T2K実験の最新結果と
今後の展望

横山将志（東京大学）

素粒子物理学の進展2012

2012年7月19日 @ 基研

ニュートリノ振動実験
この１年，この先XX年

横山将志（東京大学）

素粒子物理学の進展2012
2012年7月19日 @ 基研

目次

- イントロ：ニュートリノ振動のおさらい
- 最近の出来事
  - T2Kを中心に，θ_{13}の話
- この先数年の見通し
- さらに将来（今後10年+）の話

50年

ニュートリノフレーバー50周年

OBSERVATION OF HIGH-ENERGY NEUTRINO REACTIONS AND THE EXISTENCE OF TWO KINDS OF NEUTRINOS*

G. Danby, J-M. Gaillard, K. Goulianos, L. M. Lederman, N. Mistry, M. Schwartz,† and J. Steinberger†

Columbia University, New York, New York and Brookhaven National Laboratory, Upton, New York

(Received June 15, 1962)

Discovery of ν flavor

In the cours ... at the Brook- haven AGS, we have ob... of high-energy neutrinos with ma...

duce μ mes... and hence are v... inos involved in ...



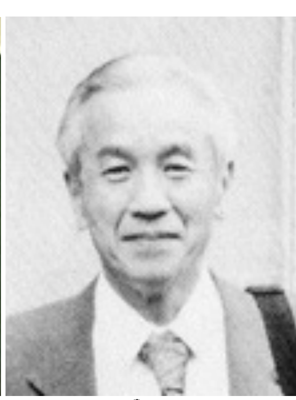
PRL **9**, 36 (1962)

Progress of Theoretical Physics, Vol. 28, No. 5, November 1962

Remarks on the Unified Model of Elementary Particles

Ziro MAKI, Masami NAKAGAWA and Shoichi SAKATA

Institute for Theoretical Physics
Nagoya University, Nagoya


ν mixing/oscillation

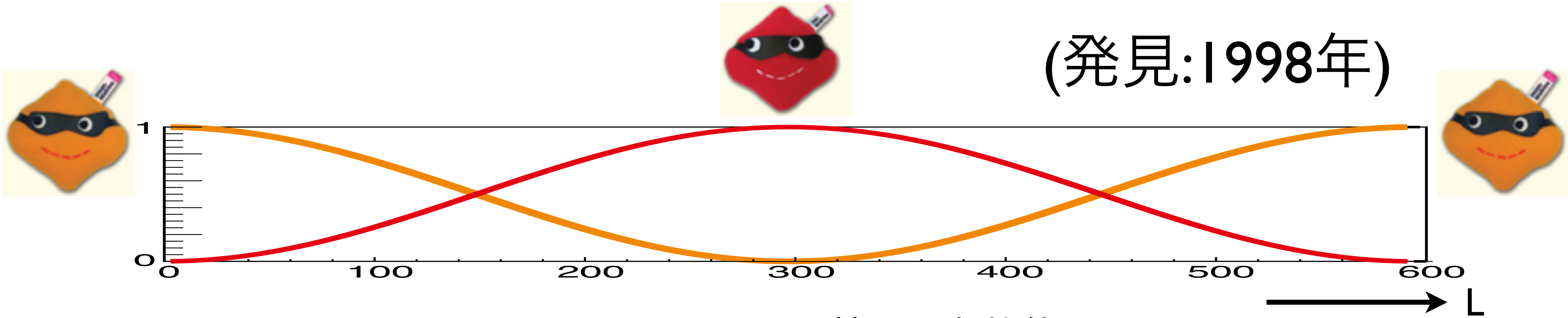
(Received June 25, 1962)

... theory of neutrino is ... of neutrinos. Based on the neutrino-mixture ... particles is constructed by generalizing the Sakata-Nagoya model.*) Our scheme gives a

Prog. Theor. Phys. **28**, 870 (1962)

ニュートリノ振動

(発見:1998年)



フレーバー固有状態　　質量固有状態

2フレーバーの場合

$|\nu_\alpha\rangle = \cos\theta|\nu_1\rangle + \sin\theta|\nu_2\rangle$

$|\nu_\beta\rangle = -\sin\theta|\nu_1\rangle + \cos\theta|\nu_2\rangle$

θ:mixing angle

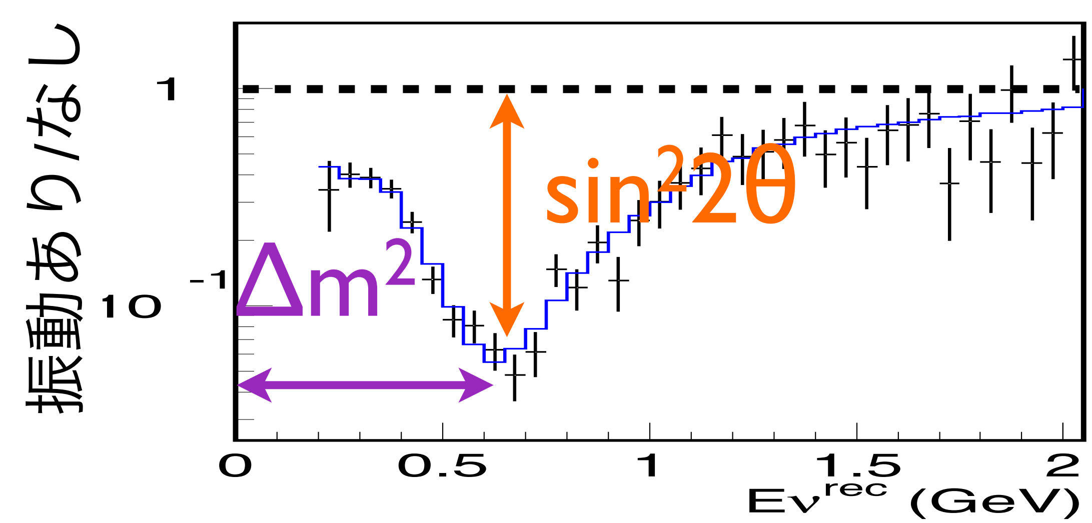
$\Delta m^2 = m_1{}^2 - m_2{}^2$

$P(\nu_\alpha \rightarrow \nu_\alpha) = 1 - \sin^2 2\theta \cdot \sin^2(1.27\Delta m^2_{[eV^2]} \cdot L_{[km]}/E_{[GeV]})$ Disappearance

$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \cdot \sin^2(1.27\Delta m^2 \cdot L/E)$ Appearance

振動数（L/E） → Δm^2

振幅 → $\sin^2 2\theta$



３世代あるので

Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix

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

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

4つの独立なパラメータ: θ_{12}, θ_{23}, θ_{13}, δ

振動確率は,

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\sum_{j>i} \mathrm{Re}(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2\frac{(m_j^2 - m_i^2)L}{4E_\nu}$$

$$\mp 2\sum_{j>i} \mathrm{Im}(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin\frac{(m_j^2 - m_i^2)L}{2E_\nu}$$

What we have learned (and not)

(LSND anomaly)

maximal? → “atmospheric” region

θ_{23}~45°

sign? → $|\Delta m^2_{32}|$~2.5×10^{-3}eV^2

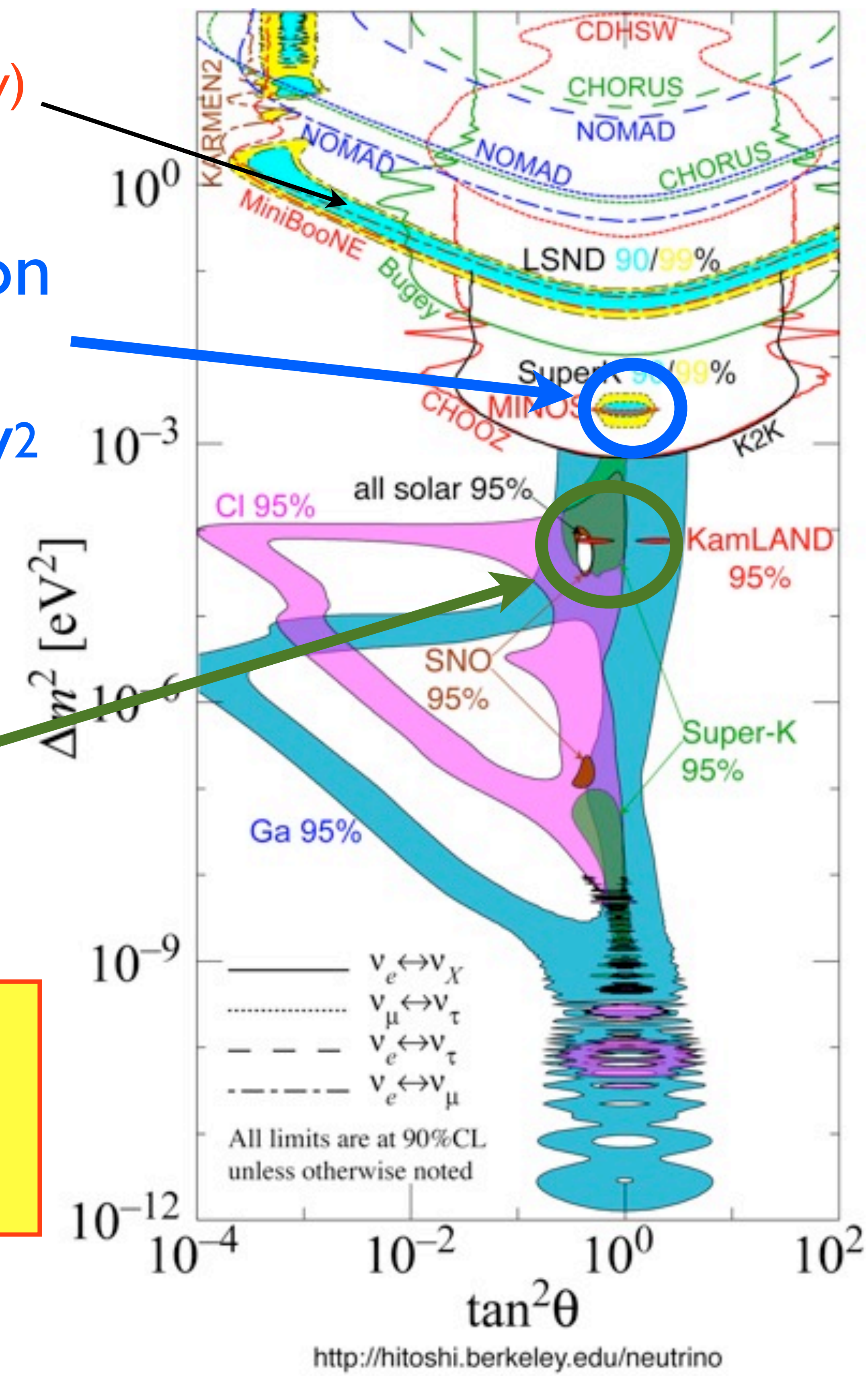
“solar” region

θ_{12}~34°

Δm^2_{21}~7.8×10^{-5}eV^2

θ_{13}<12° (before June 2011)

No information on δ (*CP*)



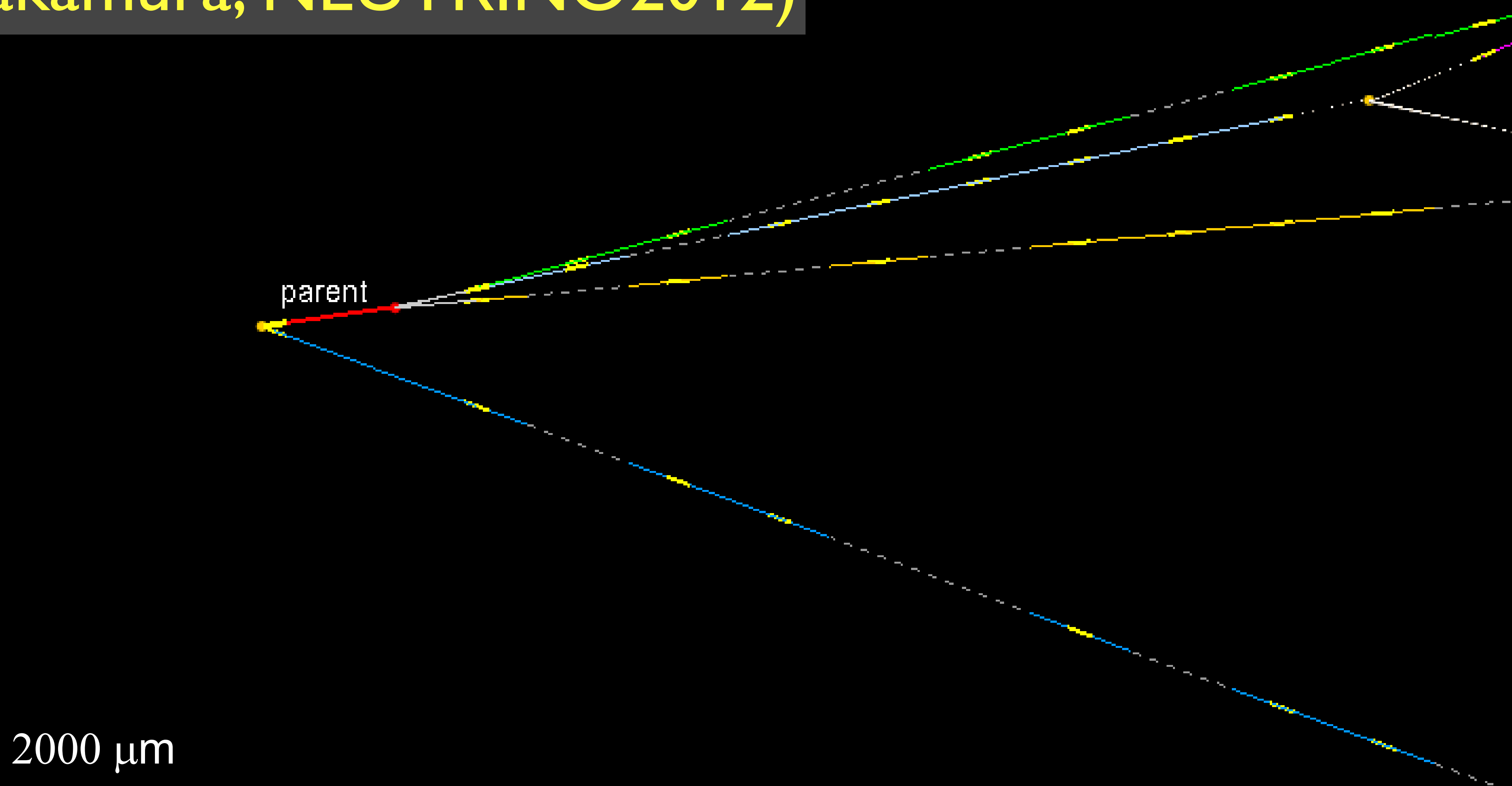
CP測るには

- νと反νを比較 → 加速器νビーム
  - "conventional" ν ビーム = ν_μ
  - $\pi^+ \rightarrow \mu^+ + \nu_\mu$: 分岐比 >99%
- DisappearanceではCP破れない→ appearance
  - ν_τ の同定は困難 (τ lifetime < ps)
- CPV → complex phase → 干渉項
  - solar (small Δm^2_{12}) と θ_{13} ("small")

Promising method : $P(\nu_\mu \rightarrow \nu_e)$ vs $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$

New ν_τ Candidate Event

Second ν_τ candidate at OPERA
(M.Nakamura, NEUTRINO2012)



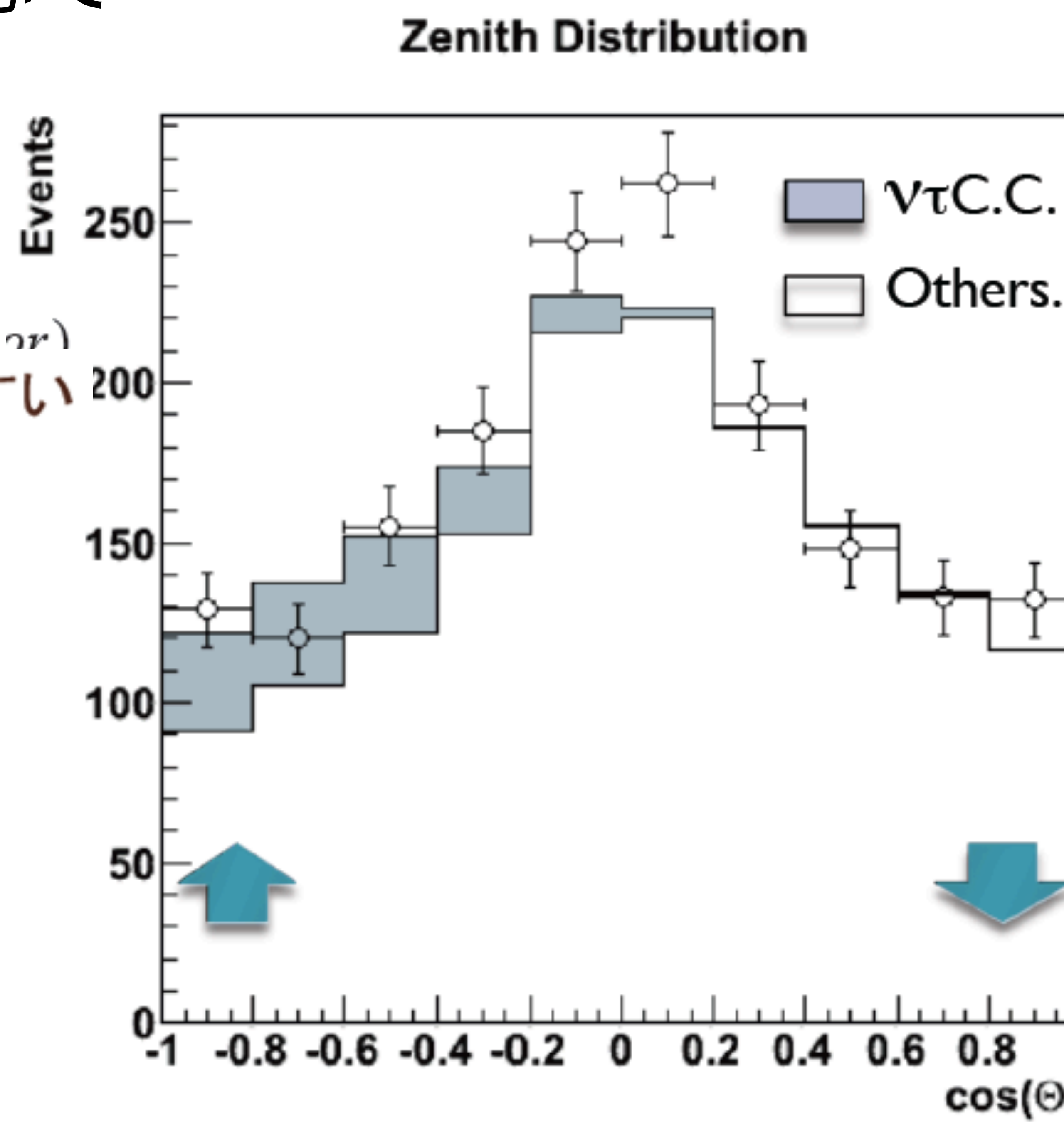
スーパーカミオカンデでも

- 大気ニュートリノの反応で「τっぽい」特徴を持つ事象を選択
  - 高エネルギー、複数リングになりやすい
  - π由来の崩壊電子が比較的多い

など

- 3.8σの有意度でτの信号を観測

arXiv:1206.0328



CP測るには

Promising method : P($\nu_\mu \to \nu_e$) vs P($\bar{\nu}_\mu \to \bar{\nu}_e$)

$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\overline{\nu_\mu} \to \overline{\nu_e})}{P(\nu_\mu \to \nu_e) + P(\overline{\nu_\mu} \to \overline{\nu_e})} \propto \frac{\sin 2\theta_{12}}{\sin \theta_{13}} \sin\delta$$

$$P(\nu_\mu \to \nu_e) \simeq \sin^2\theta_{23} \cdot \sin^2 2\theta_{13} \cdot \sin^2(1.27\Delta m^2_{13} L / E)$$

~0.5

まず θ_{13} を測る！

熾烈な国際競争

- 加速器実験
  - 日本:T2K(2009-)
  - 米国: NOvA(2013-)
- E~GeVのビームで,
  $\nu_\mu \rightarrow \nu_e$の変換を探索
  「出現」実験

- 原子炉実験
  - 欧(+日米): Double Chooz (2011-)
  - 韓: RENO (2011-)
  - 中+米: Daya Bay(2011-)
- E~MeVの$\bar{\nu}_e \rightarrow \bar{\nu}_{x(x\neq e)}$を探索
  「消失」実験

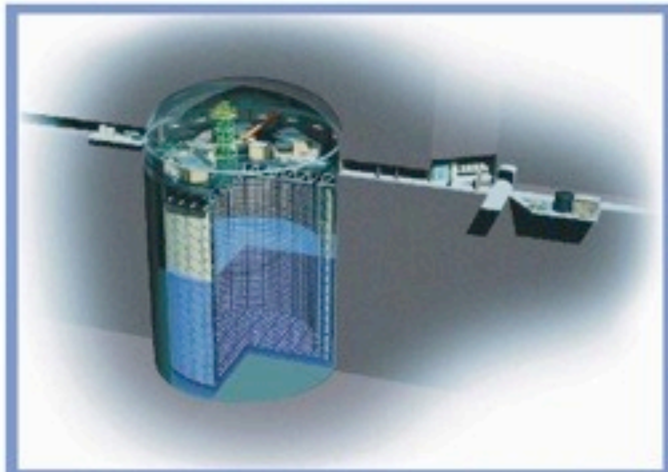
Worldwide efforts for measuring θ_{13}

2009-2012

T2K

~1 ν interaction / day

σ(νN)~10fb @1GeV



Super-Kamiokande
(ICRR, Univ.Tokyo)

J-PARC 30GeV PS
(KEK-JAEA, Tokai)

Tokai-**to(2)**-**Ka**mioka

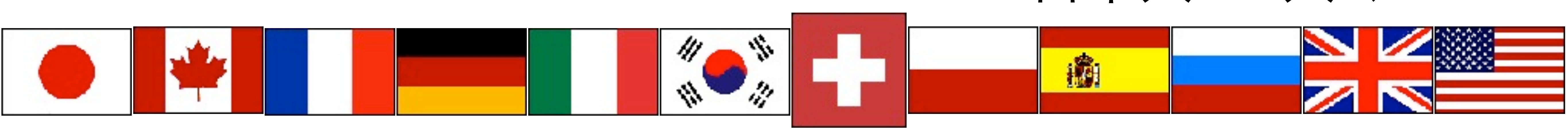
- Search for $\nu_\mu \rightarrow \nu_e$ (θ_{13})
- Precise meas. of $\nu_\mu \rightarrow \nu_\mu$ (θ_{23})
- Sterile ν, other surprise?

~10^{15} ν produced every ~3 sec
almost pure (99%) ν_μ beam

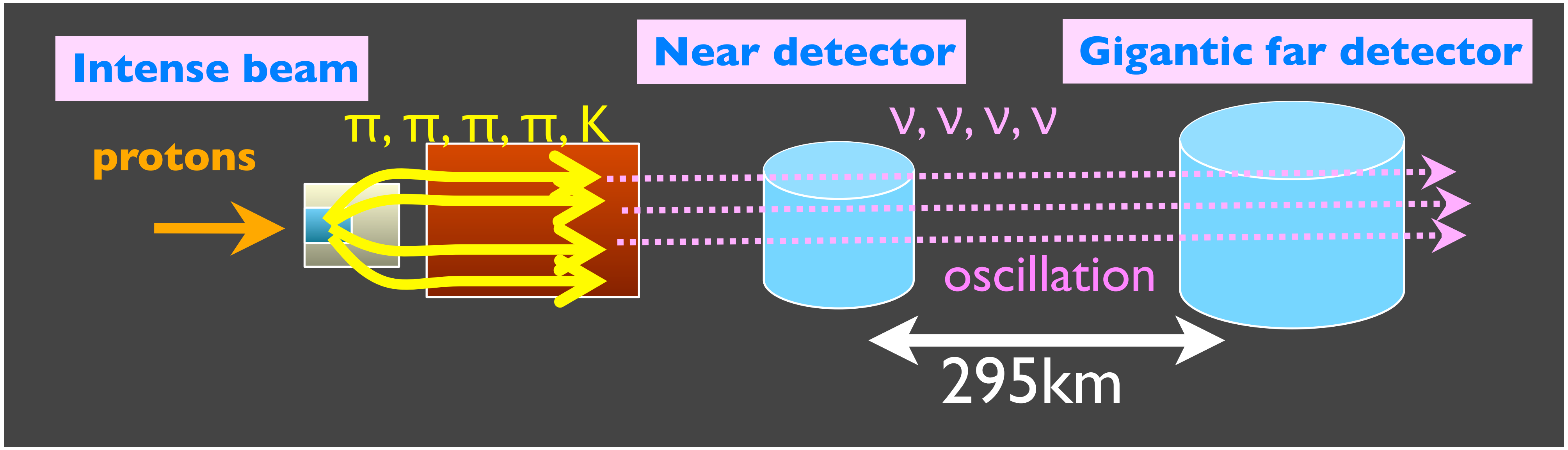
T2K collaboration

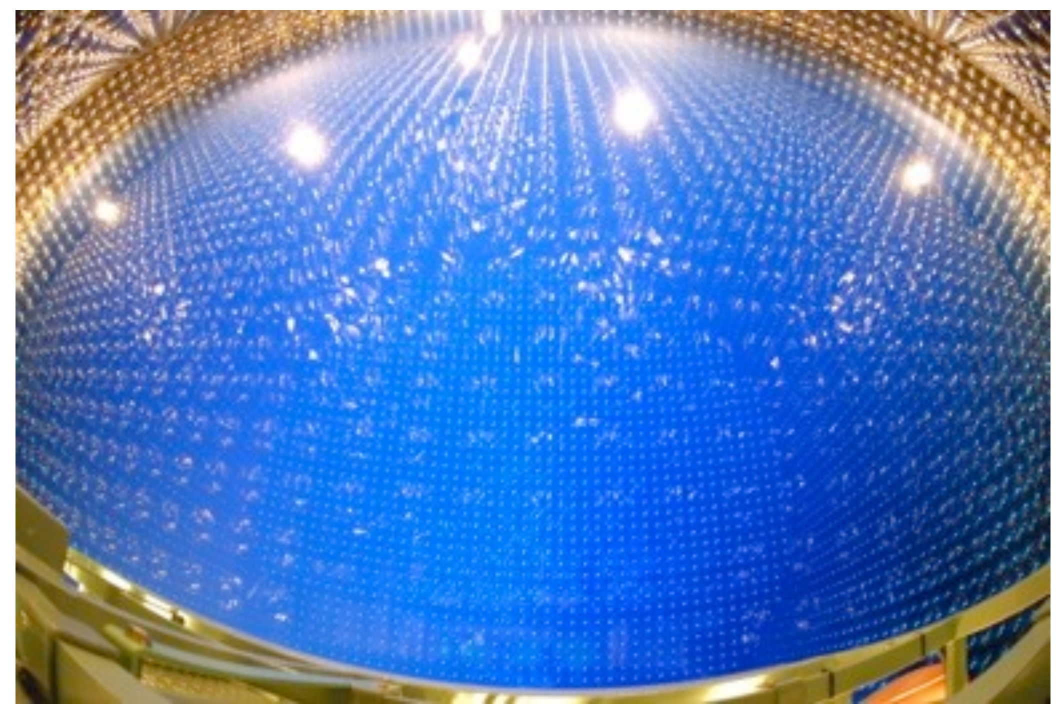
International collaboration (~500 members, 59 institutes, 12 countries）

日本人~80人くらい



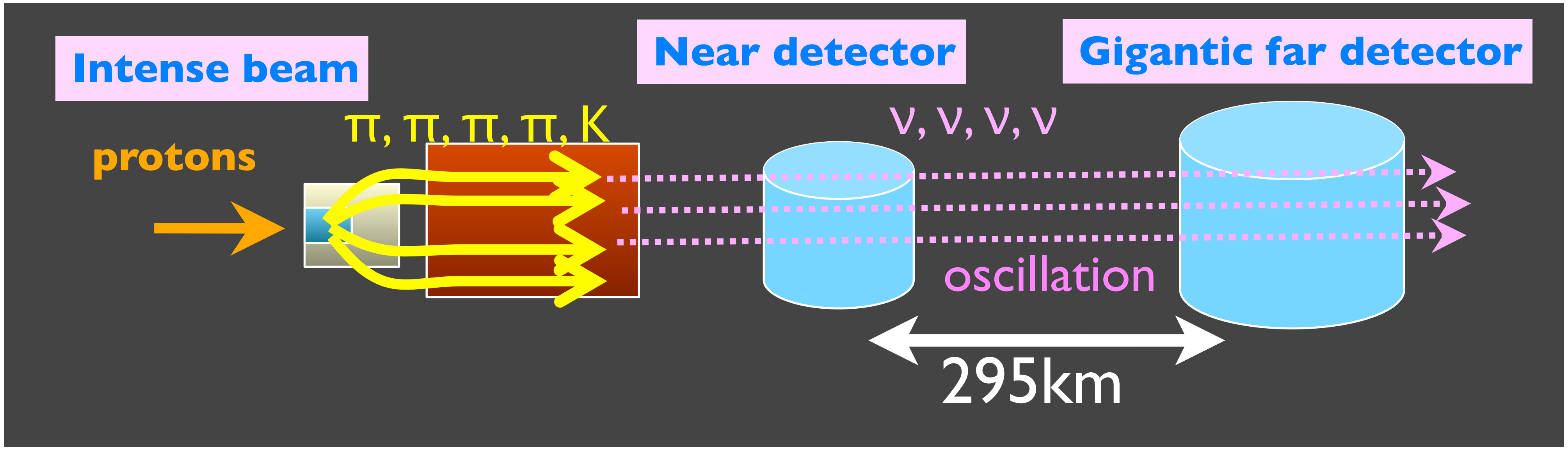
実験原理



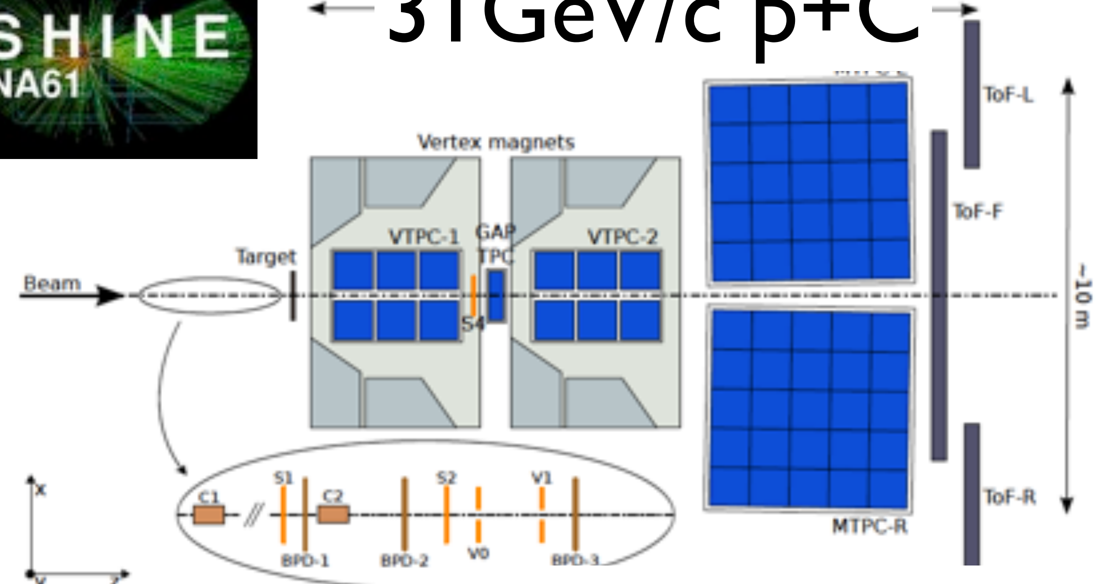


統計 ↔ 大強度ビーム，大質量検出器
系統誤差 ↔ Off-axis beam，π生成測定，前置検出器

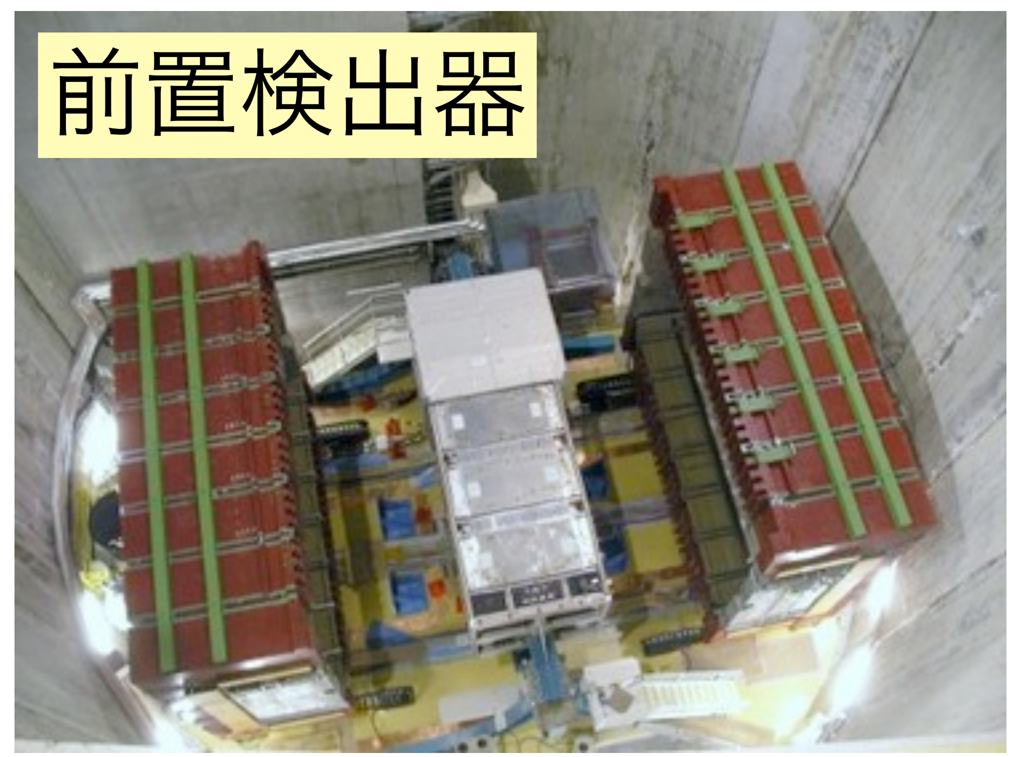
実験原理



31GeV/c p+C



NA61@CERN

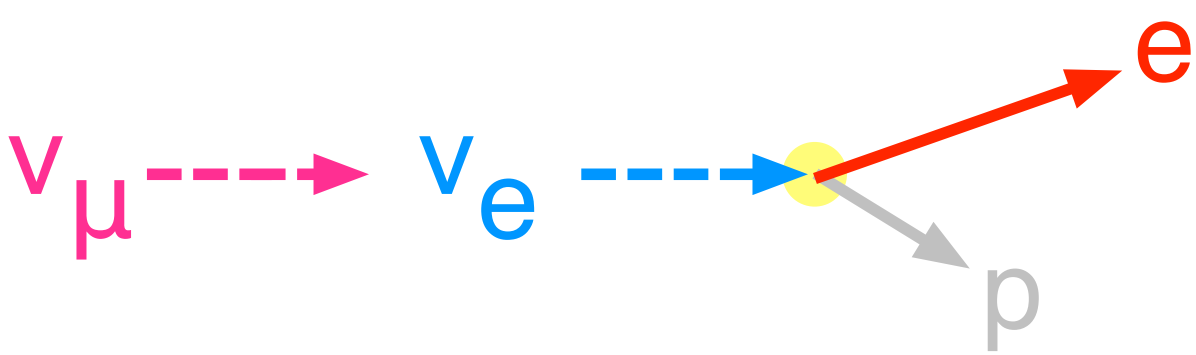


統計 ↔ 大強度ビーム，大質量検出器

系統誤差 ↔ Off-axis beam，π生成測定，前置検出器

Signal & background

- Signal = **single electron event**
  - oscillated ν_e interaction :

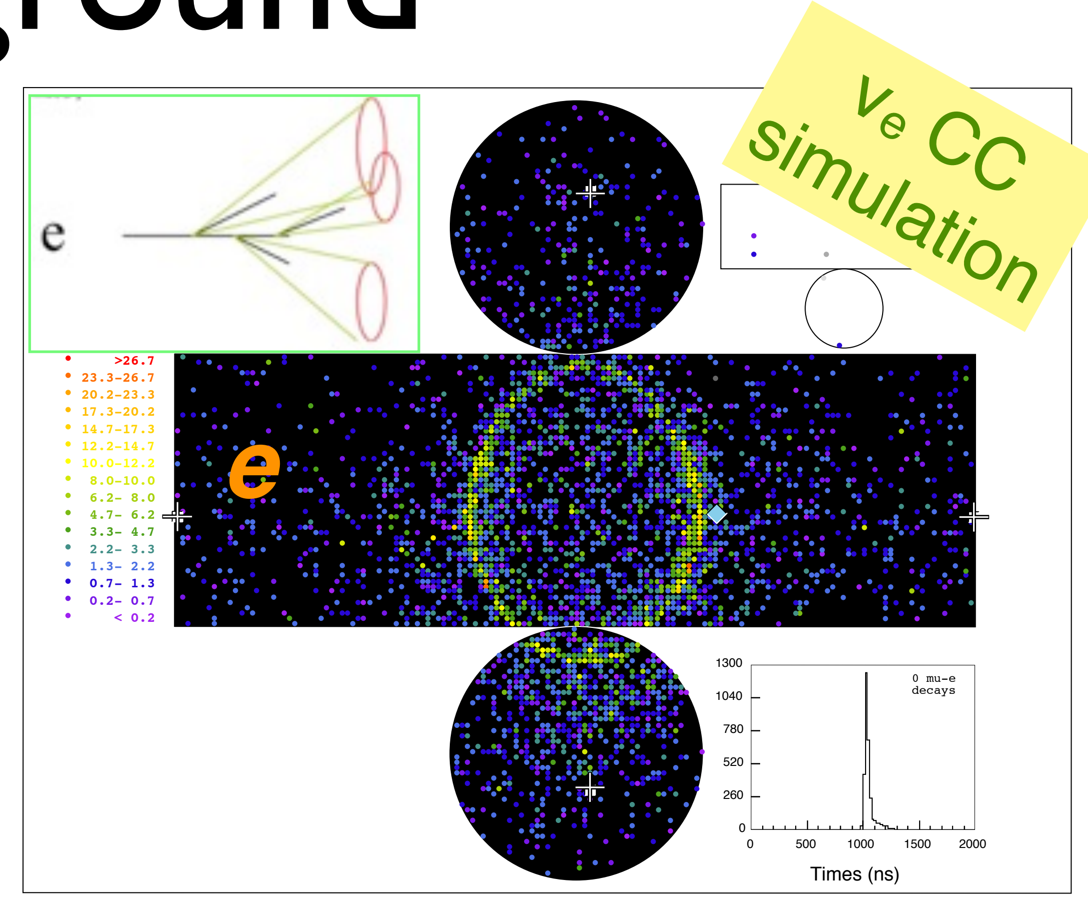


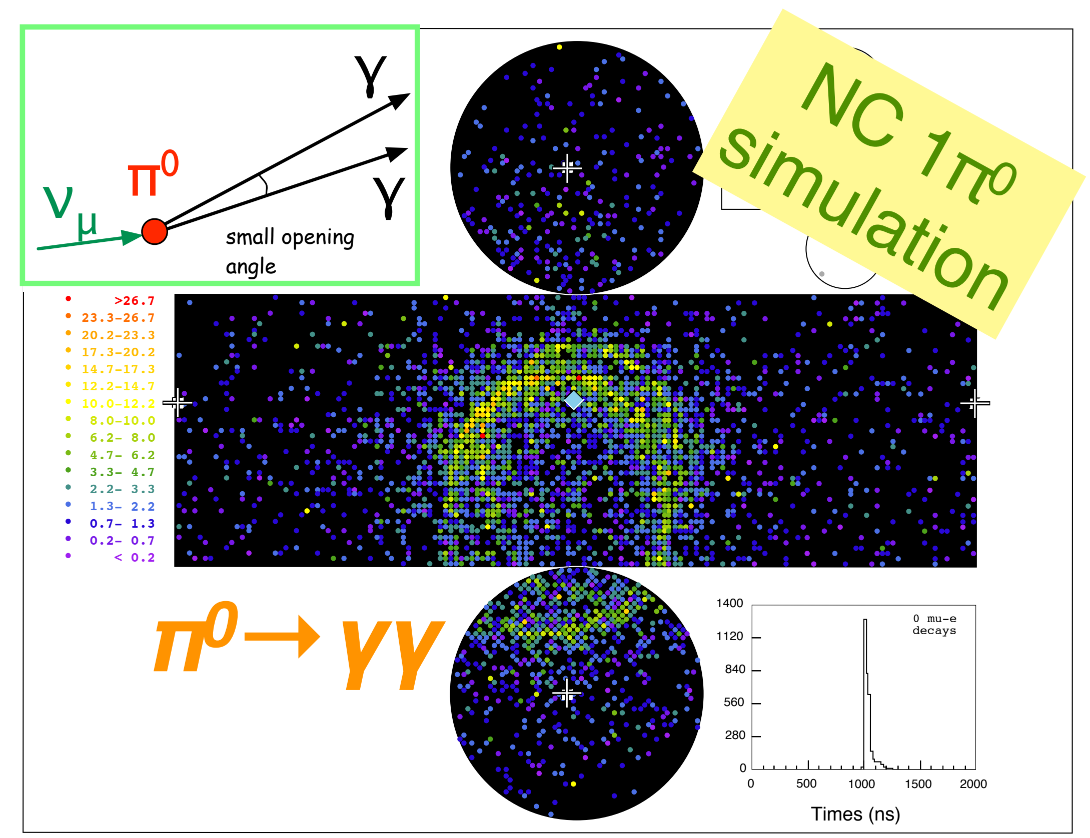
CCQE : $\nu_e + n \rightarrow$ **e** $+ p$

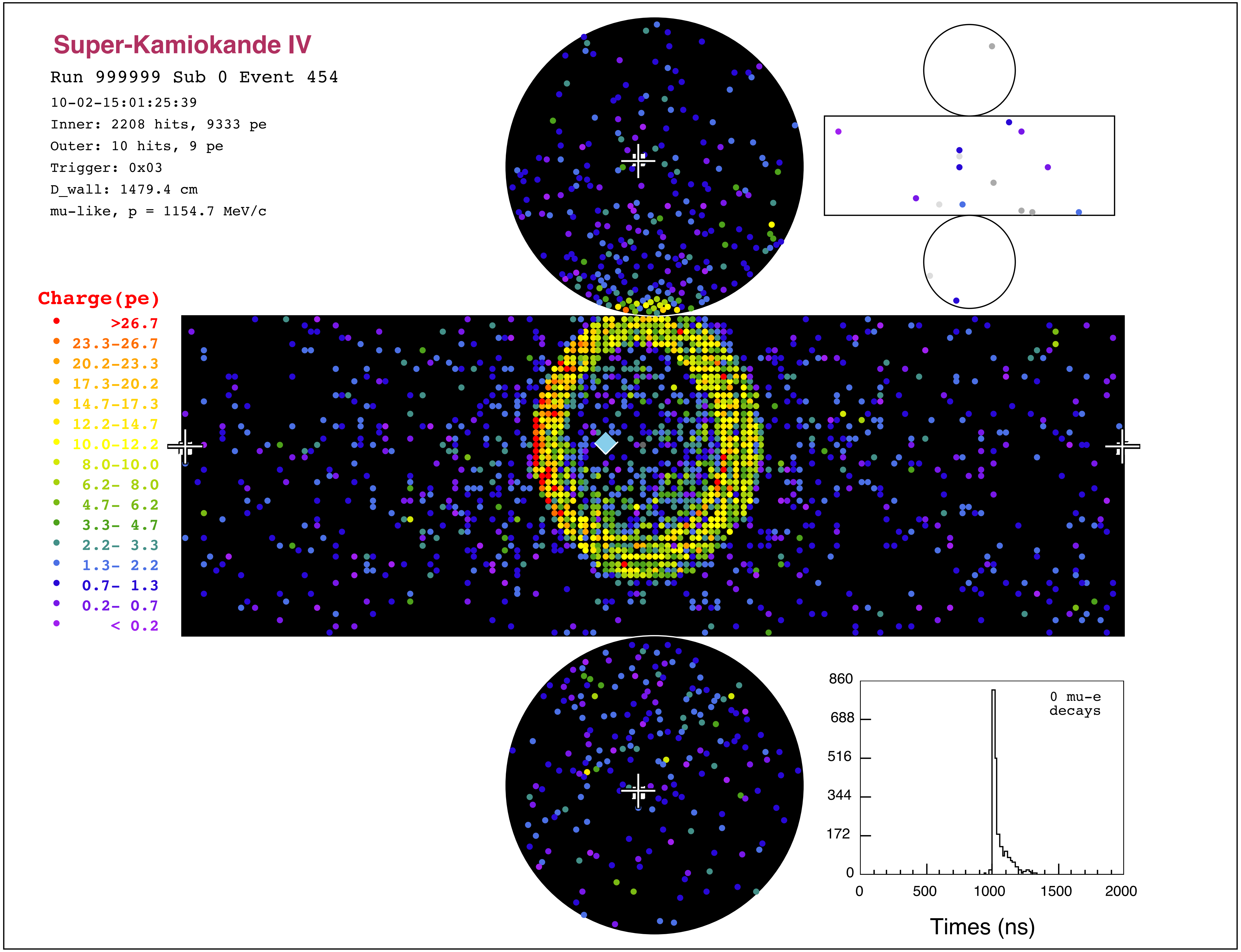
(dominant process at T2K beam energy)

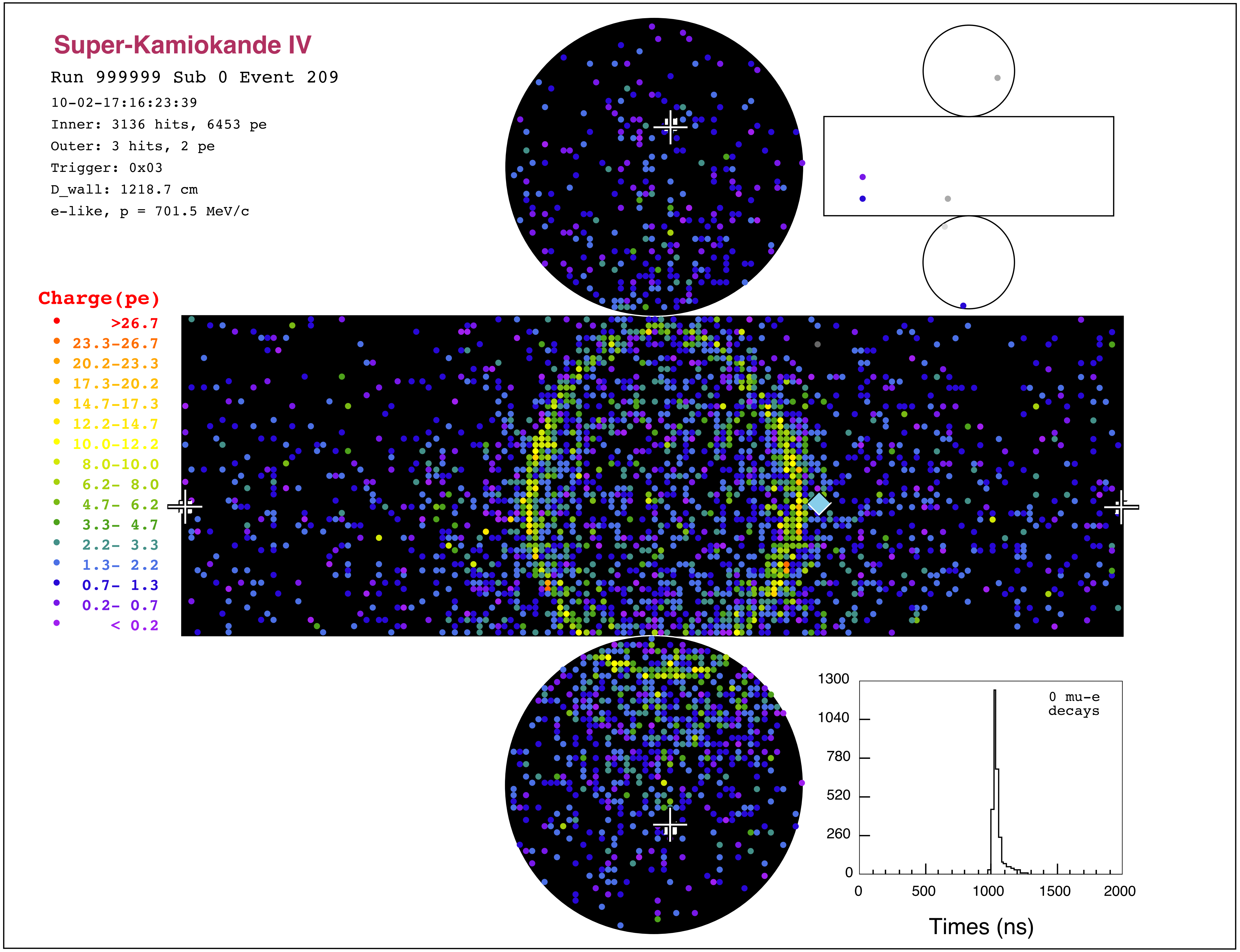
$$E_{rec} = \frac{m_n E_l - m_l^2/2 - (m_n^2 - m_p^2)/2}{m_n - E_l + p_l \cos\theta_l}$$

- Background
  - Intrinsic ν_e in the beam (from μ, K decays)
  - π^0 from NC interaction ($\pi^0 \rightarrow \gamma\gamma$)

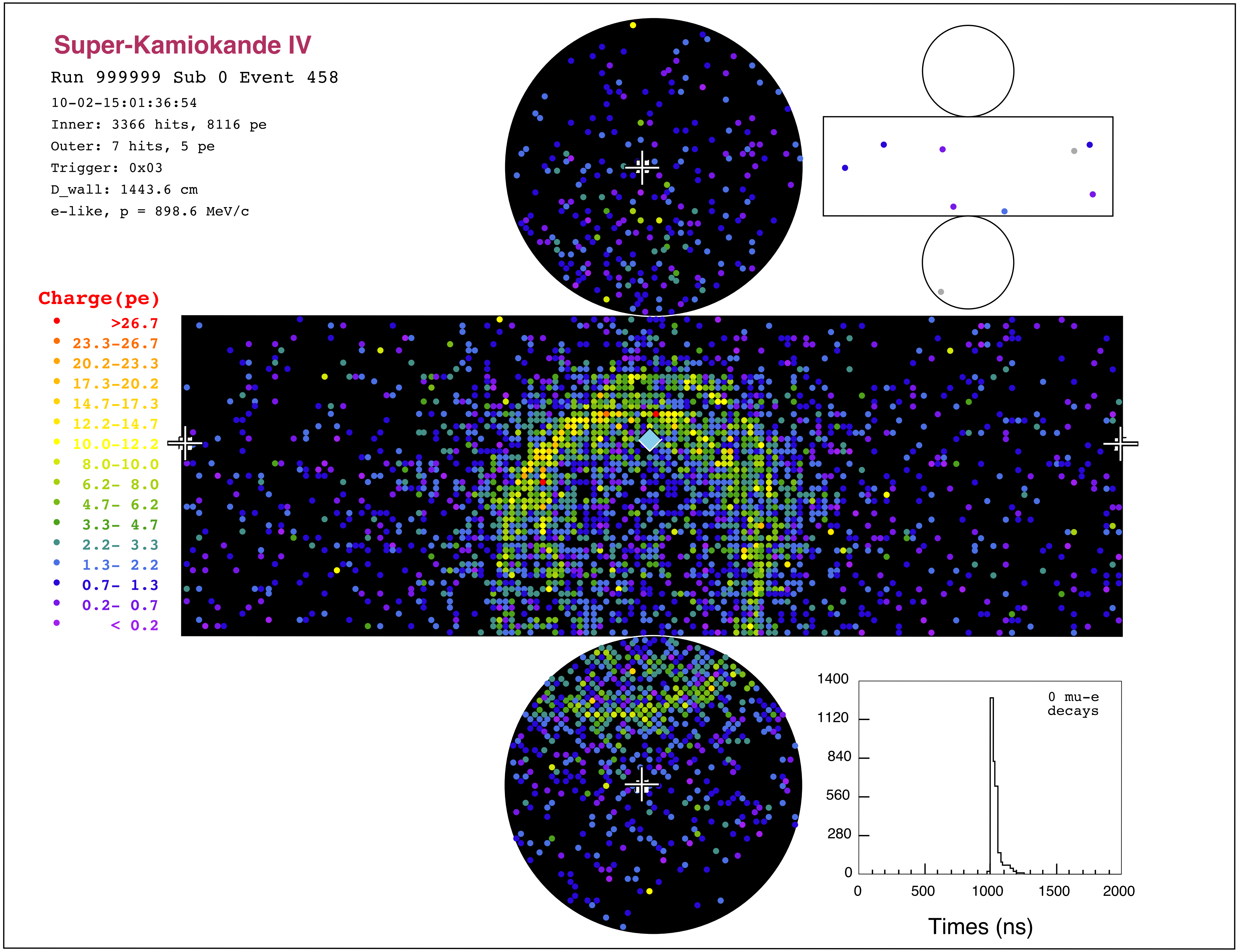





Super-Kamiokande IV
Run 999999 Sub 0 Event 454
10-02-15:01:25:39
Inner: 2208 hits, 9333 pe
Outer: 10 hits, 9 pe
Trigger: 0x03
D_wall: 1479.4 cm
mu-like, p = 1154.7 MeV/c
Charge(pe)
>26.7
23.3-26.7
20.2-23.3
17.3-20.2
14.7-17.3
12.2-14.7
10.0-12.2
8.0-10.0
6.2- 8.0
4.7- 6.2
3.3- 4.7
2.2- 3.3
1.3- 2.2
0.7- 1.3
0.2- 0.7
< 0.2
860
688
516
344
172
0
0 mu-e decays
0
500
1000
1500
2000
Times (ns)

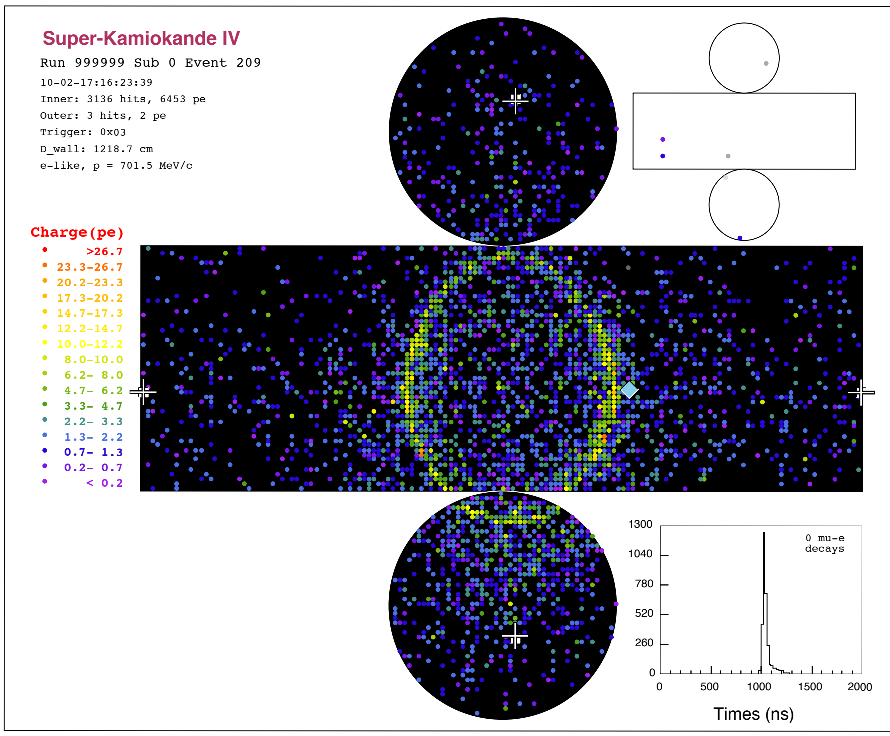


Super-Kamiokande IV
Run 999999 Sub 0 Event 209
10-02-17:16:23:39
Inner: 3136 hits, 6453 pe
Outer: 3 hits, 2 pe
Trigger: 0x03
D_wall: 1218.7 cm
e-like, p = 701.5 MeV/c
Charge(pe)
>26.7
23.3-26.7
20.2-23.3
17.3-20.2
14.7-17.3
12.2-14.7
10.0-12.2
8.0-10.0
6.2- 8.0
4.7- 6.2
3.3- 4.7
2.2- 3.3
1.3- 2.2
0.7- 1.3
0.2- 0.7
< 0.2
0 mu-e decays
1300
1040
780
520
260
0
0
500
1000
1500
2000
Times (ns)

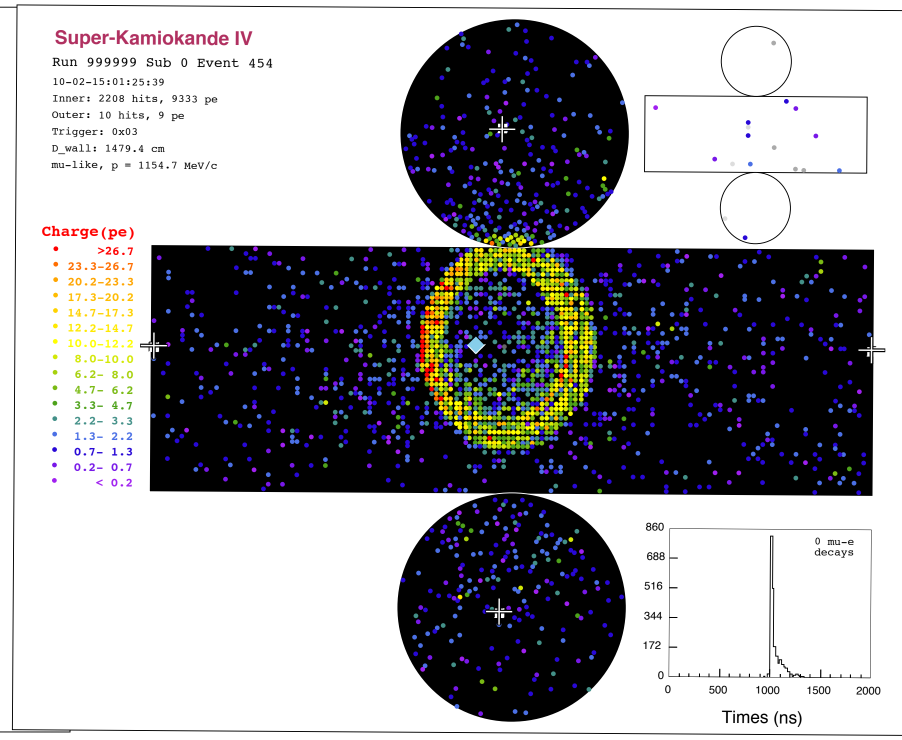

Super-Kamiokande IV
Run 999999 Sub 0 Event 458
10-02-15:01:36:54
Inner: 3366 hits, 8116 pe
Outer: 7 hits, 5 pe
Trigger: 0x03
D_wall: 1443.6 cm
e-like, p = 898.6 MeV/c
Charge(pe)
>26.7
23.3-26.7
20.2-23.3
17.3-20.2
14.7-17.3
12.2-14.7
10.0-12.2
8.0-10.0
6.2- 8.0
4.7- 6.2
3.3- 4.7
2.2- 3.3
1.3- 2.2
0.7- 1.3
0.2- 0.7
< 0.2
0 mu-e decays
1400
1120
840
560
280
0
0
500
1000
1500
2000
Times (ns)

理論屋にもできる(?)粒子識別

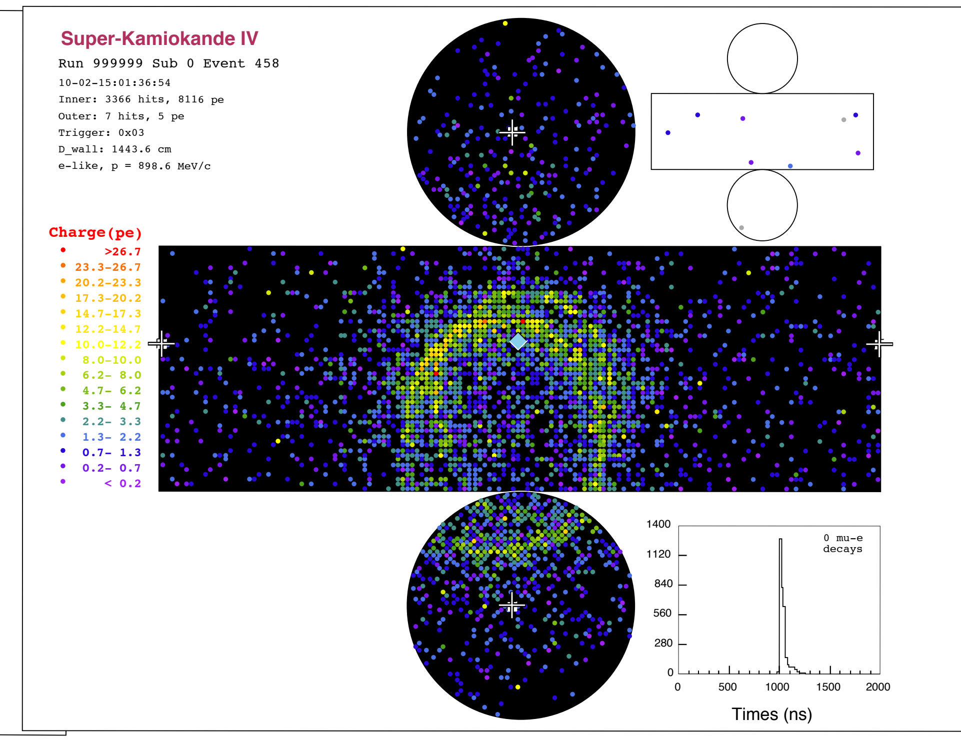
e

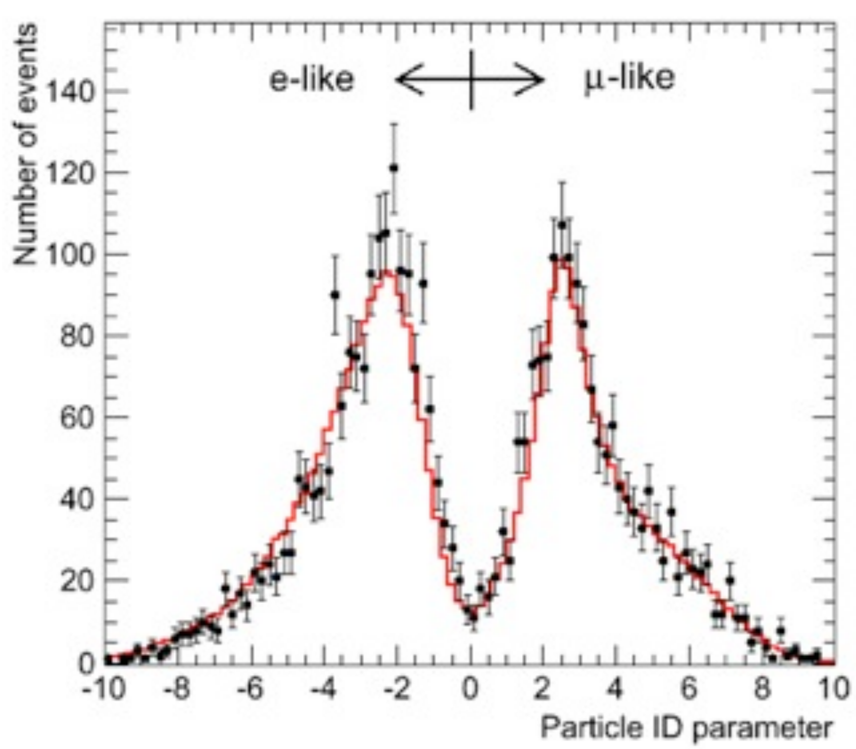


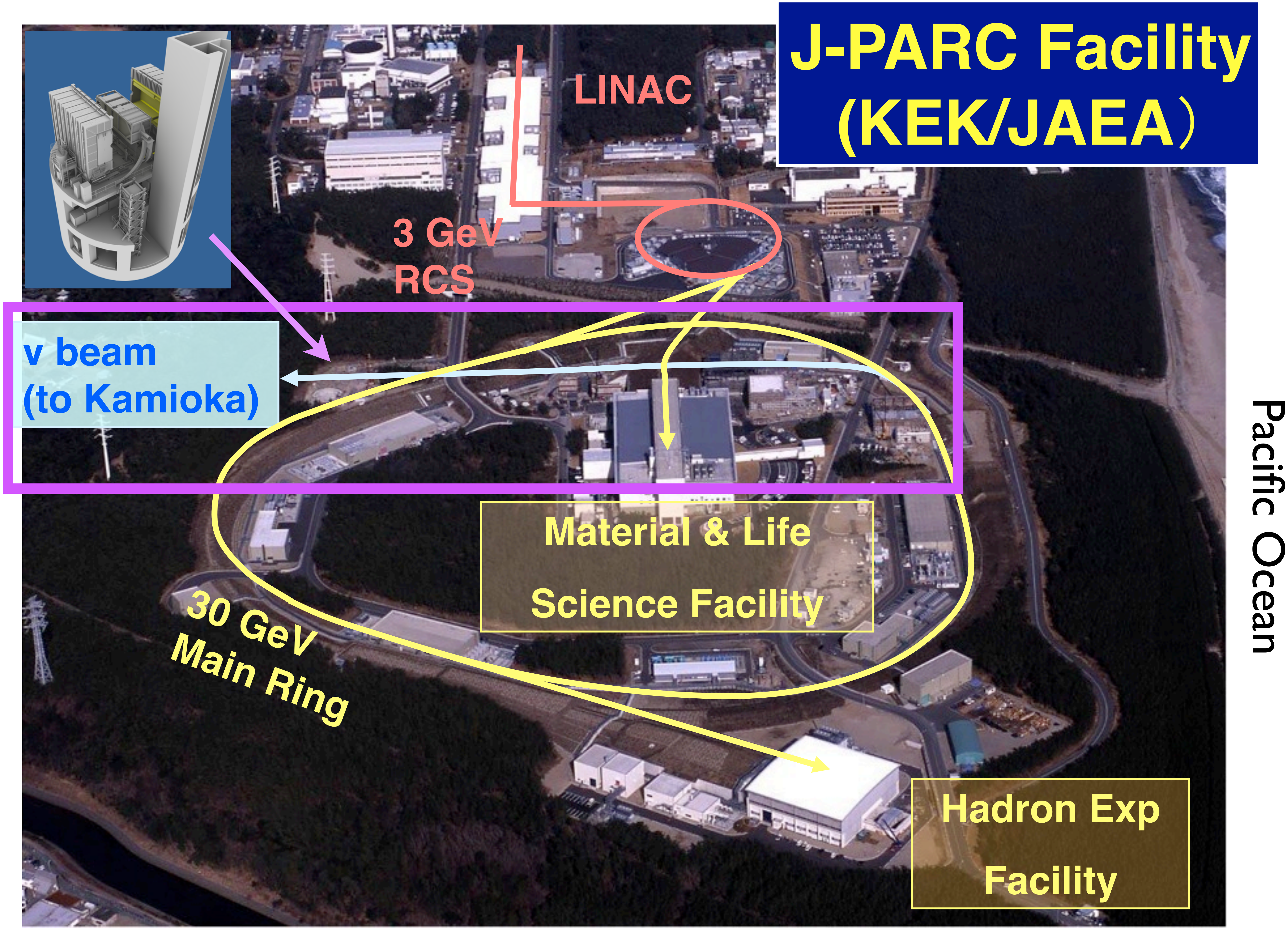
μ



$\pi^0 \to 2\gamma$






J-PARC Facility
(KEK/JAEA）
LINAC
3 GeV
RCS
ν beam
(to Kamioka)
Material & Life
Science Facility
30 GeV
Main Ring
Hadron Exp
Facility
Pacific Ocean

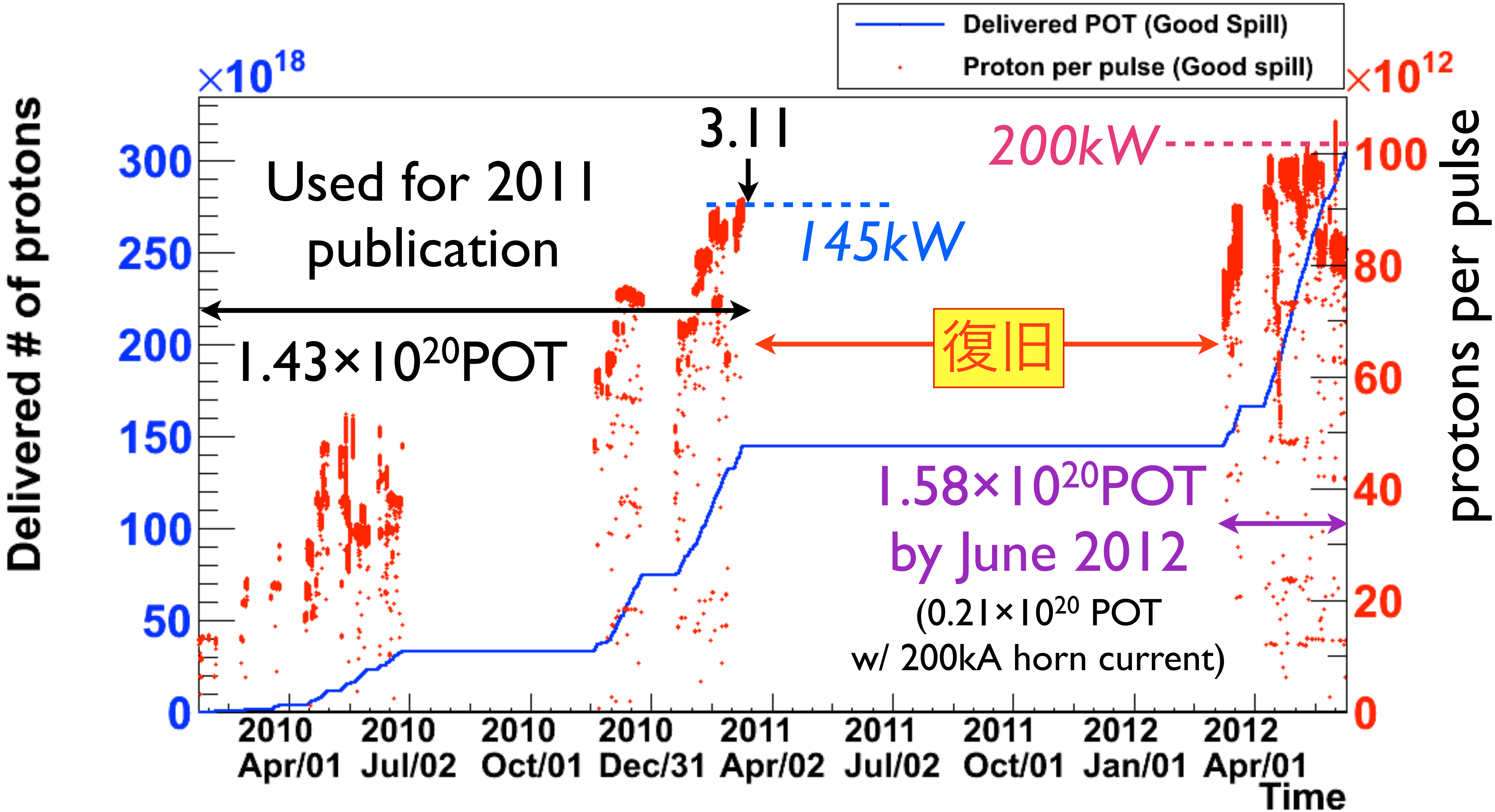
加速器ν実験の予備知識 (一般常識)

- ν実験の場合，まずとにかく数をかせぐのが重要
  - Instantaneous rateはどれだけ高くても大丈夫
    (普通の実験ではレートが高いと検出器が死ぬ)
- 陽子を加速したらとっととと全部打って次の
  加速サイクルへ（速い取り出し, FX）
  ⇔ 数秒にわたってビームを出す：遅い取り出し,SX
  - ちなみに(今の) J-PARCではFX/SX同時に運転できない
- 二次粒子の数 ∝ 陽子ビームのエネルギー × 数 (protons on target, POT)
  - 単位時間あたりの粒子生成数 ∝ kW

実験屋の事情(の一部)

- 大強度のビームは欲しいけど……
  - 熱衝撃
    - 変なところに当てると溶ける，壊れる
  - 放射線
    - dpaという単位ご存じですか
    - 放射化した空気，水，機器との戦い
  - 大電流
    - 電源，破壊……

これまでのデータ収集



本日は現在のフルデータ(3.01×10^{20}POT)による結果

(NEUTRINO2012時点では2.56×10^{20})


この下に建設担当した
ミューオンモニターが
Google map

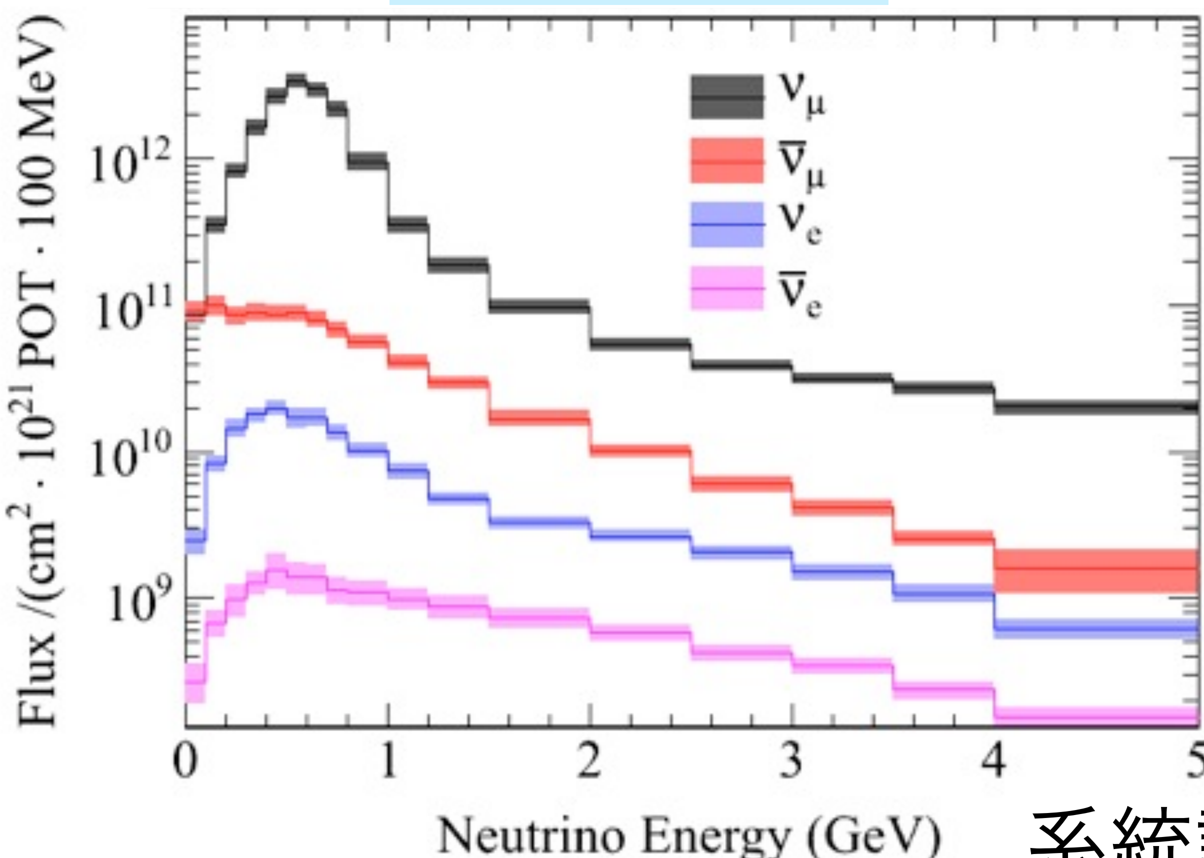

ニュートリノビームダンプ周辺、空調室外機
❖ 南側（ビーム上流から下流を見る）
55


3/24
5/13
3/24
5/13

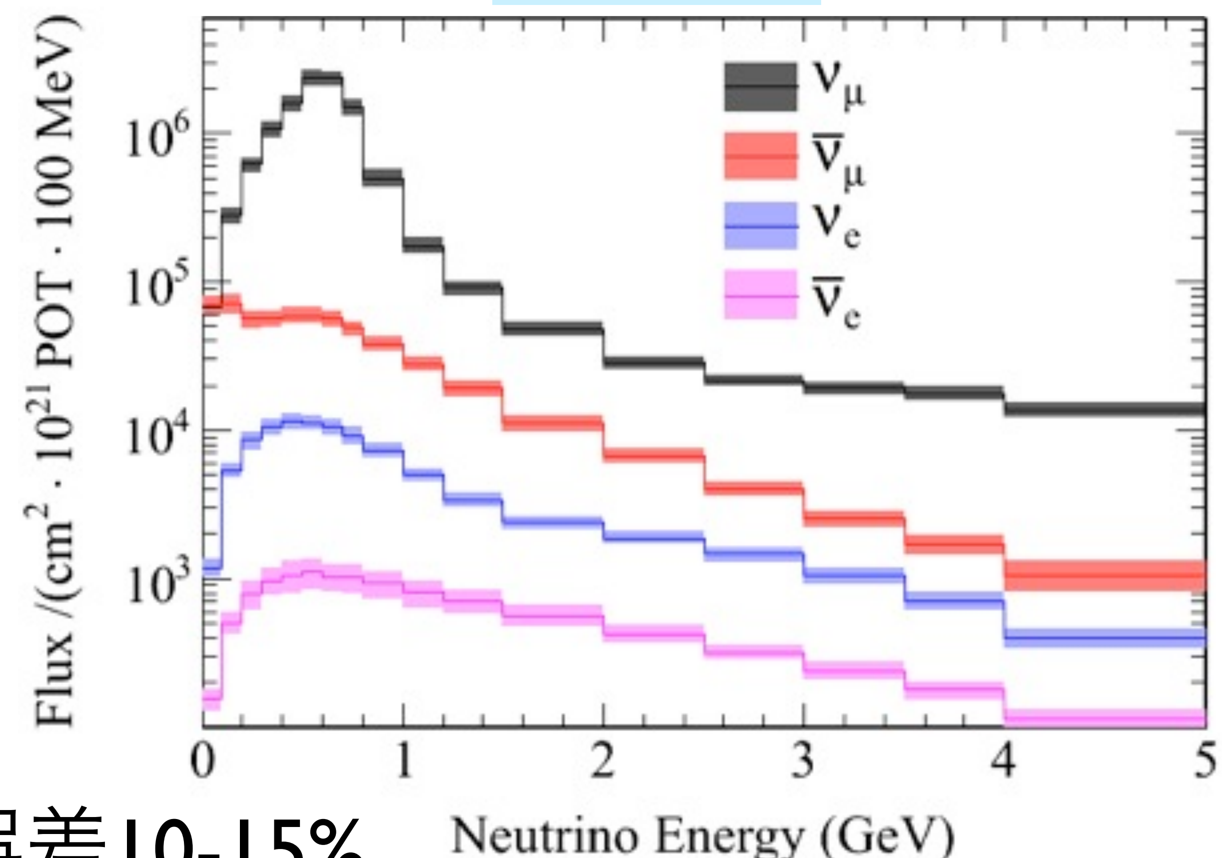
νフラックス(MC)

CERN-NA61で測定された$\pi^{\pm}$・K^{+}の生成断面積を元に

前置検出器



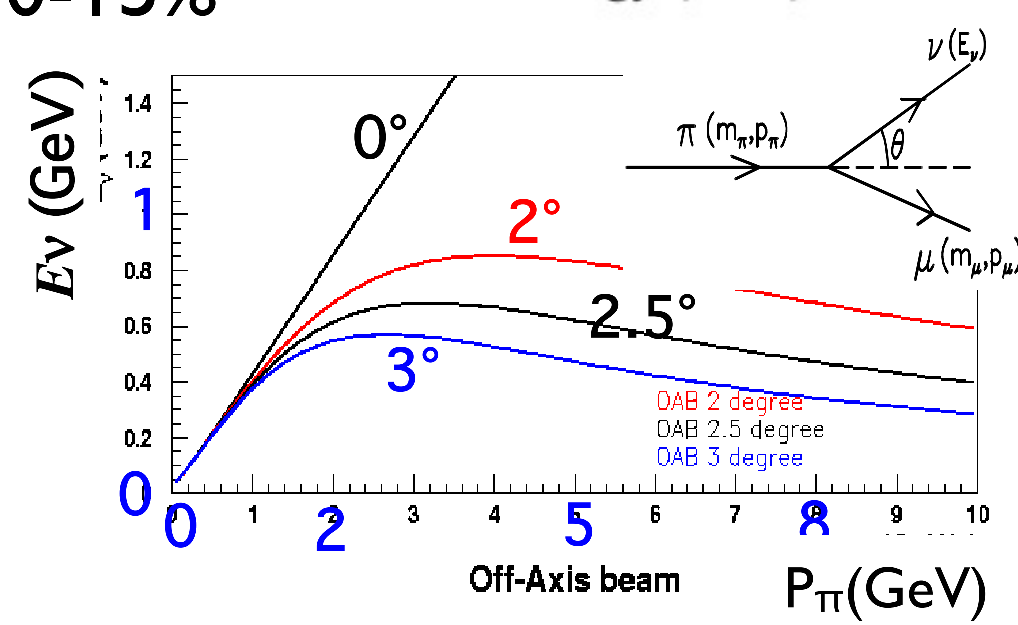
Super-K



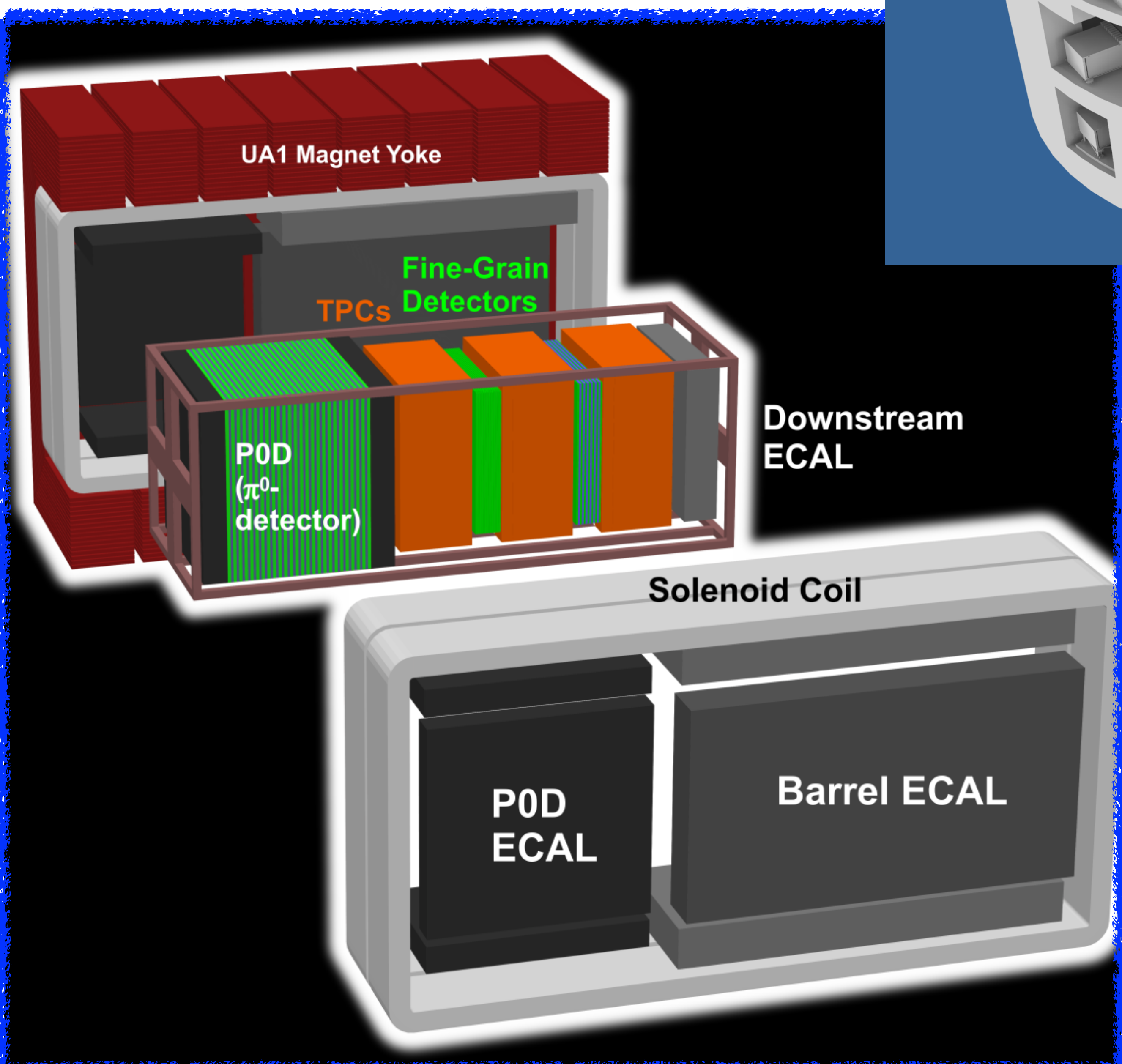
系統誤差10-15%

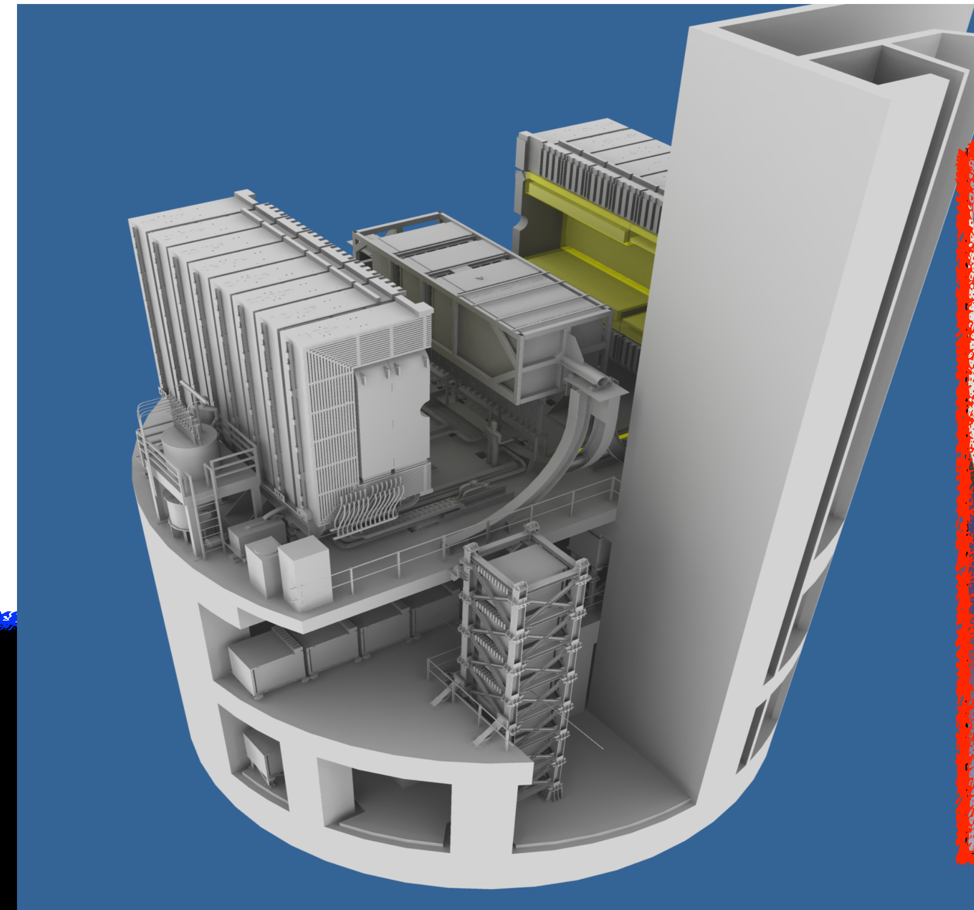
Off-axis beam

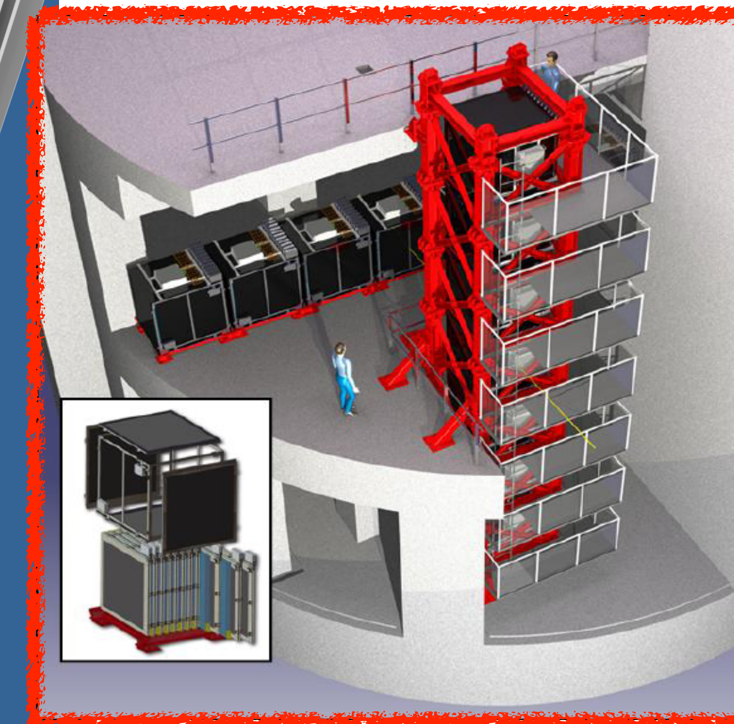
- 振動が最大となる~0.6GeVにピーク
- 高エネルギーのν(BG源)は少ない
- νeのコンタミ<1%



前置検出器



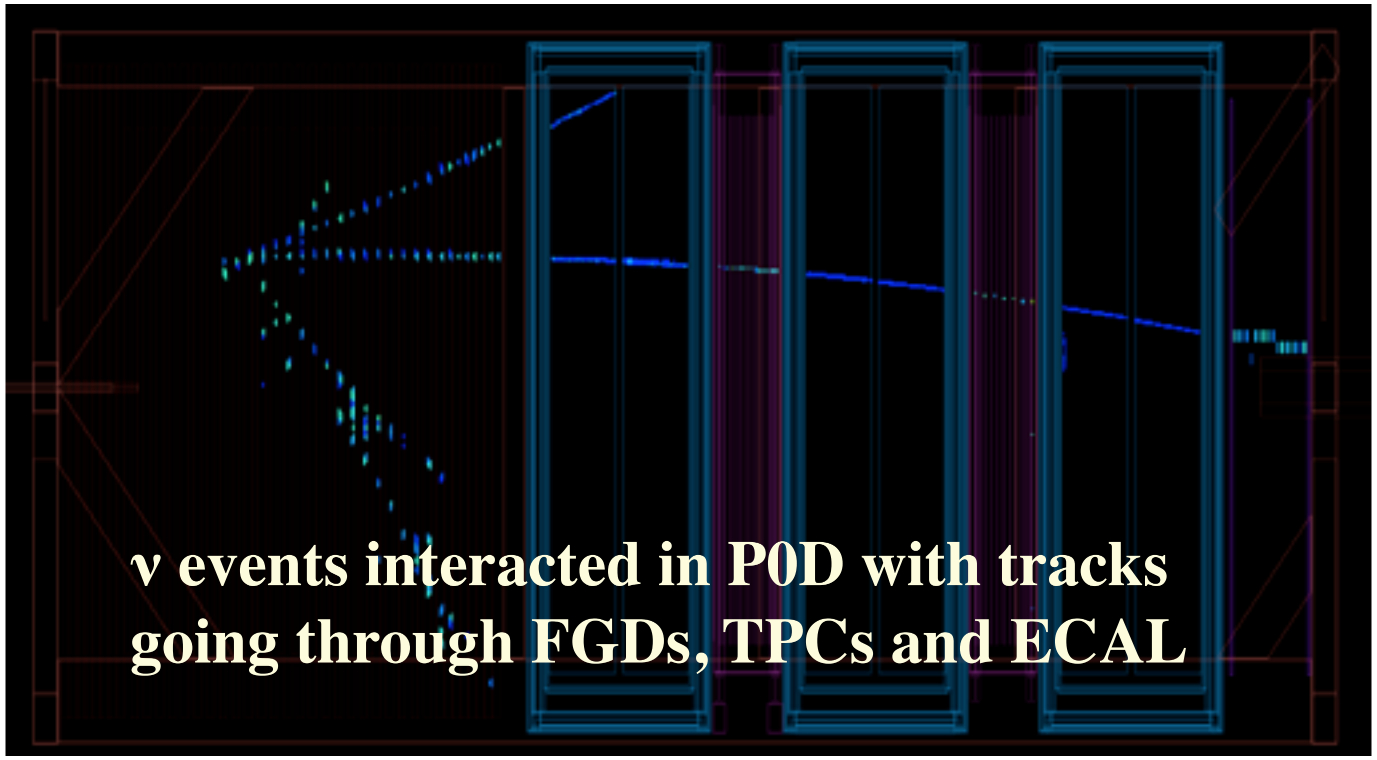




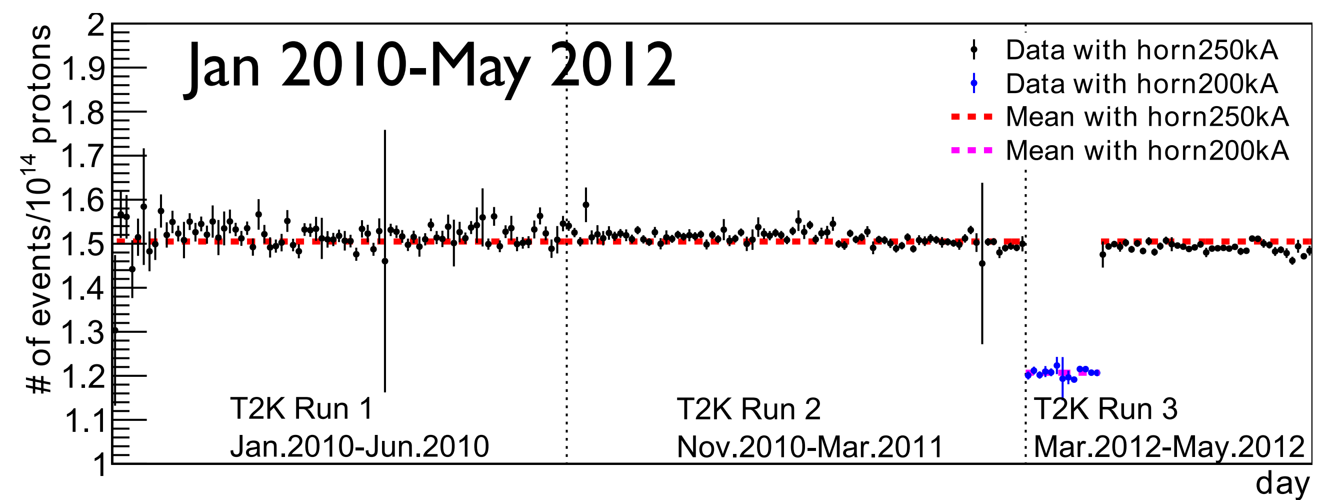
- **INGRID** @ on-axis (0 degree)
  - ν beam monitor [rate, direction, stability]

- **ND280** @ 2.5 degree off-axis
  - Normalization of Neutrino Flux
  - Measurement of neutrino cross sections.
    - Dipole magnet w/ 0.2T
    - **P0D:** π^0 Detector
    - **FGD+TPC:** Target + Particle tracking
    - **EM calorimeter**
    - **Side-Muon-Range Detector**

順調に稼働してます

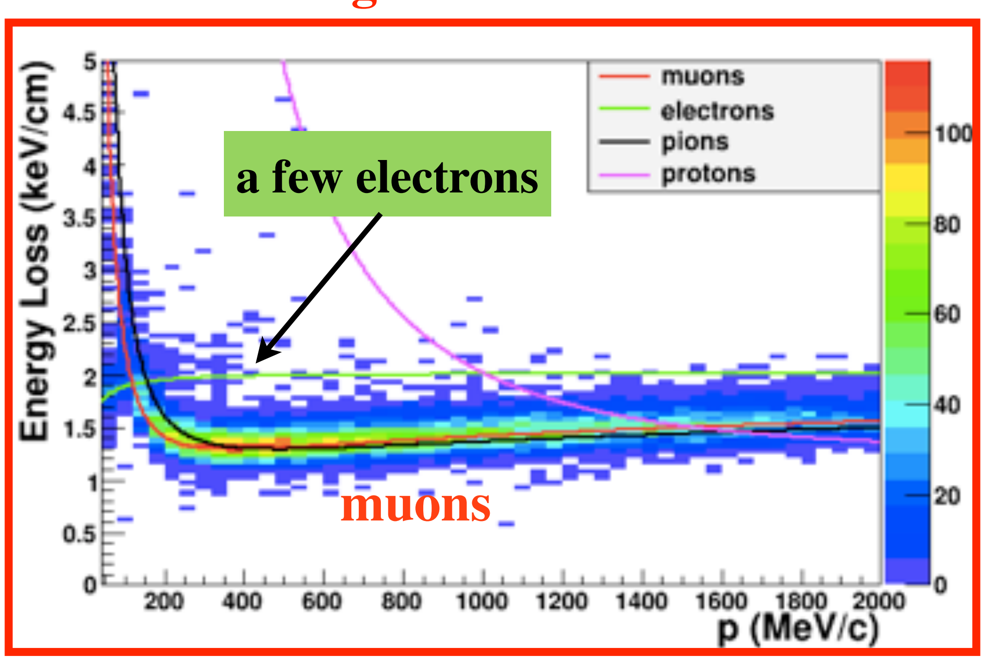


ν event rate stability by INGRID

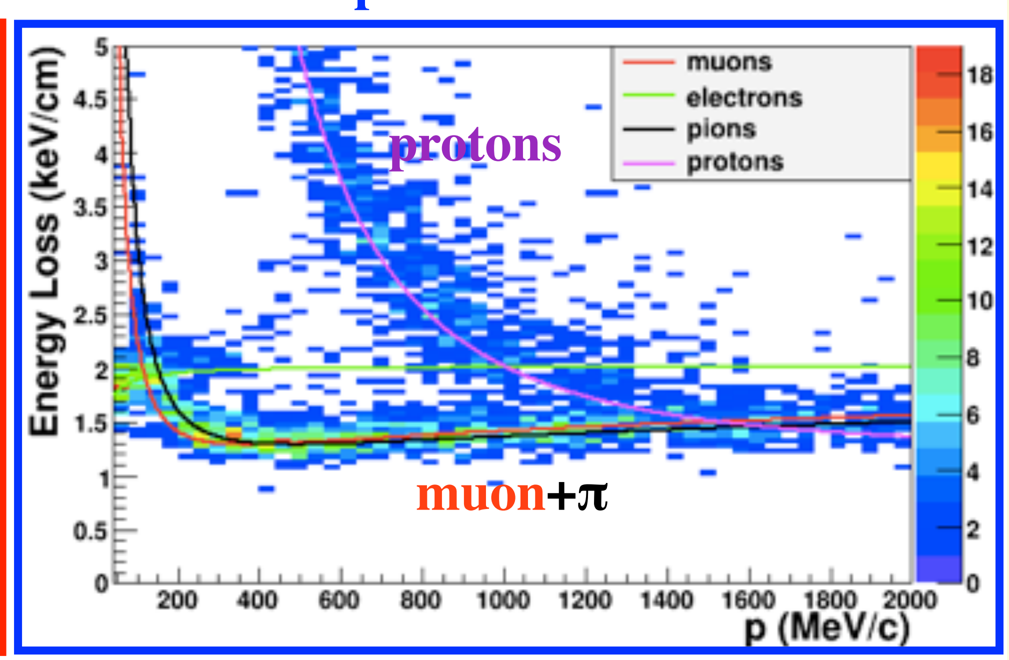


TPC PID

negative track



positive track

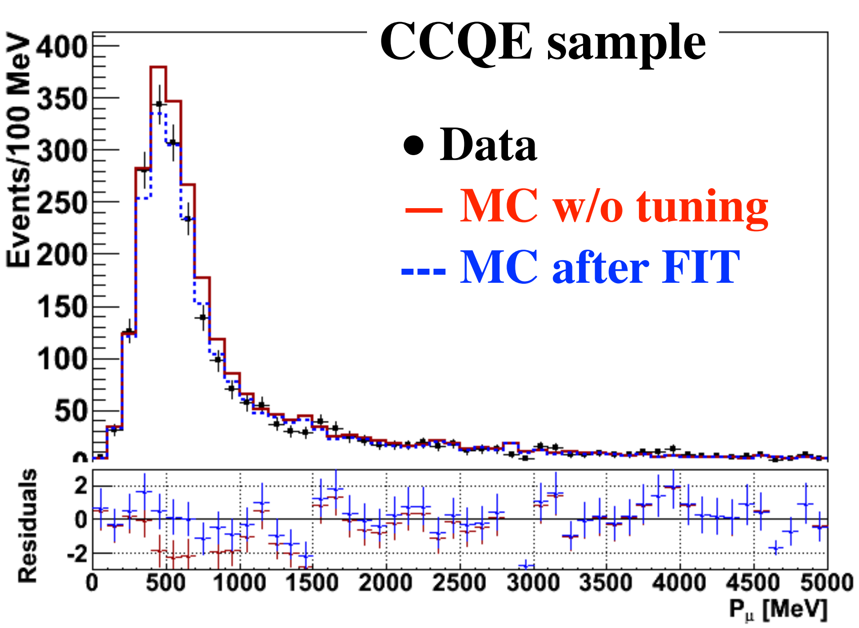


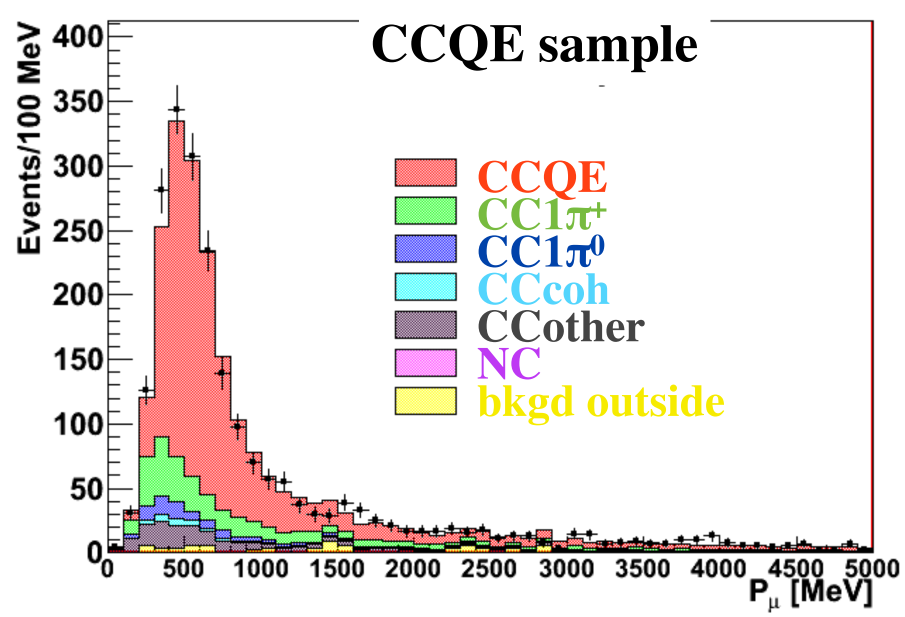
- INGRID [RUN 1-3 data]
  - ν rate stability
  - beam direction:
    - -0.01±0.33 mrad (x)
    - -0.11±0.37 mrad (y)
- ND280 [RUN 1-2 data]
  - excellent PID and tracking capability
  - identification of the neutrino interactions.

ν_μの測定@ND280

(using 1.08×10^{20}POT till Mar.2011)

Events in P_μ vs. θ_μ are used in FIT to constrain the flux and ν cross sections (MC predictions at ND280 and SK).



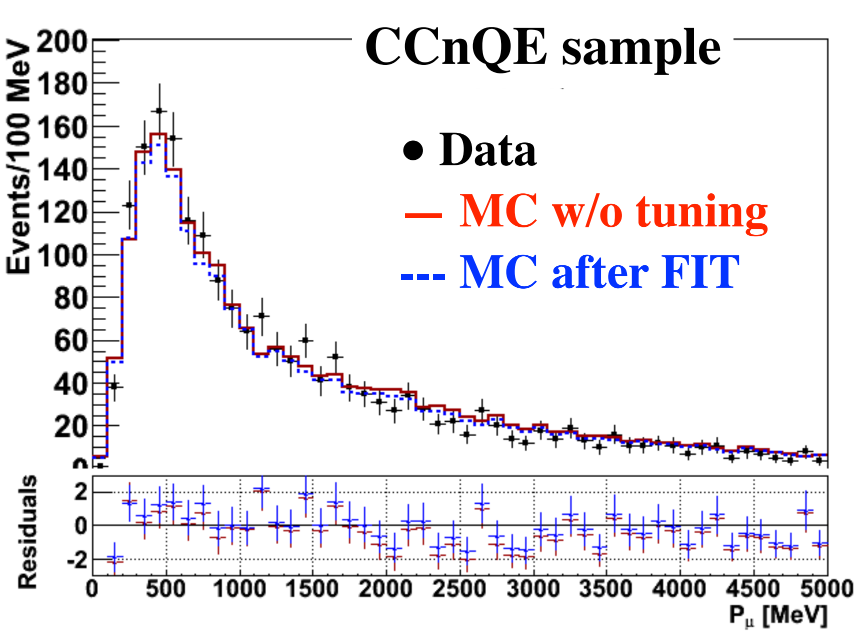


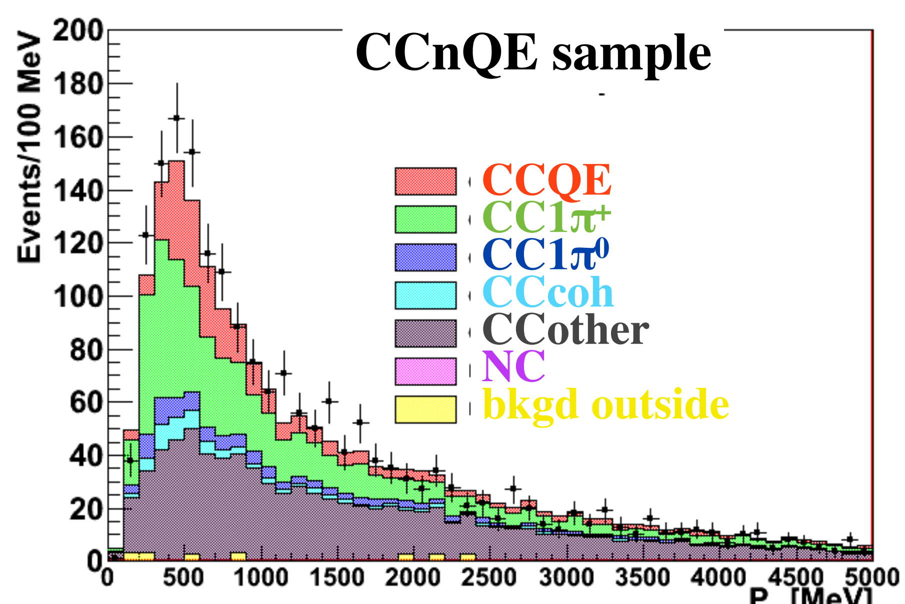
- Good negative track in FV.
- Upstream TPC veto
- muon ID by TPC

for CCQE

- **1 FGD-TPC track**
- **No decay-e in FGD**

For CCQE selection
40% eff. w/ 72% purity





2012年のデータも
変化ないことは確認
(現在アップデート中)

フラックス+断面積の制限

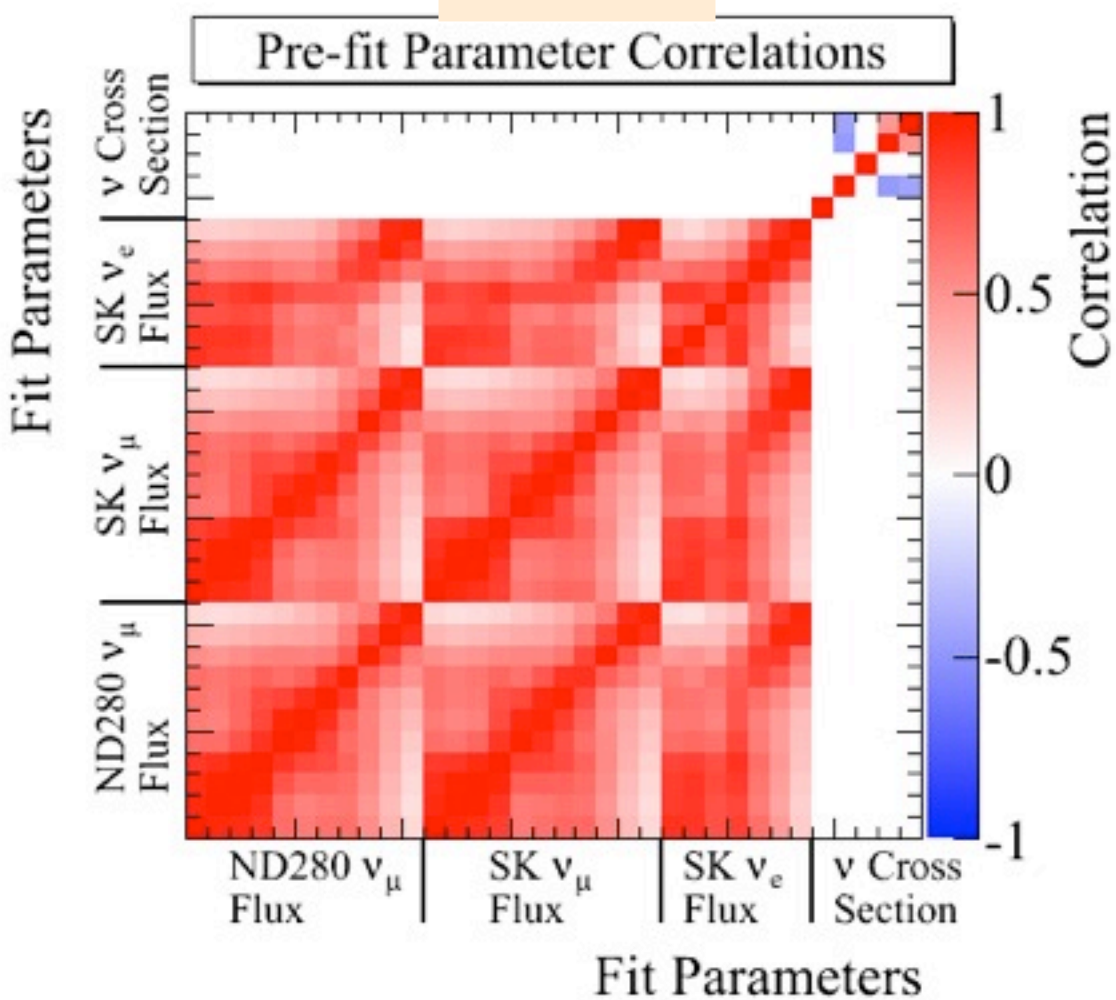
フラックスの予測
(NA61, beamline meas.)

前置検出器の測定
(p_μ, θ_μ)

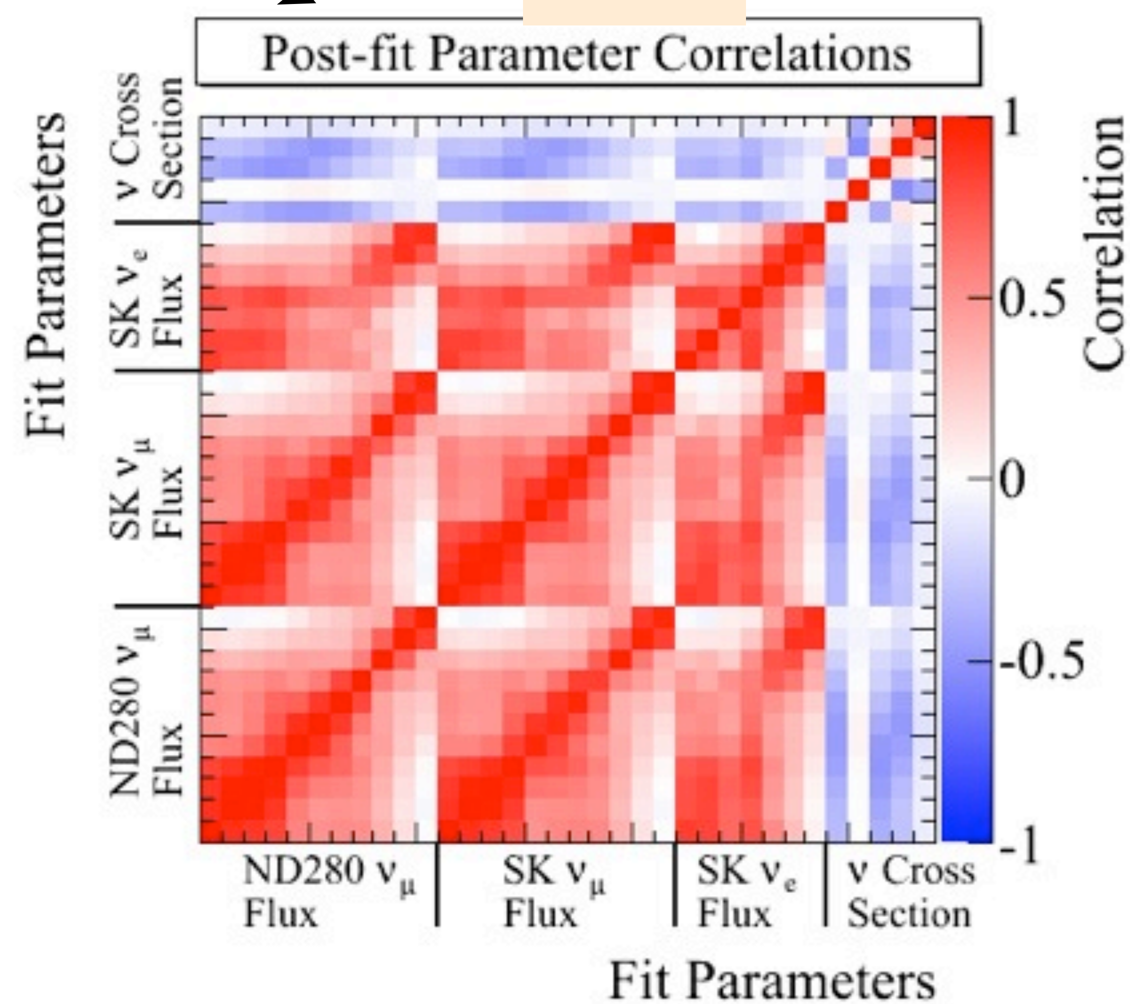
反応断面積の不定性
(過去の実験, モデル)

Correlationも全部入れてフィット

Before



After



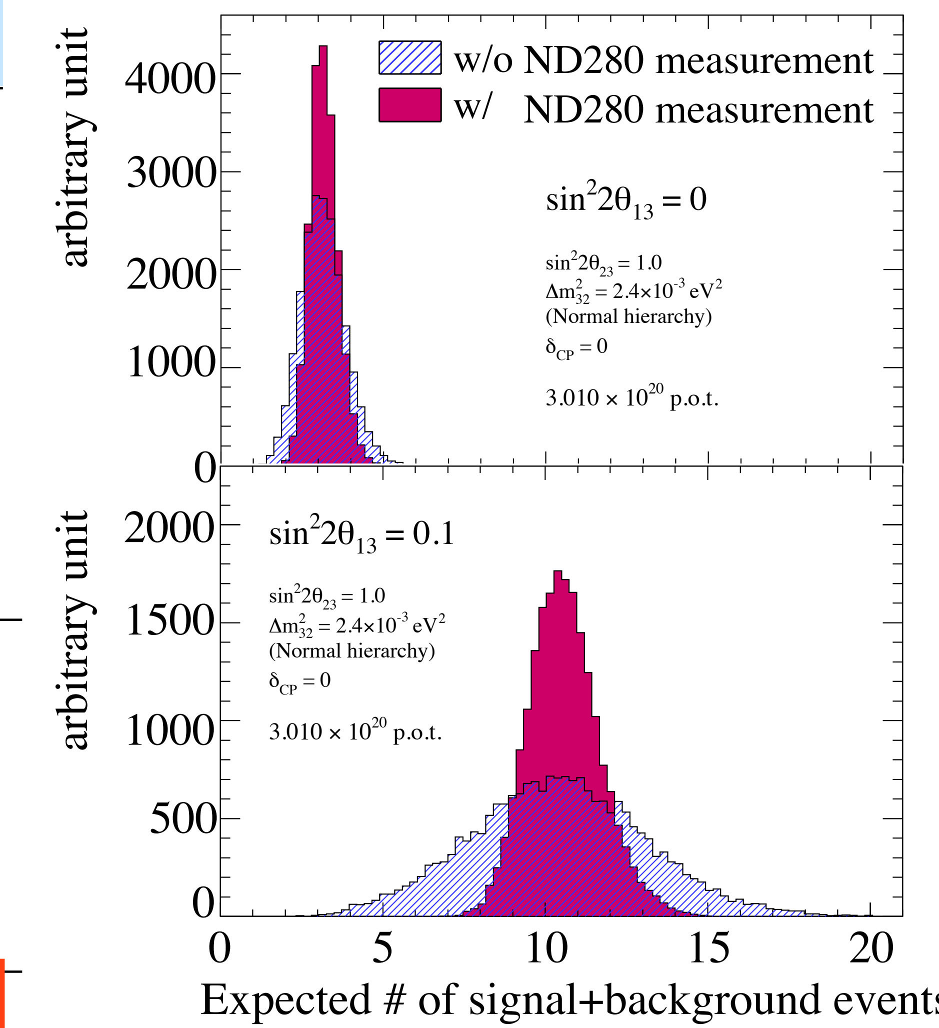
SKでの予想の不定性を減らす

The predicted number of events and systematic uncertainties

The predicted # of events w/ 3.01 x 10^{20} p.o.t.

Event category	$\sin^2 2\theta_{13} = 0.0$	$\sin^2 2\theta_{13} = 0.1$
Total	3.22±0.43	10.71±1.10
ν_e signal	0.18	7.79
ν_e background	1.67	1.56
ν_μ background (mainly NCπ⁰)	1.21	1.21
$\overline{\nu}_\mu + \overline{\nu}_e$ background	0.16	0.16

the predicted # of event distribution



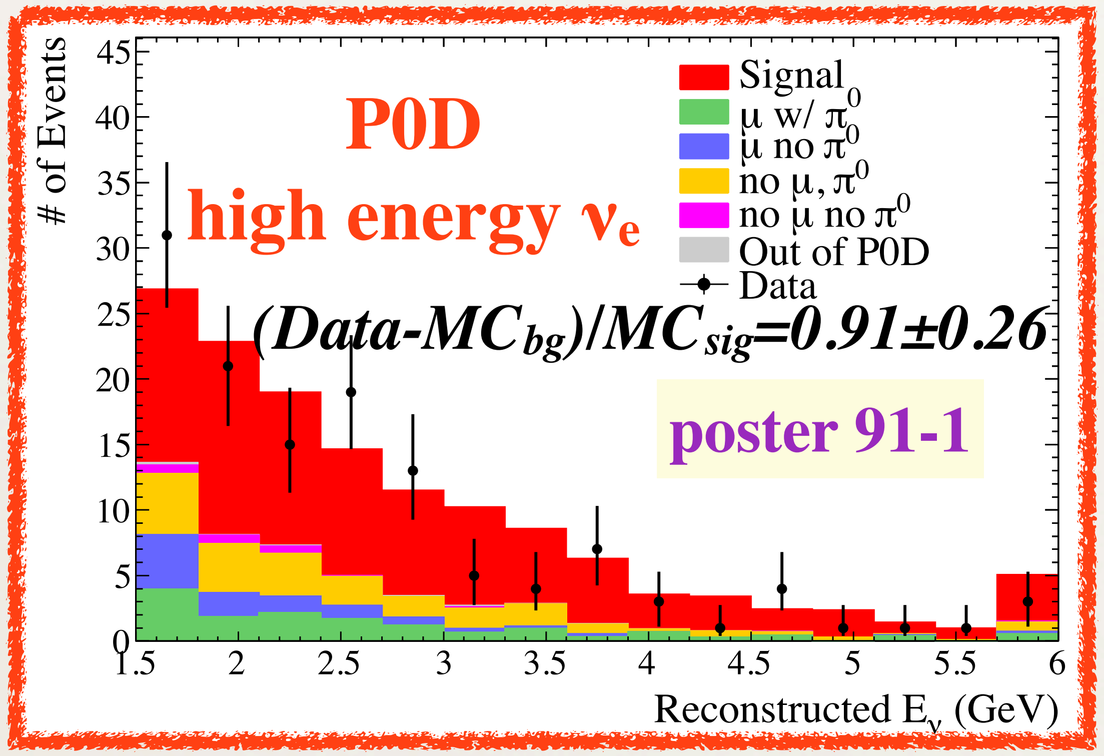
Systematic uncertainties

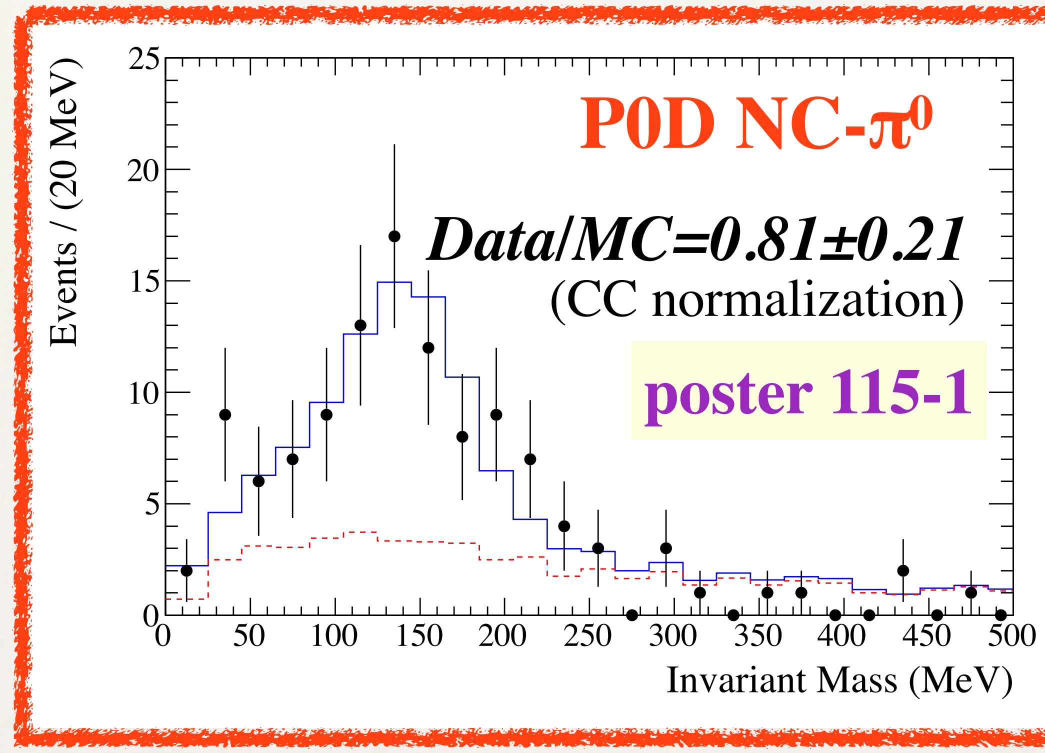
Error source	$\sin^2 2\theta_{13} = 0$	$\sin^2 2\theta_{13} = 0.1$
Beam flux+ν int. in T2K fit	8.7 %	5.7 %
ν int. (from other exp.)	5.9 %	7.5 %
Final state interaction	3.1 %	2.4 %
Far detector	7.1 %	3.1 %
Total	13.4 %	10.3 %
(T2K 2011 results:	~23%	~18%)

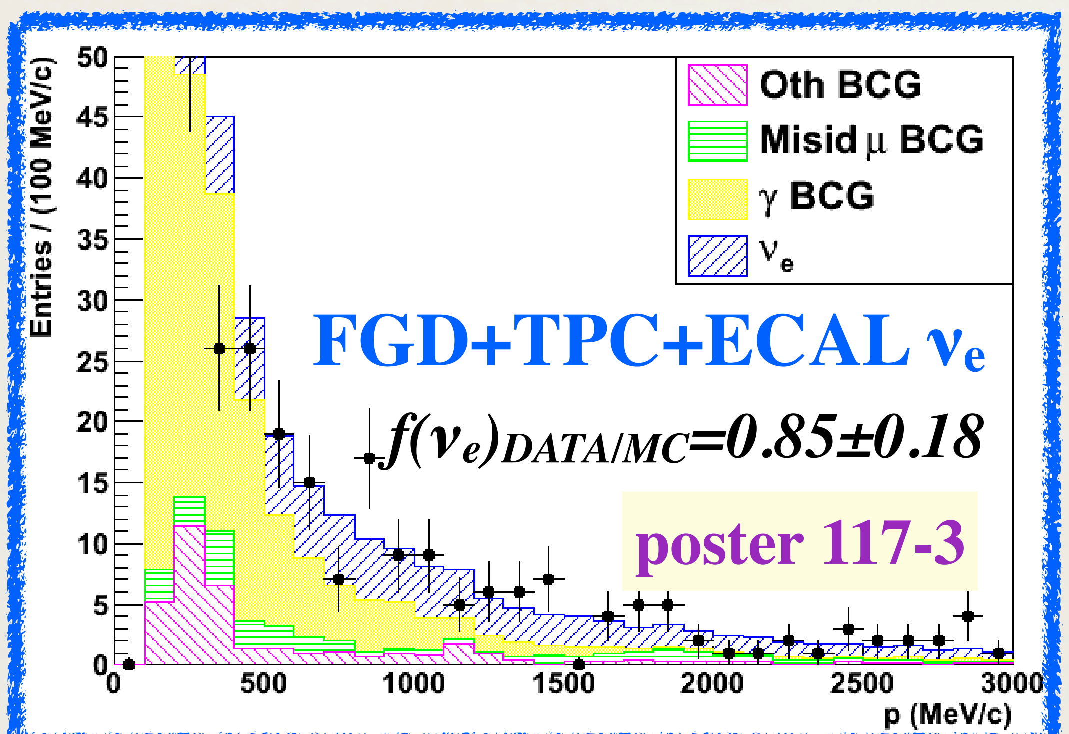
big improvement from the T2K 2011 results

Uncertainties are reduced using ND280 measurement

ND280 CC-ν_e and NC-π^0



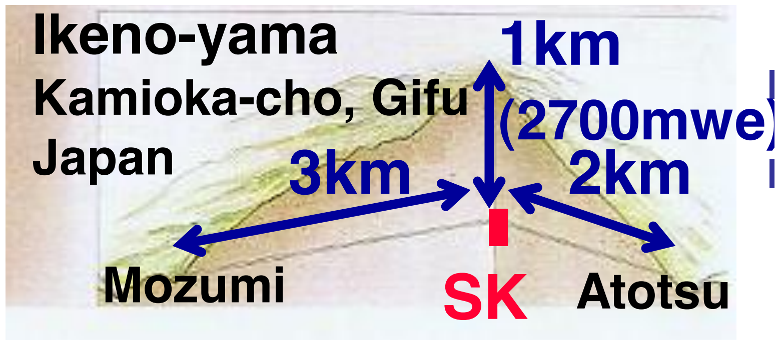


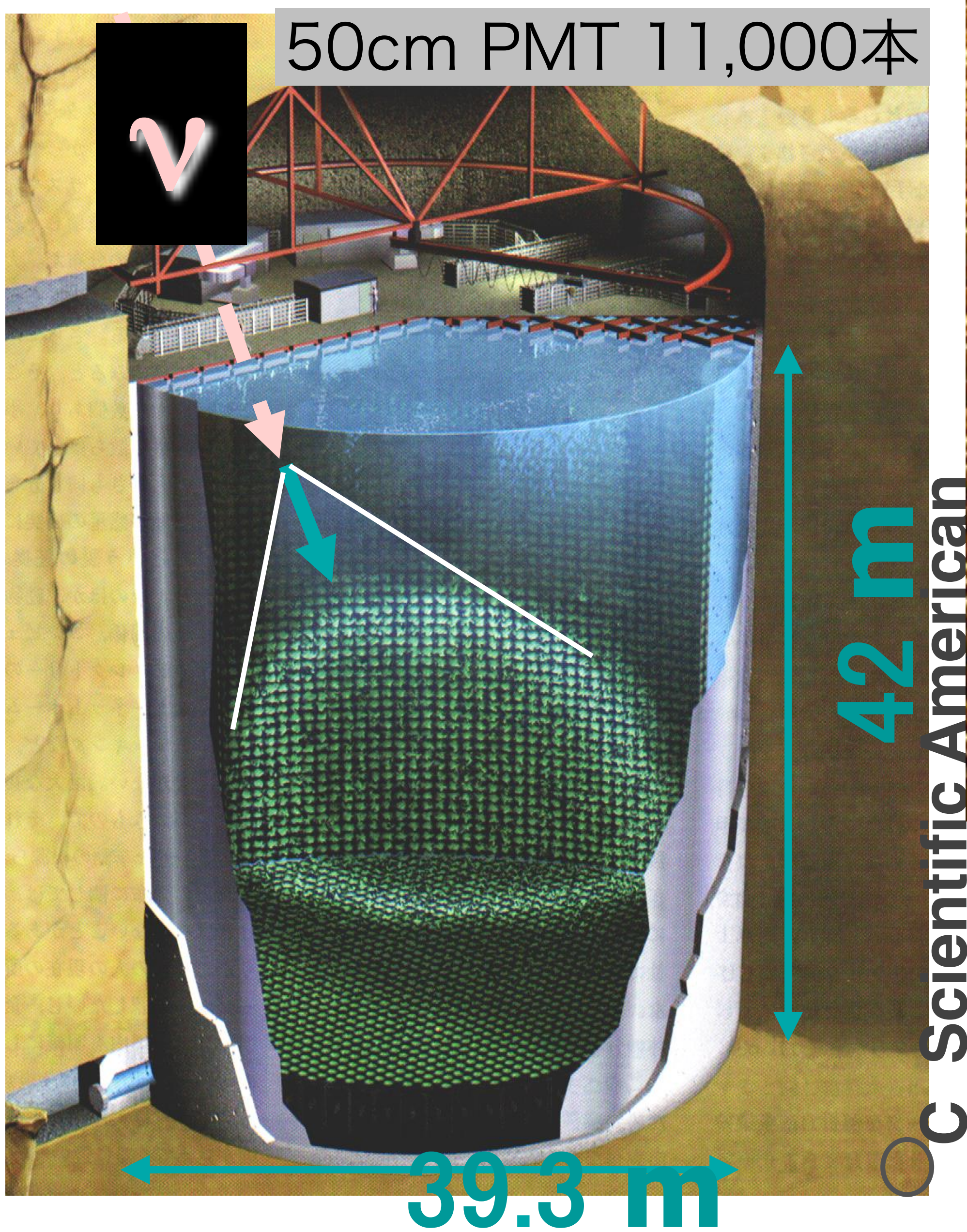


- Dominant backgrounds for Electron Neutrino Appearance are measured in ND280.
- Measurements of both CC-ν_e and NC-π^0 are consistent with the MC prediction.

- ***Check the background events at ND280 for ν_e appearance.***

スーパーカミオカンデ





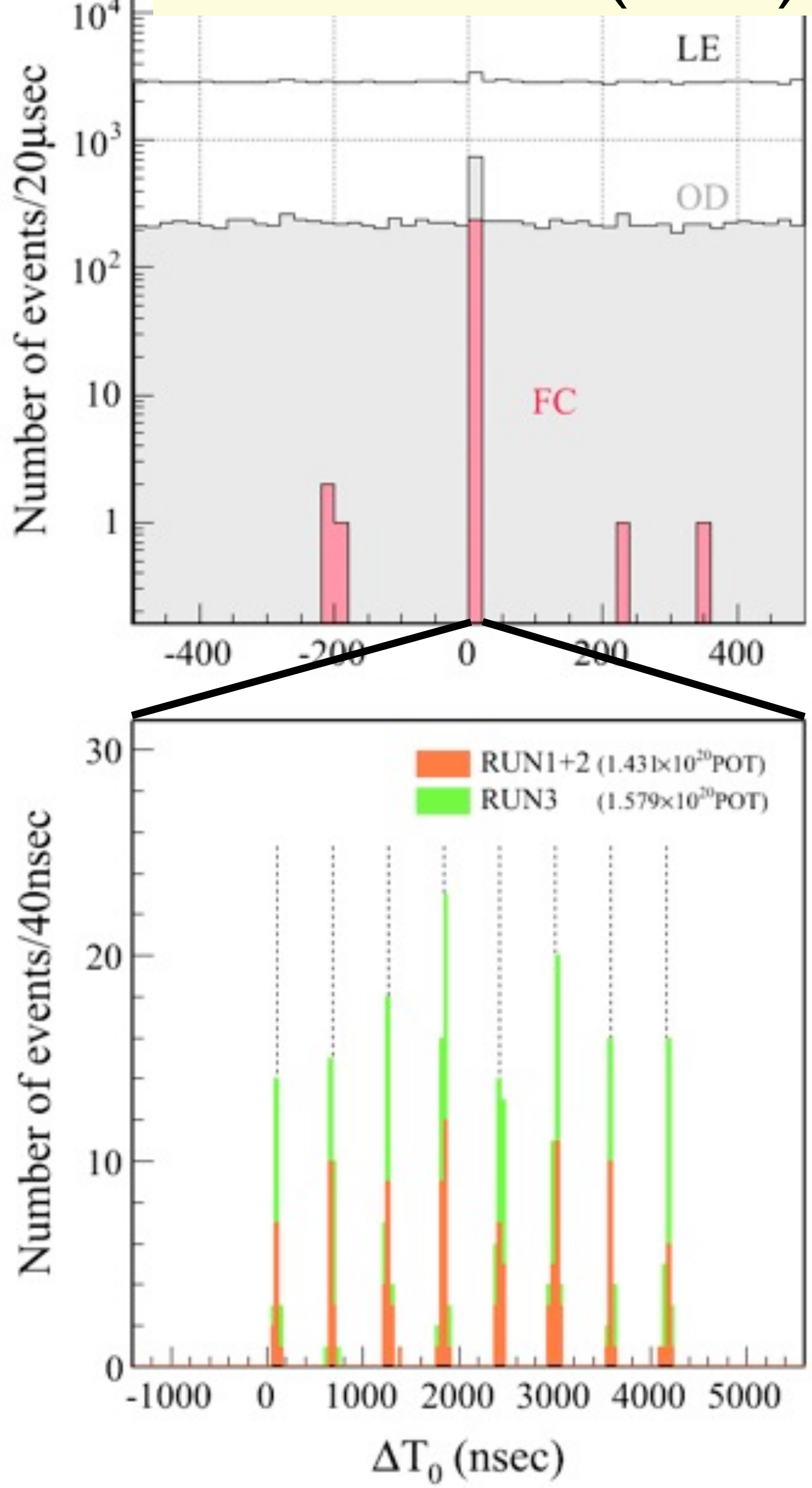
有効質量 22.5kt

T2K開始前に読み出し回路更新

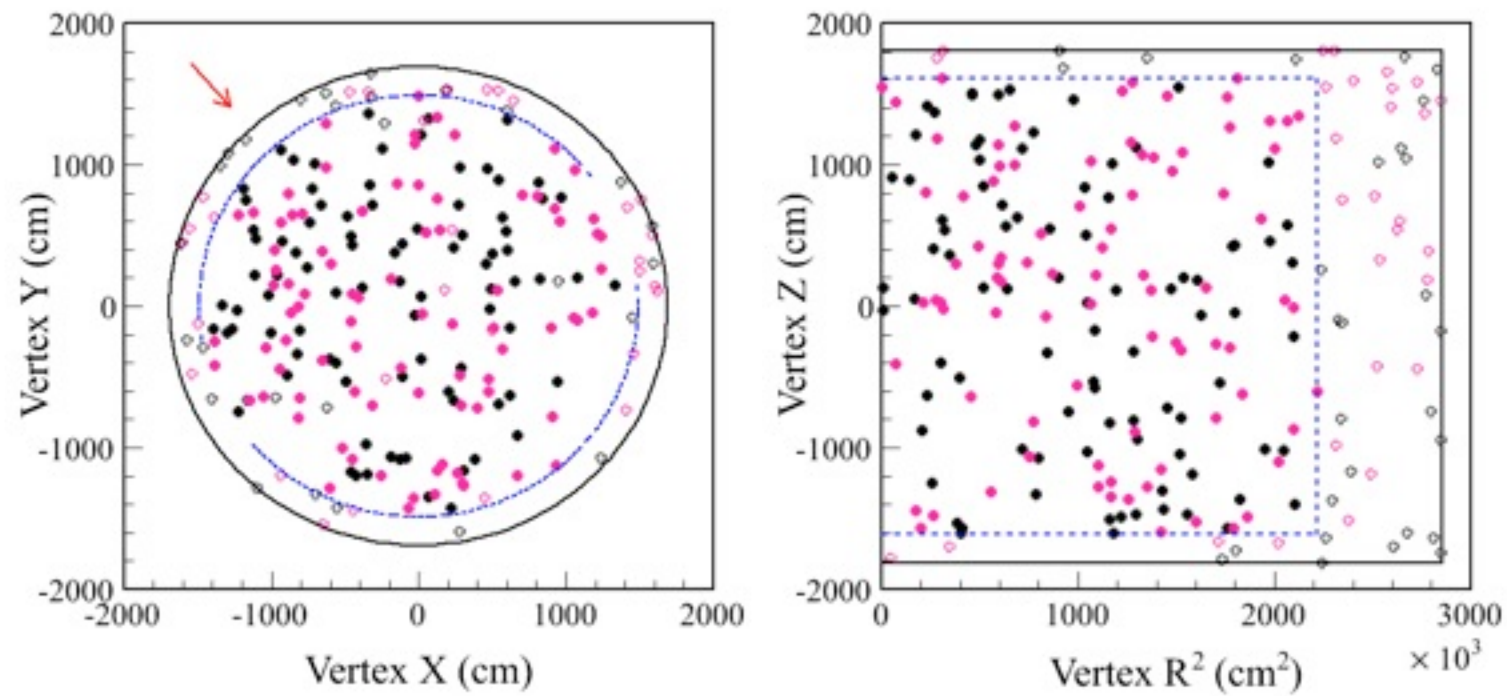
→ ±500μsのヒット<u>全て</u>記録

J-PARCからのνを選ぶ

タイミング(GPS)

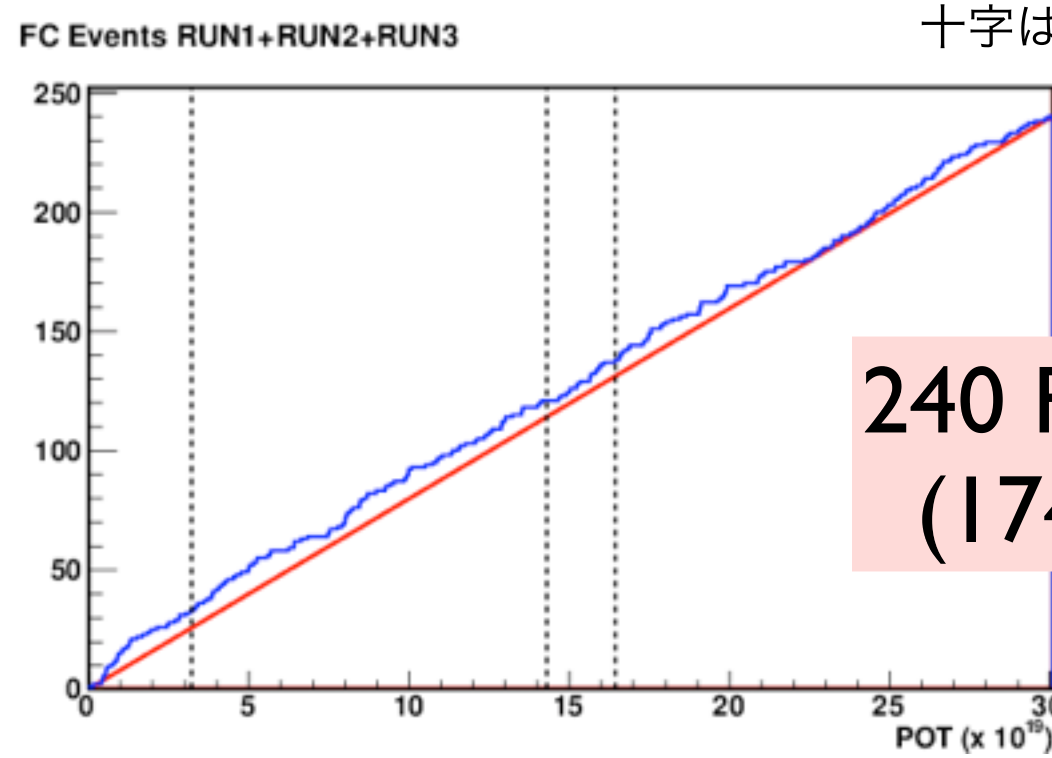


Vertex of fully contained events



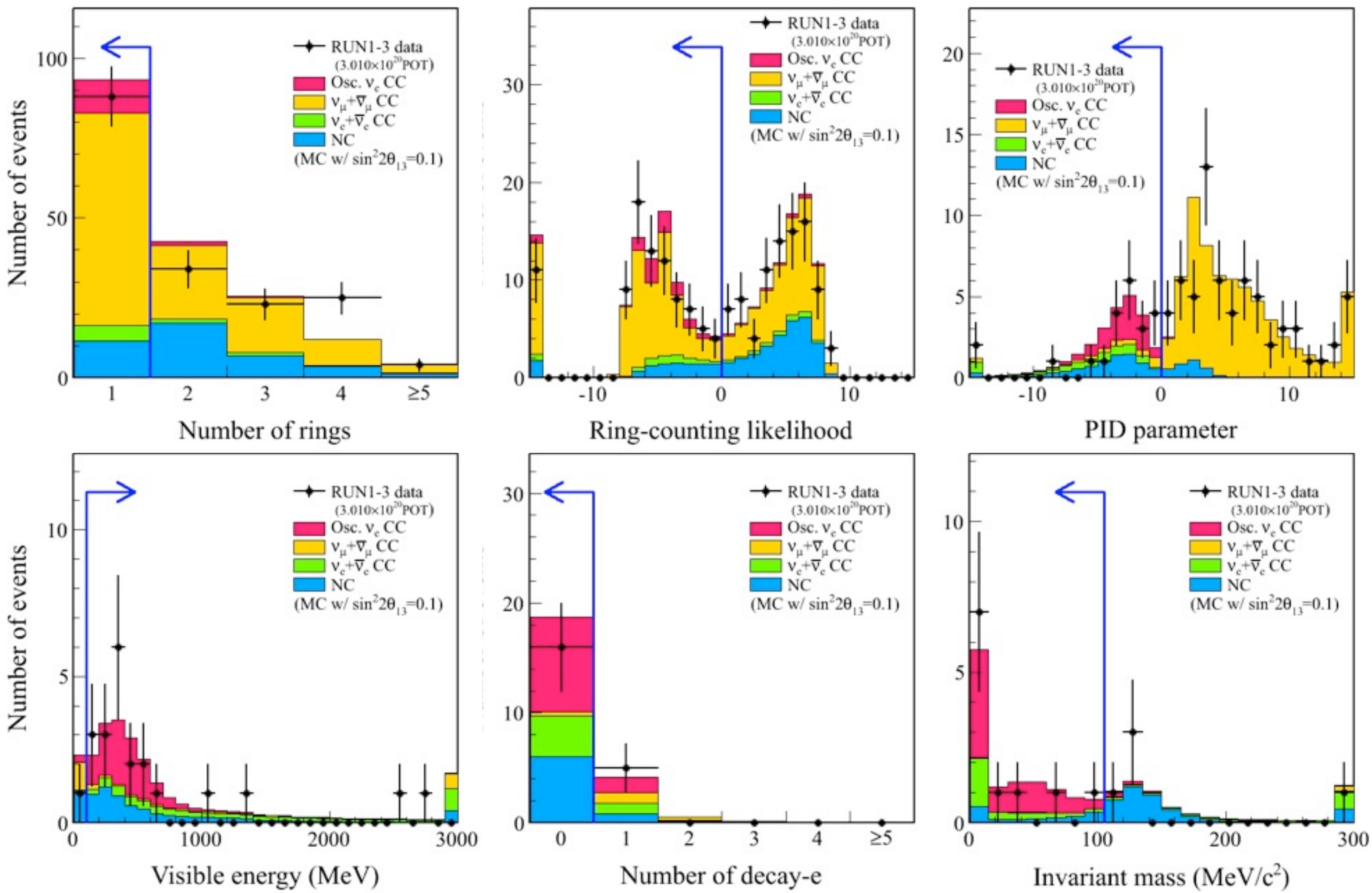
色つきが2012年のイベント

十字はout of fiducial volume



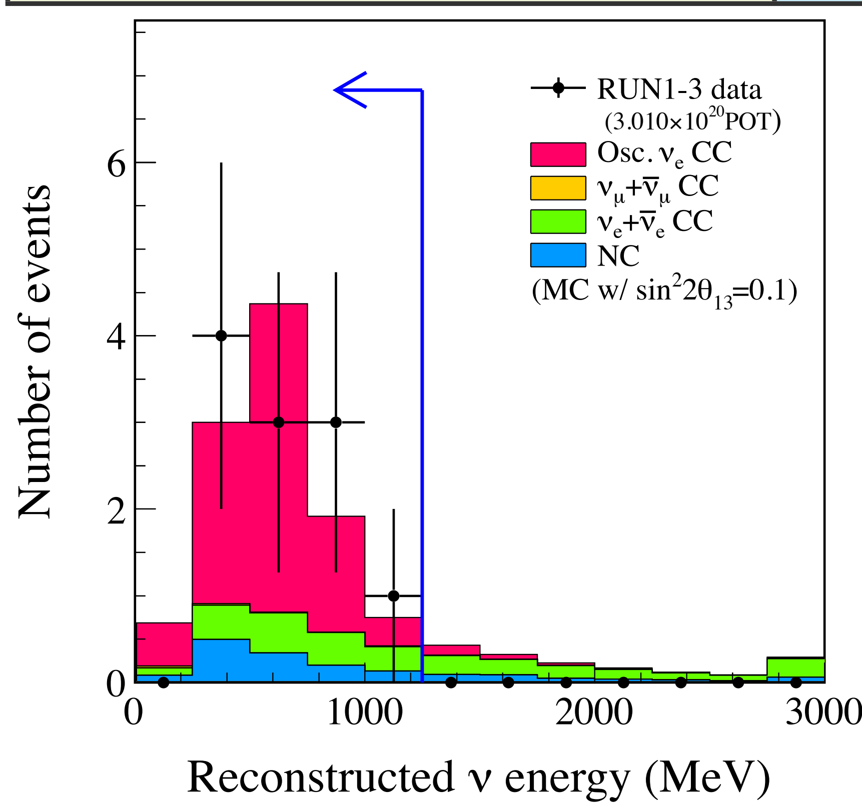
240 FC events
(174 FCFV)

電子ニュートリノ選択


Number of events
RUN1-3 data
(3.010×10^{20}POT)
Osc. ν_e CC
$\nu_\mu+\bar{\nu}_\mu$ CC
$\nu_e+\bar{\nu}_e$ CC
NC
(MC w/ $\sin^2 2\theta_{13}$=0.1)
Number of rings
Ring-counting likelihood
PID parameter
Visible energy (MeV)
Number of decay-e
Invariant mass (MeV/c^2)

ν_e candidate event selection

RUN 1+2+3 3.010×10^{20} POT	Data	MC Expectation w/ $\sin^2 2\theta_{13}=0.1$				
		Signal $\nu_\mu\to\nu_e$	BG total	CC ($\nu_\mu+\bar{\nu}_\mu$)	CC($\nu_e+\bar{\nu}_e$)	NC
Fully contained FV at beam timing	174	12.35	165.47	117.33	7.67	40.48
Single ring	88	10.39	82.78	66.41	4.82	11.55
e-like	22	10.27	15.60	2.72	4.79	8.10
E_{vis}>100MeV	21	10.04	13.53	1.76	4.75	7.01
No decay-e	16	8.63	10.09	0.33	3.76	6.00
2γ invariant mass cut	11	8.05	4.32	0.09	2.60	1.64
E_ν^{rec} < 1250 MeV (MC $\sin^2 2\theta_{13}=0$ case)	11	7.81 (0.18)	2.92 (3.04)	0.06 (0.06)	1.61 (1.73)	1.25 (1.25)
Efficiency [%]		60.7	1.0	0.0	20.0	0.9



11 candidate events are observed

$N_{exp}=3.22\pm0.43$ for $\sin^2 2\theta_{13}=0$

The probability (p-value) to observe 11 or more events with $\theta_{13}=0$ is 0.08% (3.2σ)

※ No Look Elsewhere Effect

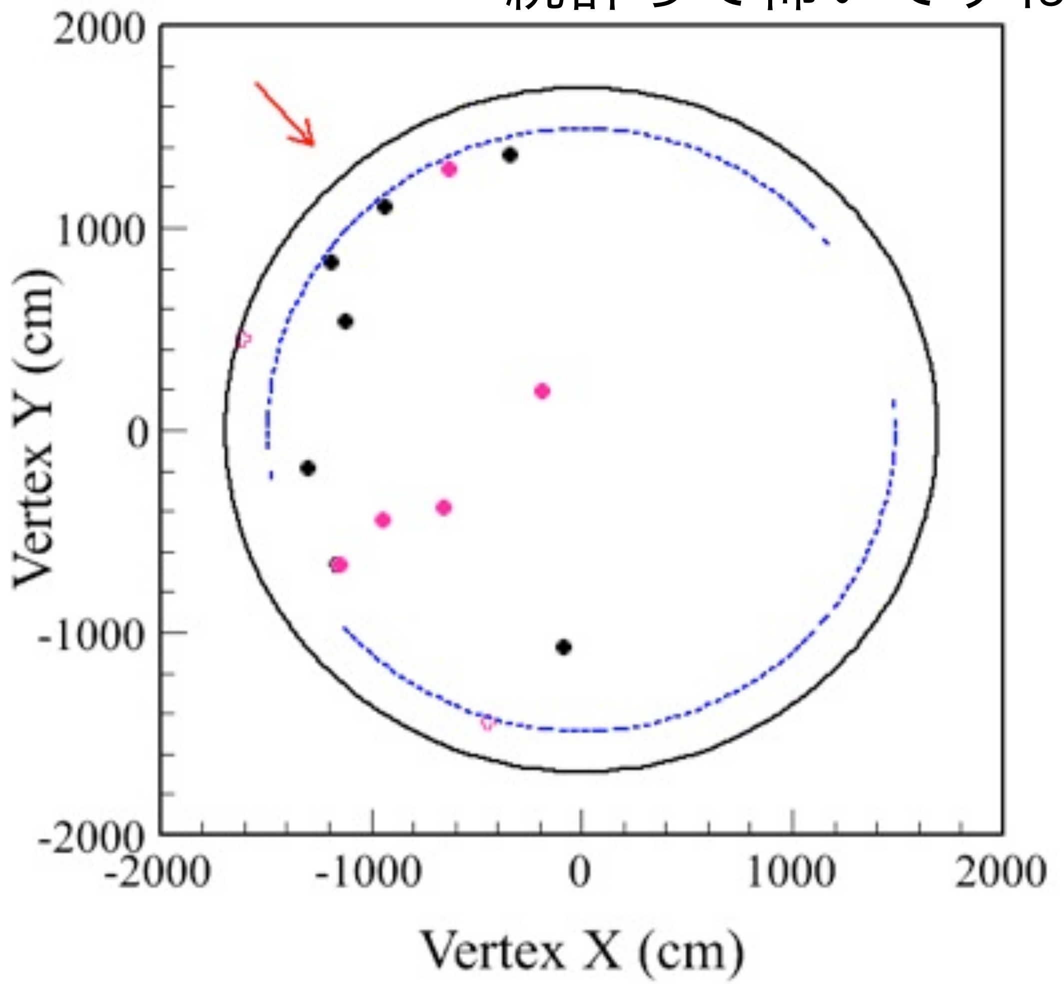
Evidence of ν_e appearance

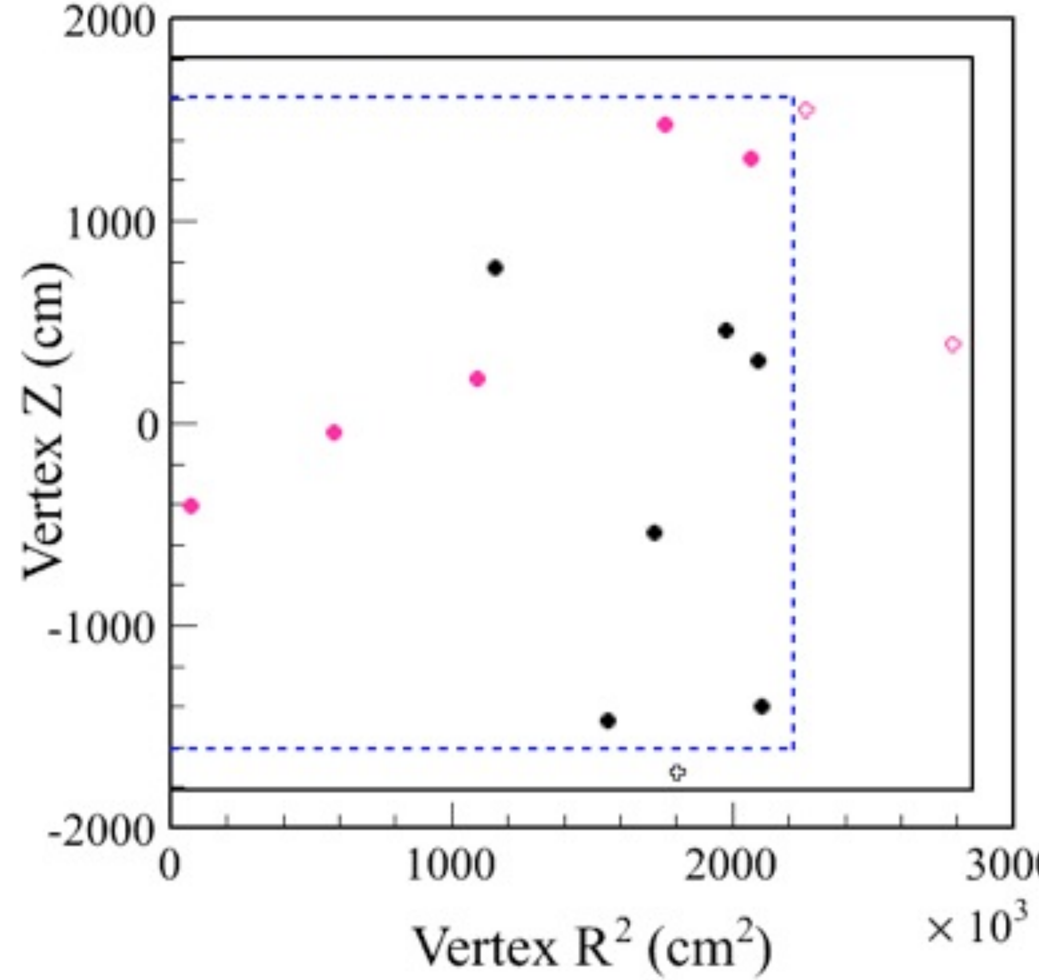
バーテックス分布

色つきが2012年のイベント

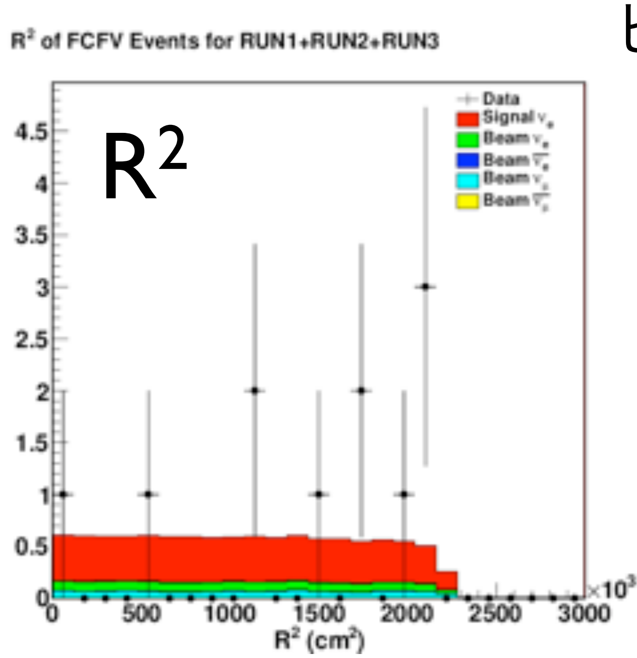
十字はout of fiducial volume

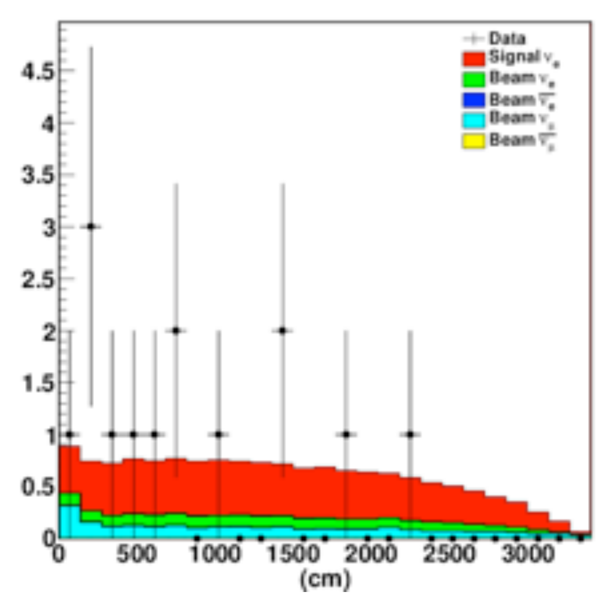
統計って怖いですね



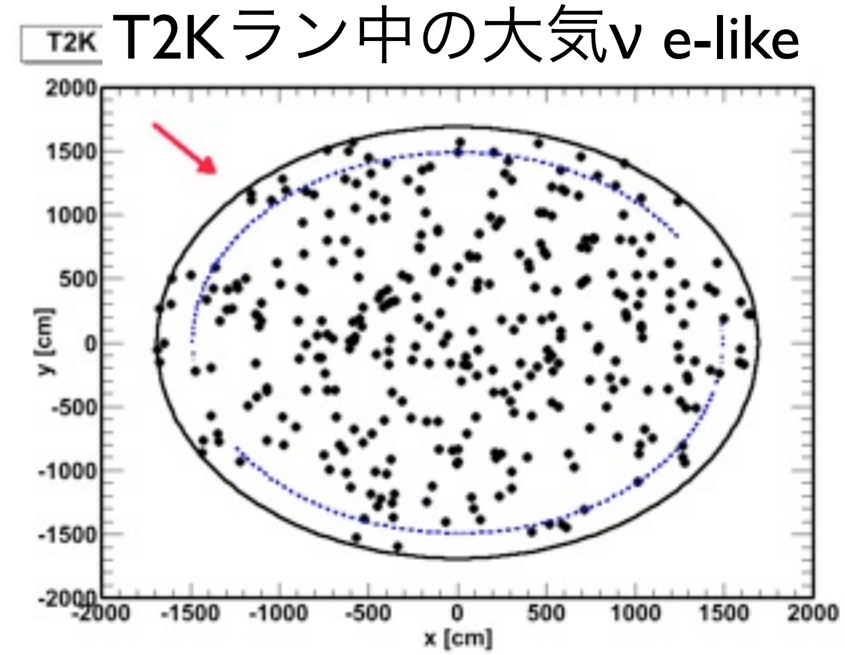


ビーム方向の壁からの距離





T2Kラン中の大気ν e-like

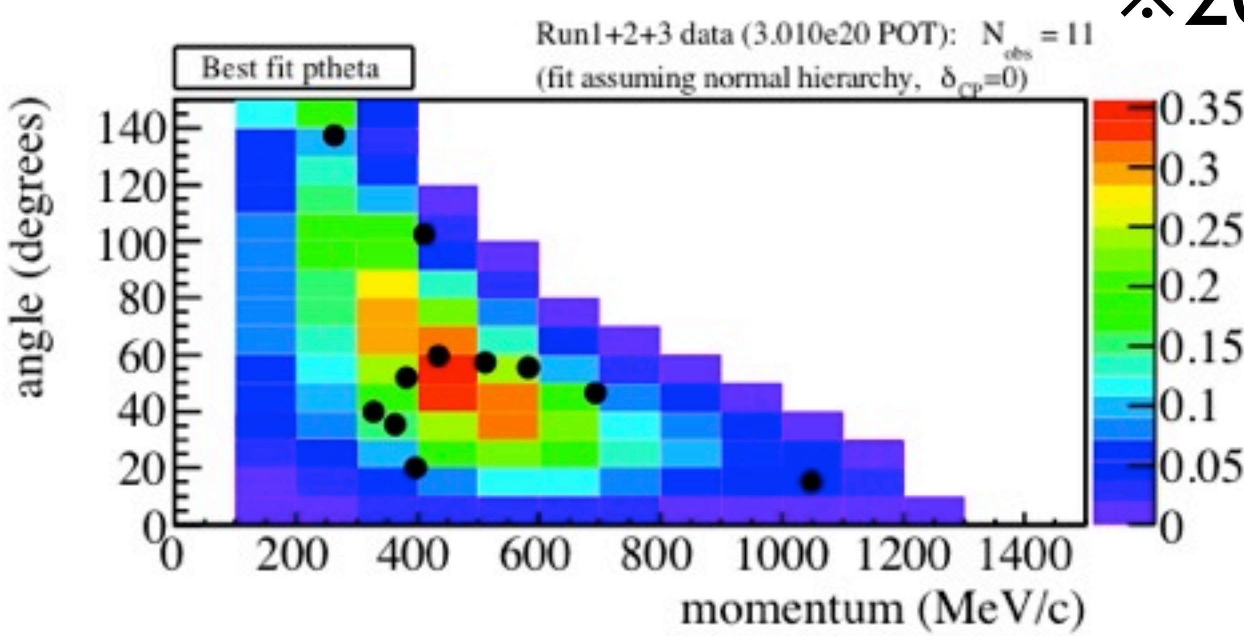


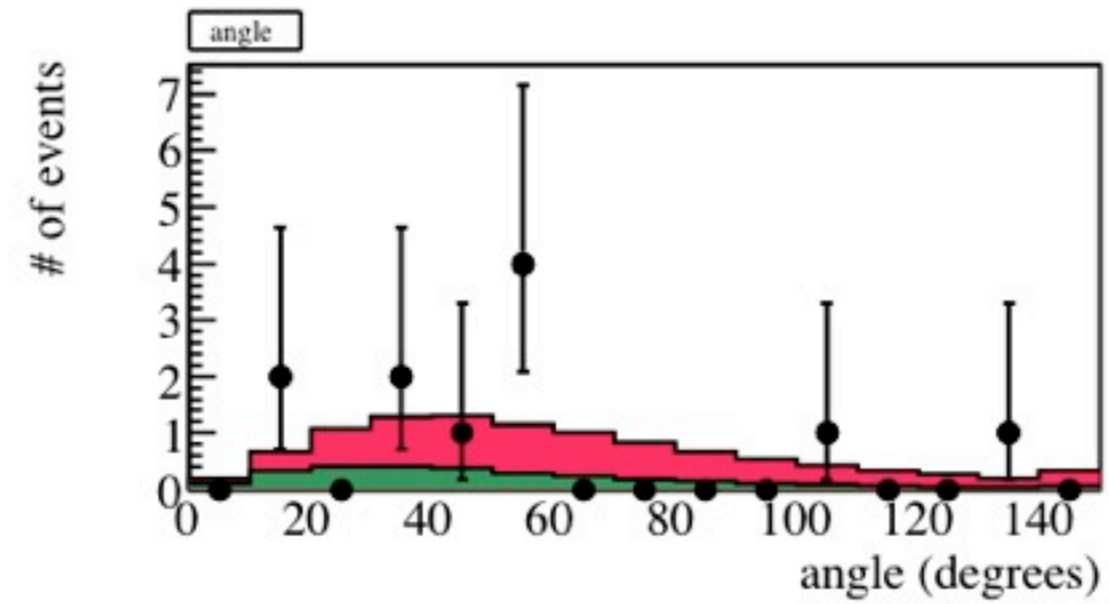
角度と運動量を使って解析

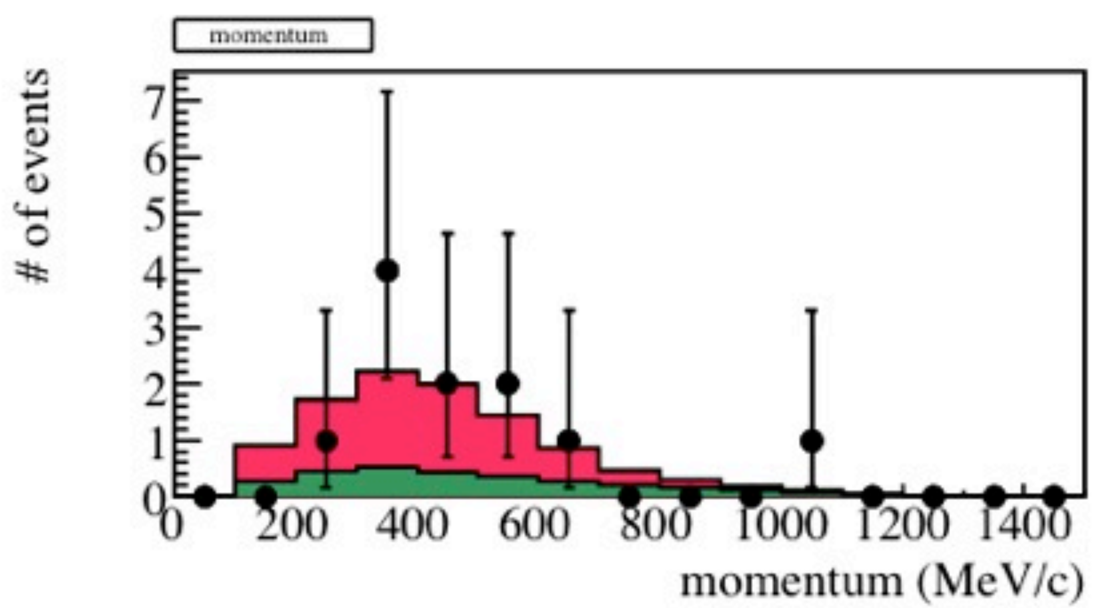
$$\mathcal{L}(N_{obs.};\boldsymbol{x};\boldsymbol{o},\boldsymbol{f}) = \mathcal{L}_{norm}(N_{obs.};\boldsymbol{o},\boldsymbol{f}) \times \mathcal{L}_{shape}(\boldsymbol{x};\boldsymbol{o},\boldsymbol{f}) \times \mathcal{L}_{syst.}(\boldsymbol{f})$$

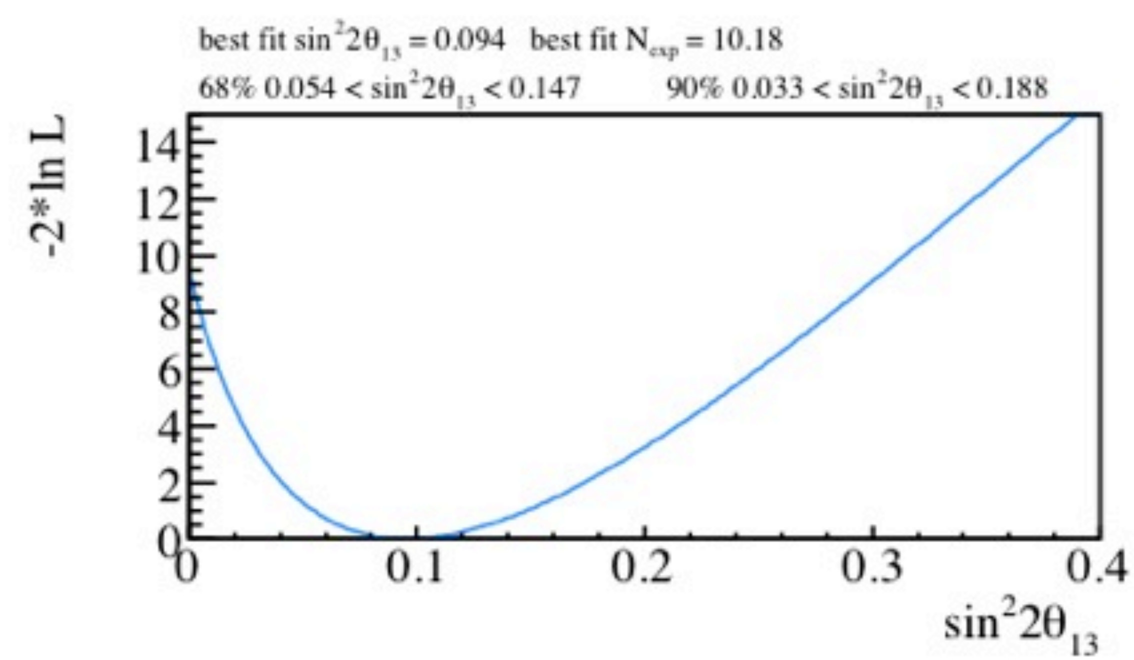
measurements, **oscillation parameters** **systematic parameters**

※2011年はイベント数の情報だけ









Results

Allowed region of $\sin^2 2\theta_{13}$ for each value of δ_{CP}

best fit w/ 68% CL error @δ_{CP}=0

normal hierarchy:

$$\sin^2 2\theta_{13} = 0.094^{+0.053}_{-0.040}$$

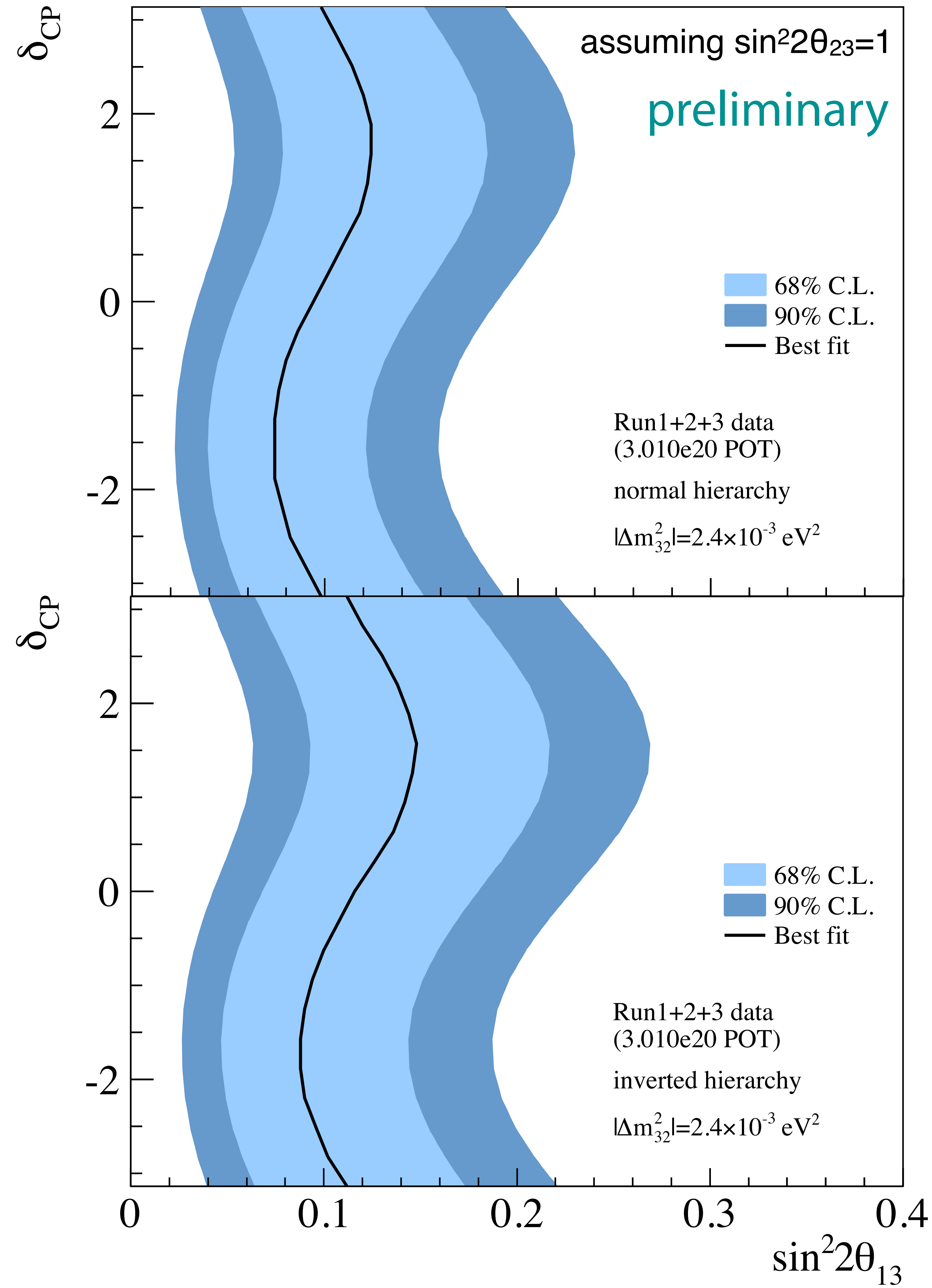
inverted hierarchy:

$$\sin^2 2\theta_{13} = 0.116^{+0.063}_{-0.049}$$

This result is consistent with rate+shape (rec. E_ν) method and rate only method

c.f 2011 result for normal (inverted) hierarchy

$$\sin^2 2\theta_{13} = 0.11^{+0.10}_{-0.06} \ (0.14^{+0.12}_{-0.07})$$

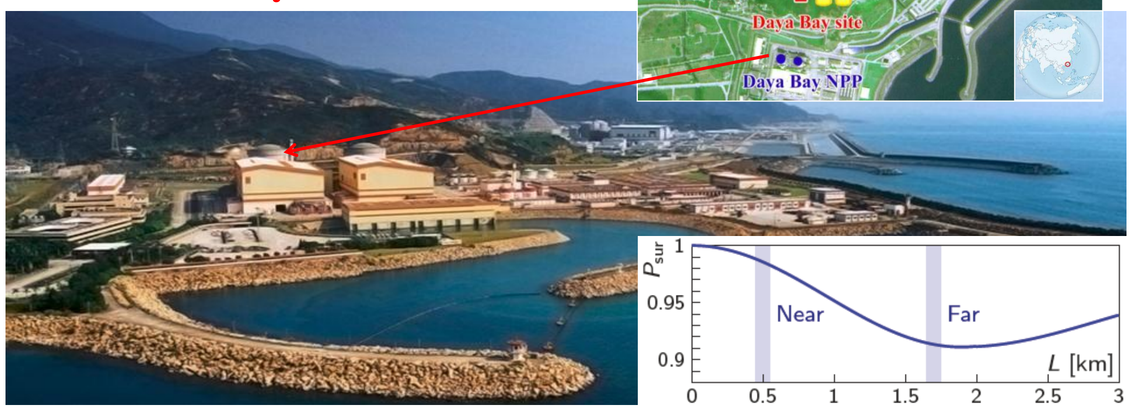


14

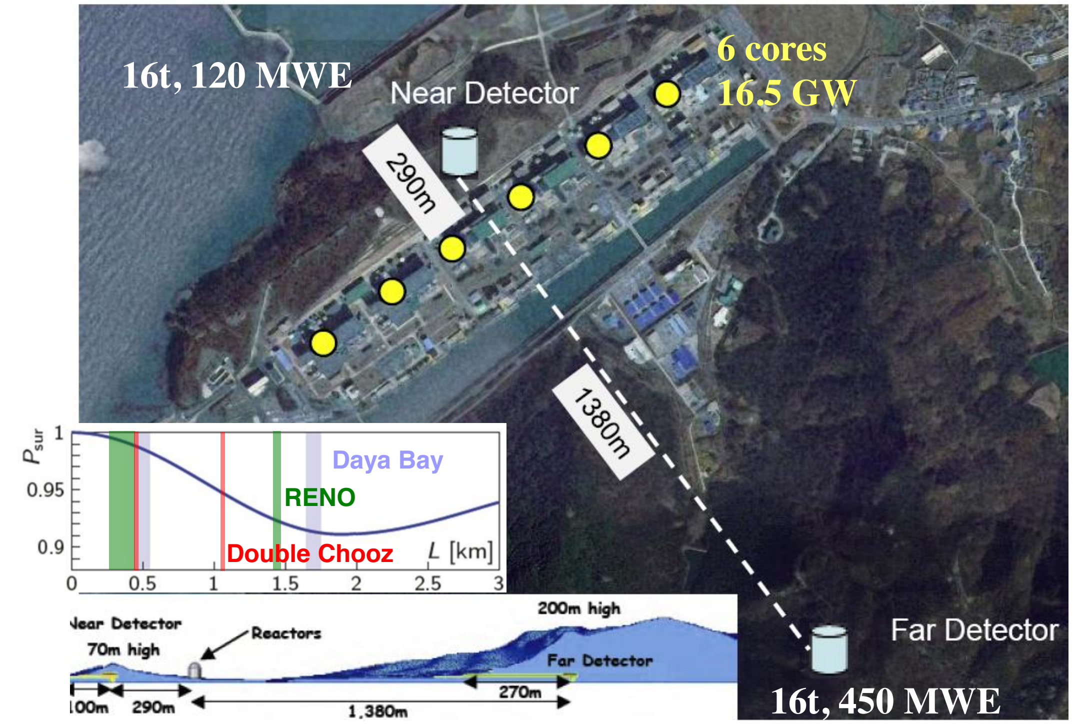
時間がないのでざっくりカット

The Daya Bay Experiment

- 6 reactor cores, 17.4 GW_{th}
- Relative measurement
  - 2 near sites, 1 far site
- Multiple detector modules
- Good cosmic shielding
  - 250 m.w.e @ near sites
  - 860 m.w.e @ far site
- Redundancy



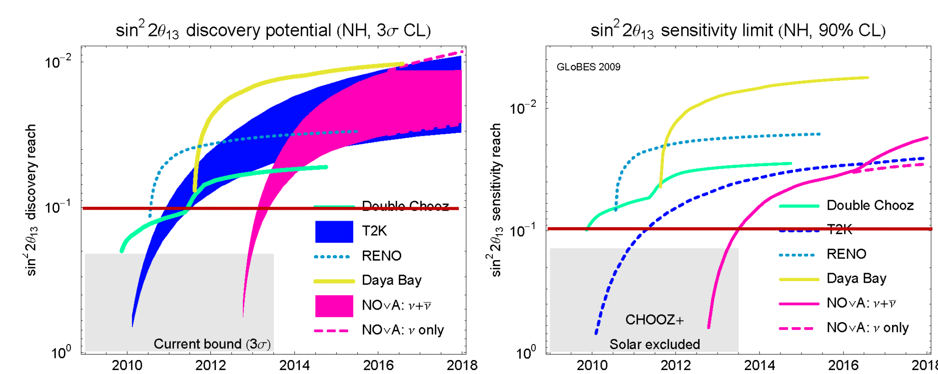
RENO



Double Chooz

Three on-going experiments

Experiment	Power (GW)	Detector(t) Near/Far	Overburden (m.w.e.) Near/Far	Sensitivity (3y,90%CL)
Daya Bay	17.4	40 / 80	250 / 860	~0.008
Double Chooz	8.5	8 / 8	120 / 300	~0.03
RENO	16.5	16 / 16	120 / 450	~0.02



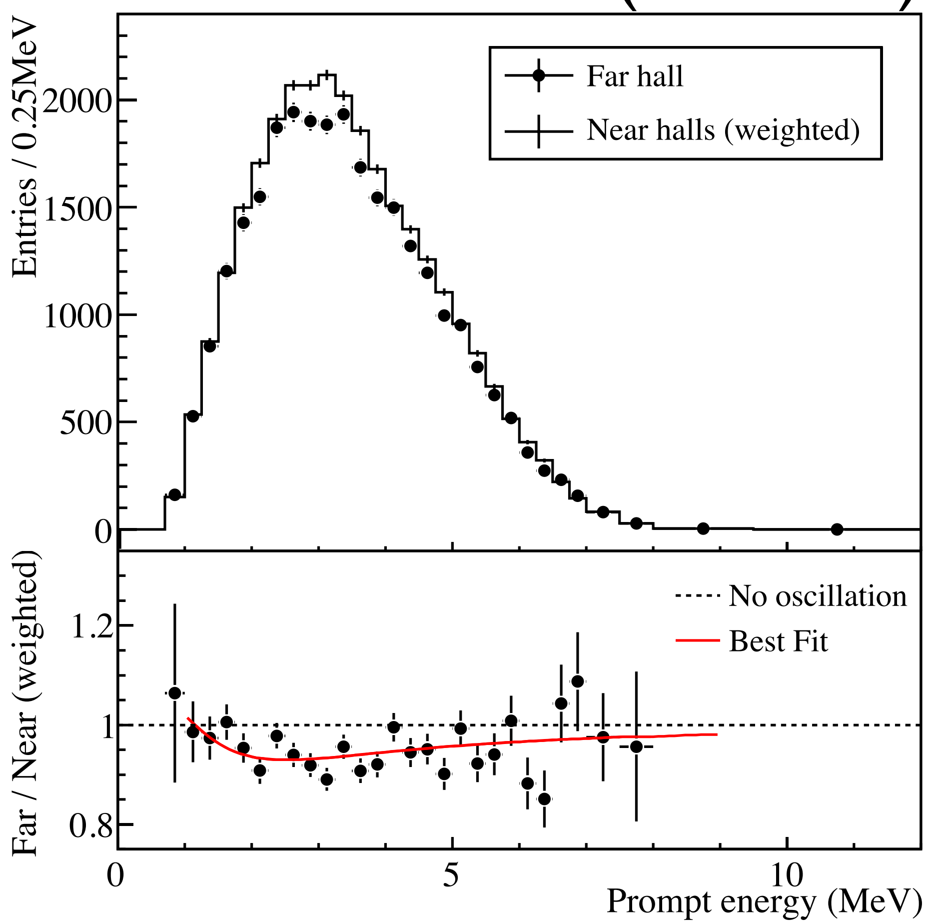
Huber et al. JHEP 0911:044, 2009

DayaBay, Double Choozについては
高エネルギーニュースに記事あります

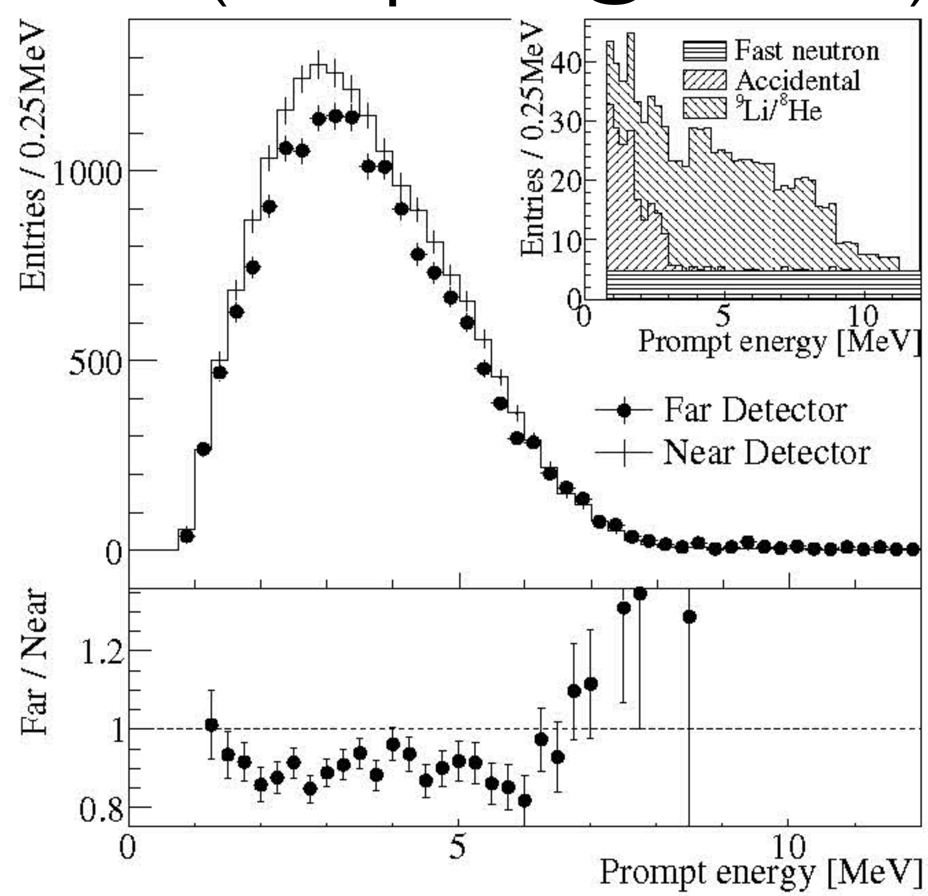
http://www.jahep.org/hepnews/

原子炉実験の最新結果

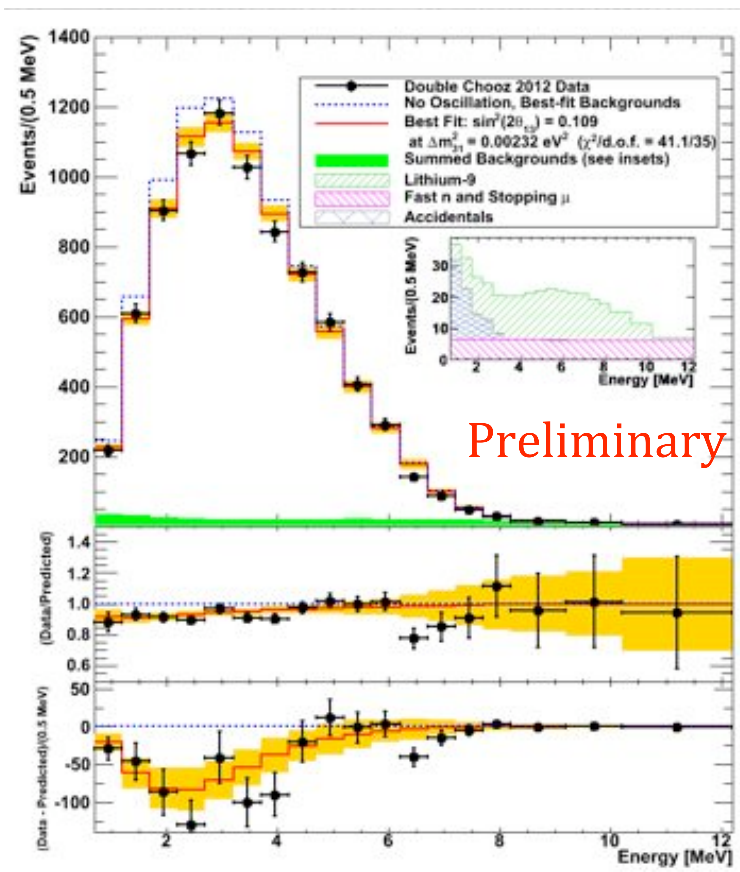
Daya Bay (NU2012)



RENO (No update @NU2012)



Double Chooz (NU2012)



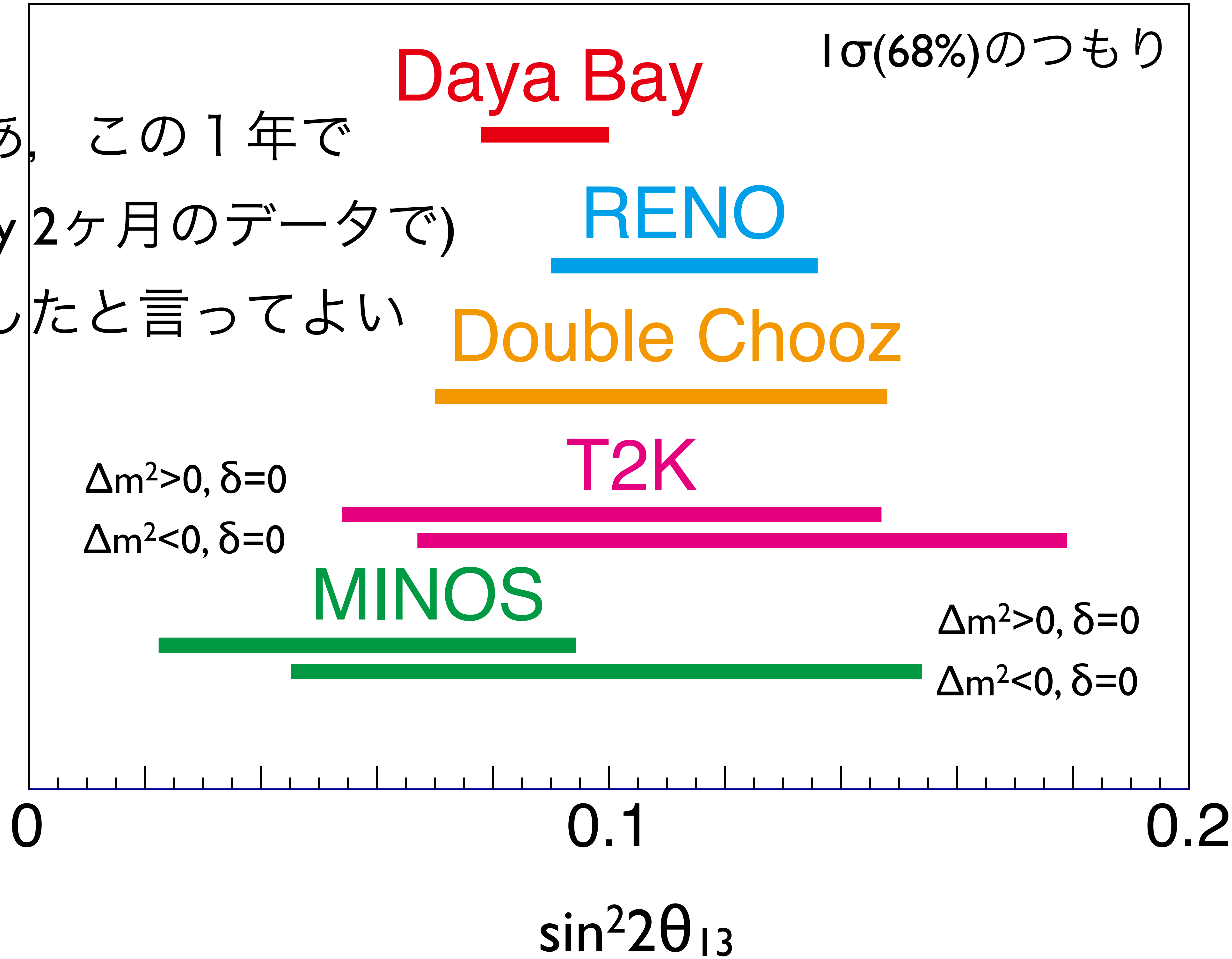
0.089±0.010(stat)±0.005(syst)

$0.113 \pm 0.013(stat) \pm 0.019(syst)$

0.109 ±0.030(stat) ±0.025(syst)

θ_{13}の現状

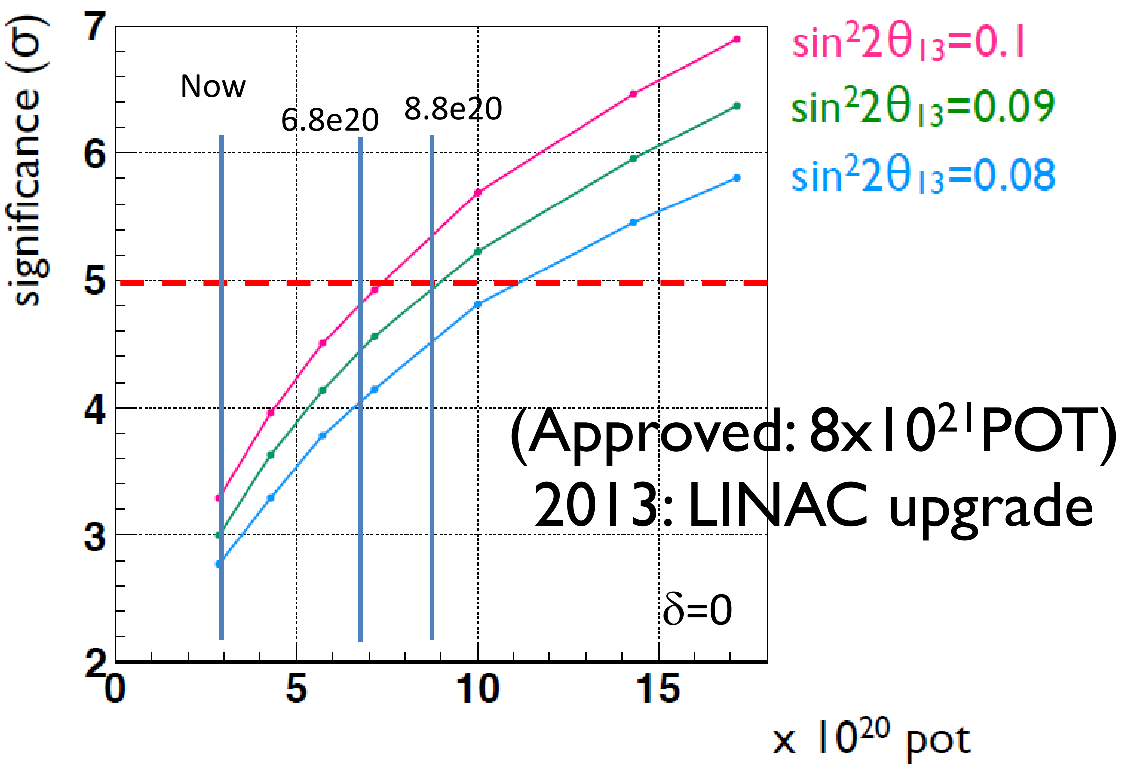
まあ，この１年で
(DayaBay 2ヶ月のデータで)
決着したと言ってよい



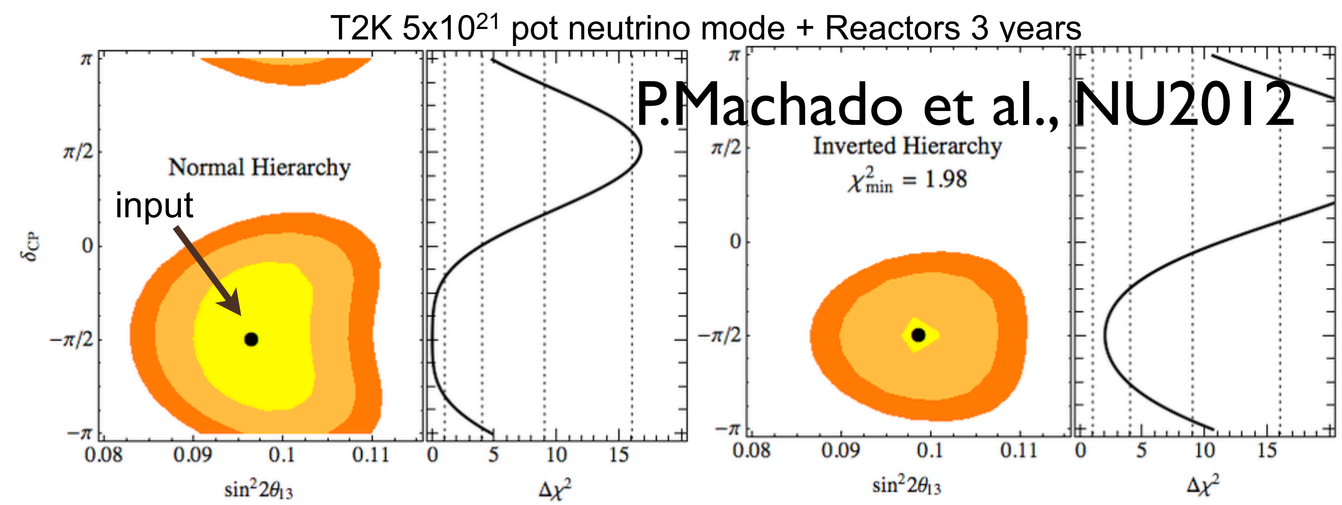
T2K今後

ν_e appearance

expected significance of ν_e appearance

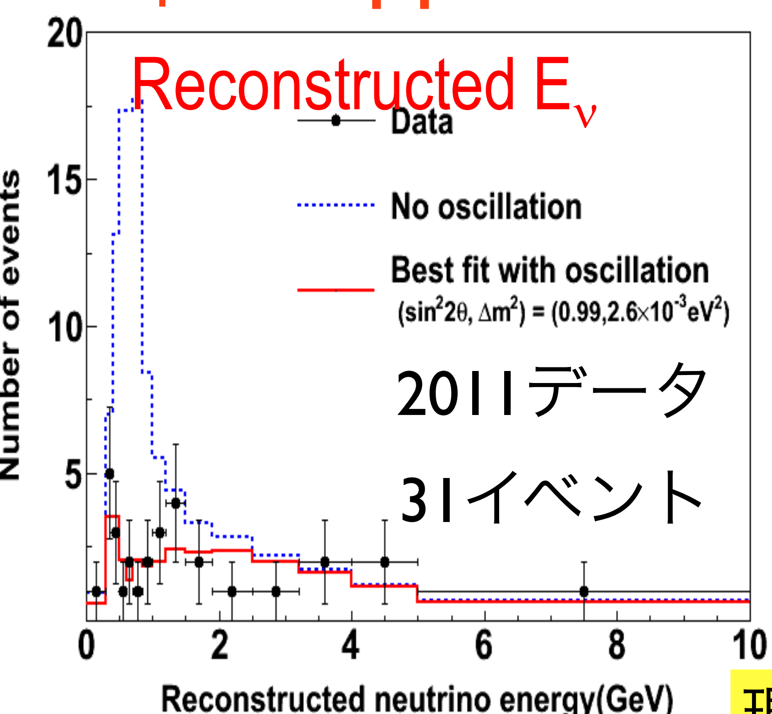


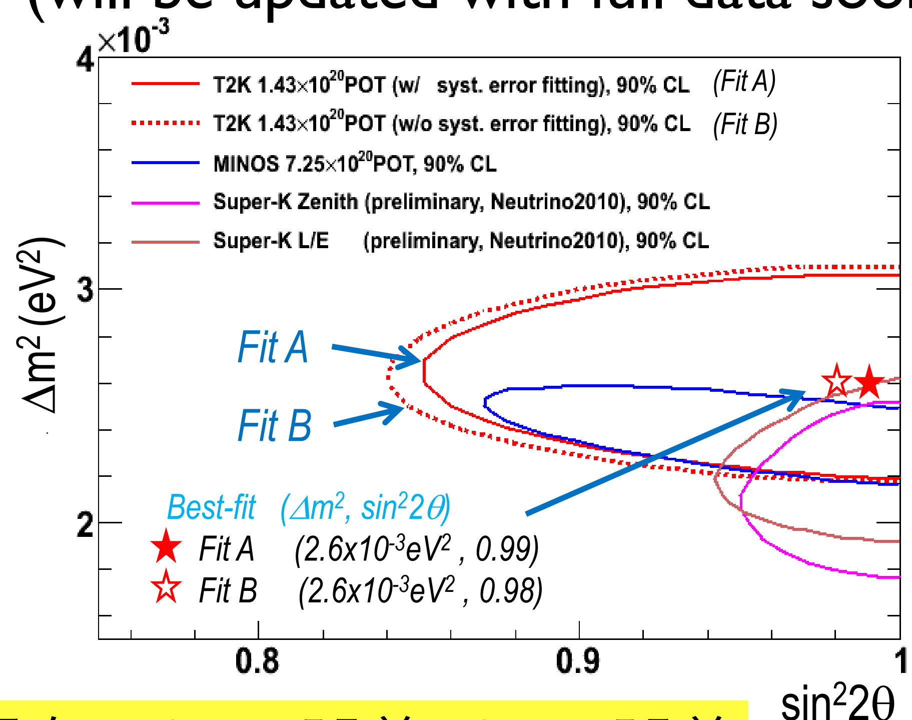
combination with reactor



ν_μ disappearance

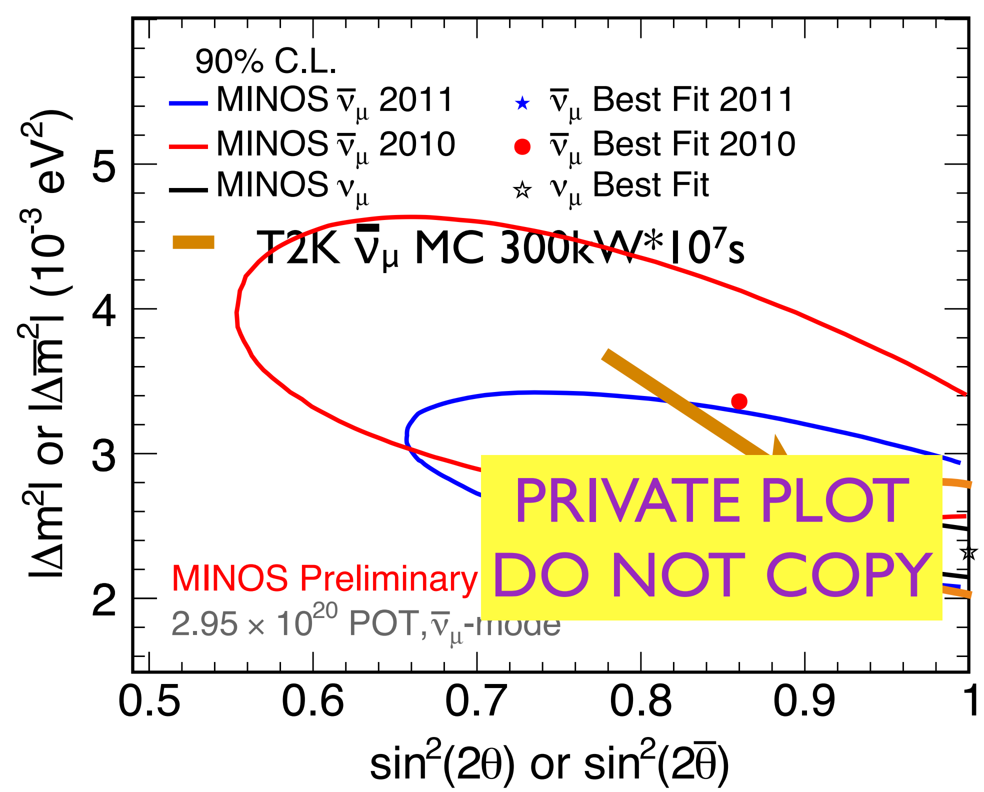
(will be updated with full data soon)





現在，θ_{23}の誤差~θ_{13}の誤差

anti-ν mode running?

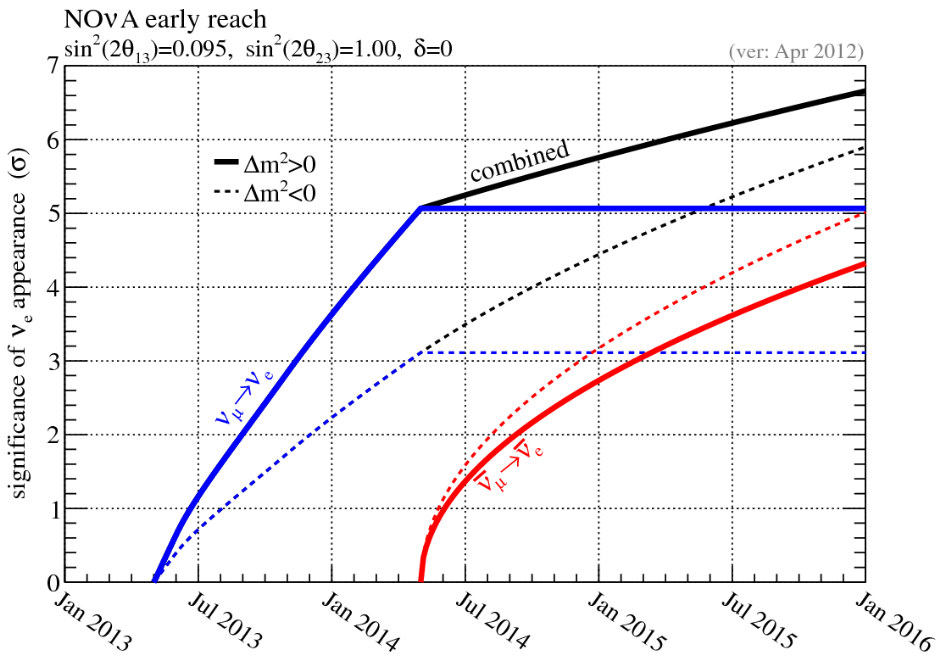


競争相手: NOνA

Early Reach

Will start with ν running

- Can switch to $\bar{\nu}_\mu$ any time, optimizing the run plan based on our or others' results
- 5σ observation of $\nu_\mu \rightarrow \nu_e$ in first year if NH
  (even with partial detector and beam commissioning!)



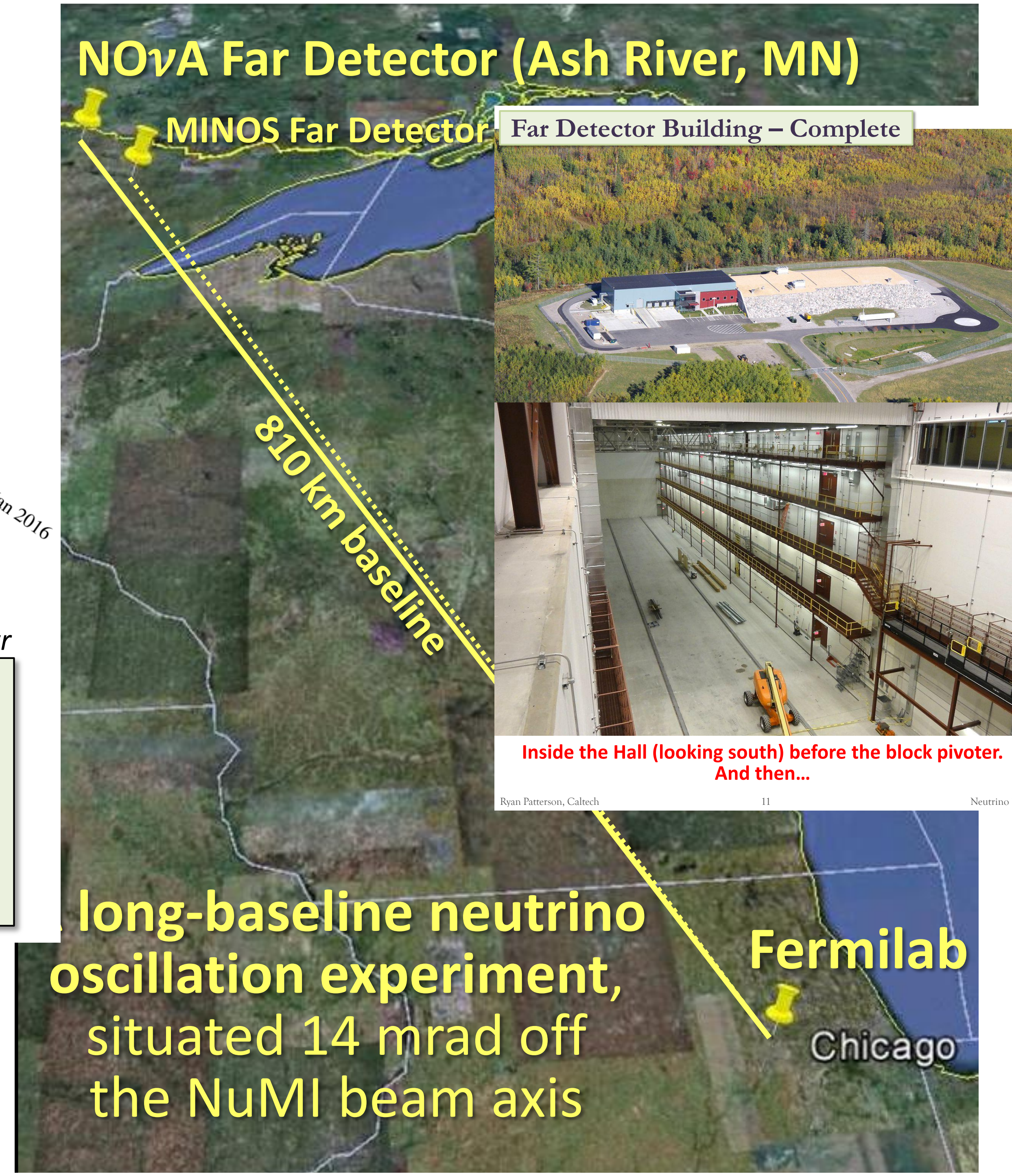
And beyond...

<u>*Nominal run plan: 3 yr (ν) + 3 yr ($\bar{\nu}$)*</u> (with 6×10^{20} p.o.t./year)

- In this talk: using *earlier analysis methods*, but including new θ_{13} knowledge
  ⇨ Taking $\sin^2(2\theta_{13}) = 0.095$
- Representative event counts for $\nu_\mu \rightarrow \nu_e$ analysis ⟶
  ⇨ *These depend greatly on the specific oscillation parameters*
- Signal efficiency: 45%
  NC fake rate: 0.1%

3 yr + 3 yr

beam = ν		$\bar{\nu}$
NC	19	10
ν_μ CC	5	<1
ν_e CC	8	5
tot. BG	32	15
$\nu_\mu \rightarrow \nu_e$	68	32



うかうかしてられない。

もっとビームを！

さて，これからX年

（で，発表時間どのくらい残ってるか）

今後のニュートリノ振動主なトピック

- θ_{23} (maximal? octant?)
  - 現在はSK大気ν→今後は加速器も(T2K, NOvA,)
- Mass hierarchy
  - こっちの方がCPより大事という人もいるみたい?
- CP violation (exists? PMNS?)
  - クォークではCKM phase起源かどうかの検証に何十年もかかった。
  - ニュートリノに関して，クォークの混合行列からのナイーブな推測は…

$\nu_\mu \rightarrow \nu_e$ 振動確率

$$
\begin{aligned}
P(\nu_\mu \rightarrow \nu_e) \;=\; & 4C_{13}^2 S_{13}^2 S_{23}^2 \cdot \sin^2 \Delta_{31} \\
& +8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21} \\
& -8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \cdot \sin\Delta_{32} \cdot \sin\Delta_{31} \cdot \sin\Delta_{21} \\
& +4S_{12}^2 C_{13}^2 (C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta) \cdot \sin^2 \Delta_{21} \\
& -8C_{13}^2 S_{12}^2 S_{23}^2 \cdot \frac{aL}{4E_\nu} (1 - 2S_{13}^2) \cdot \cos\Delta_{32} \cdot \sin\Delta_{31} \\
& +8C_{13}^2 S_{13}^2 S_{23}^2 \frac{a}{\Delta m_{13}^2} (1 - 2S_{13}^2) \sin^2 \Delta_{31}
\end{aligned}
$$

Leading

CP violating (flips sign for $\bar{\nu}$)

Solar

Matter effect

$$a = G_F N_e \sqrt{2} \simeq (4000\ \mathrm{km})^{-1}$$

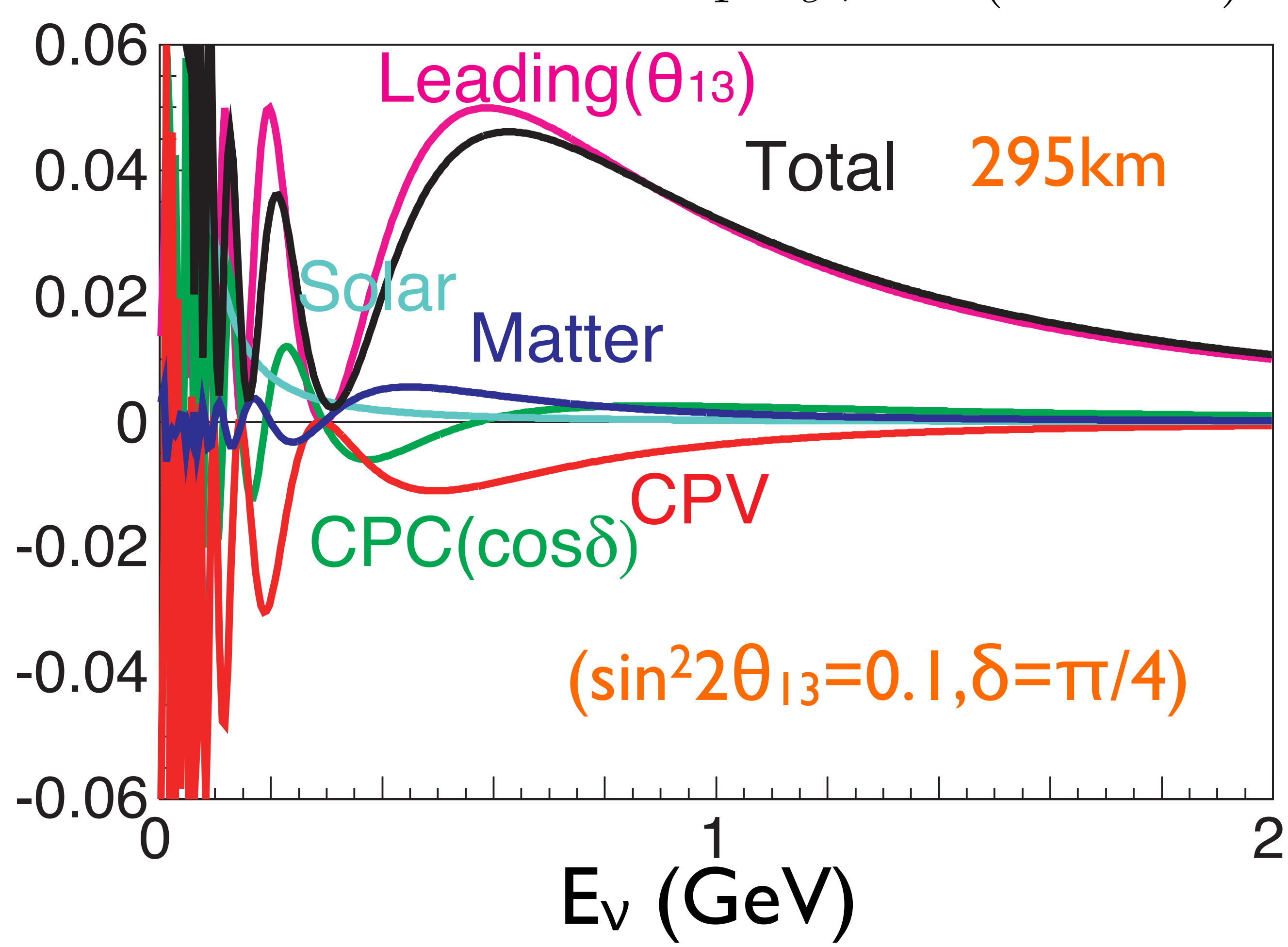
Leading term $\propto \sin^2 2\theta_{13}$

CPV term $\propto \sin 2\theta_{13}$

Matter effect $\propto \sin^2 2\theta_{13}$

For larger $\sin^2 2\theta_{13}$
signal ↑, CP asymmetry ↓
matter/CP ↑

matter/CP~0.3 for $\sin^2 2\theta_{13}$=0.1 @L=295km

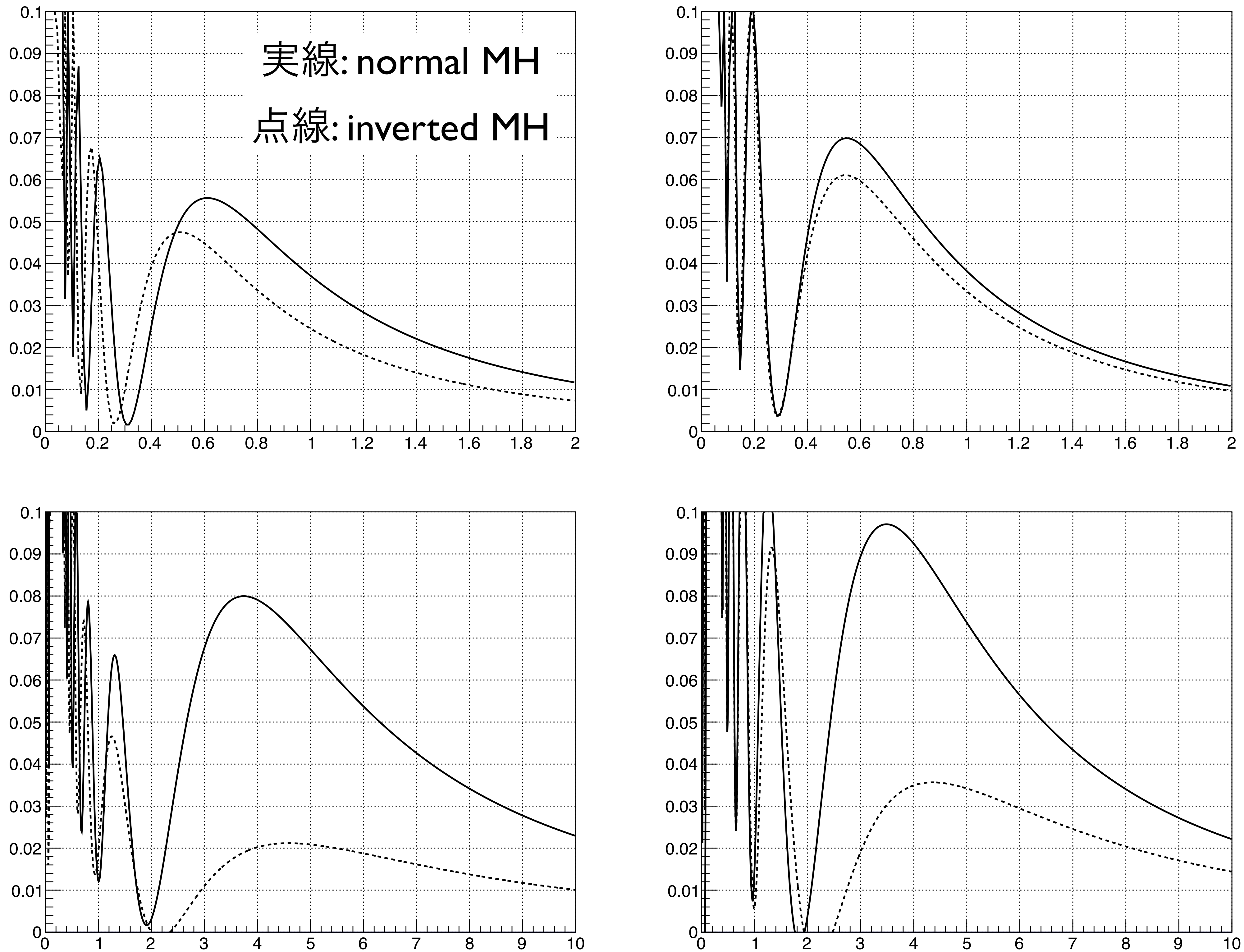


$\nu_\mu \rightarrow \nu_e$振動確率

δ=0　　δ=3/2 π

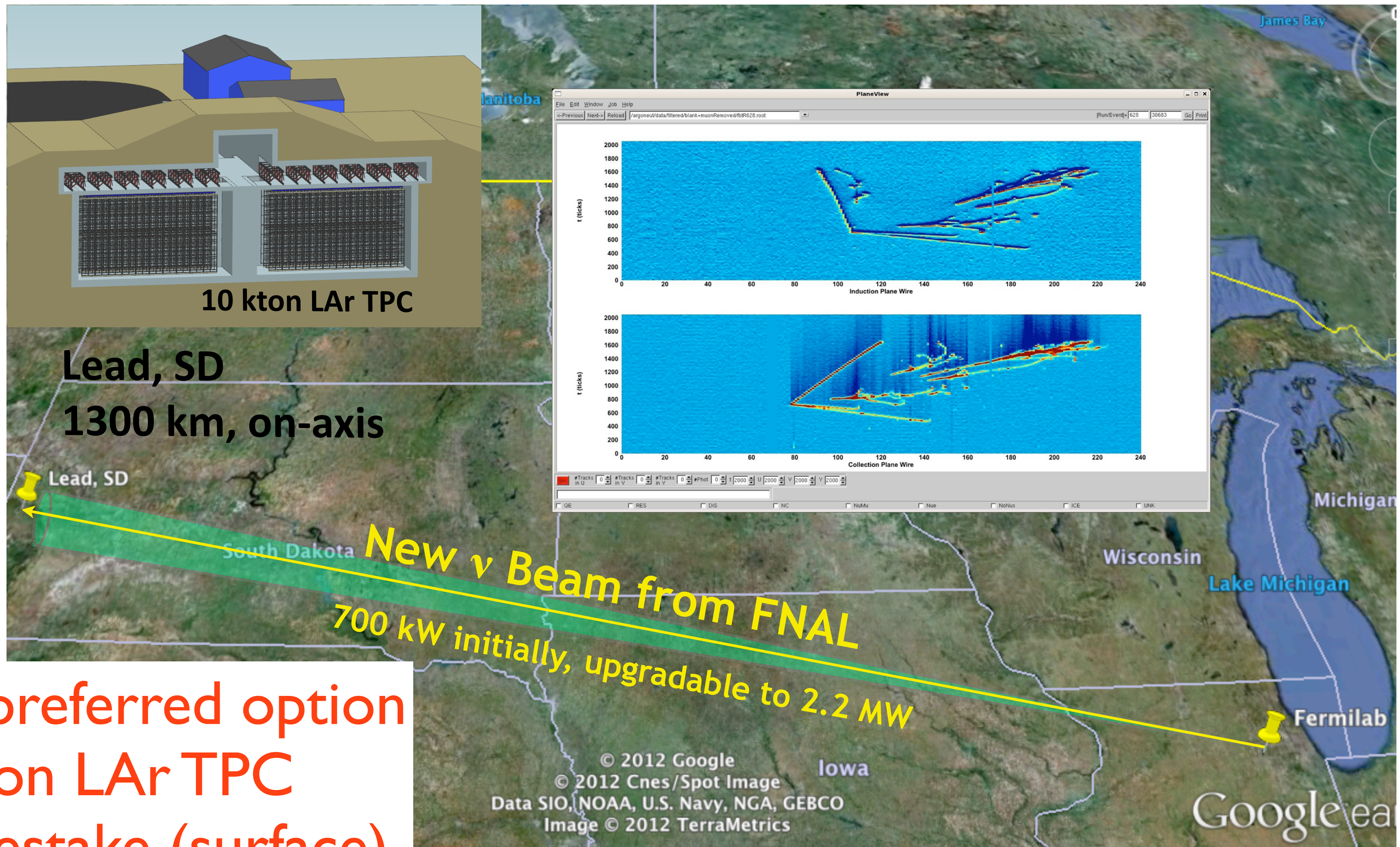
295km

2000km



アメリカ: LBNE

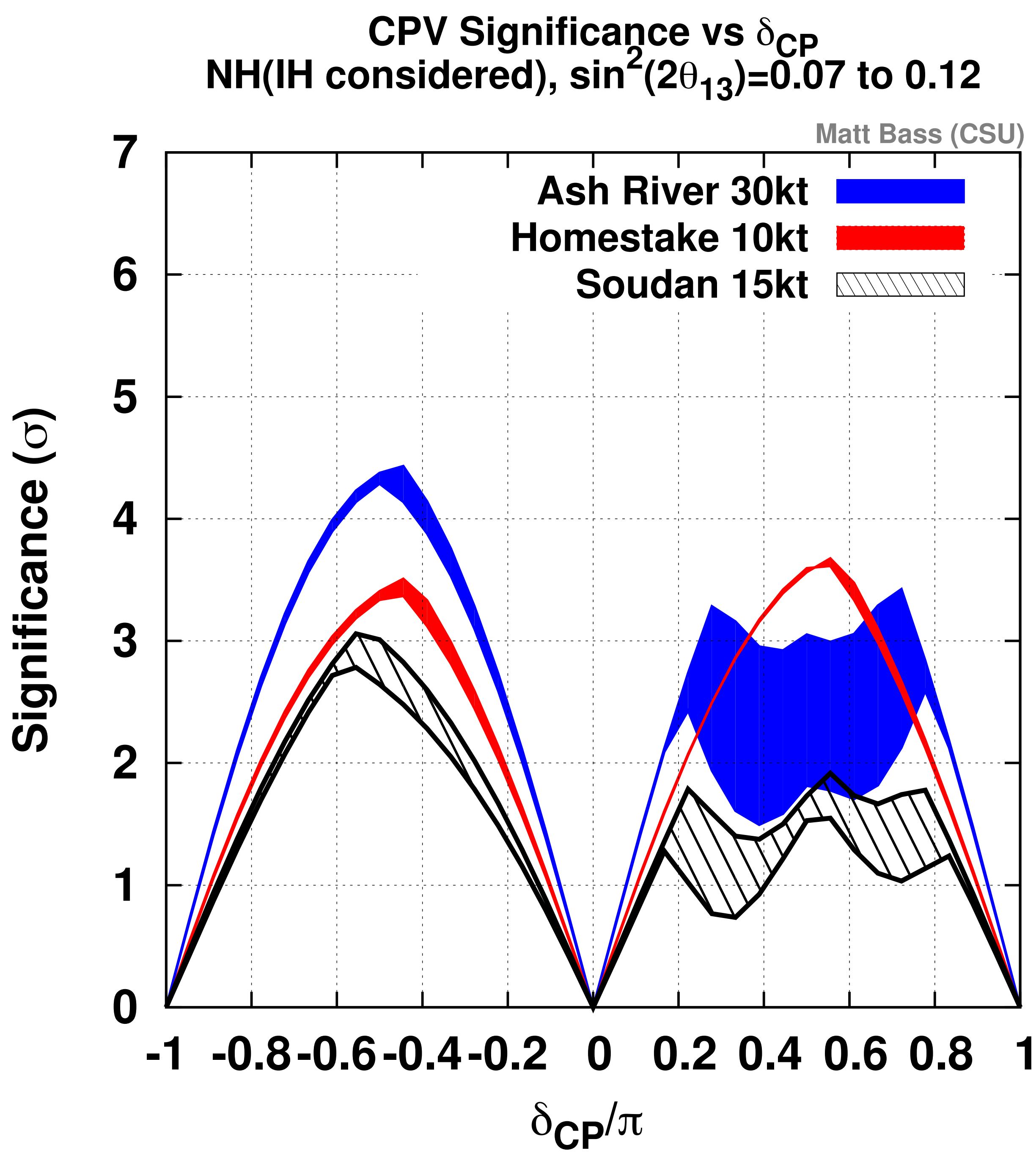
The Long-Baseline Neutrino Experiment (LBNE)

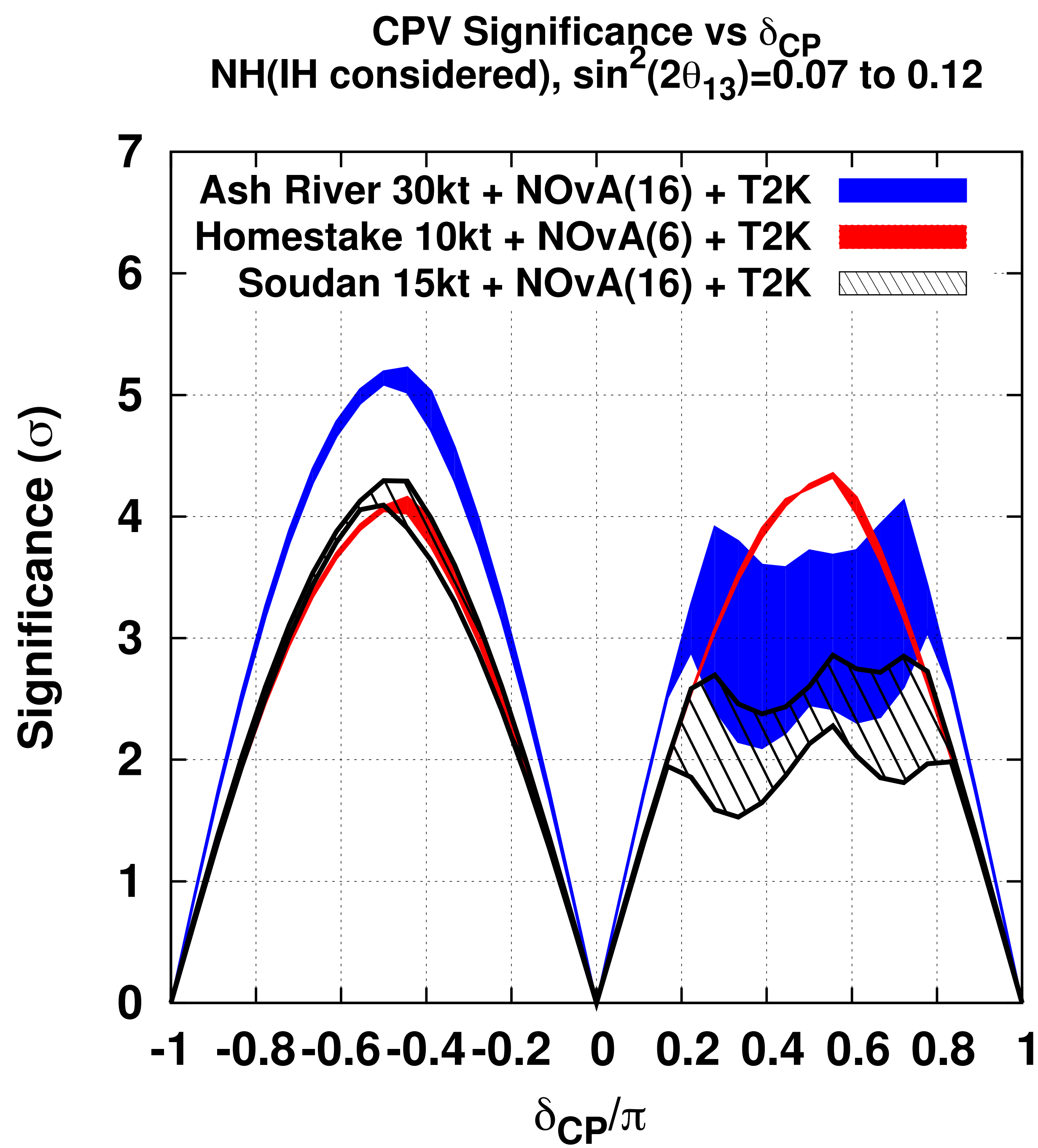


'Phase1' preferred option
10kton LAr TPC
@ Homestake (surface)

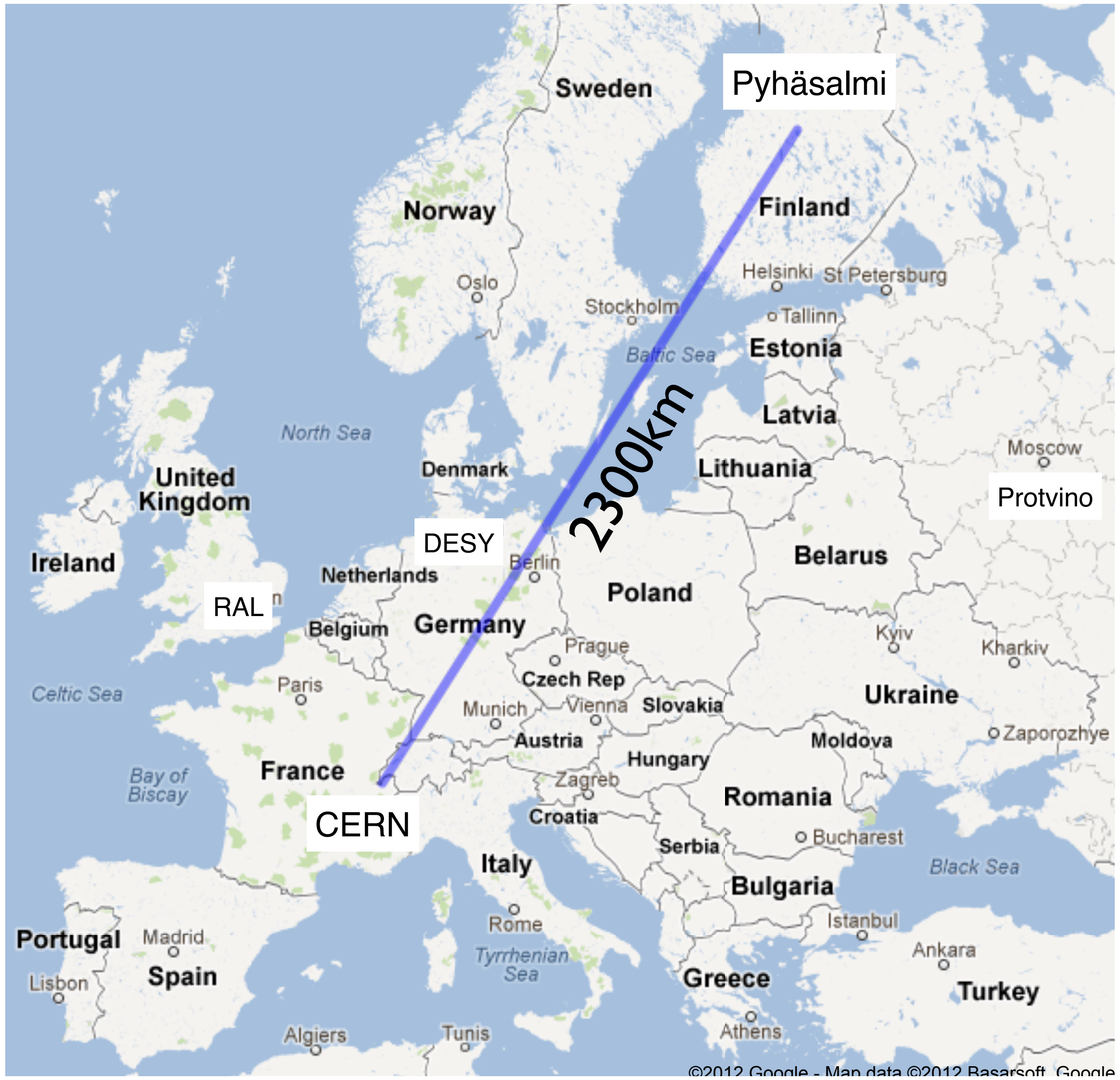
Jonathan Paley, ANL HEP Division 19

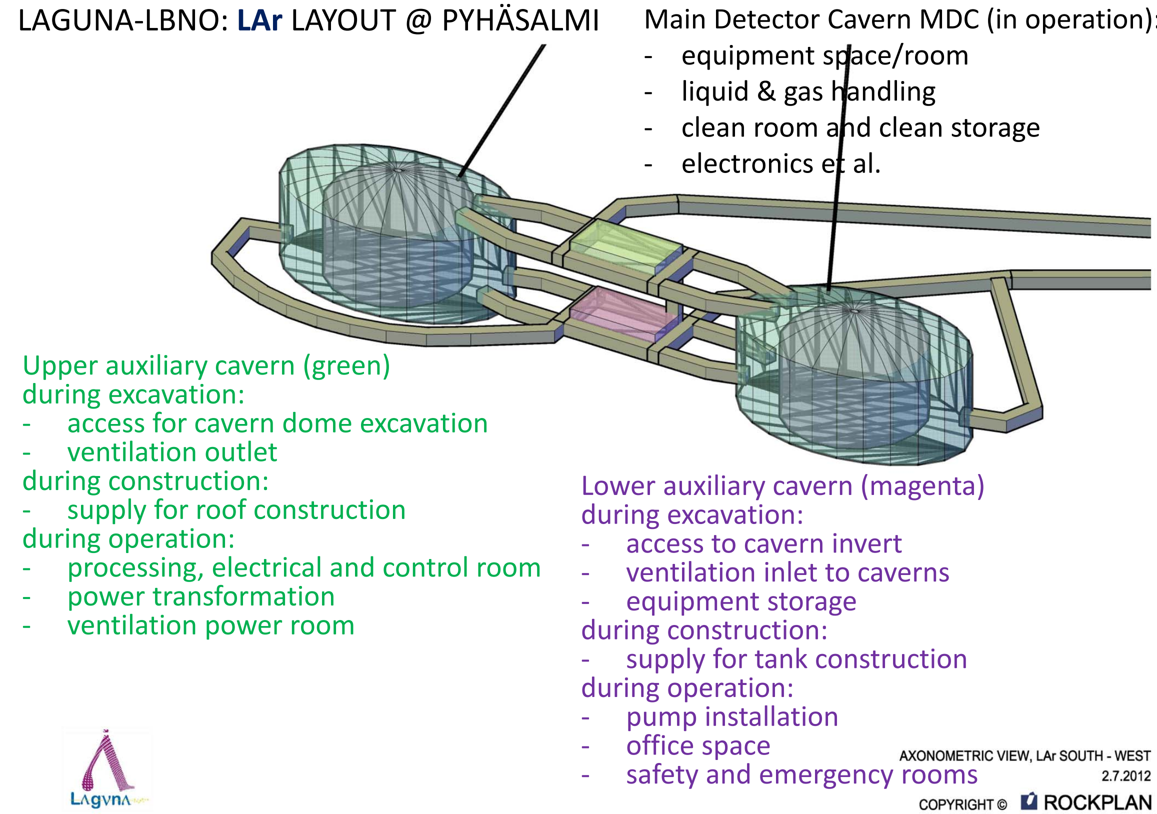
LBNE Measurement of CP-violation





ヨーロッパ: LAGUNA-LBNO





EoI to CERN-SPSC, June 2012

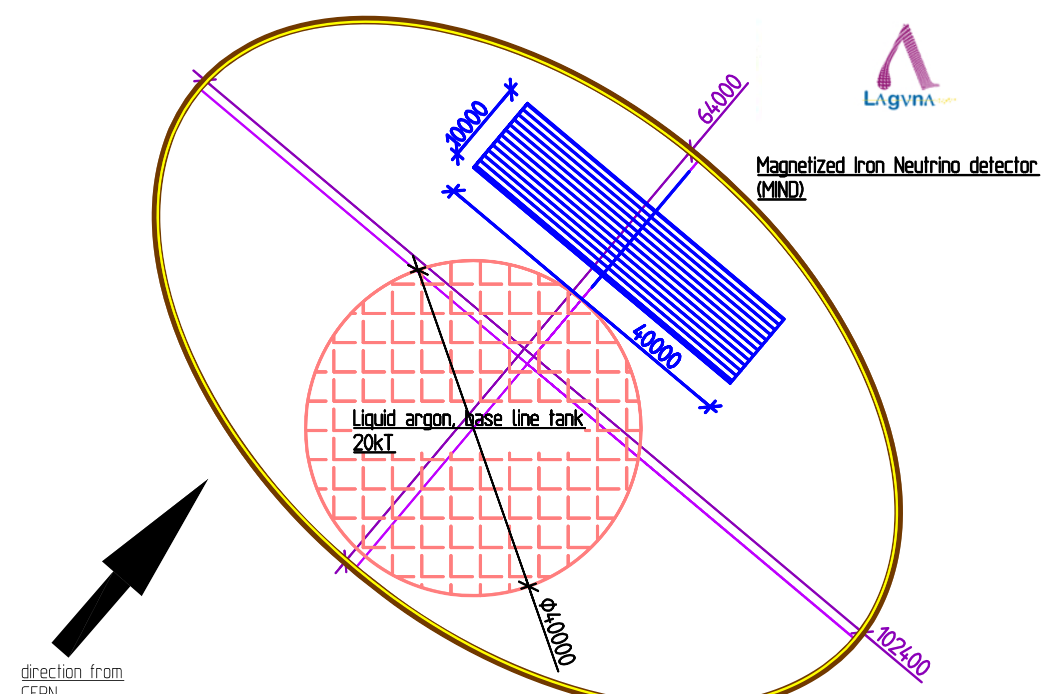
EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Expression of Interest

for a very long baseline neutrino oscillation experiment

(LBNO)

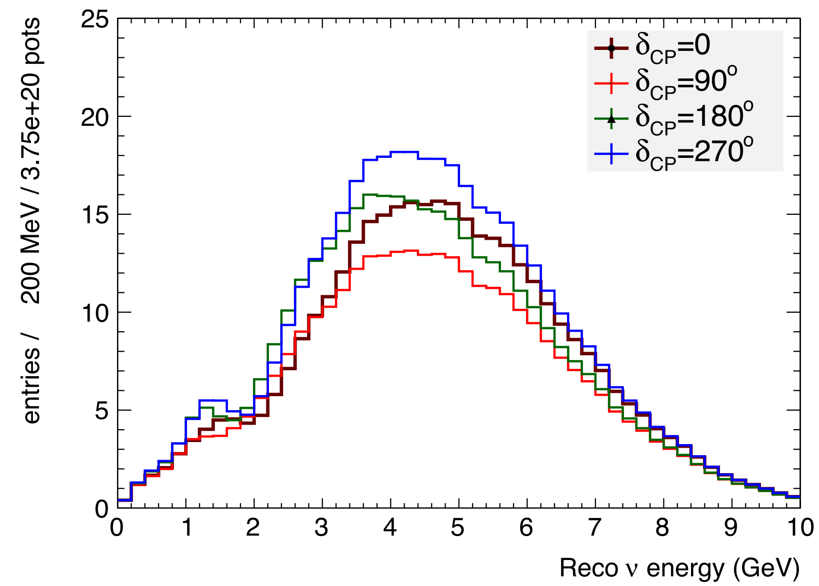
Plan: proposal by end of 2014

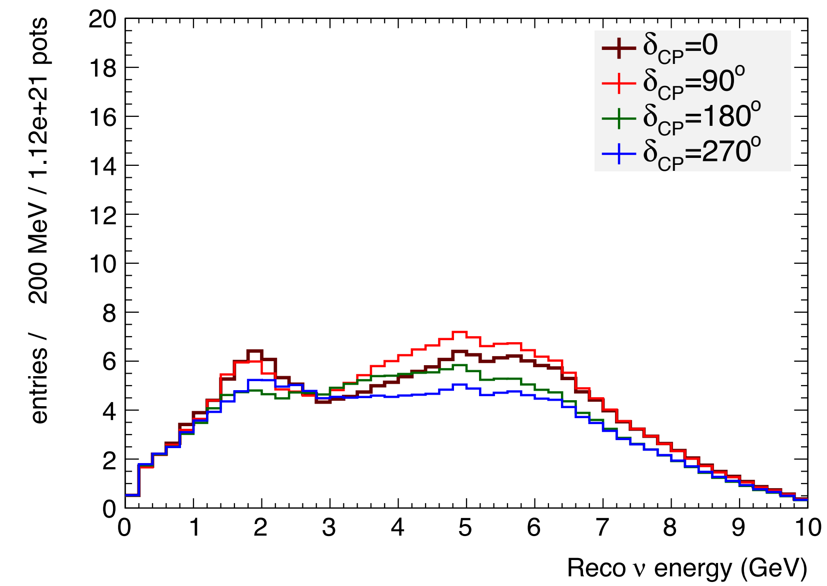


20kton LAr TPC for 1st phase

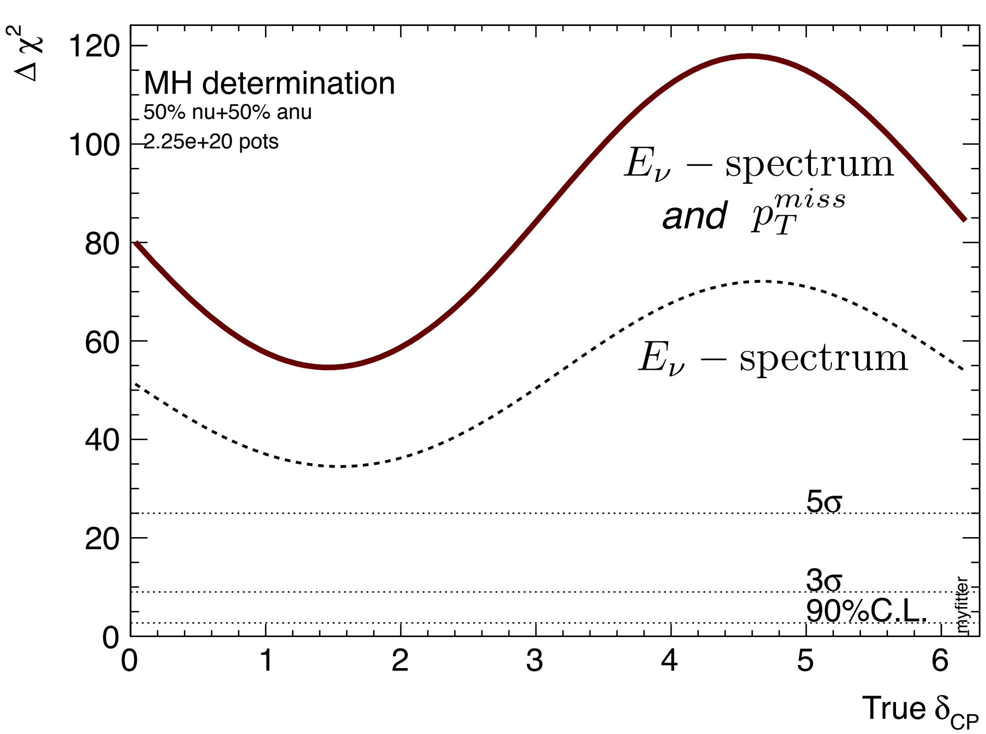
LAGUNA-LBNO

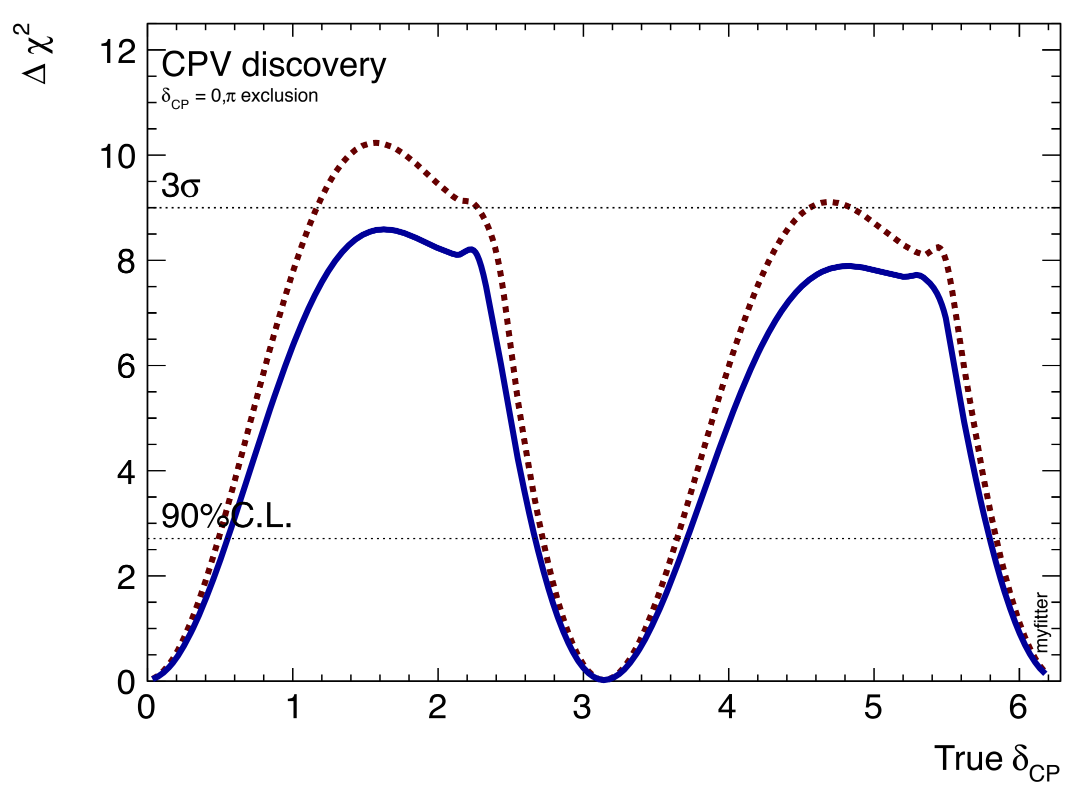
Reconstructed ν energy





From EoI

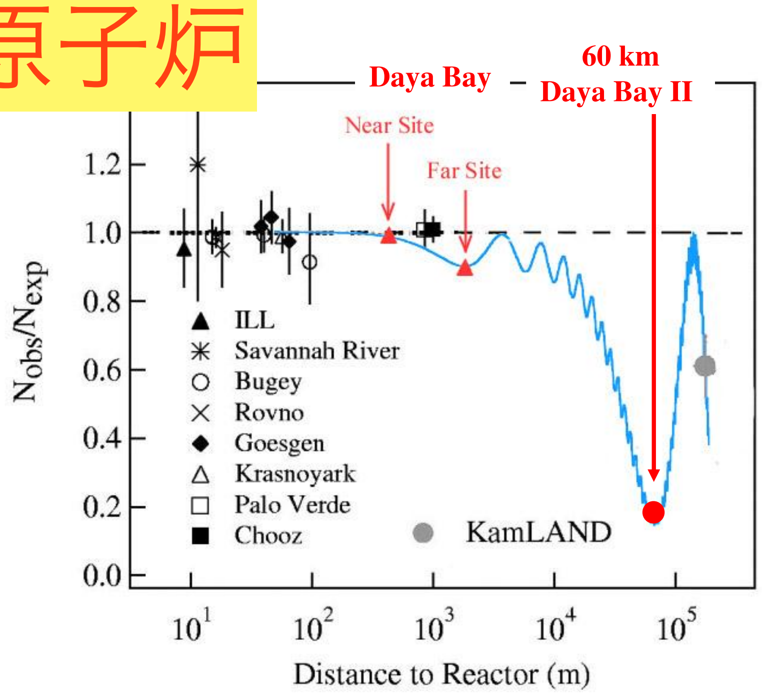




その他いろいろ（主にmass hierarchy）

Next Step: Daya Bay-II Experiment

原子炉



- 20 kton LS detector
- 3%/√E resolution
- Rich physics
  - ⇨ Mass hierarchy
  - ⇨ Precision measurement of 4 oscillation parameters to <1%
  - ⇨ Supernovae neutrino
  - ⇨ Geoneutrino
  - ⇨ Sterile neutrino
  - ⇨ Atmospheric neutrinos
  - ⇨ Exotic searches

Talk by Y.F. Wang at ICFA seminar 2008, Neutel 2011; by J. Cao at Nutel 2009, NuTurn 2012 ;
Paper by L. Zhan, Y.F. Wang, J. Cao, L.J. Wen, PRD78:111103,2008; PRD79:073007,2009

Atmospheric ν @PINGU

南極

Doug Cowen, NuSky, ICTP, June 2011

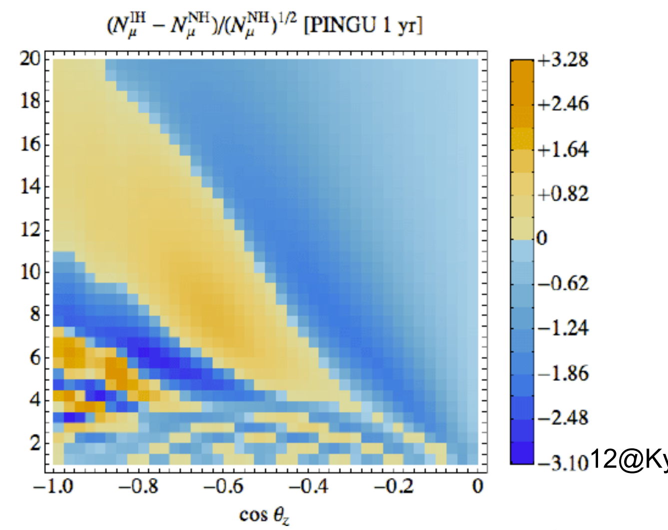
Akhmedov-Razzaque-Smirnov June 12

*IceCube → DeepCore → **PINGU***

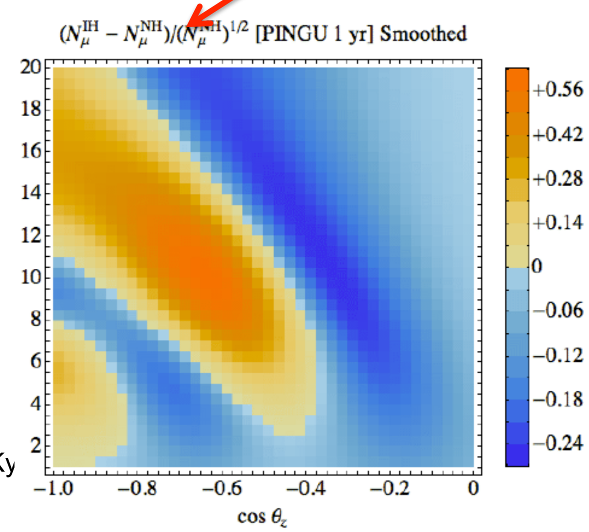
- *~20 additional strings within DeepCore*
- *lower threshold to few GeV*
- *~10 Mt effective volume*
- *construction within 1 yr, ~$25 M*

MH resolution
3σ-11σ in 5 years !

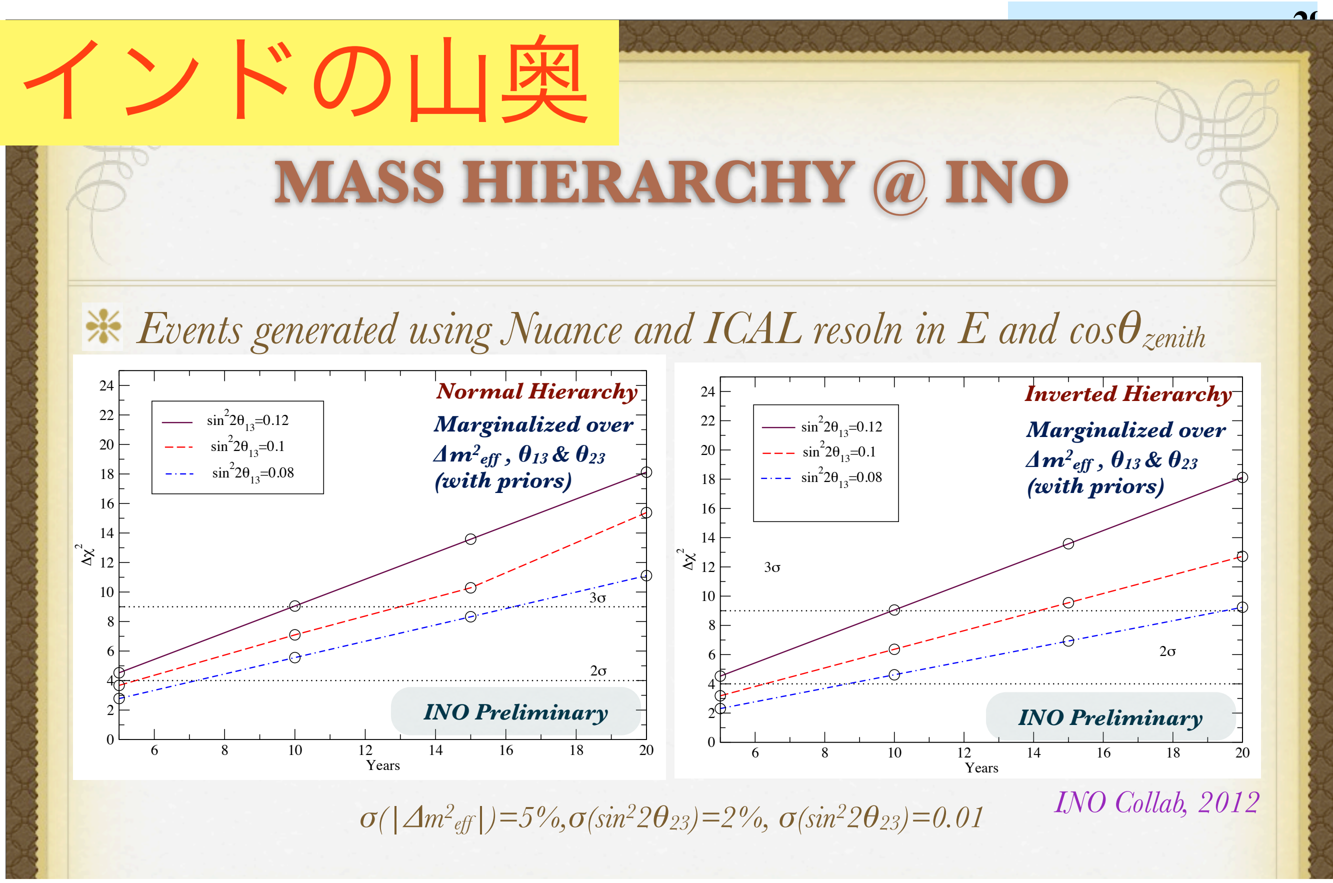
σ_E=2 GeV
σ_θ=11.25°



12@Ky

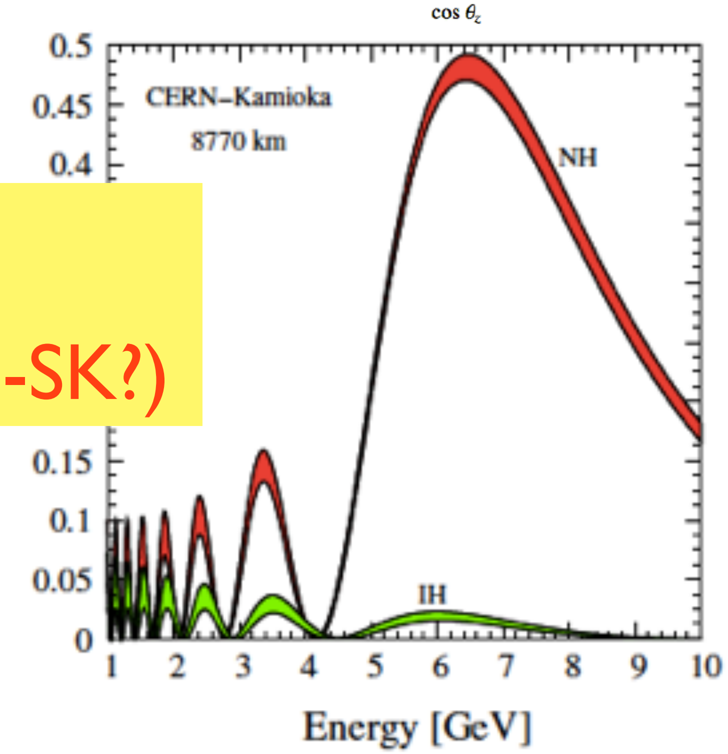


インドの山奥



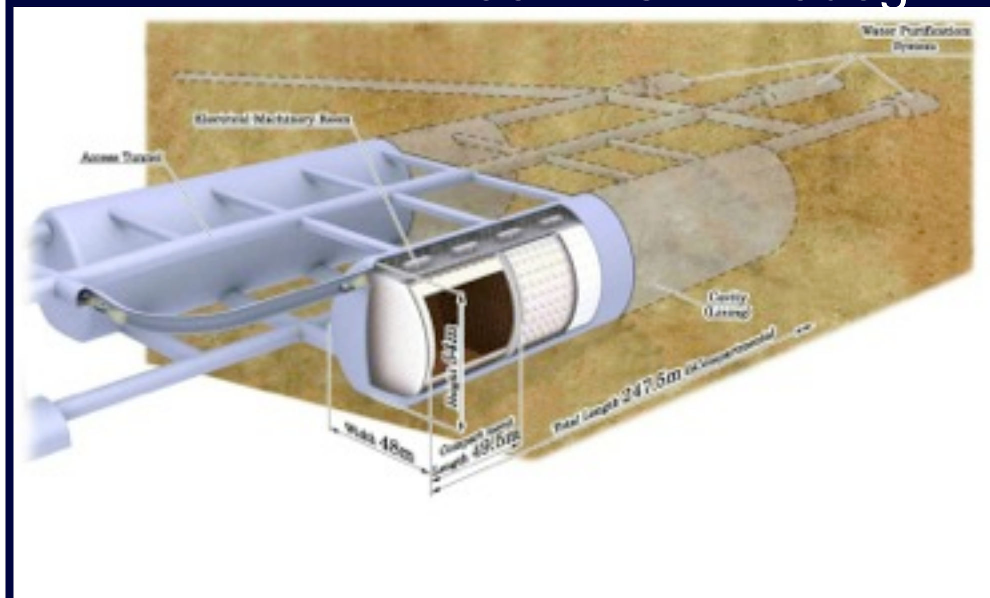
加速器

(って，CERN-SK?)



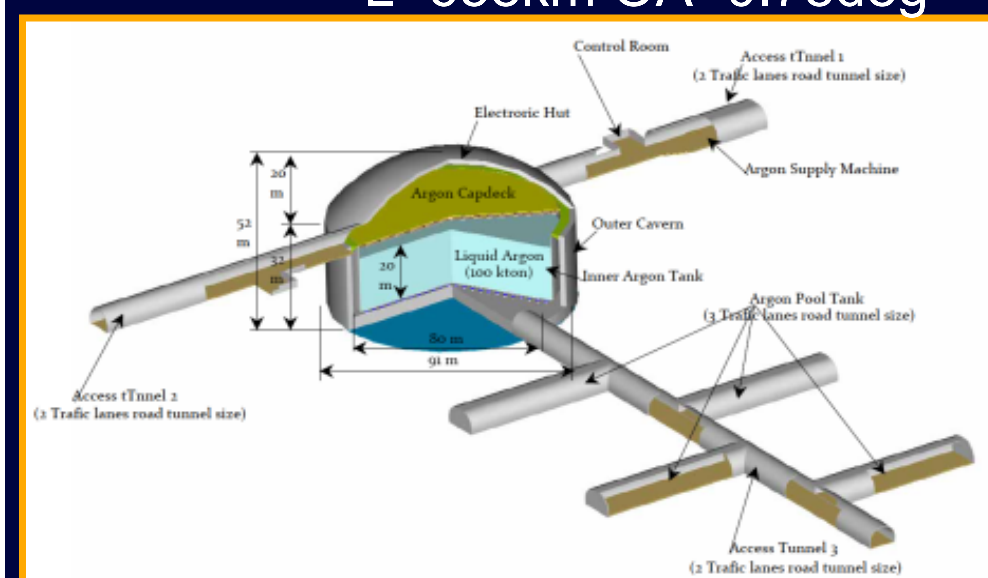
日本

J-PARC+HK @ Kamioka
L=295km OA=2.5deg

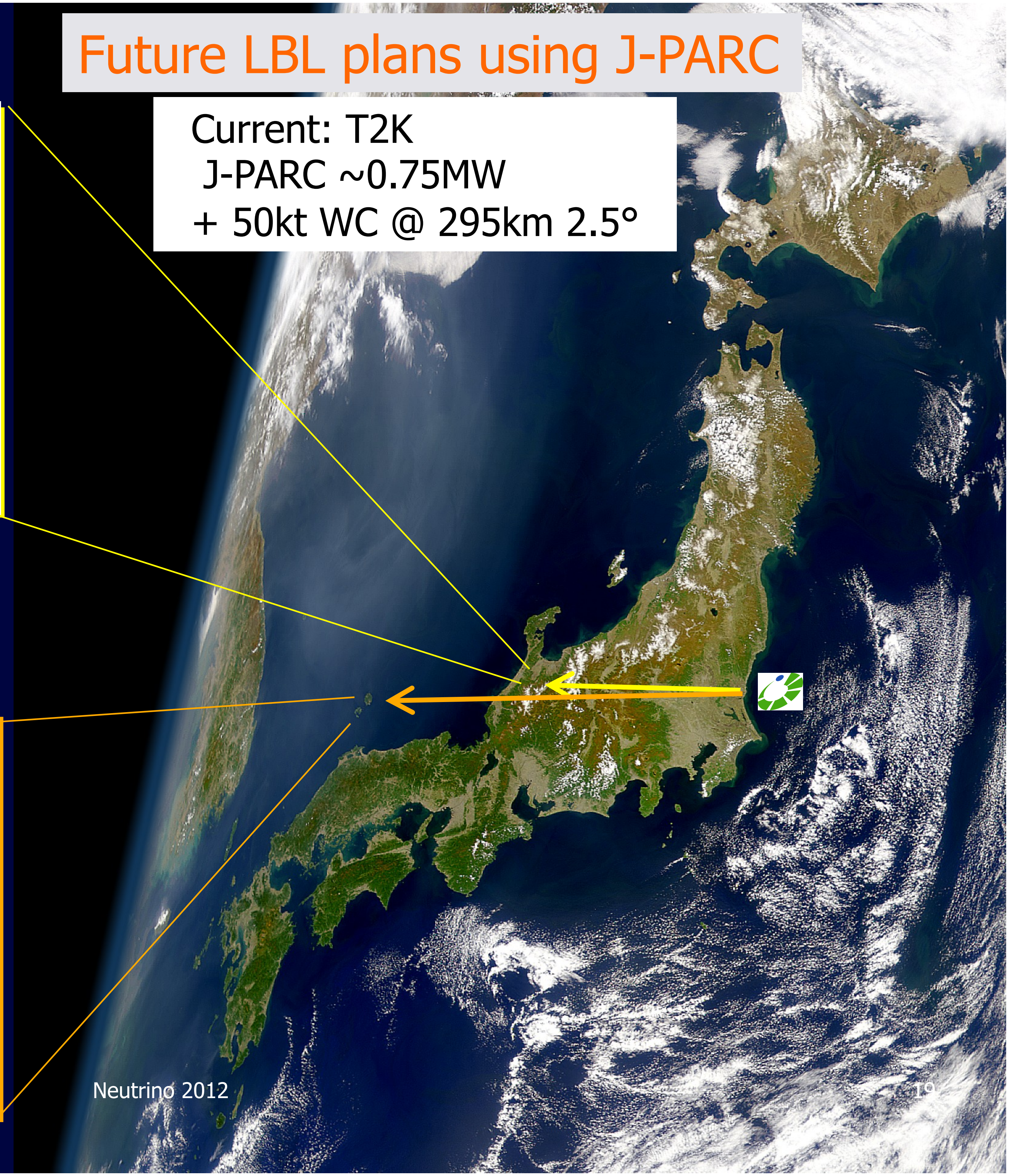


LoI: The Hyper-Kamiokande Experiment
arXiv:1109.3262v1

J-PARC+LAr @ Okinoshima
L=658km OA=0.78deg



J-PARC P32 (LAr TPC R&D), arXiv:0804.2111

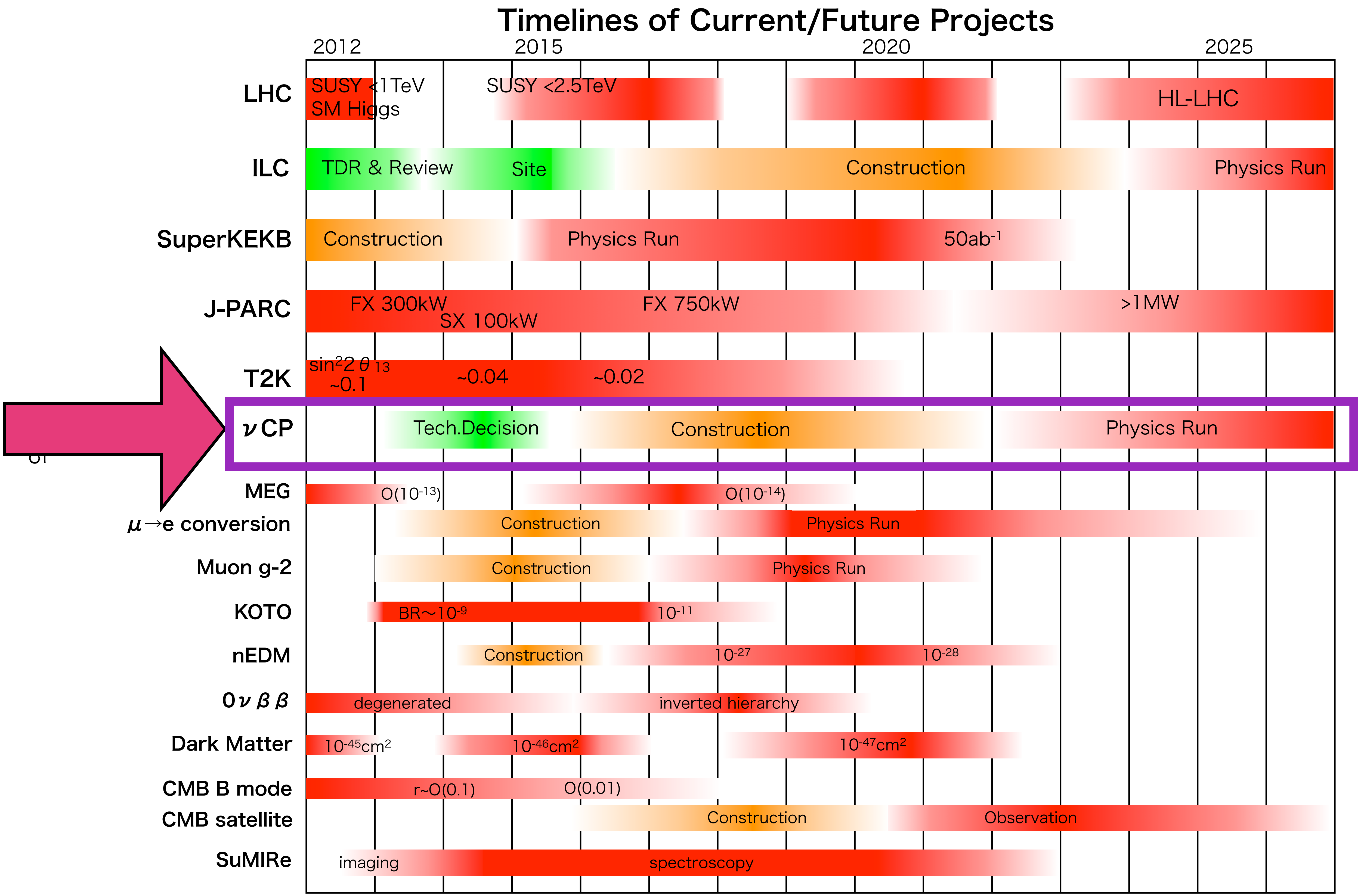


将来計画検討小委員会答申

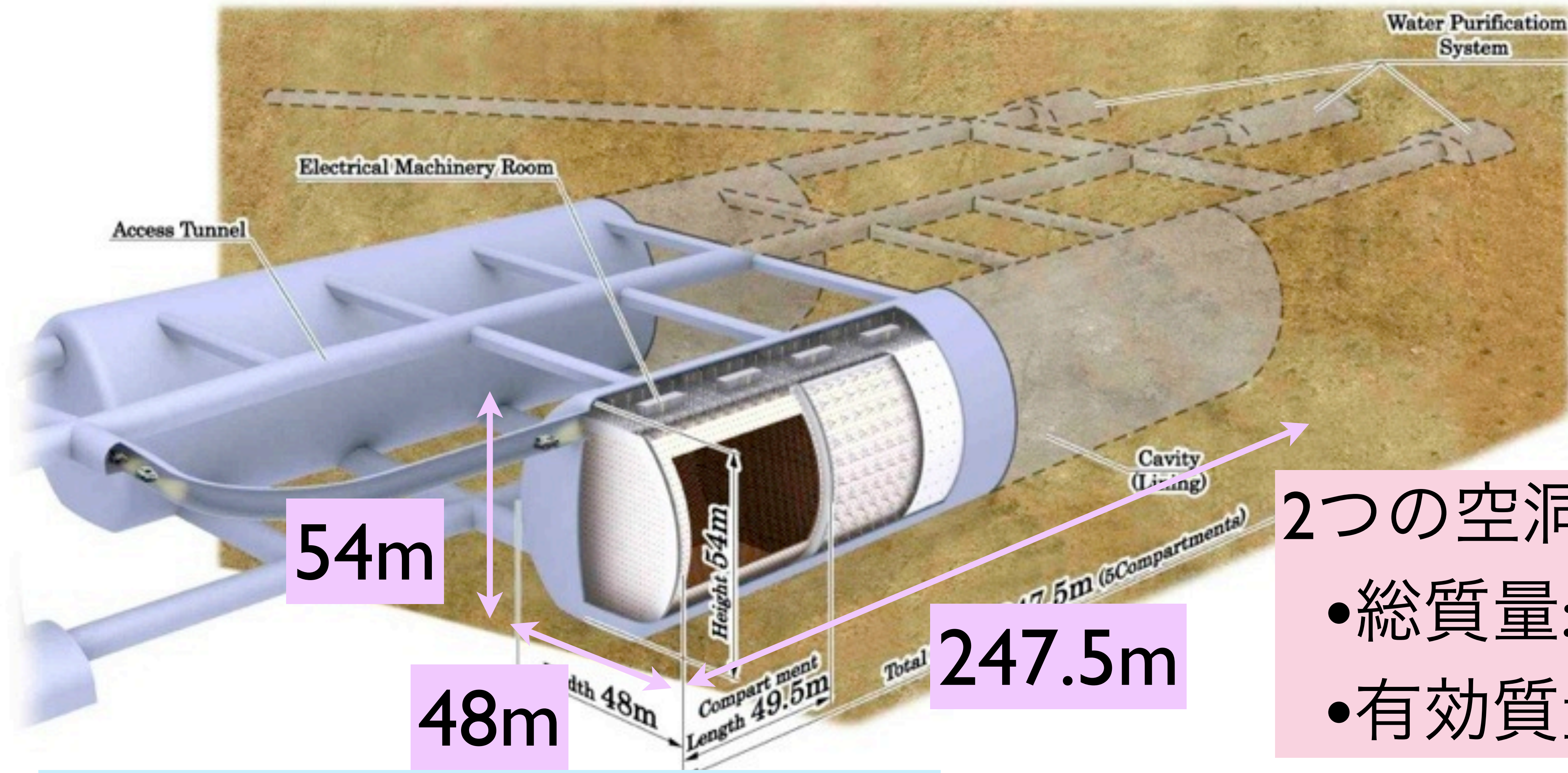
本小委員会は日本の高エネルギー物理学の基幹となる大規模将来計画に関して、以下の提言をする。

- **LHCにおいて1TeV程度以下にヒッグスなどの新粒子の存在が確認された場合、日本が主導して電子・陽電子リニアコライダーの早期実現を目指す**。特に新粒子が軽い場合、低い衝突エネルギーでの実験を早急に実現すべきである。一方でLHCおよびそのアップグレードによって間断なく新物理の探究を続けていく。新粒子・新現象のエネルギースケールがより高い場合には、必要とされる衝突エネルギーを実現するための加速器開発研究を重点強化する。

- **大きなニュートリノ混合角 θ_{13} が確認された場合、ニュートリノ振動を通したCP対称性の研究に向けて、必要とされる加速器の増強と共に、国際協力で大型ニュートリノ測定器の実現を目指す**。大型ニュートリノ測定器は、大統一理論の直接の証拠となる陽子崩壊探索に対しても十分な感度を持つようにすべきである。


Timelines of Current/Future Projects
2012
2015
2020
2025
LHC
SUSY <1TeV
SM Higgs
SUSY <2.5TeV
HL-LHC
ILC
TDR & Review
Site
Construction
Physics Run
SuperKEKB
Construction
Physics Run
50ab-1
J-PARC
FX 300kW
SX 100kW
FX 750kW
>1MW
T2K
sin22θ13
~0.1
~0.04
~0.02
νCP
Tech.Decision
Construction
Physics Run
MEG
O(10-13)
O(10-14)
μ→e conversion
Construction
Physics Run
Muon g-2
Construction
Physics Run
KOTO
BR~10-9
10-11
nEDM
Construction
10-27
10-28
0νββ
degenerated
inverted hierarchy
Dark Matter
10-45cm2
10-46cm2
10-47cm2
CMB B mode
r~O(0.1)
O(0.01)
CMB satellite
Construction
Observation
SuMIRe
imaging
spectroscopy

ハイパーカミオカンデ検出器



arXiv:1109.3262

2つの空洞
- 総質量: 0.99 Mton
- 有効質量: 0.56Mton

各空洞 → 光学的に5つに分離
- それぞれの体積はSKの約2倍
- 隔壁にもPMT

→ 性能はSKと同等

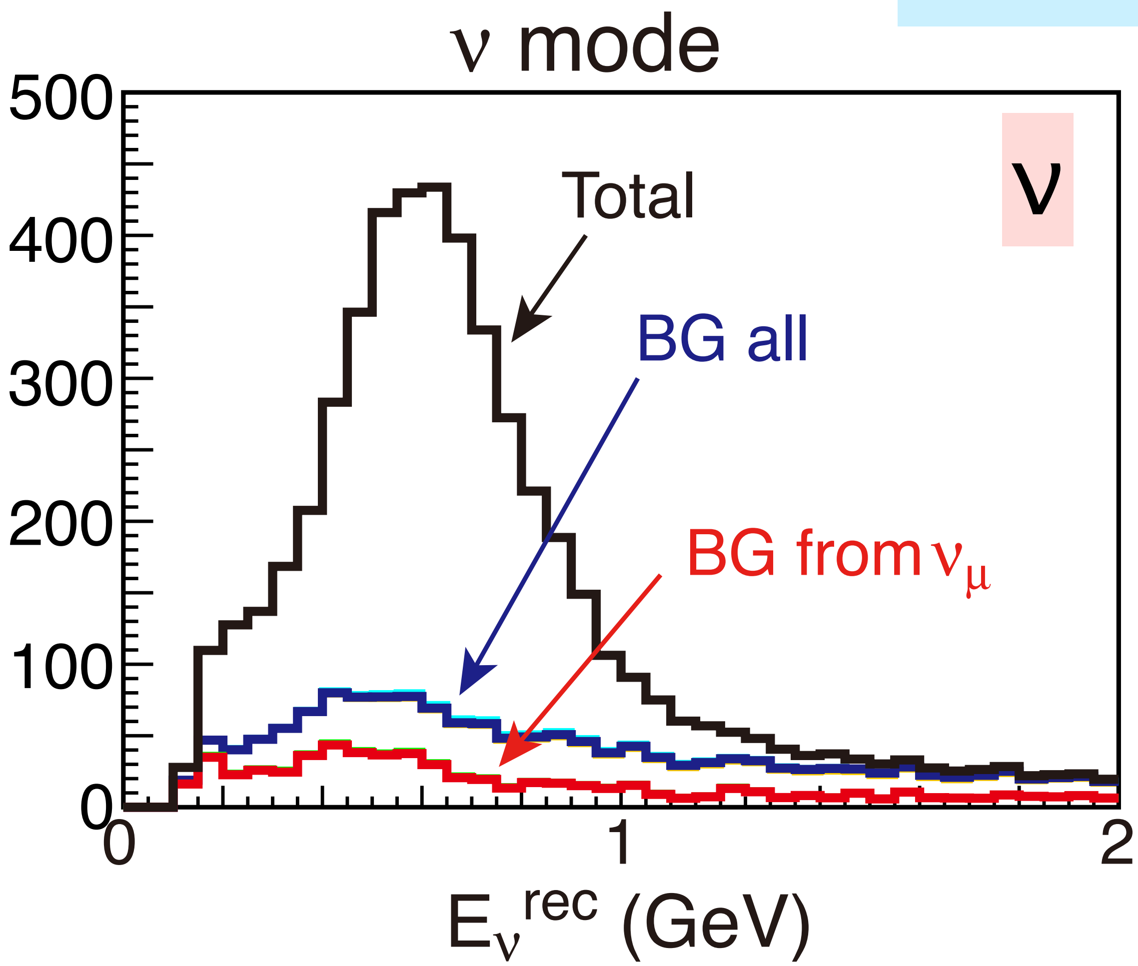
x25 Super-K

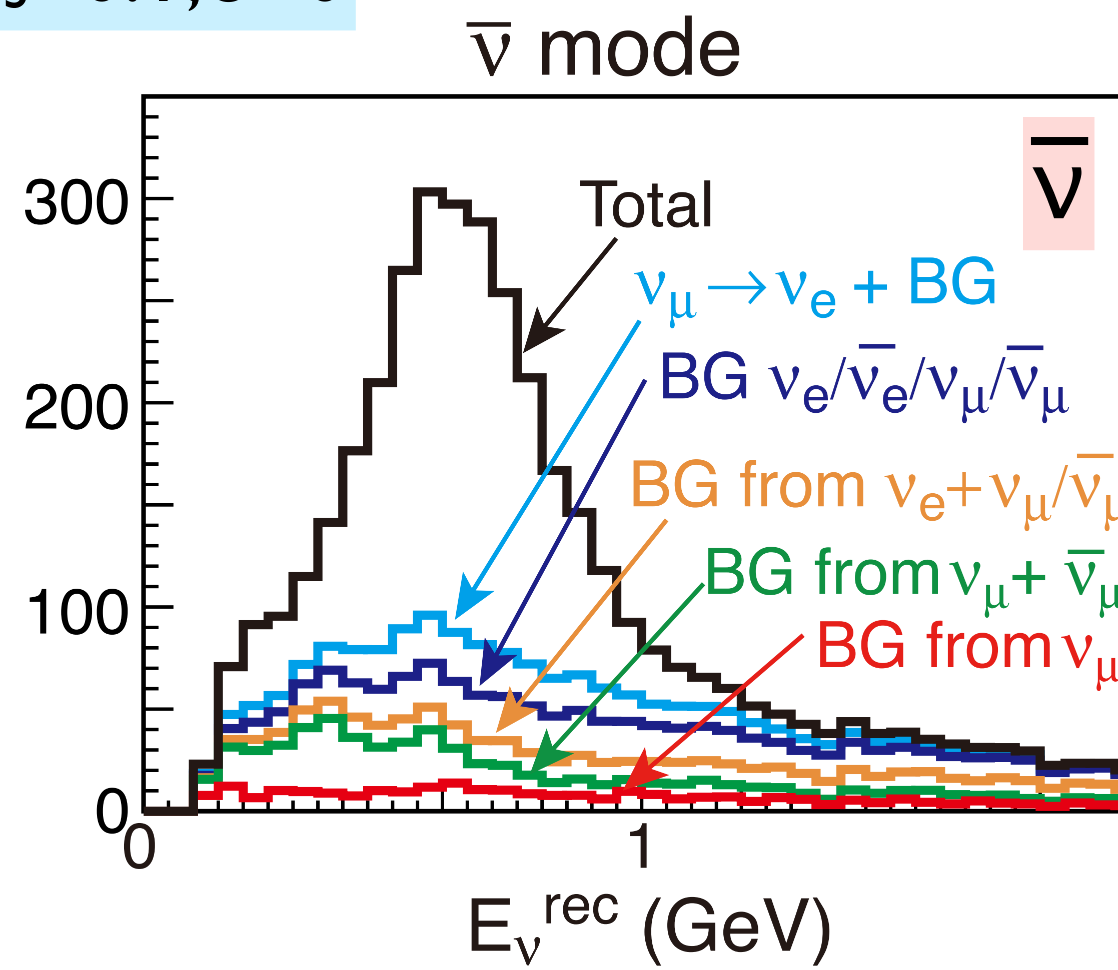
ベースラインデザイン
- 内水槽: 20% photo-coverage (=SK-II)
  - 99,000 20インチPMT
- 外水槽 (2m) : 25,000 8インチPMT

技術的に実現可能な設計

ν_e 事象候補

for $\sin^2 2\theta_{13}=0.1, \delta=0$





	信号 ($\nu_\mu \to \nu_e$ CC)	$\nu_\mu/\bar{\nu}_\mu$ CC	$\nu_e/\bar{\nu}_e$ CC	NC
ν (2.25MW · 10^7s)	3,606	35	880	649
$\bar{\nu}$ (5.25MW · 10^7s)	2,339	23	878	678

合計750kW×10年相当

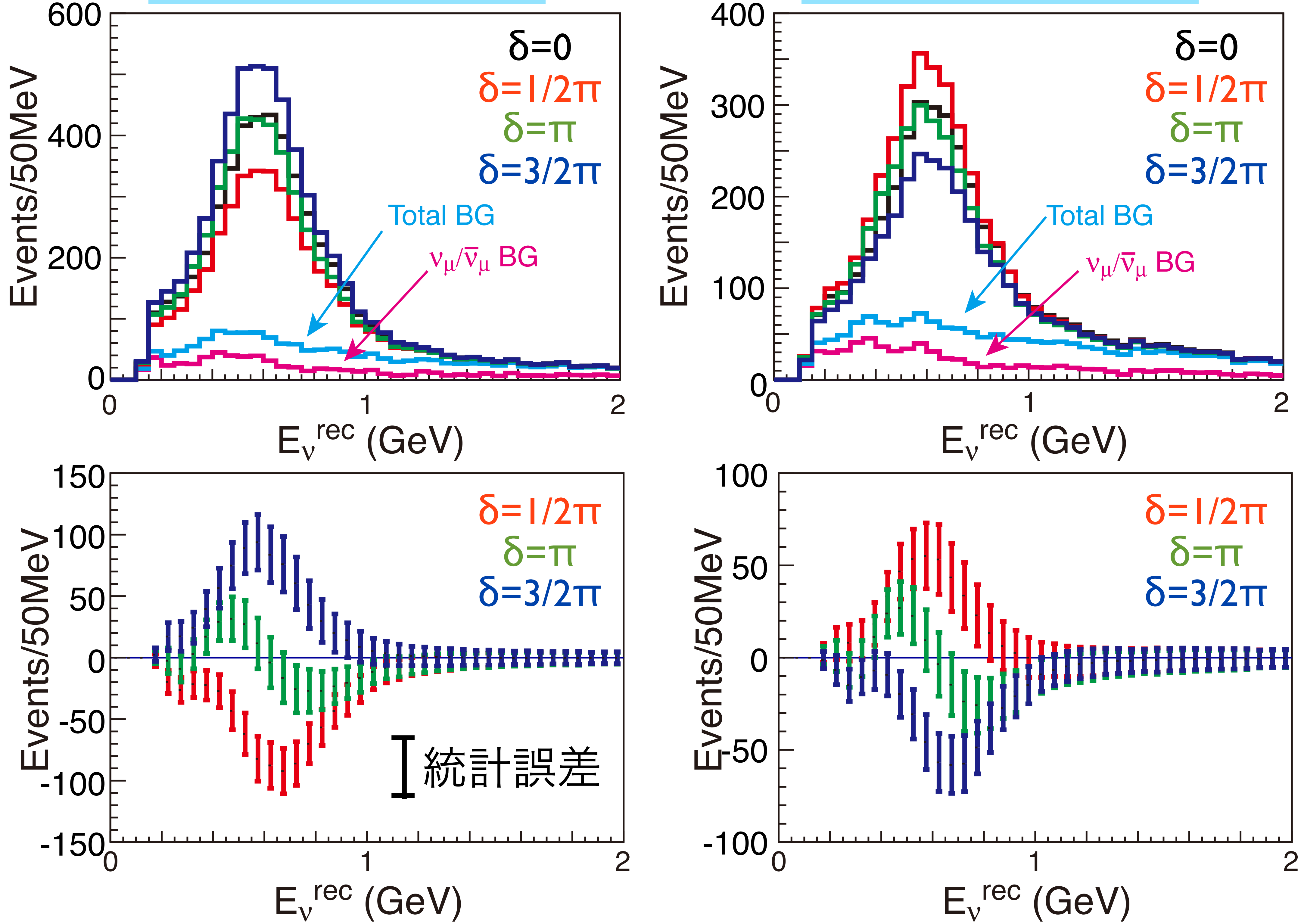
(E_ν^{rec}<2GeV)

for $\sin^2 2\theta_{13}=0.1$

ν 2.25MW×10^7s　　$\bar{\nu}$ 5.25MW×10^7s

νe 候補事象

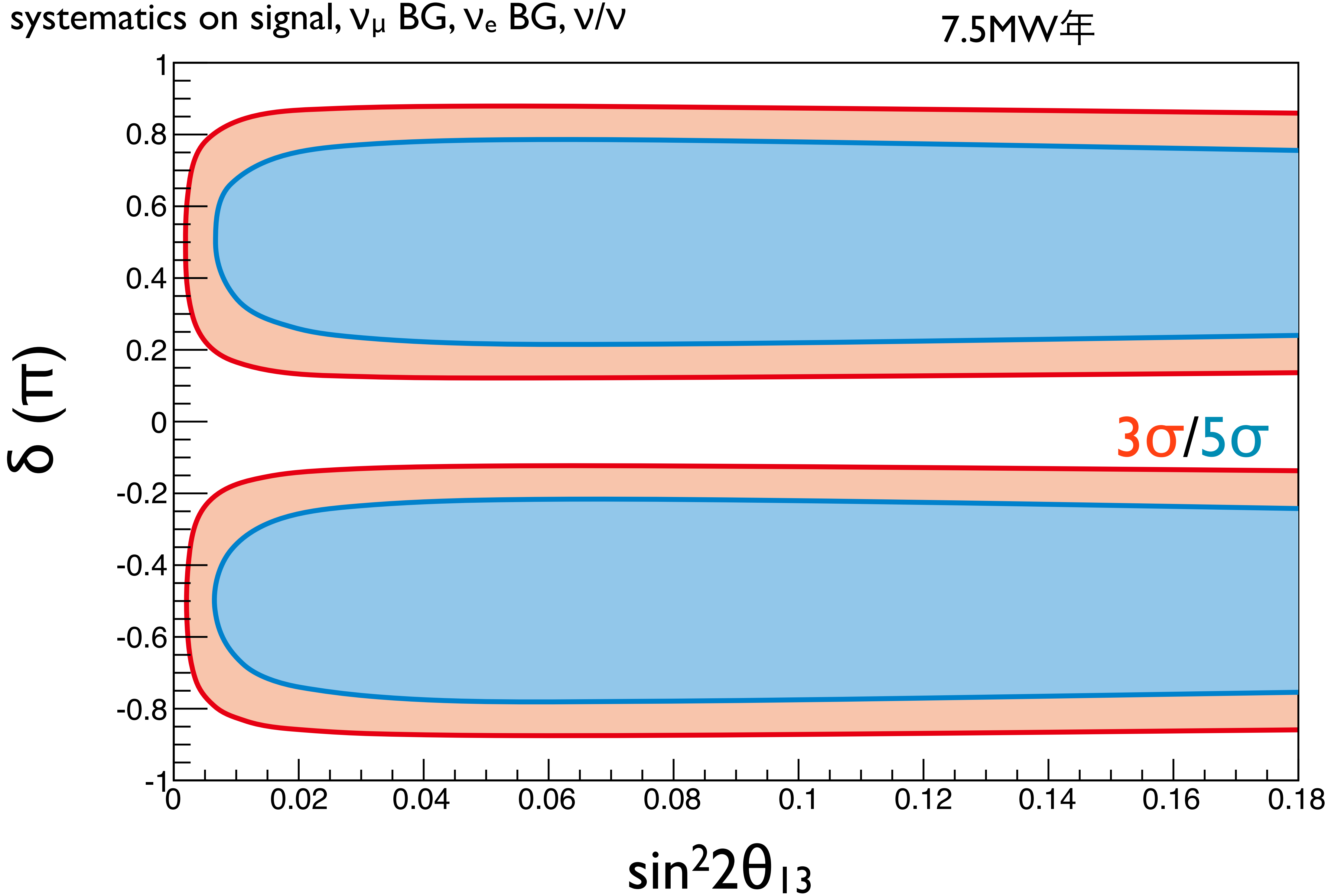
δ=0からの差



Sensitive to all values of δ (including δ=0,π)

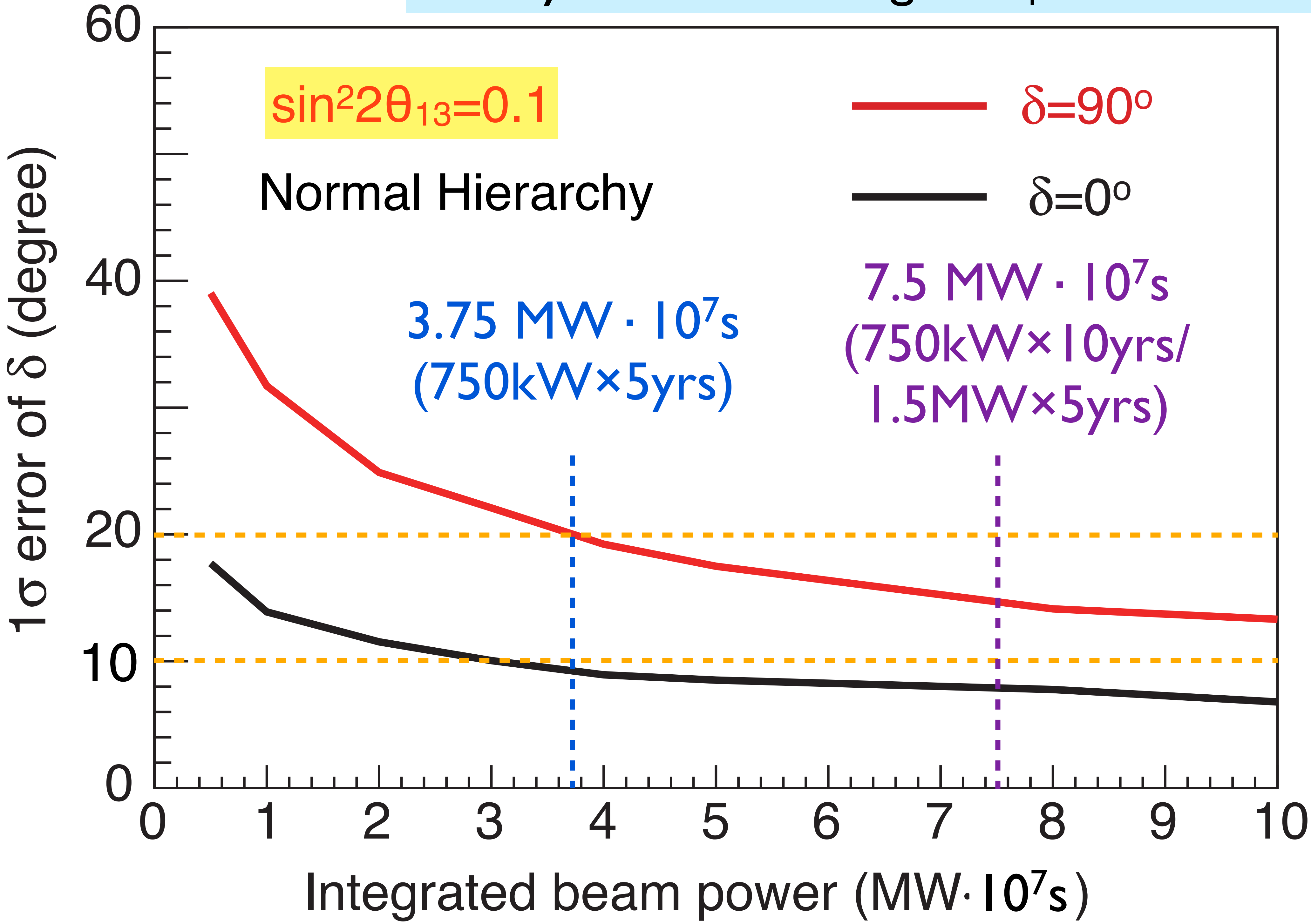
*CP*対称性の破れの感度

5% systematics on signal, ν_μ BG, ν_e BG, $\nu/\bar{\nu}$



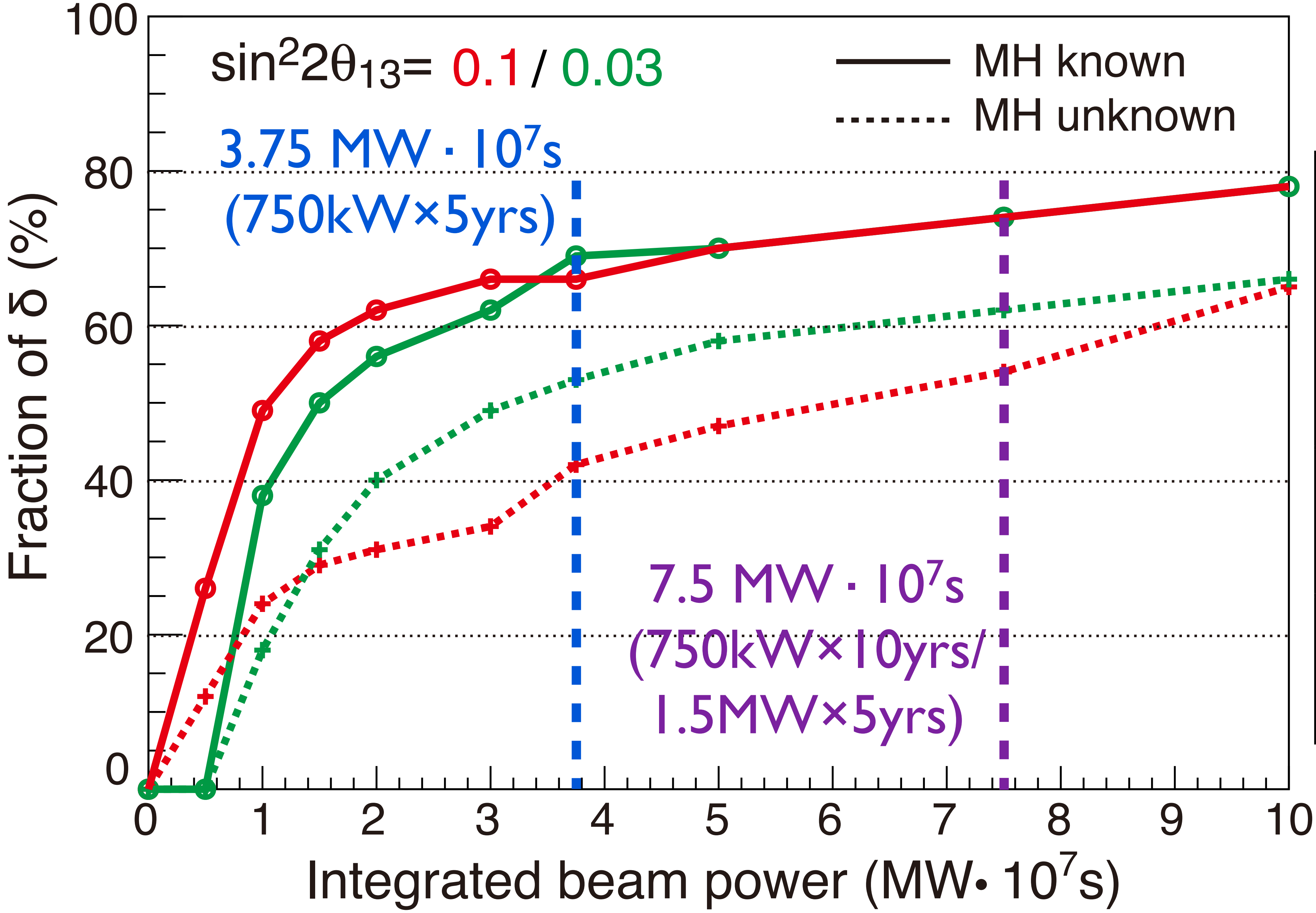
δの測定精度(1σ)

5% systematics on signal, ν_μ BG, ν_e BG, $\nu/\bar{\nu}$



CP対称性の破れの感度

CP対称性の破れを3σ以上で観測可能なδの割合



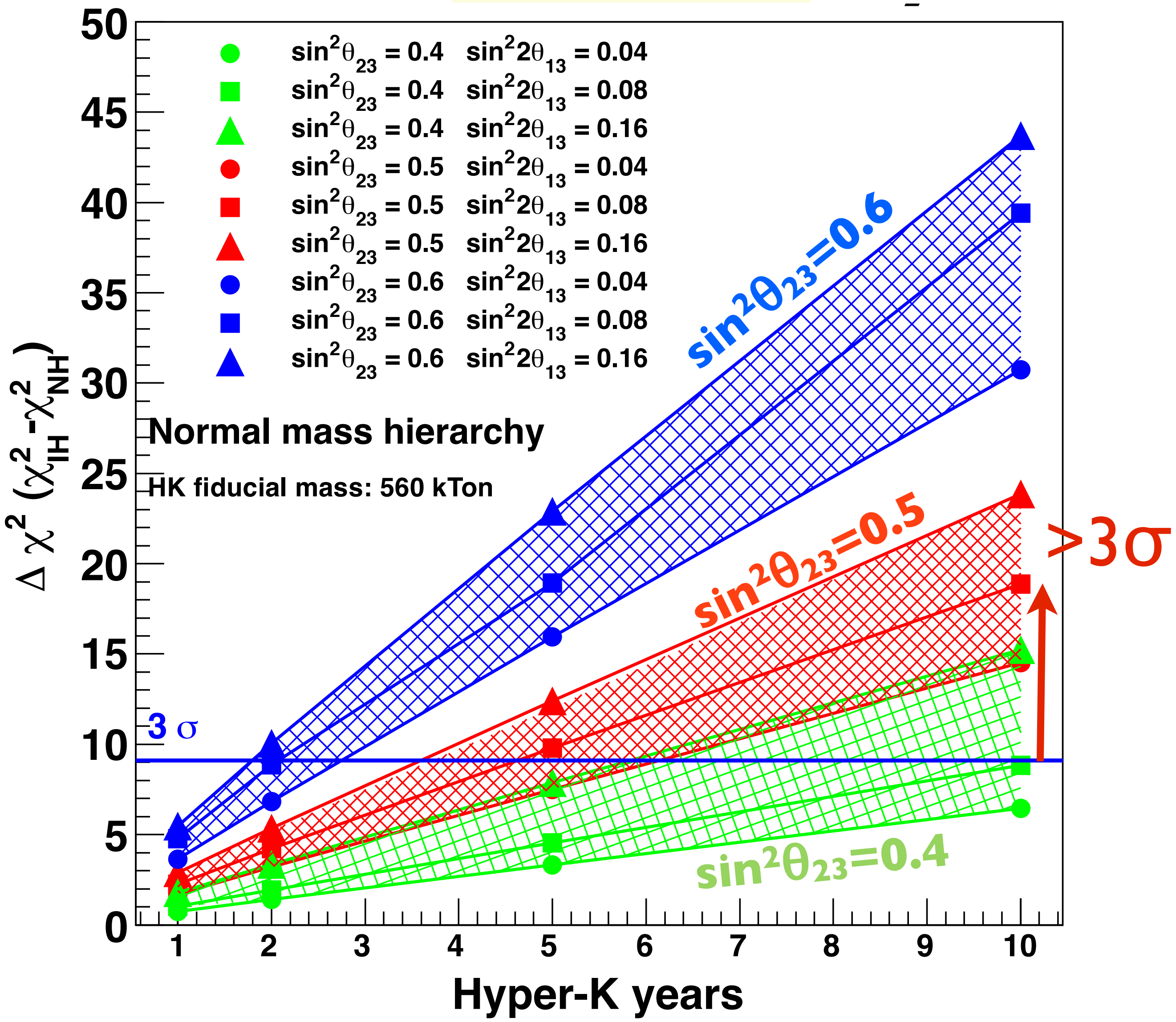
$\sin^2 2\theta_{13}$=0.1の場合

積分強度 (MW× 10^7s)	Mass hierarchy	
	known	unknown
3.75	69%	42%
7.5	74%	54%

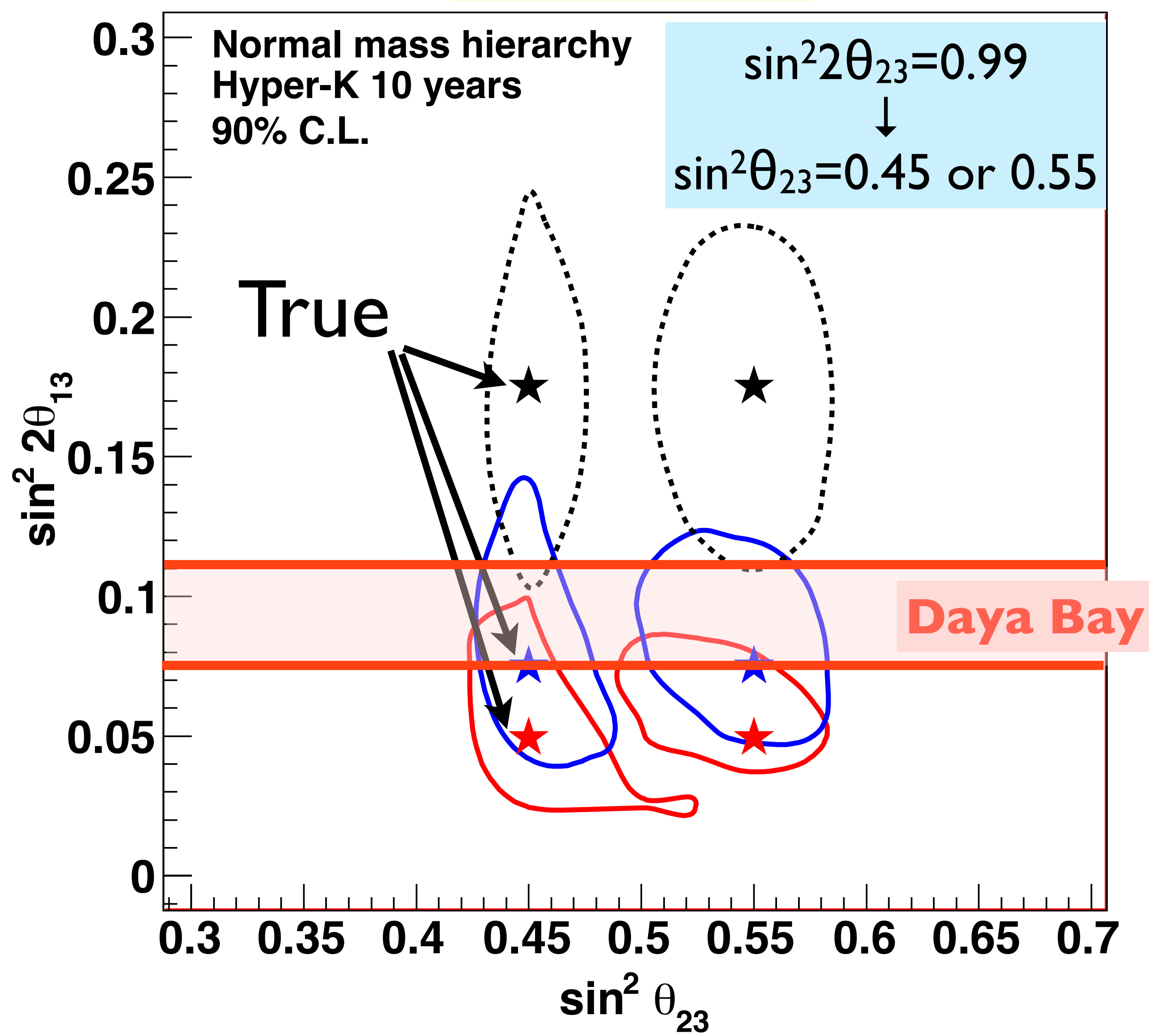
- Effect of unknown mass hierarchy is limited
  - Input from atm ν and other experiments also expected for MH

大気ニュートリノ

質量階層



θ_{23} octant

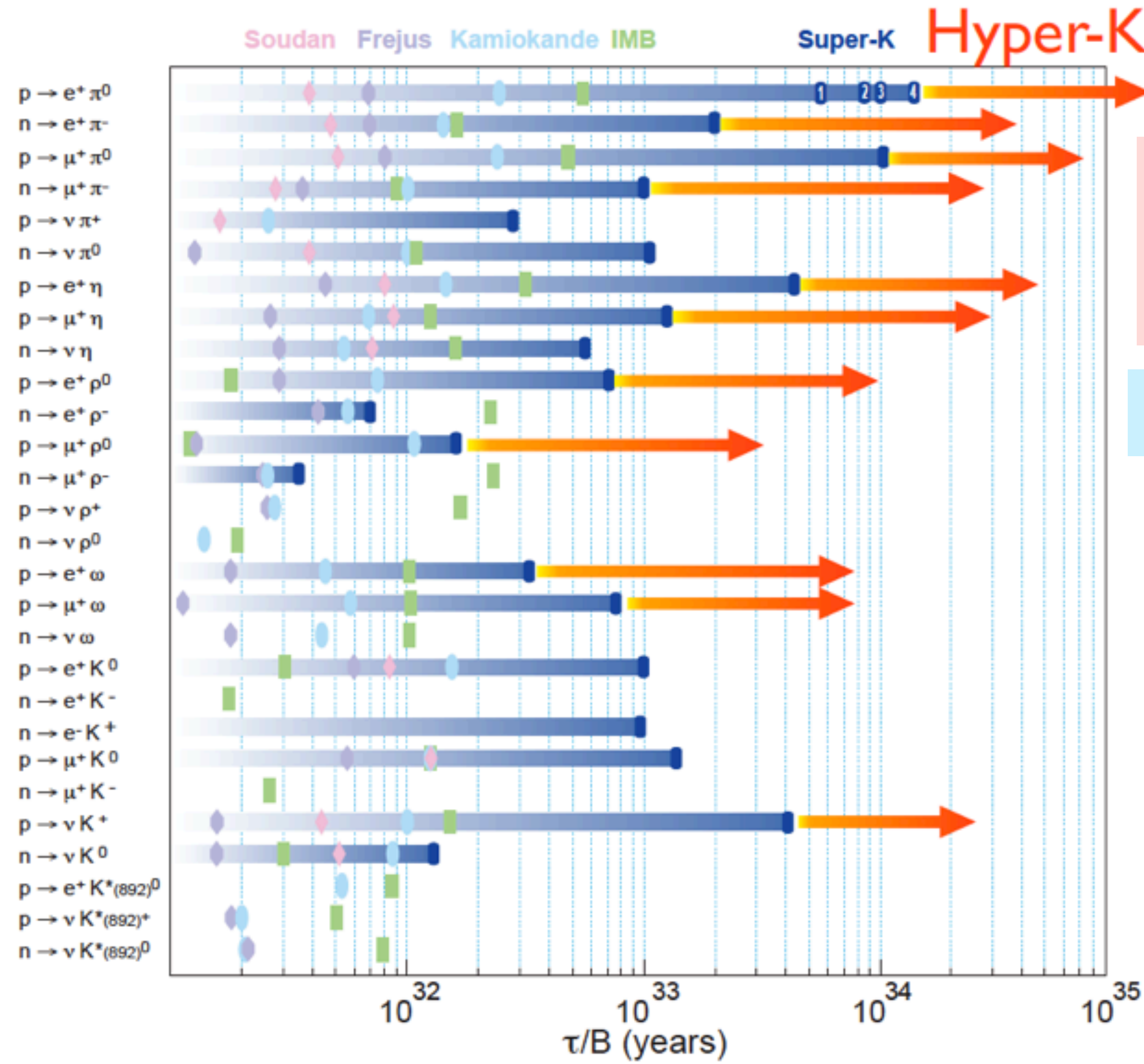


5-10年で $>3\sigma$

Resolved if $\sin^2 2\theta_{23}<0.99$

加速器νと相補的な測定

核子崩壊の探索



現在の制限(SK)の
~10 倍の感度

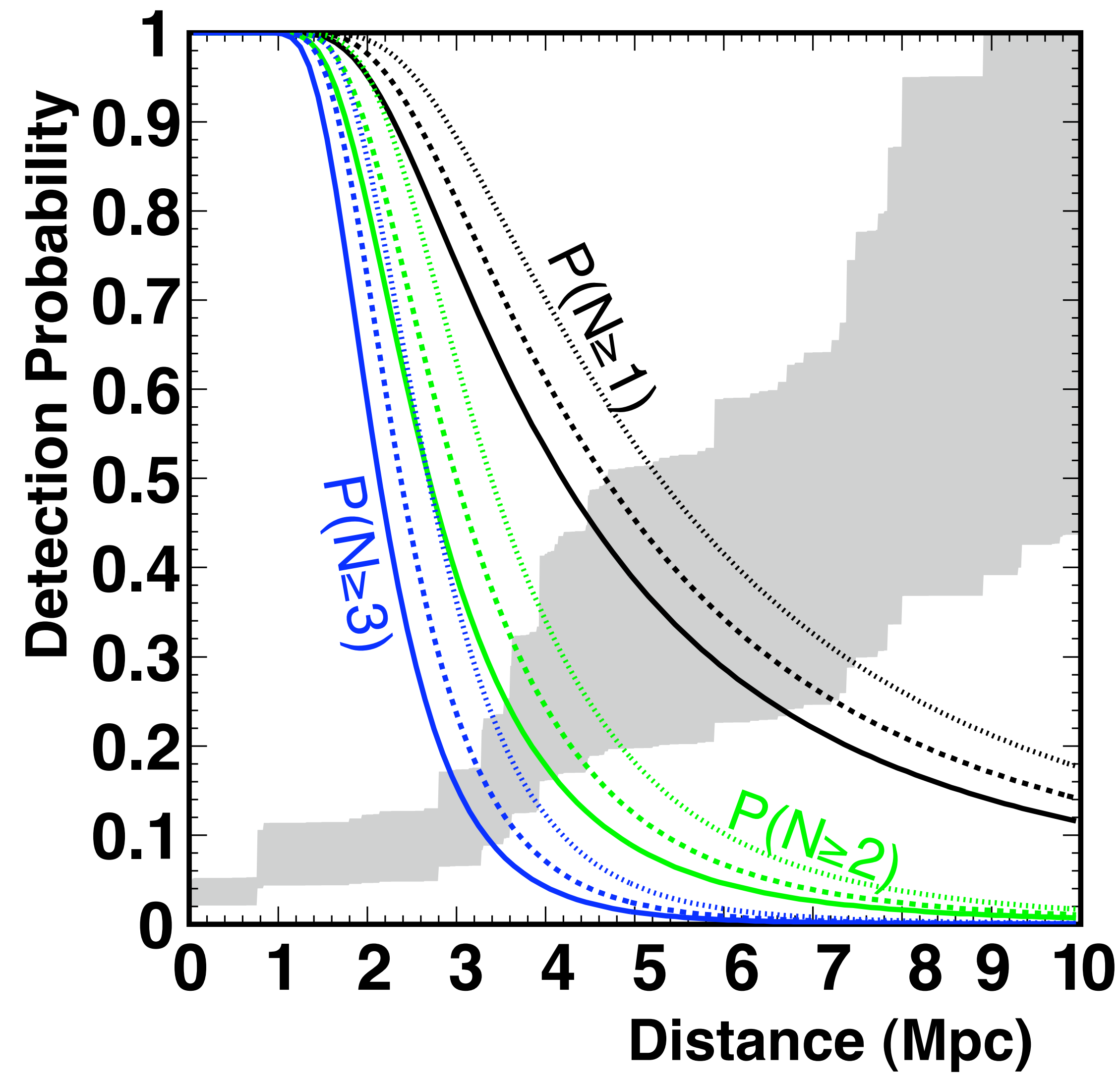
フルシミュレーション

- $p \to e^+\pi^0$:
  - 1.3×10^{35}yrs (90%CL)
  - 5.7×10^{34}yrs (3σ)
- $p \to \nu K^+$:
  - 2.5×10^{34}yrs (90%CL)
  - 1.0×10^{34}yrs (3σ)

(10 years)

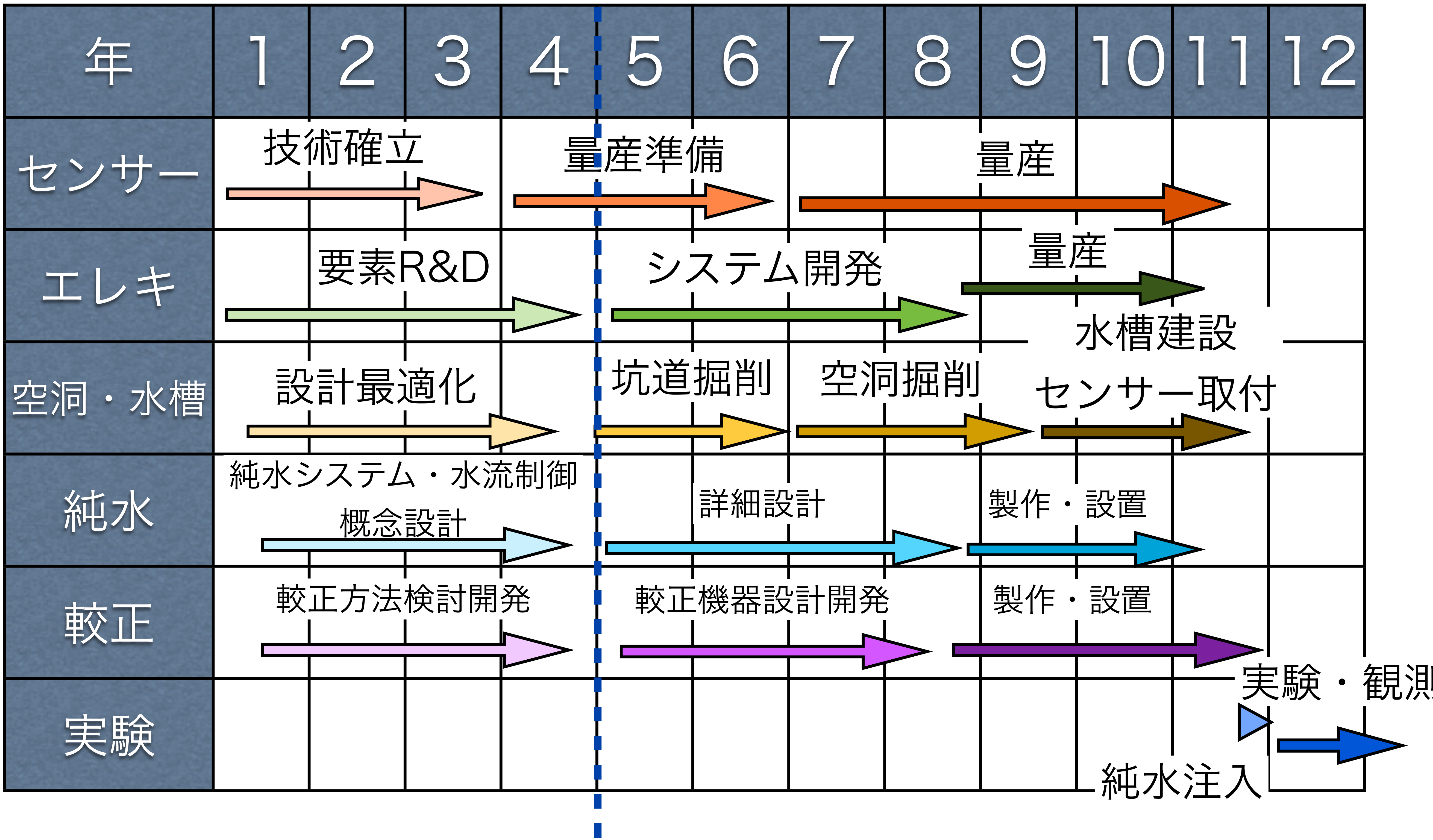
その他のトピック

- 超新星バーストν
  - Mpc程度まで感度→
- 超新星背景ν (with Gd?)
- 太陽ν精密測定
- WIMP, GRB, 太陽フレア…
- Geophysics (ν tomography of Earth)



Reference arXiv:1109.3262

全体計画 (work in progress)



en Meeting for the Hyper-Kamiokande Project (21-23 August 2012) 12/05/29 16:

More | Asia/Tokyo | English | Login

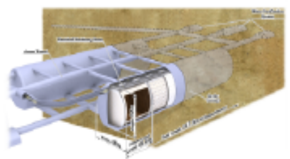
pen Meeting for the Hyper-Kamiokande Project

-23 August 2012 *Kavli Institute for the Physics and Mathematics of the Universe avli IPMU), The University of Tokyo*

/Tokyo timezone

- Overview
- mportant Dates
- all for Abstracts
  - View my abstracts
  - Submit a new abstract
- imetable
- ontribution List
- egistration
  - Registration Form
- ccess
- ccommodation

Overview



We will hold an International Open Working Group Meeting for the Hyper-Kamiokande project. Hyper-K, which we are currently developing, is designed to be the next decade's flagship experiment for the study of neutrino oscillations, nucleon decays, and astrophysical neutrinos.

The goal of this meeting is to discuss the physics potentials of Hyper-K, the design of the detector, and necessary R&D items including:

- cavern excavation
- tank liner material and its design
- photo-sensors and their support structure
- DAQ electronics and computers
- calibration systems
- water purification systems
- software development, and so on.

Participants are encouraged to submit abstracts for talks in which to present their individual interests in topics related to Hyper-K, as well as discuss possible future contributions to the project.

Moreover, we'd like to start discussion of forming an international Hyper-K working group that could become a seed for a formal Hyper-K collaboration in the future. We expect that those who are interested in joining the project will show up for this meeting.

The meeting will be open to all interested scientists and community members. However, prior registration will be required to participate. Due to capacity constraints at the meeting site we urge all interested parties to register at their earliest possible convenience.

We are looking forward to seeing you in Kashiwa,

Local Organizing Committee Members:
Yoshinari HAYATO (ICRR), Tsuyoshi NAKAYA (Kyoto), Shoei NAKAYAMA (ICRR), Yasuhiro NISHIMURA (ICRR), Kimihiro OKUMURA (ICRR), Hiroyuki SEKIYA (ICRR), Masato SHIOZAWA (ICRR), Mark VAGINS (Kavli IPMU), Roger Wendell (ICRR), Masashi YOKOYAMA (Tokyo)
[on behalf of the Hyper-Kamiokande Working Group]

hk201208@km.icrr.u-tokyo.ac.jp

Dates:	from 21 August 2012 17:00 to 23 August 2012 18:00
Timezone:	Asia/Tokyo
Location:	*Kavli Institute for the Physics and Mathematics of the Universe (Kavli IPMU), The University of Tokyo* 5-1-5 Kashiwanoha, Kashiwa city, Chiba, 277-8583 JAPAN Room: Lecture Hall
Material:	Hyper-K picture

http://indico.ipmu.jp/indico/event/7
Last modified: 28 May 2012 11:19

Powered by CDS Indico

p://indico.ipmu.jp/indico/conferenceDisplay.py?confId=7

Open Hyper-K Meeting August 21-23, 2012 Kavli IPMU, Kashiwa

- Discussion on physics potential, detector design, and R&D items
- Discussion of an international Hyper-K working group.
- All interested scientists are welcome.

参加登録受付中 (~7/31)

http://indico.ipmu.jp/indico/conferenceDisplay.py?confId=7

クォーク
カビボ角(1963)
CP非保存の発見(1964)
小林-益川(1973)

B-反B混合が大きい(1987)
BでのCP非保存(2001)
K-Mノーベル賞(2008)
何かありますかね？(201?)

クォーク	レプトン
カビボ角(1963)	牧-中川-坂田(1962)
CP非保存の発見(1964)	2-ニュートリノ(1962)
小林-益川(1973)	太陽ニュートリノ問題(1968-)
B-反B混合が大きい(1987)	ν振動の発見, θ_{23}大(1998)
BでのCP非保存(2001)	θ_{12}がLMA(2001)
K-Mノーベル賞(2008)	θ_{13}もあるよ(2012)
何かありますかね？(201?)	レプトンでのCP非保存発見(20??)

クォーク	レプトン
カビボ角(1963)	牧-中川-坂田(1962)
CP非保存の発見(1964)	2-ニュートリノ(1962)
小林-益川(1973)	太陽ニュートリノ問題(1968-)
B-反B混合が大きい(1987)	ν振動の発見, θ_{23}大(1998)
BでのCP非保存(2001)	θ_{12}がLMA(2001)
K-Mノーベル賞(2008)	θ_{13}もあるよ(2012)
何かありますかね？(201?)	レプトンでのCP非保存発見(20??)

陽子崩壊？

クォーク・レプトンの統一的理解??

新しいレベルの素粒子像??

物質優勢宇宙の理解？

(20xx?)

さてさて，これからX年

（Xにはお好きな年数をどうぞ）

※ Xが小さくなるアイデア募集中です

おわり

バックアップ・ぼつ

DRAMATIC NEUTRINO CONFERENCES IN JAPAN

NEUTRINO 1986 – Sendai

First indications by Kamiokande and IMB of an atmospheric neutrino anomaly ($\nu_\mu \rightarrow \nu_\tau$ oscillations proposed by Kamiokande at NEUTRINO 1988 in Boston)

NEUTRINO 1998 – Takayama

Atmospheric neutrino oscillations confirmed 'officially' by Superkamiokande: 1st parameter measurements.

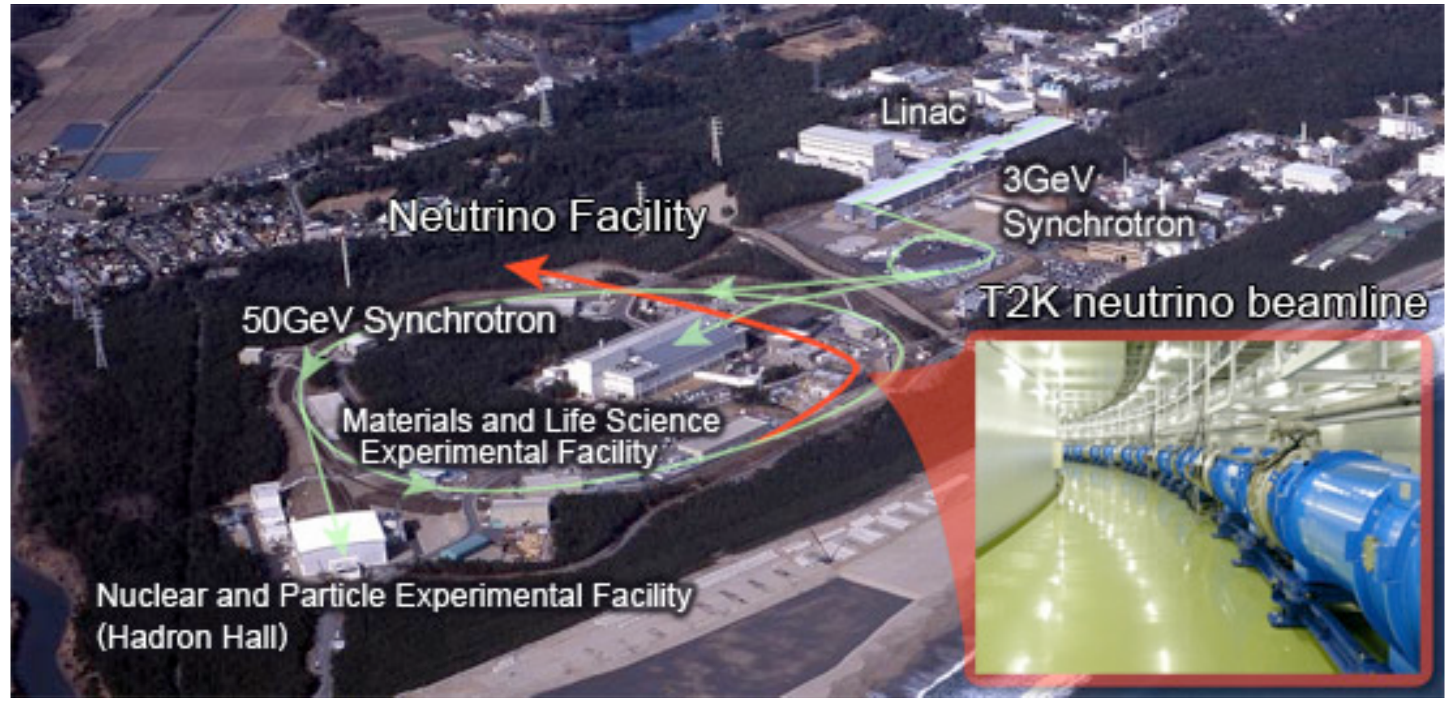
NEUTRINO 2012 – Kyoto

First measurements of θ_{13} – MINOS, T2K, DOUBLE CHOOZ, DAYA BAY, RENO -- and a host of other new results …… and

J. Schneps @NEUTRINO2012, Kyoto

J-PARC

Efforts to increase beam power



Upgrade toward design power and beyond

- LINAC upgrade in 2013 (180 to 400MeV)
- new ion source (30mA to 50mA)
- R&D on high rep. rate MR power supply
- R&D on high gradient RF core

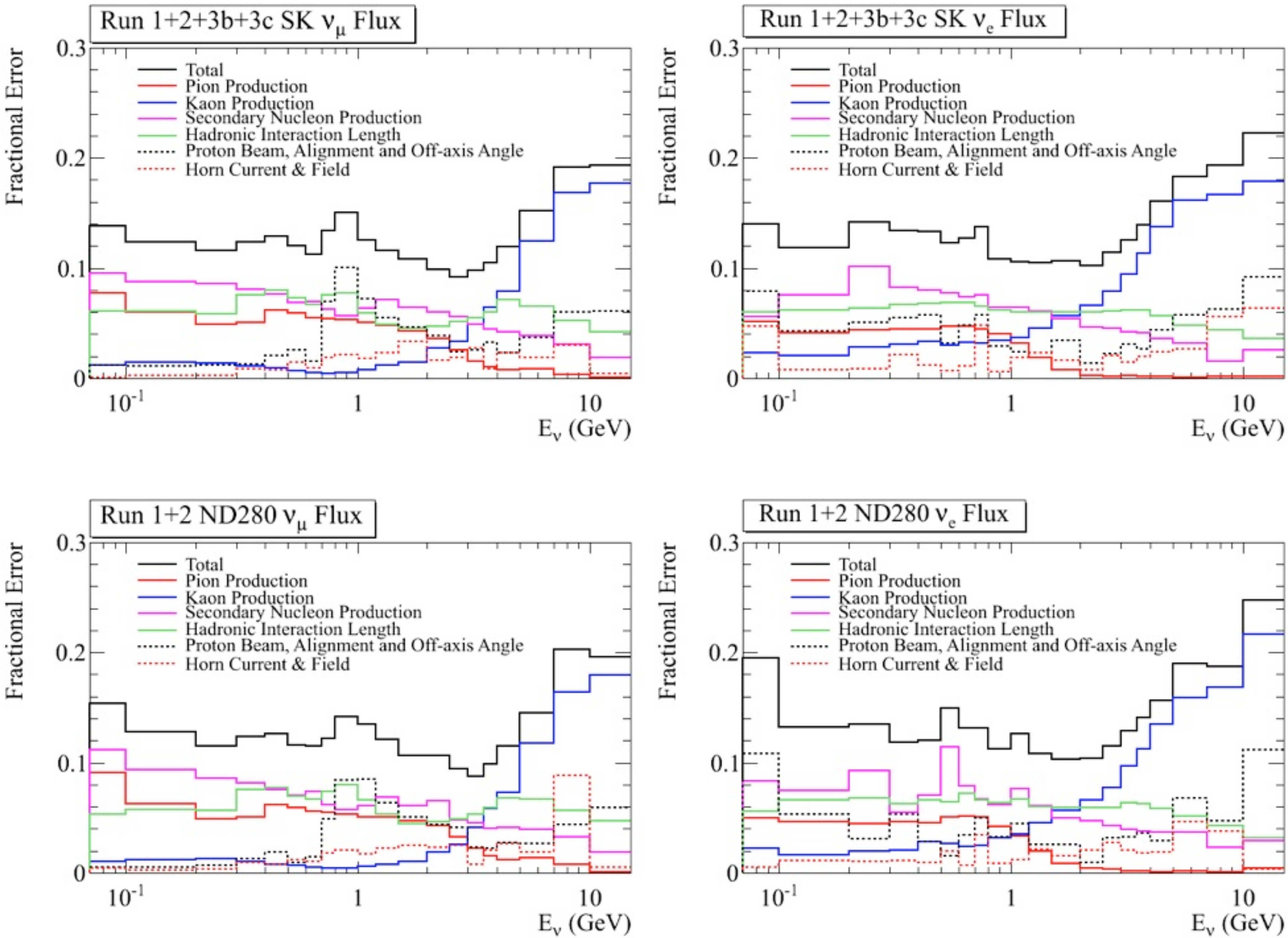
Period	Integ. No. of Proton on Target	Beam Power (kW)	
-Jun.2012	3.1E+20	170	
-Jun.2013	7.8E+20	200	
-Jun.2014	1.2E+21	250	*2
-Jun.2015	1.8E+21	250	
-Jun.2016	2.5E+21	300	
-Jun.2017	3.2E+21	300	
-Jun.2018	3.9E+21	300	
-Jun.2019	5.5E+21	700	*1
-Jun.2020	7.1E+21	700	
-Jun.2021	8.8E+21	700	

*1 Completion time of MR upgrade (assumed to be 2018) is suject to change, depending on economical situation, readiness and so on.

*2 LINAC upgrade completed

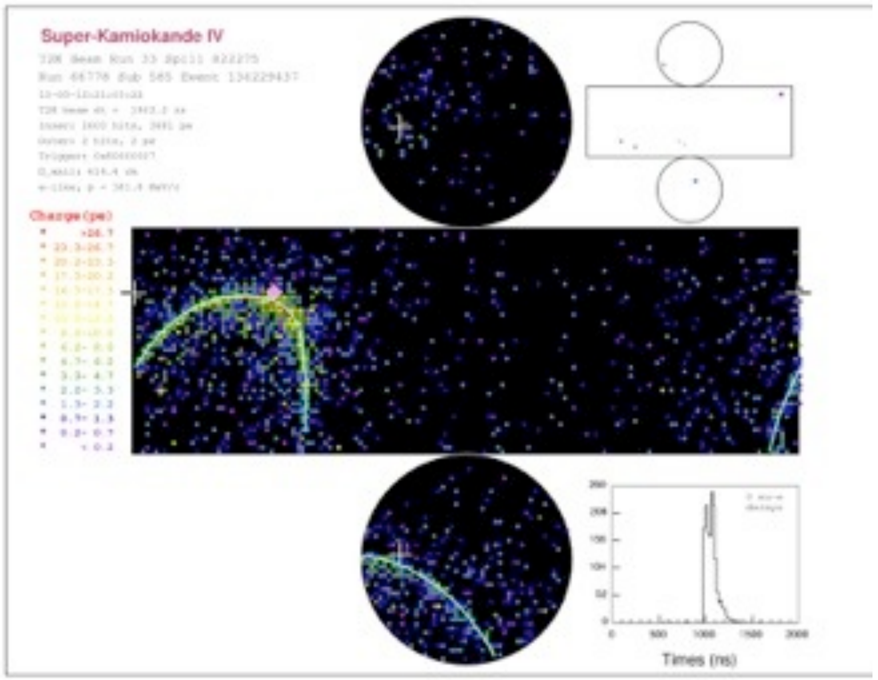
* Beam Energy 30GeV

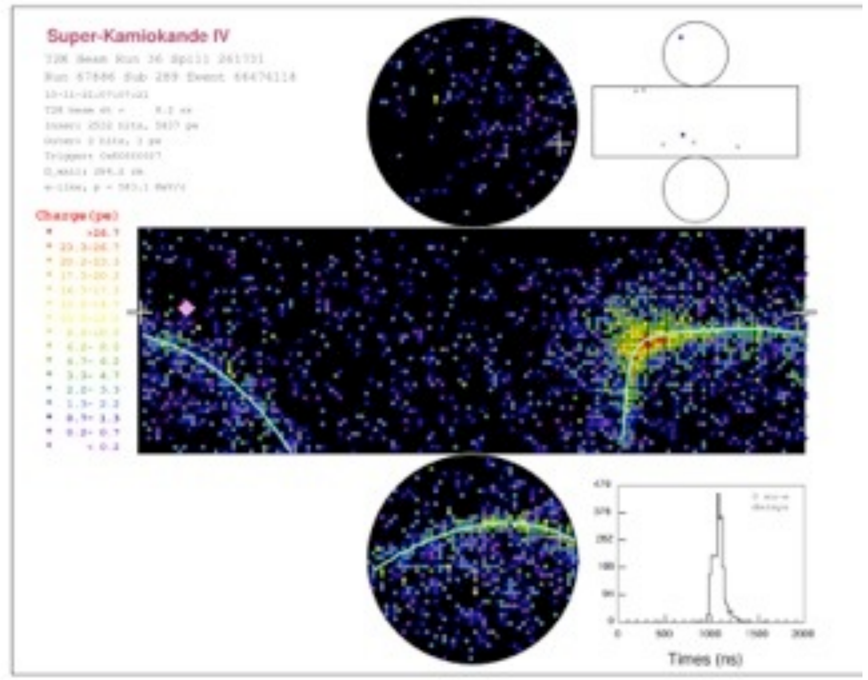
From J-PARC/KEK management

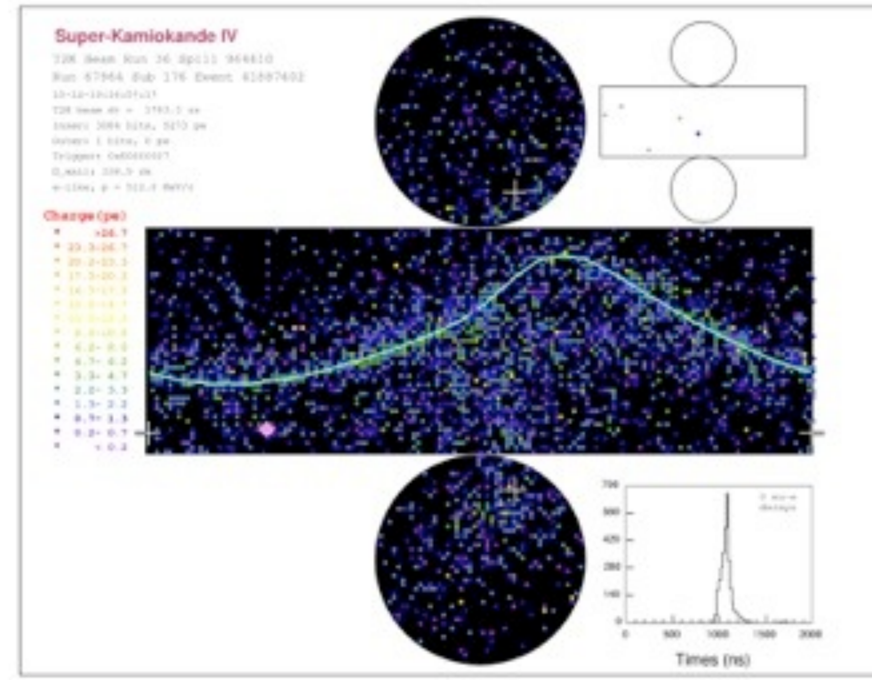

Run 1+2+3b+3c SK ν_μ Flux
Run 1+2+3b+3c SK ν_e Flux
Run 1+2 ND280 ν_μ Flux
Run 1+2 ND280 ν_e Flux
Fractional Error
E_ν (GeV)
Total
Pion Production
Kaon Production
Secondary Nucleon Production
Hadronic Interaction Length
Proton Beam, Alignment and Off-axis Angle
Horn Current & Field
0
0.1
0.2
0.3
10^{-1}
1
10

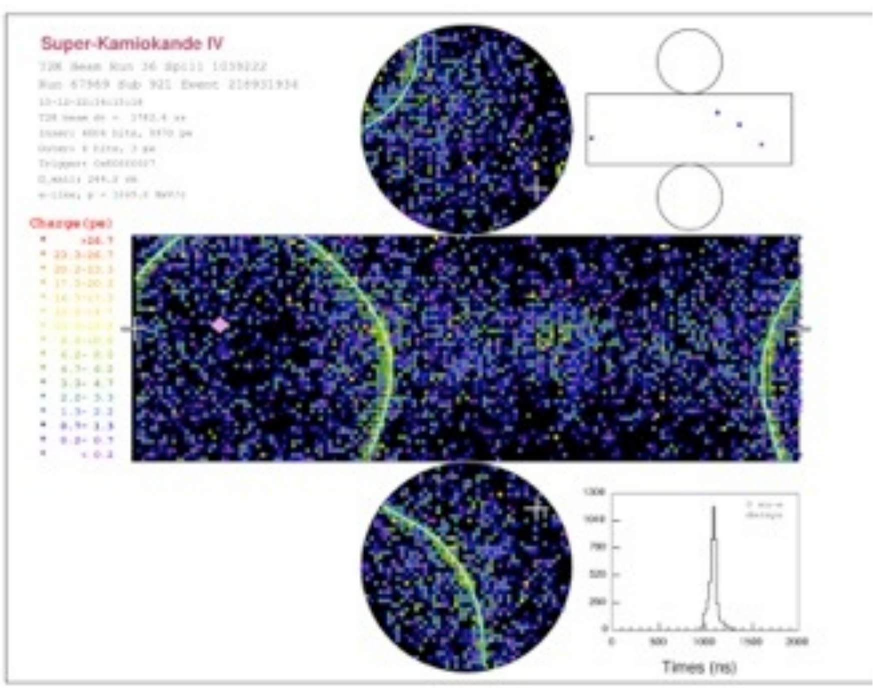
$\sin^2(2\theta_{13})=0.1$ $\Delta m^2_{32}=2.4\times10^{-3}\ eV^2$
$\sin^2(2\theta_{23})=1.0$

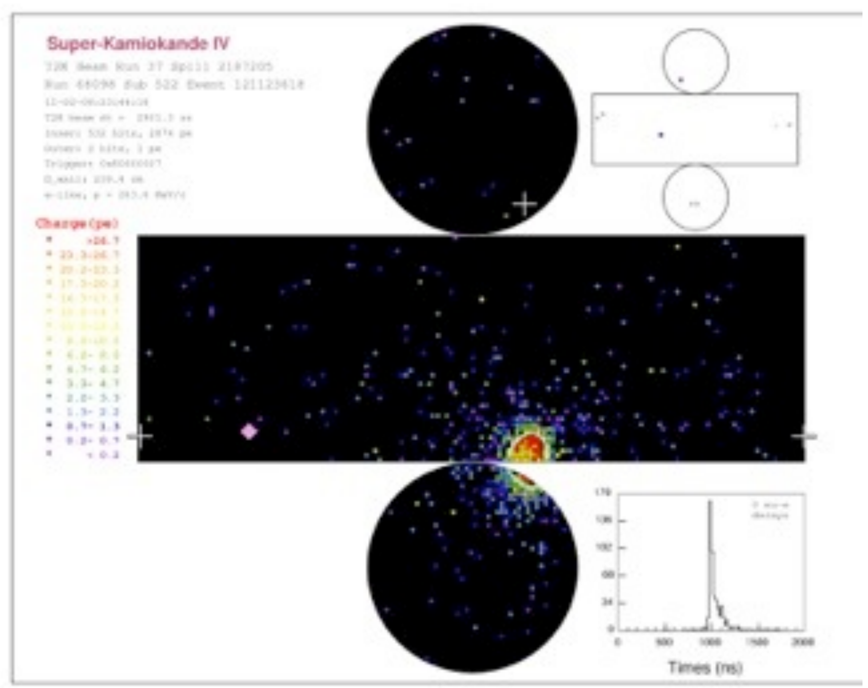
	% Errors on Sample Predictions		
	N_{ND}	N_{SK}	N_{SK}/N_{ND}
Pion Production	3.41	4.97	1.88
Kaon Production	3.48	1.17	2.99
Secondary Nucleon Production	5.46	6.61	1.34
Hadronic Interaction Length	5.78	6.55	1.89
Proton Beam, Alignment & Off-axis Angle	3.45	2.48	1.90
Horn Current and Magnetic Field	1.40	1.15	1.39
Total	10.04	10.96	4.84

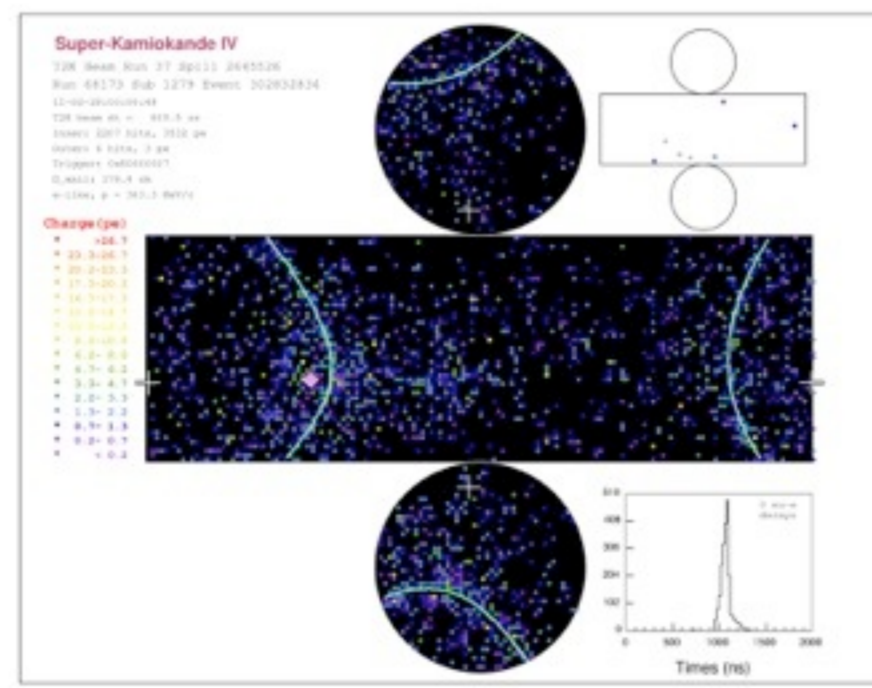

Super-Kamiokande IV
Charge (pe)
Times (ns)

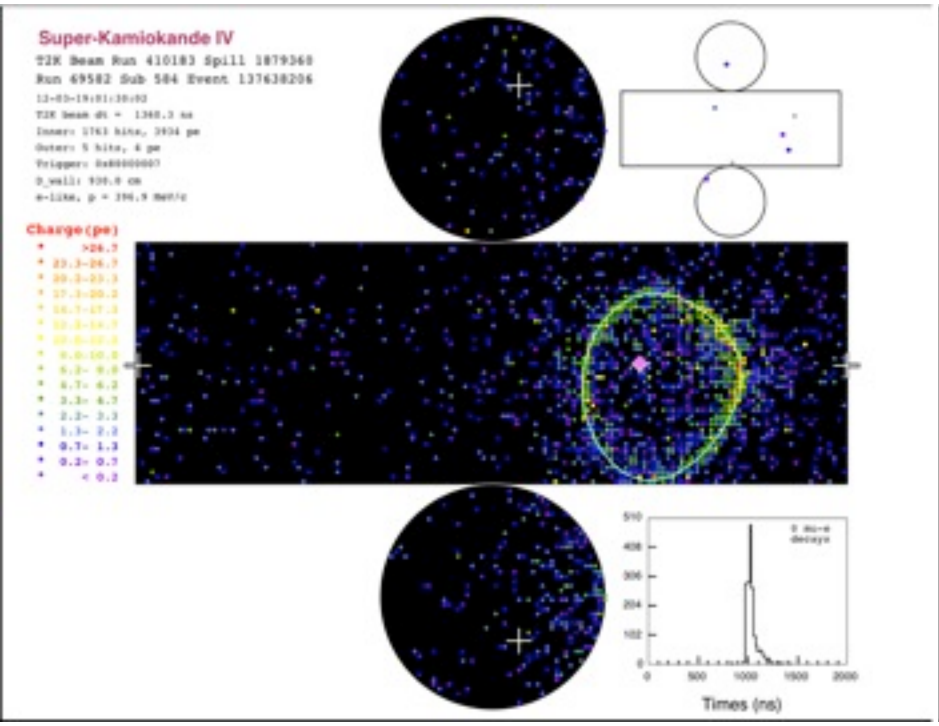

Super-Kamiokande IV
Charge (pe)
Times (ns)

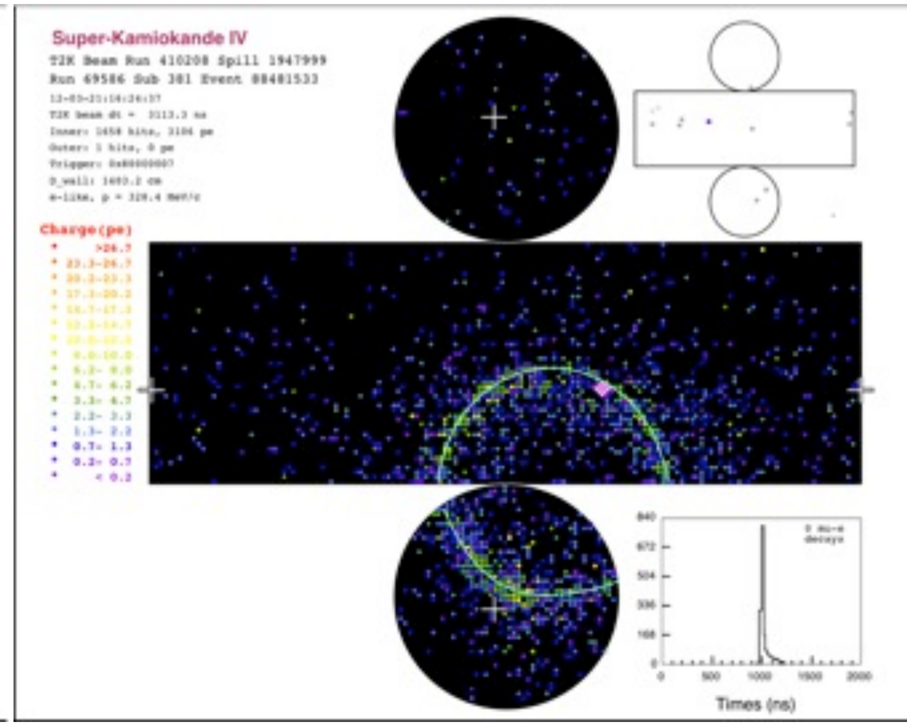

Super-Kamiokande IV
Charge (pe)
Times (ns)

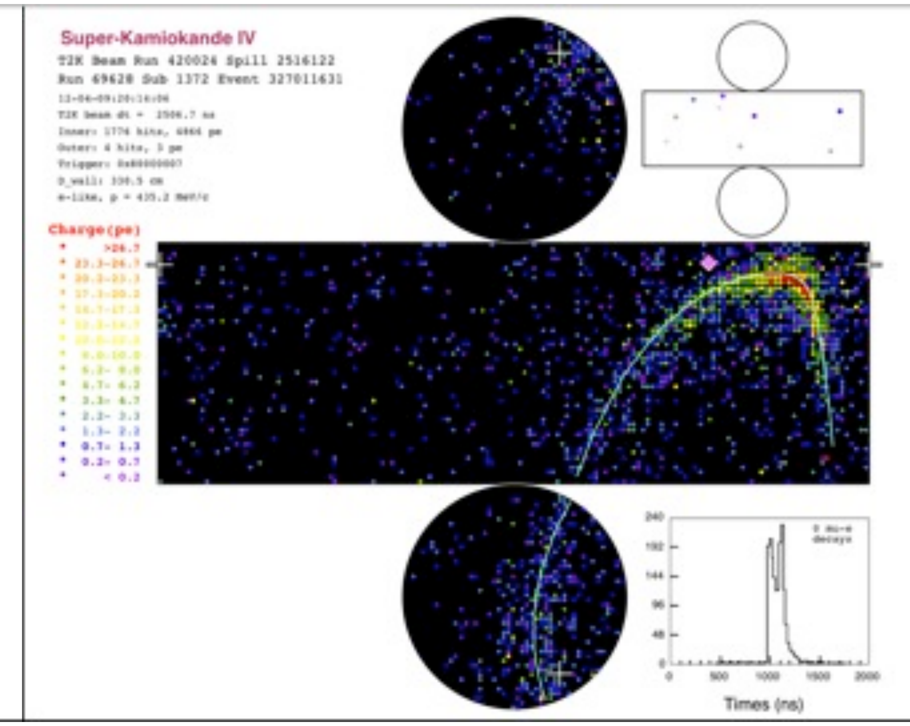

Super-Kamiokande IV
Charge (pe)
Times (ns)

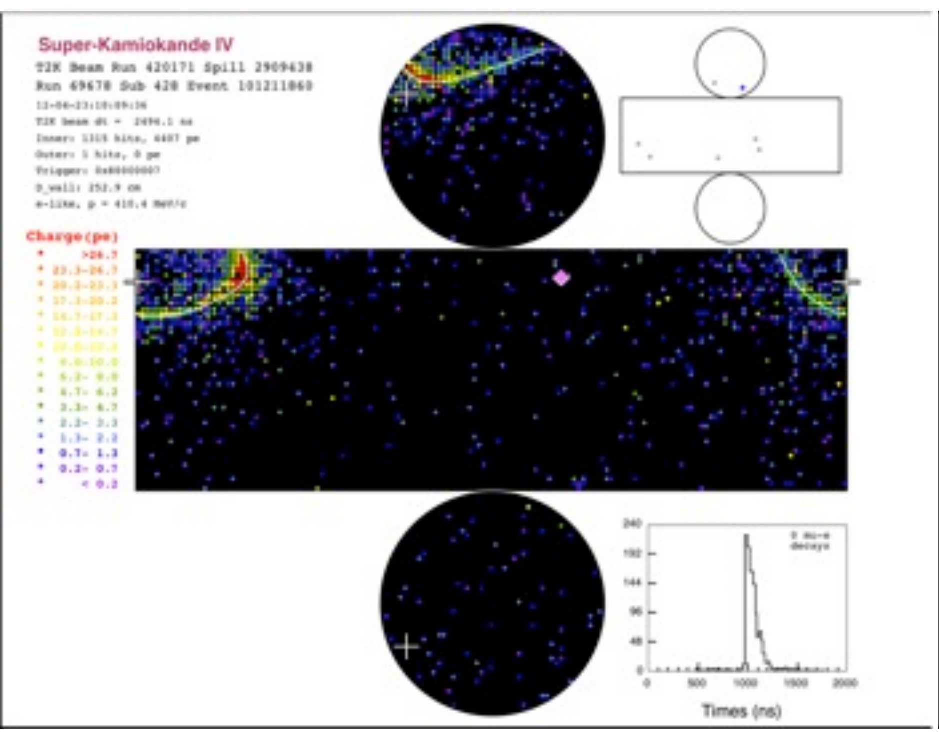

Super-Kamiokande IV
Charge (pe)
Times (ns)

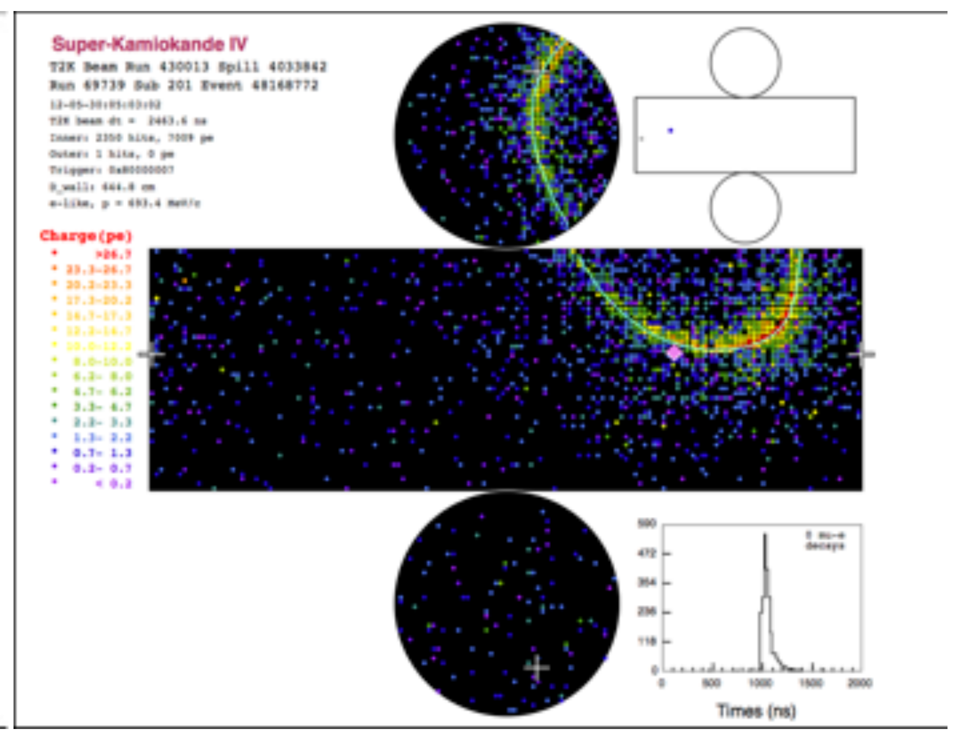

Super-Kamiokande IV
Charge (pe)
Times (ns)







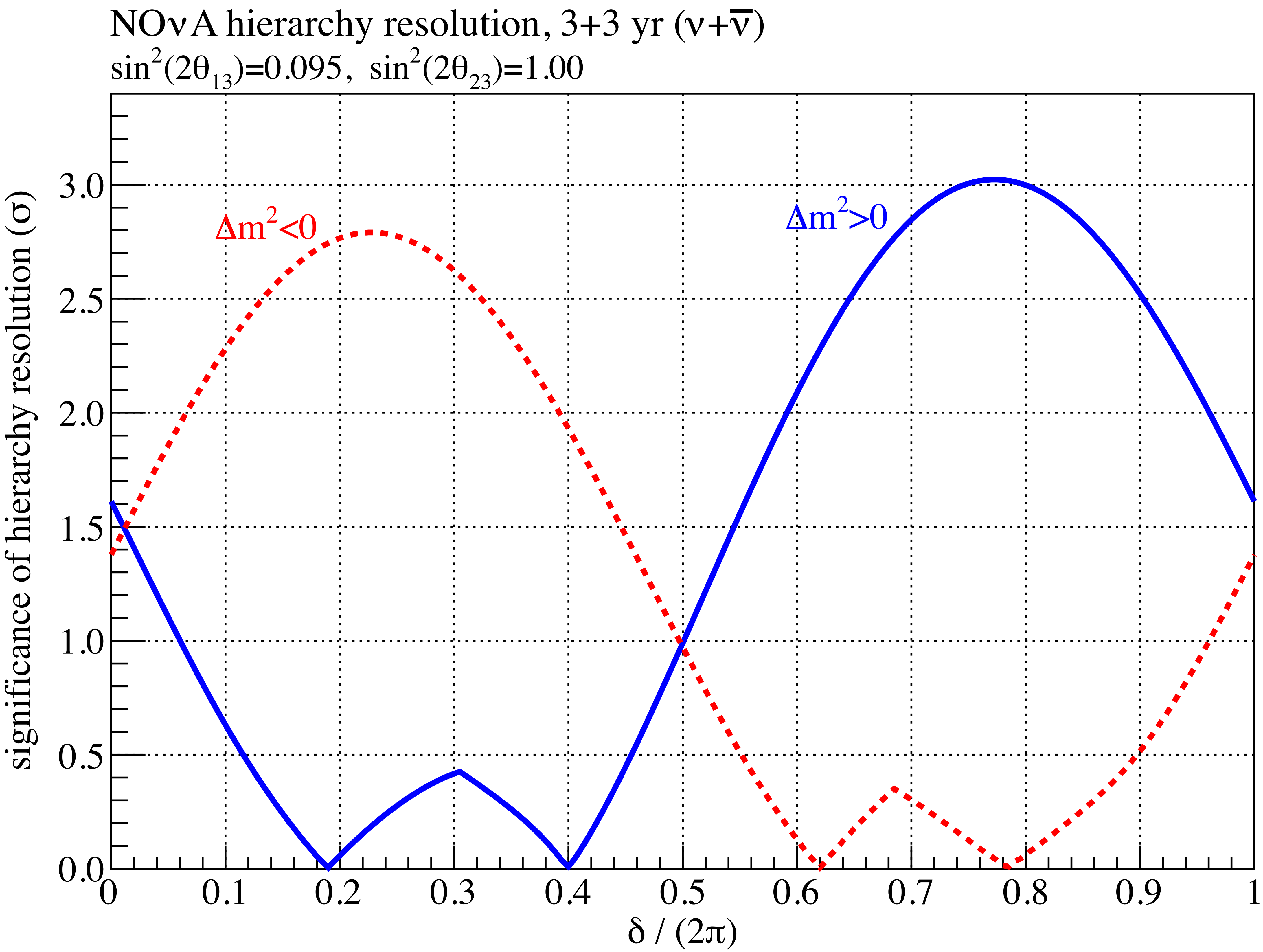




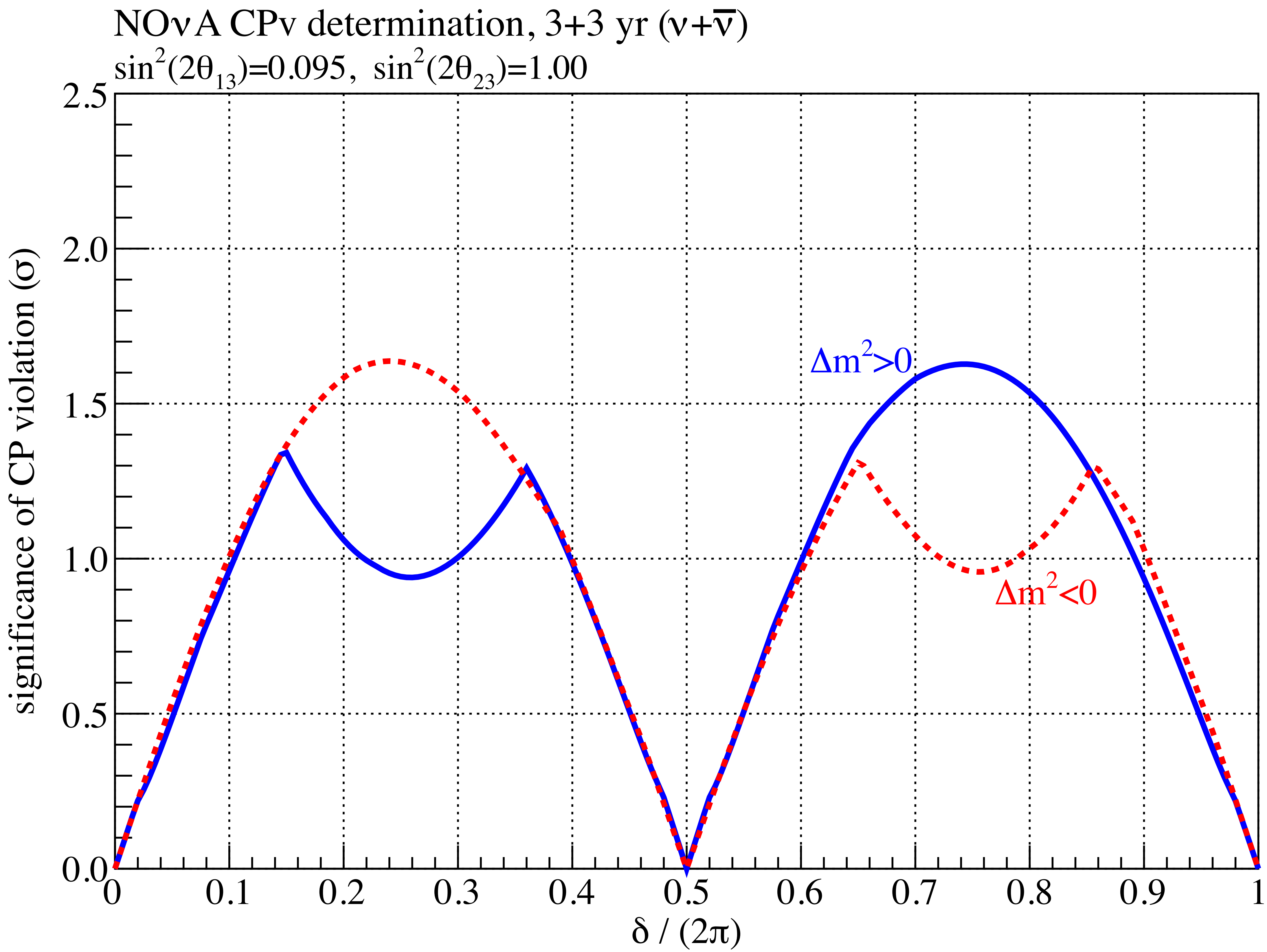
+ vertex projection

◆ beam direction from vertex

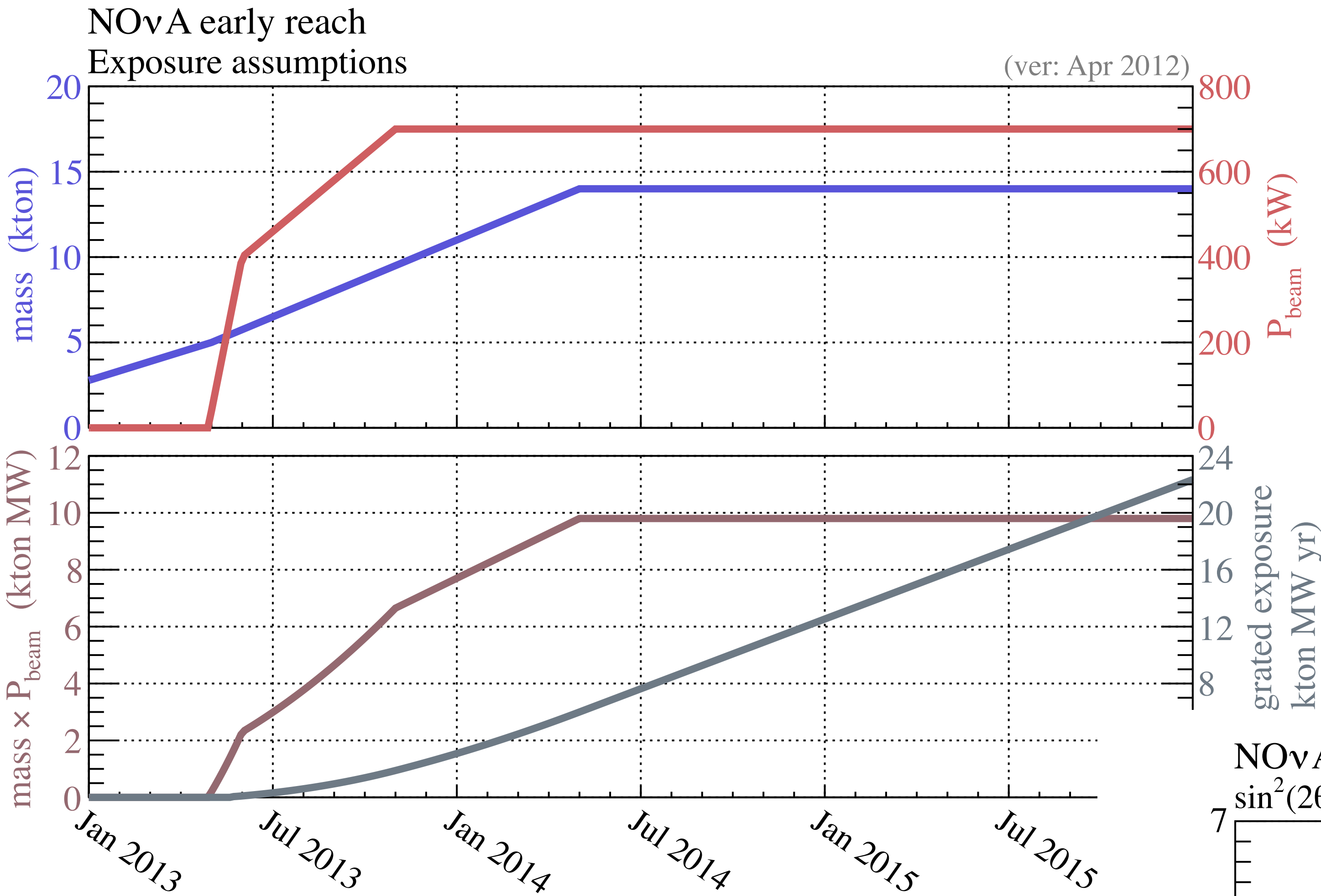
Resolution of Mass Hierarchy



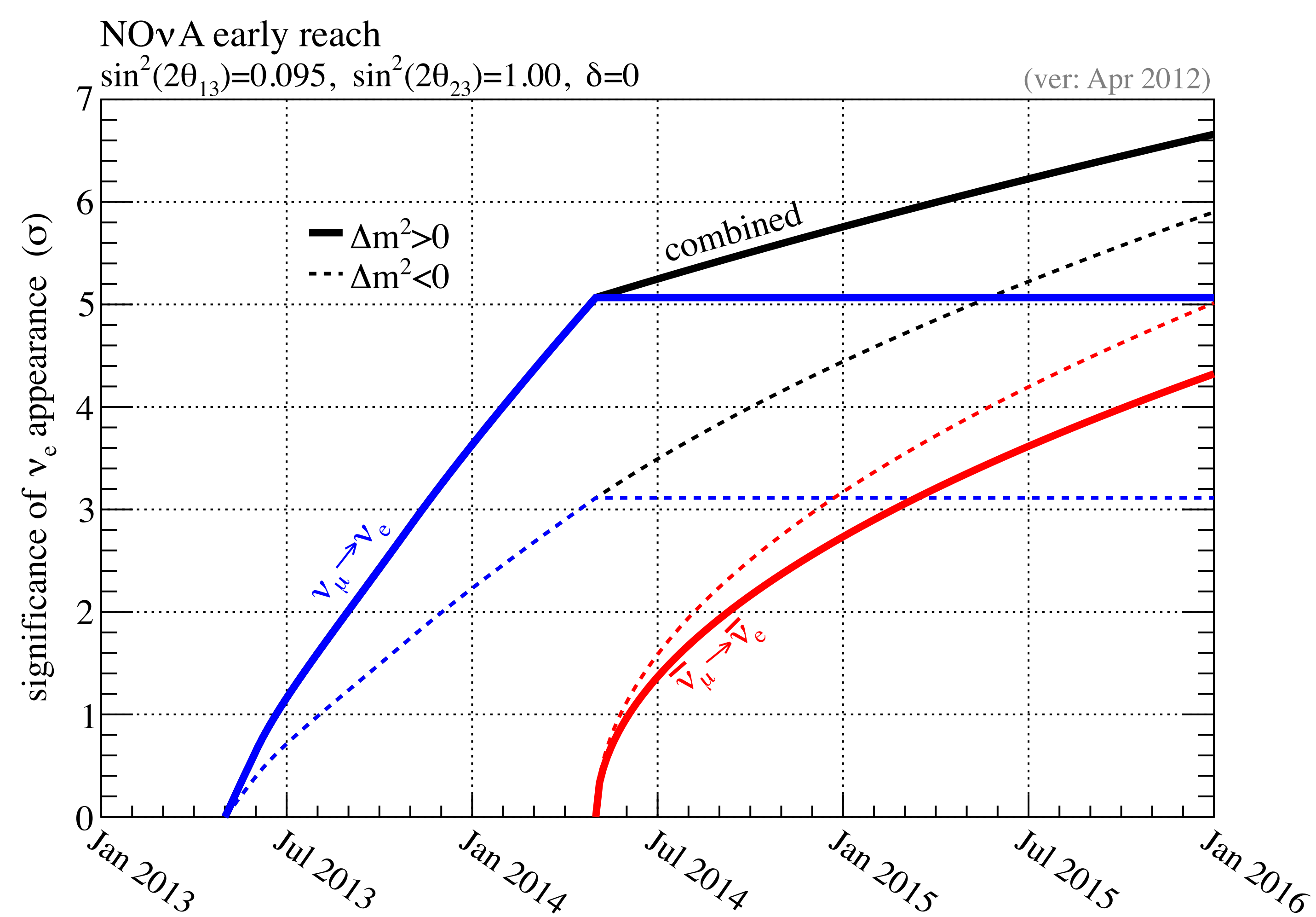
Measurement of CP-violation



Project Timeline



- Partially instrumented prototype near detector built and operated on the surface for ~1.5 years. Continues to provide invaluable data!
- Accelerator upgrades are underway at FNAL and on-schedule.
- Preparations for far detector construction underway.



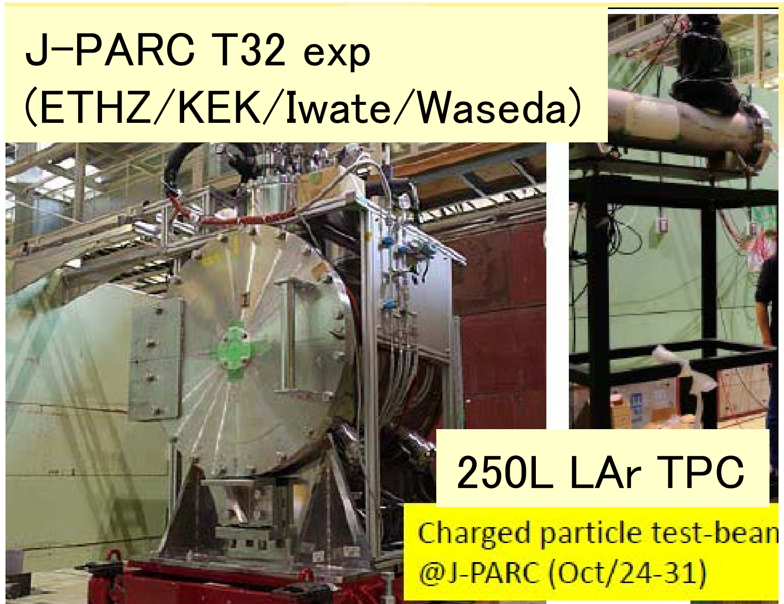
- Expect to have 5 kton built by the time beam returns in Spring of 2013 and we will be able to collect data as we build.
- Far detector to be complete by April 2014.
- Near detector to be complete in 2013.

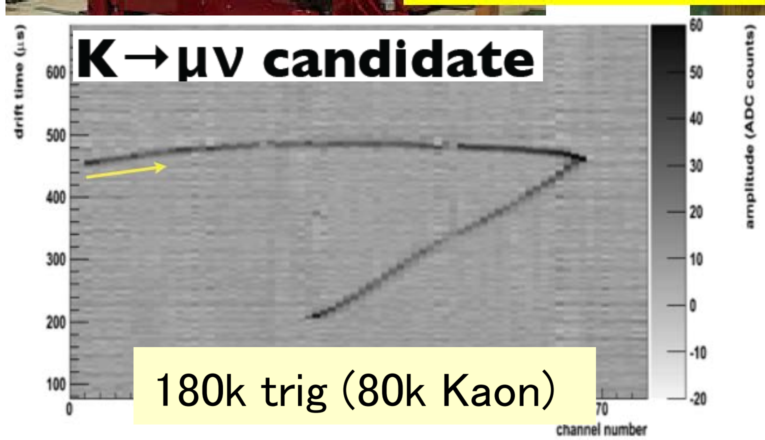
J-PARC + LAr

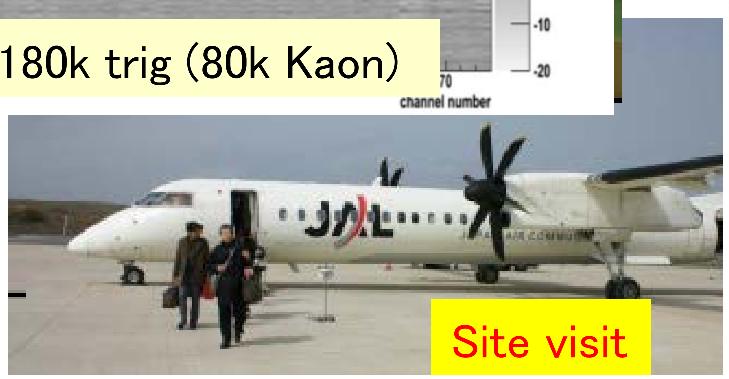
- 特徴：O(100kt)
  - Multi-trackなニュートリノ反応も検出可能
    - ニュートリノ反応をExclusiveに検出可能
    - e/π^0の識別可能なので、バックグラウンドの系統誤不定性小
  - 高いエネルギーのニュートリノも検出可能で、広いレンジのエネルギースペクトラムが測定可能
- ワイドバンドビーム（オンアクシス）での実験が可能
  - T2Kとは異なるビームライン（電磁ホーン）の最適化がありうる
- 課題
  - 期待どおりのe/π^0の識別能力があるか実証が必要
  - 大きな検出器が作れるか？がポイント
    - 実験機
    - 原型機　J–PARC T32　← いまここ
    - 実証機　(欧) ICURUS T600,（米)MicroBooNE　← 次のステップ
    - 実用機

タウンミーティング@J-PARC　2011/8/9　20

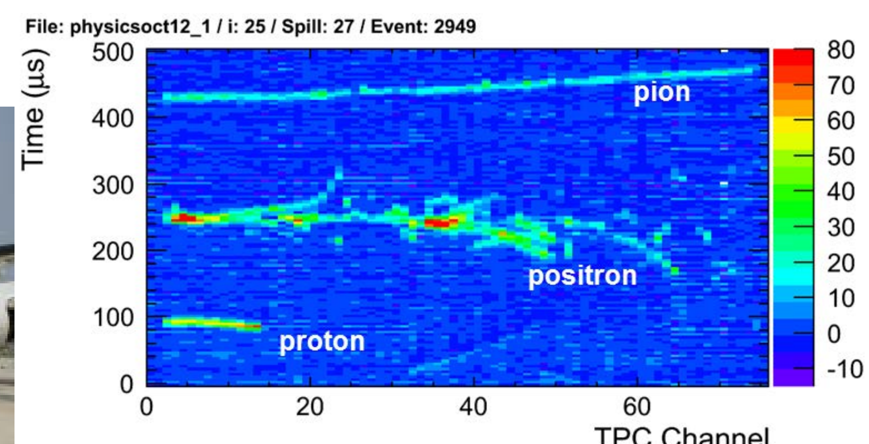
液体アルゴンTPC R&D





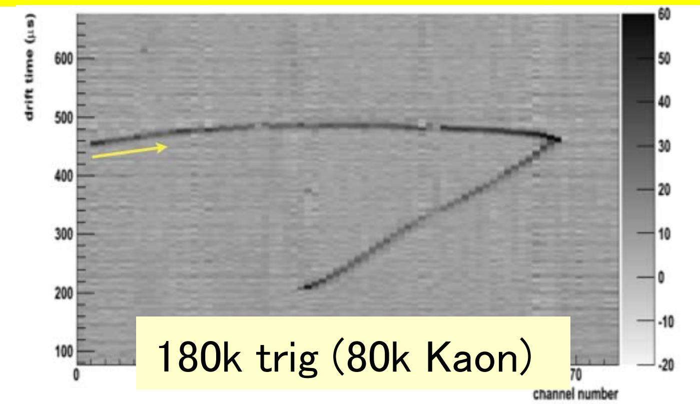


Charged particle test-beam @J-PARC T32 (data-taking during Oct/24-31)

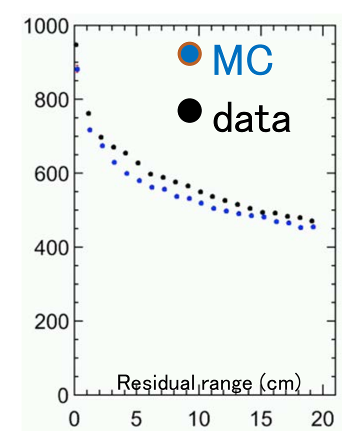


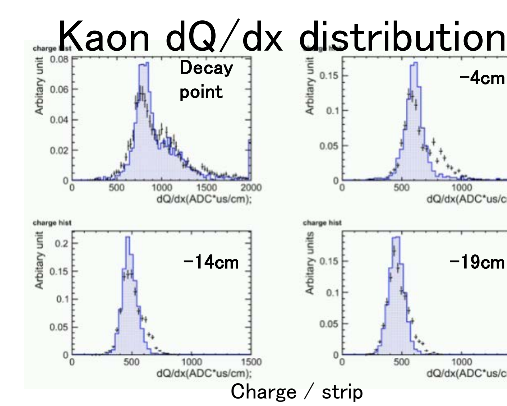
7000 800MeV/c K+ events w/ 2 LGs
35000 800MeV/c K+ events w/ one LG
40000 800MeV/c K+ w/ 1 LG and 1LB
70000 200MeV/c π+ events w/o degraders
2500 800MeV/c e+ events
1500 800MeV/c proton events

World largest Kaon sample ever taken by Lar TPC



Intensive analysis on-going

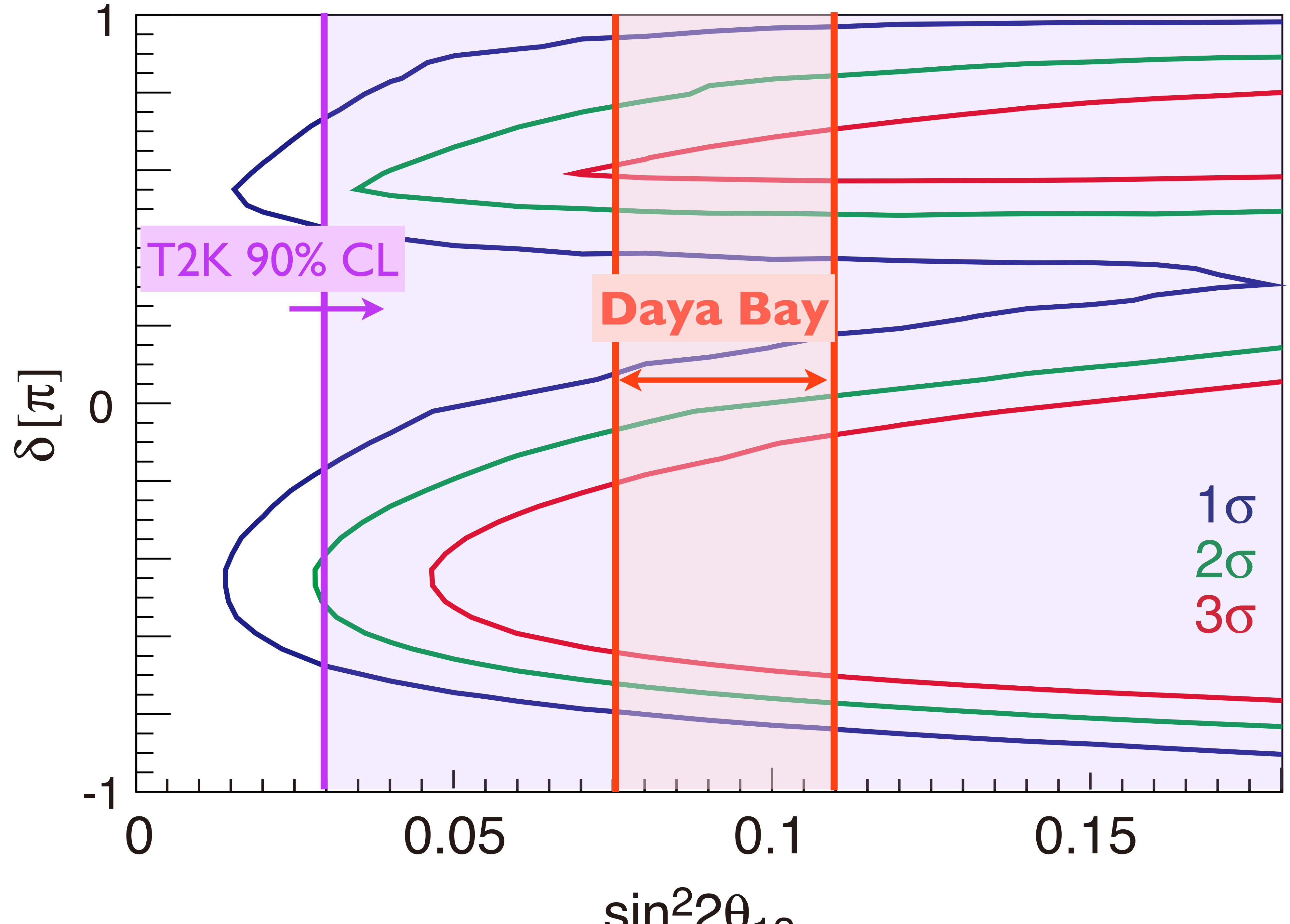




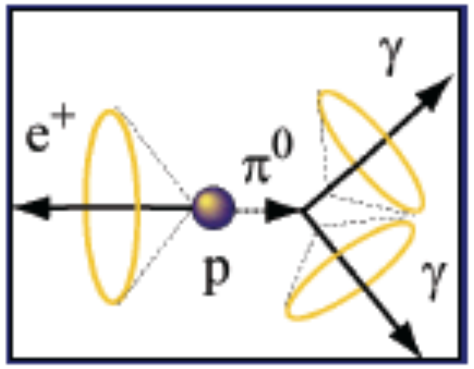
Mass hierarchy (質量階層)

Total 7.5MW×10^7s

5% systematics on signal, ν_μ BG, ν_e BG, $\nu/\bar{\nu}$



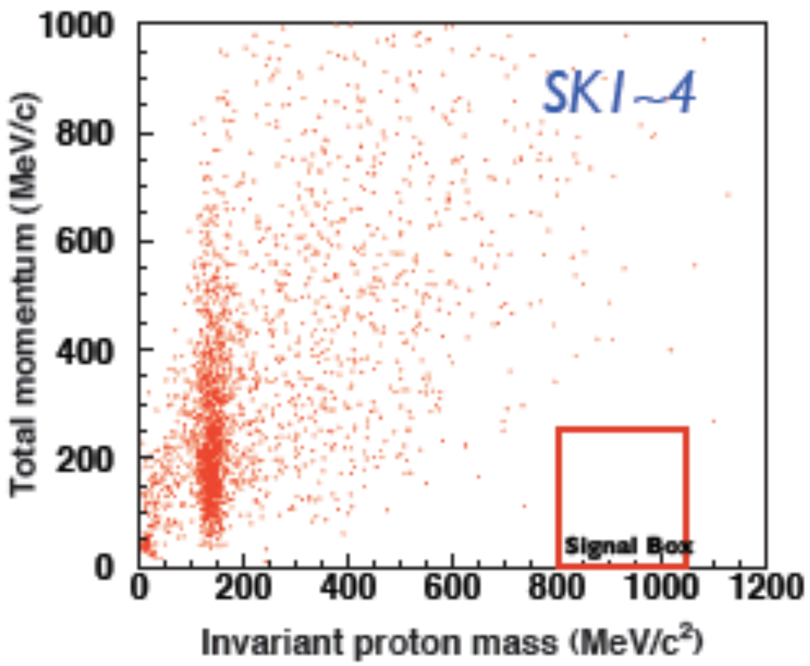
Mass Hierarchyにも感度がある

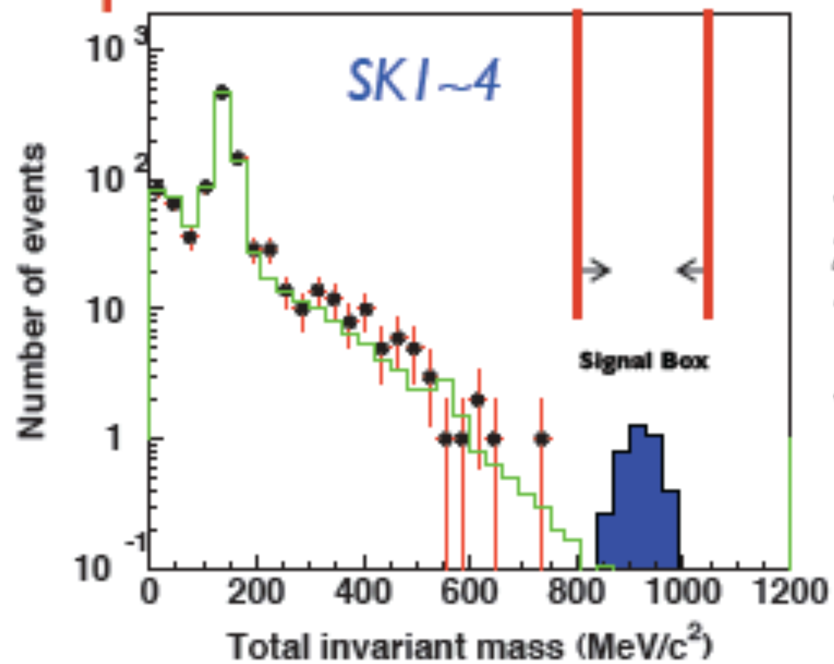


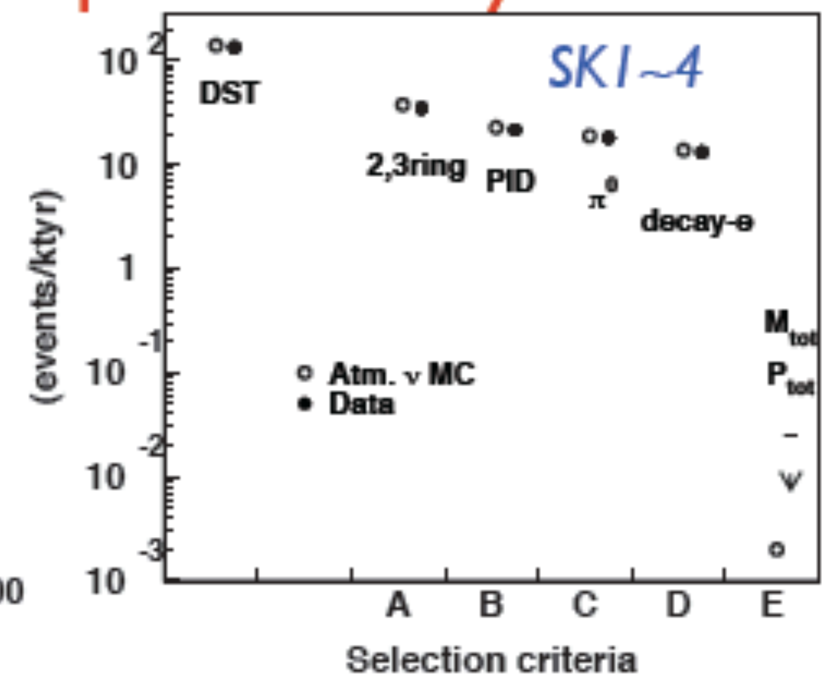
$p \rightarrow e^+ + \pi^0$ searches

Super-K cut
- 2 or 3 Cherenkov rings
- All rings are showering
- $85 < M_{\pi 0} < 185$ MeV/c² (3-ring)
- No decay electron
- $800 < M_{proton} < 1050$ MeV/c²
  $P_{total} < 250$ MeV/c

Super-K data are well reproduced by BG MC.

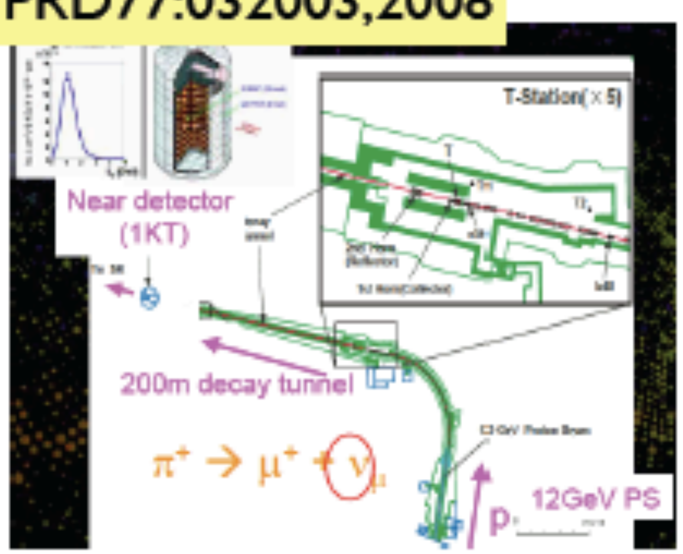






- detection efficiency = 45%
- atmospheric ν BG = 2.1±0.3(stat.)±0.8(syst.) (Mton×years)$^{-1}$
- τ_{proton}/Br > 1.3 ×10^{34} years @ 90%CL

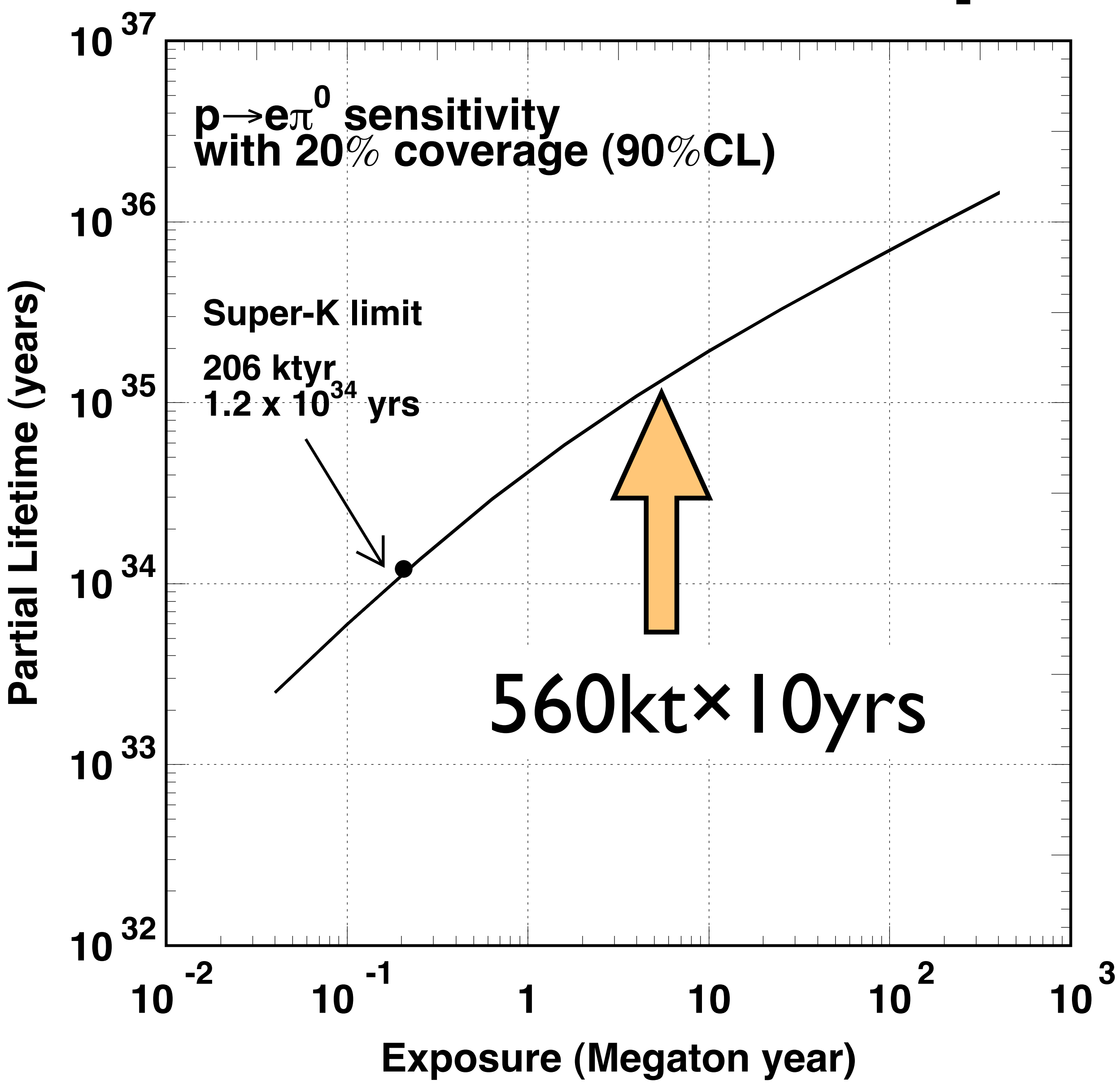
PRD77:032003,2008

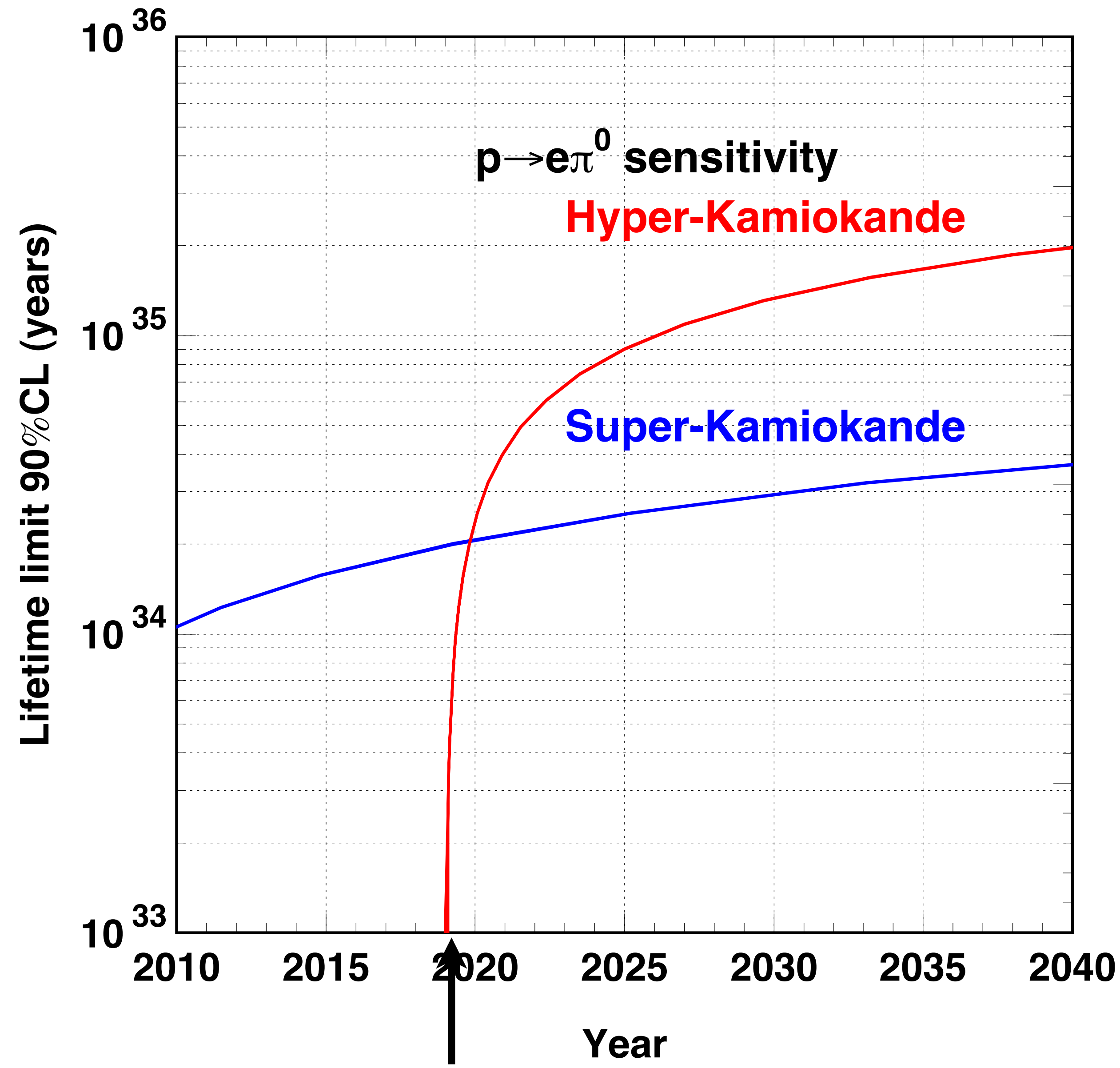


- BG measurement by accelerator ν (K2K)
  - BG=1.63+0.42/-0.33(stat.)+0.45/-0.51(syst.) (Mt×yrs)$^{-1}$ (Eν<3GeV)
  - Consistent w/ simulation 1.8±0.3(stat.)

Quality of next generation search is guaranteed.

$p \to e^{+}\pi^{0}$



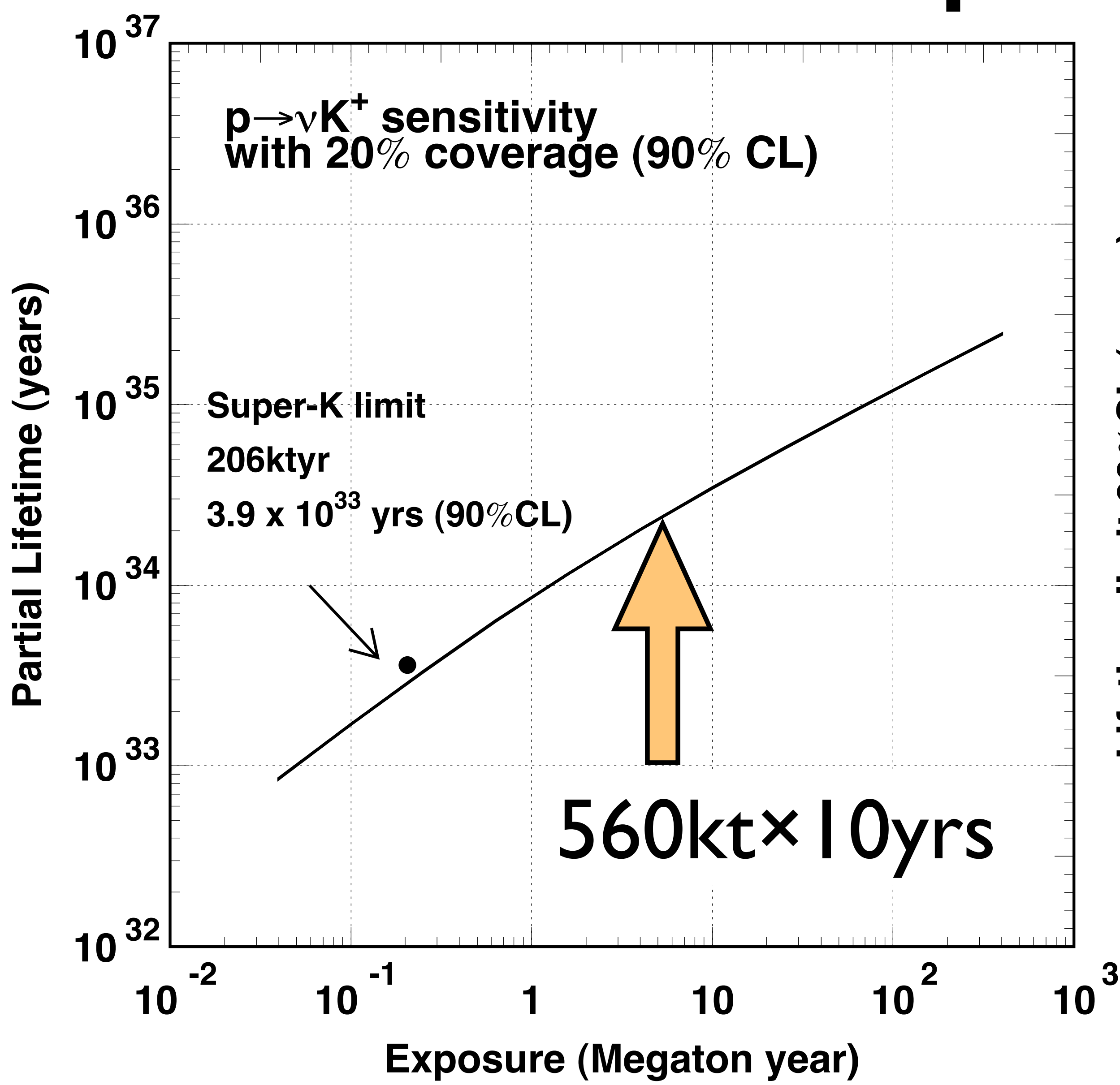


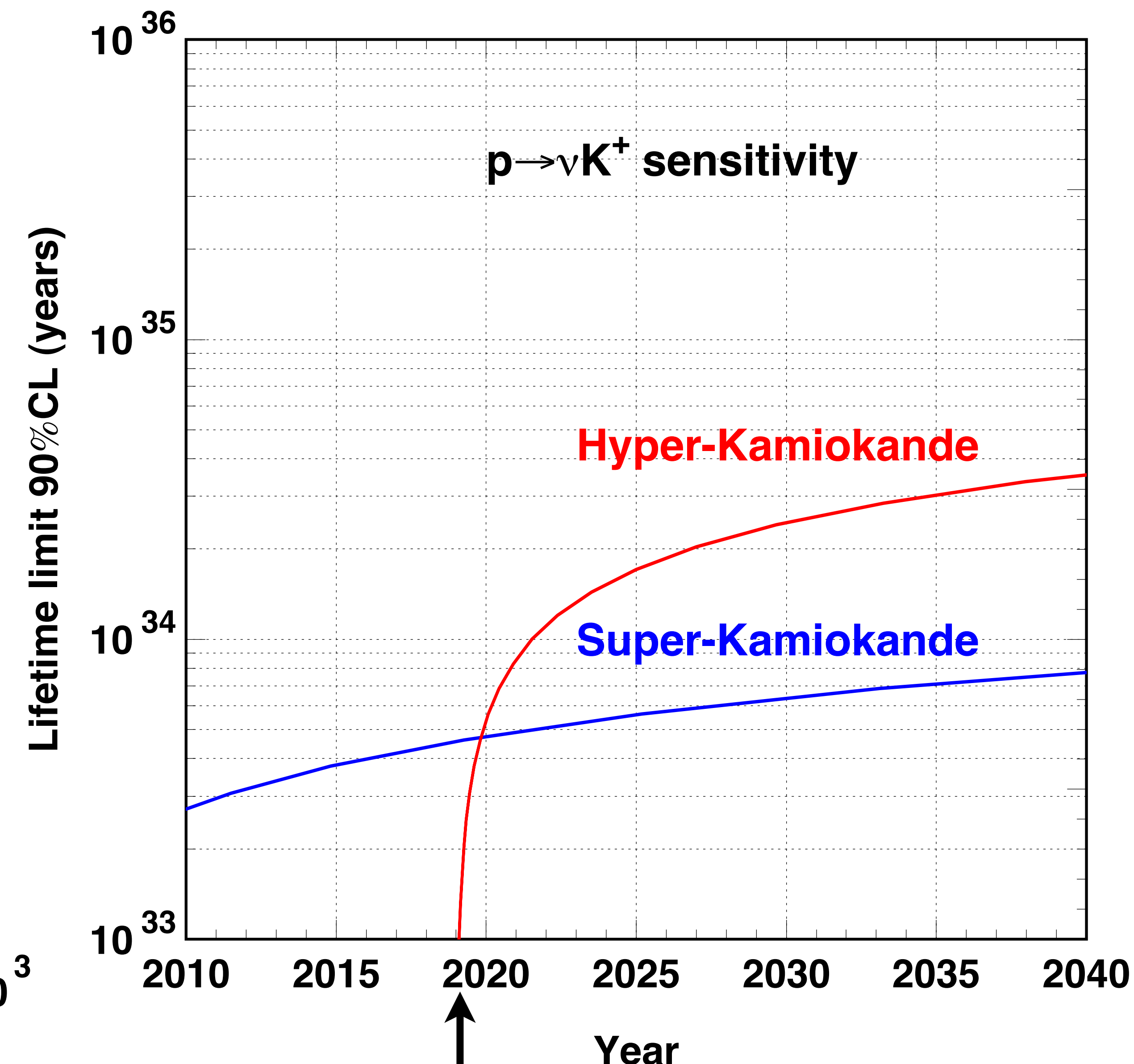
too optimistic, but

Limit with 560kt×10yrs
1.3×10^{35}yrs (90%CL)
5.7×10^{34}yrs (3σ)

HK will overtake SK in ~1year

$p \to \nu K^+$





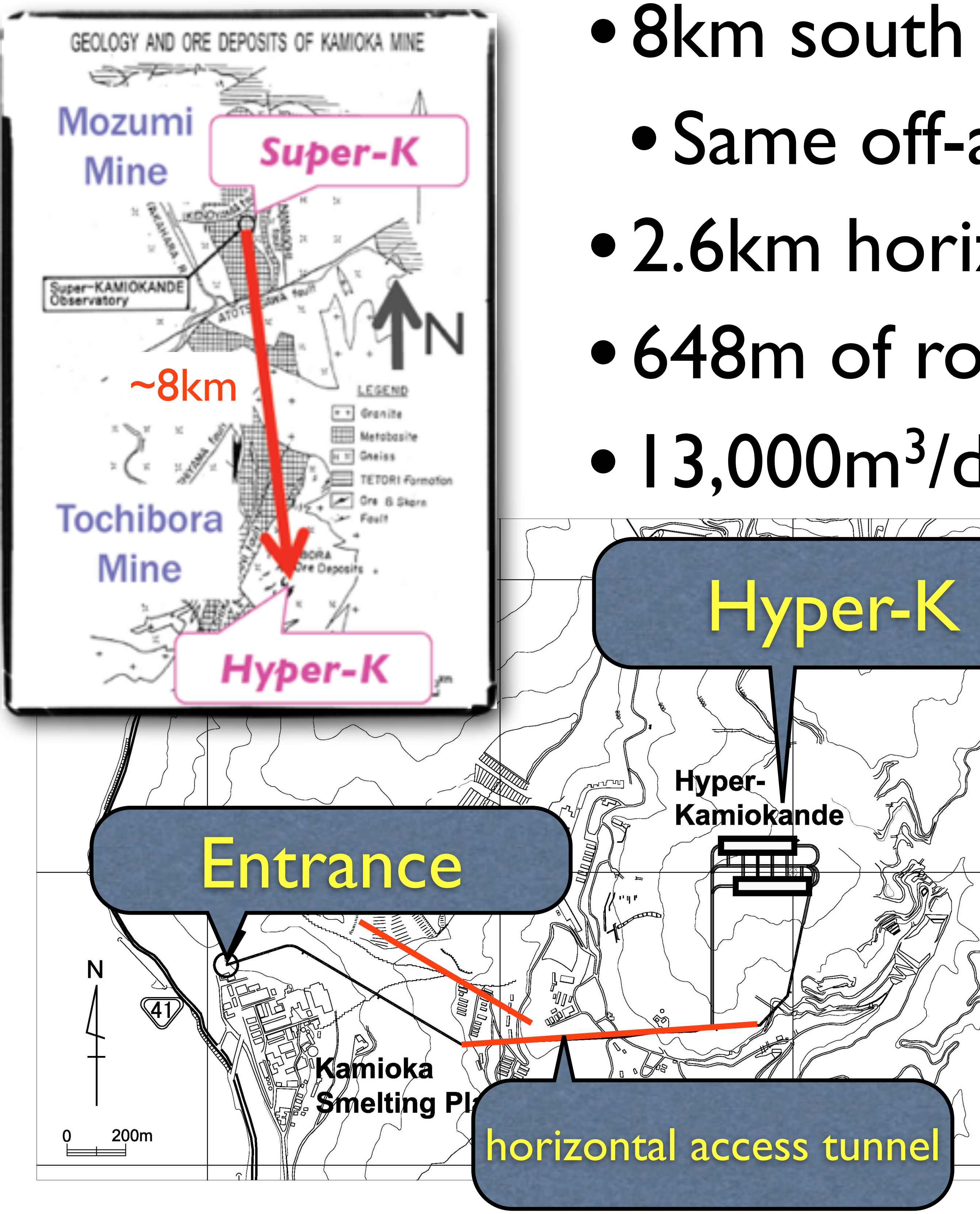
Limit with 560kt×10yrs
2.5×10^{34}yrs (90%CL)
1.0×10^{34}yrs (3σ)

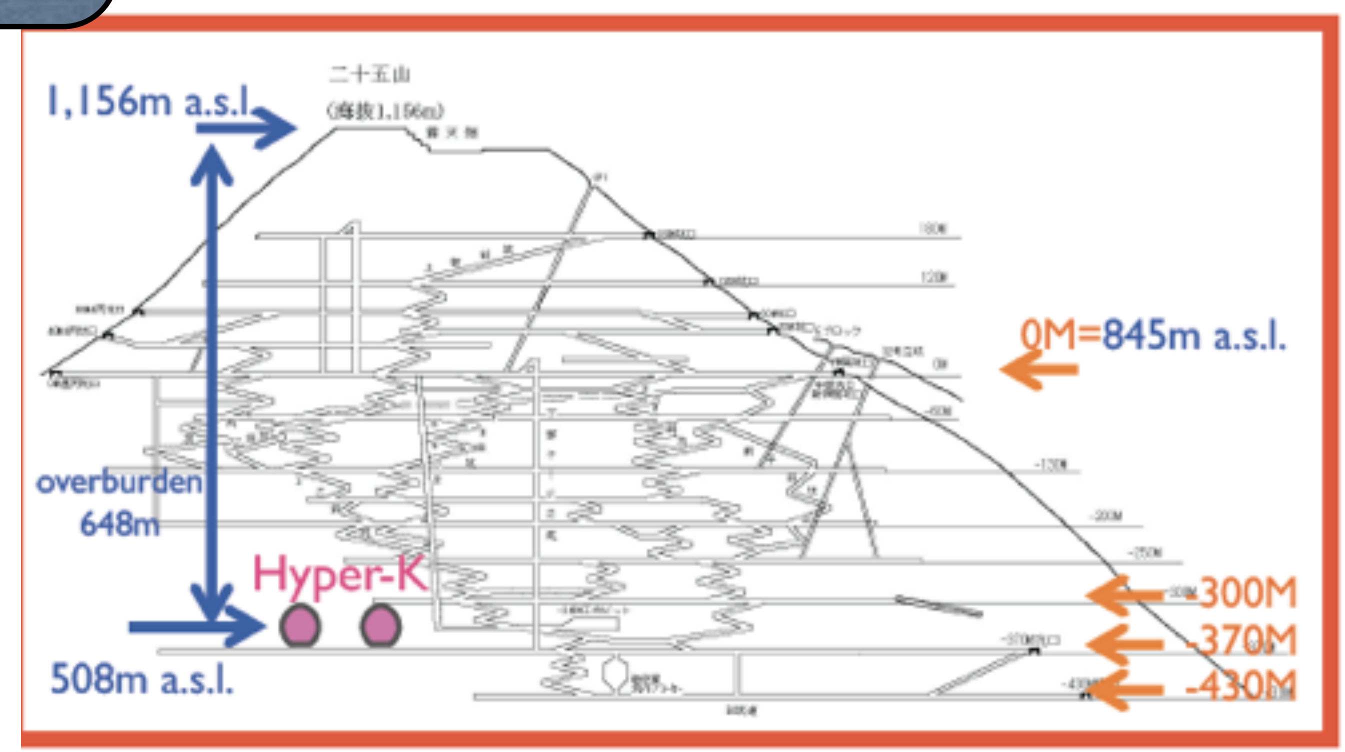
too optimistic again, but

HK will overtake SK in ~1year

Hyper-K Candidate site

- 8km south of Super-K
  - Same off-axis and baseline as T2K
- 2.6km horizontal drive
- 648m of rock (1750m.w.e.) overburden
- 13,000m^3/day natural water (1Mt/80days)

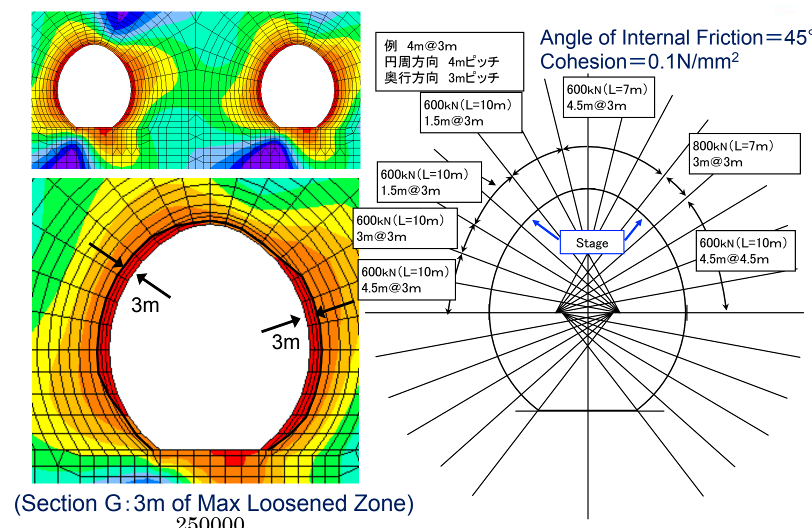




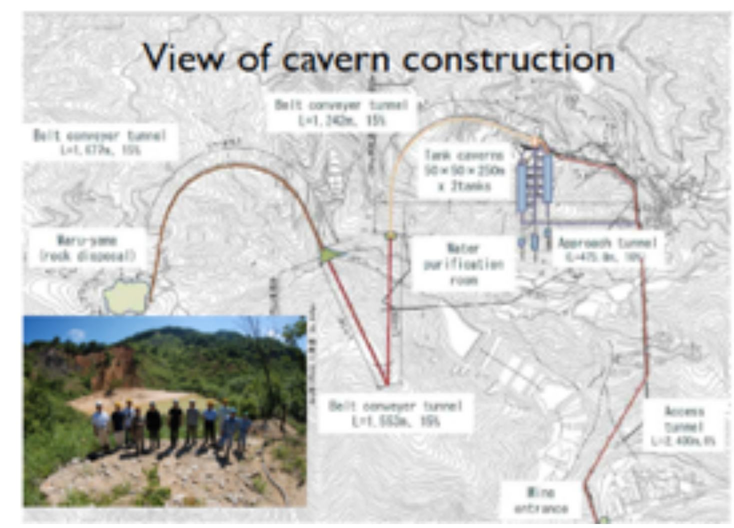
Thursday, July 19, 12

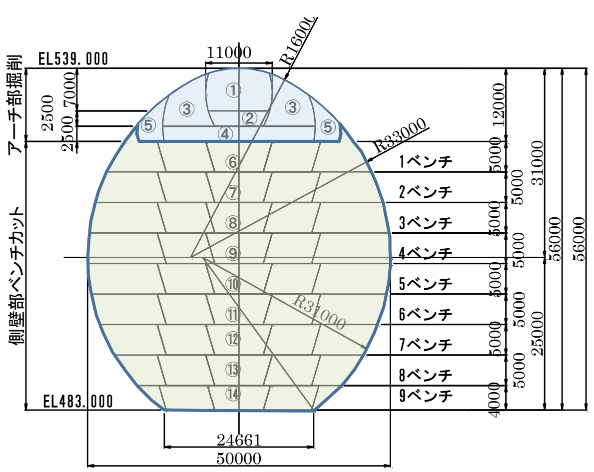
Large cavern excavation

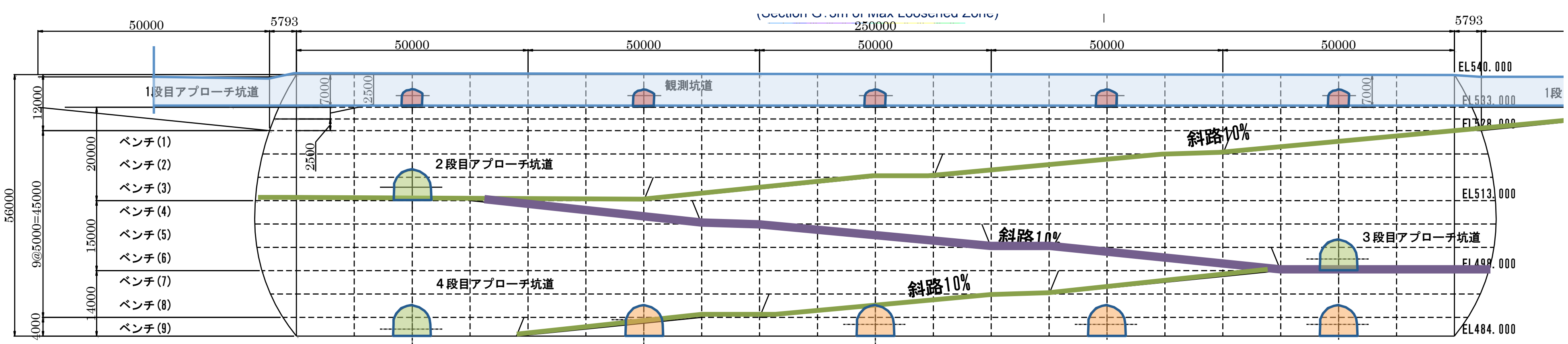
- Baseline plan developed based on geological survey & in-situ rock stress measurement
- Detailed schedule & cost estimation ongoing



(Section G：3m of Max Loosened Zone)

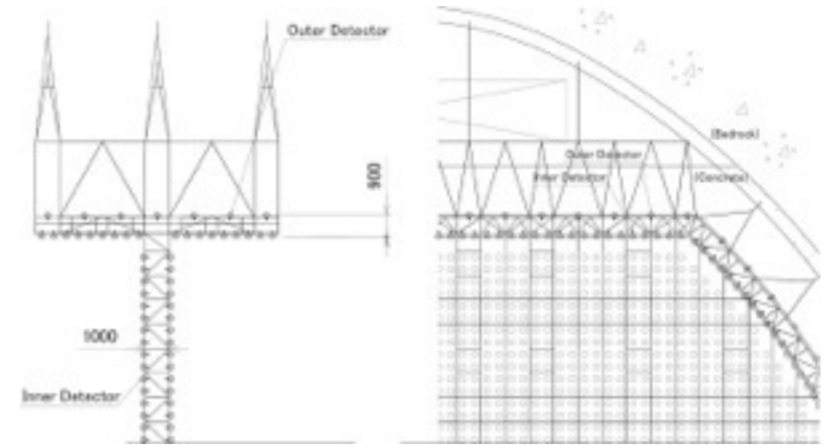


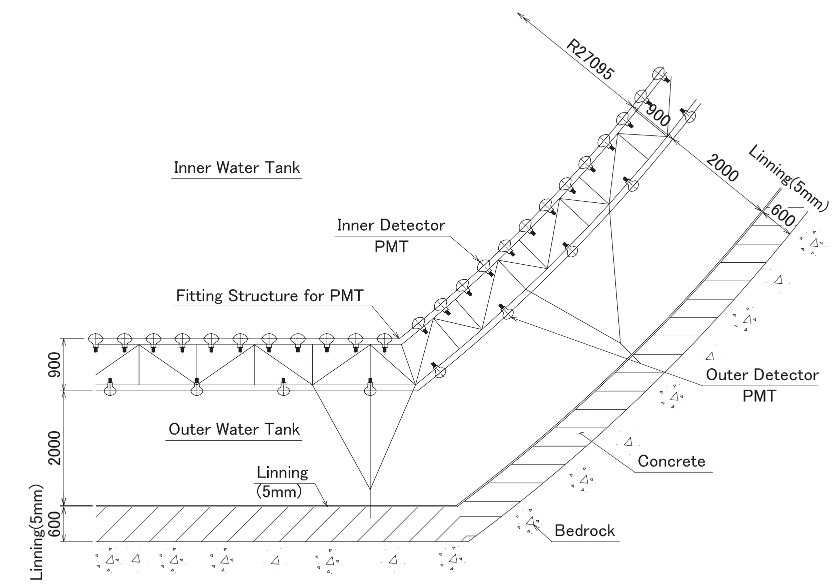


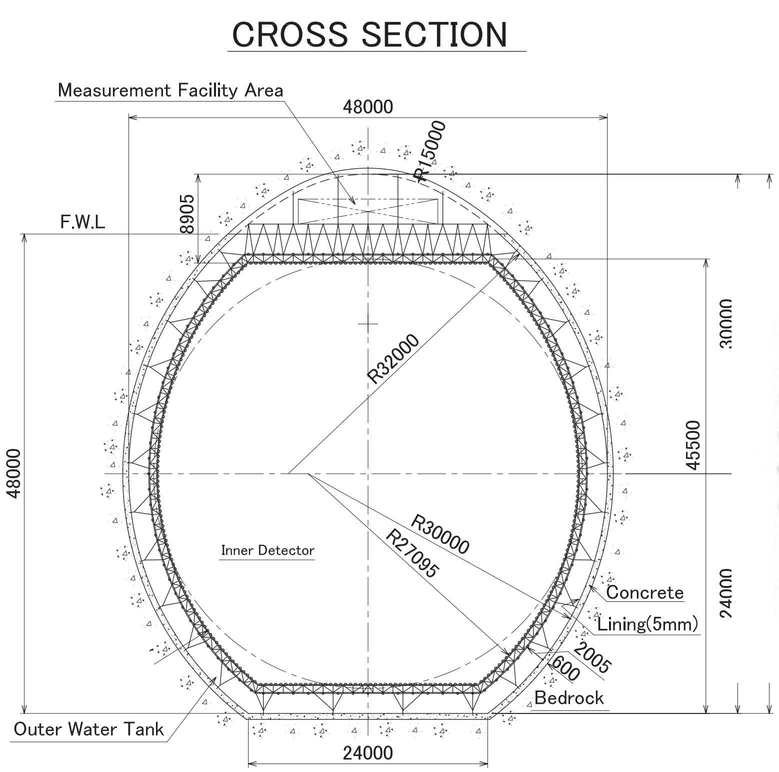


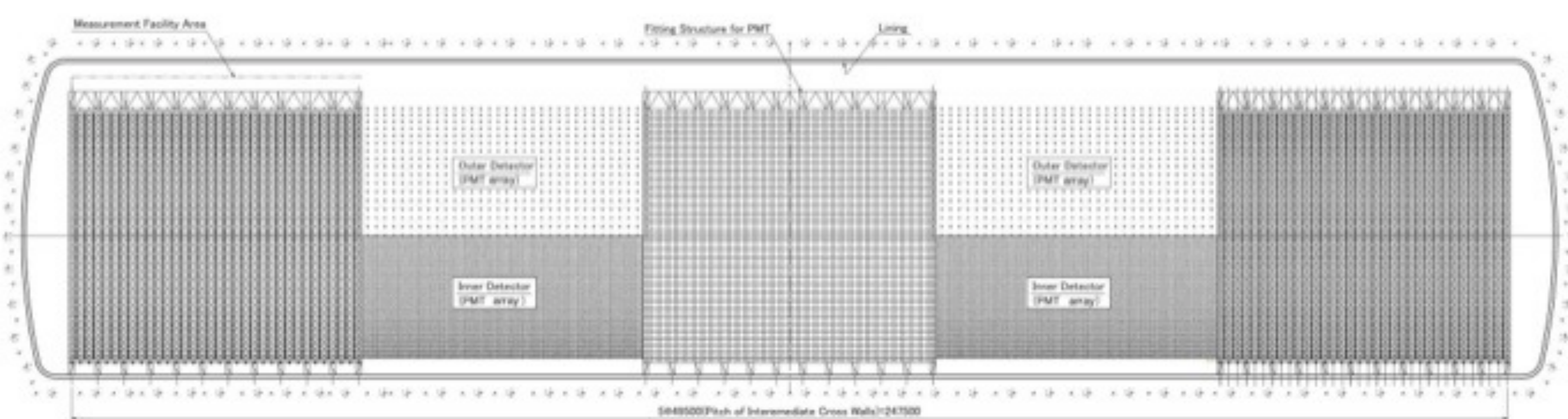
Tank

- Concrete + polyethylene liner
- PMT support structure under discussion
  - Wire support (cf. LBNE-WC)?
  - Straight wall cavern possible?









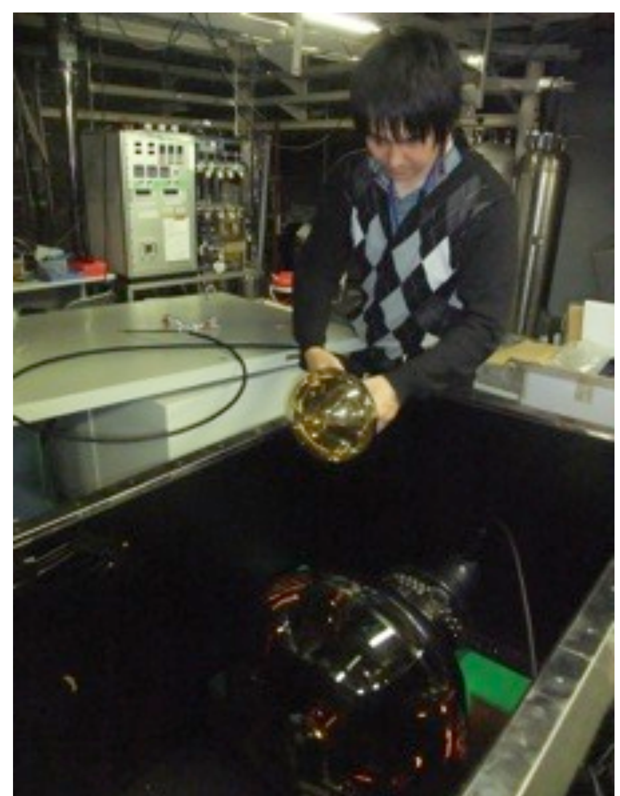
5 compartments × 2

Photo-sensor

Poster #68

- Candidates for ID sensor
  - 20" Hybrid Photo Detector (HPD)
  - Improved 20" PMT
- Proof test of 8" HPD in water tank from this summer
- 20" HPD prototype expected in ~a year

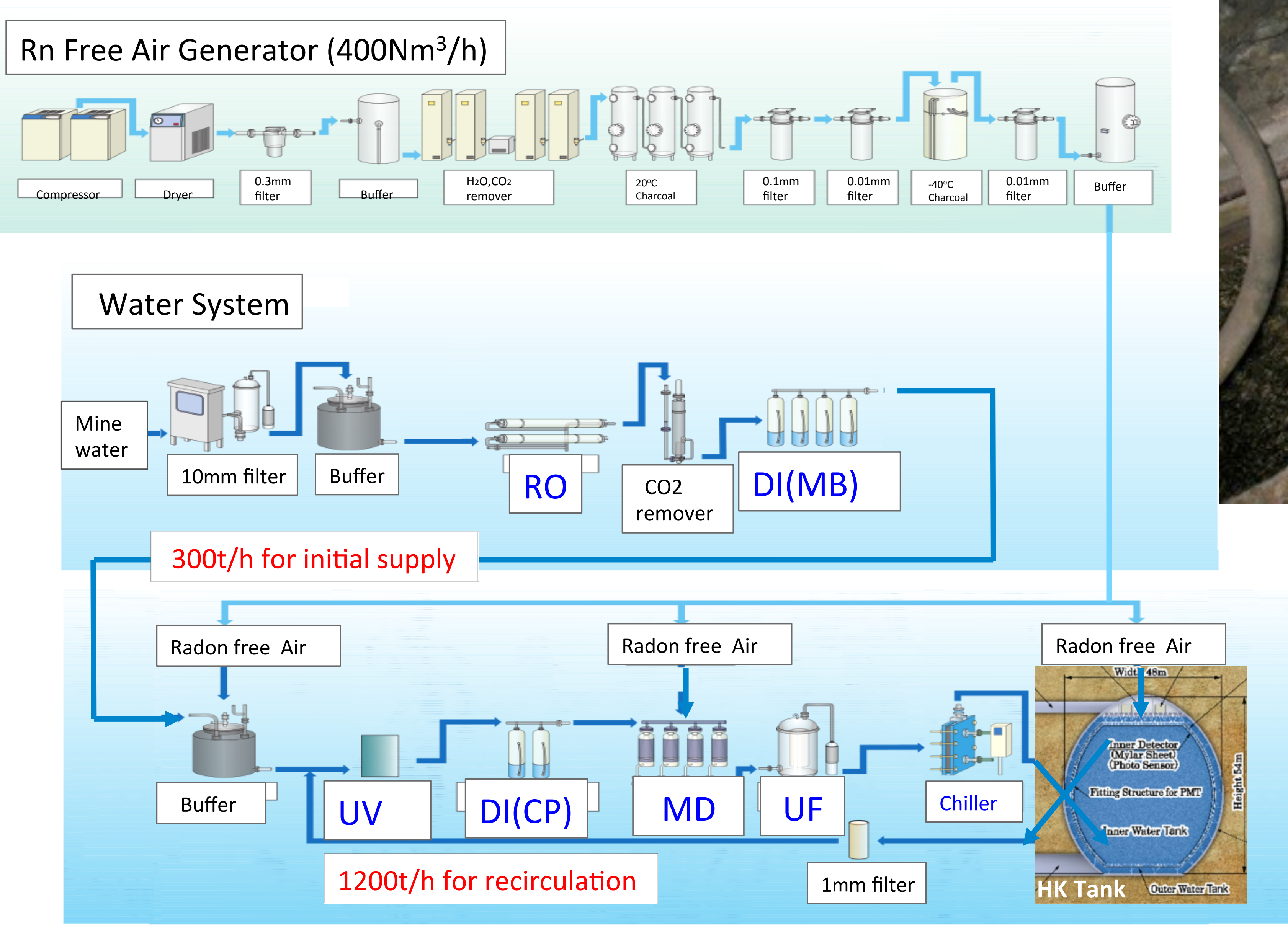
Preparation @ Kamioka



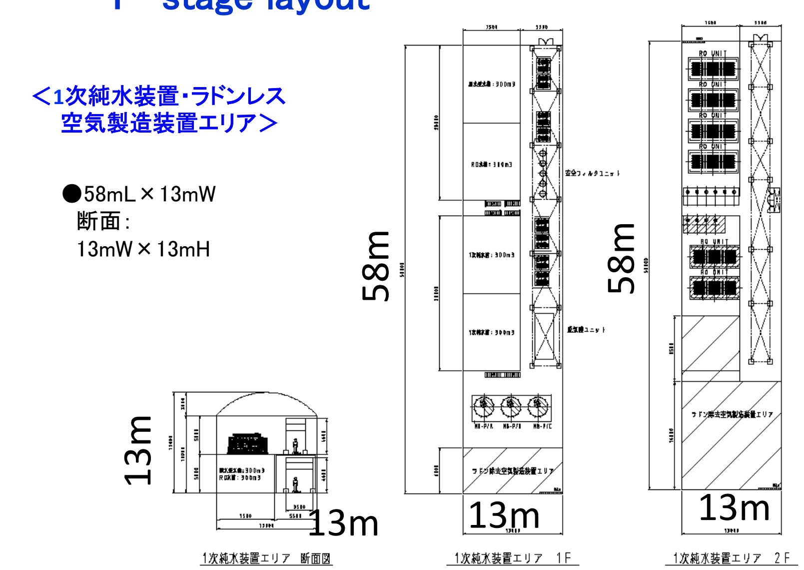
Water system

Poster #165

Based on Super-K system



1st stage layout

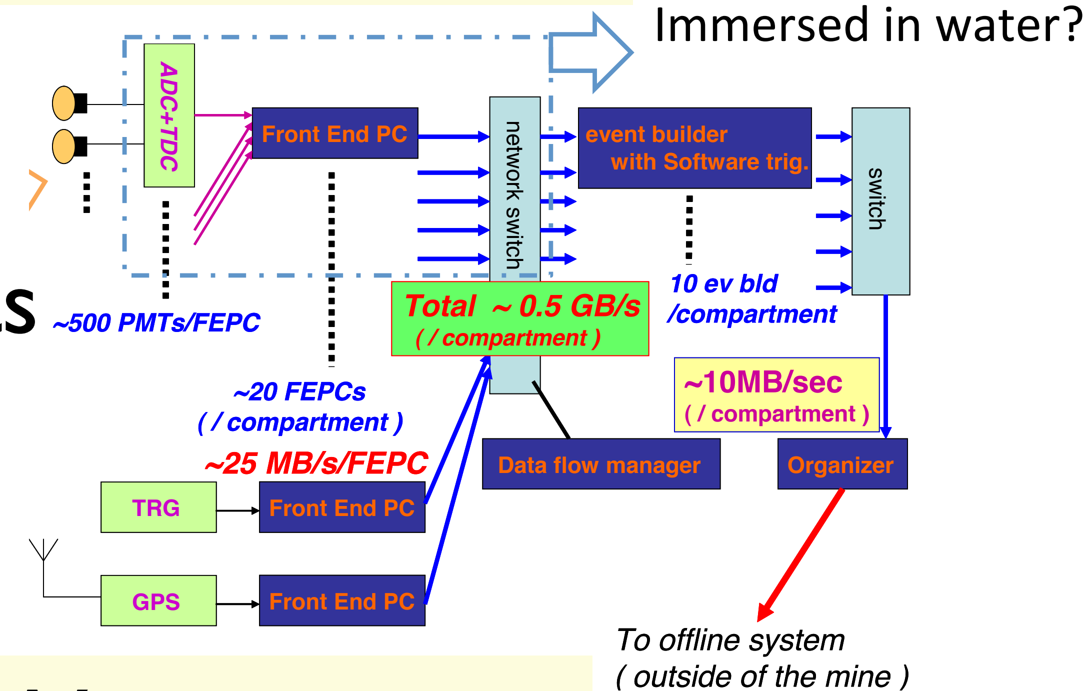


Under design with companies in Japan and US

Other R&D

- Electronics/DAQ
  - Requirements similar to Super-K
    - R&D of frontend in water starts
- Water system
  - Based on Super-K experience
  - Under design in Japan and US
- Detector calibration
  - R&D based on Super-K experience
- Dedicated software development
  - Under discussion
- …

Elec. schematics



Water system

Poster #165