Nu_03: Precise measurement of neutrino oscillation angle θ_{13} using reactor neutrinos

Masahiro Kuze
Tokyo Institute of Technoogy

TYL/FJPPL workshop
Seoul, 18 May 2016

Neutrino mixing - our physics goal

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

PMNS matrix (Pontecorvo-Maki-Nakagawa-Sakata)

ν_e, ν_μ, ν_τ : flavor eigenstates.

ν_1, ν_2, ν_3 : mass eigenstates of $m = m_1, m_2, m_3$.

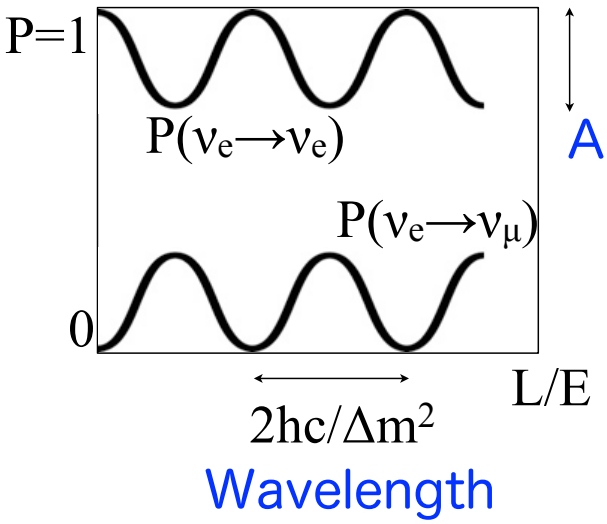
$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix}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

$c_{23}=\cos\theta_{23}$, etc.

3 mixing angles (θ_{12}, θ_{23}, θ_{13}) + 1 complex phase (δ)

Oscillation Parameters

$P(\nu_i \rightarrow \nu_j) = \sin^2 2\theta_{ij} \sin^2(1.27\Delta m^2 L/E)$
where Δm^2 (eV^2) and
L/E (km/GeV or m/MeV)



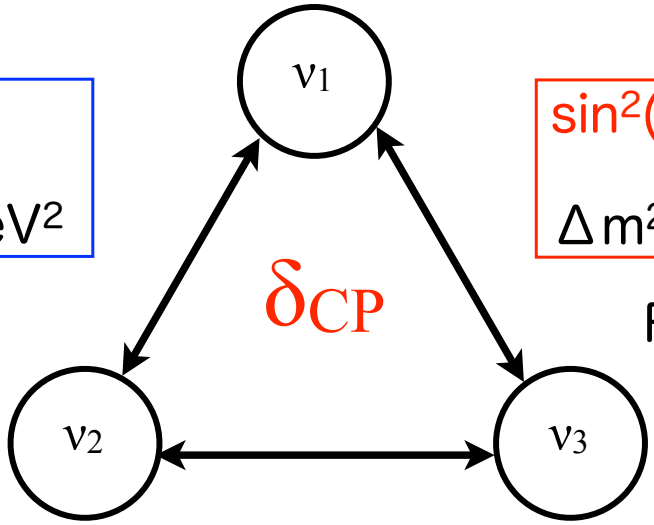
- 3 mixing angles
  θ_{12}, θ_{23}, θ_{13}
- 2 mass^2 differences
  $\Delta m^2_{32} = m_3^2 - m_2^2$
  $\Delta m^2_{21} = m_2^2 - m_1^2$
  ($\Delta m^2_{31} = \Delta m^2_{32} + \Delta m^2_{21}$)
- 1 complex phase
  δ

Status before 2011

$\sin^2(2\theta_{12}) \sim 0.8$

$\Delta m^2_{21} \sim 8\times10^{-5}\mathrm{eV}^2$

Solar-ν,
Reactor-ν



$\sin^2(2\theta_{13}) < 0.15$

$\Delta m^2_{31} \sim \Delta m^2_{32}$

Reactor-ν

$\sin^2(2\theta_{23}) \sim 1.0$

$|\Delta m^2_{32}| \sim 2.5\times10^{-3}\mathrm{eV}^2$

Atm-ν,
Acc-ν

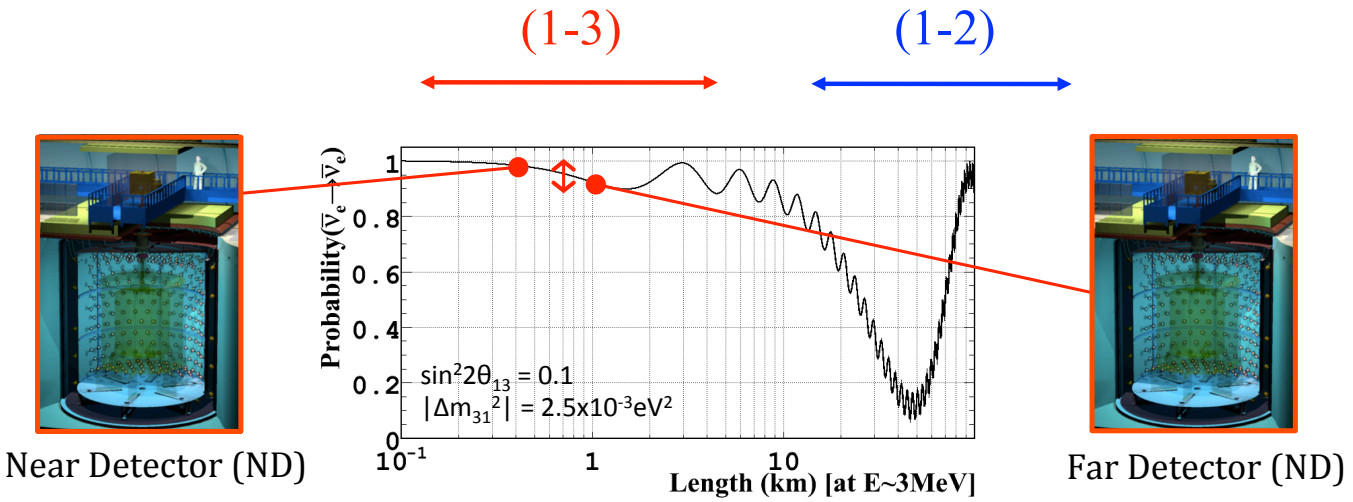
- $\theta_{12} \sim 33^\circ$, $\theta_{23} \sim 45^\circ$, but $\theta_{13} < 11^\circ$
- $|\Delta m^2_{32}| >> |\Delta m^2_{21}|$ (by factor ~30)

δ_{CP}: completely unknown

Direct θ_{13} measurement

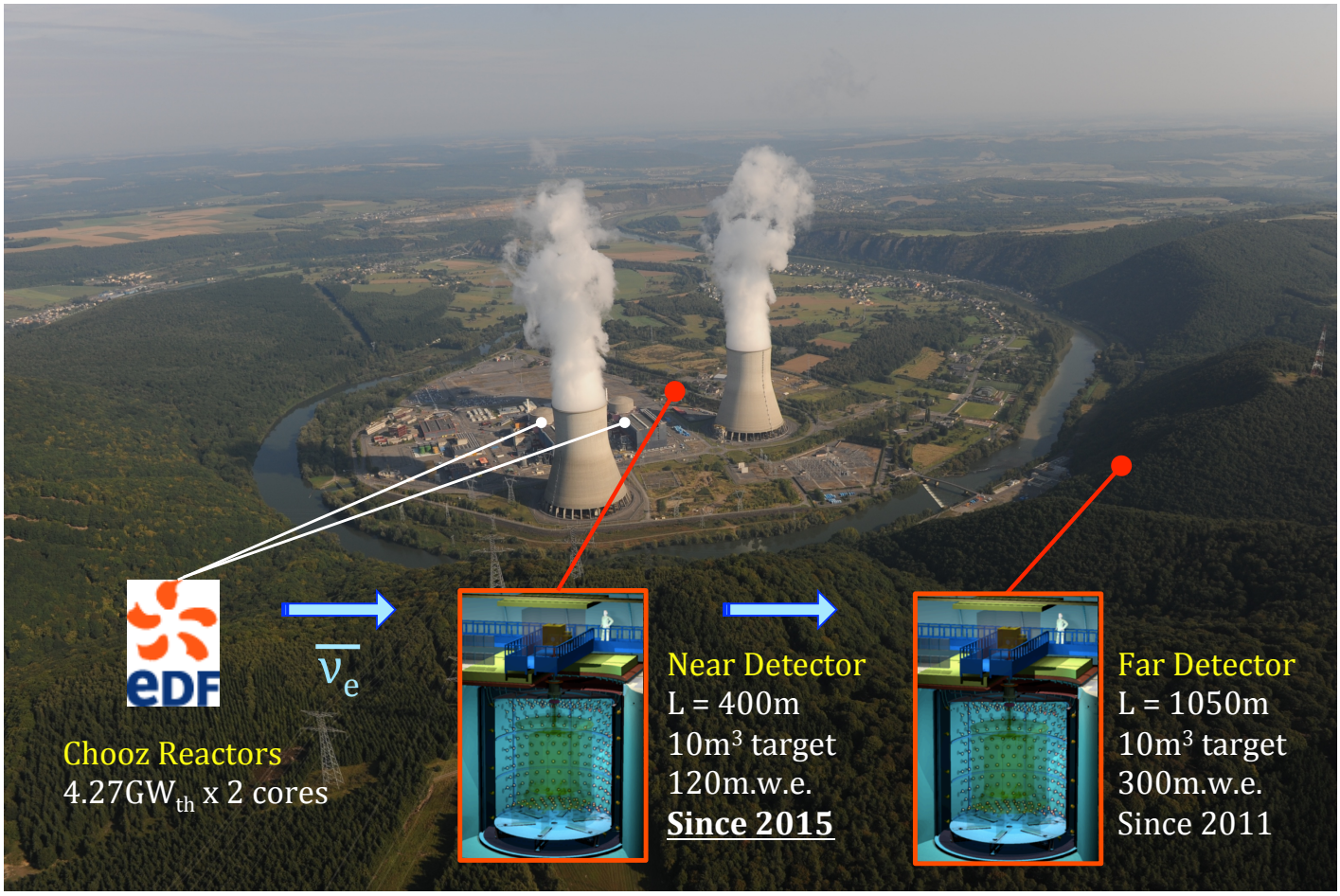
- Disappearance at (1-3) osc. maximum (L=1~2km)

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{31} L}{4E}$$ +O(10^{-3}) from Δm^2_{21} oscillation



- Cancel flux uncertainty by placing Near and Far detectors

Double Chooz experiment



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
U. Hamburg

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

Russia
INR RAS
IPC RAS
RRC
Kurchatov

Spain
CIEMAT-Madrid

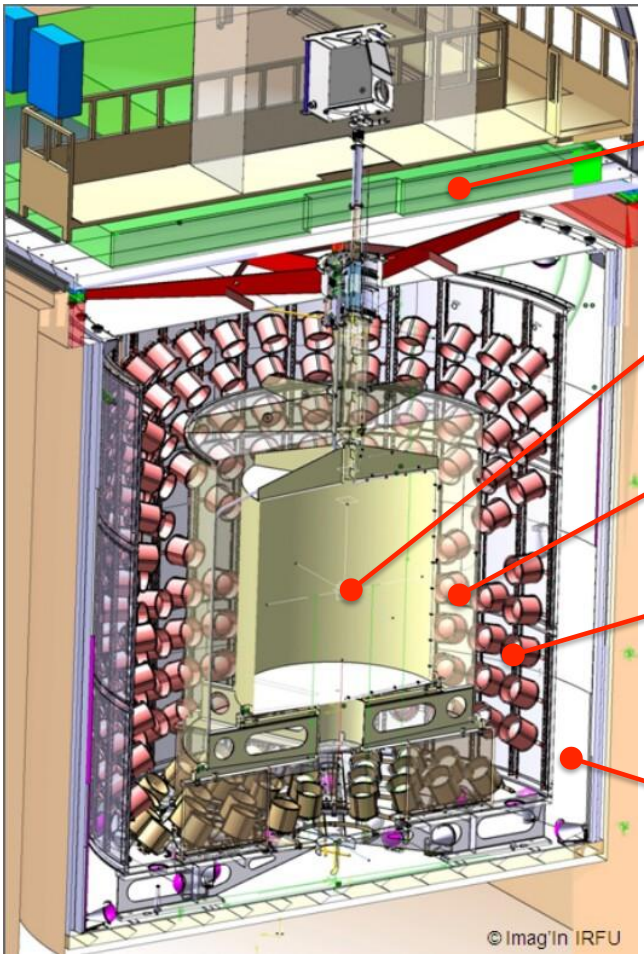
USA
U. Alabama
ANL
U. Chicago
Columbia U.
UCDavis
Drexel U.
IIT
KSU
LLNL
MIT
U. Notre Dame
U. Tennessee

Spokesperson:
H. de Kerret (IN2P3)

Project Manager:
Ch. Veyssière (CEA-Saclay)

Web Site:
www.doublechooz.org/

The Double Chooz detector



Outer Veto (OV):
Plastic scintillator strips

Inner Detector

ν-target (NT):
- Gd loaded liquid scintillator (10m^3)

γ-catcher (GC):
- Liquid scintillator (22m^3)

Buffer:
- Mineral oil (110m^3)
- 390 10-inch PMT

Inner Veto (IV):
- Liquid scintillator (90m^3)
- 78 8-inch PMT

Detection Principle

- Inverse-beta decay

  (E_{thresh}=1.8MeV)

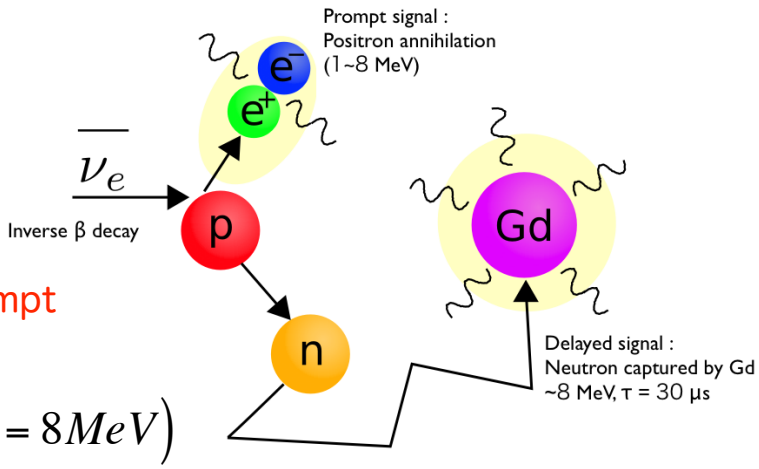
E_ν information carried by e^+

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

$$e^+ + e^- \rightarrow 2\gamma \quad \text{Prompt}$$

$$(E_\nu - 0.8MeV)$$

$$n + Gd \rightarrow Gd' + \gamma s\left(\sum E = 8MeV\right) \quad \text{Delayed}$$



n thermalization time

$\tau \sim 30\,\mu$sec

cf. KamLAND has no Gd

Hydrogen capture

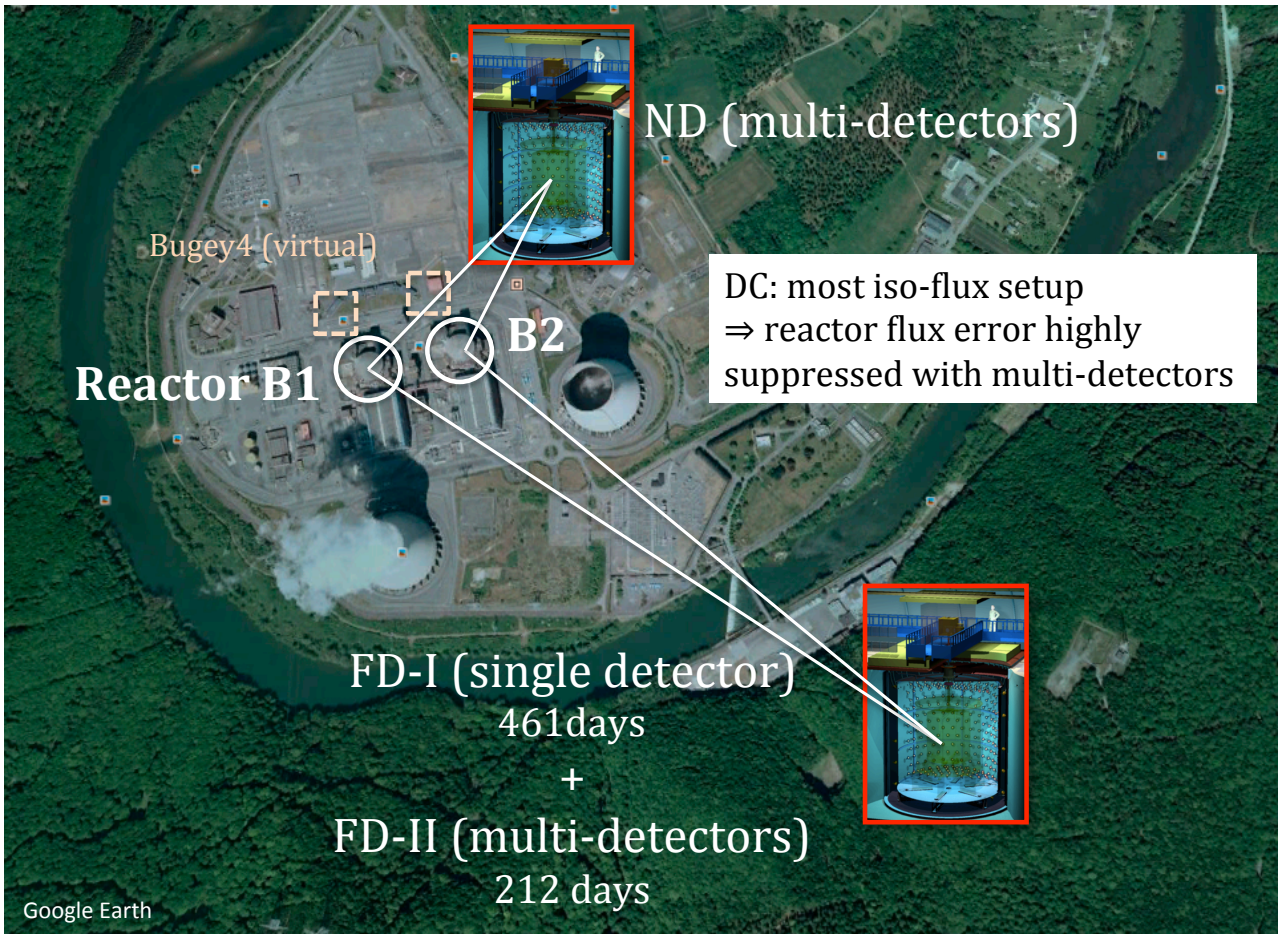
n+p→d+γ(2.2MeV)

"Delayed coincidence" drastically reduces the background.

Double Chooz and TYL/FJPPL

- 2009-12/Nu2-WP2 (H. de Kerret & F. Suekane)
  - Construction of FD and 1st measurements
- 2013-16/Nu_03 (A. Cabrera & M. Kuze)
  - Construction of ND finished end of 2014
    see talk by E. Chauveau (congratulations!)
  - Taking FD+ND data since 2015
    1st 'Double det.' preliminary result in Moriond 2016
- Tight FR/JP connection: acknowledges to TYL!
  - FR: DAQ, acrylic vessels, infrastructure, ...
  - JP: online, calibration, PMT test/installation, ...
  - and of course in analyses

Multi-detector analysis



For analysis details, see M. Ishitsuka's talk in Moriond EW

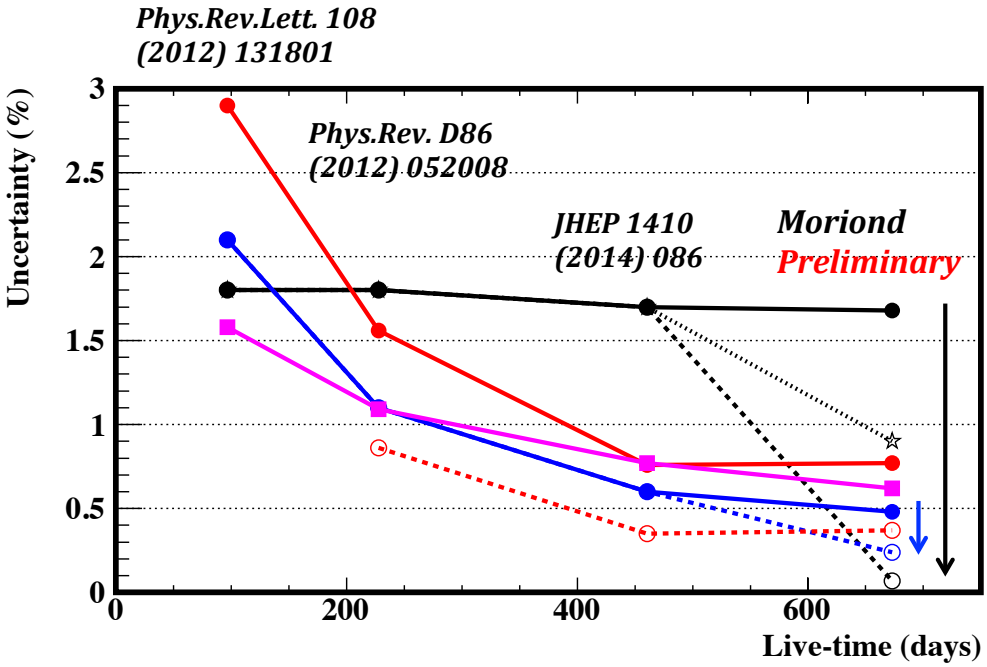
Signal and background

Double Chooz Preliminary

	FD-I	Reactor-off	FD-II	ND
Live-time (d) (after μ veto)	460.93	7.24	212.21	150.76
IBD prediction (d^{-1})	38.04±0.67	0.217±0.065	40.39±0.69	280.5±4.7
Accidental BG (d^{-1})	0.070±0.003		0.106±0.002	0.344±0.002
Fast-n + stop-μ (d^{-1})	0.586 ±0.061			3.42 ±0.23
Cosmogenic (d^{-1})	$(0.97^{+0.41}_{-0.16})$			(5.01 ±1.43)
Total prediction (d^{-1})	**39.63±0.73**	**1.85±0.30**	**42.06±0.75**	**289.3±4.9**
IBD candidates (d^{-1}) (number of events)	**37.64** (17351)	**0.97** (7)	**40.29** (8551)	**293.4** (44233)

- ND detects 7 times more neutrinos than FD
- Also larger BG due to more cosmic μ (but S/B better)

Systematic uncertainties

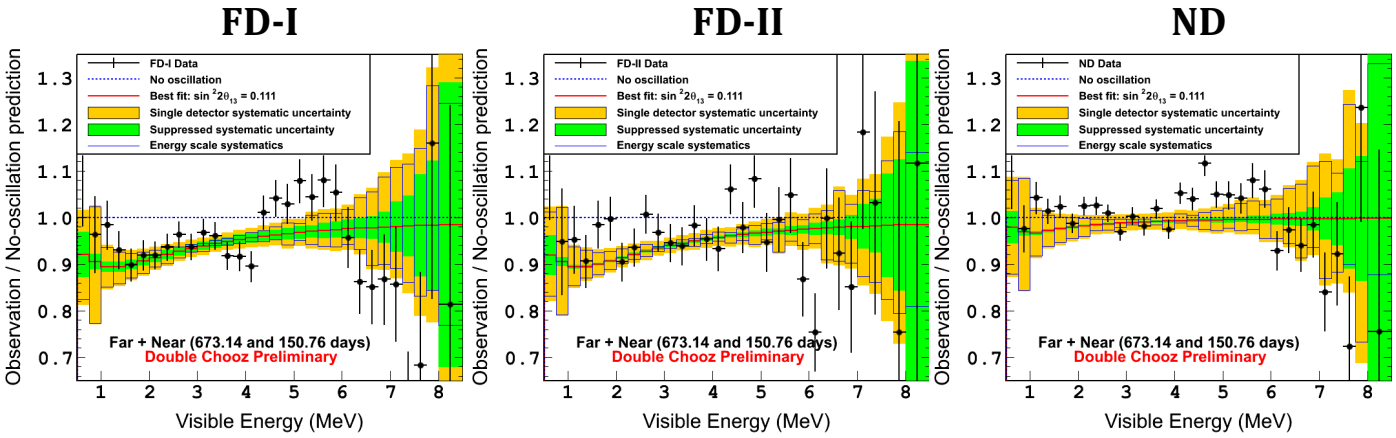


SD: single detector
MD: relative uncertainties in multiple detectors

- Signal statistics
- Reactor flux (SD)
- Reactor flux (MD)
- FD-I – FD-II relative
- Detection & E (SD)
- Detection & E (MD)
- Background
- BG (after R+S fit)

- Greatly reduced thanks to 2 detectors and in rate+shape fit
- All at sub-% level, limited by statistics now

Energy spectrum fit results



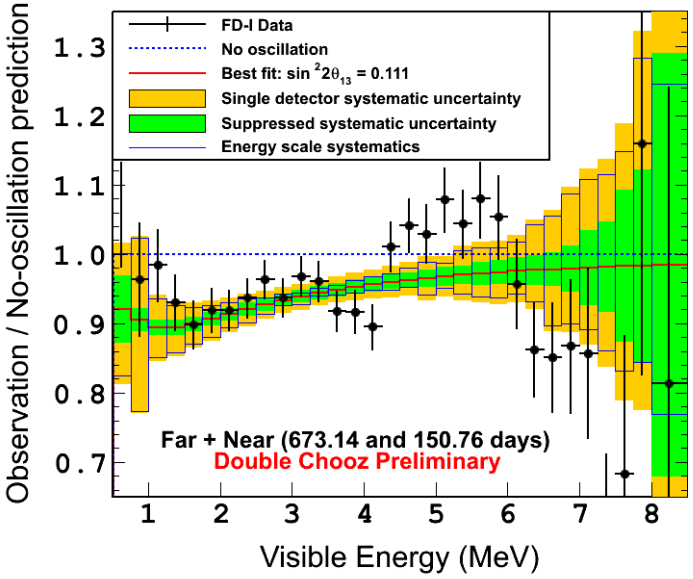
- Best-fit: $\mathbf{\sin^2 2\theta_{13} = 0.111 \pm 0.018}$ (stat.+syst.) (χ^2/dof = 128.8/120)
  - **Non-zero θ_{13} observation at 5.8σ C.L.**

Double Chooz Preliminary

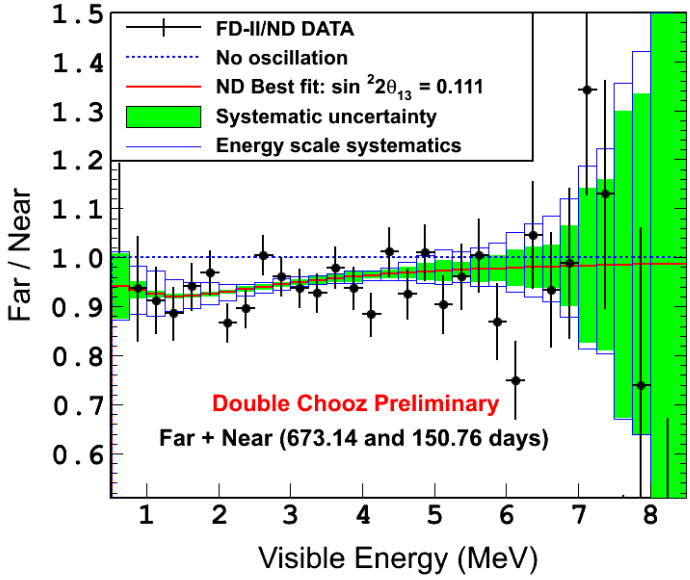
- Fit 3 data sets simultaneously (also reactor-off data)
- Last paper using FD only data: $\sin^2 2\theta_{13} = 0.09 \pm 0.03$
  → precision improved nearly by factor 2

FD/ND ratio

FD-I data/prediction

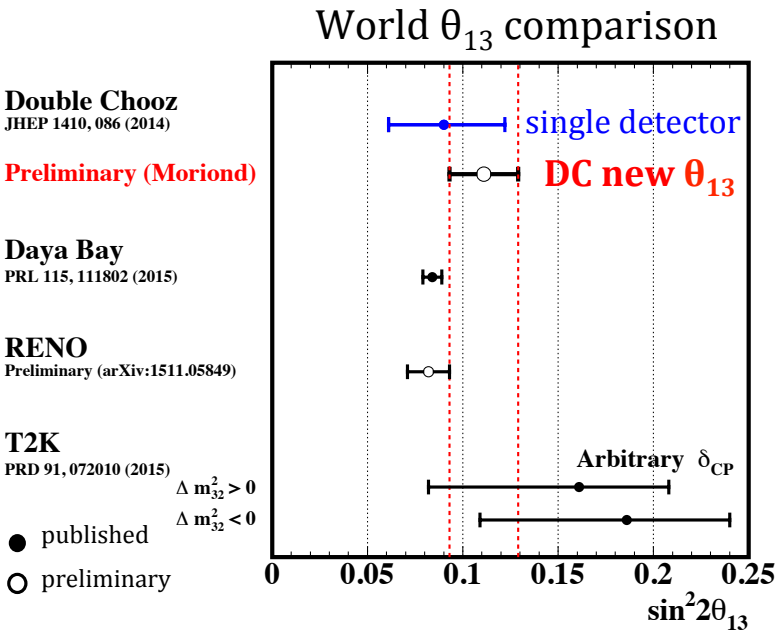


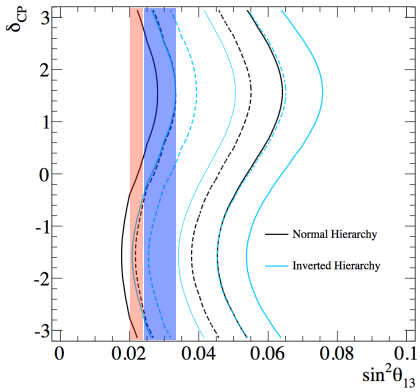
FD-II data/ ND data



- Systematic uncertainties suppressed in ND+FD comparison
- Power of 'Double' detector configuration!

World θ_{13} context





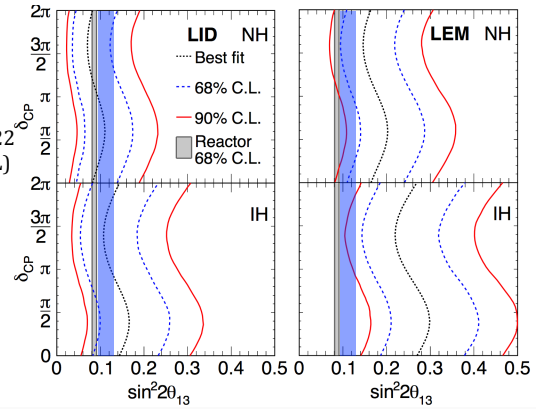
Reactor
vs. T2K

PRD91 072010 (2015)

Double Chooz 1σ
Daya Bay 1σ

Reactor
vs. NOvA

arXivL1601.05522
(accepted by PRL)



- DC θ_{13} is higher than other reactor θ_{13} by ~30% (1.4σ wrt DB)
- θ_{13} has critical implication to solve CP-violation and mass hierarchy

Conclusions

- We built and commissioned the Near Detector successfully and are taking ND+FD data

- First multi-detector analysis result released: $\sin^2 2\theta_{13} = 0.111 \pm 0.018 \quad (5.8\sigma)$

- We are statistically limited → expect to improve! very important to compare with DB/RENO

- Fruitful F-J collaboration: thanks to TYL/FJPPL