Results from the Double Chooz Experiment

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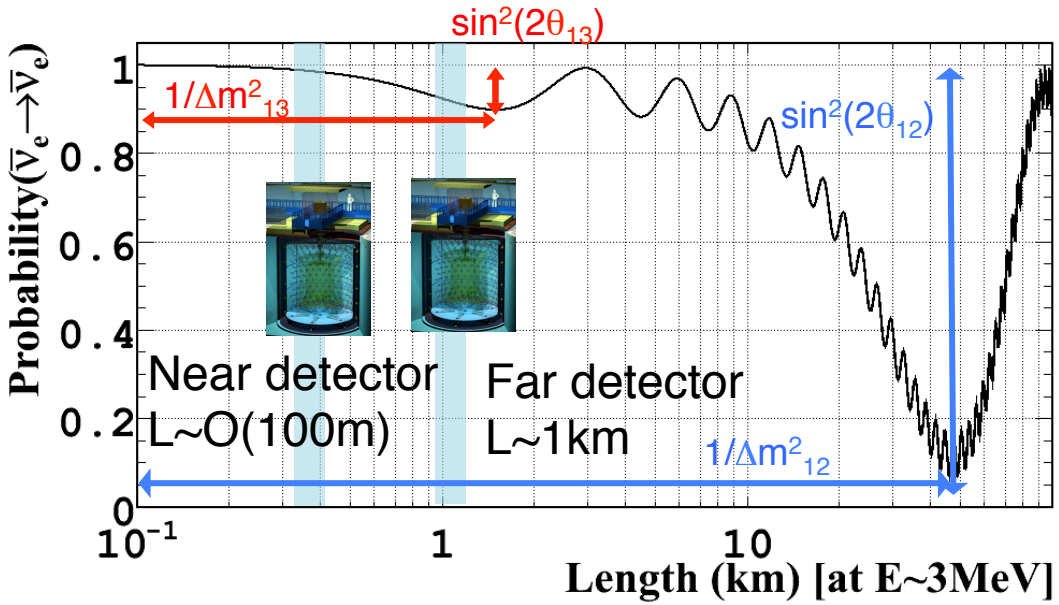
On behalf of the Double Chooz Collaboration

26/Aug/2015, Kolymbari, Crete, Greek

Introduction

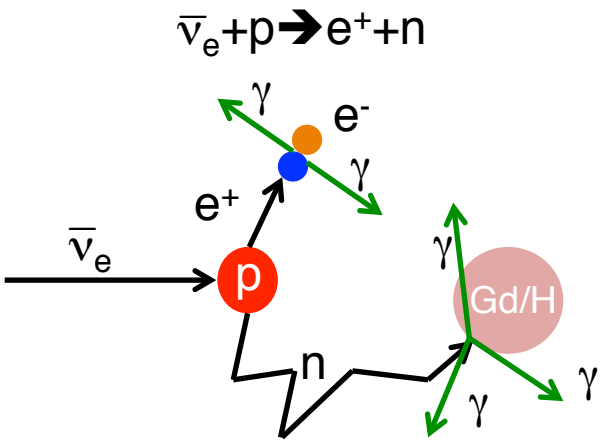


$$P = 1 - \sin^2 2\theta_{13} \sin^2 \left(1.27\, \Delta m^2_{31}(\mathrm{eV}^2)\, L/E_\nu\right)$$

- $\bar{\nu}_e$ disappearance observation by using reactors is an established method to measure θ_{13} of neutrino mixing angle.
  - Reactors are free and rich neutrino source.
  - Pure θ_{13} measurement is possible at distance of ~1km from the reactor.
- Precise θ_{13} measurement is important input for the neutrino problems.

Antineutrino Detection

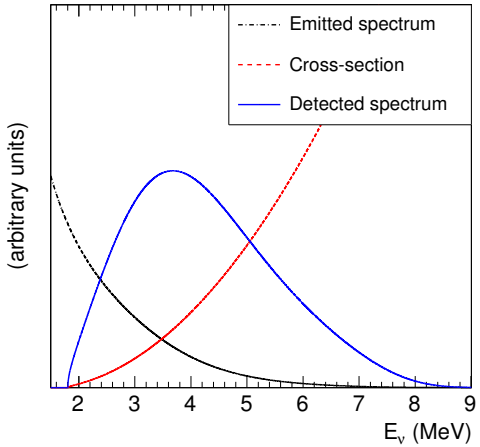
Inverse Beta Decay (IBD)



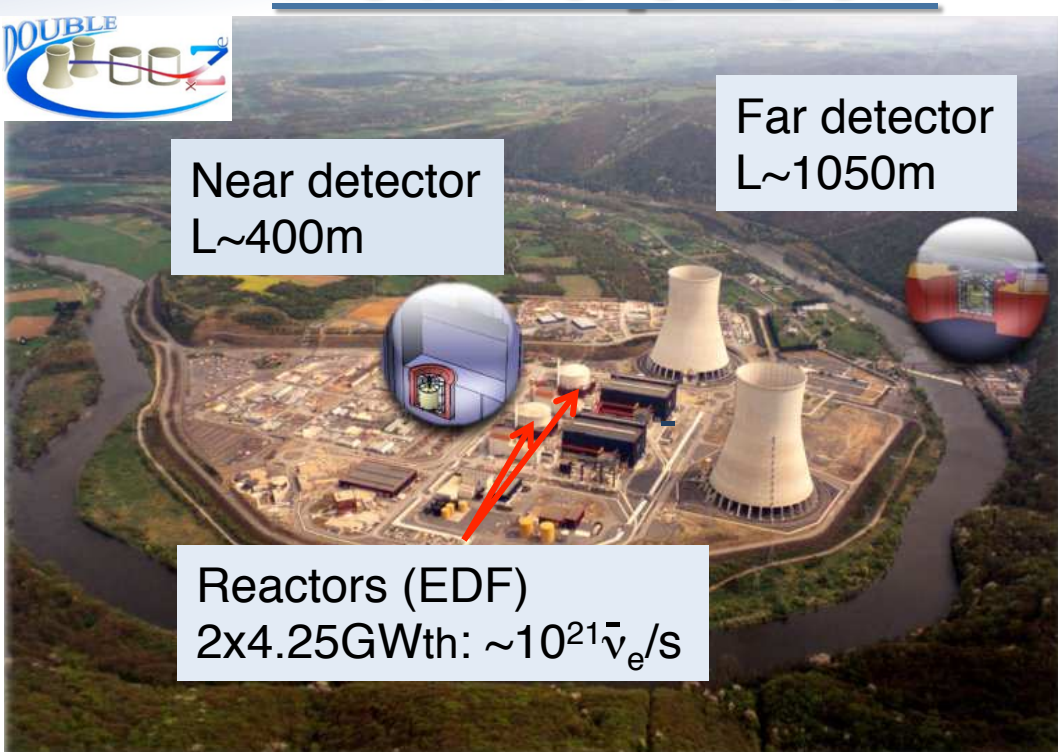
- Two different timing signals are generated at IBD event.
- Prompt signal:
  - → e^+ ionization and e^+e^- annihilation.
  - → 1-8 MeV.
- Delayed signal:
  - → Neutron capture on a nucleus.
    - → Gd capture
      - → ~8MeV, ~30μs delayed from prompt signal.
      - → Higher energy. Only in Gd-loaded region.
    - → H capture
      - → ~2.2MeV, ~200μs delay from prompt signal.
      - → Independent from Gd capture. Higher statistics.

- Prompt signal energy (visible energy) is related to the initial neutrino energy:

$$E_{vis} = E_{e^+} + 2m_e$$
$$\approx E_{\bar{\nu}_e} - \left(m_n - m_p\right) + m_e$$
$$\approx E_{\bar{\nu}_e} - 0.78\text{MeV}$$

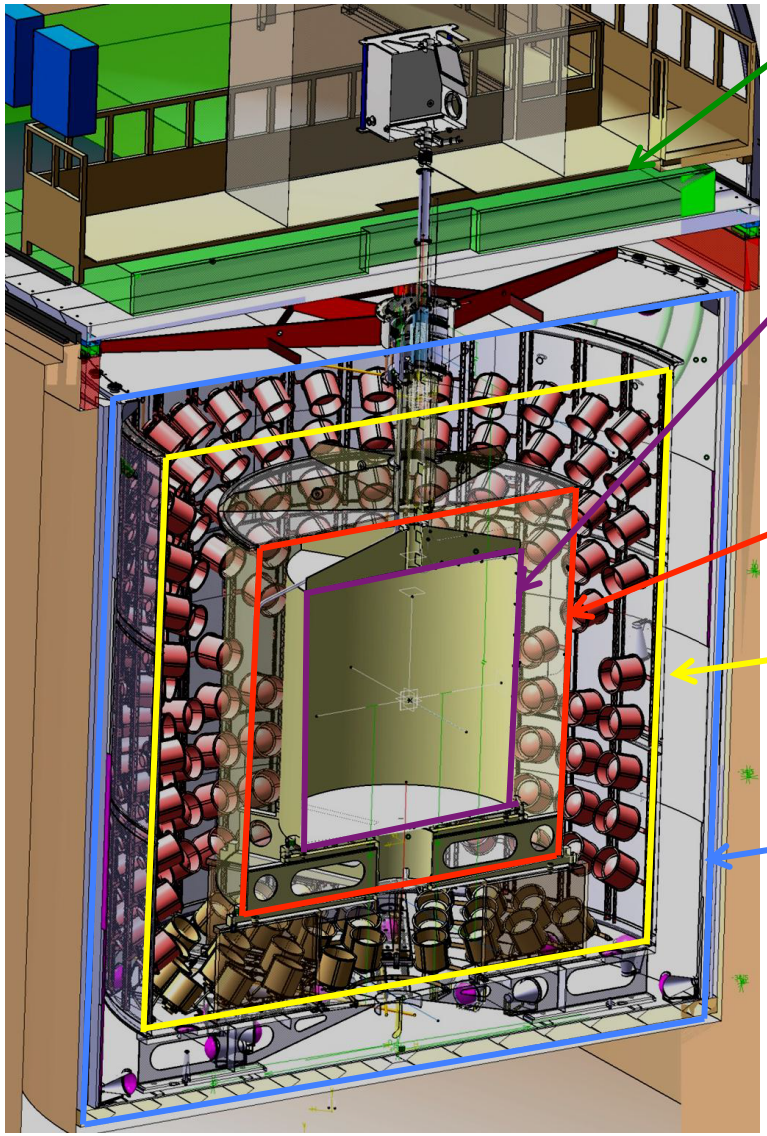


Double Chooz



- The reactor neutrino experiment at Chooz, France.
- Collaboration:
  → ~150 people from 7 countries.
  → Brazil, France, Germany, Japan, Russia, Spain and USA.
- Far detector is running since Apr/2011.
- Near detector data taking started this year.

The Double Chooz Detector



Outer veto (OV)

- Plastic scintillator strip.
- Identify cosmic μ.

Inner Detector

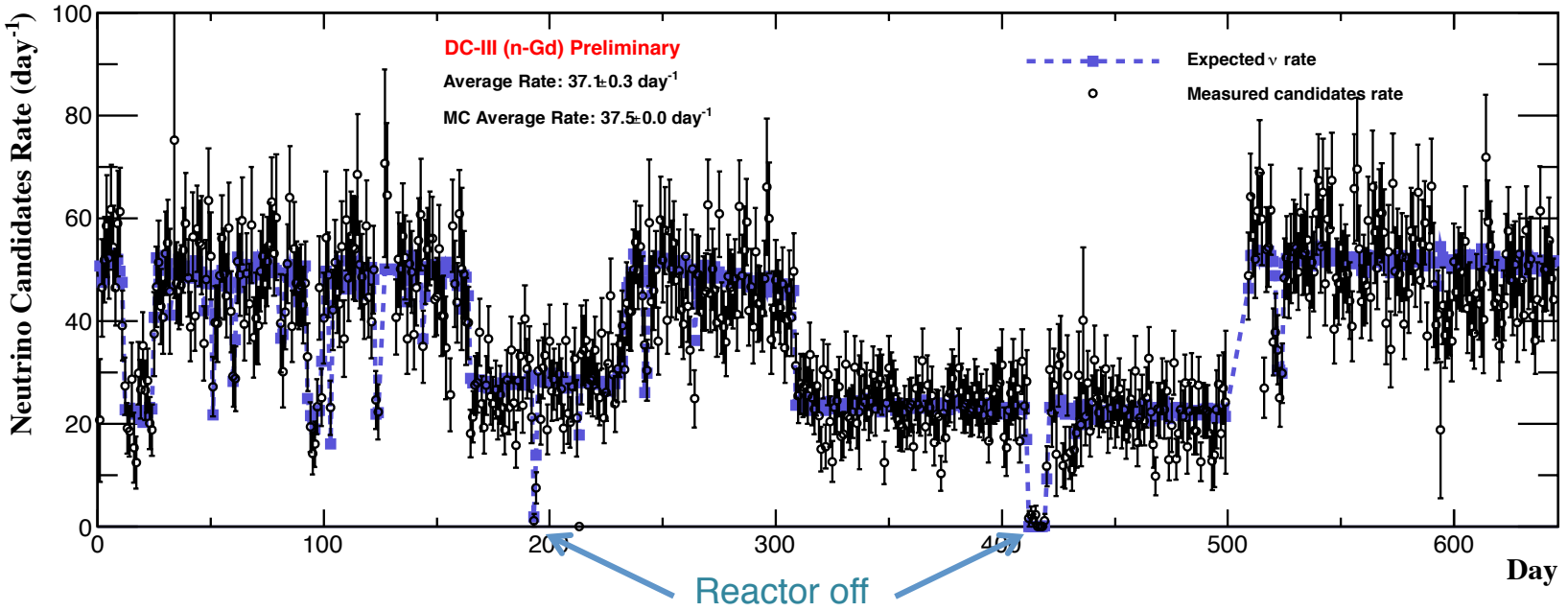
- ν-target:
  - → Gd-loaded (1 g/l) liquid scintillator (10.3m^3) in acrylic vessel.
  - → Neutrino interaction point.
- γ-catcher:
  - → Liquid scintillator (22.3m^3) in acrylic vessel.
- Buffer region:
  - → Mineral oil (110m^3) in stainless steel vessel.
  - → 390 PMTs (10”) are set in this region.

Inner veto (IV)

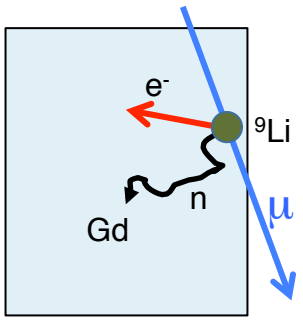
- Liquid scintillator (90m^3) with 78 PMTs (8”) in stainless steel vessel.
- Identify cosmic μ, reduce environmental γ

The Double Chooz Data

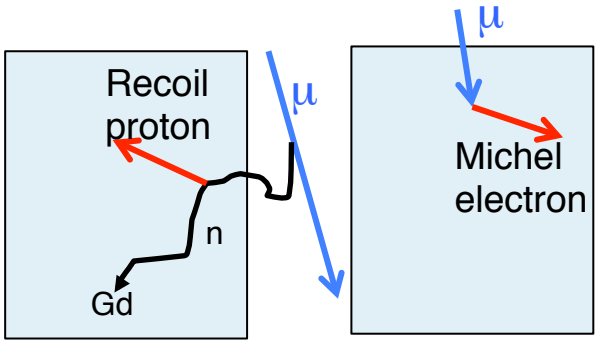
- 467.90 live days data with reactors for Gd analysis
  (Gd-III, JHEP10(2014)086).
  → Doubled events from previous result (Gd-II, PRD86(2012)052008).
  → 7.24 live days data of reactor off.
- 452.72 live days data with reactor for H analysis
  (H-III, a paper is being prepared).
  → Doubled events from previous result (H-II, PLB723(2013)66-70).
  → 7.15 live days data of reactor off.



Backgrounds



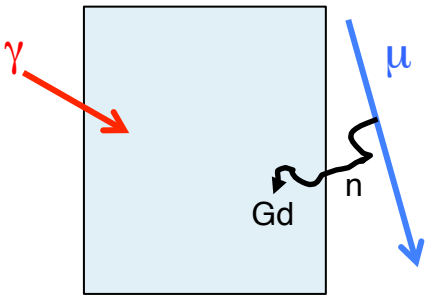
Cosmogenetic



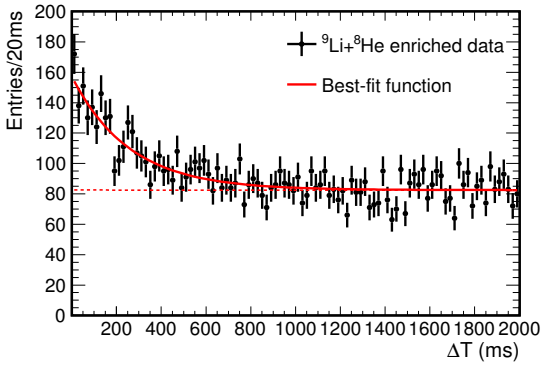
Fast neutron

Stopping μ

Correlated

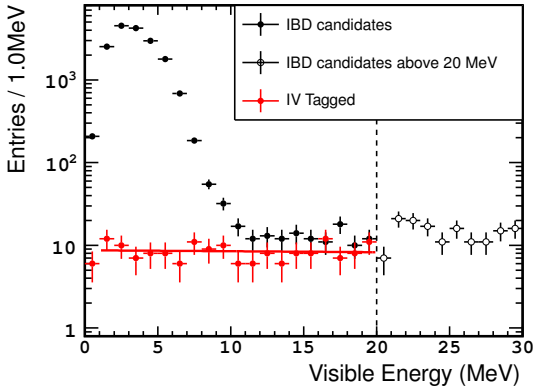


Accidental



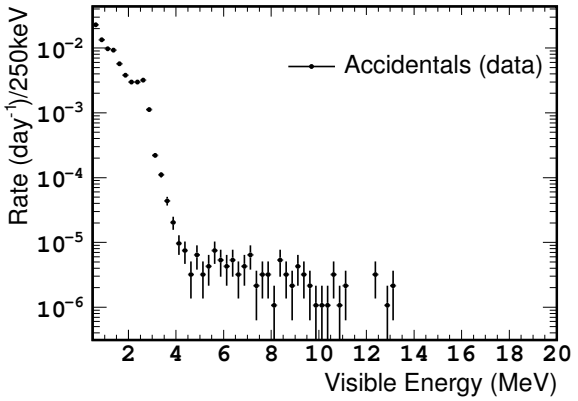
Estimated by ^{9}Li enriched data

Rate: $0.97^{+0.41}_{-0.16}$ (day^{-1})



Estimated by IV-tagged data

Rate: 0.604±0.051(day^{-1})



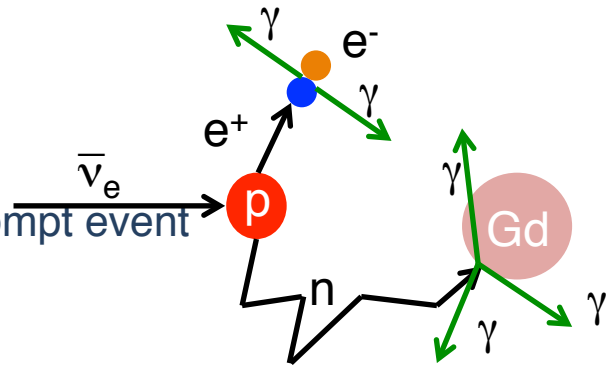
Estimated by the off-time window data

Rate: 0.070±0.003 (day^{-1})

Estimation for Gd analysis

Gadolinium Analysis

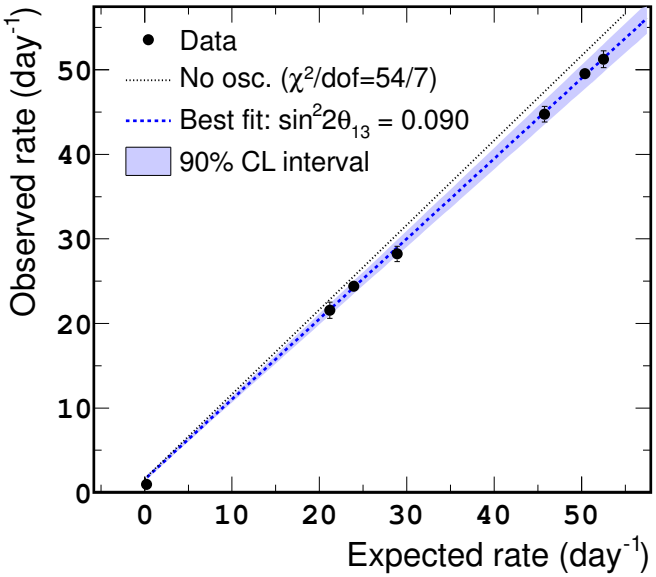
- Single event selection
  - → Veto 1ms after μ event (high energy event).
  - → Light noise event rejection.
- IBD selection
  - → $0.5 < E_{prompt} < 20$ MeV, $4 < E_{delayed} < 10$ MeV
  - → $0.5 < \Delta T < 150$ μs, $\Delta R < 100$ cm
  - → No events within 200 μs before and 600 μs after prompt event
  - → No OV hit
  - → IV-veto: for fast neutron, accidental events
  - → FV veto (vertex reconstruction goodness): for stopping μ events
  - → ^{9}Li likelihood method veto (likelihood made by ^{12}B data): for cosmogenetic events

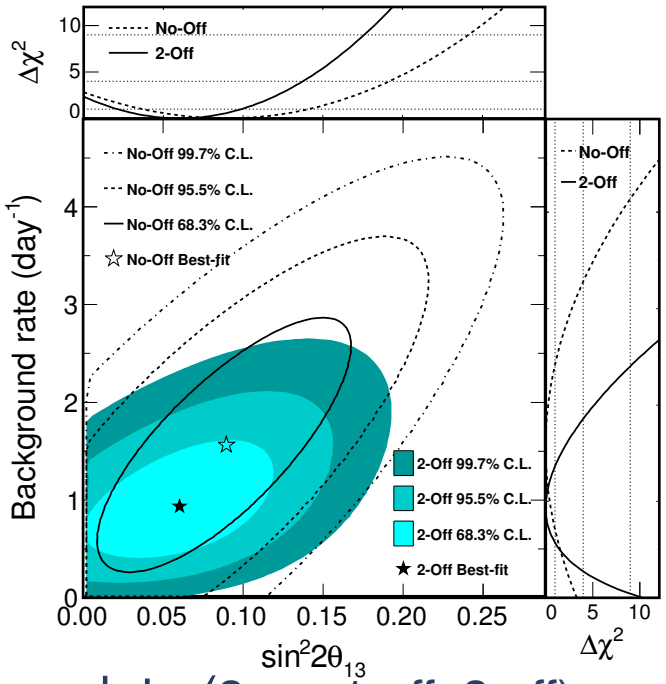


	Reactor On	Reactor Off
Live-time	460.67	7.24
IBD Candidate	17351	7
Reactor $\bar{\nu}_e$	17530±320	1.57±0.47
^{9}Li/^{8}He	447^{+189}_{-74}	$7.0^{+3.0}_{-1.2}$
Correlated	278±23	3.83±0.64
Accidental	32.3±1.2	0.508±0.019
Total	18290^{+370}_{-330}	$12.9^{+3.1}_{-1.4}$

	Uncertainty(%)	Gd-III/Gd-II
Reactor flux	1.7	1.0
Detection efficiency	0.6	0.6
^{9}Li/^{8}He	+1.1/-0.4	0.5
Correlated	0.1	0.2
Accidental	<0.1	-
Statistics	0.8	0.7
Total	+2.3/-2.0	0.8

Reactor Rate Modulation Analysis





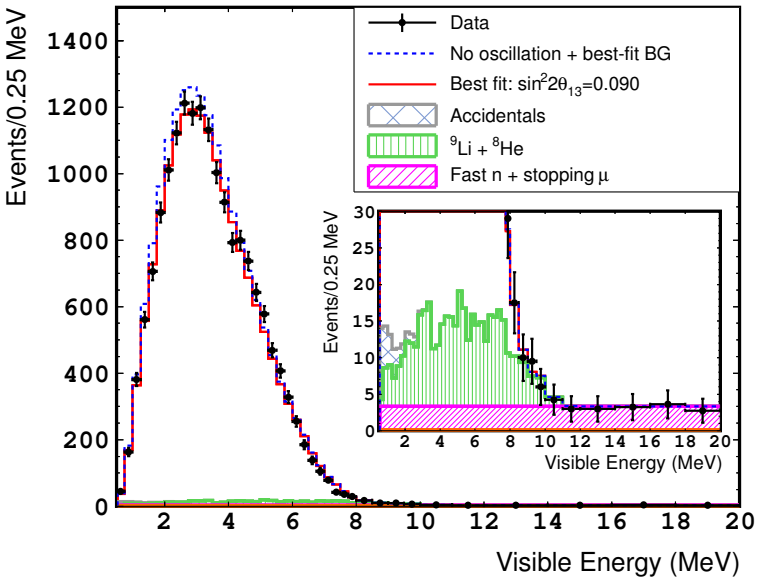
- Fit the IBD rate of different reactor power data (2-on, 1-off, 2-off)

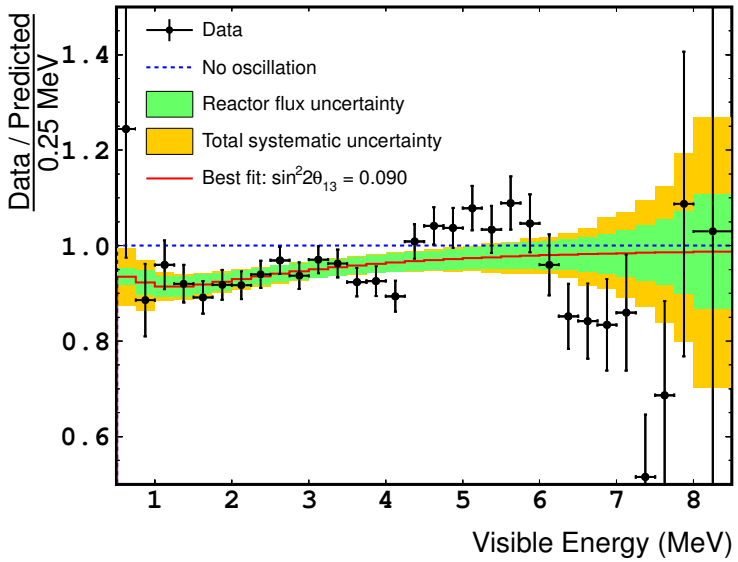
$$R^{obs} = \left(1 - \sin^2(2\theta_{13}) \sin^2\left(\frac{\Delta m^2_{13} L}{4E}\right)\right) R^{IBD} + B$$

- w/ background constraint with 2-off data:
  - $\sin^2(2\theta_{13}) = 0.090^{+0.034}_{-0.035}$, $B = 1.56^{+0.18}_{-0.16}$ (day^{-1})
- Background model independent fit (no constraint on B, unique of DC):

  → $\sin^2(2\theta_{13}) = 0.060 \pm 0.039$, $B = 0.93^{+0.43}_{-0.36}$ (day^{-1})

Rate + Shape Analysis

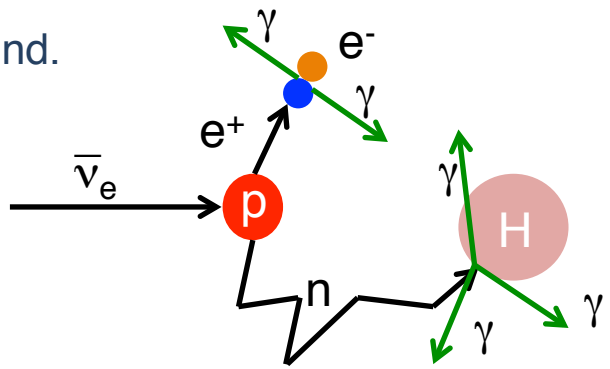




- $\sin^2(2\theta_{13})=0.090^{+0.032}_{-0.029}$
  - → χ^2/ndf = 52.2/40
  - → Background rate = 1.38±0.14 (day^{-1})
  - → 5.3% improvement of precision from Gd-II.

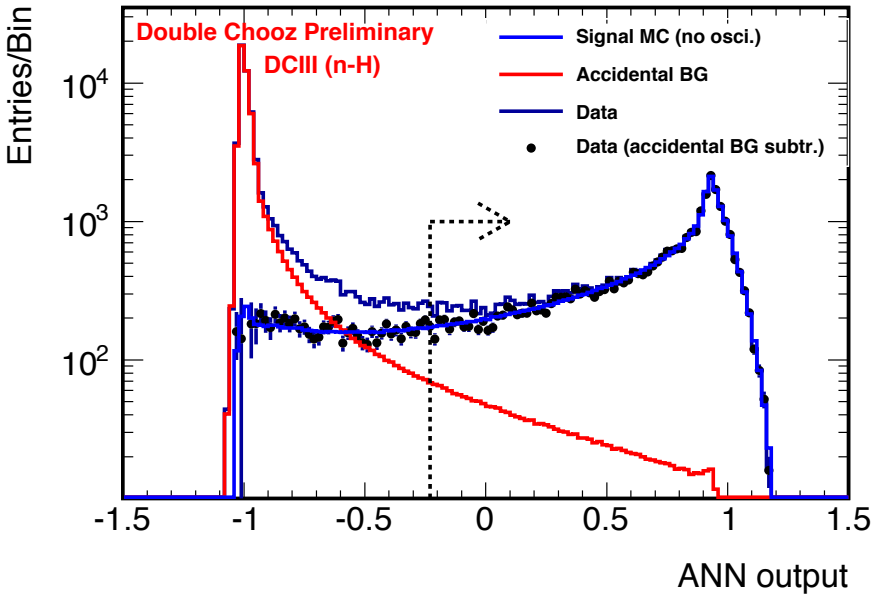
Hydrogen Analysis

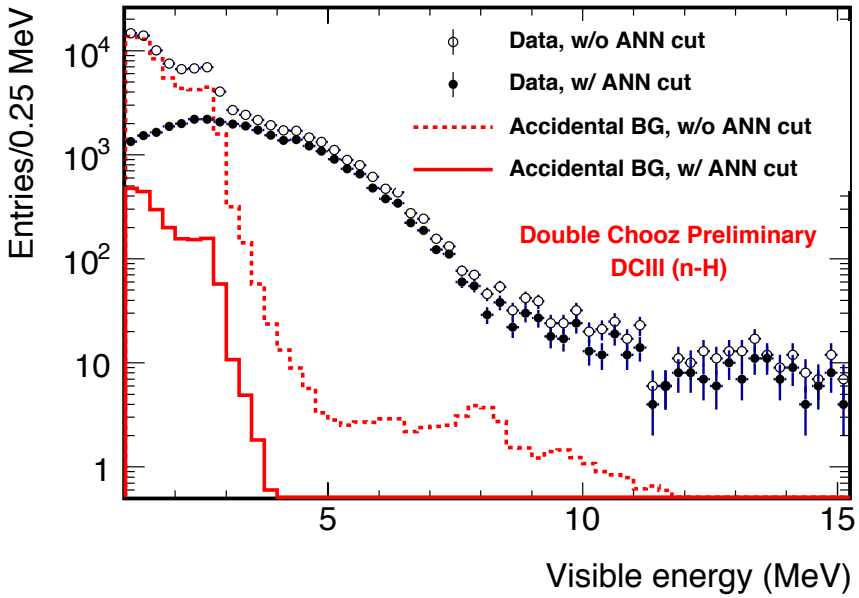
- Compared to Gd analysis
  - → Higher statistics
    - → Events in GC can be used, too.
  - → Lower delayed energy and longer ΔT of prompt-delayed events.
    - → More background.
    - → A dominant background is the accidental background.



- Single event selection
  - → Veto 1.25ms after μ event (high energy event).
  - → Light noise event rejection.
- IBD selection
  - → $1.0 < E_{prompt} < 20$ MeV
  - → $1.3 < E_{delayed} < 3$ MeV
  - → $0.5 < \Delta T < 800$ μs
  - → $\Delta R < 1200$ cm
    - → They are loose selections, and variables are used in ANN.
  - → No events within 800 μs before and 900 μs after prompt event
  - → No OV hit is required, FV veto, ^{9}Li likelihood veto, IV-veto
  - → Artificial Neural Network, Multiplicity Pulse Shape Veto (using flash-ADC information)
    - → New for H-III analysis

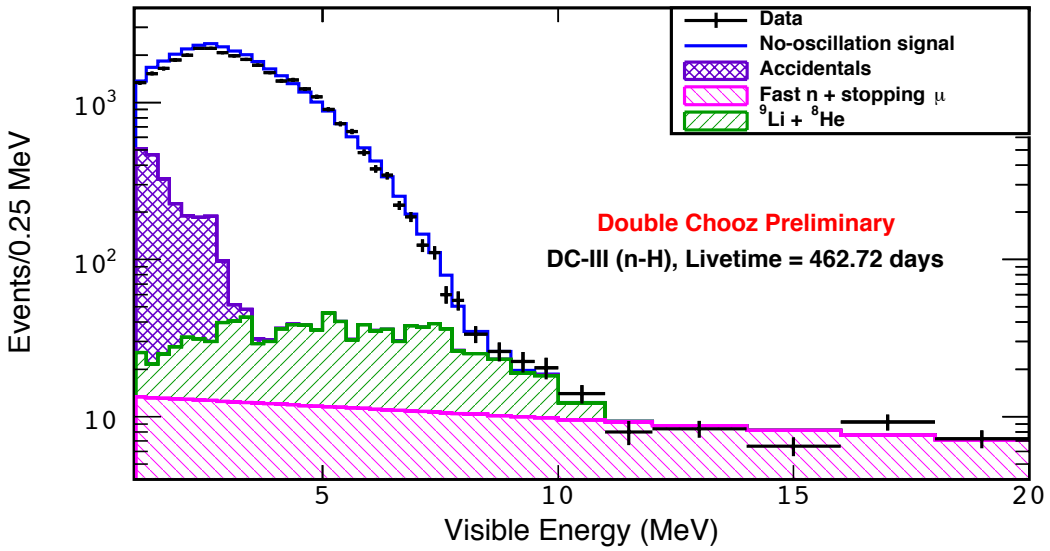
Artificial Neural Network (ANN)





- New multiple variable analysis was deployed.
  →Input variables: $E_{delayed}$, ΔT, ΔR
- Background reduction:
  →H-II (cut based): 73.45 ± 0.16 (day^{-1})
  →H-III (ANN): 4.334 ± 0.011 (day^{-1})

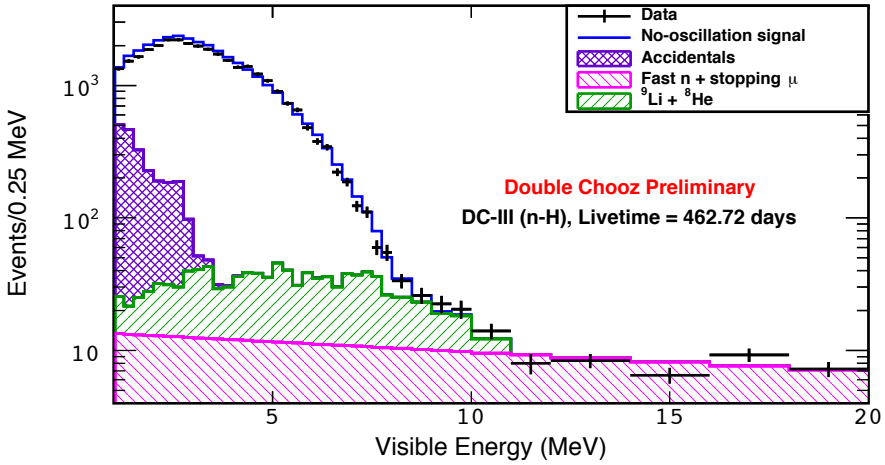
DC-III (n-H) data summary

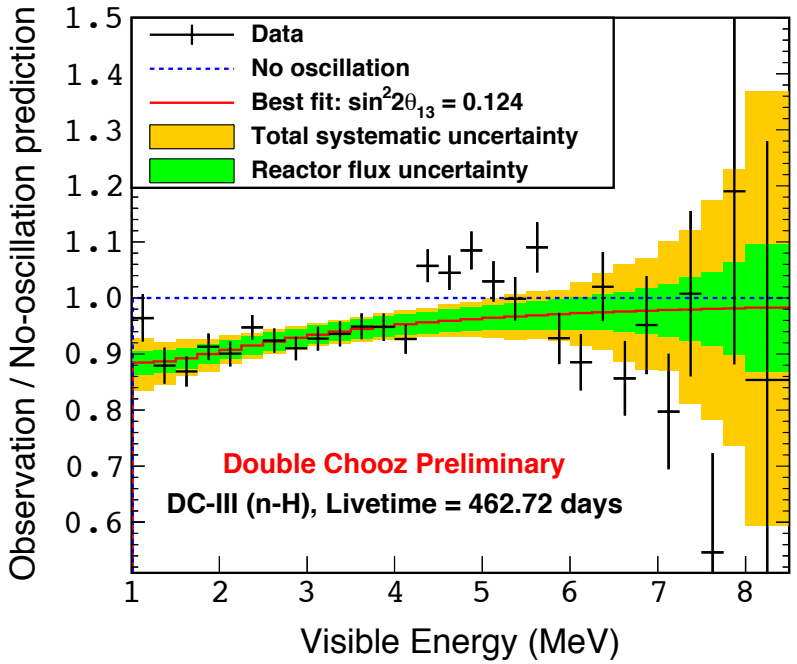


	Reactor On	Reactor Off
Live-time	455.57	7.15
IBD Candidate	31835	63
Reactor ν_e	30086±606	2.34±0.70
^{9}Li/^{8}He	433^{+260}_{-150}	$6.8^{+4.1}_{-2.4}$
Correlated	706±68	10.4±1.4
Accidental	1974.4±4.8	30.9±0.4
Total	33199^{+660}_{-630}	$50.4^{+4.4}_{-2.9}$

	Uncertainty(%)	H-III/H-II
Reactor flux	1.7	1.0
Detection efficiency	1.0	0.6
^{9}Li/^{8}He	+0.9/-0.5	0.6/0.3
Correlated	0.2	0.3
Accidental	<0.1	(0.2 at H-II)
Statistics	0.6	0.5
Total	+2.3/-2.1	0.7

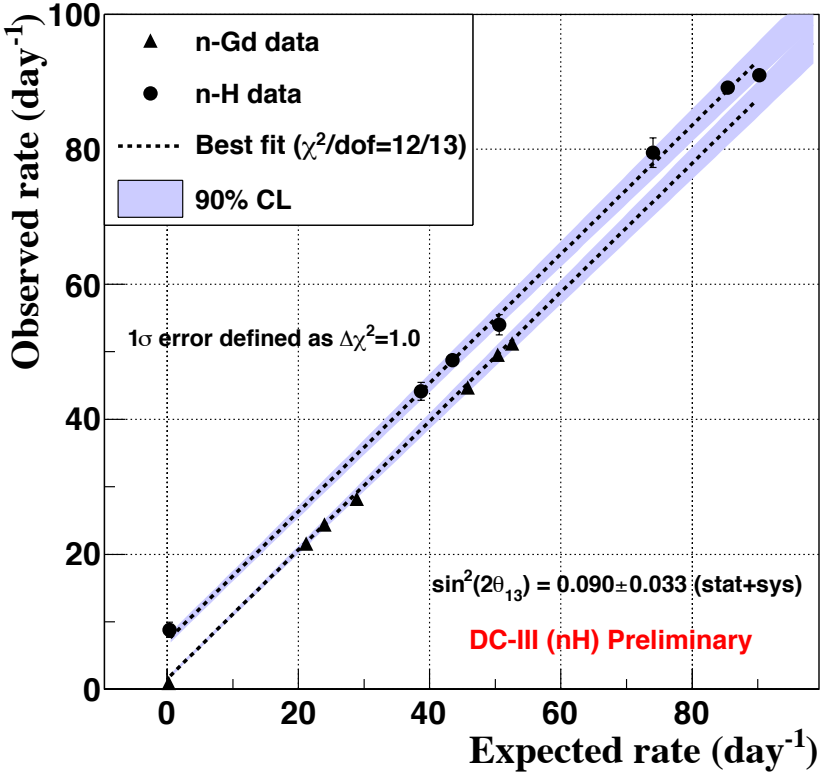
H-III Rate + Shape Analysis

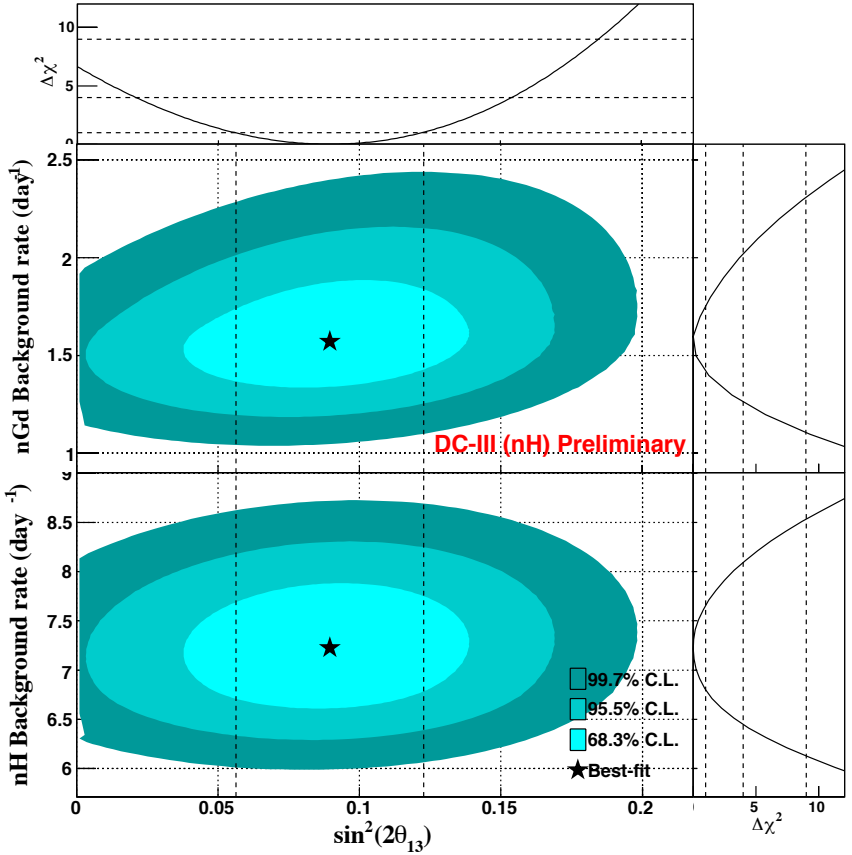




- $\sin^2(2\theta_{13})=0.124^{+0.030}_{-0.039}$
  - → H-II: $\sin^2(2\theta_{13})=0.097\pm0.048$
  - → Gd-III: $\sin^2(2\theta_{13})=0.090^{+0.032}_{-0.029}$

H+Gd Reactor Rate Modulation Analysis



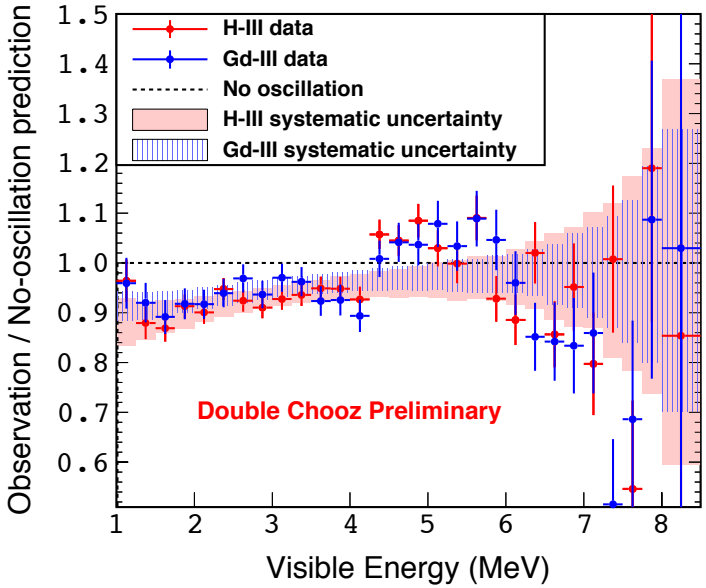


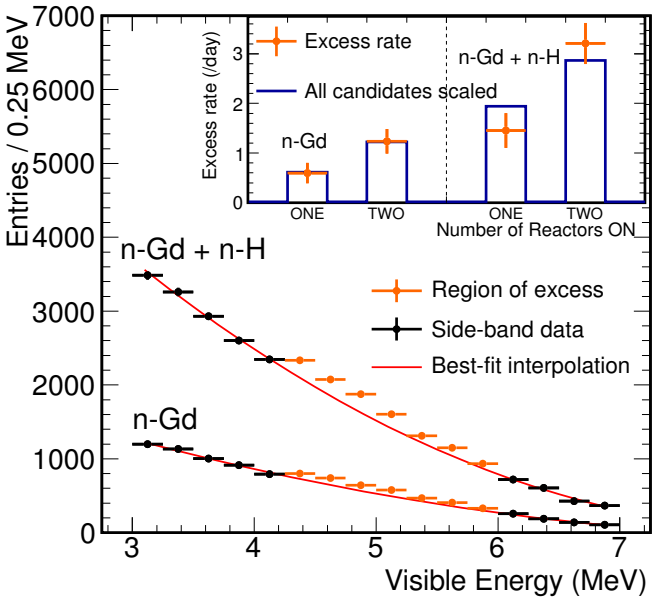
RRM analysis with background model using H+Gd data

- $\sin^2(2\theta_{13})=0.090\pm0.033$
  - → H-only: $\sin^2(2\theta_{13})=0.098^{+0.038}_{-0.039}$
  - → Gd-III: $\sin^2(2\theta_{13})=0.090^{+0.034}_{-0.035}$

No correlation between H-Gd is assumed. (It is minimal impact.)

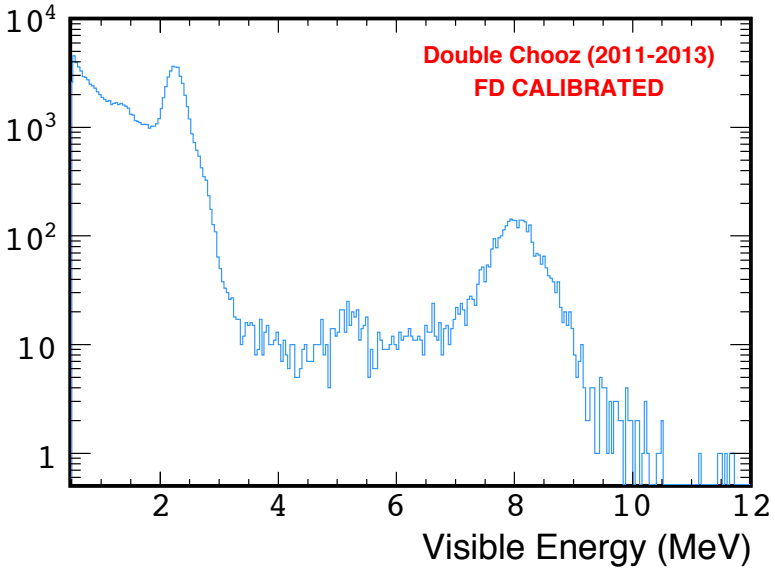
Unexpected Spectrum Distortion

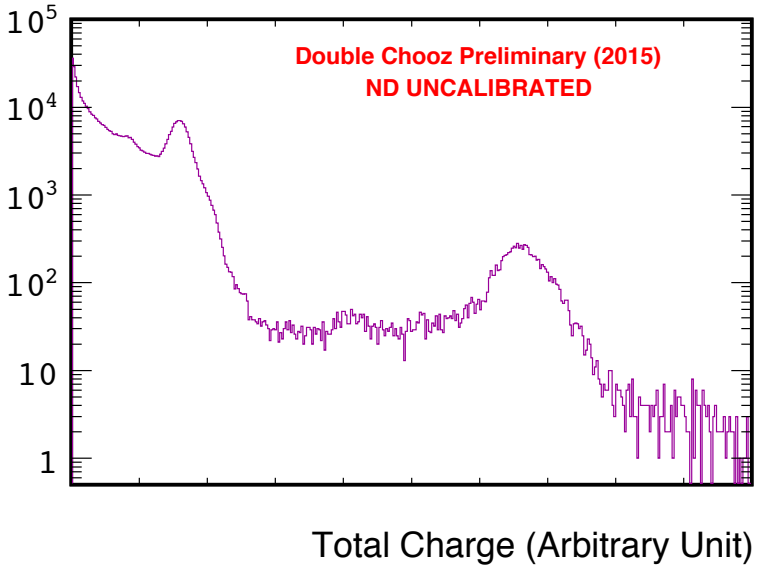


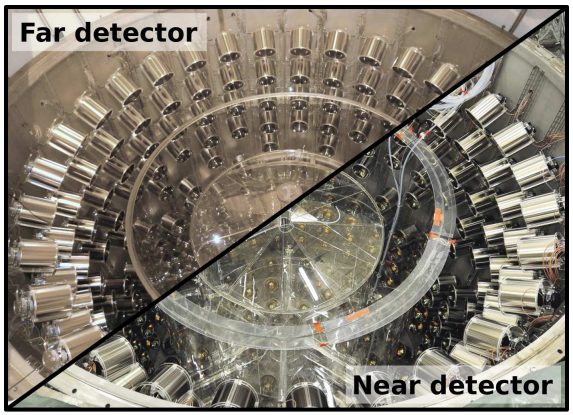


- Unexpected spectrum distortion is found above 4 MeV of the prompt energy.
  → Similar distortions are seen in both Gd and H analyses.
- Energy scale around 5 MeV is confirmed by Carbon capture events.
- No correlation with any backgrounds is found.
- Strong correlation with the reactor power is confirmed.
- The effect on θ_{13} measurement is insignificant compared to the uncertainty.

Near Detector Prospect





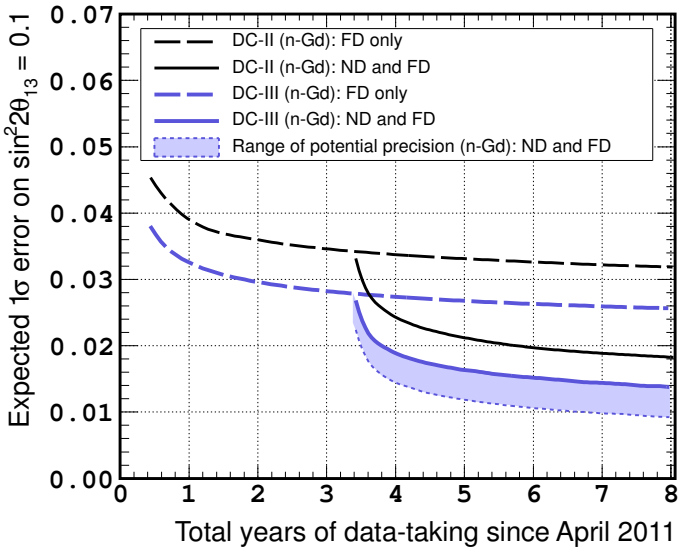


- Spallation neutron capture spectrum of early ND data compared to FD data.
  - → Similar spectrums can be seen:
  - → Indicate feasibility of IBD measurement.
  - → Radiopurity is well controlled.
  - → Shielding works as expected.
- 0.01~0.015 uncertainty of $\sin^2(2\theta_{13})$ is expected in 3 years.

Summary and Prospect

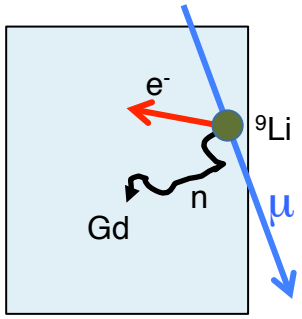
- Gd result:
  - → Reactor Rate Modulation: $\sin^2(2\theta_{13})=0.090^{+0.034}_{-0.035}$
  - → Rate+Shape: $\sin^2(2\theta_{13})=0.090^{+0.032}_{-0.029}$
- Gd+H combined result:
  - → Reactor Rate Modulation: $\sin^2(2\theta_{13})=0.090\pm0.033$

- Data taking with Near detector is on going.
  - → Drastic reduction of the systematic uncertainty is expected.
  - → Additional physics results (e.g. sterile neutrino) will come, too.



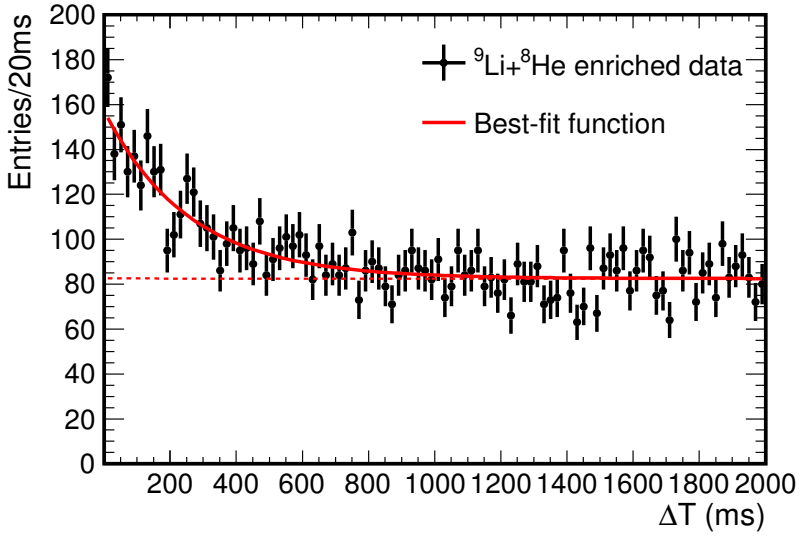
Back Up

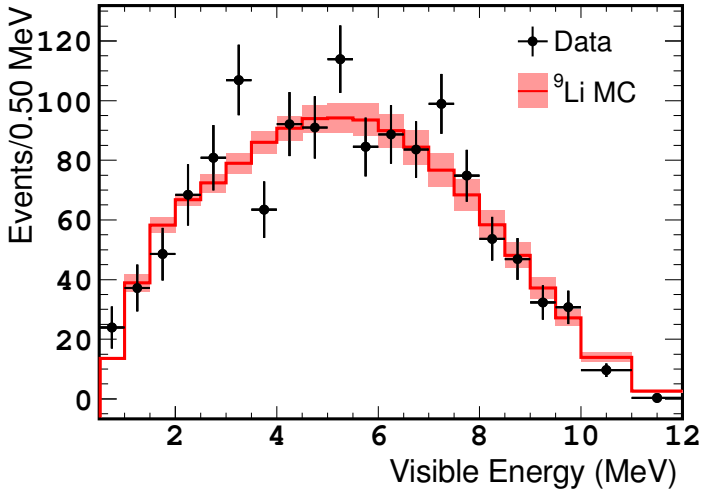
Backgrounds: ^{9}Li/^{8}He (Gd-III)



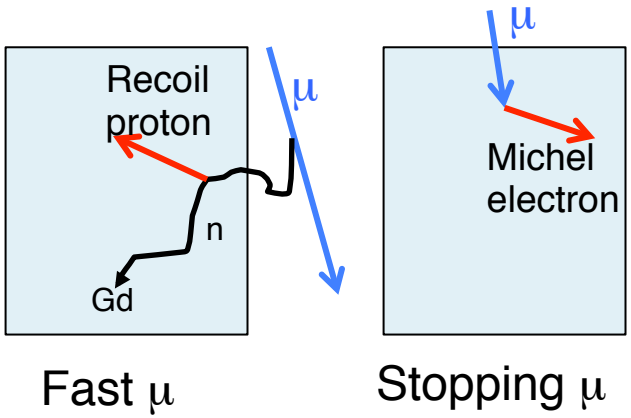
- Rejected by:
  → Likelihood veto (new).
- Measured by ^{9}Li enriched data.
  → ΔT for rate.
  → Visible energy for shape.

- Rate: $0.97^{+0.41}_{-0.16}$ (day^{-1})
  → DC-III/DC-II = 0.78



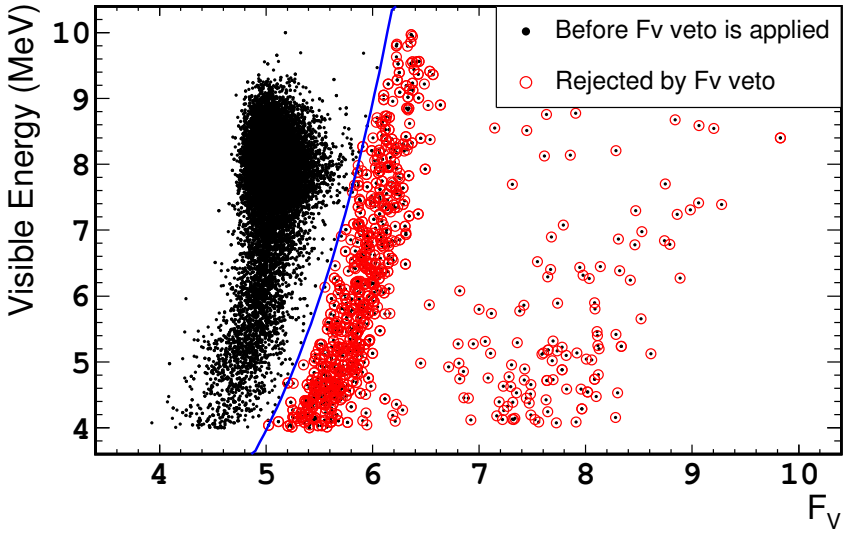


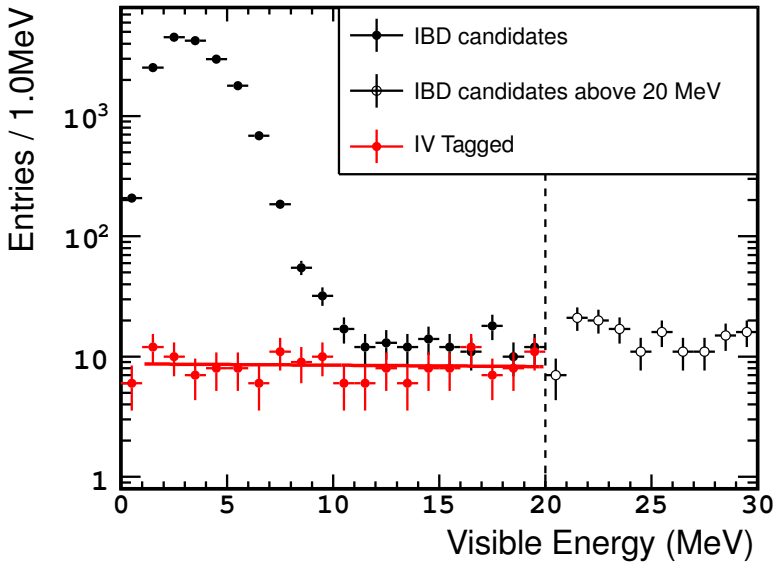
Backgrounds: Correlated Backgrounds (Gd-III)



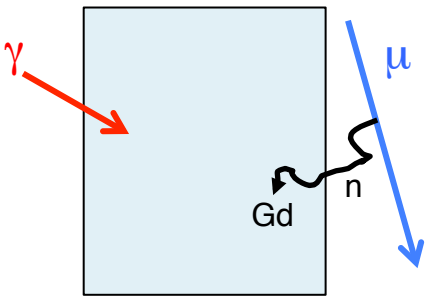
- Rejected by:
  → Vertex reconstruction goodness(F_v) (new).
  → OV cut, IV vetos.
- Measured by IV-tagged events.

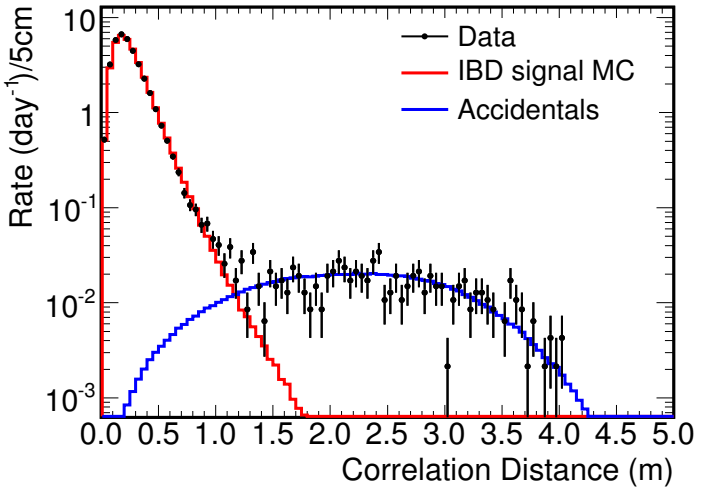
- Rate: 0.604±0.051(day^{-1})
  → DC-III/DC-II = 0.52





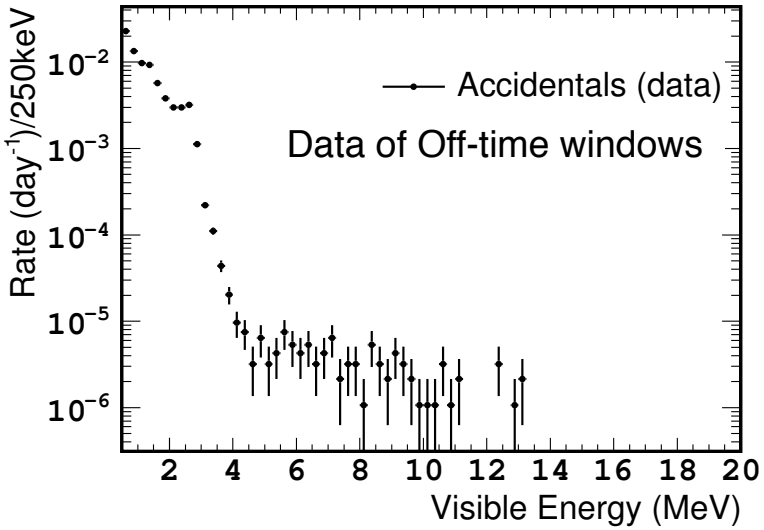
Backgrounds: Accidental Coincidences (Gd-III)



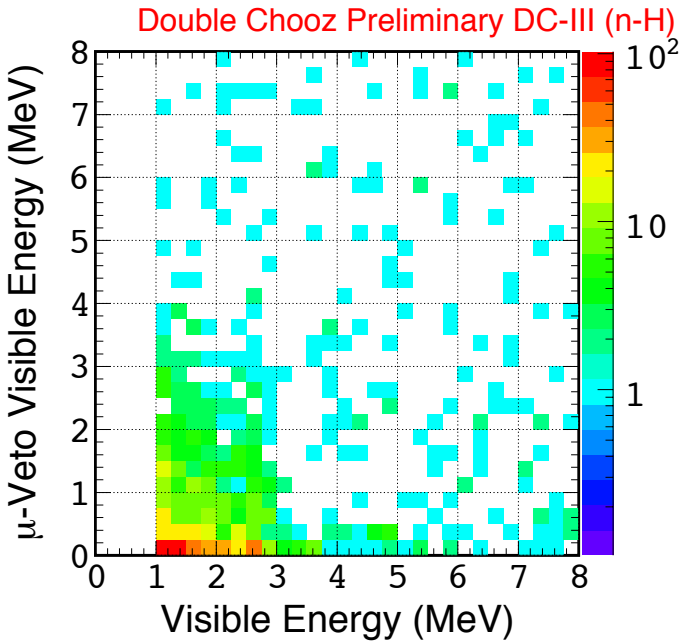


- Rejected by:
  → Correlation distance cut (new).
  → Timing cut.
- Measured by the data in off-time windows.

- Rate: 0.070±0.003 (day^{-1})
  → DC-III/DC-II = 0.27



IV veto



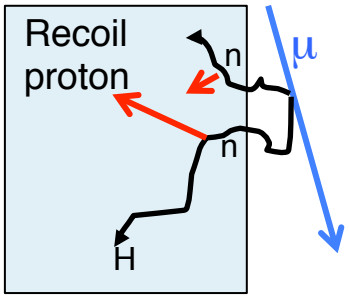
- Energy correlation between ID and IV prompt energy for rejected events by IV-veto.

  →Lower rich region is dominated by compton gammas (mainly Thallium).

  →Others are correlated background.

- ~25% of accidental BG is rejected after ANN.

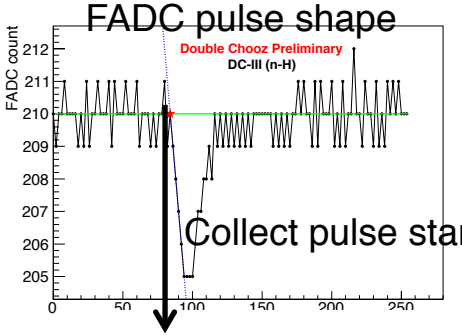
Multiplicity Pulse Shape Veto (MPS) (H-III)



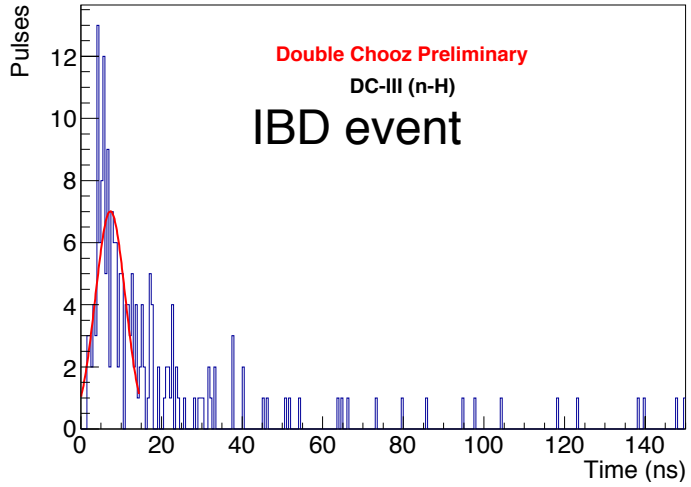
Fast neutron

- Fast neutron background:
  - → Recoiled proton acts as the prompt signal.
  - → Additional proton recoil can happen and it makes additional pulses.
    - → Can be seen in flash-ADC information.
    - → Reject if the time shift > 5ns.
  - → 25 % of fast neutron events are rejected.

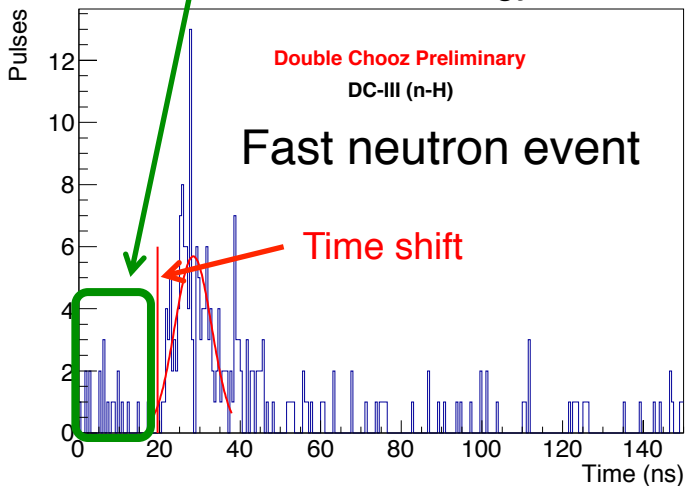
FADC pulse shape



Collect pulse starting time from all PMTs



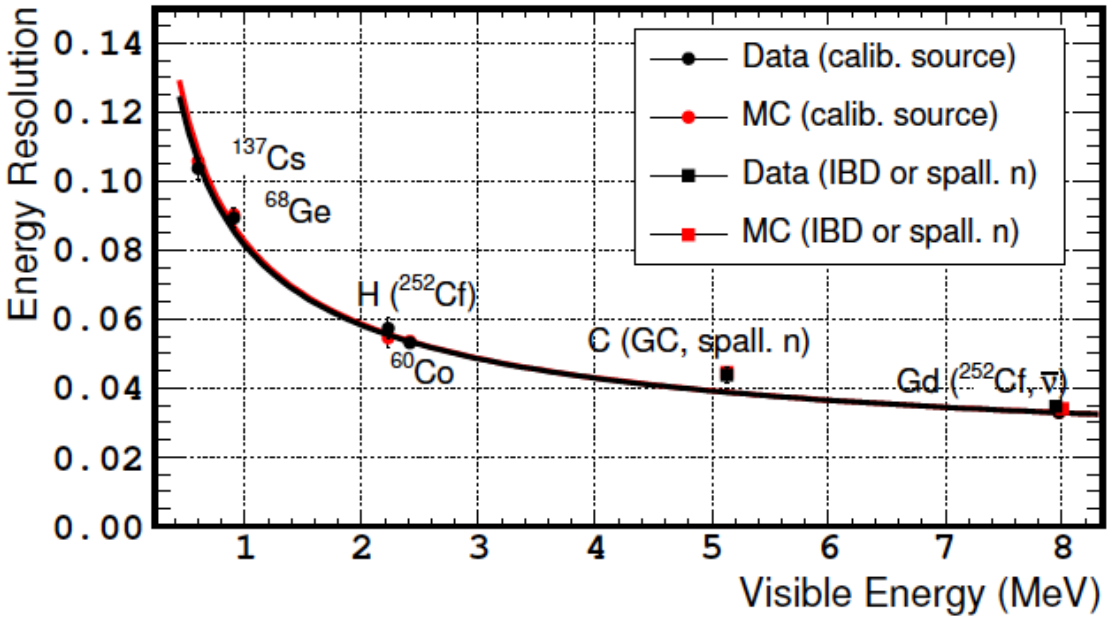
Additional low energy event



Energy calibration improvement

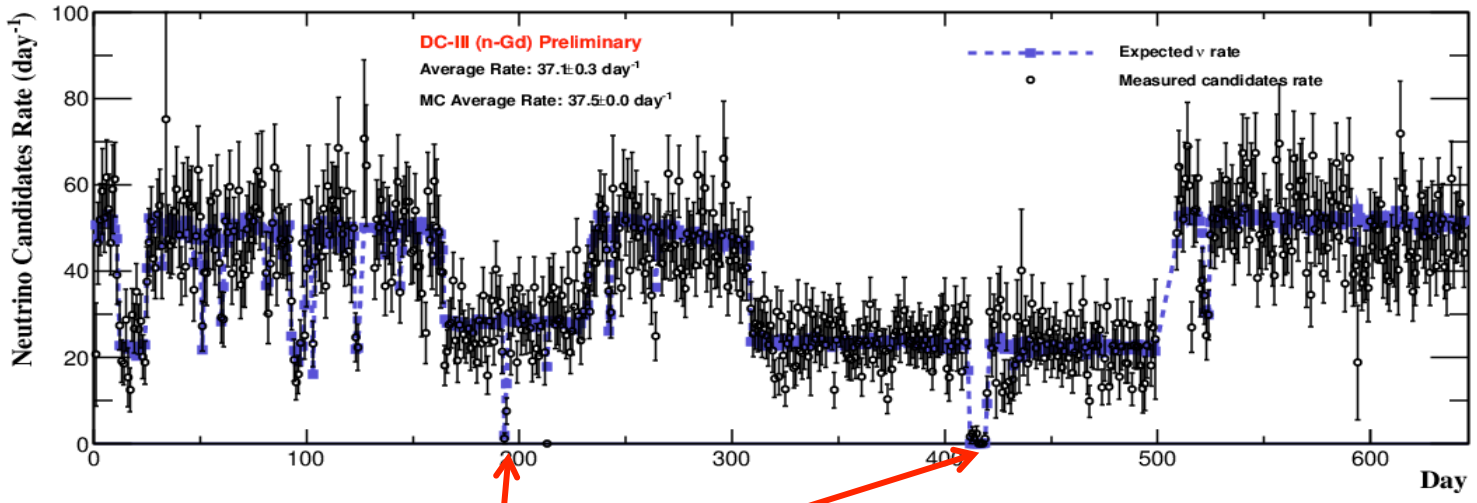
Systematic uncertainties on energy scale

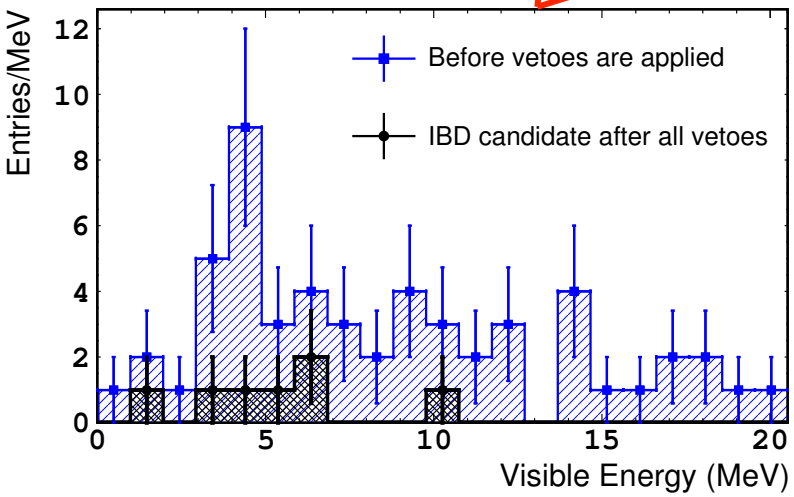
Source	Uncertainty (%)	Gd-III/Gd-II
Non-uniformity	0.36	0.84
Instability	0.50	0.82
Non-linearity	0.35	0.41
Total	0.74	0.65



Data-MC energy comparison

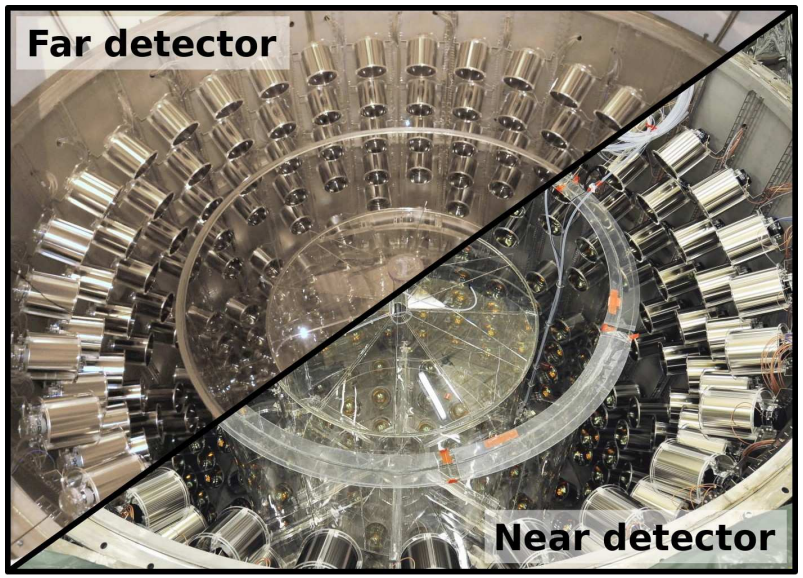
Reactor Off Data





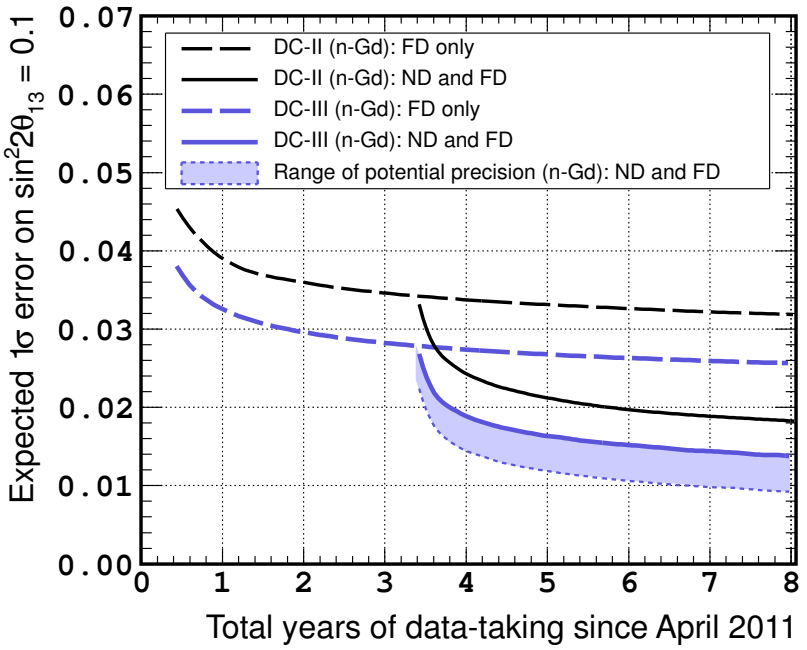
- 7.24 days data with both two reactors off.
- 7 events after all selections.
  → Expected: $12.9^{+3.1}_{-1.4}$
- Reactor off data are used to constrain the total background rate.

Near Detector Prospect

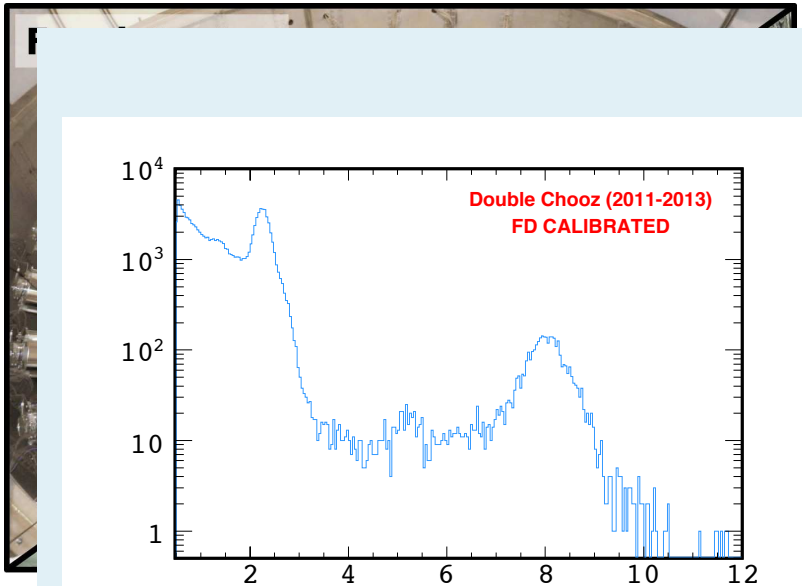


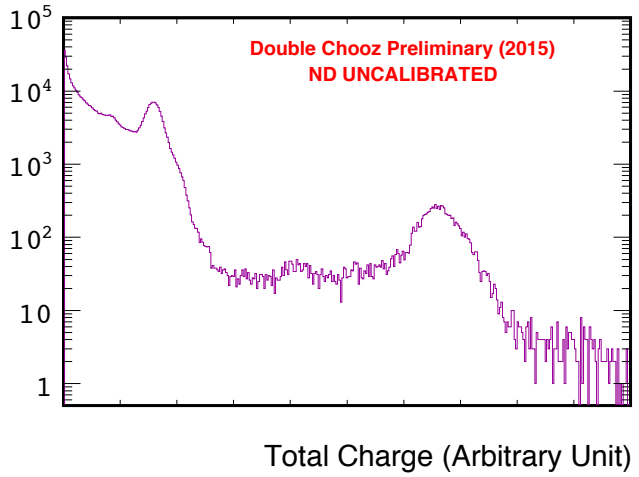
- Construction (w/o OV) was finished in the last Autumn.
- Commissioning was done and now it is starting data taking.
- New results with ND are coming soon.

- ND flux information can suppress current largest uncertainty of the reactor flux.
- 0.01~0.015 uncertainty of $\sin^2(2\theta_{13})$ is expected in 3 years.
- In addition, new analyses such sterile neutrino search can be studied.



Near Detector Prospect





- Spallation neutron capture spectrum of early ND data compared to FD data.
- Similar spectrums can be seen:
  - Indicate feasibility of IBD measurement.
  - Radiopurity is well controlled.
  - Shielding works as expected.