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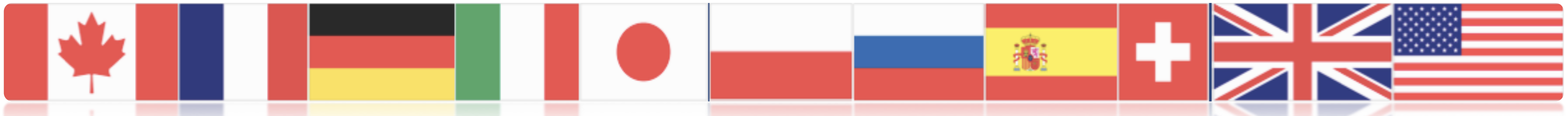
Recent Results from T2K

Jonathan Perkin on behalf of the T2K collaboration



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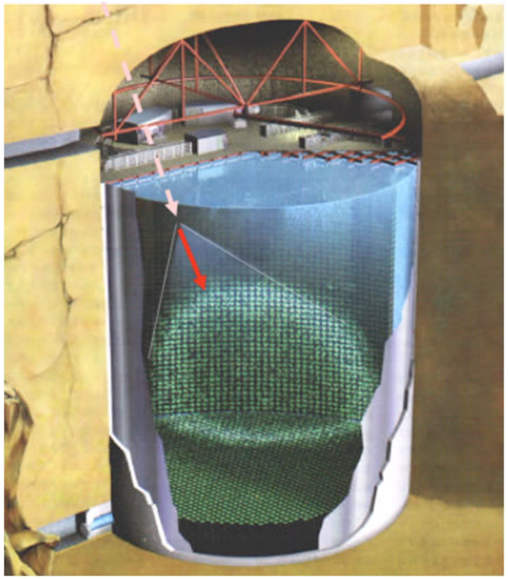
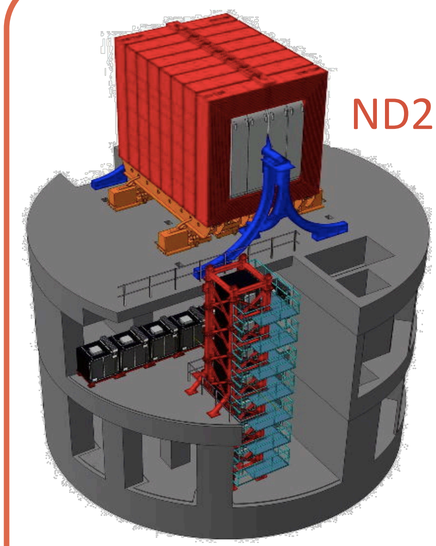
The T2K experiment



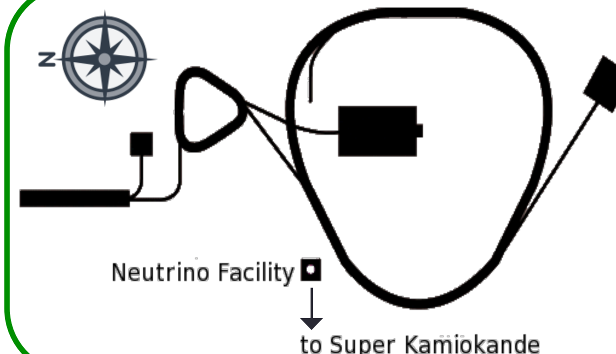
Super-KAMIOKANDE



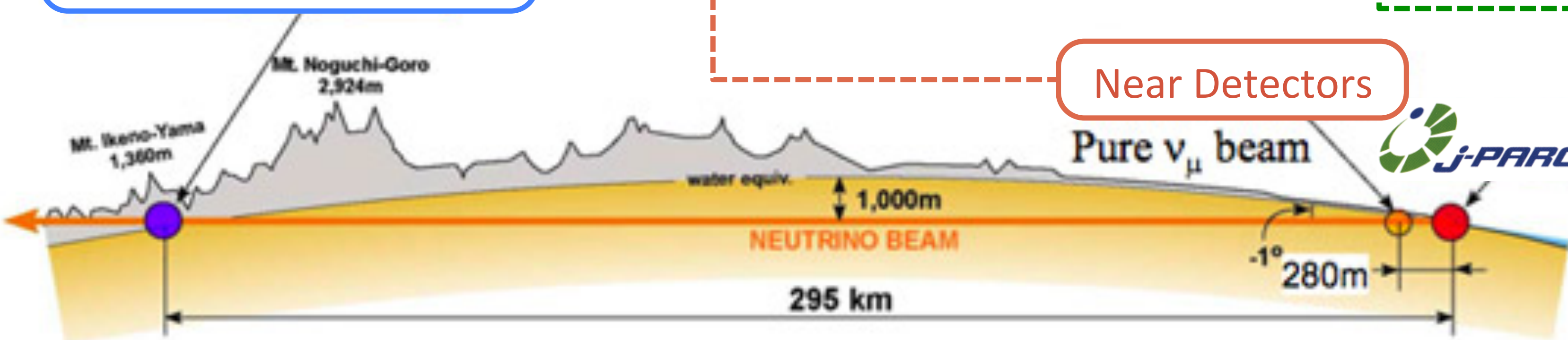
Tokai to Kamioka

$\nu_\mu \rightarrow \nu_e \quad \nu_\mu \rightarrow \nu_\mu$

~500 Collaborators
59 Institutions
11 Countries



Near Detectors



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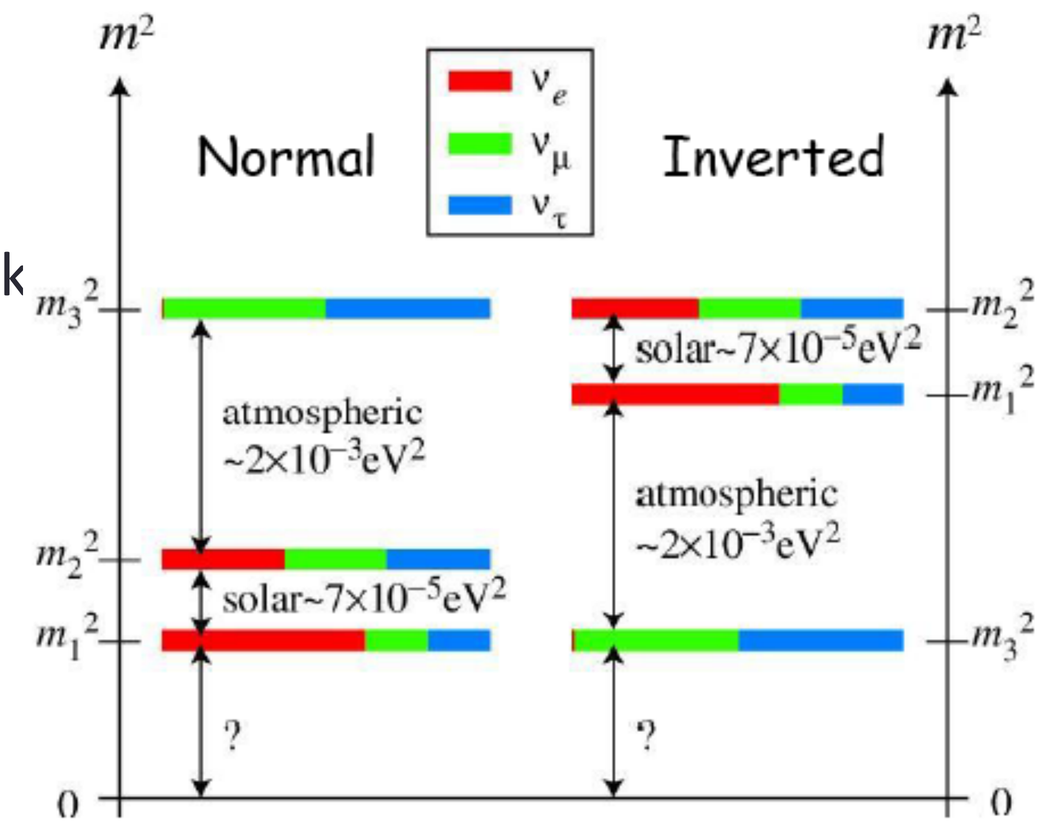
neutrino mixing

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

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{atmospheric}} \times \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix}}_{\text{reactor}} \times \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{solar}} \times \underbrace{\begin{pmatrix} e^{i\alpha_1}/2 & 0 & 0 \\ 0 & e^{i\alpha_2}/2 & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Majorana}} \times \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- flavour eigenstates ≠ mass eigenstates
- described by (decomposed) PMNS matrix
- analogous to mixing in quark sector [CKM]
  - however mixing angles are comparatively large
- neutrino mass hierarchy presently unknown
  - only mass splittings are measured

in the 3-neutrino picture



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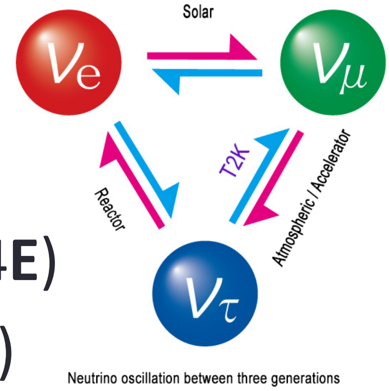
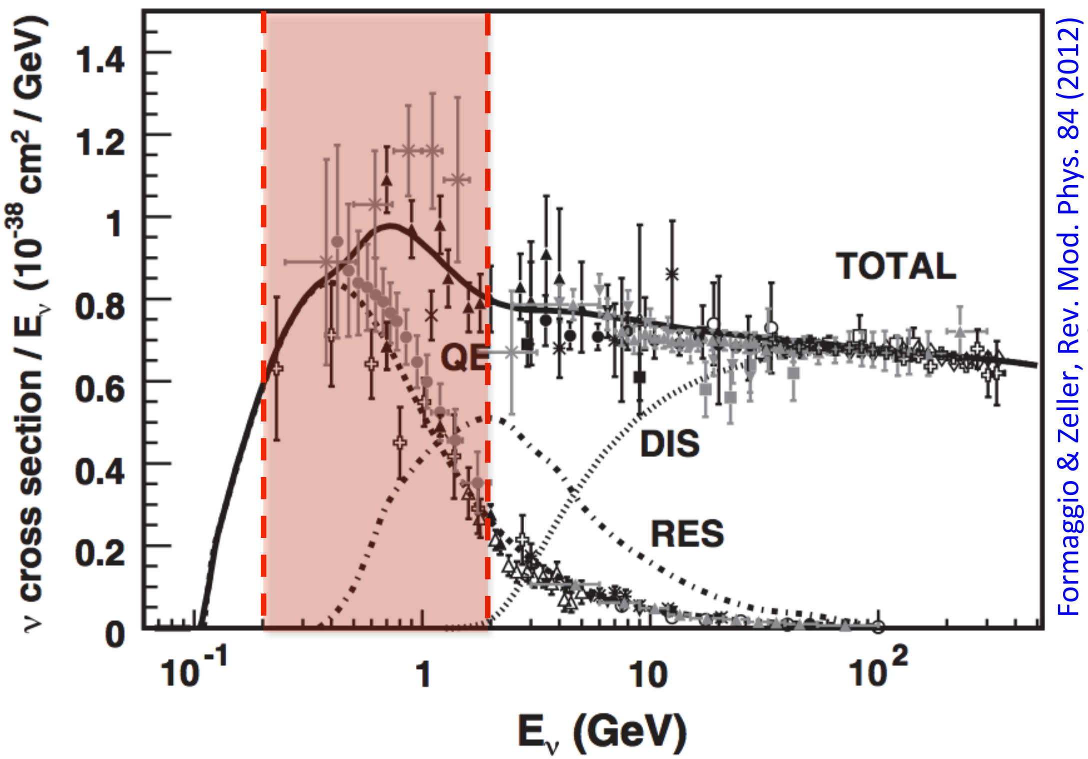
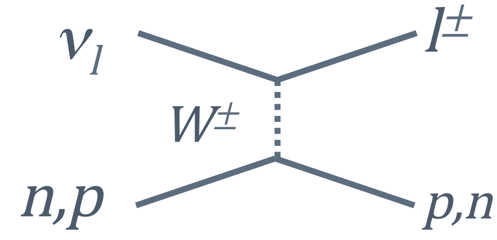
T2K physics : ν + n(p) @ 0.1-2GeV



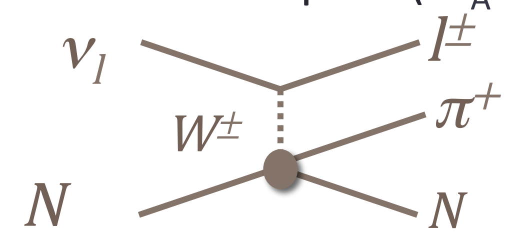
- $\nu_\mu \rightarrow \nu_e$ *appearance* ~ $\sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2(\Delta m^2_{32} \mathbf{L/4E})$
- $\nu_\mu \rightarrow \nu_\mu$ *disappearance* ~ $1-\sin^2 2\theta_{23} \sin^2 (\Delta m^2_{32} \mathbf{L/4E})$



- CCQE dominates (M_A^{QE})



- Also:
  - Resonant CC pion (M_A^{Res})



  - minimal DIS

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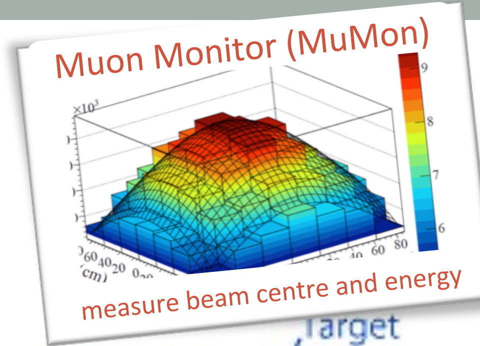
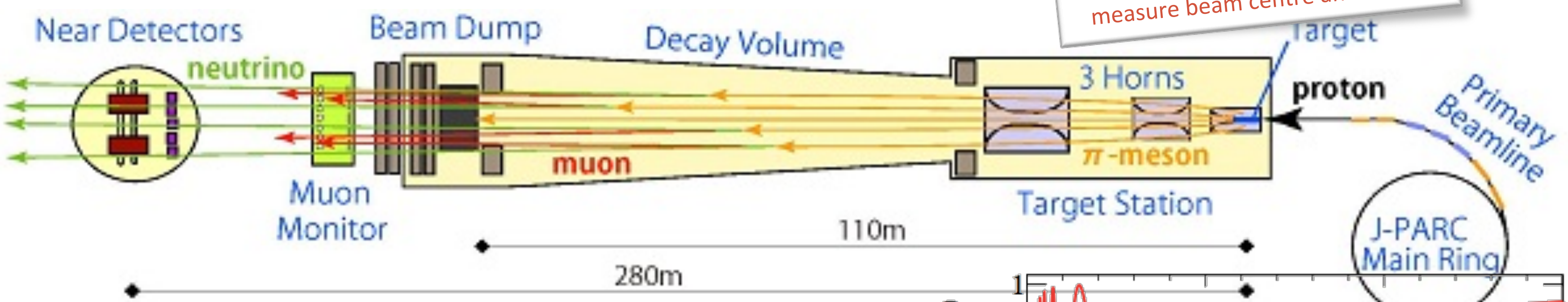
JPARC beam apparatus

- Japan **P**roton **A**ccelerator **R**esearch **C**omplex

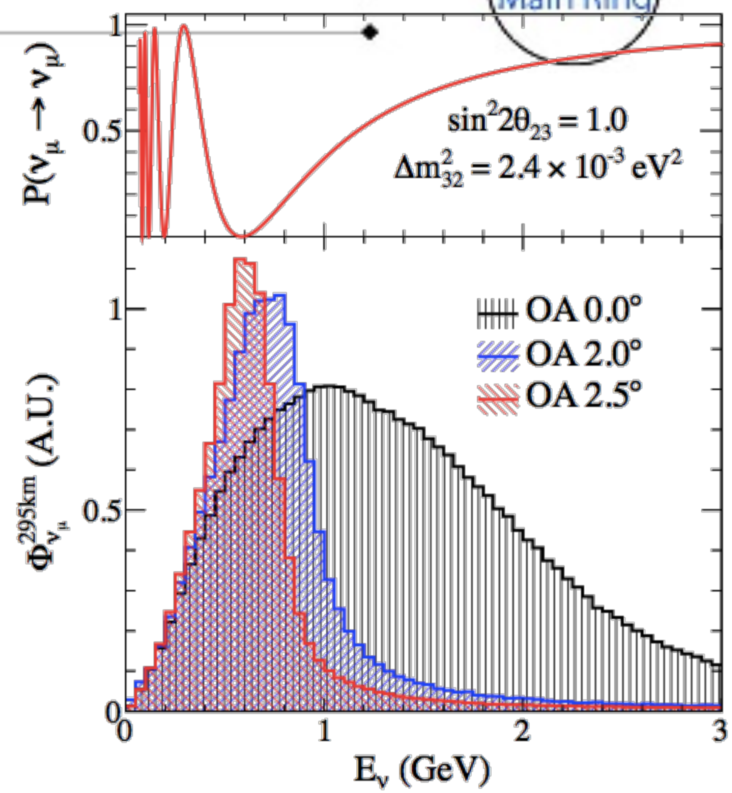




- 30 GeV protons on graphite target
- Neutrinos from pion decay in flight

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

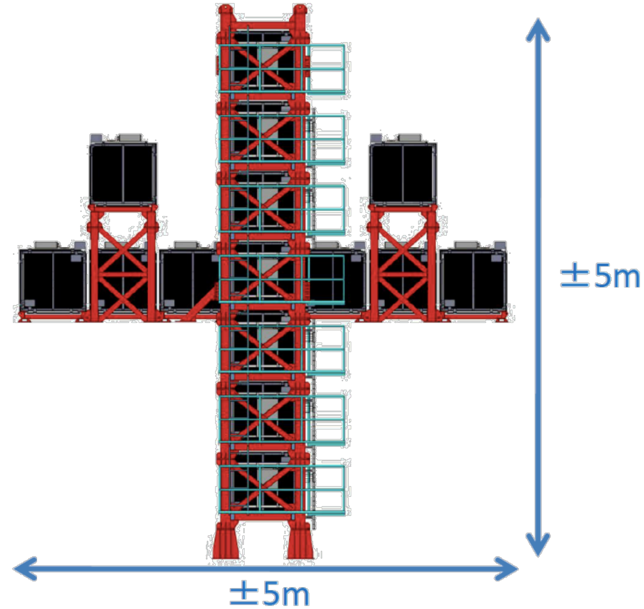
- Magnetic horn for sign selection
- Novel 2.5° off-axis beam for oscillation
  - improves monochromaticity
  - close to oscillation maximum

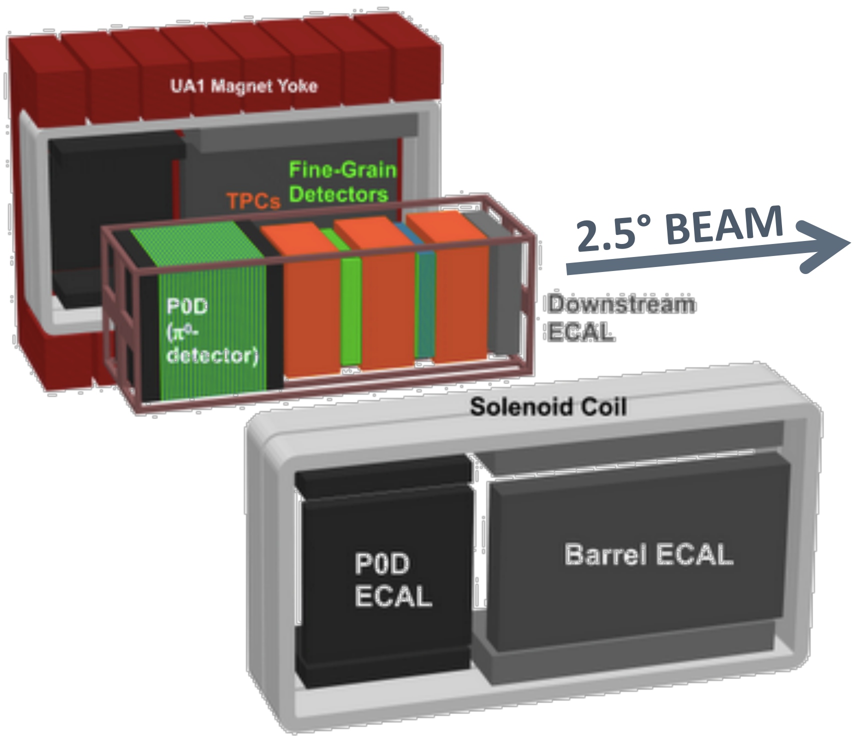


arxiv.org/1211.0469

On Axis Near Detector

- **Interactive Neutrino Grid (INGRID)**
  - 280m from target on beam axis
  - 16x iron/scintillator tracking calorimeters
  - 1x all-scintillator proton module
  - monitors beam centre, profile and CC^{inc} rate



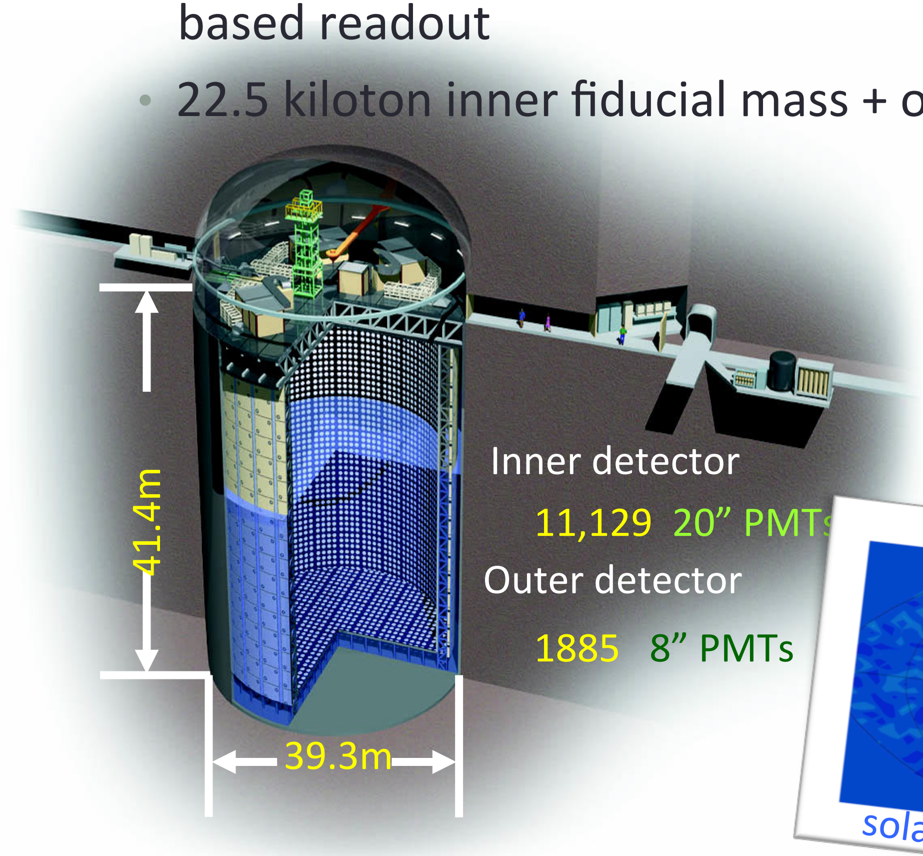


- **Near Detector @ 280m (ND280)**
  - 280m from target 2.5° from beam axis
  - Upstream π^0 detector (**P0D**)
  - 2x 0.8ton **F**ine **G**rained scintillation **D**etectors (**FGD**) with C and H_20 target
  - 3x **T**ime **P**rojection **C**hambers (**TPC**) for accurate dE/dx based PID
  - Hermetic lead/scintillator **E**lectromagnetic **Cal**orimeters (**ECAL**)
  - 0.2T refurbished UA1/NOMAD magnet

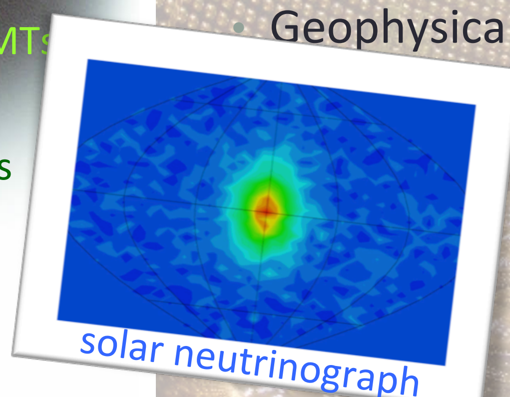
Off Axis Near Detector

T2K Far Detector : Super-K

- **Super K**amioka Neutrino Detection Experiment
  - 50 kiloton water Cherenkov detector with photomutiltipler tube (PMT) based readout
  - 22.5 kiloton inner fiducial mass + outer detector



- Can observe several sources
  - Atmospherics
  - Beamline (T2K)
  - Solar
  - Supernovae
  - Geophysical


solar neutrinograph

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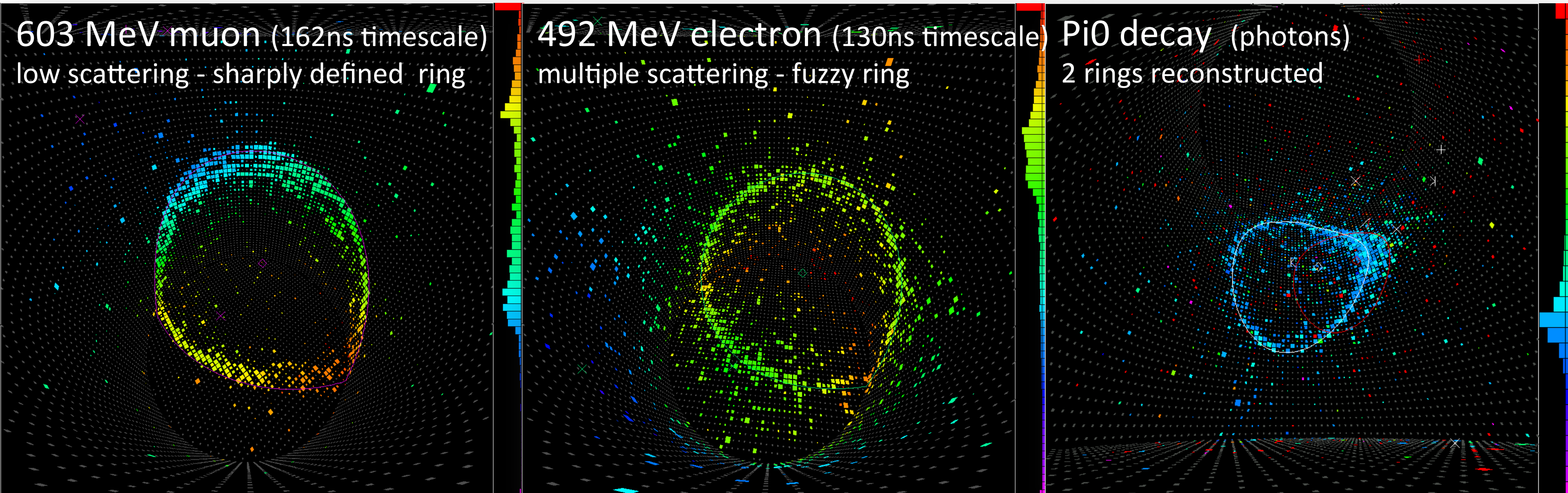
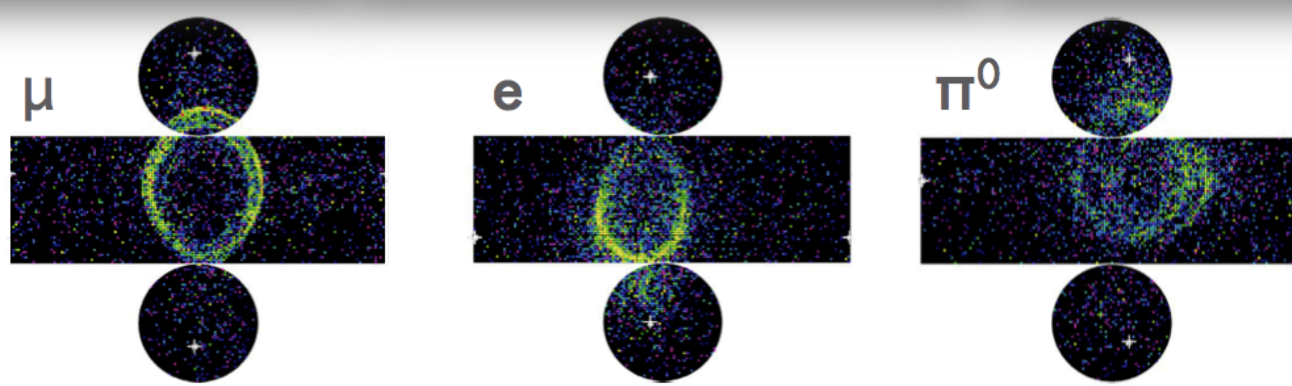
T2K Far Detector : Super-K

- Event displays (data) http://www.ps.uci.edu/~tomba/sk/tscan



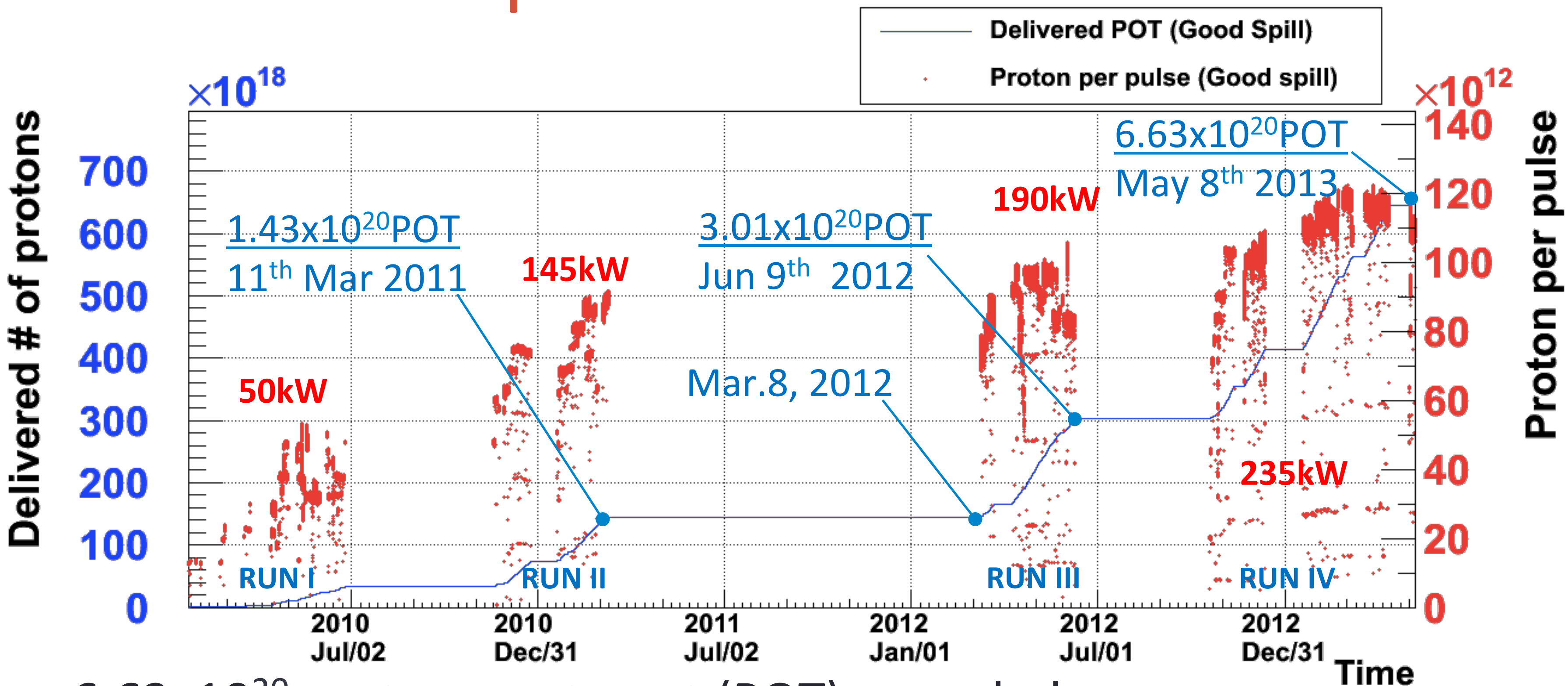
- (MC)



T2K

latest results

JPARC Beam performance



- 6.63×10^{20} protons on target (POT) recorded
- <1mrad (~16MeV [2%]) beam stability for total period
- Achieved 1.2×10^{14} protons per pulse (WR)
- 8% of design goal POT so far

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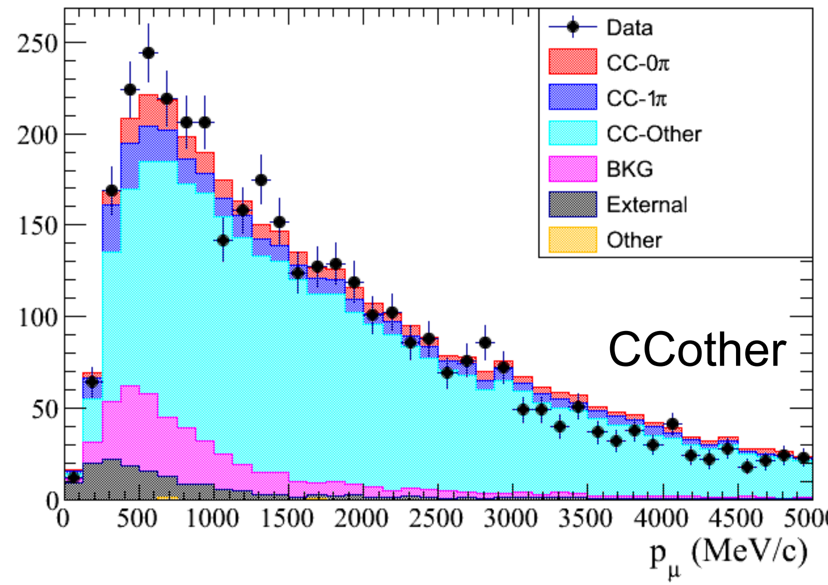
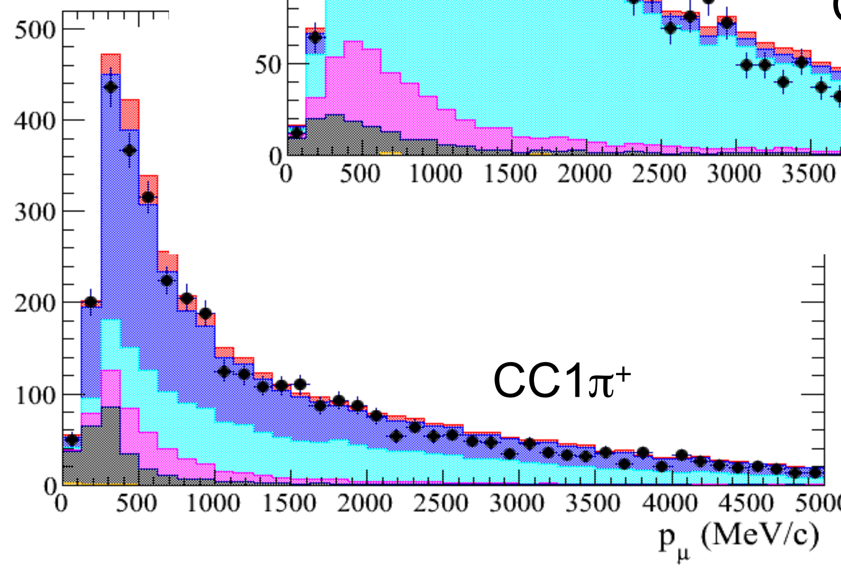
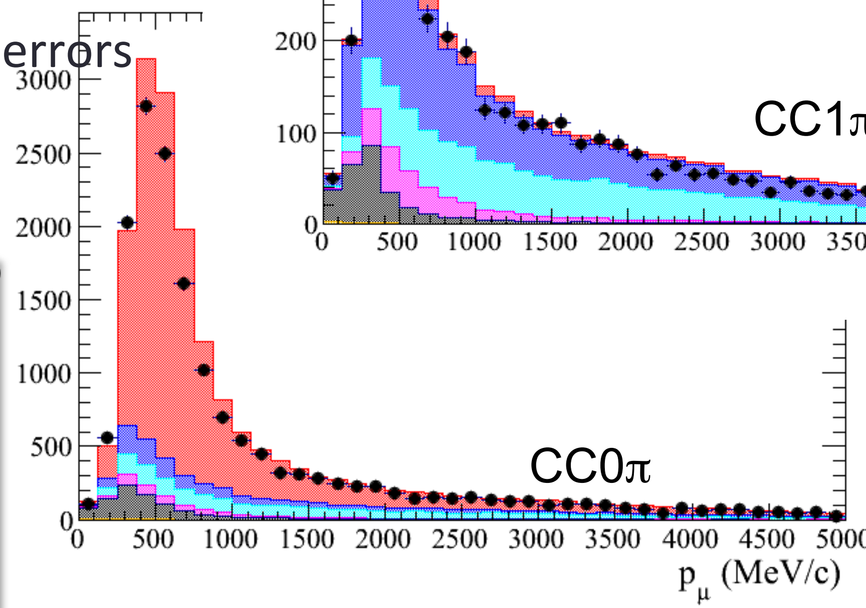
EPSHEP2013_NuMu_T2K.pdf

Near Detector Constraint

- Use ND280 to constrain flux and cross section parameters
  - propagate to Far Detector
- 2013 CC^{inc} ν_μ selection is split into 3 subsamples
  - improves data/MC agreement
  - improves parameter errors







	efficiency	purity
CC0π	50.1%	72.6%
CC1π+	29.5%	49.4%
CCOther	35.2%	73.8%

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Near Detector Constraint

- In 2012 analysis, increasing dataset (~x2POT) did not significantly improve parameter uncertainties

Parameter	1.4×10^{20}POT	3.01×10^{20}POT
M_A^{QE} (GeV)	1.19 ± 0.19	1.33 ± 0.20
M_A^{RES} (GeV)	1.14 ± 0.10	1.15 ± 0.10
CCQE Norm.	0.94 ± 0.09	0.96 ± 0.09
CC1π Norm.	1.67 ± 0.28	1.63 ± 0.29

- New 2013 analysis reduces parameter uncertainties

Parameter	2012 Analysis	2013 Analysis
M_A^{QE} (GeV)	1.33 ± 0.20	1.17 ± 0.09
M_A^{RES} (GeV)	1.15 ± 0.10	0.97 ± 0.08
CCQE Norm.	0.96 ± 0.09	0.99 ± 0.08
CC1π Norm.	1.63 ± 0.29	1.18 ± 0.18

cross section parameters and uncertainties

Analysis	$\sin^2 2\theta_{13}=0.1$	$\sin^2 2\theta_{13}=0.0$
2012	4.9%	6.5%
2013	3.5%	5.2%

oscillation parameter uncertainties

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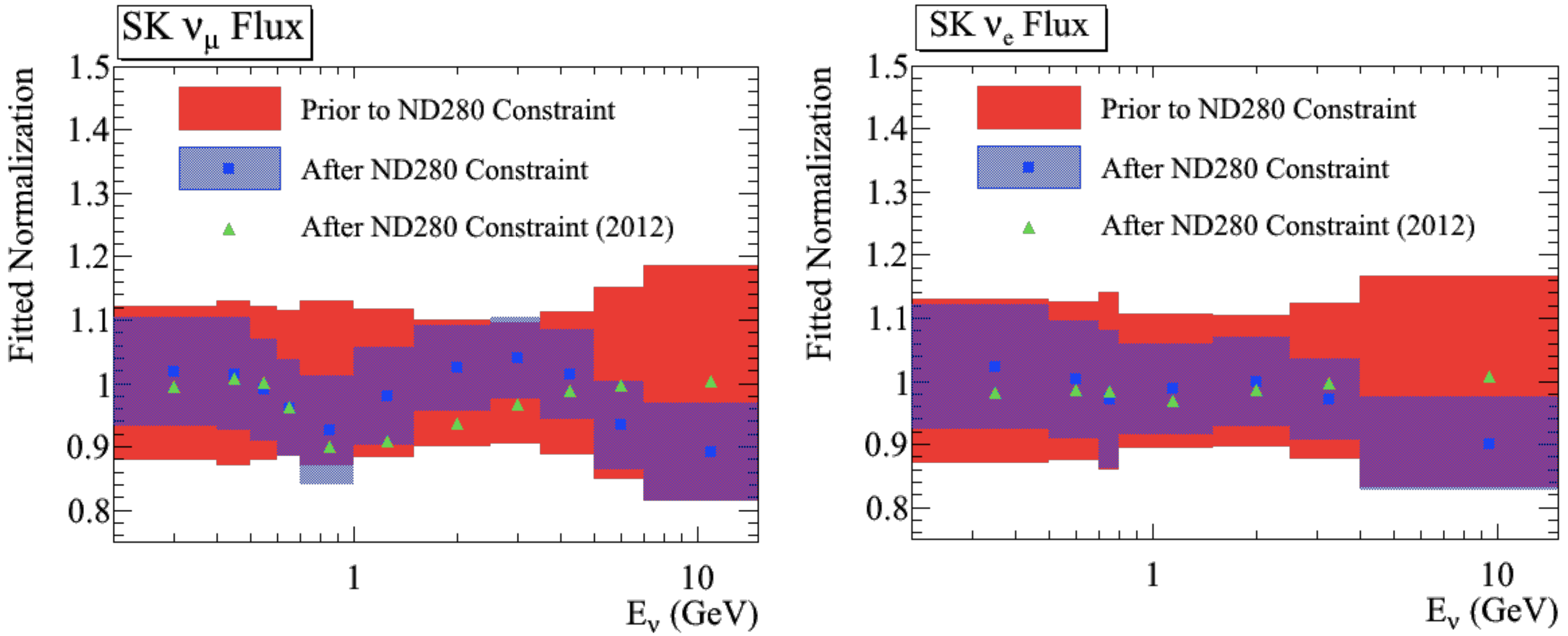
Near Detector Constraint



- Far Detector ν_μ and ν_e flux predictions constrained by 2013 analysis
  - Plots show central values and error bands for normalization parameters before and after the near detector constraint
  - Central values are changed from 2012 results: due to finer bins and new selection

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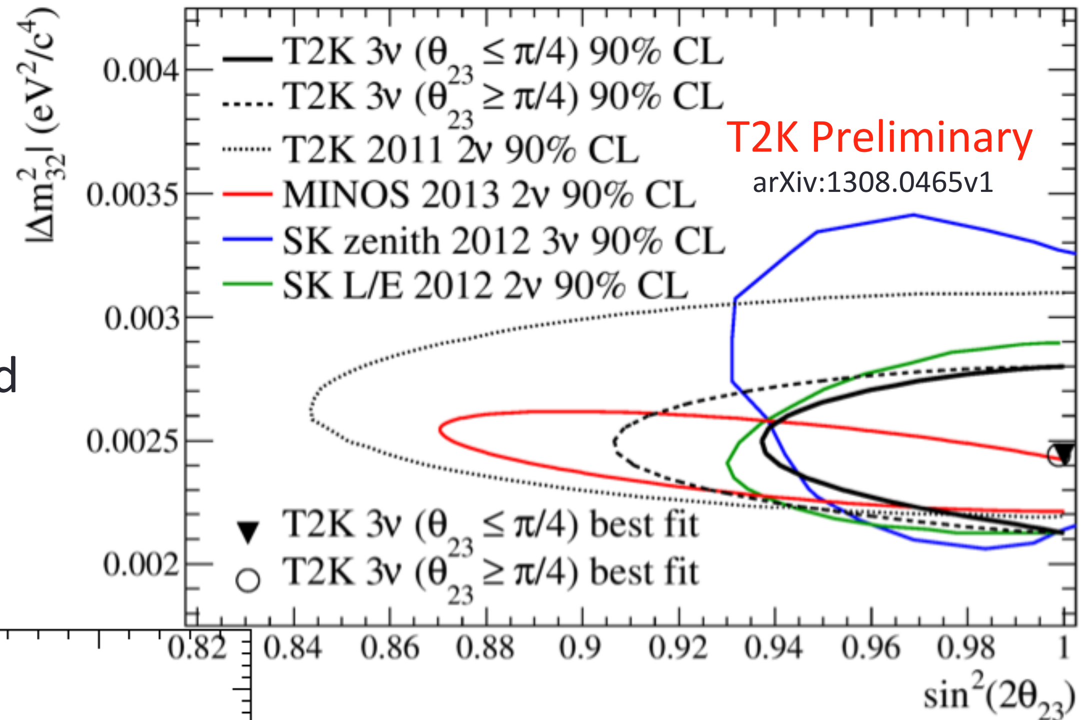
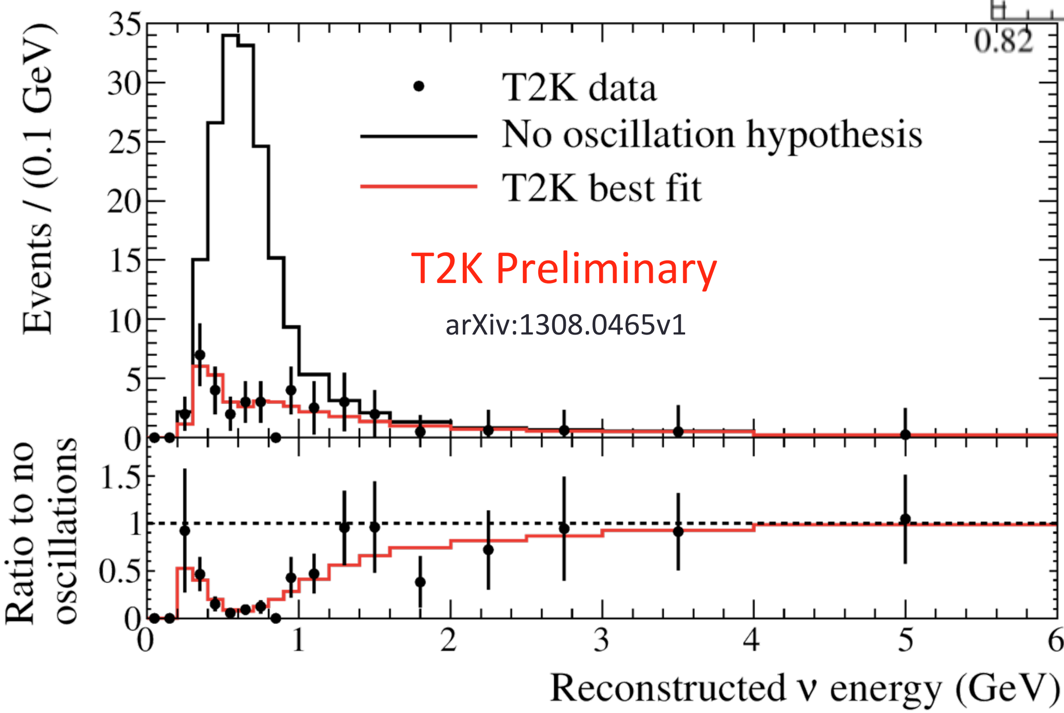
Updated ν_μ result

- 2012: **31ν_μ^{obs}** vs **104ν_μ^{exp}**
  - best fit $\sin^2(2\theta_{23})$ = 0.98 and $|\Delta m^2_{32}|$ = 2.65×10^{-3} eV^2
  - $\theta_{23}<\pi/4$ octant only



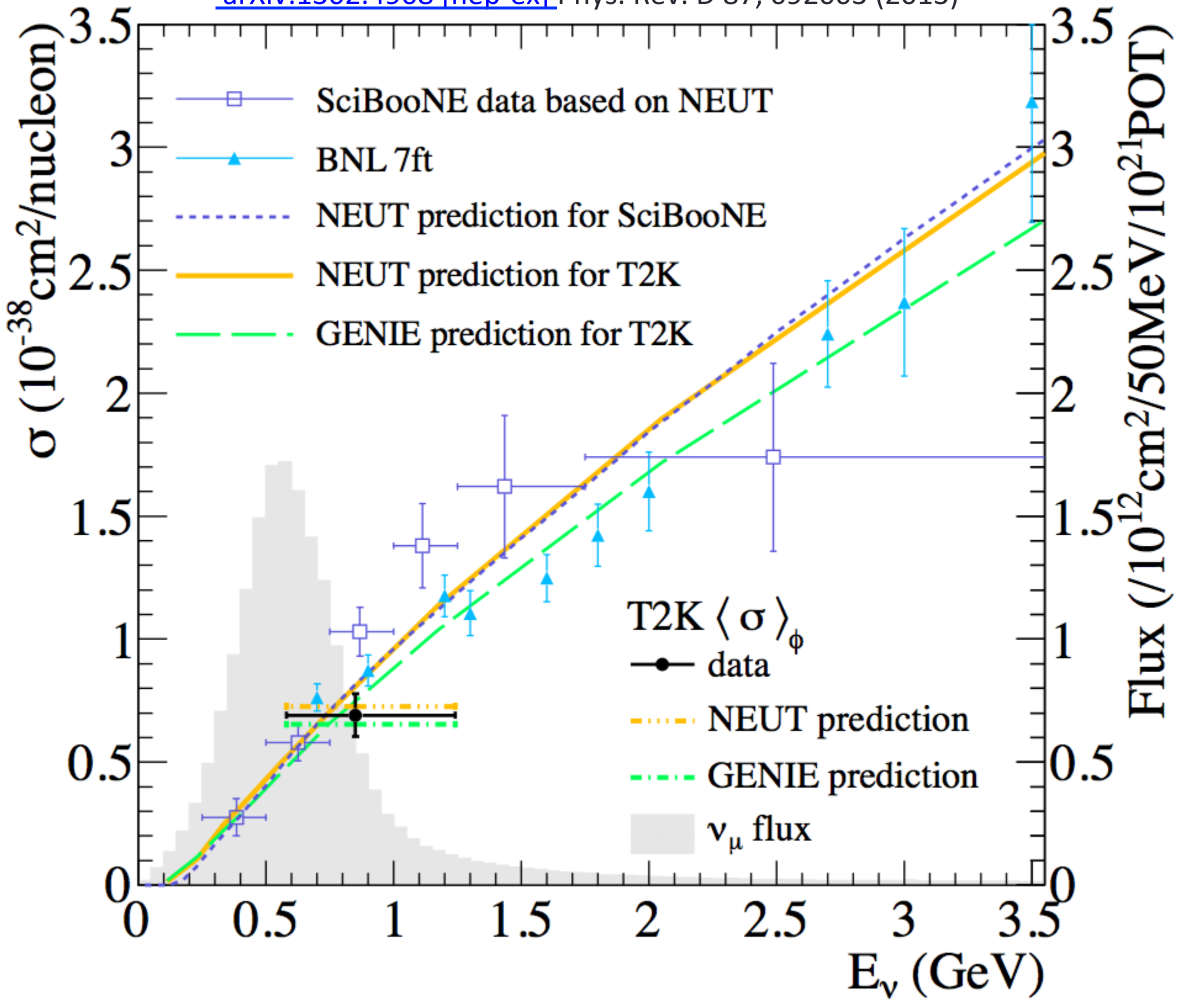


- 2013: **58 observed** ν_μ against **expectation** of **204.75** ± 16.75^{sys}
  - preliminary best fit for $\sin^2(2\theta_{23})$ = 1 is $|\Delta m^2_{32}|$ =
    2.45×10^{-3} eV^2 ($\theta_{23}<\pi/4$)
    2.44x10^{-3}eV^2 ($\theta_{23}<\pi/4$)
- shape of contour affected by octant – plot both
  - $\theta_{23}<\pi/4$ and $\theta_{23}>\pi/4$

T2K cross-sections and more

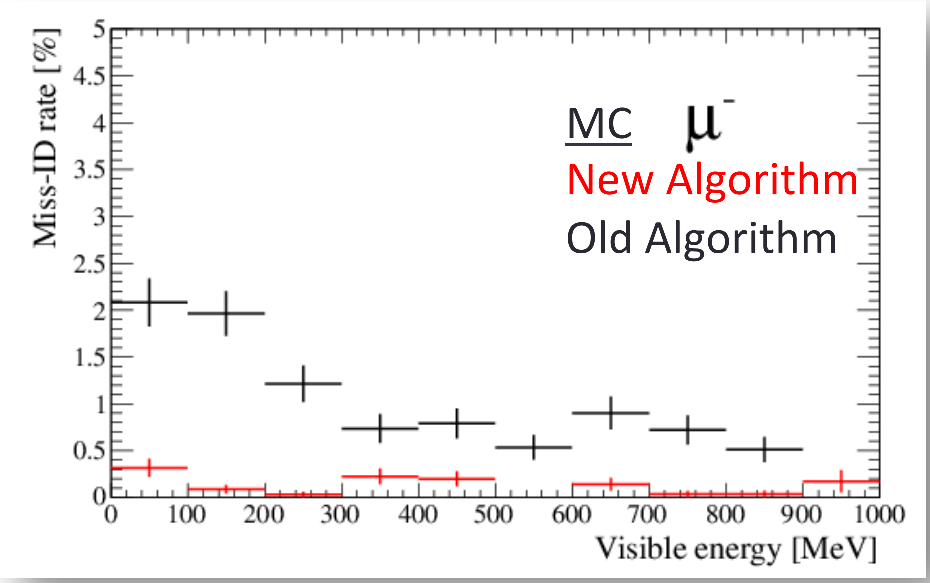
- Use ND280 ν_μ oscillation analysis to extract CC^{inc} cross section
  - 2010-11 data set (10.8×10^{19}POT)
  - carbon target (FGD fiducial mass)
  - flux prediction from MC + NA61/SHINE data
- **Other analyses underway**
  - NC π^0, CCQE, NC Elastic CCπ and CCπ^{coh}
  - Anti neutrinos
  - Steriles and other exotica
  - …

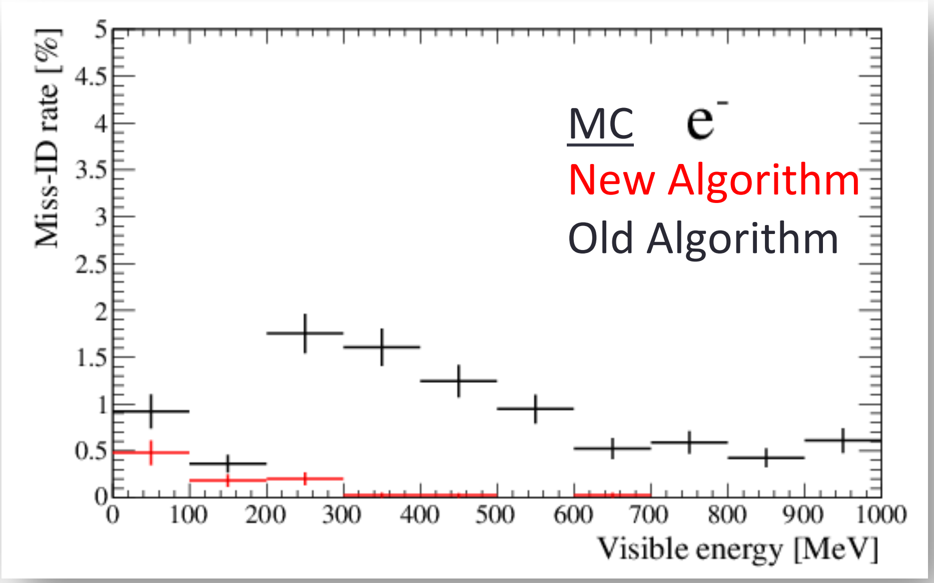
arXiv:1302.4908 [hep-ex] Phys. Rev. D 87, 092003 (2013)



2013 T2K far detector reconstruction

- for a given event topology, create a PDF for charge and time at each PMT sensor
  - charge ~ Light Yield x $\int_{\text{track length}}$ PMT solid angle x PMT response x Attenuation
    - Based on the algorithm used by MiniBooNE (NIM A608, 206 (2009))
    - no limitation on number of tracks in event
- given event PDFs select one with best fit likelihood
  - electron, muon, 1-ring, 2-ring, n-ring…
- Aids π^0 (dominant T2K FD background) rejection [70% more than 2012]
- Significant improvement on existing T2K Far Detector algorithms





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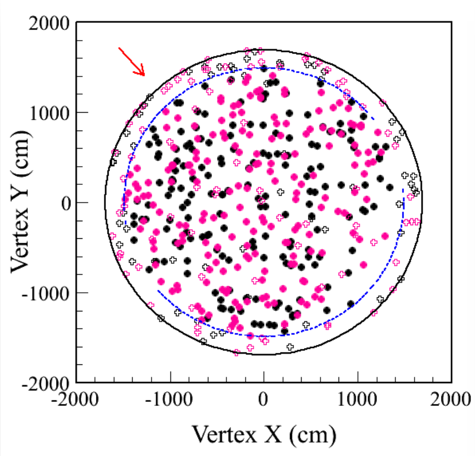
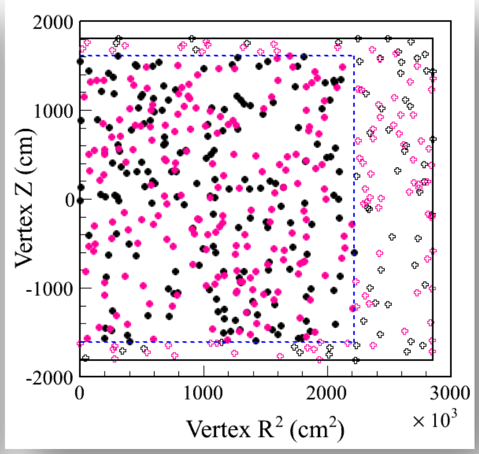
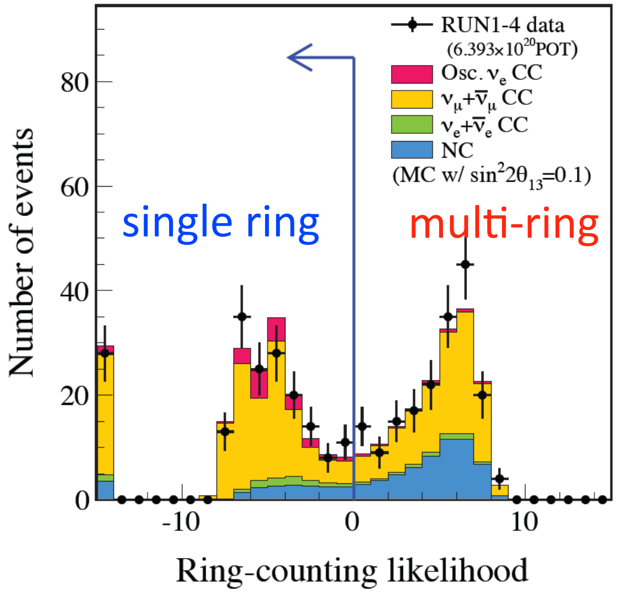
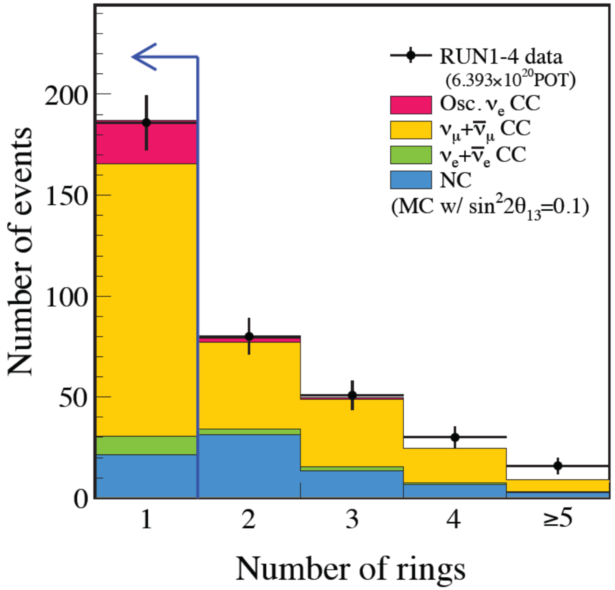
ν_e appearance

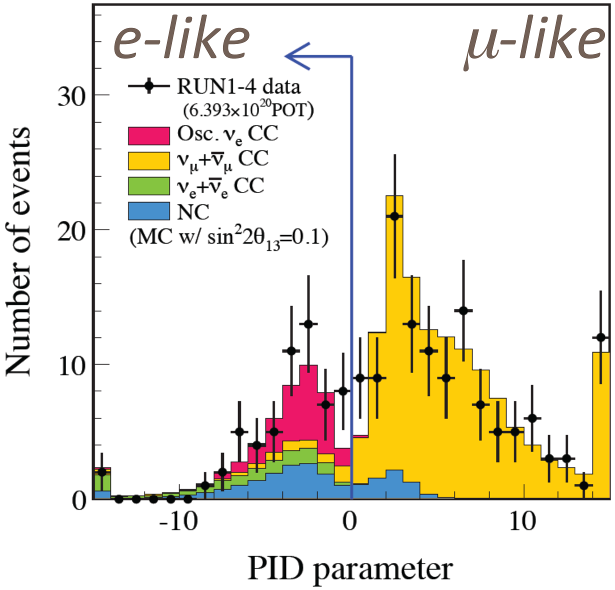
- Event selection:
  - Fully contained in fiducial volume
  - Only one reconstructed rings
  - Ring is electron like











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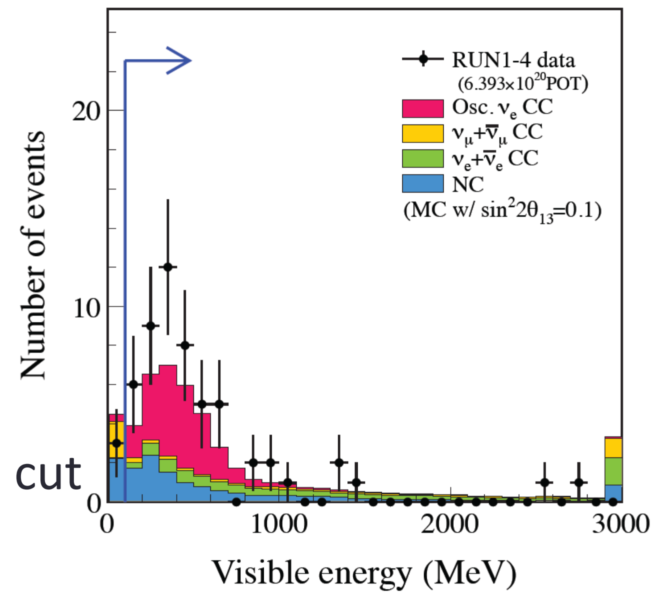
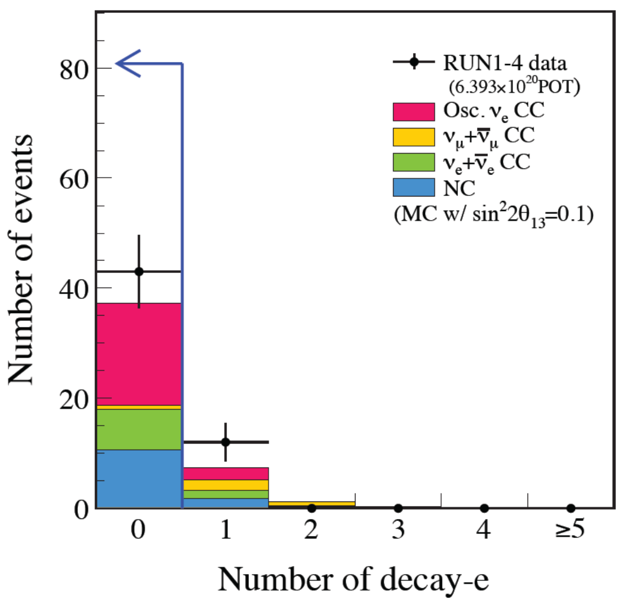
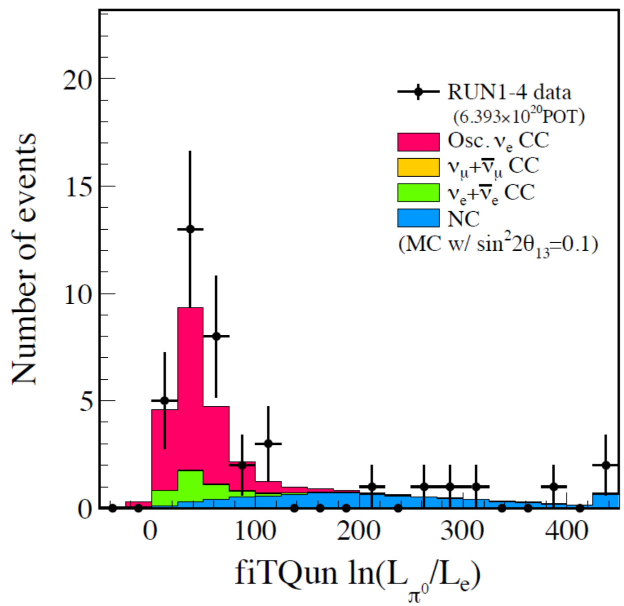
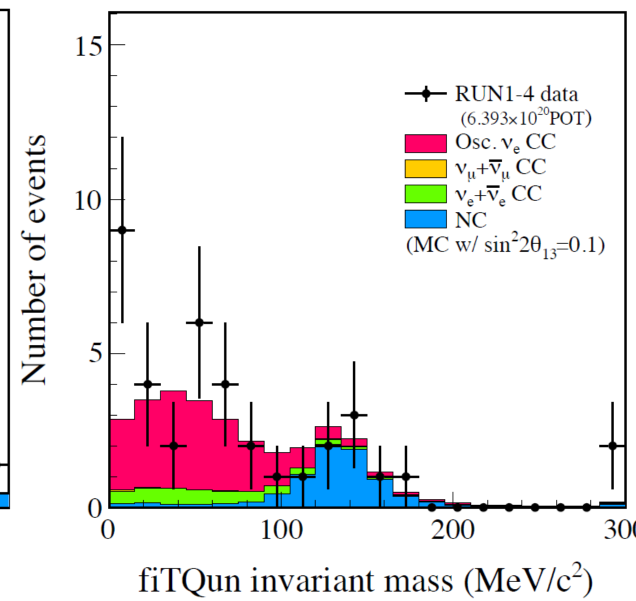
ν_e appearance

- Event selection:
  - Visible energy > 100MeV
  - No Michel Electrons
  - (2013)2D π^0 invariant mass : fiTQun likelihood cut
  - Reconstructed energy < 1.25 GeV



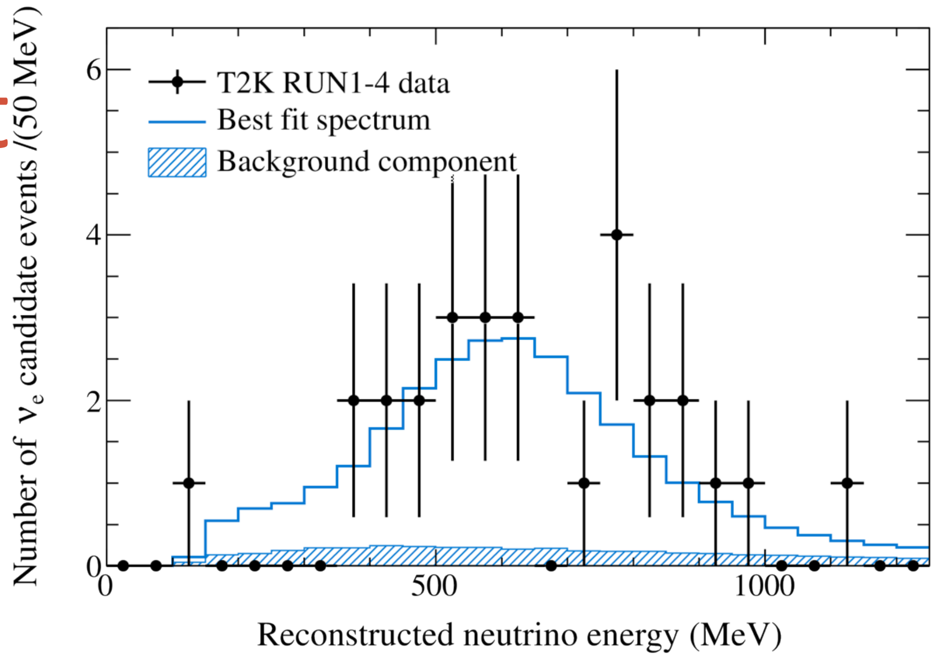


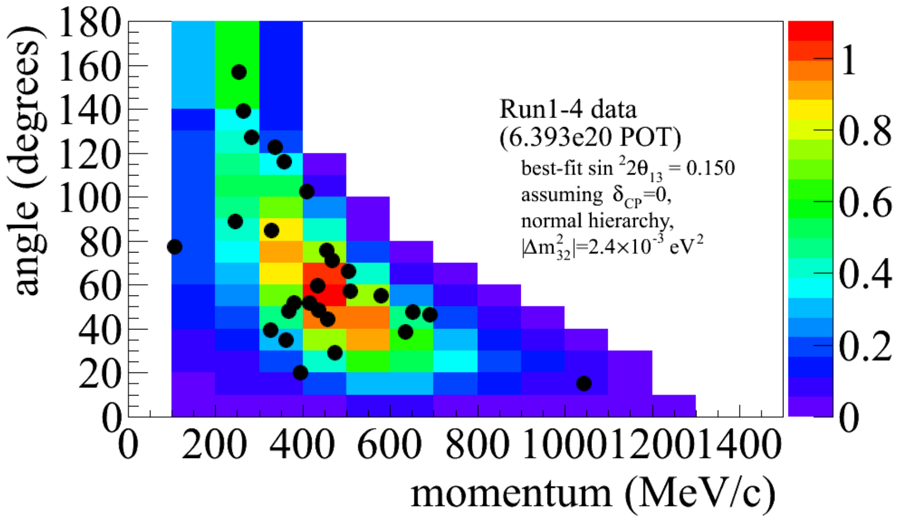




ν_e appearance result

- Null oscillation hypothesis predicts 20.4±1.8 ν_e events
  - $\sin^2 2\theta_{13} = 0.1$
  - $\sin^2 2\theta_{23} = 1$
  - $\delta^{cp} = 0$
- 4.64±0.53 background events also expected
- Oscillation parameters extracted from reconstructed neutrino kinematics
  - energy spectrum
  - momentum vs angle distribution





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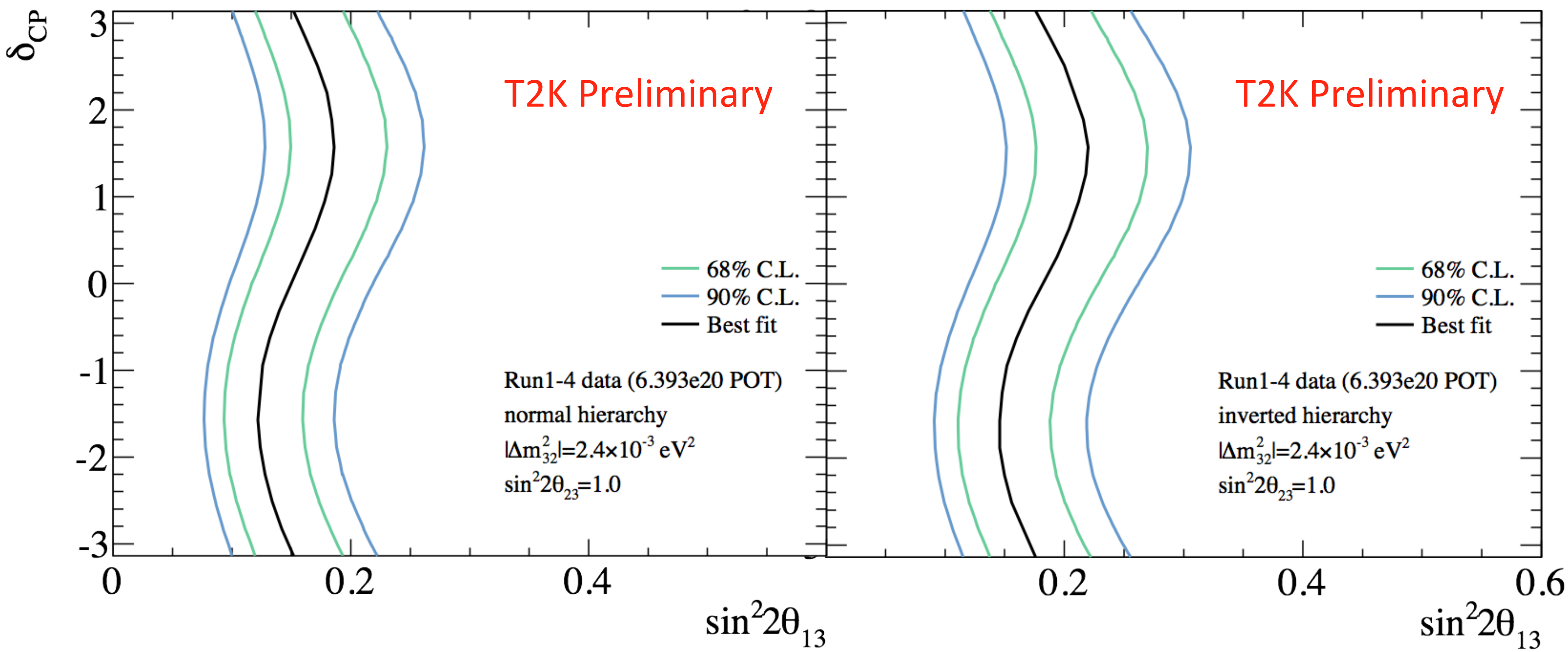
ν_e appearance result

- **28** events **observed**
  - unoscillated **expectation** of **20.4**±1.8 (for $\sin^2 2\theta_{13}$=0.1, $\sin^2 2\theta_{23}$=1, δ^{cp}=0)
- Comparing to null oscillation hypothesis gives a **7.5σ** significance for non-zero θ_{13}



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Summary

- A total of 6.63×10^{20} POT on tape
  - 6.39×10^{20} POT accumulated by April 12th, 2013 now analysed
- With only 8% of the design POT $\theta_{13}=0$ is excluded with a significance of 7.5σ ($\delta_{CP}=0$, $\sin^2 2\theta_{23}=1$)
  - via observation of the $\nu_\mu \rightarrow \nu_e$ appearance channel
  - null oscillation hypothesis predicts 20 ν_e
  - 28 ν_e are observed
- The ν_μ disappearance contours are sensitive to the octant chosen
  - both contours are provided
  - via observation of the $\nu_\mu \rightarrow \nu_\mu$ disappearance channel
  - 58 ν_μ observed vs unoscillated expectation of 204.75
- 2013 near detector constraints
  - significant improvement on parameter errors
- New T2K Far Detector reconstruction algorithm
  - 70% reduction of the π^0 background relative to the previous analysis
  - More improvement is expected as new algorithm becomes more fully integrated into T2K analyses
- Achieved steady operation of JPARC beam at 220 kW
  - further increases of beam power in future

Thank You!

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Backup Slides

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ν_μ oscillation at T2K – octant sensitivity

$P(\nu_\mu \rightarrow \nu_\mu) \approx$

$$1 - (\cos^4\theta_{13} \,.\, \sin^2 2\boldsymbol{\theta}_{\mathbf{23}} + \sin^2 2\theta_{13} \,.\, \sin^2\boldsymbol{\theta}_{\mathbf{23}}) \,.\, \sin^2 (\Delta m^2_{32} L/4E)$$

+ other terms tending to 0 at L=295km and E≈600MeV

- leading order and sub-leading order terms
  - sensitive to choice of octant $\theta_{23} \leq \pi/4$ or $\theta_{23} \geq \pi/4$

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T2K analysis concept

- $\nu_\mu \rightarrow \nu_x$ oscillation measurement
  - essentially a counting experiment
  1. measure source flux at near detector
  2. extrapolate flux to far detector and predict observed rate
  3. measure ν_μ deficit at far detector
  4. use deficit to exclude null oscillation hypothesis
- sounds simple, but…
  - many inputs required
  - many sources of uncertainty
  - many correlations to consider
  - several competing analyses

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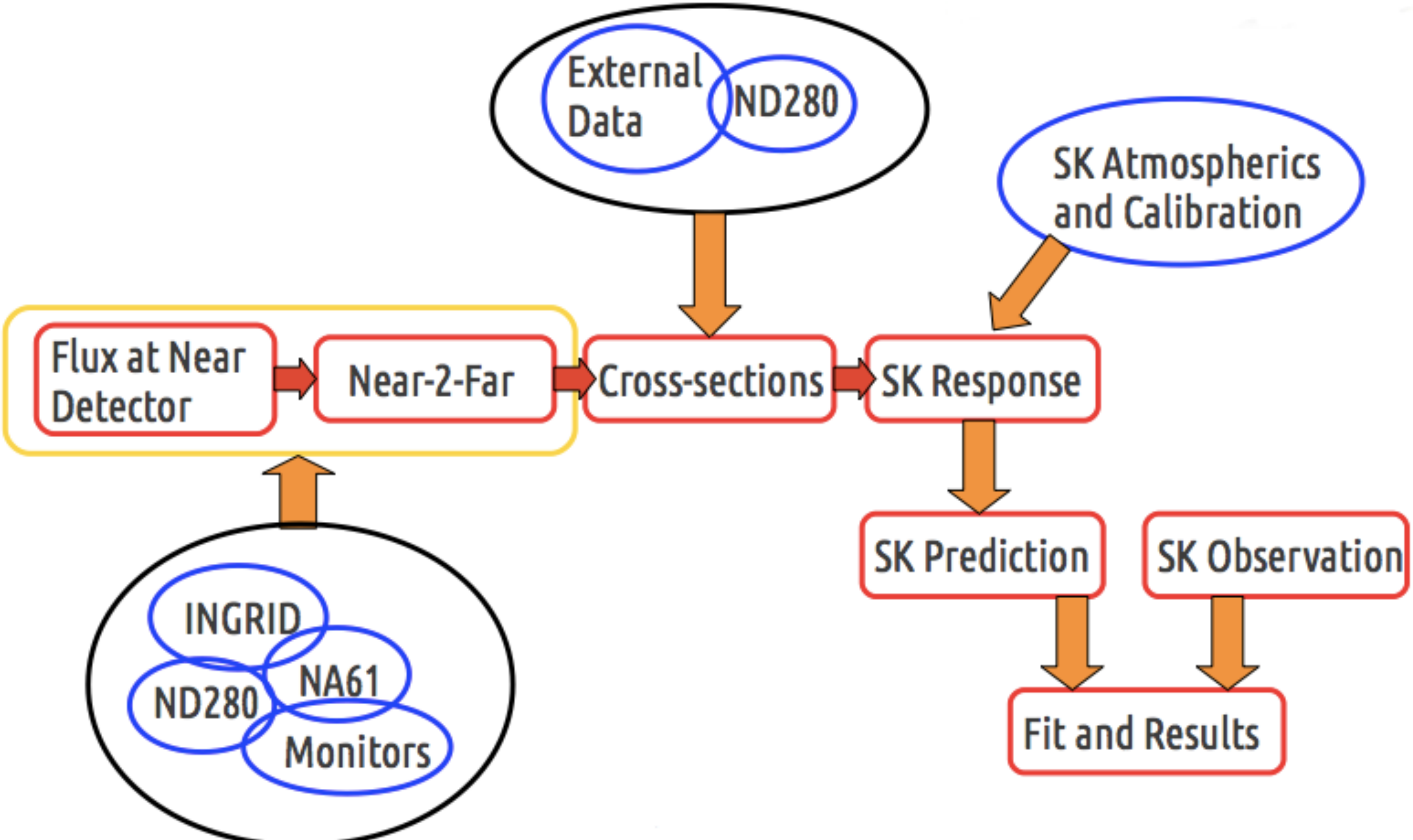
T2K analysis strategy



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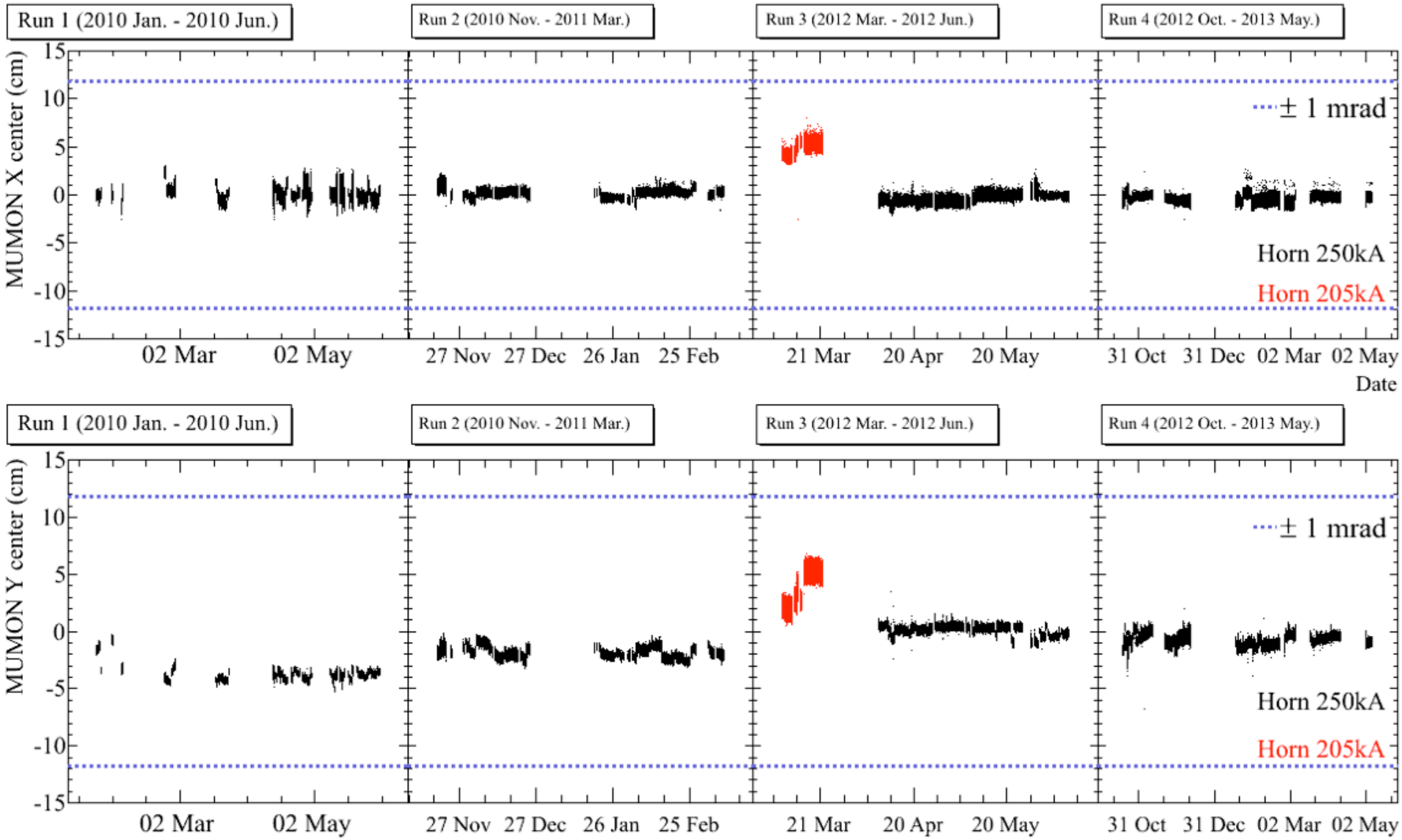
Beam Stability (MuMon)



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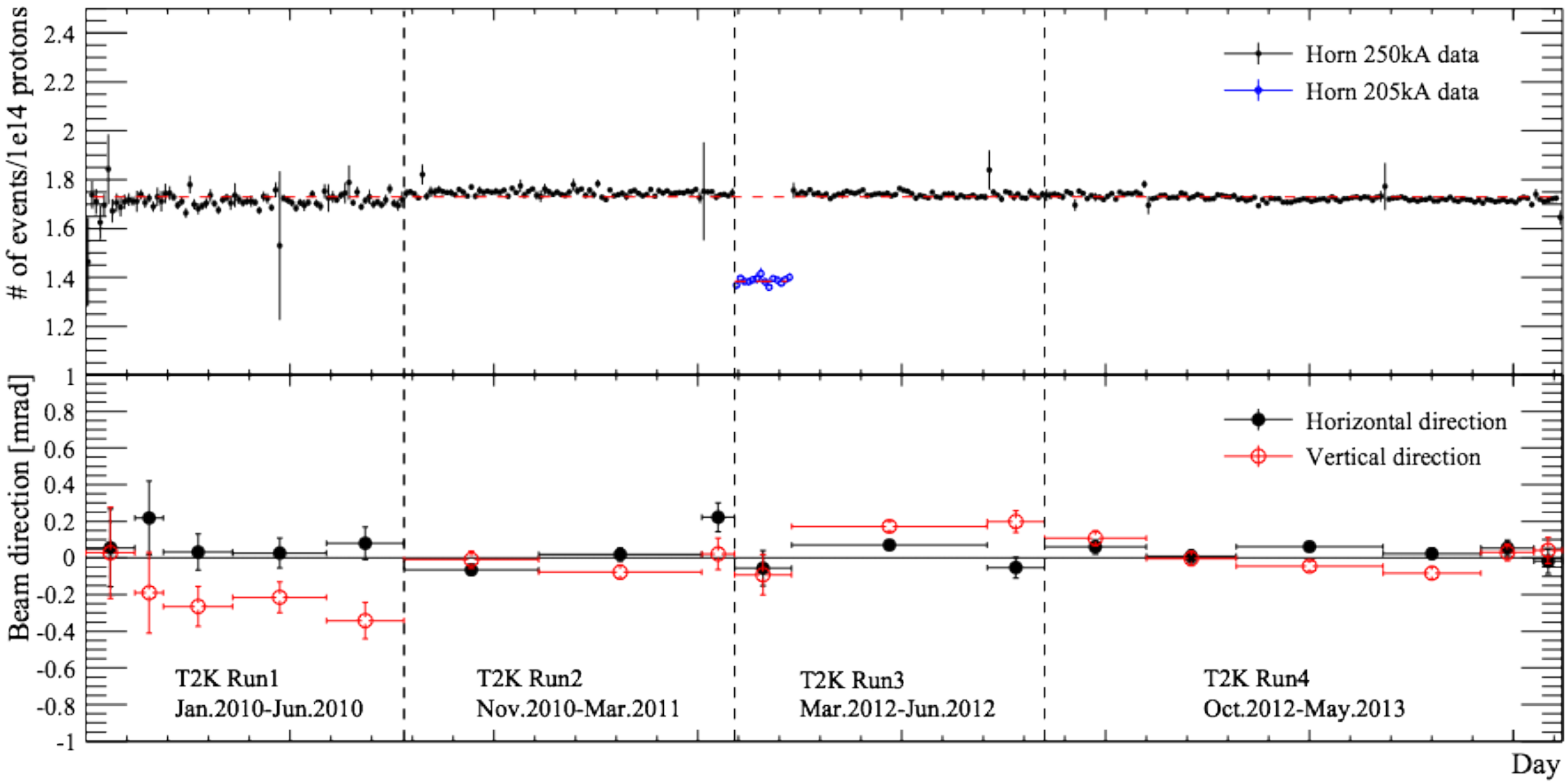
Beam Stability (INGRID)



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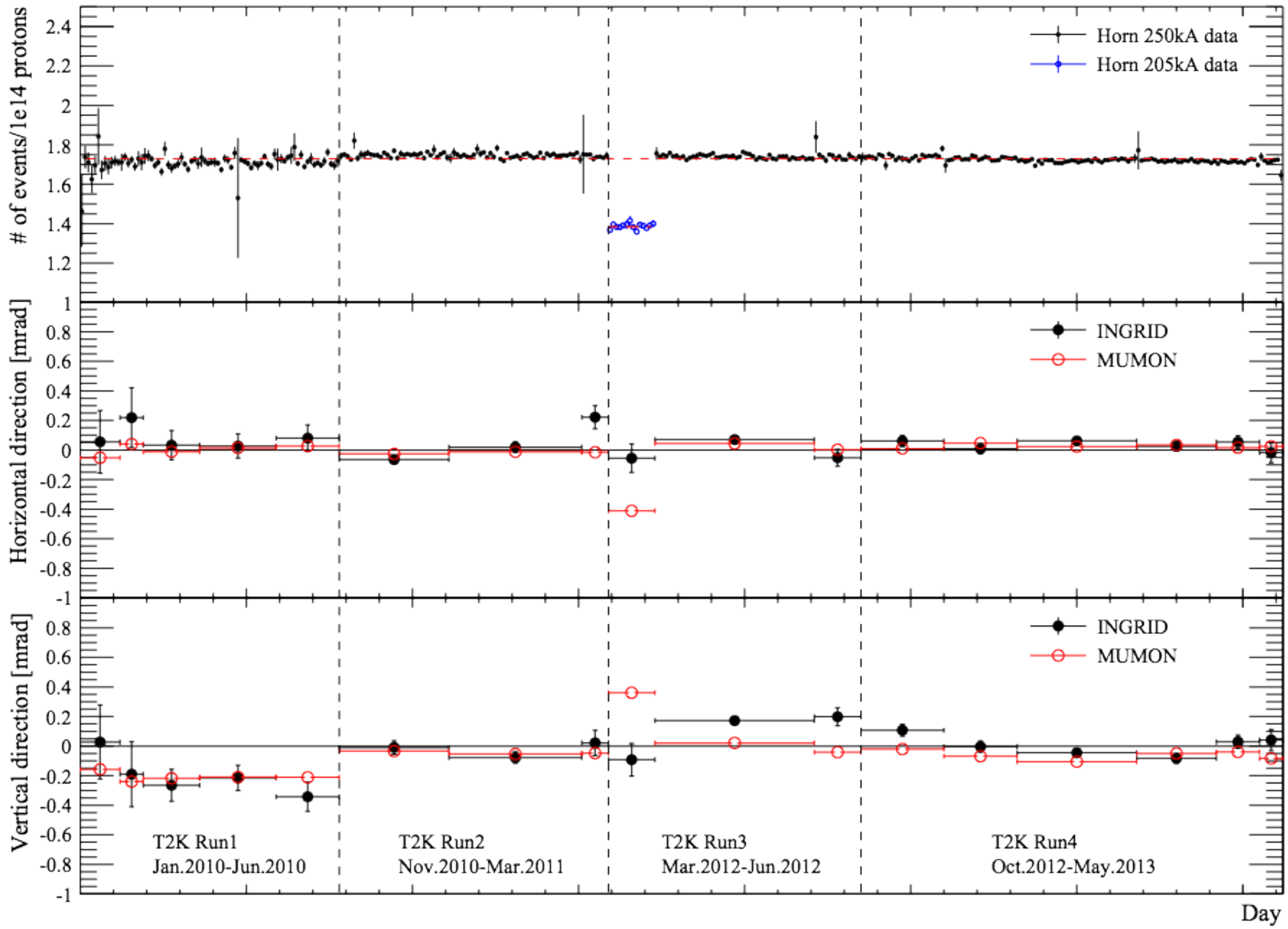
Beam Stability (ND280)



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T2K Far Detector

- Candidate events from last analysis run

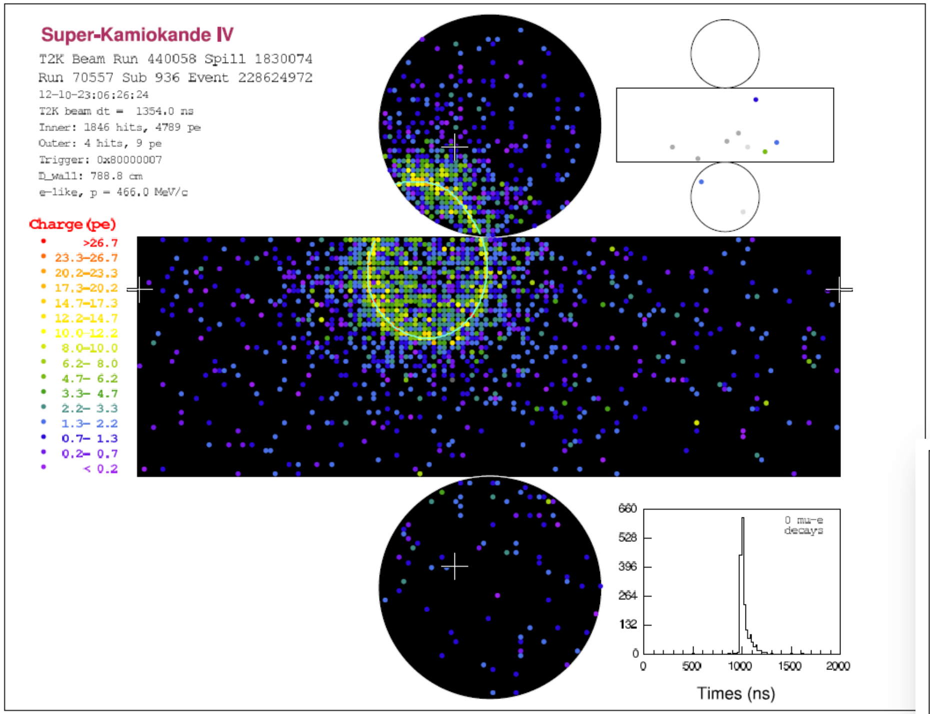
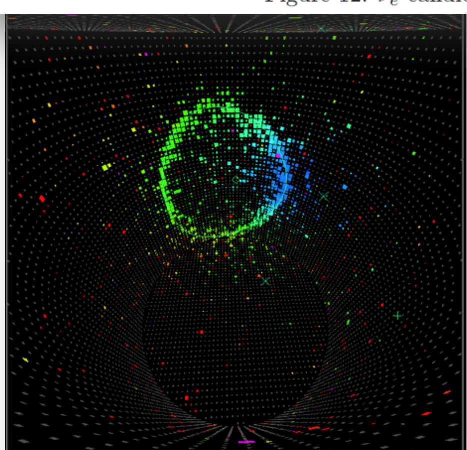


Figure 12: ν_e candidate event #12



- First reconstructed electron candidate following Tohoku earthquake

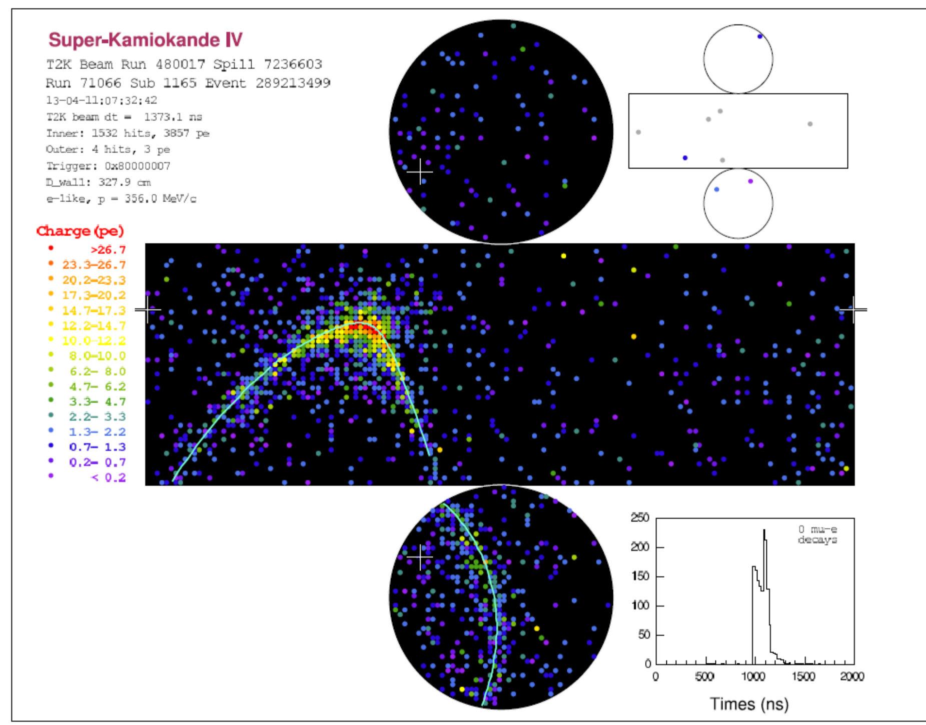


Figure 31: ν_e candidate event #31

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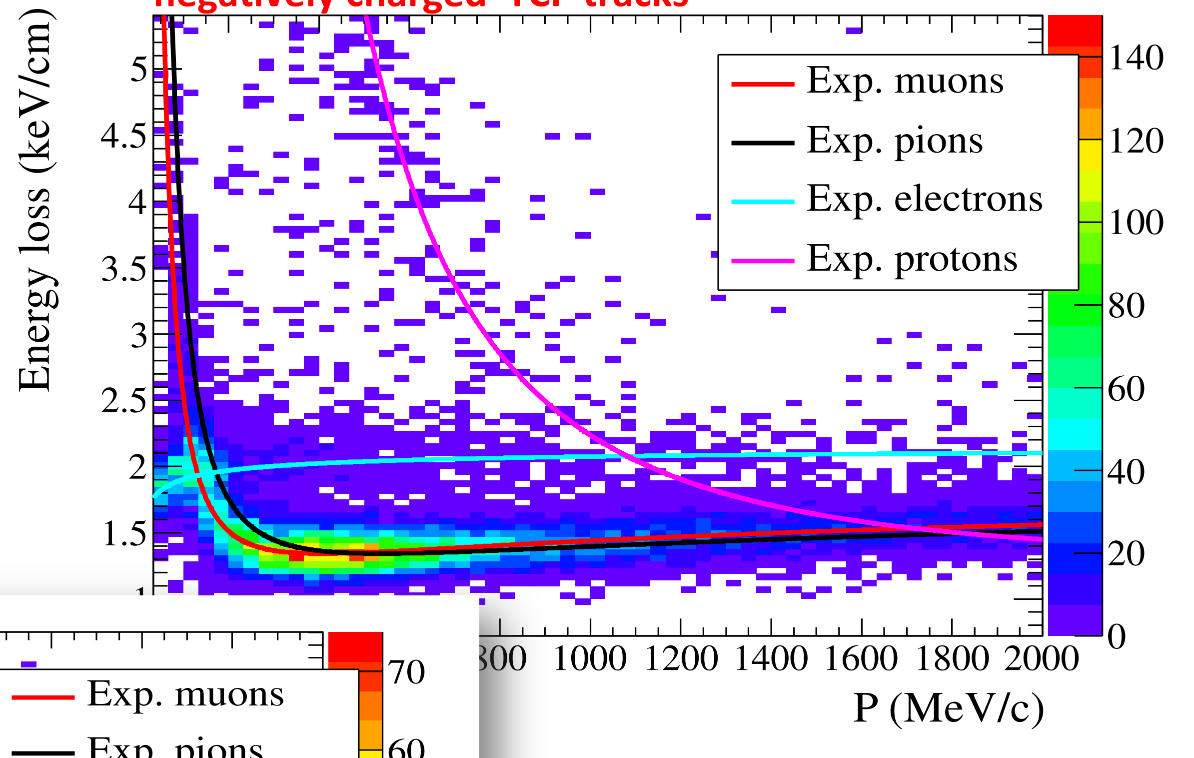
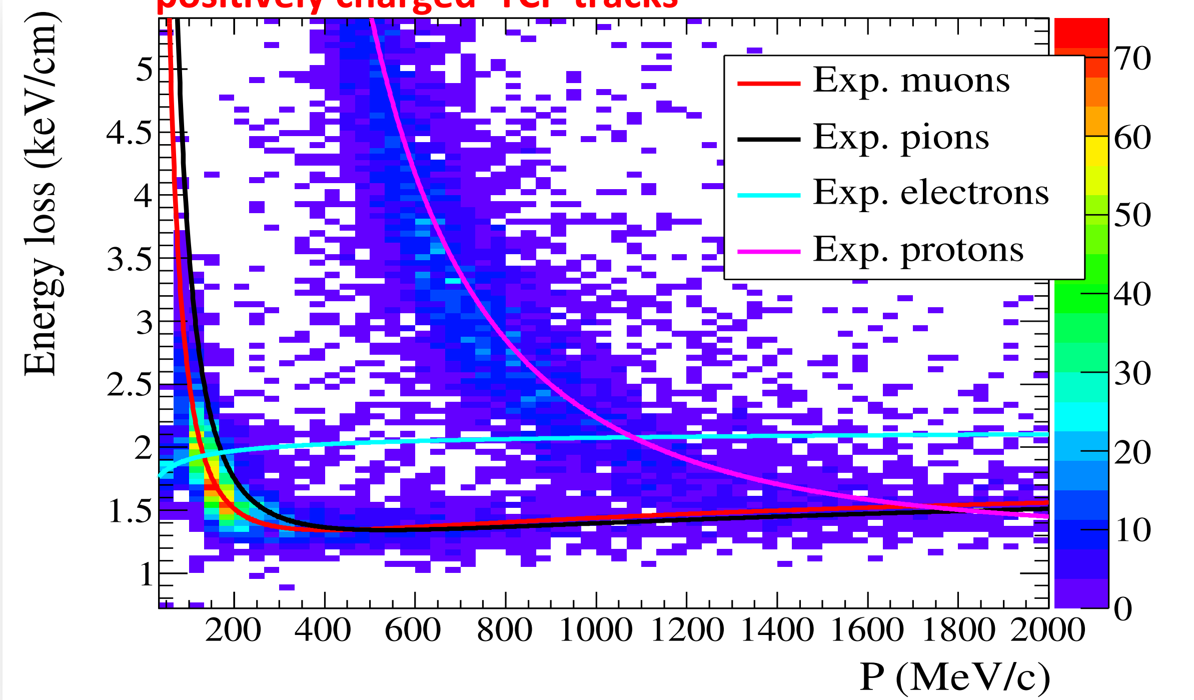
ND280 TPC

- dE/dx plots

negatively charged TCP tracks



positively charged TCP tracks



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Near Detector Constraint

Neutrino Flux Model:

- Data-driven: NA61/SHINE, beam monitor measurements
- Uncertainties: modeled by variation of normalization parameters (*b*) in bins of neutrino energy, flavor

Neutrino Cross Section Model (NEUT):

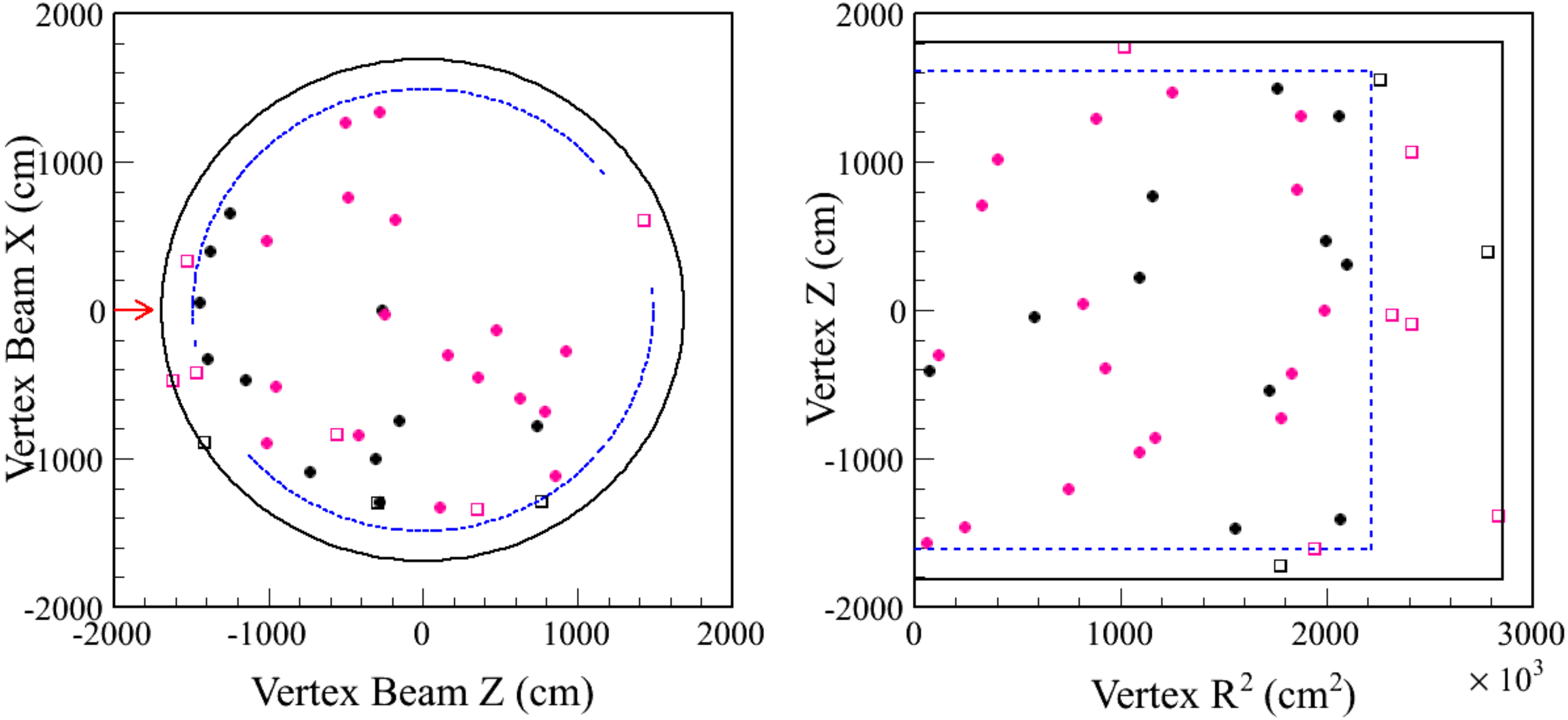
- Data-driven: External neutrino, electron, pion scattering data
- Uncertainties: modeled by variations of model parameters (M_A, p_F, E_b) and ad-hoc parameters

Constraint from ND280 Data:

- Data Samples enhanced in CC interactions with 0, 1 or multiple pions
- Fit to data constrains flux, *b*, and cross section, $x=(M_A, p_F, E_b, \textit{ad-hoc, etc.})$, parameters
- Constrained SK flux parameters and subset of cross section parameters are used to predict SK event rates

ν_e appearance

- vertex distributions



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Information from JPARC

List of all publicized information in English July 26 : Message from Director Ikeda of the J-PARC center
http://j-parc.jp/en/topics/20130726director_message.html
July 8 : J-PARC News - June 2013 (Issue #98)
http://j-parc.jp/en/news/2013/J-PARC_News-e1306.html
June 27 : A delay in suspending the operation of the accelerator complex and a delay in turning off the ventilation fans at the Hadron Experimental Facility (HD Facility)
http://j-parc.jp/en/topics/HDAccident20130627.pdf
June 21 : Results of the individual does measurements from the radioactive material leak at the HD Facility
http://j-parc.jp/en/topics/HDAccident20130621.pdf
June 21 : Postponement of the 2nd International Symposium of Science at J-PARC (J-PARC 2013)
http://j-parc.jp/en/topics/20130621director_message.html
June 18 : 2nd Accelerator Facility Accident Report to Nuclear Regulation Authority - Full Version -
http://j-parc.jp/en/topics/20130618Accident_Report.html
June 18 : Submission of the 2nd report on the radioactive material leak at the HD Facility of J-PARC
http://j-parc.jp/en/topics/HDAccident20130618_02.pdf
June 18 : On the establishment of an External Expert Panel to review the leak accident of radioactive material at the J-PARC HD Facility
http://j-parc.jp/en/topics/HDAccident20130618_01.pdf
June 13 : J-PARC News Special Issue
http://j-parc.jp/en/news/2013/J-PARC_News-e_Special-Issue1305.html
June 10 : Notification of Cancelation of Assigned Beamtime to the End of July 2013 due to the Accident at HD Facility
http://j-parc.jp/en/topics/20130610director_message.html
May 31 : Submission of the 1st report on the radioactive material leak at the HD Facility of J-PARC (Accelerator Facility Accident Report) - full version-
http://j-parc.jp/en/topics/HDAccident20130531.pdf
May 31 : A summary of the accident at HD Facility on May 23 2013 (based on the Japanese documents publicized at the J-PARC website on May 25 and May 29)
http://j-parc.jp/en/topics/summary20130531.pdf
May 30 : Extension of the 2013B call for proposals deadline
http://j-parc.jp/researcher/MatLife/en/news/20130530.html
May 29 : Message from Director of J-PARC Center
http://j-parc.jp/en/topics/20130529director_message.html
May 27 : Message from the Director of J-PARC Center to Users
http://j-parc.jp/en/topics/20130527director_message.html
May 25 : Accident of J-PARC Hadron Experimental Facility
http://j-parc.jp/en/topics/20130525presse.html