Recent results from T2K

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for T2K collaboration

March. 5, 2013
Rencontres de Moriond

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- Introduction of T2K
- Results
  - ***ν_μ disappearance : ϑ_{23}&Δm_{32} (New results in this winter)***
  - ν_e appearance: θ_{13} (shown in ICHEP 2012)
- Summary

T2K collaboration

~500 people from 11 countries

Introduction : Neutrino mixing

3 flavor neutrino mixing:

Flavor (e,μ,τ) Eigenstate $\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \boxed{U_{PMNS}} \times \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$ Mass (m_1,m_2,m_3) Eigenstate

$$\boxed{U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad \begin{matrix} c_{ij} \equiv \cos\theta_{ij} \\ s_{ij} \equiv \sin\theta_{ij} \end{matrix}}$$

Current status

Solar and reactor (KamLAND)

$$\theta_{12} = 33.6° \pm 1.0°$$

Atmospheric, accelerator

$$\theta_{23} = 45° \pm 6° \quad (90\%\text{CL})$$

Accelerator, reactor (DayaBay,DoubleChooz,RENO)

$$\theta_{13} = 9.1° \pm 0.6°!$$

Remaining questions:

- Is $\theta_{23} = \pi/4$?
- CP phase (δ) ?
- Mass hierarchy
  $m_1<m_2<m_3$? $m_3<m_1<m_2$?

Introduction : 2 modes in T2K

ν_μ disappearance

$$\text{Prob}(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \sin(1.27\, \Delta m_{32}^2 L/E)$$

Precise measurement of θ_{23}, Δm^2_{32}

ν_e appearance

$$\text{Prob}(\nu_\mu \rightarrow \nu_e) \approx \sin^2\theta_{23} \sin^2 2\theta_{13} \sin(1.27\, \Delta m_{32}^2 L/E) + \text{CPV term} + \text{Matter term} + \ldots$$

Evidence of ν_e appearance in 2012!

To answer the remaining questions,
precise measurement of all parameters are necessary

Results Shown Today

- Data: from Jan 2010 to July 2012

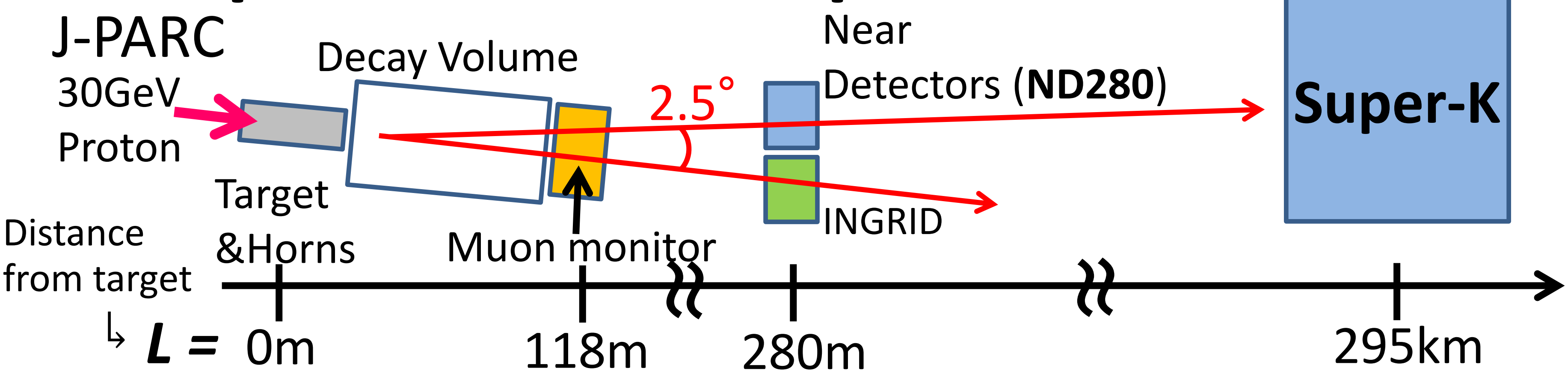
  3.01×10^{20} Protons On Target (POT)

  ~4% of T2K's target POT (7.8×10^{21}POT)

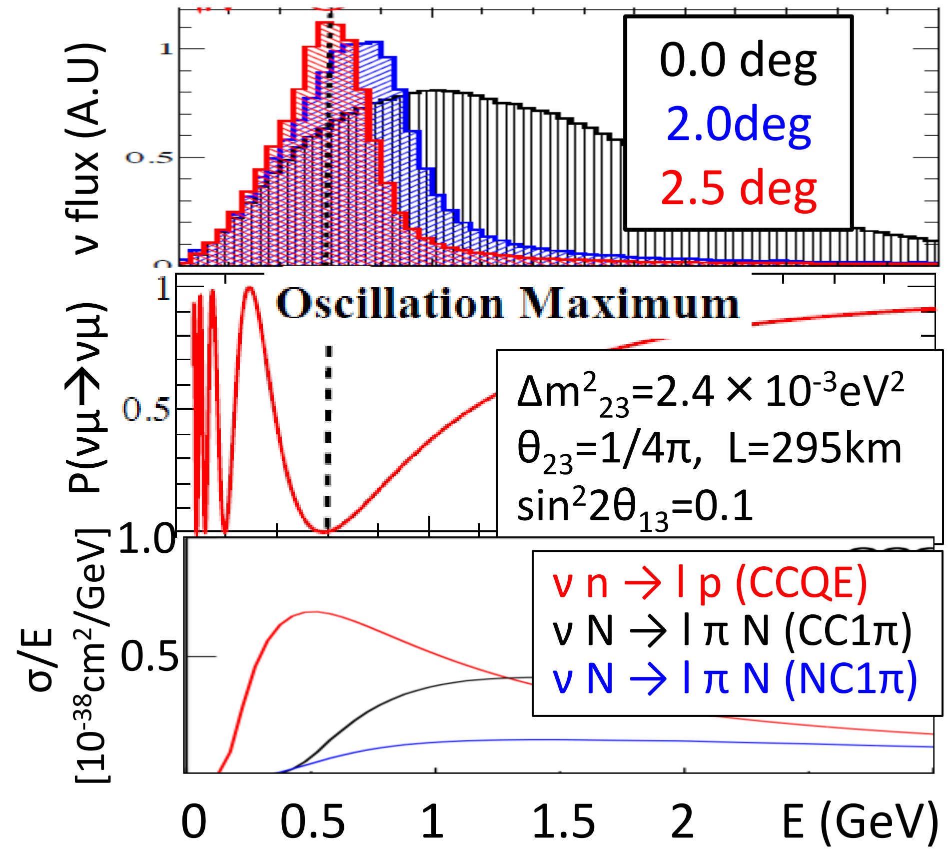
  Stable ν beam in whole period.

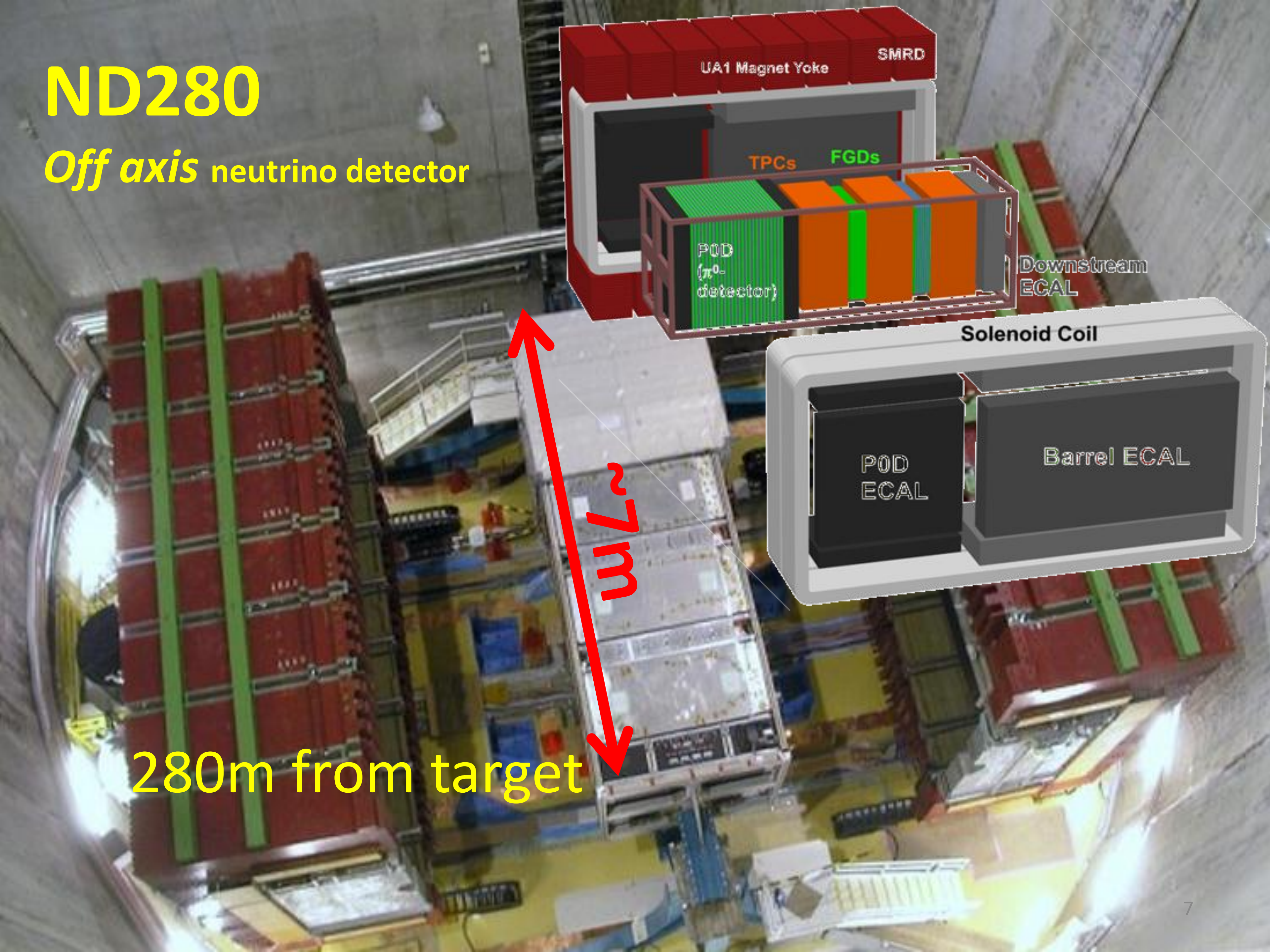
- Oscillation analysis results
  - Near detector measurement
  - **ν_μ disappearance :** θ_{23}&Δm_{32} (**New results in this winter**)
  - ν_e appearance: θ_{13} (shown in ICHEP 2012)

Experimental setup of T2K



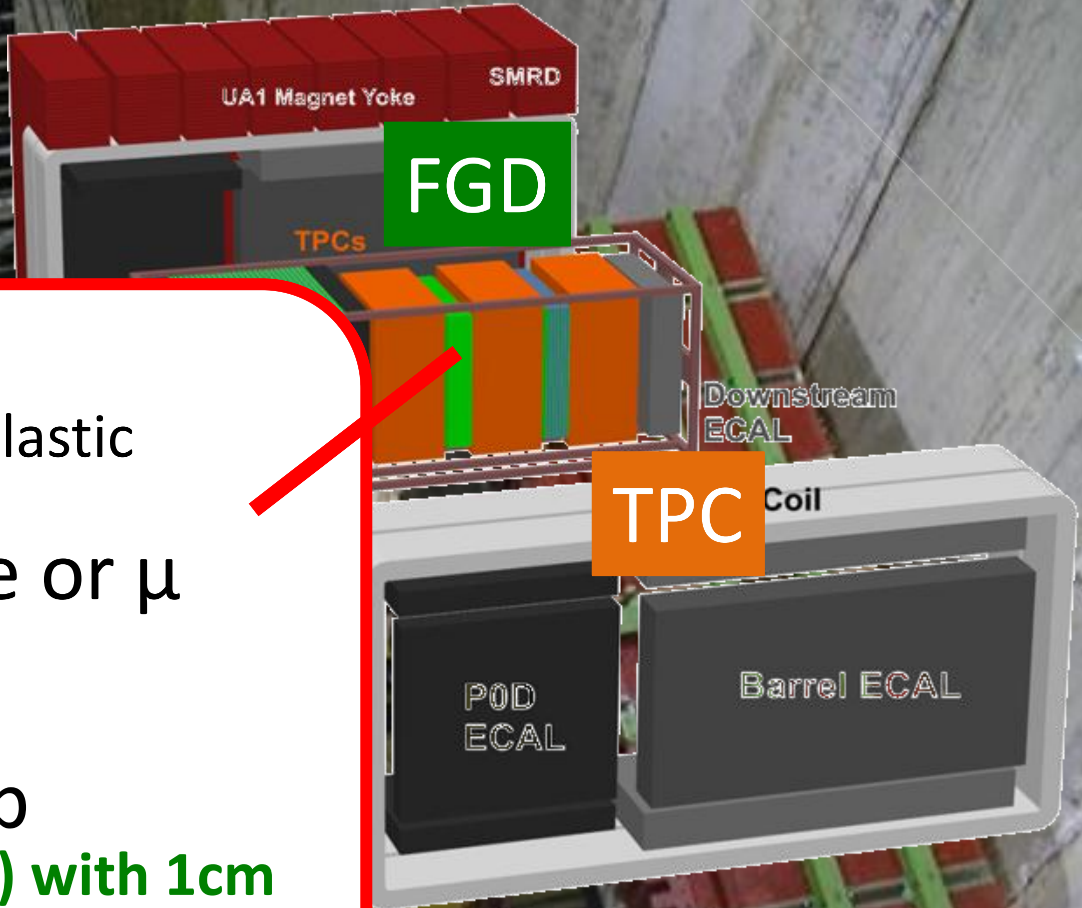
- Secondary π^+(and K^+) from 30 GeV protons focused by three E.M. horns
- ν_μ beam (mainly $\pi^+ \rightarrow \mu^+ + \nu_\mu$)
- Off axis neutrino beam(2.5°)
  - Narrow band @ osc. max
  - Reduce BG from high energy
  - ν direction stability < 1mrad



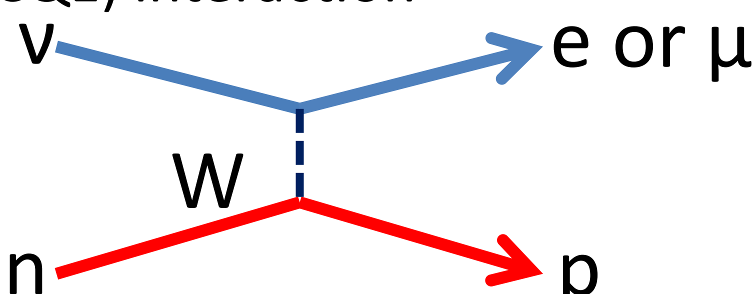

ND280
Off axis neutrino detector
UA1 Magnet Yoke
SMRD
TPCs
FGDs
P0D
(π^0-
detector)
Downstream
ECAL
Solenoid Coil
P0D
ECAL
Barrel ECAL
~7m
280m from target

ND280

Off axis **neutrino detector**



Signal:
Charged Current Quasi Elastic (CCQE) interaction



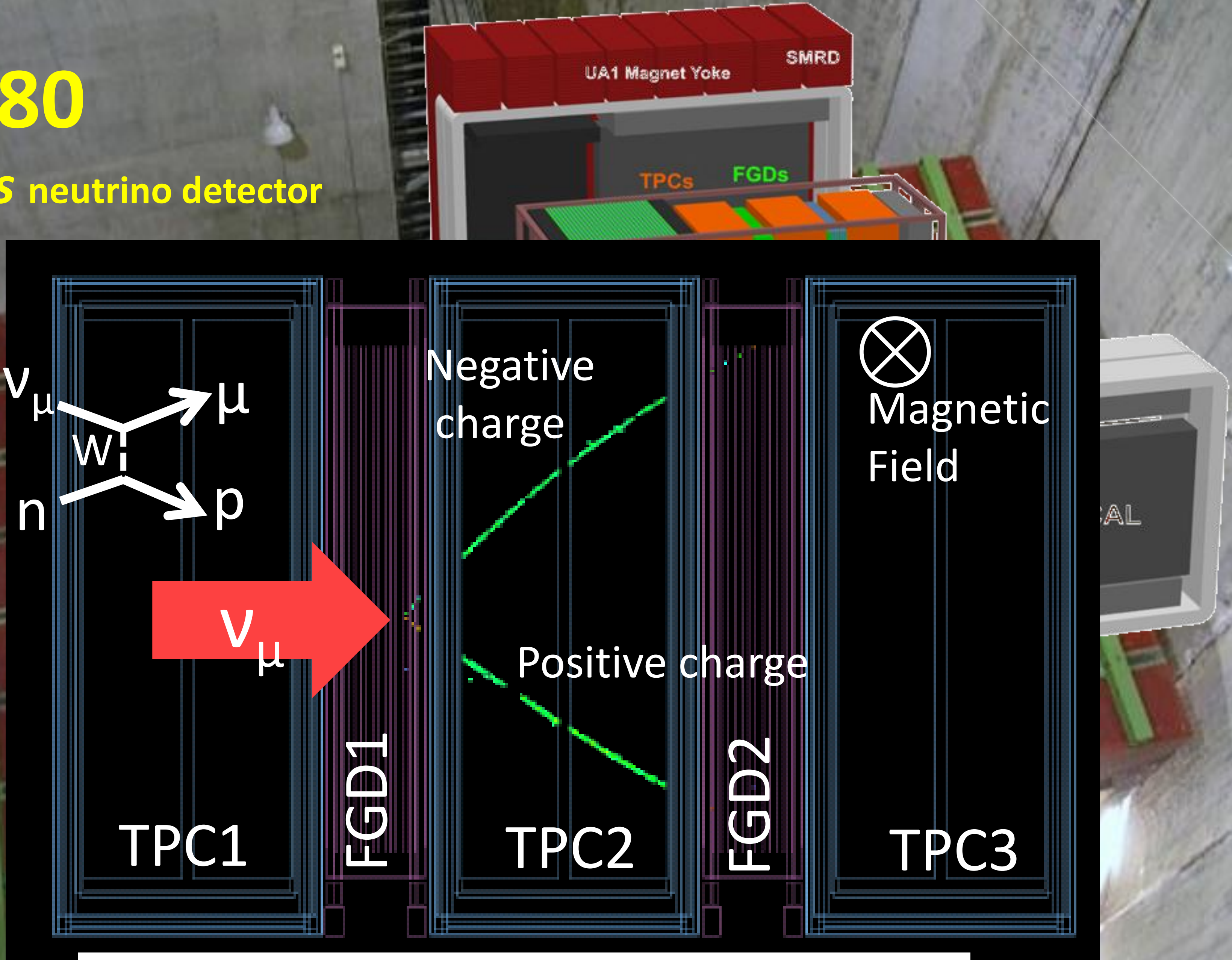
Fine Grained Detector (FGD) with 1cm square plastic scintillators (1.6ton fiducial mass) .

Tracker: FGD & TPC

TPC provides PID(de/dx,charge) and Momentum of each track.

ND280

Off axis **neutrino detector**



Event Display of CC like event

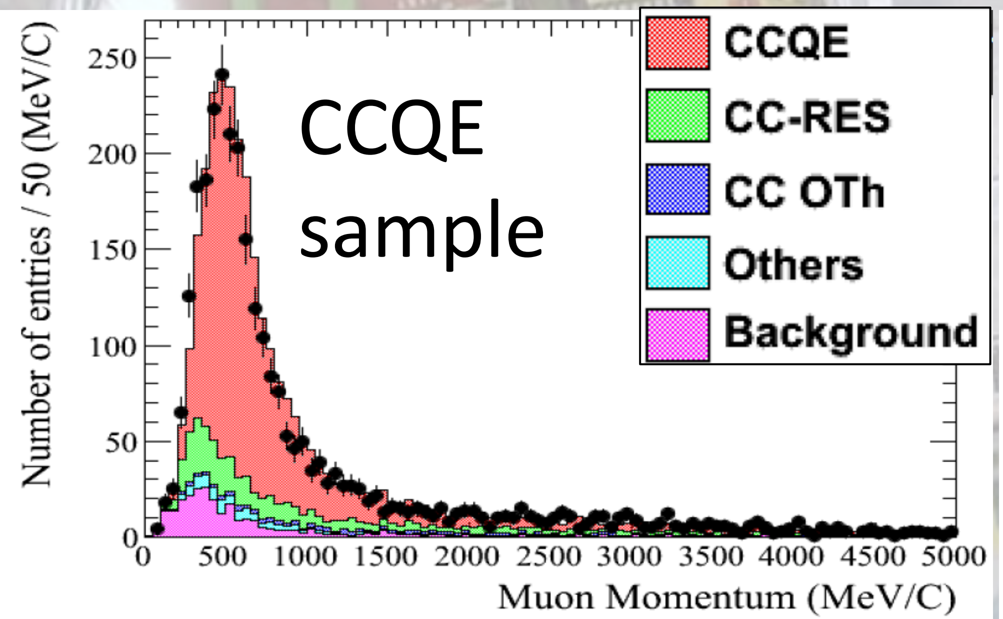
ND280

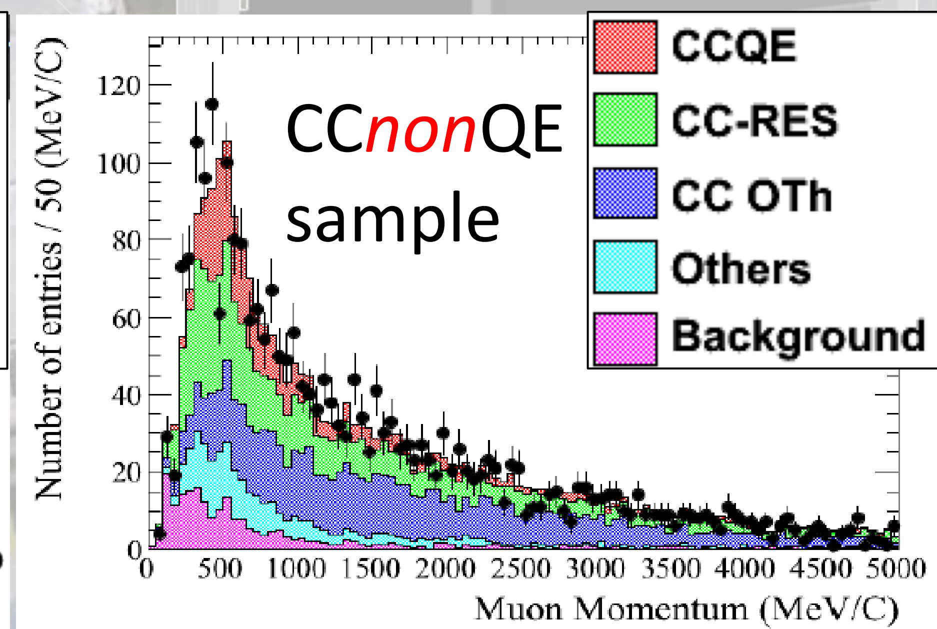
neutrino detector

CCQE selection (one μ track selection)

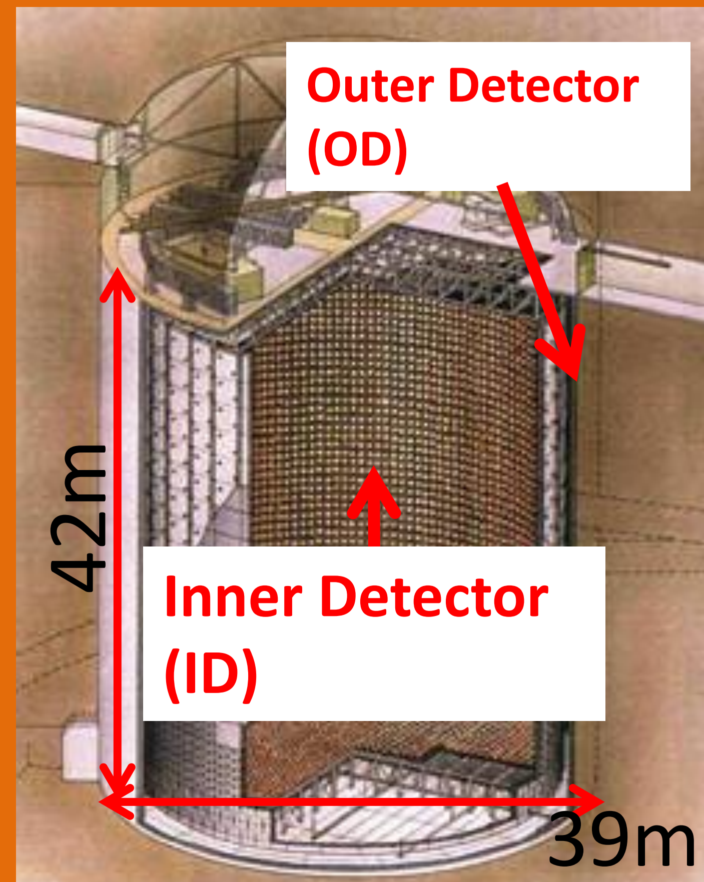
- Good μ^- candidate in FV.
- Upstream TPC veto
- muon ID by TPC
- 1 FGD-TPC track
- No decay-e in FGD

For CCQE selection
40% eff. w/ 72% purity





Far Detector : Super-Kamiokande



20inch (~50cm) PMT

11129 × 20inch PMT in ID

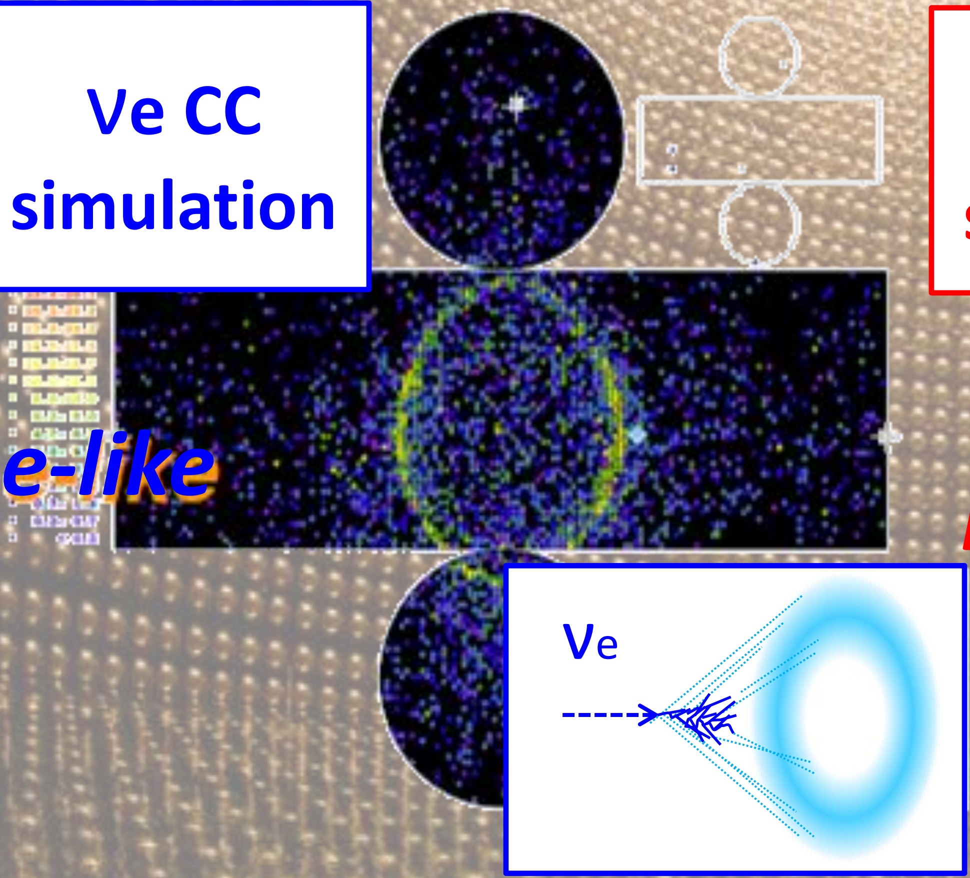
Fiducial volume is 2m from ID wall

= 22.5 kton

Particle ID technique

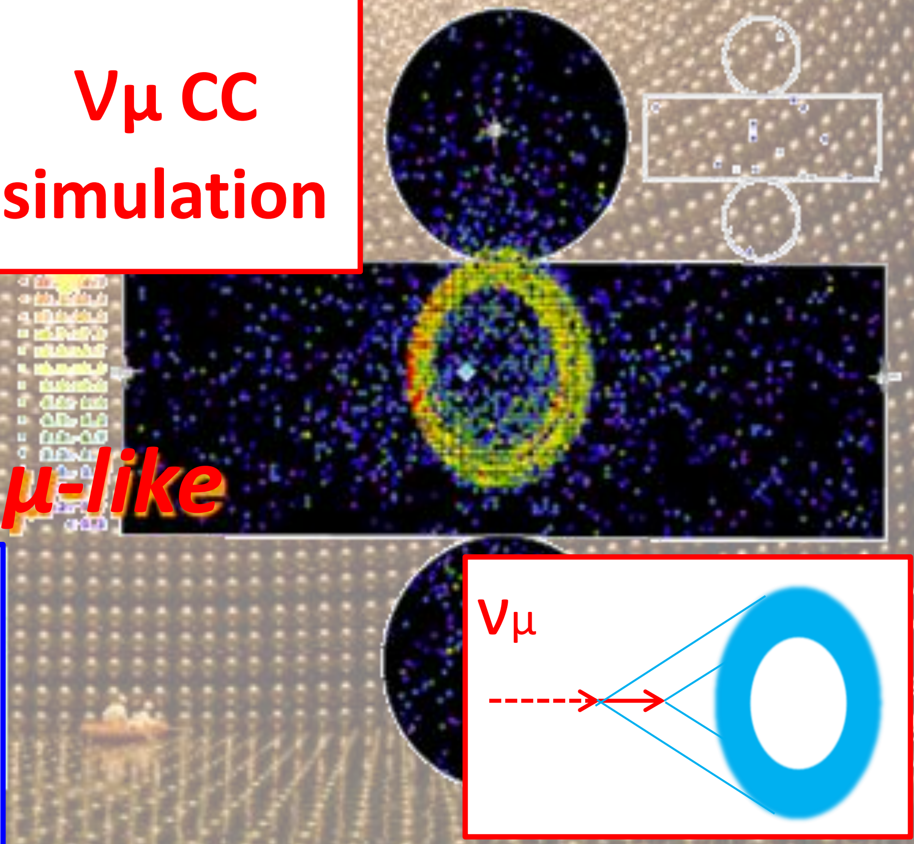
ν_e CC simulation

e-like



ν_μ CC simulation

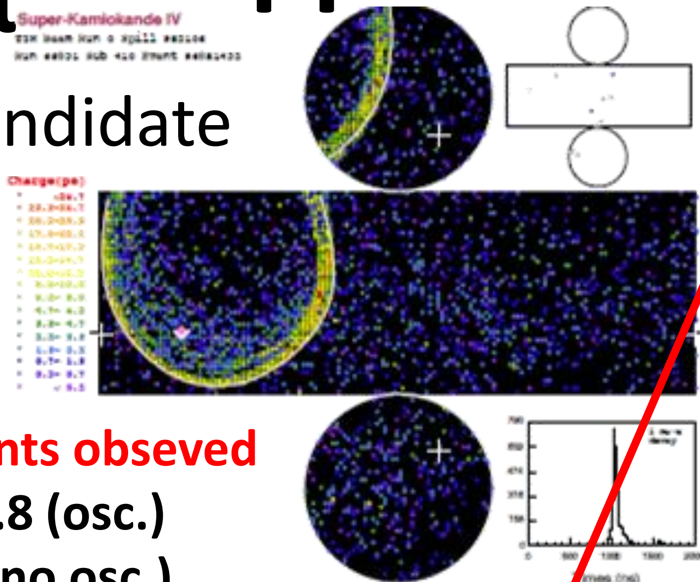
μ-like



Miss-PID probability ~ 1% !

ν_μ disappearance

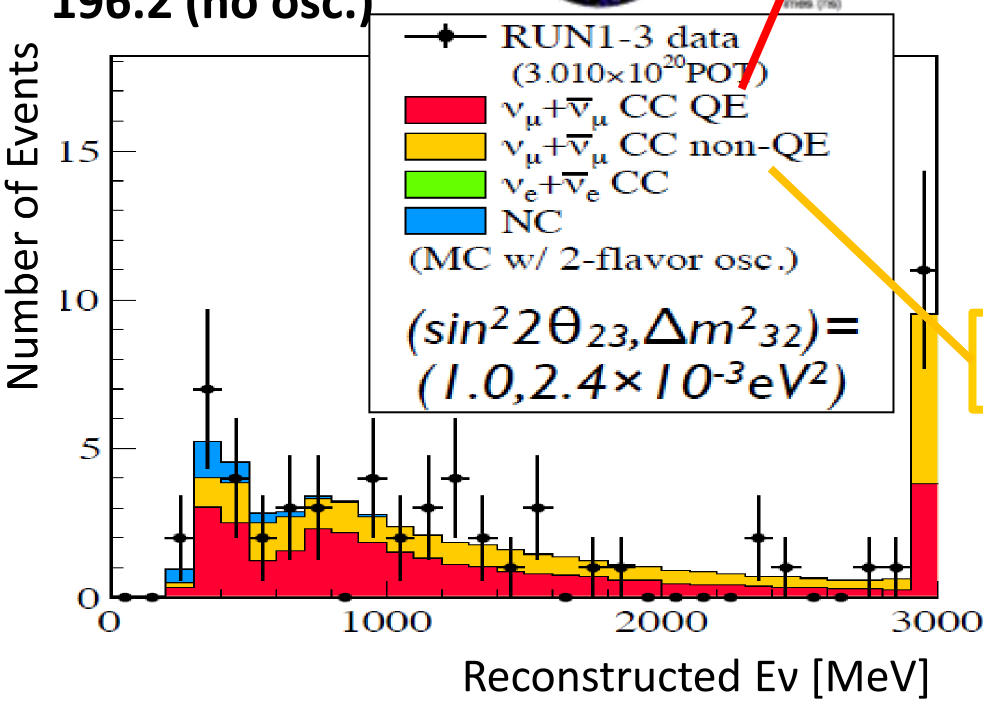
ν_μ candidate



58 events obseved

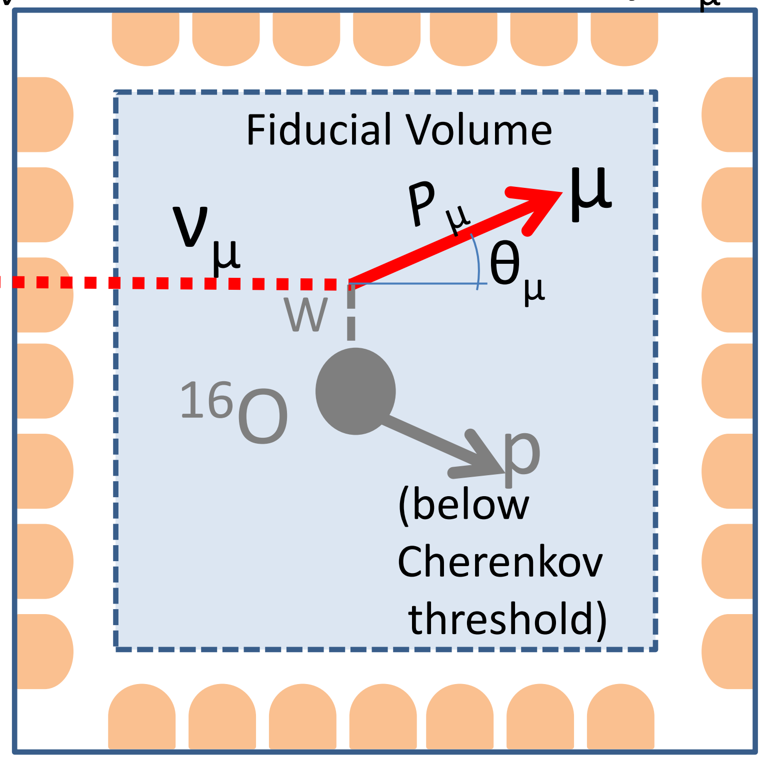
MC:57.8 (osc.)

196.2 (no osc.)

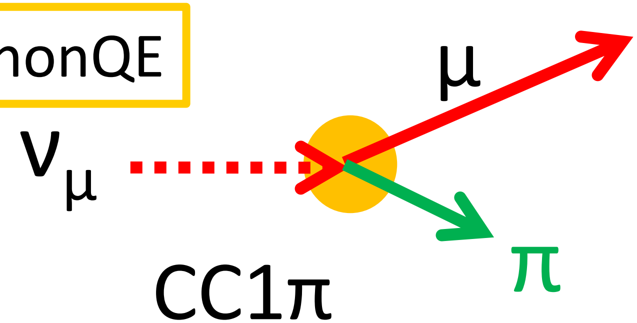


Signal (CCQE): 1ring μlike

E_ν can be reconstructed by P_μ&θ_μ



CC-nonQE



Method of ν oscillation analysis

ν Flux prediction

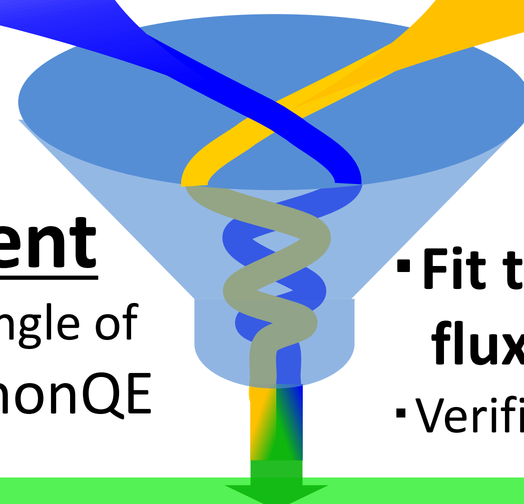
With external hadron production data especially from NA61@CERN

Neutrino Cross section

Model(NEUT), uncertainties developed with fits to external data

ND280 Measurement

Momentum and angle of ν_μCCQE and CCnonQE



- **Fit the ND280 Data to refine flux and ν-int. model**
- Verification with ν_e&π^0 data @ND280

SK prediction

Tuned MC based on ND280 measurement

Comparison

SK Measurement

ν_μ disappearance: # of events and energy spectrum

Neutrino oscillation parameter fit

2 different methods

- Maximum likelihood method with reconstructed Eν

$$\mathcal{L}(\vec{o},\vec{f}) = \mathcal{L}_{\rm norm}(\vec{o},\vec{f}) \times \mathcal{L}_{\rm shape}(\vec{o},\vec{f}) \times \mathcal{L}_{\rm syst}(\vec{f})$$

  – Where ***o*** and ***f*** are ν oscillation parameters and systematic error parameters.

  – Vacuum oscillation is used (matter effect is small)

- Likelihood-ratio method with reconstructed Eν

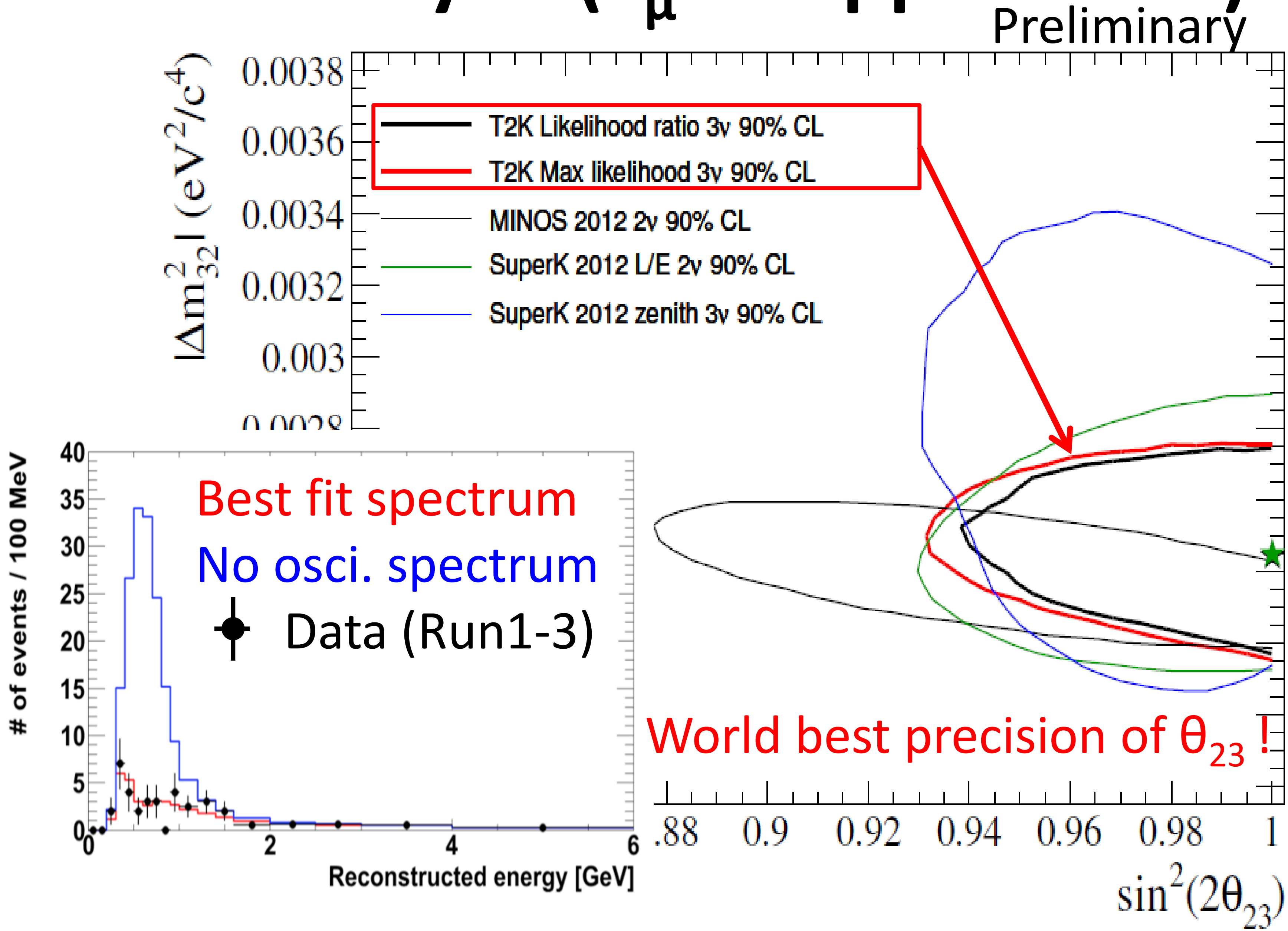
$$\chi^2 = 2\sum_{E}\left(N_{SK}^{data}\ln\frac{N_{SK}^{data}}{N_{SK}^{exp}} + (N_{SK}^{exp} - N_{SK}^{data})\right) + (\vec{f} - \vec{f_0})^T C^{-1}(\vec{f} - \vec{f_0})$$

  – N_{SK} is number of event in SK for each energy bin

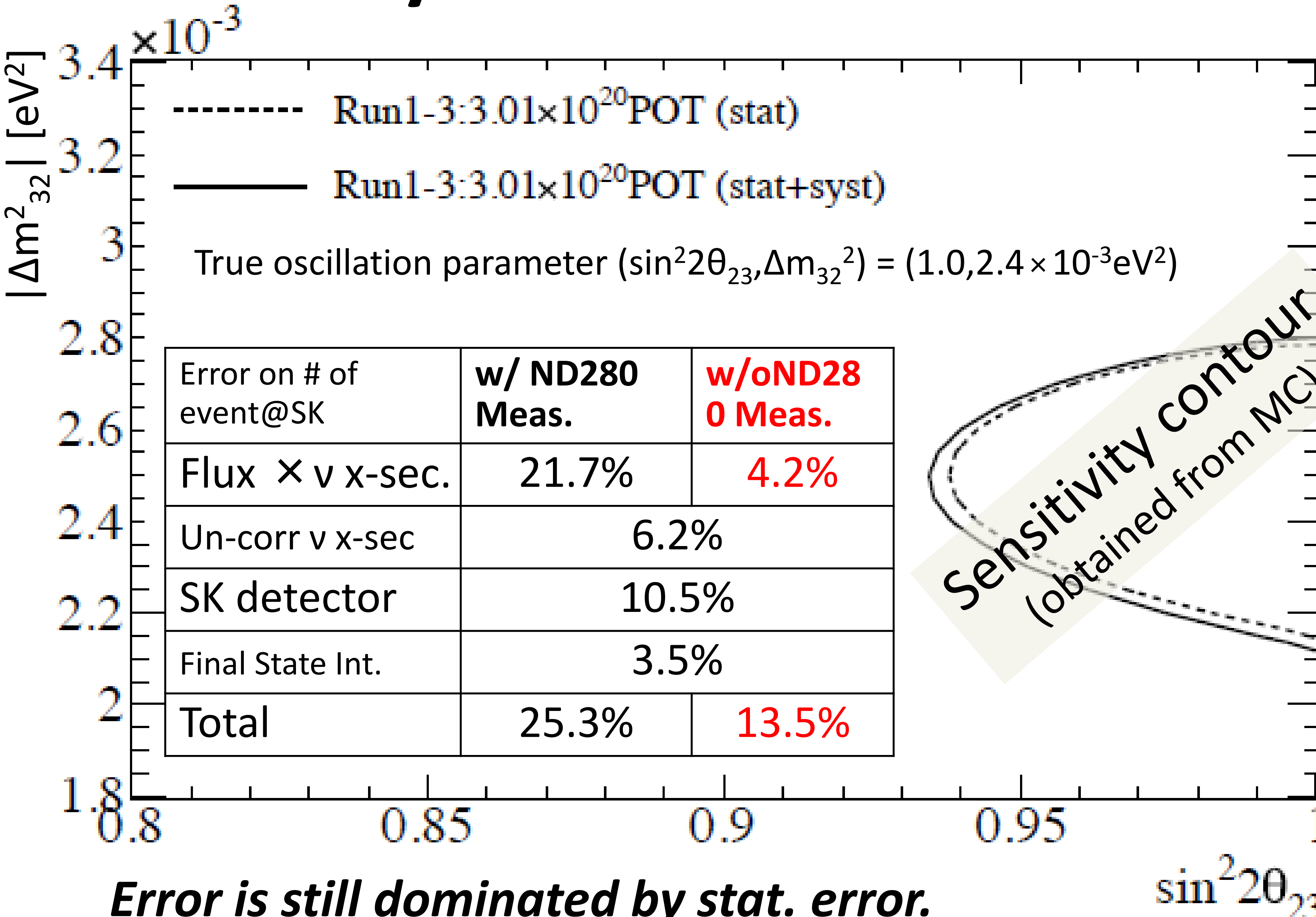
  – $\vec{f}_0$ is default systematic parameters, and C is covariance .

  – Matter effect is taken into account.

ν osc. analysis (ν_μ disappearance)



Effect of systematics



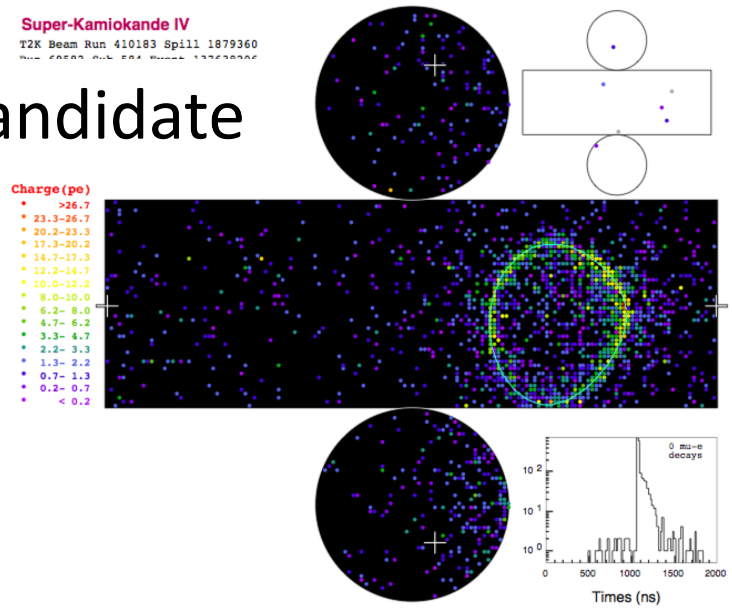
Error on # of event@SK	w/ ND280 Meas.	w/oND280 Meas.
Flux ×ν x-sec.	21.7%	4.2%
Un-corr ν x-sec	6.2%	
SK detector	10.5%	
Final State Int.	3.5%	
Total	25.3%	13.5%

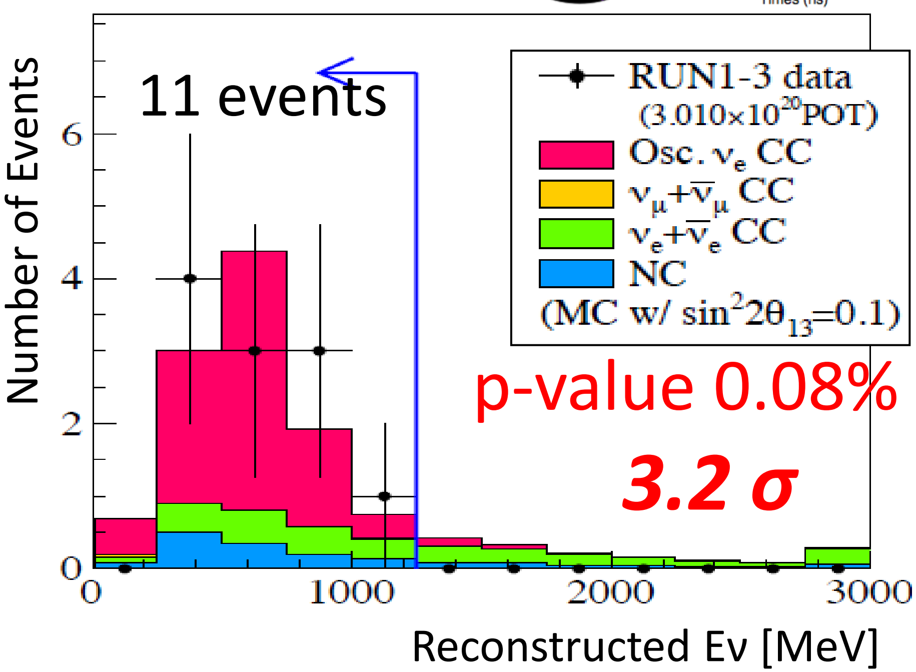
Error is still dominated by stat. error.

ν_e appearance

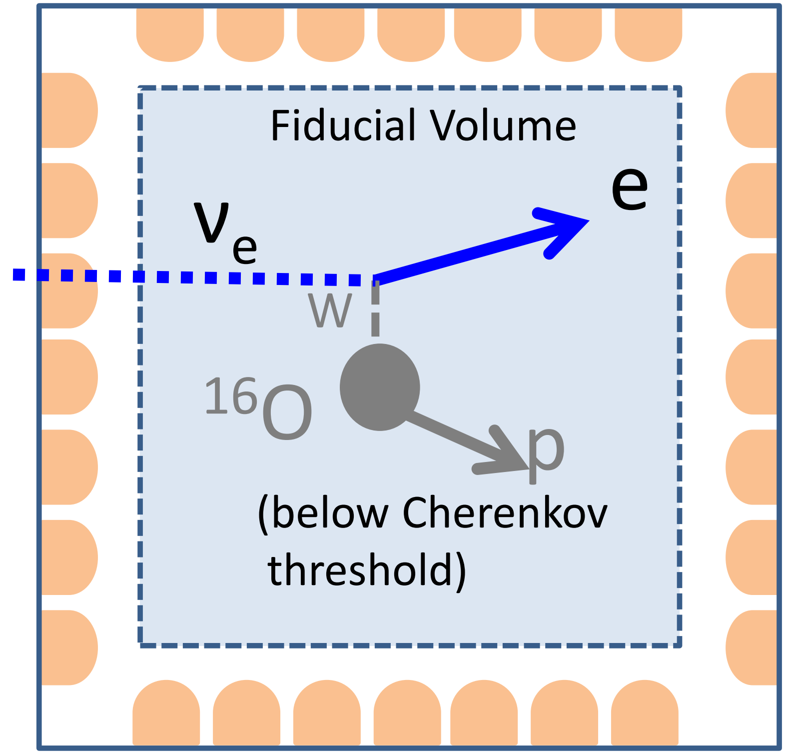
ν_e appearance

ν_e candidate

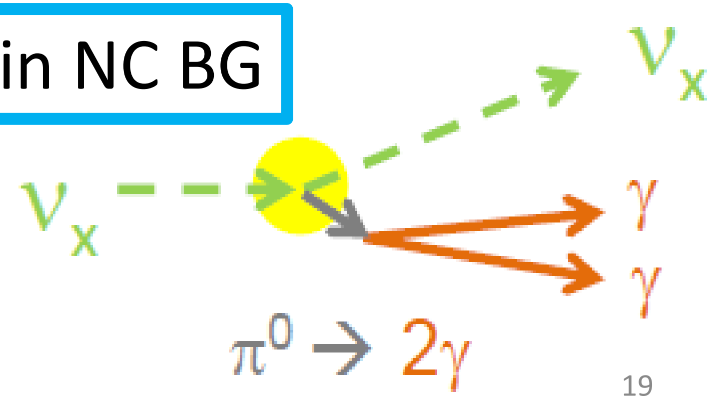




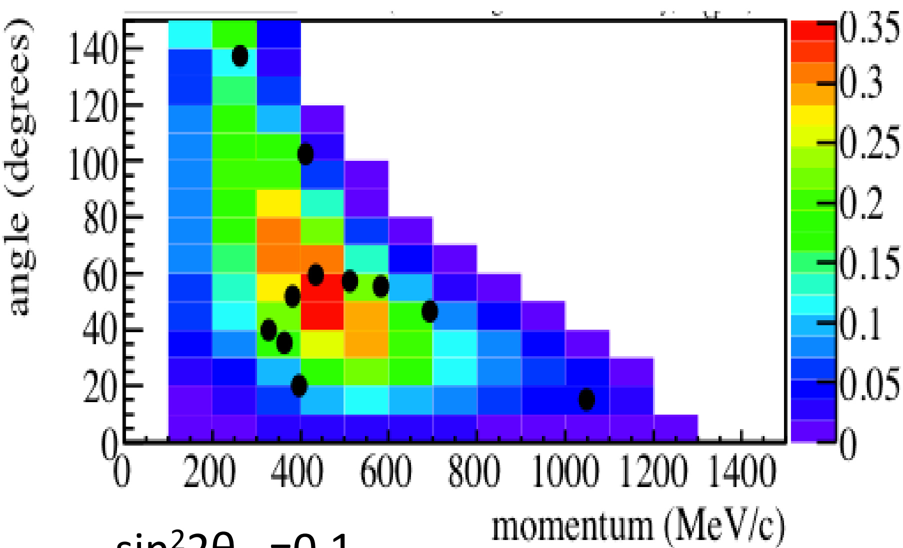
Signal (CCQE): 1ring elike

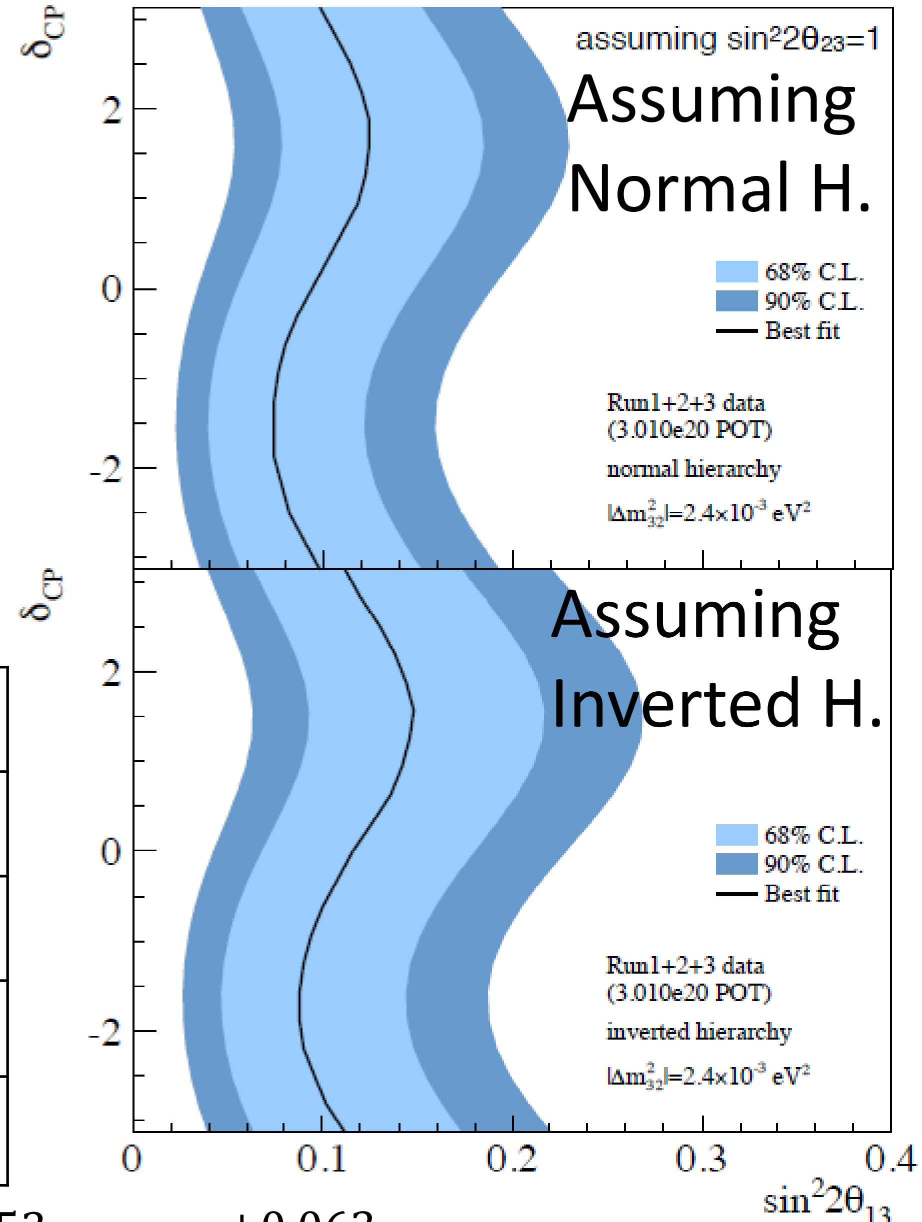


Main NC BG



ν osc. analysis (ν_e)





$\sin^2 2\theta_{13}$=0.1

Error on # of event at SK (%)	w/ ND280	w/o ND280
Flux × ν cross section	24.4	5.7
Un-correlated ν cross section	7.4	
SK +FSI+SI	3.9	
Total	25.9	10.3

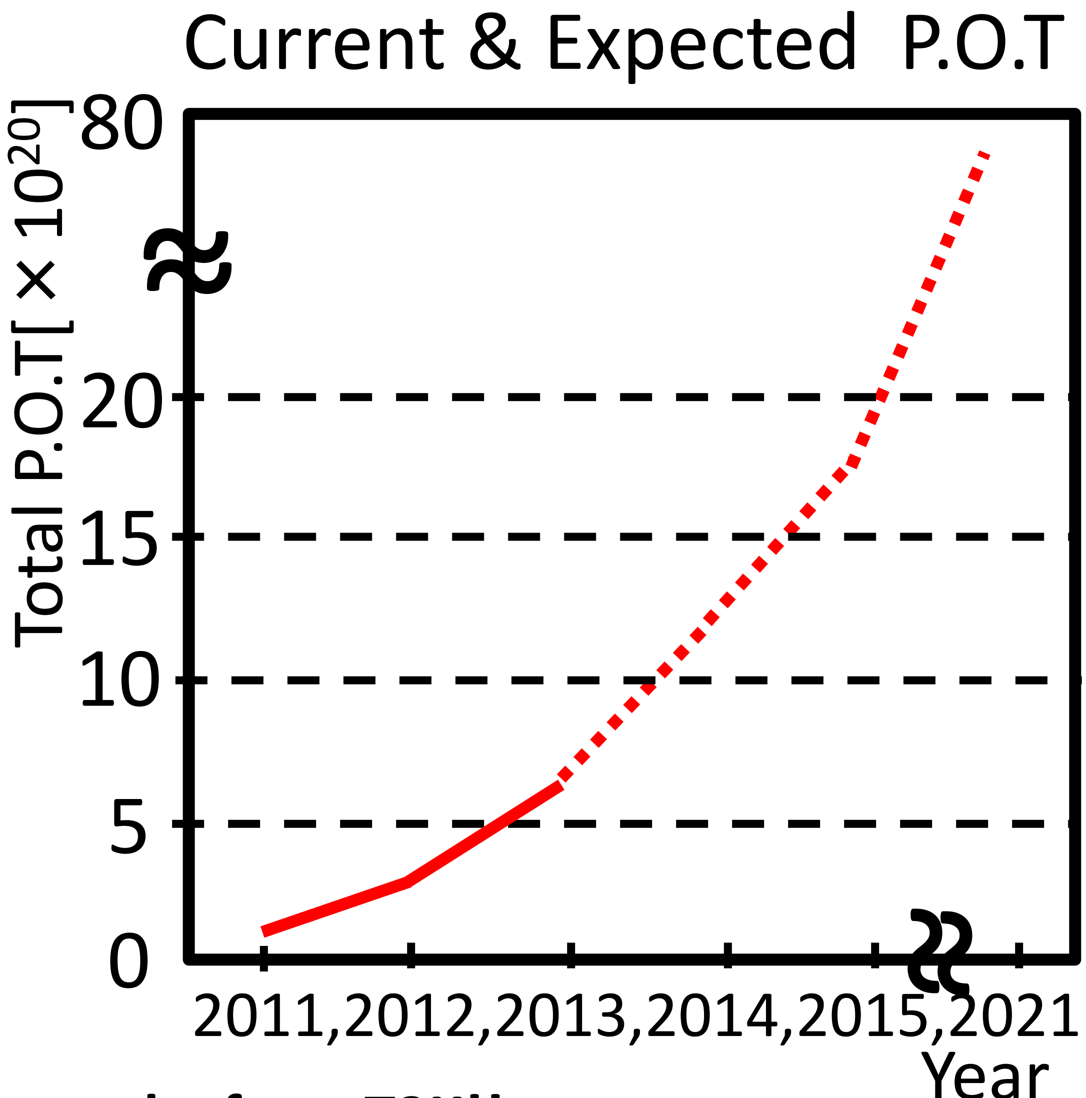
Best fit : $\sin^2 2\theta_{13}$= $0.094^{+0.053}_{-0.040}$ ($0.116^{+0.063}_{-0.049}$) for N.H. (I.H)

Data taking status & prospect

Currently beam power:
230kW
(~150kW in last year)

Very stable operation.
Almost double POT
since Run3 (as of March)

Expected P.O.T.
This year : 8×10^{20}
(5σ for ν_e appearance)
2014 : 12×10^{20}
2015 : 18×10^{20}
Goal : 78×10^{20}



Please look forward to more results from T2K!!

Summary

- T2K results are presented with 3.01×10^{20} POT (~4% of ultimate POT)
- ν_μ disappearance: World record on θ_{23}!

  $(\sin^2 2\theta_{23}, \Delta m_{23}^2) = (1.00_{-0.068}, 2.45 \pm 0.30 \times 10^{-3}\ \mathrm{eV}^2)$ 90% C.L.
- ν_e appearance: 3.2σ significance. Evidence!!

  $\sin^2 2\theta_{13} = 0.094\ ^{+0.053}_{-0.040}$ $(0.116^{+0.063}_{-0.049})$ for N.H. (I.H)

Prospect

- Keep stable data taking (current beam power ~230kW)
- 8×10^{20}POT by this summer (→ 5σ for ν_e app.)
- Aim to accumulate 12×10^{20} POT (2014) and 18×10^{20} POT (2015)

back up

Physics

CPV measurement

- CPV term in Prob($\nu_\mu \rightarrow \nu_e$) $\propto$

$$\sin\theta_{12} \cdot \boldsymbol{\sin\theta_{23}} \cdot \boldsymbol{\sin\theta_{13}} \cdot \sin\delta$$

Now we know θ_{13} is not 0!

This has opened up the possibility to measure CPV in lepton sector

Note: The largest uncertainty is on $\boldsymbol{\theta_{23}}$

***Both** ν_e appearance and ν_μ disappearance* are very important to for future CPV measurement

Unveil the lepton mixing structure

$$U_{PMNS} \approx \begin{pmatrix} 0.8 & 0.55 & 0.15 \\ -0.4 & 0.6 & 0.7 \\ 0.4 & -0.6 & 0.7 \end{pmatrix}$$

$$\delta = ?$$

$$U_{CKM} \approx \begin{pmatrix} 0.97 & 0.23 & 0.004 \\ 0.23 & 0.97 & 0.04 \\ 0.009 & 0.04 & 1 \end{pmatrix}$$

$$\delta = 69^\circ$$

We want to understand the underlying physics to explain the structure of lepton mixing with **precise measurements of parameters**

$\nu_\mu \rightarrow \nu_e$ appearance

$$P(\nu_\mu \to \nu_e) = 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2 \frac{\Delta m_{31}^2 L}{4E} \times \left(1 + \frac{2a}{\Delta m_{31}^2}\ (1 - 2S_{13}^2)\right) \quad \boxed{\theta_{13}}$$

$$+8C_{13}^2 S_{12} S_{13} S_{23}(C_{12}C_{23}\cos\delta - S_{12}S_{13}S_{23}) \cos\frac{\Delta m_{32}^2 L}{4E} \sin\frac{\Delta m_{31}^2 L}{4E} \sin\frac{\Delta m_{21}^2 L}{4E} \quad \boxed{\text{CPC}}$$

$$-8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin\frac{\Delta m_{32}^2 L}{4E} \sin\frac{\Delta m_{31}^2 L}{4E} \sin\frac{\Delta m_{21}^2 L}{4E} \quad \boxed{\text{CPV}}$$

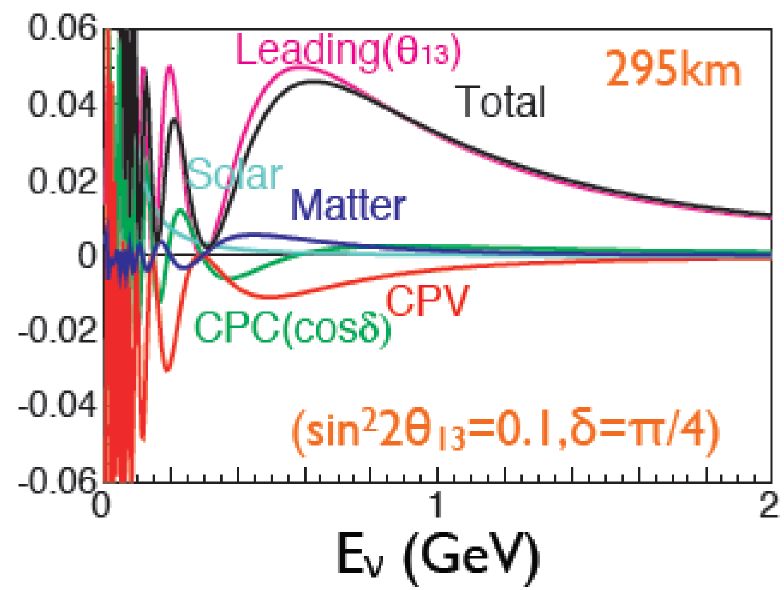
$$+4S_{12}^2 C_{13}^2 \{C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12}C_{23}S_{12}S_{23}S_{13}\cos\delta\} \sin^2\frac{\Delta m_{21}^2 L}{4E} \quad \boxed{\text{Solar}}$$

$$-8C_{13}^2 S_{13}^2 S_{23}^2 \cos\frac{\Delta m_{32}^2 L}{4E} \sin\frac{\Delta m_{31}^2 L}{4E} \frac{aL}{4E}\ (1 - 2S_{13}^2) \quad \boxed{\text{Matter effect (small in T2K)}}$$

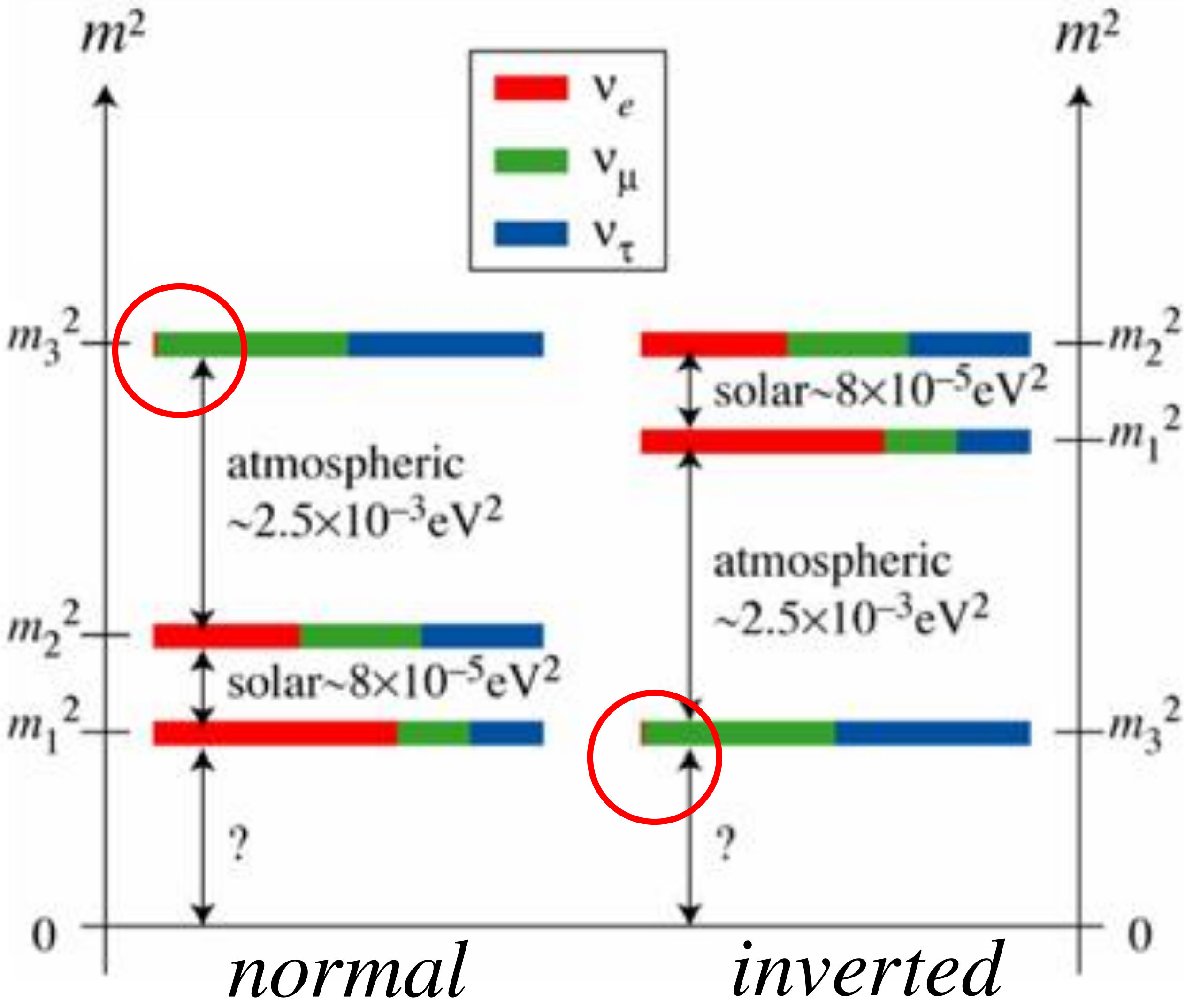
$a \rightarrow -a$, $\delta \rightarrow -\delta$ for $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$

L=295km, $\langle E_\nu \rangle$ ~0.6GeV

$$a = 7.56\times10^{-5}[\text{eV}^2]\cdot\left(\frac{\rho}{[\text{g/cm}^3]}\right)\cdot\left(\frac{E}{[\text{GeV}]}\right)$$



Mass hierarchy



Goal of T2K

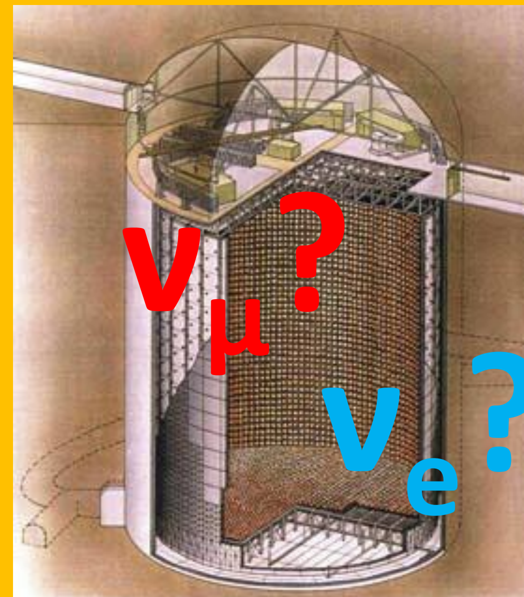
First Goal

- Discovery of $\nu_\mu \rightarrow \nu_e$ (θ_{13} measurement)
  Achieved in 2012!

Ultimate Goal

- Precision measurement of ν_μ disappearance
- Measurement (/indication/hint) of δ_{CP} and the mass hierarchy.

Super-K@Kamioka

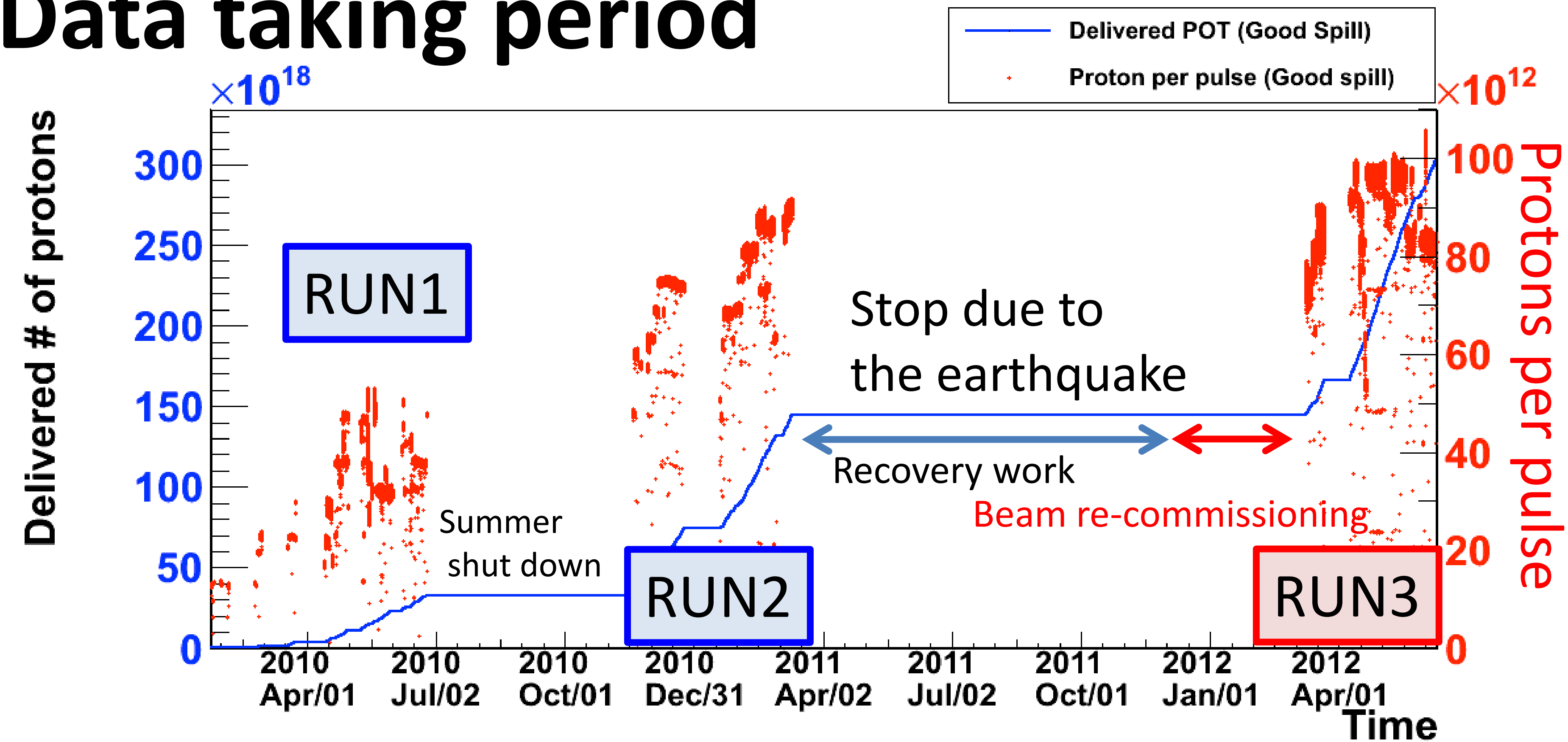


295km

J-PARC @Tokai

Beam line and monitors

Data taking period



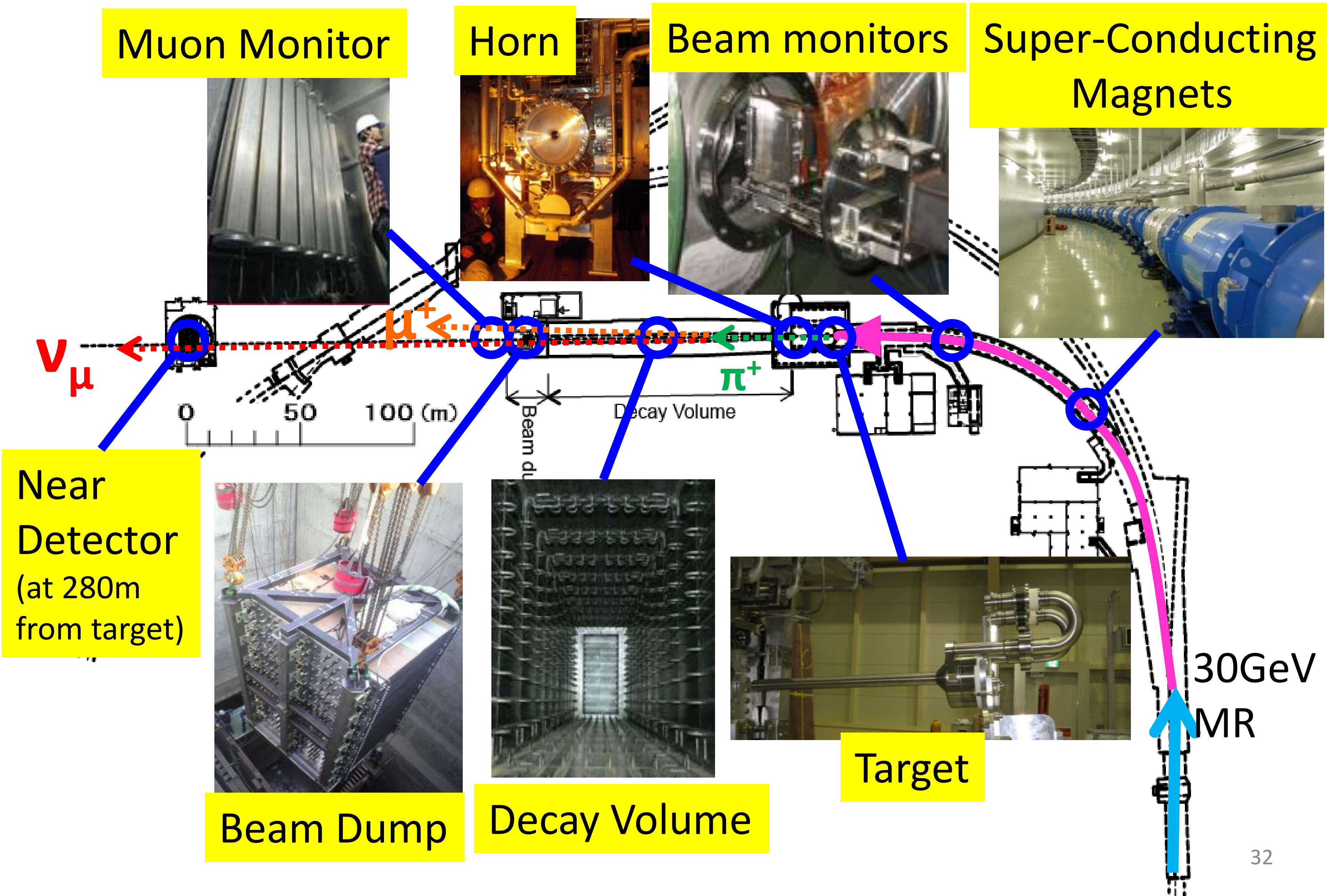
Run1-2 (2010-2011) : 1.43×10^{20} Protons on target (p.o.t.)

Run3 (2012) : 1.58×10^{20} p.o.t.

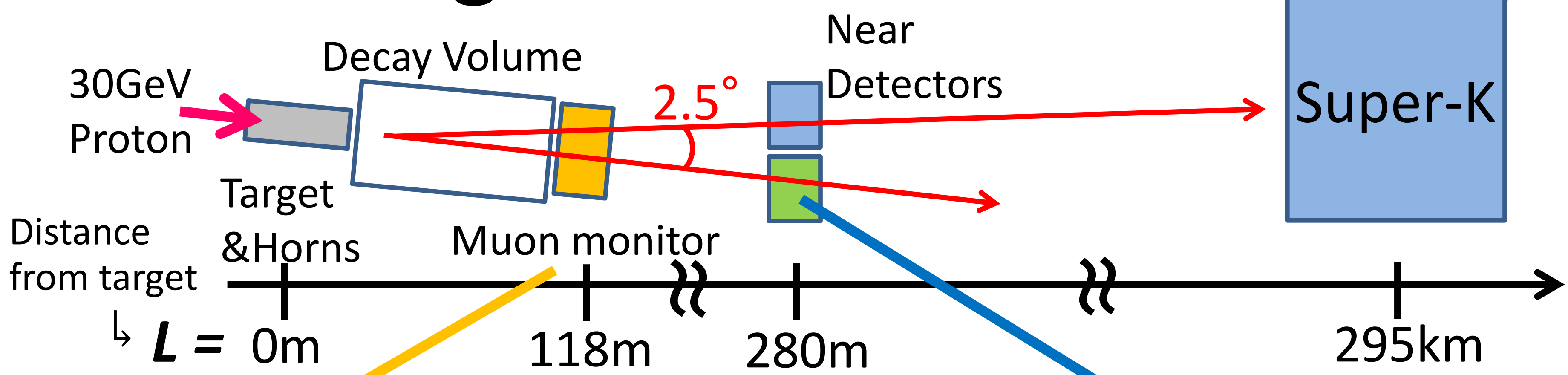
- Confirmed that the beam quality is unchanged after the earthquake
- Achieved stable 200kW beam power operation.

Total number of protons is 3.01×10^{20} p.o.t for this analysis

J-PARC neutrino beamline components

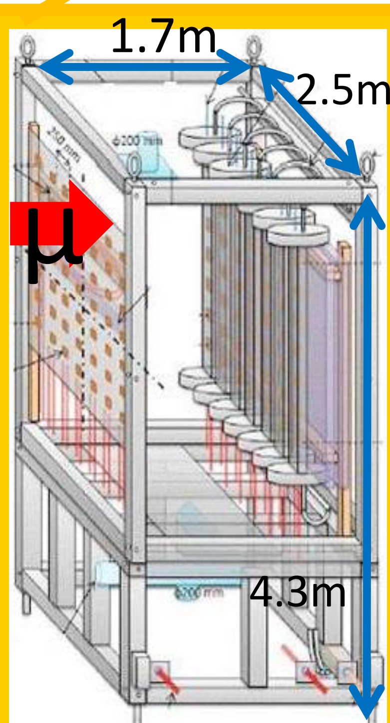


Monitoring ν beam direction



Muon monitor

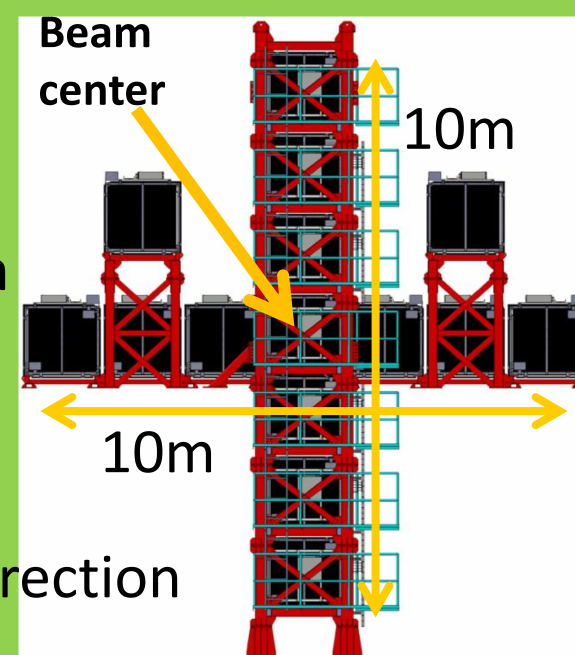
-consists of
49 Si sensors
49 Ionization chambers
-can check
Spil by spil stability.
10^5-10^7 μ /cm^2/bunch



INGRID

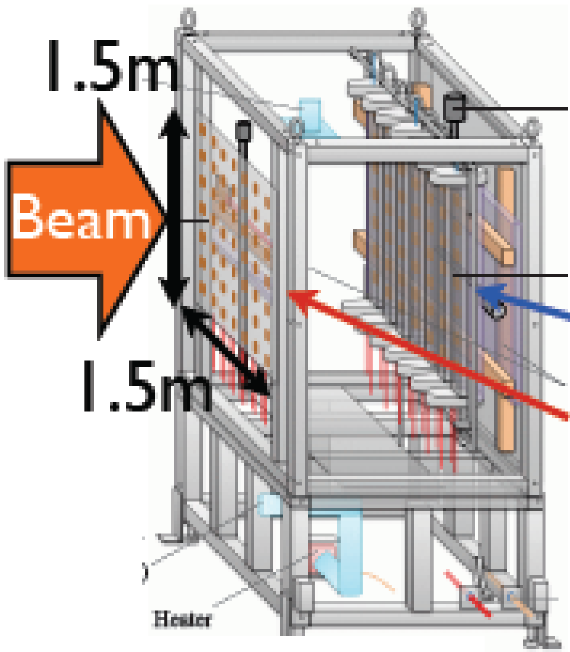
-consists of
16 modules of scintillator + Iron trackers.

- can check
actual ν beam direction
day by day.



For off axis beam → Beam direction monitors are very important

Secondary beam line monitor : Muon monitor (MUMON)



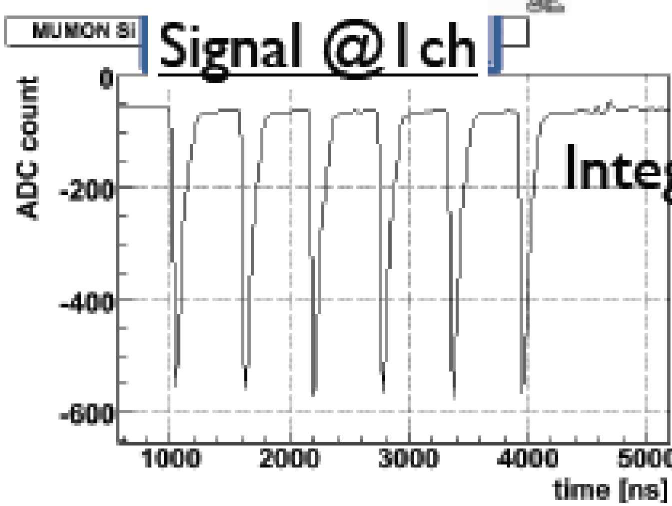
Detect decay μ from π

→Indirect measurement of ν beam direction spill-by-spill.

Ion chamber array (7×7ch)

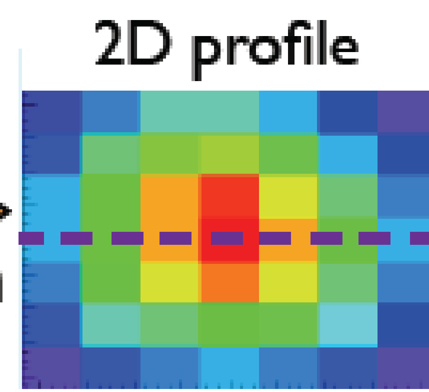
Silicon pin photo diode array (7×7ch)

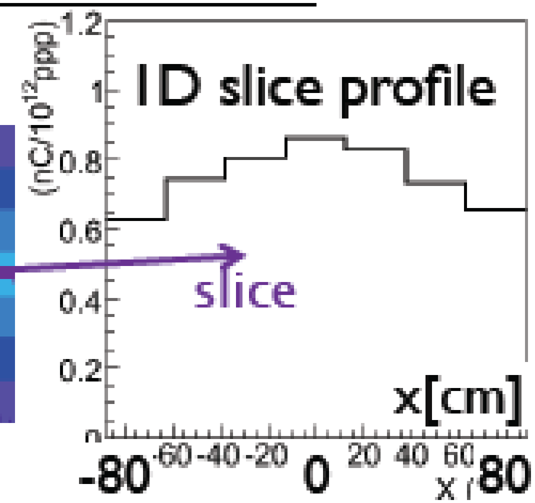
Spill-by-spill μ beam profile by fitting with Gaussian.



Integrate

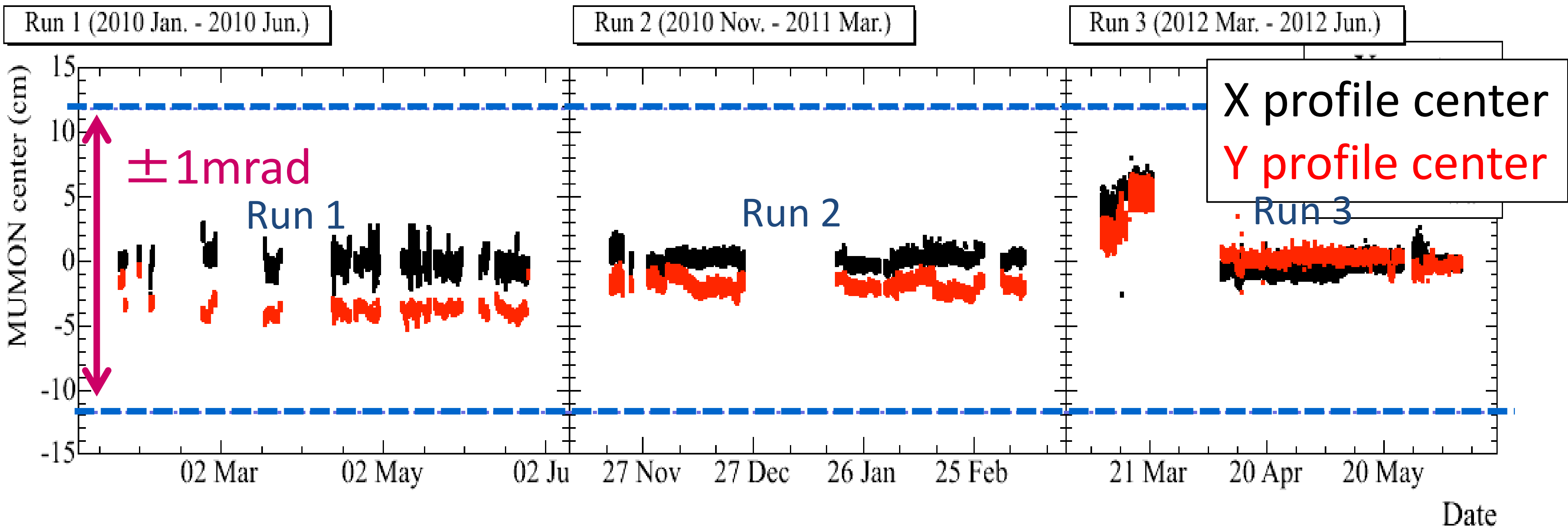
×49ch





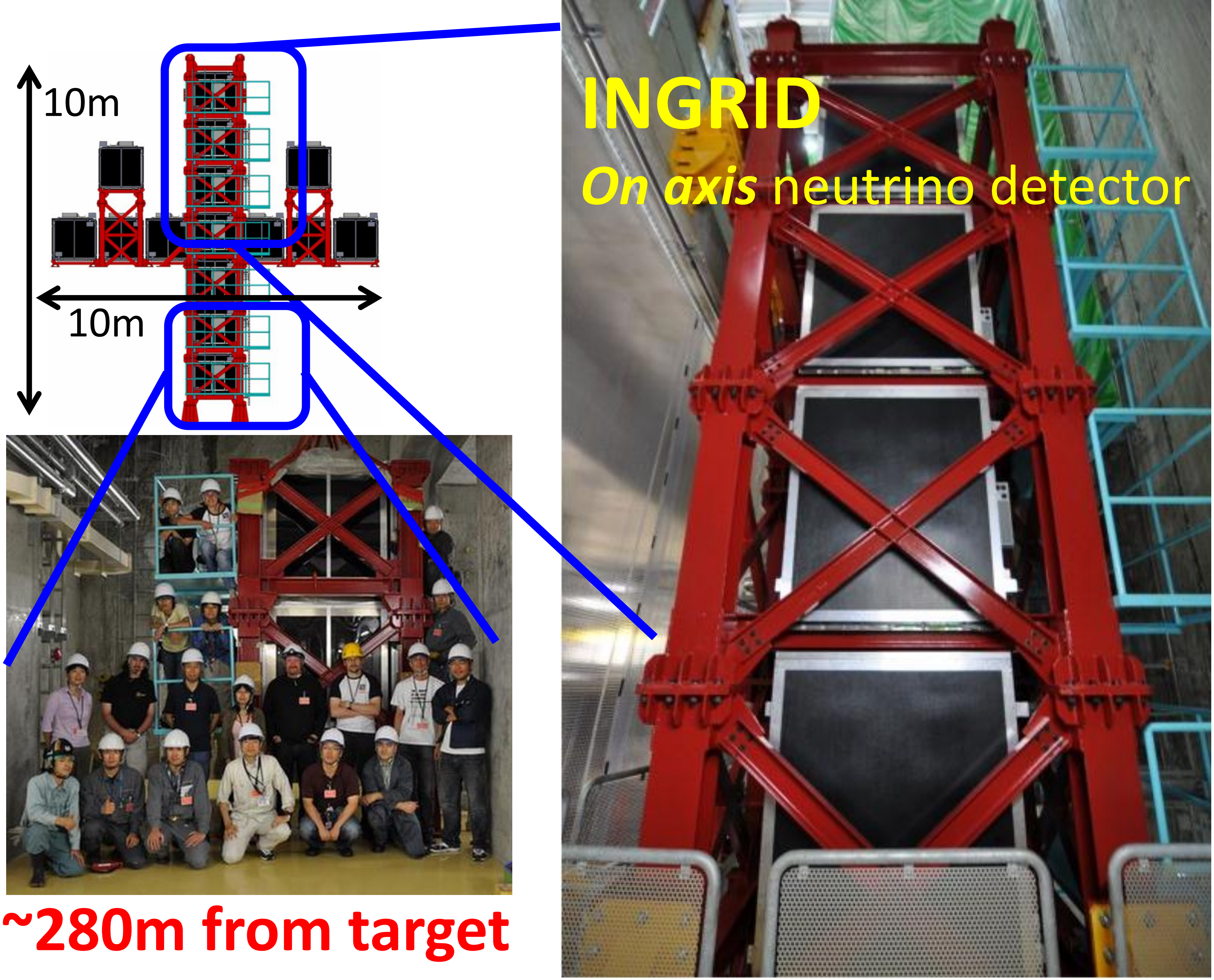
Muon beam center position by MUMON

118m from target



1mrad change makes the peak of ν spectrum by 2-3%(=error on Δm^2)

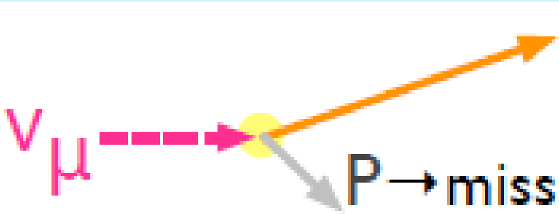
INGRID also shows good stability of neutrino beam


10m
10m
INGRID
On axis neutrino detector
~280m from target

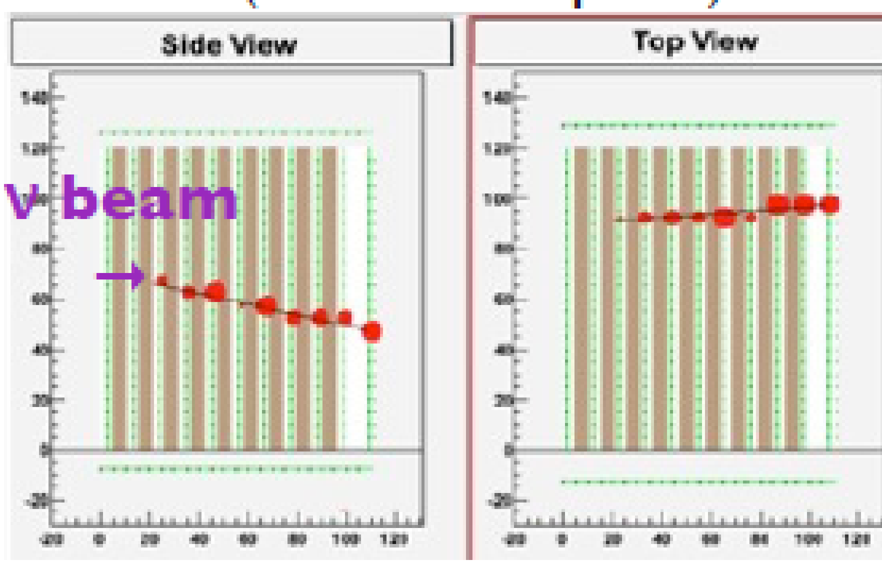
INGRID event selection

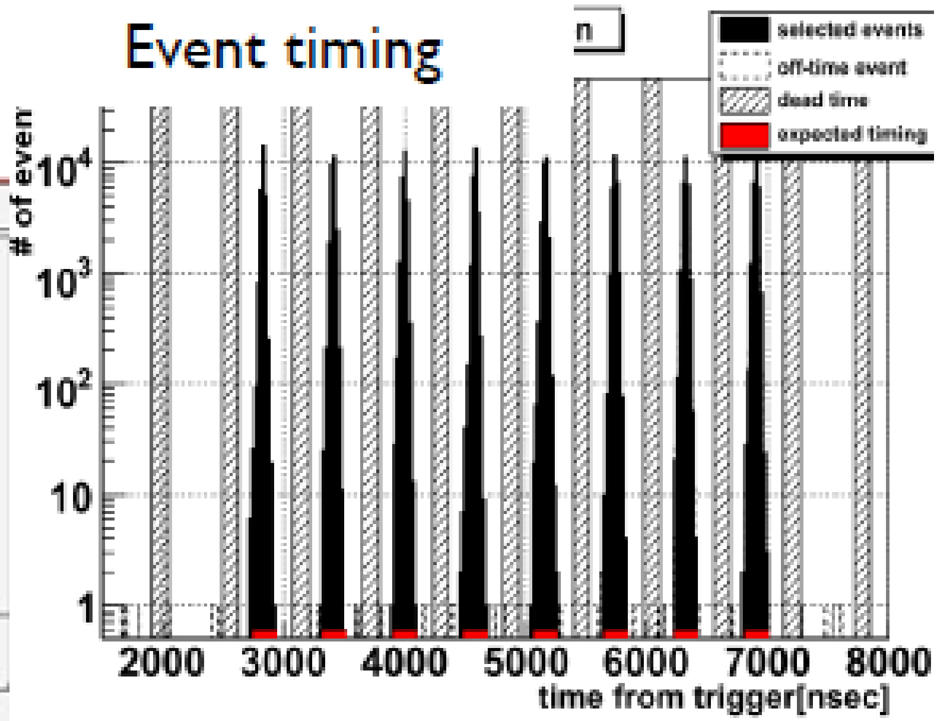
<u>Select neutrino event in FV</u>

- Coincident hits in X-Y plane & Timing cut → Reject accidental hits
- Reconstruct one track.
- Select vertex inside fiducial volume → Veto sand muon, cosmic



(due to iron-plane)

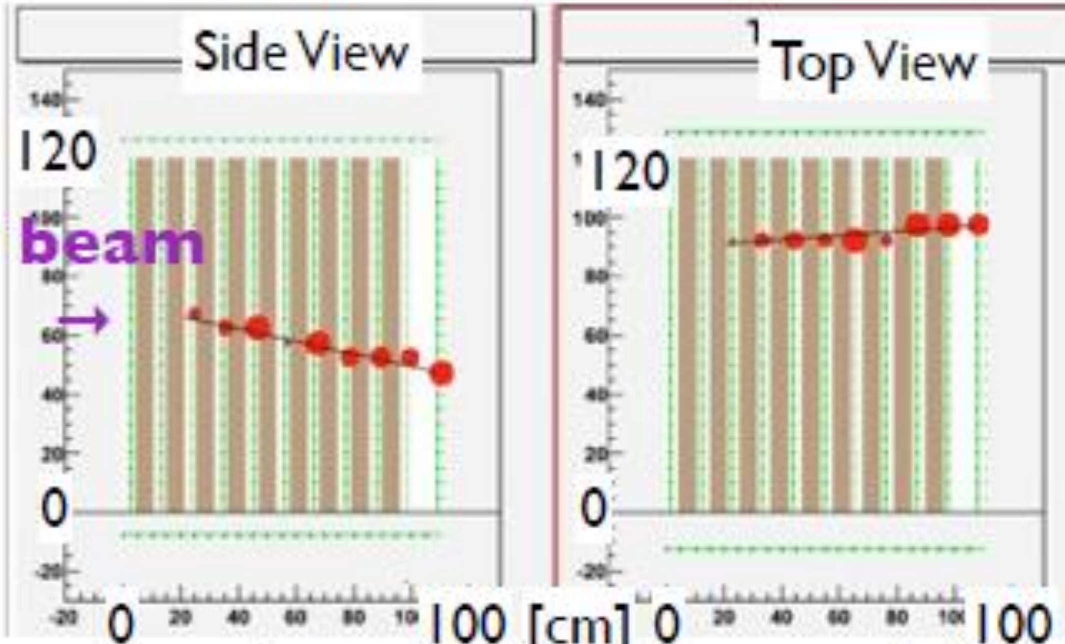




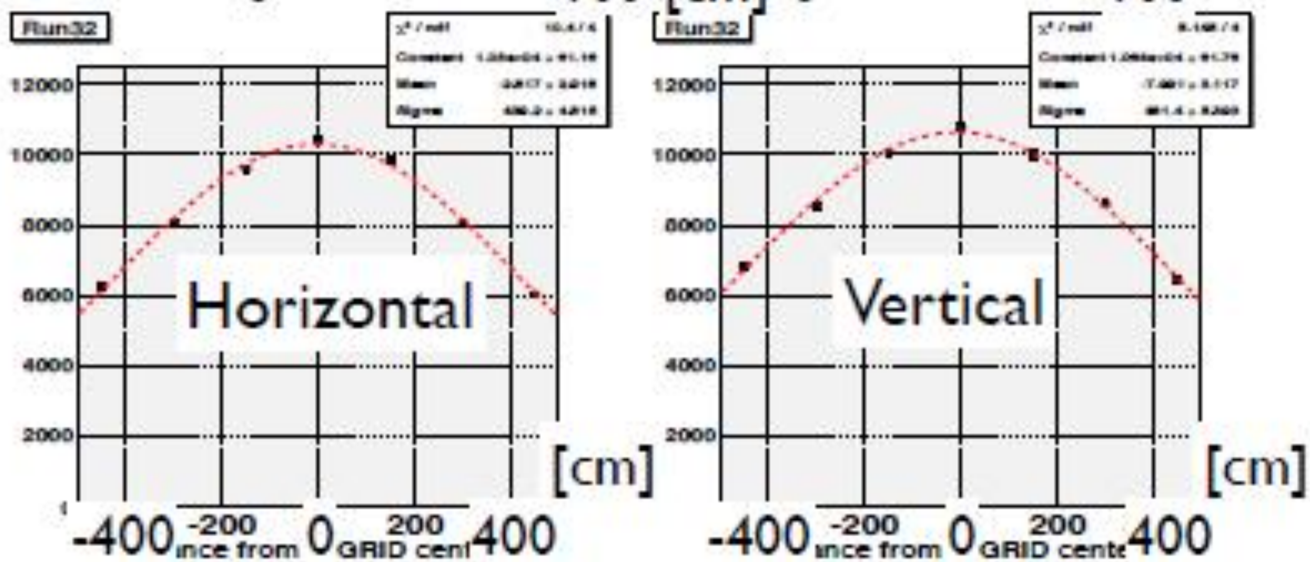
Event display of INGRID

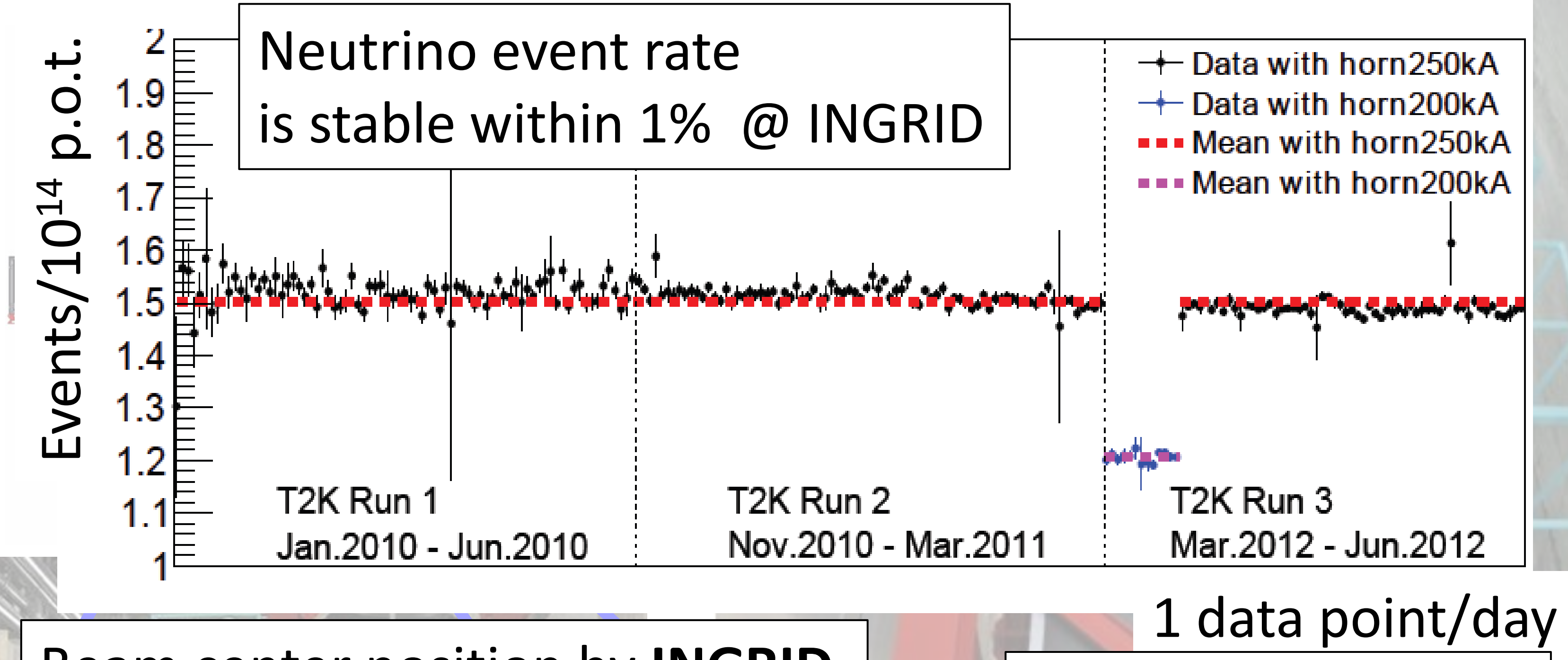
DATA.

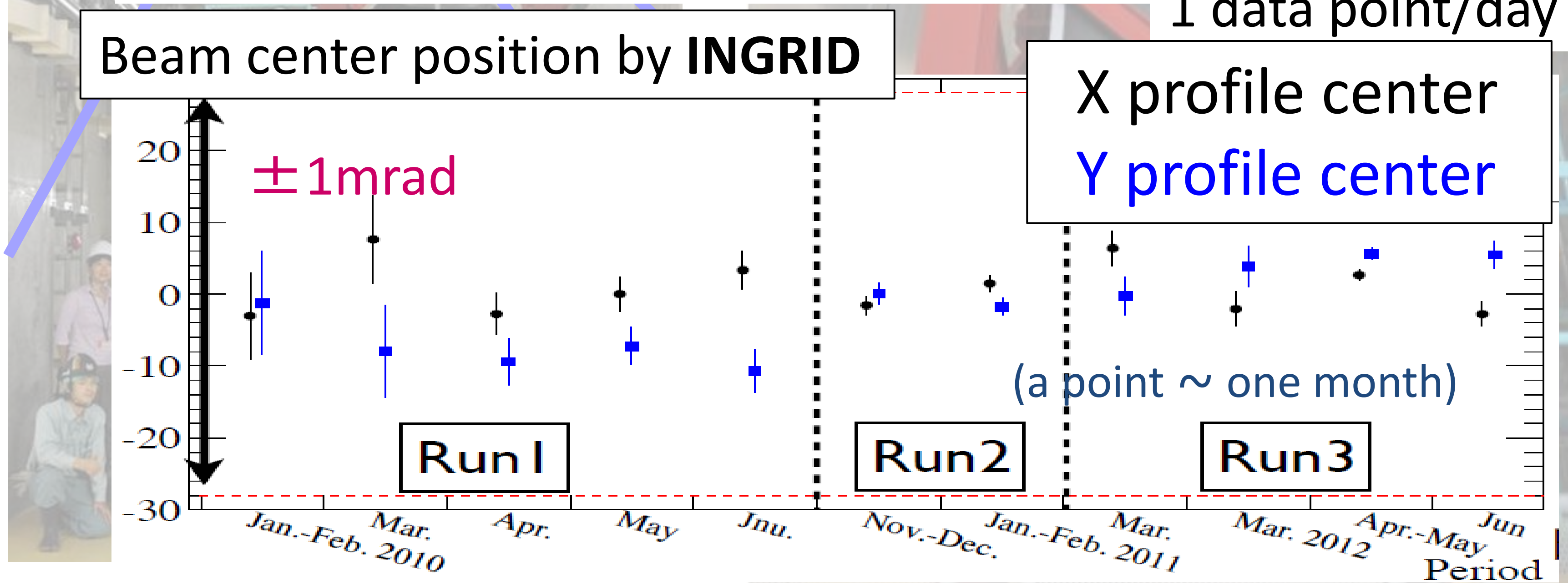
Neutrino event



Beam profile
(~1month data)





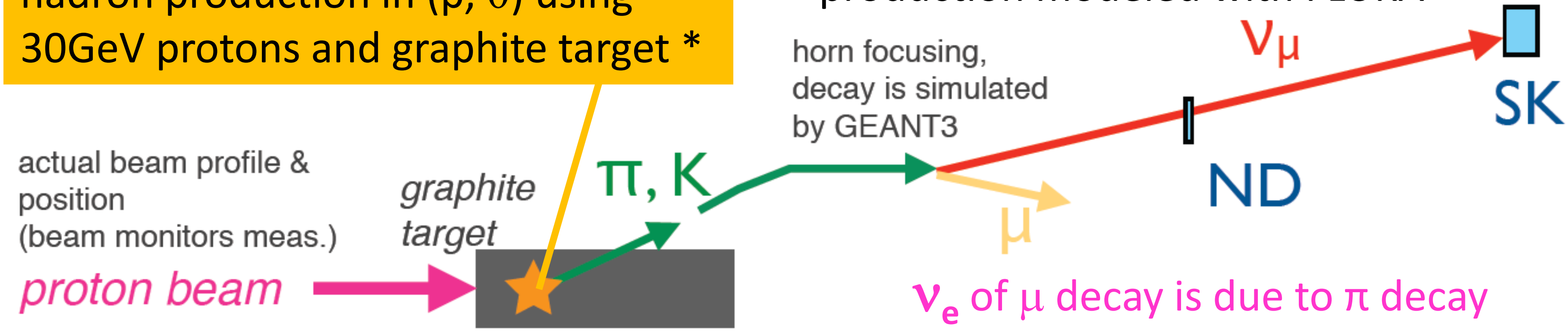


~280m from traget

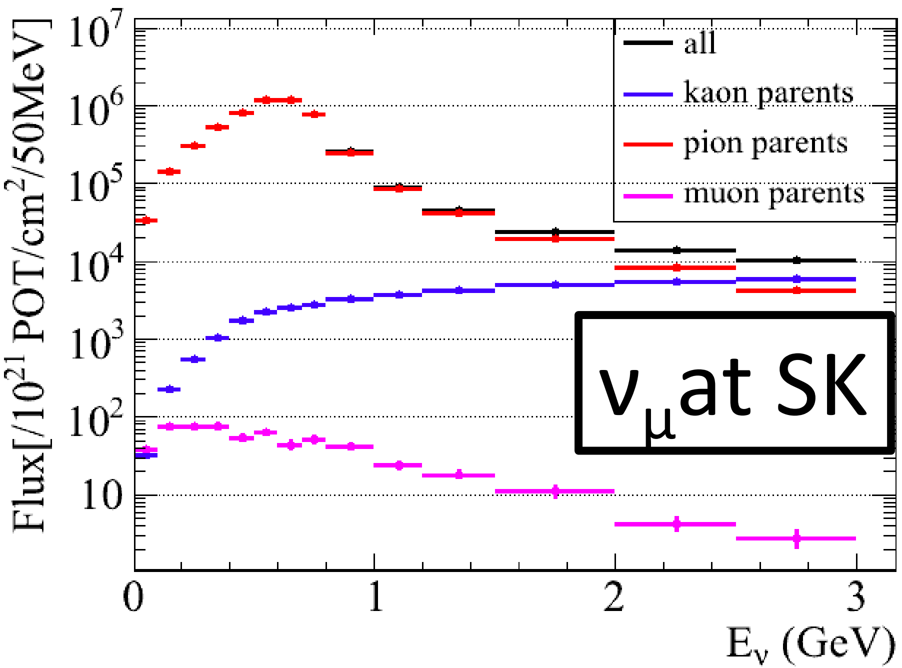
Neutrino flux prediction

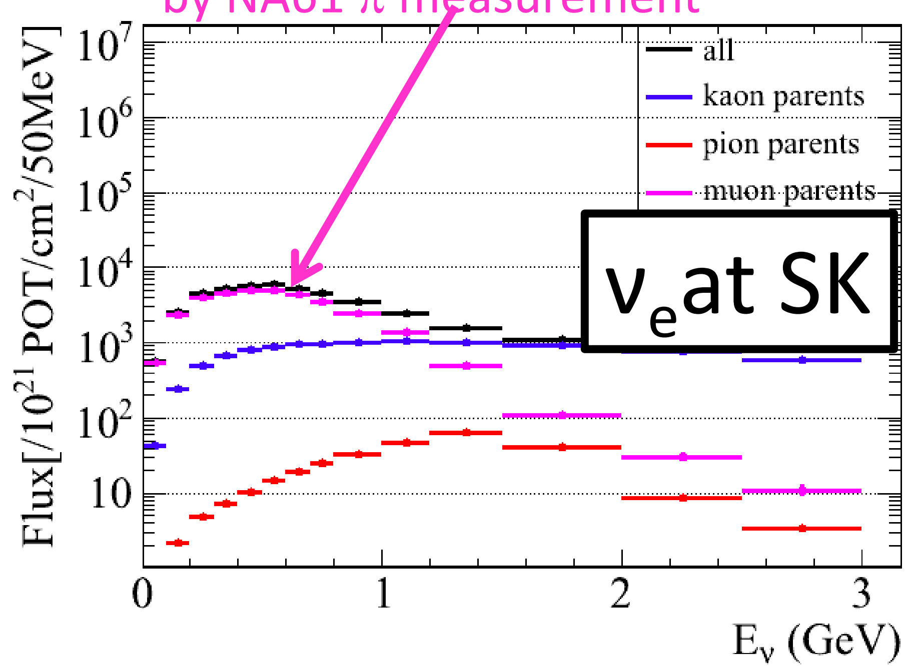
NA61/SHINE (@CERN) measured hadron production in (p, θ) using 30GeV protons and graphite target *

* π outside NA61 acceptance and production modeled with FLUKA

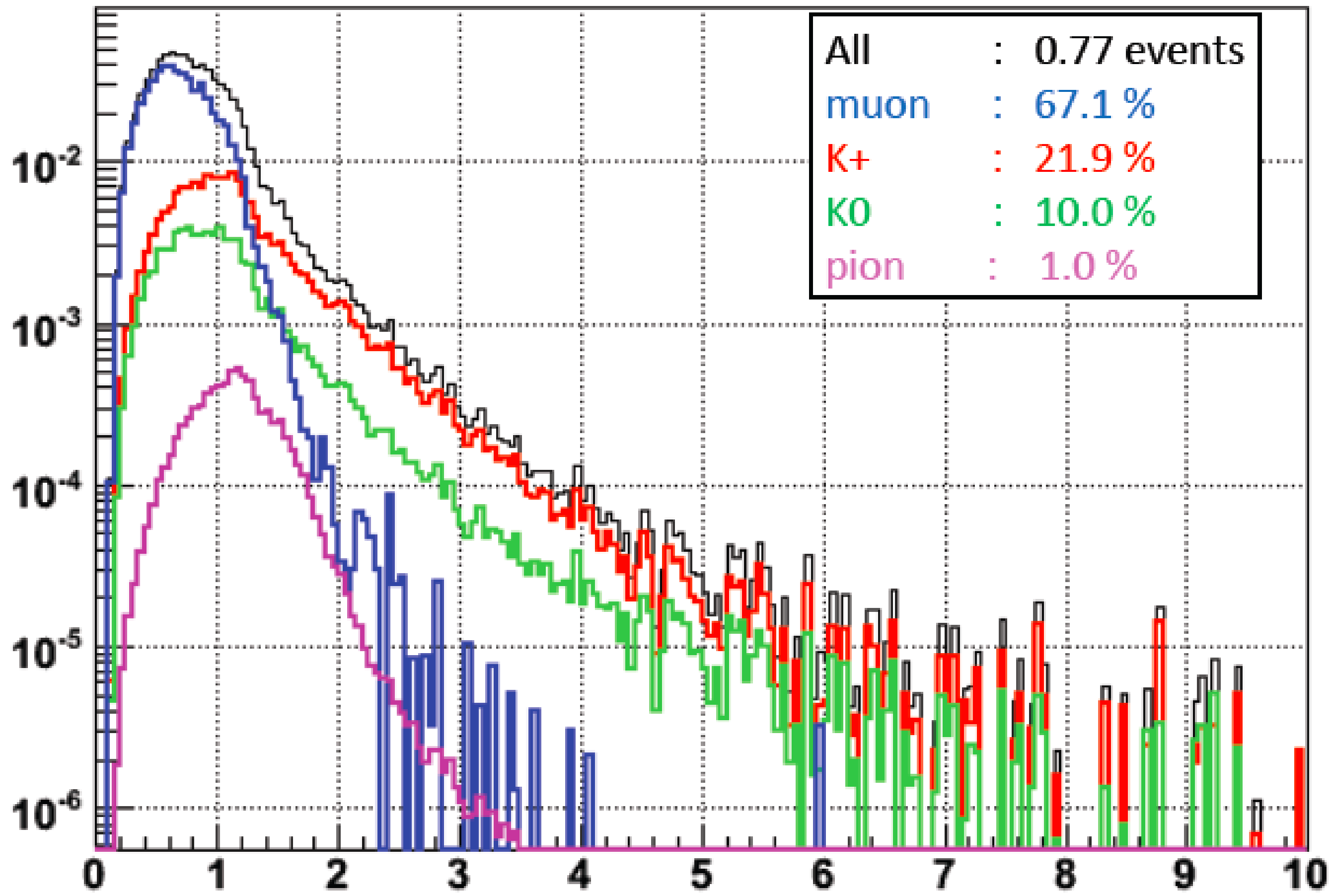


ν_e of μ decay is due to π decay
→can accurately be predicted by NA61 π measurement





SK nue BKG by beam nue

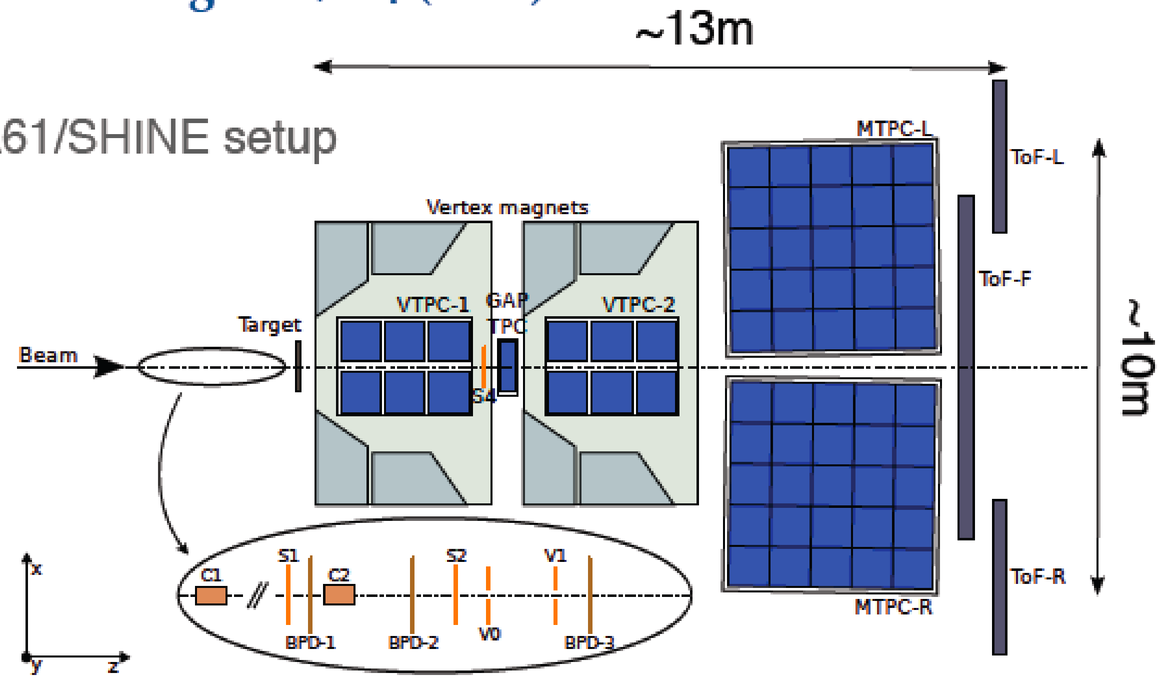


CERN NA61/SHINE measurement

Measure hadron(π, K) yield distribution in
30 GeV p + C inelastic interaction

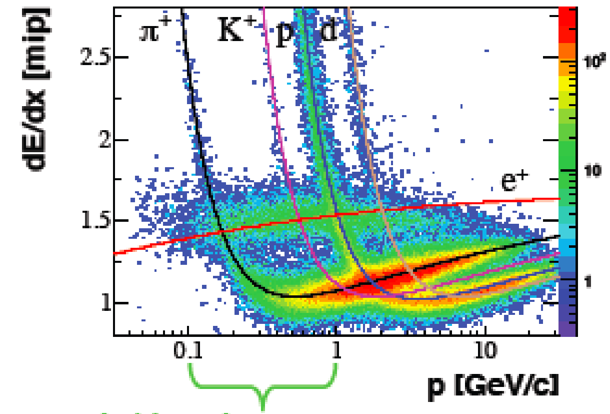
- thin target 4%λ_I (2cm)

NA61/SHINE setup



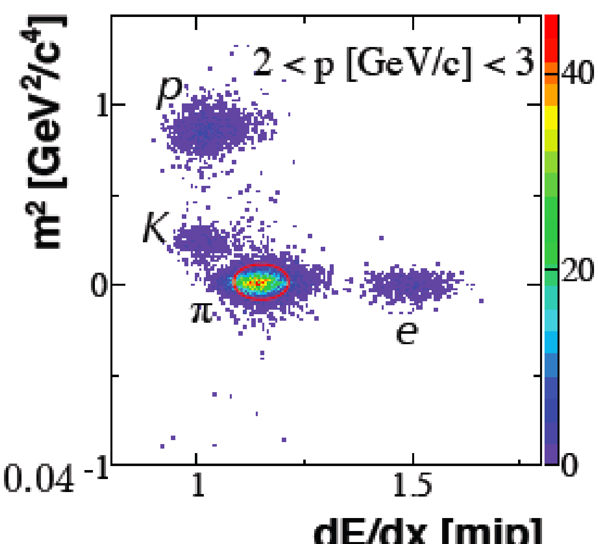
Large acceptance spectrometer + TOF

π^+ production: Two analysis for different momentum region



dE/dx at low momentum

dE/dx + ToF



detector performance

$\sigma(p)/p^2 \approx 2\times10^{-3},\ 7\times10^{-3},\ 3\times10^{-2}(\mathrm{GeV/c})^{-1}$

for $p > 5,\ p = 2,\ p = 1$ GeV/c

$\sigma(\mathrm{dE/dx})/\langle\mathrm{dE/dx}\rangle \approx 0.04$

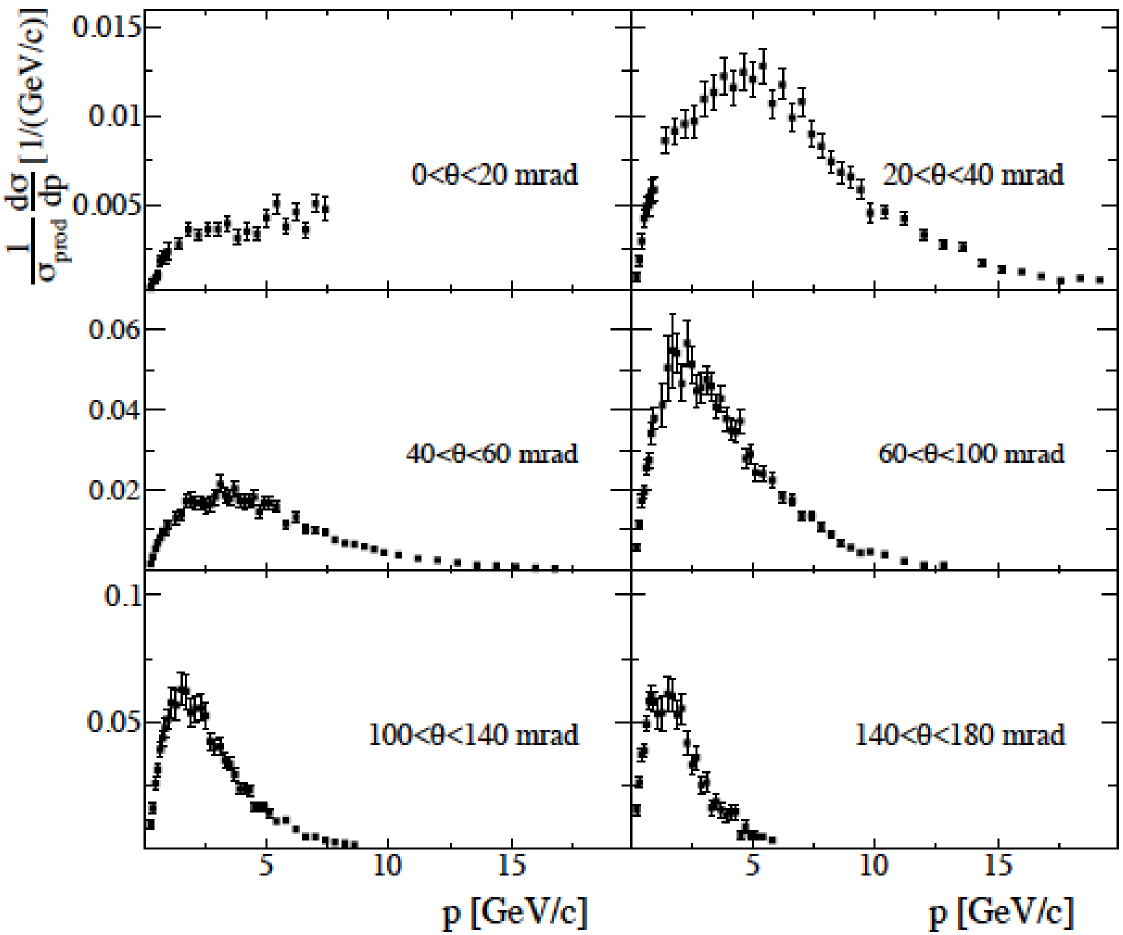
$\sigma(\text{TOF-F}) \approx 115$ ps

Results of pion production from thin target (2007 data)

N.Abgrall et al., arXiv:1102.0983 [hep-ex]
submitted to Phys.Rev.C (2011)

Differential cross section for π^+ production in 30GeV p+C

Error bars = stat. + syst. in quadrature



Systematic uncertainty was evaluated in each (p,θ) bin

typically 5-10%

The normalization uncertainty is 2.3% on the overall (p,θ)

→ *Propagate the systematic uncertainty in each (p,θ) bin into the expected number of events in T2K*

→ Input to T2K neutrino beam simulation

Near future operation plan of MR-FX

Periods	Expected beam power	Improvements / Cycle time
2011. 6-11	shutdown	Ring collimator shields, 7th and 8th RF systems, New injection kicker
2011. 12 - 2012. 6	100 - 200 kW (RCS 300 kW eq.)	Cycle time 3.2 -> 2.56 Beam loading compensation
2012. 7 – 9	shutdown	Ring collimator upgrade (0.45 -> 2 kW) 9th RF system
2012. 10 – 2013. 7	> 200 kW (2012.10~) (RCS 300-400 kW eq.)	Cycle time 2.48 -> 2.4 s Second harmonic cavities
2013. 8 – 2013. 1	shutdown	Ring collimator upgrade (2 kW -> 3.5 kW) Linac upgrade
2014. 2 – 2014. 6	> 300 kW (RCS > 600 kW eq.)	Cycle time 2.4 s

Koseki @ HK open meeting

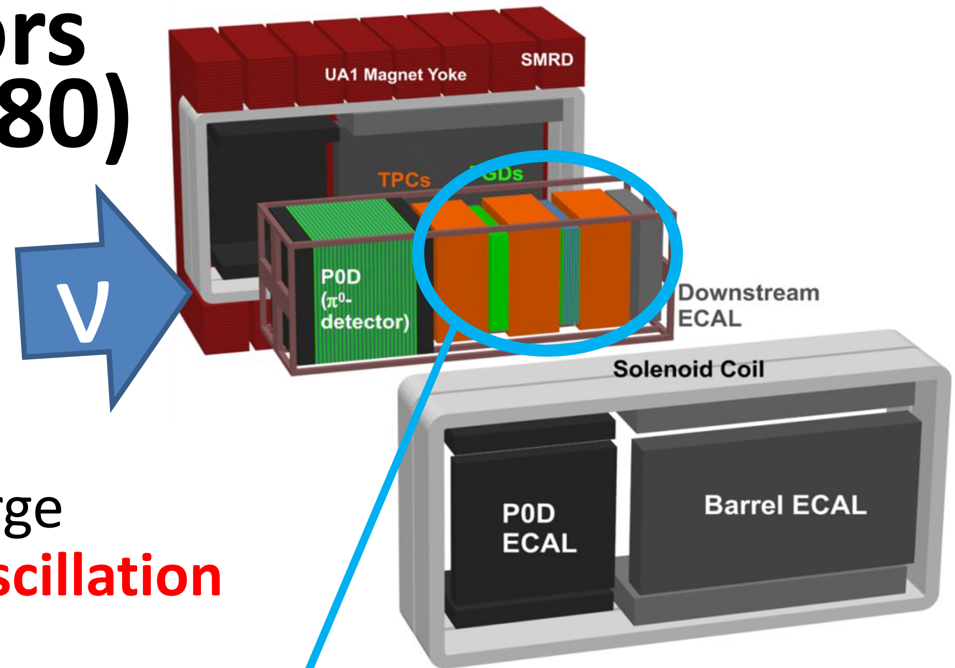
http://indico.ipmu.jp/indico/getFile.py/access?contribId=13&sessionId=3&resId=0&materialId=slides&confId=7

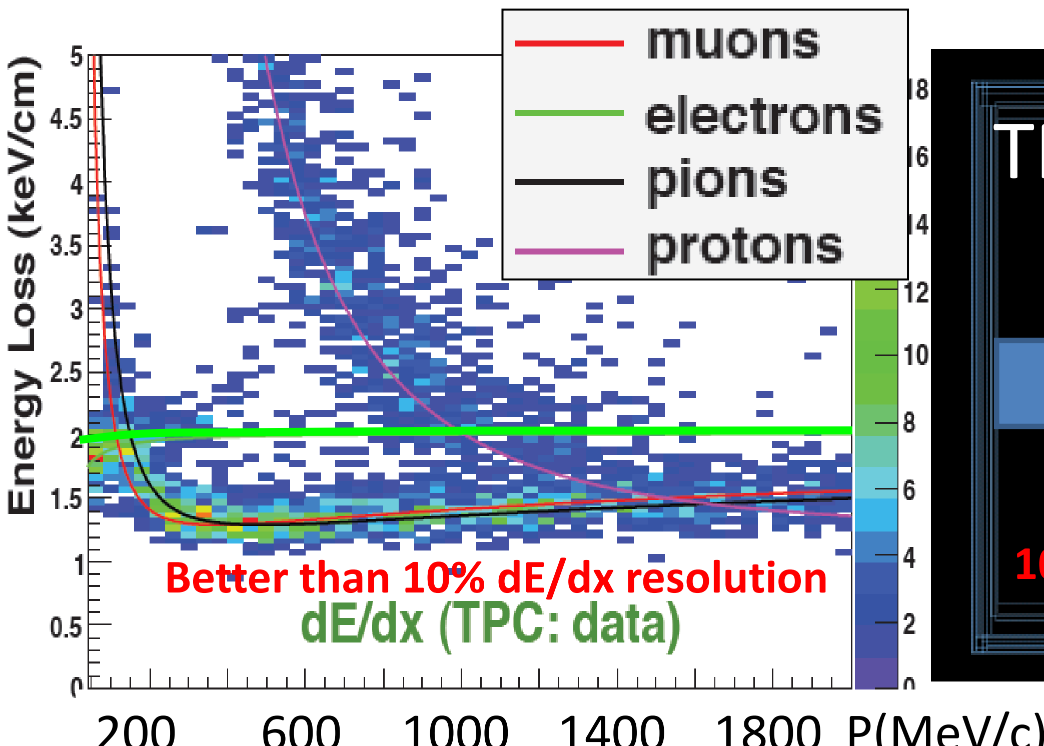
ND280

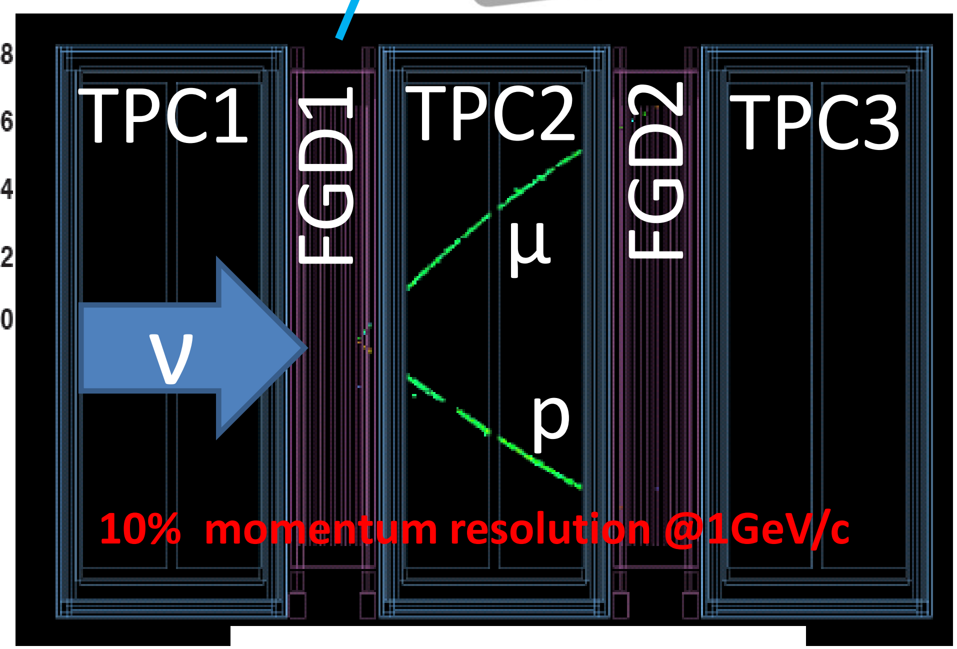
Off-axis Near Detectors (ND280)

In present analysis,
- 2 fine grained detectors (FGDs)
  - Active target
  - 1.6t fiducial mass
- 3 time projection chambers (TPCs)
  - PID(by dE/dx), Momentum, Charge

Measure ν flux/spectrum before oscillation



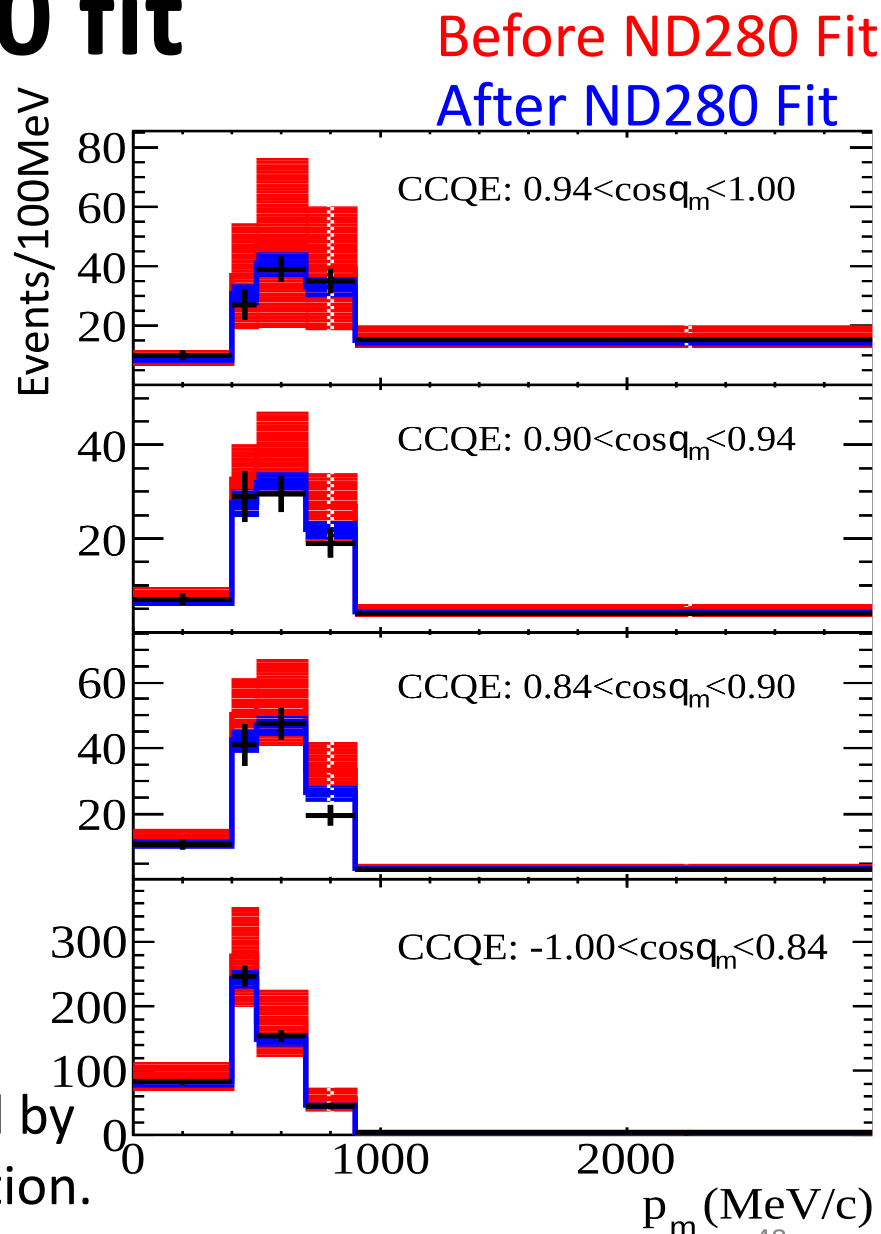




Event Display (DATA)

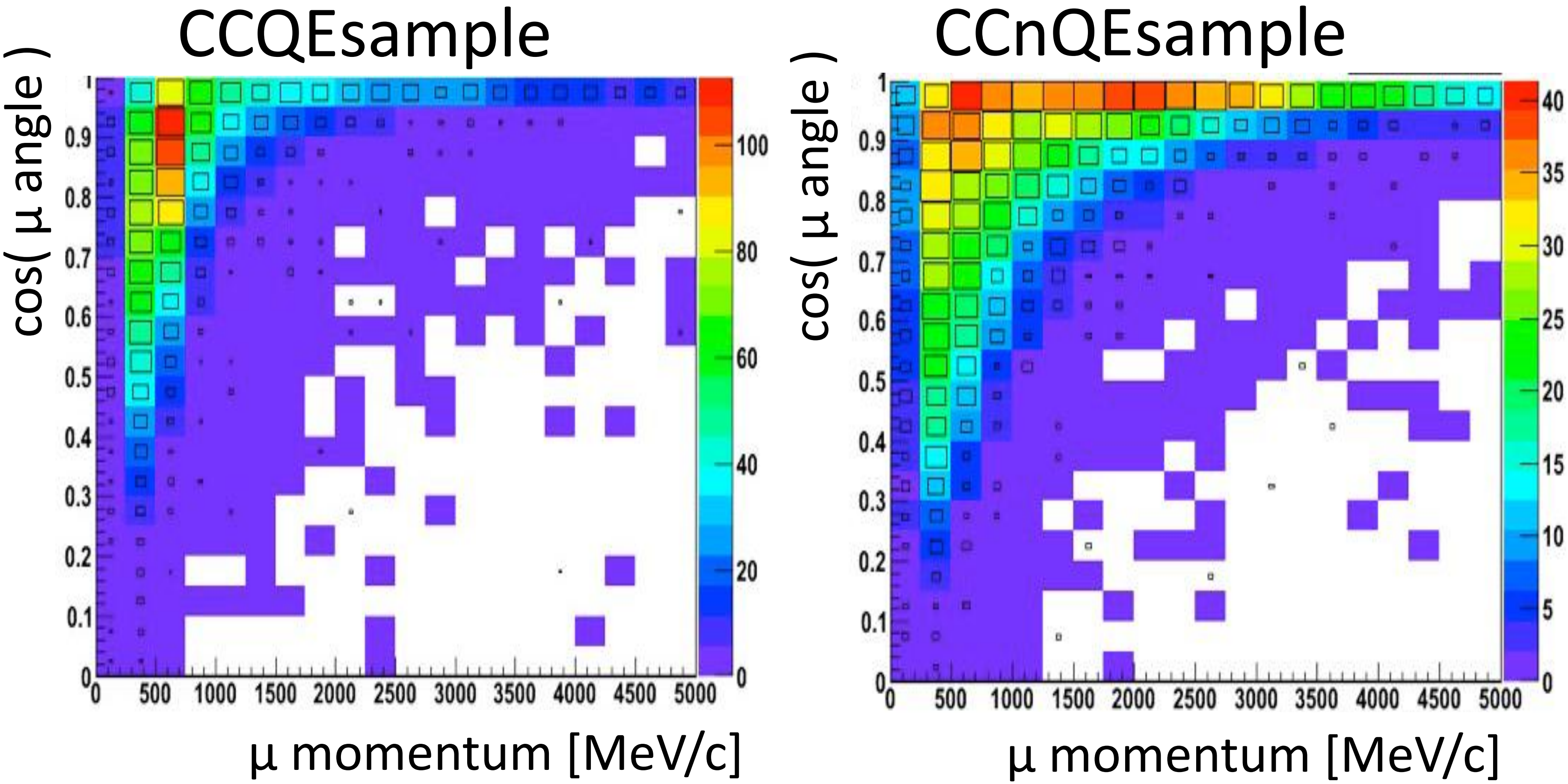
Constrain by ND280 fit

Cross section param.	Before ND280 Fit	After ND280 Fit
Axial Mass for QE (GeV)	1.21±0.45	**1.19±0.19**
Axial Mass for Resonance (non QE)(GeV)	1.16±0.11	**1.14±0.10**
CCQE Norm 0-1.5Gev	1.00±0.11	**0.94±0.09**
CC1π Norm 0-2.5 GeV	1.63±0.43	**1.67±0.28**
NC1π0 Norm.	1.19±0.43	**1.22±0.40**



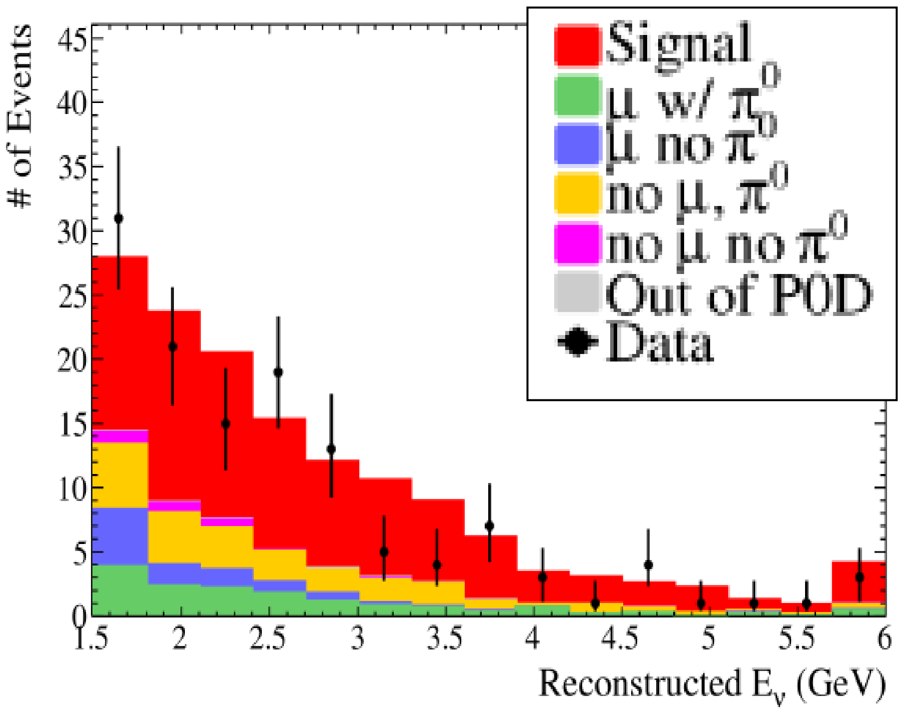
Cross section parameters are constrained by ND280 data! They are used for SK prediction.

p_μ,θ@ND280 Color : MC,Box:Data



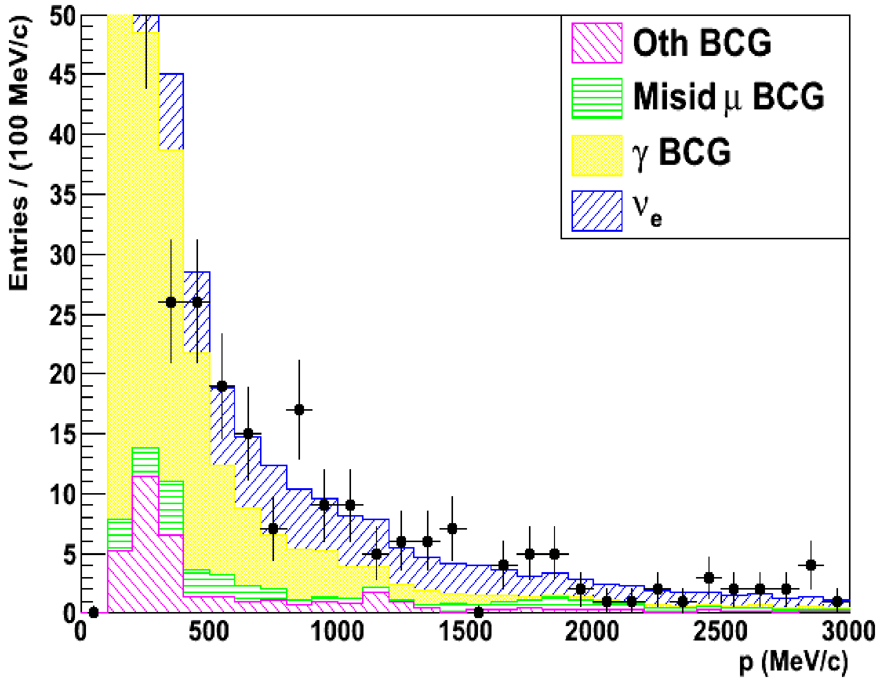
Beam ν_e measurement

POD



- Only one shower like track
- Energy threshold 1.5GeV

TPC+FGD+ECAL



- Largest negative track from FGD
- Largest track is e-like

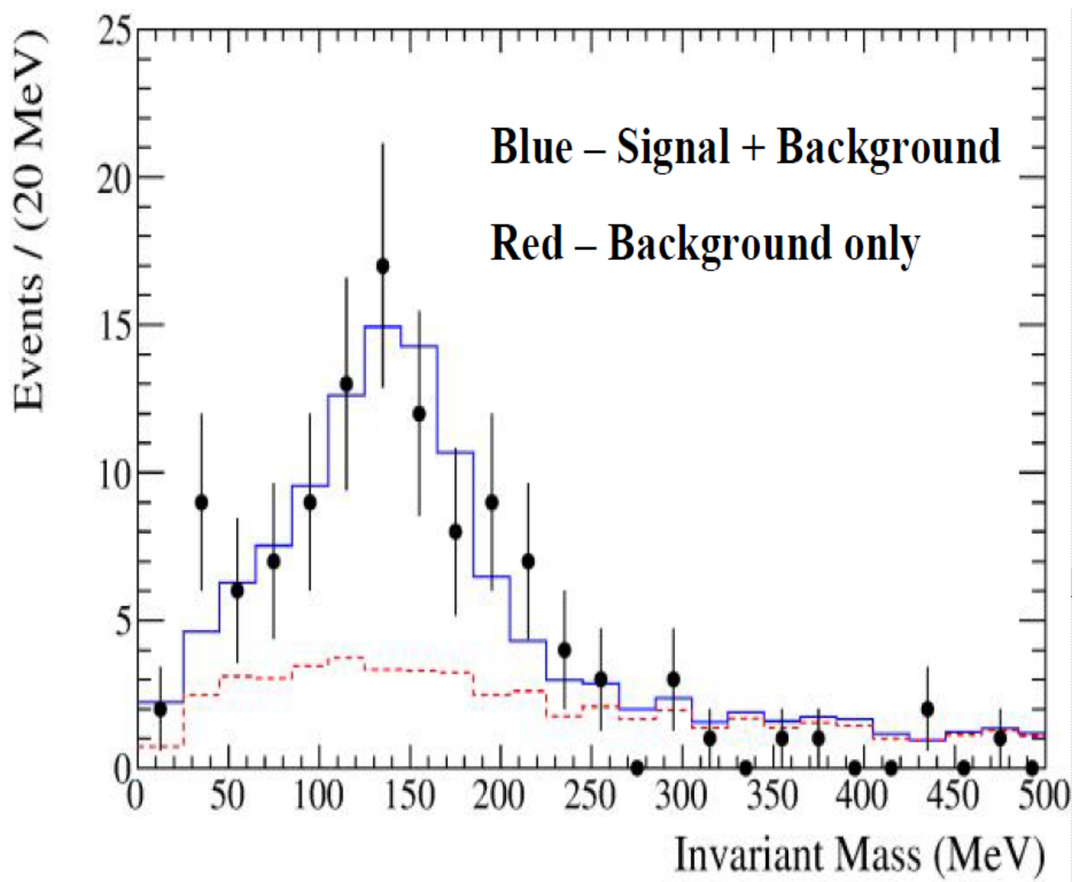
(TPC de/dx, and Ecal shower like)

MC consistents with data

POD NCπ^0 measuremsnt

- Main BG for nue appearance at SK

Selection
- no μlike track
- 2 shower like track
- no μ-decay electron
- Forward tracks
- Track distance > 5cm

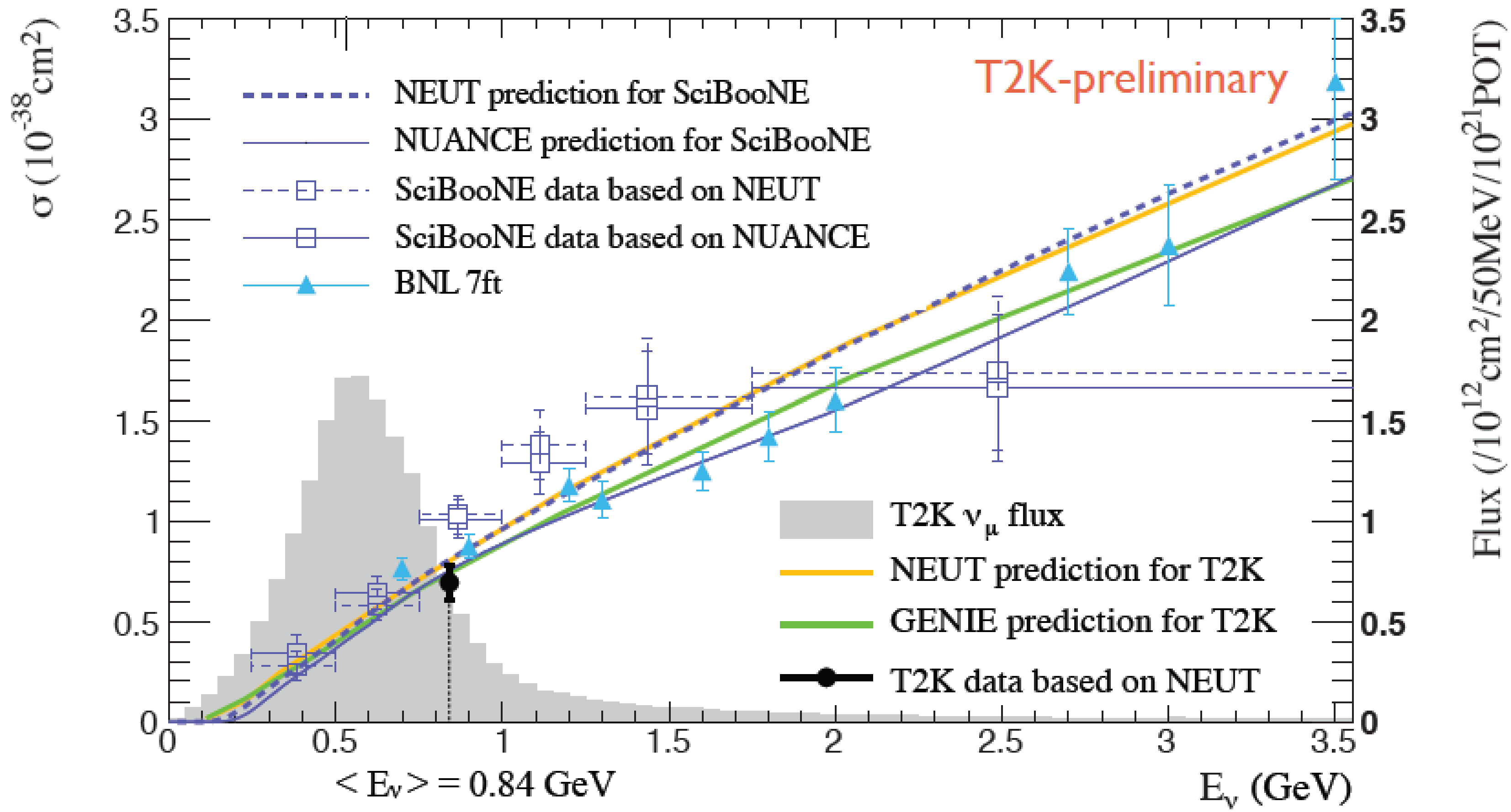


Data/MC =
0.84 ± 0.16 (stat)
± 0.18(sys)

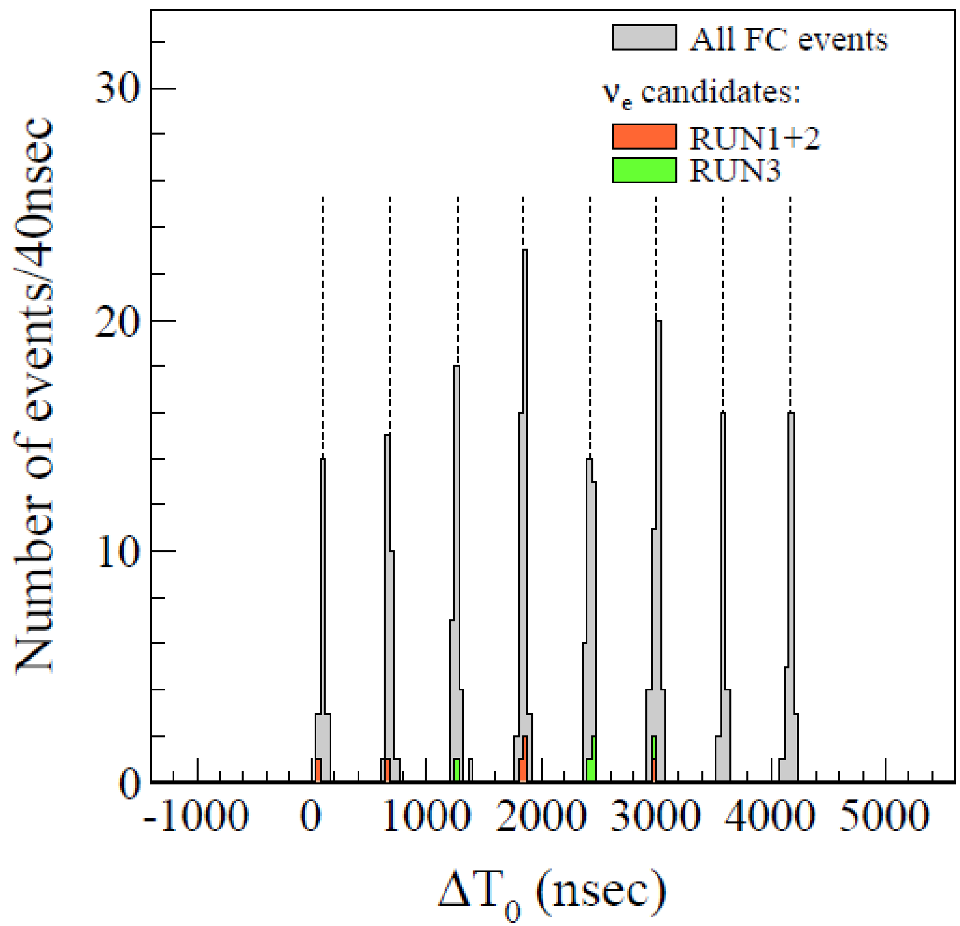
MC consistent with data

CC Inclusive cross section

$$\langle \sigma_{CC} \rangle_\phi = (6.93 \pm 0.13(stat) \pm 0.85(syst)) \times 10^{-39} \frac{\mathrm{cm}^2}{\mathrm{nucleons}}$$



SK

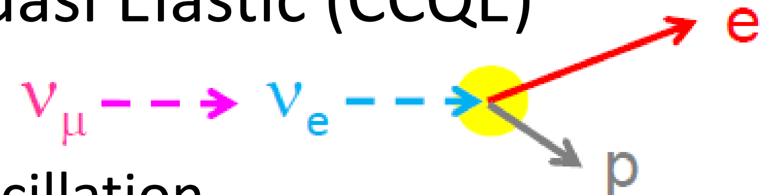


All FC events
ν_e candidates:
RUN1+2
RUN3
Number of events/40nsec
30
20
10
0
-1000
0
1000
2000
3000
4000
5000
ΔT_0 (nsec)

ν_e signal and background at Super-K

- Signal: Single electron event
  - Mainly Charged Current Quasi Elastic (CCQE)

    : $\nu_e + n \rightarrow e^- + p$

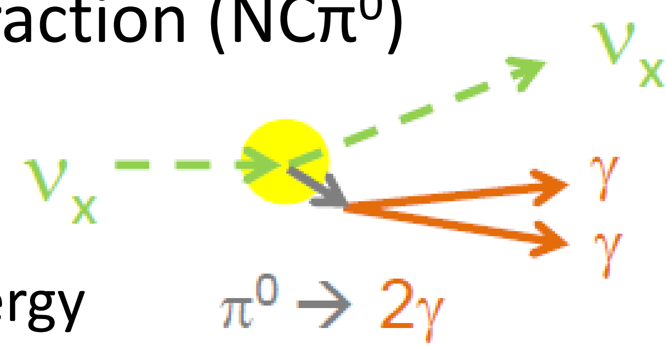


Oscillation

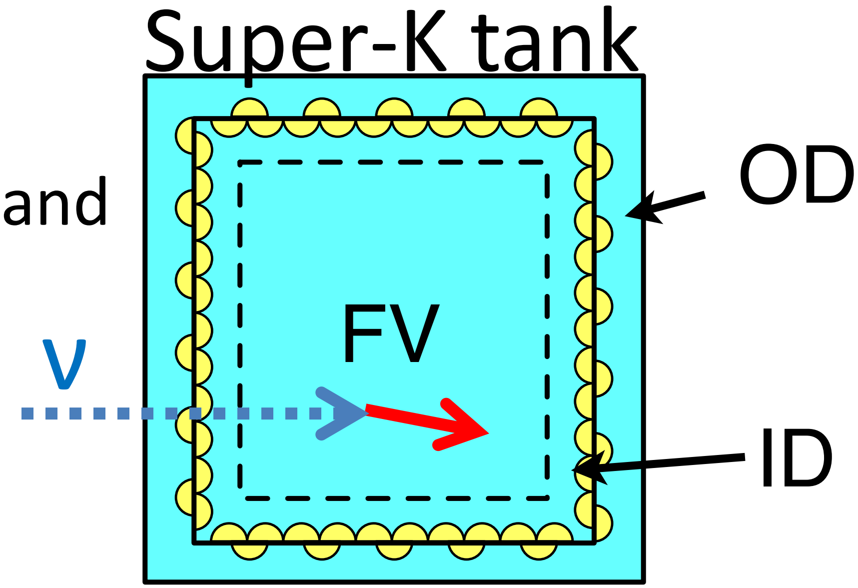
Proton is below Cherenkov Threshold

- Main background:
  - intrinsic ν_e (estimated from beam MC)
  - π^0 from Neutral Current interaction ($NC\pi^0$)
    - Overlap of 2γs
    - Missing out on 1γ

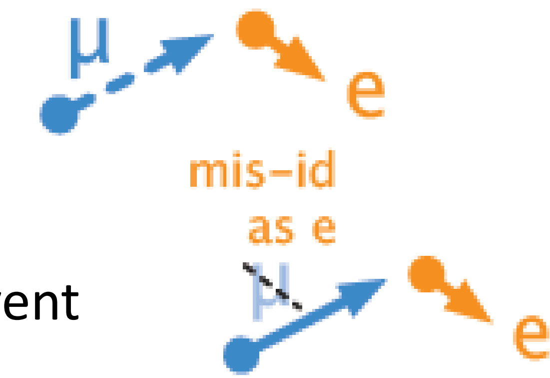
    when one of γ has very low energy



νe appearance

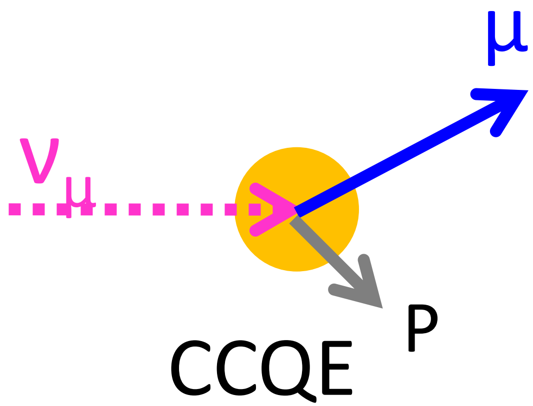


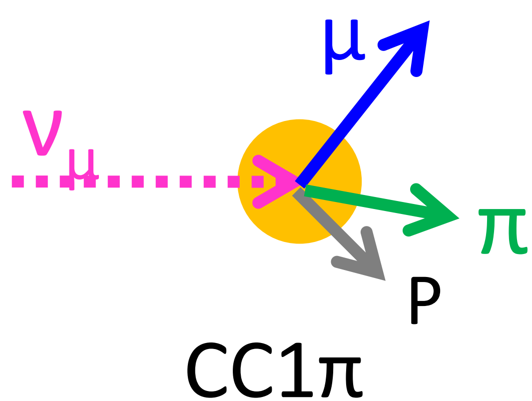
1. Events in the T2K beam timing and fully contained (FC) in ID
2. Fiducial volume cut
3. Single electron cut
   - Number of ring = 1 and e-like event
4. Visible energy > 100 MeV
   - Rejects low energy NC events and electrons from invisible μ, π decays
5. No decay electron
   - To eliminate non-CCQE, miss identified μ event
6. Invariant mass < 105 MeV
   - To eliminate NC π^0 background
7. Reconstructed energy (assuming CCQE) < 1250MeV



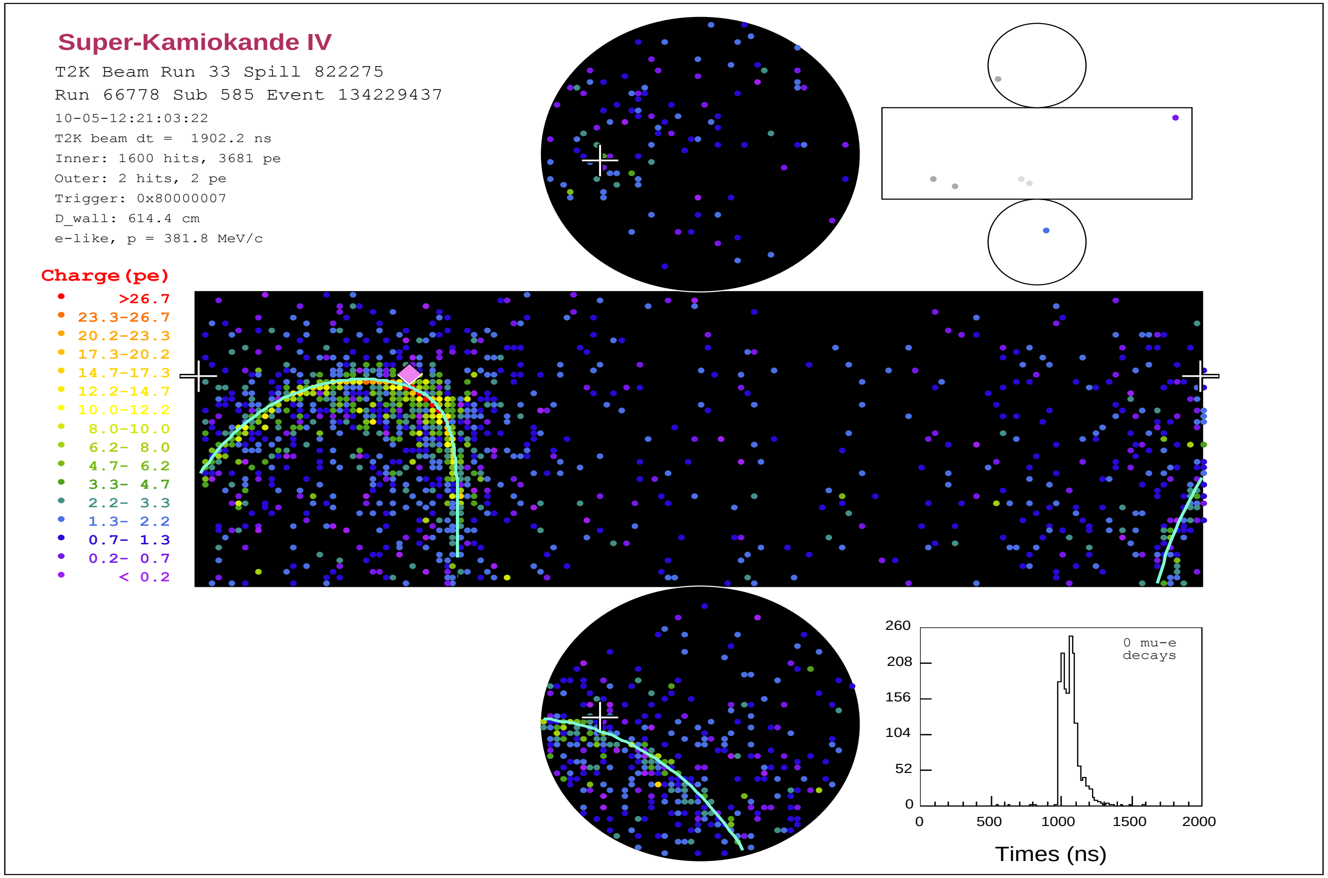
ν_μ disappearance

- Signal: Single μ event
  - CCQE enriched sample for energy spectrum measurement.
- Background:
  - CC non-QE (ex. CC1π, etc.)
- Selection criteria
  - T2K beam timing & FCFV
  - Single ring μ-like event
  - less than 2 decay electron (to reduce CC non-QE)
  - Reconstructed μ momentum > 200 MeV/c

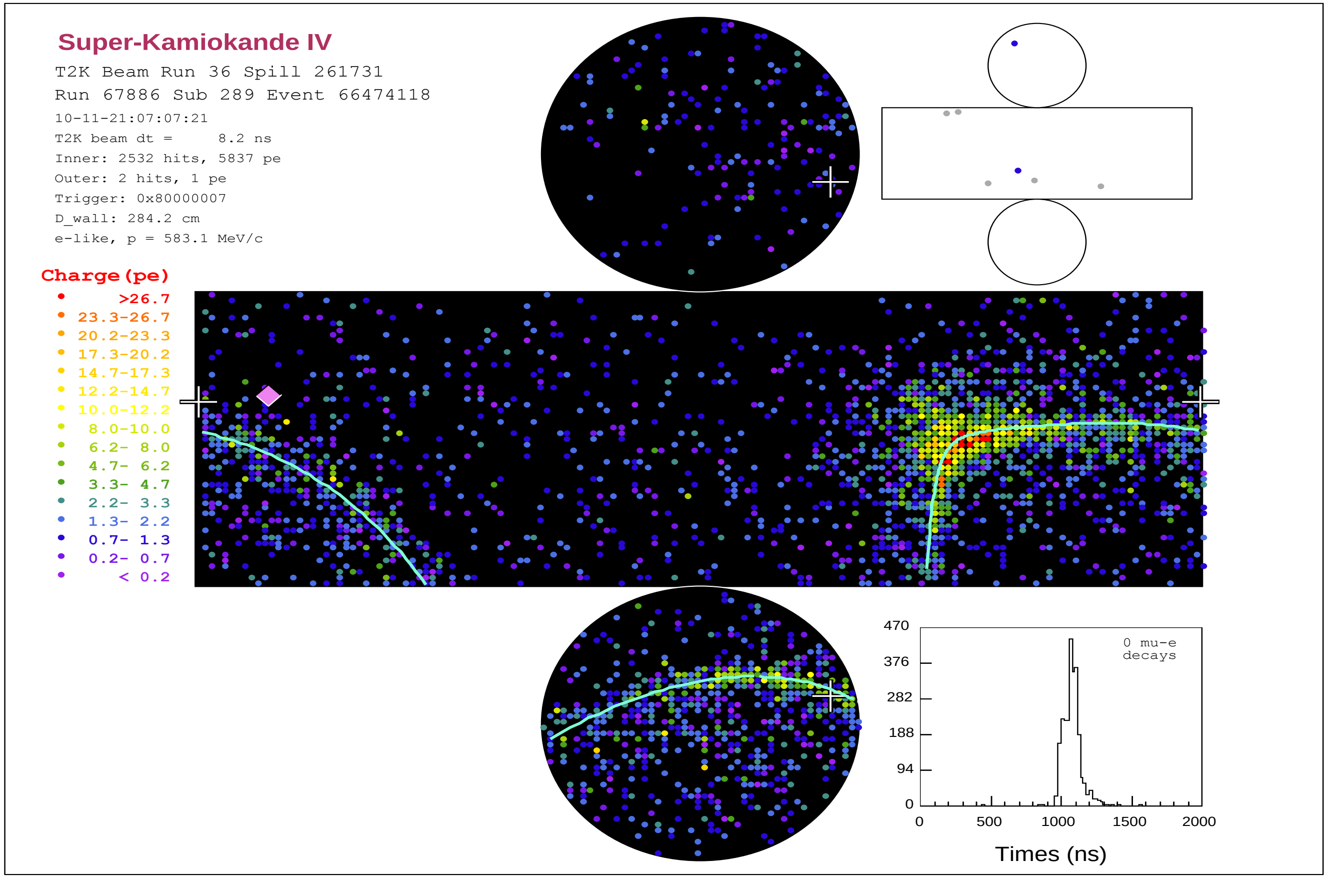




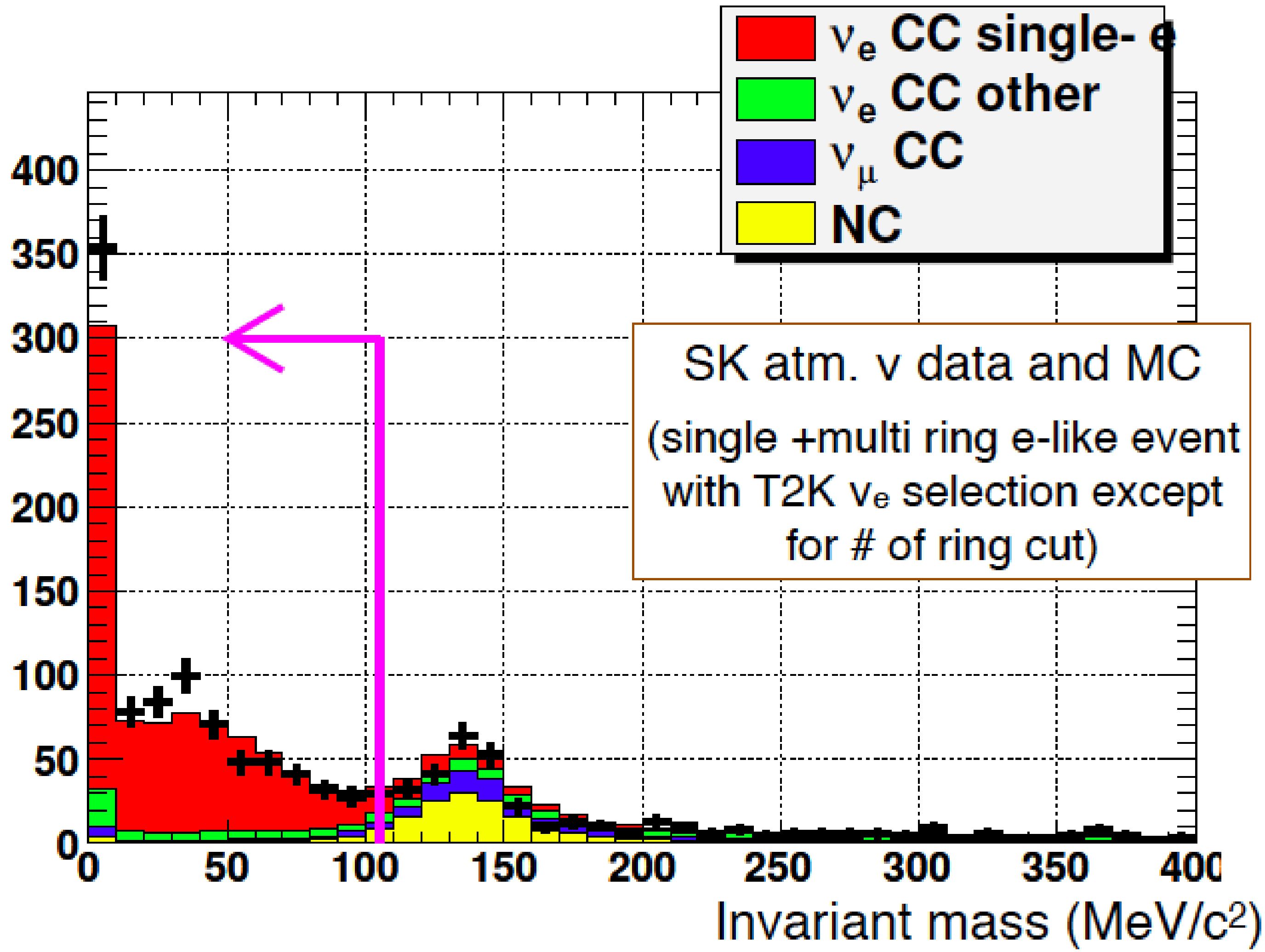
Observed ν_e candidate event (No.1)



Observed ν_e candidate event (No.2)



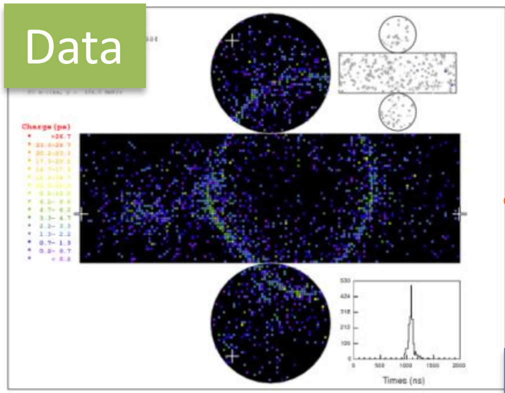
demonstrate to reconstruct invariant mass using atmospheric ν data



Systematic error on ν_e event selection at SK

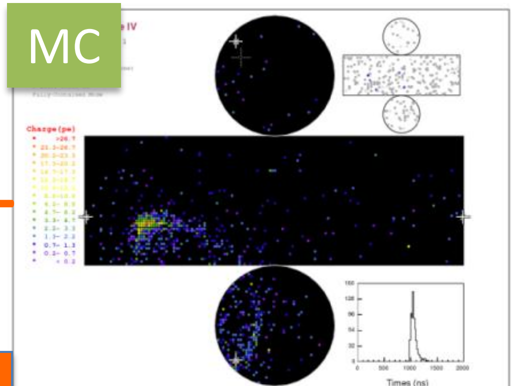
- Evaluation using various control samples (atm ν, cosmic μ, ...)
- An example : NC1π^0 rejection efficiency

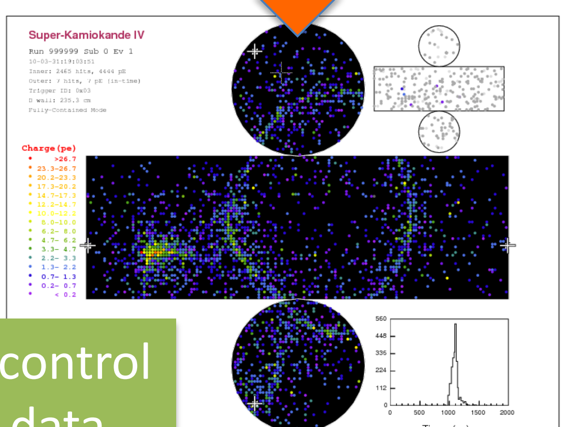
Data



+

MC

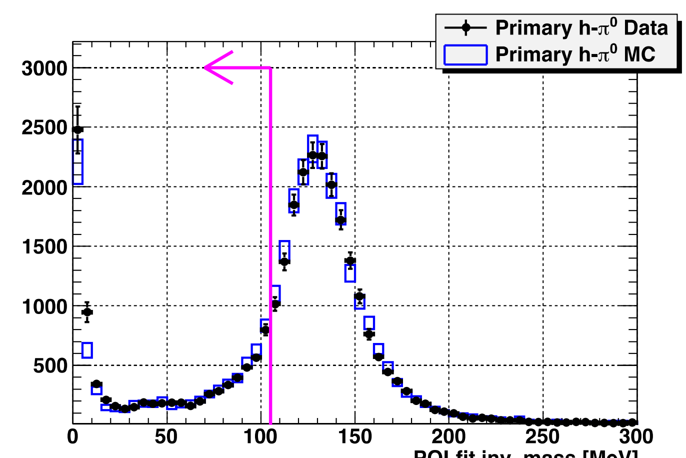




Hybrid control sample data

Real data electron ring (atm ν, ...)
+ MC simulation γ ring

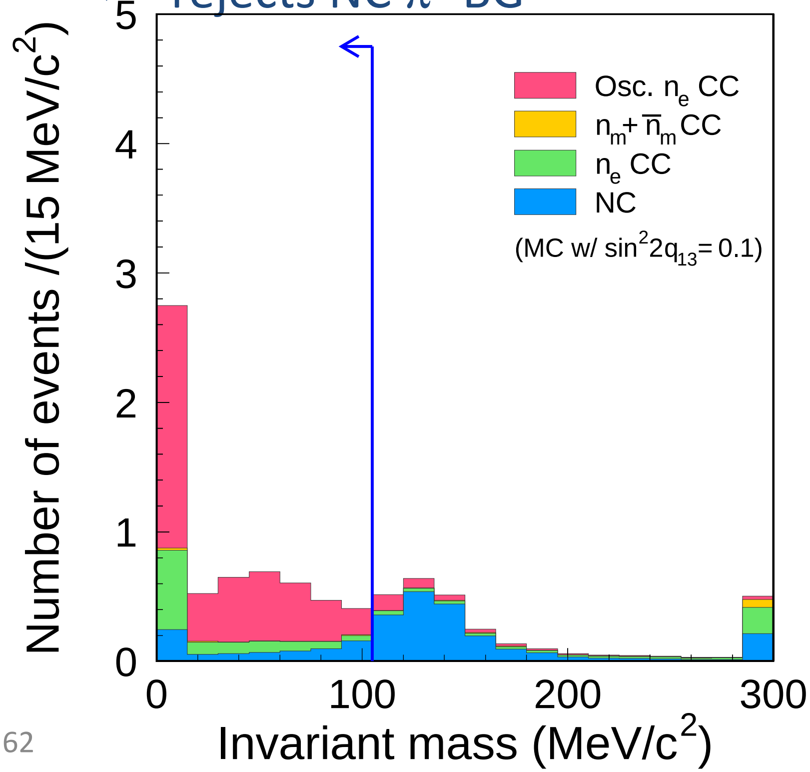
- ✓ can produce the control sample w/ same topology as T2K NC1π^0
- ✓ compare the cut efficiency btw control sample data and its MC



ν_e event selection at SK (cont'd)

6.Invariant mass of 2 γ rings forced to be found by the special fitter < 105MeV/c^2

✓ rejects NC π^0 BG



7. Reconstructed ν energy < 1250MeV

✓ rejects intrinsic beam ν_e at high energy

After applying all criteria

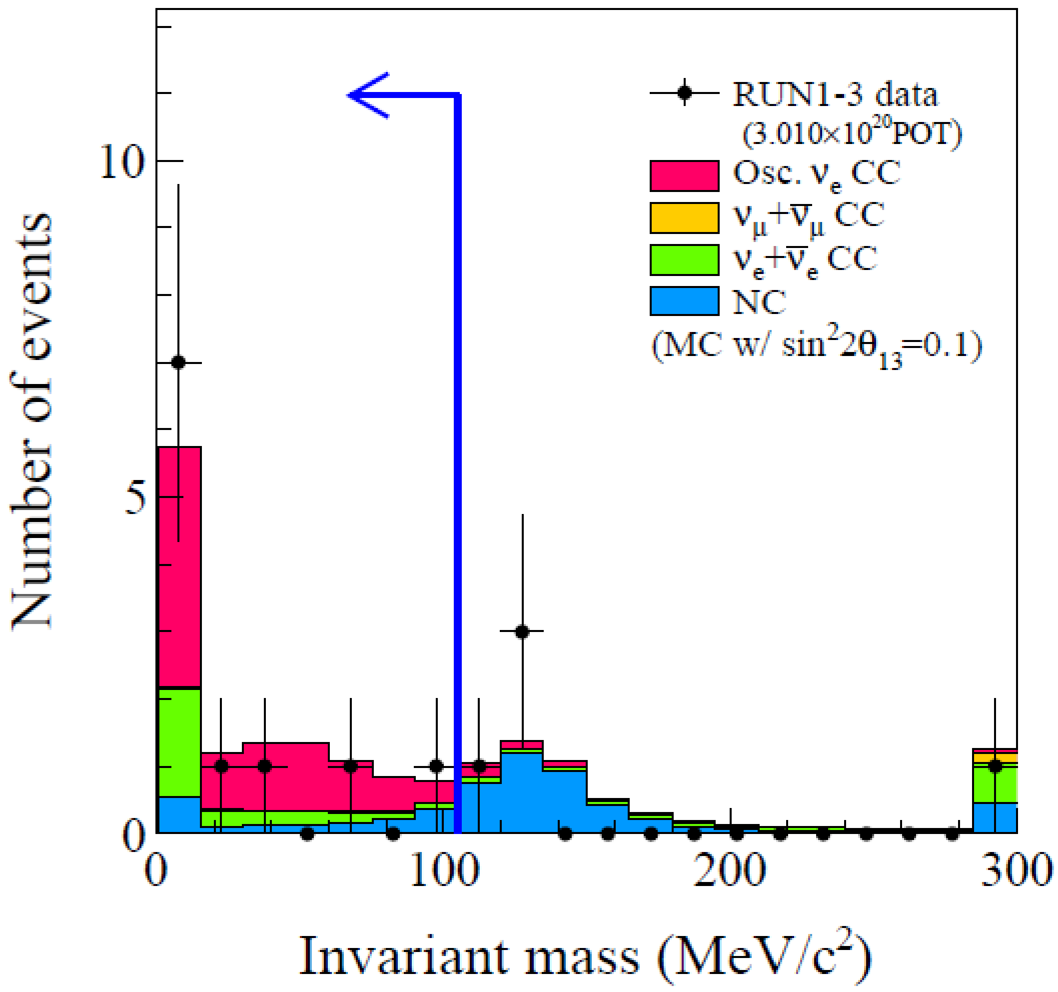
BG rejection :

- >99.9% for ν_μCC
- 77% for intrinsic beam ν_eCC
- 99% for NC

Signal efficiency :

- 66% for $\nu_\mu \rightarrow \nu_e$CC

Pi0 mass cut



RUN1-3 data
(3.010×10^20 POT)
Osc. νe CC
νμ+ν̄μ CC
νe+ν̄e CC
NC
(MC w/ sin²2θ13=0.1)
Number of events
Invariant mass (MeV/c²)
0
5
10
0
100
200
300

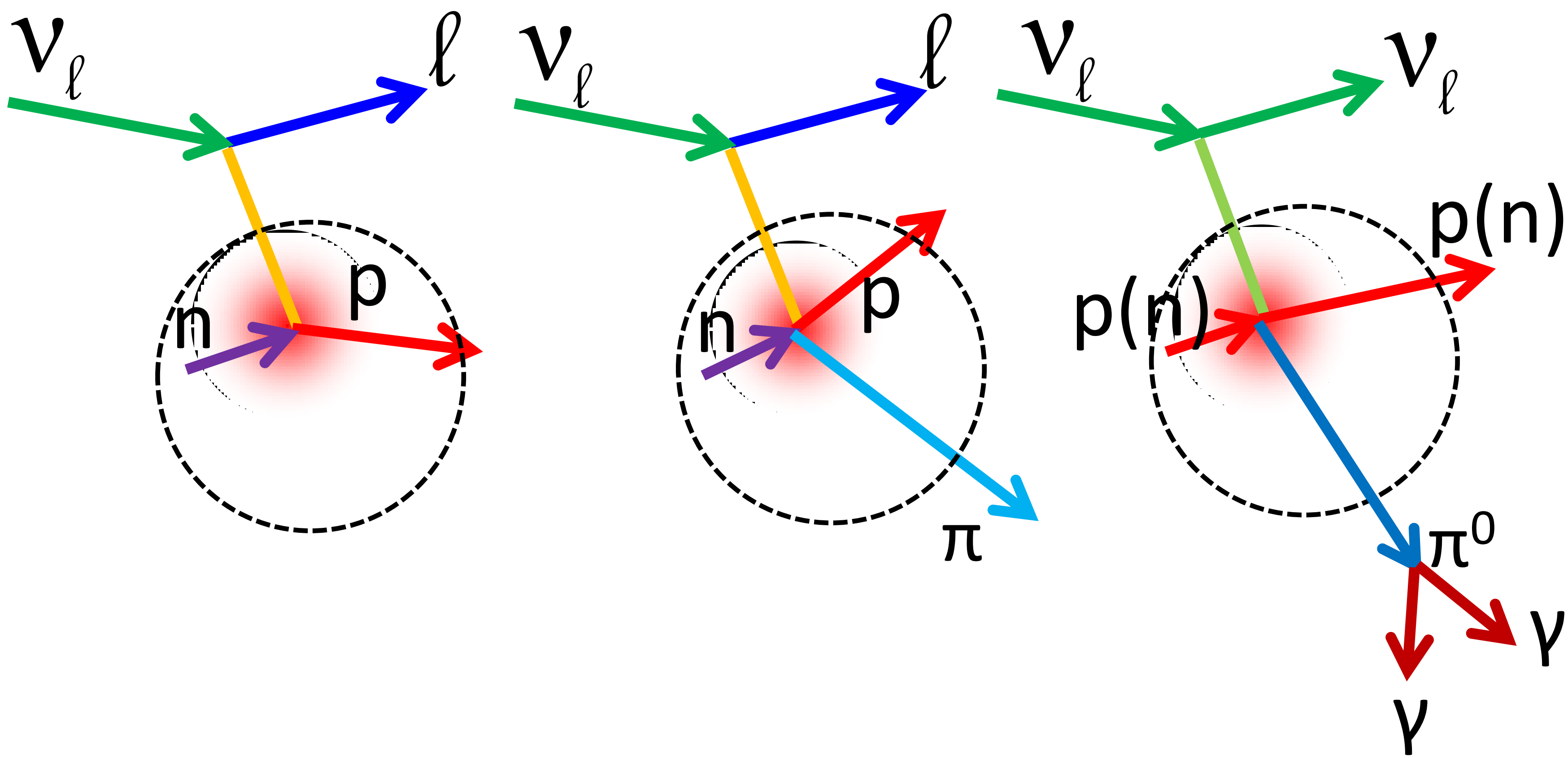
Neutrino oscillation analysis

Main nu cross section parameters

Charged Current
Quasi Elastic
(CCQE)

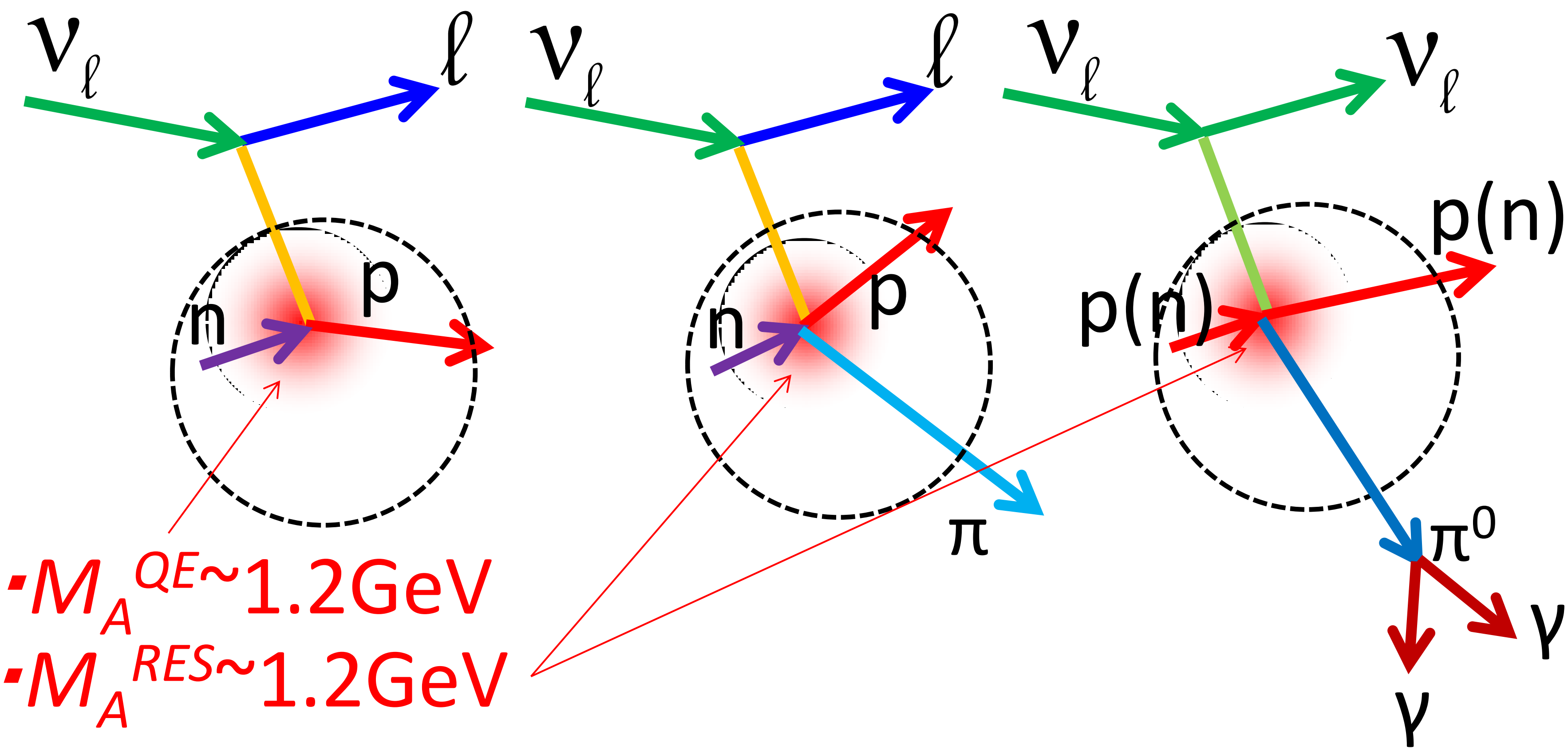
Charged Current
1 π production
(CC1π)

Neutral Current
1 π^0 production
(NC1π^0)



Main nu cross section parameters

Charged Current Quasi Elastic (CCQE)	Charged Current 1 π production (CC1π)	Neutral Current 1 π^0 production (NC1π^0)



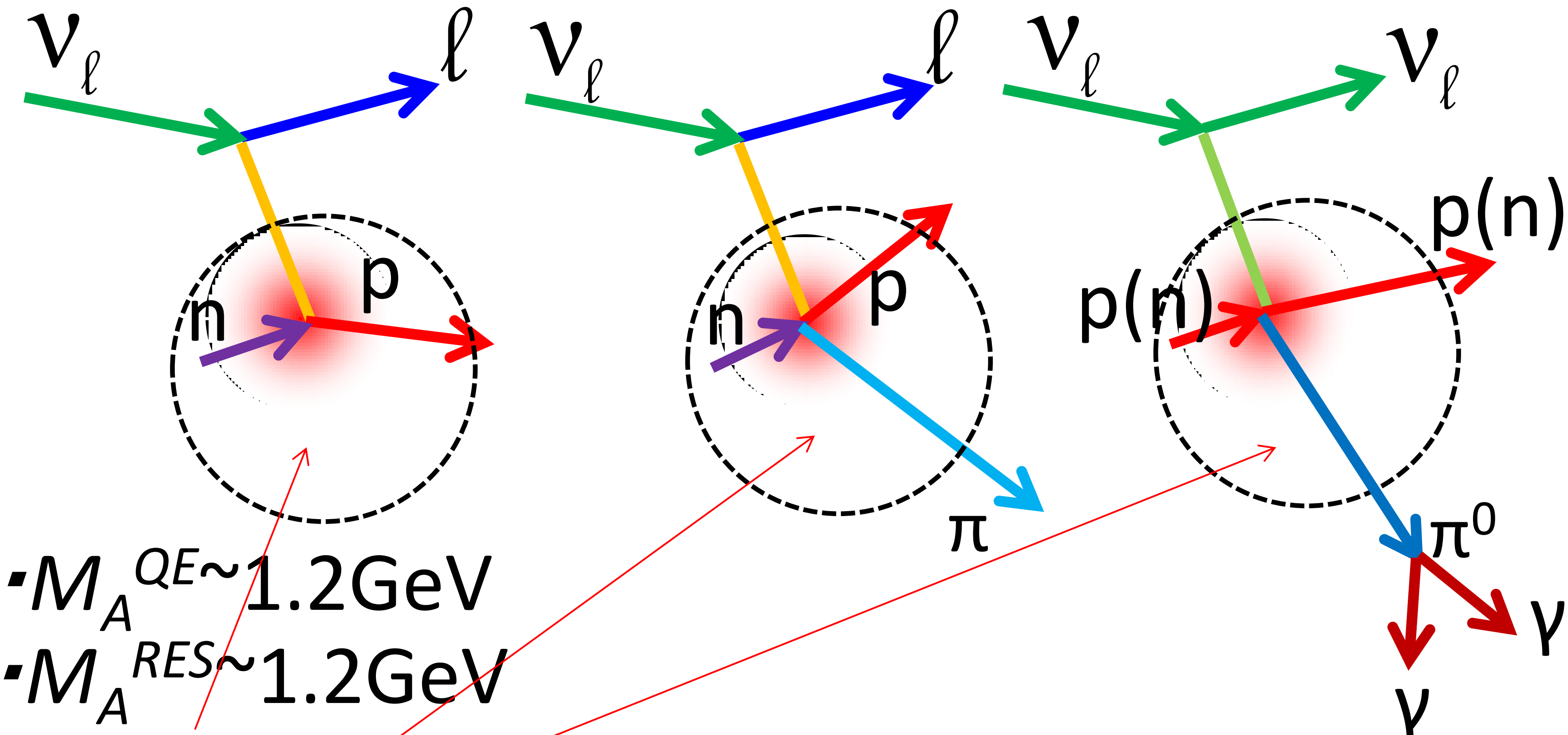
- M_A^{QE}~1.2GeV
- M_A^{RES}~1.2GeV

Main nu cross section parameters

Charged Current Quasi Elastic (CCQE)

Charged Current $1\ \pi$ production (CC1π)

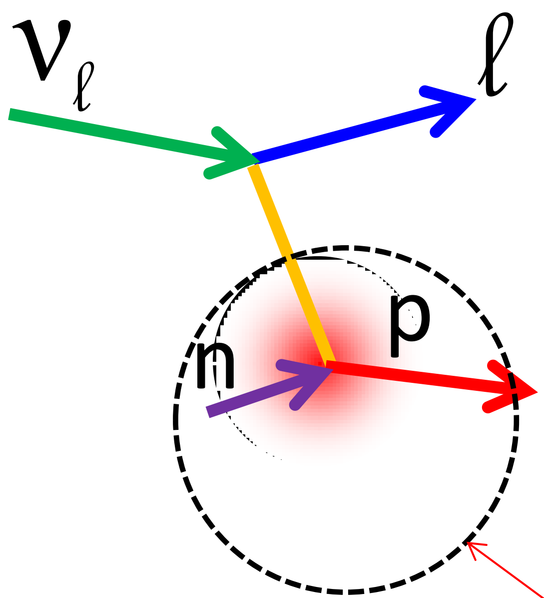
Neutral Current $1\ \pi^0$ production (NC1π^0)



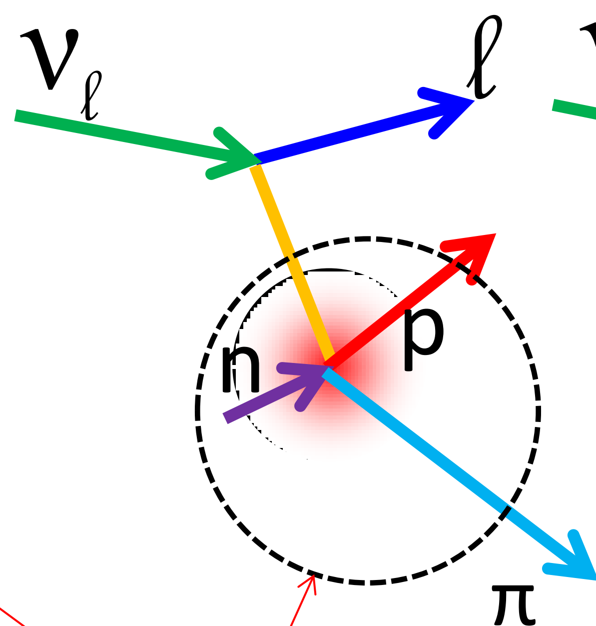
- M_A^{QE}~1.2GeV
- M_A^{RES}~1.2GeV
- p_F~200MeV/c

Main nu cross section parameters

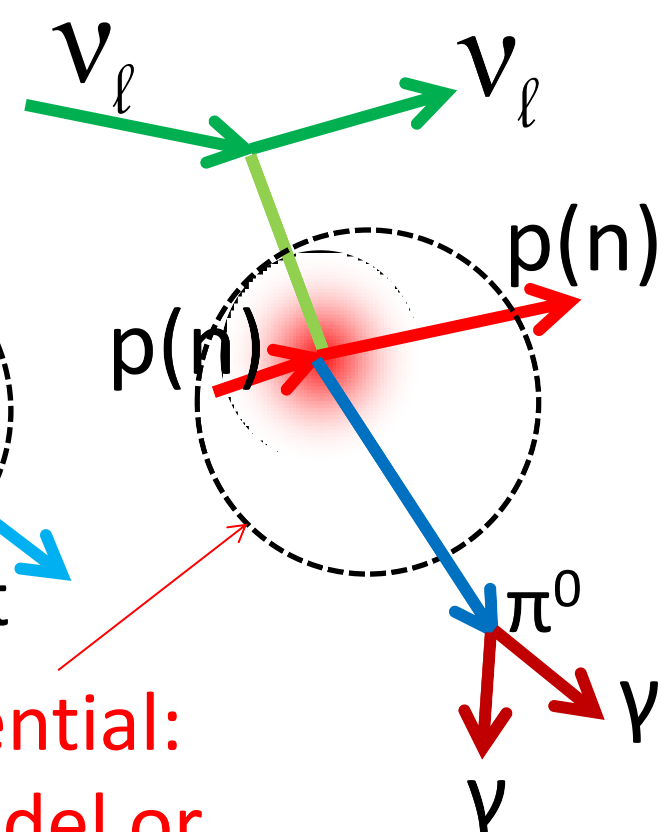
Charged Current Quasi Elastic (CCQE)



Charged Current 1 π production (CC1π)



Neutral Current 1 π^0 production (NC1π^0)



- M_A^{QE}~1.2GeV
- M_A^{RES}~1.2GeV
- p_F~200MeV/c

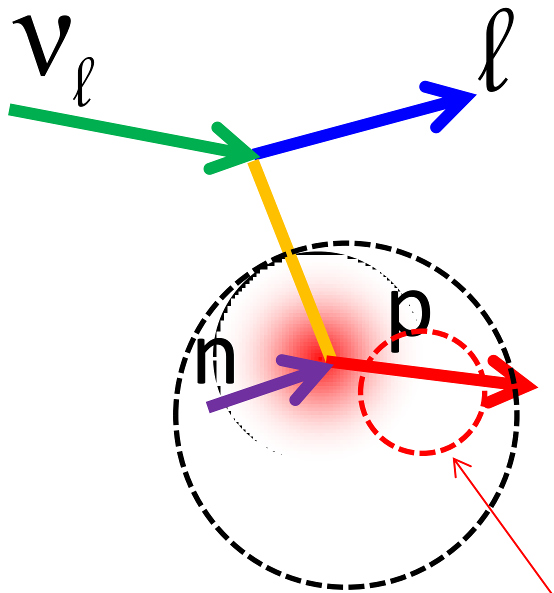
- Nuclear Potential: Fermi Gas Model or Spectral function

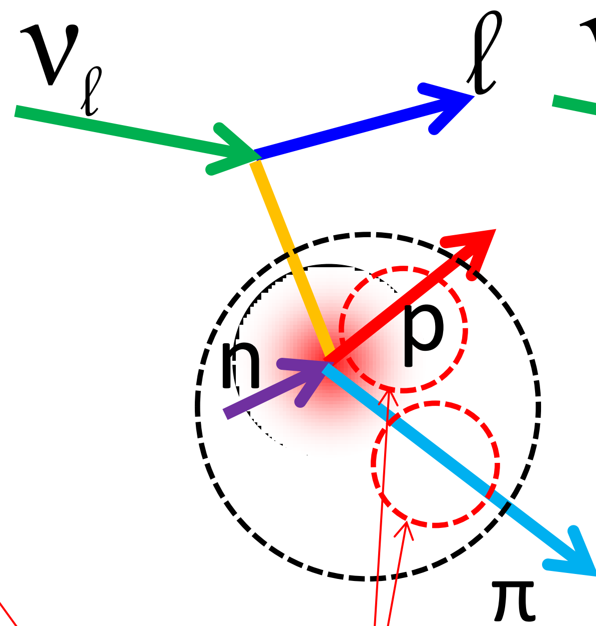
Main nu cross section parameters

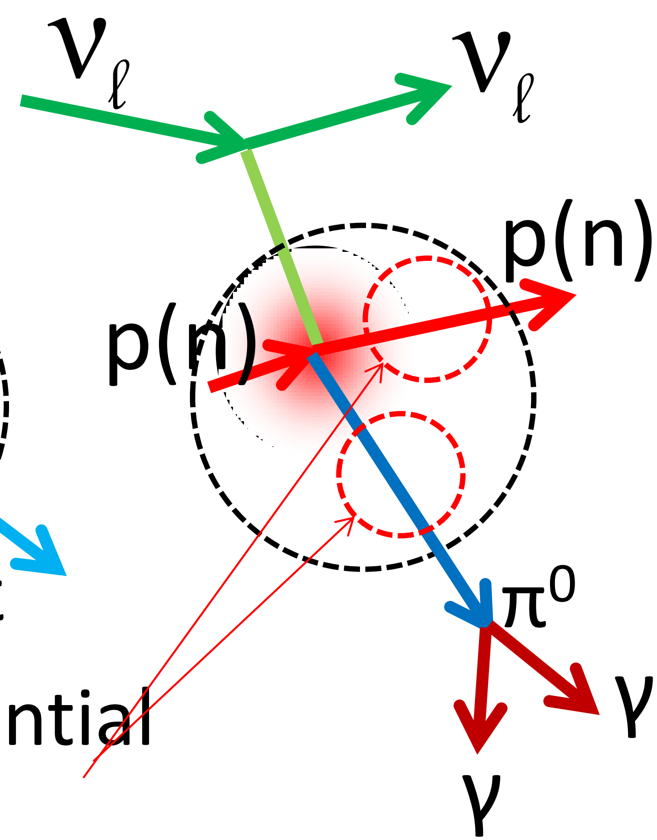
Charged Current Quasi Elastic (CCQE)

Charged Current $1\ \pi$ production ($CC1\pi$)

Neutral Current $1\ \pi^0$ production ($NC1\pi^0$)





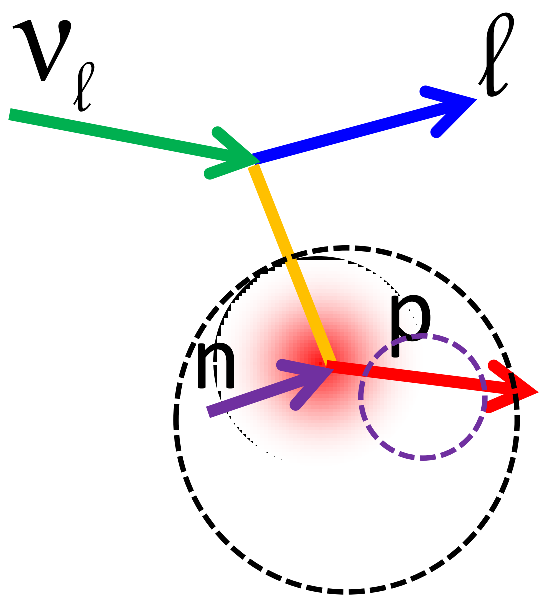


- M_A^{QE}~1.2GeV
- M_A^{RES}~1.2GeV
- p_F~200MeV/c

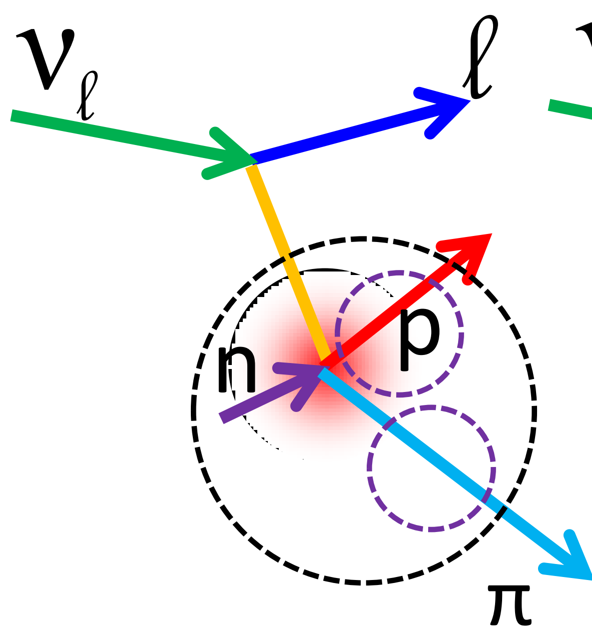
- Nuclear Potential
- Final State Interaction (FSI)

Main nu cross section parameters

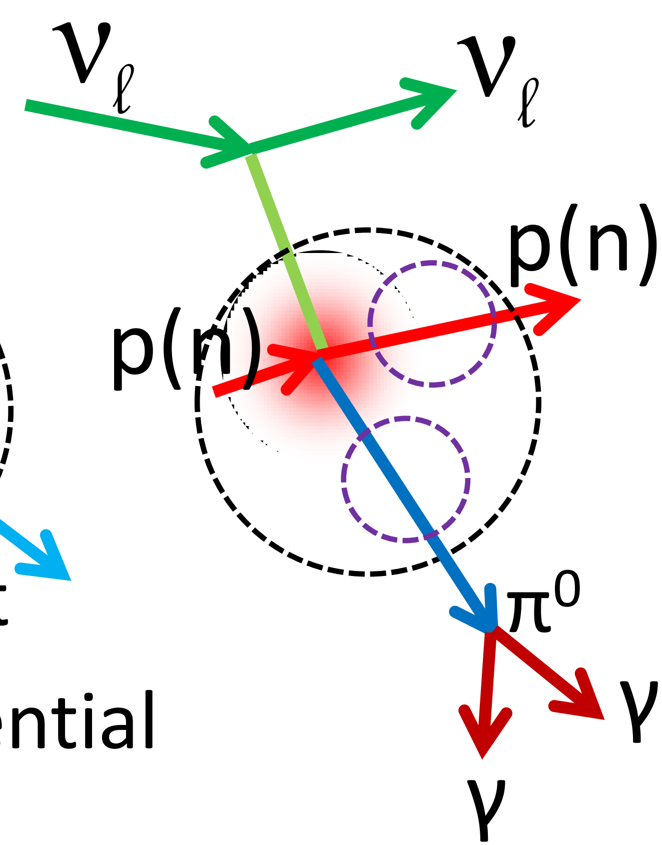
Charged Current Quasi Elastic (CCQE)



Charged Current 1 π production (CC1π)



Neutral Current 1 π^0 production (NC1π^0)

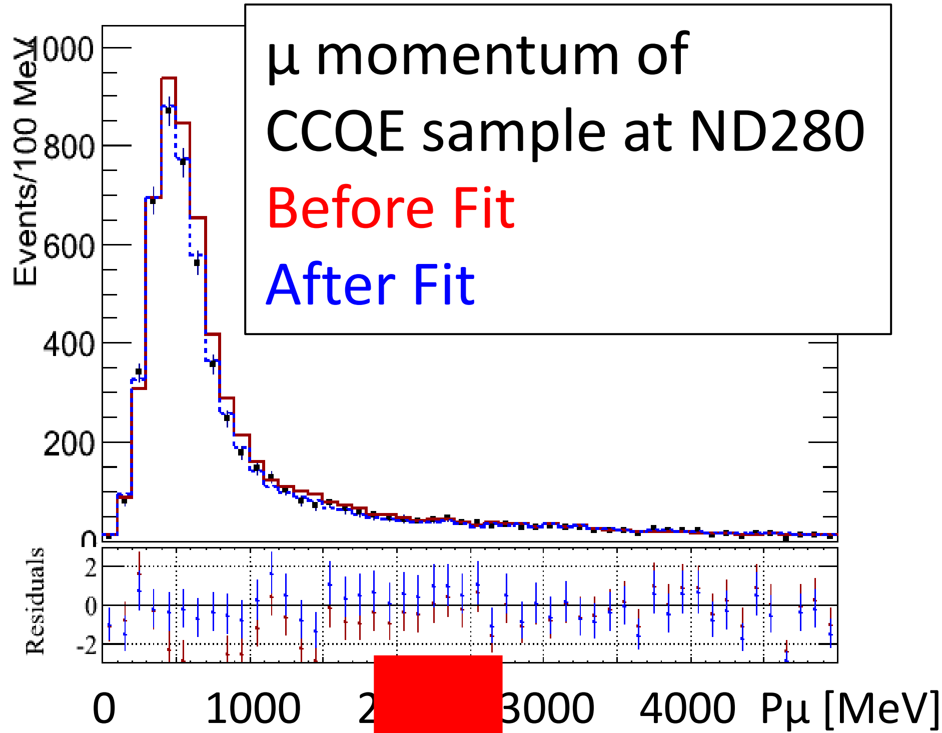


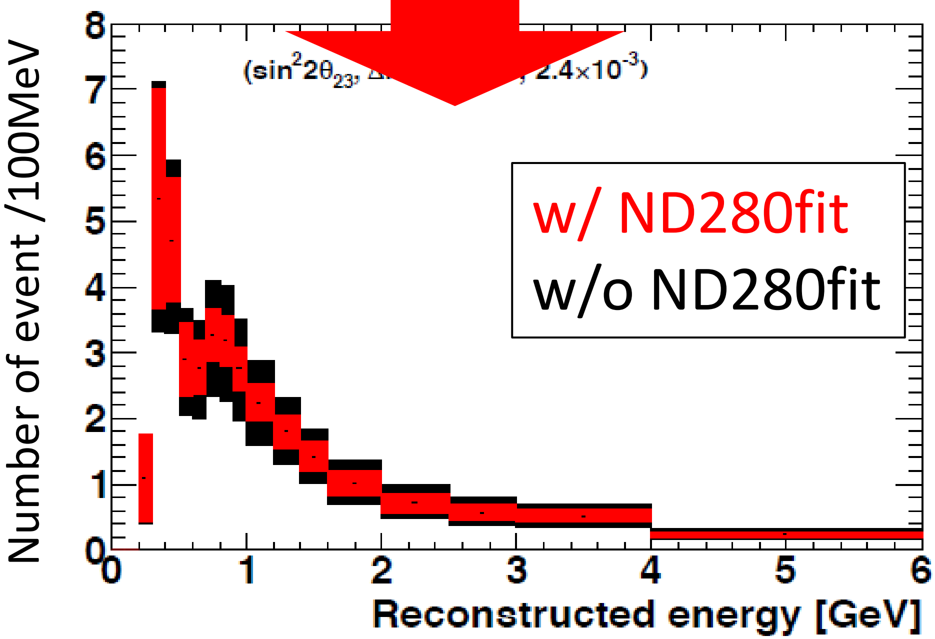
- M_A^{QE}~1.2GeV
- M_A^{RES}~1.2GeV
- p_F~200MeV/c

- Nuclear Potential
- Final State Interaction (FSI)

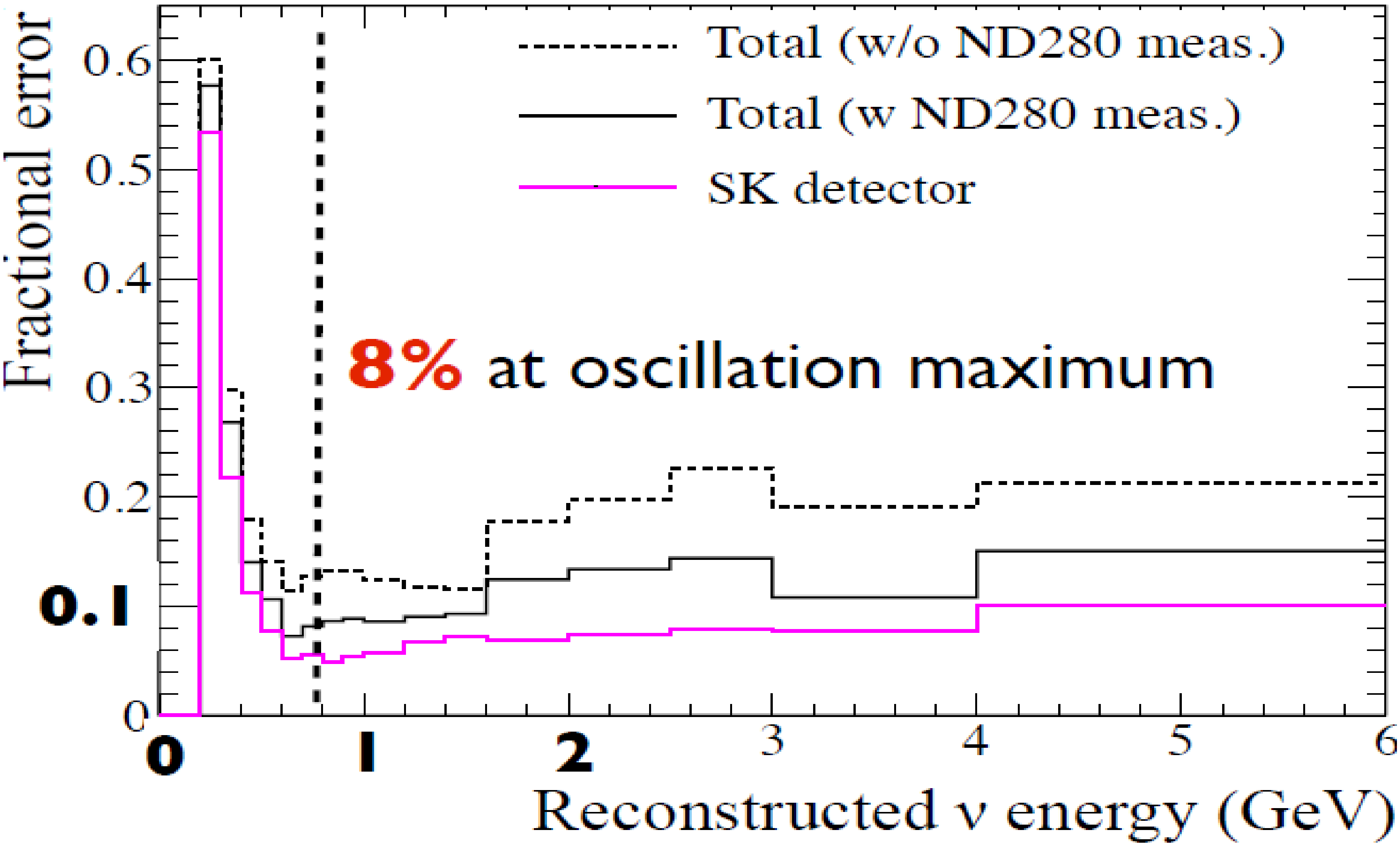
Signal prediction
(for example, ν_μ disapp.)

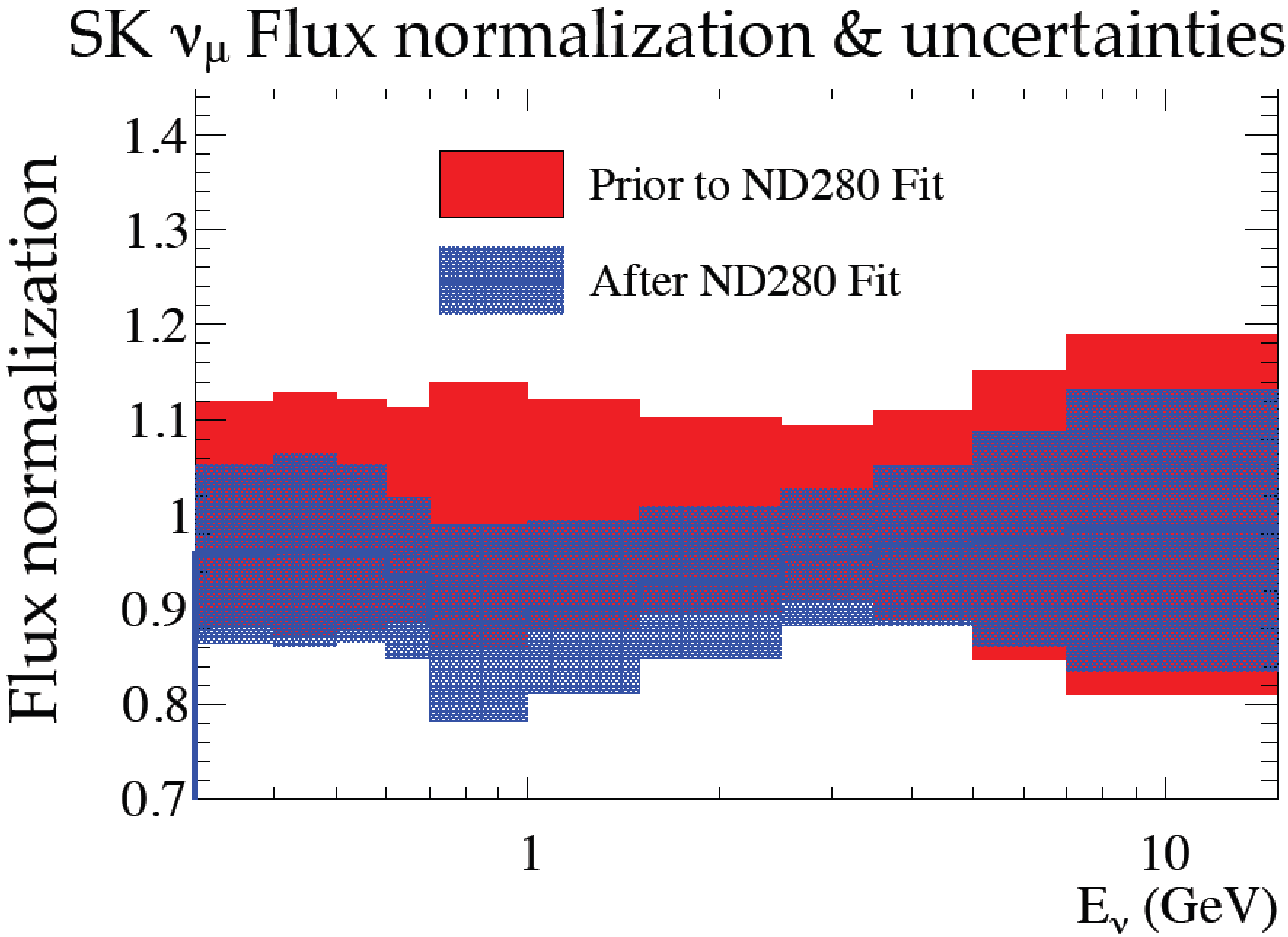
Fit ND280 data momentum and angle distribution of CCQE and CCnonQE to tune the flux and ν-cross section parameters.





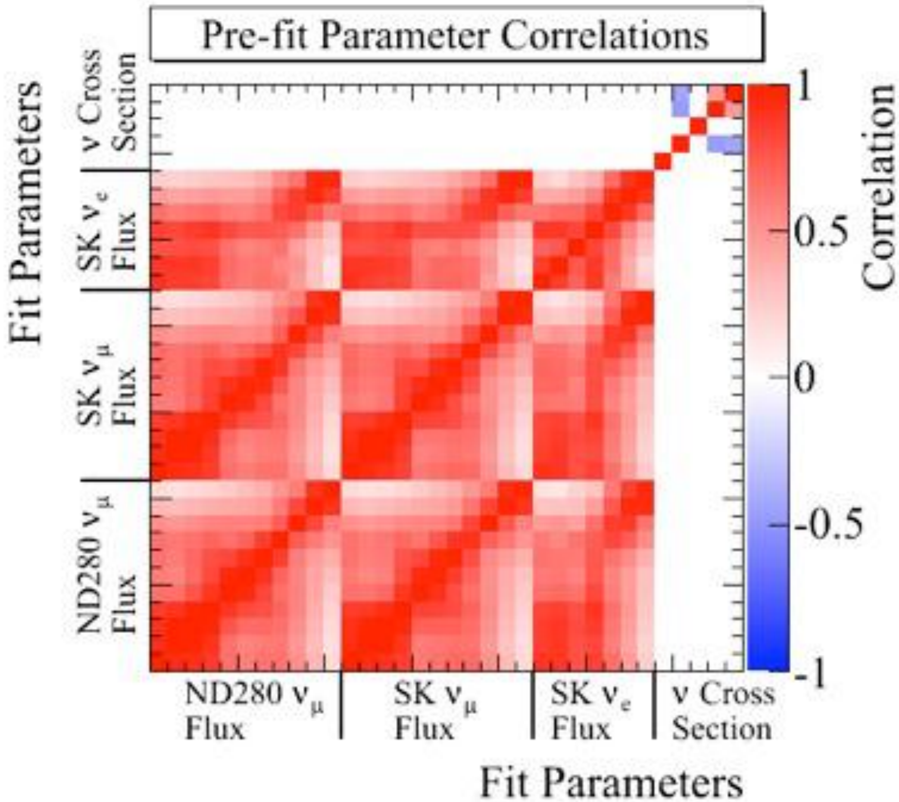
Sys on energy spectrum

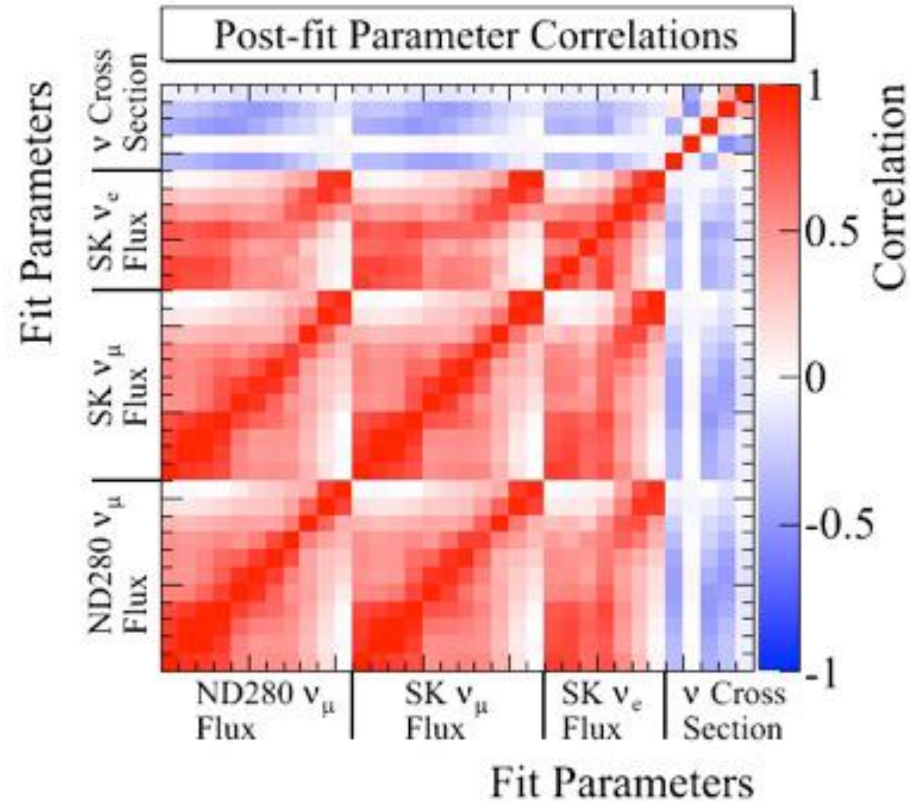




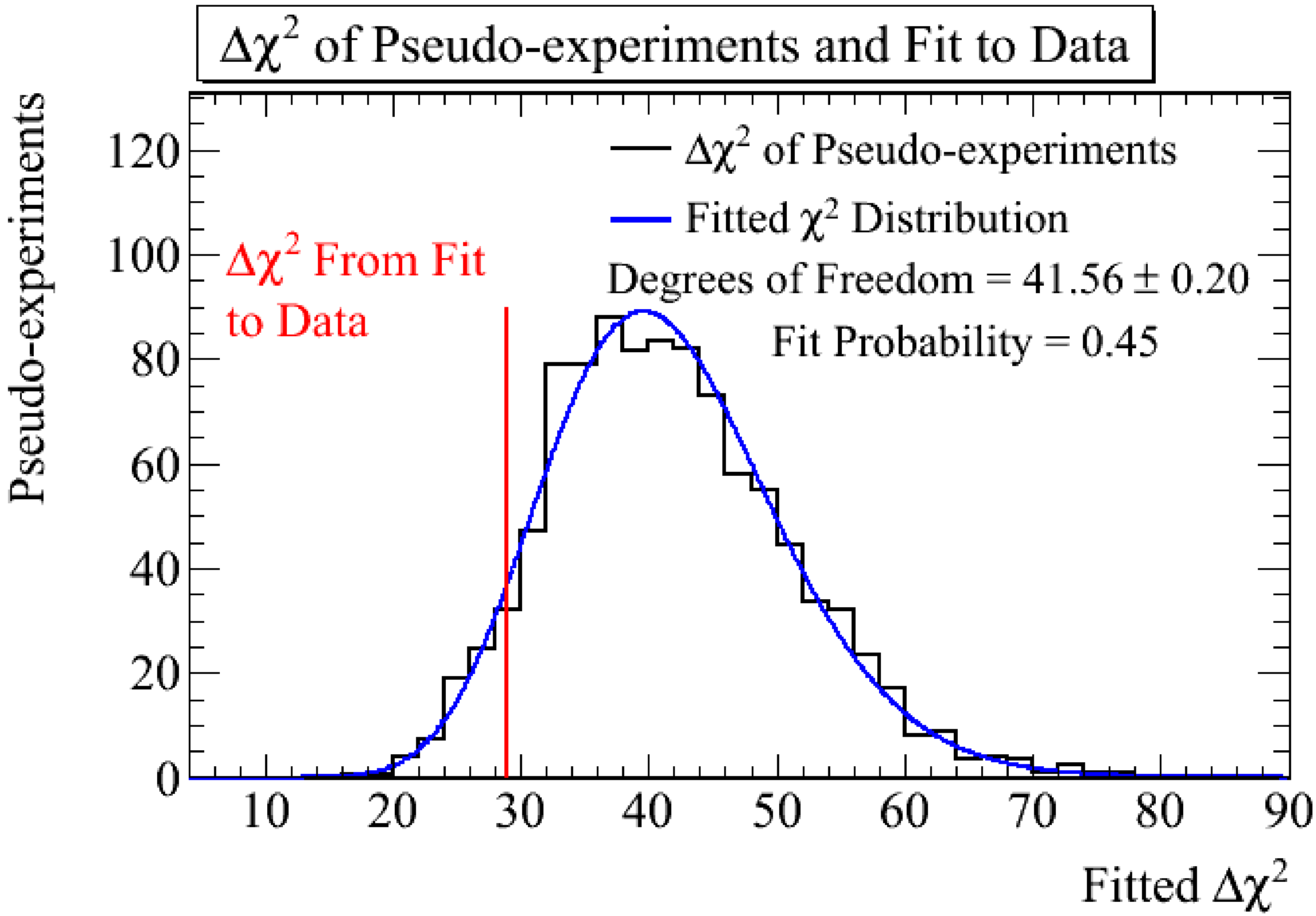
SK ν_μ Flux normalization & uncertainties
Prior to ND280 Fit
After ND280 Fit
Flux normalization
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
1
10
E_ν (GeV)

Correlation Matrix





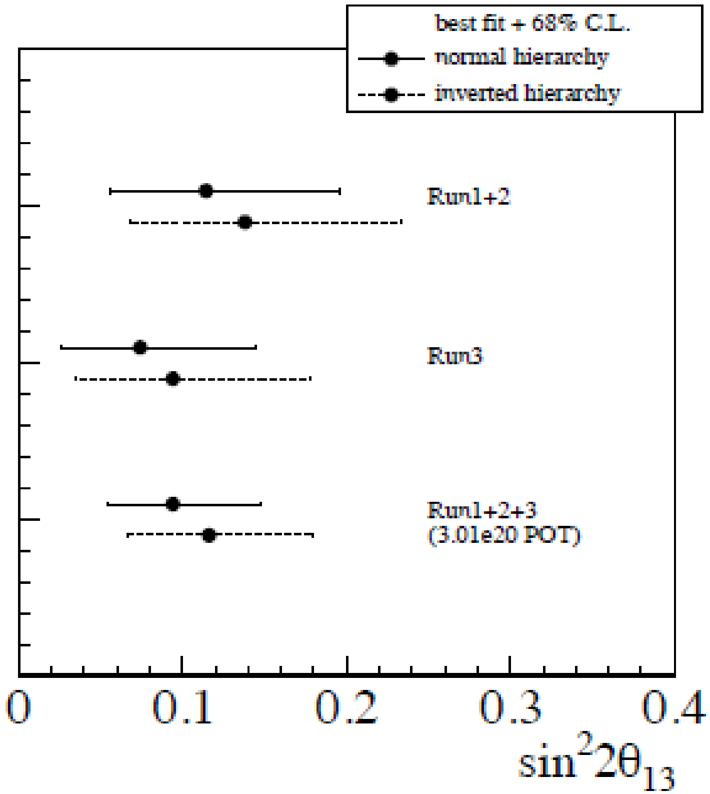
ND280フィット



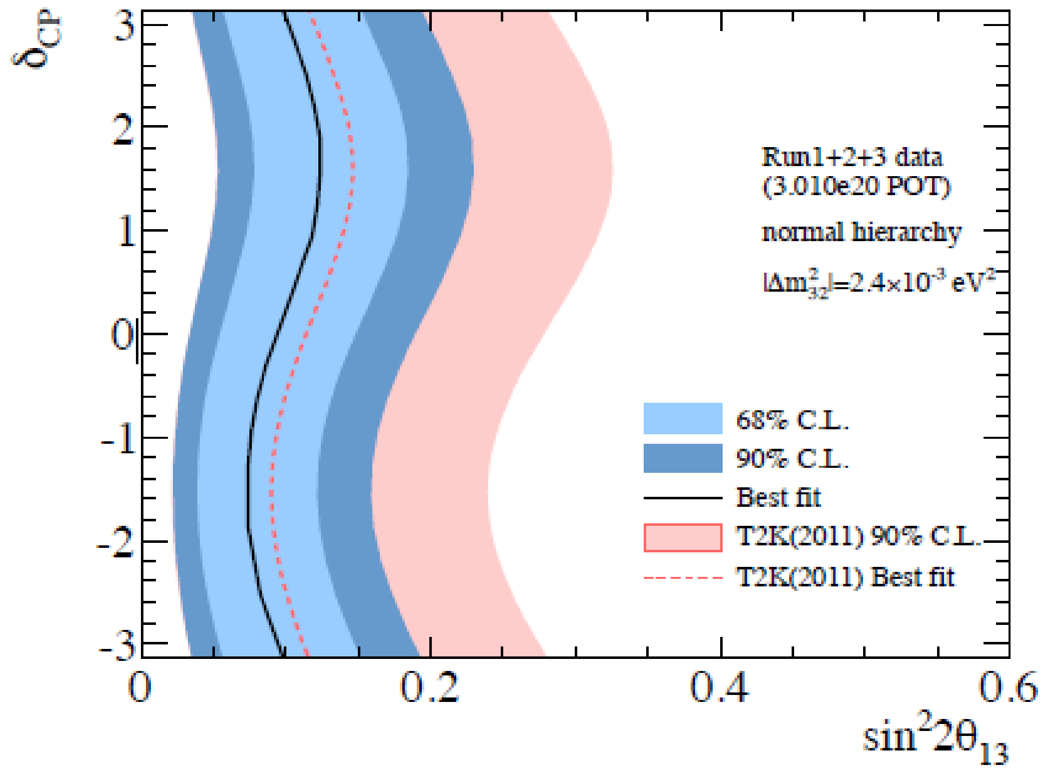
Δχ² of Pseudo-experiments and Fit to Data
Pseudo-experiments
120
100
80
60
40
20
0
Δχ² From Fit
to Data
Δχ² of Pseudo-experiments
Fitted χ² Distribution
Degrees of Freedom = 41.56 ± 0.20
Fit Probability = 0.45
10
20
30
40
50
60
70
80
90
Fitted Δχ²

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}



Results w/ Run3 only are consistent with Run1+2

This result is consistent w/ the 2011(Run1+2) results and is improved

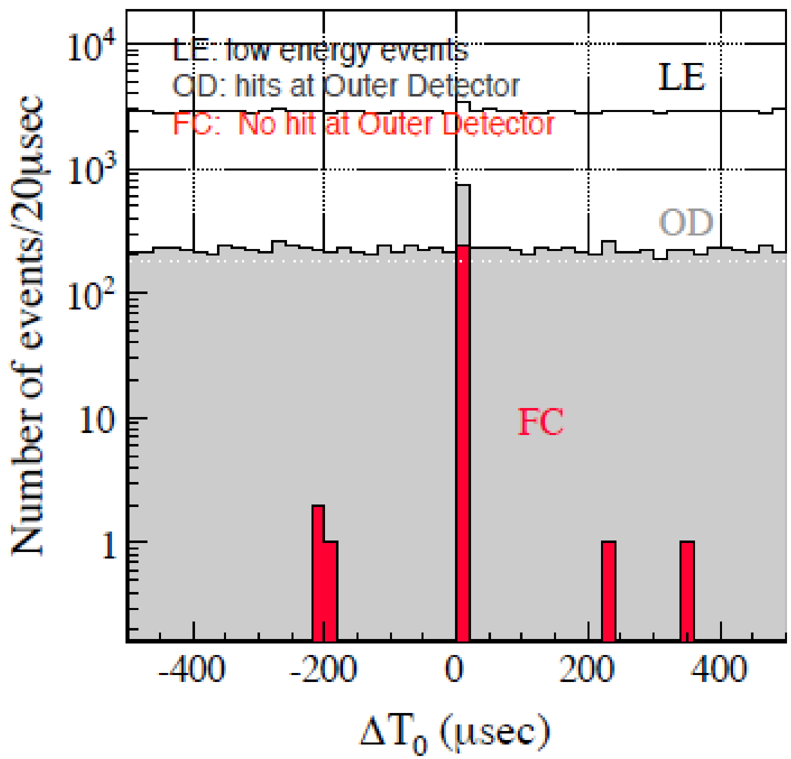
Systematic error contribution to the predicted number of events in the oscillation analysis

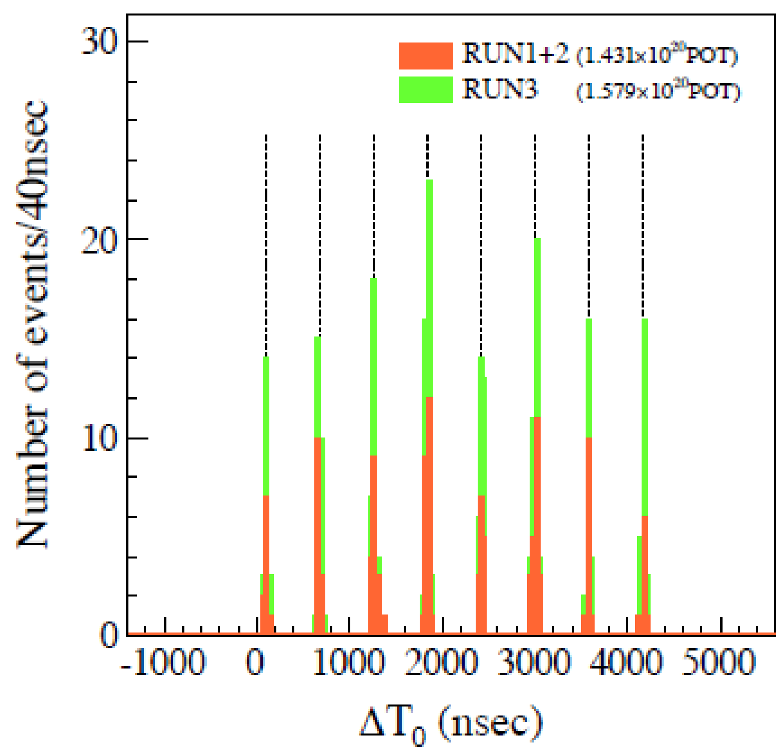
%

Error source	$\sin^2 2\theta_{13} = 0$ w/o ND280 fit	$\sin^2 2\theta_{13} = 0$ w/ ND280 fit	$\sin^2 2\theta_{13} = 0.1$ w/o ND280 fit	$\sin^2 2\theta_{13} = 0.1$ w/ ND280 fit
Beam only	10.8	7.9	11.8	8.5
M_A^{QE}	10.6	4.5	18.7	7.9
M_A^{RES}	4.7	4.3	2.3	2.0
CCQE norm. ($E_\nu < 1.5$ GeV)	4.6	3.7	7.8	6.2
CC1π norm. ($E_\nu < 2.5$ GeV)	5.3	3.7	5.5	3.9
NC1π^0 norm.	8.1	7.7	2.4	2.3
CC other shape	0.2	0.2	0.1	0.1
Spectral Function	3.1	3.1	5.4	5.4
p_F	0.3	0.3	0.1	0.1
CC coh. norm.	0.2	0.2	0.2	0.2
NC coh. norm.	2.1	2.1	0.6	0.6
NC other norm.	2.6	2.6	0.8	0.8
$\sigma_{\nu_e}/\sigma_{\nu_\mu}$	1.8	1.8	2.6	2.6
W shape	2.0	2.0	0.9	0.9
pion-less Δ decay	0.5	0.5	3.5	3.5
CC1π, NC1π^0 energy shape	2.5	2.5	2.2	2.2
SK detector eff.	7.1	7.1	3.1	3.1
FSI	3.1	3.1	2.4	2.4
SK momentum scale	0.0	0.0	0.0	0.0
Total	21.5	13.4	25.9	10.3

T2K Far detector events at beam timing

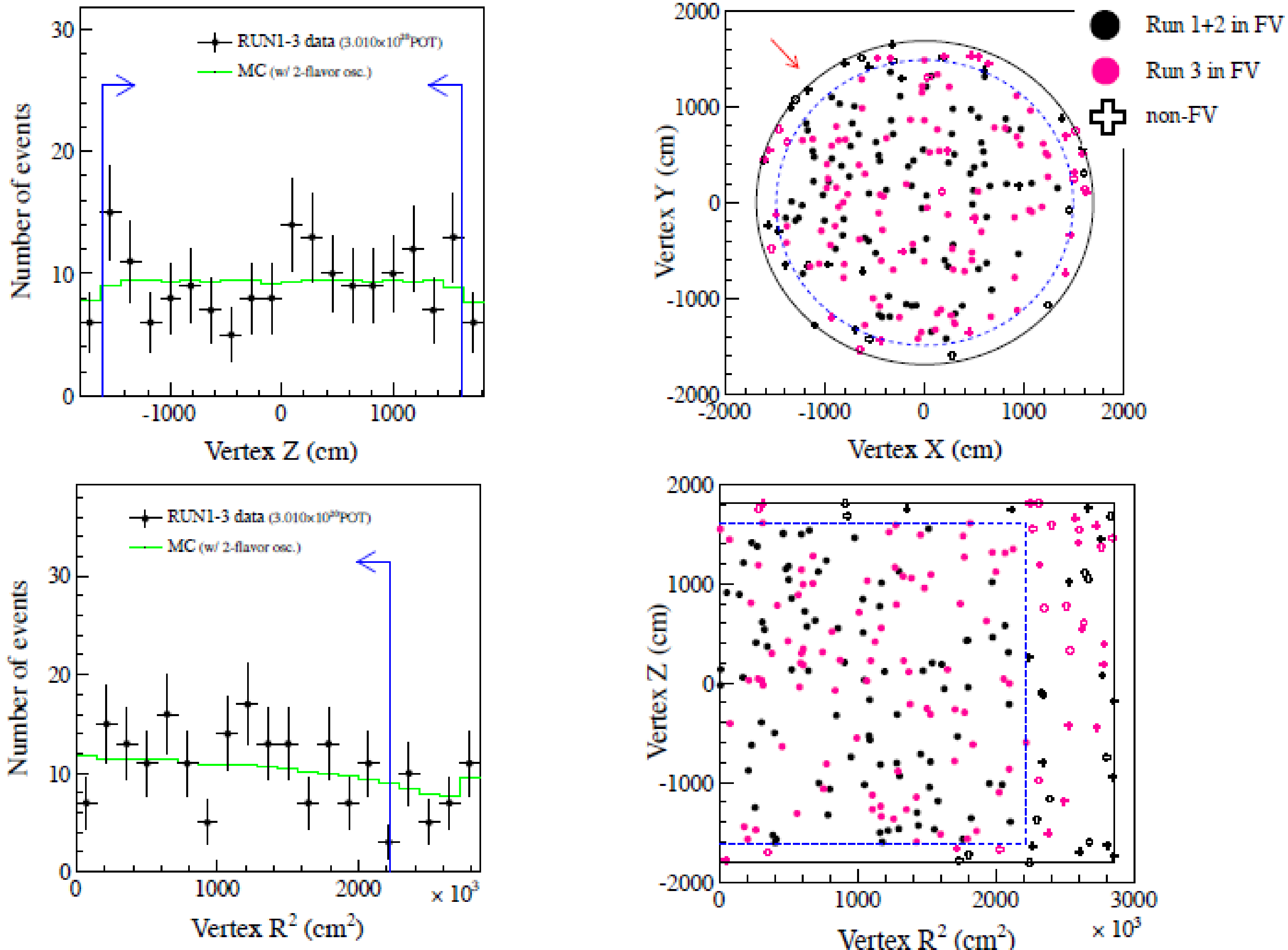
- Events at the T2K beam timing synchronized by GPS



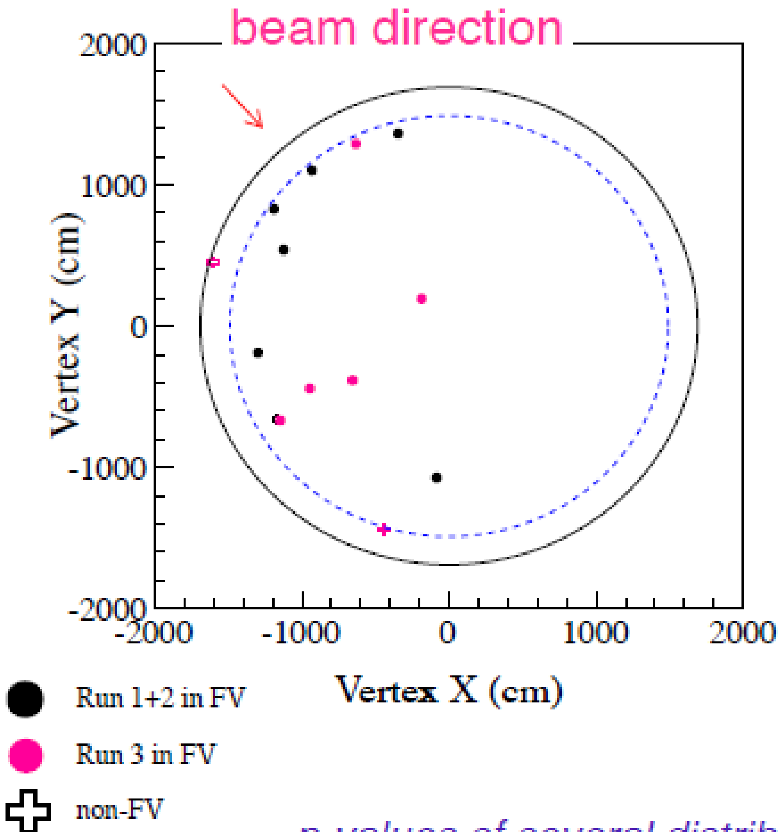


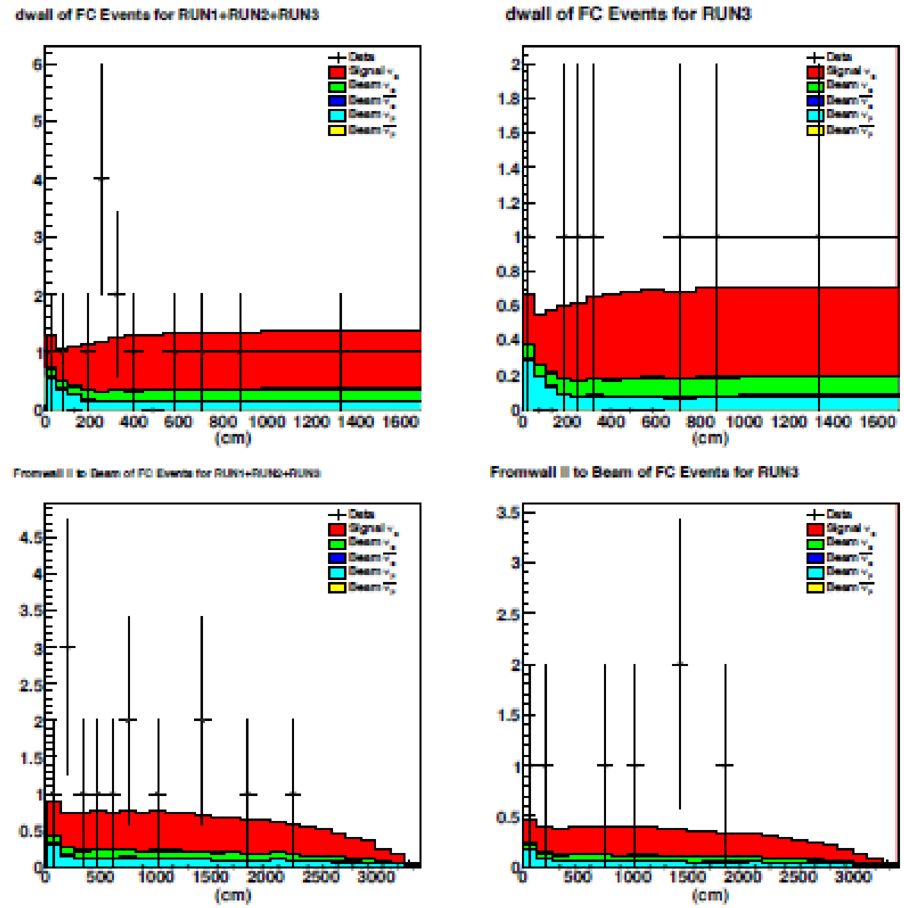
$\Delta T_0 = T_{GPS}@SK - T_{GPS}@J\text{-}PARC - TOF(\sim 985\mu sec)$

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



Vertex distribution

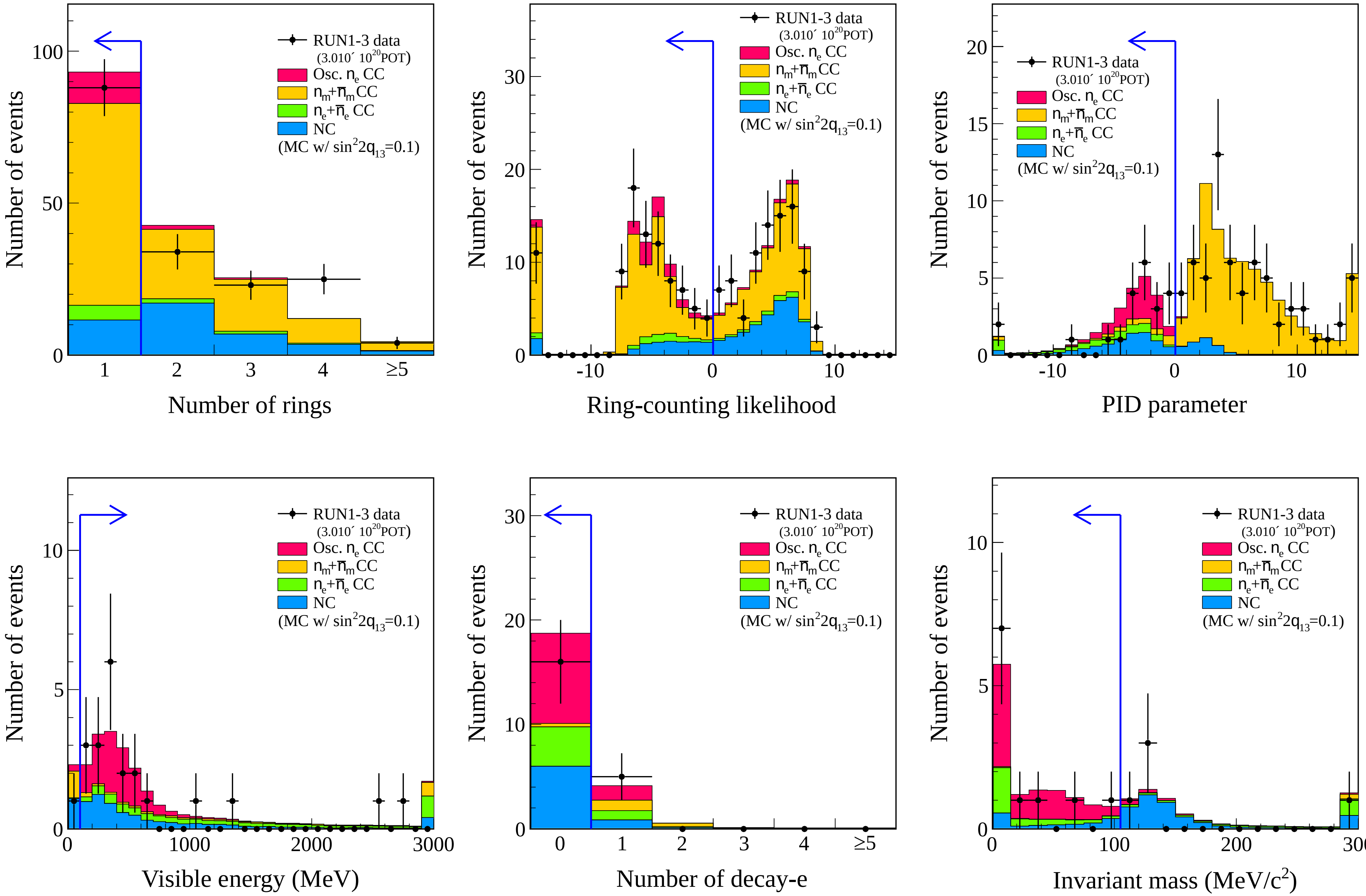




p-values of several distribution are calculated w/ toy MC

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

Nue Selection



NuMu Selection