Recent Results From the T2K Experiment

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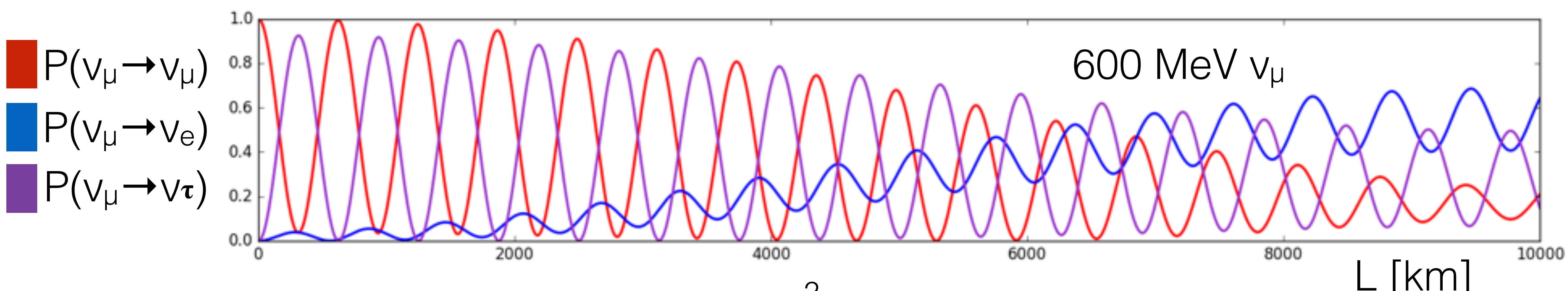
Neutrino Flavor Oscillations

- Neutrino flavor states are not mass eigenstates
- The Hamiltonian for a propagating neutrino is diagonal in the mass basis
- Each mass component has a different oscillation frequency
- For a flavor state, these phases interfere as the neutrino propagates
- This interference results in **neutrino flavor oscillations**

$$H \approx \begin{bmatrix} \frac{m_1^2}{2E} & 0 & 0 \\ 0 & \frac{m_2^2}{2E} & 0 \\ 0 & 0 & \frac{m_3^2}{2E} \end{bmatrix}$$

$$|\nu_\alpha(t)\rangle = e^{-iHt}\,|\nu_\alpha\rangle = \sum_j U^*_{\alpha j} e^{-i\frac{m_j^2}{2E}t}\,|\nu_j\rangle$$

$$|\,\langle \nu_\beta | \nu_\alpha(t)\rangle\,|^2 = P_{\nu_\alpha \to \nu_\beta}(t) \neq 0$$



Neutrino Mixing Parameters

- Standard parameterization of the unitary matrix that relates the mass and flavor states: the PMNS matrix.(Pontecorvo-Maki-Nakagawa-Sakata)
- The matrix is parameterized with three angles, and one non-trivial complex phase: **$\{\theta_{12},\theta_{23},\theta_{13},\delta_{CP}\}$**

$$s_{ij} = \sin\theta_{ij}, c_{ij} = \cos\theta_{ij}$$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Current Knowledge of Mixing and Masses

measured from solar and long-baseline reactor experiments

$$\sin^2\theta_{12} = 0.306^{+0.018}_{-0.015}$$

$$\Delta m^2_{12}[10^{-5}eV^2] = 7.58^{+0.22}_{-0.26}$$

measured from atmospheric and accelerator ν_μ disappearance

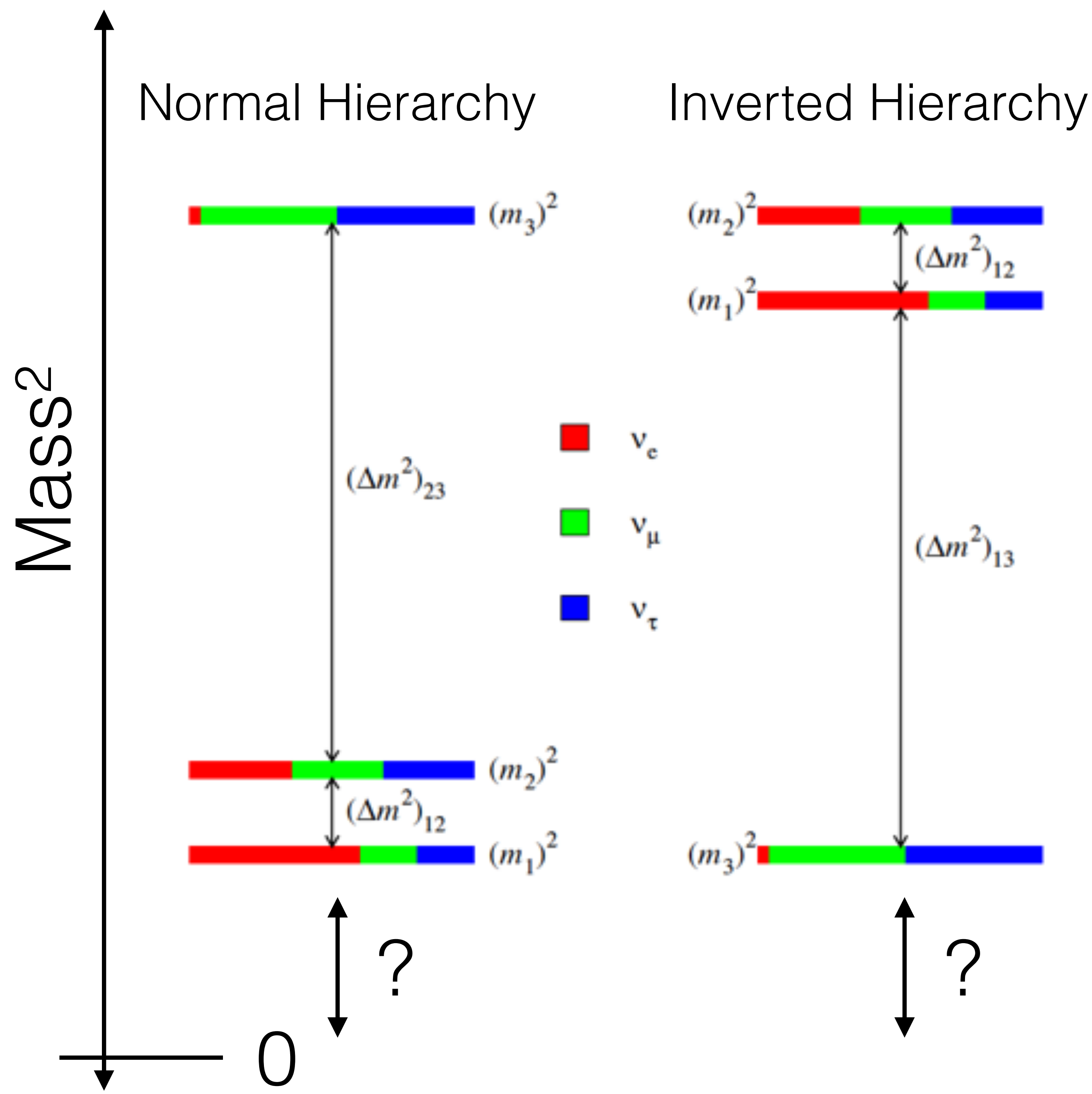
$$\Delta m^2_{23}[10^{-3}eV^2] = 2.35^{+0.16}_{-0.09}$$

$$\sin^2\theta_{23} = 0.514^{+0.055}_{-0.056}$$

recently measured with short-baseline reactor and long baseline accelerator experiments

$$\sin^2\theta_{13} = 0.021^{+0.007}_{-0.008}$$

goal for future experiments: $\delta_{CP} = ?$



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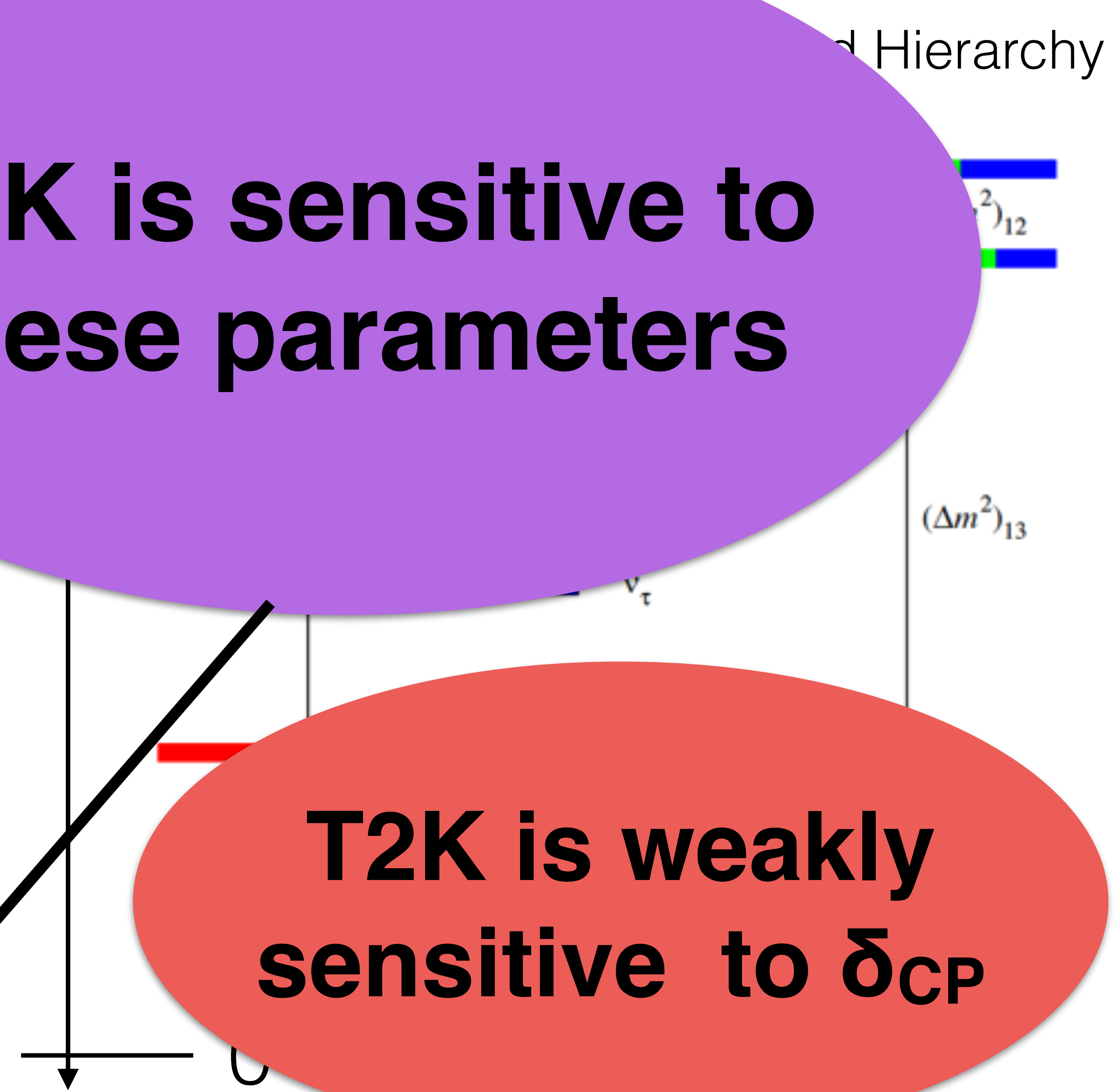
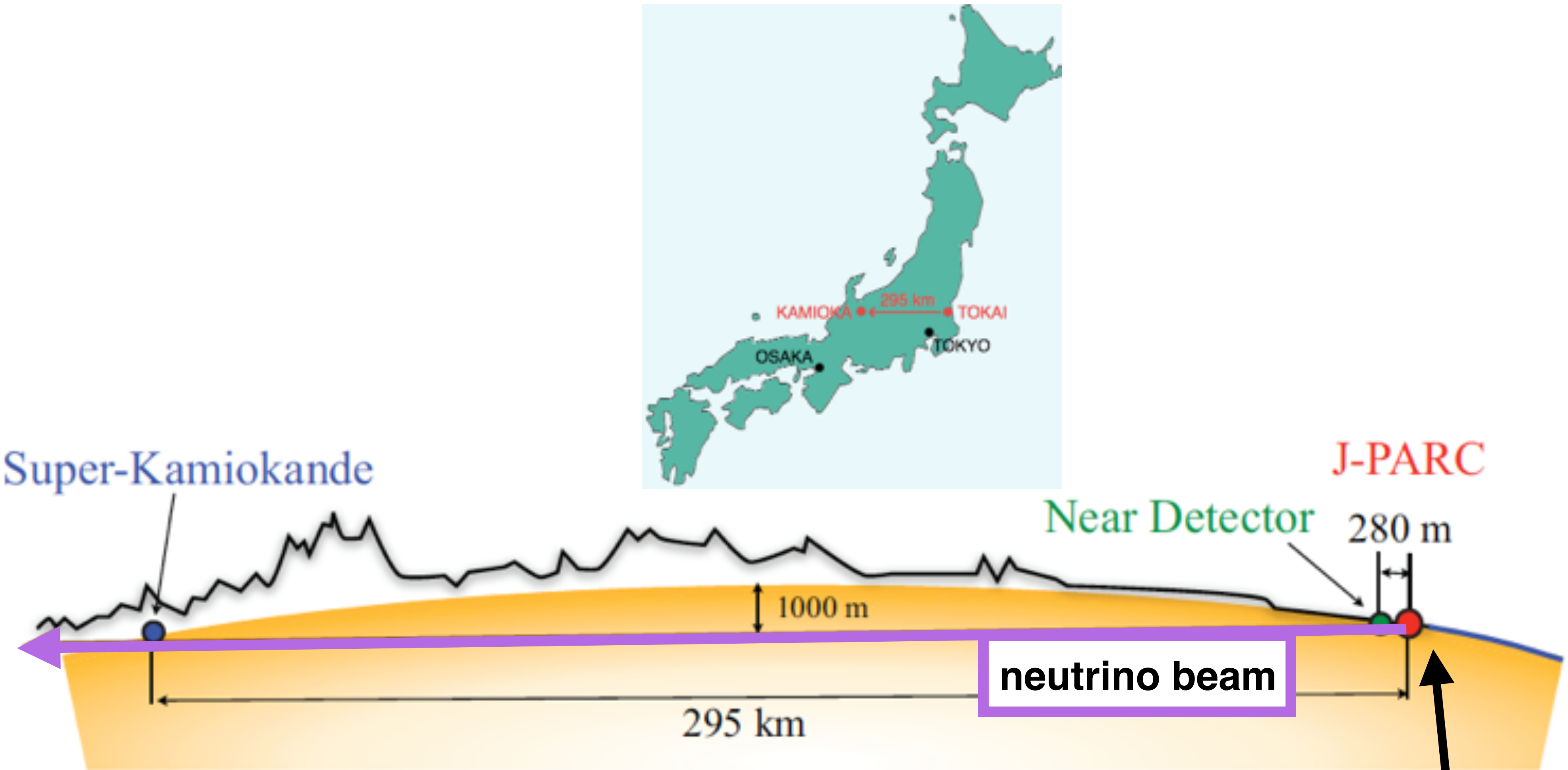


T2K is sensitive to these parameters

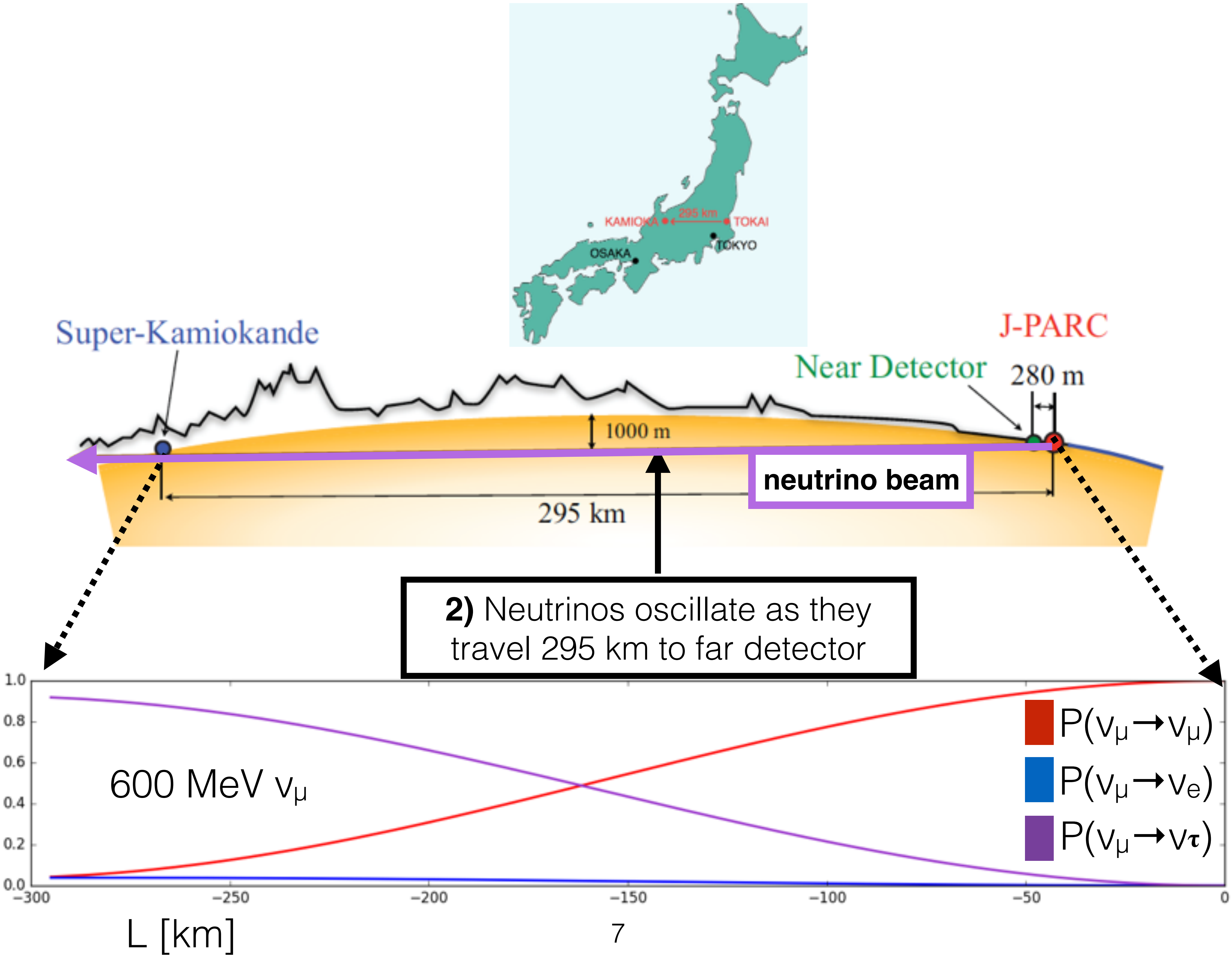
T2K is weakly sensitive to δ_{CP}

The T2K Experiment



1) Produce neutrino beam of known flavor

The T2K Experiment



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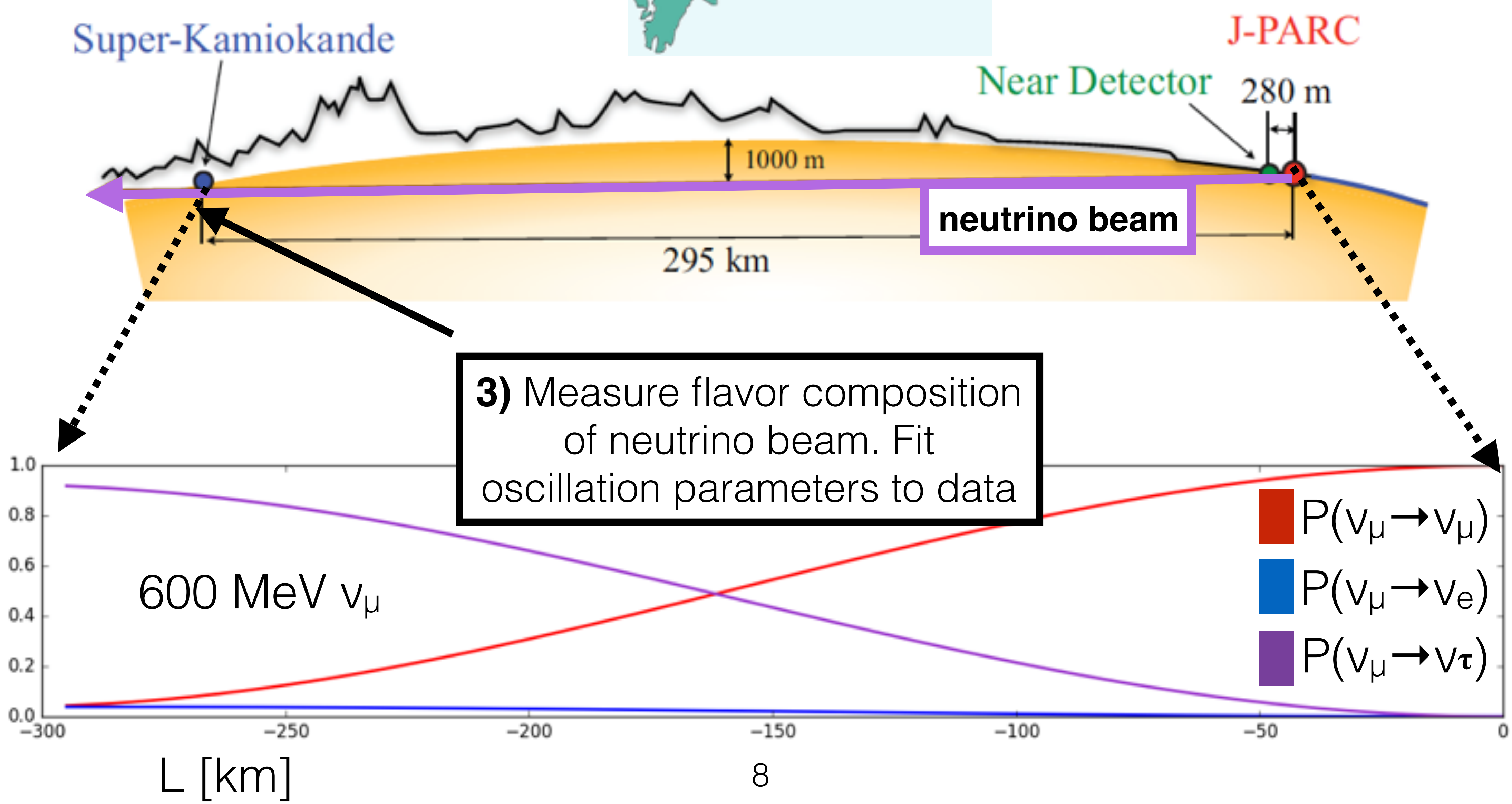

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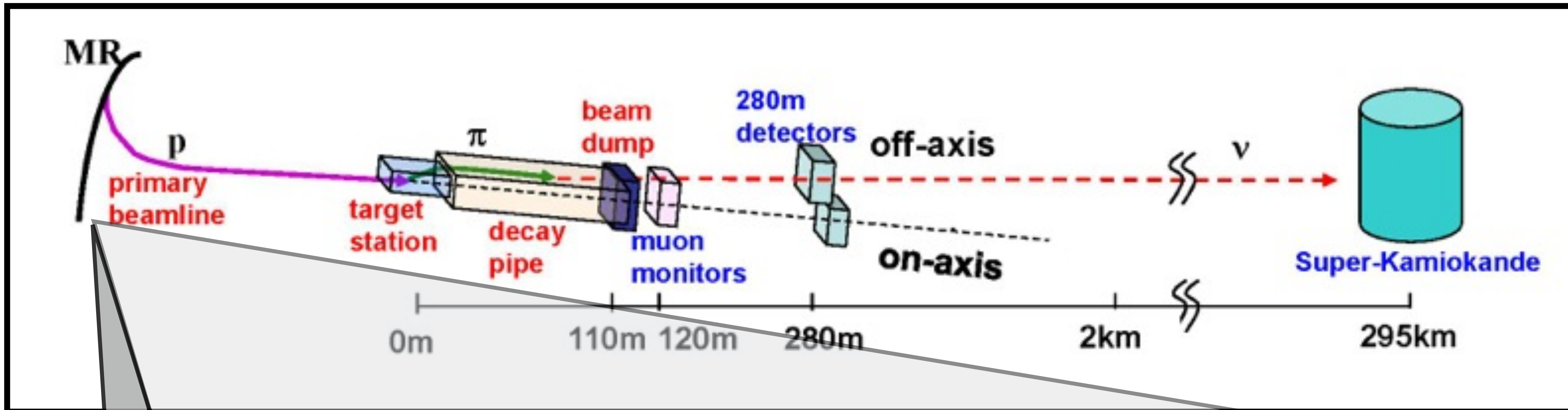

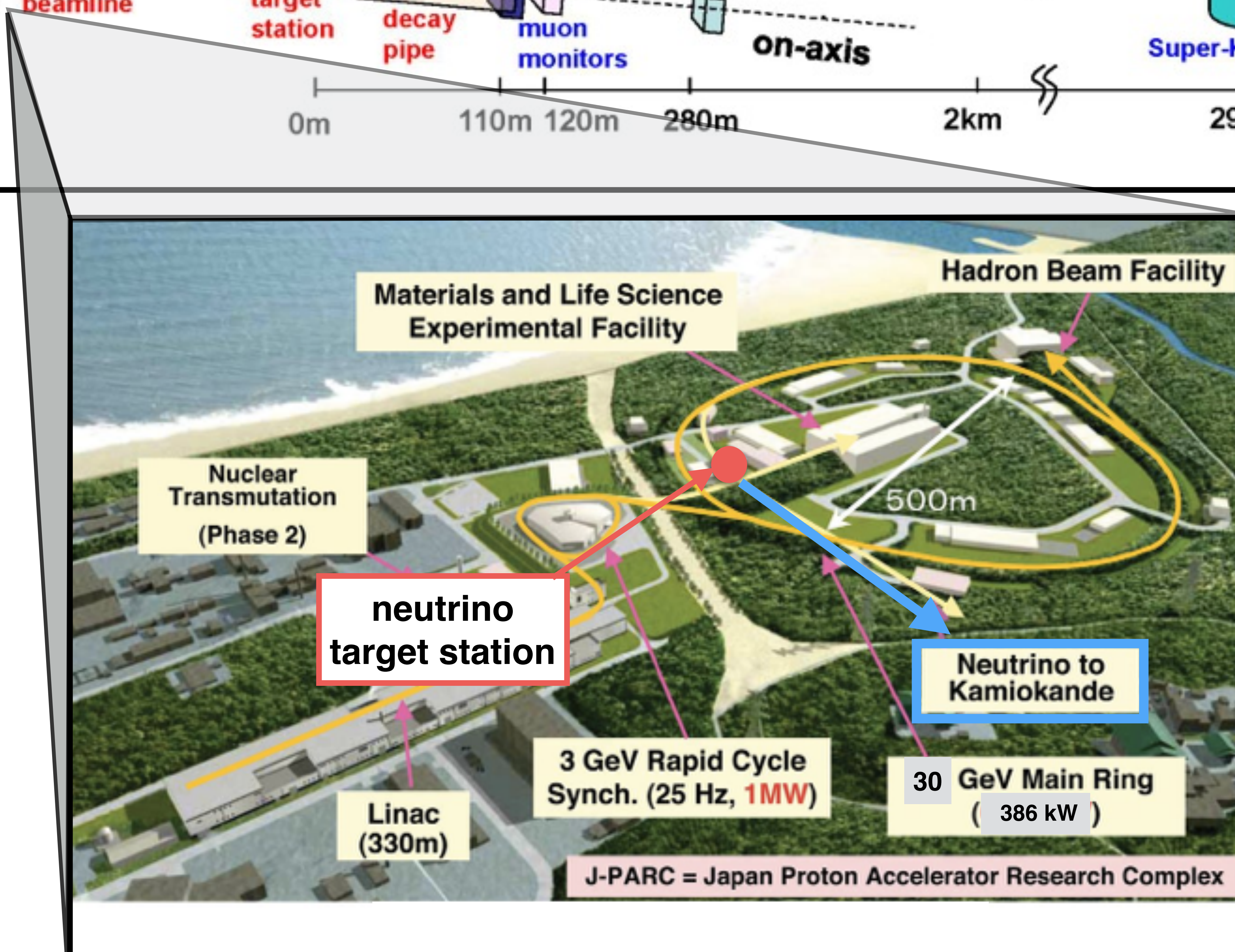

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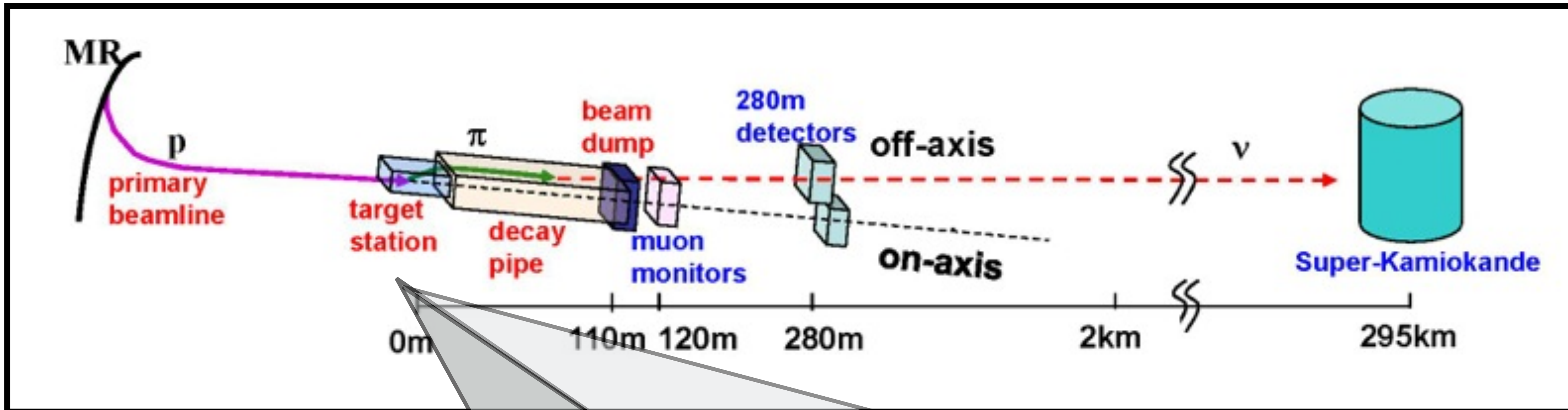
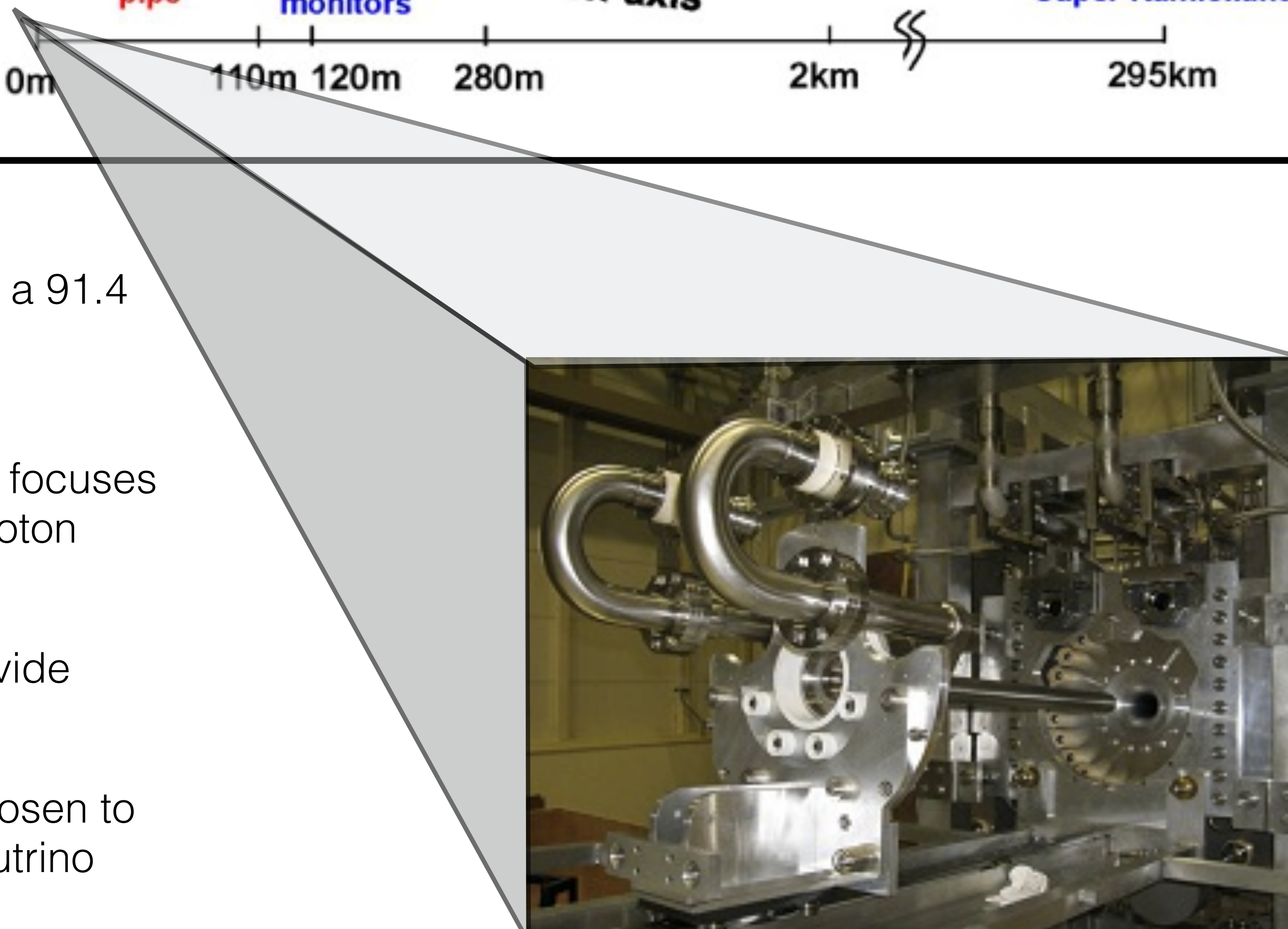


- 30 GeV protons impinge on a 91.4 cm graphite target
- Target is located within an electromagnetic "horn" that focuses hadrons (pions) from the proton collisions
- Two downstream horns provide additional focusing
- Direction of horn current chosen to focus positive particles (neutrino mode) or negative particles (antineutrino mode)



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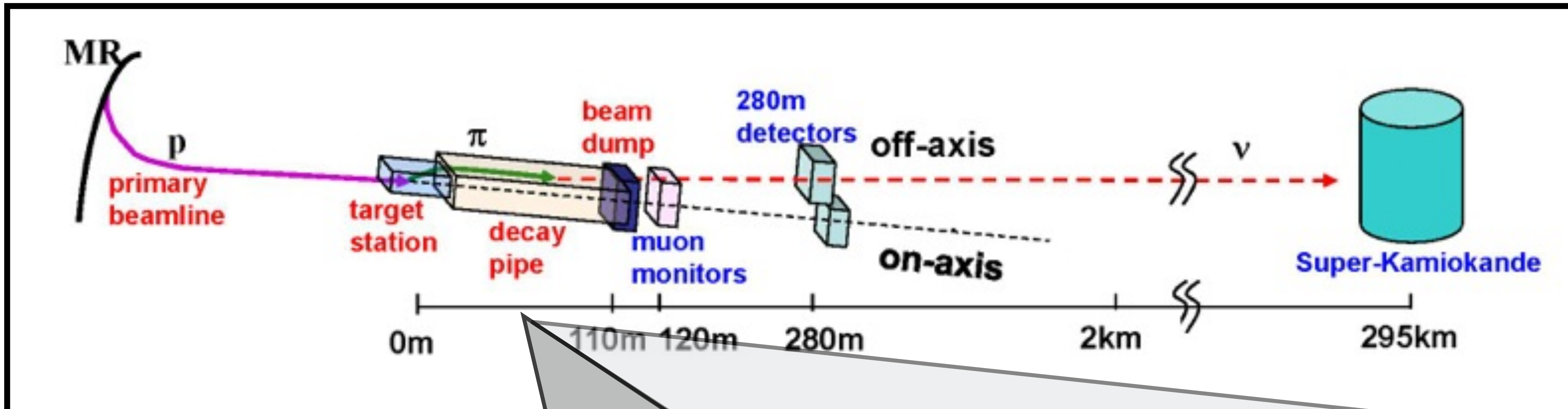
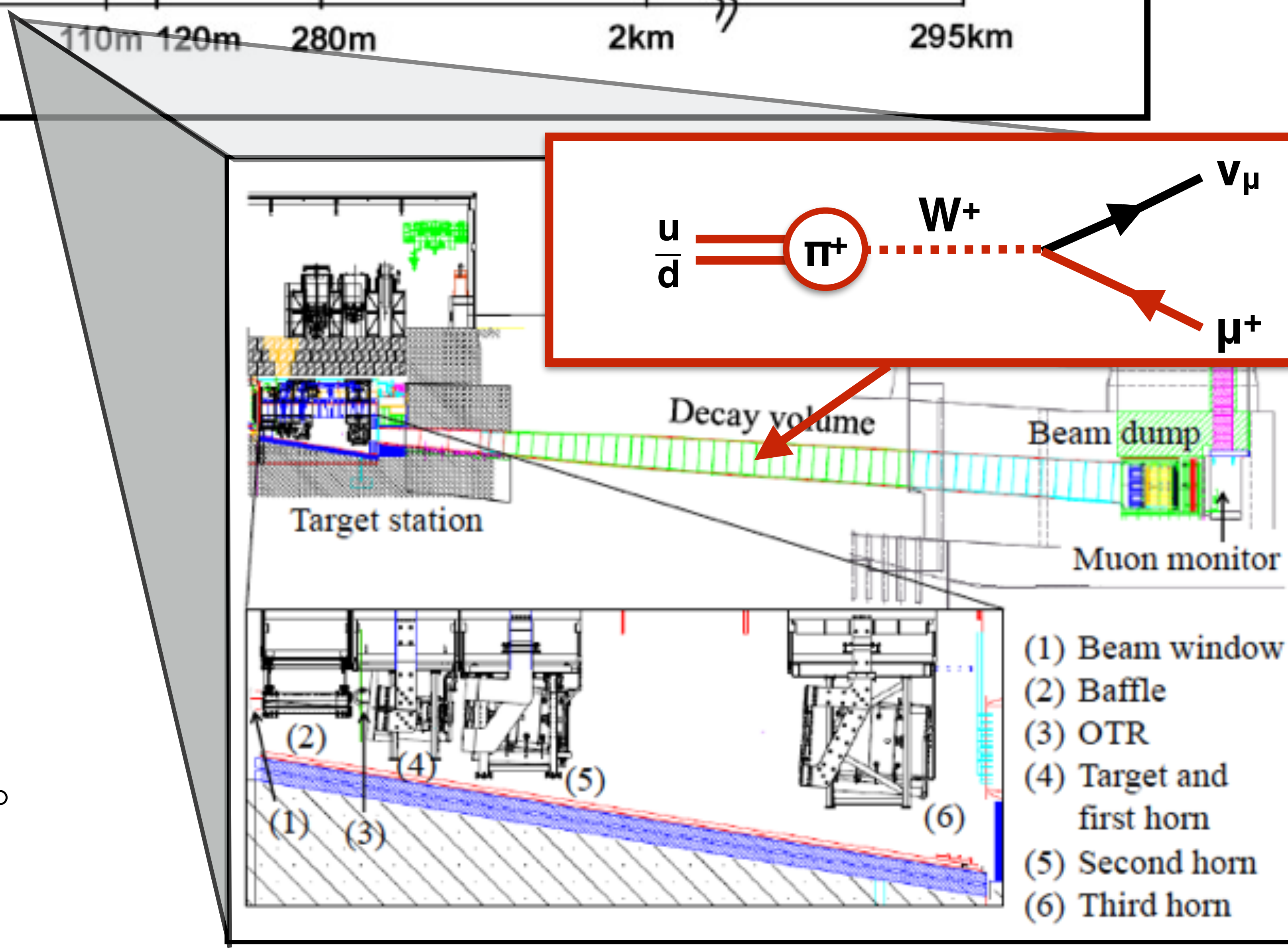


- Pions are allowed to decay in 96 m helium-filled decay volume
- Pion decays in flight result in ν_μ (or anti-ν_μ) beam in direction of pion momentum
- neutrino beam directed 2.5° from far detector



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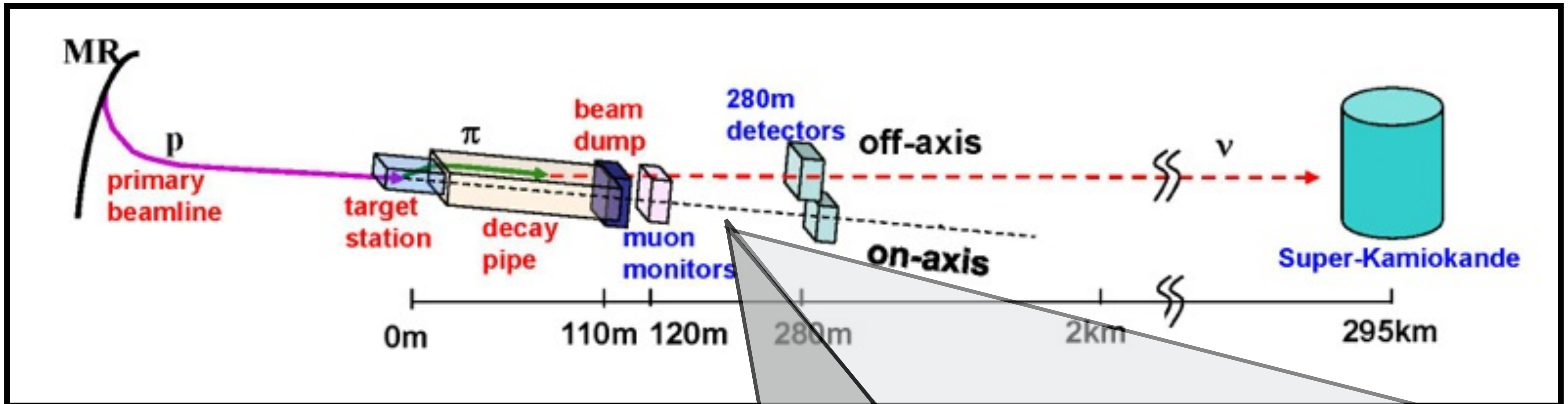
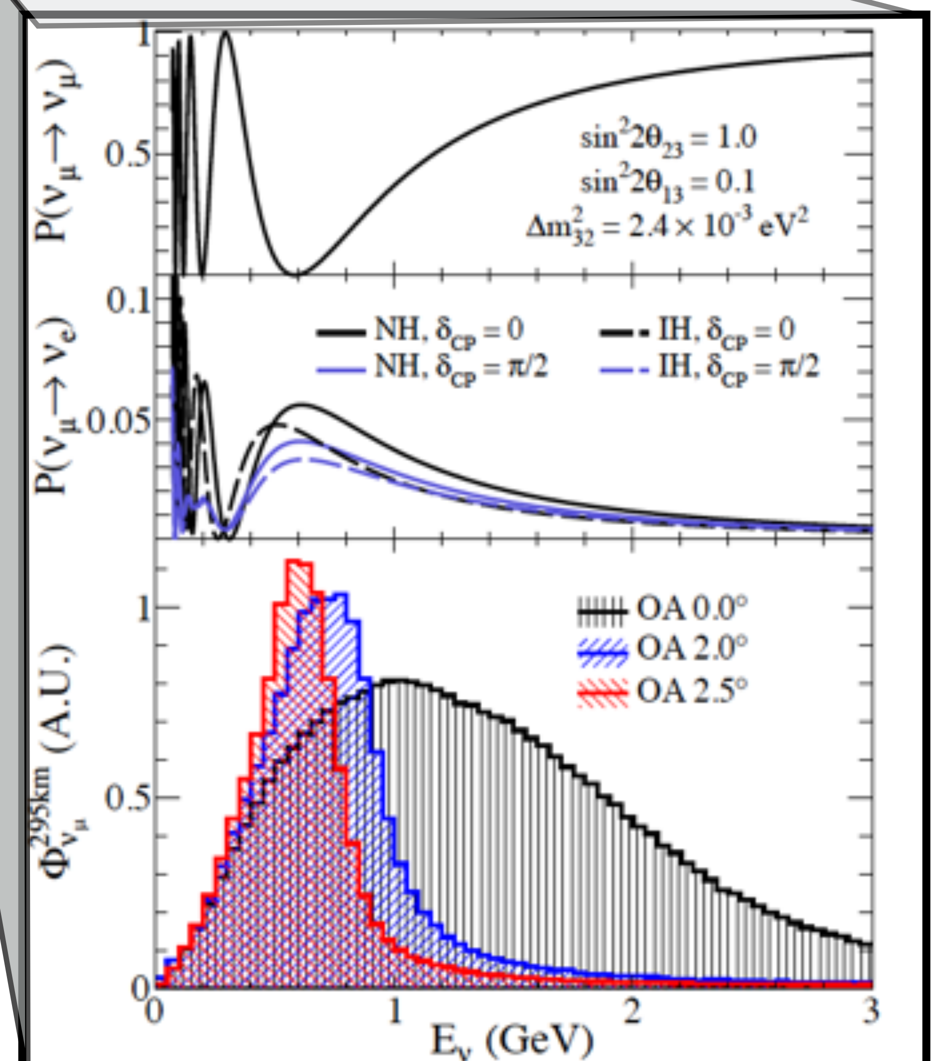
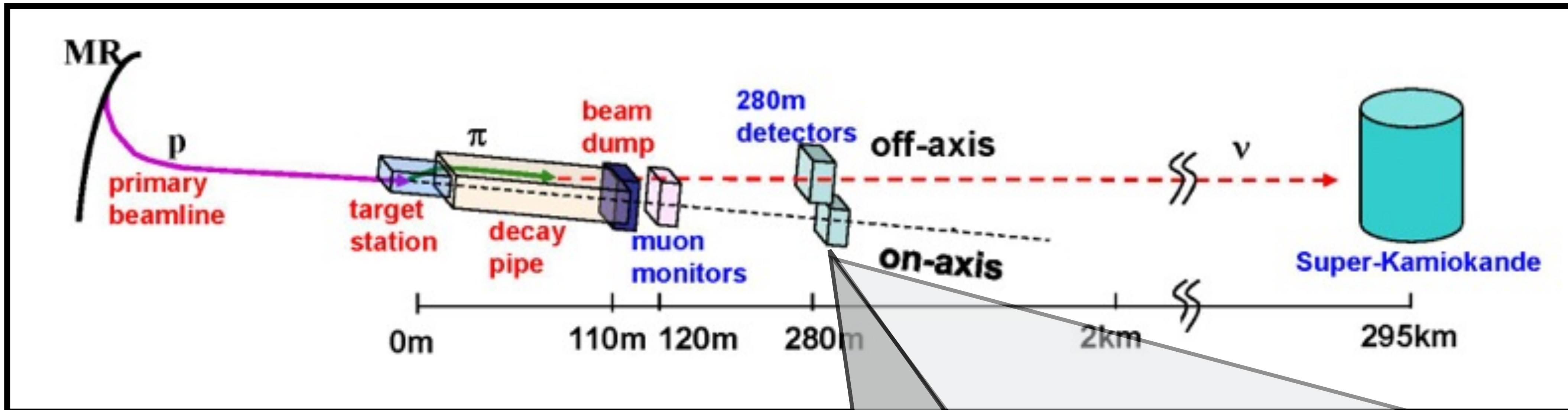


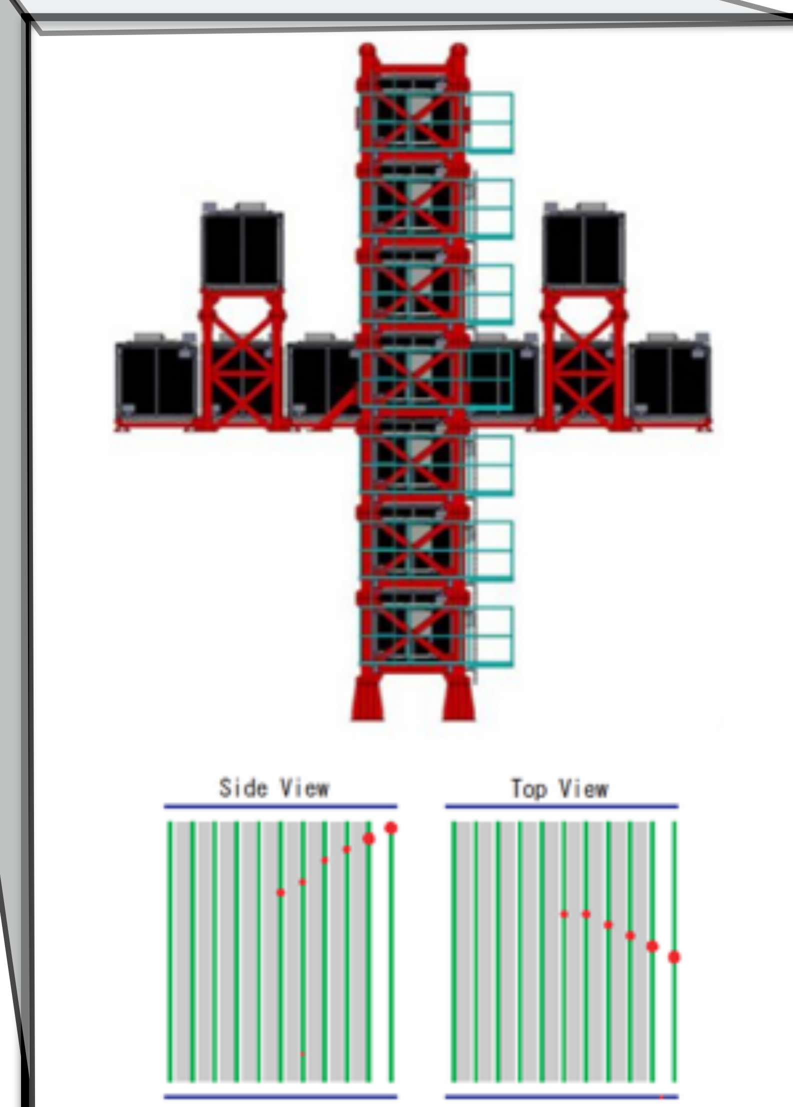
- Why use an off-axis beam?
- Narrow-band neutrino beam tuned to maximize oscillation signal at Super-Kamiokande
- Remove high-energy backgrounds



The T2K Experiment



- INGRID detector is on beam axis
- Consists of 16 modules of sandwiched scintillator and and iron layers
- Uses neutrino event rate to measure center of neutrino beam to 0.006 degrees



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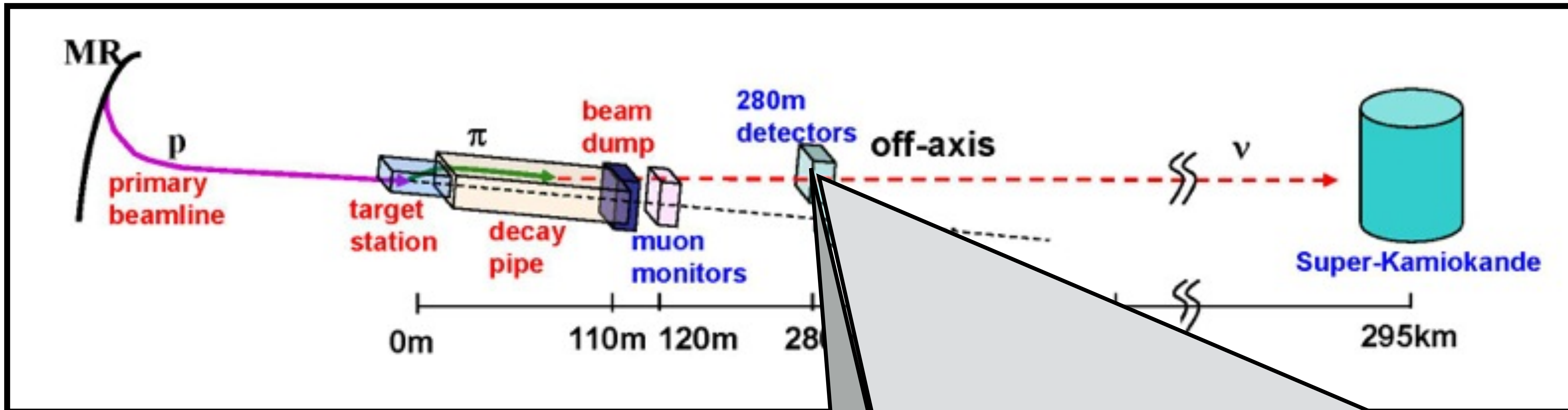
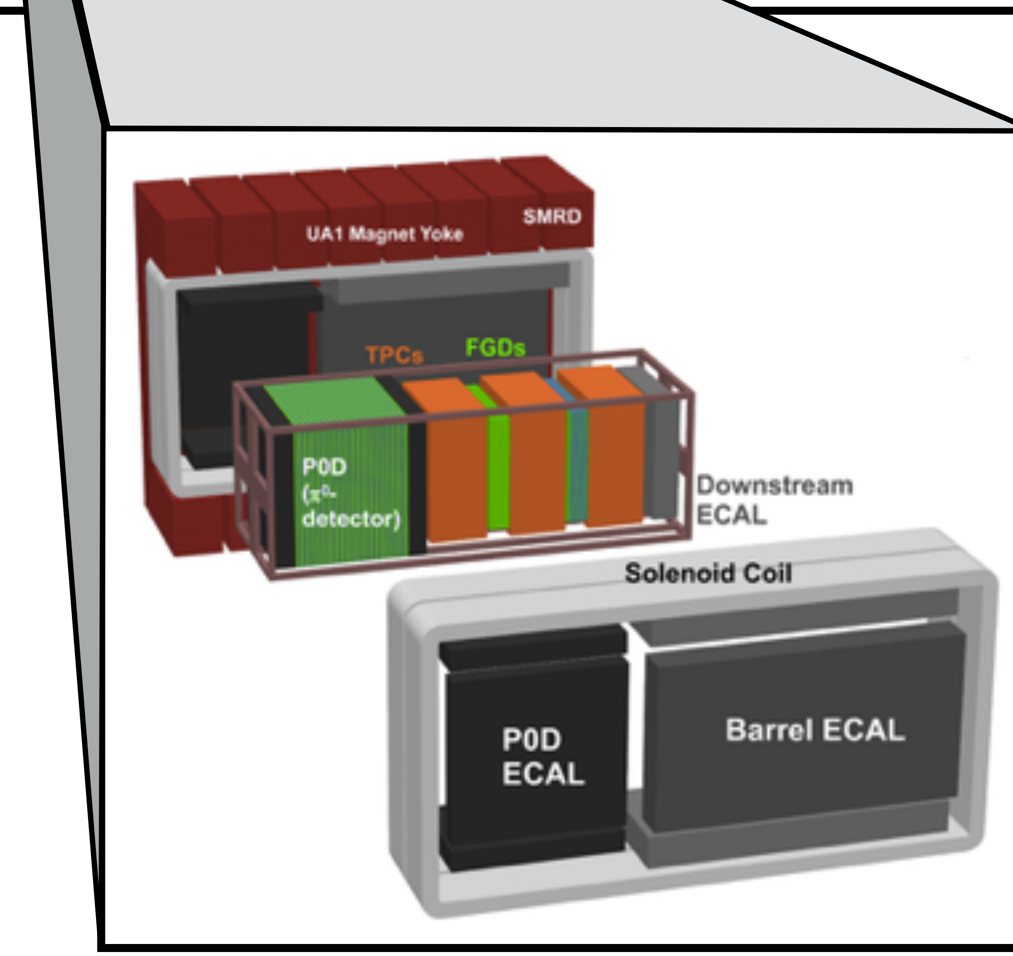


- ND280 detector is located off-axis at the same angle as the far detector

- Multiple components immersed in magnetic field

- ND280 data provides important constraint for un-oscillated neutrino flux



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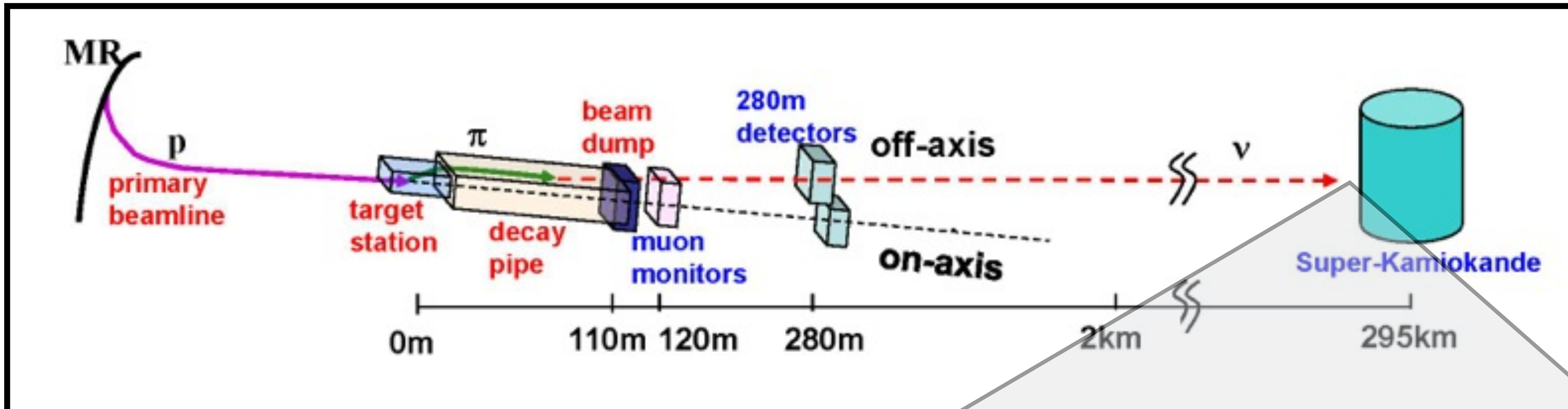
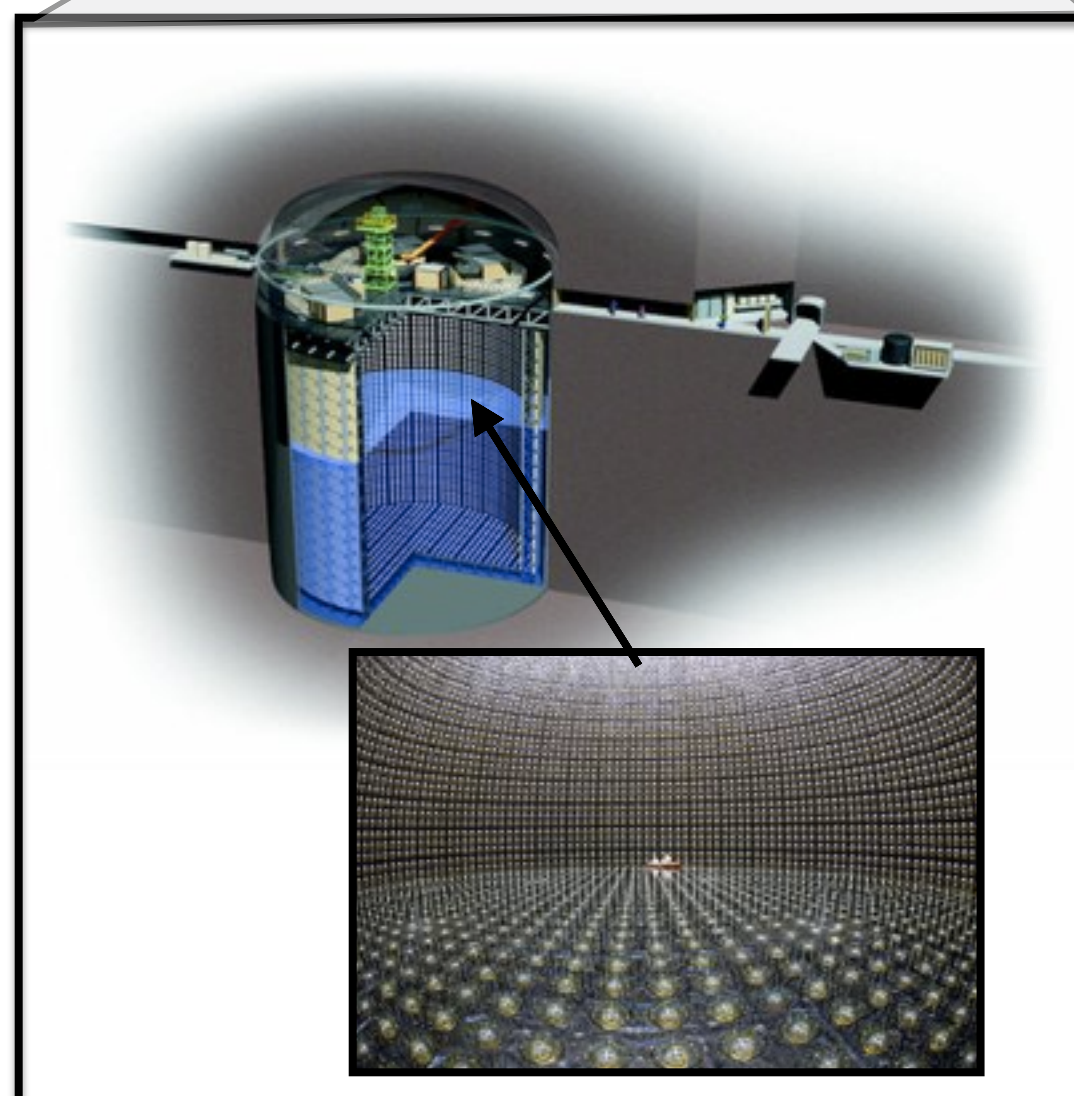


- Super-Kamiokande is the far detector at 295 km from target
- Consists of a 22.5 kton fiducial volume ring-imaging water Cherenkov detector
- Water volume separated into an inner detector (ID) for imaging Cherenkov rings and outer detector (OD) for vetoing entering backgrounds



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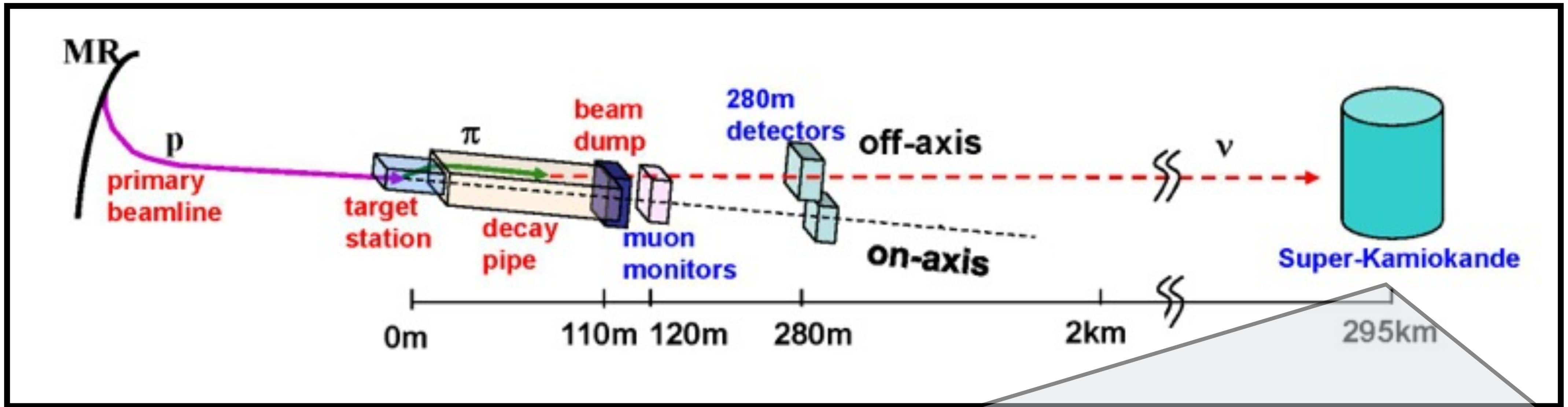
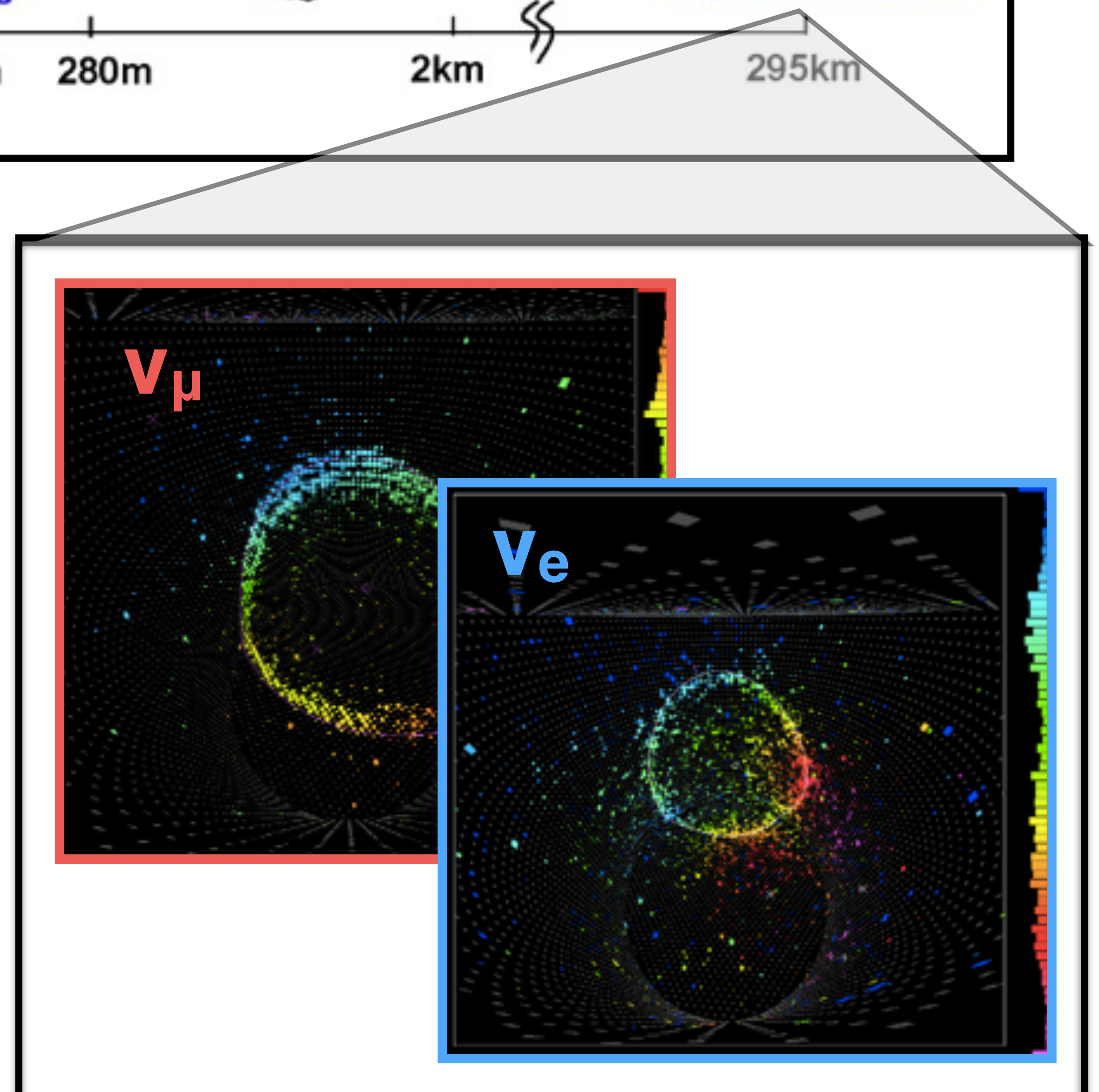
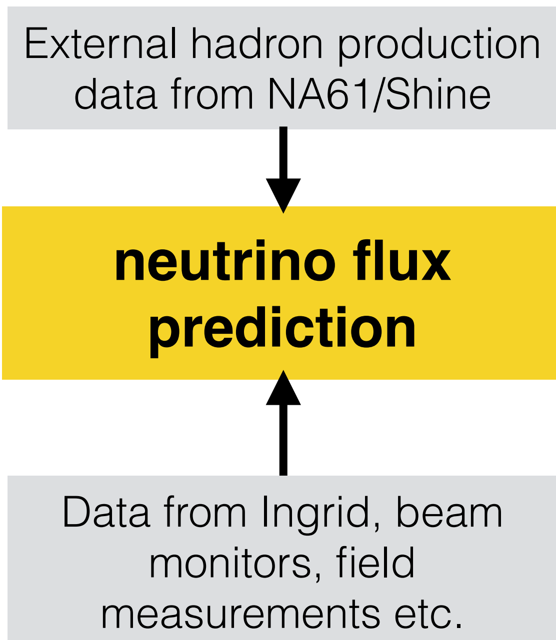


- SK PID depends on characteristics of Cherenkov ring
- Muons produce thick rings with well defined edges
- Electrons produce thin, fuzzy rings from electromagnetic showers



Analysis Strategy



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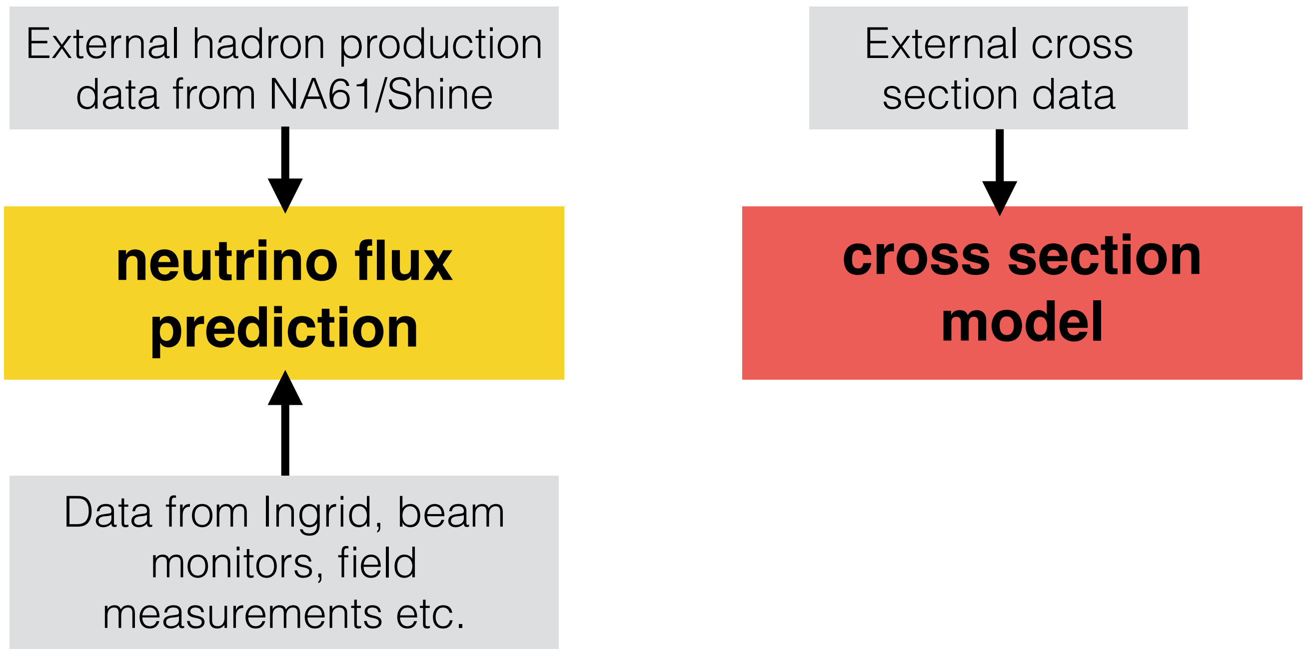

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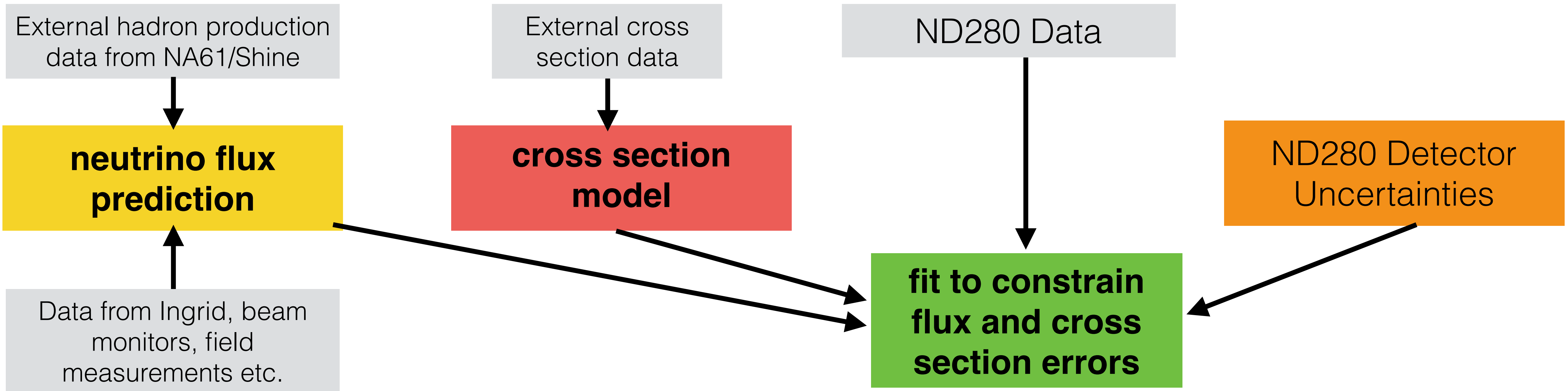

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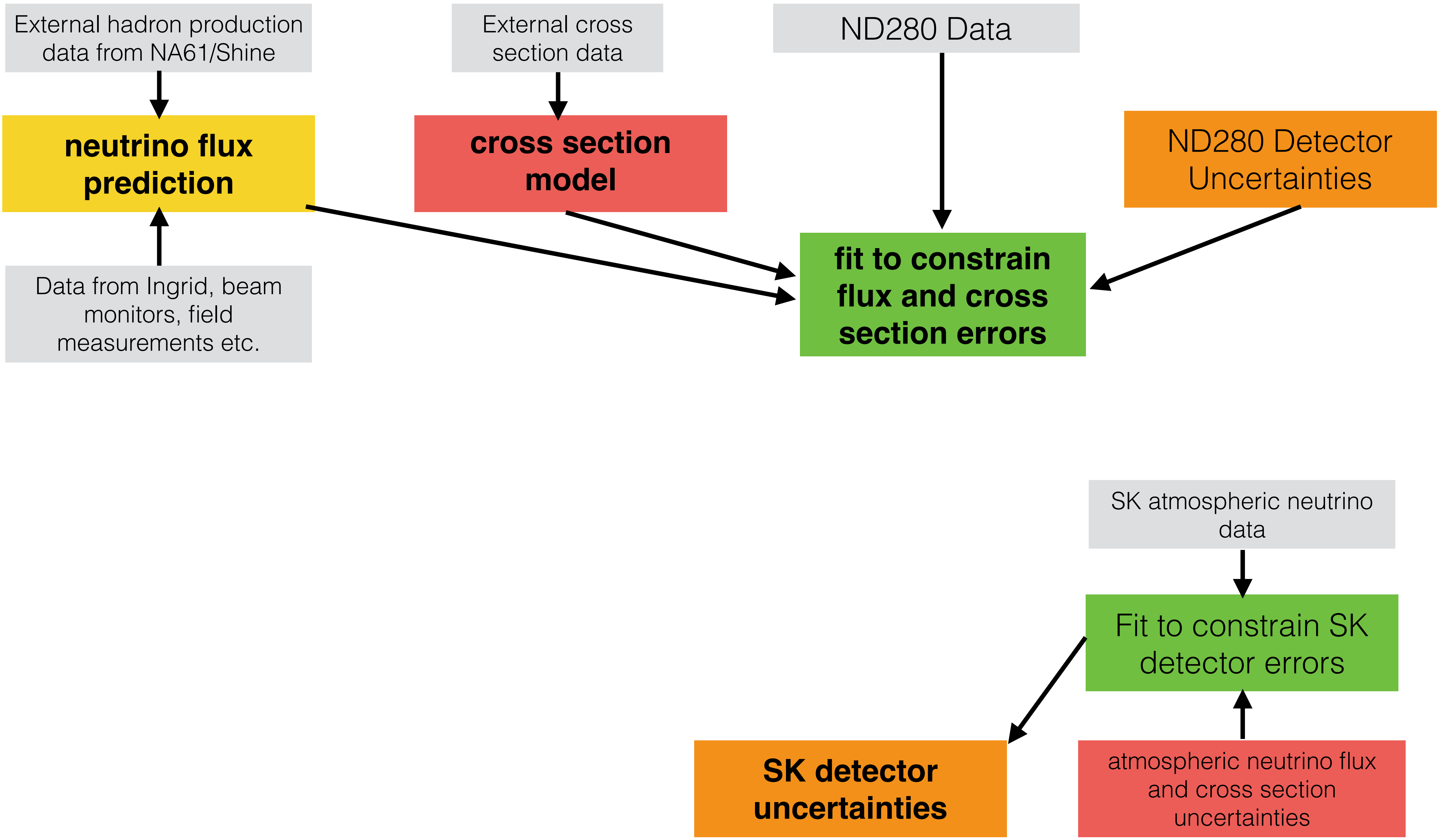

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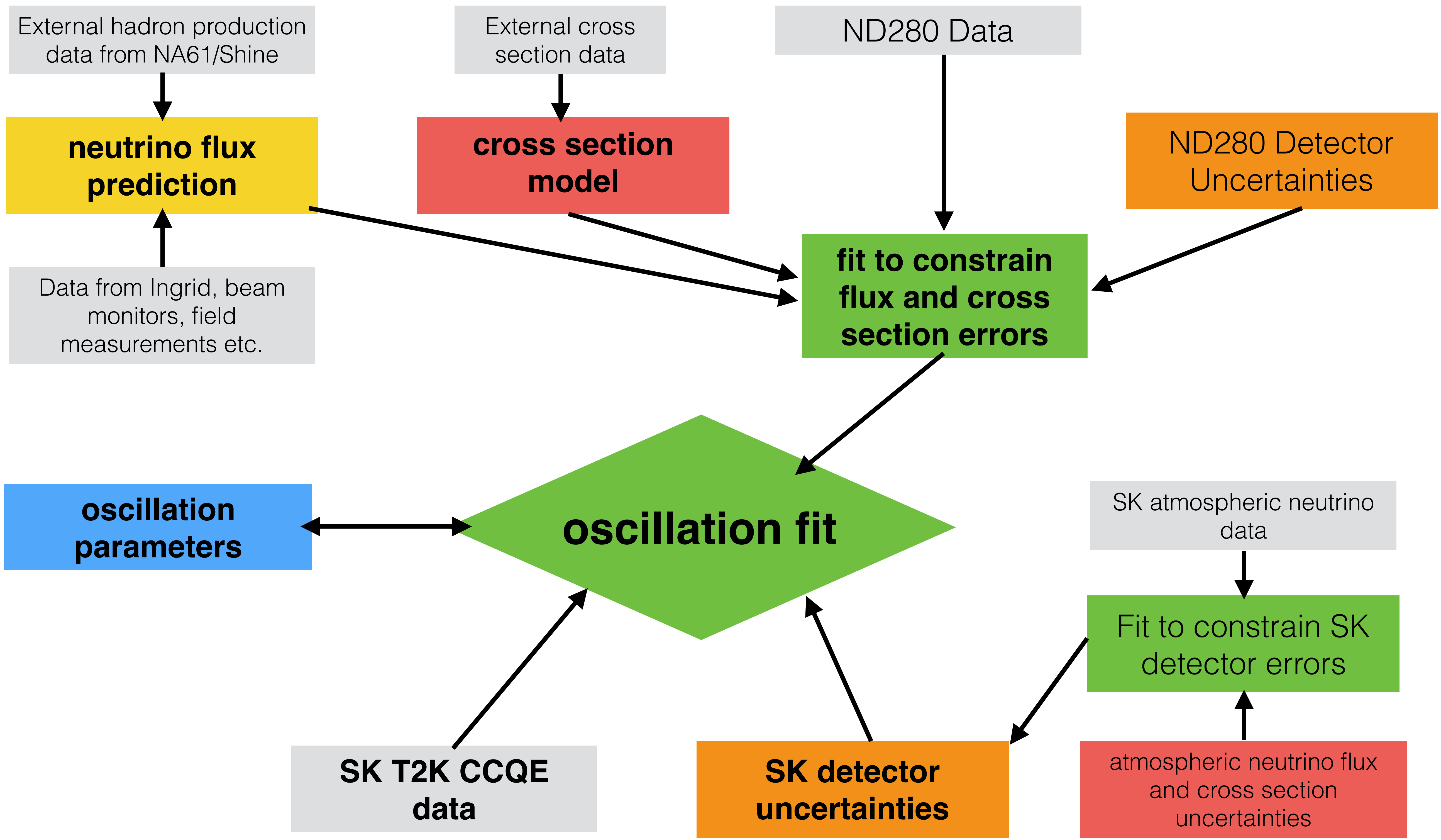
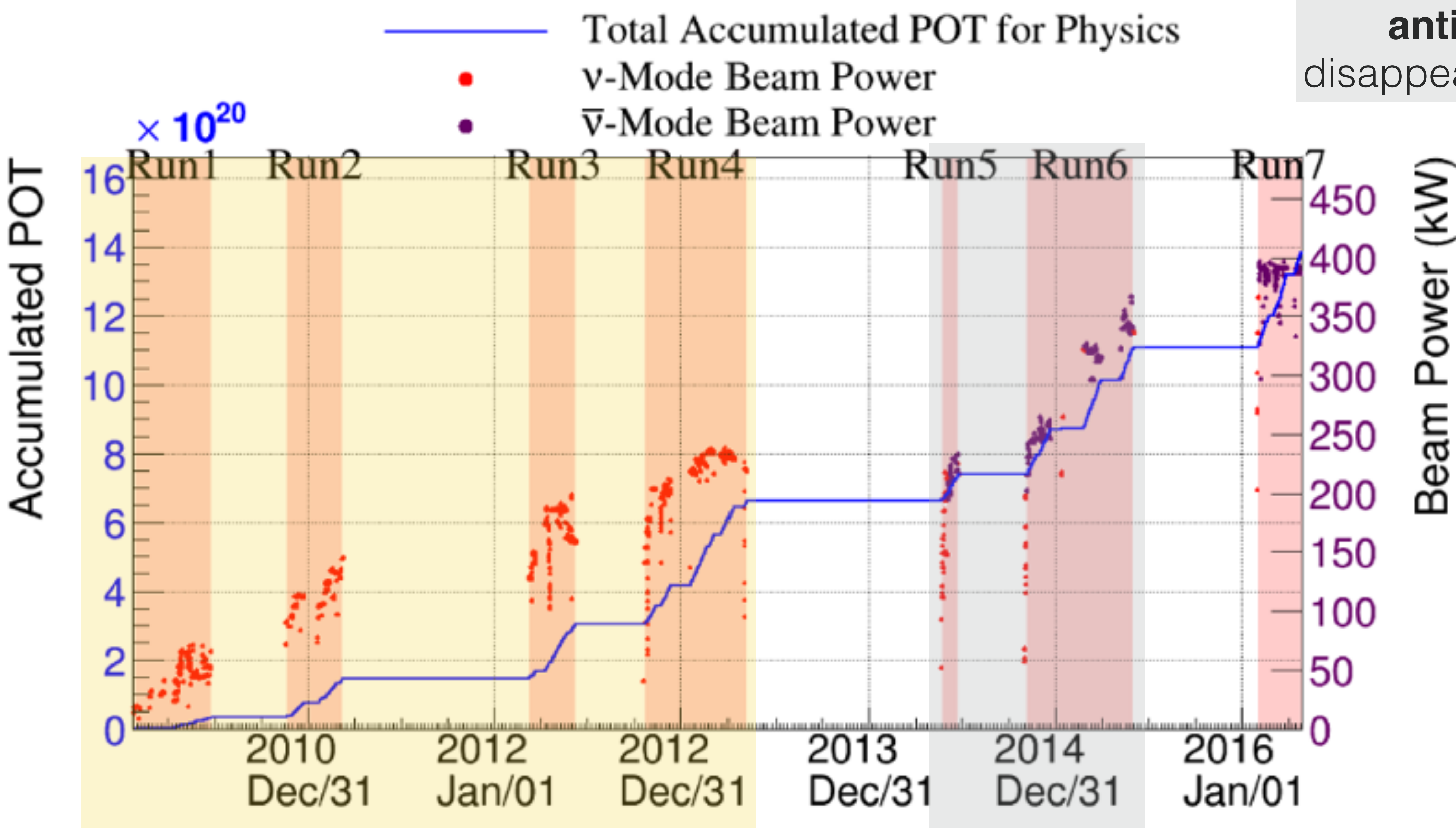


Beam History

data set for **neutrino** disappearance and appearance results

data set for **antineutrino** disappearance results

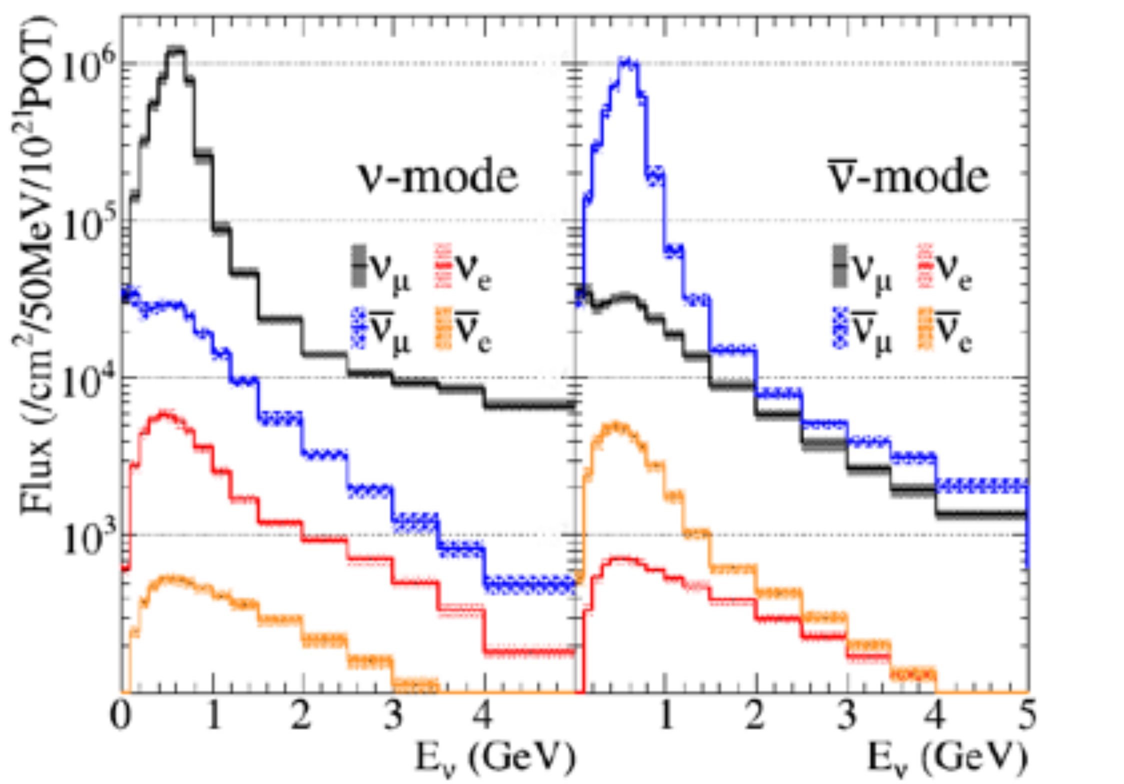


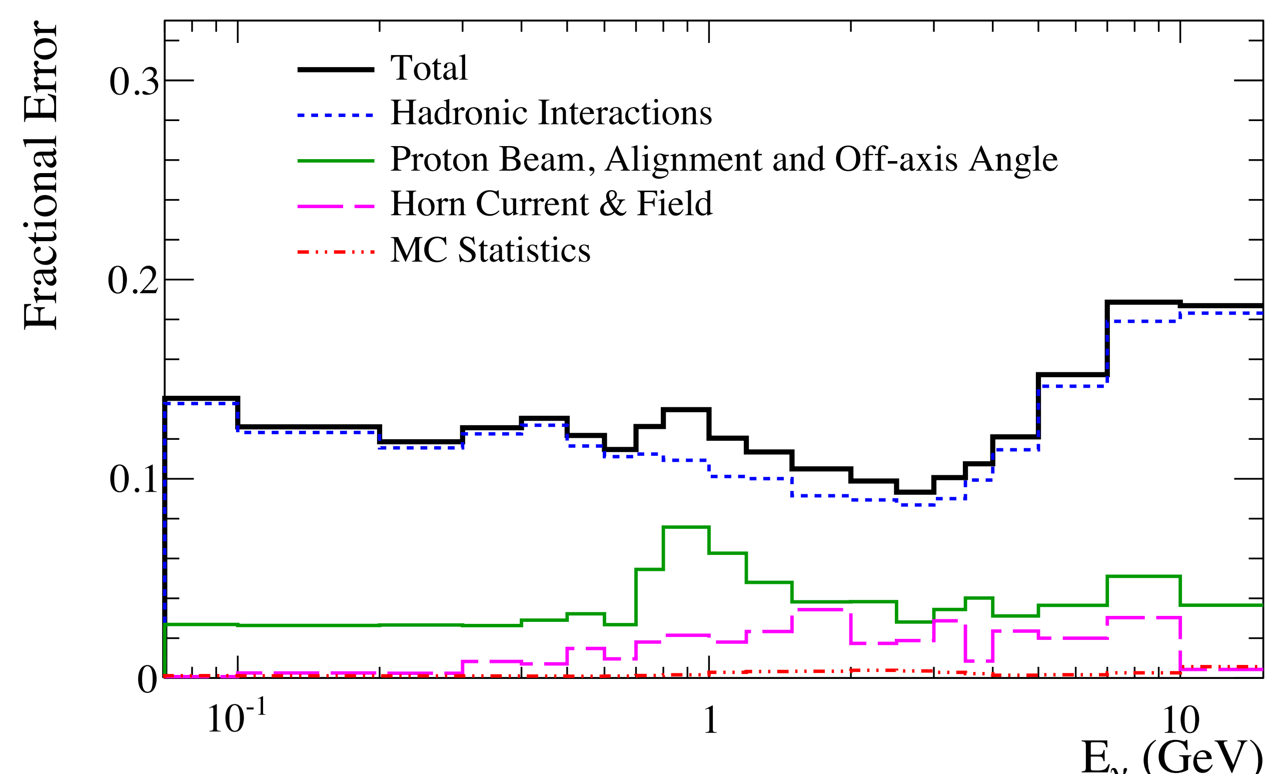
26 April 2016
POT total: 1.3844×10^{21}

nu-mode POT: 7.124×10^{20} (51.46%)
nubar-mode POT: 6.720×10^{20} (48.54%)

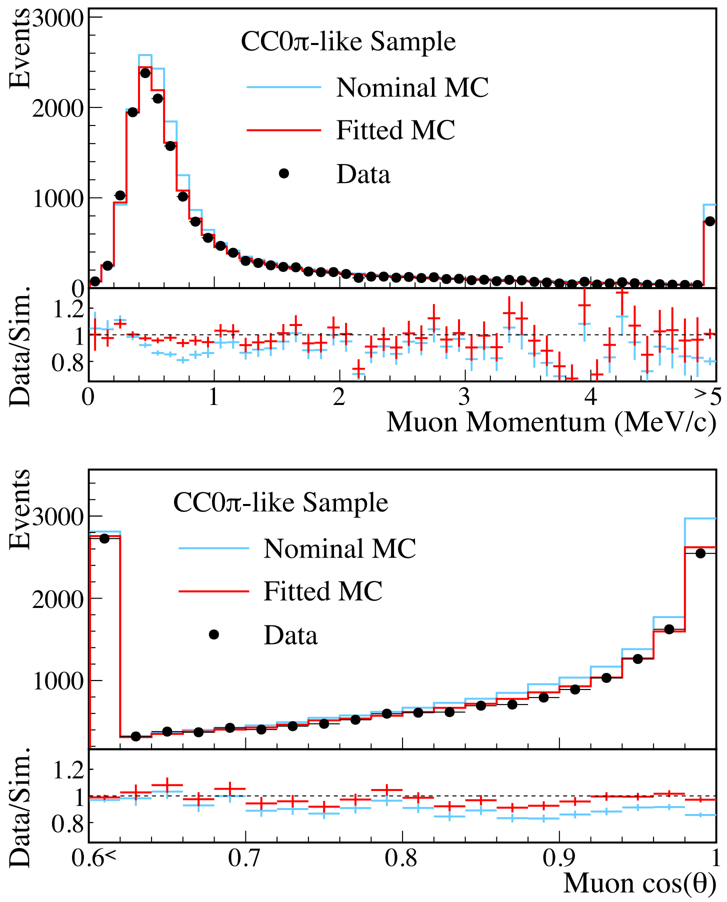
Neutrino Flux Prediction

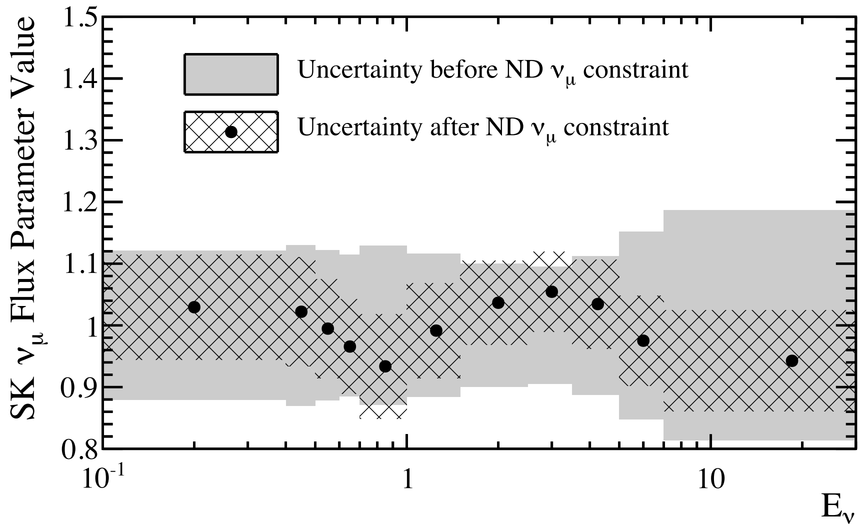
- Neutrino beam is dominated by ν_μ from pion decays
- Uncertainty is dominated by uncertainties in hadronic interactions, esp. hadron production
- NA61/SHINE hadron production data helps improve these uncertainties



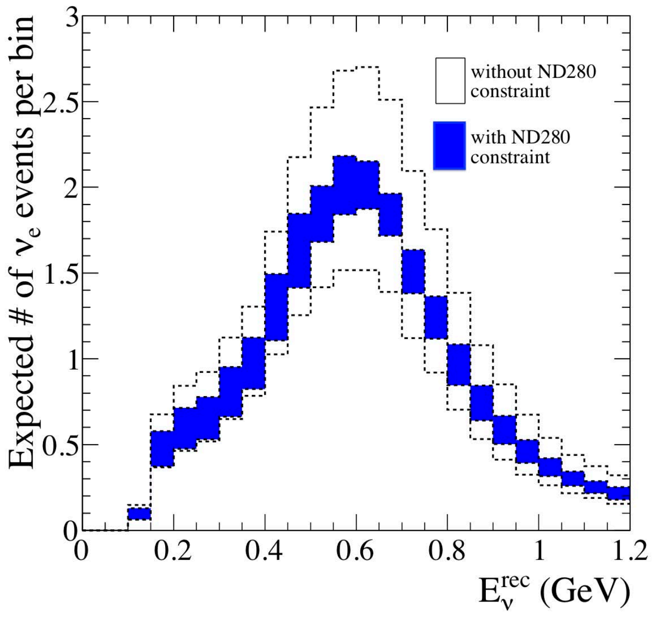


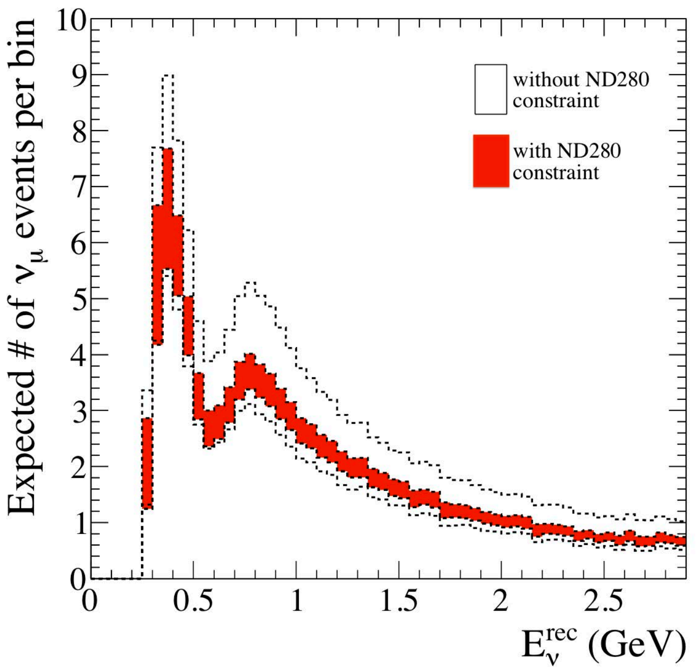
Near Detector Constraint





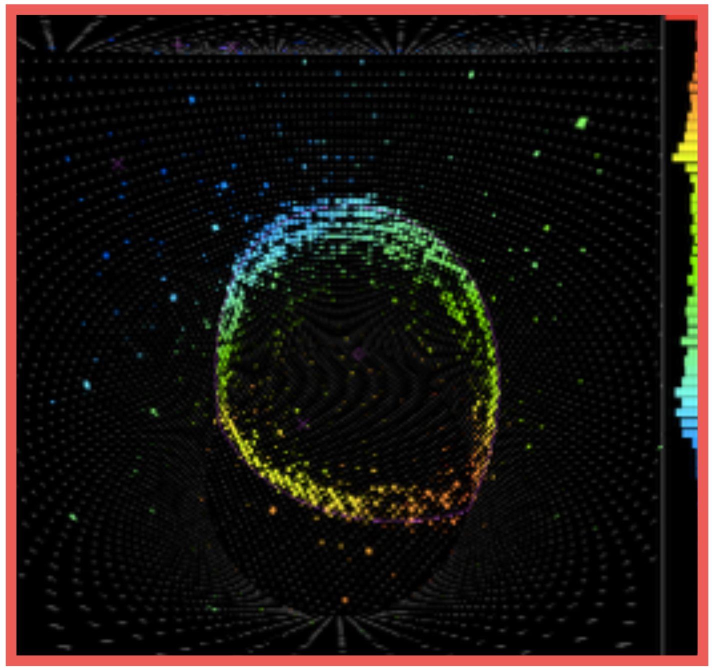
- Flux and cross section uncertainties are constrained by fit to ND280 data
- Significant reduction in flux uncertainties at SK
- Uncertainty in SK event rate also reduced significantly
- Remaining uncertainty dominated by difference in nuclear target between ND280 and SK





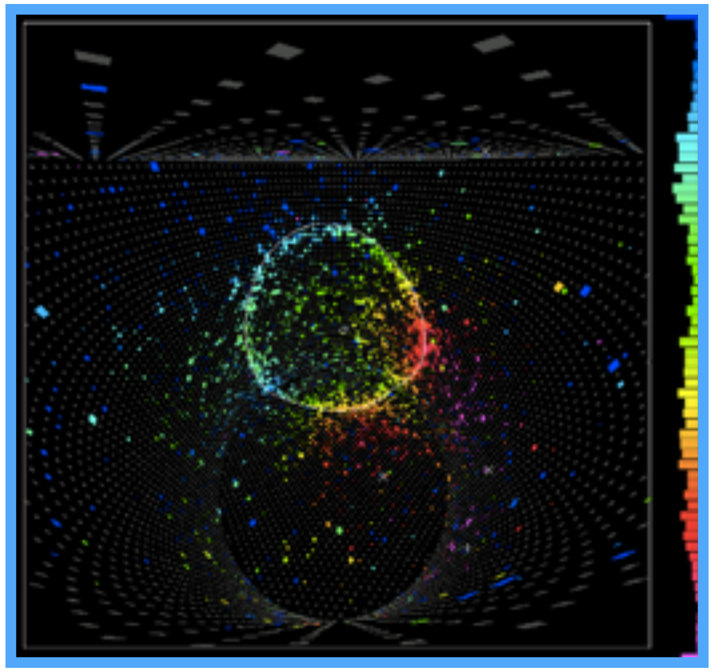
SK Event Selection

ν_μ Selection



- Pre-selection: beam timing, fully contained cuts
- Fiducial volume cut (>200 cm from wall)
- Single ring
- μ-like ring
- Reconstructed momentum > 200 MeV
- <= 1 decay electron

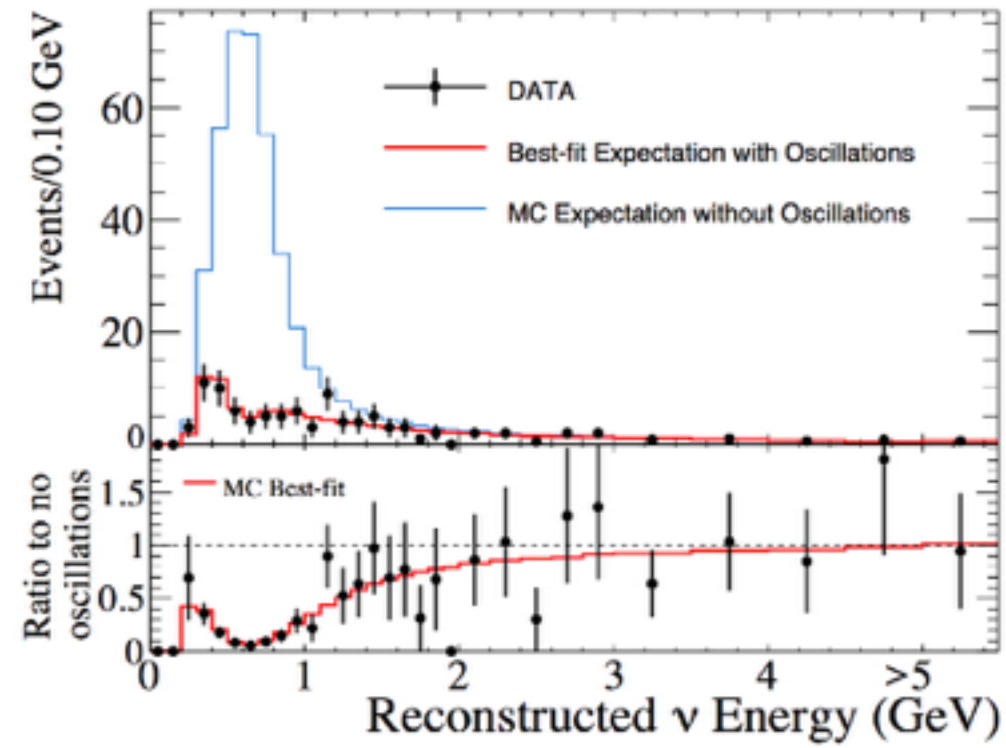
ν_e selection

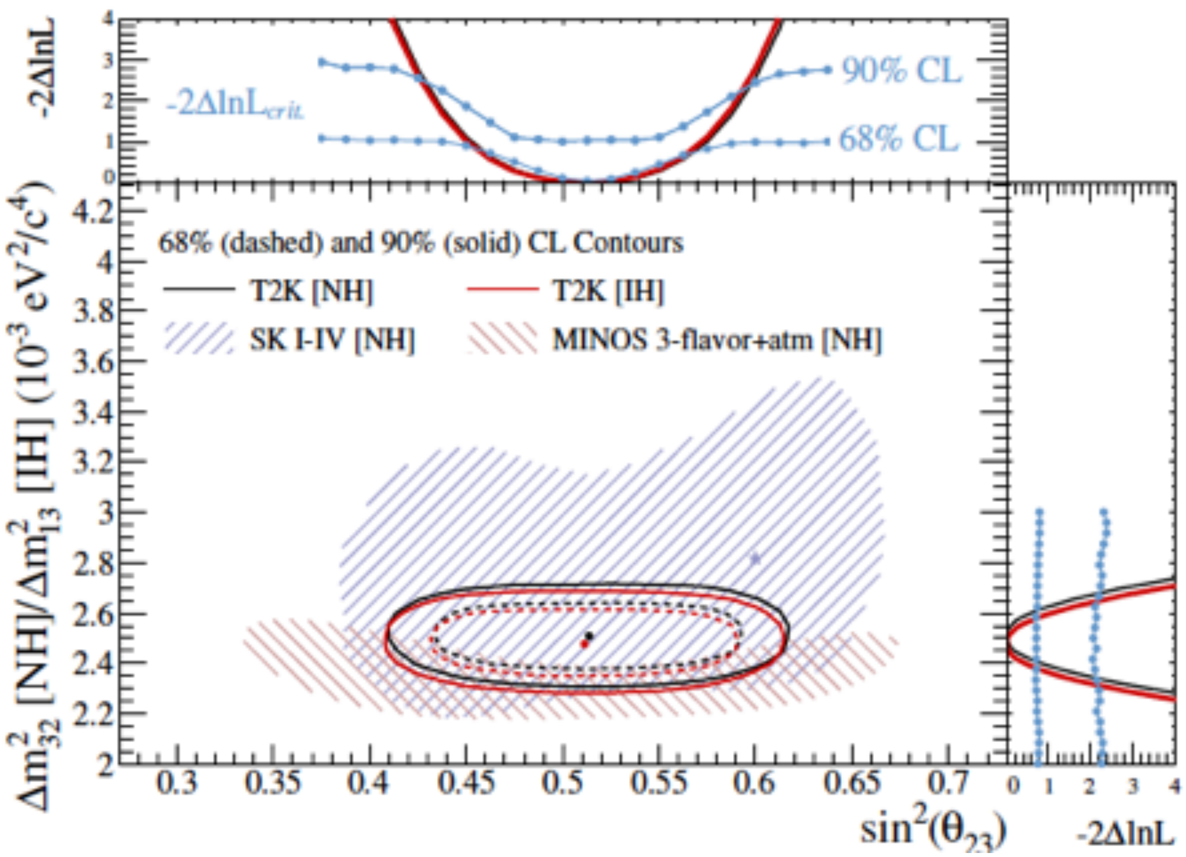


- Pre-selection: beam timing, fully contained cuts
- Fiducial volume cut (>200 cm from wall)
- One e-like ring
- 100 MeV< Visible energy < 1250 MeV
- No decay electron
- Neutral pion rejection cut

ν_μ Disappearance Results

- Observed ν_μ neutrino spectrum shows clear evidence of ν_μ disappearance





- results:

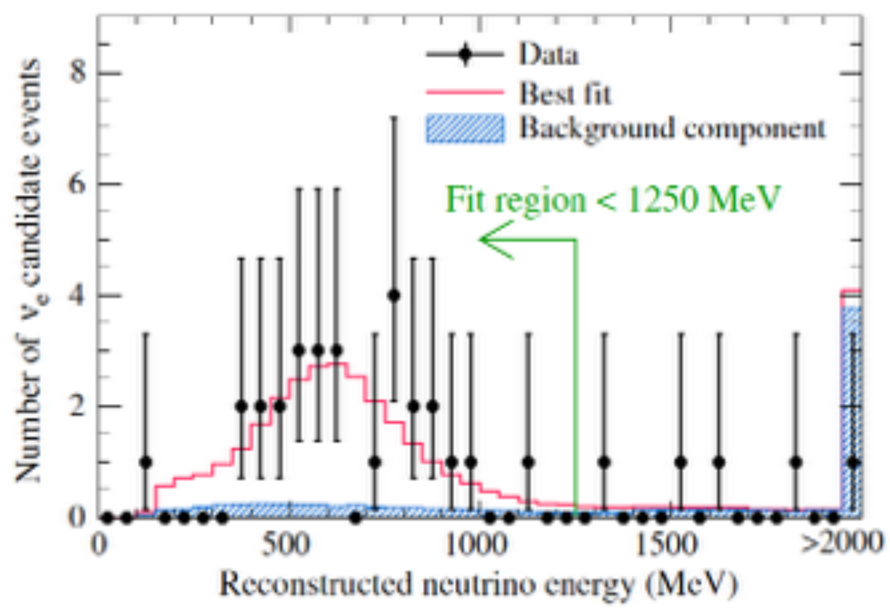
$$\sin^2\theta_{23} = 0.514^{+0.055}_{-0.056}$$

$$\Delta M^2 = 2.51^{+0.1}_{-0.1} \times 10^{-3} eV^2$$

- **World's best constraint on θ_{23}!**

Phys. Rev. Lett. 112, 181801

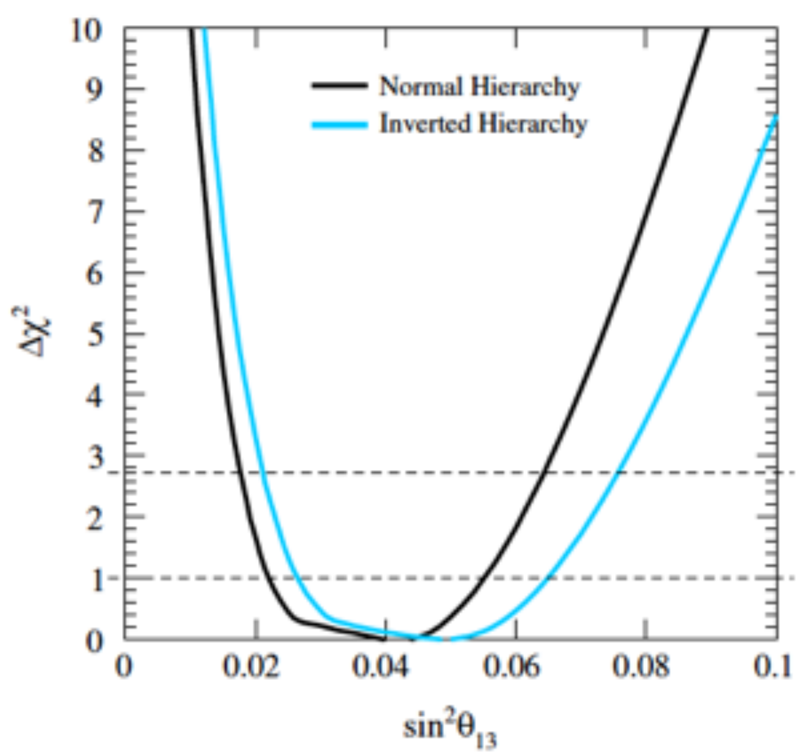
ν_e Appearance Results

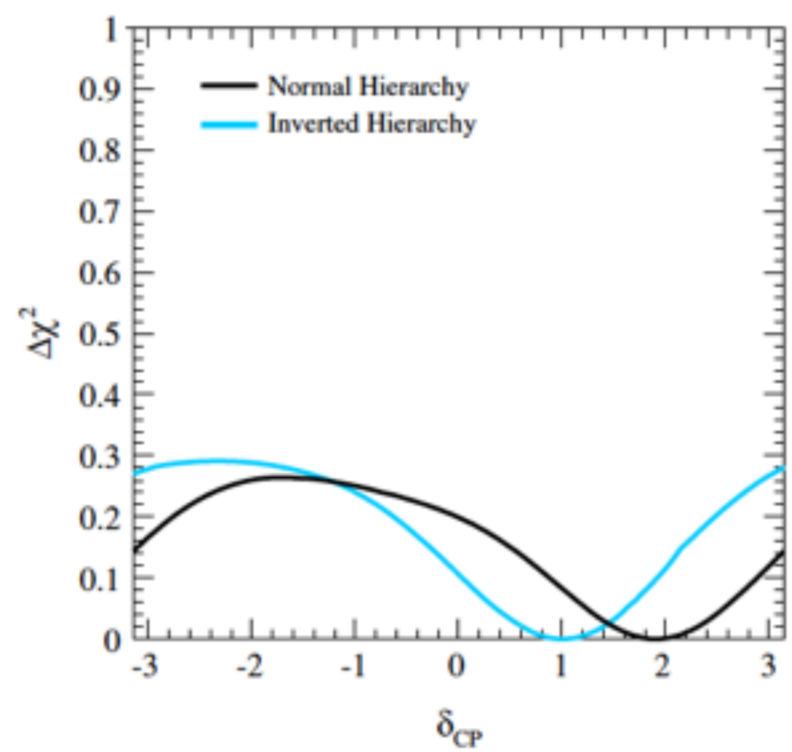


- Observed 28 ν_e candidate events with a background of 4.92 ±0.55 events
  - **7.3σ significance**
- T2K measurement without external constraints:

$$\sin^2\theta_{13} = 0.042^{+0.013}_{-0.021}(\text{NH}) \quad \sin^2\theta_{13} = 0.049^{+0.015}_{-0.021}(\text{IH})$$

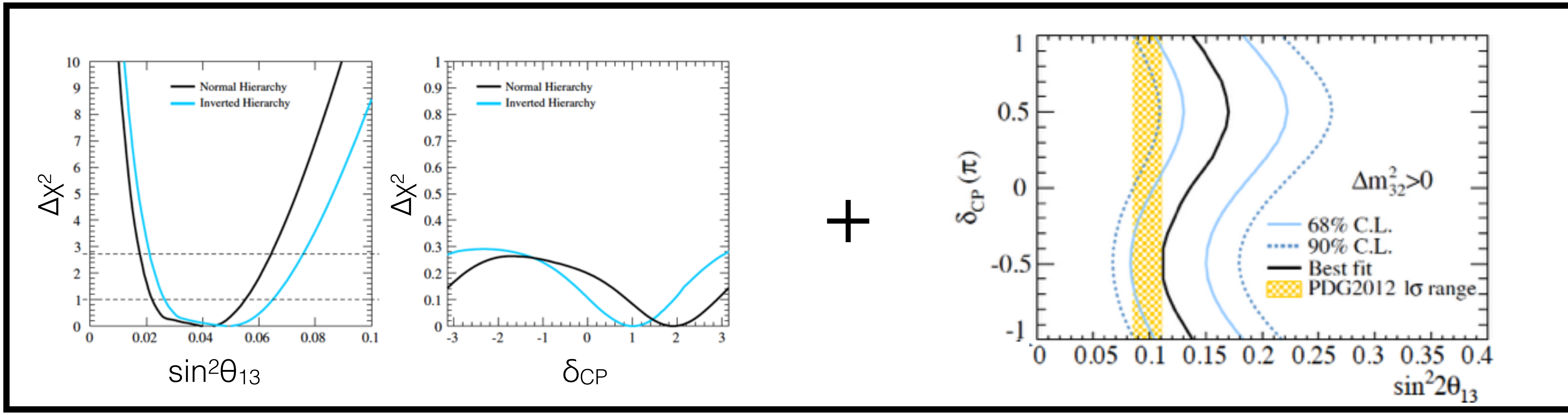
- Realization of key physics goal with small fraction of lifetime POT!
- No significant constraint on δ_{CP} from T2K alone



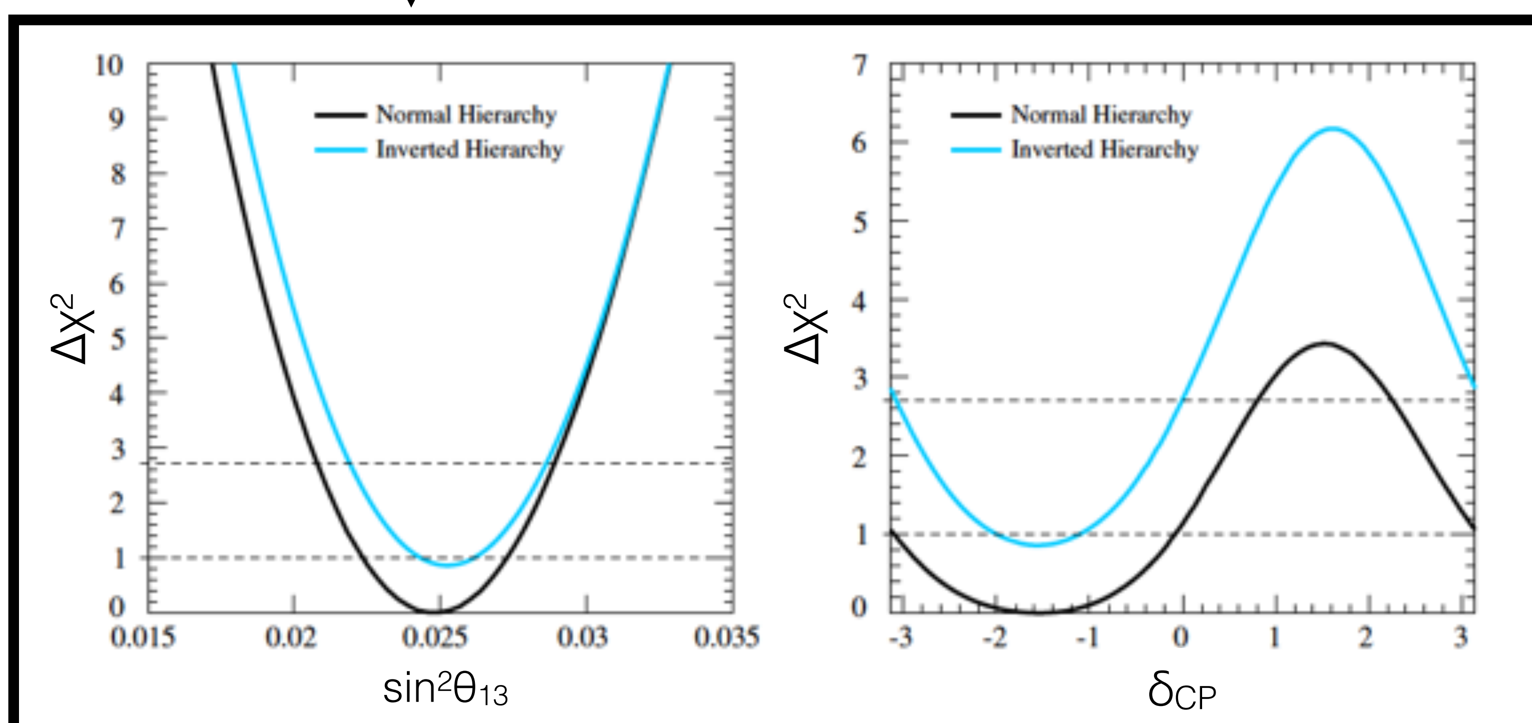


PRL **112,** 061802 (2014)

ν_e Results With Reactor

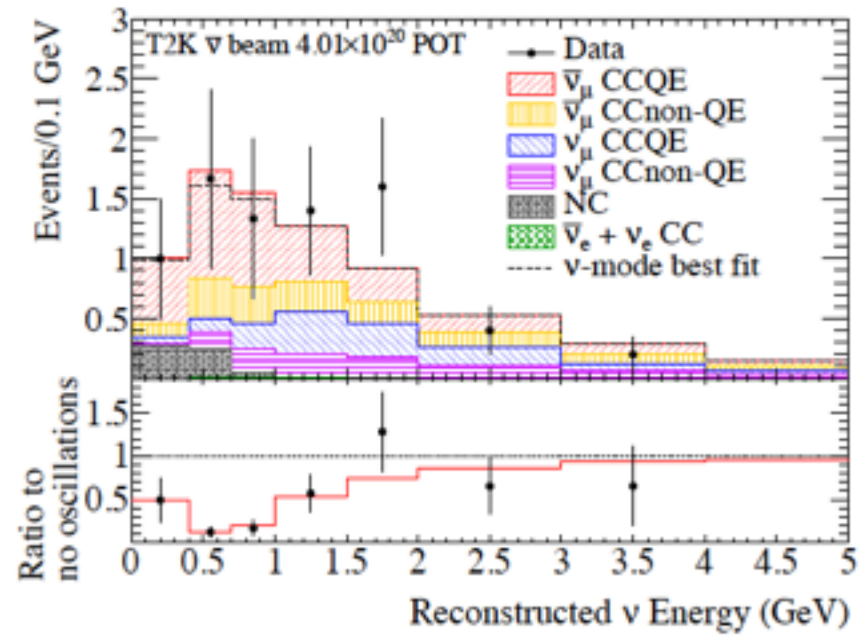


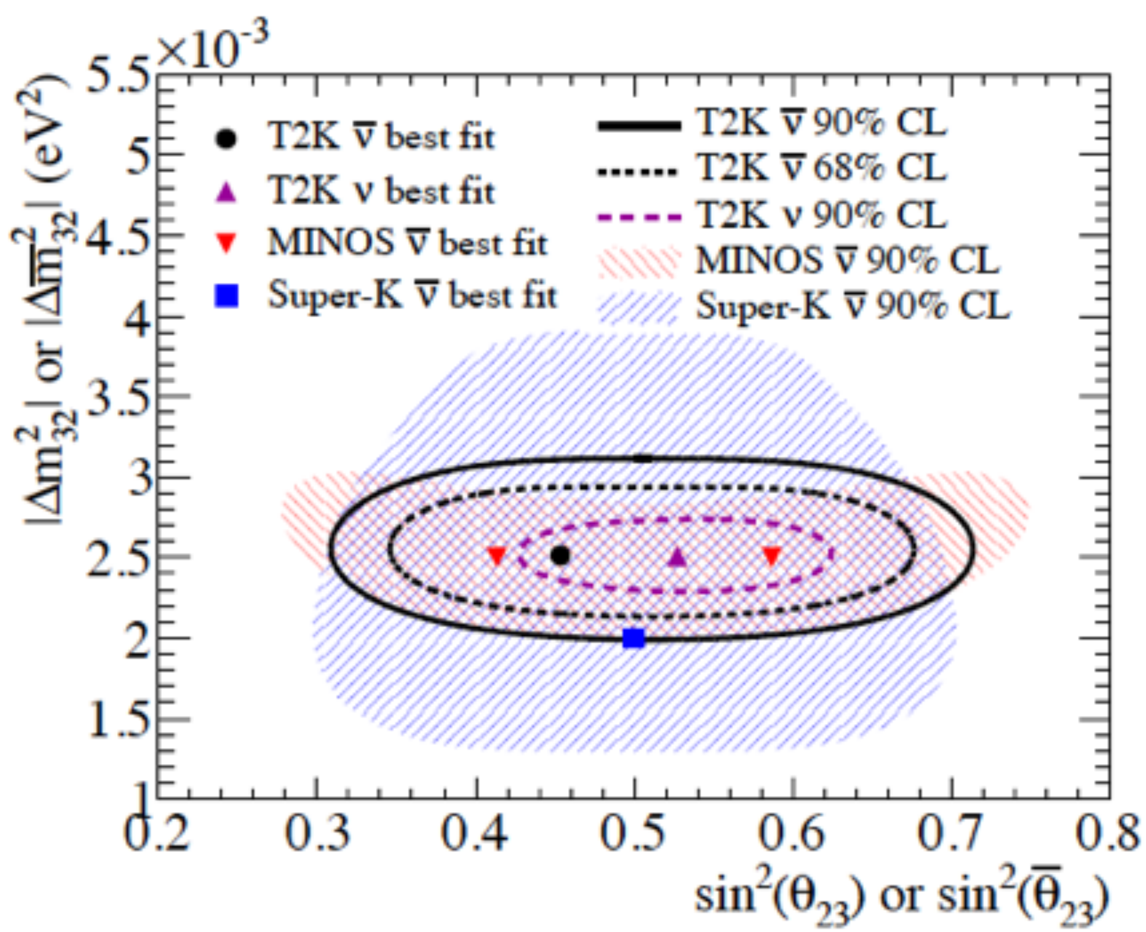
- With addition of reactor constraint on θ_{13}, T2K is able to provide some constraint on δ_{CP}
- Preference for δ_{CP} = -π/2
- Excluded regions at 90% CL:
  - [0.15, 0.83]π (NH)
  - [-0.08, 1.09]π (IH)



Antineutrino Disappearance Results

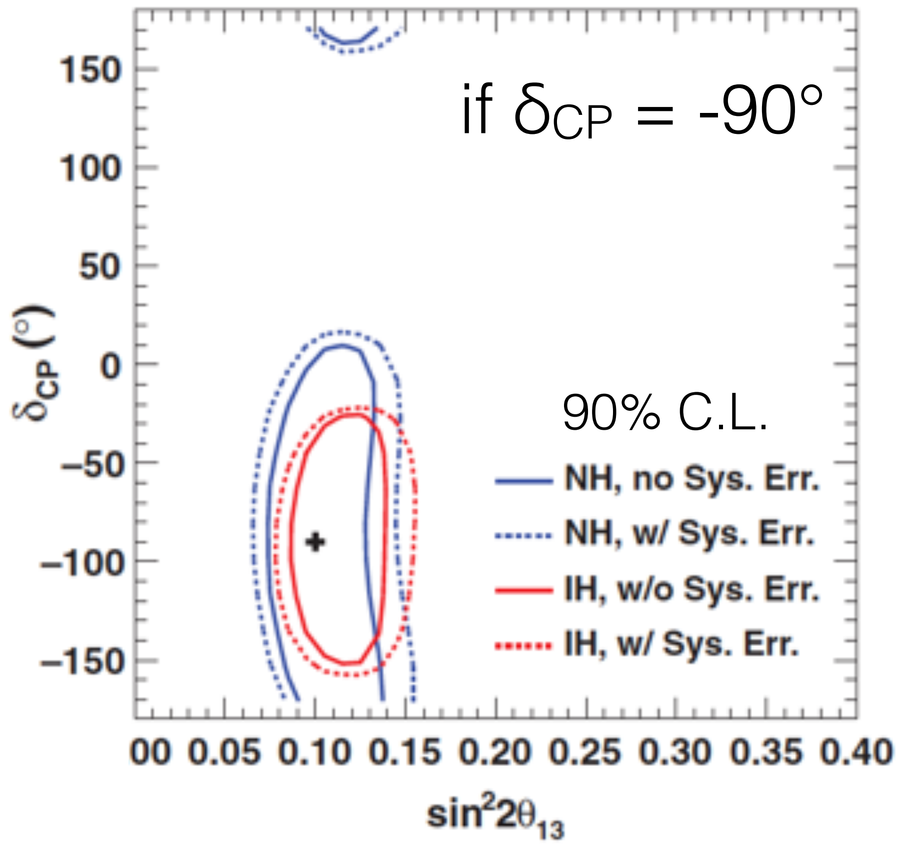
- **Disappearance results:**
  - Observed 34 candidate anti-ν_μ events in far detector.
  - Oscillation parameters consistent with MINOS, T2K neutrino results
- **Appearance results**:
  - Observed just 3 anti-ν_e candidate events in far detector
    - Background is ~1 event
    - No significant discriminating power yet
  - See combined neutrino and antineutrino results from T2K later this summer!



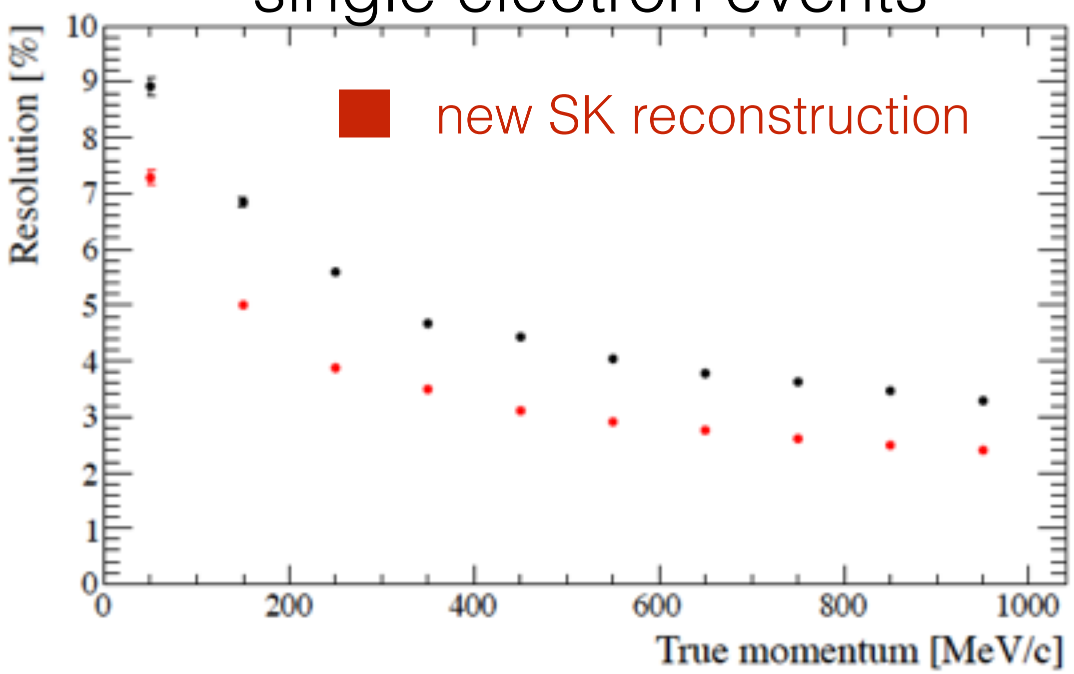


Future Prospects

- Working toward goal of 7.8×10^{21} POT
  - 50%-50% split between neutrino and antineutrino modes for maximum δ_{CP} sensitivity
- New reconstruction algorithm at SK:
  - Currently used for neutral pion rejection
  - Many potential future benefits to oscillation analysis:
    - Improved kinematic reconstruction
    - Improved background rejection
    - More event samples
    - Possibly larger SK fiducial volume



single electron events



Summary

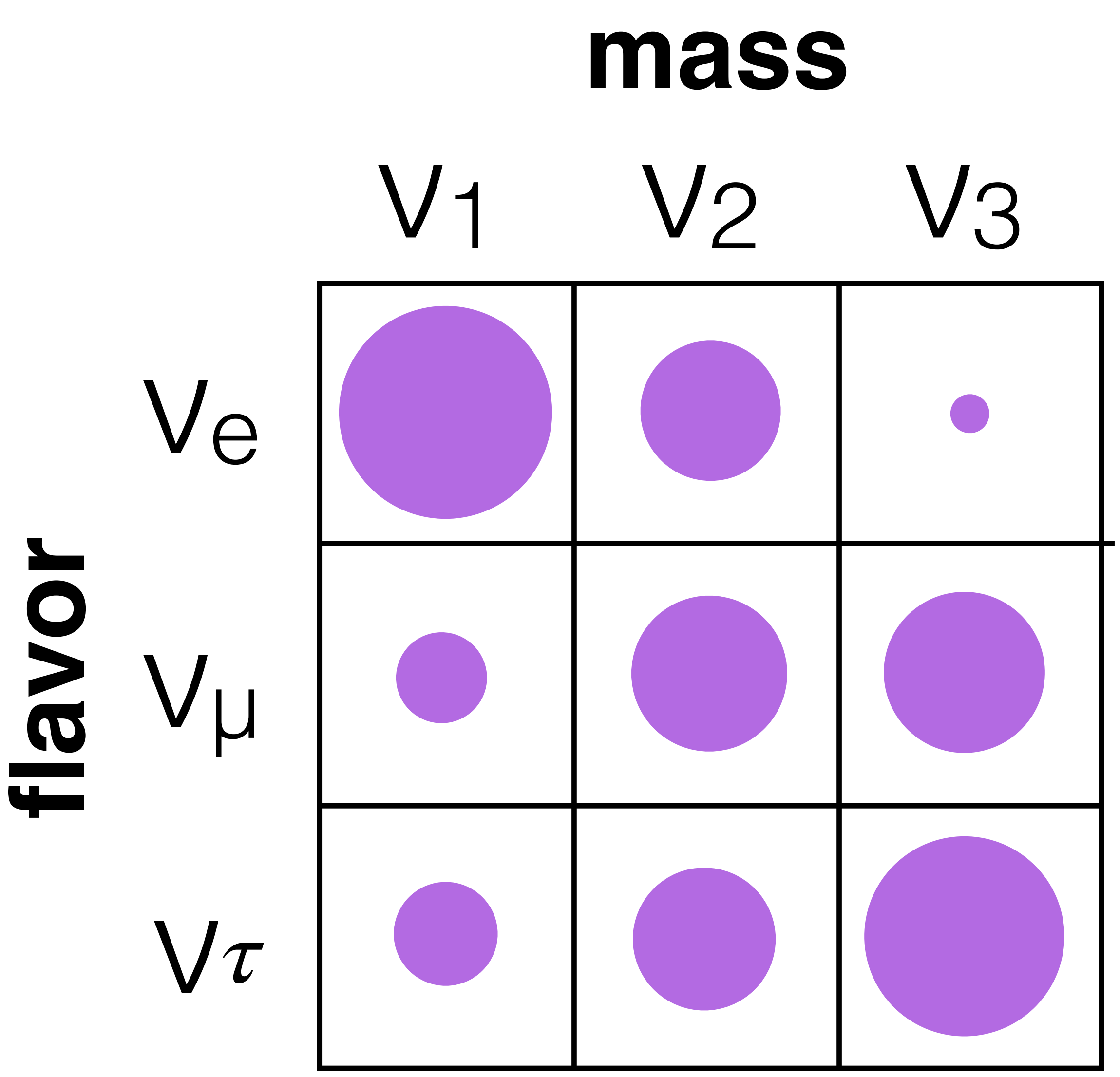
- T2K has realized significant oscillation results with just a small fraction (17%) of total expected POT
    - World's leading measurement on θ_{23}
    - Confirmation of ν_e appearance and non-zero θ_{13}
    - Combined with reactor data, some constraints on δ_{CP}
    - Measurement of antineutrino disappearance consistent with neutrino result
- T2K currently running in antineutrino mode
    - More antineutrino oscillation results coming this summer
- Goal is 7.8×10^{21} POT with 50% neutrino mode, 50% antineutrino mode
- Future improvements to event reconstruction at SK will further increase precision on oscillation results
- Exclusion of some regions of δ_{CP} possible with future statistics using only T2K data

The T2K Collaboration

Supplementary Slides

Neutrino Mixing

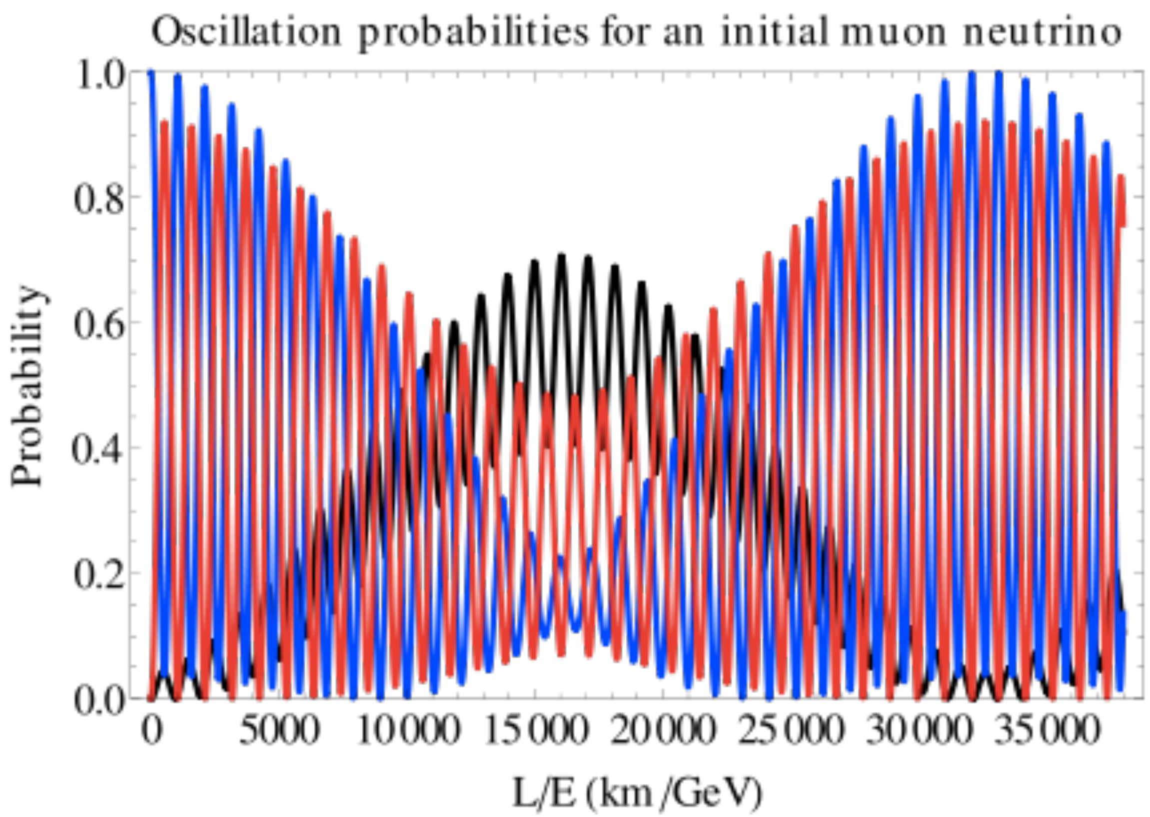
- Neutrino flavor states are not mass eigenstates
- Neutrinos from weak decays are in a superposition of mass states
- Significant mixing between flavor and mass states!

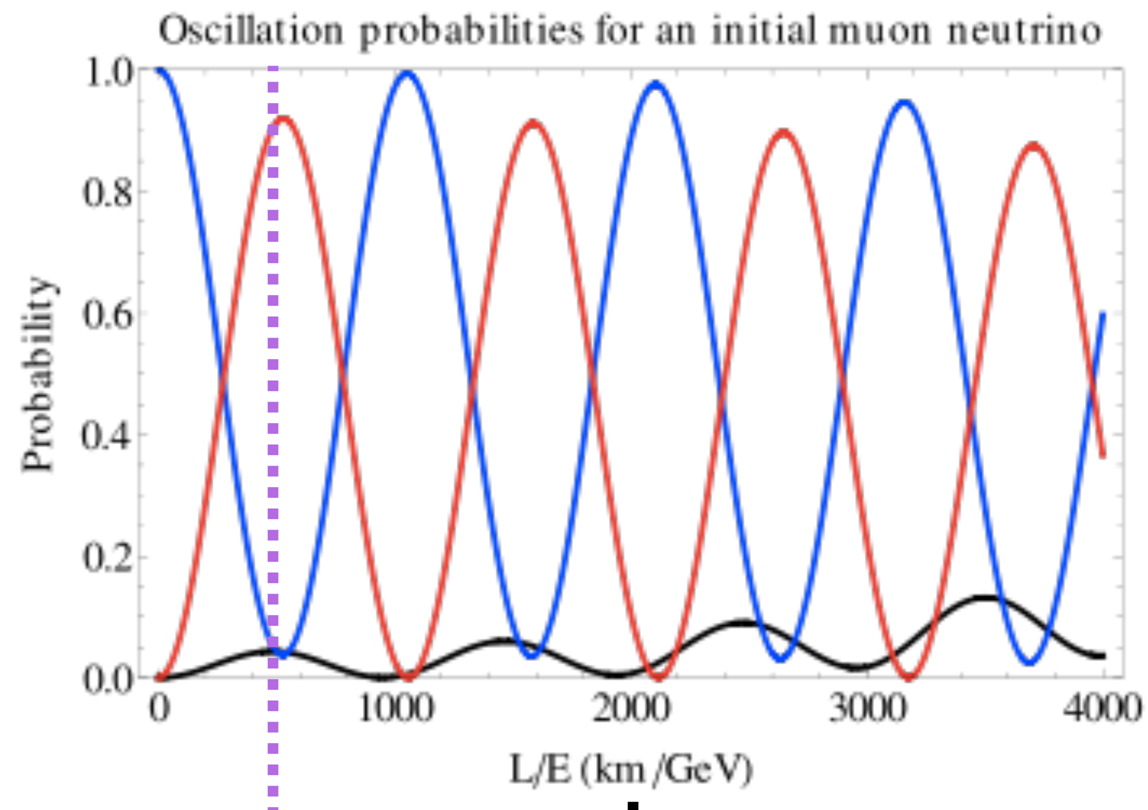


The Standard Model Neutrino

neutrino oscillations

■ ν_e ■ ν_μ ■ ν_τ





T2K L/E

- By experimentally observing neutrino oscillations we can estimate the values for the mixing parameters in the PMNS matrix, as well as the neutrino mass splittings.

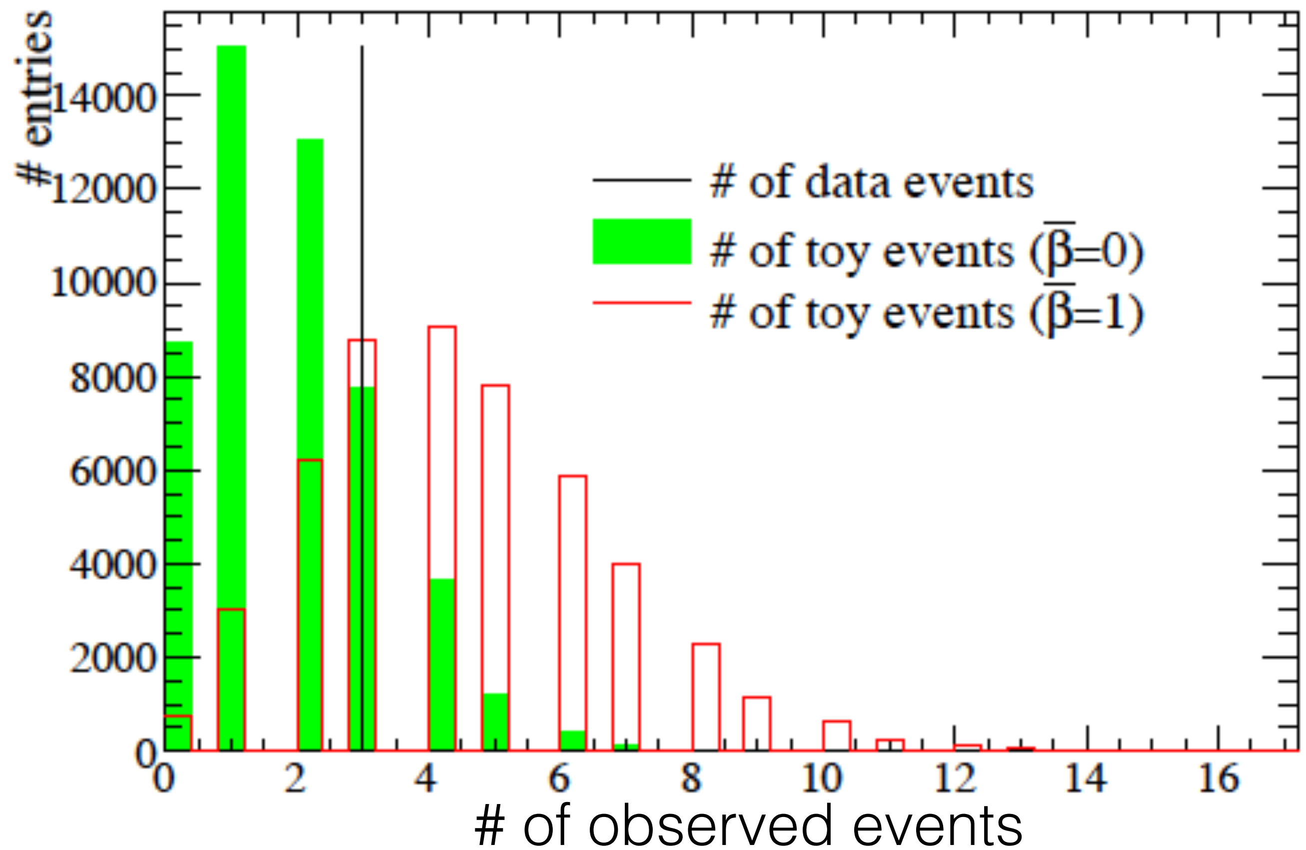
$$P(\nu_\mu \to \nu_\mu) \approx 1 - \sin^2 2\theta_{23} \sin^2 \frac{\Delta m^2_{32} L}{E}$$

$$P(\nu_\mu \to \nu_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \frac{\Delta m^2_{31} L}{E}$$

http://upload.wikimedia.org/wikipedia/en/1/12/Oscillations_muon_long.svg

Antineutrino Appearance Results

- **Appearance results**:
  - Observed just 3 anti-ν_e events in far detector
    - No significant discriminating power yet, need more data
  - See combined neutrino and antineutrino results from T2K later this summer!



	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = +\pi/2$
Sig $\bar{\nu}_\mu \to \bar{\nu}_e$	1.961	2.636	3.288
Bkg $\nu_\mu \to \nu_e$	0.592	0.505	0.389
Bkg NC	0.349	0.349	0.349
Bkg other	0.826	0.826	0.826
Total	3.729	4.315	4.851

Flux Uncertainties Breakdown

Error source	Uncertainty in SK flux near peak (%)	
	ν_μ	ν_e
Beam current normalization	2.6	2.6
Proton beam properties	0.3	0.2
Off-axis angle	1.0	0.2
Horn current	1.0	0.1
Horn field	0.2	0.8
Horn misalignment	0.4	2.5
Target misalignment	0.0	2.0
MC statistics	0.1	0.5
Hadron production		
Pion multiplicities	5.5	4.7
Kaon multiplicities	0.5	3.2
Secondary nucleon multiplicities	6.9	7.6
Hadronic interaction lengths	6.7	6.9
Total hadron production	11.1	11.7
Total	11.5	12.4

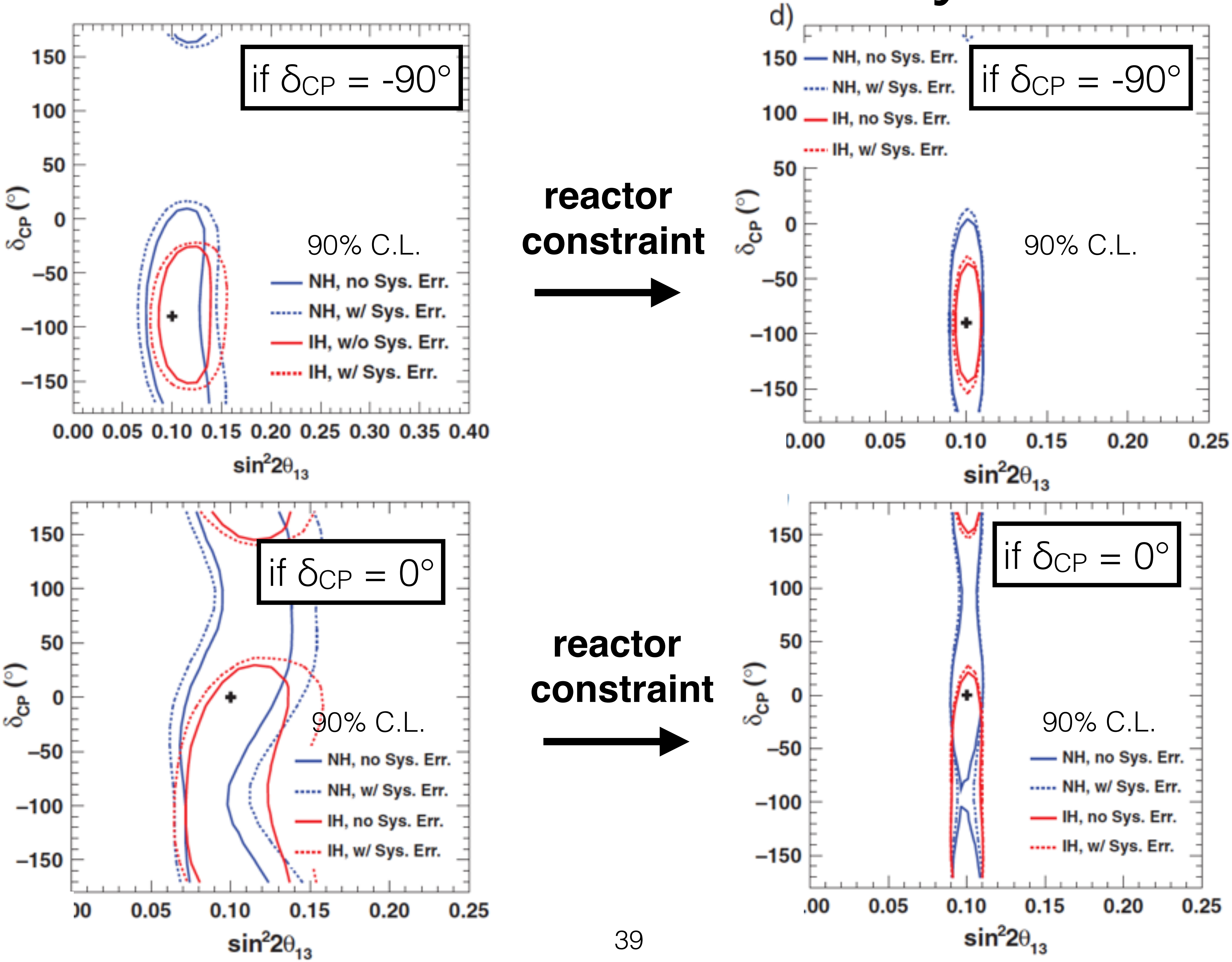
Near Detector Cross Section Model

- Use NEUT 5.1.4.2 event generator
- 1→Common parameter,
  2→Independent parameter,
  3→Unconstrained parameter
- Parameters tuned w/MiniBooNE Data

	Units	Nominal value	Penalty	Best fit	Error
M_A^{RES}	GeV/c^2	1.21		1.41	0.22
W shape	MeV/c^2	87.7		42.4	12
$x^{CCcoh\pi}$		1		1.423	0.462
$x_1^{CC1\pi}$		1		1.15	0.32
x^{CCOth}		0	0.4	0.360	0.386
$x^{NCcoh\pi}$		1	0.3	0.994	0.293
$x^{NC1\pi^0}$		1		0.963	0.330
$x^{NC1\pi^\pm}$		1	0.3	0.965	0.297
x^{NCOth}		1	0.3	0.987	0.297

Parameter	E_ν/GeV Range	Units	Nominal	Error	Category
M_A^{QE}	all	GeV/c^2	1.21	0.45	1
x_1^{QE}	$0 < E_\nu < 1.5$		1.0	0.11	1
x_2^{QE}	$1.5 < E_\nu < 3.5$		1.0	0.30	1
x_3^{QE}	$E_\nu > 3.5$		1.0	0.30	1
p_F ^{12}C	all	MeV/c	217	30	2
E_B ^{12}C*	all	MeV	25	9	2
p_F ^{16}O	all	MeV/c	225	30	2
E_B ^{16}O*	all	MeV	27	9	2
x_{SF} for C	all		0 (off)	1 (on)	2
x_{SF} for O	all		0 (off)	1 (on)	2
M_A^{RES}	all	GeV/c^2	1.41	0.22	1
$x_1^{CC1\pi}$	$0 < E_\nu < 2.5$		1.15	0.32	1
$x_2^{CC1\pi}$	$E_\nu > 2.5$		1.0	0.40	1
$x^{NC1\pi^0}$	all		0.96	0.33	1
$x^{CCcoh\pi}$	all		1.0	1.0	3
x^{CCOth}	all		0.0	0.40	3
$x^{NC1\pi^\pm}$	all		1.0	0.30	3
$x^{NCcoh\pi}$	all		1.0	0.30	3
x^{NCOth}	all		1.0	0.30	3
W Shape	all	MeV /c^2	87.7	45.3	3
x^{PDD}	all		1.0	1.0	3
CC ν_e	all		1.0	0.03	3
$\nu/\bar{\nu}$	all		1.0	0.40	3
$\vec{x}^{FSI}$	all		Section III B 1		3

Future Sensitivity

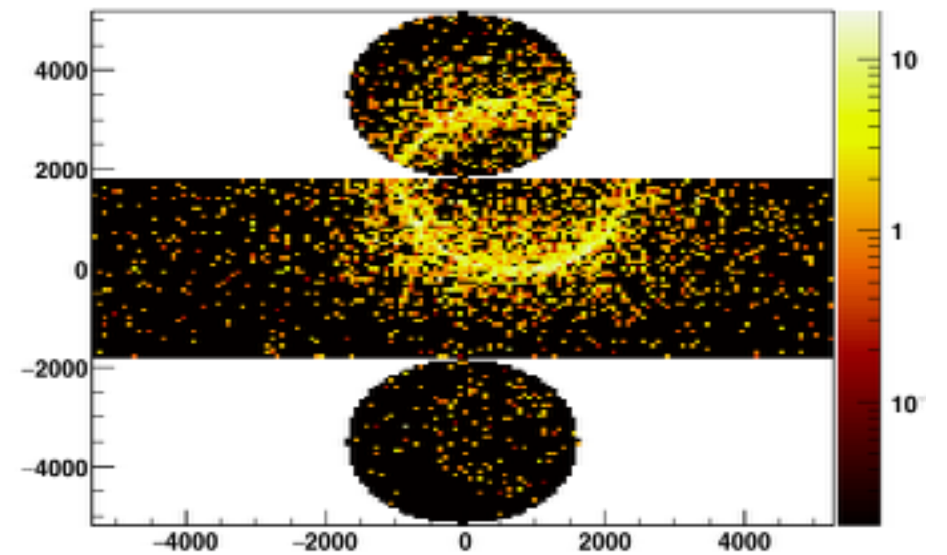


fiTQun

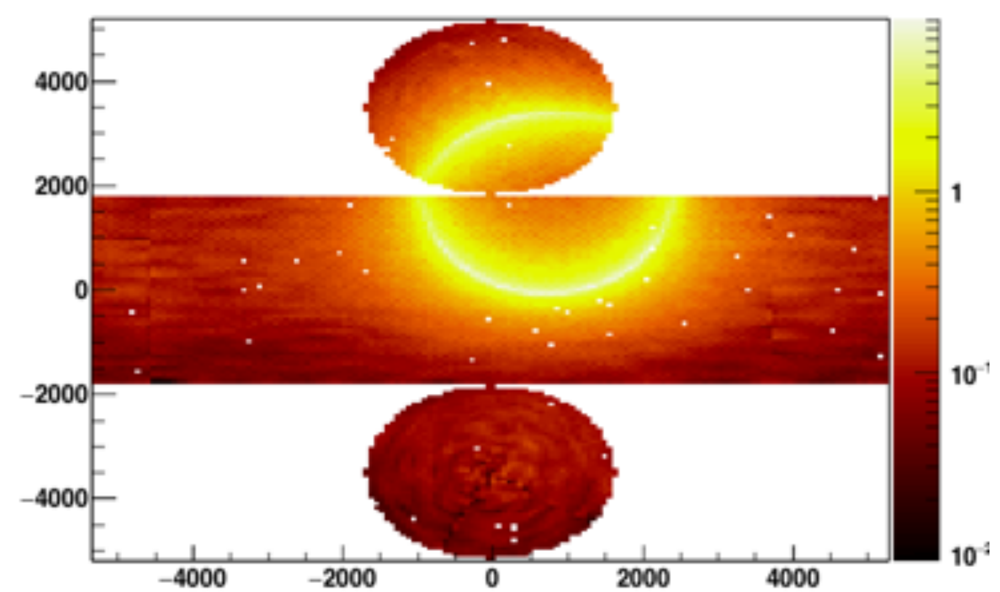
A new algorithm for event reconstruction at SK

- Create predicted charge and time distributions from a set of track parameters
- Calculate the likelihood of the observed distributions given the predicted distributions
- Maximize likelihood to find best-fit track parameters
- Compare the likelihoods of various topology hypotheses to find best hypothesis for an event

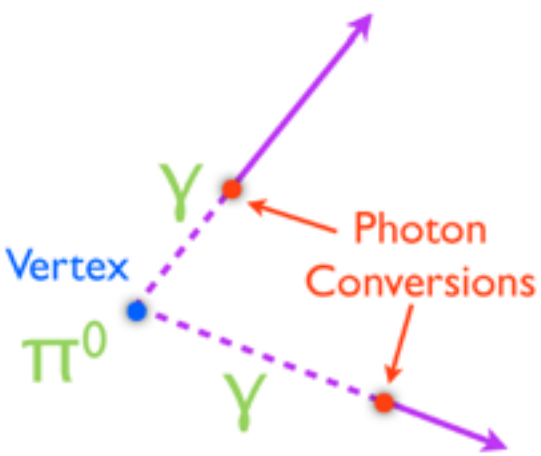
Observed Charge

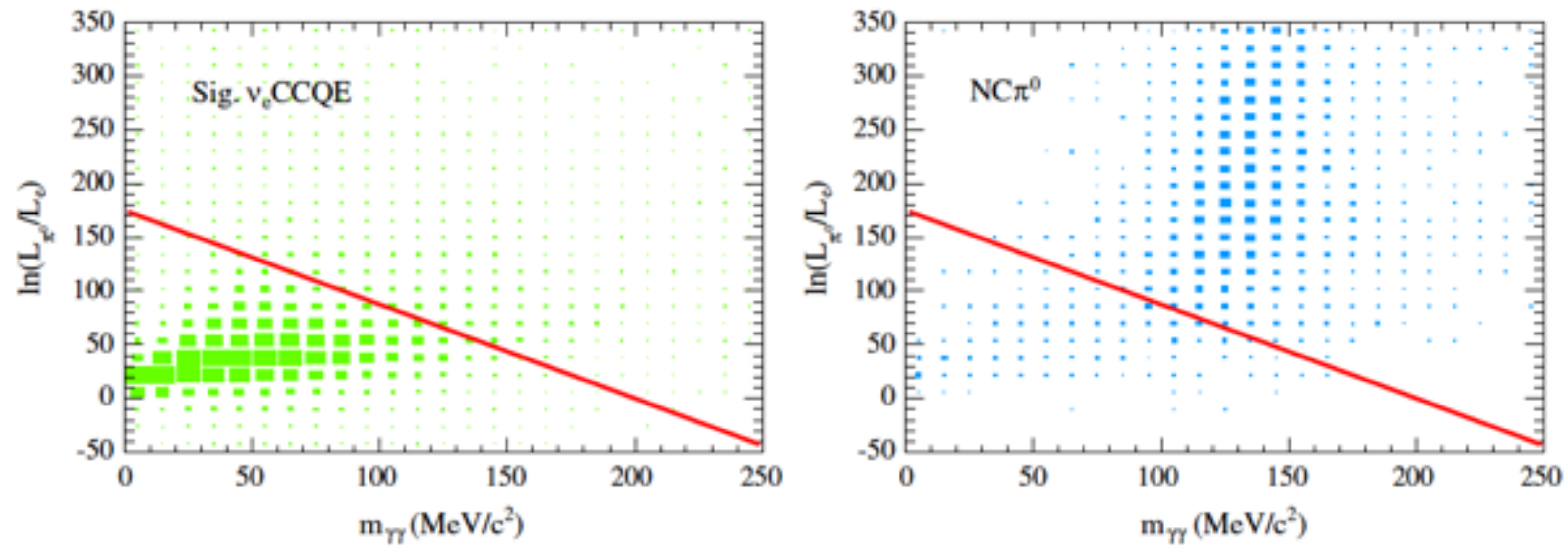


Predicted Charge

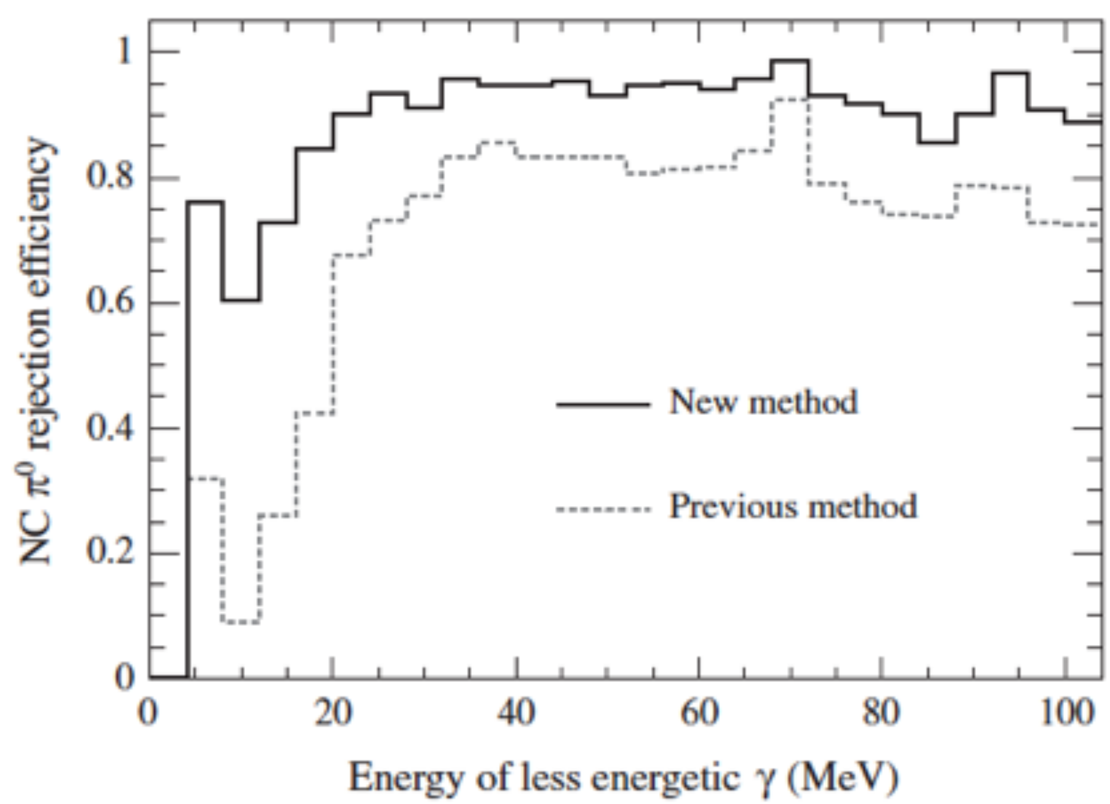


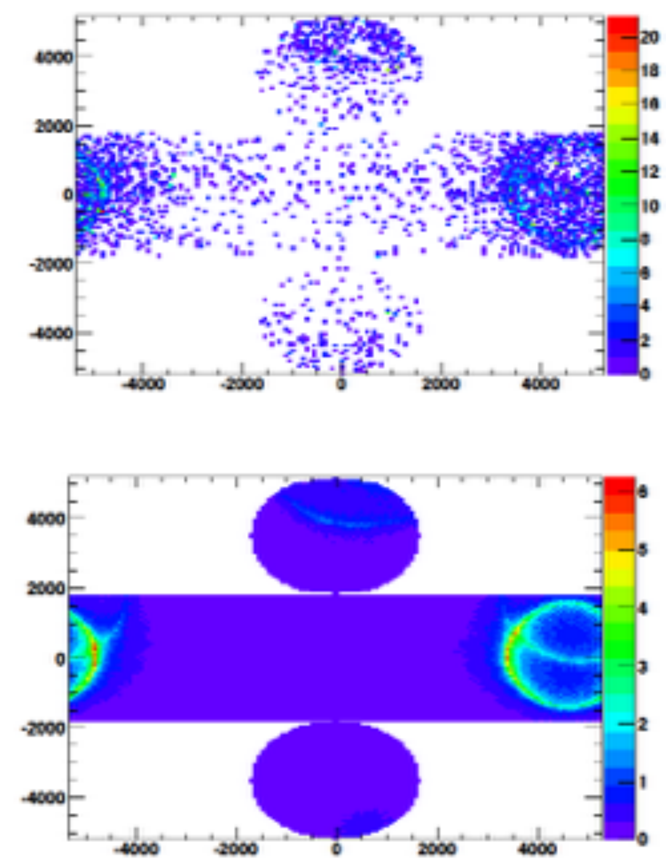
fiTQun Performance





- fiTQun has a dedicated π^0 hypotheses for rejecting NC background events in ν_e sample
- Drastic improvement over previous method
- Currently used in T2K oscillation analysis!





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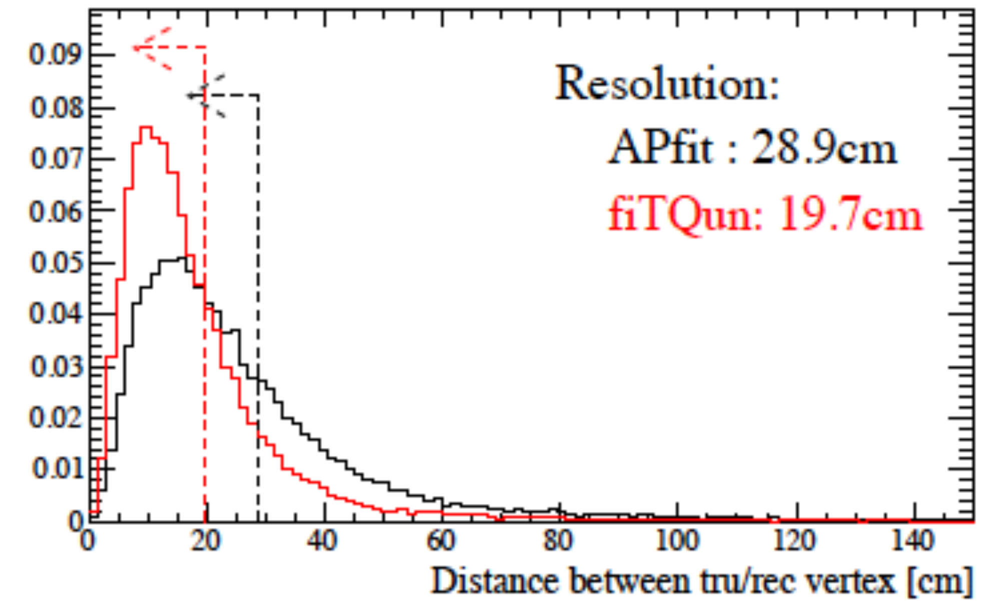
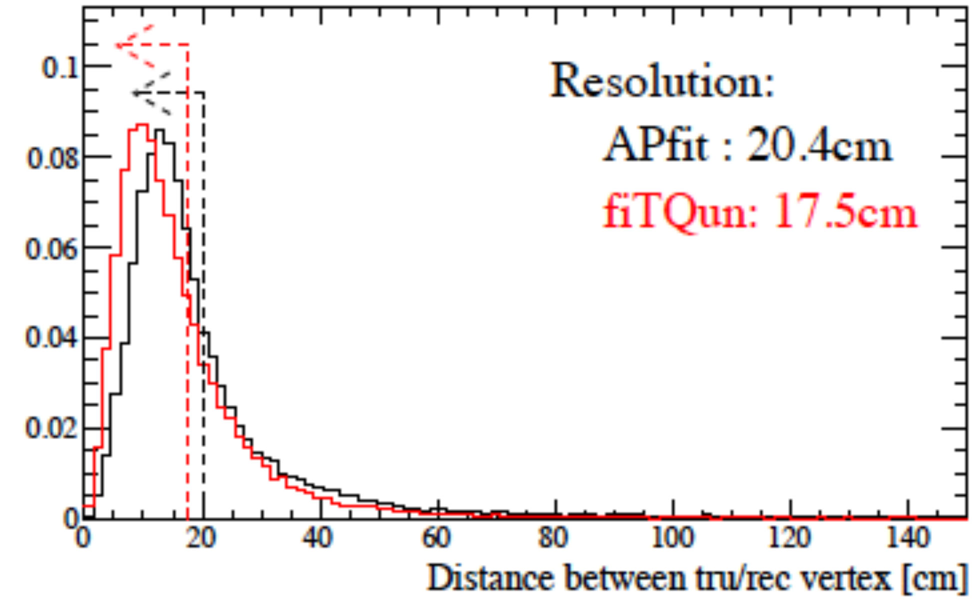
fiTQun Performance

- fiTQun boasts considerable improvements that are currently NOT used in the T2K analysis
- Single ring Improvements include:
    - Better vertex resolution

electrons



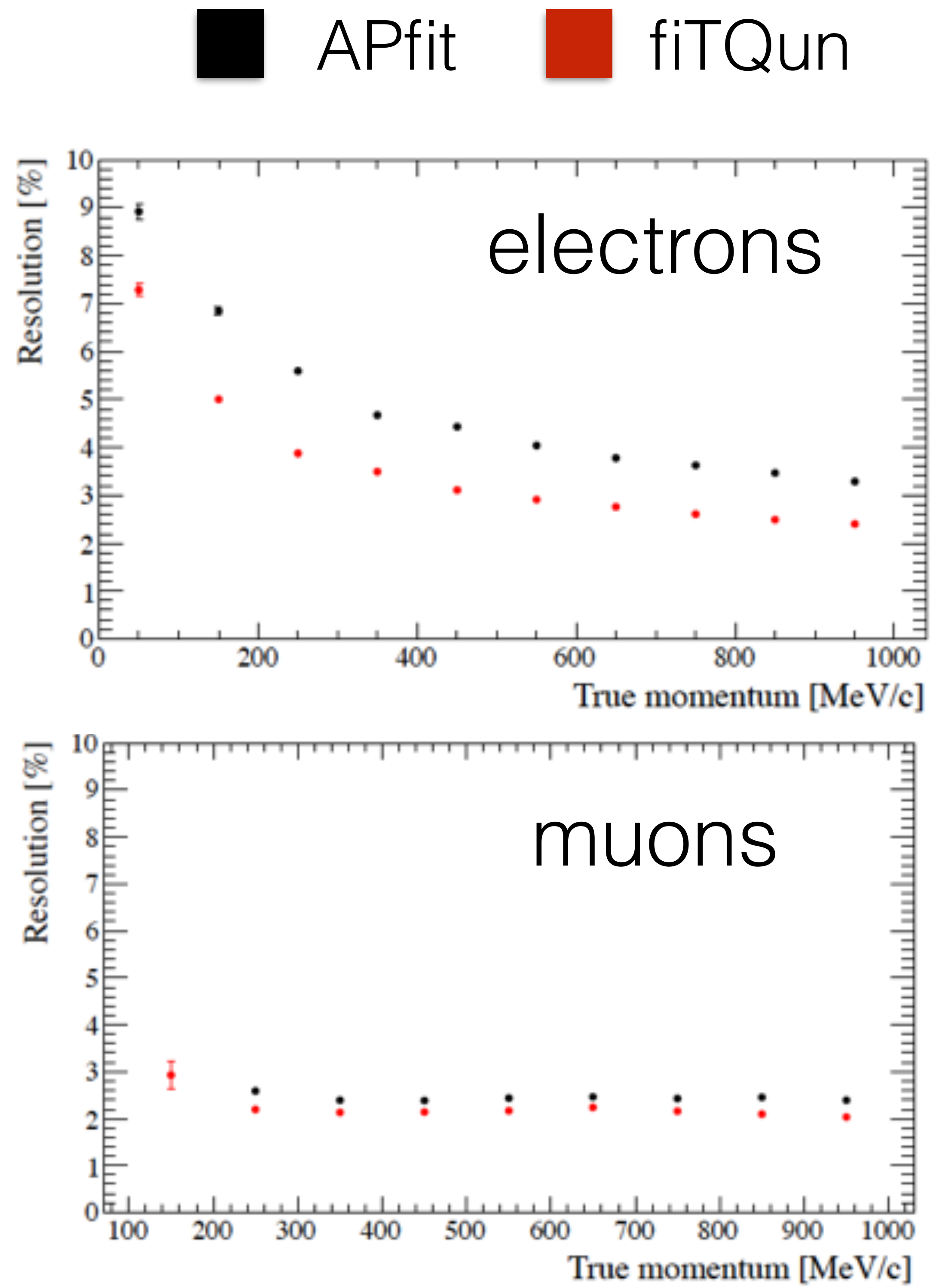
muons



source: T2K TN-146

fiTQun Performance

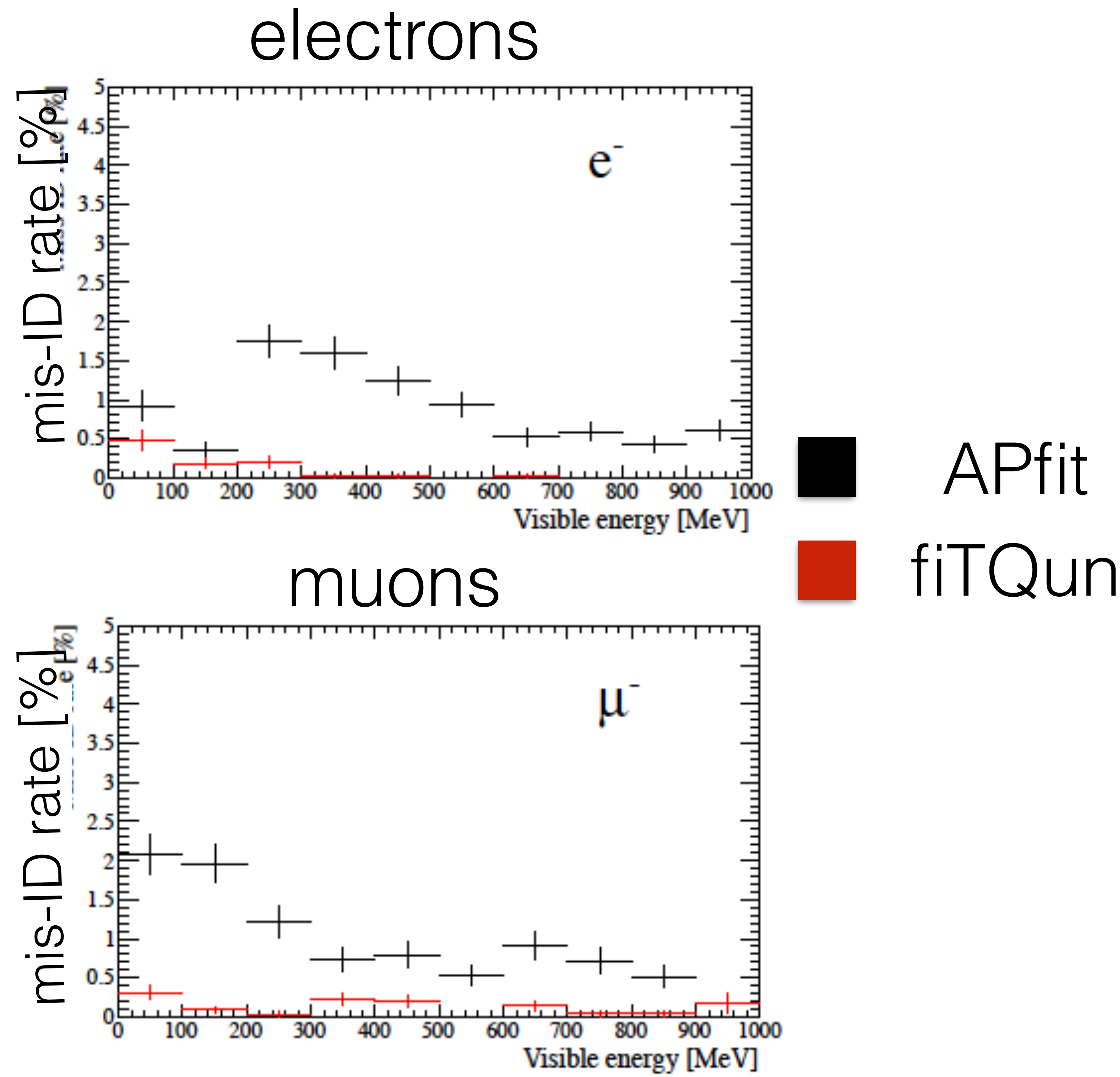
- fiTQun boasts considerable improvements that are currently NOT used in the T2K analysis
- Single ring Improvements include:
  - Better vertex resolution
  - Improved momentum reconstruction →



source: T2K TN-146

fiTQun Performance

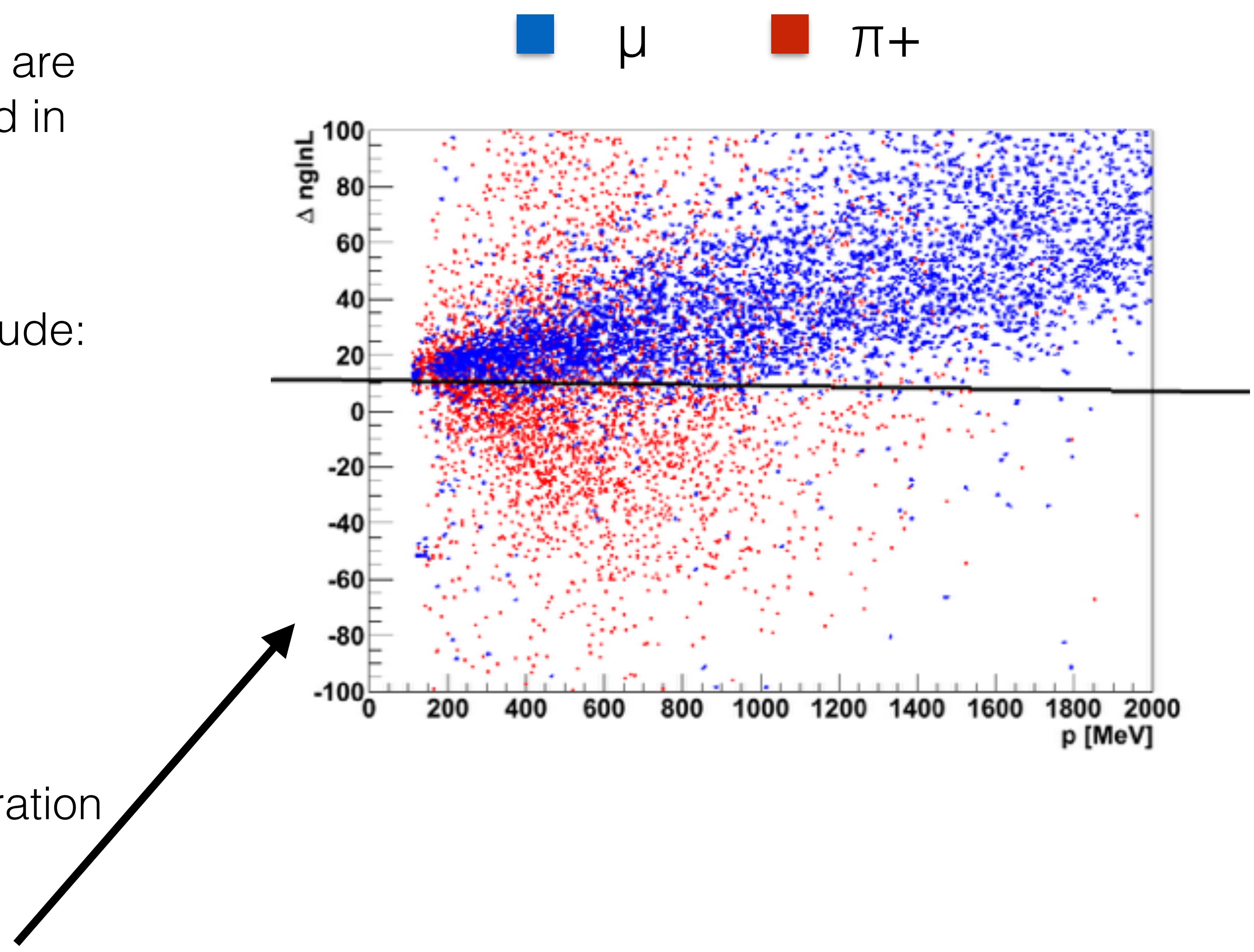
- fiTQun boasts considerable improvements that are currently NOT used in the T2K analysis
- Single ring Improvements include:
  - Better vertex resolution
  - Improved momentum reconstruction
  - Better e-μ separation



source: T2K TN-146

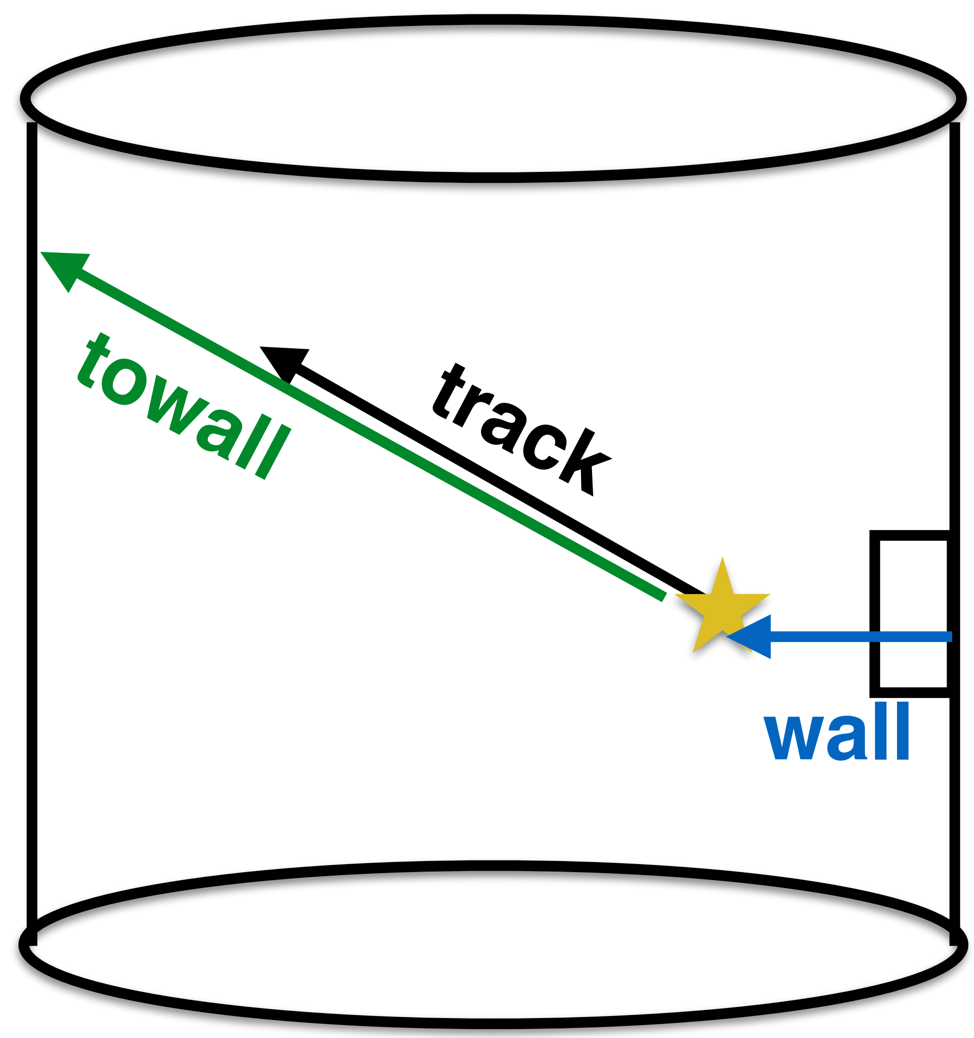
fiTQun Performance

- fiTQun boasts considerable improvements that are currently NOT used in the T2K analysis
- Single ring Improvements include:
    - Better vertex resolution
    - Improved momentum reconstruction
    - Better e-μ separation
    - Charged pion rejection



fiTQun Fiducial Volume

- The SK fiducial volume cut should also be re-evaluated for fiTQun
  - Current FV cut: wall > 200 cm from inner detector (ID) wall
- This is another area in which fiTQun can improve the oscillation analysis
- Events near the ID that point away from wall still have well-resolved Cherenkov rings
  - Can we use these events by cutting on **towall** instead?

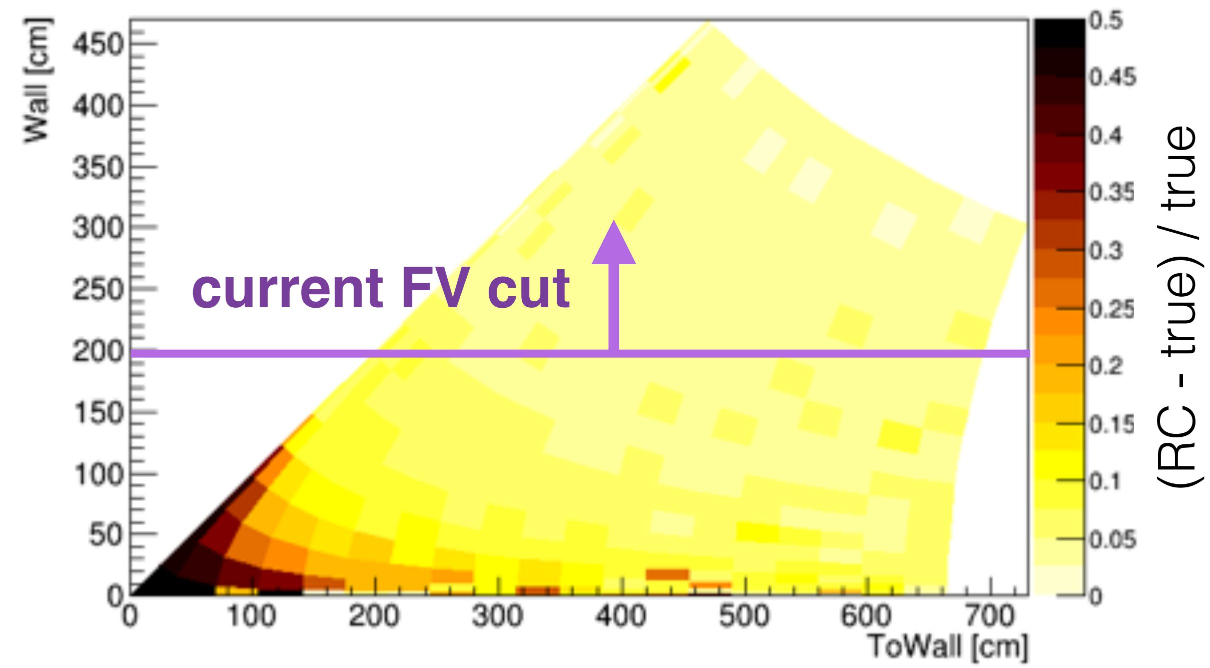


source: T2K TN-146

fiTQun Fiducial Volume

- MC studies show that fiTQun performs reasonably well near the current FV cut boundary
- The values of both wall and towall affect the quality of the reconstruction
- A better fiducial volume cut could potentially increase statistics by 10-20%
- Need to be careful about entering backgrounds as well as biases and distortions in the reconstruction

fractional difference between true and RC momentum



difference between true and RD direction