Latest results from Double Chooz experiment with two detectors

Neutrino Frontier Workshop 2016 @ Kaga
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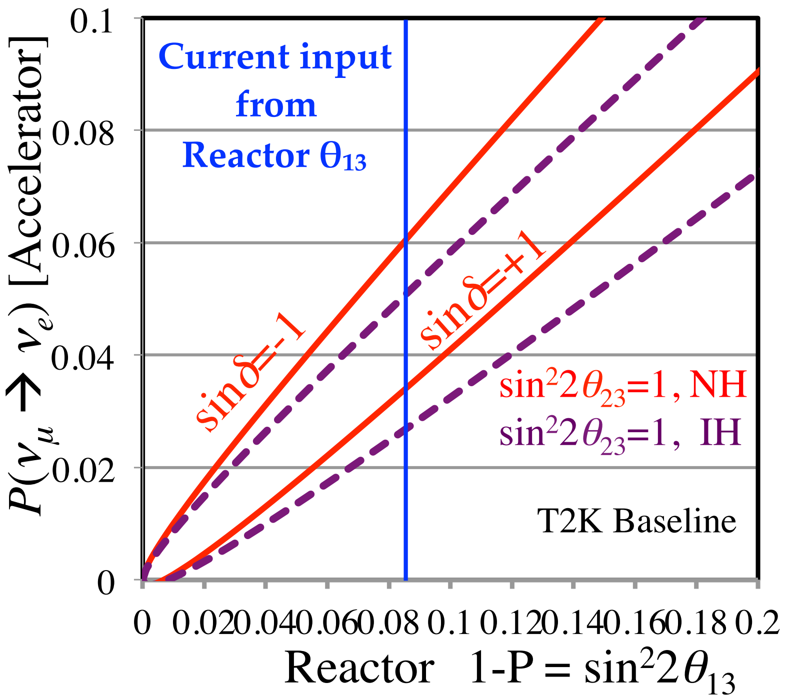
Why θ_{13} with reactor ν?

Toward global understanding of neutrino oscillation:

- CP violation ($-1 < \sin\delta_{CP} < 1$)
- Mass hierarchy ($\Delta m^2_{32} > 0$ or $\Delta m^2_{32} < 0$)
- Octant of θ_{23} ($\theta_{23} > \pi/4$ or $\theta_{23} < \pi/4$)

} Measurement by $\nu_\mu \to \nu_e$ oscillation has parameter dependences w/ θ_{13}



From F. Suekane's talk @ Workshop for Neutrino programs with Facilities in Japan

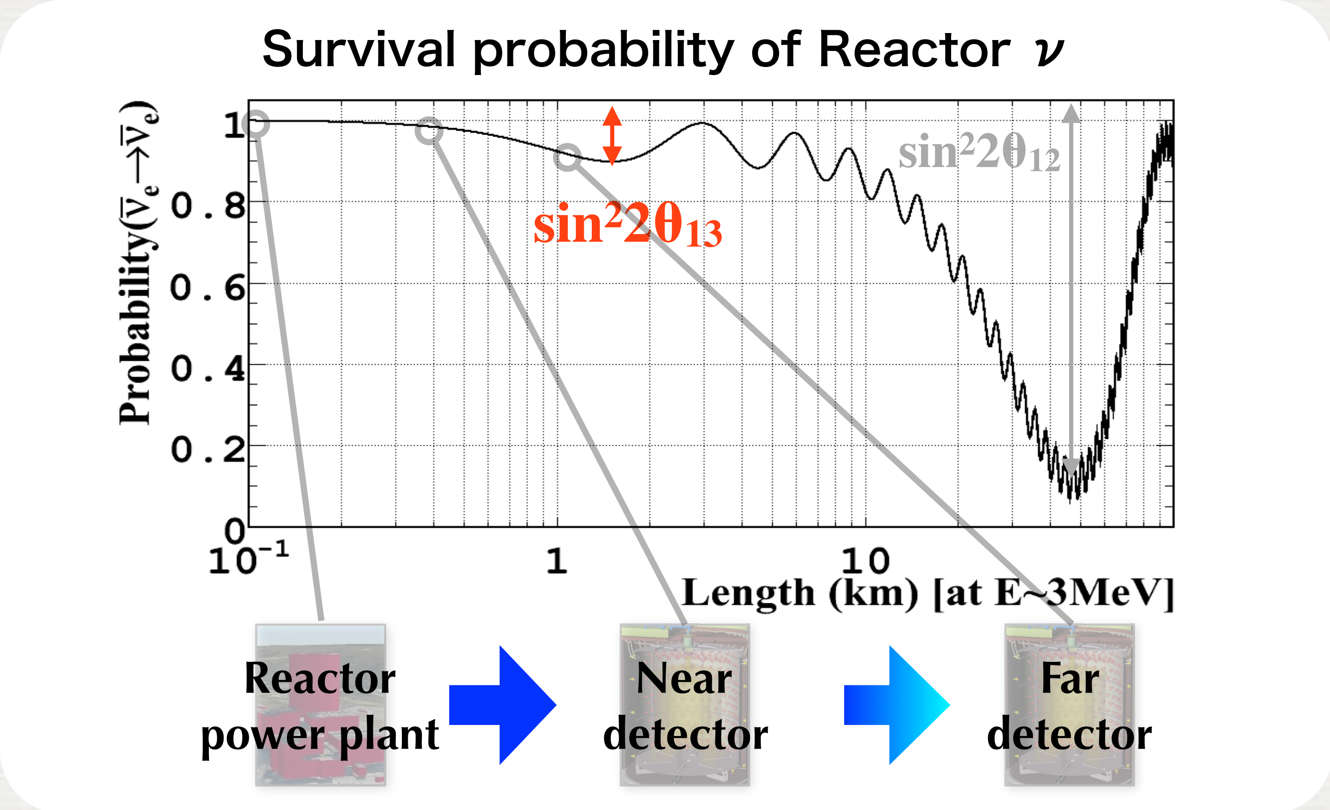
$$P\left(\nu_\mu \to \nu_e; \Phi_{31} = \pi/2\right) \sim \frac{\sin^2 2\theta_{13}}{2\left(1-\left(L/L_0\right)\right)^2} - 0.043\frac{\sin 2\theta_{13}}{1-\left(L/L_0\right)}\sin\delta$$

→ Complementary between $P(\nu_\mu \to \nu_e)$ and Reactor θ_{13}

Reactor θ_{13} is essential to resolve the parameter dependences

→ Aiming to have more **robust $\sin^2\theta_{13}$** with **better precision**

θ_{13} measurement with reactor ν



- Reactor is a free and rich electron antineutrino source
- Direct measurements of θ_{13} with no parameter dependence
- Detection by delayed coincidence technique reducing background
- Suppression of systematic errors with two identical detectors

Experimental site @ Chooz, France

Reactors

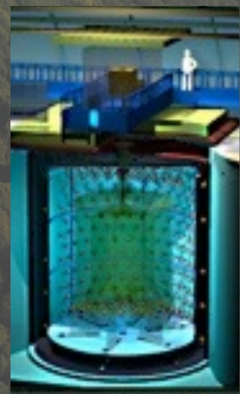
Two reactor cores
4.27 GW_{th} for each core

Near detector

L = ~ 400 m
~120 m.w.e.

Operating since 2015

Far detector



L = ~ 1050 m
~300 m.w.e.

Operating since 2011

Two detectors data taking is started since beginning of 2015

Double Chooz collaboration

Brazil
CBPF
UNICAMP
UFABC

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

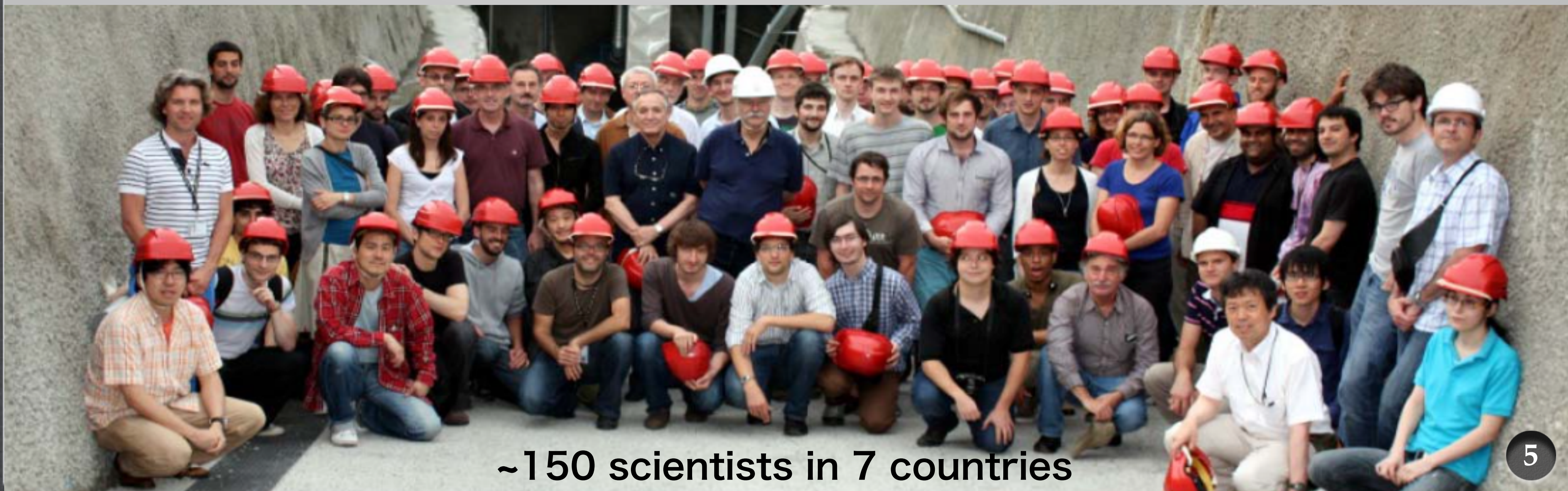
Germany
EKU
Tübingen
MPIK
Heidelberg
RWTH
Aachen
TU München

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

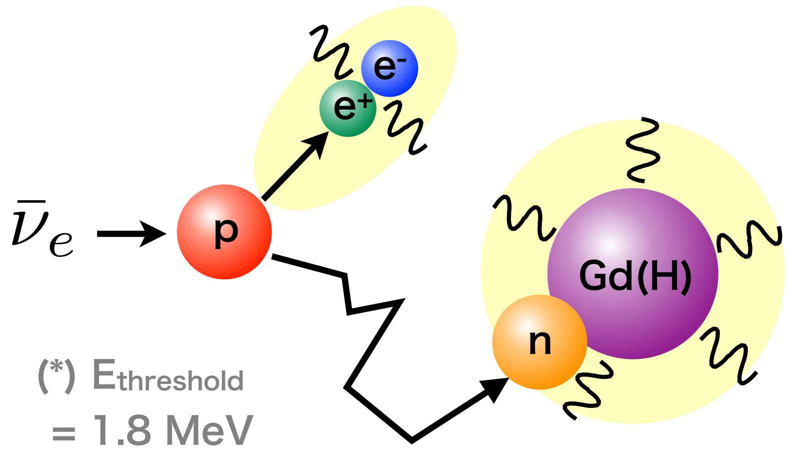
USA
U. Alabama
ANL,U. Chicago
Columbia U.
UC Davis
Drexel U.
IIT, KSU, MIT,
U. Notre Dame
U. Tennessee
Virginia Tech



~150 scientists in 7 countries

Detection principle

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



Delayed coincidence:

- Prompt signal

  e^+ ionization & annihilation: E_{prompt} = 1~8 MeV
- Delayed signal

  n capture on Gd (H): $E_{delayed}$ = ~8 (~2.2) MeV
- Time coincidence of those

  τ ~ 30 (~220) μs for Gd (H)

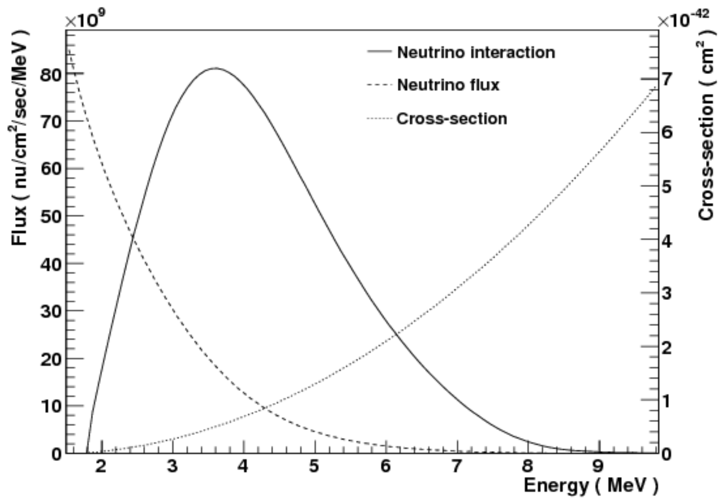
→ Two independent samples (Gd & H)

Relation of energy between prompt signal and reactor ν

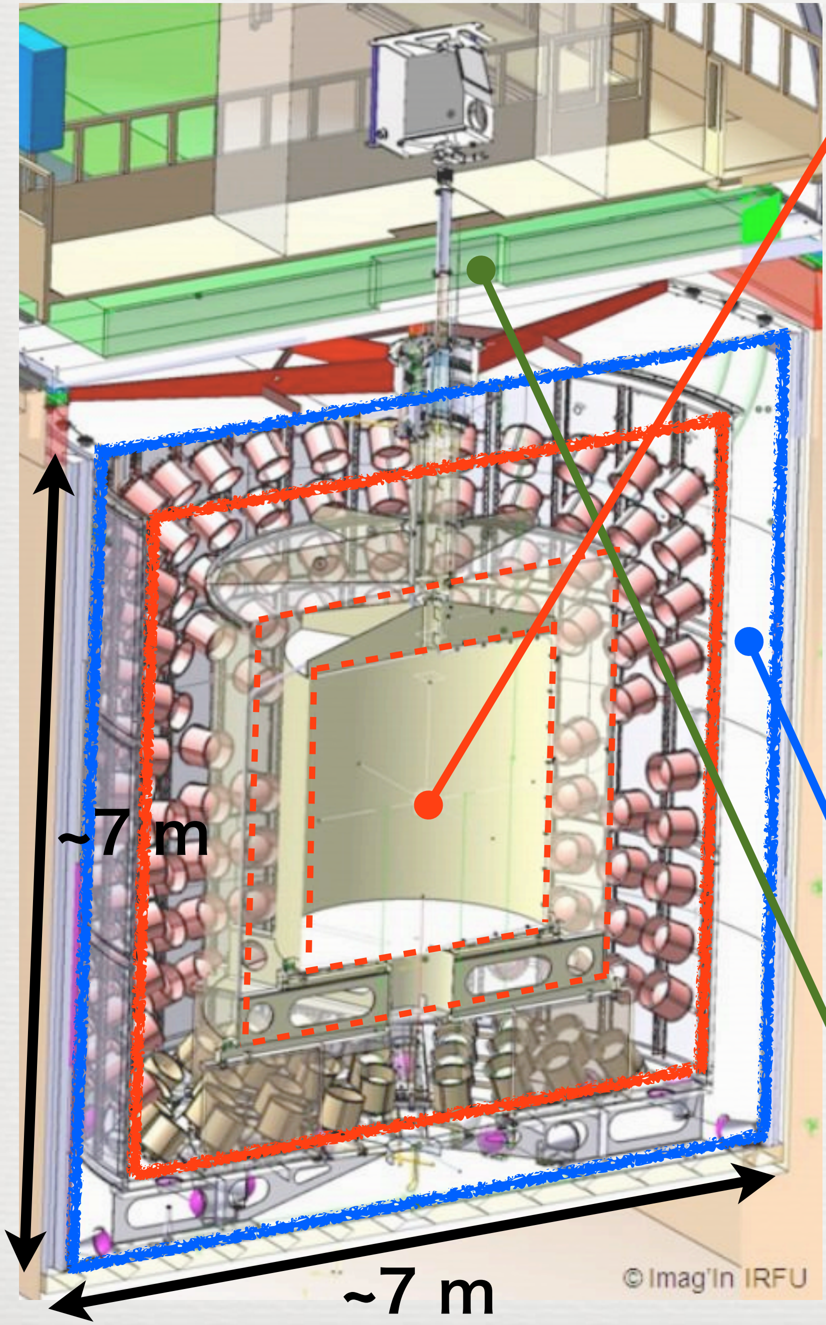
$$E_{vis} = E(kin)_{e^+} + 2m_e$$
$$\simeq E_{\bar{\nu}_e} - (M_n - M_p) + m_e$$
$$\simeq E_{\bar{\nu}_e} - 0.782\,\mathrm{MeV}$$

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

Spectral shape of ν energy



Double Chooz detector



Inner Detector (ID) - three cylindrical layers

ν-target region ··· Capture on Gd

- Gd-loaded (1 g/l) liquid scintillator (10.3 m^3)

γ-catcher region ··· Capture on H

- 22.3 m^3 liquid scintillator

Buffer region

- 110 m^3 mineral oil & 390 low-BG 10" PMTs

Detectors for background veto

Inner veto (IV)

- Liquid scintillator & 78 8" PMTs

Outer veto (OV)

- Plastic scintillator strip + WLS fiber + MAPMT

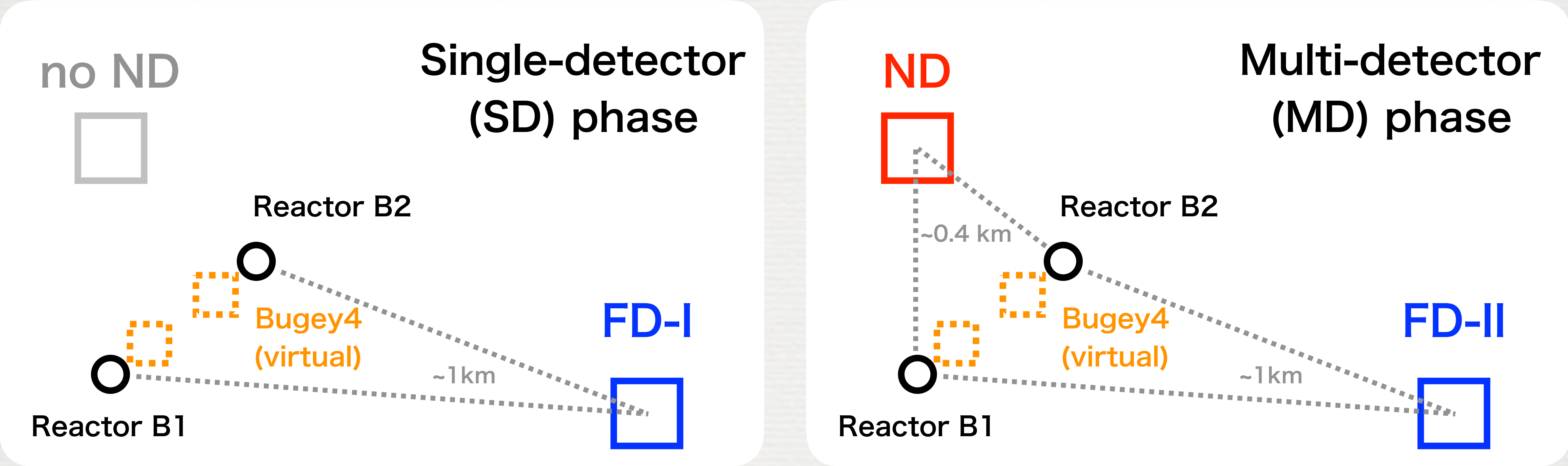
Double Chooz milestones

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:

Latest results with **two detectors** & **Gd+H analysis**

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

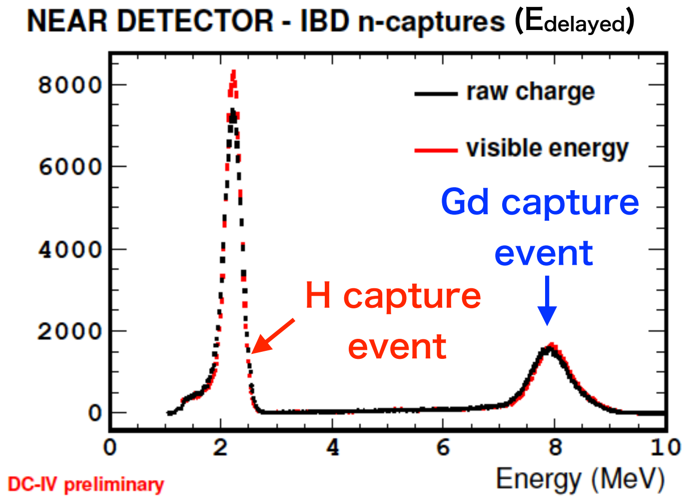
MD phase (2R2D setup : FD-II & ND data)

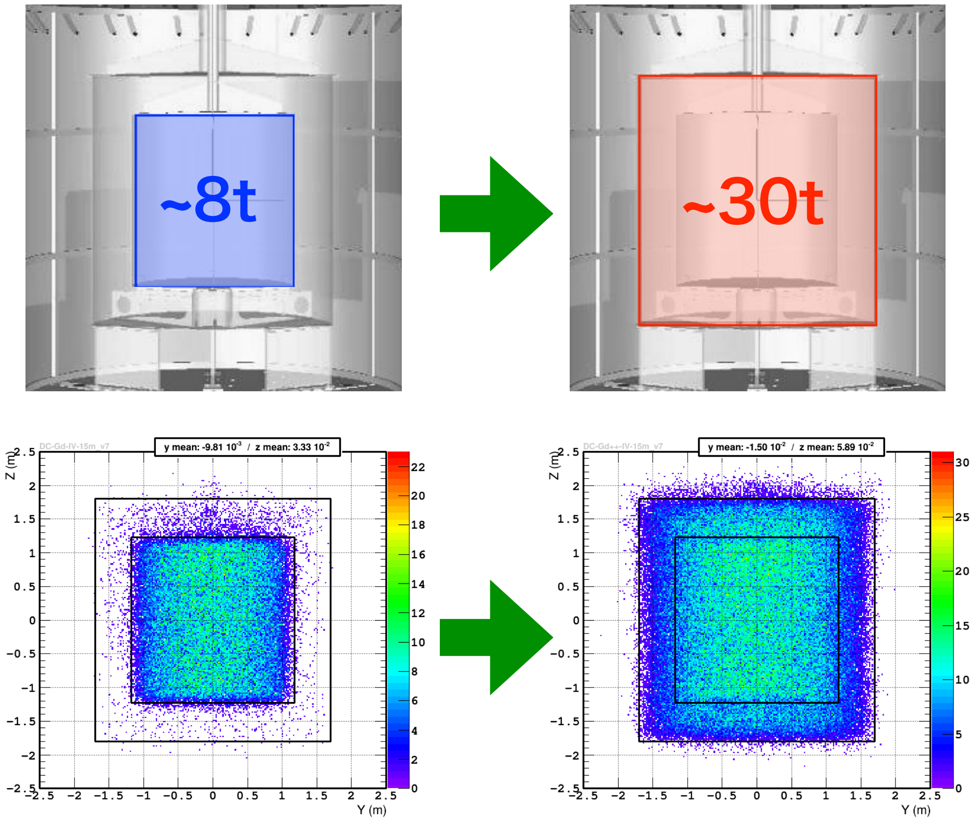
- Nearly iso-flux setup can suppress ν flux error (~0.1% of total flux precision)
- Identical detector cancels correlated errors like detection efficiency

Boosted statistics by Gd+H analysis

Preceding experiments in aspect of statistics (DayaBay & RENO)

→ New strategy: Enlargement of effective volume





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

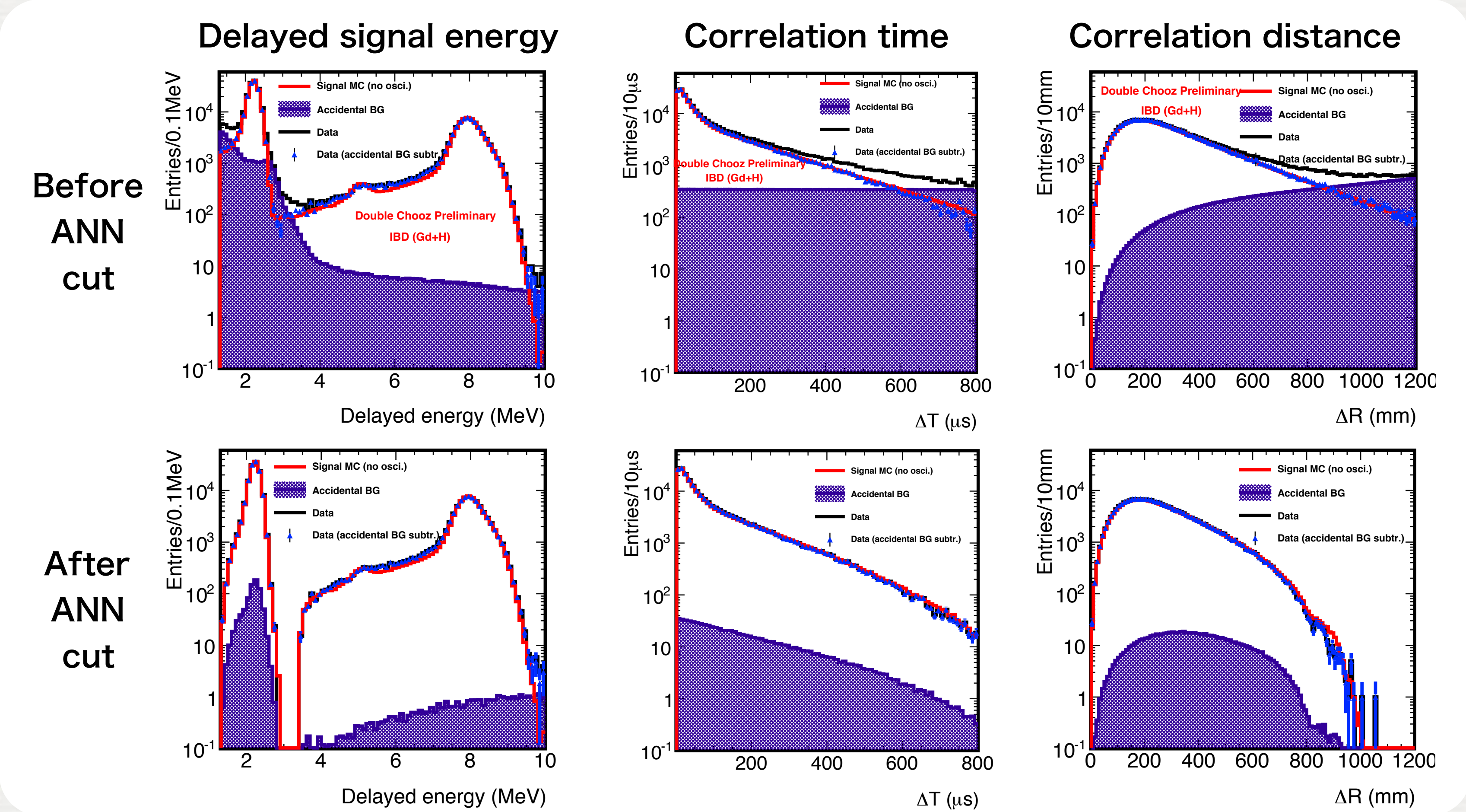
~2.5 times

Increased statistics by longer running period (SD: 480 days & MD: 380 days) with ~2.5 times boosted by Gd+H analysis

ANN cut for accidental coincidence

Accidental BG is increased by lowering $E_{delayed}$ cut for Gd+H analysis

→ ANN (artificial neural network) is applied using 3 input variables



Accidental BG contamination is significantly reduced

→ Negligible impact to θ_{13} measurement. This allows Gd+H analysis

BG veto & leak @ ND

Backgrounds

(pink) ((blue)) : mimic prompt (delayed) signal

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

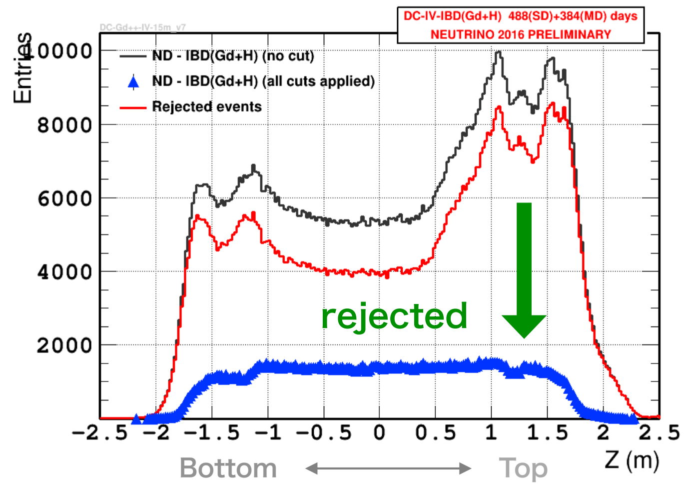
→ <u>Vetoed by dedicated cuts like ANN</u>

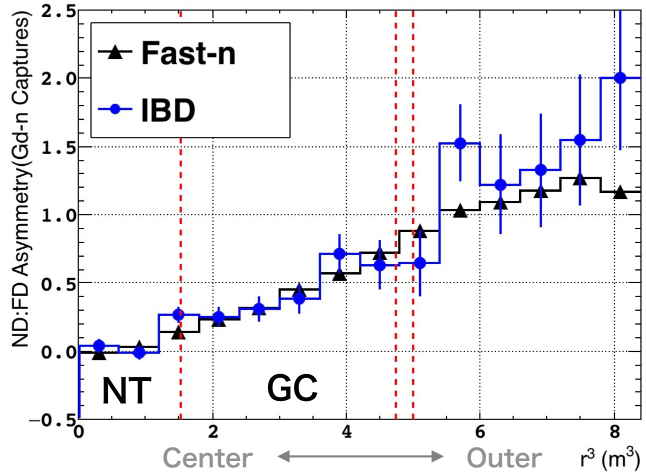
LS on Buffer @ ND

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

Gd concentration in GC @ ND

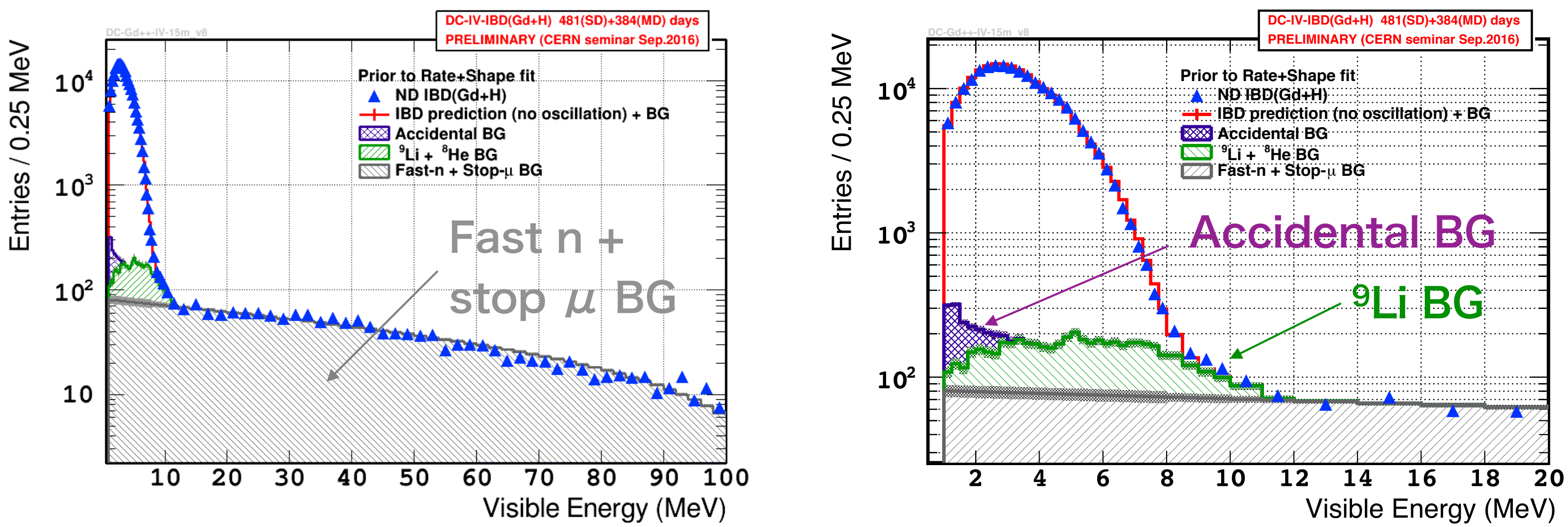
- Found in comparison with ND and FD
  - → <u>No effect in Gd+H analysis (w/ both volumes)</u>
  - → Estimating effect to Gd analysis (x-check)





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)

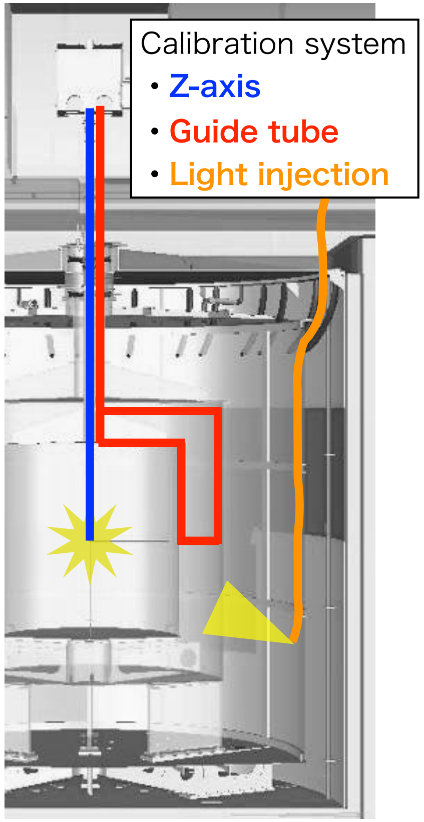


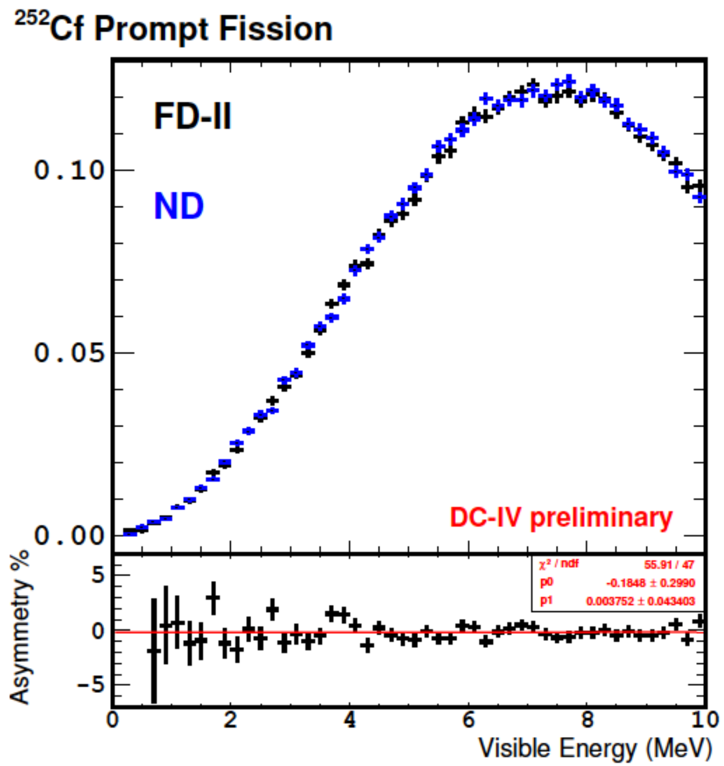
- <u>All backgrounds have characteristic spectrum</u>
- Both “Rate & Shape” are used in oscillation analysis except for ^{9}Li rate
  → ^{9}Li BG rate is constrained by the shape in the fit

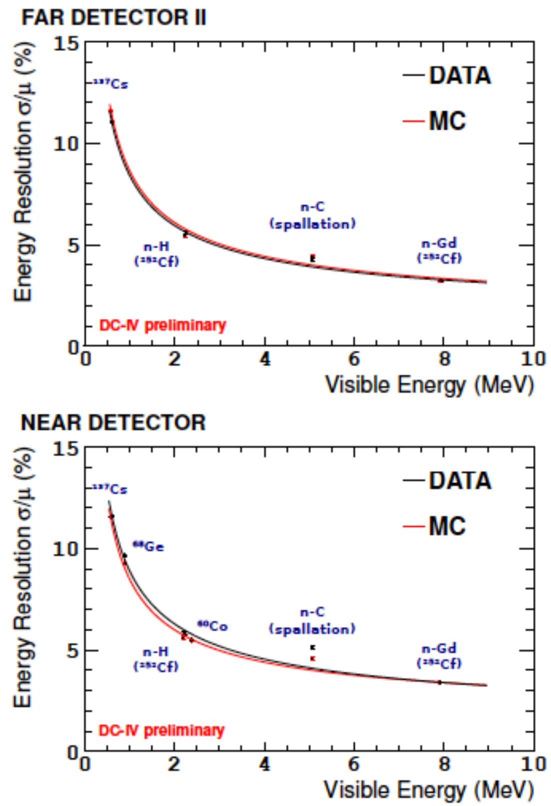
Detector responce

<u>Important to understand detector responce in ND and FD</u>

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

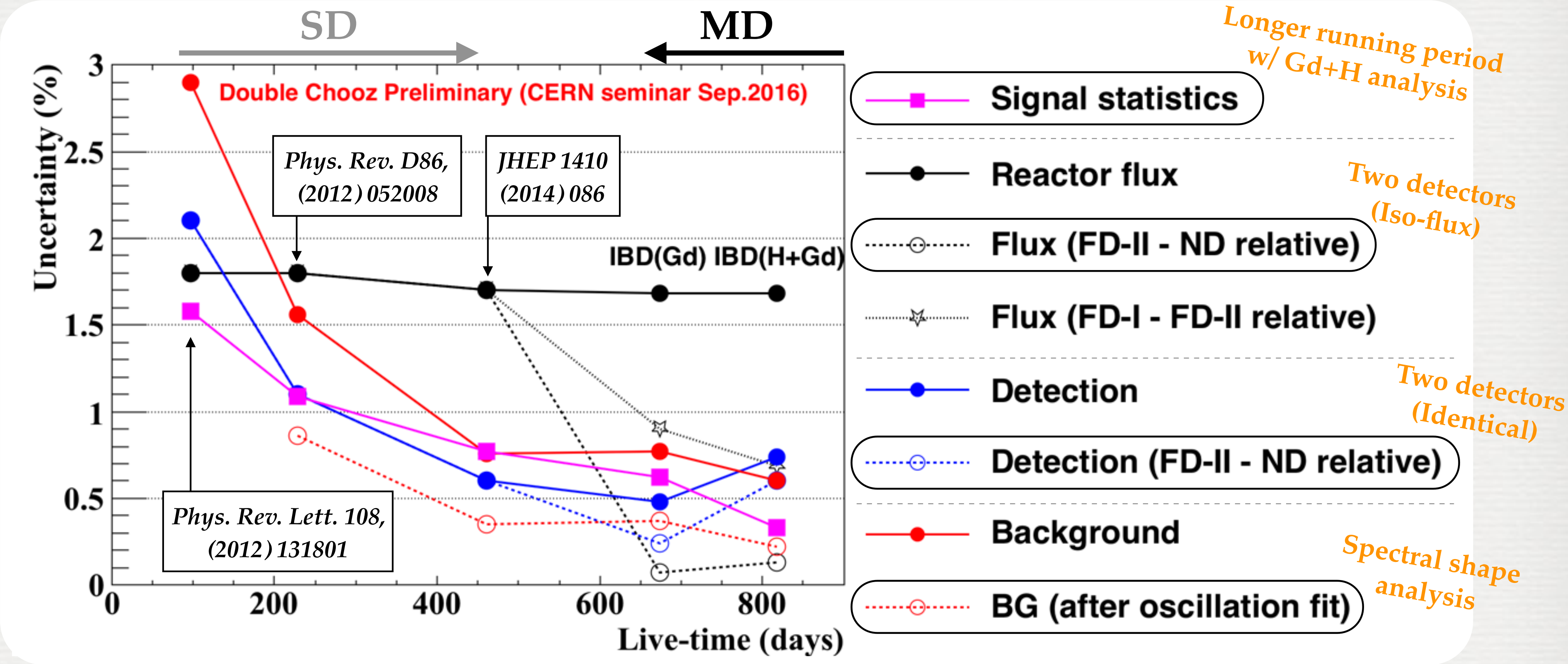






Detector performances are validated. Confirmed well tuned MC

Systematic uncertainty



SD phase:

- Improved uncertainties. Reactor ν flux error was dominant

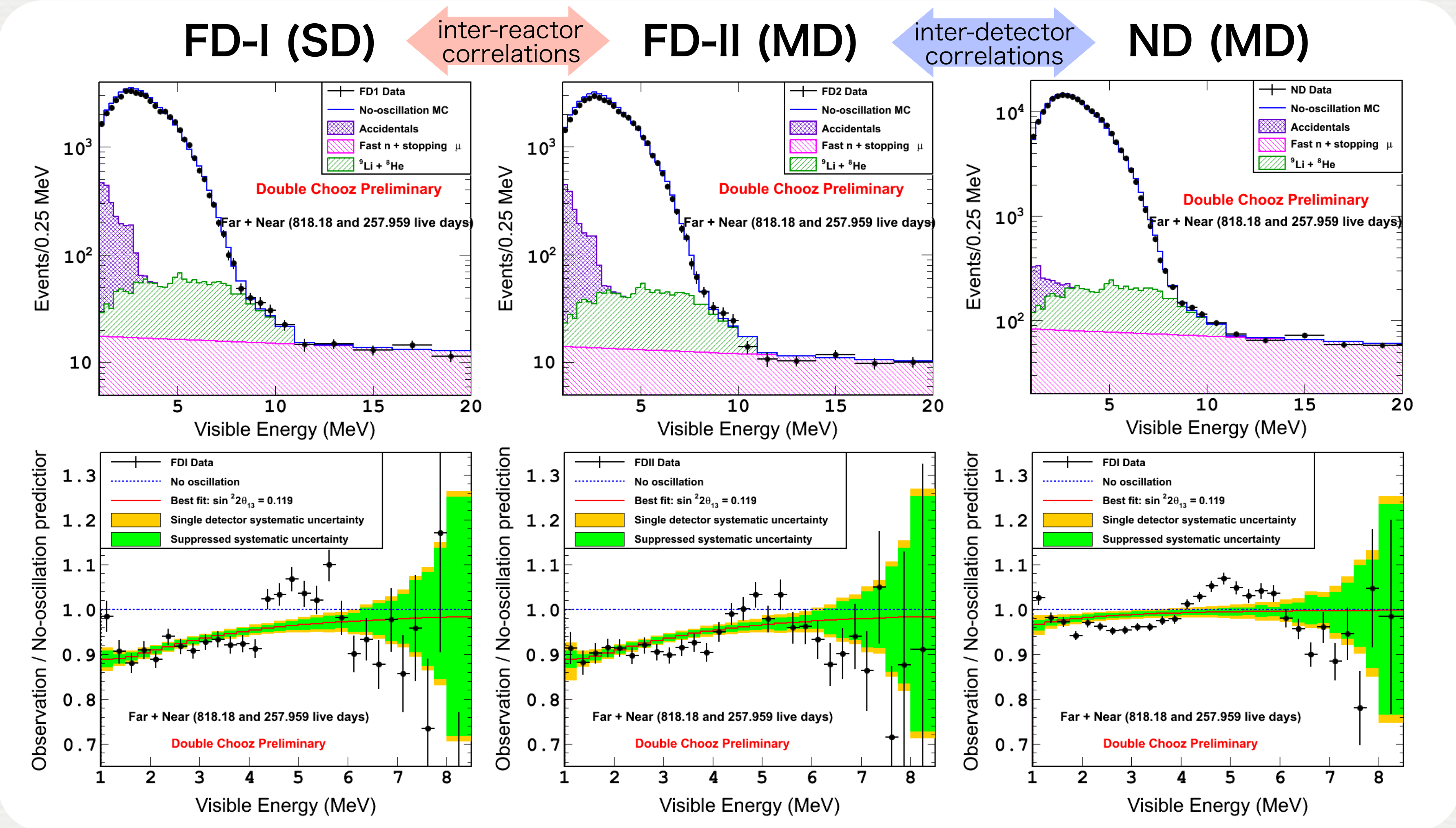
MD phase:

- Improved statistics by Gd+H analysis. Flux error is strongly suppressed
- Detection systematics is main source to limit in Gd+H analysis

(Proton number estimation is conservative at this point → Future improvement)

Oscillation fit result

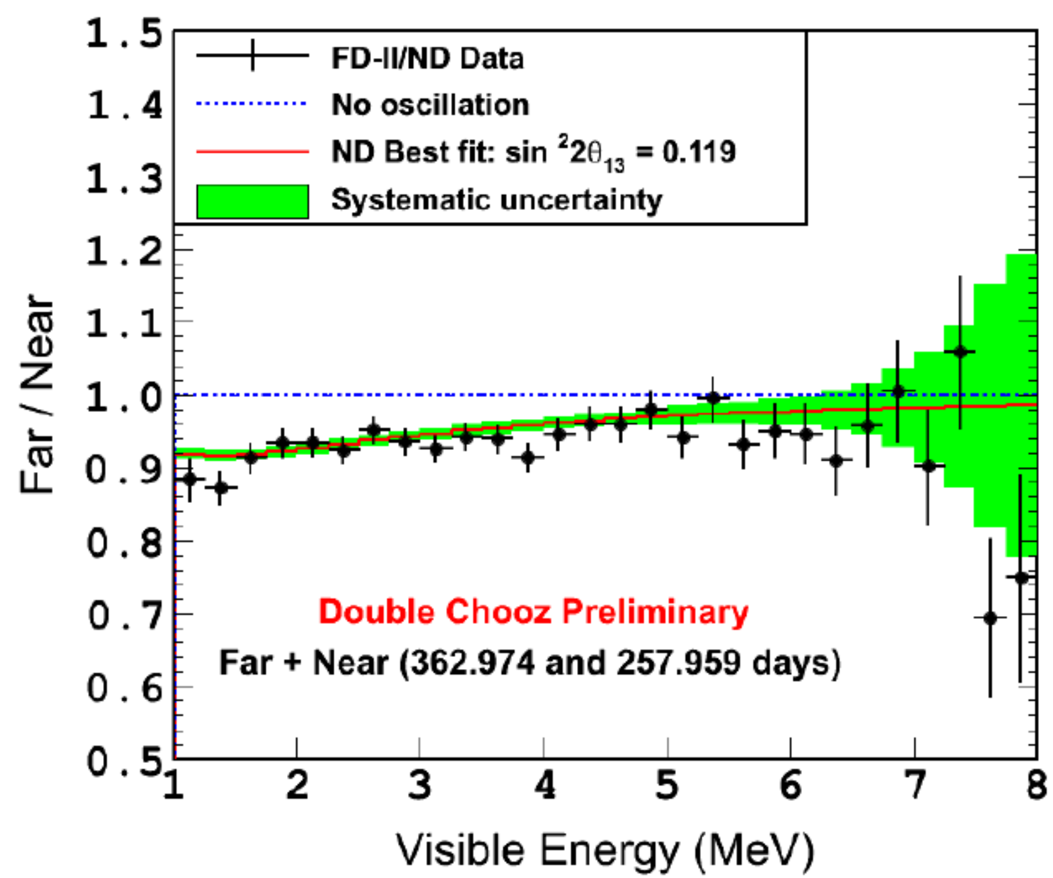
Simultaneous χ^2 fit with Data-to-MC comparison for each data set



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

cf.) Latest FD only results (Gd): **$\sin^2 2\theta_{13} = 0.09 \pm 0.03$** with 52.2/40

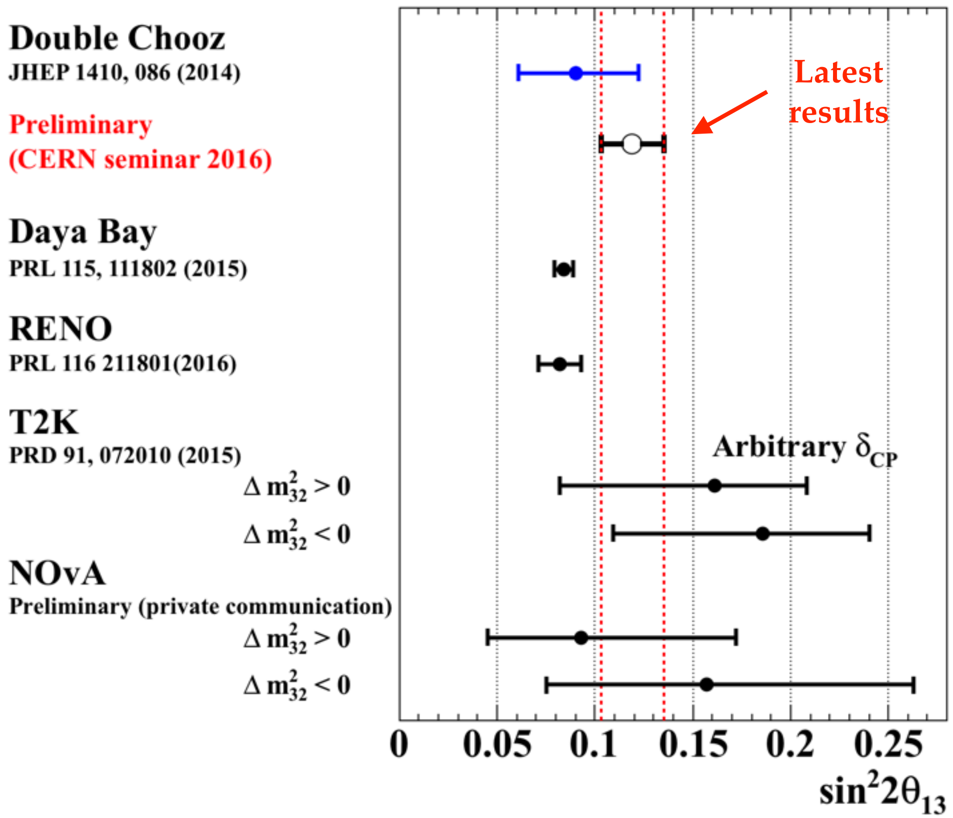
FD-II/ND ratio



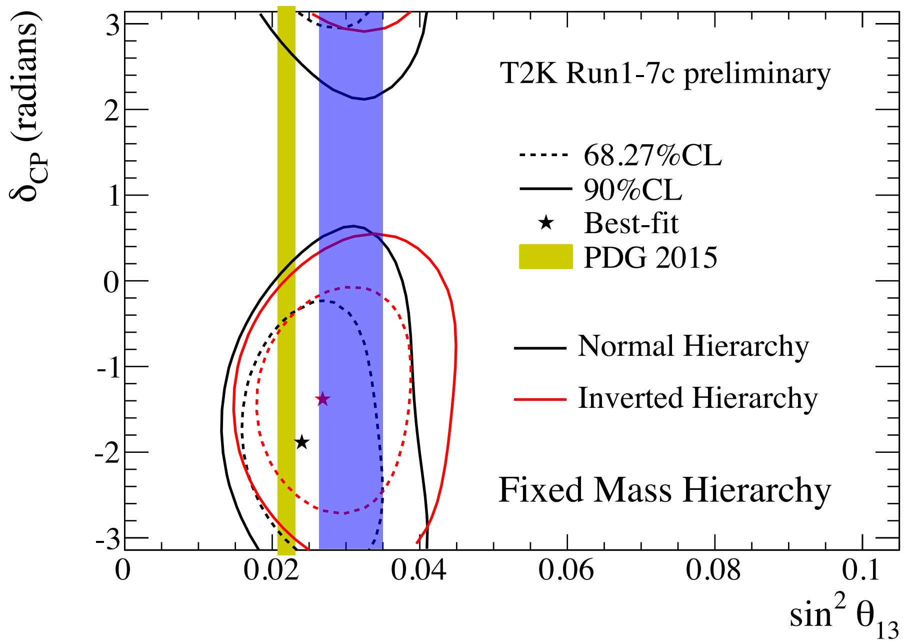
Common deviation is cancelled in FD-II/ND ratio

→ The deviation comes from flux prediction (under investigation)

Current θ_{13} in the world



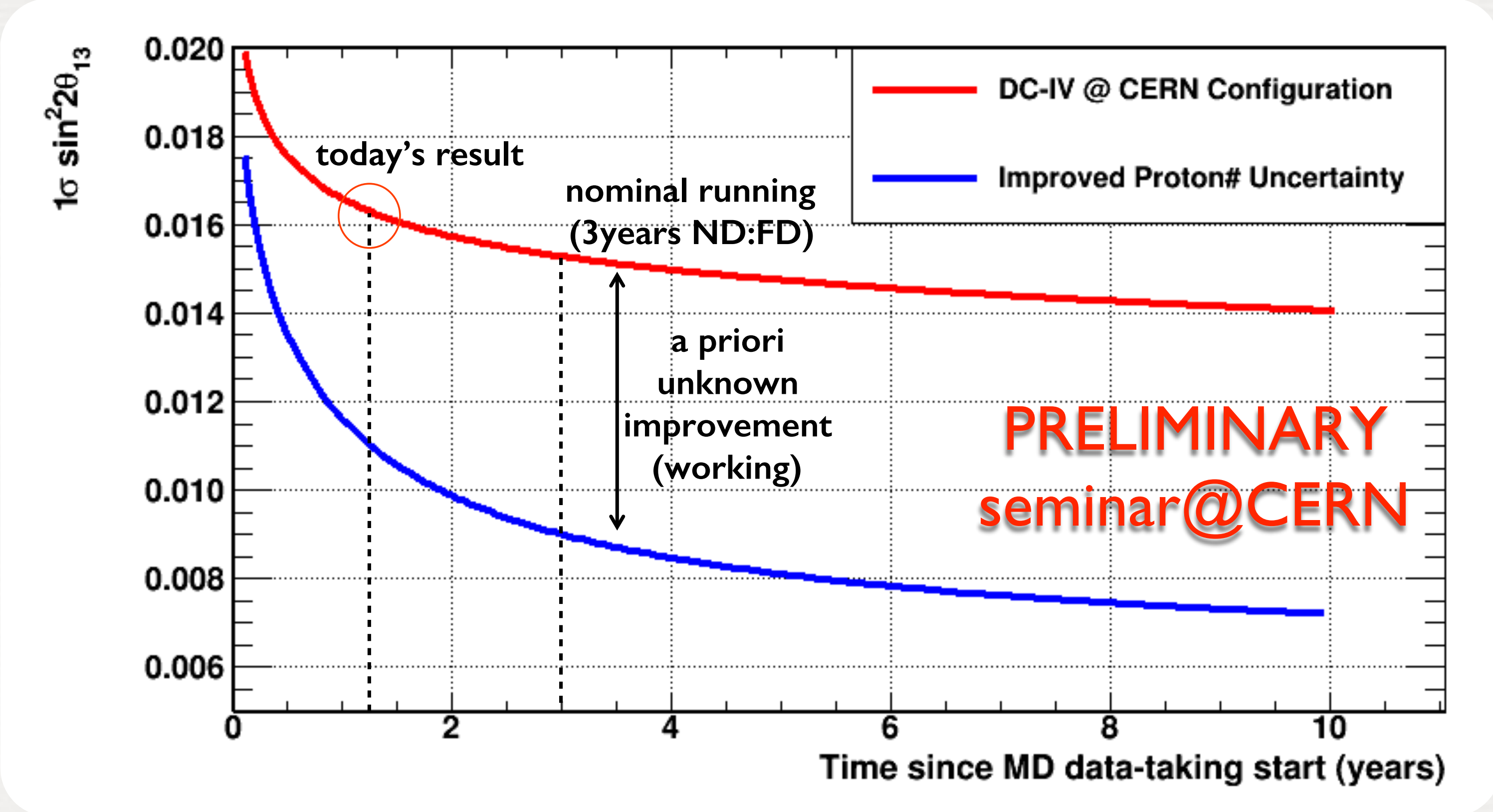
T2K result @ ICHEP 2016



- ~2σ tension with latest DayaBay result ($\sin^2 2\theta_{13}$ = 0.084 ± 0.005)
- Broader range of δ_{CP} is allowed if large θ_{13}

→ It is still not so significant but further validation is desirable

Future prospects



- Better precision with increased statistics and improved systematics
  → Uncertainty on proton number is next target
- 1st workshop on 3 reactor ν experiments was held (Oct. 2016 @ Seoul)
  → Redundancy check: Reviewed analyses each other. Further communication
  → Ultimate goal: Combined θ_{13} results from the reactor ν community

Conclusion

Reactor θ_{13} is a key for current/future $\nu_\mu \rightarrow \nu_e$ experiments

・To resolve oscillation parameter dependence (δ_{CP}, MH, θ_{23})

→ Both robustness and precision of reactor θ_{13} are important

Latest θ_{13} results is presented

・Suppression of systematic errors by Two detectors

・Improved statistics & Enlarging effective volume by Gd+H analysis

→ $\sin^2 2\theta_{13} = 0.119 \pm 0.016$ (cf. 0.09 ± 0.03 for latest results w/ FD only)

Further effort is ongoing

・Possible improvement by better understandings of systematics

・Redundancy check with reactor neutrino experiments

→ More robust and better precision measurement

・Other physics program with high statistics

e.g.) Directionality, Sterile ν search, Precision measurement of reactor ν spectrum