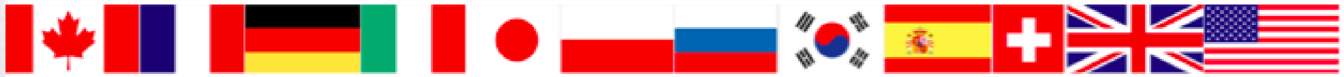
T2K実験の新しい結果
New Results from the T2K Experiment

2012/July/10

T. Ishii

for the T2K collaboration

T2K Collaboration



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] W. Coleman,[31] G. Collazuol,[24] K. Connolly,[57] A. Curioni,[15] A. Dabrowska,[17] I. Danko,[38] R. Das,[11] G. S. Davies,[29] S. Davis,[57] M. Day,[41] G. De Rosa,[23] J. P. A. 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+ J. Caravaca, Y. Kanazawa, P. Sinclair, O. Perevozchikov

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U. Pittsburgh
U. Rochester
Stony Brook U.
U. Washington

~500 physicists
from 12 countries

T2K (Tokai-to-Kamioka) experiment

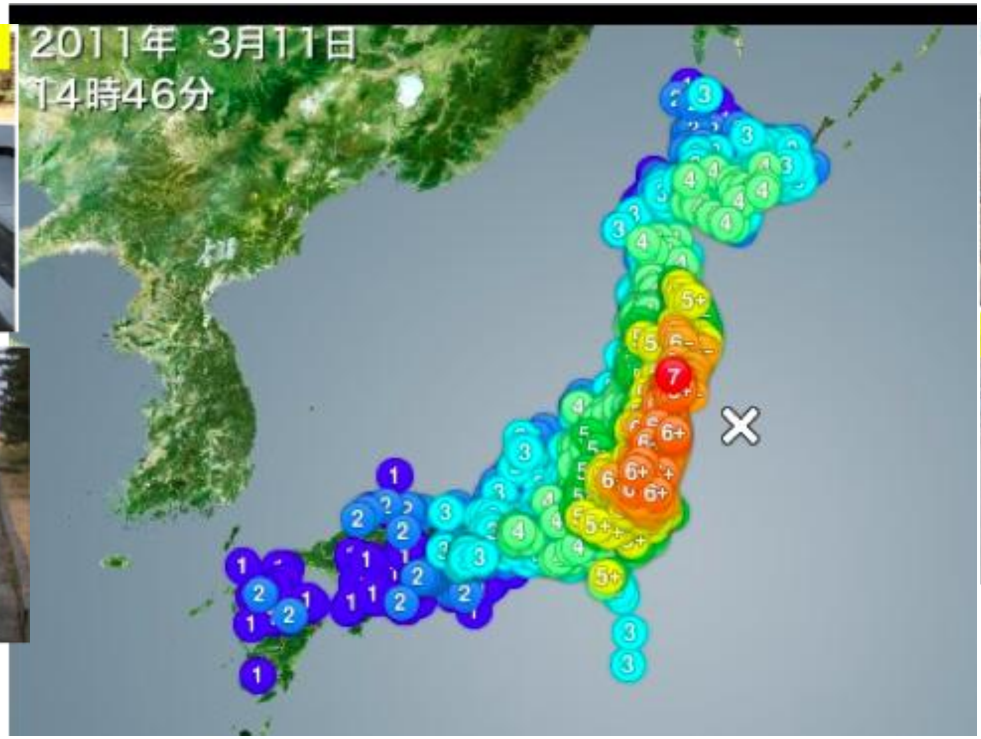
T2K Main Aims:

★ Discovery of $\nu_\mu \rightarrow \nu_e$ oscillation (ν_e appearance)

★ **Precision measurement of ν_μ disappearance**

2011 ν_μ results : Phys.Rev. D 85, 031103(R), 2012

T2K/J-PARC recovery after the BIG earthquake on March 11, 2011



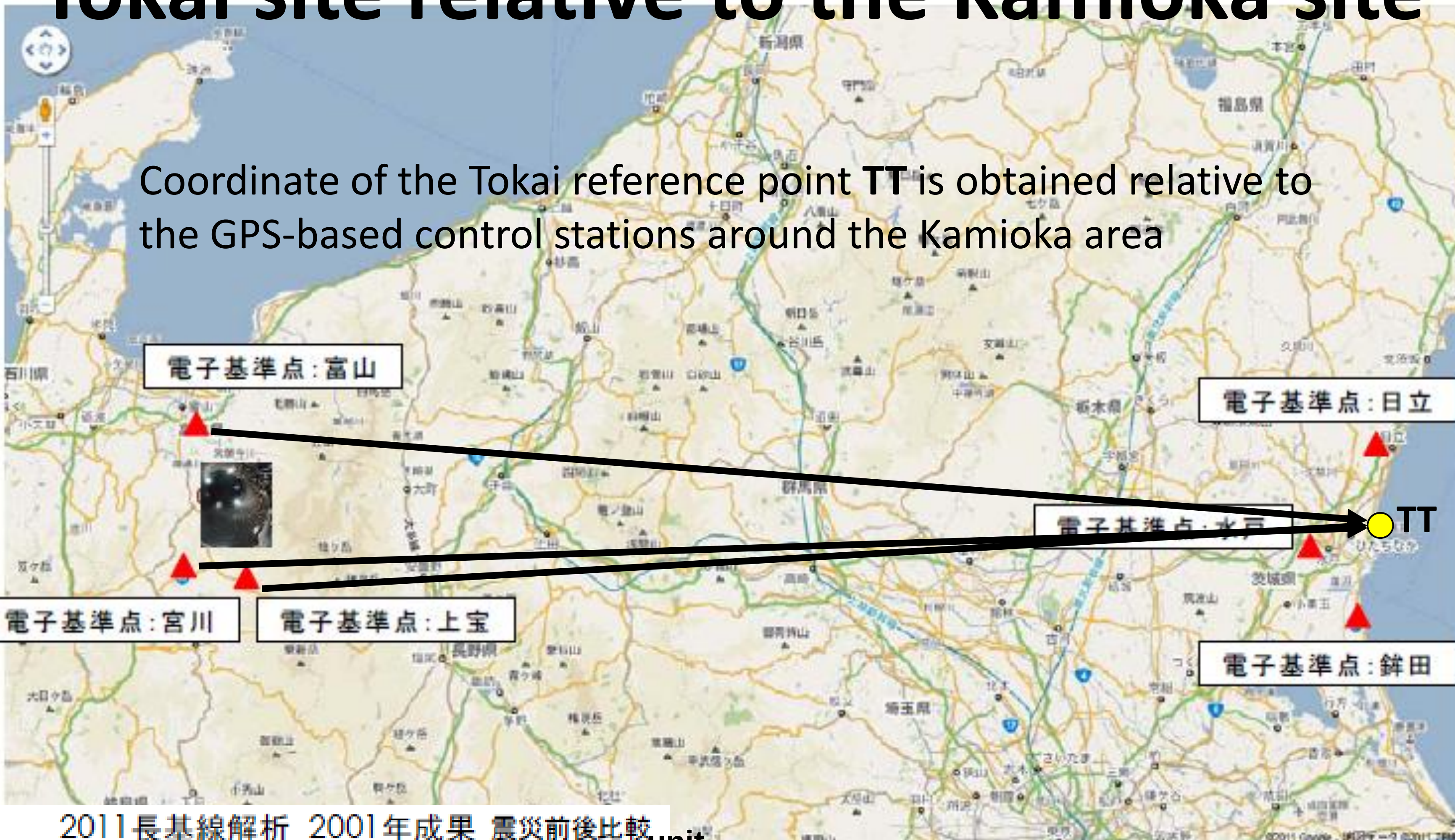
09:30 Key was on.

On Dec.9, 2011, J-PARC LINAC operation restarted!!!
On Dec.24, 2011, Neutrino events were observed at T2K-ND280!!

- 復旧にご協力いただいたKEK内外の方、特に加速器及び施設関係の皆様に深く感謝します。

Check of the displacement of the Tokai site relative to the Kamioka site

Coordinate of the Tokai reference point **TT** is obtained relative to the GPS-based control stations around the Kamioka area



2011長基線解析　2001年成果　震災前後比較

unit in *m*

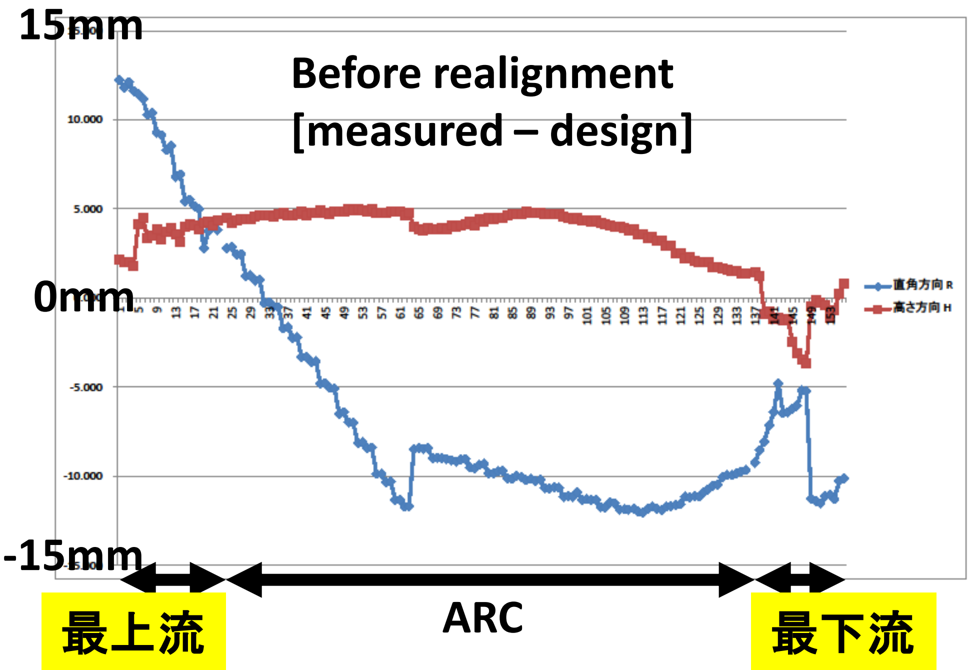
	(B)	(A)	(B)-(A)
X	50779.644	50779.805	-0.161
Y	69322.500	69321.594	0.906
H	33.894	34.250	-0.356

TT moved south by 16cm, east by 91cm and down by 36cm. (systematic error is ~30cm) Rotation was within 0.03mrad.

One example of the recovery work

一次ビームライン

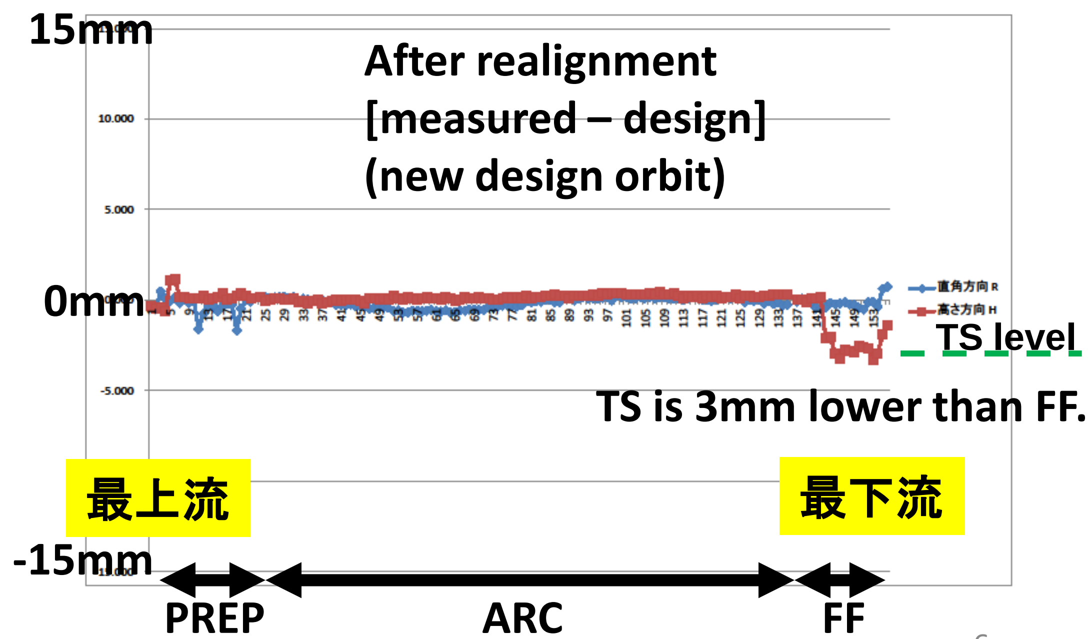
primary-beamline magnets were realigned



Realignment was done based on the May 2011 survey results.
The beam orbit was also redesigned.

--- ΔR :horizontal direction

--- ΔH :height



Introduction

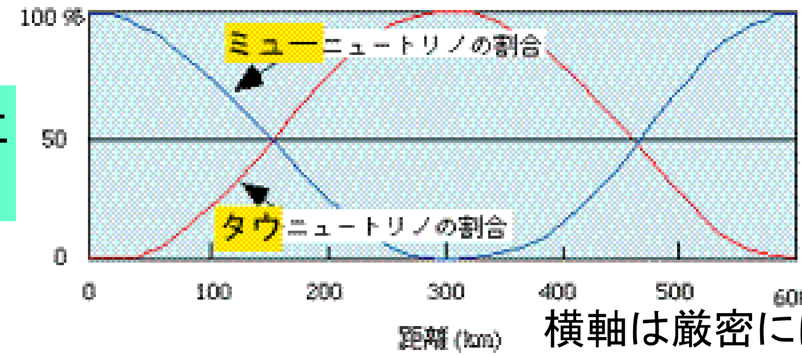
ニュートリノ振動

現象

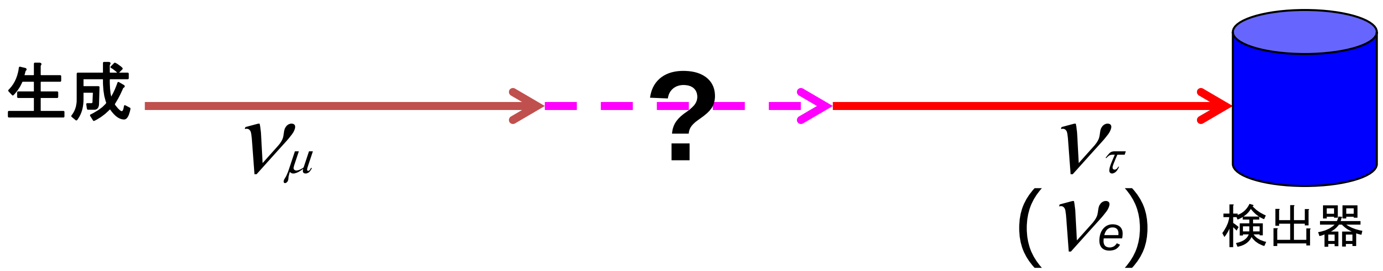
ニュートリノは3種類ある。$(\nu_e, \nu_\mu, \nu_\tau)$

ある種類のニュートリノが飛行中に他の種類に周期的に変化する。

（加速器ではν_μができる）



横軸は厳密にはL/E



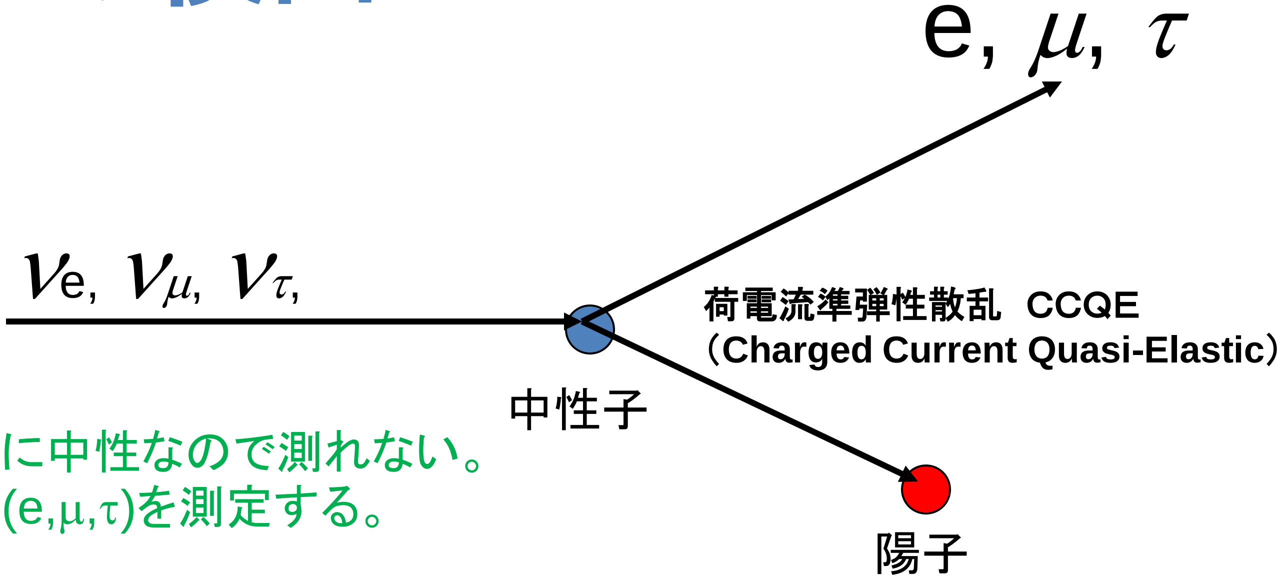
T2Kの場合、Lは一定なのでエネルギー分布を調べることになる

- 量子力学的効果（質量の固有状態の混合状態）
- ニュートリノが質量を持たないと起こらない。

量子力学のマクロの世界への発現であり
非常に小さいニュートリノ質量を測るほとんど唯一の方法

ニュートリノの検出

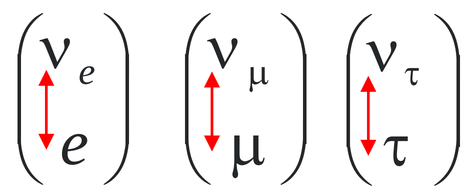
代表的な反応



ニュートリノ自身は電気的に中性なので測れない。
反応でできた荷電レプトン(e,μ,τ)を測定する。

エネルギー閾値

(荷電レプトンは重いので
エネルギー保存則より)



$\nu_e \rightarrow e$ $:E_\nu > 0.5\text{MeV}$

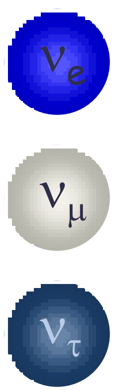
$\nu_\mu \rightarrow \mu$ $:E_\nu > 110\text{MeV}$

$\nu_\tau \rightarrow \tau$ $:E_\nu > 3.5\text{GeV}$

T2Kの場合、ピークエネルギーが
1GeV以下のナローバンドビーム
なので ν_τ はこの反応(荷電流反
応)を起こさない。

ニュートリノの3世代混合

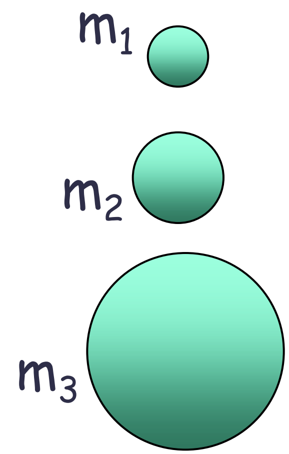
フレーバー固有状態



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \mathrm{U}_{\mathrm{MNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

ユニタリー行列

質量固有状態



$$\mathrm{U}_{\mathrm{MNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & +c_{23} & +s_{23} \\ 0 & -s_{23} & +c_{23} \end{pmatrix} \begin{pmatrix} +c_{13} & 0 & +s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & +c_{13} \end{pmatrix} \begin{pmatrix} +c_{12} & +s_{12} & 0 \\ -s_{12} & +c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

大気、加速器　　加速器、原子炉、(大気)　　太陽、原子炉

ニュートリノ振動をつかさどる6個のパラメータ

θ_{12}, θ_{23}, θ_{13}, δ

$\Delta m_{12}{}^2$, $\Delta m_{23}{}^2$, $\Delta m_{13}{}^2$

未知！

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

$\Delta m_{ij} = m_i{}^2 - m_j{}^2$

Physics Motivation

★Discovery of $\nu_\mu \rightarrow \nu_e$ oscill.

This is a direct detection of neutrino flavor mixing in "appearance" mode

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2(\Delta m^2_{31} L/4E)$$

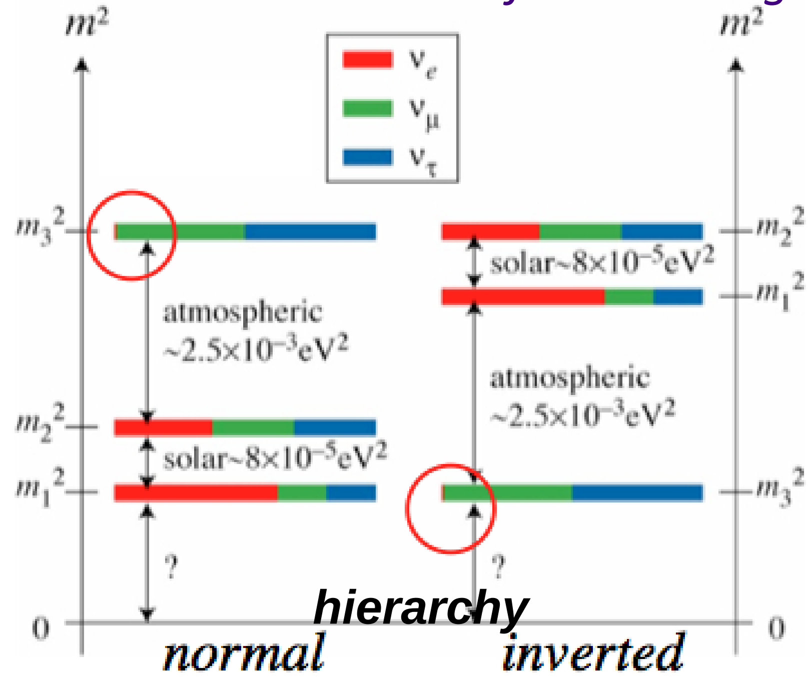
$$+ (\text{CPV term}) + (\text{matter term}) \ldots$$

$$\text{CPV term} \propto \sin\theta_{12} \sin\theta_{13} \sin\theta_{23} \sin\delta$$

$\nu_\mu \rightarrow \nu_e$ oscill. means θ_{13} is not zero.

Non-zero θ_{13} opens a possibility to measure CP violation in lepton sector

Current knowledge on Neutrino mass & three flavor mixing



Mixing angle: θ_{12}, θ_{23}, θ_{13}

$\theta_{12} = 34° \pm 3°$ $\quad \theta_{23} = 45° \pm 5°$

θ_{13} measurement

$\sin^2 2\theta_{13} = 0.11^{+0.10}_{-0.06}$ (T2K 2011)

(assuming $\delta_{CP}=0$, $\sin^2 2\theta_{23}=1$, $\Delta m^2_{32}=2.4 \times 10^{-3}$ (NH))

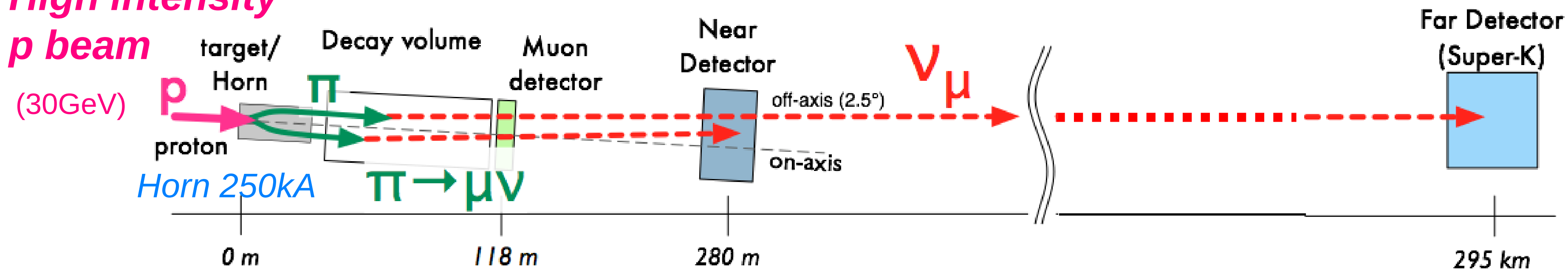
p-value for $\theta_{13}=0$ is 0.007 (2.5σ)

First indication of non-zero θ_{13}

Phys.Rev.Lett. 107, 041801, 2011

δ is not known yet

T2K Beam Principle



Intense & high quality beam

* Off-axis ν_μ beam

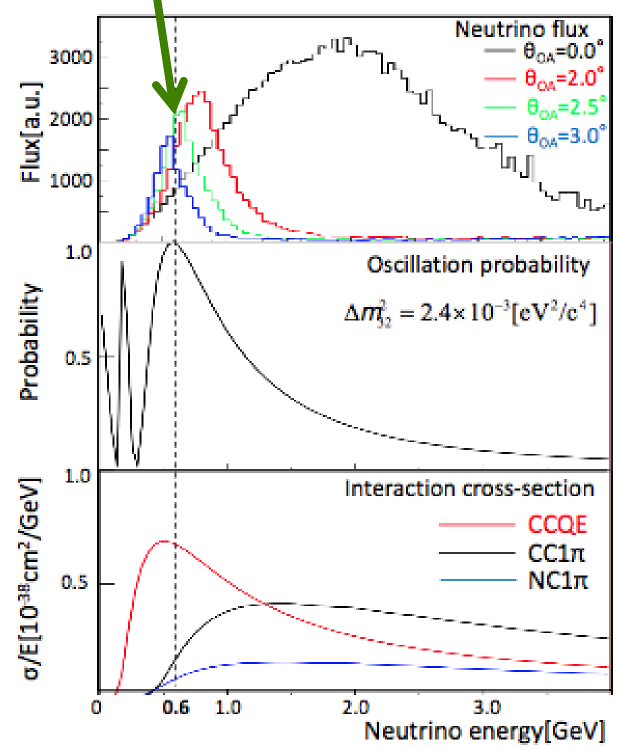
- Low energy narrow band beam
- E_ν peak around oscillation maximum (~0.6GeV)
- Small high energy tail
  → reduce background events
  (e.g. NC1π^0 is one of background of ν_e search)

* Small intrinsic beam ν_e fraction (~1%) from μ,K decays

π, K production is measured in CERN NA61 exp. for the flux calculation

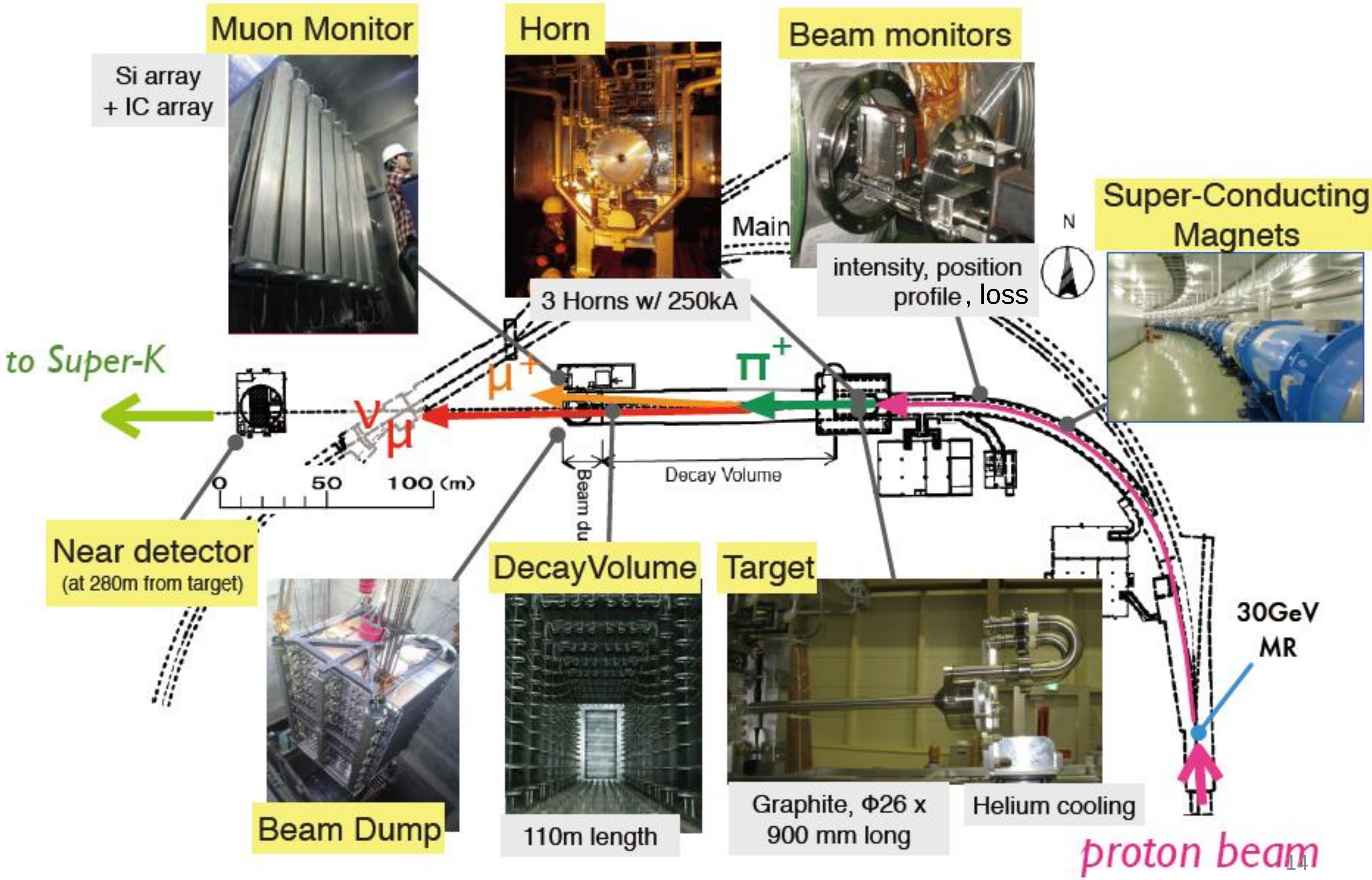
Phys.Rev.C84:034604(2011), Phys.Rev.C85:035210(2012)

T2K off-axis angle is 2.5°



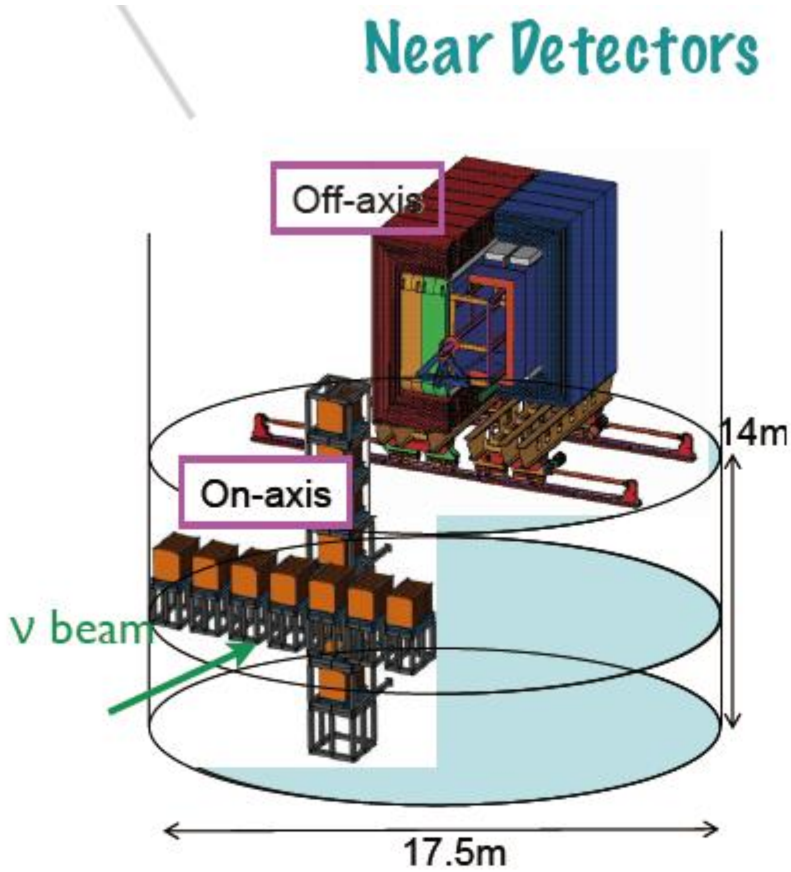
Beamline Facility/Detectors

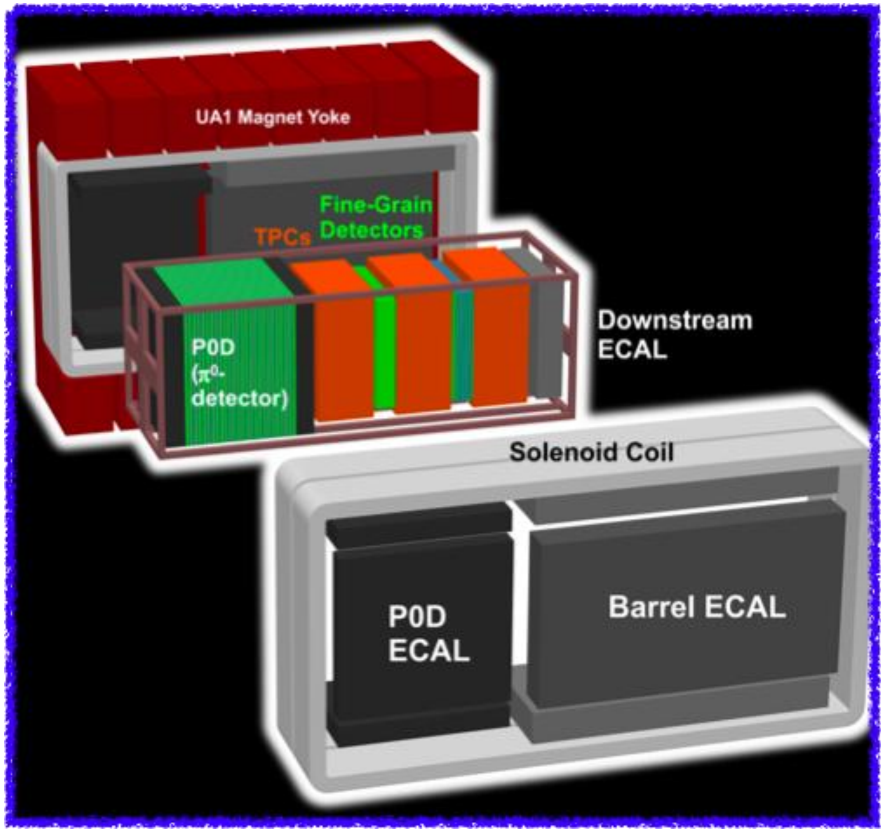
J-PARC Neutrino Beam Facility



ND280

Near Detector @ 280m from the target

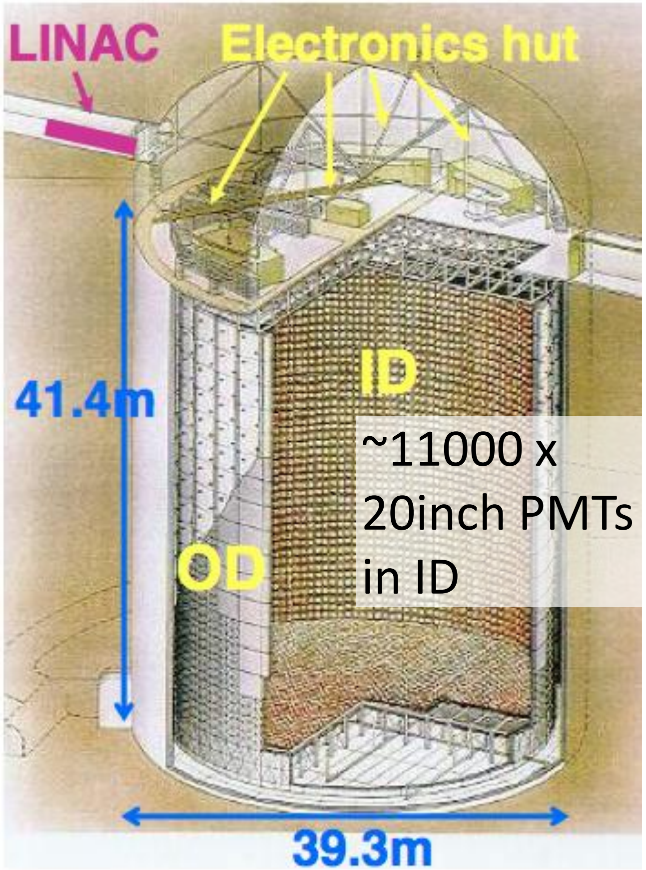




- **ND280** @ 2.5 degree off-axis
  - Normalization of Neutrino Flux
  - Measurement of neutrino cross sections.
- Dipole magnet w/ 0.2T
- **FGD+TPC:** Target + Particle tracking
- **P0D:** π^0 Detector
- **EM calorimeter**
- **Side-Muon-Range Detector**

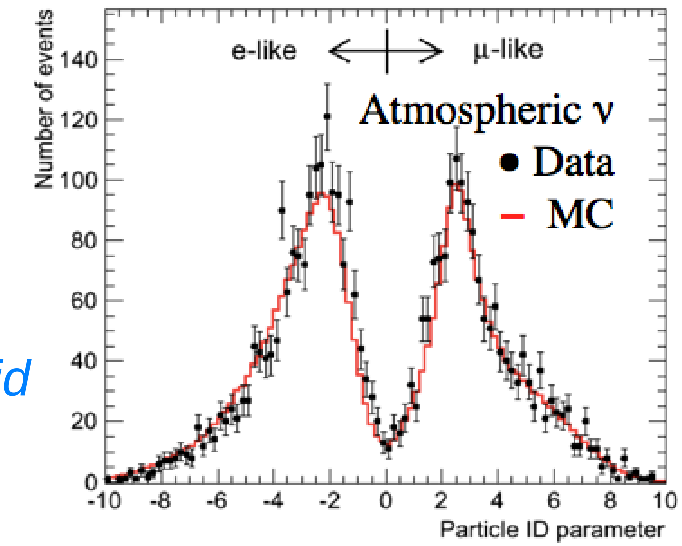
- **INGRID** @ on-axis (0 degree)
- ν beam monitor [rate, direction, and stability]

Far Detector (Super-K)

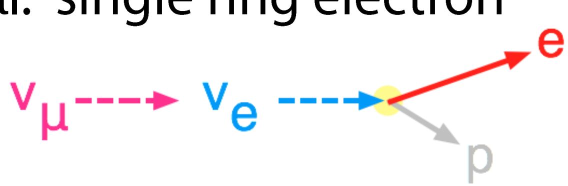


- Water Cherenkov detector w/ fiducial volume 22.5kton
- Record all the hit PMTs within ±500μsec centered at the beam arrival time
- Detector performance is well-matched at sub GeV
  - Good e-like (shower ring) / μ-like separation

Probability that μ is mis-id as electron is ~1%



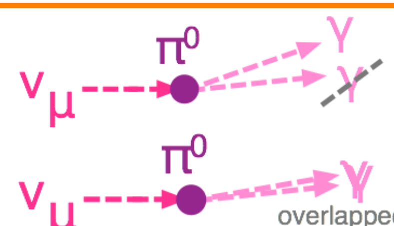
Signal: single ring electron



Background:

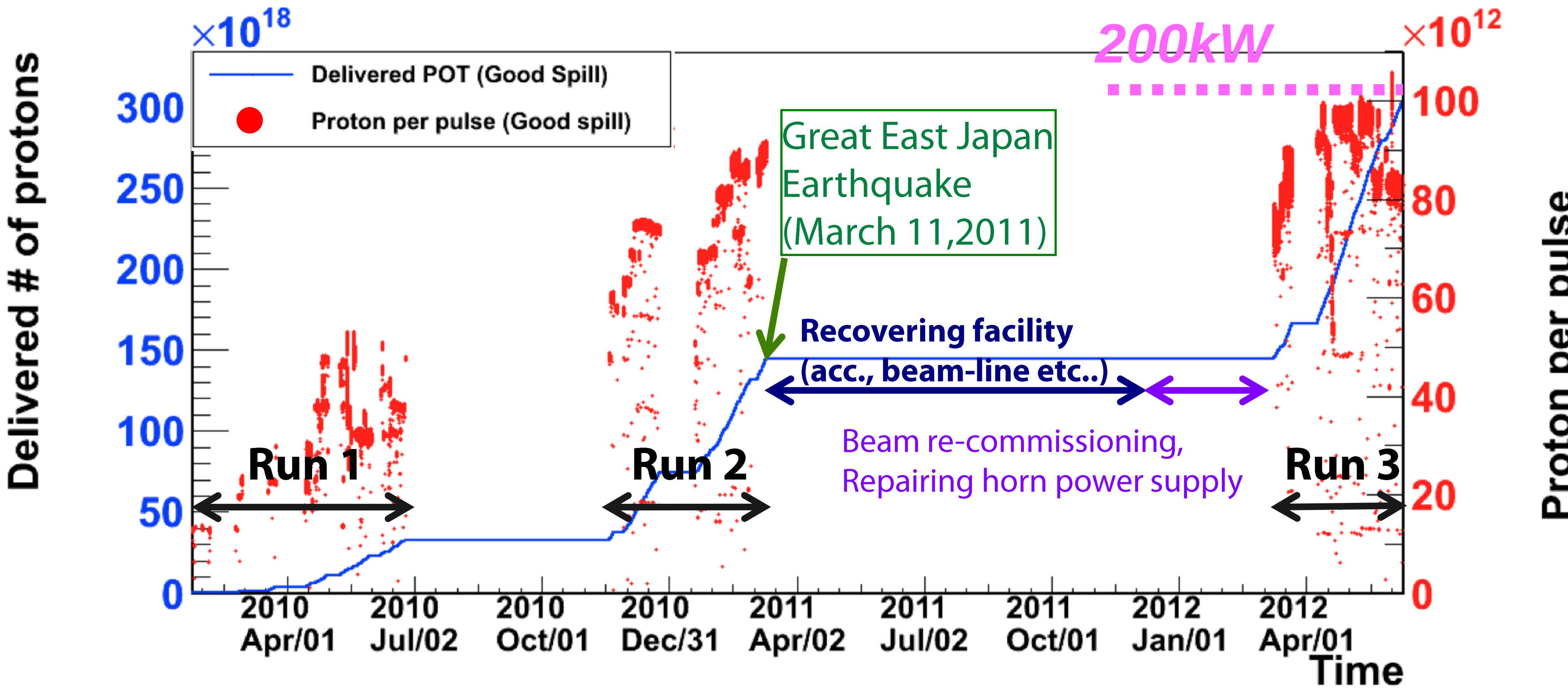
intrinsic νe in beam

π^0 from NC interaction



Data taking

Data Accumulation



Run1 + 2 (2010-2011)
1.43 x 10^{20} p.o.t.

* ND280 Run1+2 data is used for oscillation analysis

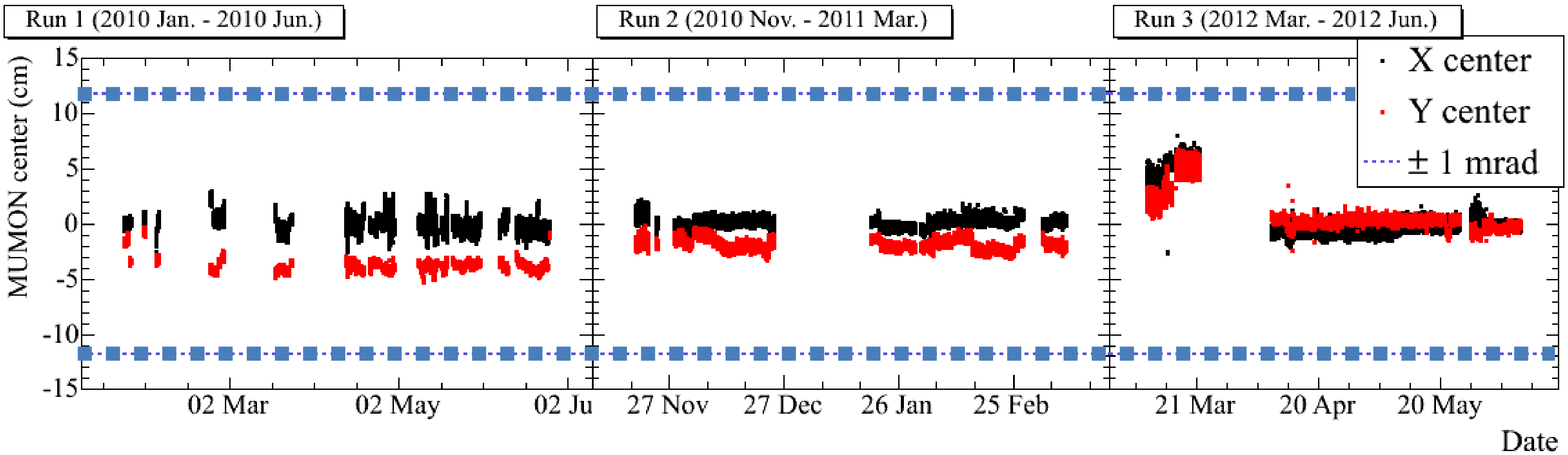
Run3 (2012) : 1.58 x 10^{20} p.o.t

* including 0.21 x 10^{20} p.o.t. with 200kA horn operation (13% flux reduction at peak) (250kA horn current for nominal operation)
* Stable data taking is achieved up to ~190kW

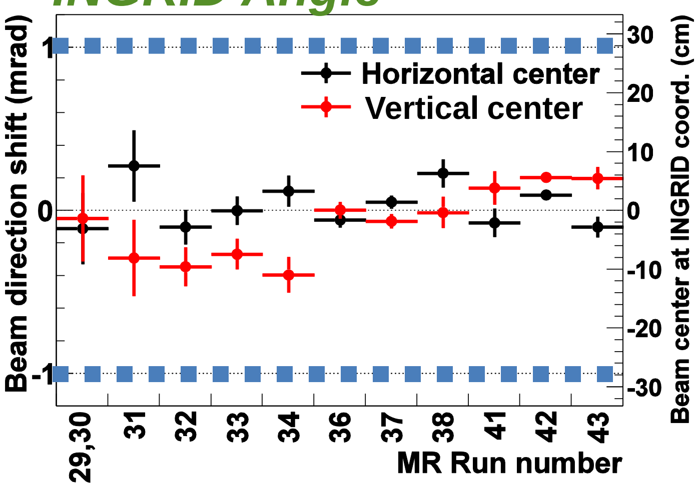
Data for today's talk (full Run1+2+3) = 3.01 x 10^{20} p.o.t.
(Run1+2 for disappearance)

Beam Quality

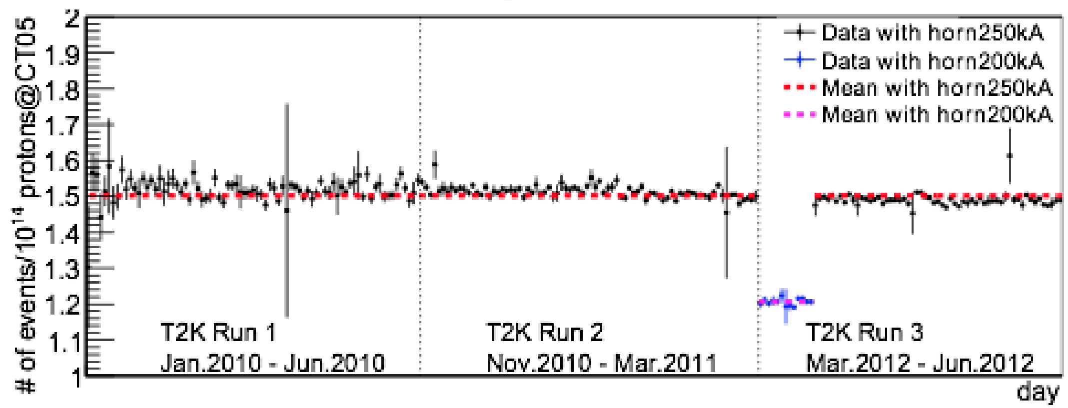
MUMON Angle (monitored pulse-by-pulse and controlled)



INGRID Angle



INGRID Rate/# of protons

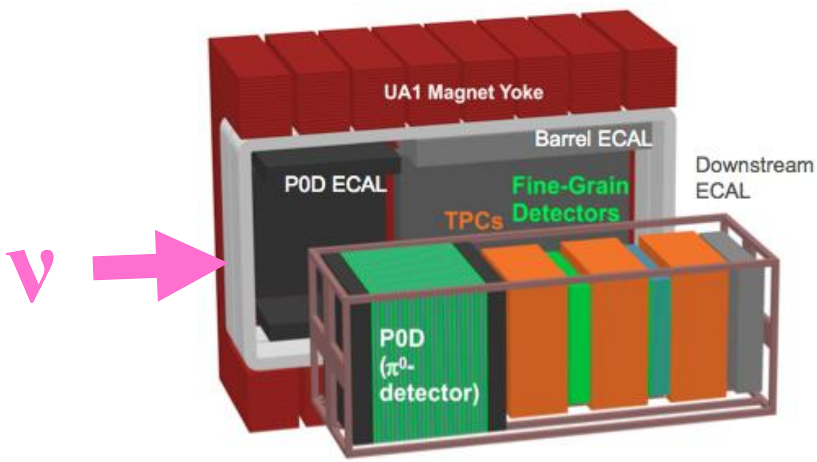


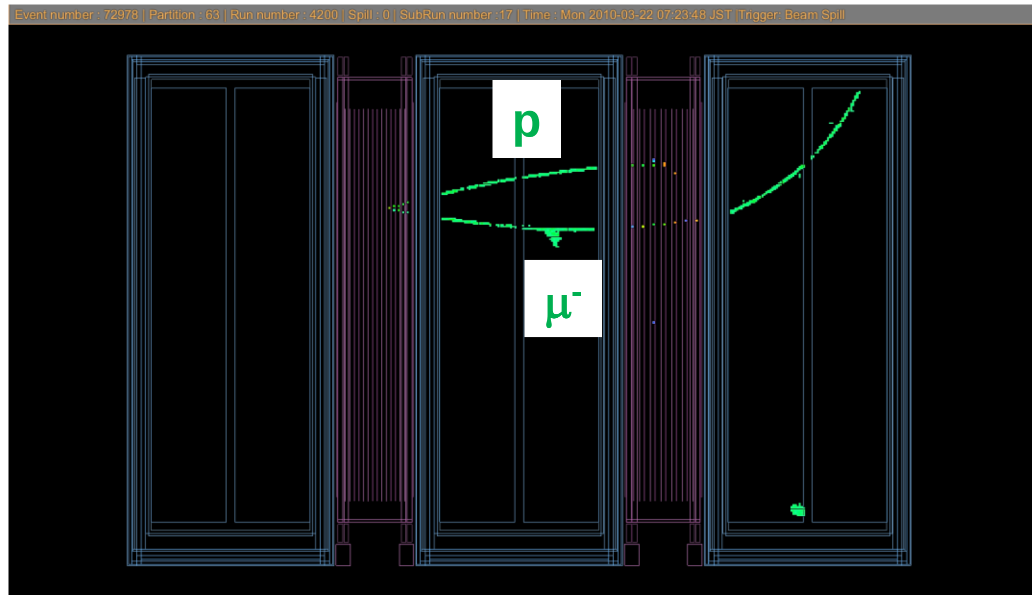
Event rate is stable

Beam angle is well within 1mrad, which corresponds to negligible (2%) shift of the Eν peak

Near detector measurements

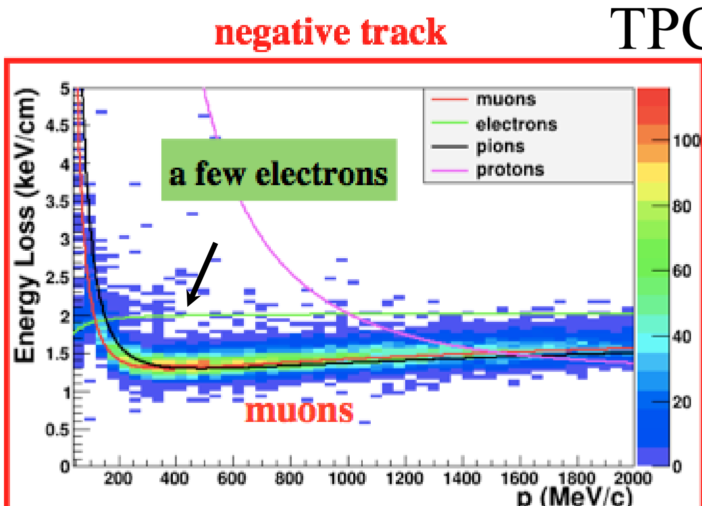
Off-axis detector (ND280)

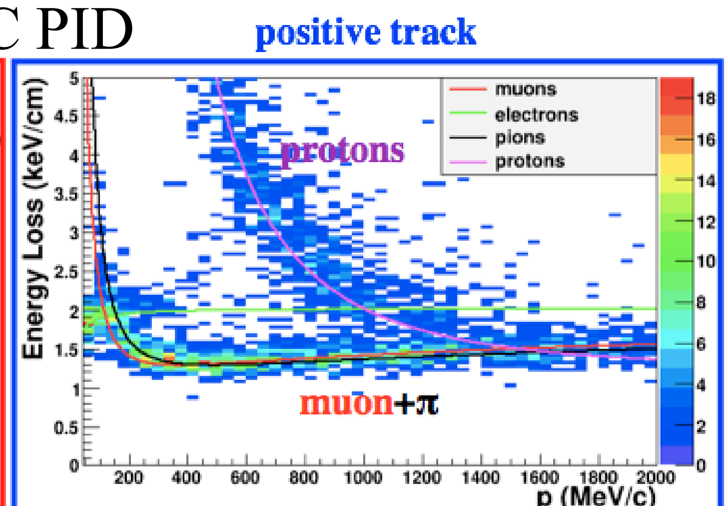




Real Charged Current Quasi-Elastic event interacted in FGD1

TPC PID





Data analysis at Near

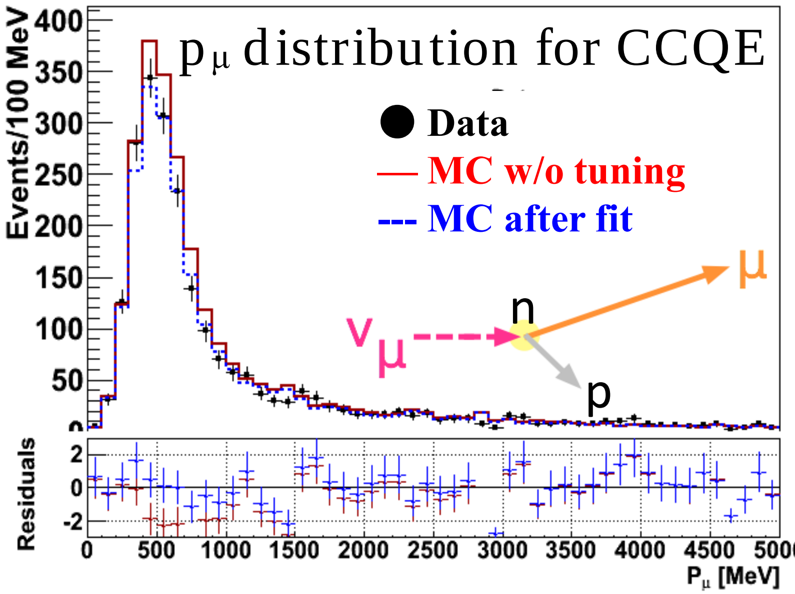
Flux & ν int. cross section fit w/ ND measurement

- Making use of a good performance of the ND tracker (FGD+TPC), CCQE and nonQE enhanced samples are selected

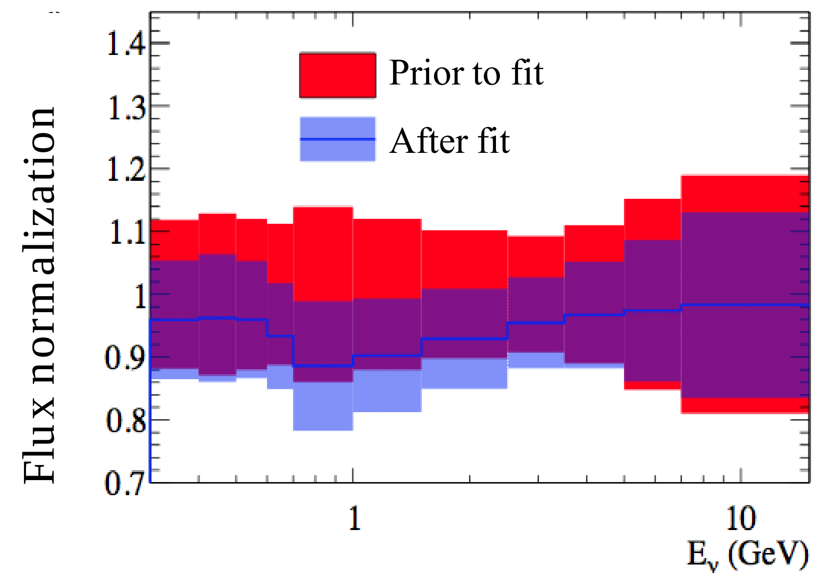
- To predict neutrino events at the far detector, we make a fit to (p_μ, θ_μ) distribution for the CCQE and nonQE enhanced samples

- Fit results are extrapolated to the prediction at the far detector

By use of the ND280 information, systematic errors are improved



T2K far ν_μ flux normalization & uncertainties

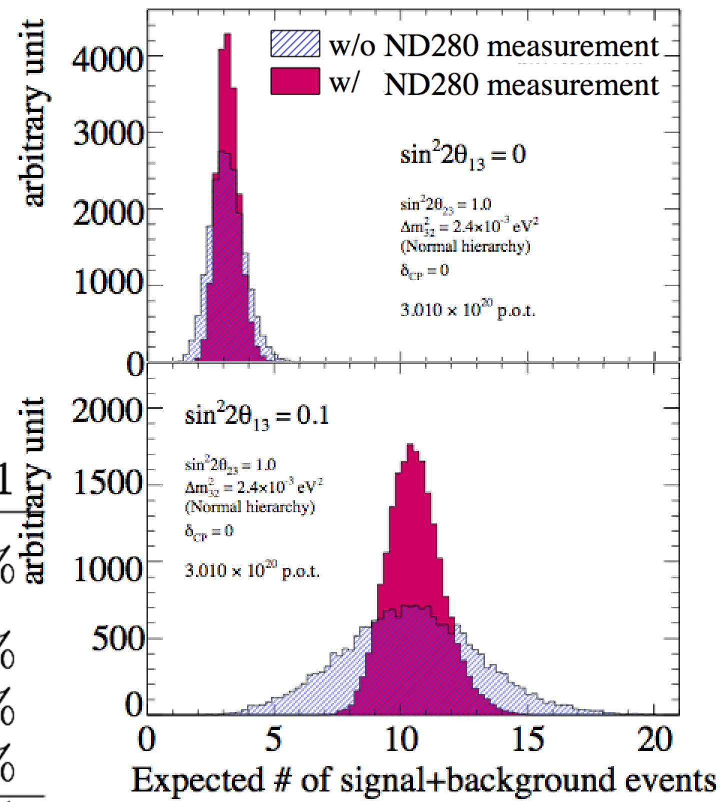


The predicted number of events and systematic uncertainties

The predicted # of events w/ 3.01 x 10^{20} p.o.t.

Event category	$\sin^2 2\theta_{13} = 0.0$	$\sin^2 2\theta_{13} = 0.1$
Total	3.22±0.43	10.71±1.10
ν_e signal	0.18	7.79
ν_e background	1.67	1.56
ν_μ background(mainly NCπ^0)	1.21	1.21
$\overline{\nu}_\mu + \overline{\nu}_e$ background	0.16	0.16

the predicted # of event distribution



Systematic uncertainties

Error source	$\sin^2 2\theta_{13} = 0$	$\sin^2 2\theta_{13} = 0.1$
Beam flux+ν int. in T2K fit	8.7 %	5.7 %
ν int. (from other exp.)	5.9 %	7.5 %
Final state interaction	3.1 %	2.4 %
Far detector	7.1 %	3.1 %
Total	13.4 %	10.3 %
(T2K 2011 results:	~23%	~18%)

big improvement from the T2K 2011 results

Uncertainties are reduced using ND280 measurement

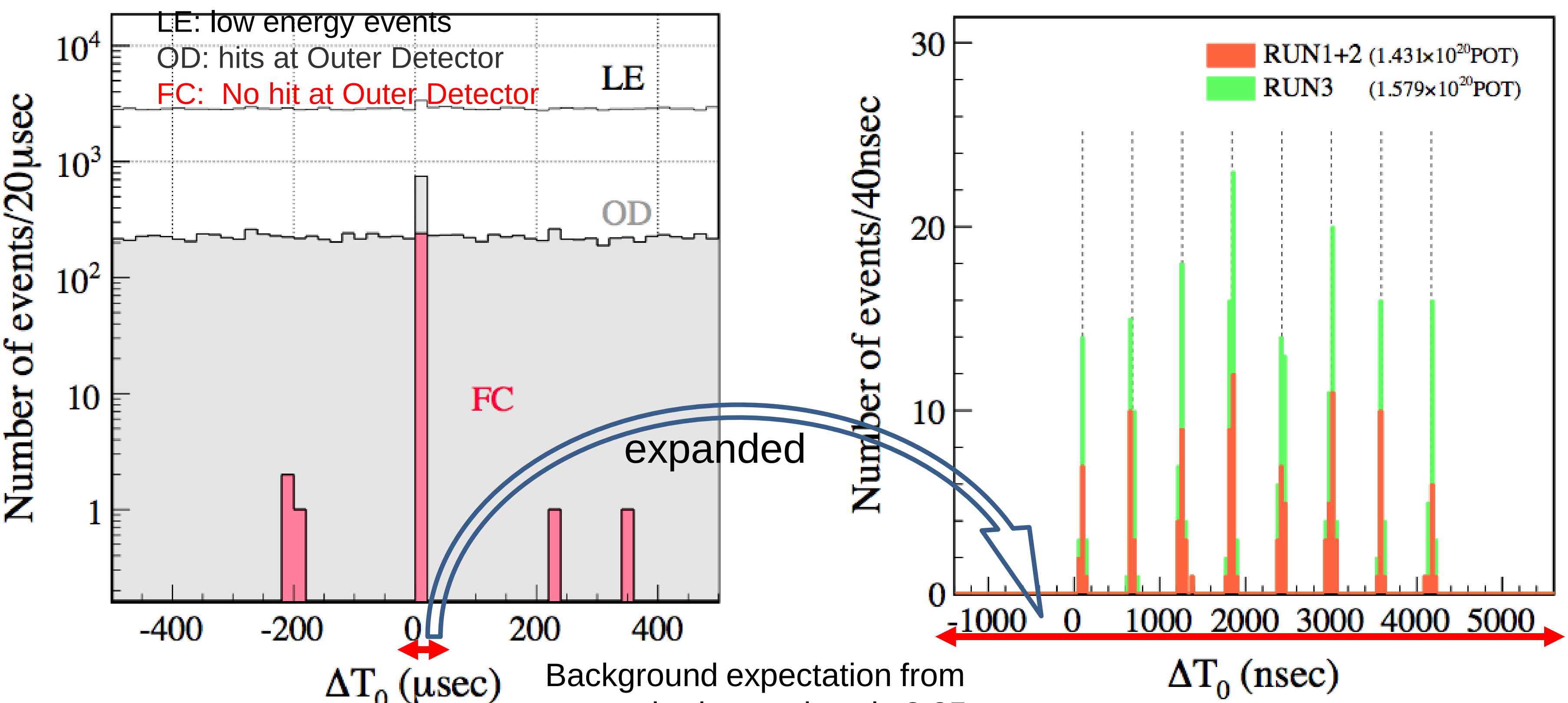
Data reduction at Far

Far detector events at beam timing

- Events at the T2K beam timing synchronized by GPS

relative event timing to the spill timing

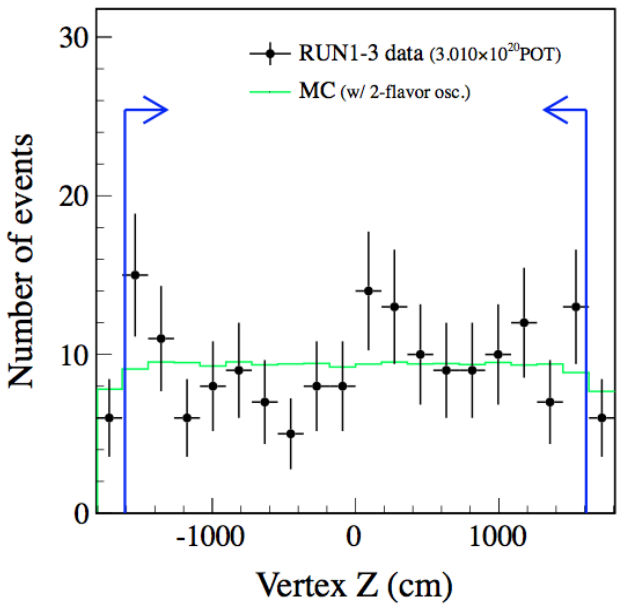
Clear beam structure !

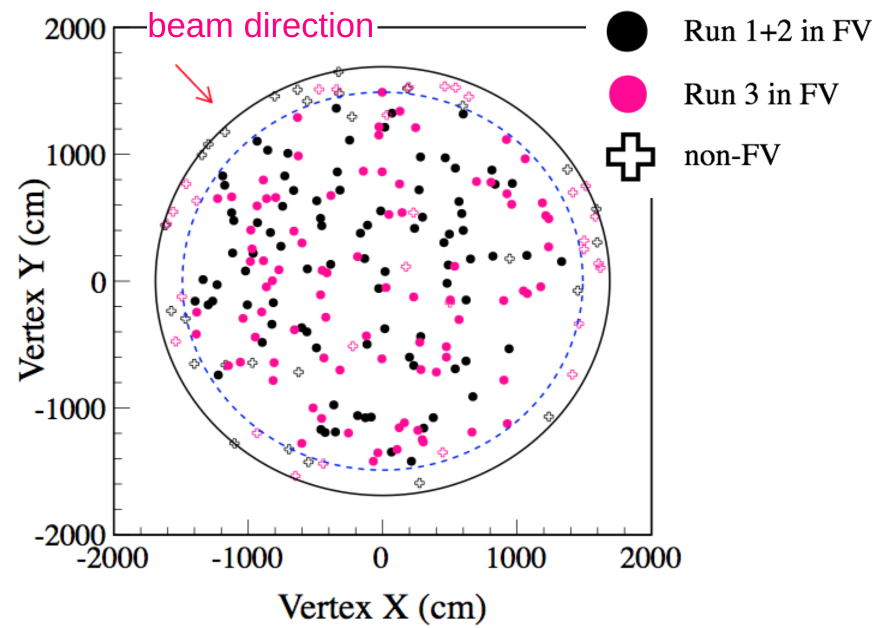


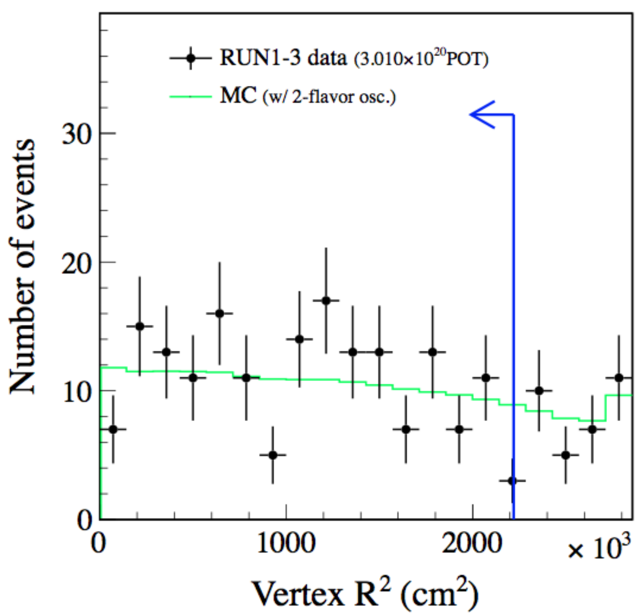
Background expectation from atmospheric neutrinos is 2.85

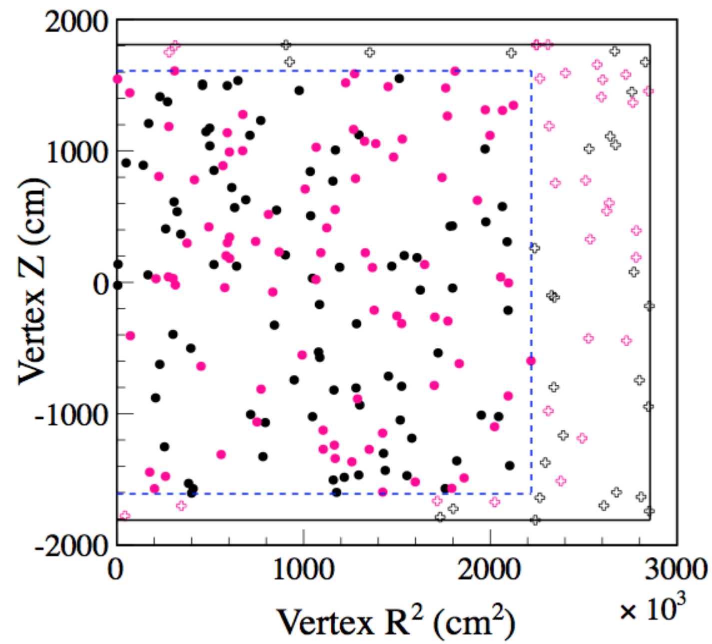
$\Delta T_0 = T_{GPS}@SK - T_{GPS}@J\text{-}PARC - TOF(\sim 985\mu sec)$

Fiducial volume cut **(distance between recon. vertex and wall > 200cm)**

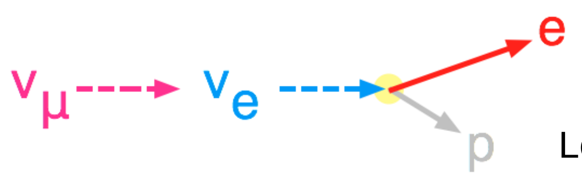








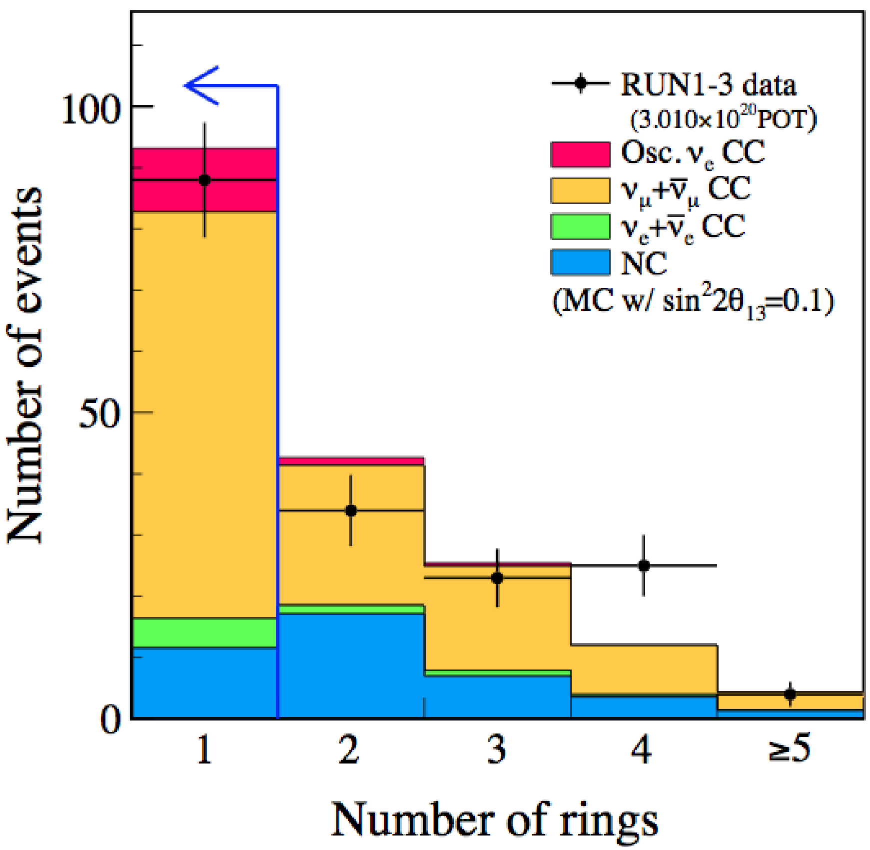
Selection of ν_e appearance events



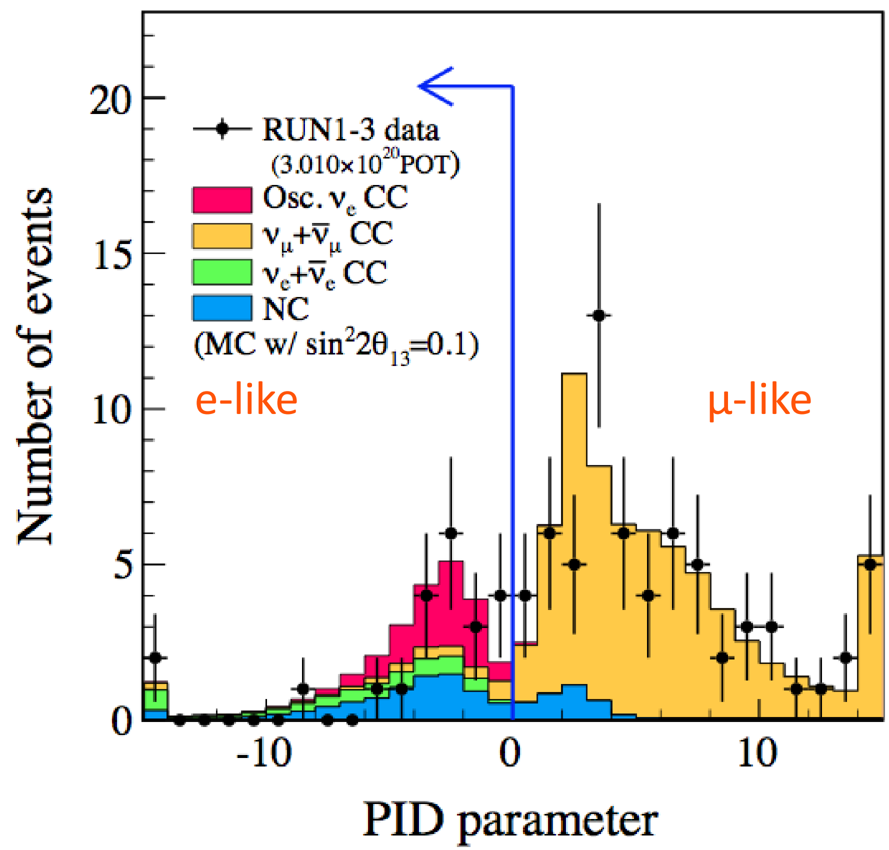
e-like (shower ring)

Low energy proton does not emit Cherenkov light

Number of Cherenkov ring = 1

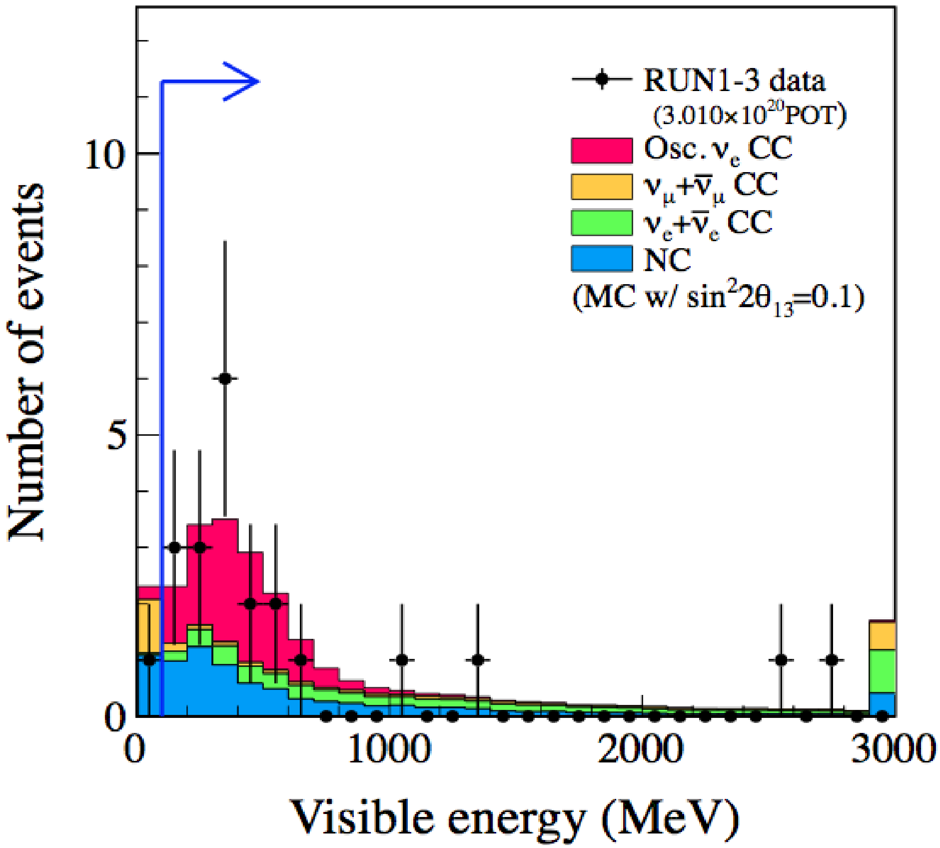


The ring is e-like

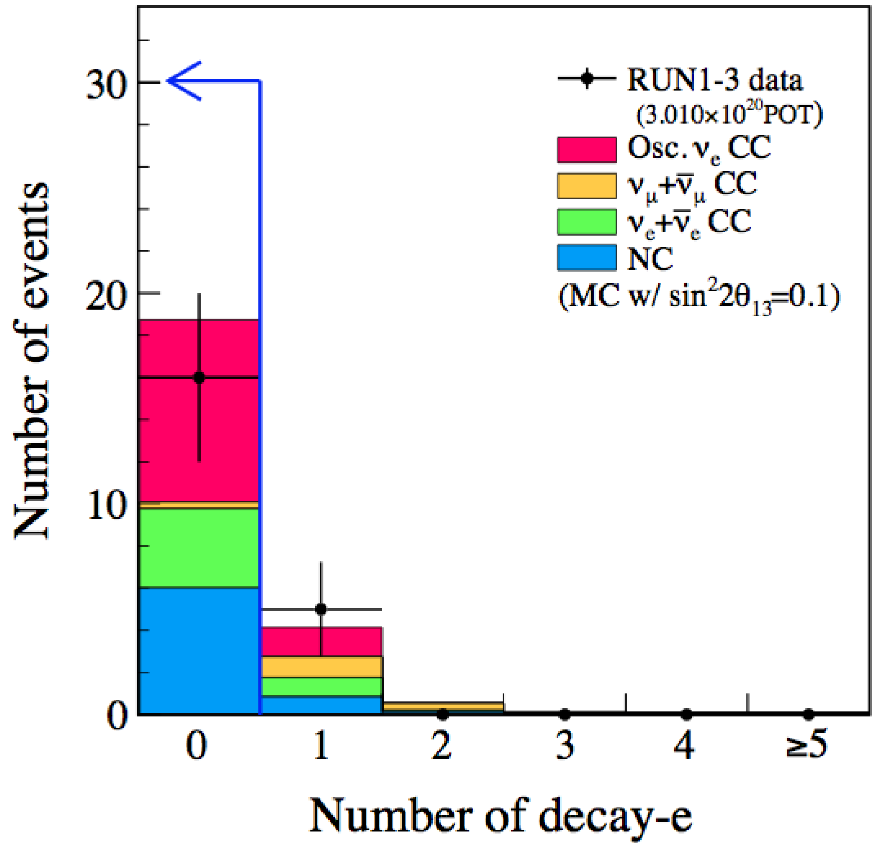


Selection of ν_e appearance events

Visible energy > 100 MeV
to reject $\nu_\mu+\bar{\nu}_\mu$ CC & NC background

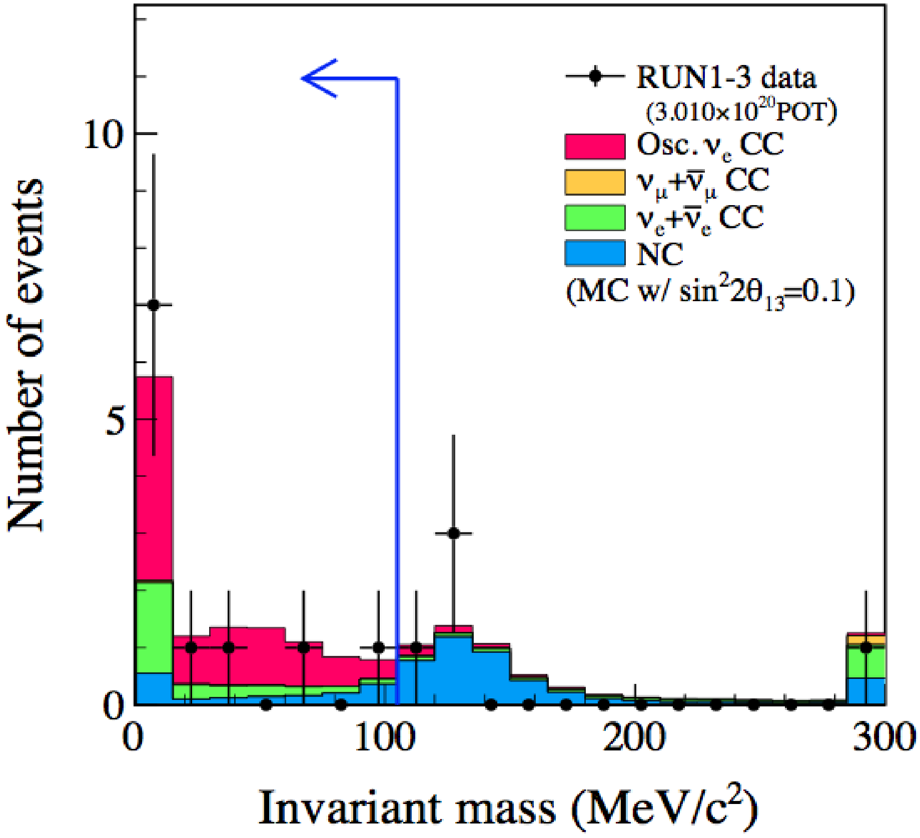


No decay-electron cut
(decay electron comes from μ or π)

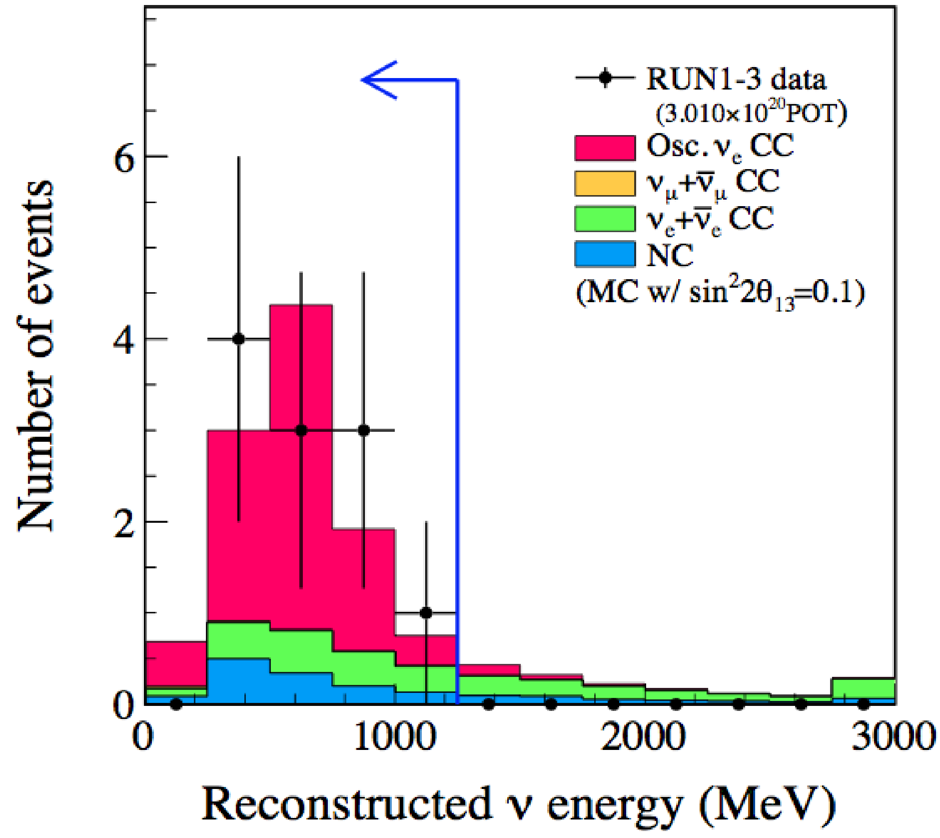


Selection of ν_e appearance events

Force 2nd ring in the PMT hits
Invariant mass cut (M_{inv} < 105 MeV/c^2)
to reject remaining NC π^0 background

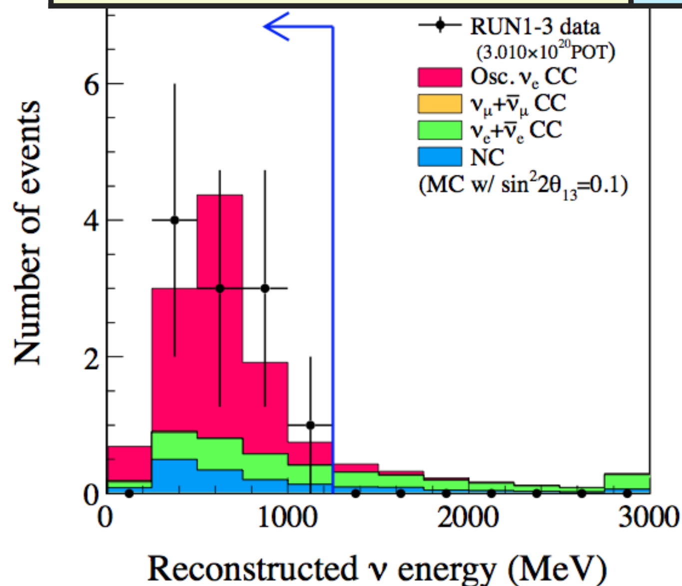


Reconstructed ν energy cut
(E_{rec} < 1250 MeV) to reject
intrinsic beam ν_e



ν_e candidate event selection

RUN 1+2+3 3.010×10^{20} POT	Data	MC Expectation w/ $\sin^2 2\theta_{13}=0.1$				
		Signal $\nu_\mu \to \nu_e$	BG total	CC ($\nu_\mu+\bar{\nu}_\mu$)	CC($\nu_e+\bar{\nu}_e$)	NC
Fully contained FV at beam timing	174	12.35	165.47	117.33	7.67	40.48
Single ring	88	10.39	82.78	66.41	4.82	11.55
e-like	22	10.27	15.60	2.72	4.79	8.10
E_{vis}>100MeV	21	10.04	13.53	1.76	4.75	7.01
No decay-e	16	8.63	10.09	0.33	3.76	6.00
2γ invariant mass cut	11	8.05	4.32	0.09	2.60	1.64
E_ν^{rec} < 1250 MeV (MC $\sin^2 2\theta_{13}=0$ case)	11	7.81 (0.18)	2.92 (3.04)	0.06 (0.06)	1.61 (1.73)	1.25 (1.25)
Efficiency [%]		60.7	1.0	0.0	20.0	0.9



11 candidate events are observed

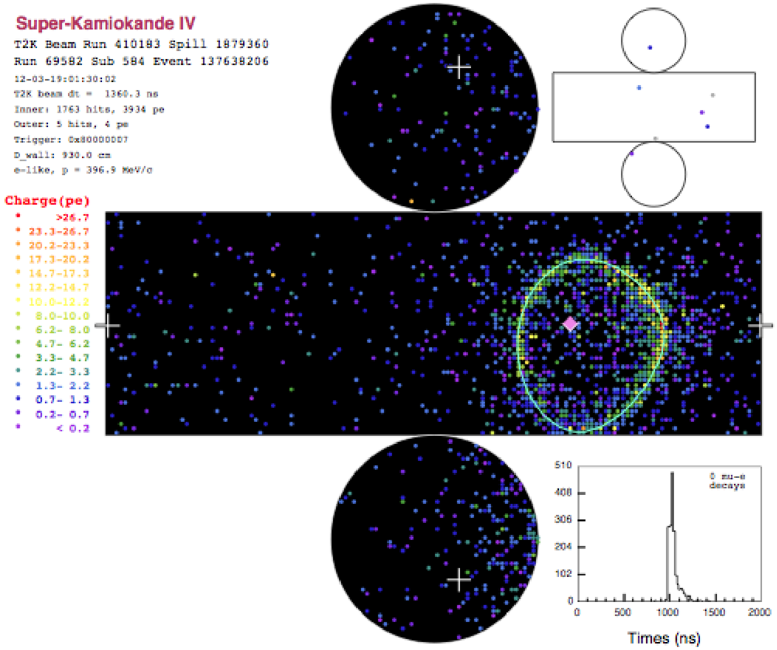
$N_{exp}=3.22\pm0.43$ for $\sin^2 2\theta_{13}=0$

The probability (p-value) to observe 11 or more events with $\theta_{13}=0$ is 0.08% (3.2σ)

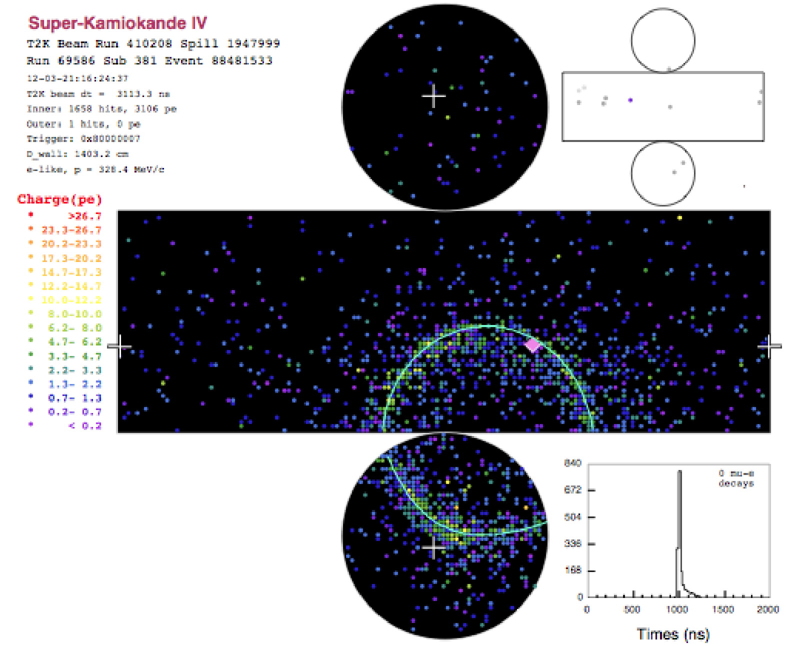
Evidence of ν_e appearance

ν_e candidate events (Run3)

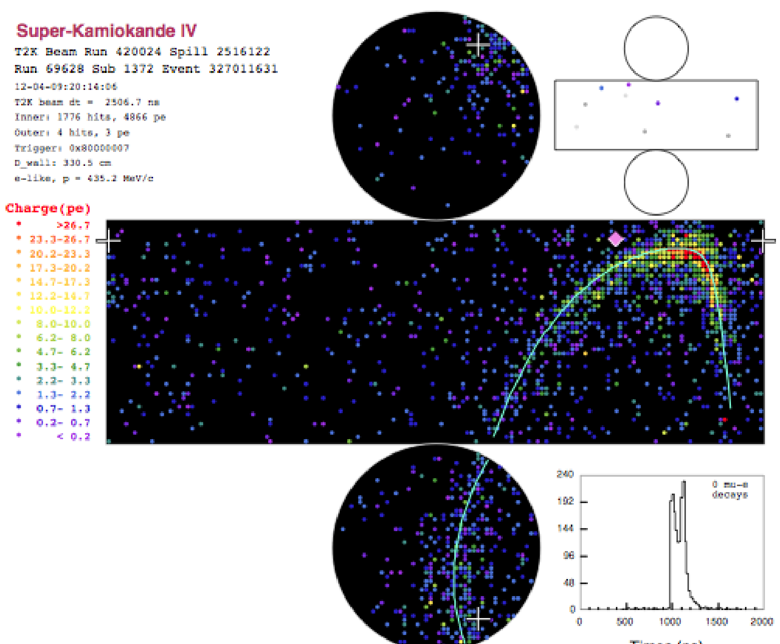
#7



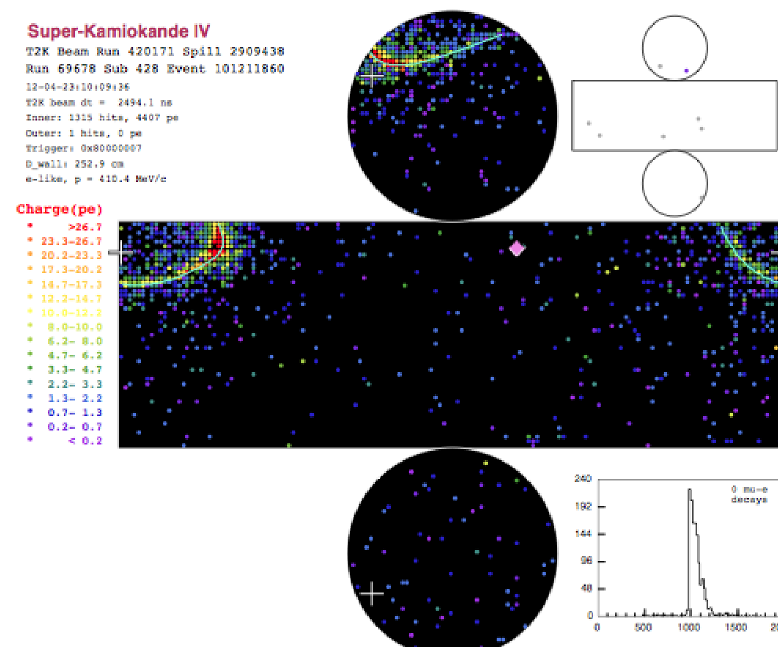
#8



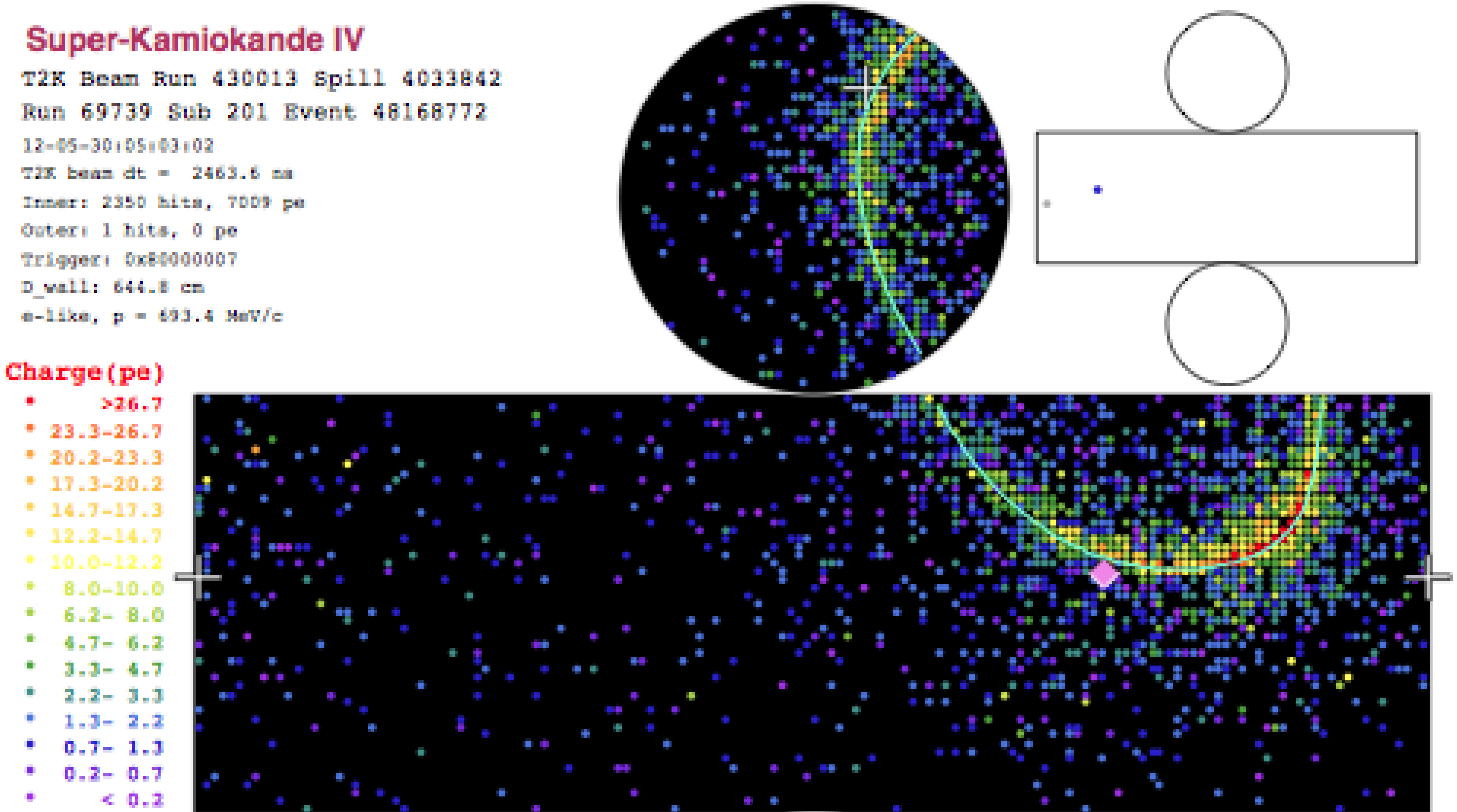
#9

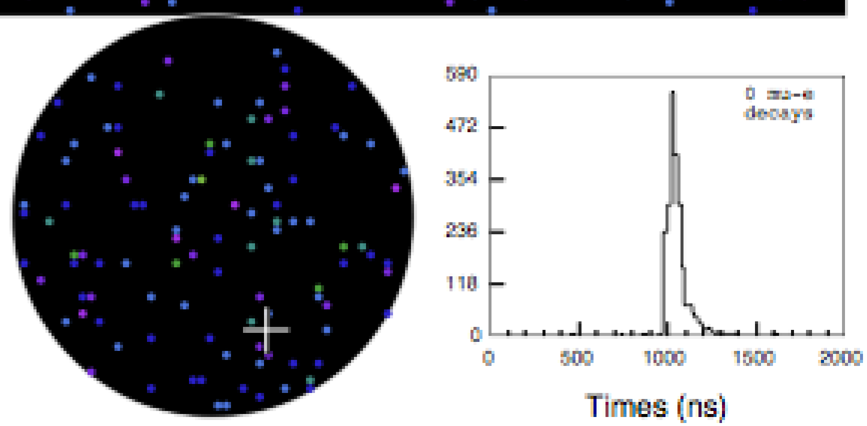


#10



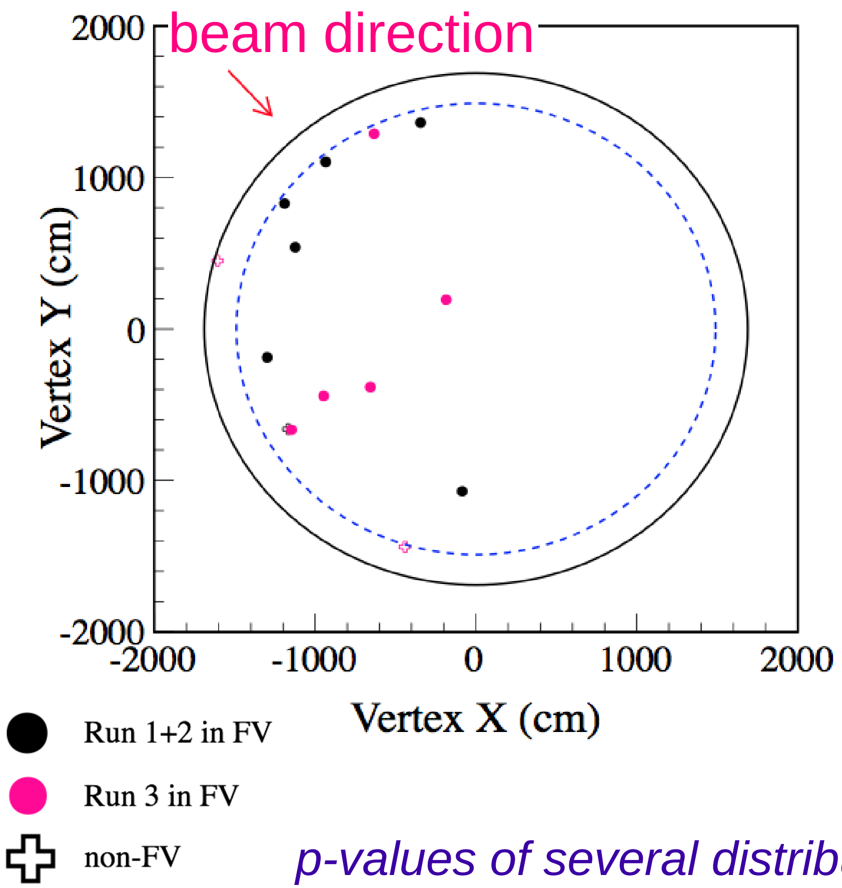
New ν_e candidate event (Run3)

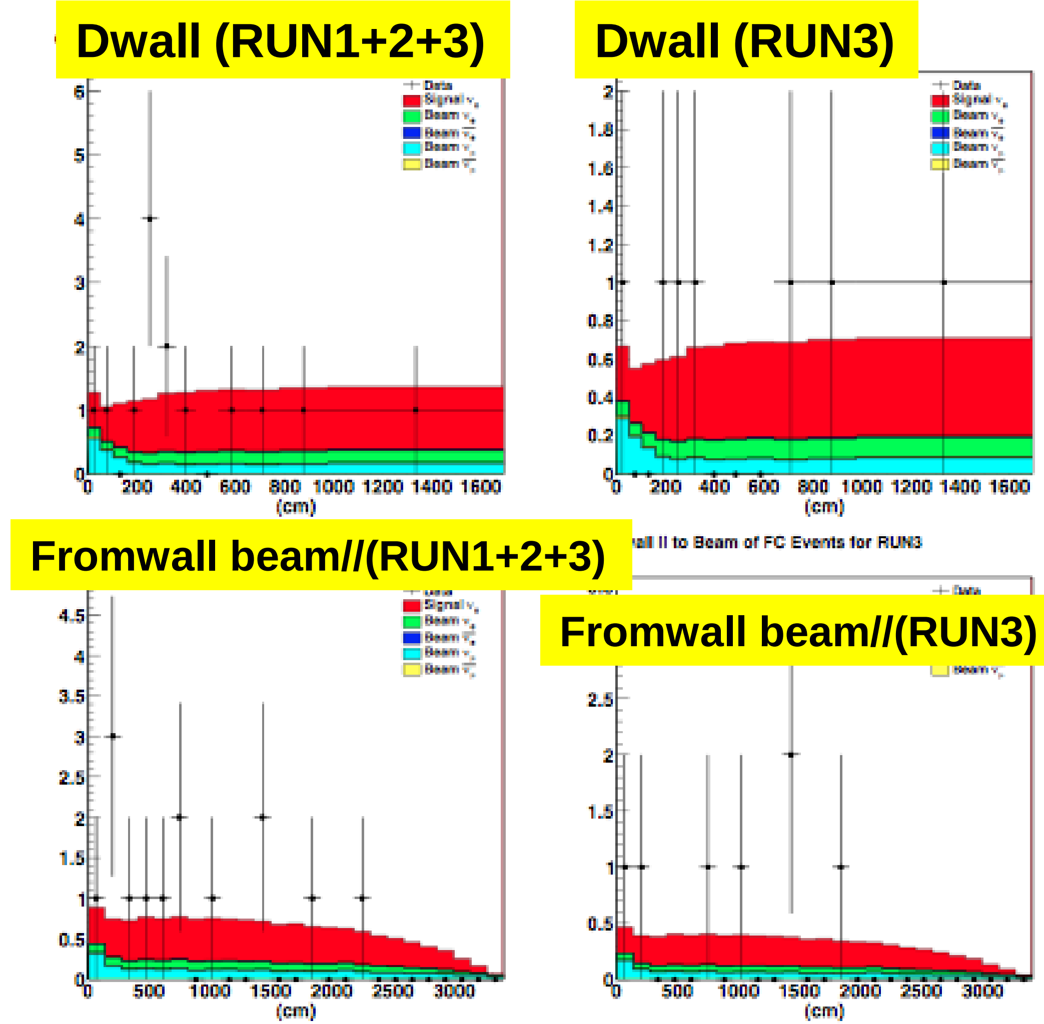




visible energy : 693.4 MeV
# of decay-e : 0
2γ Inv. mass : 1.2 MeV/c^2
recon. energy : 943.1 MeV

Vertex distribution





p-values of several distribution are calculated w/ toy MC

	RUN1+2	RUN3	RUN1+2+3
$Dwall$	22.9%	94.7%	39.4%
$Fromwall$ beam$_{\|\|}$	1.34%	35.2%	6.05%
$R^2 + Z$	10.5%	74.6%	32.4%

Oscillation analysis

Oscillation analysis

For the 2011 oscillation analysis, only number was used. This time, analyses which use both number and shape are also performed to get better sensitivity on θ_{13}.

- We use three analysis methods:
  1. Maximum likelihood Fit of the Number and 2D-distribution of electron momentum p_e & angle θ_e
  2. Maximum likelihood Fit of the Number and reconstructed neutrino energy E_ν^{rec} distribution
  3. “Number only” analysis = Single-bin counting experiment analysis (with Feldman-Cousins technique)
- All three methods demonstrate consistent results

Oscillation parameter fit (Method 1)

Performing an extended maximum likelihood fit to extract $\sin^2 2\theta_{13}$

$$\mathcal{L}(N_{obs.}, \boldsymbol{x}, \boldsymbol{o}, \boldsymbol{f}) = \mathcal{L}_{norm}(N_{obs.}; \boldsymbol{o}, \boldsymbol{f}) \times \mathcal{L}_{shape}(\boldsymbol{x}; \boldsymbol{o}, \boldsymbol{f}) \times \mathcal{L}_{syst.}(\boldsymbol{f})$$

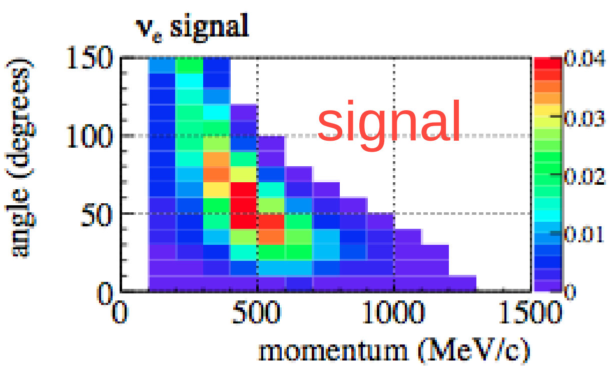
measurements, **oscillation parameters** **systematic parameters**

見つかった11イベントのすべての情報を使う

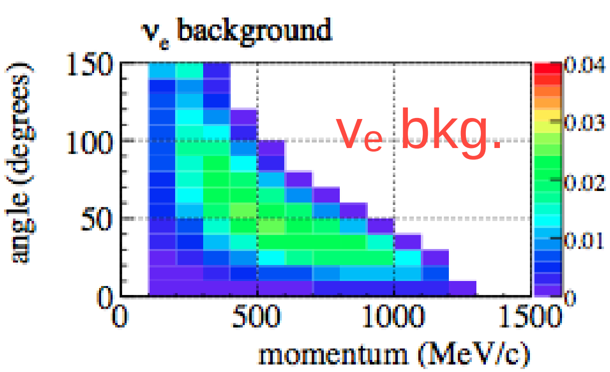
Fit data with
number + (p_e, θ_e) shape (2 dimensional)

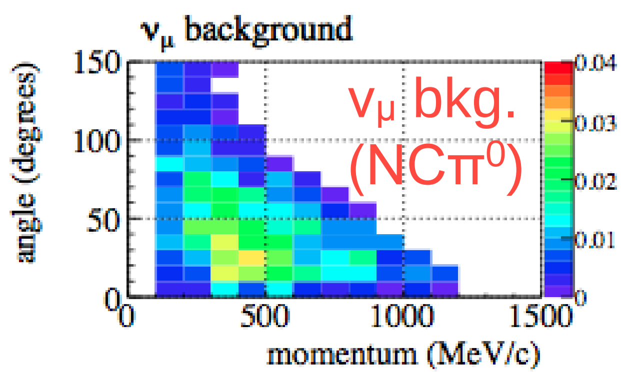
ν oscillation parameters fixed:

- $\Delta m_{21}^2 = 7.6 \times 10^{-5}\ \mathrm{eV}^2$
- $\Delta m_{32}^2 = \pm 2.4 \times 10^{-3}\ \mathrm{eV}^2$
- $\sin^2 2\theta_{12} = 0.8704$, $\sin^2 2\theta_{23} = 1.0$

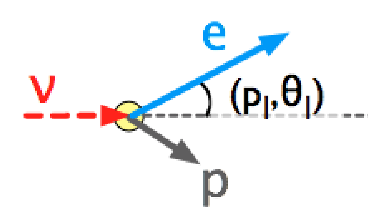


differences in p_e-ϑ_e distribution allow to have a better discrimination of signal events from backgrounds





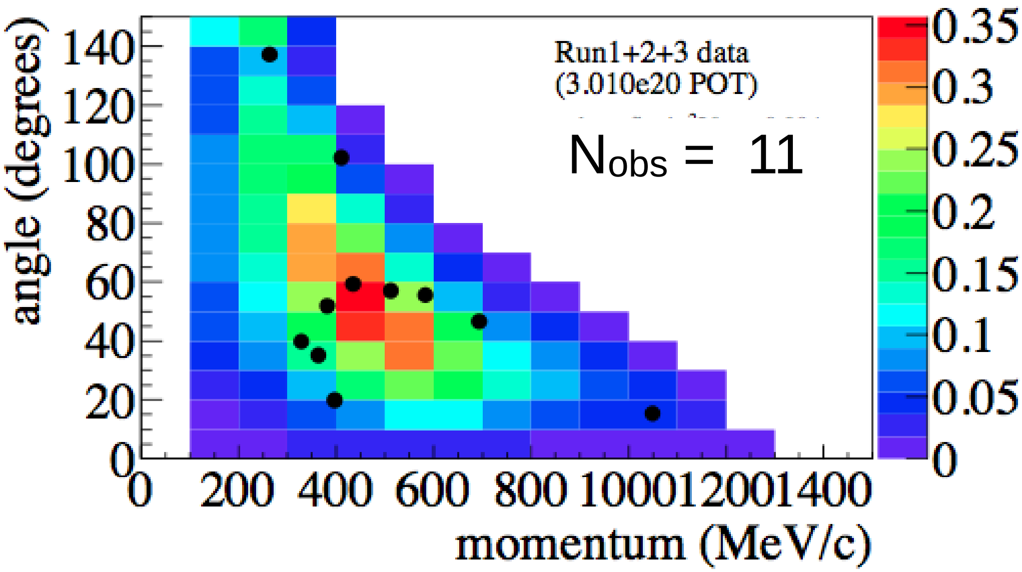
+ anti-ν_e, anti-ν_μ bkg.



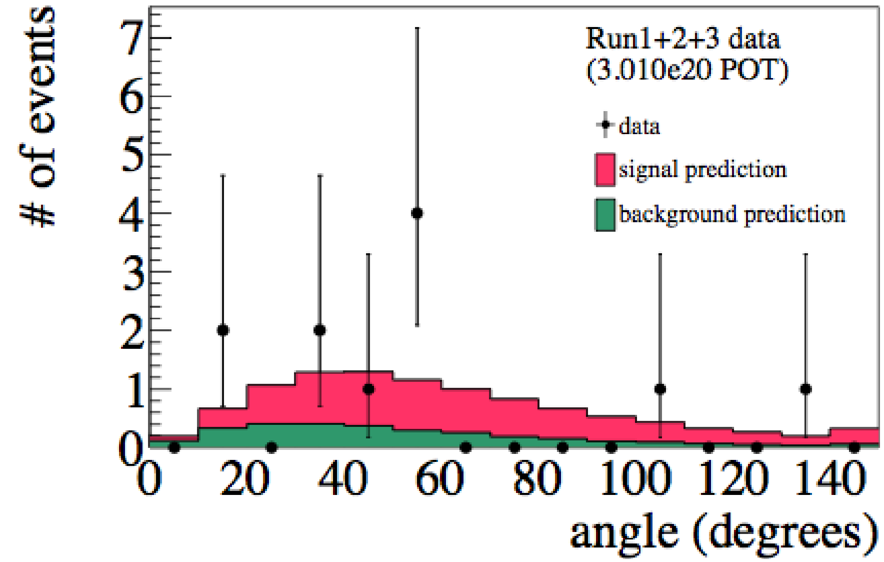
Results

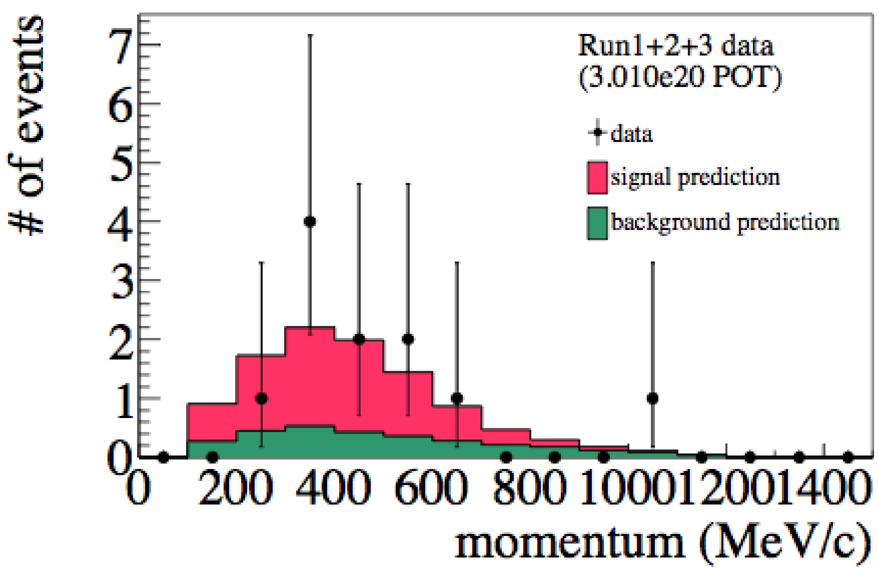
assuming $\delta_{CP}=0$, normal hierarchy

$|\Delta m^2_{32}|=2.4\times10^{-3}\ eV^2$, $\sin^2 2\theta_{23}=1$



(prediction histograms are based with best-fit $\sin^2 2\theta_{13}$)





preliminary

best fit w/ 68% CL error:

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

90% C.L. allowed region:

$$0.033 < \sin^2 2\theta_{13} < 0.188$$

$N_{best\text{-}fit}$ = 10.18

Results

Allowed region of $\sin^2 2\theta_{13}$ for each value of δ_{CP}

best fit w/ 68% CL error @δ_{CP}=0

normal hierarchy:

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

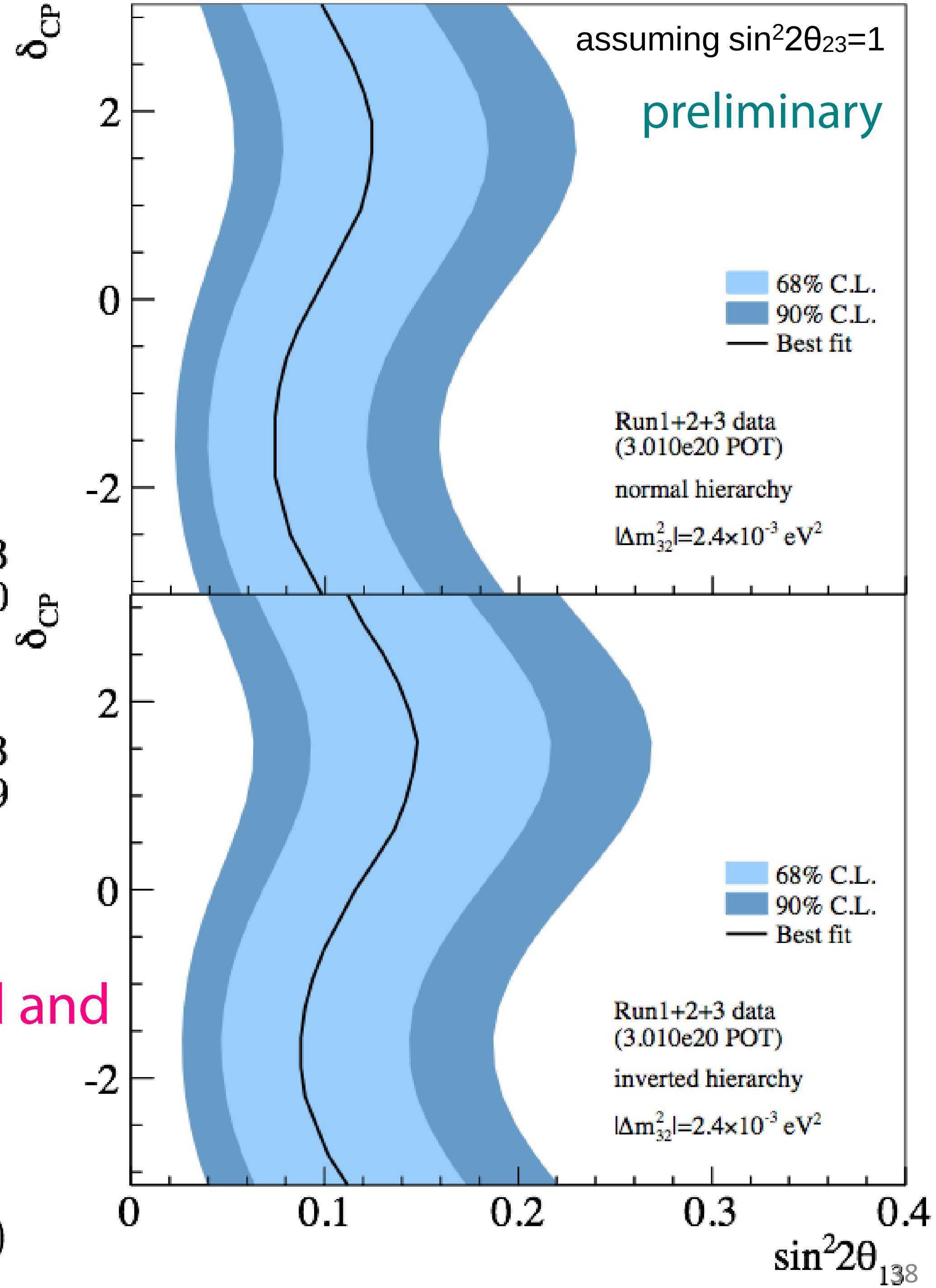
inverted hierarchy:

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

This result is consistent with number+shape (rec. E_ν) method and number only method

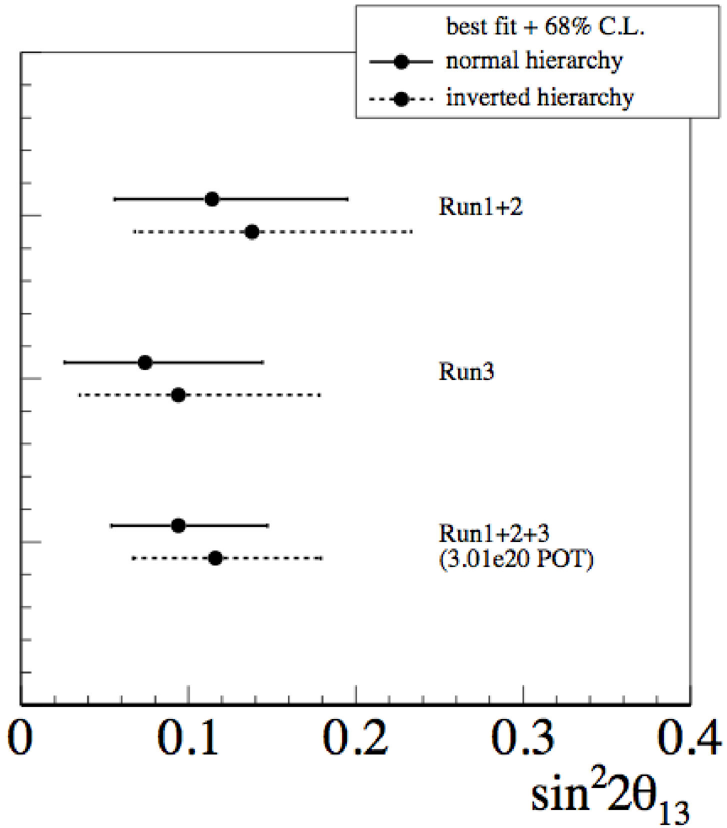
c.f 2011 result for normal (inverted) hierarchy

$$\sin^2 2\theta_{13} = 0.11^{+0.10}_{-0.06}\ (0.14^{+0.12}_{-0.07})$$

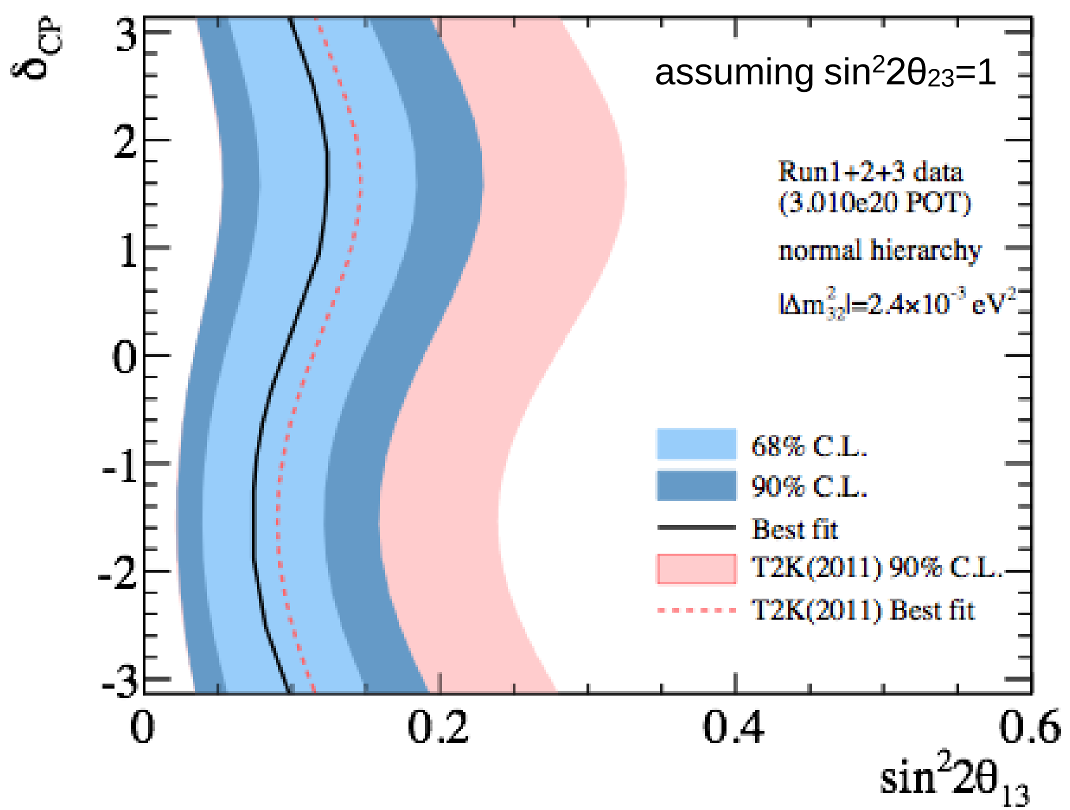


Comparison w/ 2011 results

Best-fit + 68% C.L. error for individual run period



Allowed region of $\sin^2 2\theta_{13}$ for each value of δ_{CP}



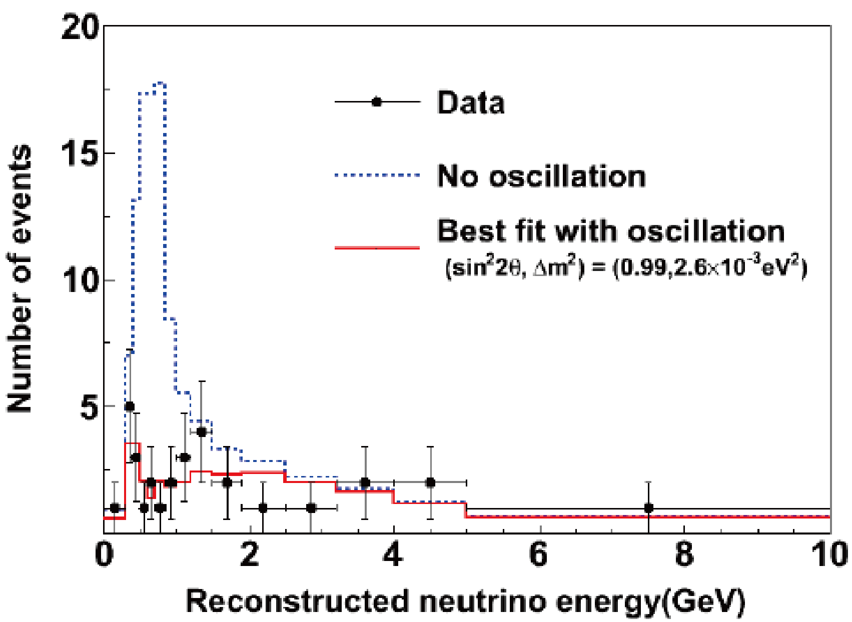
Error is reduced by analyzing full Run1+2+3 data, and new result is consistent with 2011(Run1+2) result

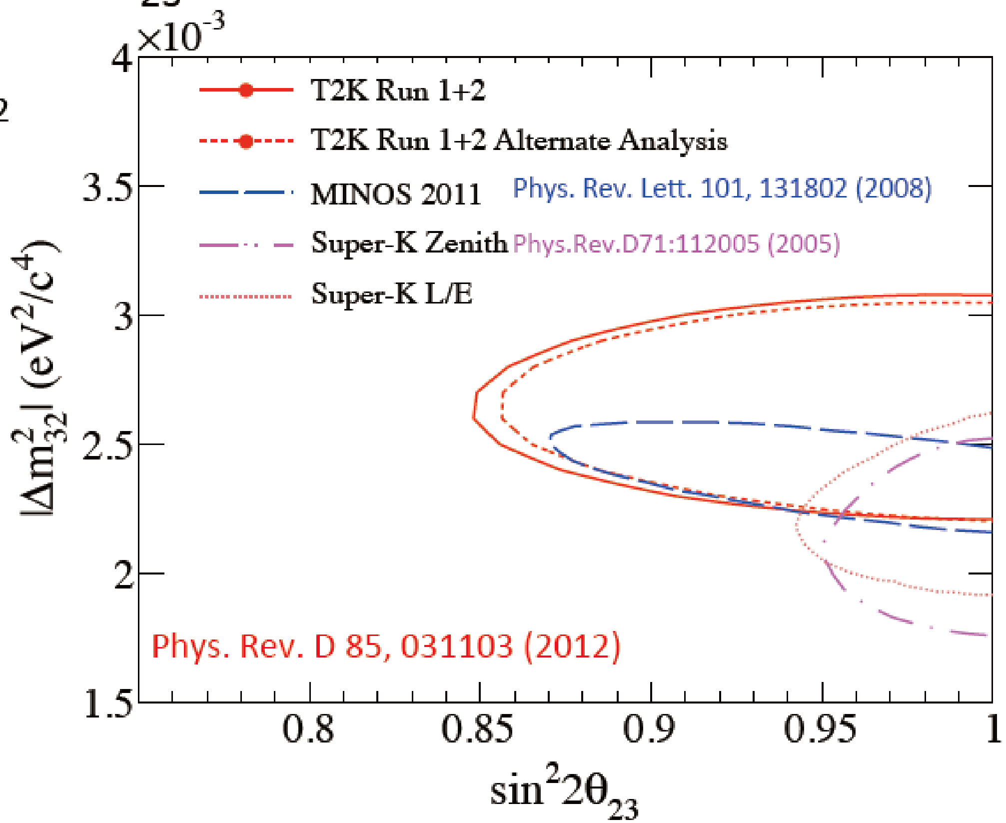
Disappearance analysis

ν_μ Disappearance (Run1+2)

- 31 ν_μ candidate events were observed in RUN1+2 data.
  - 103.6 events are expected in case of no oscillation.
  - $|\Delta m^2_{32}|=2.65^{+13.8}_{-13.4} \times 10^{-3}\ eV^2$, $\sin^2 2\theta_{23} = 0.98$

Event selection
Single-ring & μ-like & p_μ>200MeV/c & # of decay-e < 2





- Result of RUN1+2+3 data will be presented soon.

Summary & Outlook

Summary & Outlook

- **We report new results on ν_e appearance based on full data taken before summer shutdown (3.01×10^{20} p.o.t. ~4% exposure of T2K's goal)**
  - 11 candidate events is observed
  - p-value is 0.08% (equivalent to 3.2σ)
  - $\sin^2 2\theta_{13} = 0.094^{+0.053}_{-0.040}$
    - for $\Delta m^2_{32} = 2.4 \times 10^{-3}$ eV^2(NH), $\delta_{CP}=0$, $\sin^2 2\theta_{23}=1$

Evidence of ν_e appearance
→ open a possibility to measure CP violation in the lepton sector

- **Apparent ν_μ disappearance is observed and consistent contour is obtained with other experiments (1.43×10^{20} p.o.t.)**
- **We want to accumulate ~8×10^{20} p.o.t before the summer shutdown of 2013 in order to obtain definitive answer on ν_e appearance phenomenon**
- **After the LINAC upgrade in 2013, we need further beam power-up to precisely measure the oscillation parameters (including θ_{23}) for exploration of the lepton sector**