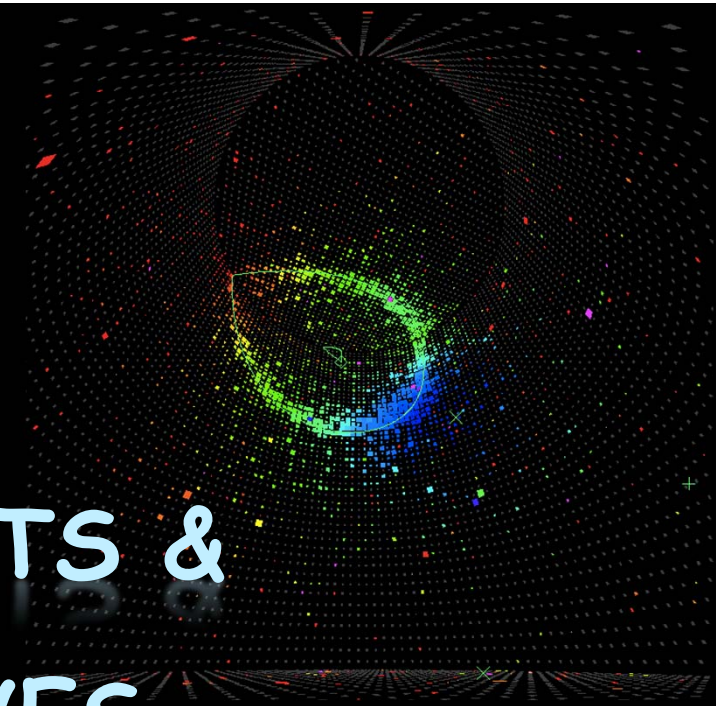


T2K RESULTS & PERSPECTIVES

NEUTRINO OSCILLATION WORKSHOP

12TH SEPTEMBER 2012

M.G. Catanesi INFN Bari
for the T2K Collaboration

The T2K Collaboration

~500 members, 59 Institutes, 12 countries

Canada
TRIUMF
U. Alberta
U. B. Columbia
U. Regina
U. Toronto
U. Victoria
U. Winnipeg
York U.

France
CEA Saclay
IPN Lyon
LLR E. Poly.
LPNHE Paris

Germany
Aachen U.

Italy
INFN, U. Bari
INFN, U. Napoli
INFN, U. Padova
INFN, U. Roma

Japan
ICRR Kamioka
ICRR RCCN
KEK
Kobe U.
Kyoto U.
Miyagi U. Edu.
Osaka City U.
U. Tokyo

Poland
IFJ PAN, Cracow
NCBJ, Warsaw
U. Silesia, Katowice
U. Warsaw
Warsaw U. T.
Wroklaw U.

Russia
INR

S. Korea
Chonnam N. U.
Dongshin U.
Seoul N. U.

Spain
IFAE, Barcelona
IFIC, Valencia

Switzerland
ETH Zurich
U. Bern
U. Geneva

United Kingdom
Imperial C. London
Lancaster U.
Oxford U.
Queen Mary U. L.
STFC/Daresbury
STFC/RAL
U. Liverpool
U. Sheffield
U. Warwick

USA
Boston U.
Colorado S. U.
Duke U.
Louisiana S. U.
Stony Brook U.
U. C. Irvine
U. Colorado
U. Pittsburgh
U. Rochester
U. Washington

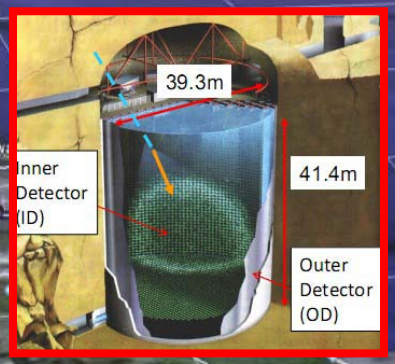
Physics motivations

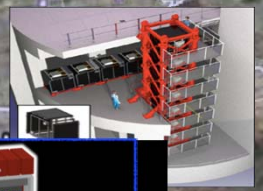
- High sensitivity search for θ_{13}
  - Direct detection of neutrino flavour mixing in "appearance" mode
- Precision measurement of θ_{23}, Δm^2_{23}
  - $\theta_{23} = 45° \pm 5°$ (T2K can distinguish the octant)
- Neutrino X-sections below 1GeV @ ND280
- Exotic Searches

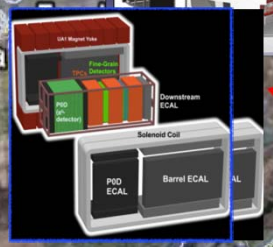
Until now T2K collected 3.01 10^{20} p.o.t. (world record) . They correspond only to 4% of the approved p.o.t by J-PARC program advisory committee

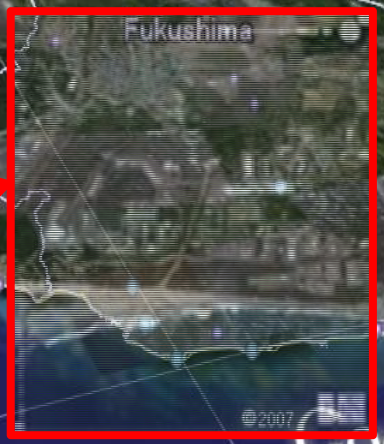
The results shown today are only the appetizer of the T2K final menu

T2K Beam & Detectors



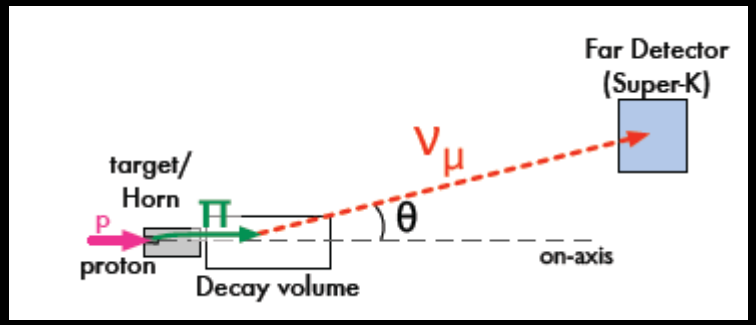


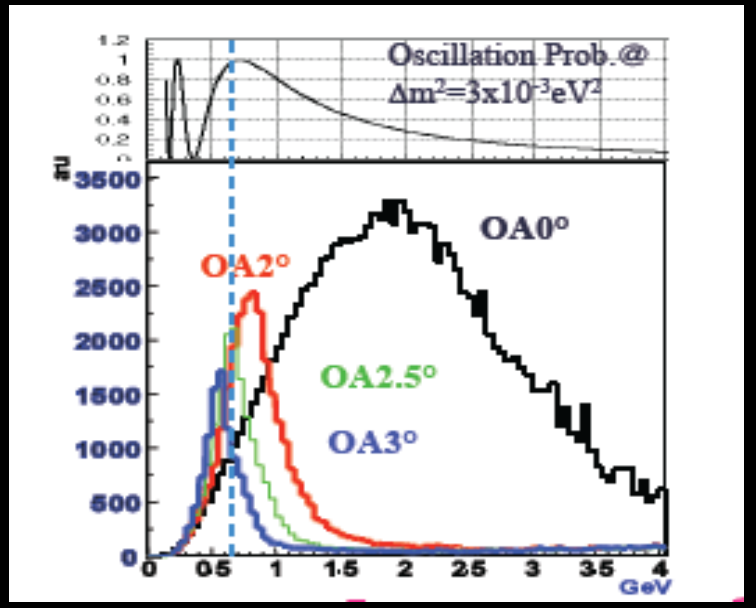




Kobe
Osaka
Kyoto
Kanazawa
Tsu
Nagoya
Gifu
Nagano
Japan
Shizuoka
Kofu
Hachioji
Tokyo
Saitama
Kanagawa
Yokohama
Kawasaki
Chiba
Mito
Niigata
Sado
Awa-shima
Honshu
J-PARC
E135°
E137°
E139°
E141°
N37°
N35°
Image NASA
© 2007 Europa Technologies
Image © 2007 TerraMetrics
© 2007 ZENRIN
Google™
Pointer 36° 23'41.59" N 139° 11'54.71" E elev 665 m
Streaming 100%
Eye alt 223.17 km

Off-axis beam: intense & narrow-band beam





Beam energy @ oscillation max: Ev ~ 0.6 GeV

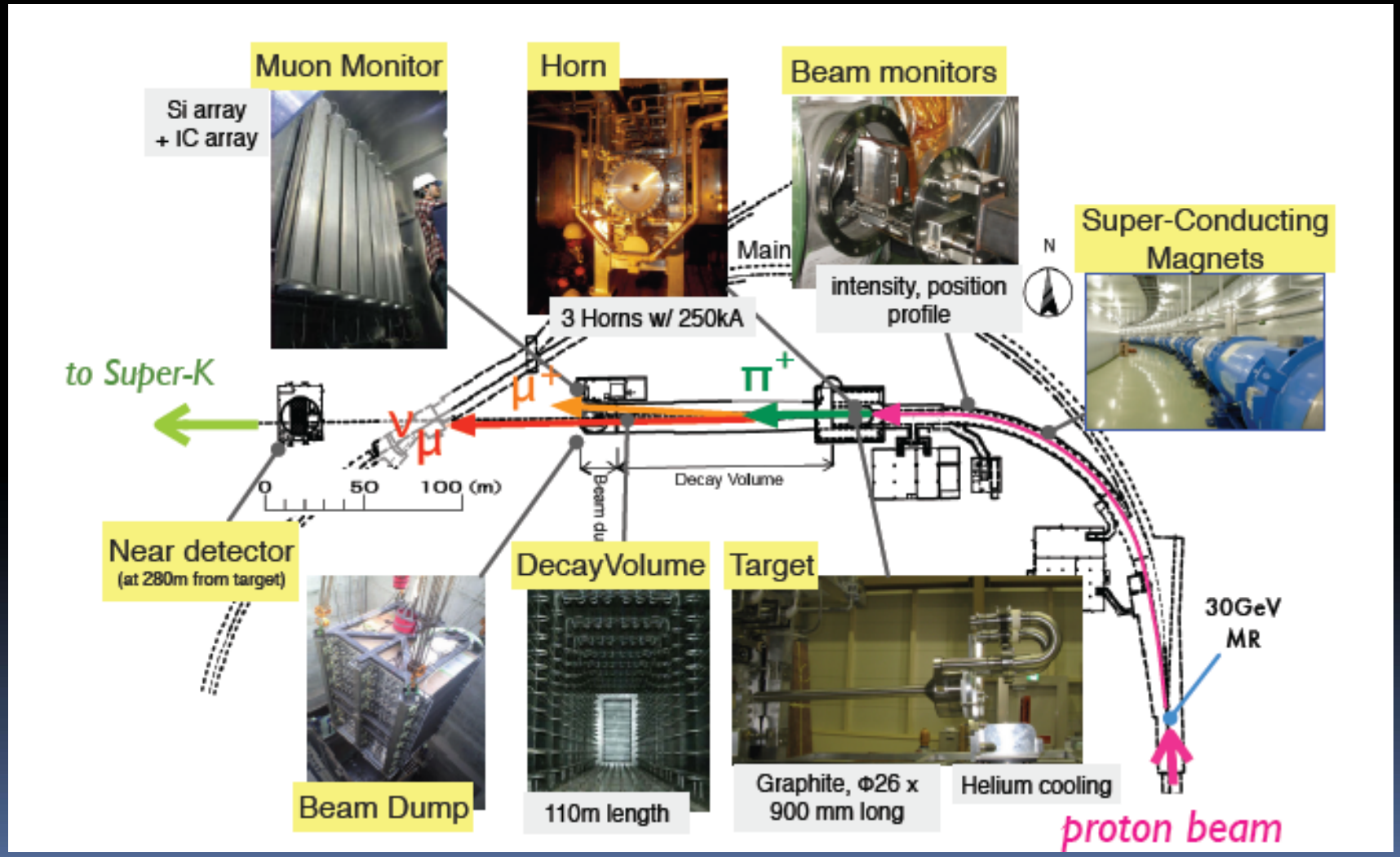
Important to keep beam direction stable (T2K off-axis angle is 2.5°)

-> maximize physics sensitivity

Small high energy tail

-> minimize background

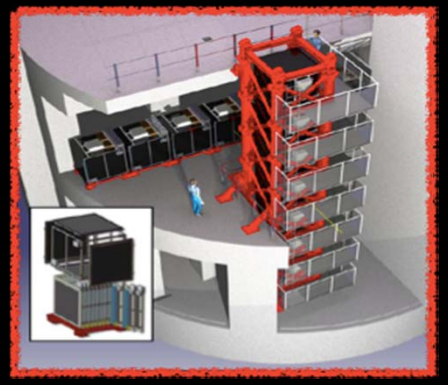
J-PARC Neutrino beam facility

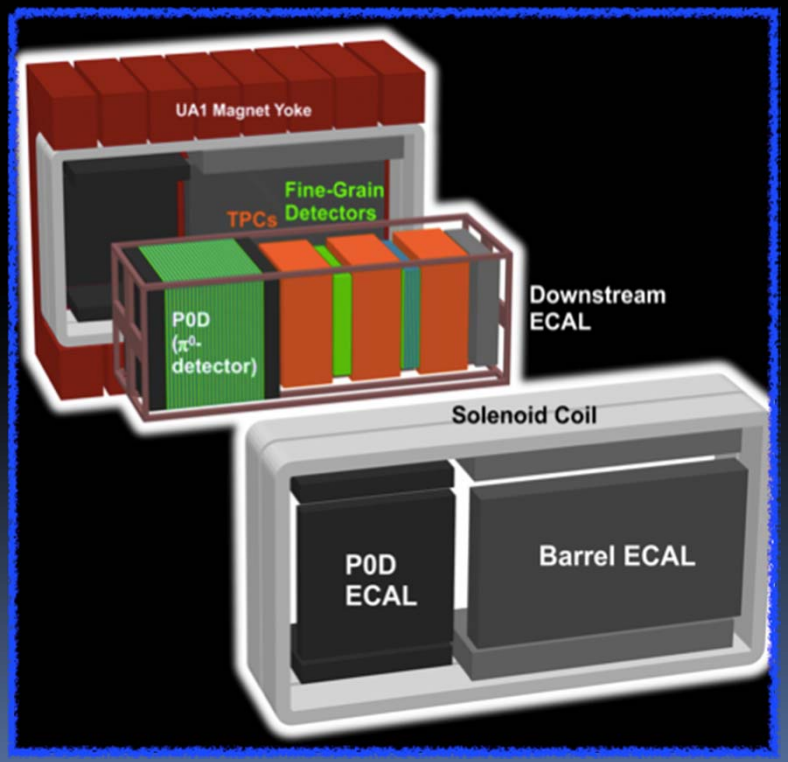


ND280

Near Detector @ 280m from the target

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



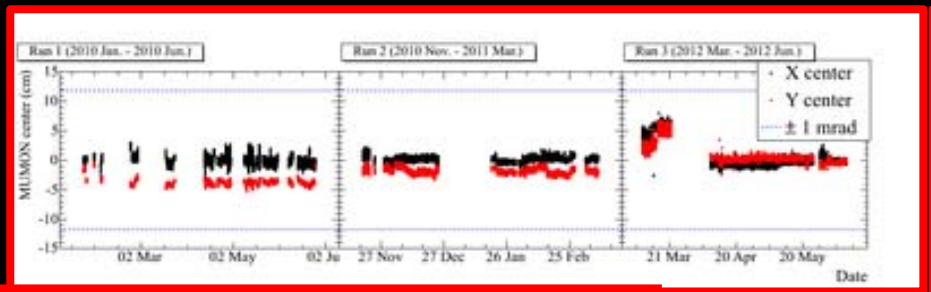


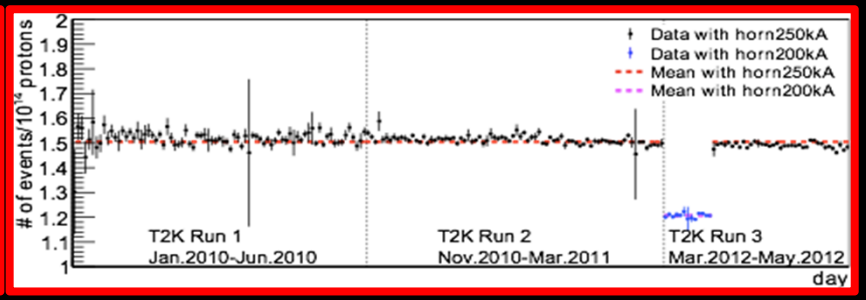
- **ND280** @ 2.5 degree off-axis
  - Normalization of Neutrino Flux
  - Measurement of neutrino cross sections.

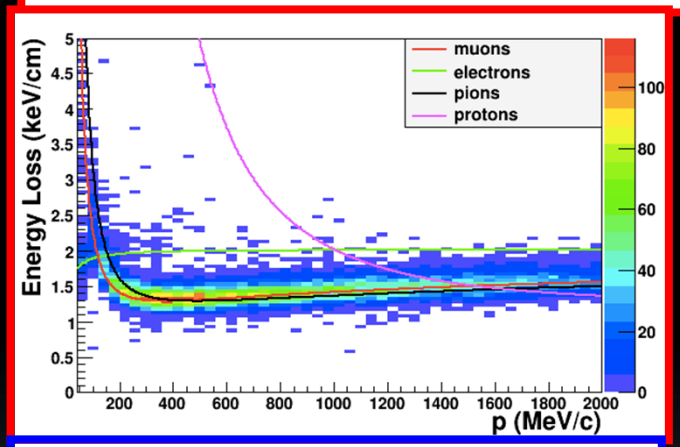
- Dipole magnet 0.2T
- **P0D**: π^0 Detector
- **FGD+TPC**: Target + Particle tracking
- EM calorimeter
- Side-Muon-Range Detector

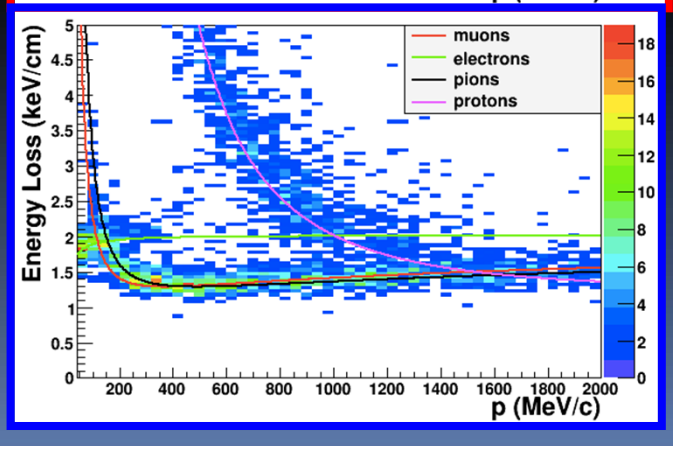
ND280 Performances

Stability of beam direction (< 1mrad) and rate by INGRID





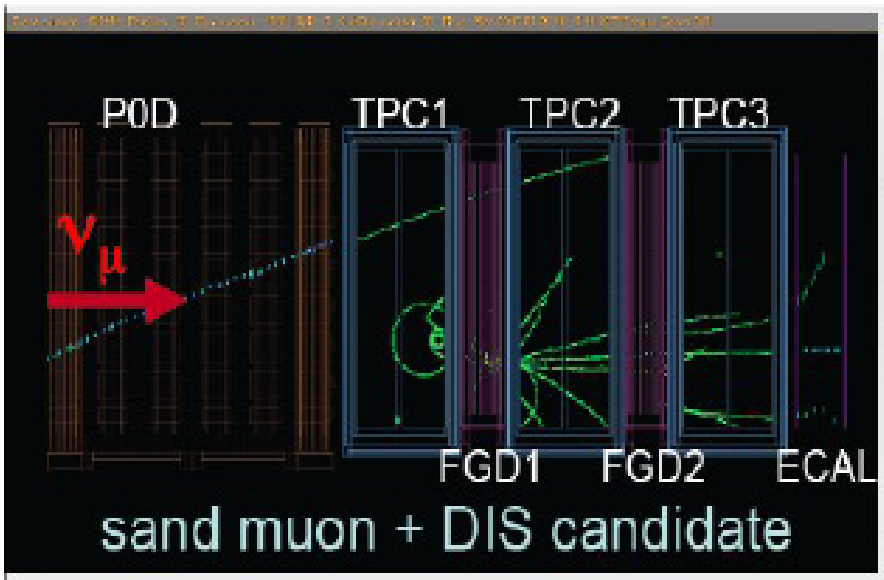


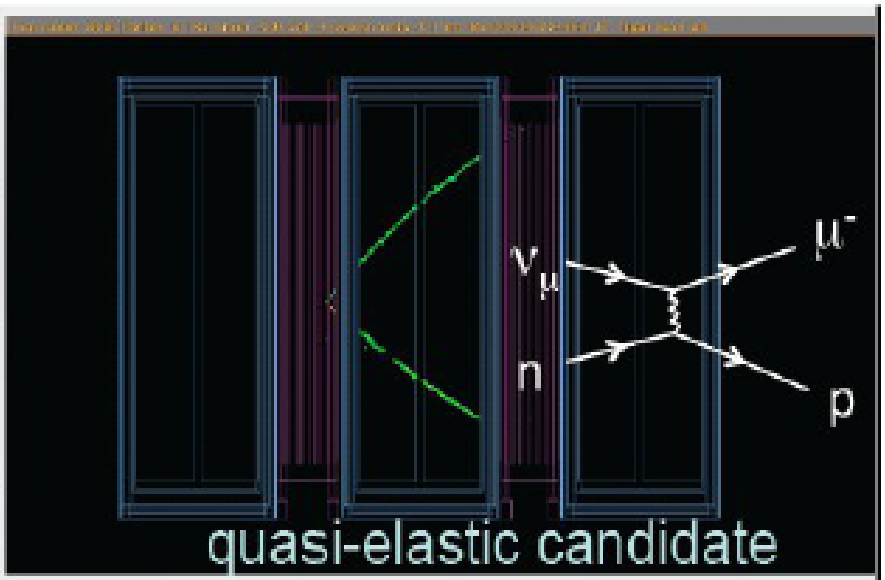


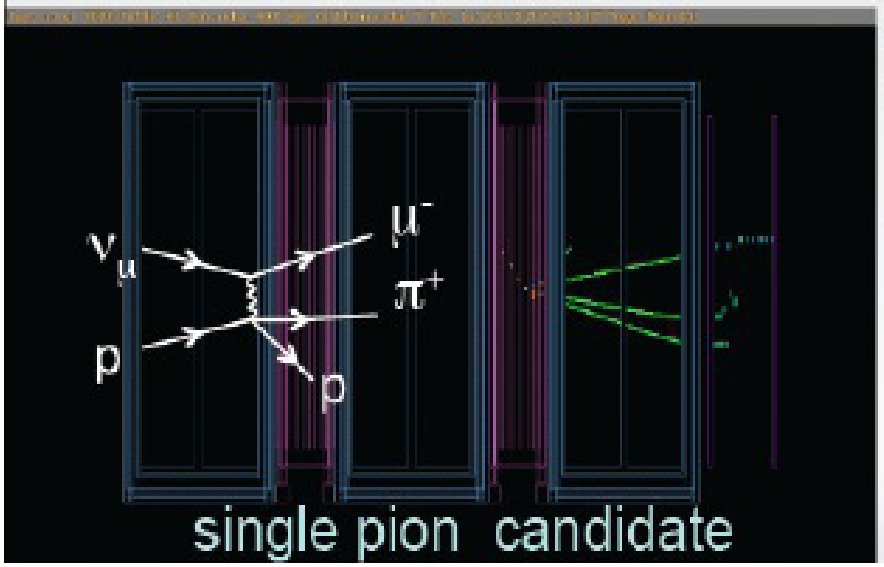
ν_μ CC events rate measurement by ND280 off Axis

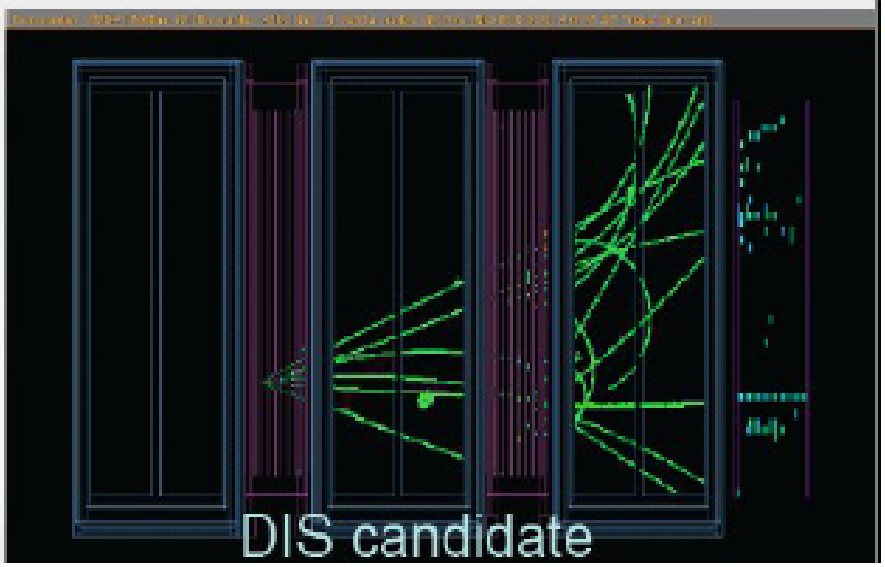
- UA1 magnet (0.2 T)
- Fine Grained Detector (FGD) (target)
- Time Projection Chambers (TPC)
  - Momentum Res. < 10%
  - PID (< 10% dE/dx Res.)

ND280 off-axis event gallery

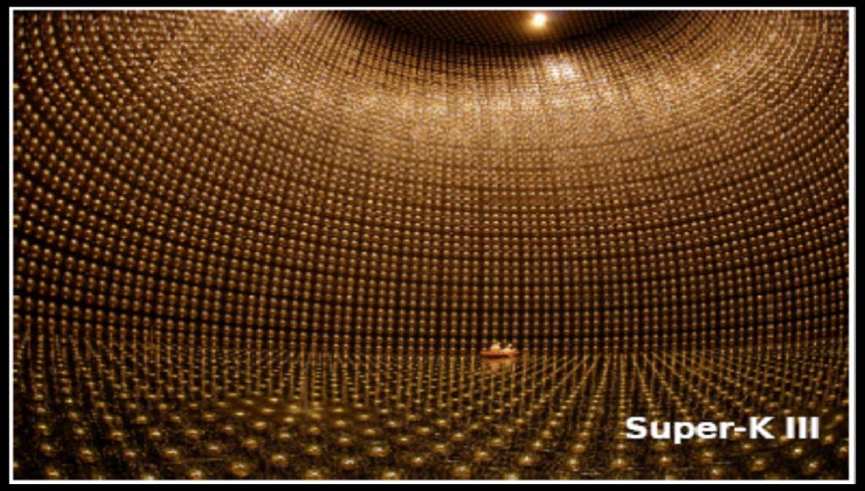


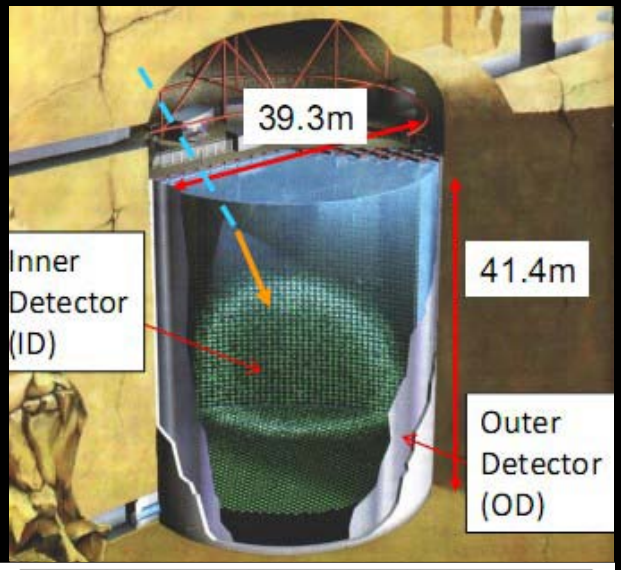


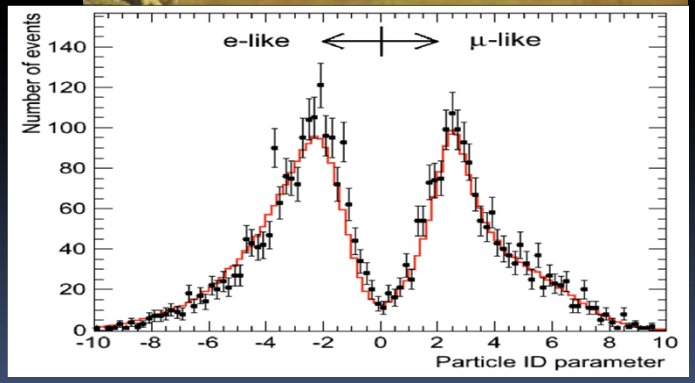




T2K-Far Detector: Super-Kamiokande







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

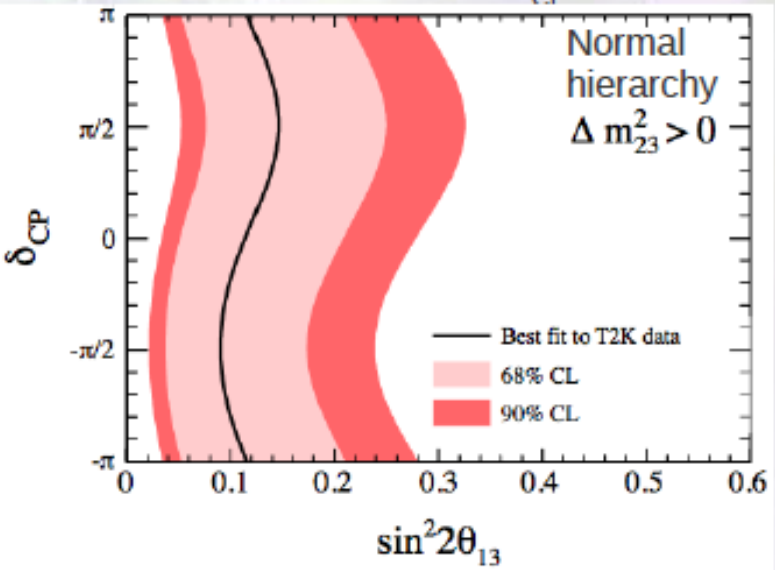
- 50 kton Water Cherenkov detector 1 km underground
- Typically 61% ν_e signal eff. 95% π_0 rejection
- 32 kton inner volume (22.5 kton fiducial volume)
- 2 m outer volume to identify entering particles

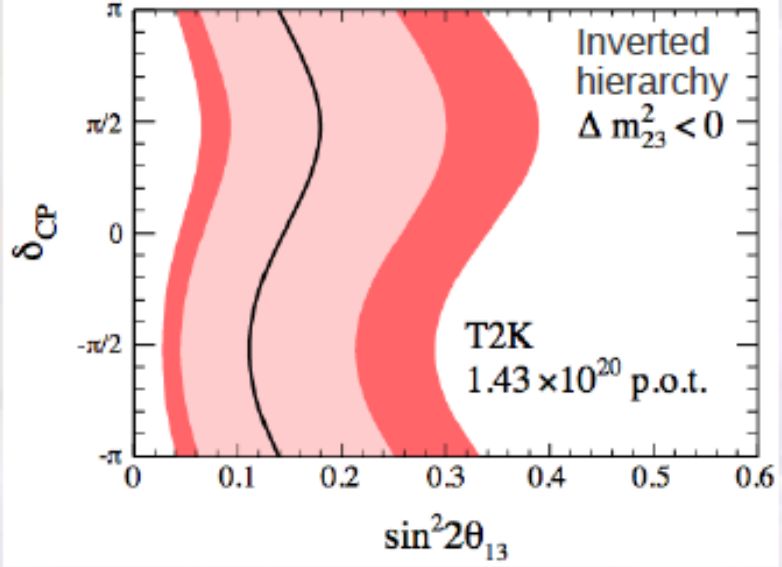
All triggers in +/- 0.5 ms of neutrino arrival time are recorded

T2K ν_e Appearance Analysis 2011 (Run1+2)

First indication of θ_{13} non zero

- Probability of observing 6 events if $\sin^2(2\theta_{13})=0$ → 0.7% (2.5σ significance)
- Feldman-Cousins unified method used to construct the confidence intervals.
- Confidence intervals for δ_{CP} versus $\sin^2 2\theta_{13}$:





90% interval and best fit (for $\sin^2(2\theta_{23})=1$, $\Delta m^2_{23}=2.4\times10^{-3}$ eV^2, $\delta_{CP}=0$):

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

Inverted hierarchy, δ=0:
- Best fit → $\sin^2(2\theta_{13})=0.14$
- $0.04<\sin^2(2\theta_{13})<0.34$ @90% C.L.

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

ν_μ disappearance result 2011 : Run 1+2

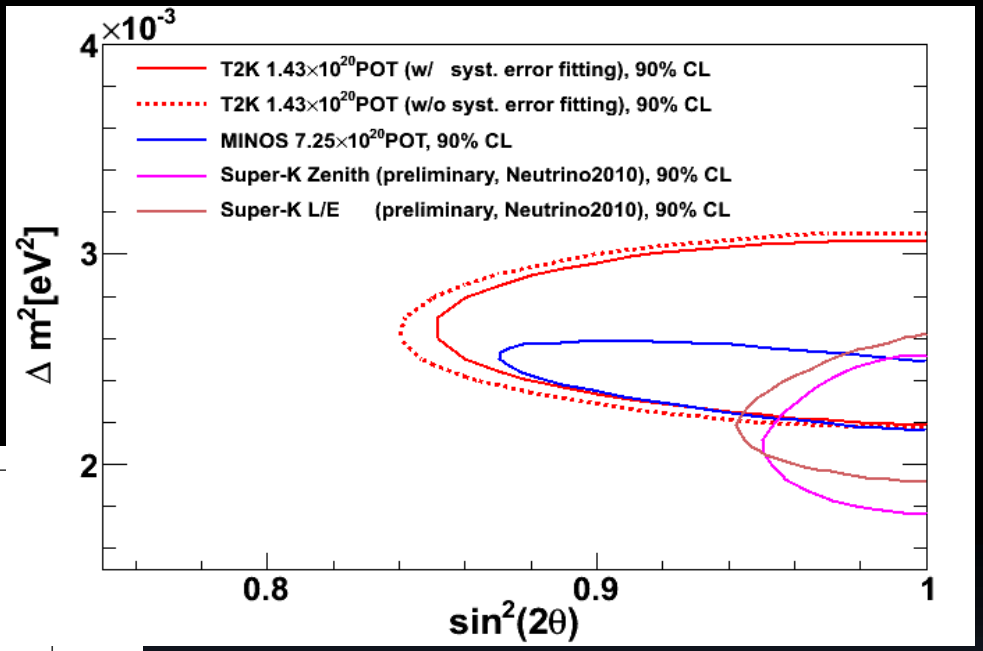
PHYSICAL REVIEW D 85, 031103(R) (2012)

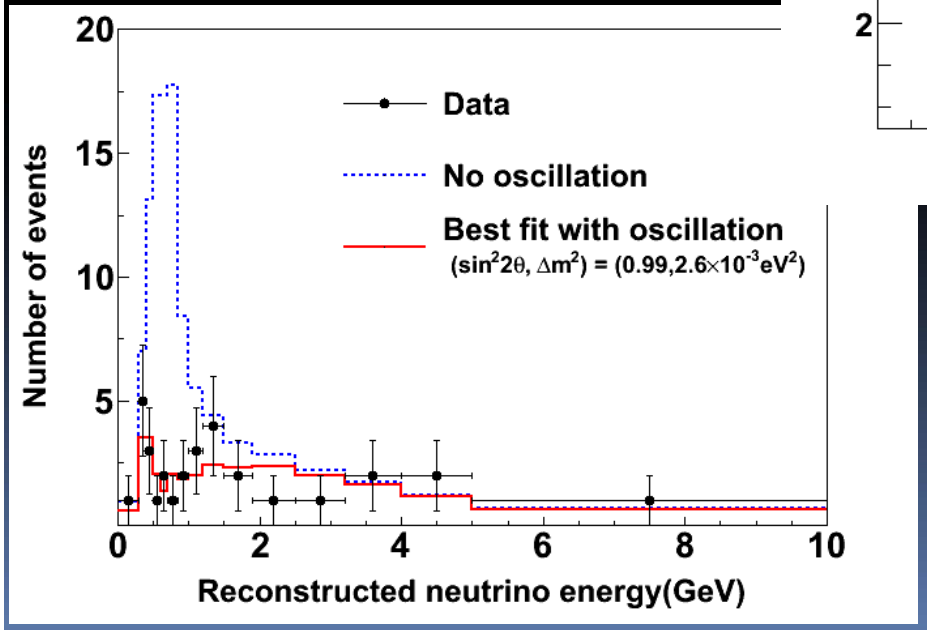
Best Fit:

$\sin^2 2\theta_{23} = 0.98$

$\Delta m^2_{23} = 2.65 \times 10^{-3}$ eV^2

With only 2% of the final statistics



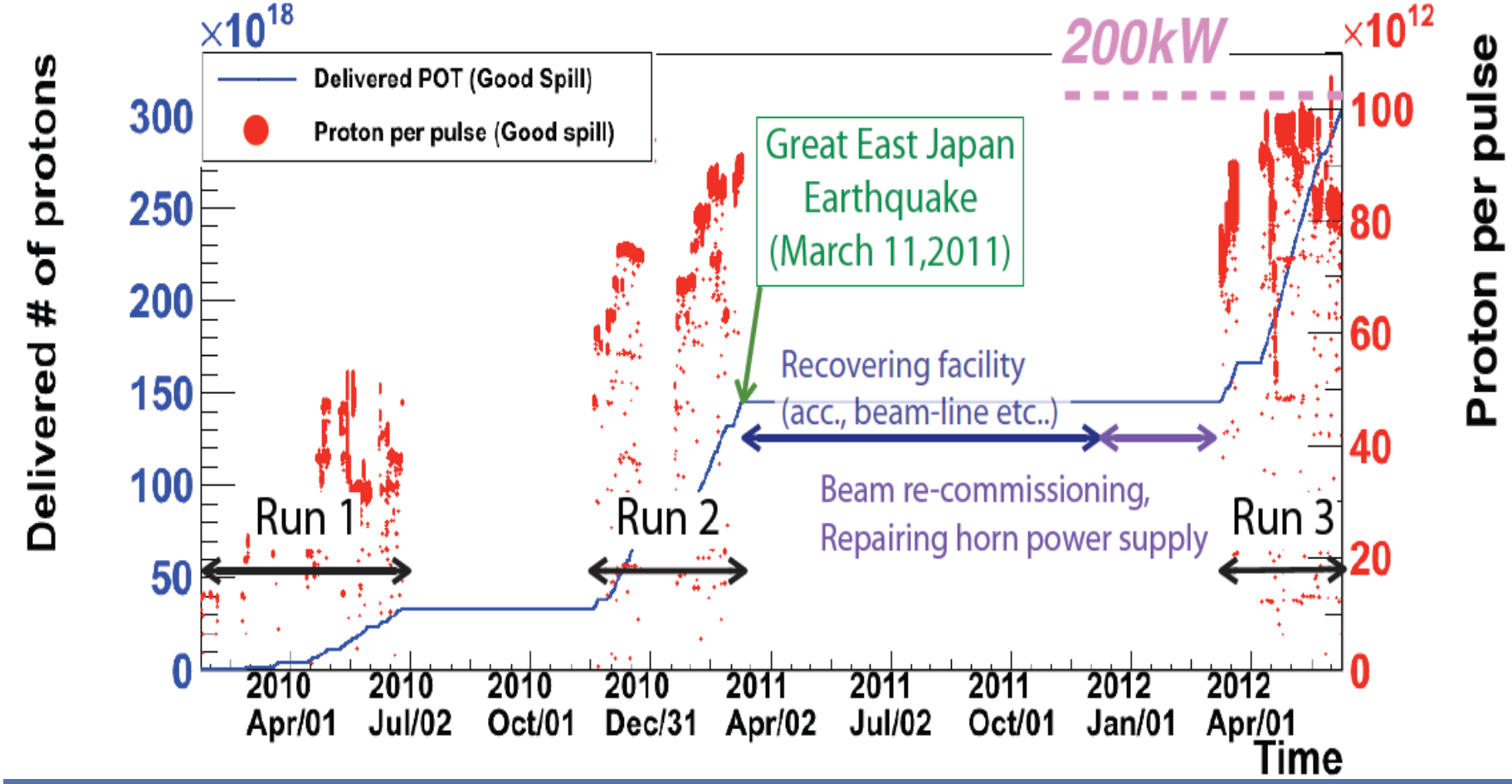


Upgraded results are coming

Data Sample = 3.01 10^{20} p.o.t.

- Run 1 + Run 2 = 1.43 10^{20} p.o.t.
- Run 3 = 1.58 10^{20} p.o.t.

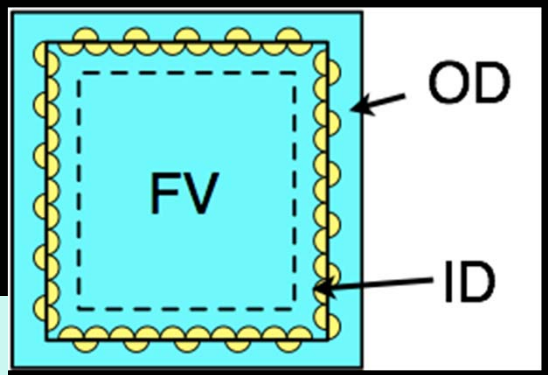
more that a factor 2 vs 2011 and +18% vs Neutrino 2012



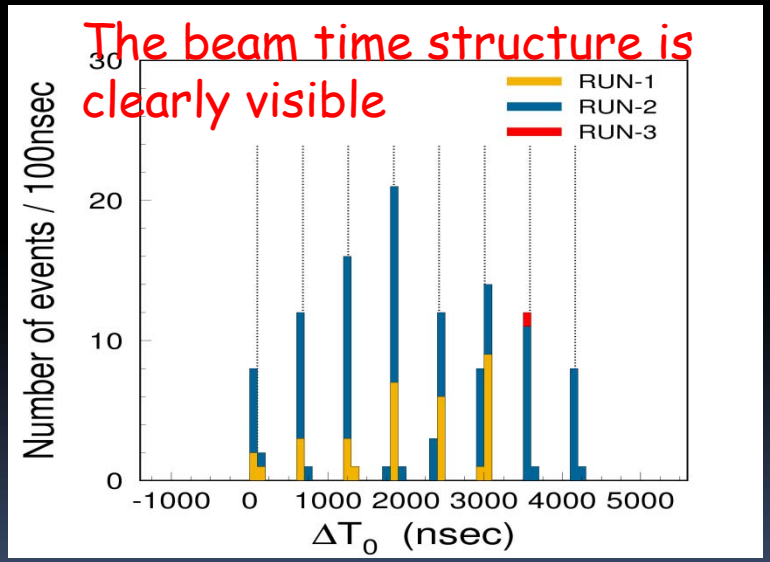
ν_e candidate selection @T2K

1. T2K Beam timing
2. Fully-Contained events (FC)
3. Vertex is in the Fiducial Volume (FV)

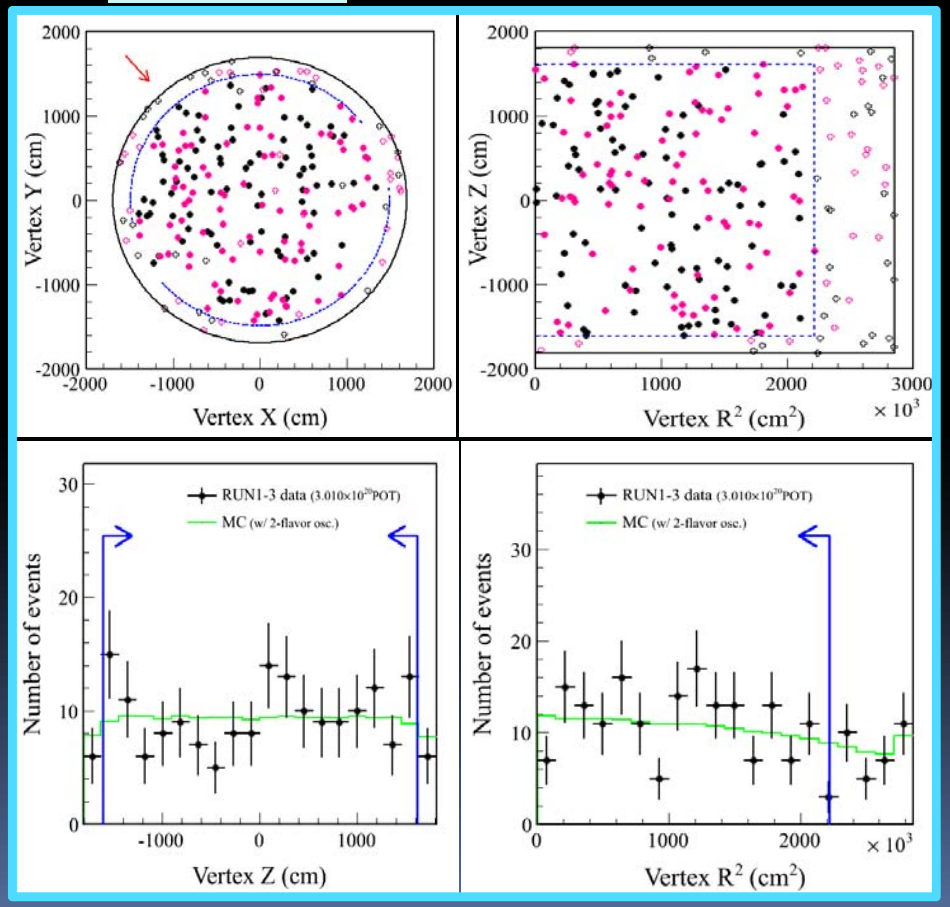
174 FCFV events



RUN1+2
RUN3



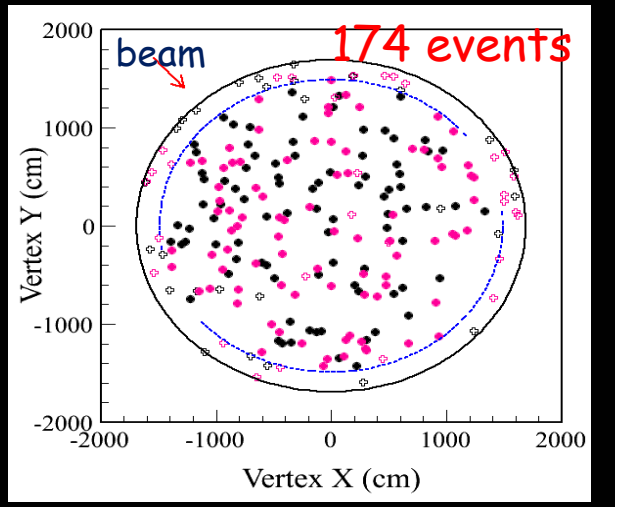
ΔT_0 is corrected for neutrino flight length difference and photon travel length difference in the SK tank by using reconstructed vertex position.

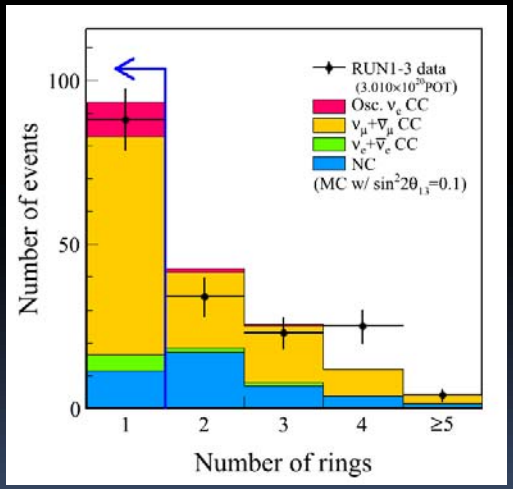


ν_e candidate selection (2)

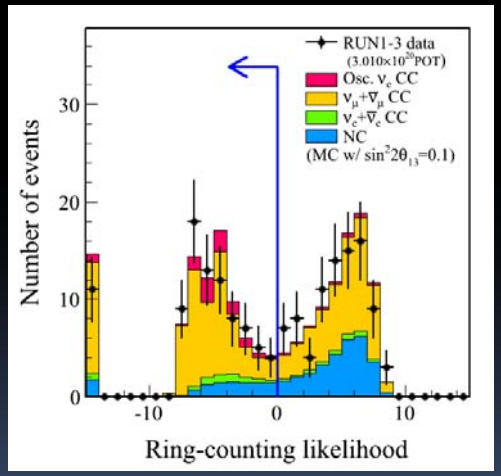
FCFV

1. 1 Cherenkov Ring
2. Electron-like
3. Visible Energy > 100 MeV

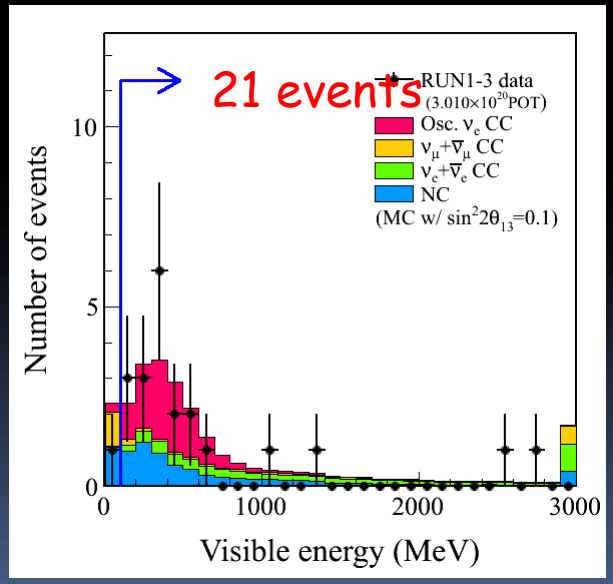




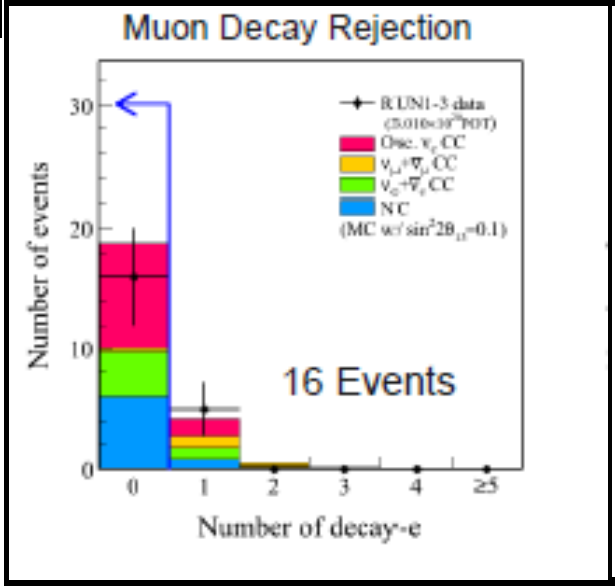
1 ring

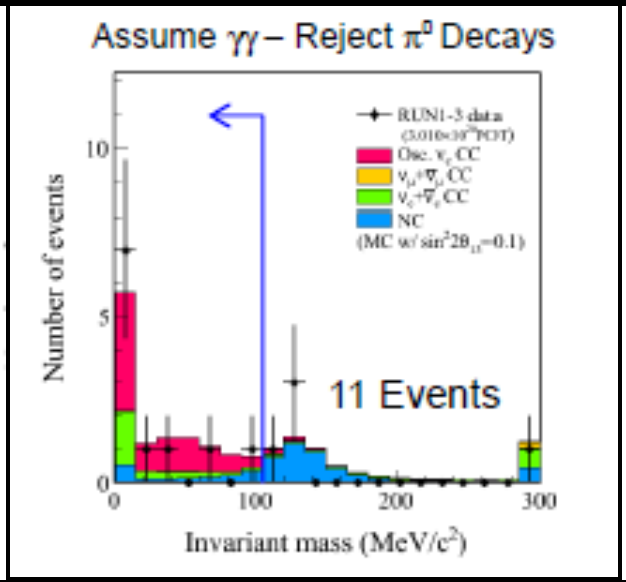


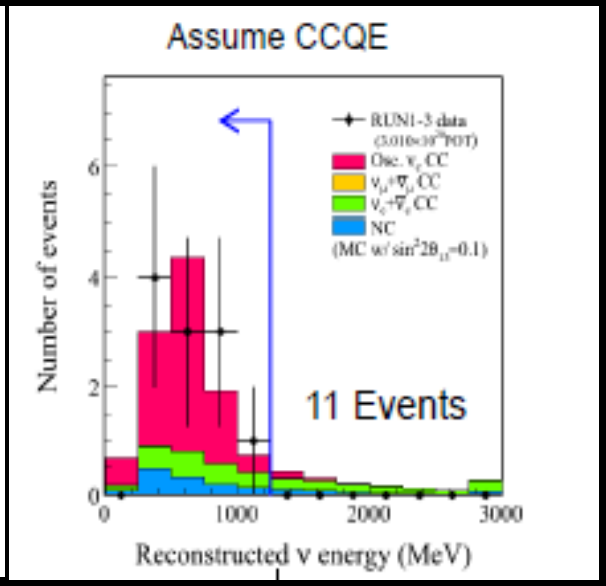
P-Id

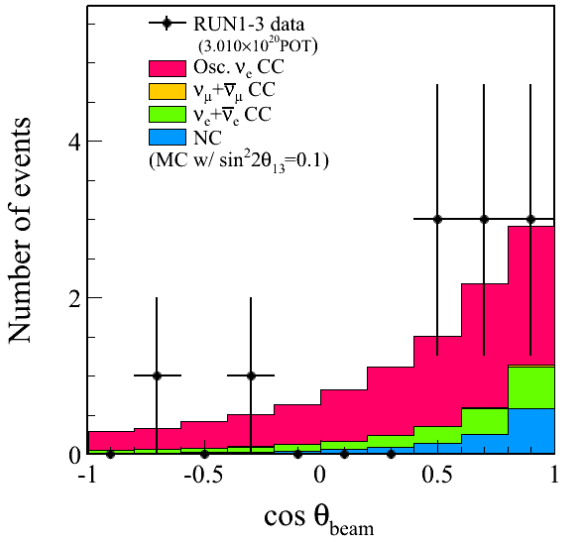


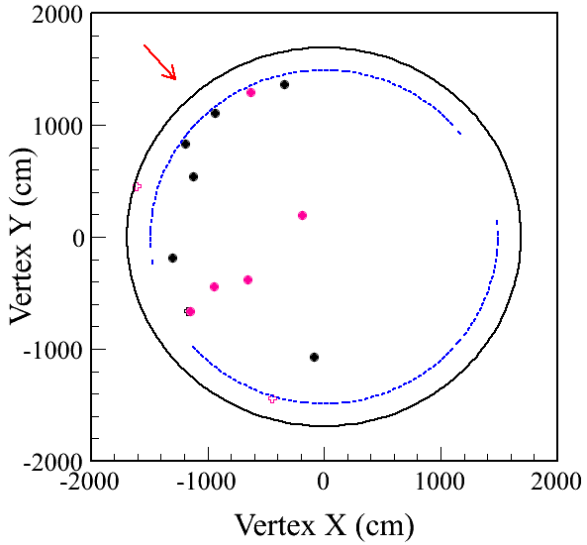
Final ν_e selection







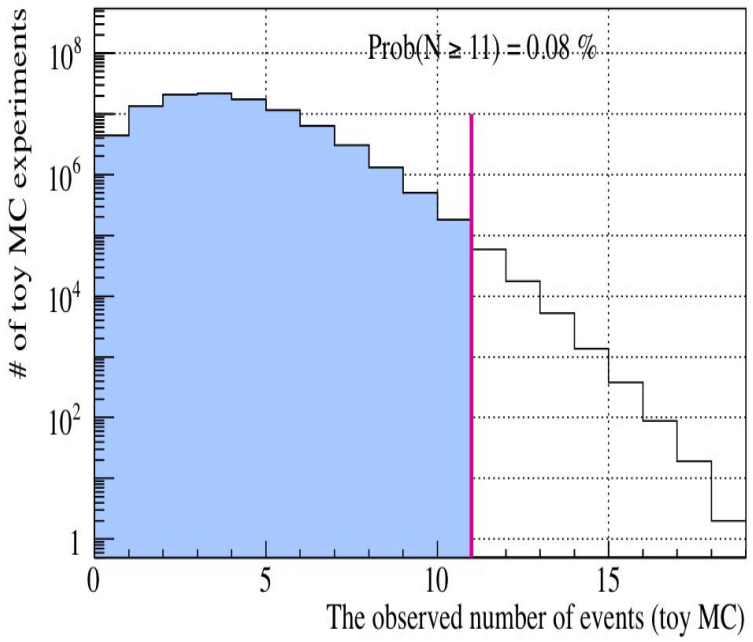




events in the final sample = 11

Summary Table

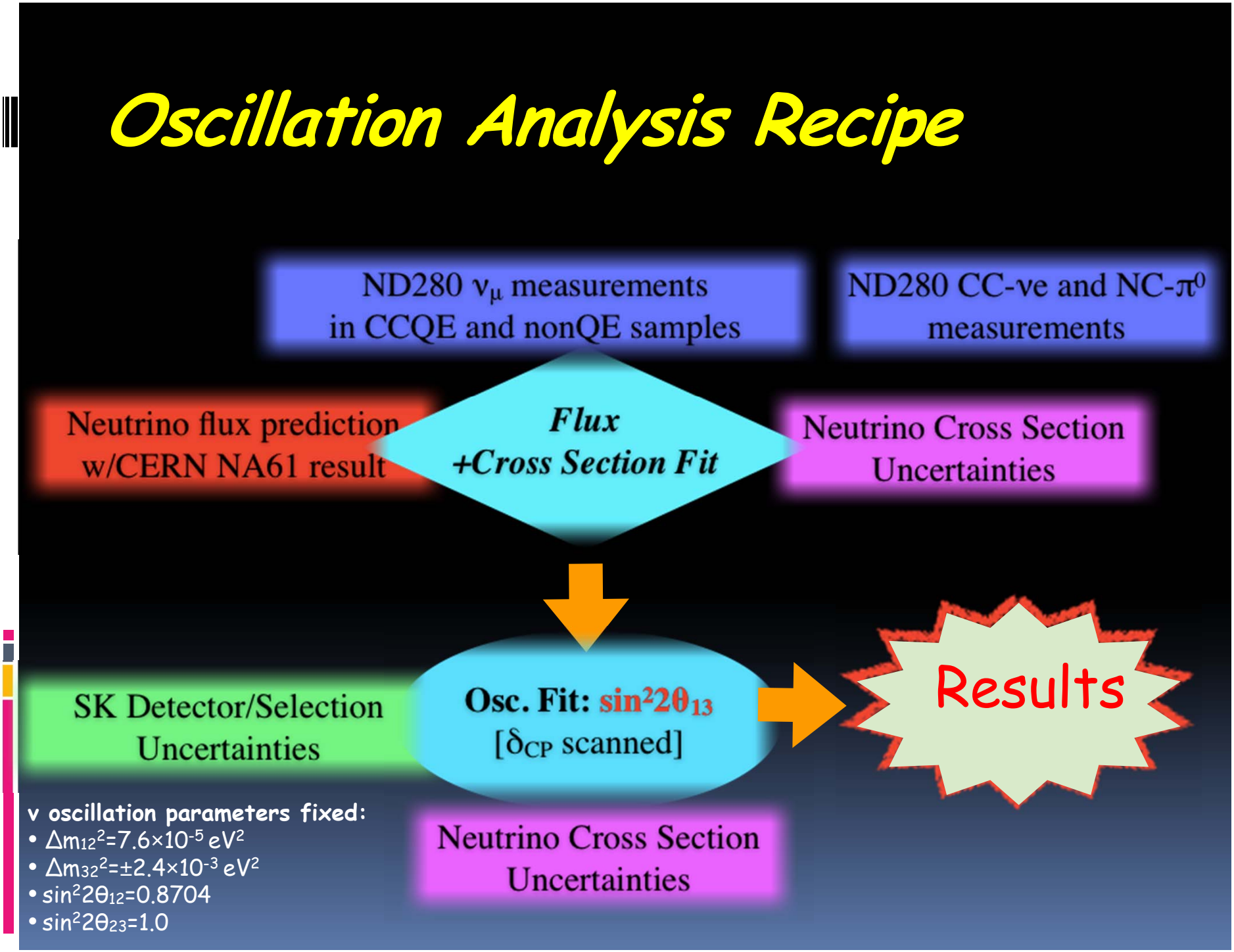
RUN1+2+3 3.010x10^{20}POT	MC Expectations w/ $\sin^2 2\theta_{13}$=0.1					Data
	$\nu_\mu+\bar{\nu}_\mu$ CC	$\nu_e+\bar{\nu}_e$ CC	NC	BG total	Signal	
True FV	154.54	8.03	132.89	295.46	12.86	-
FCFV	117.33	7.67	40.48	165.47	12.35	174
One-ring	66.41	4.82	11.55	82.78	10.39	88
e-like	2.72	4.79	8.10	15.60	10.27	22
E_{vis}>100MeV	1.76	4.75	7.01	13.53	10.04	21
No decay-e	0.33	3.76	6.00	10.09	8.63	16
POLfit mass	0.09	2.60	1.64	4.32	8.05	11
E_ν^{rec}<1250MeV	0.06	1.61	1.25	2.92	7.81	11



The probability (p-value) to observe 11 events with 3.22±0.43 (sys.) BG events is 0.08% (3.2σ)

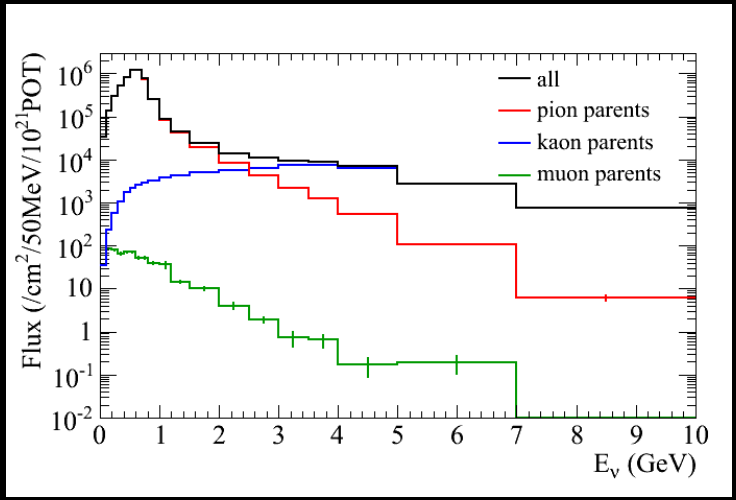
"Evidence of Electron Neutrino Appearance"

Oscillation Analysis Recipe

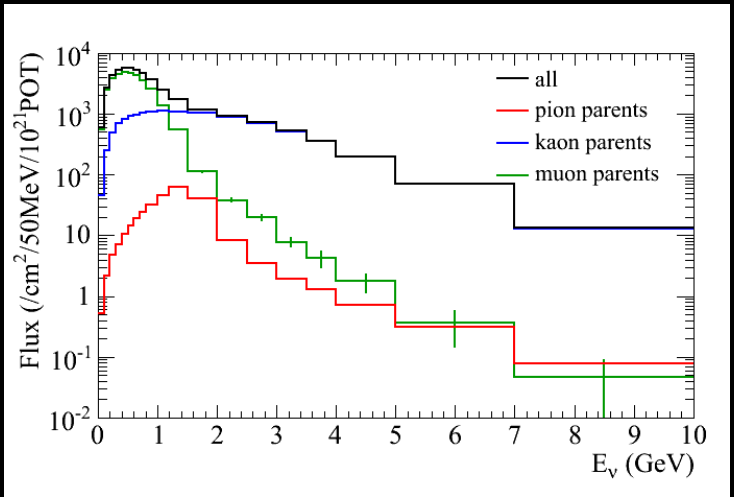


Neutrino flux prediction w/CERN NA61 results

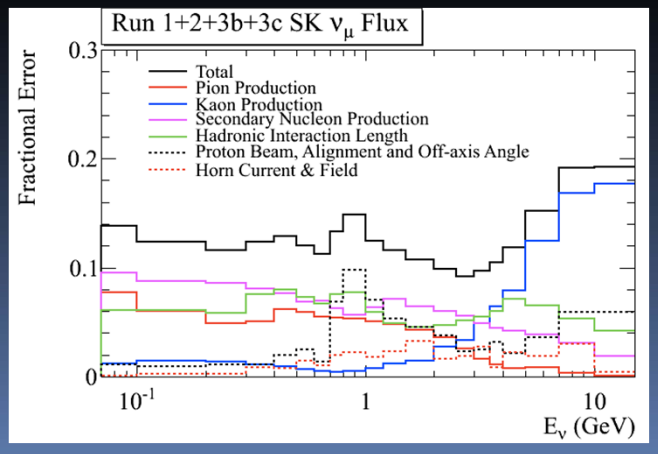
ν_μ@SK

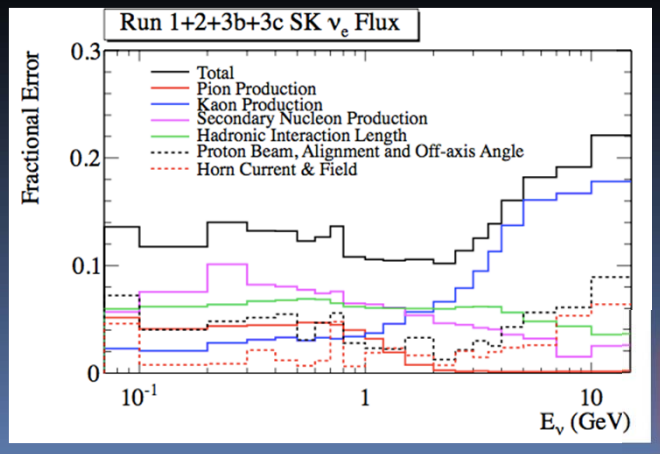


ν_e@SK



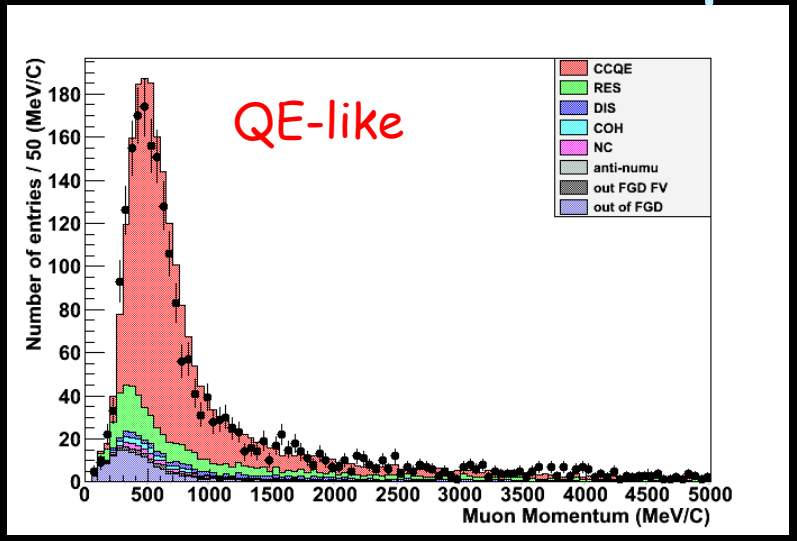
ν_μ, ν_e, anti-ν_μ, anti-ν_e energy dependent errors with full correlations @SK and @ND280 are included

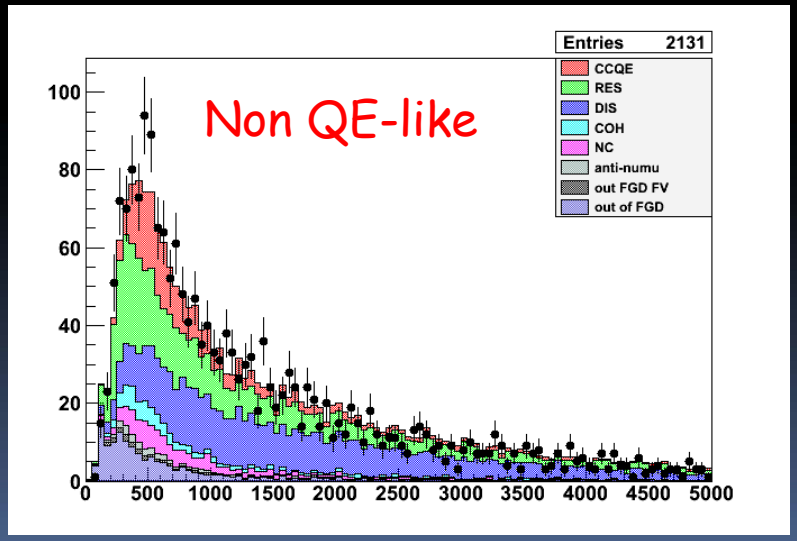




Errors: 10~15%

Near detector Spectrum Measurement

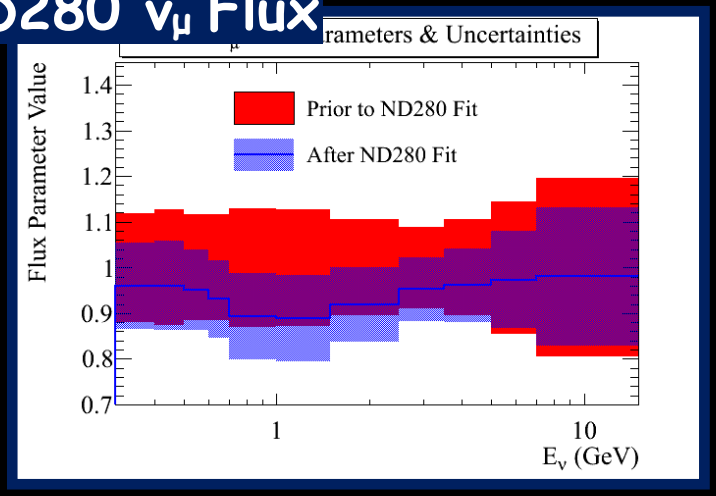




- Select CC $\nu\mu$ events
  - Vertex inside FGD,
  - Upstream veto
  - 1 negative μ measured by TPC
- Divide into CCQE-like and non-QE-like sample
- Measure the muon track's momentum and angle, and use the p,q distribution for both QE-like and nonQE-like events to constrain flux and cross-section

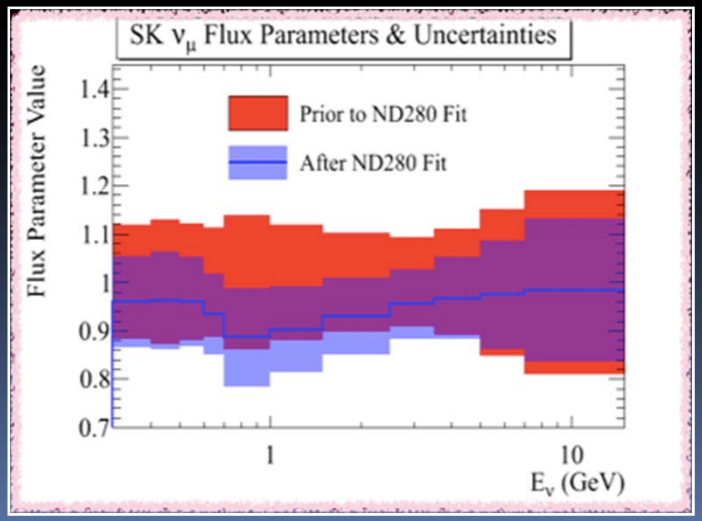
Flux + Cross section FIT output

ND280 ν_μ Flux

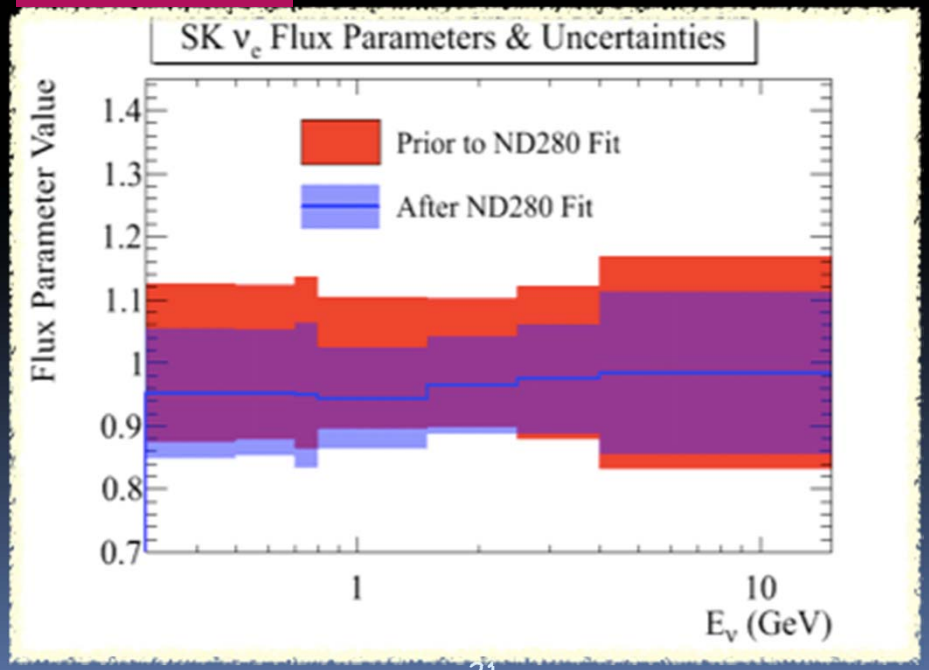


Near detector data constrains combination of flux cross-sections. Flux at ND is highly correlated with flux at SK, since neutrinos are produced by the same decaying particles in the beam.

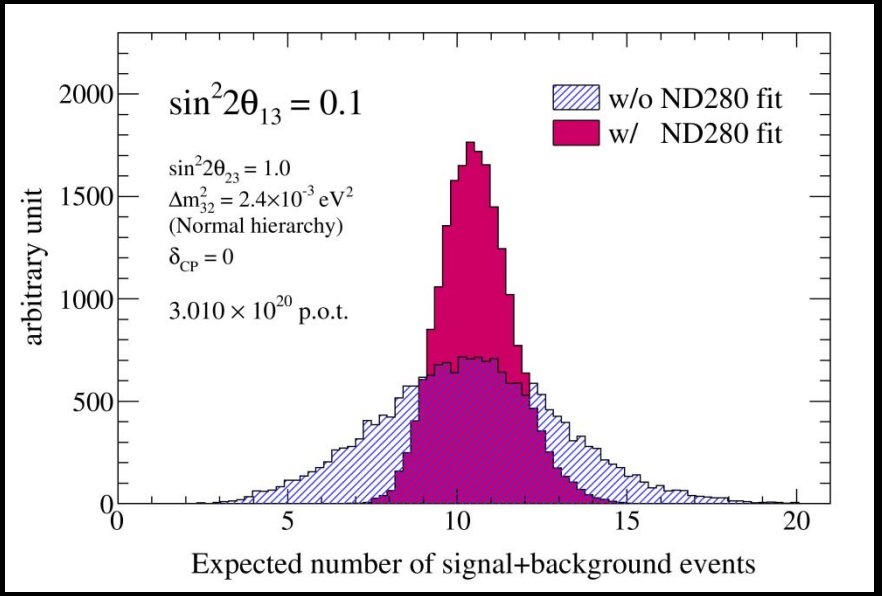
SK ν_μ Flux



SK ν_e Flux



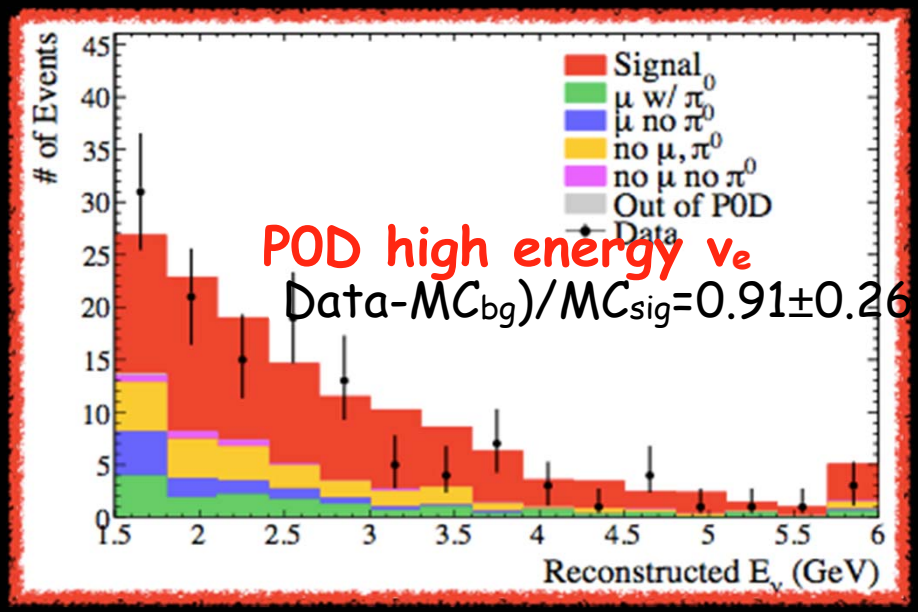
Using ND280 constraints, uncertainties greatly reduced

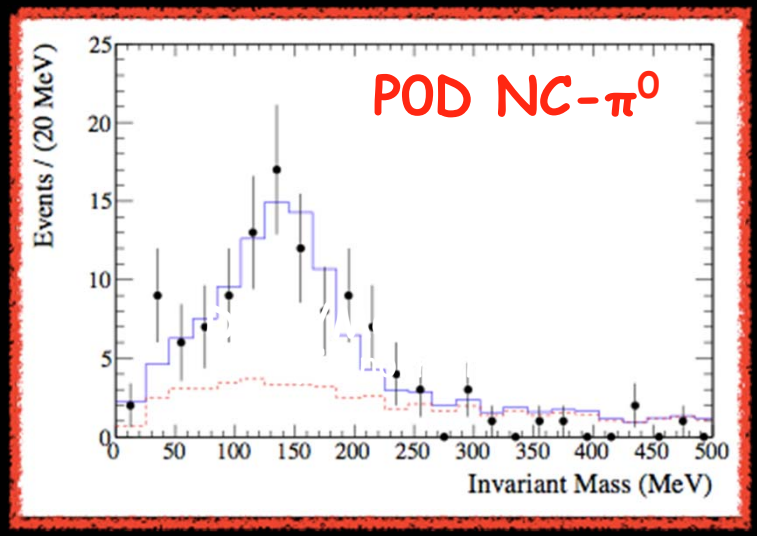


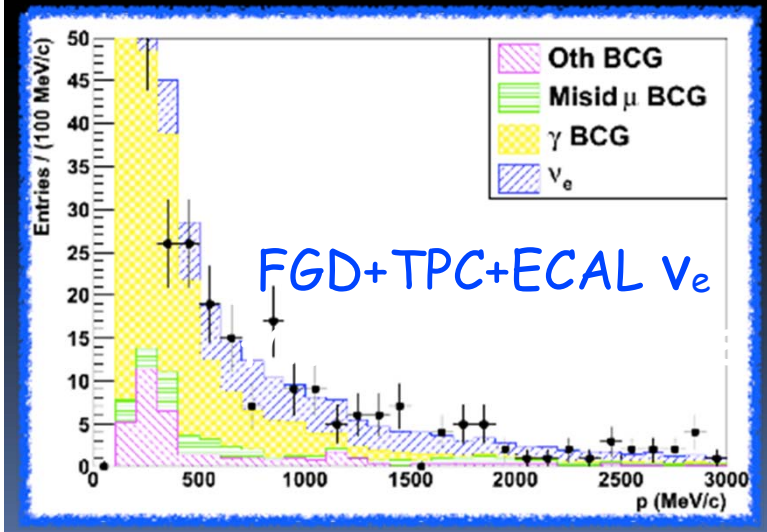
Error source	$\sin^2 2\theta_{13} = 0$	$\sin^2 2\theta_{13} = 0.1$
Beam flux+ν int. in T2K fit	8.7 %	5.7 %
ν int. (from other exp.)	5.9 %	7.5 %
Final state interaction	3.1 %	2.4 %
Far detector	7.1 %	3.1 %
Total	13.4 %	10.3 %

(T2K 2011 results: ~23% ~18%)

ND280 CC-ν_e and NC-π^0 (cross-check)

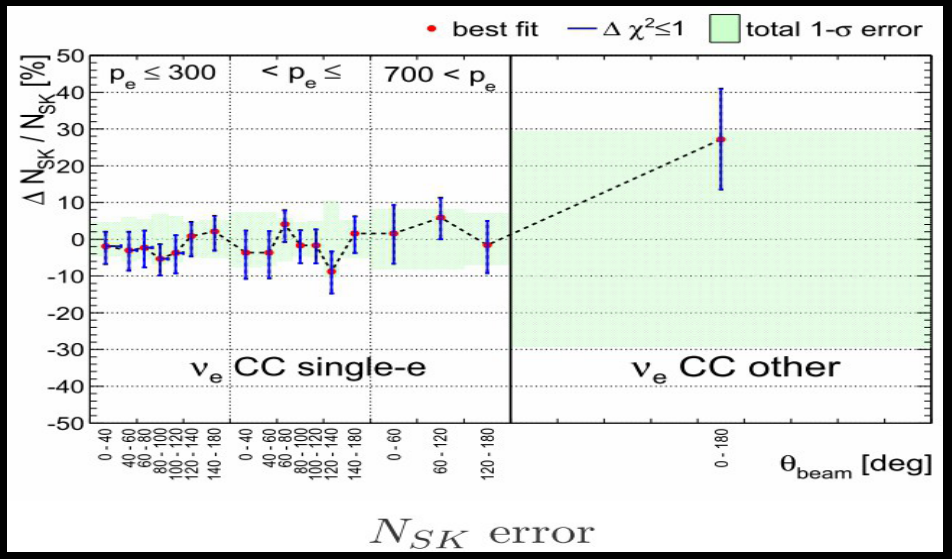






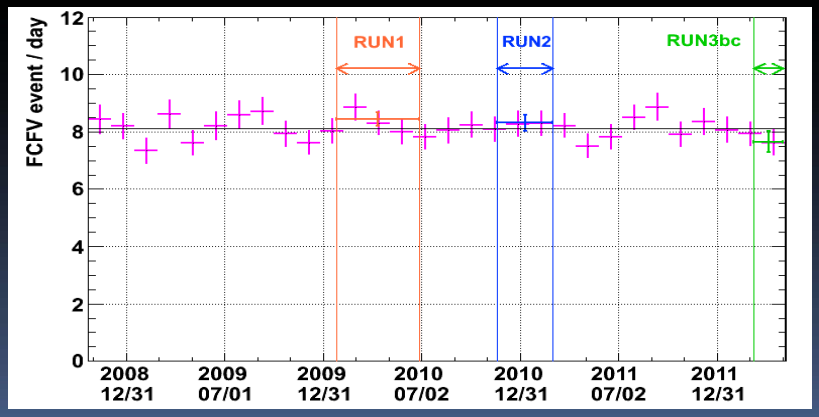
- The Dominant backgrounds for Ve appearance can be measured in ND280.
- Both CC-ν_e and NC-π^0 are consistent with the MC prediction.

SK systematics errors

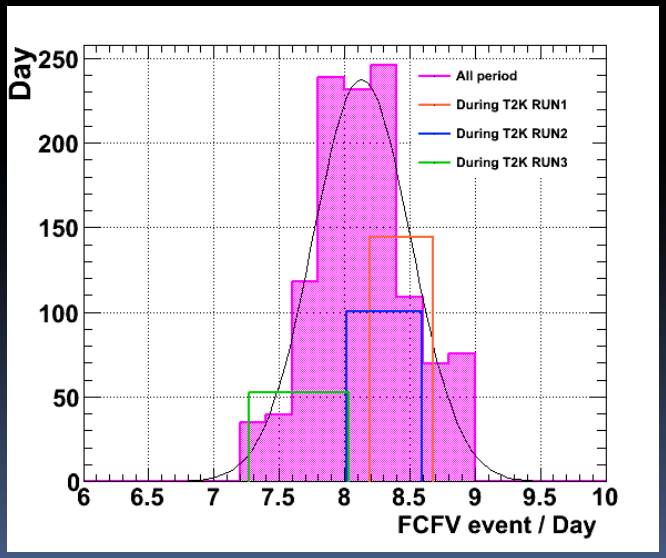


Detector efficiency systematics are determined primarily from atmospheric neutrino data.

Systematic uncertainties evaluated as function of electron direction & momentum



Event rate of atmospheric neutrino data.



Event rate stability

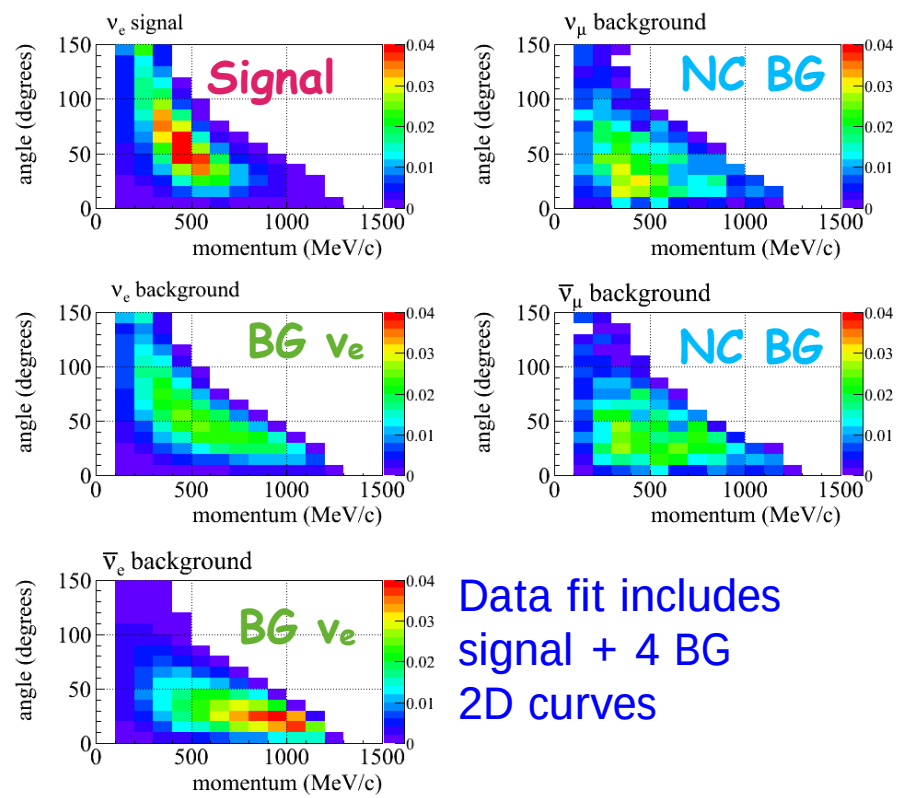
Oscillation Analysis FIT (3 methods)

Method-1: Maximum likelihood Fit w/ **Rate + (p_e, θ_e)**

Method-2: Maximum likelihood Fit w/ **Rate reconstructed E_ν**

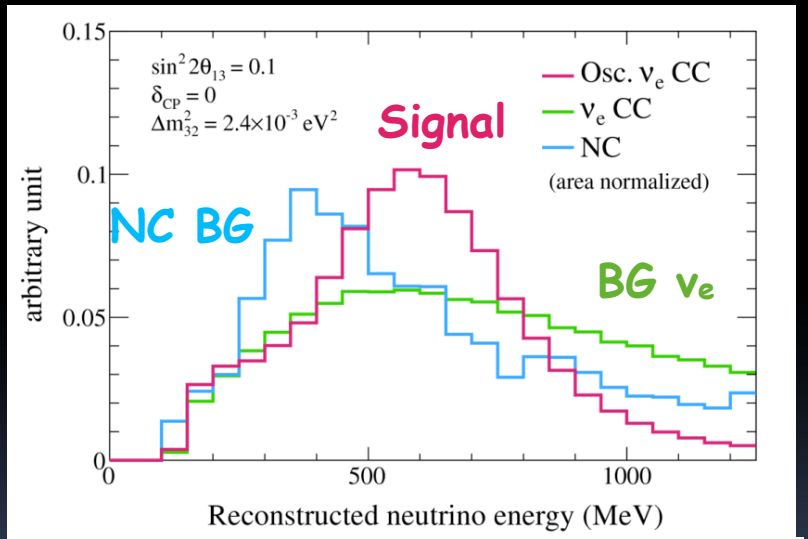
Method-3: Feldman&Cousins for Rate only

Method-1



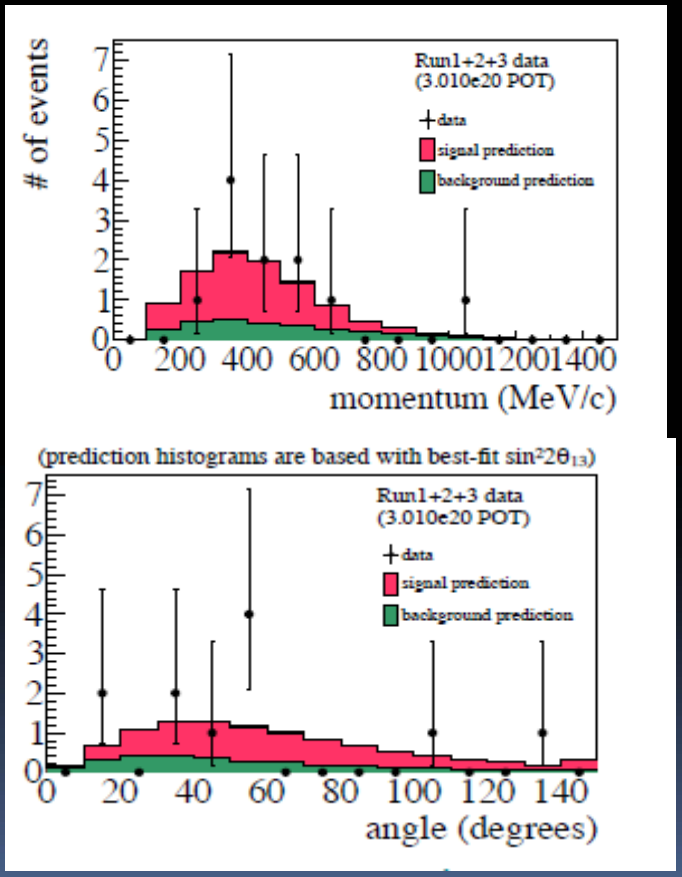
Data fit includes signal + 4 BG 2D curves

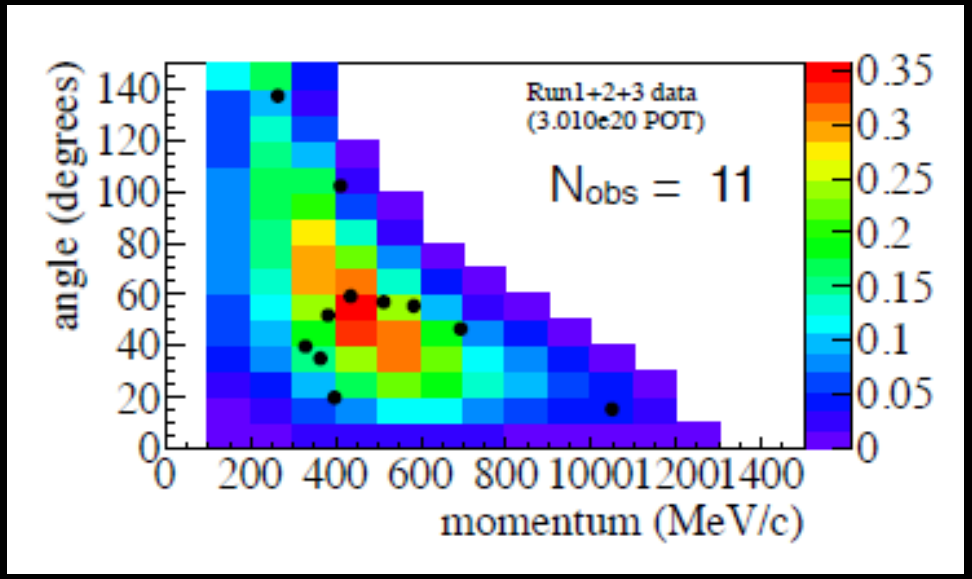
Method-2



Data fit includes signal + 2 BG 1-D curves

Results: Method 1 (preliminary):





assuming $\delta_{CP}=0$, normal hierarchy
$|\Delta m_{23}^2|=2.4\times10^{-3}$ eV^2, $\sin^2 2\theta_{23}=1$

best fit w/ 68% CL error:

- $\sin^2 2\theta_{13} = 0.094\ ^{+0.053}_{-0.040}$
- Nbest-fit = 10.18

Method 2 & 3 produce consistent results

θ_{13} vs δ_{cp}

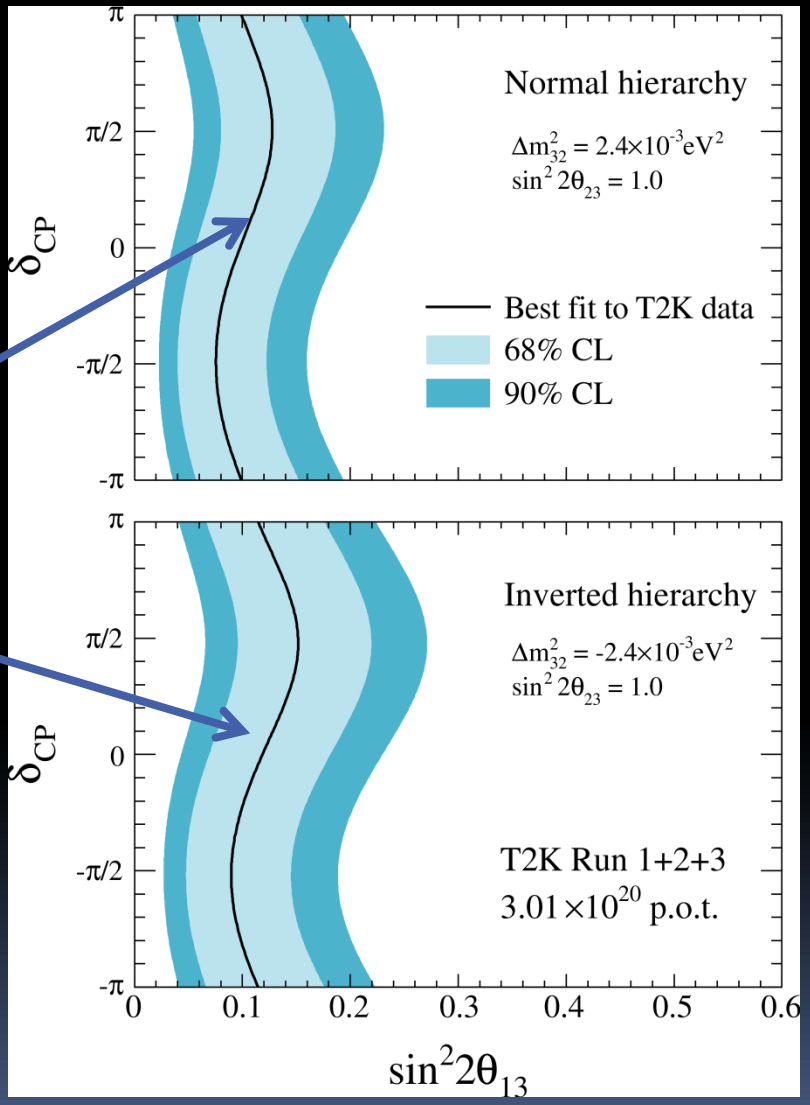
best fit w/ 68% CL error
assuming $\delta_{cp} = 0$

normal hierarchy:

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

inverted hierarchy:

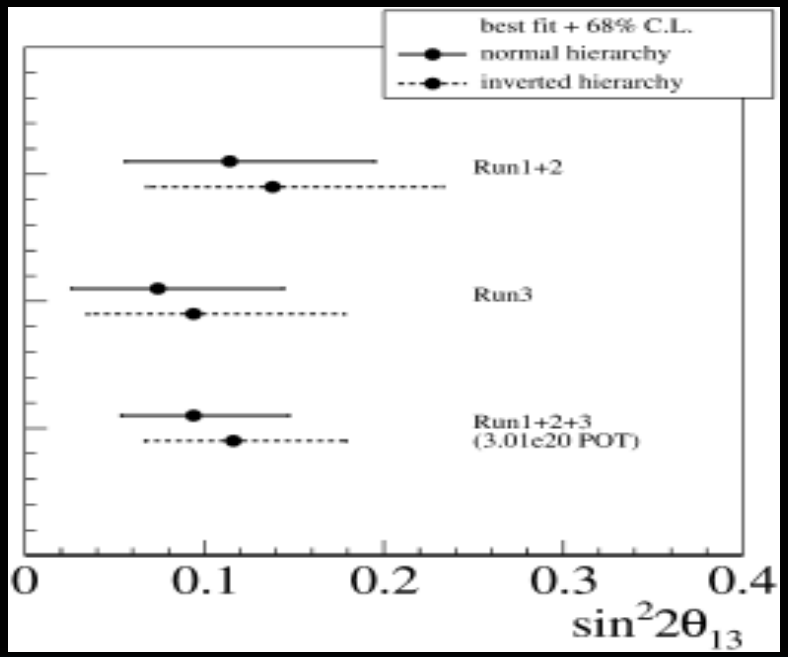
$$\sin^2 2\theta_{13} = 0.116^{+0.063}_{-0.049}$$

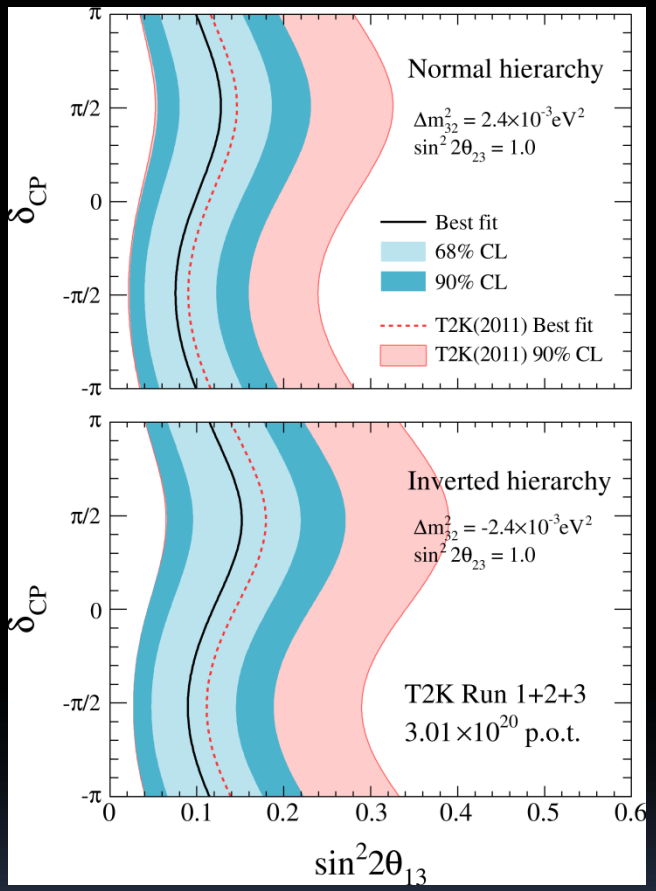


ν oscillation parameters fixed:

- $\Delta m_{12}^2 = 7.6\times10^{-5}\ eV^2$
- $\Delta m_{32}^2 = \pm 2.4\times10^{-3}\ eV^2$
- $\sin^2 2\theta_{12} = 0.8704$
- $\sin^2 2\theta_{23} = 1.0$

Consistency with previous results:





The results obtained in different runs are all consistent.

The new result improves the previous one and remains compatible

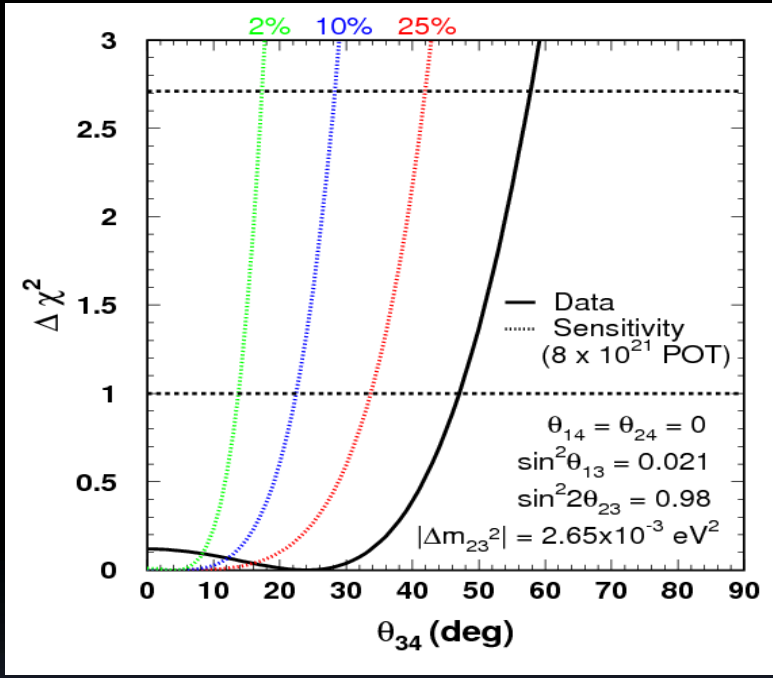
Future Perspectives:

- Update on results from ν_μ disappearance coming shortly: measurement of θ_{23} with the θ_{13} value from reactor experiments relevant to explore sub-leading terms.
- Future high power runs are planned:
  - 8×10^{20} POT (2013) $\rightarrow$ 12×10^{20} POT (2014) $\rightarrow$ 18×10^{20} POT (2015)

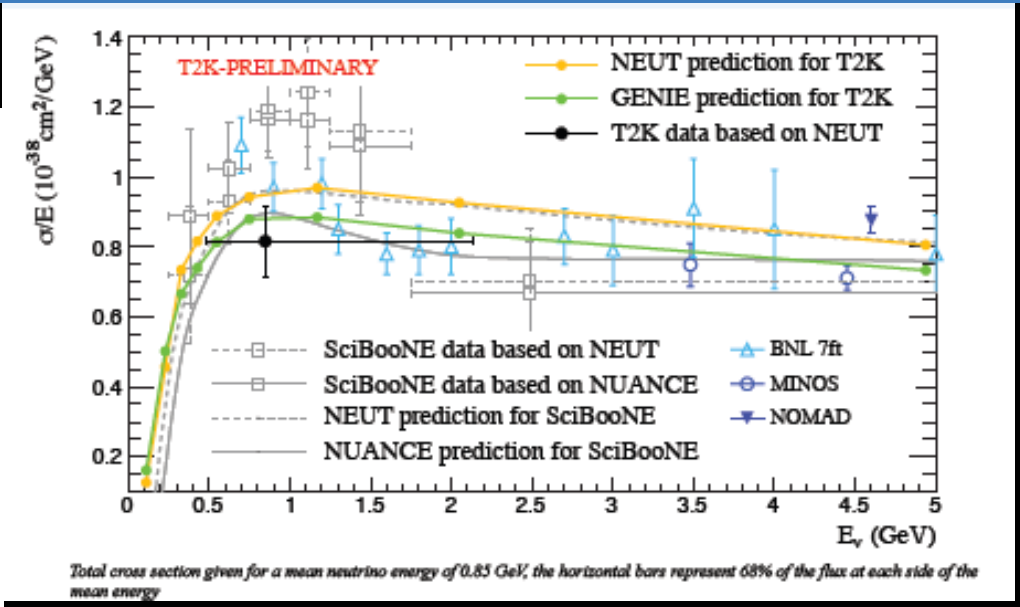
This will allow us

- more precise measurement of $P(\nu_\mu \rightarrow \nu_e)$:
  - => Measure θ_{13} at 5 σ level or better
  - => assess sub-leading effects such as CP violation, possible new physics from ν_e appearance.
  - Plenty of ND280 X-sections measurements.
  - Possible hints from Sterile Neutrinos @ND280 & @SK

Examples:



NuMu Inclusive Charged Current Flux Averaged Cross Section Measurement at the T2K Near Detector



Total cross section given for a mean neutrino energy of 0.85 GeV, the horizontal bars represent 68% of the flux at each side of the mean energy

For more details see the James Dobson talk

Measuring the event rate of NC de-excitation γ-rays at a 295 km far detector, in SK it is possible to search for the depletion of the total flux of T2K beam neutrinos via oscillations into sterile neutrinos.

Conclusions

- Results presented on ν_e appearance search using current T2K 3.01×10^{20} POT (or ~4% of T2K's proposed exposure)
  - 11 candidate events observed
  - P-Value is 0.0008 (equivalent to 3.2σ for excluding $\Theta_{13}=0$)
  - Confirms and improves our previous result.
- Our $\nu\mu$ disappearance is still based on 1.43×10^{20} POT but will be updated soon :
  - Important input to CPV searches
- Future high power runs are planned:
  - 8×10^{20} POT (2013) $\rightarrow$ 12×10^{20} POT (2014) $\rightarrow$ 18×10^{20} POT (2015)

A LOT OF NEW DATA ARE COMING: STAY TUNED !

Backup

Ground Level Damage....

LINAC

RCS (elec yard)

Severe subsidence here and there (1~2m depth)
Near by piping/cabling were damaged

Neutrino (TS)

LINAC

Neutrino (Dump)

Neutrino (Dump)

....Being Rapidly Repaired

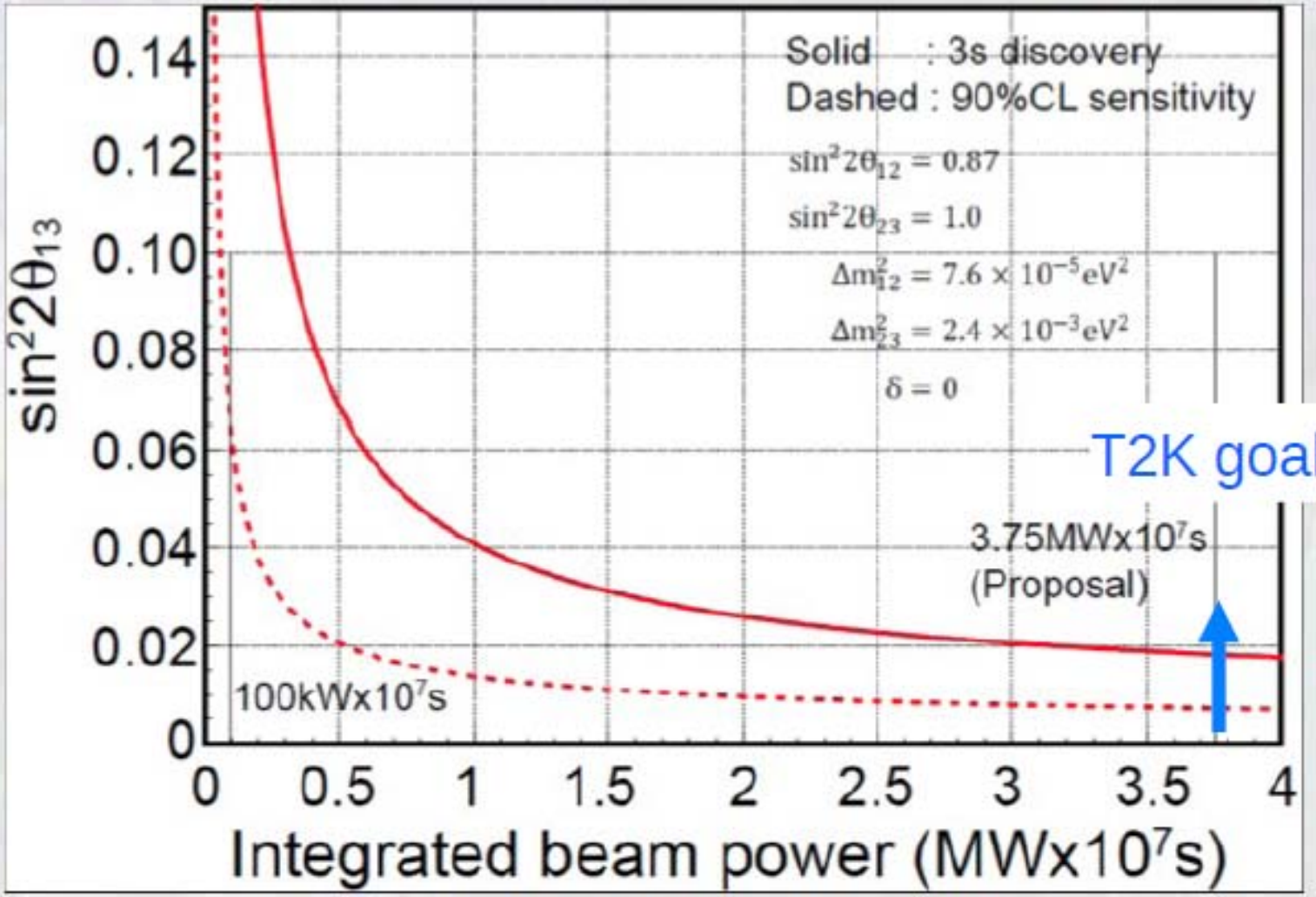
RCS

RCS

Neutrino (dump)

Neutrino (dump)

T2K θ_{13} Sensitivity



Final results with 3.75 x 10^7 MW*sec (8 x 10^{21} POT)

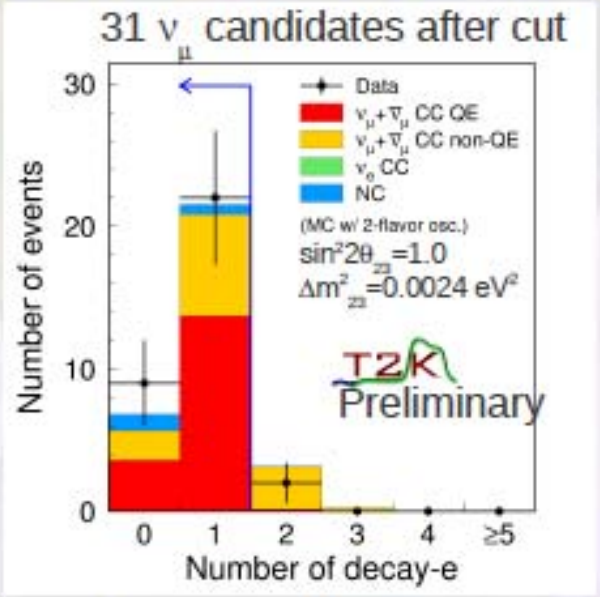
T2K ν_μ Results

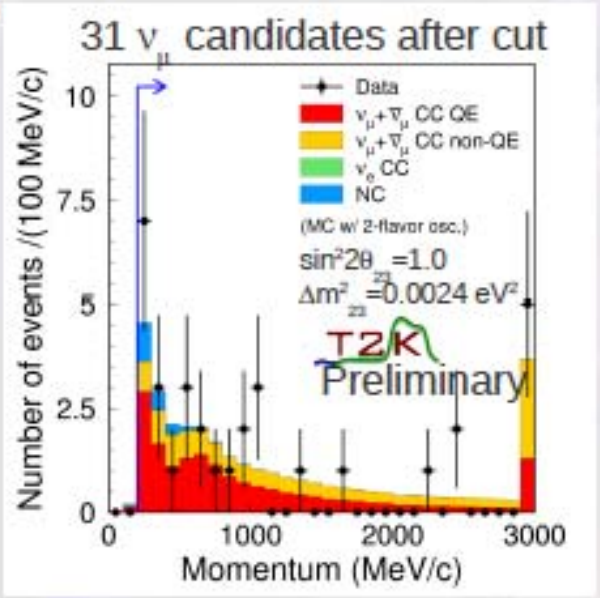
- 33 μ-like events are selected with PID likelihood.

- Additional cuts:
  - Less than 2 decay electrons
  - Reconstructed μ momentum larger than 200 MeV

Expected final sample composition:
- CCQE(61%) CCnQE (32%), NC(6%), ν_e(<1%)

- 31 events pass all the selections, 104 expected w/o oscillations → null-oscillation hypothesis excluded at 4.5σ





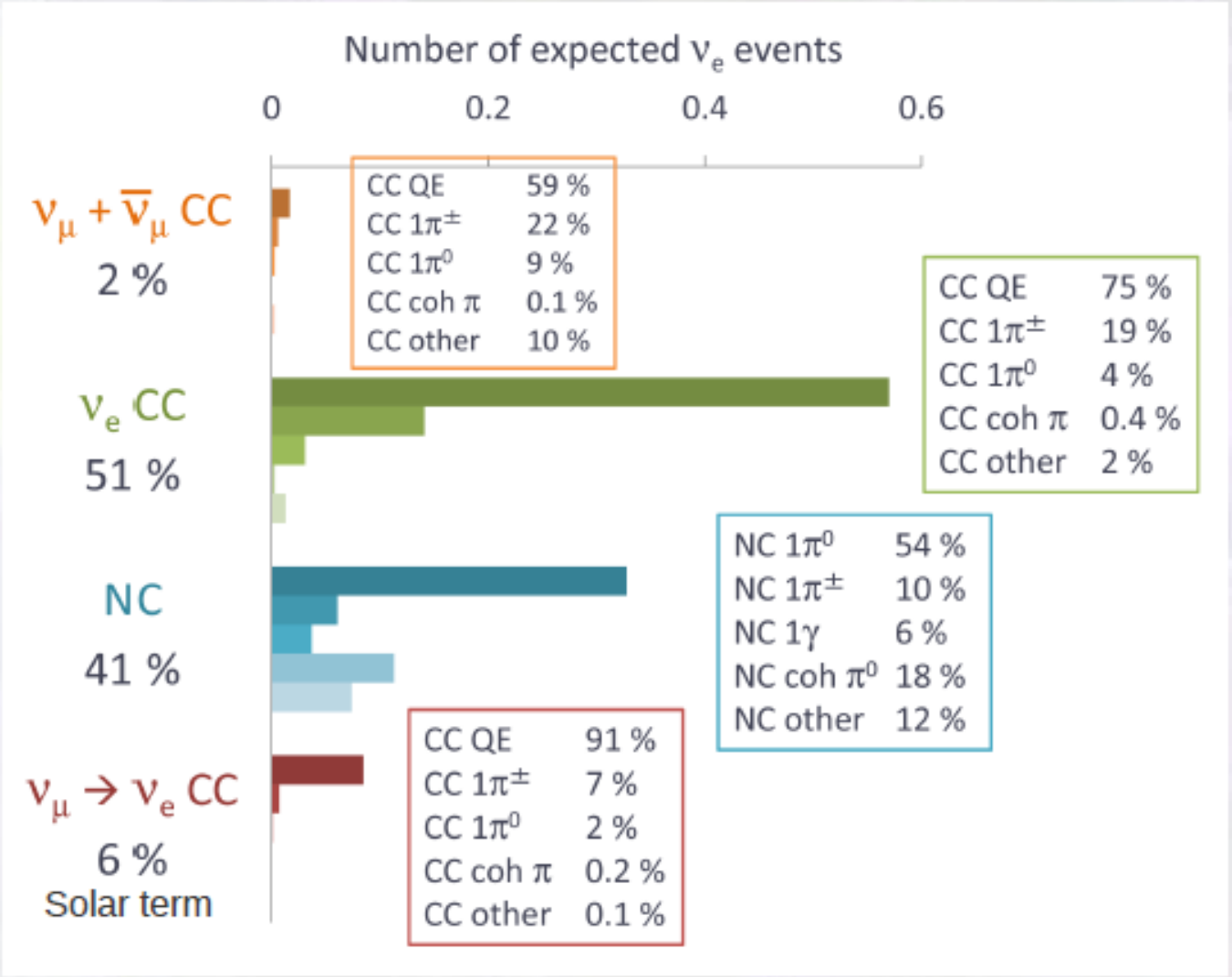
Systematics on SK expected events:

$N^{SK}_{exp.}$ error table

Error source	$\sin^2 2\theta = 1.0, \Delta m^2 = 2.4$	Null Oscillation
SK Efficiency	+10.3% 10.3%	+5.1% -5.1%
Cross section and FSI	+8.3% -8.1%	+7.8% -7.3%
Beam Flux	+4.8% -4.8%	+6.9% -5.9%
ND Efficiency and Overall Norm.	+6.2% -5.9%	+6.2% -5.9%
Total	+15.4% -15.1%	+13.2% -12.7%

Far Detector ν_e Background

$\sin^2(2\theta_{13}) = 0$

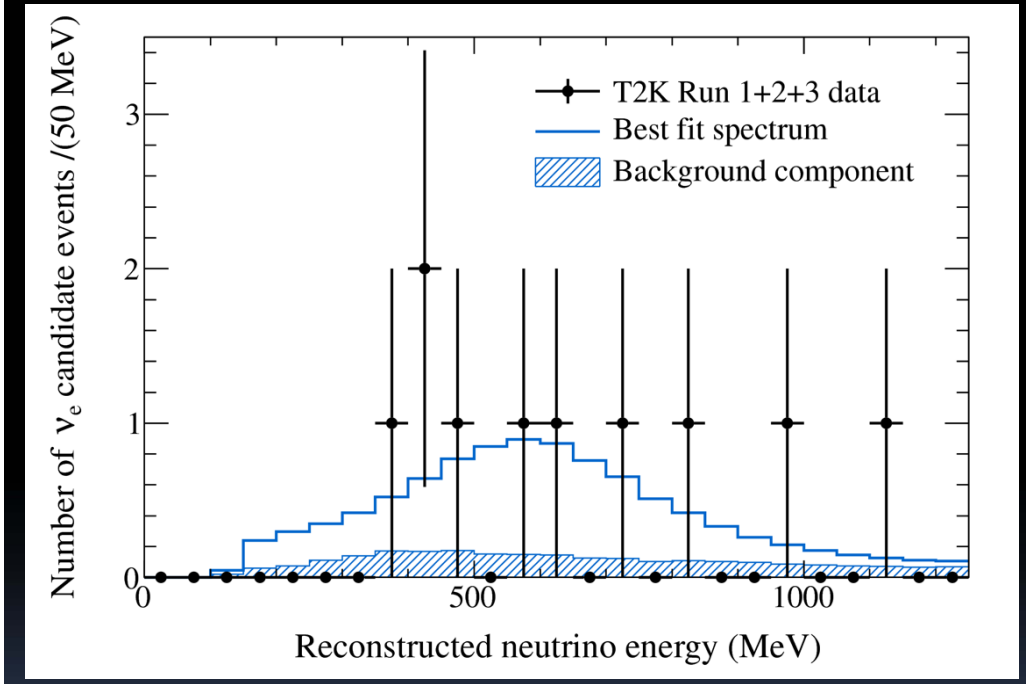


Neutrino Cross Section Uncertainties
(Model parameters used in the cross section FIT)

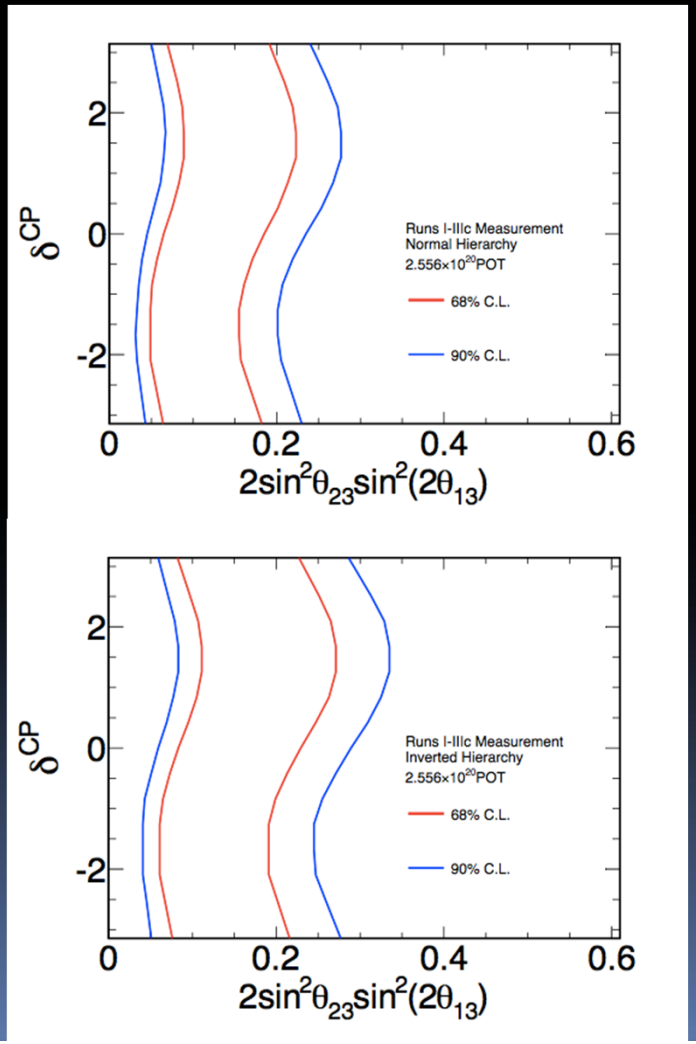
model parameters	Before FIT	After FIT
CCQE M_A [GeV]	1.21±0.45	**1.19±0.19**
CC1π(resonance) M_A [GeV]	1.16±0.11	**1.14±0.10**
Fermi momentum surface P_F [MeV]	217±30	224.6±23.5
Spectral Function	0[off] - 1[on]	0.04±0.21
CC-other cross section shape	0.0±0.4	-0.05±0.35
CCQE E-dependence	1.0±0.11, 1.0±0.11, 1.0±0.11	**0.94±0.09**, 0.92±0.23, 1.18±0.25
CC1π(resonance) E-dep.	1.63±0.43, 1.0±0.4	**1.67±0.28**, 1.10±0.30
NC-π^0 cross sections	1.19±0.43	**1.22±0.40**
CC-coherent π cross section	1−1	from other experiments
NC-coherent π cross section	1.0±0.3	from other experiments
NC other cross section	1.0±0.3	from other experiments
W shape in resonance model [MeV]	87.7±45.3	from other experiments
π-less Δ decay	0.0±0.2	from other experiments
CC-1π,rNC-1π^0 energy shape	0.0±0.5	from other experiments

Results (method-2,3)

method-2 (w/ E_ν^{rec})



method-3



All three results are consistent.