[Nu_03] Precise measurement of the neutrino oscillation angle θ_{13} using $\bar{\nu}_e$ from nuclear reactors with Double Chooz experiment

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on behalf of the Double Chooz collaboration

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TYL/FJPPL Workshop, Bordeaux
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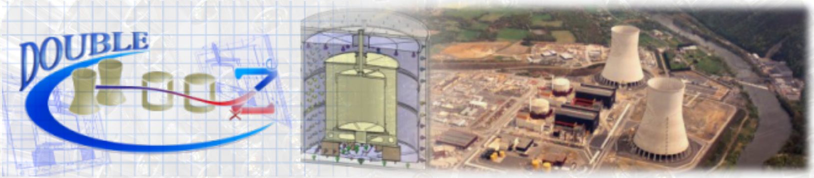
France-Japan Particle Physics
Toshiko Yuasa Lab.

Double Chooz

理系じゃなくてもわかる楽しいRCNS教室

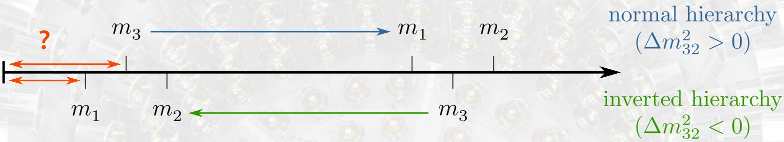
Outline



- Introduction to θ_{13} measurement and Double Chooz experiment
- 2013 – 2014 activity report:
  – New θ_{13} results with the far detector "DC-III (n-Gd)"
  – Status of the near detector integration
- Prospect for coming phase with both detectors

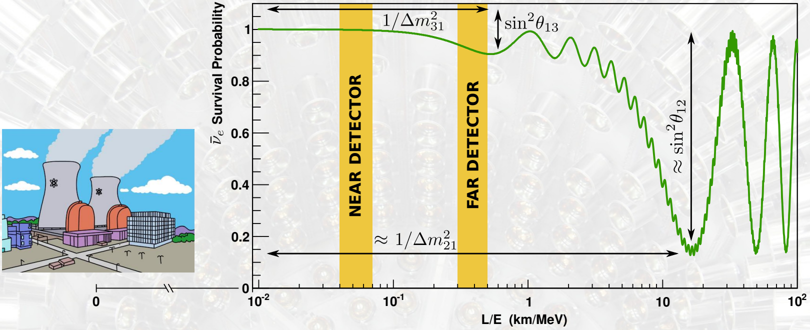
Neutrino physics and importance of θ_{13}

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \underbrace{\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}}_{\text{atmospheric } \nu} \underbrace{\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13}\end{pmatrix}}_{\text{reactor+accelerator } \nu} \underbrace{\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}}_{\text{solar } \nu} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$



- neutrino: extremely small mass, no charge, weak interaction only $\rightarrow$ arduous detection
- flavor eigenstates $(\nu_e, \nu_\mu, \nu_\tau) \neq (\nu_1, \nu_2, \nu_3)$ mass eigenstates
  $\rightarrow$ PMNS mixing matrix + flavor oscillating during propagation of neutrinos
- mixing parameters: θ_{12}, θ_{23}, θ_{13}, Δm^2_{32}, Δm^2_{21} and δ_{CP}
- recent discovery of $\theta_{13} > 0$ (2011) $\rightarrow$ remaining unknown: sign of Δm^2_{32} and δ_{CP}
- precise measurement of θ_{13} = critical step to probe **mass hierarchy** and **leptonic CP violation**

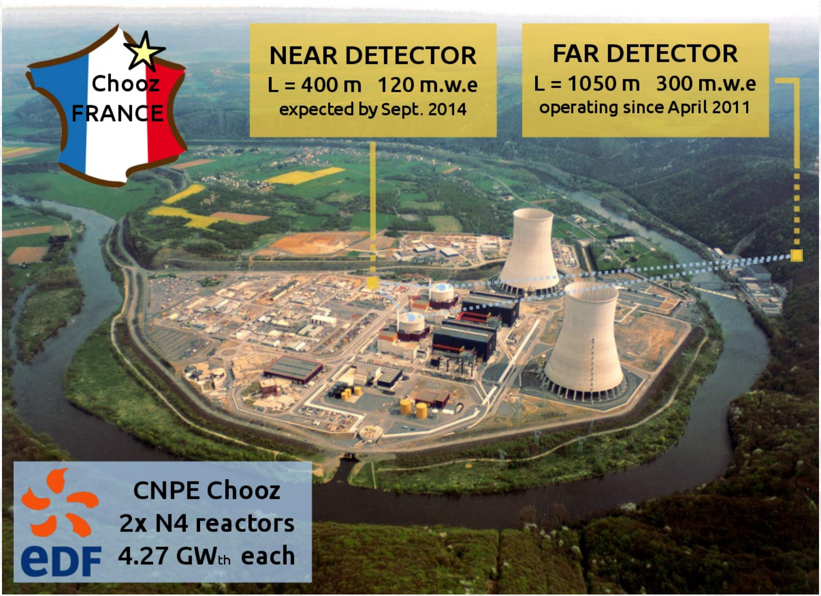
Measurement of θ_{13} with reactor neutrinos



$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \sin^2(2\theta_{13}) \sin^2\left(\frac{\Delta m^2_{31} \mathrm{L}}{4\ \mathrm{E}}\right) + O(10^{-3}) \quad \text{for L/E} \lesssim 1$$

- survival probability depends of L/E_ν $\rightarrow$ measurement based on **rate and shape** deformation
- **reactor neutrinos**: pure $\bar{\nu}_e$, high intensity ($\sim 10^{21}$ $\bar{\nu}_e$/sec), low energy $\rightarrow$ short baseline, no oscillation parameters correlation and no matter effect (**direct measurement**)
- precise measurement of θ_{13} by **2 identical detectors** (cancel flux & efficiency uncertainties)
  – far detector $\rightarrow$ disappearance of $\bar{\nu}_e$ around first minimum
  – near detector $\rightarrow$ unoscillated neutrino flux

Double Chooz experimental layout



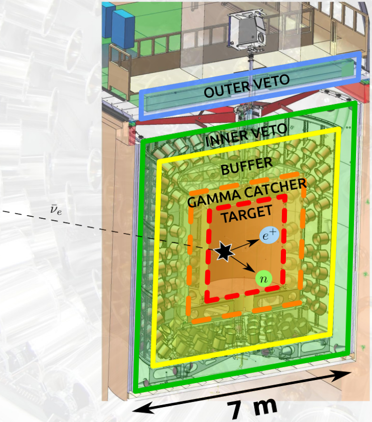
Principle of $\bar{\nu}_e$ detection

INVERSE BETA DECAY on proton (thresold > 1.8 MeV)

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

prompt signal: scintillation + e^+ annihilation
$E_{prompt} \approx E(\nu_e) - 0.8$ MeV

delayed signal: γ ray(s) from neutron capture
n-Gd $E_{delayed} \approx 8.0$ MeV $\Delta T \approx 30$ μs
or n-H $E_{delayed} \approx 2.2$ MeV $\Delta T \approx 200$ μs



Neutrino target:
liquid scintillator PXE + Gd

Gamma catcher:
liquid scintillator PXE (no Gd)

Buffer volume:
transparent mineral oil
with 390 x 10" PMTs assembly

Inner Veto:
liquid scintillator (LAB)
with 78 x PMTs 8"

Outer Veto:
plastic scintillator strips

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.
UC Davis
Drexel U.
U. Hawaii
IIT
KSU
LLNL
MIT
U. Notre Dame
U. Tennessee

150 scientists in 7 countries
$\approx$ 60 from France + Japan
Spokesperson: Hervé de Kerret (CNRS/IN2P3)
Project manager: Christian Veyssière (CEA Saclay)

France + Japan contribution on Double Chooz

Highlight of leadership

- Project management
- Inner-detector PMTs
- PMT readout + electronics
- Online + DAQ
- Calibration
- Energy reconstruction
- Reactor neutrino prediction
- Analysis

...

Nu_03 leadership

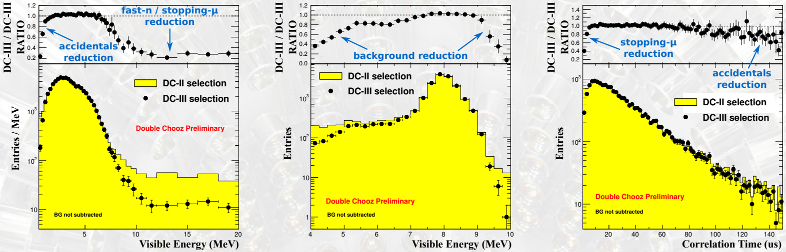
- Anatael Cabrera
  (APC, CNRS/IN2P3)
- Masahiro Kuze
  (Tokyo Institute of Technology)

Recent Publication (collaboration wide)

- *Background Independent Measurement of θ_{13} in Double Chooz*
  Y.Abe et al., ArXiv: 1401.5981
- *First Measurement of θ_{13} from Delayed Neutron Capture on Hydrogen in the Double Chooz Experiment*
  Y.Abe et al., Phys. Lett. B723, 66-70 (2013)
- *Direct Measurement of Backgrounds using Reactor-Off Data in Double Chooz*
  Y.Abe et al., Phys. Rev. D87, 11102 1-7 (2013)

NEW RESULTS (2014) WITH THE FAR DETECTOR

New event selection



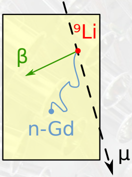
— Prompt — — Delayed — — ΔT —

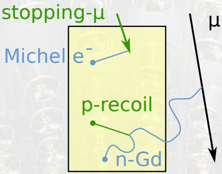
	DC-II (2012)	DC-III (2014)
Prompt Energy	0.7 – 12.2 MeV	0.5 – 20 MeV
Delayed Energy	4 – 10 MeV	6 – 12 MeV
Δ t	2 – 100 μs	0.5 – 150 μs
Δ R	n/a	$<$ 1 m
isolation window	[-100, +400] μs	[-200, +600] μs

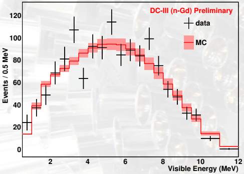
- **muon veto:** $\Delta t_{last-\mu} > 1$ ms
- **OV veto:** no OV hit coincident with prompt
- **^{9}Li veto:** likelihood method trained with ^{12}B
  ^{9}Li rejection $> 50\%$ with dead time $< 0.5\%$
- **“FV veto”:** point-like characterisation of energy deposit (reject stopping muons)
- **IV veto:** reject fast-neutrons and accidentals
- **light noise:** improved criteria on charge isotropy and simultaneity of PMT signals

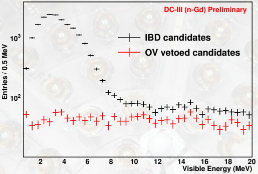
opened selection cut (more signal) + new vetos (less background)

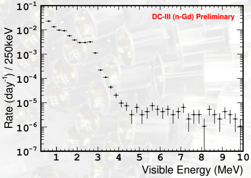
Neutrino backgrounds











Cosmogenetic background

β-n emitter (mainly ^{9}Li)

- $0.97\ ^{+0.41}_{-0.16}$ /day

previously: 1.25 ± 0.54 /day

Correlated background

fast neutrons, stopping-μ

- 0.60 ± 0.05 /day

previously: 0.67 ± 0.20 /day

Accidental background

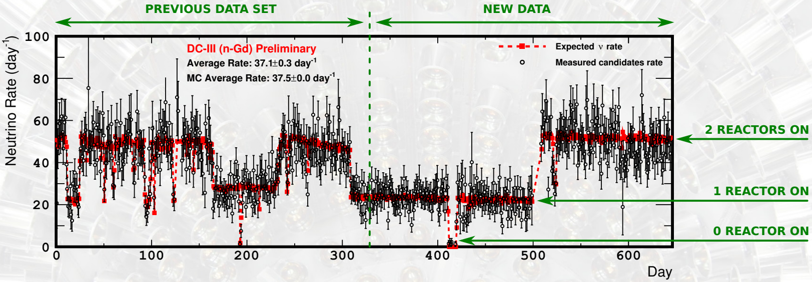
natural radioactivity

- 0.070 ± 0.005 /day

previously: 0.261 ± 0.002 /day

less background + more precise measurement of rate and shape

Neutrino candidates

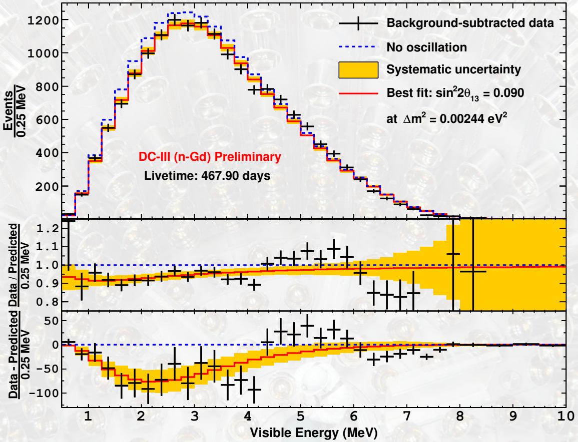


New Gd data set

- data from April 2011 to January 2013
- live time: 467.9 days (previously: 227.9 days)
  → including 7.5 days of two reactors OFF data
- 17'358 neutrinos candidates (previously: 8'249 candidates)

statistics of neutrino candidates is doubled

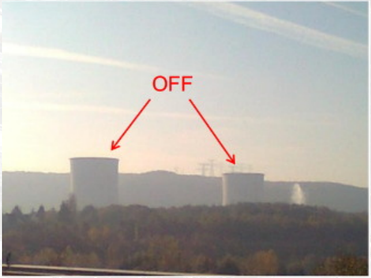
2014 Rate + Shape results (Gd)

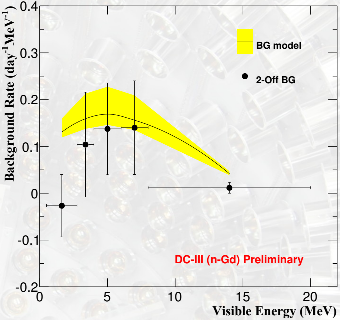


$$\sin^2(2\theta_{13}) = 0.090\ ^{+0.035}_{-0.028}$$ previous results: 0.109 ± 0.039

- excellent spectral distortion in 0.5 – 4 MeV (region constraining θ_{13} fit)
- origin of E/L structure > 4 MeV under investigation (integrated effect negligible on θ_{13})

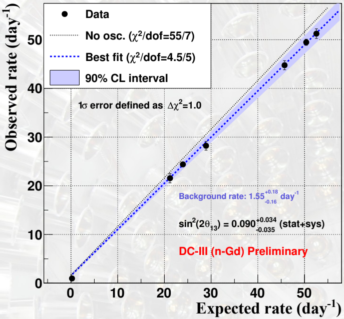
2014 Two reactors OFF results

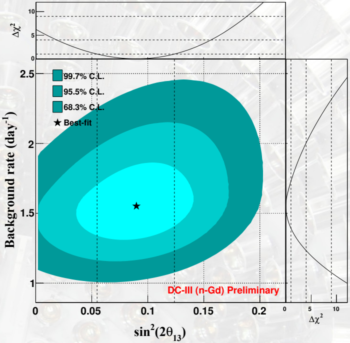




- only experiment with 7.5 days of data with all reactors OFF
  $\rightarrow$ unique opportunity to measure background
- observed events rate: 0.97 ± 0.37 /day vs expected: $1.78\ ^{+0.43}_{-0.19}$ /day
  $\rightarrow$ good agreement in 4 – 8 MeV region, deficit is observed outside

2014 Reactor Rate Modulation analysis

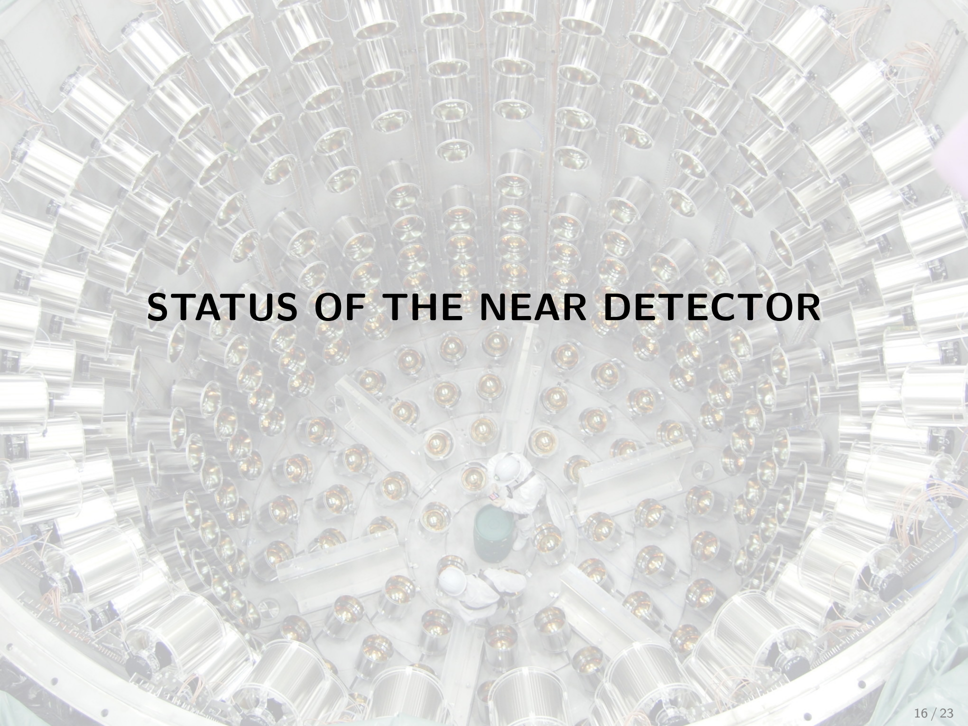




- exploit the 100 % variation in reactor power   unique with Double Chooz
- independent measurement of θ_{13} (slope) and background (intercept):

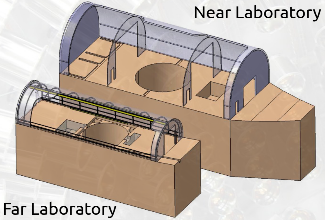
$$\sin^2(2\theta_{13}) = 0.090 \begin{smallmatrix} +0.034 \\ -0.035 \end{smallmatrix} \qquad \text{background rate} = 1.55 \begin{smallmatrix} +0.18 \\ -0.16 \end{smallmatrix} \text{/day}$$

- consistent with rate+shape fit and OFF-OFF data
- most precise "rate-only" measurement



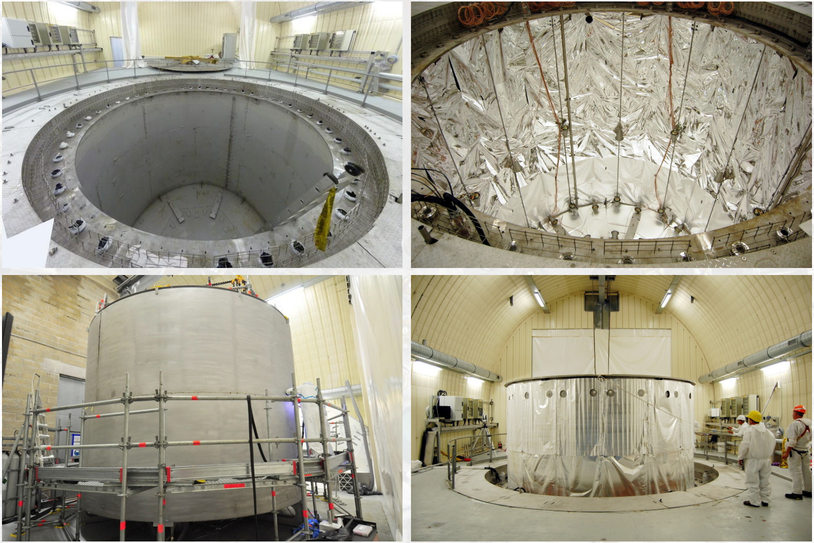
STATUS OF THE NEAR DETECTOR

Near Laboratory



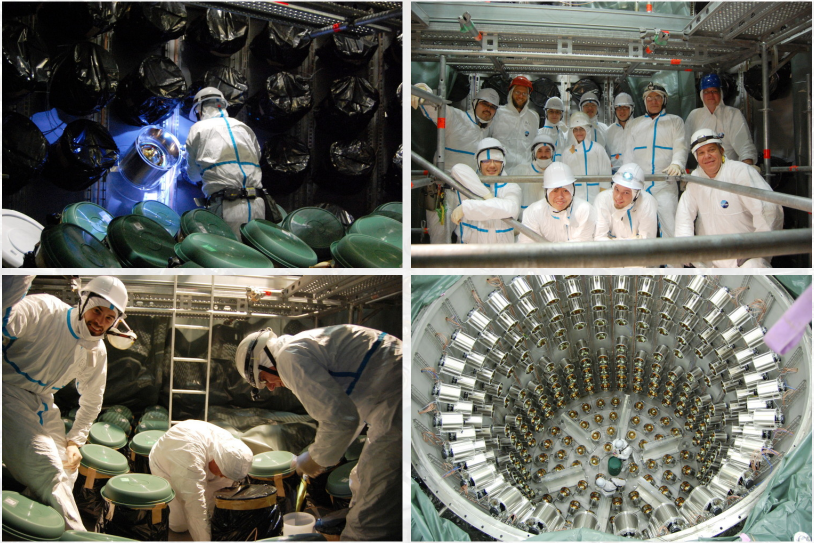
- larger laboratory divided into 3 clean rooms (ISO 5 class air system) in order to parrallelise integration tasks for $\approx$ 1 year construction
- digging of tunnel + underground laboratory started in 2011
- laboratory fully delivered on May 2013 $\rightarrow$ beginning of the detector integration

Near detector integration progress (1)



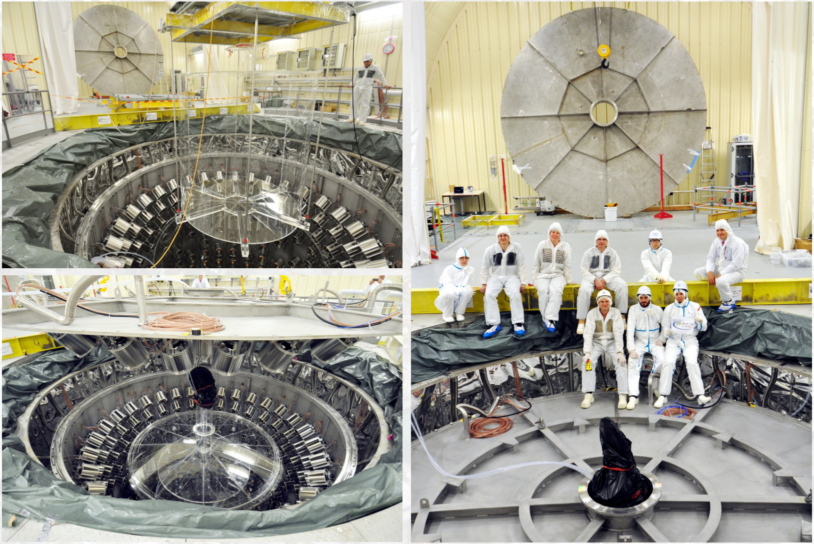
Jul/Sep 2013: IV vessel, IV PMTs, buffer vessel welding and installation into IV

Near detector integration progress (2)



Oct/Dec 2013: integration of 330 bottom+side buffer PMTs

Near detector integration progress (3)



Jan/Apr 2014: integration of acrylic vessels and buffer closure (30th April)

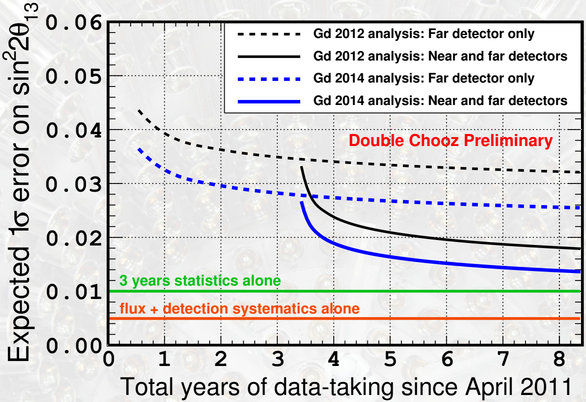
Near detector integration progress (4)

May/Jun 2014: last IV PMTs, IV closure, preparation for filling

Summer 2014: filling and commissioning

First detection of neutrinos expected in Sept 2014

Future prospect with near+far detector



- remarquable improvement with the new Gd analysis
- first data near the detector will improve rapidly the precision (projection based on current background model → improvement expected & in preparation)
- expect to challenge a final sensitivity of ≈ 0.01 on $\sin^2(2\theta_{13})$

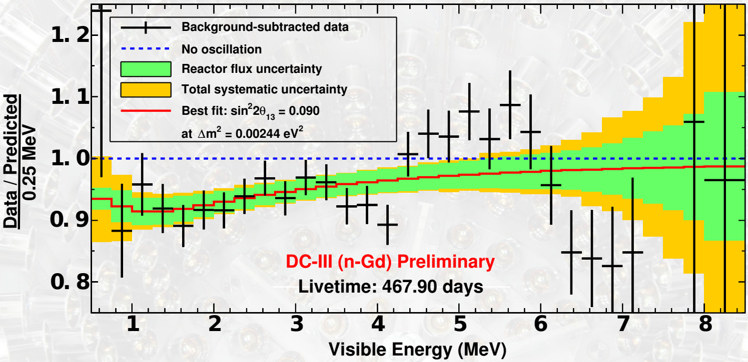
Talk summary

- **New results with far detector:**
  – more statistics, improved selection and background rejection
  – $\sin^2 2\theta_{13} = 0.090\ ^{+0.035}_{-0.028}$ fully consistent with previous publications
  – new improved H analysis to follow
- **Near detector integration:**
  – almost fully completed over the past year
  – filling and commissioning to come soon
  – detection of first neutrinos expected in Sept. 2014
- **Coming phase with both detectors:**
  – quick cancellation of systematics of flux and detection efficiency
  – target a final precision of ≈ 10 % on $\sin^2(2\theta_{13})$
  – investigate further the E/L structure above 4 MeV

- Important contribution from France+Japan through FJPPL program
- **Support from TYL for [Nu_03] highly appreciated for coming work:** near detector commissioning, filling and on-site shift (mainly travels Japan/France)

BACKUP

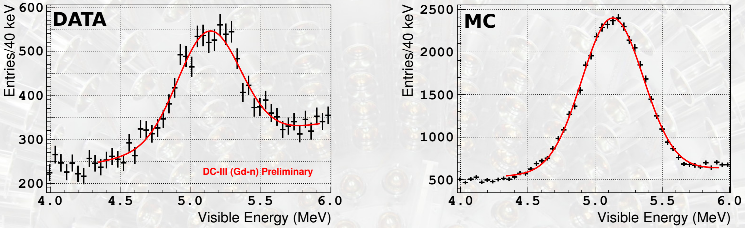
E/L structure investigation: robustness of rate+shape fit



- test rate+shape fit with an additional/hypothetical background: n-C-capture-like peak ($\approx$ 5 MeV) with several normalisations and shapes
- largest deviation observed: 0.3 σ on $\sin^2(2\theta_{13})$, 0.1 σ on ^{9}Li rate, $<$ 0.1 σ on others

$\rightarrow$ **negligible impact on θ_{13}**

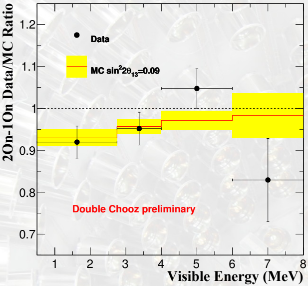
E/L structure investigation: possible culprits



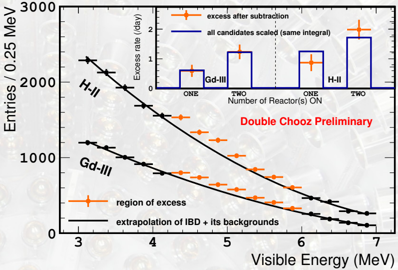
n-C peak reconstruction in GC

- **detection systematics:** no impact on shape
- **energy reconstruction:** C-n peak in GC with Δ(data,MC) $<$ 0.5 % $\rightarrow$ disfavored
- **background:** constrained $\rightarrow$ possible but not only the sole cause
- **reactor flux:** possible

E/L structure investigation: correlation with reactor neutrino flux



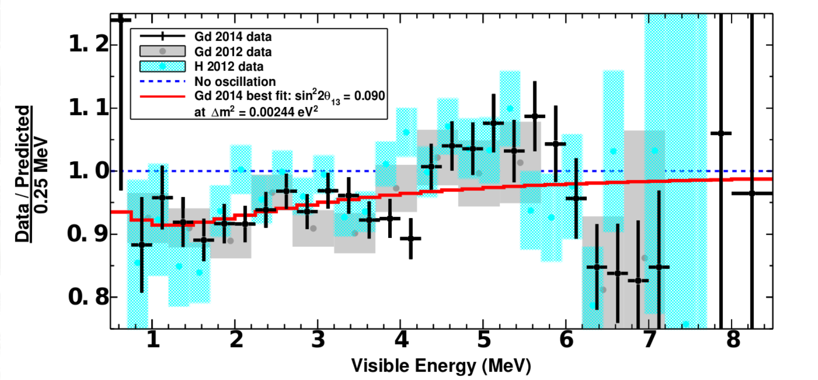
“2-ON data” – “1-ON data”



investigation of 4 – 6 MeV region (excess)

- 2 reactors ON data – 1 reactor ON data = pure 1-ON data (background free)
  → deviation consistent with observation on rate+shape fit result
- investigation of the region 4 – 6 MeV (excess of neutrino candidates):
  → rate is correlated with flux of reactor neutrinos (empirical data-driven observation)

E/L structure vs previous DC results



- same pattern observed in DC-II results
  with different selection (Gd, H) and detector volume (H)
- better resolved with DC-III (more statistics, better energy scale and less background)