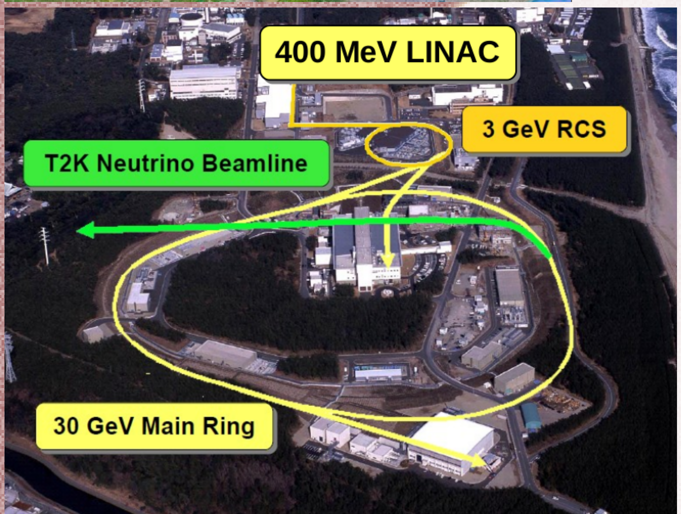


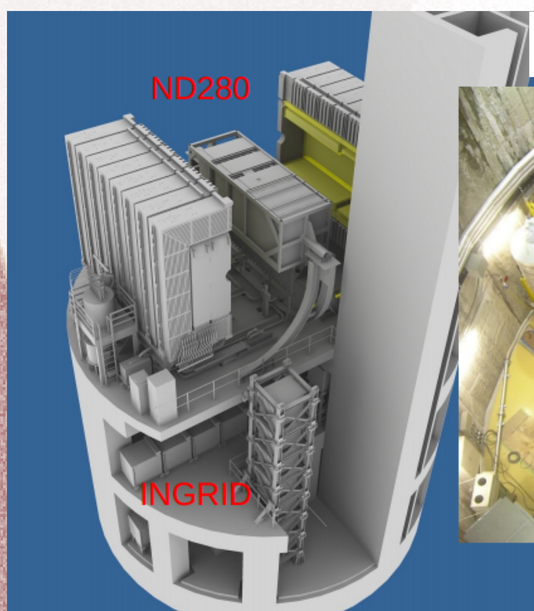
Present and future neutrino oscillation physics with T2K

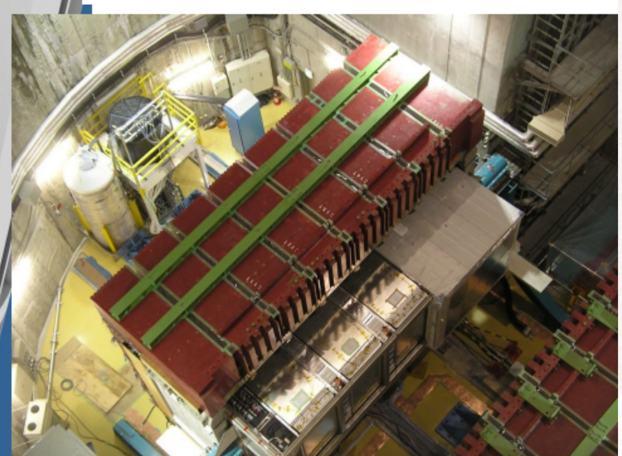
A.Longhin (INFN-LNF)

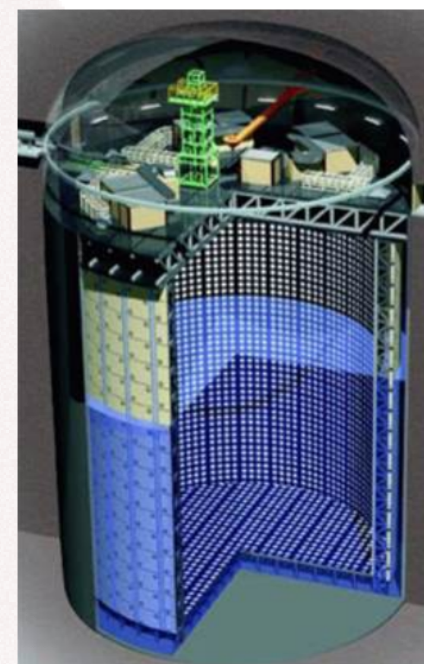
INFN Istituto Nazionale di Fisica Nucleare

T2K

JENNIFER **meeting**
Roma, 11/06/2015







ν mixing and oscillations

Mass eigenstates (ν_1,ν_2,ν_3) ↔ weak eigenstates (ν_e,ν_μ,ν_τ) $|\nu_\alpha(t)\rangle = \sum_{i=1}^{3} U^*_{\alpha i}|\nu_i(t)\rangle$

U: PMNS matrix

T2K → Δm^2_{31}, θ_{23}, θ_{13}

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & e^{-i\delta}s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta}s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Δm^2_{31}		Δm^2_{21}
SuperK, K2K, MINOS, OPERA, T2K	Chooz, Daya Bay, RENO T2K, MINOS, NOvA	SuperK, SNO, KamLAND
atmospheric+LBL	Chooz	solar+KamLAND

$\sin^2 2\theta_{13}$

- < 0.15 – before 2011 – CHOOZ limit (90% CL)
- 0.11 (0.14) – T2K best fit of 2011 (2.5 σ)
- 0.092 ± 0.017 – Daya Bay, 2012 (5.2 σ)
- **T2K 2013 – 7.5σ**

PDG2014

Θ_{23} = 45.8 ± 3.2°

Θ_{12} = 33.4 ± 0.85°

Θ_{13} = 8.88 ± 0.39°

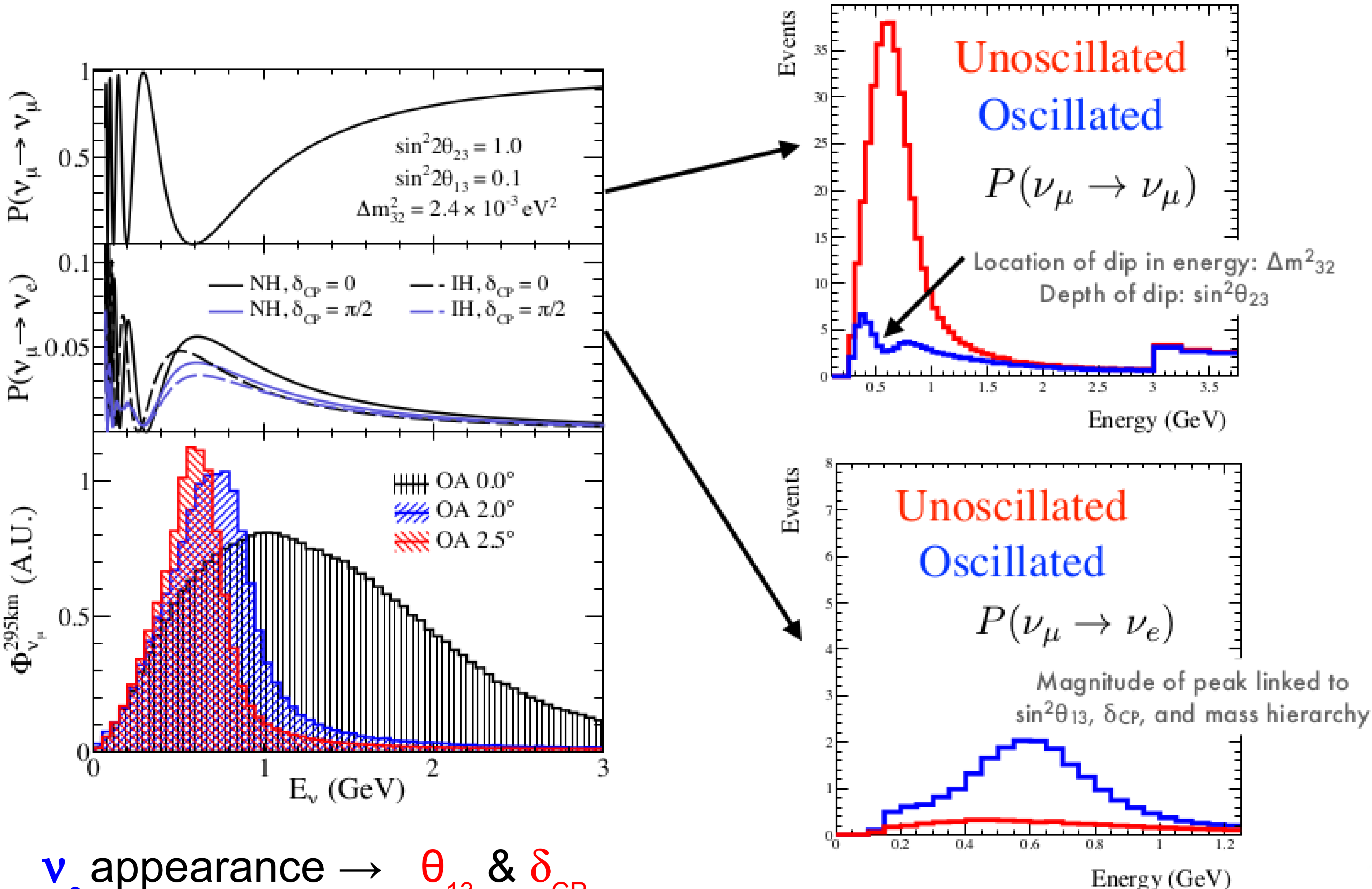
$\Delta m^2_{21} = (7.53 \pm 0.18)10^{-5}$ eV^2

$|\Delta m^2_{32}| = (2.44 \pm 0.06)10^{-3}$ eV^2

Still unknown: CP violation? mass hierarchy ($m_{1,2} \lessgtr m_3$)? $\theta_{23} = 45^\circ$?

More PMNS symmetries? Majorana/Dirac ?

Long baseline neutrino oscillation

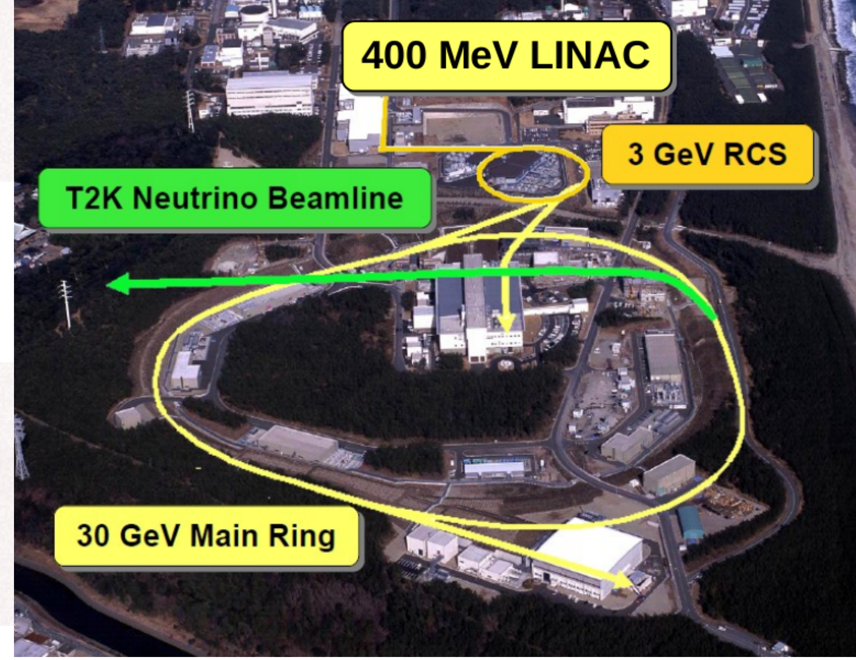


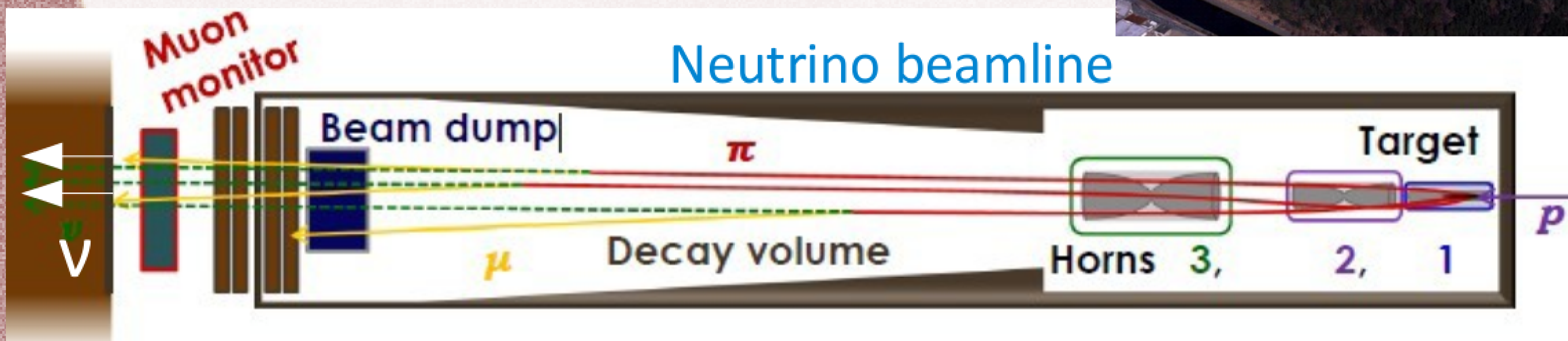
ν_e appearance → θ_{13} & δ_{CP}

ν_μ disappearance → θ_{23} & Δm^2_{23}

T2K

500 members
59 istitutes
11 countries

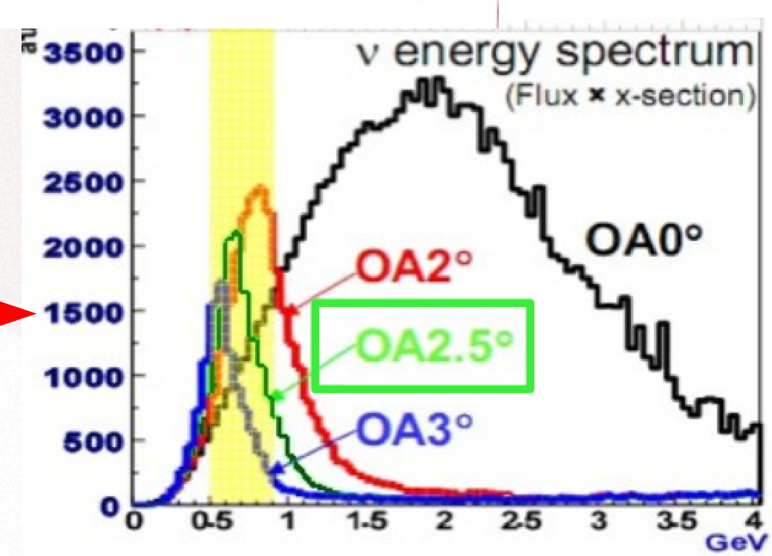




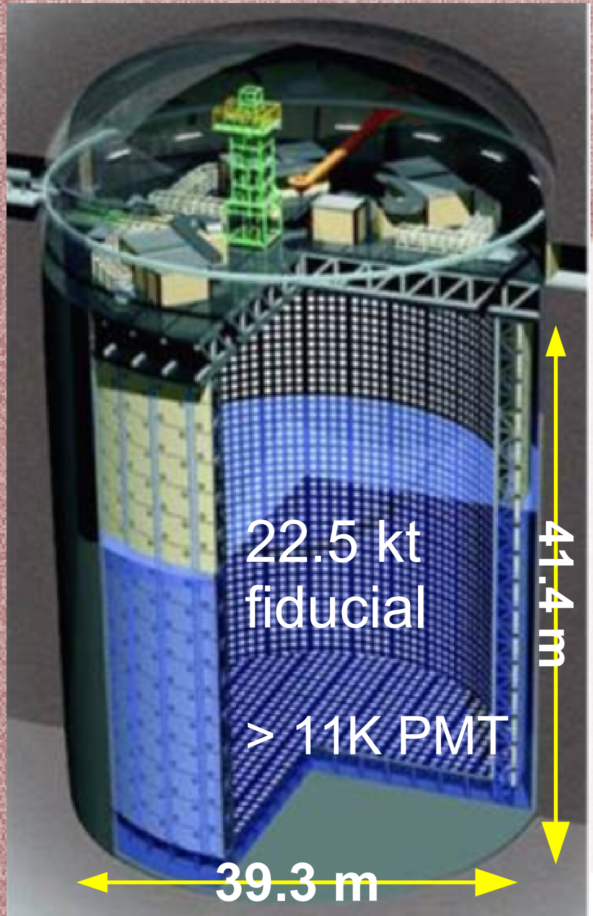
← 30 GeV

First "off-axis" beam

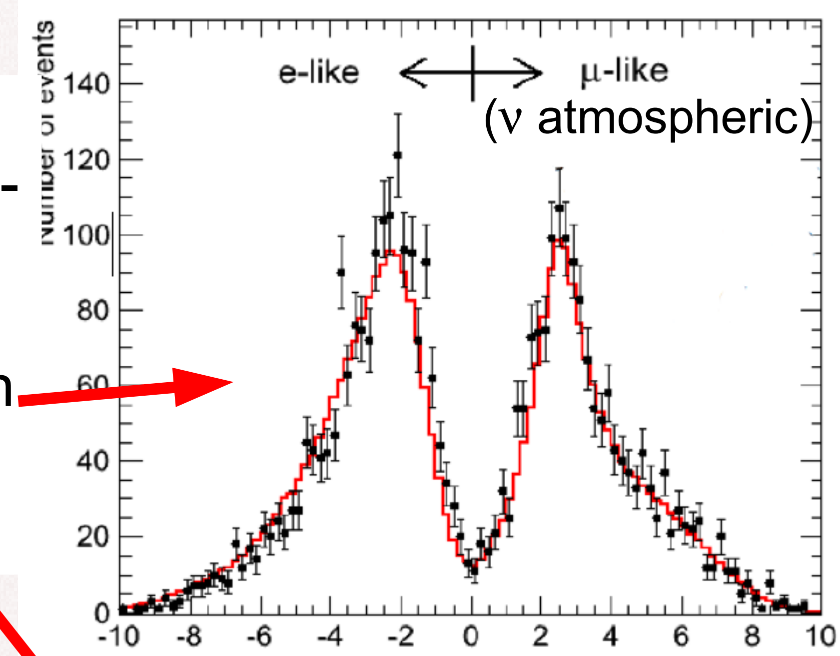
- 2.5° → peak at ~ 0.6 GeV
- Enriched in Quasi-elastic interactions (good measurement of E_ν)
- Reduced instrinsic ν_e background
- Reduced NC π^0 ~backg. from D.I.S.
- Double detector: **280 m and 295 km**

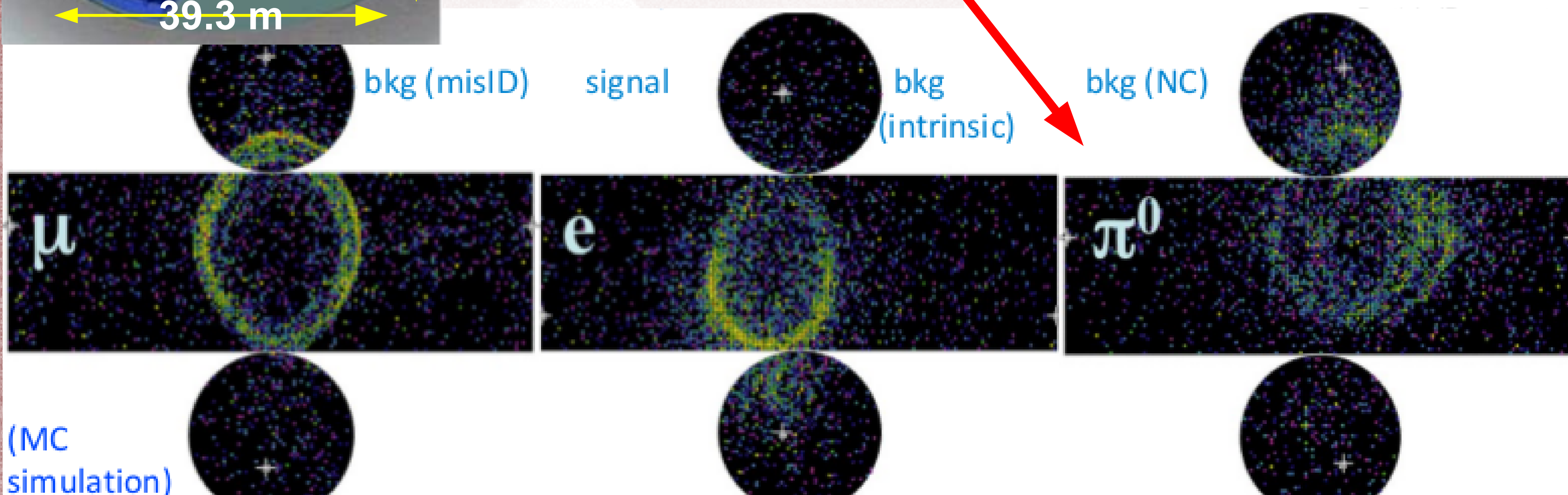


The far detector (295 km): Super-Kamiokande



- Water Cherenkov
  - $\Delta E/E$ ~10% for quasi-elastic (QE) interactions
- Excellent μ/e separation
- π^0 detection
  - 2 “e-like” rings





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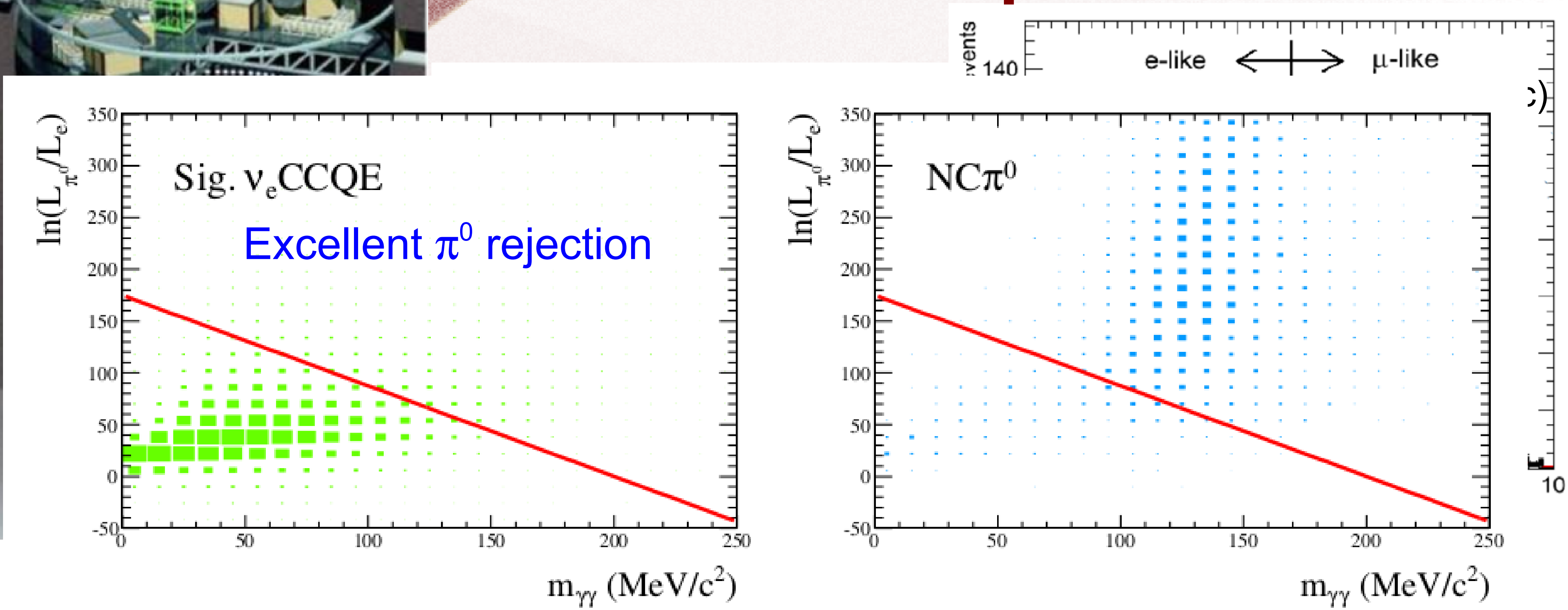
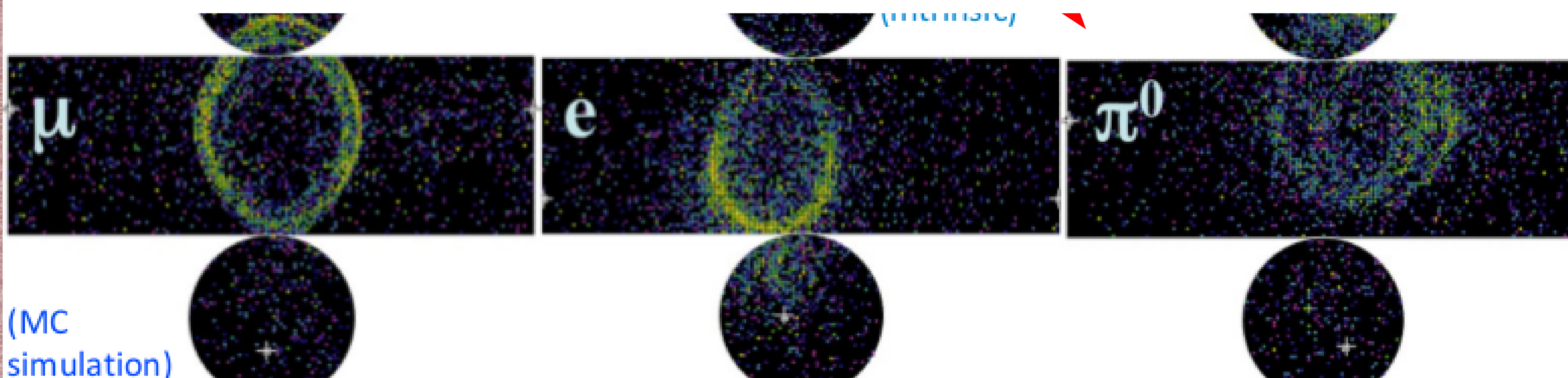


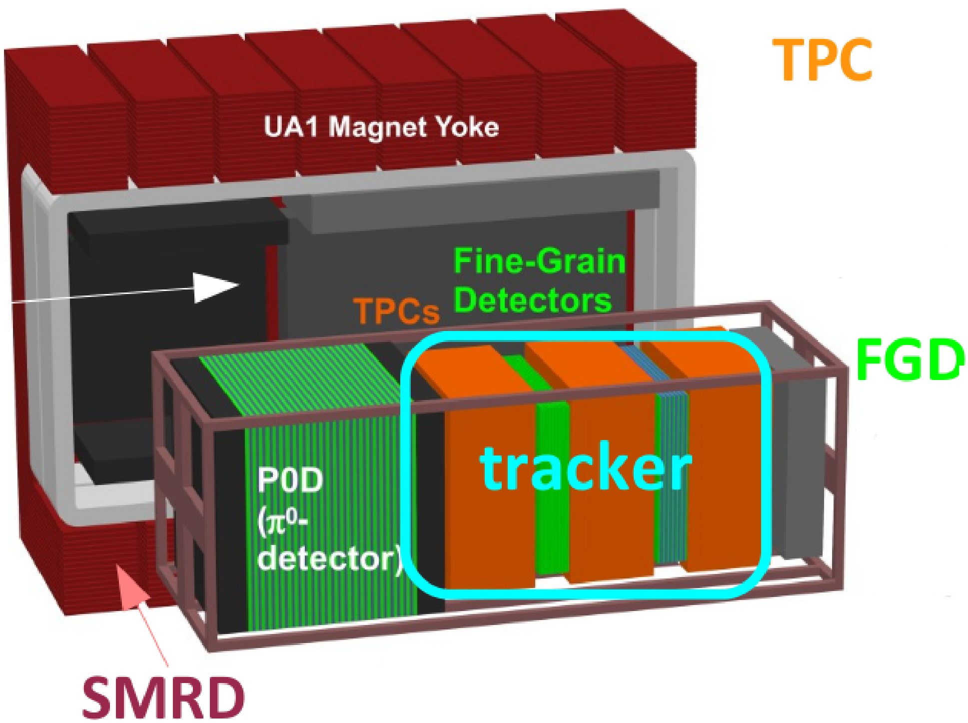


The near detector (280 m)

ND280 (off-axis)

Measures ν_μ & ν_e fluxes and cross-sections

Magnet B = 0.2 T
TPC: p measurement + particle-ID with dE/dx
FGD: Fine grained detectors (2 x 0.8 t): Proton tagging
SMRD: magnitized muon range detector



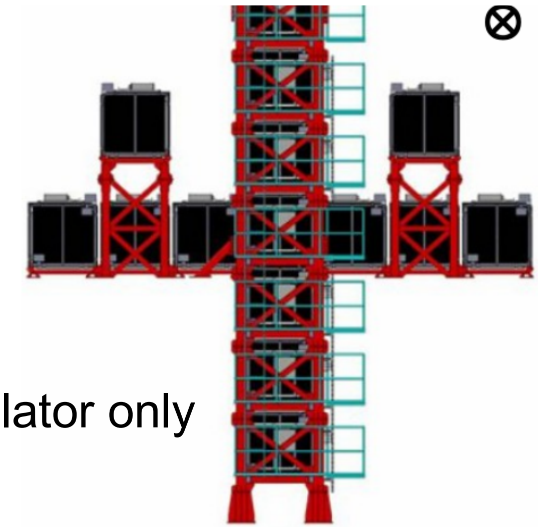
P0D: pi-zero detector (Pb/brass-H_2O-scintillator)
ECAL: electromagnetic calorimeter

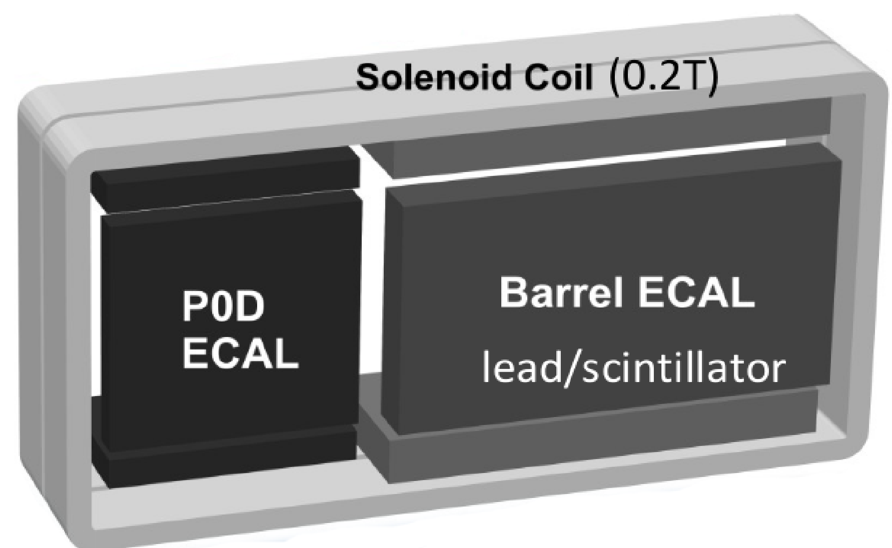
INGRID (on-axis)

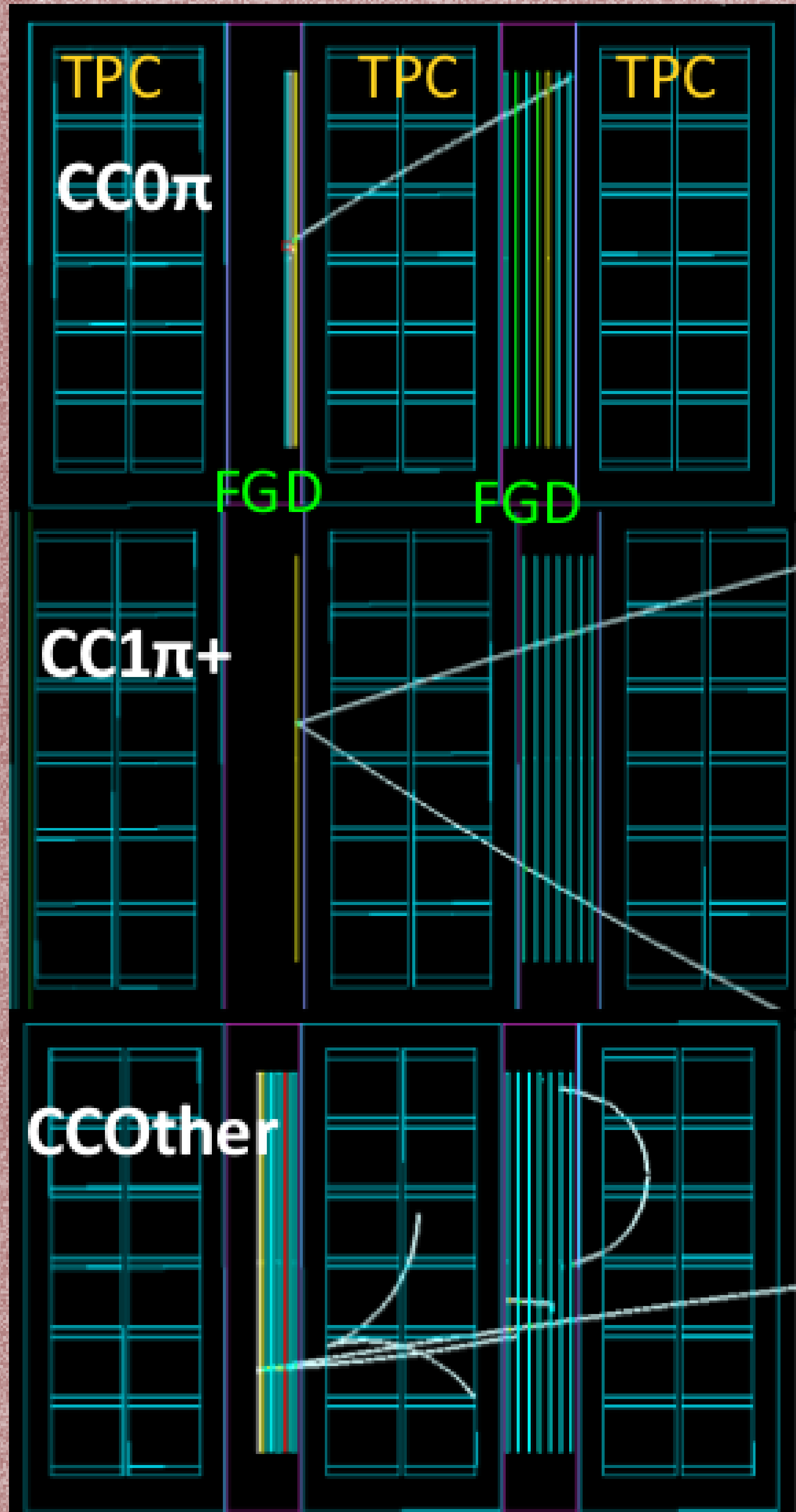
ν_μ CC rate → beam profile

Fe/scintillator tracking calorimeter

16 modules
central one scintillator only

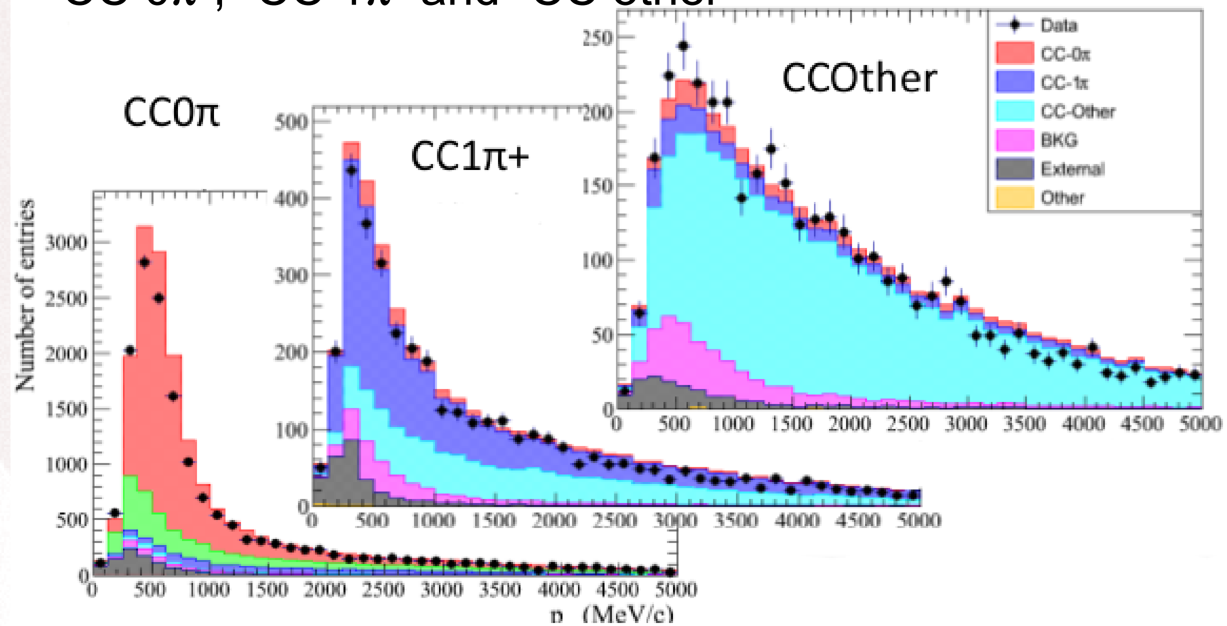


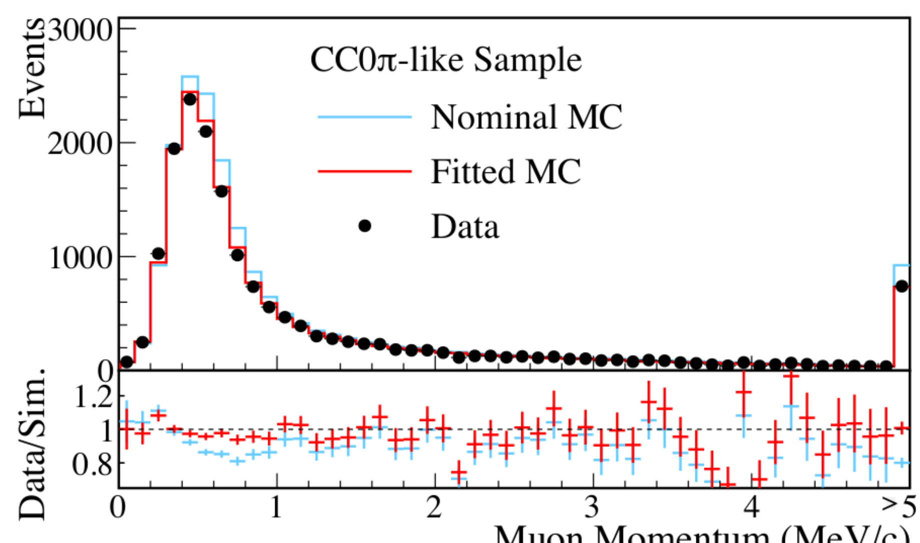




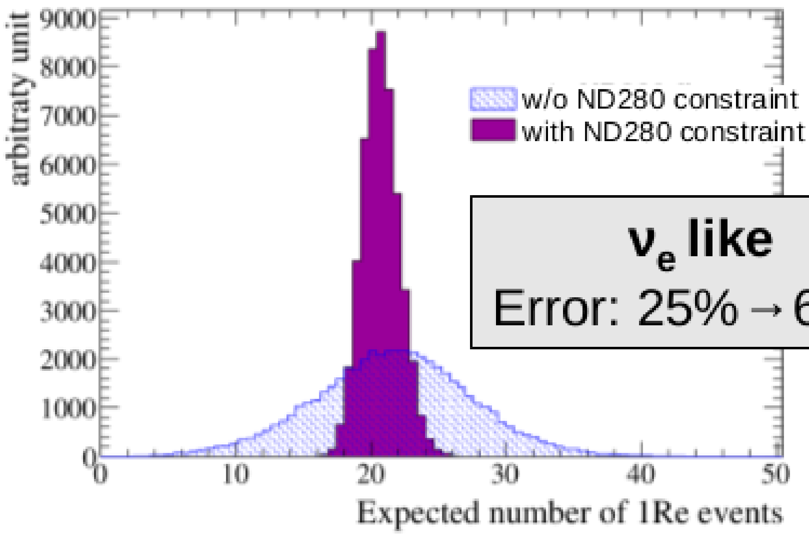
Off-axis near detector analysis

Fit of ν_μ spectrum to constrain flux X cross-section (ν_μ also constrain ν_e via correlation in the production mechanism). 3 subsamples with final state π "CC 0π", "CC 1π" and "CC other"

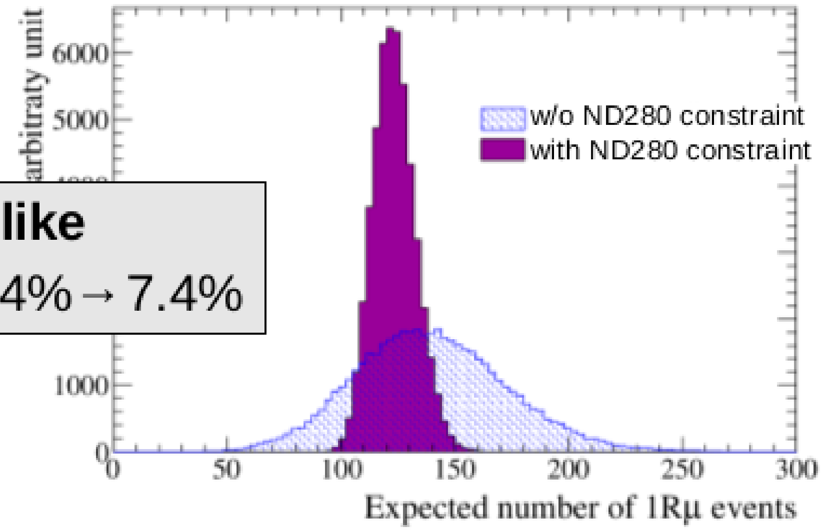




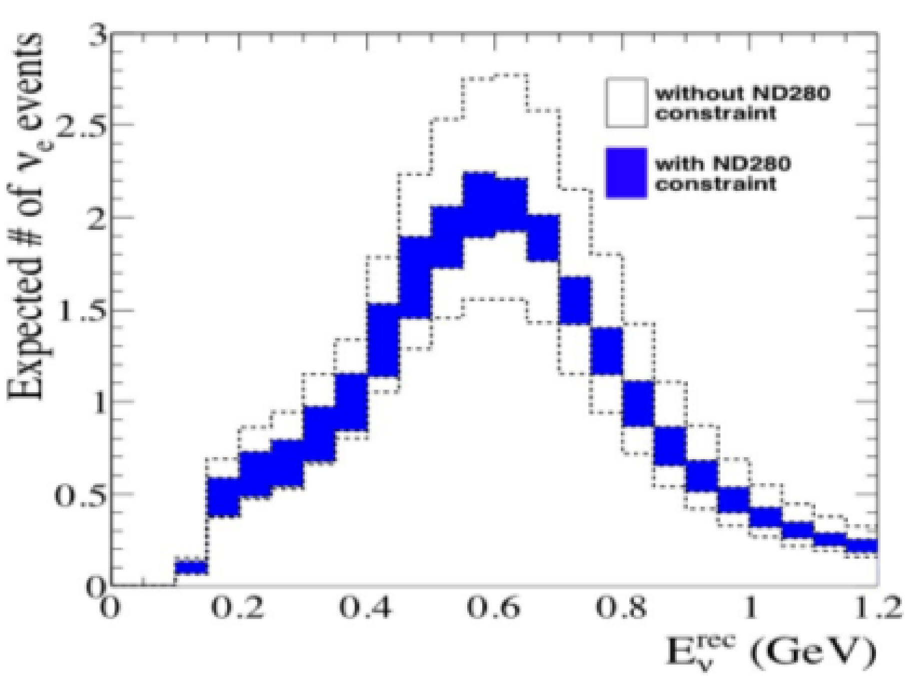
“Impact” of the near detector

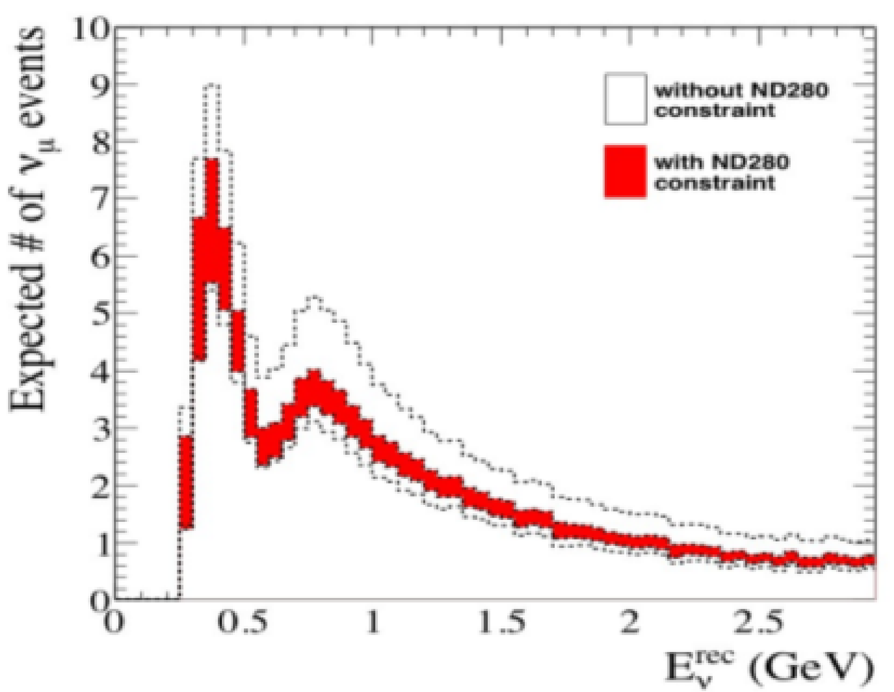


ν_e like
Error: 25% → 6.3%



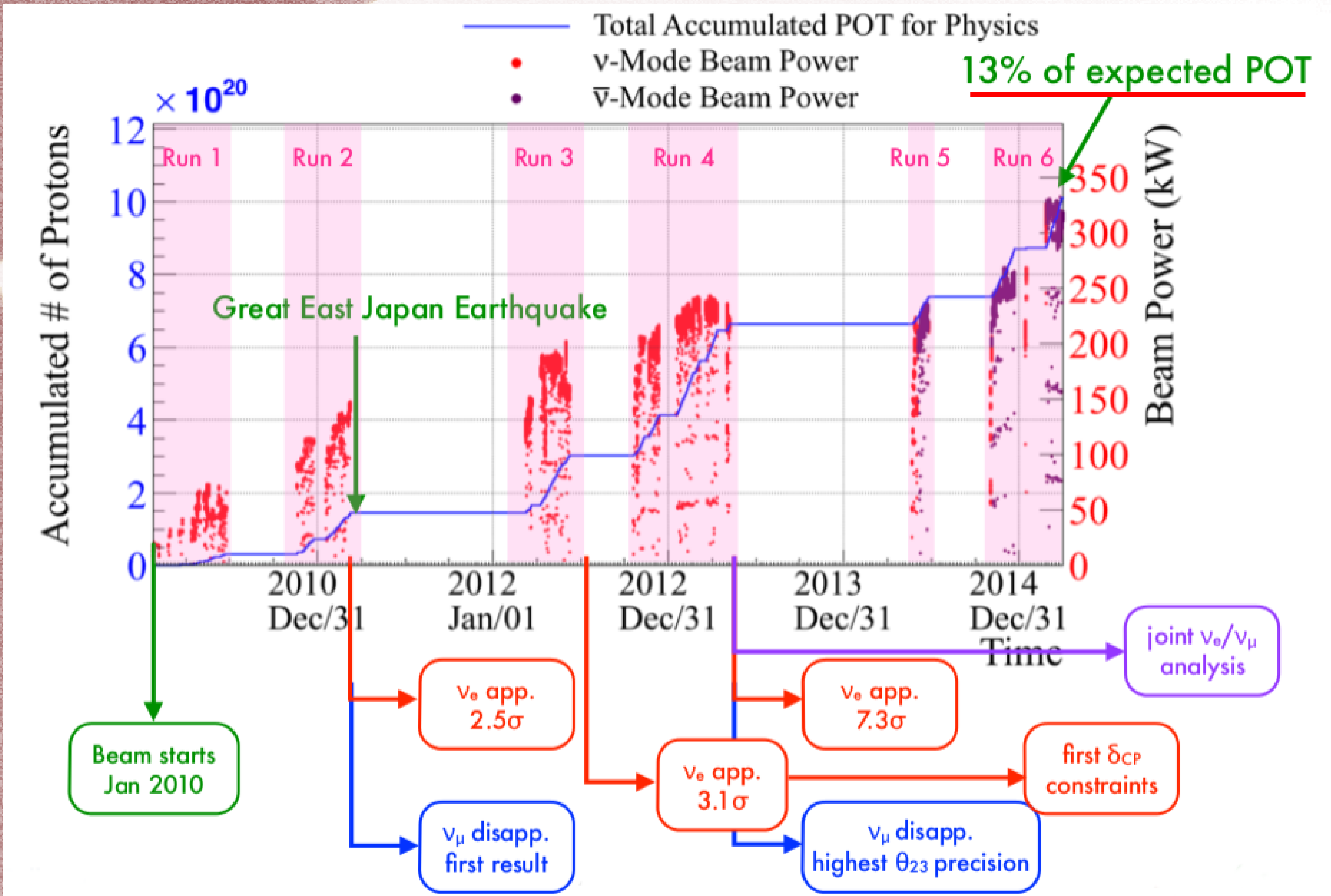
ν_μ like
Error: 23.4% → 7.4%





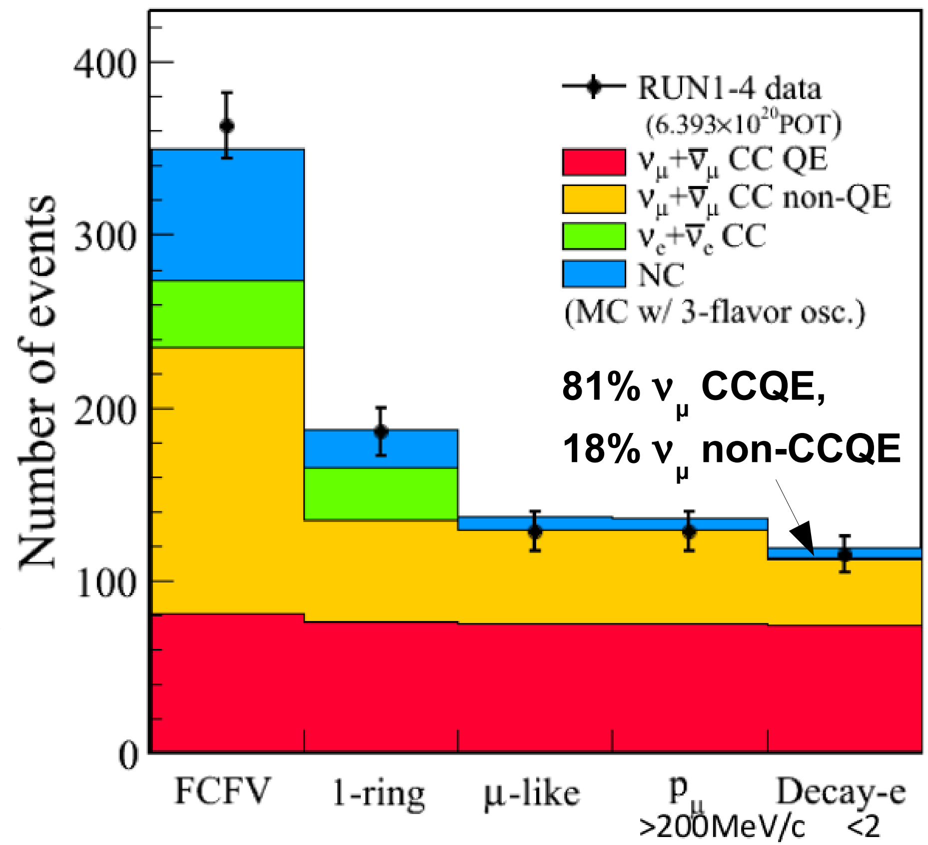
Data sample

> 10^{21} pot (60% nu, 40% anti-nu mode)
365 kW achieved recently!

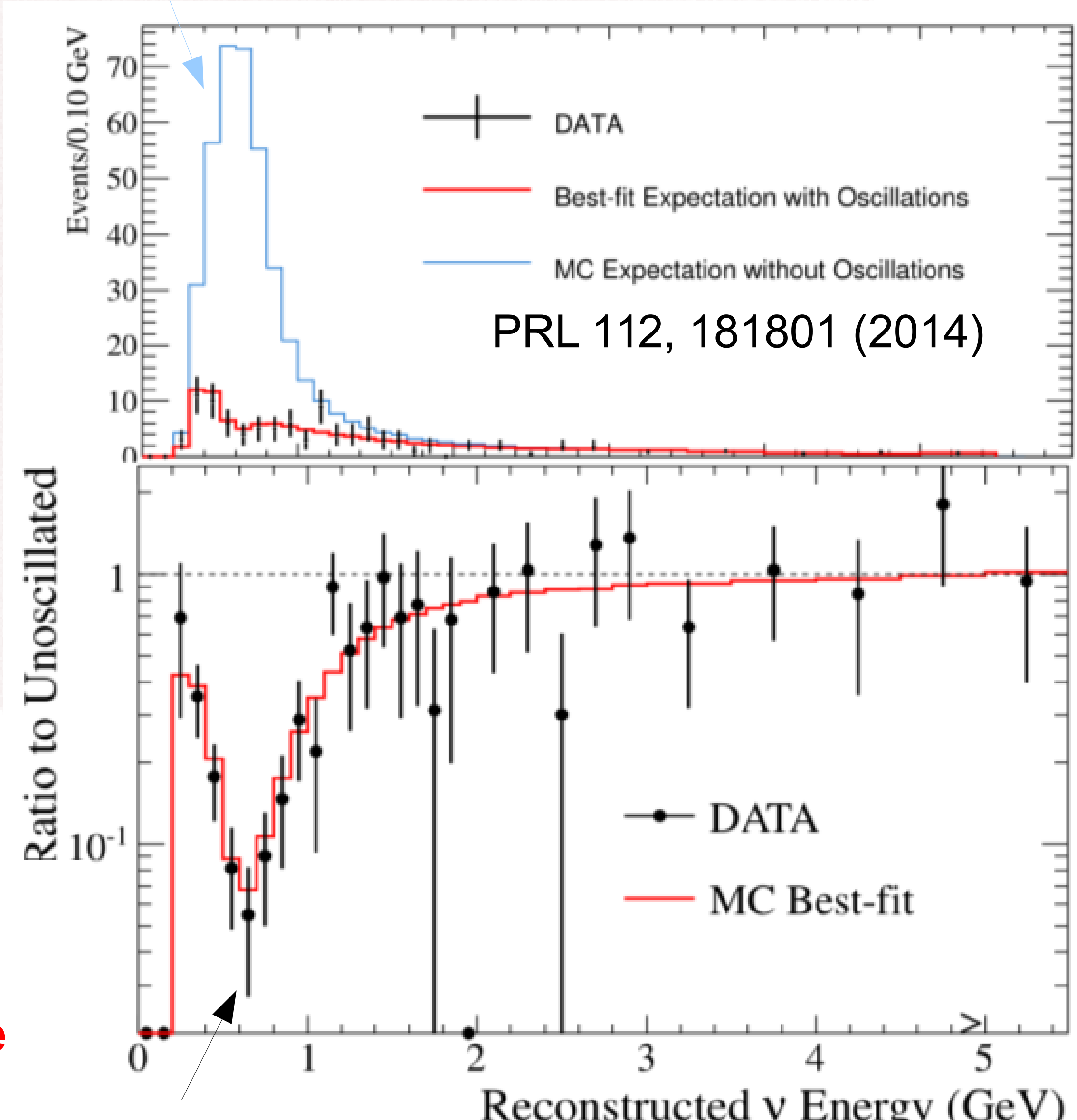


ν_μ disappearance

Data selection
($6.57 \cdot 10^{20}$ POT)



446 ± 23 exp. (no osc.) 120 obs.



First beam designed for a precise determination of Δm_{23}^2 (maximal suppression exactly at peak – not the case f.e. in MINOS)

10% energy resolution
(CC QE formula)

ν_μ disappearance: Δm^2_{23} & $\sin^2 2\theta_{23}$

3ν scheme

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - (\underbrace{\cos^4\theta_{13}\sin^2 2\theta_{23}}_{\text{leading}} + \underbrace{\sin^2 2\theta_{13}\sin^2\theta_{23}}_{\text{sub-leading}})\sin^2\frac{\Delta m^2_{32} L}{4E}$$

θ_{23} dependence
non $\pi/4$ symmetric
(sub-leading term)

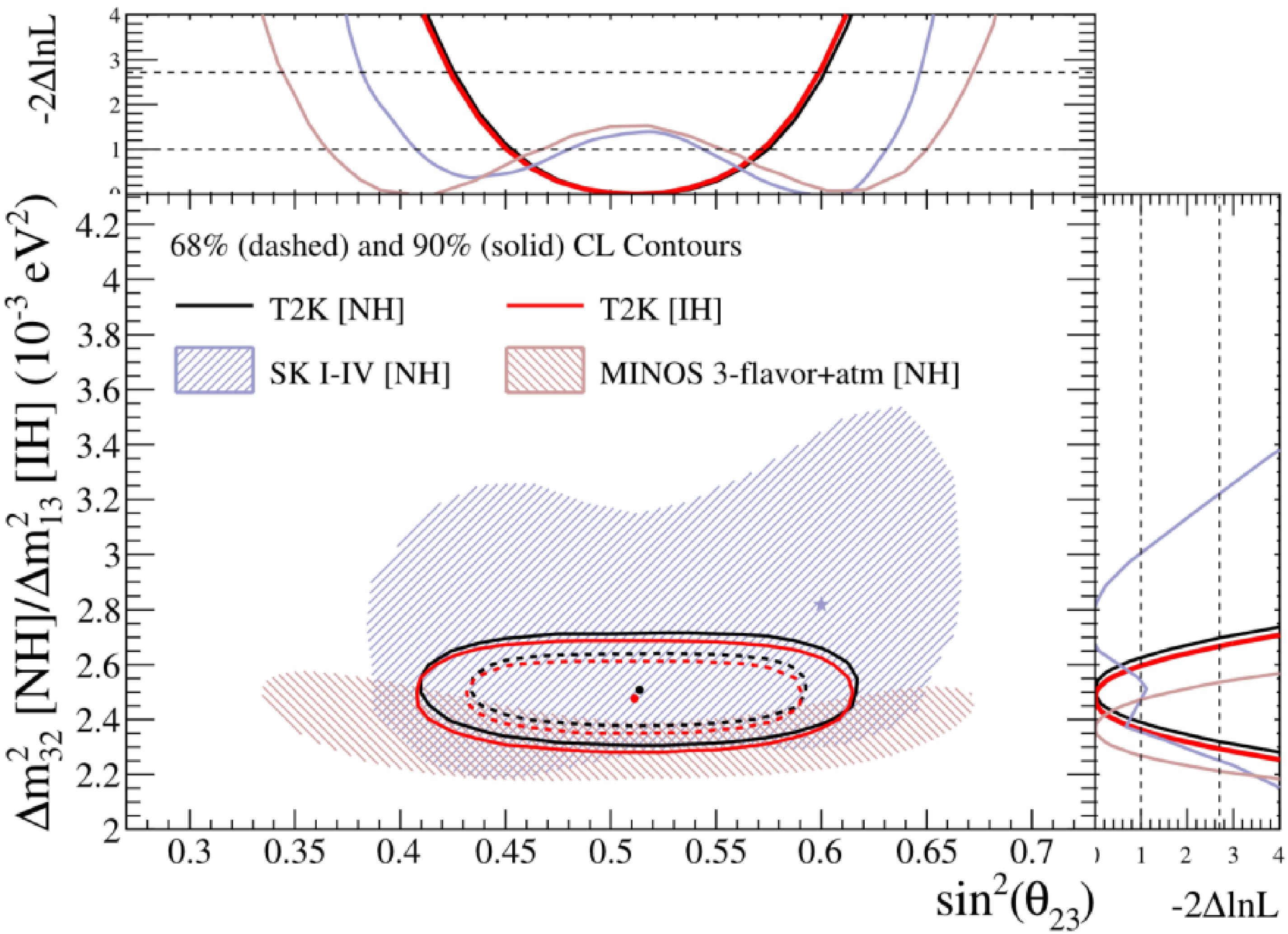
Normal hierarchy (NH)
$\sin^2\theta_{23} = 0.514^{+0.055}_{-0.056}$
$|\Delta m^2_{32}| = (2.51 \pm 0.10)\ 10^{-3}\ eV^2$

Inverted hierarchy (IH)
$\sin^2\theta_{23} = 0.511 \pm 0.055$
$|\Delta m^2_{32}| = (2.48 \pm 0.10)\cdot 10^{-3}\ eV^2$

- θ_{23} : world leading

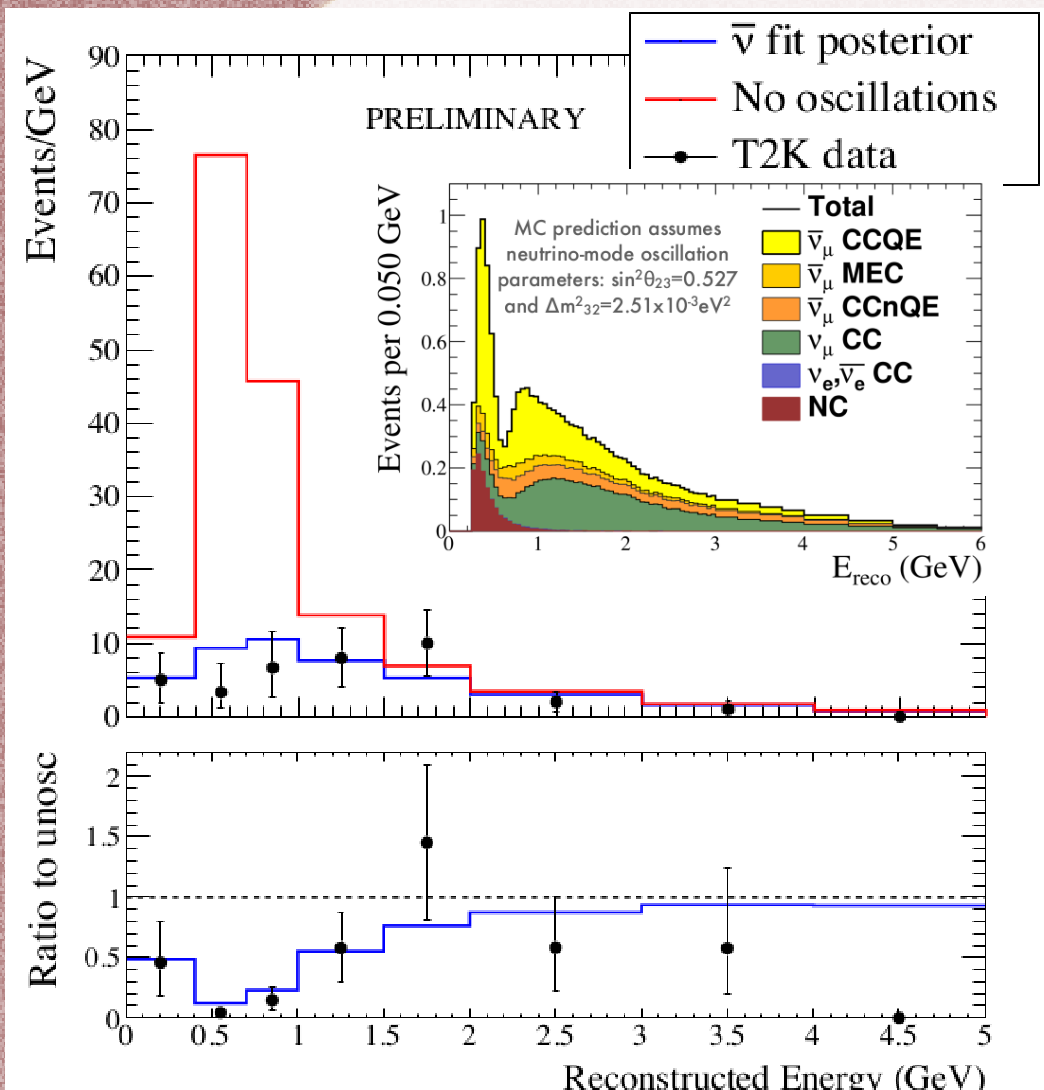
(improved SK atm. ν)

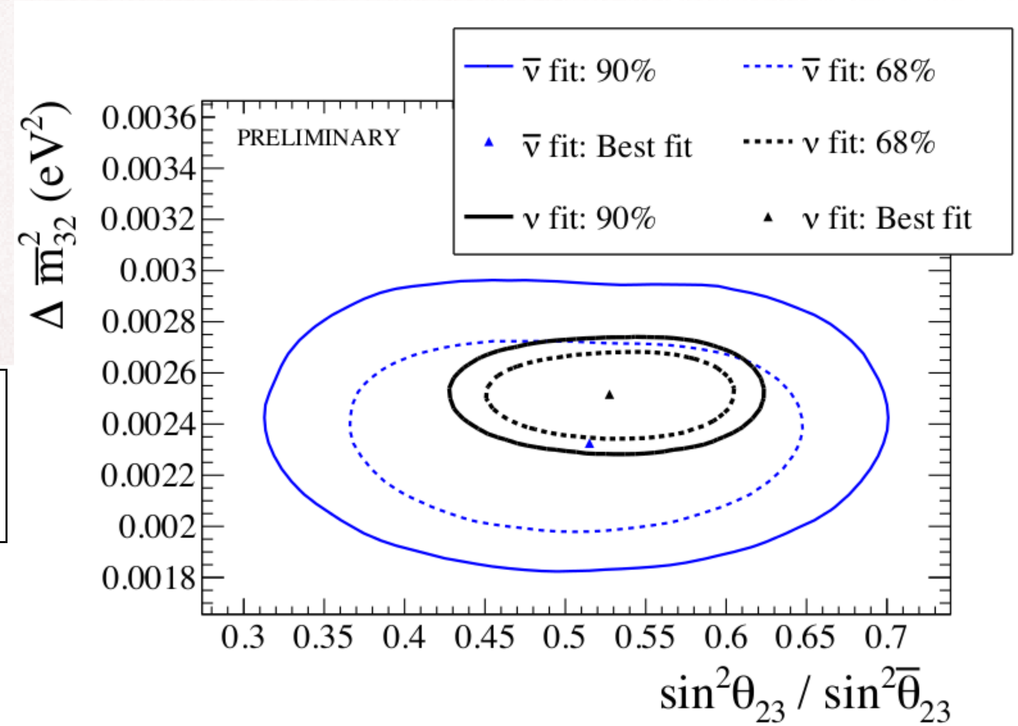
- Δm^2 : close to MINOS

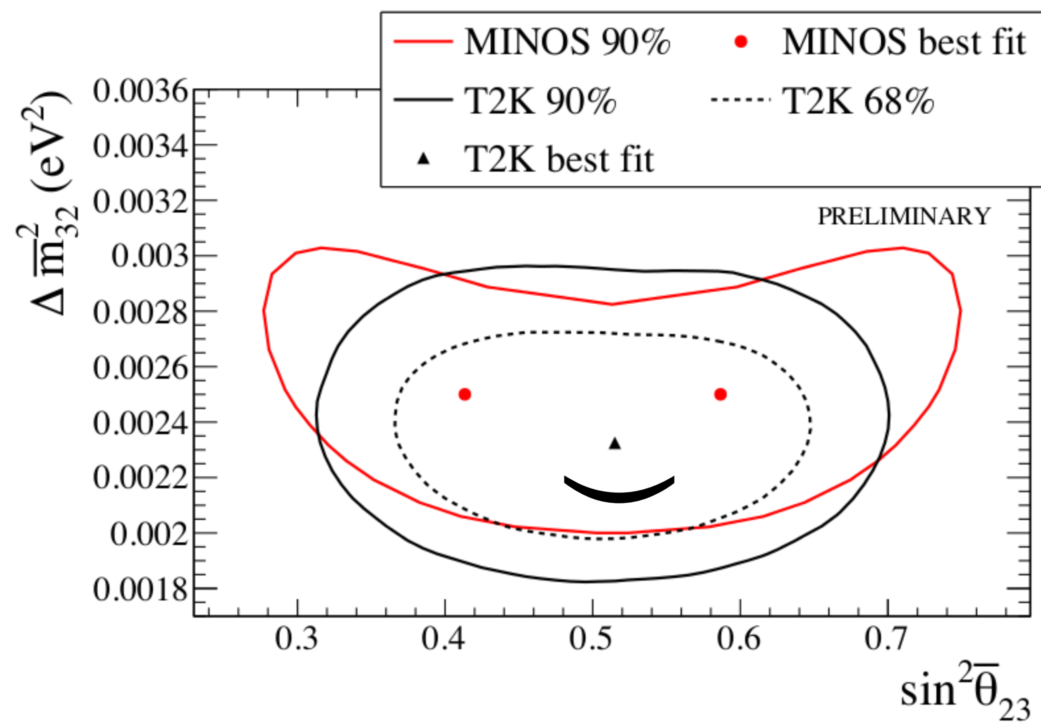


$\bar{\nu}_\mu$ disappearance

Fresh! 18 May 2015
Based on 0.43e20 pot (first anti-nu run of 2014). 4e20 POT additional available.







ν_e appearance

28 ν_e like events

80% purity (60% beam ν_e, 20% Ncπ^0), 66% eff.

Expected $\nu_\mu \rightarrow \nu_e$: (20.4 ± 1.8)

($\sin^2 2\theta_{13} = 0.1$, $\sin^2 2\theta_{23} = 1.0$, $\delta_{CP}=0$, N.I.)

background: (4.64 ± 0.53) 3.2 (beam ν_e), 0.9ν_μ NCπ^0 0.4 ν_e solar term, 0.3 anti-ν

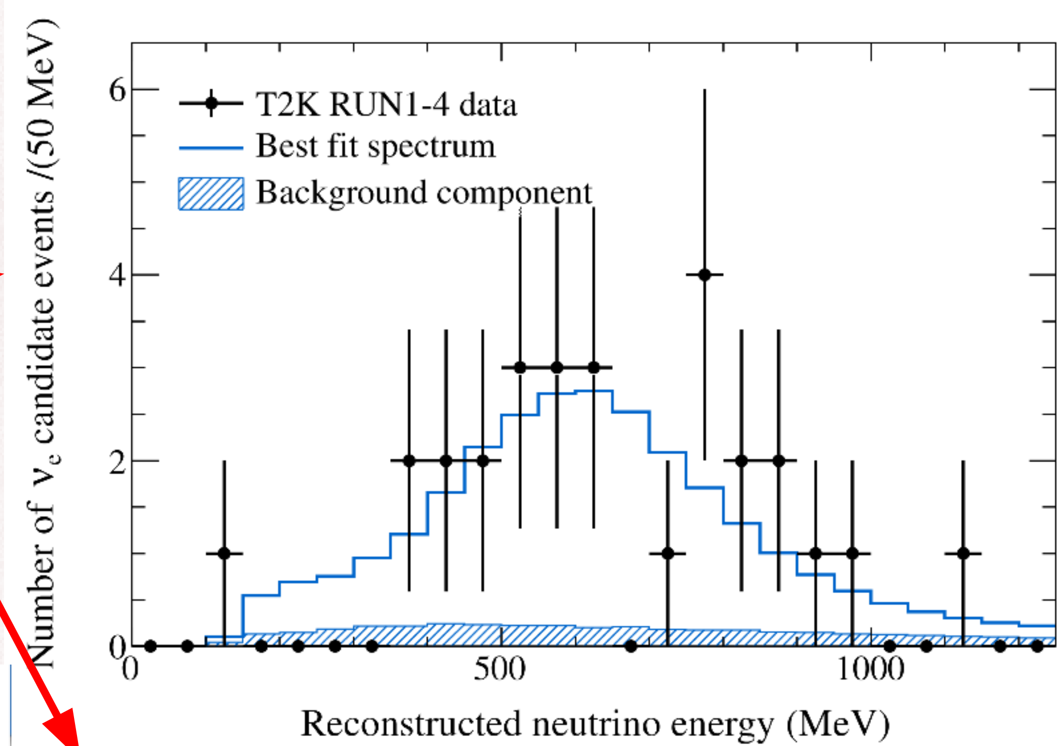
Independent analyses:

1) E(ν_e) spectrum

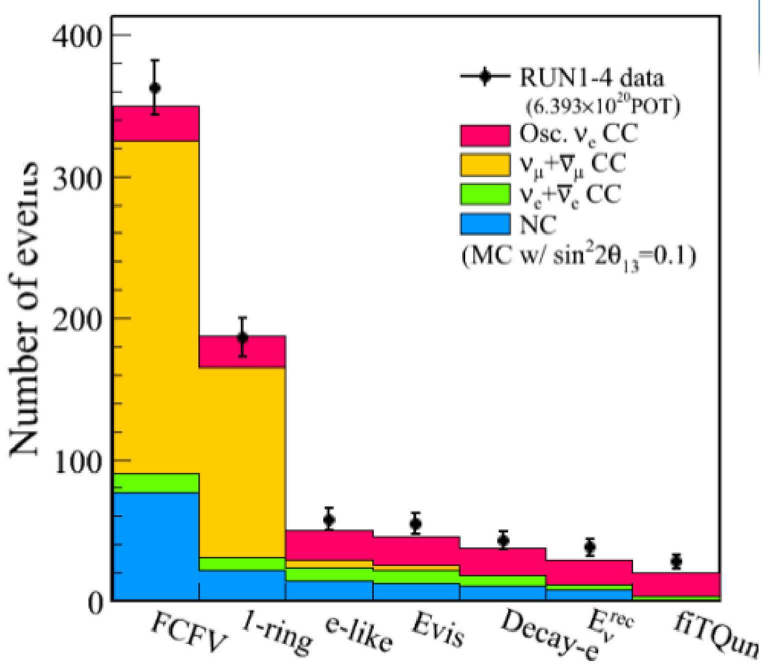
2) θ and p distributions for the e-cand.

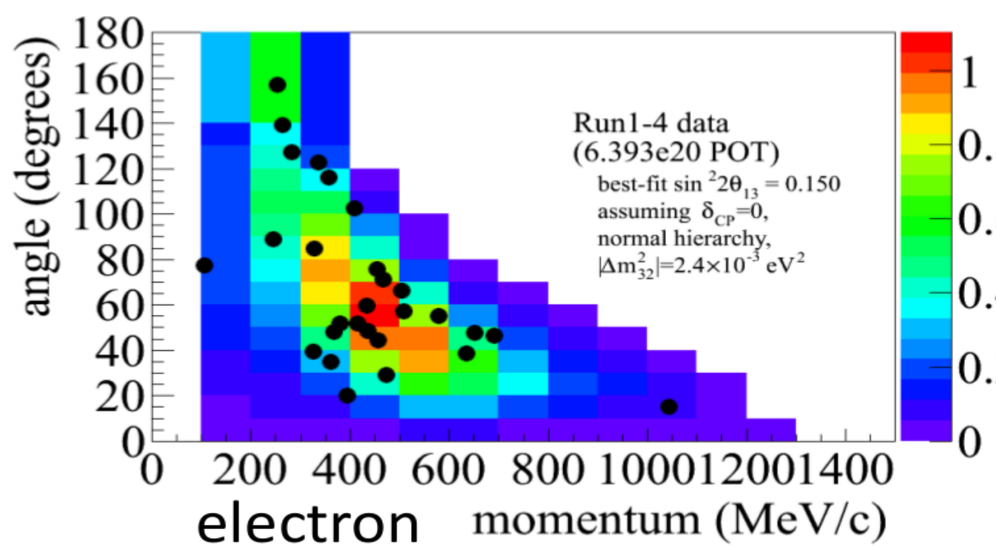
θ_{13}= 0 7.5 σ exclusion (5.5 exp.)

First "appearance" > 5 σ



Data reduction at SK →



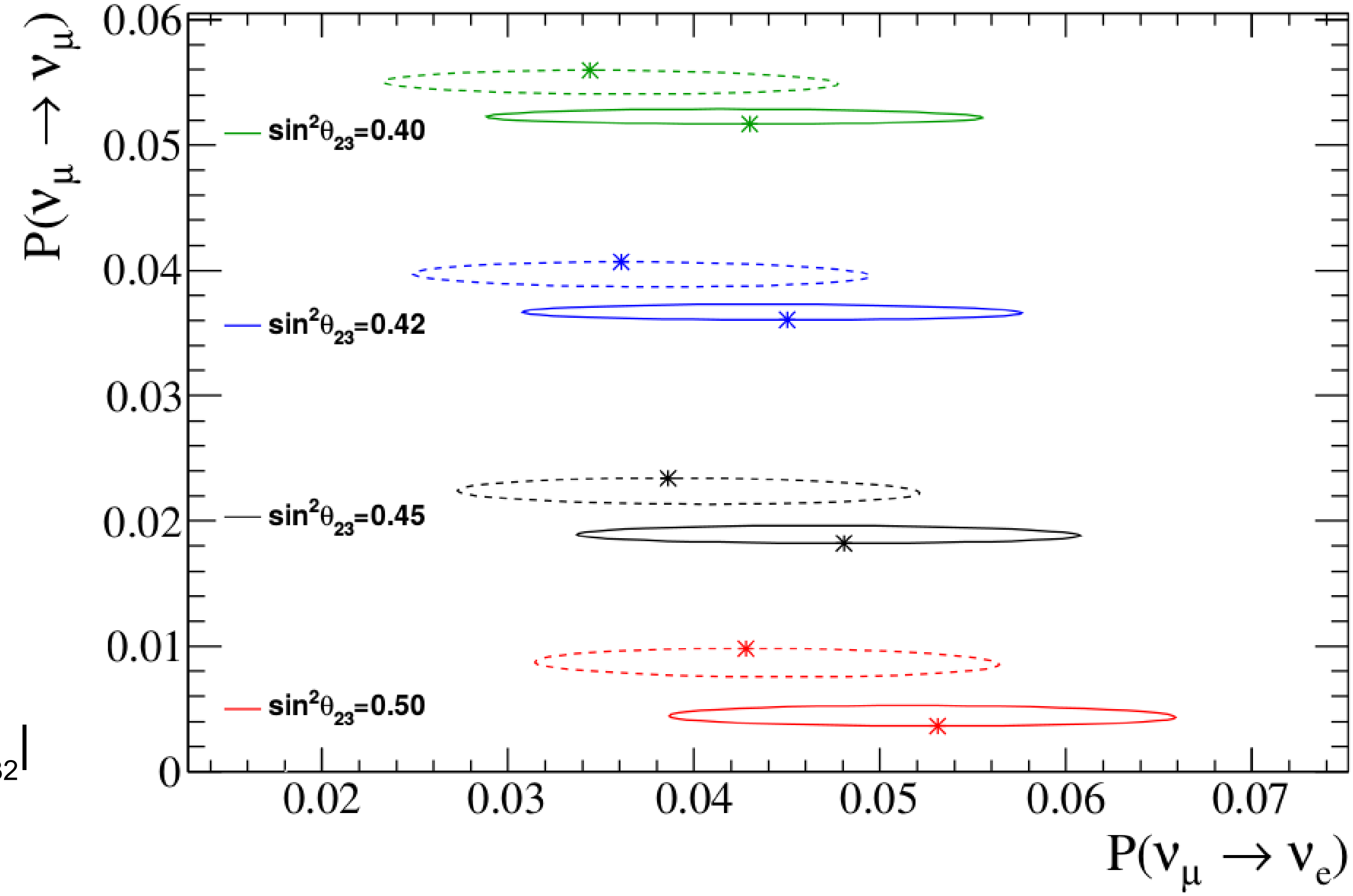


Joint $\nu_\mu + \nu_e$ analysis

Solid: normal hierarchy
Dashed: inverted hierarchy

Rich phenomenology

- δ_{CP} : phase of the ellipses
- δ_{CP} driven by ν_e app.
- θ_{23} by ν_μ disapp.
- Hierarchy-θ_{23}: similar effects



Previously:
- ν_e appearance → θ_{13}, δ
- ν_μ disappearance → θ_{23} , $|\Delta m^2_{32}|$

But observables depend of all 4 parameters
→ joint analysis

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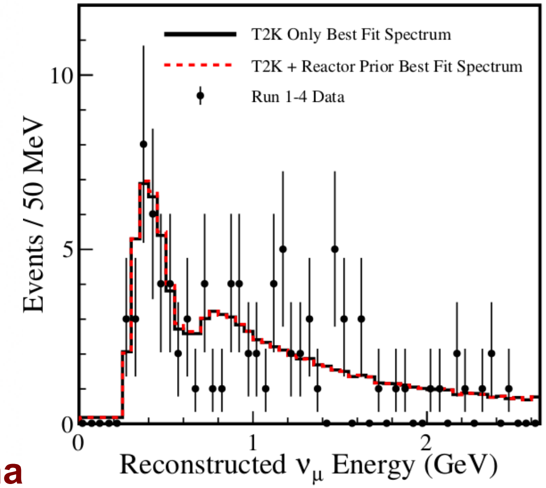
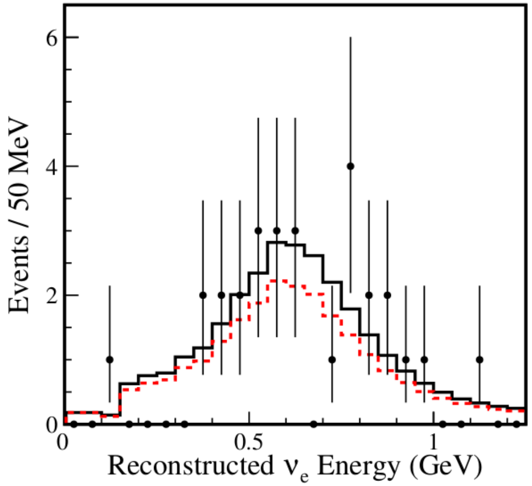
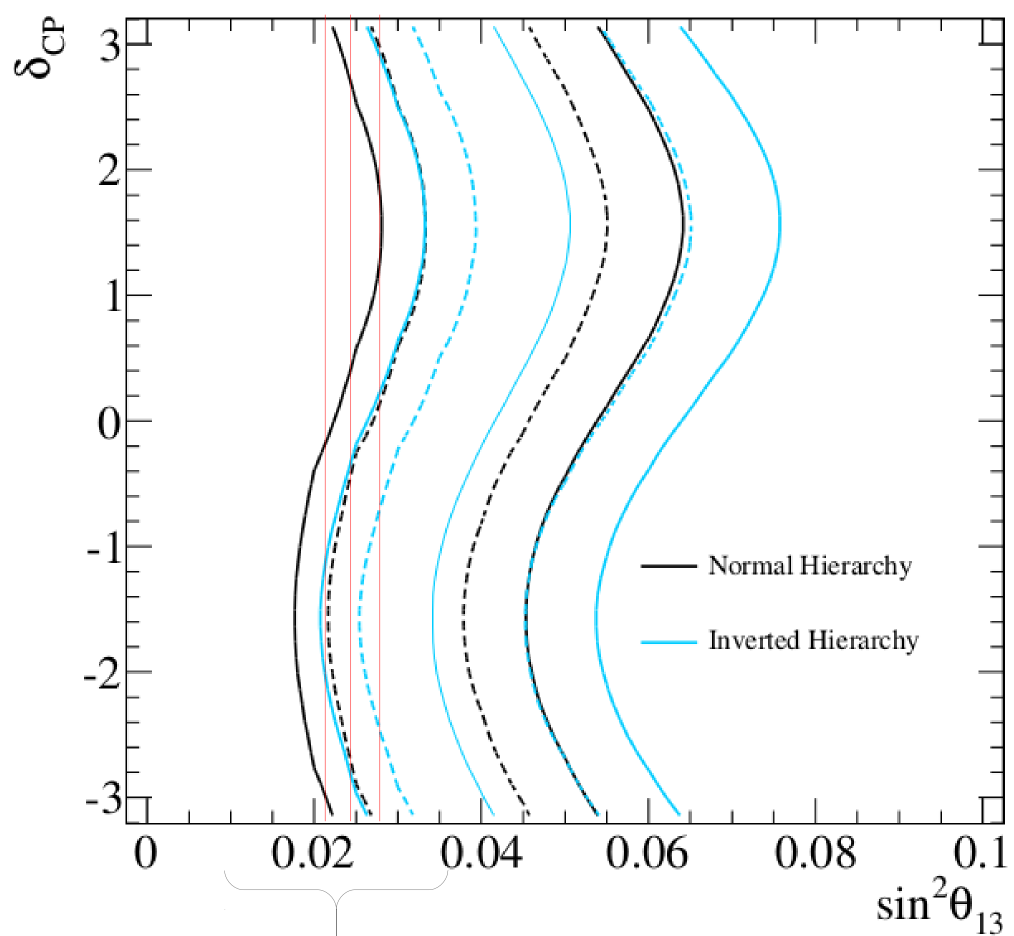




Joint $\nu_\mu + \nu_e$ analysis

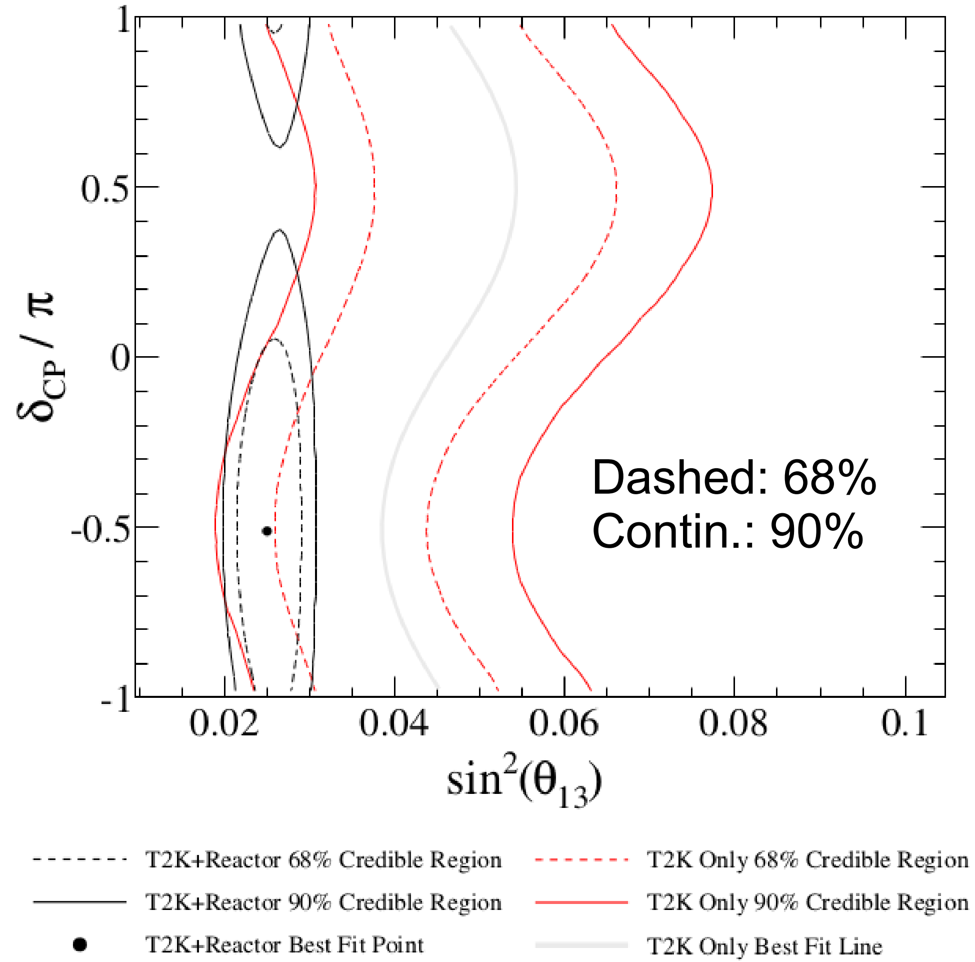
T2K alone

reactors 0.0243 ± 0.0026



combined

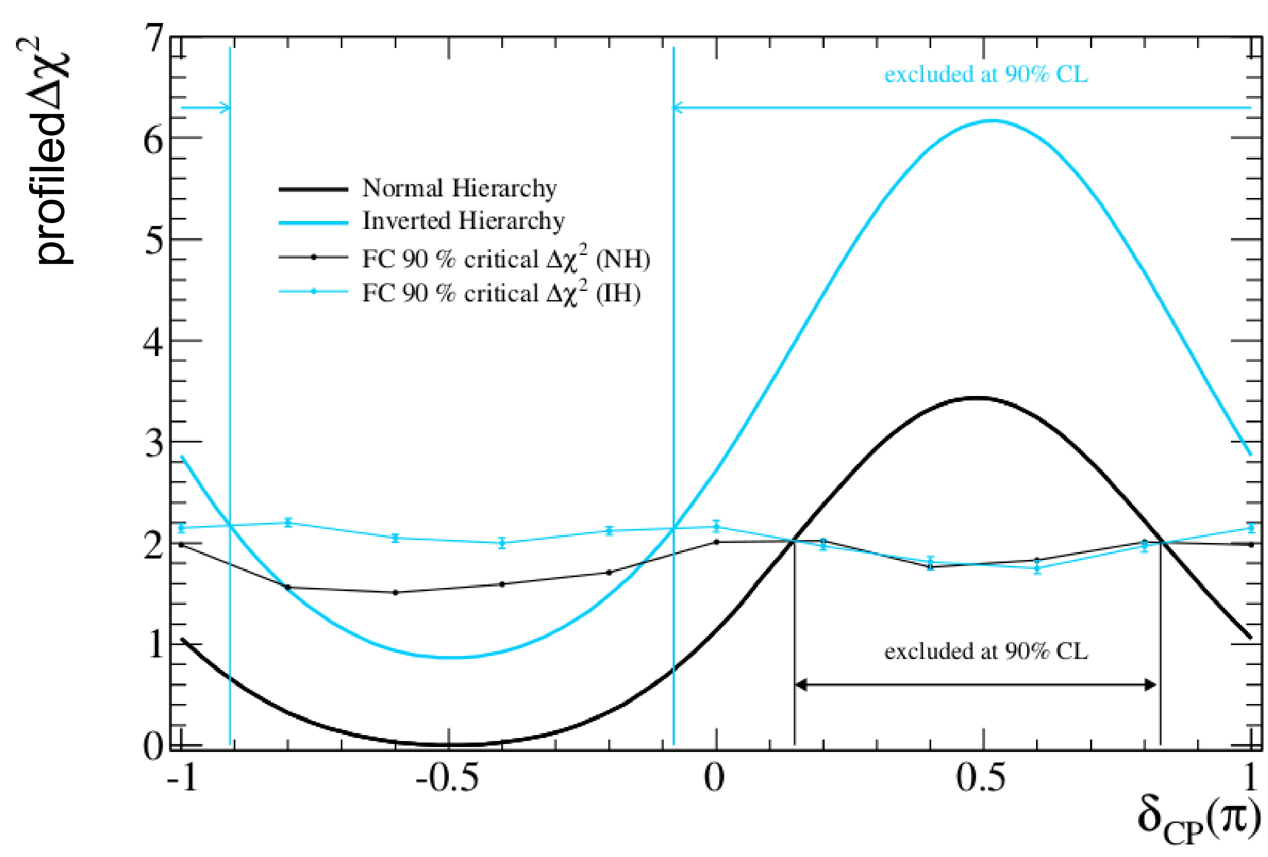
T2K + reactors



Inverted hierarchy decreases ν_e appearance → makes excess of ν_e events more compelling for $\delta_{CP} = -\pi/2$

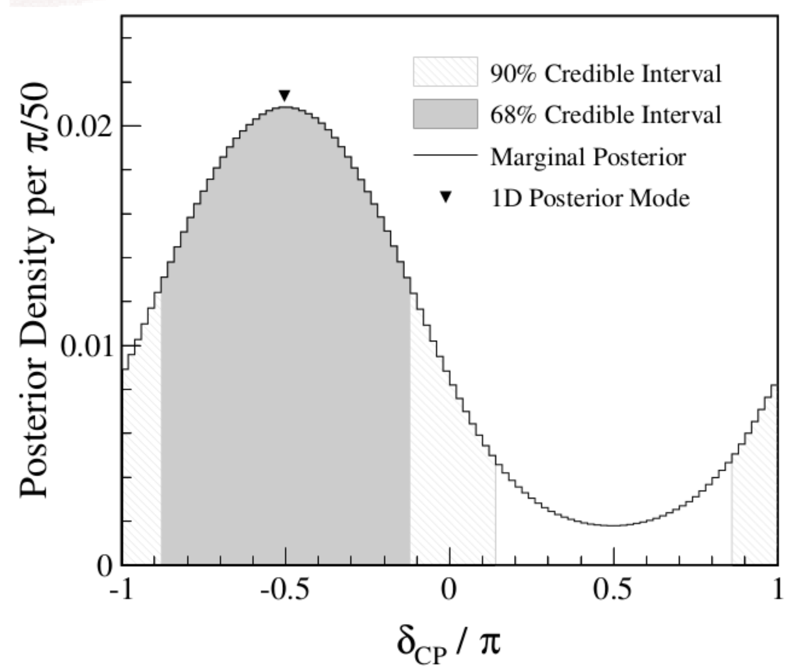
Joint $\nu_\mu + \nu_e$ analysis

At 90% CL T2K excludes
δ_{CP} = [0.15,0.83] π (N.I.)
δ_{CP} = [−0.08,1.09] π (I.H.)



Frequentist

Bayesian



	NH	IH	Sum
$\sin^2\theta_{23} \leq 0.5$	0.165	0.200	0.365
$\sin^2\theta_{23} > 0.5$	0.288	0.347	0.635
Sum	0.453	0.547	1.0

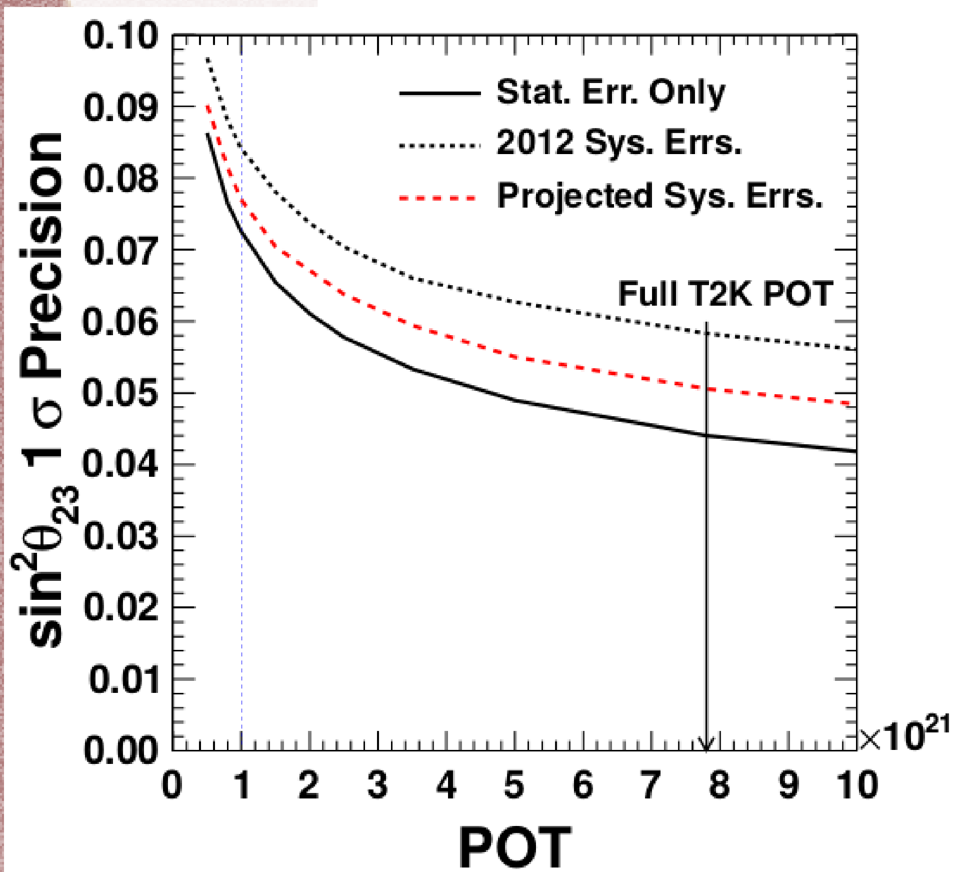
T2K potential: θ_{23} and Δm^2_{32}

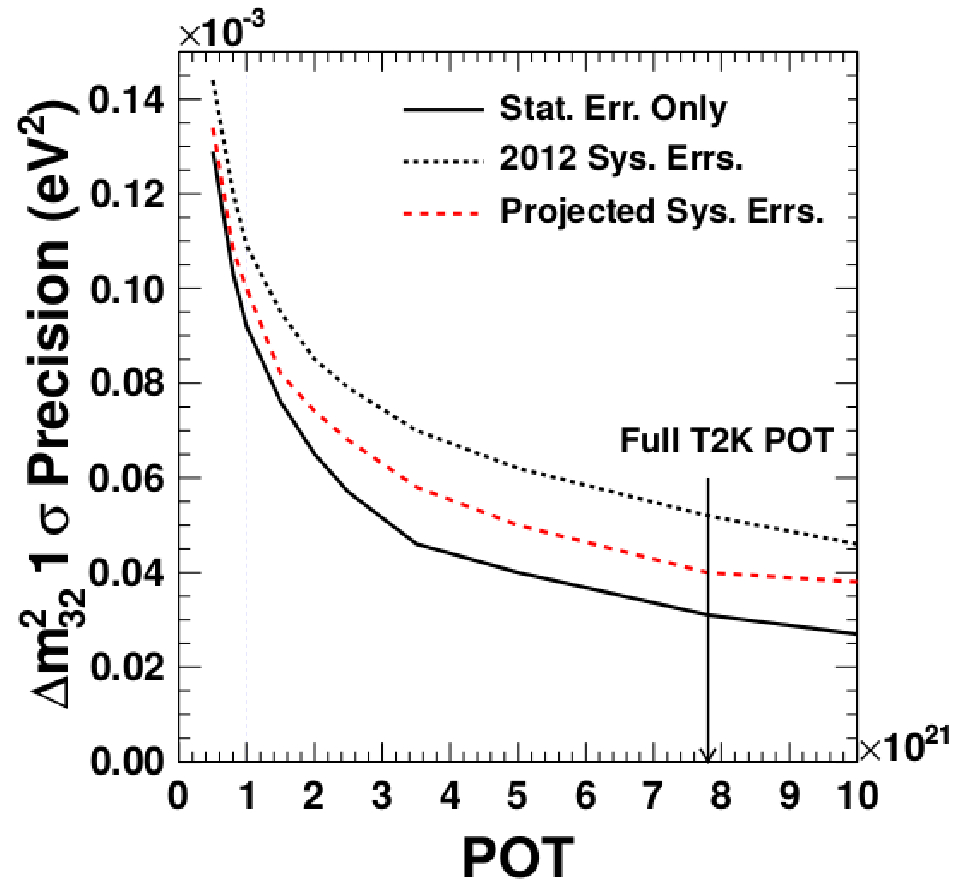
7.8e21 POT+2012 syst. err. + 50-50% ν-anti-ν

390 ν_μ CCQE, 130 anti-ν_μ CCQE

$\sigma(\sin^2\theta_{23})$ = 0.05 (10%)

$\sigma(\Delta m^2_{32})$ = 0.04 x 10^{-3} eV^2 (1.6%)

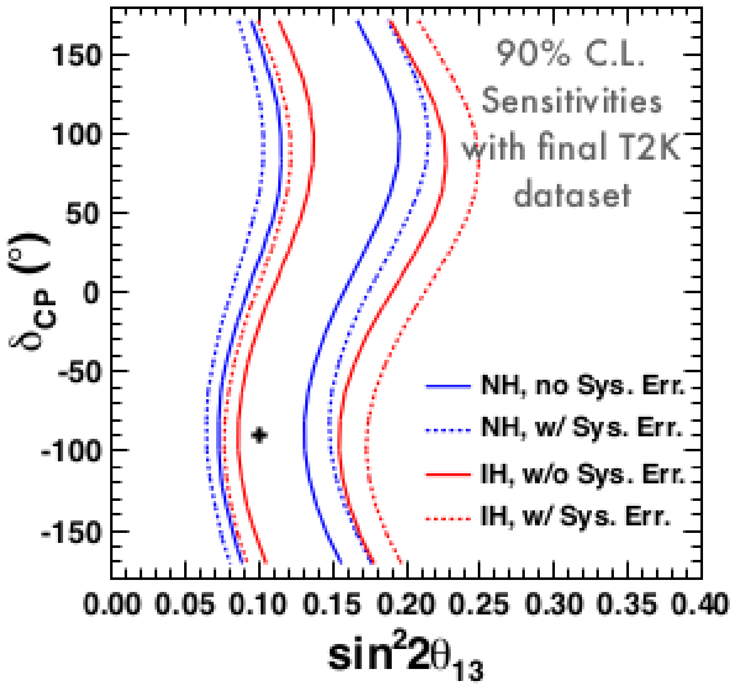




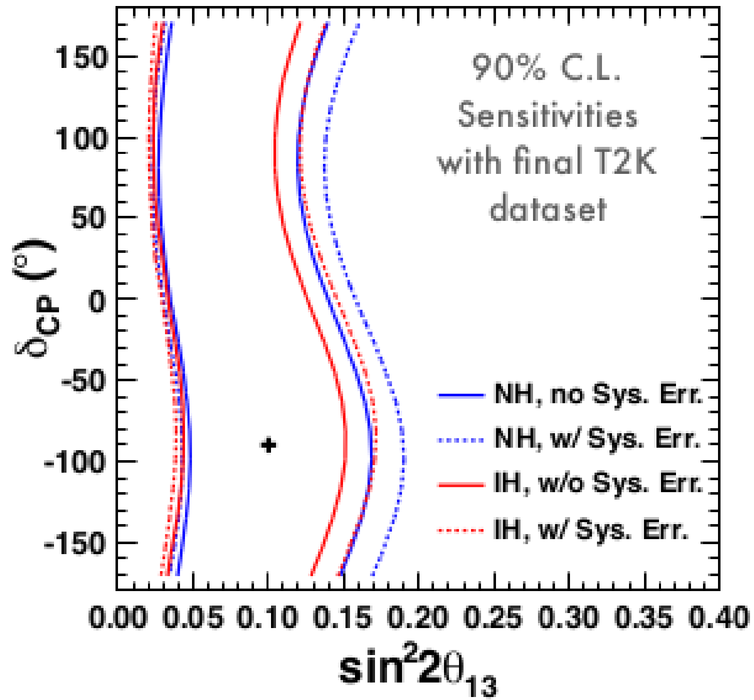
PTEP 2015 (2015) 4, 043C01

Prog. Theor. Exp. Phys. (2015) 043C01

Neutrino mode



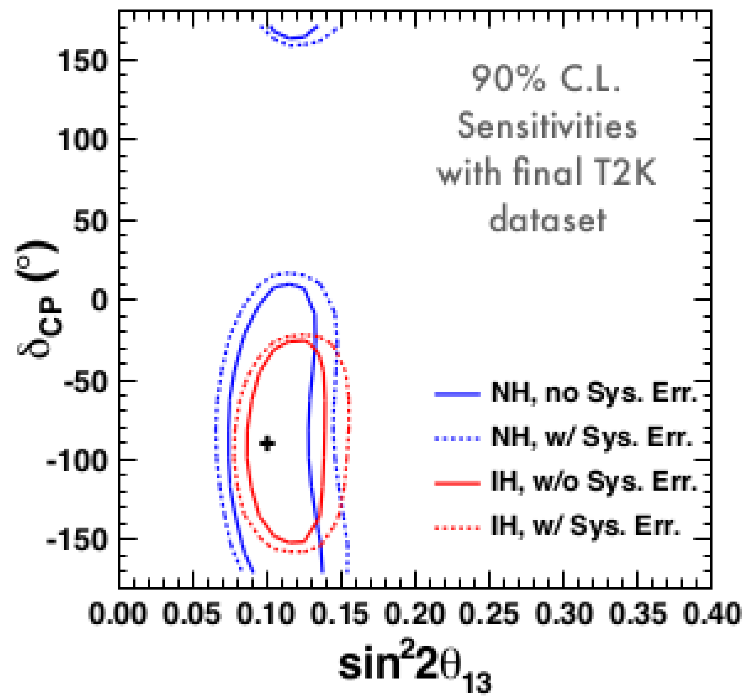
Anti-neutrino mode



T2K potential: δ_{CP}

100 ν_e 25 anti-ν_e

Combination



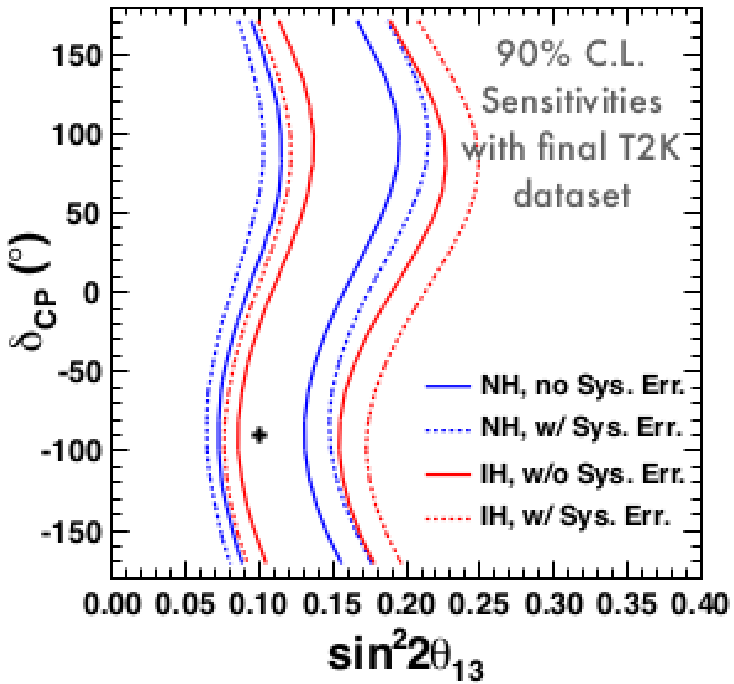
Can potentially measure δ_{CP} with T2K data alone using 50%-50% nu-antinu mode if $\delta_{CP} = -\pi/2$.

PTEP 2015 (2015) 4, 043C01

T2K potential: CPV

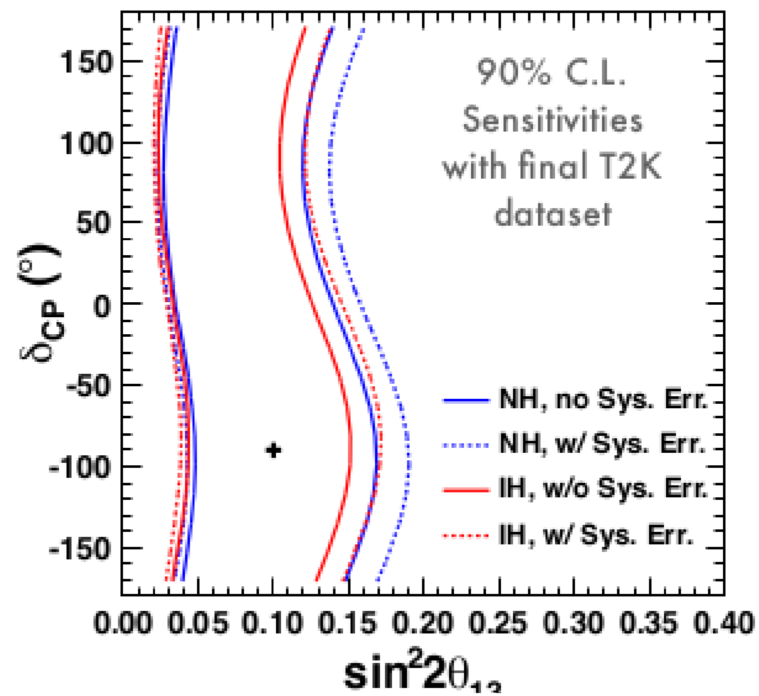
PTEP 2015 (2015) 4, 043C01

Neutrino mode



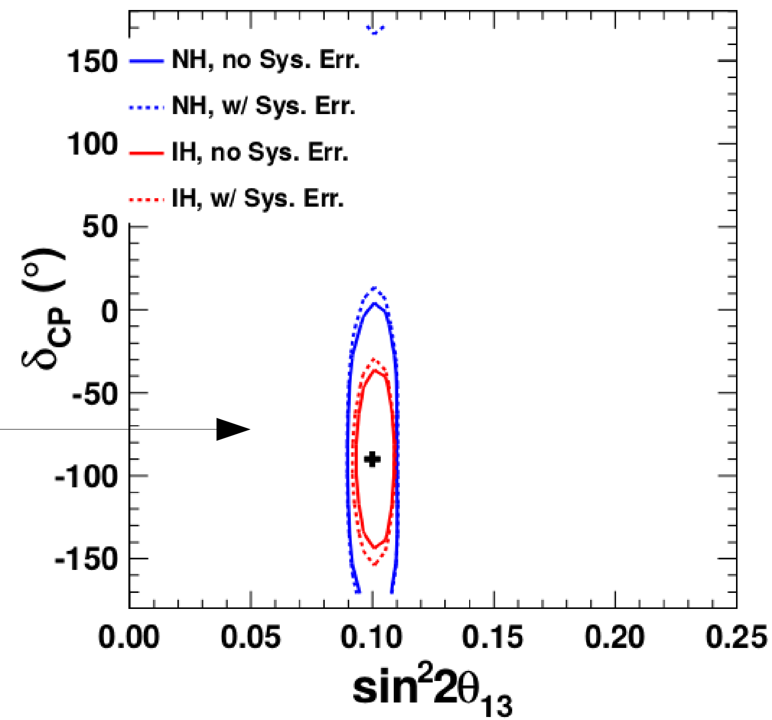
Prog. Theor. Exp. Phys. (2015) 043C01

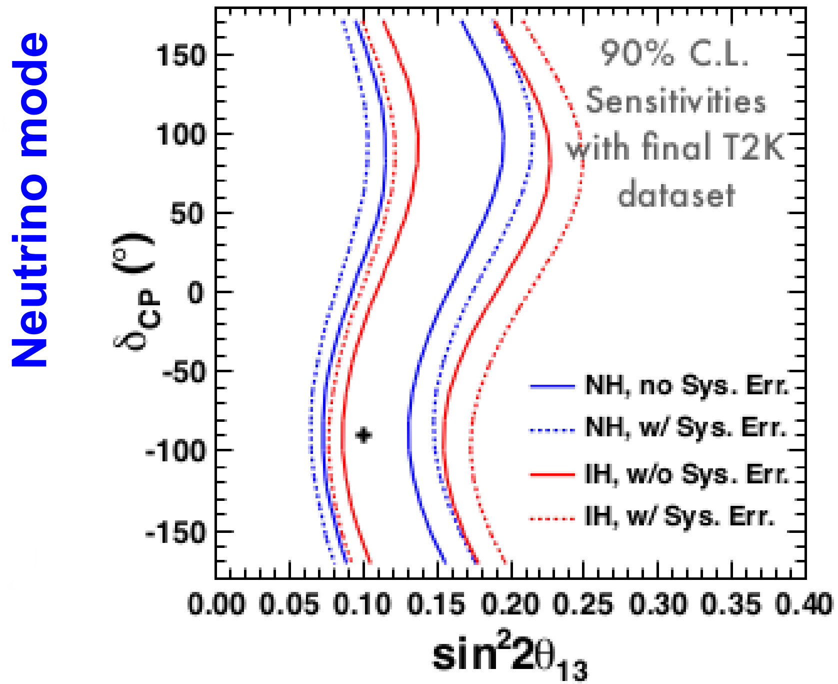
Anti-neutrino mode

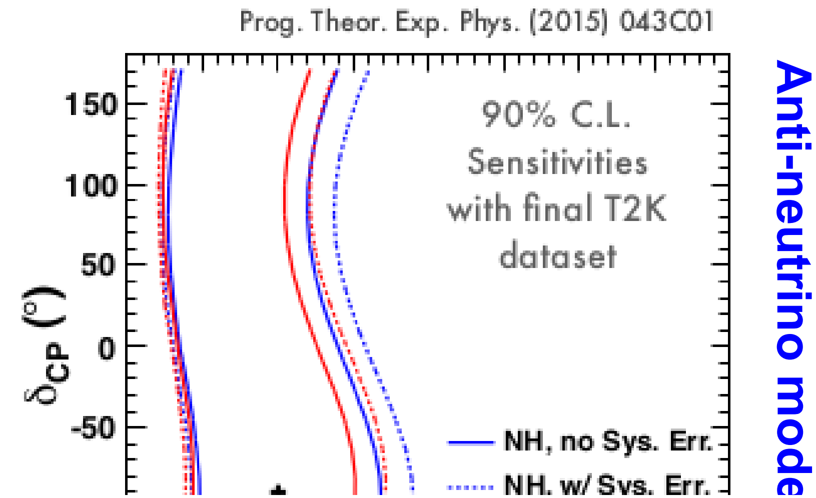


Combining with an ultimate θ_{13} measurement from reactors ($\delta(\sin^2 2\theta_{13})/\sin^2 2\theta_{13}$ = 5% ~ Daya-Bay syst. err.) T2K could exclude sinδ=0 (= no CPV) at > 90 % CL for δ ~ -π/2

Combination + reactors

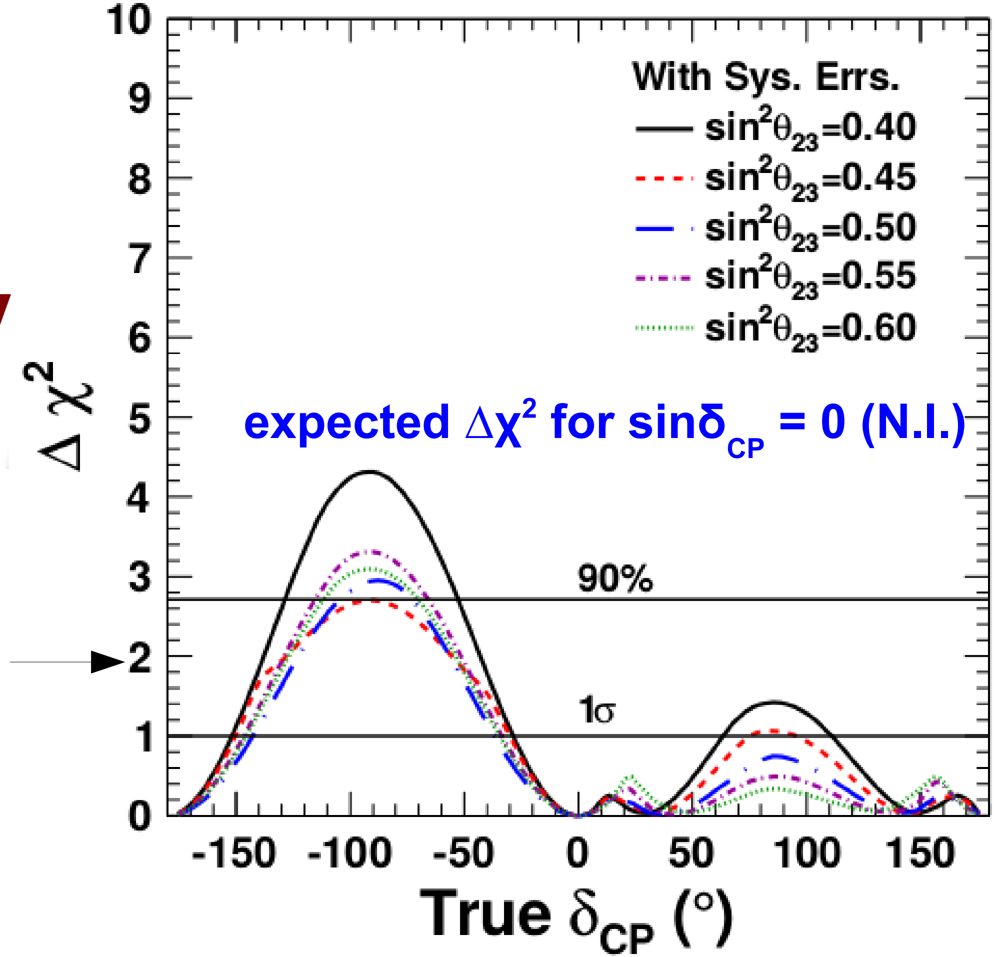






T2K potential: CPV

PTEP 2015 (2015) 4, 043C01



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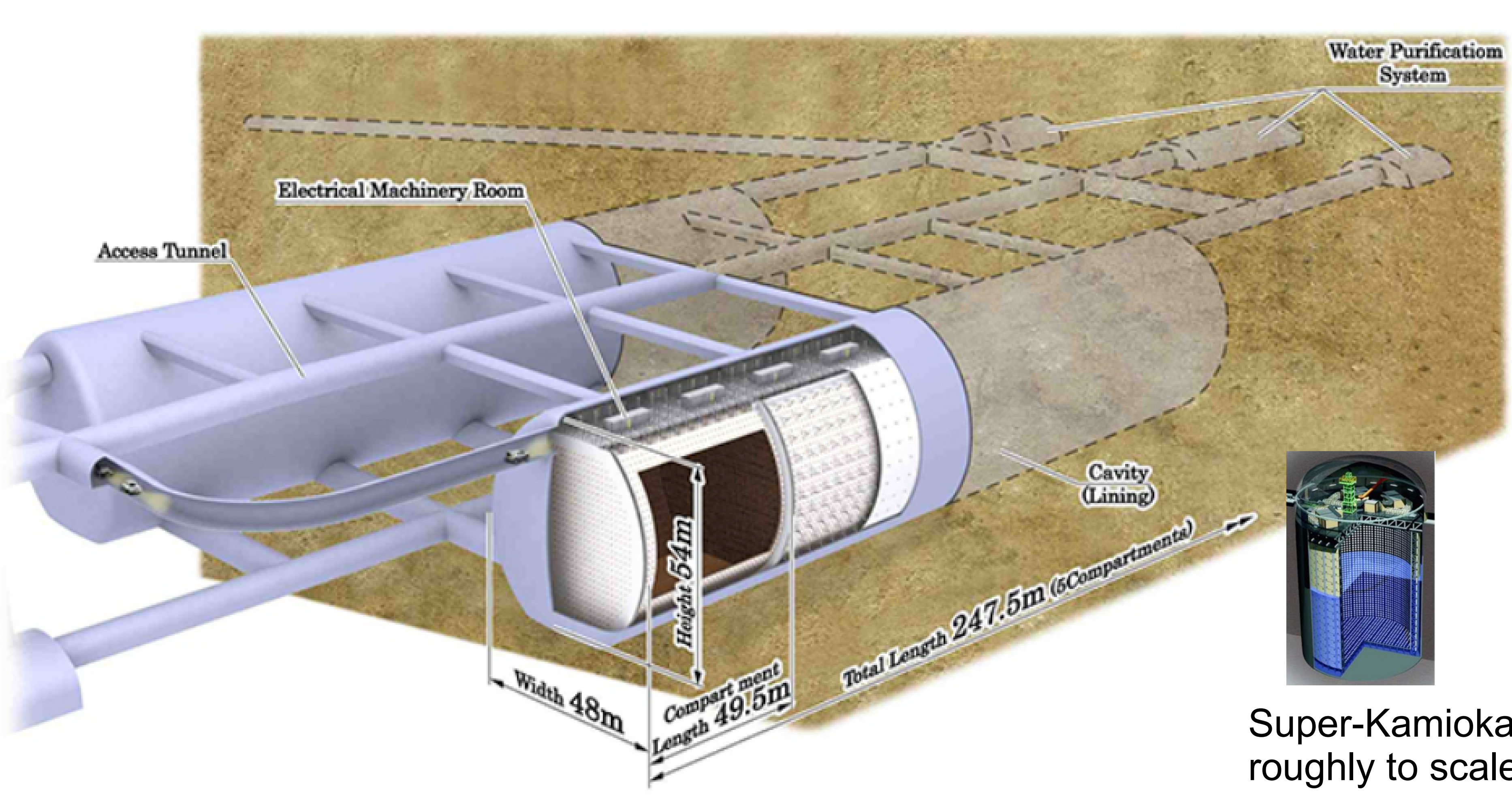
Hyper-Kamiokande



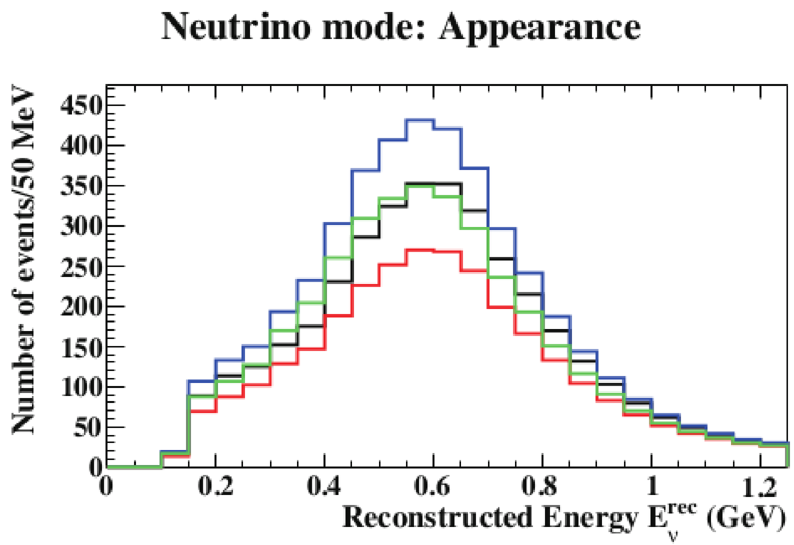
Super-Kamiokande
roughly to scale

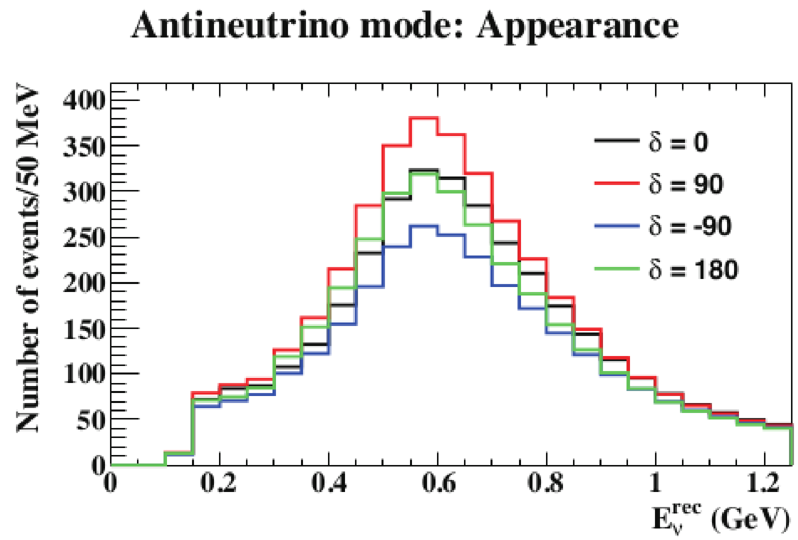
Ring-imaging water Cherenkov detector
Tochibora mine: 648 m rock overburden (1.750 mwe)
2.5 deg. 295 km (as Super-K)

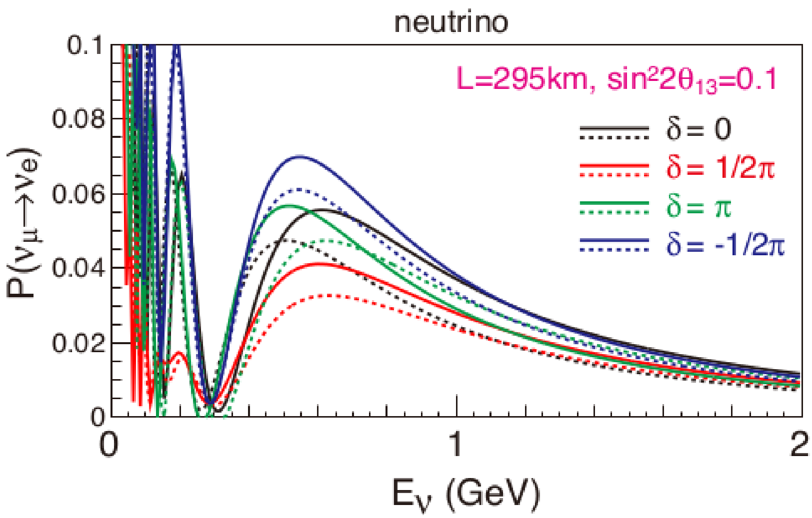
1 Mton mass

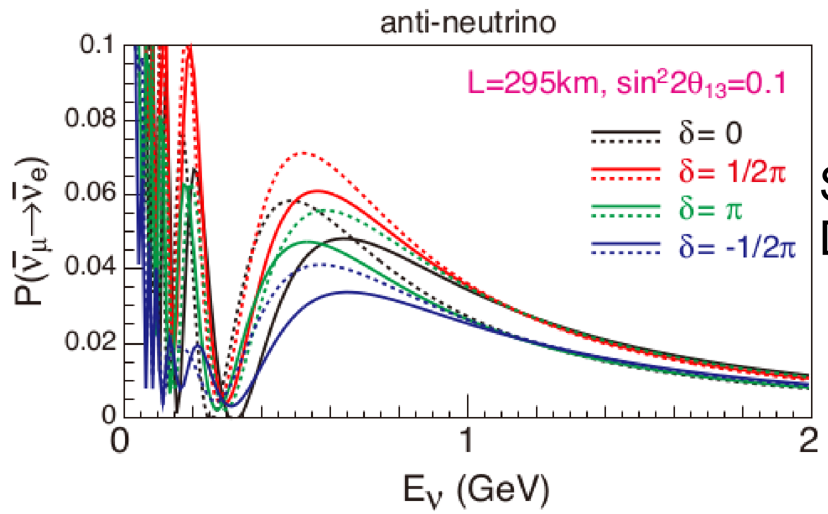
99.000 20” PMTs 20% photo-coverage
25.000 8” PMTs
Light attenuation > 100 m @ 400 nm

Hyper-K: ν_e samples & δ_{CP}







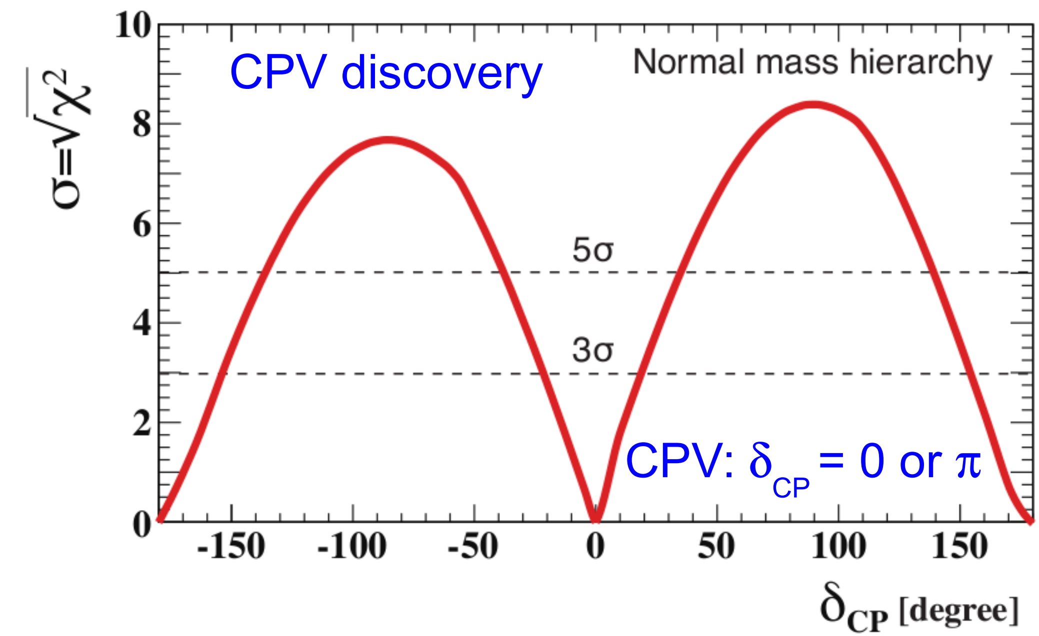


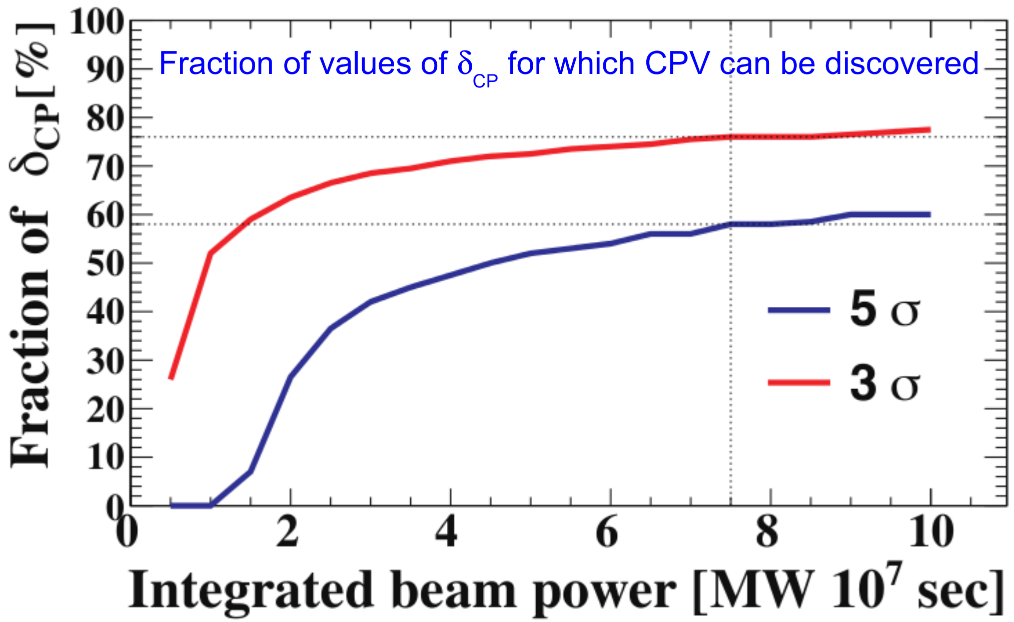
Solid = norm. hier.
Dashed = inv. hier.

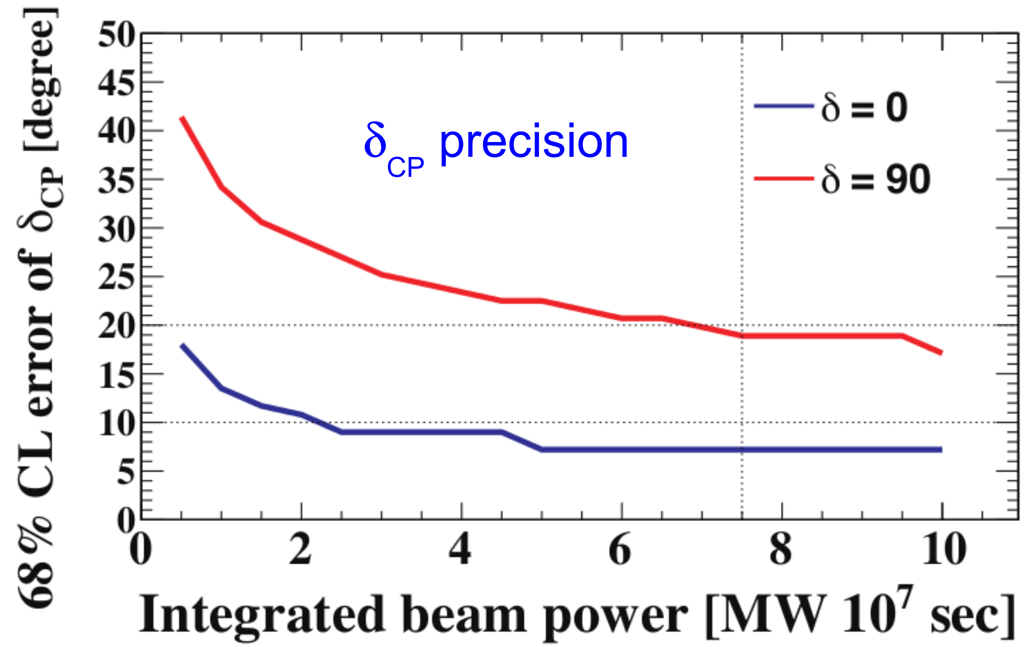
	signal		BG						Total
	$\nu_\mu \to \nu_e$	$\bar{\nu}_\mu \to \bar{\nu}_e$	ν_μ CC	$\bar{\nu}_\mu$ CC	ν_e CC	$\bar{\nu}_e$ CC	NC	BG Total	
ν mode	3016	28	11	0	503	20	172	706	3750
$\bar{\nu}$ mode	396	2110	4	5	222	396	265	891	3397

Hyper-K: CPV reach and δ_{CP} precision

Well known detector technology + analysis. Robust/realistic estimation of systematic uncertainties

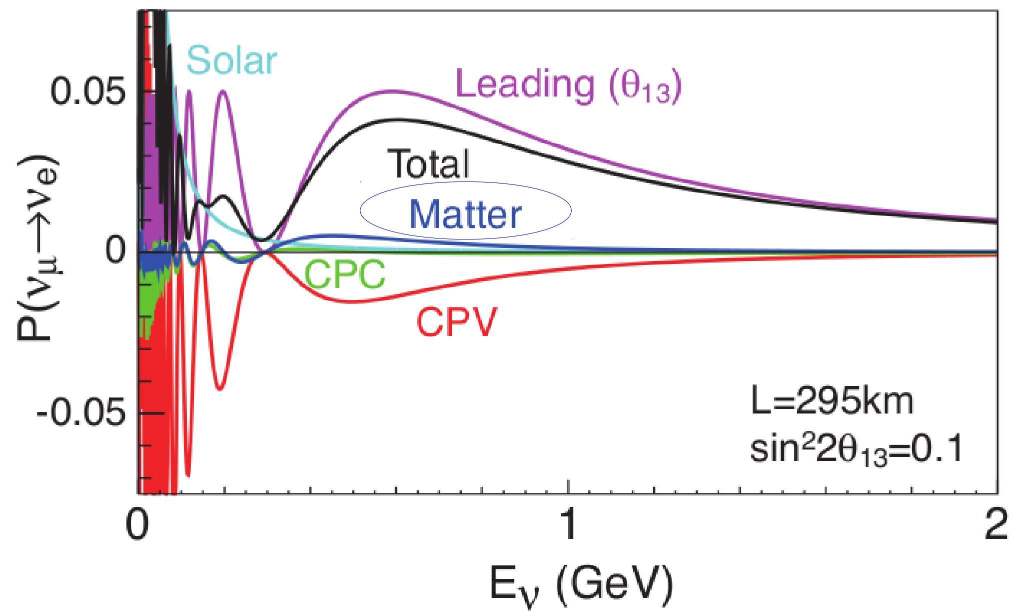


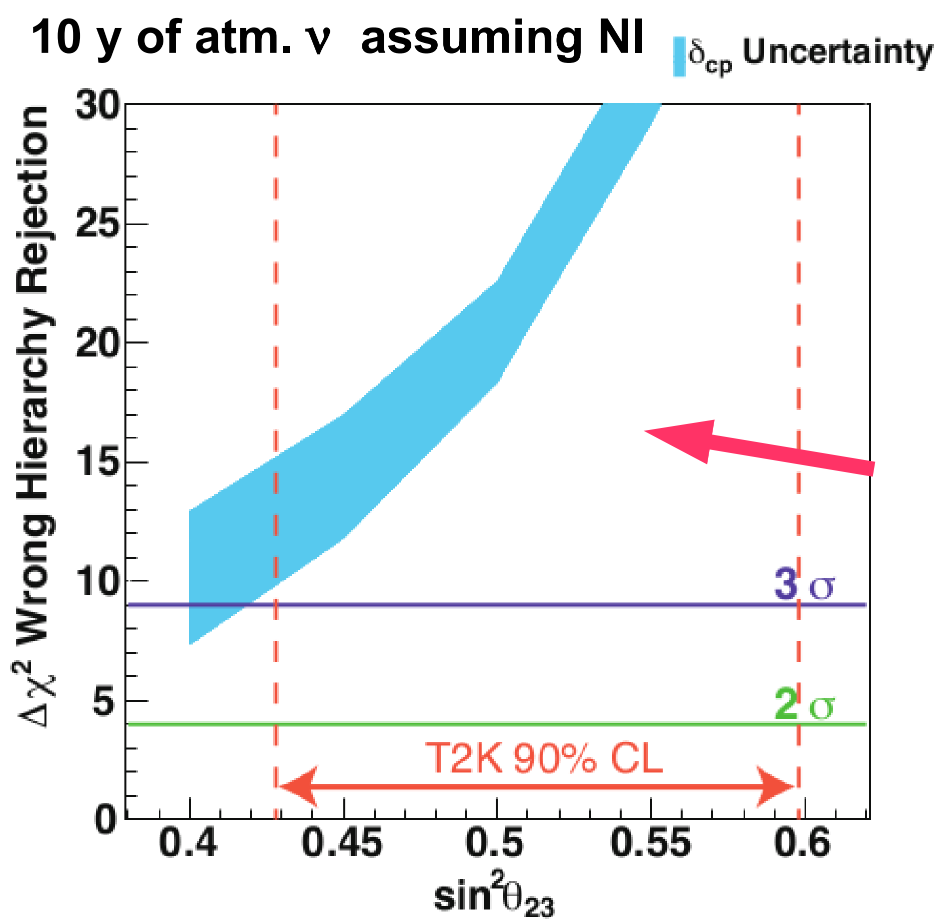




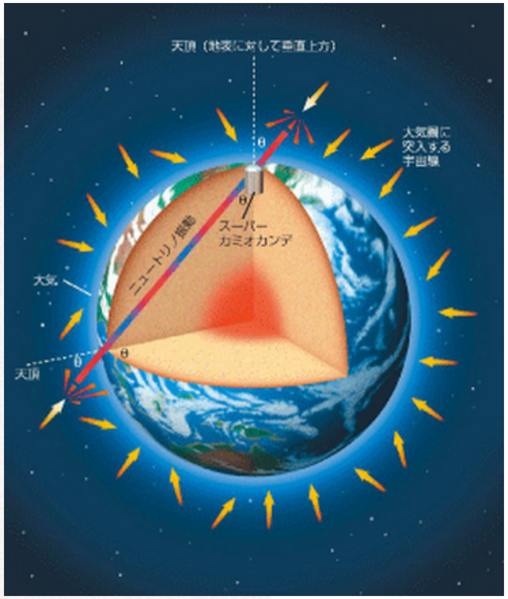
Hyper-K atmospheric data

295 km → small matter effects
→ limited contribution from
CPV induced by matter effects
→ clean measurement of
genuine CPV

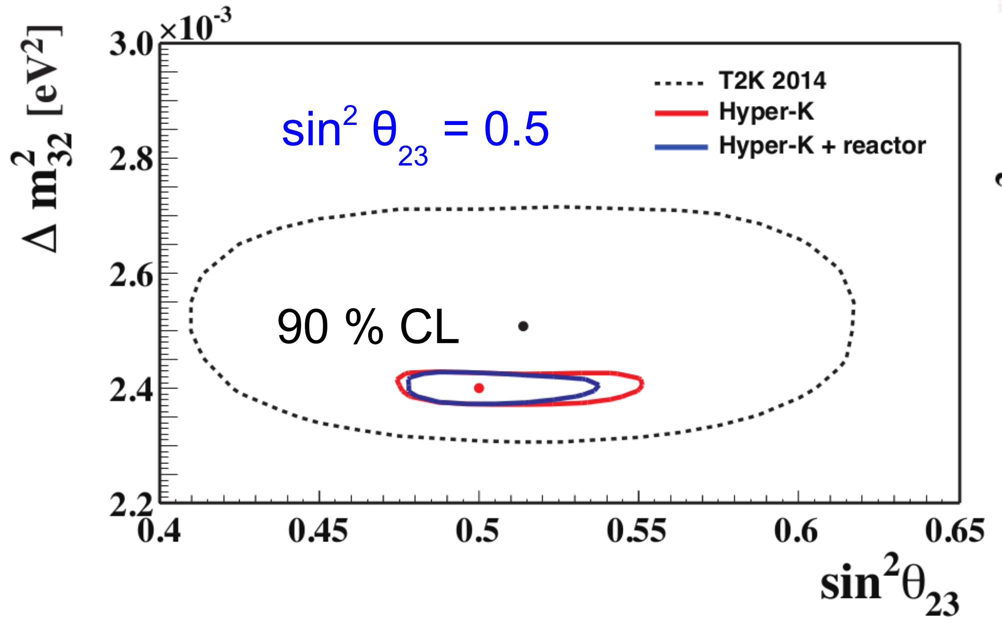


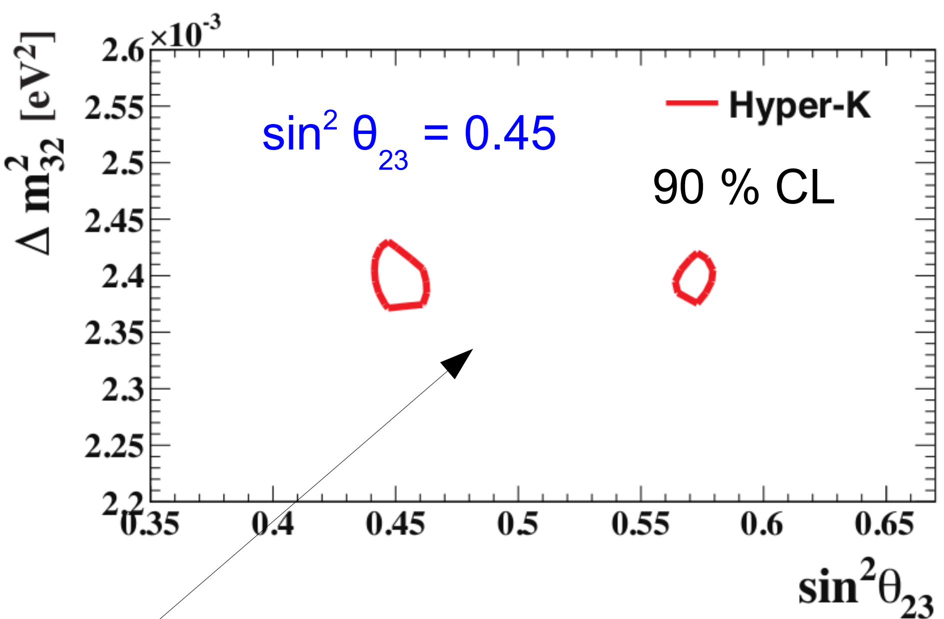


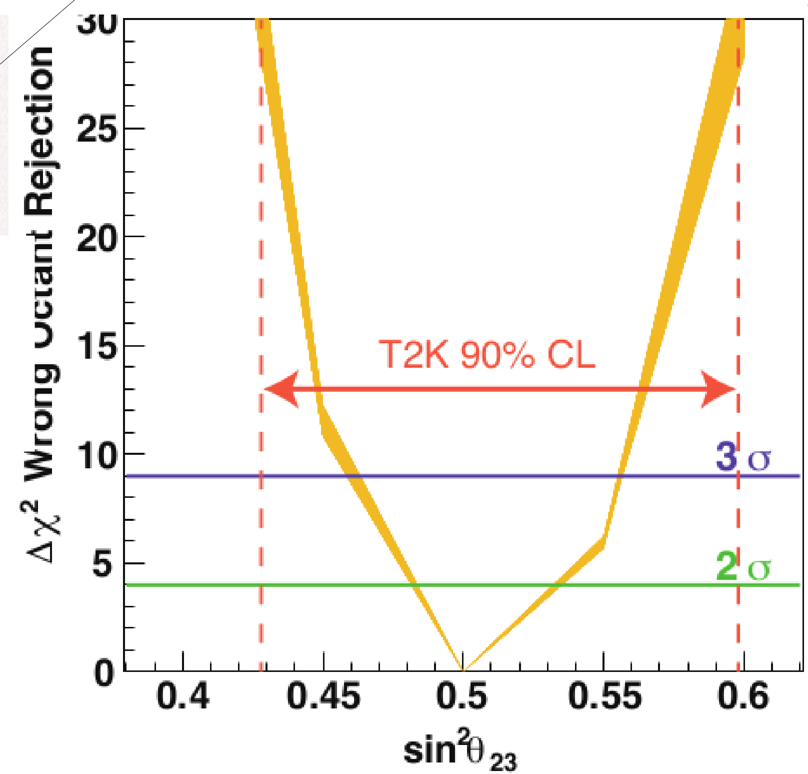
Would mass hierarchy be still unknown by the time of Hyper-K: use large samples of atmospheric neutrinos for which matter effects are definitely large.



Hyper-K: θ_{23} octant





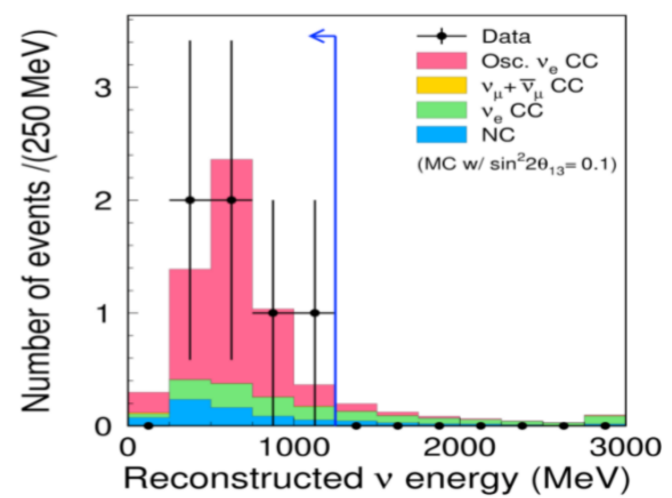


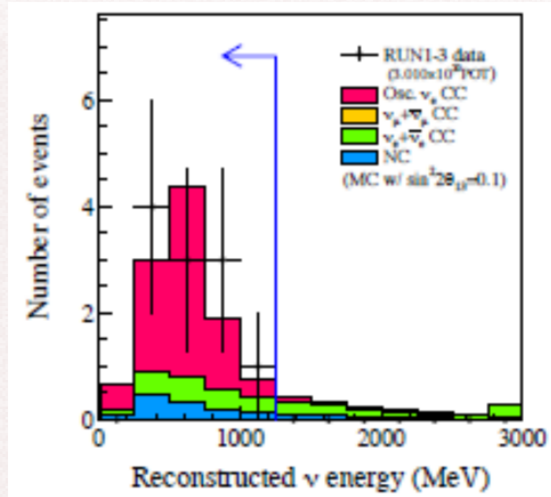
Octant degeneracy can be solved using reactor data and atmospheric neutrino data

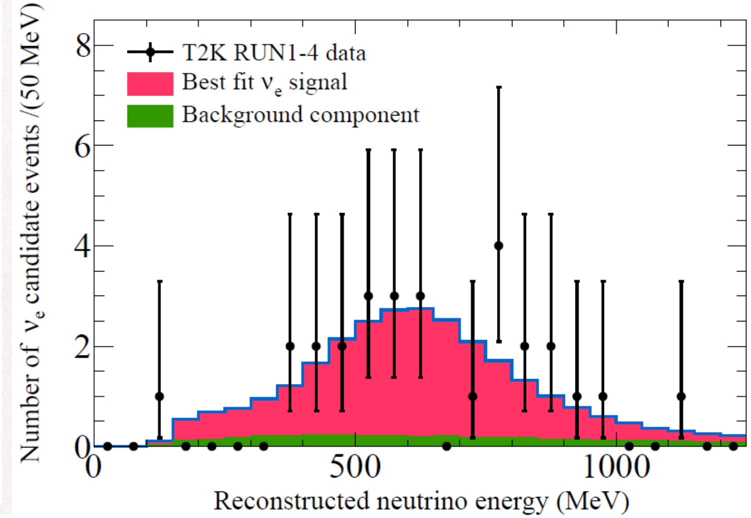
06/2011, 6 ν_e (1.5 ± 0.3 BG) $\theta_{13}\neq 0$ @ **2.5 σ**

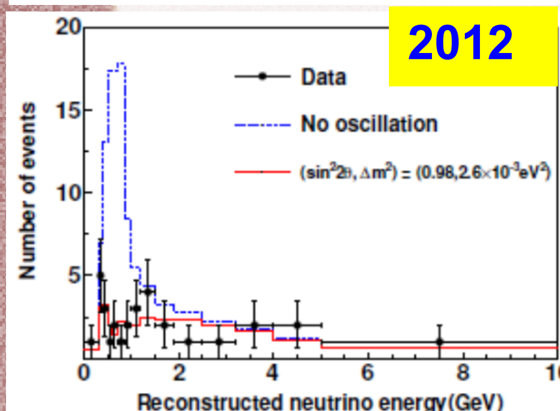
2012, 11 ν_e (3.2 ± 0.4) BG **3.2 σ**

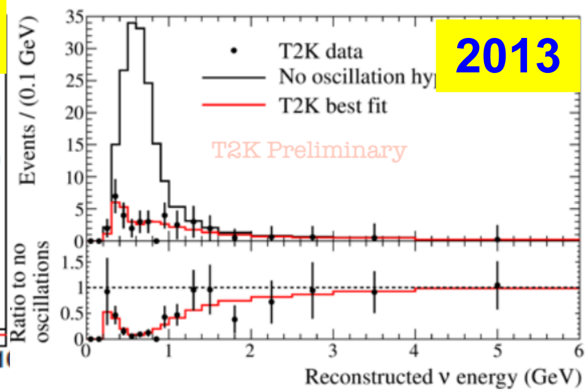
2013, 28 ν_e (4.6 ± 0.5) BG **7.5 σ**

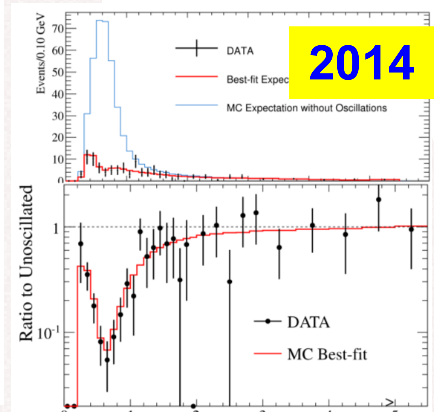


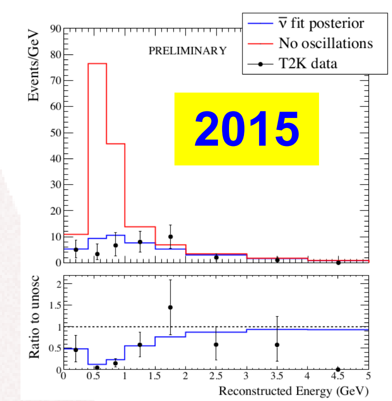












T2K with 13% of the final POT: **90% CL exclusion for some δ_{CP} regions. Best fit at $-\pi/2$ = maximal CPV**. **World leading θ_{23}** measurement. Large space for **improvement with nominal POT** in next years. **Hyper-K** can constraint CP violation in the leptonic sector with high probability/precision. After the first results on anti-ν_μ disappearance the **anti-ν_e appearance** analysis with 4e20 pot is **foreseen soon**, **stay tuned!**

Supplementary slides

T2K collaboration

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

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

Germany
- U. Aachen

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

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

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

Russia
- INR

Spain
- IFIC, Valencia
- U. A. Barcelona

Switzerland
- ETH Zurich
- U. Bern
- U. Geneva

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

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

Near & Far sites: KEK/JAEA, ICRR

Oscillation analysis strategy

Neutrino cross-section models and uncertainties

- NEUT interaction generator
- Constraints from external data

Near detector systematic uncertainties

Neutrino flux prediction

- Simulation of hadronic interactions in target
- Propagation and decay of secondary particles
- Tuned to experimental results (CERN NA61)

Fit of near detectors events (ND280)

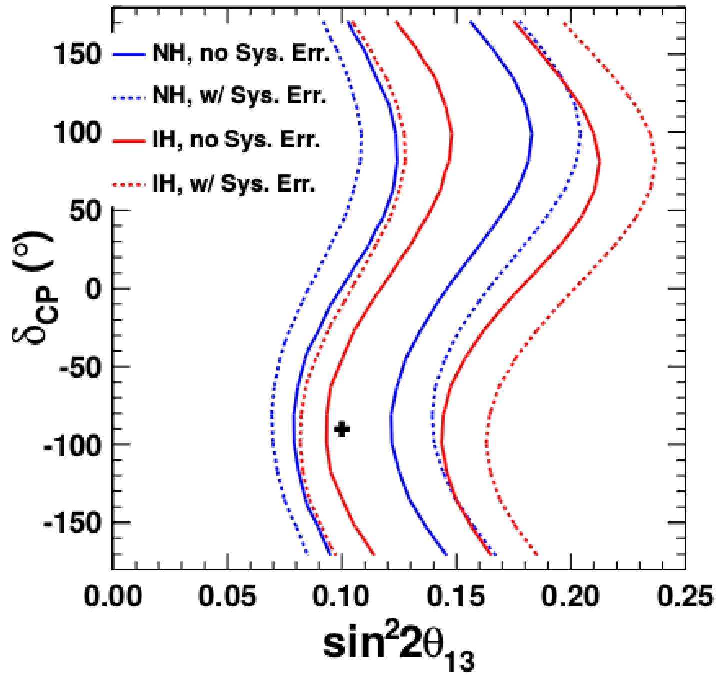
Constrain flux and some of the Neutrino interaction uncertainties

Fit of far detector events using PMNS model

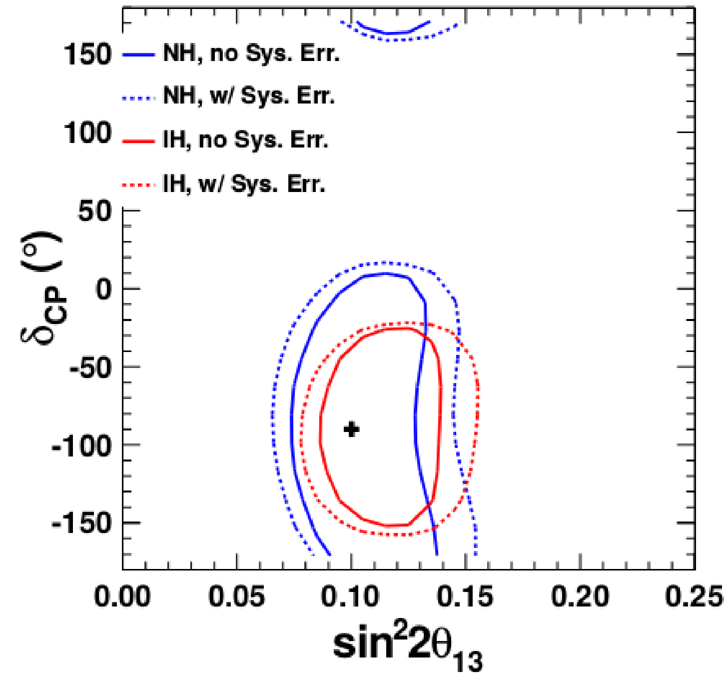
Far detector systematic uncertainties

Evaluated using atmospheric ν and π^0 control sample

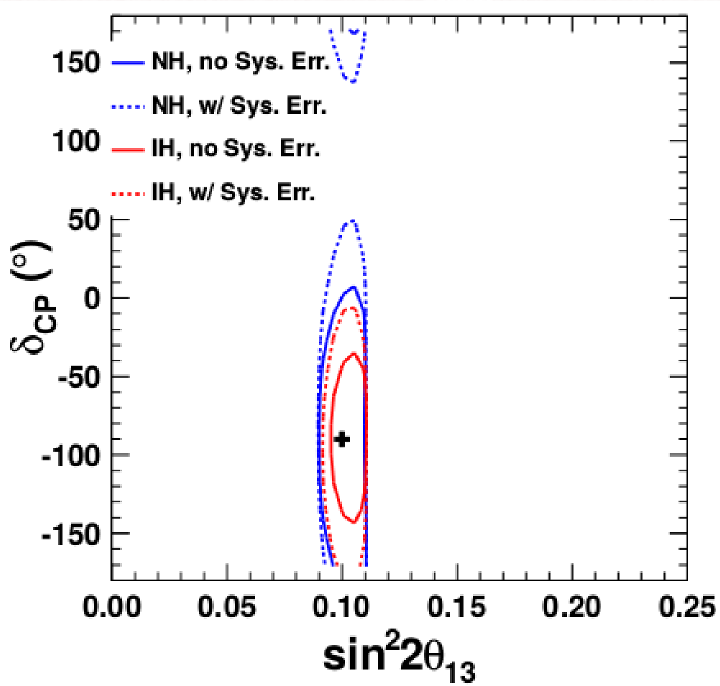
Oscillation parameters estimations

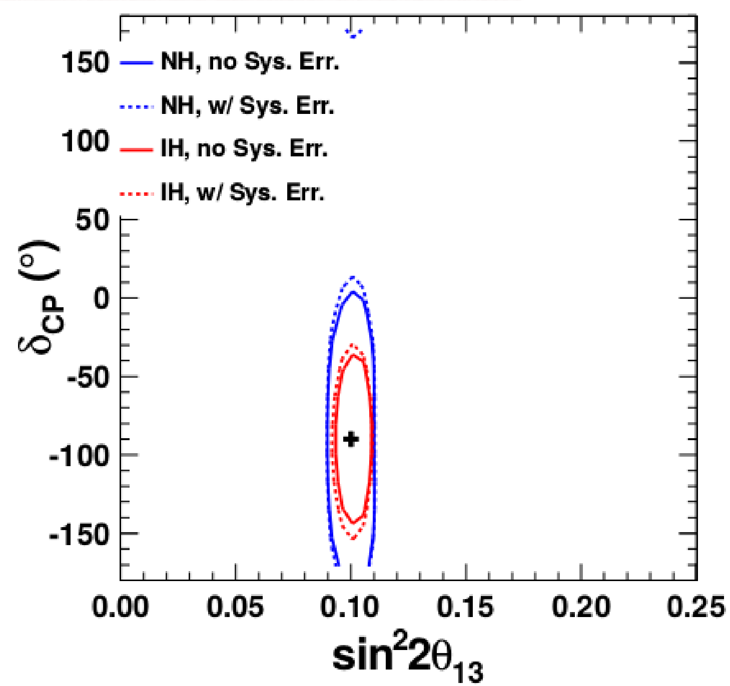


(a) 100% ν-mode.

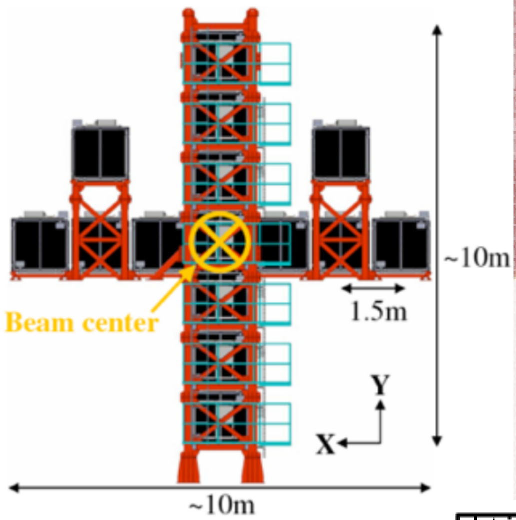


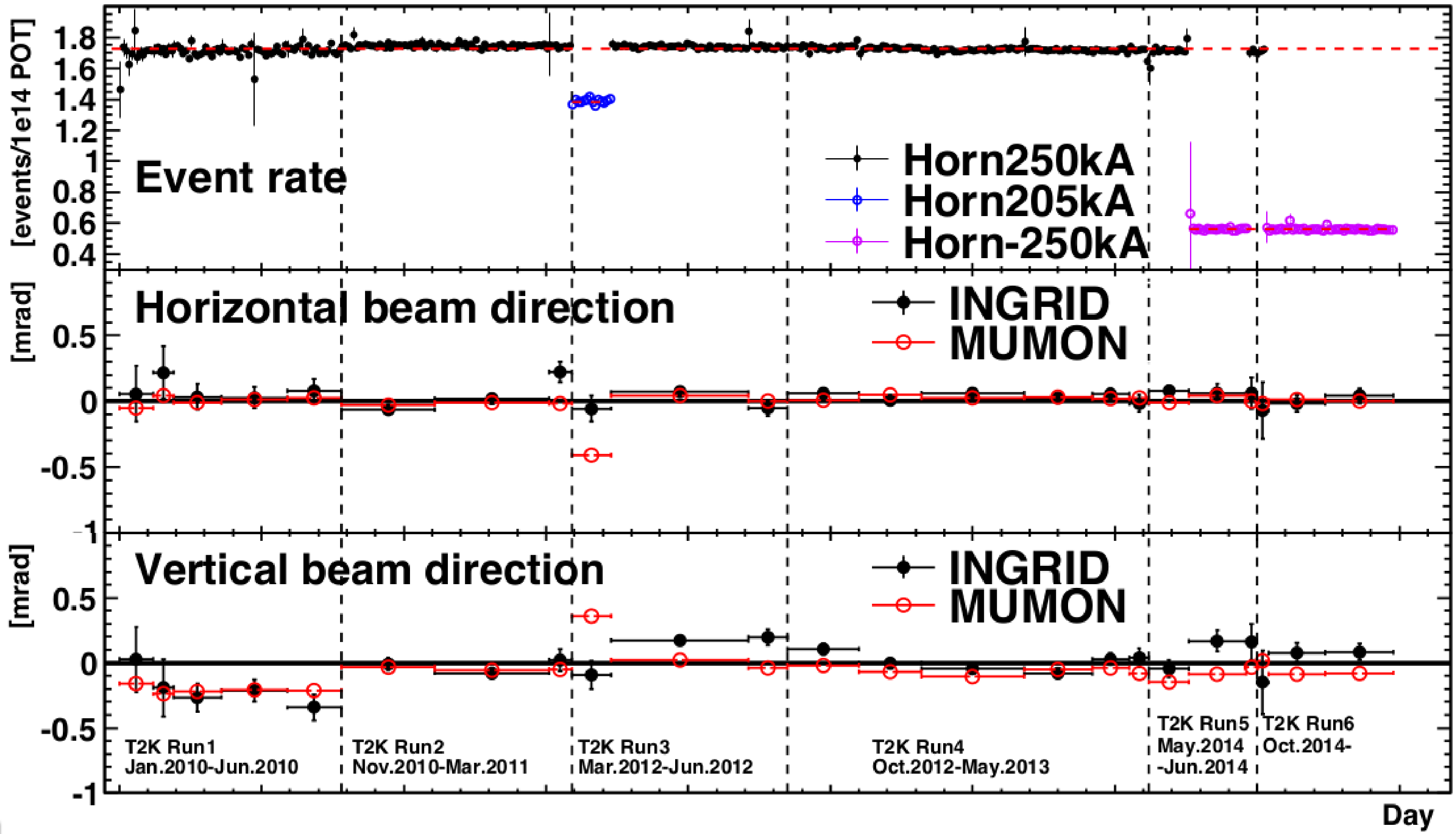
(b) 50% ν-, 50% $\bar{\nu}$-mode.





Beam stability





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

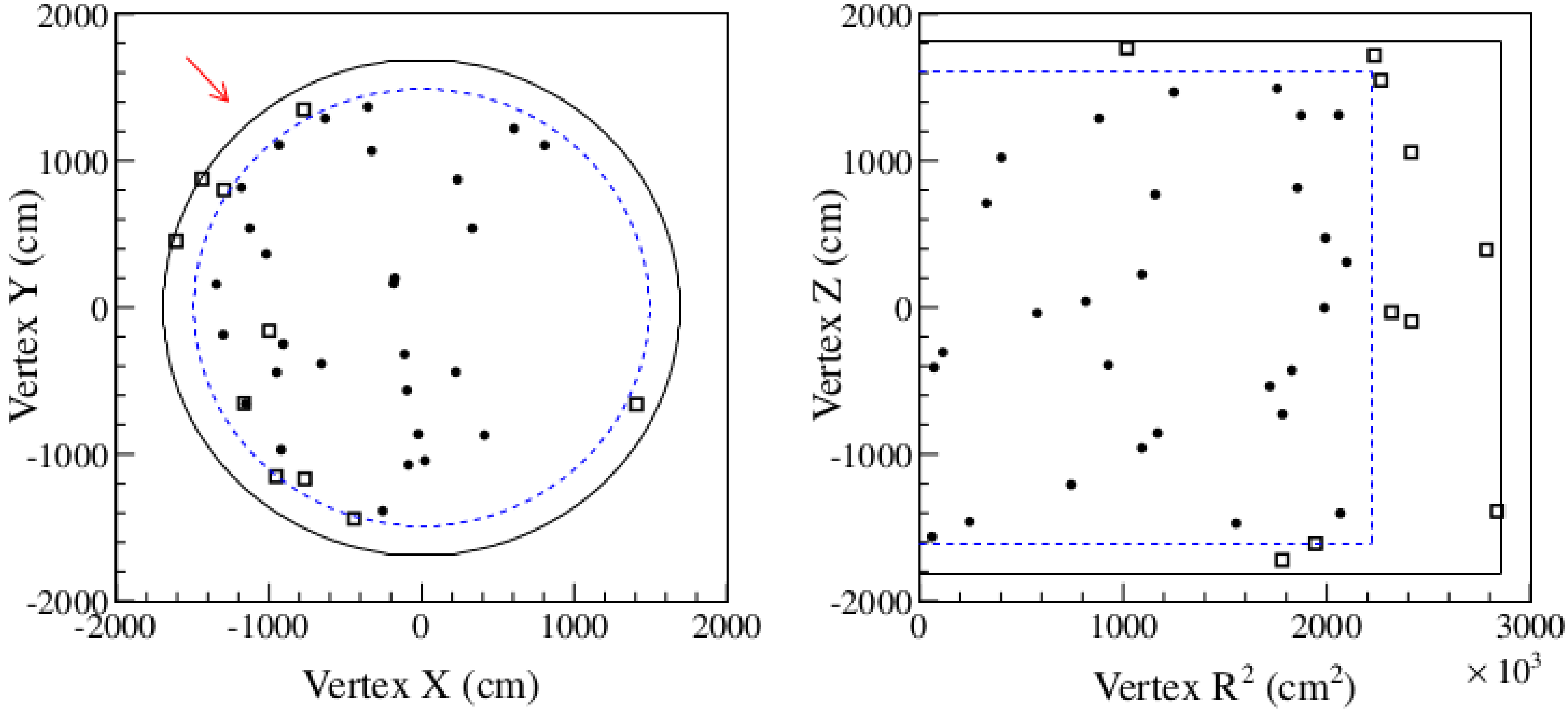
Category	source	Near/Far detectors	# of params
Beam	Beam flux prediction	common	25
ν interactions	Constrained by ND280	common	8
	Unconstrained by ND280	independent	12
Far detector	SK detector efficiency	independent	52+6
	SK momentum scale	independent	1
FSI	Final State Interactions Secondary interaction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

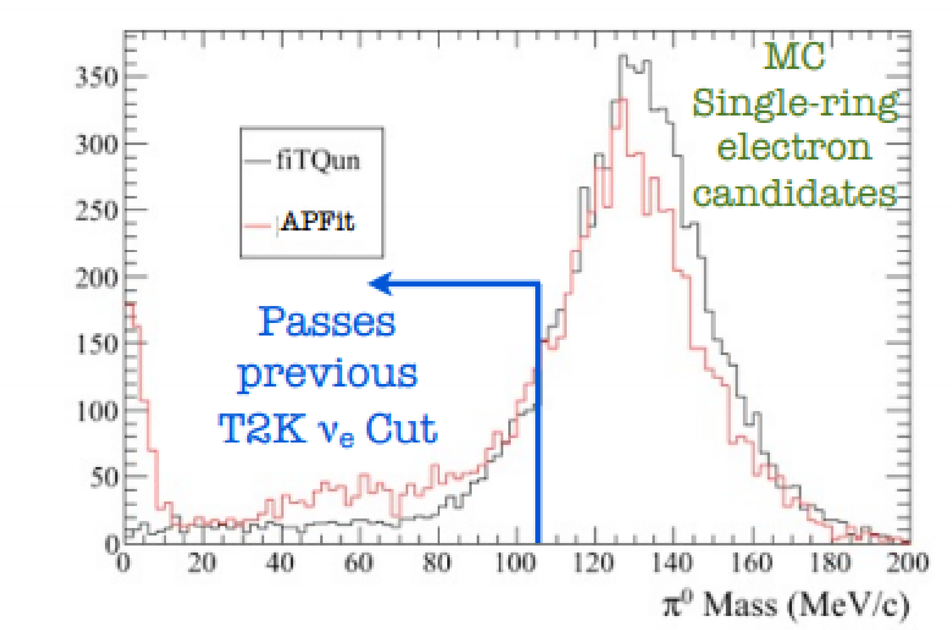
Effect on predicted number of ν_e and ν_μ events (%)

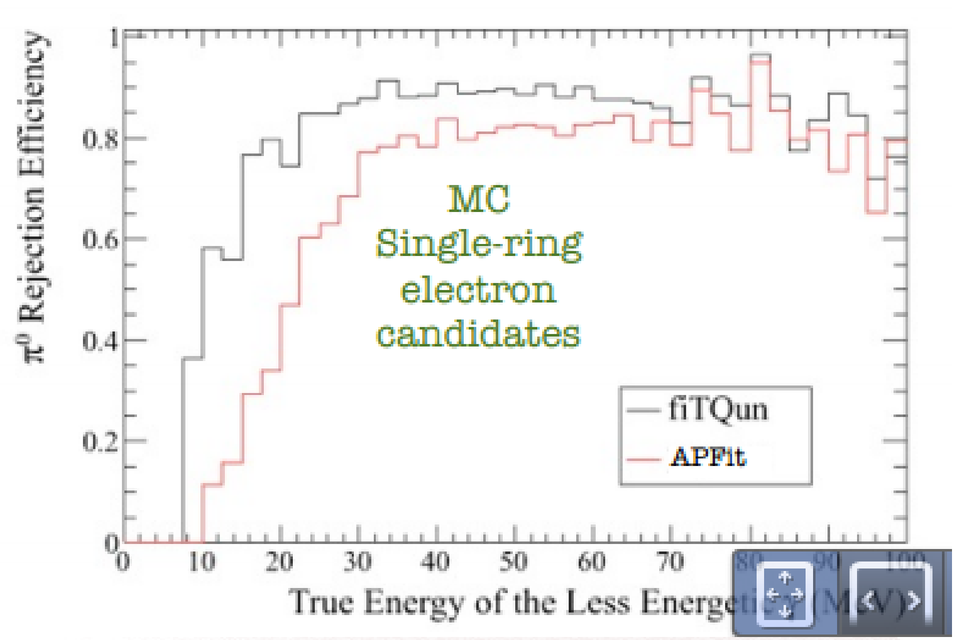
Error source	1Re sample	1Rμ sample
Beam only	7.41	6.08
M_A^{QE}	3.07	2.76
M_A^{Res}	1.02	2.36
CCQE norm.	6.22	4.60
CC1π norm.	2.03	2.99
NC1π^0 norm.	0.43	N/A
CC other shape	0.12	0.89
Spectral Function	1.11	0.21
E_b	N/A	0.21
p_F	0.11	0.14
CC coh. norm.	0.24	0.81
NC coh. norm.	0.24	N/A
NC 1$\pi^\pm$ norm.	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**


2000
1000
0
-1000
-2000
-2000
-1000
0
1000
2000
Vertex Y (cm)
Vertex X (cm)
2000
1000
0
-1000
-2000
0
1000
2000
3000
Vertex Z (cm)
Vertex R^2 (cm^2)
$\times 10^3$

π^0 Fit Performance

- Previous T2K ν_e appearance cut:
  $m_{\pi 0}$ < 105 MeV/c²
- The π^0 mass tail is much smaller for fiTQun
  - Significant spike at zero mass in previous fitting algorithm (**APFit**)
- **Lower plot:**
  π^0 rejection efficiency vs lower photon energy
  - fiTQun is more sensitive to lower energy photons





ND280

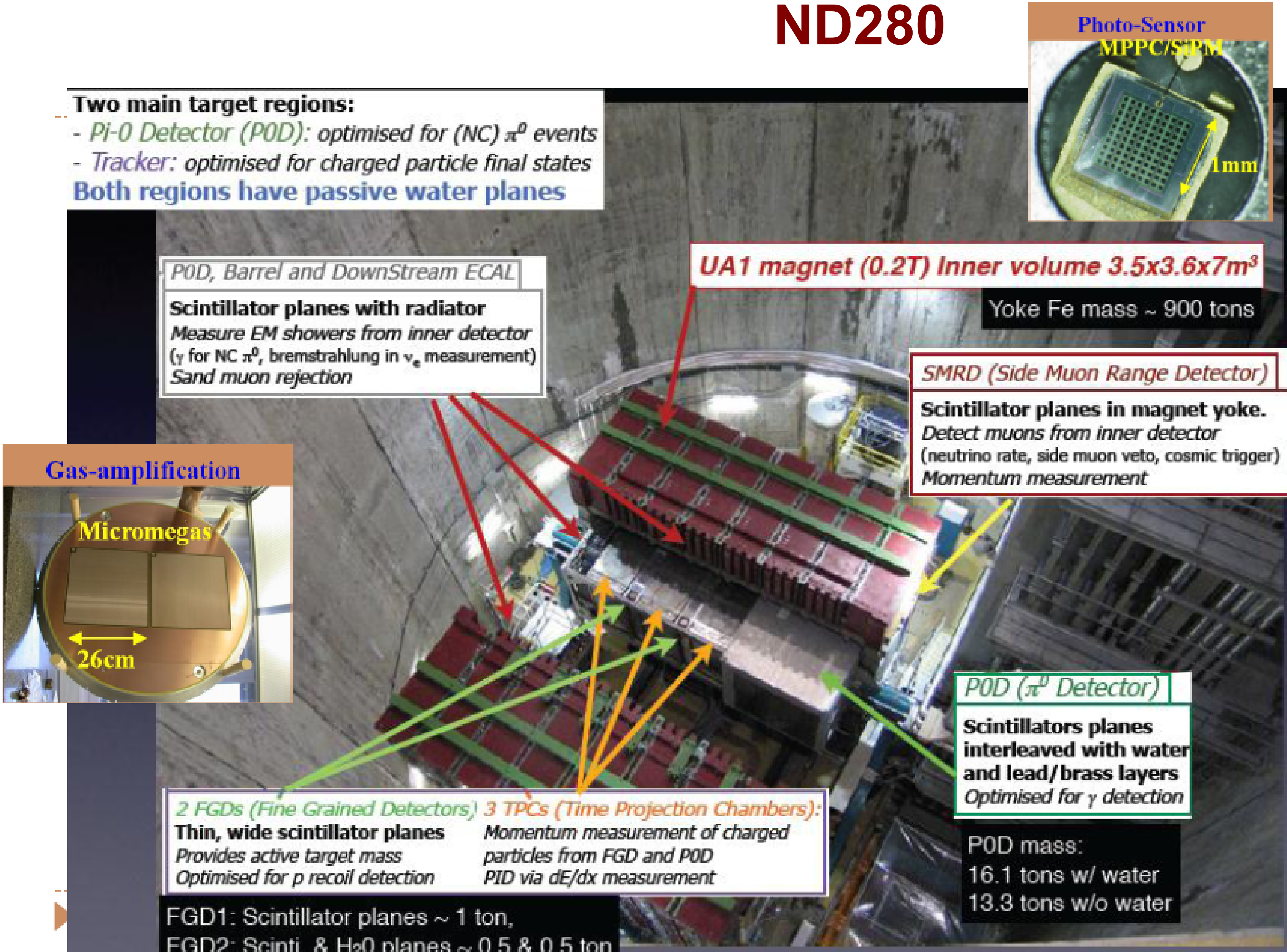
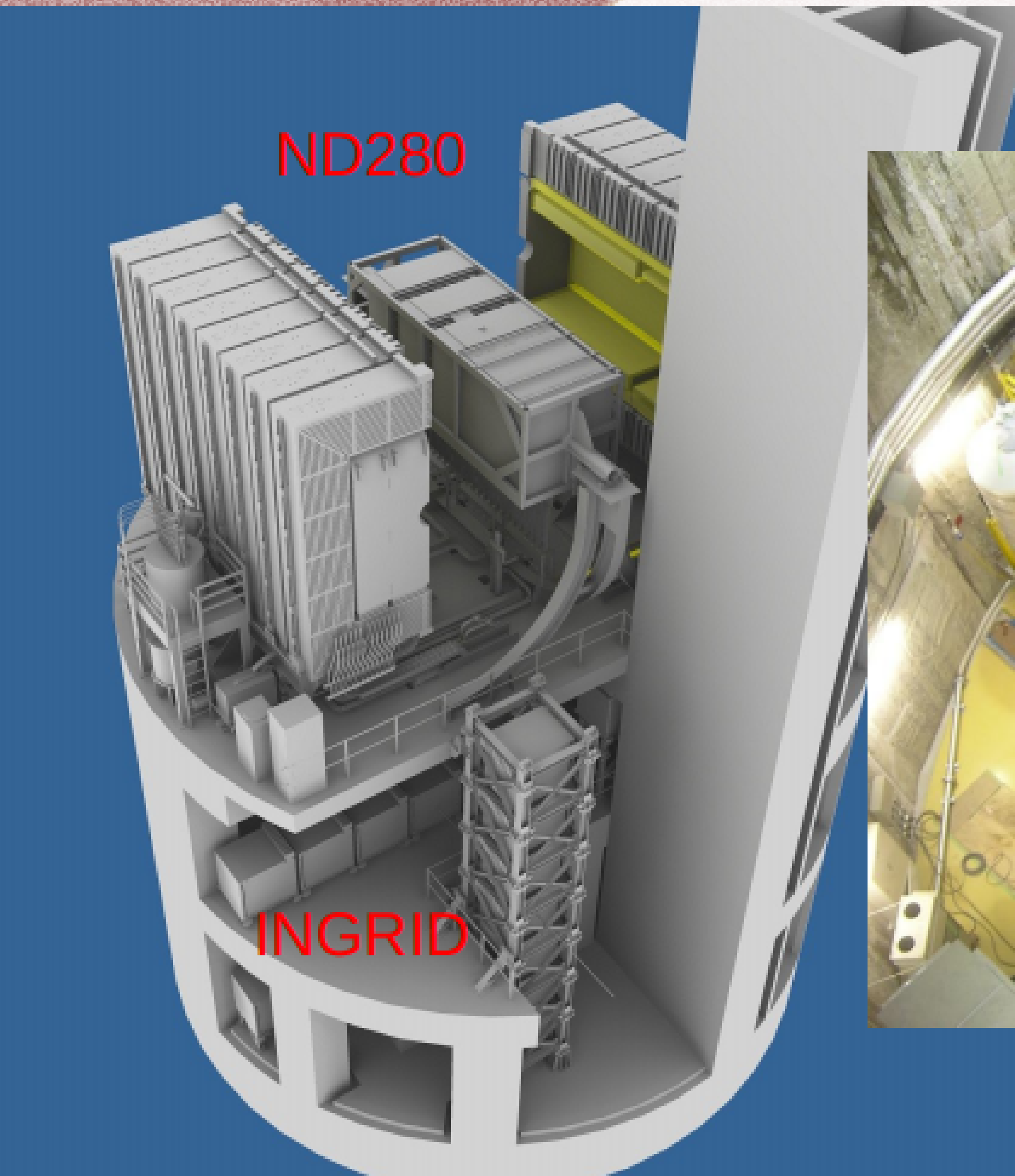
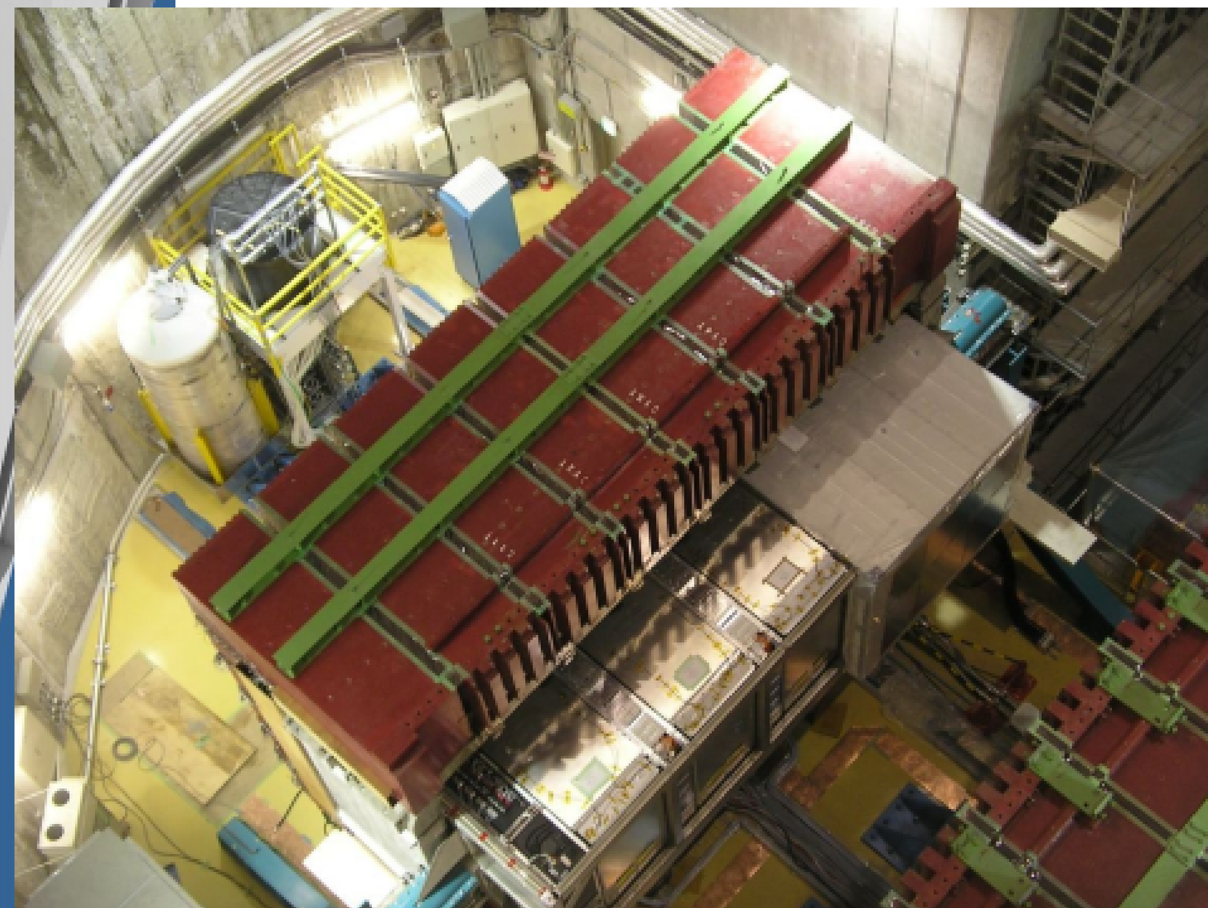


Photo-Sensor
MPPC/SiPM
1mm
Two main target regions:
- Pi-0 Detector (P0D): optimised for (NC) π^0 events
- Tracker: optimised for charged particle final states
Both regions have passive water planes
P0D, Barrel and DownStream ECAL
Scintillator planes with radiator
Measure EM showers from inner detector
(γ for NC π^0, bremstrahlung in ν_e measurement)
Sand muon rejection
UA1 magnet (0.2T) Inner volume 3.5x3.6x7m^3
Yoke Fe mass ~ 900 tons
SMRD (Side Muon Range Detector)
Scintillator planes in magnet yoke.
Detect muons from inner detector
(neutrino rate, side muon veto, cosmic trigger)
Momentum measurement
Gas-amplification
Micromegas
26cm
P0D (π^0 Detector)
Scintillators planes interleaved with water and lead/brass layers
Optimised for γ detection
P0D mass:
16.1 tons w/ water
13.3 tons w/o water
2 FGDs (Fine Grained Detectors)
Thin, wide scintillator planes
Provides active target mass
Optimised for p recoil detection
3 TPCs (Time Projection Chambers):
Momentum measurement of charged particles from FGD and P0D
PID via dE/dx measurement
FGD1: Scintillator planes ~ 1 ton,
FGD2: Scinti. & H_2O planes ~ 0.5 & 0.5 ton

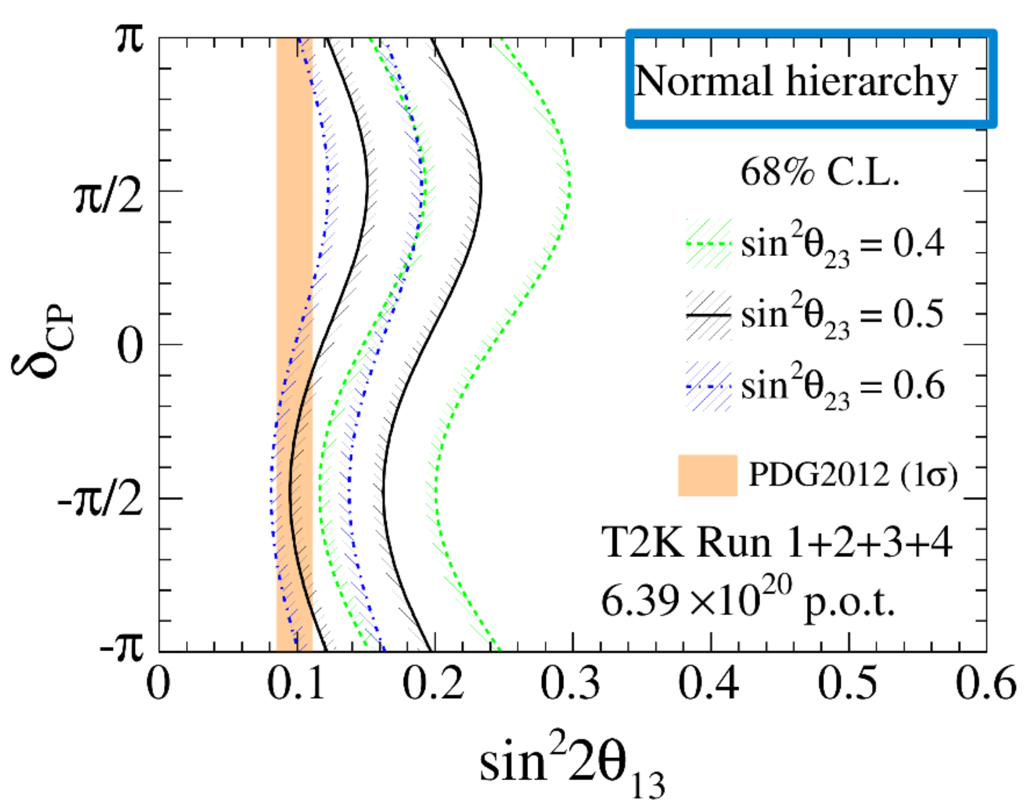
ND280

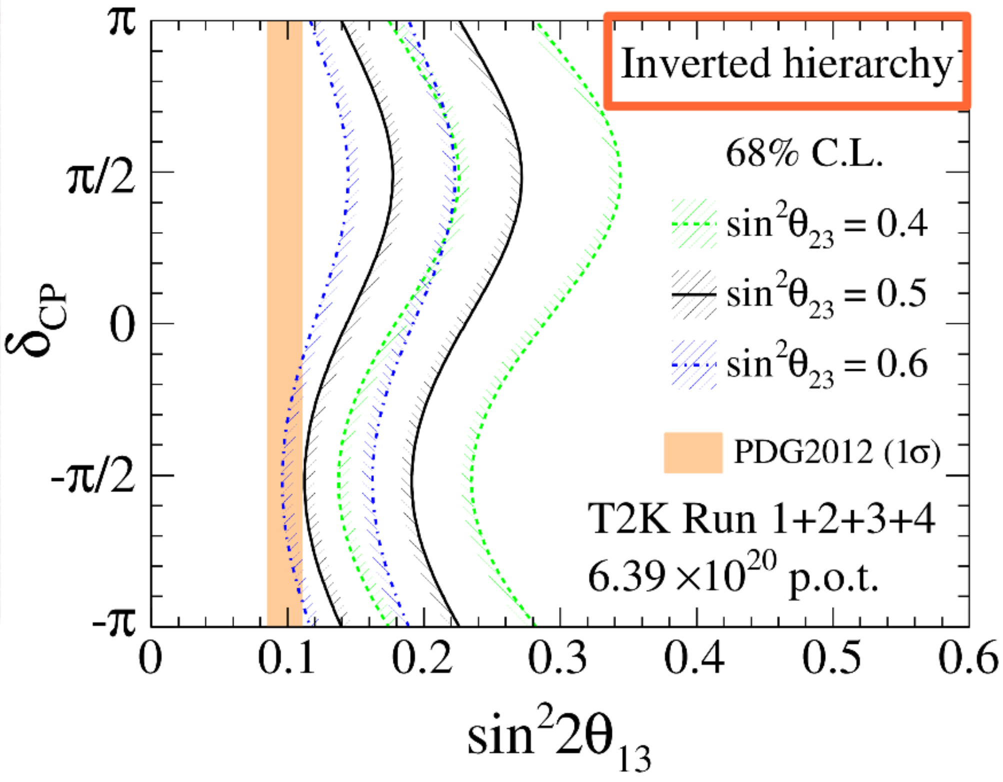




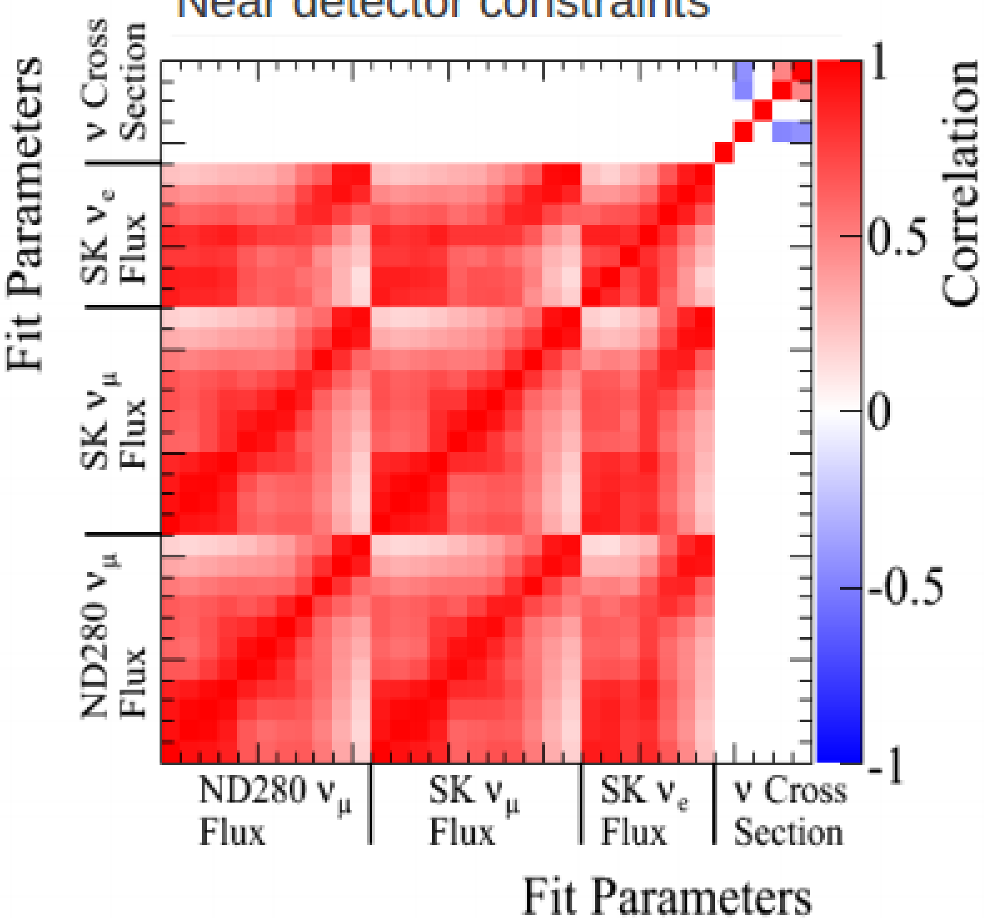
Appearance of ν_e & θ_{23}

$$P_{\mu\rightarrow e} \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \left(\frac{\Delta m^2_{31} L}{4E}\right)$$





Correlations before including
Near detector constraints



Correlations after including
Near detector constraints