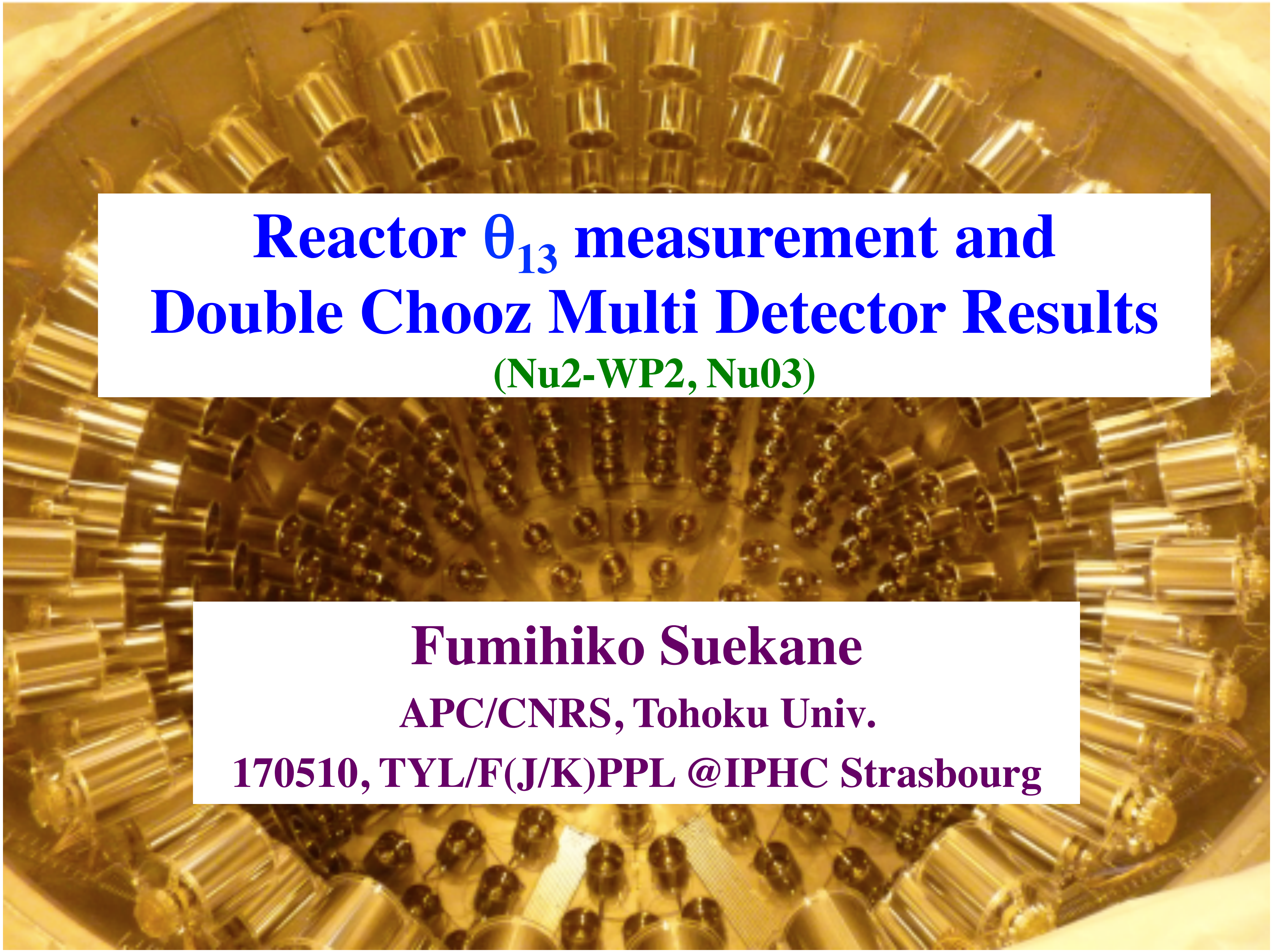


Reactor θ_{13} measurement and Double Chooz Multi Detector Results

(Nu2-WP2, Nu03)

Fumihiko Suekane

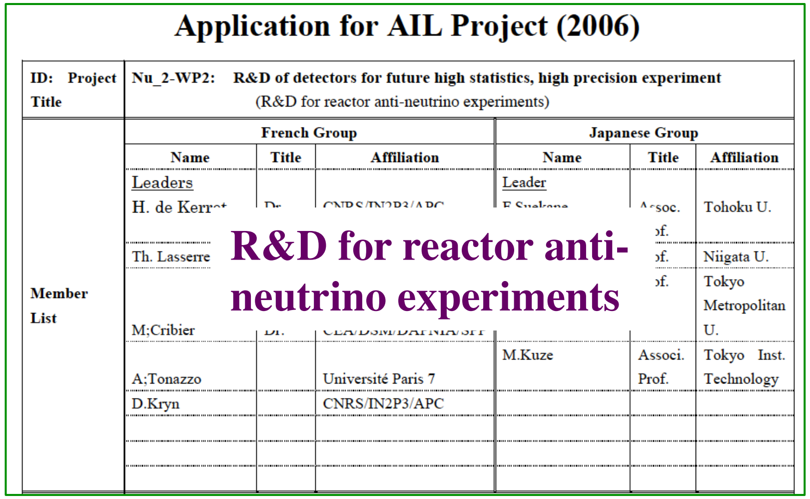
APC/CNRS, Tohoku Univ.

170510, TYL/F(J/K)PPL @IPHC Strasbourg

Contents of this talk

- * FJPPL and Double Chooz experiment
- * Neutrino Oscillation and Reactor θ_{13} measurement
- * Double Chooz θ_{13} Result
- * Measured θ_{13} and CPV measurement
- * Summary

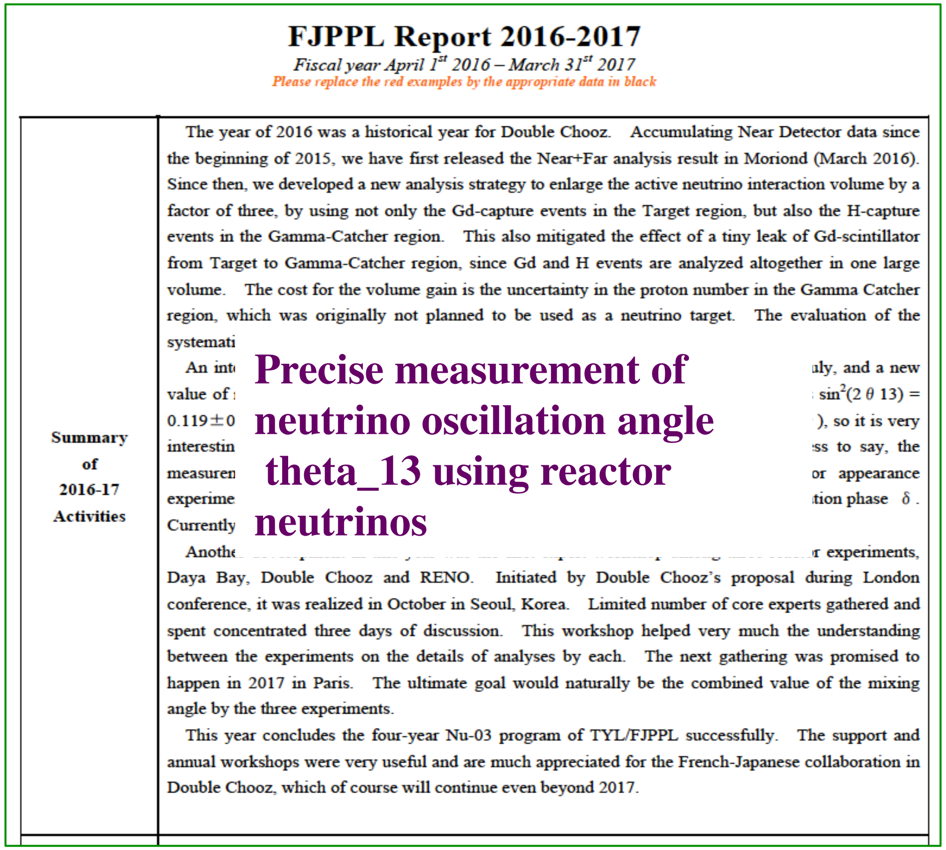
FJPPL and Double Chooz



Application for AIL Project (2006)

ID: Project Title	**Nu_2-WP2: R&D of detectors for future high statistics, high precision experiment** (R&D for reactor anti-neutrino experiments)					
Member List	**French Group**			**Japanese Group**		
	Name	**Title**	**Affiliation**	**Name**	**Title**	**Affiliation**
	Leaders			Leader		
	H. de Kerret	Dr.	CNRS/IN2P3/APC	F.Suekane	Assoc. Prof.	Tohoku U.
	Th. Lasserre				of.	Niigata U.
					of.	Tokyo Metropolitan U.
	M;Cribier	Dr.	CEA/DSM/DAPNIA/SPP			
	A;Tonazzo		Université Paris 7	M.Kuze	Associ. Prof.	Tokyo Inst. Technology
	D.Kryn		CNRS/IN2P3/APC			

R&D for reactor anti-neutrino experiments



FJPPL Report 2016-2017

Fiscal year April 1st 2016 – March 31st 2017

Please replace the red examples by the appropriate data in black

Summary of 2016-17 Activities	The year of 2016 was a historical year for Double Chooz. Accumulating Near Detector data since the beginning of 2015, we have first released the Near+Far analysis result in Moriond (March 2016). Since then, we developed a new analysis strategy to enlarge the active neutrino interaction volume by a factor of three, by using not only the Gd-capture events in the Target region, but also the H-capture events in the Gamma-Catcher region. This also mitigated the effect of a tiny leak of Gd-scintillator from Target to Gamma-Catcher region, since Gd and H events are analyzed altogether in one large volume. The cost for the volume gain is the uncertainty in the proton number in the Gamma Catcher region, which was originally not planned to be used as a neutrino target. The evaluation of the systemati An int … ly, and a new value of … $\sin^2(2\theta 13)$ = 0.119±0 …), so it is very interestin … ss to say, the measuren … or appearance experime … tion phase δ. Currently Anothe … r experiments, Daya Bay, Double Chooz and RENO. Initiated by Double Chooz's proposal during London conference, it was realized in October in Seoul, Korea. Limited number of core experts gathered and spent concentrated three days of discussion. This workshop helped very much the understanding between the experiments on the details of analyses by each. The next gathering was promised to happen in 2017 in Paris. The ultimate goal would naturally be the combined value of the mixing angle by the three experiments. This year concludes the four-year Nu-03 program of TYL/FJPPL successfully. The support and annual workshops were very useful and are much appreciated for the French-Japanese collaboration in Double Chooz, which of course will continue even beyond 2017.

Precise measurement of neutrino oscillation angle theta_13 using reactor neutrinos

In 2006, KASKA group (planned reactor θ_{13} exp. in Japan) joined Double Chooz group and applied to FJPPL.

DCJapan group has been funded for ~$5M for DC thanks to JSPS grants in aid.

In 2017, the FJPPL-DC is successfully finishing, after the measurements of θ_{13}.

FJPPL and Double Chooz

Nu2-WP2
H.Kerret
F.Suekane

Nu03
C.Anatael
M.Kuze

June	2006	Double Chooz proposal	arXiv:0606025[hep-ex]
May	2008	Started FD construction	
Apr.	2011	Started FD data taking	
Nov.	2011	1st θ_{13} result (Gd)	Reported in LowNu2011 Phys. Rev. Lett. 108 (2012) 131801
June	2012	Started ND construction	
Sep.	2012	2nd θ_{13} result (Gd)	Phys. Rev. D 86 (2012) 052008
June	2013	1st θ_{13} result (H)	Phys. Lett. B 723 (2013) 66
Oct.	2014	3rd θ_{13} result (Gd)	JHEP 10 (2014) 086
Jan.	2015	Started ND data taking	
Jan.	2016	2nd θ_{13} result (H)	JHEP 01 (2016) 163
Mar.	2016	θ_{13} result w/ two detectors (Gd)	Reported in Moriond 2016
Sep.	2016	θ_{13} result w/ two detectors (Gd+H)	Reported in CERN seminar https://indico.cern.ch/event/548805/

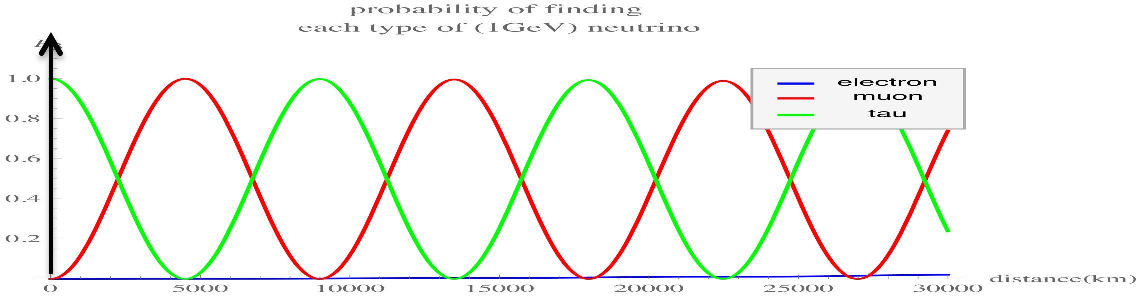
➔ **This talk: summary of 10+ years of FJPPL/DC activities.**

What is Neutrino Oscillation?

Electron stays as electron while it travels in space.

$$e^- \longrightarrow e^-$$

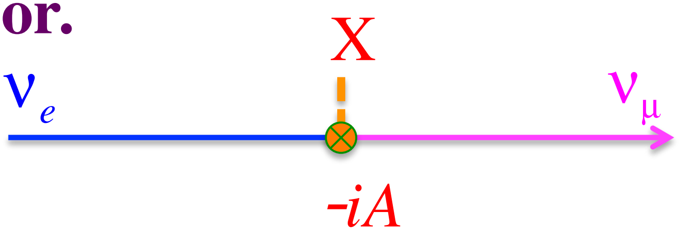
However, neutrinos change their flavors periodically.



This phenomenon is called neutrino oscillation

What causes the neutrino to oscillate?

We do not know yet. But in order for N.O. to exist, something(X) has to change ν flavor.

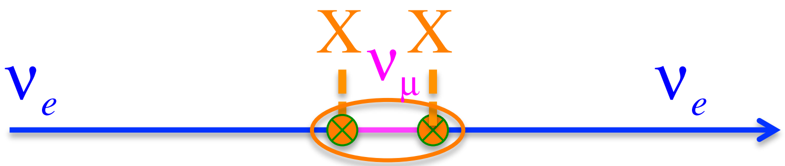


"A" indicates the strength of the transition (amplitude).

In this case the equations of motion of ν are

$$\boxed{\frac{d}{dt}\nu_e = -iA\nu_\mu, \quad \frac{d}{dt}\nu_\mu = -iA\nu_e}$$

or

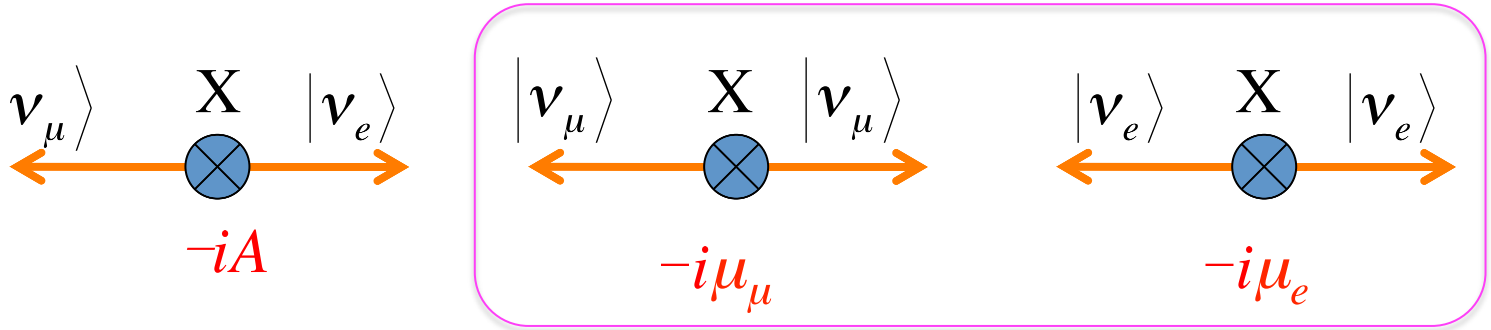


$$m = \pm A$$

$$\boxed{\frac{d^2}{dt^2}\nu_e = -A^2\nu_e}$$

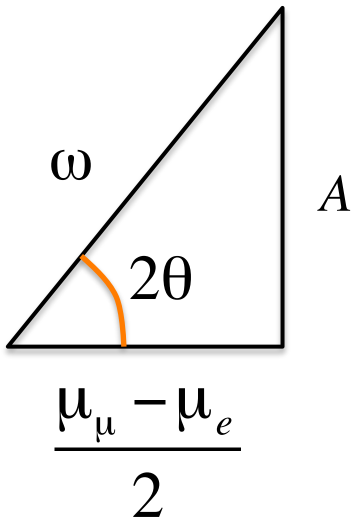
➔ If this transition exists, neutrinos obtain mass.

ν oscillation



If there are self-transitions, the mass eigenstate become the superposition of flavor eigenstate;

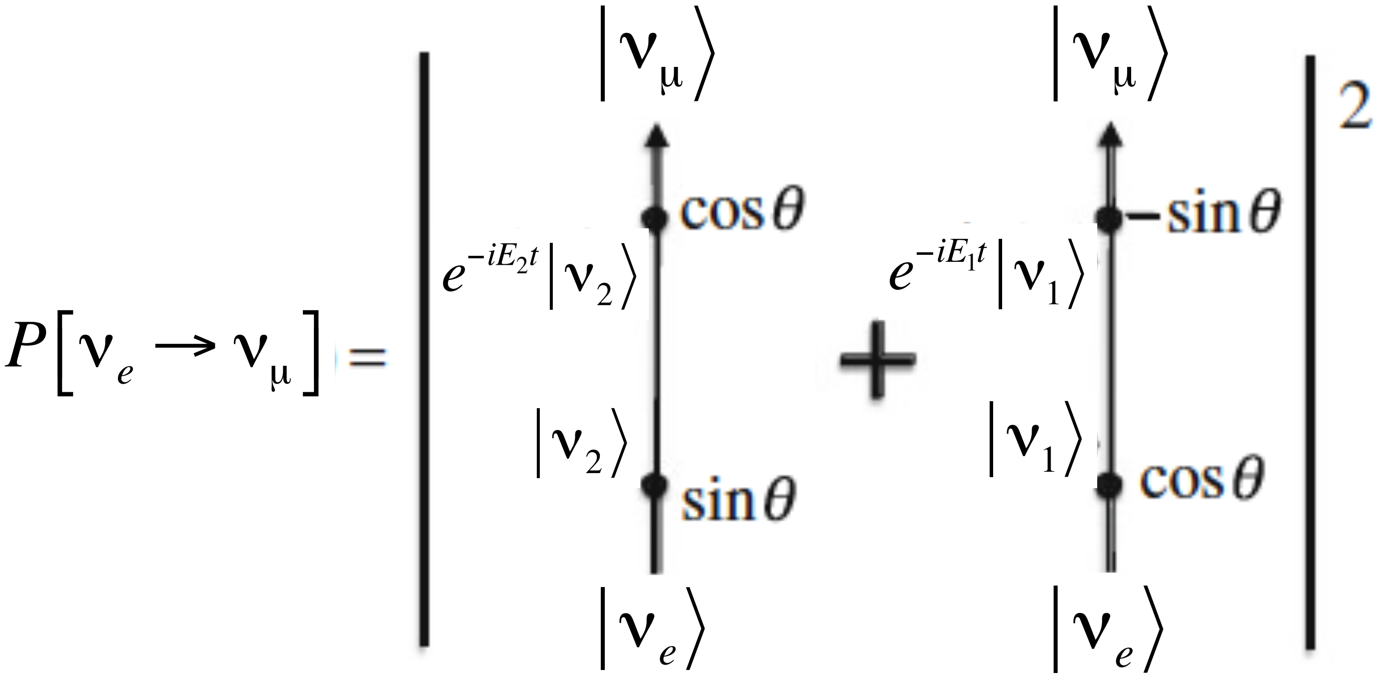
$$\begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}$$



The neutrino masses are

$$\begin{cases} m_1 = \bar{\mu} - \omega \\ m_2 = \bar{\mu} + \omega \end{cases}, \quad \bar{\mu} = \frac{\mu_\mu + \mu_e}{2}, \quad \omega = \frac{A}{\sin 2\theta}$$

Oscillation probability



$$P[\nu_e \rightarrow \nu_\mu] = \left|\sin\theta\cos\theta e^{-iE_1 t} - \sin\theta\cos\theta e^{-iE_2 t}\right|^2$$

$$\boxed{\rightarrow \sin^2 2\theta \sin^2 \frac{m_2^2 - m_1^2}{4E} L}$$

Oscillations are playing important roles

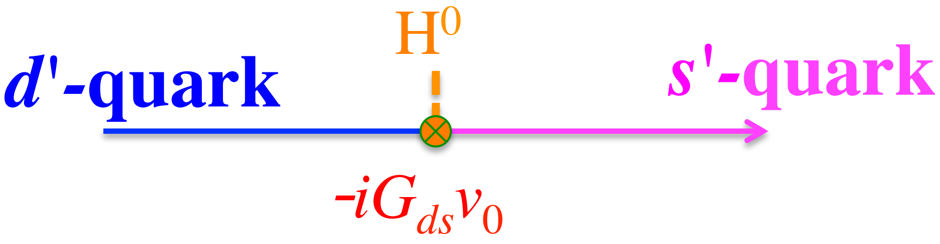
- ✱ $K^0 \Leftrightarrow \overline{K^0}$, $B^0 \Leftrightarrow \overline{B^0}$ **Oscillation.** ➔ **CP violation/**
- ✱ **spin precession by B (=$|\Uparrow\rangle \Leftrightarrow |\Downarrow\rangle$ oscillation)** ➔ **Formation of Q.M.**
- ✱ $|u\bar{u}\rangle \Leftrightarrow |d\bar{d}\rangle$ **oscillation in** π^0 ➔ **Hadron mass pattern**
- ✱ $d \Leftrightarrow s$ **oscillation** ➔ **Cabbibo angle, quark mass.**
- * $B \Leftrightarrow W_3$ **oscillation** ➔ **Weinberg angle,**

➔ **We have learned a lot from these "Oscillations"**

We should be able to learn more from ν oscillations, also.

Comparison with quark case

For quark case, there are similar transitions which causes the quark masses, Cabbibo angle and CP violation. The transition is caused by the Yukawa Coupling to the Higgs field



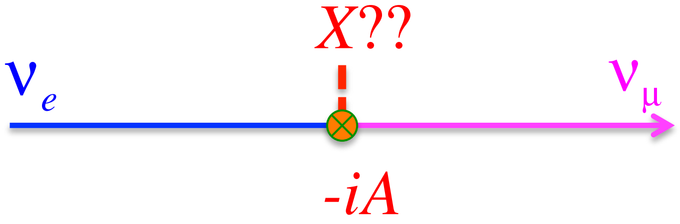
H^0

***d'*-quark** **s'-quark**

$-iG_{ds}v_0$

$$\tan 2\theta_C = \frac{2G_{ds}}{G_{ss}-G_{dd}}, \quad m_d = \bar{G}_{ds} - \frac{G_{ds}}{\sin 2\theta_C}, \quad m_s = \bar{G}_{ds} + \frac{G_{ds}}{\sin 2\theta_C}$$

For neutrino case, we do not know what *X* is.



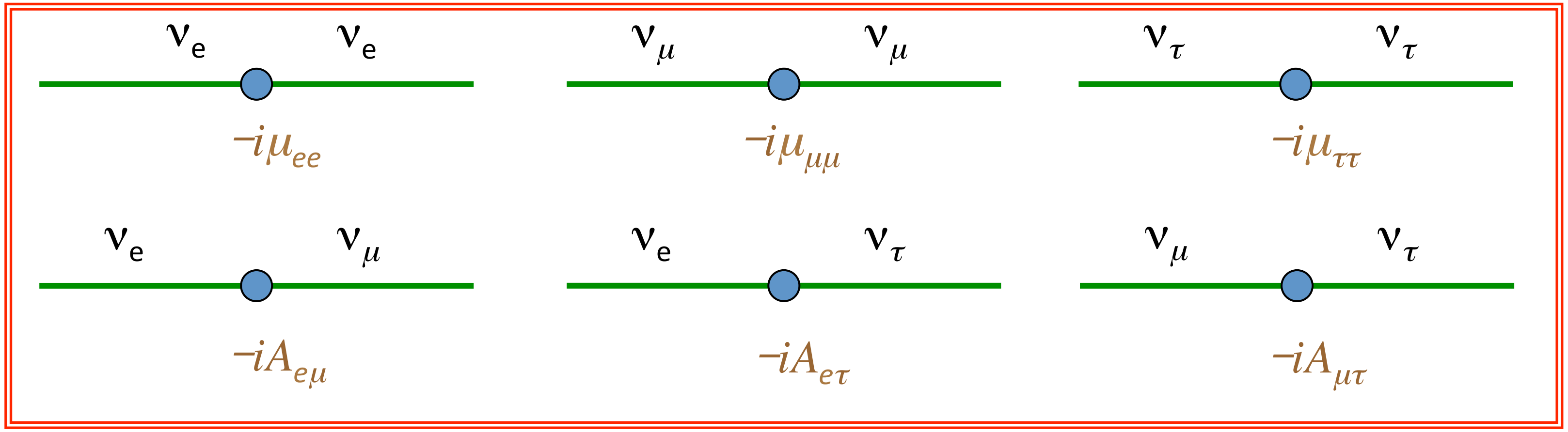
X??

ν_e ν_μ

$-iA$

Study of N.O. = Study of *X*

3 Flavor Neutrino Case



$A_{\alpha\beta}$ can be complex number

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

There are 6 oscillation parameters;

$\theta_{12}, \theta_{23}, \theta_{13}, \delta_{CP}, \Delta m^2_{12}, \Delta m^2_{23}$

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

Prehistory (<2006) of Double Chooz

Atmospheric (Super Kamioka, etc.)
Accelerator (K2K, MINOS)

$$\boxed{P\left[\nu_\mu \to \nu_\mu : @\Delta m^2_{23}\right] \sim 1 - \sin^2 2\theta_{23} \frac{\Delta m^2_{23}}{4E}}$$

$\sin^2 2\theta_{23} \sim 1$, $|\Delta m^2_{23}| \sim 3\text{x}10^{-3}\ \text{eV}^2$

Solar (SNO etc.)
Reactor (KamLAND)

$$\boxed{P\left[\nu_e \to \nu_e : @\Delta m^2_{12}\right] \sim 1 - \sin^2 2\theta_{12} \frac{\Delta m^2_{12} L}{4E}}$$

$\sin^2 2\theta_{12} \sim 0.85$, $\Delta m^2_{12} \sim 8\text{x}10^{-5}\ \text{eV}^2$

Reactor (Chooz, PaloVerde)

$$P\left[\nu_e \to \nu_e : @\Delta m^2_{23}\right] \sim 1 - \sin^2 2\theta_{13} \frac{\Delta m^2_{23} L}{4E}$$

$\sin^2 2\theta_{13} < 0.1$

$$\boxed{\theta_{12}},\ \boxed{\theta_{23}},\ \underbrace{\theta_{13},\ \delta_{CP},}\ \boxed{\Delta m^2_{12}},\ \boxed{\Delta m^2_{23}}$$

➔ θ_{13} & δ_{CP} **measurements were next important step.**

(1) Reactor Measurement of θ_{13}:

$$P\left[\bar{\nu}_e \rightarrow \bar{\nu}_e; @\Delta m^2_{23}\right] \sim 1 - \sin^2 2\theta_{13}$$

➔ **Pure measurement of θ_{13}.**

⇦ **Double Chooz**

(2) Accelerator Measurement :

$$\boxed{P\left[\nu_\mu \rightarrow \nu_e; @\Delta m^2_{23}\right] \sim 0.5\sin^2 2\theta_{13} - 0.04\sin 2\theta_{13}\sin\delta_{CP}}$$

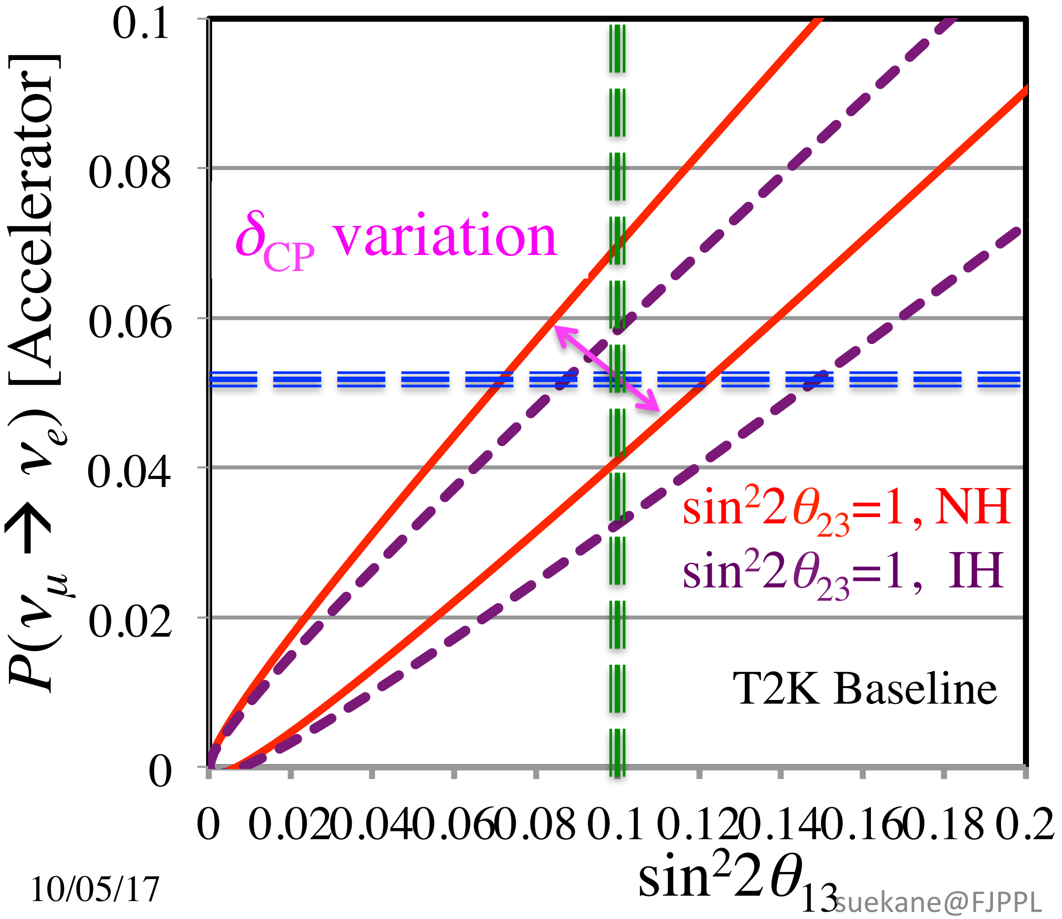
➔ **Depends on both θ_{13} & δ_{CP}**

$$\boxed{(1) + (2) \Rightarrow \theta_{13}\ \&\ \delta_{CP}}$$

Reactor Accelerator complementarity

$$P\left[\nu_\mu \to \nu_e ;@\Delta m^2_{23}\right] \sim \frac{0.5\sin^2 2\theta_{13}}{\left(1-a_m\right)^2} - 0.04\frac{\sin 2\theta_{13}}{1-a_m}\sin\delta_{CP}$$

(Matter effect exists. ~+/-0.05 for T2K. Sign depends on the mass hierarchy.)



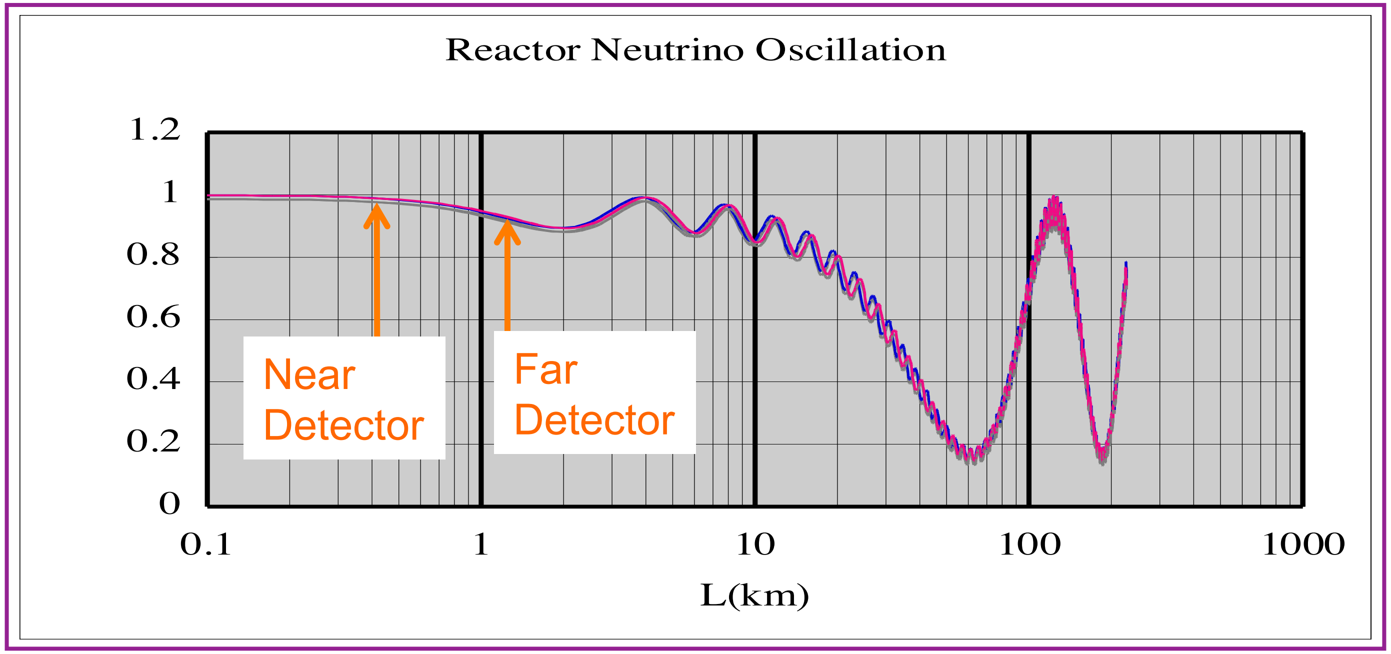
If a_m is known, δ_{CP} can be determined by combining reactor and accelerator experiments.

Reactor measurement of θ_{13}

$$P\left[\bar{\nu}_e \to \bar{\nu}_e ; @\Delta m^2_{23}\right] \sim 1 - \sin^2 2\theta_{13}$$

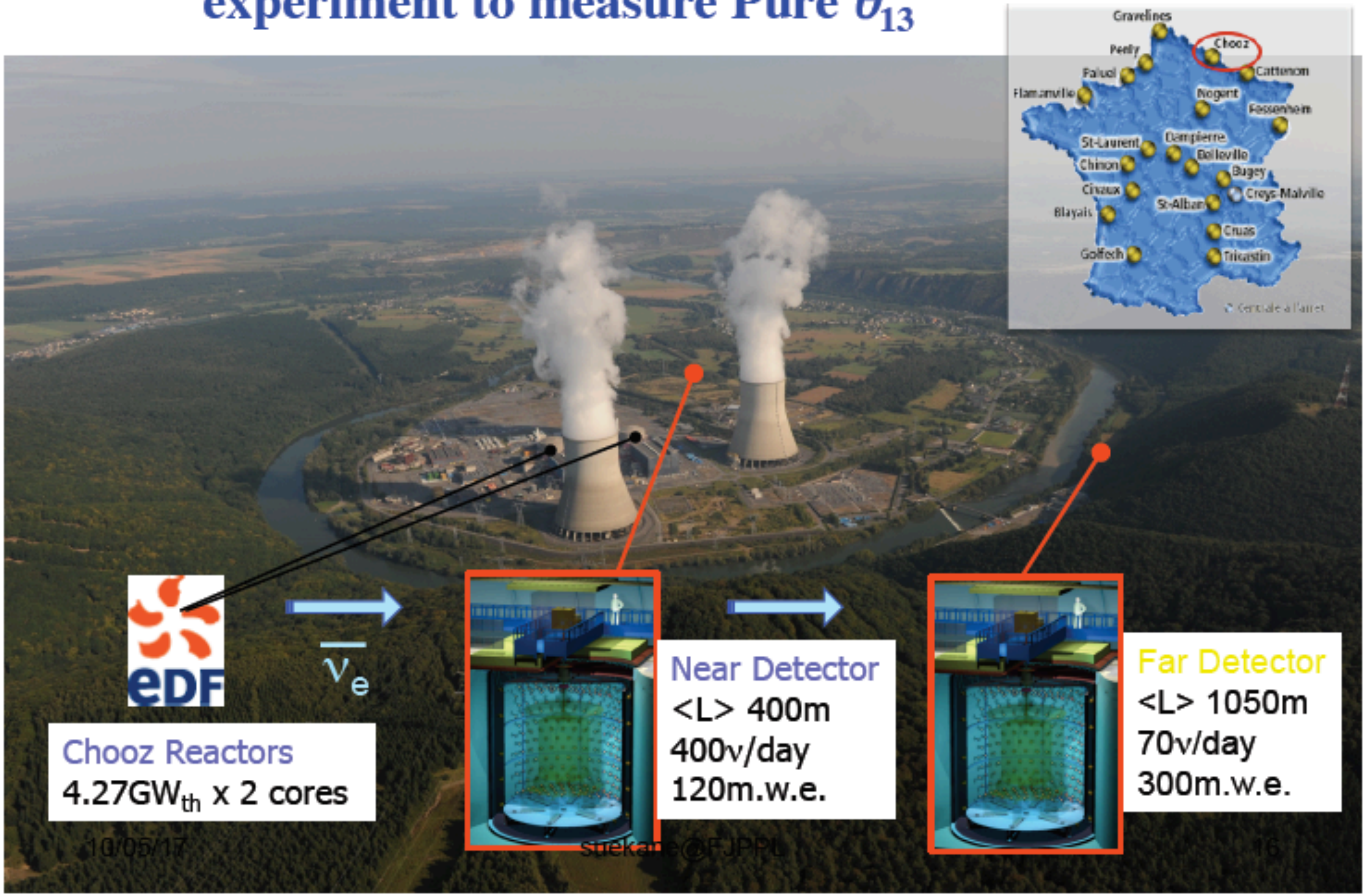
Difficulty: To achieve $\delta\sin^2 2\theta_{13}=0.01$, we need to distinguish 99000 events from 100000 events.
However, usually we suffer from a few % of error on both ν flux and detection efficiency.

$$P\left(\bar{\nu}_e \to \bar{\nu}_e\right)$$



➔ Near/Far multi detector scheme:
Use Near detector to cancel the systematic errors

Then we are performing Double Chooz experiment to measure Pure θ_{13}



$\bar{\nu}_e$

Chooz Reactors
$4.27GW_{th}$ x 2 cores

Near Detector
<L> 400m
400ν/day
120m.w.e.

Far Detector
<L> 1050m
70ν/day
300m.w.e.

Double Chooz collaboration

Brazil
CBPF
UNICAMP
UFABC

France
APC
CEA/DSM/
IRFU:
SPP, SPhN
SEDI, SIS
SENAC
CNRS/IN2P3:
Subatech
IPHC

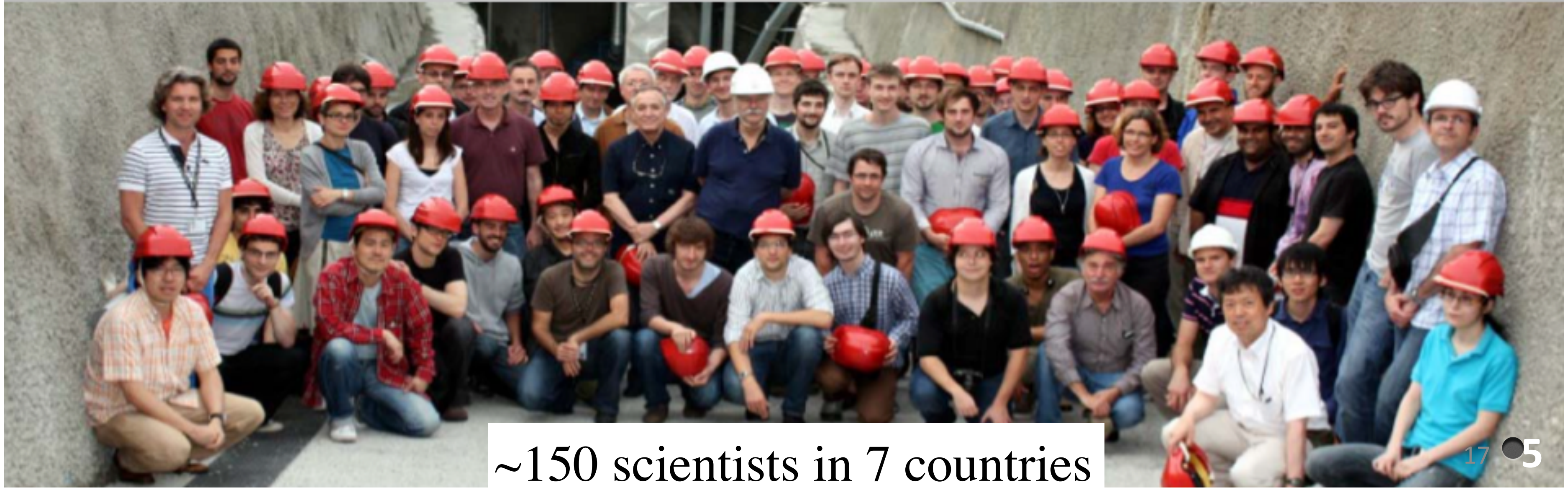
Germany
EKU
Tübingen
MPIK
Heidelberg
RWTH
Aachen
TU München

Japan
Tohoku U.
Tokyo Inst. Tech.
Tokyo Metro. U.
Kitasato U.
Kobe U.
Tohoku Gakuin U.
Hiroshima Inst.
Tech.

Russia
INR RAS
IPC RAS
RRC
Kurchatov

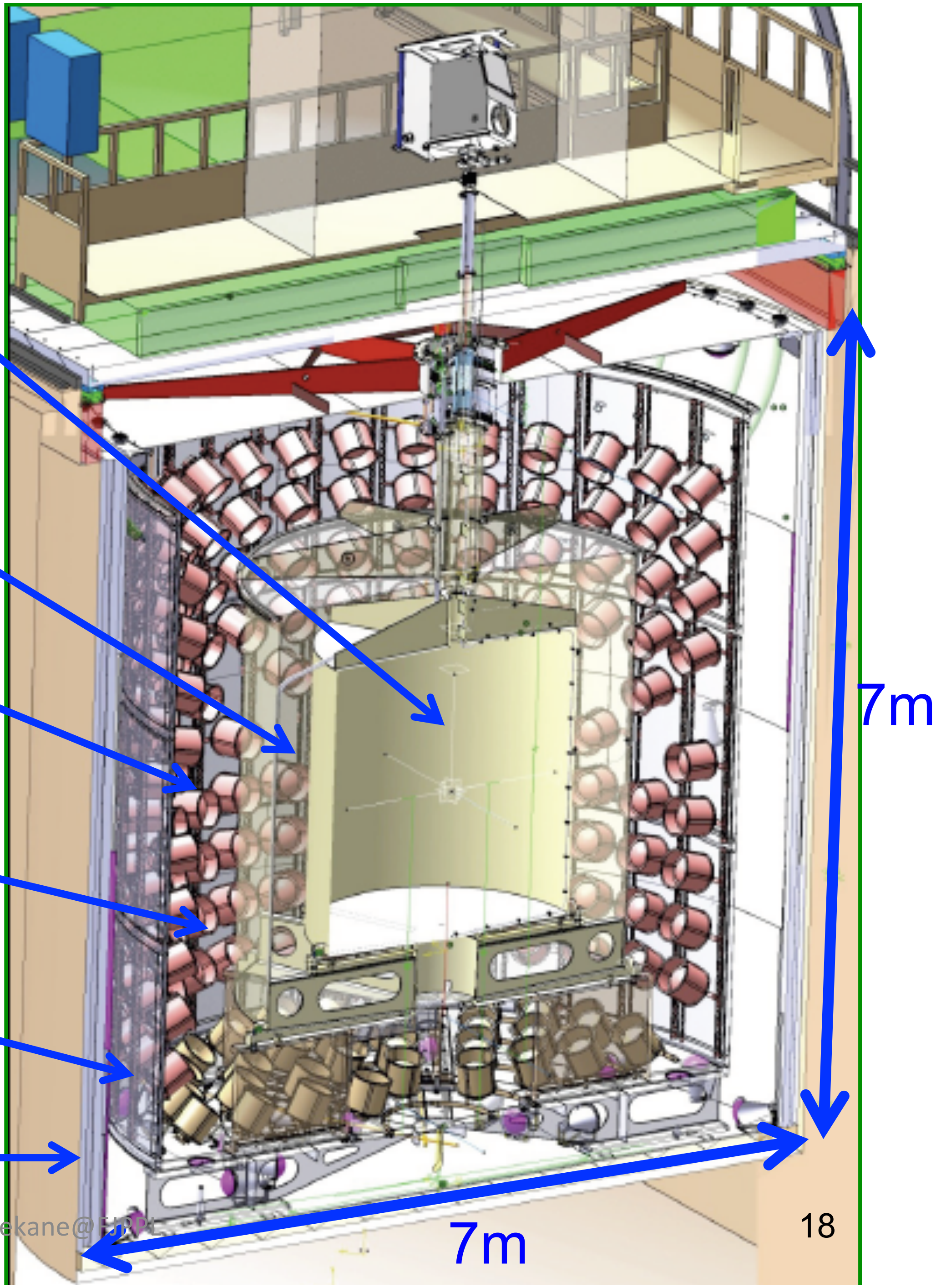
Spain
CIEMAT-
Madrid

USA
U. Alabama
ANL,U. Chicago
Columbia U.
UC Davis
Drexel U.
IIT, KSU, MIT,
U. Notre Dame
U. Tennessee
Virginia Tech



~150 scientists in 7 countries

Main Components of DC Detector



Target ν :
$10m^3$ Gd loaded Liquid Scintllator
8mmt Acrylic Tank

γ Catcher :
$22m^3$ Liquid Scintillator
12mmt Acrylic Tank

Light Detection:
390 Low BKG 10” PMTs

Buffer oil :
$110m^3$ Paraffine Oil
3mmt Stainless Steel Tank

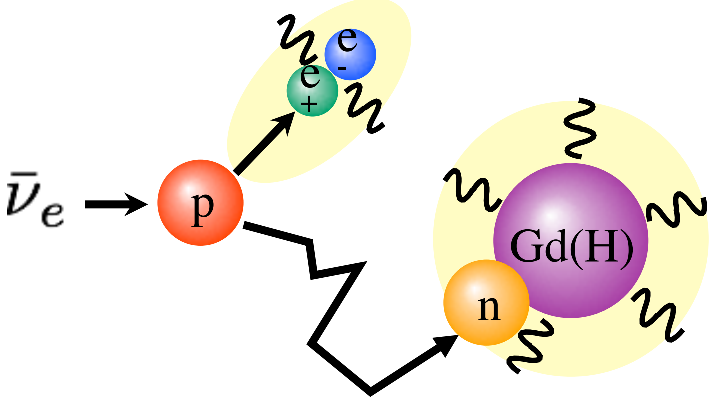
Inner Muon Veto :
$90m^3$ LS + 78 8” PMTs

shield:
15cmt Iron (Far),water (Near)

Detection principle

Inverse Beta Decay

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



$$E_\nu = E_{\text{vis}} + 0.78\ \text{MeV}$$

→ θ_{13} oscillation analysis w/ <u>spectral shape</u> gives further constraint

Delayed coincidence:

- <u>Prompt signal</u>

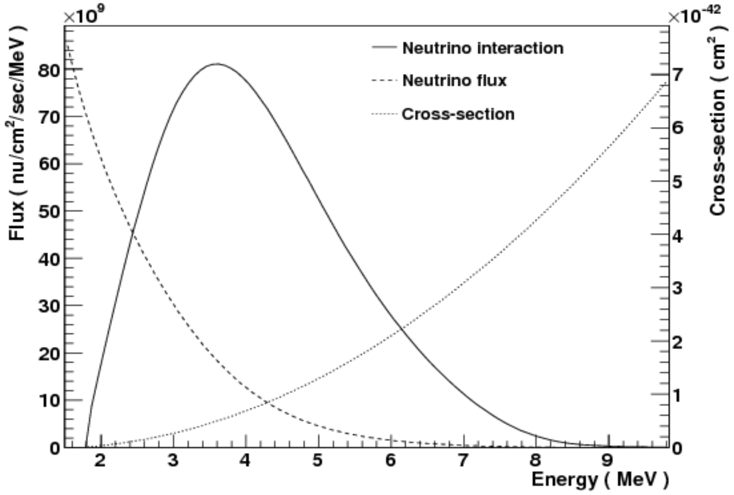
  e^+ ionization & annihilation:

  E_{prompt} = 1~8 MeV
- <u>Delayed signal</u>

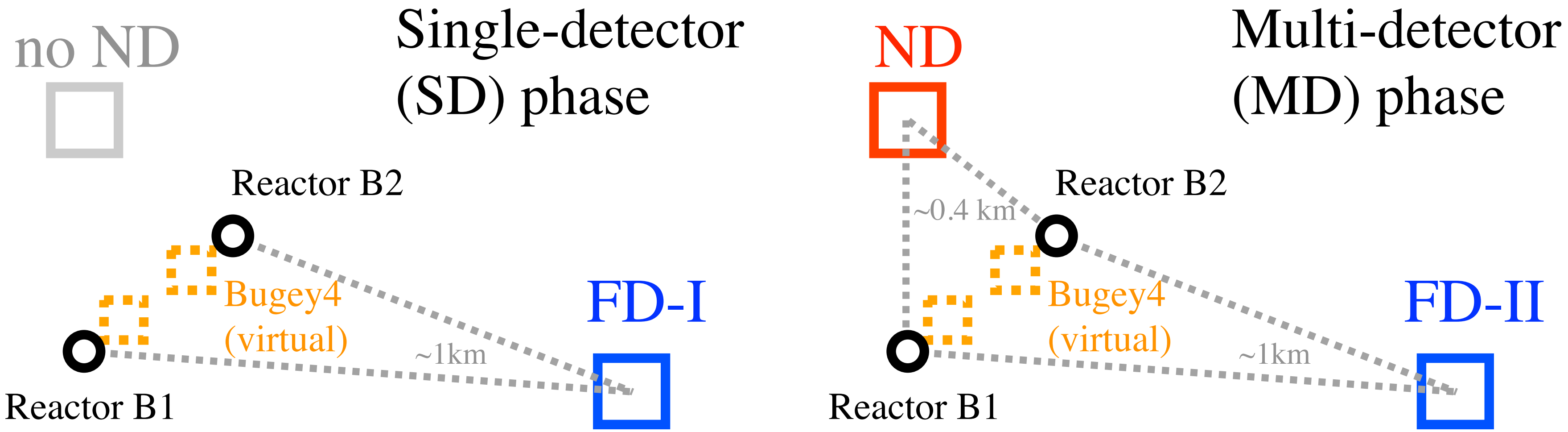
  n capture on Gd (H):

  E_{delayed} = ~8 (~2.2) MeV
- <u>Time coincidence of those</u>

Spectral shape of ν energy



Error suppression by two detectors



(*) FD-I and FD-II data
from same detector

SD phase (2R1D setup : FD-I & Reactor-off data)

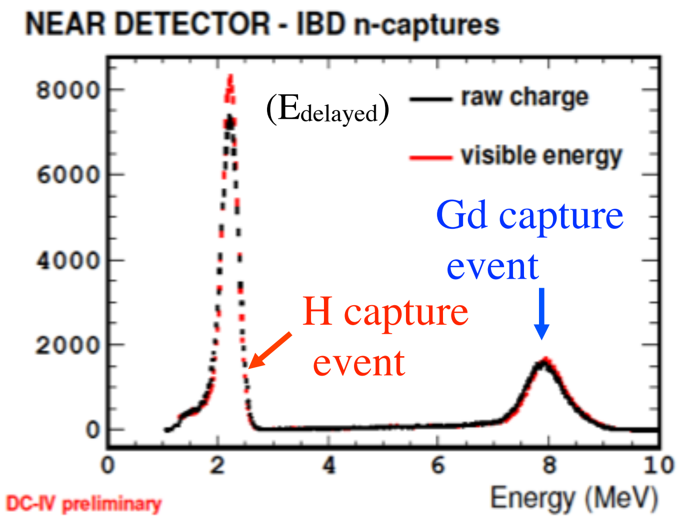
- Bugey4 is used as an anchor of reactor ν flux (~1.7% of total flux precision)
- Reactor-off data (~7 days) is used to constrain BG

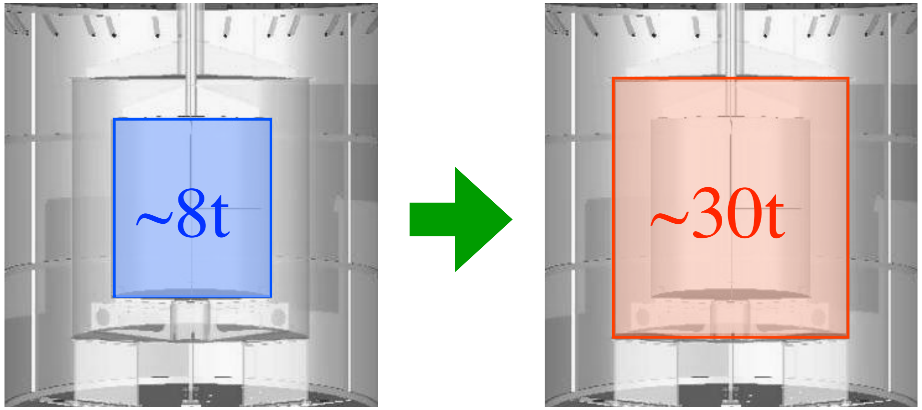
MD phase (2R2D setup : FD-II & ND data)

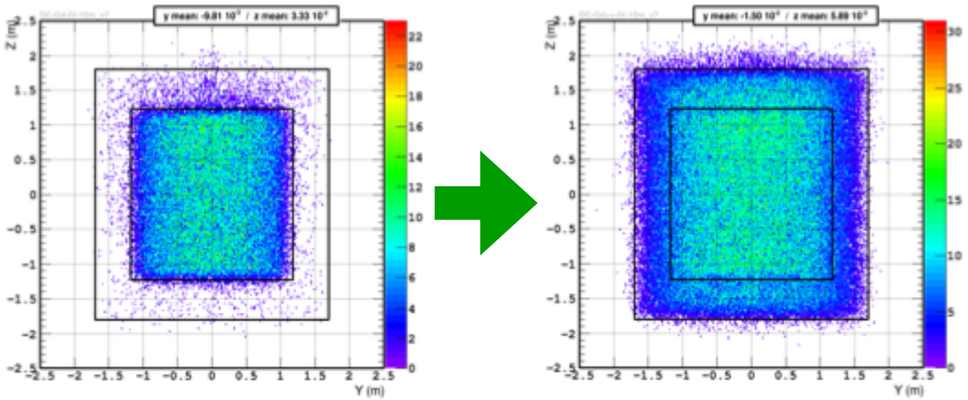
- Nearly iso-flux setup can suppress ν flux error (~0.1% of total flux precision)
- Identical detector cancels correlated errors like detection efficiency

Boosted statistics by Gd+H analysis

Enlargement of ν target volume







IBD rate	Gd analysis	Gd+H analysis
FD	~40 d^{-1}	~100 d^{-1}
ND	~300 d^{-1}	~800 d^{-1}

~2.5 times

N_ν ~2.5 times of original design by Gd+H analysis, trading off a part of cancellation of detection efficiency systematics.

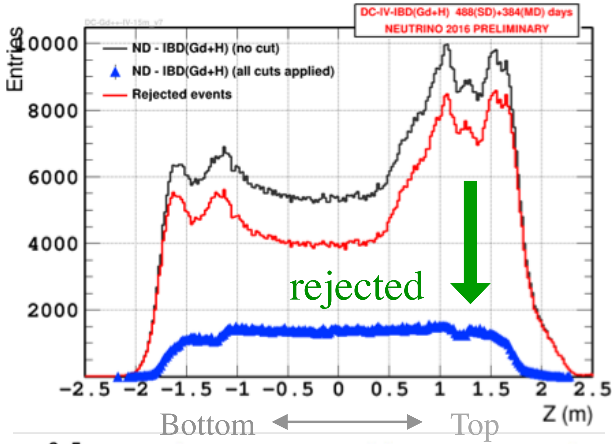
BG veto & leak @ ND

🟥 (🔵) : mimic prompt (delayed) signal

Backgrounds

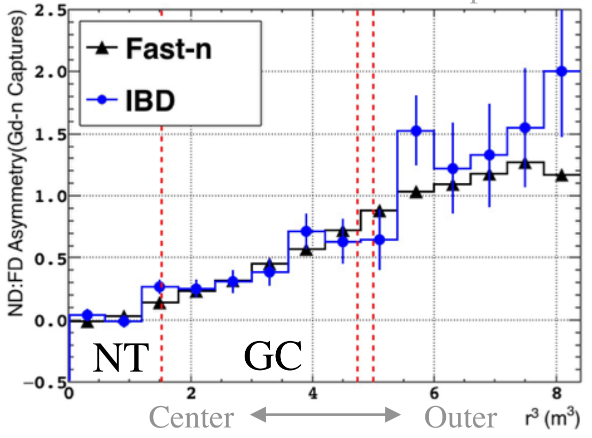
- Accidental coincidence: e.g.) environmental γ + spallation n
- Fast n / Stopping μ: $n + p \rightarrow \text{recoil } p + n$ $\quad \mu \rightarrow e + \nu + \nu$
- Spallation product: e.g.) $^9\mathrm{Li} \rightarrow {}^8\mathrm{Be} + e + \nu + n$

→ Vetoed by dedicated cuts like ANN



LS on Buffer @ ND

- Increased Stop-μBG. Rejected by BG veto
  → No effect in our analysis (ND:FD consistent)
- Cause is not evident (Filling or Running?)
  → Monitoring stability

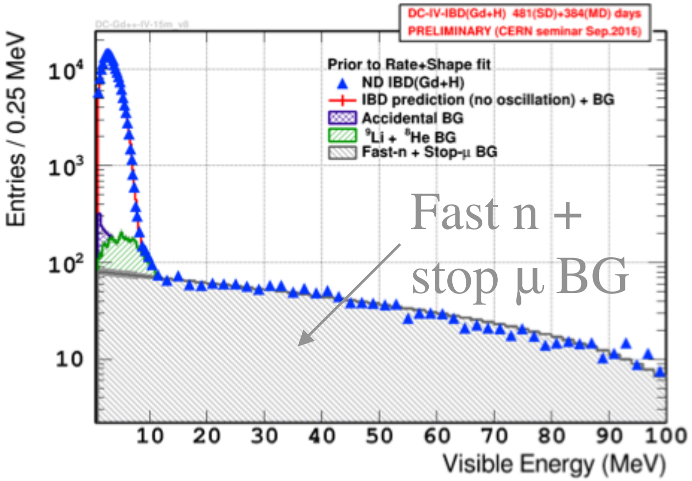


Gd concentration in GC @ ND

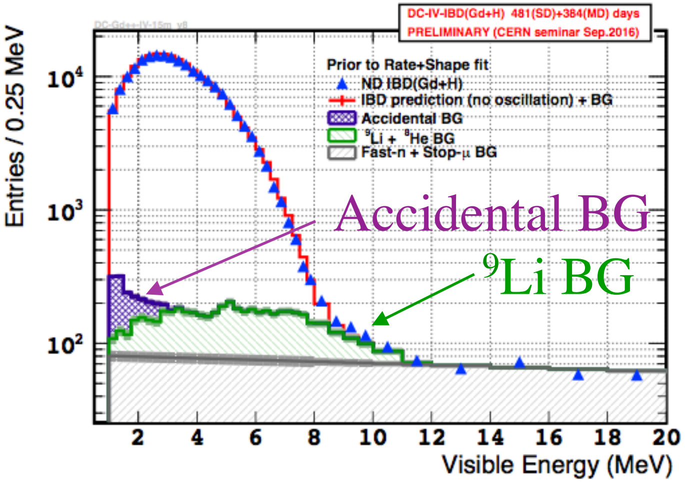
- Found in comparison with ND and FD
  → No effect in Gd+H analysis (w/ both volumes)
  → Estimating effect to Gd analysis (x-ch

Remaining BG estimation

- All backgrounds are measured from data
  - -Accidental BG: Off-time coincidence (Rate & Shape)
  - -Fast n + Stopping μ BG : High energy window (Rate)
    IV/OV tagging (Shape)
  - -^{9}Li BG : ^{9}Li enriched data (Shape)



Fast n + stop μ BG



Accidental BG

^{9}Li BG

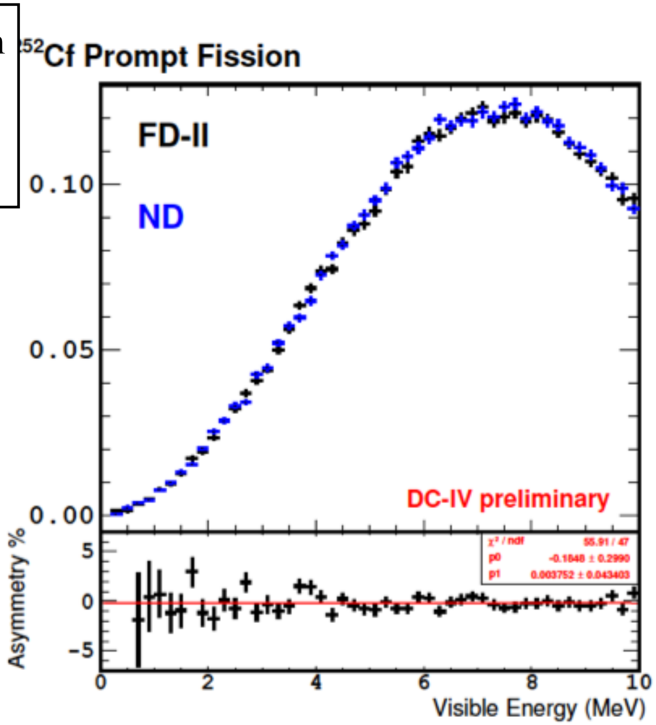
- <u>All backgrounds have characteristic spectrum</u>
- Both “Rate & Shape” are used in oscillation analysis except for ^{9}Li rate
  → ^{9}Li BG rate is constrained by the shape in the fit

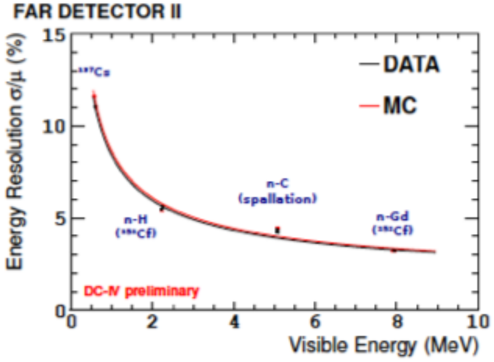
Detector responce

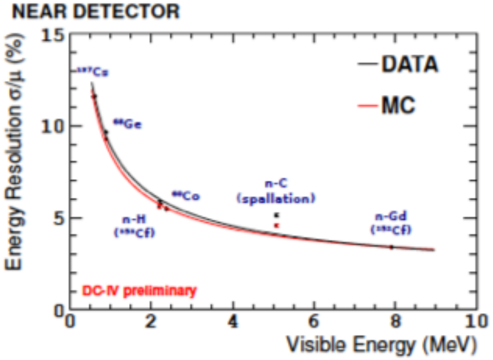
Important to understand detector responce in ND and FD

- Electronics calibration by the Light injection system
- Energy calibration by deployment and natural sources

Calibration system
- Z-axis
- Guide tube
- Light injection



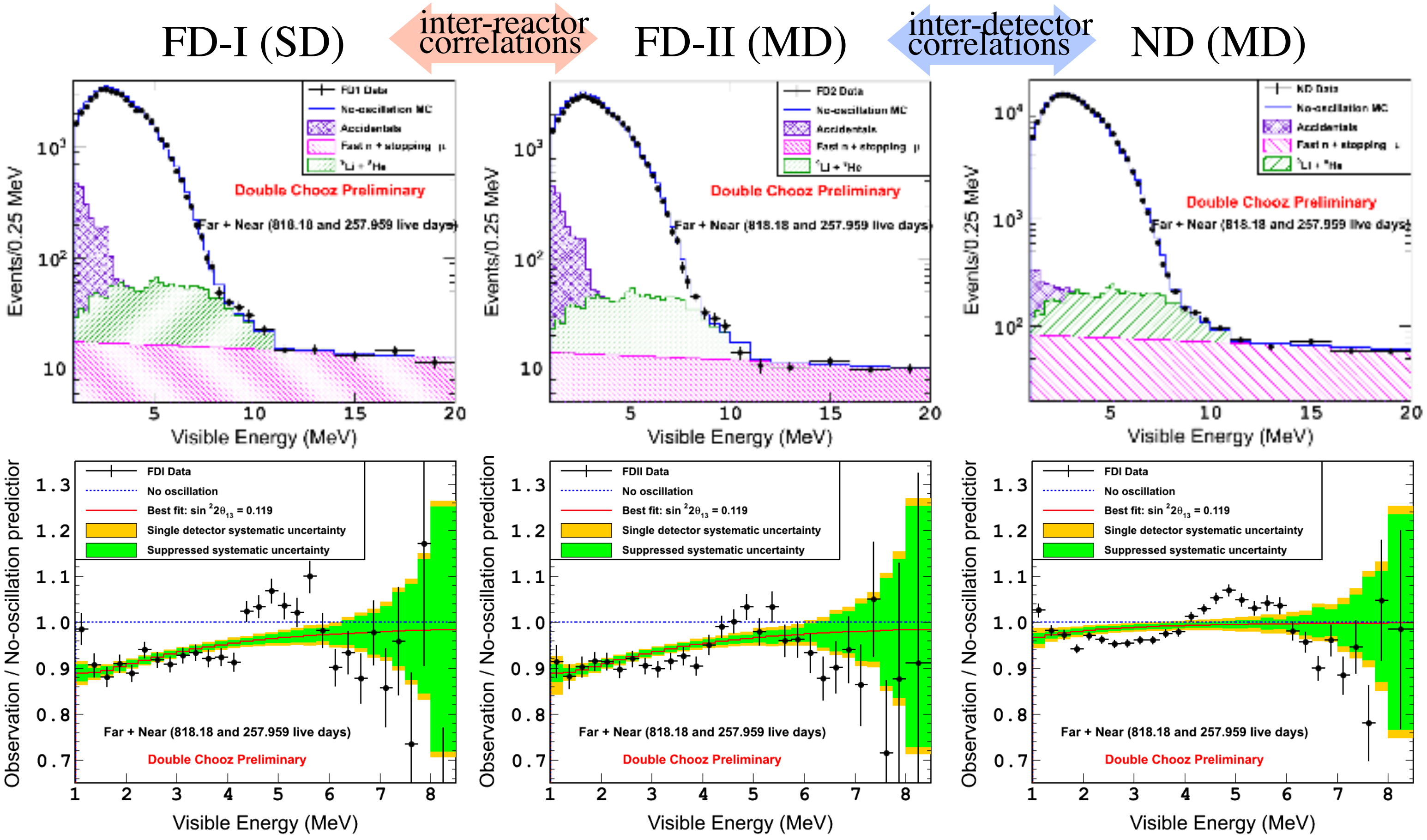




Detector performances are validated. Confirmed well tuned MC

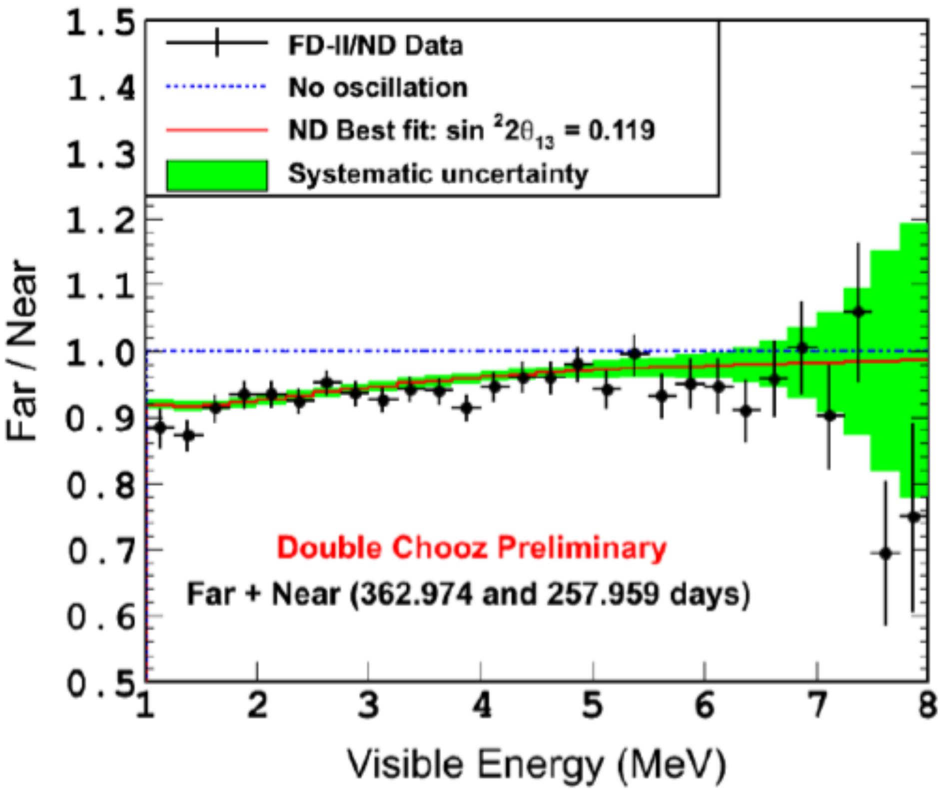
Oscillation fit result

Simultaneous χ^2 fit with Data-to-MC comparison for each data set



FD-I (SD) ⟷ inter-reactor correlations ⟷ FD-II (MD) ⟷ inter-detector correlations ⟷ ND (MD)

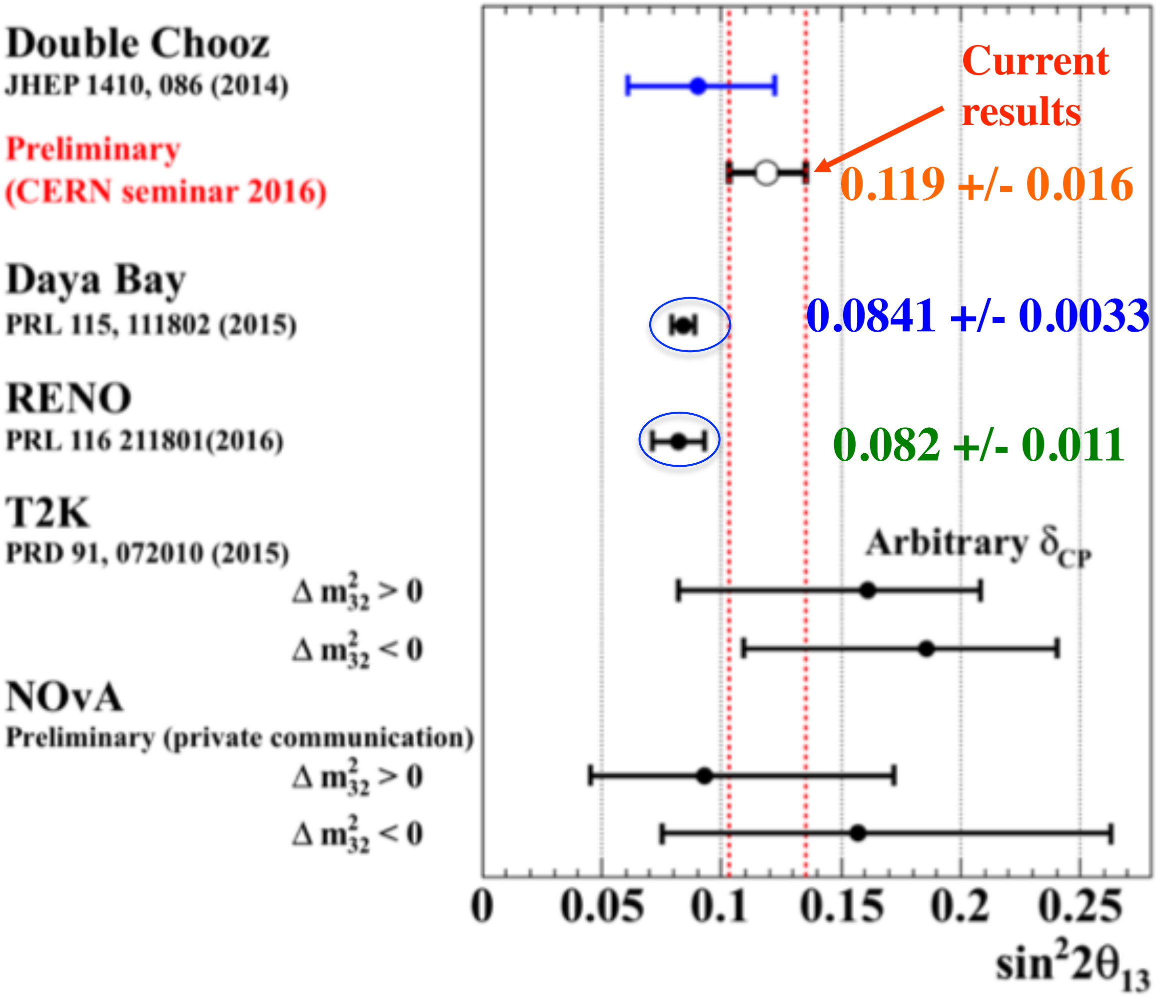
FD-II/ND ratio



Common deviation is cancelled in FD-II/ND ratio
→ The deviation comes from flux prediction (under investigation)

$\sin^2 2\theta_{13} = 0.119 \pm 0.016$(preliminary)
with χ^2/ndf = 236.2/114

Current θ_{13} in the world



Current results

0.119 +/- 0.016

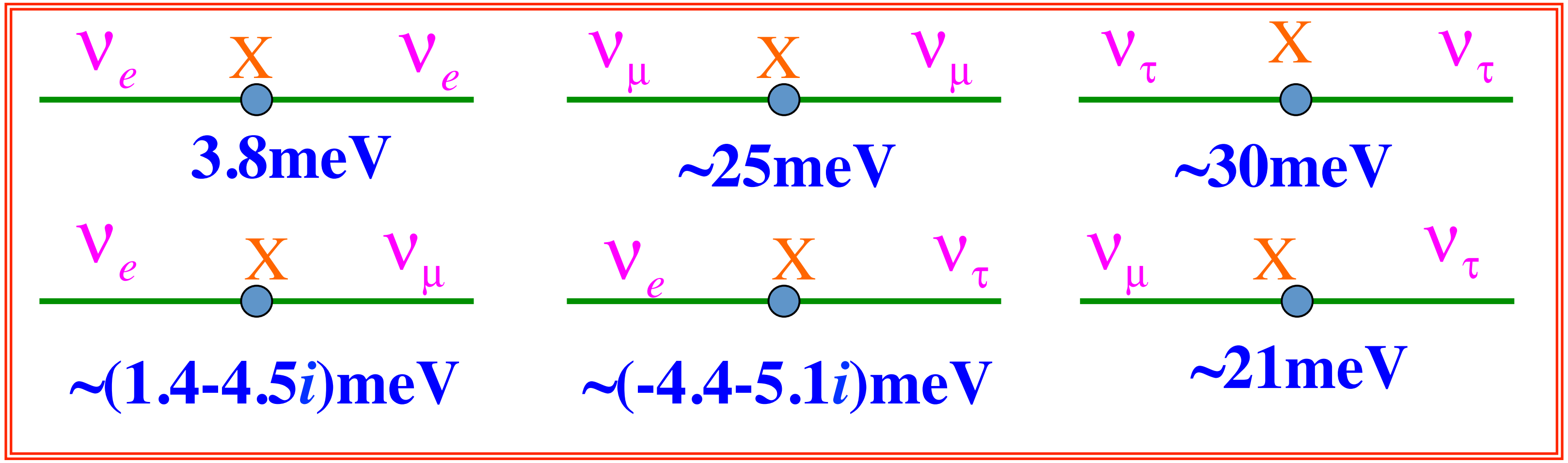
0.0841 +/- 0.0033

0.082 +/- 0.011

~2σ/ difference from DayaBay/RENO

Neutrino transition amplitudes

Assumption: $m_3 > m_1 \sim 0$,



ν_e X ν_e

3.8meV

ν_μ X ν_μ

~25meV

ν_τ X ν_τ

~30meV

ν_e X ν_μ

~(1.4-4.5*i*)meV

ν_e X ν_τ

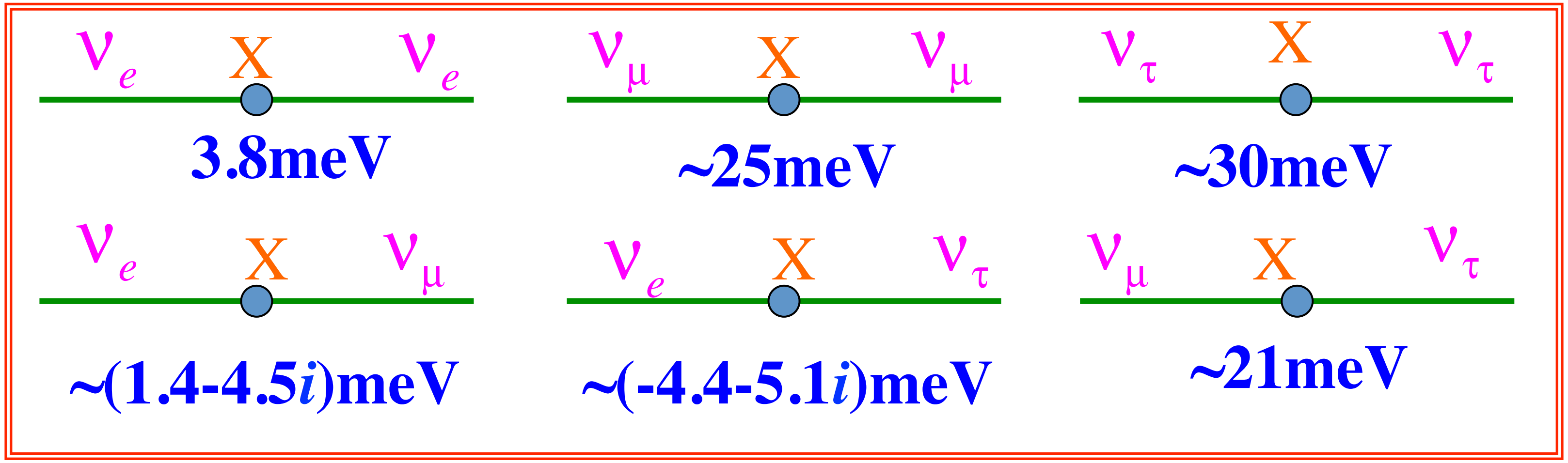
~(-4.4-5.1*i*)meV

ν_μ X ν_τ

~21meV

Neutrino transition amplitudes

Assumption: $m_3 > m_1 \sim 0$,



ν_e X ν_e

3.8meV

ν_μ X ν_μ

~25meV

ν_τ X ν_τ

~30meV

ν_e X ν_μ

~(1.4-4.5*i*)meV

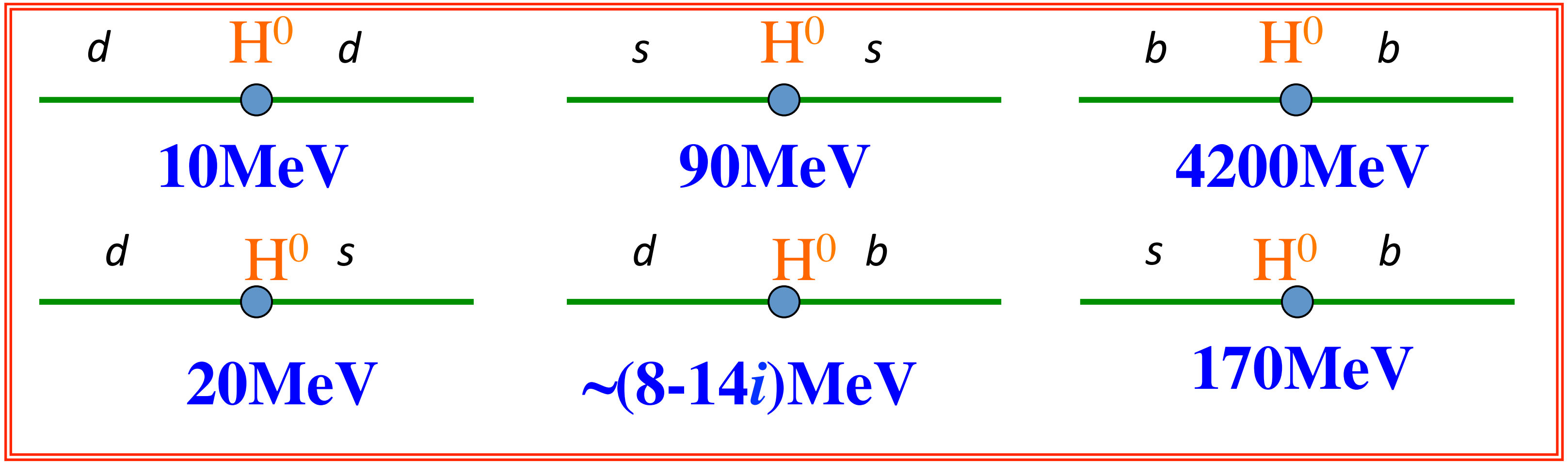
ν_e X ν_τ

~(-4.4-5.1*i*)meV

ν_μ X ν_τ

~21meV

Comparison to the quark transition amplitudes



d H^0 *d*

10MeV

s H^0 *s*

90MeV

b H^0 *b*

4200MeV

d H^0 *s*

20MeV

d H^0 *b*

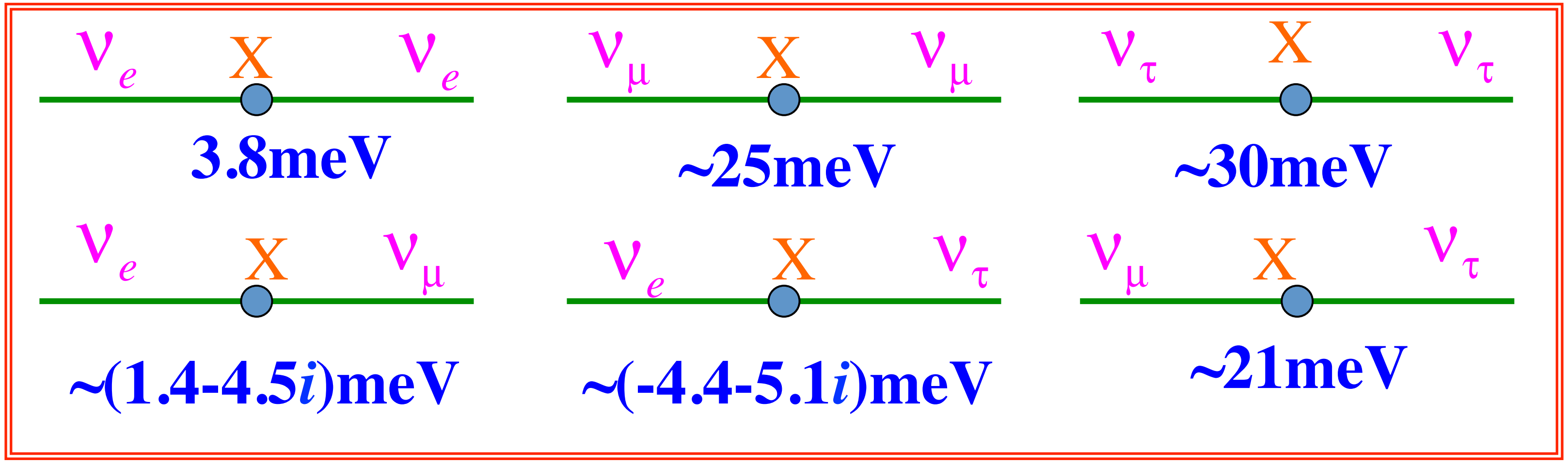
~(8-14*i*)MeV

s H^0 *b*

170MeV

Neutrino transition amplitudes

Assumption: $m_3 > m_1 \sim 0$,



ν_e X ν_e: 3.8meV

ν_μ X ν_μ: ~25meV

ν_τ X ν_τ: ~30meV

ν_e X ν_μ: ~(1.4-4.5i)meV

ν_e X ν_τ: ~(-4.4-5.1i)meV

ν_μ X ν_τ: ~21meV

A is very small for X!!   What is X??

θ_{13} and the CP Violation measurement

(matter effect ignored)

*** CP asymmetry of N.O.:**

$$A_{CP}=\frac{P[\nu_\mu\to\nu_e]-P[\bar{\nu}_\mu\to\bar{\nu}_e]}{P[\nu_\mu\to\nu_e]+P[\bar{\nu}_\mu\to\bar{\nu}_e]}\sim-\left|\frac{\Delta m^2_{12}}{\Delta m^2_{31}}\right|\frac{\pi\sin 2\theta_{12}}{\tan\theta_{23}\sin 2\theta_{13}}\sin\delta_{CP}$$

$$\sim\boxed{-\frac{0.09}{\sin 2\theta_{13}}\sin\delta_{CP}}$$

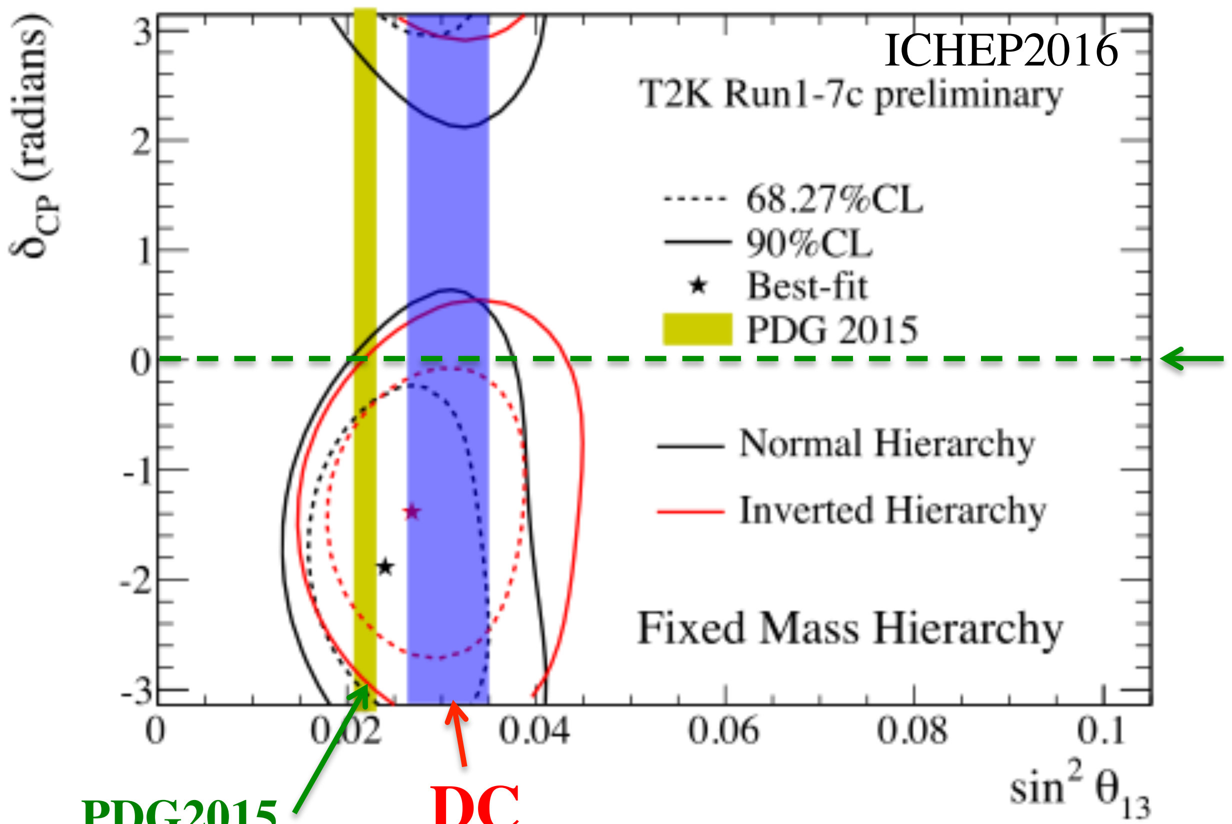
From measured A_{CP}, δ_{CP} is calculated as,

$$\sin\delta_{CP}\sim-11\times\sin 2\theta_{13}\times A_{CP}$$

The error of δ_{CP} is,

$$\frac{\delta(\sin\delta_{CP})}{\sin\delta_{CP}}=\frac{\delta(\sin 2\theta_{13})}{\sin 2\theta_{13}}\oplus\frac{\delta A_{CP}}{A_{CP}}=\boxed{\frac{1}{2}\frac{\delta(\sin^2 2\theta_{13})}{\sin^2 2\theta_{13}}}\oplus\frac{\delta A_{CP}}{A_{CP}}$$

T2K result and Reactor θ_{13}.



← NO CPV

PDG2015

DC

- **Broader range of δ_{CP} is allowed if large θ_{13}**

→ The discripancy is not so significant now but <u>further studies are necessary</u>

Analysis Expert Workshop among DC, DB and RENO groups

The result of the current 3 reactor experiments will remain the most precise θ_{13} value in the foreseen future.
➔ It is important to determine θ_{13} as precise and reliable as possible now.

The 1st analysis expert workshop among DC, DB and RENO groups was held in Korea in August 2016, initiated by the Double Chooz group.

The purpose of the workshop is to unify the 3 experiments at deep analysis level and obtain the single best value of θ_{13}.

The 2nd workshop is planned at APC in May 2017.

Summary

* Double Chooz has joined FJPPL since 2006.

- In the 1st phase, it successfully reported the first reactor θ_{13} result in 2011. (Nu2-WP2)
- In the 2nd phase, it is successfully reporting the precise θ_{13} result using 2 detectors. (Nu03)

* The measured θ_{13} value at DC is, $\sin^2 2\theta_{13} = 0.119 \pm 0.016$.

* There is some difference between DC and DB/RENO results.

* Started discussion among the DC/DC/RENO analysis experts.

* The precision of the θ_{13} measurement will improve and we can see the tension develops or shrinks.