The Hyper-Kamiokande experiment: Long Baseline Sensitivity

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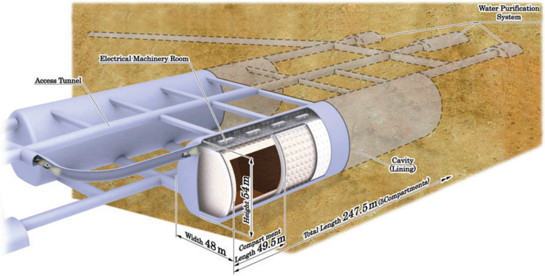
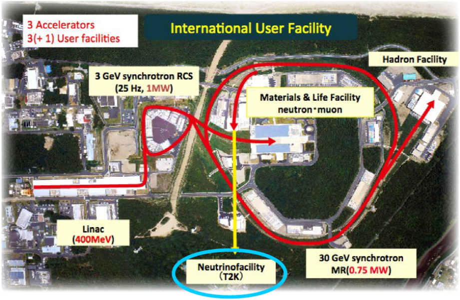
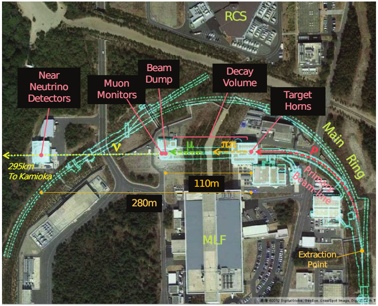
The Hyper-Kamiokande Experiment



- Proposed successor to successful Super-Kamiokande.
- Baseline design:
  - 50kT→990kT total volume.
  - 22.5kT→560kT fiducial volume
  - 11k 20" PMTs→99k 20" PMTs (20% coverage)
  - 25k 8" PMTs for outer veto detector.
  - 10 optically segmented volumes
- Near detector proposals: see talk A. Minamino.

The neutrino beam at J-PARC





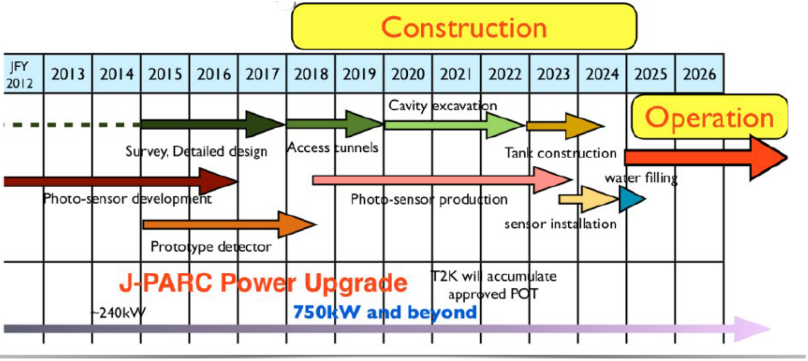
- Several upgrades planned to reach 750kW beam power for T2K in the next few years (current beam power at 340 kW).
- Discussion ongoing for feasibility beyond 1MW.

Photosensors candidates for HyperK

20inch:

- Standard SK PMT: 20y experience, reliable, well known, but low CE, QE and TTS, expensive.
- HQE Box&Line 20": under development, better performance, same type of techology.
- Development of 20" Hybrid PD with avalanche diode (HPD): under development, superior performance, new technology, high risk.

Hyper-Kamiokande Timeline



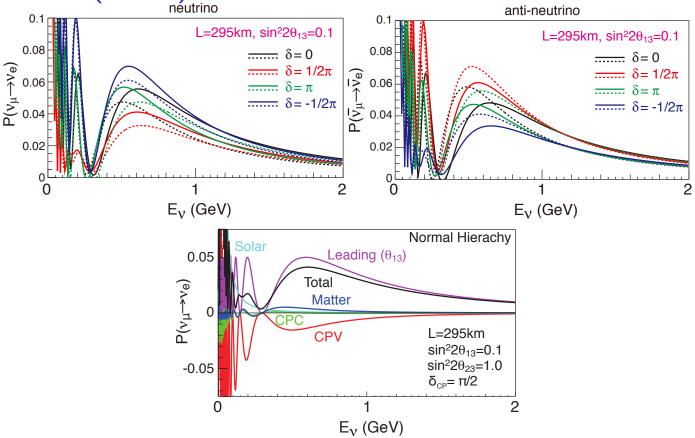
Neutrino Oscillations

$$
\underbrace{\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}}_{\text{Flavor eigenstate}} = \overbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}^{\substack{\text{Atmospheric+Accelerator} \\ \text{(Super-K, T2K, MINOS, IceCube)}}} \overbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix}}^{\substack{\text{Accelerator+Reactor} \\ \text{(Daya-Bay, RENO, Double-Chooz, T2K)}}} \overbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}^{\substack{\text{Solar+Reactor} \\ \text{(SNO, KamLAND)}}}
$$

$$
\times \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_{21}/2} & 0 \\ 0 & 0 & e^{i\alpha_{31}/2} \end{pmatrix}}_{\substack{\text{Dirac vs Majorana} \\ (\nu\text{-less double } \beta\text{-decay})}} \underbrace{\begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}}_{\text{Mass eigenstate}}
$$

- Unitary transformation from mass eigenstates $\nu_i (i = 1, 2, 3)$ to flavor eigenstates $\nu_\alpha (\alpha = e, \mu, \tau)$.
- Unitary matrix: $c_{ij} \equiv \cos\theta_{ij}$, $s_{ij} \equiv \sin\theta_{ij}$, δ_{CP}, the Dirac CP-violating phase and $\alpha_{31,21}$, the Majorana phases.
- Since non-zero measurement of θ_{13}: all mixing angles known and δ_{CP} accessible.

CP violation (CPV) with ν vs $\bar{\nu}$



- CPV needs non-zero mixing angles.
- CPV can be probed through difference between neutrino and anti-neutrino appearance:

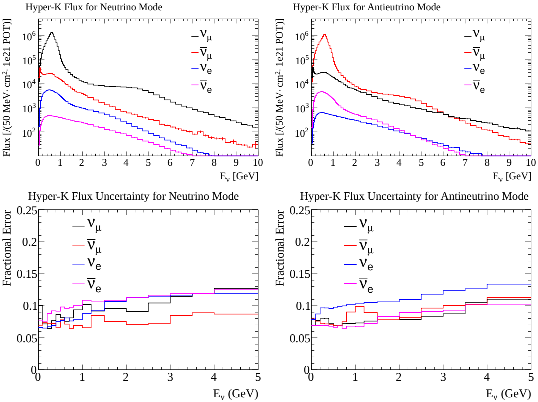
$$P(\nu_\mu \to \nu_e) - P(\overline{\nu}_\mu \to \overline{\nu}_e) = -16 s_{12} c_{12} s_{23} c_{23} s_{13} c_{13}^2 \sin\delta_{CP} \sin\left(\frac{\Delta m_{21}^2 L}{4E_\nu}\right) \sin\left(\frac{\Delta m_{32}^2 L}{4E_\nu}\right) \sin\left(\frac{\Delta m_{31}^2 L}{4E_\nu}\right)$$

- At L = 295 km, $E_\nu \approx$0.6 GeV: effect of CP violation up to 28% while matter effect only 7%.

Oscillation analysis for Hyper-K sensitivity

- At least 750kW beam power expected at start of experiment ($\sim$2026)
- Assumed 7.5MW$\times 10^7$s (1.56×10^{22} POT).
- Nominal beam sharing $\nu - \bar{\nu}$: 1:3.
- In each of the 10 compartiments reconstruction performance is similar as SK-IV: use full SK full detector MC with Hyper-K statistics.

Neutrino and anti-neutrino flux with J-PARC beam



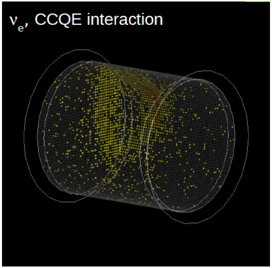
- Neutrino flux is estimated by T2K collaboration by tuning MC modeling of hadronic interactions to NA61/SHINE data.
- Currently thin target used, while new tuning based on T2K replica-target data (90cm target) is ongoing.
- For flux uncertainty on HyperK unoscillated flux: assume tuning based on replica target data and assume increased horn current from 250kA to 320kA.

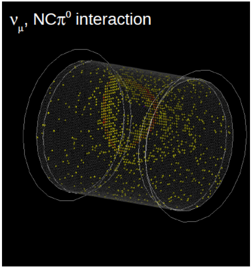
$\Rightarrow$ See talk M. Hartz for details.

Event selection

- Based on selection for Super-K and T2K.
- Fully contained inside fiducial volume (FCFV): reconstructed vertex position at least 2m from the wall due to degrading reconstruction performance and larger backgrounds.
- Visible energy greater than 30 MeV.
- Enhance CCQE: only select events with one Cherenkov ring.

ν_e Selection

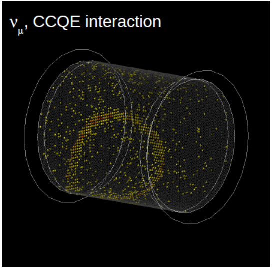




$\nu_e/\overline{\nu}_e$ Selection:

- The reconstructed ring is identified as electron-like (e-like).
- The visible energy (E_{vis}) is greater than 100 MeV.
- There is no decay electron associated to the event.
- The reconstructed energy (E_ν^{rec}) is less than 1.25 GeV.
- In order to reduce the background from mis-reconstructed π^0 events, additional criteria using the reconstructed π^0 mass and the ratio of the best-fit likelihoods of the π^0 and electron fits is applied.

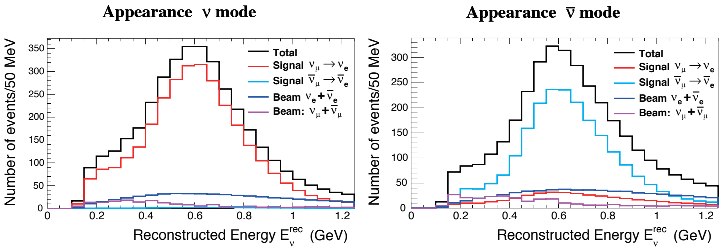
ν_μ Selection



$\nu_\mu/\overline{\nu}_\mu$ Selection:

- The reconstructed ring is identified as muon-like (μ-like).
- The reconstructed muon momentum is greater than 200 MeV/c.
- There is at most one decay electron associated to the event.

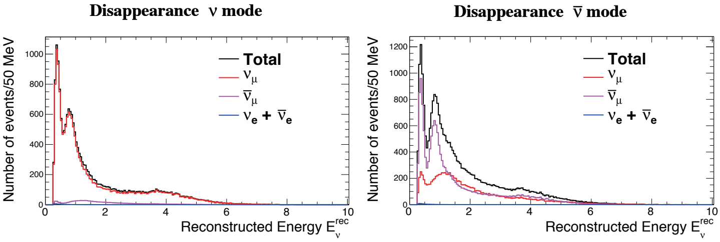
ν_e Appearance ($\nu_\mu \rightarrow \nu_e$)



- Large statistics!
- Dominant background is intrinsic $\nu_e$contamination in beam in neutrino mode.
- Suppression of mis-identified π^0 from improved π^0 rejection.
- In anti-neutrino mode also larger wrong-sign background.

	signal		BG					Total
	$\nu_\mu \rightarrow \nu_e$	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	ν_μ CC	$\bar{\nu}_\mu$ CC	ν_e CC	$\bar{\nu}_e$ CC	NC	
ν mode	**3016**	28	11	0	503	20	172	3750
$\bar{\nu}$ mode	396	**2110**	4	5	222	396	265	3397

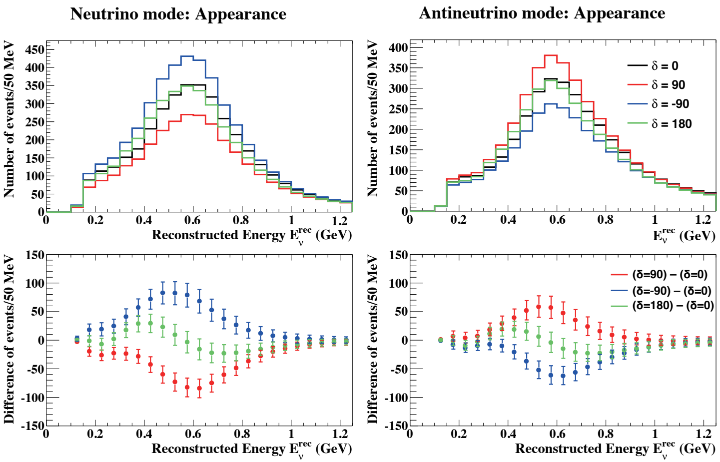
ν_μ Disappearance ($\nu_\mu \to \nu_\mu$)



- In neutrino mode, mostly ν_μ.
- In antineutrino mode, significant wrong-sign $\nu_\mu$contribution.

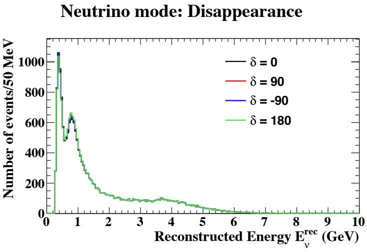
	ν_μ CC	$\bar{\nu}_\mu$ CC	ν_e CC	$\bar{\nu}_e$ CC	NC	$\nu_\mu \to \nu_e$	Total
ν mode	**17225**	1088	11	1	999	49	19372
$\bar{\nu}$ mode	10066	**15597**	7	7	1281	6	26964

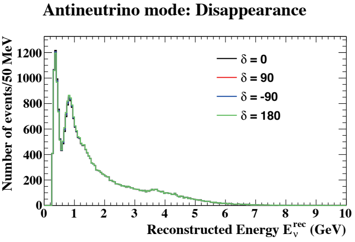
Effect of CPV on ν_e appearance



- Clear effect of CPV in ν_e appearance difference.
- Also shape information relevant for CPV!

Effect of CPV on ν_μ disappearance





- Difference in disappearance energy distribution very small as expected.

Systematic Uncertainties

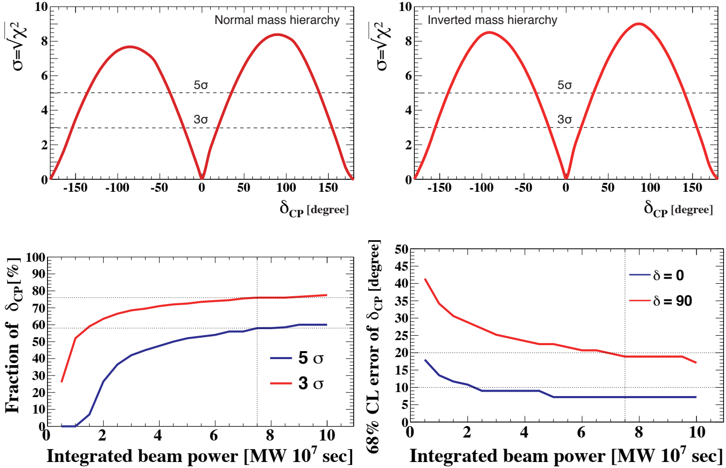
		Flux & ND-constrained cross section	ND-independent cross section	Far detector	Total
ν mode	Appearance	3.0	1.2	0.7	3.3
	Disappearance	2.8	1.5	1.0	3.3
$\overline{\nu}$ mode	Appearance	5.6	2.0	1.7	6.2
	Disappearance	4.2	1.4	1.1	4.5

Based on experience and prospects of T2K

- Flux and near detector cross section errors: Assume same as current constraints by T2K near detector fit.
- Unconstrained cross section errors: Will be reduced as more samples are added to near detector fit (eg. water samples).
- Far detector efficiency and reconstruction uncertainty: Estimated using atmospheric neutrino control sample. Will be reduced due to huge statistics in Hyper-K.

$\Rightarrow$ See talk M.Hartz on Thursday.

CP Sensitivity

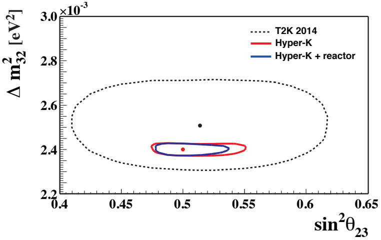


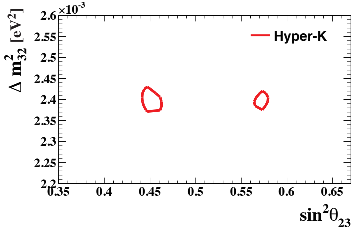
If Mass Hierarchy known:

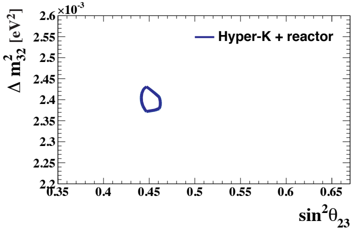
- Fraction for which $\sin\delta_{CP}=0$ can be excluded with more than 3(5)σ is 76%(58%).
- δ_{CP} precision is better than 19° for 7.5MW$\times 10^7$s.

Sensitivity to Δm^2_{32} and $\sin^2\theta_{23}$

True $\sin^2\theta_{23}$	$\sin^2\theta_{23}$	Δm^2_{32} (10^{-5}eV^2)
0.45	0.006	1.4
0.50	0.015	1.4
0.55	0.009	1.5

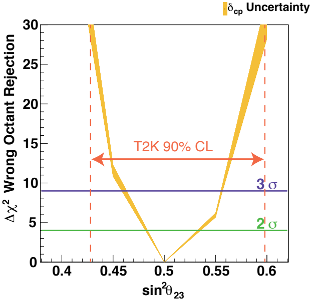


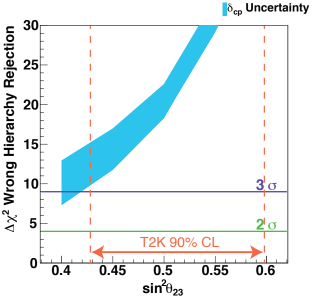




- $\sin^2 2\theta_{23}$ and Δm^2_{23} also free parameters in OA fit.
- Octant degeneracy resolved with a constraint from reactor experiments

Atmospheric ν: Octant and Mass Hierarchy Sensitivity

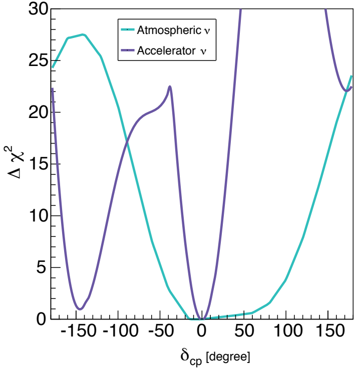


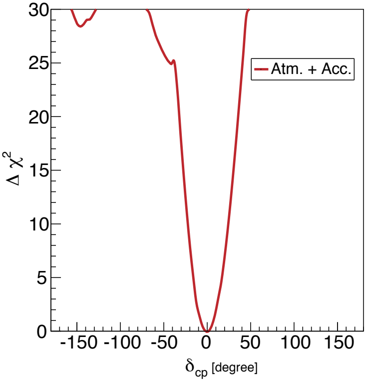


Assuming 10y exposure:

- Octant resolution with reactor θ_{13}: wrong octant rejection for $\sin^2\theta_{23} < 0.46$ or > 0.56.
- If mass hierarchy not yet known: Hyper-K can determine mass hierarchy using its atmospheric neutrino sample.

Combine Accelerator and Atmospheric Data





- If mass hierarchy unknown, several minima because unable to separate CP violation from matter effects.
- Combination of accelerator and atmospheric data resolves ambiguity!

Hyper-Kamiokande: broad range of physics

	Physics target	Sensitivity	Conditions
Neutrino Oscillation Physics	Neutrino study w/ J-PARC ν		$7.5\,\text{MW} \times 10^7\,\text{s}$
	$-$ CP phase precision	$<19°$	@ $\sin^2 2\theta_{13} = 0.1$, mass hierarchy known
	$-$ CPV discovery coverage	$76\%\ (3\sigma)$, $58\%\ (5\sigma)$	@ $\sin^2 2\theta_{13} = 0.1$, mass hierarchy known
	$-$ $\sin^2\theta_{23}$	± 0.015	1σ @ $\sin^2\theta_{23} = 0.5$
Atmospheric Neutrino Physics	Atmospheric neutrino study		10 yr observation
	$-$ MH determination	$>3\sigma$ CL	@ $\sin^2\theta_{23} > 0.4$
	$-$ θ_{23} octant determination	$>3\sigma$ CL	@ $\sin^2\theta_{23} < 0.46$ or $\sin^2\theta_{23} > 0.56$
Proton Decay	Nucleon decay searches		10 yr data
	$-$ $p \to e^+ + \pi^0$	1.3×10^{35} yr (90% CL UL)	
		5.7×10^{34} yr (3σ discovery)	
	$-$ $p \to \bar{\nu} + K^+$	3.2×10^{34} yr (90% CL UL)	
		1.2×10^{34} yr (3σ discovery)	
Astroparticle Physics	Astrophysical neutrino sources		
	$-$ ^{8}B ν from Sun	200 ν/day	7.0 MeV threshold (total energy) w/ osc.
	$-$ Supernova burst ν	170 000–260 000 ν	@ Galactic center (10 kpc)
		30–50 ν	@ M31 (Andromeda galaxy)
	$-$ Supernova relic ν	830 ν/10 yr	
	$-$ WIMP annihilation at Sun		5 yr observation
	(σ_{SD}: WIMP–proton spin-dependent cross section)	$\sigma_{SD} = 10^{-39}\,\text{cm}^2$	@ $M_{\text{WIMP}} = 10\,\text{GeV}$, $\chi\chi \to b\bar{b}$ dominant
		$\sigma_{SD} = 10^{-40}\,\text{cm}^2$	@ $M_{\text{WIMP}} = 100\,\text{GeV}$, $\chi\chi \to W^+W^-$ dominant
...			

- High energy physics: accelerator neutrinos and atmospheric neutrinos.
- Low energy physics: Solar neutrinos, Supernova neutrinos, WIMP neutrinos.
- Nucleon decay.

Conclusion

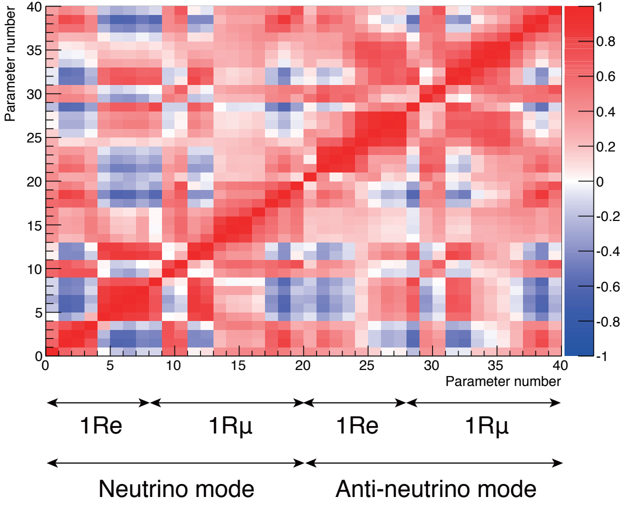
- Proto-collaboration formed in Jan. 2015.
- Rich physics programme.
- Next generation multi-purpose experiment:
  - Ability to measure δ_{CP}at 3σ for 76% of its phase space!
  - Solve octant degeneracy and mass hierarchy, θ_{23}, Δ^2_{32} with combination of atmospheric and accelator neutrinos.
- Data taking starts around 2025 according to current schedule.

Backup

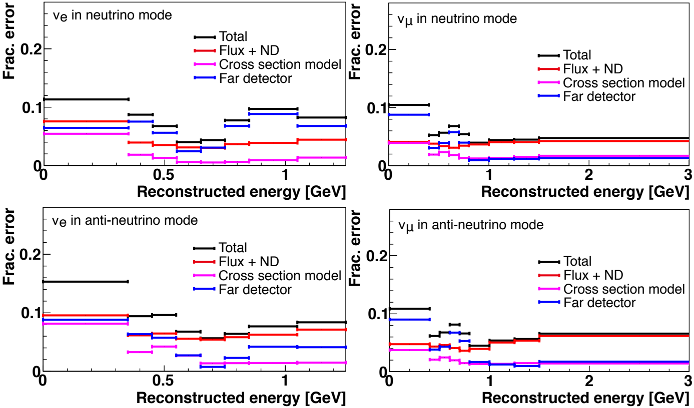
Treatment of Oscillation parameters in fit

Parameter	Nominal value	Treatment
$\sin^2 2\theta_{13}$	0.10	Fitted
δ_{CP}	0	Fitted
$\sin^2 \theta_{23}$	0.50	Fitted
Δm^2_{32}	$2.4 \times 10^{-3}\ \mathrm{eV}^2$	Fitted
Mass hierarchy	Normal or Inverted	Fixed
$\sin^2 2\theta_{12}$	0.8704	Fixed
Δm^2_{21}	$7.6 \times 10^{-5}\ \mathrm{eV}^2$	Fixed

Systematic Uncertainties



Systematic Uncertainties



Expected uncertainty on Δm^2_{32} and $\sin^2\theta_{23}$

True $\sin^2\theta_{23}$	0.45		0.50		0.55	
Parameter	Δm^2_{32} (eV^2)	$\sin^2\theta_{23}$	Δm^2_{32} (eV^2)	$\sin^2\theta_{23}$	Δm^2_{32} (eV^2)	$\sin^2\theta_{23}$
NH	1.4×10^{-5}	0.006	1.4×10^{-5}	0.015	1.5×10^{-5}	0.009
IH	1.5×10^{-5}	0.006	1.4×10^{-5}	0.015	1.5×10^{-5}	0.009

- Expected 1σ uncertainty for different true values of $\sin^2\theta_{23}$.
- Reactor constraint on $\sin^2 2\theta_{13} = 0.1 \pm 0.005$ is imposed.