Hints of δ_{CP} with T2K

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Pizza Seminar, 11 June 2014

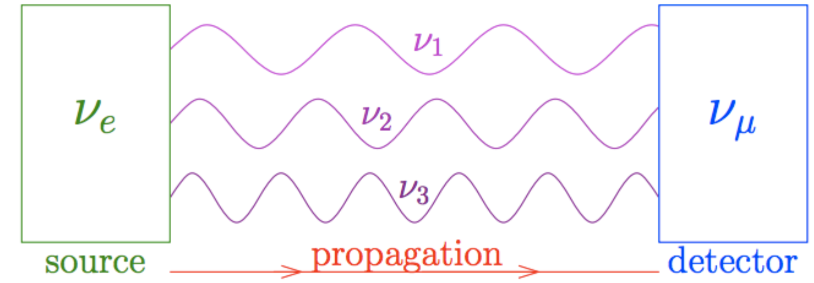
Intro

- T2K has recently published the conclusive observation (7.5σ) of the appearance of a electron neutrino starting from a beam of muon-neutrinos
- The results and the details of the oscillation analysis procedure have been fully described few months ago in the contest of a colloquium
- **Today I will focus on how the T2K results address the question of the determination of CP violation in the lepton sector (determination of the value of δ_{CP})**

Menu del día :

- Neutrino oscillations in a nutshell
- Short reminder of the T2K experiment
- Observation of the ν_e appearance
  - review of the published results
  - constraints on δ_{CP}
- T2K future sensitivity to δ_{CP}

Neutrino oscillations



by C.Giunti

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

atmospherics + LBL **reactor + LBL** **solar**

$c_{ij} = \cos\vartheta_{ij}$
$s_{ij} = \sin\vartheta_{ij}$

- Neutrino oscillations are governed by **5 parameters :**
  - Three mixing angles ($\vartheta_{12}, \vartheta_{23}, \vartheta_{13}$)
  - Two independent squared masse differences (Δm^2_{21} , Δm^2_{32})
  - 1 CP-violating phase
- Each one of this parameter has an accuracy dominated by a specific class of experiment

Parameter	Value	
$\sin^2 2\theta_{12}$	0.857 ± 0.024	solar
$\sin^2 2\theta_{23}$	> 0.95	LBL (T2K) + atmospherics (SK)
$\sin^2 2\theta_{13}$	0.095 ± 0.010	SBL reactors (Daya Bay, RENO)
Δm^2_{21}	$(7.5 \pm 0.20) \times 10^{-5}$ eV^2	LBL reactors (KamLAND)
$\|\Delta m^2_{32}\|$	$(2.32^{+0.12}_{-0.08}) \times 10^{-3}$ eV^2	LBL + atmospherics
δ_{CP}	unknown	-

CP violation term in the leptonic sector

- Similarly to the quark sector, also in the lepton sector we could have CP violation
- A direct measurement of CP violation could be performed by measuring the asymmetry, if any, between the neutrino and anti-neutrino oscillation probability

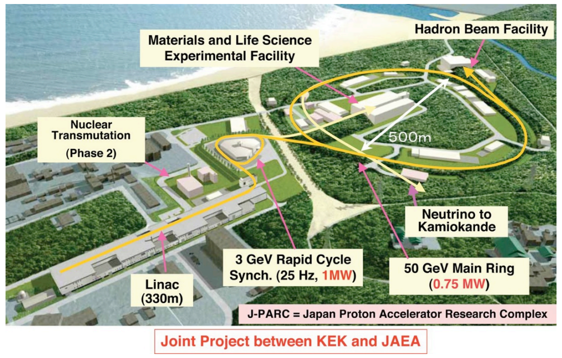
$$a = \frac{P(\nu_\mu \to \nu_e) - P(\overline{\nu_\mu} \to \overline{\nu_e})}{P(\nu_\mu \to \nu_e) + P(\overline{\nu_\mu} \to \overline{\nu_e})}$$

- However neutrino oscillation experiment offer the possibility to investigate CP violation in the lepton sector through measuring the CP phase δ_{CP}
- The relatively large value of ϑ_{13} has enhanced the physics potential of LBL accelerator experiment (T2K !).
- The sensitivity to discover δ_{CP} depends to the other oscillation parameters. Nevertheless within certain parameters phase space ranges, δ_{CP} as become accessible to the current LBL experiment → **T2K already put some constraints**

The T2K experiment

- Long baseline neutrino oscillation experiment in Japan (Tokai to Kamioka)
- muon neutrinos produced from a 30GeV proton beam (JPARC)
- neutrinos detected in 2 points
  - at the near detector (**ND280**) at 280 m
  - at the far detector (**Super-Kamiokande**) at 295 Km

Japan Proton Accelerator Research Complex **(JPARC)**

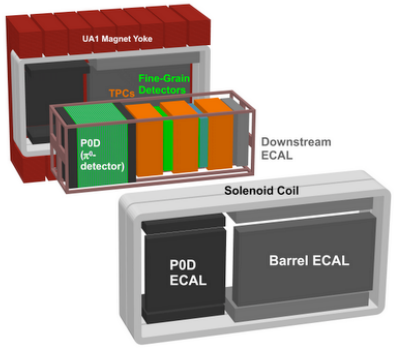


Two main goals :

- **ν_μ disappearance $P(\nu_\mu \rightarrow \nu_\mu)$:** measure Δm^2_{32} and ϑ_{23}

- **νe appearance $P(\nu_\mu \rightarrow \nu_e)$:** measure ϑ_{13} and constrain δ_{CP}

Far Detector
(~300Km)



Near Detector
(@~280m)

ν_e appearance

octant term | delta CP term

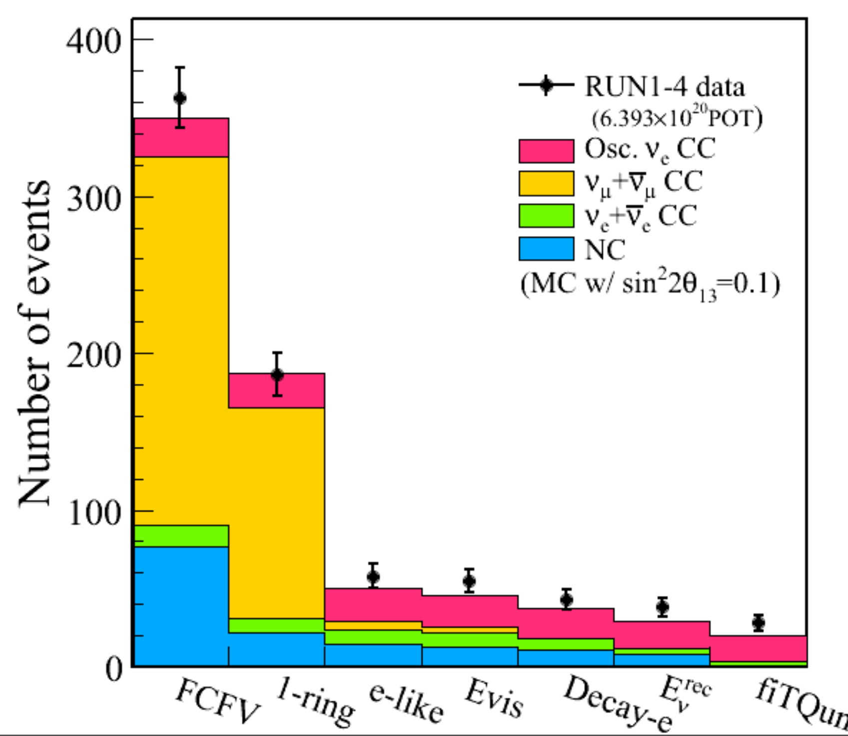
$$P(\nu_\mu \to \nu_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{32}L}{4E_\nu} - \frac{\sin 2\theta_{12}\sin 2\theta_{23}}{2\sin\theta_{13}}\sin\frac{\Delta m^2_{21}L}{4E_\nu}\sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{32}L}{4E_\nu}\sin\delta_{CP}$$

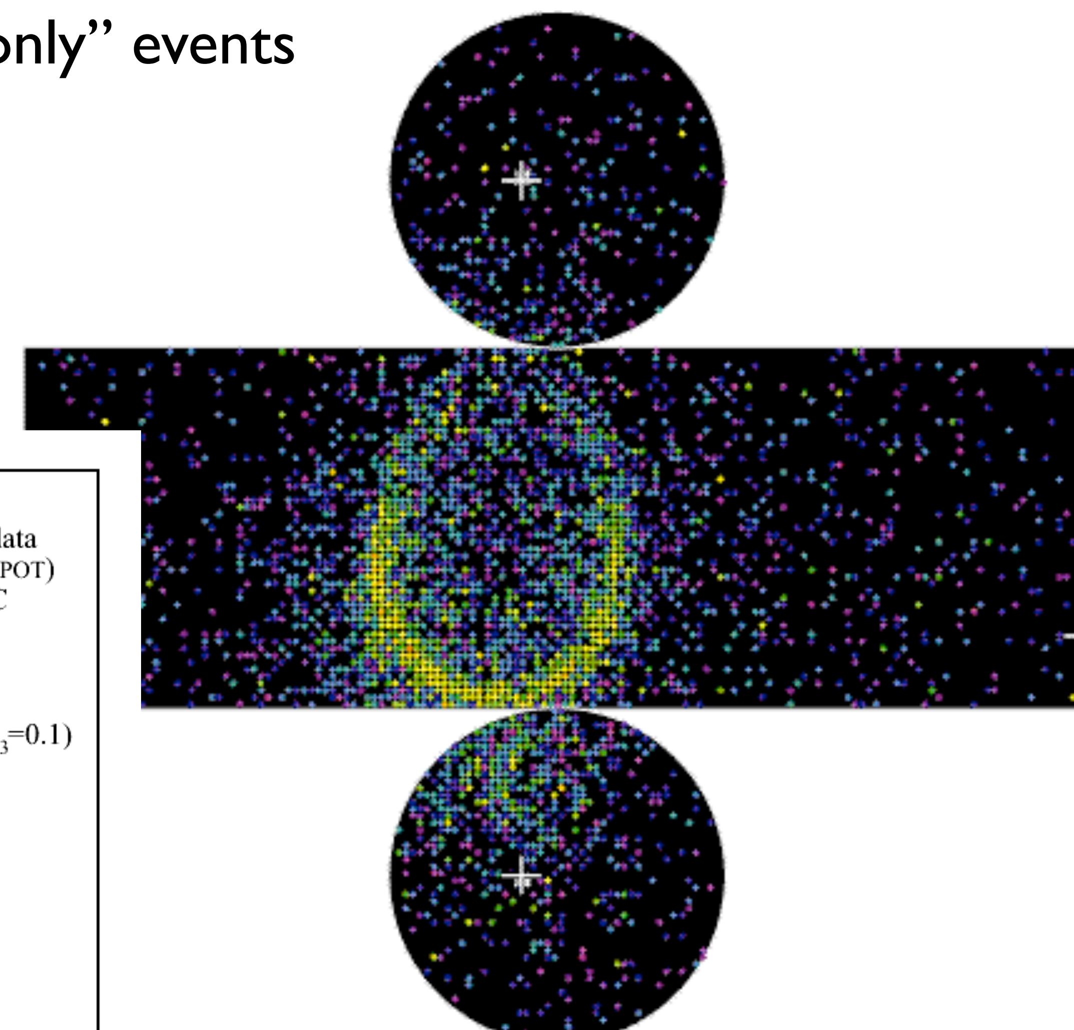
$$+(\text{CP even term, solar term, matter effect term})$$

$$+(\text{CP even term, solar term, matter effect term})$$

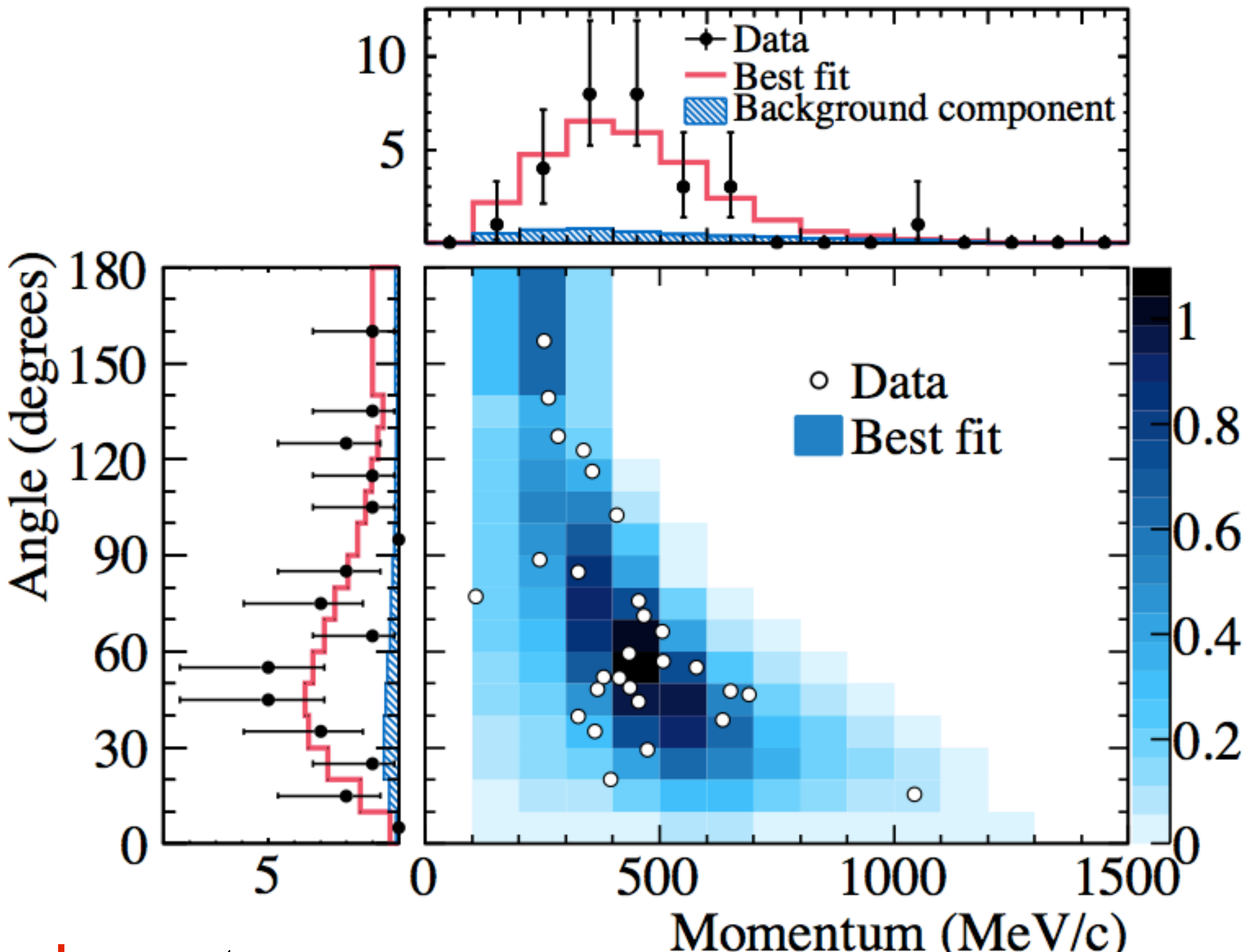
CCQE candidates at SK selected looking for "one-electron-only" events

- fully contained single electron-like ring
- $p_e > 100$ MeV and no decay e^- (Michel electrons)
- E_ν reconstructed using the QE approximation
- π^0 background rejection





ν_e appearance



28 observed events

21.6 expected events @ $\sin^2 2\vartheta_{13} = 0.1$ $\delta CP = 0$, $\sin^2 2\vartheta_{23} = 0.5$

4.92 ± 0.55 expected background events

ν_e appearance

$$\mathcal{L} = \mathcal{L}_{norm} \times \mathcal{L}_{shape} \times \mathcal{L}_{syst}$$

$\mathcal{L}_{syst}$ → Systematic parameter constraint term

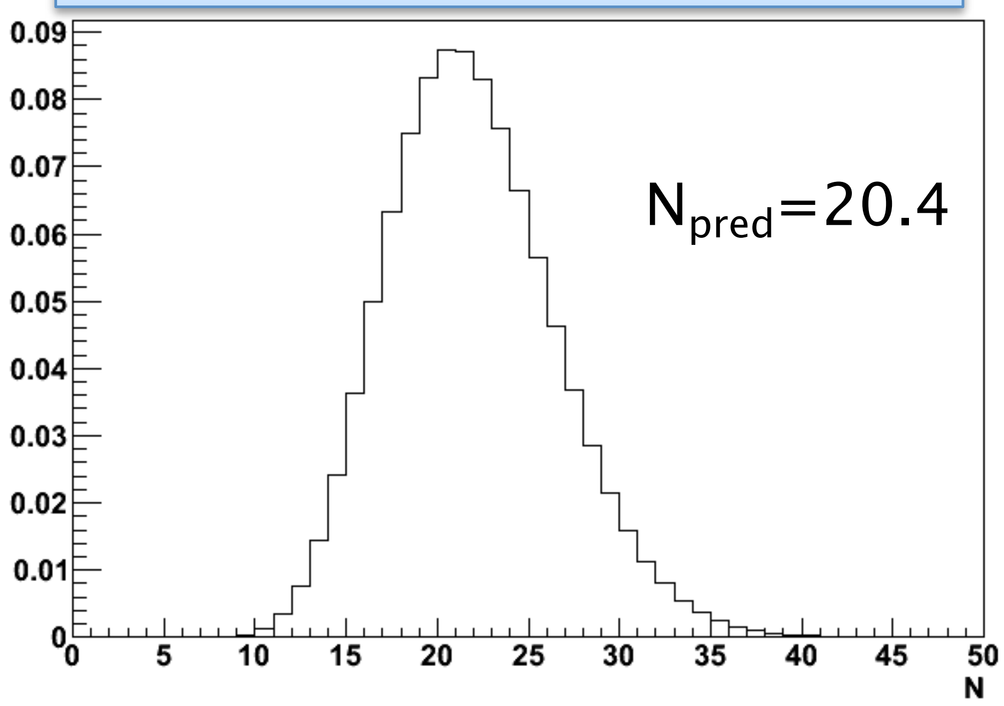
$\mathcal{L}_{norm}$ → $Poisson(N_{obs})_{\text{mean}=N_{pred}}$

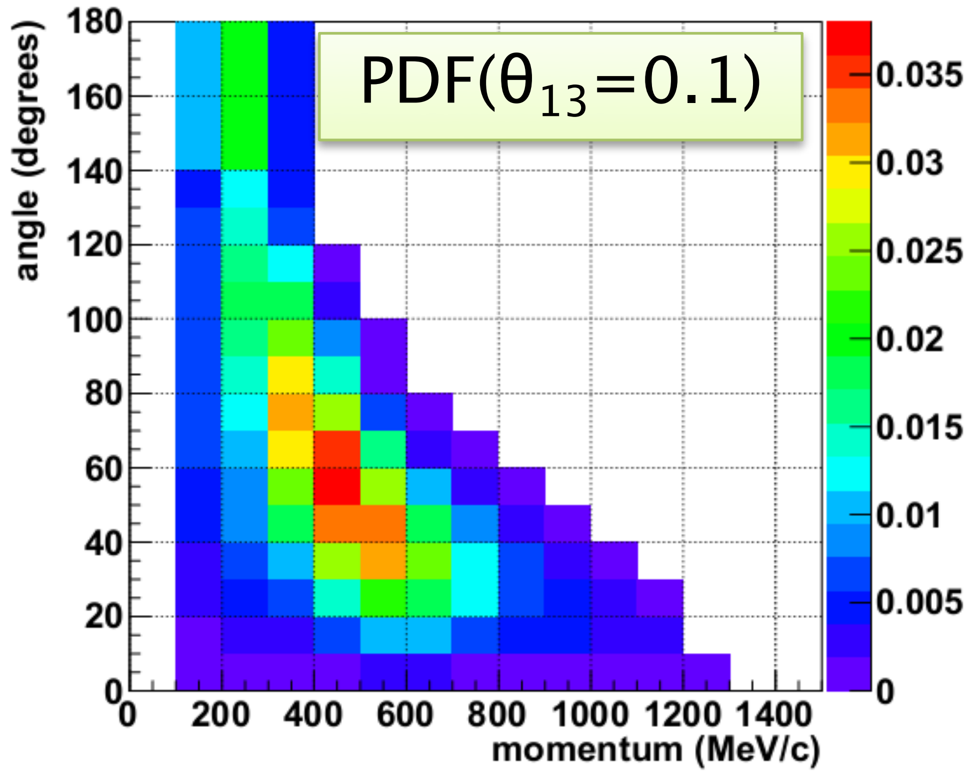
$\mathcal{L}_{shape}$ → $\prod_{i=1}^{N_{obs}} \phi(p_i, \theta_i)$

$\mathcal{L}_{norm}$ is the probability to have N_{obs} when the predicted number of events is the Poisson distribution with mean = N_{pred}.

$\mathcal{L}_{shape}$ is the product of the probabilities that each event has (p_i, θ_i). Φ: Predicted p-θ distribution (PDF) .

Poisson distribution (θ_{13}=0.1)





ϑ_{13} best fit values

$$P(\nu_\mu \to \nu_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{32}L}{4E_\nu} - \frac{\sin 2\theta_{12}\sin 2\theta_{23}}{2\sin\theta_{13}}\sin\frac{\Delta m^2_{21}L}{4E_\nu}\sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{32}L}{4E_\nu}\sin\delta_{CP}$$

$= 0$

$$+(\text{CP even term, solar term, matter effect term})$$

- To extract the best fit values for ϑ_{13} we need to make some assumptions on the other oscillation parameters.
- Let's take :
  - $\sin^2\vartheta_{12}=0.306$,
  - $\Delta m^2_{21}=7.6\times10^{-5}eV^2$

    ← from solar experiment

  - $\sin^2\vartheta_{23}=0.5$,
  - $|\Delta m^2_{32}|=2.4\times10^{-3}eV^2$

    ← from T2K disappearance measurement

  - **$\delta_{CP} = 0$**

Best fit value for Normal Hierarchy

$$\sin^2\theta_{13} = 0.140^{+0.038}_{-0.032}$$

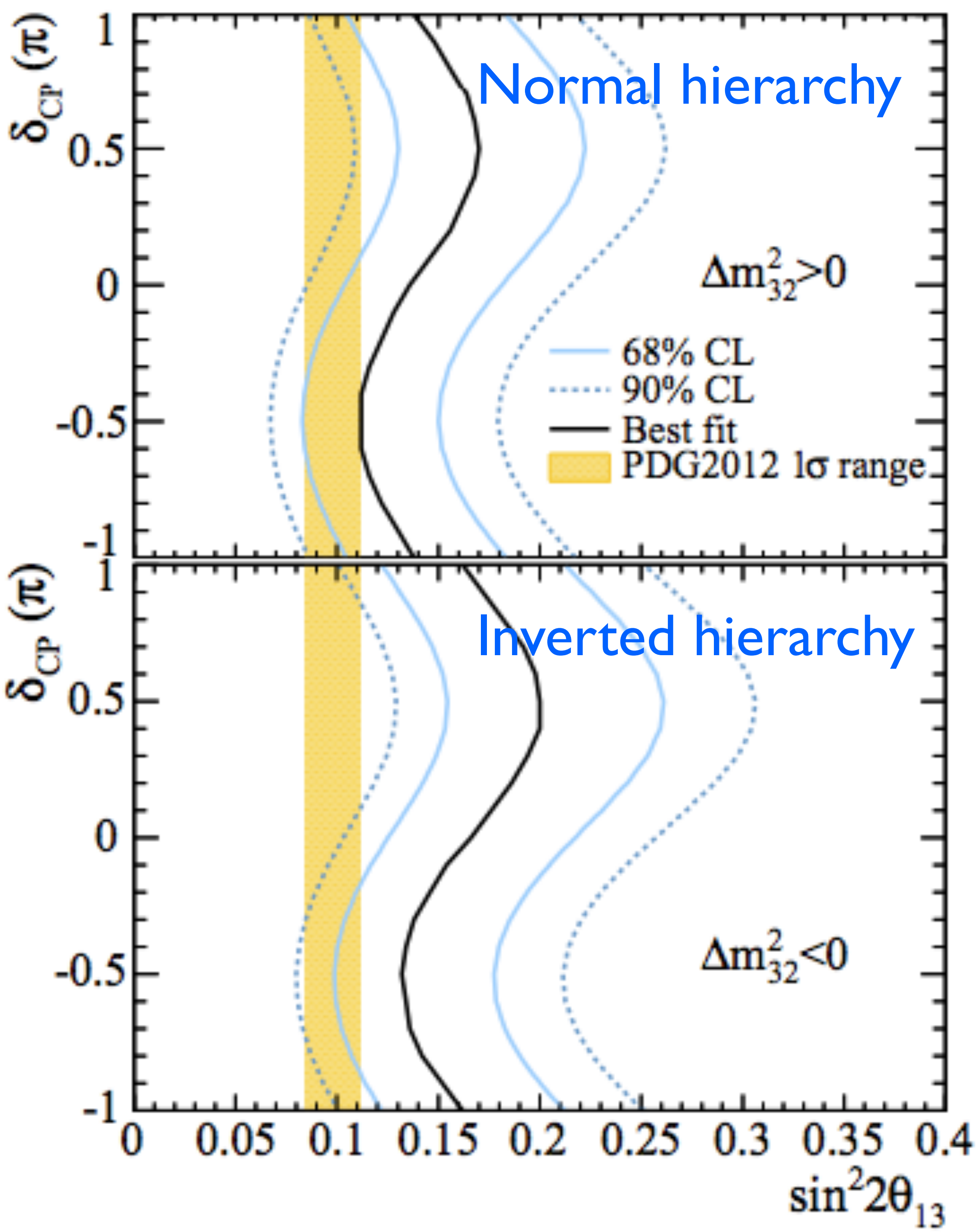
Best fit value for Inverted Hierarchy

$$\sin^2\theta_{13} = 0.170^{+0.045}_{-0.037}$$

Constraining δ_{CP}

- We repeat the same exercise for each value of δ_{CP} to extract the allowed region of $\sin^2 2\theta_{13}$
- Comparing the results from reactor data we observe a better overlap for negative values of δ_{CP}

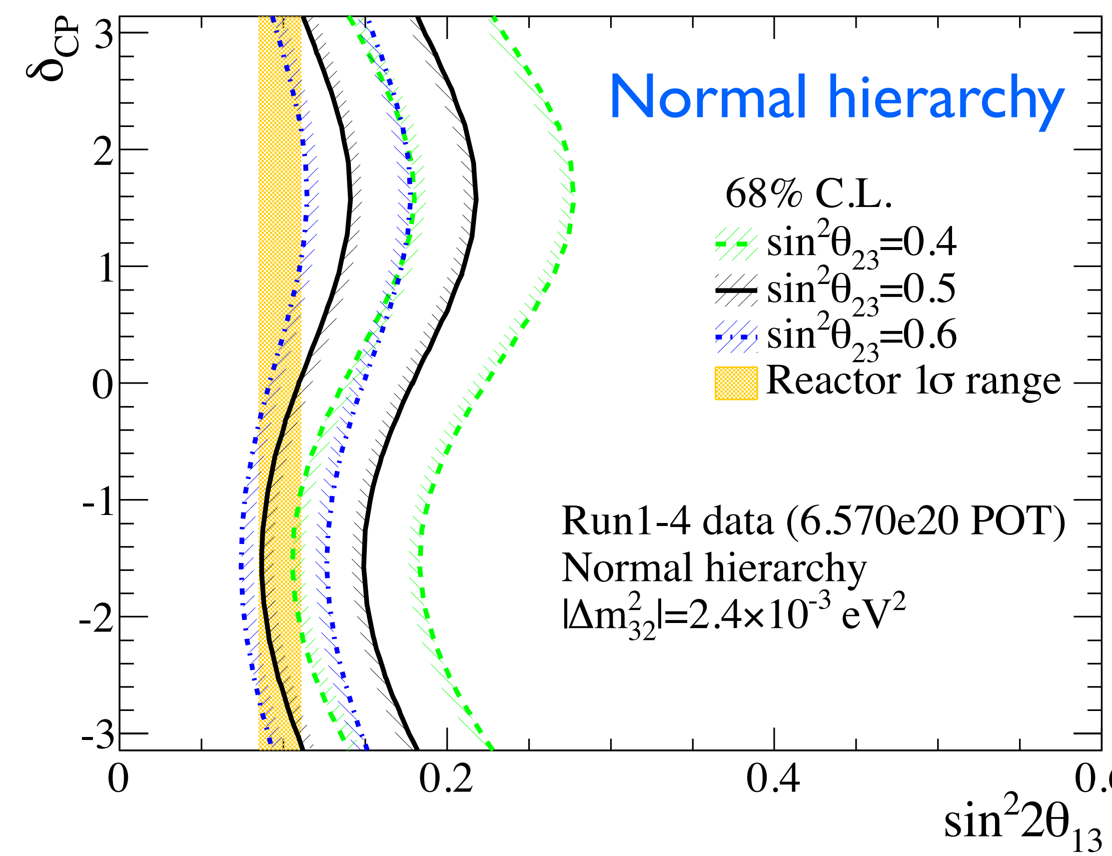
PRL 112, 061802 (2014)



Yellow band: average ϑ_{13} value from PDG 2012

$\vartheta_{13} = 0.098 \pm 0.013$

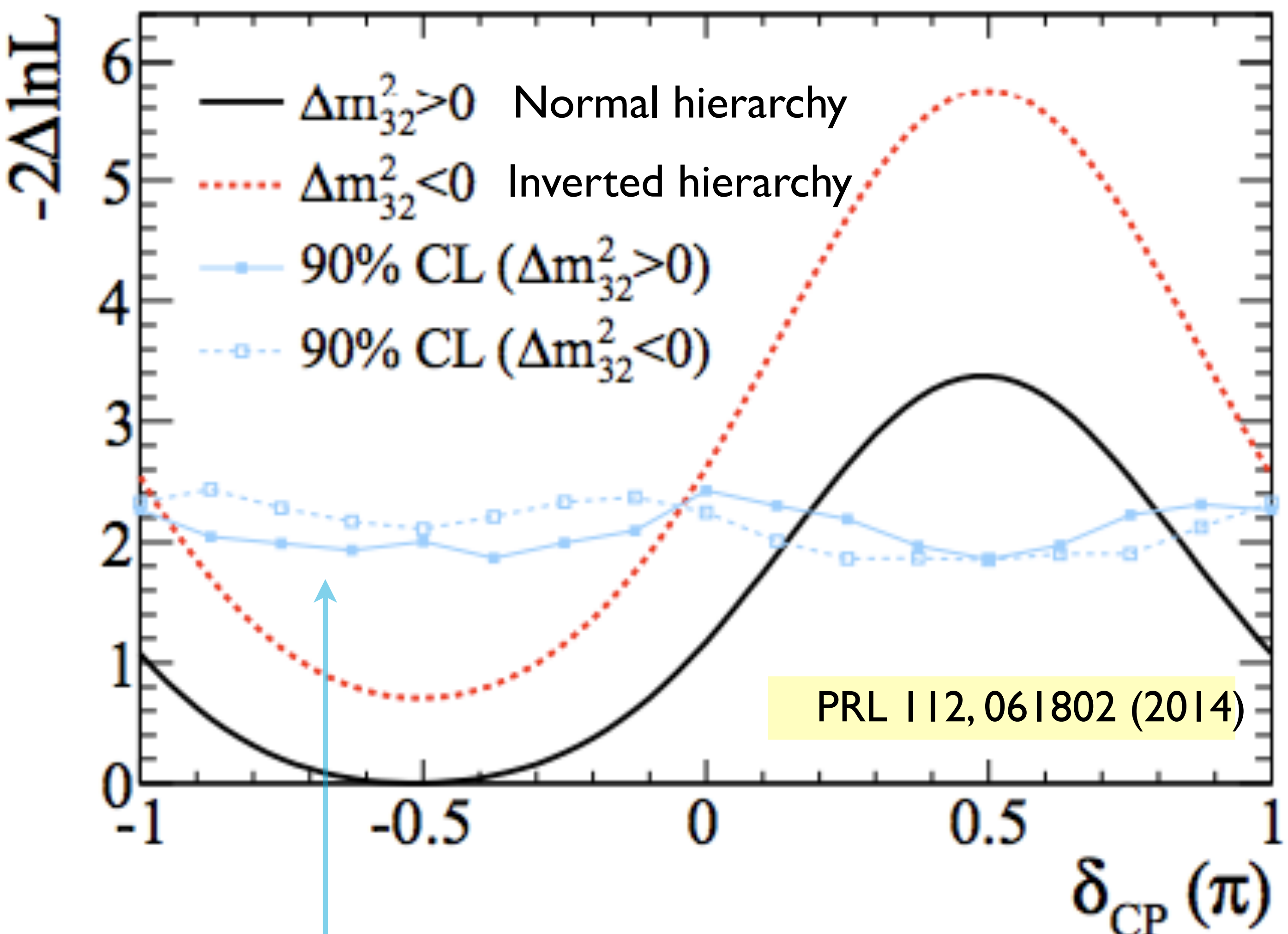
Dependence of the best fit values to the ϑ_{23} angle



Constraining δ_{CP}

- **By the T2K appearance analysis constraint on δ_{CP}** can be extracted considering other measurements (SBL reactors data) to constrain the values of ϑ_{13}
  - Addition of a further constraint term in the likelihood function

$$\mathcal{L} = \mathcal{L}_{norm} \times \mathcal{L}_{shape} \times \mathcal{L}_{syst} \times \mathcal{L}_{const}$$



Regions above the lines are excluded @90% CL

Excluded regions @ 90% CL

Normal hierarchy ($\Delta m^2_{32} > 0$):

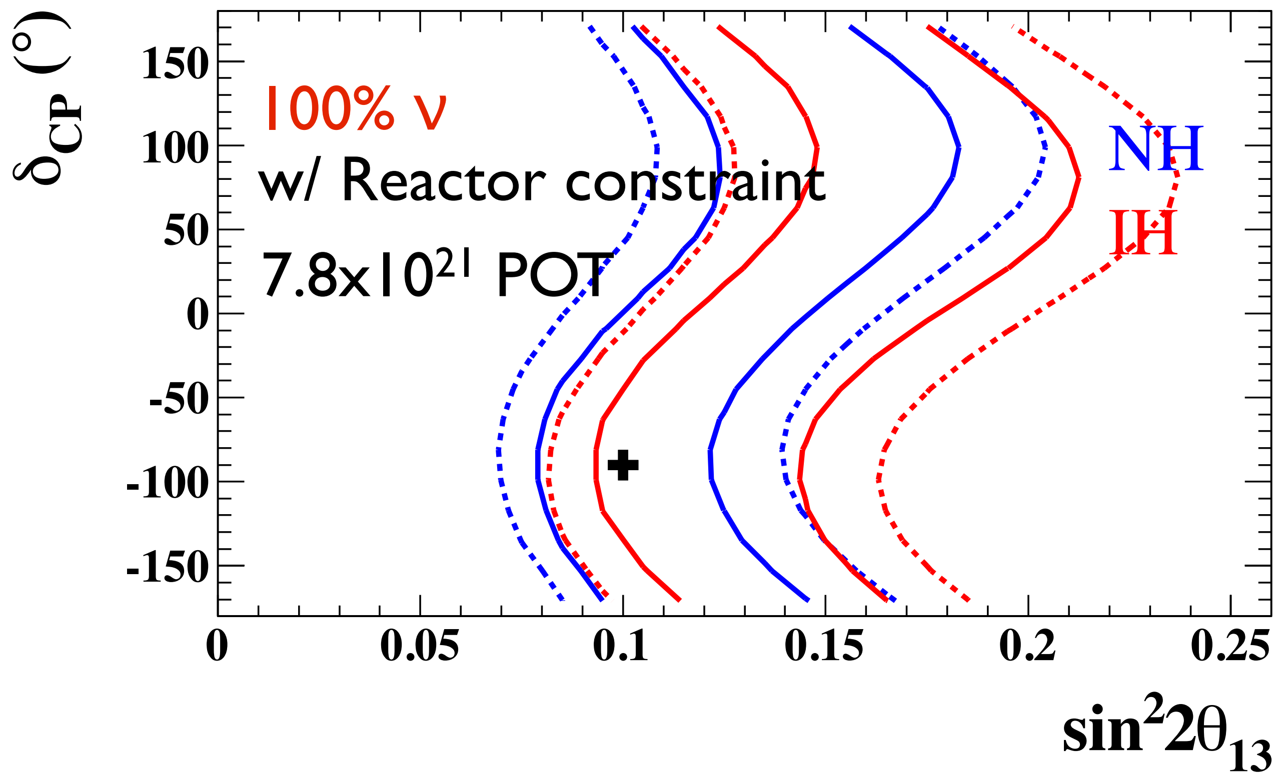
$0.19\ \pi < \delta_{CP} < 0.80\ \pi$

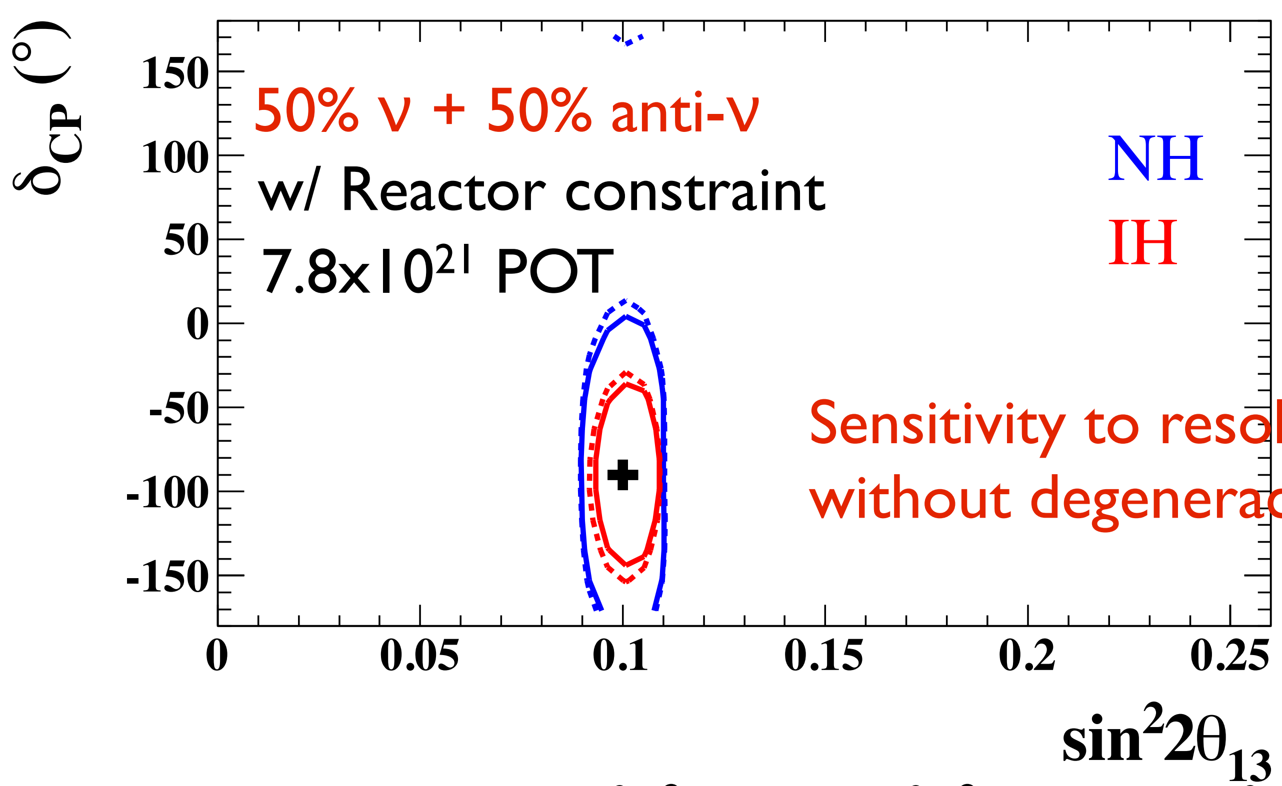
Inverted hierarchy ($\Delta m^2_{32} < 0$):

$-\pi < \delta_{CP} < -0.97\ \pi$

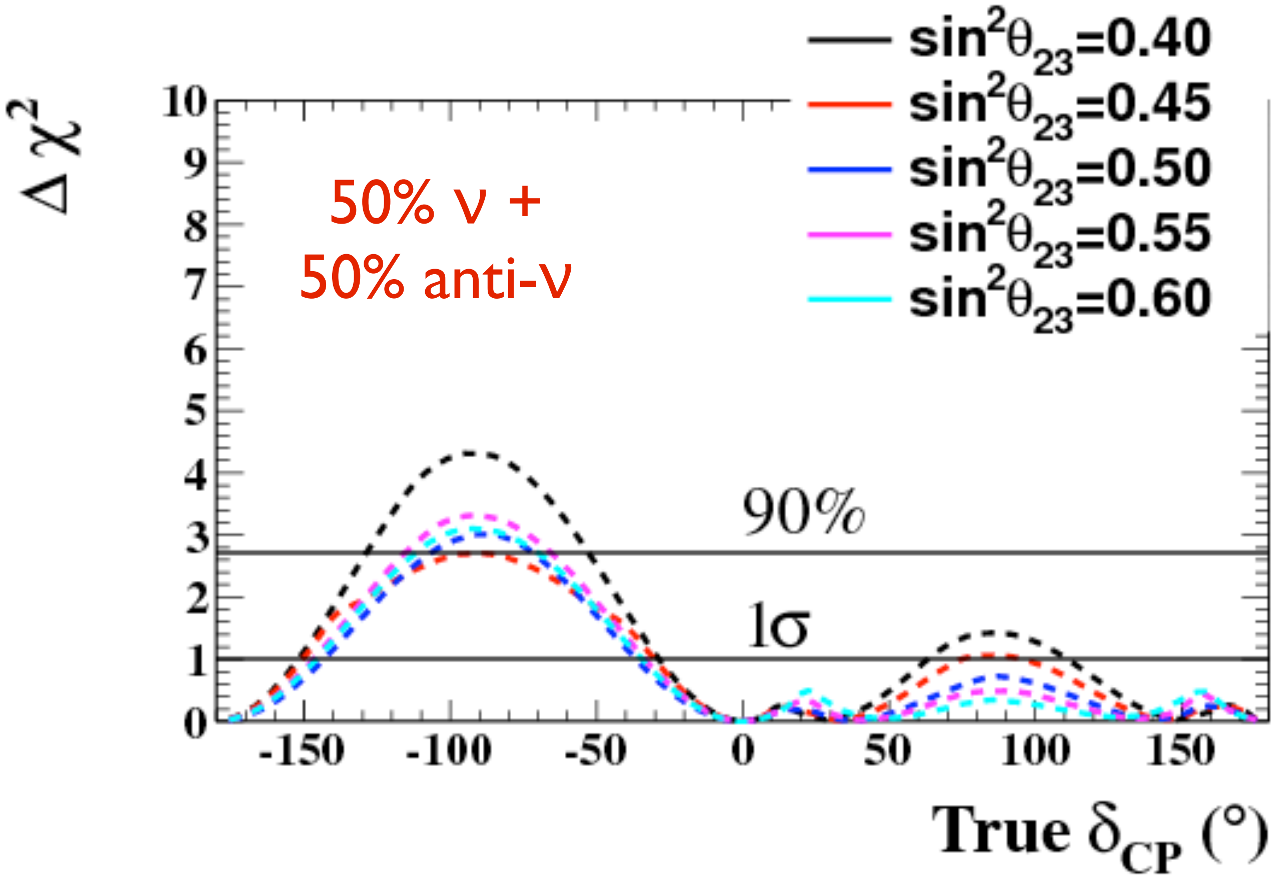
$-0.04 < \delta_{CP} < \pi$

T2K future sensitivity δ_{CP}





Sensitivity to resolve δ_{CP} without degeneracies

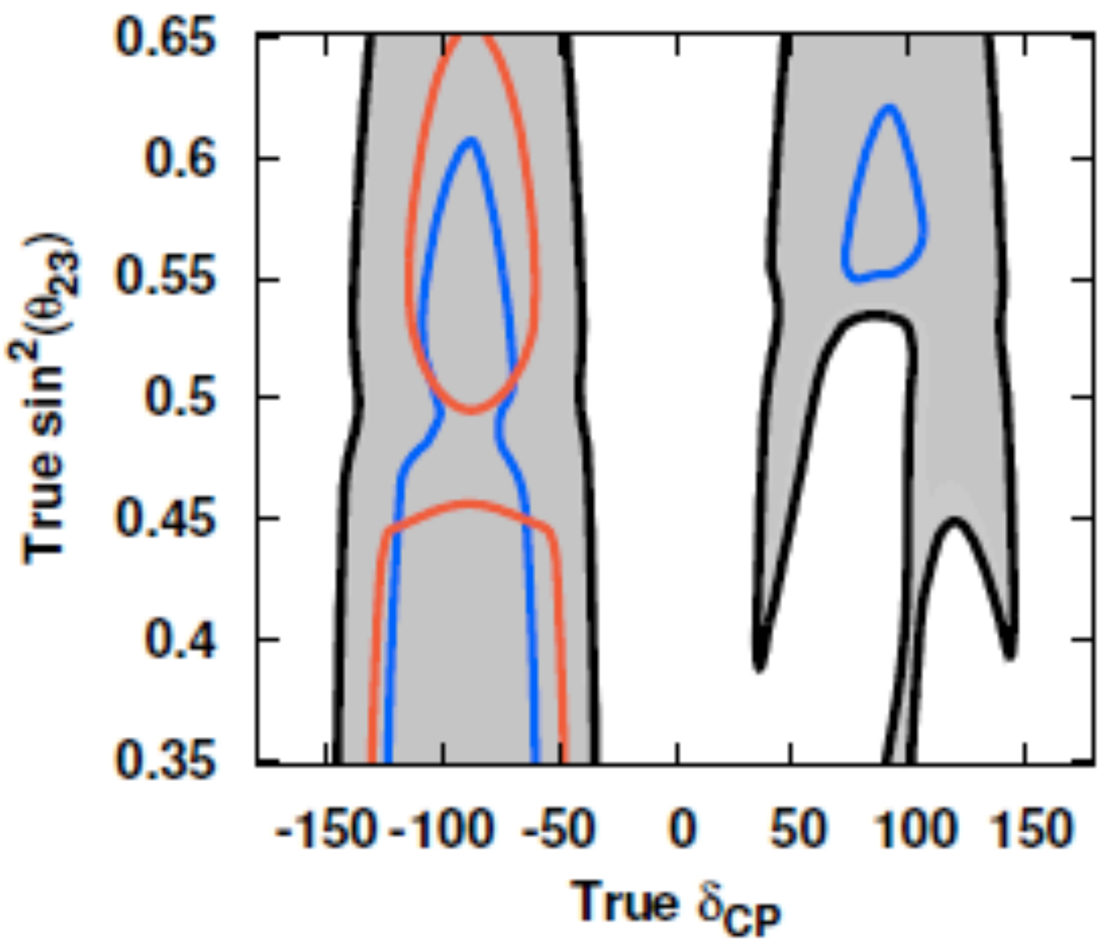


Assumed true value (**+**) for :
δ_{CP} =-90°, Normal Hierarchy

Assuming as true values : $\sin^2 2\vartheta_{13}$ =0.1, $\sin^2 2\vartheta_{23}$ =0.5, Δm^2_{32} = 2.4x10⁻³eV², Normal Hierarchy

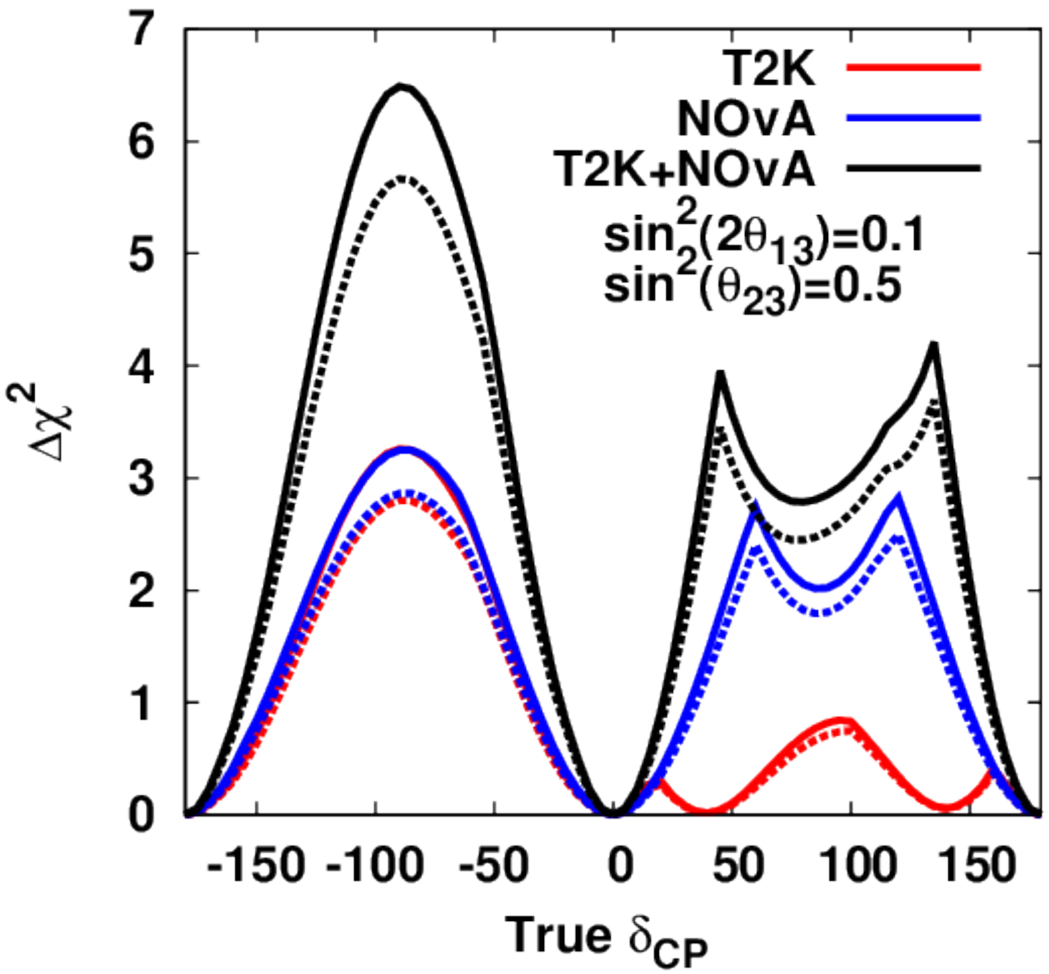
T2K+Nova Future sensitivity δ_{CP}

Region where δ_{CP} can be discovered at 90% CL



T2K alone | Nova alone | T2K+ Nova

Sensitivity to $\sin\delta \neq 0$



solid (dash) : w/o (w/) systematics

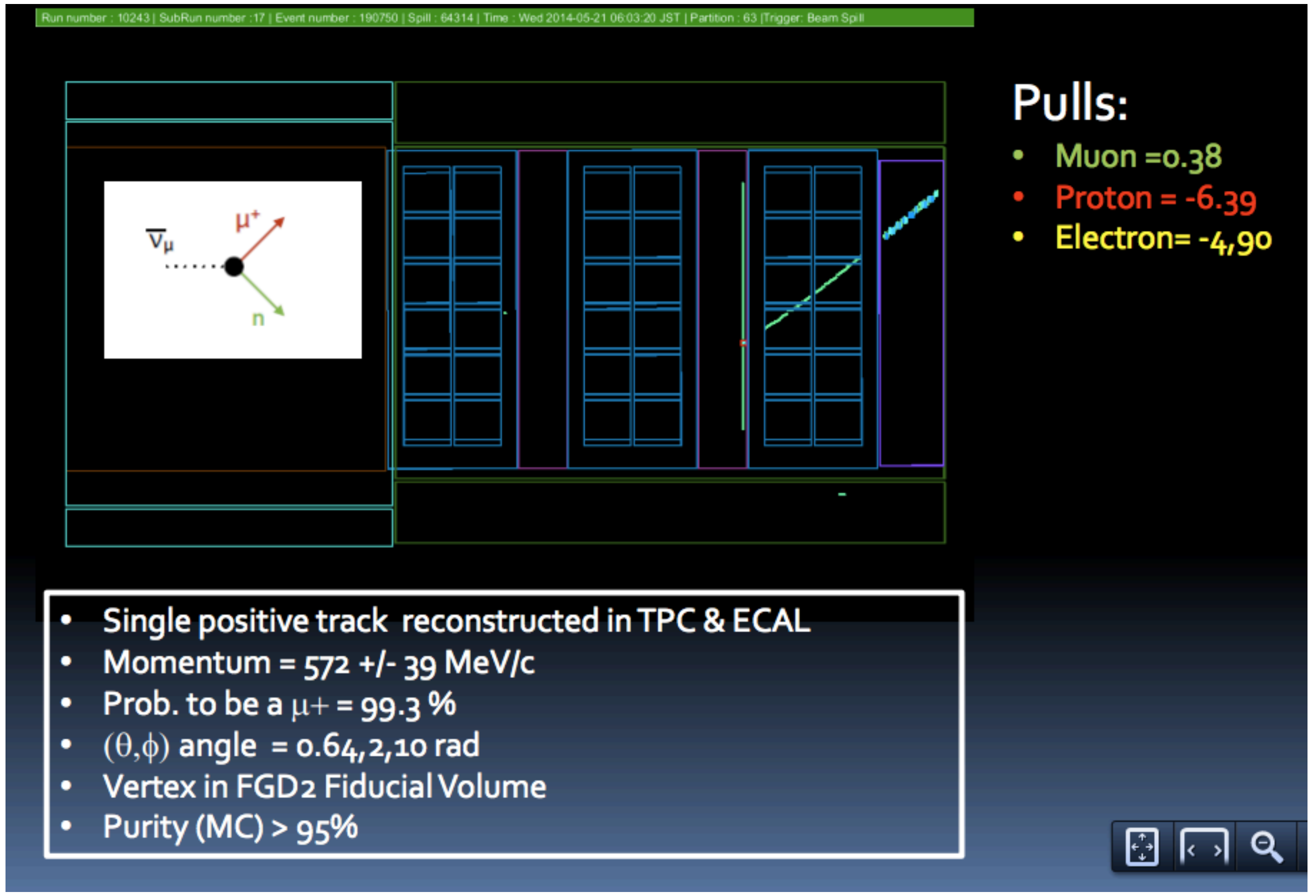
Assuming true values : $\sin^2 2\vartheta_{13} = 0.1$, $\Delta m^2_{32} = 2.4\times10^{-3}eV^2$

Conclusions

- T2K has provided for the first time some constraints to the still unknown oscillation parameter, δ_{CP}
- T2K results show a preference for a non-zero CP violation term and this tendency is confirmed and increasingly pronounced while performing global fits

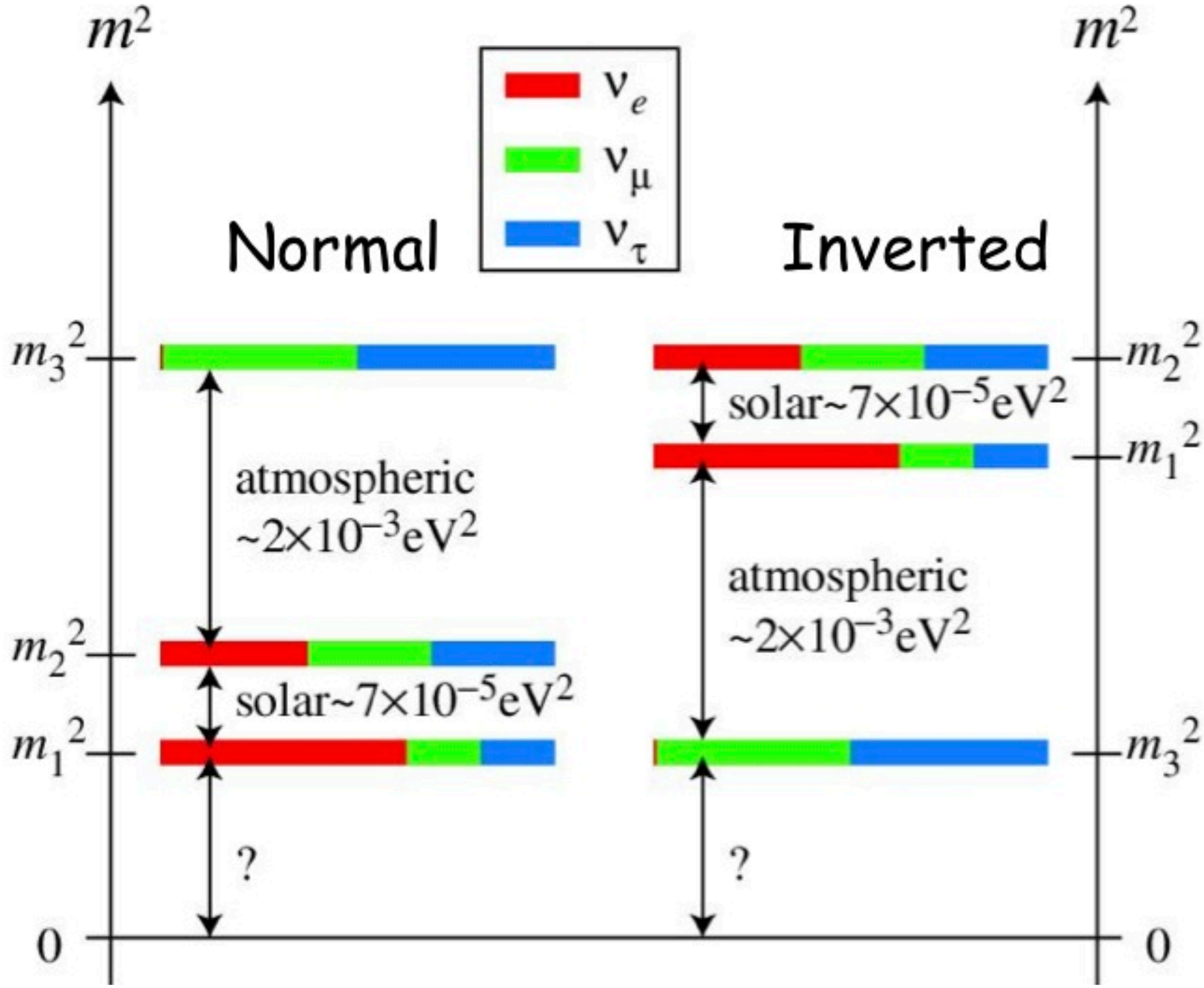
- Running in **anti-neutrino mode** and **combining the results with Nova** will enhance the power of T2K
- The data taken has recently restarted. This year **pilot run in anti-neutrino mode**

First anti-νμ candidate →

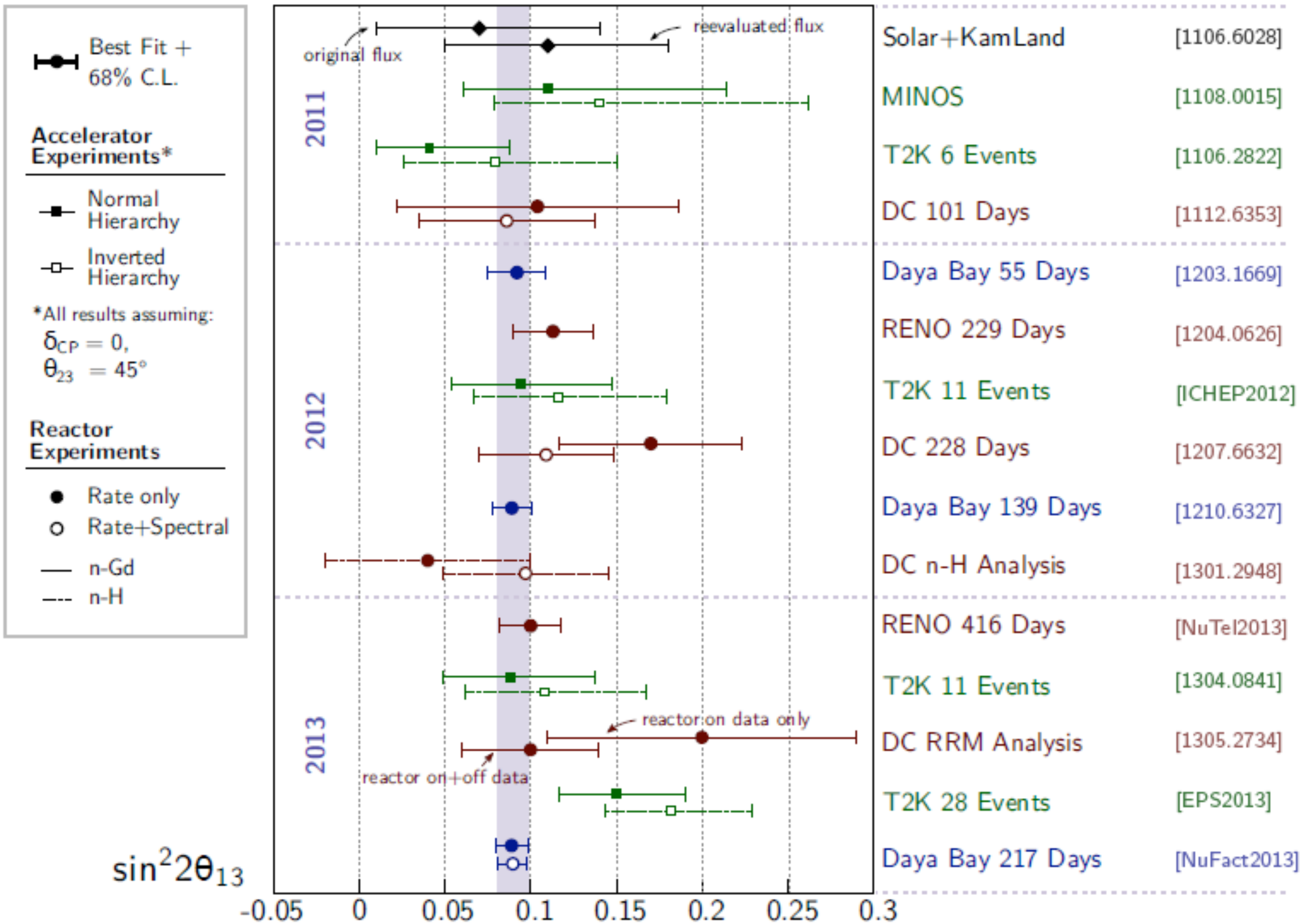


Back up

Mass Hierarchy



measuring ϑ_{13}: accelerator vs reactors



Compilation from Soeren Jetter (HEP), NuFact 2013

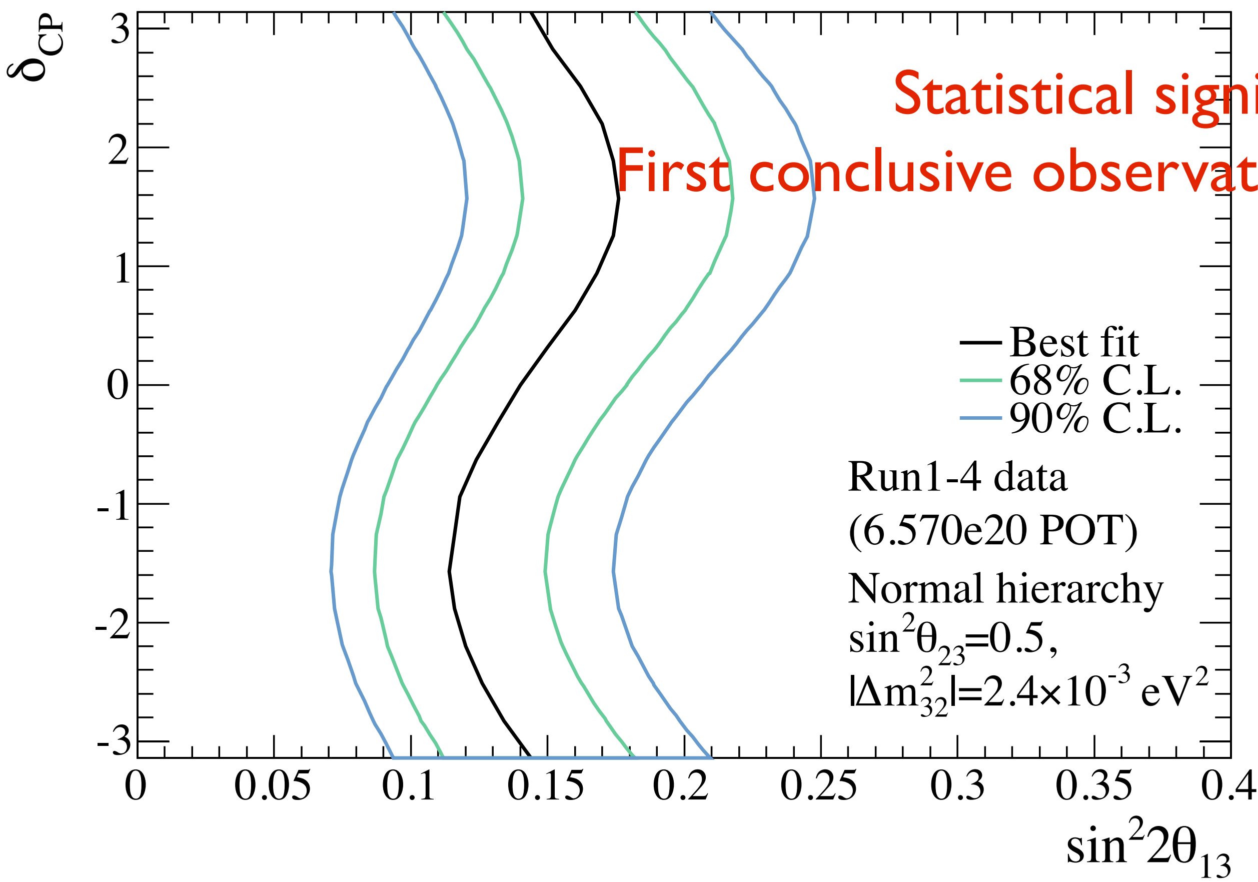
ν_e appearance

Nota Bene: plots are **1D contour**, showing the **allowed region** of $\sin^2 2\theta_{13}$ **for each value** of δ_{CP}

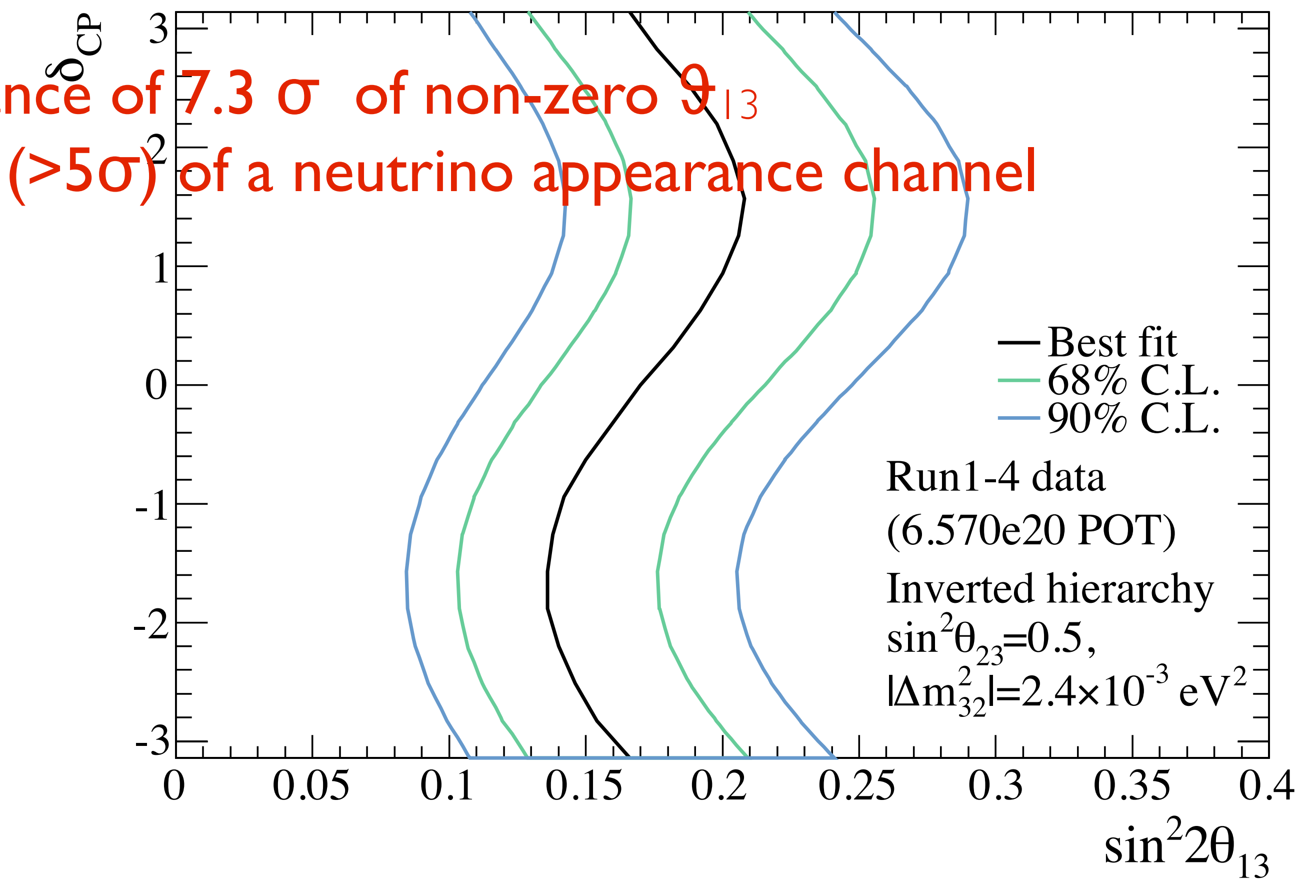
Statistical significance of 7.3 σ of non-zero ϑ_{13}

First conclusive observation (>5σ) of a neutrino appearance channel

Normal hierarchy



Inverted hierarchy



Best fit values estimated @ $\sin^2\vartheta_{12}=0.306$, $\Delta m^2_{21}=7.6\times10^{-5}\text{eV}^2$, $\sin^2\vartheta_{23}=0.5$, $|\Delta m^2_{32}|=2.4\times10^{-3}\text{eV}^2$

Best fit value :

$$\sin^2\theta_{13} = 0.140^{+0.038}_{-0.032}$$

Best fit value :

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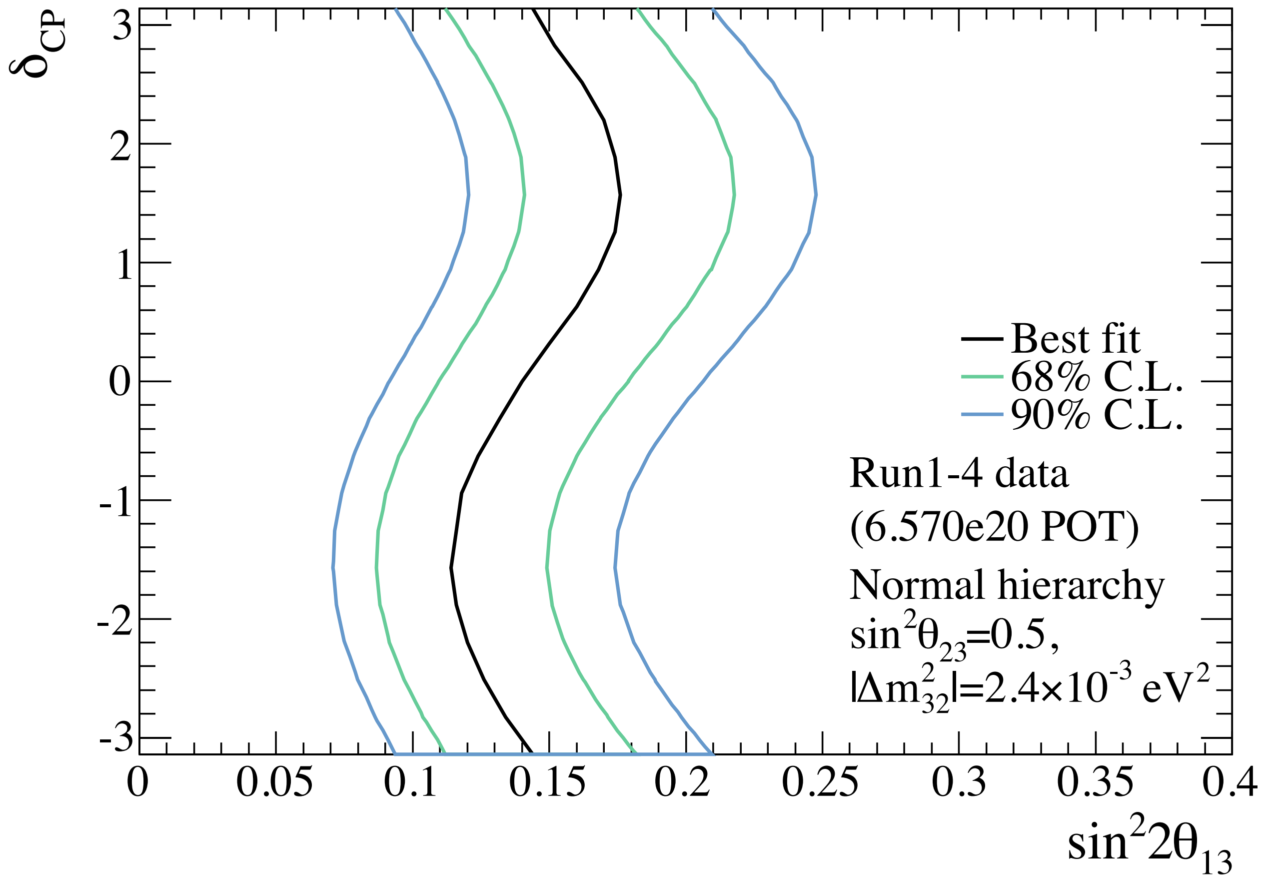
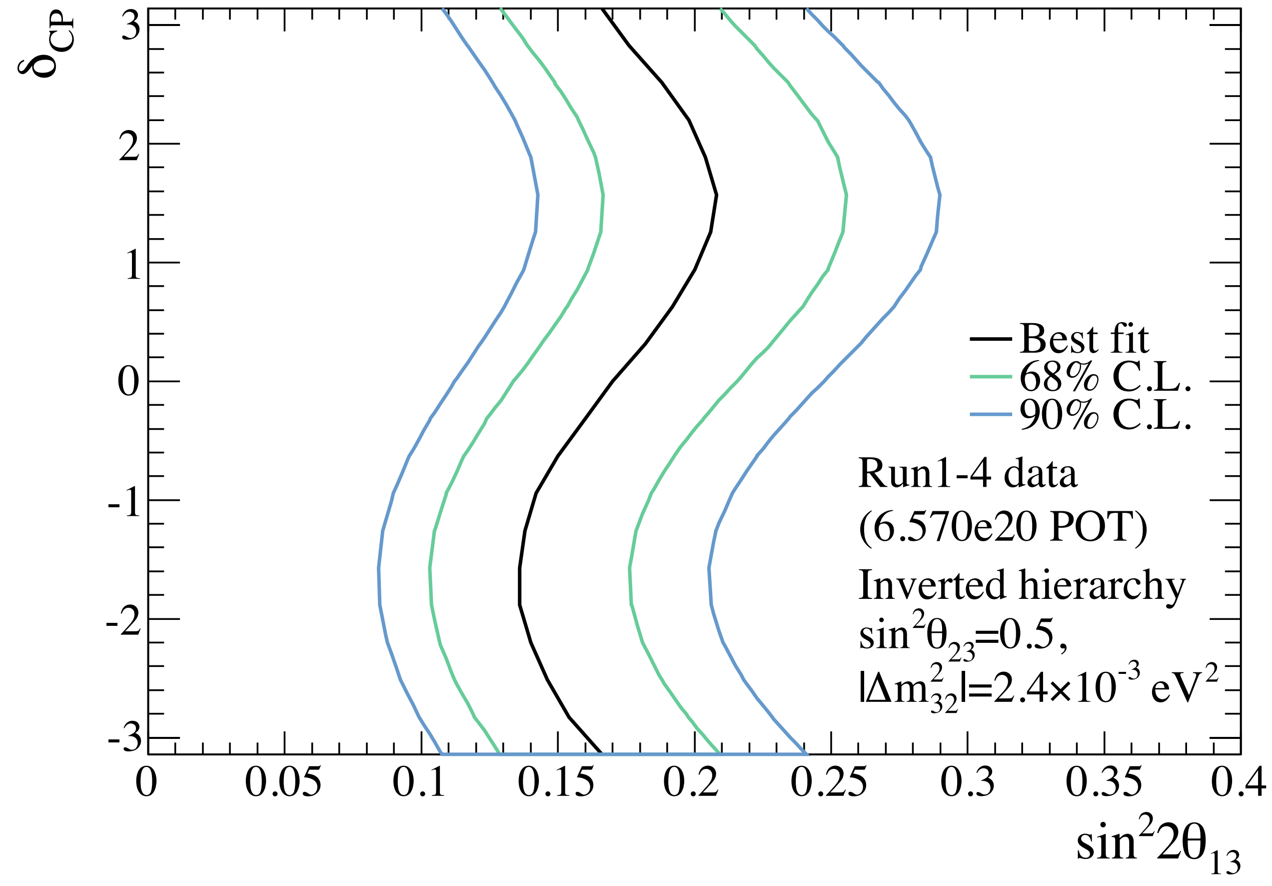

δ_{CP}
$\sin^2 2\theta_{13}$
Best fit
68% C.L.
90% C.L.
Run1-4 data
(6.570e20 POT)
Normal hierarchy
$\sin^2\theta_{23}$=0.5,
$|\Delta m^2_{32}|=2.4\times10^{-3}$ eV^2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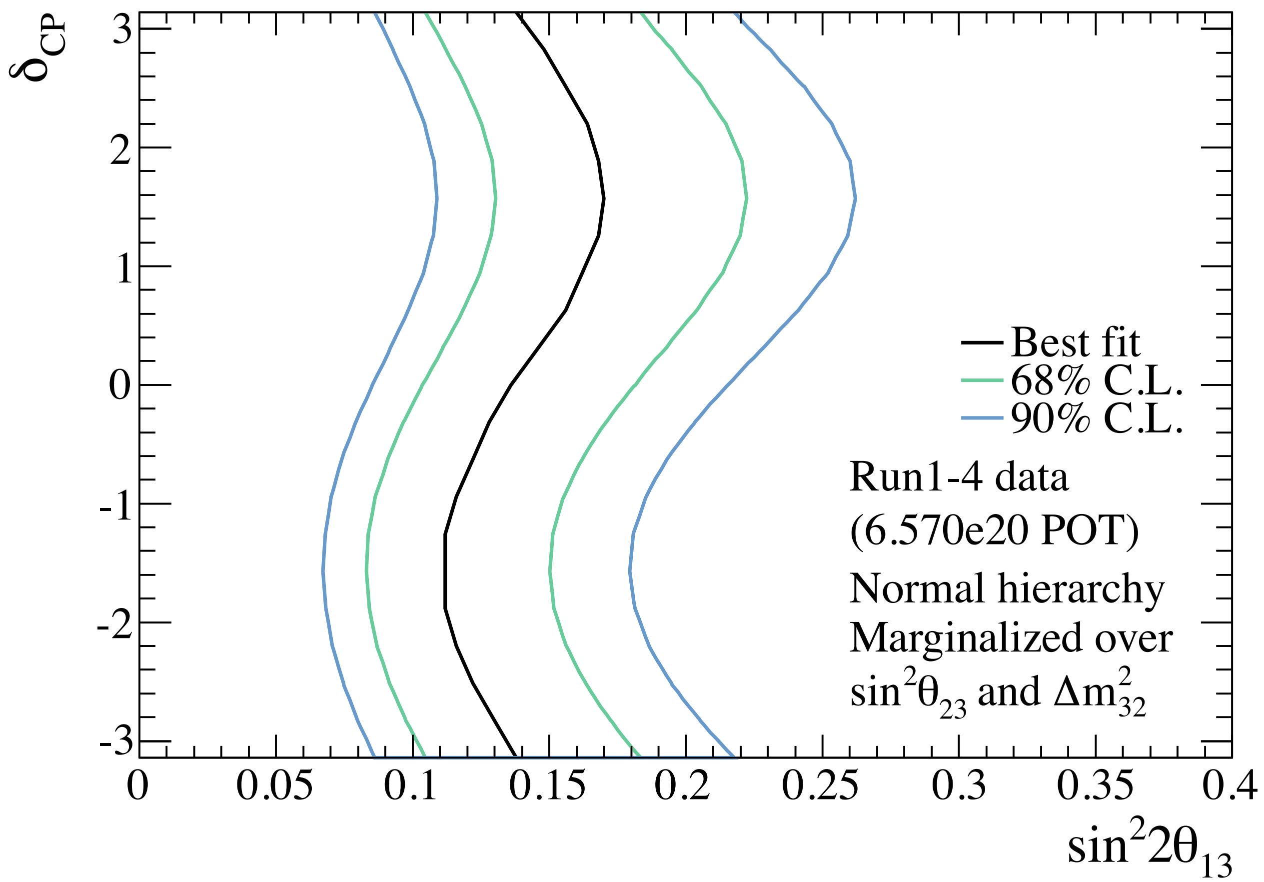
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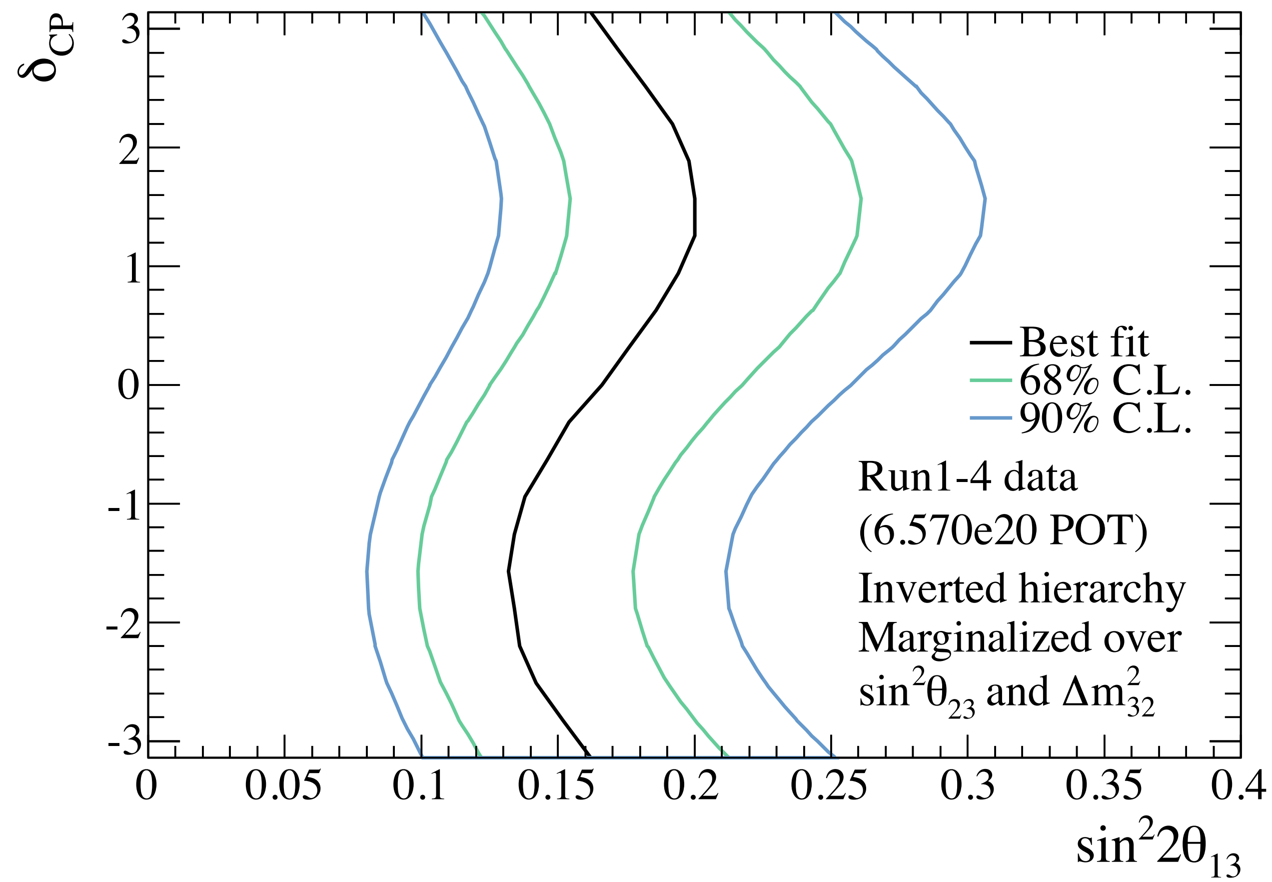
Normal hierarchy
Marginalized over
$\sin^2\theta_{23}$ and Δm^2_{32}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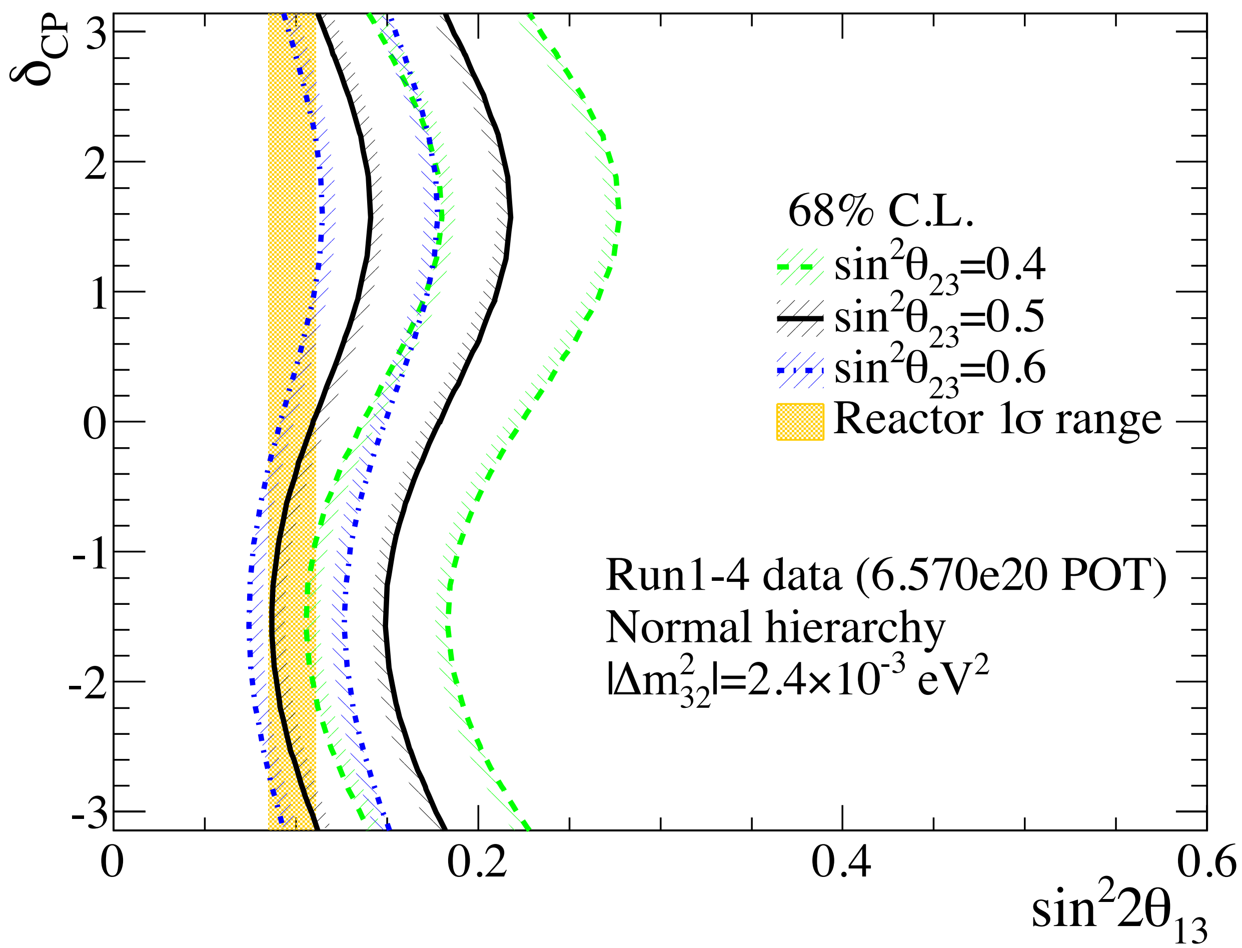
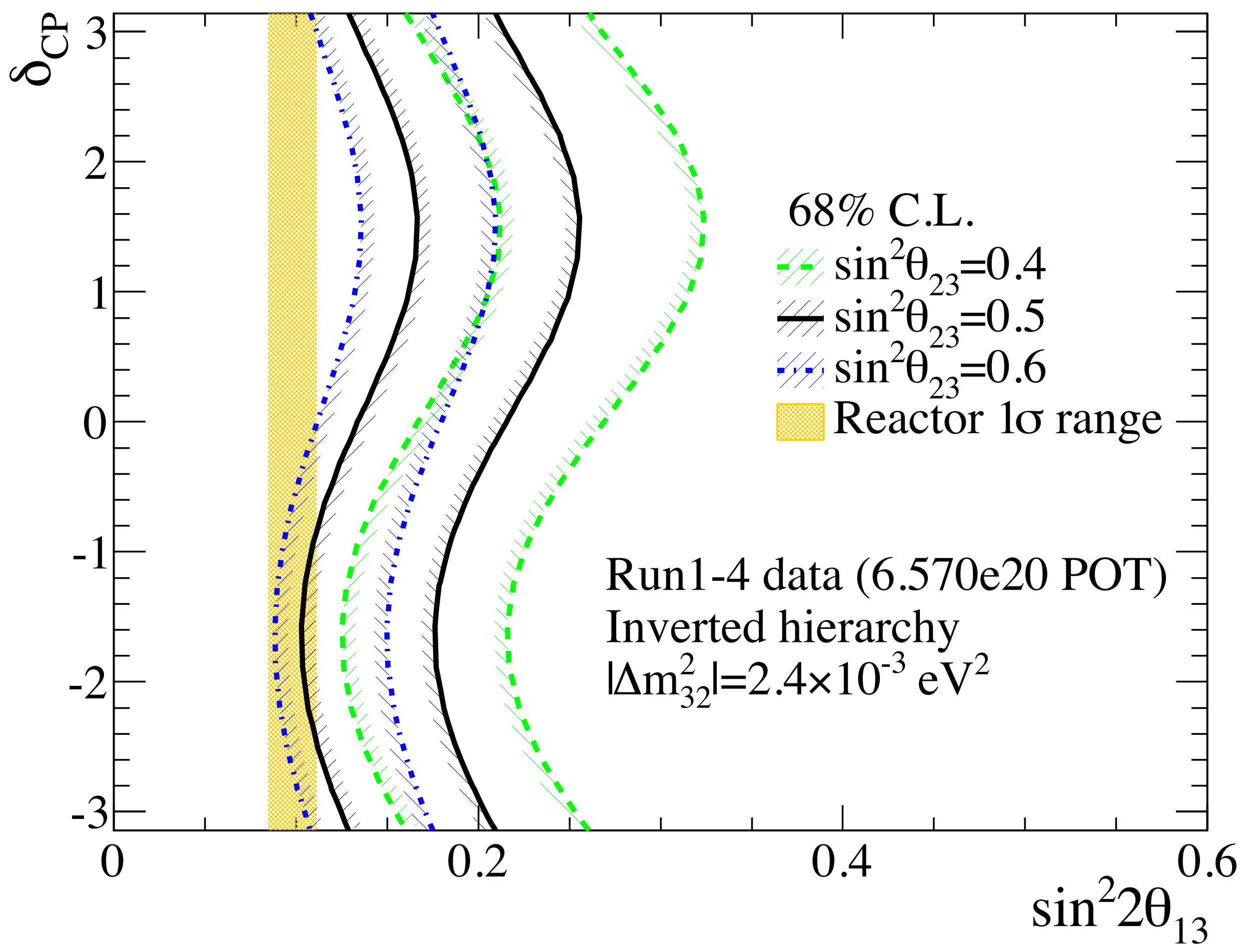
ν_e appearance



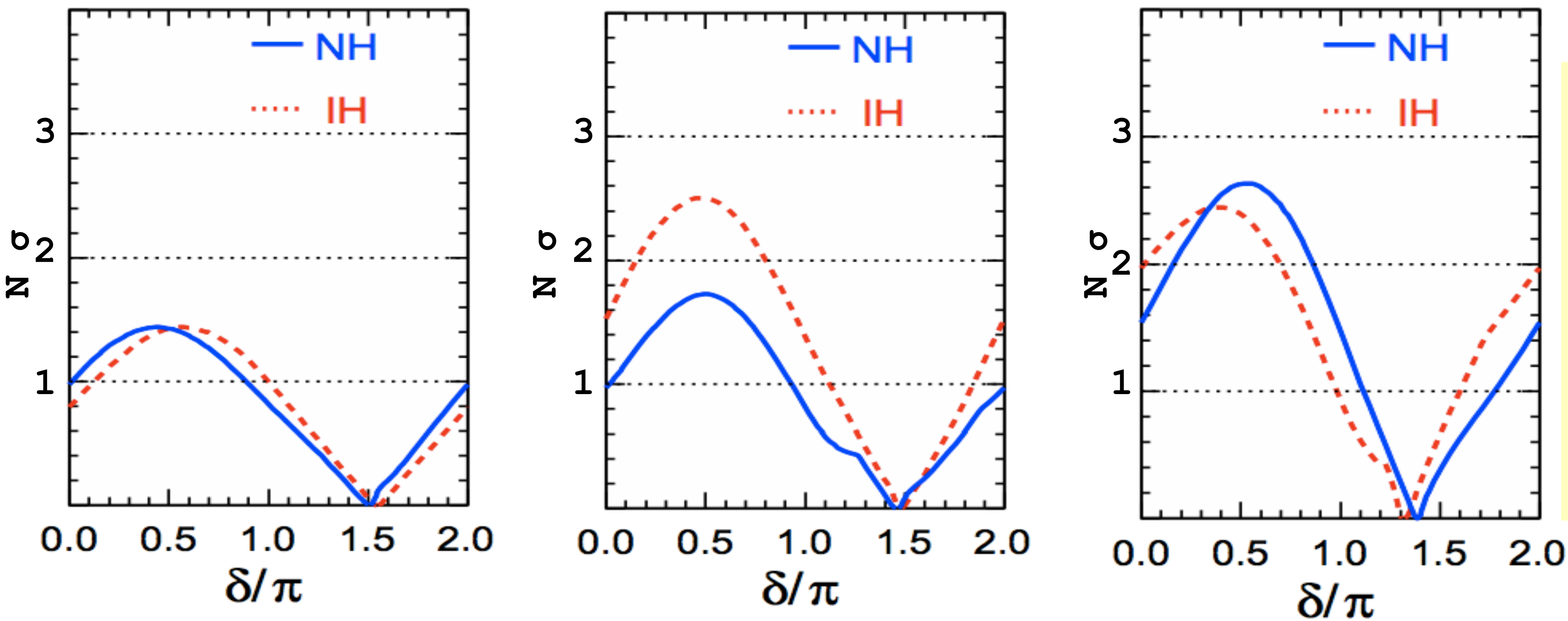


Global fits

Bounds on δ_{CP} parameter are given in standard deviation away from the best fit

$$N\sigma = \sqrt{\chi^2 - \chi^2_{min}}$$

LBL Acc + Solar +KamLand | LBL Acc + Solar +KamLand +SBL Reactors | LBL Acc + Solar +KamLand +SBL Reactors + SK atm



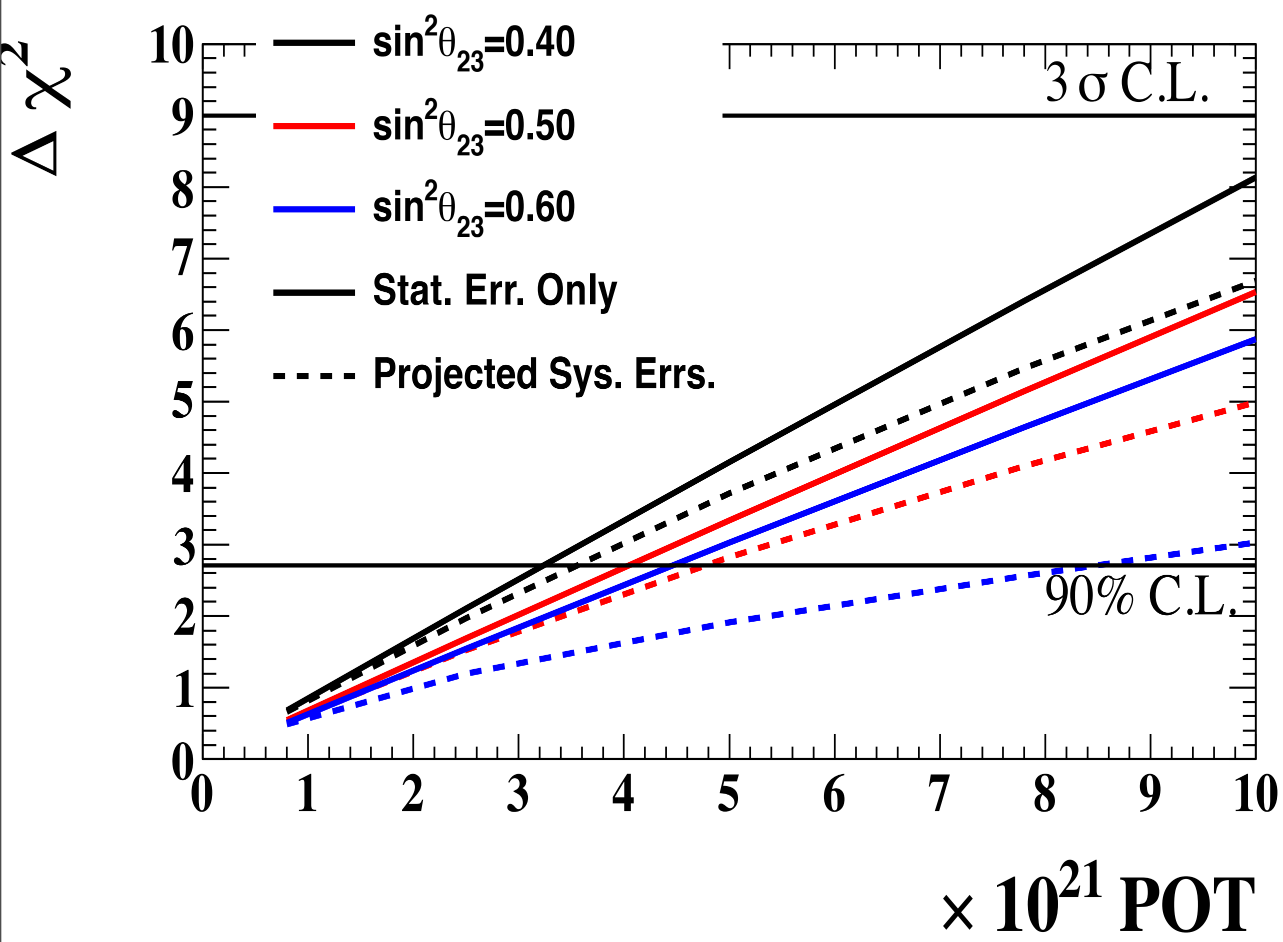
Capozzi, Fogli et al. arXiv:1312.2878

Where : **LBL Acc** : T2K, MINOS
Solar : SNO, BOREXINO
SBL Reactors : Daya Bay , RENO
Atmospherics : SuperKamiokande

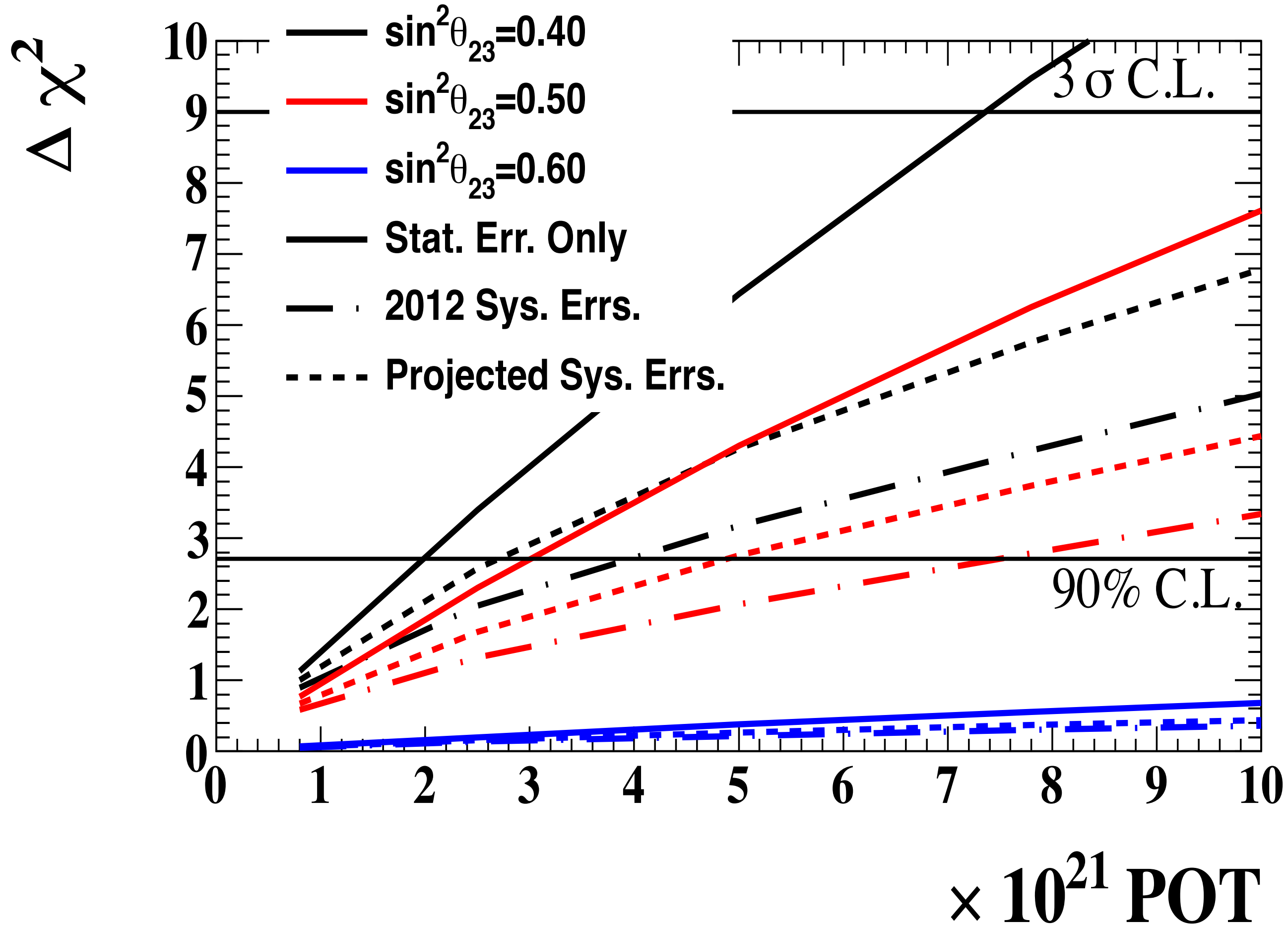
Sensitivity vs POT

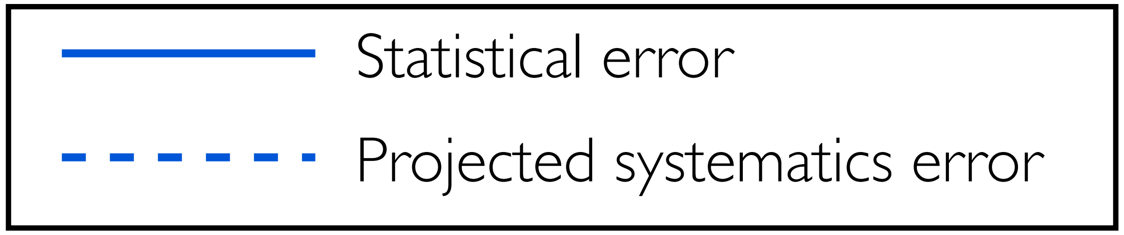
T2K sensitivity to reject the null hypothesis ($\sin\delta_{CP} = 0$) as a function of POT

100% ν



50% ν + 50% anti-ν





The sensitivity is computed for δ_{CP} = +90° and **Inverted Hierarchy**

Future sensitivities studies

- using signal efficiency, background and systematics from 2012 analyses
    - fits are performed by calculation dchi2 using a binned likelihood method for the appearance and disappearance reconstructed energy spactra
    - when performing fits, all oscillation parameters but sin22theta_12 and Deltam2_12 are considered unknown
    - when reactor constraints are used the error is fixed at 0.005 (error from Daya Bay 2012 analyses)

Parameter	$\sin^2 2\theta_{13}$	δ_{CP}	$\sin^2 \theta_{23}$	Δm^2_{32}	Hierarchy	$\sin^2 2\theta_{12}$	Δm^2_{12}
Nominal Value	0.1	0	0.5	2.4×10^{-3} eV^2	normal	0.8704	7.6×10^{-5} eV^2