Results from T2K

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ND280
T2K

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T2K Overview

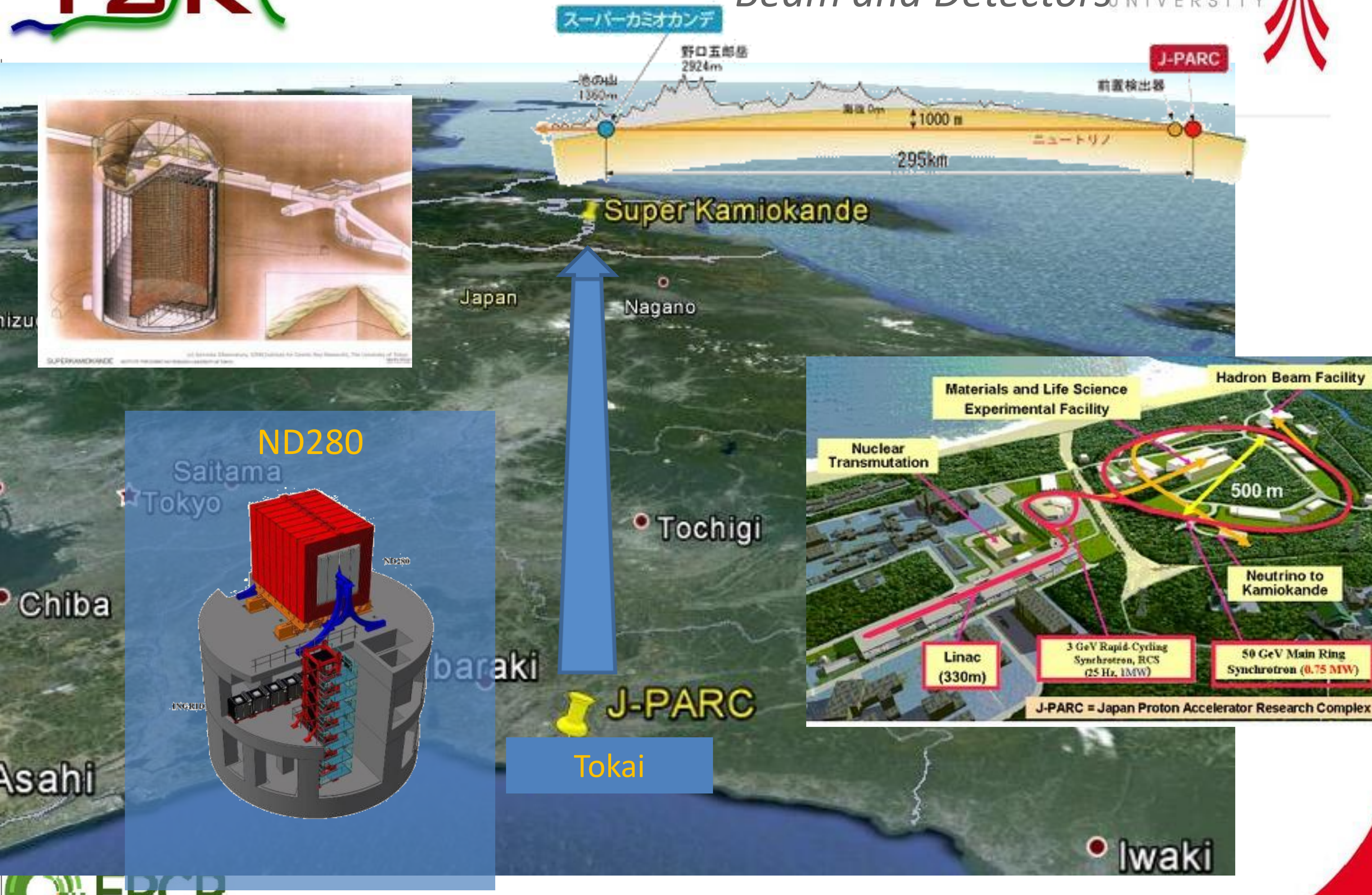
Physics Goals

T2K - Long Baseline Accelerator based Neutrino Experiment

- Observe ν_e appearance and measure θ_{13}
- Observe ν_μ disappearance and measure θ_{23}
- Measure ν cross sections
- Search for exotic neutrinos

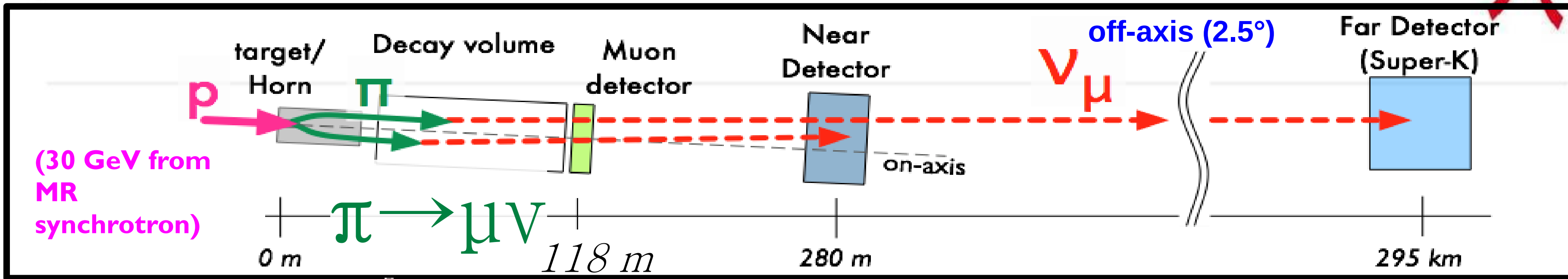
T2K Overview

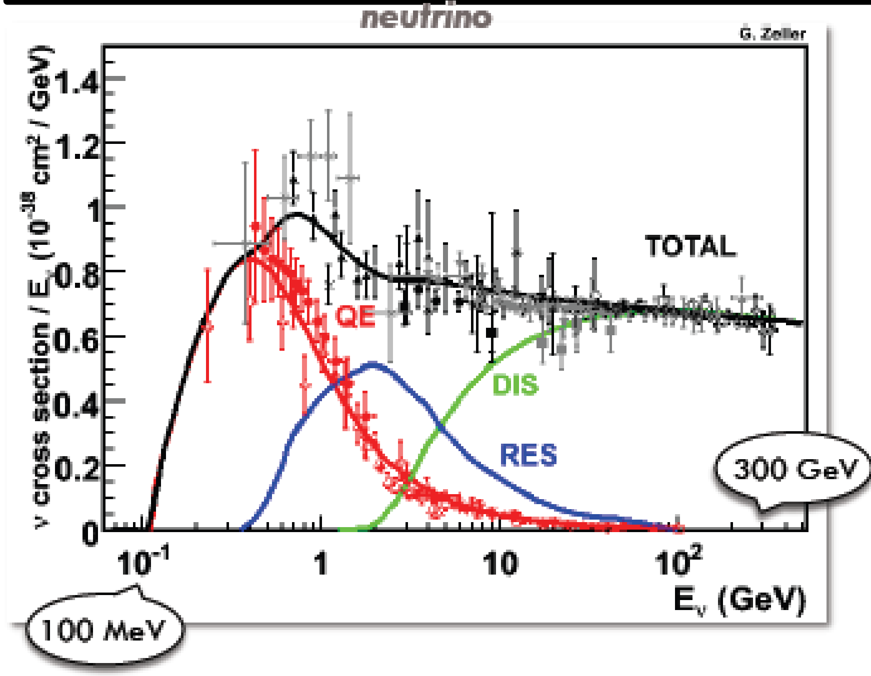
Beam and Detectors

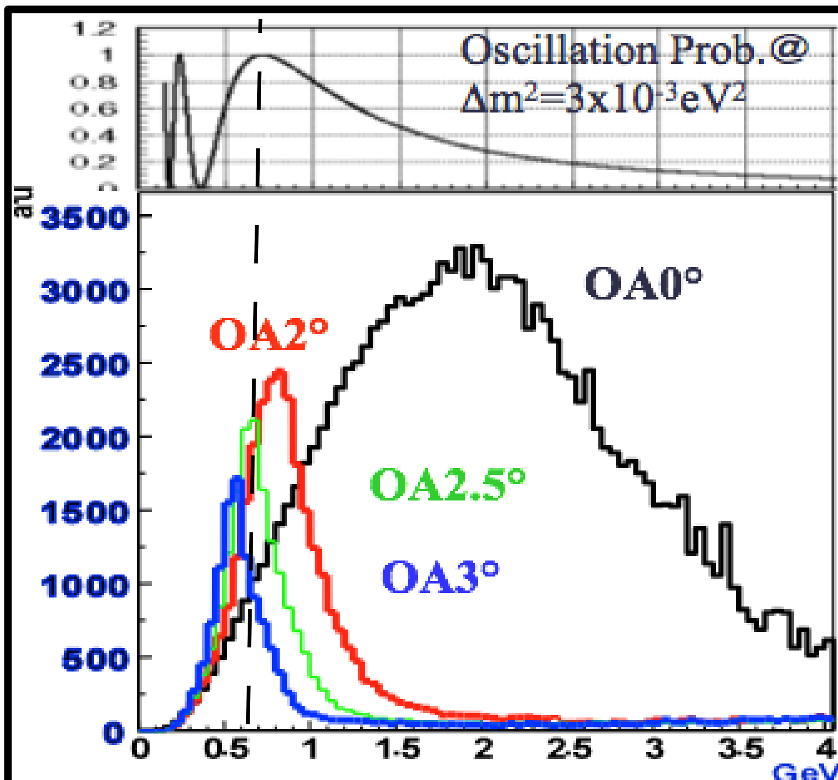


T2K Overview

Neutrino Beam

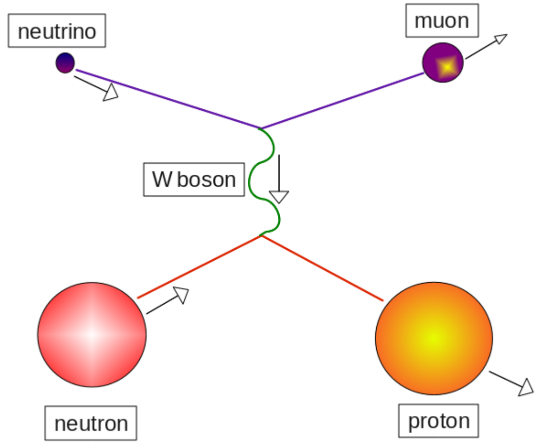






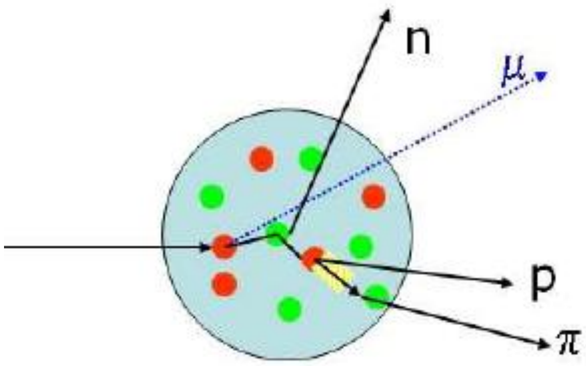
Charge Current Quasi-Elastic

What we'd like:



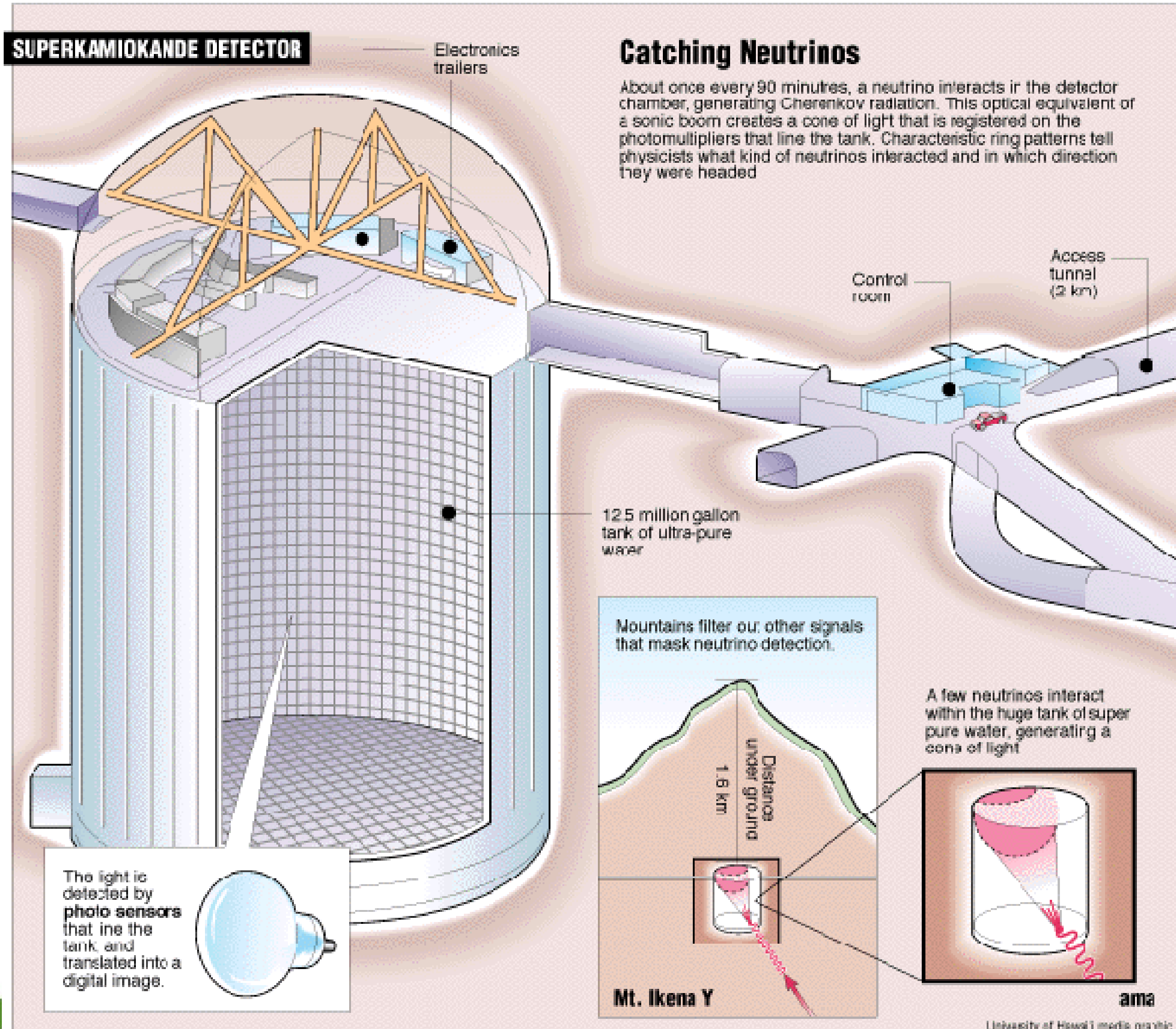
Nucleon changes but doesn't break up.

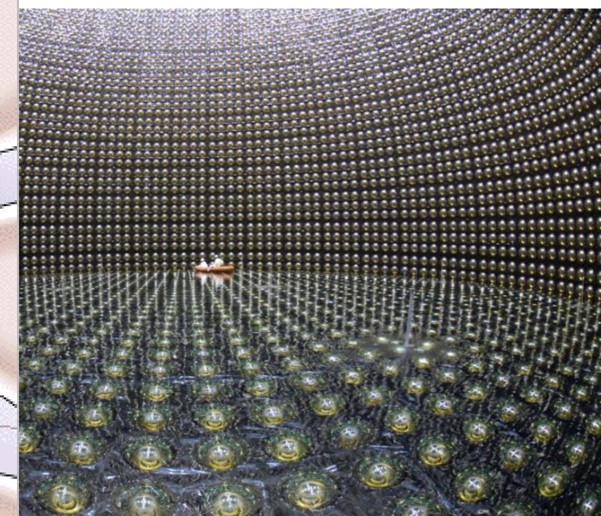
What we have:



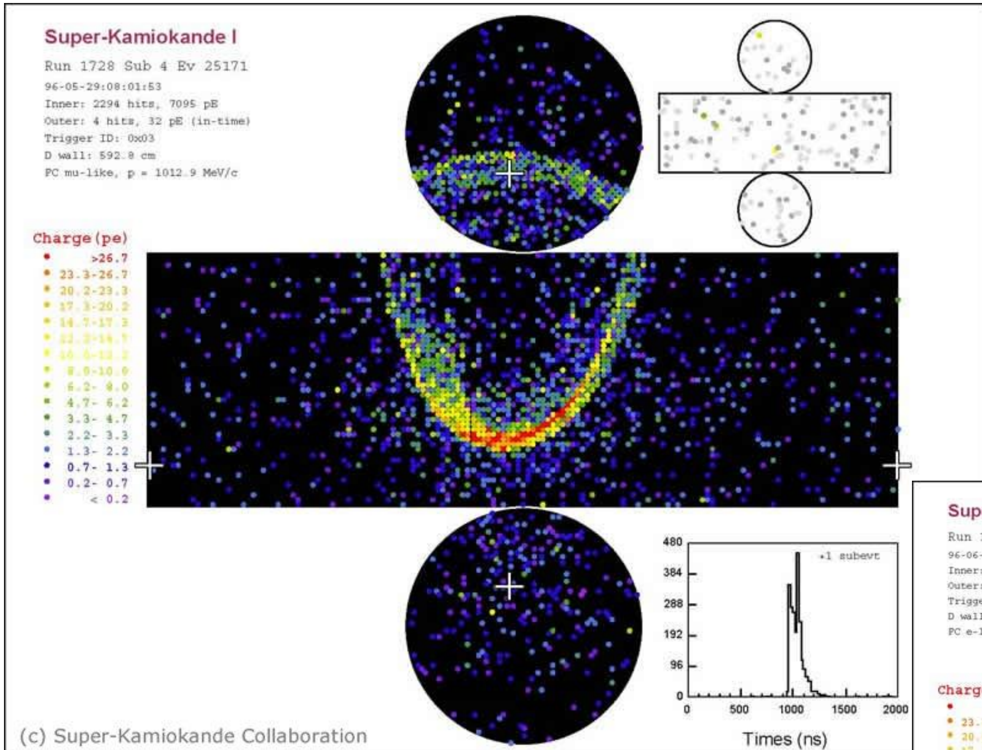
"Final State Interactions" confuse the picture

Super Kamiokande (“SK”)

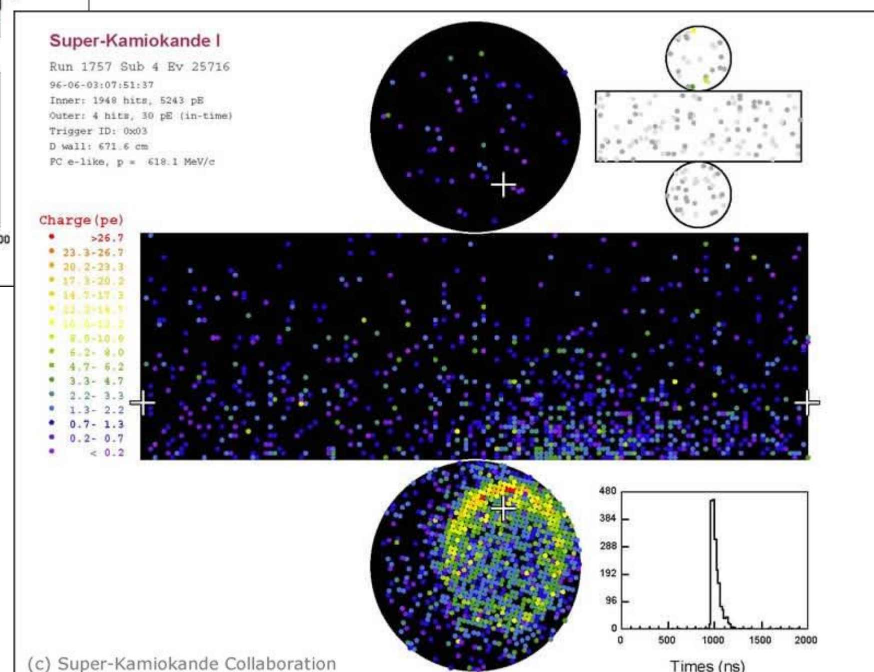




Super Kamiokande events

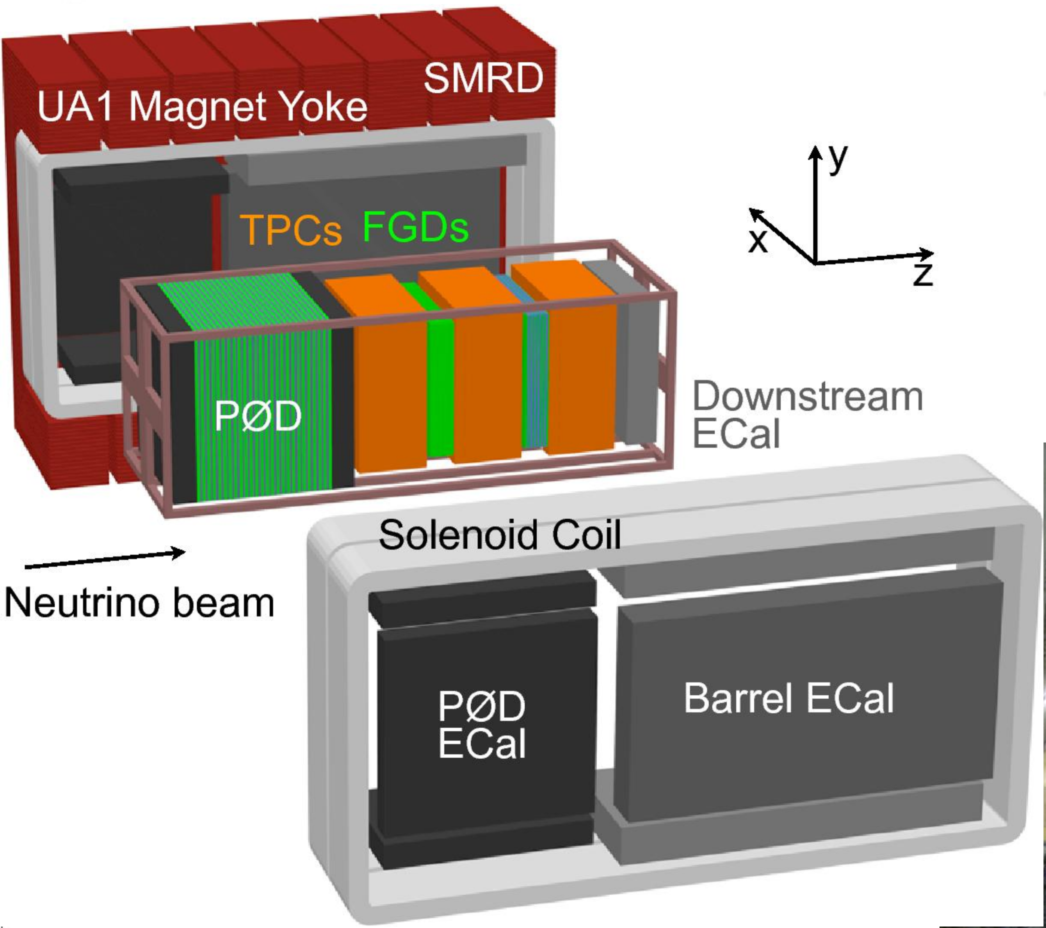


Electron event



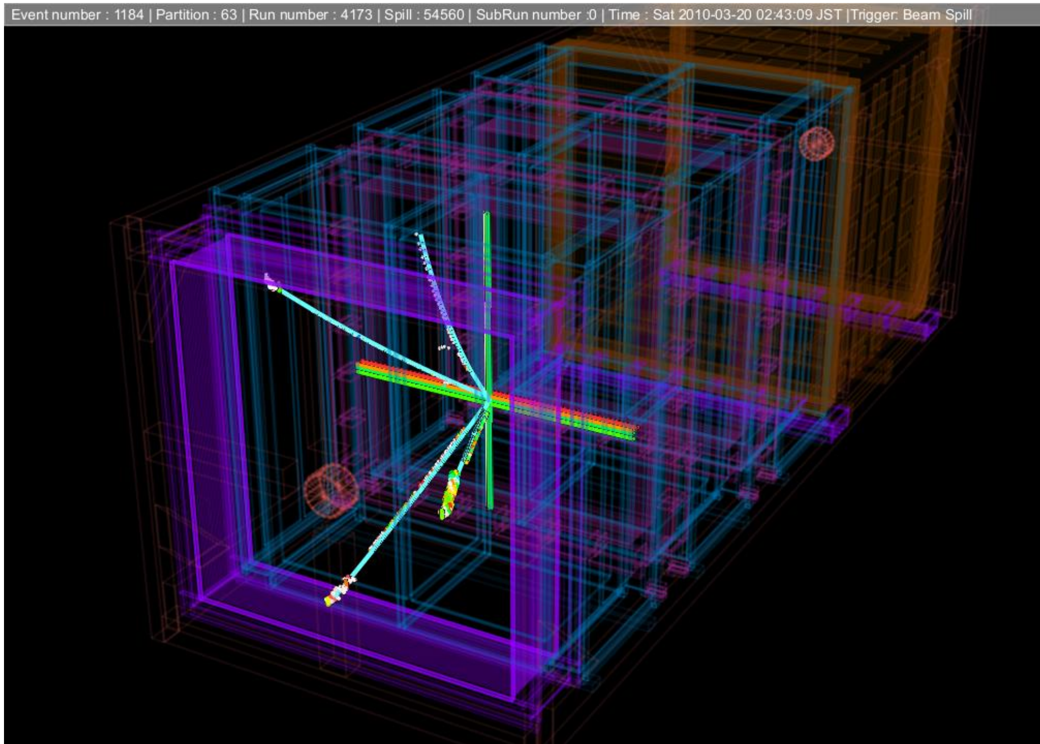
Muon event

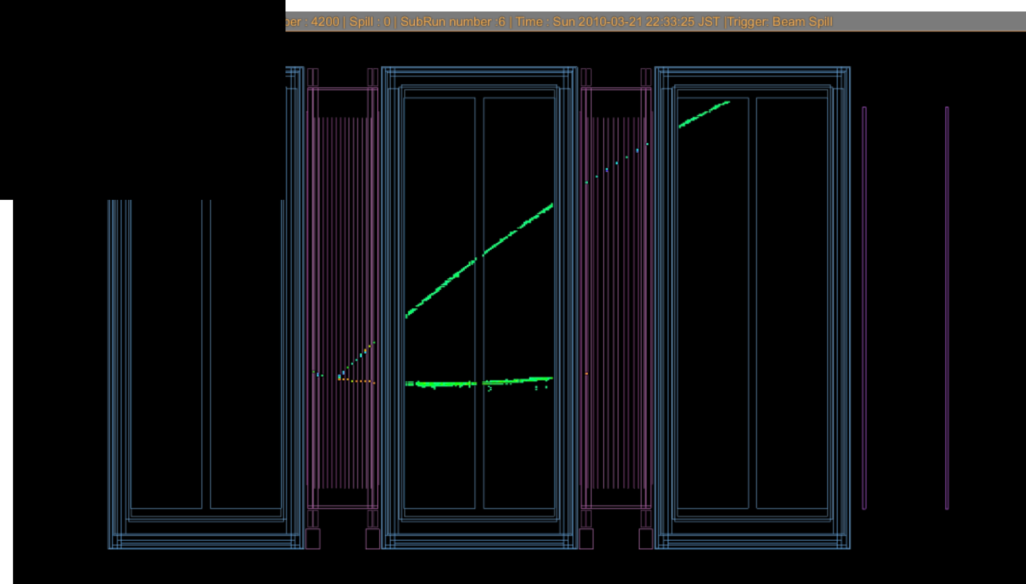
ND280



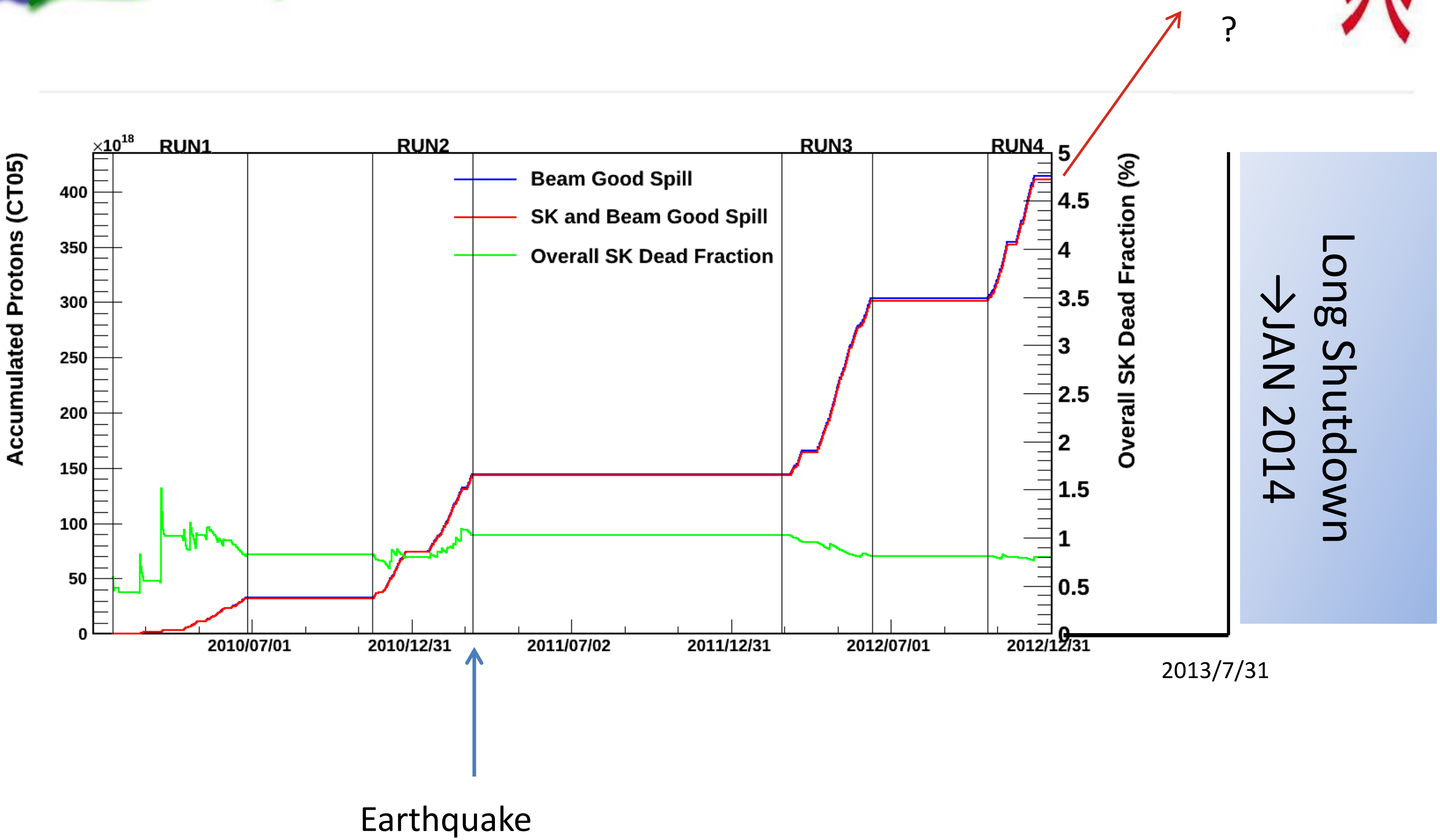
UA1 Magnet Yoke
SMRD
TPCs
FGDs
PØD
y
x
z
Downstream ECal
Solenoid Coil
Neutrino beam
PØD ECal
Barrel ECal

ND280 Events





T2K Data – Run Periods



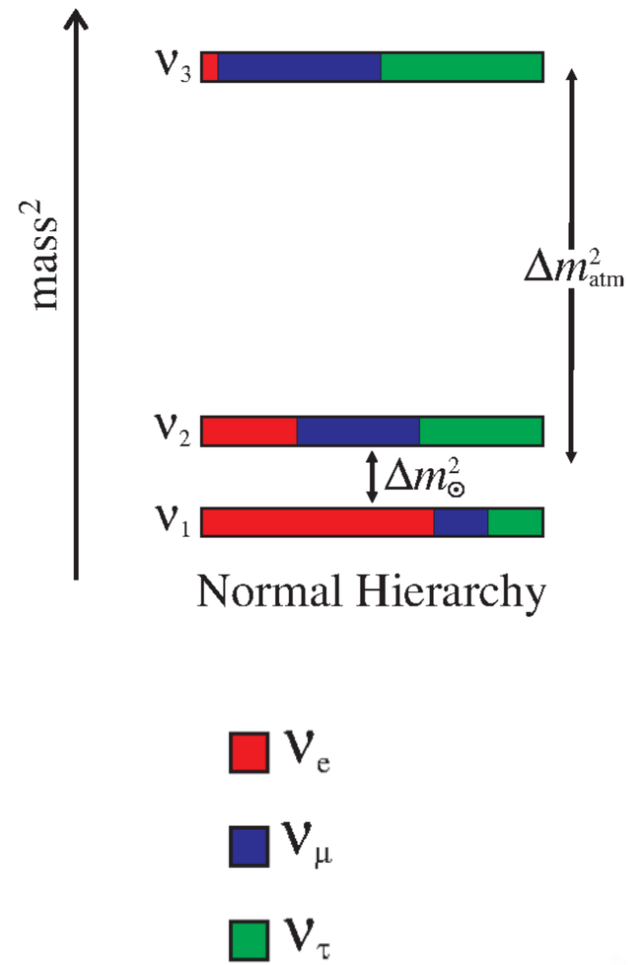
Neutrino Oscillations

PMNS=>Pontecorvo-Maki-Nakagawa-Sakata

Neutrino mixing (PMNS) matrix is:

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3}\\ U_{\mu1} & U_{\mu2} & U_{\mu3}\\ U_{\tau1} & U_{\tau2} & U_{\tau3}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

*Plotted for $U_{e3} \pm \sqrt{0.05}i$



$\Delta m^2_{21} \equiv \Delta m^2_{sol} = 7.6\times10^{-5}\ eV^2$

$|\Delta m^2_{31}| \approx |\Delta m^2_{32}| \equiv \Delta m^2_{atm} = 2.4\times10^{-3}\ eV^2$

$\Theta_{13} = 9^o$

$\Theta_{12} = 34^o$

$\Theta_{23} = 45^o$

Slide from P. Litchfield

Angle parameterisation

The mixing matrix is commonly parameterised as the product of two rotations and a unitary transformation. Writing $s_{ij} = \sin\theta_{ij}$, and $c_{ij} = \cos\theta_{ij}$:

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

The choice of parameterisation is convenient as the **solar** and **atmospheric** disappearance amplitudes can be approximated as functions of $\boldsymbol{\theta_{12}}$ and $\boldsymbol{\theta_{23}}$, respectively.

This approximation only works to the extent that the third angle $\boldsymbol{\theta_{13}}$ is small.

Slide from P. Litchfield

In the standard parameterisation, it turns out that

$$U_{e3} = \sin\theta_{13}\, e^{-i\delta}, \quad \text{and therefore} \quad \sin\theta_{13} = |U_{e3}|.$$

The value of $\sin\theta_{13}$ particularly significant because a zero element in the mixing matrix would have eliminated the possibility of (KM-mechanism) leptonic CP violation.

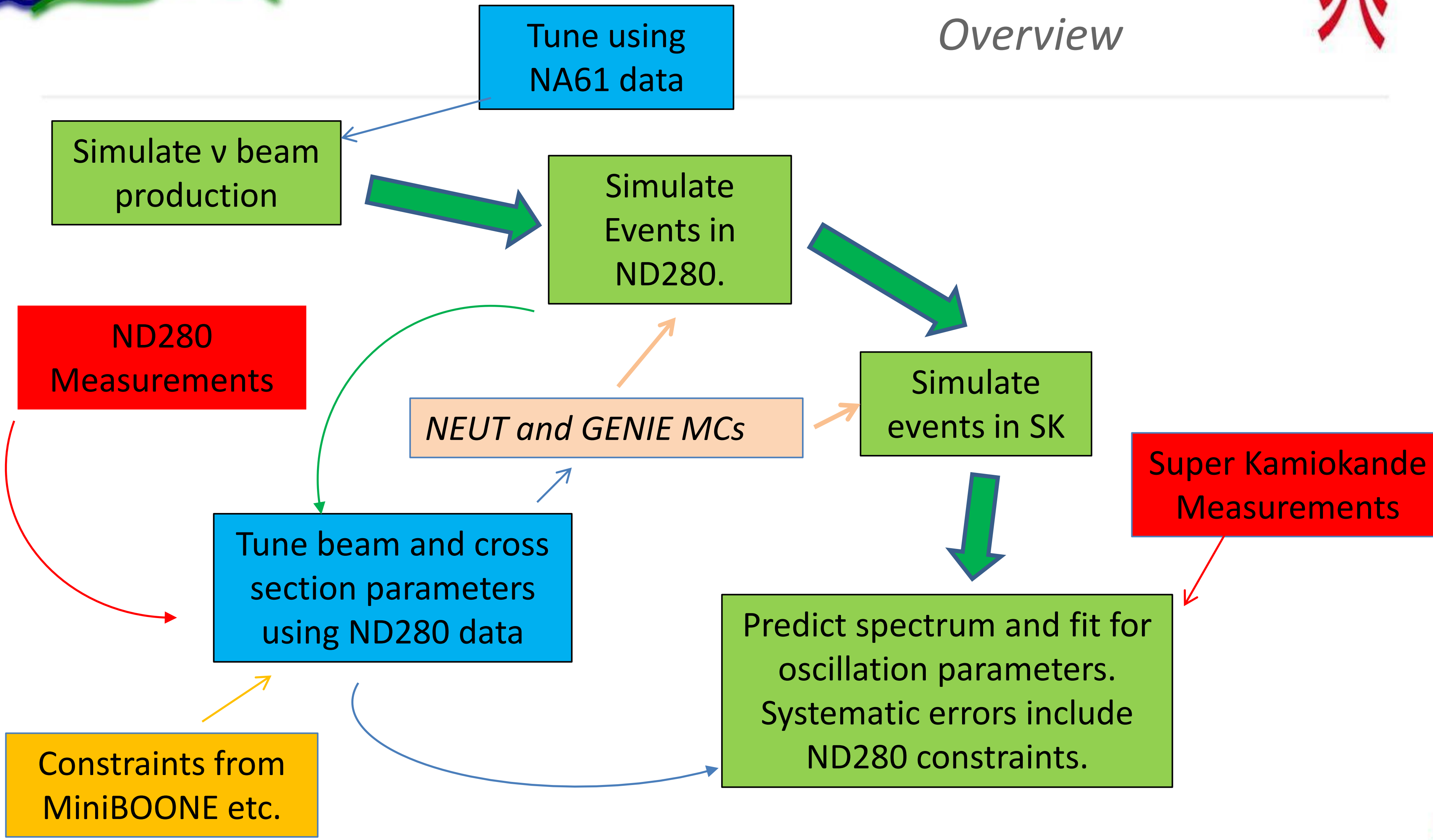
The future program of neutrino physics is strongly dependent on the size of $\boldsymbol{\theta_{13}}$.

To study, need channels involving $\langle \nu_e | \nu_3 \rangle$. The most accessible are $\bar{\nu}_e \to \bar{\nu}_e$ (reactor) and $\boldsymbol{\nu_\mu \to \nu_e}$ **(accelerator)** at first 'atmospheric' maximum (L/km ~ 0.5 × E/MeV)

Slide from P. Litchfield

T2K Oscillation Analysis

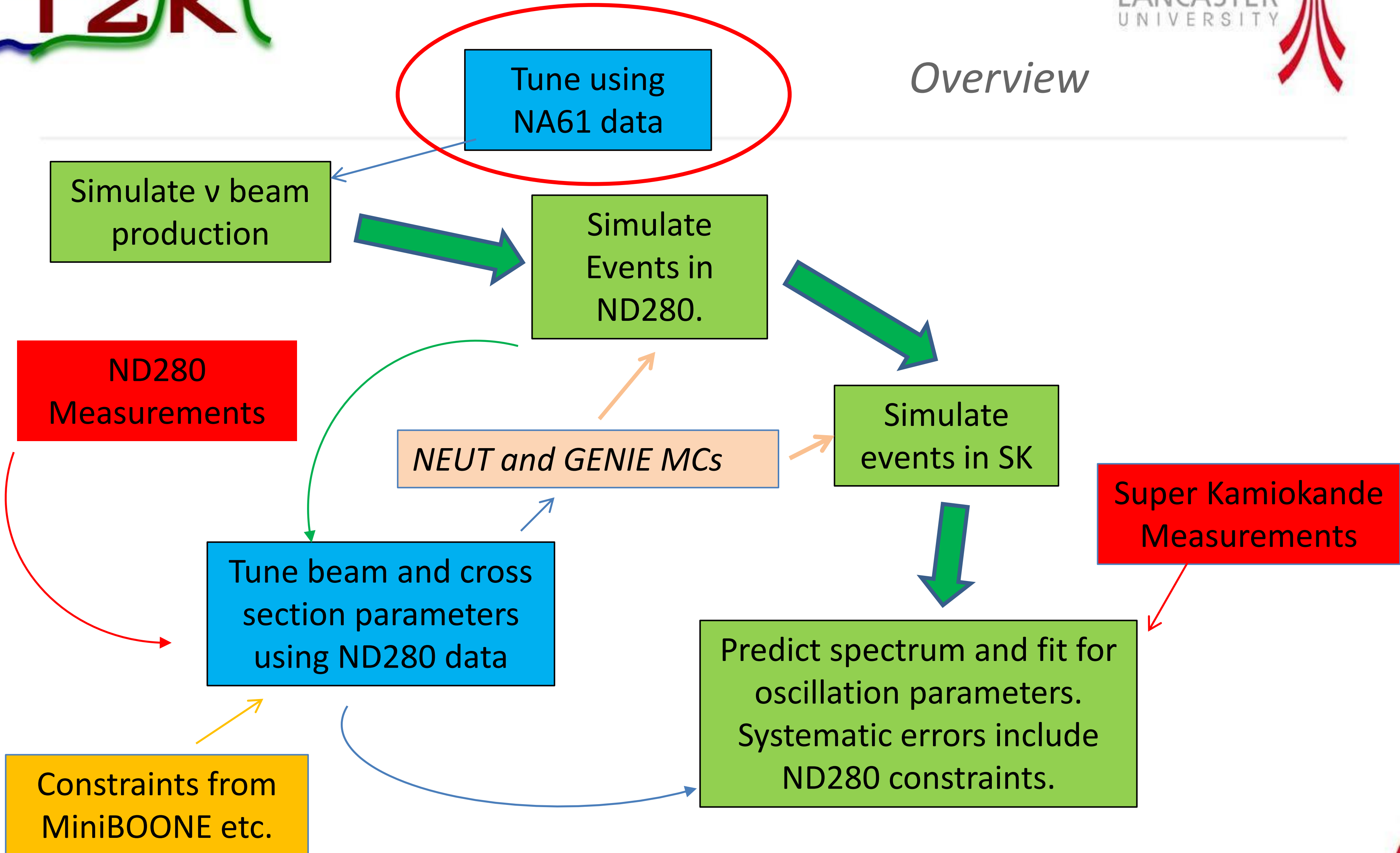
Overview



Use event reweighting to model effect of varying parameters.

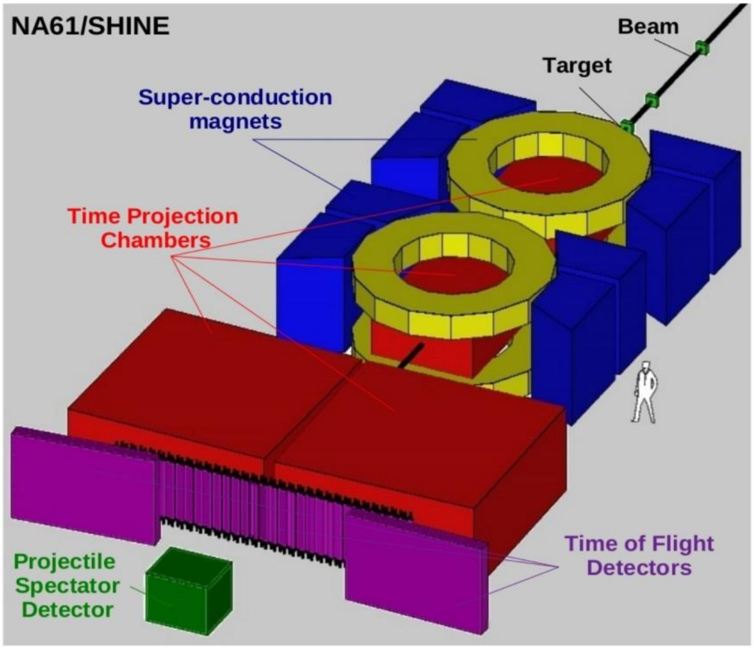
T2K Oscillation Analysis

Overview



Use event reweighting to model effect of varying parameters.

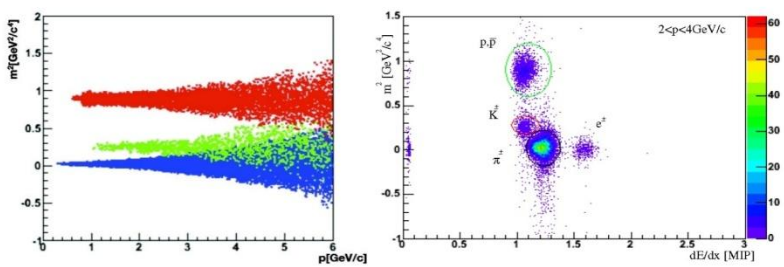
NA61 / SHINE



NA61 is a large acceptance hadron spectometer with excellent capabilities for momentum, charge and mass measurements. The experimental facility consists of Time Projection Chambers, Time of Flight and Projectile Spectator Detectors.

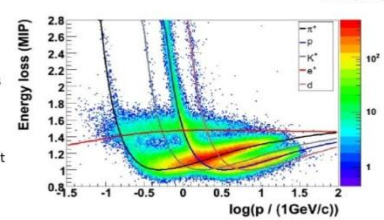
Physics goals

... Hadron production reference measurements for neutrino (T2K) and cosmic-ray (Pierre Auger Observatory, KASCADE-Grande and KASCADE) experiments. ...



Particle identification capabilities for protons, kaons, pions and electrons:

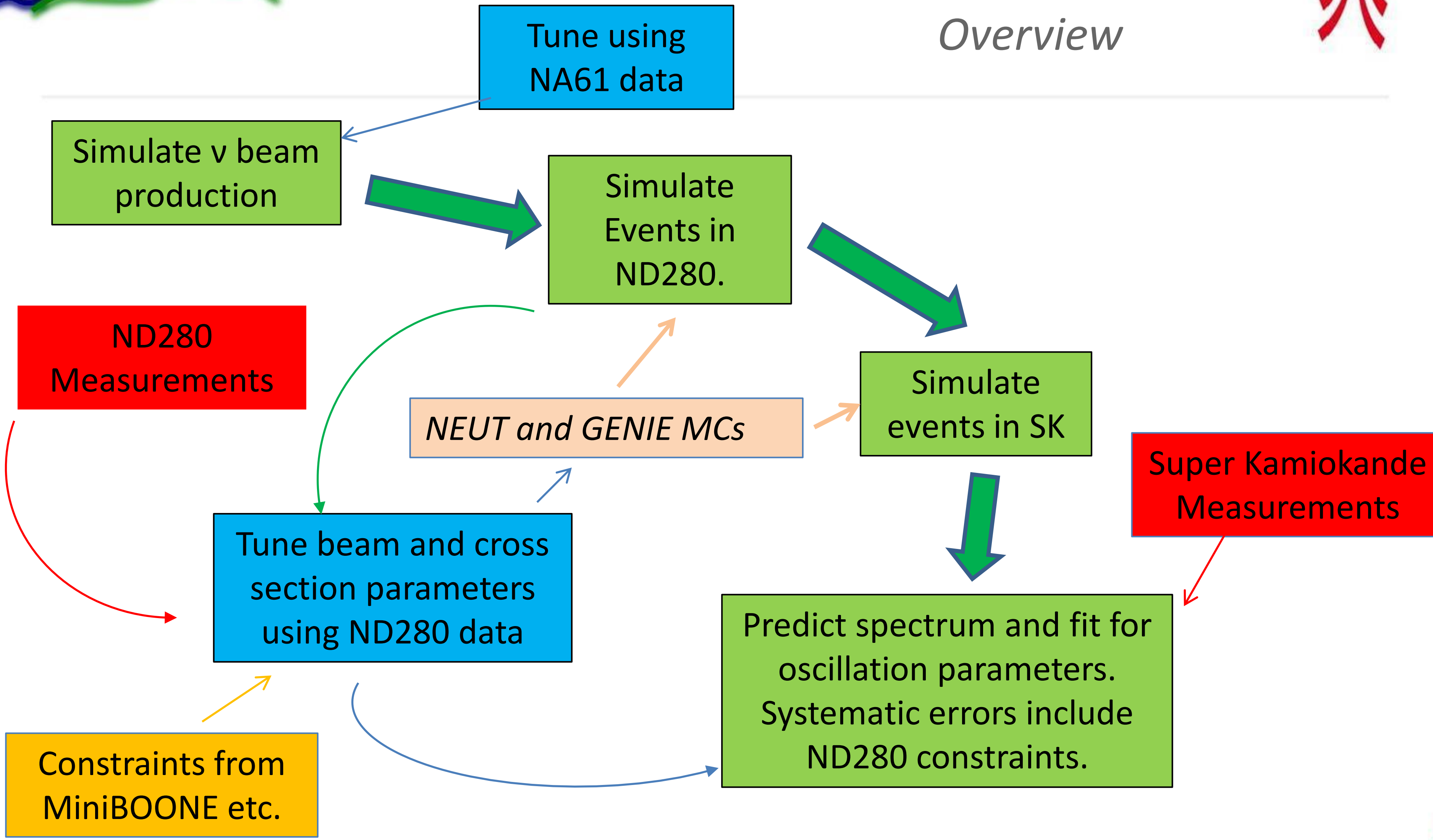
- Specific energy loss vs. momentum (Bethe-Bloch plot) - lower right
- Reconstructed mass vs. specific energy loss - upper right
- Reconstructed mass vs. momentum - upper left



Phys.Rev. C84 (2011) 034604

T2K Oscillation Analysis

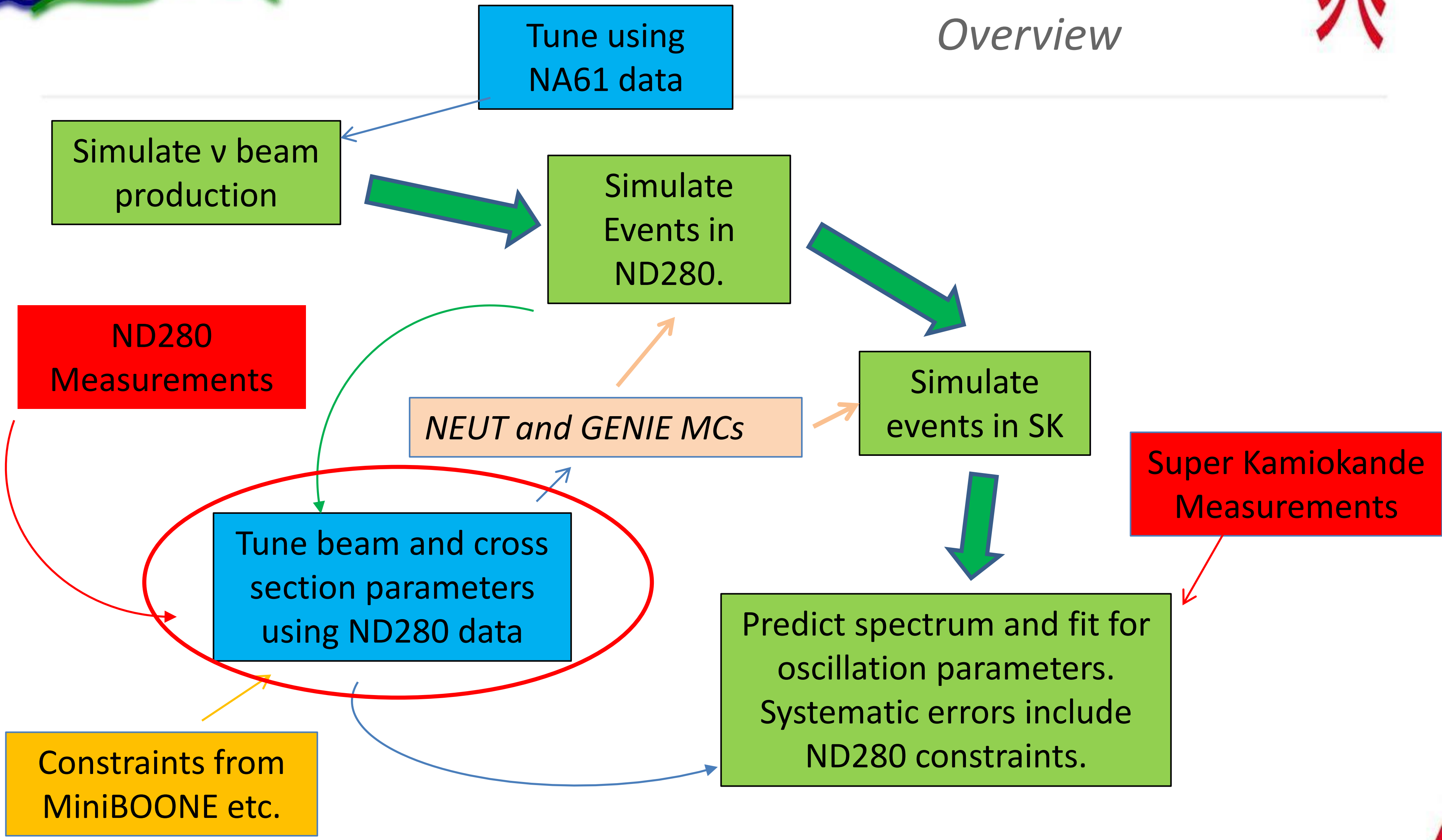
Overview



Use event reweighting to model effect of varying parameters.

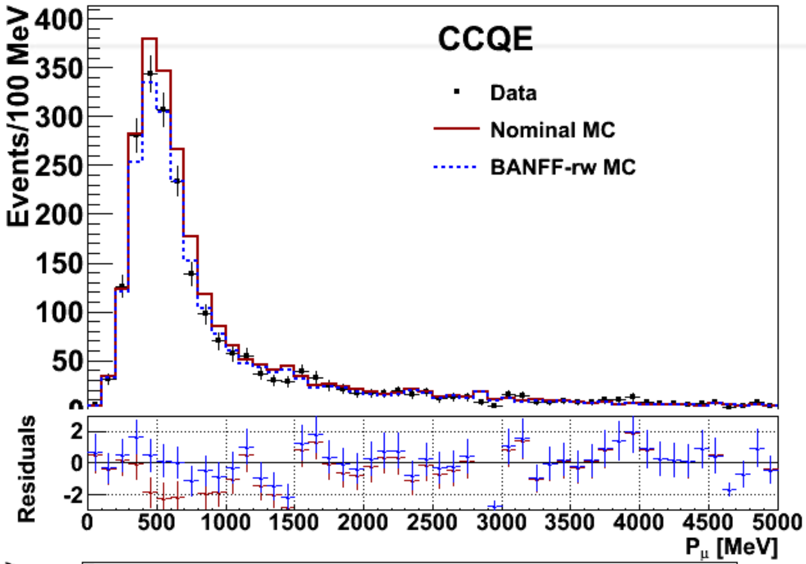
T2K Oscillation Analysis

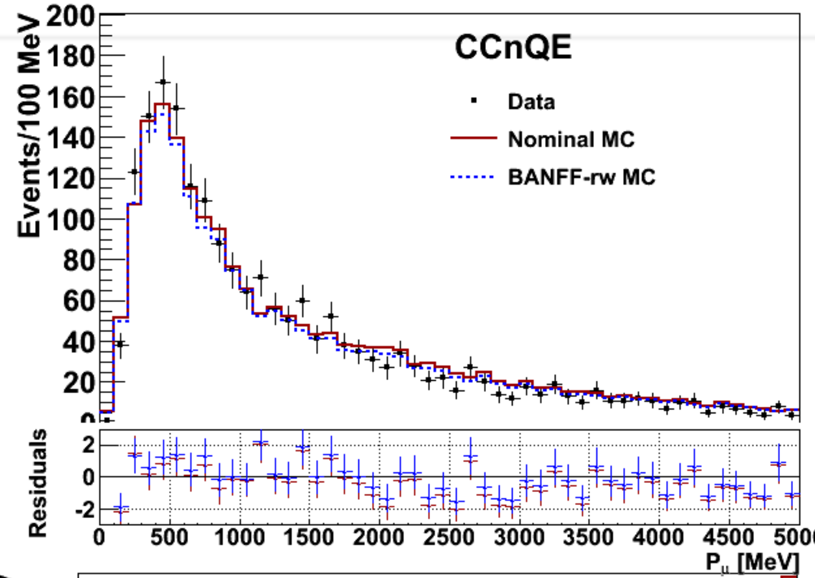
Overview

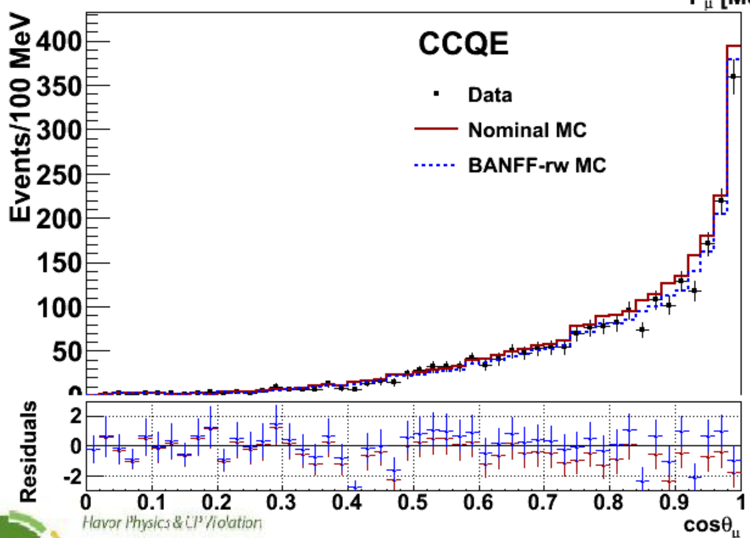


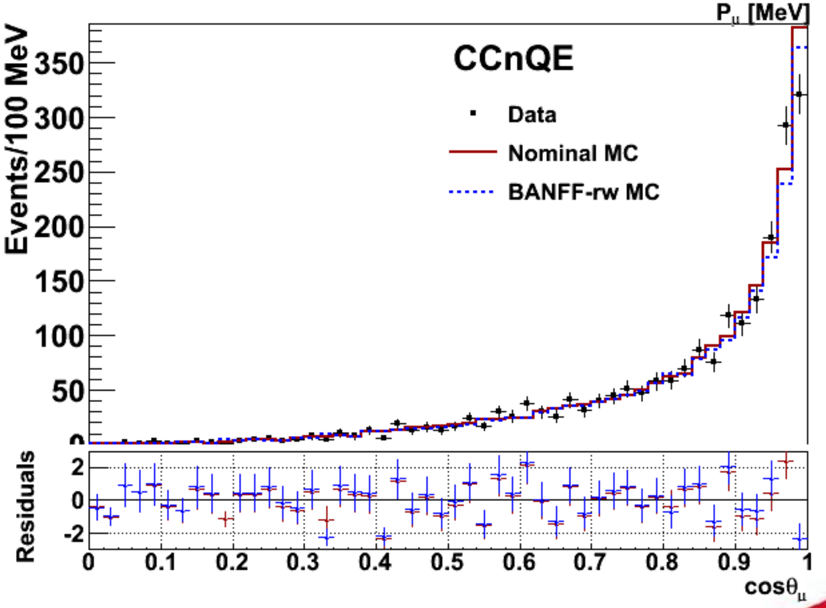
Use event reweighting to model effect of varying parameters.

What are ND280 Inputs?



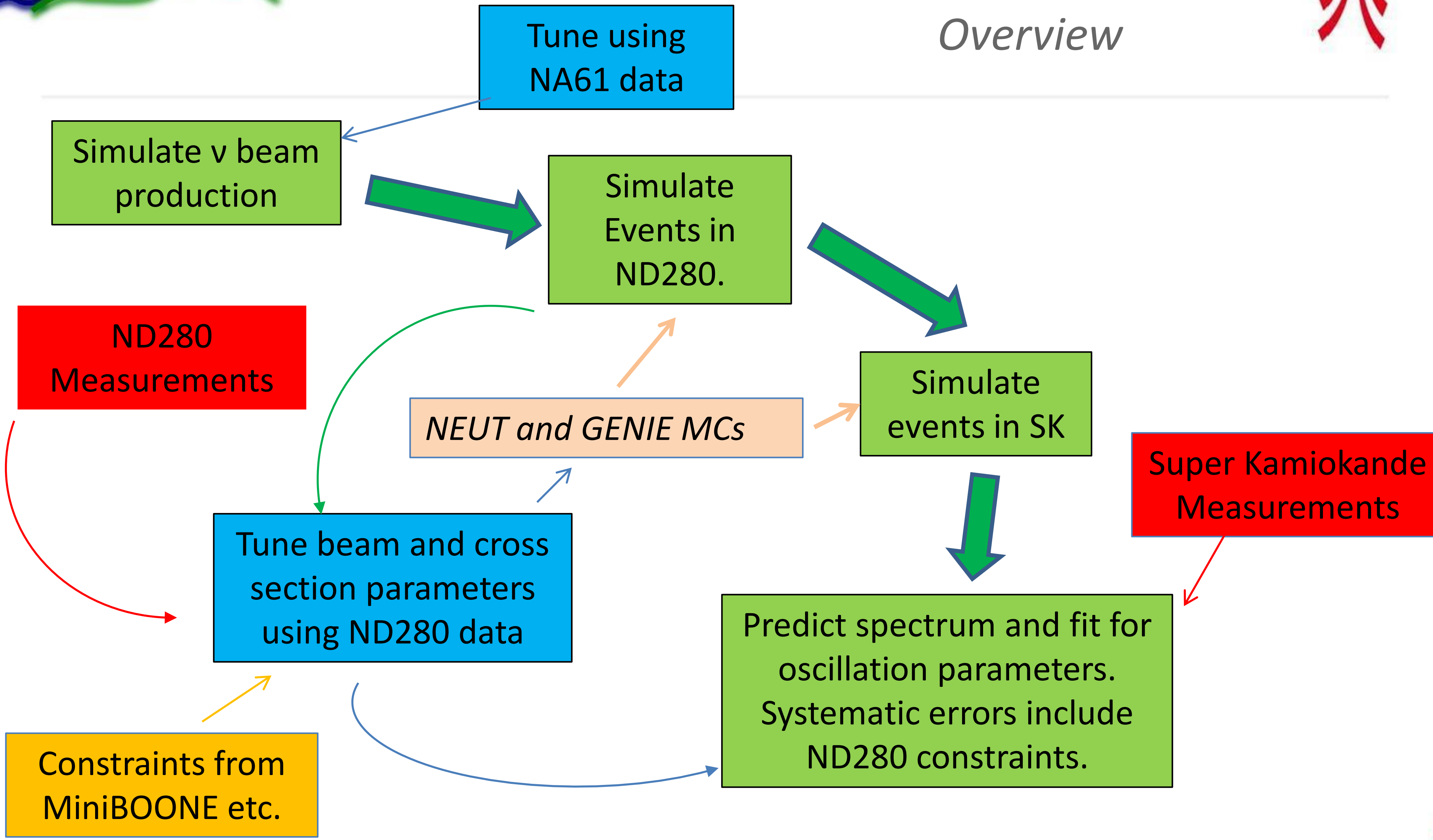






T2K Oscillation Analysis

Overview



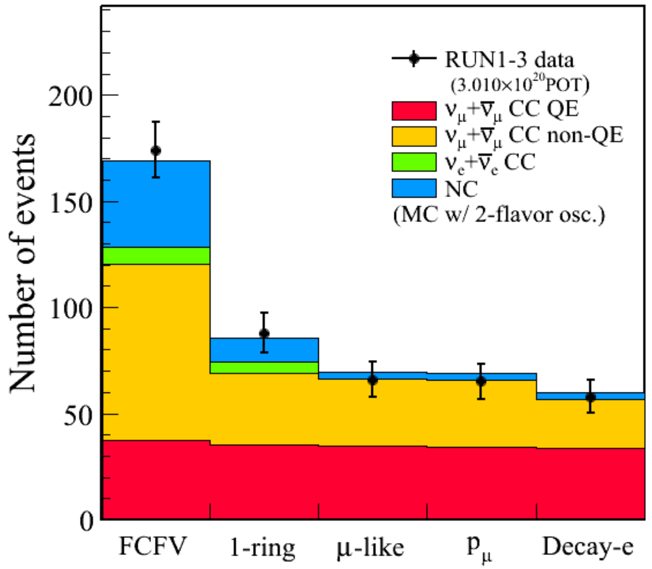
Use event reweighting to model effect of varying parameters.

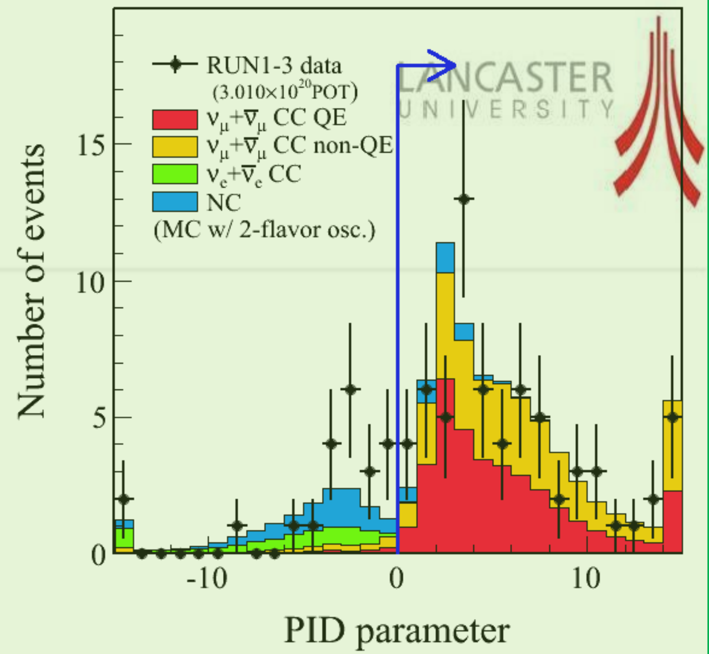
Muon neutrino disappearance

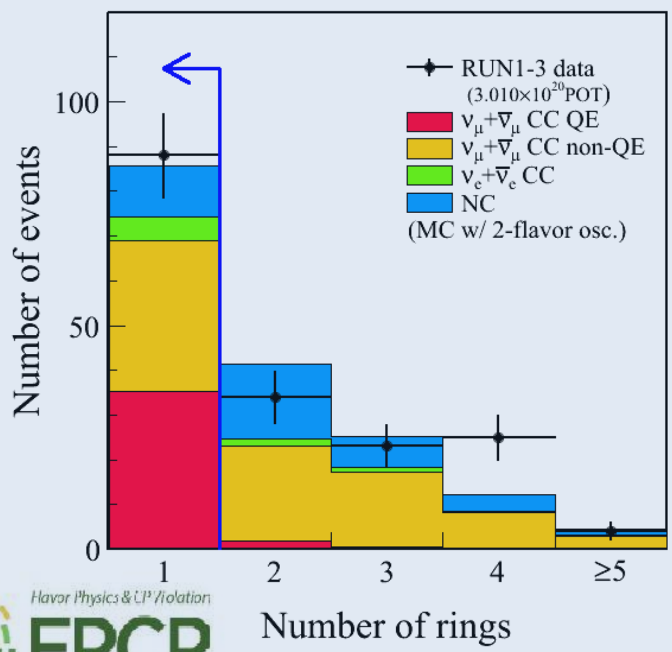
Overview

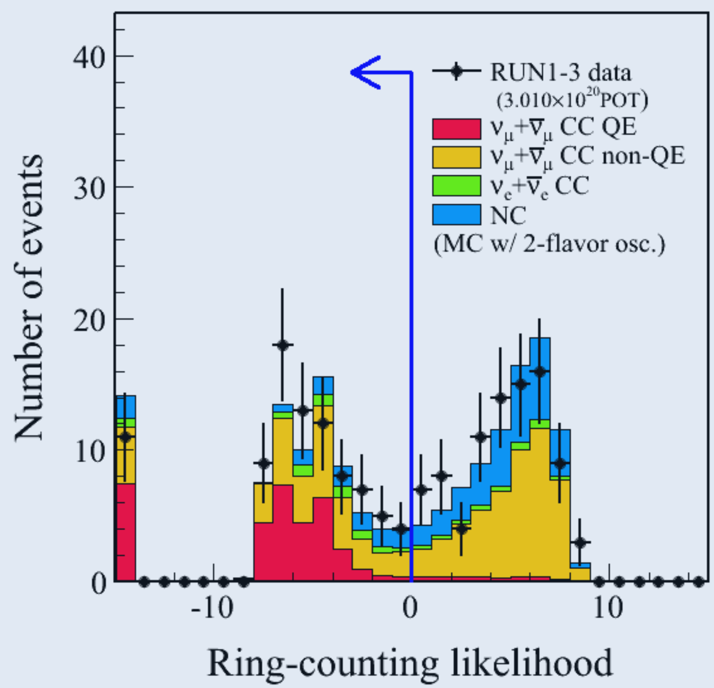
- Observe muon neutrinos from J-PARC in Super Kamiokande
- Predict number using beam MC constrained by ND280 measurements
- Fit reconstructed neutrino energy spectrum and thus
- Measure $sin^2 2\theta_{23}$, and Δm_{32}

ν_μ Selection at Far Detector (SK)









ν_μ Event Selection contd.

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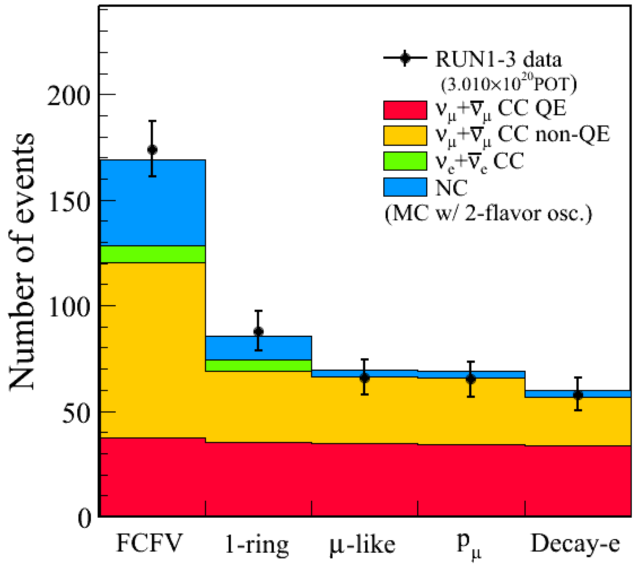
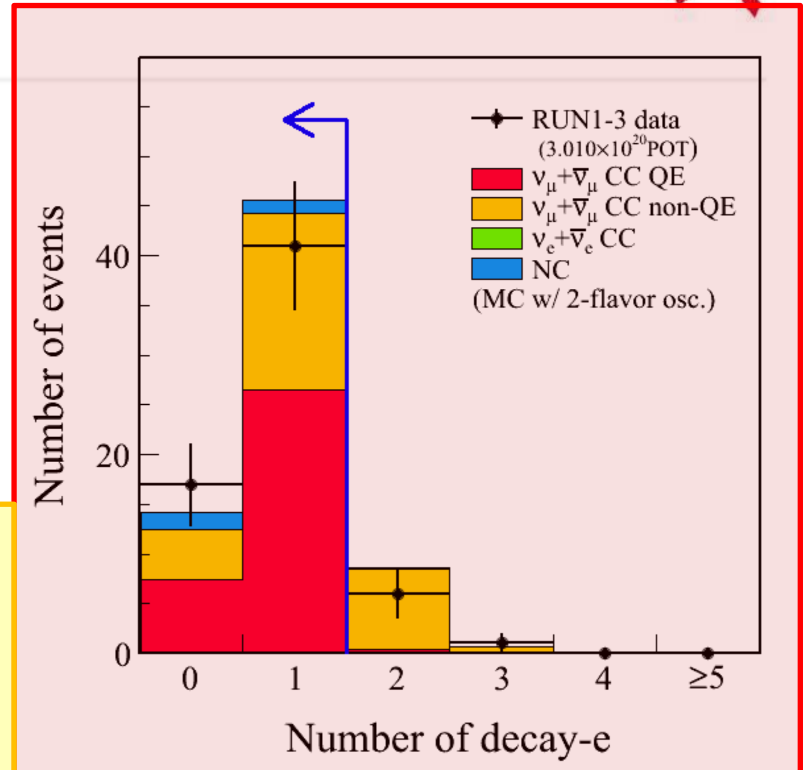
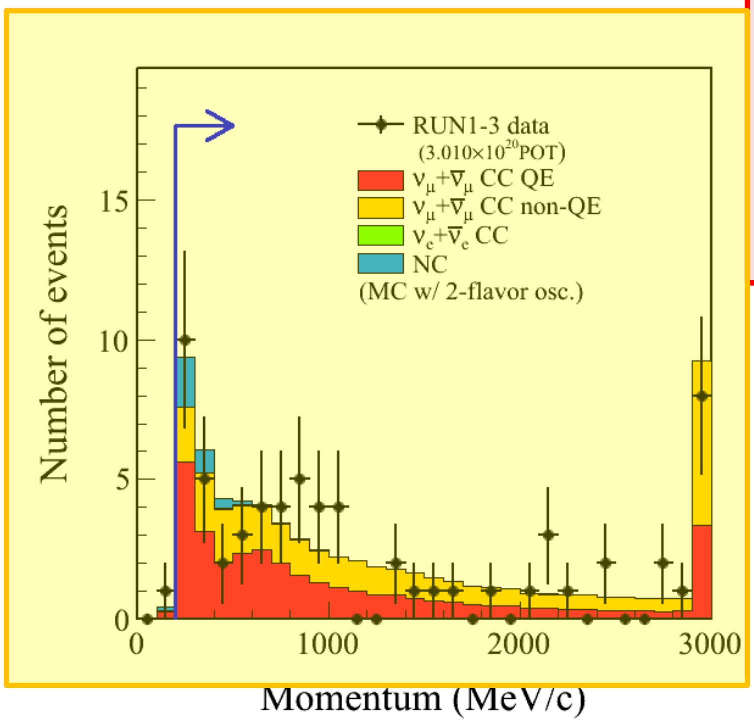




> 200 MeV/c



Electron observed later in time than μ consistent with beng from decay of μ.

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Muon Neutrino Disappearance

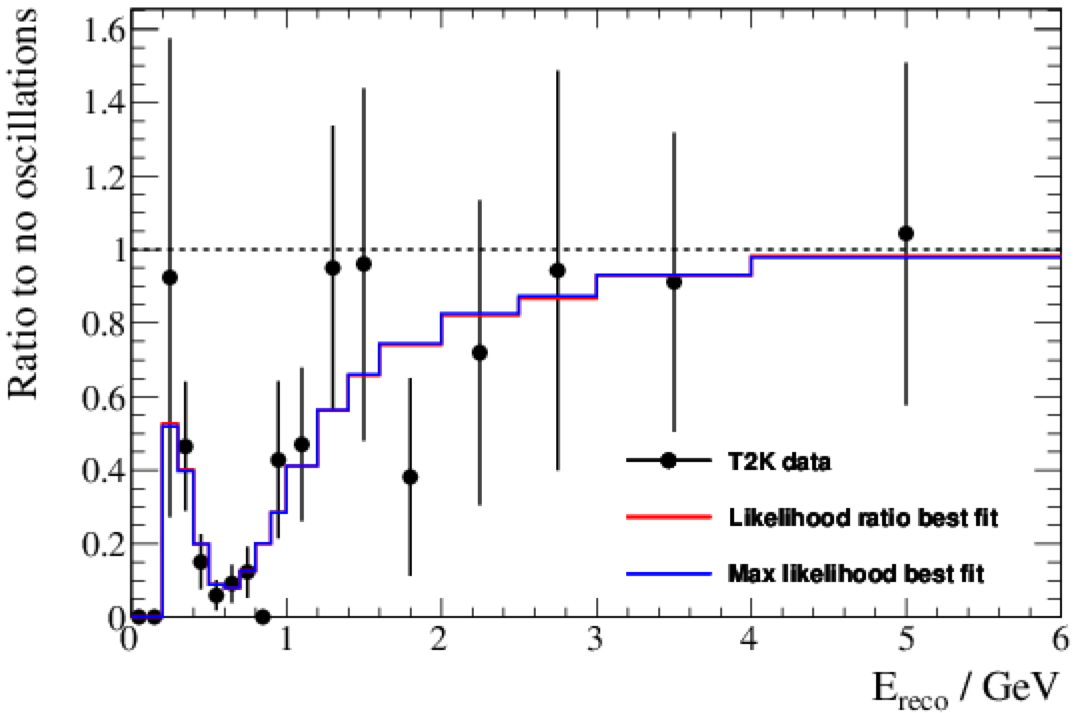
Count number of muon neutrino events in Super Kamiokande

RUN1+2+3 3.010×10^{20}POT	Data	MC Expectations w/ oscillation				
		MC total	$\nu_\mu+\bar{\nu}_\mu$ CCQE	$\nu_\mu+\bar{\nu}_\mu$ CC non-QE	$\nu_e+\bar{\nu}_e$ CC	NC
True FV	-	299.35	49.67	109.50	8.62	131.56
FCFV	174	168.86	37.60	82.80	8.24	40.23
One-ring	88	85.65	35.27	33.67	5.28	11.43
μ-like	66	69.67	34.58	31.61	0.04	3.43
p_μ>200MeV/c	65	69.25	34.34	31.54	0.04	3.33
$N_{dcy\text{-}e}$<=1	58	59.86	33.90	22.73	0.04	3.19
Efficiency [%]	-	20.0	68.2	20.8	0.4	2.4

95% CC – of which 64% CCQE

Muon Neutrino Disappearance

Plot spectrum as a function of reconstructed ν energy.
Fit for oscillation parameters.



Oscillation Fitting

Results

90% Confidence Level allowed region:

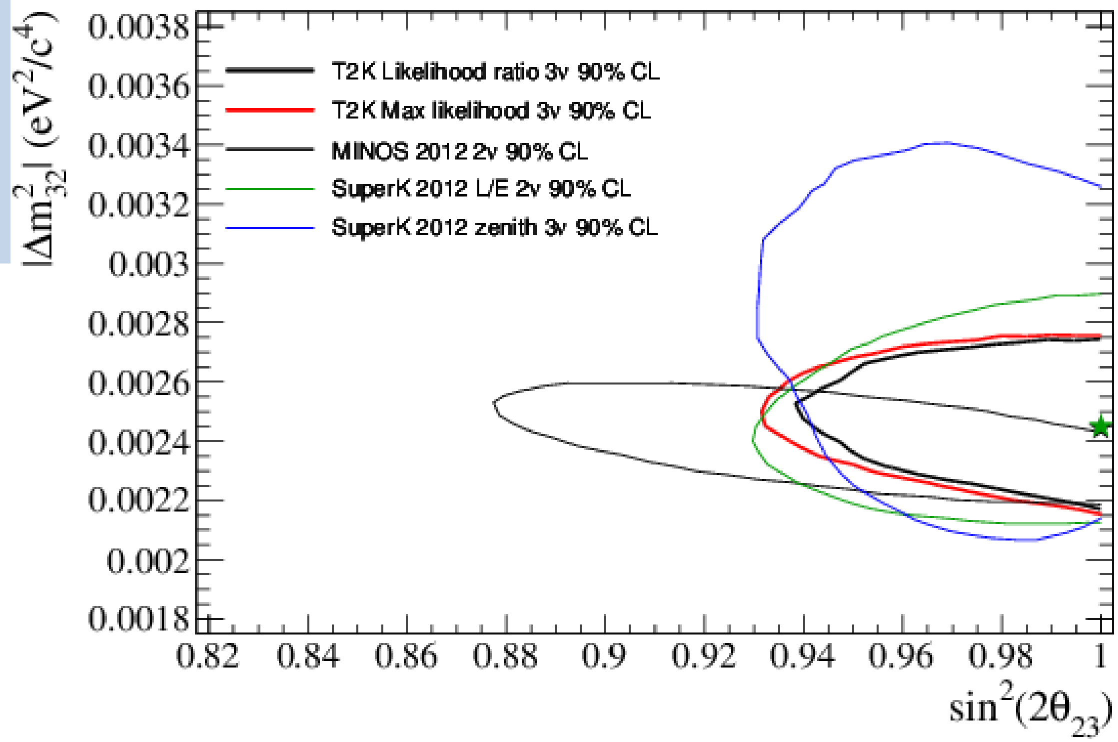
$2.14 \times 10^{-3}\, eV^2/c^4 < |\Delta m_{32}| < 2.76 \times 10^{-3}\, eV^2/c^4$

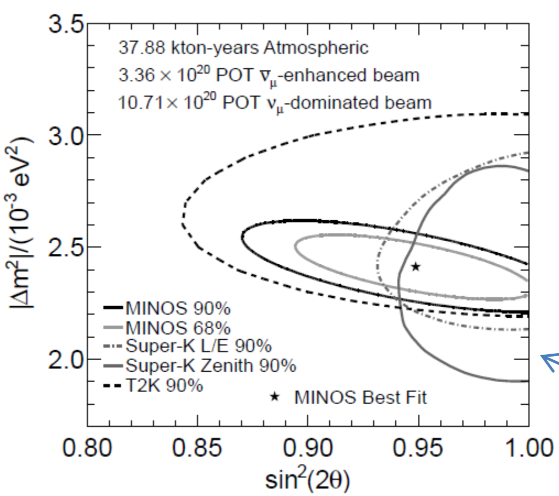
$sin^2 2\theta_{23} > 0.957$

Best fit values:

$|\Delta m_{32}| = 2.44 \times 10^{-3}\, eV^2/c^4$

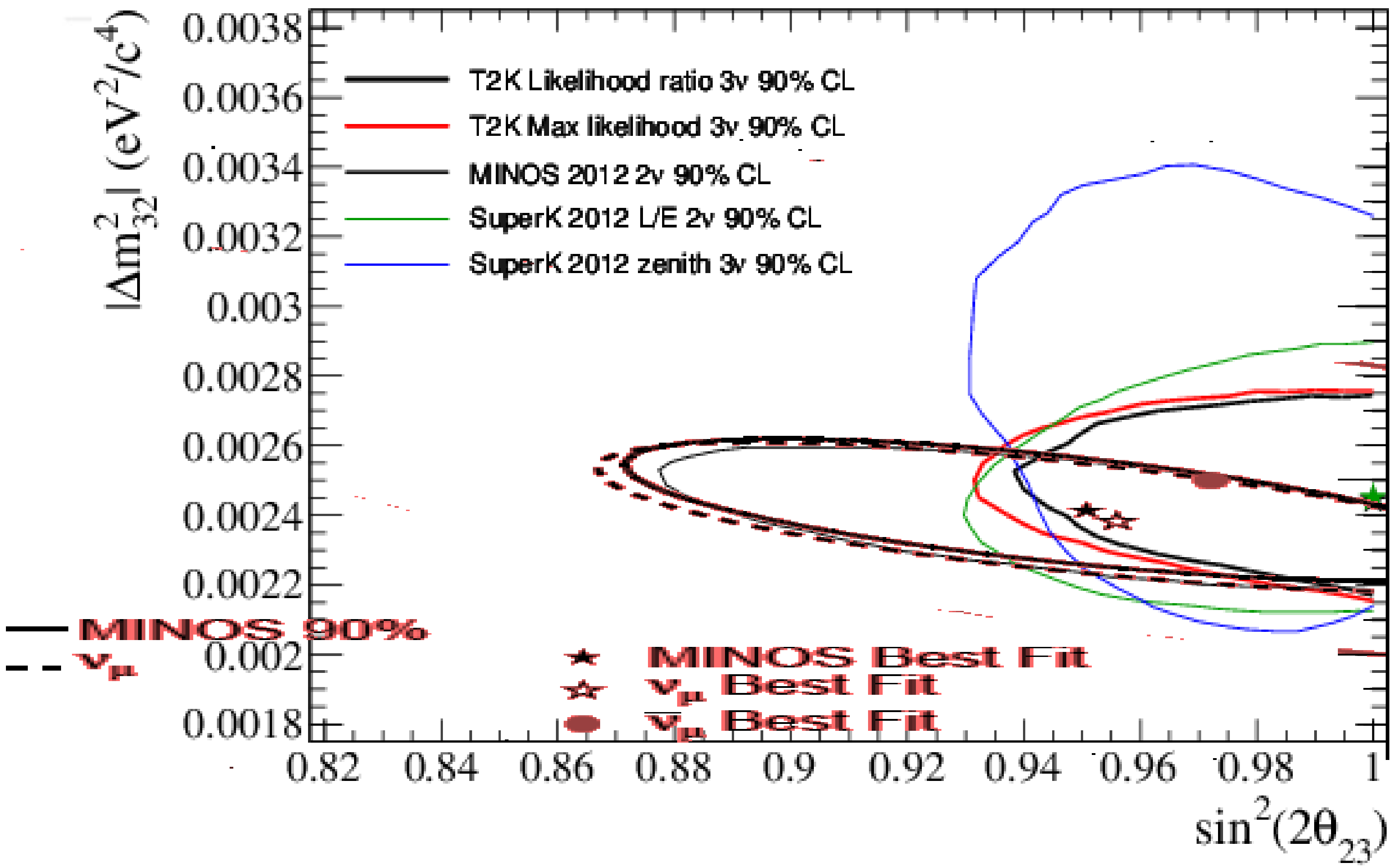
$sin^2 2\theta_{23} = 1.0$





New MINOS result: combined fit of beam and atmospheric results
http://uk.arxiv.org/abs/1304.6335
8th May 2013

Latest MINOS Result Overlaid on T2K



Electron Neutrino Appearance

Recent history

- 2011 result
  - Observed 6 events
    - (Run 1 and 2 data – before earthquake 11 March 2011)
  - $0.03 < sin^2 2\theta_{13} < 0.28$
    - for δCP=0 and normal hierarchy.
- Reactor results
  - 29 Dec 2011 Double Chooz $0.017 < \sin^2 2\theta_{13} < 0.16$. (90% CL)
  - 8 March 2012 Daya Bay announces 5.2σ measurement of θ_{13}

  $sin^2 2\theta_{13} = 0.092 \pm 0.016 \text{ (stat)} \pm 0.005 \text{ (syst)}$

  Confirmed 1 month later by RENO

  See talk by Kwong Lau
- Our new result
  - Run1 + Run2 + Run 3

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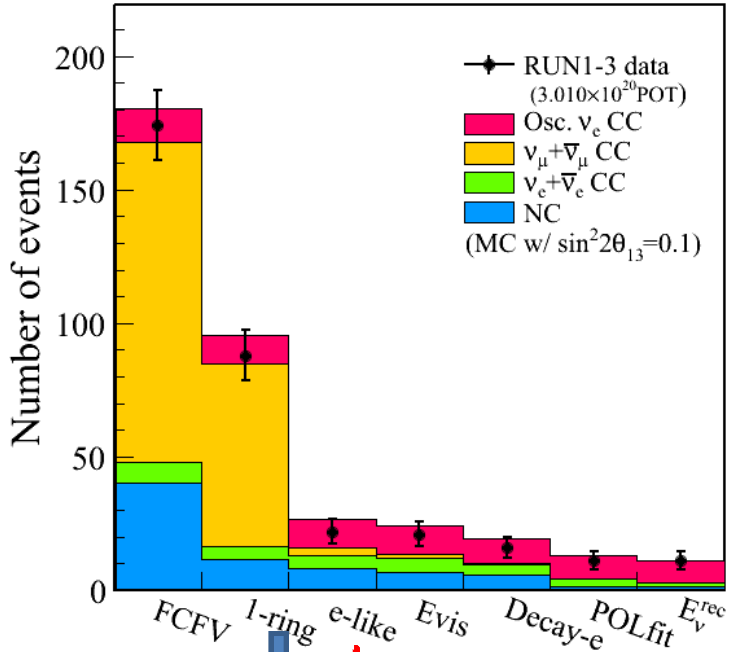
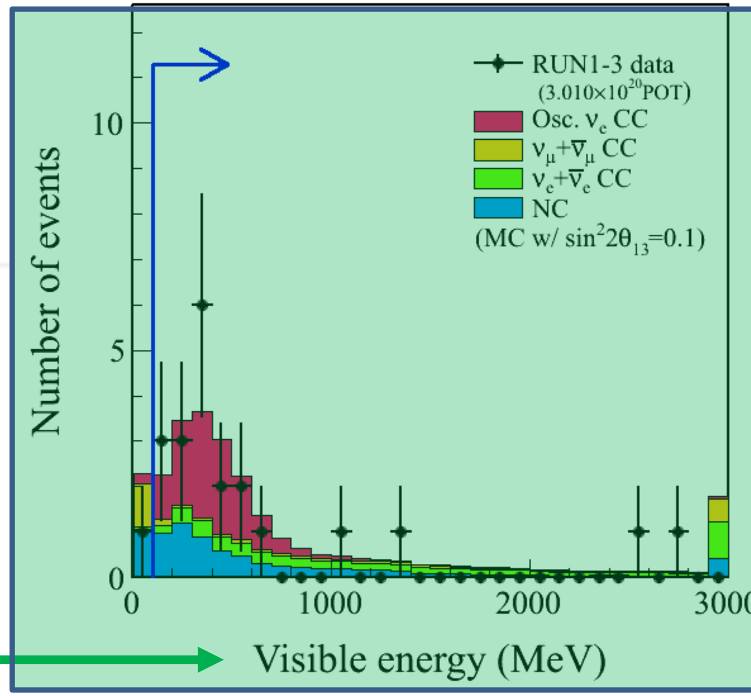
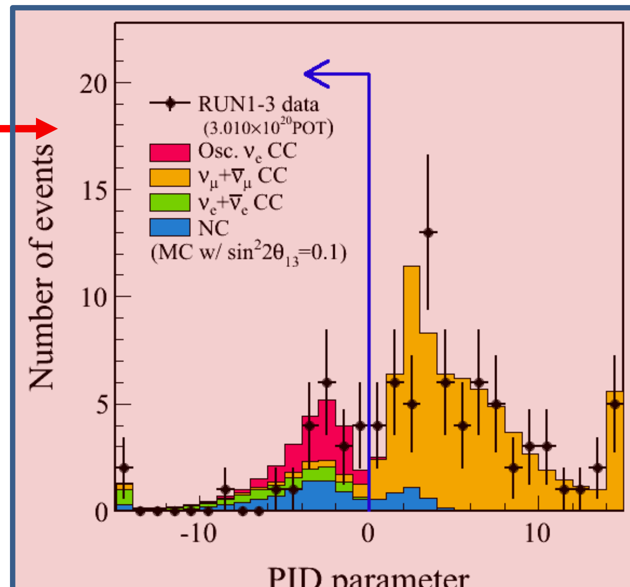
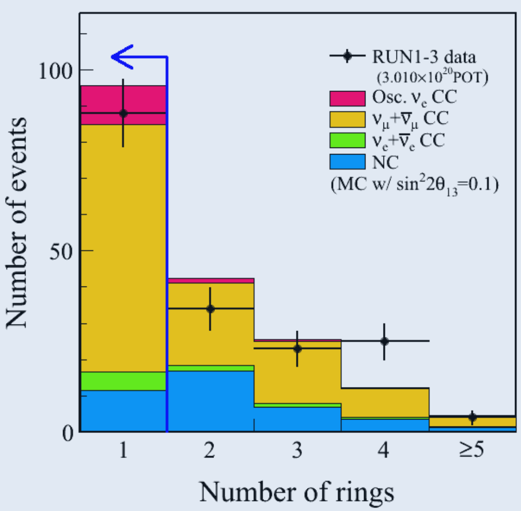
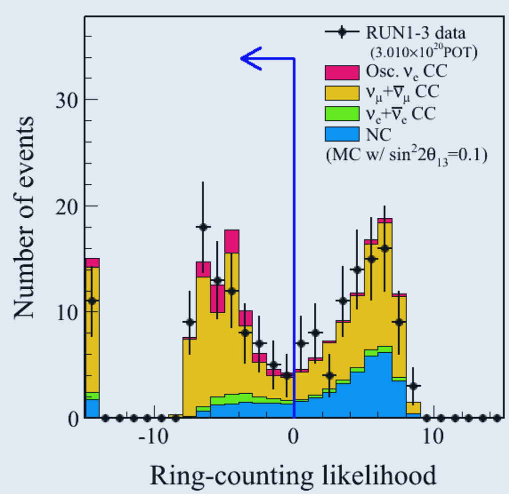
Electron Neutrino
Candidate Selection (at SK)





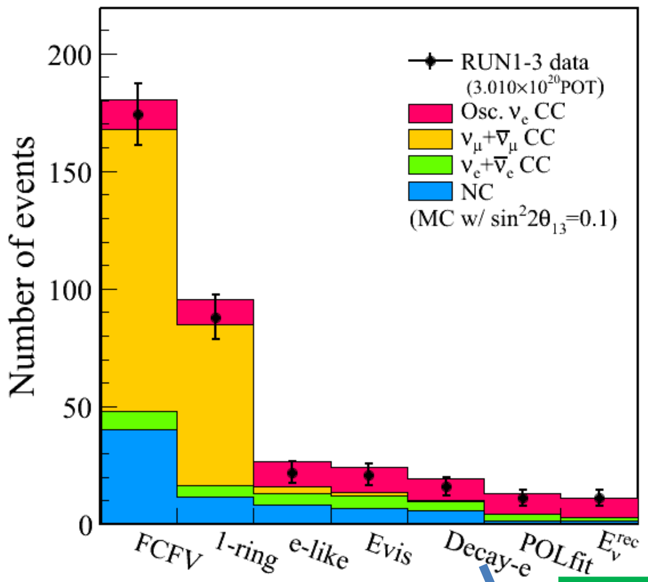


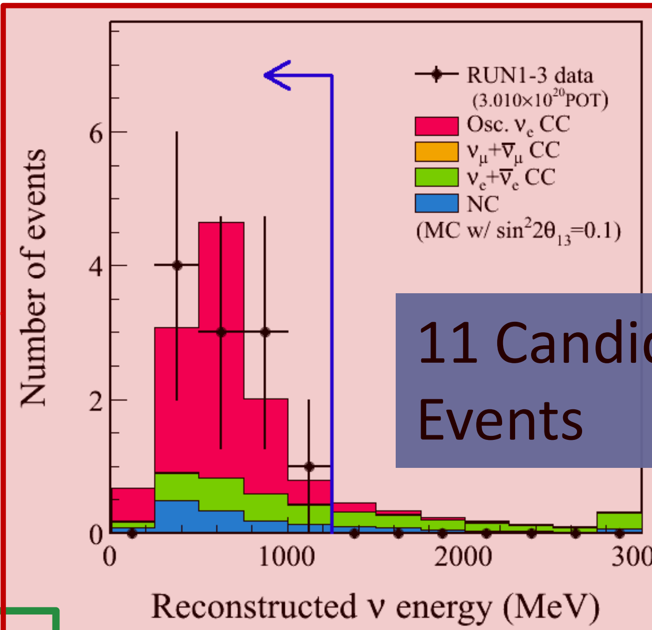




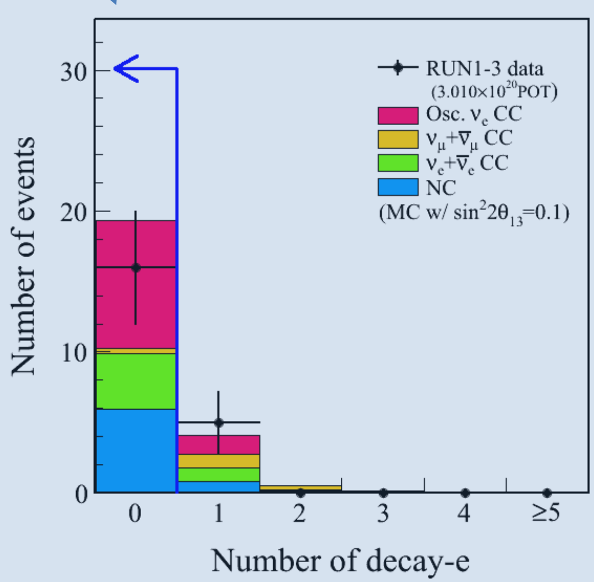
Electron Neutrino

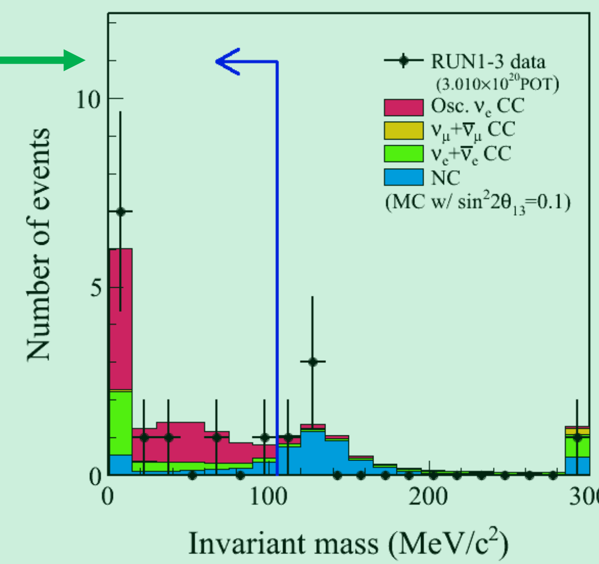
Candidate Selection (continued)



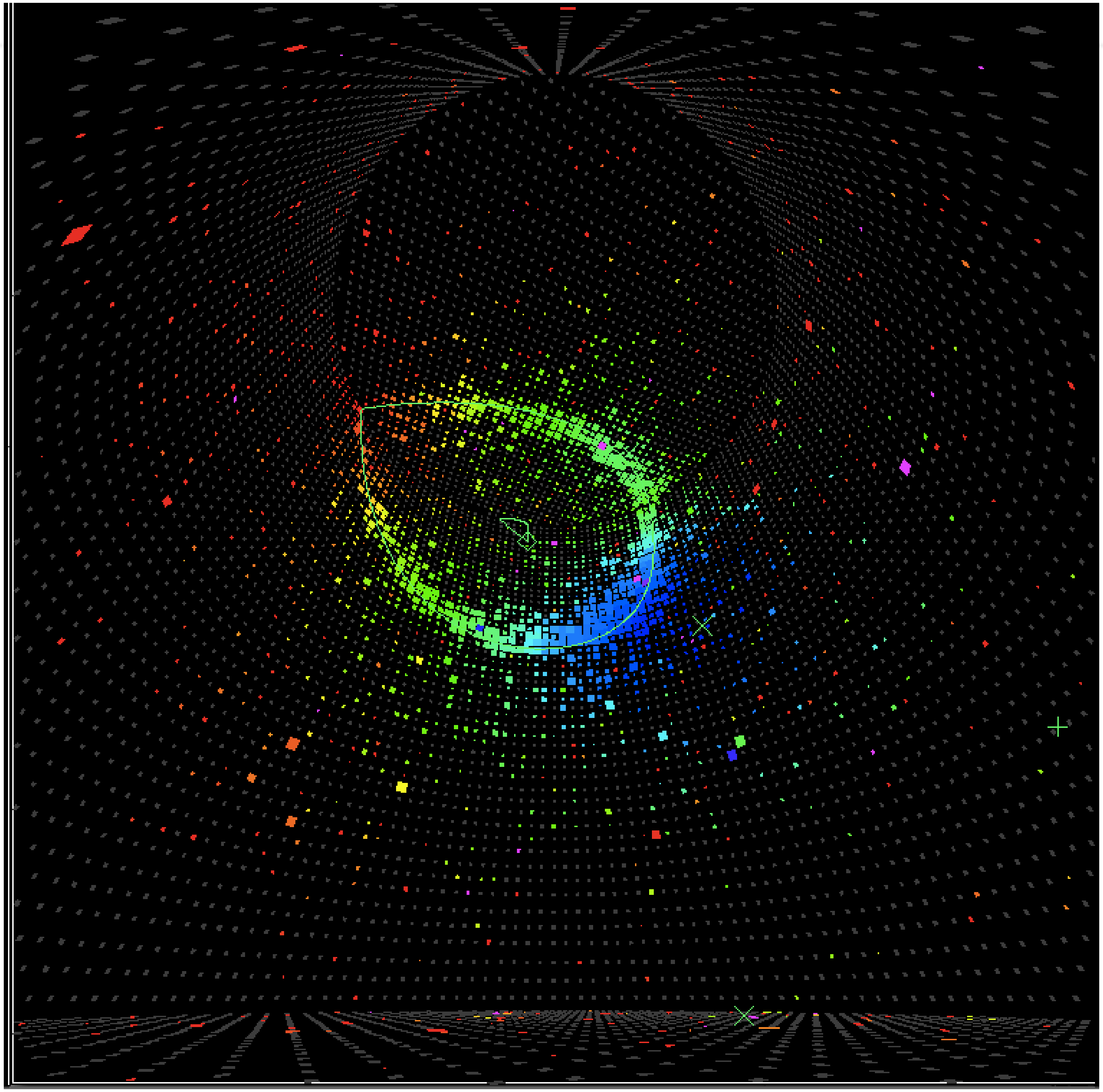


11 Candidate Events

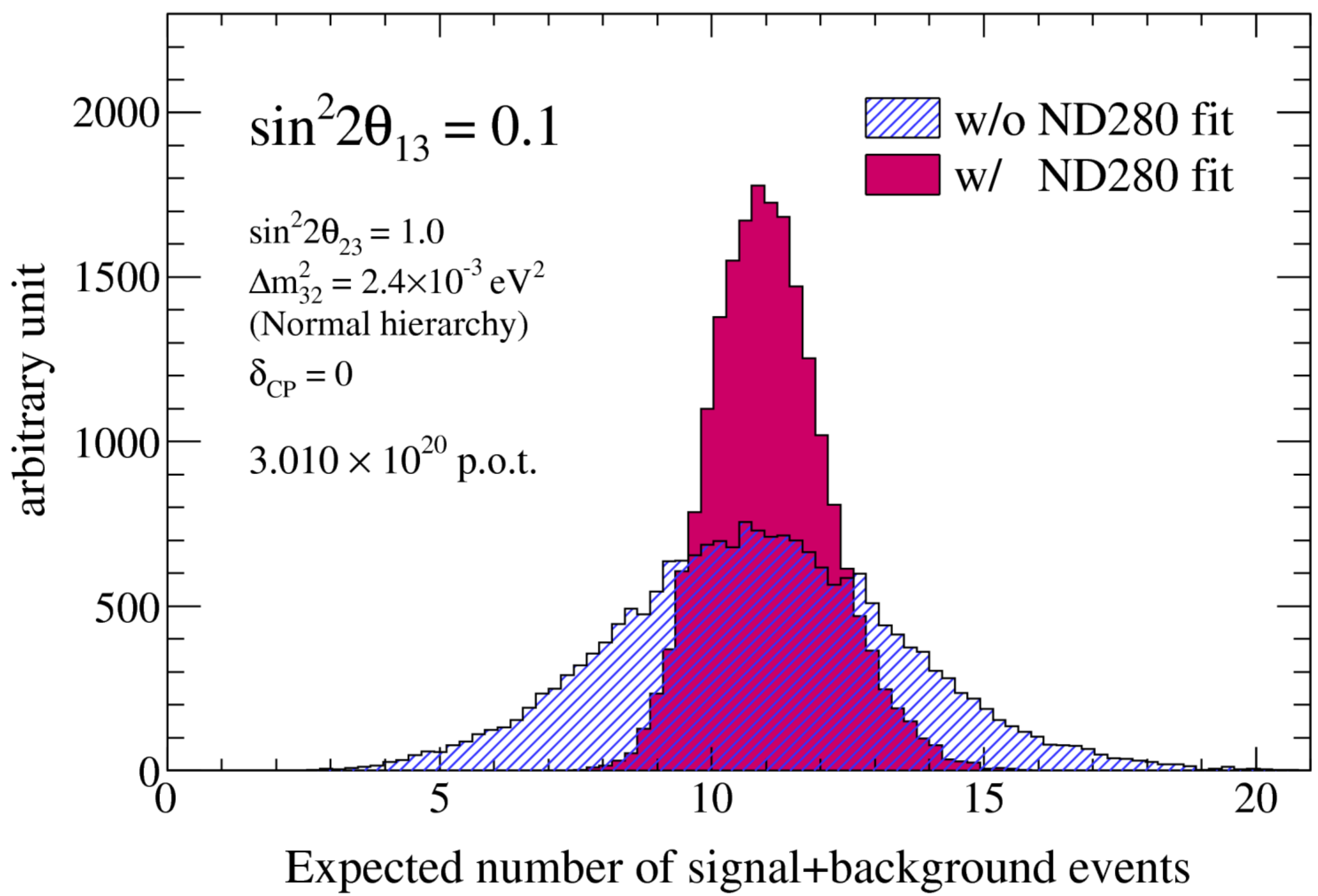




ν_e candidate #11

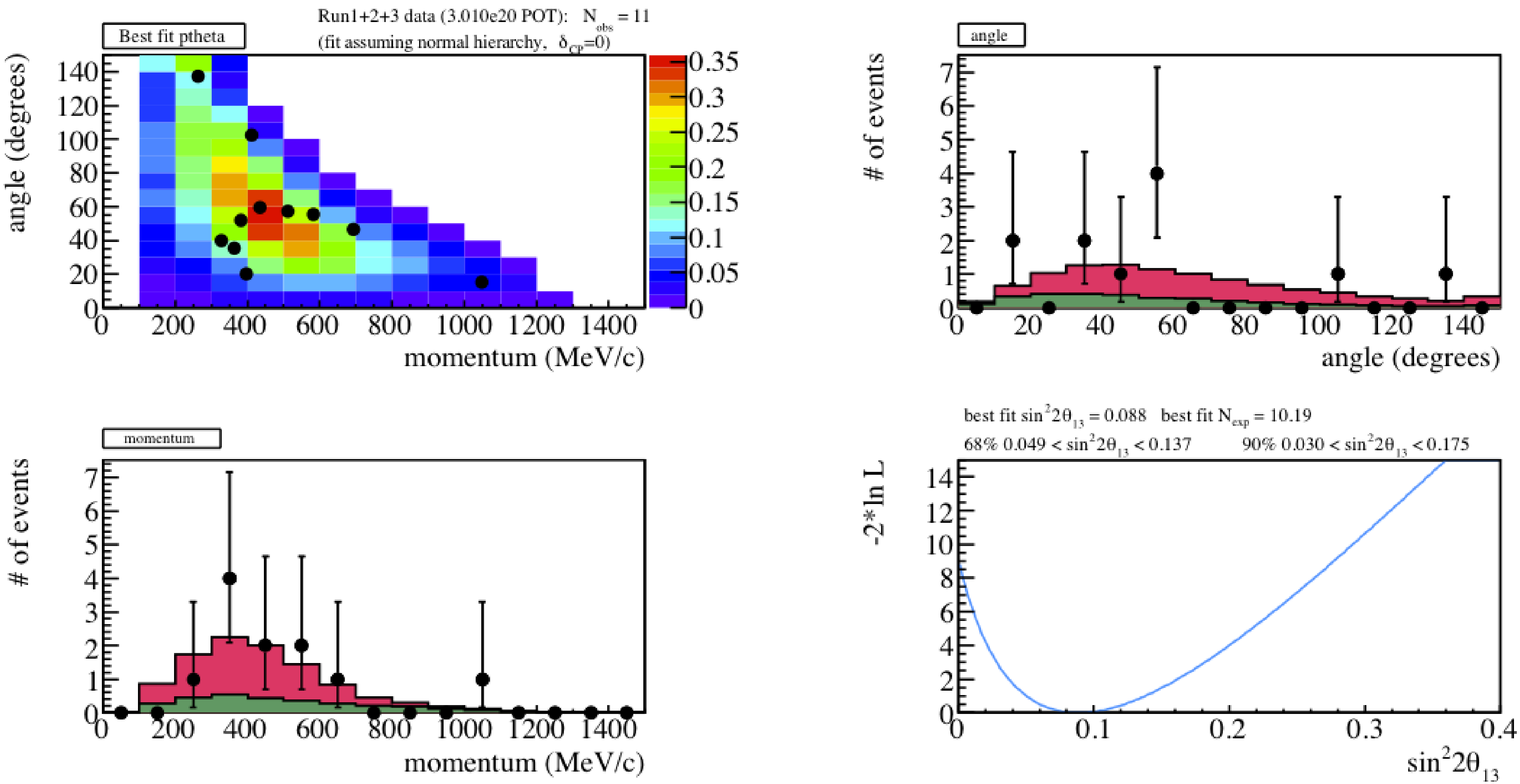


Effect of ND280 Constraint



Electron Neutrino

Summary



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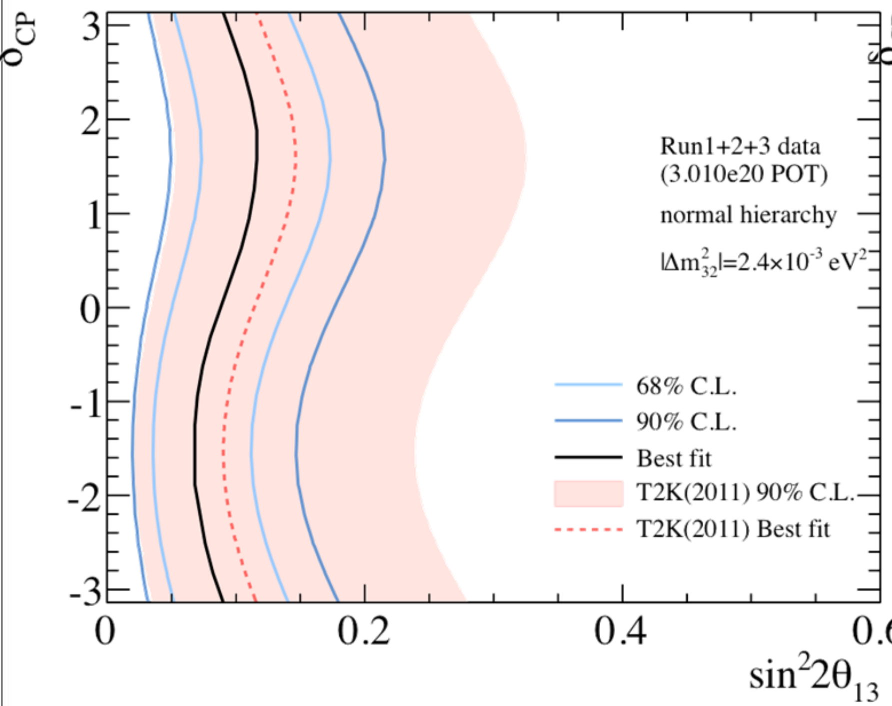
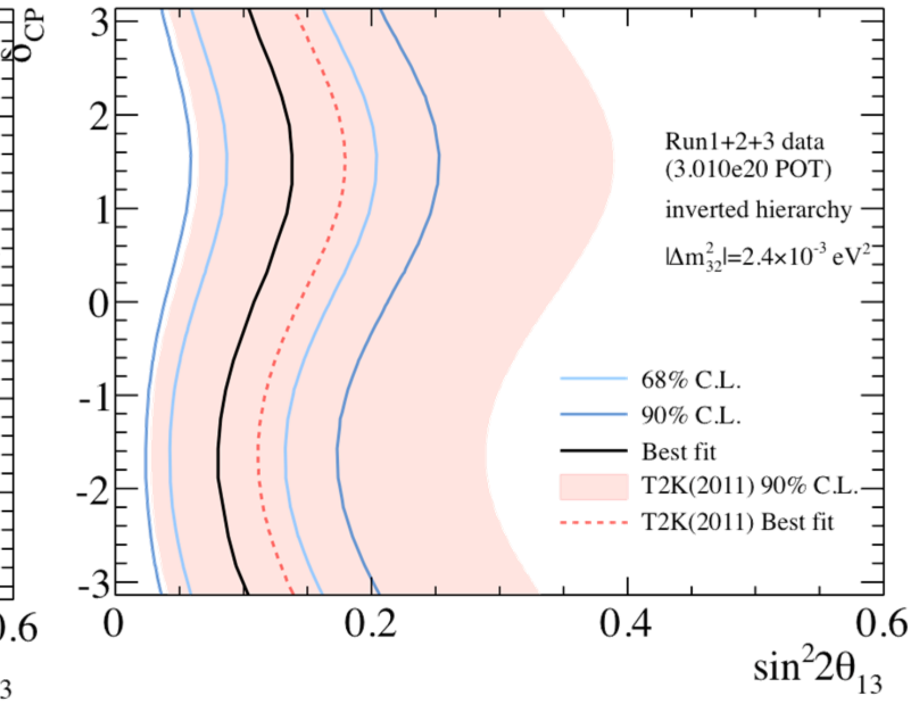
Electron Neutrino

Fit results

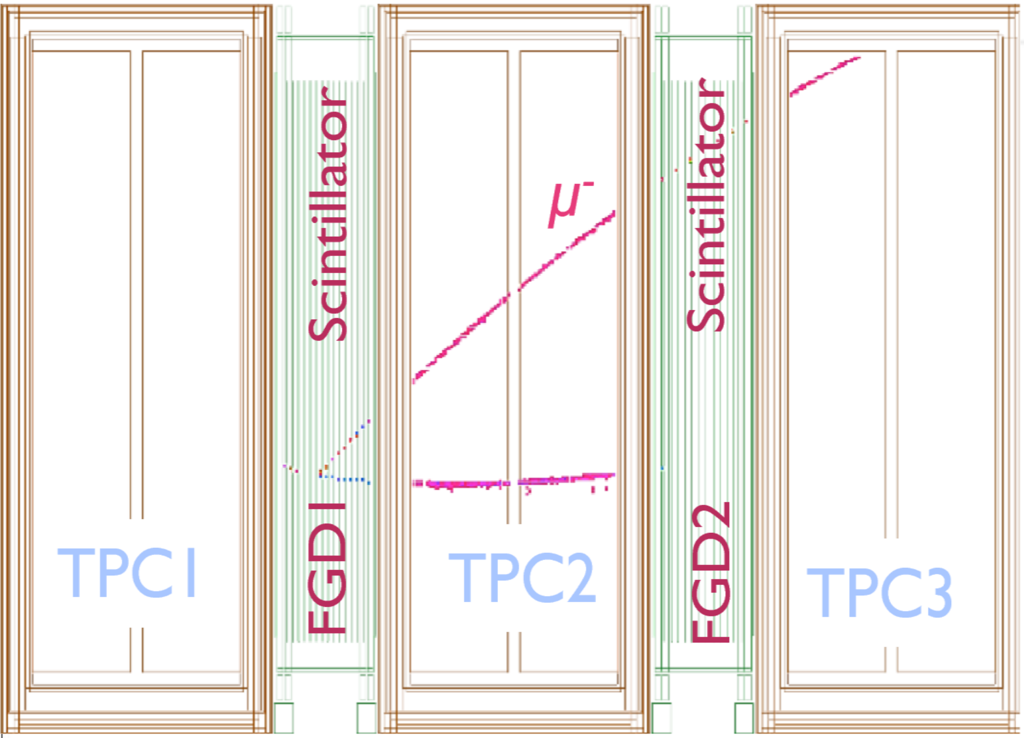




$0.030 < \sin^2 2\theta_{13} < 0.175$ (90%CL)

$0.038 < \sin^2 2\theta_{13} < 0.212$ (90%CL)

CC Inclusive Cross Section



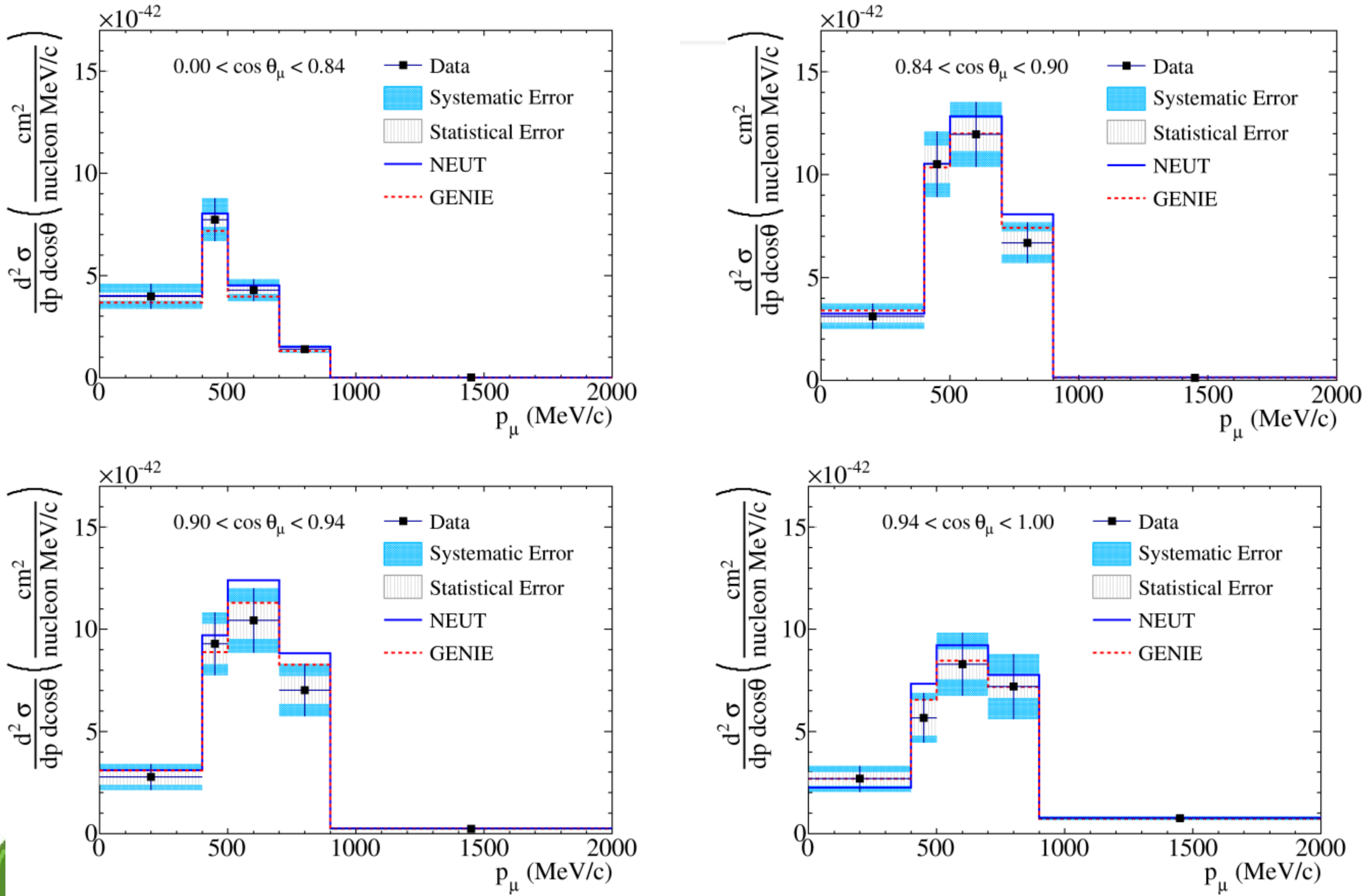
- ND280 Run1 and 2 data
- Detect ν_μ in FGD1 of ND280
  - Good Data Quality
  - >0 -ve track in TPC
  - Track starts in FGD1
  - dE/dx of -ve track consistent with μ
  - No activity upstream of FGD
- Unfold to true μ p/θ bins
- Convert to differential cross section

Efficiency = 50%
Purity = 88%

Main backgrounds:
Events not in FGD1
Neutral current

CC Inclusive

Results (Binned)



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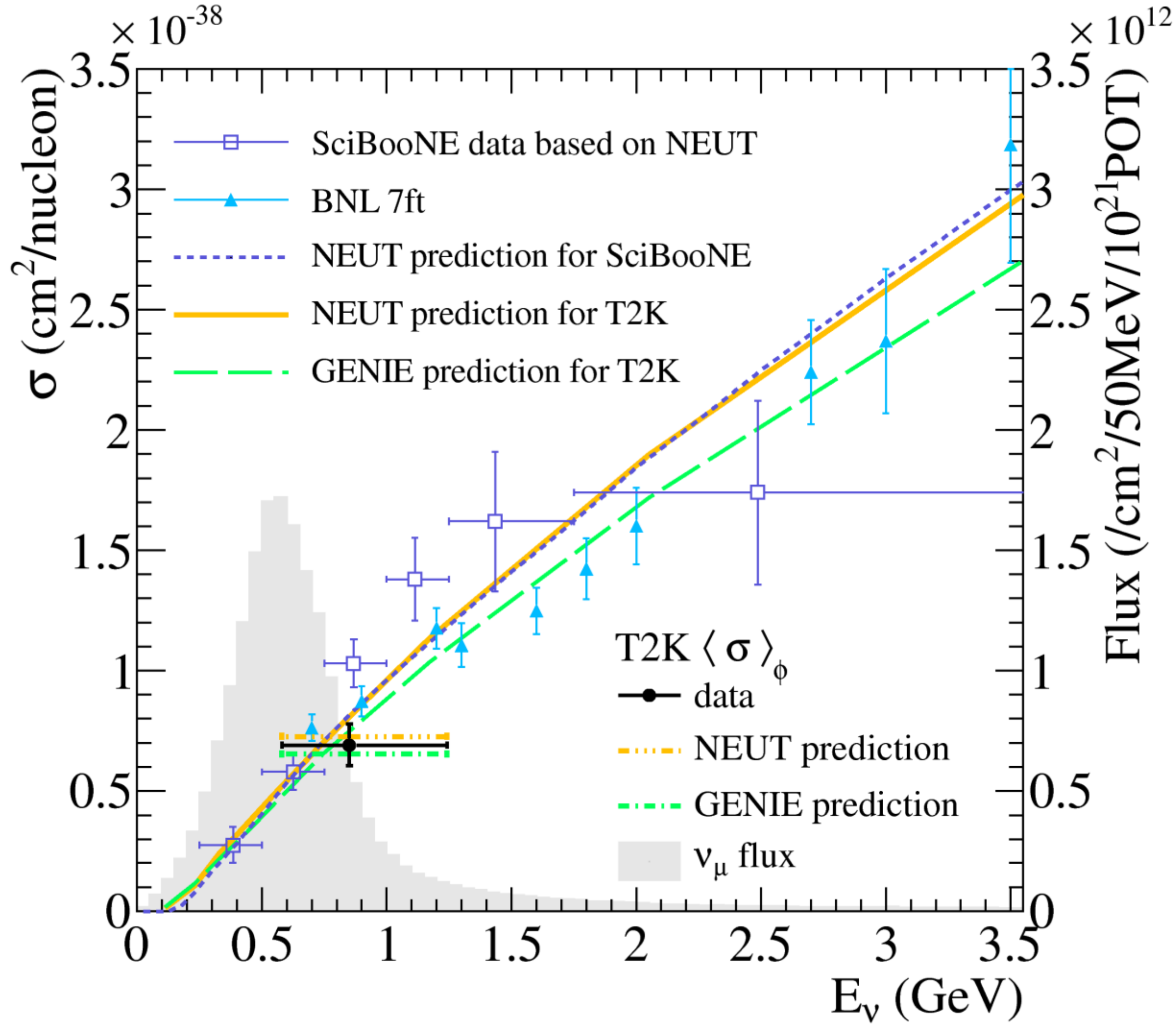
$<\sigma_{CC}>_{\phi}=(6.93\pm0.13(stat)\pm0.85(syst)\times10^{-39}cm^2/nucleon$



Future Prospects

Current Run / Near Term

- More data
  - Plan is to collect sufficient data before long shutdown for a 5σ measurement of θ_{13}
- Improved reconstruction
- More ND280 cross section measurements
- Which will all help to produce more accurate measurement.

Future Prospects

Future Runs / Long Term

- More of the above and..
- Anti neutrino running?
- Synergies with NOVA...
- Possible sensitivity to CP violation.

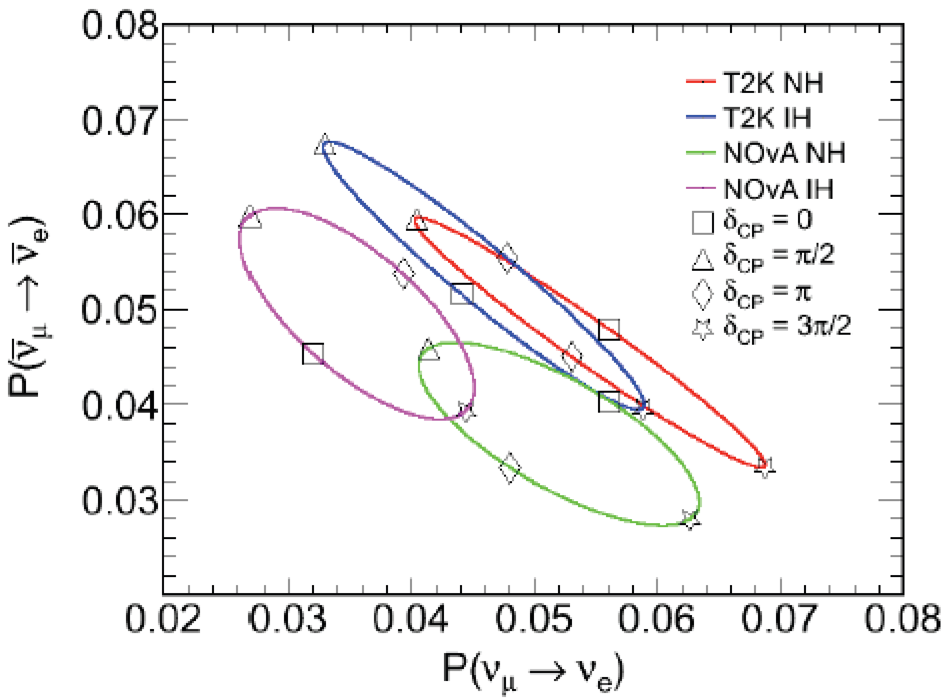
NOVA:
Long baseline experiment Fermilab -> Ash River (810 km)
=> Larger matter effects than T2K
Off Axis
E=2GeV
First beams now (Spring 2013)
Detector completed this time next year
Expect 5σ on θ_{13} by May 2014

Summary

- T2K is well on the way to achieving its original Physics Goals
  - Electron neutrino appearance
  - Muon neutrino disappearance
  - Neutrino cross sections
- Lots more to come in the next few years

BACKUP

$P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ with matter effects



$\sin^2(2\theta_{12}) = 0.87$
$\sin^2(2\theta_{13}) = 0.1$
$\sin^2(2\theta_{23}) = 1.0$
$\Delta m_{12}^2 = 7.6\times10^{-5}$ eV^2
$|\Delta m_{32}^2| = 2.32\times10^{-3}$ eV^2

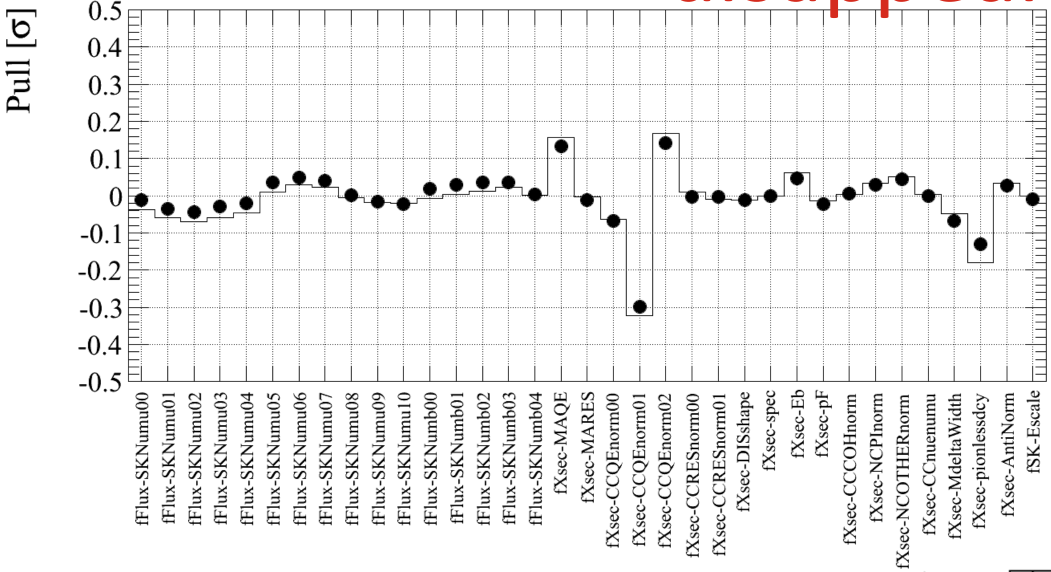
Earth crust density = 2.6 g/cm^3
NH = normal mass hierarchy
IH = inverted mass hierarchy
T2K energy = 0.6 GeV
NOvA energy = 2.0 GeV

T2K might be able to measure δ_{CP} if it is close to $3\pi/2$ (normal hierarchy) or $\pi/2$ (inverted hierarchy). However for most values of δ_{CP}, its effects are entangled with those of the mass hierarchy.

NOvA might be able to measure δ_{CP} if it is between π-2π (normal hierarchy) or 0-π (inverted hierarchy).

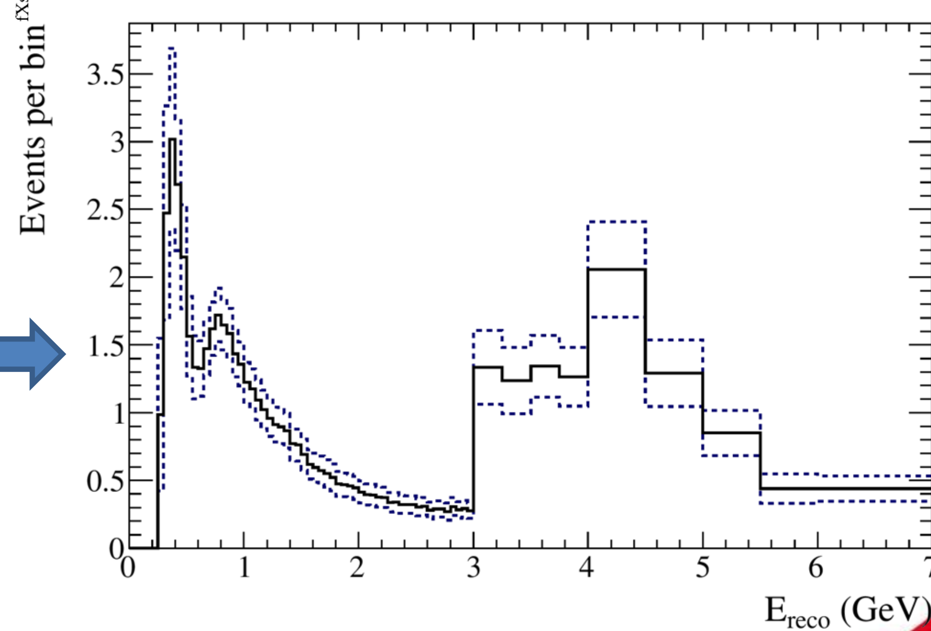
Note that, for $\delta_{CP} = 0$, $P(\nu_\mu \rightarrow \nu_e) \neq P(\nu_\mu\text{bar} \rightarrow \nu_e\text{bar})$. This is due to matter effects.

Systematic errors -ν_μ disappearance

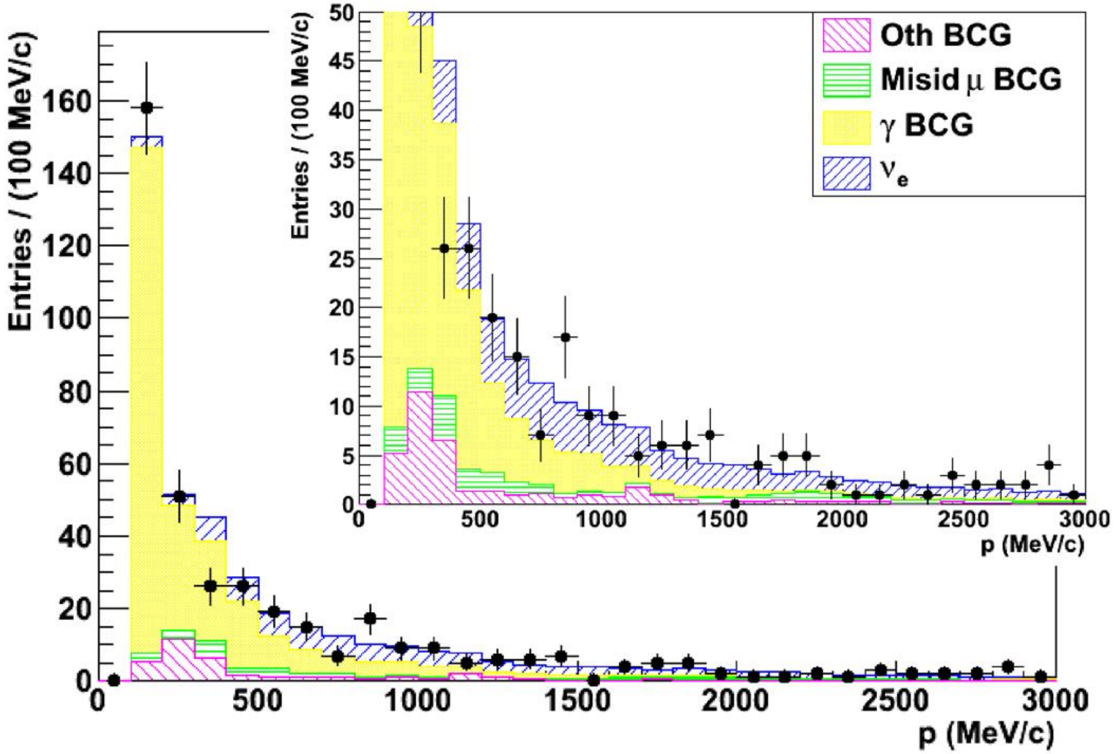


Pulls of systematic parameters at the best fit point using two different fitting methods (histogram/ points)

Total error envelope calculated as ±1σ spread of bin contents using 100k toy MC experiments generated with randomized systematic parameters. All systematic parameters and their correlations were taken into account.



Results in 2012: ν_e flux



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Unfold to find true bins of muon momentum and angle

Differential cross section definition:

$$\langle \frac{\partial^2 \sigma}{\partial p_\mu \partial \cos\theta_\mu} \rangle_{kl} = \frac{N^{\rm int}_{kl}}{T \phi \Delta p_{\mu,k} \Delta \cos\theta_{\mu,l}}$$

- $N^{\rm int}_{kl}$: # of interactions in true bin
- T: # of target nucleons
- ϕ: flux

2D binning: (k,l) → 1D binning: k

Method

Unfolding

$$N^{\rm int}_k \approx \widehat{N}_k = \frac{U_{kj}}{\epsilon_k}(N^{sel}_j - B_j)$$

- U_{kj}: un-smearing matrix
- ϵ_k: efficiency
- N^{sel}_j: # of sel. events
- B_j: background in rec. bin

unfolding based on Bayes' theorem

$$U_{kj} = P(k|j) = \frac{P(j|k)P(k)}{\sum_\alpha P(j|\alpha)}$$

U_{kj} = probability to have an interaction in bin k, when having reconstructed the event in bin j

recc → true