Adding SK 2Rpi0 sample to T2K OA

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Student Seminar
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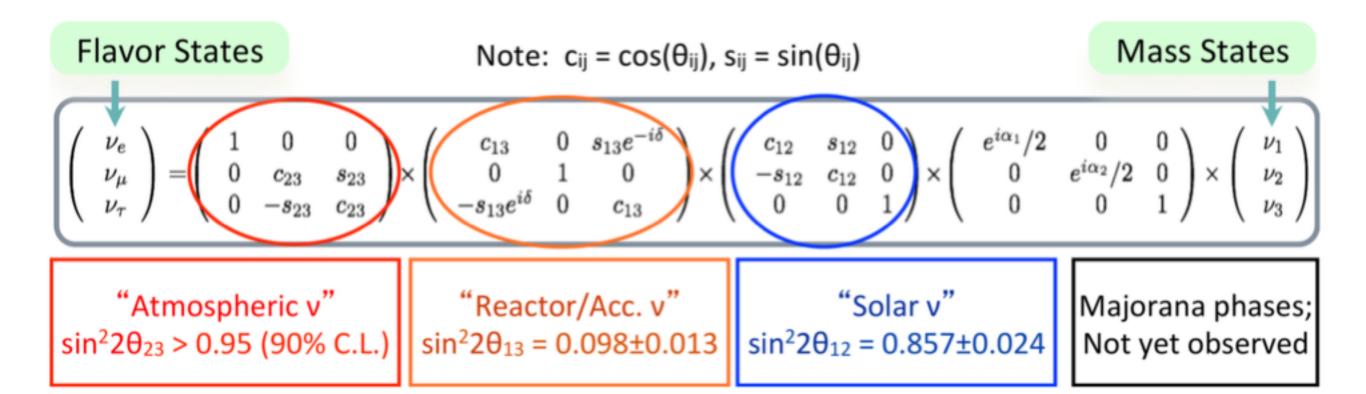# Overview

- Introduction: Oscillations at T2K

- Four sample joint oscillation analysis

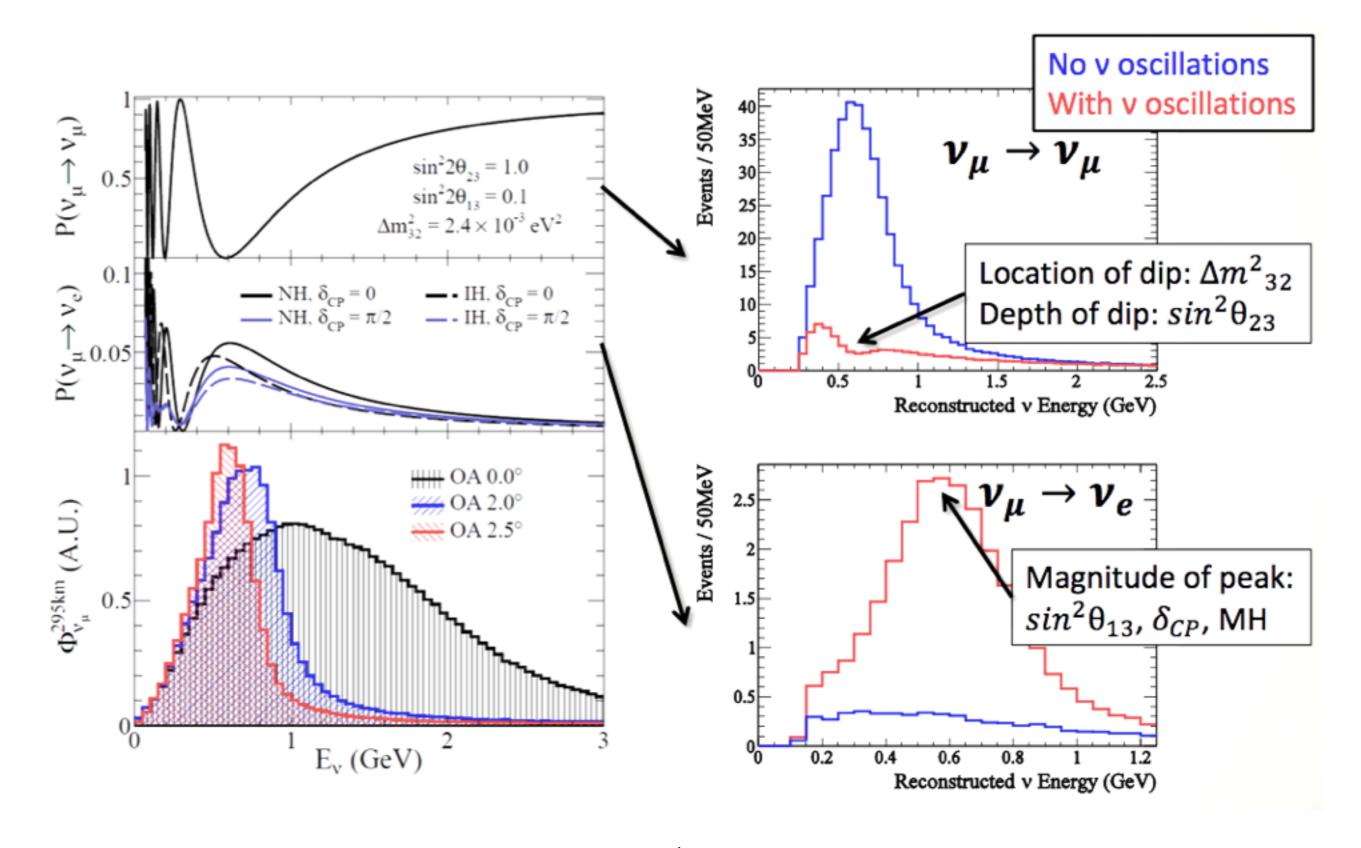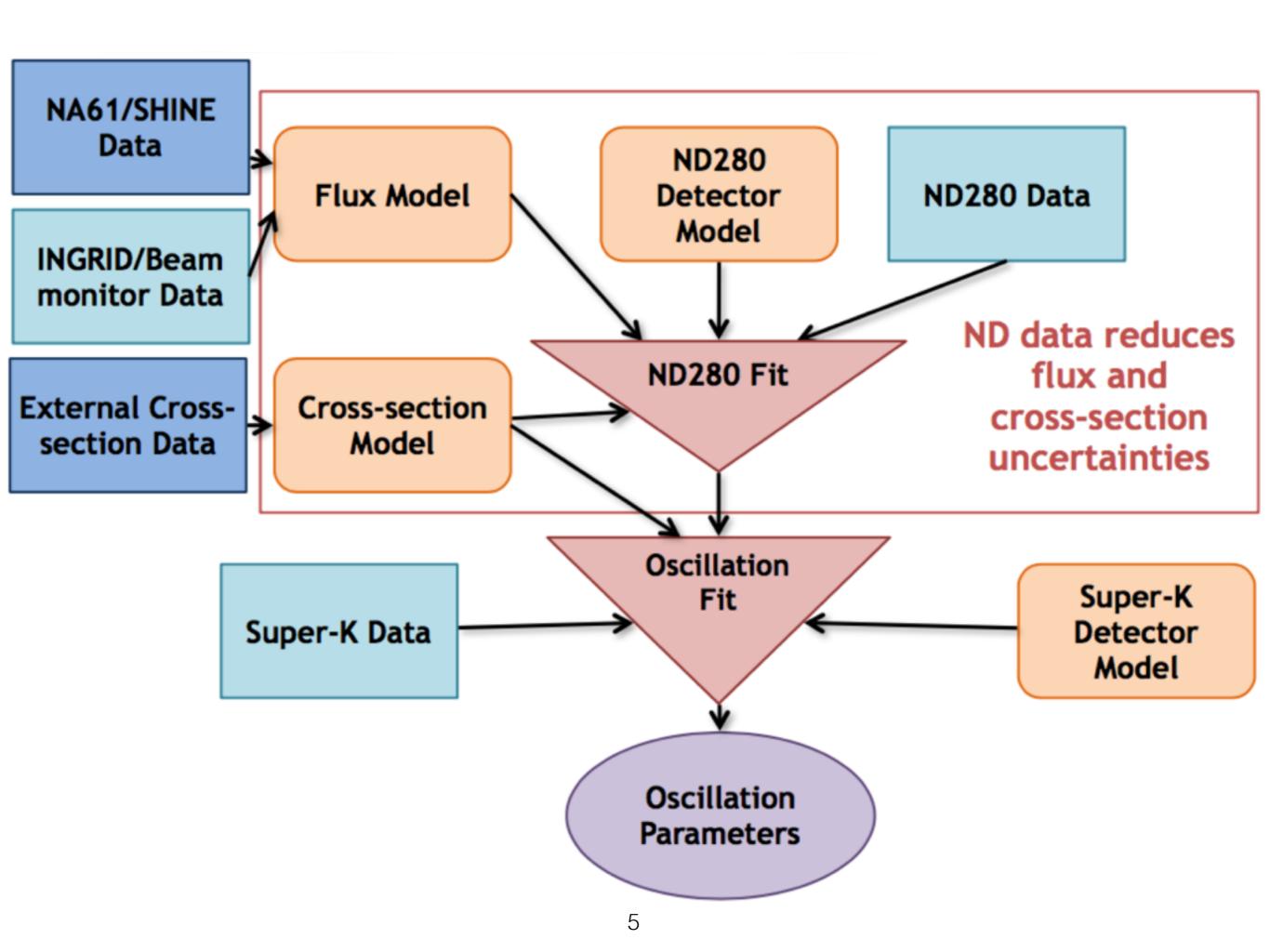- Additional 2Rpi0 sample to oscillation analysis

Neutrino Mixing

Flavor States

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

Mass States

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

"Atmospheric ν" $\sin^2 2\theta_{23} > 0.95$ (90% C.L.)	"Reactor/Acc. ν" $\sin^2 2\theta_{13} = 0.098 \pm 0.013$	"Solar ν" $\sin^2 2\theta_{12} = 0.857 \pm 0.024$	Majorana phases; Not yet observed

- T2K can observe ν_μ disappearance and ν_e appearance

- Sensitive to $\sin^2\theta_{23}$, $\sin^2\theta_{13}$, Δm^2_{32}, δ

- Not sensitive to solar parameters $\sin^2\theta_{12}$, Δm^2_{21}

Oscillations at T2K

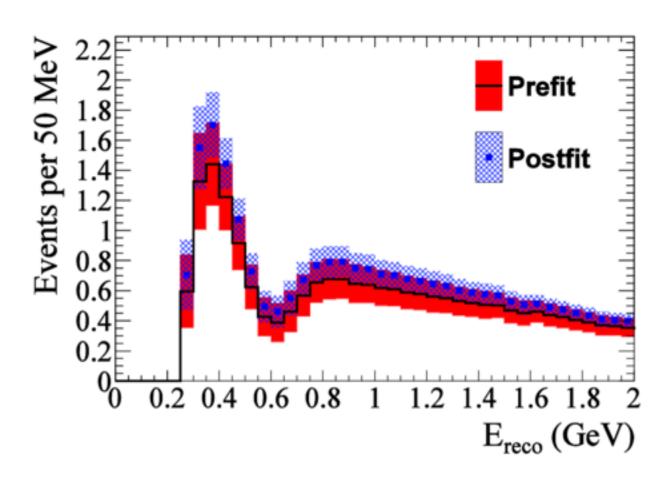ND data reduces flux and cross-section uncertainties

Near Detector constraint at SK

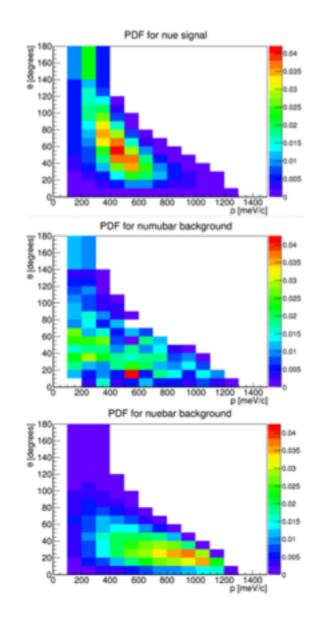- The near detector significantly reduces the systematic uncertainty in the predicted event rate at SK

Systematics		Without	With ND
Flux and xsec	Common to ND/SK	10.7%	2.4%
	All	10.8%	2.5%
FSI+SI at SK		1.8%	
SK detector		4.7%	
Total		12.0%	4.0%
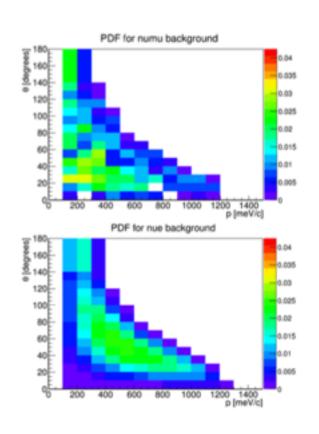
Four Sample Joint Oscillation Analysis

- Previous analysis: 1Rμ only for v_μ dis. and 1Re only for v_e app.

- Simultaneous fit to all 4 SK samples (FHC/RHC 1Rμ and FHC/RHC 1Re)

- FHC/RHC 1Re: bin in p and θ

- Shape information give additional power to separate the signal from the background

- FHC/RHC 1Rμ: bin in Erec

- Properly take into account the effect of the uncertainties on other oscillation parameters when trying to measure one of them.
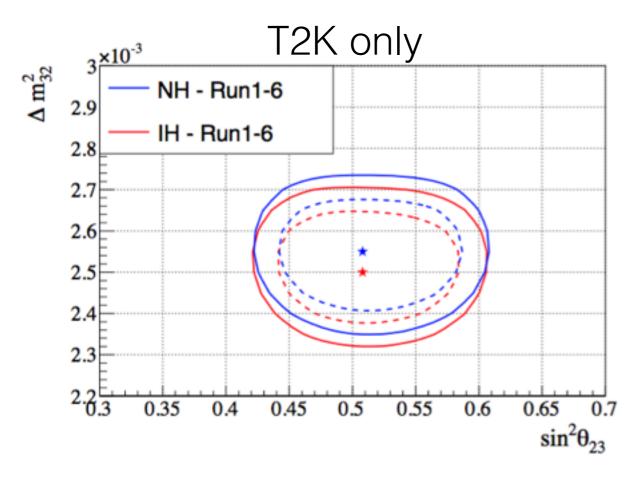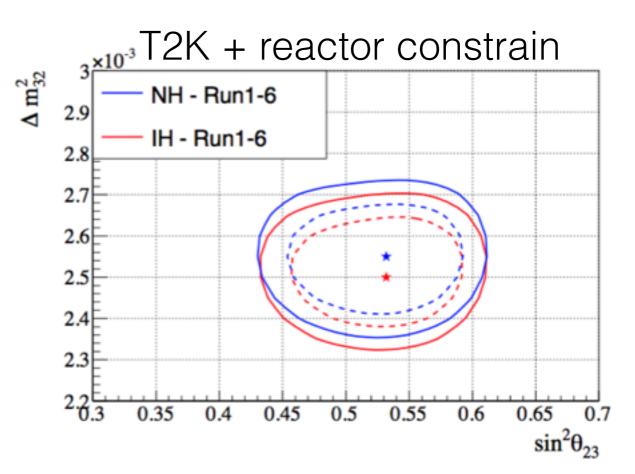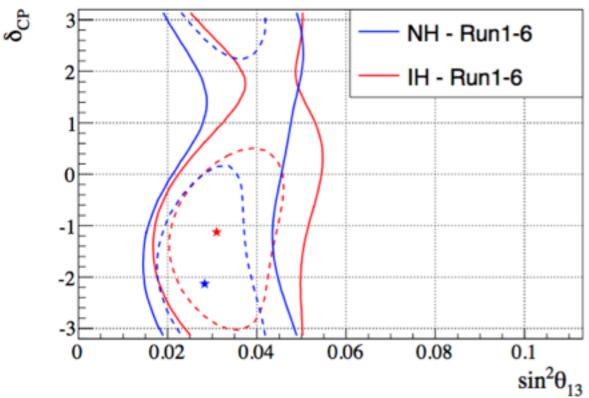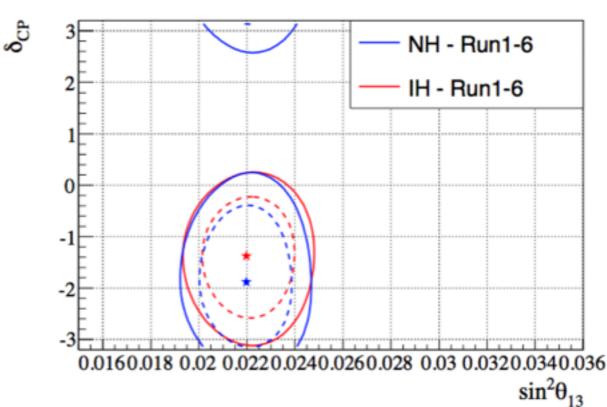
Results (Not official yet!)

T2K only

T2K + reactor constrain

Adding SK 2Rpi0 sample

Aim: Implement the 2Rpi0 sample to oscillation analysis code and update OA result.

- Can help constraint some systematic parameters such as NCpi0 normalisation error

- A few % of this sample are from CC events so they are sensitive to oscillation parameters.

1. Produce basic distributions using existing T2K-SK data and MC.

2. Using p-theta binning for oscillation analysis, achieve better/similar sensitivity by adding 2Rpi0 sample with systematic errors.

3. Deduce how accurate the systematic errors of pi0 needs to be.

4. To reduce these errors, atmospheric data/hybrid-pi0 data studies might be needed.

NCpi0 Selection at SK

Signal definition: Neutrino neutral current interaction that has one and only one pi0 in the final state and no other mesons.

1. FCFV

2. 2 e-like rings

3. No decay electrons

4. Resulting rings have reconstructed invariance mass between 85-185 MeV/c^2

Signal	osc nue	numu CC	nue CC	NC	Total
23.01	0.37	0.17	0.08	2.07	25.69
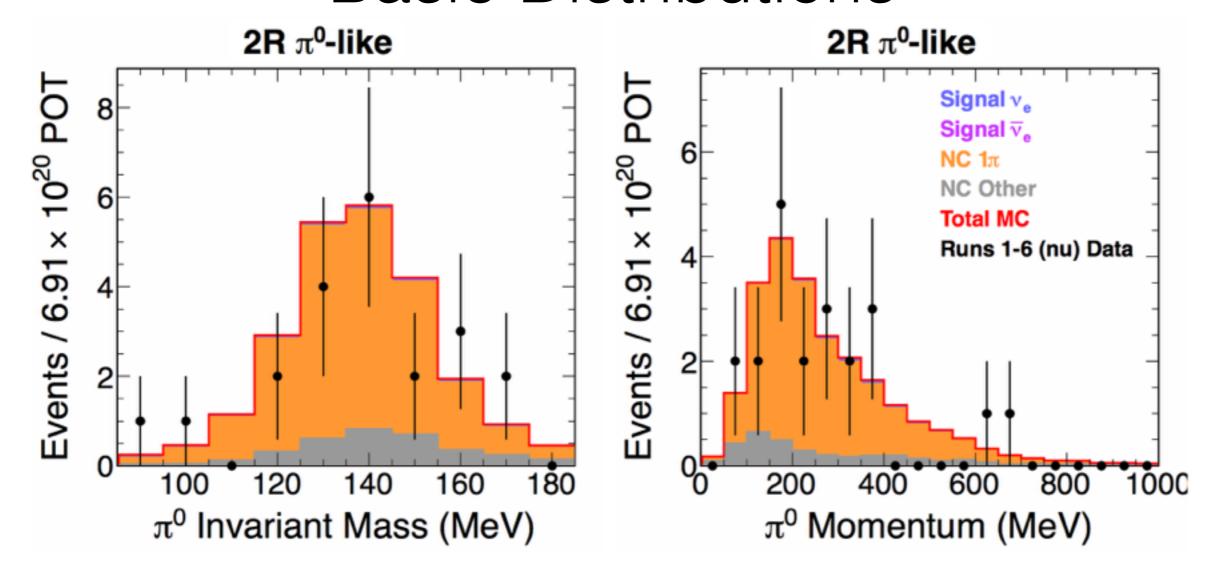
Run 1-6: 6.91 x10^{20} POT

selection	%
efficiency	56.5
purity	89.5

Basic Distributions

- Found 21 events from data
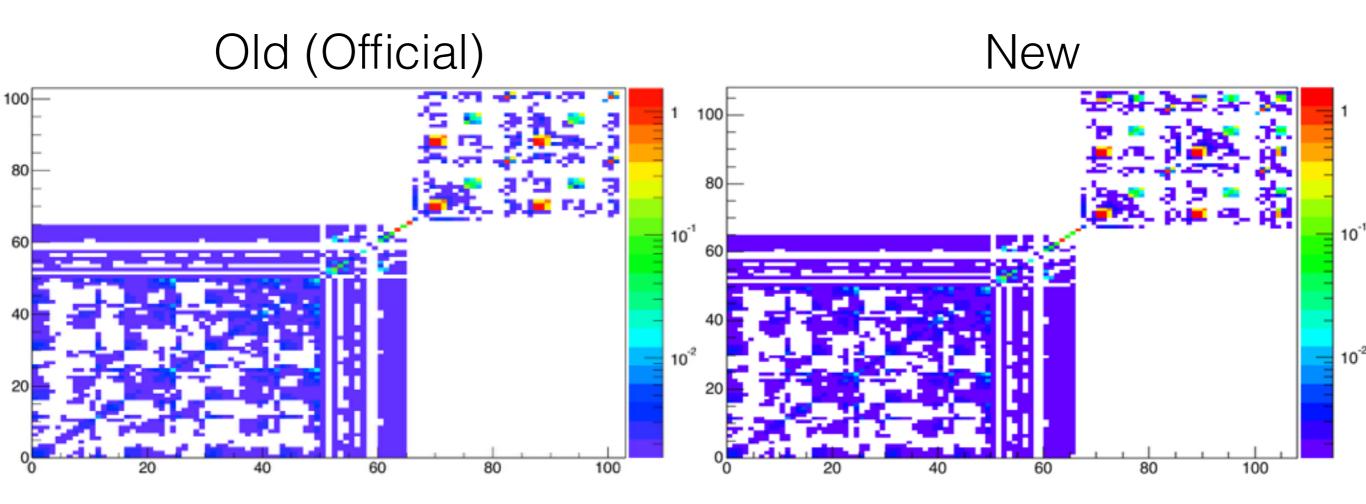
- Found 25.69 events from MC

Systematic Error Re-evaluation

- Initial study: 4 diagonal terms of pi0 systematics were added without correlation with other samples

- 1 bin for each SK event category: sig nue CC, numu CC, bkg nue, NC

- To get correlation, re-generate SK detector matrix and FSI+SI covariance matrix

- Also added back NCpi0 norm error

- Total number of parameters: 103 → 108

Full Covariance Matrix for Nominal+new sample

Old (Official)   New

Bins 1-50: Beam flux parameters
Bins 51-67: Correlated xsec and interaction parameters
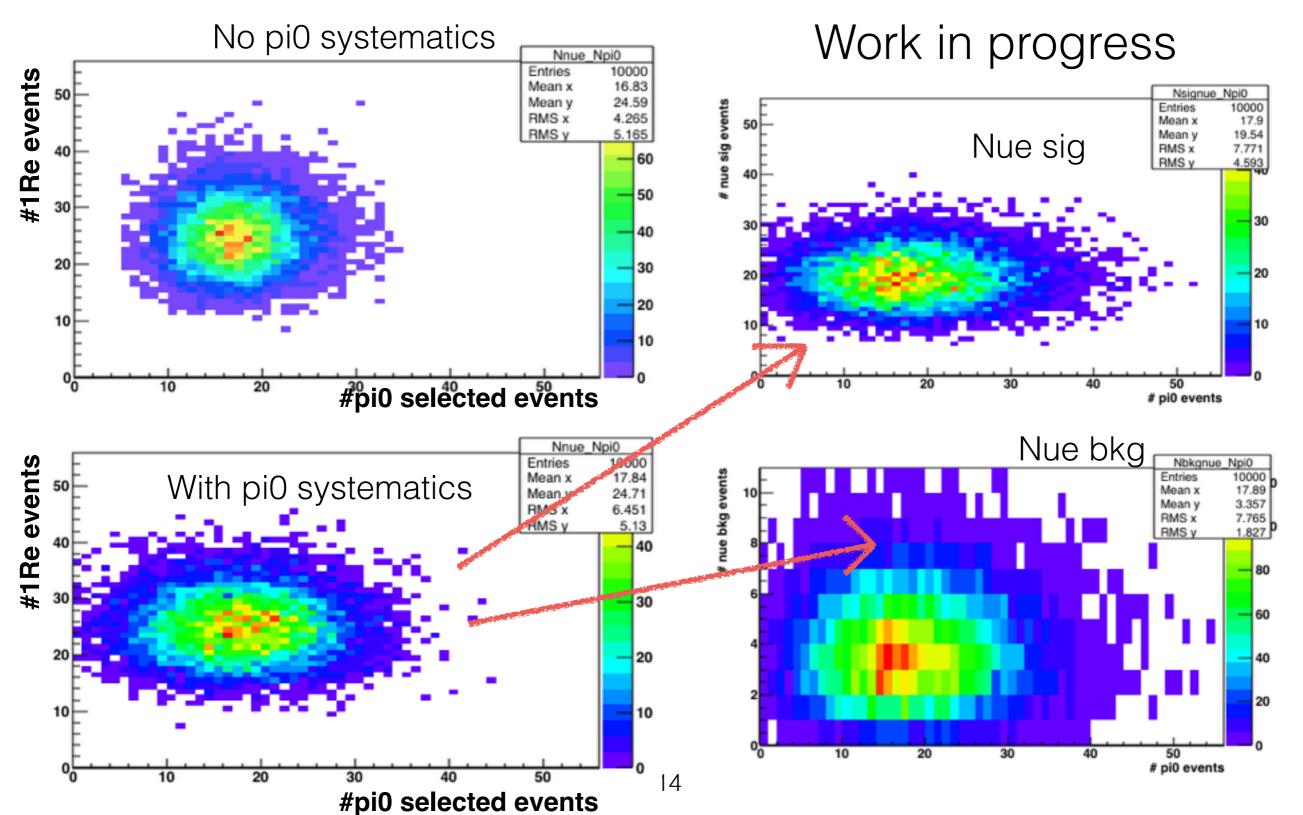Bins 68-103: SKdet+FSI+PN errors for nominal sample
Bins 104-107: SKdet+FSI errors for 2Rpi0 sample
Bin 108: SK momentum scale error

Preliminary study on Effect on Number of events

- Generate 10000 toy experiments and study number of events distributions

No pi0 systematics

Work in progress
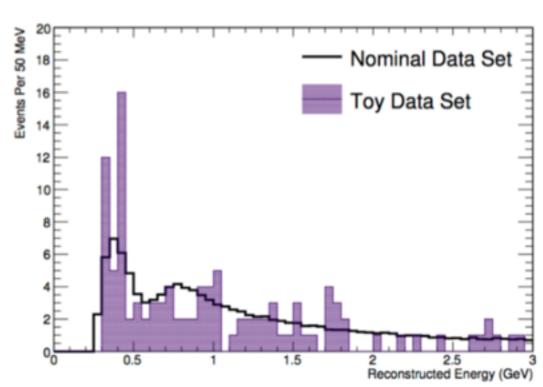
Sensitivity check with new sample

- Use "Asimov" dataset: Treat nominal MC as data (instead of throwing/sampling from prediction to create toy data)

- Any difference between input and best-fit point is due to fitter (not statistical errors)

- Binned Poisson likelihood is used for Asimov dataset

$$\mathcal{L}_{\mathrm{Asimov}}(N_{\mathrm{obs}}, \boldsymbol{x}, \boldsymbol{o}, \boldsymbol{f}) = \prod_{i=1}^{Emax} P_{\mathrm{Poisson}}(N_{\mathrm{pred}}(i), N_{\mathrm{obs}}(i)) \times \mathcal{L}_{\mathrm{syst}}(\boldsymbol{f})$$

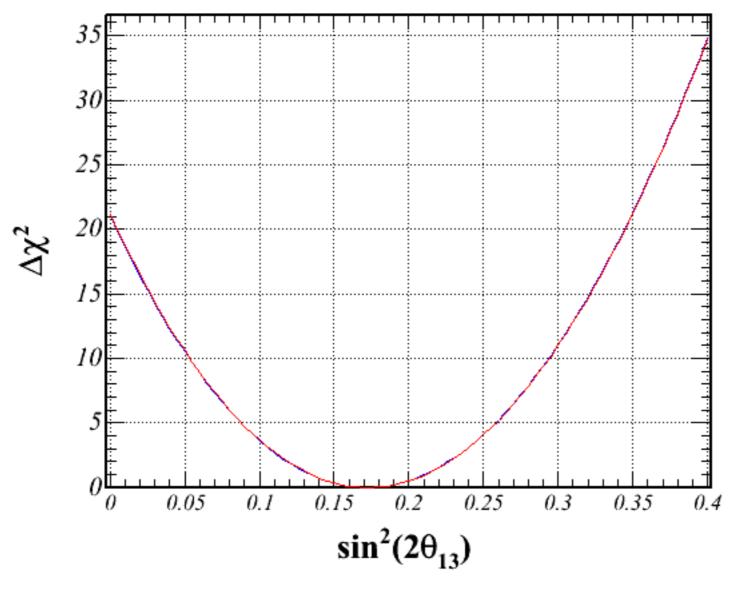- Using number of expected and observed 2Rpi0 events as inputs to likelihood calculation

- Only one bin for the 2Rpi0 sample

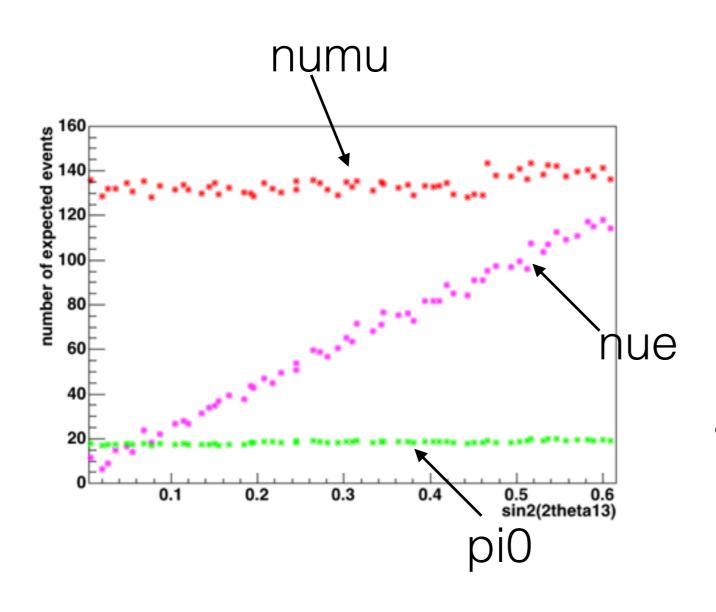# Sensitivity Check without Systematic Uncertainty

- Blue: nominal (numu+nue) sample

- Red: nominal + new sample

- Asimov dataset is used for this sensitivity study

- Marginalized over the other oscillation parameters using 10000 throws, with T2K best fit value of $\sin^2(2\theta_{13}) = 0.162$

- Found $\sin^2(2\theta_{13}) = 0.17$ for nominal and nominal+new sample

Sensitivity Check with Systematic Uncertainty

numu

nue

pi0
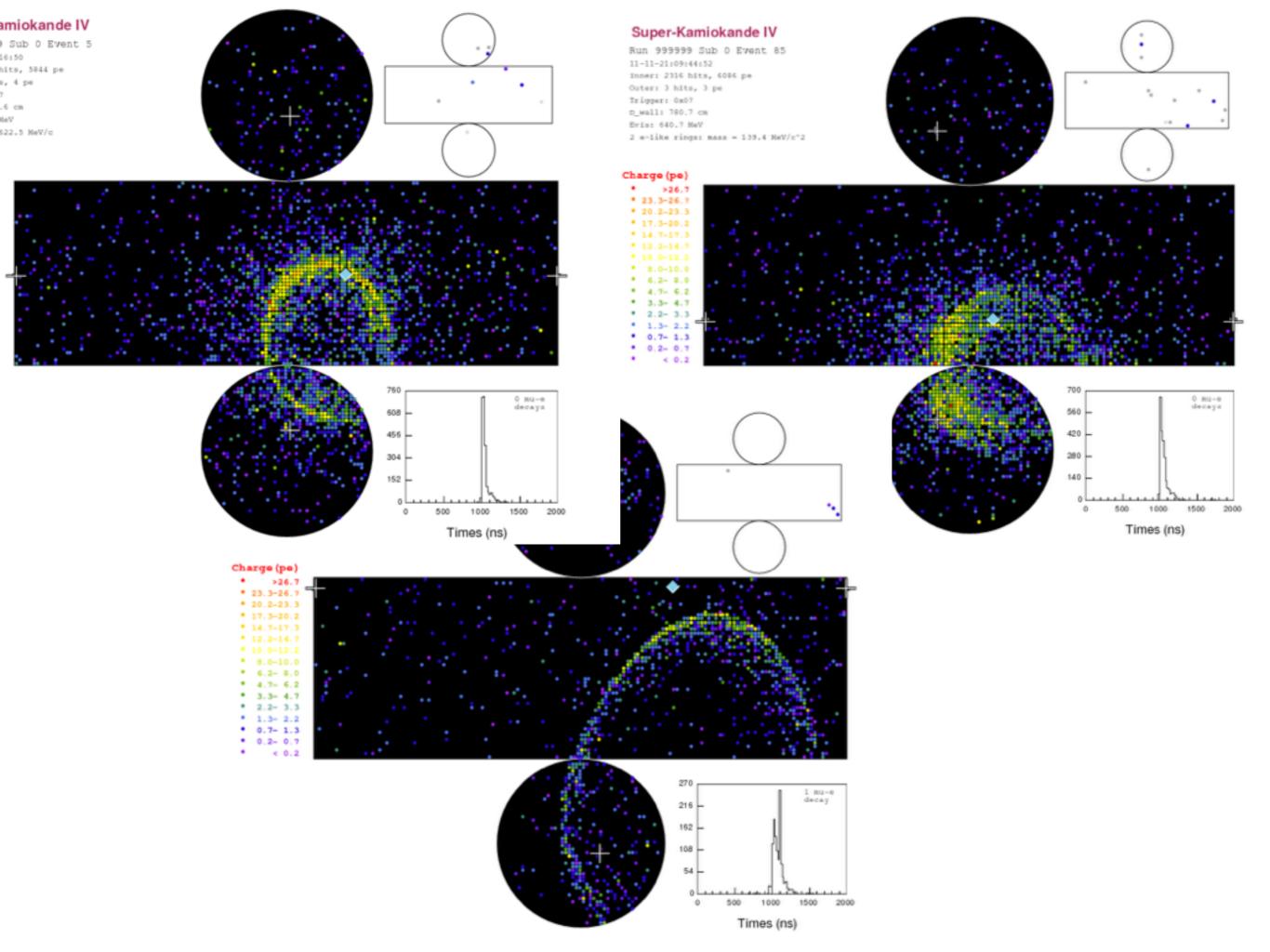
- Number of expected 2Rpi0 events has little effect to change of $\sin^2(2\theta_{13})$

Other physics studies with this sample

- NCpi0 xsec can be derived from the 2Rpi0 sample, but stats too small still

- Sterile neutrino study: anomalous disappearance or appearance of active neutrinos could be a sign of sterile neutrinos

- Improve pi0 rejection efficiency for nue selection

- Data fit and comparison with MC

Super-Kamiokande IV
Run 999999 Sub 0 Event 85
11-11-21:09:44:52
Inner: 2316 hits, 6086 pe
Outer: 3 hits, 3 pe
Trigger: 0x07
D_wall: 780.7 cm
Evis: 640.7 MeV
2 e-like rings: mass = 139.4 MeV/c^2

Charge (pe)
>26.7
23.3-26.7
20.2-23.3
17.3-20.2
14.7-17.3
12.2-14.7
10.0-12.2
8.0-10.0
6.2- 8.0
4.7- 6.2
3.3- 4.7
2.2- 3.3
1.3- 2.2
0.7- 1.3
0.2- 0.7
< 0.2

Charge (pe)
>26.7
23.3-26.7
20.2-23.3
17.3-20.2
14.7-17.3
12.2-14.7
10.0-12.2
8.0-10.0
6.2- 8.0
4.7- 6.2
3.3- 4.7
2.2- 3.3
1.3- 2.2
0.7- 1.3
0.2- 0.7
< 0.2

0 mu-e
decays

1 mu-e
decay

Times (ns)

Conclusion

- Neutrino oscillations at T2K and how we measure oscillation parameters

- Recent effort of 4 sample joint oscillation analysis and result

- Addition sample to oscillation analysis might have little effect on sensitivity to $\sin^2(2\theta_{13})$, but may have other physics interests
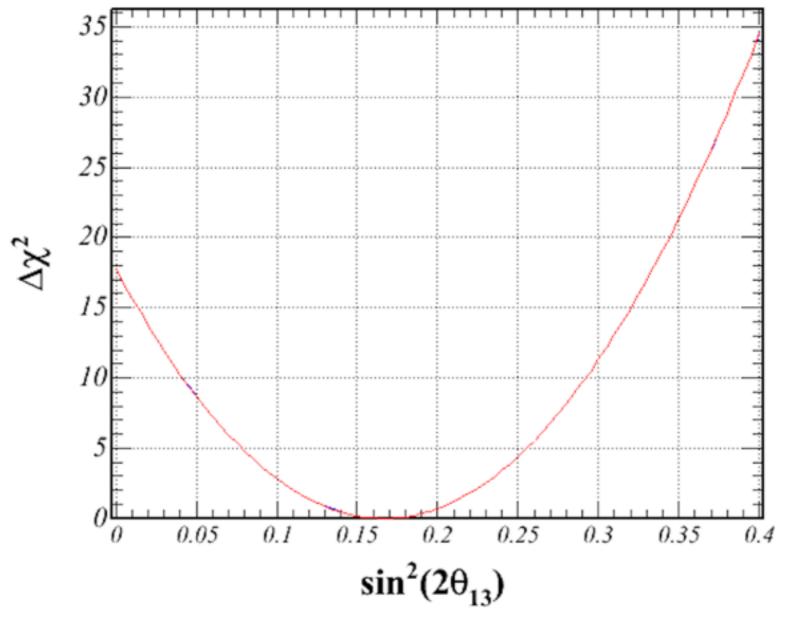
Extra Slides

Versions

Reference (TN-148)

- NEUT 5.1.4.2, SKDETSIM 13.80

- Reweighted from flux 11a to flux 11bv3.2

- Reconstructed using APfit version 13a

- Using 14a MC

- 13a nominal flux

- skdetsim-v13p90

- NEUT 5.3.2

- 14b SK software (apfit_14b, fiTQun_v4r0)

- MC files taken from iRODS: t2ksk.14a.neut5.3.2.13a_tuned_v1r0.250ka.fine.nu*_x_nu*.root

- data from /disk/sklb/t2k/2013Sept_fitqun_run1-4full

Sensitivity Check without Systematic Uncertainty

- Blue: nominal sample
- Red: nominal + new sample

- Sensitivity check with other parameters fixed