UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES

Overview of the T2K techniques

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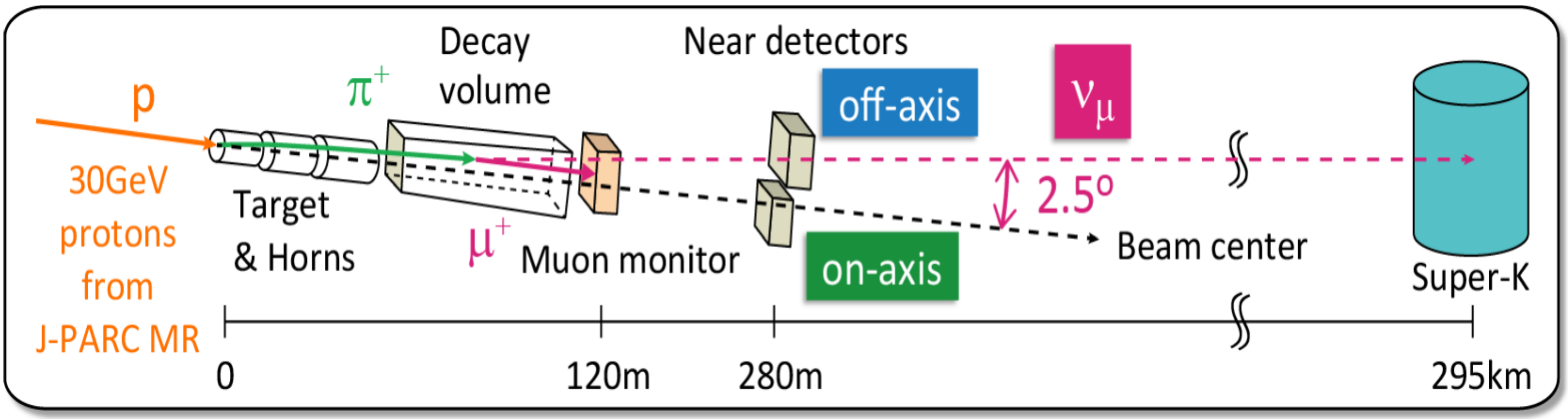
Design principle: the off-axis angle



Near Detector: $$N_{ND} \sim \Phi(E_\nu)\sigma(E_\nu)\epsilon_{ND}$$

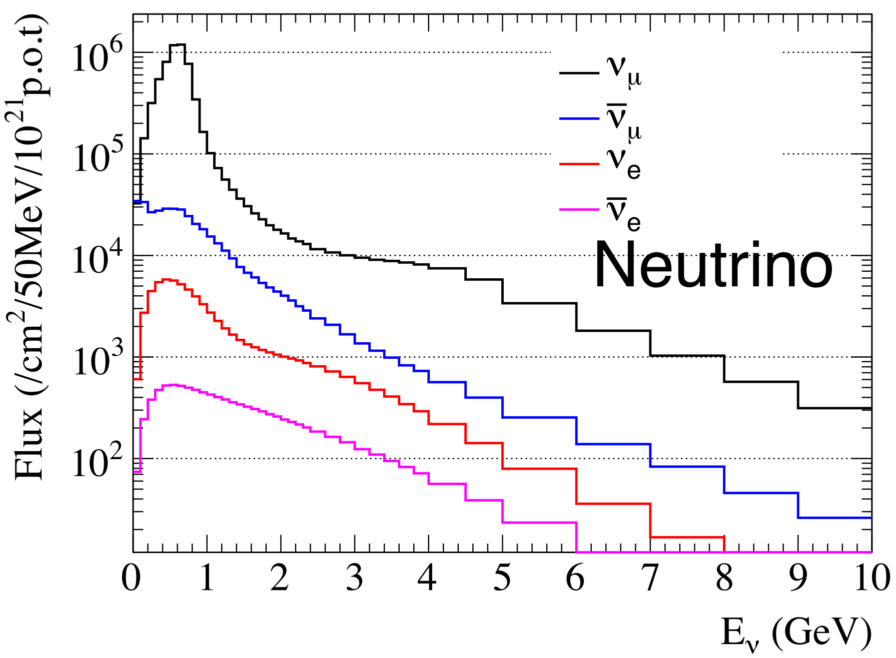
Flux | Cross Section | Detector Efficiency | Oscillation probability

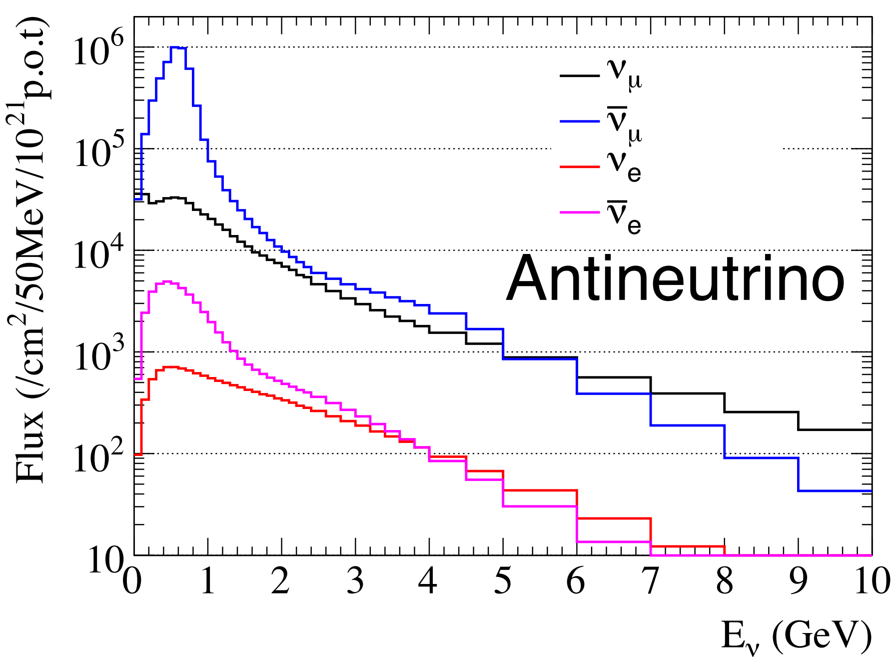
Far Detector: $$N_{FD} \sim \Phi(E_\nu)\sigma(E_\nu)\epsilon_{FD}P_{osc}(E_\nu)$$

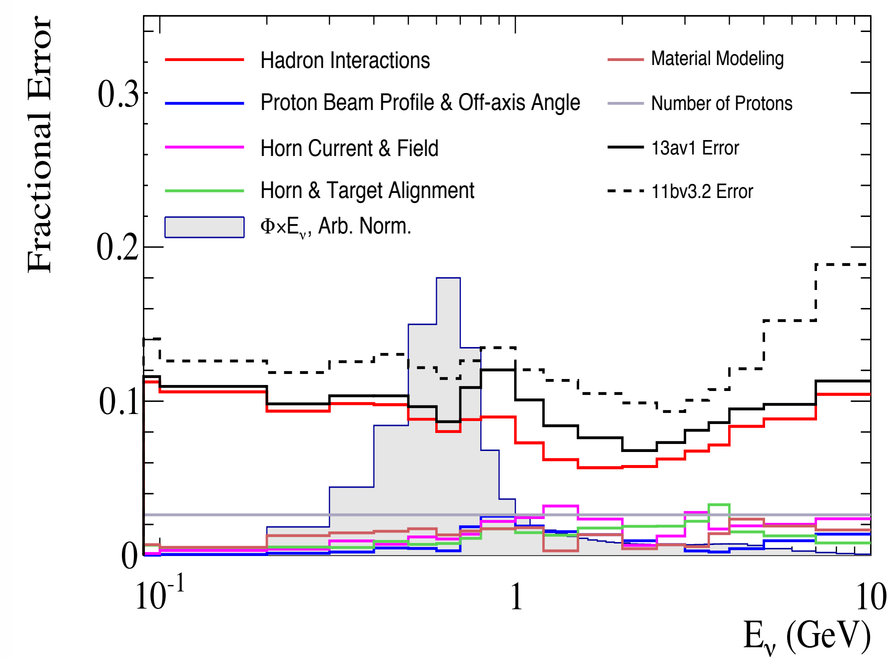
- Systematic errors enter the modeling of flux, cross section and detector
- To reduce errors on the models use the measurements at the Near Detector

Neutrino and antineutrino flux prediction

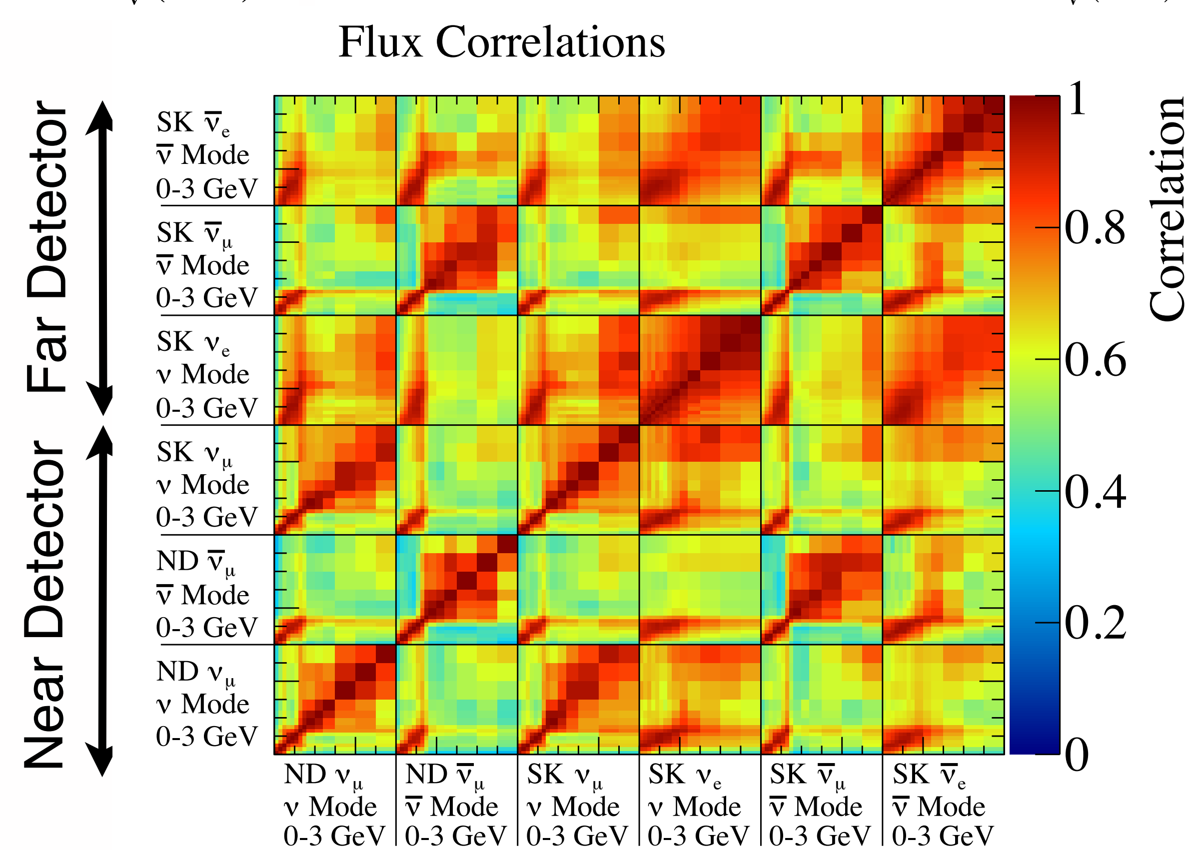
- Neutrino flux prediction tuned with hadron spectra measured at NA61/SHINE
- Flux systematic uncertainty reduced from ~30% to ~10% (thin target data)





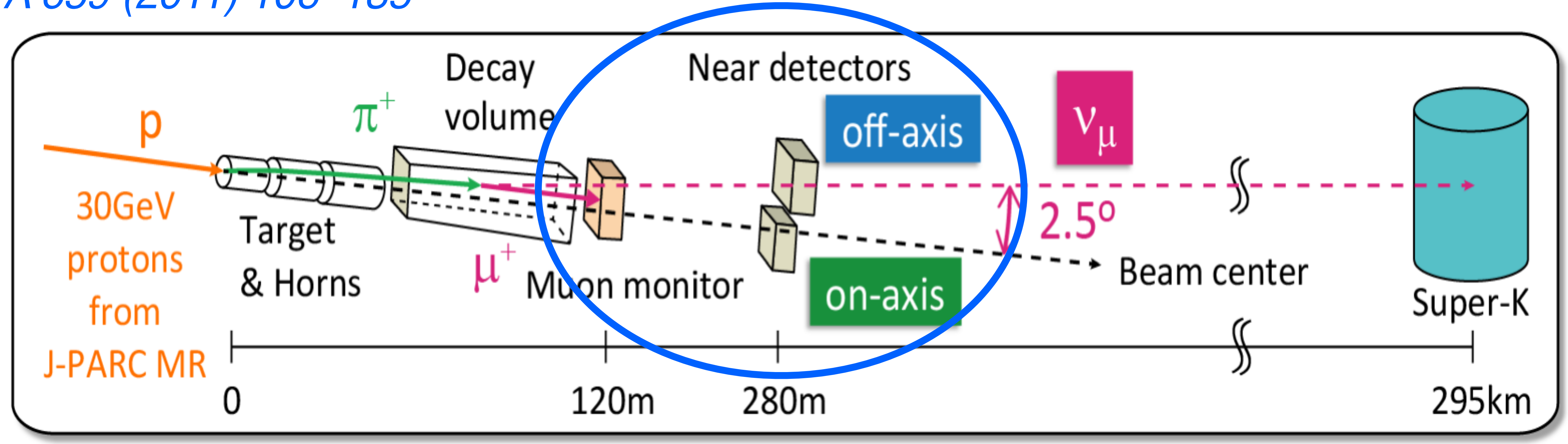


- Less than 1% intrinsic electron (anti)neutrino component at the peak
- <10% of wrong-sign background (ν_μ in $\bar{\nu}_\mu$ beam)
- Prediction of flux correlations between near / far detector, neutrino / antineutrino beam, ν_μ / ν_e is used

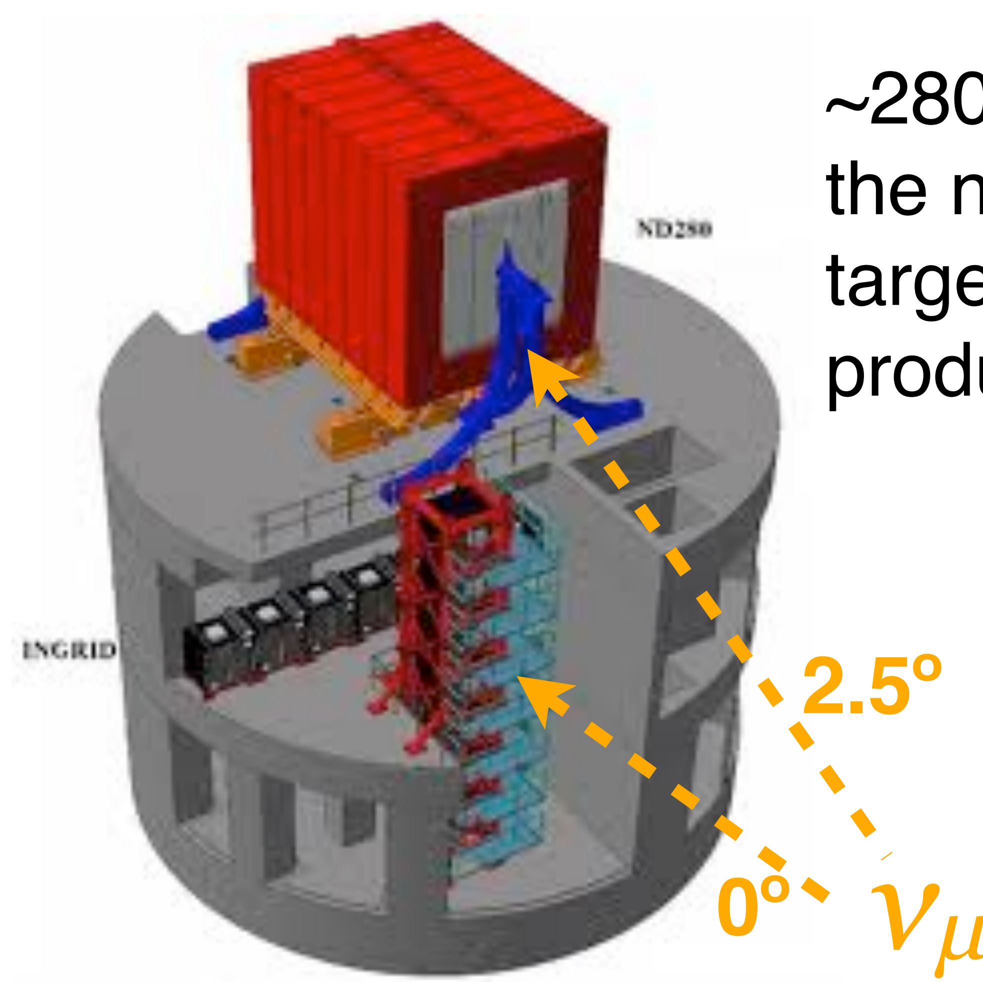


T2K near detector complex

NIM A 659 (2011) 106–135



- **Muon monitor:**
  - spill-by-spill monitoring of the beam
- **On-axis detector:**
  - INGRID
  - measure beam intensity / direction
- **Off-axis detector:**
  - 2.5° off-axis magnetized detector
  - precise measurement of neutrino flux and cross section
  - measure wrong-sign background (20-30% ν_μ in $\overline{\nu}_\mu$ beam after interaction)



~280 m from the neutrino target production

T2K near detector complex

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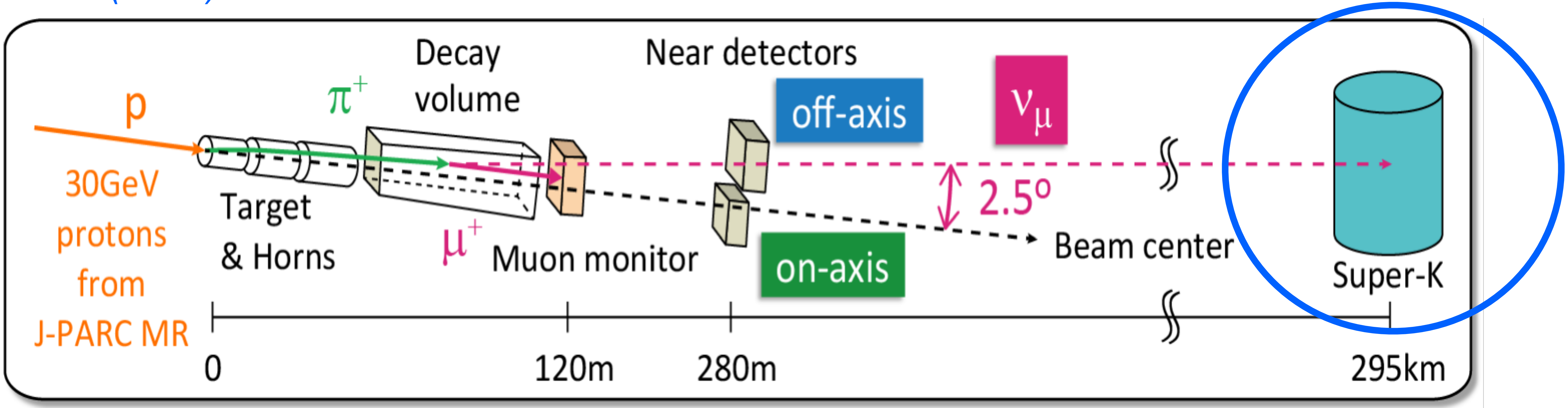
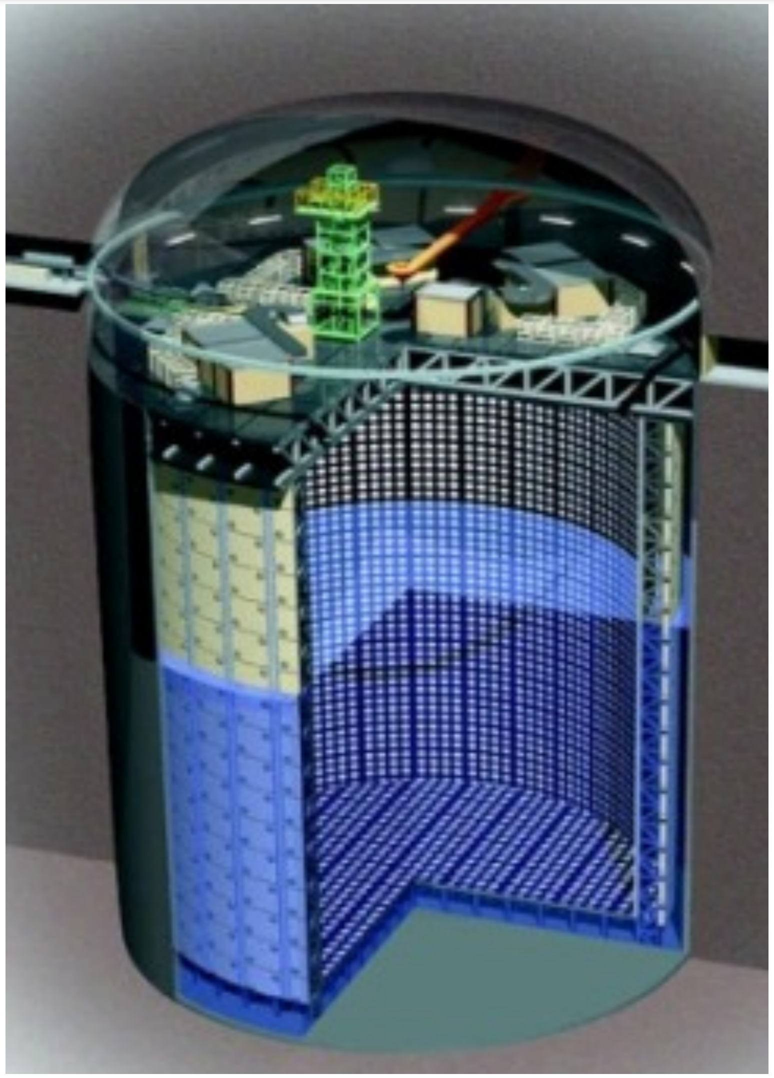
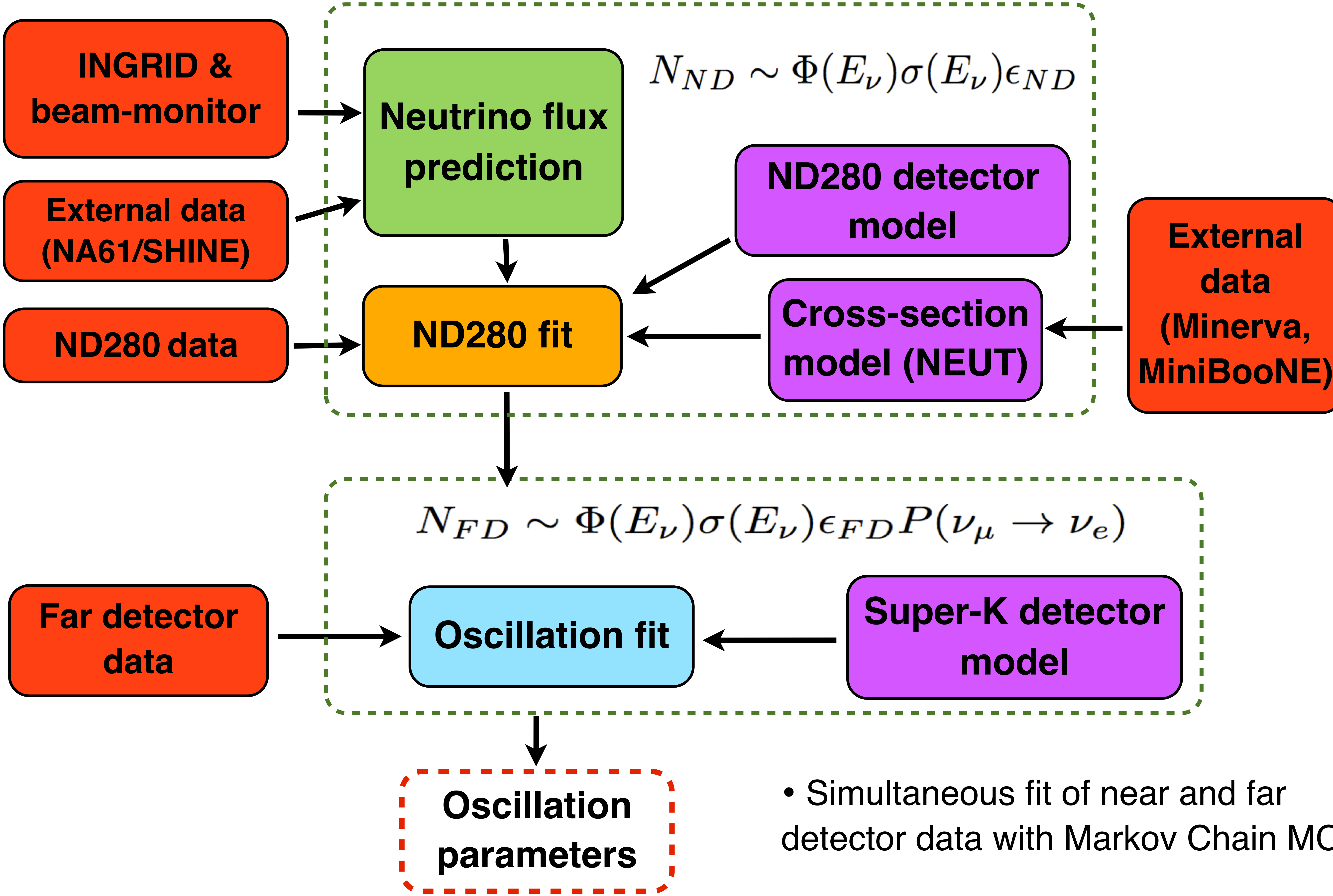


- Located in Mozumi mine
  - 2700 m.w.e overburden
- Water Cherenkov detector (50 kton)
- Fiducial mass 22.5 kton
- Inner detector
  - 11129 20-inch PMTs
- Outer veto detector
  - 1885 8-inch PMTs
  - determine fully-contained events
- T2K beam event: ±500 μs window

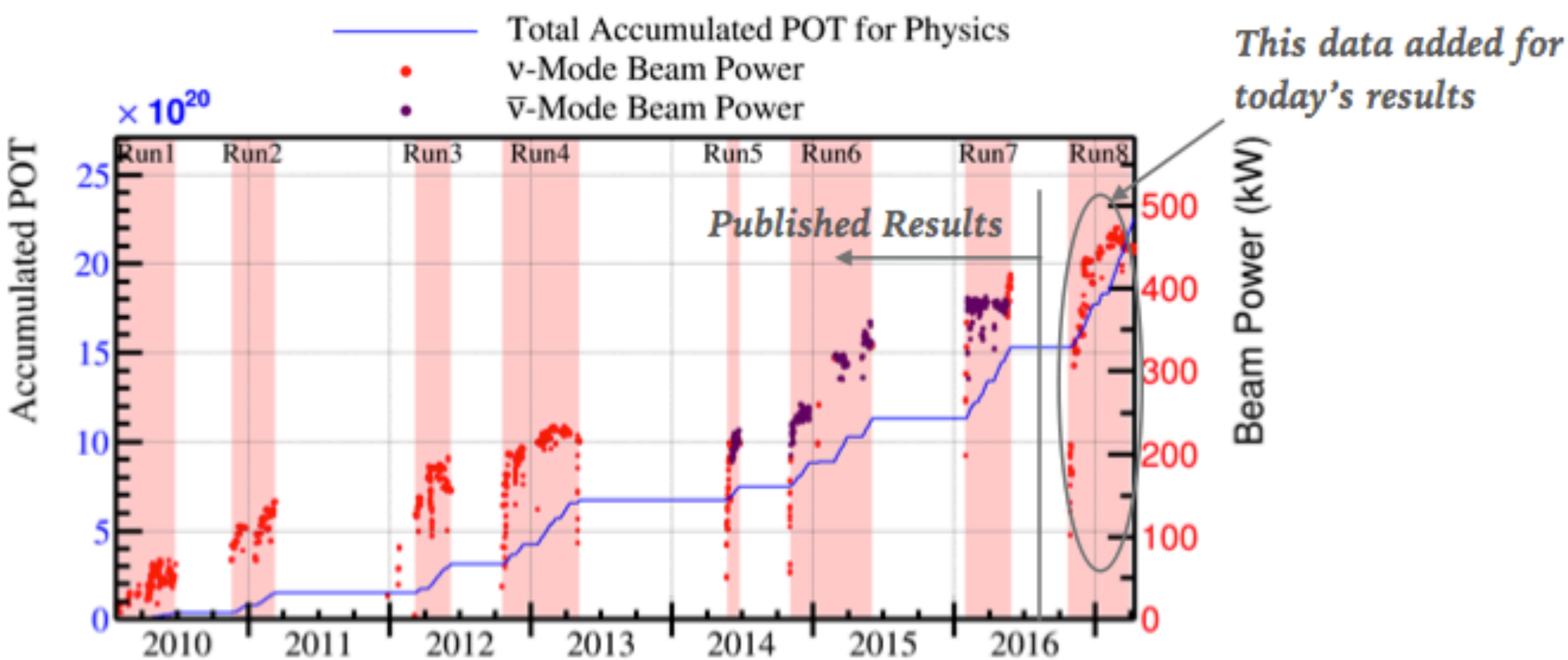


Strategy for oscillation analyses



- Simultaneous fit of near and far detector data with Markov Chain MC

T2K data collection



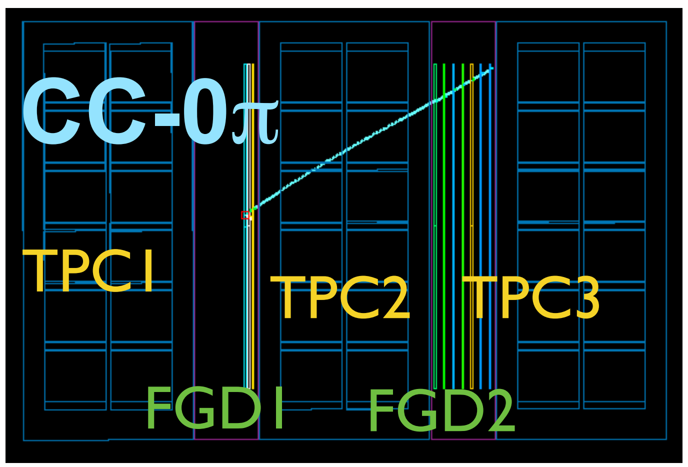
- Accumulated about 29% of the approved T2K protons-on-target (POT)
  - 14.7×10^{20} POT in neutrino mode
  - 7.6×10^{20} POT in antineutrino mode
- Phys. Rev. Lett. 118 (2017) no.15, 151801 - PRL Editor's Suggestion
- arXiv:1707.01048
- Stable operation with 470 kW beam power
- New results presented in August at KEK laboratory

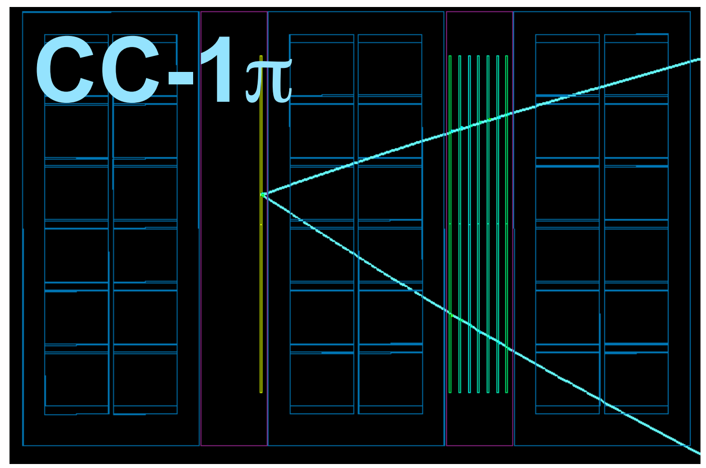
  https://kds.kek.jp/indico/event/25337/material/slides/0.pdf

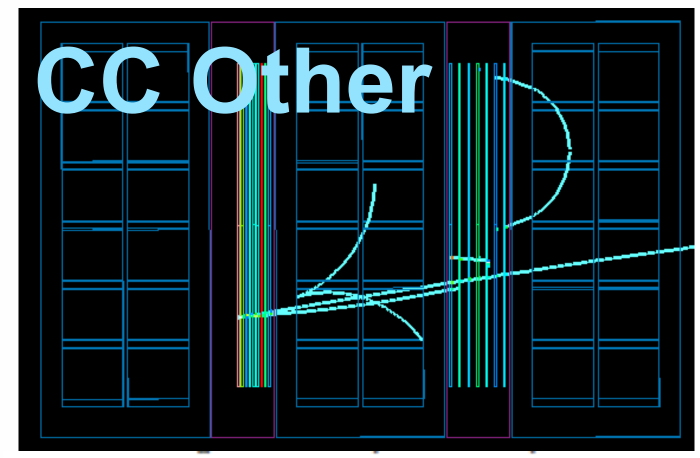
Near Detector Fit: the samples

- Antineutrino samples: 1 μ^+ candidates (CC-1track) + CC-Ntracks
- Neutrino samples: 1 μ^- candidates (CC-0π) + 1π^+ (CC-1π) + CC other
- Simultaneous analysis of neutrino and antineutrino data (μ momentum/angle)
- Additional samples to measure wrong-sign background (ν_μ in ν_μ-bar)

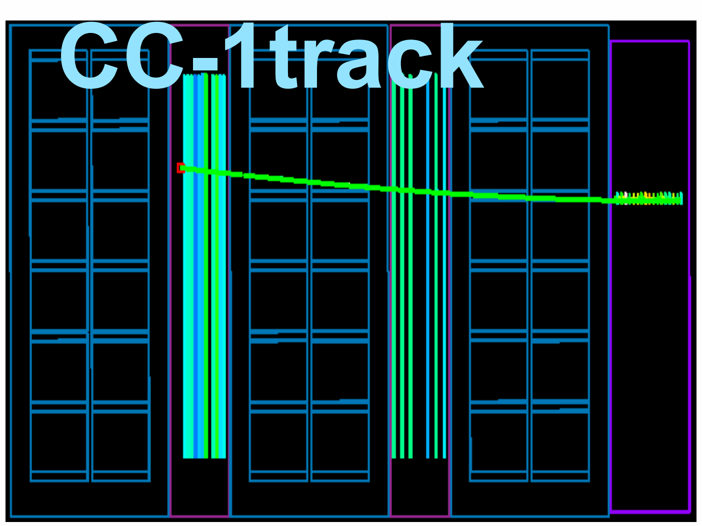
Neutrino samples

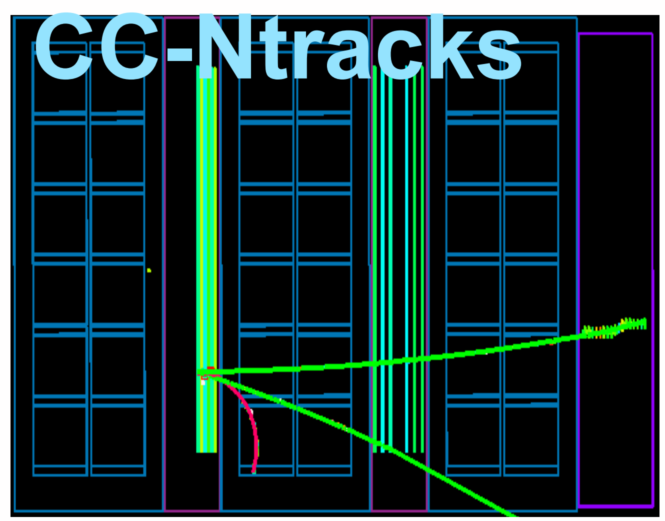


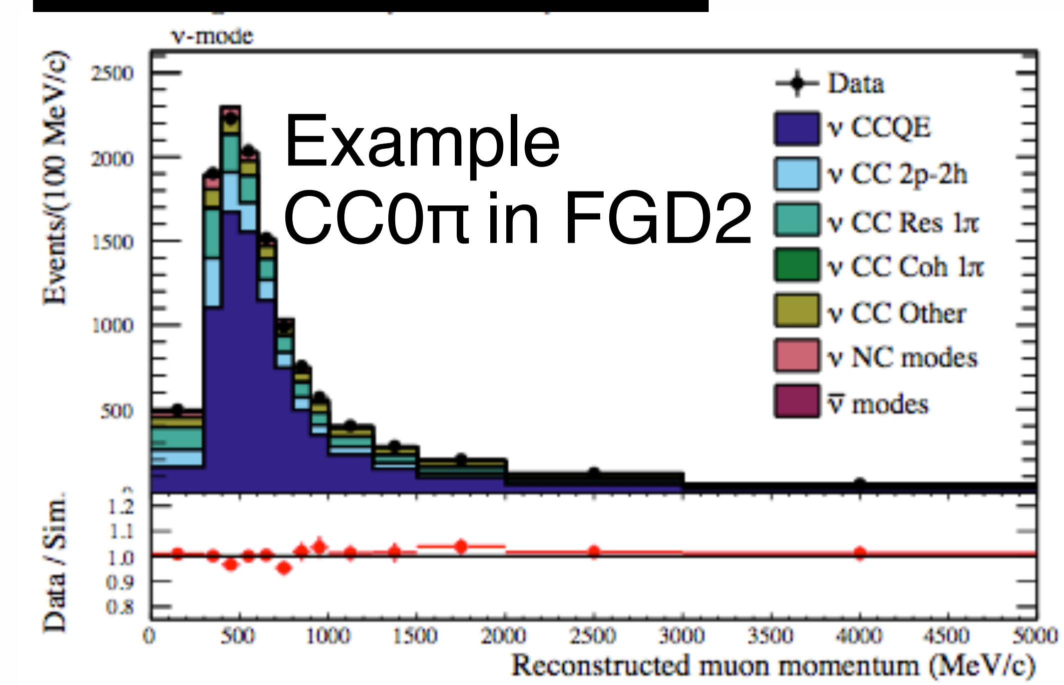




Antineutrino samples



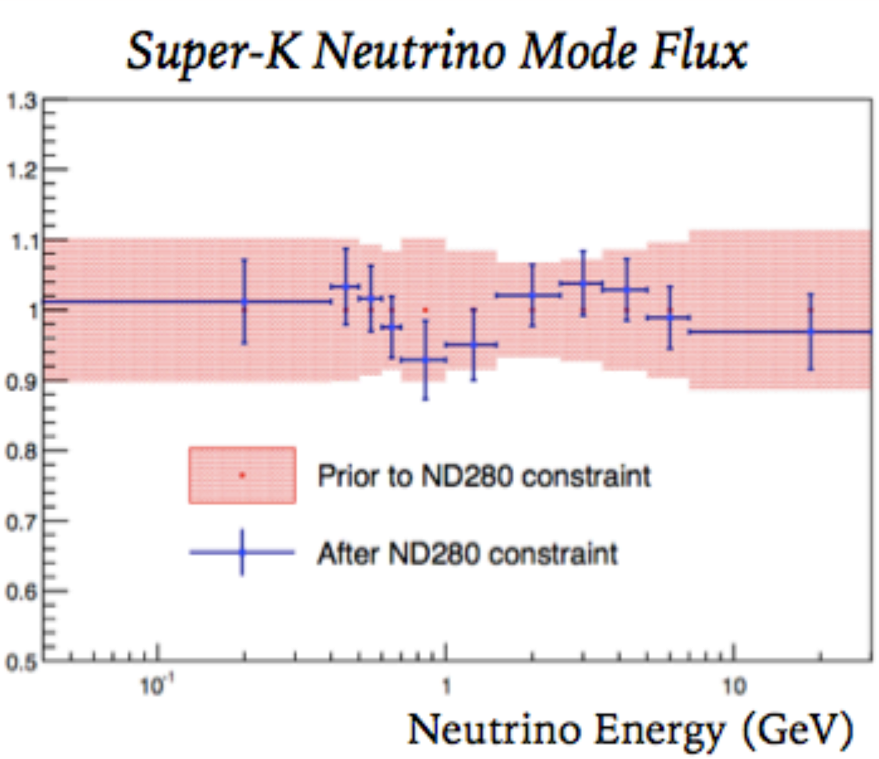


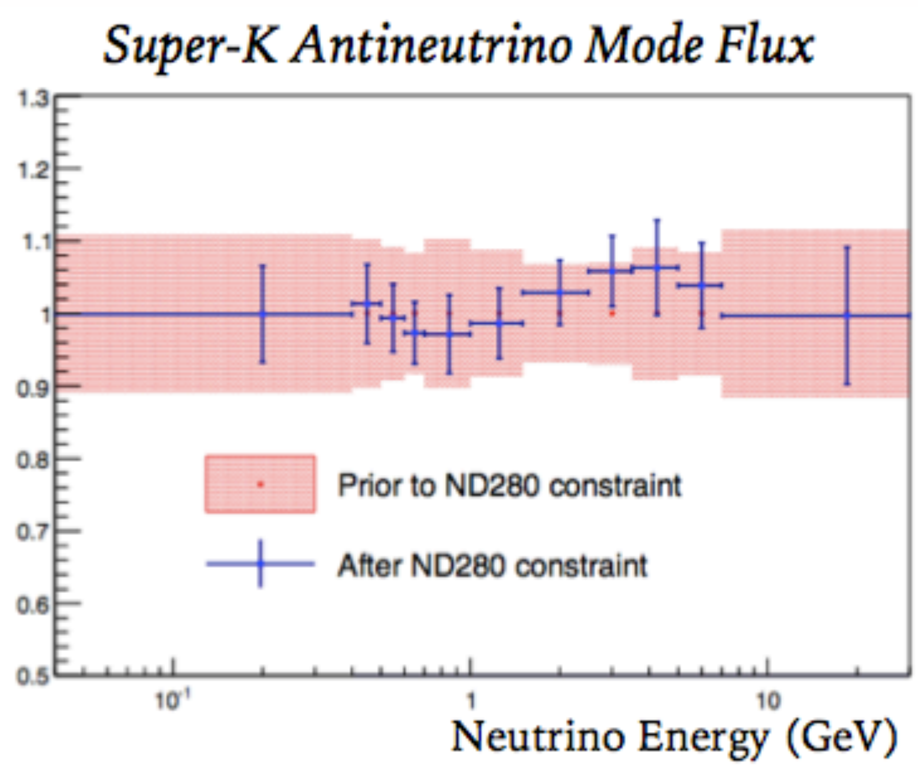


T2K Preliminary

- Maximum binned likelihood fit
- Fit parameters are constrained by a gaussian penalty term (except a few)

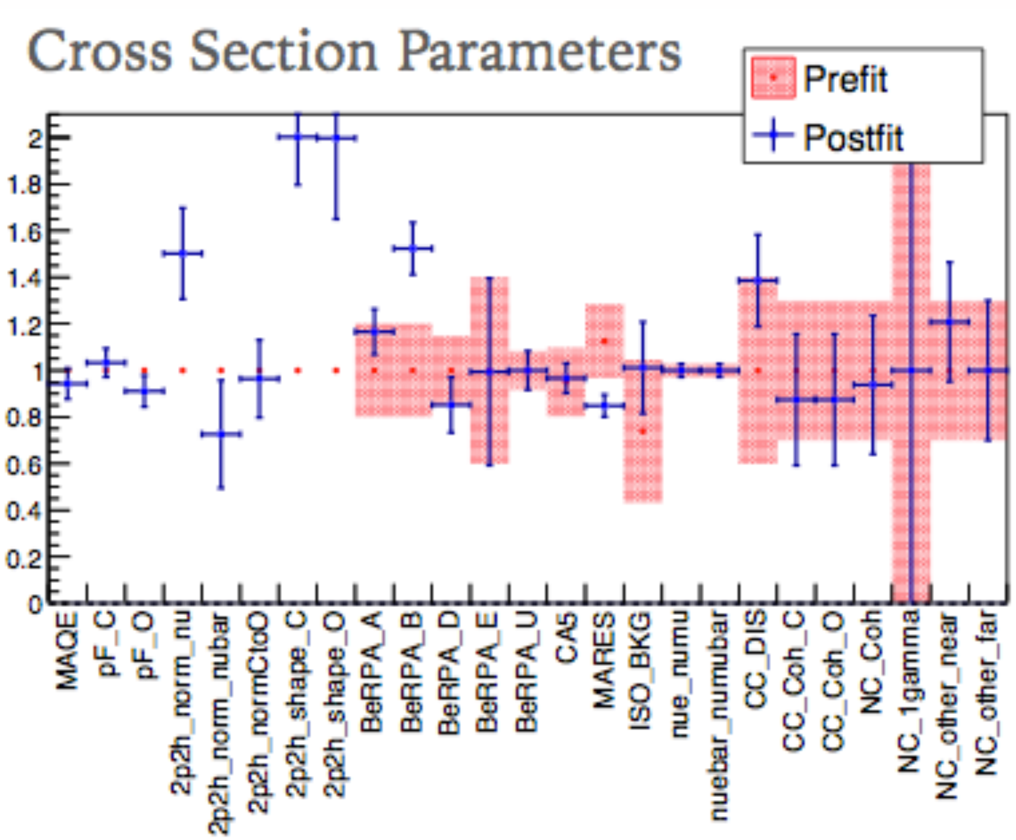
Near Detector Fit: flux and cross-section uncertainties





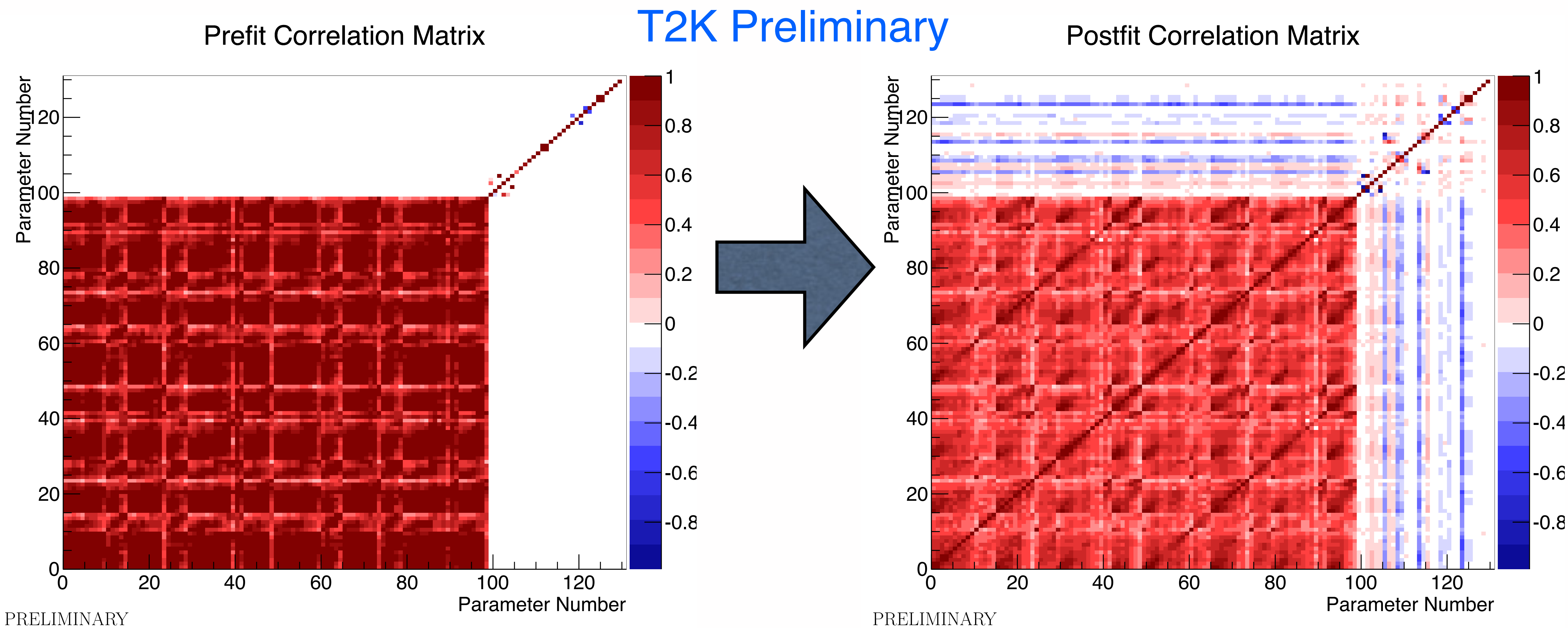
Measure neutrino flux and cross section at ND280

T2K Preliminary



- Different fit parameters as a function of true, reco energy, flavor and interaction mode
  - normalization parameters (e.g. flux, xsec)
  - modelled with non-linear response functions (e.g. MAQE, 2p2h, RPA, etc...)
- The fit reproduces well data: p-value=0.47
- Best-fit parameter values and covariance matrix are obtained and used to constrain systematics in the oscillation measurement

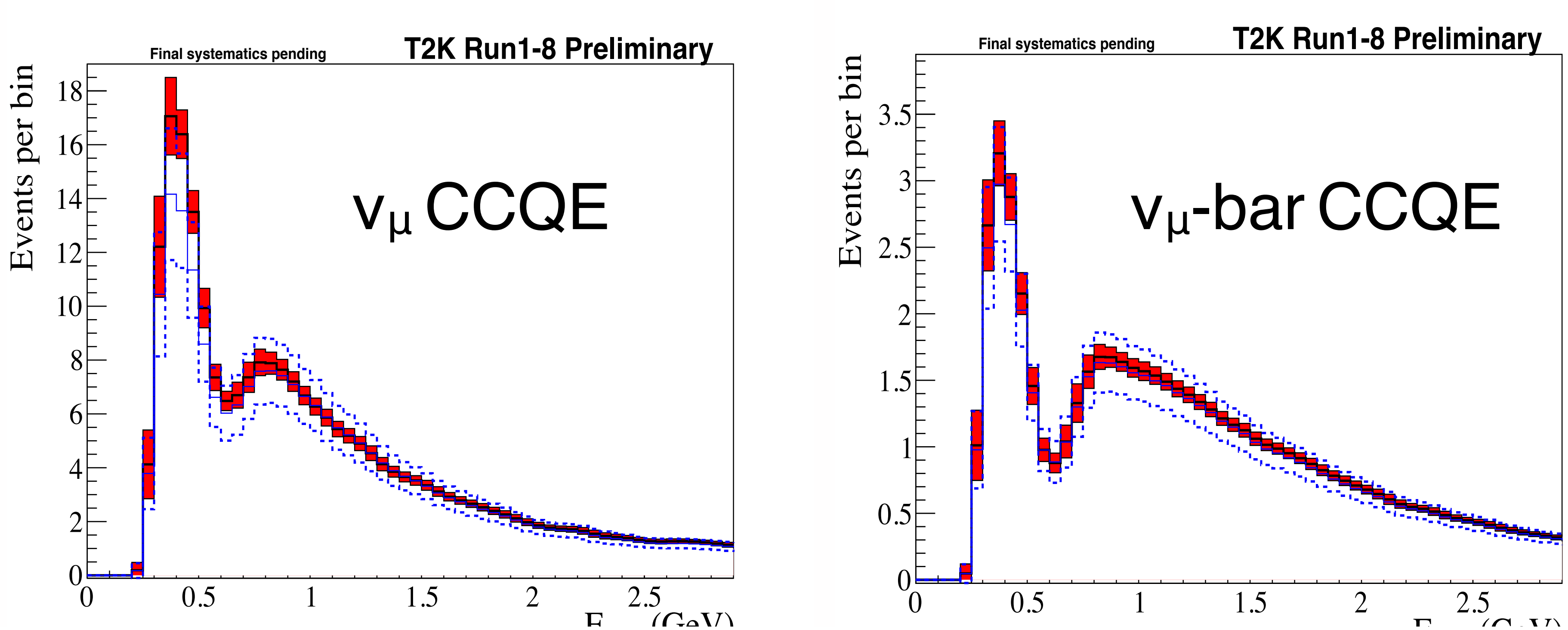
Near Detector Fit: flux and cross-section uncertainties



- Anti-correlations between neutrino flux and cross-section parameters

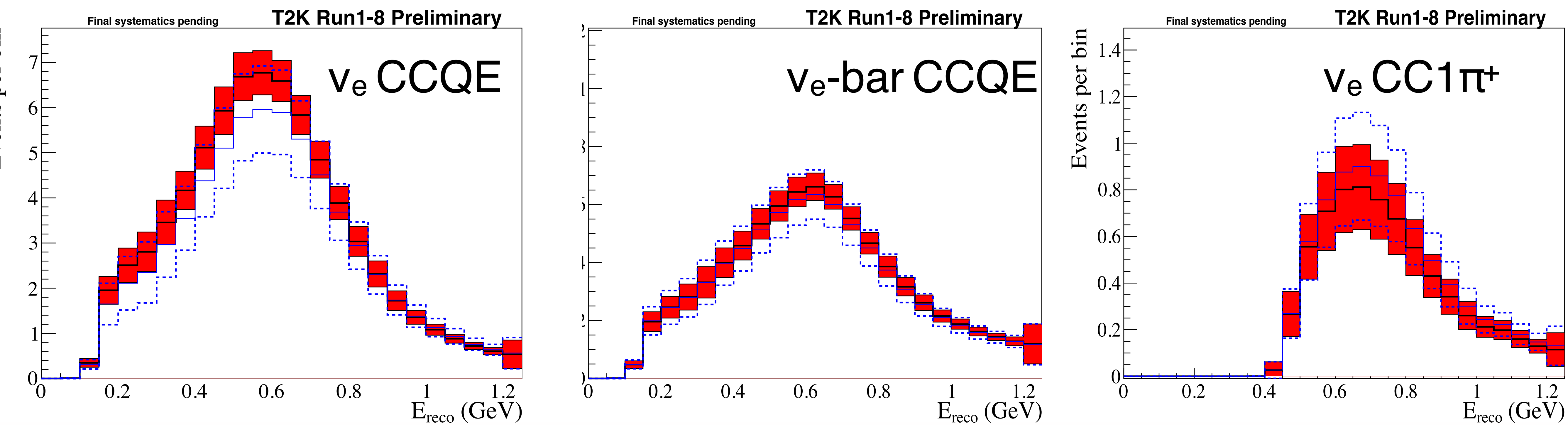
- The covariance matrix will be used to constrain the flux and cross-section systematic parameters in the neutrino oscillation analysis

Joint neutrino and antineutrino analysis



- Costrained with ND280 data

- Not constrained by ND280 data



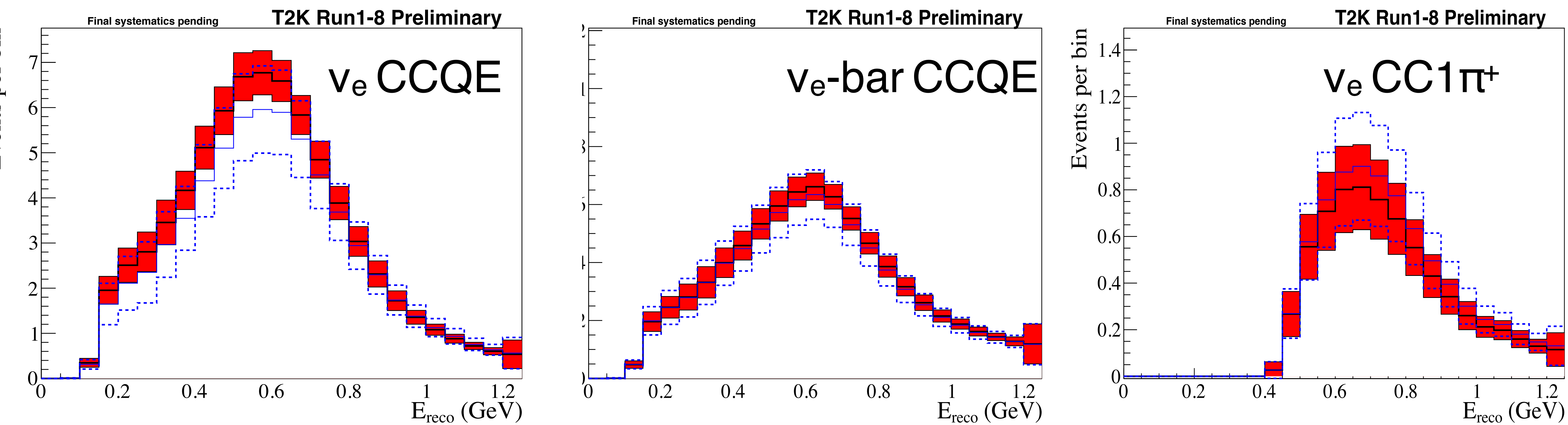
- Impact of systematic uncertainties that can be constrained by the ND280 data on the total Super-K # of events from ~13% to ~3% after the fit
- Statistical uncertainties still dominant (more details in backup)

Joint neutrino and antineutrino analysis

	1Rmu		1Re			
Error Source	FHC	RHC	FHC	RHC	FHC 1 d. e.	FHC/RHC
SK Detector	1.9	1.6	3.0	4.2	16.5	1.6
SK FSI+SI+PN	2.2	2.0	2.9	2.5	11.3	1.6
SK Detector+FSI+SI+PN	2.9	2.5	4.2	4.8	19.2	2.1
ND280 const. flux & xsec	3.3	2.7	3.2	2.9	4.1	2.5
$\sigma(\nu_e)/\sigma(\nu_\mu)$, $\sigma(\bar{\nu}_e)/\sigma(\bar{\nu}_\mu)$	0.0	0.0	2.6	1.5	2.6	3.1
NC1γ	0.0	0.0	1.1	2.6	0.3	1.5
NC Other	0.3	0.3	0.1	0.3	1.0	0.2
Syst. Total	4.4	3.8	6.3	6.4	19.6	4.7

- Costrained with ND280 data

- Not constrained by ND280 data



- Impact of systematic uncertainties that can be constrained by the ND280 data on the total Super-K # of events from ~13% to ~3% after the fit
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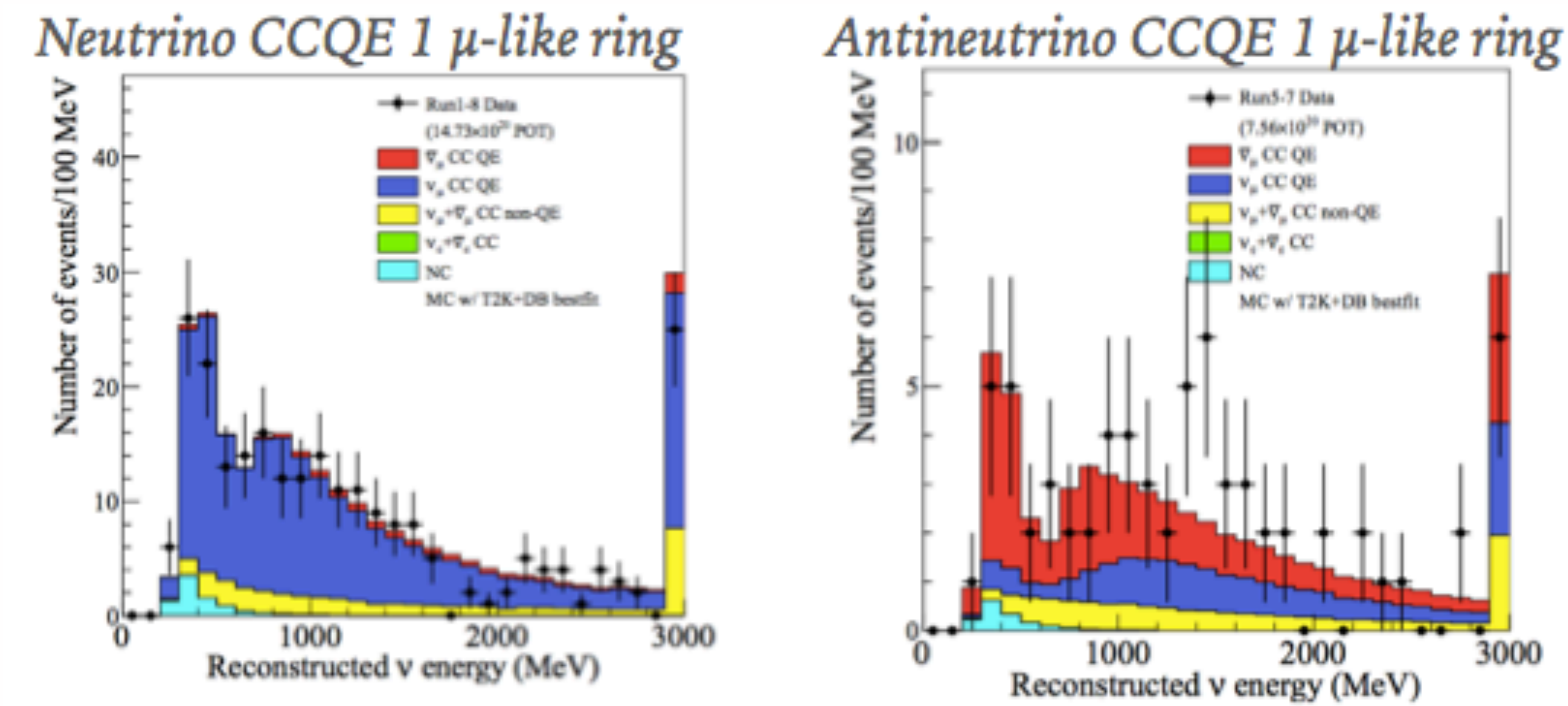
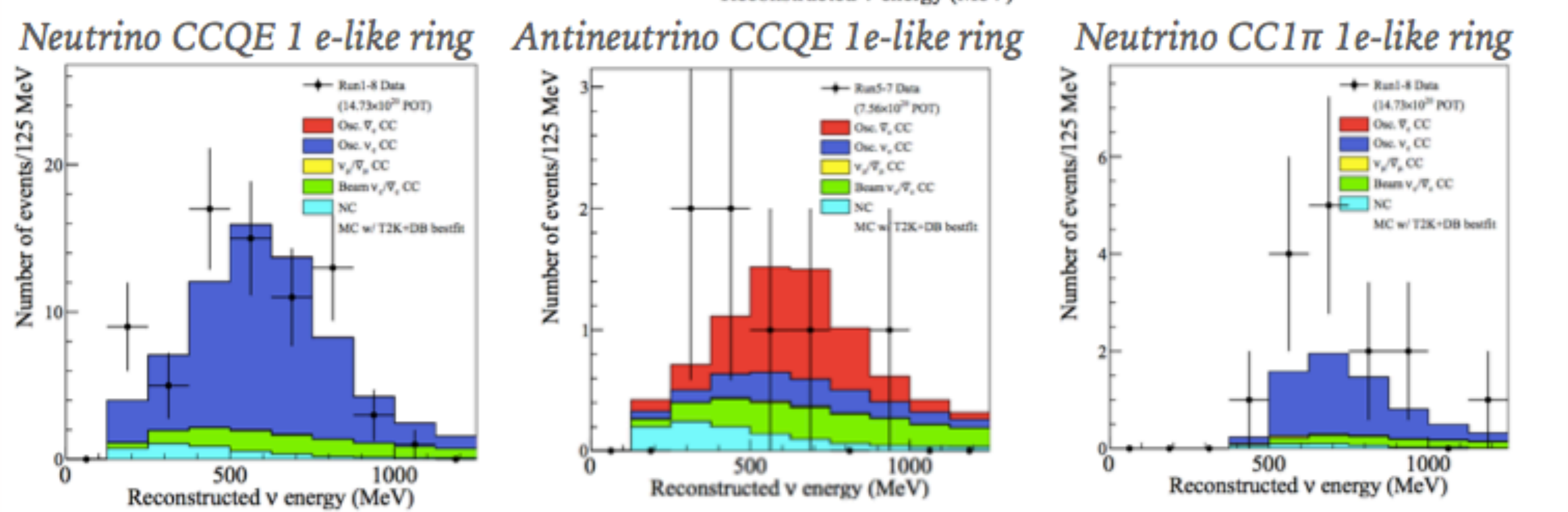
Joint neutrino and antineutrino analysis

- Joint fit of all 5 samples at the far detector



Observed spectra

T2K Preliminary



Joint neutrino and antineutrino analysis

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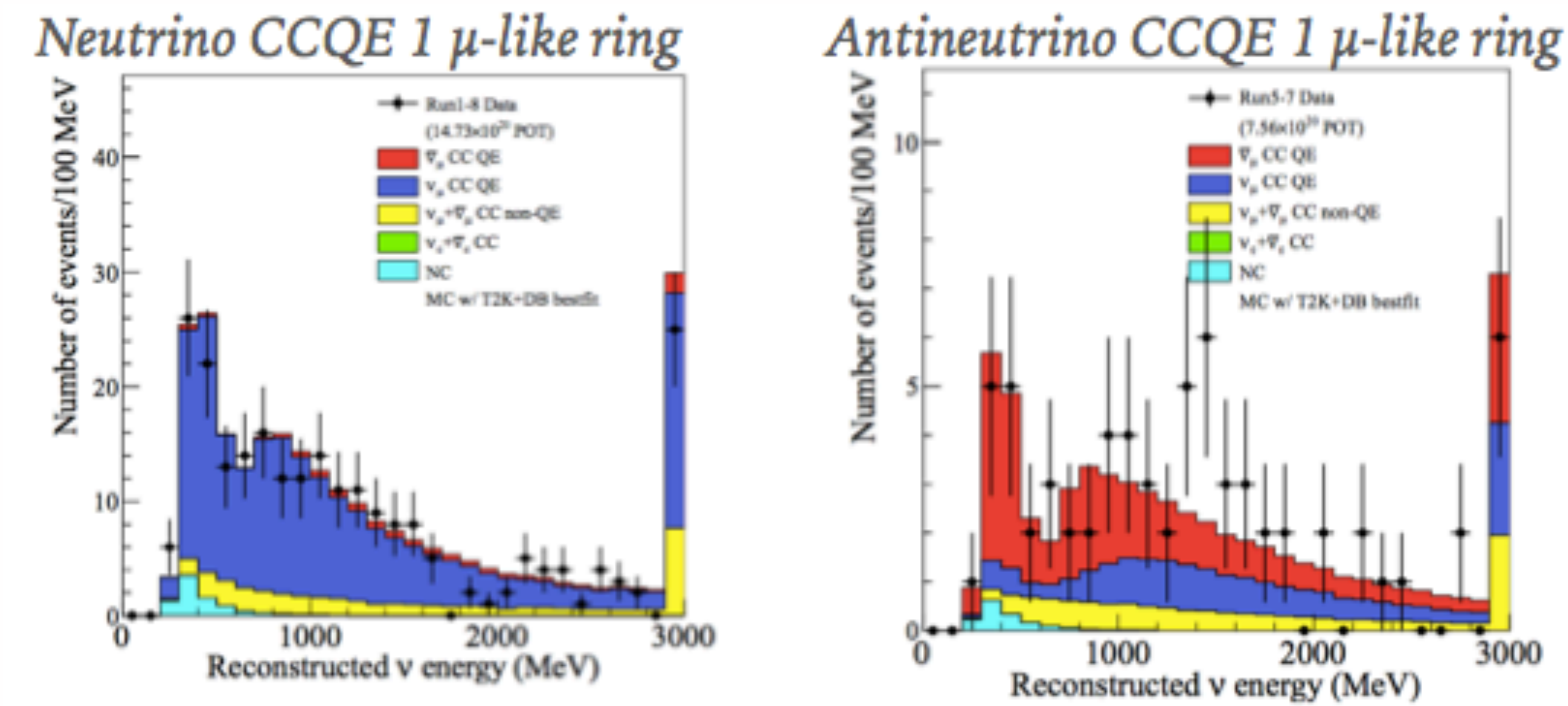


Observed spectra

T2K Preliminary

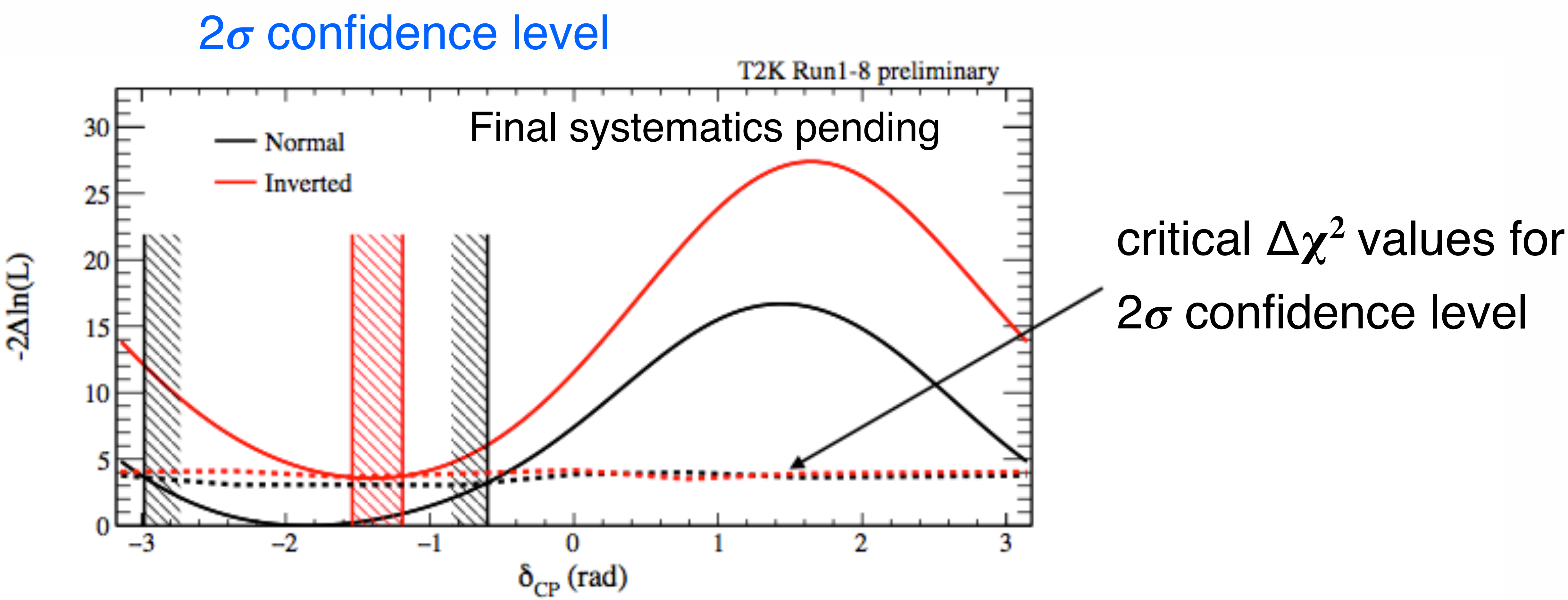
- Marginalize all the systematic parameters and oscillation parameters "not of interest"
- π(a) is the prior used to marginalize

$$\lambda_{marg}(\vec{\theta}) = \int_A \lambda(\vec{\theta};\mathbf{a})\pi(\mathbf{a})d\mathbf{a} = \frac{1}{n}\sum_{i=1}^{n}\lambda(\vec{\theta};\mathbf{a}_i)$$

  - ND fit covariance matrix for flux and xsec
  - Covariance matrix evaluated with SuperK atmospheric data for detector systematics
  - PDG or flat priors for neutrino oscillation parameters (reactors for $\sin^2 2\Theta_{13}$)

Results

- Feldman-Cousins to get the right coverage

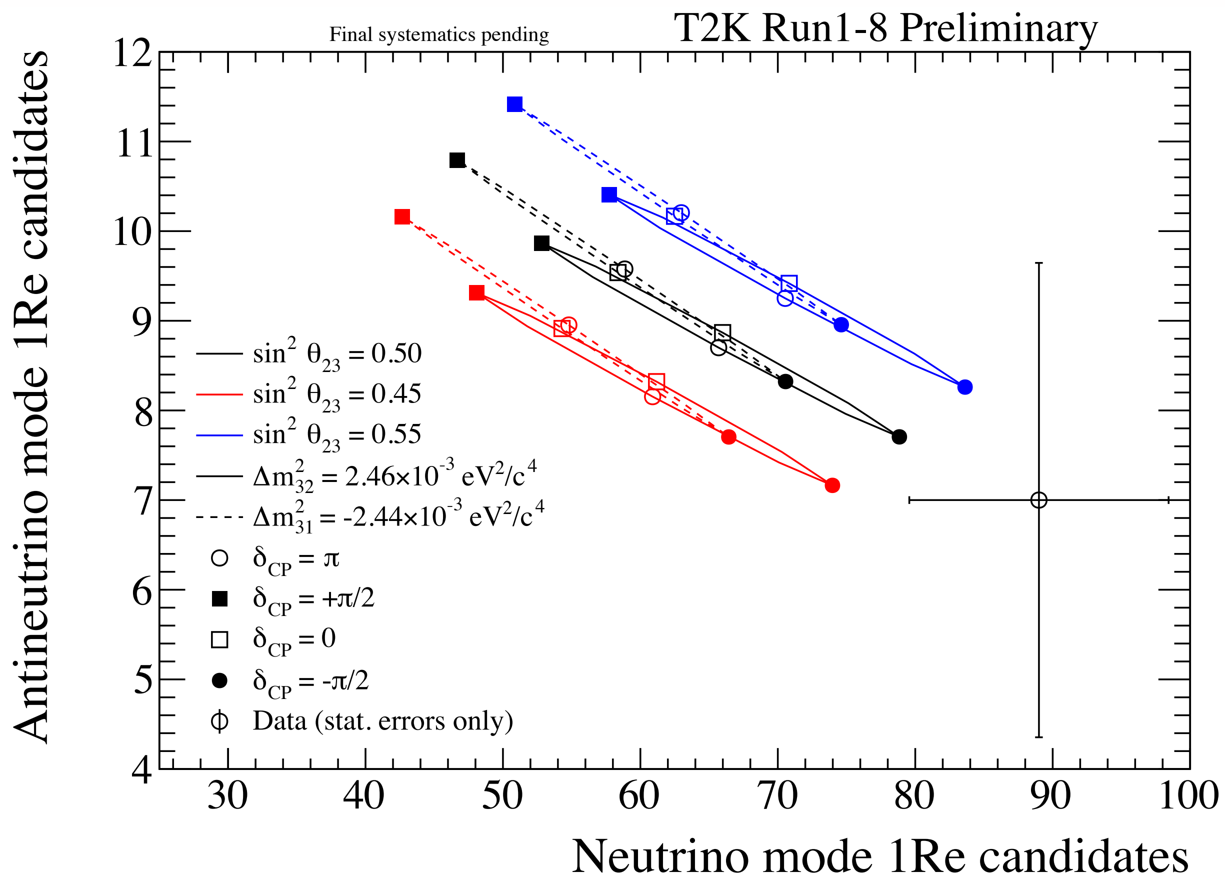


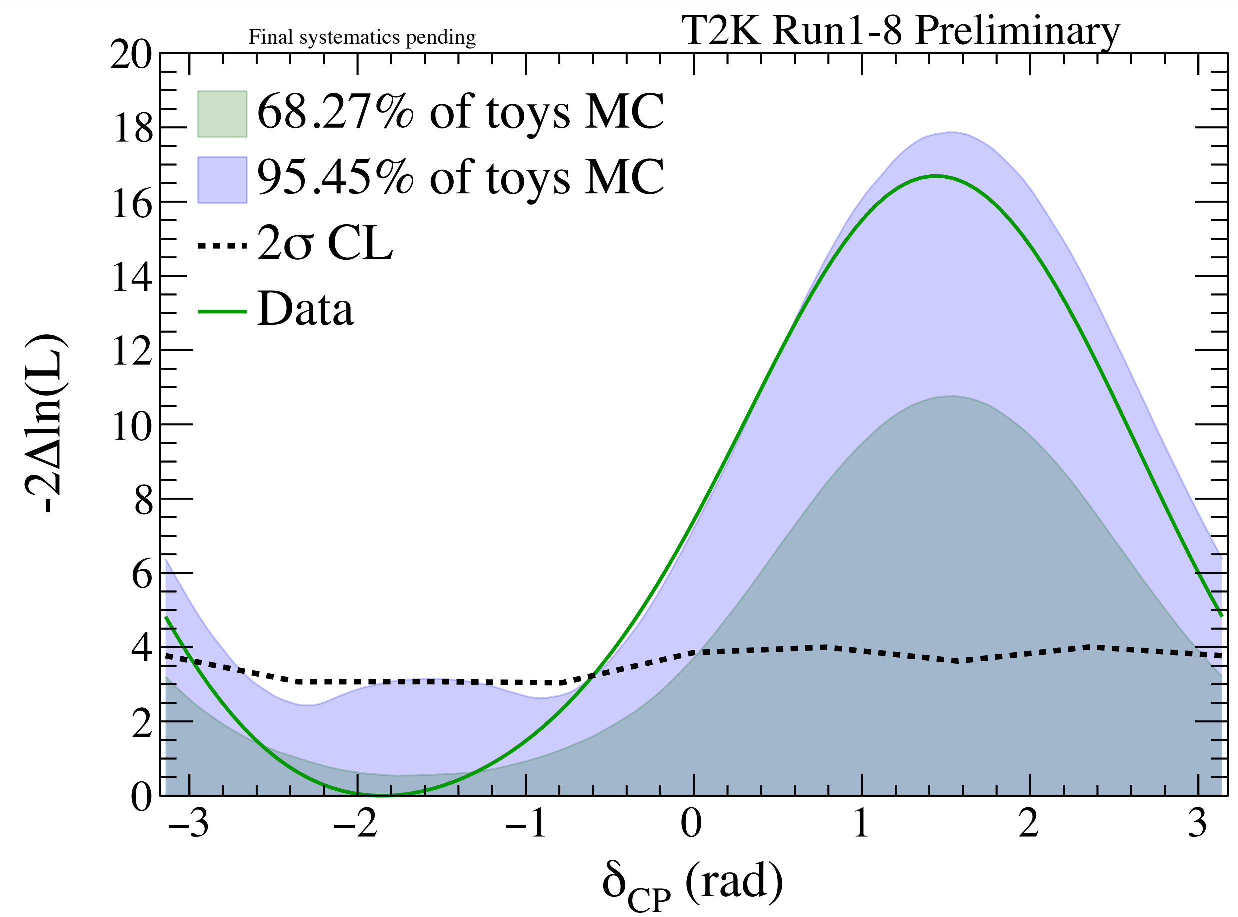
- Best-fit δ_{CP} is -1.833 radians
- Normal Ordering is favored by the T2K data
- CP conserving values (0, π) are excluded with a significance of 2σ

- Bayesian joint fit of Near and Far detector (MCMC): validation of the near to far detector extrapolation

Measured Vs Sensitivity

- Data constrain δ_{CP} more than the sensitivity
- How likely can this happen?
- Perform many pseudo-experiments at $\delta_{CP} = -\pi/2$ and Normal Ordering

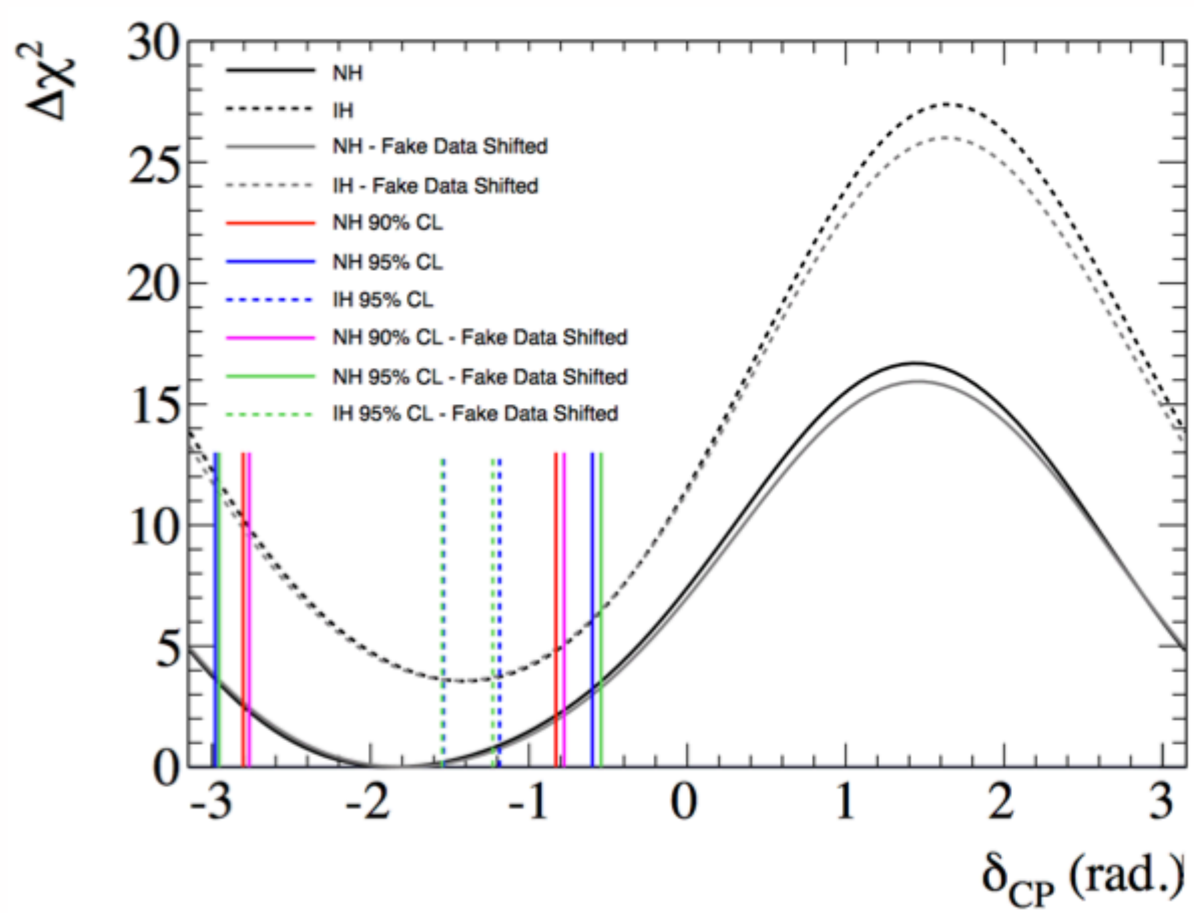




- Data $\Delta\chi^2$ falls within the 95.45% of the pseudo-experiments
- 30% of pseudo-experiments exclude $\delta_{CP}=0$ at 2σ
- 25% of pseudo-experiments exclude $\delta_{CP}=\pi$ at 2σ

Effect of different models on oscillation analysis

- Neutrino interaction models are constantly updated
- Check robustness of T2K results against potential mis-modeling, due to models not yet included in the MC
- Generate fake data sets consistent with variations of the cross-section model (data-driven or different assumptions in the model)
- Fit the fake data set with the MC currently used in the oscillation analysis (both near and far detector)
- Evaluate potential biases on the measured neutrino oscillation parameters
- Full study performed with the 2016 model and statistic
- Work in progress
- Details of the 2016 studies can be found in arXiv:1707.01048



No significant impact on the δ_{CP} measured intervals

How can we improve the sensitivity?

- More precise measurements of the unoscillated neutrino interactions

    - full acceptance

    - lowest momentum threshold

    - more data

- Continue interactions with theoreticians: “we” need improved models (and generators), “they” need more and better data

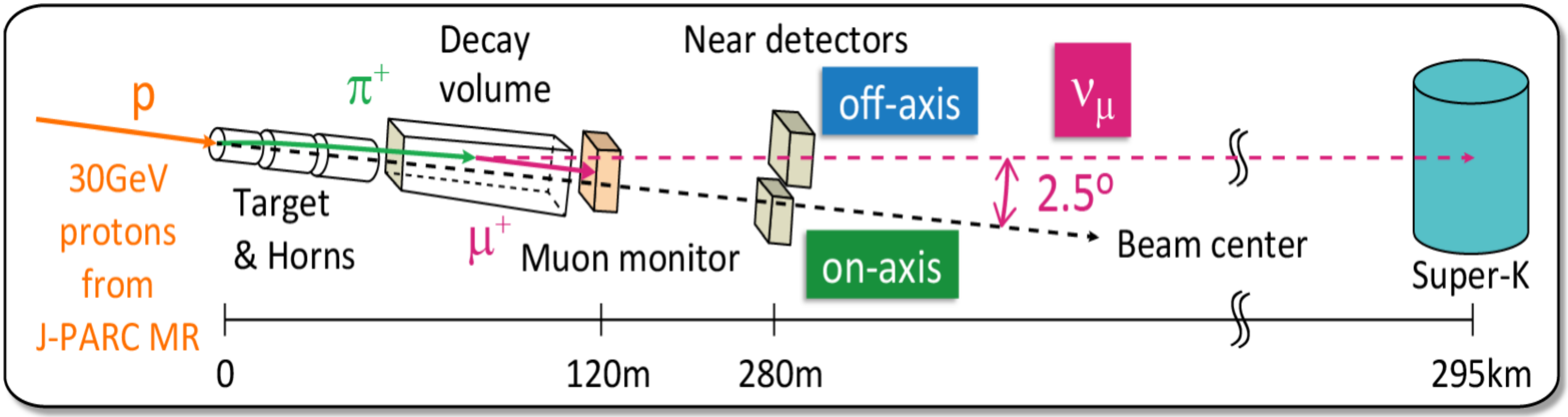
    - new cross-section measurements (T2K has an extensive program)

    - fake data studies

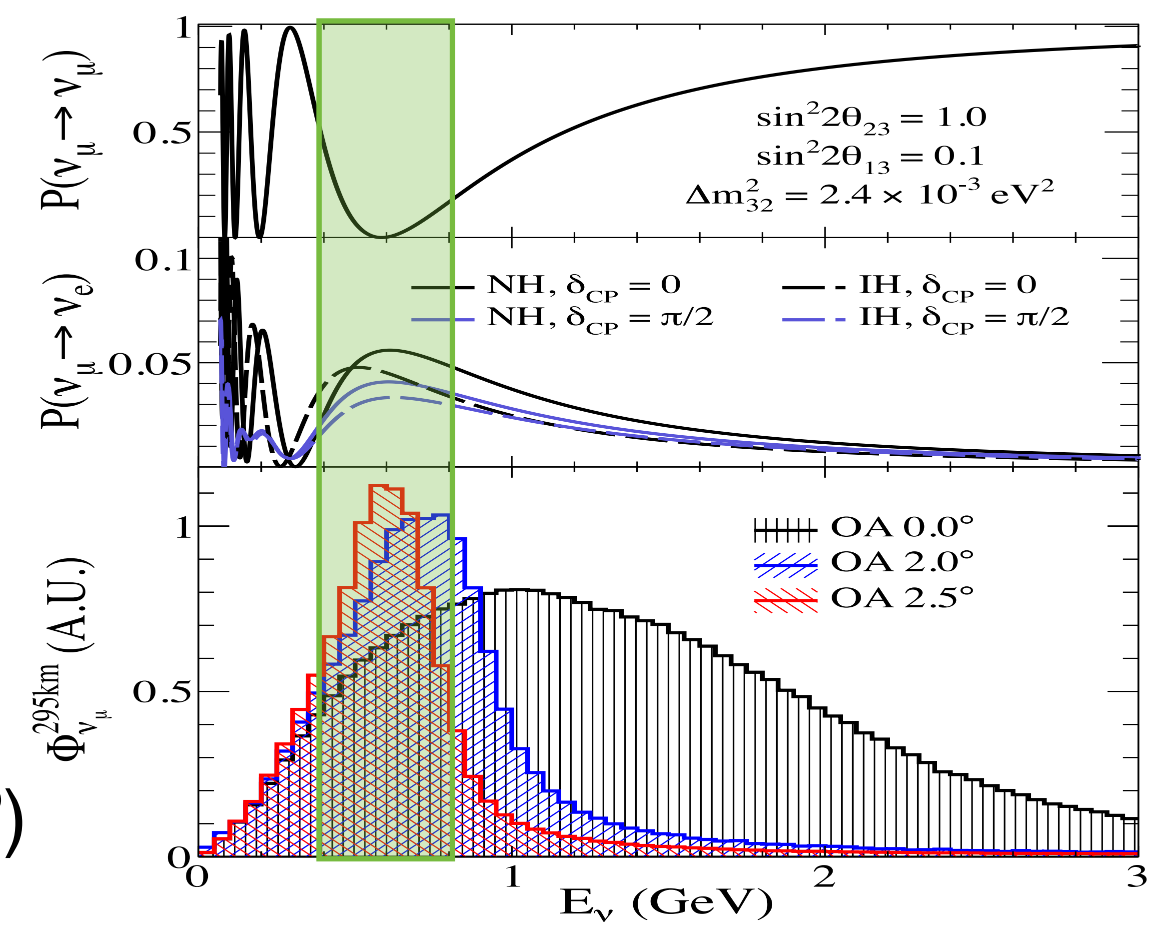
- Higher statistics analysis (e.g. T2K-II, Hyper-K, DUNE) may require optimized statistical tools and more CPU resources...

BACKUP

Design principle: the off-axis angle

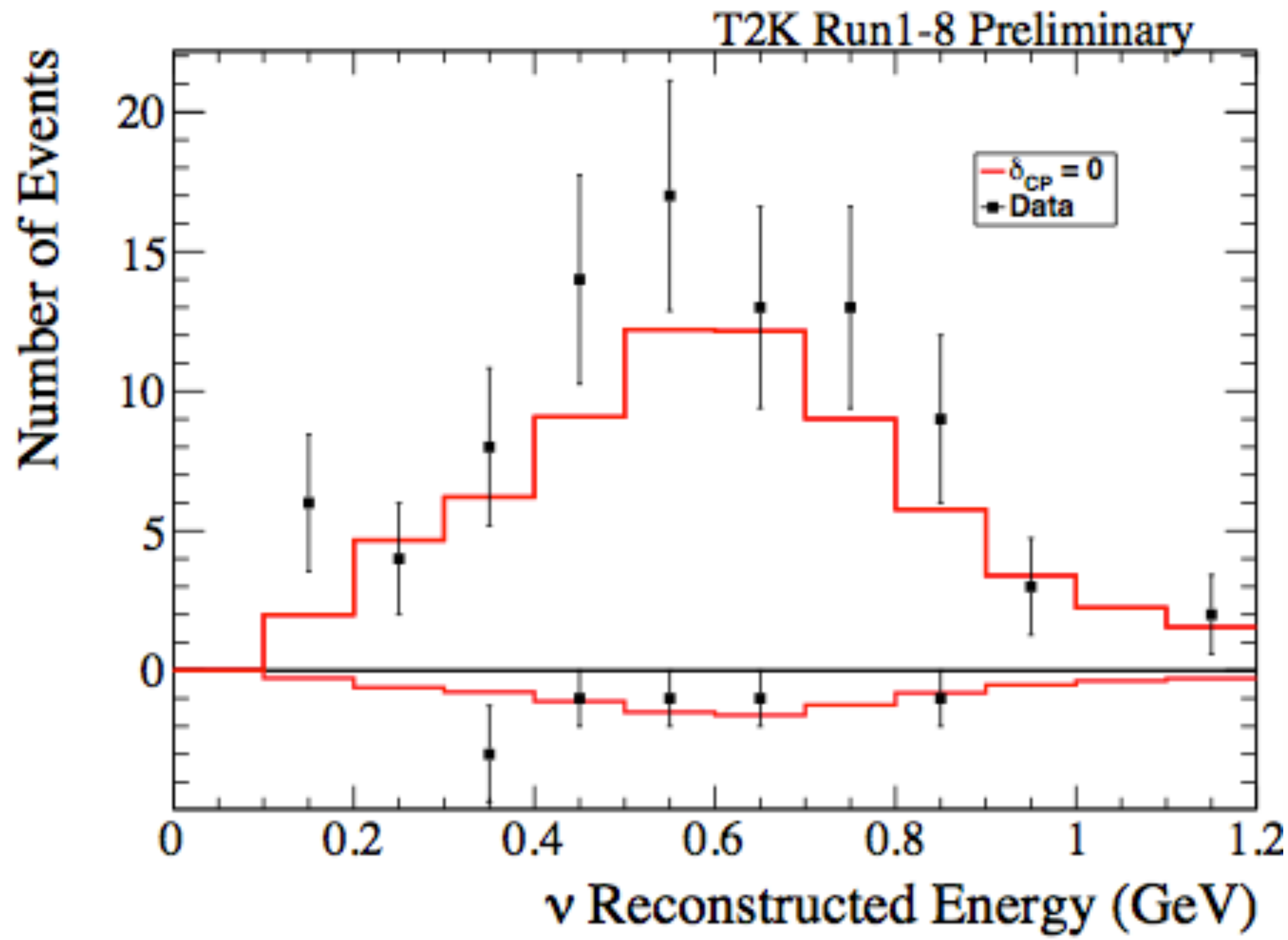


- 30 GeV proton beam on 90 cm long graphite target
- ν_μ and $\overline{\nu}_\mu$ produced by pion and kaon decay:
  - $\pi^+ \to \mu^+ + \nu_\mu$
  - $\pi^- \to \mu^- + \overline{\nu}_\mu$
- Invert magnet polarity to produce a $\overline{\nu}_\mu$ beam
- First off-axis neutrino beam experiment (2.5°)



  - narrow spectrum peaked at 0.6 GeV, on the expected oscillation maximum

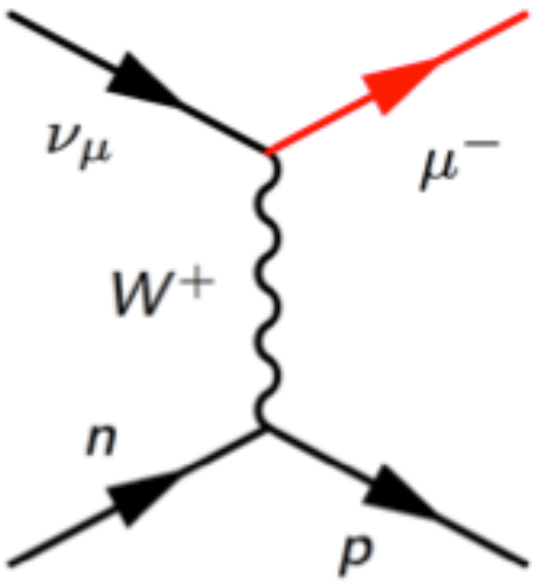
	Set A	Set B
$\sin^2\theta_{12}$	0.304	0.304
$\sin^2\theta_{23}$	0.528	0.45
$\sin^2\theta_{13}$	0.0219	0.0219
Δm^2_{12}	7.53×10^{-5} eV^2	7.53×10^{-5} eV^2
Δm^2_{23}	2.509×10^{-3} eV^2	2.509×10^{-3} eV^2
δ_{CP}	-1.601	0



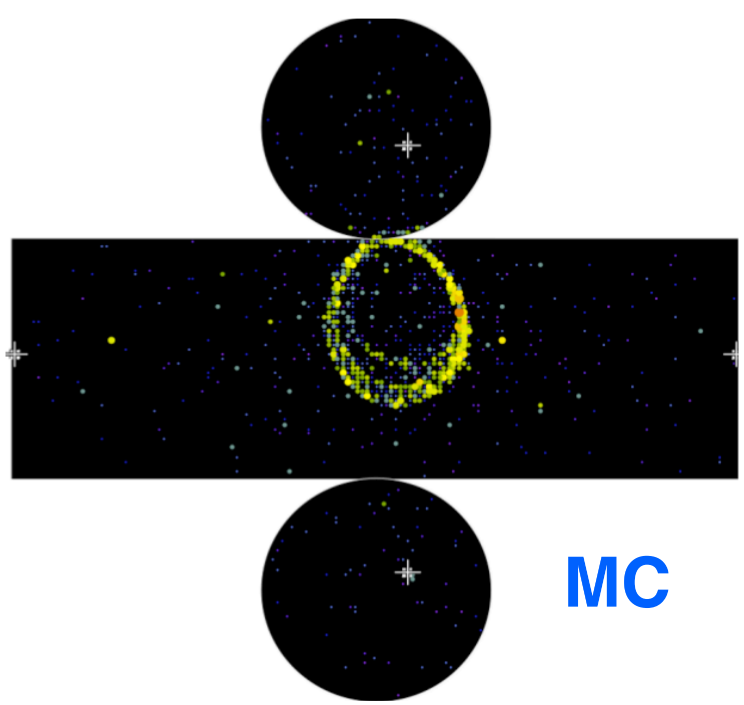
Sample	Predicted Rates (pars except δ_{CP} take set A values)				Observed Rates
	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = \pi/2$	$\delta_{CP} = \pi$	
CCQE 1-Ring e-like ν-mode	73.5	61.5	49.9	62.0	74
CC1π 1-Ring e-like ν-mode	6.92	6.01	4.87	5.78	15
CCQE 1-Ring e-like $\bar{\nu}$-mode	7.93	9.04	10.04	8.93	7
CCQE 1-Ring μ-like ν-mode	267.8	267.4	267.7	268.2	240
CCQE 1-Ring μ-like $\bar{\nu}$-mode	63.1	62.9	63.1	63.1	68

Super-Kamiokande events

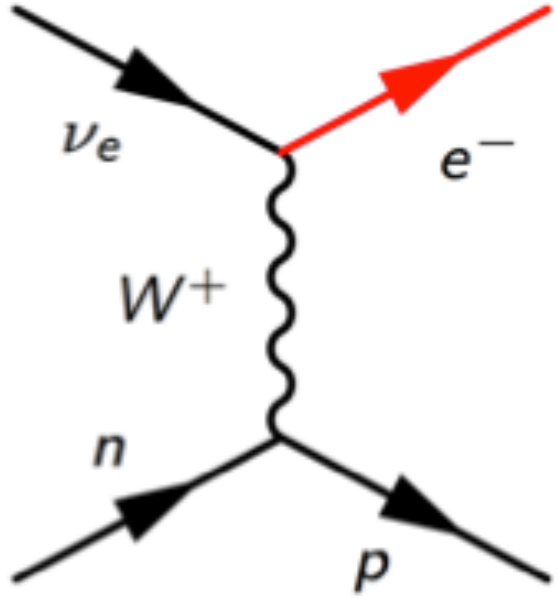
ν_μ CCQE



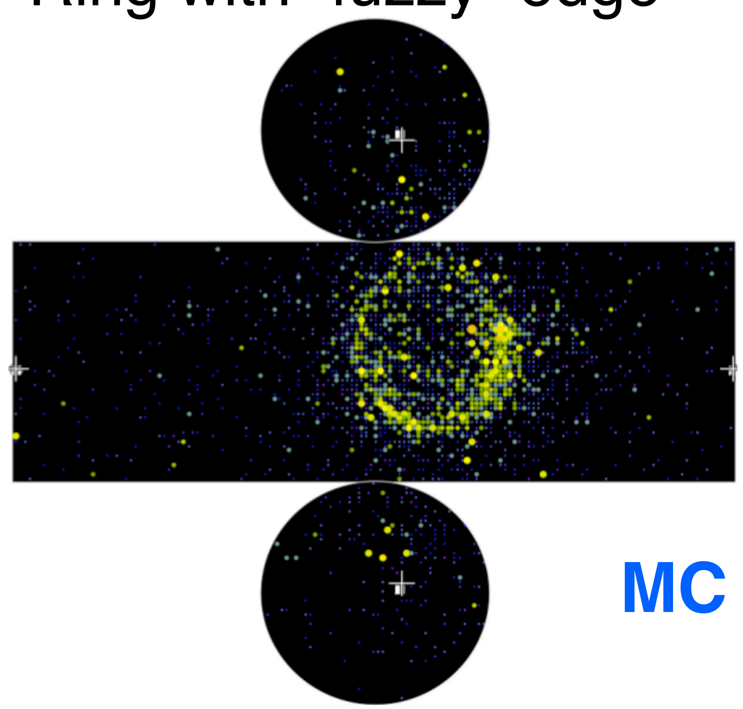
- 1 Cherenkov ring (protons below threshold)
- Low scattering
- Ring with sharp edge



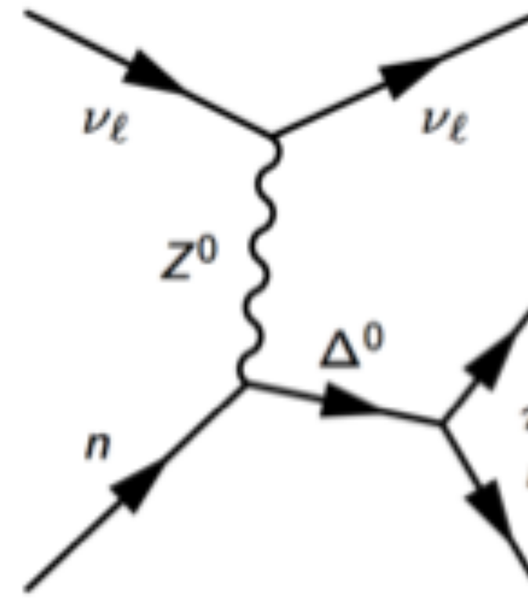
ν_e CCQE



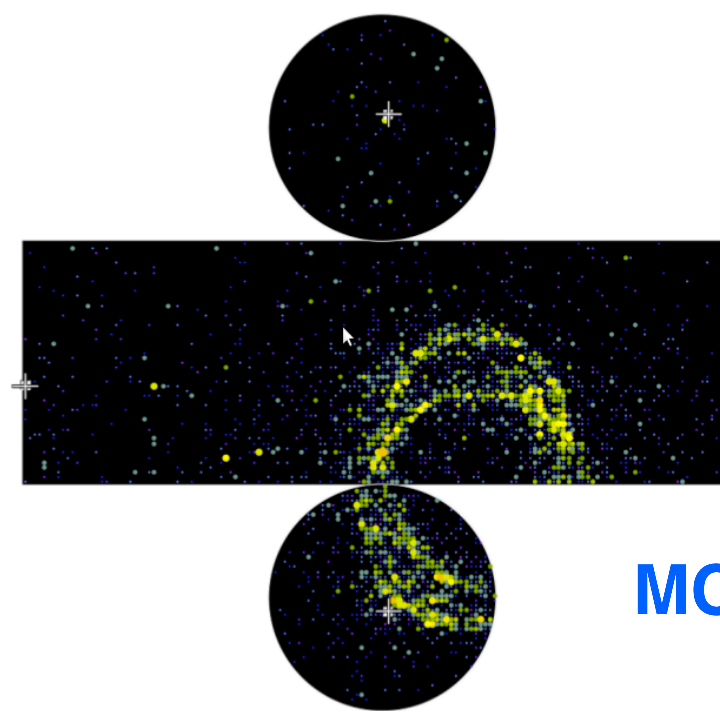
- 1 Cherenkov ring
- Multiple scattering
- EM shower
- Ring with “fuzzy” edge



Background



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



- Probability to misidentify a muon as an electron is smaller than 1%

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

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

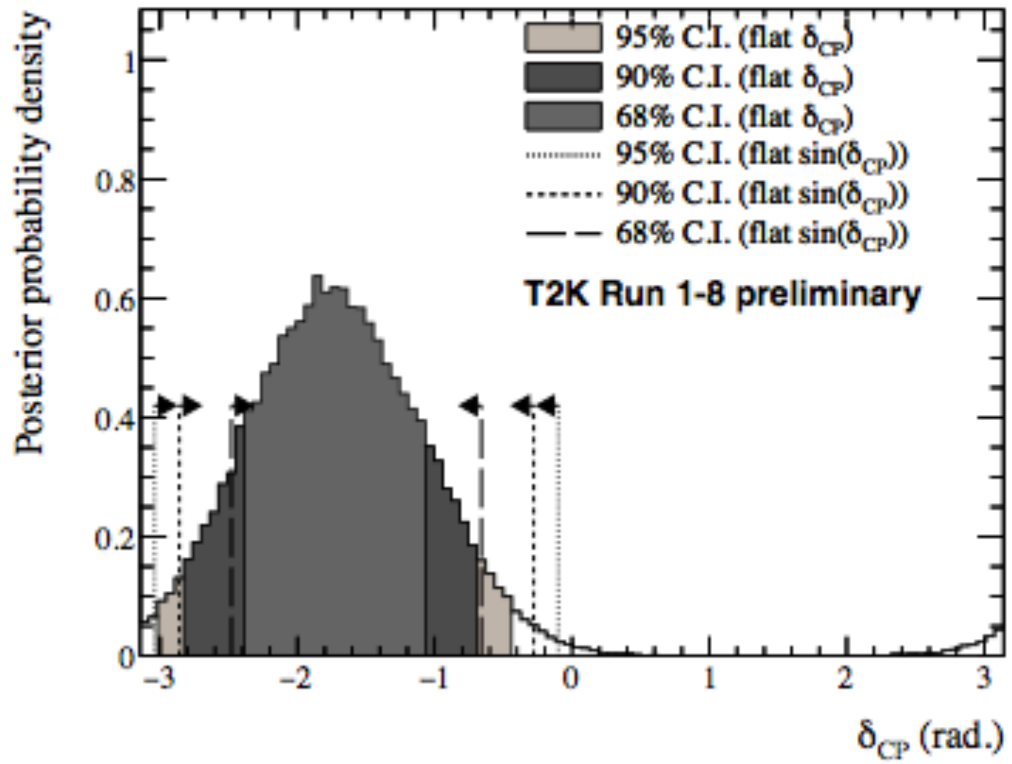
$$+ O(\alpha^2)$$

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

- The leading term defines the octant $\Theta_{23}>45°$ or $\Theta_{23}<45°$
- All mass splittings and mixing angles have been measured to be non-zero: second order term can violate the CP symmetry if $\sin\delta_{CP} \neq 0$

Bayesian analysis

- Produce posterior probability distributions and credible intervals in Bayesian analysis
- Two choices for priors: flat in δ_{cp} and flat in $\sin(\delta_{cp})$



The 2σ confidence interval:
Flat prior on δ_{cp}: [-3.02, -0.44] radians
Flat prior on $\sin(\delta_{cp})$: [-3.04, -0.10] radians

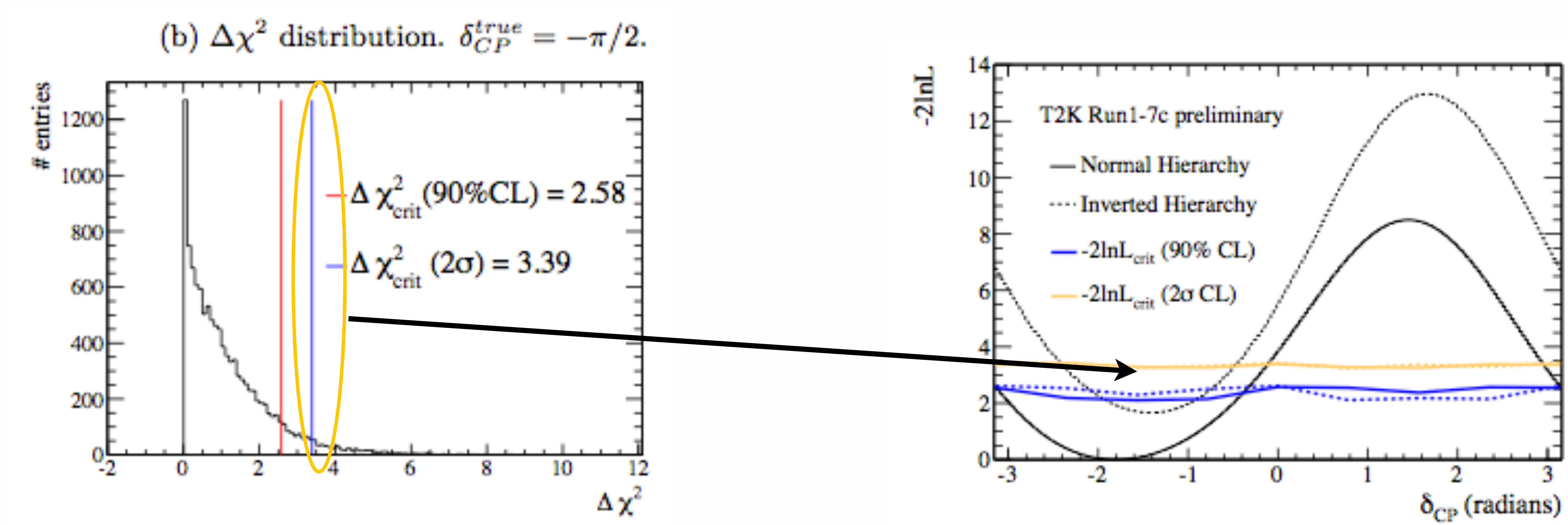
CP conserving values $(0,\pi)$ fall outside of the 2σ intervals

	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Sum
NH ($\Delta m^2_{32} > 0$)	0.193	0.674	0.868
IH ($\Delta m^2_{32} < 0$)	0.026	0.106	0.132
Sum	0.219	0.781	

Statistical methods

• Hybrid Bayesian-Frequentist analysis (confidence intervals):

- scan $\Delta\chi^2 = -2\ln\lambda_{marg}$ surface as a function of e.g. δ_{CP}
- if $\Delta\chi^2 > \Delta\chi^2_{crit}$ --> excluded at X%CL
- Use Feldman-Cousins method: MC method to evaluate $\Delta\chi^2_{crit}$
- Two analyses: VALOR using Ereco-Θ (primary analysis) and p-Θ



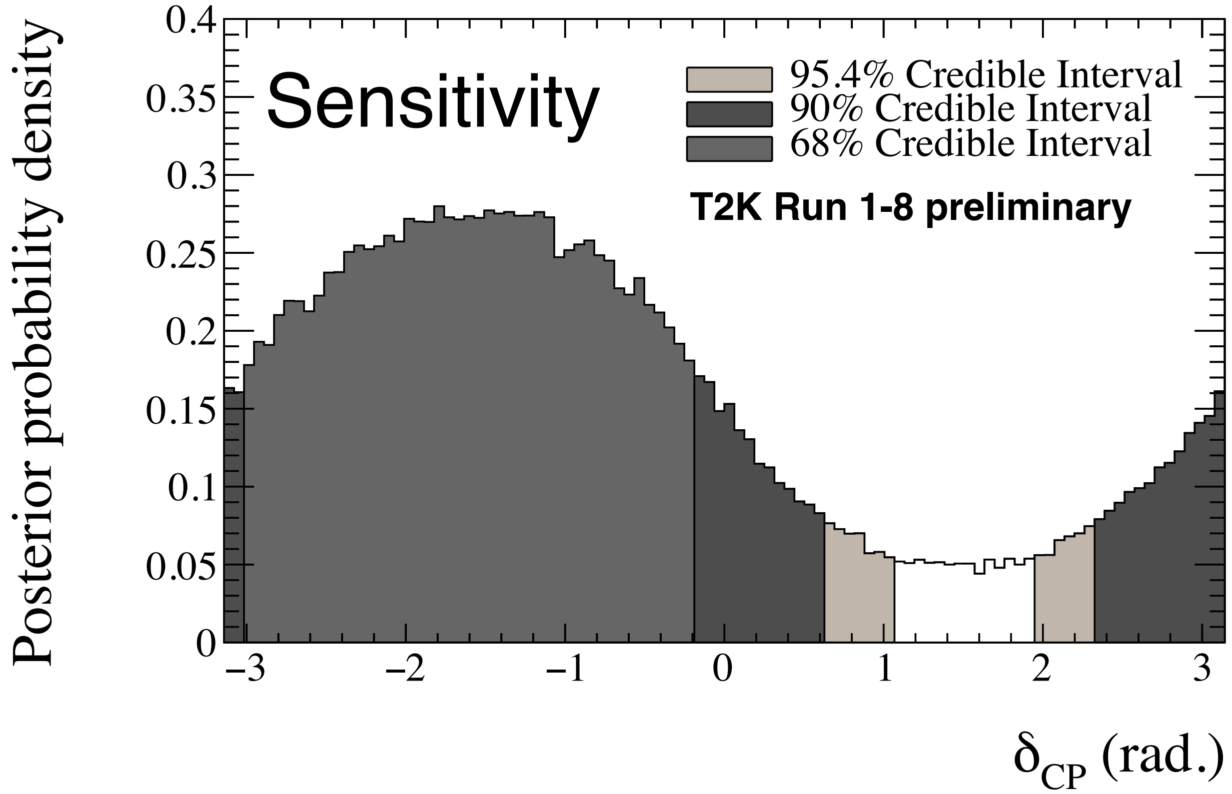
Statistical methods

• Hybrid Bayesian-Frequentist analysis (confidence intervals):

- scan $\Delta\chi^2 = -2\ln\lambda_{marg}$ surface as a function of e.g. δ_{CP}
- if $\Delta\chi^2 > \Delta\chi^2_{crit}$ --> excluded at X%CL
- Use Feldman-Cousins method: MC method to evaluate $\Delta\chi^2_{crit}$
- Two analyses: VALOR using Ereco-ϴ, p-ϴ analysis

• Fully Bayesian analysis (credible intervals):

- Markov Chain MC
- Bayesian intervals: weighted by the prior on δ_{CP}
- Using Ereco-ϴ
- Joint fit of Near and Far detector: validation of the near to far detector extrapolation



Agreement between all the 3 analyses