Details on T2K Neutrino Oscillation analysis

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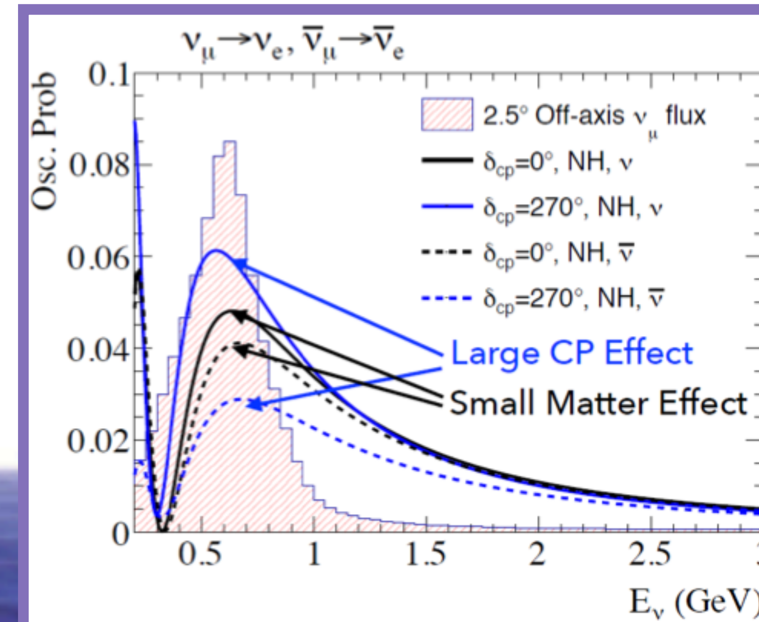
on behalf of the T2K collaboration

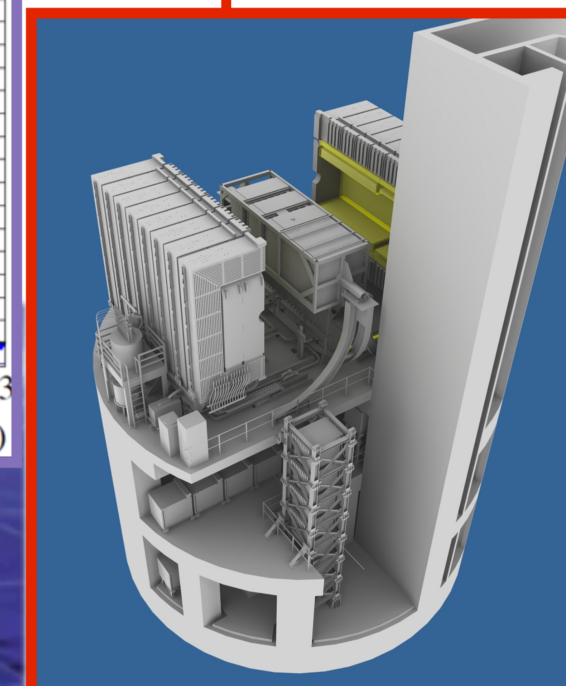
NuFact, Virginia Tech 2018

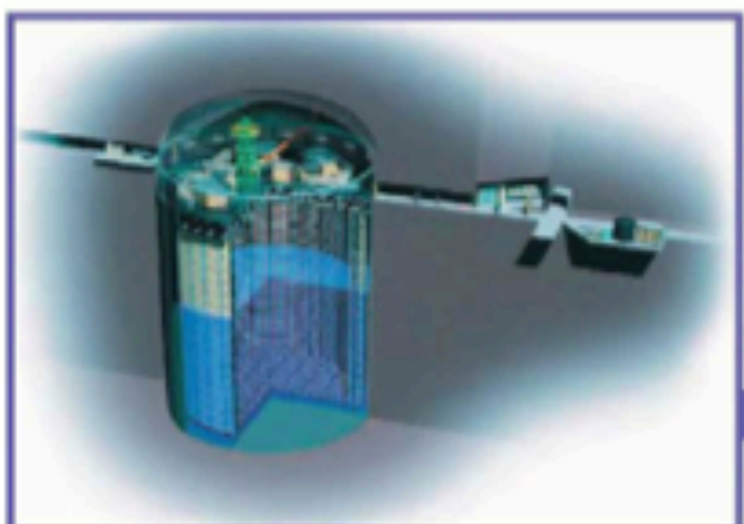
The T2K experiment

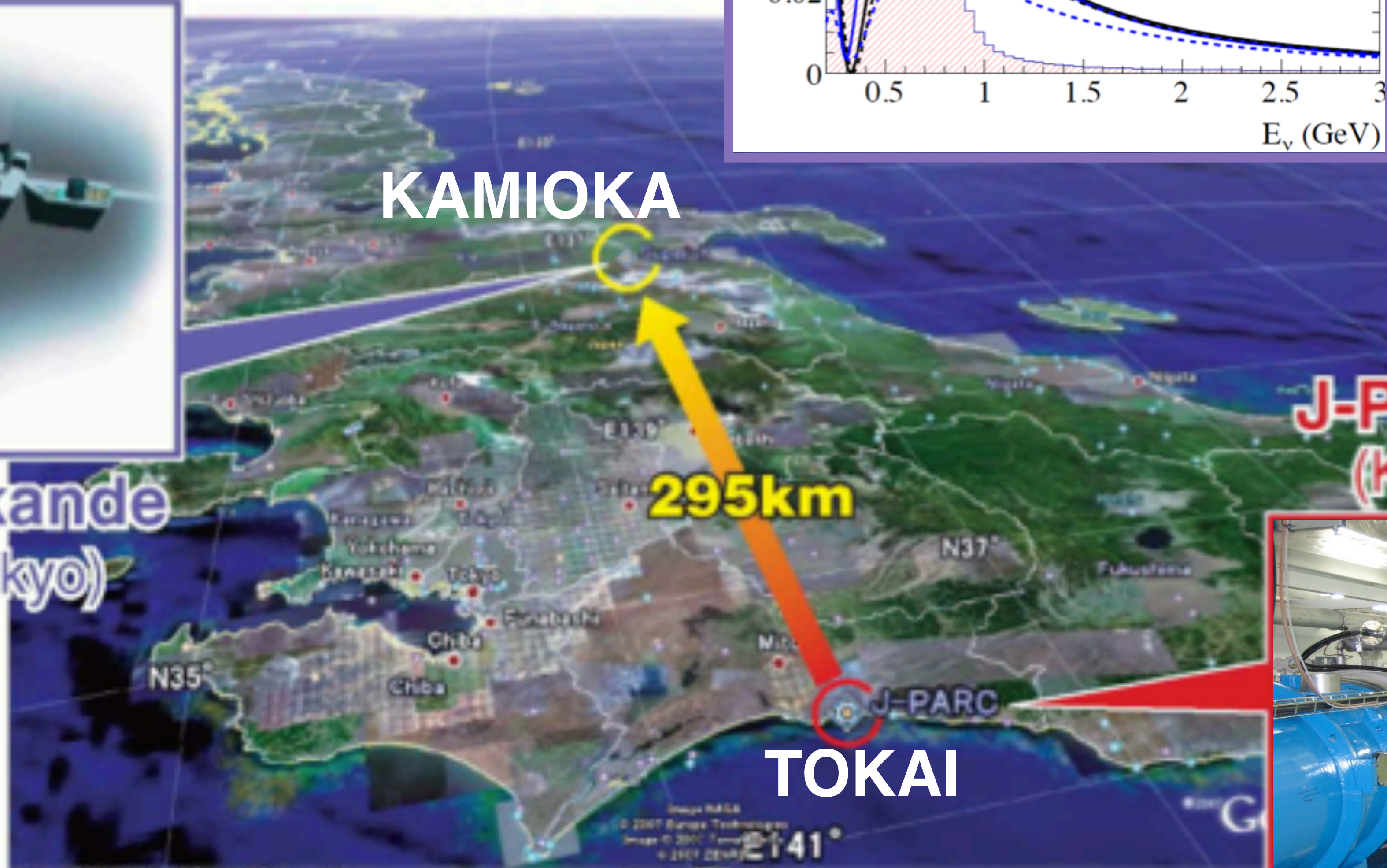
- Intense muon (anti)neutrino beam from J-PARC to Super-Kamiokande (295 km from target production): measure oscillated neutrino flux
- Unoscillated neutrino event rate is measured at the near detector (~280m)
- Observation at far detector (295km) of
  - ✦ muon (anti)neutrino disappearance
  - ✦ electron (anti)neutrino appearance



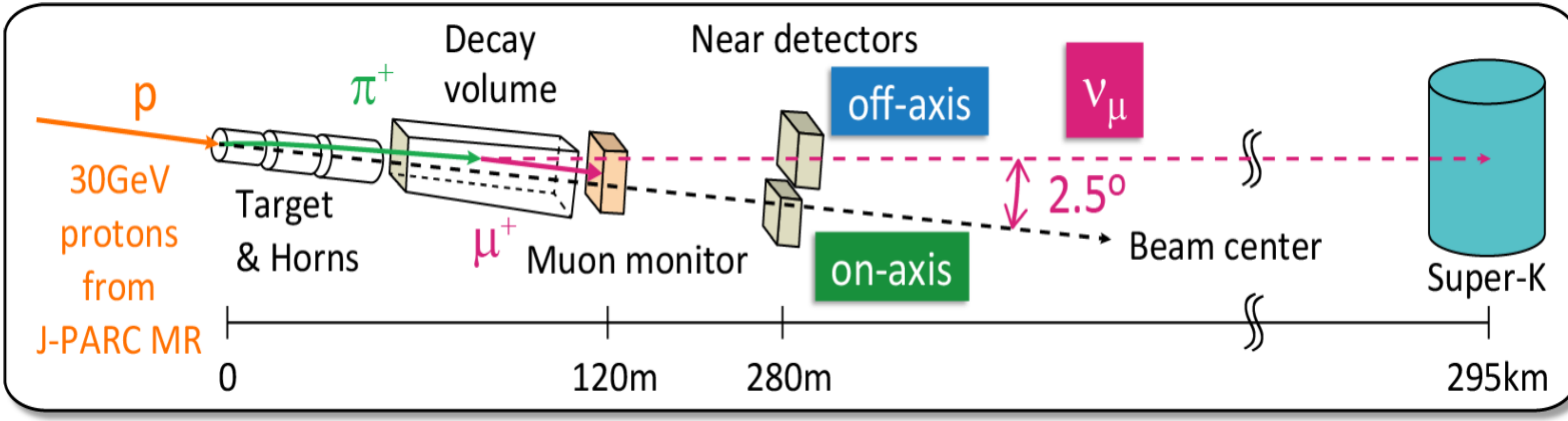
Near detector complex



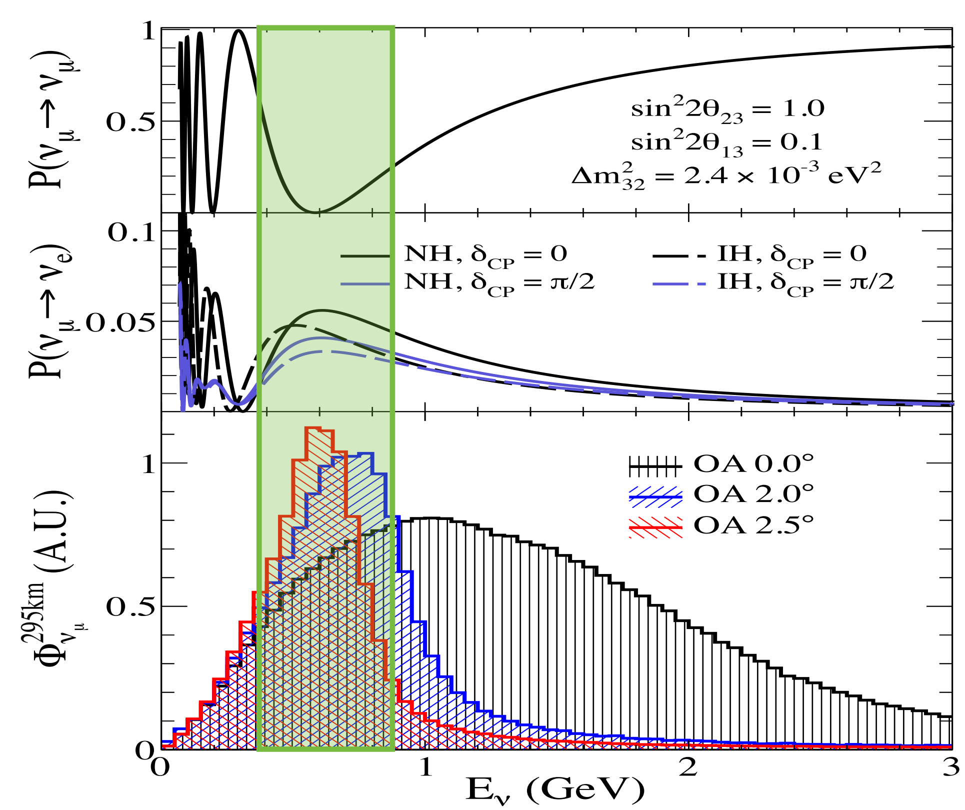




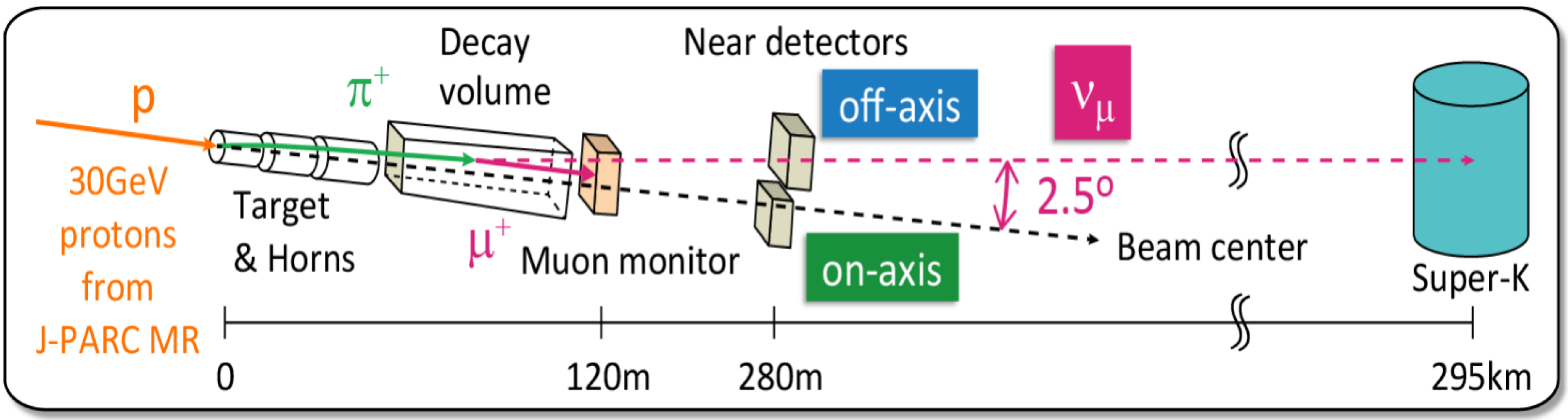
The T2K experiment



- 30 GeV proton beam on 90 cm long graphite target
- ν_μ and $\overline{\nu}_\mu$ produced by pion and kaon decay
- First off-axis neutrino beam experiment (2.5°)
  - ✦ narrow spectrum peaked at 0.6 GeV
- Magnetized Near Detector
  - ✦ 2 scintillator detectors, 3 TPCs, E.M. calorimeter
- Far Detector is Super-K (water Cherenkov)
- See the following talks for more details:
  - ✦ "Results and prospects from T2K" (Stephen Dennis)
  - ✦ "Recent Results from the T2K Near Detector" (Xianguo Lu)



The T2K experiment



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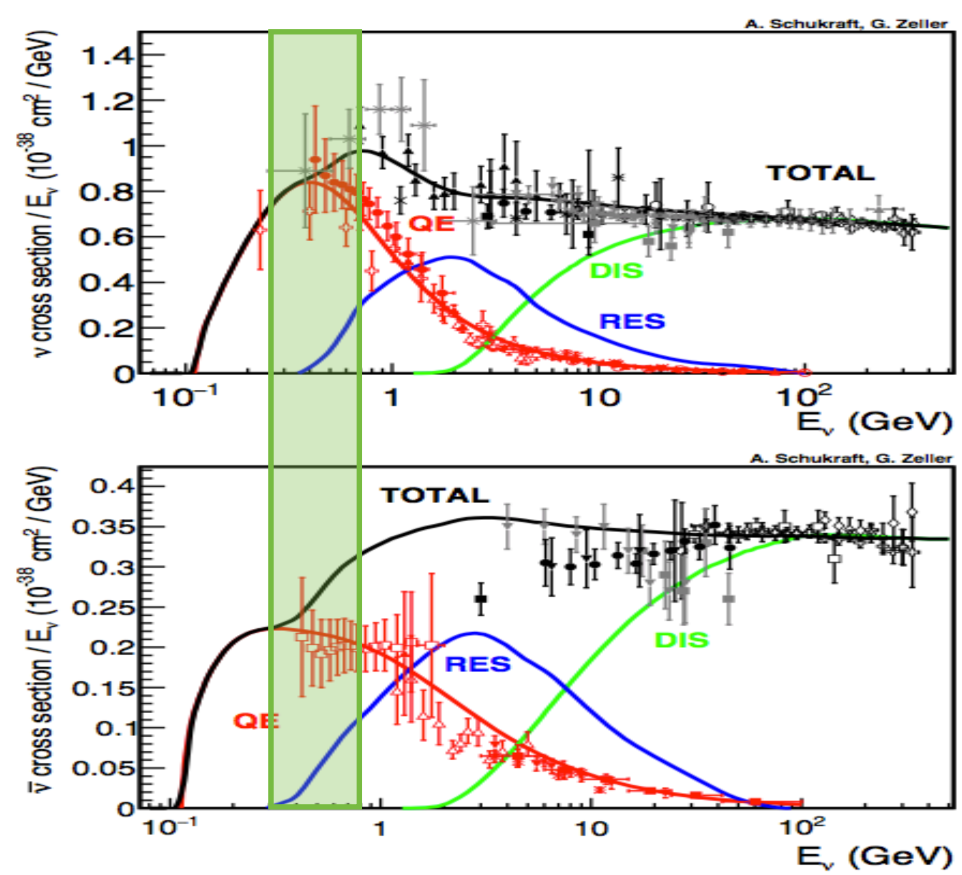


T2K near detector complex

NIM A 659 (2011) 106–135

- **On-Axis detector: INGRID**

  ✦ measure beam intensity and direction

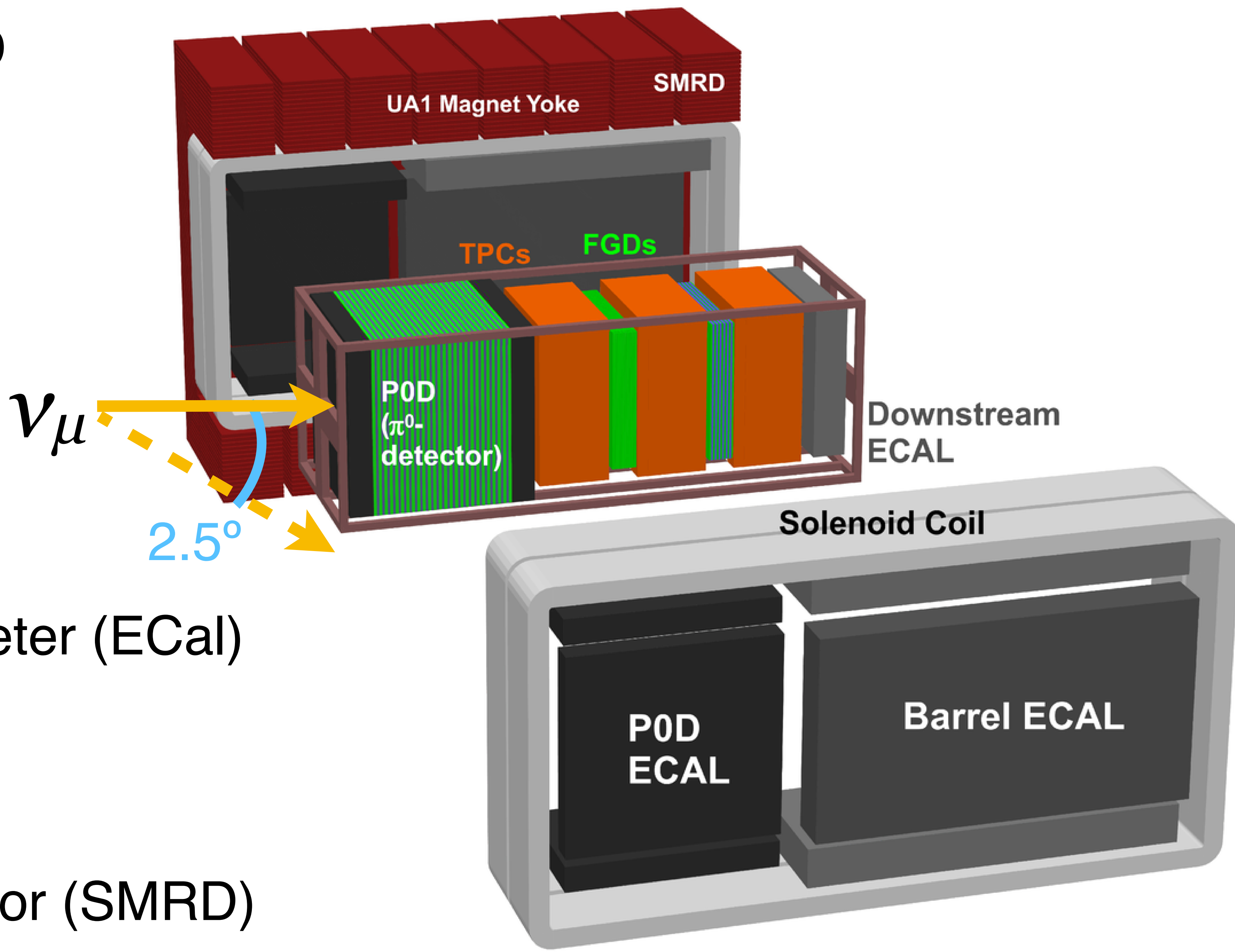
- **Off-axis detector: ND280**

  ✦ 0.2 T dipole magnet

  ✦ Electromagnetic Calorimeter (ECal)

  ✦ π^0 detector (P0D)

  ✦ Side Muon Range Detector (SMRD)

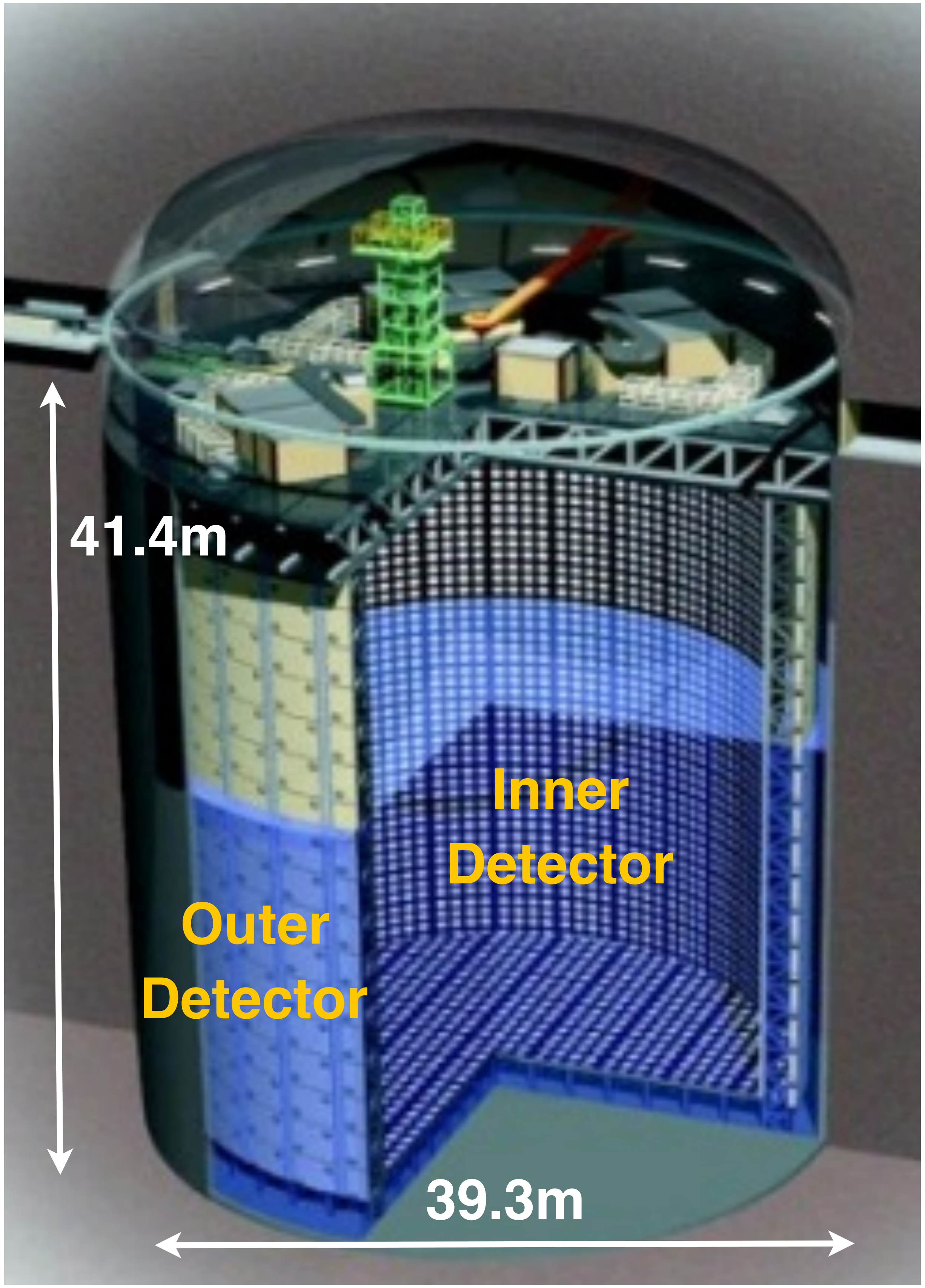


✦Tracker: 2 active neutrino targets + 3 Time Projection Chambers

- For more details see “Recent Results from the T2K Near Detector” (Xianguo Lu)

T2K far detector: Super-Kamiokande

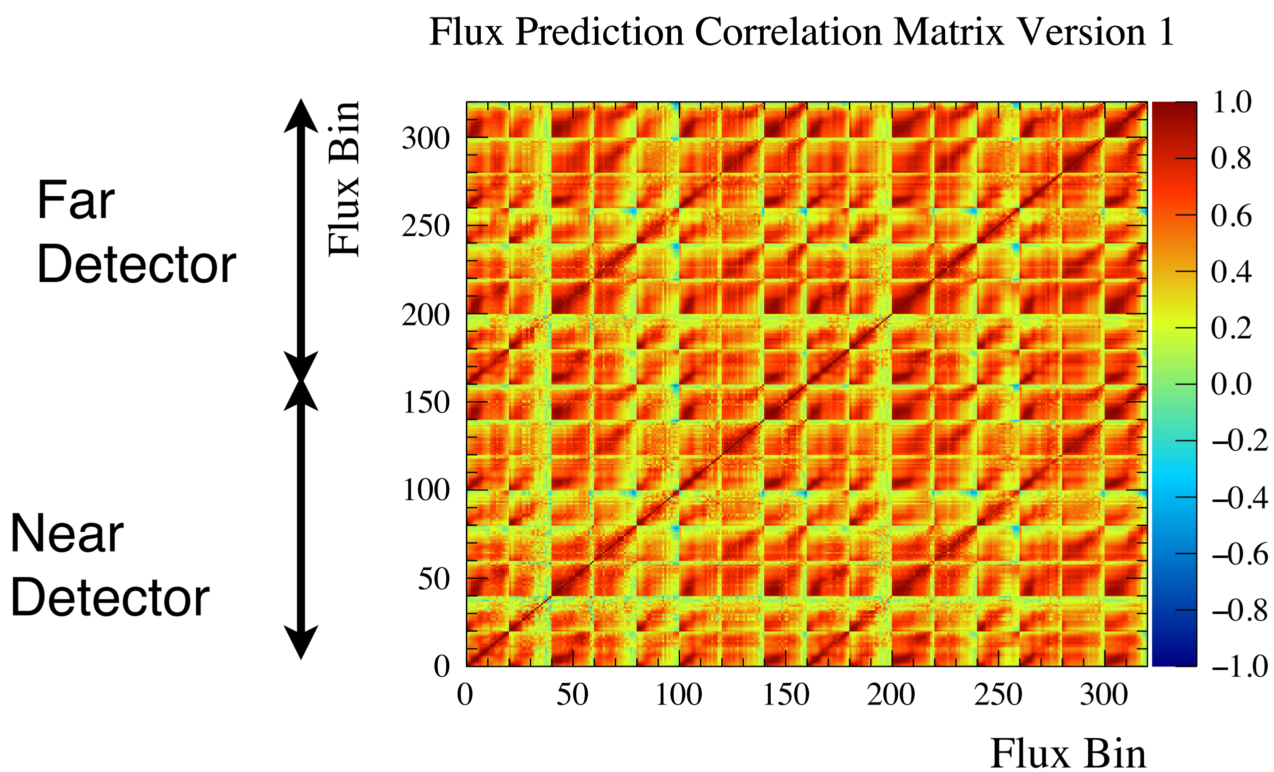
- Located in Mozumi mine
  - 2700 m.w.e overburden
- Water Cherenkov detector (50 kton)
- Inner detector
  - 11129 20-inch PMTs
- Outer veto detector
  - 1885 8-inch PMTs
  - determine fully-contained events
- New DAQ system: no dead time
- T2K beam event: ±500 μs window

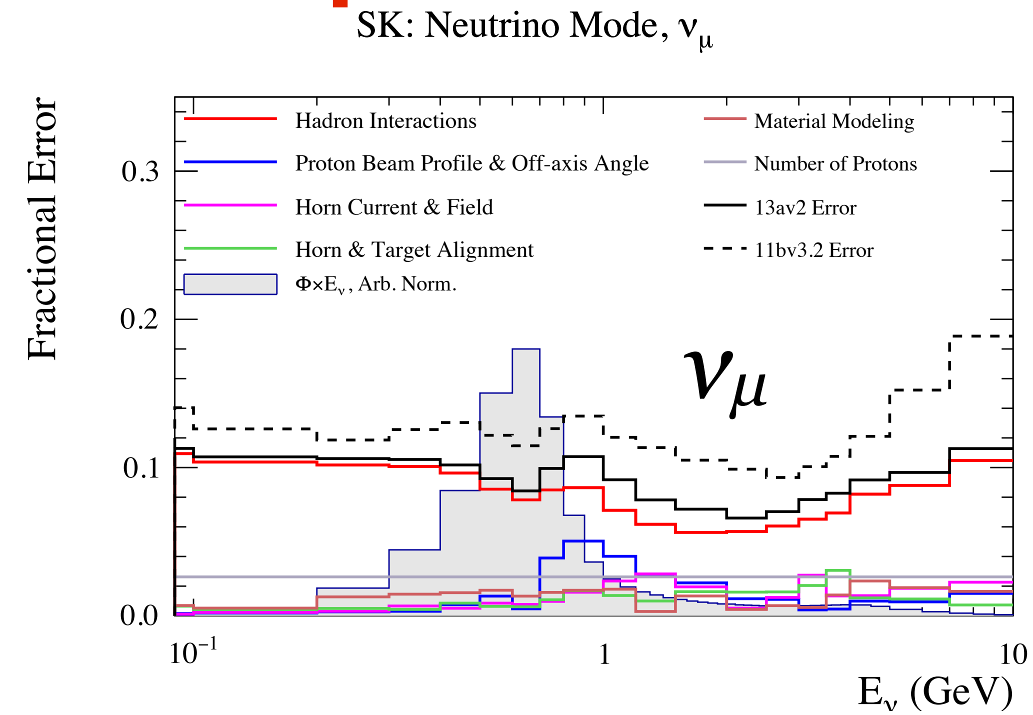


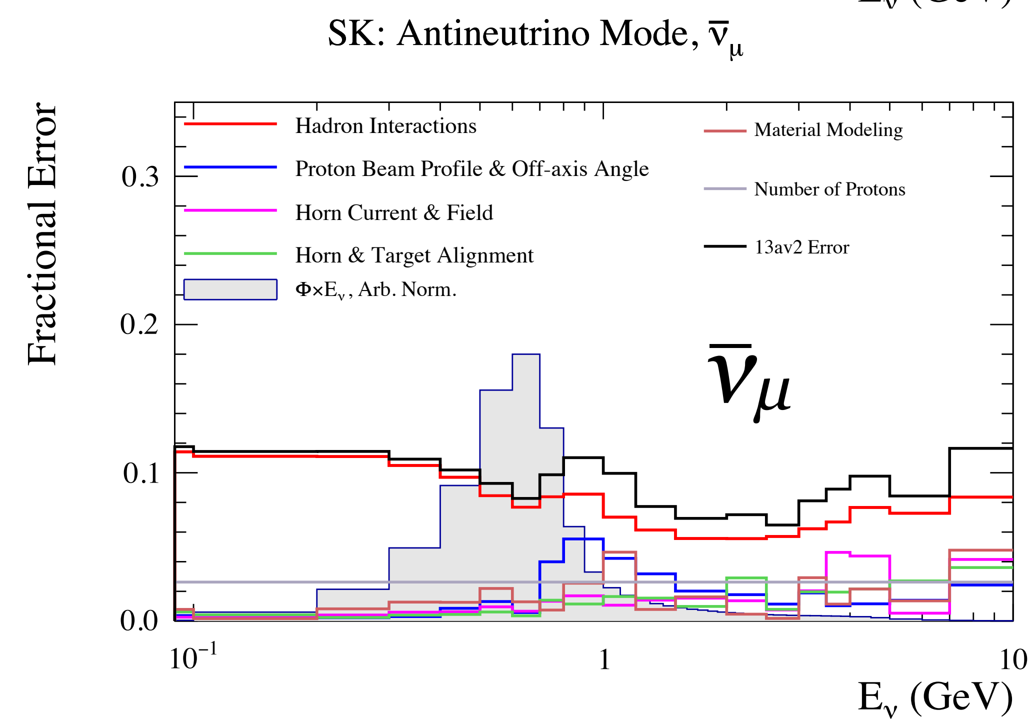
Neutrino and antineutrino flux prediction

• Neutrino flux prediction tuned with hadron spectra measured at NA61/SHINE

• Flux systematic uncertainty reduced from ~30% to ~10% (thin target data)





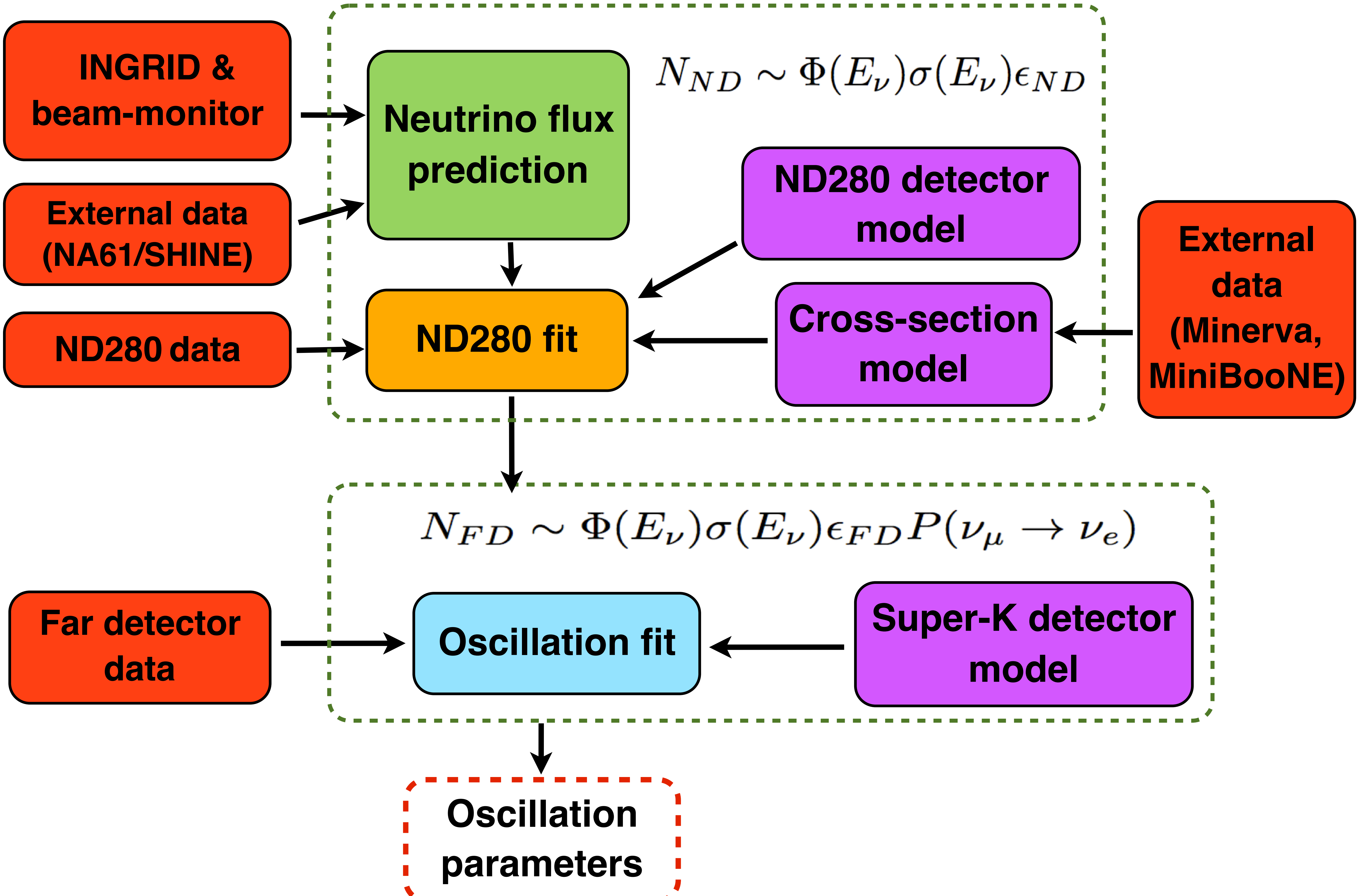


• Less than 1% intrinsic ν_e component at the peak

• <10% of wrong-sign background (ν_μ in $\bar{\nu}_\mu$ beam), ~30% after ν interaction

• Prediction of flux correlations near / far detector, ν / $\bar{\nu}$ beam, ν_μ / ν_e is used

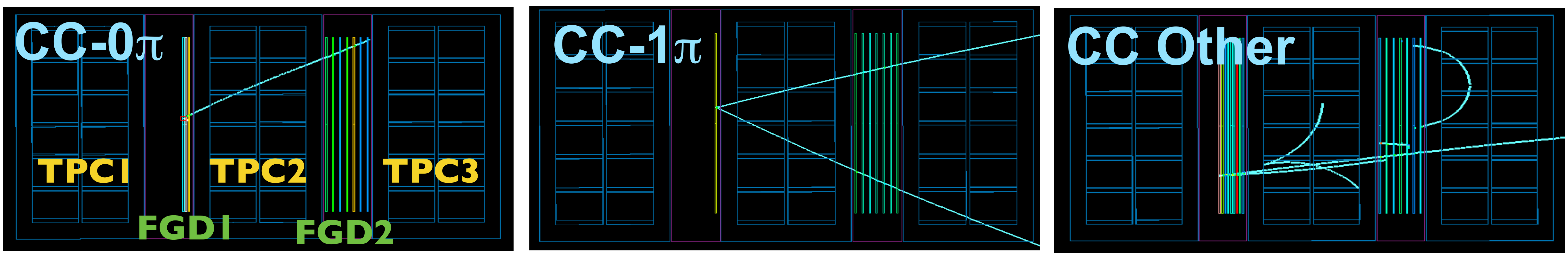
Strategy for oscillation analyses

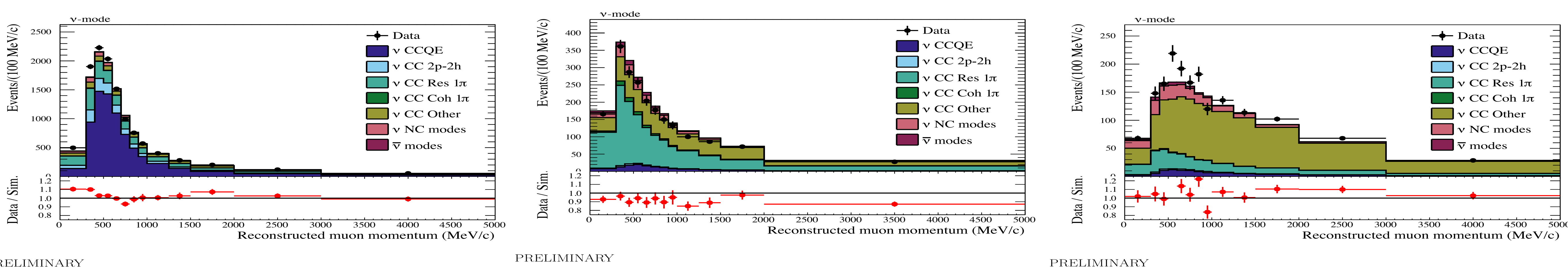


Near Detector neutrino event samples

- Sub-divide samples by neutrino interaction candidate:
  - ✦ CC-0 pions, CC-1 pion, CC-Other for ν beam
  - ✦ CC-1 track, CC N-tracks for $\bar{\nu}$ beam
- Select also ν events in $\bar{\nu}$ beam —> estimation of “wrong-sign background”
- Measure neutrino interactions both in
  - ✦ Plastic scintillator, Fine-Grain Detector 1 (FGD1)
  - ✦ Water, Fine-Grain Detector 2 (FGD2), 50% scintillator + 50% water

Distributions before the Near Detector fit (ν beam, FGD1)

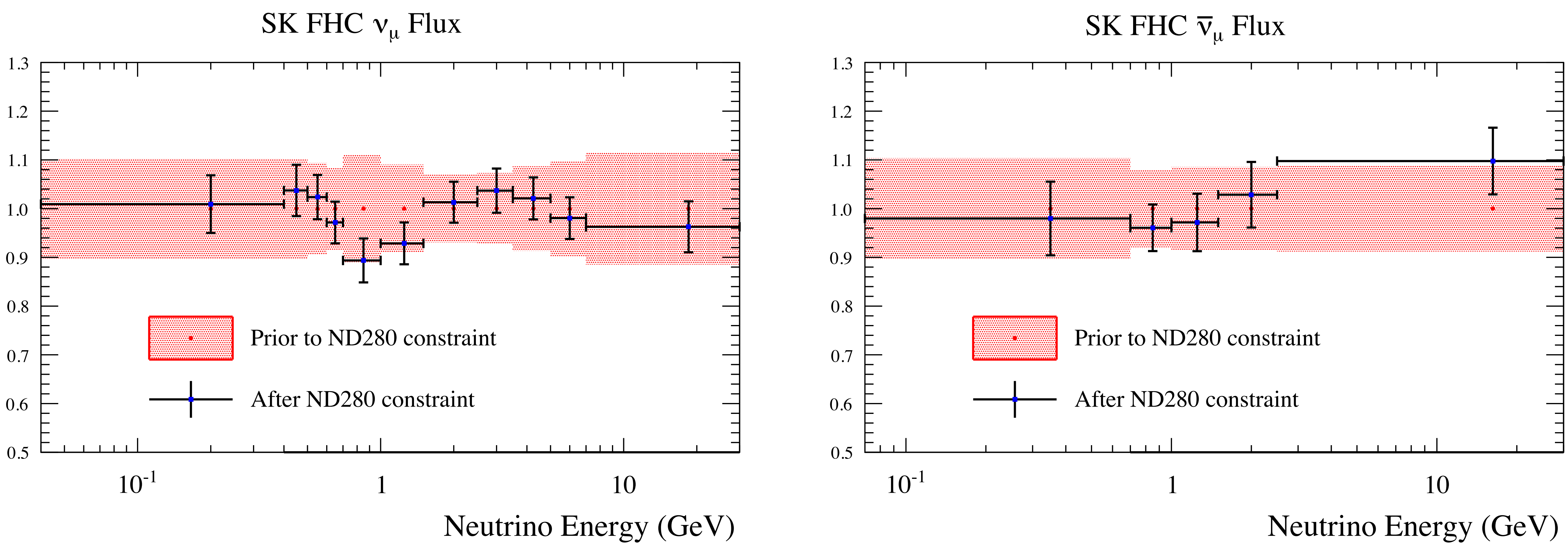




Parametrize the analysis templates in momentum and lepton angle

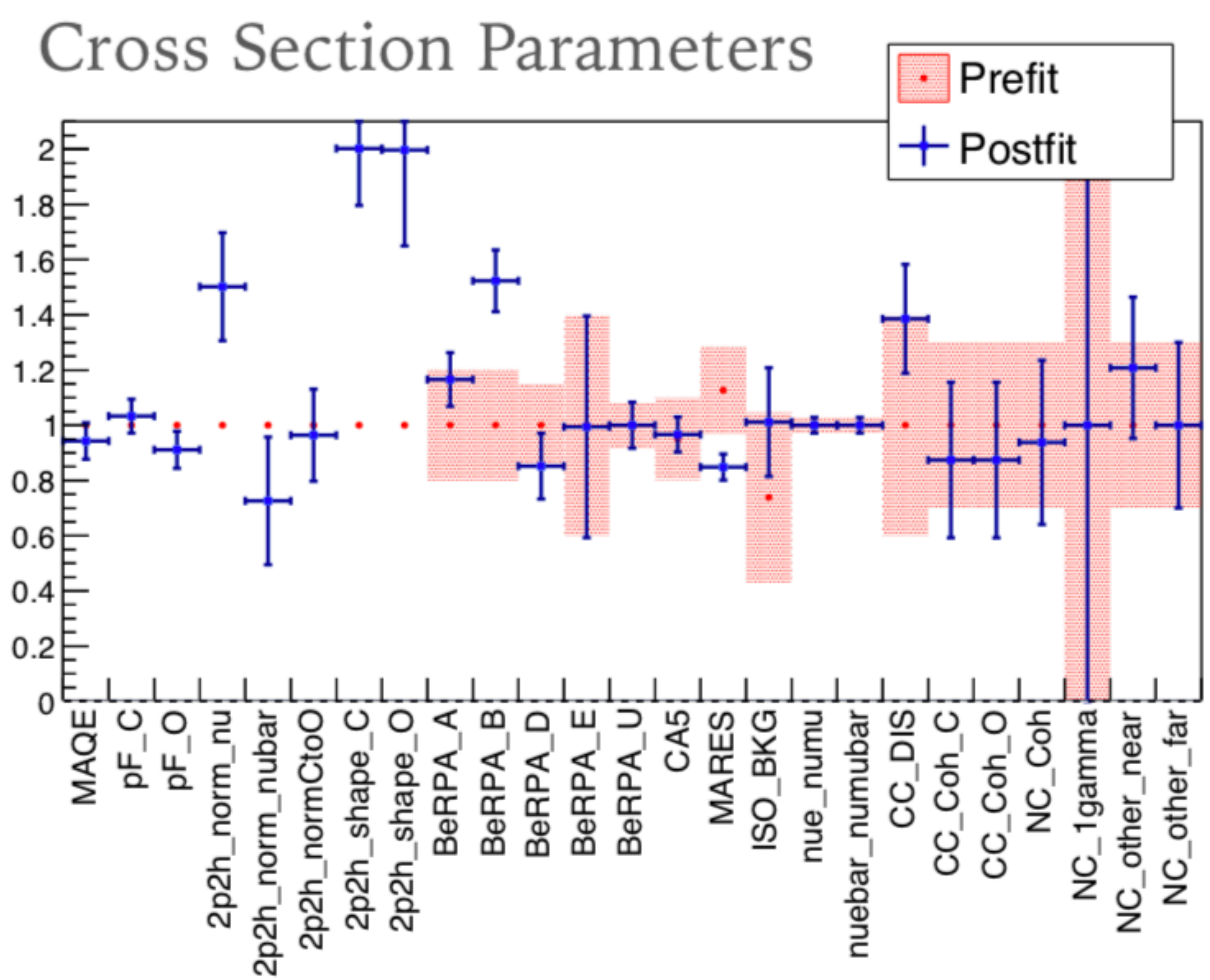
Near Detector Fit: flux and cross-section uncertainties

- A joint fit of all the event samples is performed
    - ✦ Minimization of negative log-likelihood over all the systematic parameters
- Super-K flux parameters have no effect in the analysis spectra
- Driven by correlations with ND280 flux parameters



- Flux post-fit parameters are generally near their nominal value of 1.0
- Most of the parameters fall within 1 standard deviation of their assigned prior uncertainty

Near Detector Fit: flux and cross-section uncertainties



CCQE and 2p2h parameters have no prior constraint

The $\sigma(\nu_e)$ and NC at the far-detector analysis are not constrained by the ND280 data

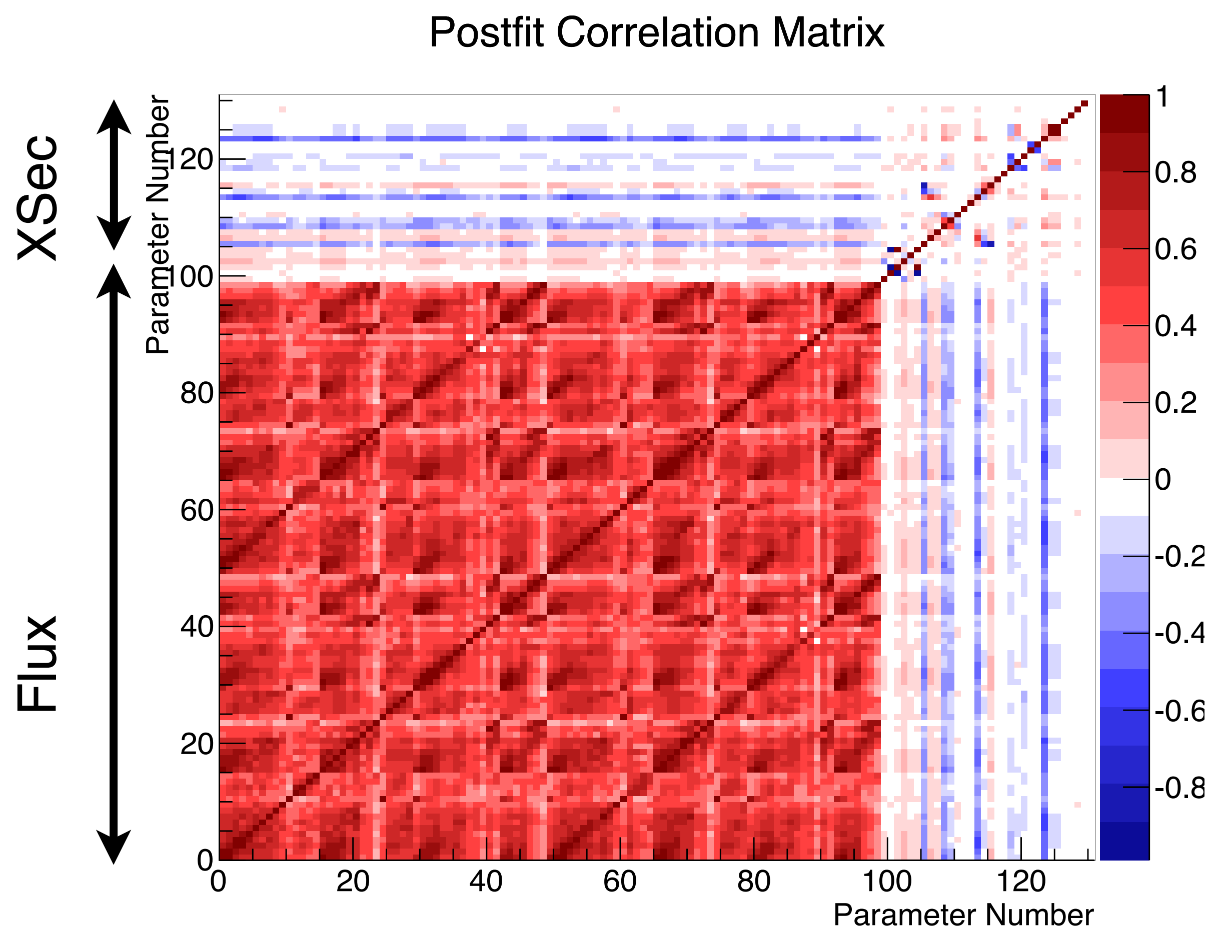
- 2p2h for neutrinos enhanced by ~50%
- 2p-2h shape Δ-enhanced component is increased to maximum
- Cross section (RPA) enhanced at Q^2 below 1 GeV^2

For more details on the cross-section model and results

✦ "The Role of Cross Sections in the Oscillation Analysis: The T2K experience" (Clarence Wret)

Near Detector Fit: flux and cross-section uncertainties

- We perform a goodness-of-fit test to evaluate the compatibility of our model with the data
- The p-value for the model is 0.47 —> good agreement
- Independent Bayesian analysis is performed with Markov-Chain MC method to cross check the results
    - ✦ consistency between frequentist and bayesian analysis



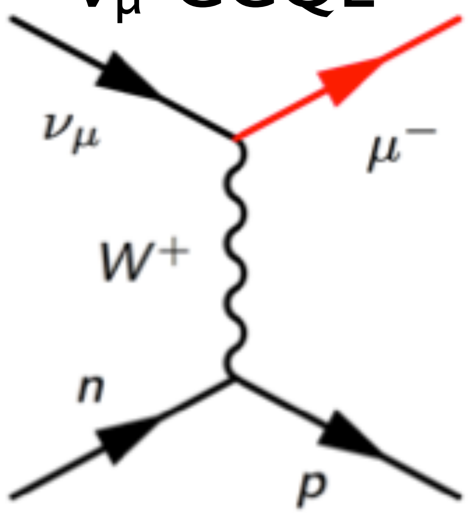
- The fit covariance matrix is used as prior in the far-detector analysis

- Systematic uncertainties in neutrino oscillation analyses from 12-17% to 4-9%

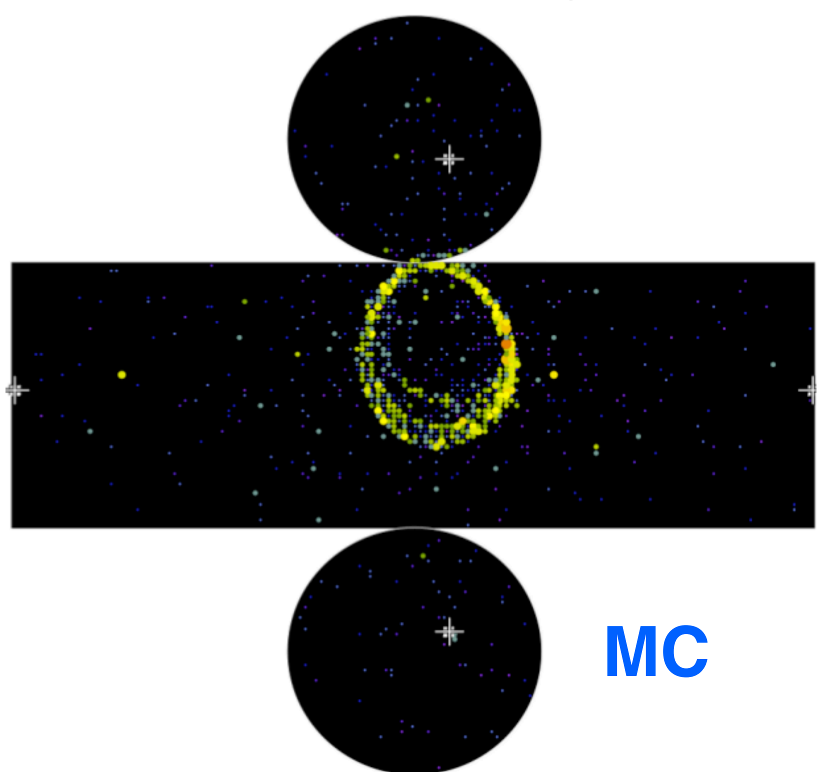
Far detector neutrino events

- Excellent μ / e separation

ν_μ CCQE

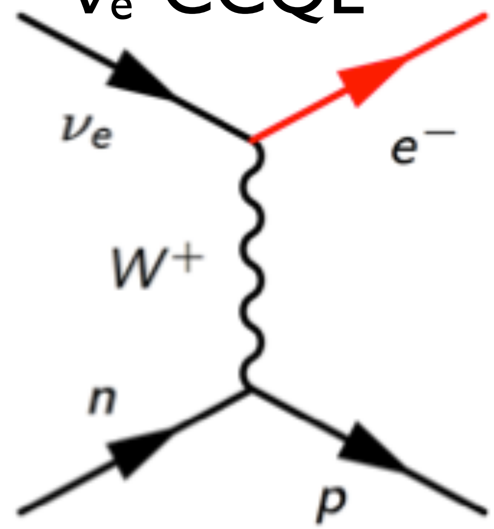


- 1 Cherenkov ring
- Low scattering
- Ring with sharp edge
- Protons below Cherenkov threshold

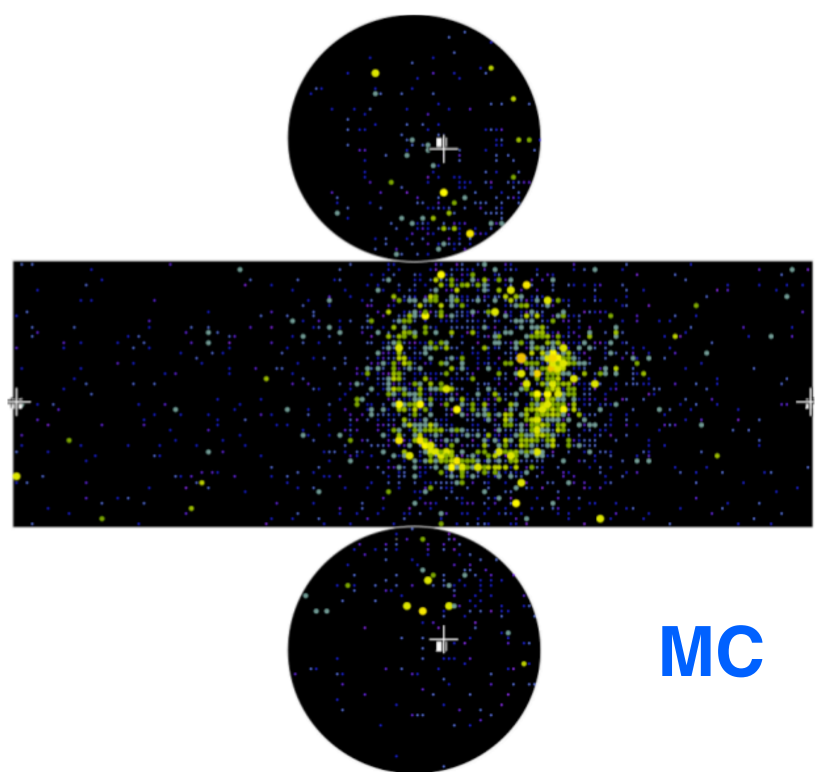


MC

ν_e CCQE

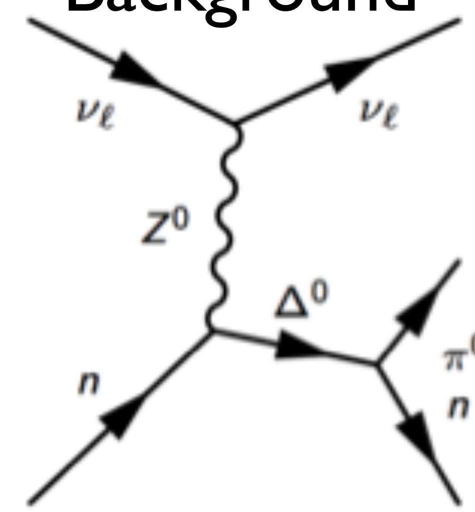


- 1 Cherenkov ring
- Multiple scattering
- EM shower
- Ring with “fuzzy” edge

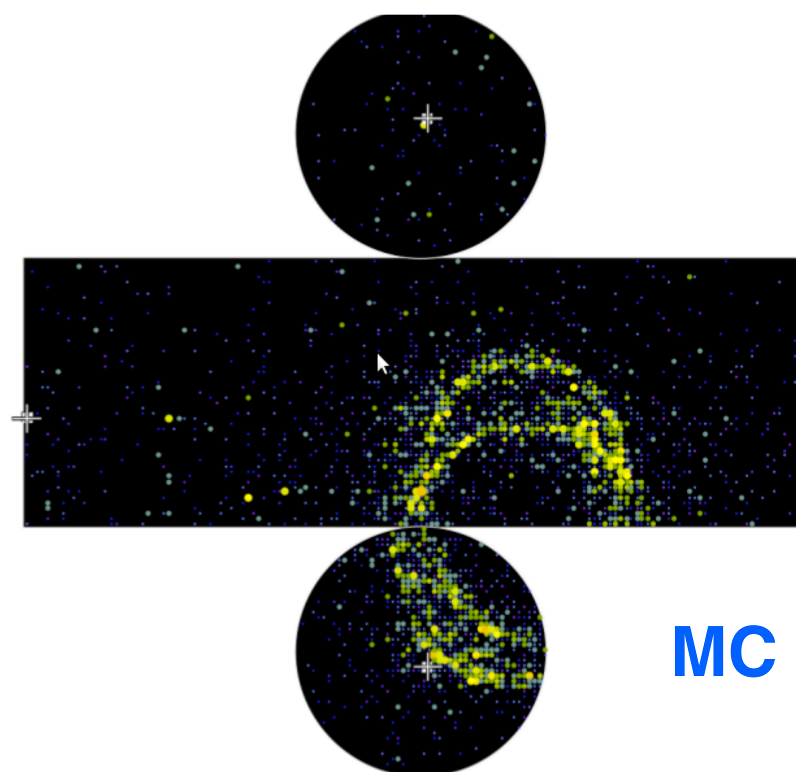


MC

Background

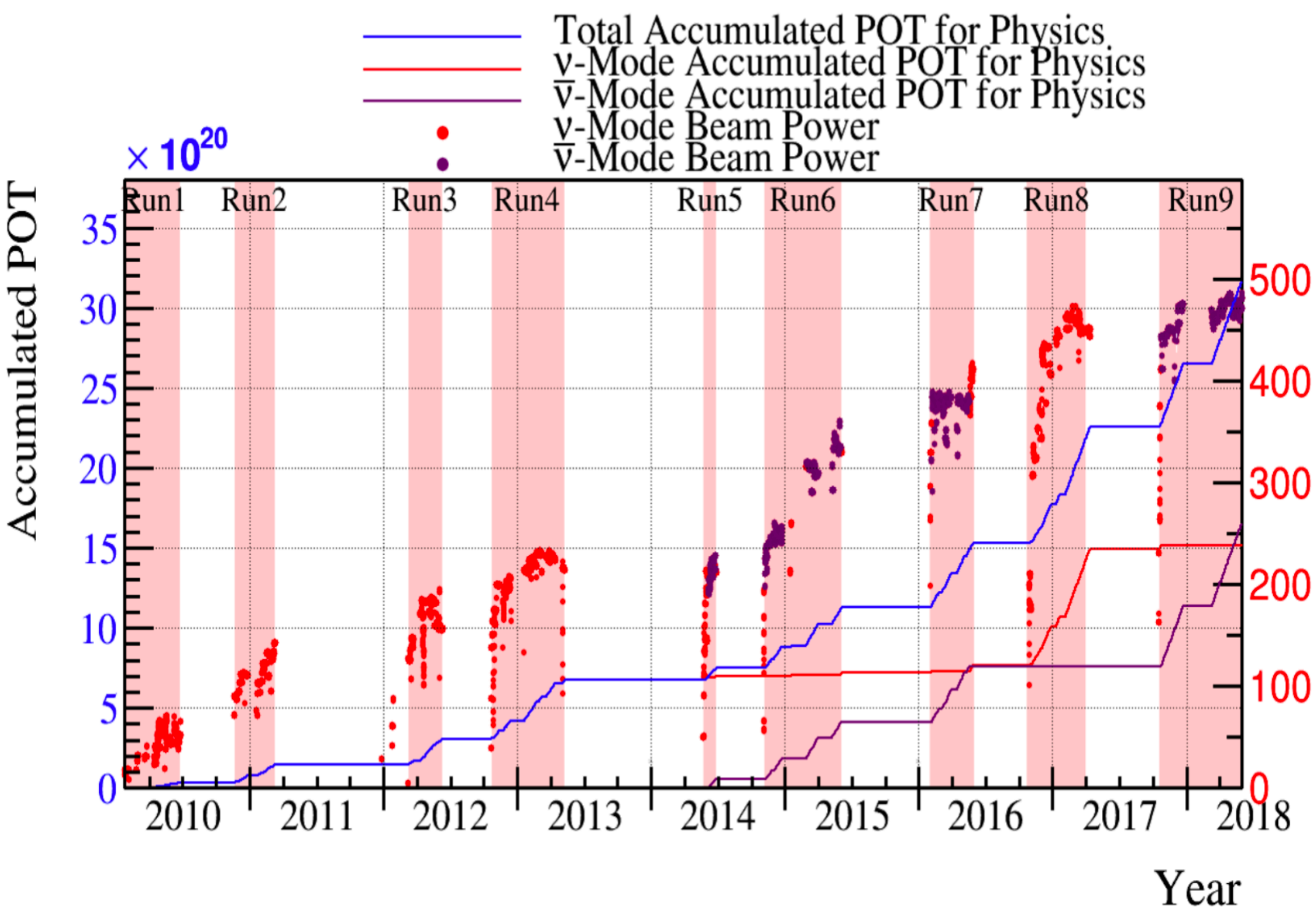


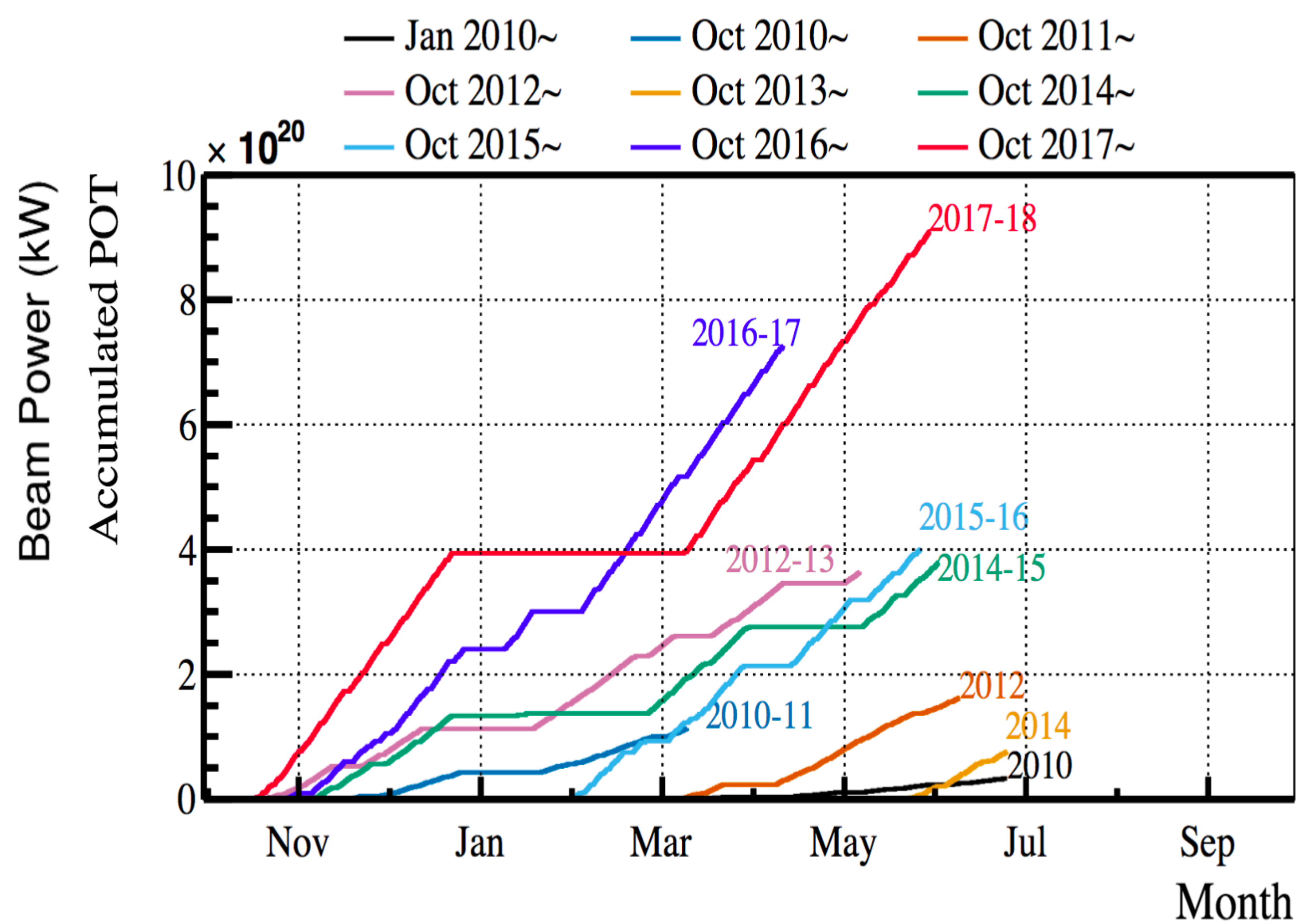
- 2 Cherenkov rings
- EM shower from $\pi^0 \rightarrow \gamma\gamma$
- Can be misidentified as an electron



MC

T2K delivered protons on target (POT)



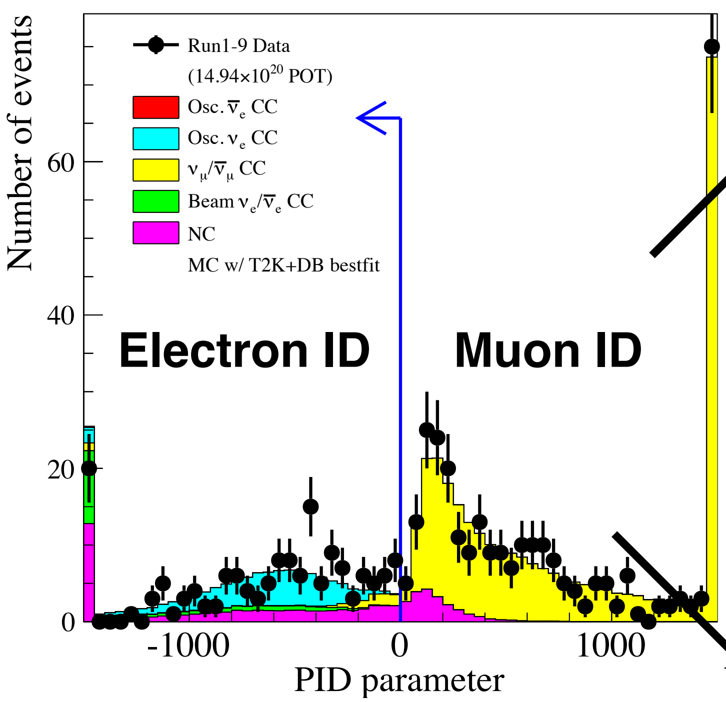


- Now running stable at ~500 kW
- Achieved ~9 x 10^{20} POT from October 2017 to summer 2018
- ν beam: 15.1 x 10^{20} POT —> analyzed 14.9 x 10^{20} POT
- $\bar{\nu}$ beam: 16.5 x 10^{20} POT —> analyzed 11.2 x 10^{20} POT

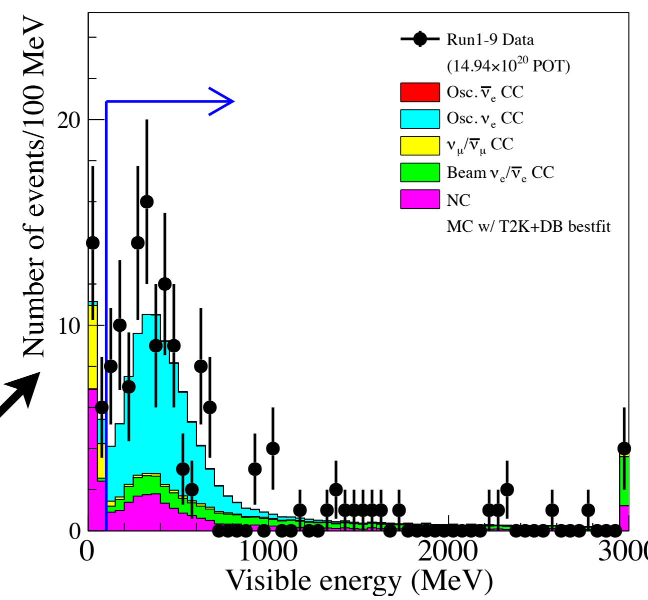
Event selection at Far Detector

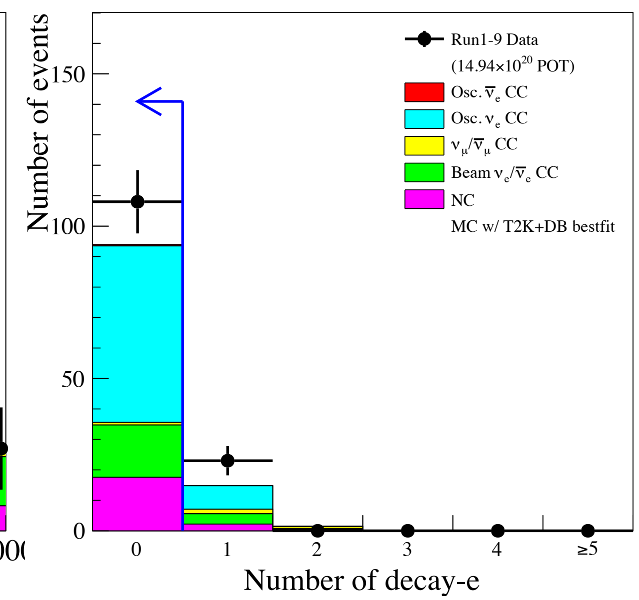
- Cuts common to all event sample selections:
  - ✦ fully contained in fiducial volume, single ring event, PID cut

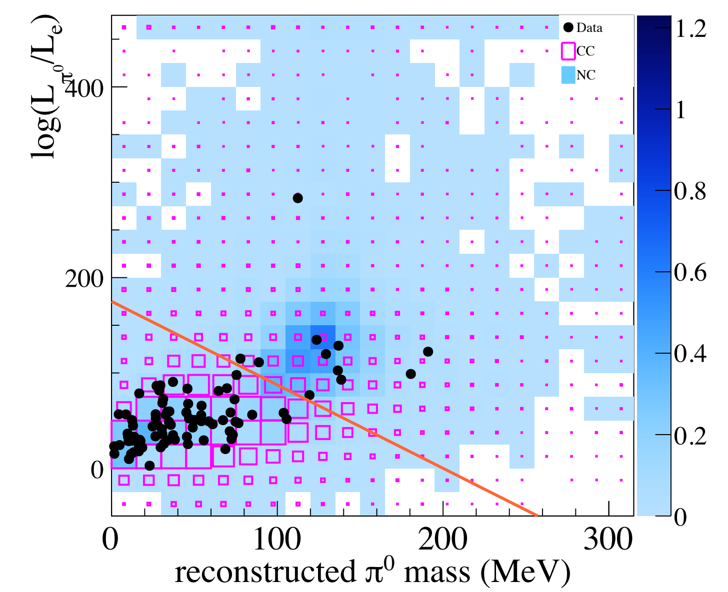
CCQE ν_e selection

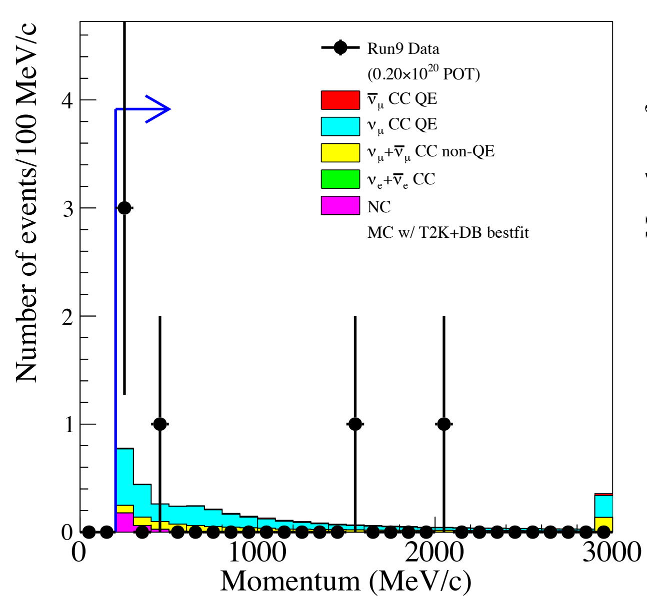


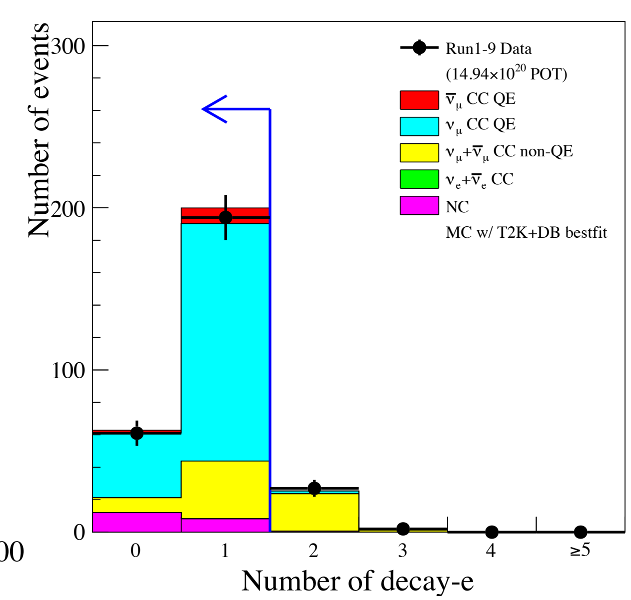
CCQE ν_μ selection

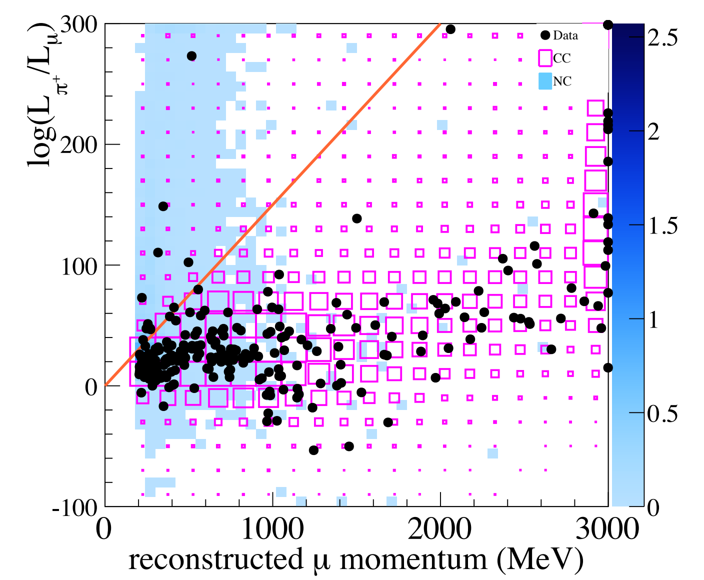








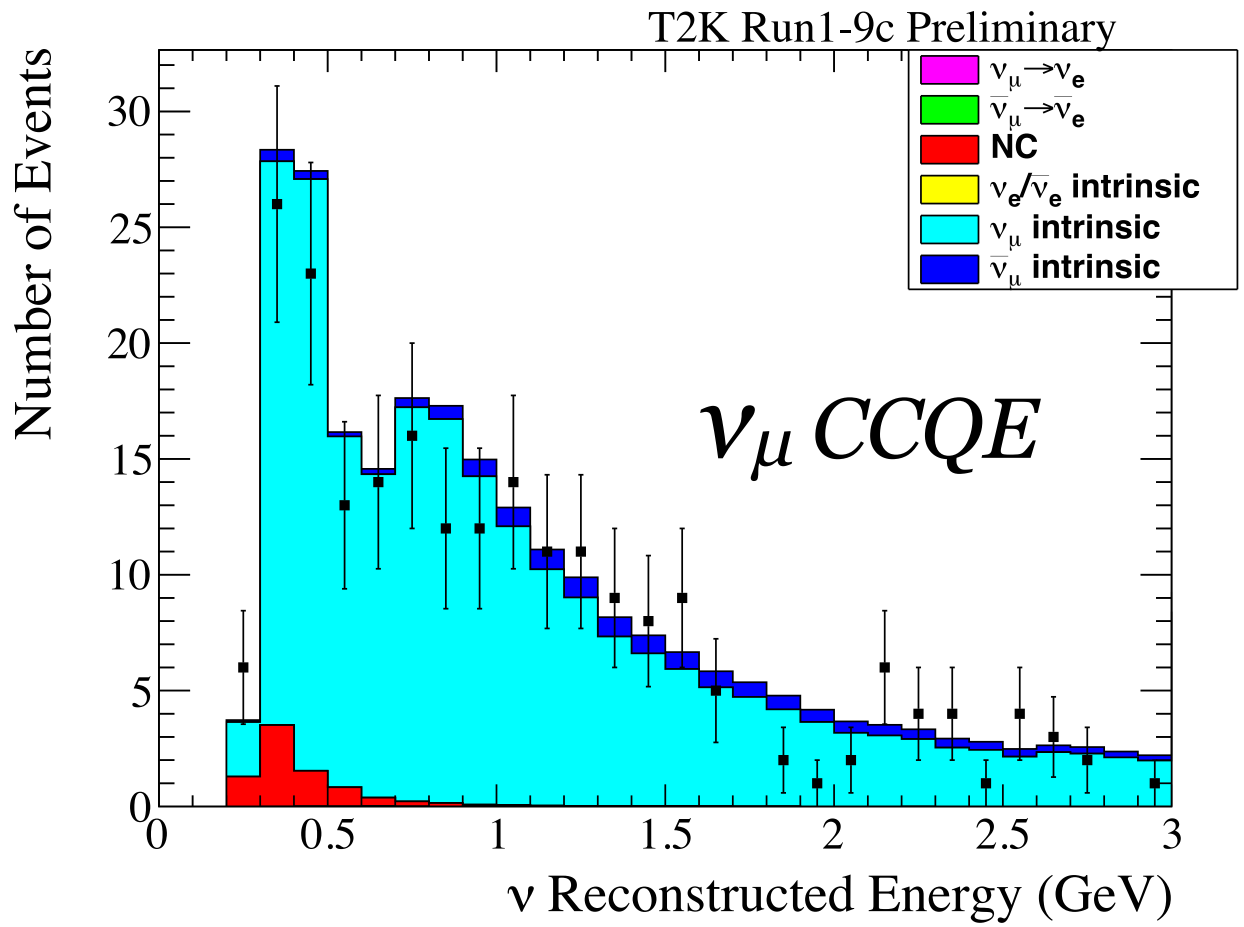


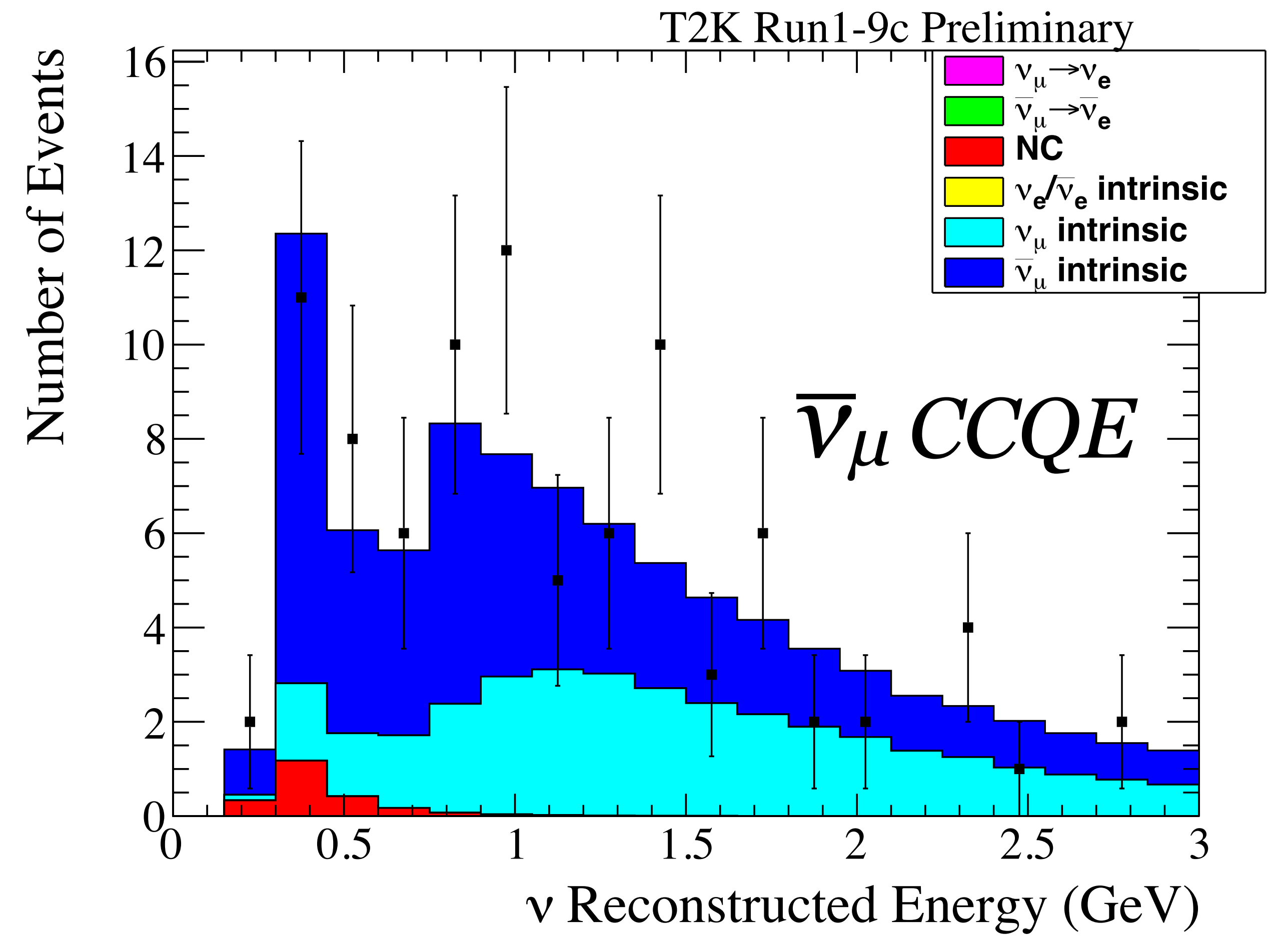


New reconstruction algorithm for pion rejection

- ν_μ CCQE: 1 muon ring and ≤ 1 decay electron (ν and $\bar{\nu}$)
- ν_e CCQE: 1 electron and 0 decay electrons (ν and $\bar{\nu}$)
- ν_e CC1π: 1 electron and 1 decay electron (no $\bar{\nu}$ due to π^- abosorption)

Far Detector ν_μ / $\bar{\nu}_\mu$ event samples



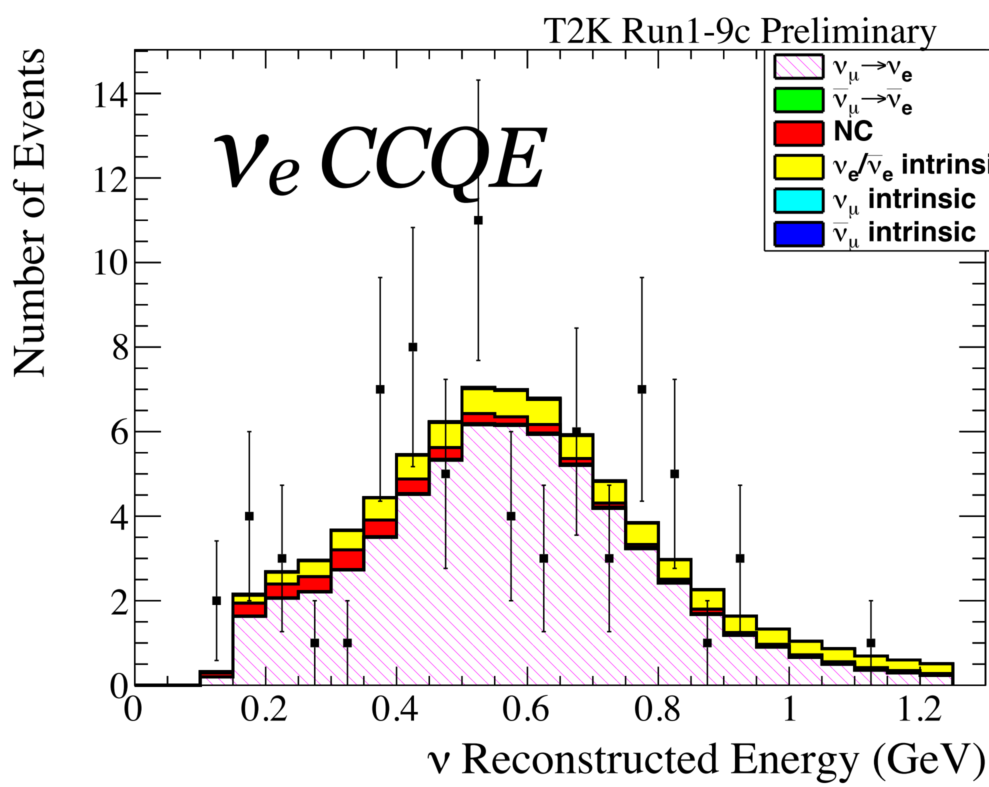


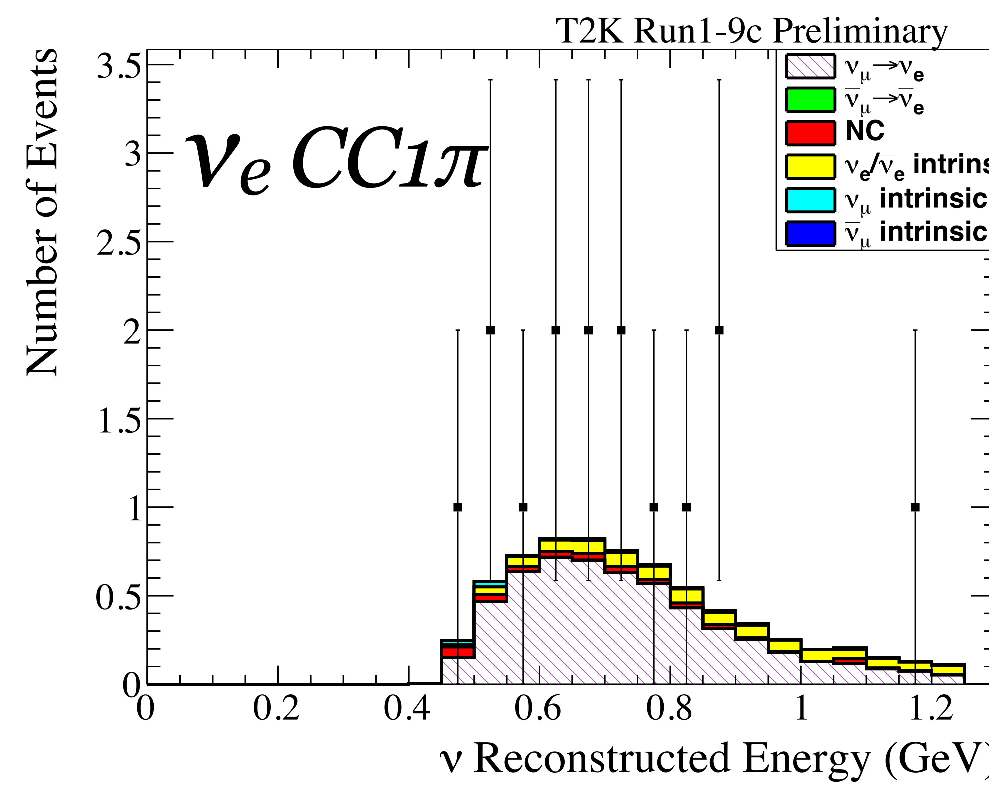
Event rate			
Beam mode	Not Oscillated	Oscillated (maximal mixing)	Observed
neutrino	1211.4	268.2	243
antineutrino	314.3	95.3	102

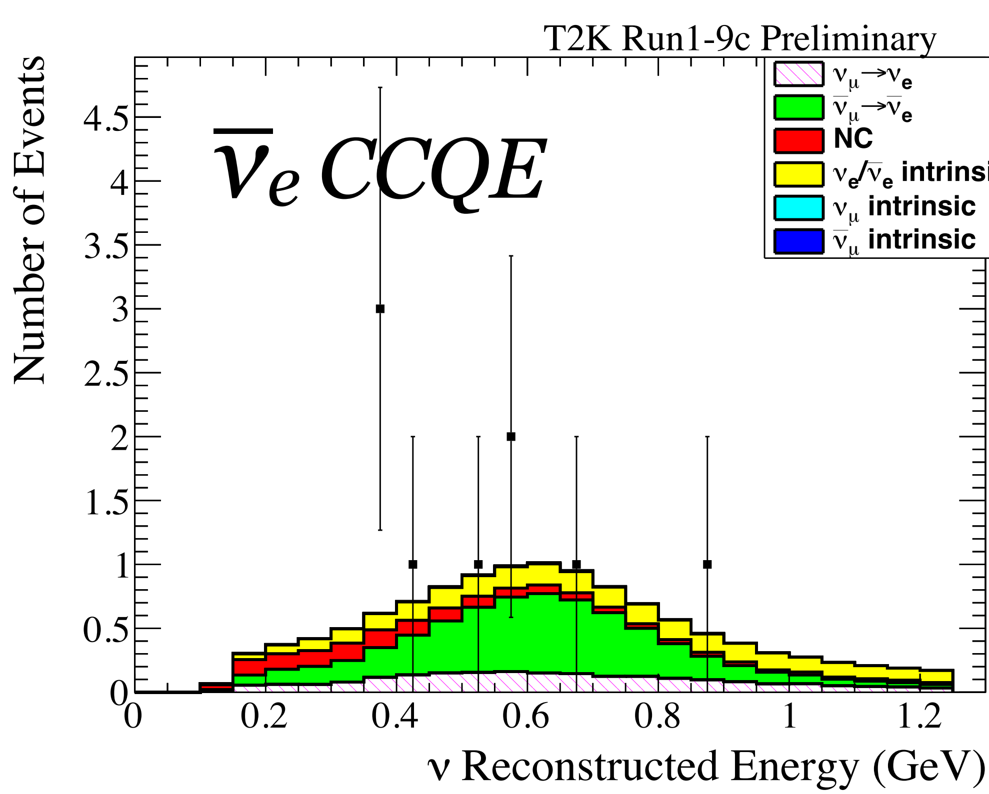
Systematic error		
Beam mode	w/o ND280	ND280 constrained
neutrino	14.5%	4.9%
antineutrino	12.2%	4.3%

- Event rate very close to prediction for maximal mixing hypothesis

Far Detector ν_e / $\bar{\nu}_e$ event samples







True δ_{CP} - Normal Ordering					
	-π/2	0	π	+π/2	Observed
ν_e CCQE	73.8	61.6	62.2	50.1	75
$\bar{\nu}_e$ CCQE	11.8	13.4	13.3	14.9	9
ν_e CC1π	6.9	6.0	5.8	4.9	15

Systematic errors		
Sample	w/o ND280	ND280 constrained
ν_e CCQE	17.1%	8.8%
$\bar{\nu}_e$ CCQE	14.1%	7.0%
ν_e CC1π	21.6%	18.3%

- Observed number of events shows a slightly larger asymmetry compared to the prediction for δ_{CP}=-π/2 and Normal Ordering

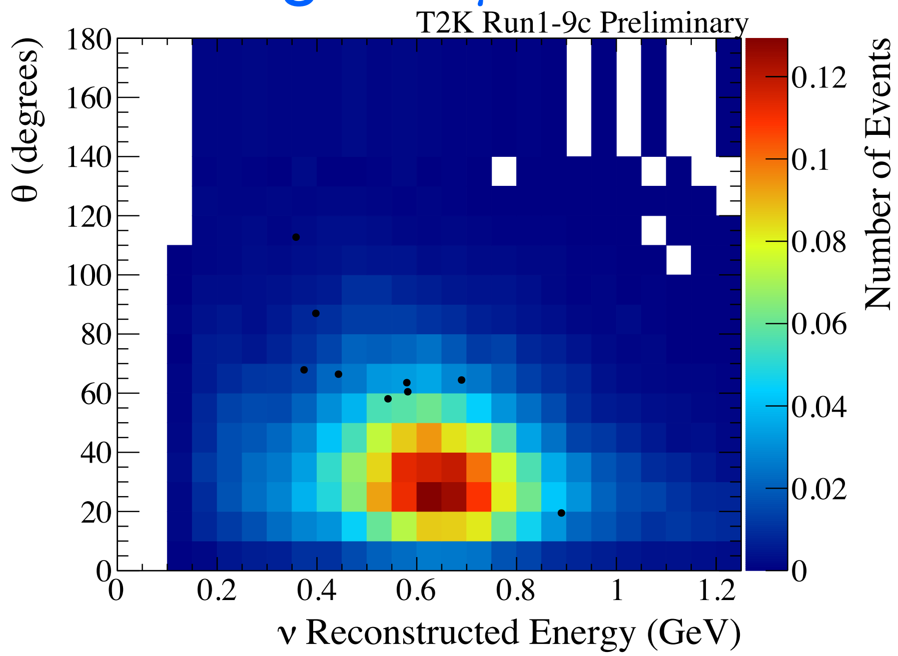
Analysis strategy

- Three different analyses differentiate by statistical approach and analysis templates (all use a binned likelihood)
- Two hybrid-frequentist analyses
  - Integrate over the systematic parameters and the oscillation parameters "not-of-interest"
  - Define 1D confidence intervals with Feldman&Cousins approach
  - They differentiate by the kinematical variables used ν_e and $\overline{\nu}_e$ candidate samples: {E_{reco},θ} and {p,θ}
- Fully bayesian analysis
  - Markov Chain MC is used for sampling of the posterior probability distribution
  - Produce Bayesian credible intervals —> converge to confidence intervals if everything is gaussian
  - Joint fit of Near and Far detector samples —> also cross check the Near Detector fit results (see slide 10)
  - Use {E_{reco},θ} for templates in ν_e and $\overline{\nu}_e$ candidate samples

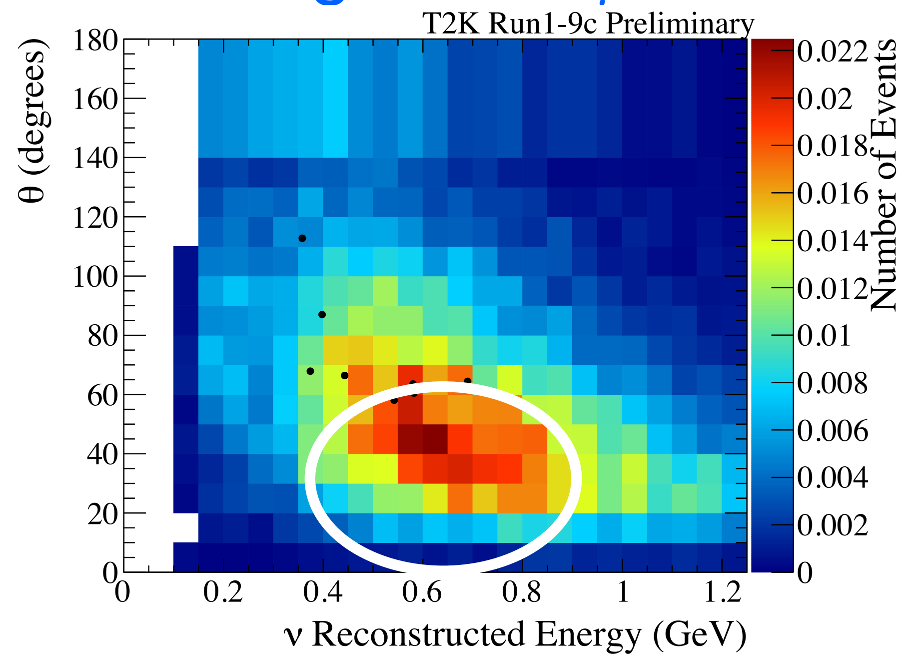
$\nu_e / \bar{\nu}_e$ analysis templates

- Reco. Energy (CCQE hypothesis) directly related to oscillation probability

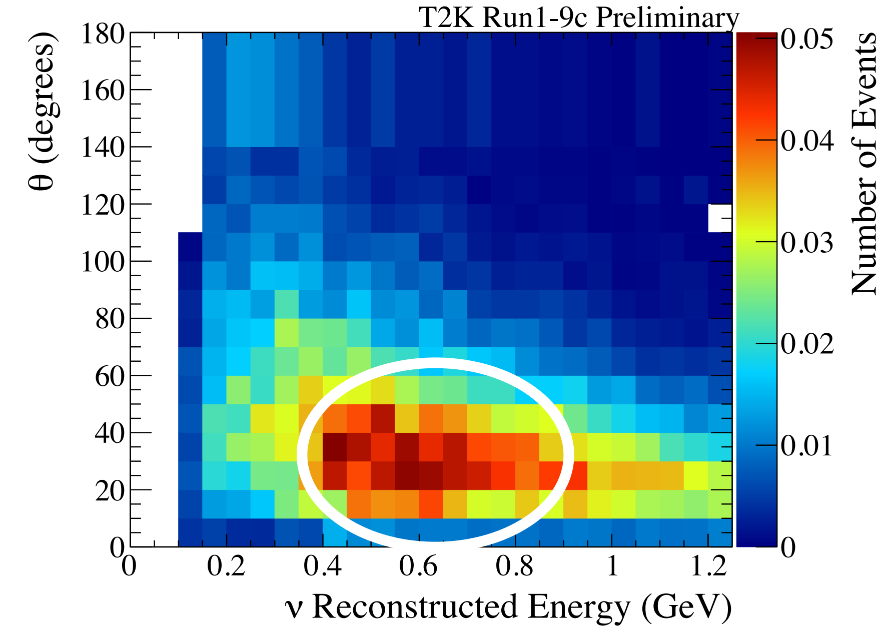
Signal $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$



Background $\nu_\mu \rightarrow \nu_e$

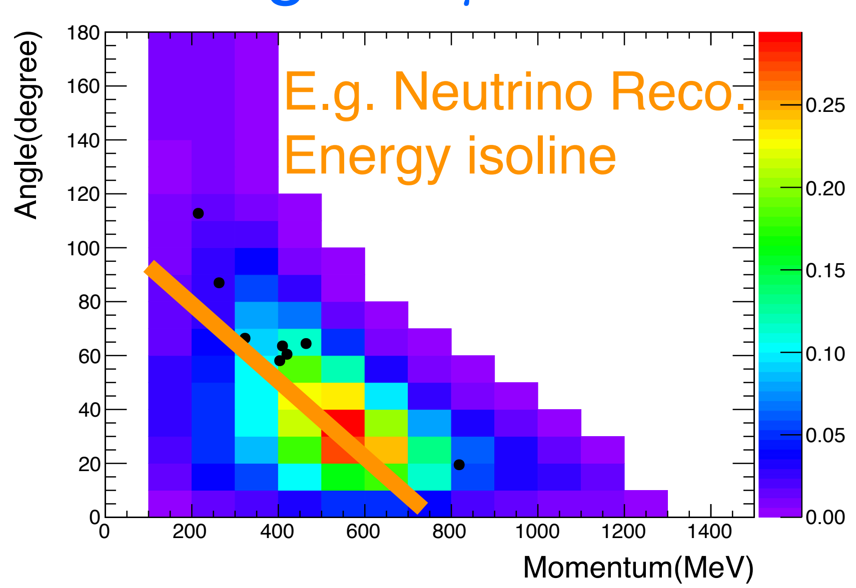


All events



- Momentum is the kinematical variable measured at Super-K

Signal $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$



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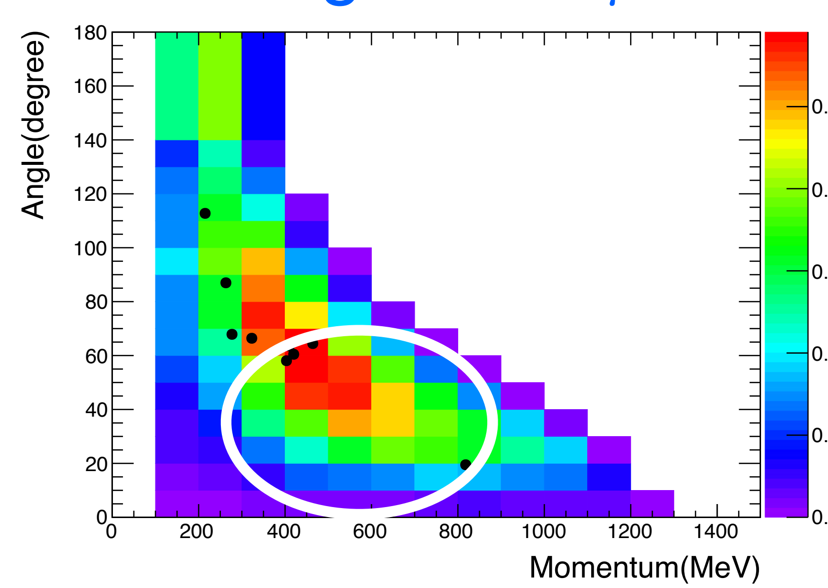

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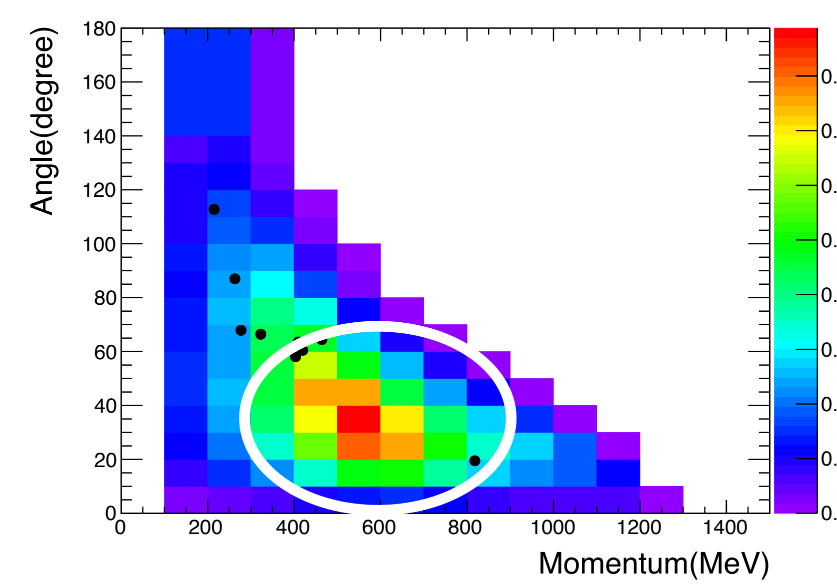


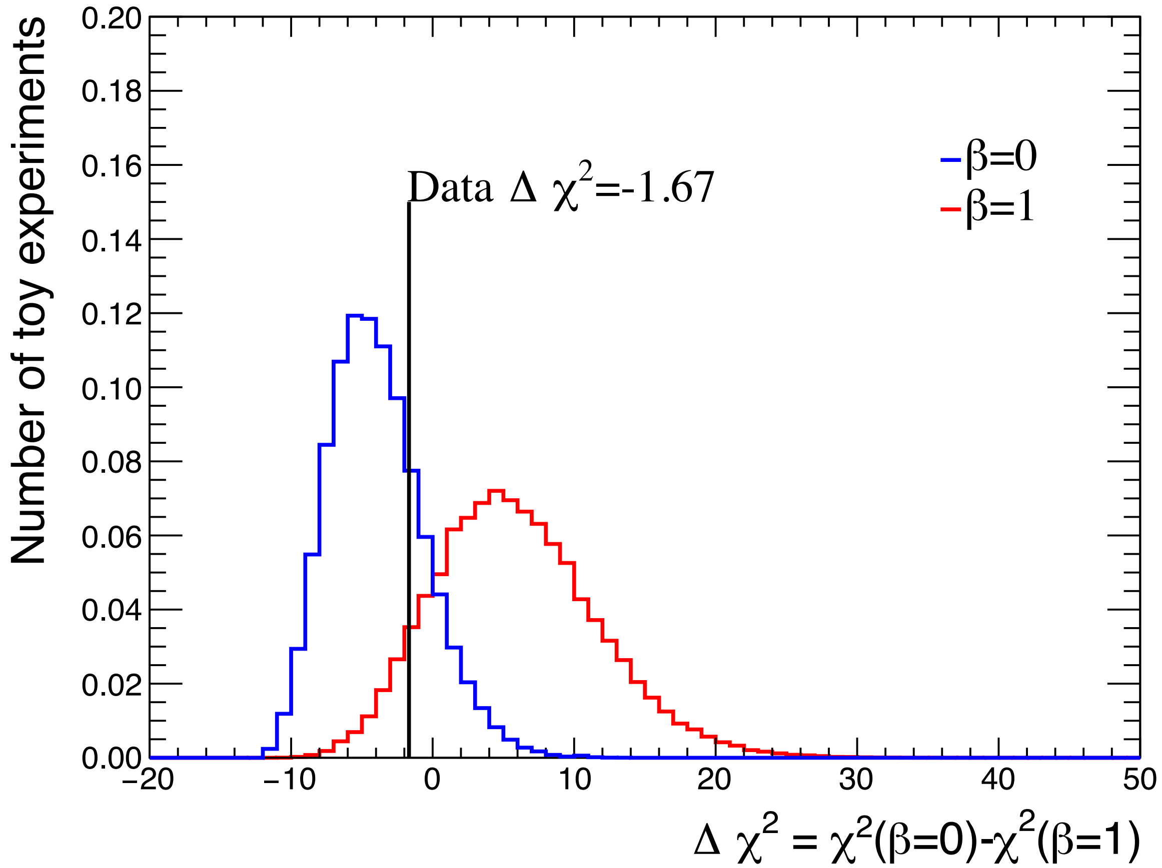
- The lepton angle helps to separate the ν from $\bar{\nu}$ components
- Important to diversify the analysis for a stronger validation of the results

Search for $\bar{\nu}_e$ appearance

- $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance not yet observed in T2K
- Test of electron antineutrino appearance hypothesis:

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = \beta \times P_{\mathrm{PMNS}}(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$$

  - ✦ β = 0: no $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance
  - ✦ β = 1: $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance consistent with PMNS framework



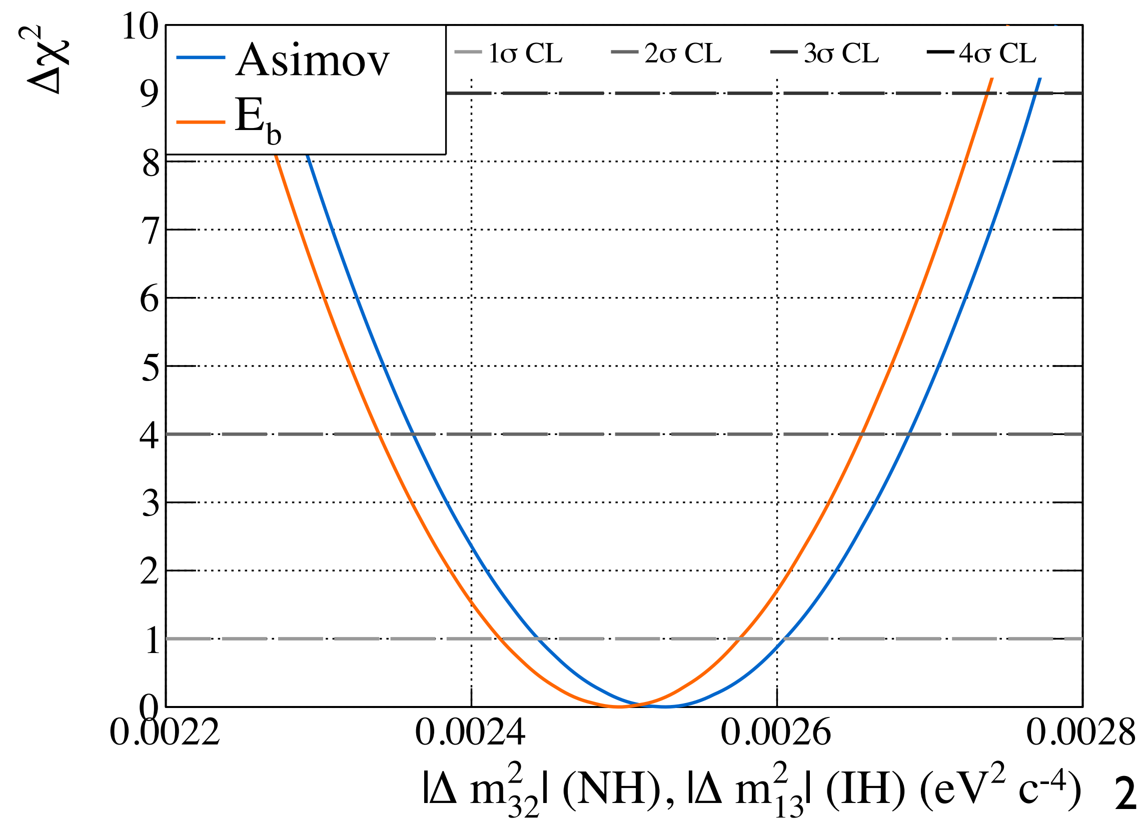
Likelihood ratio: L(β=0) / L(β=1)

P-value	Signal	Background
rate+shape	0.087	0.233

- Use a rate+shape analysis with constraint on Θ_{13} from reactors
- No evidence of $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ with new full data set

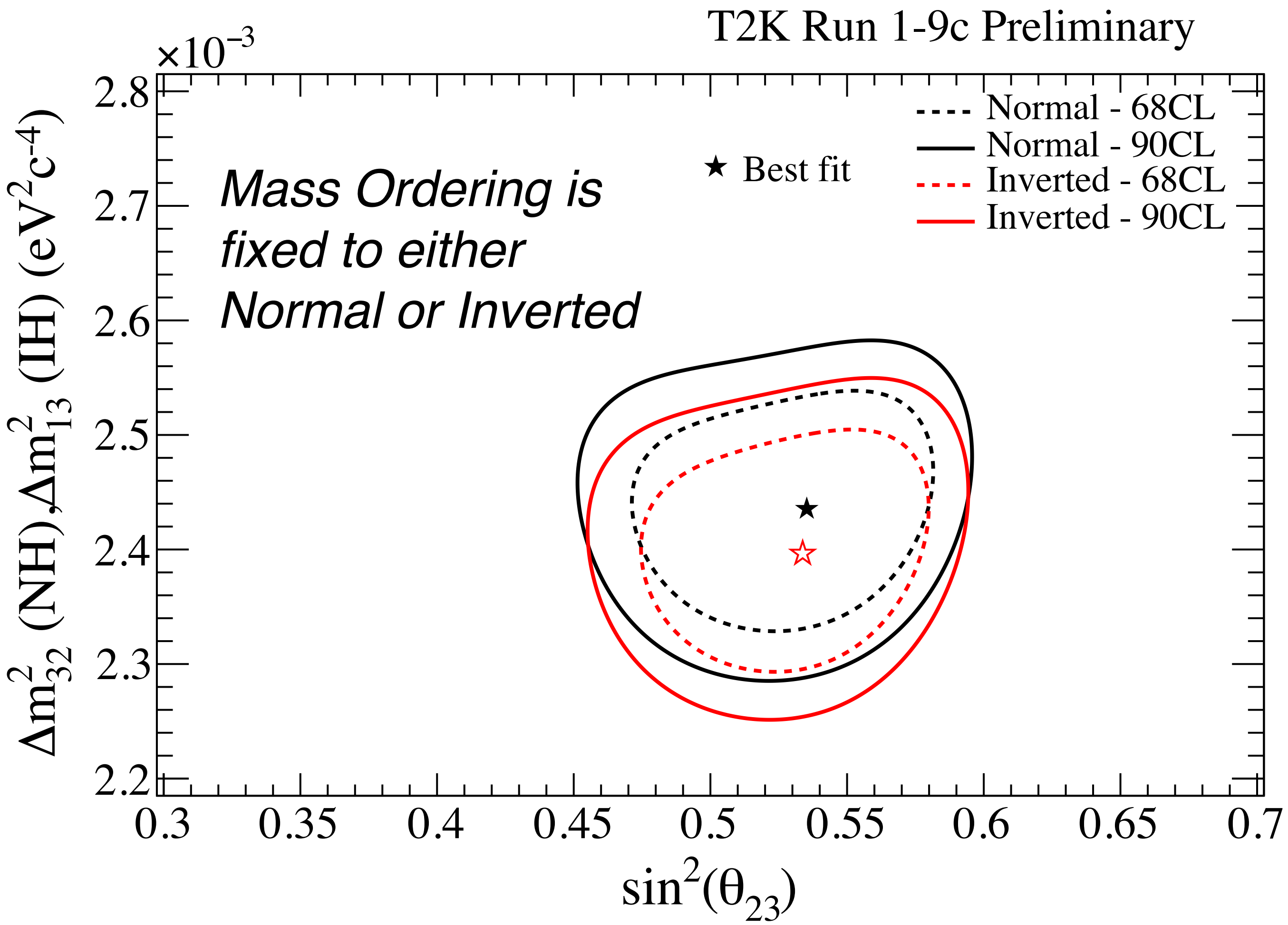
Impact of cross-section mismodeling

- Study the impact of cross-section systematics not yet included in the analysis
- Procedure:
  - ✦ build simulated data with alternative neutrino cross-section models (both at Near and Far Detectors)
  - ✦ Fit simulated data at the Near detector and produce a new covariance matrix
  - ✦ Fit simulated data at the Far detector using the new covariance matrix as prior P.D.F.
- Check the bias to the oscillation parameters with respect to the contour obtained by fitting the nominal MC
  - ✦ Acceptable if 25% of the uncertainty or 50% of the systematic uncertainty
- Biases observed in $\sin^2\theta_{23}$ and Δm^2_{32}
  - ✦ Added new binding energy systematic parameter (2-7% effect)
  - ✦ Smear the likelihood after the fit to include effects on Δm^2_{32}



Confidence intervals $\sin^2\theta_{23}$ and $|\Delta m^2_{32}|$

- Results mostly depend on ν_μ / $\overline{\nu}_\mu$ candidate samples
- ν_e / $\overline{\nu}_e$ candidate samples have sensitivity to the octant



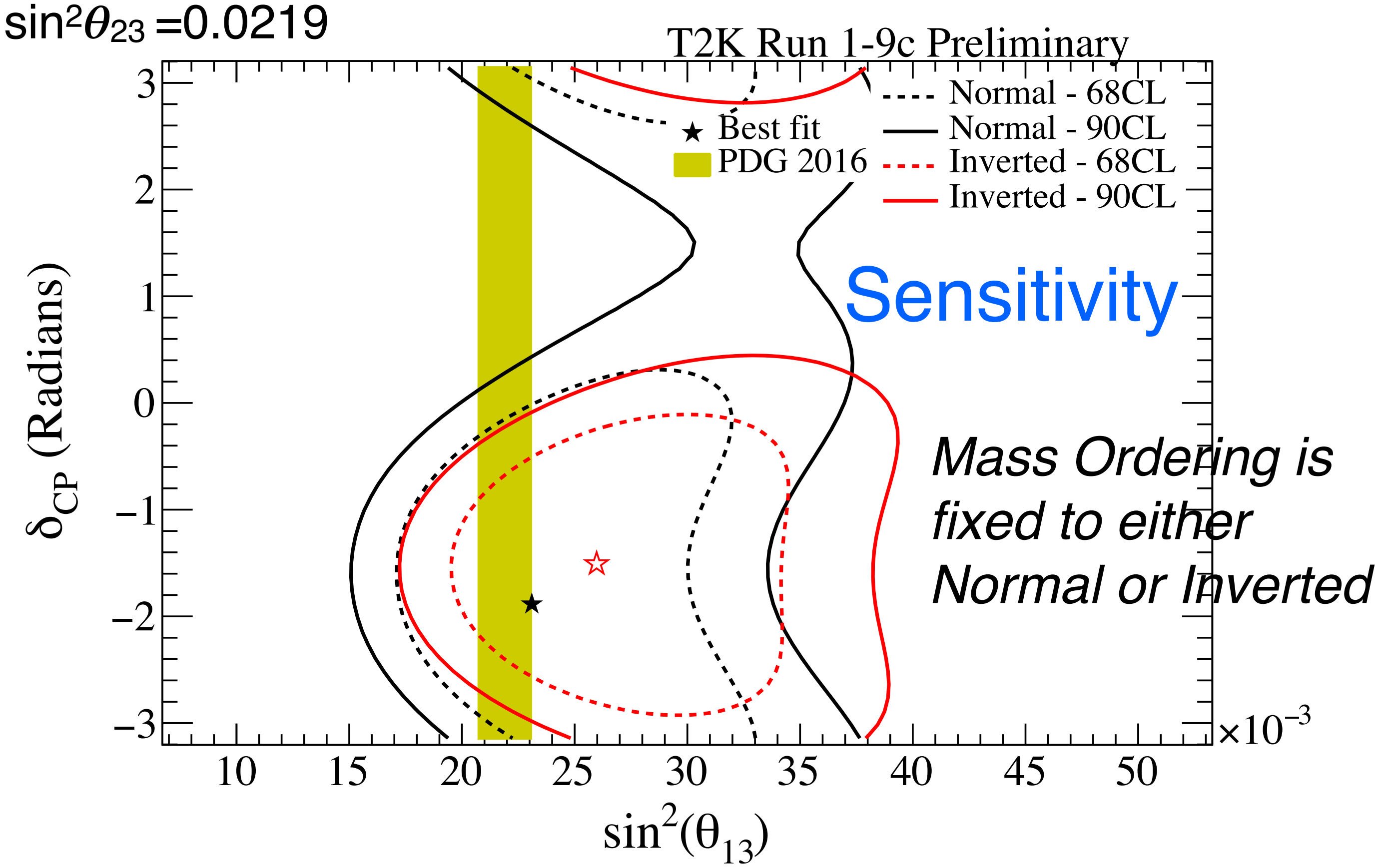
- Contours with constant $\Delta\chi^2$ method (gaussian approximation)

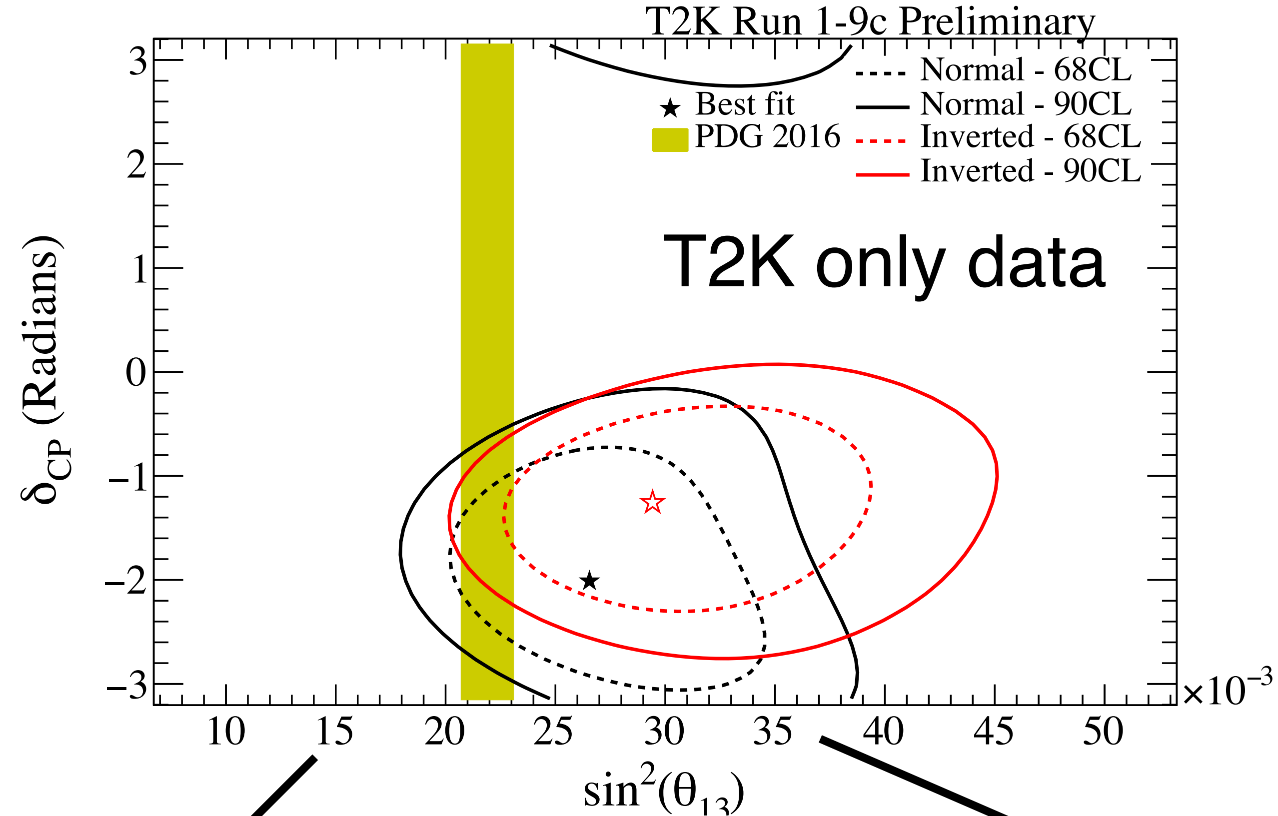
- T2K data consistent with maximal disappearance

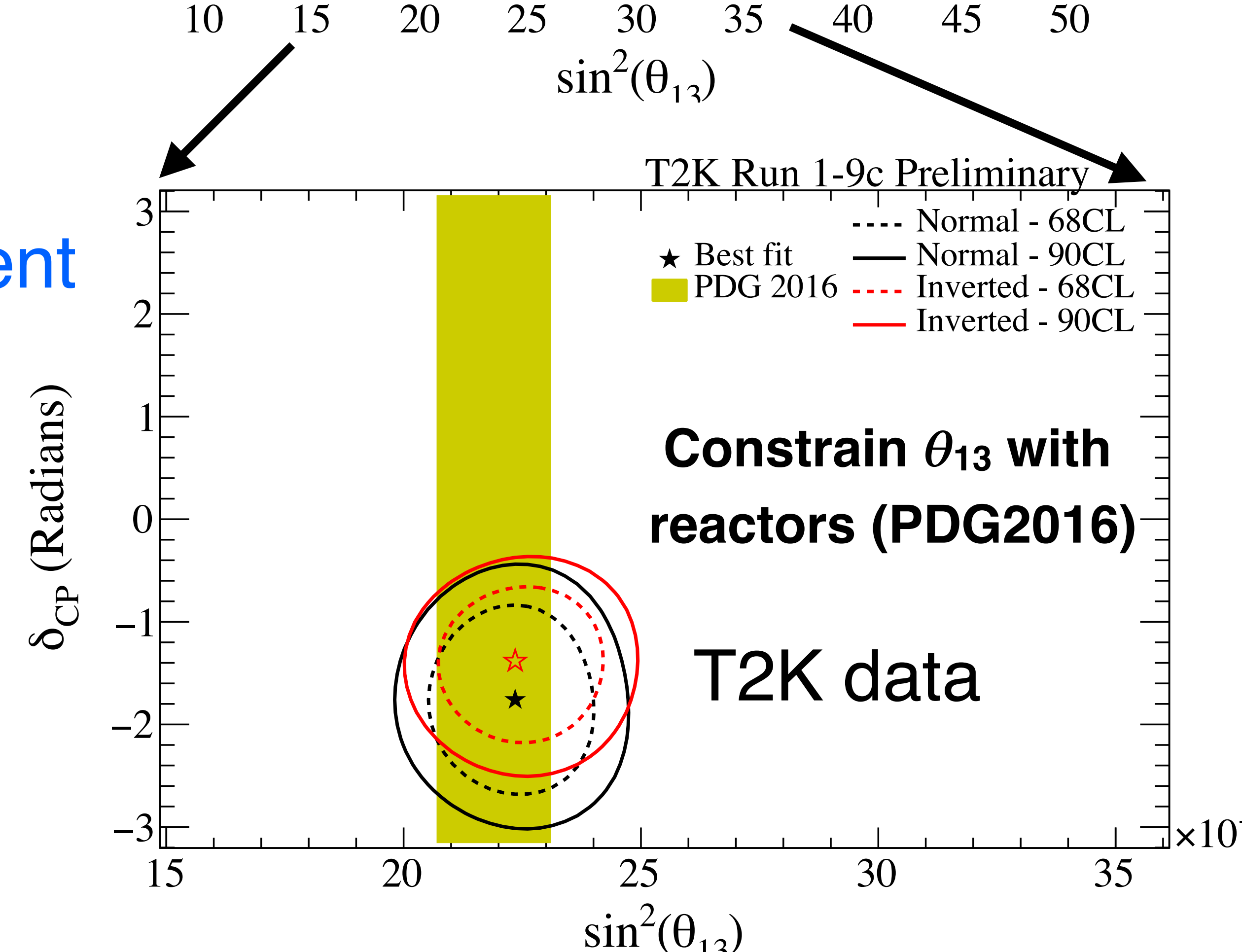
	Normal Ordering		Inverted Ordering	
	Best-fit	1σ Interval	Best-fit	1σ Interval
$\sin^2\theta_{23}$	0.536	0.490 - 0.567	0.536	0.495 - 0.567
$\lvert\Delta m^2_{32}\rvert$ ($\times 10^{-3}$ eV^2)	2.43	2.37 - 2.50	2.41	2.35 - 2.47

Confidence intervals $\sin^2\Theta_{13}$ and δ_{CP}

NH, δ_{CP} = -1.601
$\sin^2\theta_{23}$ =0.528
$\sin^2\theta_{23}$ =0.0219



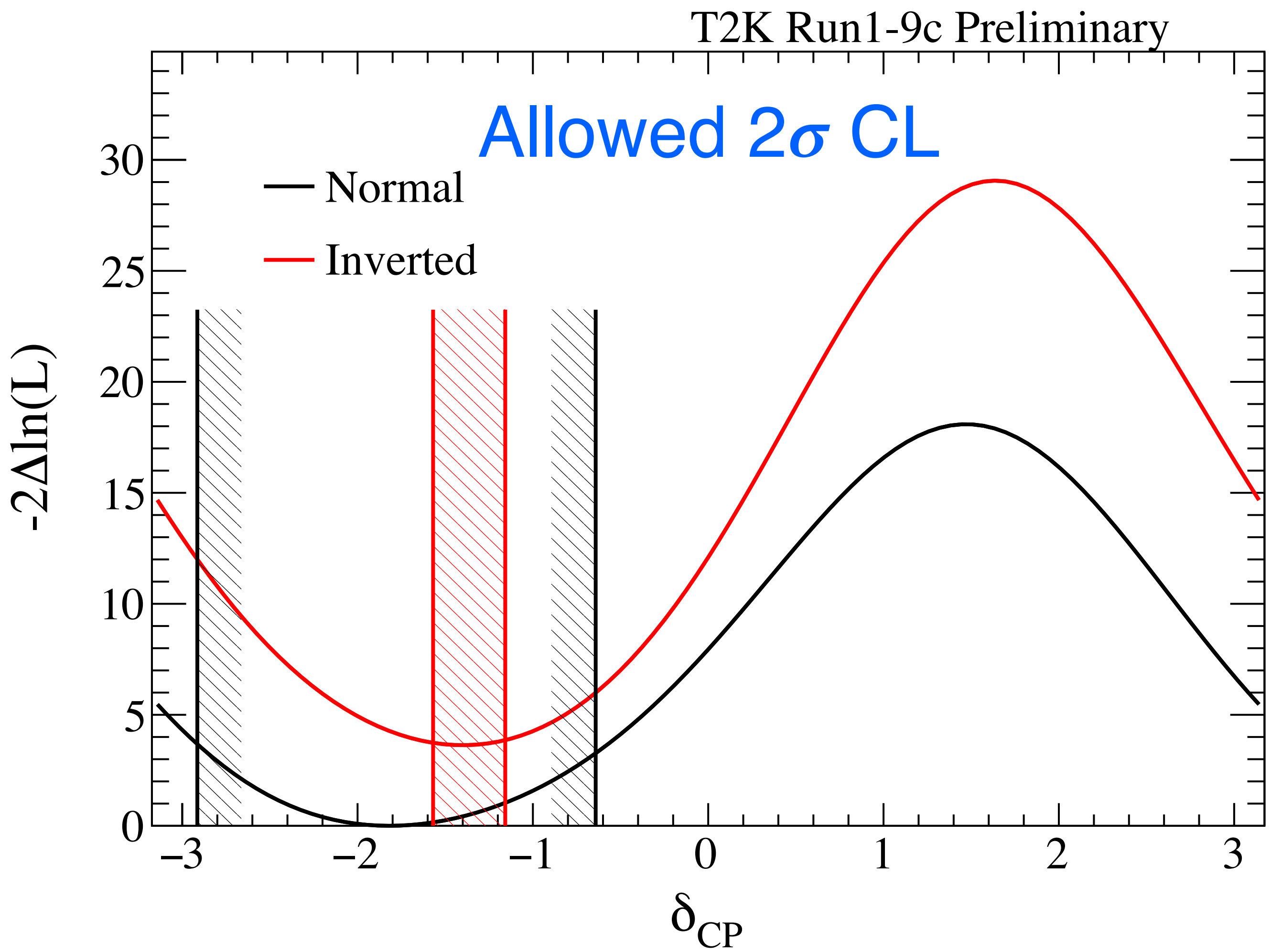




- Agreement with the reactors' measurement
- T2K data disfavor region of δ_{CP} at $+\pi/2$
- Preference for $-\pi/2$ for both normal and inverted ordering
- Confidence intervals are slightly tighter than expected ones

Confidence intervals of δ_{CP}

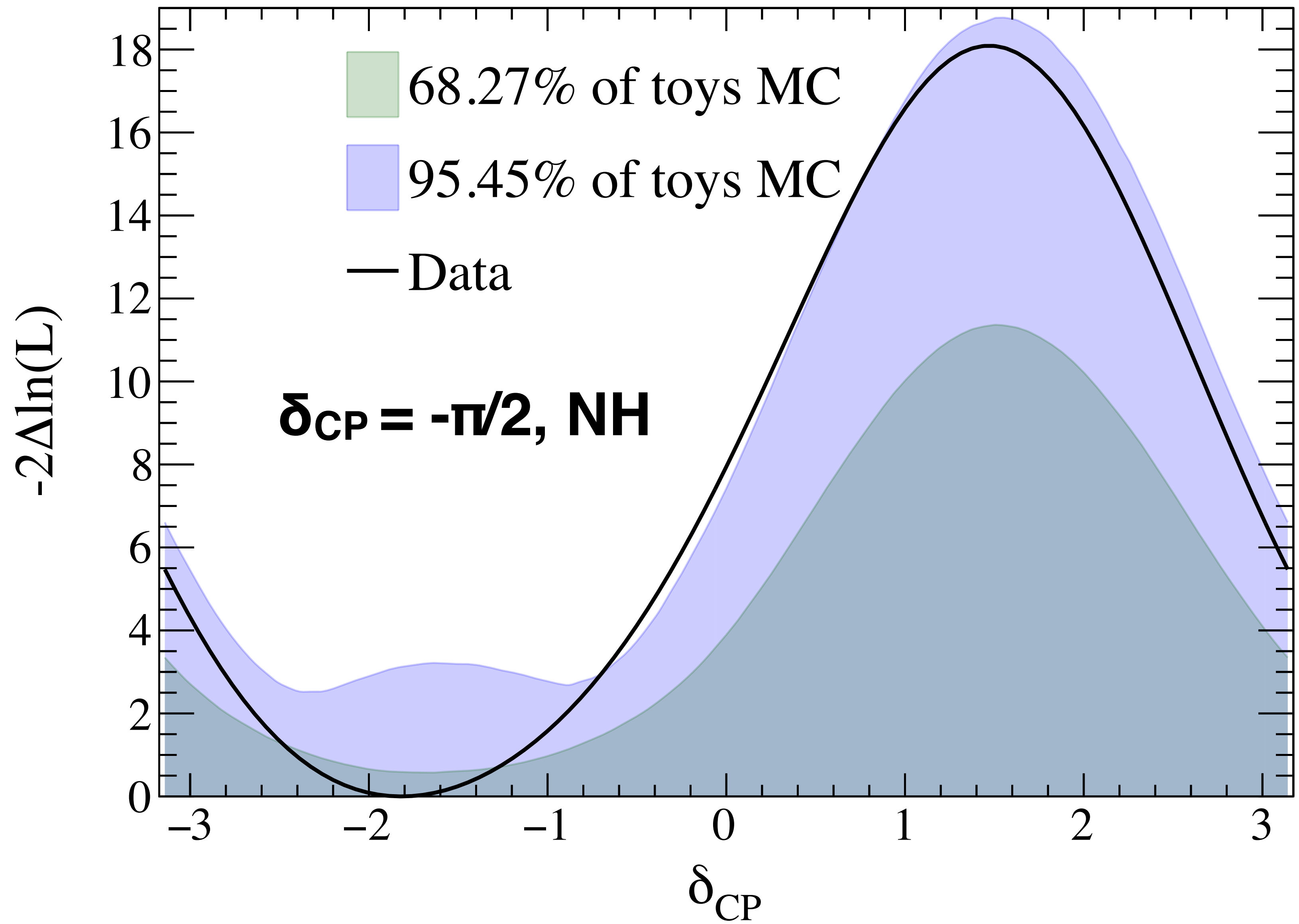
- Confidence intervals were computed with Feldman-Cousins method
- Integrate over θ_{13} using the PDF from reactors' measurement (PDG-2016)



- The best-fit is δ_{CP} = -1.82 radians and Normal Ordering
- Both δ_{CP} = 0 and π are excluded at 2σ CL
- Allowed 2σ CL region: - Normal Ordering: [-2.91,-0.64]
  - Inverted Ordering: [-1.57,-1.16]
- Preference for maximal CP violation and Normal Ordering

Comparison between sensitivity and data results

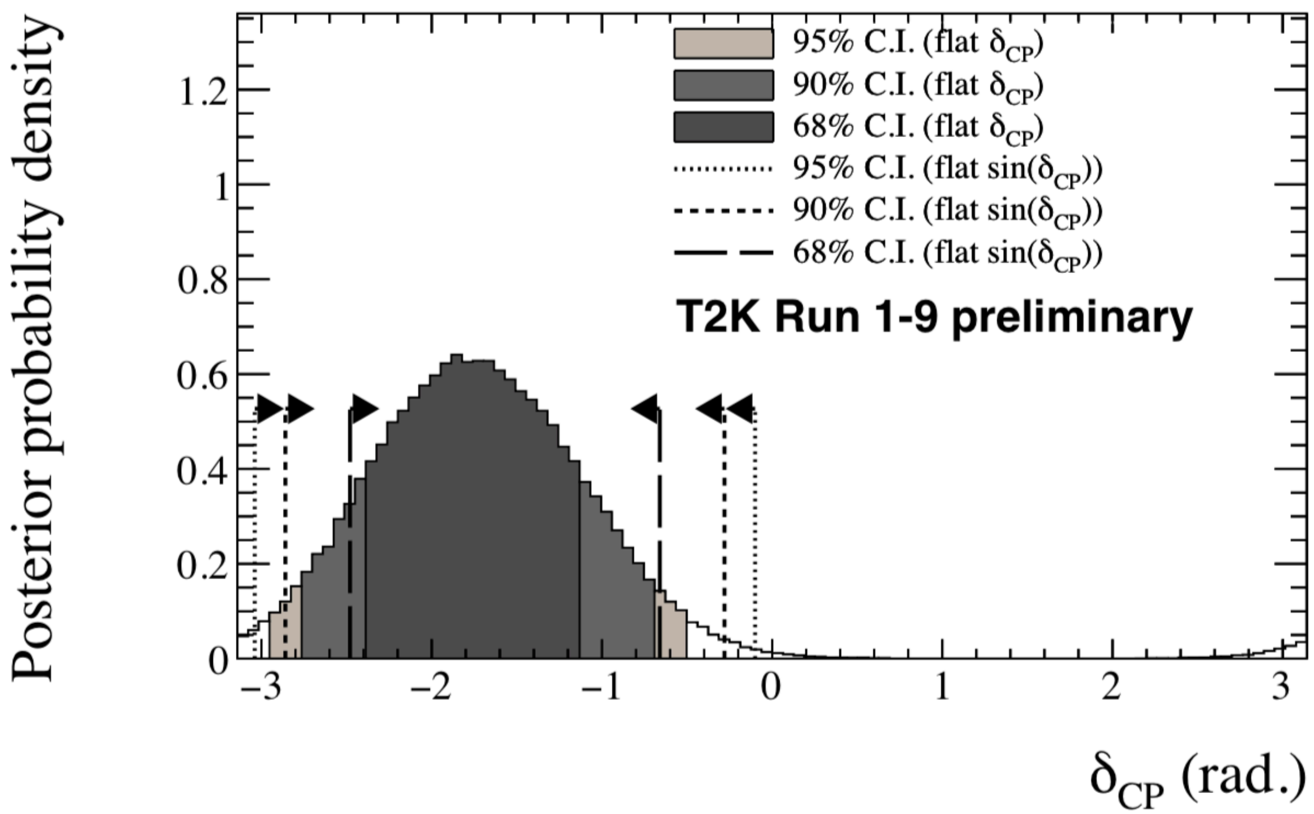
- Toy MC study to compare the experiment sensitivity to the observed data set



- About 5% of toy MC experiments show stronger exclusion than T2K data
- If Nature is $\delta_{CP} = -\pi/2$ and Normal Ordering:
  - ✦ The # of MC experiments that exclude δ_{CP}=0,π (both) at 2σ is 19%

The Bayesian analysis

- Estimate Credible Intervals (CI) with MCMC
- Joint analysis of Near and Far Detectors datasets



- Results with different priors:
  - ✦ Flat prior on δ_{CP}
  - ✦ Flat on $\sin(\delta_{CP})$
- Both $\delta_{CP} = 0, \pi$ outside 95% CI

- Bayes factor shows the preferred octant and Mass Ordering hypothesis
- Same prior probability to each Octant / Mass Ordering option

	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Sum
NH ($\Delta m^2_{32} > 0$)	0.204	0.684	0.888
IH ($\Delta m^2_{32} < 0$)	0.023	0.089	0.112
Sum	0.227	0.773	1

- Preference for upper Octant and Normal Ordering

Summary

- Almost doubled the data since 2017 last data analysis
- No evidence for $\overline{\nu}_e$ appearance yet
- T2K data prefer maximal ν_μ disappearance
- Exclude CP conservation hypothesis with significance of 2σ CL
- T2K data favor $\delta_{CP} \sim -\pi/2$ and NH
- Proposal for extending T2K to reach 3σ sensitivity to CP violation

  ✦ See “T2K Near Detector upgrades and plans for T2HK” talk (Thorsten Lux)

BACKUP

Neutrino oscillations at T2K

$$P(\nu_\mu \to \nu_\mu) \simeq 1 - (\cos^4\theta_{13}\sin^2 2\theta_{23})\sin^2\left(\Delta m^2_{31}\frac{L}{4E}\right)$$

E ~ 0.6 GeV
L ~ 295 km

- Precise measurement of $\sin^2 2\Theta_{23}$
- Test of CPT by comparing measured $\nu_\mu \to \nu_\mu$ with $\bar{\nu}_\mu \to \bar{\nu}_\mu$

Phys. Rev. D64 (2001) 053003

$$P(\nu_\mu \to \nu_e) \simeq \sin^2 2\theta_{13} \times \sin^2\theta_{23} \times \frac{\sin^2[(1-x)\Delta]}{(1-x)^2}$$

Leading term

CP violating

$$-\alpha\sin\delta_{CP} \times \sin^2 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23} \times \sin\Delta\frac{\sin[x\Delta]}{x}\frac{\sin[(1-x)\Delta]}{(1-x)}$$

"+" for antineutrino

CP conserving

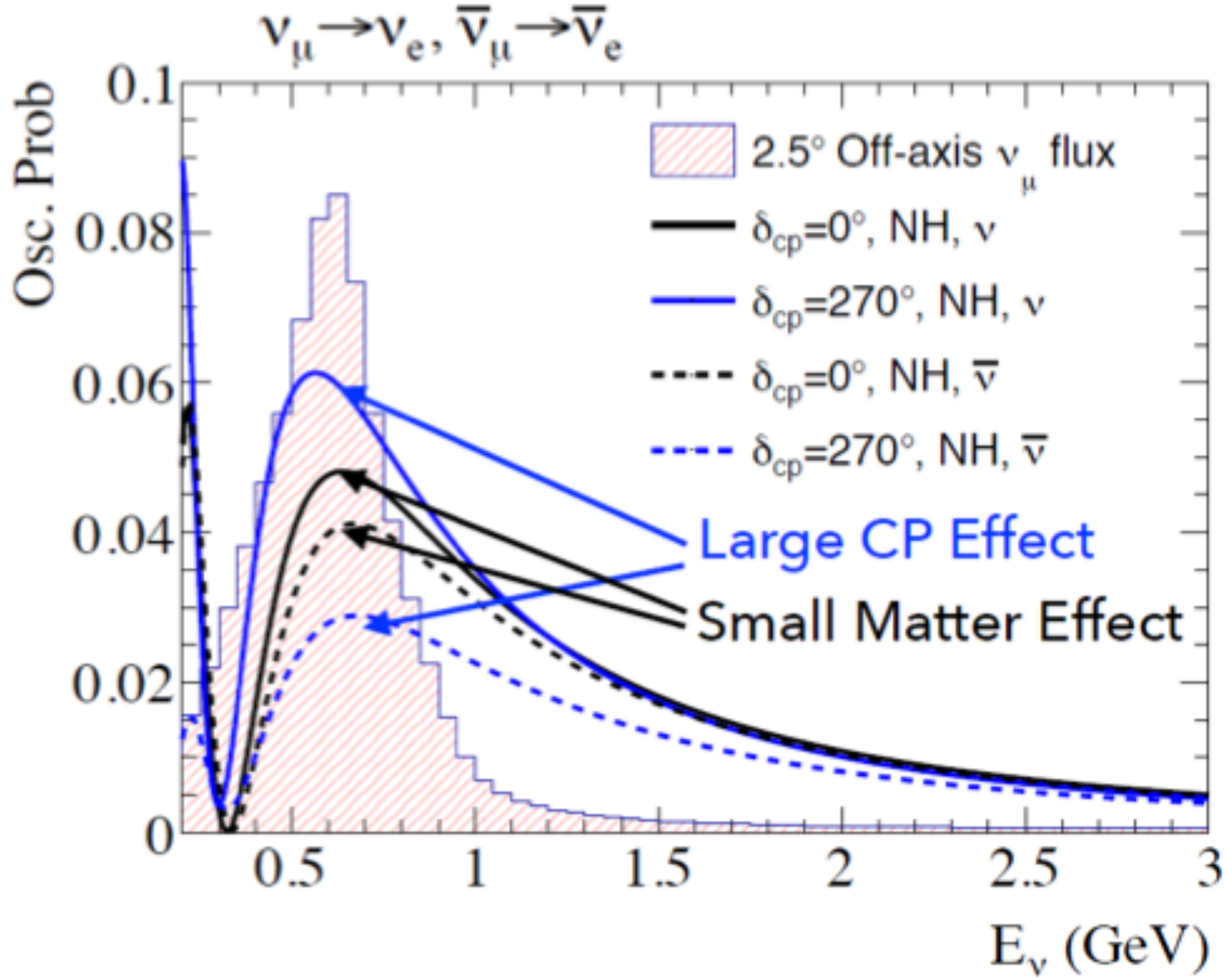
$$\alpha\cos\delta_{CP} \times \sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23} \times \cos\Delta\frac{\sin[x\Delta]}{x}\frac{\sin[(1-x)\Delta]}{(1-x)}$$

$$+ O(\alpha^2)$$

$$x = \frac{2\sqrt{(2)}G_F N_e E}{\Delta m^2_{31}} \quad \alpha = \left|\frac{\Delta m^2_{21}}{\Delta m^2_{31}}\right| \sim \frac{1}{30} \quad \Delta = \frac{\Delta m^2_{31}L}{4E}$$

- δ_{CP} and Mass Ordering have similar effects
- Effect of δ_{CP} on $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ is about ±20-30%
- Effect of Mass Ordering is about ±10%

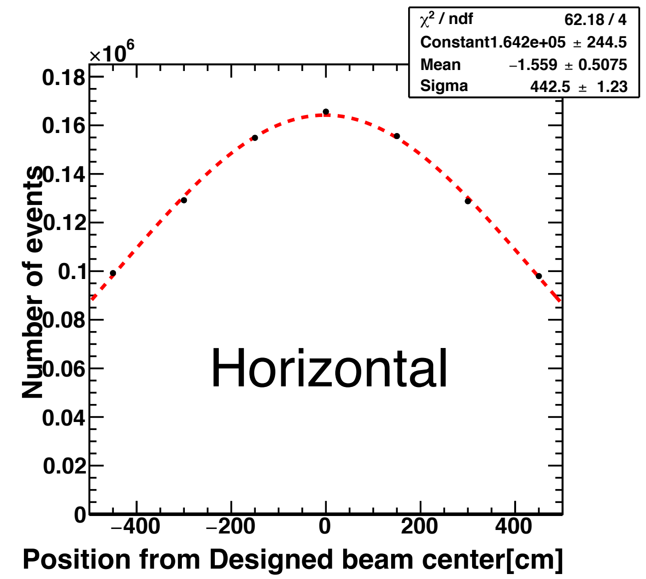
Effect of CP violation at T2K

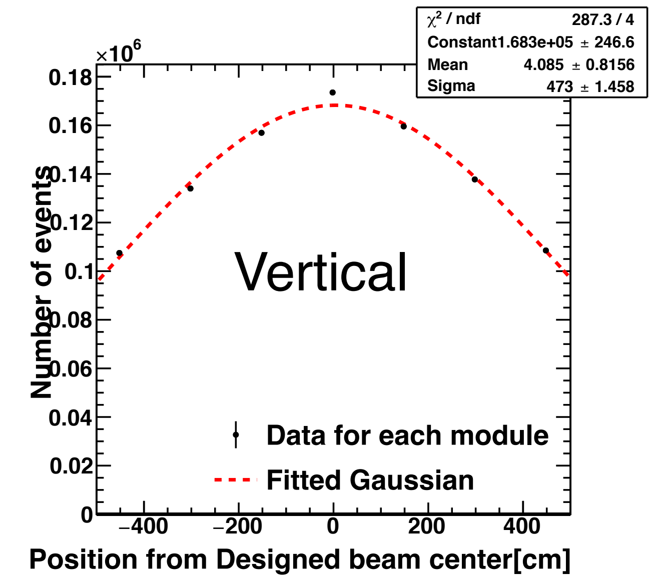


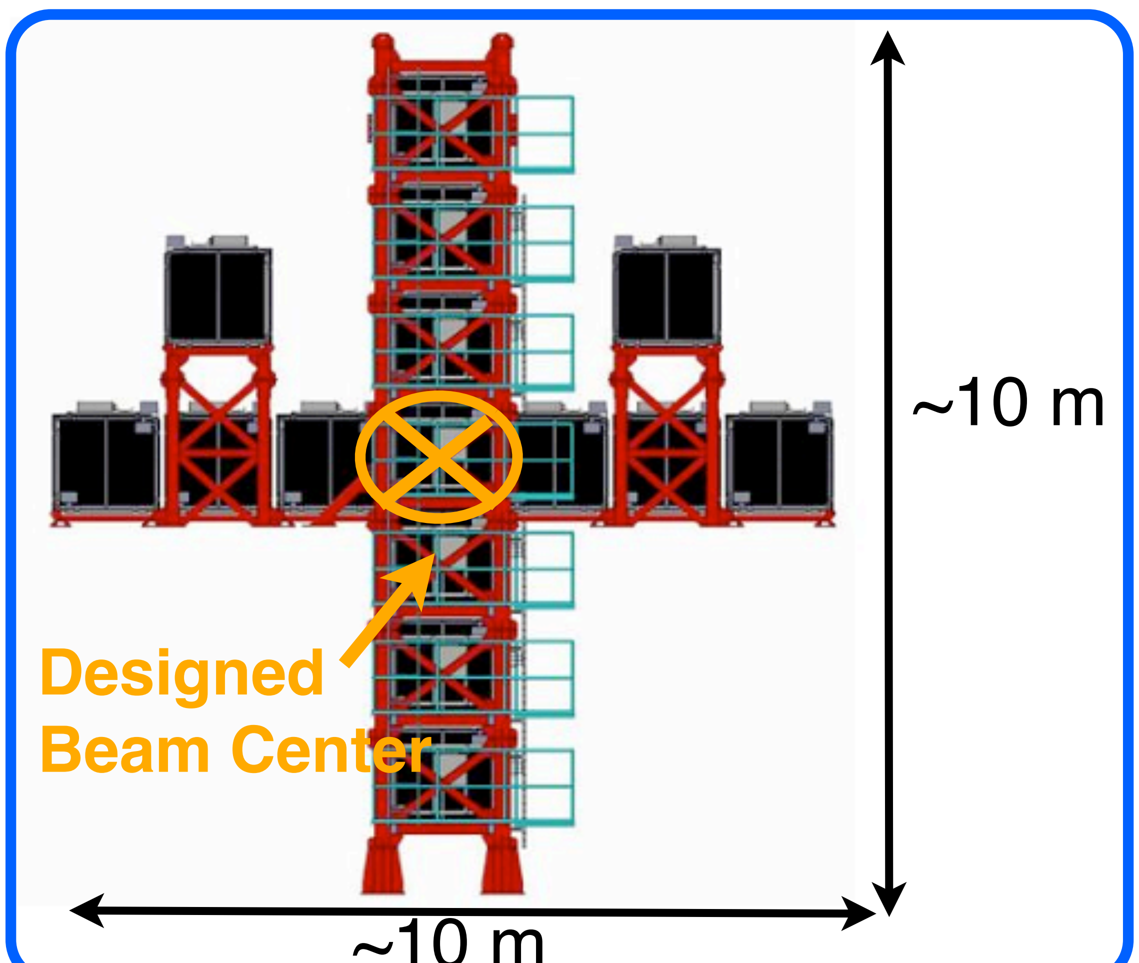
- Asymmetric effect on P($\nu_\mu \to \nu_e$) and P($\bar{\nu}_\mu \to \bar{\nu}_e$):
  - δ_{CP} = -π/2 → maximizes P($\nu_\mu \to \nu_e$) and minimizes P($\bar{\nu}_\mu \to \bar{\nu}_e$)
  - δ_{CP} = +π/2 → minimizes P($\nu_\mu \to \nu_e$) and maximizes P($\bar{\nu}_\mu \to \bar{\nu}_e$)
- δ_{CP} and Mass Ordering have similar effects
- Effect of δ_{CP} on $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ is about ±20-30%
- Effect of Mass Ordering is about ±10%

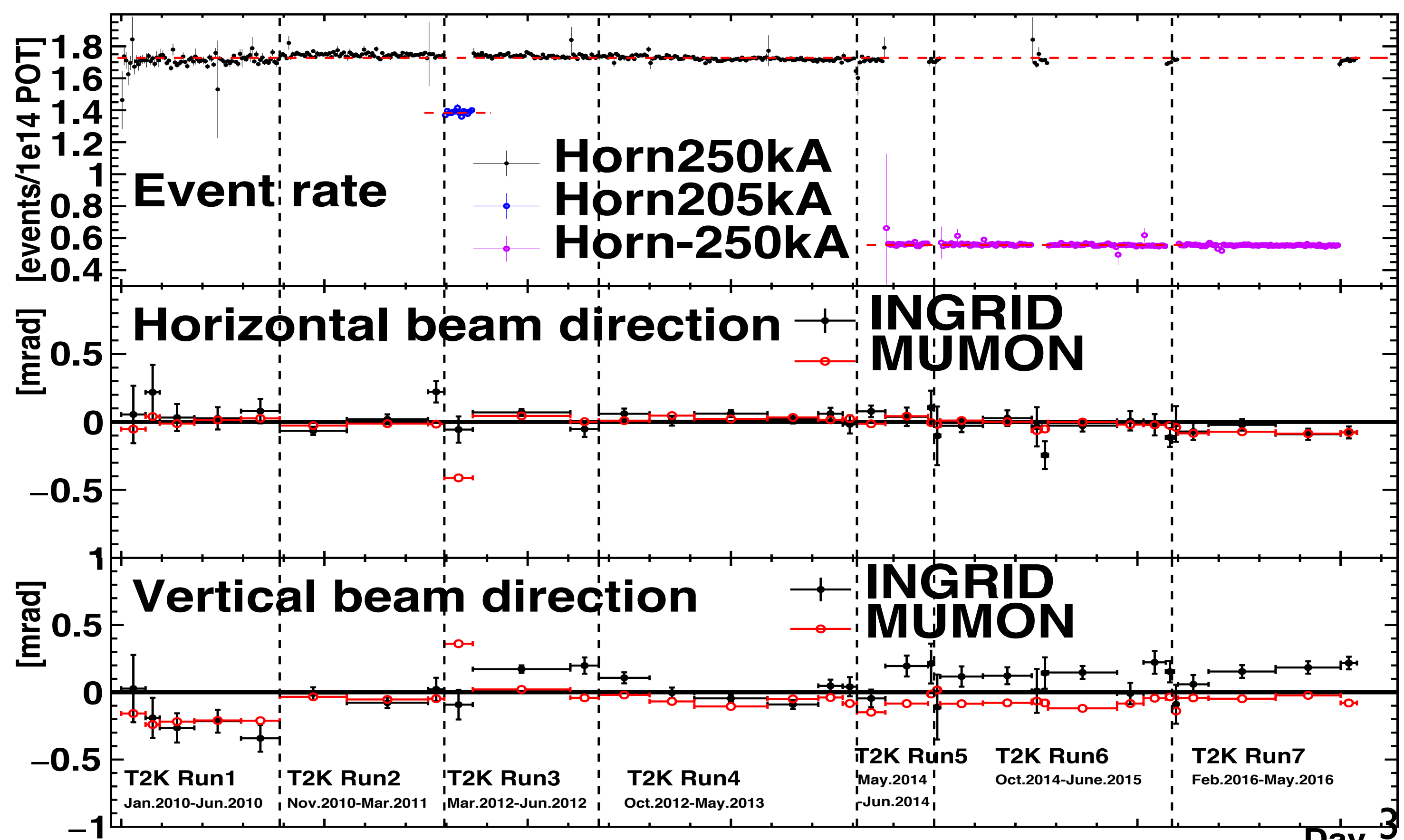
The On-Axis detector: INGRID

- 16 modules iron/scintillator tracking detectors (0-0.9° degrees off-axis)
- Measure neutrino beam profile (reconstruct muons tracks from ν_μ interactions)
- Beam direction stable within 1 mrad
  ~2% shift to peak in off-axis ν energy
- Protons On Target (POT) normalized event rate stable better than 1%







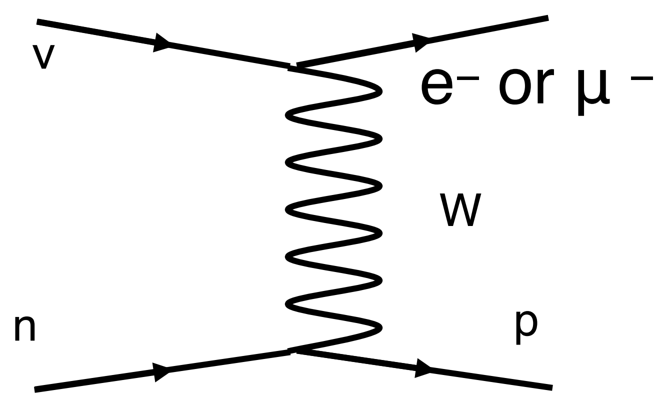


(Anti)Neutrino interactions at T2K

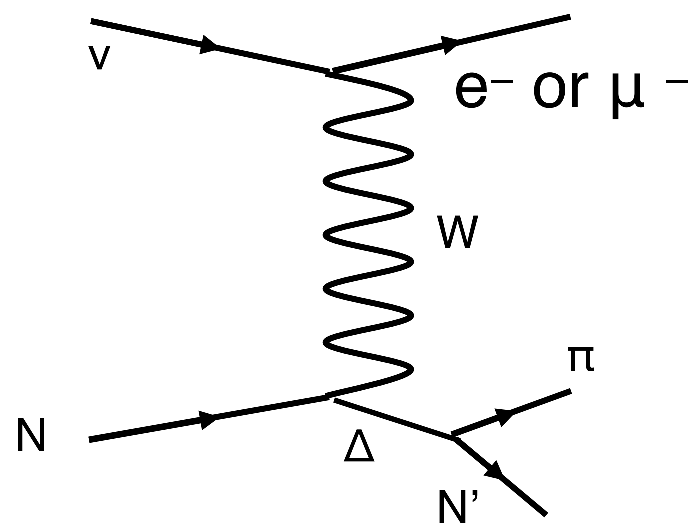
- The dominant neutrino interaction mode is Charge-Current Quasi-Elastic

Neutrino energy from lepton momentum and angle in CCQE hypothesis:
- 2 body kinematics
- assume target nucleon at rest

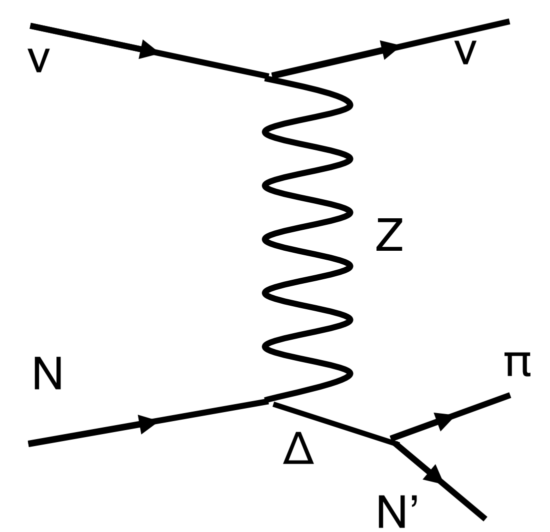
Charged-Current Quasi-Elastic (CCQE)



Charged-Current π



Neutral-Current π

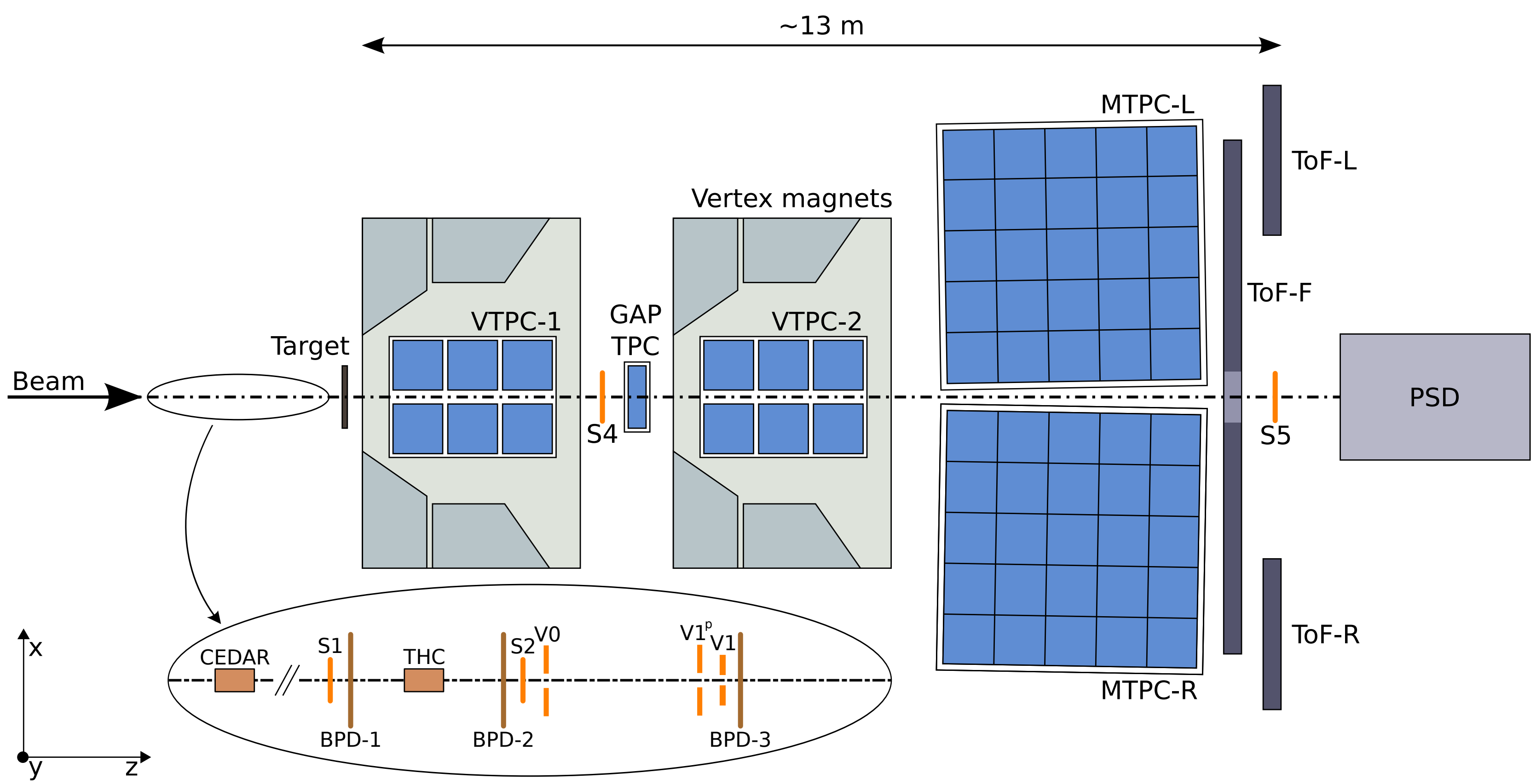


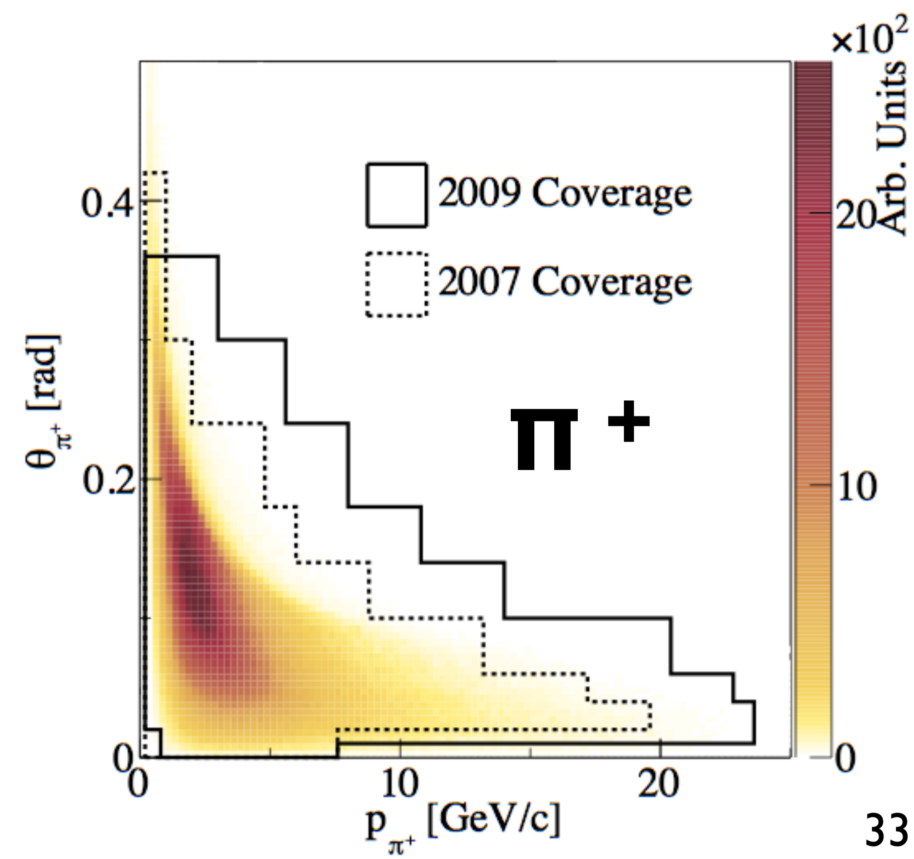
Other cross-section components

- CCQE-like multinucleon interaction (2 nucleons in the final state)
- Charged-current single-pion production (CCπ)
- Neutral-current single-pion production (NCπ)

NA61/SHINE experiment at CERN SPS

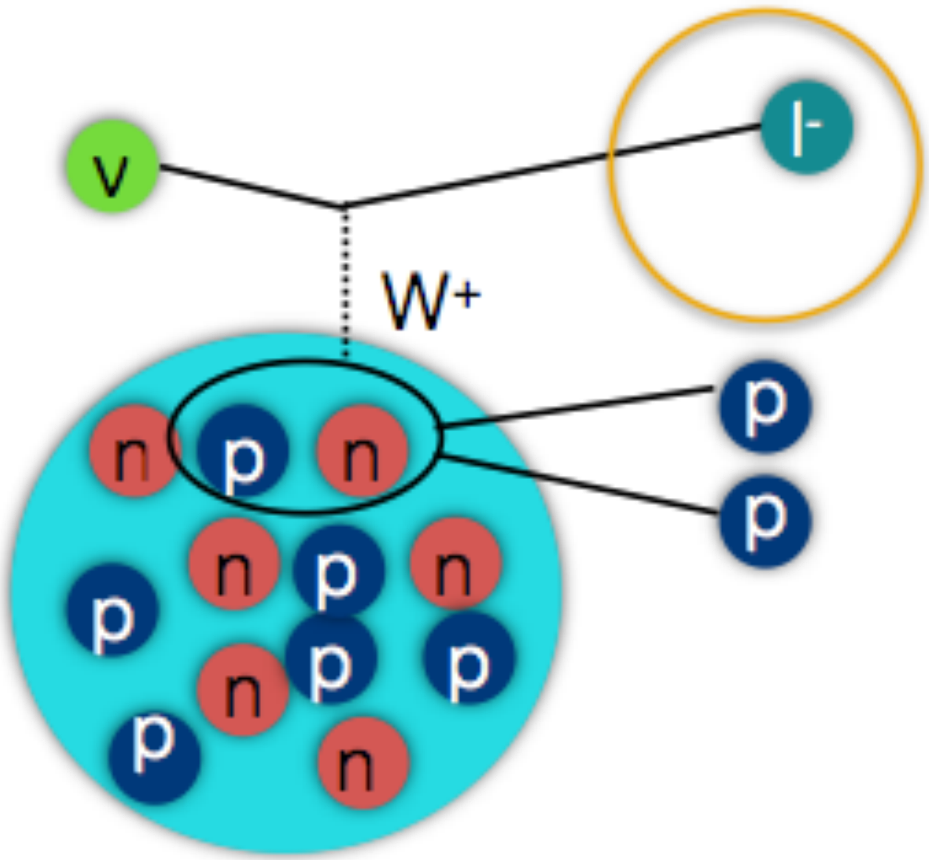
- Large-acceptance detector with very good capabilities of charge and mass measurements
- Located in the CERN North Area
- Cover almost the full {p,Θ} T2K phase space
- Measure pion, proton and kaon production with a 31 GeV/c proton beam on a carbon target
    - Thin 2cm target (4%λ_I) (*Eur. Phys. J. C 76, 84 (2016)*)
    - T2K replica target (published $\pi^\pm$ yields: *Eur. Phys. J. C 76, 617 (2016)*)

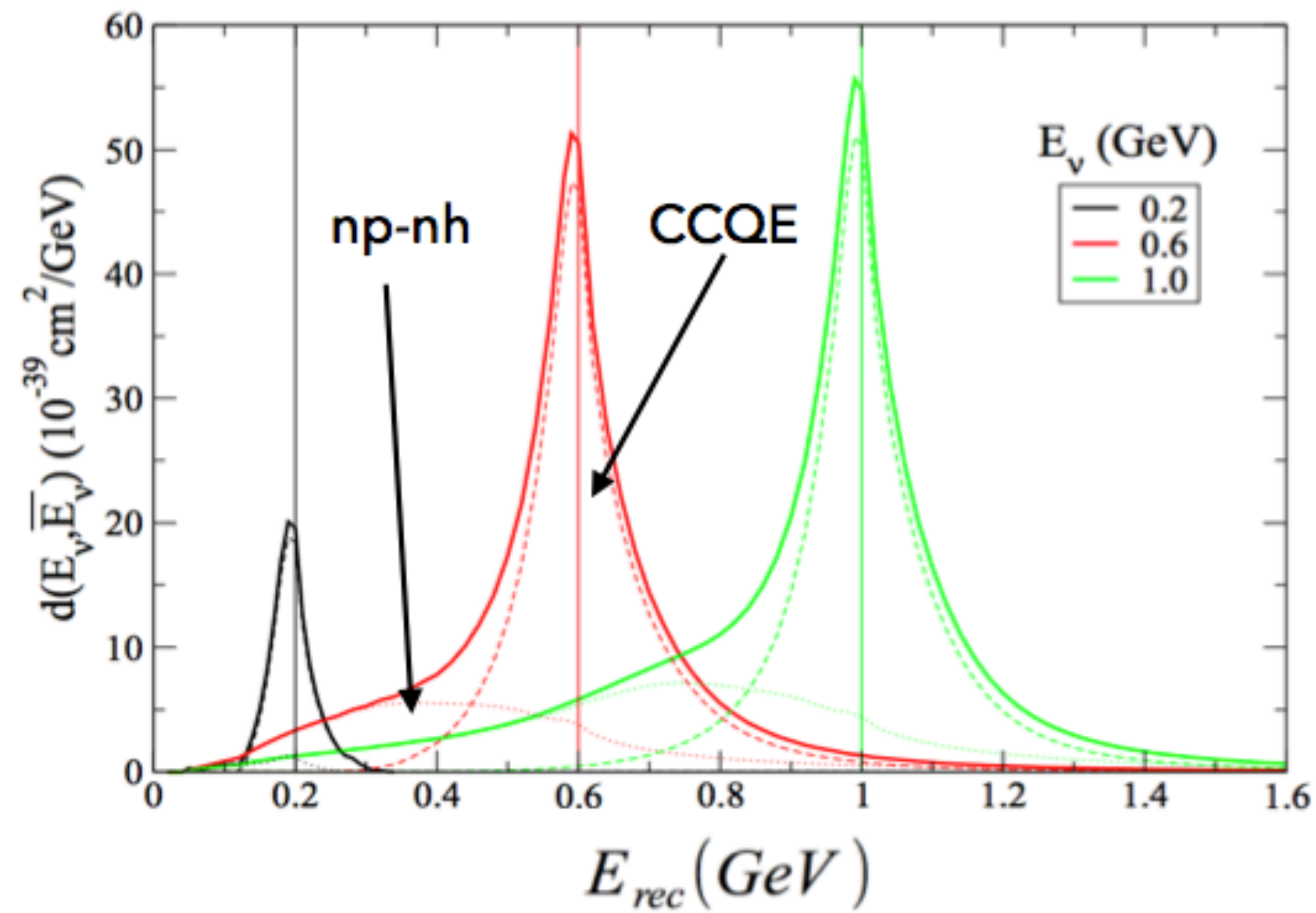




Non-CCQE interactions

- Often only the lepton in the final state is visible
- Neutrino interaction observed as CCQE-like but it's non-CCQE
- More nucleons interact with the neutrino: multi-nucleon (np-nh)





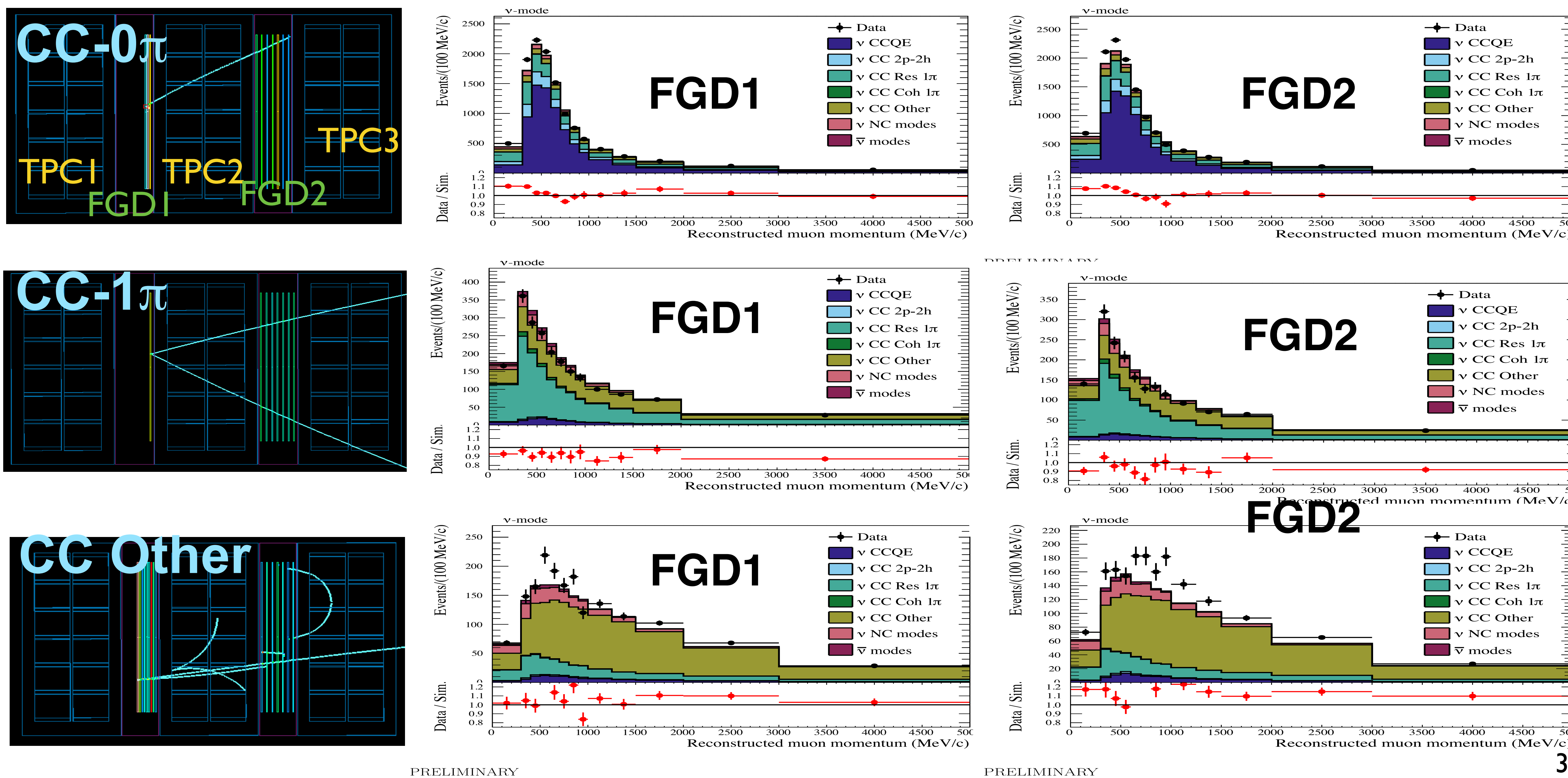
Nieves et al. PRC 83 045501 (2011)
Martini et al. Phys.Rev. D87 (2013) 013009

- The final state kinematic is different → bias in neutrino energy reconstruction
- Analogous bias can be observed if the outgoing pion is absorbed
- Important for future detectors to improve sensitivity to these interactions

Near Detector data analysis: ν beam - ν candidates

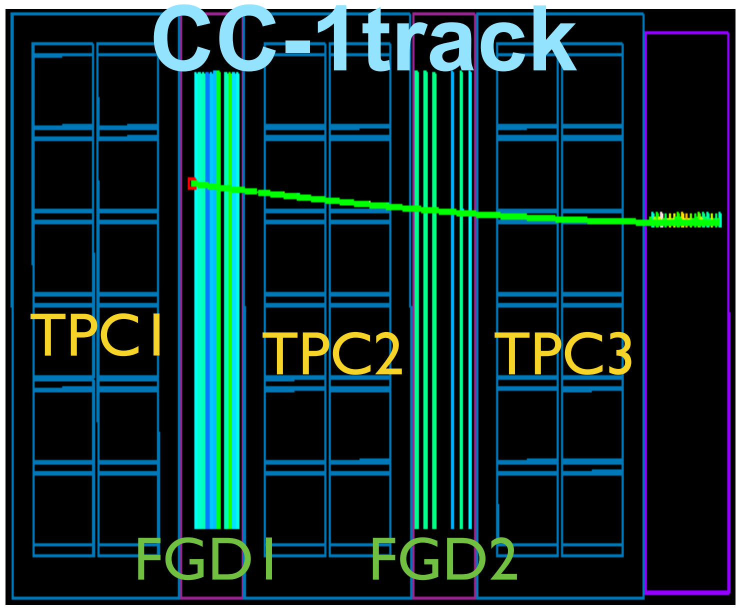
- Sub-divide samples by neutrino interaction candidate:
  - ✦ CC-0 pions, CC-1 pion, CC-Other for Neutrino beam
  - ✦ CC-1 track, CC N-tracks for AntiNeutrino beam
- Parametrize the analysis templates in momentum and lepton angle

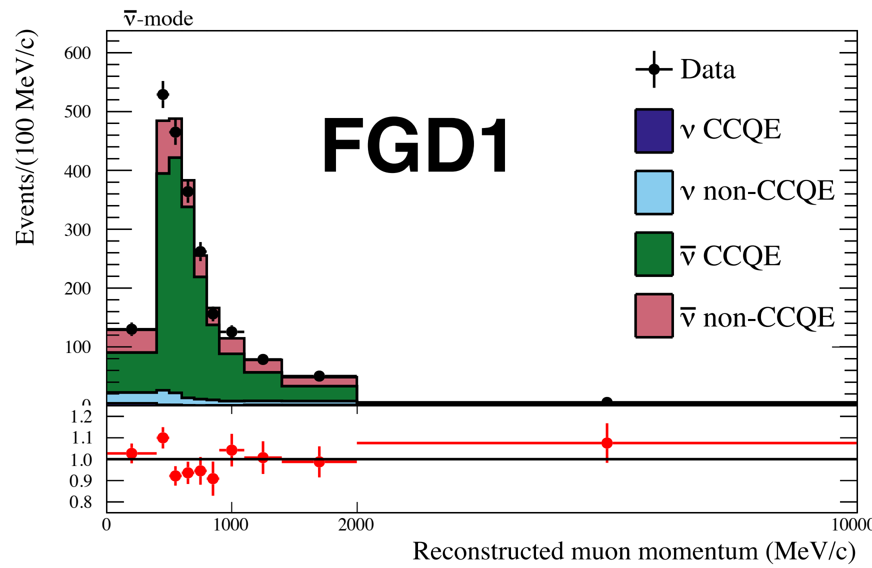
Distributions before the Near Detector fit



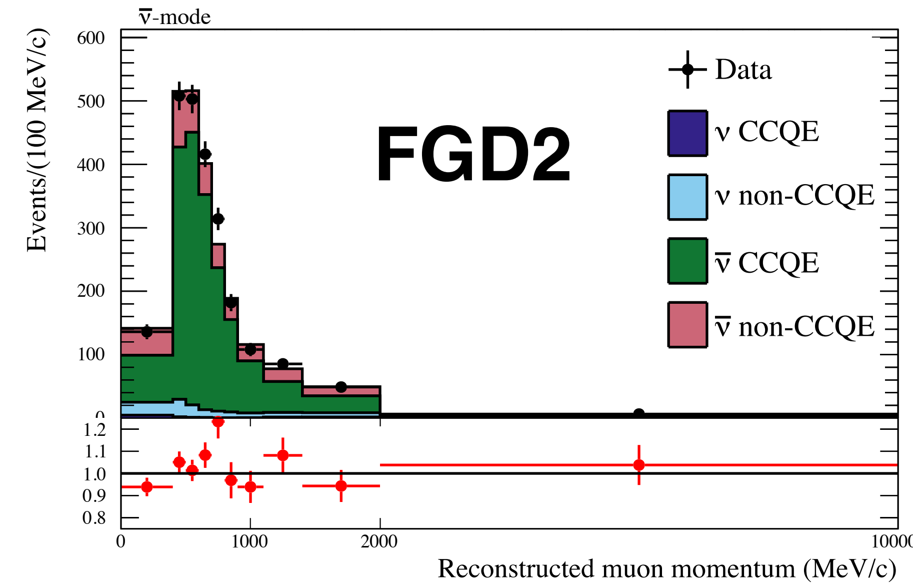
Near Detector data analysis: $\bar{\nu}$ beam - $\bar{\nu}$ candidates

Distributions before the Near Detector fit

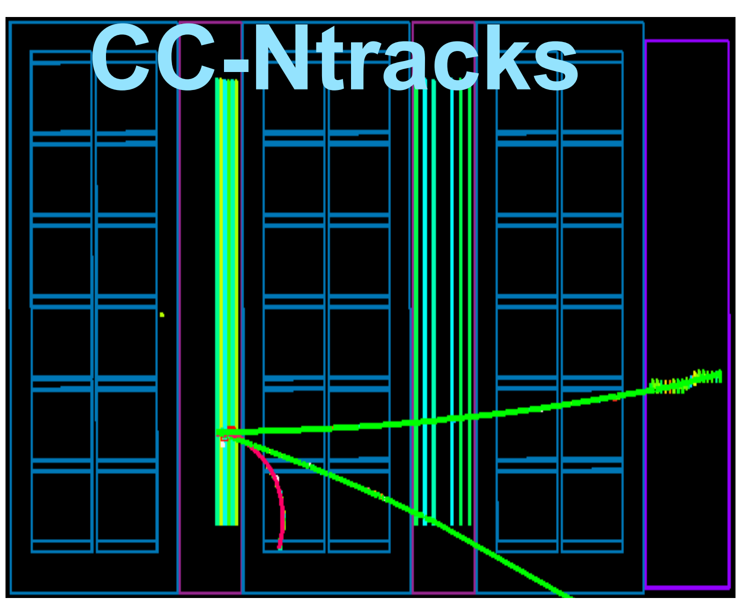


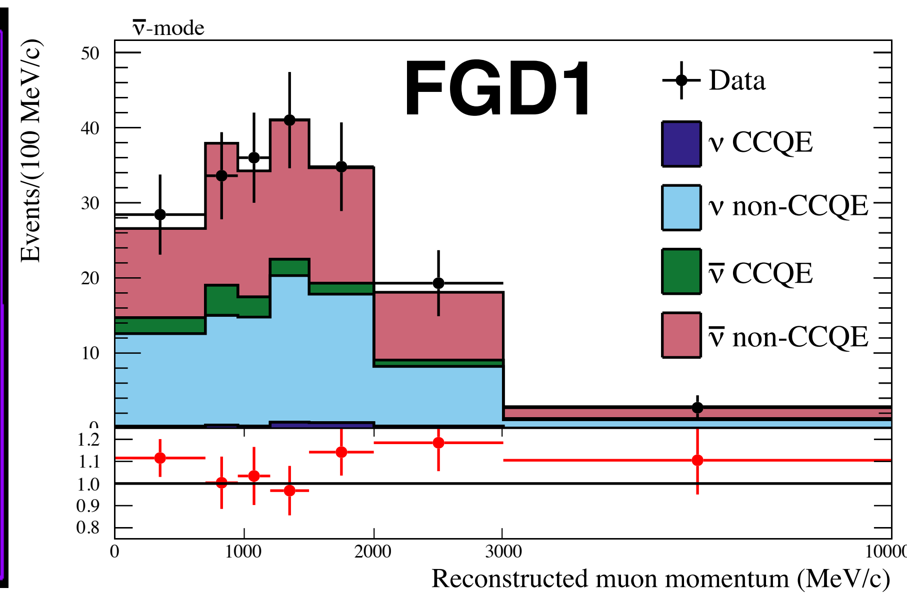


PRELIMINARY



PRELIMINARY





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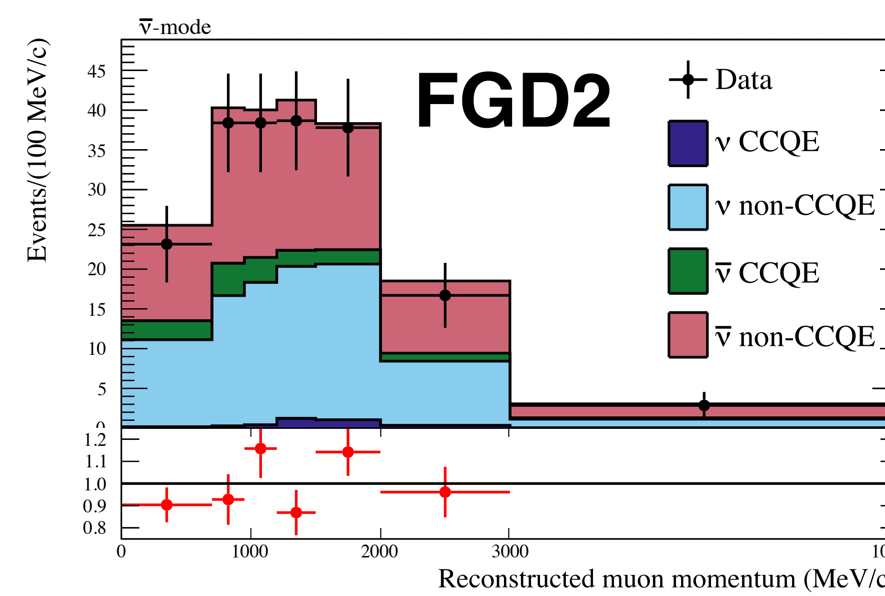
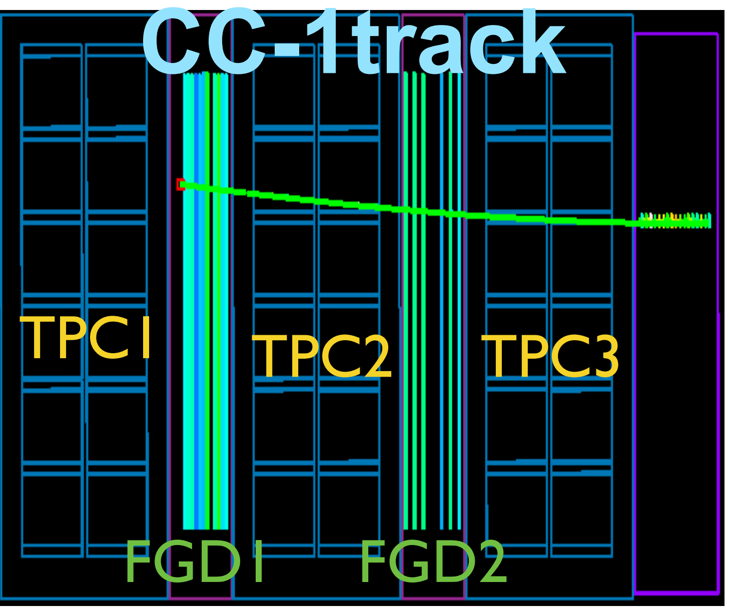
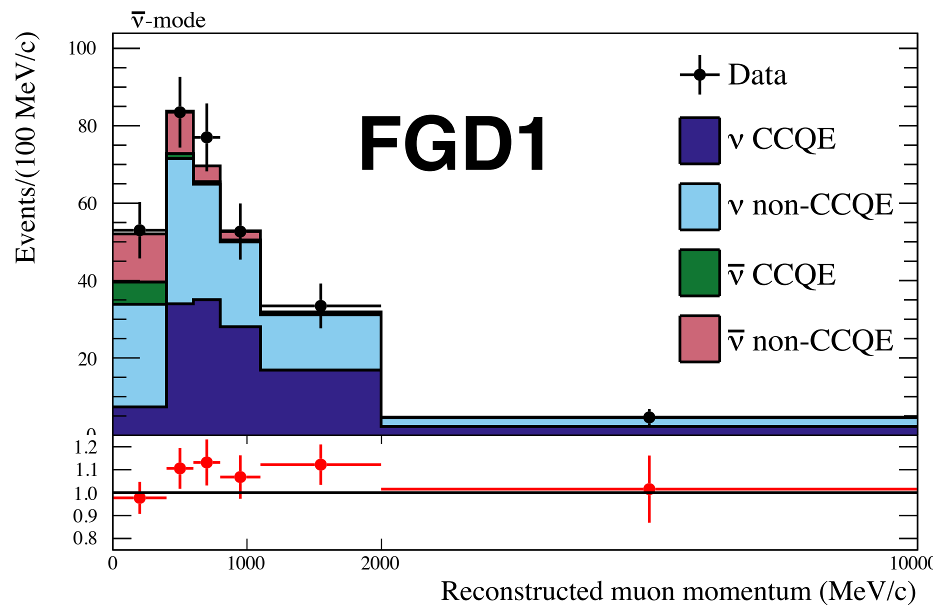


PRELIMINARY

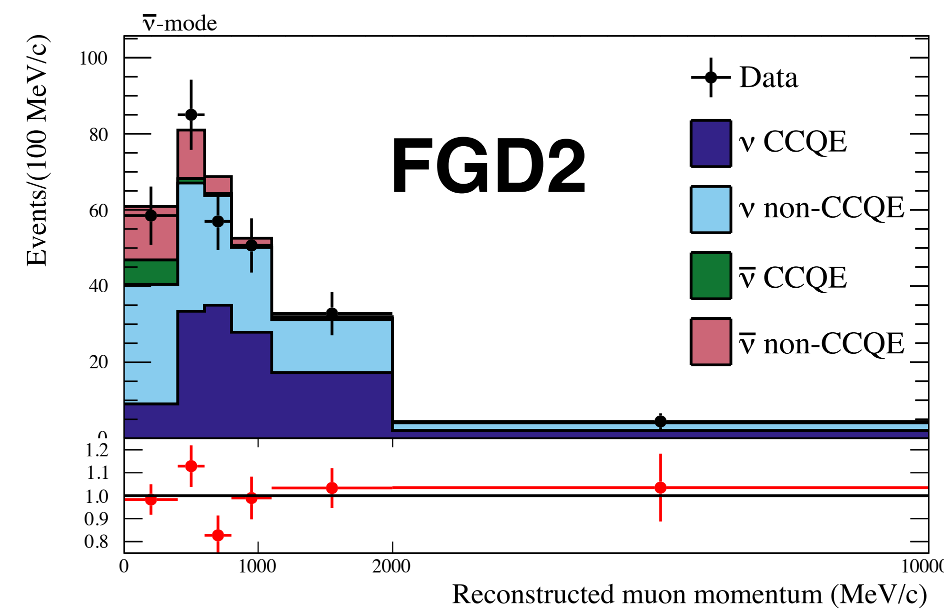
Near Detector data analysis: $\bar{\nu}$ beam - ν candidates

Distributions before the Near Detector fit

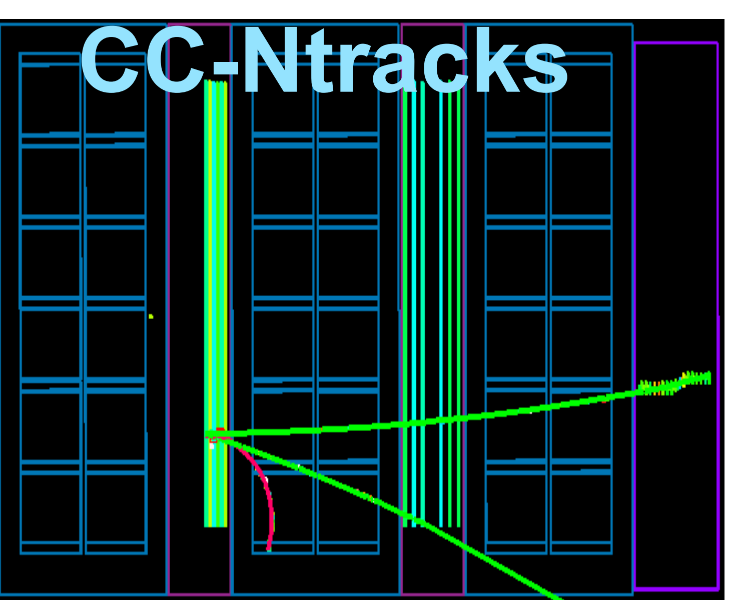


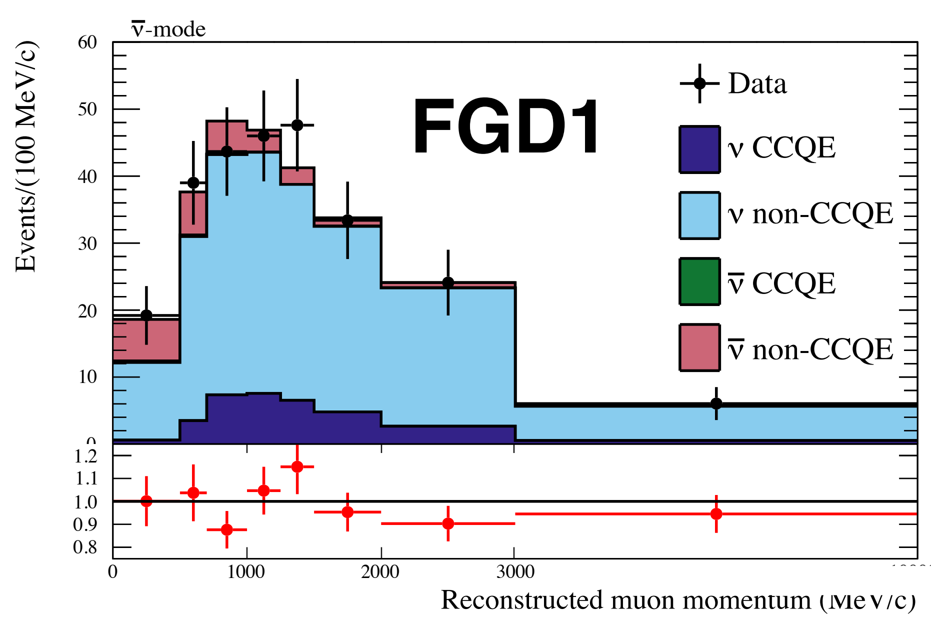


PRELIMINARY



RELIMINARY





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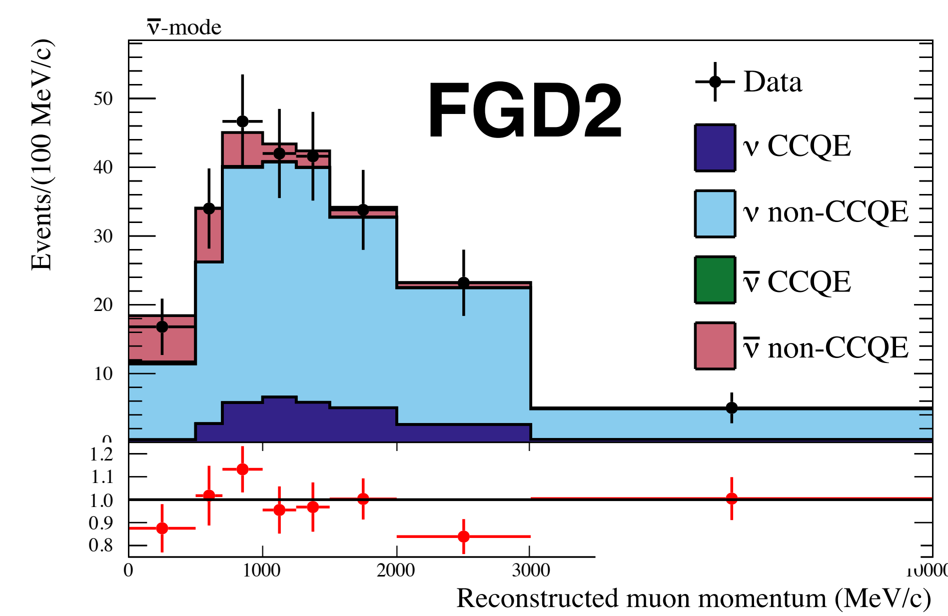


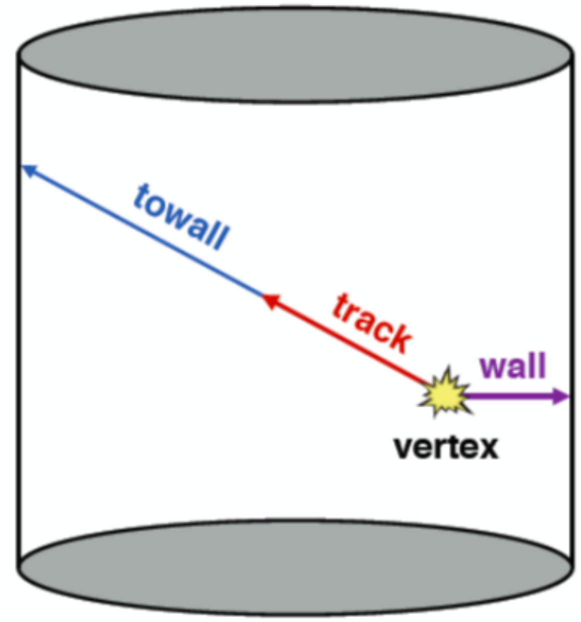
PRELIMINARY

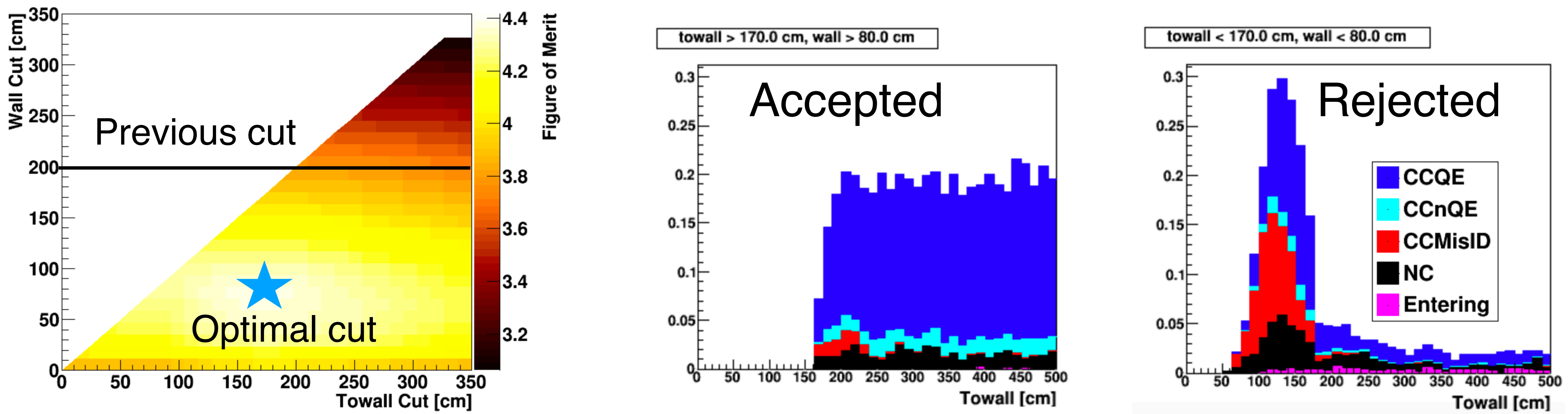
Impact of systematic uncertainties

	FHC 1R-μ	RHC 1R-μ	FHC 1R-e	FHC 1R$-e$ +d.e.	RHC 1R-e	FHC / RHC
ND prediction	2.9%	2.7%	3.0%	2.9%	3.8%	2.3%
Unconstrained	0.3%	0.3%	2.8%	3.0%	2.9%	3.4%
Binding Energy	3.4%	1.7%	7.3%	3.7%	3.0%	2.3%
SK Detector	3.3%	2.8%	4.1%	4.4%	17.4%	2.1%
Total	**4.9%**	**4.3%**	**8.8%**	**7.0%**	**18.3%**	**5.9%**
Stat $\sqrt{N}$ $\delta = \pi/2$ $\delta = -\pi/2$	6.1%	10.2%	11.6 ~ 14.1%	38.0 ~ 45.1%	29.1 ~ 25.9%	—

Event selection at Far Detector

- Use charge and time likelihood for ring-event hypothesis
  - ✦ Electron-, muon-, and pi0- like rings
  - ✦ Improved event reconstruction
- Likelihood is maximized for each event

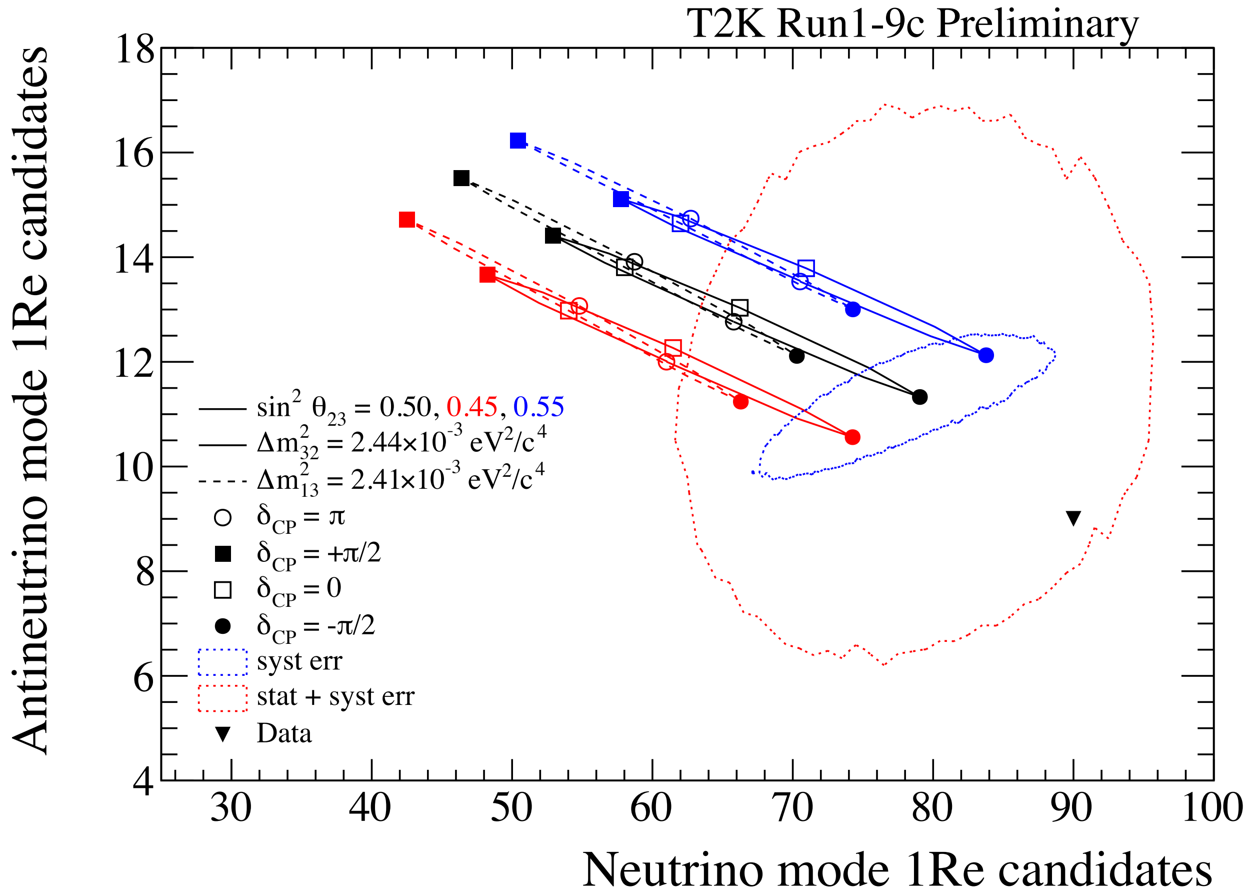




- Maximized a sensitivity metric including systematics and statistical uncertainties on cosmics and atmospheric neutrino data

Predicted vs observed # of events

- Compare the observed # of ν_e and $\bar{\nu}_e$ events with the prediction for:
  - δ_{CP} = -π/2, 0, π, +π/2
  - $\sin^2\Theta_{23}$ = 0.45, 0.55
  - Normal and Inverted Ordering



CP violation (δ_{CP}≠0,π) gives different oscillation probabilities for

- $\nu_\mu \rightarrow \nu_e$
- $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

- Observed number of events shows a slightly larger asymmetry compared to the prediction for δ_{CP}=-π/2 and Normal Ordering
  - few more ν_e candidates than predicted
  - few less $\bar{\nu}_e$ candidates than predicted