XVIth International Workshop on Neutrino Factories and Future Neutrino Facilities

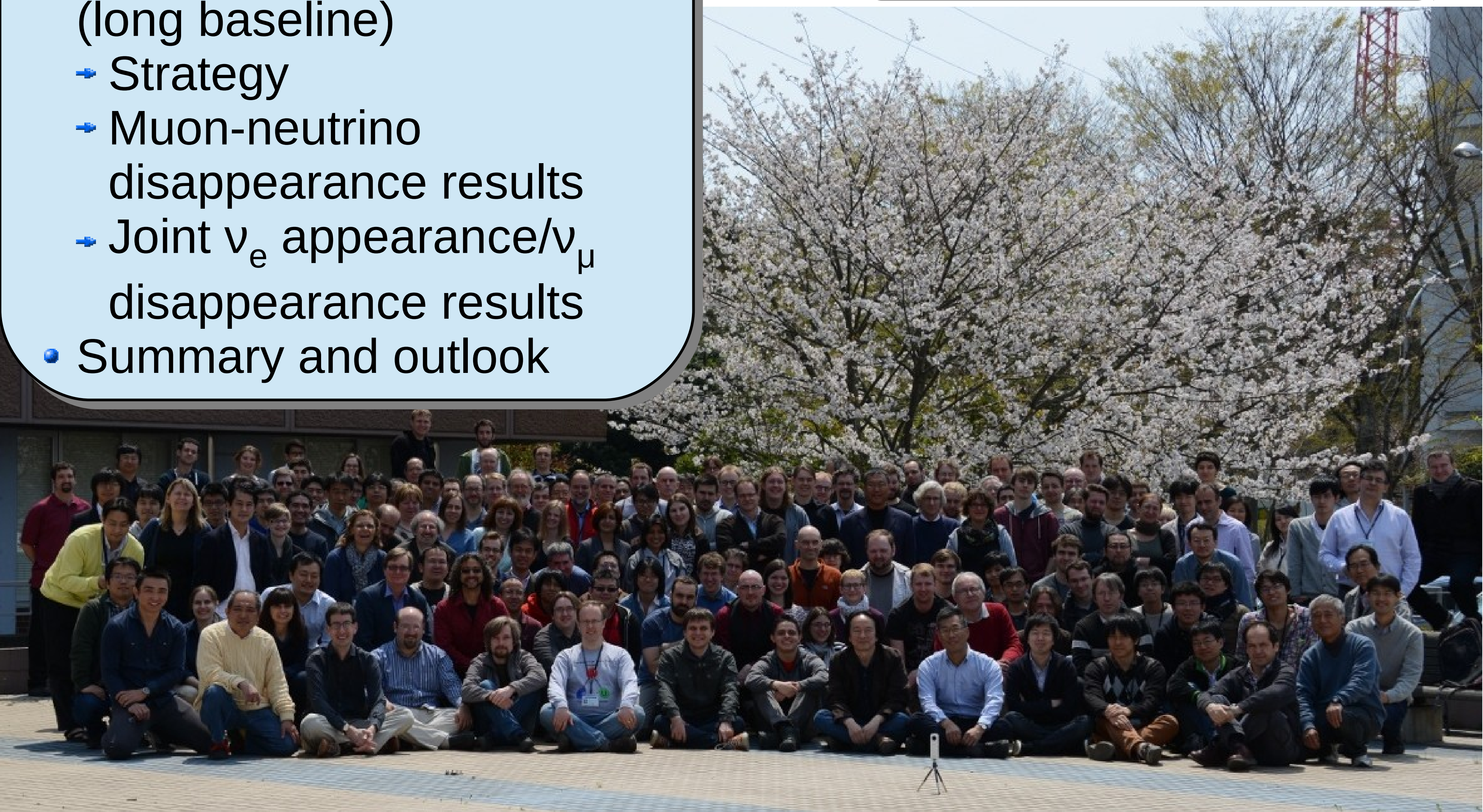
T2K neutrino oscillation results

C. Bronner for the T2K collaboration
August 26th, 2014

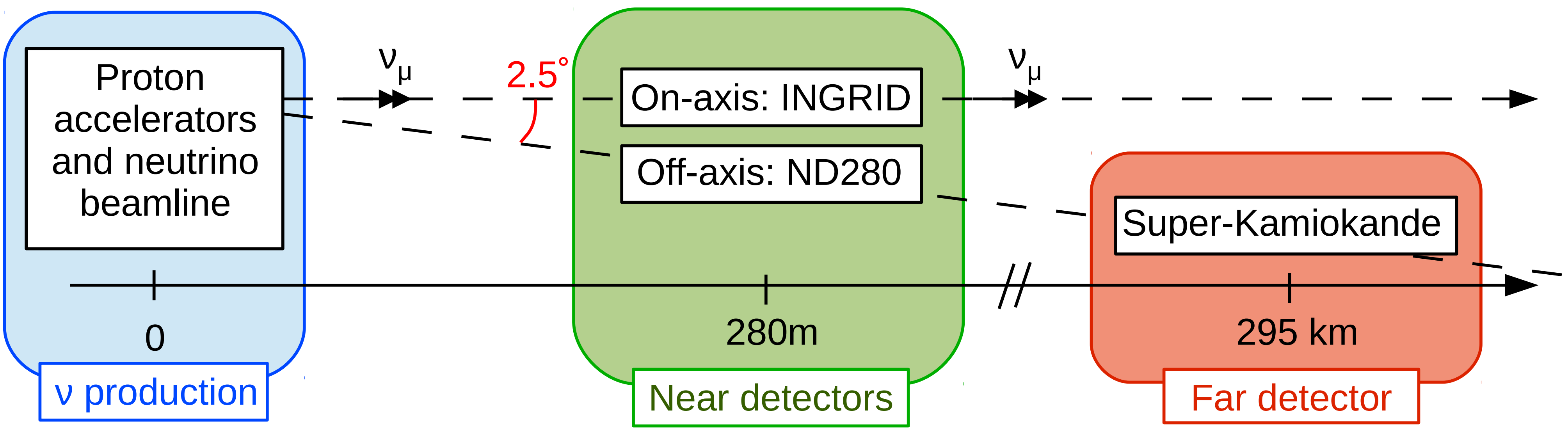
Outline

- The T2K experiment
- Neutrino oscillation analysis (long baseline)
  - Strategy
  - Muon-neutrino disappearance results
  - Joint ν_e appearance/ν_μ disappearance results
- Summary and outlook

See presentation by J. Caravaca for short baseline oscillations



The T2K experiment
Overview



- Long baseline (295 km) neutrino oscillation experiment
- Off-axis beam
- Almost pure ν_μ beam produced by an accelerator

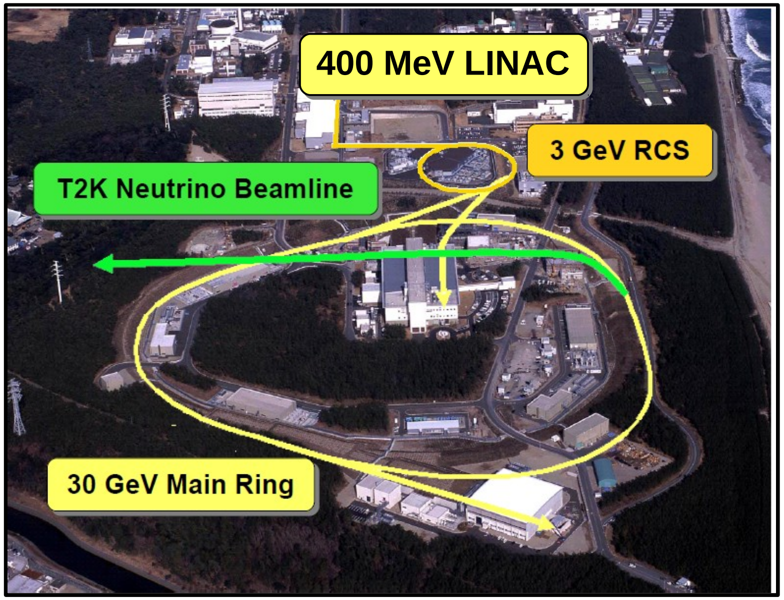
<u>At the far detector, looking for:</u>

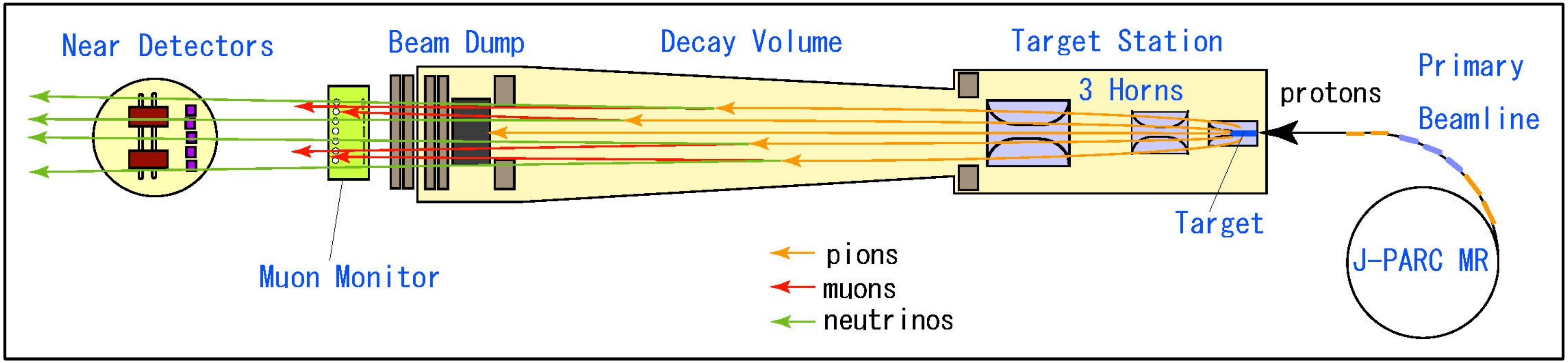
- $\nu_\mu \rightarrow \nu_e$ appearance
- $\nu_\mu \rightarrow \nu_X$ disappearance

to measure/constrain θ_{13}, θ_{23}, $|\Delta m^2_{32/31}|$ and δ

The T2K experiment
Neutrino production

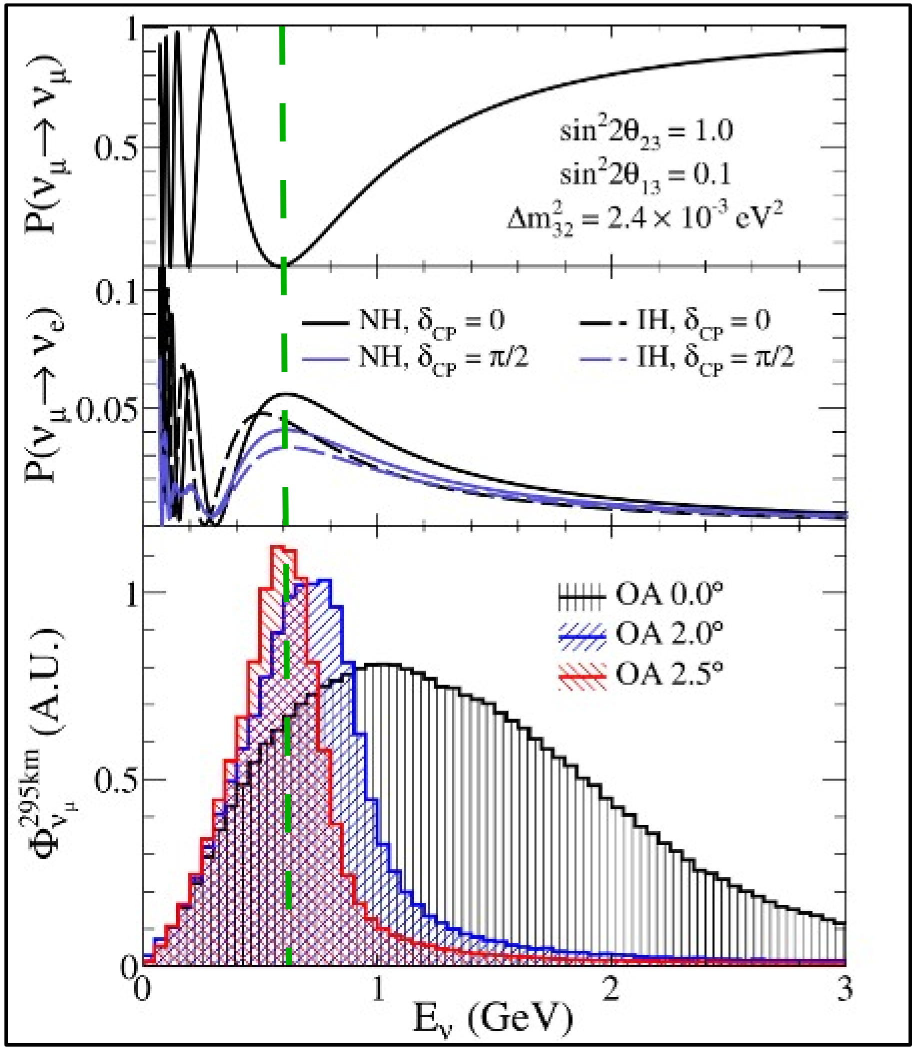
Conventional neutrino beam
Produced from 30 GeV protons
delivered by the J-PARC
accelerators complex

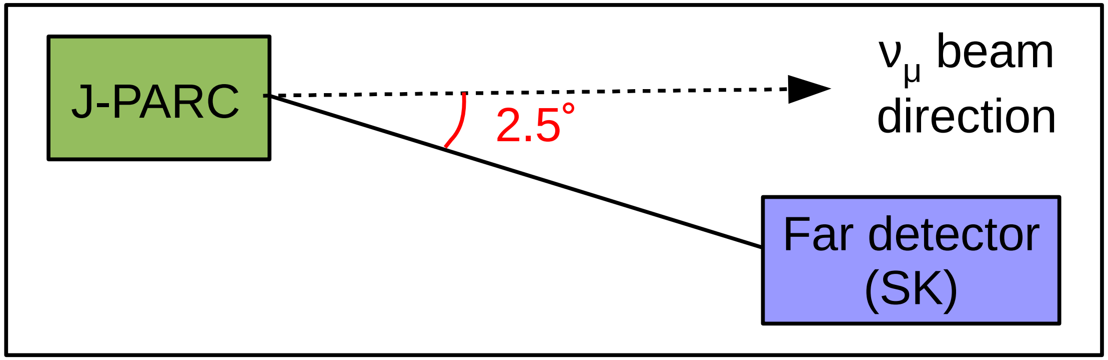




Obtain an **almost pure ν_μ beam**, with an intrinsic ν_e component of a few %

The T2K experiment
Off-axis beam



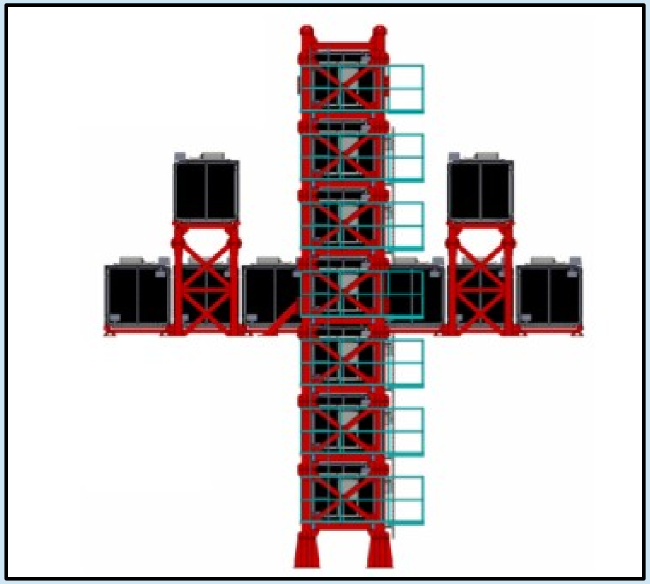


- Narrow band neutrino beam, peaked at oscillation maximum (0.6 GeV)
- Reduces high energy tail
- Reduces intrinsic ν_e contamination of the beam
- Interactions dominated by CCQE mode

The T2K experiment
Near detectors

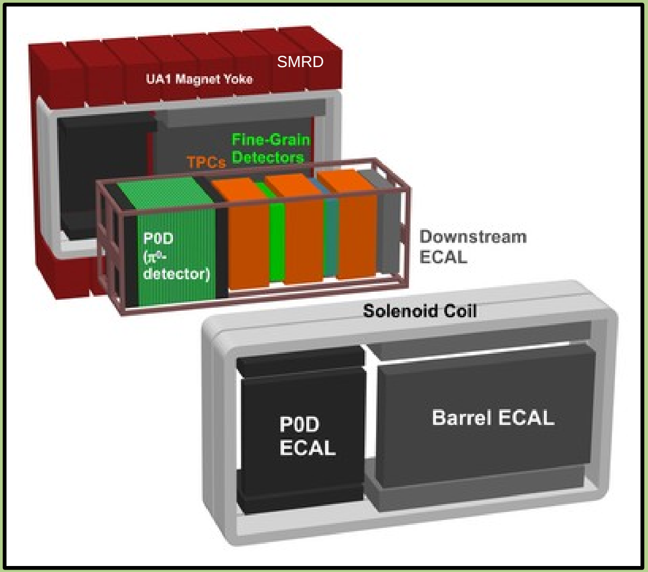
Located 280 meters from the target

On-axis detector INGRID (Interactive Neutrino GRID)



- 16 identical modules made of iron and scintillators
- 'counting neutrinos' by reconstructing muon tracks from ν_μ interactions
- Monitors neutrino beam: rate, direction and stability

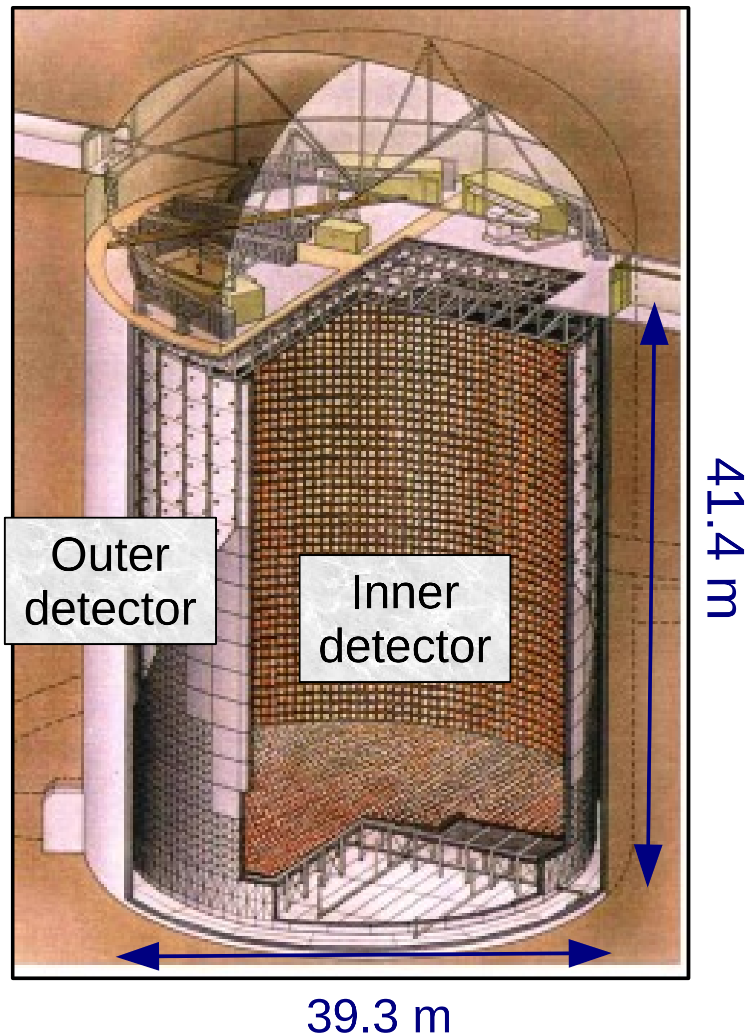
Off-axis detector ND280



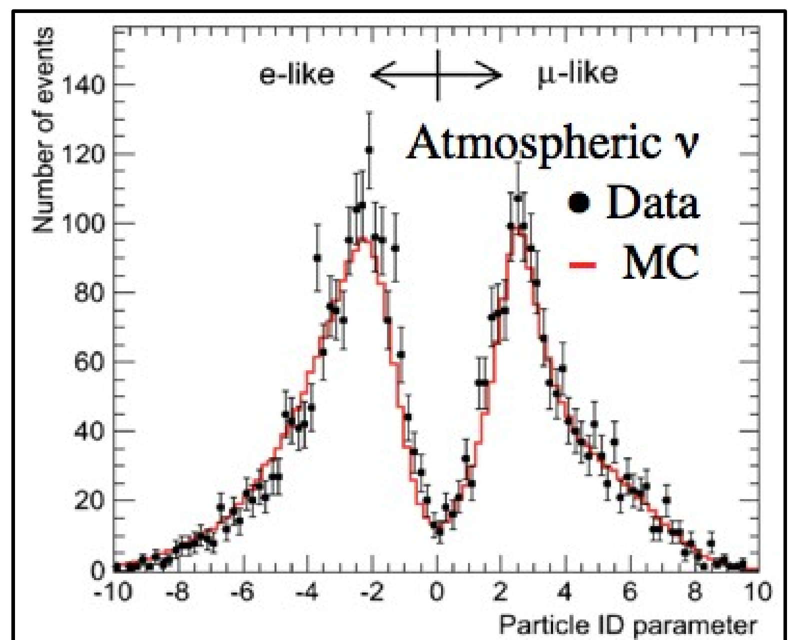
- Several detectors inside a 0.2 T magnetic field
- Used to constrain neutrino flux and interaction systematics (in oscillation analysis - also used for other measurements)

The T2K experiment
Far detector: Super-Kamiokande

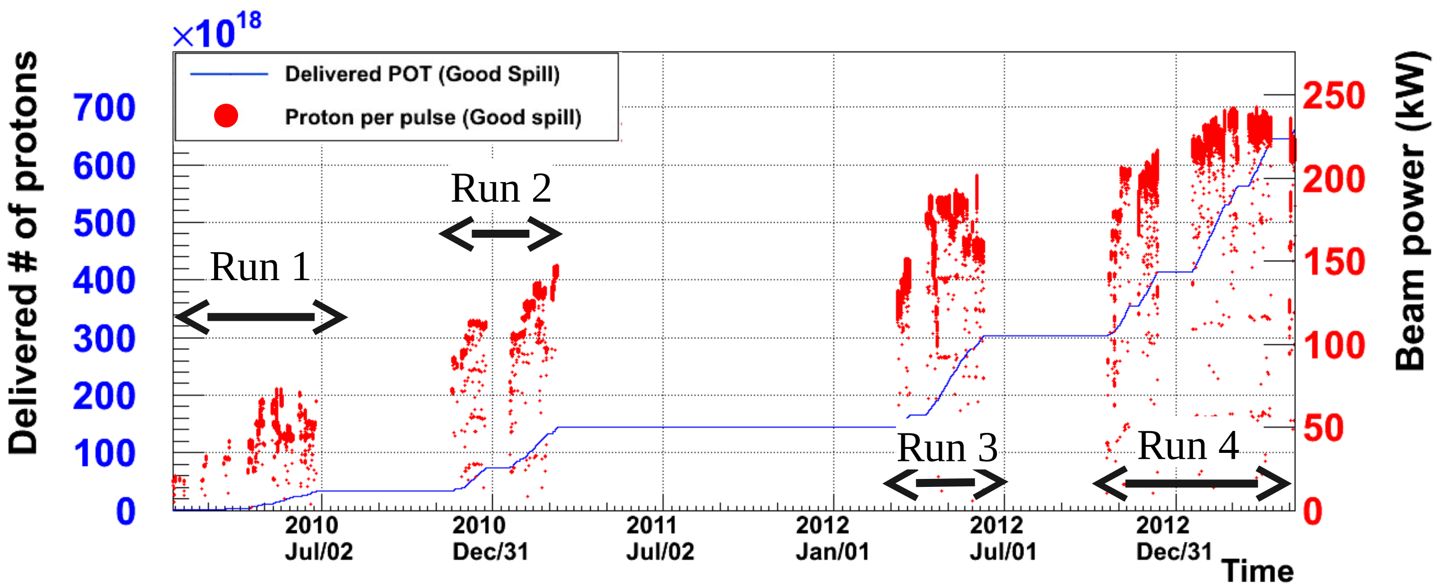
Located 295 km from the target
Synchronized with beamline via GPS



- 50 kt (22.5 kt fiducial) water Cherenkov detector
- Operational since 1996: well understood detector
- Good separation between ν_μ and ν_e interactions

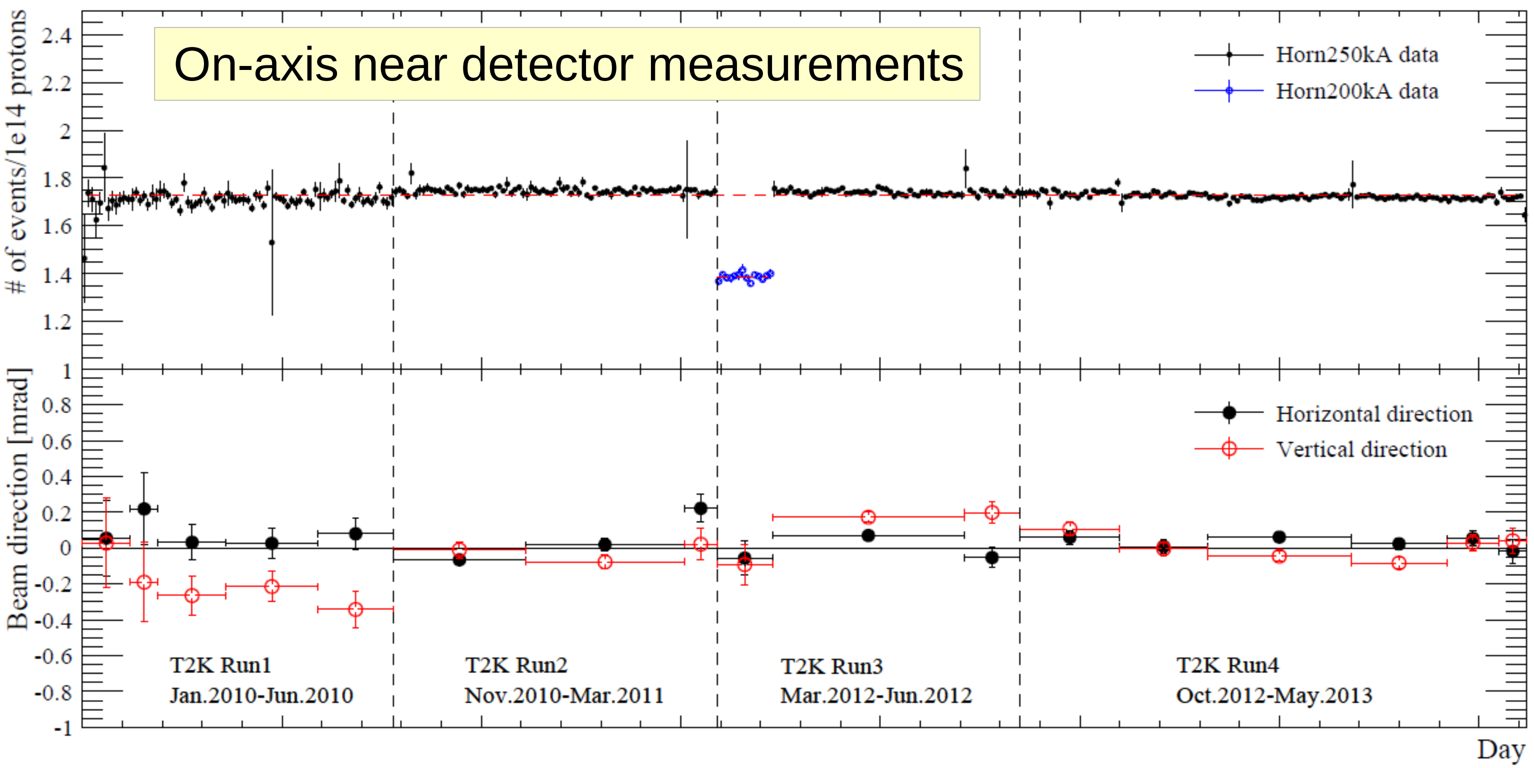


The T2K experiment
Run 1-4 dataset



6.63 x 10^{20} POT
(6.57 x10^{20} for analysis)

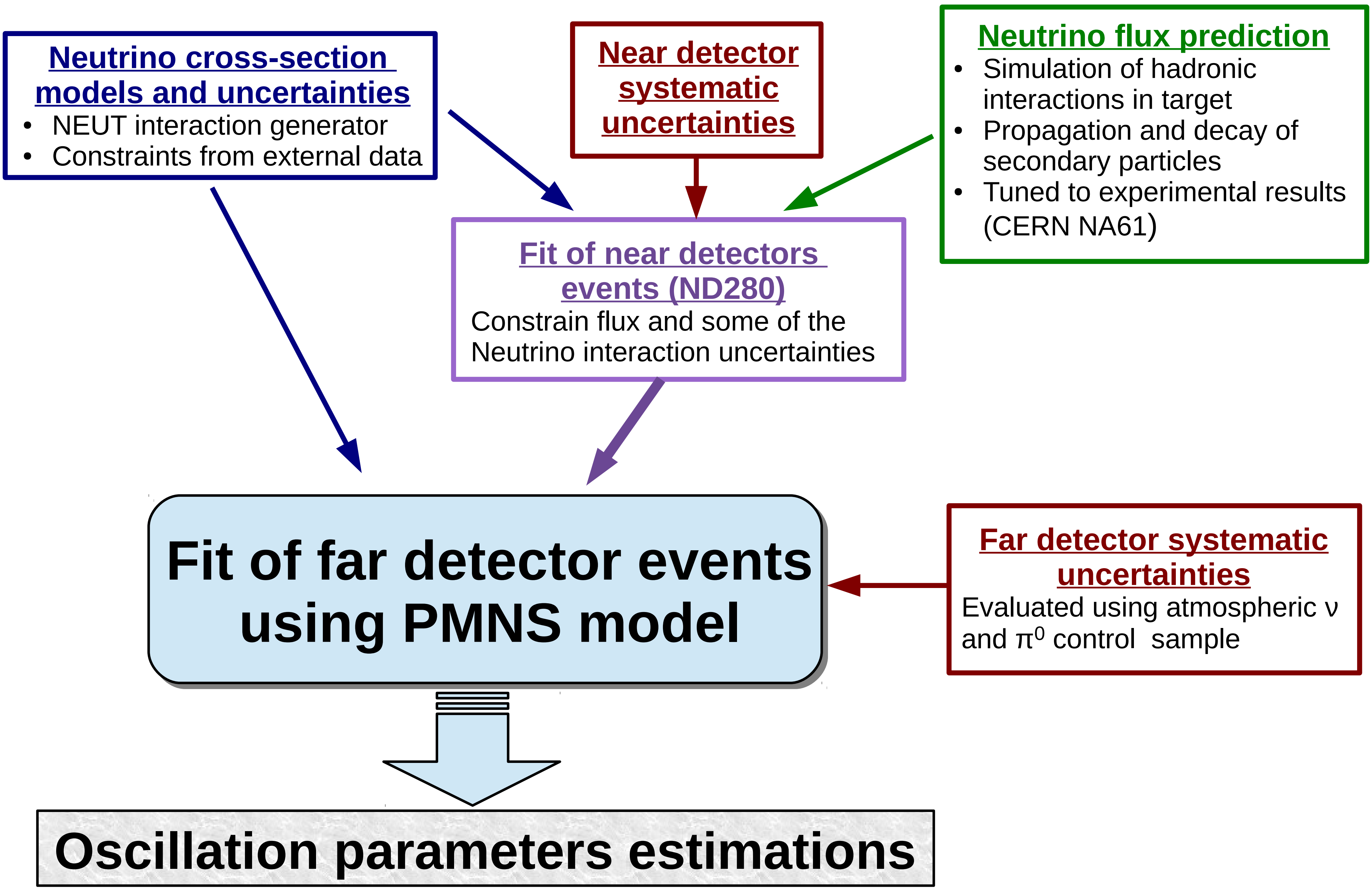
Run 5 including anti-neutrino running mode started in 2014 but data not used here.



Stable event rate

Stable beam direction
(target: within 1mrad)

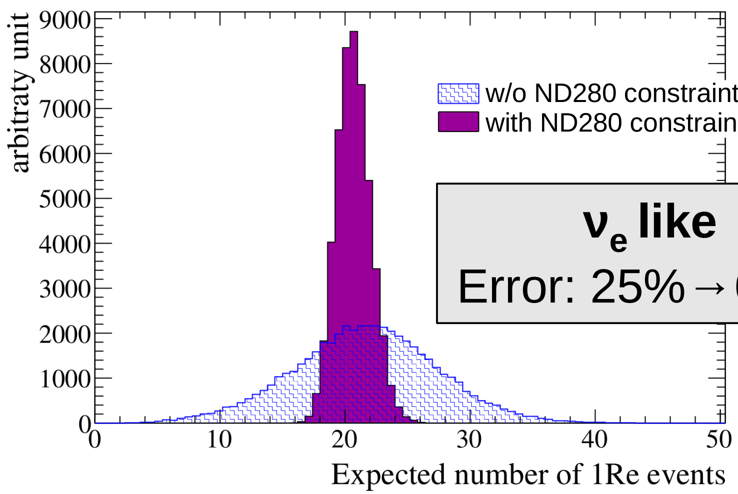
Oscillation analysis Strategy



Oscillation analysis
Near detectors measurements

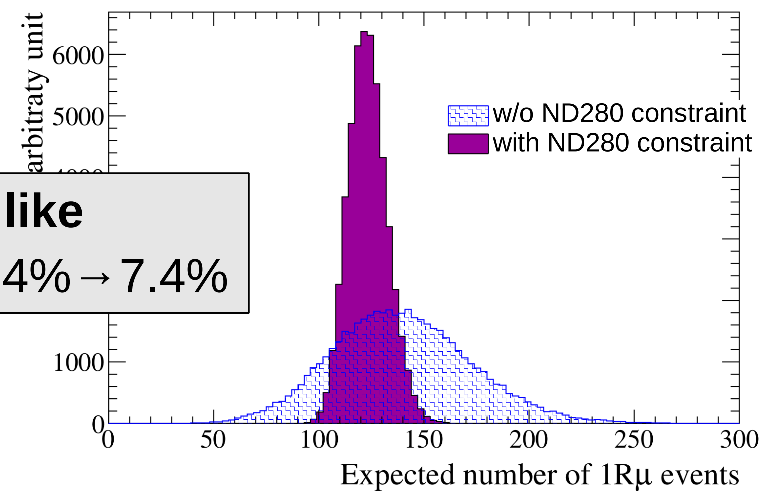
Measurements at the near detectors siginificantly improve the prediction of neutrino event rates and spectra at the far detector

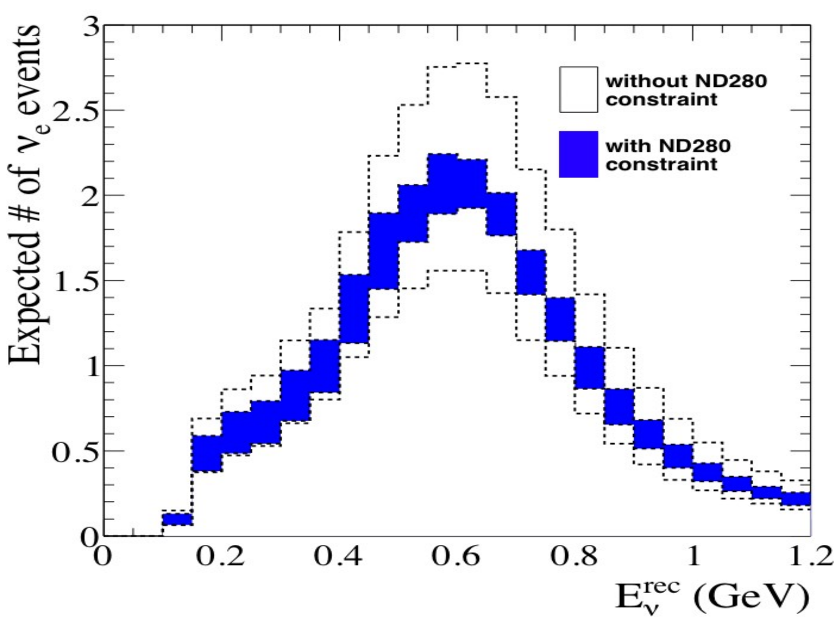
$\sin^2(2\theta_{13})=0.1$
$\delta=0$
$\Delta m^2_{32}=2.4\times10^{-3}\ eV^2/c^4$
$\sin^2(\theta_{23})=0.5$
Normal hierarchy

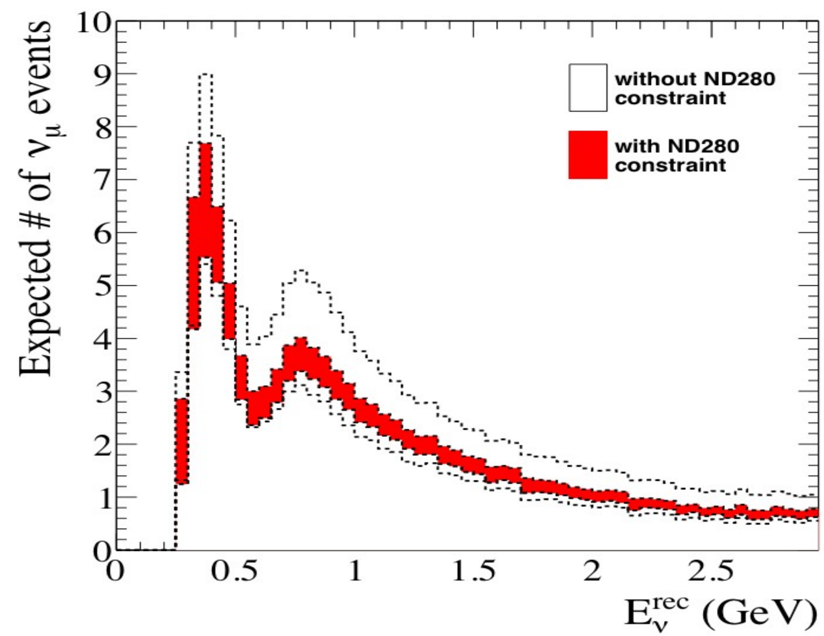


ν_e like
Error: 25% → 6.3%

ν_μ like
Error: 23.4% → 7.4%

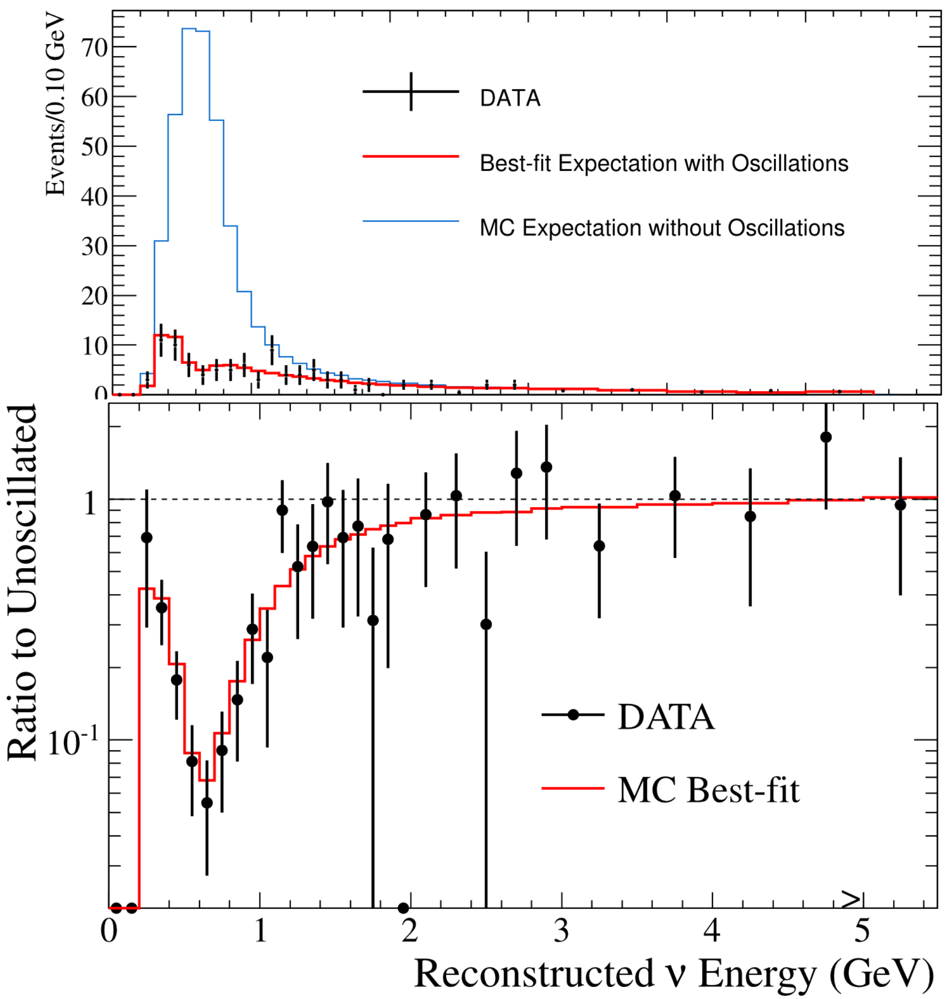


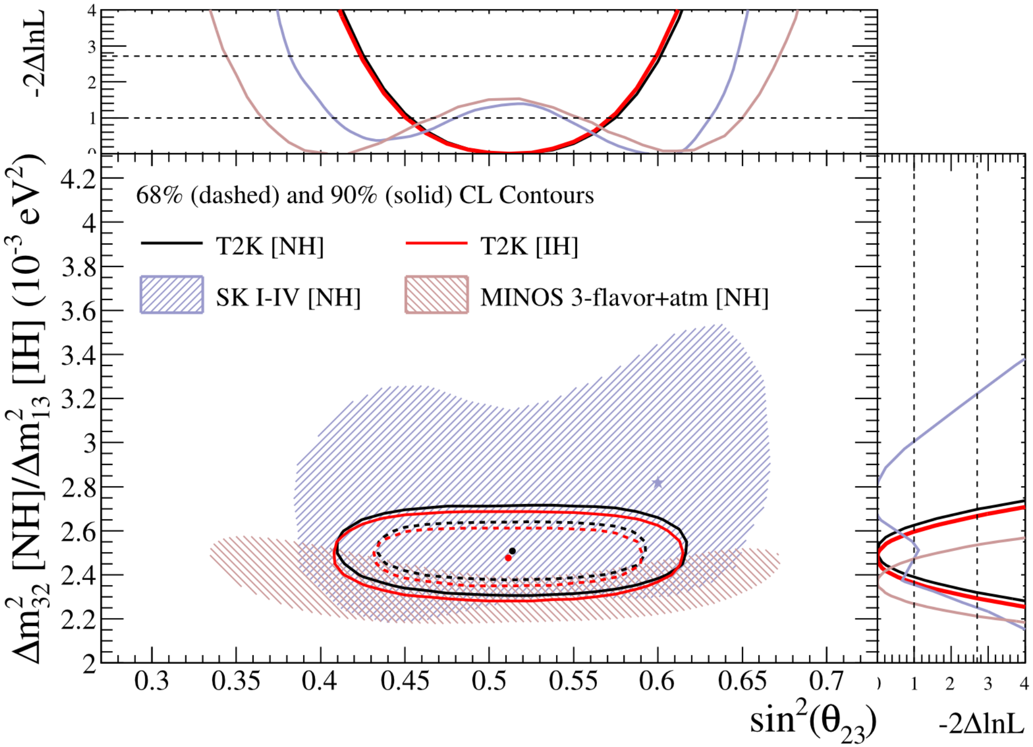




Oscillation analysis
Muon neutrino disappearance

PRL 112, 181801 (2014)





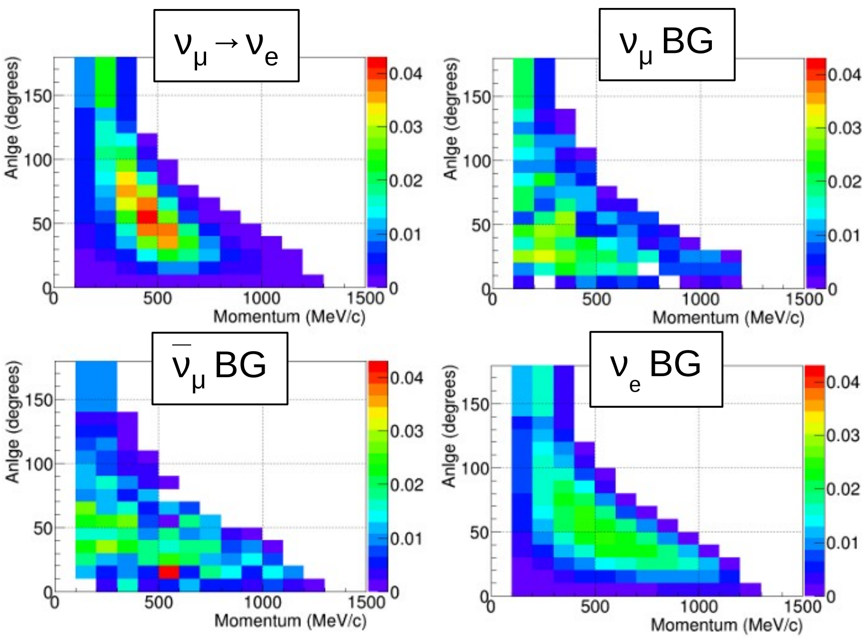
Parameter	Normal hierarchy	Inverted hierarchy
$\sin^2(\theta_{23})$	$0.514^{+0.055}_{-0.056}$	0.511 ± 0.055
$\lvert\Delta m^2_{32/31}\rvert$ (10^{-3} ev^2/c^4)	2.51 ± 0.10	2.48 ± 0.10

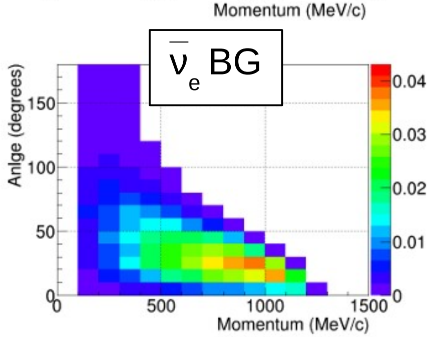
Uncertainties indicate 68% confidence intervals obtained with Feldman-Cousins unified approach

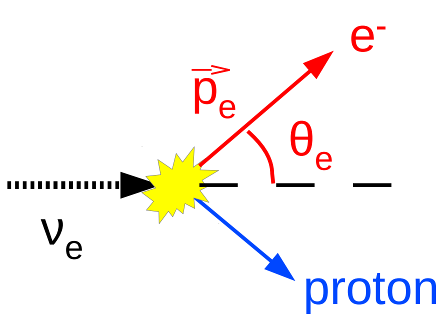
Oscillation analysis
Joint ν_e/ν_μ analyses

Previously:
- ν_e appearance → θ_{13}, δ
- ν_μ disappearance → θ_{23}, $|\Delta m^2|$

But observables depend of all 4 parameters → joint analyses







4 joint T2K analyses
(Presenting only one here)

Extended maximum likelihood fit

$$L = L_{nue} \times L_{numu} \times L_{sys}$$

$$L_{nux} = L_{norm} \times L_{shape}$$

Number of events

Shape of the distribution of a reconstructed quantity for the events

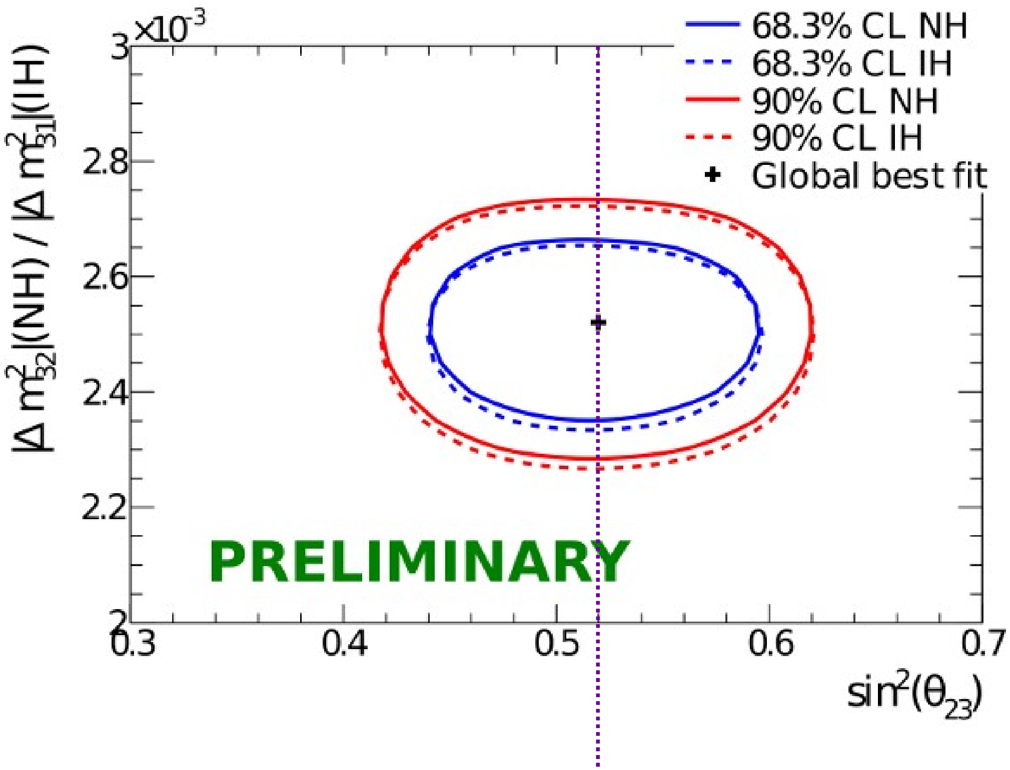
ν_e: (p_e, θ_e)

ν_μ: E_{rec}

Bayesian treatment of nuisance parameters (marginal likelihood)

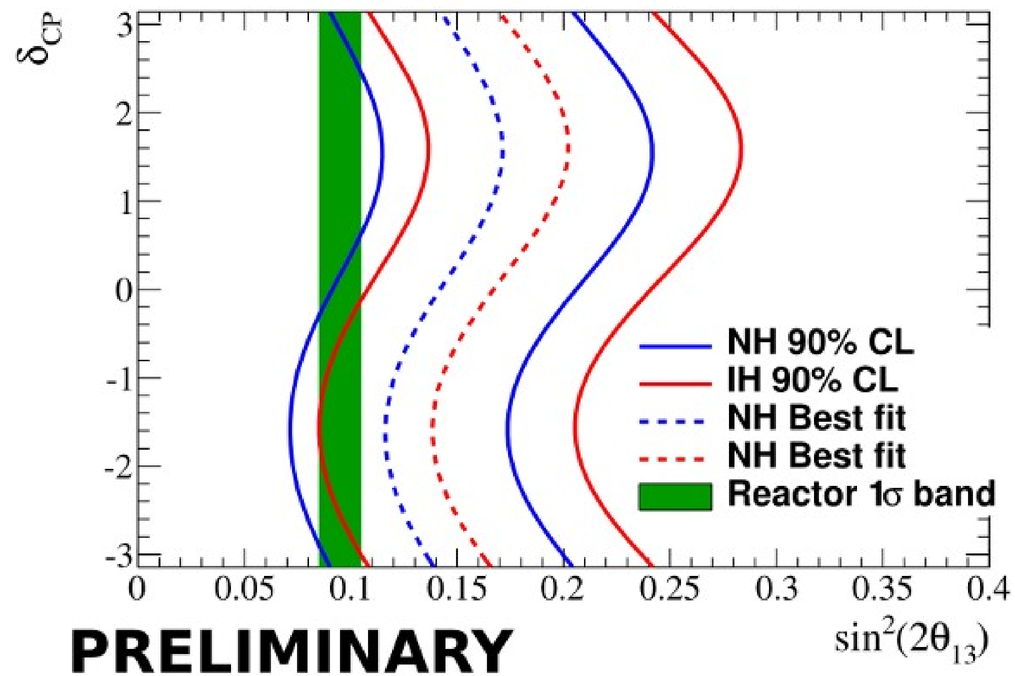
Joint ν_e/ν_μ analyses
T2K only results

Atmospheric parameters



$\sin^2(\theta_{23})$=0.52: Maximal disappearance for the best fit value of θ_{13}

Fit for $\sin^2(2\theta_{13})$ for different fixed values of δ



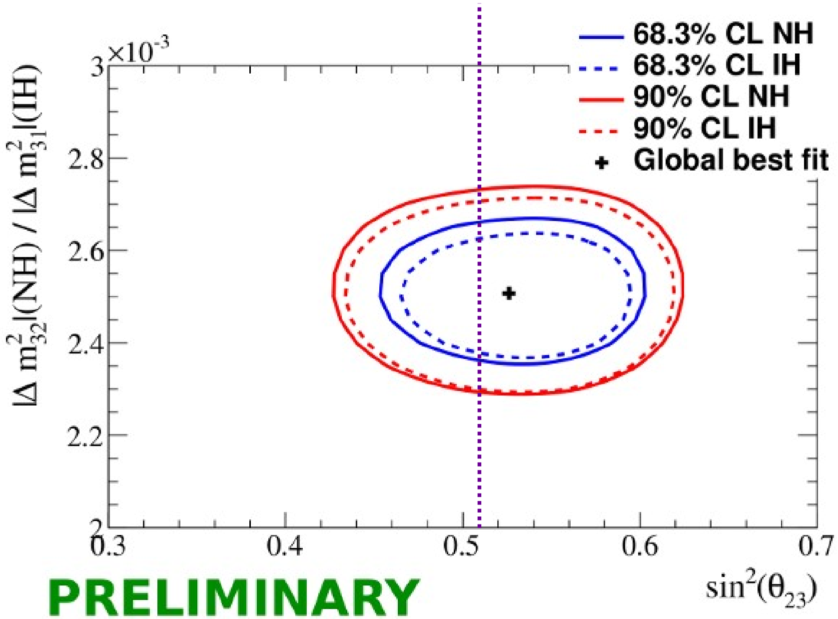
Reactor values from PDG 2013

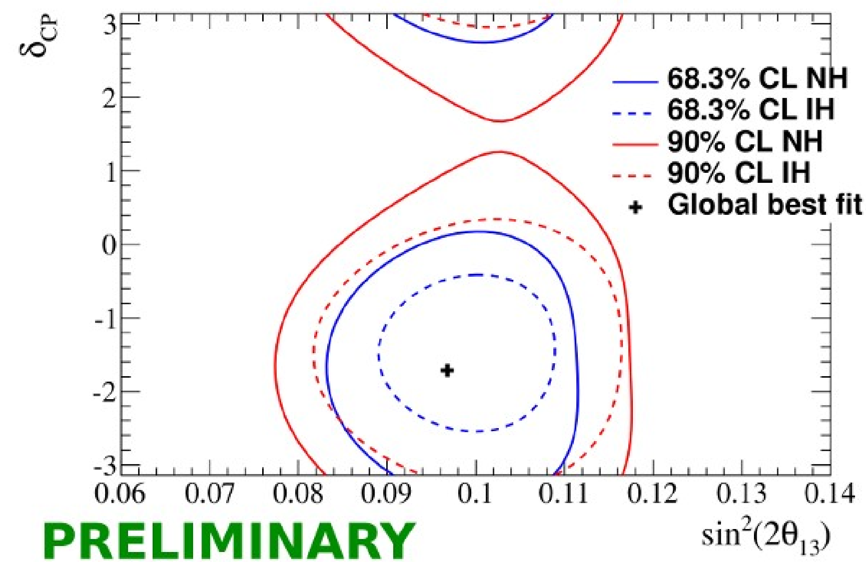
$\sin^2(2\theta_{13})$=0.095± 0.01

Joint ν_e/ν_μ analyses
T2K + reactor

Using reactor experiments results: extra constraint term in the likelihood $\sin^2(2\theta_{13})=0.095\pm 0.01$

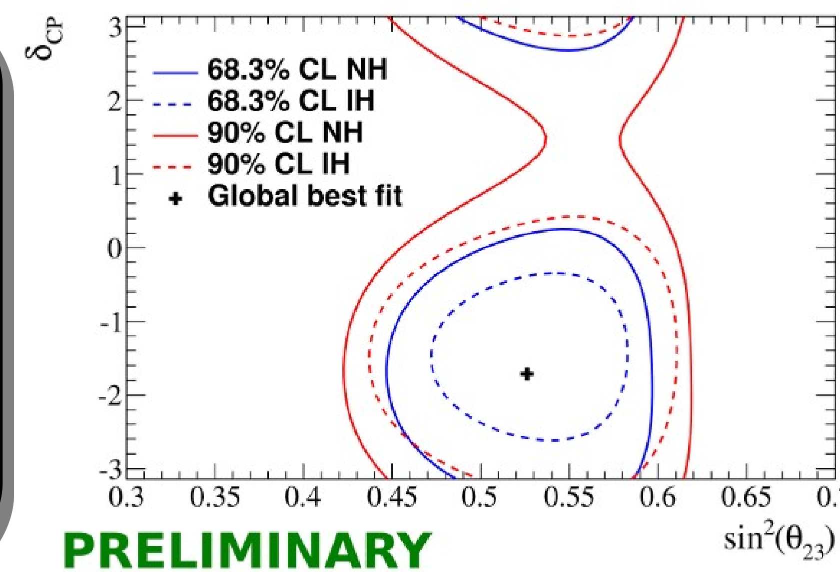
$\sin^2(\theta_{23})=0.513$: Maximal disappearance for the best fit value of θ_{13}





Posterior probabilities of different models (Bayesian)

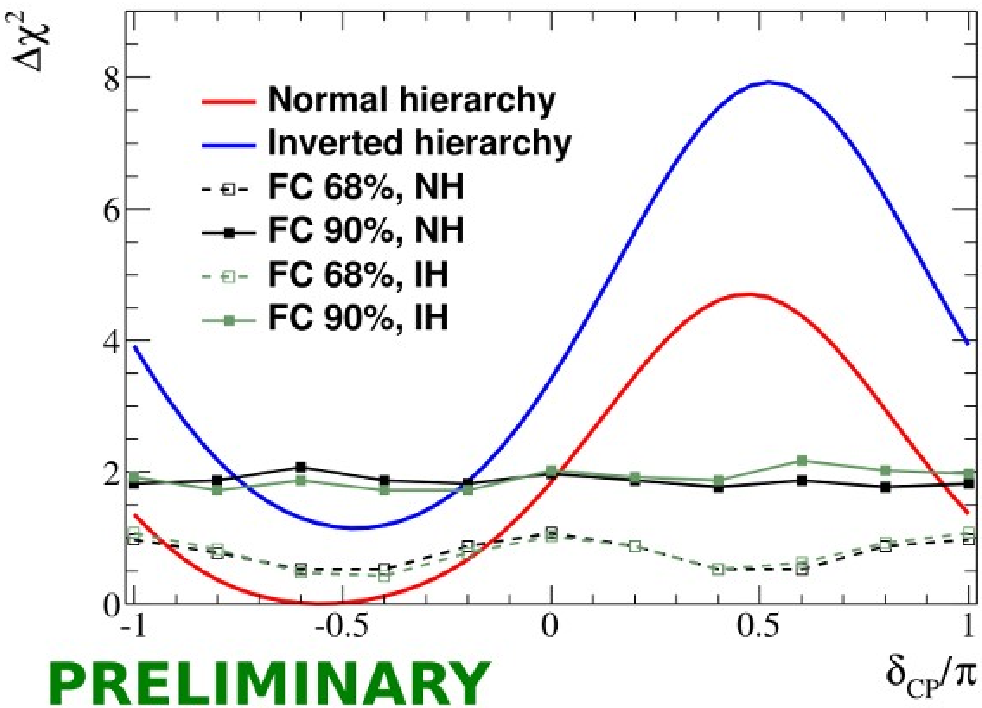
	Normal hierarchy	Inverted hierarchy	Line total
$\sin^2(\theta_{23})<0.5$	0.186	0.080	0.266
$\sin^2(\theta_{23})>0.5$	0.503	0.231	0.734
Column total	0.689	0.311	1



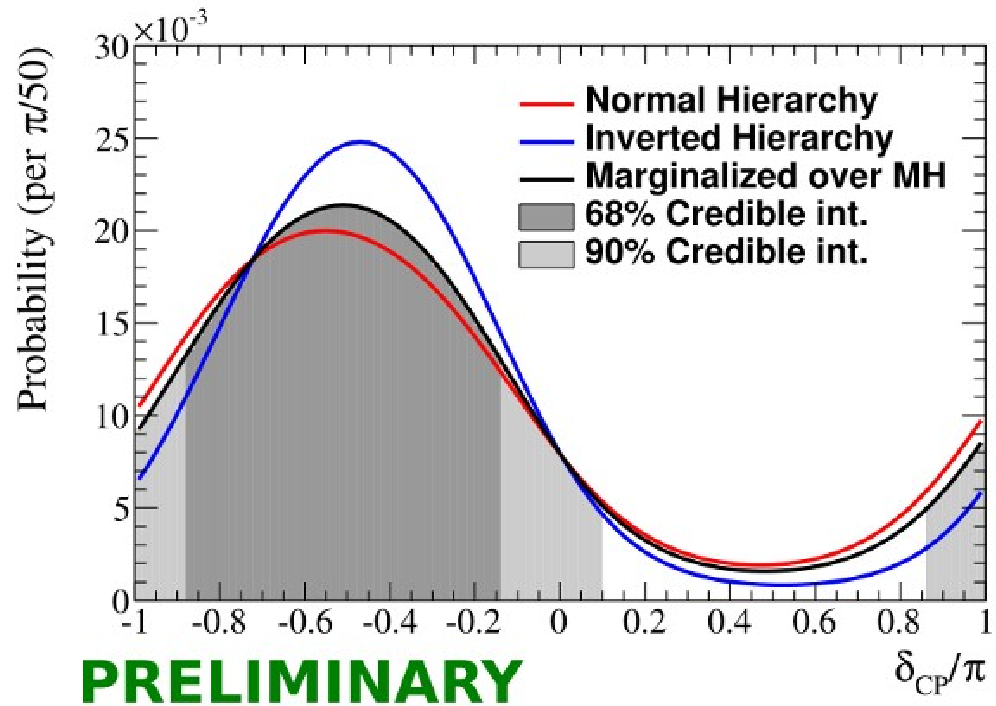
Joint ν_e/ν_μ analyses
T2K + reactor: δ_{CP}

Using reactor experiments results:
$\sin^2(2\theta_{13})=0.095\pm 0.01$

Frequentist



Bayesian



Mass hierarchy	Outside of 68% CL interval	Outside of 90% CL interval
Normal	$[-\pi; -2.92] \cup [-0.46; \pi]$	$[0.06; 2.95]$
Inverted	$[-\pi; \pi]$	$[-\pi; -2.29] \cup [-0.71; \pi]$

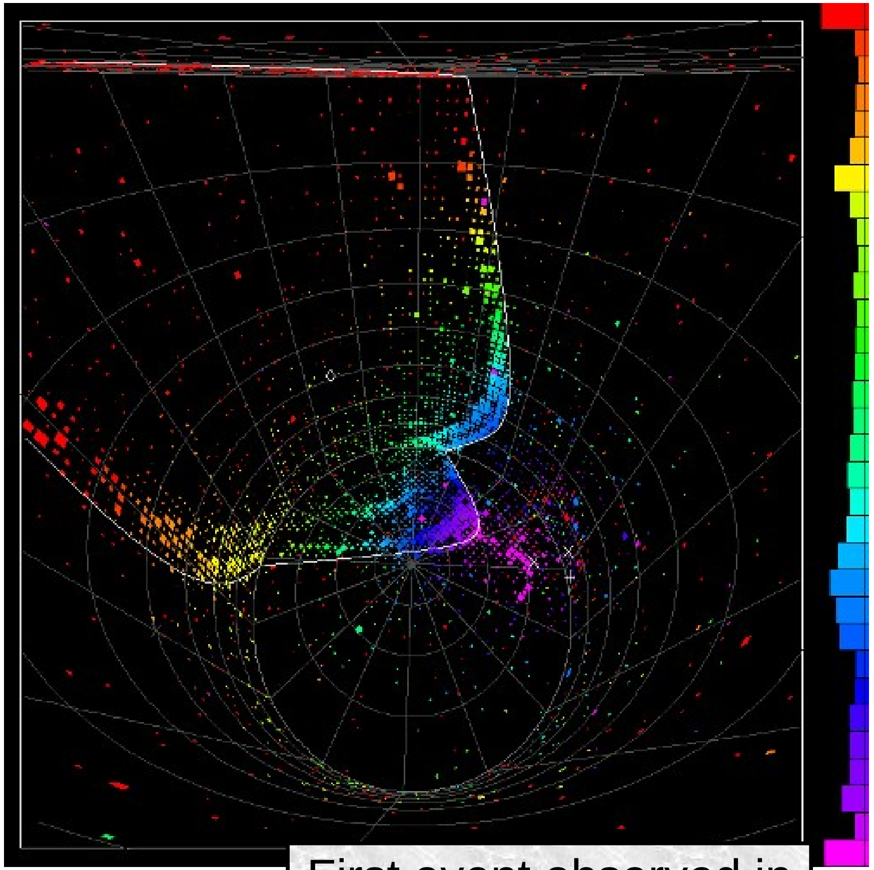
In both cases the likelihood as a function of δ is obtained by integrating over the other (nuisance) parameters

Summary - outlook

- Presented T2K oscillation results with first four years of data
  - World best measurement of $\sin^2(\theta_{23})$
  - T2K prefers slightly larger values of $\sin^2(2\theta_{13})$ than reactor experiments

- Presented oscillation results combining T2K data with reactor experiments results
  - Shows a preference for values of δ around $-\pi/2$
  - Some parts of $[-\pi; \pi]$ are outside of the 90% CL intervals for δ
  - Favors normal hierarchy and octant $\sin^2(\theta_{23})>0.5$

- Dataset used here corresponds to 6.57×10^{20} POT. This is only 8% of the target 7.8×10^{21} POT



First event observed in anti-neutrino mode

- Started taking data in anti-neutrino mode in 2014

Additional slides

The T2K experiment
The collaboration

T2K is an international collaboration of about 500 members from 11 countries

Canada
U. Alberta
U. B. Columbia
U. Regina
U. Toronto
TRIUMF
U. Victoria
U. Winnipeg
York U.

France
CEA Saclay
IPN Lyon
LLR E. Poly.
LPNHE Paris

Germany
U. Aachen

Japan
ICRR Kamioka
ICRR RCCN
Kavli IPMU
KEK
Kobe U.
Kyoto U.
Miyagi U. Edu.
Okayama U.
Osaka City U.
Tokyo Metro U.
U. Tokyo

Spain
IFIC, Valencia
IFAE, Barcelona

Poland
NCBJ, Warsaw
IFJ PAN, Cracow
T. U. Warsaw
U. Silesia, Katowice
U. Warsaw
U. Wroklaw

Switzerland
ETH Zurich
U. Bern
U. Geneva

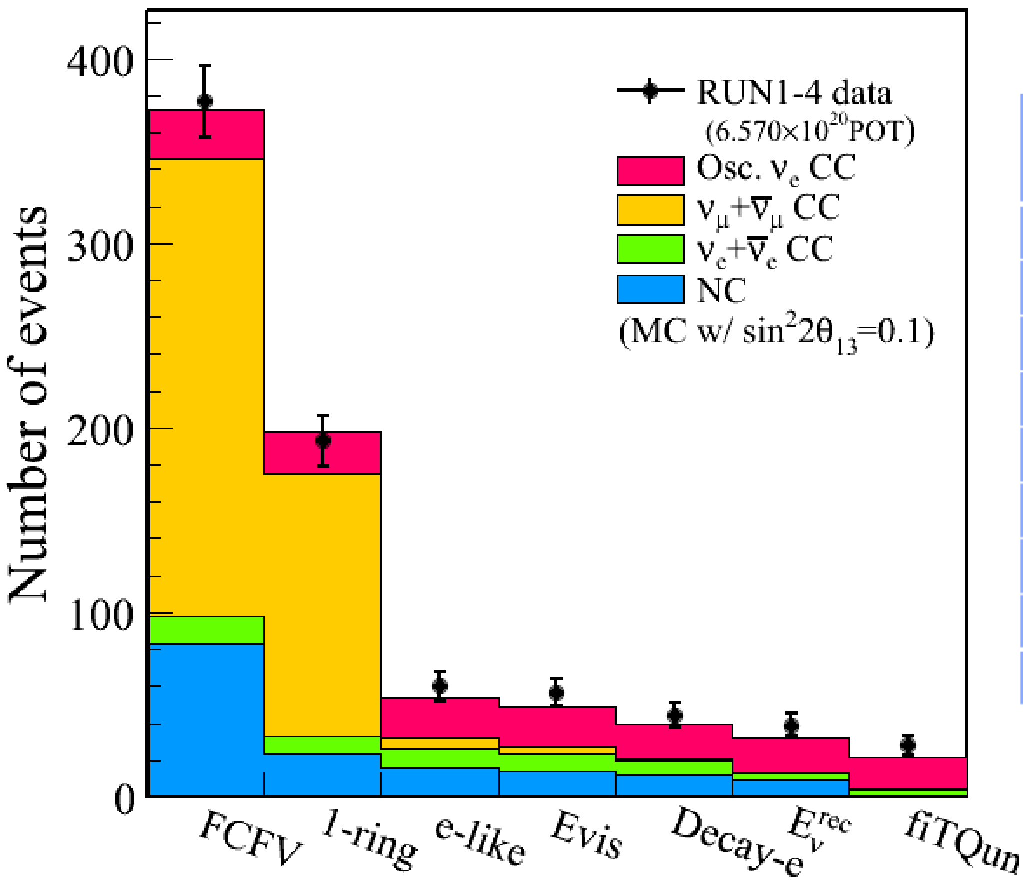
Russia
INR

USA
Boston U.
Colorado S. U.
U. Colorado
Duke U.
U. C. Irvine
Louisiana S. U.
U. Pittsburgh
U. Rochester
Stony Brook U.
U. Washington

Italy
INFN, U. Bari
INFN, U. Napoli
INFN, U. Padova
INFN, U. Roma

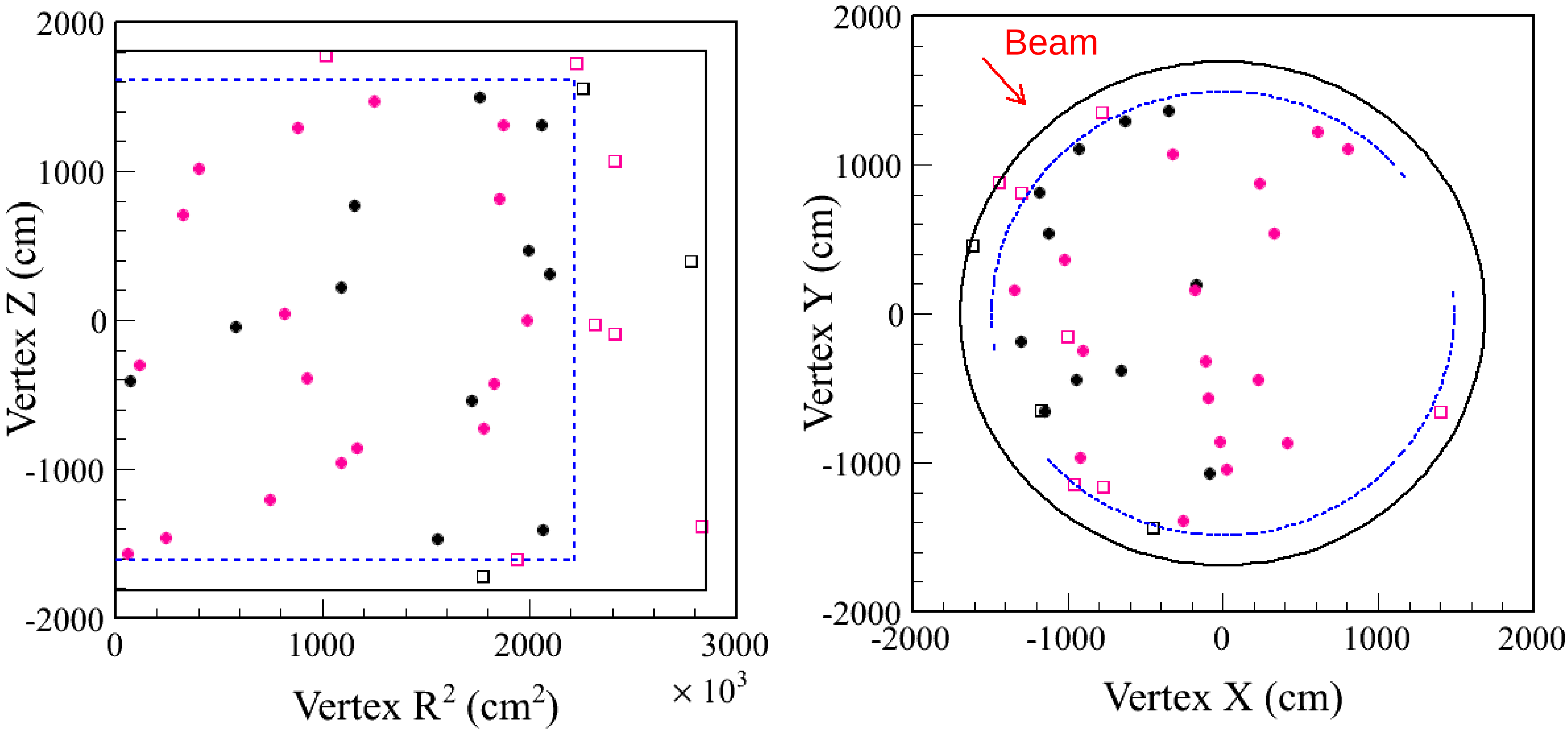
UK
Imperial C. L.
Lancaster U.
Liverpool U.
Queen Mary U. L.
Oxford U.
Sheffield U.
STFC/RAL
STFC/Daresbury
Warwick U.

The T2K experiment
Run 1-4 dataset: ν_e candidate events

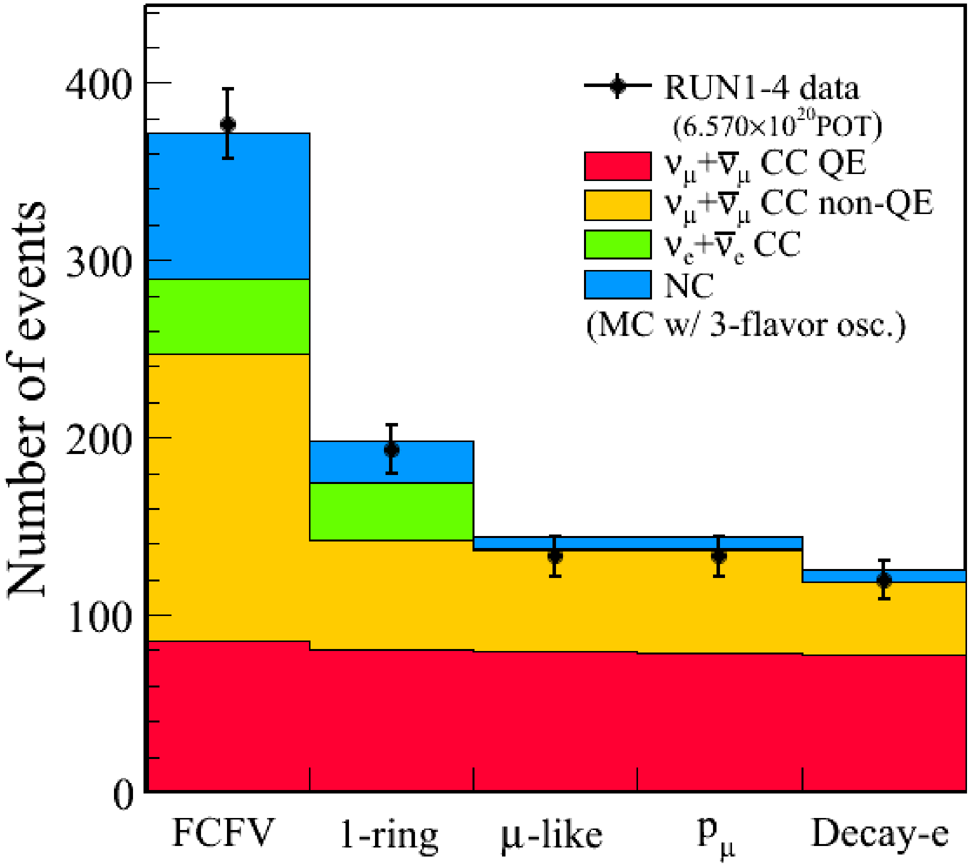


RUN1-4 6.570×10^{20}POT	MC Expectations w/ $\sin^2 2\theta_{13}$=0.1					Data
	$\nu_\mu+\bar{\nu}_\mu$ CC	$\nu_e+\bar{\nu}_e$ CC	NC	BG total	Signal	
True FV	325.67	15.97	288.11	629.75	27.07	-
FCFV	247.75	15.36	83.02	346.13	26.22	377
One-ring	142.44	9.82	23.46	175.72	22.72	193
e-like	5.63	9.74	16.35	31.72	22.45	60
E_{vis}>100MeV	3.66	9.68	13.99	27.32	22.04	57
No decay-e	0.69	7.87	11.84	20.40	19.63	44
E_ν^{rec}<1250MeV	0.21	3.73	8.99	12.94	18.82	39
fiTQun π^0	0.07	3.24	0.96	4.27	17.32	28
Efficiency [%]	0.0	20.3	0.3	0.7	64.0	-

The T2K experiment
Run 1-4 dataset: ν_e candidate events

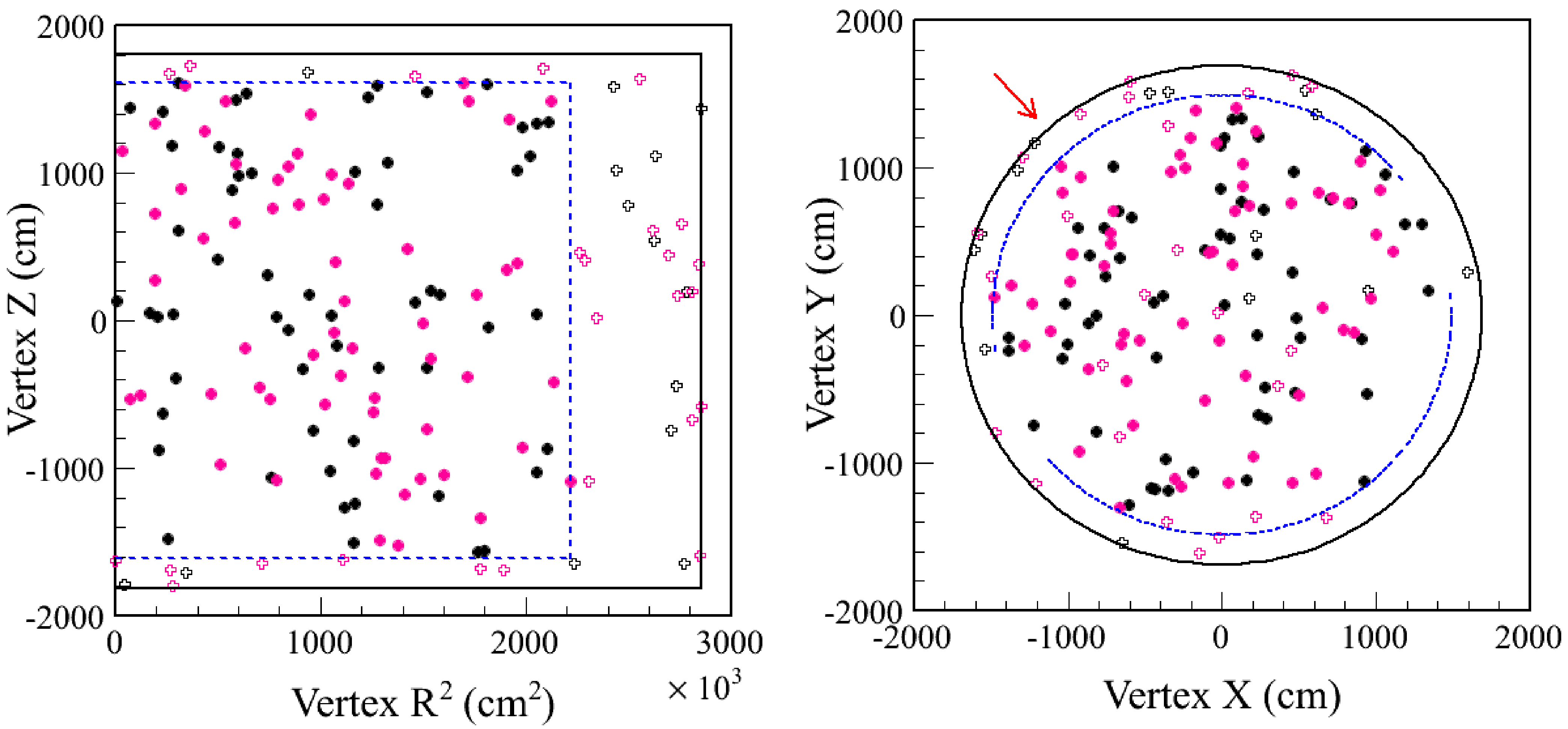


The T2K experiment
Run 1-4 dataset: ν_μ candidate events

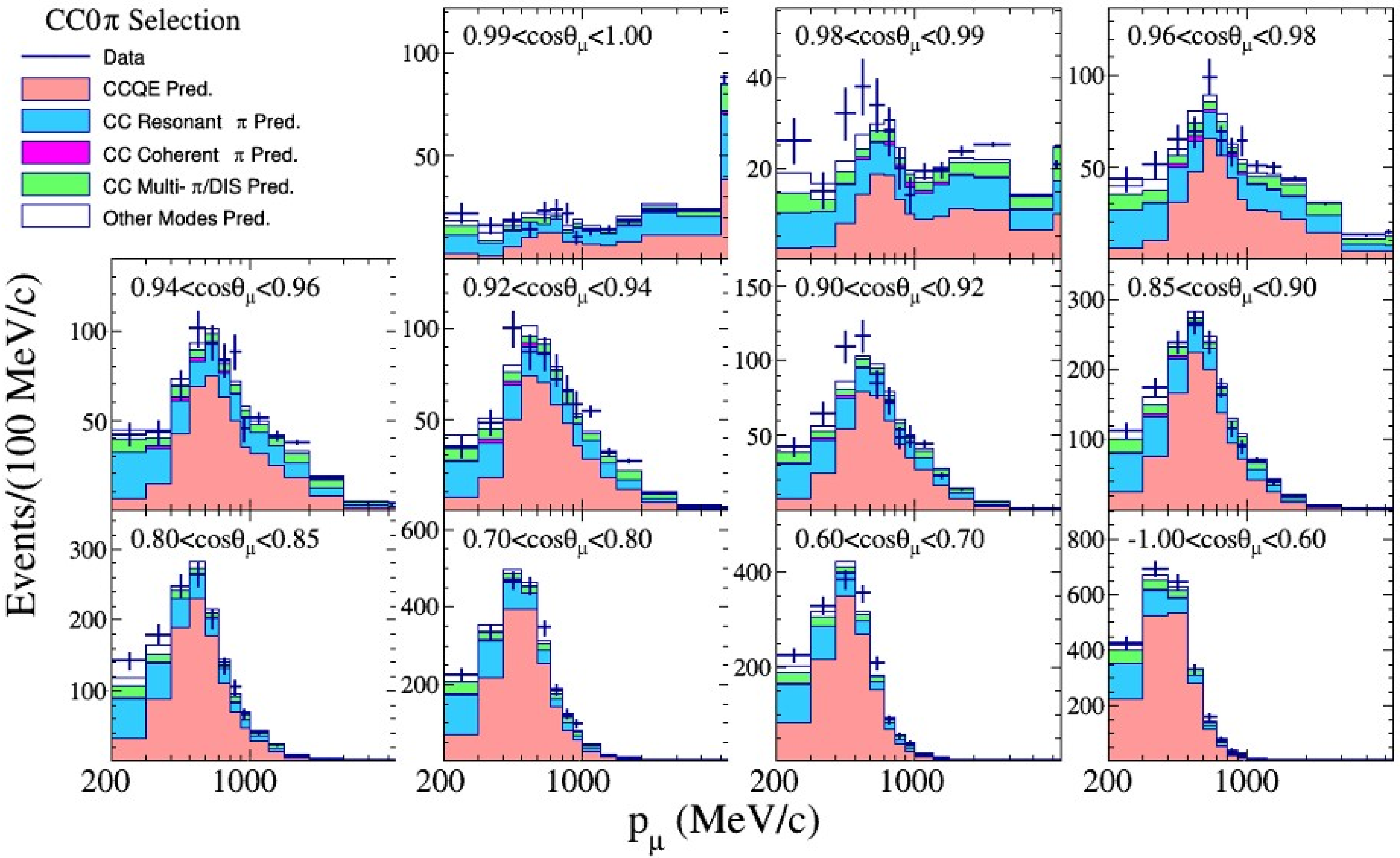


RUN1+2+3+4 6.393×10^{20}POT	Data	MC Expectations w/ $\sin^2 2\theta_{13}$=0.1				
		MC total	ν_μ+antiν$_\mu$ CCQE	ν_μ+antiν$_\mu$ CC non-QE	ν_e+antiν$_e$ CC	NC
Interactions in FV	549	656.83	111.71	213.96	43.05	288.11
FCFV	377	372.35	85.55	162.2	41.58	83.02
Single-ring	193	198.44	80.57	61.87	32.54	23.46
μ-like PID	133	144.28	79.01	57.8	0.35	7.11
p_μ>200MeV/c	133	143.99	78.84	57.77	0.35	7.04
N_{dcy-e}<=1	120	125.85	77.93	40.78	0.35	6.78
Efficiency [%]	-	19.2	69.8	19.1	0.8	2.4

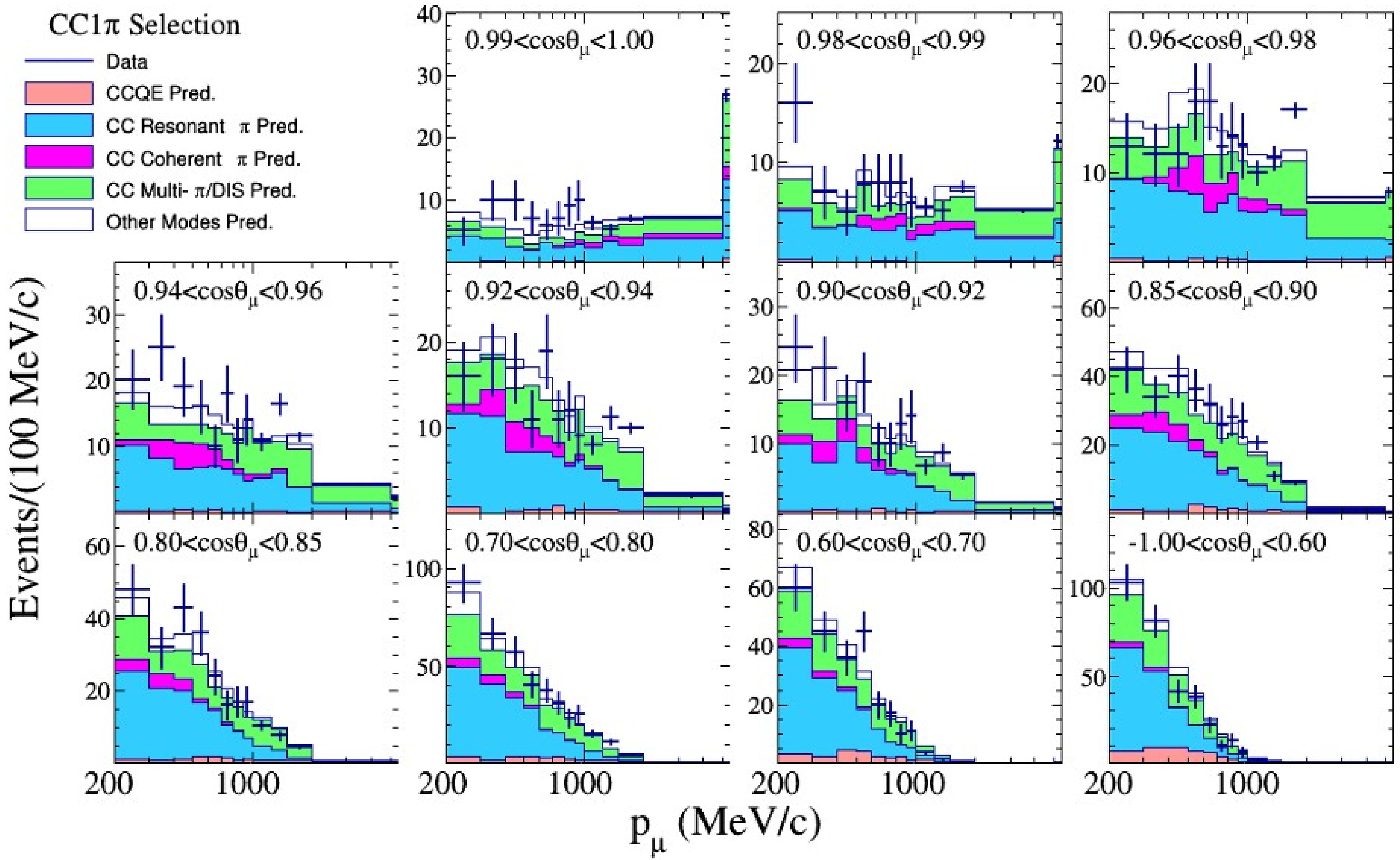
The T2K experiment
Run 1-4 dataset: ν_μ candidate events



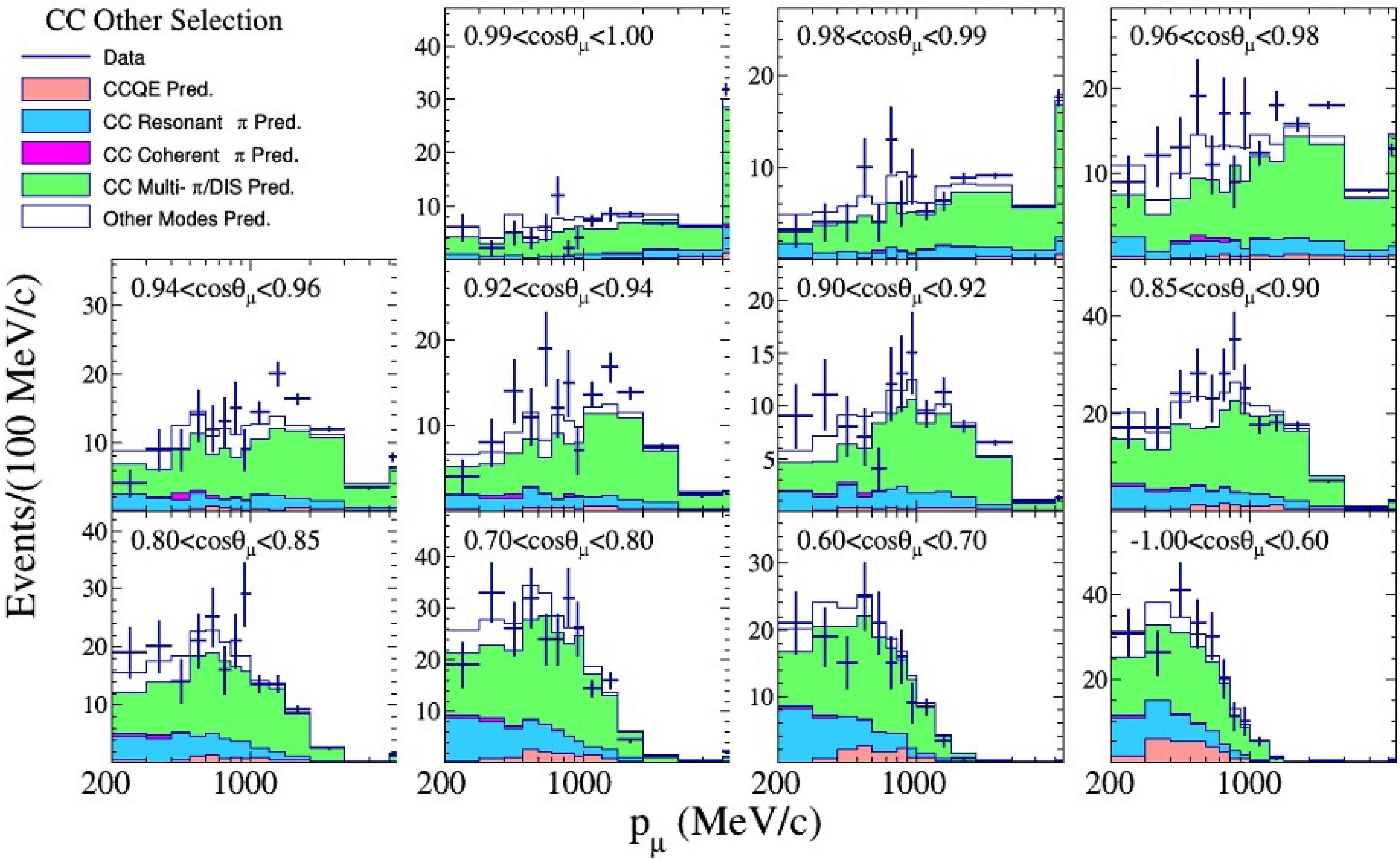
Oscillation analysis
Near detectors measurements



Oscillation analysis
Near detectors measurements



Oscillation analysis
Near detectors measurements



Oscillation analysis
Near detectors measurements

Number of events in the different ND280 samples

Number of Events

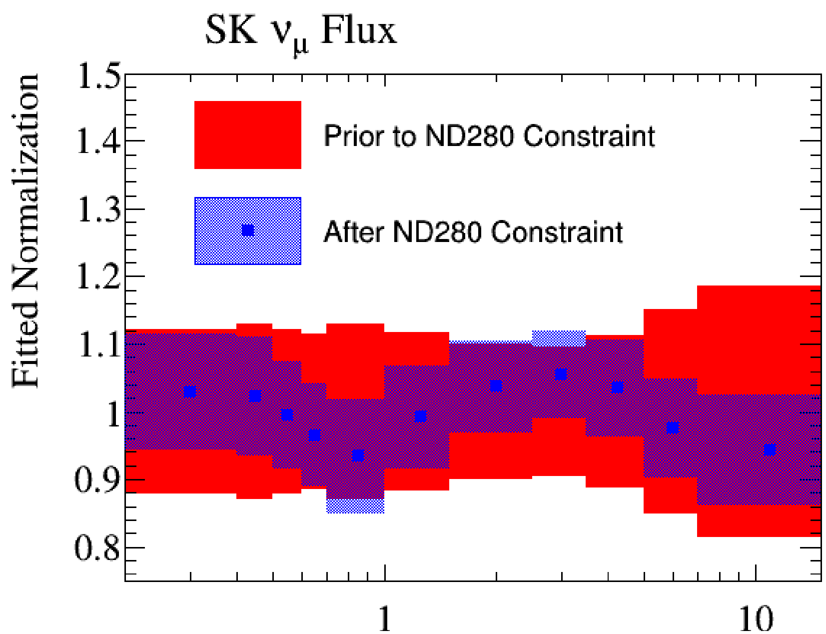
Selection	Data	MC (before ND280 constraint)	MC (after ND280 constraint)
CC0π	17369	19980	17352
CC1π	4047	4953	4110
CC Other	4173	4545	4119
CC Inclusive	25589	29477	25581

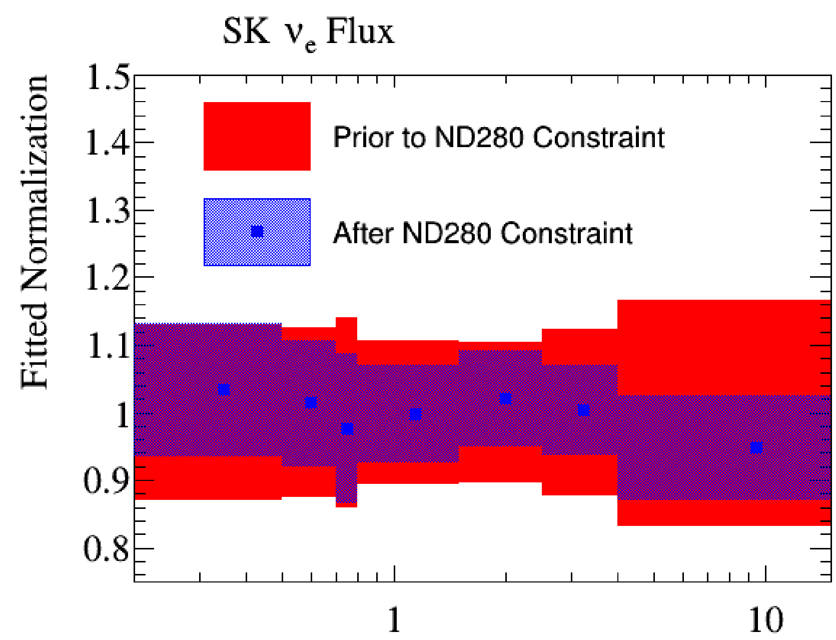
Oscillation analysis
Near detectors measurements

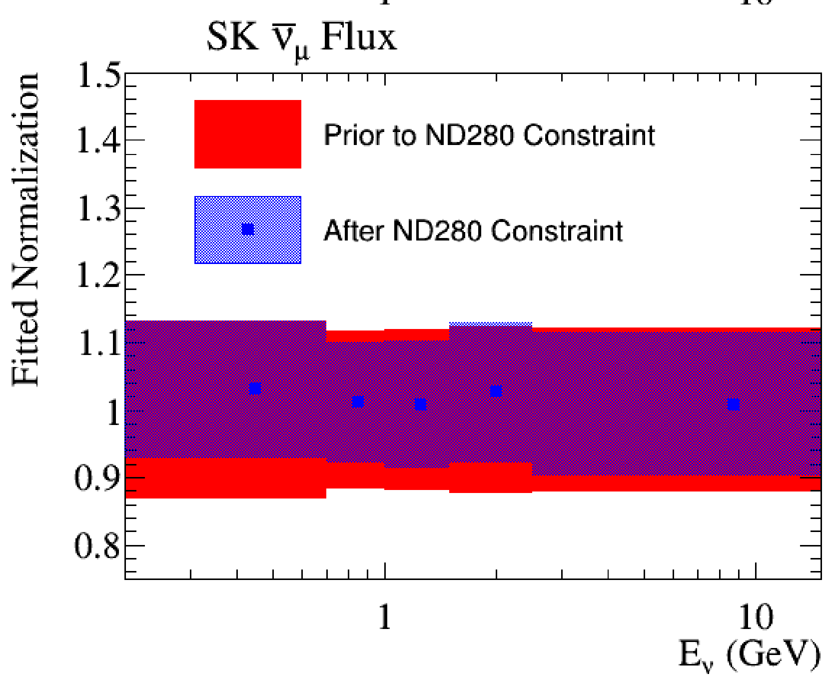
Effect of near detector measurements on neutrino interaction parameters:

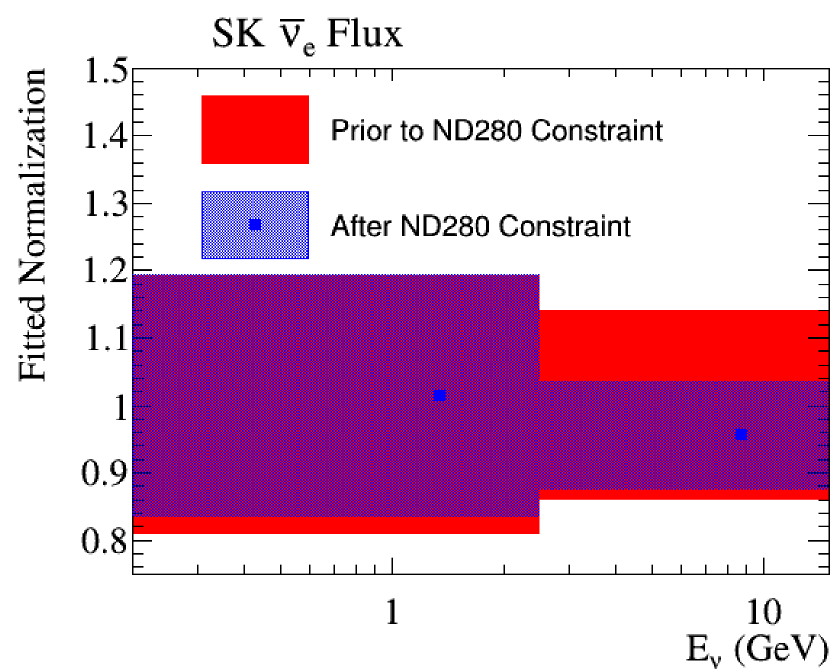
Parameter	Prior to ND280 Constraint	After ND280 Constraint
M_A^{QE} (GeV)	1.21 ± 0.45	1.240 ± 0.072
M_A^{RES} (GeV)	1.41 ± 0.22	0.965 ± 0.068
CCQE Norm. E_ν<1.5 GeV	1.00 ± 0.11	0.966 ± 0.076
CCQE Norm. 1.5<E_ν<3.5 GeV	1.00 ± 0.30	0.93 ± 0.10
CCQE Norm. E_ν>3.5 GeV	1.00 ± 0.30	0.85 ± 0.11
CC1π Norm. E_ν<2.5 GeV	1.15 ± 0.32	1.26 ± 0.16
CC1π Norm. E_ν>2.5 GeV	1.00 ± 0.40	1.12 ± 0.17
NC1π^0 Norm.	0.96 ± 0.33	1.14 ± 0.25

Oscillation analysis
Near detectors measurements: flux uncertainty









Joint ν_e/ν_μ analyses
Systematic uncertainties

1Re: 1 ring electron-like (ν_e)
1Rμ: 1 ring muon like (ν_μ)

List of the systematic parameters

Category	source	Near/Far detectors	# of params
Beam	Beam flux prediction	common	25
ν interactions	Constrained by ND280	common	8
	Unconstrained by ND280	independent	12
Far detector	SK detector efficiency	independent	52+6
	SK momentum scale	independent	1
FSI	Final State Interactions Secondary interaction	independent	52+6
PN	Photo-nuclear effect	independent	52

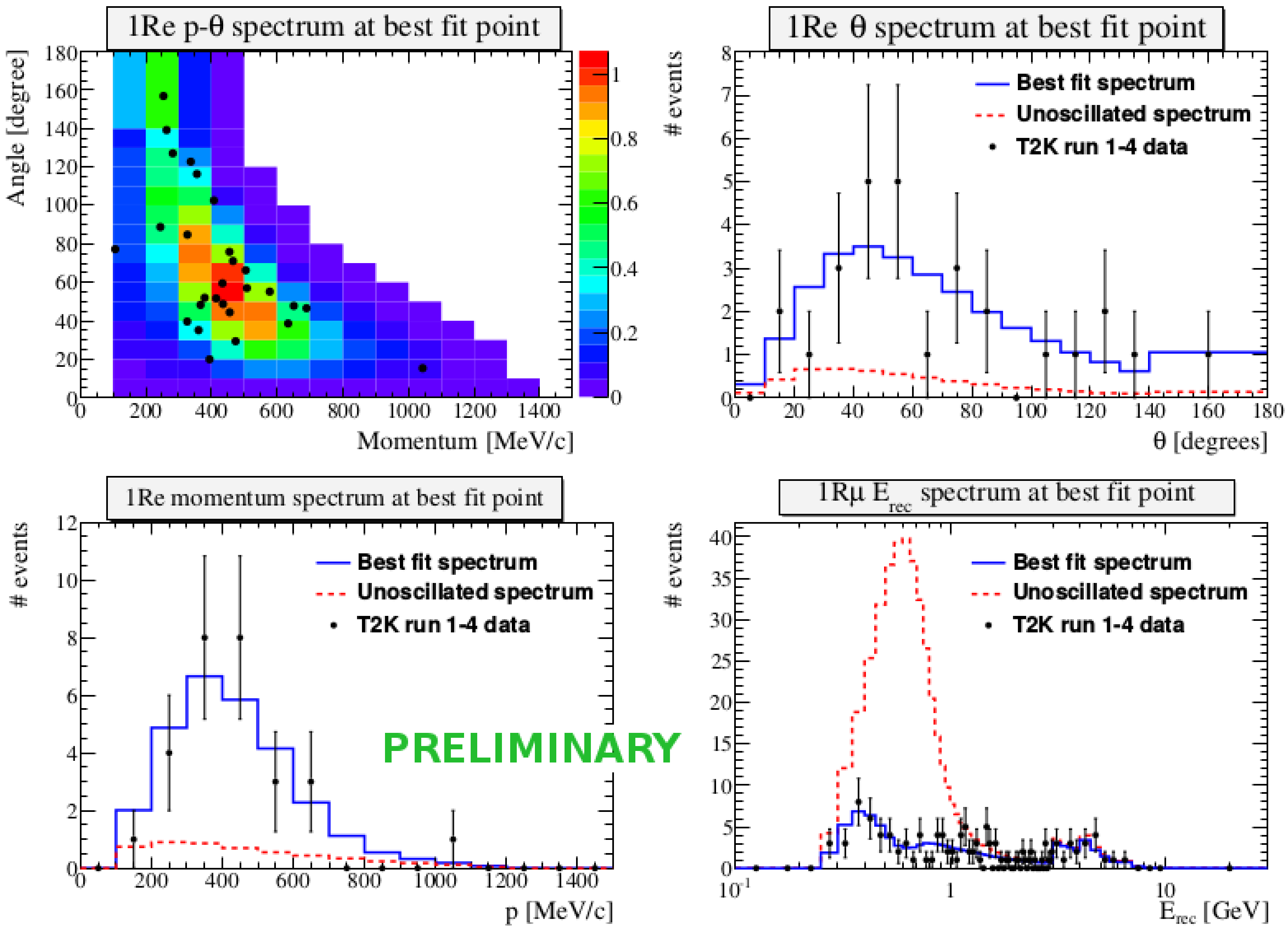
Effect on predicted number of ν_e and ν_μ events (%) Grouped by category of uncertainty

Error category	1Re sample	1Rμ sample
Constrained by near detectors measurements	2.92	2.73
Other ν interactions uncertainties	4.39	4.55
Far detector	3.56	4.92
Total	**6.28**	**7.35**

Effect on predicted number of ν_e and ν_μ events (%)

Error source	1Re sample	1Rμ sample
Beam only	7.41	6.08
M_A^{QE}	3.07	2.76
M_A^{Res}	1.02	2.36
CCQE norm.	6.22	4.60
CC1π norm.	2.03	2.99
NC1π^0 norm.	0.43	N/A
CC other shape	0.12	0.89
Spectral Function	1.11	0.21
E_b	N/A	0.21
p_F	0.11	0.14
CC coh. norm.	0.24	0.81
NC coh. norm.	0.24	N/A
NC 1$\pi^\pm$ norm.	N/A	0.76
NC other norm.	0.5	0.86
$\sigma_{\nu_e}/\sigma_{\nu_\mu}$	2.86	<0.01
$\sigma_{\bar{\nu}}/\sigma_\nu$	0.14	1.2
W shape	0.23	0.26
pion-less Δ decay	2.0	4.03
SK parameters	3.56	4.92
SK momentum scale	0	0
Total	**6.28**	**7.35**

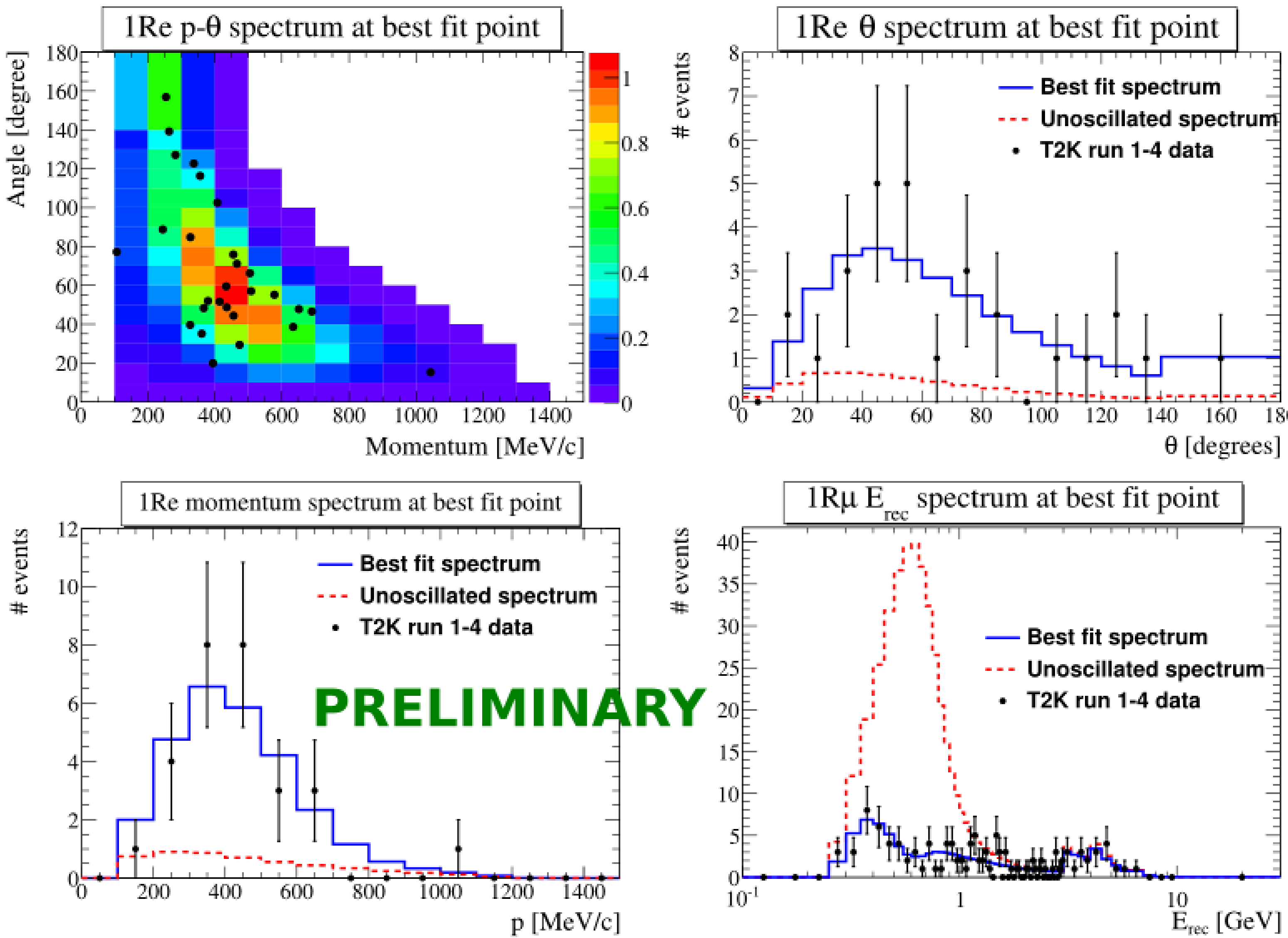
Joint ν_e/ν_μ analyses
Best fit spectra



1Re: 1 ring electron-like (ν_e)
1Rμ: 1 ring muon like (ν_μ)

T2K Run1-4 only
Normal hierarchy

Joint ν_e/ν_μ analyses
Best fit spectra

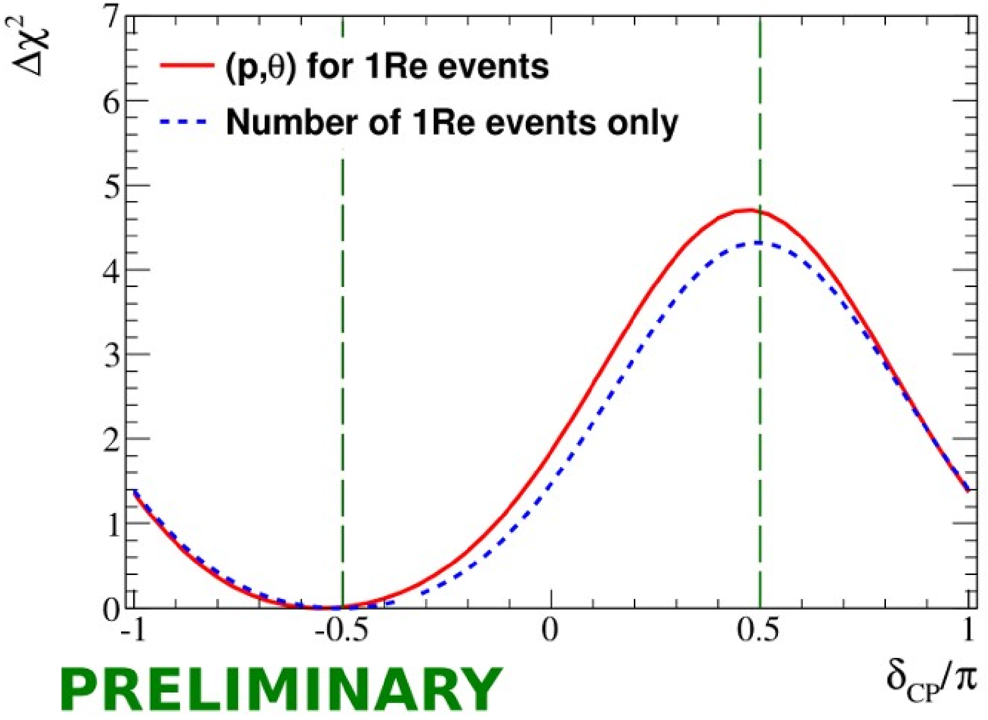


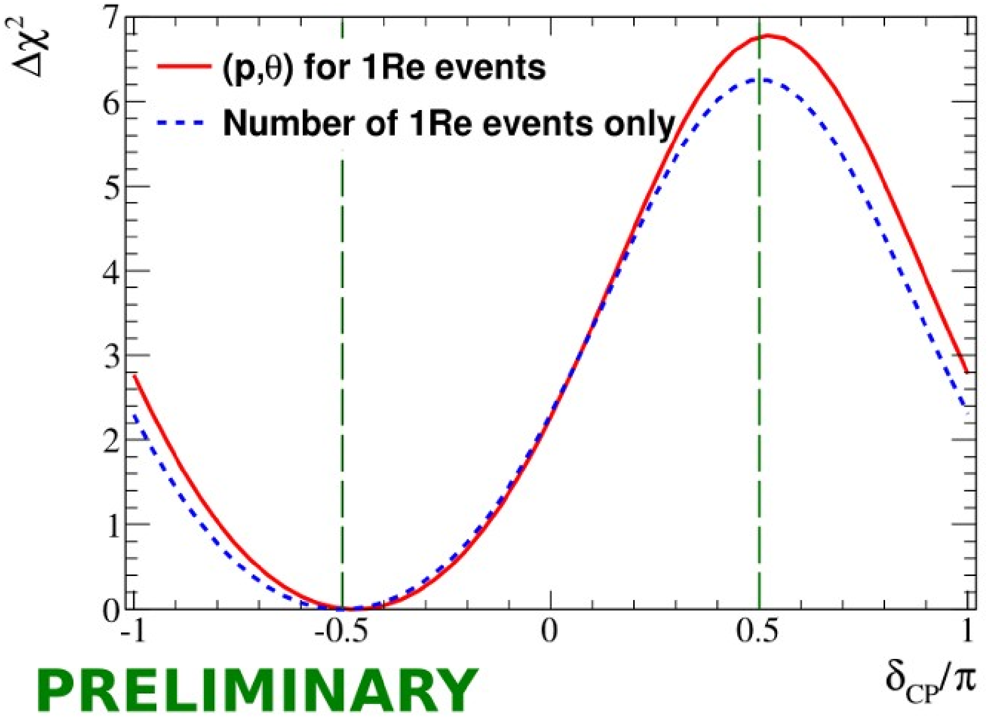
1Re: 1 ring electron-like (ν_e)
1Rμ: 1 ring muon like (ν_μ)

T2K Run1-4 only
Inverted hierarchy

Joint ν_e/ν_μ analyses
Effect of ν_e p-θ shape information

Using p-θ shape information when fitting for δ moves the minimum/maximum of the $\Delta\chi^2$ curve away from ± π/2 (green dashed lines)



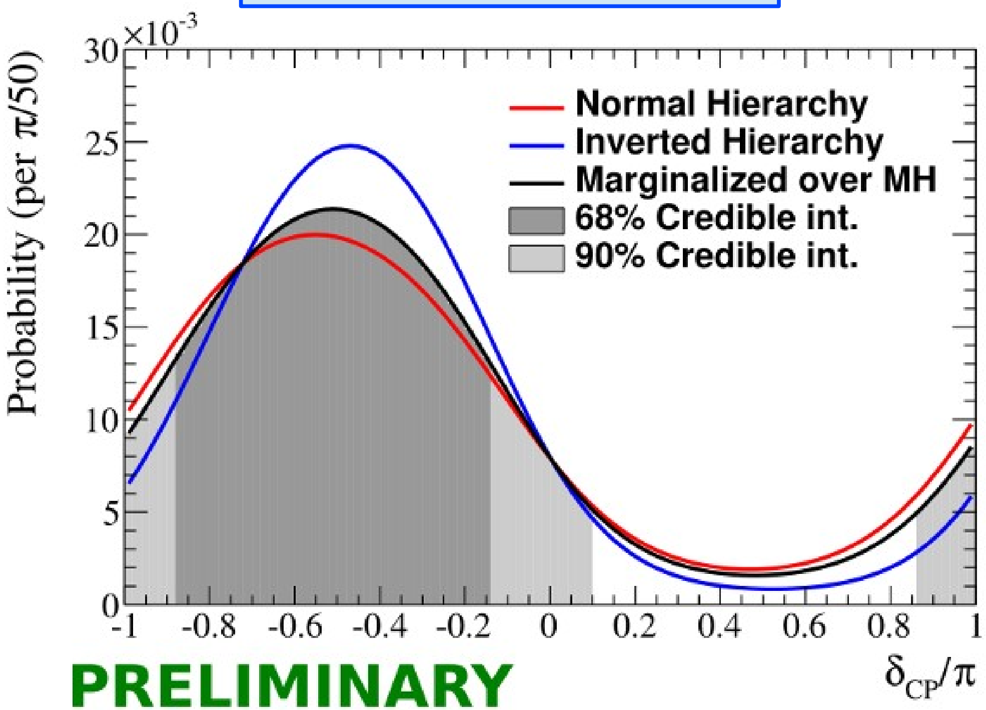


T2K Run1-4 + reactor ($\sin^2(2\theta_{13})=0.095\pm 0.01$)

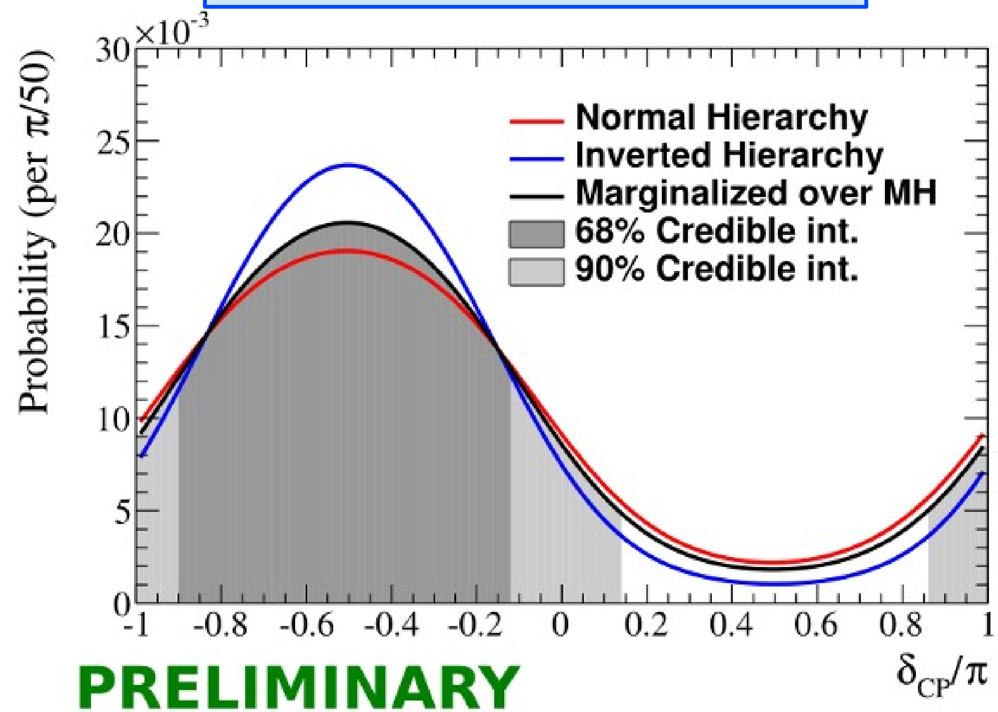
Joint ν_e/ν_μ analyses
Effect of ν_e p-θ shape information

Using p-θ shape information when fitting for δ moves the maximum/minimum of the posterior probability away from ± π/2.

(p,θ) for ν_e-like events



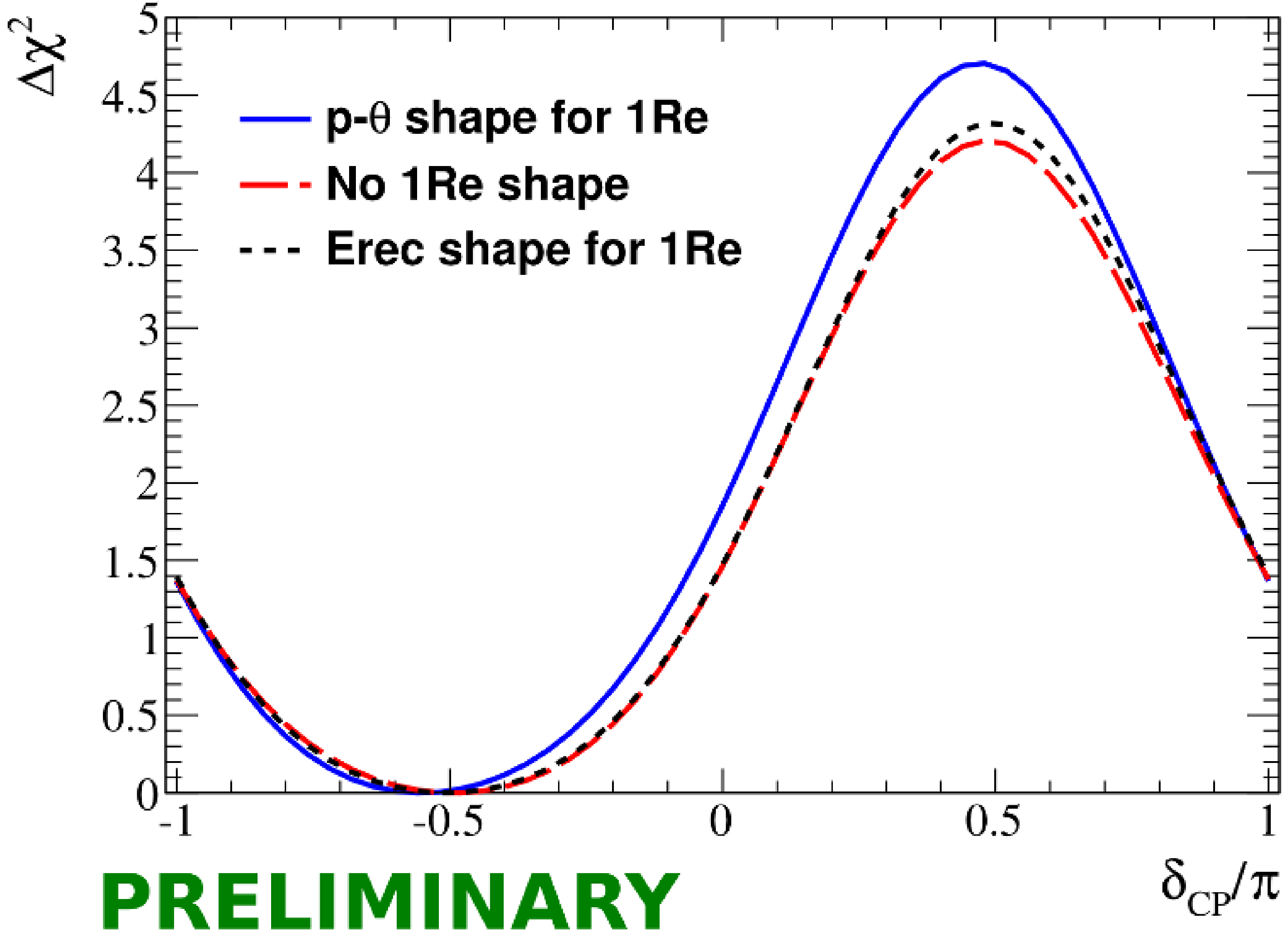
Number of ν_e-like events only



T2K Run1-4 + reactor ($\sin^2(2\theta_{13})$=0.095± 0.01)

Joint ν_e/ν_μ analyses
Effect of ν_e shape information

Result of the fit for δ changes slightly with the shape information used for ν_e-like events

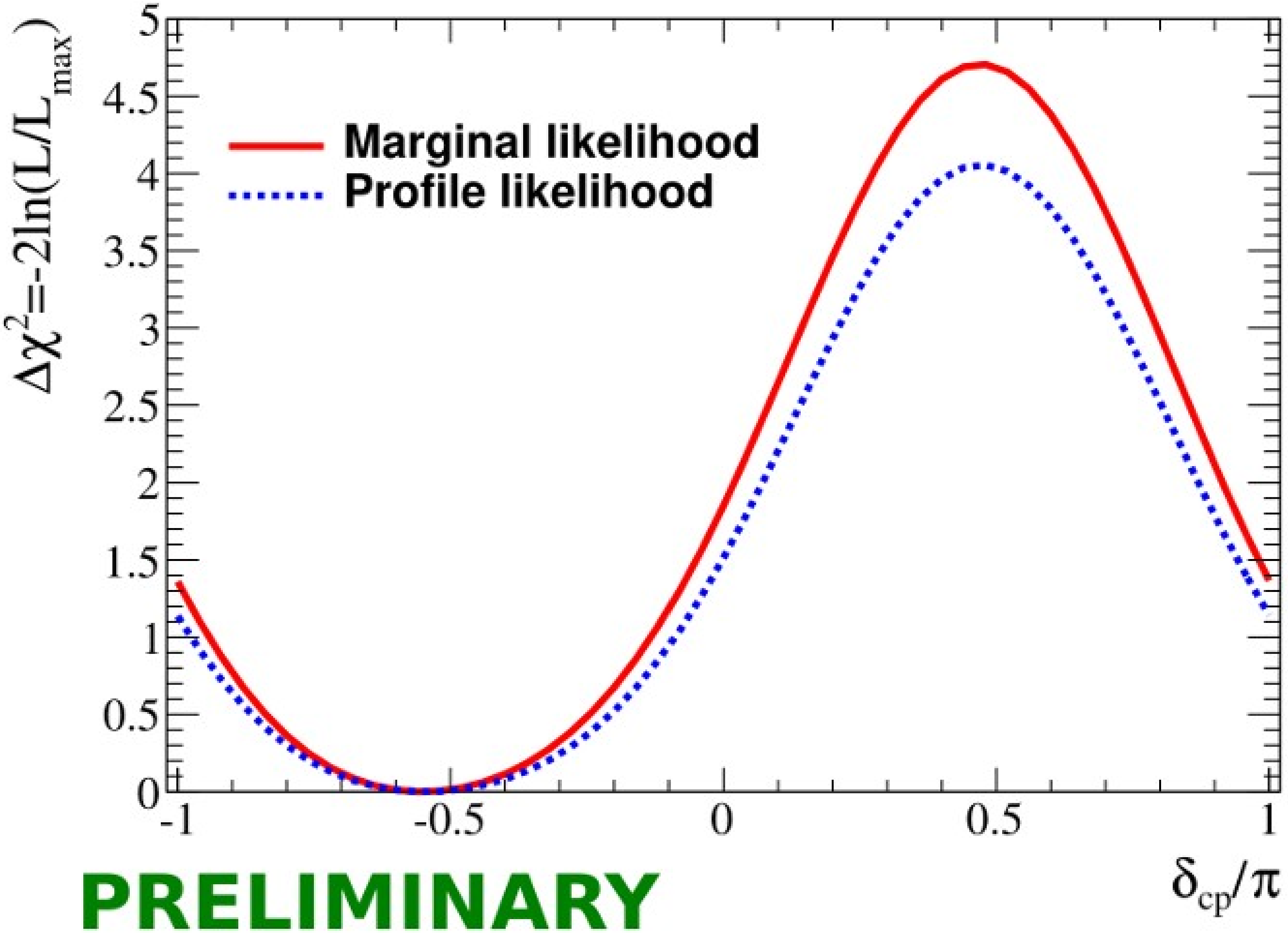


T2K Run1-4 + reactor ($\sin^2(2\theta_{13})$=0.095± 0.01)
Normal hierarchy

Joint ν_e/ν_μ analyses
Effect of treatment of systematic parameters

The two different treatments of the systematic parameters give different $\Delta\chi^2$ curves when fitting for δ in the normal hierarchy:

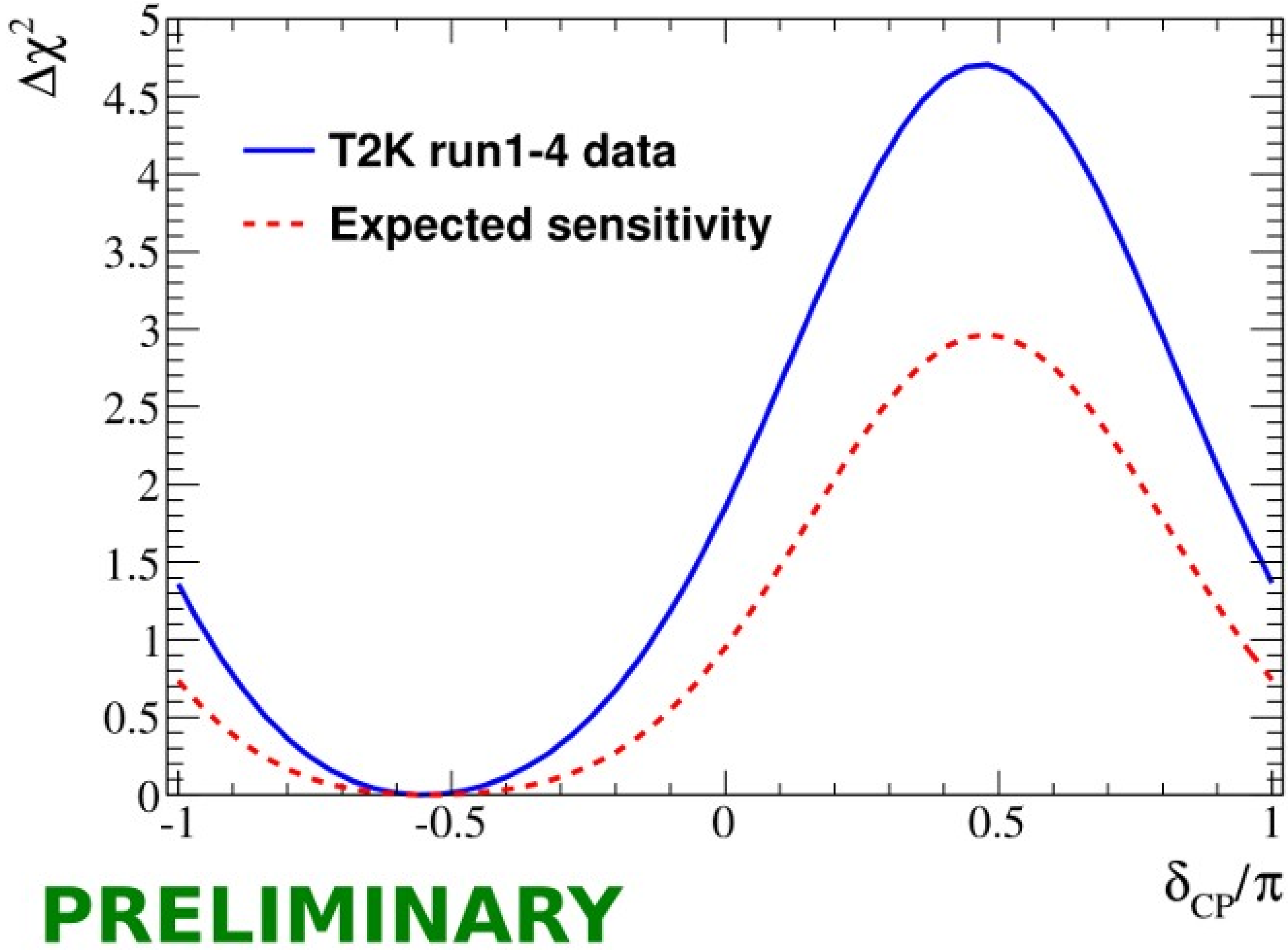
- Marginalization: the likelihood is integrated over the nuisance parameters for each value of δ
- Profiling: the likelihood is maximized with respect to the nuisance parameters for each value of δ



T2K Run1-4 + reactor ($\sin^2(2\theta_{13})=0.095\pm 0.01$)
Normal hierarchy

Joint ν_e/ν_μ analyses - T2K + reactor: δ_{CP}
Comparison to senstitivity

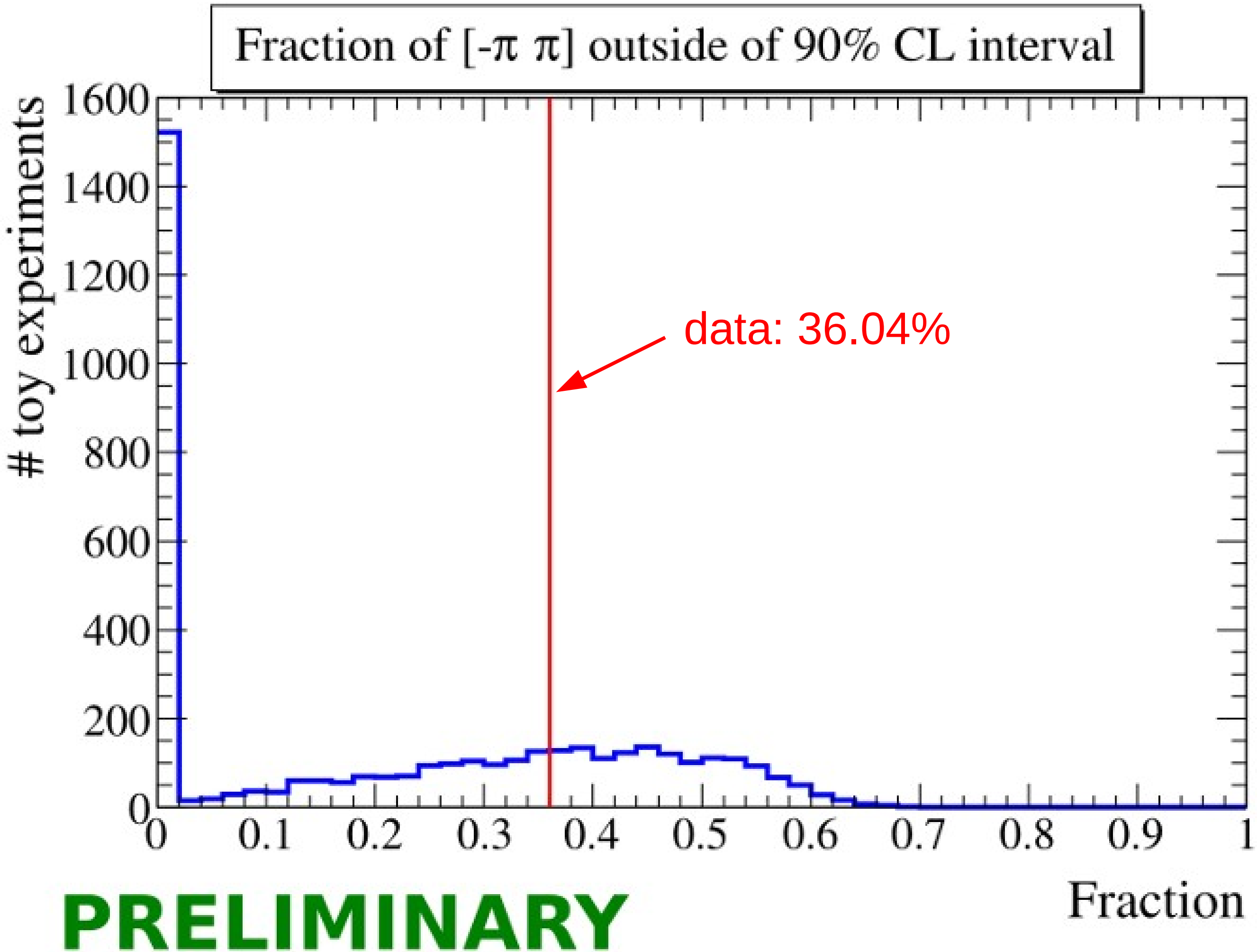
Comparing result of data fit to expected sensitivity at best fit point (obtained with 10k toy experiments)



T2K Run1-4 + reactor ($\sin^2(2\theta_{13})$=0.095± 0.01)
Normal hierarchy

Joint ν_e/ν_μ analyses - T2K + reactor: δ_{CP} Comparison to senstitivity

Looking at the distribution of the fraction of [-π; π] outside of the 90% CL interval for 4k toy experiments generated at the best fit point and comparing to result of data fit:



33.4 % of the toy experiments have a larger value than the data for this fraction.

T2K Run1-4 + reactor ($\sin^2(2\theta_{13})$=0.095± 0.01)
Normal hierarchy

Joint ν_e/ν_μ analyses
Four T2K joint analyses

Joint frequentist 1 (JF1)
Profiling
Erec shape for 1Re and 1Rμ

Joint Bayesian 1 (JB1)
Bayesian analysis based on MCMC
Simultaneous SK/ND280 fit
Event by event reweighting
Marginalization
Erec shape for 1Re and 1Rμ

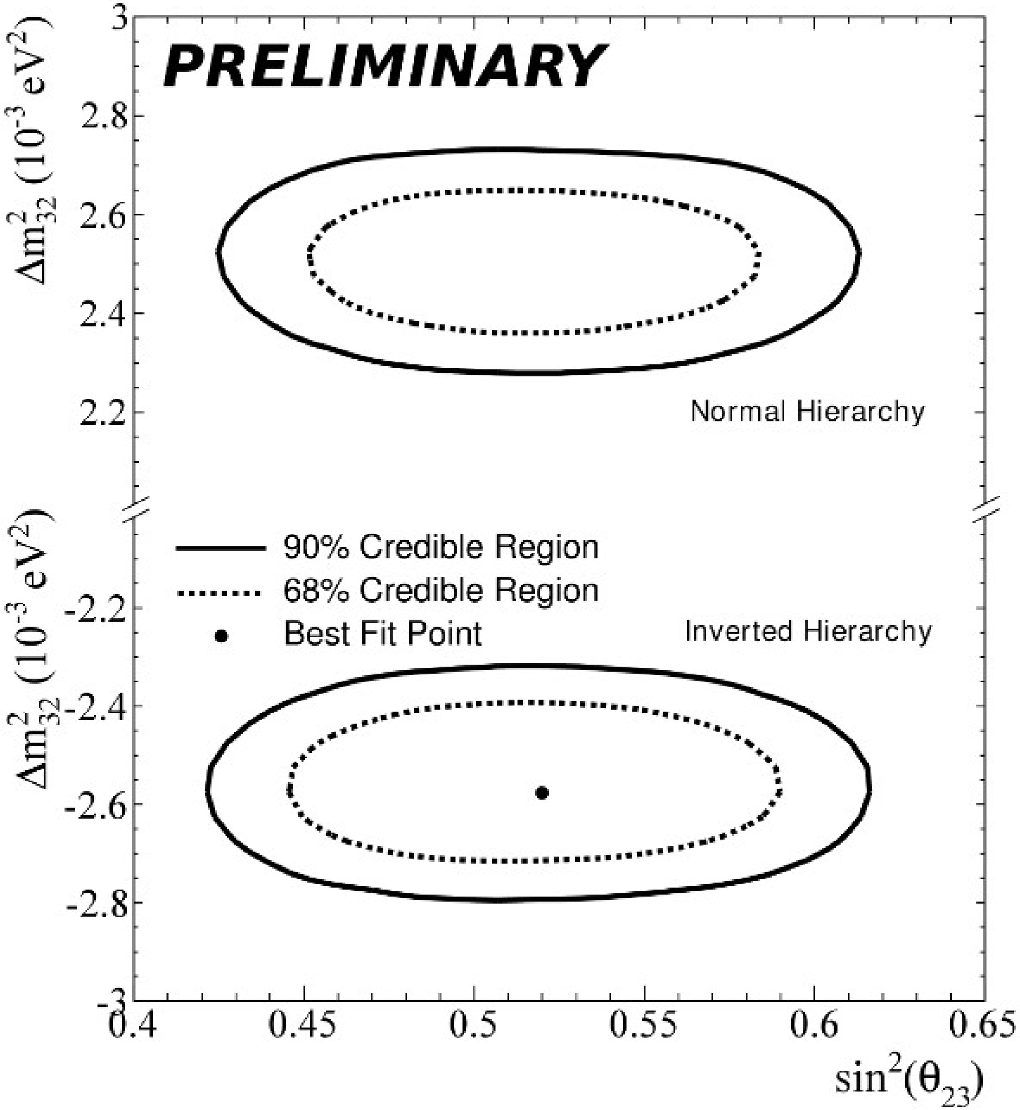
Joint frequentist 2 (JF2)
Systematic errors encoded in a covariance matrix binned in reconstructed energy
Profiling
Erec shape for 1Re and 1Rμ

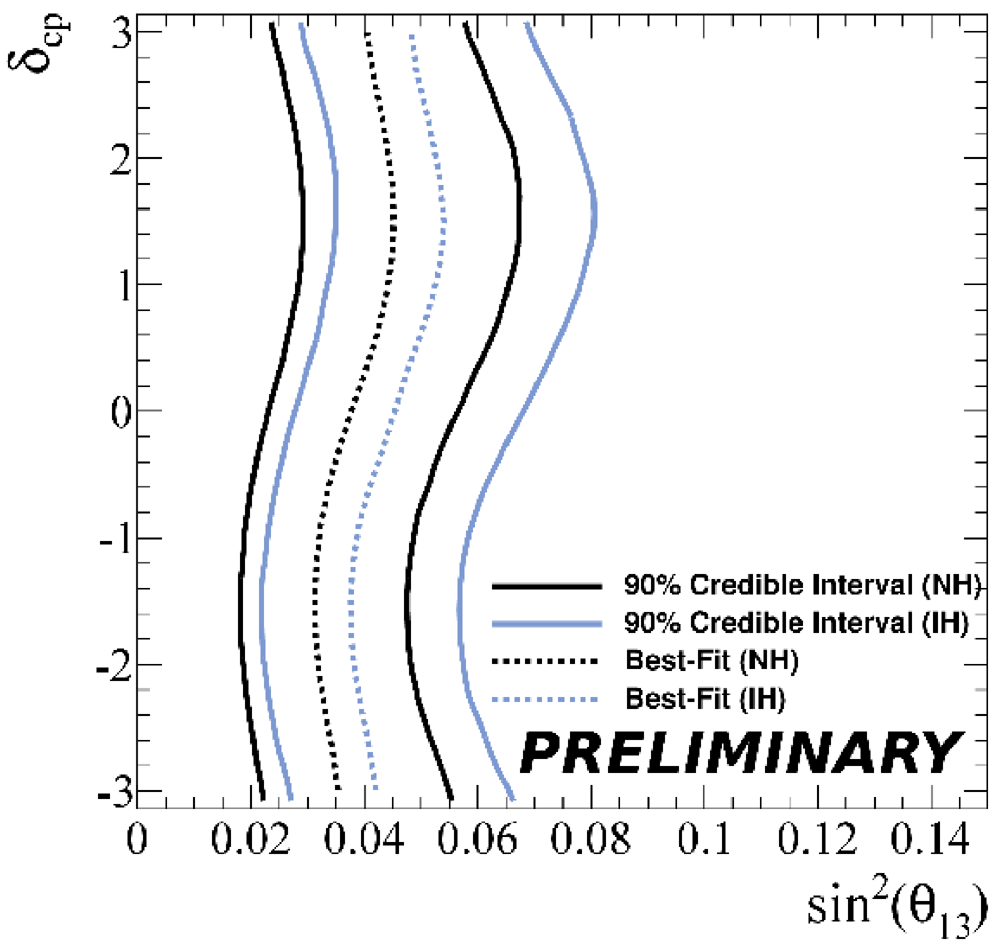
Joint Bayesian 2 (JB2)
Both Bayesian and hybrid Bayesian - frequentist analyses
Marginalization
Erec shape for 1Rμ
(p, θ) or Erec shape for 1Re

Results shown in the main part of this presentation

1Re: 1 ring electron-like (ν_e)
1Rμ: 1 ring muon like (ν_μ)

Joint ν_e/ν_μ analyses
Results from other joint analyses - JB1

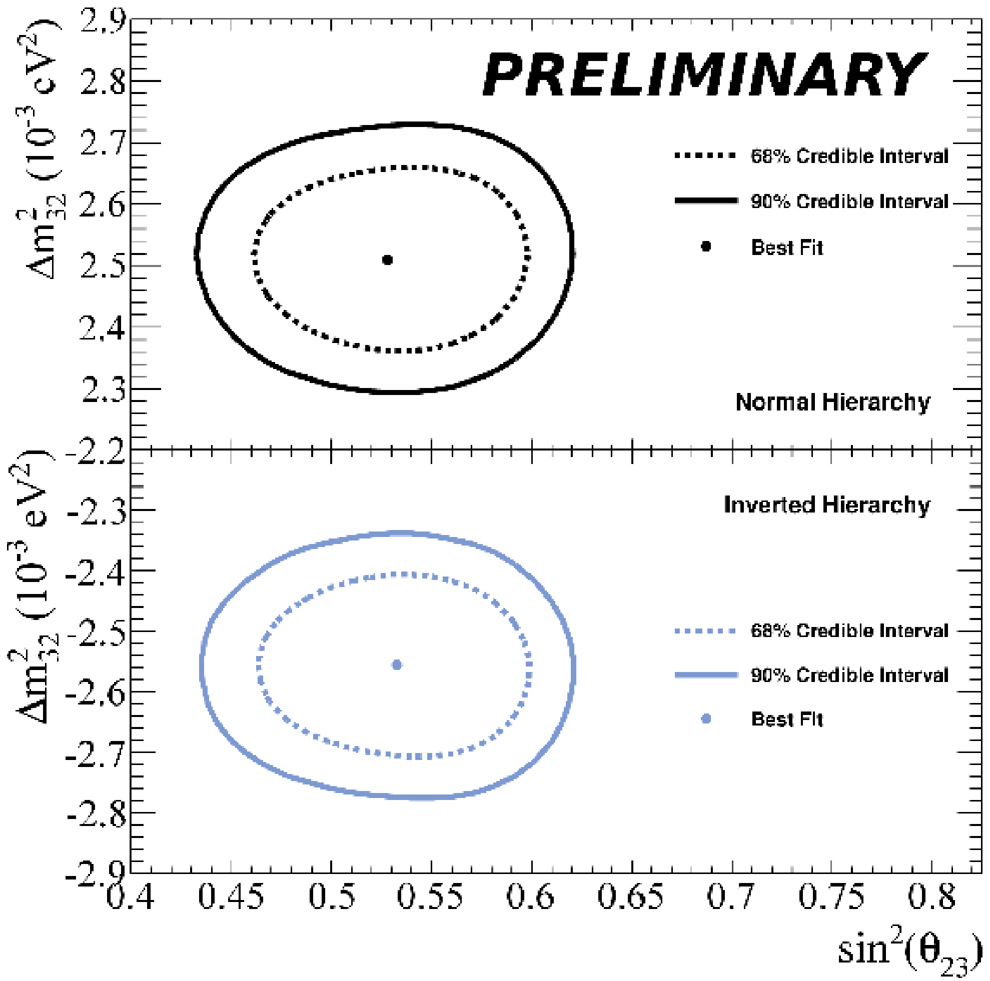


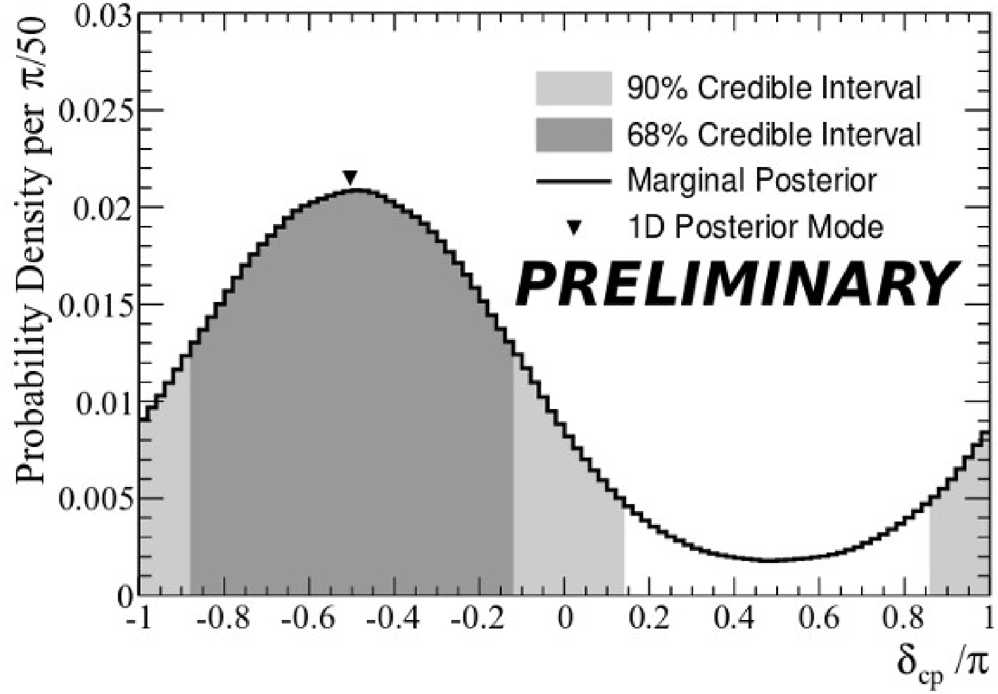


Credible intervals (Bayesian)

T2K Run1-4 only
(no reactor)

Joint ν_e/ν_μ analyses
Results from other joint analyses - JB1



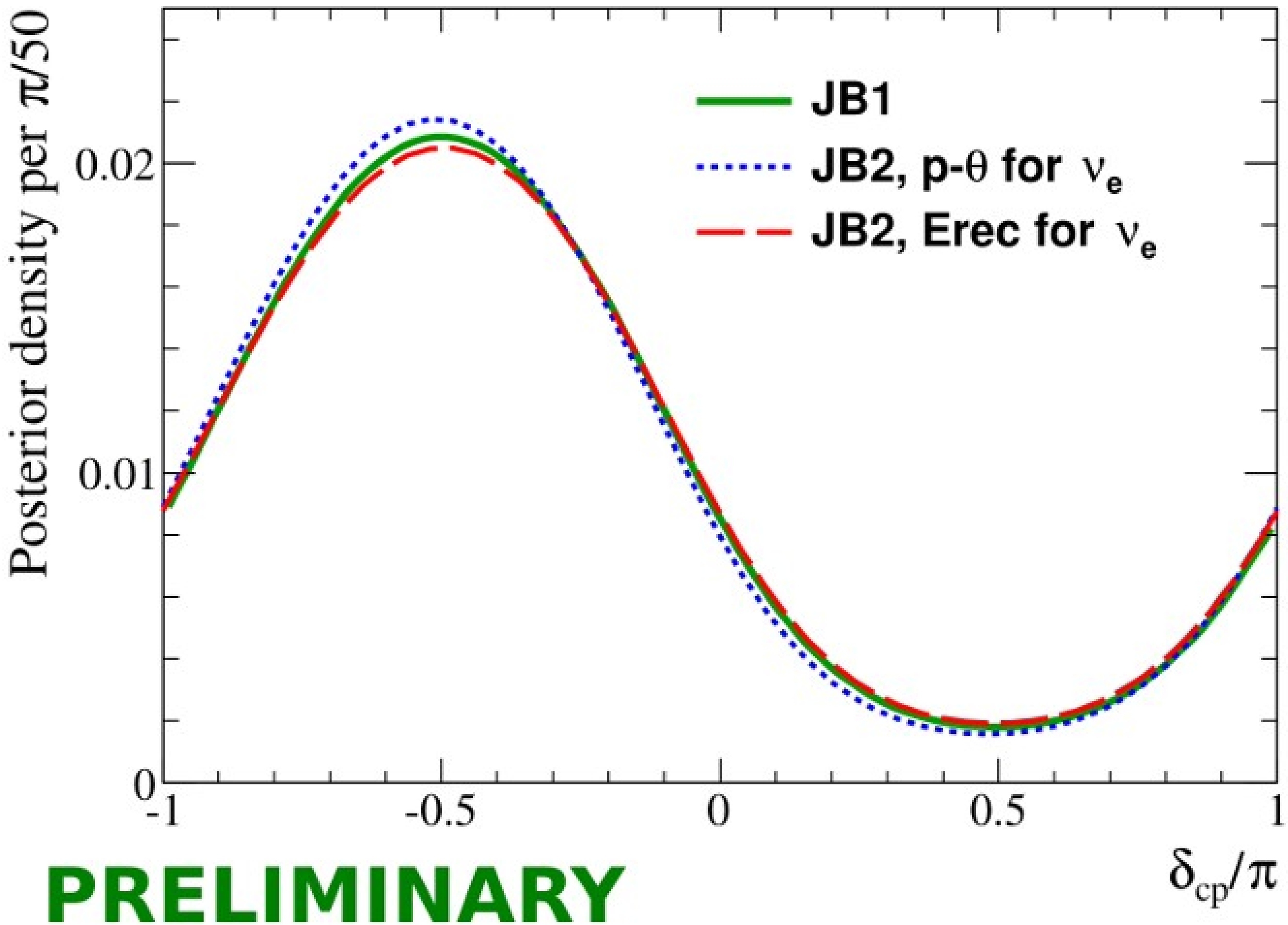


Credible intervals (Bayesian)

T2K Run1-4 + reactor
($\sin^2(2\theta_{13})$=0.095± 0.01)

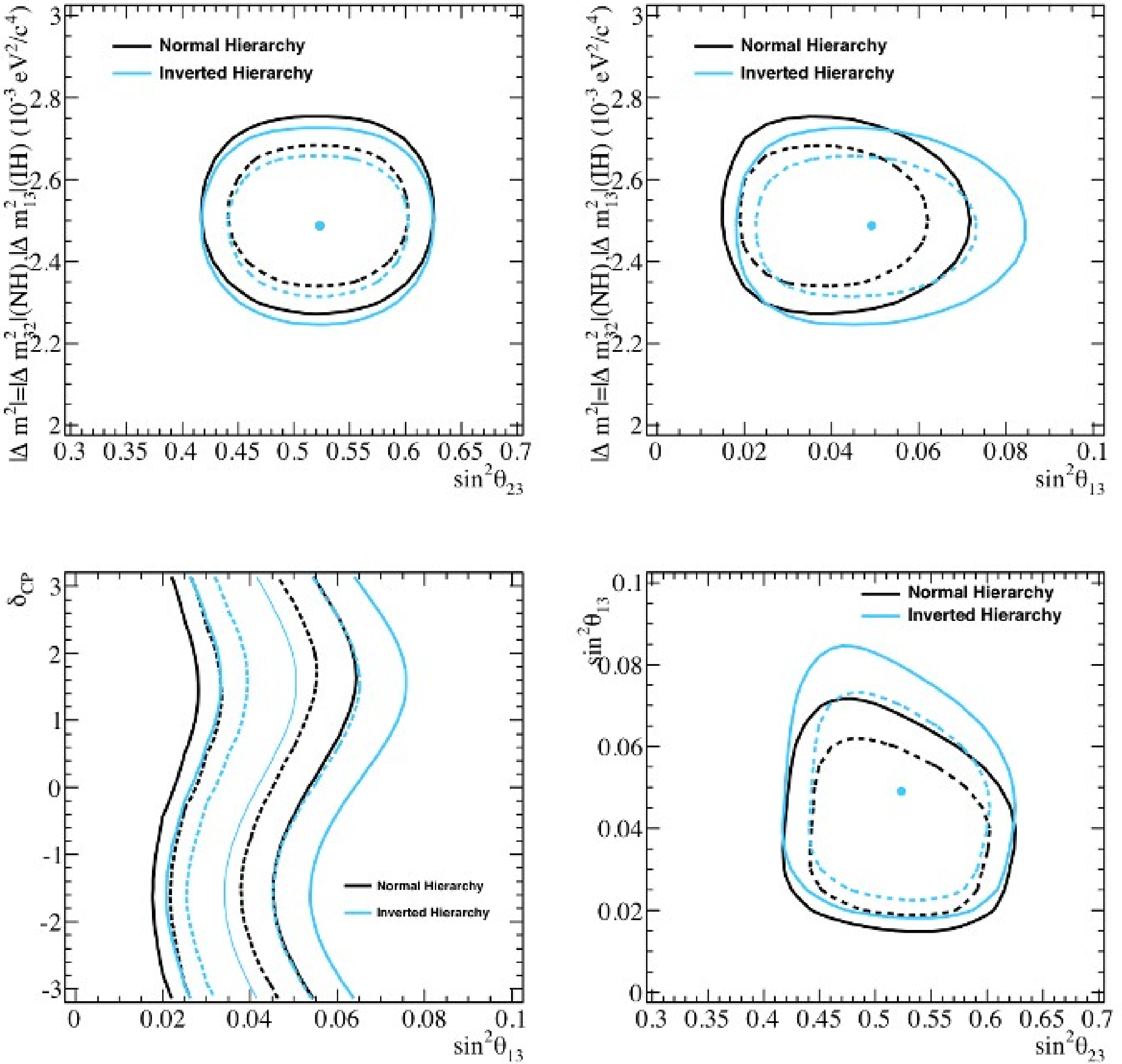
Joint ν_e/ν_μ analyses
Comparing results from the two joint Bayesian analysis

The two Bayesian joint analyses give compatible results for the posterior probability for δ when marginalizing over the mass hierarchies:



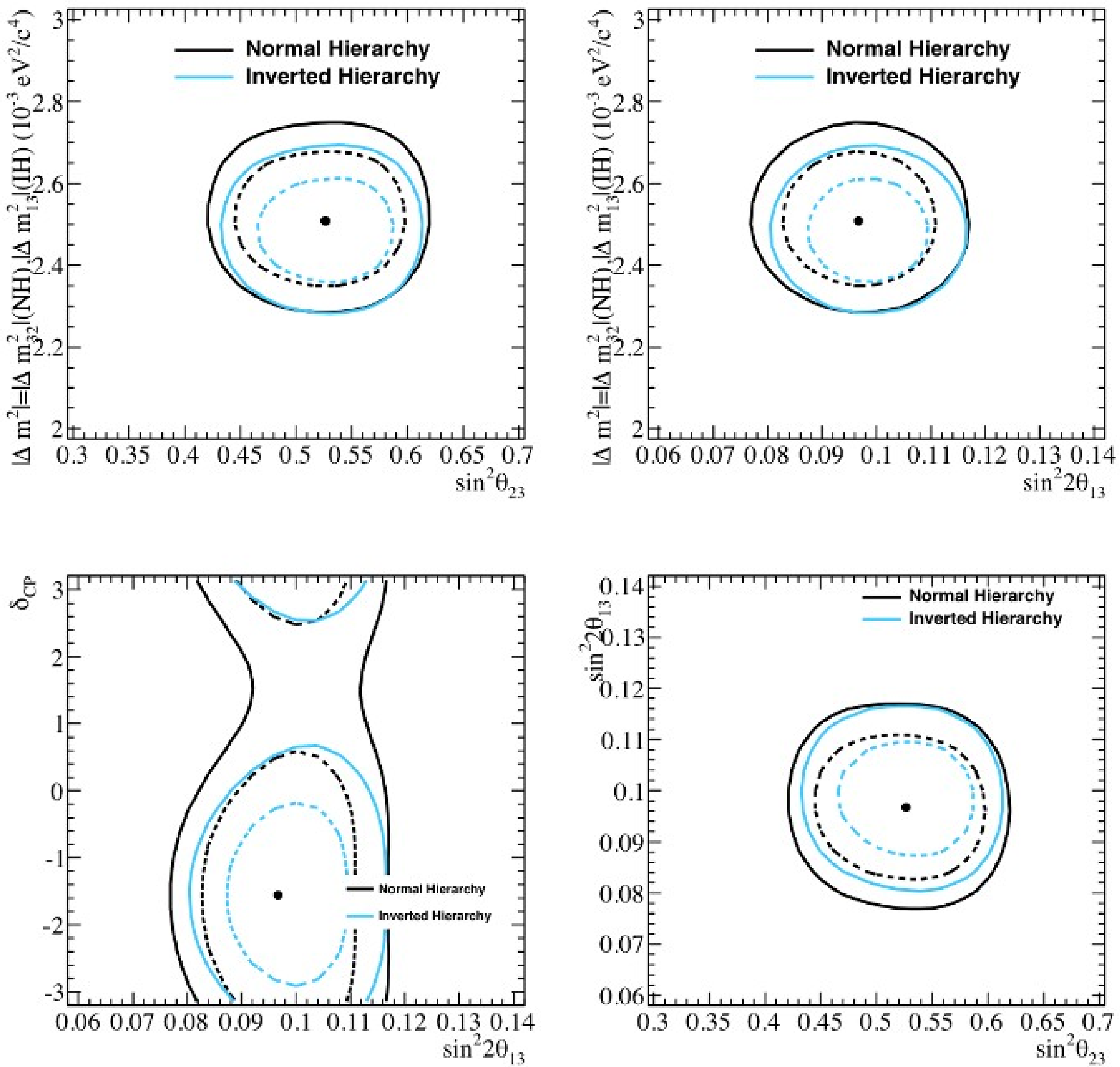
T2K Run1-4 + reactor ($\sin^2(2\theta_{13})$=0.095± 0.01)

Joint ν_e/ν_μ analyses
Results from other joint analyses - JF1



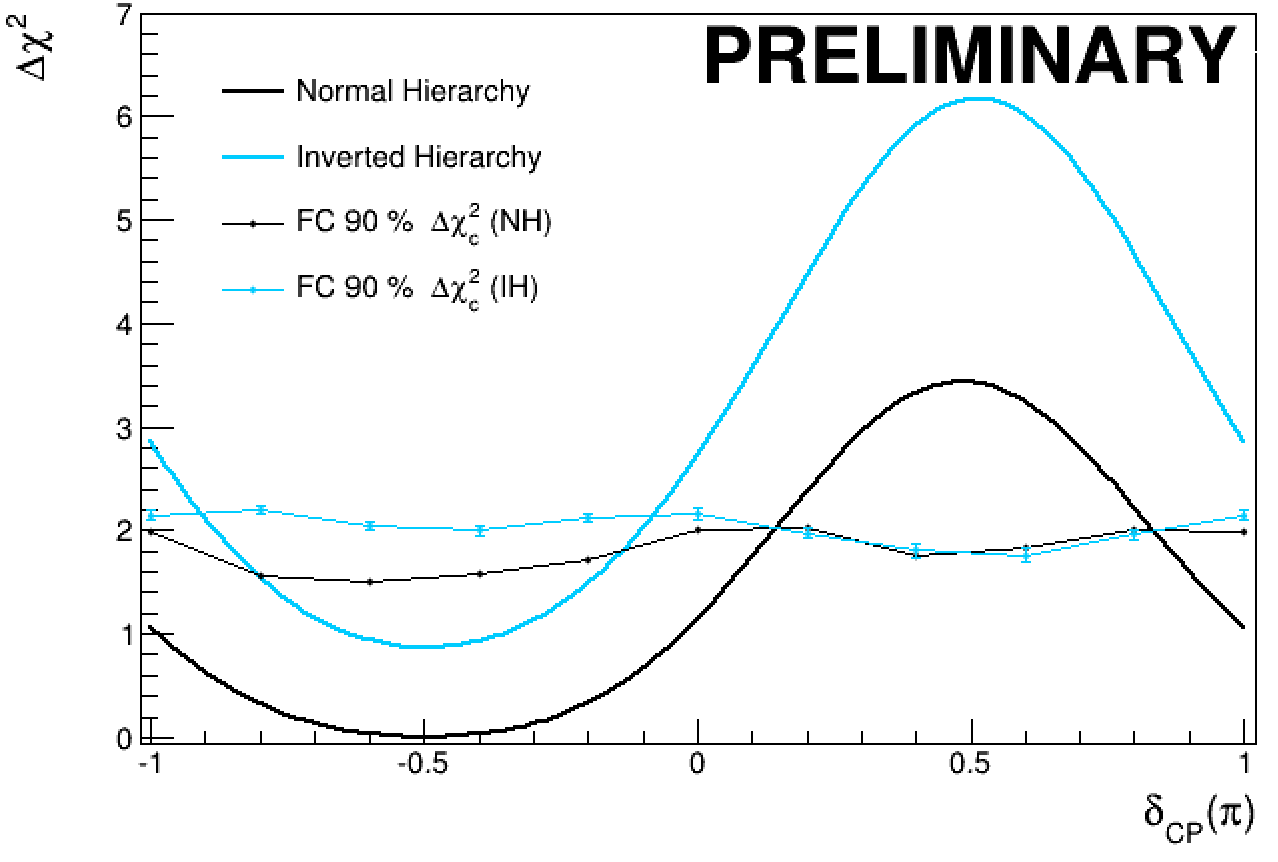
T2K Run1-4 only
(no reactor)

Joint ν_e/ν_μ analyses
Results from other joint analyses - JF1



T2K Run1-4 + reactor
($\sin^2(2\theta_{13})$=0.095± 0.01)

Joint ν_e/ν_μ analyses
Results from other joint analyses - JF1



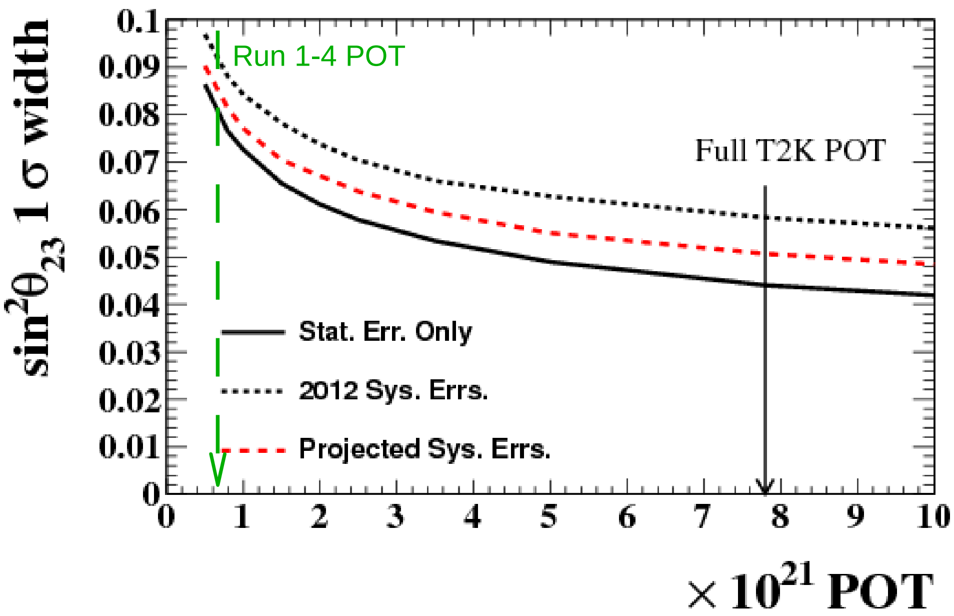
T2K Run1-4 + reactor
($\sin^2(2\theta_{13})$=0.095± 0.01)

Future sensitivity $\sin^2\theta_{23}$

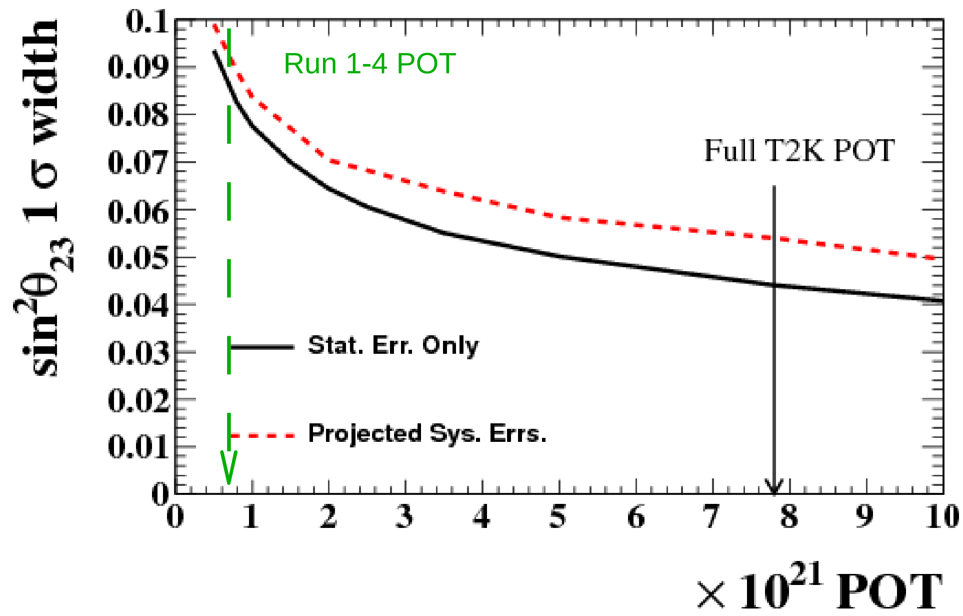
$\sin^2(2\theta_{13})=0.1$
$\delta=0$
$\Delta m^2_{32}=2.4\times10^{-3}\ \mathrm{ev}^2/c^4$
$\sin^2(\theta_{23})=0.5$
Normal hierarchy
Ultimate reactor constraint
$(\sin^2(2\theta_{13})=0.1\pm 0.005)$

Expected precision on the value of $\sin^2\theta_{23}$ for various running hypothesis:

100% ν mode



50% ν mode and 50% $\bar{\nu}$ mode

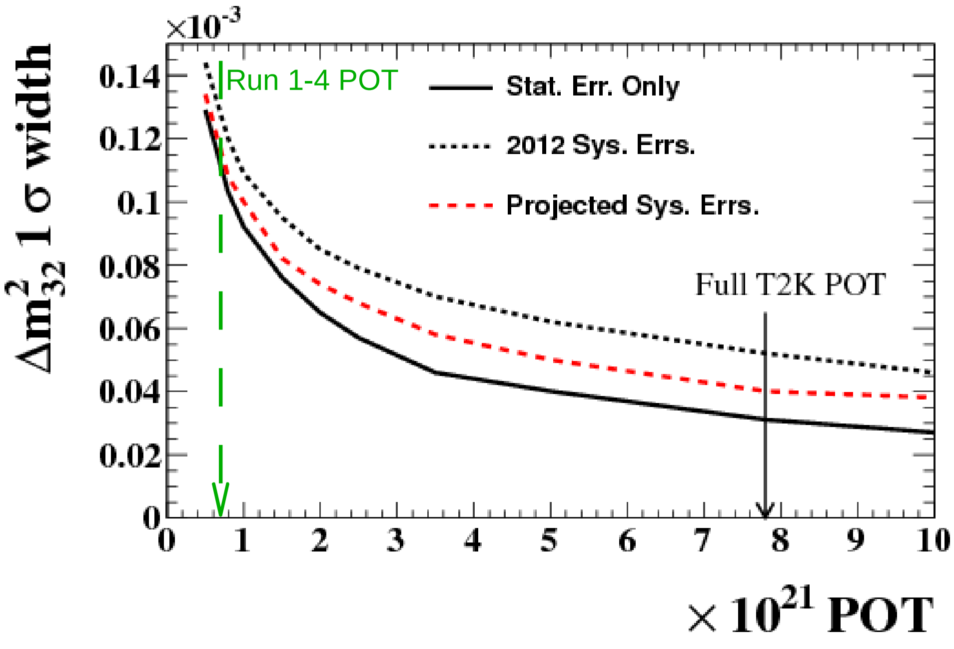


Future sensitivity Δm^2_{32}

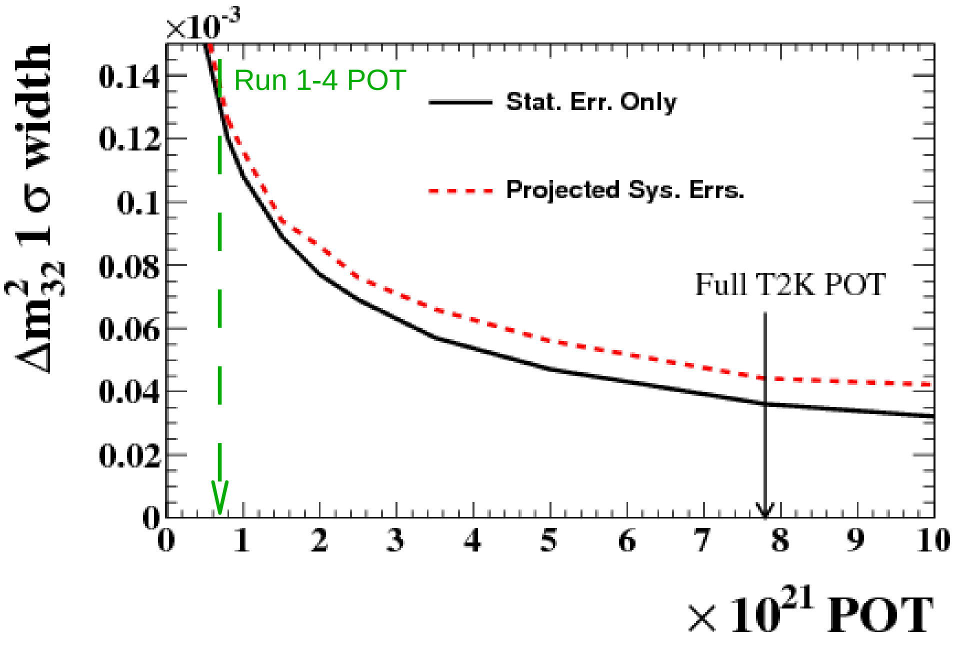
$\sin^2(2\theta_{13})=0.1$
$\delta=0$
$\Delta m^2_{32}=2.4\times10^{-3}\ ev^2/c^4$
$\sin^2(\theta_{23})=0.5$
Normal hierarchy
Ultimate reactor constraint
($\sin^2(2\theta_{13})=0.1\pm 0.005$)

Expected precision on the value of Δm^2_{32} for various running hypothesis:

100% ν mode



50% ν mode and 50% $\bar{\nu}$ mode

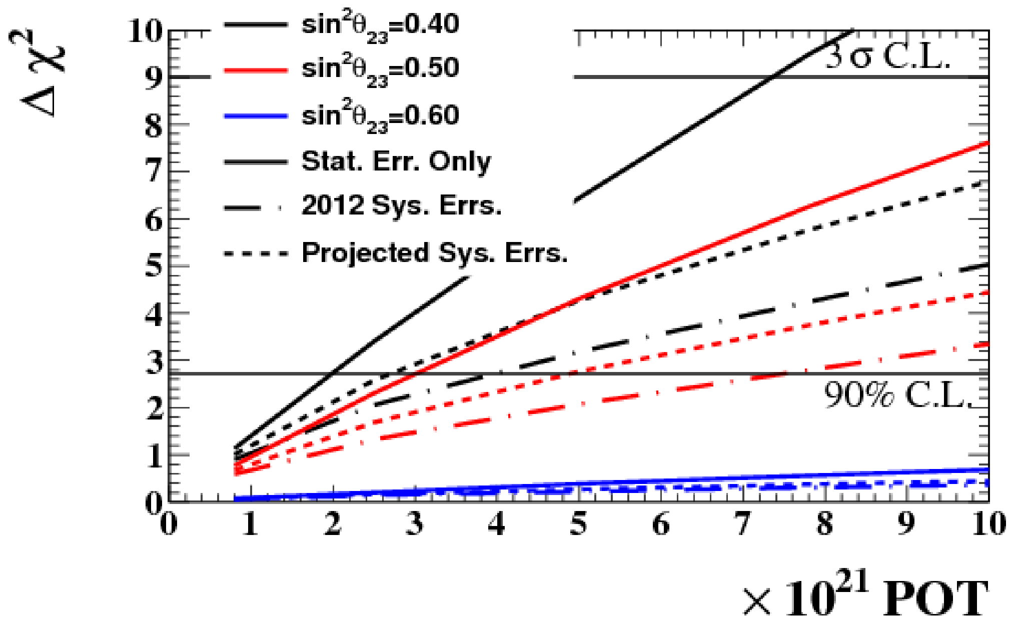


Future sensitivity δ_{CP}

$\sin^2(2\theta_{13})=0.1$
$\delta=\pi/2$
$\Delta m^2_{32}=2.4\times10^{-3}\ ev^2/c^4$
$\sin^2(\theta_{23})=0.5$
Inverted hierarchy
Ultimate reactor constraint
$(\sin^2(2\theta_{13})=0.1\pm 0.005)$

$\Delta\chi^2$ to resolve $\delta\neq0$

100% ν mode



50% ν mode and 50% $\bar{\nu}$ mode