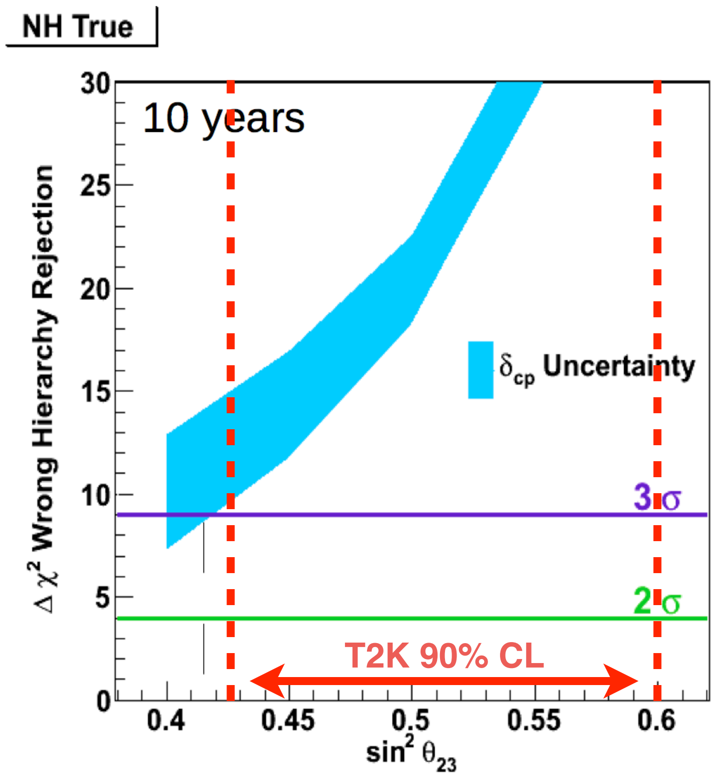
Hyper-K Systematics

NuInt2015

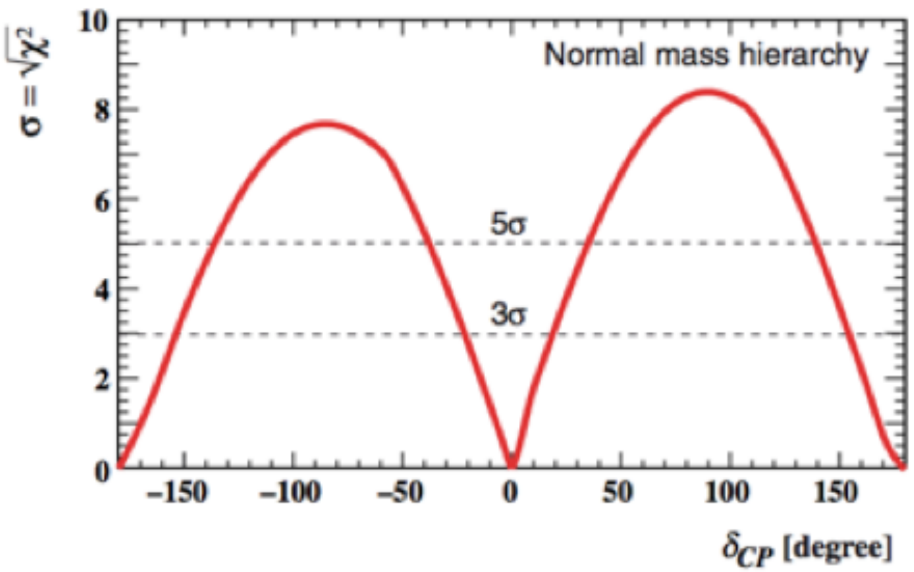
Raj Shah (RAL & Oxford)
On behalf of the Hyper-K collaboration

Hyper-K

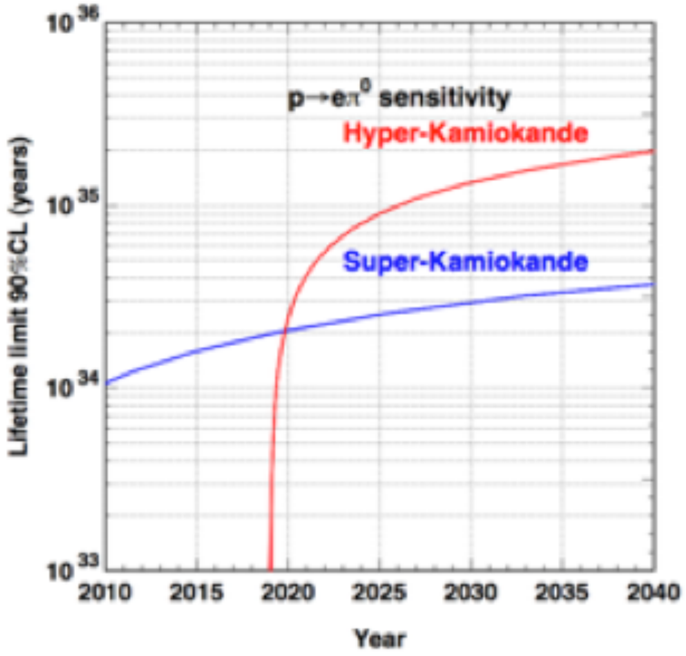
Atmospheric



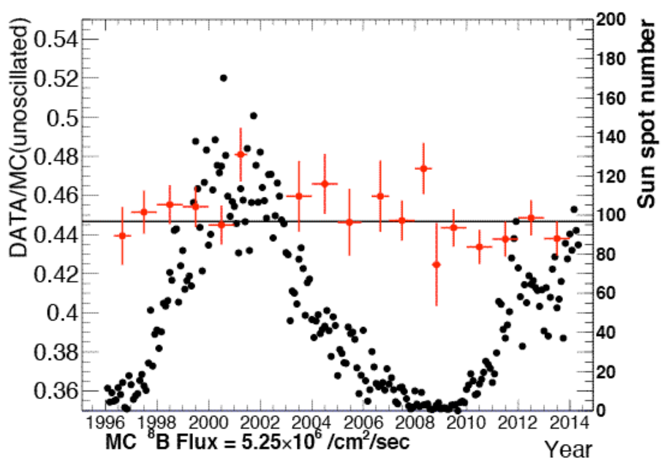
T2K/HK

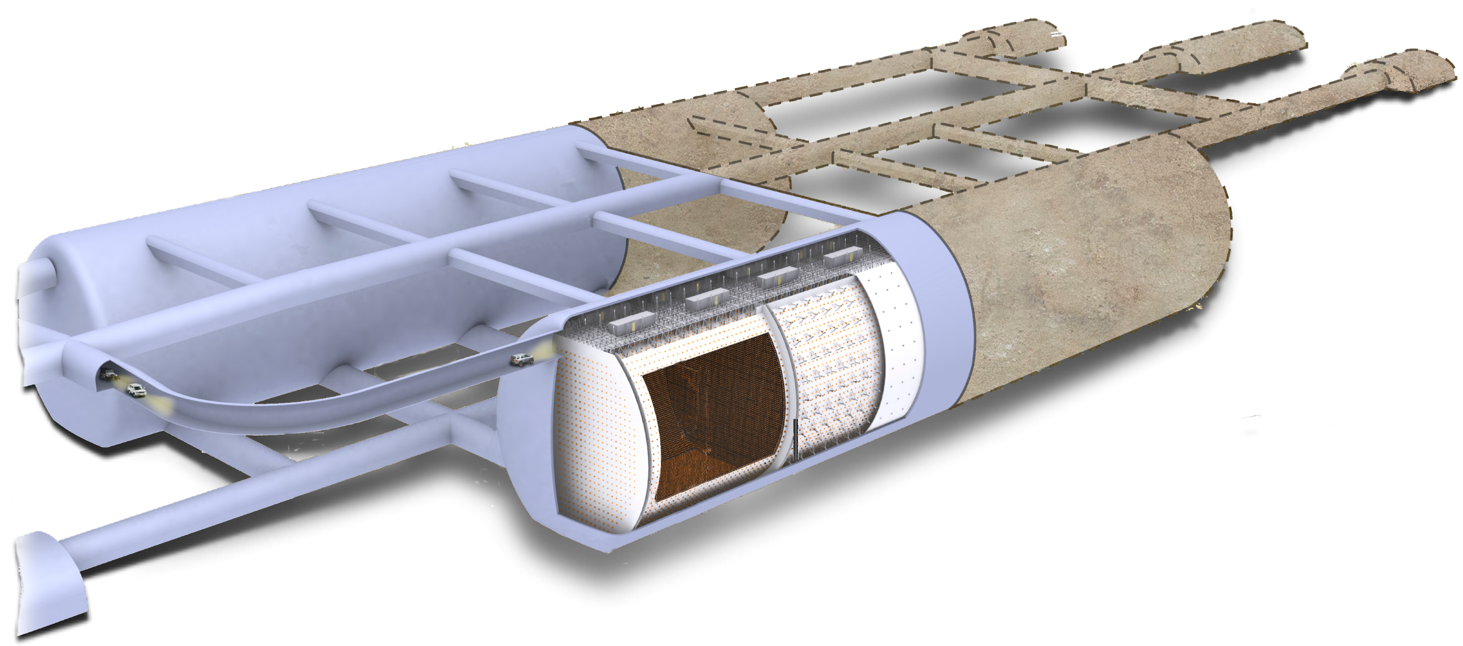


Nucleon Decay

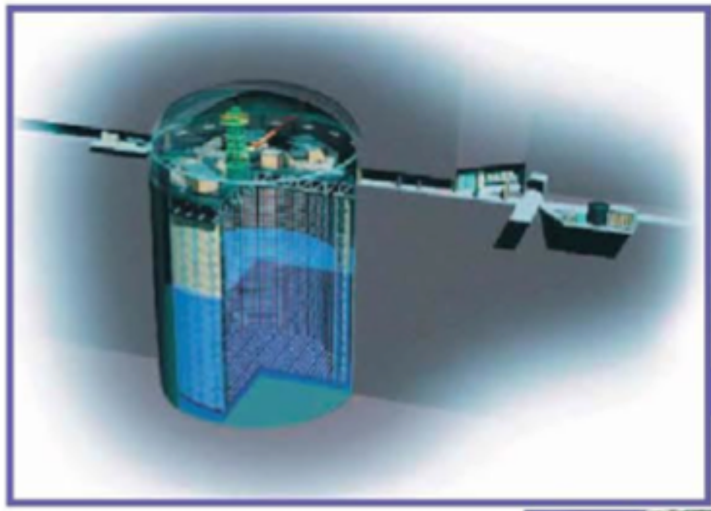


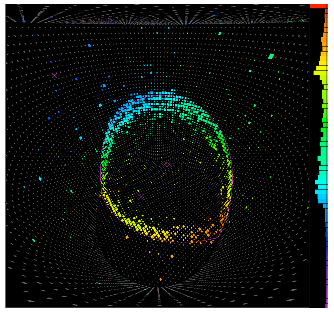
Astrophysical

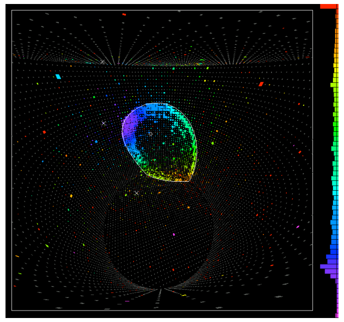




T2K

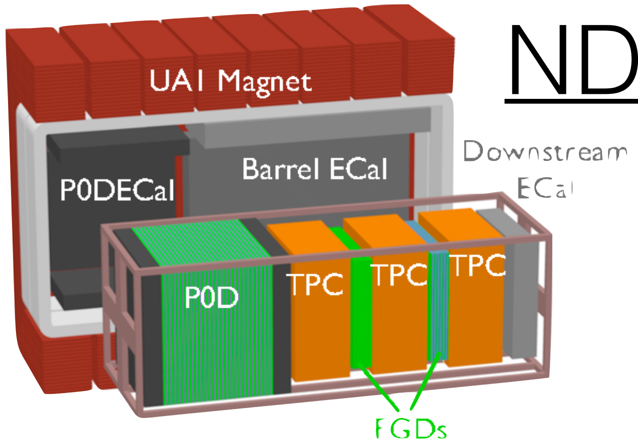




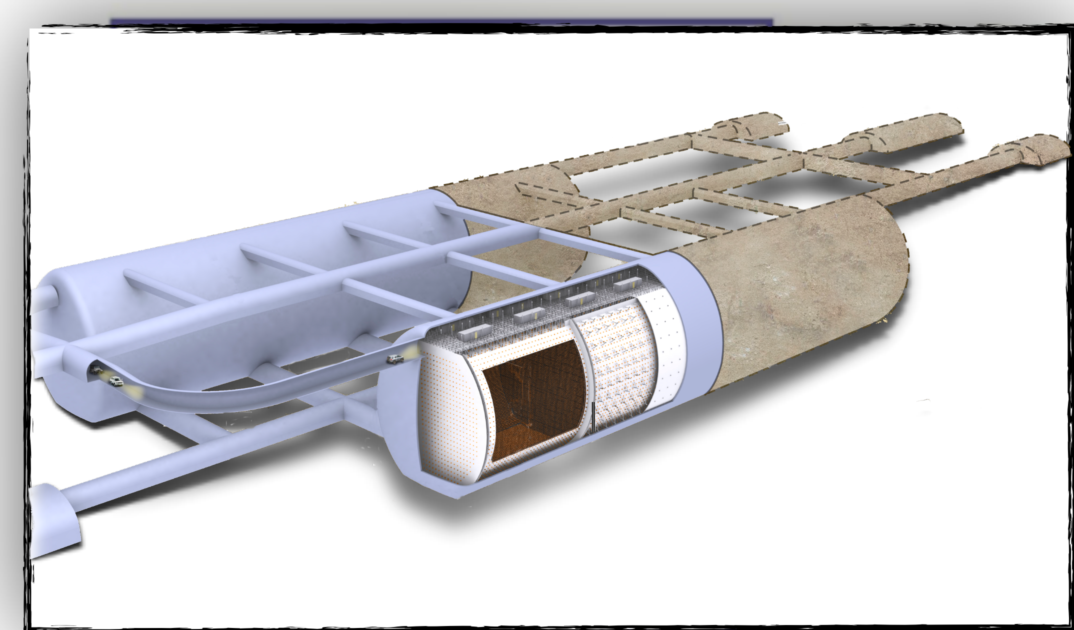


50 kT (22.5 FV)
330 kW Beam power

ND280



Hyper-K



Systematics

Stronger focusing horns

Gd Doping

Water based ND

(Friday - K. Yamamoto, M. Scott)

Statistics

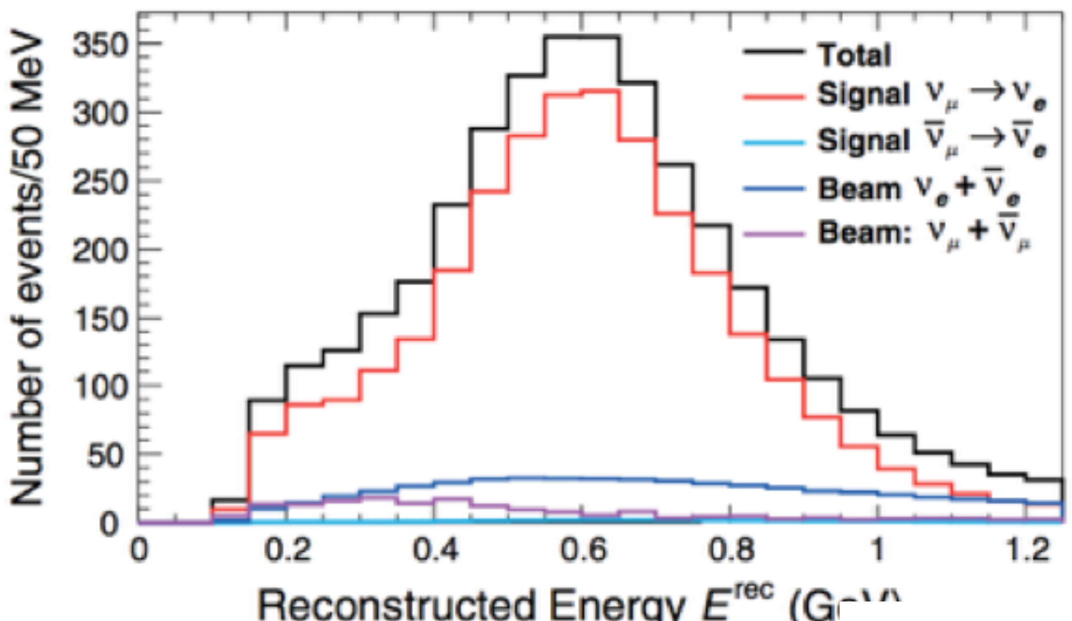
1 Megaton (0.5 FV)

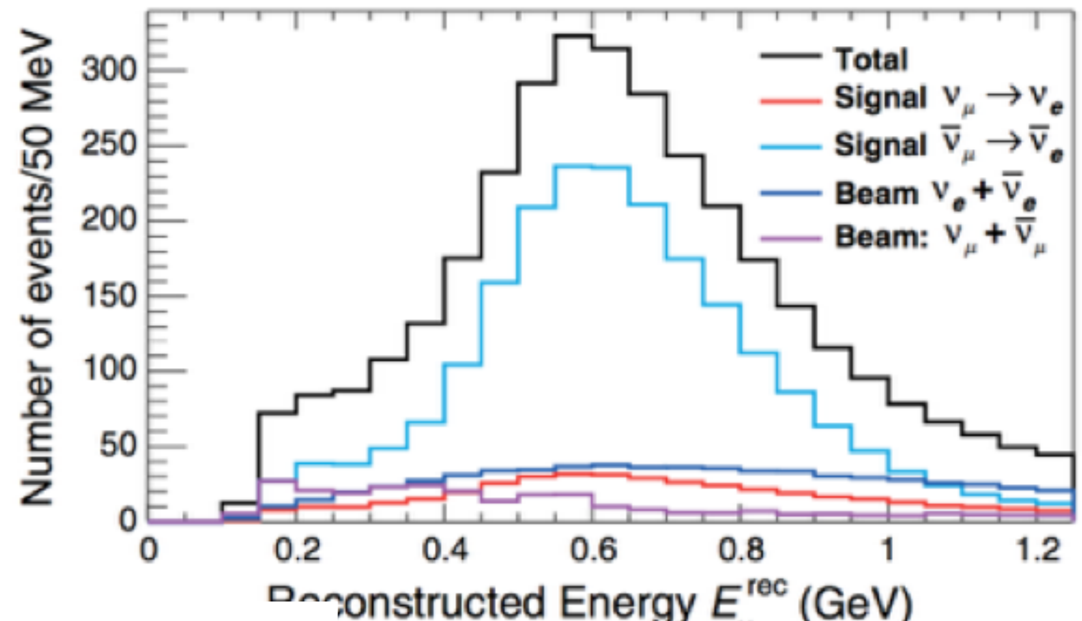
>1 MW Beam power

Predicted event rate

ν - mode   anti ν - mode

1R$_e$

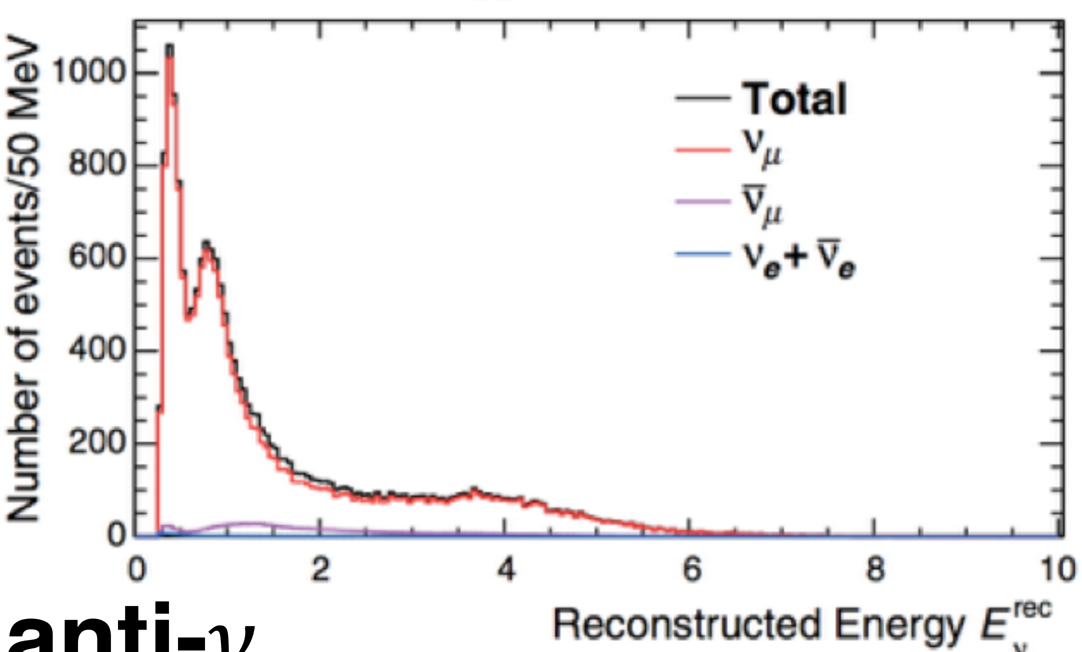




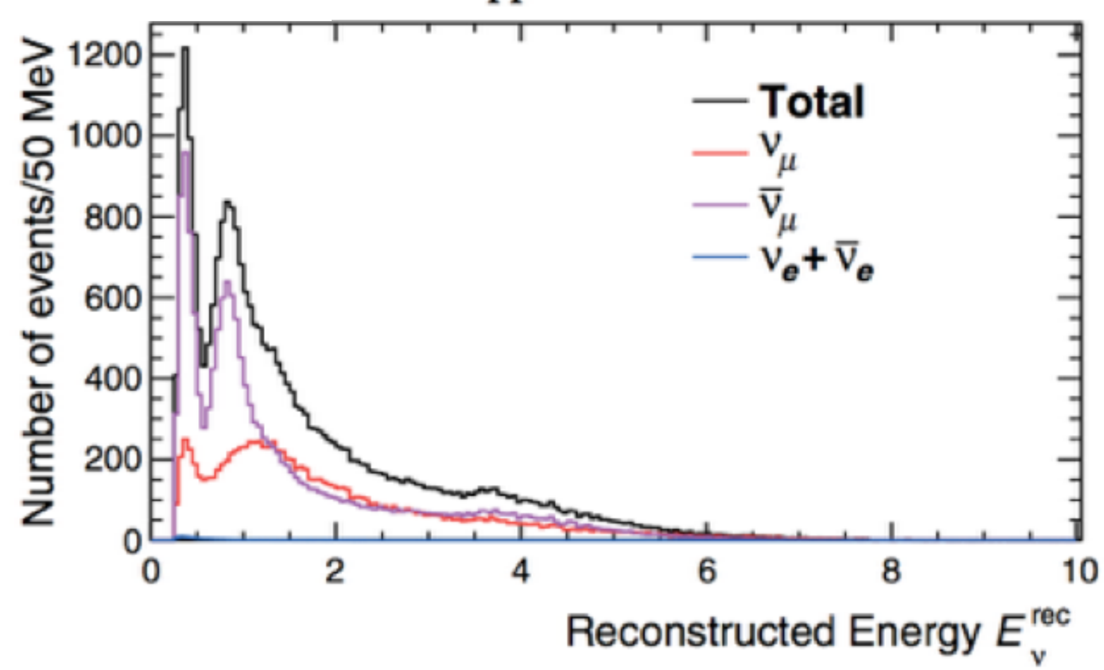
7.5 MW x 10^7

Disappearance ν mode

1R$_\mu$



Disappearance $\bar{\nu}$ mode

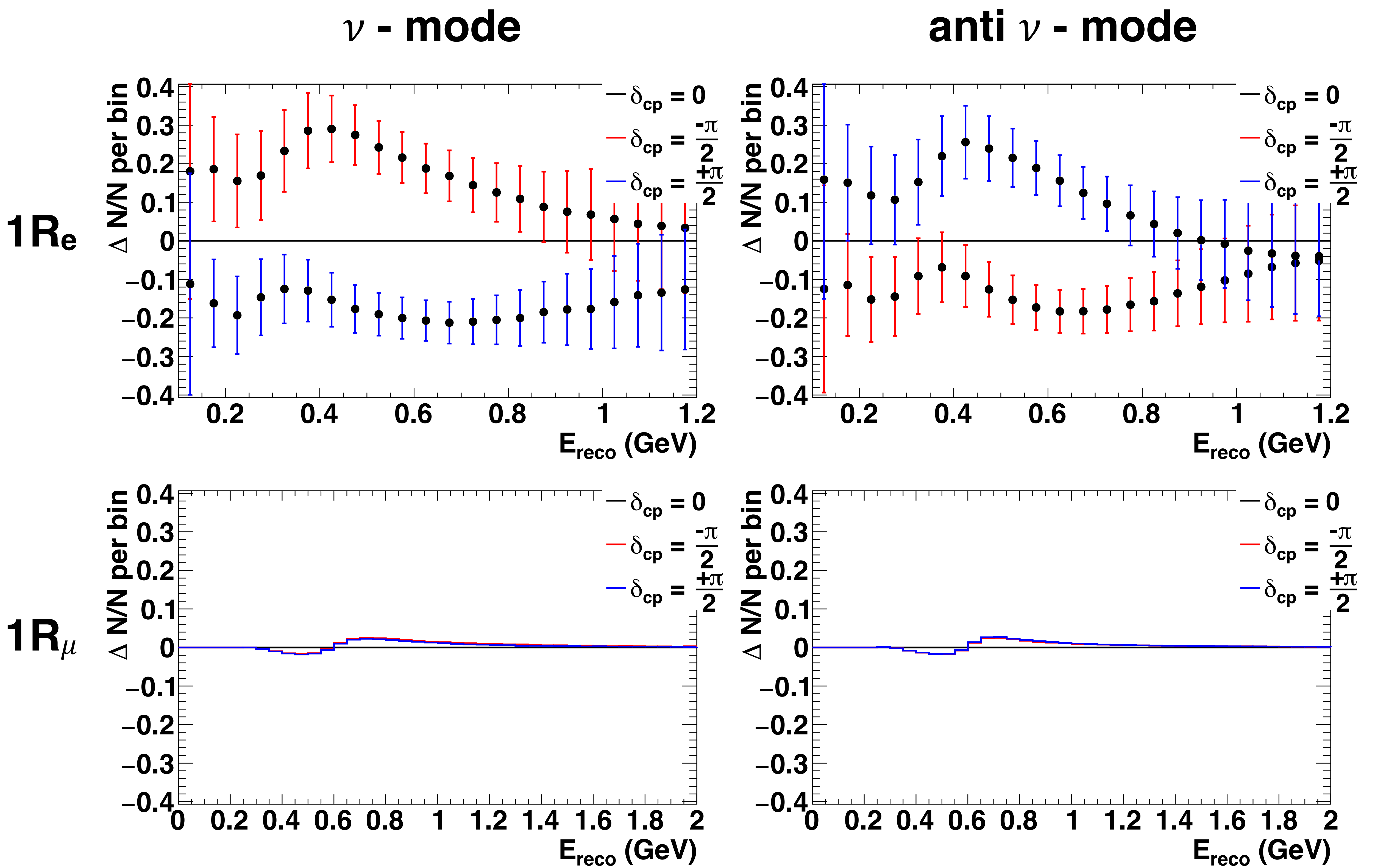


1:3 ν:anti-ν

Studies

- **Sensitivity to CP violation**
- **Sensitivity to exclude maximal mixing**

δcp



ν - mode
anti ν - mode
1Re
1Rμ
Δ N/N per bin
δcp = 0
δcp = -π/2
δcp = +π/2
Ereco (GeV)

Official HK sensitivity

Based on (2013) T2K model and ND constraints

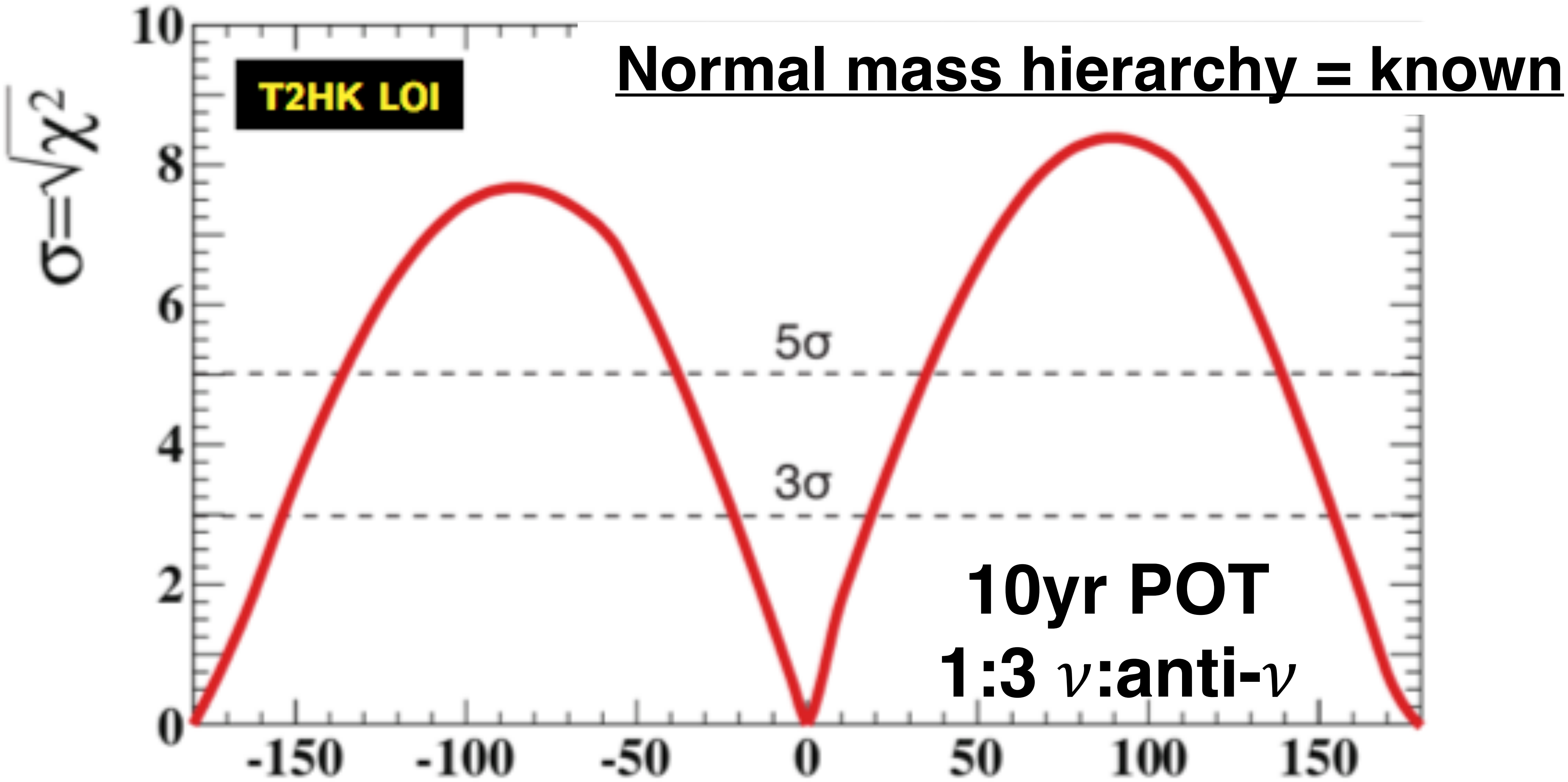
PTEP 2015, 053C02

		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
$\bar{\nu}$ mode	Appearance	5.6	2.0	1.7	6.2
	Disappearance	4.2	1.4	1.1	4.5

- Correlated ND-SK flux and x-sec - <u>0 correlation between running modes</u>
- Reduction in ND-independent x-sec errors - water ND
- Reduced HK detector errors - stronger constraint from control samples

CPV sensitivity

$\sin^2(\theta_{23}) = 0.5$ $\sin^2(2\theta_{13}) = 0.1 \pm 0.005$

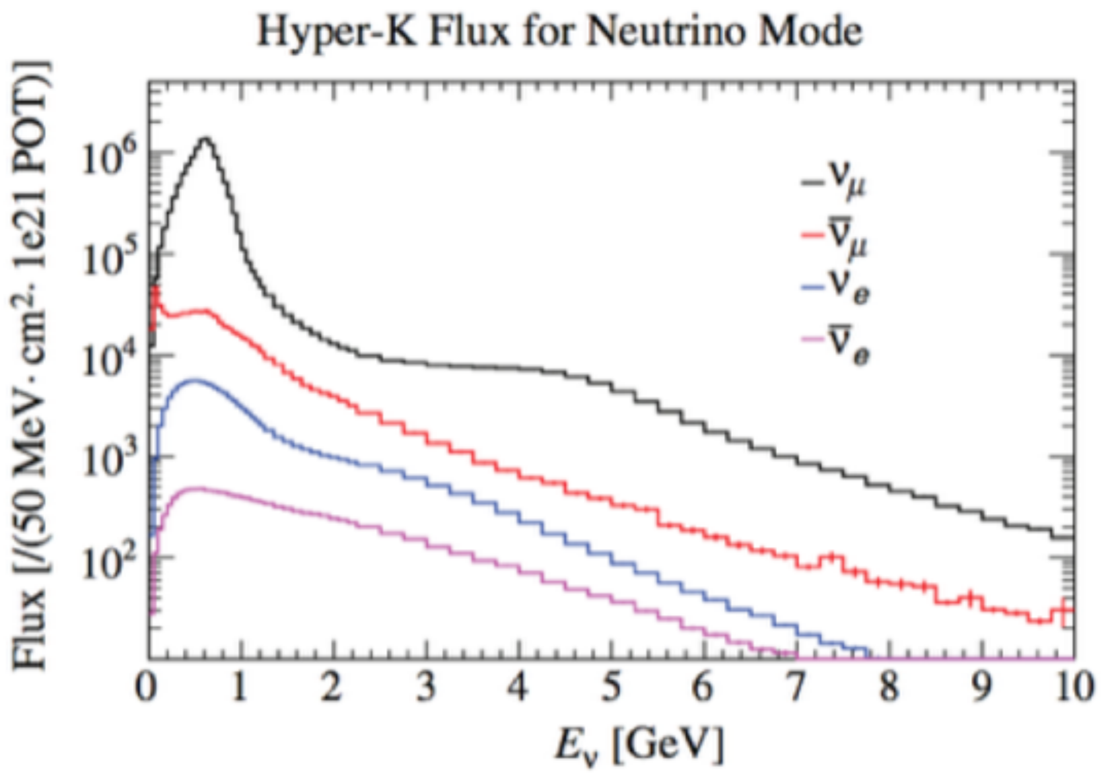


58% of δcp space at 5σ and 76% at 3σ

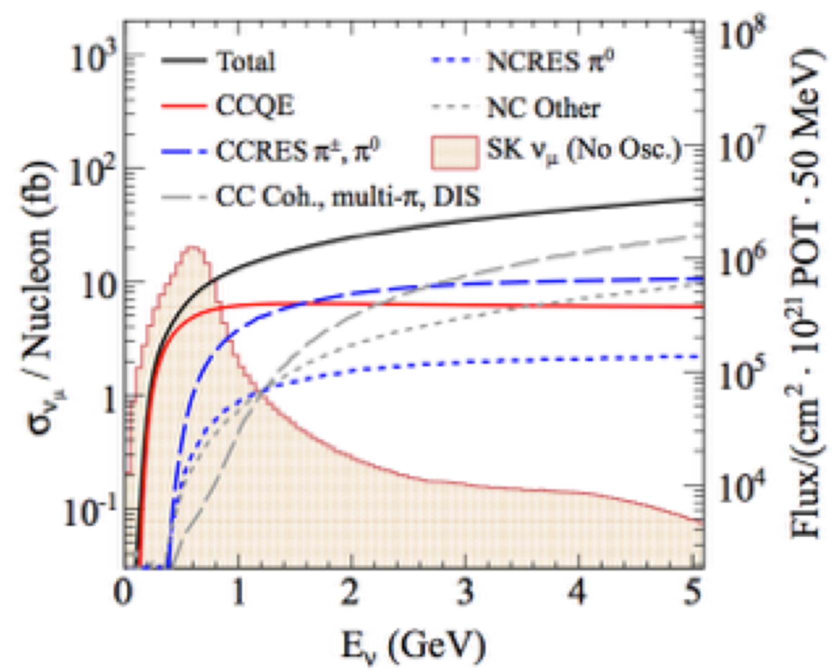
Updated sensitivity study coming soon!

Sources of Error

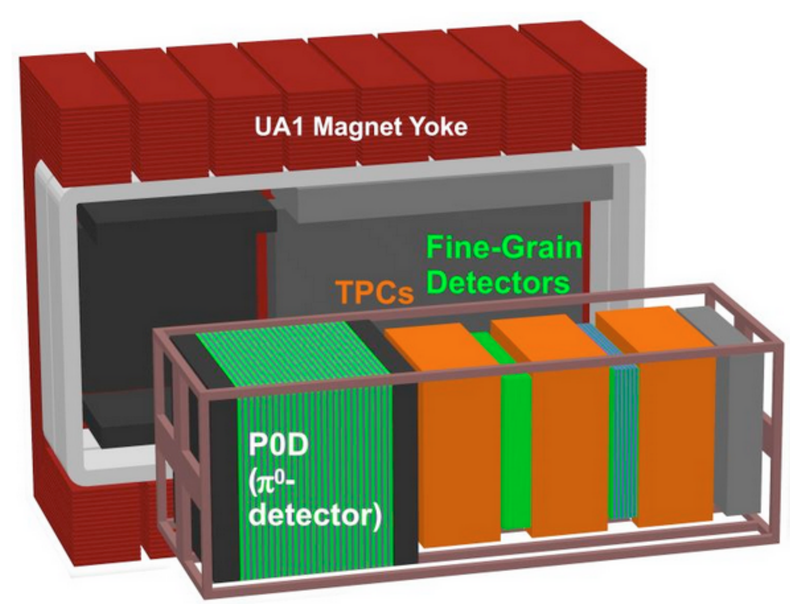
Flux



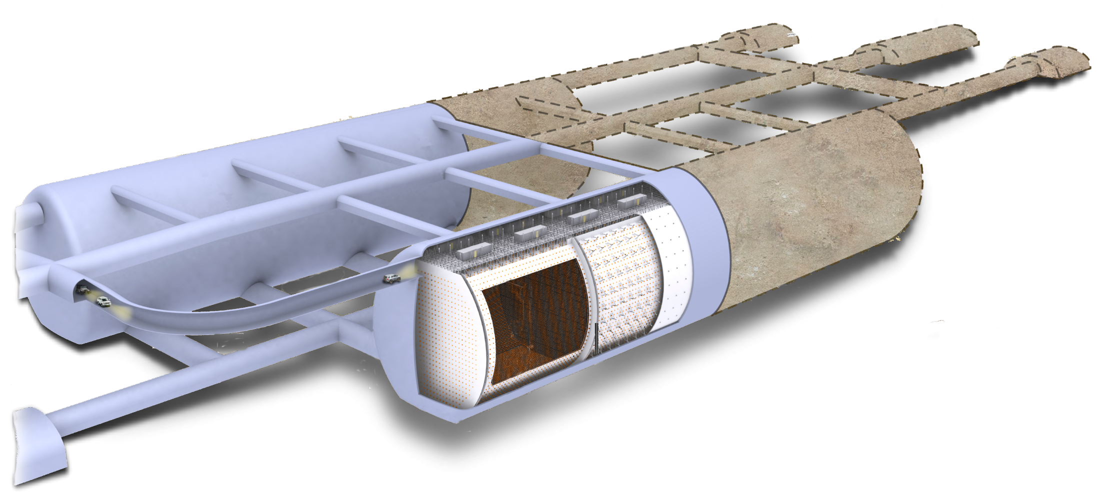
Interaction



ND Detector

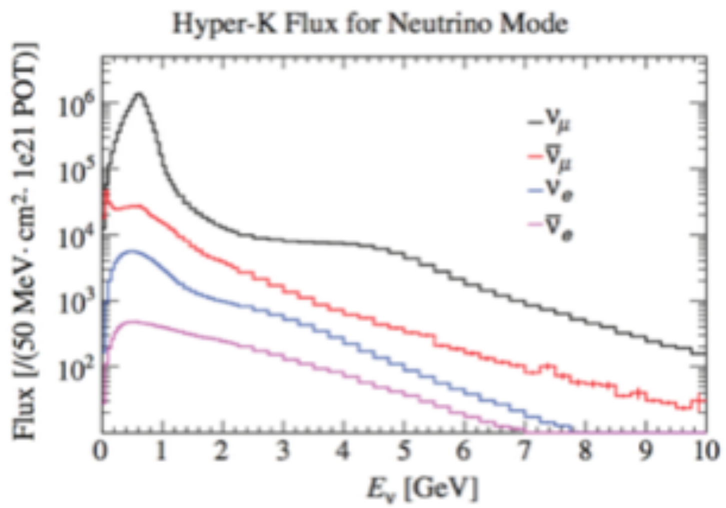


HK Detector

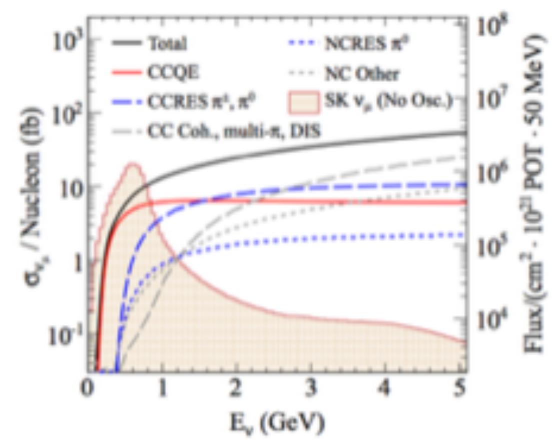


Systematic studies

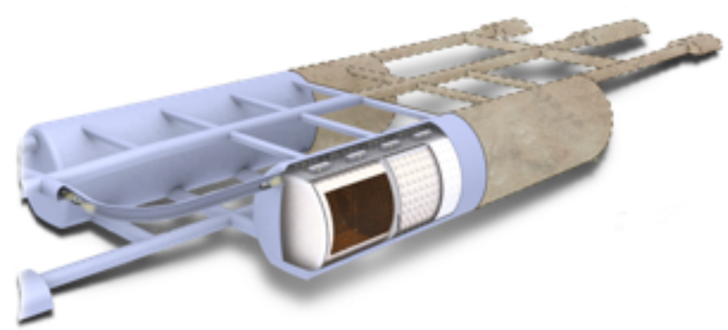
Flux



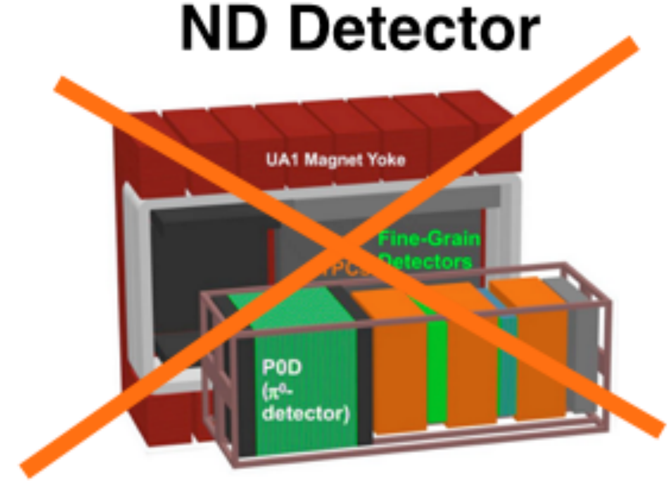
Interaction



HK Detector

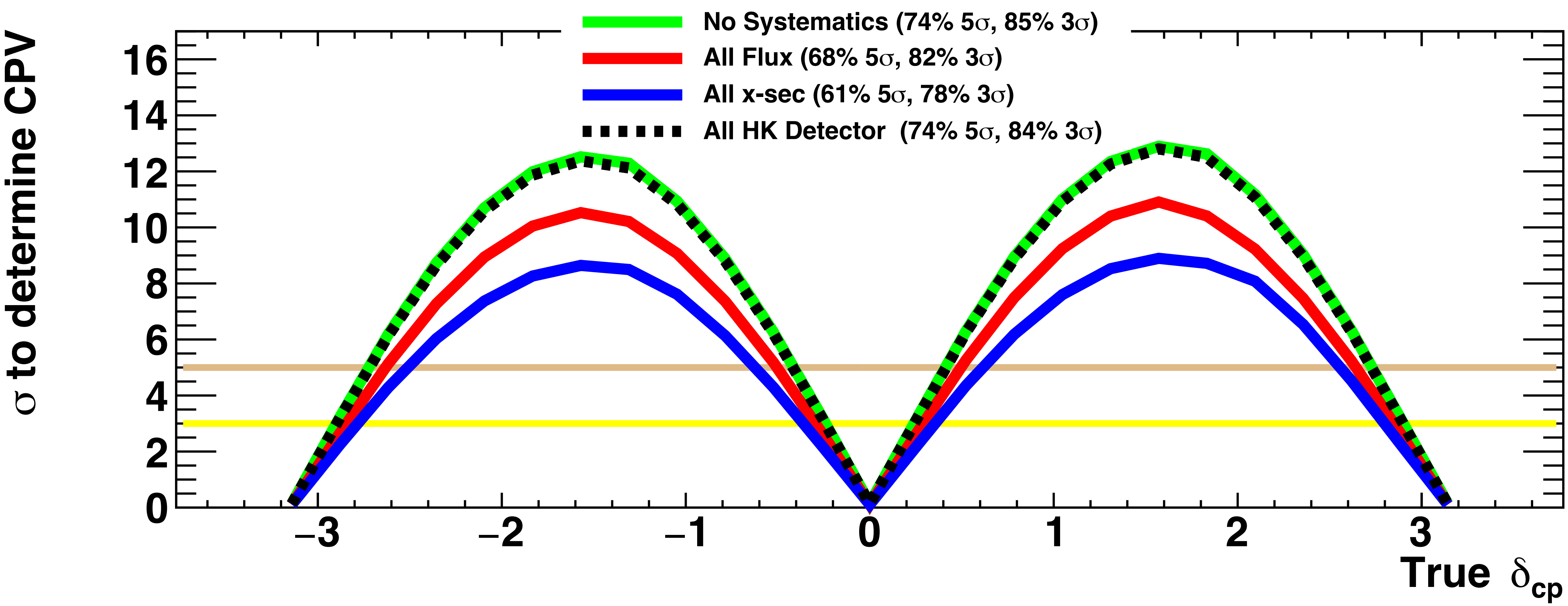


ND Detector



- Motivate requirements from ND constraint
- Identify dominant systematics
- **No** ND constraint applied

Sensitivity studies



HK Detector <1% effect

Flux Errors next biggest

Interaction uncertainties dominate!

Interaction model

Neut model v5.3.2 - Tuned - Nieves 2p-2h

Shape

CCQE- Relativistic Fermi Gas + Random Phase approximation

Fermi Momentum (5%)

Binding Energy (33%)

MaQE (6%)

Constrained from external data MiniBooNE + Minerva

Pion - CC and NC - Rein-Sehgal production model

Nucleon - **Δ** axial current form factor (12%)

Isospin 1/2 continuum background (15%)

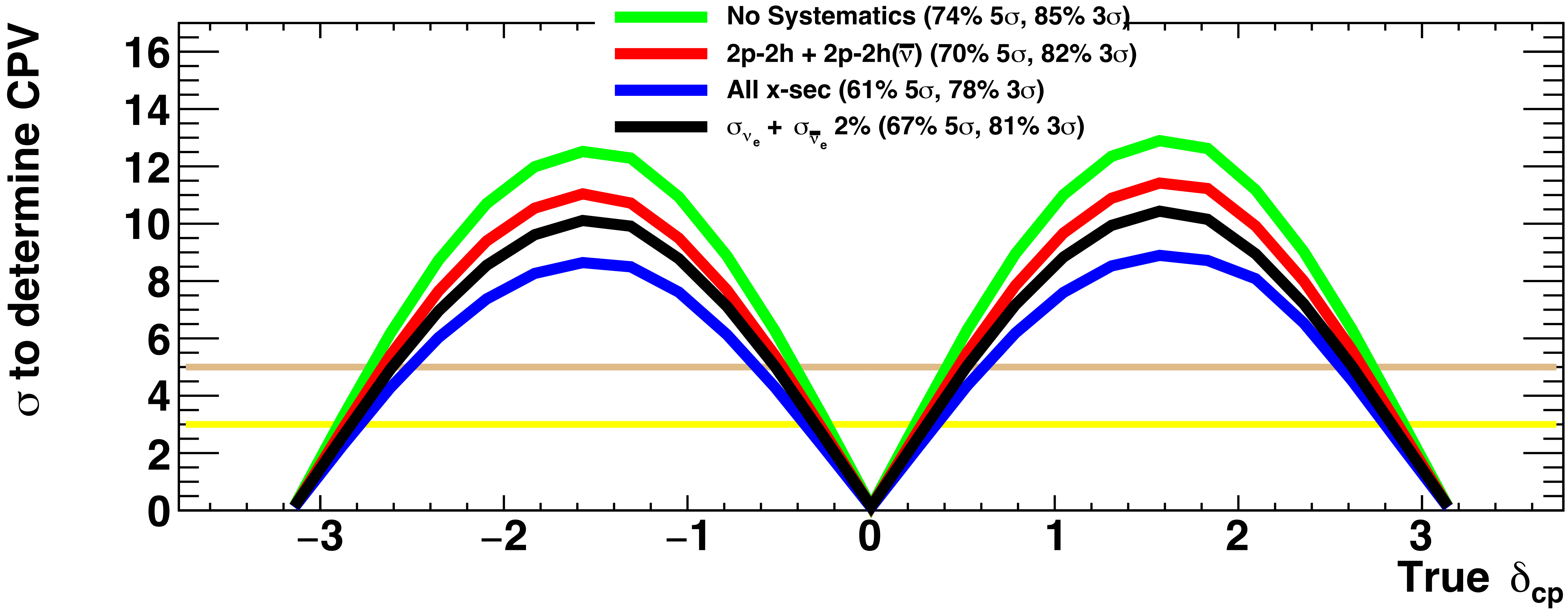
MaRes (16%)

DIS + multi Pion ($0.4/E_\nu$)

Normalisation uncertainties

2p-2h (100%), 2p-2h anti-ν (100%), CC Coherent (100%), NC Coherent (30%), NC ($\overline{\pi,\mathrm{coh}}$) (30%), CC ν_e (2%), CC anti ν_e (2%)

ν_e - anti ν_e + 2p-2h



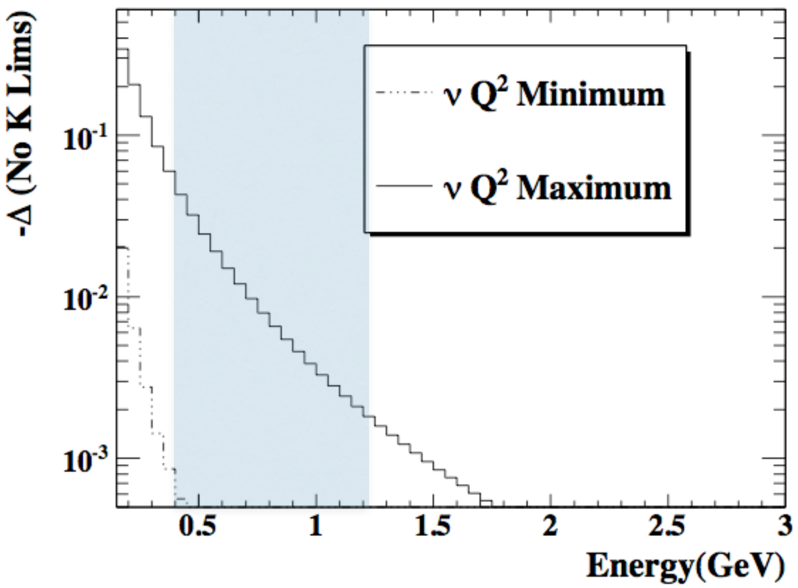
Big contribution from ν_e - anti ν_e

$\sigma\nu_e$ not currently constrained by T2K ND280

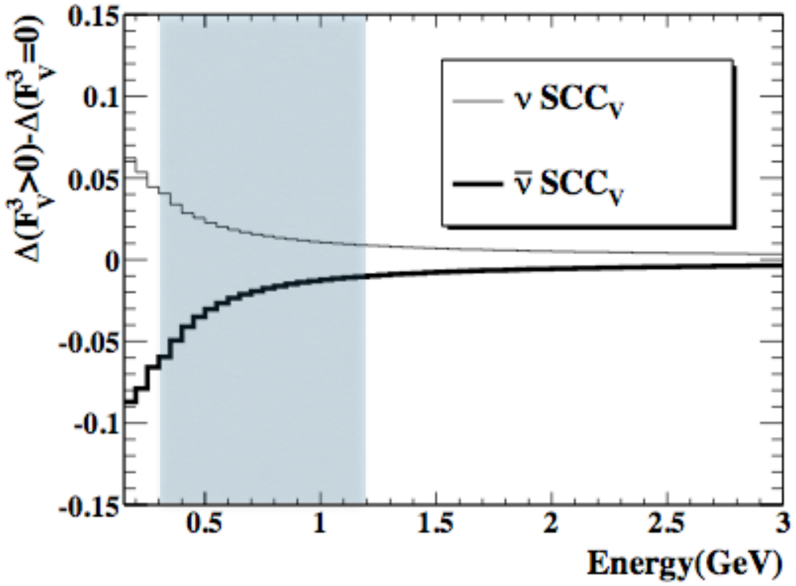
2p-2h parameters next largest

ν_e - anti ν_e Uncertainty

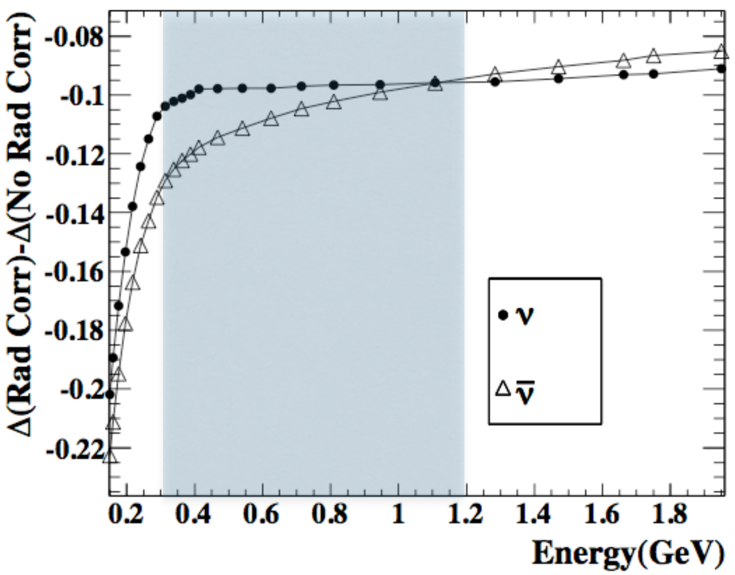
Kinematics



Second Class Currents



Radiative corrections



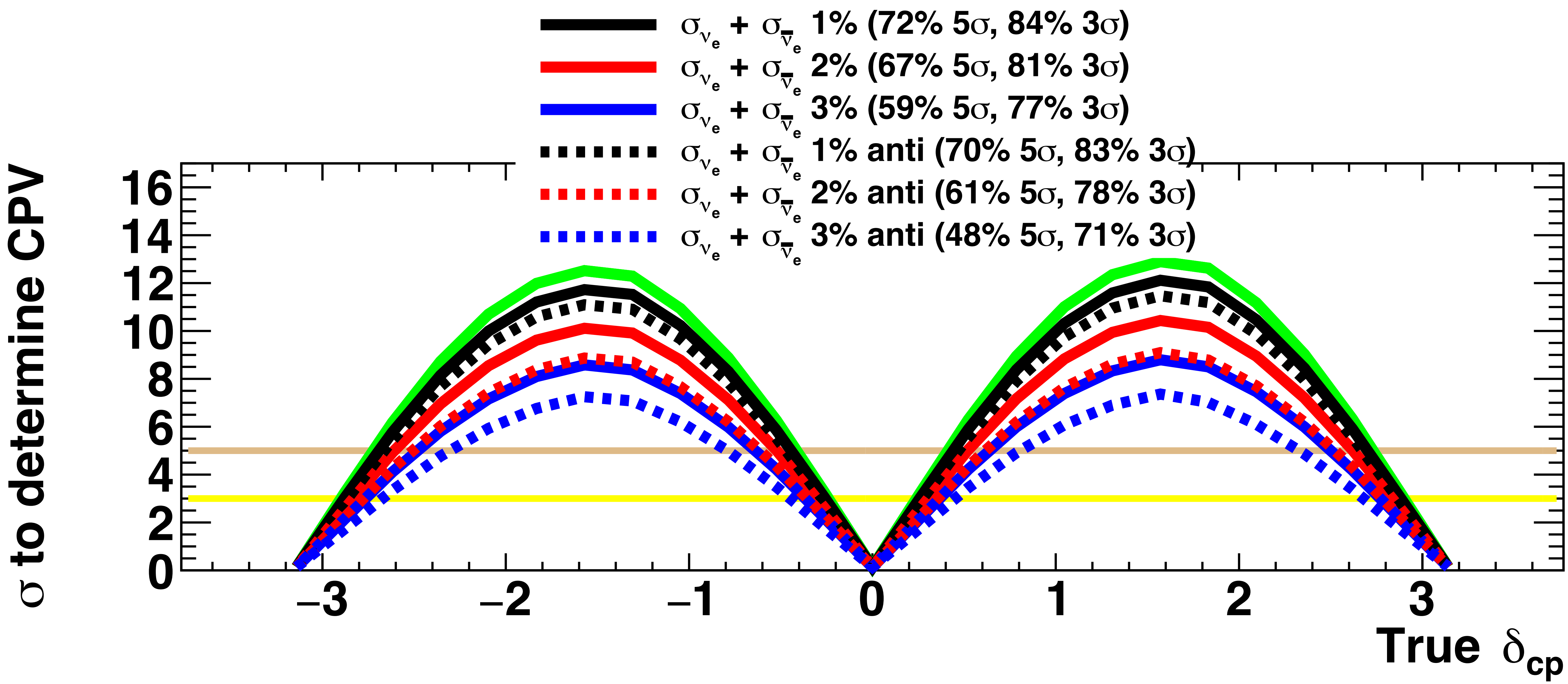
Day & McFarland (Phys.Rev. D86 (2012) 053003)

Kinematic allowed region

Second class currents (anti-correlated)

Radiative corrections need to be calculated!

ν_e - anti ν_e

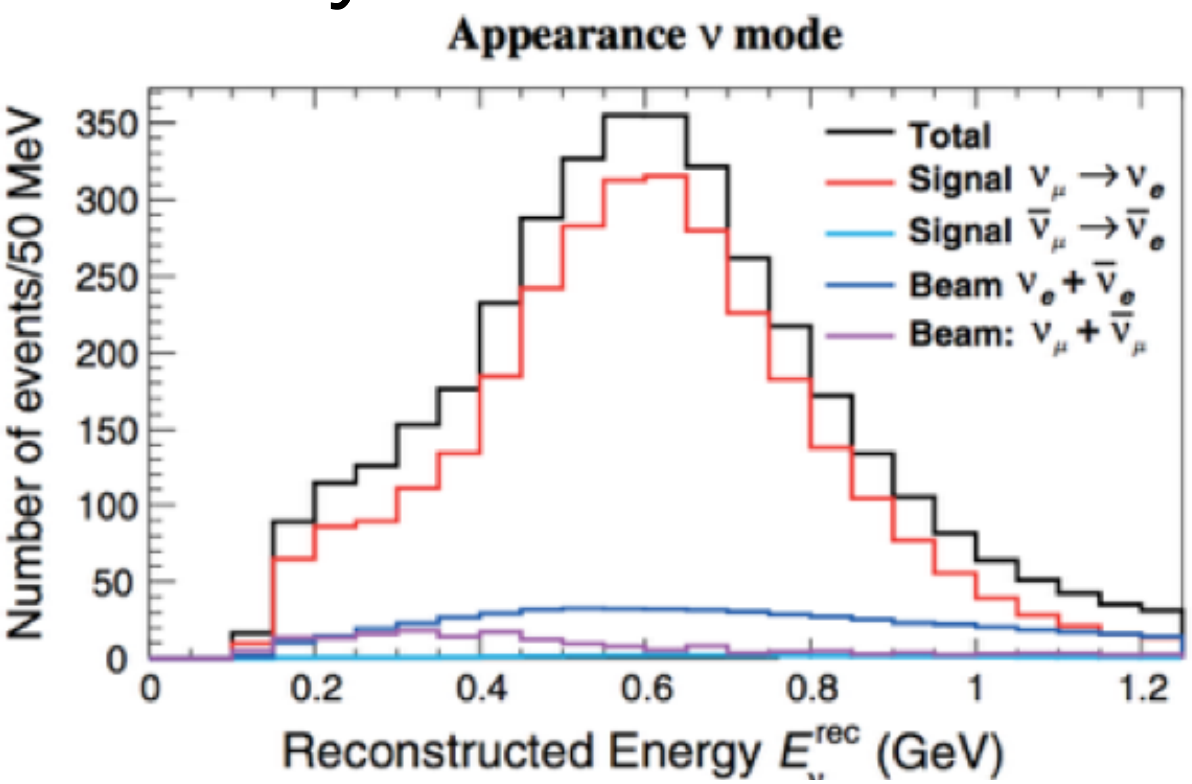


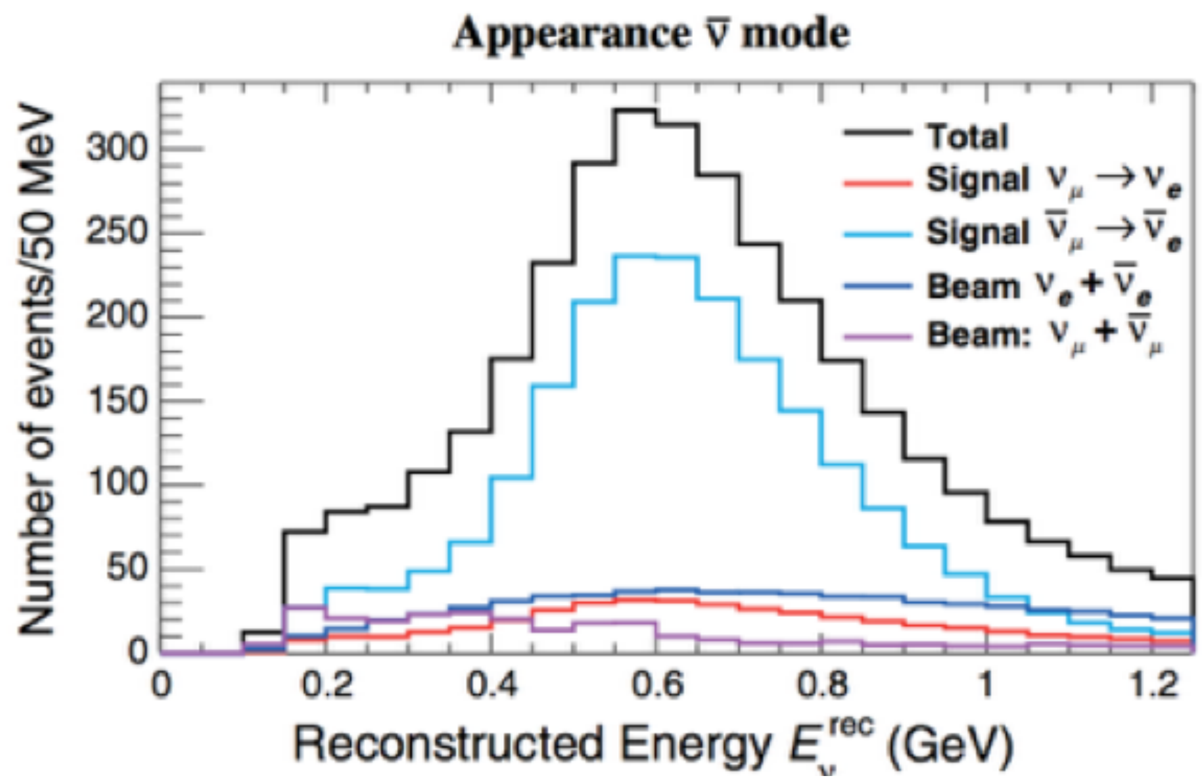
ν_e - anti ν_e anti-correlation significant

~1% constraint to maximise HK potential

Flux

2 Systematic effects identified and studied



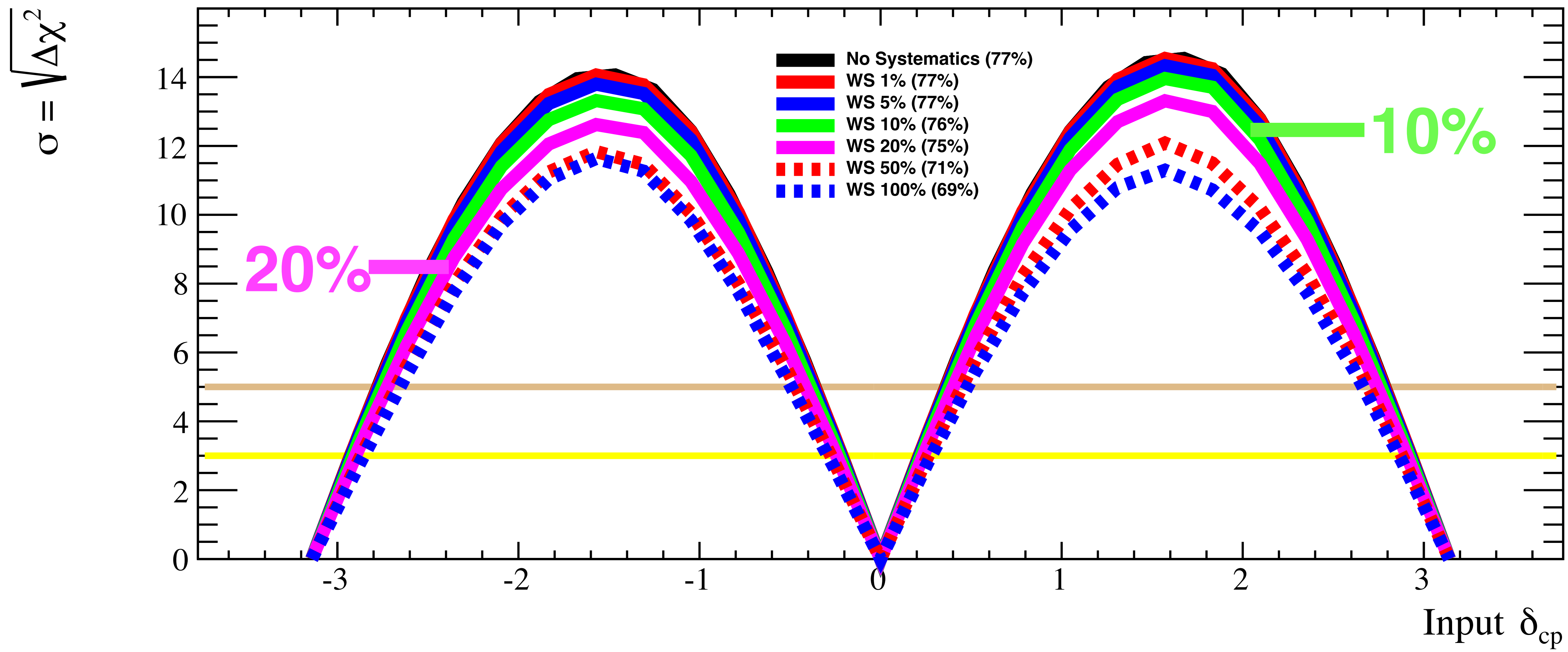


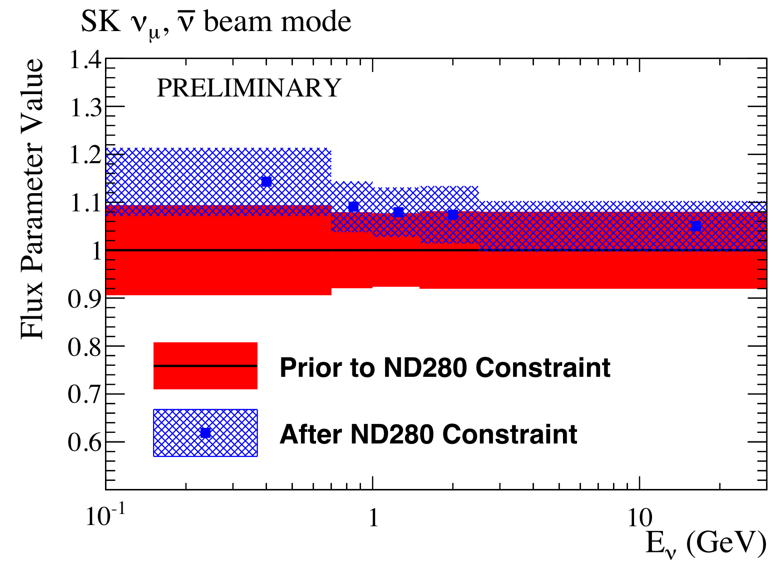
	signal		BG					total
	$\nu_\mu \rightarrow \nu_e$	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	ν_μ CC	$\bar{\nu}_\mu$ CC	ν_e CC	$\bar{\nu}_e$ CC	NC	
ν mode	3016	28	11	0	503	20	172	3750
$\bar{\nu}$ mode	396	2110	4	5	222	396	265	3397

Fraction of wrong sign flux in anti-ν_e

Intrinsic ν_e in both ν_e and anti-ν_e

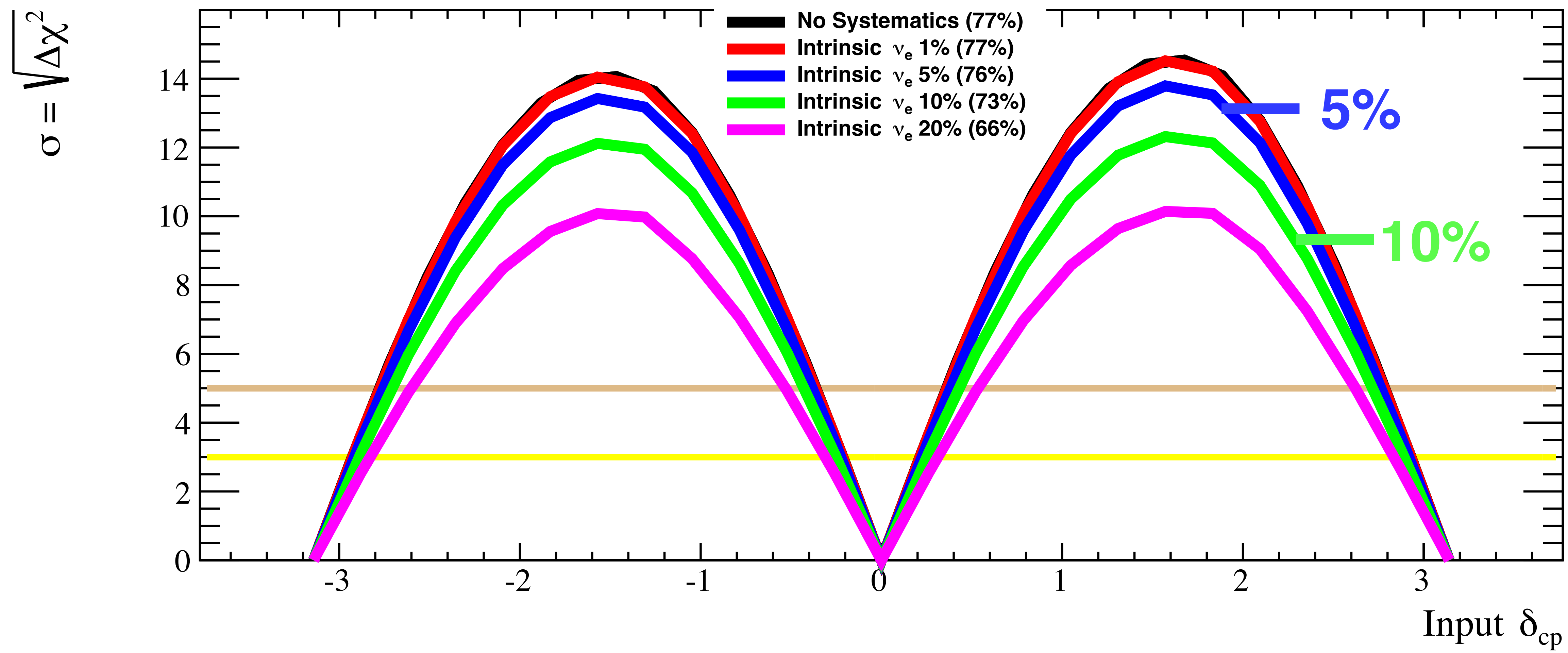
Wrong Sign Background



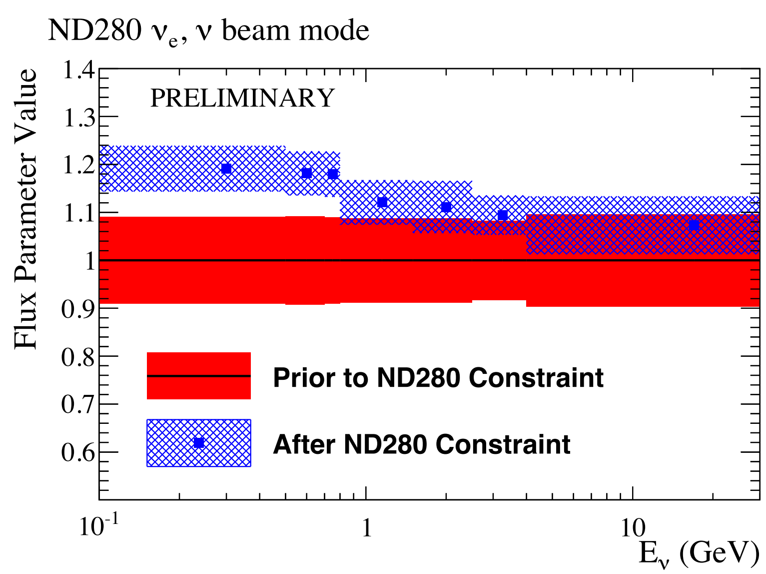


Negligible effect below ~10% error
Current T2K (magnetised) ND ~ 7% ->
Focusing 250kA - > 320kA

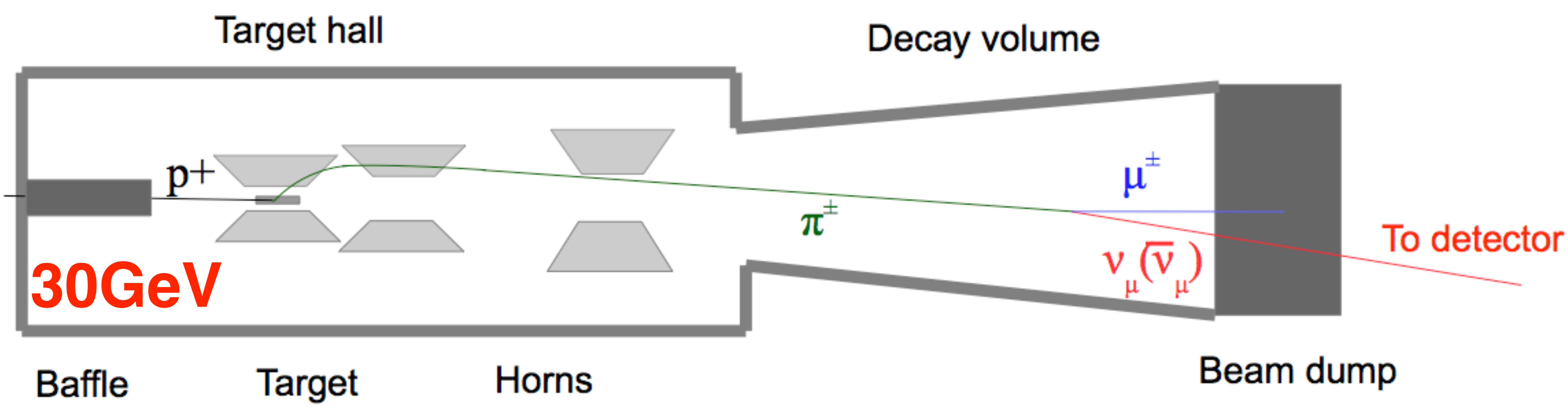
Intrinsic ν_e



Need a constraint between 1-5%
Current T2K ND has ~5% error ->
(Comes from ν_μ-ν_e correlations)



Flux Uncertainties



- Proton beam uncertainties
- Target and hadron production uncertainties
- Horn field uncertainties
- Alignment uncertainties

Data from NA61/SHINE

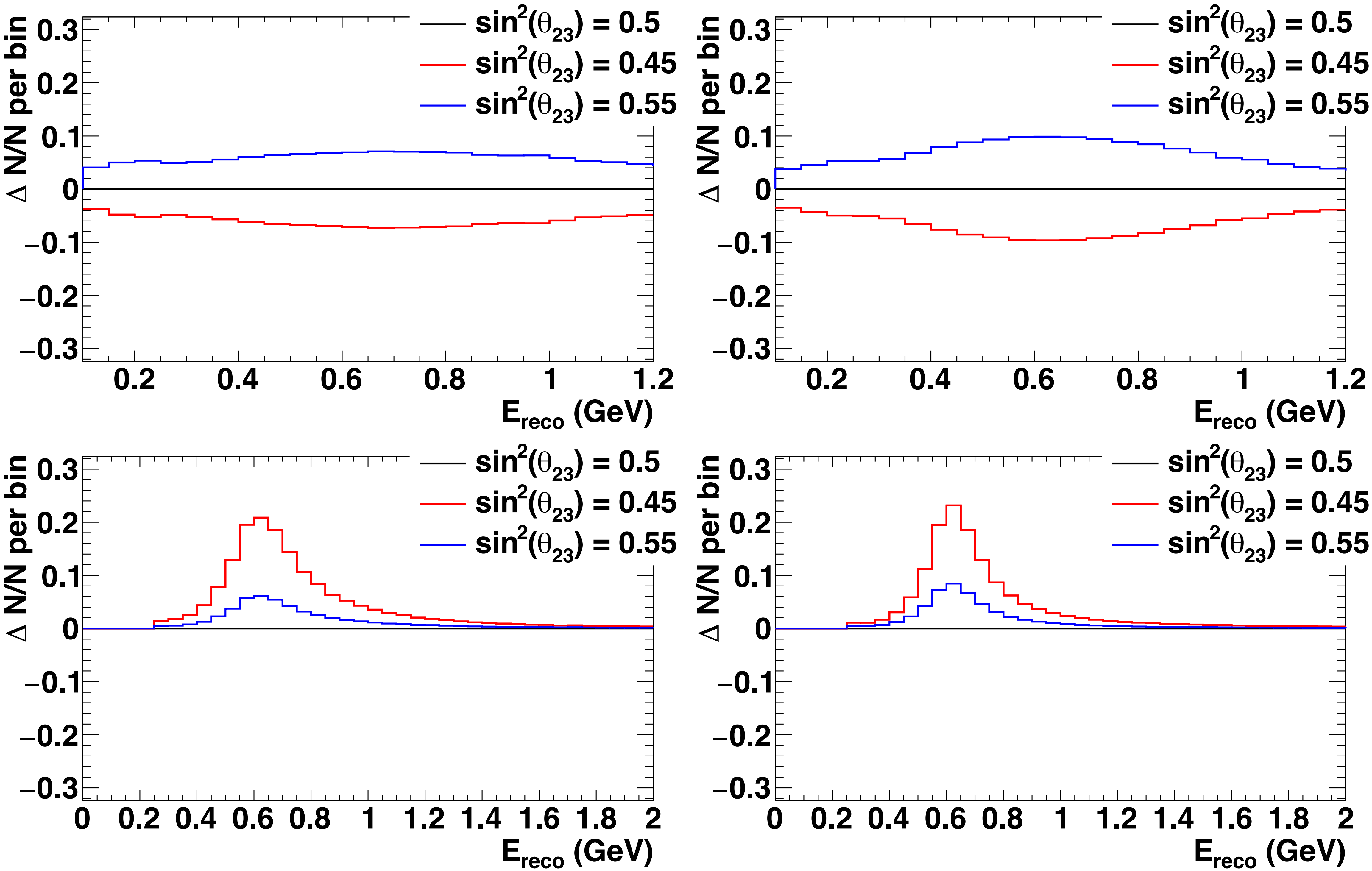
Non maximal θ_{23}

$\sin^2(\Theta_{23}) \neq 0.5$

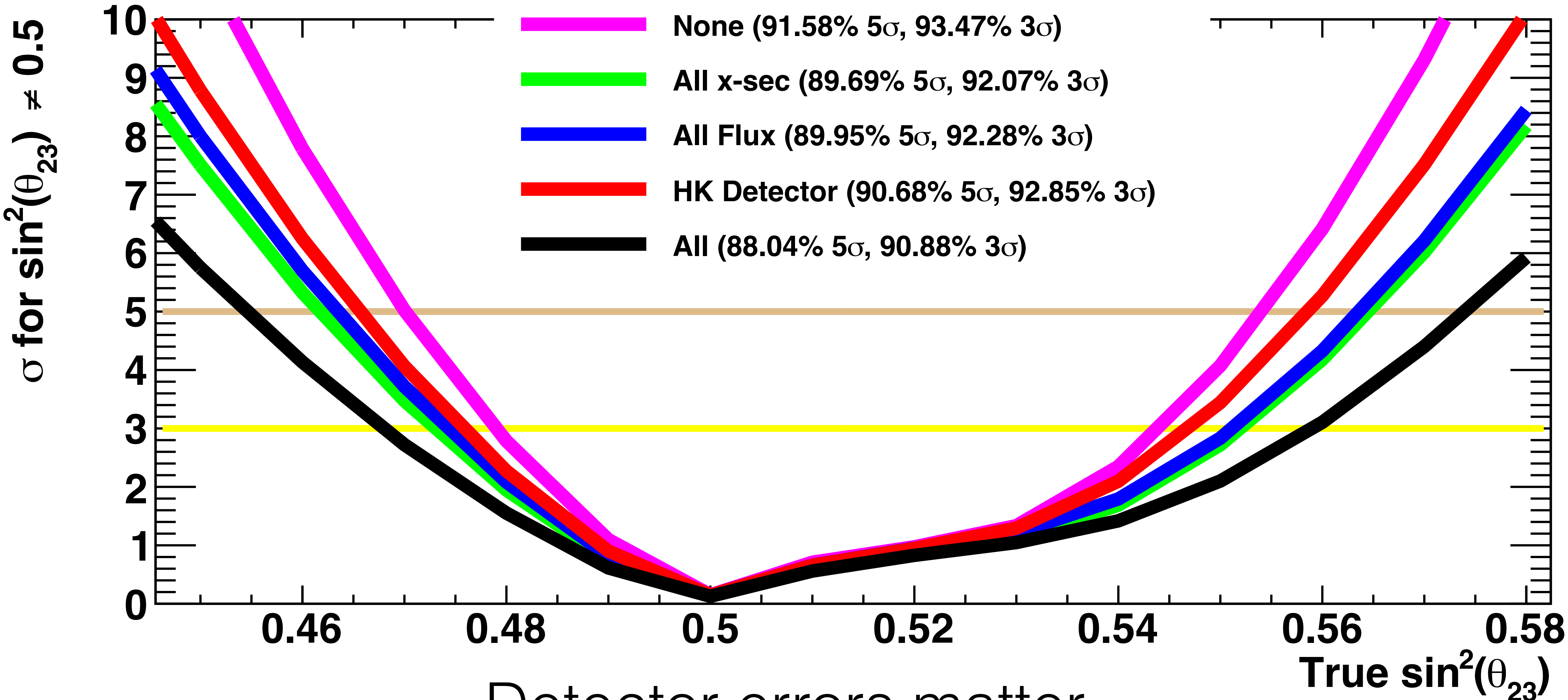
ν - mode | anti ν - mode

1R$_e$

1R$_\mu$



$\sin^2(\Theta_{23}) \neq 0.5$



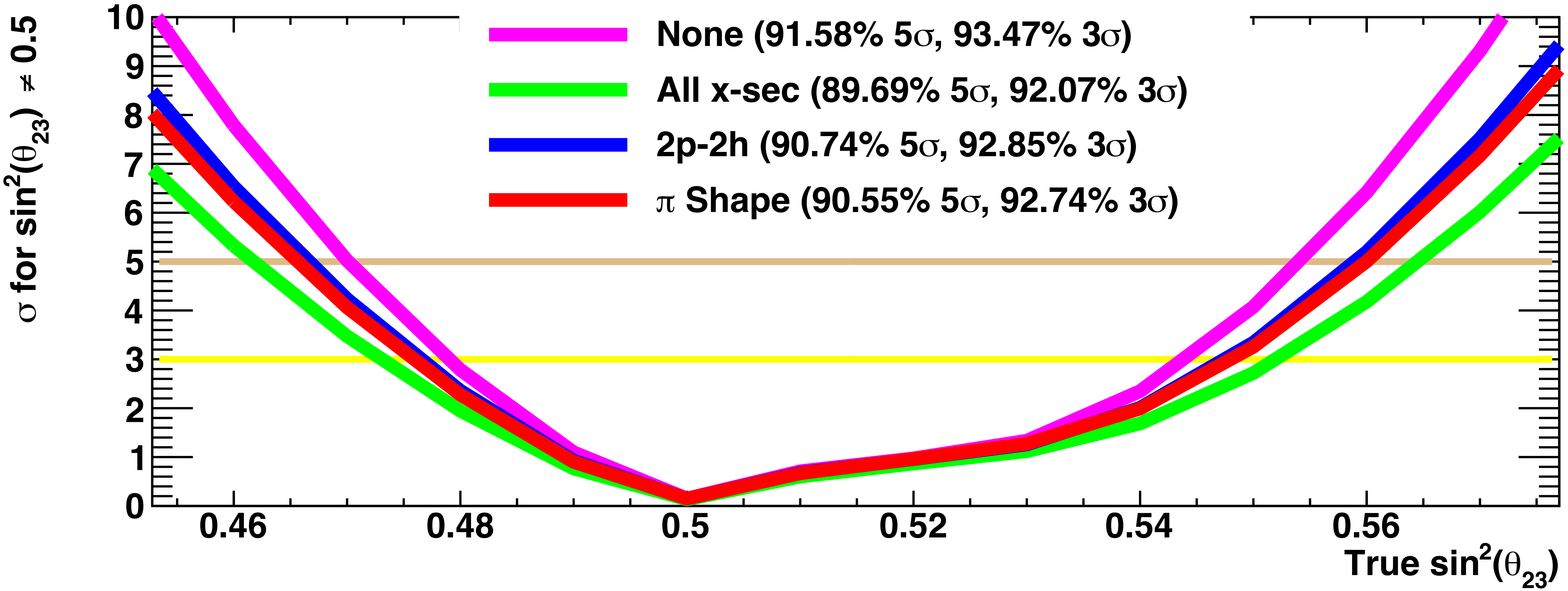
Detector errors matter

Flux and X-Sec errors approx equal effect

No dominant effect as in δ_{cp}

Studied x-sec in detail

$\sin^2(\Theta_{23}) \neq 0.5$ - XSec



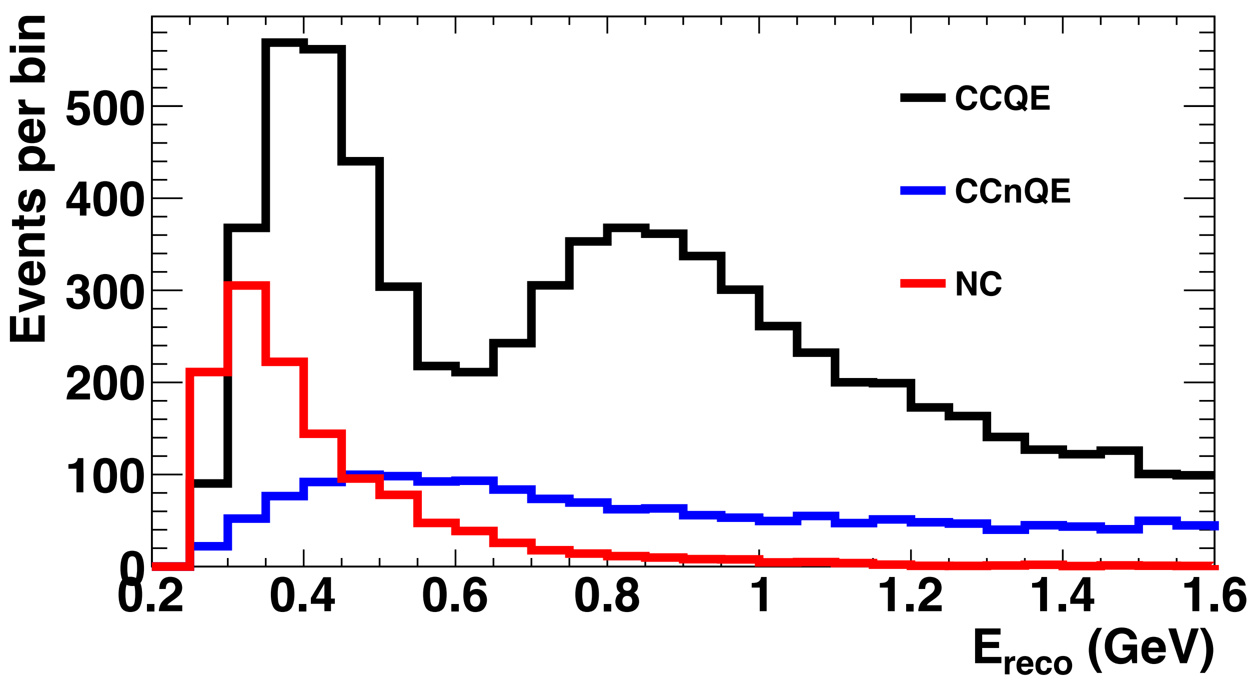
No dominant uncertainty

π shape + 2p-2h have similar effects

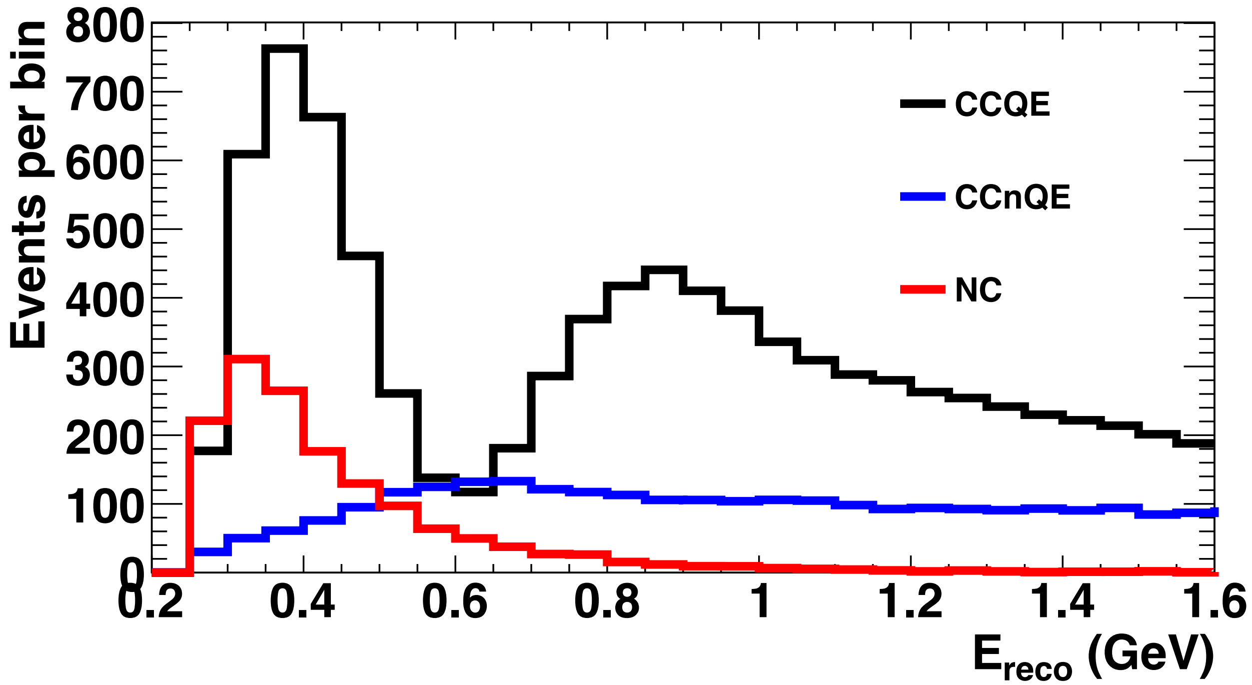
Minimal effect from including CCQE shape errors!

$\sin^2(\Theta_{23})$

ν - mode



anti ν - mode



Measurement depends on shape at dip!

NC

- Same in ν and anti-ν
- Dominates are low E

CCnQE (with 2p2h)

- Significant at osc dip
- > CCQE in anti-ν

Summary

CPV

- ν_e + anti ν_e errors dominate
- 2p-2h and anti - 2p-2h errors next largest
- Both explicitly have ν + anti ν differences

Non-Maximal θ_{23}

- No dominant source of error
- Flux and Detector still under study
- From x-sec, 2p-2h and Pion have biggest effect

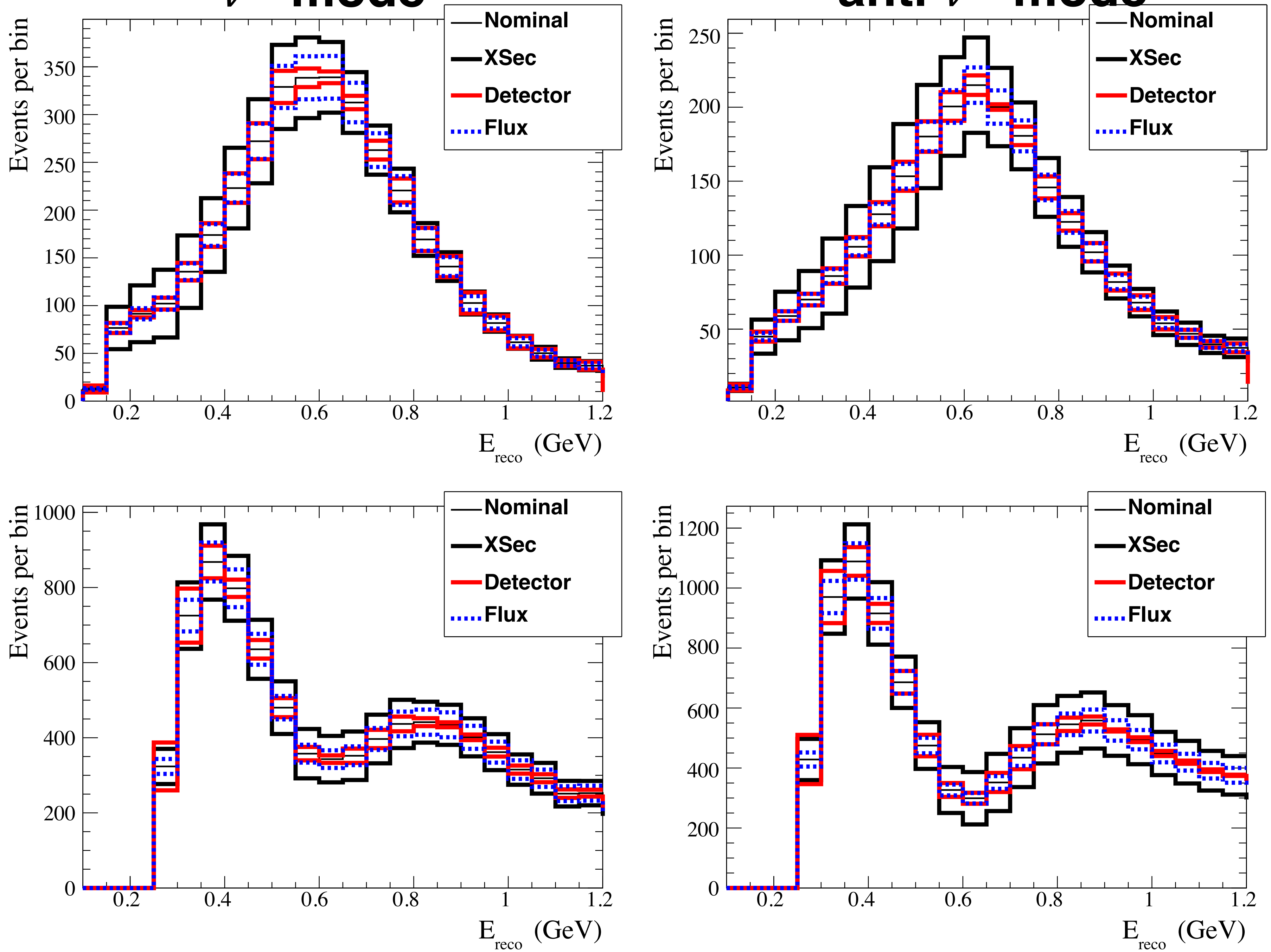
Backups

Systematic envelopes

ν - mode | anti ν - mode

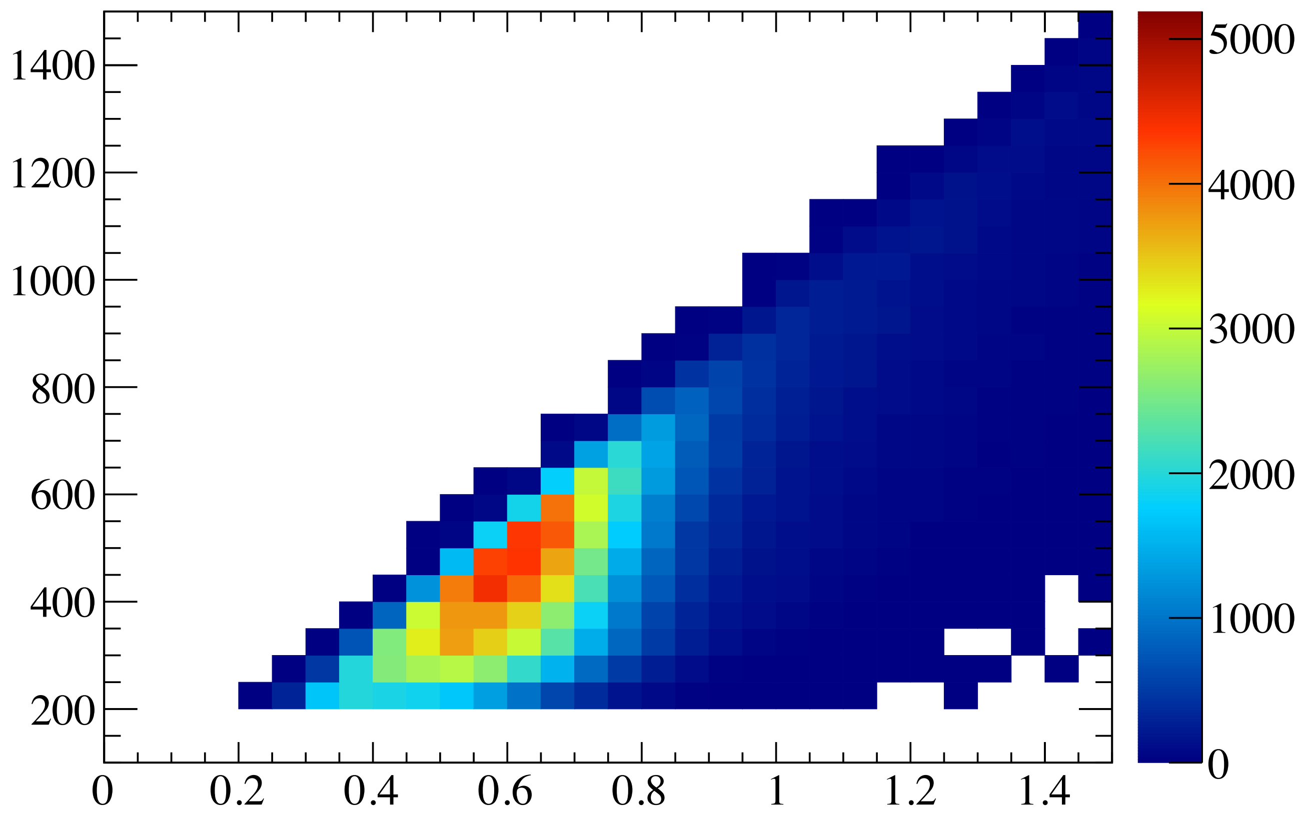
1Re

1R$_\mu$

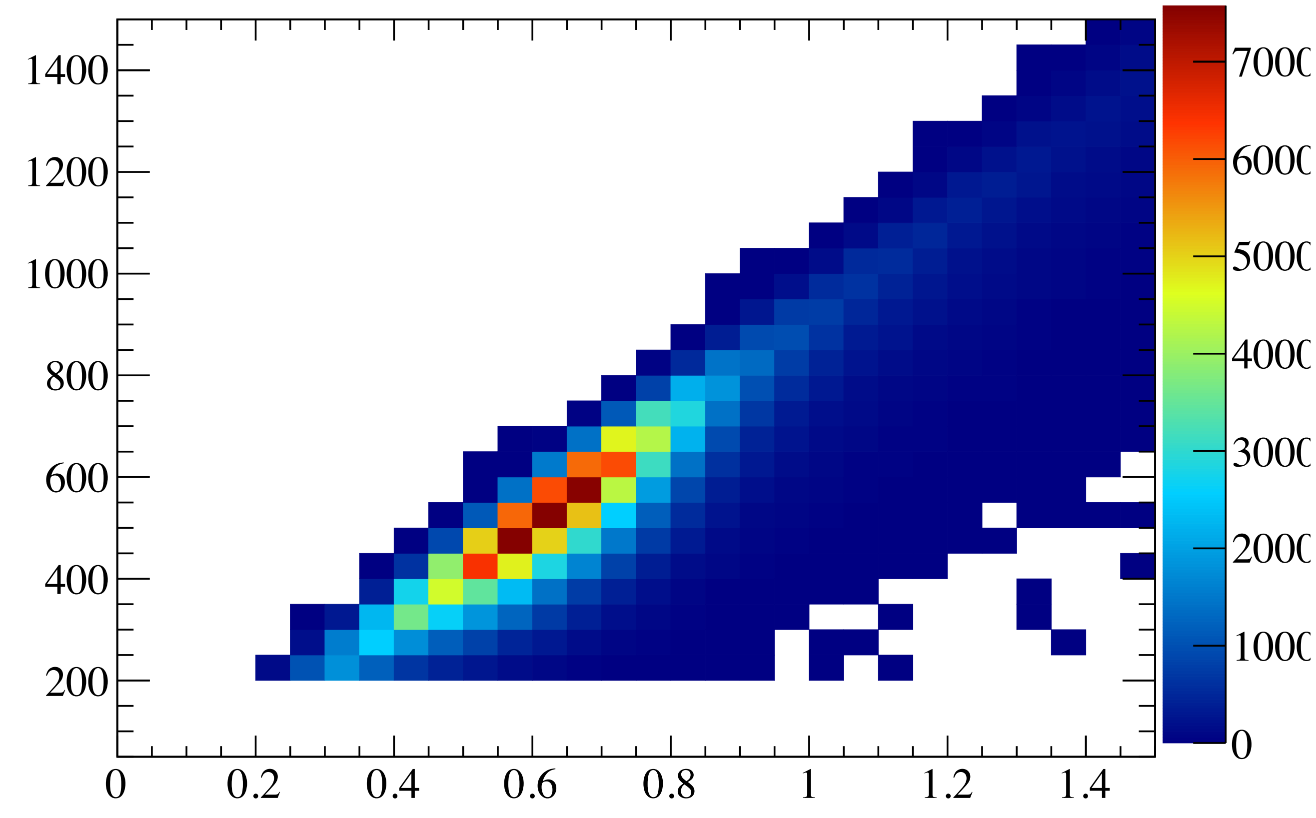


CCQE Reconstruction

ν - mode



anti ν - mode



$$E_\nu^{\mathrm{rec}} = \frac{m_p^2 - (m_n - E_b)^2 - m_l^2 + 2(m_n - E_b)E_l}{2(m_n - E_b - E_l + p_l \cos\theta_l)}$$

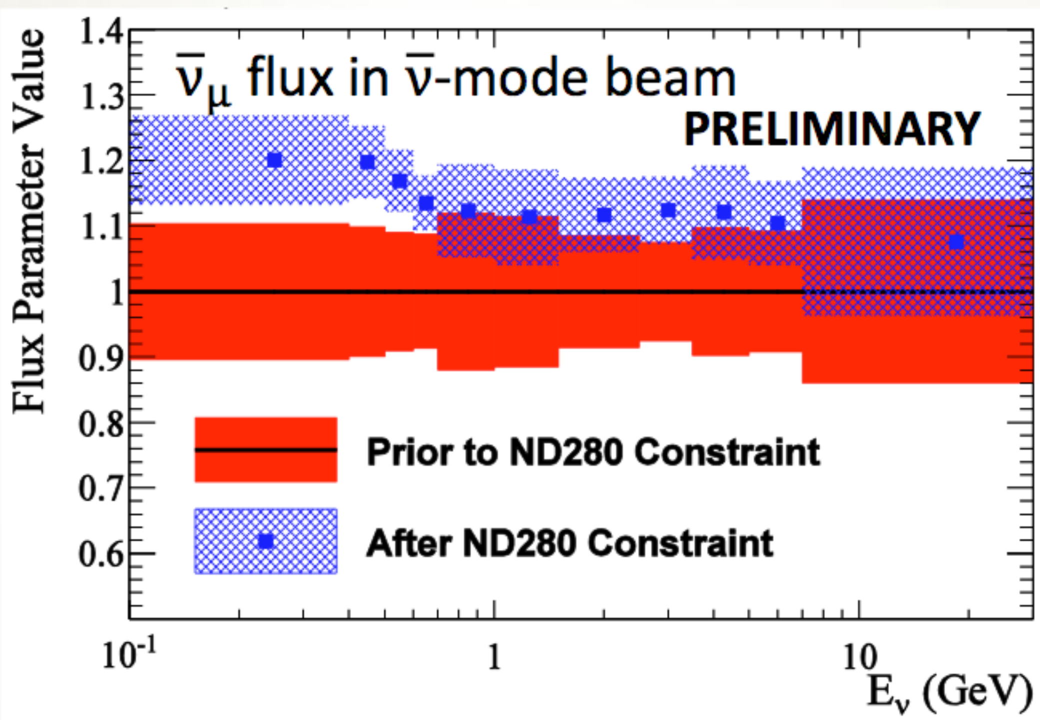
Model and Errors

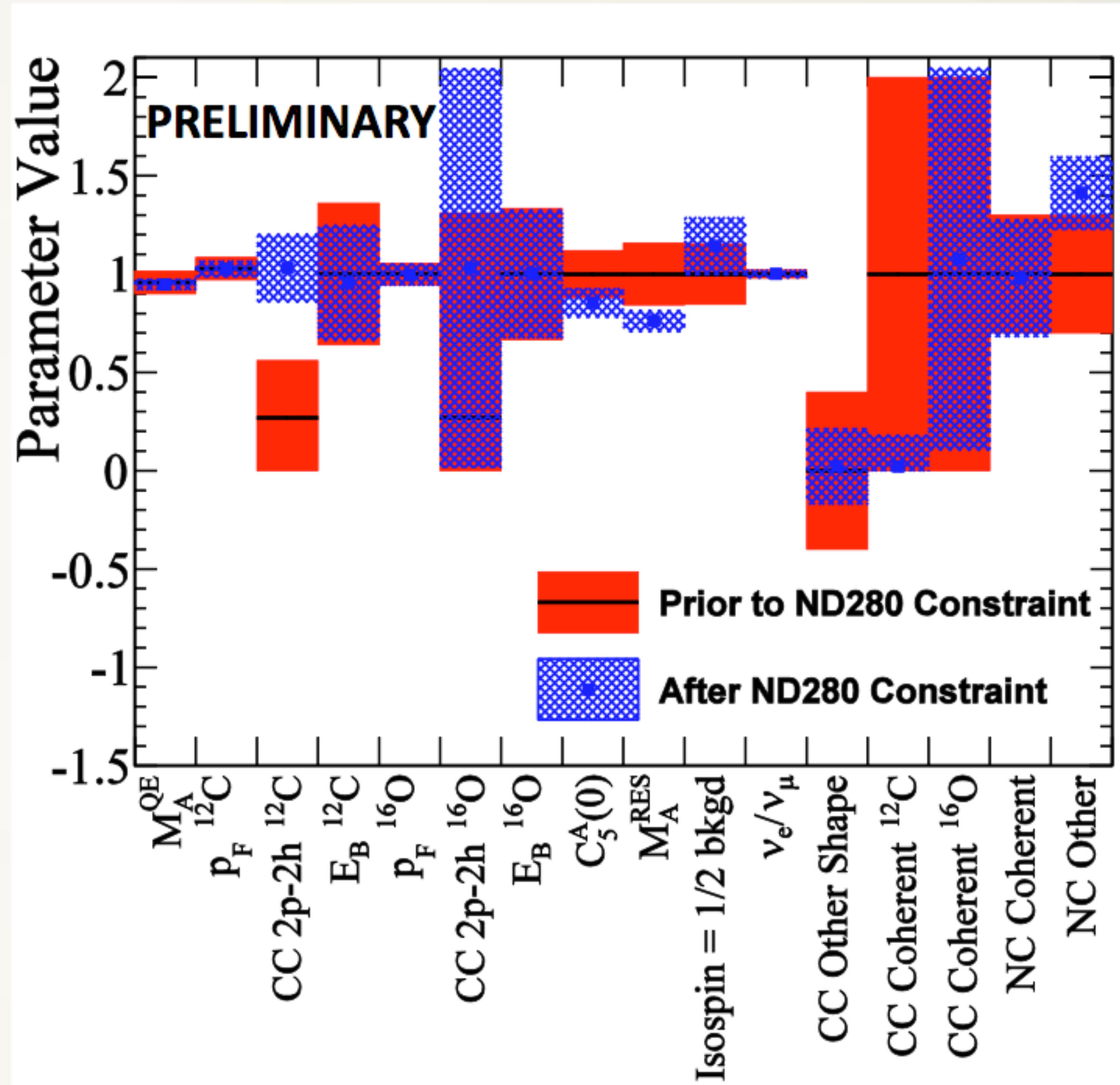
Parameter	Validity Range	Nominal	Error	Class
M_A^{QE}	all	1.15 GeV/c^2	0.06	shape
p_F ^{12}C	200 - 275 MeV/c	223 MeV/c	0.06	shape
MEC ^{12}C	all	0.27	0.29	norm
E_B ^{12}C	12 - 42 MeV	25 MeV	0.36	shape
p_F ^{16}O	200 - 275 MeV/c	225 MeV/c	0.05	shape
MEC ^{16}O	all	0.27	1.04	norm
E_B ^{16}O	12 - 42 MeV	27 MeV	0.33	shape
$CA5^{RES}$	all	1.01	0.12	shape
M_A^{RES}	all	0.95 GeV/c^2	0.16	shape
Isospin=$\frac{1}{2}$ Background	all	1.3	0.15	shape
ν_e/ν_μ	all	1.0	0.02	norm
CC Other Shape	all	0.0	0.40	shape
CC Coh ^{12}C	all	1.0	1.00	norm
CC Coh ^{16}O	all	1.0	1.00	norm
NC Coh	all	1.0	0.30	norm
NC Other	all	1.0	0.30	norm

T2K ND constraint

Near Detector Fit

- Predicted flux at Super-K is generally increased
- Some cross-section parameters are significantly different to prior values
- In general error on parameters is decreased



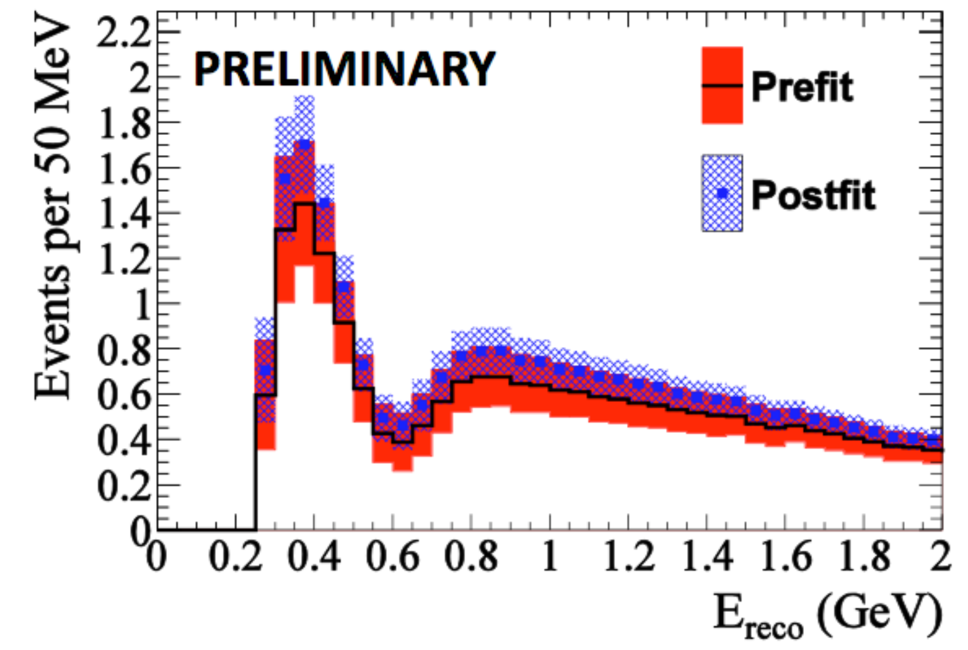


K Duffy NuFact 2015

T2K ND constraint

Near Detector Constraint at Super-K

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

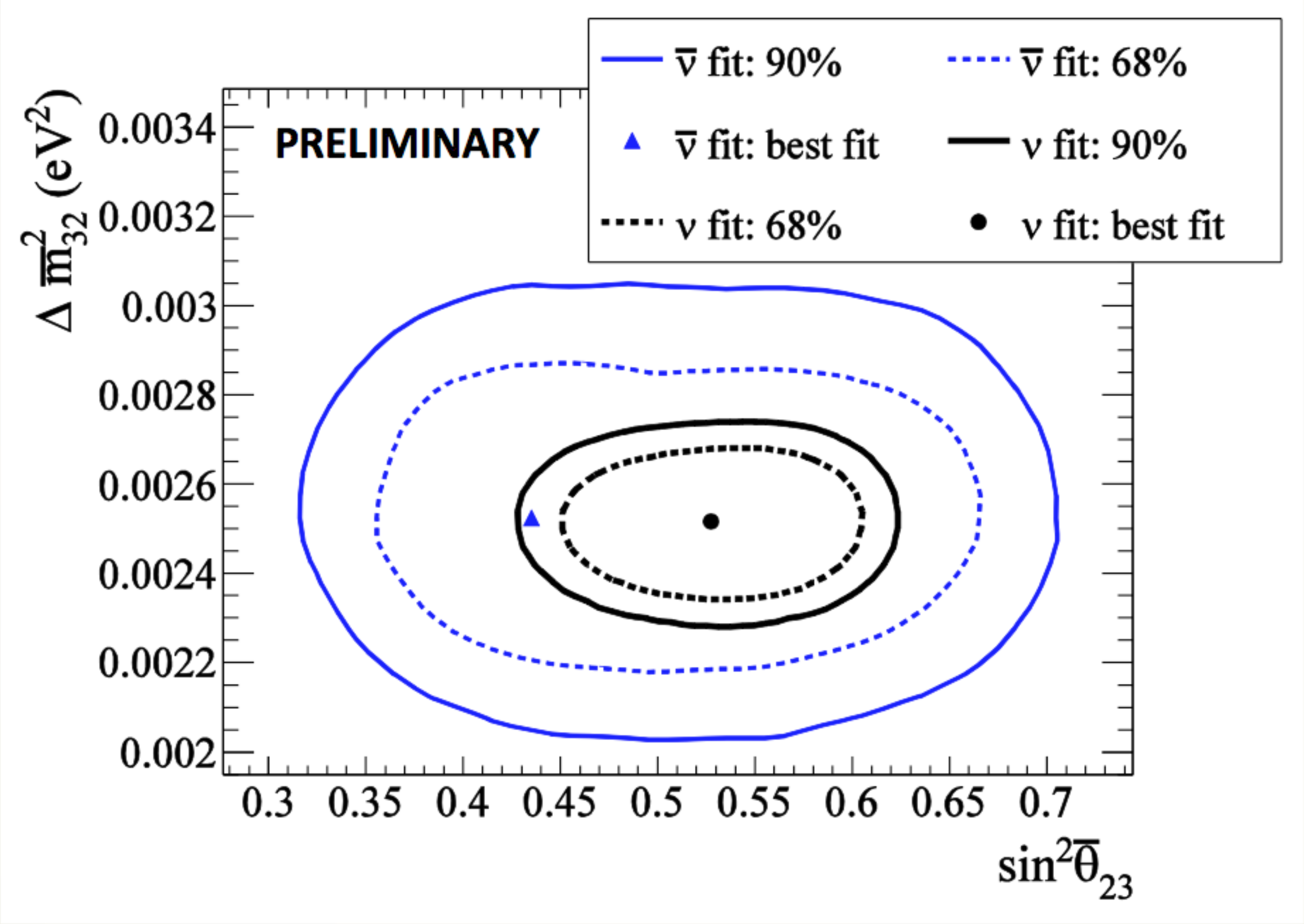


Systematic			Without ND	With ND
Flux and Cross-section	Common to ND280/SK		9.2%	3.4%
	Super-K Only	Multi-nucleon effect on oxygen	9.5%	
		All Super-K Only	10.0%	
	All		13.0%	10.1%
Final State Interaction/Secondary Interaction at Super-K			2.1%	
Super-K Detector			3.8%	
Total			14.4%	11.6%

K Duffy
NuFact 2015

$\bar{\nu}_\mu$ disappearance: Comparison to T2K $\nu_\mu + \nu_e$ fit

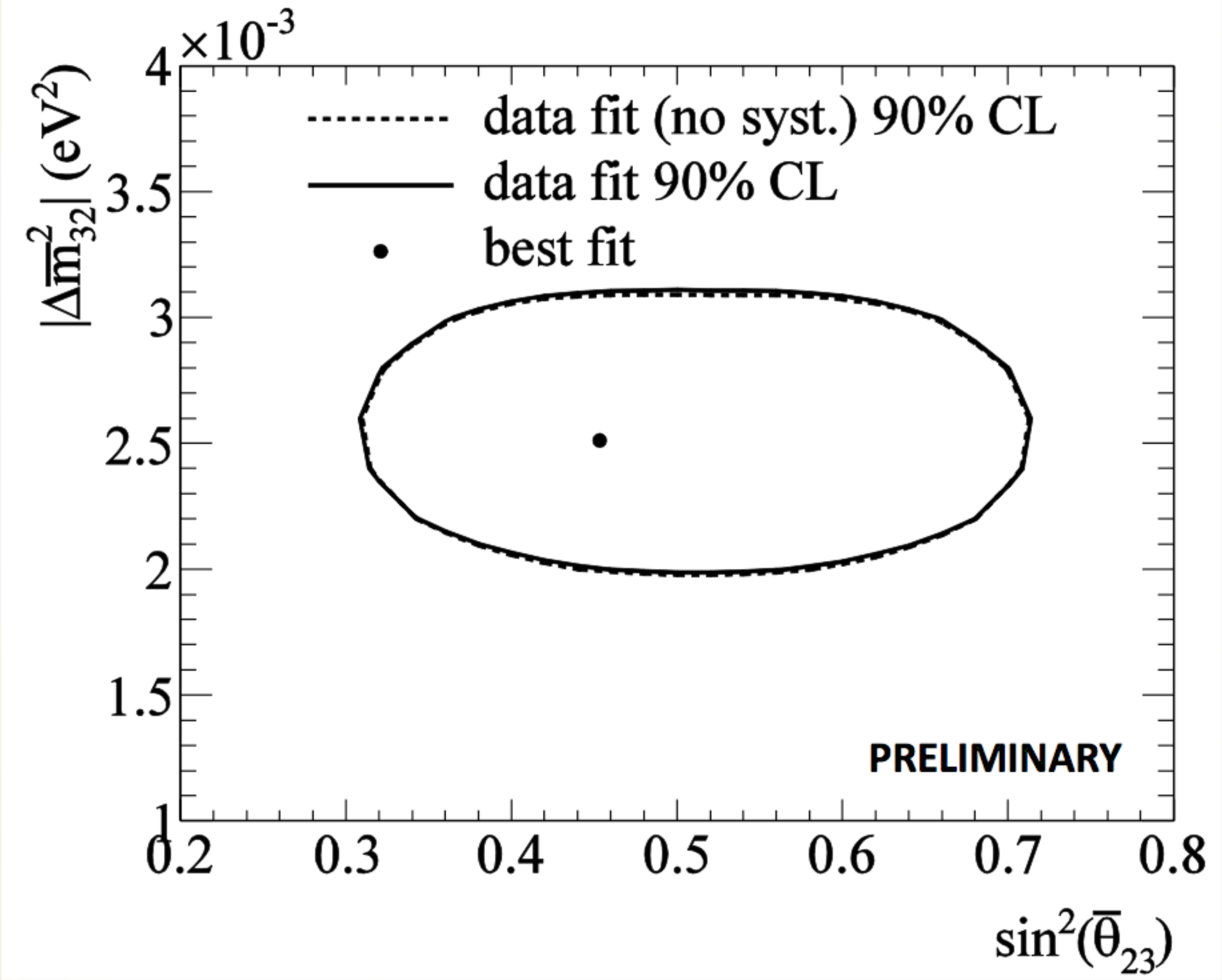
K Duffy NuFact 2015



- Results are consistent between neutrinos and antineutrinos
- Antineutrino analysis has much larger contours

$\bar{\nu}_\mu$ disappearance: Effect of systematics

K Duffy NuFact 2015



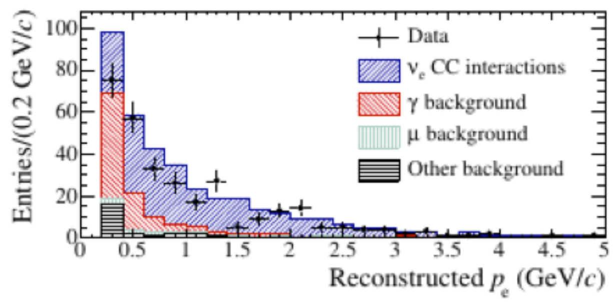
Analysis is still very much statistics-dominated

17/18

T2K ν_e xsec

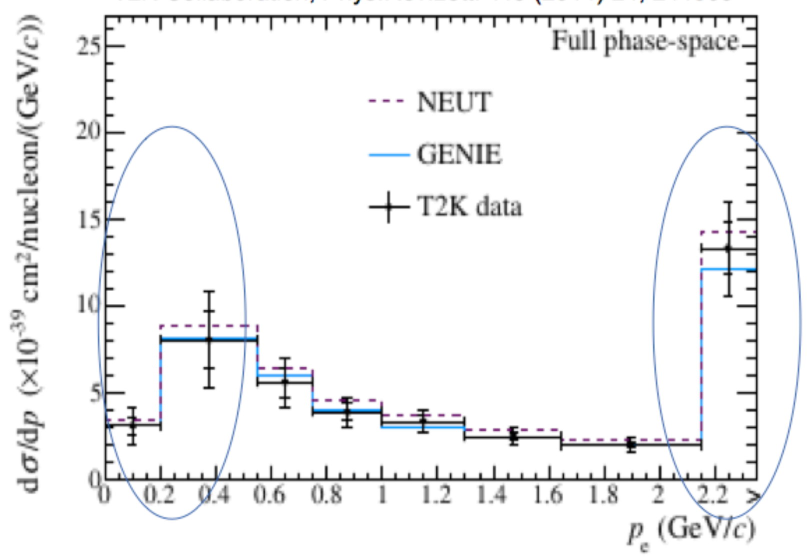
Important for oscillation : $\nu_\mu \rightarrow \nu_e$ appearance

- **ν_e on C**: flux ~1 % → stringent selection



unfolding

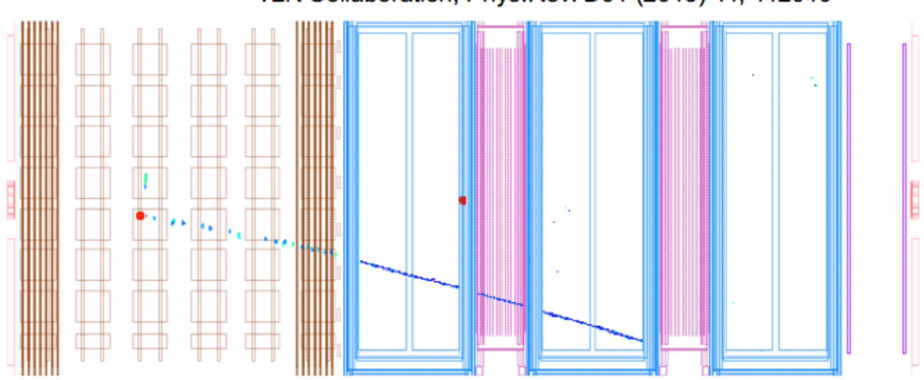
T2K Collaboration, Phys.Rev.Lett. 113 (2014) 24, 241803



- $\pi^0 \rightarrow \gamma$ background 70 % from out-of-fiducial-volume constrained from data (2.1 % systematics)
- large model-dependence where very small efficiency (otherwise stat. limited)

- **ν_e on water with T2K P0D filled with water or emptied (air)**

T2K Collaboration, Phys.Rev. D91 (2015) 11, 112010



- requires forward electrons (θ<45°) + shower/track variable to remove μ and π^0

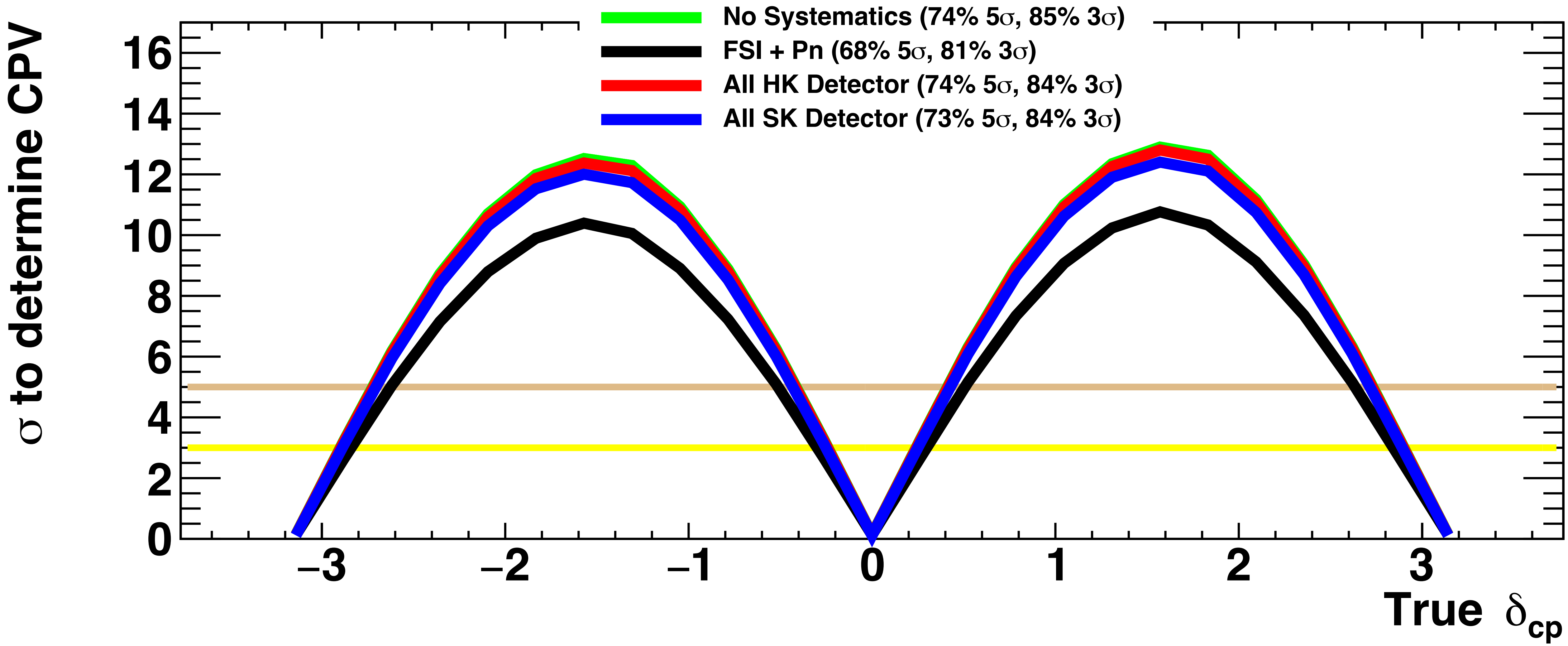
	MC Signal	MC Background	MC Total	Data
Water	196.1 ± 4.8	56.7 ± 2.7	252.8 ± 5.5	230
On-Water	60.2 ± 2.6	14.5 ± 1.3	74.7 ± 2.9	
Not-Water	135.9 ± 4.0	42.2 ± 2.3	178.2 ± 4.6	
Air	173.6 ± 4.6	97.4 ± 3.6	271.0 ± 5.8	257

- subtraction of air data from water data
→ large statistical uncertainties (syst dominated by detector)

$$R_{on\ water} = (water - air)_{data} / MC_{on\ water} = 0.87 \pm 0.33\,(stat.) \pm 0.21\,(syst)$$

Sara Bolognesi - NuFact15

Det + FSI + PN



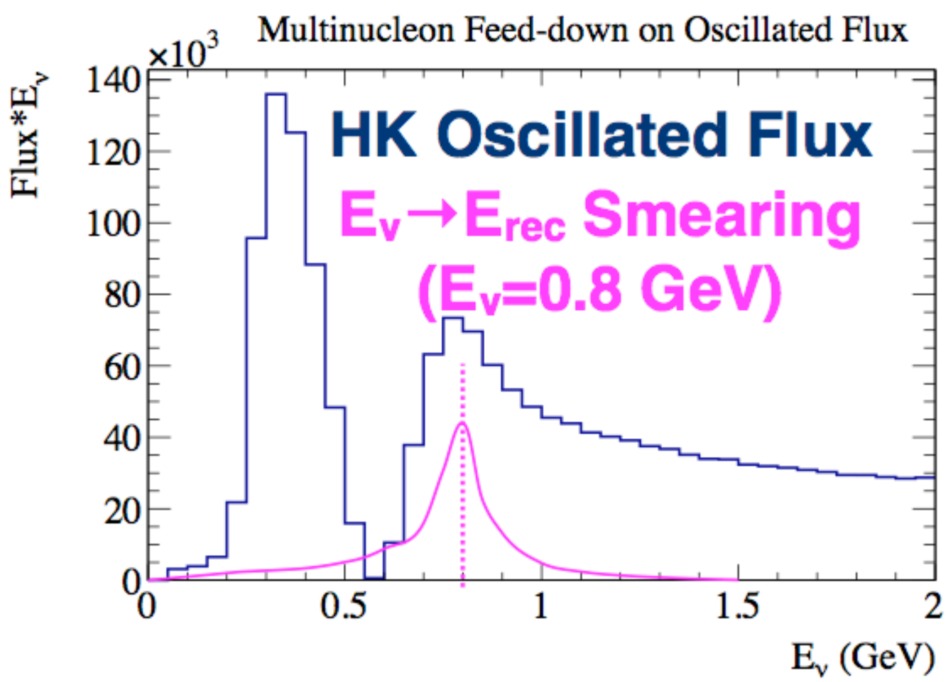
Detector errors have little effect even at SK level

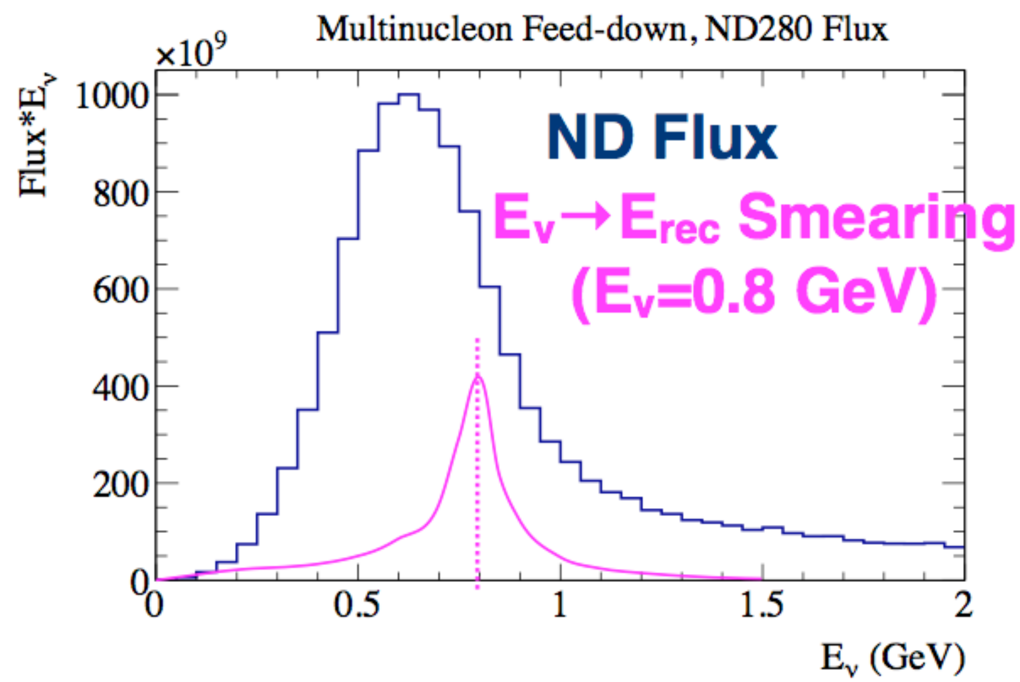
(~100% correlated between ν and anti - ν modes)

FSI + Photo-nuclear currently uncorrelated

$\sin^2(\theta_{23})$ - MEC

- The problem of energy reconstruction was covered in the neutrino-nucleus theory overview by M. Martini on Monday (12:30)
  - Non-QE interactions have a reconstructed energy that can deviate significantly from the true energy
  - Constraining this effect with near detector data is challenging since the near detector flux is broad and different from the far detector flux



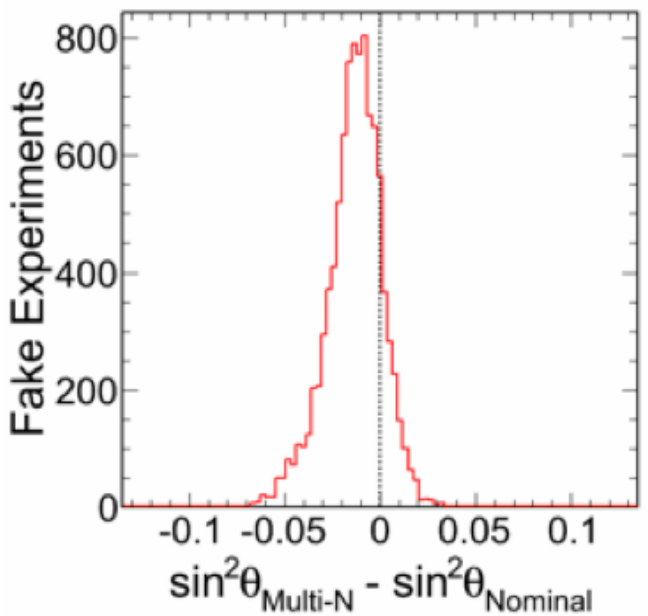


M Hartz NuFact2015

$\sin^2(\theta_{23})$ - MEC

- The uncertainty on the energy smearing due to nuclear effects has a large impact on the ν_μ disappearance measurement since smeared events fill in the "dip" region
- HK aims for 1-3% precision on $\sin^2\theta_{23}$ (depends on the true value)
- T2K studied the impact of np-nh modeling uncertainty
  - Generate toy data with an ad-hoc np-nh model
  - Fit the toy data with the NEUT model (includes pion-less delta decay)
  - Evaluate the bias on the fitted oscillation parameters

The average bias in the fitted $\sin^2\theta_{23}$ was 3%



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