HyperK sensitivity studies with simple-fitter

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Introduction: Simple Fitter

Characteristics of the simple fitter

- Simultaneous fit of appearance and disappearance spectra from both neutrino and anti-neutrino running;
- It uses shape information from reconstructed energy spectrum;
- It corresponds to a binned likelihood: for each energy bin compares the expected number of events for a given value of the oscillation parameters, to the expected number of events in this bin for the true value of the oscillation parameters.
- Systematic parameters are handled in a particular way:
  - Each systematic parameter correspond to a region of reconstructed energy and reweights the number of events in the corresponding energy bin (each energy bin is only reweighted by one nuisance parameters);
  - Sigma of each parameter and correlations between the parameters are given by a covariance matrix, which is obtained by toy MC;
- Selection cuts are the same as for the T2K ν_e and ν_μ analyses;

Simple Fitter has been used for **T2K Future Sensitivity** studies and **Hyper-K sensitivity studies in the J-PARC 2014 LoI** $\rightarrow$ See Yokoyama-san's talk yesterday or back-up slides;

Introduction: Simple Fitter

Parameters considered, unless overwhise stated

- Beam power: 7.5 MW x year $\rightarrow$ 1.56 10^{22} POT;
- Horn current: $\pm$320 kA;
- $\nu : \bar{\nu} \rightarrow$ 1:3;

Parameter	$\sin^2 2\theta_{13}$	δ_{CP}	$\sin^2 \theta_{23}$	Δm^2_{32}	$\sin^2 2\theta_{12}$	Δm^2_{12}
Nominal	0.10	0	0.5	2.4×10^{-3}	0.8794	7.6×10^{-5}
Treatment	Fitted	Fitted	Fitted	Fitted	Fixed	Fixed

Covariance matrix takes into account 3 sources for systematic errors:

- Parameters constrained by near detector fit
- Parameters non-constrained by near detector fit
- Far detector and finale state interactions: fully correlated between neutrino and anti-neutrino running;

Introduction: Error treatment

	Source	T2K	Hyper-K
I	Fit to Near detector[1]	T2K	T2K
II	CC Other shape[2]	0.4	0
	Spectral function[2]	1.0	0
	Fermi momentum[2]	0.138	0
	Binding energy[2]	0.36	0
	CC Coherent[3]	1	0.5
	NC Other[3]	0.3	0.3
	NC Coherent[3]	0.3	0.3
	Pion-less Δ decay[3]	0.2	0.05
	CC $\sigma_{\nu_e}/\sigma_{\nu_\mu}$	not used	0.03
	CC $\sigma_\nu/\sigma_{\bar{\nu}}$	not used	0.06
III	Final State Interactions	T2K	T2K
	Far detector[4]	T2K	T2K/$\sqrt{20}$

1. Conservative assumption;
2. Measured in current near detector fit;
3. Constrained by new near detector and Hyper-K samples;
4. Atmospheric control sample larger for Hyper-K;

Update on these error studies in Mark's talk tomorrow!

Introduction: updates

- 2014 LoI sensitivity (see Yokoyama-san's talk or back-up slides) has been updated considering:

1. CP sensivity vs $\nu : \bar{\nu}$ running ratio;
2. CP sensivity vs true value of $\sin^2(\theta_{23})$;
3. Sensitivity to mass hierarchy;
4. θ_{23} octant discrimination;

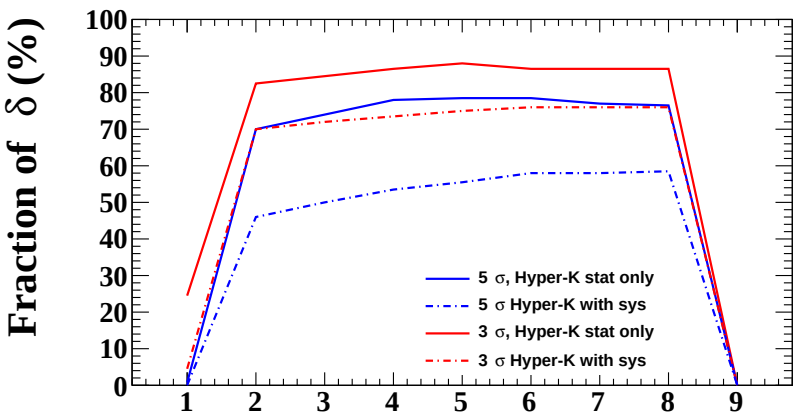
CP sensivity vs $\nu : \bar{\nu}$ running ratio

- For the 2014 LoI we chose the $\nu : \bar{\nu}$ running ratio to be 1:3, in order to have roughly the same number of ν_e ($\bar{\nu_e}$) events in ν and $\bar{\nu}$ mode;
- Study different running ratios:

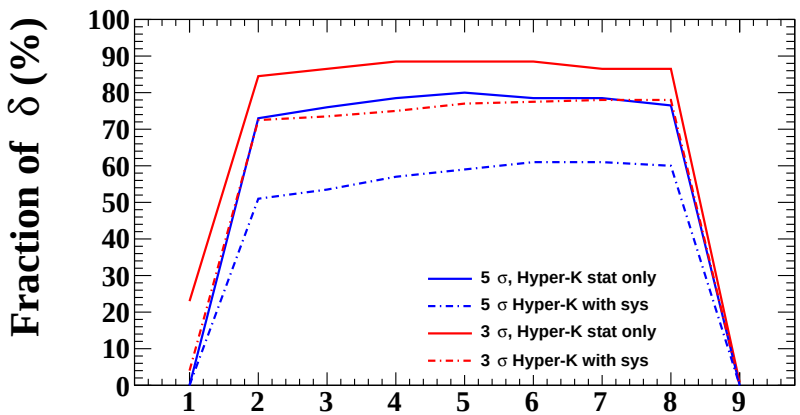
1. All ν;
2. $\nu : \bar{\nu}$ 3:1
3. $\nu : \bar{\nu}$ 2:1
4. $\nu : \bar{\nu}$ 1:1
5. $\nu : \bar{\nu}$ 1:2
6. $\nu : \bar{\nu}$ 1:3
7. $\nu : \bar{\nu}$ 1:4
8. $\nu : \bar{\nu}$ 1:5
9. All $\bar{\nu}$

3/5 σ coverage of δ_{CP} space: **without reactor constraint**

Normal hierarchy



Inverted hierarchy



CP sensivity vs $\nu : \bar{\nu}$ running ratio

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3/5 σ coverage of δ_{CP} space: **with reactor constraint**

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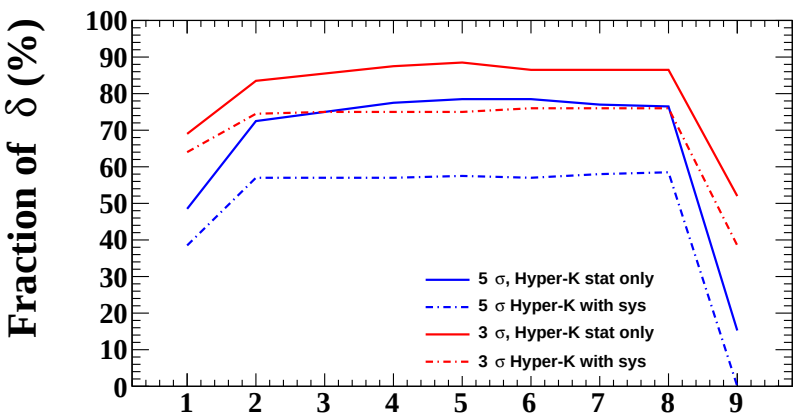

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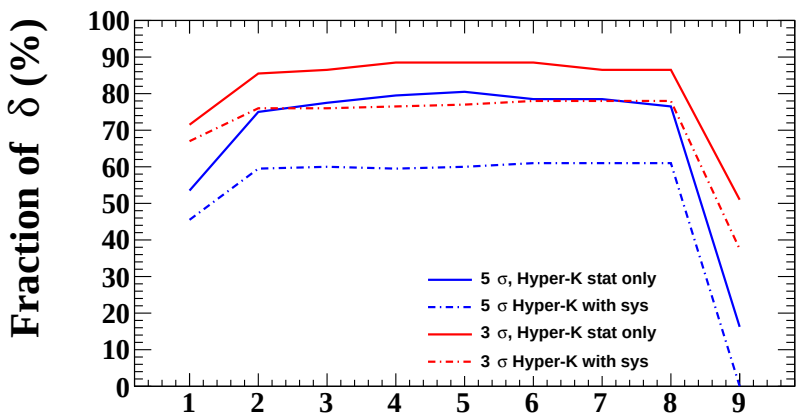

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1 σ error of δ_{CP}: **without reactor constraint**

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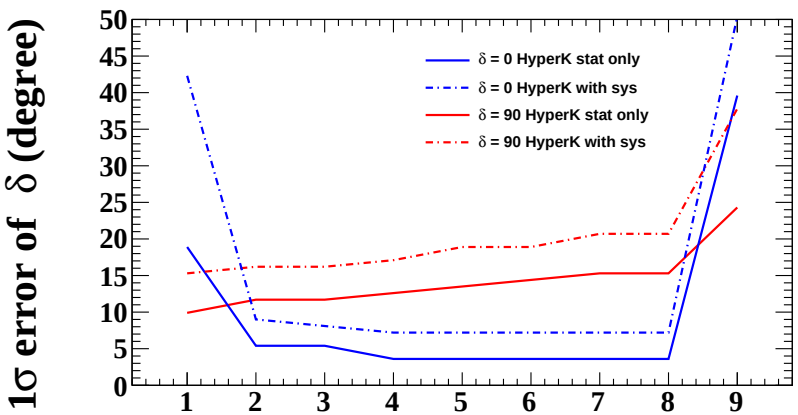

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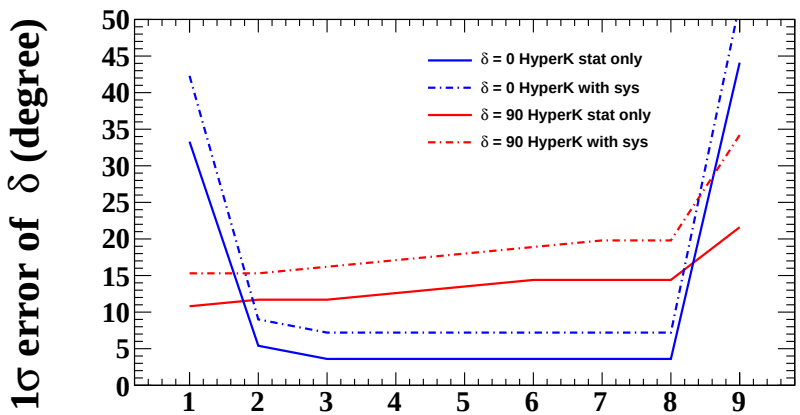

CP sensivity vs ν : $\bar{\nu}$ running ratio

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1 σ error of δ_{CP}: **with reactor constraint**

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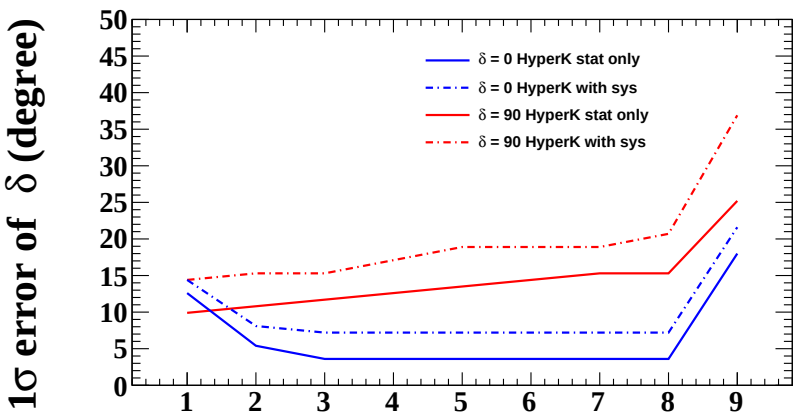

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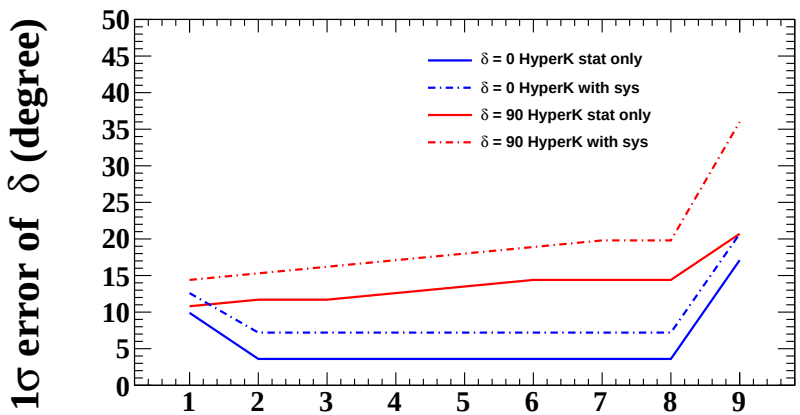


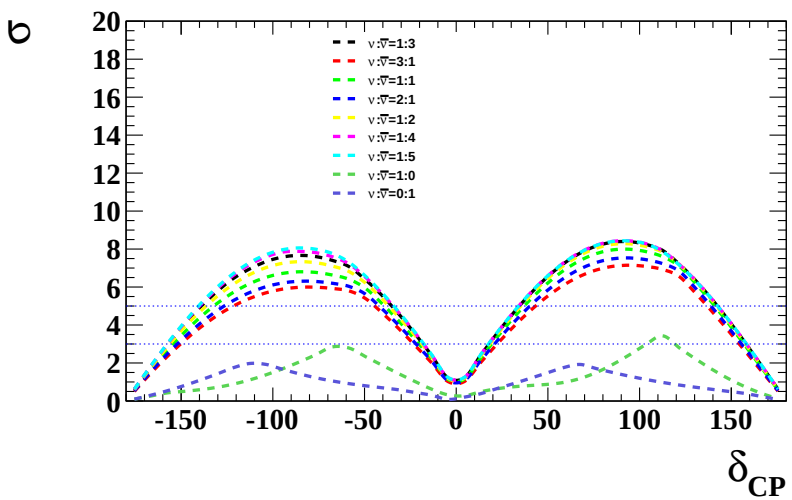
Sensitivity to δ_{CP} discovery

Difference between $\chi^2(\delta_{TRUE})$ and $\chi^2(\sin\delta = 0)$: $\sigma = \sqrt{\Delta\chi^2}$

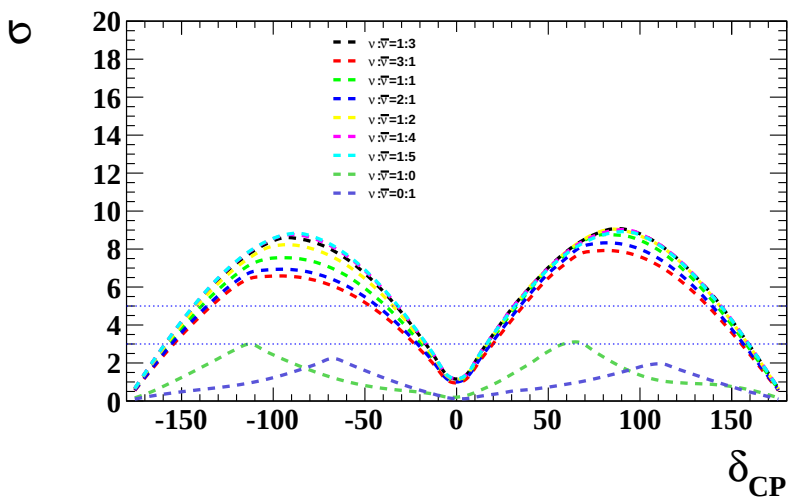
- Without reactor contraint
- Only contours with systematic errors are shown

- Unknown octant
- Known mass hierarchy

Normal hierarchy



Inverted hierarchy



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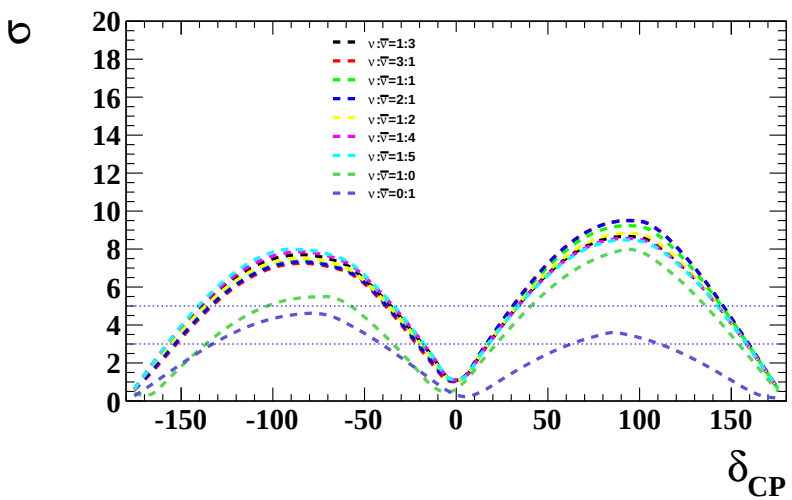

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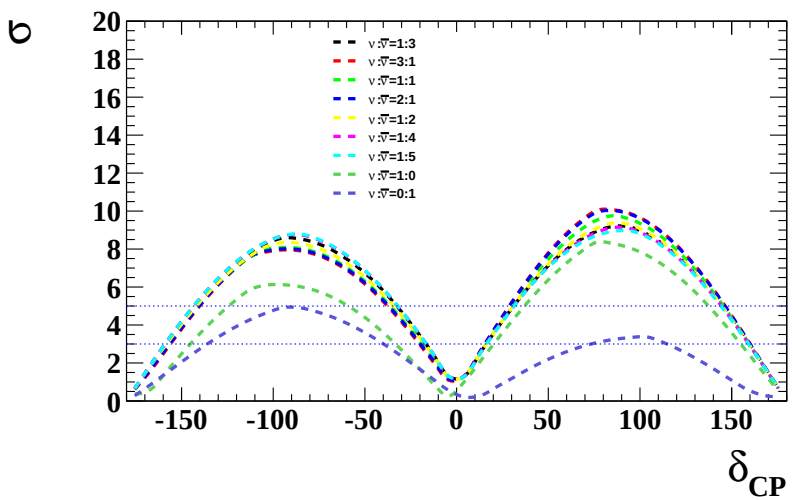


Sensitivity to δ_{CP} discovery

- δ_{CP} coverage prefers a smaller $\nu : \bar{\nu}$ running ratio;
- with reactor constraint, fraction of δ_{CP} space covered at 3 σ (5 σ) is constant for all mixed running ratios at 76% (58%);
- δ_{CP} error is larger with more $\bar{\nu}$ running, but always smaller than 20 degrees for all δ_{CP} values;

as far as we have a mix of neutrino and anti-neutrino running and reactor constraints are considered, there doesn't seem to be a big difference in the δ_{CP} contours

- We might want to consider different criteria to decide the $\nu : \bar{\nu}$ running ratio, such as cross-sections and systematic uncertainties.

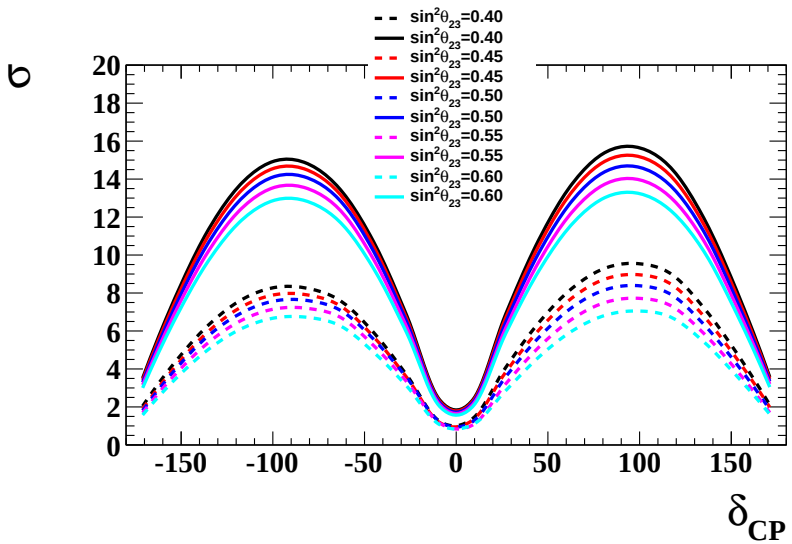
CP sensivity vs true value of $sin^2(\theta_{23})$

Difference between $\chi^2(\delta_{TRUE})$ and $\chi^2(\sin\delta = 0)$: $\sigma = \sqrt{\Delta\chi^2}$

- Without reactor contraint
- Solid line without systematic error; dashed line with systematic error

- Unknown octant
- Known mass hierarchy

Normal hierarchy



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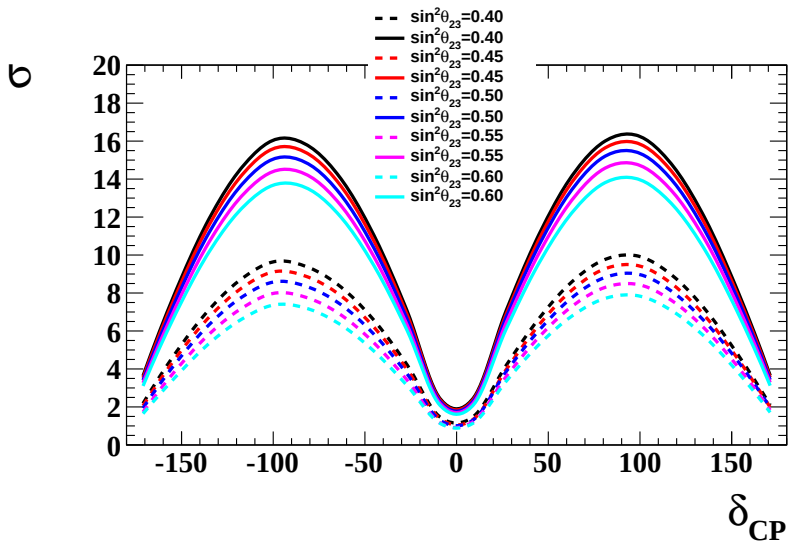
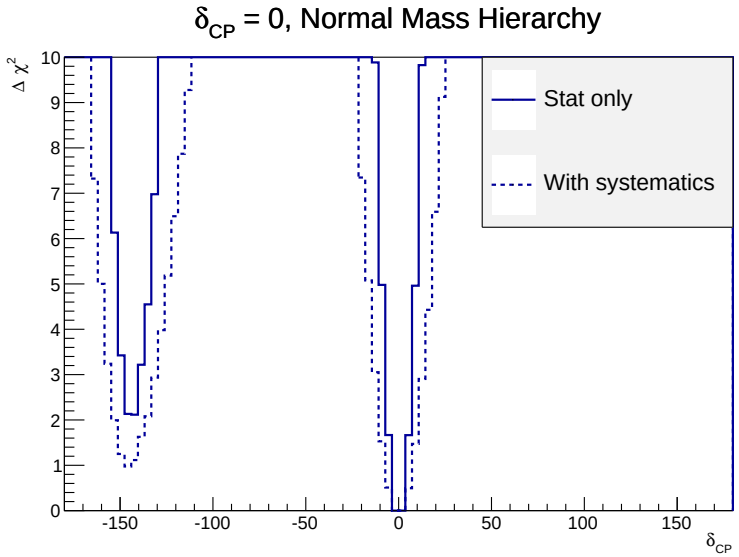
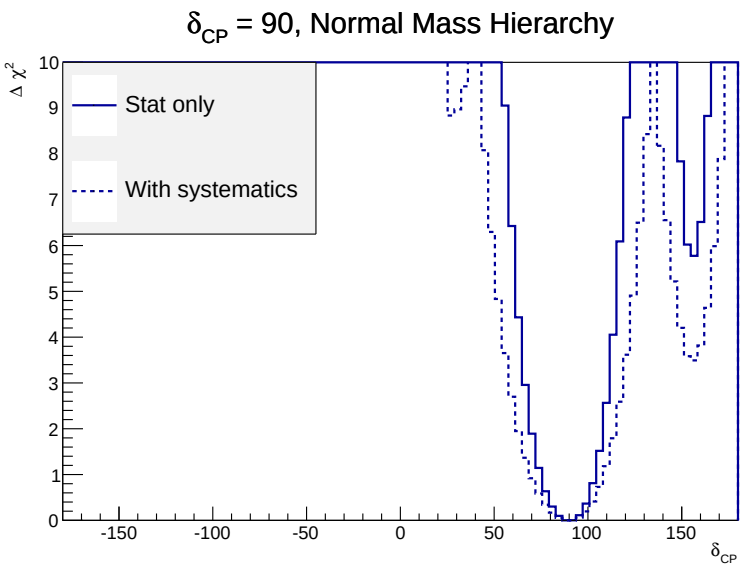


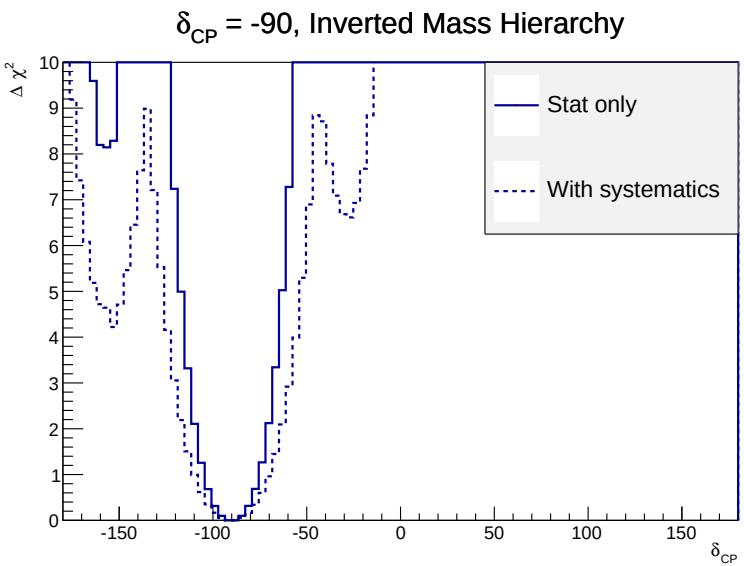
CP sensivity is highly dependent on true value of $\sin^2(\theta_{23})$

Sensitivity to mass hierarchy

- In 2014 J-PARC LoI we showed sensitivity to mass hierarchy of long-baseline and atmospheric data together.
- What can T2HK say about the mass hierarchy?
- $\Delta\chi^2$ contours evaluated with **unknown** mass hierarchy;
- In all plots $\sin^2\theta_{23} = 0.5$;

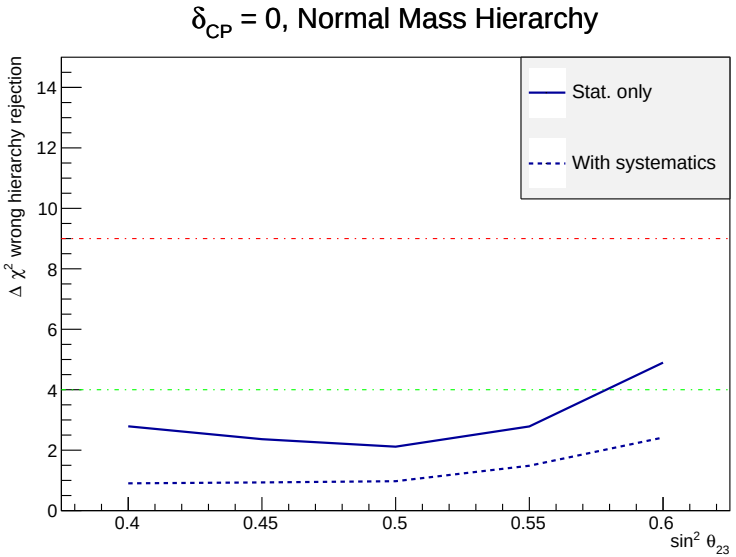


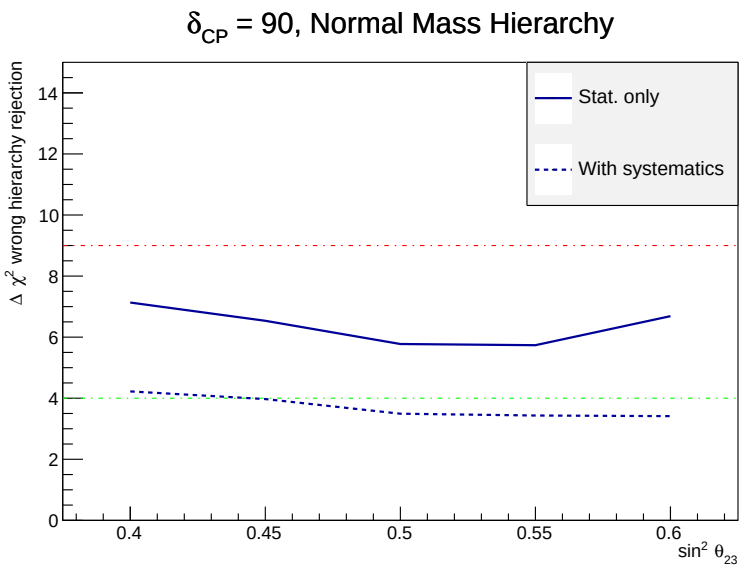


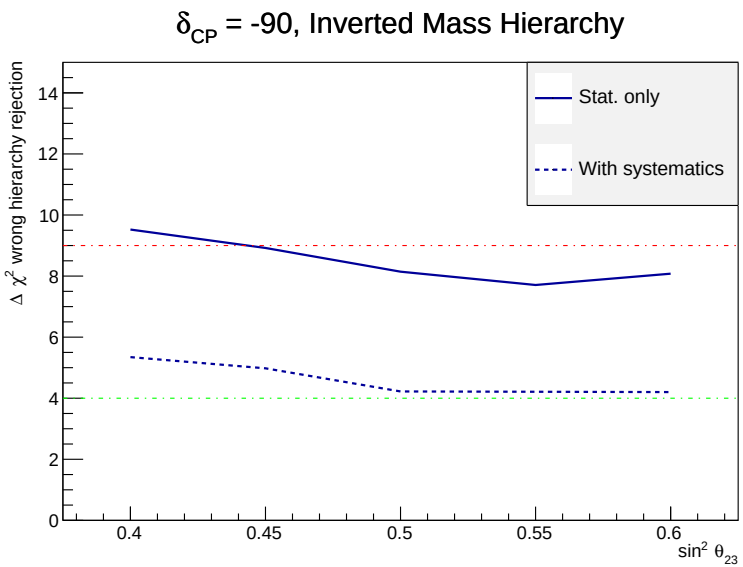


Sensitivity to mass hierarchy

- In 2014 J-PARC LoI we showed sensitivity to mass hierarchy of long-baseline and atmospheric data together.
- What can T2HK say about the mass hierarchy?
- Wrong mass hierarchy rejection for different values of $\sin^2\theta_{23}$







Sensitivity to mass hierarchy

- Mass hierarchy sensitivity is around 1 σ for all values of $\sin^2\theta_{23}$ if $\delta_{CP} = 0$ and normal MH;
- Mass hierarchy sensitivity is around 2 σ for all values of $\sin^2\theta_{23}$ if $\delta_{CP} = 90$ and normal MH or $\delta_{CP} = -90$ and inverted MH;
- Official Hyper-K strategy is to combine accelerator and atmospheric data $\rightarrow$ see J-PARC LoI 2014;

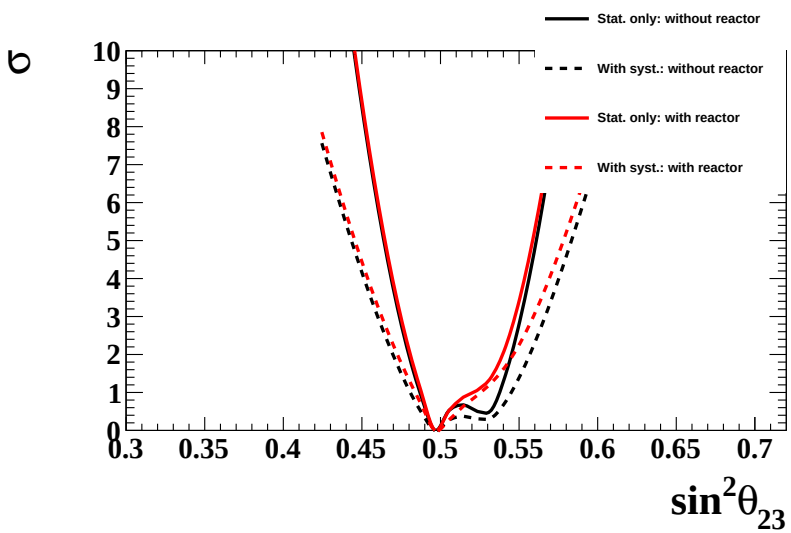
θ_{23} octant discrimination

- In the 2014 LoI we showed that adding the reactor constraint we could distinguish the octant;

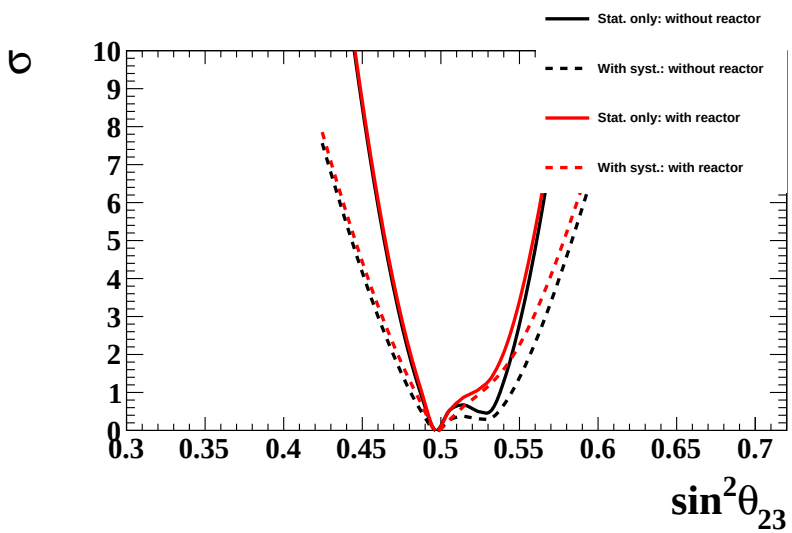
- $\sin^2\theta_{23} = 0.5$
- $\delta_{CP} = 90$

- Solid line without systematic error; dashed line with systematic errors;

Normal hierarchy



Inverted hierarchy



[0] 2D maps of atmospheric sector in back-up slides

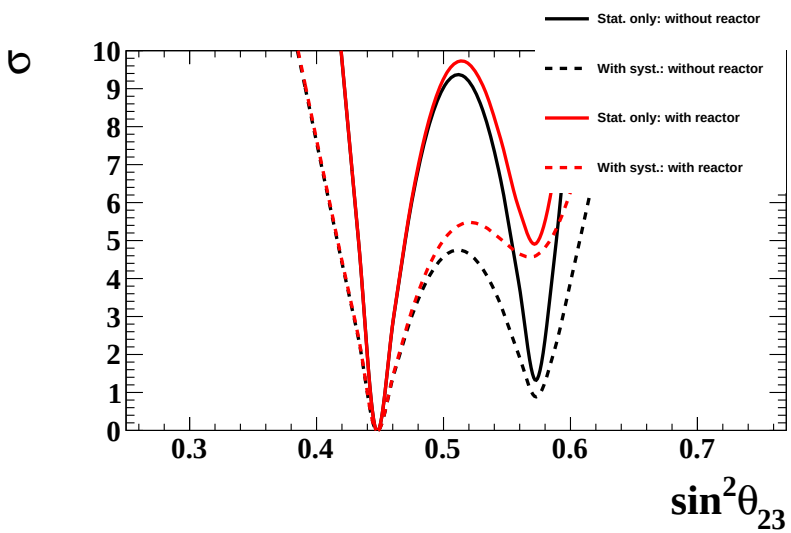
θ_{23} octant discrimination

- In the 2014 LoI we showed that adding the reactor constraint we could distinguish the octant;

- $\sin^2\theta_{23} = 0.45$
- $\delta_{CP} = 90$

- Solid line without systematic error; dashed line with systematic errors;

Normal hierarchy



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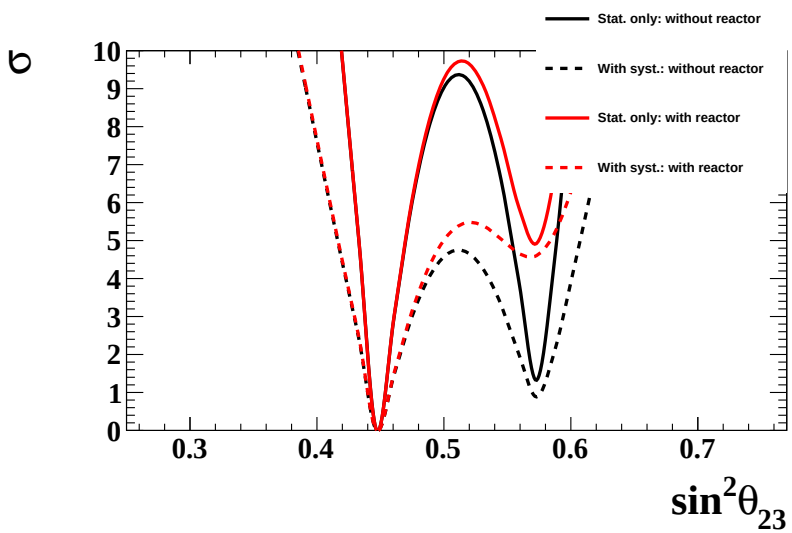

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θ_{23} octant discrimination

- In the 2014 LoI we showed that adding the reactor constraint we could distinguish the octant;

- $\sin^2\theta_{23} = 0.55$
- $\delta_{CP} = 90$

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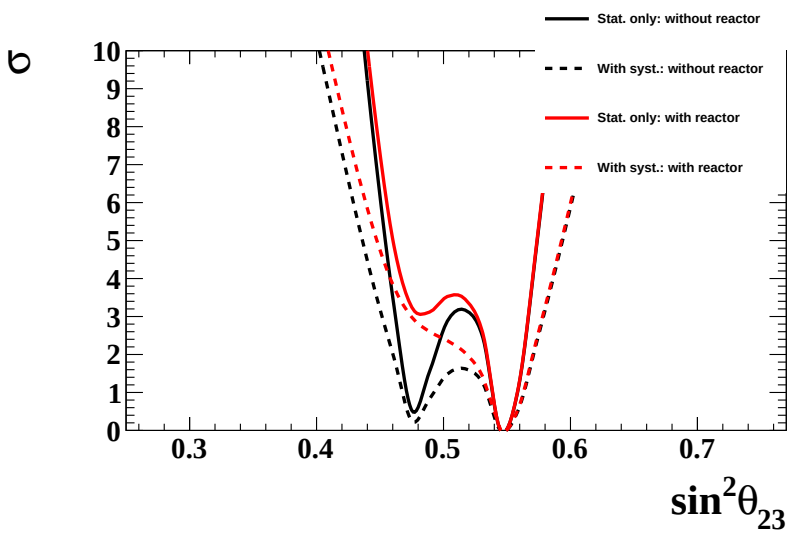

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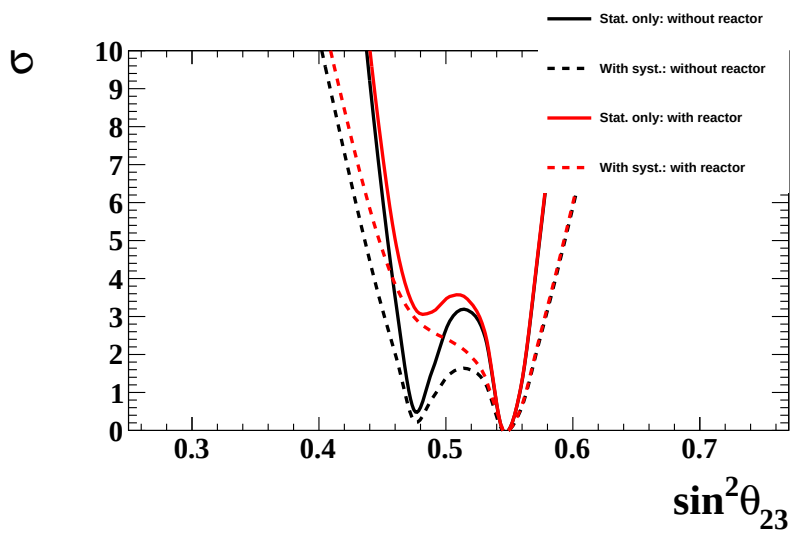

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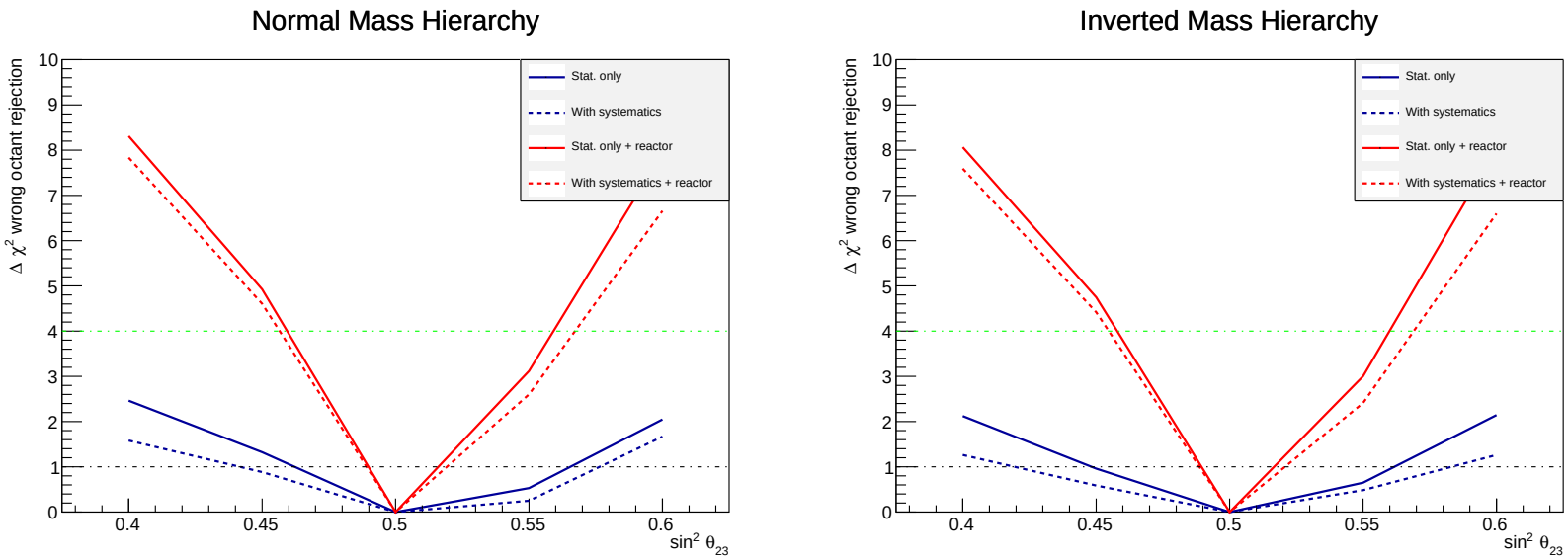
Sensitivity to octant discrimination

- Wrong octant rejection for different values of $\sin^2\theta_{23}$



- without reactor constraint: 1 σ level if $\sin^2\theta_{23} < 0.45$ or $\sin^2\theta_{23} \geqslant 0.6$;
- with reactor constraint: 2 σ level if $\sin^2\theta_{23} < 0.45$ or $\sin^2\theta_{23} > 0.57$;

- Official Hyper-K strategy is to combine accelerator and atmospheric data;

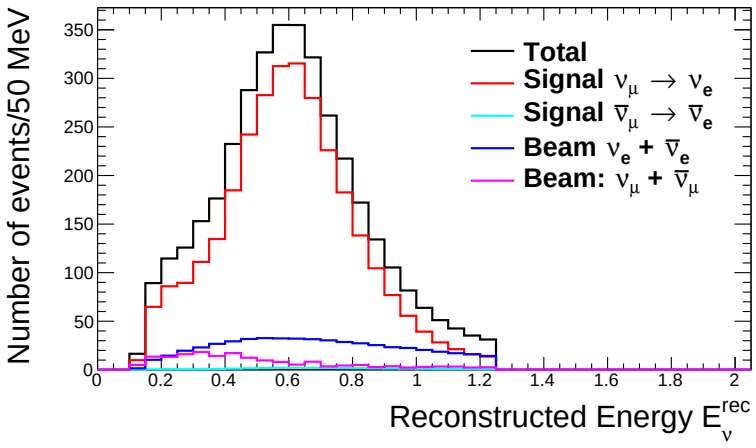
Summary

- $\nu/\bar{\nu}$ running ratio studies:
  - as far as we have a mix of neutrino and anti-neutrino running and reactor constraints are considered, there doesn't seem to be a big difference in the δ_{CP} contours;
- CP sensivity is highly dependent on true value of $\sin^2(\theta_{23})$
- Mass hierarchy sensitivity is around 2 σ for all values of $\sin^2\theta_{23}$ if $\delta_{CP} = 90$ and normal MH or $\delta_{CP} = -90$ and inverted MH;
- Octant discrimination:
  - without reactor constraint: 1 σ level if $\sin^2\theta_{23} < 0.45$ or $\sin^2\theta_{23} \geqslant 0.6$;
  - with reactor constraint: 2 σ level if $\sin^2\theta_{23} < 0.45$ or $\sin^2\theta_{23} > 0.57$;
- Update on systematic error treatment in Mark's presentation tomorrow;

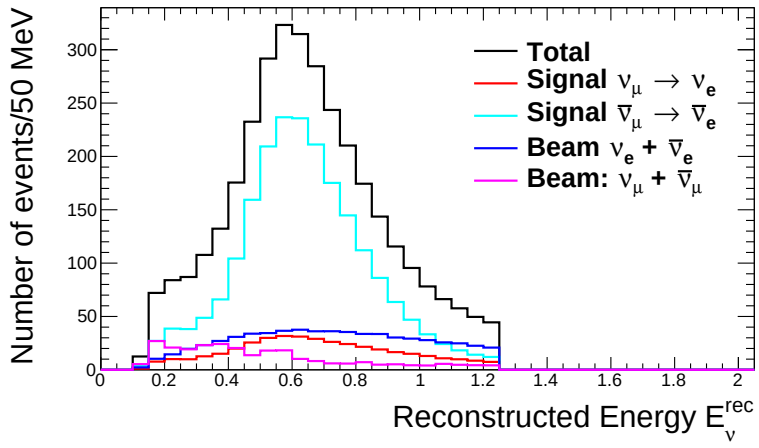
BACK UP SLIDES

Expected spectra at Hyper-K

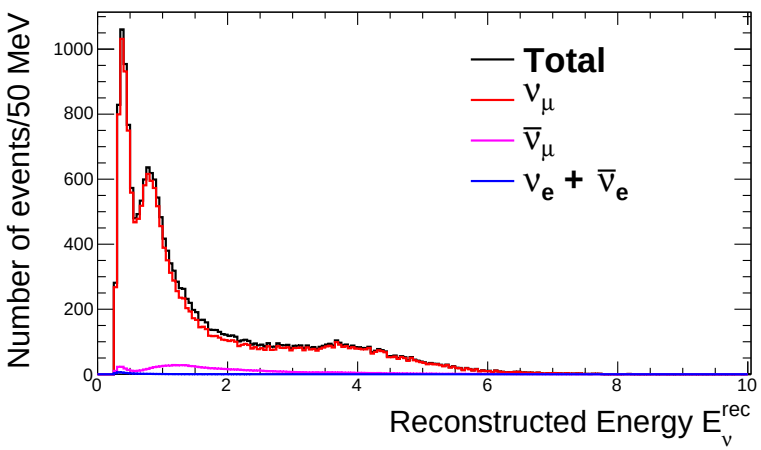
Appearance ν mode



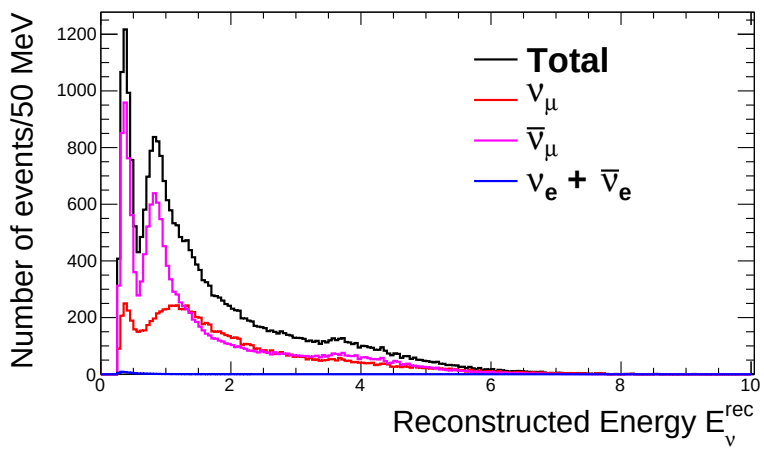
Appearance $\bar{\nu}$ mode



Disappearance ν mode

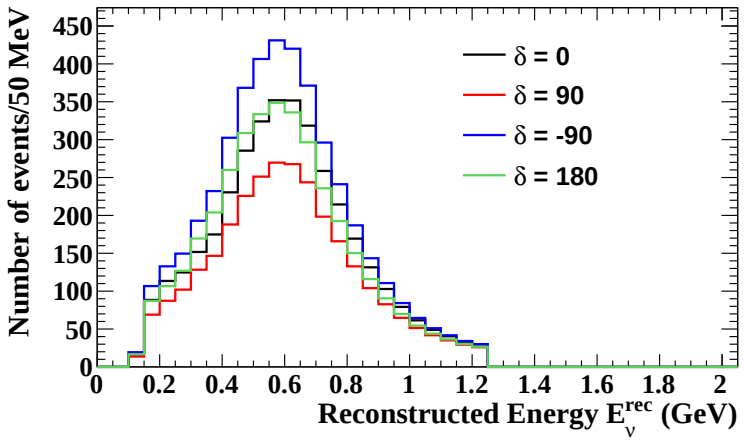


Disappearance $\bar{\nu}$ mode

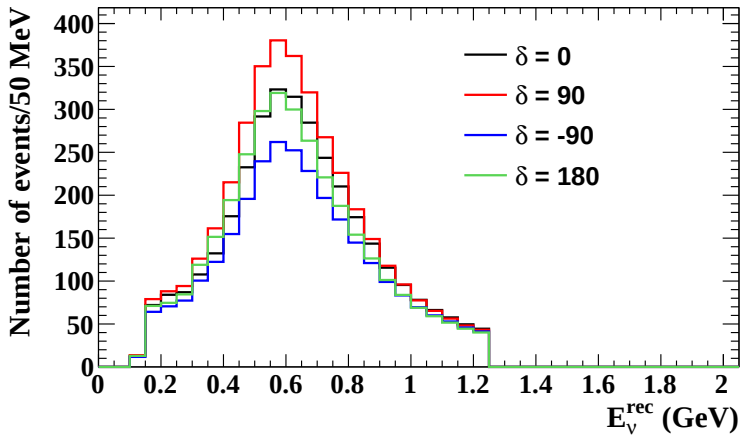


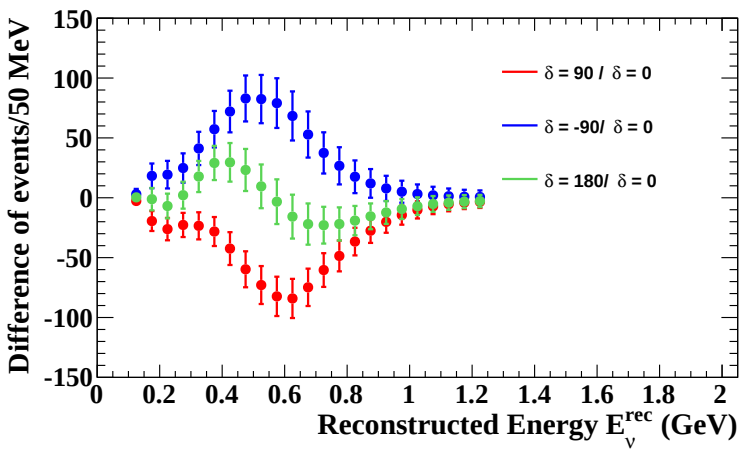
Effect of δ_{CP} at Hyper-K

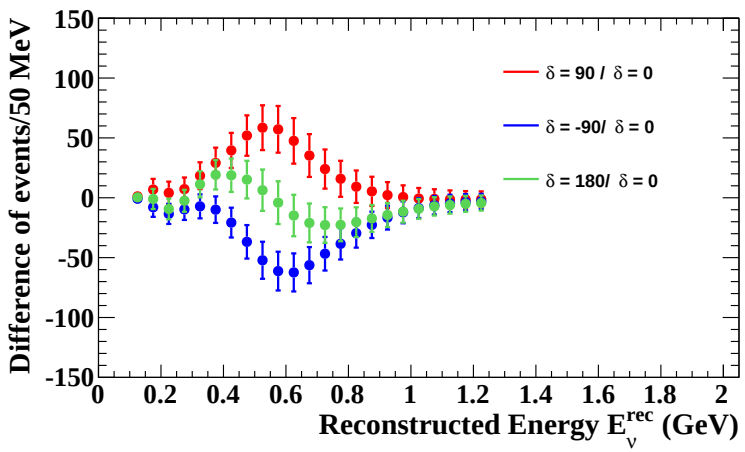
Neutrino mode: Appearence



Antineutrino mode: Appearence







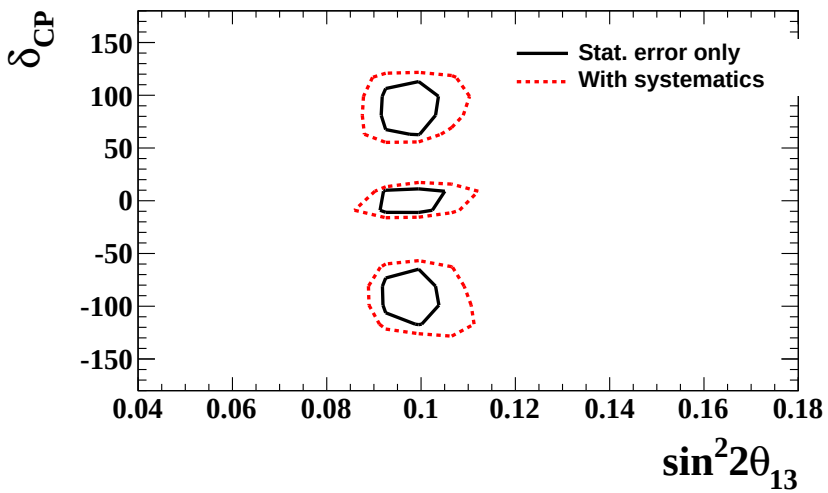
Sensitivity to appearance parameters

CP sensivity studies assuming three values of δ_{CP} (-90, 0, 90) and two values of the mass hierarchy (normal and inverted)

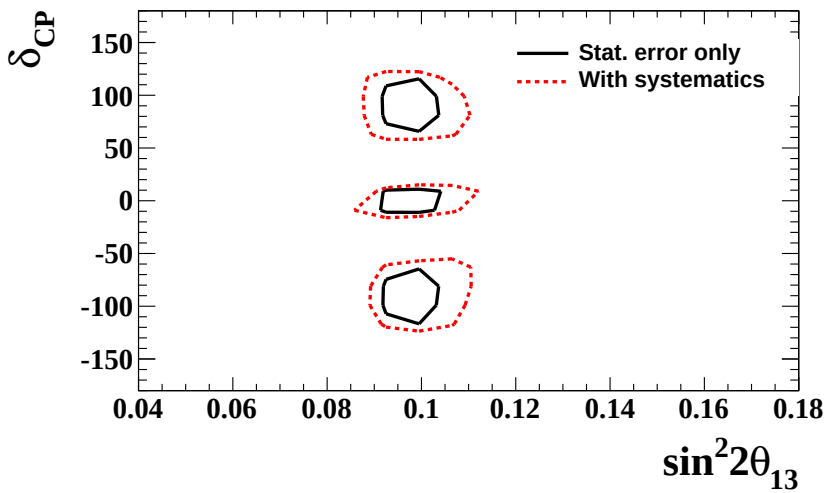
- $\sin^2 2\theta_{13} = 0.10$
- $\Delta m^2_{32} = 0.0024$ eV^2
- $\sin^2 \theta_{23} = 0.50$

- Without reactor contraint
- Solid line without systematic error; dashed line with systematic errors;

Normal hierarchy



Inverted hierarchy



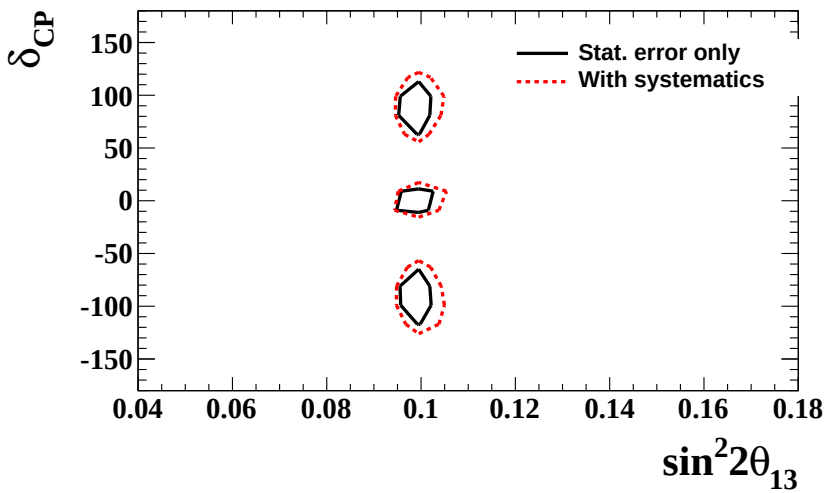
Sensitivity to appearance parameters

CP sensivity studies assuming three values of δ_{CP} (-90, 0, 90) and two values of the mass hierarchy (normal and inverted)

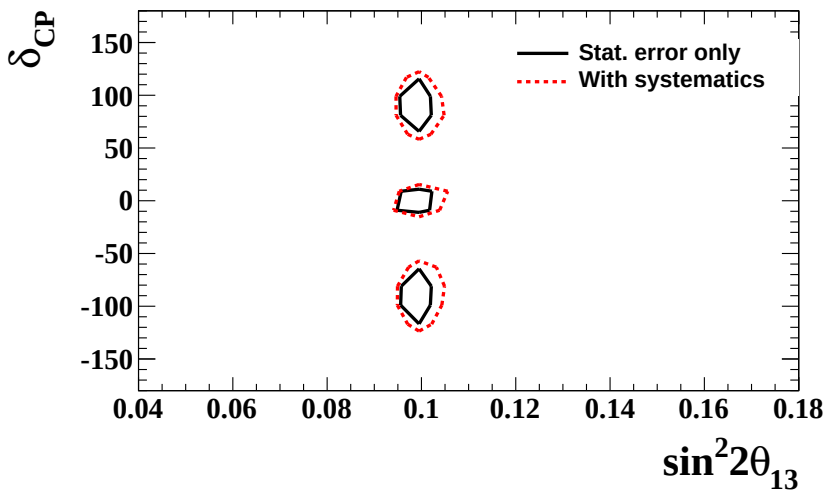
- $\sin^2 2\theta_{13} = 0.10$
- $\Delta m^2_{32} = 0.0024$ eV^2
- $\sin^2 \theta_{23} = 0.50$

- With reactor contraint
- Solid line without systematic error; dashed line with systematic errors;

Normal hierarchy



Inverted hierarchy

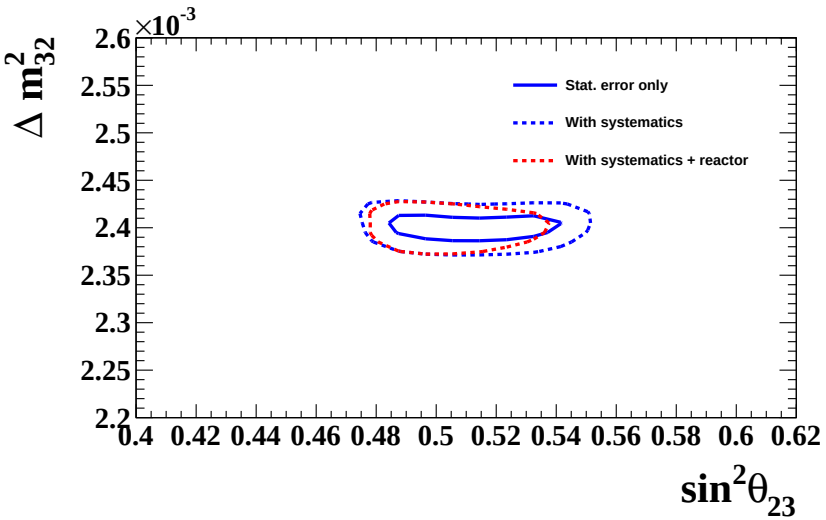


Sensitivity to disappearance parameters

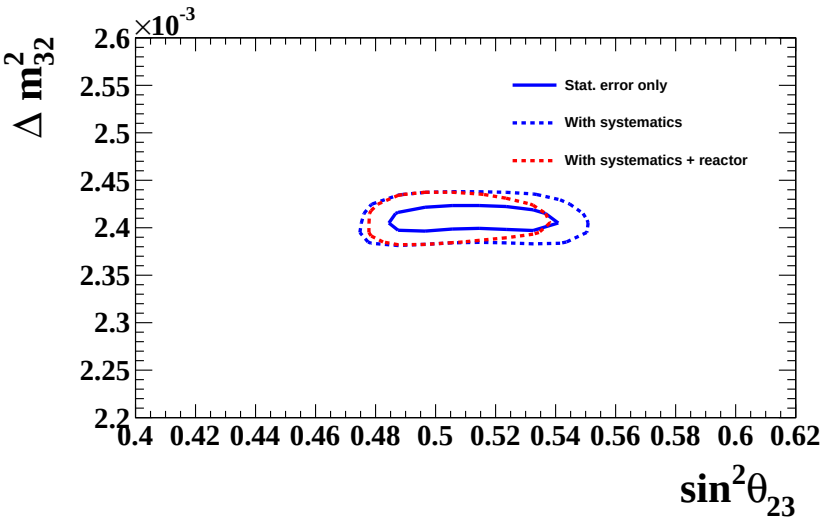
Sensivity studies to the atmospheric sector assuming two values of the mass hierarchy (normal and inverted)

- $\sin^2 2\theta_{13} = 0.10$
- $\Delta m^2_{32} = 0.0024$ eV^2
- $\sin^2 \theta_{23} = 0.50$
- $\delta_{CP} = 90$
- Solid line without systematic error; dashed line with systematic errors;

Normal hierarchy



Inverted hierarchy

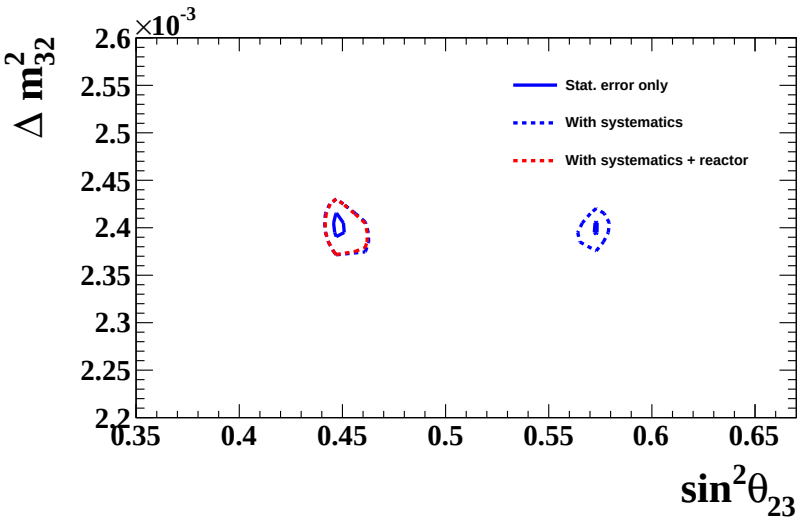


Sensitivity to disappearance parameters

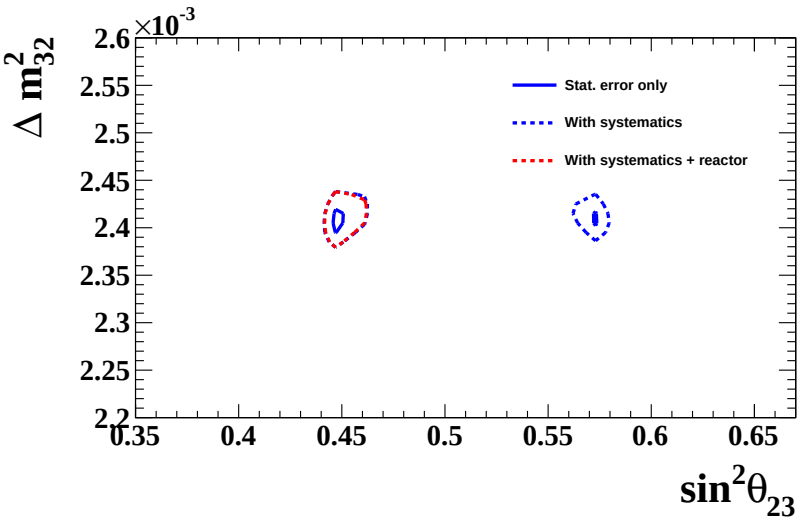
Sensivity studies to the atmospheric sector assuming two values of the mass hierarchy (normal and inverted)

- $\sin^2 2\theta_{13} = 0.10$
- $\Delta m^2_{32} = 0.0024$ eV^2
- $\sin^2 \theta_{23} = 0.45$
- $\delta_{CP} = 90$
- Solid line without systematic error; dashed line with systematic errors;

Normal hierarchy



Inverted hierarchy



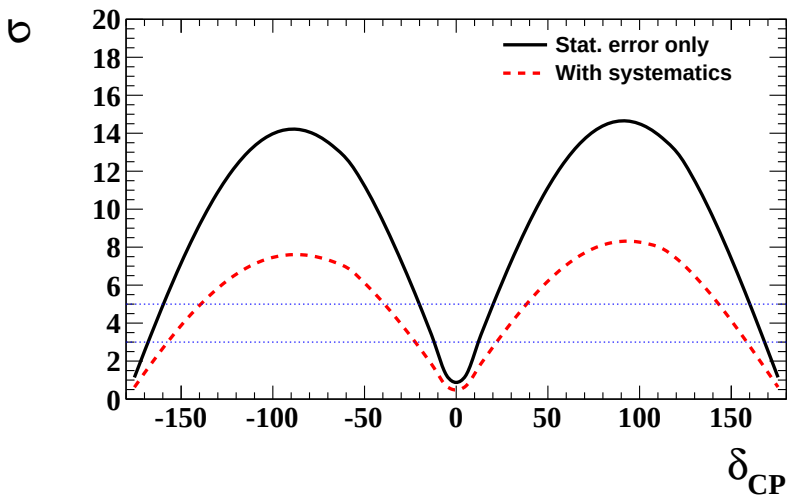
Sensitivitity to δ_{CP} discovery

Difference between $\chi^2(\delta_{TRUE})$ and $\chi^2(\sin\delta = 0)$: $\sigma = \sqrt{\Delta\chi^2}$

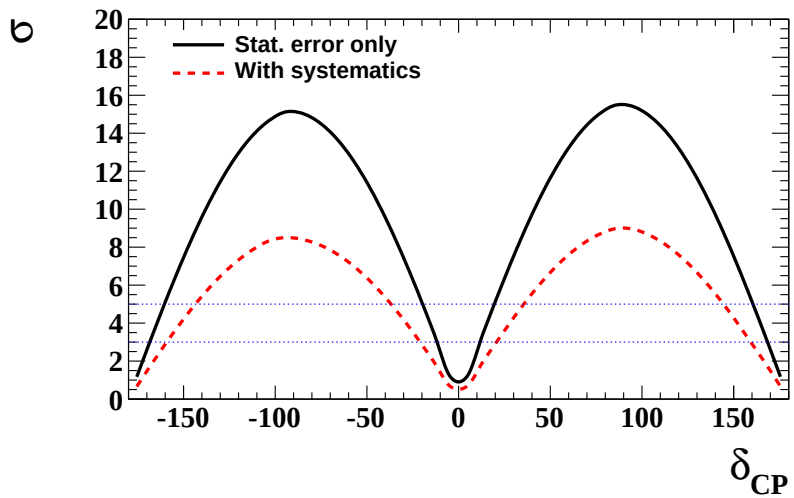
- $\sin^2 2\theta_{13} = 0.10$
- $\Delta m^2_{32} = 0.0024$ eV^2
- $\sin^2\theta_{23} = 0.50$

- Without reactor contraint
- Unknown octant
- Solid line without systematic error; dashed line with systematic errors;

Normal hierarchy



Inverted hierarchy



Sensitivitity to δ_{CP} discovery

- (left) Fraction of δ_{CP} space for which $\sin\delta_{CP} = 0$ can be excluded with $3\sigma/5\sigma$.
- (right) 1 σ uncertainty as a function of the integrated beam power;
- At Hyper-K full statistics the 76% (58%) of δ_{CP} space covered at 3σ (5σ) with better than 19 degrees uncertainty;