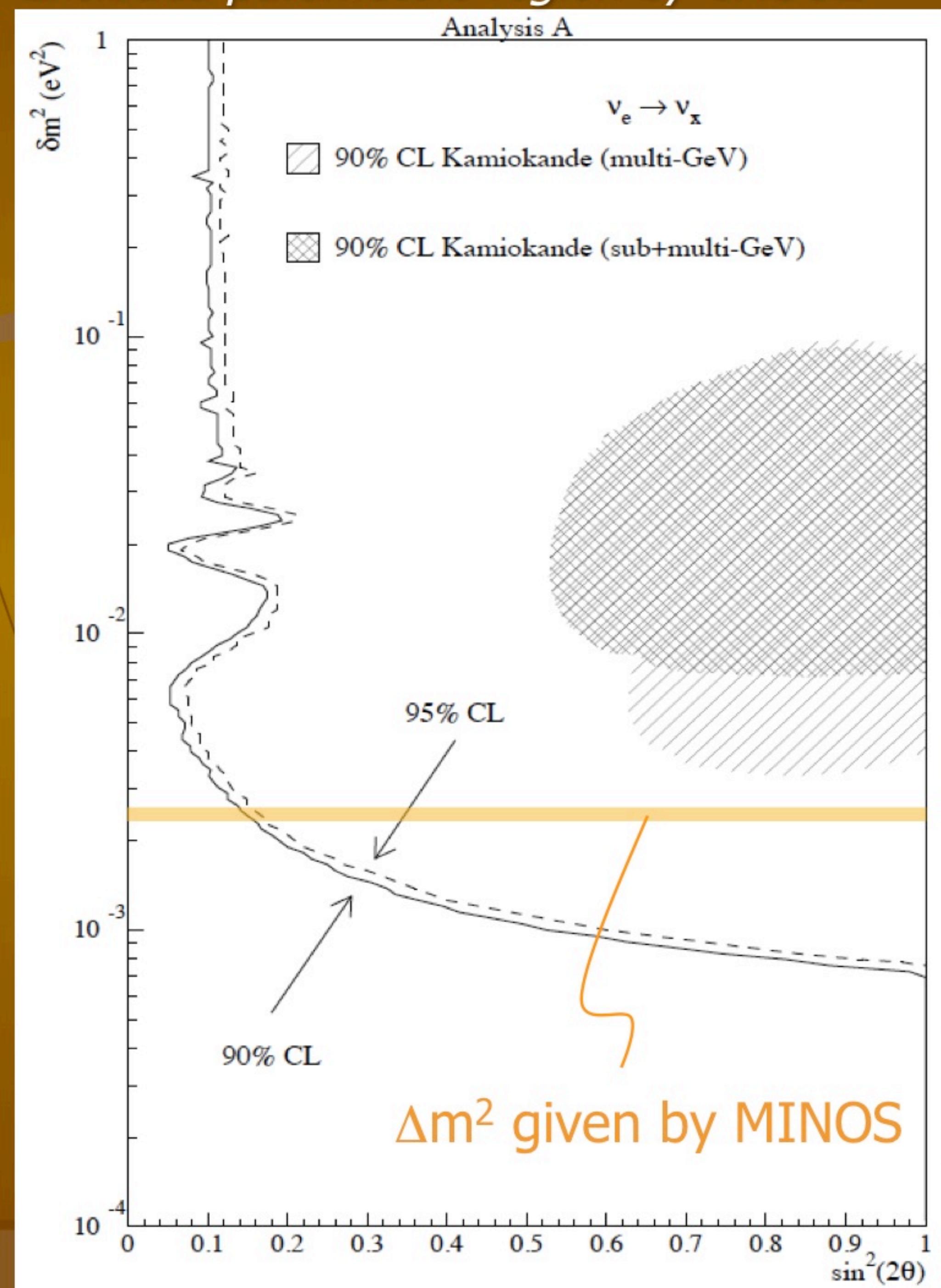


Best limit given by CHOOZ reactor ν experiment

Ratio of data to MC prediction as a function of reconstructed energy (CHOOZ)



Excluded parameters region by CHOOZ



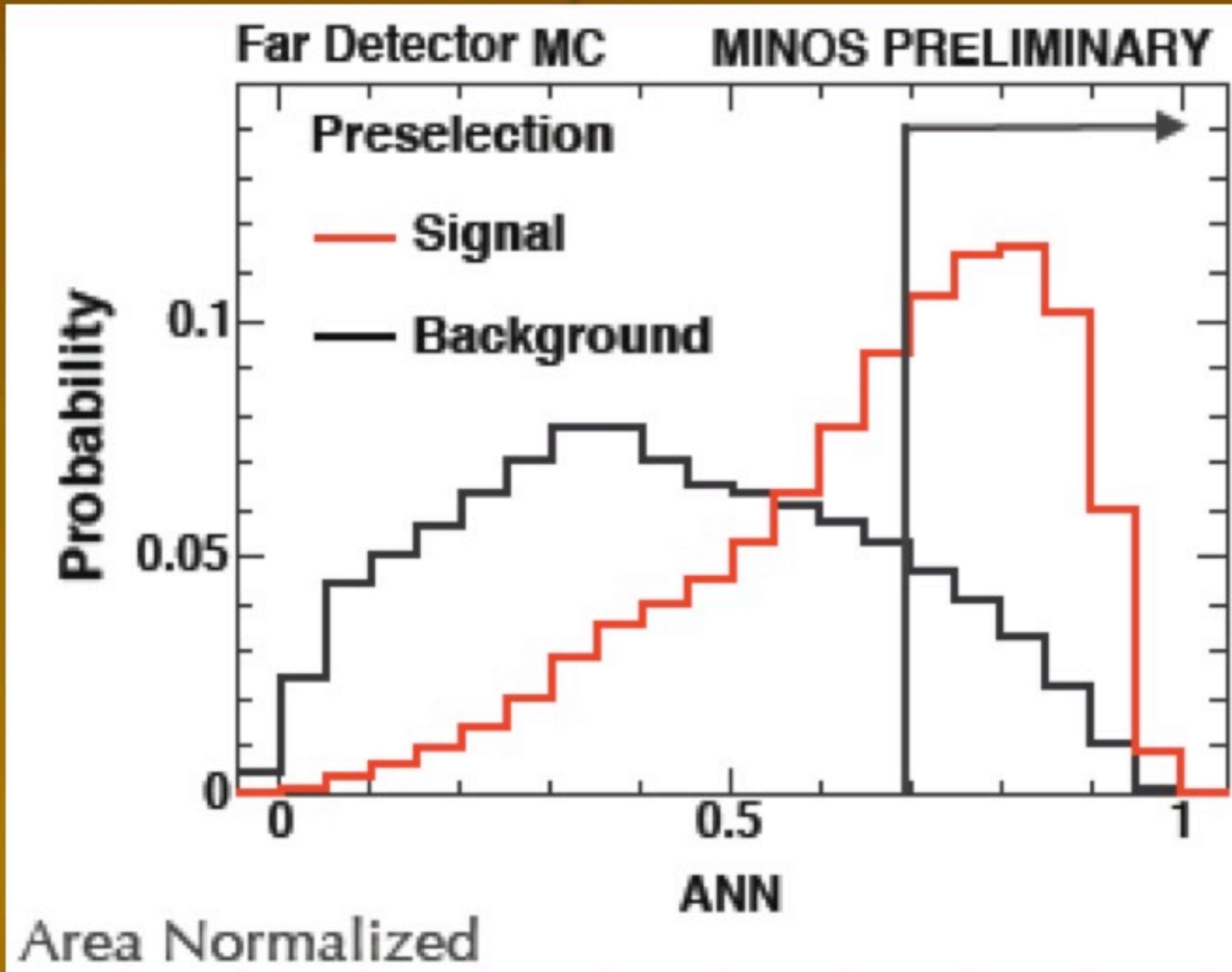
- Observed reactor neutrino data at a distance of 1km was consistent with no oscillation prediction.
- Current best limit to θ_{13} mixing angle is given by CHOOZ:

$$\sin^2 2\theta_{13} < 0.15 \quad (\text{for } \Delta m^2 \sim 2.5 \times 10^{-3} \text{ eV}^2)$$

Search for ν_e appearance signal in MINOS

From slide by M. Sanchez at FNAL Joint Experimental-Theoretical Physics Seminar

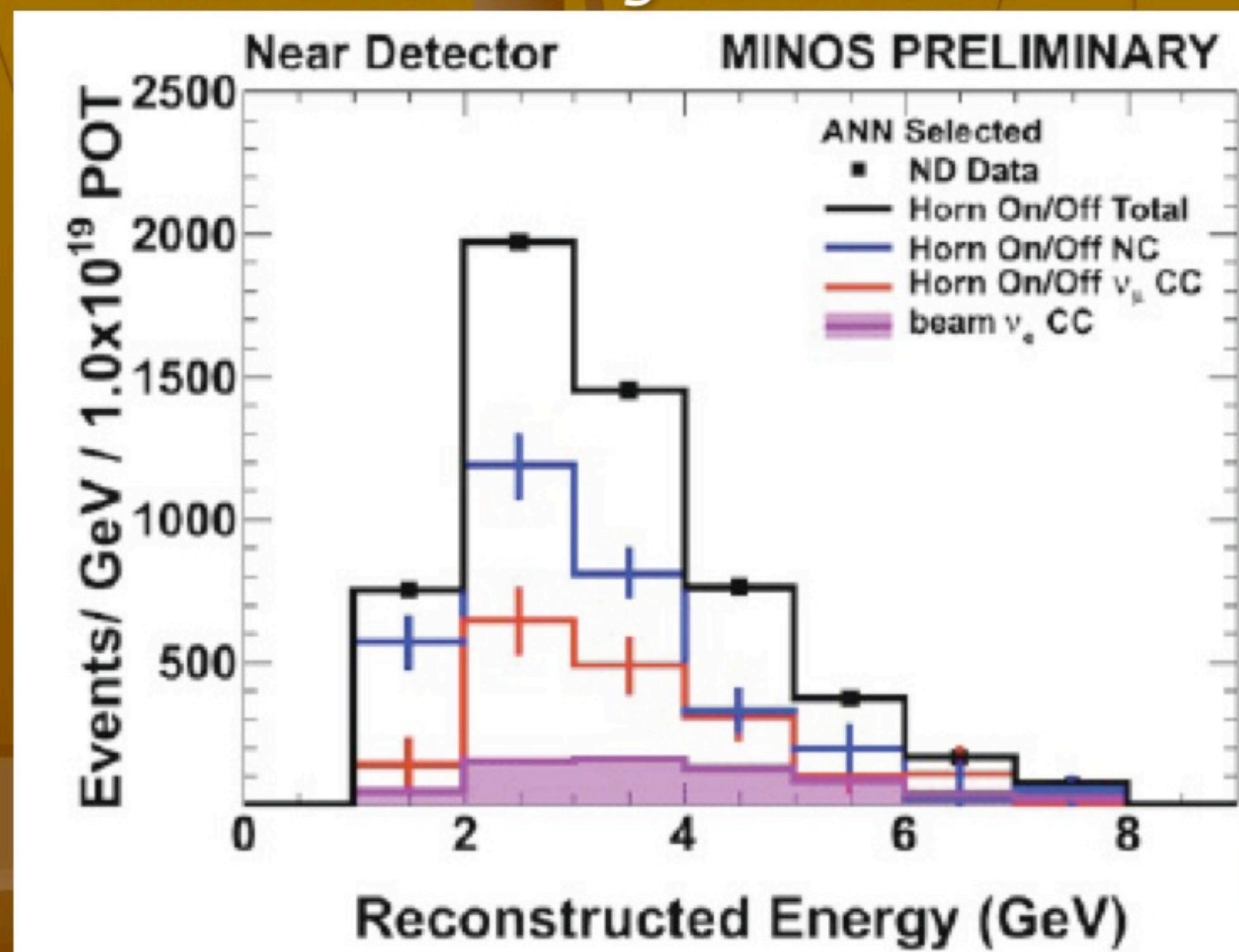
PID estimator by ANN



- Search for $\nu_\mu \rightarrow \nu_e$ oscillation as a consequence of non-zero θ_{13}
- ν_e candidate selection by ANN based on event length, width and shower shape.
 - Signal efficiency 41%
 - NC rejection >92.3%
 - ν_μ CC rejection >99.4%

Data-driven background at ND

- Measurement at near detector is extrapolated to predict background spectrum at far detector.
- Data-driven technique to estimate BG.
 - Comparison of two beam configurations.
 - Study of hadron shower in ν_μ CC events.
- Blind analysis at far detector after study using sideband data.

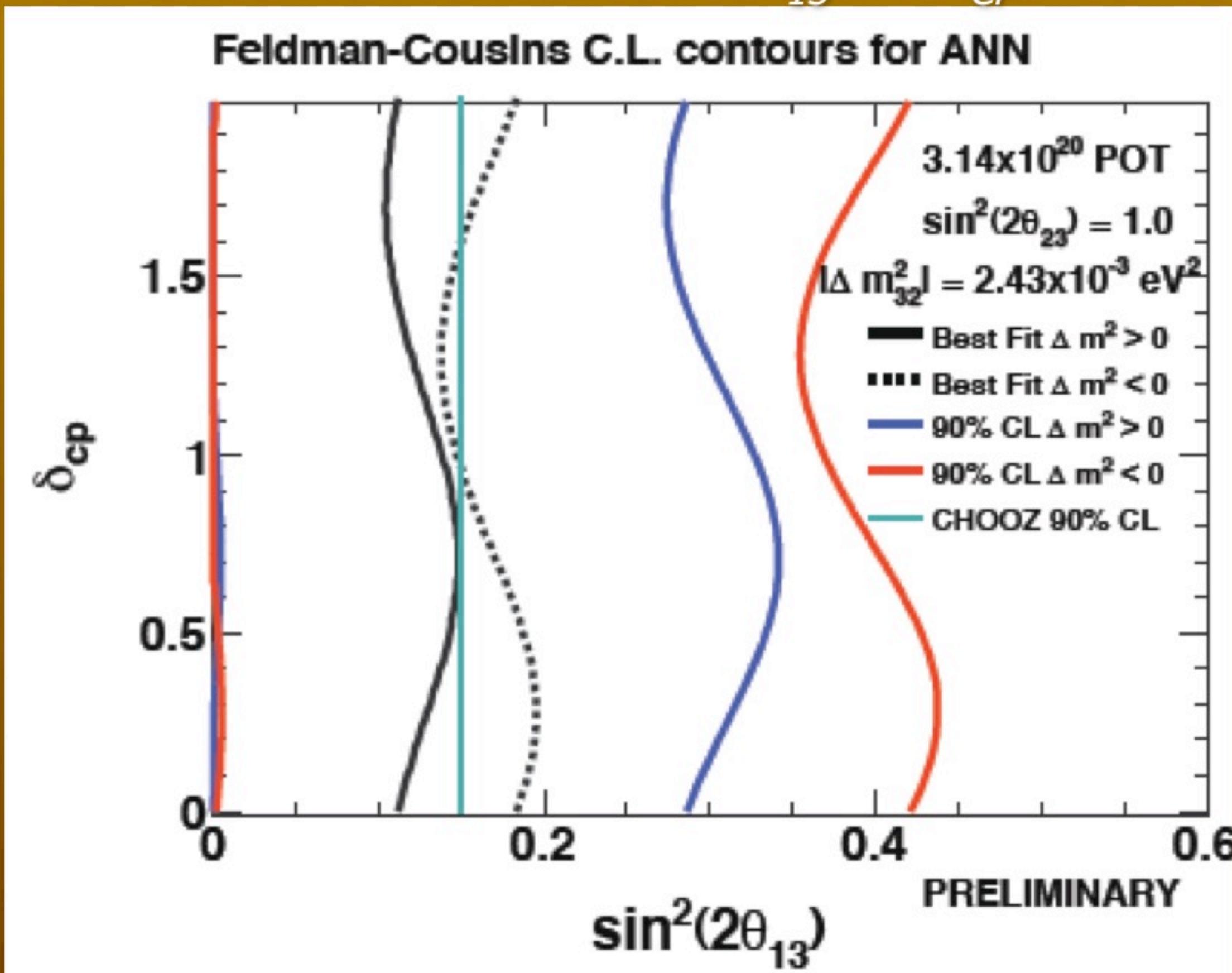


Initial results for θ_{13} search from MINOS

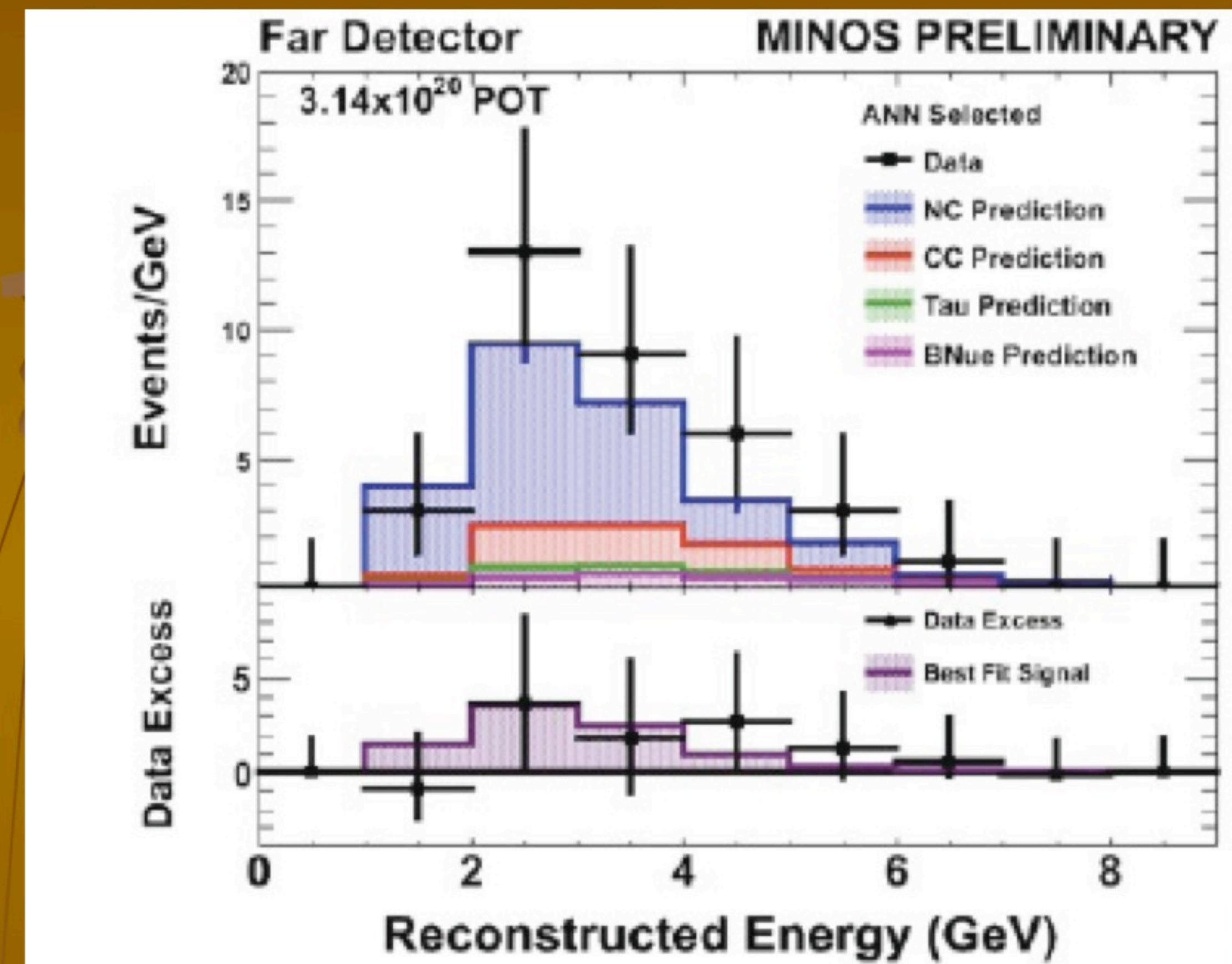
From slide by M. Sanchez at FNAL Joint Experimental-Theoretical Physics Seminar

- 35 ν_e candidate events observed.
- Expected background events is $27 \pm 5(\text{stat}) \pm 2(\text{sys})$
 NC: 18.2, ν_μ CC: 5.1, ν_τ CC: 1.1,
 ν_e beam: 2.2

90% C.L. limits in $\sin^2 2\theta_{13}$ vs. δ_{CP}



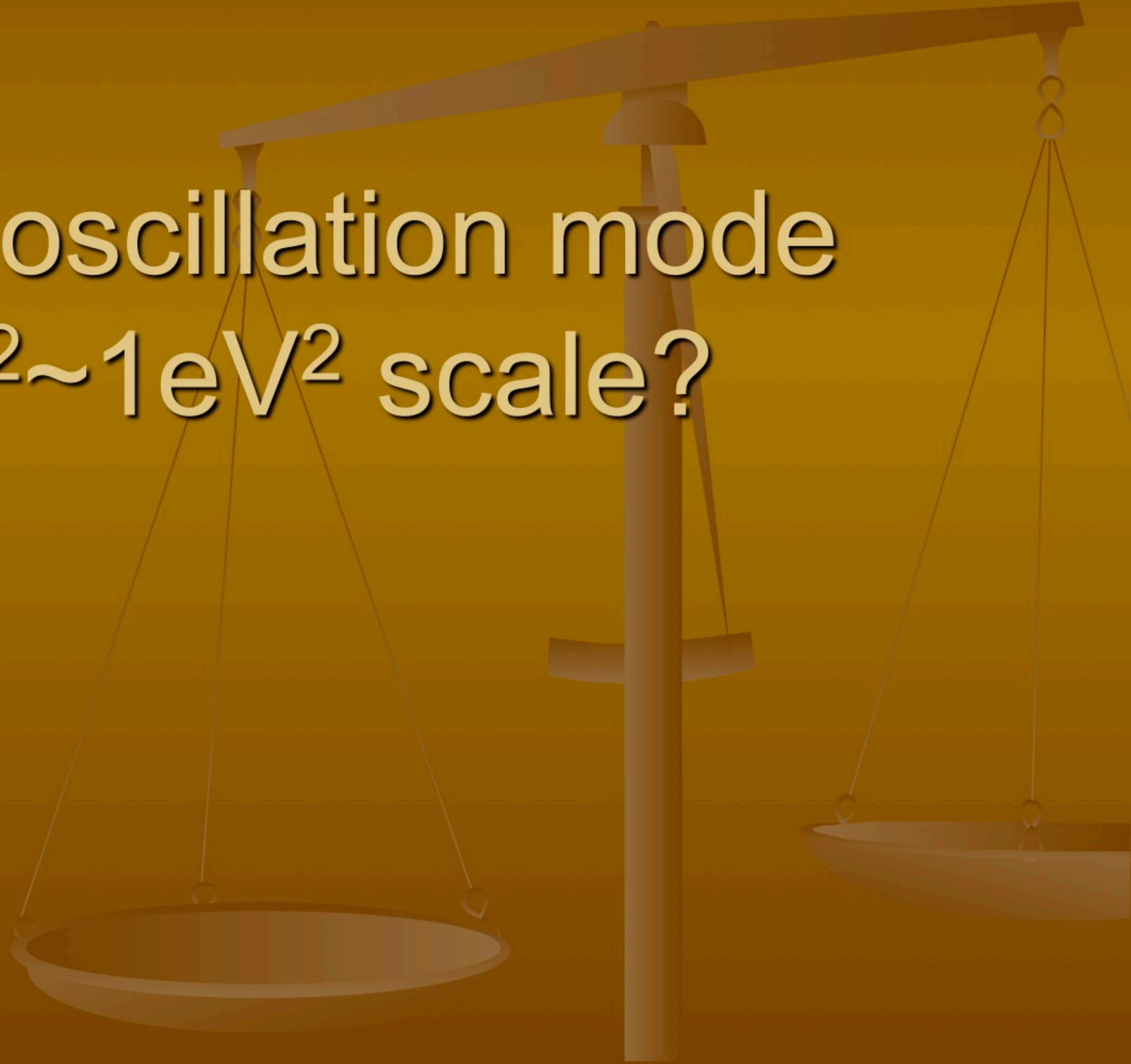
ν_e candidates at FD with BG predictions



- 90% C.L. limit (at MINOS best-fit for Δm_{23}^2 and $\sin^2 2\theta_{23}$).

$$\sin^2 2\theta_{13} < 0.29 \quad (\text{for } \Delta m^2 > 0, \delta = 0)$$

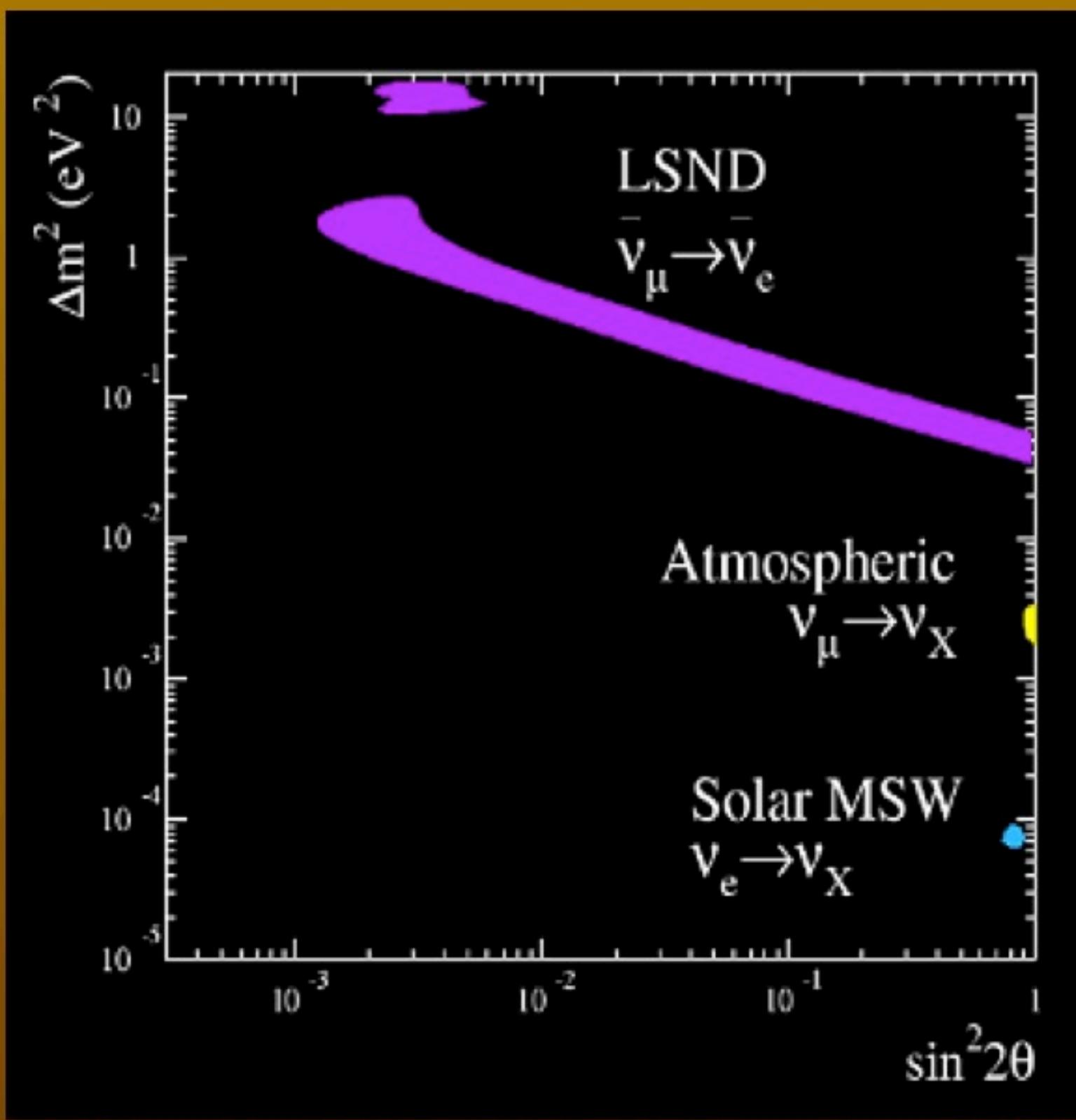
$$\sin^2 2\theta_{13} < 0.42 \quad (\text{for } \Delta m^2 < 0, \delta = 0)$$



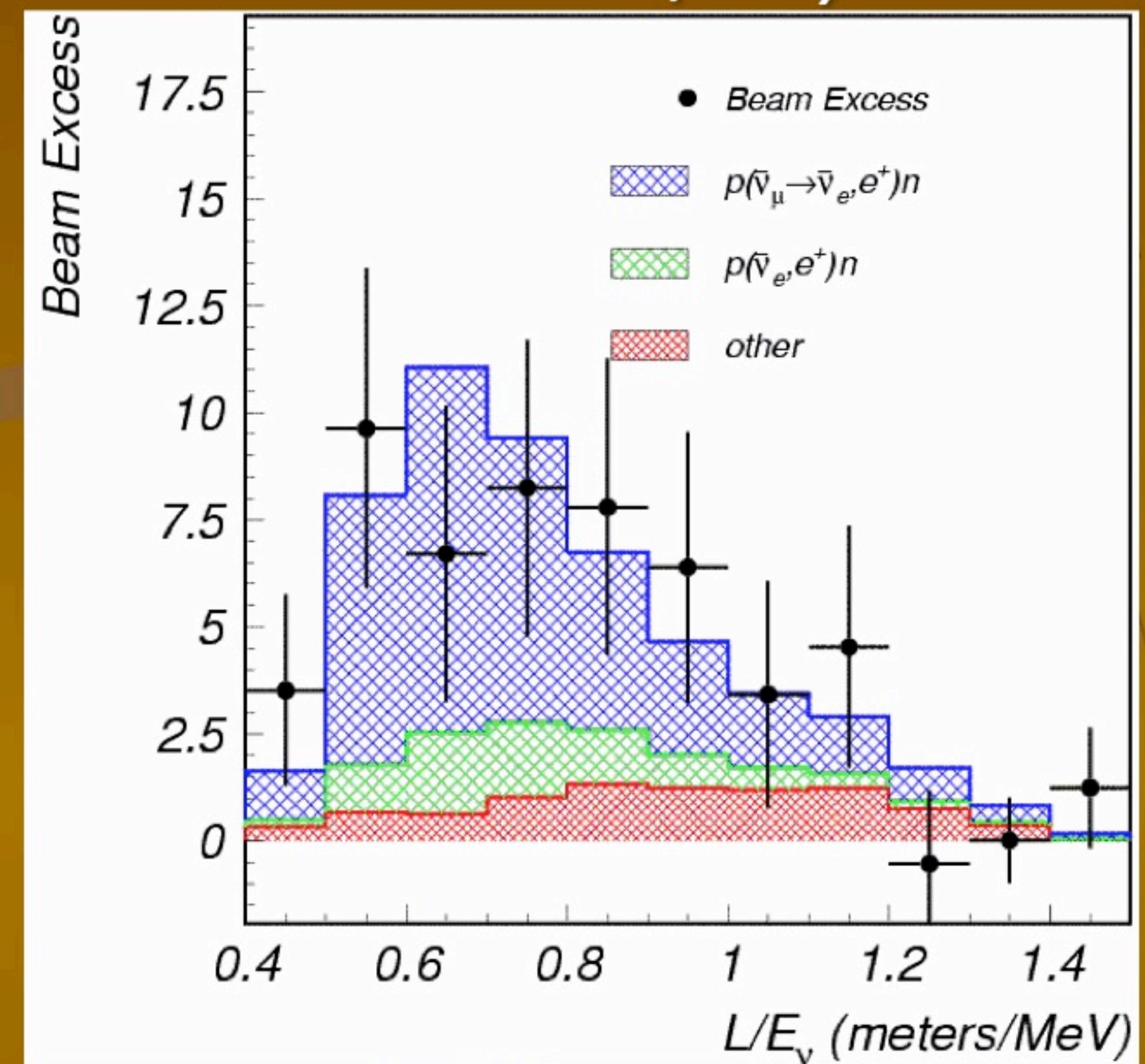
Another oscillation mode
at $\Delta m^2 \sim 1 \text{ eV}^2$ scale?

Prehistory of MiniBooNE

- Three active neutrinos (LEP, 1990)
- $\nu_\mu \rightarrow \nu_x$ (ν_x is not ν_e dominant) oscillation at $\Delta m^2 \sim 3 \times 10^{-3} \text{ eV}^2$ scale (SK, 1998)
- $\nu_e \rightarrow \nu_x$ oscillation at $\Delta m^2 \sim 8 \times 10^{-5} \text{ eV}^2$ (SK +SNO, 2000)
- LSND(1993-1998): Signal of $\nu_\mu \rightarrow \nu_e$ oscillation at $\Delta m^2 \sim 1 \text{ eV}^2$ scale.



Measurement of L/E by LSND



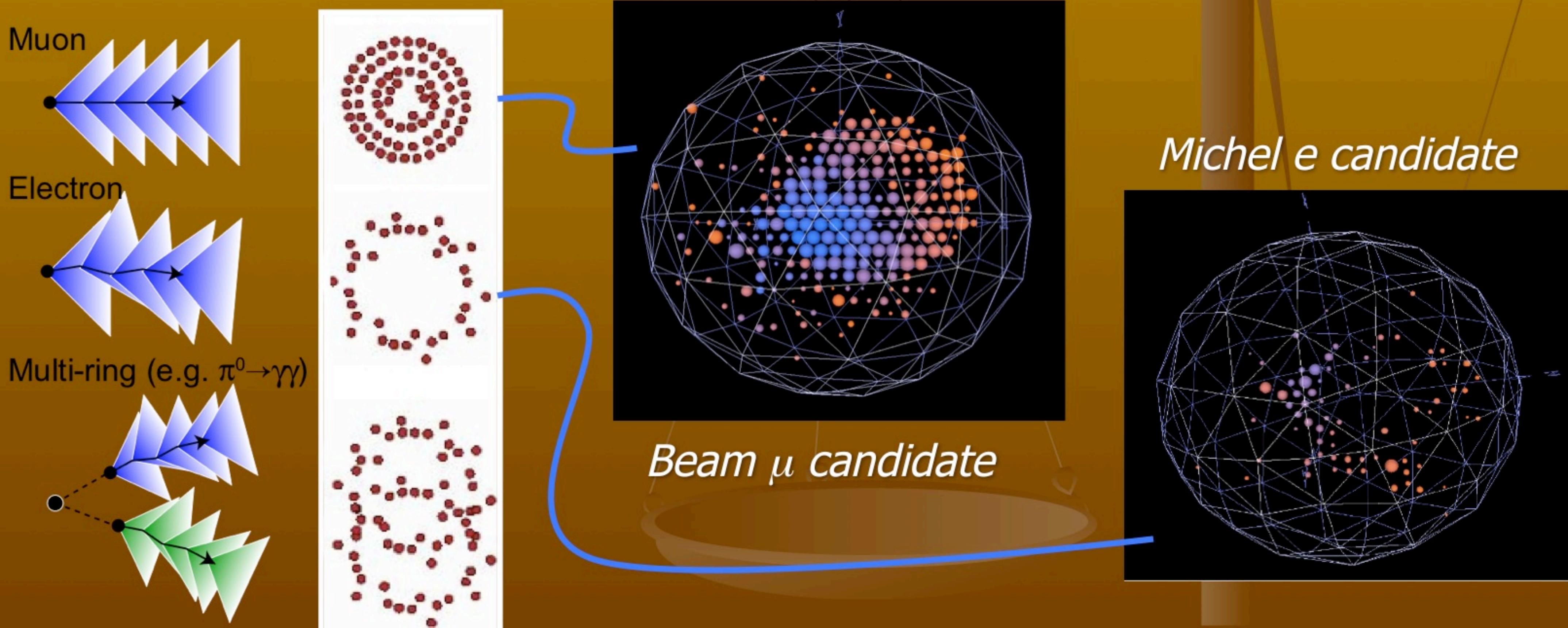
3 mass difference scales inconsistent with
3 active neutrino mixing. \Rightarrow sterile neutrinos?

Motivate another experiment to conclude oscillation at
LSND L/E with intense beam and improved detector.
 \Rightarrow MiniBooNE

LSND: $L/E \sim 30\text{m}/50\text{MeV}$
MiniBooNE: $L/E \sim 500\text{m}/800\text{MeV}$

Detection of neutrinos in MiniBooNE

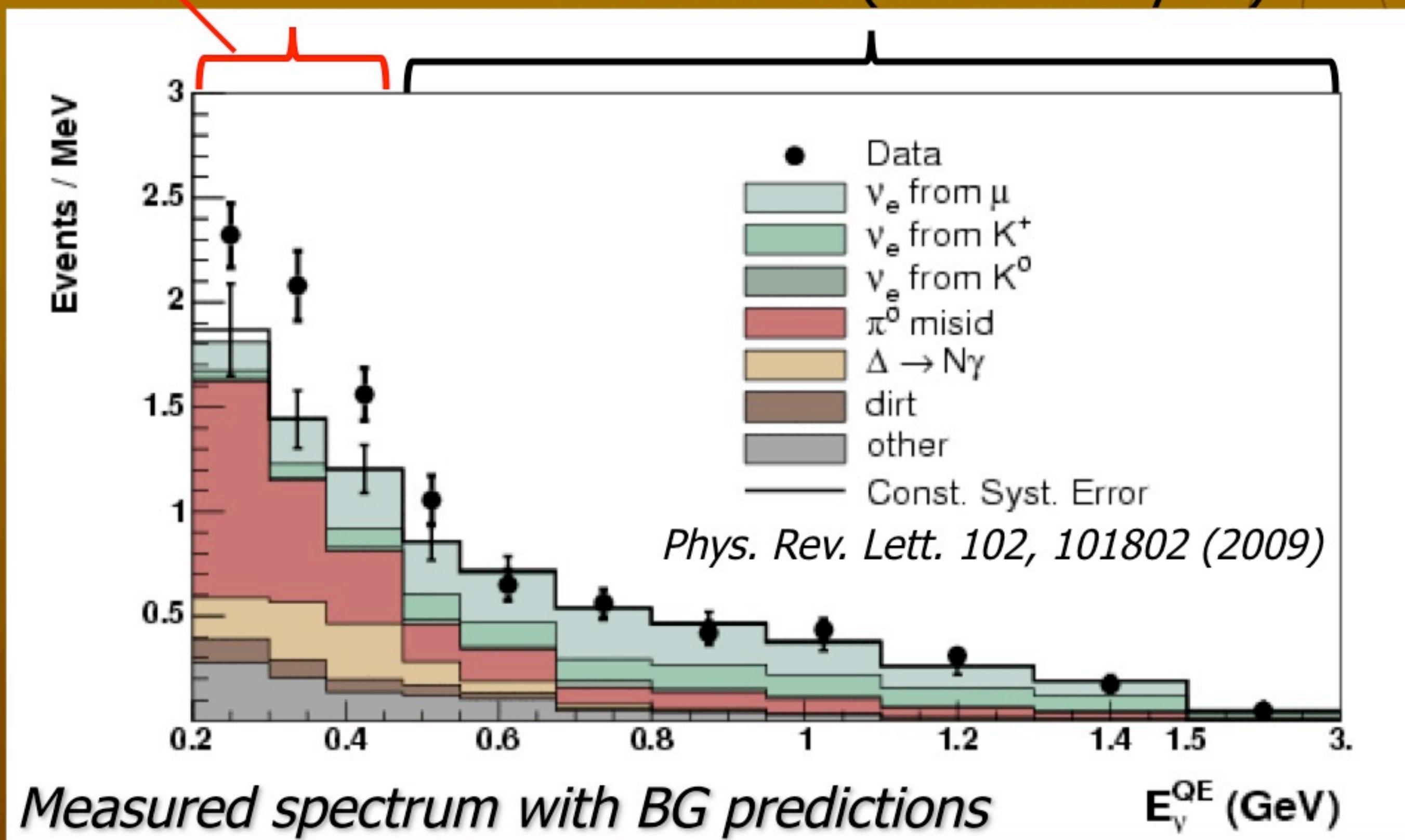
- Pure muon neutrino beam:
 - Created from Fermilab Booster 8GeV proton beam (peak at 800MeV).
 - Neutrino and anti-neutrino operation.
- Neutrino detector:
 - 800tons of mineral oil target.
 - Both Cherenkov and scintillator light monitored by 1280 PMT's.
 - μ/e separation by the ring image.



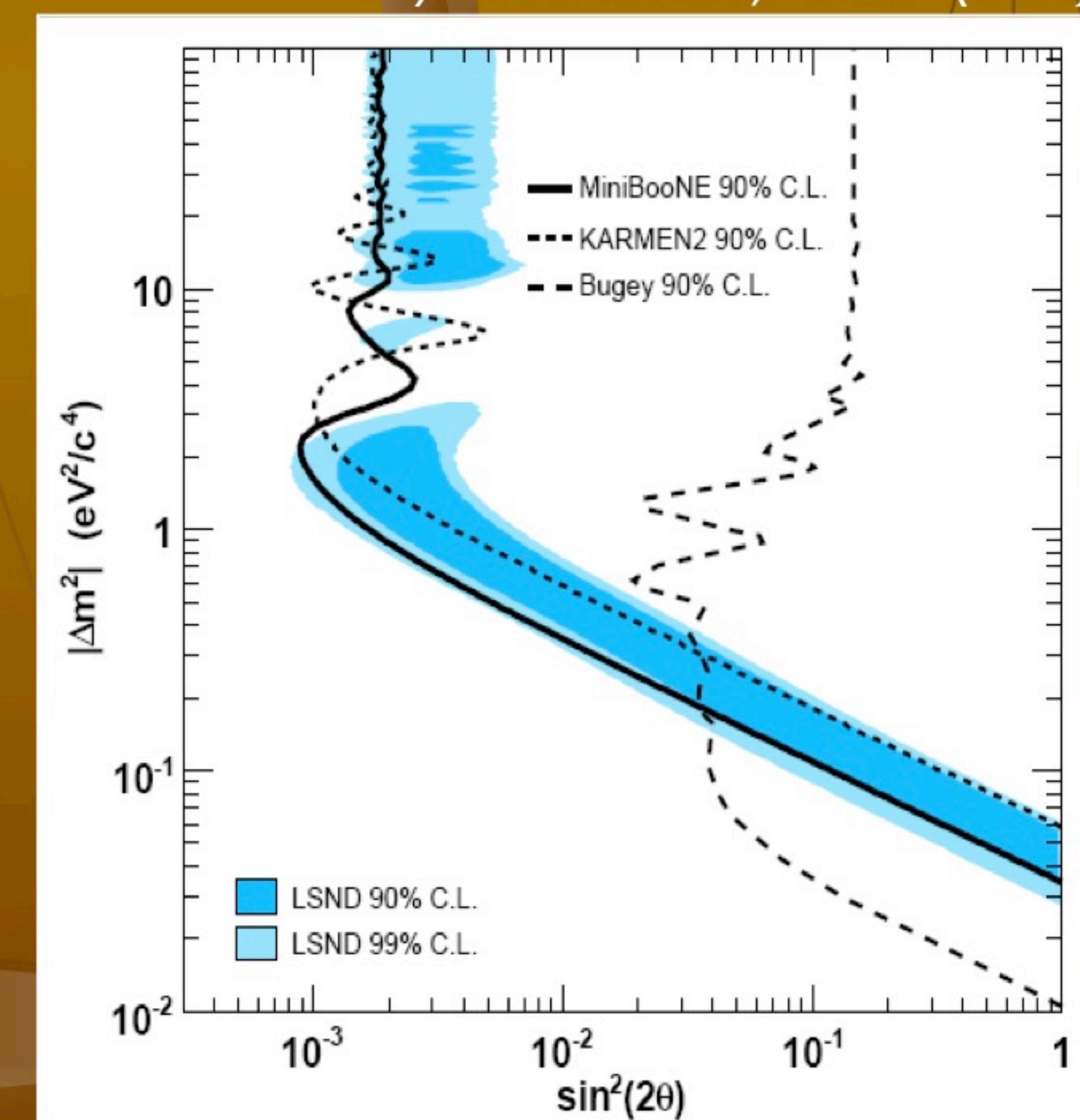
Oscillation not confirmed in MiniBooNE

- No significant excess of electron events above background.
- Data-BG = $22 \pm 19 \pm 35$ events for $475 \sim 1250$ MeV
- Data is consistent with no $\nu_\mu \rightarrow \nu_e$ oscillation at LSND Δm^2 scale.
- Unexpected low energy excess (out of fit region) observed.
 - New physics? Background? MC modeling?
 - Various theoretical and background studies have been made, but not yet concluded.

Used in fit (blind analysis)



90% C.L. limits in $\sin^2 2\theta$ vs. Δm^2
Phys. Rev. Lett. 98, 231801 (2007)

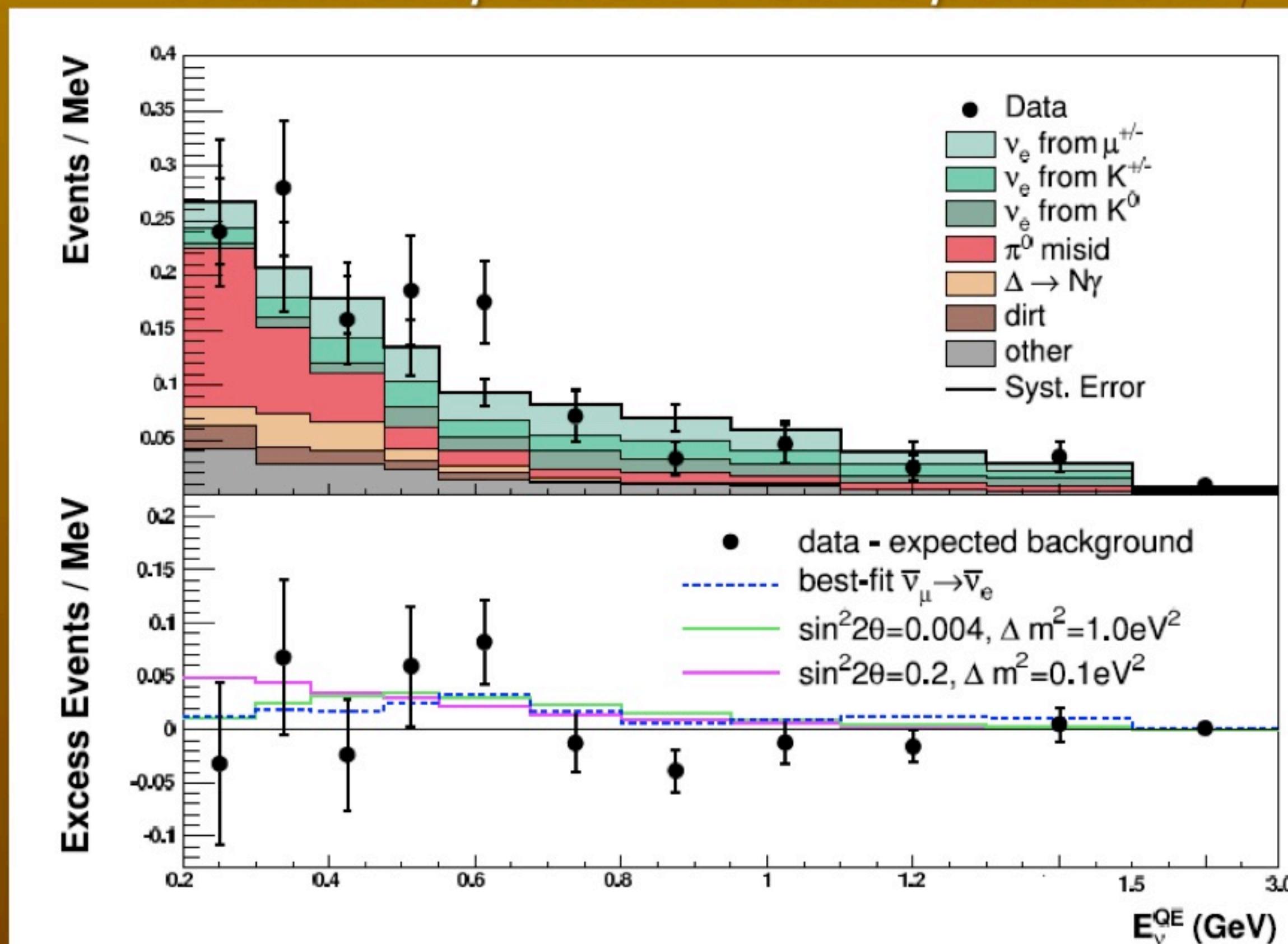


Results from MiniBooNE anti- ν running

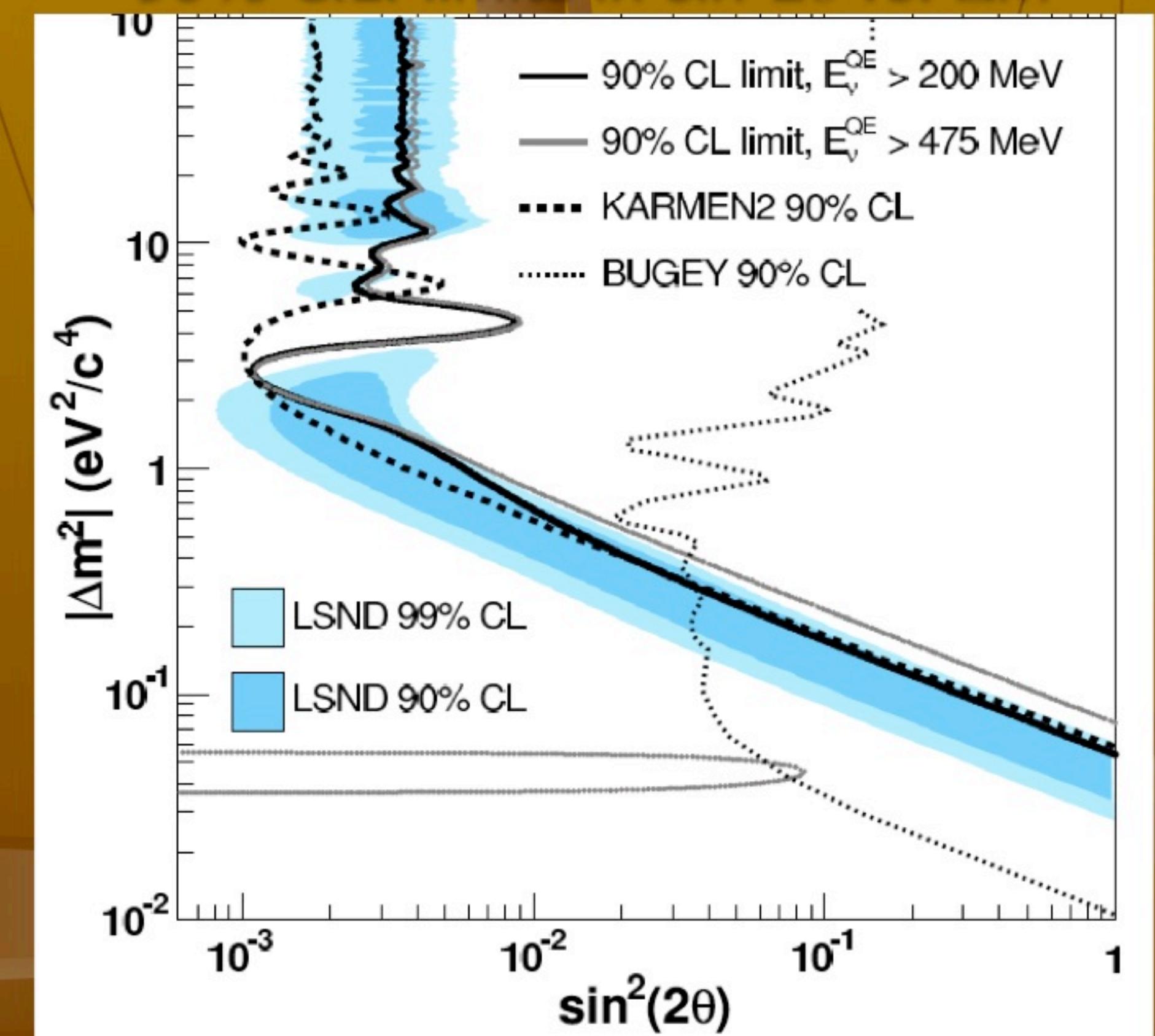
arXiv:0904.1958

- No significant excess of electron events above background.
- 144 electron events were observed for 200~3000MeV, while expectation of the background is 139.2 ± 17.6 events.
- Data is consistent with no $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation at LSND Δm^2 scale, although not conclusive to full LSND region.
- No excess was confirmed in low energy region below 475MeV.

Measured spectrum with BG predictions



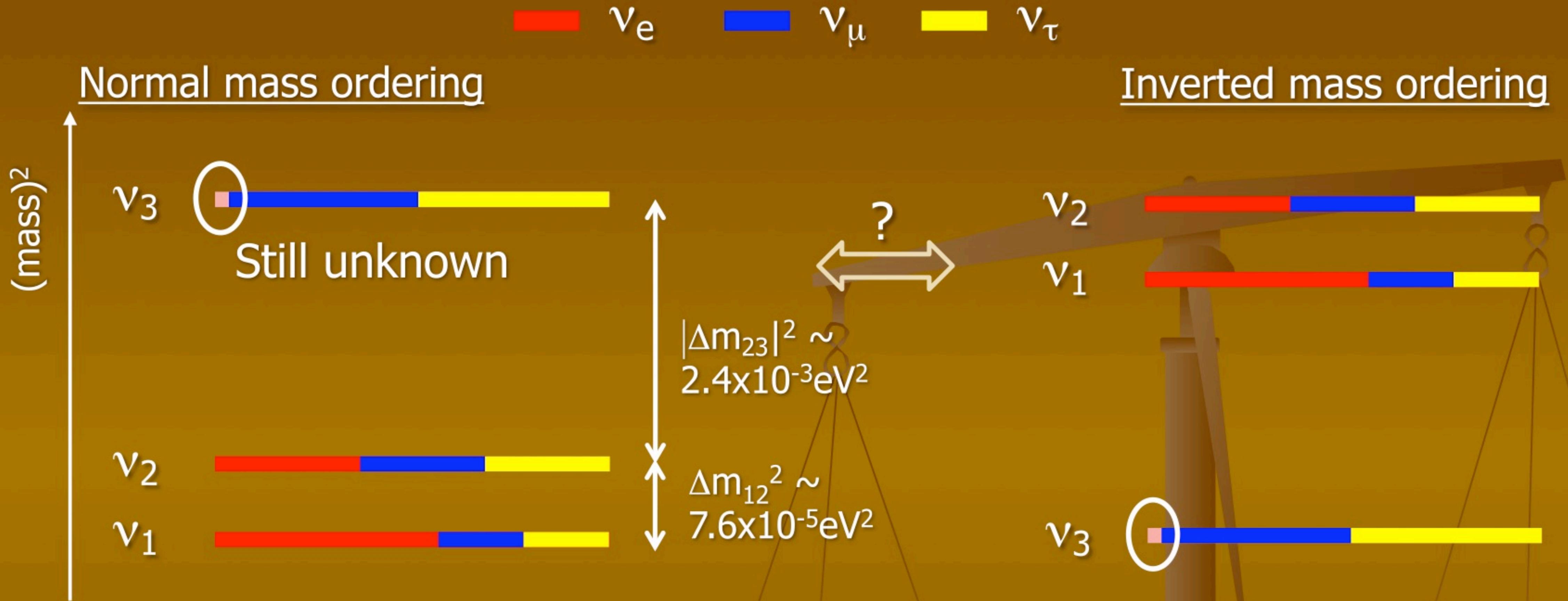
90% C.L. limits in $\sin^2 2\theta$ vs. Δm^2





What comes next?

Remaining questions



- How small is mixing angle θ_{13} ?
- Is CP violated in neutrino sector? If so, how large?
- Which mass hierarchy in neutrinos? Normal or inverted?
- Is θ_{23} maximal mixing?

Note: Measurement of θ_{13} is essential to realize future experiments to determine CP-violation phase δ and mass ordering in neutrino sector.

Two approaches to search for θ_{13}

- Reactor neutrino oscillation: Double-Chooz, Daya-Bay, RENO...

$$P\left[\overline{\nu}_e \rightarrow \overline{\nu}_e\right] \approx 1 - \boxed{\sin^2 2\theta_{13}} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right) + O(10^{-3})$$

- Sensitive to θ_{13} .

- Long-baseline with ν_μ beam: T2K, NOvA ...

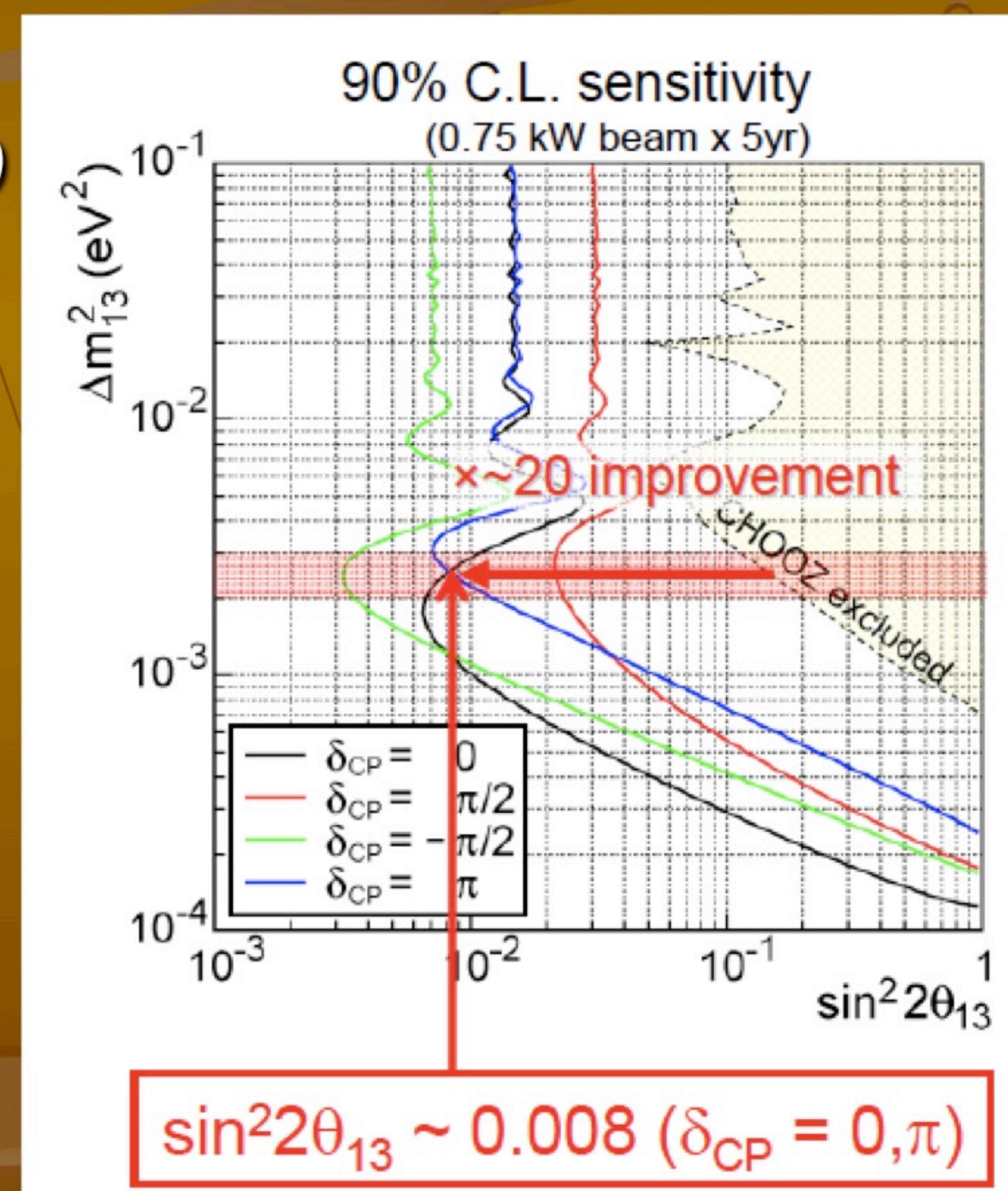
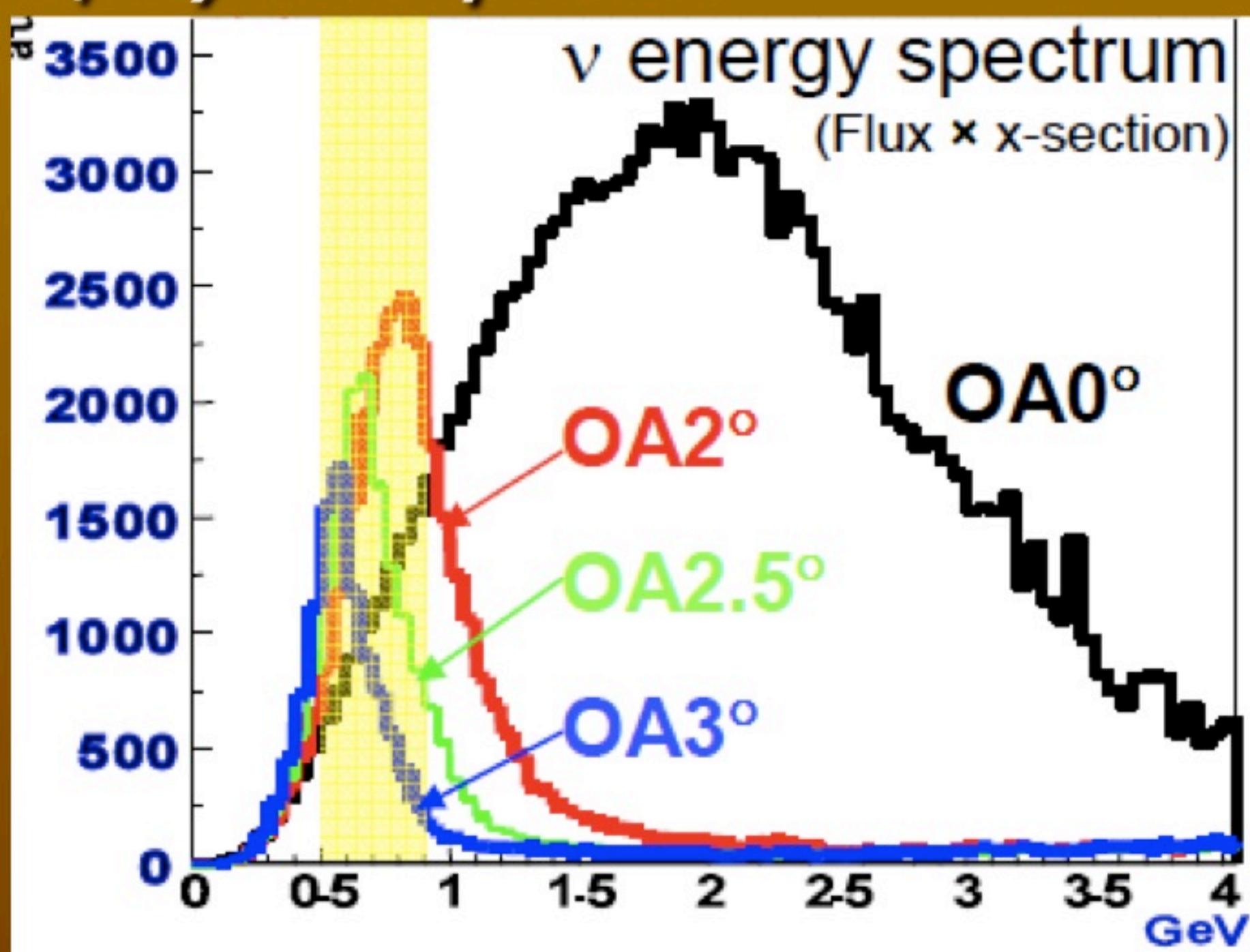
$$\begin{aligned} P\left[\nu_\mu(\overline{\nu}_\mu) \rightarrow \nu_e(\overline{\nu}_e)\right] &= \boxed{\sin^2 2\theta_{13}} \boxed{s_{23}^2} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right) - \frac{1}{2} s_{12}^2 \boxed{\sin^2 2\theta_{13}} \boxed{s_{23}^2} \left(\frac{\Delta m_{21}^2 L}{2E}\right) \sin\left(\frac{\Delta m_{31}^2 L}{2E}\right) \\ &\quad + 2 \boxed{J_r} \cos \delta \left(\frac{\Delta m_{21}^2 L}{2E}\right) \sin\left(\frac{\Delta m_{31}^2 L}{2E}\right) \mp 4 \boxed{J_r} \sin \delta \left(\frac{\Delta m_{21}^2 L}{2E}\right) \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right) \\ &\quad \pm \cos 2\theta_{13} \boxed{\sin^2 2\theta_{13}} \boxed{s_{23}^2} \left(\frac{4Ea(x)}{\Delta m_{31}^2}\right) \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right) \\ &\quad \mp \frac{a(x)L}{2} \boxed{\sin^2 2\theta_{13}} \cos 2\theta_{13} \boxed{s_{23}^2} \sin\left(\frac{\Delta m_{31}^2 L}{2E}\right) + c_{23}^2 \sin^2 2\theta_{12} \left(\frac{\Delta m_{21}^2 L}{4E}\right)^2 \end{aligned}$$

- θ_{13} , δ_{CP} , mass hierarchy and θ_{23} (\Rightarrow parameters degeneracy).
- Matter effects.
- Neutrino and anti-neutrino running.

Search for $\nu_\mu \rightarrow \nu_e$ oscillations by T2K

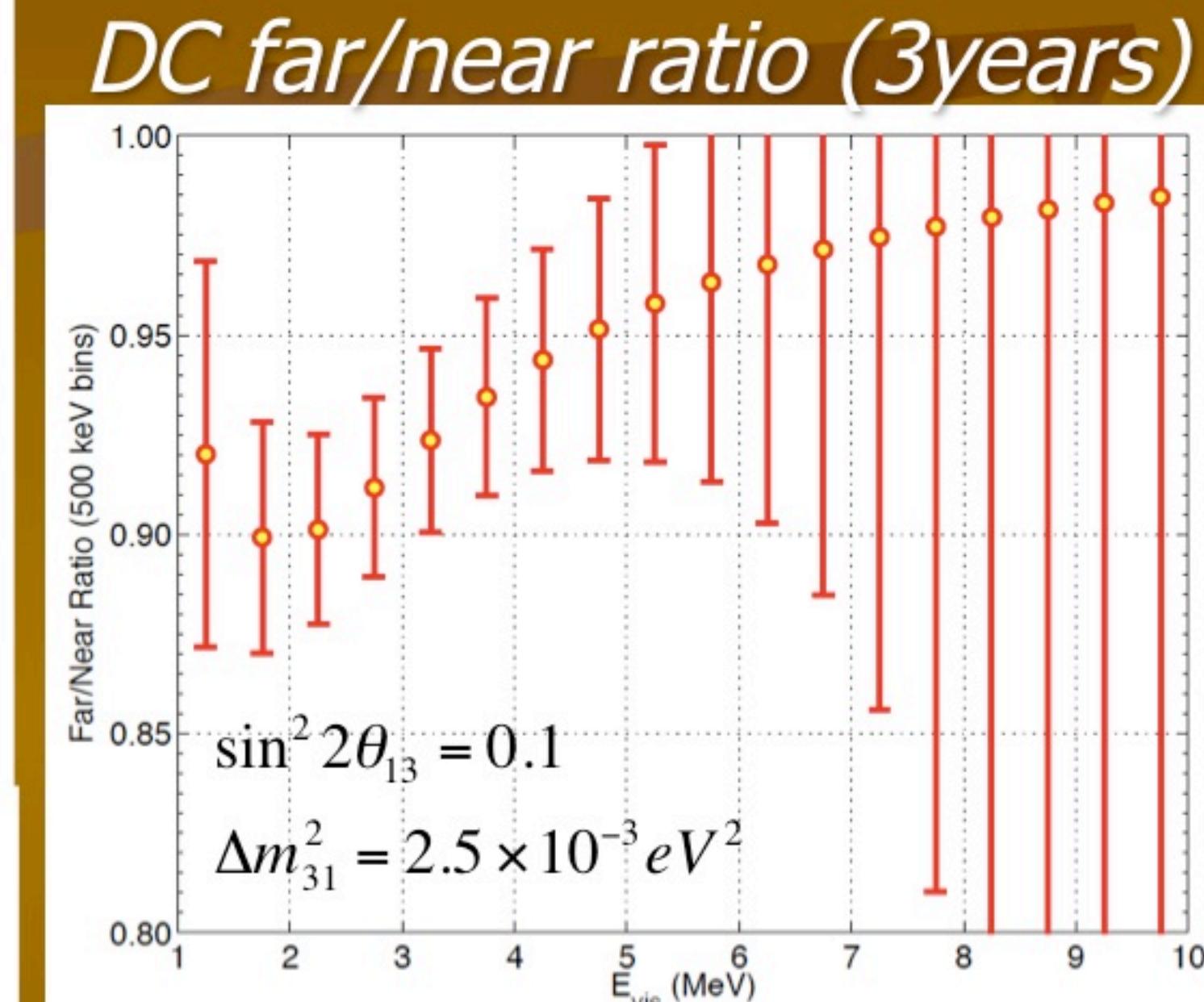
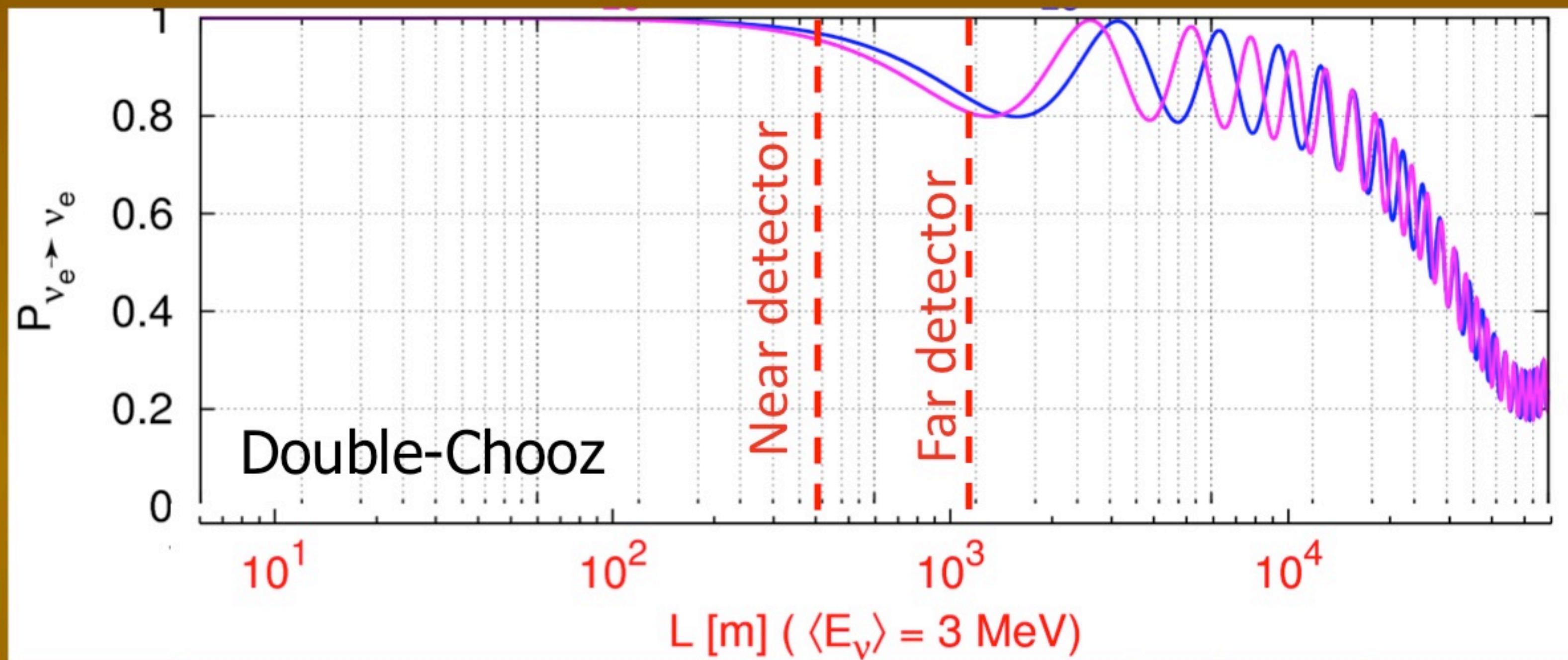
From slide by I. Kato at Neutrino 2008

- Narrow band ν_μ beam from J-PARC by off-axis method.
- Far detector (=SK) at L=295km, with near detectors at 280m.
- Quasi-elastic interactions are dominant around the peak at 700MeV.
- Major background is π^0 from NC int..
- Neutrino beam commissioning in 2009
(first neutrino beam on April 23!).
- Sensitivity: $\sin^2 2\theta_{13} \sim 0.008$ (assuming $\delta = 0, \pi$) in 5 years.

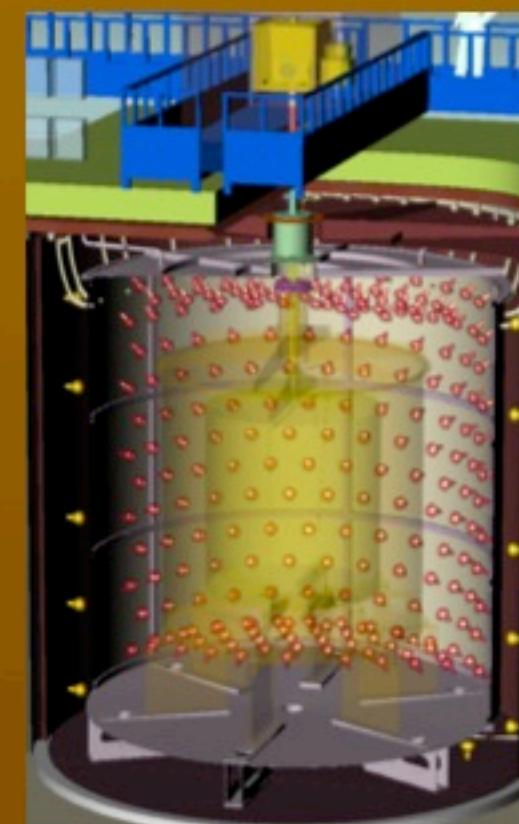


Precise measurement of θ_{13} by Double-Chooz reactor neutrino experiment

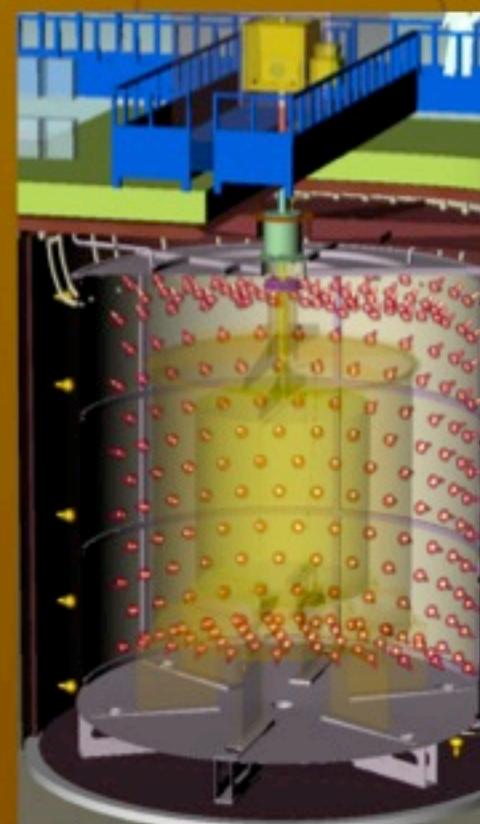
- Search for disappearance signal in reactor anti-electron neutrinos.



$\bar{\nu}$ source (reactor)
 $4.27 \text{ GW}_{\text{th}} \times 2 \text{ cores}$



Near detector
 $L = 400 \text{ m}$



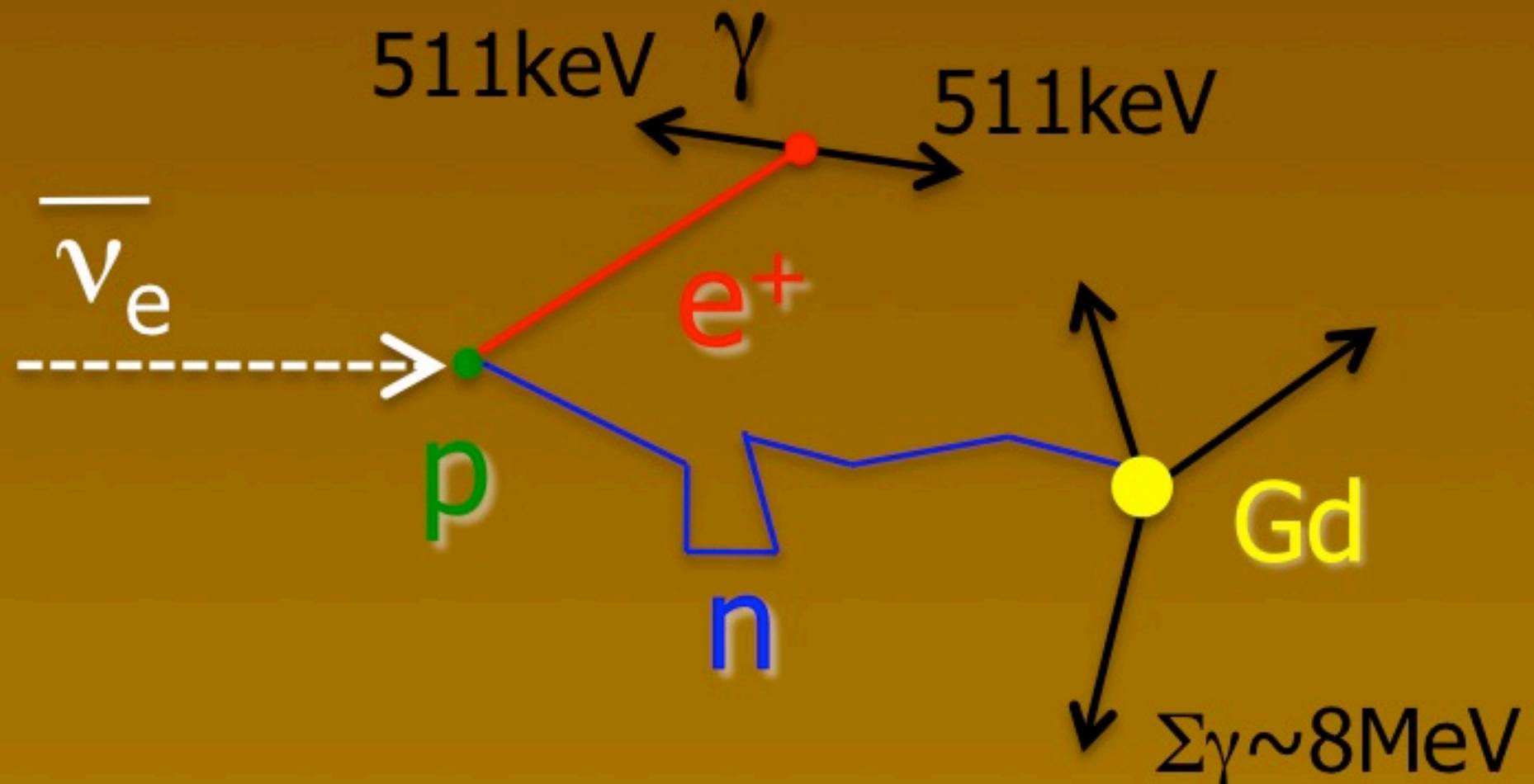
Far detector
 $L = 1050 \text{ m}$

Systematic errors on

- Neutrino flux
 - Number of target protons
 - Detection efficiency
- are canceled by two detector technique.

Neutrino signal and background in Double-Chooz

Neutrino signal



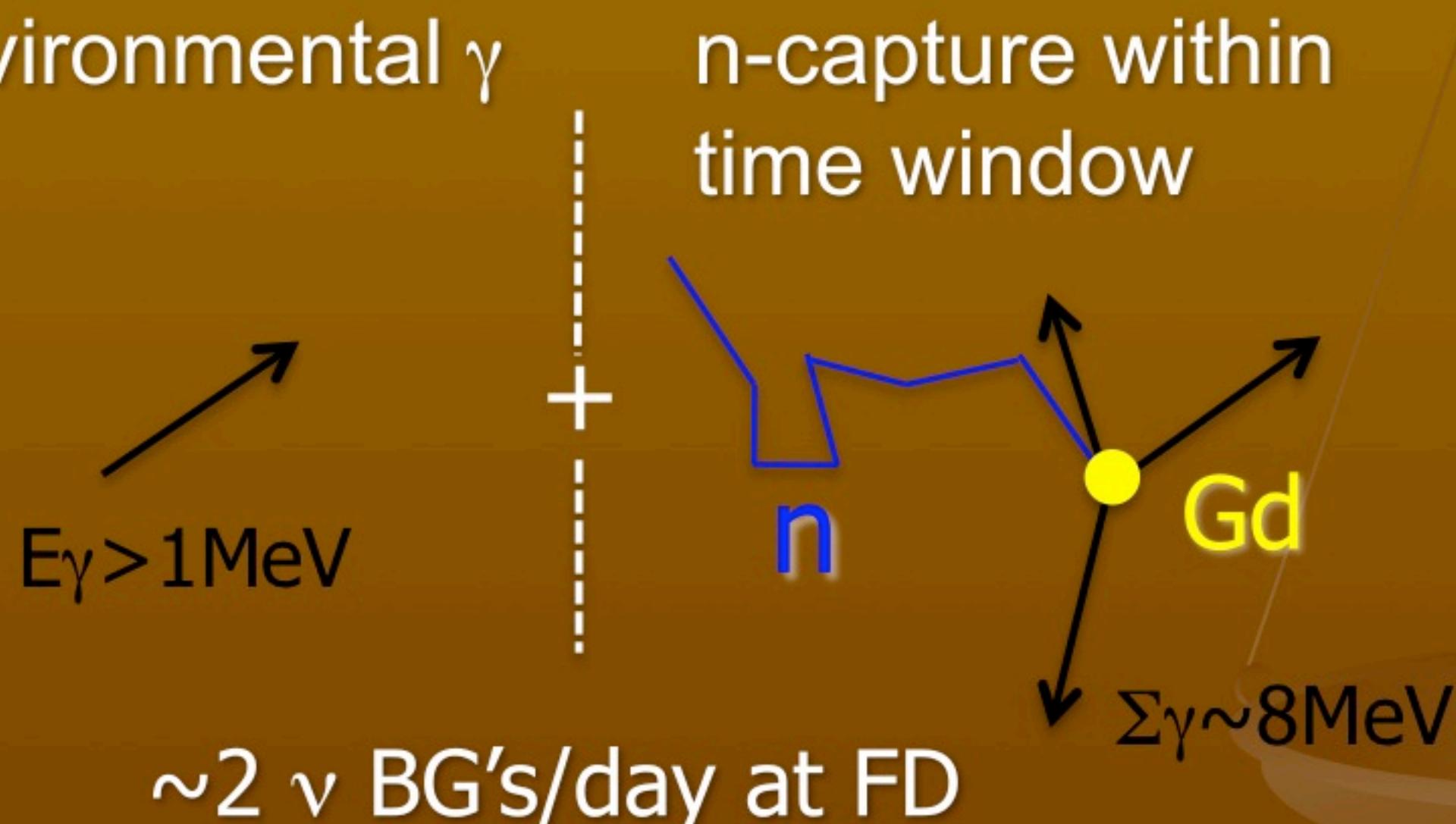
Prompt signal: e^+ ($1 \sim 8 \text{ MeV}$)
 $\rightarrow E_\nu = E_{\text{vis}} + 0.8 \text{ MeV}$
Delayed signal: n-capture by Gd ($\sim 8 \text{ MeV}$)
Time correlation: $\tau \sim 30 \mu\text{s}$

69 ν signal's/day at far detector (FD)

Background

Accidental Background

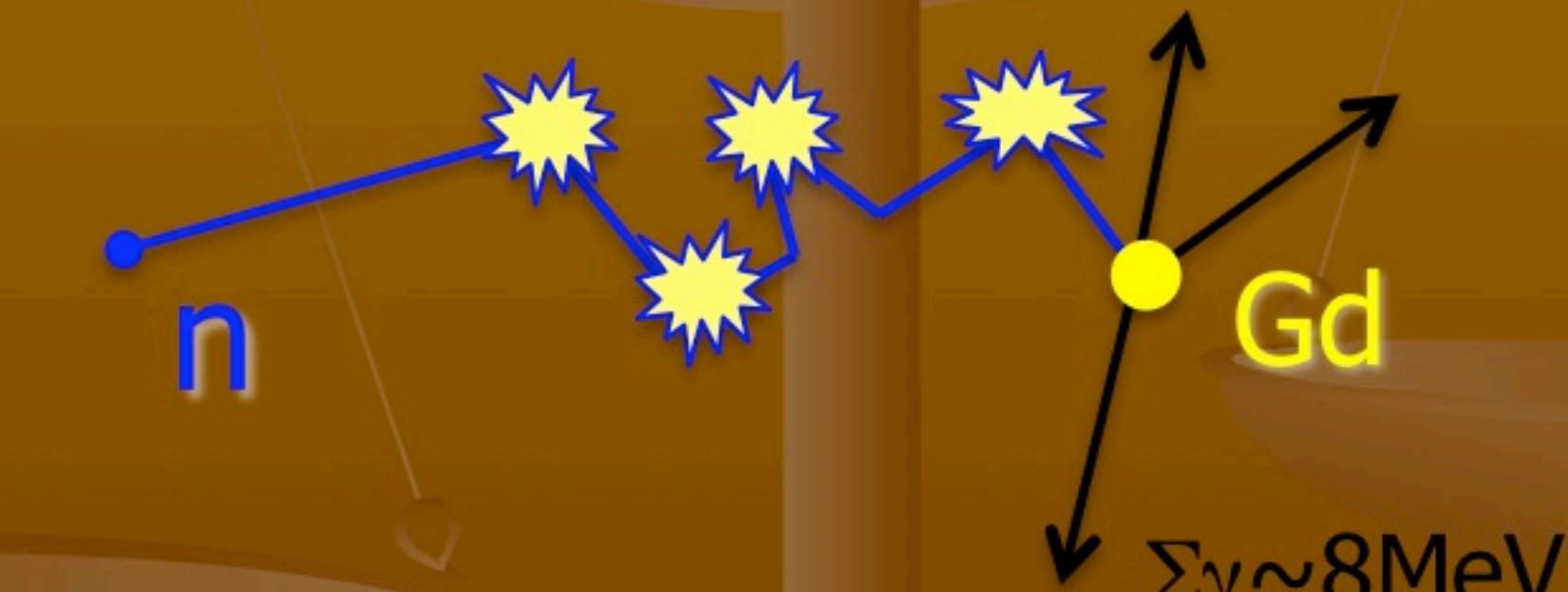
Environmental γ



$\sim 2 \nu \text{ BG's/day at FD}$

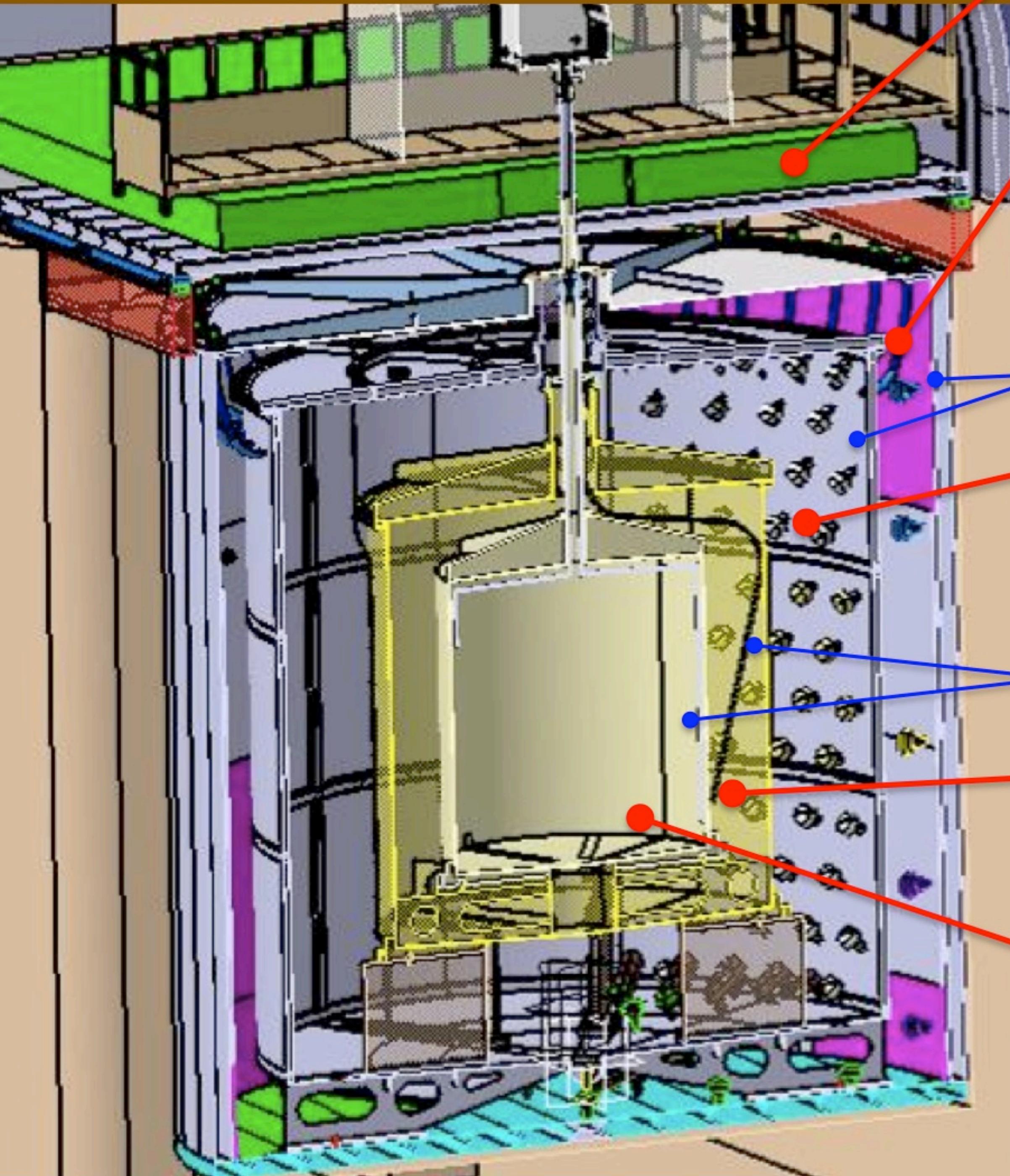
Correlated Background

Eg. Fast neutron with recoil proton signals \rightarrow n-capture by Gd



$\sim 1.6 \nu \text{ BG's/day at FD}$

Double-Chooz detector



Outer Veto (Plastic scintillator)

Identification of cosmic ray muons

Inner Veto

(90m³ Liquid scintillator & 78 PMT's)

Detection of cosmic ray muons and fast neutrinos

Steel Vessel & PMT support structure

Buffer(110m³ Mineral oil & 390 PMT's)

Reduction of fast neutron from surrounding rock and environmental gamma's from PMT

Acrylic Vessel

γ -Catcher(22.3m³ Liquid scintillator)

Measurement of total 8MeV gammas from n-capture by Gd in target volume

ν -Target

(10.3m³ Gd loaded (1g/l) liquid scintillator)

Target for neutrino signals (prompt positron + delayed gamma's from n-capture by Gd)

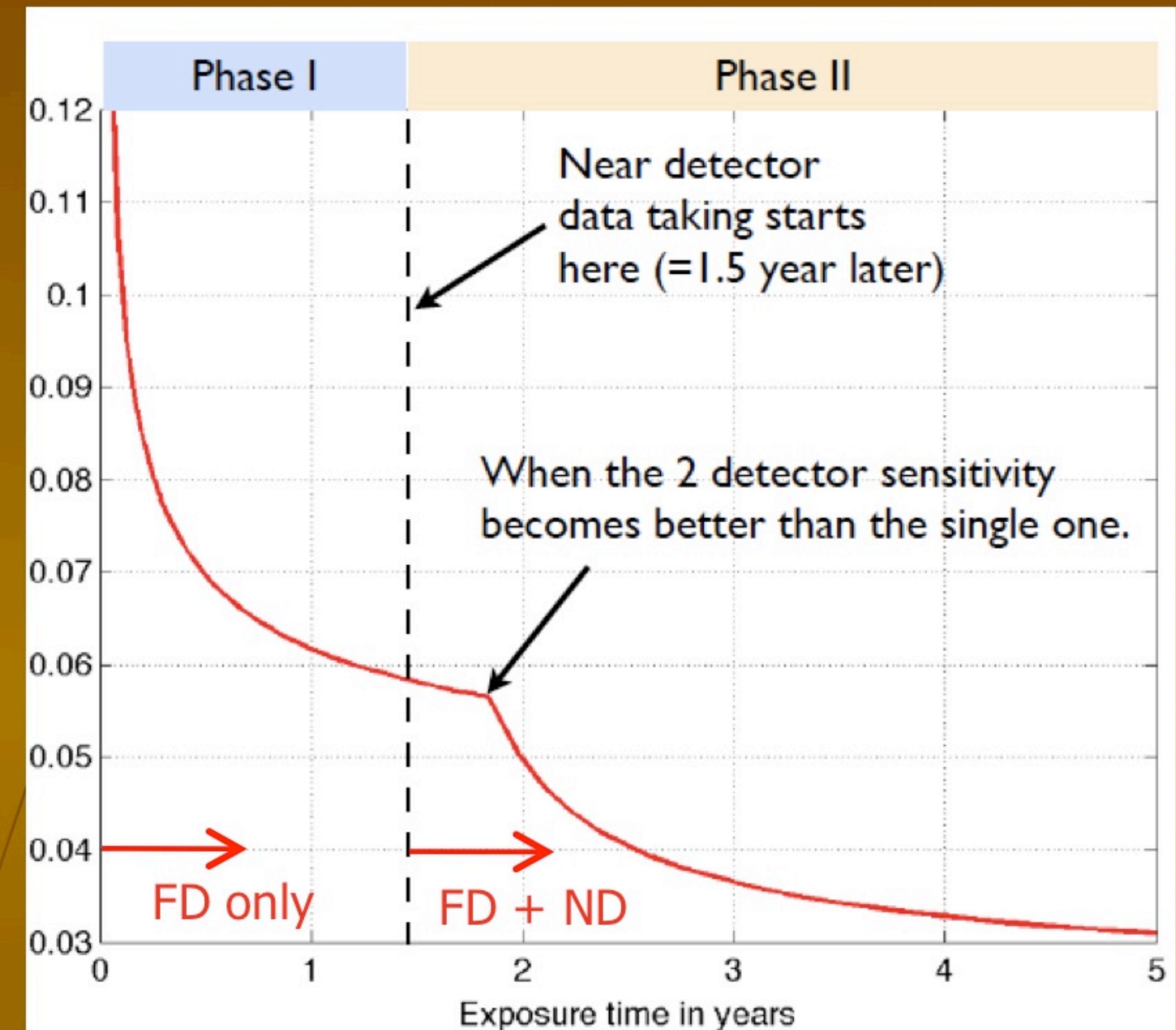
Double-Chooz sensitivity to θ_{13}

Improvements from CHOOZ

Stat. error **2.7% → 0.5%**

Syst. errors (FD + ND)

Neutrino flux	1.9%	→ <0.1%
Reactor power	0.7-2%	→ <0.1%
H/C ratio	1.2%	→ <0.2%
Spatial effects	1.0%	→ <0.1%
Selection eff.	1.5%	→ ~0.3%
Total	2.7%	→ <0.6%



- Far detector is currently under installation at CHOOZ.
- Far detector commissioning scheduled at end of 2009.
- Sensitivity reach to $\sin^2 2\theta_{13} \sim 0.06$ by FD single detector analysis.
- 2010~: Near detector installation.
- Sensitivity reach to $\sin^2 2\theta_{13} \sim 0.03$ in 2013 with two detectors.

Conclusion

- Neutrino oscillation is established last decade by several experiments using various neutrino sources: atmospheric, solar, reactor, artificial neutrino beam (and maybe supernova in future).
- Neutrino oscillation and existence of neutrino mass was a breakthrough to physics beyond the standard model.
- Neutrino oscillation experiments are now in precision measurement stage, with better than 10% accuracy.
- Next generation experiments using reactor neutrinos or neutrino beam are under construction targeting measurement of θ_{13} .
- Discussion for future projects to measure CP-violation and determine mass hierarchy in neutrino sector may be accelerated according to the measurement of θ_{13} .