長基線ニュートリノ振動実験とニュートリノの質量階層構造

CPもね(｡･ω･｡)ﾉ♡

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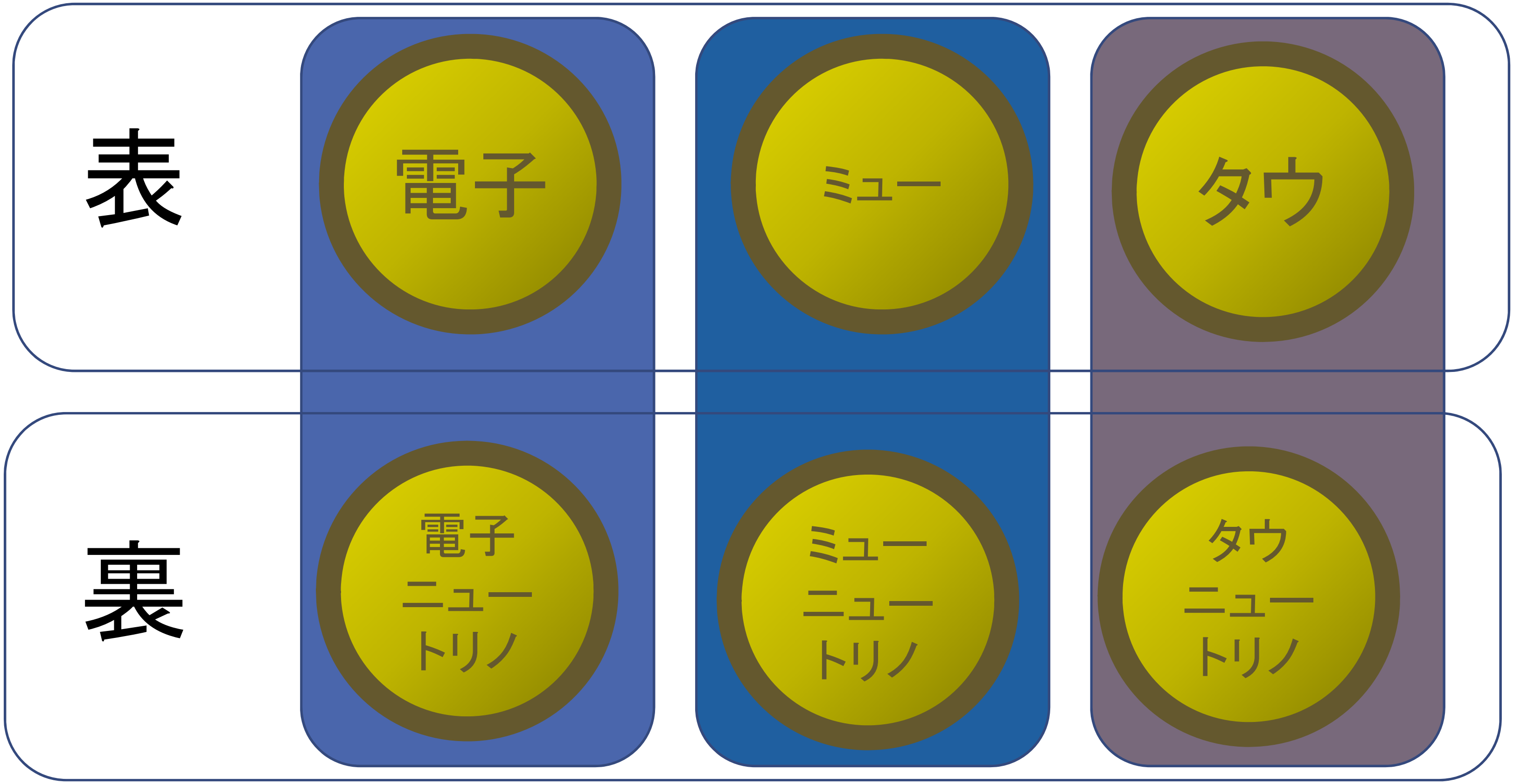


電子、ミュー粒子、タウ粒子それぞれに対応したニュートリノがある。
っていうか、我々は

電子の裏側を電子ニュートリノ

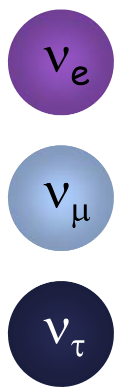
ミュー粒子の裏側をミューニュートリノ

タウ粒子の裏側をタウ粒子

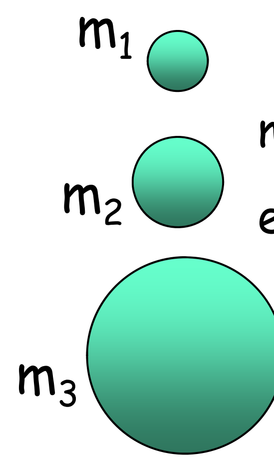
と名付けた。(1960年代)

名前を付けた後に質量があることがわかった。フレーバー ≠ 質量の固有状態

Weak eigenstates



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \mathrm{U}_{\mathrm{MNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



mass eigenstates

クォークも同じ。
uクォーク の相棒は、d, c, t クォークの重ね合わせ状態。

混合行列はユニタリー行列、すなわち複素数を含み粒子と反粒子で異なる

N世代の場合に、物理的に意味を持つ自由度は
N(N-1)/2の実数 (オイラー角)と(N-1)(N-2)/2の複素位相角で表される。

- N=2 → 1個の実数のみ (θ_c) CP対称性や破れない！
- N=3 → 3個の混合角と1個の複素位相角

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

$$(c_{ij} = \cos\theta_{ij}, s_{ij} = \sin\theta_{ij})$$

$\theta_{12}, \theta_{23}, \theta_{13}$
$+ \delta$ (+2 Majorana phase)
$\Delta m_{12}, \Delta m_{23}, \Delta m_{13}$

クォークとレプトンの混合行列の比較

quark

lepton

$$U_{CKM} \approx \begin{pmatrix} 0.97 & 0.23 & 0.004 \\ 0.23 & 1.01 & 0.04 \\ 0.008 & 0.04 & 0.89 \end{pmatrix} \quad U_{PMNS} \approx \begin{pmatrix} 0.82 & 0.55 & 0.16 \\ -0.49 & 0.52 & 0.55 \\ 0.20 & -0.65 & 0.70 \end{pmatrix}$$

CKM (quark sector) δ~60°
PMNS (lepton sector) δ~?

Leptonic CPV can be much larger than Quark's

$\delta_{CP}^{CKM} \sim 60° \sim 70°$ looks large, but cannot explain matter-dominant universe.

δ_{CP} is dependent on definition.

Jarlskog Invariant : independent of definition. show the size of CP violation effect.

$$J_{CP} \equiv Im\left(U_{\mu 3} U_{e3}^{*} U_{e2} U_{\mu 2}^{*}\right) = \frac{1}{8} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \cos\theta_{13} \sin\delta_{CP}$$

$$J_{CP}^{CKM} \approx 3 \times 10^{-5}$$

$$J_{CP}^{PMNS} \approx 0.03 \sin\delta_{CP}$$

PDG2015 "NEUTRINOMASS,MIXING, AND OSCILLATIONS"

A value of $|\sin\theta_{13}\sin\delta| \gtrsim 0.09$, and thus $\sin\theta_{13} \gtrsim 0.09$, is a necessary condition for a successful "flavoured" leptogenesis with hierarchical heavy Majorana neutrinos when the CP violation required for the generation of the matter-antimatter asymmetry of the Universe is provided entirely by the Dirac CP violating phase in the neutrino mixing matrix [191]. This condition is comfortably compatible both with the measured value of $\sin^2\theta_{13}$ and with the best fit value of $\delta \cong 3\pi/2$.

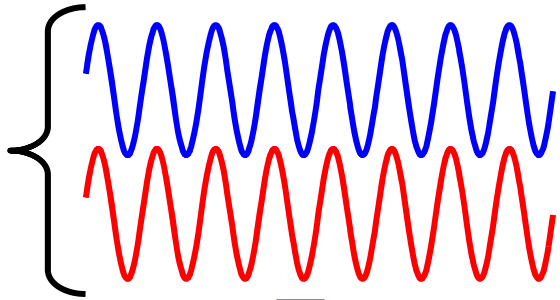
$|\sin\theta_{13}\sin\delta| \geq 0.09 \rightarrow |\sin\delta| \geq 0.58$

ニュートリノ振動でCPの破れが見えたからといって、即物質優勢宇宙を説明できる訳ではないが、物質優勢宇宙を説明できるくらい大きなCPの破れの源となる得る、ということ。

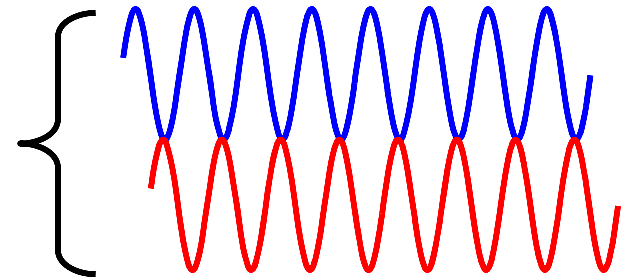
全貌を理解するには、Majorana位相も重要。

ニュートリノ振動

ミュー
ニュートリノ

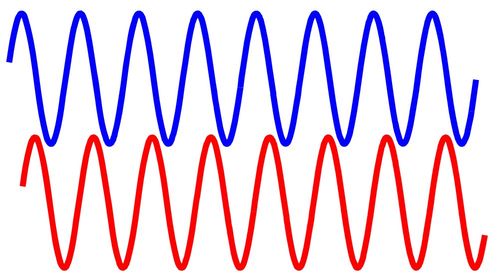


タウ
ニュートリノ

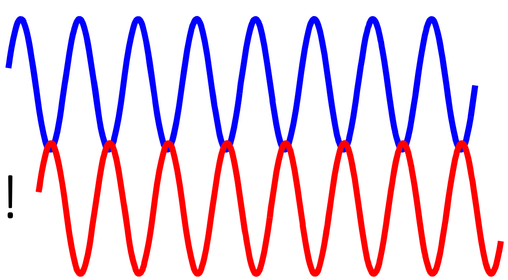


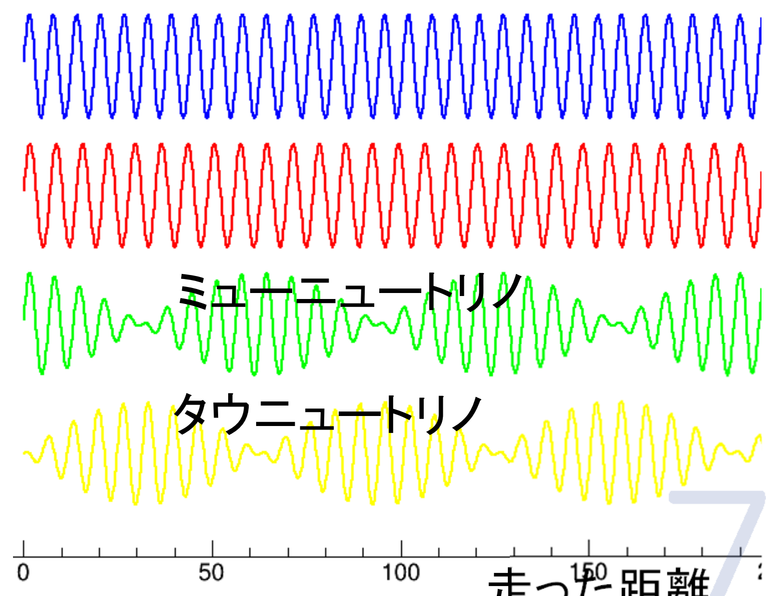
質量Aの波と質量Bの波は異なる速さで進む

数百キロメータ
進むうちに



タウニュートリノ!





Appearance vs. Disappearance

Why disappear?

How is the neutrino flavor identified?

Neutrino flavor is tagged via charged current (CC) interaction.

threshold energy

$\nu_e + n \rightarrow e^- + p$	0 MeV for ν_e
$\nu_\mu + n \rightarrow \mu^- + p$	110 MeV for ν_μ
$\nu_\tau + n \rightarrow \tau^- + p$	3.5 GeV for ν_τ

At $E\nu$ < Ethreshold,

that flavor is not observed and recognized as disappearance.

$$\left|\nu_\alpha\right\rangle = U_{\alpha 1}\left|\nu_1\right\rangle + U_{\alpha 2}\left|\nu_2\right\rangle + U_{\alpha 3}\left|\nu_3\right\rangle = U_{\alpha i}\left|\nu_i\right\rangle$$

エネルギーEで、L飛ぶと

$$\left|\nu_\alpha(L)\right\rangle = U_{\alpha i} e^{-i\frac{m_i^2}{2E}L}$$

$$\therefore \left\langle \nu_\beta \mid \nu_\alpha(L)\right\rangle = U^*_{\beta i} U_{\alpha i} e^{-i\frac{m_i^2}{2E}L}$$

β=αの時

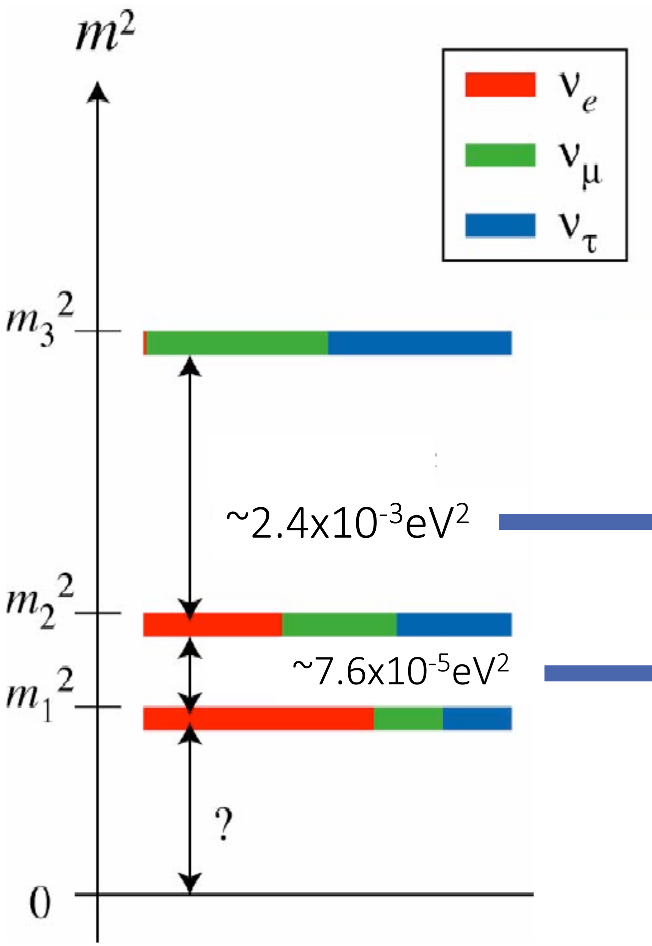
$$\left\langle \nu_\alpha \mid \nu_\alpha(L)\right\rangle = \left|U_{\alpha i}\right|^2 e^{-i\frac{m_i^2}{2E}L}$$

！！！混合行列の実数部しかない！
CPが破れない！！！
CPの破れを測るには出現が必要！

二世代の場合

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2}{E}L\right)$$

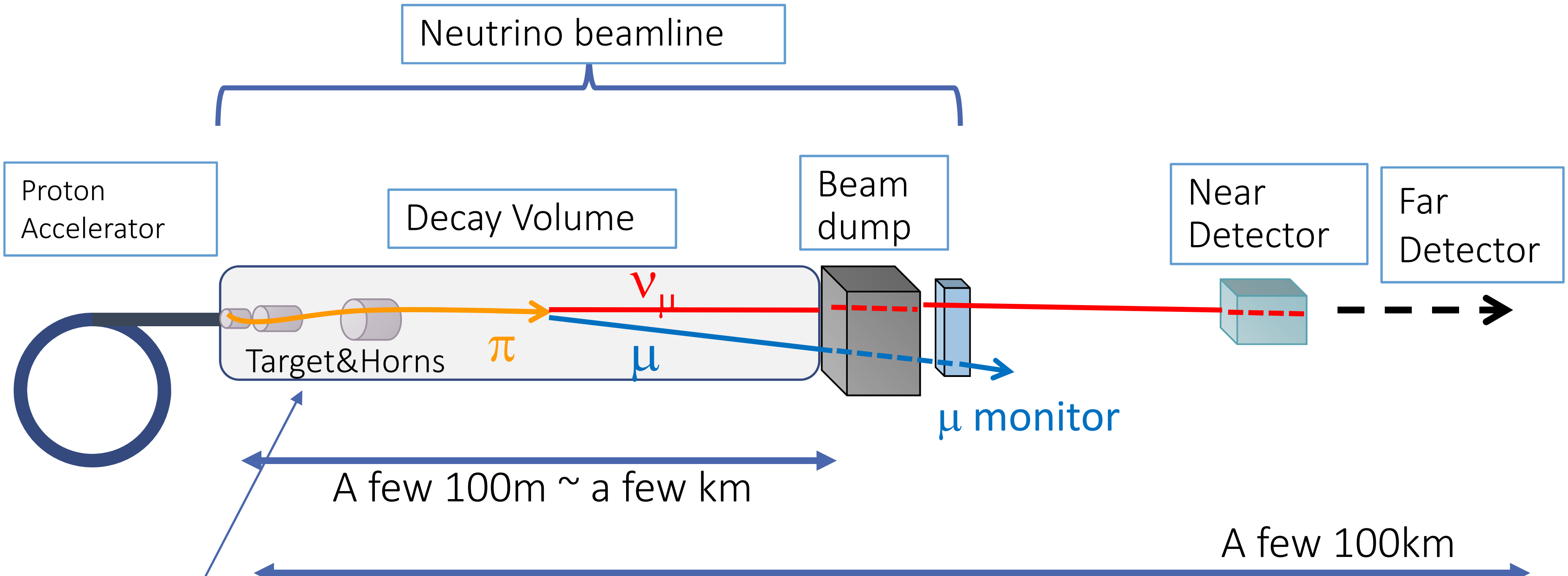
基線長



~300 km @ Eν=700 MeV

~50 km @ Eν=3 MeV

加速器ニュートリノ振動実験



ホーンの電流の向きを変えることで、ミューオンニュートリノを主成分としたビームか反ミューオンニュートリノを主成分んとしたビームかを切り替えられる。

Example:
~1ν/cm^2/s at T2K Far detector(295km away)
(@750kW proton beam power)

加速器長基線ニュートリノ実験

3-flavor Oscillation (simplified)

L is too small,
or E is too high
for $\Delta m_{21}{}^2$ to oscillate

Oscillation Probabilities when $|\Delta m_{32}^2| \frac{L}{4E} \sim \frac{\pi}{2}$

neglect $\Delta m_{21}{}^2$ term because $\Delta m_{21}^2 \ll |\Delta m_{32}^2| \approx |\Delta m_{31}^2|$

- θ_{23} :ν_μ disappearance

$$P_{\mu \to \mu} \approx 1 - \sin^2 2\theta_{23} \sin^2\left(1.27 \Delta m^2 L / E_\nu\right)$$

$$\Delta m^2 \approx \Delta m_{23}^2 \approx \Delta m_{13}^2$$

Common

- θ_{13}:ν_e appearance

$$P_{\mu \to e} \approx \sin^2 \theta_{23} \cdot \sin^2 2\theta_{13} \cdot \sin^2\left(1.27 \Delta m^2 L / E_\nu\right)$$

ν_e appearance (complete version in vacuum)

$$P(\nu_\mu \to \nu_e) = 4C_{13}{}^2 S_{13}{}^2 S_{23}{}^2 \sin^2\Phi_{31}$$

Leading including

$$+8C_{13}{}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cos\Phi_{32} \sin\Phi_{31} \sin\Phi_{21}$$

CP conserving

$$-8C_{13}{}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \boxed{\sin\delta} \sin\Phi_{32} \sin\Phi_{31} \sin\Phi_{21}$$

CP violating

$$+4S_{12}{}^2 C_{13}{}^2 (C_{12}{}^2 C_{23}{}^2 + S_{12}{}^2 S_{23}{}^2 S_{13}{}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta) \sin^2\Phi_{21}$$

Solar

$\theta_{12} = 33.6^\circ \pm 1.0^\circ$

$\theta_{23} = 45^\circ \pm 6^\circ$ (90%CL)

$\theta_{13} = 9.1^\circ \pm 0.6^\circ$

$$\Phi_{ij} = \frac{\Delta m_{ij}^2 L}{4E}$$

Max. 27% asymmetry (violation) by CP phase for $\theta_{13} = 9.1^\circ$, $\theta_{23}=45^\circ$

ν_e appearance (complete version in vacuum)

At oscillation maximum,

$$P(\nu_\mu \rightarrow \nu_e) = 4C_{13}{}^2 S_{13}{}^2 S_{23}{}^2 \sin^2 \Phi_{31}$$ θ13

~~$$+8C_{13}{}^2 S_{12}S_{13}S_{23}(C_{12}C_{23}\cos\delta - S_{12}S_{13}S_{23})\cos\Phi_{32}\sin\Phi_{31}\sin\Phi_{21}$$~~ CPC

$$-8C_{13}{}^2 C_{12}C_{23}S_{12}S_{13}S_{23}\sin\delta\sin\Phi_{32}\sin\Phi_{31}\sin\Phi_{21}$$ CPV

~~$$+4S_{12}{}^2 C_{13}{}^2 (C_{12}{}^2 C_{23}{}^2 + S_{12}{}^2 S_{23}{}^2 S_{13}{}^2 - 2C_{12}C_{23}S_{12}S_{23}S_{13}\cos\delta)\sin^2\Phi_{21}$$~~ Solar

$C_{ij} = \cos\theta_{ij}, S_{ij} = \sin\theta_{ij},\qquad \Phi_{ij} = \Delta m_{ij}^2 \frac{L}{4E_\nu}$

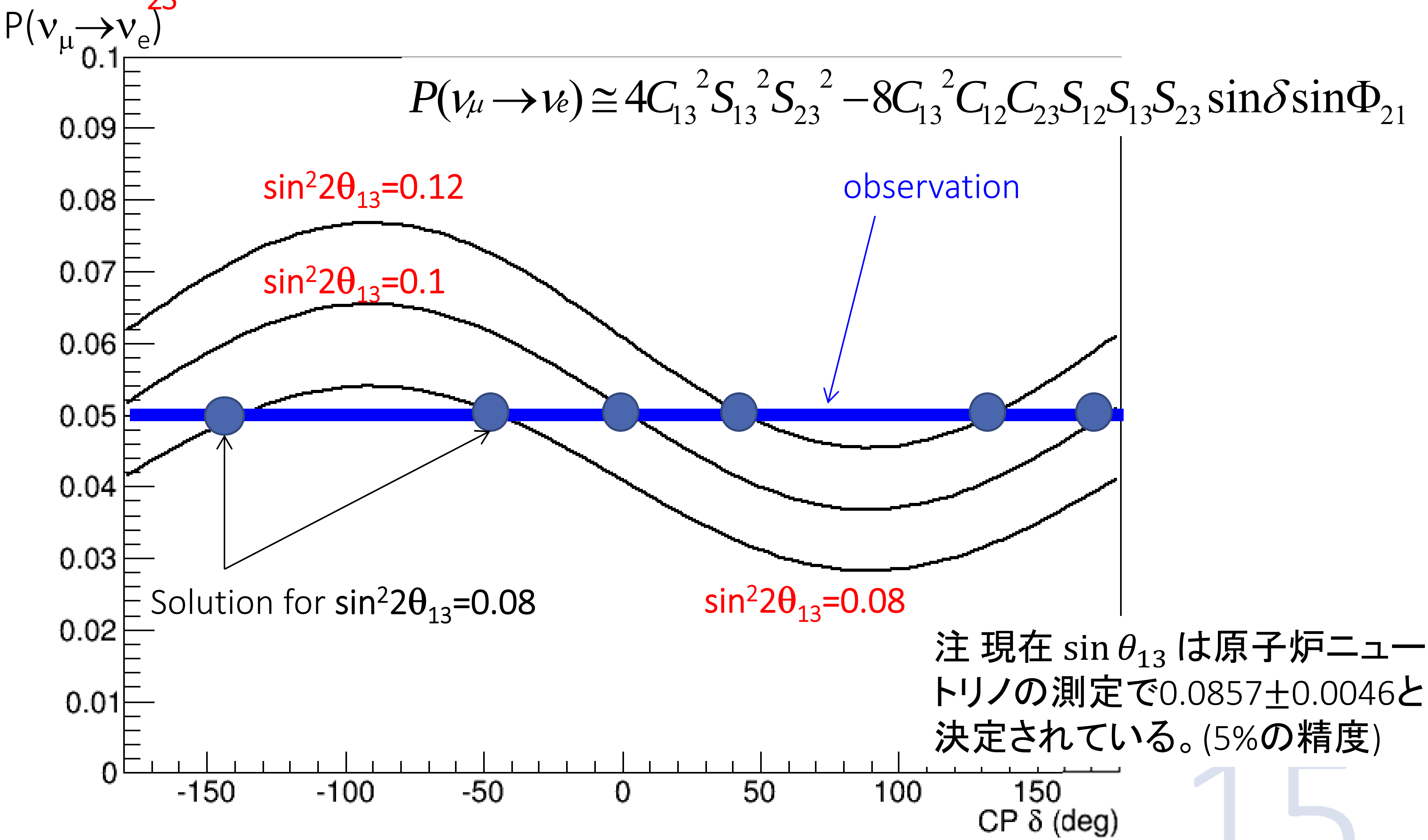
$$P(\nu_\mu \rightarrow \nu_e) \cong 4C_{13}{}^2 S_{13}{}^2 S_{23}{}^2 - 8C_{13}{}^2 C_{12}C_{23}S_{12}S_{13}S_{23}\sin\delta\sin\Phi_{21}$$

Observation

ν_μ to ν_e oscillation probability

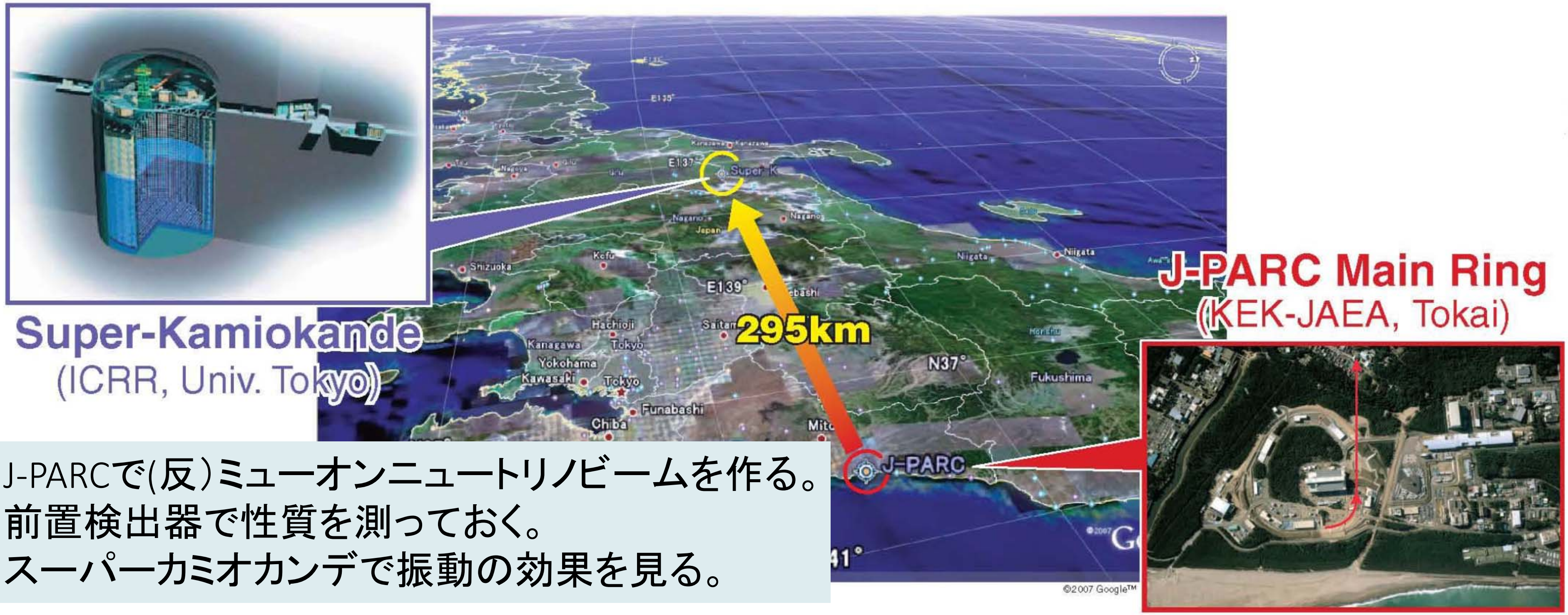
at oscillation maximum

$\sin^2 2\theta_{23}=1$ in vacuum

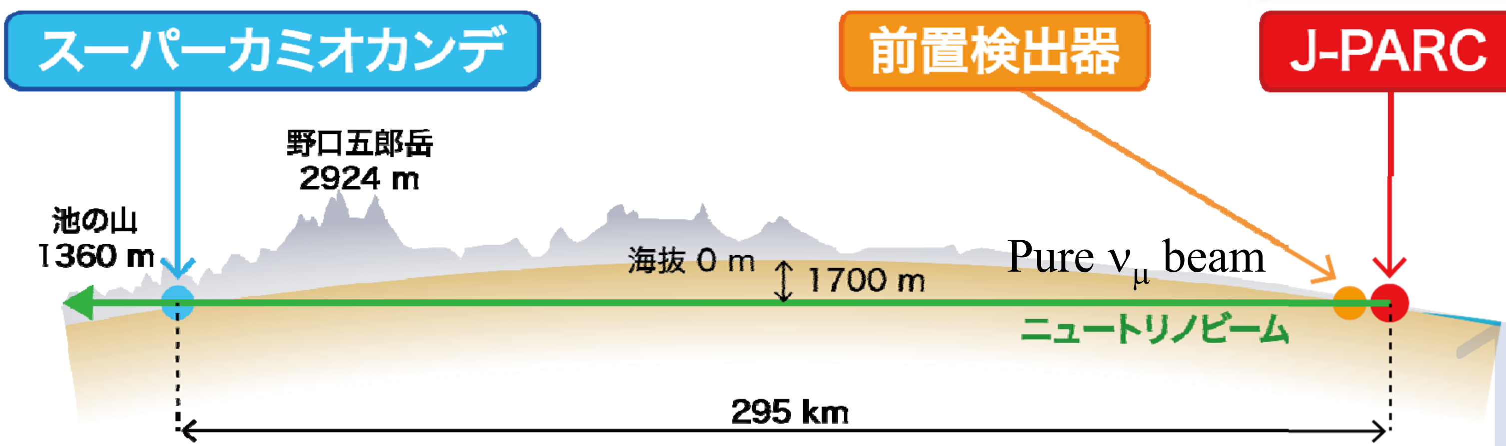


注 現在 $\sin\theta_{13}$ は原子炉ニュートリノの測定で0.0857±0.0046と決定されている。(5%の精度)

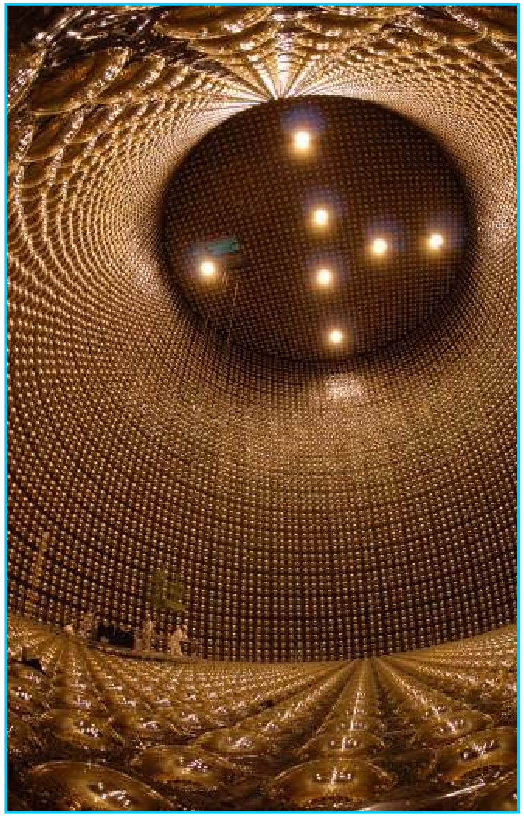
T2K (Tokai to Kamioka) 実験



J-PARCで(反)ミューオンニュートリノビームを作る。
前置検出器で性質を測っておく。
スーパーカミオカンデで振動の効果を見る。



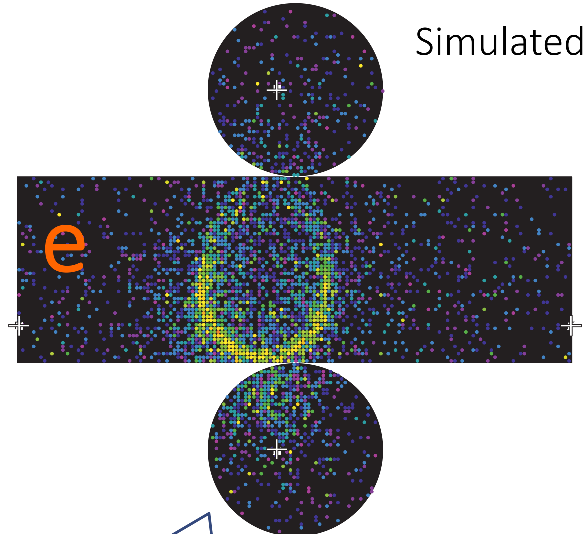
T2K Far Detector – Super Kamiokande



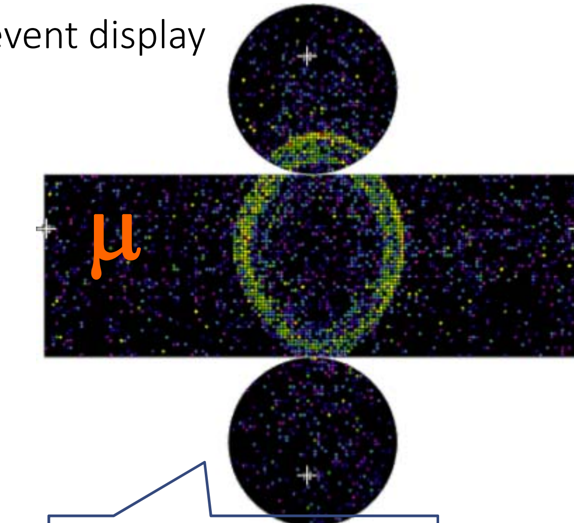
Water-Cherenkov Detector

Very good PID for sub-GeV particles
mis-identification ~1%

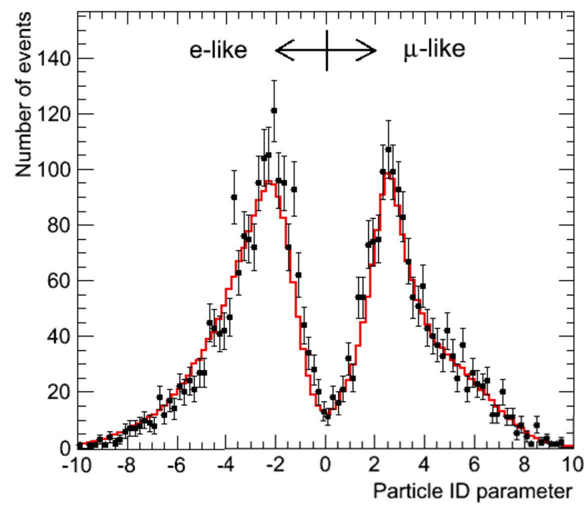
Simulated event display



Signal for ν_e appearance



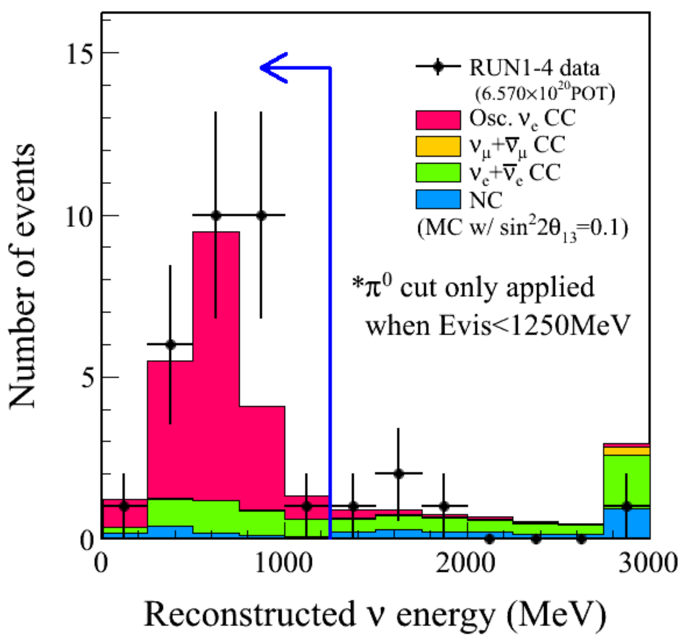
Signal for ν_μ disappearance



PRL **112,** 061802 (2014)
Selected for a Viewpoint in *Physics*
PHYSICAL REVIEW LETTERS
week ending 14 FEBRUARY 2014

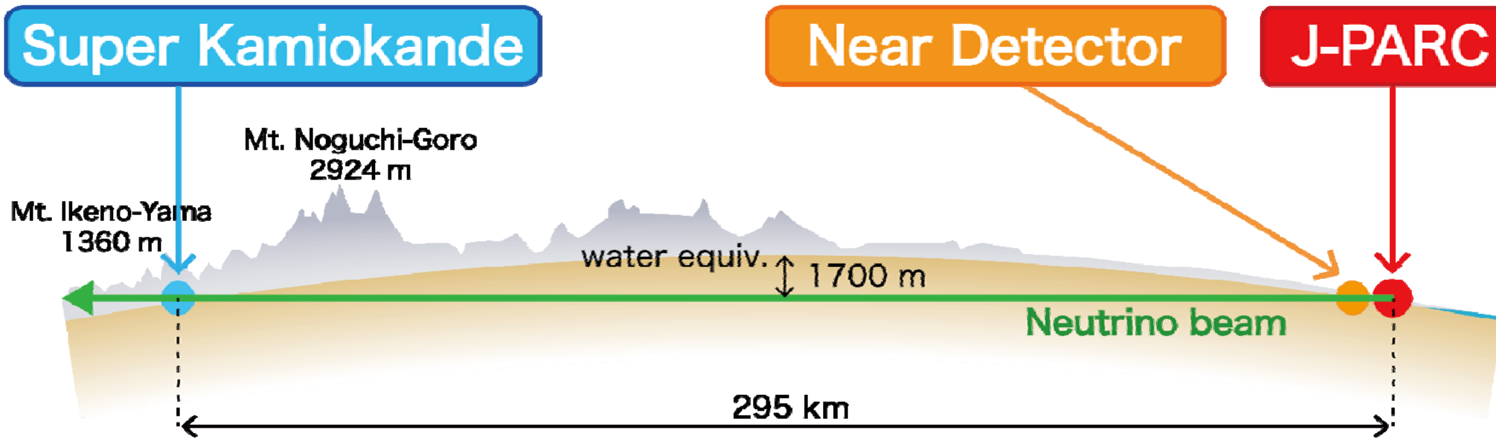
Observation of Electron Neutrino Appearance in a Muon Neutrino Beam

The T2K experiment has observed electron neutrino appearance in a muon neutrino beam produced 295 km from the Super-Kamiokande detector with a peak energy of 0.6 GeV. A total of 28 electron neutrino events were detected with an energy distribution consistent with an appearance signal, corresponding to a significance of 7.3σ when compared to 4.92 ± 0.55 expected background events. In the Pontecorvo-Maki-Nakagawa-Sakata mixing model, the electron neutrino appearance signal depends on several parameters including three mixing angles θ_{12}, θ_{23}, θ_{13}, a mass difference Δm^2_{32} and a CP violating phase δ_{CP}. In this neutrino oscillation scenario, assuming $|\Delta m^2_{32}| = 2.4 \times 10^{-3}\ \mathrm{eV}^2$, $\sin^2\theta_{23} = 0.5$, and $\Delta m^2_{32} > 0$ ($\Delta m^2_{32} < 0$), a best-fit value of $\sin^2 2\theta_{13} = 0.140^{+0.038}_{-0.032}$ ($0.170^{+0.045}_{-0.037}$) is obtained at $\delta_{CP} = 0$. When combining the result with the current best knowledge of oscillation parameters including the world average value of θ_{13} from reactor experiments, some values of δ_{CP} are disfavored at the 90% C.L.

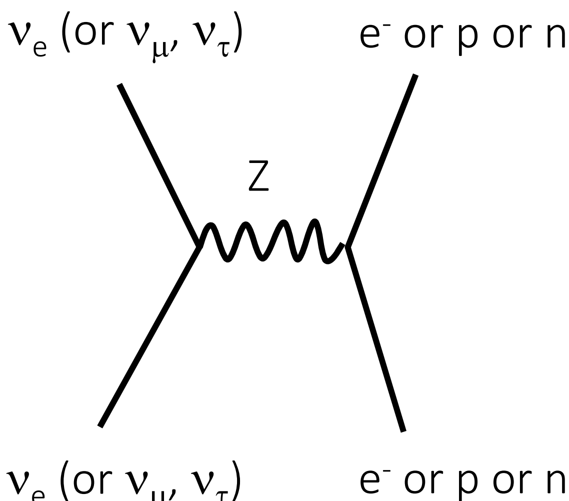


2014年 appearance現象が、初めて5σ以上の有意性で確立！
レプトンセクターにおけるCP対称性の破れの測定が視野に。

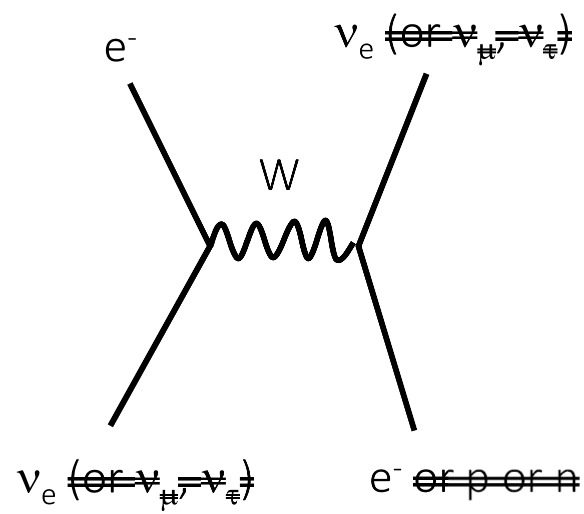
ところで、Earth is not symmetric about flavor nor CP



終状態を変えないような相互作用も、位相は変えてしまう。(ポテンシャルとして感じる)



NC interaction



CC interaction

Time evolution of wave function $\exp(-iHt)$

Hamiltonian in vacuum

$$-U\begin{pmatrix} p_1 & 0 & 0 \\ 0 & p_2 & 0 \\ 0 & 0 & p_3 \end{pmatrix}U\dagger \simeq -p_1 + \frac{1}{2E}U\begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m_{21}^2 & 0 \\ 0 & 0 & \Delta m_{31}^2 \end{pmatrix}U^\dagger$$

Hamiltonian of the interaction with matter

$$\begin{pmatrix} \sqrt{2}G_F n_e & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

n_e: electron density

(Opposite sign for ν and $\bar{\nu}$)

The part which affect the phase is,

$$H \approx U\begin{pmatrix} 0 & 0 & 0 \\ 0 & \frac{\Delta m_{21}^2}{2E} & 0 \\ 0 & 0 & \frac{\Delta m_{31}^2}{2E} \end{pmatrix}U + \begin{pmatrix} \frac{a}{2E} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

- ✓ 伝搬時の位相を変化させる。
- ✓ さらに、見かけの混合を変えてしまう。（MSW効果）

This cannot be solved analytically.

$$a \equiv 2\sqrt{2}G_F n_e E = 7.56\times10^{-5}\,\mathrm{eV}^2 \frac{\rho}{\mathrm{gcm}^{-3}}\frac{E}{GeV}$$

More complete eq. of ν_e appearance (1st order for matter effect)

$$P(\nu_\mu \to \nu_e) = 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2\Phi_{31}\left(1+\frac{2a}{\Delta m_{31}^2}\left(1-2S_{13}^2\right)\right)$$

Leading including matter effect

$$+8C_{13}^2 S_{12}S_{13}S_{23}(C_{12}C_{23}\cos\delta - S_{12}S_{13}S_{23})\cos\Phi_{32}\sin\Phi_{31}\sin\Phi_{21}$$

CP conserving

$$-8C_{13}^2 C_{12}C_{23}S_{12}S_{13}S_{23}\sin\delta\sin\Phi_{32}\sin\Phi_{31}\sin\Phi_{21}$$

CP violating

$$+4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12}C_{23}S_{12}S_{23}S_{13}\cos\delta)\sin^2\Phi_{21}$$

Solar

$$-8C_{13}^2 S_{13}^2 S_{23}^2 (1-2S_{13}^2)\frac{aL}{4E}\cos\Phi_{32}\sin\Phi_{31}$$

Matter effect (This is small)

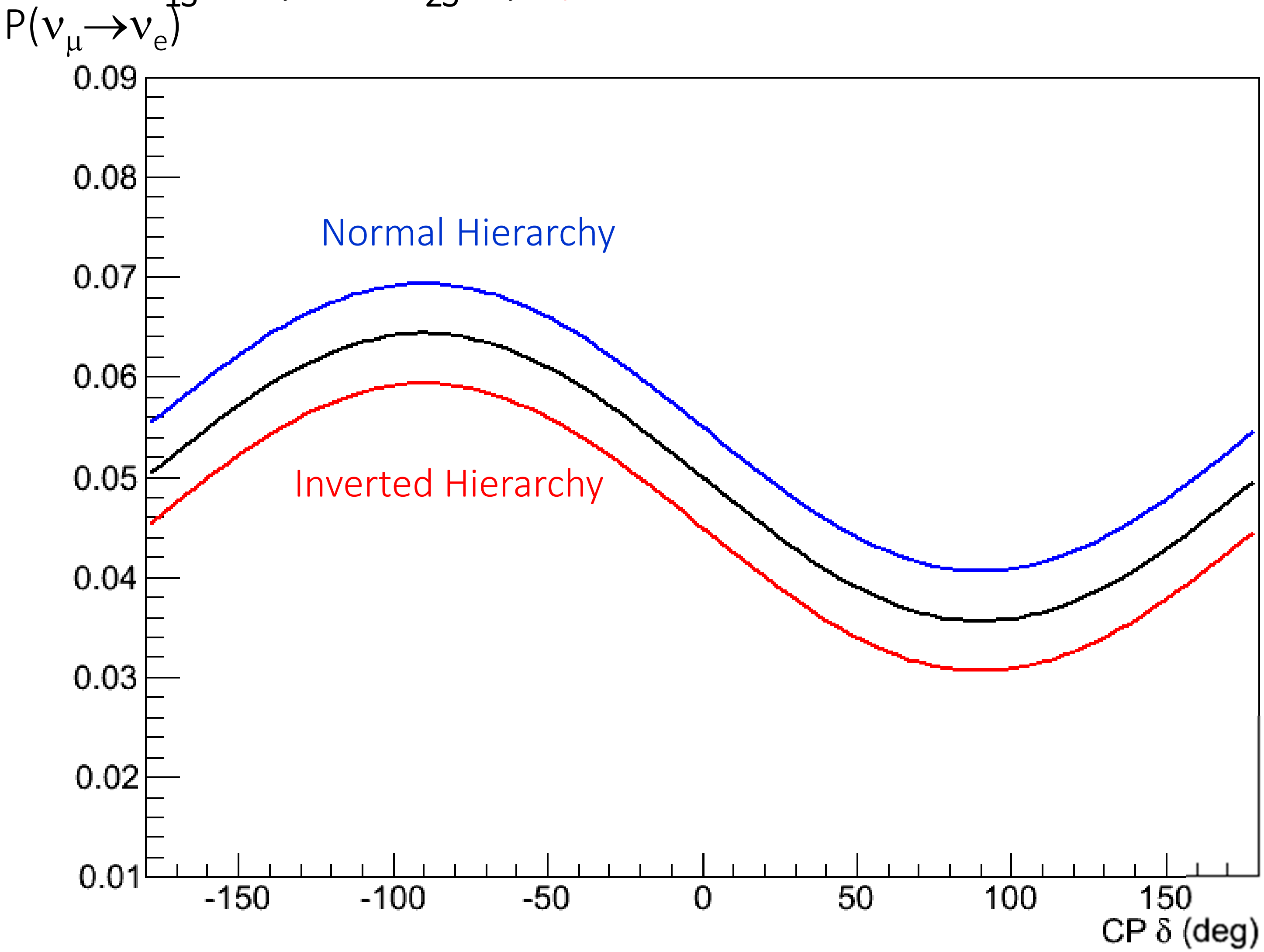
$$a = 7.56\times10^{-5}[\mathrm{eV}^2]\cdot\left(\frac{\rho}{[\mathrm{g/cm}^3]}\right)\cdot\left(\frac{E}{[\mathrm{GeV}]}\right)$$

$-a$ for $\bar{\nu}$

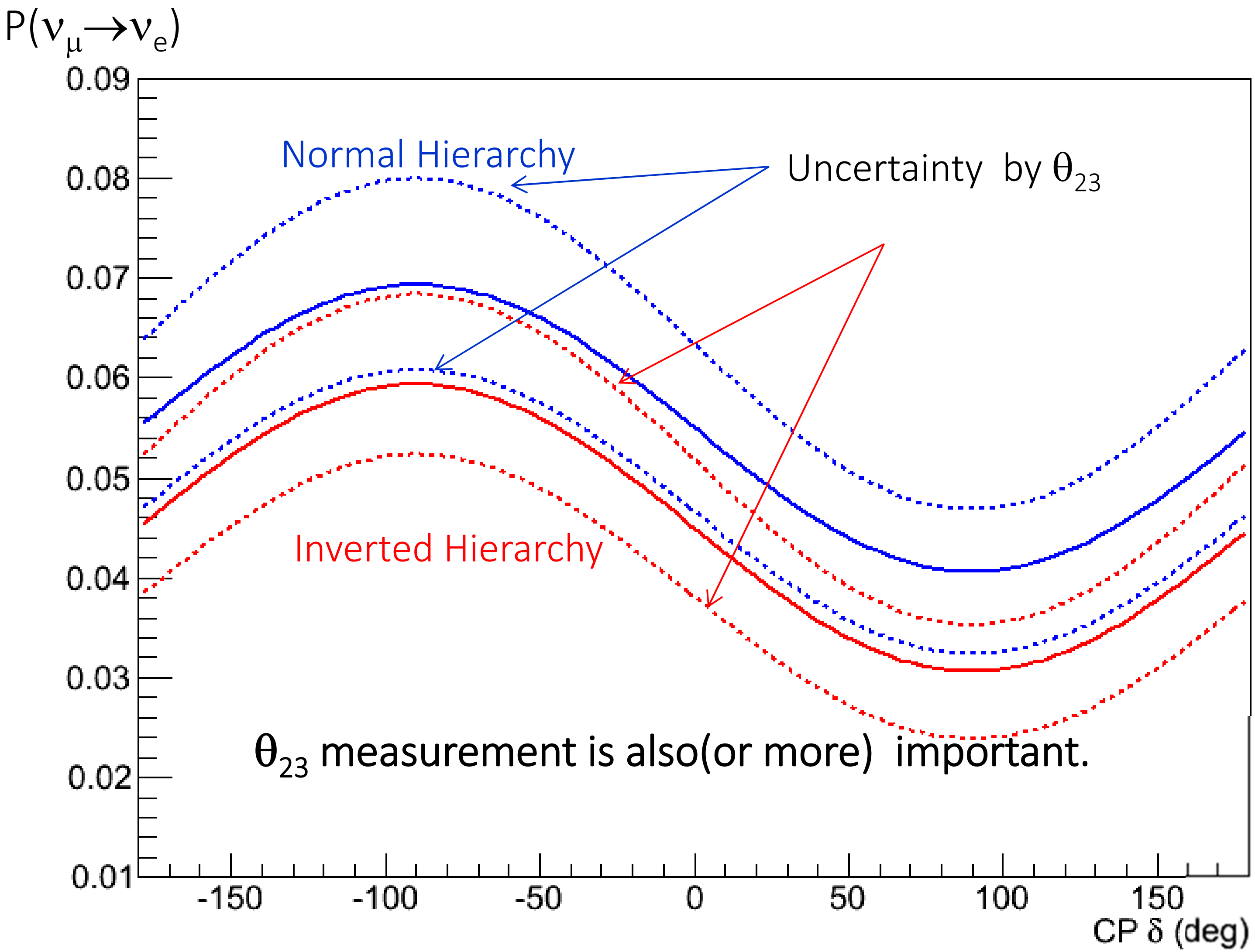
ν_μ to ν_e oscillation probability

at oscillation maximum

$\sin^2 2\theta_{13}=0.1$, $\sin^2 2\theta_{23}=1$, w/ matter effect

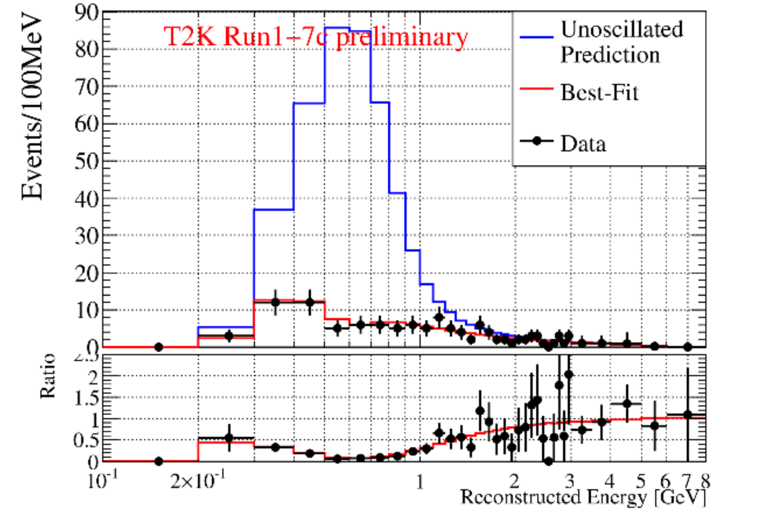


Actually, w/ θ_{23} uncertainty



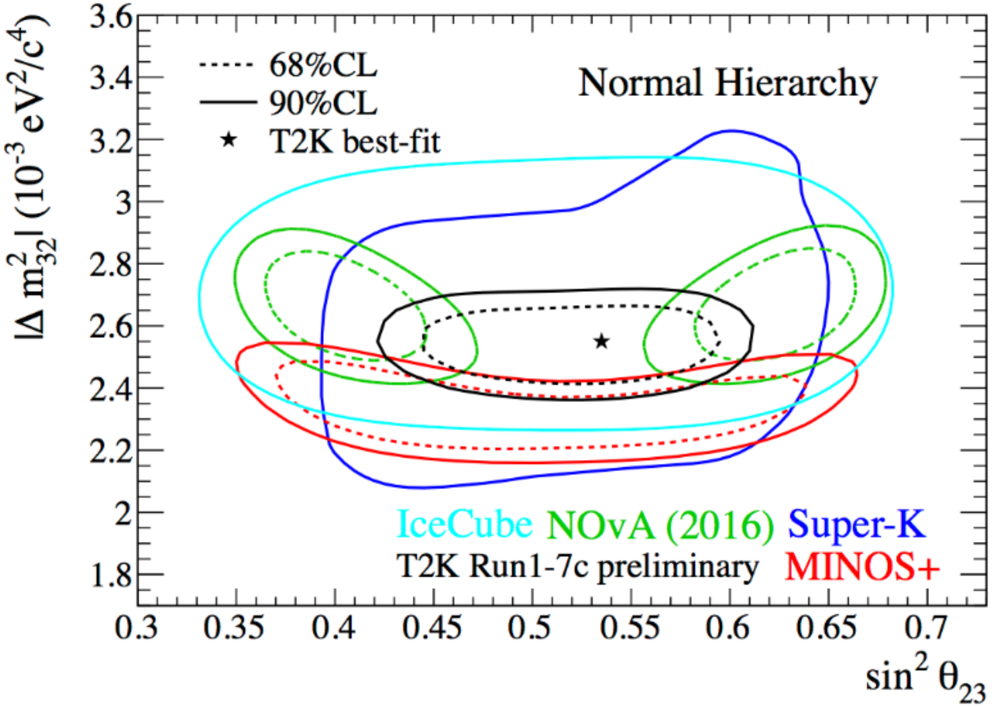
θ_{23} measurement is also(or more) important.

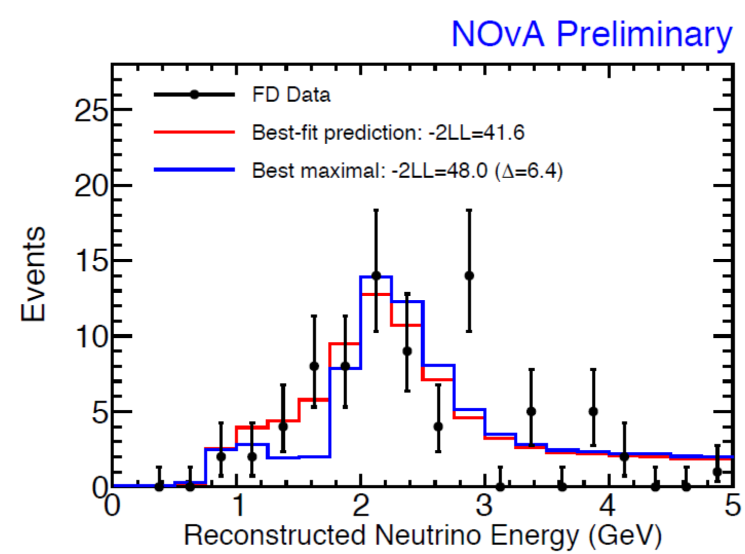
$\Delta m^2_{32}, \sin^2\theta_{23}$
2016 result



ν_μ disappearance spectrum

P. Vahle, Neutrino 2016





2016 T2K Expected number of (anti)ν_e events

		$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = +\pi/2$	$\delta_{CP} = \pi$
ν-mode run	Normal	28.7	24.2	19.6	24.1
	Inverted	25.4	21.3	17.1	21.3
$\bar{\nu}$-mode run	Normal	6.0	6.9	7.8	6.8
	Inverted	6.5	7.4	8.4	7.4

内訳

	$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = +\pi/2$	$\delta_{CP} = \pi$
$\bar{\nu}_\mu \to \bar{\nu}_e$	2.8	3.8	4.8	3.8
$\nu_\mu \to \nu_e$	1.0	0.9	0.7	0.8
other bkg.	2.2			

$@\sin^2\theta_{23} = 0.53$

＊ 反ニュートリノは、断面積が1/3くらいになるので、データを貯めるのが大変。

$\boldsymbol{\nu_e}$ and $\boldsymbol{\bar{\nu}_e}$ selected event

Expectation @$\sin^2\theta_{23} = 0.53$

		$\boldsymbol{\delta_{CP} = -\frac{\pi}{2}}$	$\boldsymbol{\delta_{CP} = 0}$	$\boldsymbol{\delta_{CP} = +\frac{\pi}{2}}$	$\boldsymbol{\delta_{CP} = \pi}$
ν-mode run	Normal	28.7	24.2	19.6	24.1
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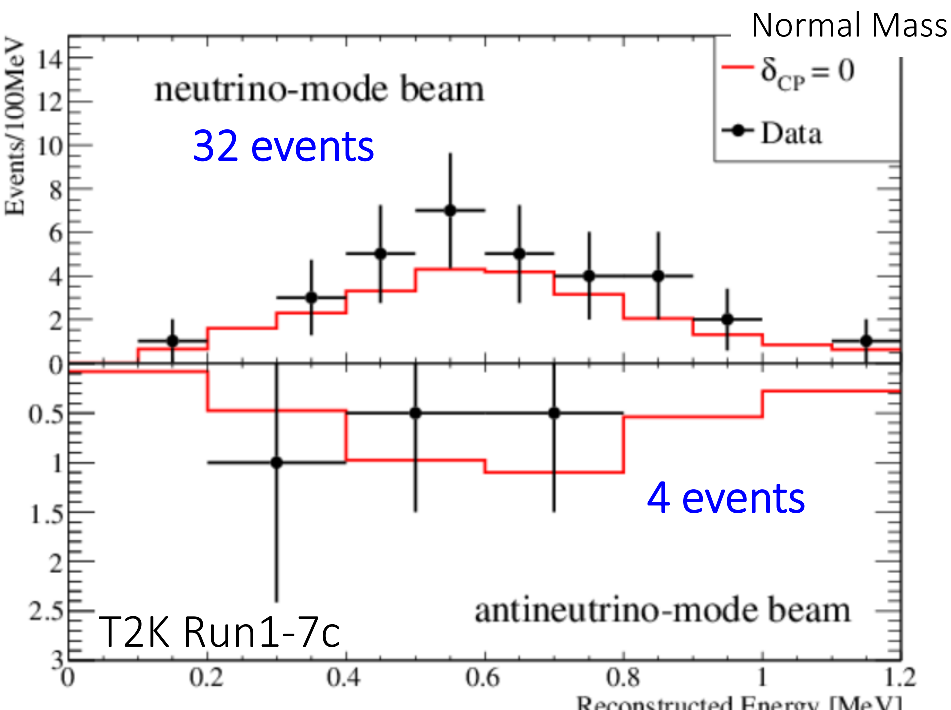
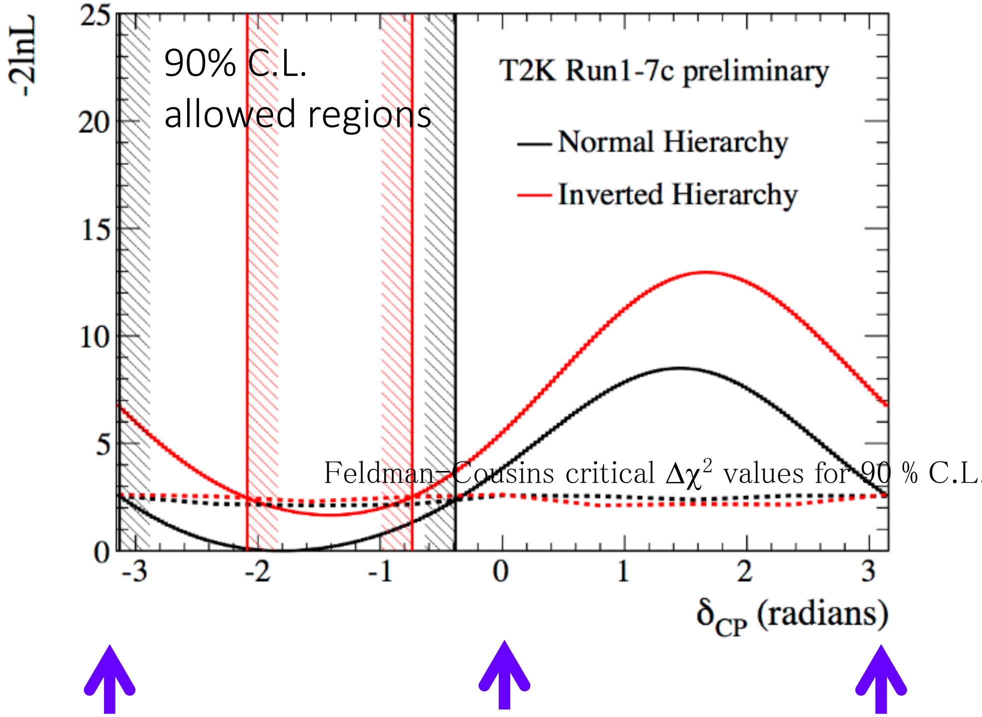
$\bar{\nu}$-mode run	Normal	6.0	6.9	7.8	6.8
	Inverted	6.5	7.4	8.4	7.4



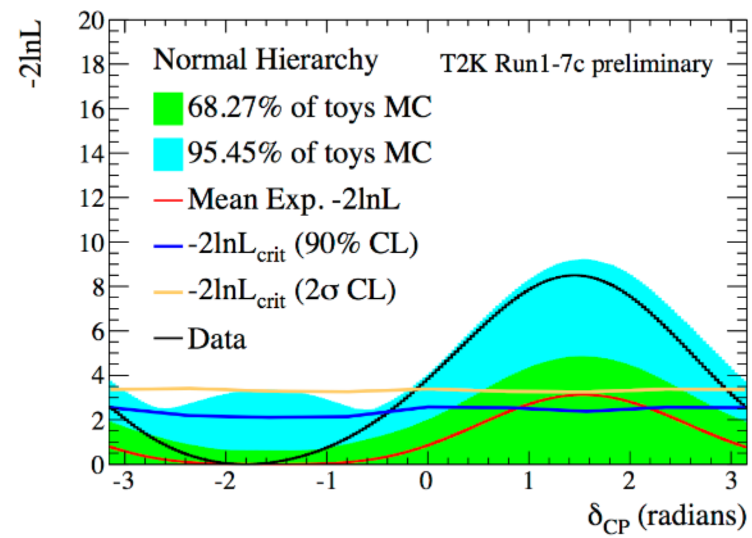
統計的ふらつきのせいだろうが、AsymmetryがPMNSで予想される最大よりも大きい！

δ_{CP} Confidence Level

$\Delta\chi^2$ v.s. δ_{CP} T2K + reactors θ_{13}



comparison to sensitivity at $\delta_{CP} = -\frac{\pi}{2}$, NO

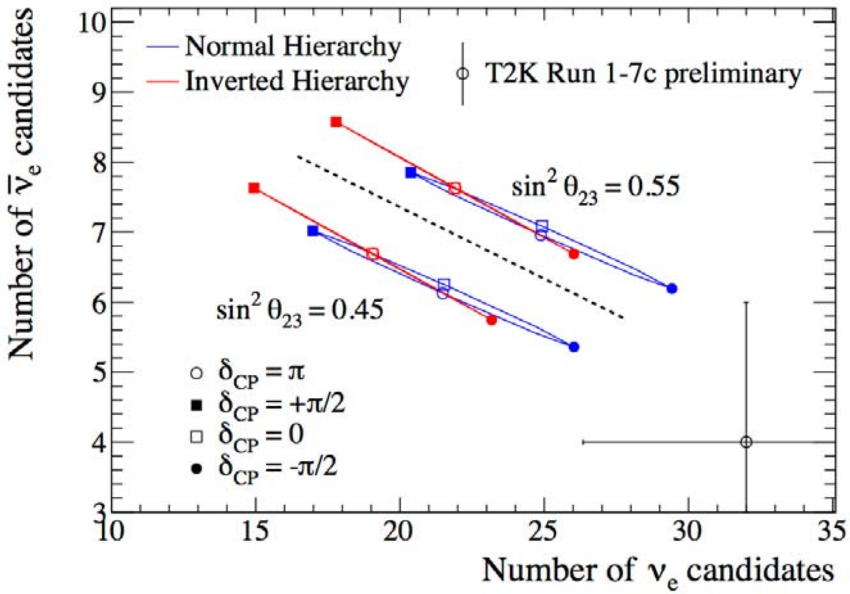


no CPV

90% Confidence Interval:

Normal mass ordering	$(-3.13rad, -0.39rad.) = (-179°, -22°)$
Inverted mass ordering	$(-2.09rad, -0.74rad.) = (-120°, -42°)$

significance to mass hierarchy



$\Delta\chi^2$にもとづくp-valueはあまり正当に評価できない。
IHに対するp-valueは低いがNHに対しても低いから。

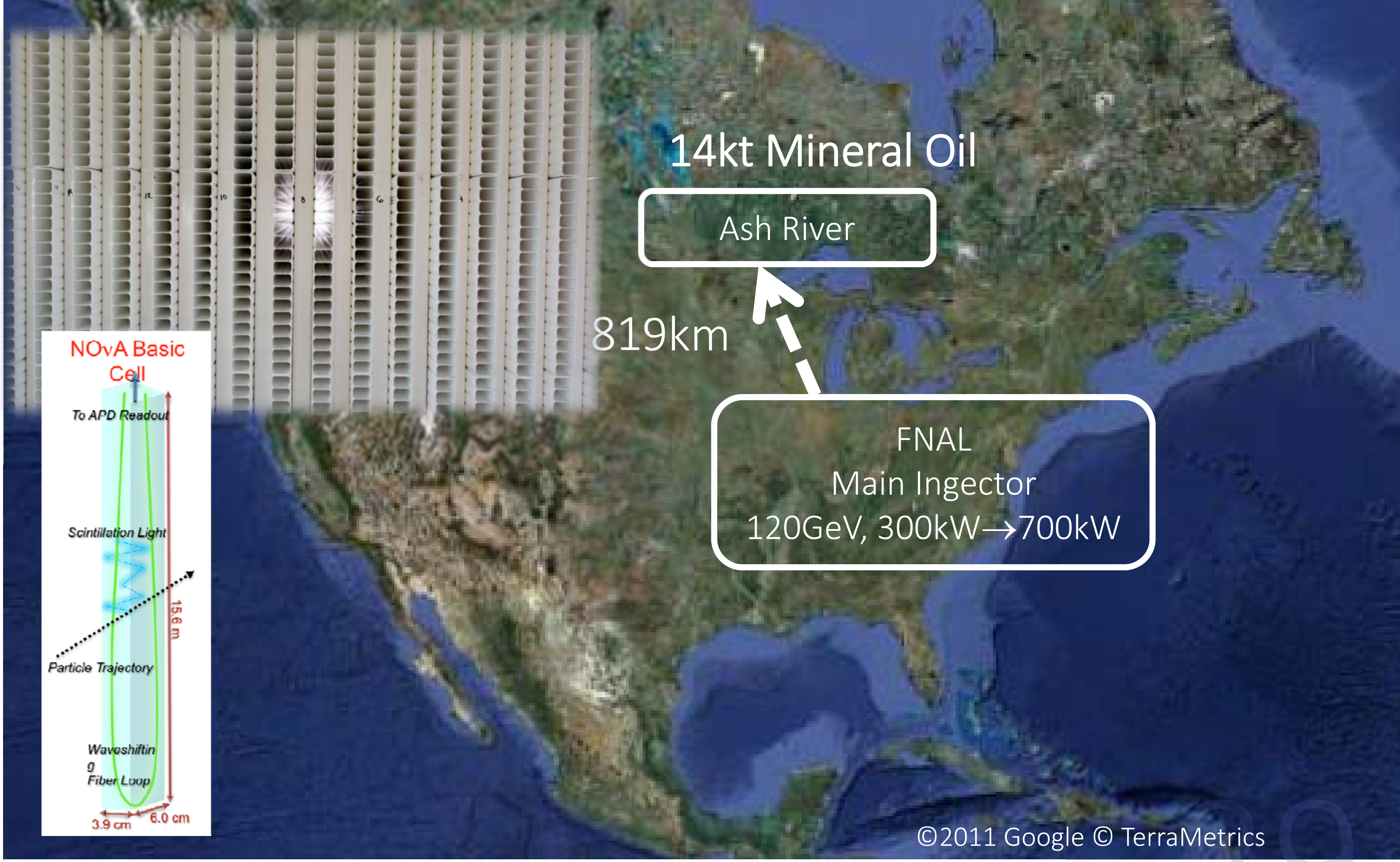
代わりにBayesian posterior probabilityをリリースした。

	Normal	Inverted	sum
$\theta_{23} < 45°$	29%	10%	39%
$\theta_{23} > 45°$	46%	14%	61%
sum	75%	25%	100%

T2K Run1-7c preliminary

NHである確率は75%....

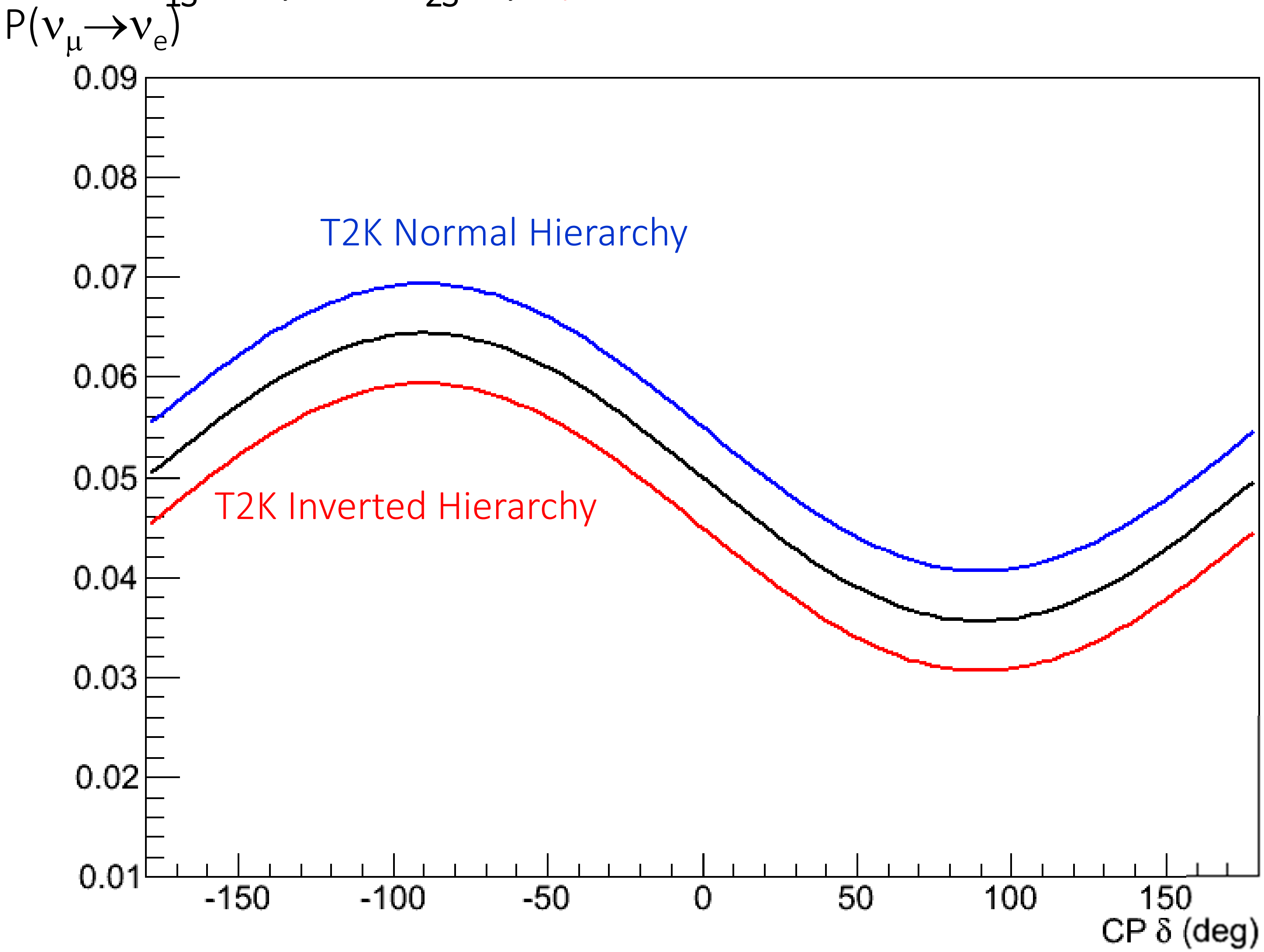
NuMI Off-Axis ν_e Appearance Experiment



ν_μ to ν_e oscillation probability

at oscillation maximum

$\sin^2 2\theta_{13}=0.1$, $\sin^2 2\theta_{23}=1$, w/ matter effect



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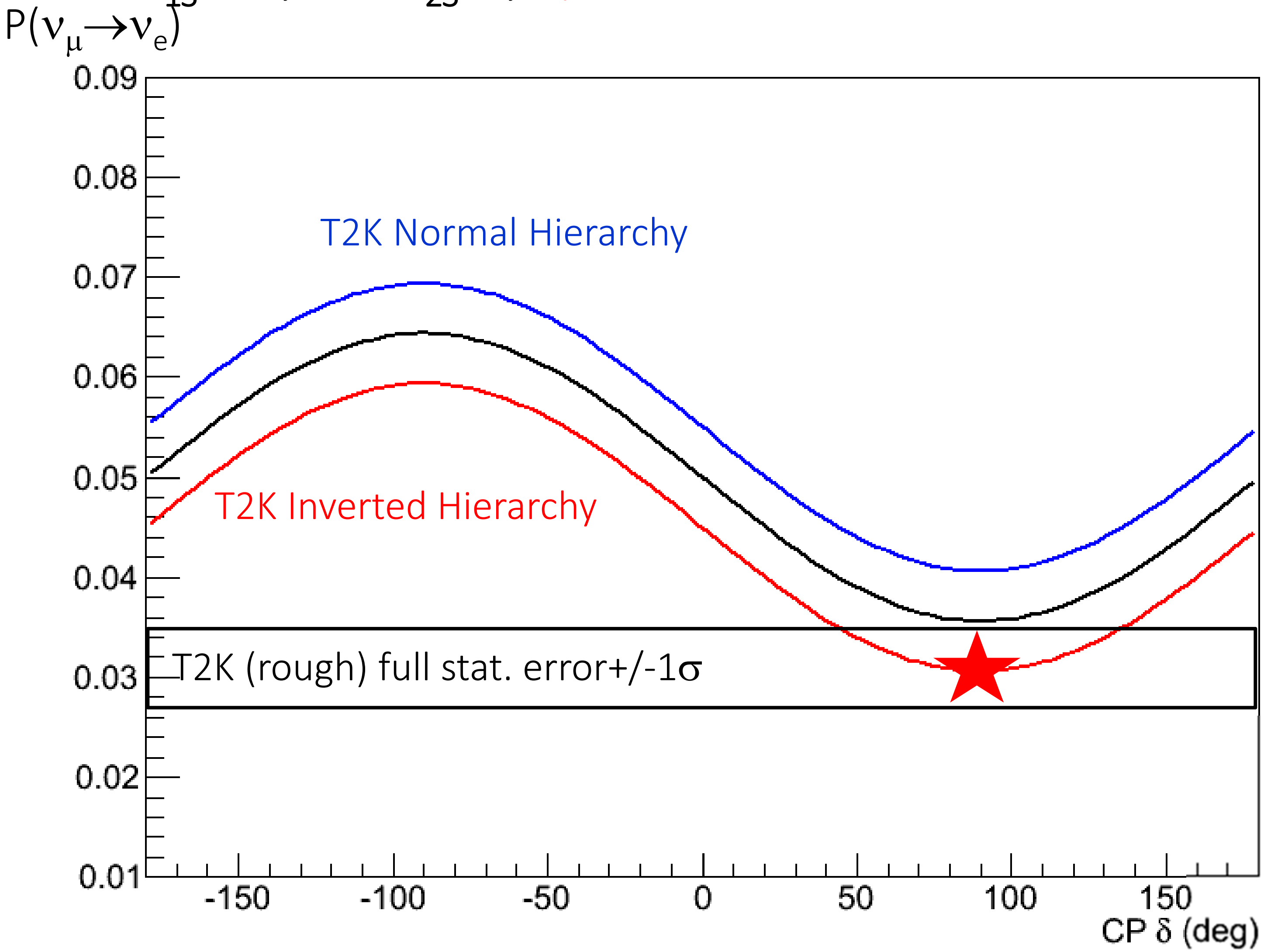

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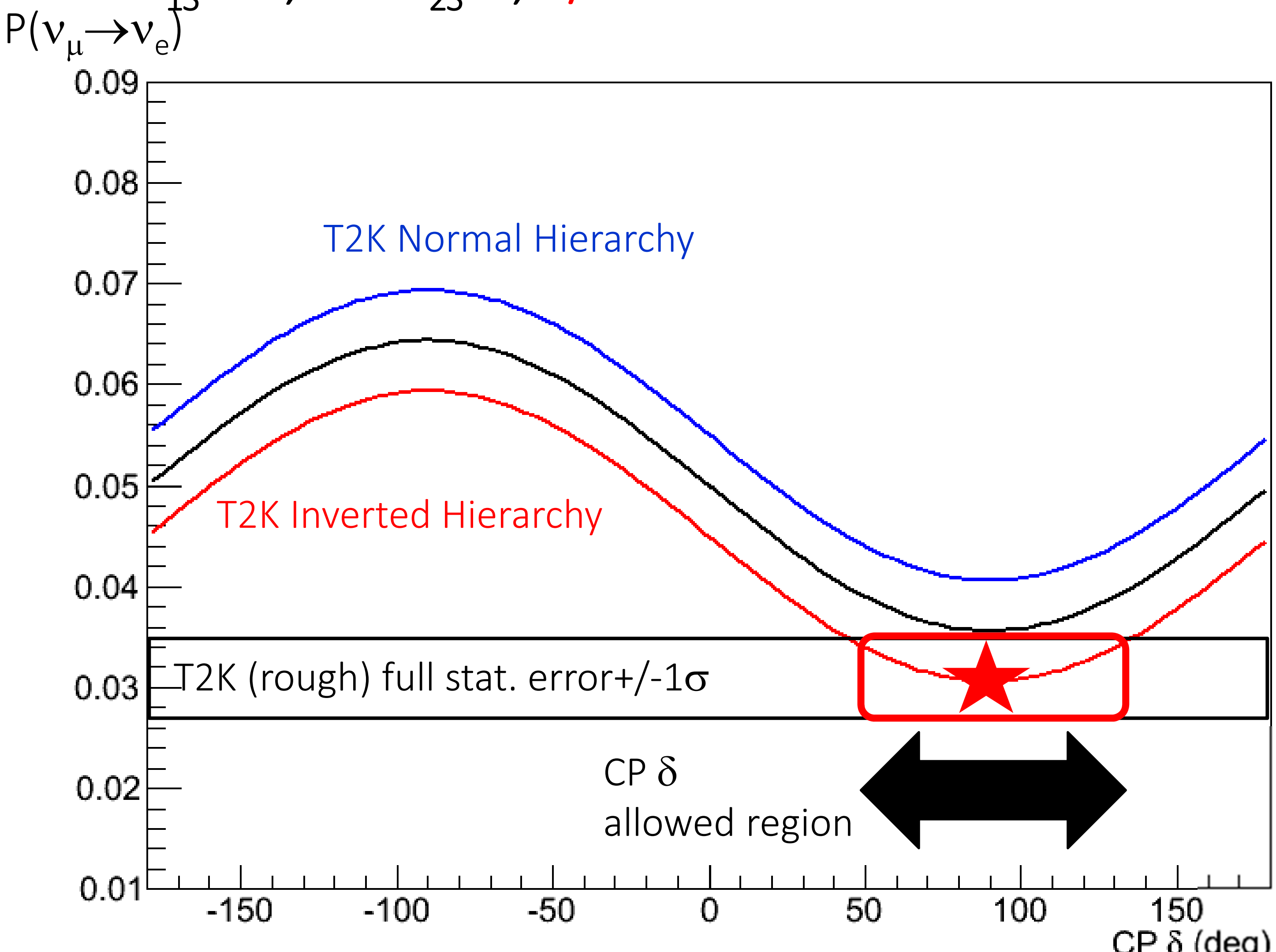

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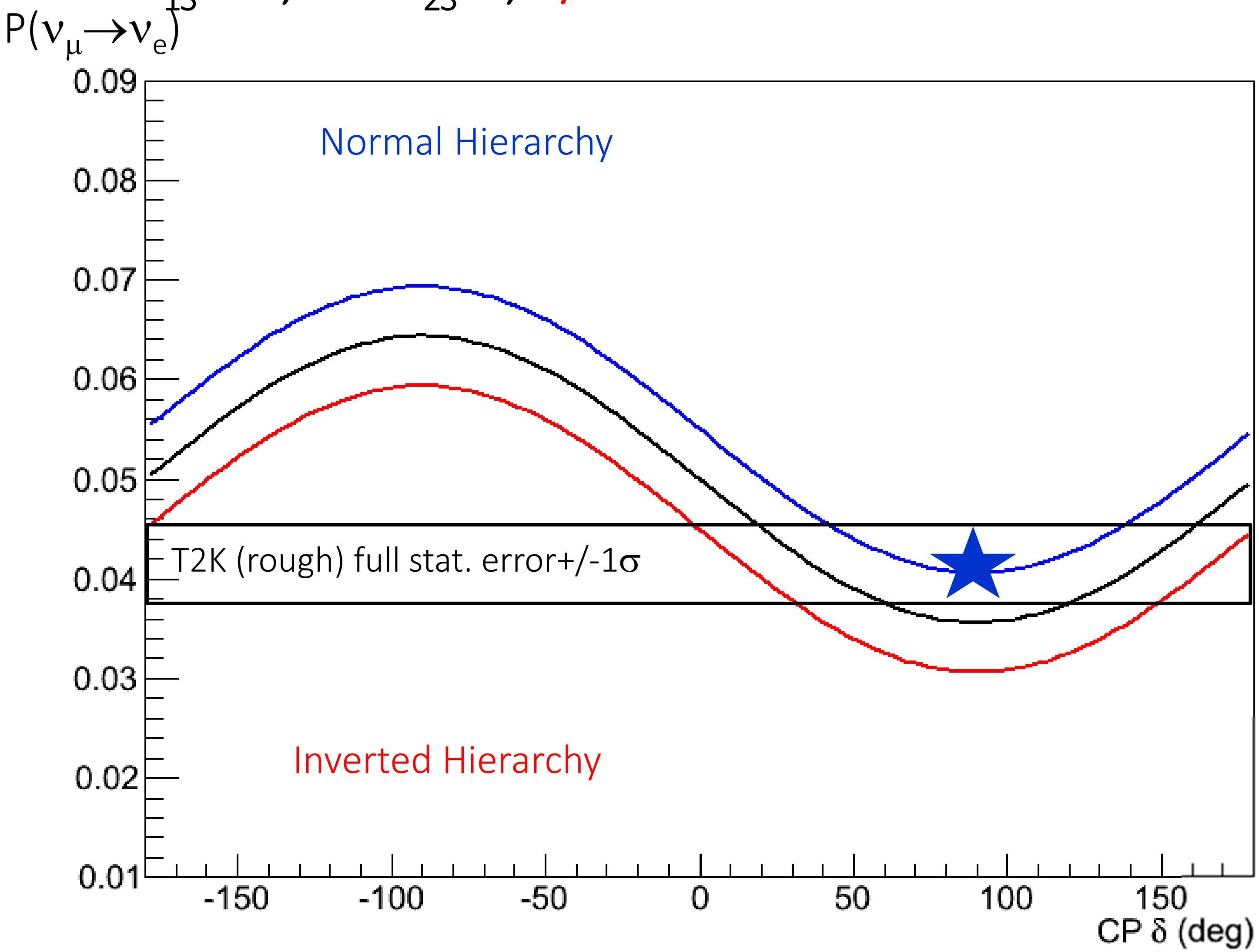

ν_μ to ν_e oscillation probability

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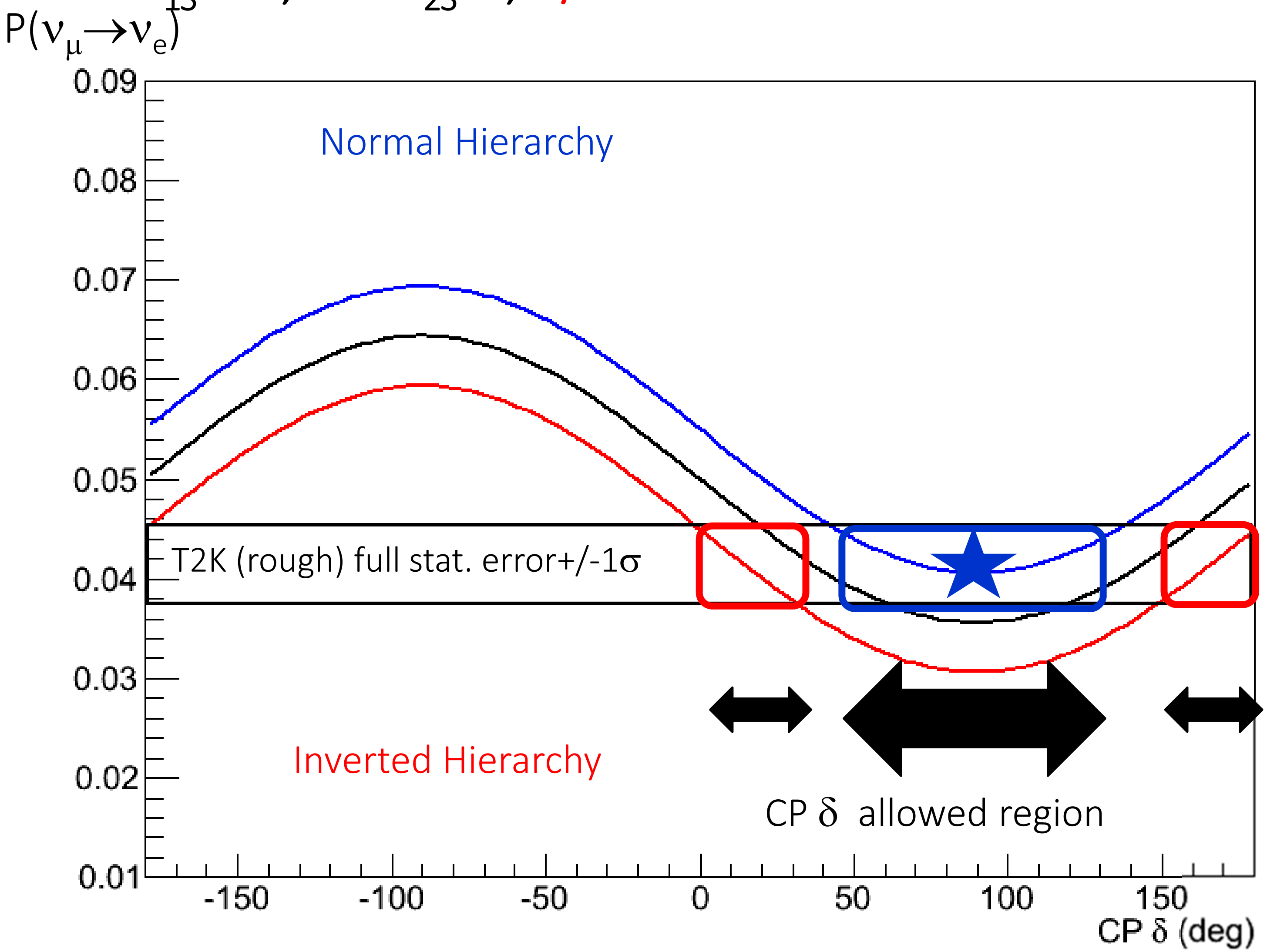
$\sin^2 2\theta_{13}$=0.1, $\sin^2 2\theta_{23}$=1, w/ matter effect



ν_μ to ν_e oscillation probabil

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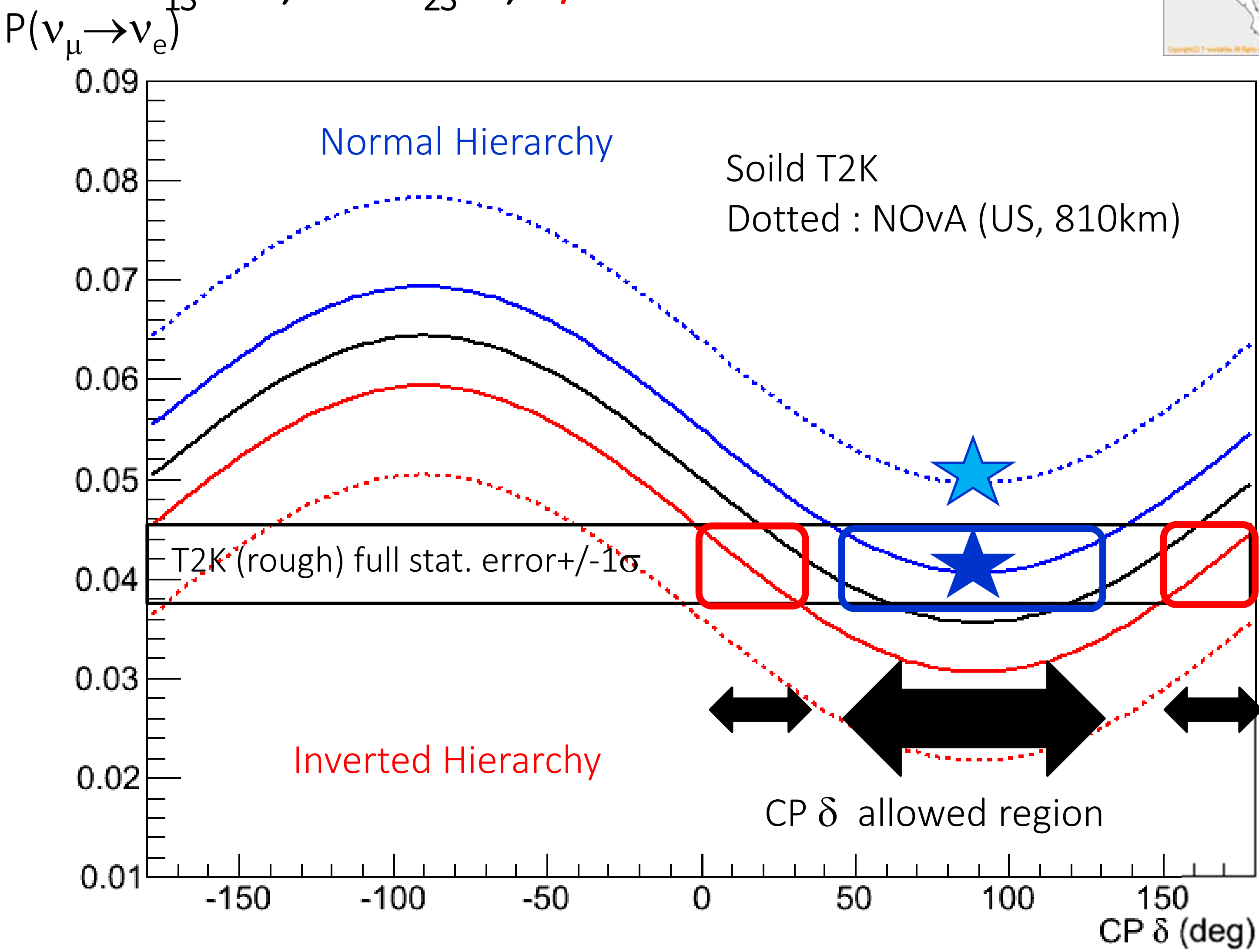
$\sin^2 2\theta_{13}=0.1$, $\sin^2 2\theta_{23}=1$, w/ matter effect



ν_μ to ν_e oscillation probability

at oscillation maximum

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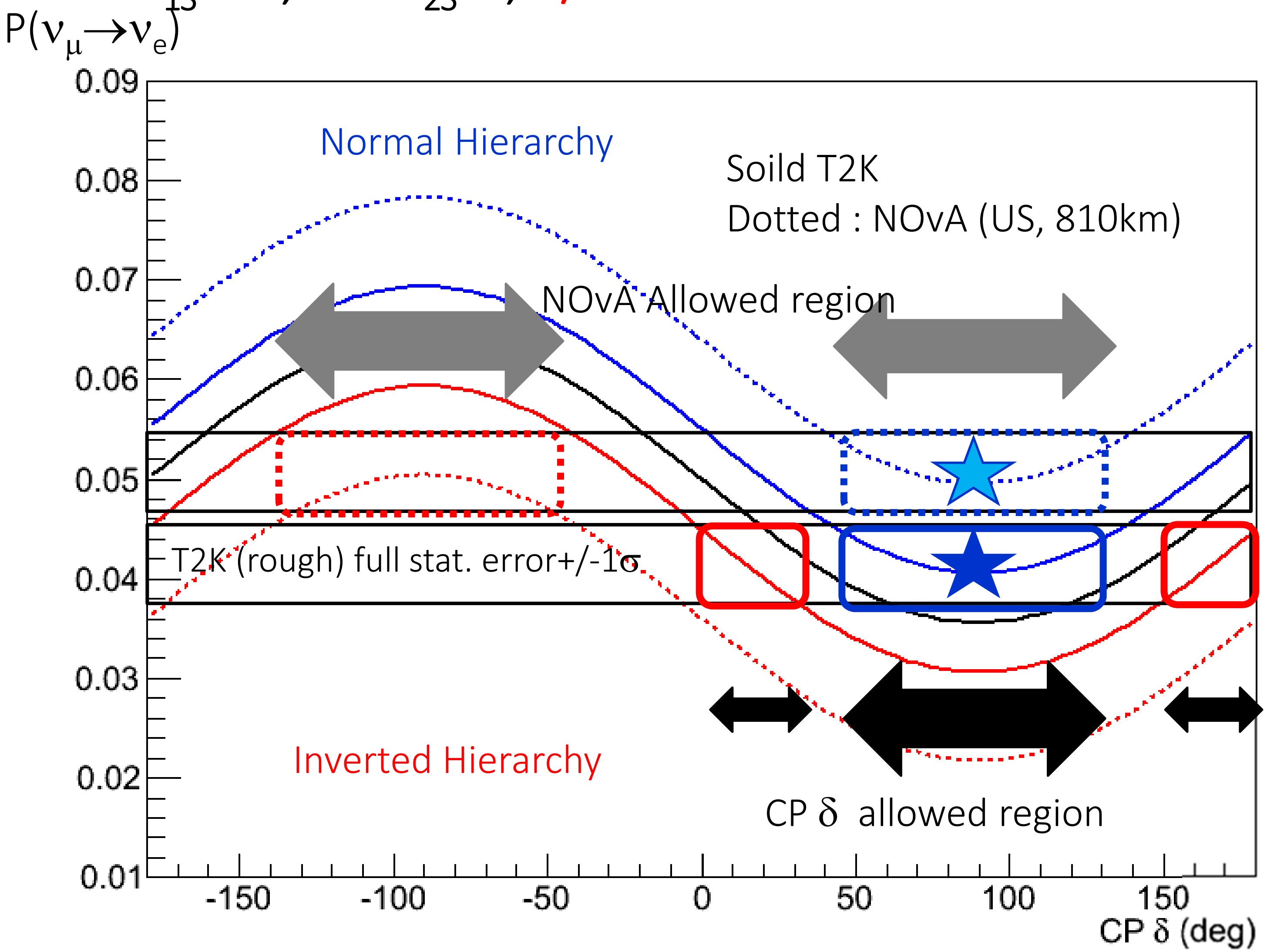

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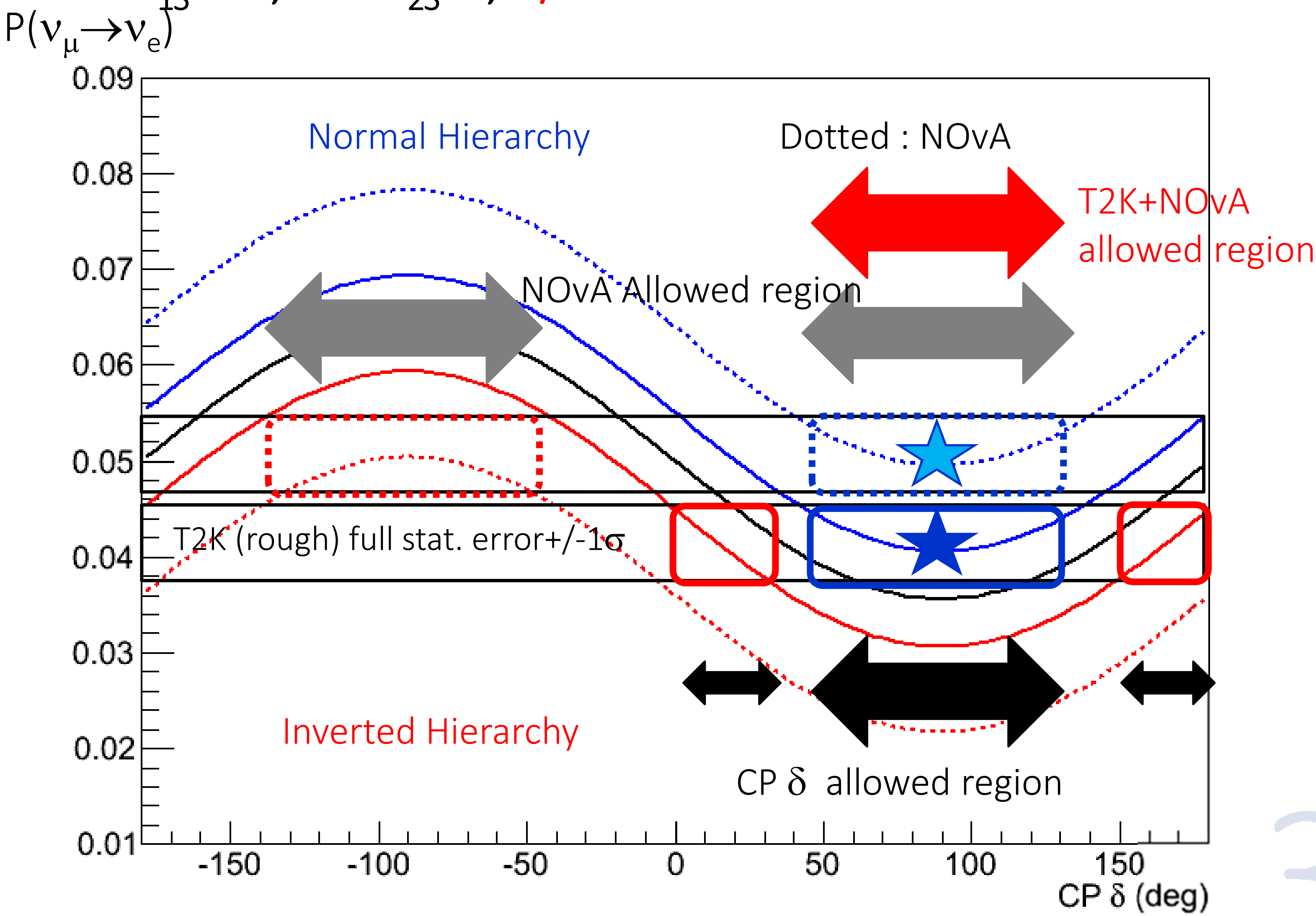
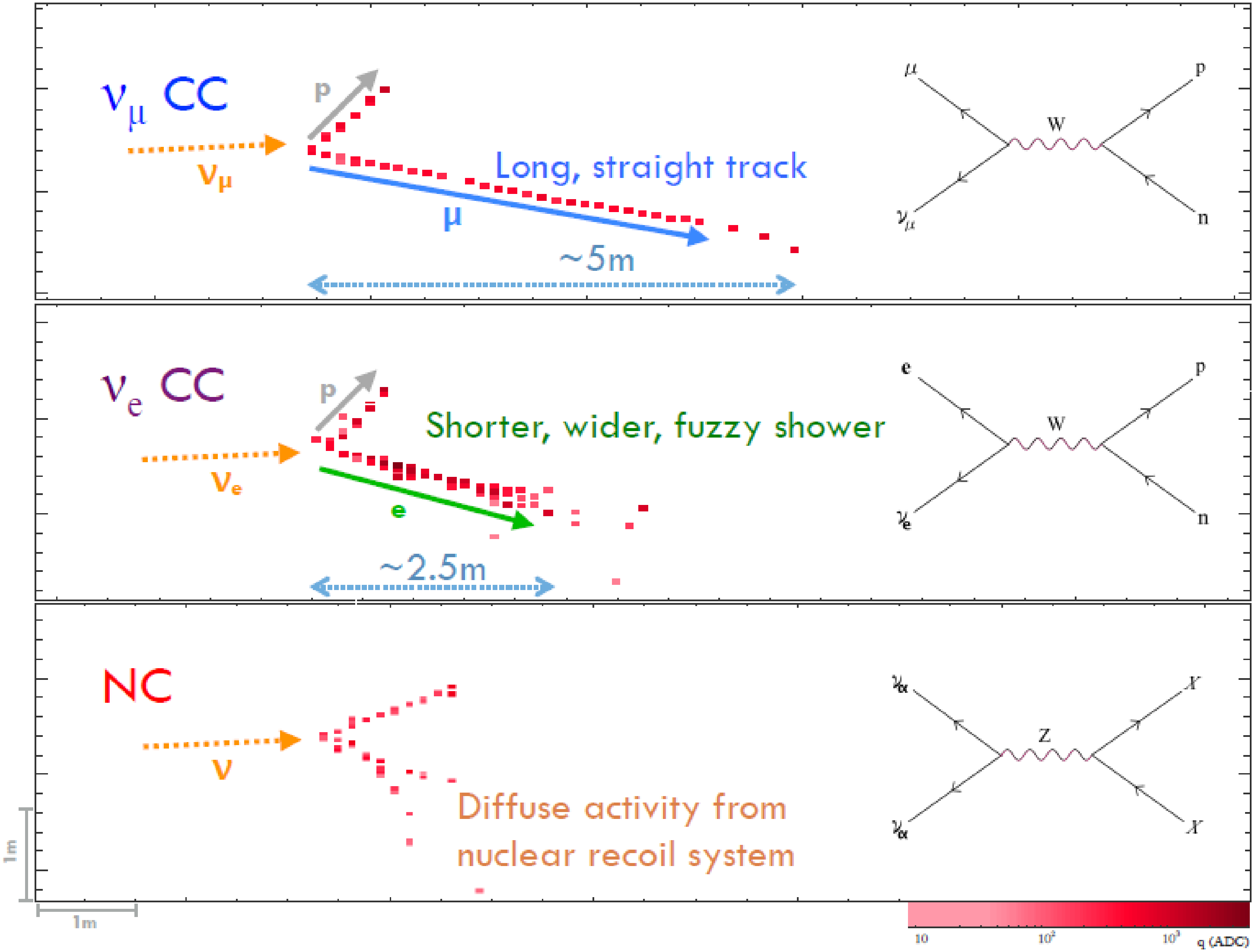


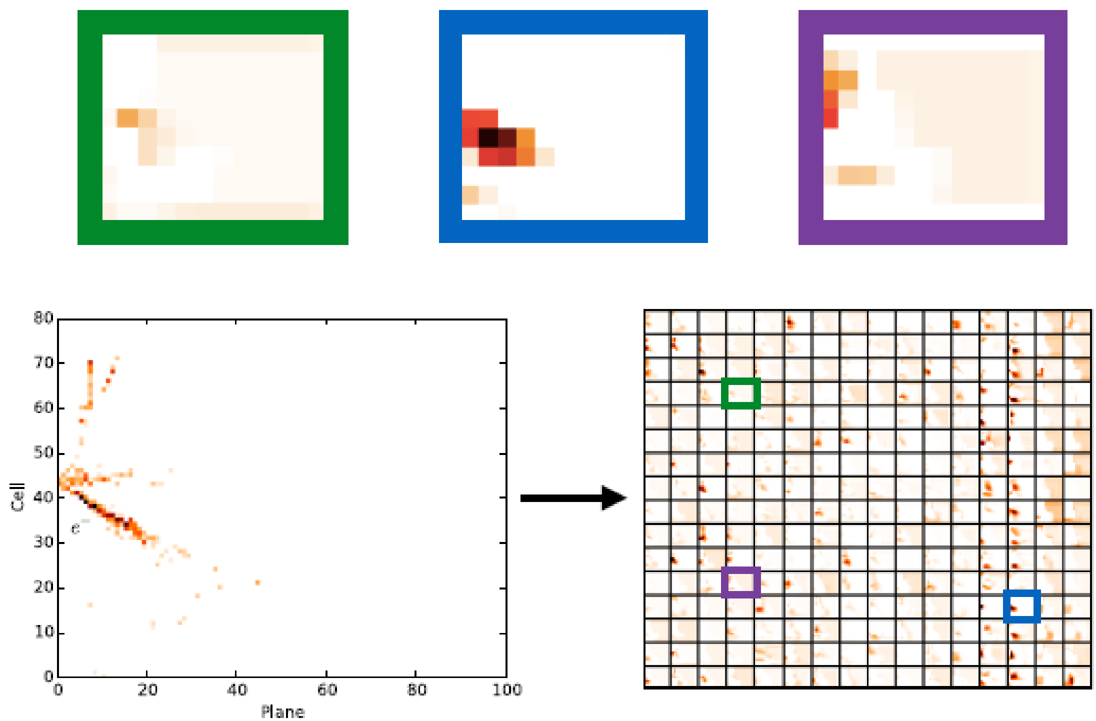
Event Selection

See Poster P1.033 by G. Davies and C. Backhouse for details on Reconstruction



Improved Event Selection

- This analysis features a new event selection technique based on ideas from computer vision and deep learning



- Calibrated hit maps are inputs to Convolutional Visual Network (CVN)
- Series of image processing transformations applied to extract abstract features
- Extracted features used as inputs to a conventional neural network to classify the event

A. Aurisano et al., arXiv:1604.01444
Posters P1.028 by A. Radovic, P1.032 by F. Psihas and A. Himmel for more detail

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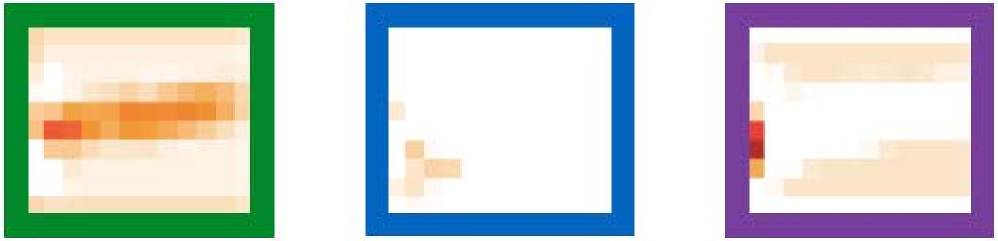

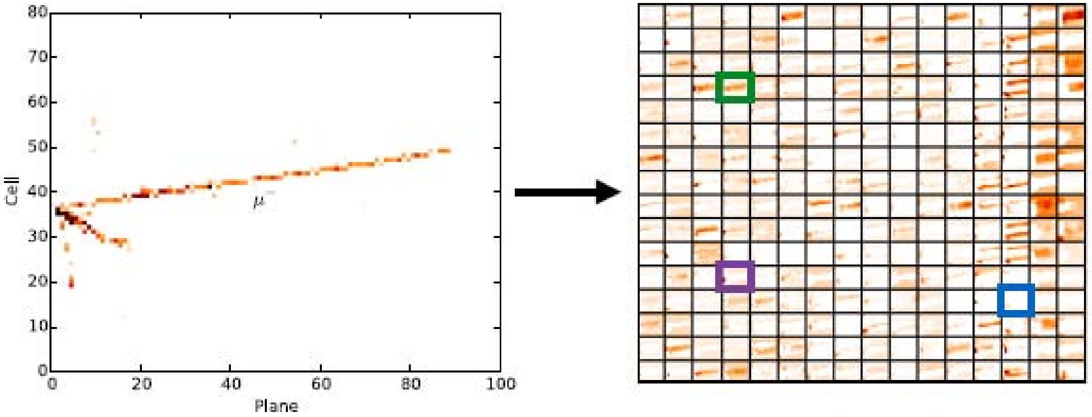

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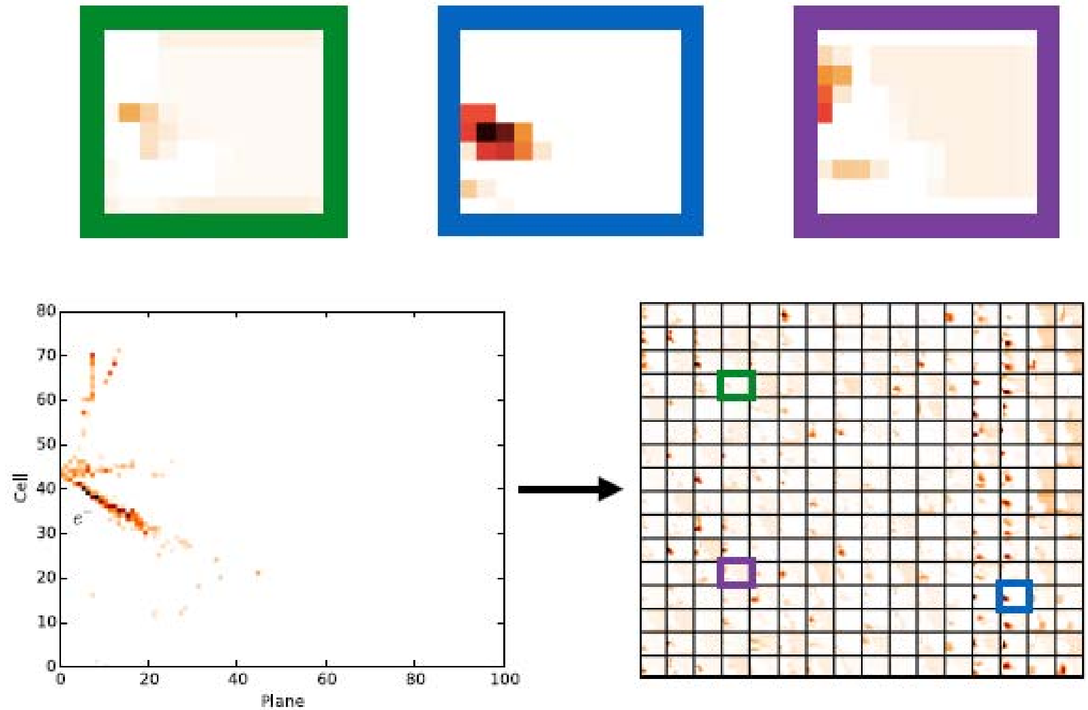


Improvement in sensitivity from CVN equivalent to 30% more exposure

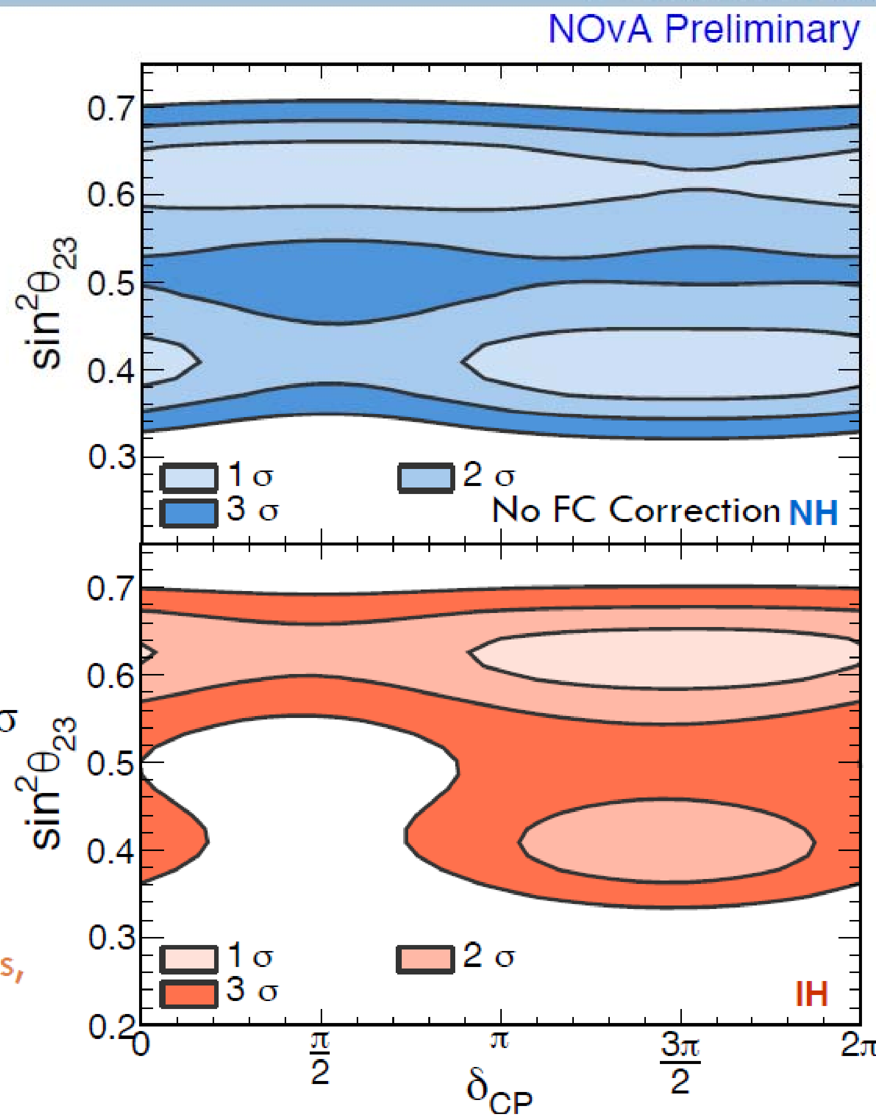
Contours

$\sin^2 2\theta_{23}$が0.5からずれたため、
NOvA単独では制限できない状況。

- Fit for hierarchy, δ_{CP}, $\sin^2\theta_{23}$
  - Constrain Δm^2 and $\sin^2\theta_{23}$ with NOvA disappearance results
  - Not a full joint fit, systematics and other oscillation parameters not correlated
- Global best fit Normal Hierarchy

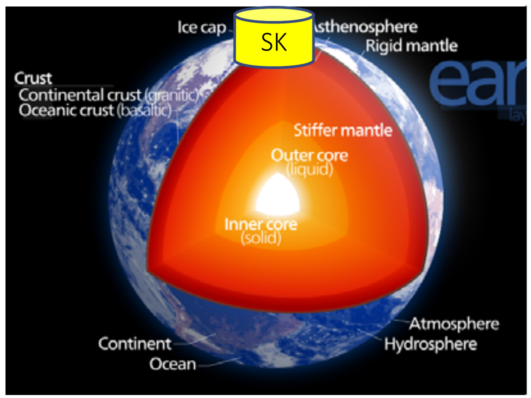
$$\delta_{CP} = 1.49\pi$$
$$\sin^2(\theta_{23}) = 0.40$$

  - best fit IH-NH, $\Delta\chi^2$=0.47
  - both octants and hierarchies allowed at 1σ
  - 3σ exclusion in IH, lower octant around $\delta_{CP}=\pi/2$

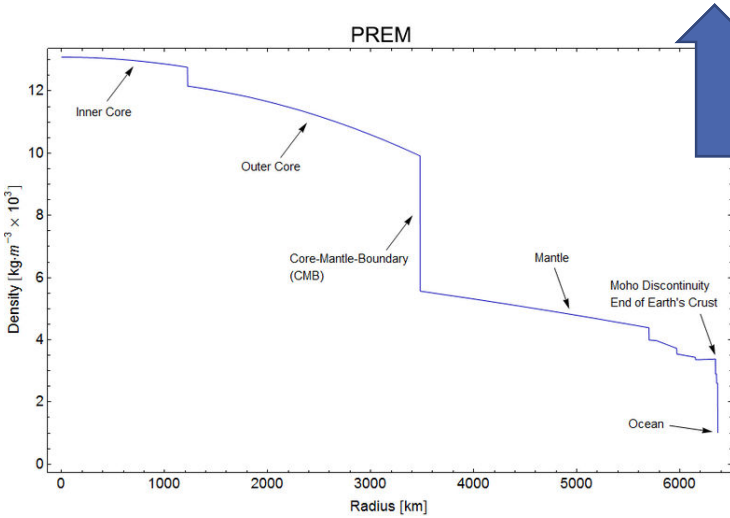


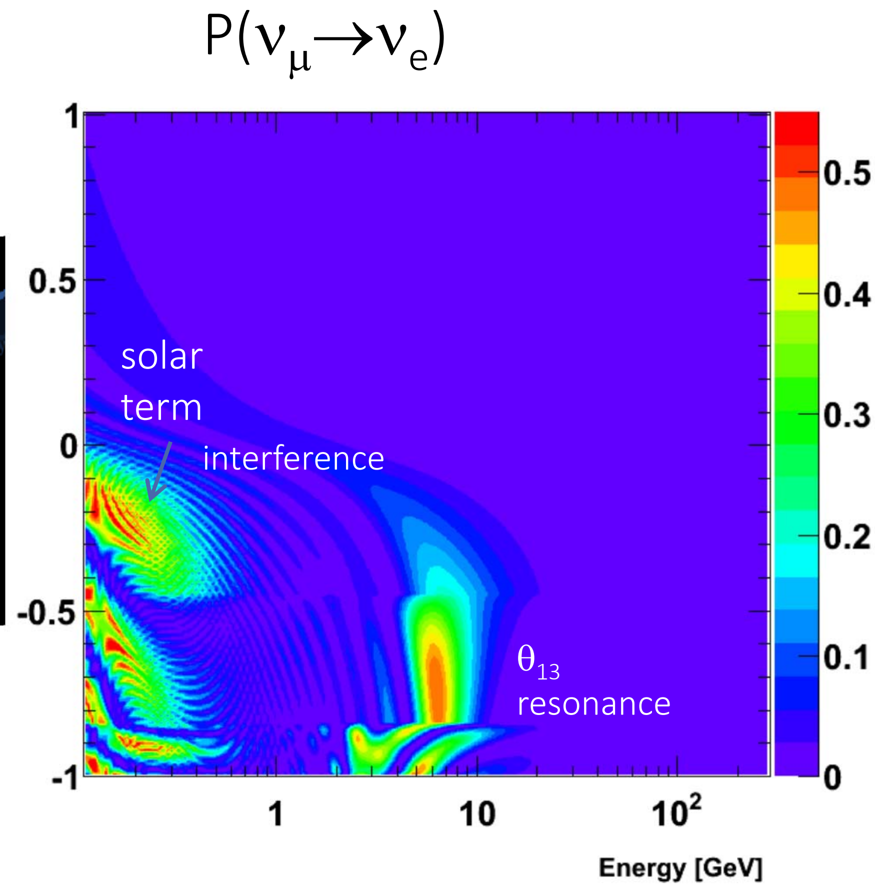
Antineutrino data will help resolve degeneracies, particularly for non-maximal mixing
Planned for Spring 2017

Atmospheric neutrino



wikipediaから画像転載





Resonance occurs only for (anti-) neutrinos under the normal (inverted) hierarchy.

MSW effect 二世代の場合で考える

$$H \approx \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} 0 & 0 \\ 0 & \frac{\Delta m^2}{2E} \end{pmatrix} \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} + \begin{pmatrix} \sqrt{2}G_F n_e & 0 \\ 0 & 0 \end{pmatrix}$$

$$= \begin{pmatrix} \frac{\Delta m^2}{2E}\sin^2\theta + \sqrt{2}G_F n_e & -\frac{\Delta m^2}{2E}\sin\theta\cos\theta \\ -\frac{\Delta m^2}{2E}\sin\theta\cos\theta & \frac{\Delta m^2}{2E}\cos^2\theta \end{pmatrix}$$

固有値は、

$$\frac{1}{2}\left[\frac{\Delta m^2}{2E} + \sqrt{2}G_F n_e \pm \sqrt{\underbrace{\left(\frac{\Delta m^2}{2E}\cos 2\theta - \sqrt{2}G_F n_e\right)^2}_{A^2} + \underbrace{\left(\frac{\Delta m^2}{2E}\right)^2 \sin^2 2\theta}_{B^2}}\right]$$

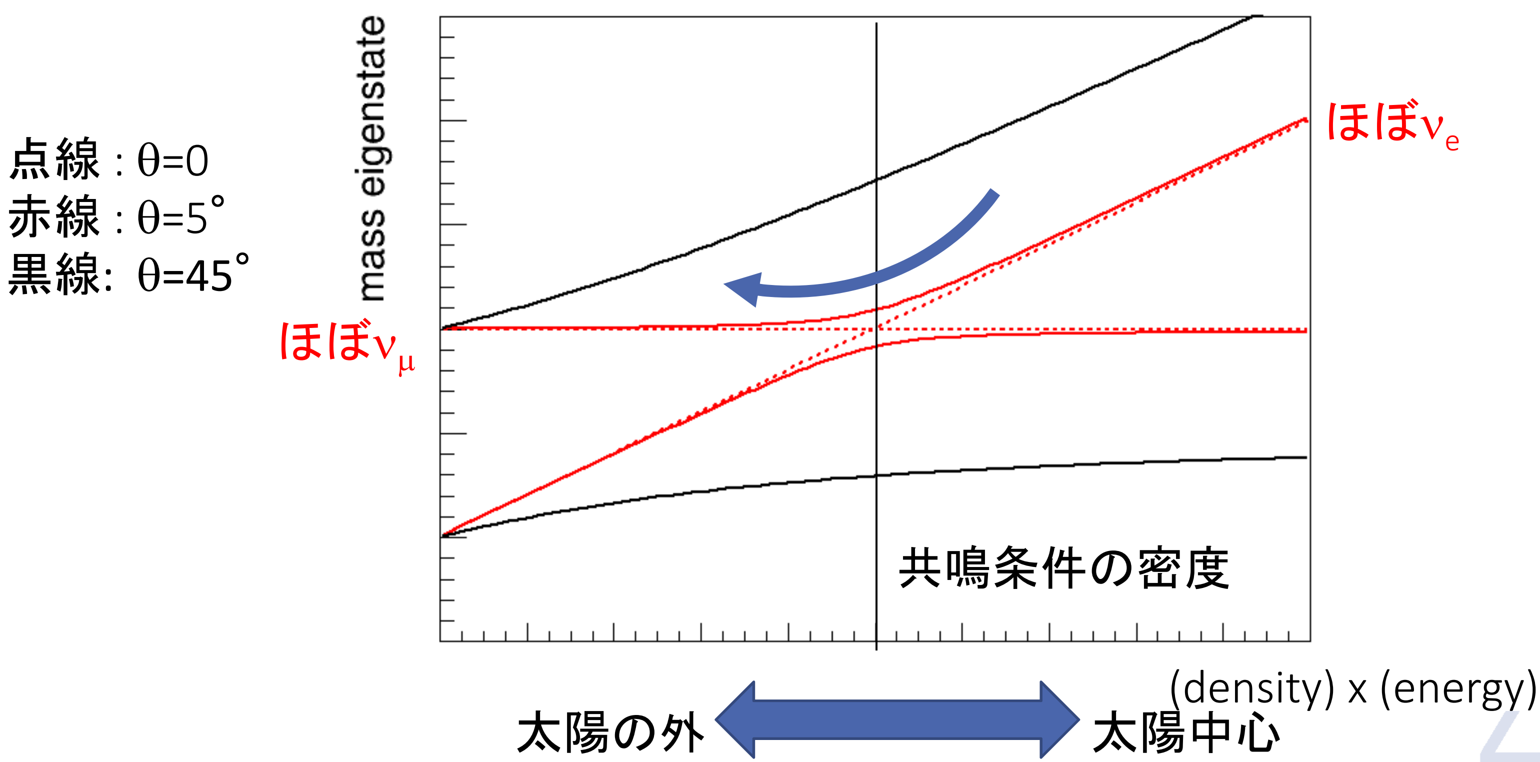
有効混合角は

$$\tan 2\theta_{matter} = \frac{B}{A} = \frac{\sin 2\theta}{\cos 2\theta - \frac{2\sqrt{2}G_F n_e E}{\Delta m^2}}$$

$$\tan 2\theta_{matter} = \frac{\sin 2\theta}{\cos 2\theta - \frac{2\sqrt{2}G_F n_e E}{\Delta m^2}} \Rightarrow n_e = \frac{\Delta m^2 \cos 2\theta}{2\sqrt{2}G_F E}$$ で最大混合に! = 共鳴条件

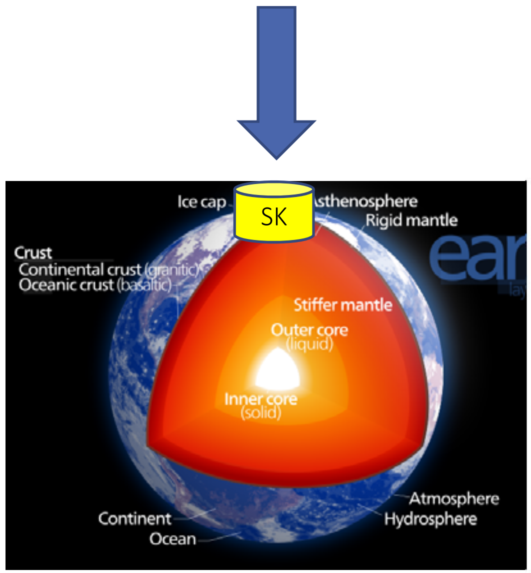
質量固有値 $$\frac{1}{2}\left[\frac{\Delta m^2}{2E} + \sqrt{2}G_F n_e \pm \sqrt{\left(\frac{\Delta m^2}{2E}\cos 2\theta - \sqrt{2}G_F n_e\right)^2 + \left(\frac{\Delta m^2}{2E}\right)^2 \sin^2 2\theta}\right]$$

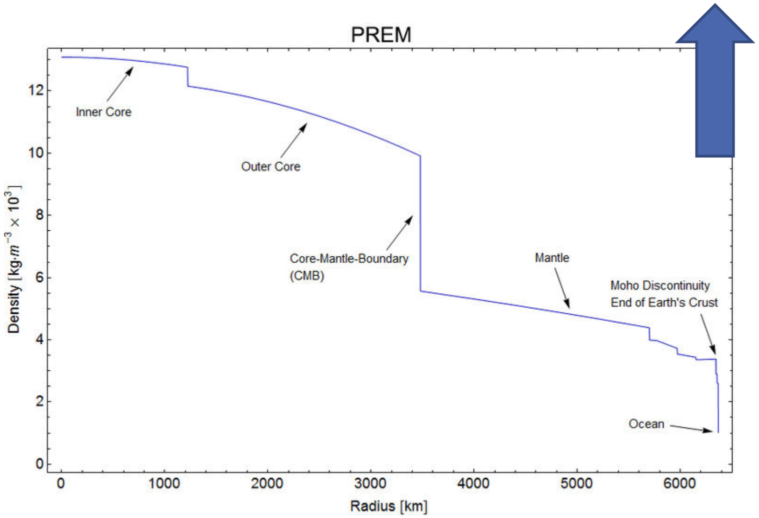
$\theta = 0$の時のみ、$\Delta m^2_{matter,1}$と$\Delta m^2_{matter,2}$が交差する。



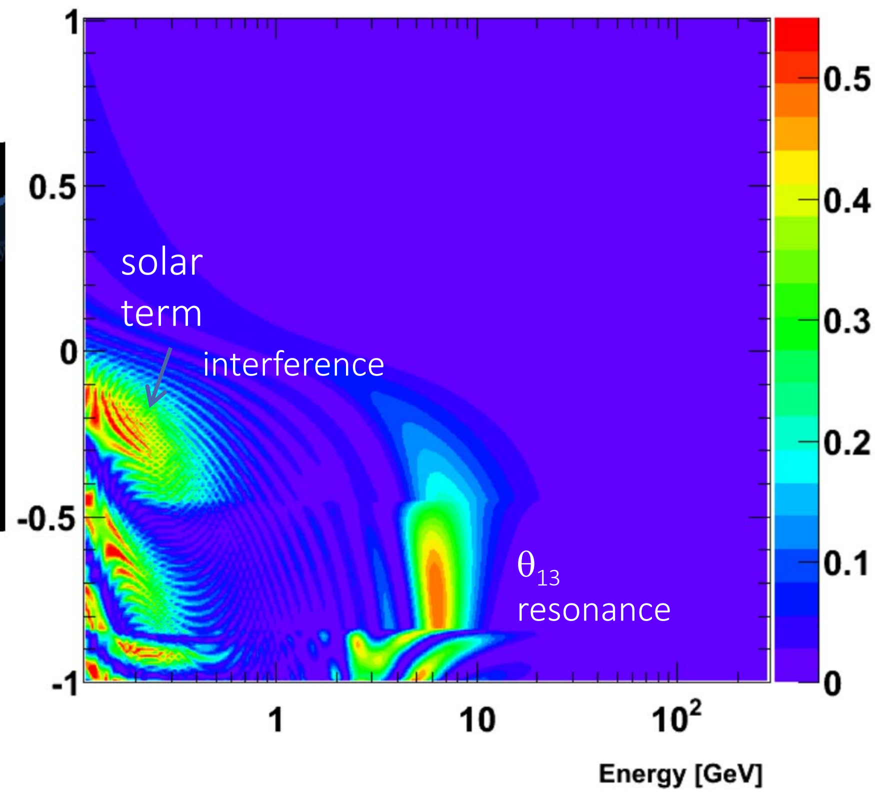
Atmospheric neutrino

wikipediaから画像転載



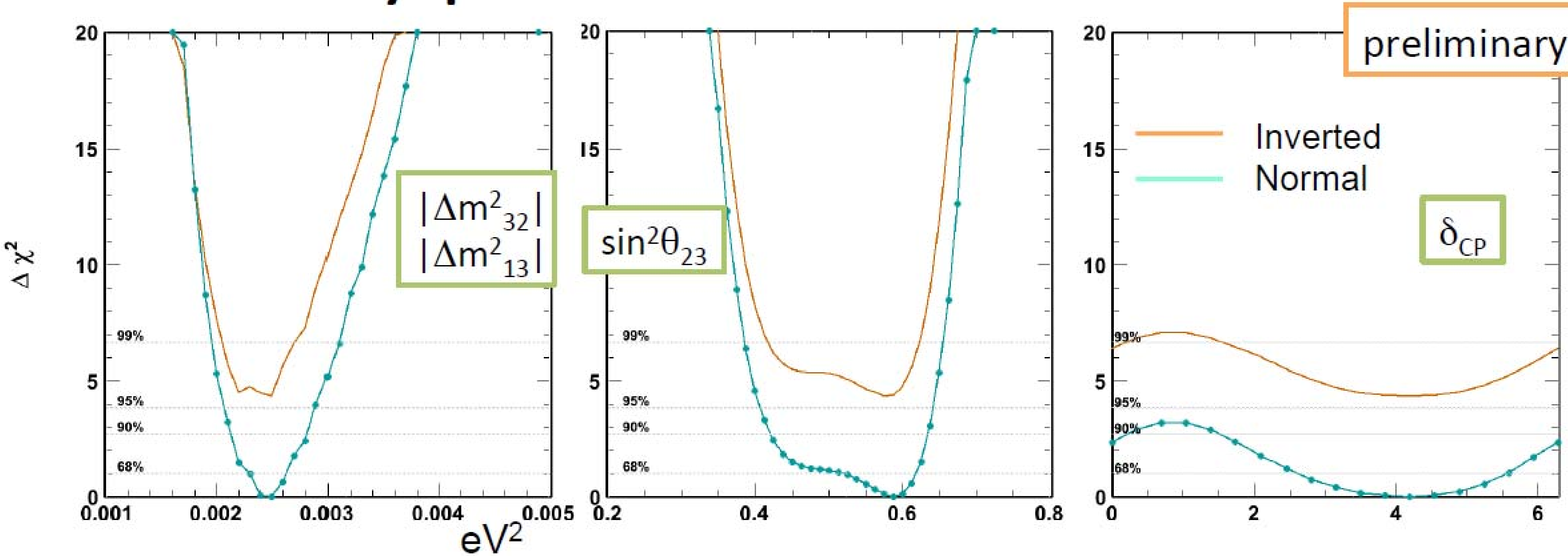


$P(\nu_\mu \rightarrow \nu_e)$



Resonance occurs only for (anti-) neutrinos under the normal (inverted) hierarchy.

SK only parameter determination



Fit (517 dof)	χ^2	$\sin^2\theta_{13}$	δ_{CP}	$\sin^2\theta_{23}$	$\|\Delta m^2_{32}\|$ eV^2
SK (IH)	576.08	0.0219 (fix)	4.189	0.575	2.5×10^{-3}
SK (NH)	571.74	0.0219 (fix)	4.189	0.587	2.5×10^{-3}

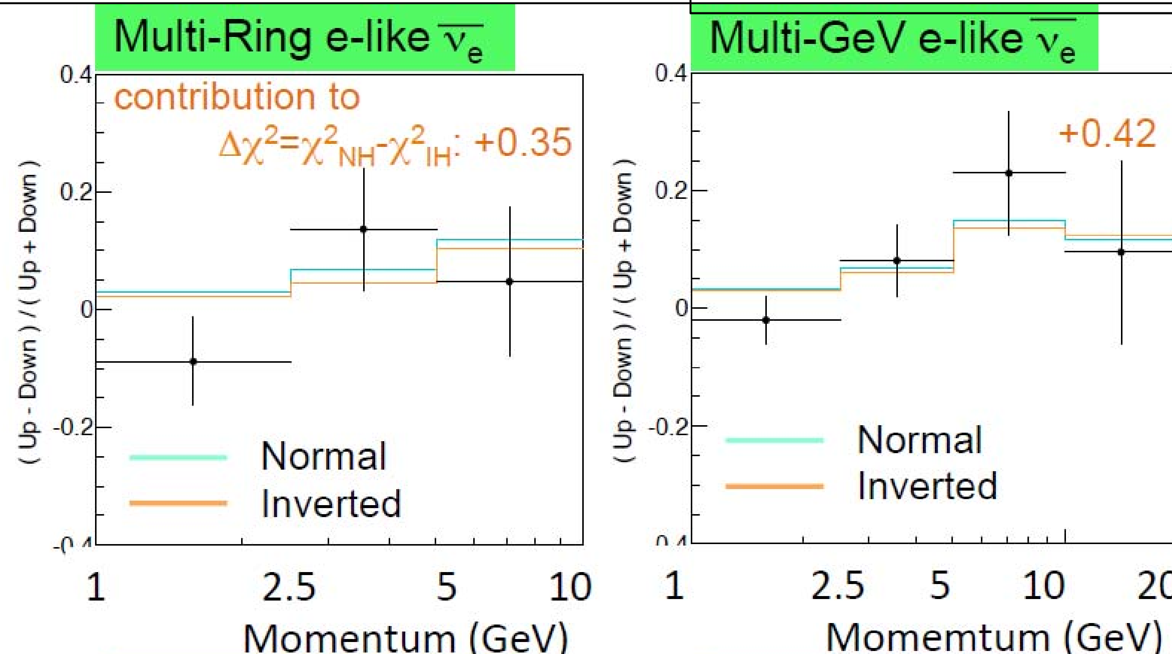
- SK only (θ_{13} fixed): $\Delta\chi^2 = \chi^2_{NH}-\chi^2_{IH}= -4.3$ (-3.1 expected)
- Under IH hypothesis, the probability to obtain $\Delta\chi^2$ of -4.3 or less is 0.031 ($\sin^2\theta_{23}$=0.6) and 0.007 ($\sin^2\theta_{23}$=0.4). Under NH hypothesis, the probability is 0.45 ($\sin^2\theta_{23}$=0.6).

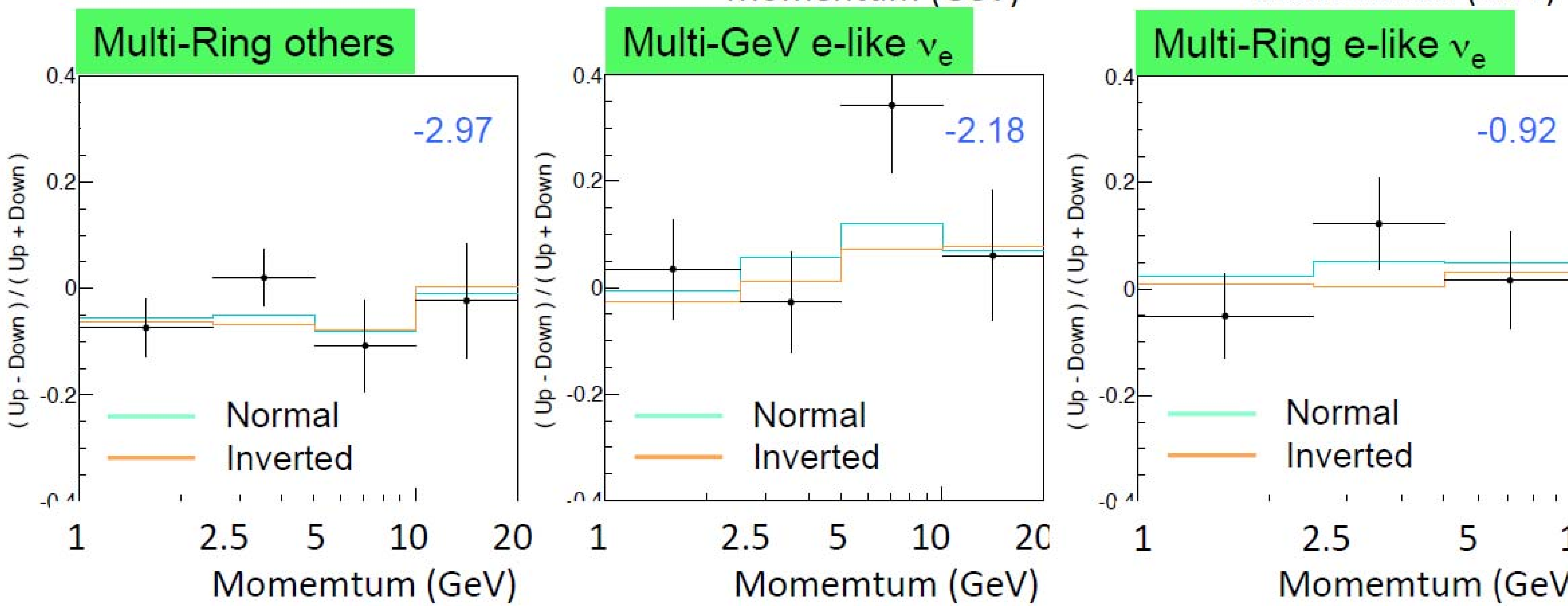
S.Moriyama, neutrino2016

Hierarchy Sensitive Samples

$$\frac{\text{UP-DOWN}}{\text{UP+DOWN}}$$

as a func. of p

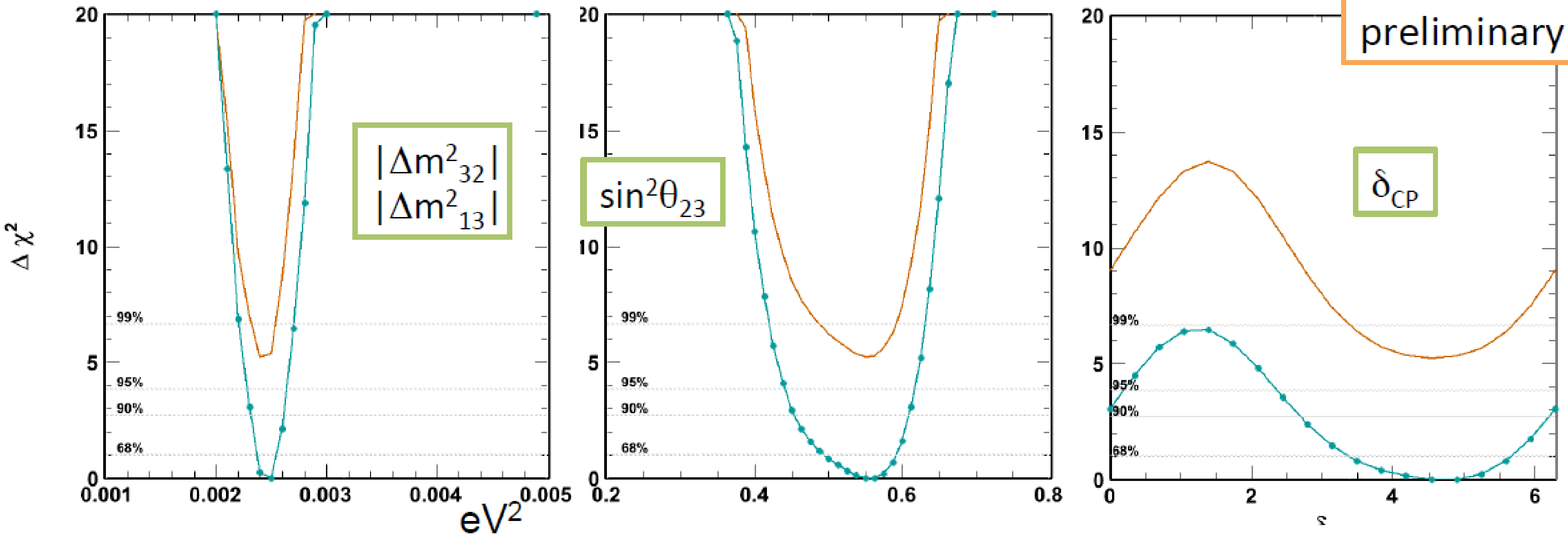




S.Moriyama, neutrino2016

SK+T2K ν_μ, ν_e parameter determination

Not a joint analysis, fit external data using publicly available T2K info.

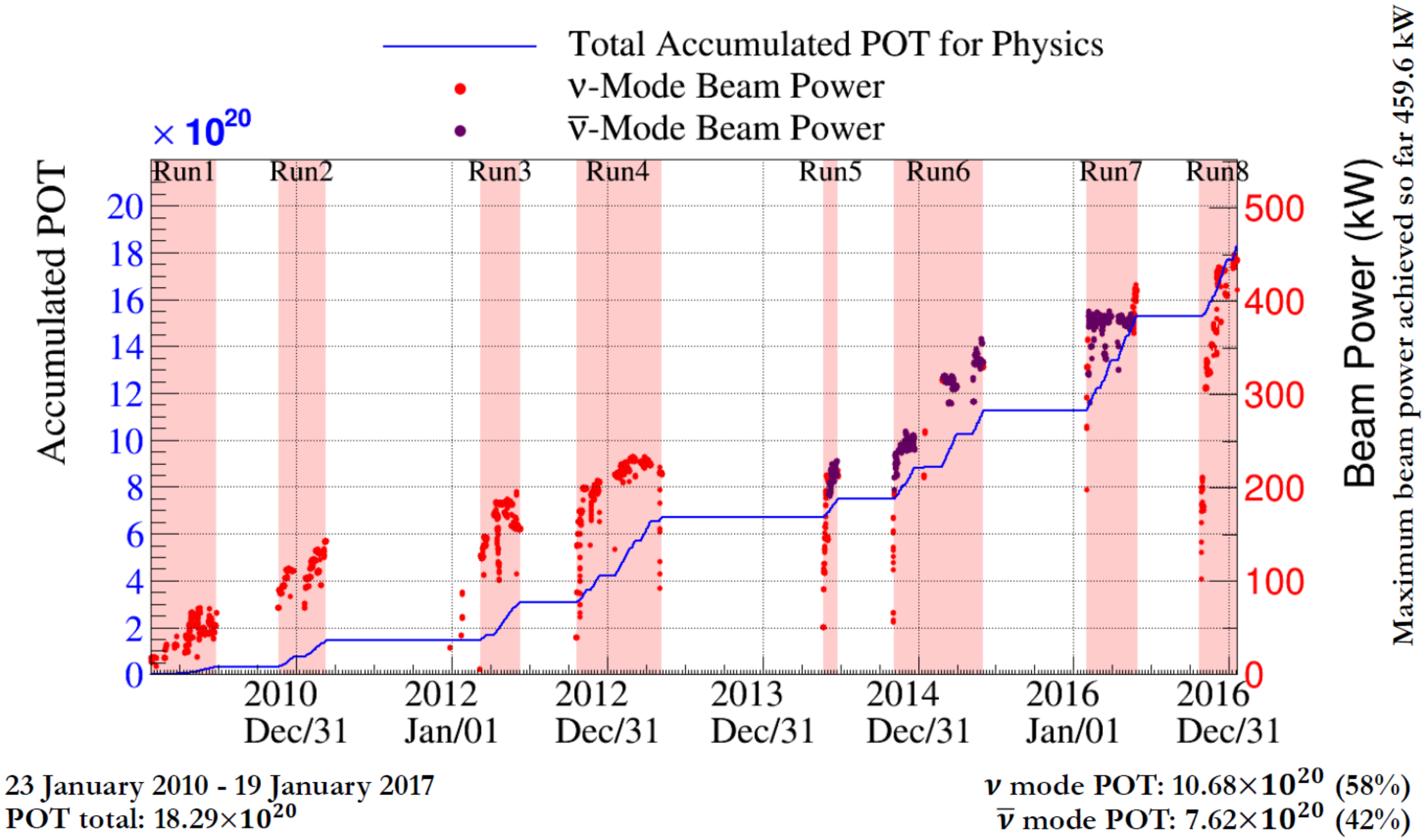


Fit (585 dof)	χ^2	$\sin^2\theta_{13}$	δ_{CP}	$\sin^2\theta_{23}$	$\lvert\Delta m^2_{32}\rvert$ eV^2
SK+T2K (IH)	644.82	0.0219 (fix)	4.538	0.55	2.5×10^{-3}
SK+T2K (NH)	639.61	0.0219 (fix)	4.887	0.55	2.4×10^{-3}

- SK+T2K (θ_{13} fixed): $\Delta\chi^2 = \chi^2_{NH} - \chi^2_{IH} = -5.2$
  (-3.8 exp. for SK best, -3.1 for combined best)
- Under IH hypothesis, the probability to obtain $\Delta\chi^2$ of -5.2 or less is 0.024 ($\sin^2\theta_{23}$=0.6) and 0.001 ($\sin^2\theta_{23}$=0.4). NH: 0.43 ($\sin^2\theta_{23}$=0.6)

今後の見通し

Proton delivery to T2K



Stable operation at 450kW achieved (first design goal: 750kW)

(Ep=30GeV) x (230Tp/5us pulse) x (2.48sec cycle)

Number of protons on target (POT)

18.3×10^{20} accumulated (10.7×10^{20} for nu & 7.6×10^{20} anti−nu)

7.8×10^{21} aimed as original T2K goal

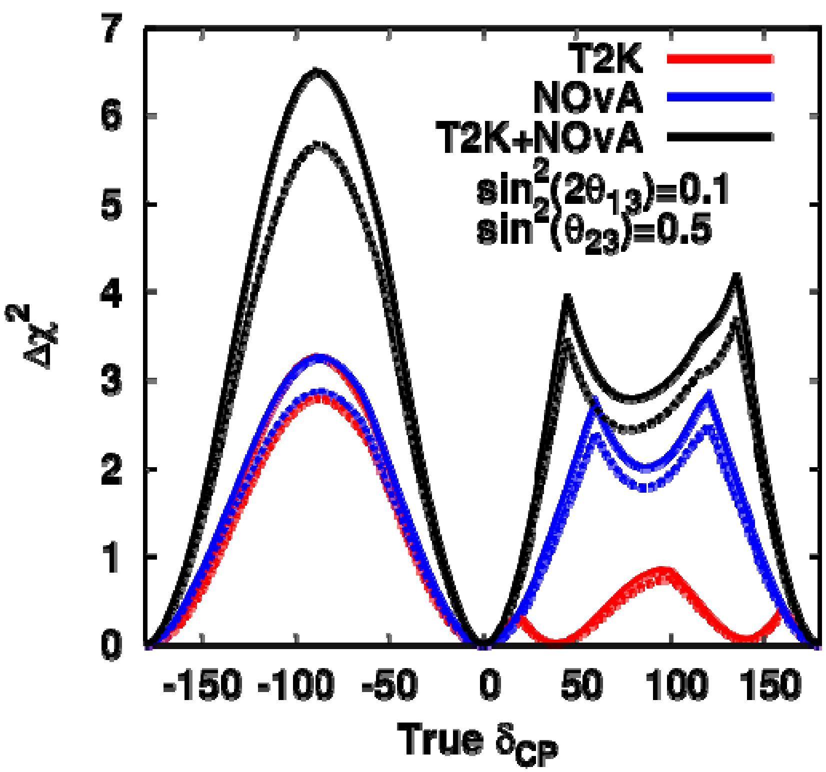
T2K+NOvA sensitivity

Assuming both experiments run 50% ν-mode, 50% anti-ν mode.

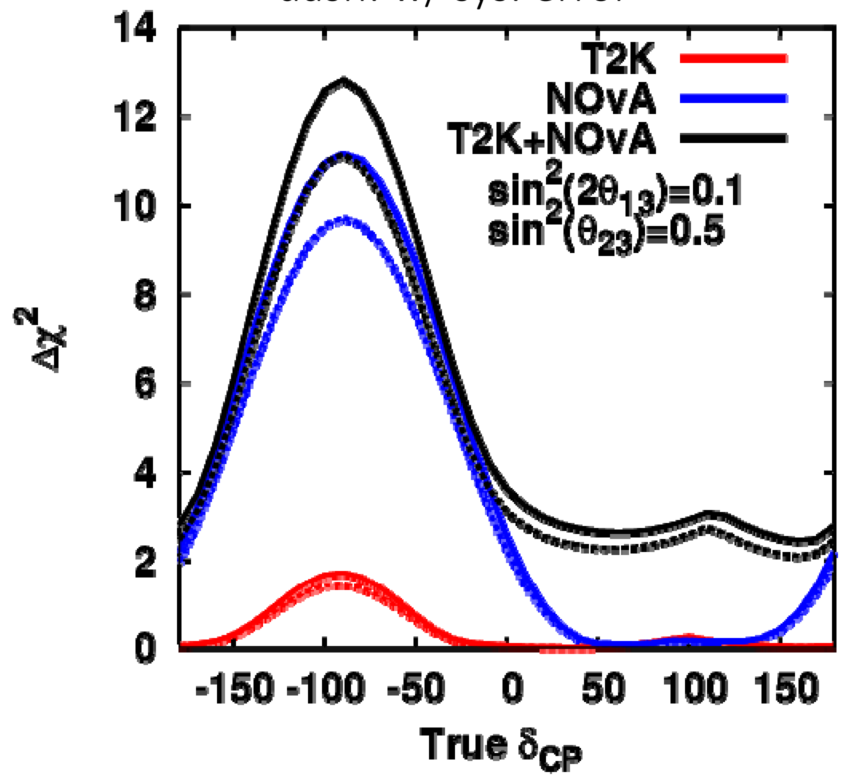
with 5% normalization uncertainty on signal and 10% normalization uncertainty on background.

Shown is NH case.

solid : w/o sys. error
dash: w/ sys. error



sensitivity to non-zero CP-violating term

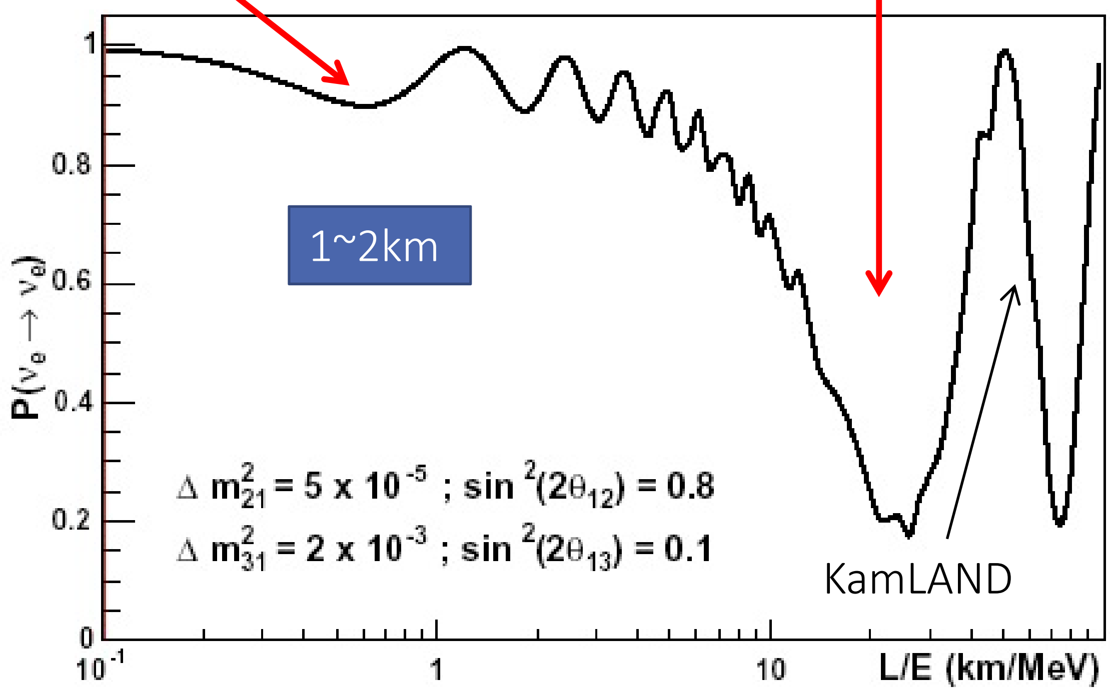


sensitivity to resolve MH

Disappearance of $\bar{\nu}_e$ from reactor

$$P_{e\to e} \approx 1 - \sin^2 2\theta_{12} \cdot \sin^2\left(1.27\,\Delta m^2_{21} L / E_\nu\right)$$

$$P_{e\to e} \approx 1 - \sin^2 2\theta_{13} \cdot \sin^2\left(1.27\,\Delta m^2_{31} L / E_\nu\right)$$

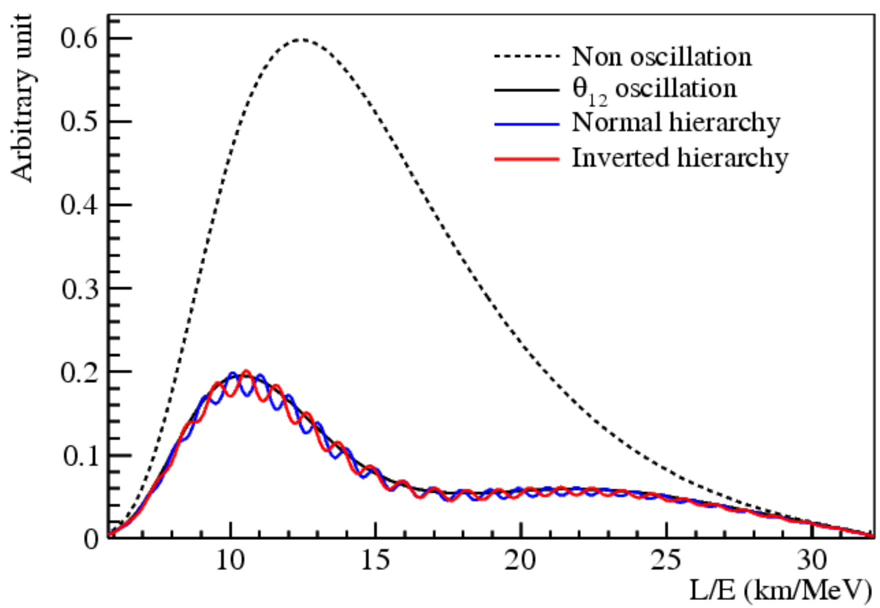


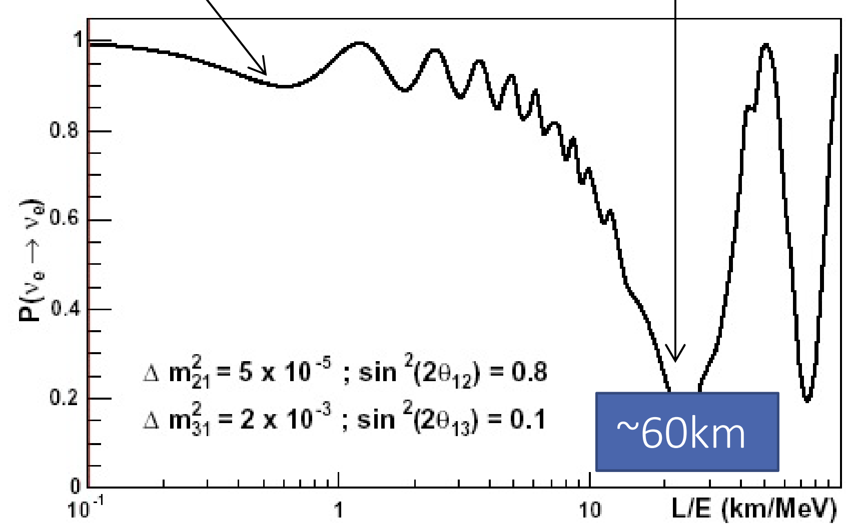
Reactor Next step -Mass Hierarchy-

$$\begin{aligned}
P_{ee}(L/E) &= 1 - P_{21} - P_{31} - P_{32} \\
P_{21} &= \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21}) \\
P_{31} &= \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31}) \\
P_{32} &= \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32})
\end{aligned}$$

$$P_{e\to e} \approx 1 - \sin^2 2\theta_{12} \cdot \sin^2\left(1.27\,\Delta m^2_{21} L / E_\nu\right)$$

$$P_{e\to e} \approx 1 - \sin^2 2\theta_{13} \cdot \sin^2\left(1.27\,\Delta m^2_{31} L / E_\nu\right)$$



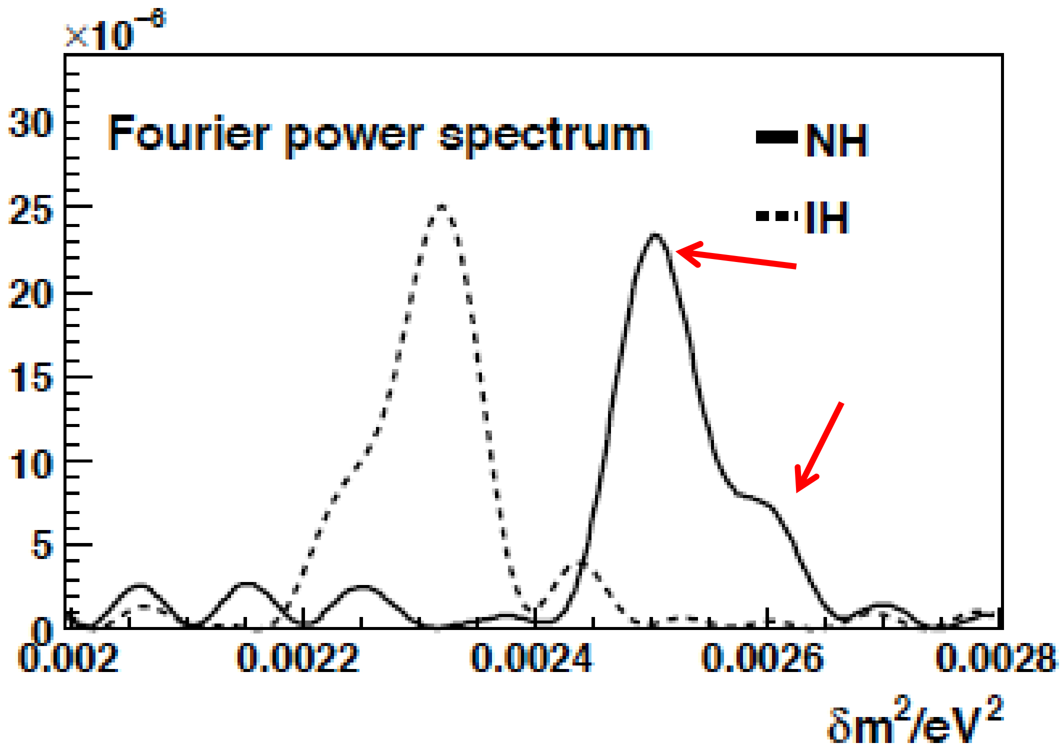


Reactor Next step Mass Hierarchy

$$
\begin{aligned}
P_{ee}(L/E) &= 1 - P_{21} - P_{31} - P_{32} \\
P_{21} &= \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21}) \\
P_{31} &= \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31}) \\
P_{32} &= \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32})
\end{aligned}
$$

$$
\begin{aligned}
\theta_{12} &= 34.4^\circ \\
\cos^2(\theta_{12}) &= 0.68 \\
\sin^2(\theta_{12}) &= 0.32
\end{aligned}
$$

Need
- ~20kt(!) LS detector
- 2~3%/√E resolution

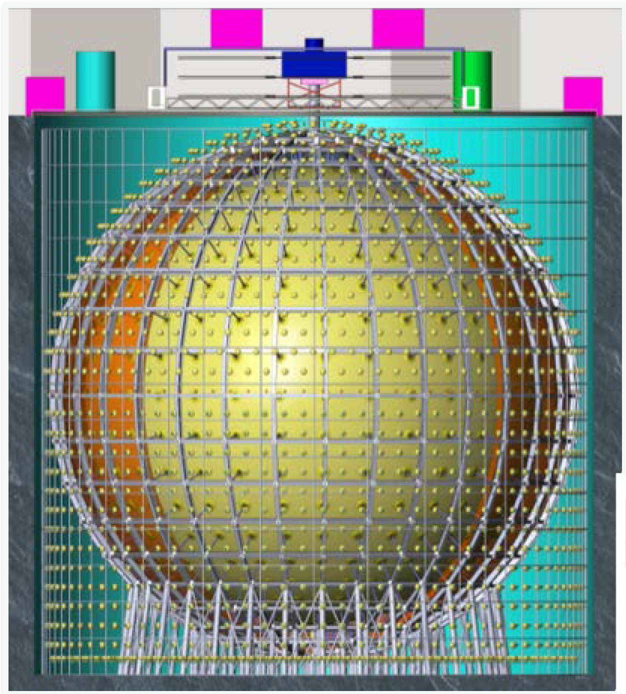


JUNO

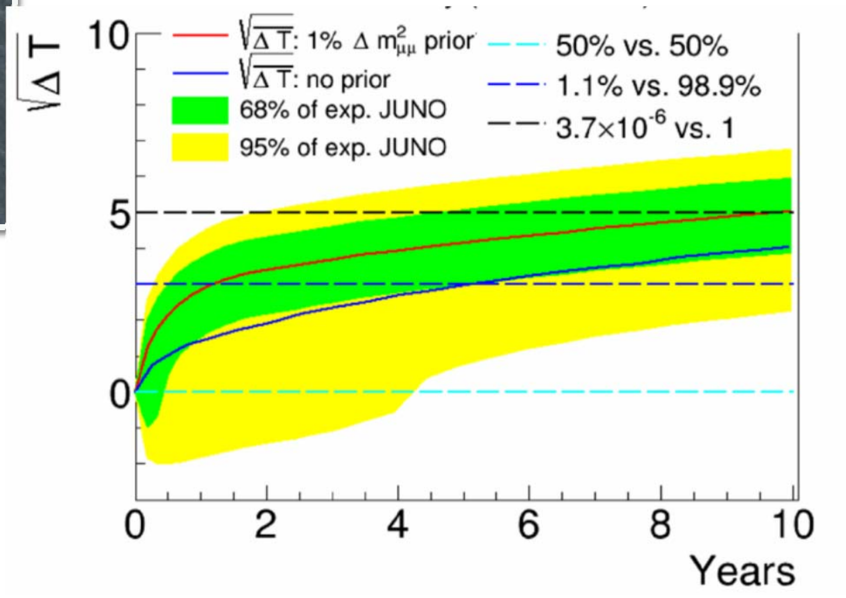
- LS large volume: ➔ for statistics
- High Light(PE) ➔ for energy resolution

Steel Truss
Holding PMTs
~17000 x 20"
~34000 x 3"

Acrylic Sphere
filled with 20 kt LS

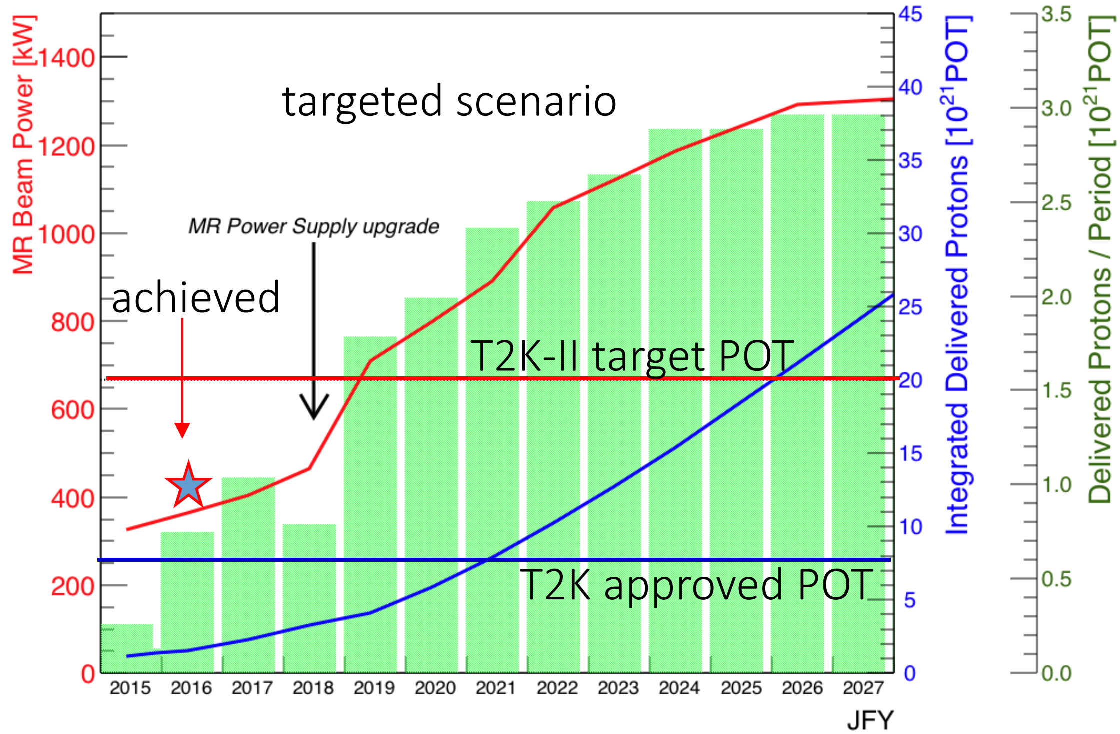


2020年実験開始予定



T2K-II target statistics and systematics

- ✓Target Beam power 1.3 MW
- ✓20×10^{21} POT by 2025~2026
- ✓Increase effective statistics by up to 50%
- ✓ horn current, SK fiducial volume, new event samples
- ✓Reduce systematic error ~6% → ~4%

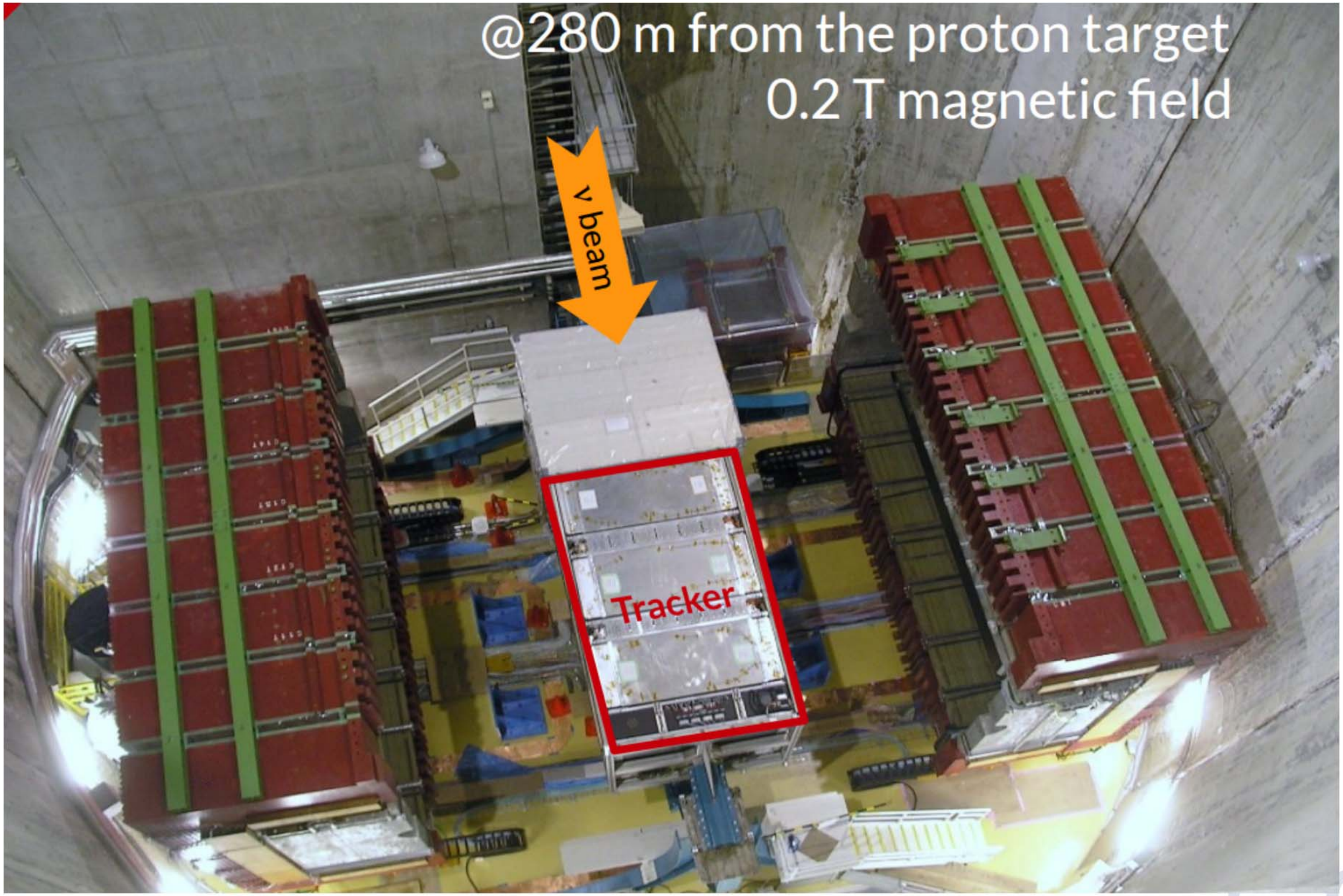


Expected number of events (1:1 $\nu:\bar{\nu}$ running case)

ν_e sample : 455 evts ± 20% change depending on δ_{CP}

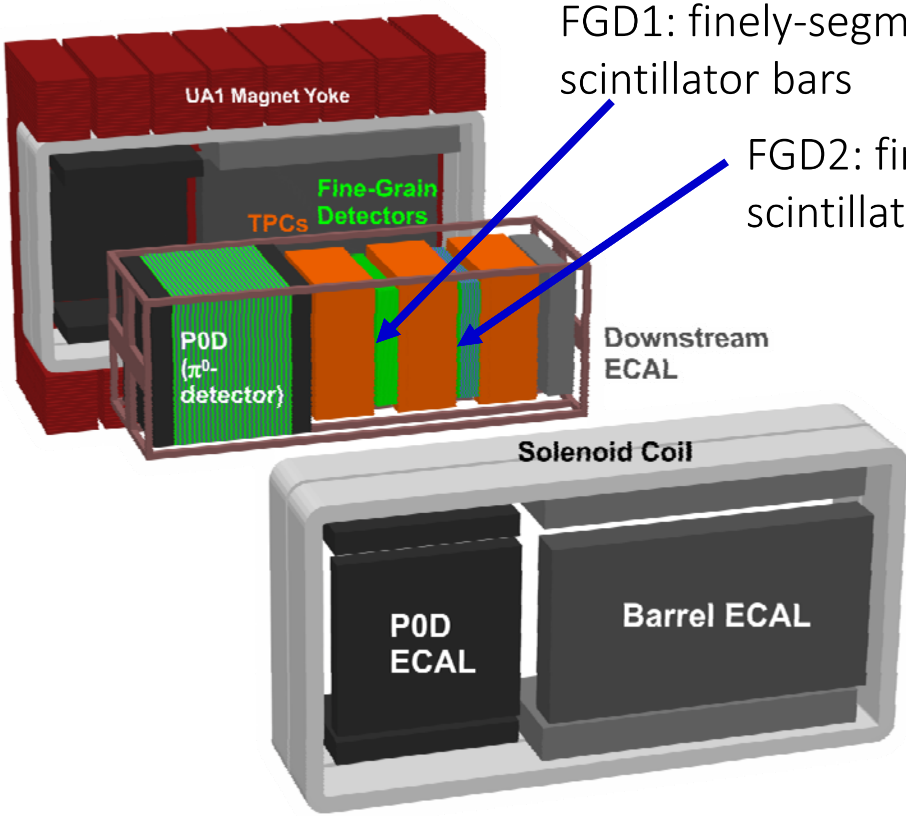
$\bar{\nu}_e$ sample : 129 evts ± 13% change depending on δ_{CP}

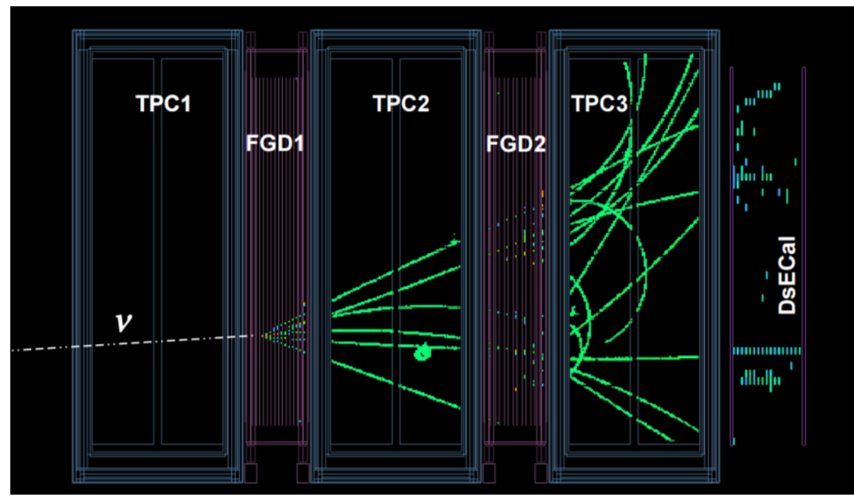
The T2K off-axis near detector: ND280

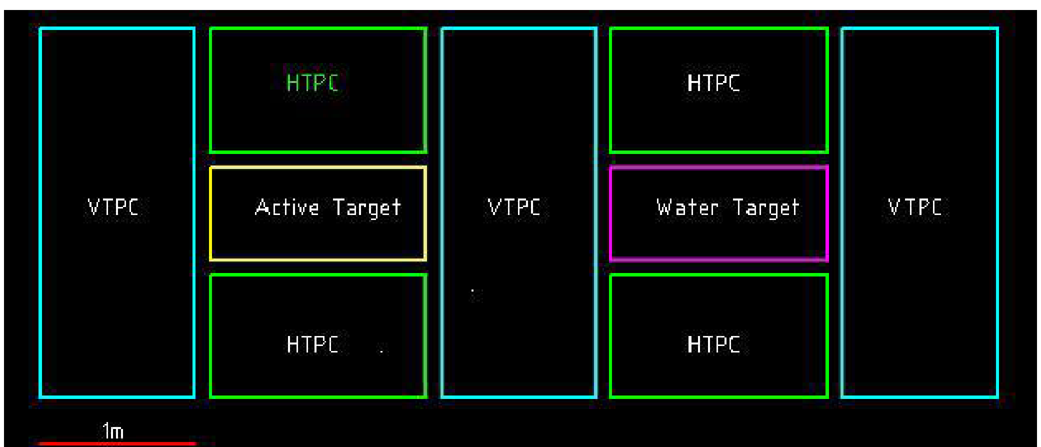


FGD1: finely-segmented scintillator bars

FGD2: finely-segmented scintillator bars + water

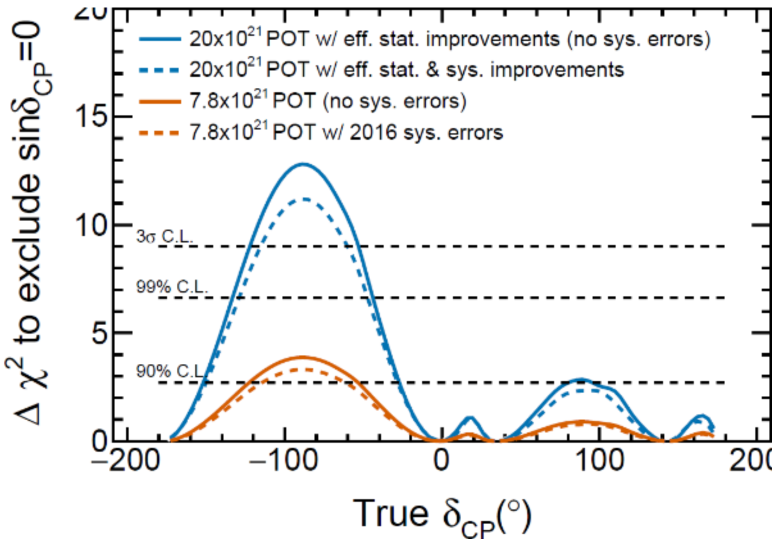


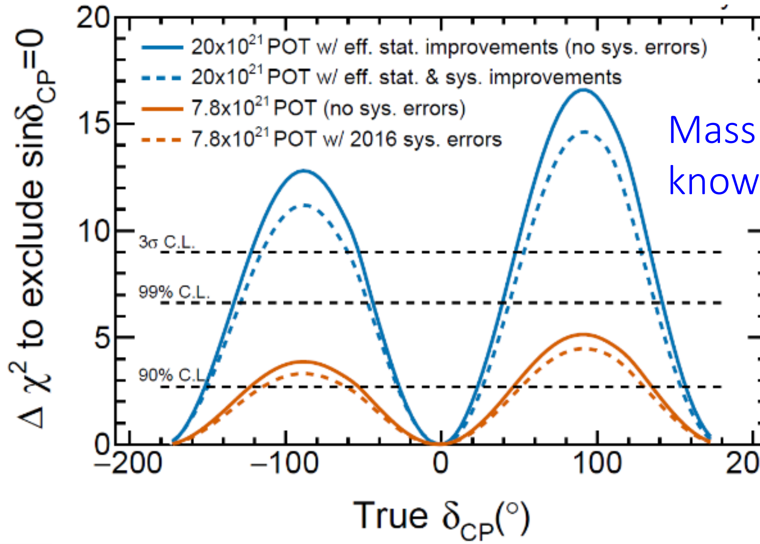




立体角を広げるために、
2020年頃までに
メジャーアップグレード

http://arxiv.org/abs/1607.08004

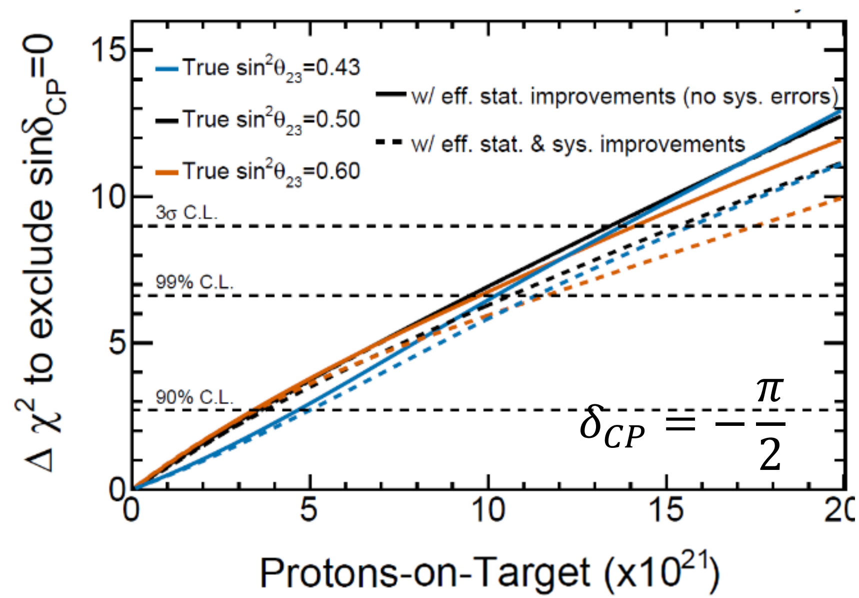




Mass hierarchy known case

Assuming 1:1 $\nu:\bar{\nu}$ running

- >3σ C.L. for $\delta_{CP} = -\frac{\pi}{2}$
- 99% C.L. for ~50% of δ_{CP} if mass hierarchy known

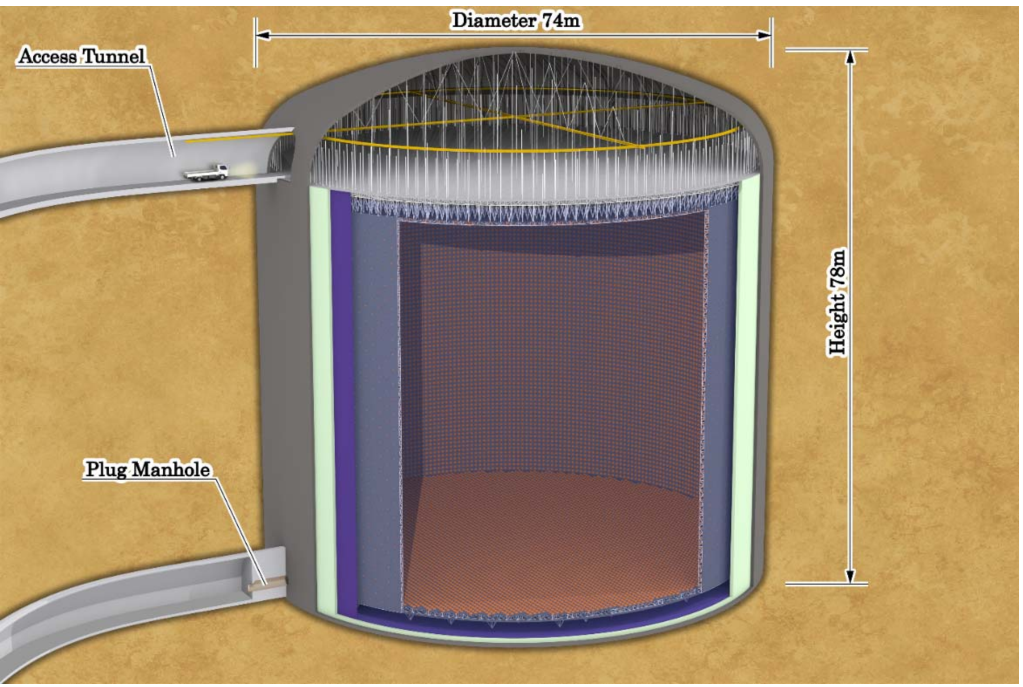


T2K-II Sensitivity to CP-violation

Hyper-Kamiokande

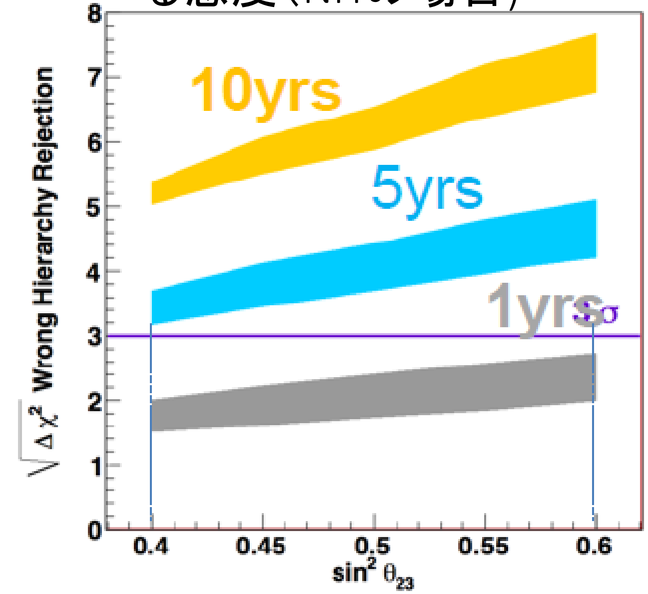
2026年頃までに建設するのを目標としている。

韓国にも同じ規模のタンクを作る計画が議論されている



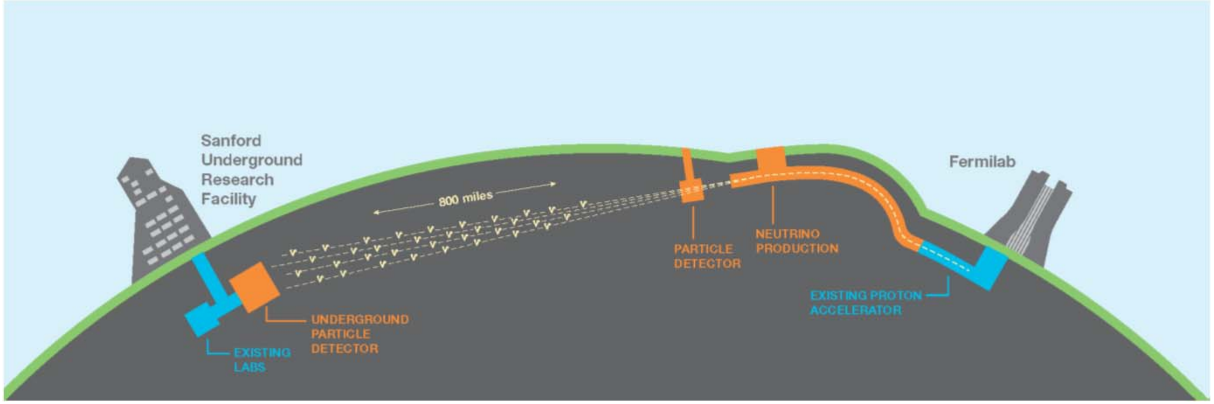
スーパーカミオカンデの約10倍(x2の可能性も)

Mass Hierarchyに対する感度（NHの場合）

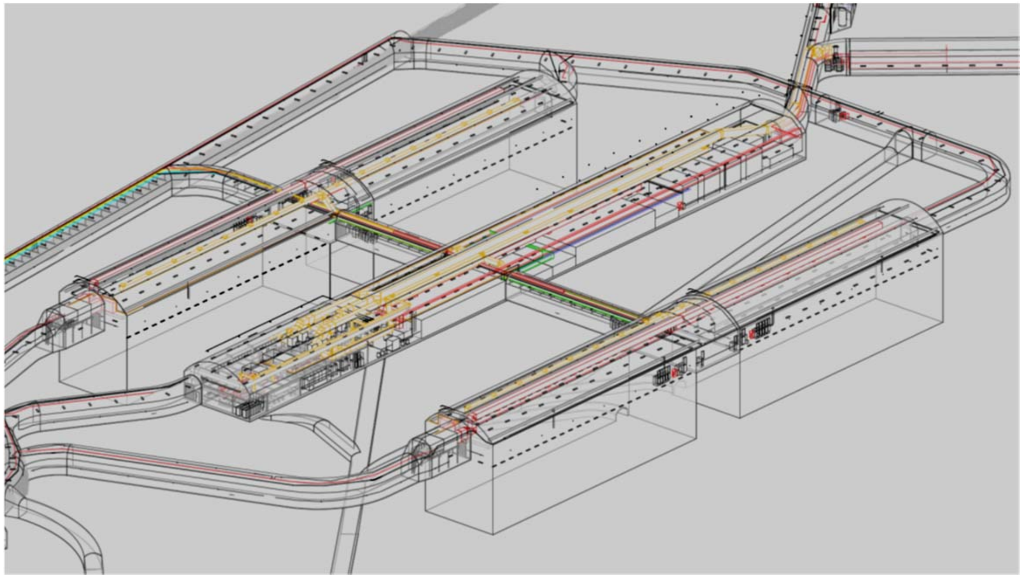


J-PARCニュートリノ、大気ニュートリノ両方を使っている。

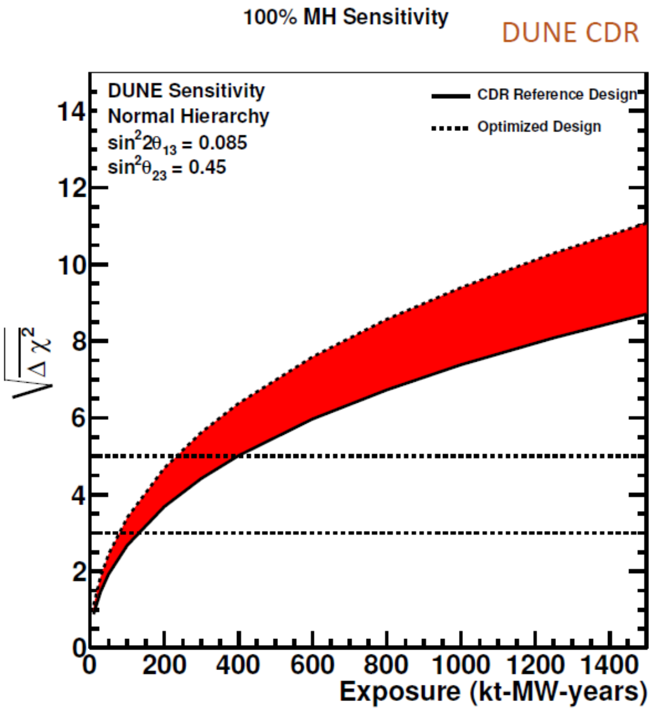
DUNE



- 基線長1,300km
- ビーム強度 1.2 MW
- 10-kt x 4個の 液体アルゴン検出器
- 2026年開始を目指している

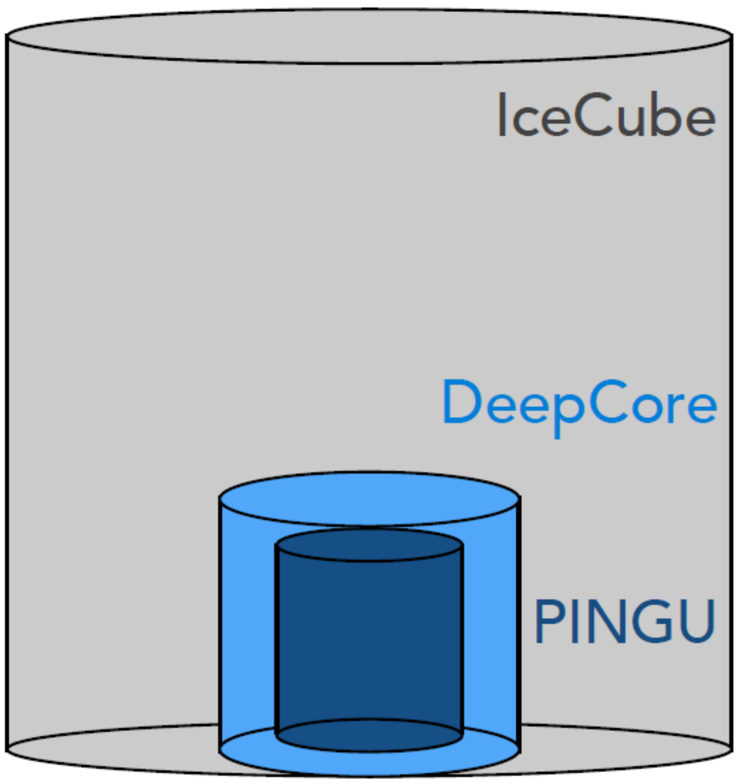


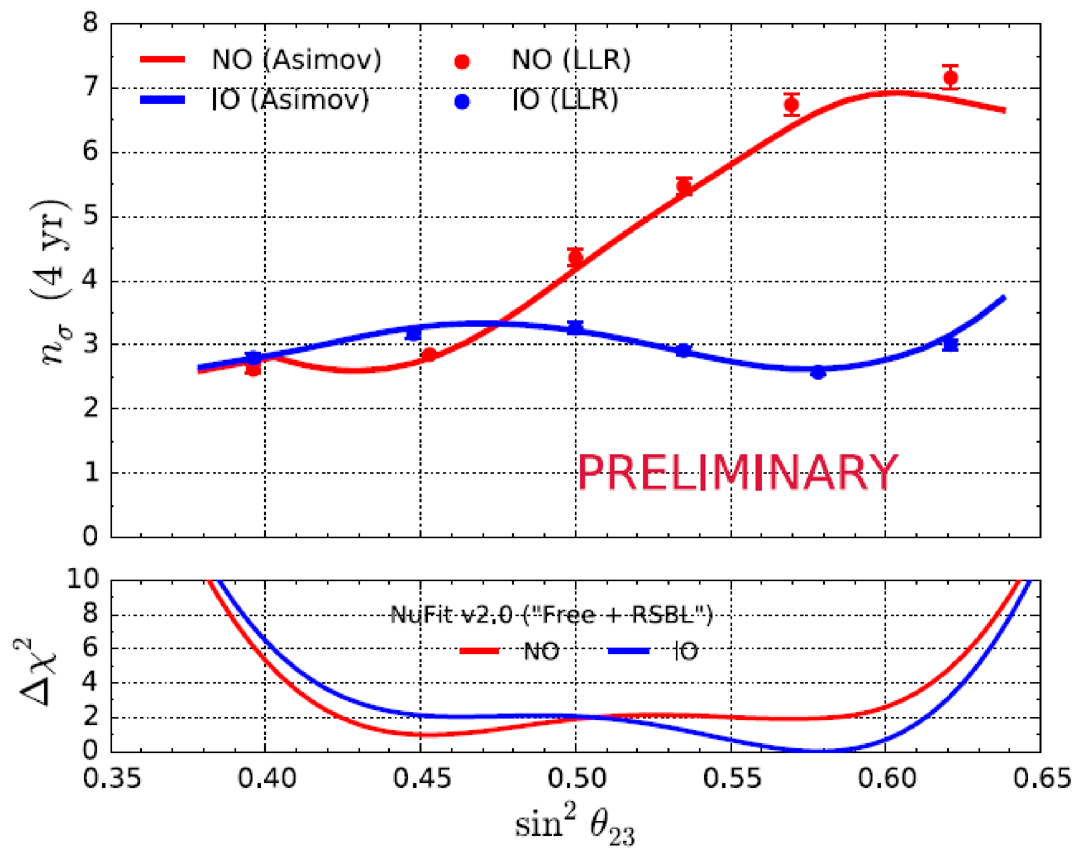
DUNE CDR



IceCube PINGU

建設に5年



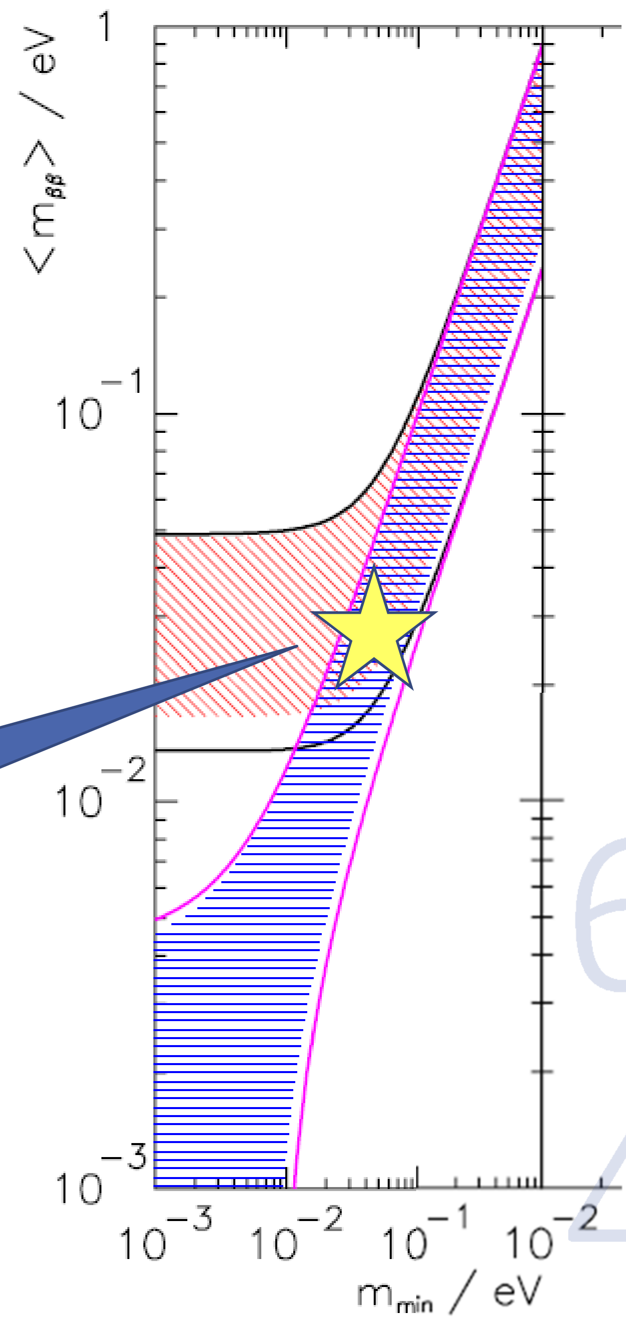


まとめ

ニュートリノ振動、確実に進んでいます。

CPの破れが見える前夜？

MHも数年で決まるかも。



市川の予言
- δ=–90°
- NH
- m_1~0.02eV

みんなが幸せ