ニュートリノ振動研究の現状と展望

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シンポジウム「地下実験による宇宙・素粒子・原子核研究」
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Neutrino Oscillation

Current understanding of PMNS matrix:

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

Atmospheric, LBL

$$\Delta m^2_{32} \simeq 2.4 \times 10^{-3}\mathrm{eV}^2$$
$$\sin^2\theta_{23} = 0.4 \sim 0.6$$

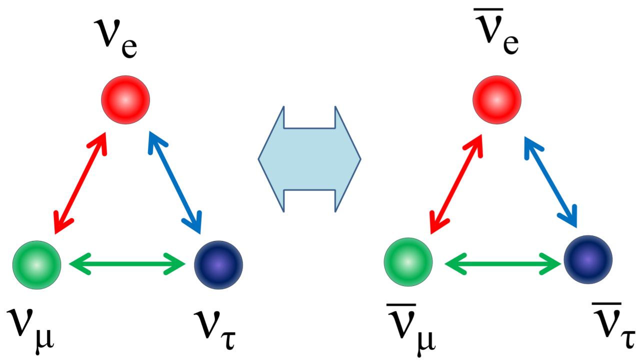
Reactor, LBL

$$\sin^2\theta_{13} \simeq 0.021$$

Solar, KamLAND

$$\Delta m^2_{21} \simeq 7.5 \times 10^{-5}\mathrm{eV}^2$$
$$\sin^2\theta_{12} \simeq 0.30$$

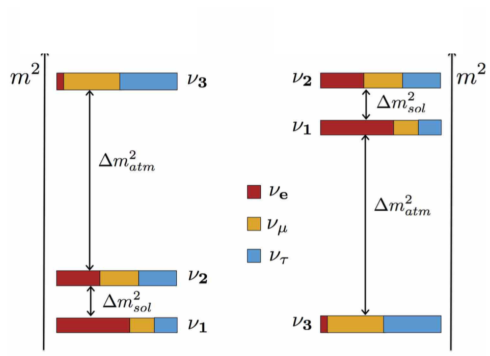
Still unknown:



Leptonic CP (δ_{CP})

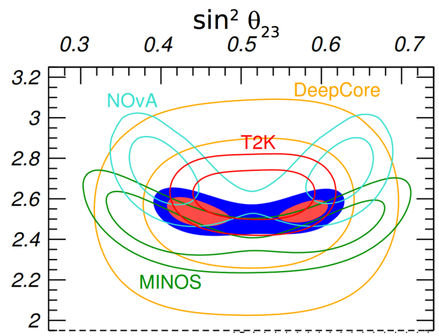
Normal ($\Delta m^2_{32}>0$)

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

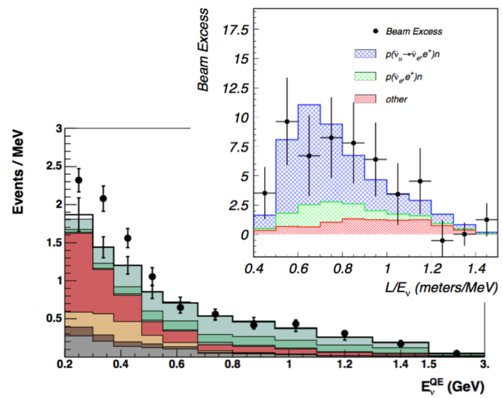


Mass Hierarchy
(Mass Ordering)

Others:



θ_{23} Octant

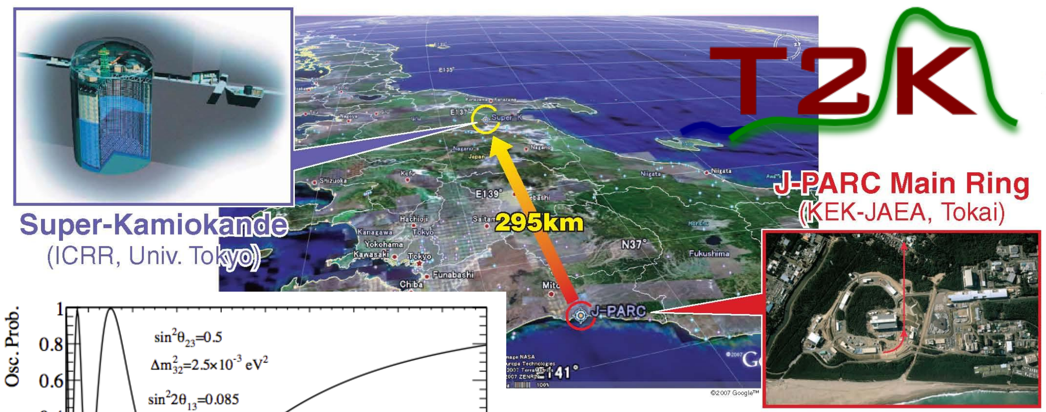


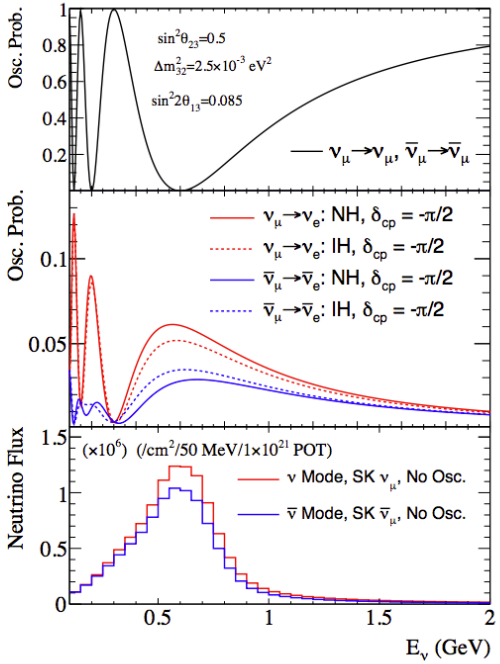
Sterile

加速器ニュートリノによるニュートリノ振動測定：

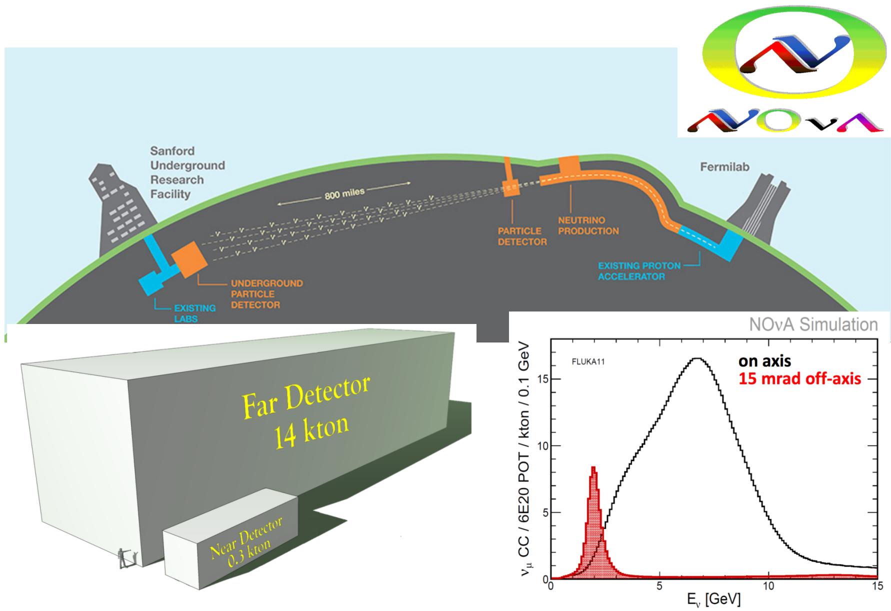
1. Δm^2_{32} and θ_{23} by ν_μ disappearance

2. θ_{13} and δ_{CP} by $P(\nu_\mu \to \nu_e)$ and $P(\bar{\nu}_\mu \to \bar{\nu}_e)$

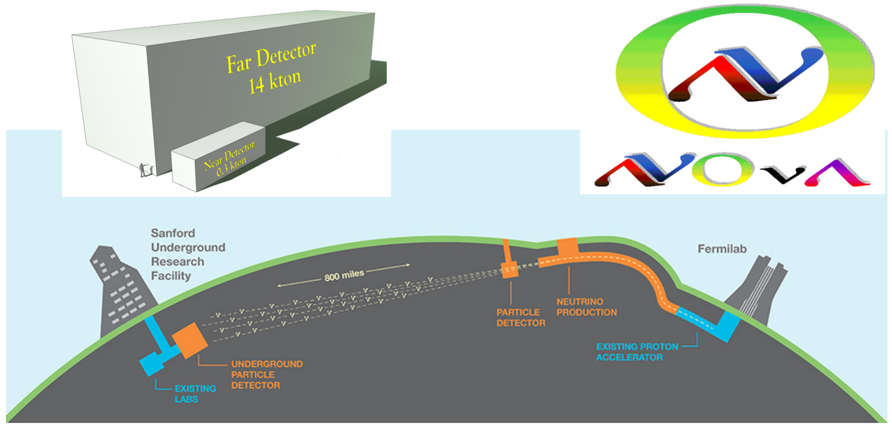




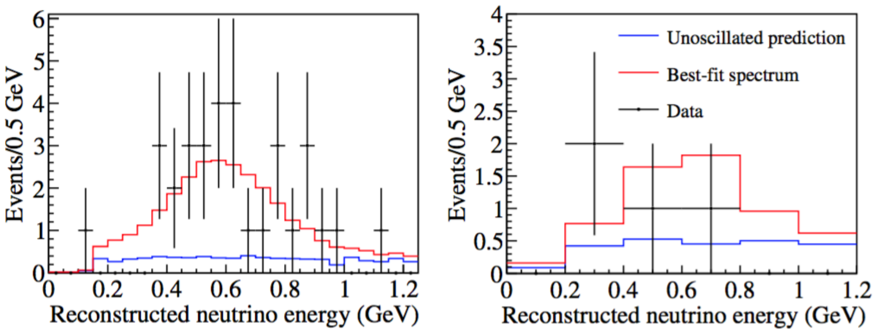
- ν_μ ($\bar{\nu}_\mu$) beam from J-PARC
- 2.5 deg off-axis beam (peak Eν ~600 MeV)
- L ~ 295km
- FD: Super-K detector

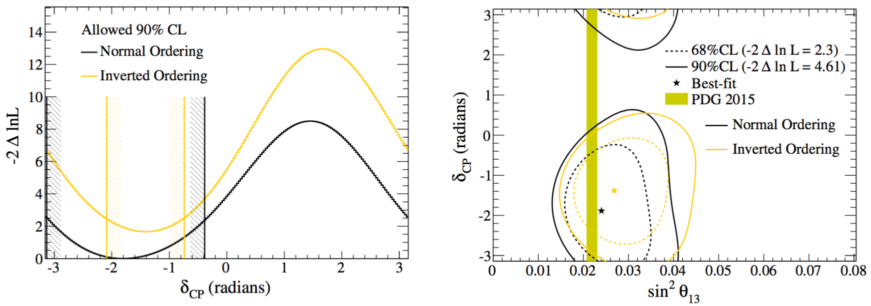


- NuMI ν_μ ($\bar{\nu}_\mu$) beam (FNAL)
- 15 mrad (0.86 deg) off-axis
- L ~ 810km (ND ~ 1km)
- FD: 14kton (16mx16mx60m) with ~2/3 LS

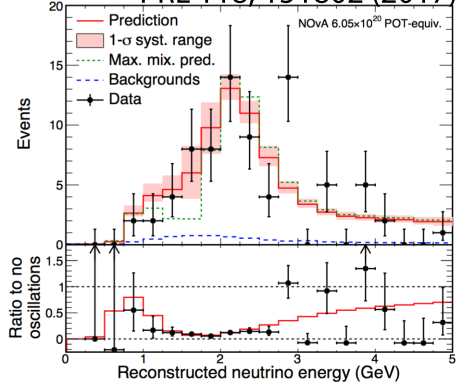


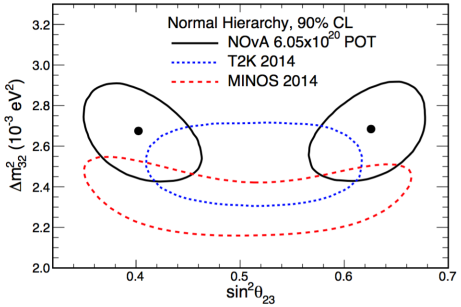
PRL 118, 151801 (2017)



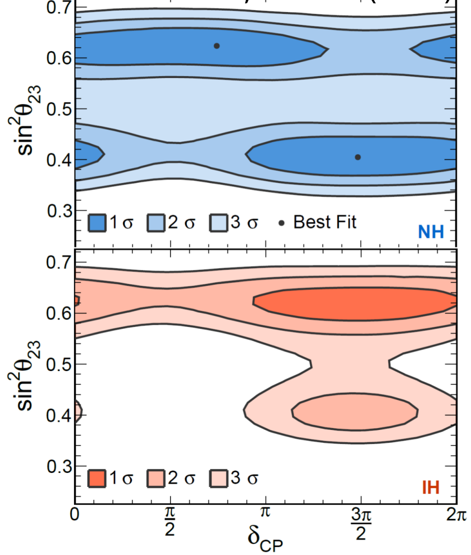


PRL 118, 151802 (2017)





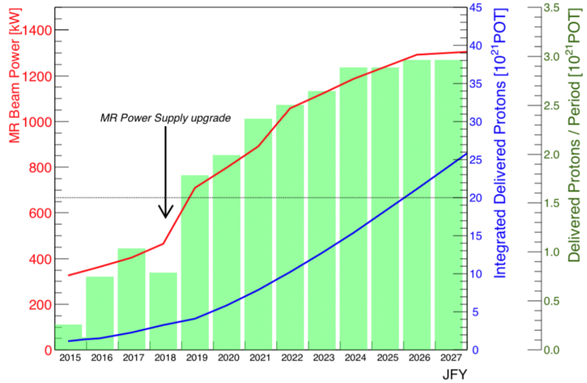
PRL 118, 231801 (2017)

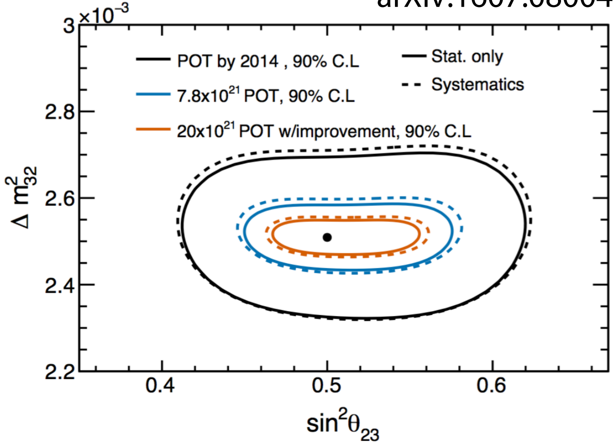


- Combined analysis with four samples ($\nu_\mu, \nu_e, \bar{\nu}_\mu, \bar{\nu}_e$)
- CP conservation ($\sin\delta=0$) excluded in 90% CL
- 最新の結果 → 企画講演 (14pS36)

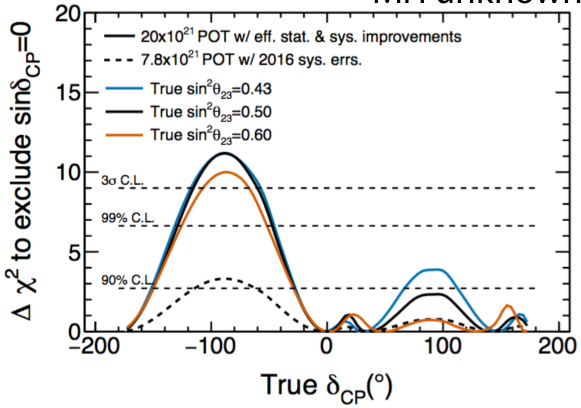
- 6.05×10^{20} POT for ν-mode (taking $\bar{\nu}$ beam)
- Disfavored $\delta=0\sim\pi$ for IH
- 2.6σ tension with maximal mixing

arXiv:1607.08004

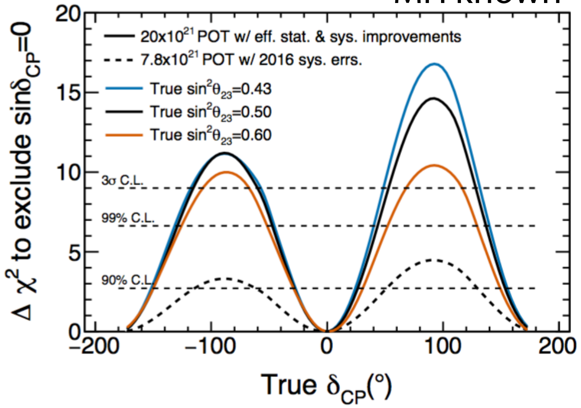




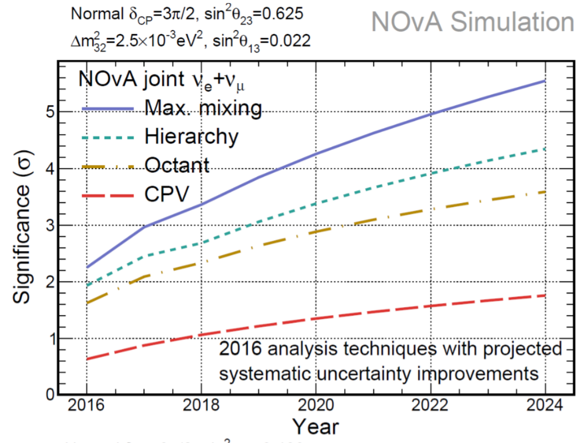
MH unknown

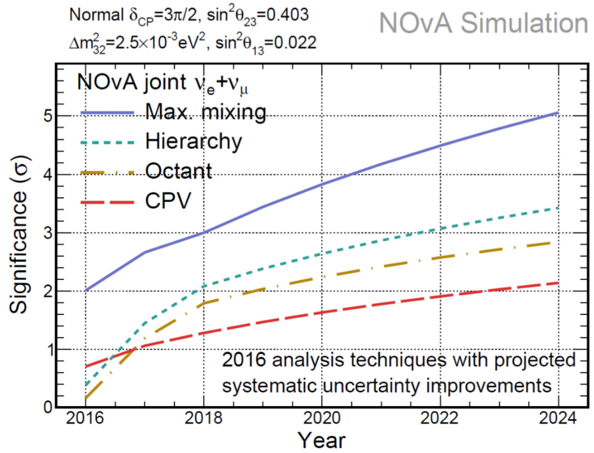


MH known



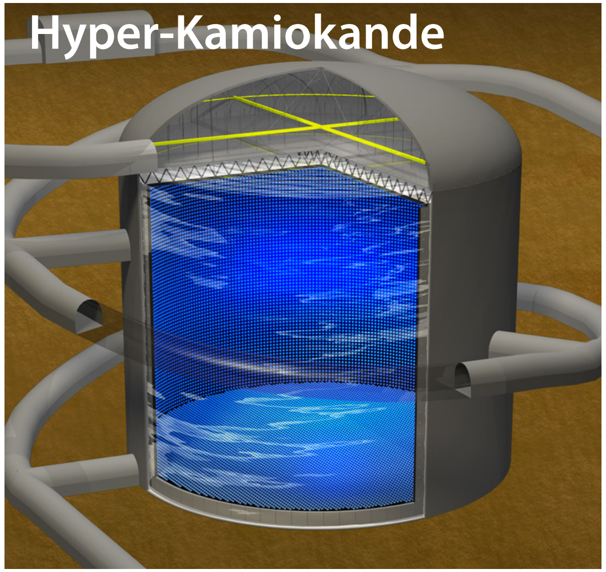
- T2K-II: Proposal for 20x10[21] POT until 2026
- Increase signal rate by 50% and reduce syst. error
- CP sensitivity: 3 σ or higher for δ_{CP} ~ -π/2
- $\Delta\theta_{23}$ ~ 1.7° (0.7°) for $\sin^2\theta_{23}$=0.5 (0.43,0.6)





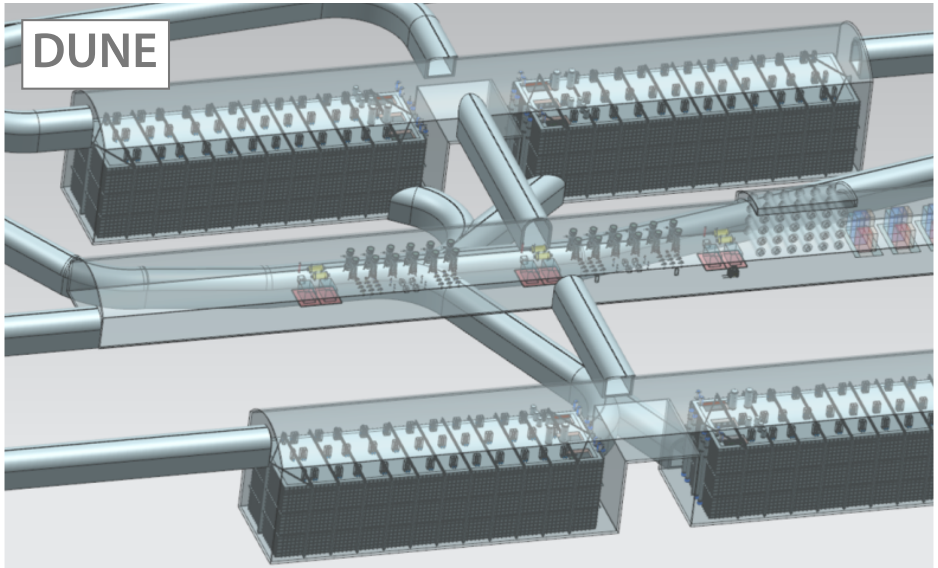
- 3σ to exclude maximal mixing in 2018
- 3σ for MH in 2020~2022

Hyper-K & DUNE



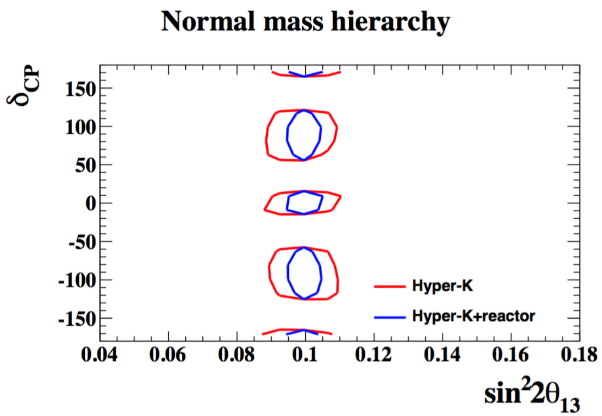
- Water Cherenkov detector
- 190 kton fiducial volume (1tank conf.) corresponding to ~10 times of Super-K
- 40,000 PMT (~40% coverage) of improved photo-detection efficiency(x2 compared to SK PMT)
- Increase 2.2 MeV gamma detection eff. by n-H capture

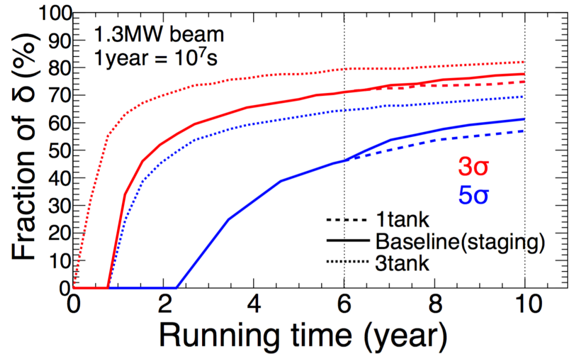
- Liquid Argon detector based time projection chamber technique (TPC)
- Though fiducial mass is relatively small (40 kton), high resolution imaging would offer possibilities to discriminate ν and $\bar{\nu}$



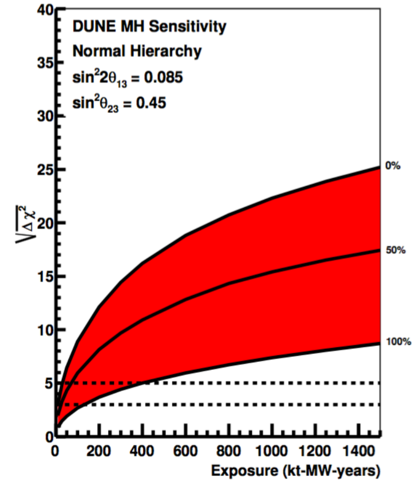
Hyper-K & DUNE CP Sensitivities

Hyper-Kamiokande





DUNE



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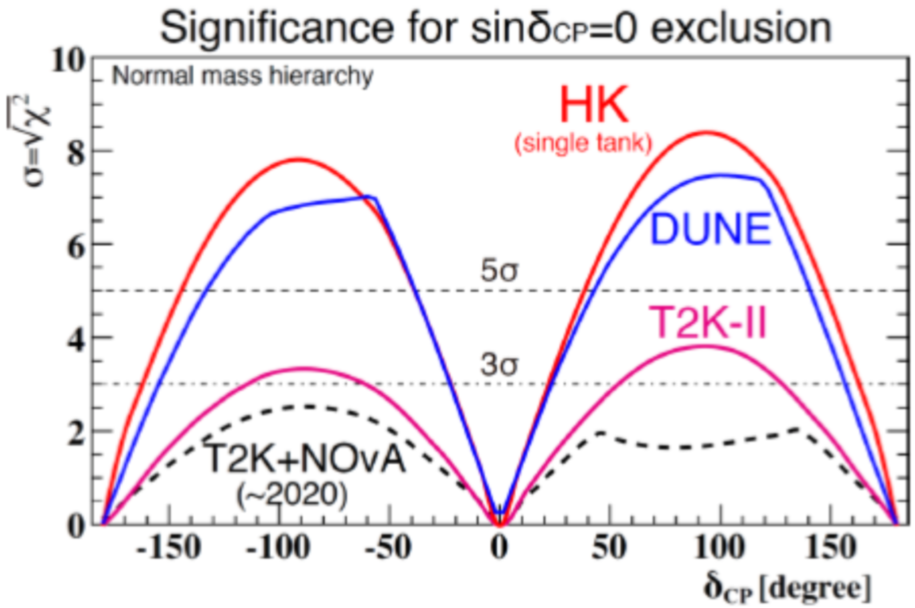


→ 詳細は次の講演

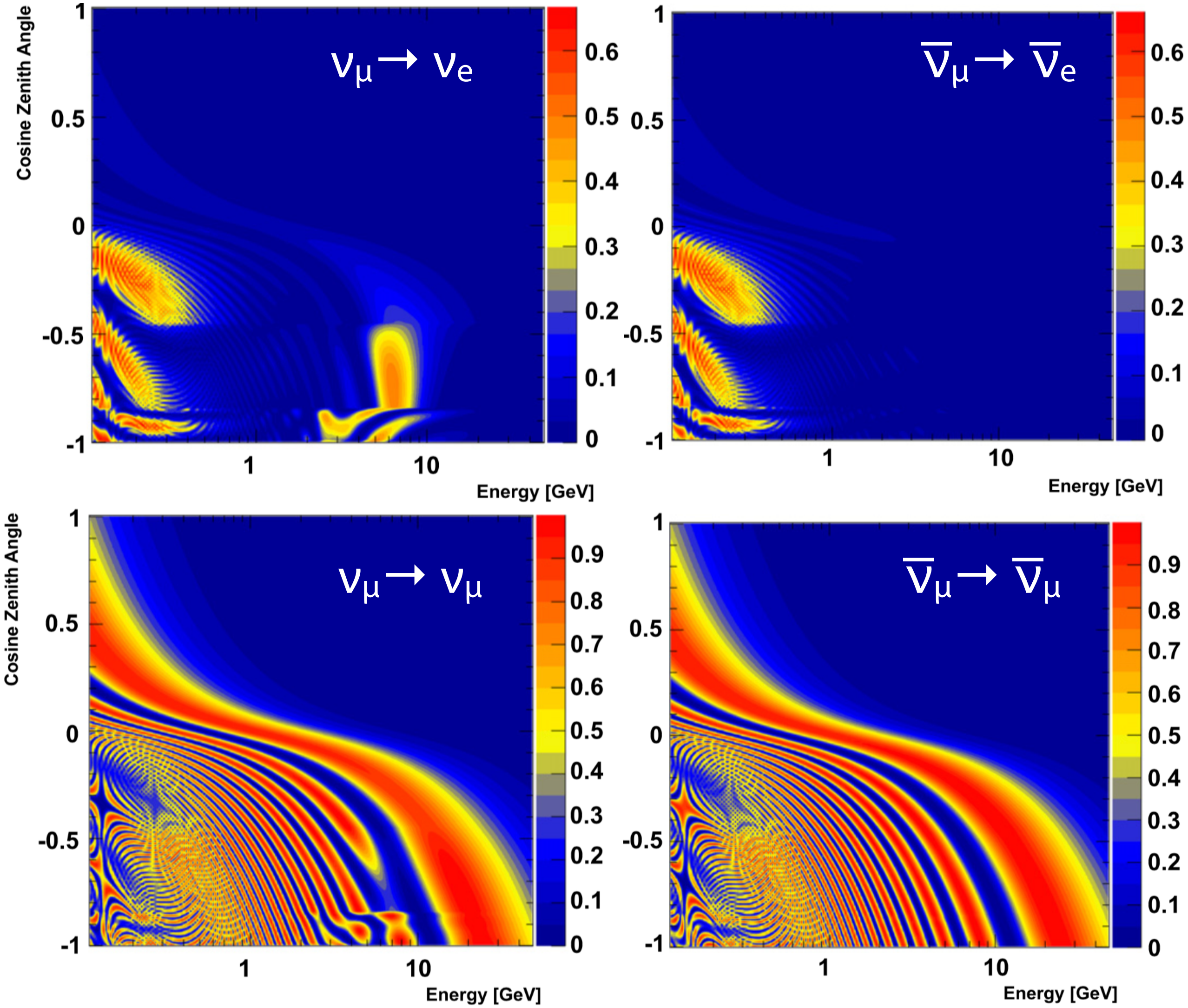
（田中さん12pU11-8）

Mass hierarchy （質量階層性）

- 加速器ニュートリノ
  - Nova
- 原子炉ニュートリノ
  - JUNO
- 大気ニュートリノ
  - SK、PINGU、ORCA、INO、Hyper-K、DUNE

Matter Effect and Mass Hierarchy

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



- Neutrino is affected by additional potential due to forward scattering with electrons (**matter effect**)

$$i\frac{d\nu(t)}{dt} = H_0\nu(t) \qquad H_0 \rightarrow H_0 + \frac{1}{2E}\begin{pmatrix} A & 0 \\ 0 & 0 \end{pmatrix}$$

- Effective mixing an $A = \pm 2\sqrt{2}G_F E_\nu n_e$

$$\sin 2\theta_{13}^M = \frac{\sin 2\theta_{13}}{\sqrt{\left(\frac{A}{\Delta m^2_{32}} - \cos 2\theta_{13}\right)^2 + \sin^2 2\theta_{13}}}$$

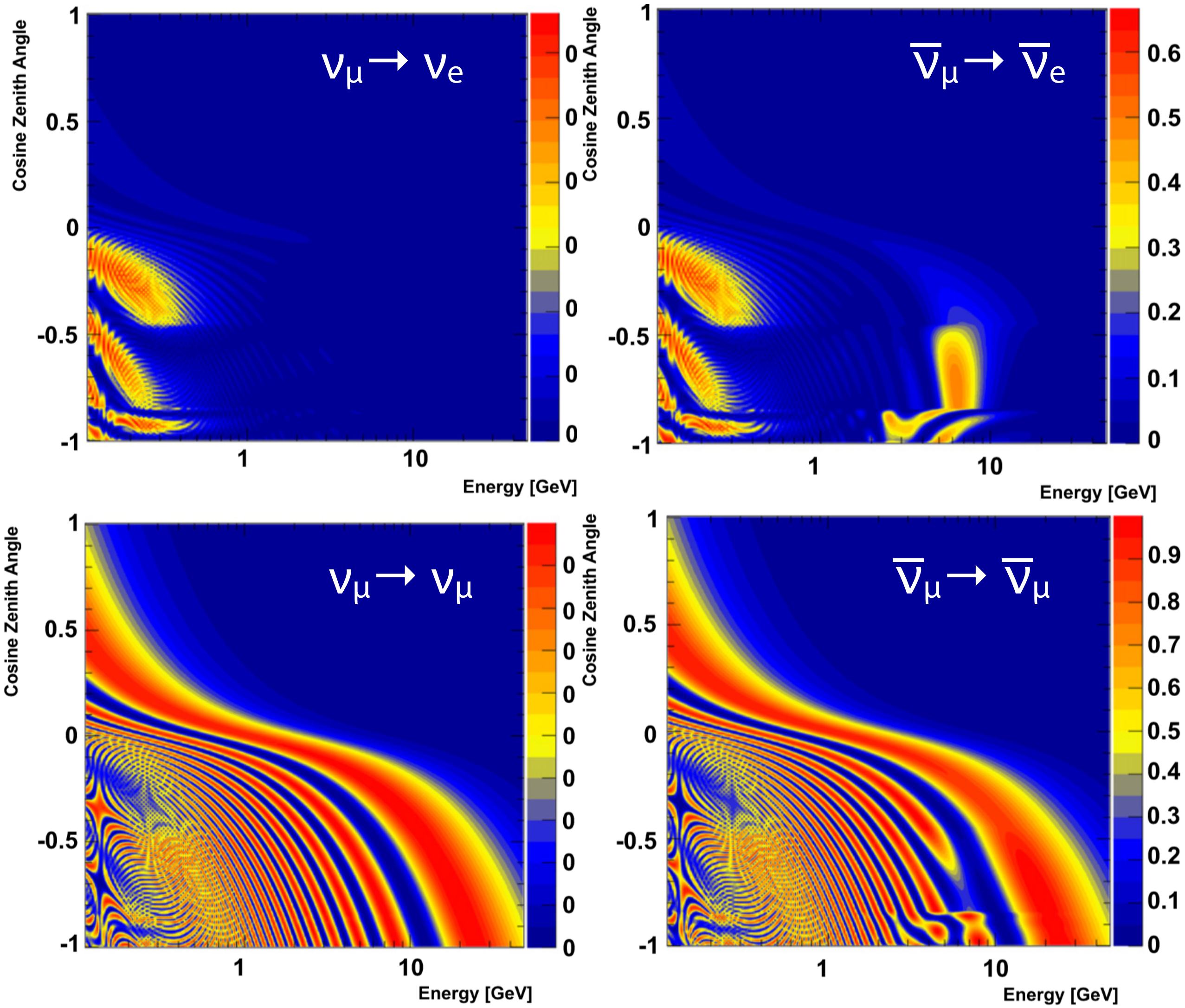
- At resonance region in multi-GeV:

$$A \sim \Delta m^2_{32}\cos 2\theta_{13} \quad \rightarrow \quad \theta_{13}^M \gg \theta_{13}$$

- Presence of resonance depends:
  - $\nu / \bar{\nu}$ ($A \rightarrow -A$)

Matter Effect and Mass Hierarchy

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



- Neutrino is affected by additional potential due to forward scattering with electrons (**matter effect**)

$$i\frac{d\nu(t)}{dt} = H_0\nu(t) \qquad H_0 \rightarrow H_0 + \frac{1}{2E}\begin{pmatrix} \mathrm{A} & 0 \\ 0 & 0 \end{pmatrix}$$

$$A = \pm 2\sqrt{2}G_F E_\nu n_e$$

- Effective mixing angle in matter:

$$\sin 2\theta_{13}^M = \frac{\sin 2\theta_{13}}{\sqrt{\left(\frac{A}{\Delta m^2_{32}} - \cos 2\theta_{13}\right)^2 + \sin^2 2\theta_{13}}}$$

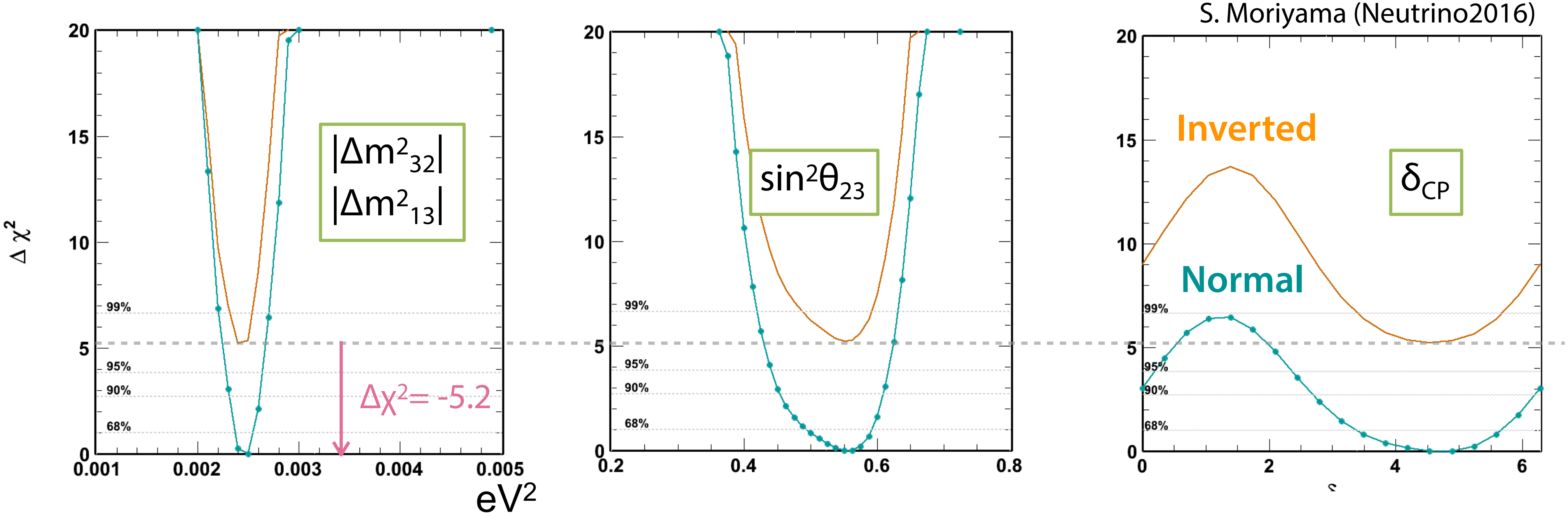
- At resonance region in multi-GeV:

$$A \sim \Delta m^2_{32}\cos 2\theta_{13} \quad \rightarrow \quad \theta_{13}^M \gg \theta_{13}$$

- Presence of resonance depends:
  - **ν / $\bar{\nu}$ (A→ -A)**
  - **Mass hierarchy (Δm^2_{32}→-Δm^2_{32})**

Three Flavor Fit (w/ reactor and T2K constraints)

S. Moriyama (Neutrino2016)

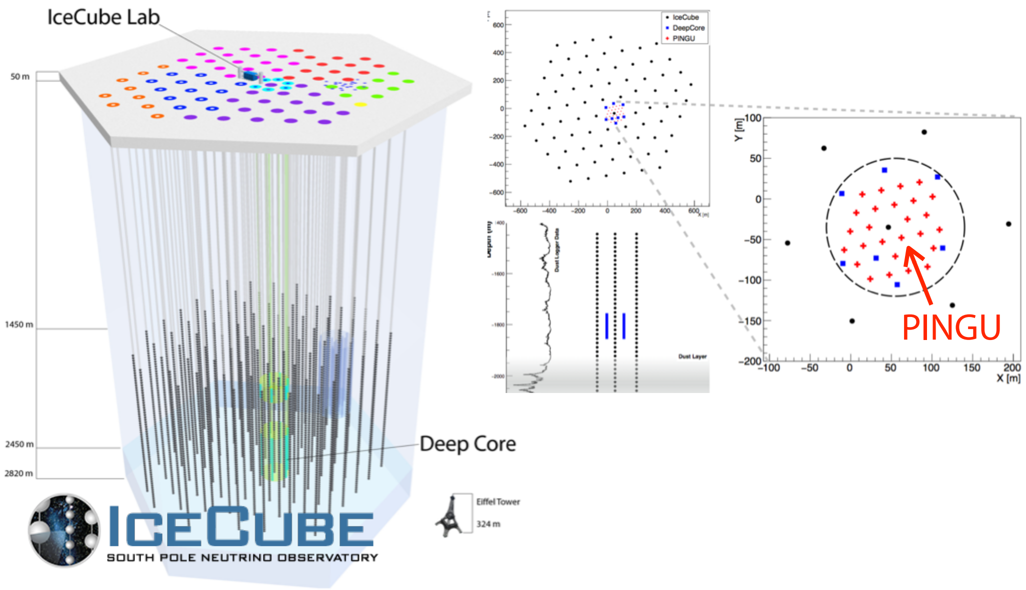


- **Normal hierarchy is weakly preferred:** $\Delta\chi^2 = \chi^2_{NH}-\chi^2_{IH} = -5.2$ (-3.8 exp. for SK best, -3.1 for combined best)
- p-value of Inverted hypothesis is 0.024 ($\sin^2\theta_{23}$=0.6) and 0.001 ($\sin^2\theta_{23}$=0.4).

	δ_{CP}	$\sin^2\theta_{23}$	$\|\Delta m^2_{32}\|$ (eV^2)
Inverted	4.189	0.575	2.5×10^{-3}
Normal	4.189	0.587	2.5×10^{-3}
Inverted	4.538	0.55	2.5×10^{-3}
Normal	4.887	0.55	2.4×10^{-3}

w/ T2K constraint

PINGU and ORCA

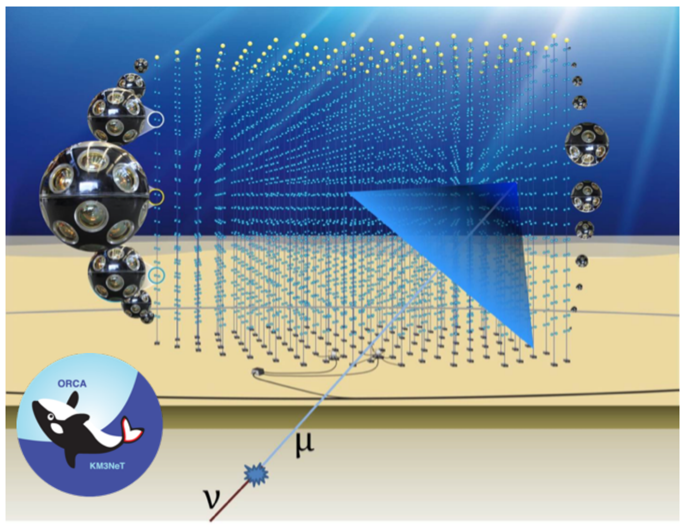


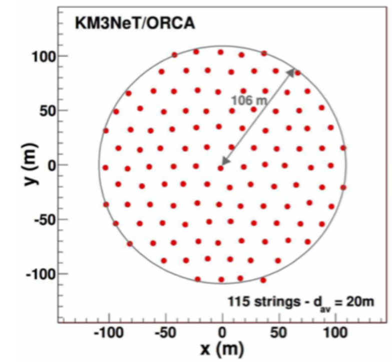
IceCube / PINGU:

- Inner detector configuration of IceCube/DeepCore at South pole
  - 6 Mton effective mass
- Lower threshold (~GeV) with 22 m spacing of string
- ~60,000 atm. ν / year expected

KM3NET / ORCA:

- Low energy branch of KM3NeT in Mediterranean Sea
- Dense array of multi-PMT digital optical modules (DOMs)



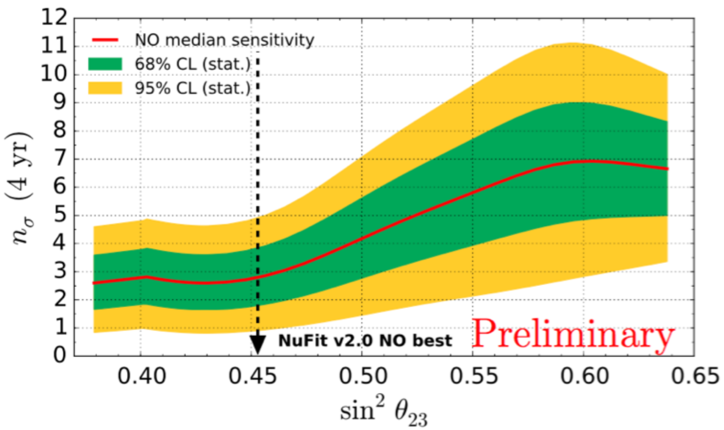


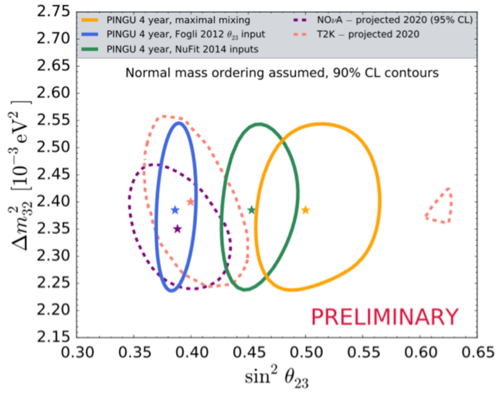
	ARCA	ORCA
Location	Italy	France
String dist. [m]	90	20
DOM spacing [m]	36	6
Volume [10^6 m^3]	~500	~3.8

PINGU / ORCA Sensitivities

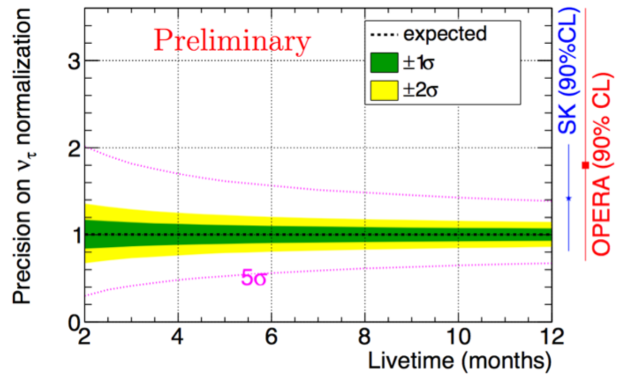
Mass Hierarchy | **θ_{23} Octant** | **ν_τ Appearance**

PINGU

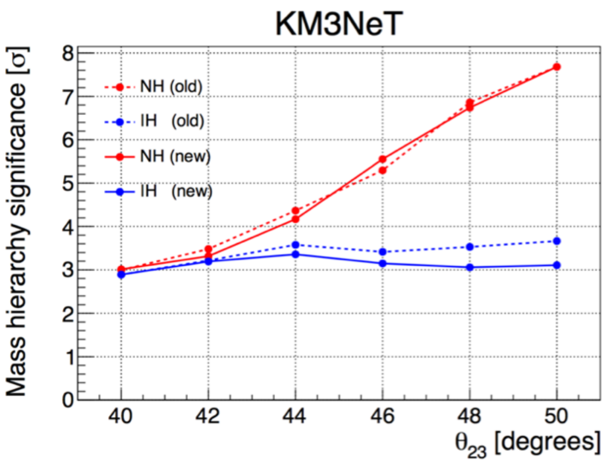


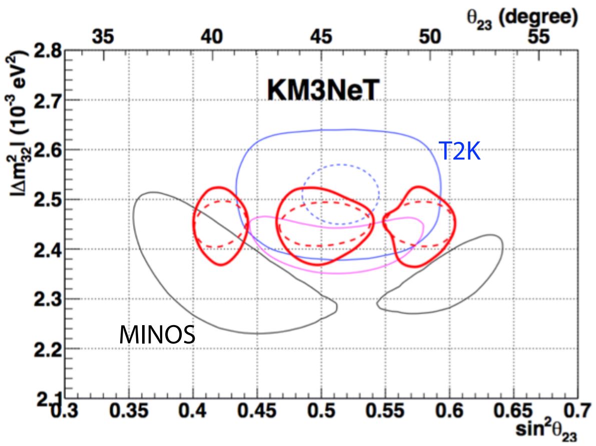


J. Phys. G44, 054006 (2017)

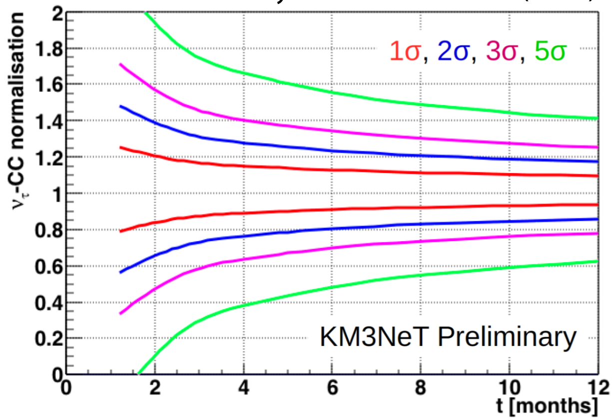


ORCA

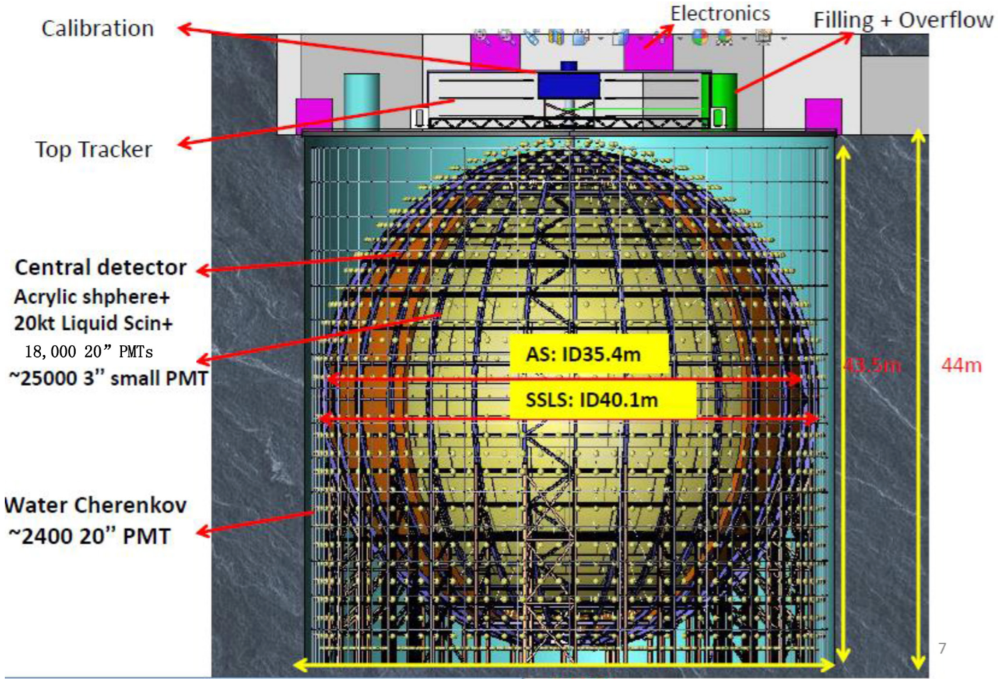


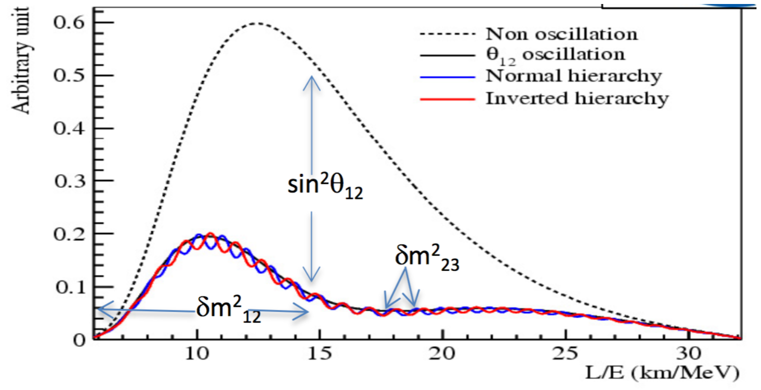


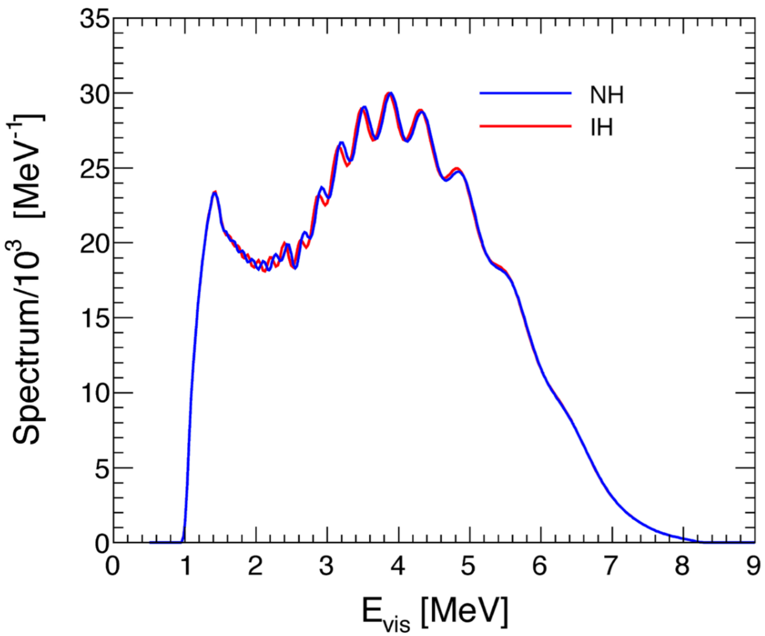
J. Phys. G43 no.8 084001 (2016)



JUNO (Jiangmen Underground Neutrino Osvsevatory)

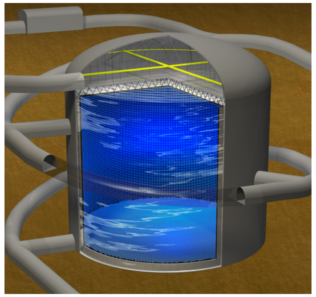


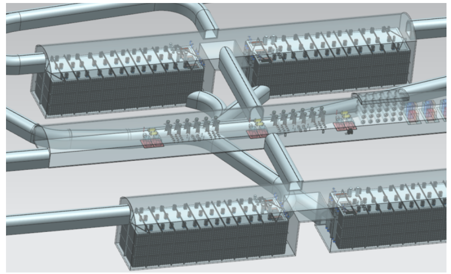




- 20kton Liquid Sci. in China
- ~80% photo coverage (ΔE ~3%/$\sqrt{E}$)
- Reactor power: 36 GW, L ~ 50 km
- Precise measurement of reactor ν by MH

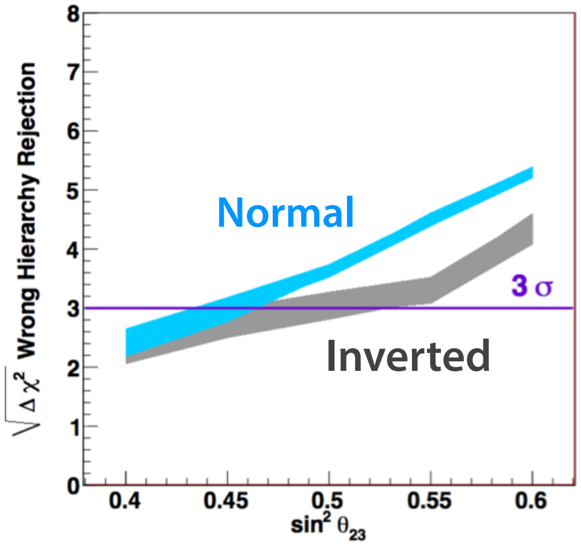
Hyper-K & DUNE Atmospheric Sensitivities

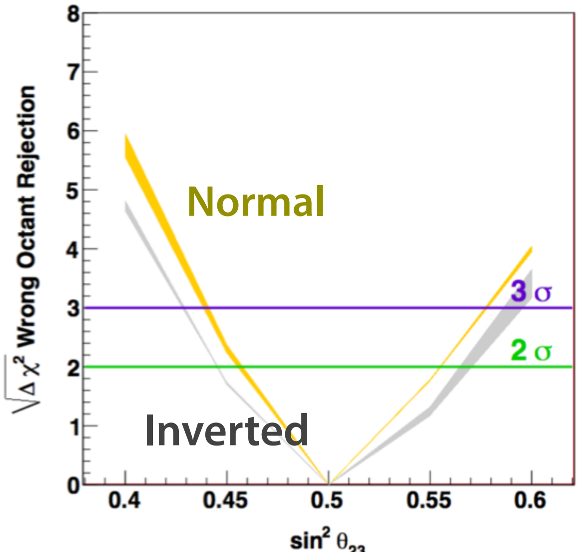


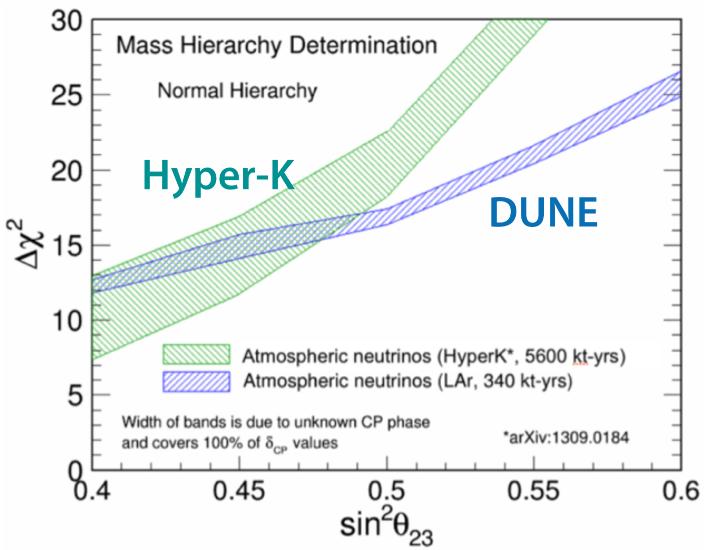


KEK Preprint 2016-21
ICRR-Report-701-2016-1

arXiv.1512.06148





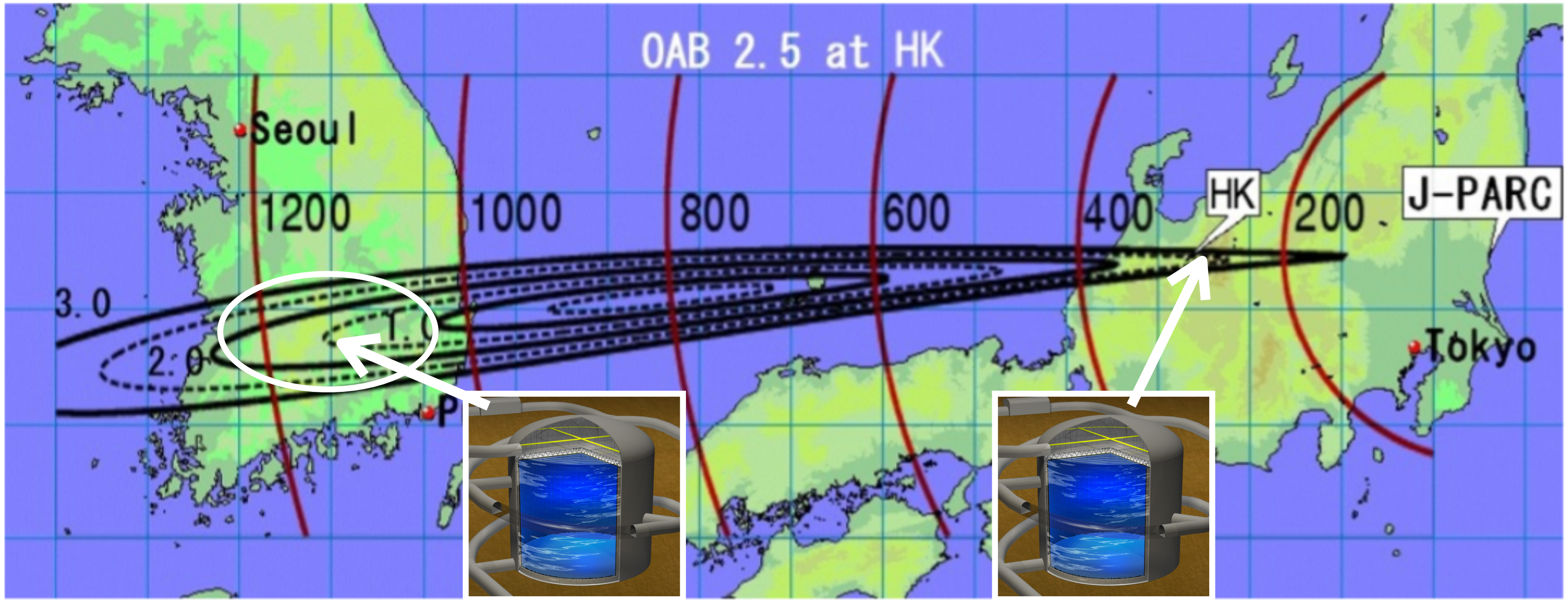


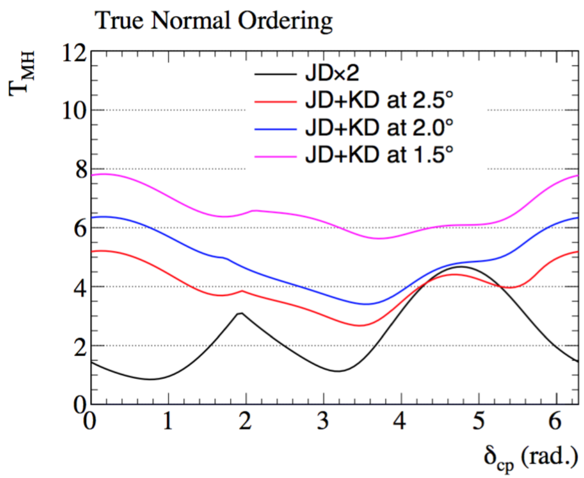
- **>3σ sensitivity for both MH cases** for $\sin^2\theta_{23}>0.45$ with 10yr data (2.6Mtonyr)
- Possible to discriminate θ_{23} octant at **>3σ for $|\theta_{23}-45|>4$deg**

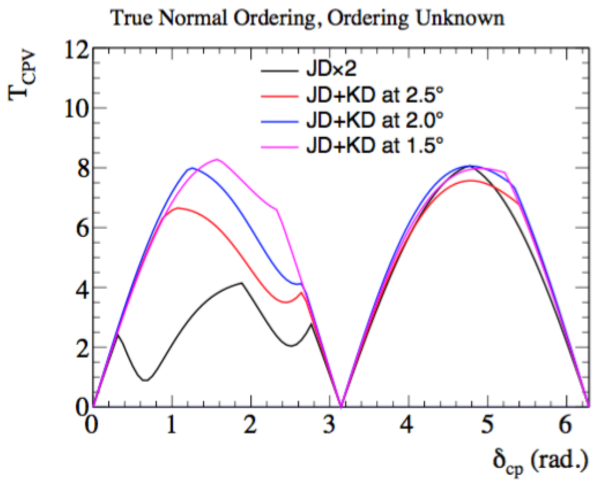
- **Comparable MH sensitivity** to Hyper-K due to high detector resolution

T2HKK option

arXiv.1611.06118

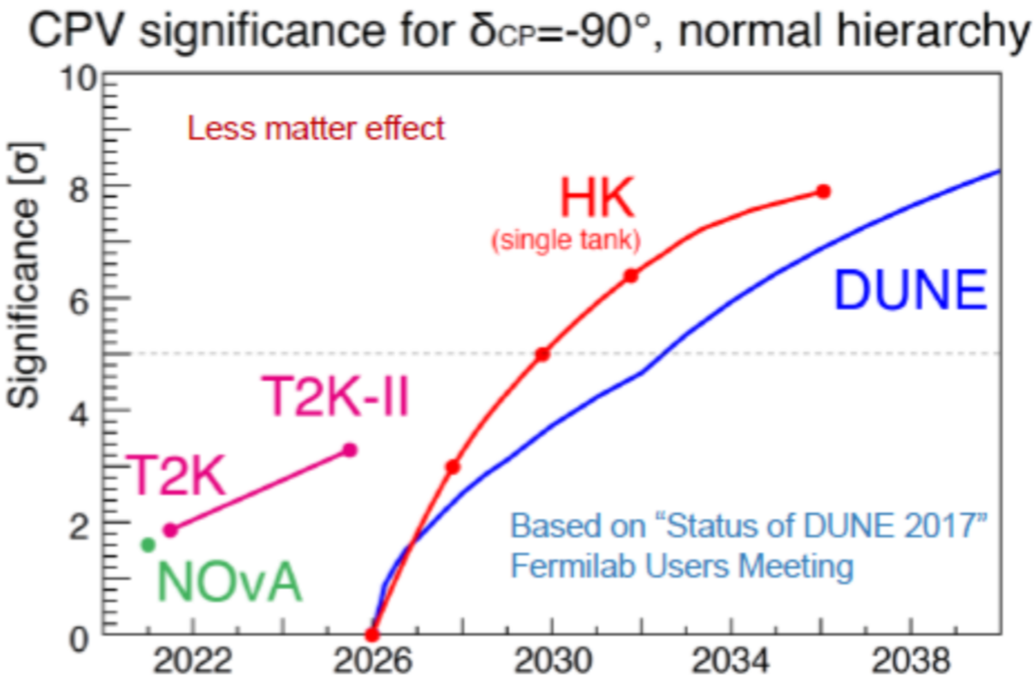




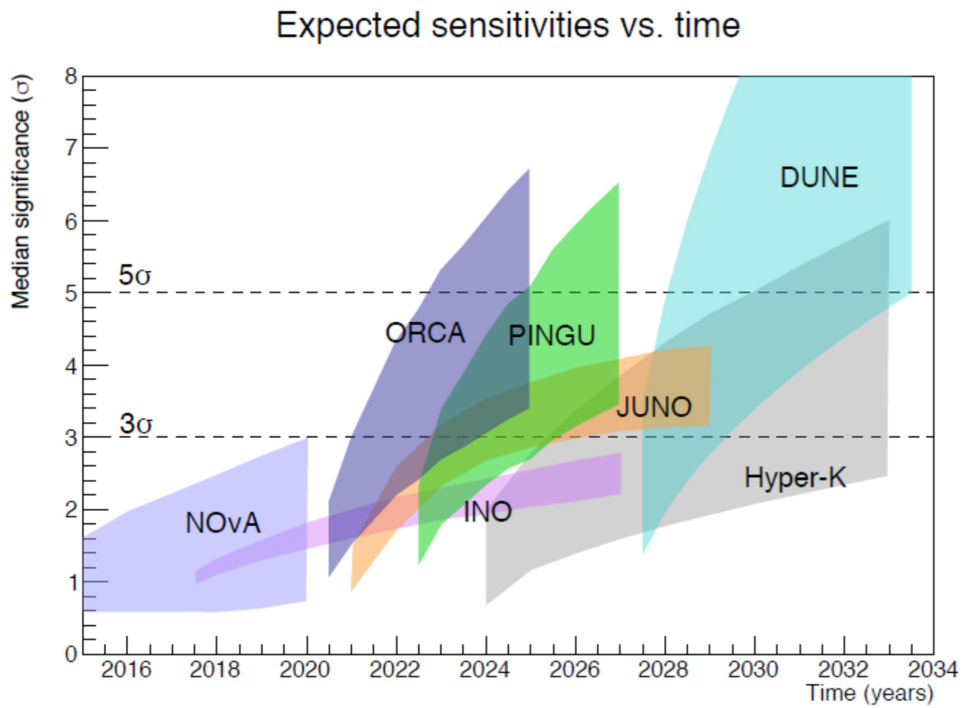


- 2nd HK in Korea
  - L =1000~1300 km
  - 1.5~2.5° off-axis
- Better MH sensitivity
- Better CP coverage

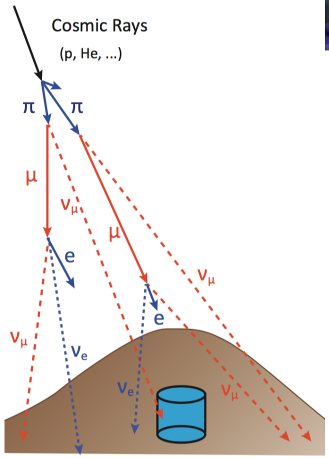
CP

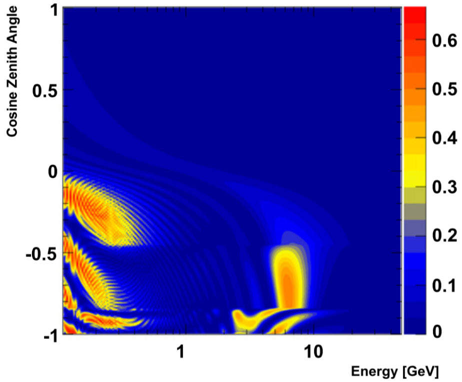


Mass hierarchy



(originally from JHEP 1403 (2014) 028)



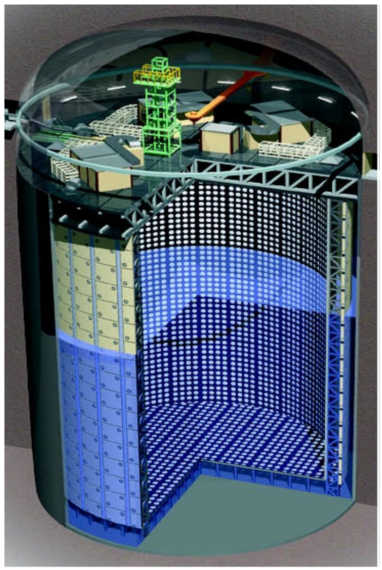


加速器νでのCP測定

大気νでの質量階層性

↓

ニュートリノ・反ニュートリノ
の振動確率の差異を測定



検出器：スーパーカミオカンデ
レプトン電荷による反ニュートリノ識別不可

↓

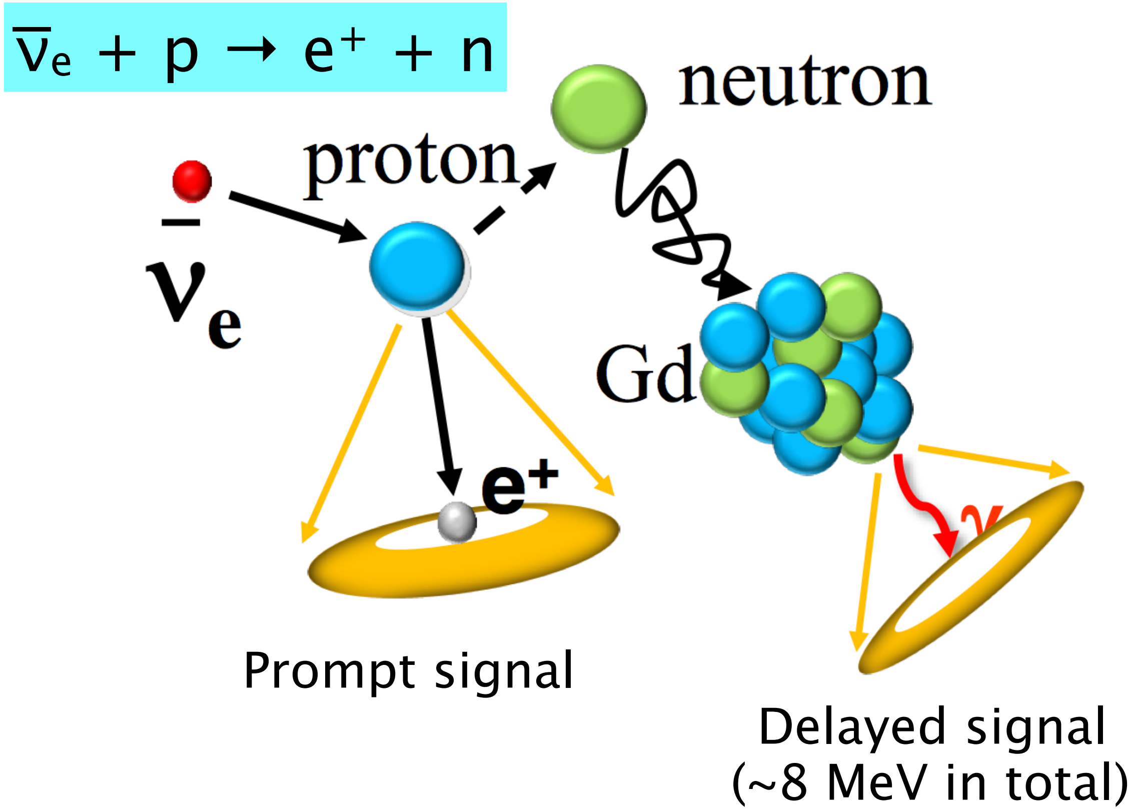
SK-Gd による反跳中性子検出

↓

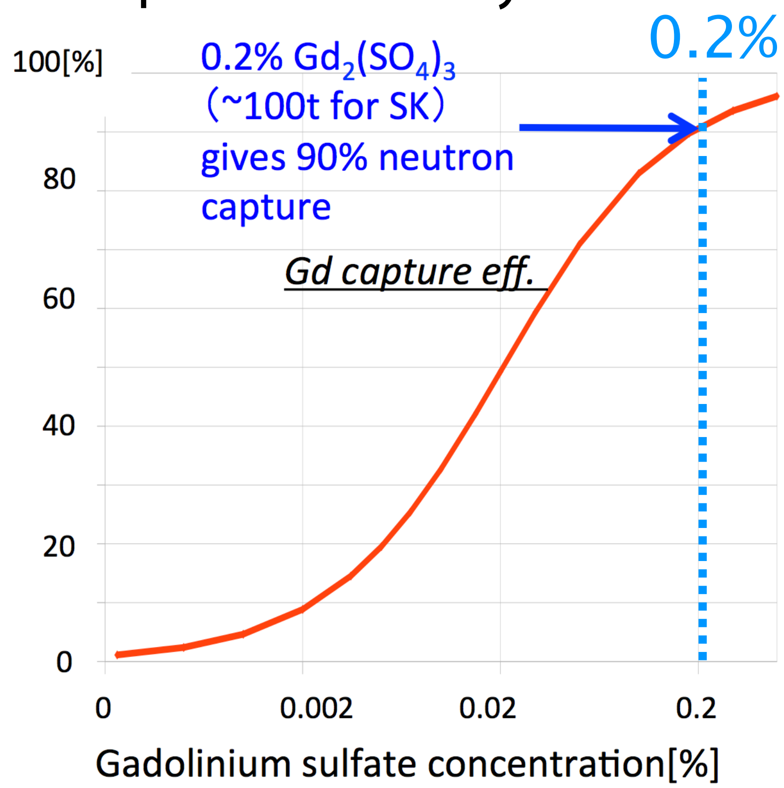
CP、質量階層性測定へのインパクト？

SuperK-Gd project

PRL93,171101 (2004)

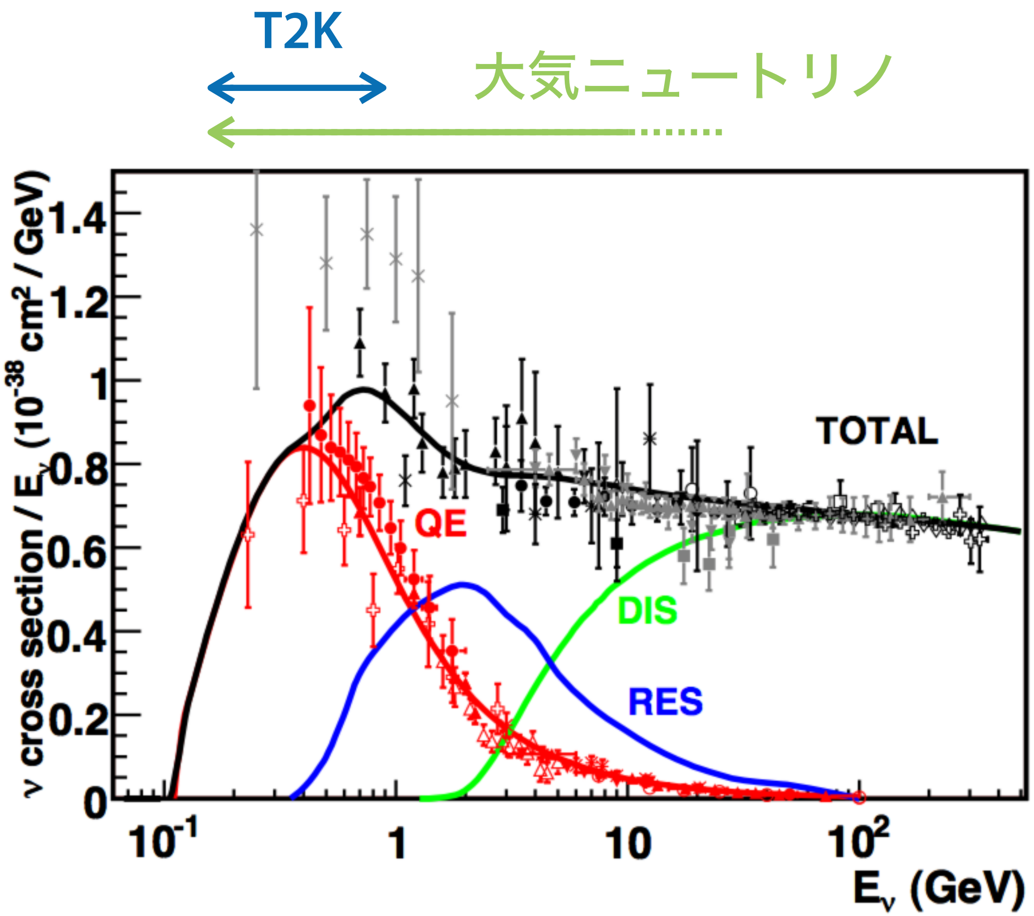


Capture efficiency:



- Add 0.2% $Gd_2(SO_4)_3$ in water to enhance neutron capture
- multiple gammas (~8MeV in total) emitted from Gd by neutron capture
- Possible to identify anti-neutrino interaction with delayed coincidence

中高エネルギー領域（100MeV〜）での
ニュートリノ断面積



ニュートリノCCQE：

$$\nu_e + n \rightarrow e^- + p$$

反ニュートリノCCQE：

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

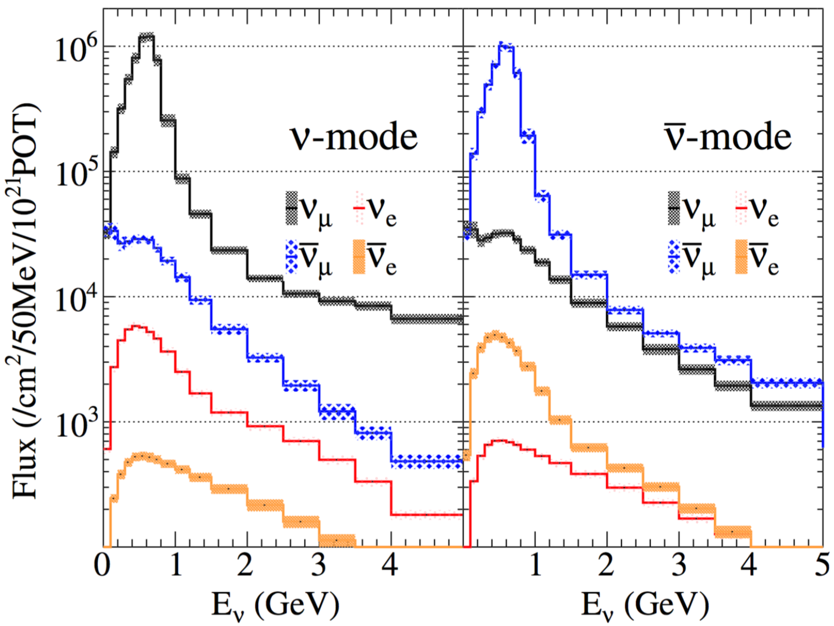
- sub-GeVでは Charged-Current Quasi-Elastic (CCQE) が 大半
- 一方、高エネルギー側では
  - 他の相互作用モードの増加
  - 2次ハドロン相互作用効果（後述）
- SK-Gdで中性子検出効率向上により、T2Kや大気ニュートリノでも反ニュートリノ識別が期待

Wrong Sign background

Number of Events expected for T2K-II

(10×10^{21} POT for each ν and ν̄ mode)

T2K ν and ν̄ flux:



$\otimes$

ニュートリノ断面積:

$\sigma(\nu) \sim 3 \times \sigma(\bar{\nu})$

ν_μ disappearance

arXiv:1607.08004

	Total	Beam CC ν_μ	Beam CC $\bar{\nu}_\mu$	Beam CC $\nu_e + \bar{\nu}_e$	$\nu_\mu \to \nu_e +$ $\bar{\nu}_\mu \to \bar{\nu}_e$	NC
ν-mode ν_μ sample	2735.0	2393.0	158.2	1.6	7.2	175.0
$\bar{\nu}$-mode $\bar{\nu}_\mu$ sample	1283.5	507.8	707.9	0.6	1.0	66.2

ν-mode → ν̄-mode

signal → x 1/3

wrong sign → x 3

ν_e appearance

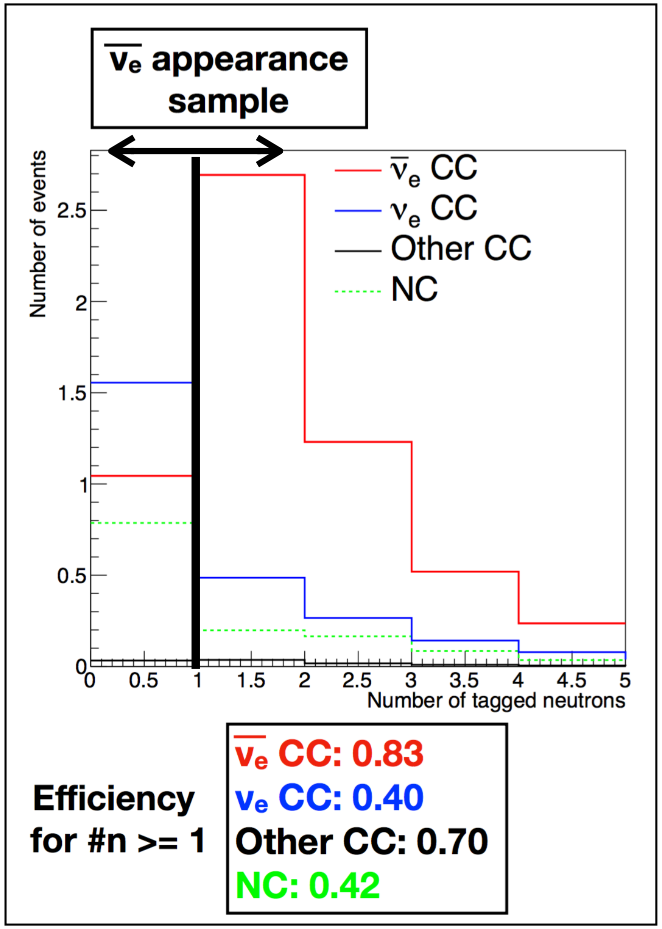
	True δ_{CP}	Total	Signal $\nu_\mu \to \nu_e$	Signal $\bar{\nu}_\mu \to \bar{\nu}_e$	Beam CC $\nu_e + \bar{\nu}_e$	Beam CC $\nu_\mu + \bar{\nu}_\mu$	NC
ν-mode	0	467.6	356.3	4.0	73.3	1.8	32.3
ν_e sample	$-\pi/2$	558.7	448.6	2.8	73.3	1.8	32.3
$\bar{\nu}$-mode	0	133.9	16.7	73.6	29.2	0.4	14.1
$\bar{\nu}_e$ sample	$-\pi/2$	115.8	19.8	52.3	29.2	0.4	14.1

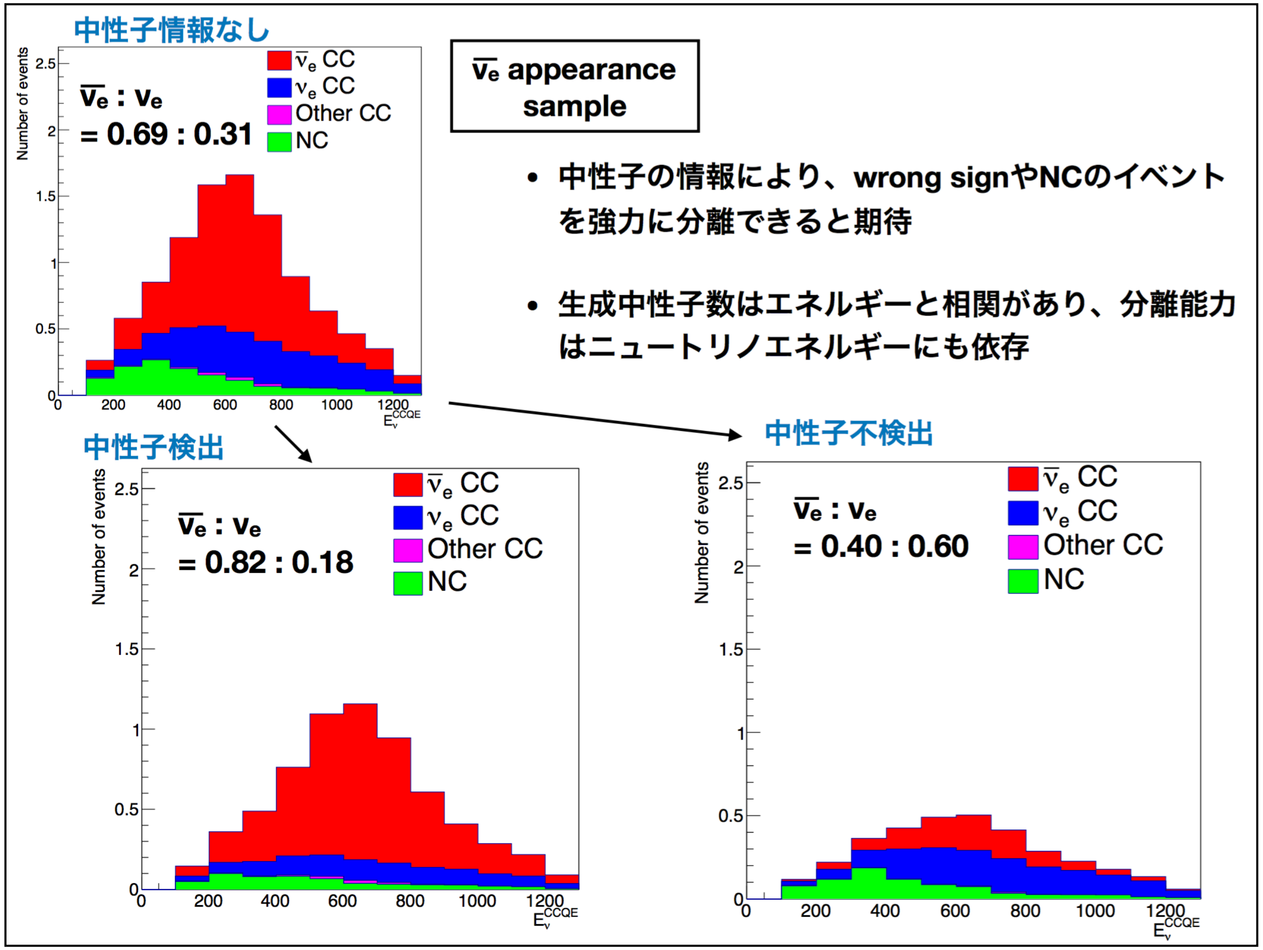
wrong sign が δ_{CP}による signal 事象数変化を

（わずかだが）弱める方向に働く

T2K 反νビームモードでの
電子事象における中性子検出数

中島さんの講演（12aU32-12）

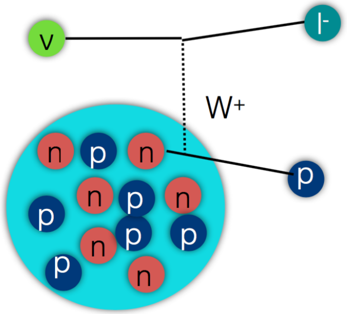




- 中性子の情報により、wrong signやNCのイベントを強力に分離できると期待
- 生成中性子数はエネルギーと相関があり、分離能力はニュートリノエネルギーにも依存

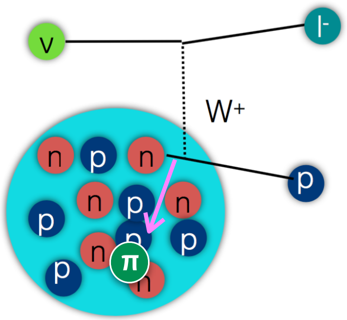
→ Wrong Sign （ν_e CC） やNC成分の分離に期待

$1\mu + 0\pi$ events :



1. CCQE

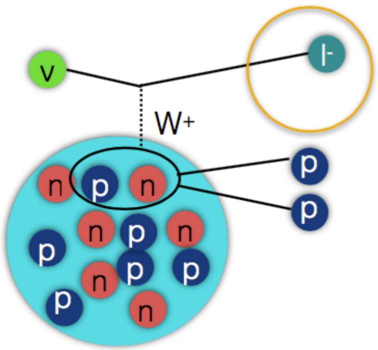
$\nu_\mu + n \rightarrow \mu^- + p$



2. π stuck

$\nu_\mu + N \rightarrow \mu^- + N' + \pi$

(π absorbed or below E_{Ch})



3. multi-nucleon or 2p-2h:

$\nu_\mu + (n,p) \rightarrow \mu^- + (p,p)$

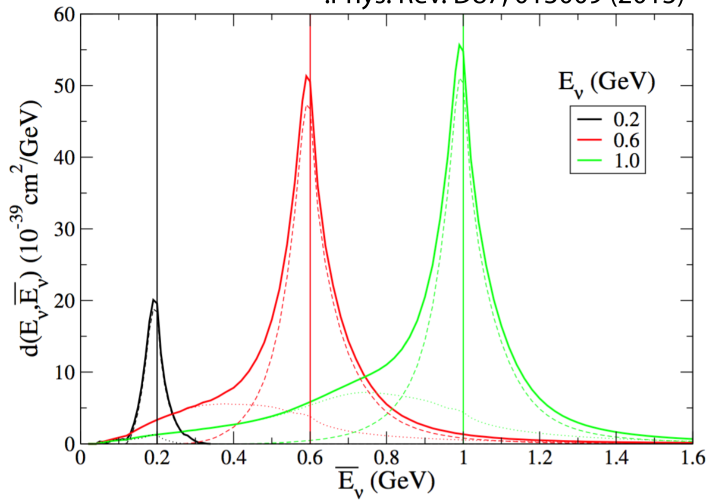
only μ- is visible in the detector

CCQE反応を仮定したニュートリノ

エネルギー再構成:

$$E_\nu^{\mathrm{rec}} = \frac{m_p^2 - (m_n - E_b)^2 - m_e^2 + 2(m_n - E_b)E_e}{2(m_n - E_b - E_e + p_e \cos\theta_e)}$$

.Phys. Rev. D87, 013009 (2013)

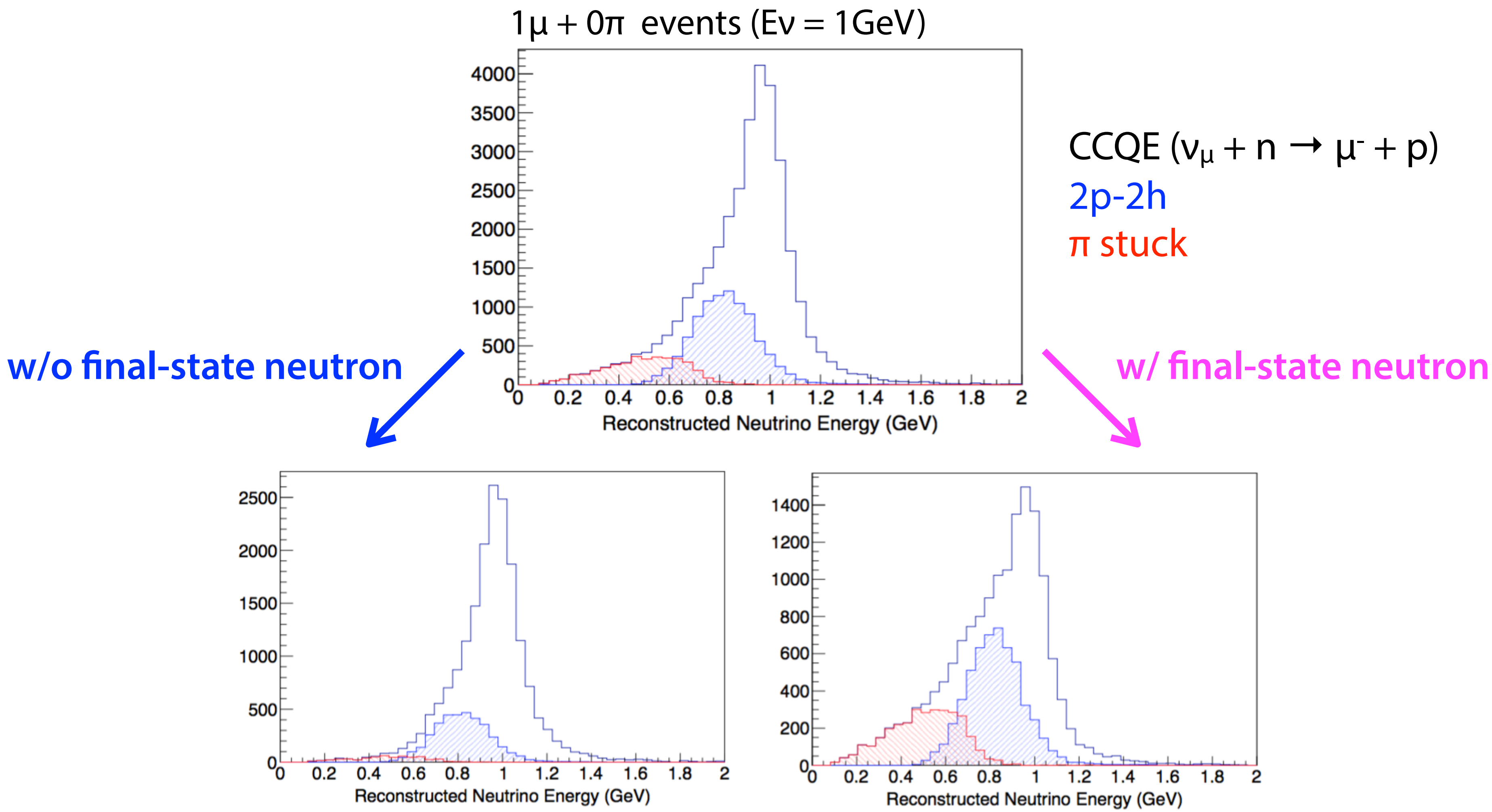


2および3の事象ではニュートリノエネルギーが低く見積もられる

→　振動測定での系統誤差の要因

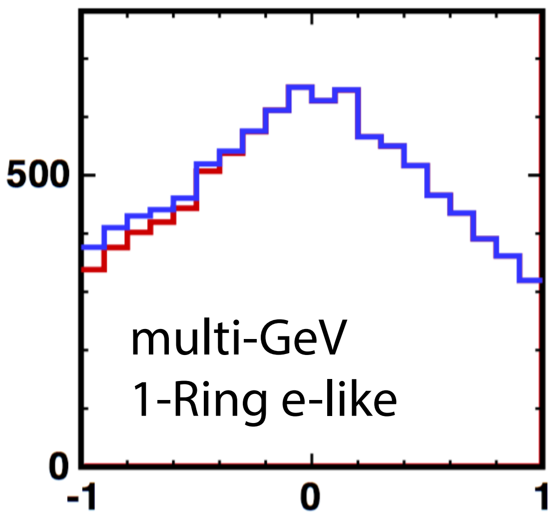
中性子情報による混入事象の分離

arXiv:1707.08222



- CCQE事象選別の精度向上
- 中性子情報によるニュートリノ相互作用の理解

大気ν質量階層性測定へのインパクト

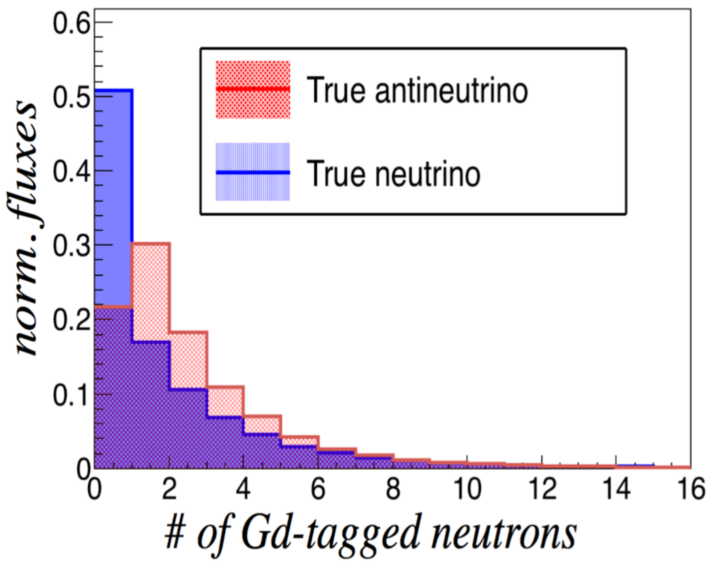


Normal (NH)
Inverted (IH)

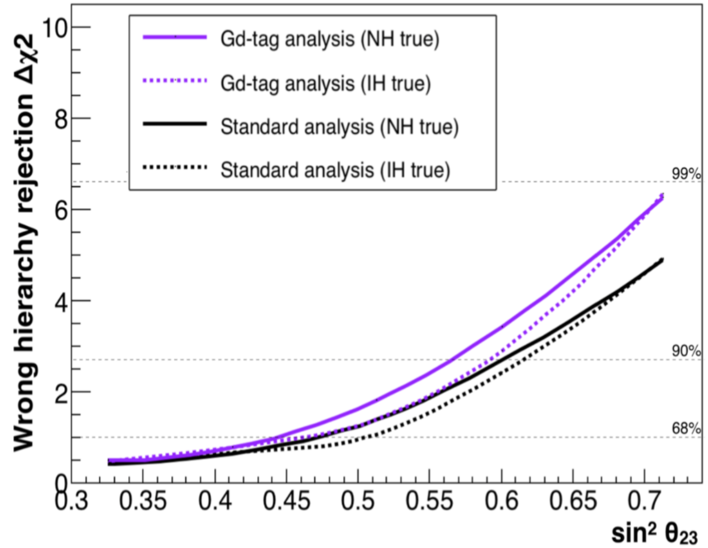
その他：

- NCバックグラウンドの除去
- 中性子数を考慮したニュートリノエネルギー再構成と分解能の向上

中性子検出数

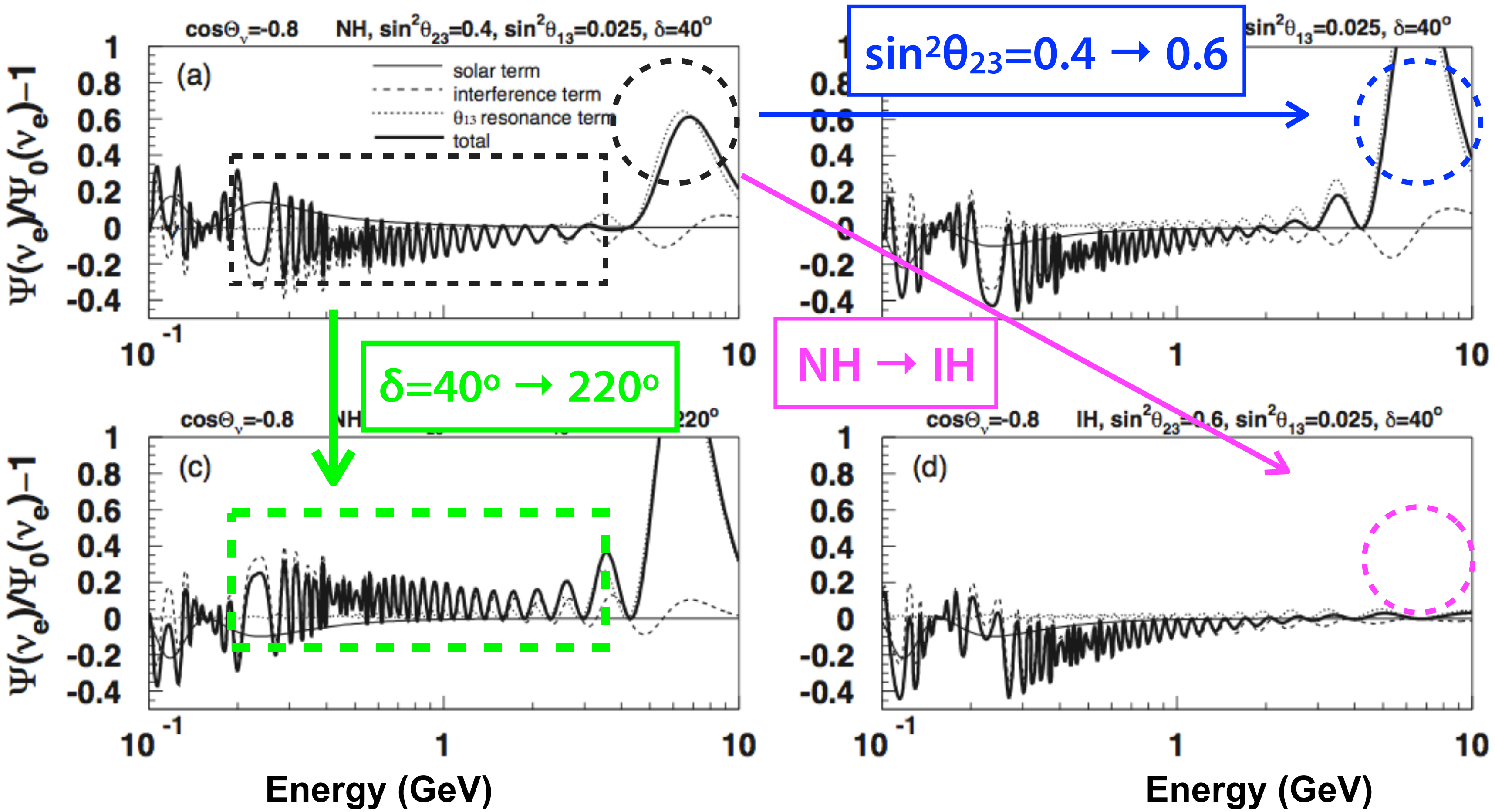


質量階層性感度



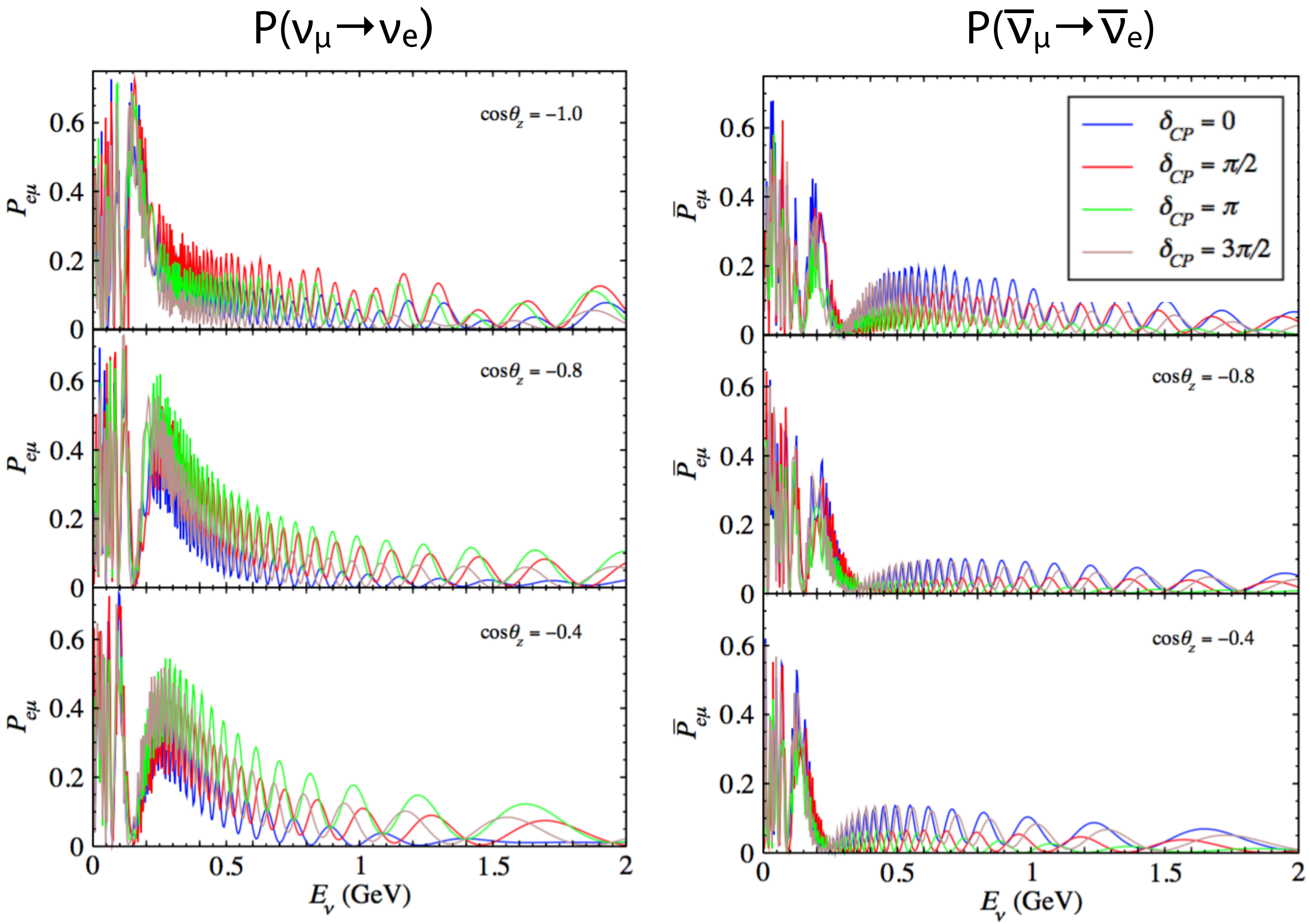
$\nu_\mu \rightarrow \nu_e$ 振動による大気 νe フラックスの変化

$$\frac{\Psi(\nu_e)}{\Psi_0(\nu_e)} - 1 \approx P_2 \cdot (r \cdot \cos^2\theta_{23} - 1)$$
$$-r \cdot \sin\tilde{\theta}_{13} \cdot \cos^2\tilde{\theta}_{13} \cdot \sin 2\theta_{23} \cdot (\cos\delta \cdot R_2 - \sin\delta \cdot I_2)$$
$$+2\sin^2\tilde{\theta}_{13} \cdot (r \cdot \sin^2\theta_{23} - 1),$$



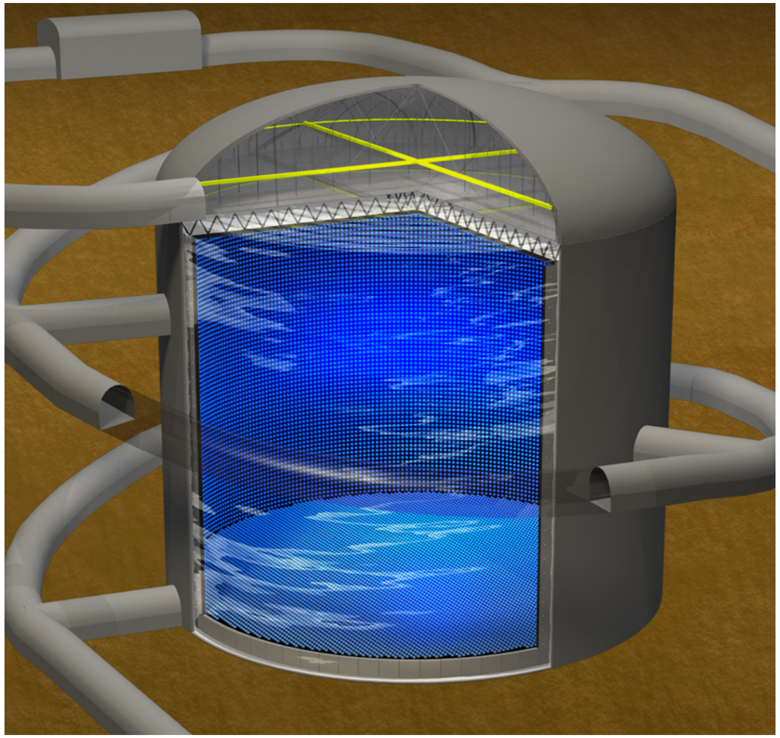
大気ν における δ_{CP} による $\nu_\mu \to \nu_e$ 振動の変化

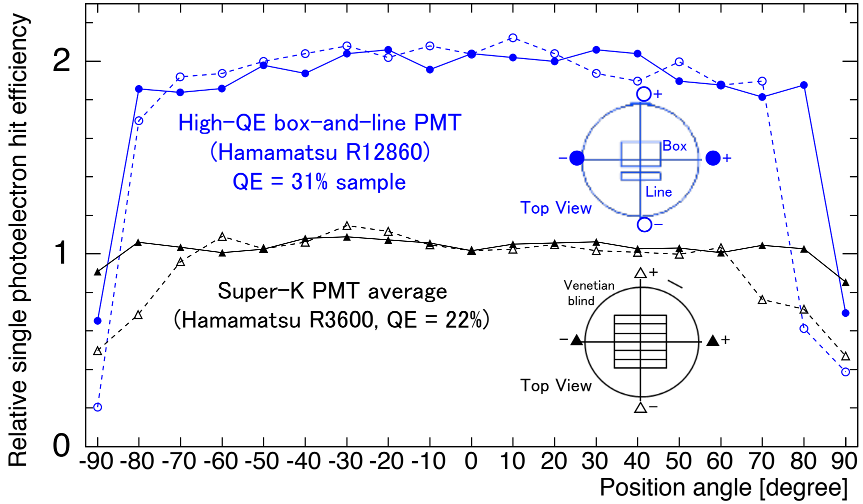
arXiv:1406.1407

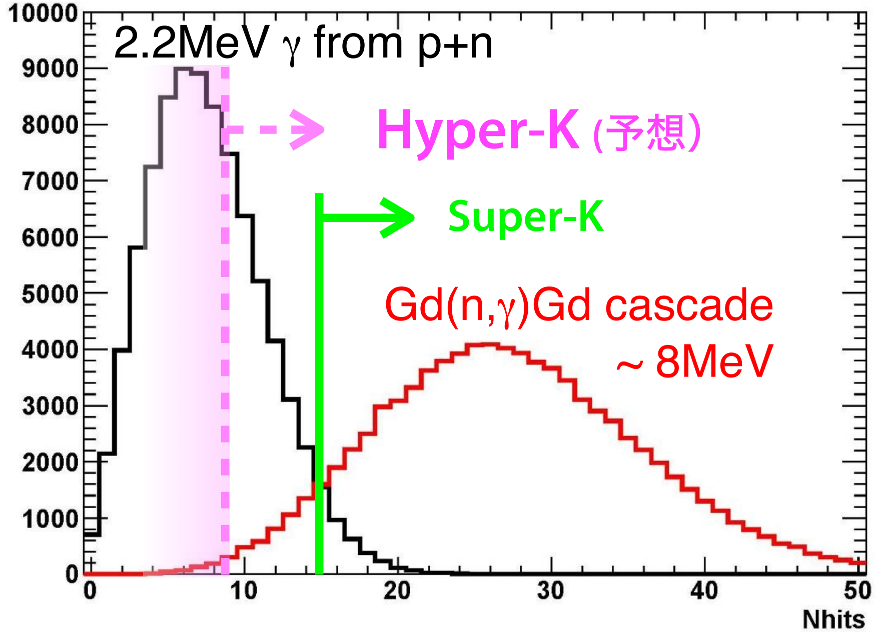


→ 大気ニュートリノでのδ_{CP}感度向上の可能性

ハイパーカミオカンデへの応用







- 新開発 B&L PMTにより光収集効率が倍増
- n-P捕獲からの2.2 MeV ガンマ線による中性子検出効率が向上
- SK-Gdでの中性子研究はHKにも活用可能

まとめ

- CP測定

  T2K, Nova

- Mass hierarchy
  - 大気ニュートリノ：　SK、PINGU、ORCA、INO
  - 加速器： Nova
  - 原子炉ニュートリノ：JUNO

- Hyper-K, DUNE, T2HKKへ

- SK-Gdによるスーパーカミオカンデ検出器の高度化