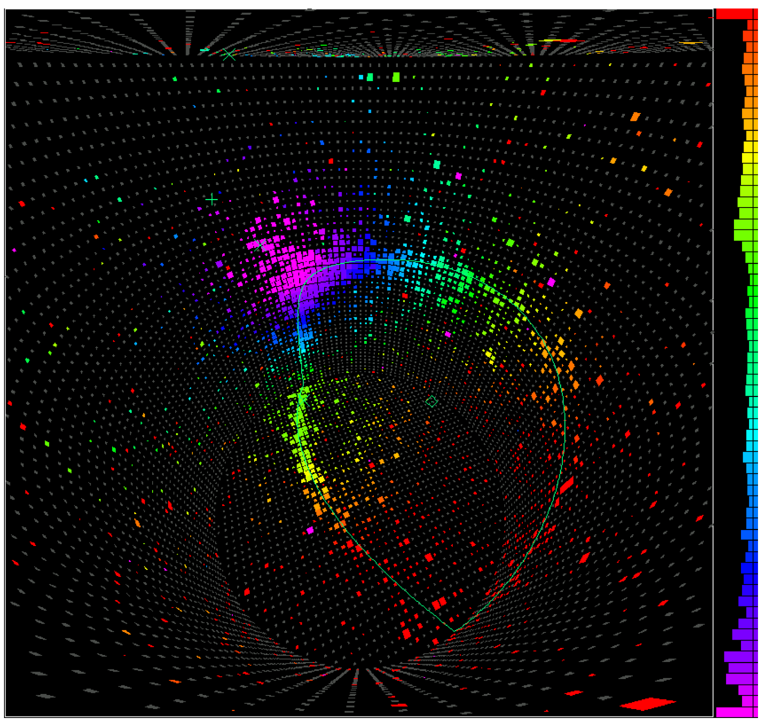
T2K実験

- ν_e appearance search – Phys. Rev. Lett. 107, 041801 (2011)
- ν_μ disappearance measurement – Preliminary result



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２０１１年１２月１７日

平成23年度宇宙線研究所
共同利用研究成果発表会

平成23年度共同利用研究採択課題

- 「東海to神岡長基線ニュートリノ実験T2K」
  - 代表者: 小林 隆
  - 査定額: 10万円(旅費)
- 「加速器データを用いたν相互作用シミュレーションの研究」
  - 代表者: 早戸 良成
  - 査定額: 5万円(旅費)
- 「T2K実験におけるν_e出現事象探索のための研究」
  - 代表者: 中山 祥英
  - 査定額: なし

T2K (Tokai-to-Kamioka) experiment

Intense ν_μ beam from J-PARC toward Super-Kamiokande

~500 members from 58 institutes, 12 nations

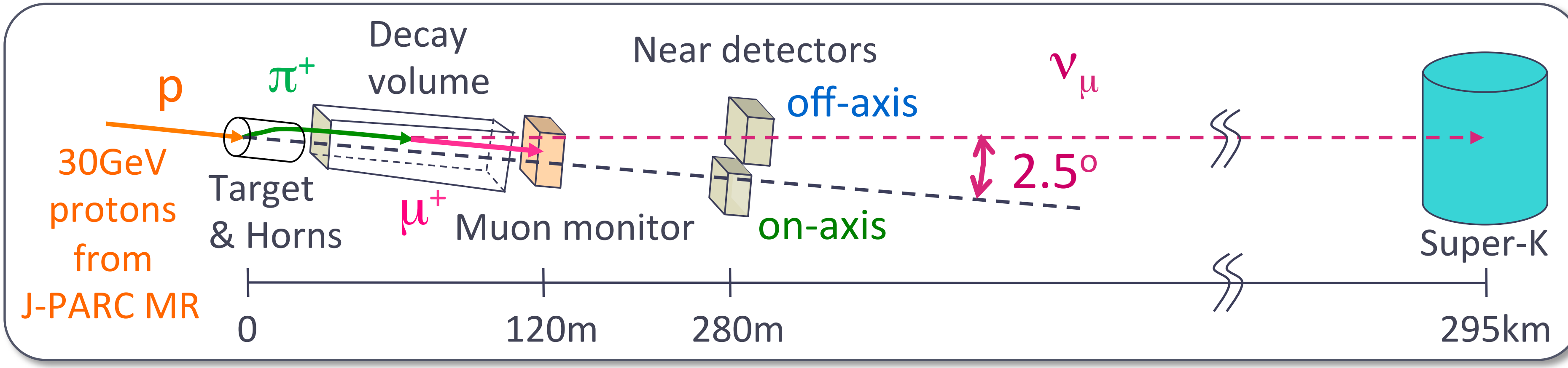
Primary goals :

- **Discovery of ν_e appearance by $\theta_{13} \neq 0$**

  Measure non-zero θ_{13} (sensitivity >10 times better than CHOOZ limit)

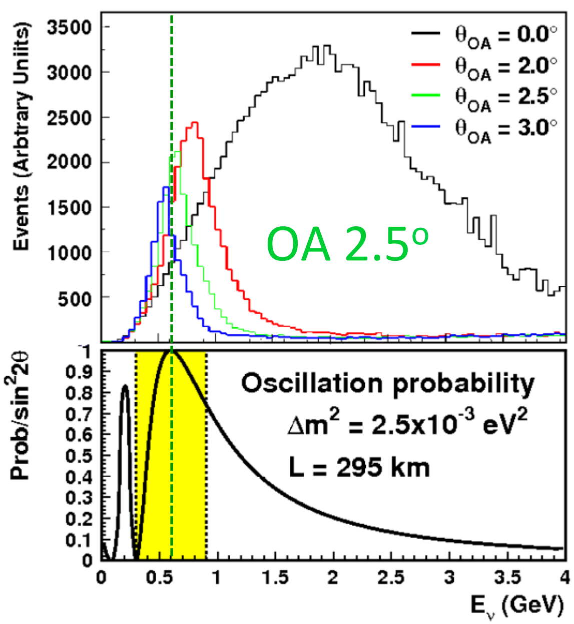
- **Precision measurement of ν_μ disappearance**

  $\delta(\Delta m^2_{23}) \sim 1 \times 10^{-4}$ eV^2 , $\delta(\sin^2 2\theta_{23}) \sim 0.01$



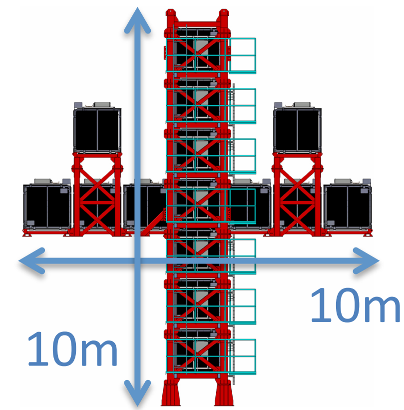
Off-axis ν beam

- Intense narrow-band @ osc. max. (~0.6GeV)
- Reduce high energy tail which creates BG



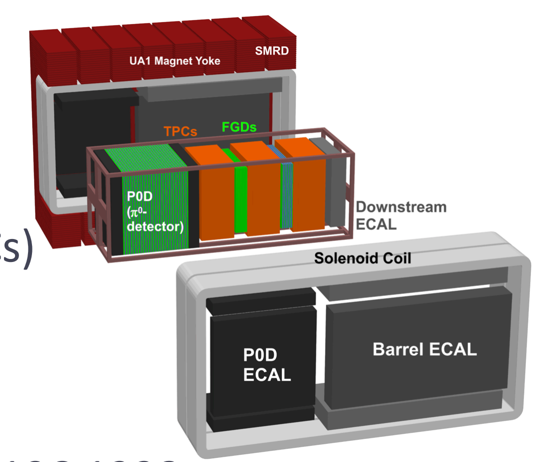
On-axis detector (INGRID)

- direct ν beam day-by-day monitoring (direction, intensity and profile)
- 16 cubic modules. Sandwich of iron plates and scintillator planes



Off-axis detector (ND280)

- measure ν flux/spectrum before oscillations
- 2 Fine Grained Detectors (FGDs)
- 3 Time Projection Chambers (TPCs)
  PID by dE/dx in gas
- P0D (π^0 detector), ECAL, SMRD



NIM A 659 (2011) 106-135, arXiv:1106.1238

Far detector : Super-Kamiokande

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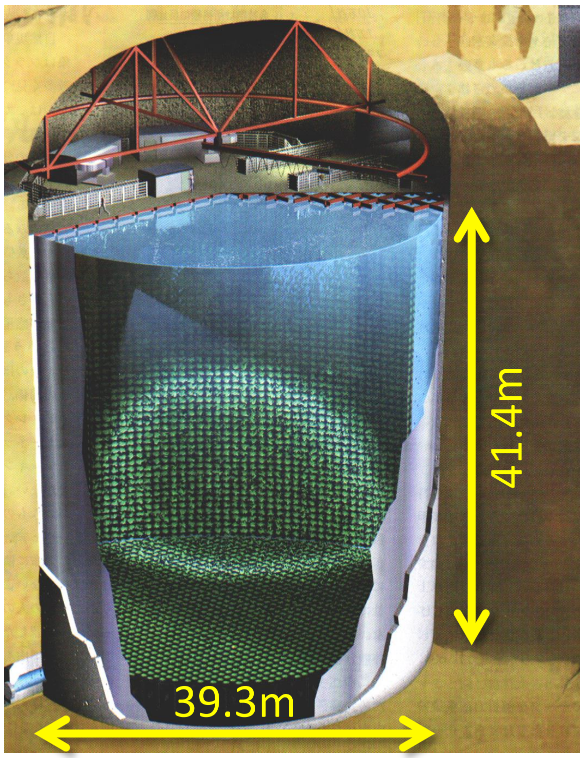
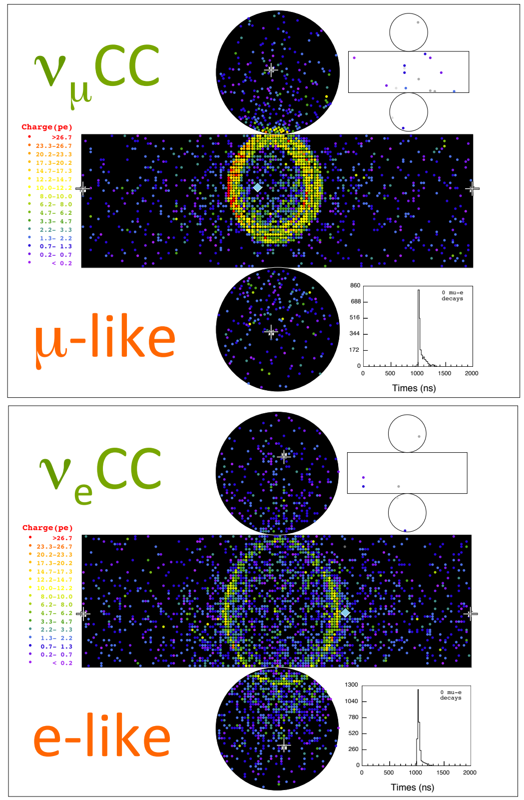
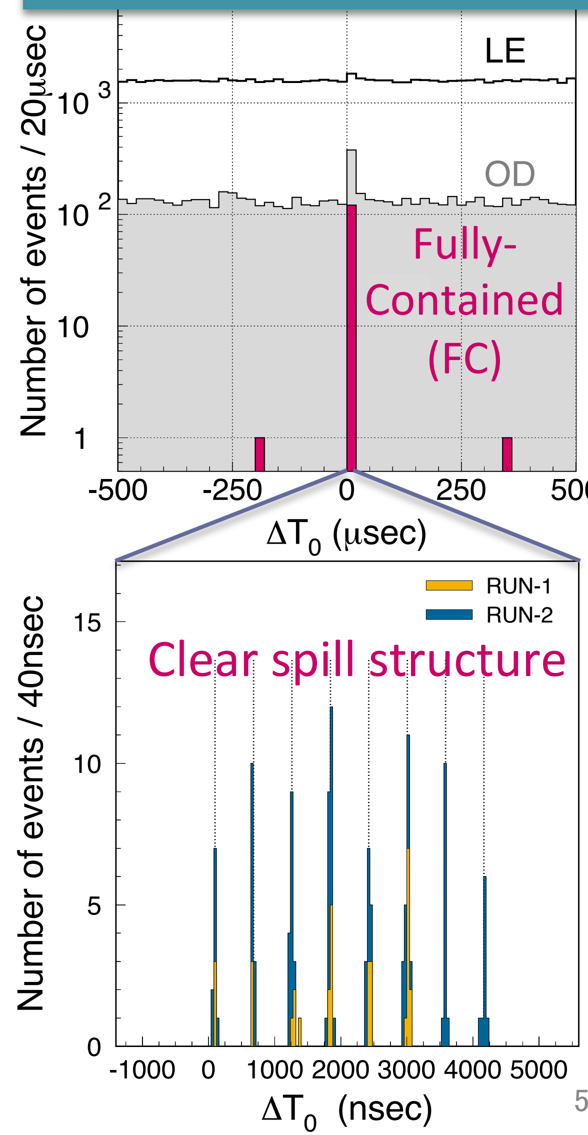


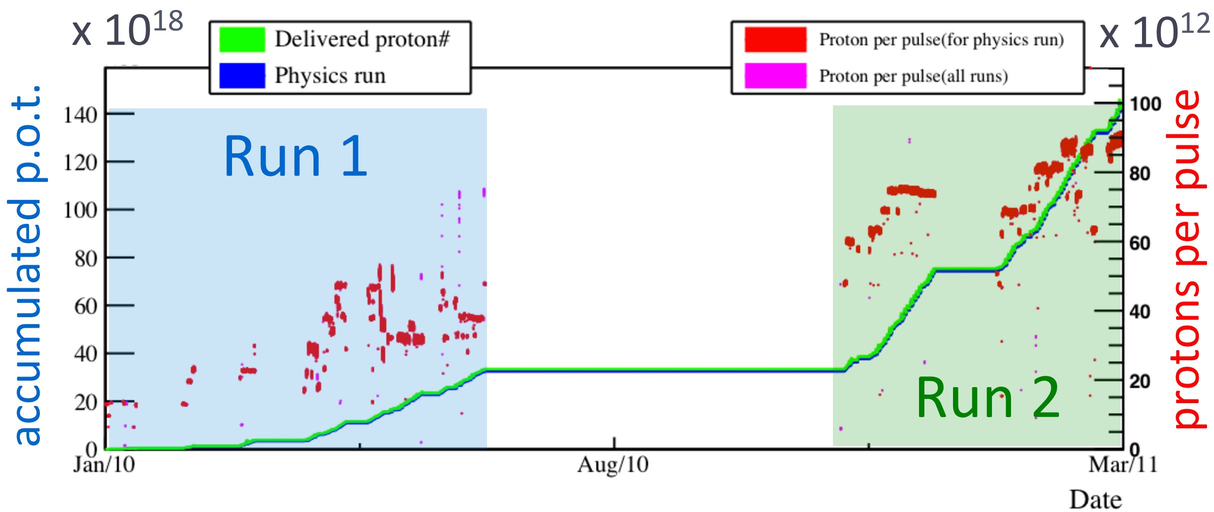


Observed SK event timing (relative to beam arrival time)



- Water Cherenkov detector, 22.5kton fiducial mass
- Excellent μ/e PID using ring-shape & opening angle (mis-ID probability ~1%)
- T2K: Realtime recording of all PMT hits within ±500μsec of beam arrival time by using GPS

Beam data used in present analyses



Run 1 (2010 Jan - 2010 Jun)

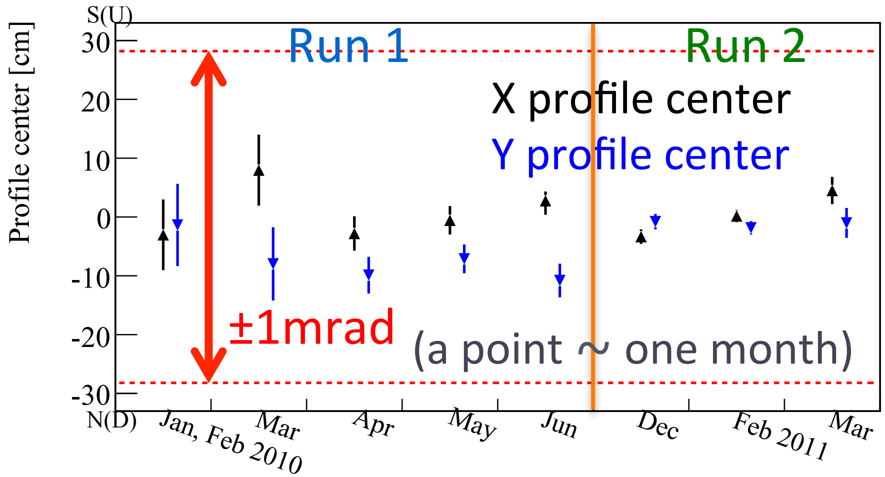
50kW stable operation

Run 2 (2010 Nov - 2011 Mar)

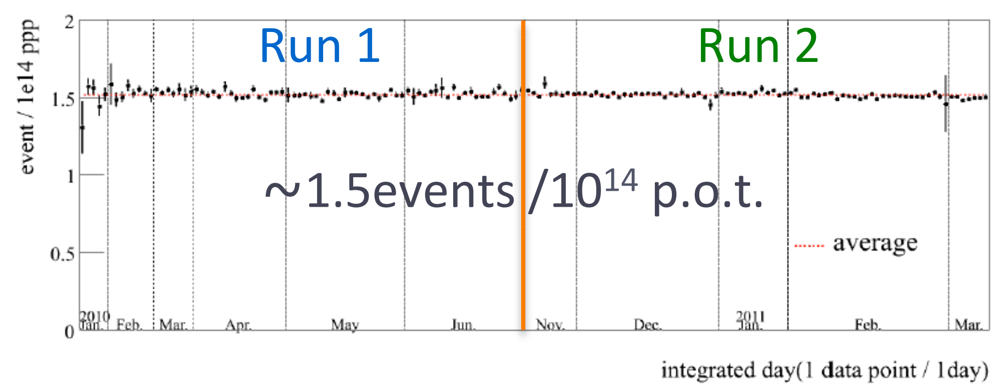
reached 145kW

Total p.o.t. : 1.43 x 10^{20}

~2% of T2K final goal



ν beam center measured by INGRID well within ±1mrad (δE<<2%@SK)



INGRID interaction rate stable for Run 1 & 2

(Beam direction & intensity also monitored by Muon Monitor spill-by-spill)

Oscillation analysis

Super-K Measurements :

- ν_e appearance
  → counting analysis
- ν_μ disappearance
  → rate & spectrum shape

ND280 Measurements :

- Inclusive ν_μCC measurement
- ν_e measurement as cross-check

Normalize SK MC prediction by ND ν_μCC rate

$$N_{SK}^{\exp} = \frac{R_{ND}^{\mu,Data}}{R_{ND}^{\mu,MC}} \times N_{SK}^{MC}$$

Observation/Expectation comparison to extract oscillation parameters

Far/Near sys. error cancellation

ND280 / Super-K MC simulations

Neutrino Flux :
Detailed MC simulation of beamline with input from proton beam monitors & external hadron data

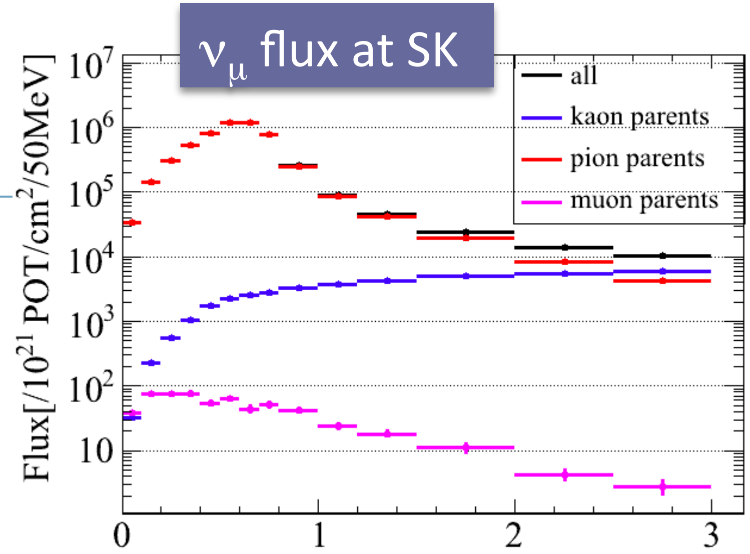
Neutrino Interaction :
Model (NEUT) tuned/constrained with external data

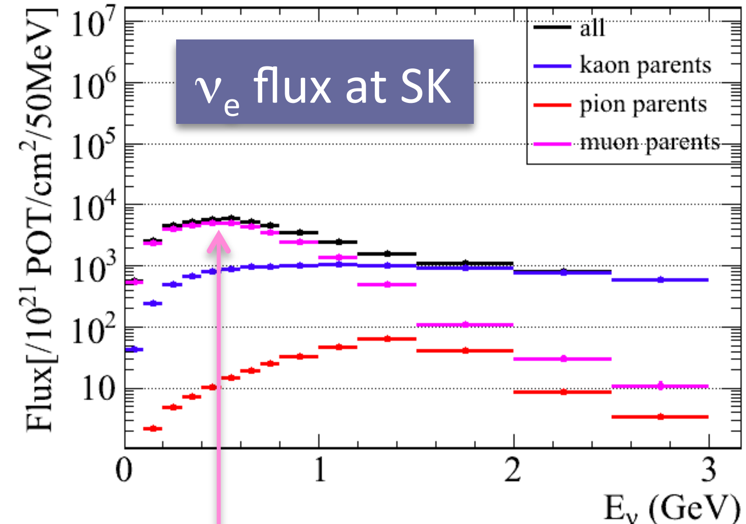
→ Detector simulations

Neutrino flux prediction

T2K beam simulation based on hadron production measurements

- NA61/SHINE (@CERN) measured hadron production in (p, θ) using 30GeV protons and graphite target
- π outside NA61 acceptance and K production modeled with FLUKA





Error source (ν_e analysis)	$R_{ND}^{\mu,\,MC}$	N_{SK}^{MC}	$\frac{N_{SK}^{MC}}{R_{ND}^{\mu,\,MC}}$
Pion production	5.7%	6.2%	2.5%
Kaon production	10.0%	11.1%	7.6%
Nucleon production	5.9%	6.6%	1.4%
Production x-section	7.7%	6.9%	0.7%
Proton beam position/profile	2.2%	0.0%	2.2%
Beam direction measurement	2.7%	2.0%	0.7%
Target alignment	0.3%	0.0%	0.2%
Horn alignment	0.6%	0.5%	0.1%
Horn abs. current	0.5%	0.7%	0.3%
Total	15.4%	16.1%	8.5%

Partial error cancellation after ND correction

μ decay is dominated at low E_ν

$$\pi^+ \rightarrow \mu^+ \nu_\mu\ ,\ \ \mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e$$

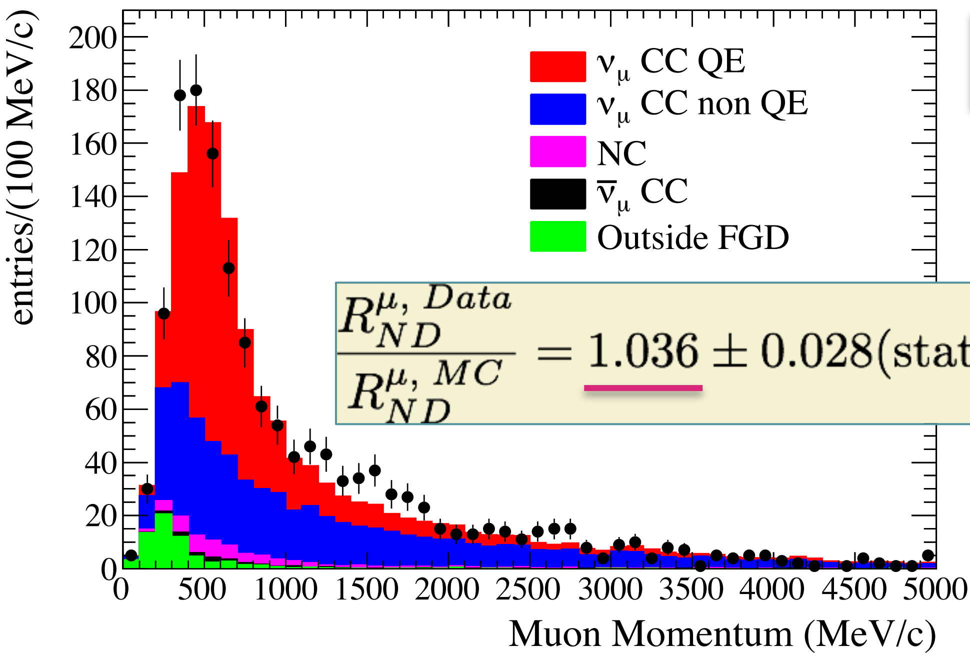
→ can accurately be predicted by NA61 π measurement

ND280 measurements

Using Run 1 data (2.9 x 10^{19} p.o.t.)

Inclusive ν_μCC measurement

Tracks starting in FGD and identified as μ by TPC dE/dx and curvature

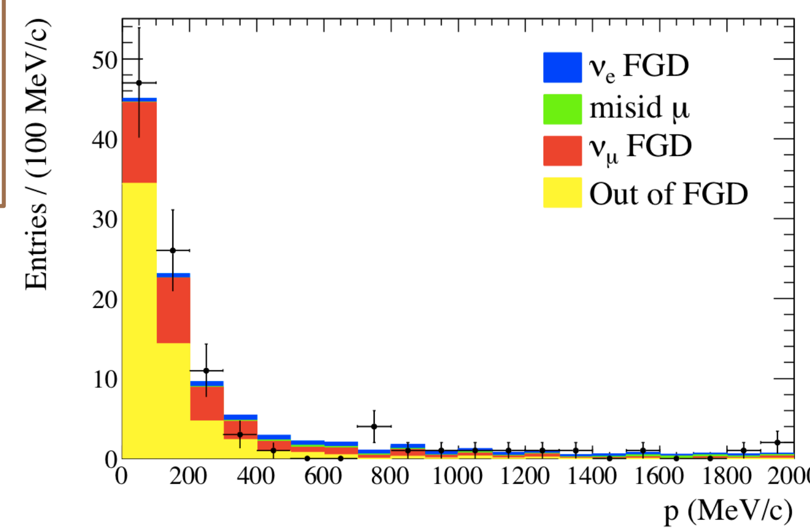


$$\frac{R^{\mu,\,Data}_{ND}}{R^{\mu,\,MC}_{ND}} = 1.036 \pm 0.028(\text{stat.})^{+0.044}_{-0.037}(\text{det. syst.}) \pm 0.038(\text{phys. syst.})$$

Intrinsic beam ν_e measurement

TPC dE/dx to select electron tracks

$R(\nu_e/\nu_\mu) = 1.0 \pm 0.7(\text{stat.}) \pm 0.3(\text{sys.})\ \%$



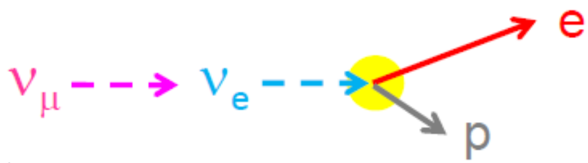
Data consistent with MC based on NA61 data and ν interaction simulation

ν_e appearance analysis

T2K ν_e event selection

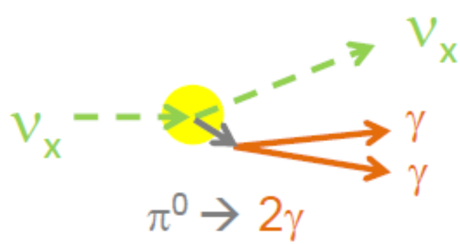
Number of remaining events after each cut

Signals : Single-electron events by osc. ν_e CCQE



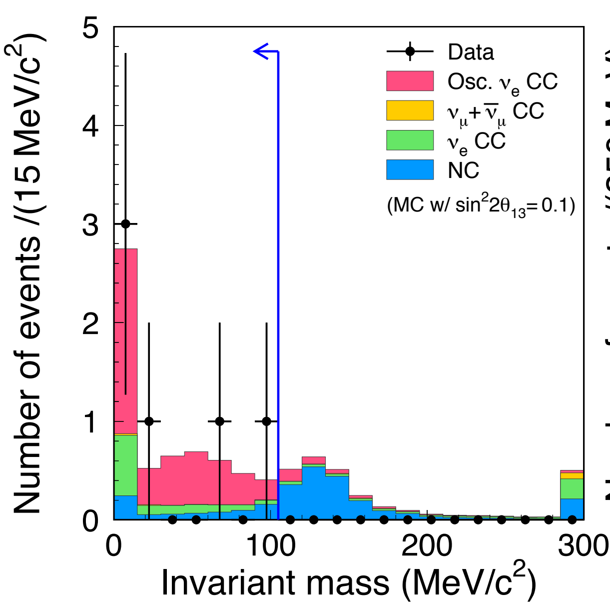
Backgrounds :

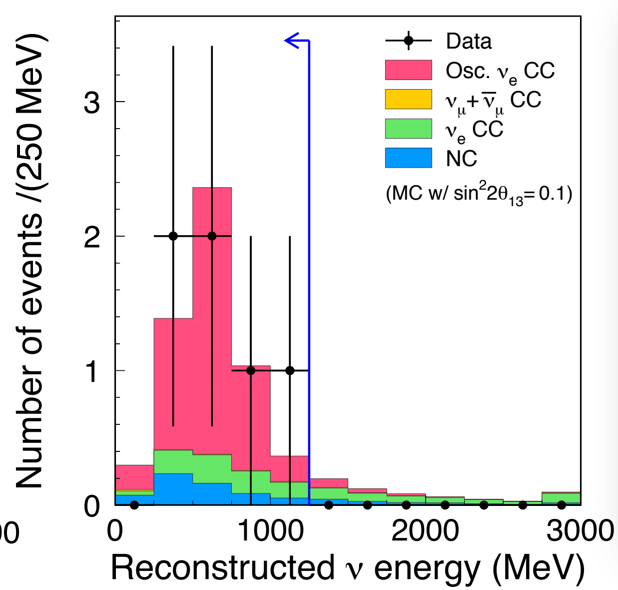
- ✓ Intrinsic beam ν_e
- ✓ NC π^0 events
  - overlap of 2 γ rings
  - asymmetric decay

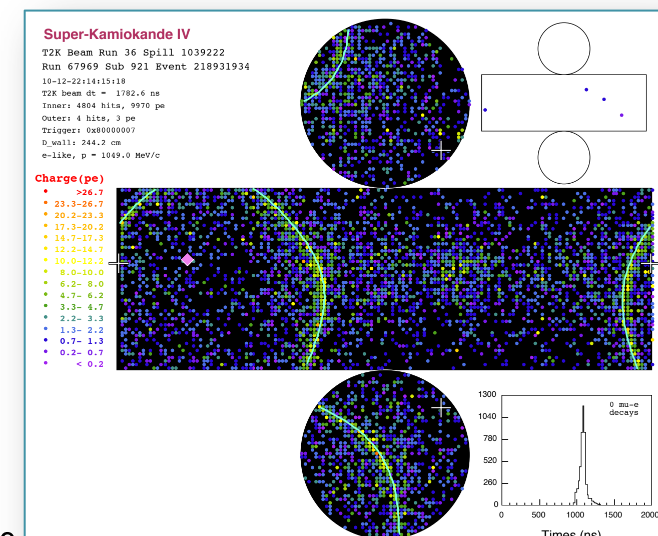


- Beam timing, FC, fiducial (88)
- Single-ring electron-like (8)
- Visible energy > 100MeV (7)
- No delayed electron signal (6)
- Invariant mass < 105MeV/c^2 (6)
- Rec. ν energy < 1250MeV (6)

→ 6 events observed



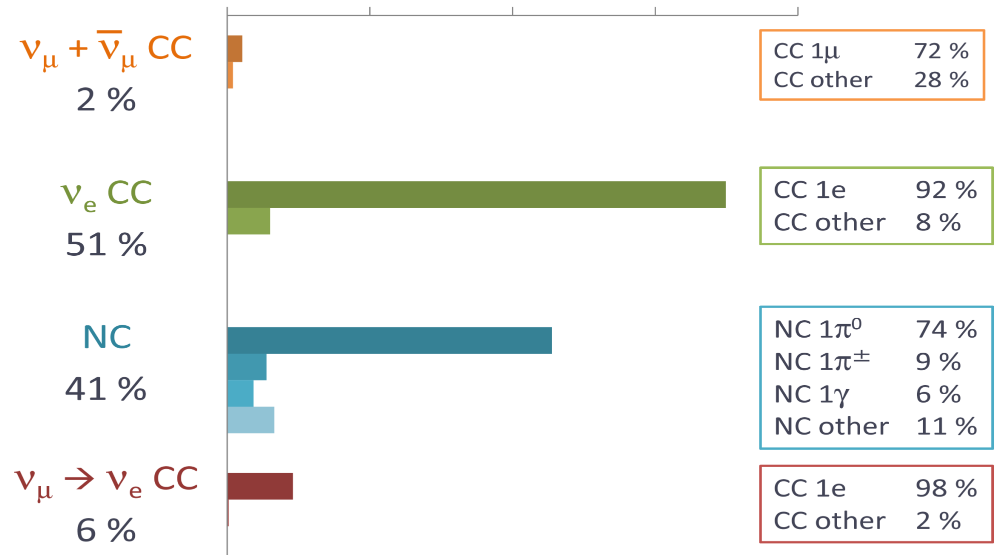




Expected number of ν_e events (θ_{13}=0)

(Δm^2_{23}=2.4x10^{-3} eV^2, $\sin^2 2\theta_{23}$=1.0)

Source	N_{SK}^{exp} (events)
Beam ν_μ CC	0.03
Beam ν_e CC	0.8
NC	0.6
Solar $\nu_\mu \rightarrow \nu_e$	0.1
Total	**1.5**



error source	syst. error
ν flux	$\pm 8.5\%$
ν int. cross section	$\pm 14.0\%$
Near detector	$^{+5.6}_{-5.2}\%$
Far detector	$\pm 14.7\%$
Near det. statistics	$\pm 2.7\%$
Total	$^{+22.8}_{-22.7}\%$

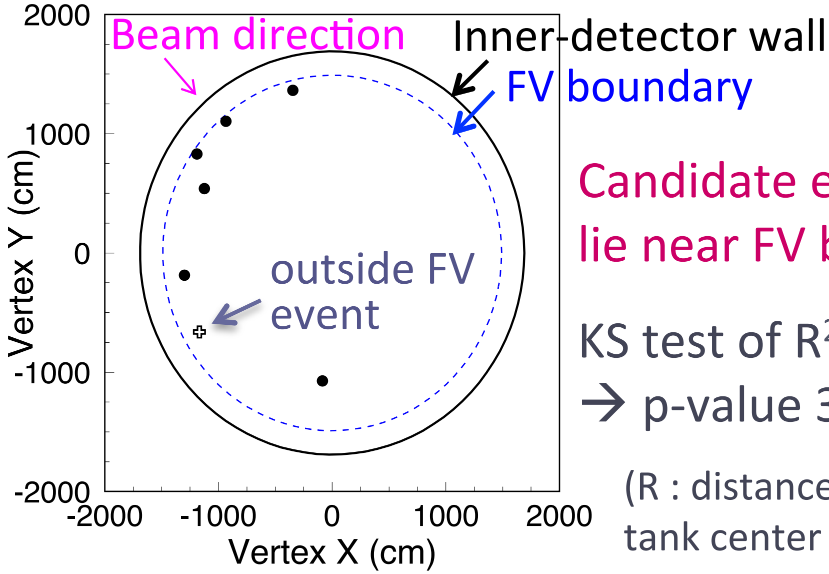
Dominated by hadron production uncertainties

Dominated by FSI and NC$1\pi^0$ cross-section uncertainties

Dominated by ring-counting, PID and invariant mass cut uncertainties

Expected number of events for θ_{13}=0 : 1.5 ± 0.3 (sys.) events

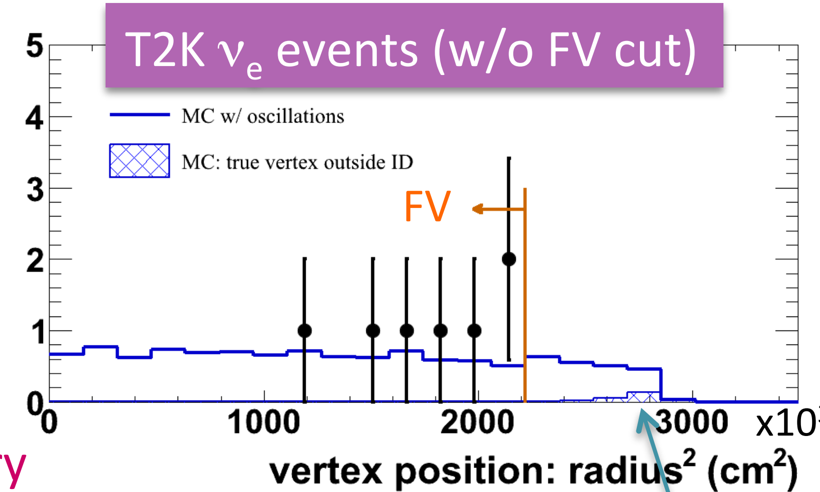
Vertex distribution

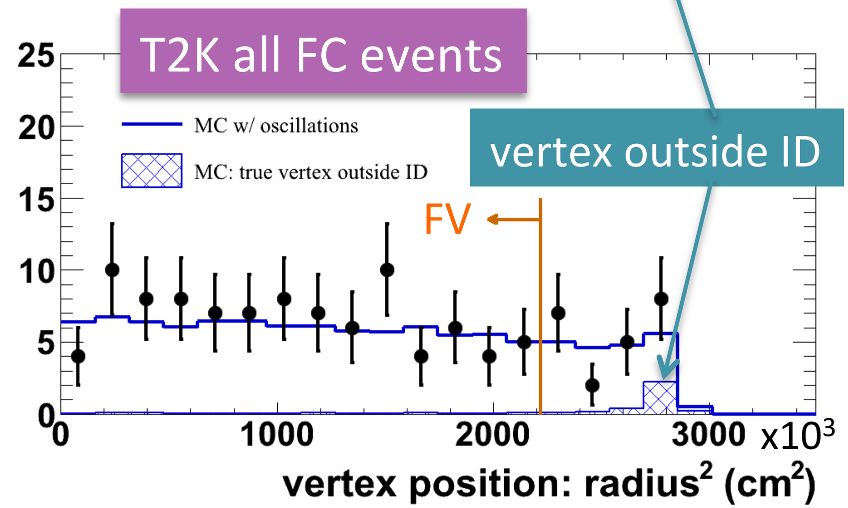


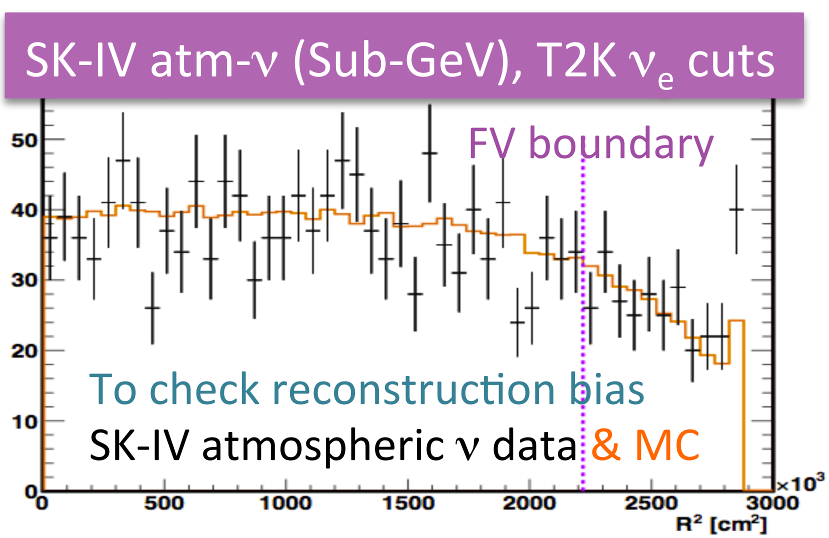
Candidate events lie near FV boundary

KS test of R^2 dist.
→ p-value 3%

(R : distance from tank center axis)







→ *Nice agreement both inside/outside FV*

Outside FV / Outer-detector events

→ *No anomalies near edge of FV*

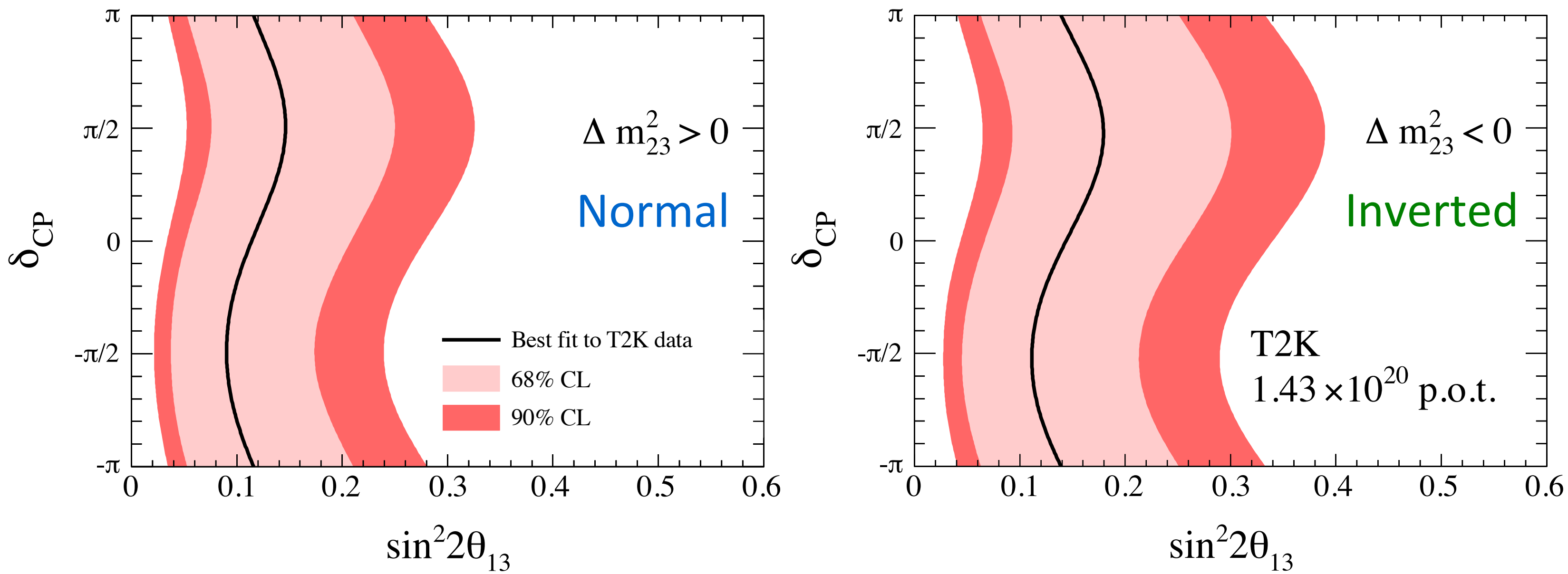
Simulation study of beam-induced BG by mis-ID μ, n, K, etc. from outside

→ *Very few ($3x10^{-3}$) events in FV*

ν_e appearance search result with 1.43×10^{20} p.o.t. data

Prob. of observing ≥6 events if $\theta_{13}=0$ → 0.7% (2.5σ)

For $\sin^2 2\theta_{23}=1$ and $\Delta m^2_{23}=2.4\times10^{-3}$ eV^2



(Feldman-Cousins method used to produce the confidence intervals)

Normal hierarchy, $\delta=0$: $\sin^2 2\theta_{13}$ = 0.11 (best fit), 0.03-0.28 (90% C.L.)

Inverted hierarchy, $\delta=0$: $\sin^2 2\theta_{13}$ = 0.14 (best fit), 0.04-0.34 (90% C.L.)

Published in Phys. Rev. Lett. 107, 041801 (2011)

Preliminary !

ν_μ disappearance analysis

T2K ν_μ event selection

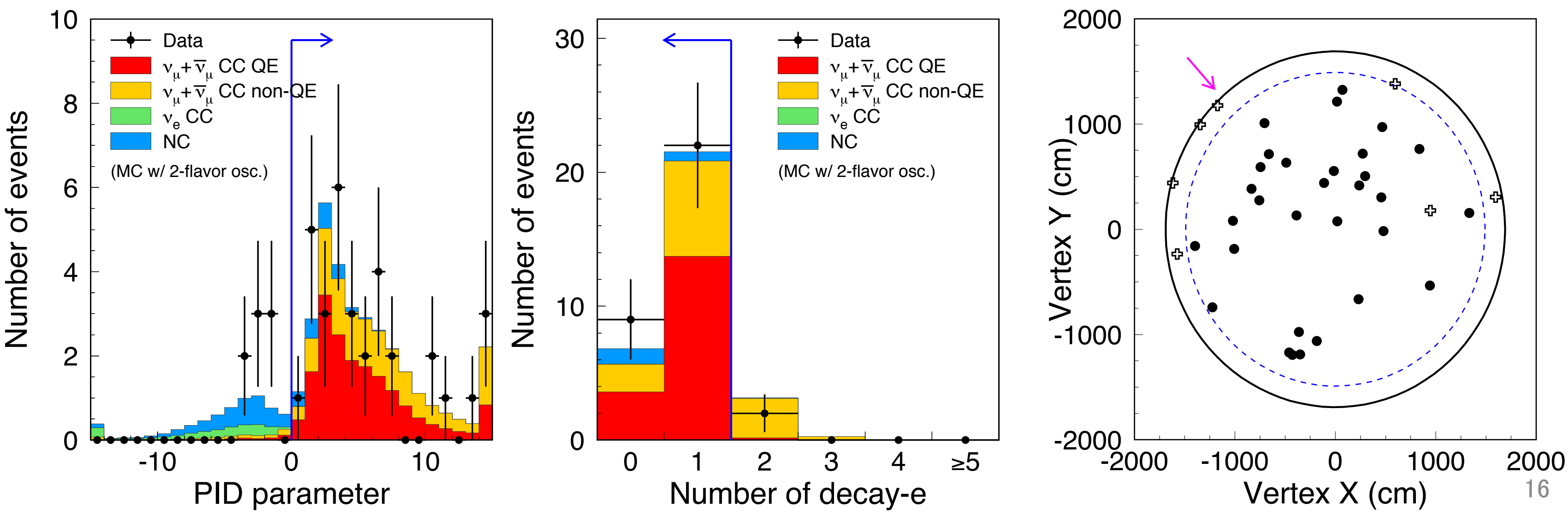
Select ν_μCCQE enriched sample

- Beam timing, fully-contained, fiducial
- Single-ring muon-like
- Rec. μ momentum > 200MeV/c
- # of delayed electrons ≤ 1

→ 31 events observed

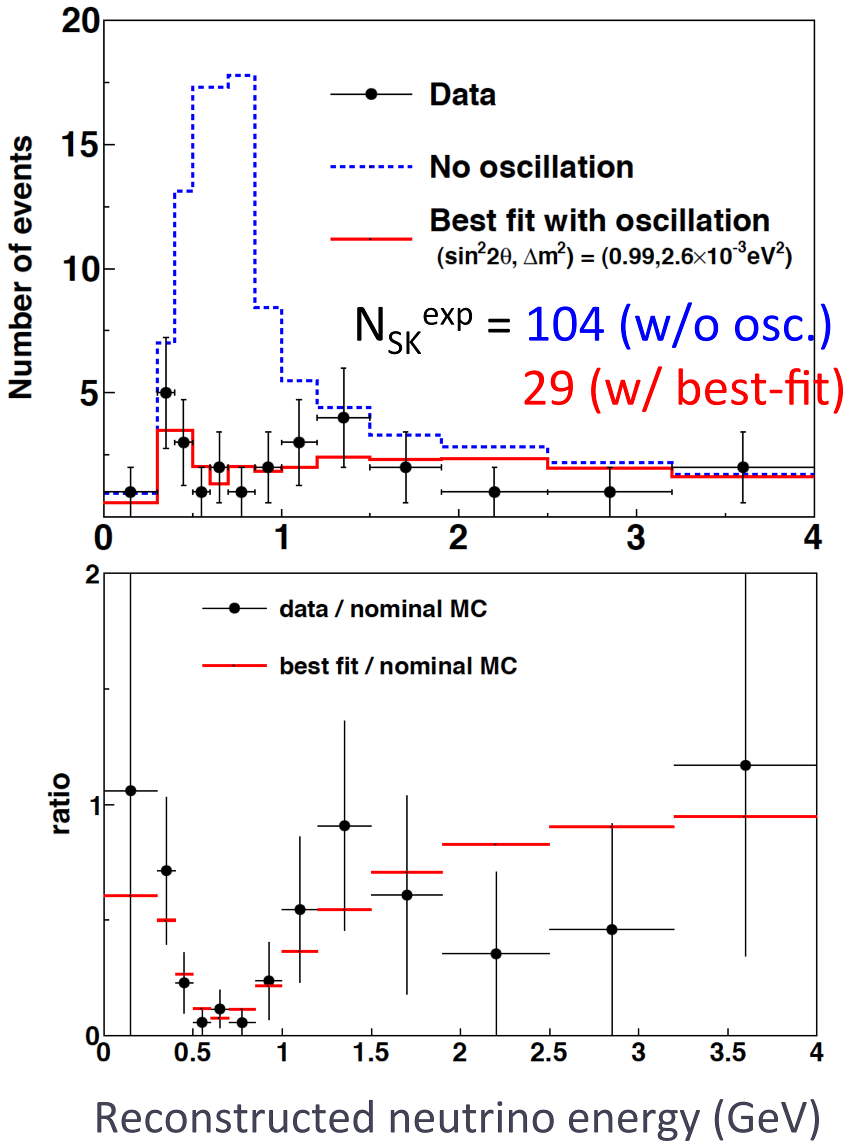
Composition of the final sample

Source	w/ osc.	w/o osc.
ν_μ CCQE	61%	82%
ν_μ CC non-QE	32%	17%
ν_e CC	0.05%	0.01%
NC	6%	2%



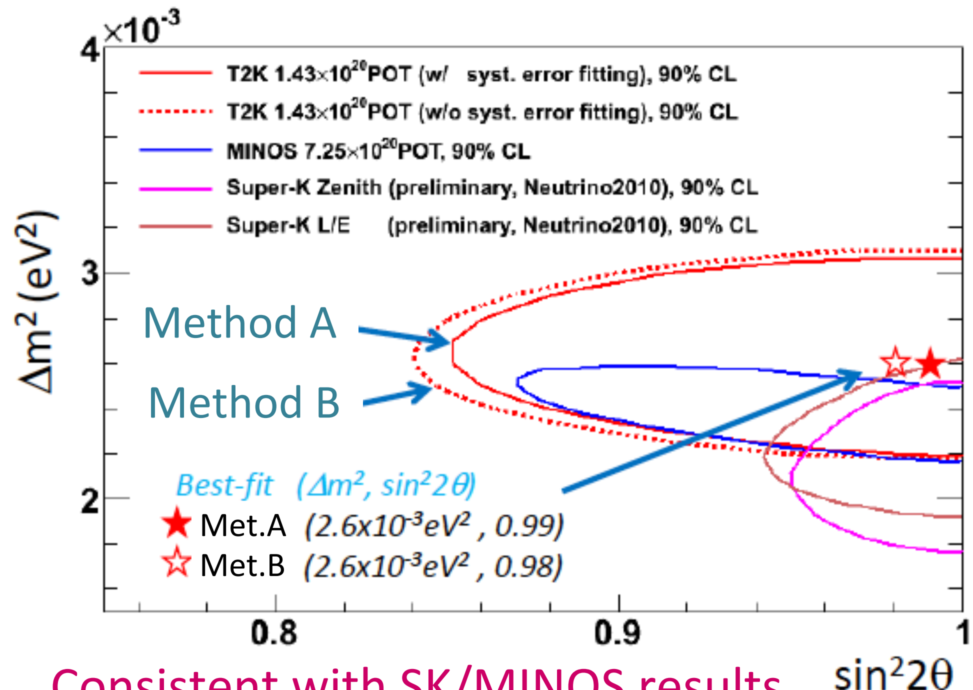
ν_μ analysis result

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(2\theta_{23})\sin^2\left(\frac{1.27\Delta m^2_{23} L(km)}{E_\nu(GeV)}\right)$$



Method A : Un-binned maximum likelihood with systematic error parameter fitting

Method B : χ^2 for binned spectrum without systematic parameter fitting



Consistent with SK/MINOS results

An oscillatory pattern is clearly seen !

Conclusions

- ν_e appearance / ν_μ disappearance results from the first off-axis long-baseline ν experiment using 1.43×10^{20} p.o.t. data
- Indication of ν_e appearance via non-zero θ_{13}
  - 6 candidate events observed, while 1.5±0.3 expected if θ_{13}=0
    → probability = 0.7 % (2.5σ significance)
- First ν_μ disappearance result from T2K
  - 31 events observed, while 104 expected in case of null-oscillation
  - 90% C.L. allowed region consistent with SK/MINOS

T2K next steps

- Need more data (only 2% of the planned final exposure)
  - to establish ν_e appearance, to measure osc. parameters precisely
  - will resume physics data taking in January 2012
  - → 0.5 MW x 10^7 s (1×10^{21} p.o.t.) by Summer 2013

    Conclude $\theta_{13} \neq 0$ (>5σ if the present T2K best-fit is the answer)

- Analysis improvements
  - reduce flux prediction uncertainties using new NA61 data
  - reduce SK systematics for sub-dominant events
  - ν_e appearance analysis using energy spectrum
  - more detailed ND data analyses (ν_μCCQE/CCnQE , ν_e , …)
  - reduce cross section uncertainties using T2K ND data