



反ニュートリノでの測定を開始した T2K実験の最新結果

市川温子 京都大学
for the T2K collaboration

- 初めの5分間：ニュートリノ振動の説明
知っている人は説明の粗さ探しをしてください。(または寝るのも可)
(または、パワーポイントアニメーション技術を楽しんでください)
- 次の5分間: 反ニュートリノも測ると何がわかるのか？
知っている人は説明の粗さ探しをしてください。(または寝るのも可)
- 次の10分間：T2K実験の最近
- 次の20分間：T2K実験の最新結果
 - neutrino2016の結果を見た人へ
 - CPTテストが新しくリリースされました!
 - データが1週間分、増えています!
 - 新しいappearance sampleのデータをオープン!
- 最後の5分間: 今後の展望

内容

それぞれ重さが違う



軽い



重い

クォーク

アップ	チャーム	トッブ
ダウン	ストレンジ	ボトム
電子	ミュー	タウ
電子ニュートリノ	ミューニュートリノ	タウニュートリノ

電荷が
違う

レプトン

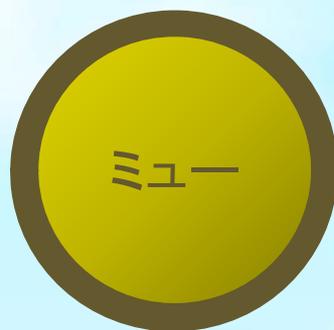


電荷を持ってない。重さも(ほとんど)ない。

どうやって区別する？

物質を構成する素粒子

電子、ミュー粒子、タウ粒子は物質に当たって「弱い力」でひっくり返ると



- 電子は、物質中で弱い力を受けて**電子ニュートリノ**になる
- ミュー粒子は、**ミューニュートリノ**になる。
- タウ粒子は、**タウニュートリノ**になる。

コインの表と裏

ニュートリノは、物質に当たって「弱い力」でひっくり返ると



- 電子ニュートリノは、物質中で弱い力を受けて電子になる
- ミューニュートリノは、ミュー粒子になる。
- タウニュートリノは、タウ粒子になる。

コインの表と裏

表

電子

ミュー

タウ

裏

電子
ニュー
トリノ

ミュー
ニュー
トリノ

タウ
ニュー
トリノ

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。

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)

電子ニュートリノを裏返したら電子しか出てこない。ミュー粒子やタウ粒子には決してならない(と1990年ころまで)思われていた

- 地下1000メートル
- 50,000トンの水タンク
- 11,146 20 inch(~50cm)
光電子増倍管

電子

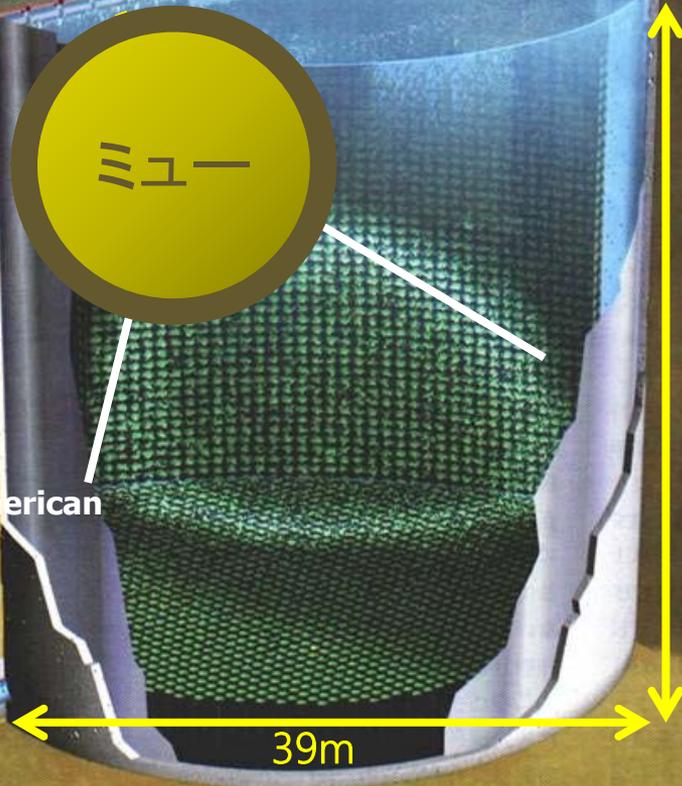
42m

39m

© Scientific American

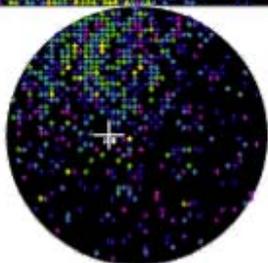
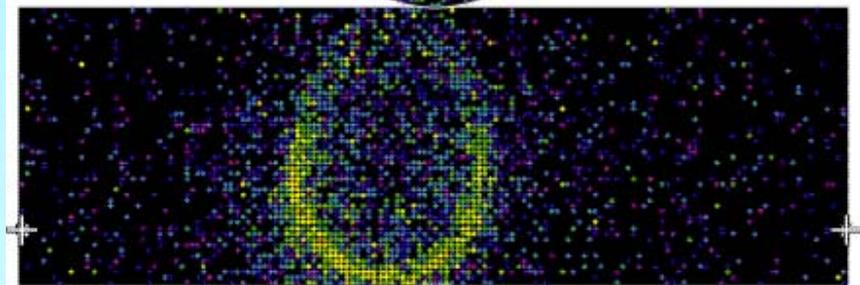
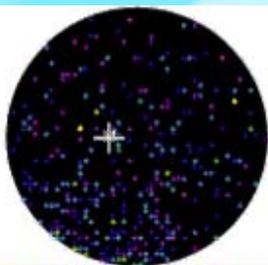
スーパーカミオカンデ検出器

- 地下1000メートル
- 50,000トンの水タンク
- 11,146 20 inch(~50cm) 光電子増倍管

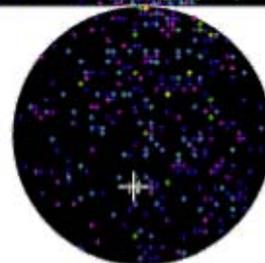
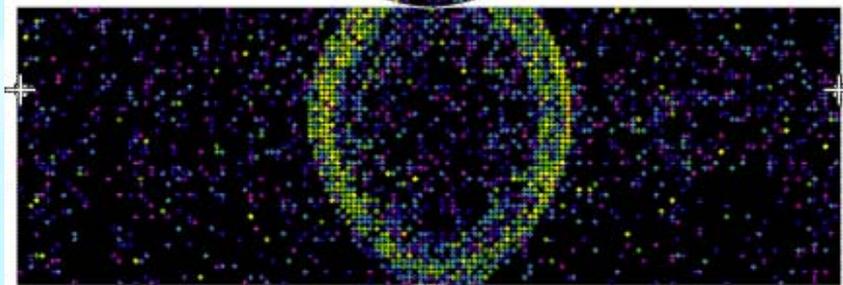
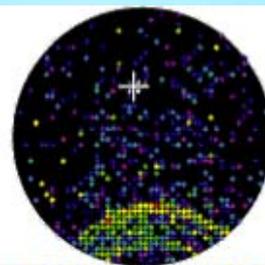


スーパーカミオカンデ検出器

電子

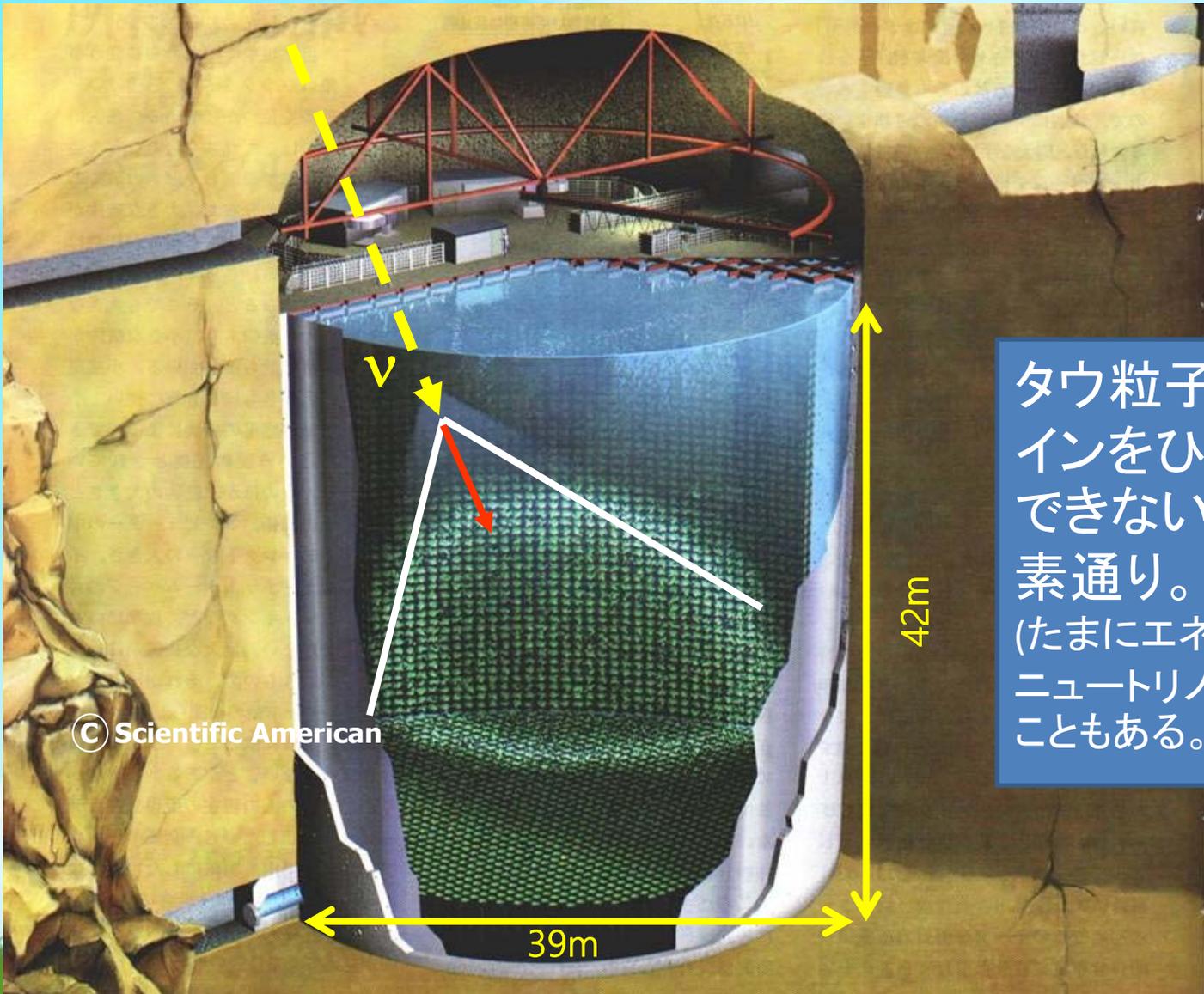


ミュー



電子ニュートリノが来たのか、ミューニュートリノが来たのかを区別できる。

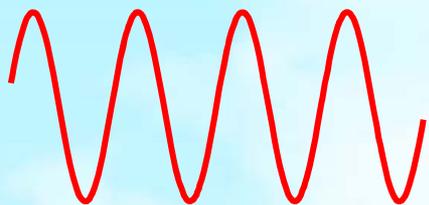
スーパーカミオカンデは
電子とミュー粒子を区別できる



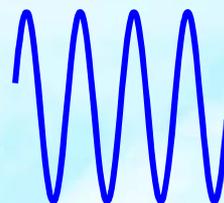
タウ粒子は重いので、コインをひっくり返すことができない。。
素通り。
(たまにエネルギーの高いタウニュートリノが来るとひっくり返ることもある。)

タウニュートリノが来ると。。。

周波数が低い(波長が長い)

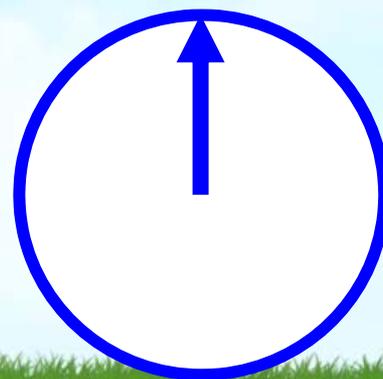
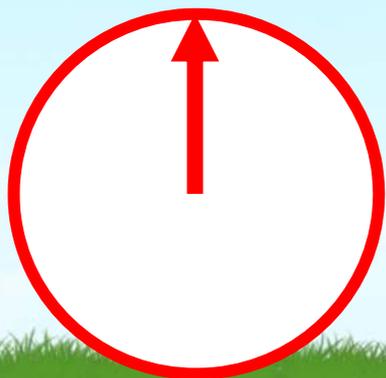


周波数が高い(波長が短い)



エネルギーが大きいほど周波数が高い
同じエネルギーでも、重い粒子は周波数が高い

周波数が違う、ということは、粒子がそれぞれ進み方の違う時計を持っているようなもの

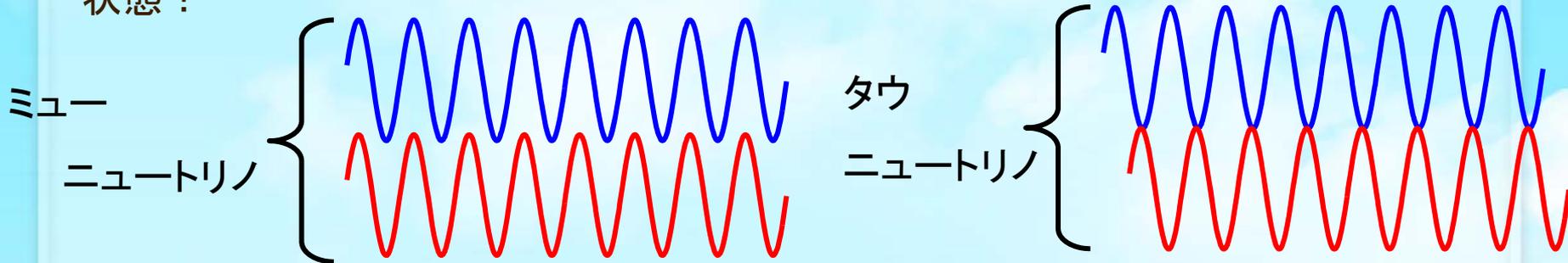


素粒子は空間を波のように伝わっていく

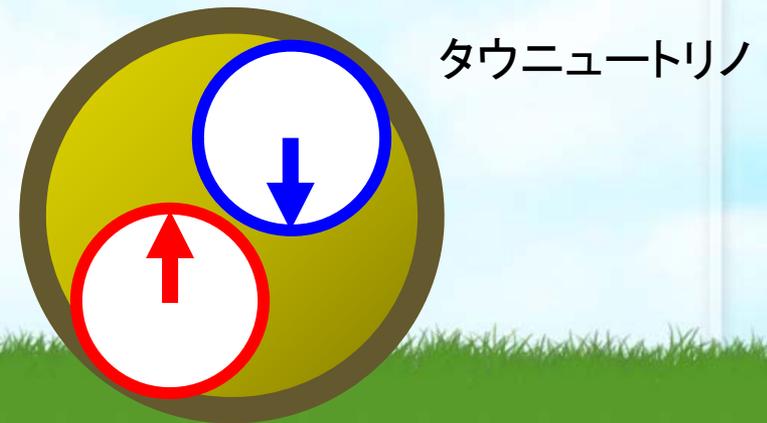
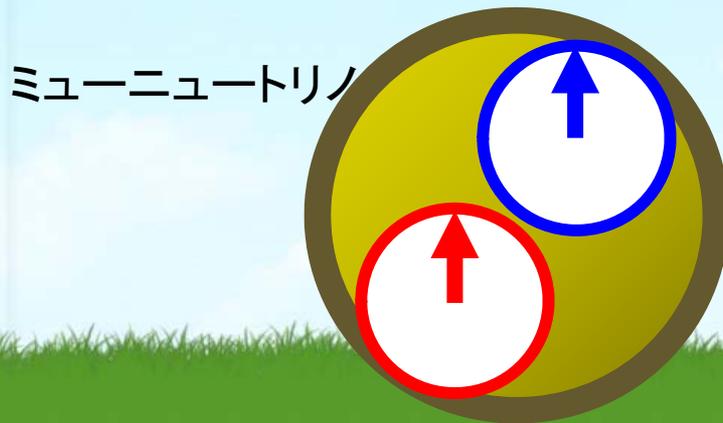
重さによる種類分けと、コインの裏表で決める種類が同じとは限らない。

違っていたら？

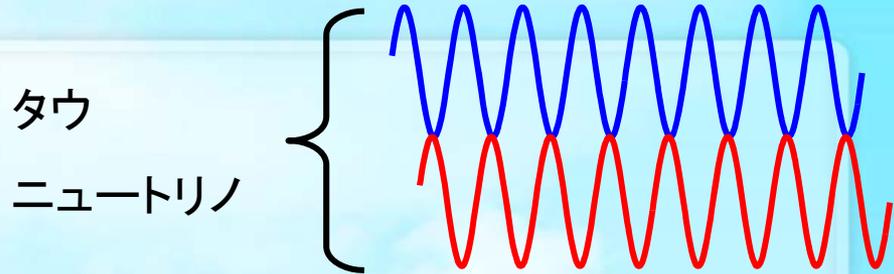
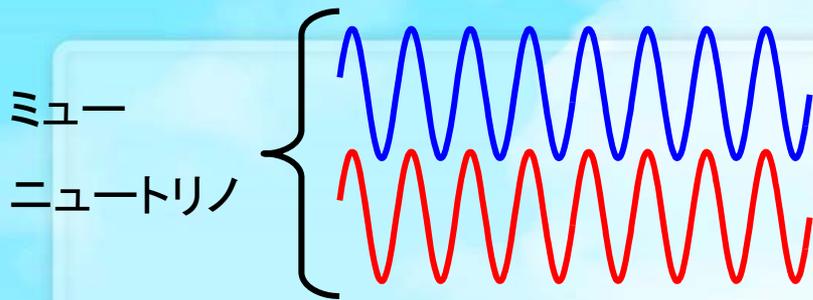
ミューニュートリノとと思っているものは、何種類かの異なる質量をもった波の重なった状態！



電子ニュートリノ、ミューニュートリノ、タウニュートリノのそれぞれのニュートリノが何種類かの進み方の異なる時計を持っていることになる！

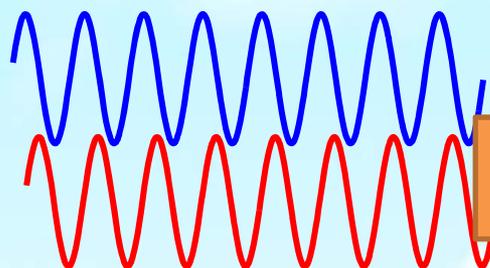


ニュートリノに(ごくわずかの)重さがあったら？

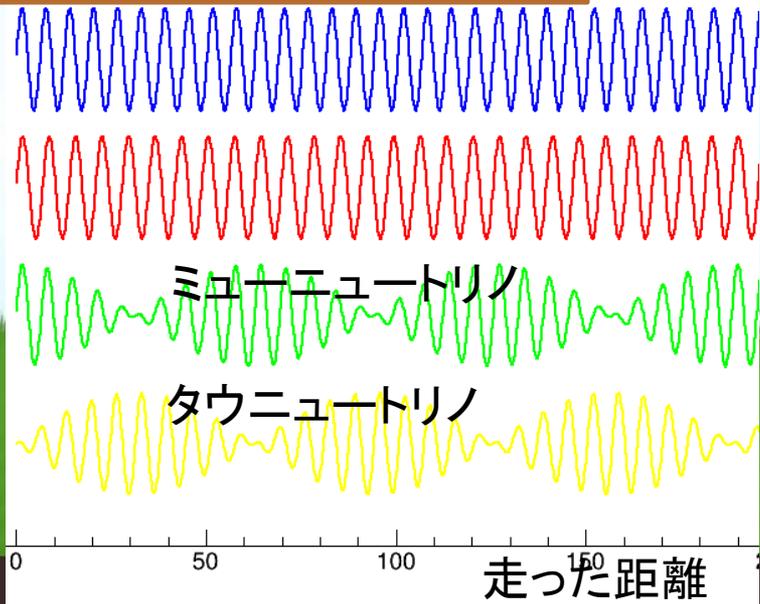
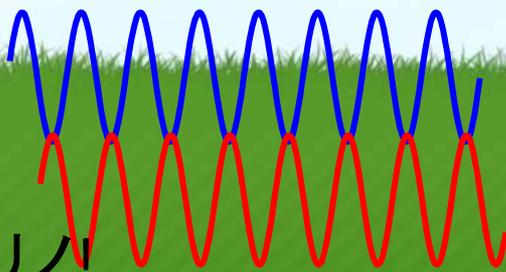
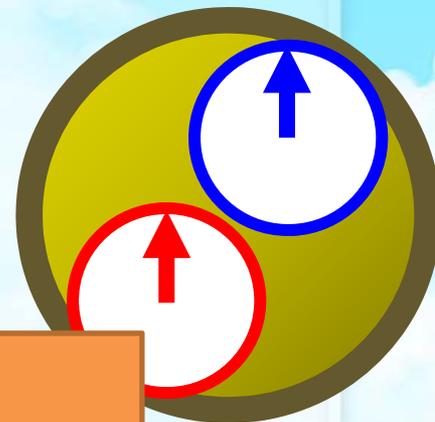


Aの波とBの波は異なる速さで進む

数百キロメートル進むうちに



ニュートリノ振動!





Super-Kamiokande
(ICRR, University of Tokyo)

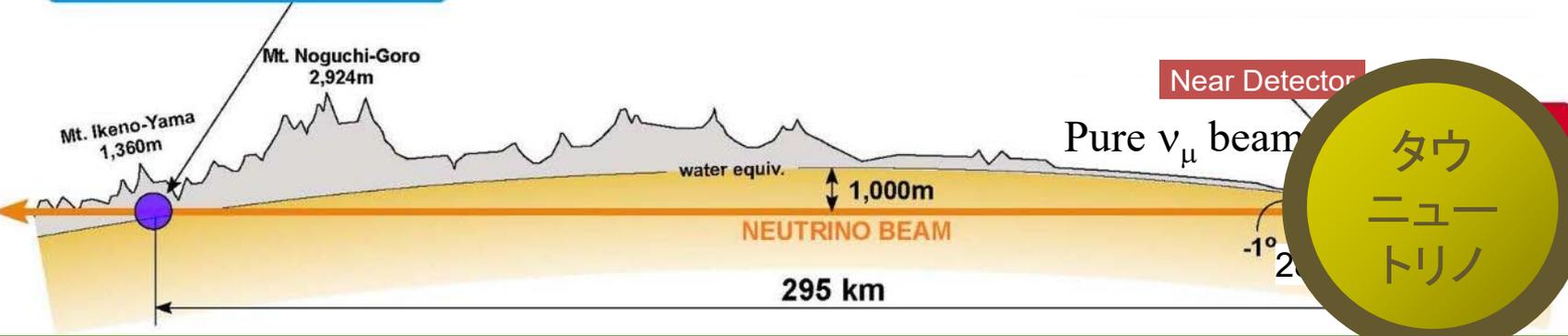


J-PARC Main Ring
(KEK-JAEA, Tokai)



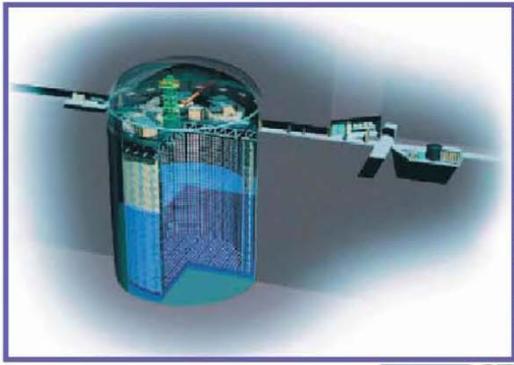
J-PARCで作ったミューニュートリノの大部分がタウニュートリノになって、スーパーカミオカンデを素通りする。

Super-KAMIOKANDE



タウ
ニュートリノ

T2K (Tokai to Kamioka)
長基線ニュートリノ振動実験



Super-Kamiokande

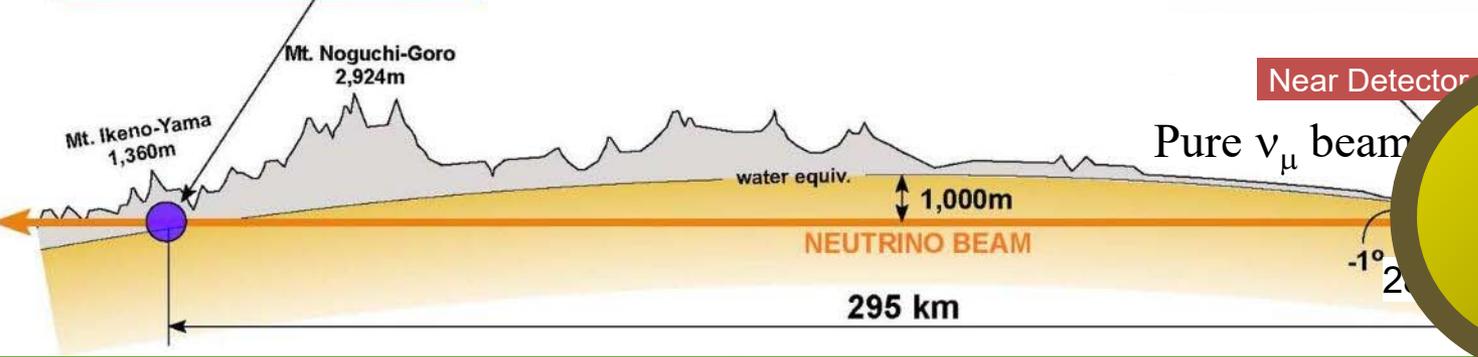


J-PARC Main Ring
(KEK-JAEA, Tokai)



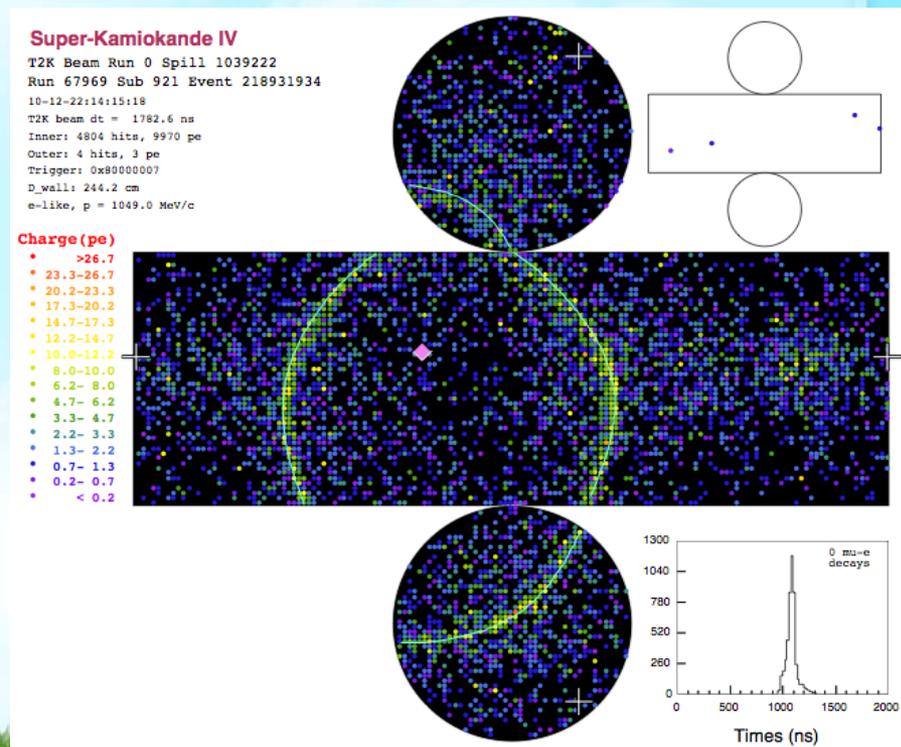
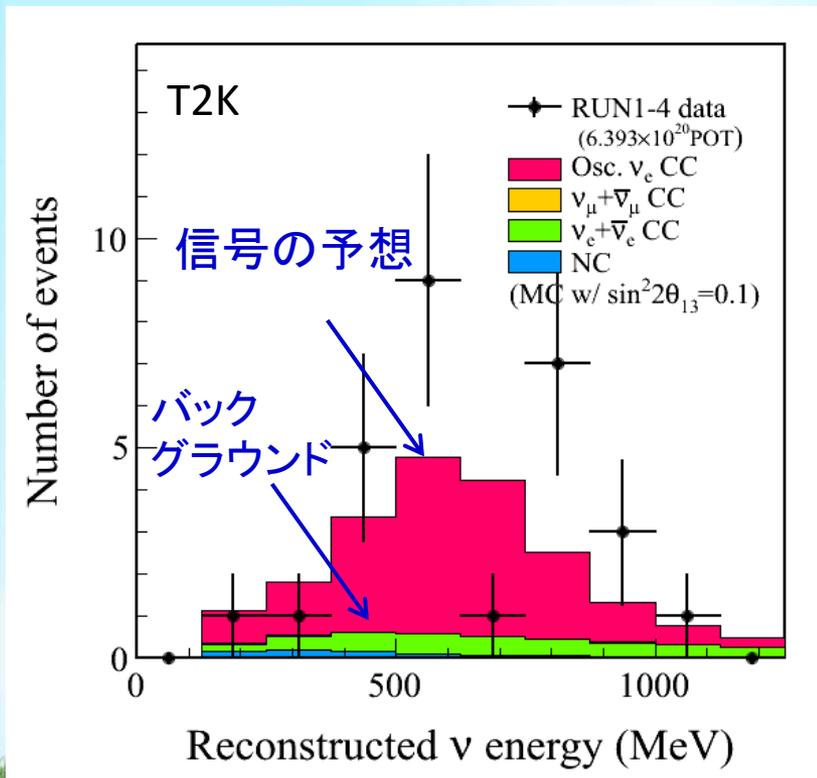
T2Kでは稀に電子ニュートリノになって、スーパーカミオカンデで捕まえられるのを探す。

Super-KAMIOKANDE



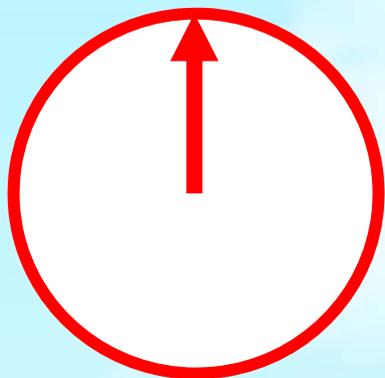
T2K (Tokai to Kamioka) 長基線ニュートリノ振動実験

最大約5%が変化 (20回に1回電子ニュートリノに変わる)



28個 見つかった！ 2013年7月 (7.3 σ)

- 粒子の持っている時計は、逆回転することがある！



逆回転する粒子は、反対符号の電気を運んでいるように見える。
電子：マイナスの電気を運ぶ。
逆回転している電子：プラスの電気を運ぶ ← 反電子（陽電子）

いよいよ反粒子の登場

物質を構成する素粒子

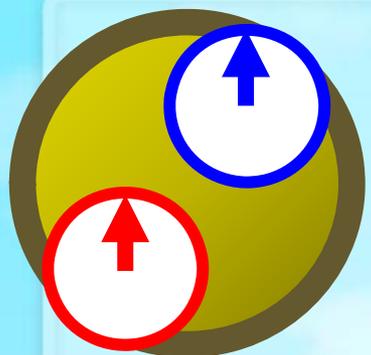
電荷 $+\frac{2}{3}e$ のクォーク	u	c	t
電荷 $-\frac{1}{3}e$ のクォーク	d	s	b
電荷0のレプトン (ニュートリノ)	ν_e	ν_μ	ν_τ
電荷 $-e$ のレプトン	e	μ	τ

反素粒子 上に $\bar{\quad}$ をつける。

電荷 $-\frac{2}{3}e$ のクォーク	\bar{u}	\bar{c}	\bar{t}
電荷 $+\frac{1}{3}e$ のクォーク	\bar{d}	\bar{s}	\bar{b}
電荷0のレプトン (ニュートリノ)	$\bar{\nu}_e$	$\bar{\nu}_\mu$	$\bar{\nu}_\tau$
電荷 $+e$ のレプトン	\bar{e}	$\bar{\mu}$	$\bar{\tau}$

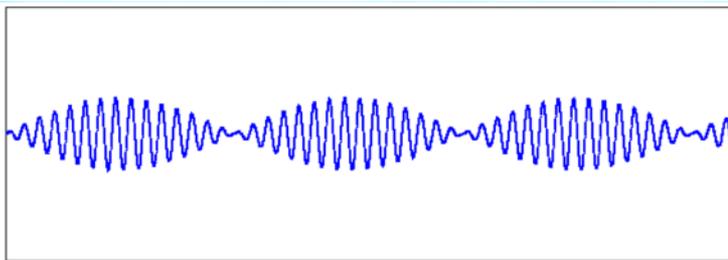
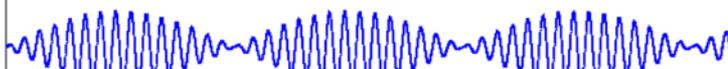
反粒子

時計が二つの場合。

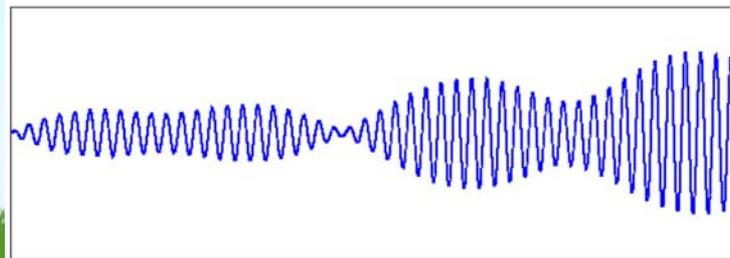
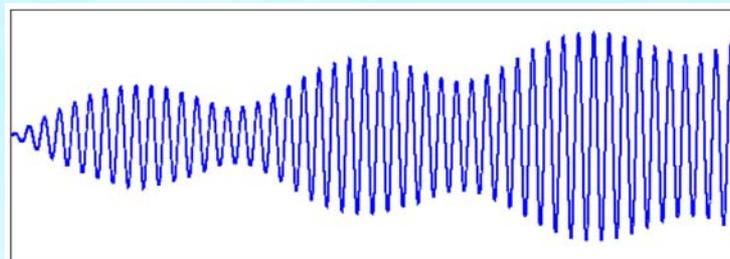
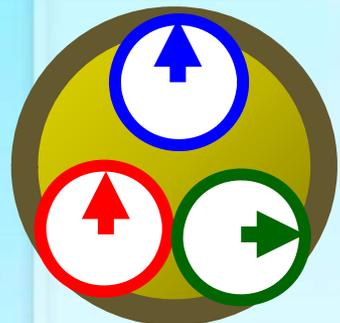


ニュートリノ

作ったのとは別のニュートリノが現れる波の様子



二つの針をどこから始めても、結果は同じ。



時計が三つの場合は、三つ目の針の場所によって、結果が違ってしまふ。

粒子と反粒子が異なる振る舞い方をしてしまふ！

物質・反物質対称性(CP)の破れ！(小林・益川の理論)

CPの破れはクォークでは見つかっているが、ニュートリノではまだ見つかっていない。

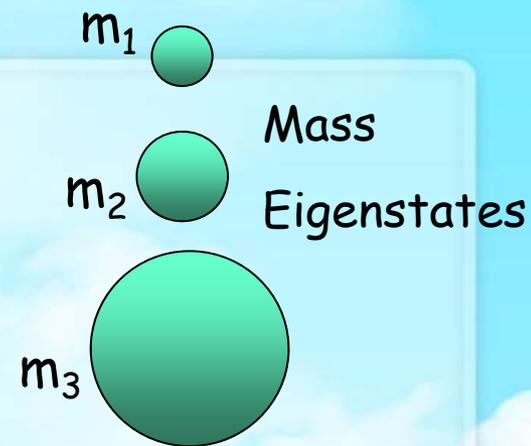
反ニュートリノ

ニュートリノは3種類あるので重さも3種類(=時計が3つ)

Weak
Eigenstates



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{\text{MNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



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

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

$\theta_{12}, \theta_{23}, \theta_{13} + \delta$ (+ 2 Majorana phases)

$$\Delta m_{12}^2, \Delta m_{23}^2$$

$$\Delta m_{ij}^2 = m_i^2 - m_j^2$$

Mixing Matrix

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

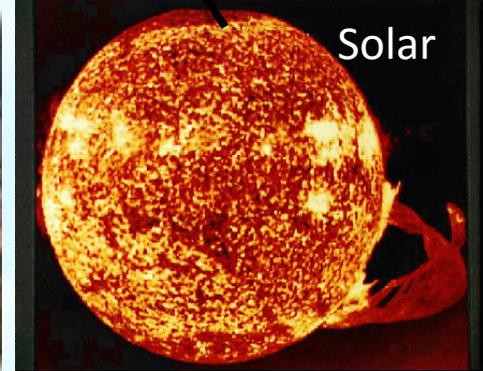
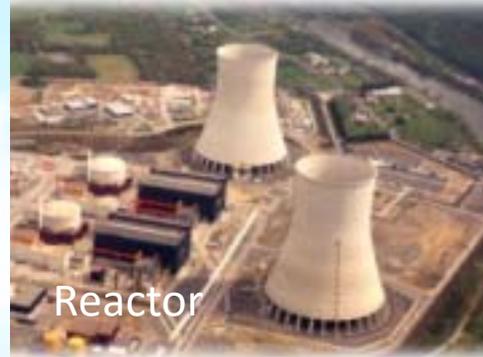
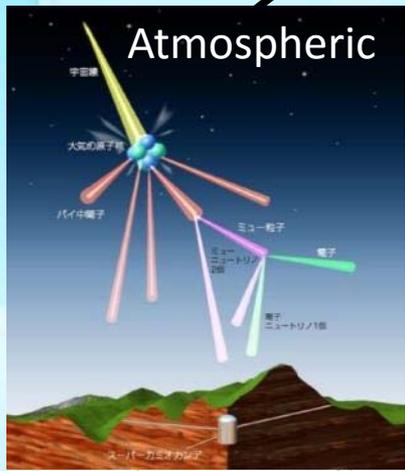
$$U_{\text{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & +c_{23} & +s_{23} \\ 0 & -s_{23} & +c_{23} \end{pmatrix} \begin{pmatrix} +c_{13} & 0 & +s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & +c_{13} \end{pmatrix} \begin{pmatrix} +c_{12} & +s_{12} & 0 \\ -s_{12} & +c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$\theta_{23}, |\Delta m_{32}^2|$

$\theta_{13}, \delta_{CP} (, MO)$

$\theta_{13}, |\Delta m_{32}^2| (, MO)$

$\theta_{12}, \Delta m_{21}^2$



Neutrino Oscillation Measurements

CP phase
KEY to understand the origin of
matter dominant universe

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

Unknown

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

$$\theta_{12} = 33^\circ \pm 1^\circ$$

$$\theta_{23} = 46^\circ \pm 3^\circ \quad 45^\circ ?$$

$$\theta_{13} = 8.9^\circ \pm 0.4^\circ$$

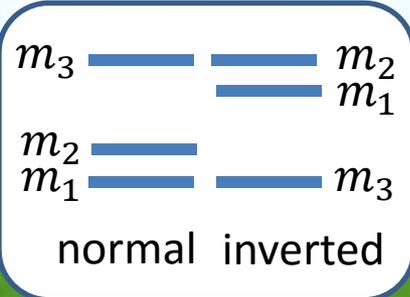
Unknown Mass Ordering

normal: $m_1 < m_2 \ll m_3$

inverted: $m_3 \ll m_1 < m_2$

$$\Delta m_{21}^2 = 7.5 \pm 0.2 \times 10^{-5} \text{ eV}^2$$

$$\times \sim 30 \rightarrow |\Delta m_{32}^2| = 2.44 \pm 0.06 \times 10^{-3} \text{ eV}^2$$



Big Impact
on 0ν double- β decay
search
(hence on Majorana ν
confirmation)
inverted \rightarrow 1 ton
detector
normal \rightarrow > 100 ton
detector

One Page Summary

$\delta_{CP}^{CKM} \sim 60^\circ \sim 70^\circ$ 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.

$$J_{CP} \equiv \text{Im}(U_{\mu 3} U_{e 3}^* U_{e 2} U_{\mu 2}^*) = \frac{1}{8} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \cos \theta_{13} \sin \delta_{CP}$$
$$J_{CP}^{CKM} \approx 3 \times 10^{-5}$$

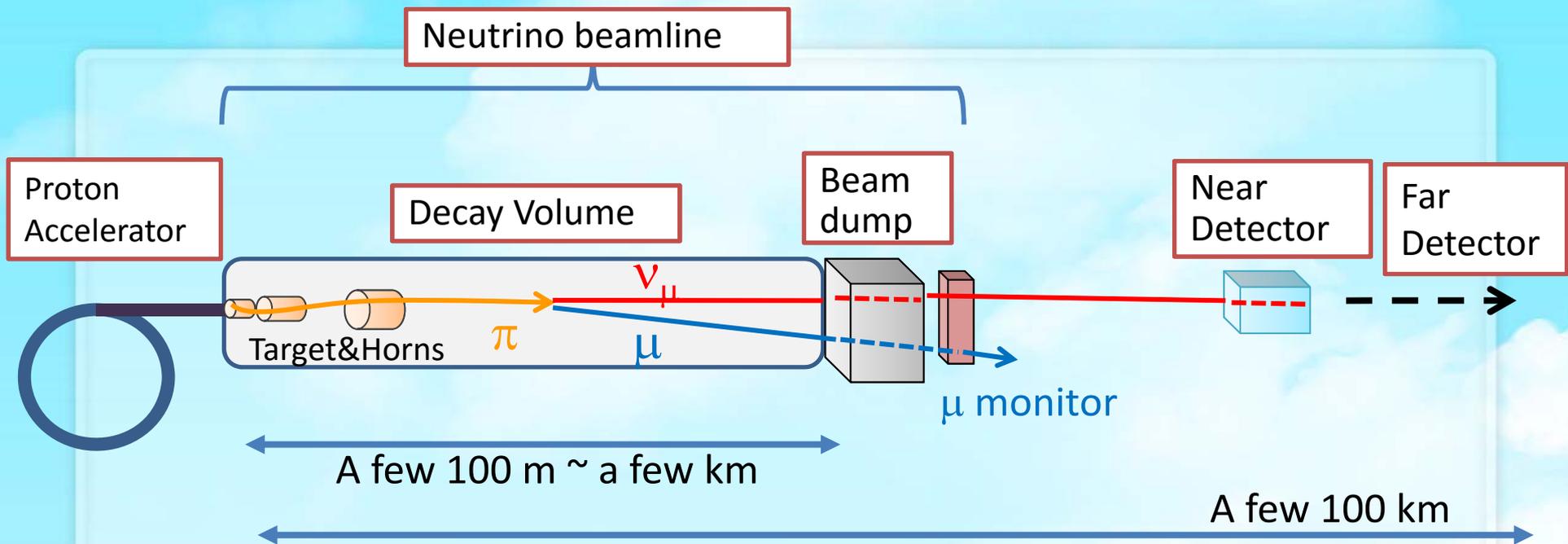
$$J_{CP}^{PMNS} \approx 0.03 \sin \delta_{CP}$$

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。

Leptonic CPV can be much larger than Quark's



Toroidal magnetic field by 'horn' focuses

$$\pi^+ \rightarrow \nu_{\mu} \text{ beam}$$

or

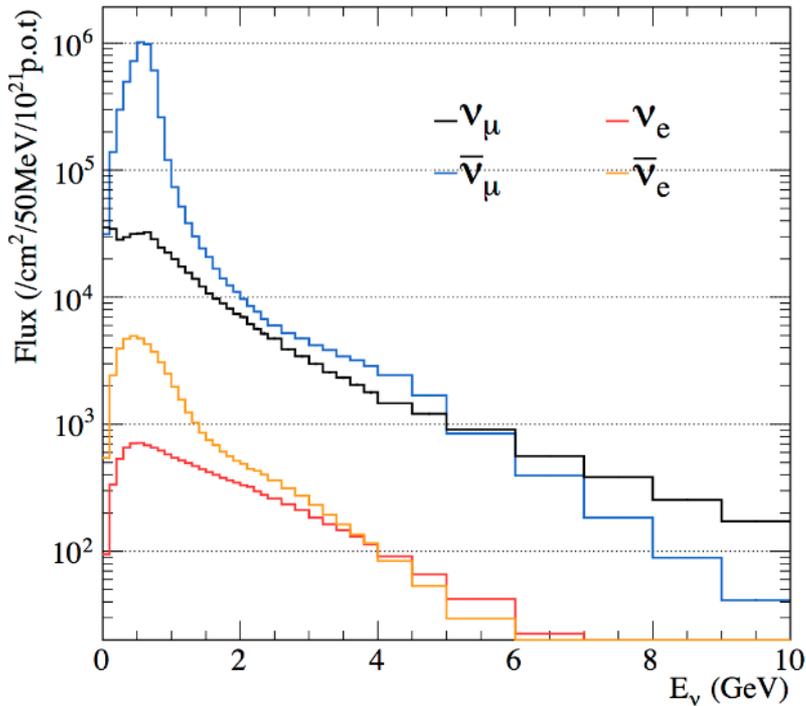
$$\pi^- \rightarrow \bar{\nu}_{\mu} \text{ beam}$$

Example:

$\sim 1 \nu/\text{cm}^2/\text{s}$ at T2K far detector (295 km away)
 (@750 kW proton beam power)

Components of the Long-Baseline Neutrino Experiment

antineutrino($\bar{\nu}$)-mode flux

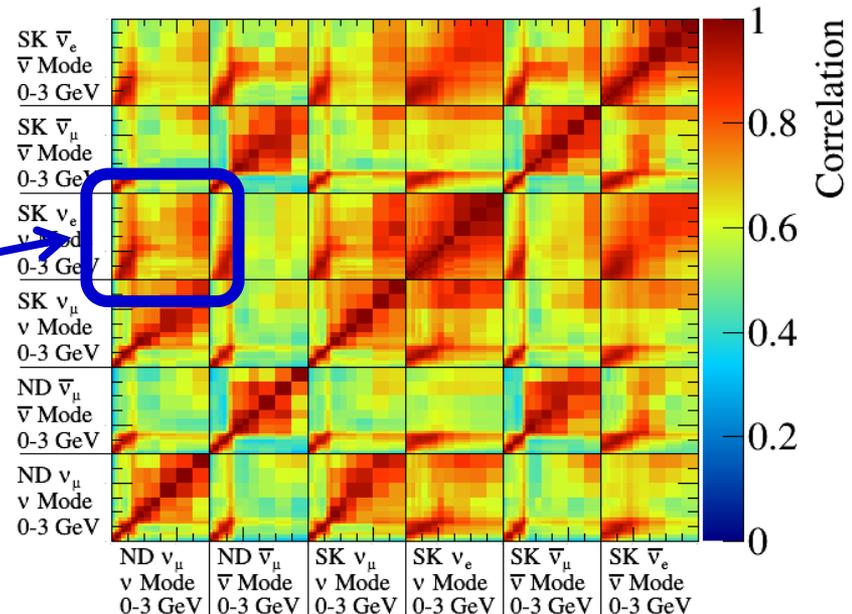


- flux peak ~ 0.6 GeV \approx oscillation maximum
- $\bar{\nu}$ flux is $\sim 10\%$ less than ν flux.
- (anti-) ν_e contamination $< 1\%$
- based on CERN NA61/SHINE p-C data (collaborating work)
- careful beam monitoring
- $\sim 8\%$ uncertainty at peak
- near-to-far extrapolation $\ll 2\%$ uncertainty

Correlation between
Near flux and Far flux

T2K Neutrino Flux

Flux Correlations



mixing matrix (PMNS)

$\nu_\alpha \rightarrow \nu_\beta$ oscillation

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

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

if $\beta = \alpha$ (disappearanceだけを測る場合)

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

Imaginary part vanishes!

CPの破れを見るのは、Appearanceの測定が必要。

Neutrino oscillation formula

$$\Delta m^2 \approx \Delta m_{32}^2 \approx \Delta m_{31}^2$$

$$P_{\mu \rightarrow x} \approx 1 - \left(\underbrace{\sin^2 2\theta_{23}}_{\text{Leading-term}} + \underbrace{\sin^2 \theta_{23} \cdot \sin^2 2\theta_{13}}_{\text{Next-to-leading}} \right) \sin^2 \left(\underbrace{\frac{\Delta m^2 L}{4E_\nu}}_{\text{Energy dependent maximum at } \sim 0.6 \text{ GeV for } L=295\text{km}} \right)$$

Cannot distinguish θ_{23} and $90^\circ - \theta_{23}$

ν_μ disapp. probability depends on $\sin^2 2\theta_{13}$ $\sin^2 \theta_{23}$ to second order
 -> Can be used in combination with known $\sin^2 2\theta_{13}$ to resolve the θ_{23} octant

ν_μ disappearance probability for long-baseline accelerator experiment

Leading term $\sim 5\%$ at oscillation maximum

θ_{13} と θ_{23} で決まる。 θ_{13} は原子炉測定で良く測られている。

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

θ_{13}

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

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

$$C_{ij} = \cos \theta_{ij}, S_{ij} = \sin \theta_{ij}$$

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

$$\delta \rightarrow -\delta \text{ for } P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$$

CP-violating term introduced by interference
up to $\pm 27\%$ of leading term

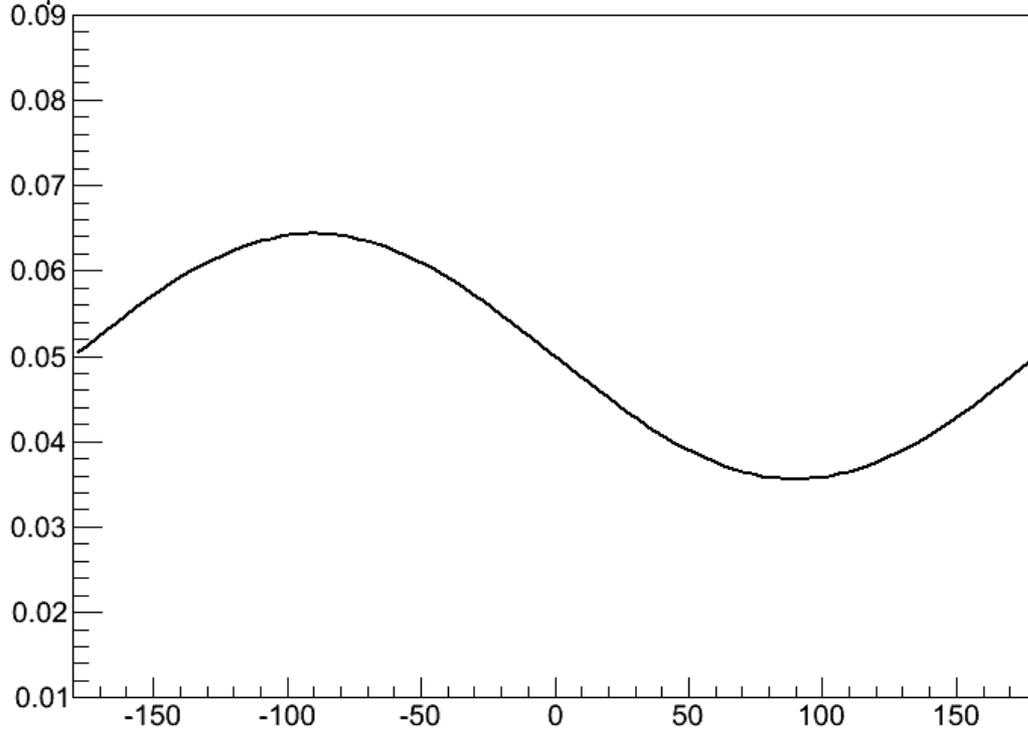
ν_e appearance probability for long-baseline
accelerator experiment (in vacuum)

$$P(\nu_\mu \rightarrow \nu_e) \cong 4C_{13}^2 S_{13}^2 S_{23}^2$$

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

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

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



$\pm 27\%$ effect for
 $\theta_{23} = 45^\circ$

ν_e appearance probability **at oscillation**
maximum

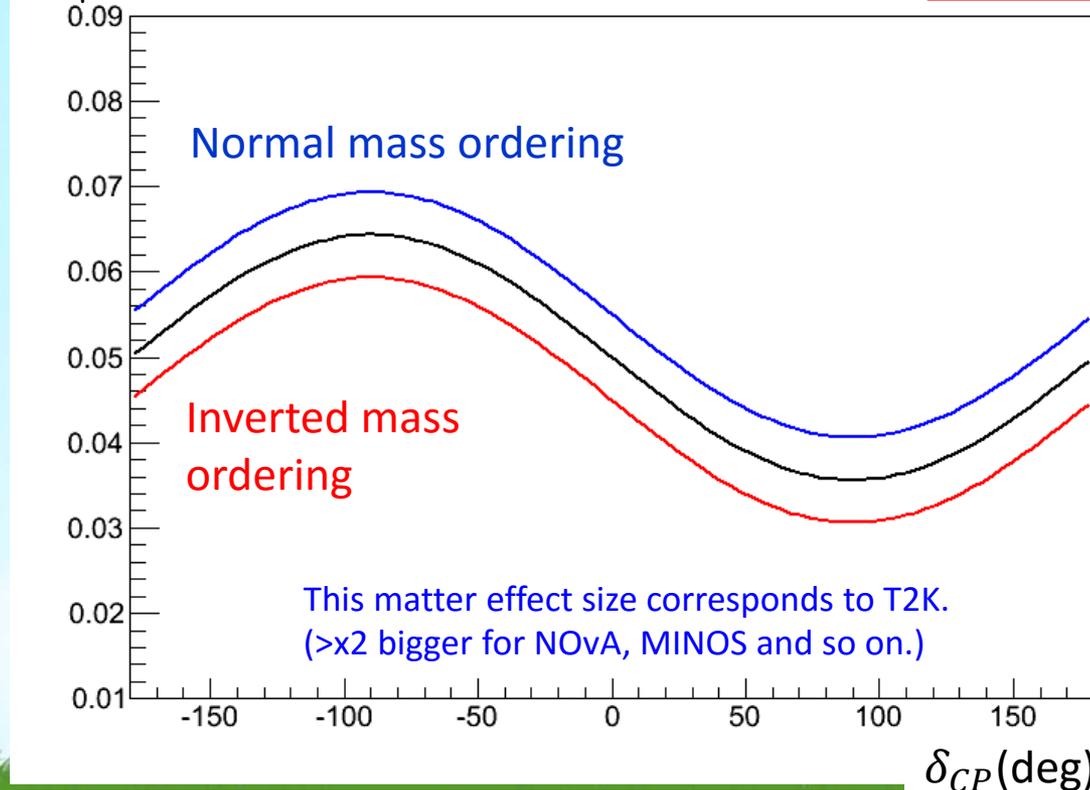
$$P(\nu_\mu \rightarrow \nu_e) \cong 4C_{13}^2 S_{13}^2 S_{23}^2 \left(1 + \frac{2a}{\Delta m_{31}^2} \right) - 8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \Phi_{21} \sin\delta$$

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

Matter effect

$$a \equiv 2\sqrt{2}G_F n_e E = 7.56 \times 10^{-5} \text{ eV}^2 \frac{\rho}{\text{gcm}^{-3}} \frac{E}{\text{GeV}}$$

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



ν_e feels different potential than ν_μ and ν_τ in earth.

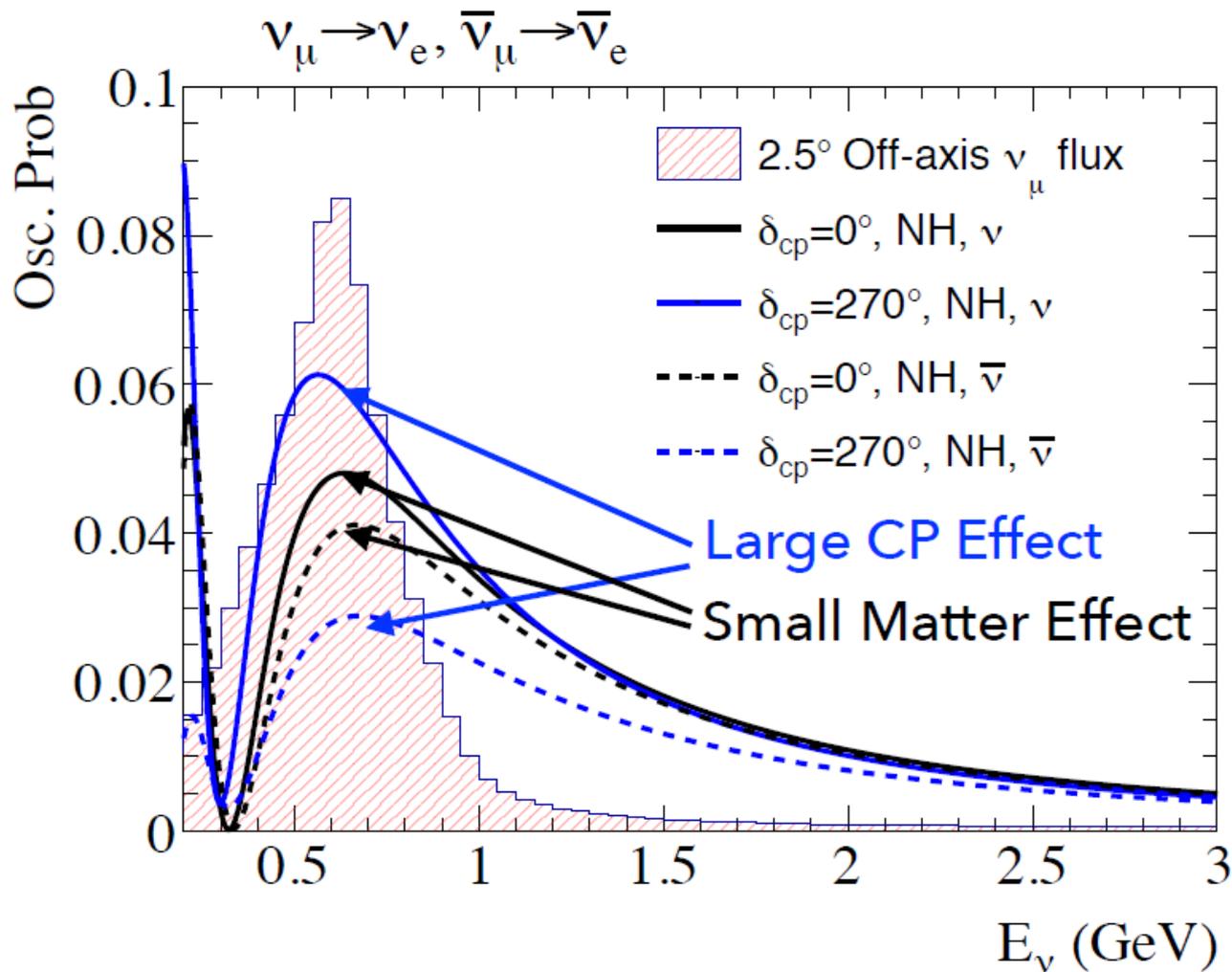


$\pm 27\%$ effect for $\theta_{23} = 45^\circ$

$$\delta \rightarrow -\delta, \quad \mathbf{a} \rightarrow -\mathbf{a}$$

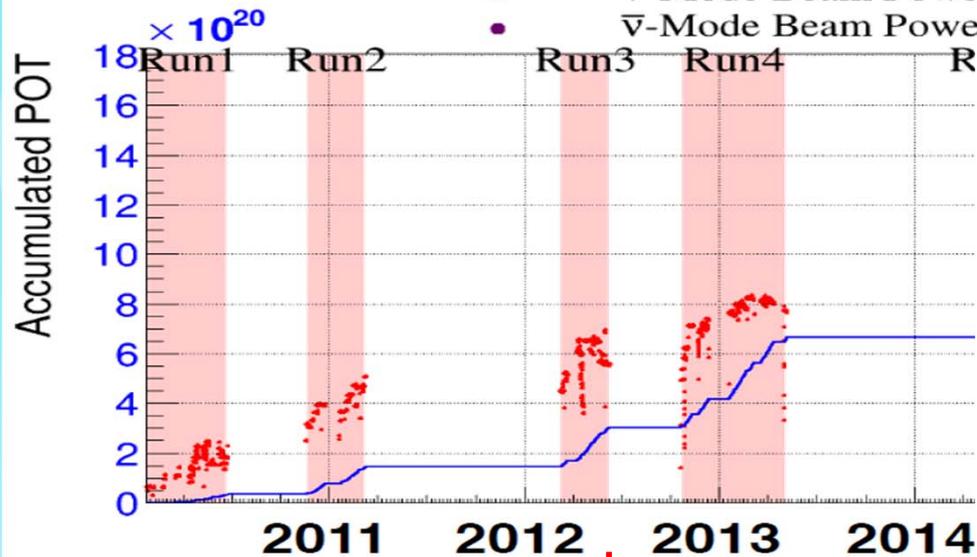
for $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$

ν_e appearance probability at oscillation maximum



ν_e appearance probability and T2K flux

POT = protons-on-target



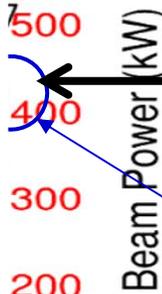
Total Accumulated POT for Physics

ν -Mode Beam Power

$\bar{\nu}$ -Mode Beam Power



'Run1-7c' data
19% of goal



420 kW!

big improvements
on beam intensity!

target cooling He
leak problem

ν_e appear.
 2.5σ

first constraint on δ_{CP}

ν_e appear.
 3.1σ

ν_e appear.
 7.3σ

27 May 2016
POT total: 1.510×10^{21}

ν -mode POT: 7.57×10^{20} (50.14%)
 $\bar{\nu}$ -mode POT: 7.53×10^{20} (49.86%)

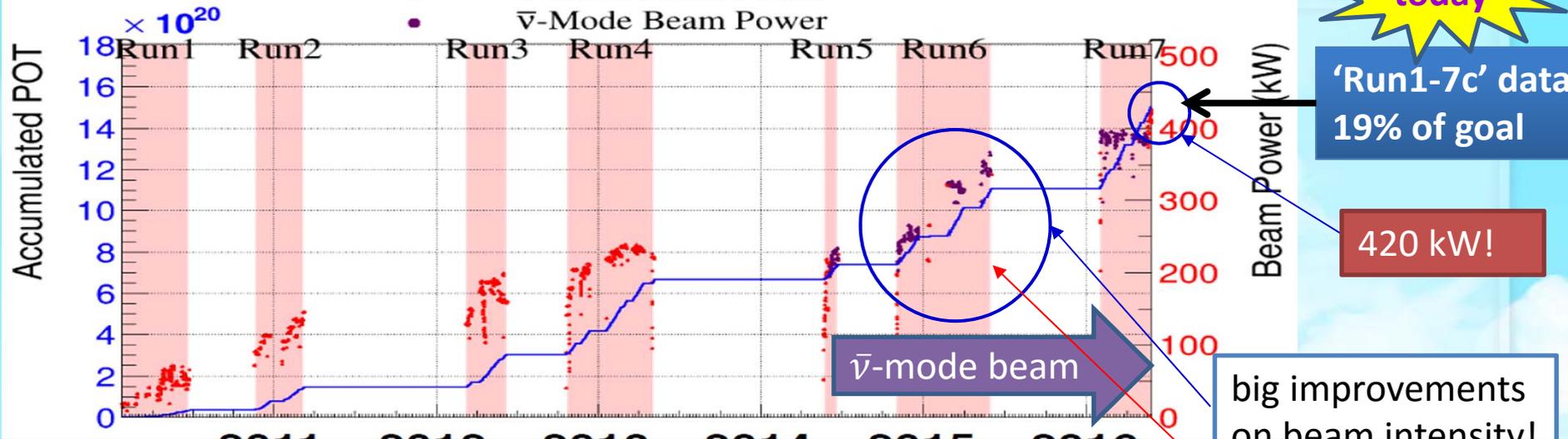
T2K data taking and physics release history

POT = protons-on-target

Total Accumulated POT for Physics

ν -Mode Beam Power

$\bar{\nu}$ -Mode Beam Power



加速器、施設、事務の皆様に
感謝！

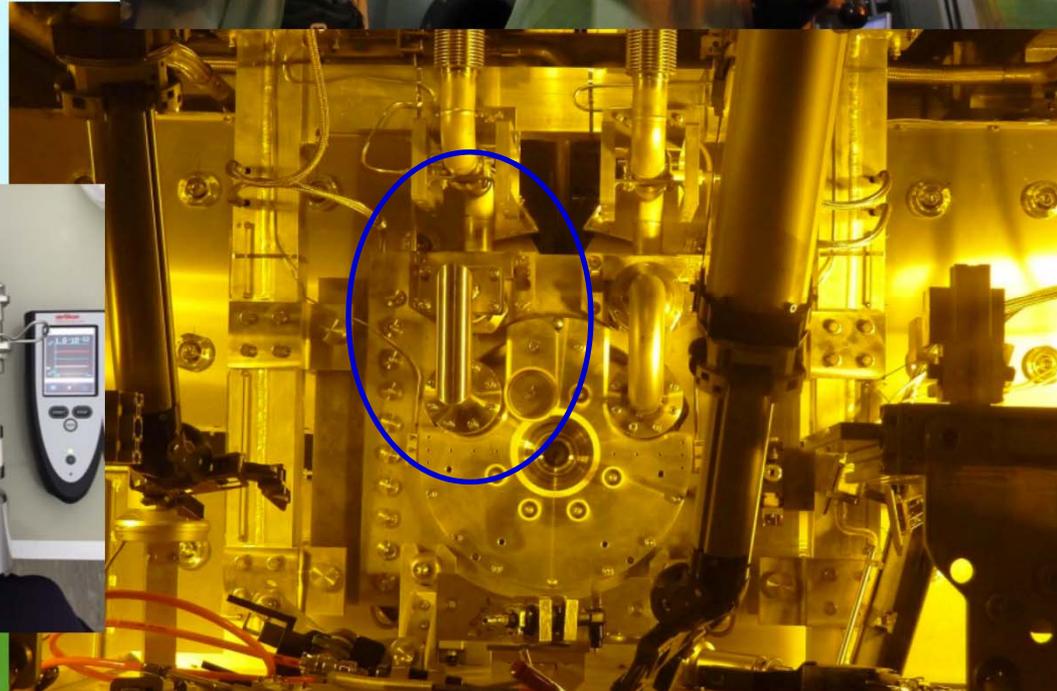
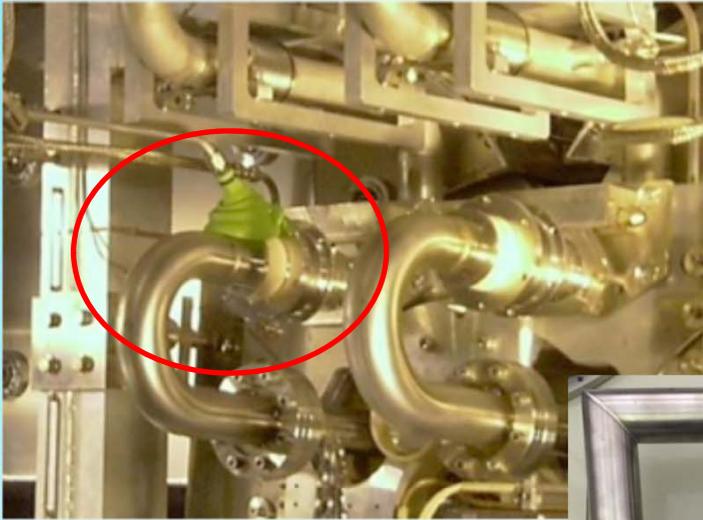
あ、あと機構長、所長、センター長にも。

27 May 2016
POT total: 1.510×10^{21}

ν -mode POT: 7.57×10^{20} (50.14%)
 $\bar{\nu}$ -mode POT: 7.53×10^{20} (49.86%)

T2K data taking and physics release history

- Tiny leakage of target cooling Helium gas was found in July 2015.

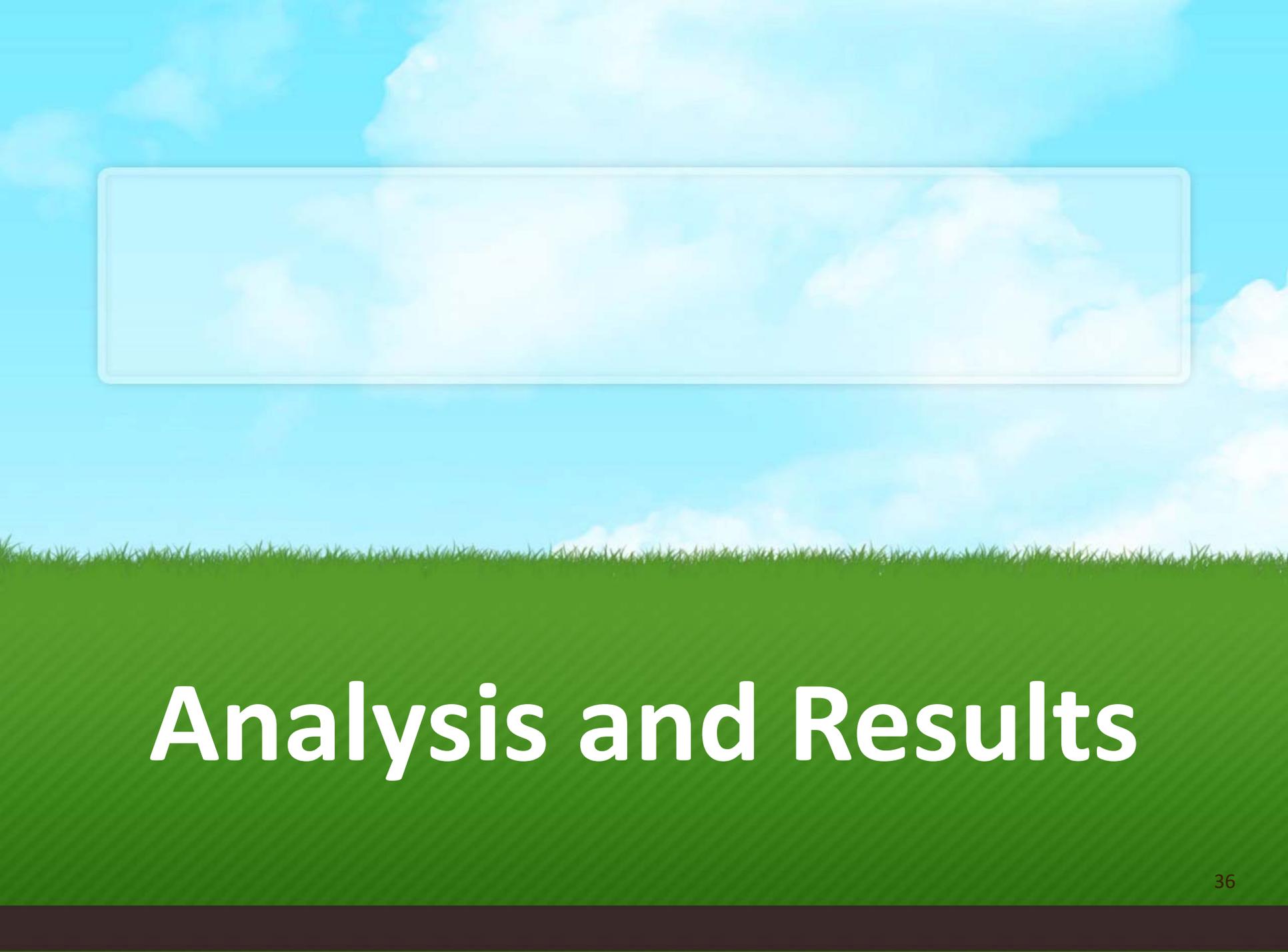


Target cooling pipe repair



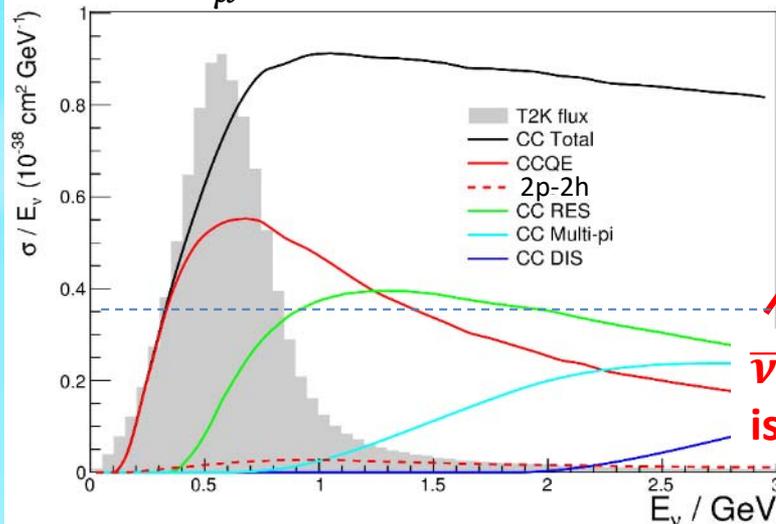
<http://www.triumf.ca/current-events/remote-handling-help-desk> に
本番の画像あり。

Target cooling pipe repair – movie from rehearsal–

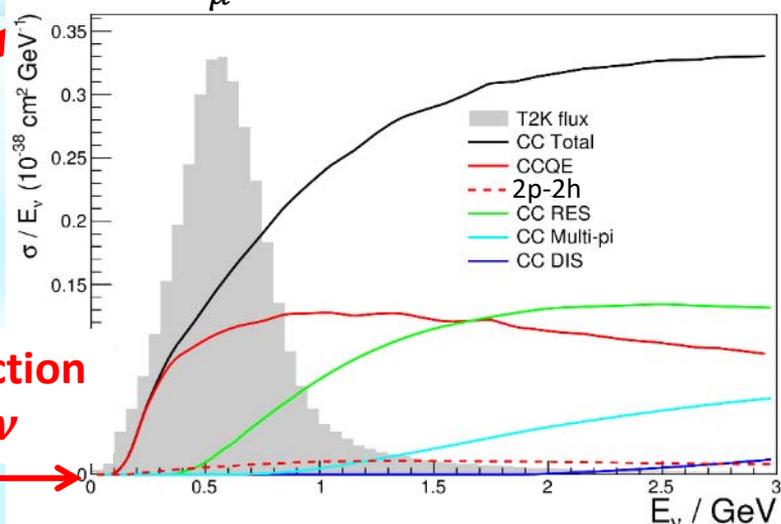


Analysis and Results

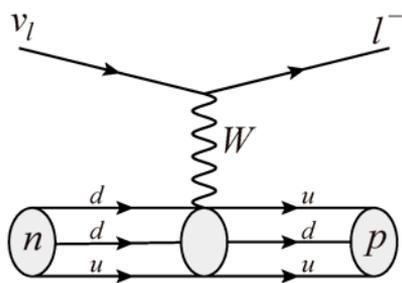
ν_μ -nucleus cross section



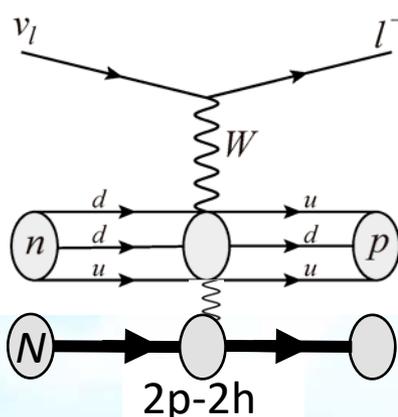
$\bar{\nu}_\mu$ -nucleus cross section



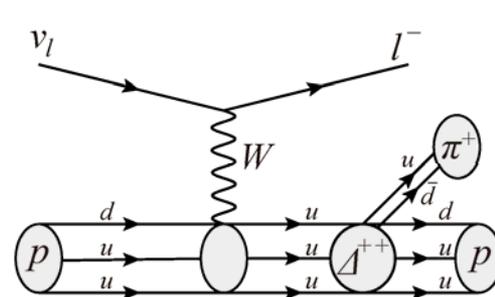
$\bar{\nu}$ cross section is ~1/3 of ν



CCQE Main Signal
(Charged Current Quasi-Elastic)



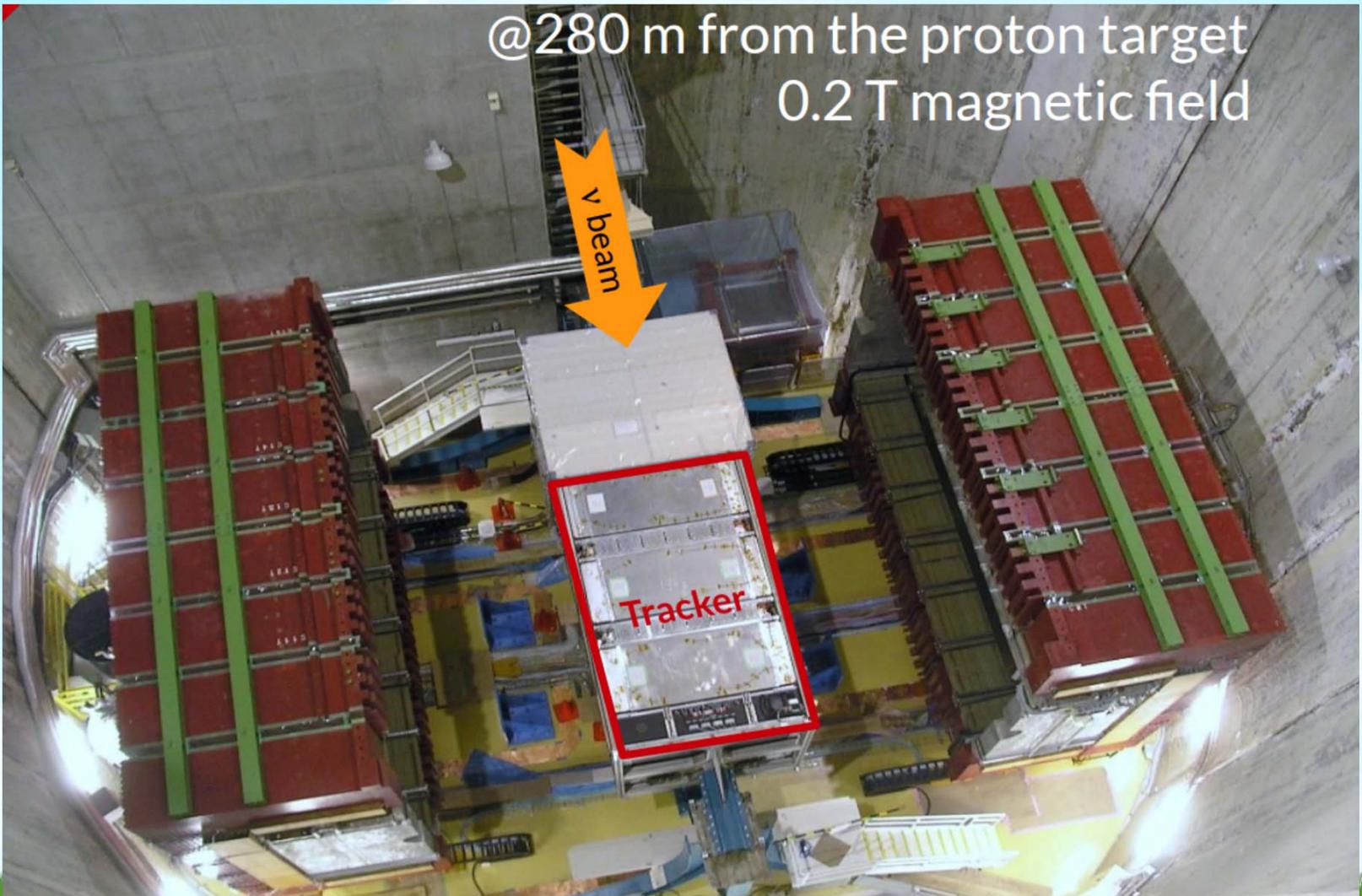
2p-2h



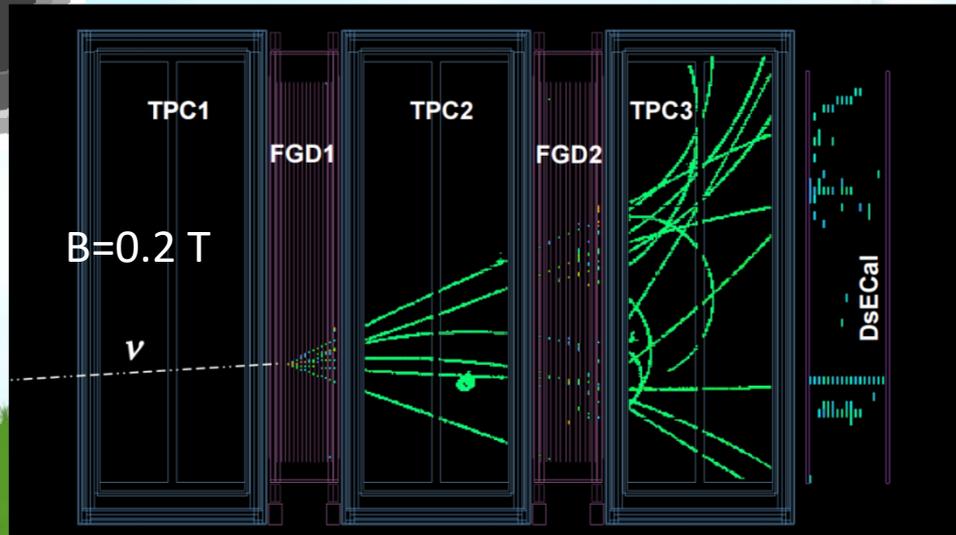
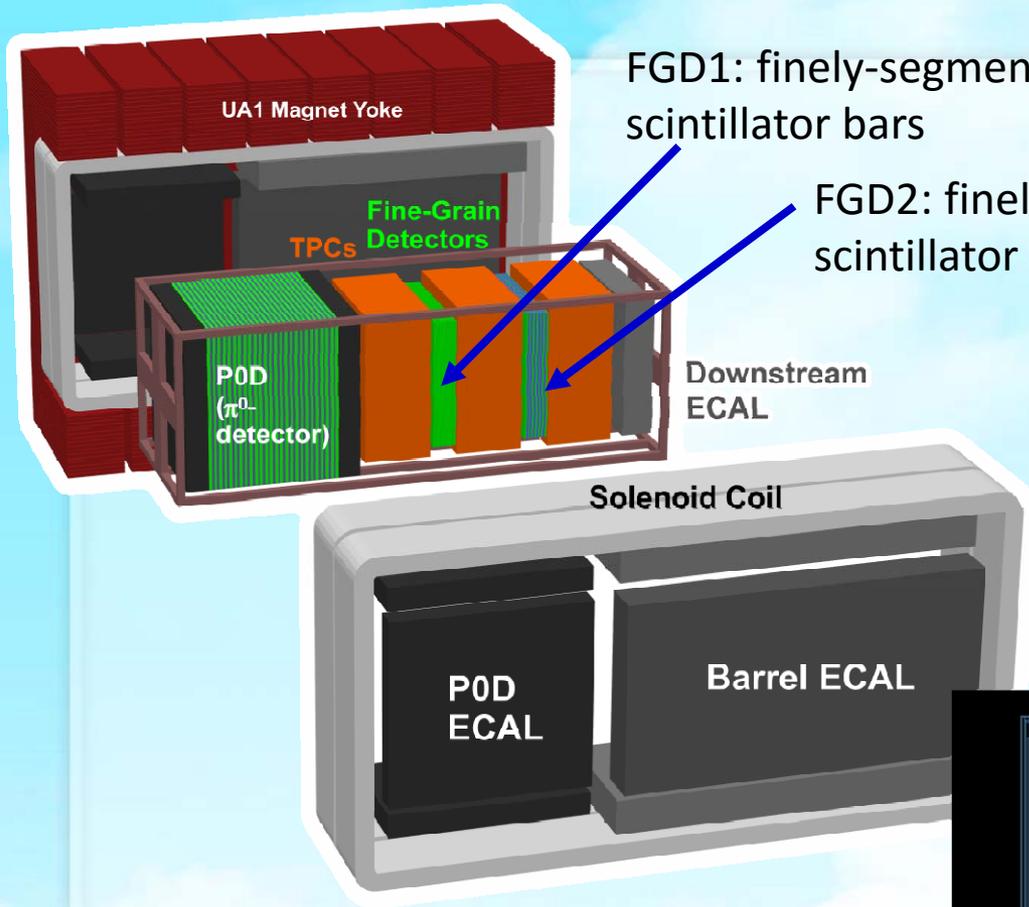
CC resonant-pion production

Complexity due to multi-body interaction in nucleus. Cannot be derived from 1st principle → measurement is important!

(anti-)neutrino-nucleus interaction



The T2K off-axis near detector: ND280

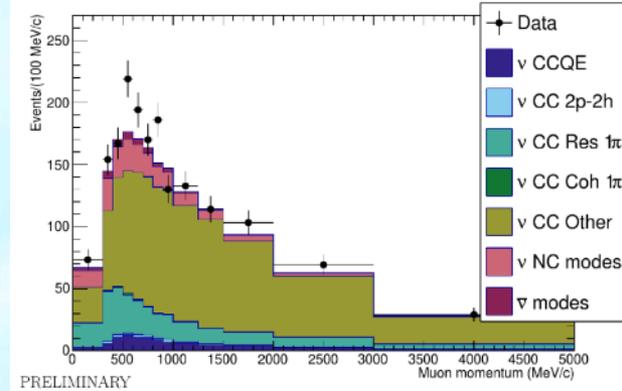
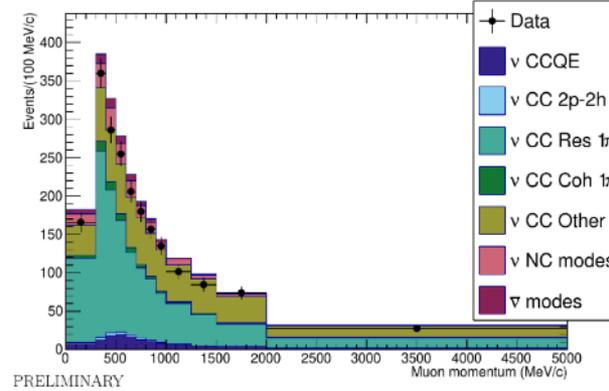
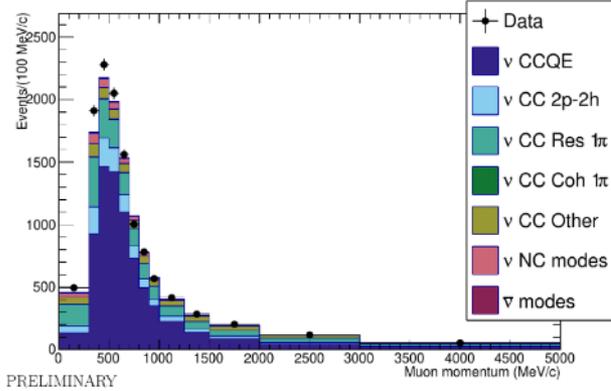


off-axis near detector : ND280

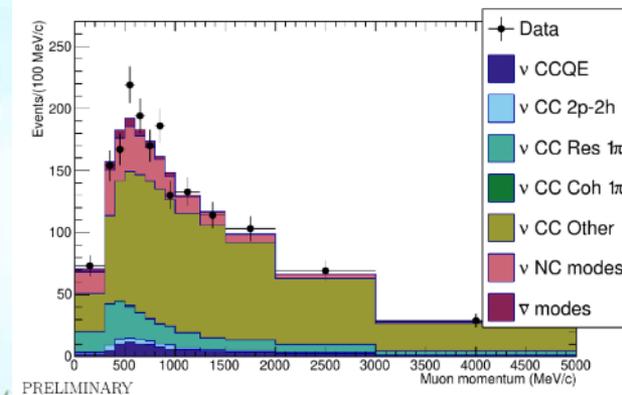
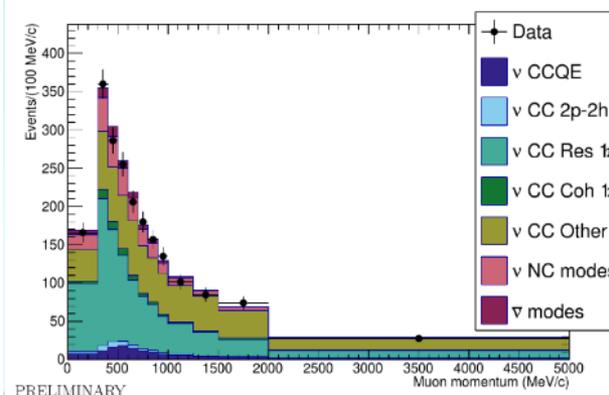
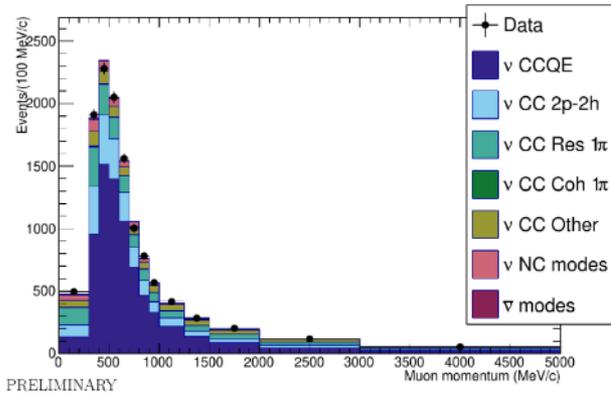
CC0 π sample

CC1 π^+ sample

CC other sample



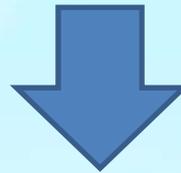
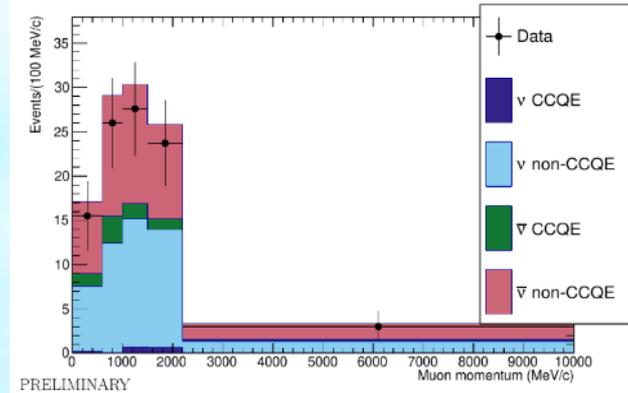
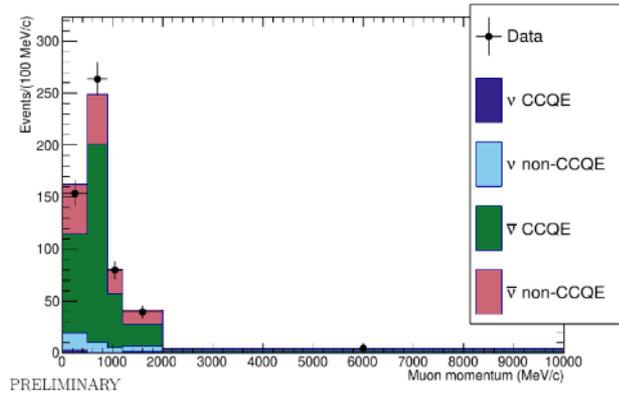
tuning flux and cross section by fitting data
((p, θ) distribution of samples)



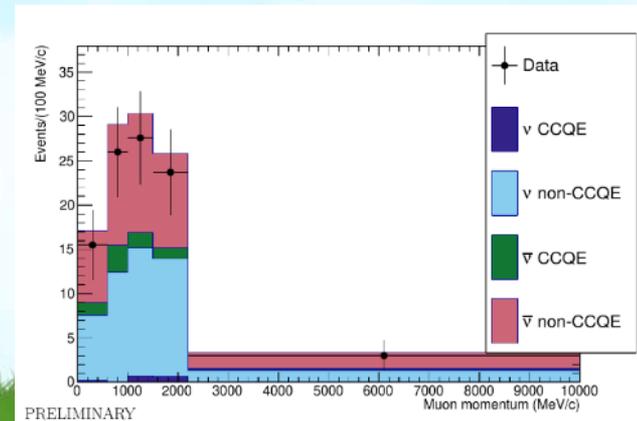
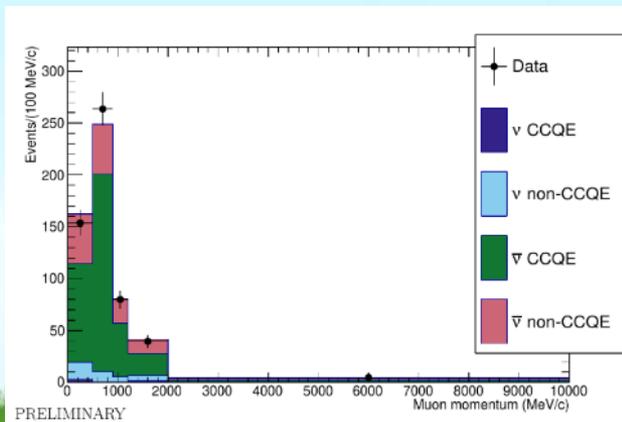
neutrino measurement at ND280

CC 1track sample

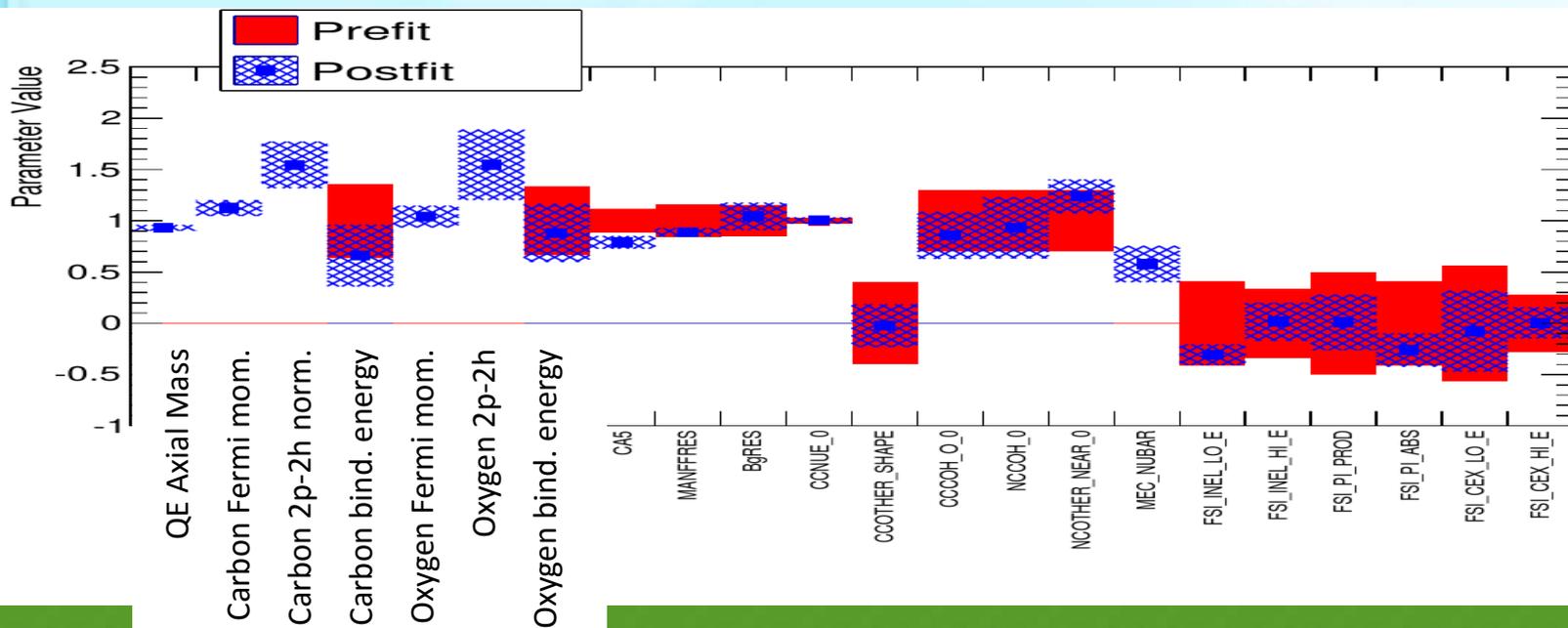
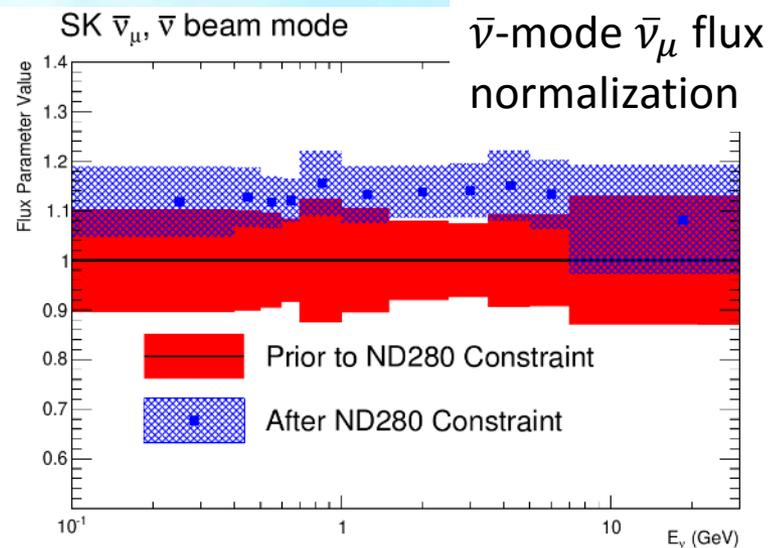
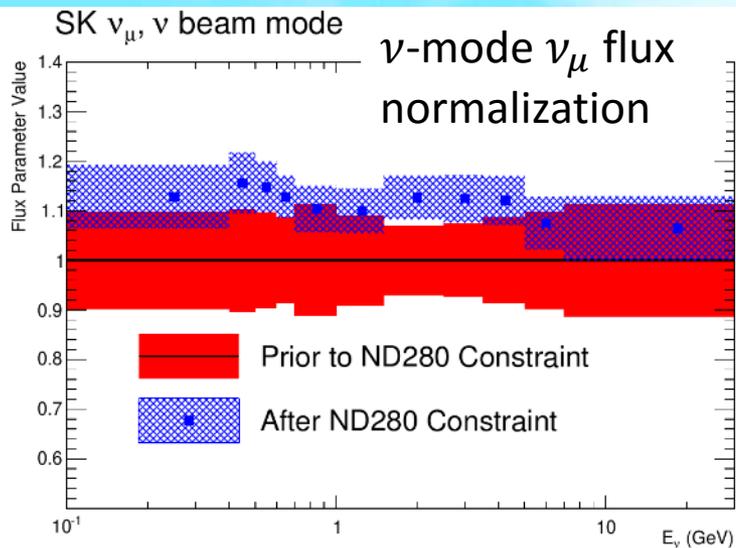
CC >1 track sample



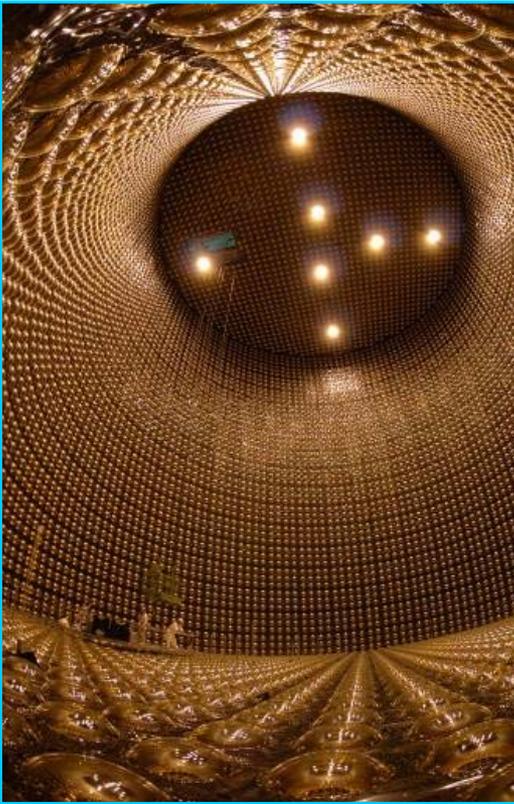
tuning flux and cross section by fitting data
((p, θ) distribution of samples)



antineutrino measurement at ND280

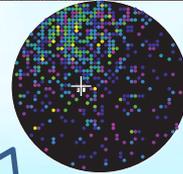
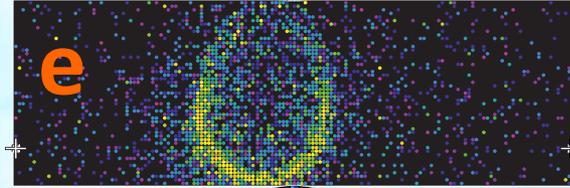
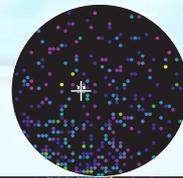


flux and cross section tuning by ND280 data 42



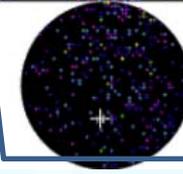
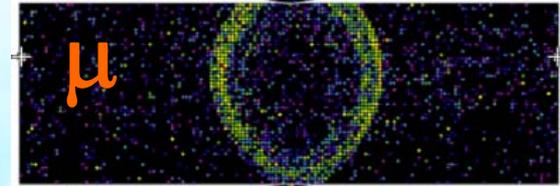
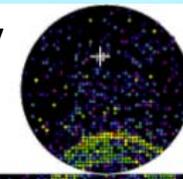
Water-Cherenkov Detector

Very good PID for sub-GeV particles
mis-identification $\sim 1\%$

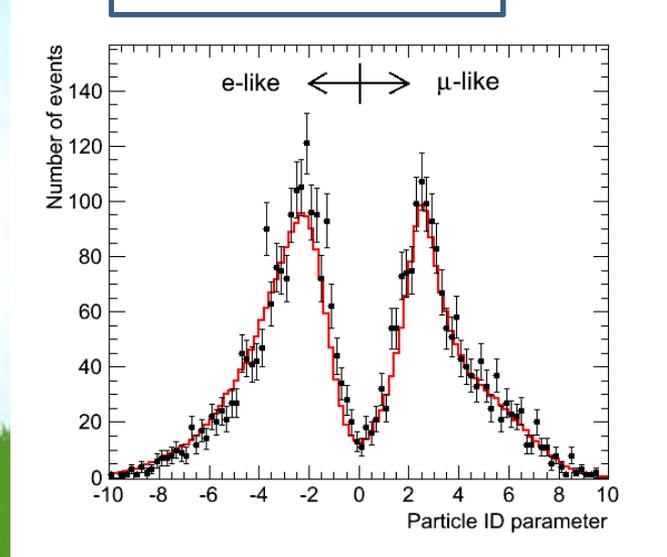


Signal for ν_e appearance

Simulated event display



Signal for ν_μ disappearance



T2K Far Detector – Super Kamiokande -

(anti)muon neutrino candidates

ν -mode run	136
$\bar{\nu}$ -mode run	64

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

(anti)electron neutrino candidates

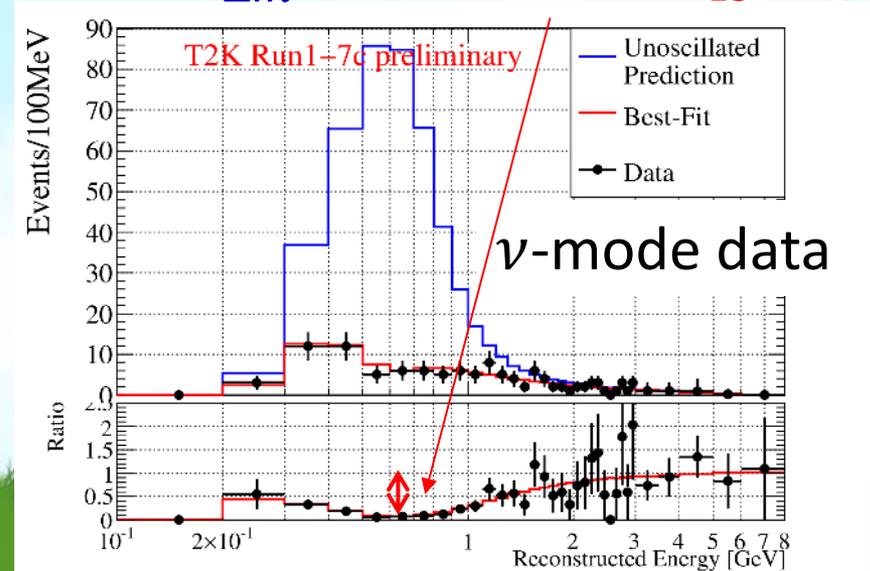
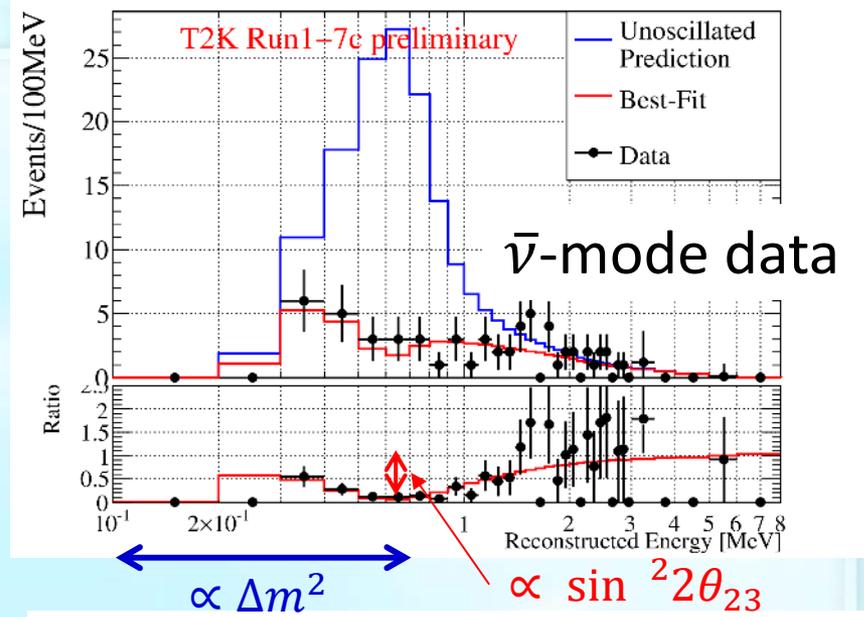
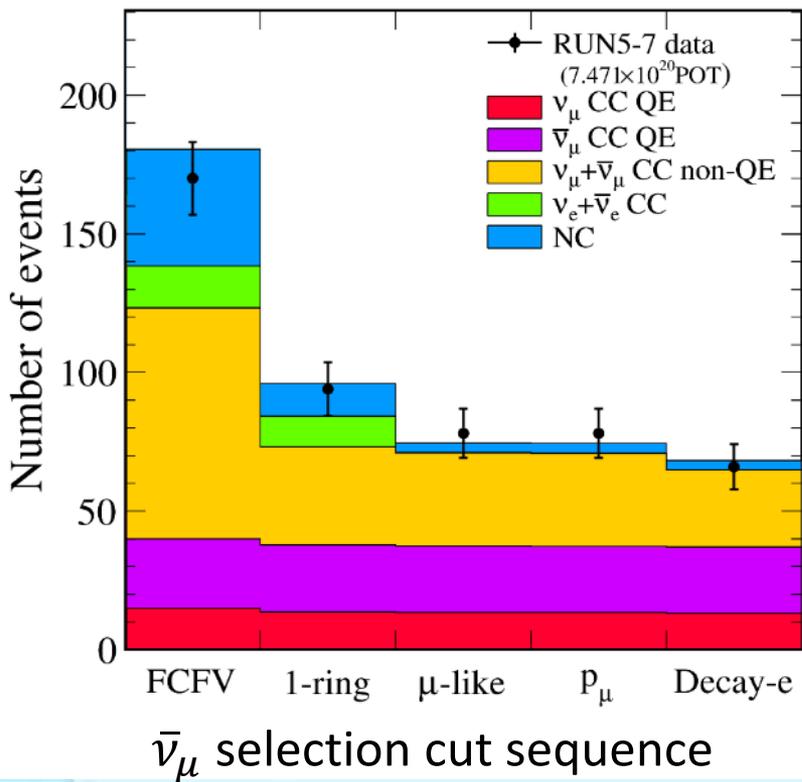
		$\delta_{CP} = -\pi/2$	$\delta_{CP} = 0$	$\delta_{CP} = +\pi/2$	$\delta_{CP} = \pi$
ν -mode run	Normal	28.7	24.2	19.6	24.1
	Inverted	25.4	21.3	17.1	21.3
$\bar{\nu}$ -mode run	Normal	6.0	6.9	7.8	6.8
	Inverted	6.5	7.4	8.4	7.4

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

Expected number of events

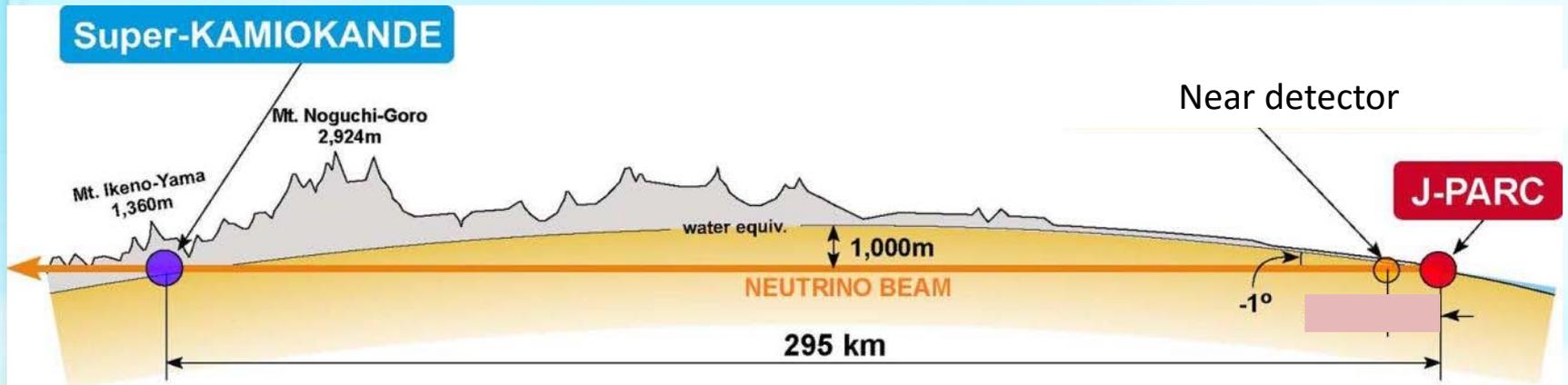
Source of Uncertainty	ν 1Re	$\bar{\nu}$ 1Re	ν 1Re/ $\bar{\nu}$ 1Re
SK Detector	2.3%	3.1%	1.6%
SK Final State and Secondary Interactions	2.6%	2.4%	3.5%
Flux and X-sec constrained by ND280	2.9%	3.2%	2.3%
NC 1 γ	1.5%	3.0%	1.5%
ν_e and $\bar{\nu}_e$	2.6%	1.5%	3.1%
NC Other	0.2%	0.3%	0.2%
Total	5.5%	6.3%	5.9%

Uncertainty on the predicted number of events



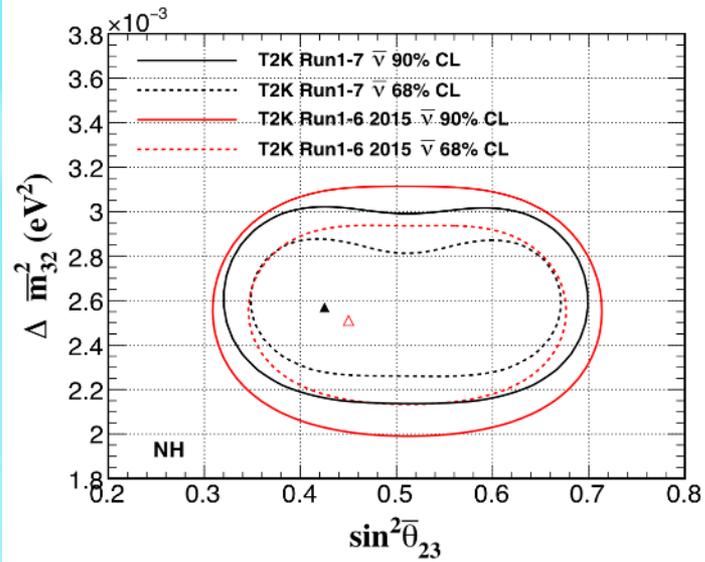
ν_μ and $\bar{\nu}_\mu$ event selection result

- CPT theorem $\Rightarrow P(\nu_\mu \rightarrow \nu_\mu) = P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu)$
- $\nu_\mu/\bar{\nu}_\mu$ disappearance is insensitive to matter effect.
- If we observe $P(\nu_\mu \rightarrow \nu_\mu) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu)$, it may be due to CPT violation or non-standard interaction with matter.

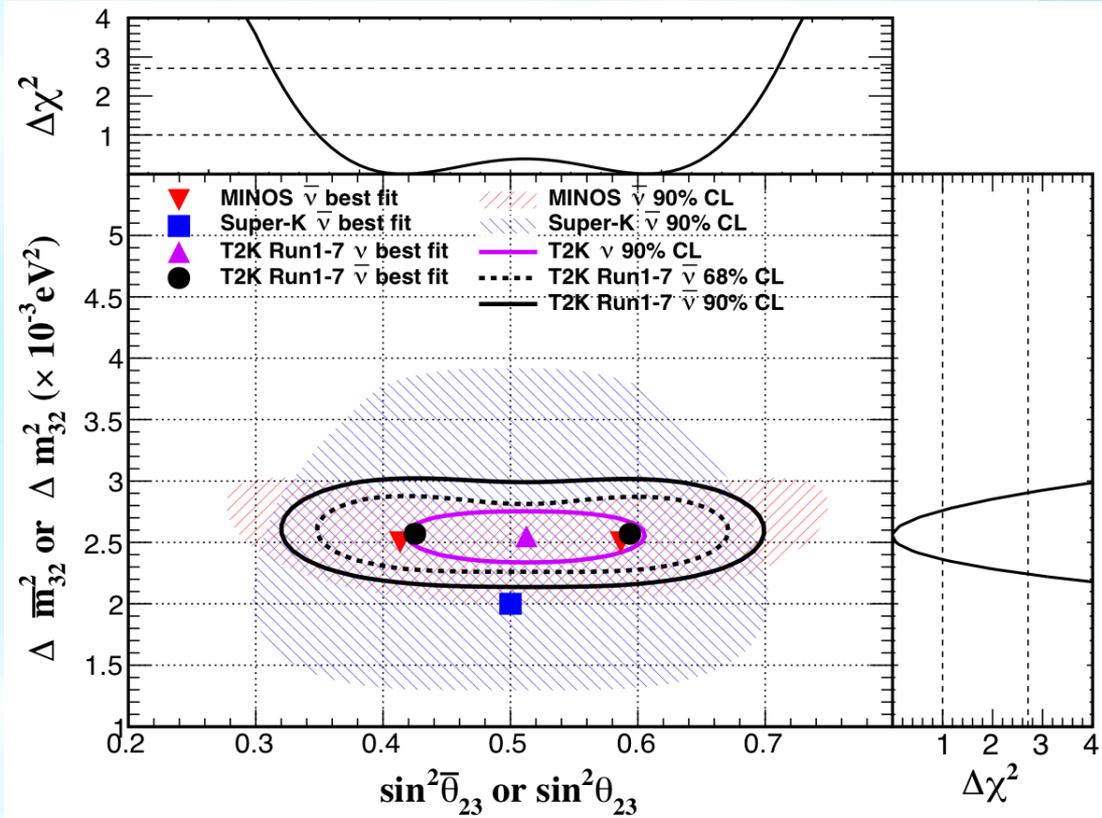


$\bar{\nu}_\mu$ disappearance

Comparison to previous result

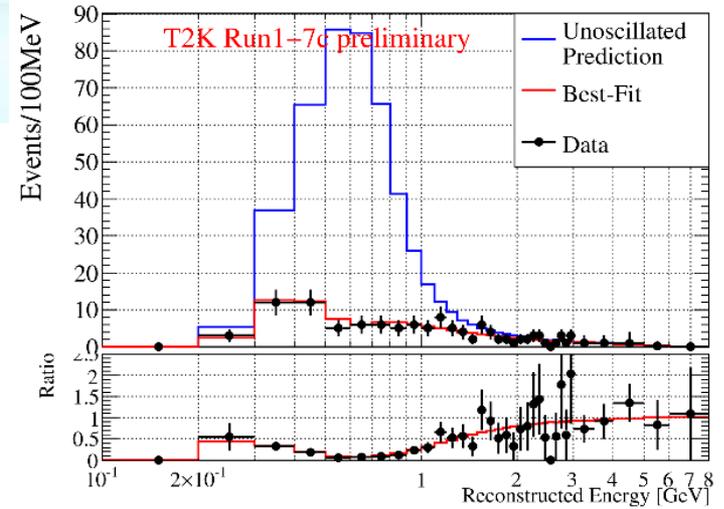
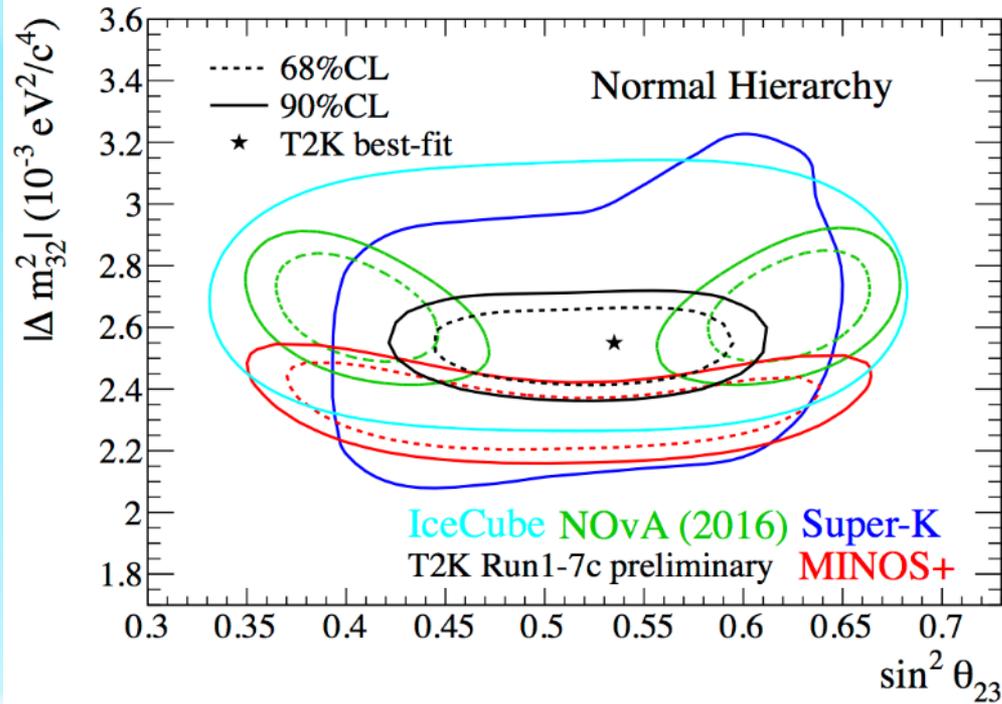


Consistent with $\bar{\nu}_\mu$ disappearance

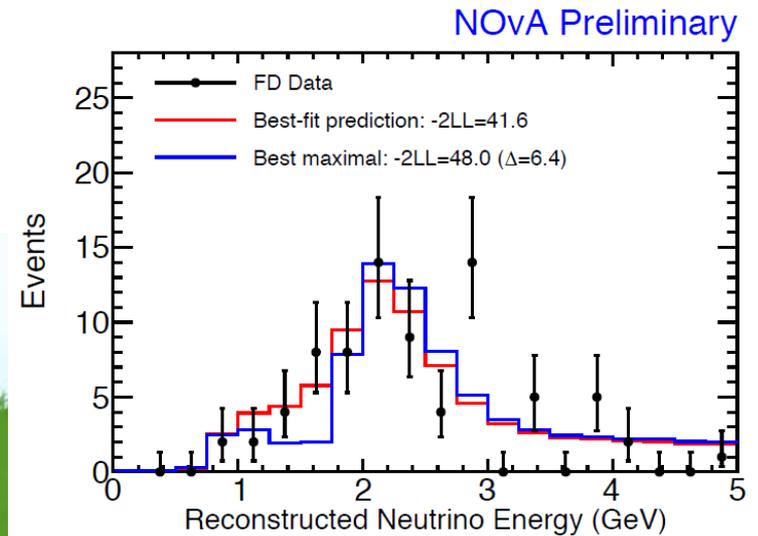


$\bar{\nu}_\mu$ disappearance

Joint fit of $(\nu_{\mu}, \nu_e, \bar{\nu}_{\mu}, \bar{\nu}_e)$ samples
to determine
 $(\Delta m_{32}^2, \sin^2 \theta_{23}, \delta_{CP}, \text{mass ordering})$

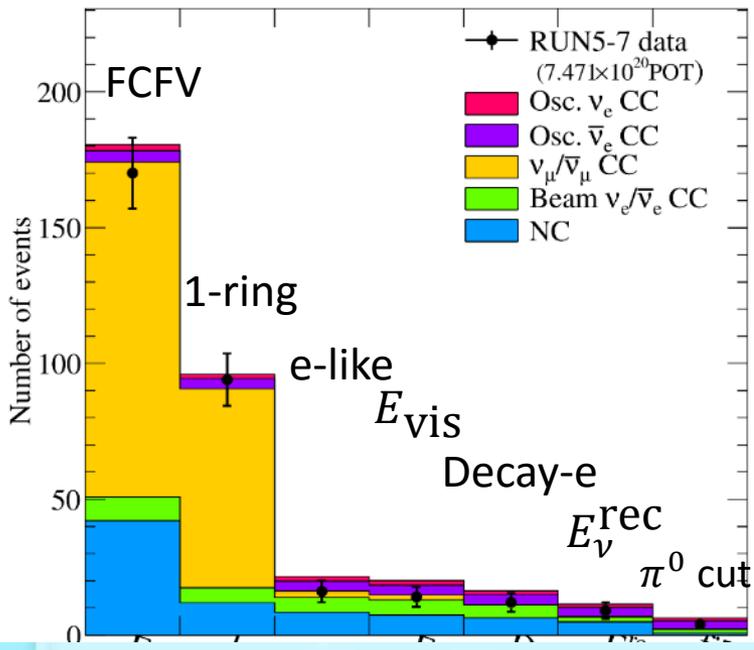


P. Vahle, Neutrino 2016

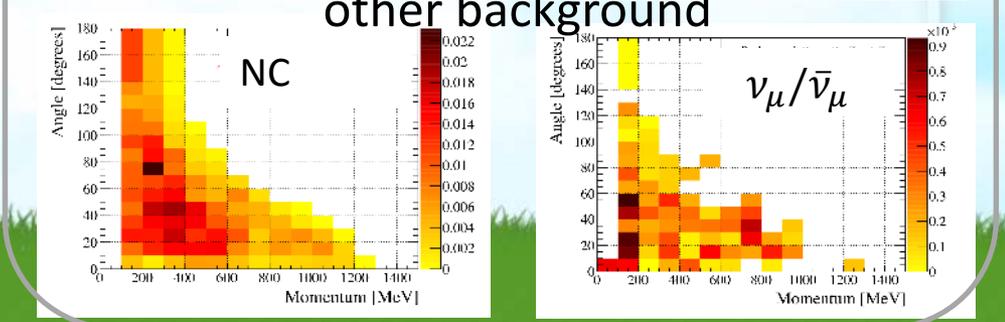
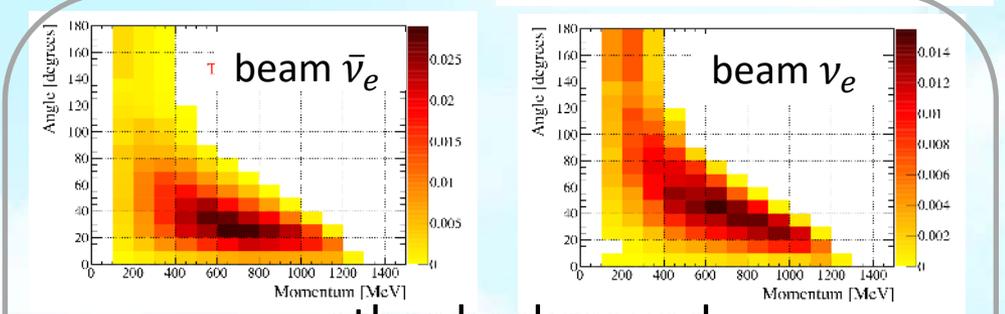
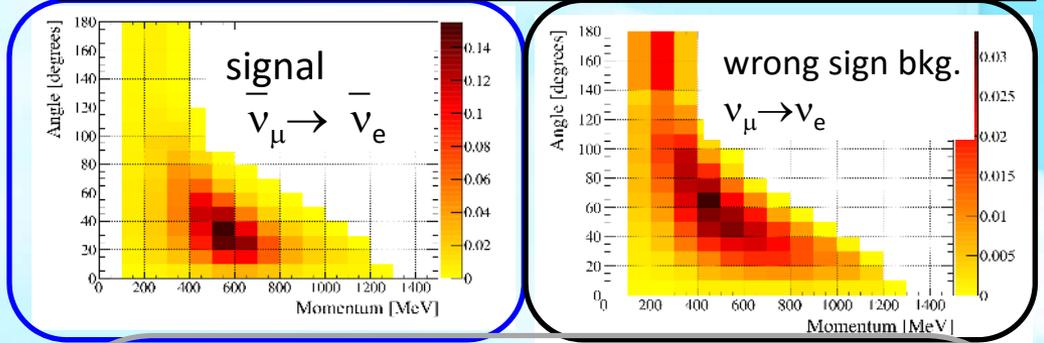


$\Delta m_{32}^2, \sin^2 \theta_{23}$

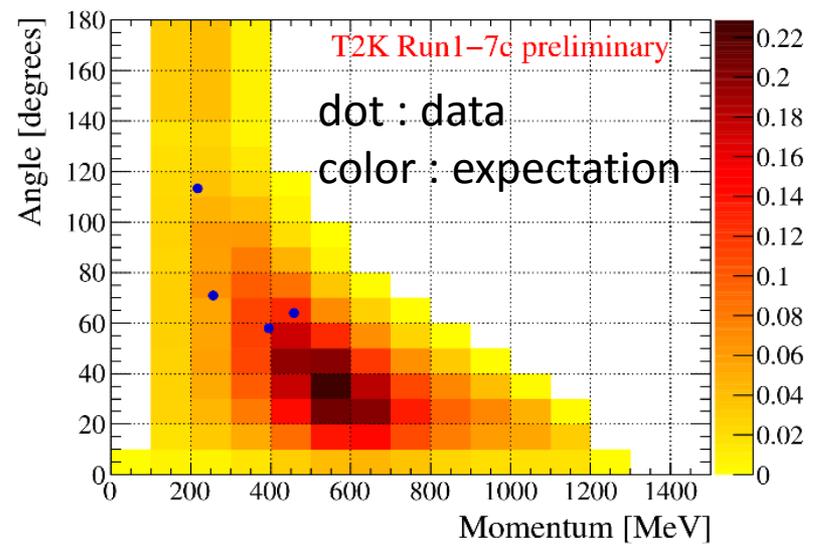
$\bar{\nu}_e$ selection cut sequence



expected distribution for signal and background



p - θ distribution of emitted electron

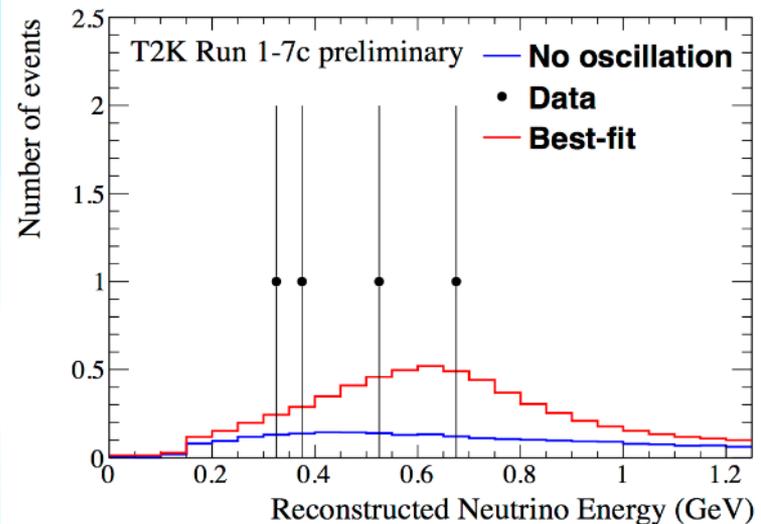
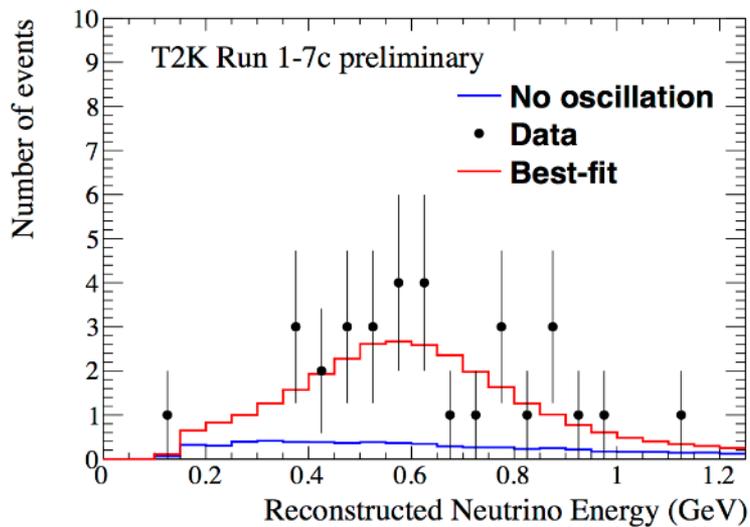


$\bar{\nu}_e$ event selection result

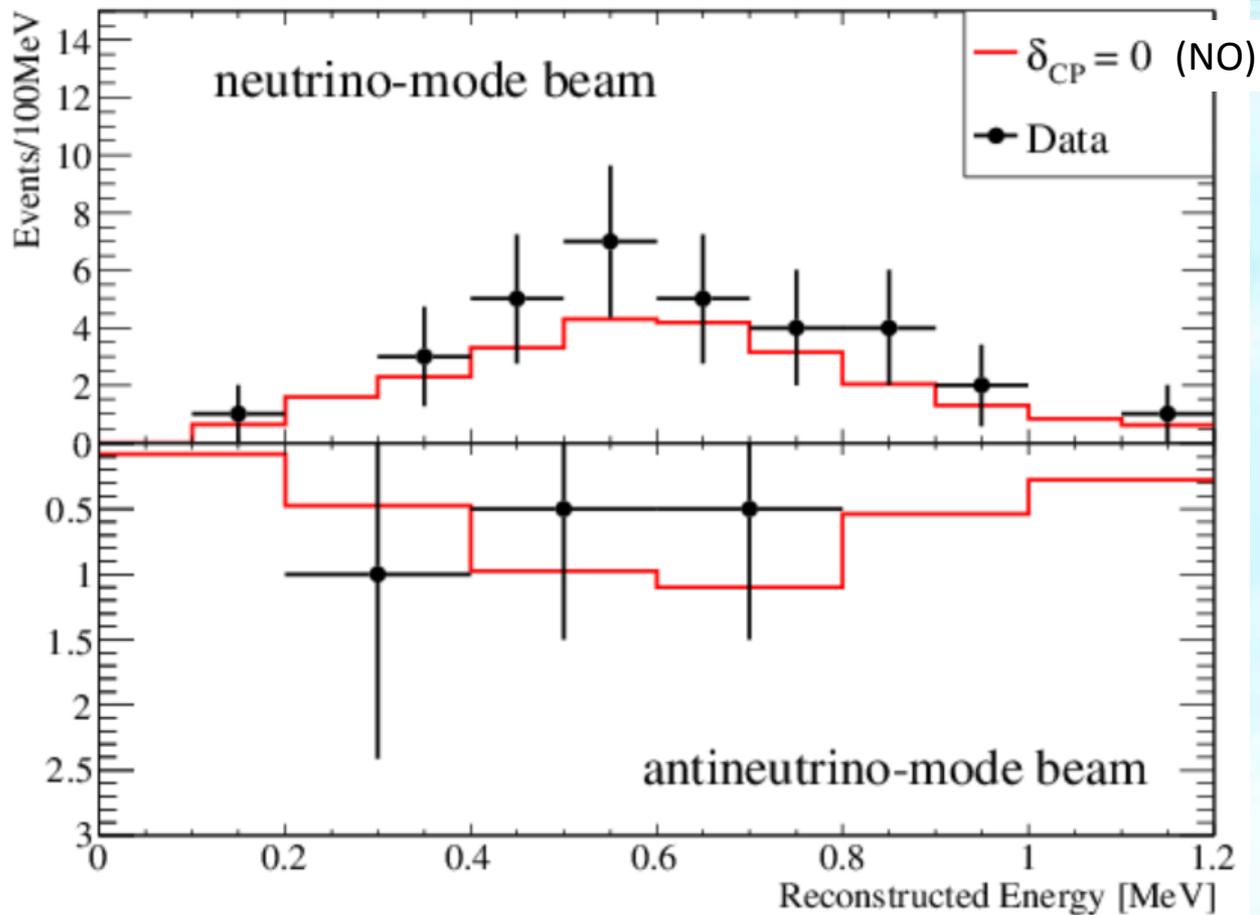
$$\delta_{CP} = -\frac{\pi}{2} \quad \delta_{CP} = 0 \quad \delta_{CP} = +\frac{\pi}{2} \quad \delta_{CP} = \pi$$

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

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



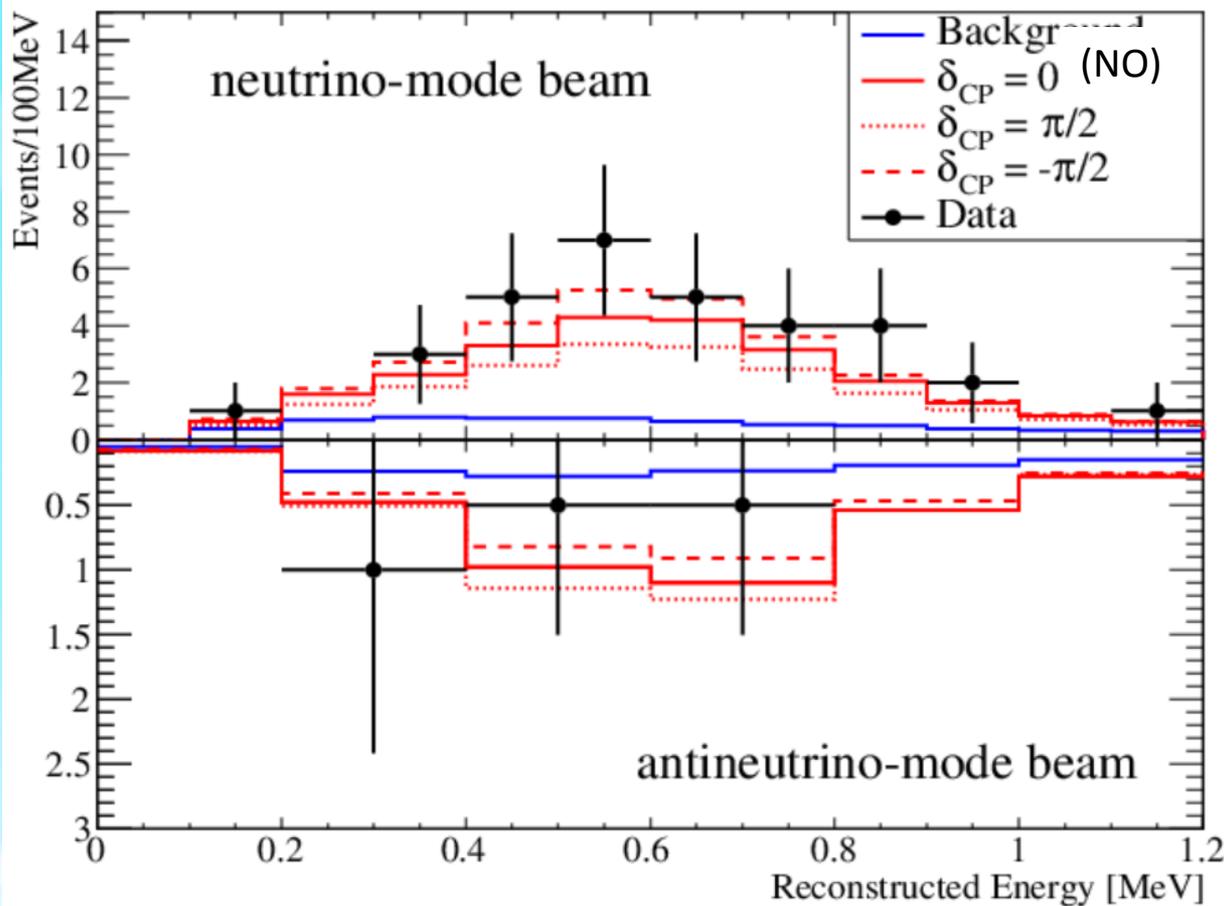
ν_e and $\bar{\nu}_e$ selected event distributions



neutrino2016の発表時
 32 ν_e events
 今回、 ν -modeで1週間分追加合計

T2K Run1-7c

ν_e and $\bar{\nu}_e$ selected event distributions

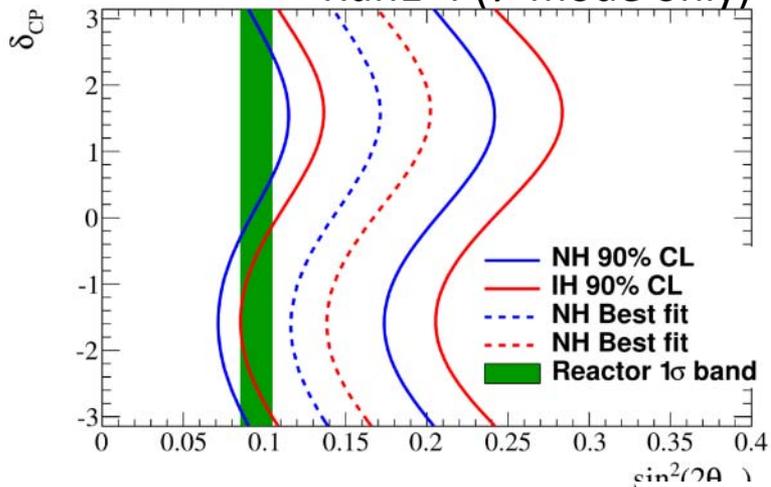


neutrino2016の発表時
 32 ν_e events
 今回、 ν -modeで1週間分追加
 合計32 ν_e events

T2K Run1-7c

ν_e and $\bar{\nu}_e$ selected event distributions

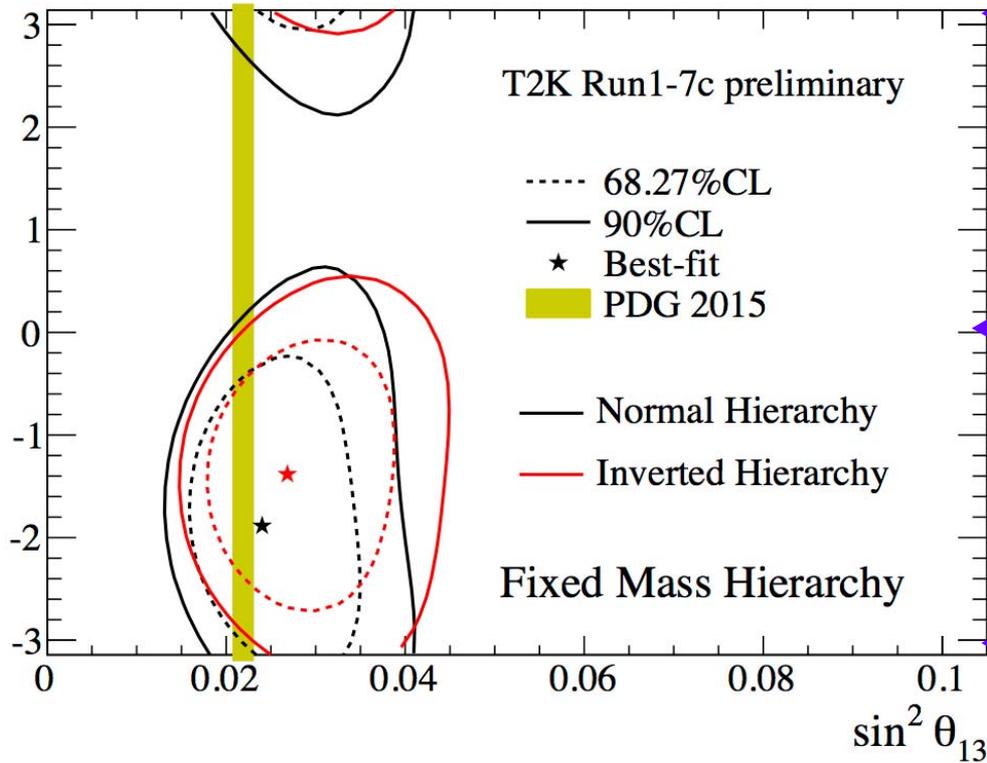
Run1-4 (ν -mode only)



Fits uses both momentum and angle information.

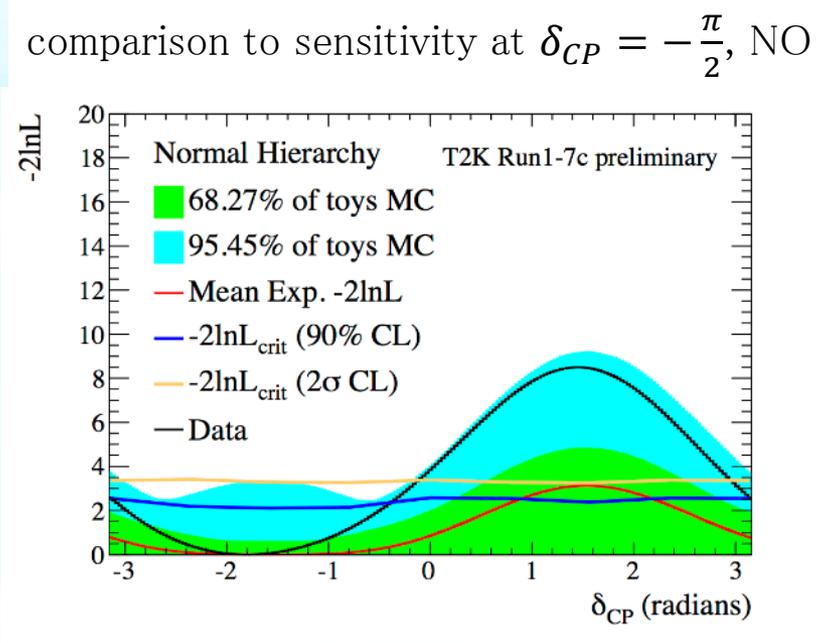
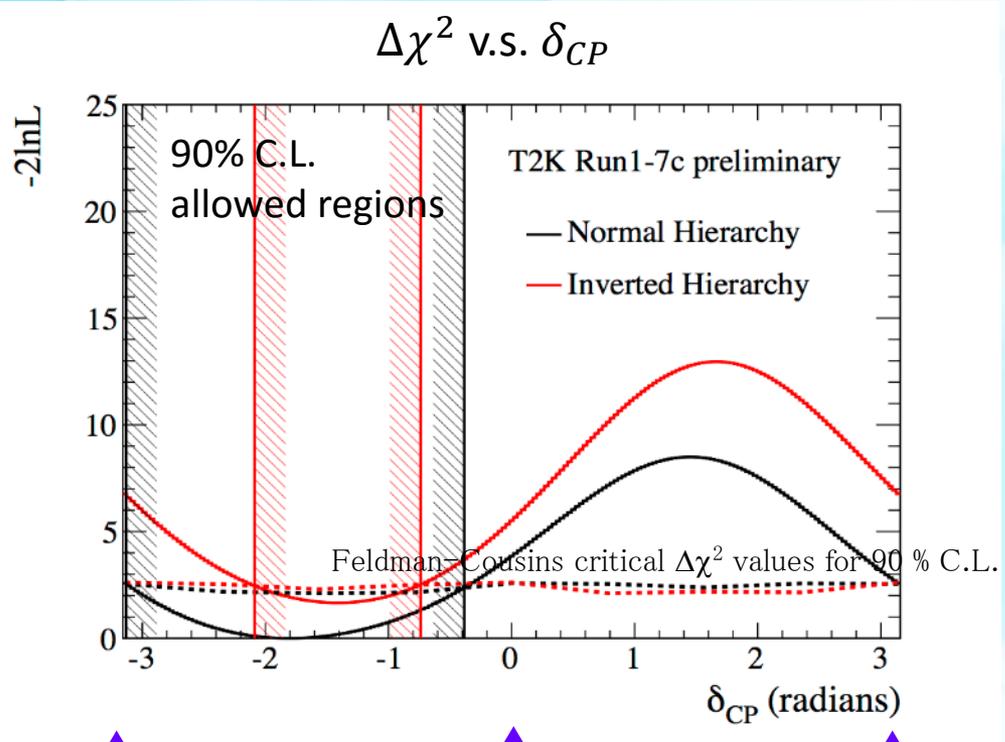
reactor measurement band

δ_{CP} (radians)



no CPV

δ_{CP} vs $\sin^2 \theta_{13}$

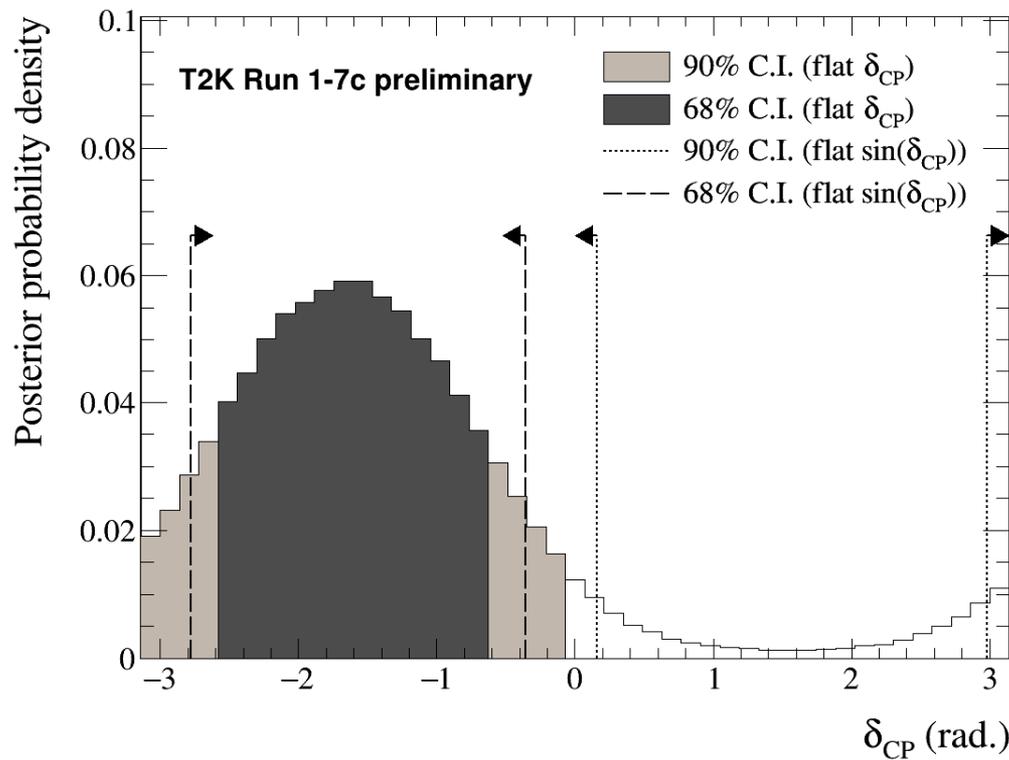


no CPV

90% Confidence Interval:

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

δ_{CP} Confidence Level

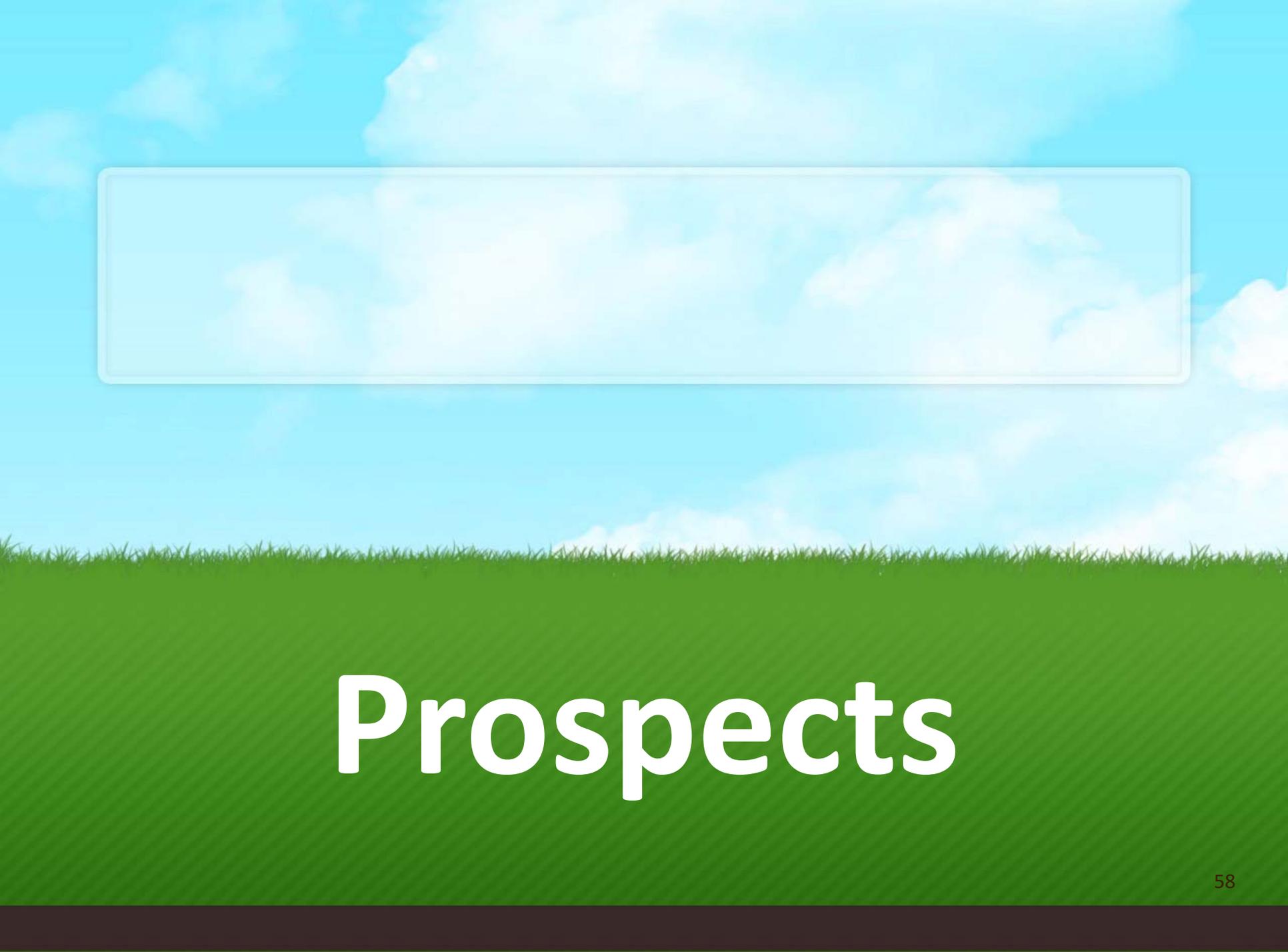


T2K Run1-7c preliminary

Weak preference on normal mass ordering and $\theta_{23} > 45^\circ$

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

Bayesian Posterior Probabilities

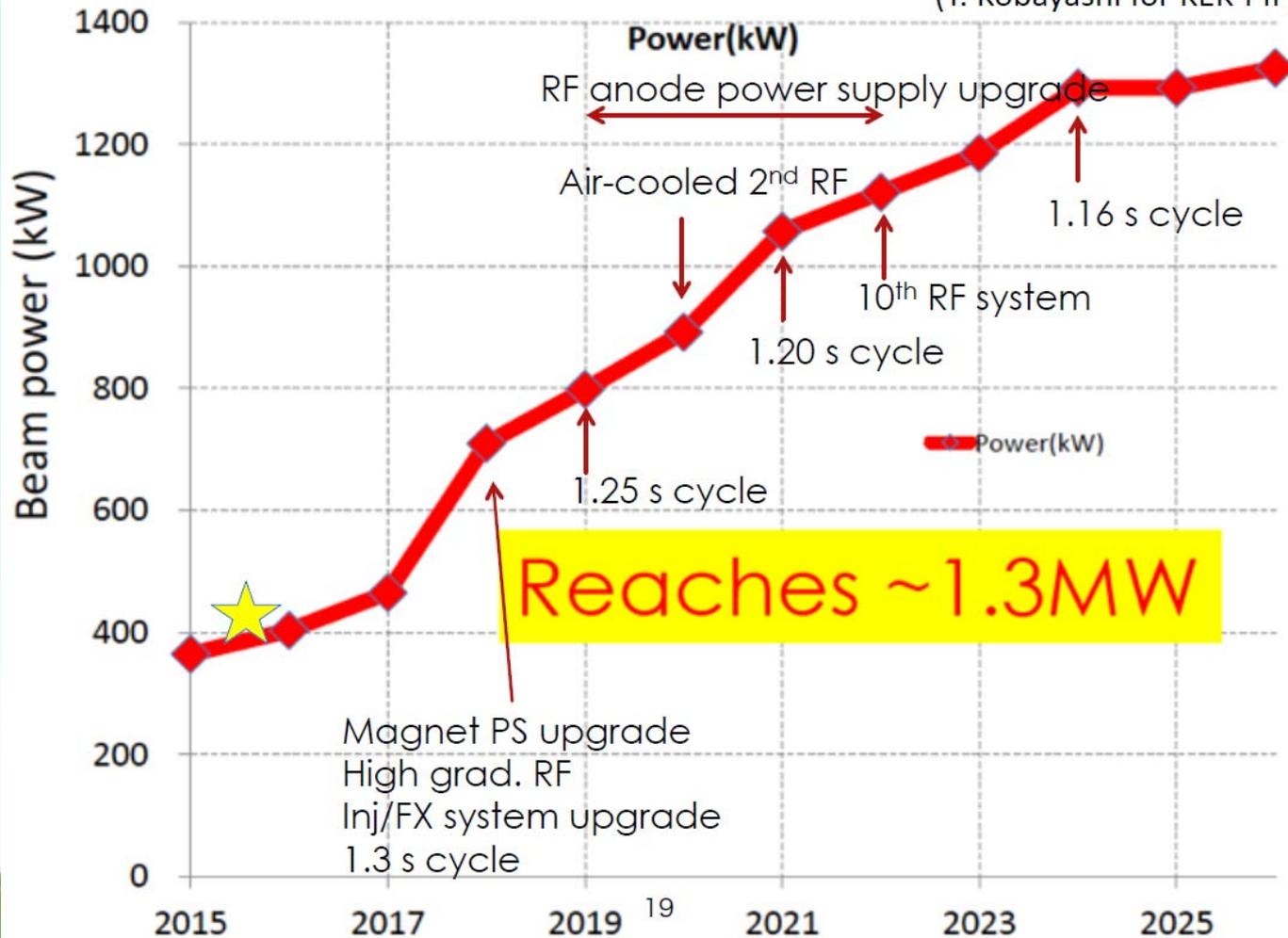


A background image featuring a bright blue sky with scattered white clouds. At the bottom, there is a horizontal strip of vibrant green grass. In the upper half of the image, there is a large, empty, light blue rounded rectangular box with a thin white border.

Prospects

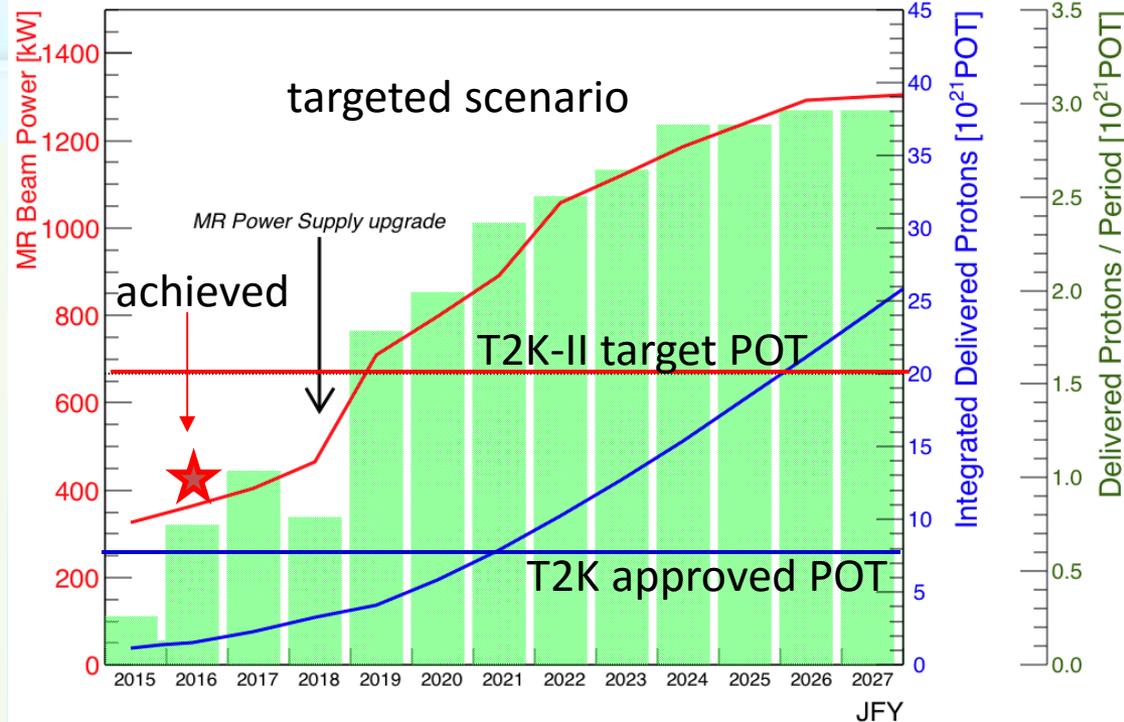
Beam power projection

(T. Kobayashi for KEK-PIP)



J-PARC Intensity Upgrade Plan

- 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 $\sim 6\%$
 - $\rightarrow \sim 4\%$

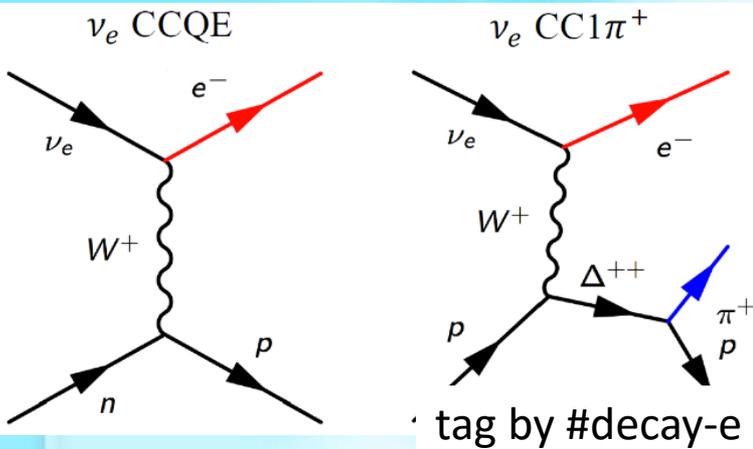


Expected number of events (1:1 ν : $\bar{\nu}$ running case)

ν_e sample : 455 evts $\pm 20\%$ change depending on δ_{CP}

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

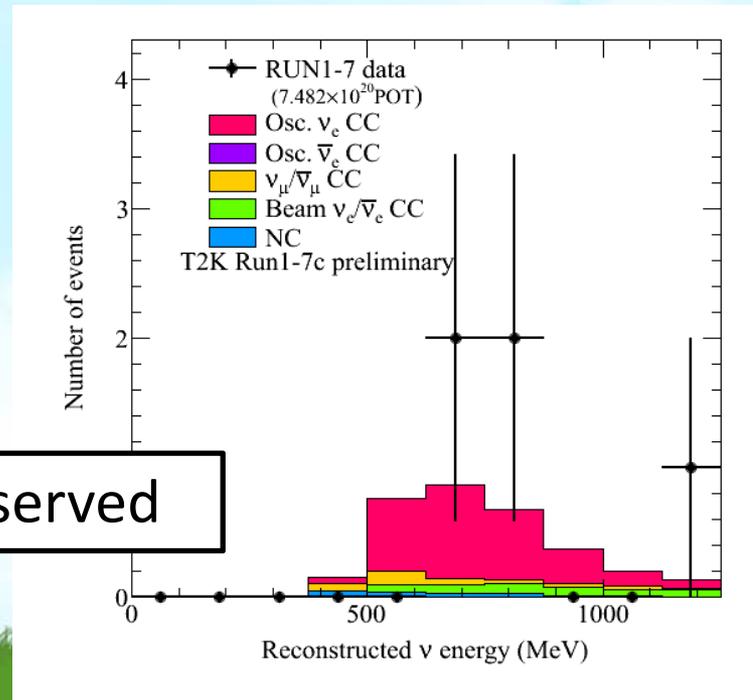
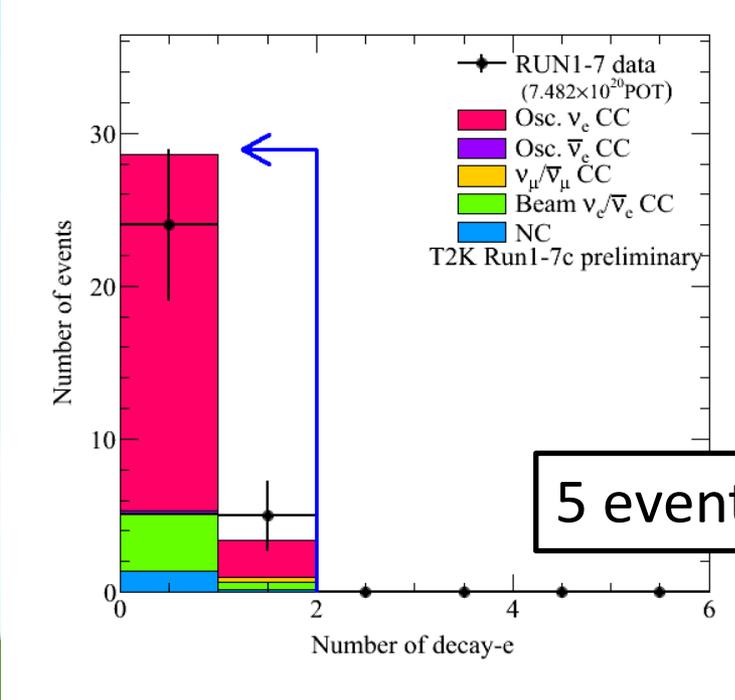
T2K-II target statistics and systematics



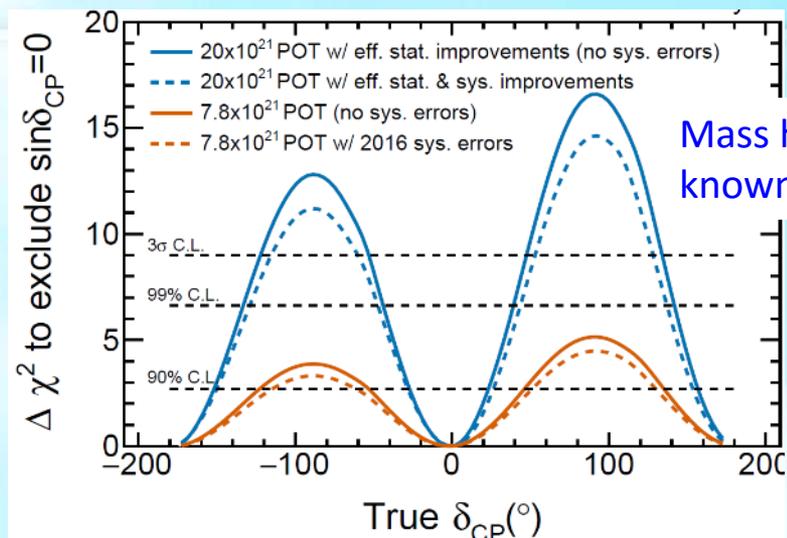
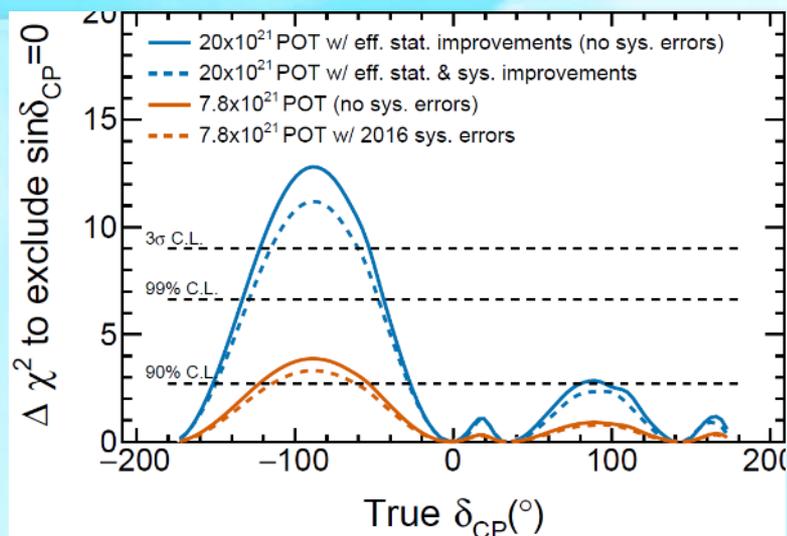
Expected number of events
(for normal mass ordering)

δ_{CP}			
$-\frac{\pi}{2}$	0	$+\frac{\pi}{2}$	π
3.1	2.8	2.3	2.7

~10% increase
of statistics



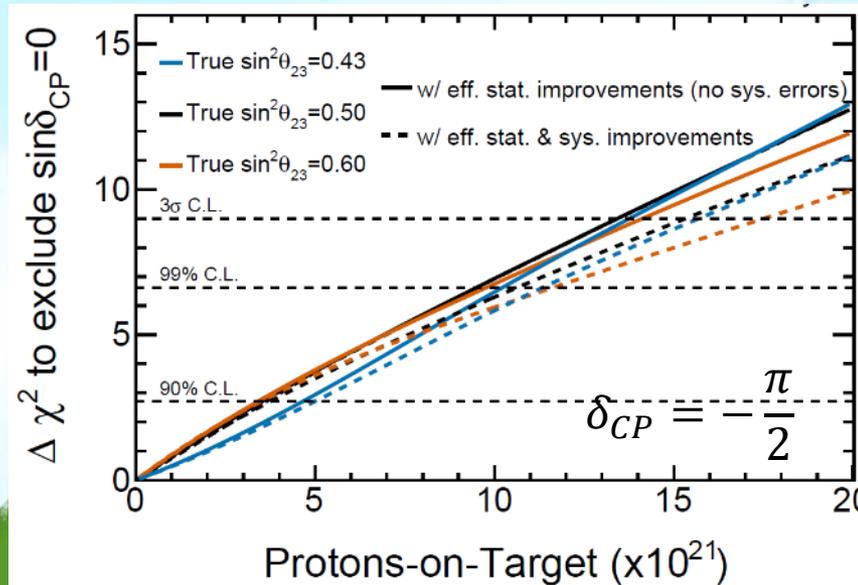
Example of additional samples: CC1 π^+ sample



Mass hierarchy known case

Assuming 1:1 ν : $\bar{\nu}$ running

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



T2K-II Sensitivity to CP-violation

- J-PARC MR power has reached $\sim 420\text{kW}$
- 反ニュートリノビームでデータを取り始めた!
 - 7.57×10^{20} protons-on-target w/ neutrino beam
 - 7.53×10^{20} protons-on-target w/ antineutrino beam
 - 19% of goal statistics
- We observe 32 ν_e and 4 $\bar{\nu}_e$ candidates, when we expect around 24 and 7 respectively with no CP violation (assuming normal mass ordering)
- δ_{CP} 90% Confidence Interval
 - ($-179^\circ, -22^\circ$) for normal mass ordering
 - ($-120^\circ, -42^\circ$) for inverted mass ordering
- To discover CPV, need more data! but may be reachable by T2K(-II)!

Summary