Обнаружение осцилляций мюонных нейтрино в электронные нейтрино эксперименте Т2К

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ИЯИ РАН

XI Марковские чтения
ИЯИ РАН, 14 мая 2013 г.

ν oscillations and mixing

Standard Model: neutrinos are *massless* particles

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

atmospheric

solar

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}}_{\text{atmospheric}} \boxed{\begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{-i\delta} & 0 & \cos\theta_{13} \end{pmatrix}} \underbrace{\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{solar}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

link between atmospheric and solar

***U* parameterization:** three mixing angles θ_{12} θ_{23} θ_{13} and CP violating phase δ

$$\Delta m_{ij}^2 = m_i^2 - m_j^2 \qquad \Delta m_{12}^2 + \Delta m_{23}^2 + \Delta m_{31}^2 = 0$$

⇒ **two independent Δm^2**

$$\Delta m_{12}^2 = \Delta m_{sol}^2 \approx 7.5\times 10^{-5}\,\mathrm{eV}^2 \qquad \Delta m_{23}^2 \cong \Delta m_{31}^2 = \Delta m_{atm}^2 \approx 2.4\times 10^{-3}\,eV^2$$

$\theta_{12}\sim 34^0$ $\theta_{23}\sim 45^0$

?? θ_{13} , mass hierarchy , δ ??

Importance of θ_{13}

- Zero value of θ_{13} would be a hint on a new symmetry (tri-bi-maximal)

- Zero value of θ_{13} would eliminate a possibility for the CKM mechanism in neutrino mixing

- A non-zero value of θ_{13} opens a door for searching of leptonic CP violation

- A non-zero (and not small) value of θ_{13} gives good chances for measurement of mass hierarchy and CP violation in neutrino oscillations using present neutrino beams and detectors

The size of θ_{13} $\rightarrow$ Future Program of neutrino physics

Sensitivity to oscillation parameters of accelerator LBL experiments

- ν_μ disappearance

$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2\theta_{23}\sin^2 1.27\frac{\Delta m^2_{32}L}{E_\nu}$$

sensitive to parameters θ_{23} and Δm^2_{32}

- ν_e appearance

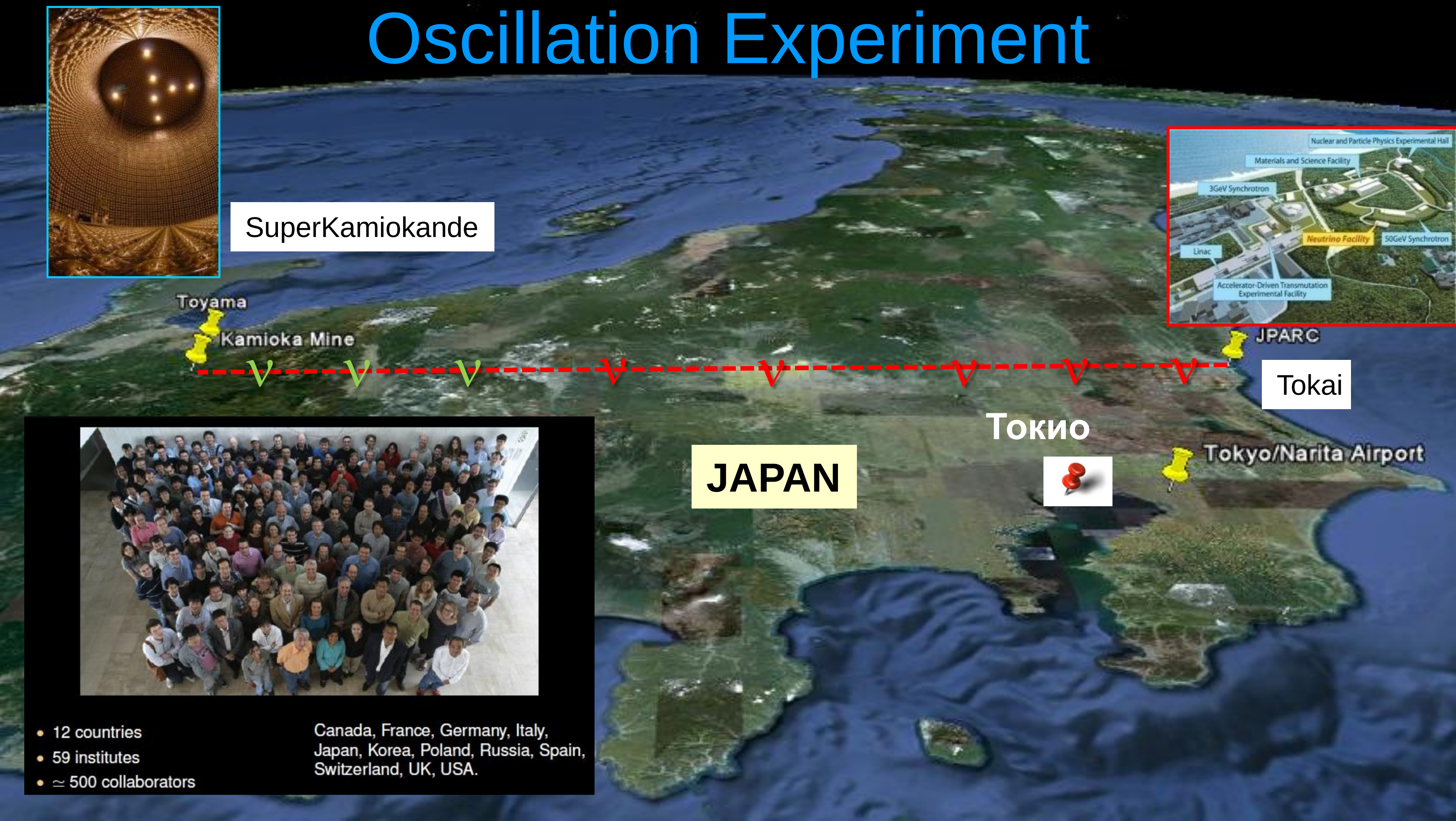
$$P(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{31}L}{4E_\nu} + \text{CPV term} + \text{subleading terms}$$

sensitive to parameter θ_{13}

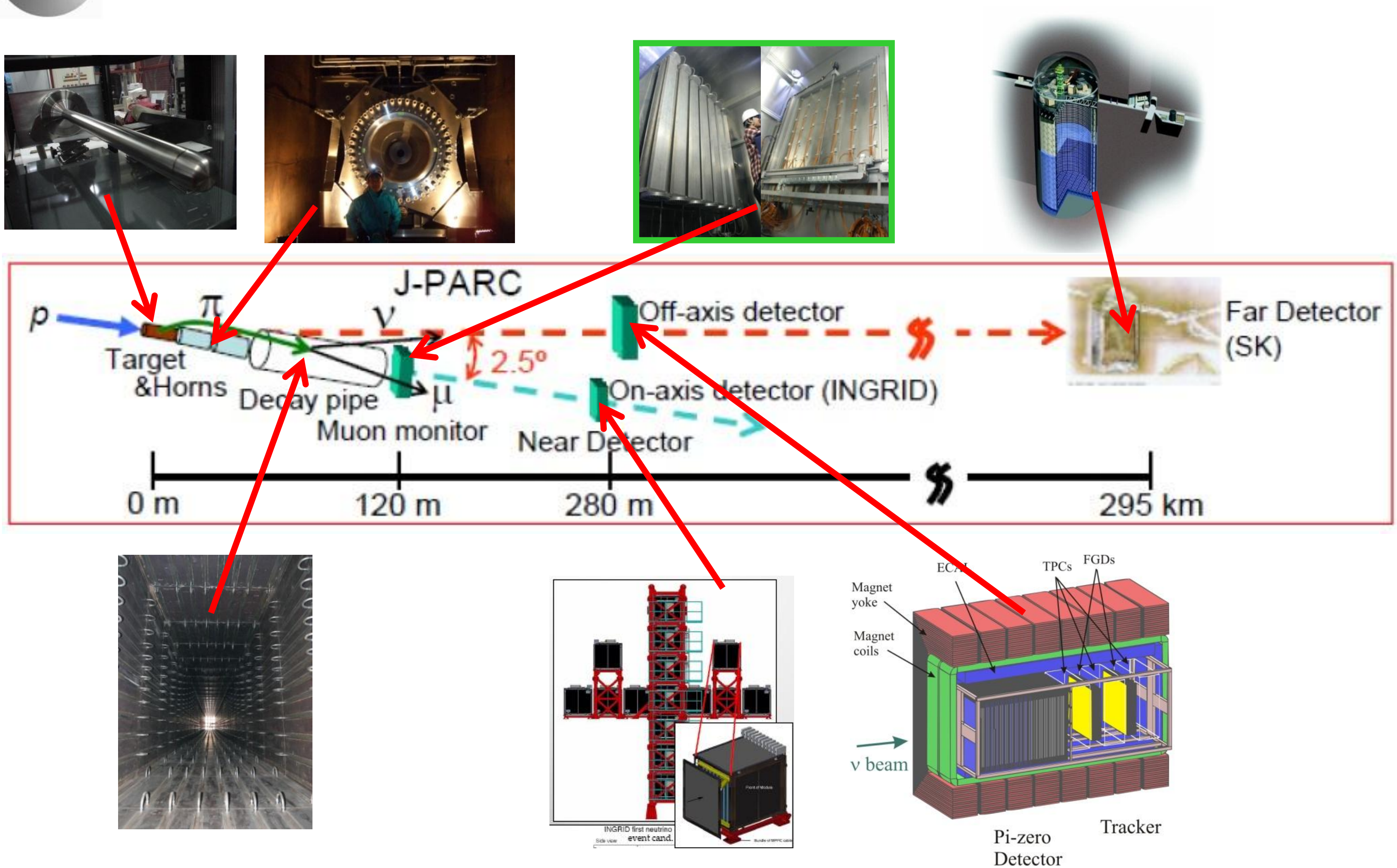
sensitive to parameter δ

containing matter effect terms - change sign for $\bar{\nu}_\mu$ - mass hierarchy

Long-Baseline Neutrino Oscillation Experiment

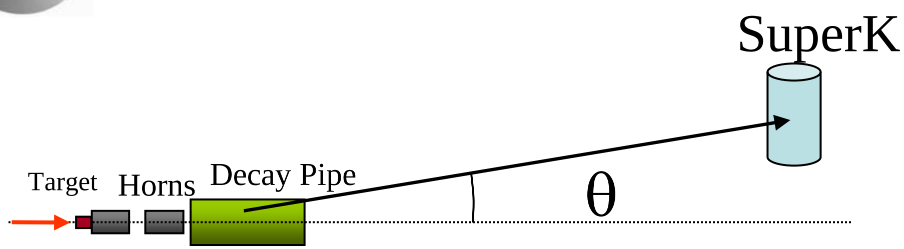


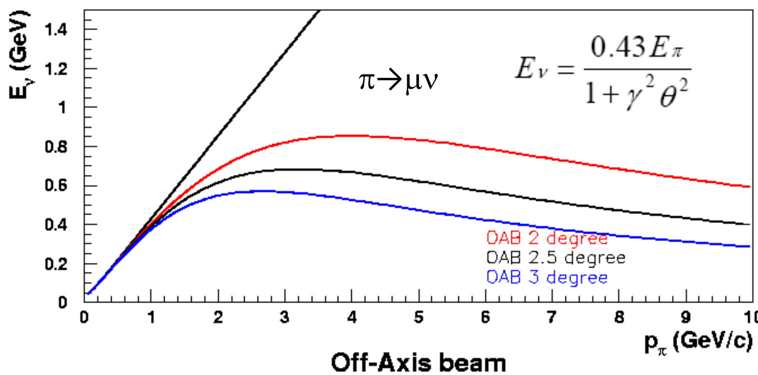
T2K layout

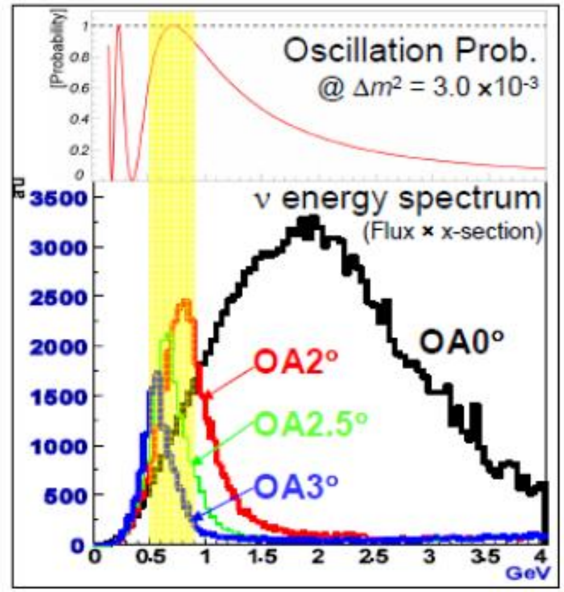


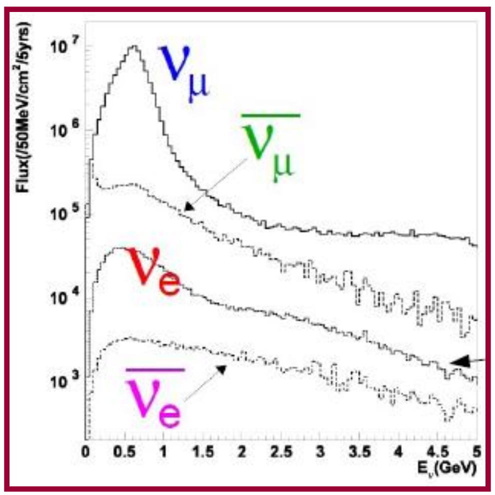
J-PARC
p
π
ν
μ
Target
&Horns
Decay pipe
Muon monitor
Off-axis detector
2.5°
On-axis detector (INGRID)
Near Detector
Far Detector
(SK)
0 m
120 m
280 m
295 km
INGRID first neutrino
event cand.
Magnet
yoke
Magnet
coils
ECAL
TPCs
FGDs
ν beam
Pi-zero
Detector
Tracker

T2K off-axis ν beam









- 750 (now 235) kW 30 GeV proton beam at JPARC
- Quasi-monochromatic ν_μ (95%) beam
- Peak energy ~700 MeV tuned to oscillation maximum
- ~0.4% ν_e at peak energy
- Reduced high energy tail → reduces background

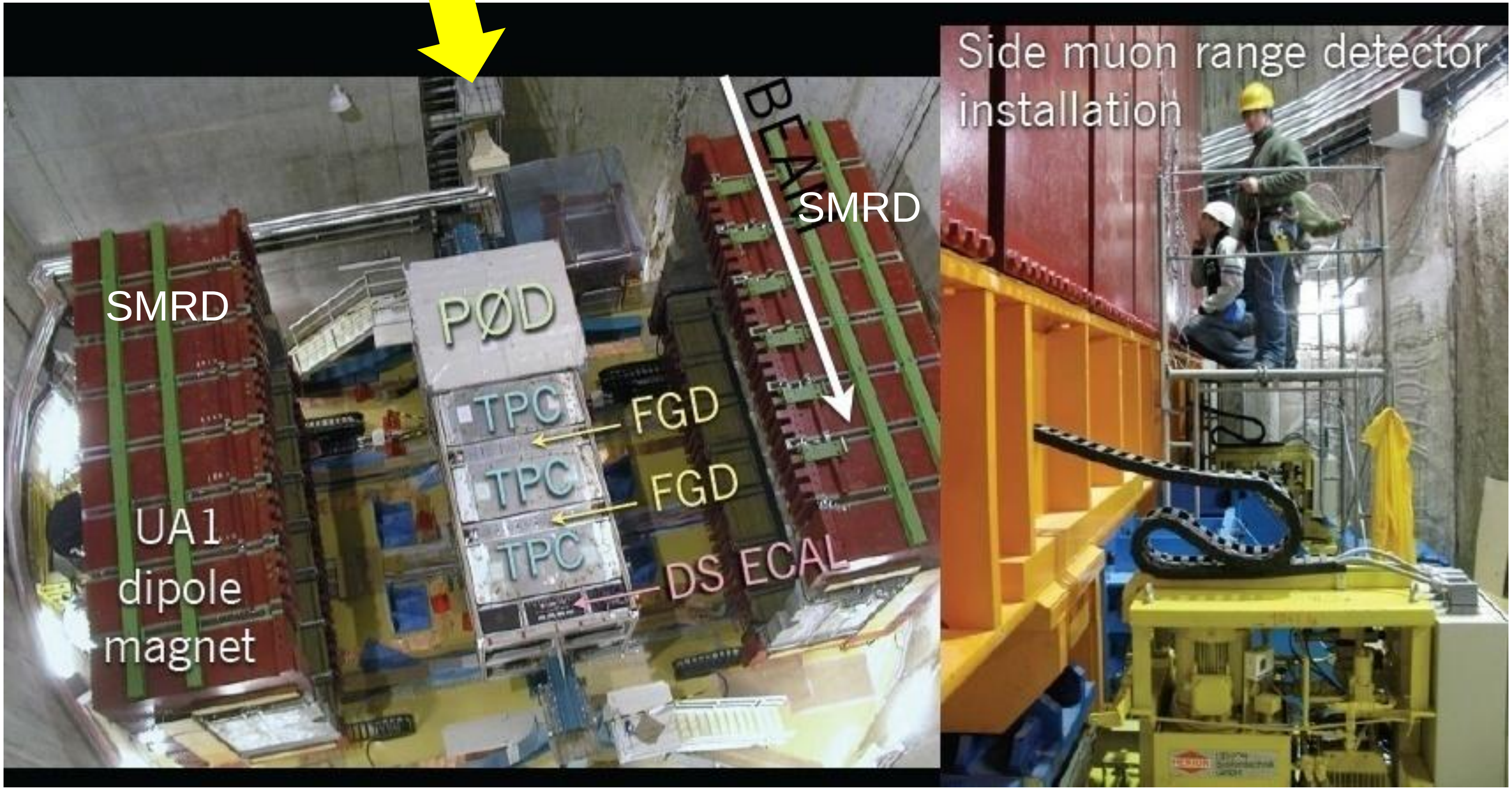
T2K can measure:
- Appearance
($\nu_\mu \to \nu_e$)
- Disappearance
($\nu_\mu \to \nu_\mu$)

Off-axis near detector (ND280)

Measurement of unoscillated ν beam,
Composition,
Normalisation,
Cross section measurements

ν beam

Completed in 2009

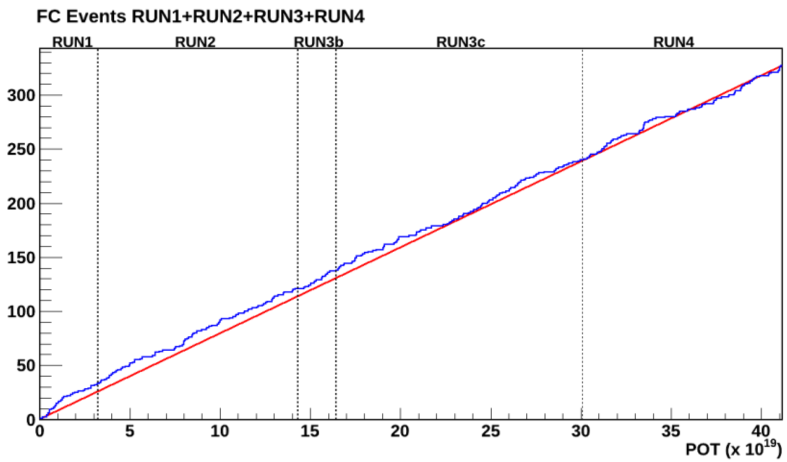


INR contribution: SMRD detector

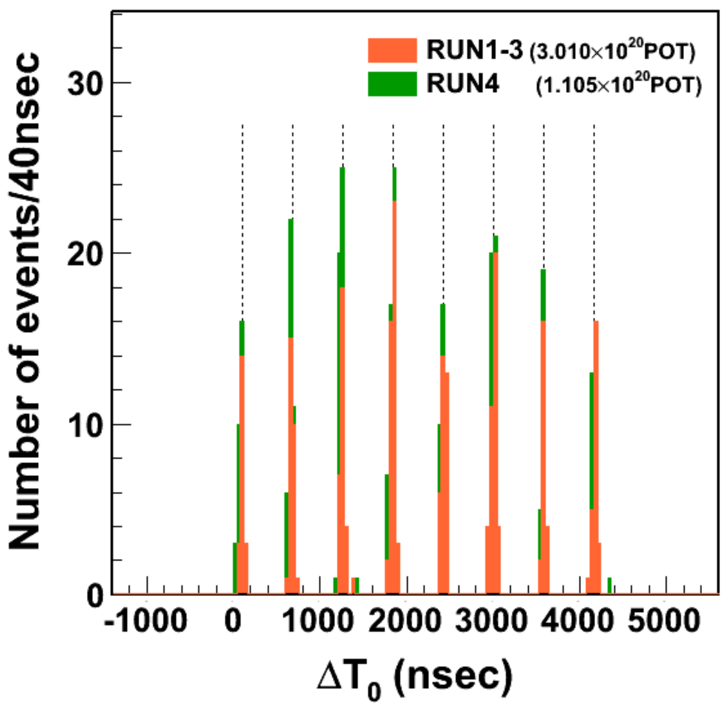
T2K events at SK

FC events for 4.5×10^{20} POT

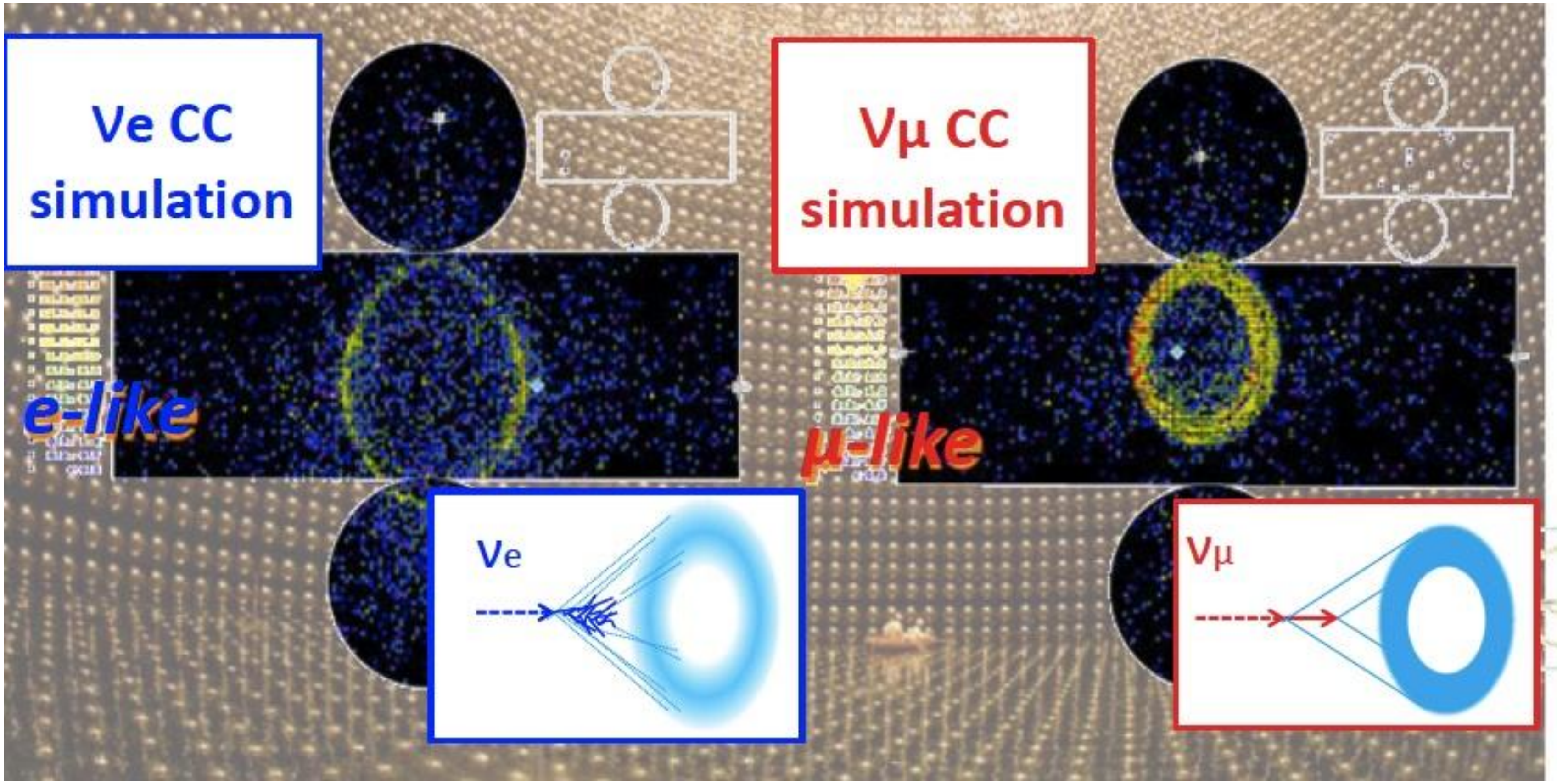
KS p-value = 65.7%



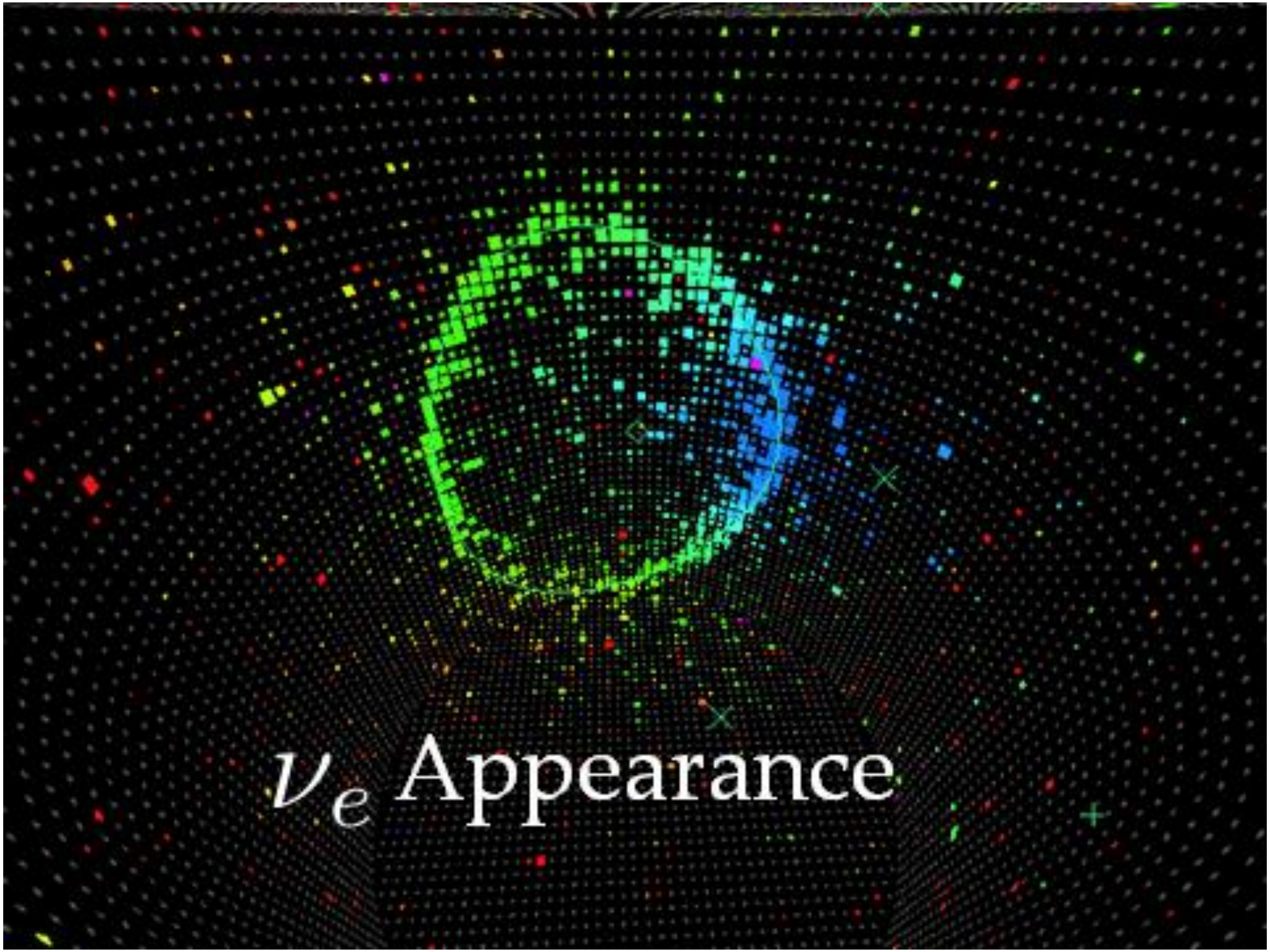
T2K neutrinos detected by SK
Timing structure (8 bunches)
of proton beam



Particle ID



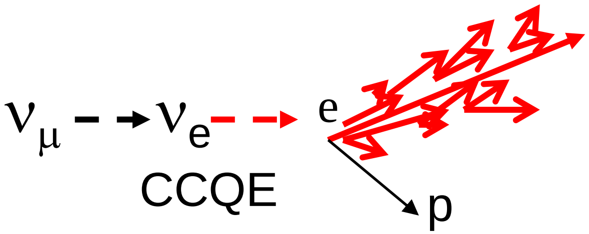
ν_μ/ν_e **misidentification probability ~ 1%**

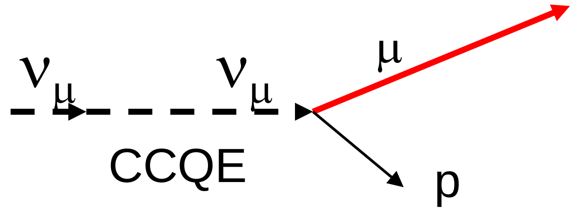

ν_e Appearance

ν_μ / ν_e events in T2K

Signals and Backgrounds

SIGNALS





electrons

EM shower

Multiple Scattering

$\rightarrow$ Ring has "fuzzy" edge

electron is relativistic

$\rightarrow$ Opening angle is maximal

muons

Low Scattering

$\rightarrow$ Ring has sharp edge

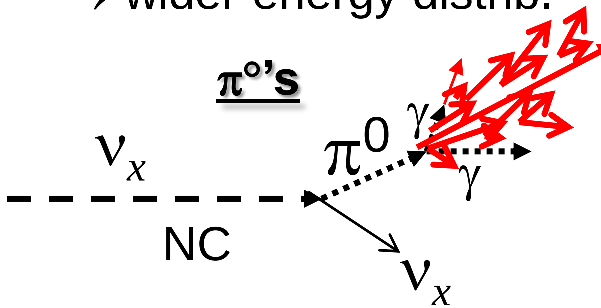
BKG

electrons

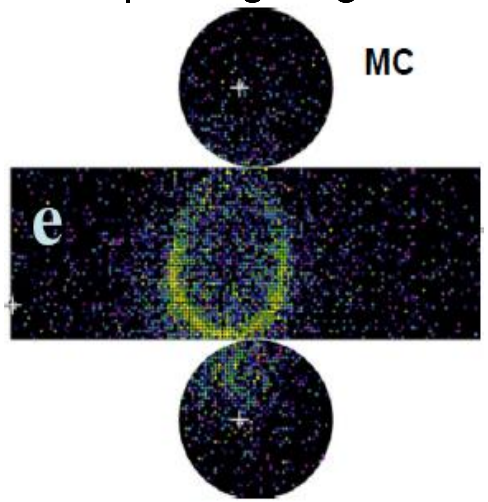
Beam intrinsic ν_e (<1%)

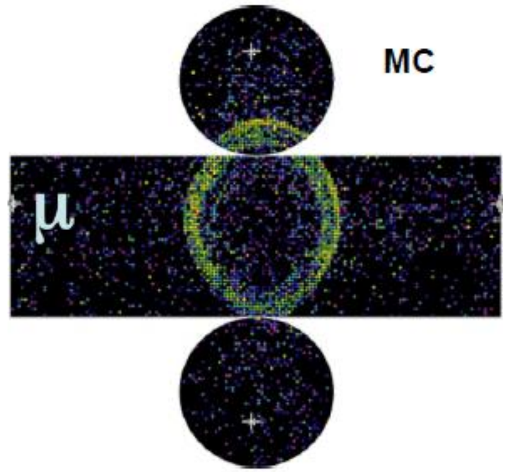
$\rightarrow$ wider energy distrib.

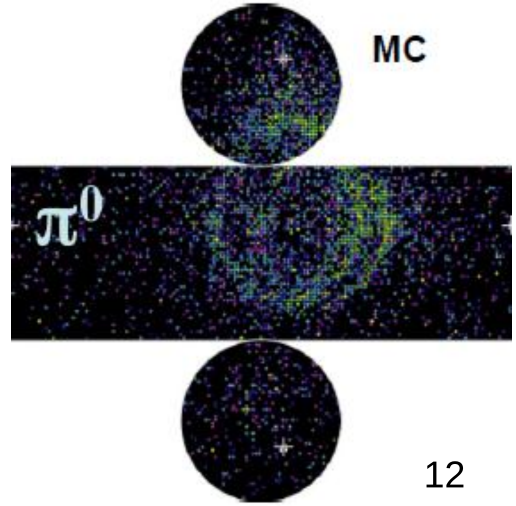
π^o's



EM showers of γ's from π° can fake an electron



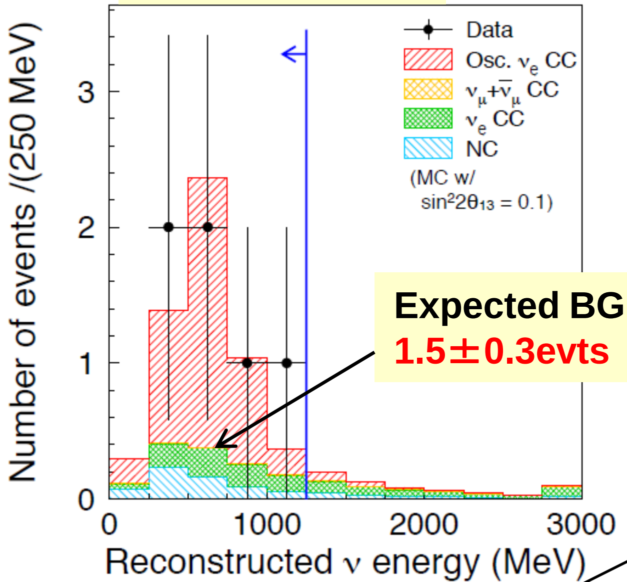




First T2K result

published in June 2011

6 ν_e events



Expected BG
1.5±0.3evts

1.43x10^{20} POT
January 2010 –
March 2011

About two years ago, T2K published FIRST clear indication of electron neutrino appearance ($\theta_{13} \neq 0$)

Then,

1 - Confirmation from MINOS

2 - Precise measurements by
Double Chooz
Daya Bay
RENO

Selected for a Viewpoint in *Physics*
PRL 107, 041801 (2011) PHYSICAL REVIEW LETTERS week ending 22 JULY 2011

Indication of Electron Neutrino Appearance from an Accelerator-Produced Off-Axis Muon Neutrino Beam

K. Abe,[49] N. Abgrall,[16] Y. Ajima,[18,†] H. Aihara,[48] J. B. Albert,[13] C. Andreopoulos,[47] B. Andrieu,[37] S. Aoki,[27] O. Araoka,[18,†] J. Argyriades,[16] A. Ariga,[3] T. Ariga,[3] S. Assylbekov,[11] D. Autiero,[32] A. Badertscher,[15] M. Barbi,[40] G. J. Barker,[56] G. Barr,[36] M. Bass,[11] F. Bay,[3] S. Bentham,[29] V. Berardi,[22] B. E. Berger,[11] I. Bertram,[29] M. Besnier,[14] J. Beucher,[8] D. Beznosko,[34] S. Bhadra,[59] F. d.M. M. Blaszczyk,[8] A. Blondel,[16] C. Bojechko,[53] J. Bouchez,[8,*] S. B. Boyd,[56] A. Bravar,[16] C. Bronner,[14] D. G. Brook-Roberge,[5] N. Buchanan,[11] H. Budd,[41] D. Calvet,[8] S. L. Cartwright,[44] A. Carver,[56] R. Castillo,[19] M. G. Catanesi,[22] A. Cazes,[32] A. Cervera,[20] C. Chavez,[30] S. Choi,[43] G. Christodoulou,[30] J. Coleman,[30]

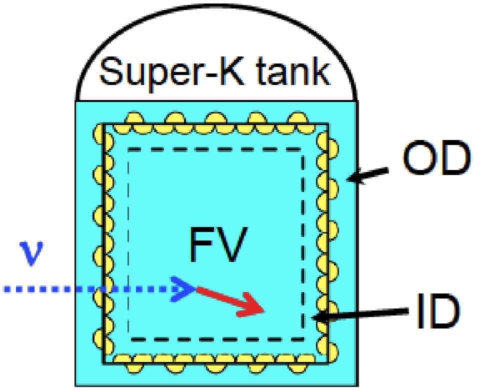
The T2K experiment observes indications of $\nu_\mu \to \nu_e$ appearance in data accumulated with 1.43×10^{20} protons on target. Six events pass all selection criteria at the far detector. In a three-flavor neutrino oscillation scenario with $|\Delta m^2_{23}| = 2.4 \times 10^{-3}$ eV^2, $\sin^2 2\theta_{23} = 1$ and $\sin^2 2\theta_{13} = 0$, the expected number of such events is 1.5 ± 0.3(syst). Under this hypothesis, the probability to observe six or more candidate events is 7×10^{-3}, equivalent to 2.5σ significance. At 90% C.L., the data are consistent with $0.03(0.04) < \sin^2 2\theta_{13} < 0.28(0.34)$ for $\delta_{CP} = 0$ and a normal (inverted) hierarchy.

DOI: 10.1103/PhysRevLett.107.041801 PACS numbers: 14.60.Pq, 13.15.+g, 25.30.Pt, 95.55.Vj

Selection of ν_e events

T2K statistics for 3.1×10^{20} POT

- Event time compatible with expected arrival time
- Fully contained in the fiducial volume (>2m from the wall)



FV : Fiducial Volume
> 2m from wall

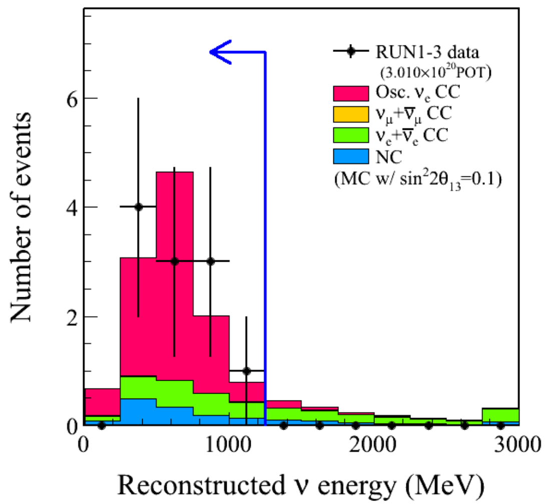
ν_e events

Fully-contained events with:

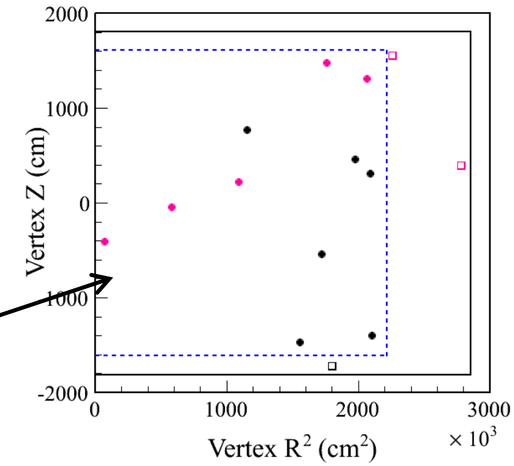
- **1 electron-like ring**
- **No decay electron**
- **No pi0-like invariant mass from 2nd ring**
- **100 MeV < Energy < 1250 MeV**

ν_e events

Energy spectra of ν_e events

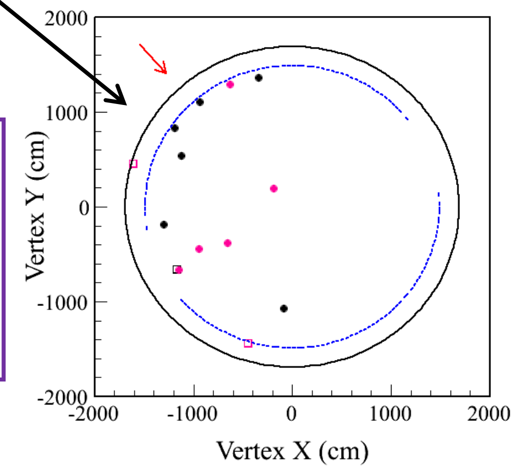


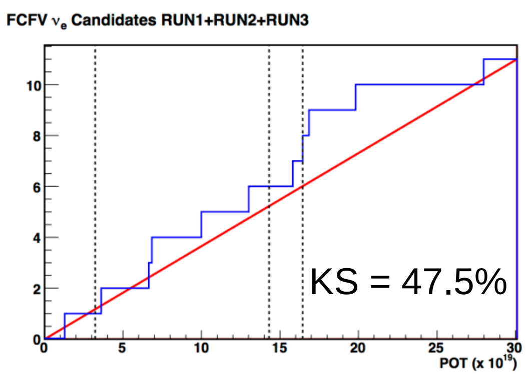
3.01x10^{20} POT
Statistics accumulated from January 2010 to July 2012



● Run1 + Run2 + ● Run3

p-value = 6%





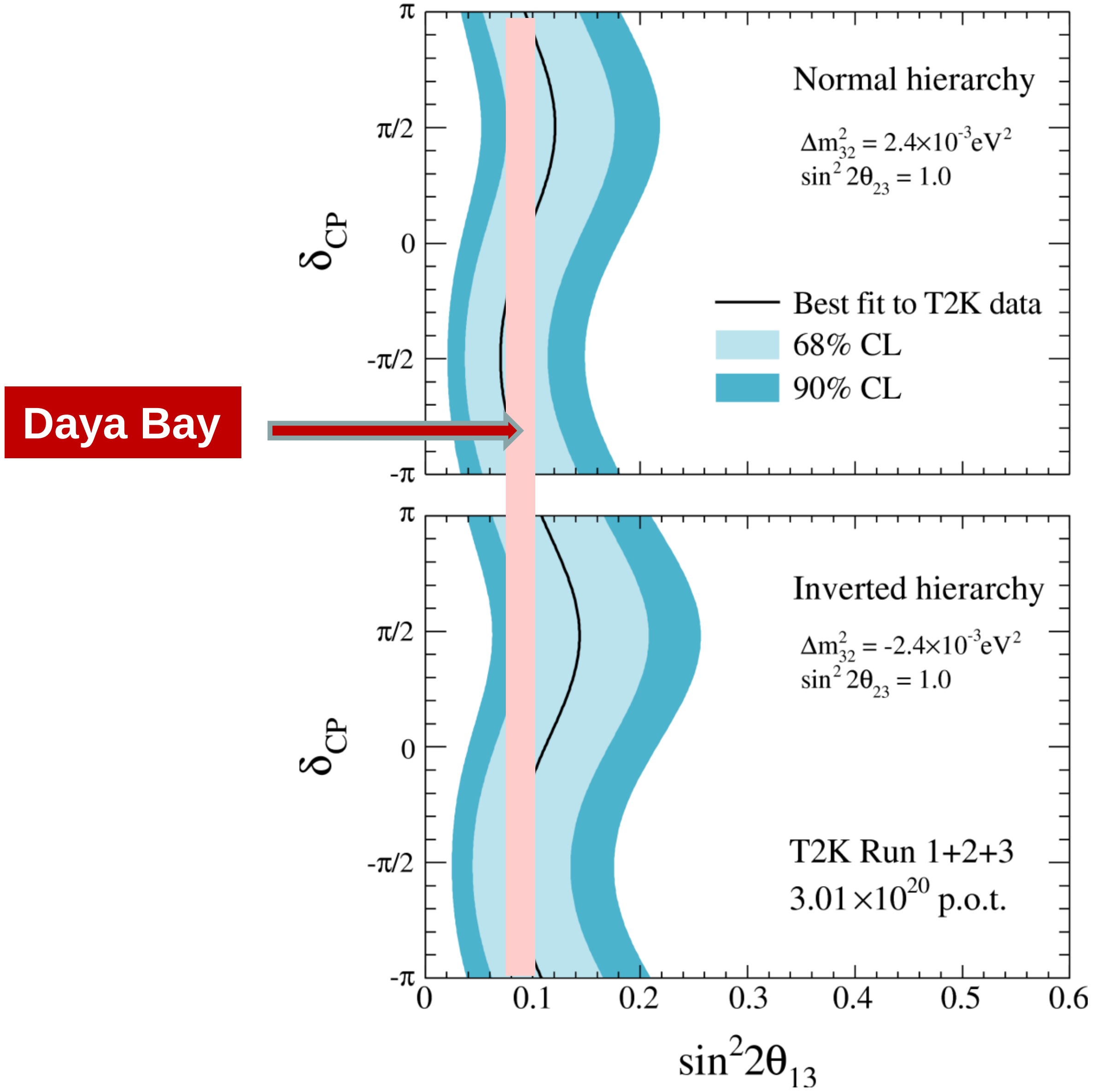
Event Category	$\sin^2 2\theta_{13} = 0$	$\sin^2 2\theta_{13} = 0.1$
Total	**3.22 ± 0.43**	**10.71 ± 1.10**
ν_e Signal	0.18	7.79
Intrinsic ν_e Background	1.67	1.56
ν_μ Background (mostly π^0)	1.12	1.12
$\bar{\nu}_e + \bar{\nu}_\mu$ Background	0.16	0.16

Detected 11 evens
Expected 3.3 ±0.4(syst) events
for θ_{13}=0, NH and δ = 0

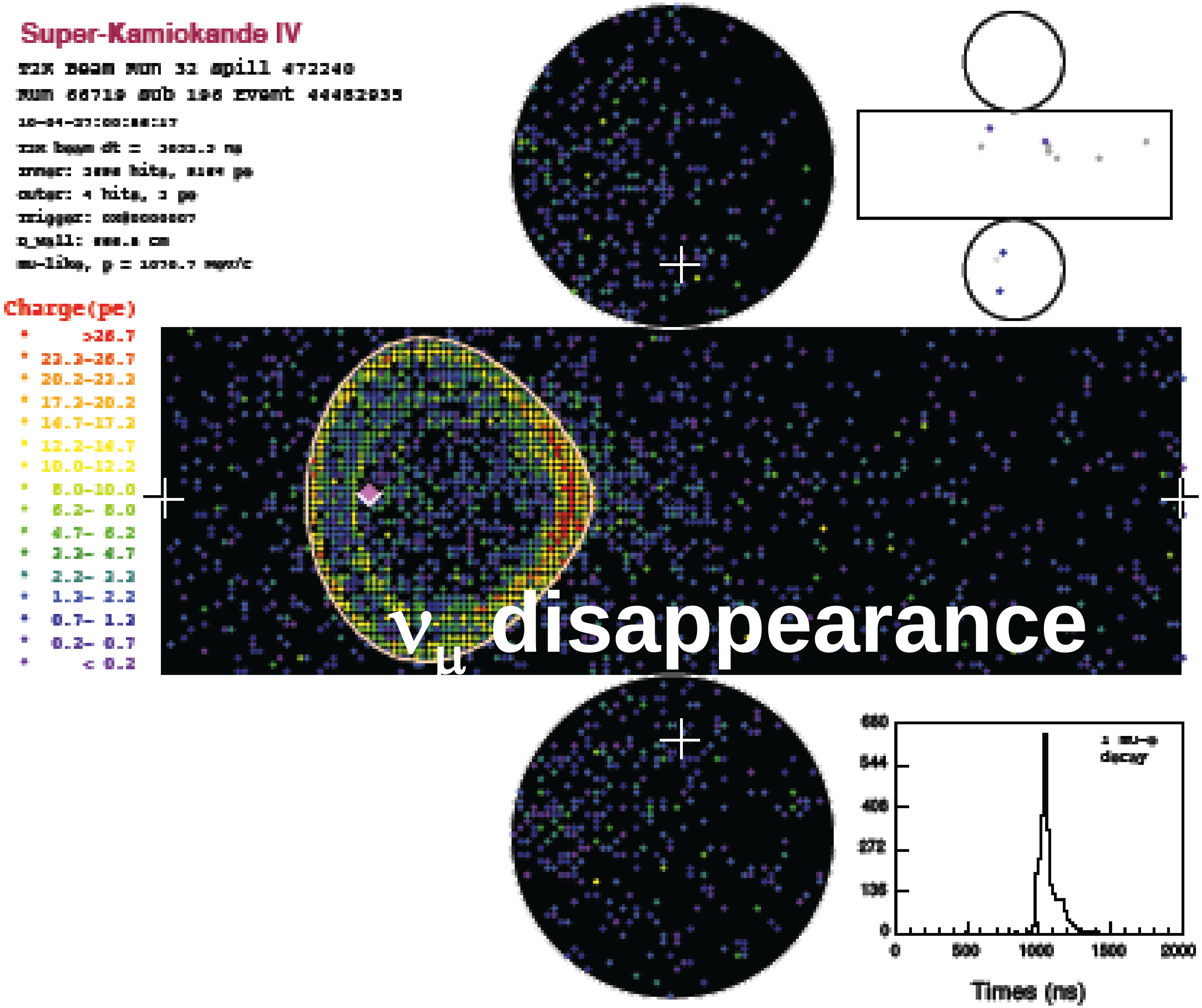
3.1σ observation of $\nu_\mu \rightarrow \nu_e$

T2K Collaboration, arXiv:1304.0841

θ_{13} and δ



ν_μ disappearance



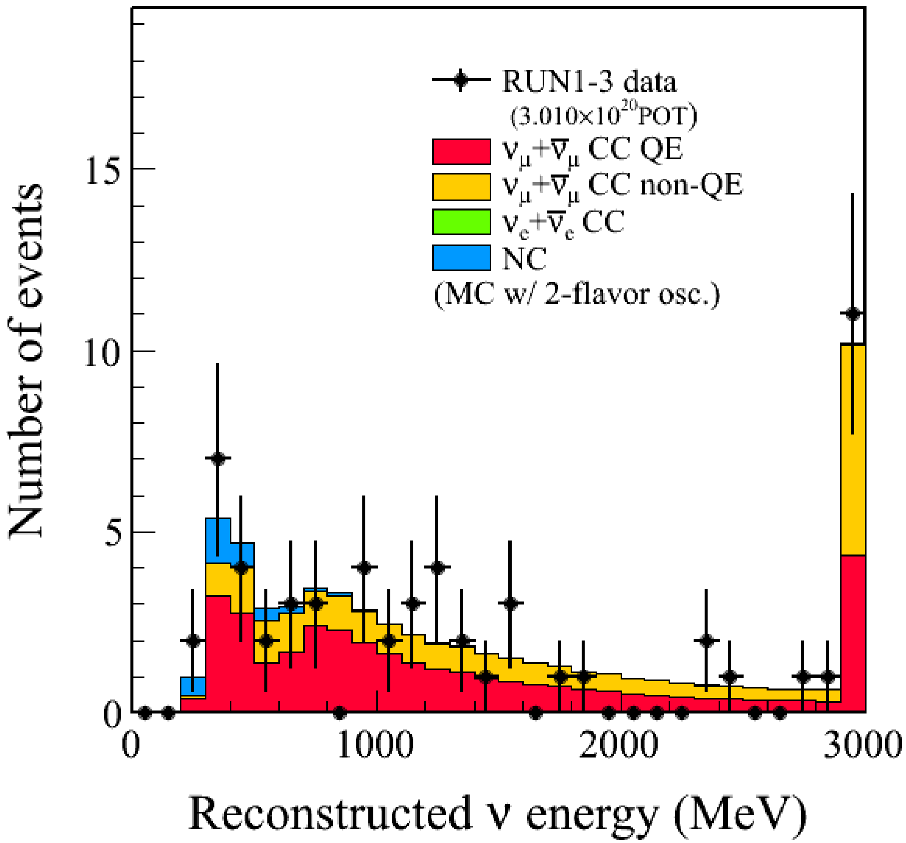
ν_μ events

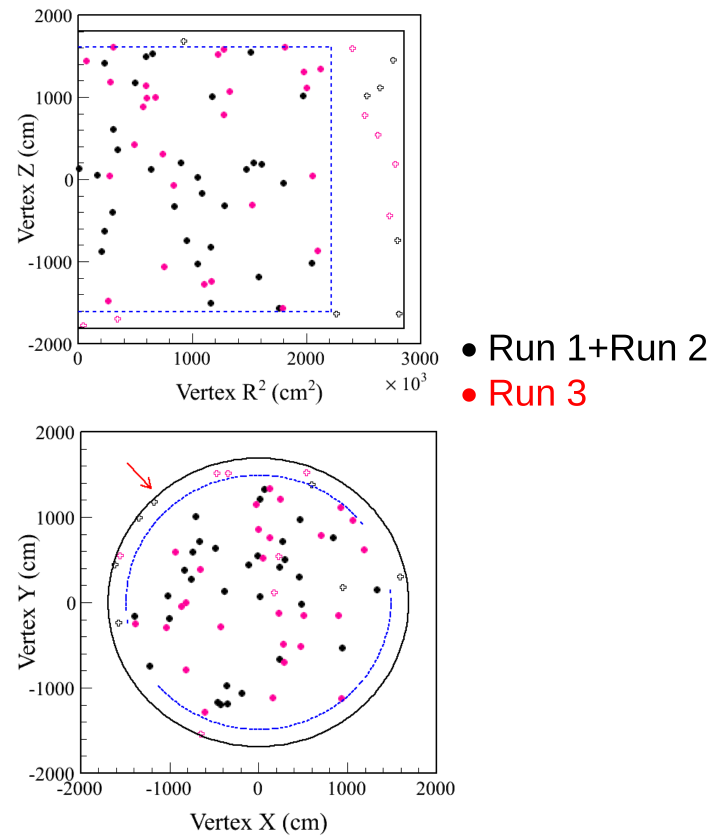
3.1x10[20] POT

Measurement: 58 events observed

Monte Carlo: 196.2 events no oscillations

Monte Carlo: 57.8 events with oscillations

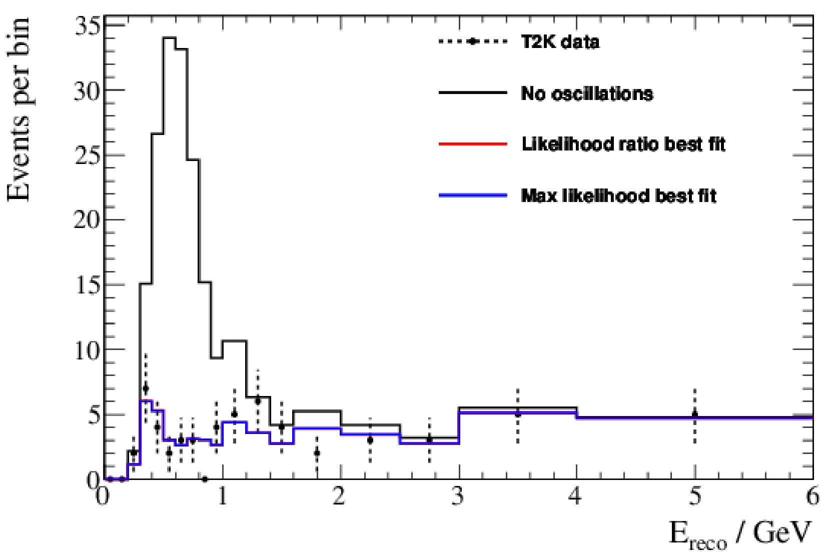


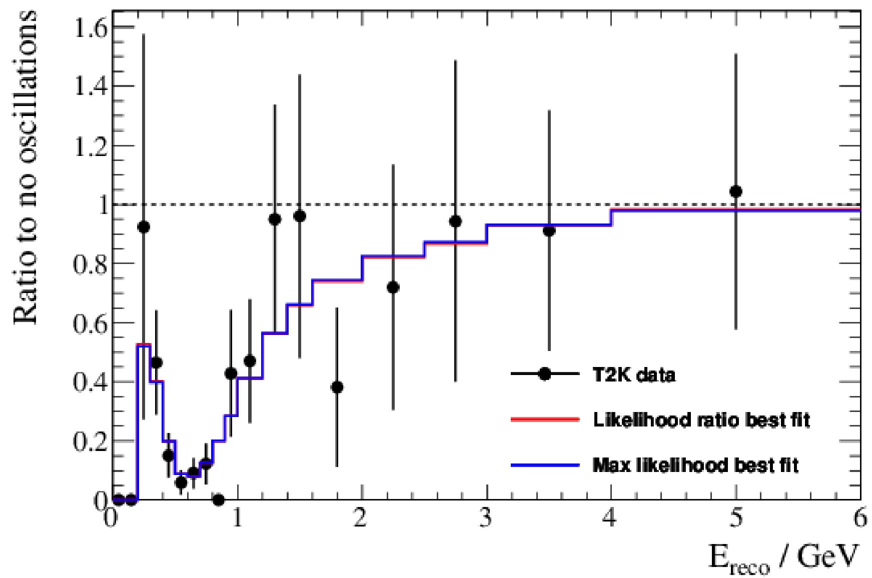


Oscillation fit

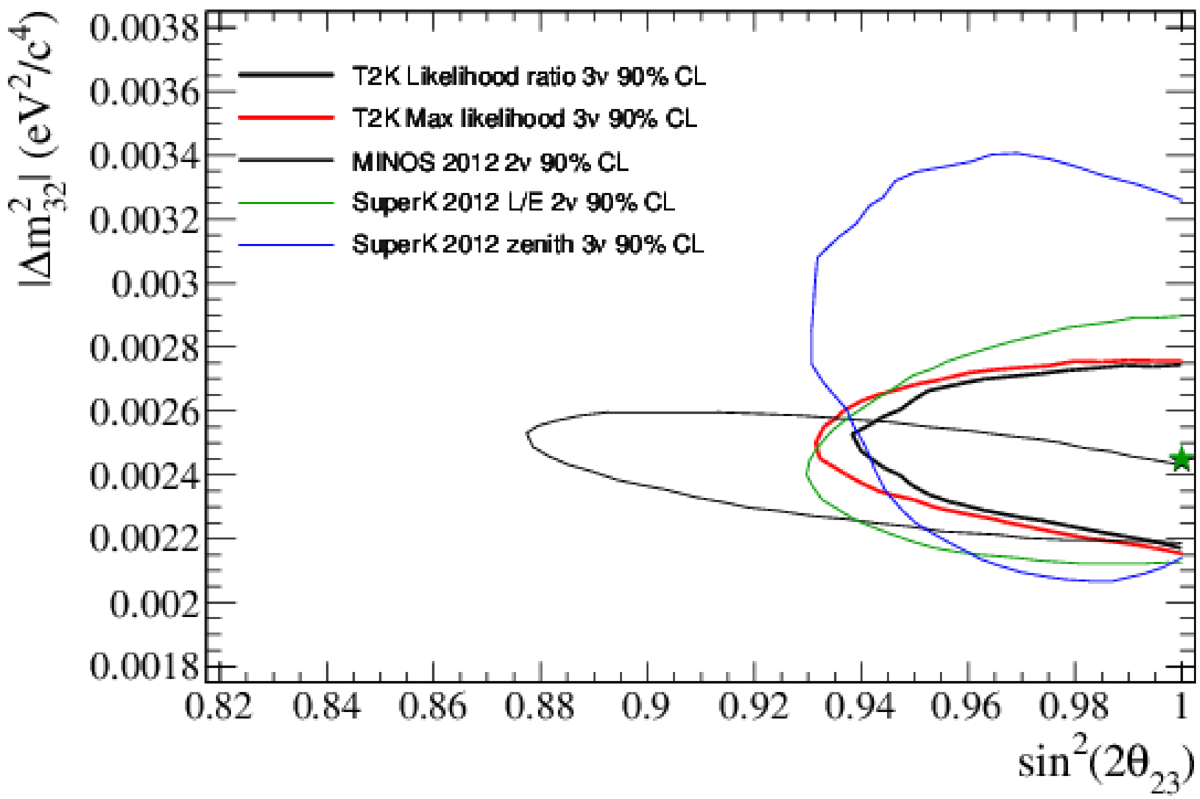
Maximum Likelihood fit

Best fit results: $\sin^2 2\theta_{23} = 1.00$ $\Delta m^2_{32} = 2.45 \times 10^{-3}\mathrm{eV}^2$





"Atmospheric" parameters



T2K obtained best sensitivity to mixing angle θ_{23}

Method	Δm^2_{32} (x 10^{-3} eV^2/c^4)	$\sin 2(2\theta_{23})$
Likelihood Ratio	2.443	1.0
Max. Likelihood	2.45	1.0

90% CL

$$2.14 \times 10^{-3} eV^2 < |\Delta m^2_{32}| < 2.76 \times 10^{-3} eV^2$$

$$\sin^2 2\theta_{23} > 0.957$$

Neutrino Mixing

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

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

Atmospheric:	$38^o < \theta_{23} < 52^o$	**Super-K, MINOS**
CP sector:	$\theta_{13} = (9 \pm 0.6)^o$	**Daya Bay, Reno, DChooz, T2K, MINOS**
Solar:	$\theta_{12} = (34 \pm 1)^o$	**SNO, KamLAND**

$\theta_{23} = \pi/4$, or $> \pi/4$, or $< \pi/4$??

T2K $\rightarrow$ best precision for θ_{23}

J_{CP}

$\theta_{13} \neq 0$

Strength of CP violation in neutrino oscillations

Jarkslog invariant J_{CP}

$$J_{CP} = \mathrm{Im}(U_{e1}U_{\mu 2}U^*_{e2}U^*_{\mu 1}) = \mathrm{Im}(U_{e2}U_{\mu 3}U^*_{e3}U^*_{\mu 2}) =$$

$$= \cos\theta_{12}\sin\theta_{12}\cos^2\theta_{13}\sin\theta_{13}\cos\theta_{23}\sin\theta_{23}\sin\delta$$

all mixing angles $\neq 0 \rightarrow J_{CP} \neq 0$ if $\delta \neq 0$

Quark sector $J_{CP} \approx 3\times 10^{-5}$

Lepton sector $J_{CP} \sim 0.02\times\sin\delta$

neutrinos

$$V_{MNS} \sim \begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

quarks

$$V_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{pmatrix}$$

Real chance to test CP violation in neutrino oscillations

Large θ_{13} $\rightarrow$ T2K next step?

Next goal:

High statistics with muon ν's, anti-ν run $\rightarrow$ Initial search for CP violation

Leading

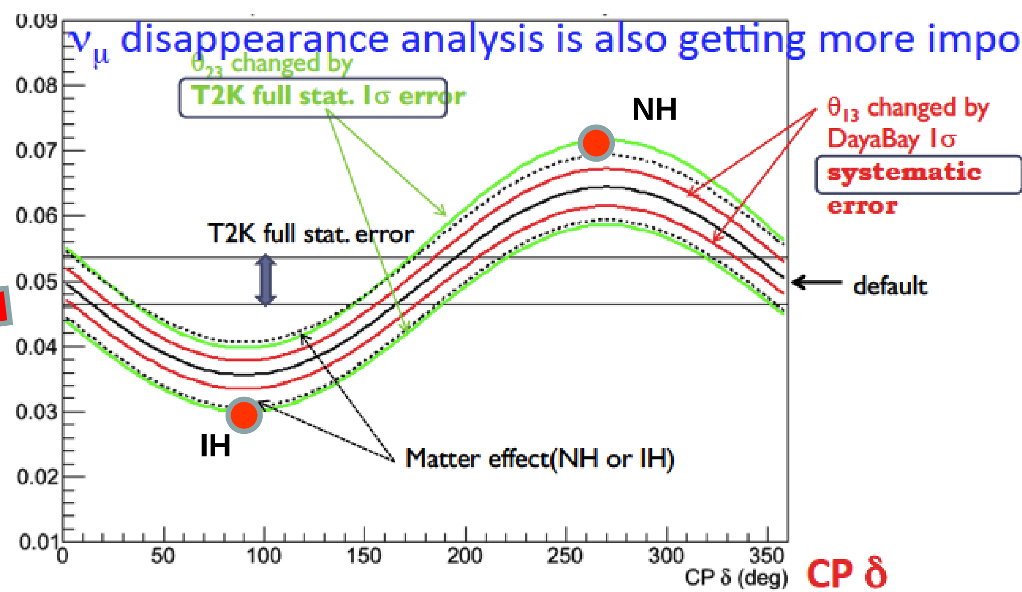
CP violating (flips sign for $\bar{\nu}$)

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

Solar

Matter effect

$P(\nu_\mu \rightarrow \nu_e)$



Chance to find *a hint* on CP violation, in case:

IH and $\delta \sim \pi/2$

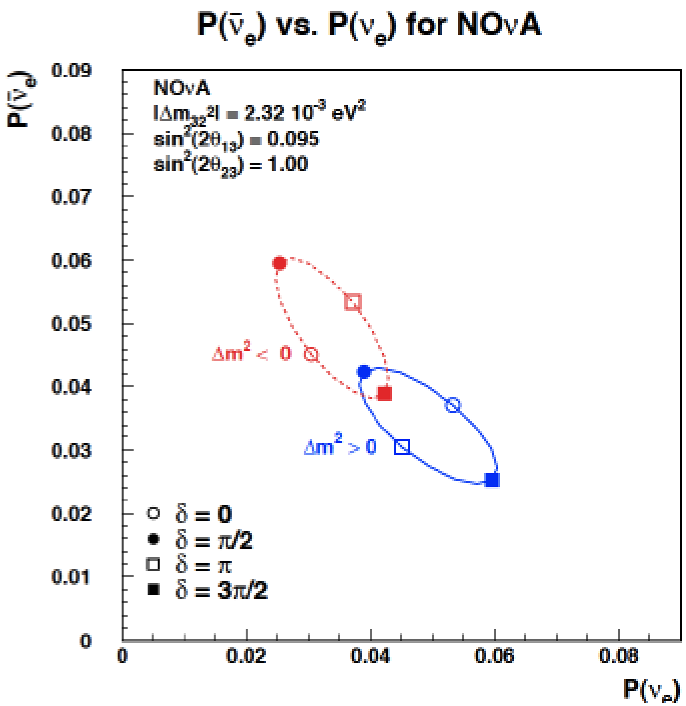
NH and $\delta \sim 3\pi/2$

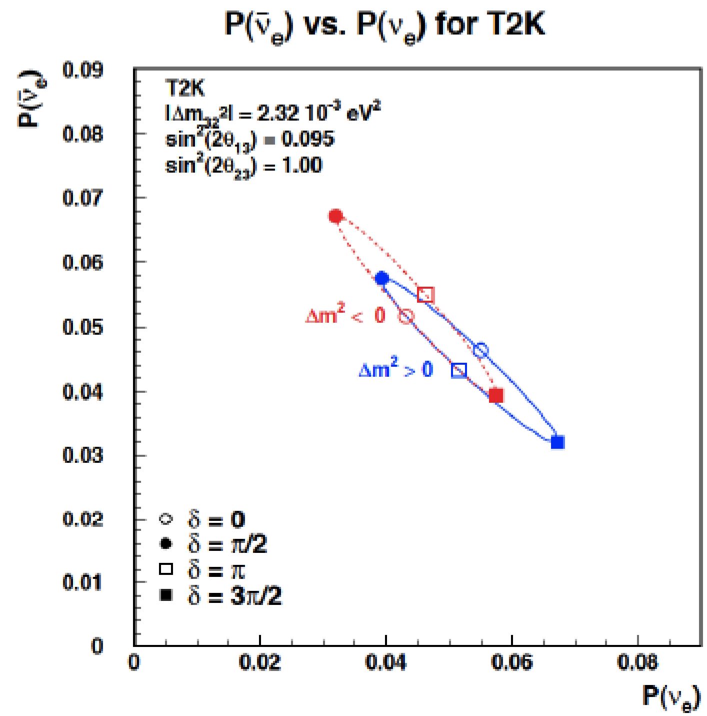
T2K and Nova (I)

G.Feldman, LBNE Workshop, 2012

Nova, neutrinos from FNAL

Possible measurement of mass hierarchy and CP violation





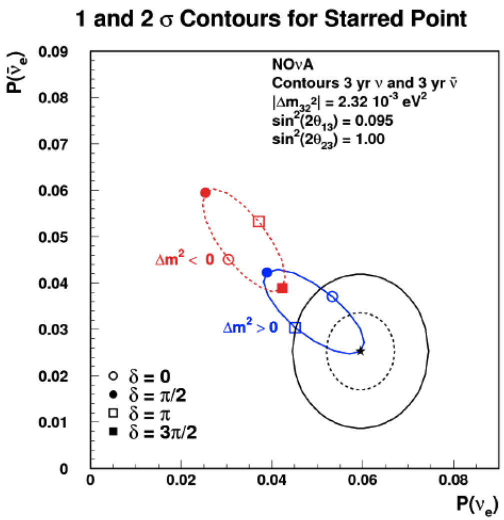
For $\sin^2 2\theta_{13}=0.1$, approximately (at 90%C.L.):

- MH: ≈50% coverage
- CPV: ≈30-40% coverage

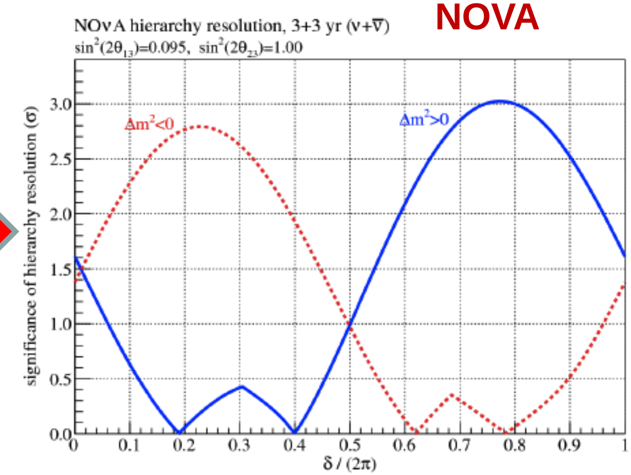
T2K and Nova (II)

Example of
NOVA result for:
3 years of nu beam
3 years of anti-nu beam

assumption
$\sin^2 2\theta_{13} = 0.1$
$\sin^2 2\theta_{23} = 1.0$

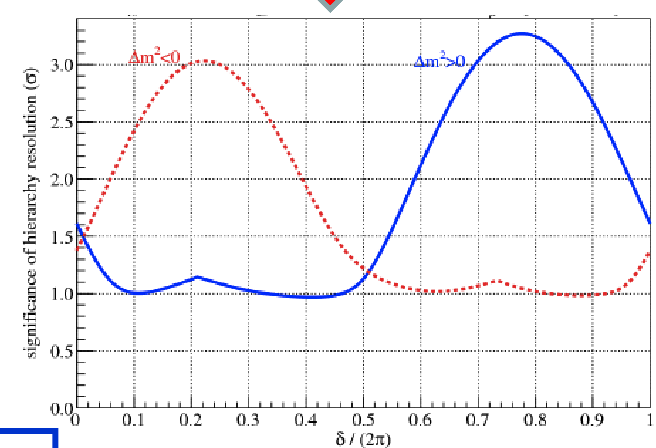


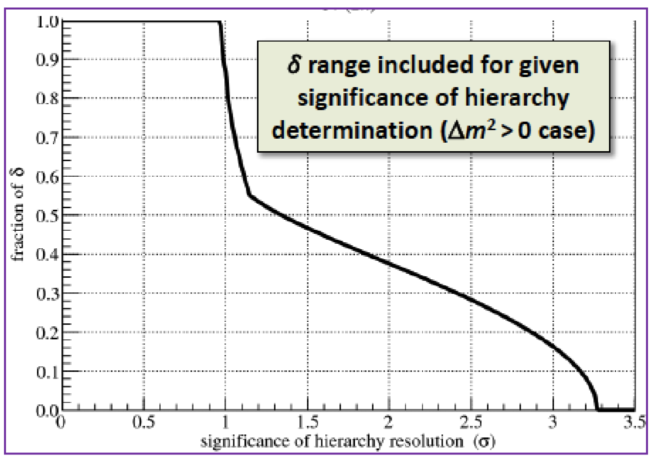
NOVA



T2K: 5.5×10^{21} POT

Combined NOVA + T2K





MH significance of 2.5σ for only ~30% of δ

Conclusion

- **T2K:**
  - **Observation of $\nu_\mu \to \nu_e$ appearance at 3.1σ significance**
  - **Precision measurement of "atmospheric" parameters**
  - **Continue data taking. Expected to accumulate 7.5×10^{20} POT by August 2013 $\to$ $> 5\sigma$ significance for $\nu_\mu \to \nu_e$**

- **Large θ_{13} opens door for searching of CP-violation in lepton sector**

- **Time to start MH and δ measurements** спасибо за внимание!