Θ_{13} measurement in reactor antineutrino experiments

Guang Yang (PhD student)
Argonne National Lab
Illinois Institute of Technology

ANL HEP Young Scientist Symposium
Feb.16, 2016

Facts of the Neutrinos

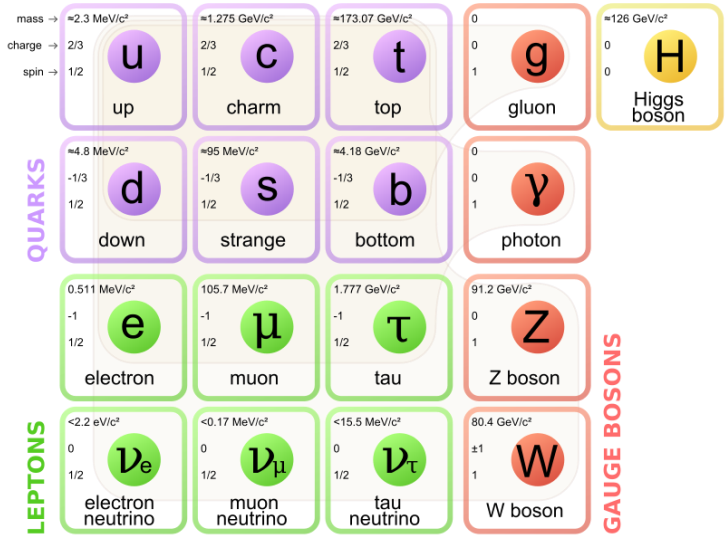
- Pauli proposed the existence of neutrino in 1930.

- Neutrino is the most abundant particle in the universe but extremely hard to detect.

- Neutrinos participate in weak interaction.

- So far, three generations of neutrinos are detected.

- Only left handed neutrinos and right handed antineutrinos are found.



- Neutrinos originate in certain types of radioactive decay or nuclear reactions such as those that take place in the Sun, in nuclear reactors, in particle accelerators, and relic neutrinos in the universe or when cosmic rays hit atoms.

Neutrino Oscillation

-Ray Davis' Homestake Experiment found that neutrinos from the sun have measured rate ~ 1/3 of expectation rate. An explanation: Neutrinos are massive and they can oscillate with large mixing angle.

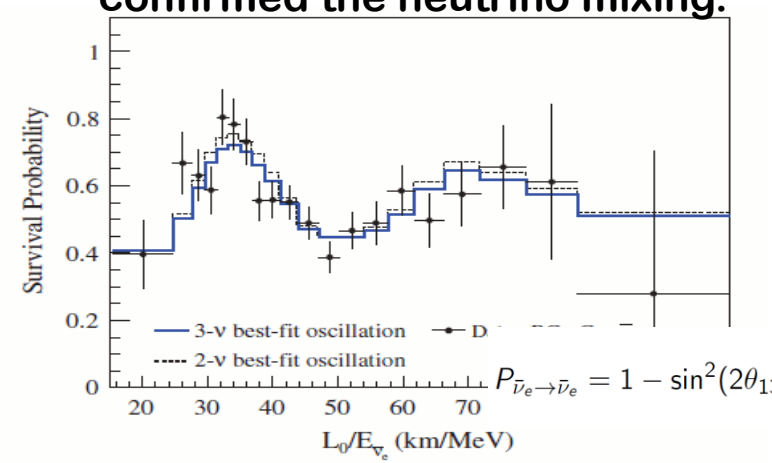
- The neutrino mixing among the 3 flavors is :

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = U^{PMNS} \times \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix} =$$

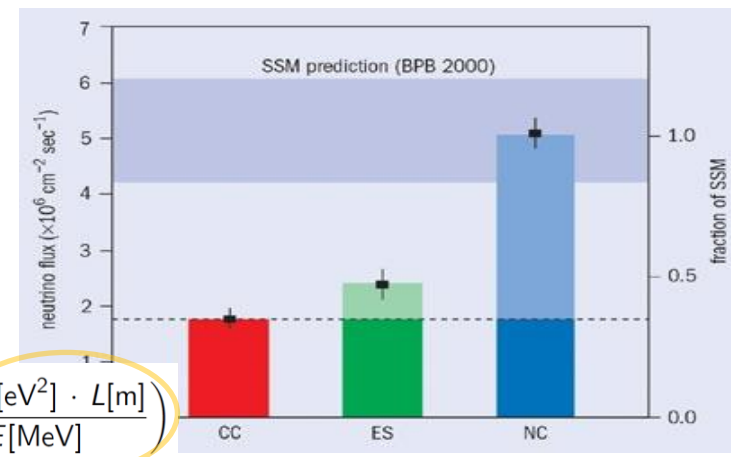
$$\begin{pmatrix} c_{12}c_{13} & s_{12}s_{13} & s_{13}e^{-i\delta_{CP}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{CP}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{CP}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{CP}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{CP}} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

-Neutrinos propagate in mass state but interact in flavor state.

-SNO experiment demonstrated the neutrino oscillation and KamLAND confirmed the neutrino mixing.



$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \sin^2(2\theta_{13})\sin^2\left(1.27\frac{\Delta m^2_{13}[\mathrm{eV}^2]\cdot L[\mathrm{m}]}{E[\mathrm{MeV}]}\right)$$



Neutrino Oscillation

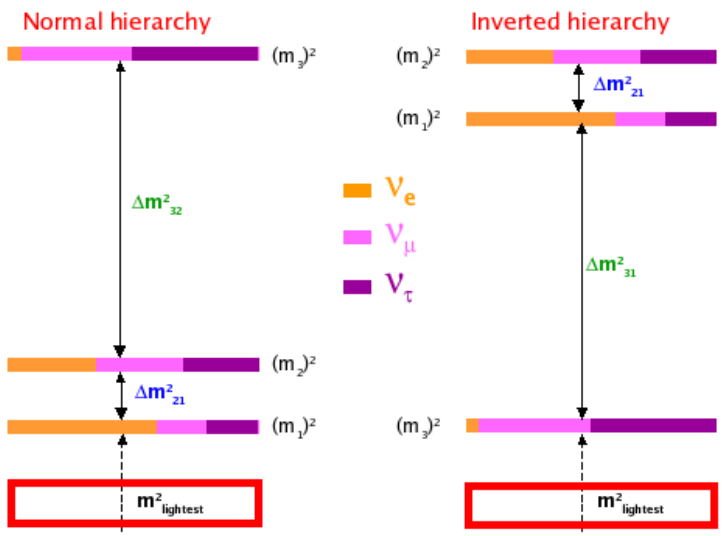
- Neutrino mixing can be parameterized by PMNS matrix.
- PNMS matrix can be broken down into three 3×3 matrices:

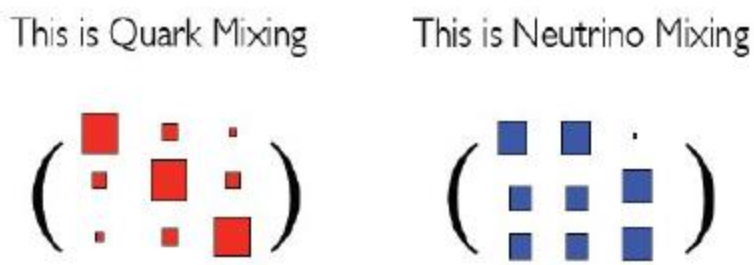
$$(c_{ij} \equiv \cos\theta_{ij}, \quad s_{ij} \equiv \sin\theta_{ij})$$

$$U = \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}\cdot e^{i\delta} \\ & 1 & \\ -s_{13}\cdot e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} 1 & & \\ & e^{i\alpha} & \\ & & e^{i\beta} \end{pmatrix}$$

Solar | Atmospheric Reactor | Atmospheric | Majorana Phases only 0ν ®®

- Each mixing angle related to a mass splitting between the two mass states.





Different neutrino experiments

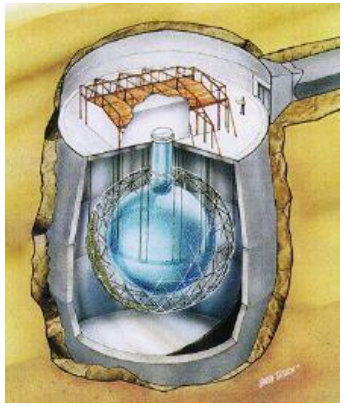
Solar: BOREXINO, SNO…

Atmospheric: Super-K…

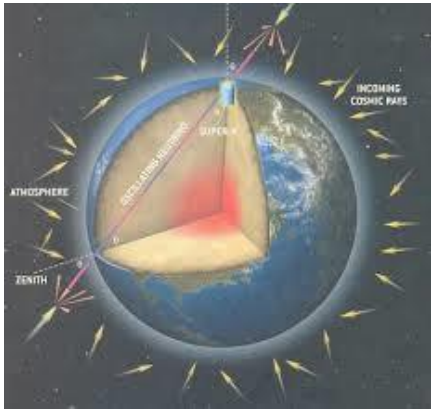
Accelerator: MINOS, NOvA, T2K…

Reactor: Daya Bay, Double Chooz, RENO, KamLAND…

Cosmic: IceCube…



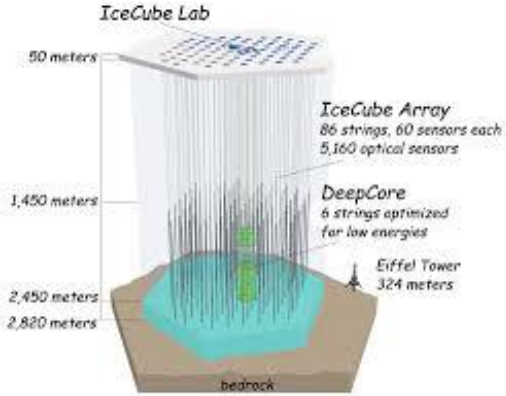
SNO ($\nu_e \rightarrow \nu_{\mu,\tau}$)



Super-K($\nu_\mu \rightarrow \nu_\tau$)

NOvA

Daya Bay ($\bar{\nu}_e \rightarrow \bar{\nu}_e$)



IceCube

Open questions

- Is the neutrino mass hierarchy normal or inverted?
  - We do know the sign of Δm_{21}^2 but do not know the sign of Δm_{31}^2.
  - Several experiments including NOvA, JUNO, PINGU might measure the mass hierarchy and DUNE will for sure.

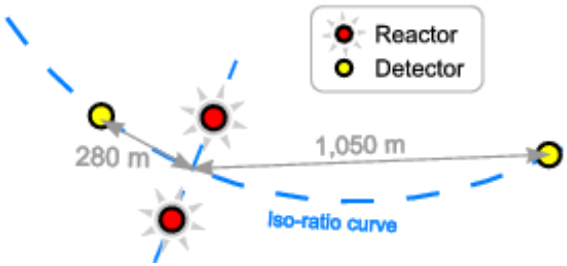
- Is there a CP-violation in neutrino sector?
  - With a non-zero Θ_{13}, one has the possibility to measure the CP-violation phase by comparing the difference in neutrino and antineutrino appearance probabilities.

- Is neutrino Majorana or Dirac particle?
  - Neutrinoless double beta decay

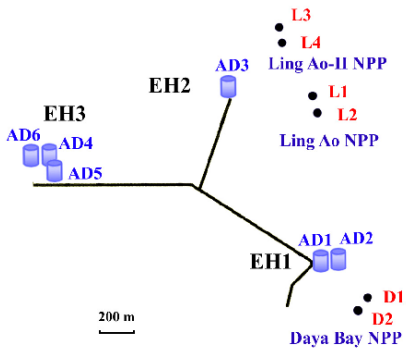
- Are there sterile neutrinos?
  - See-saw mechanism

θ_{13} reactor measurement

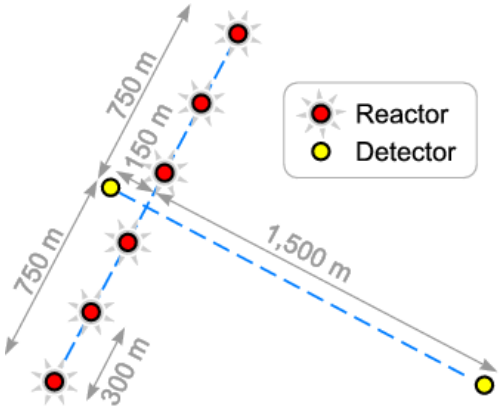
Double Chooz

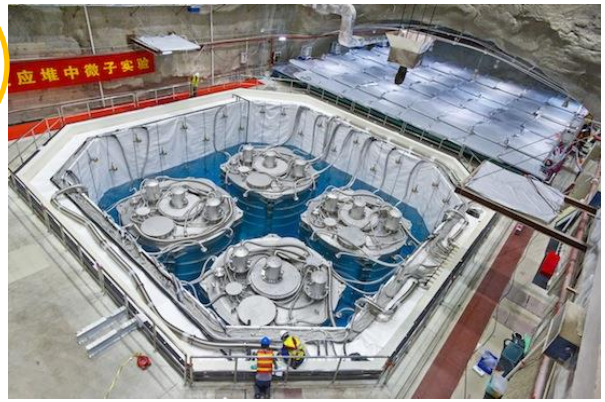


Daya Bay



RENO





Double Chooz Collaboration







Brazil
CBPF
UNICAMP
UFABC

France
APC
CEA/DSM/IRF
U:
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

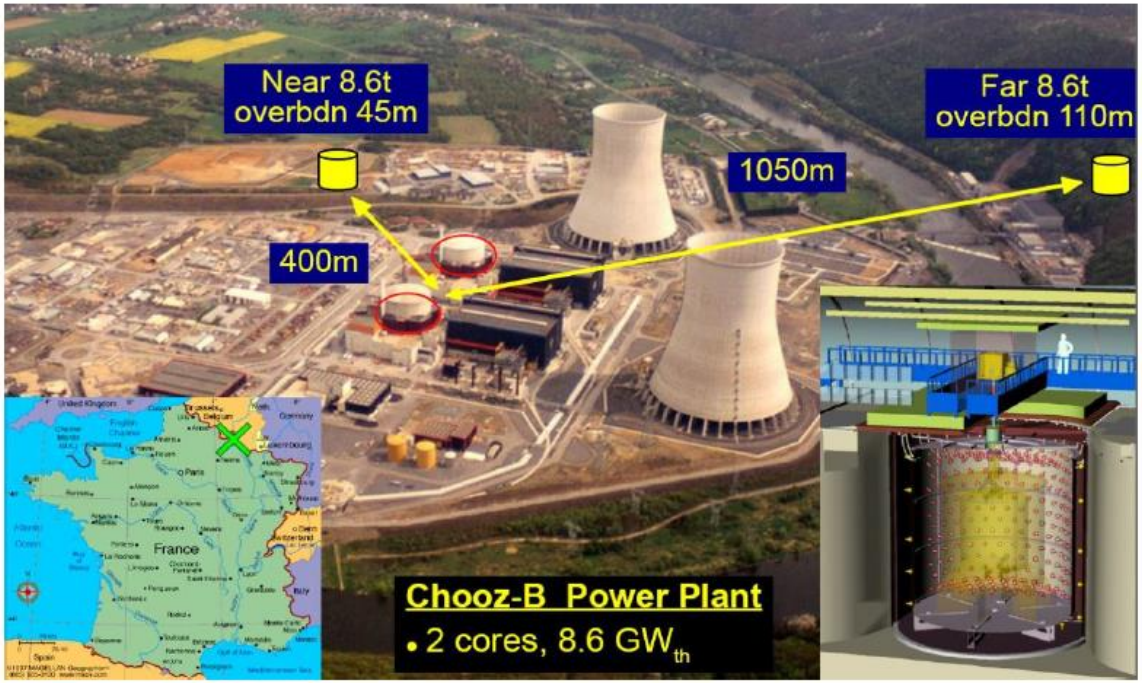
USA
U. Alabama
ANL
U. Chicago
Columbia U.
UCDavis
Drexel U.
IIT
KSU
LLNL
MIT
U. Notre Dame
U. Tennessee

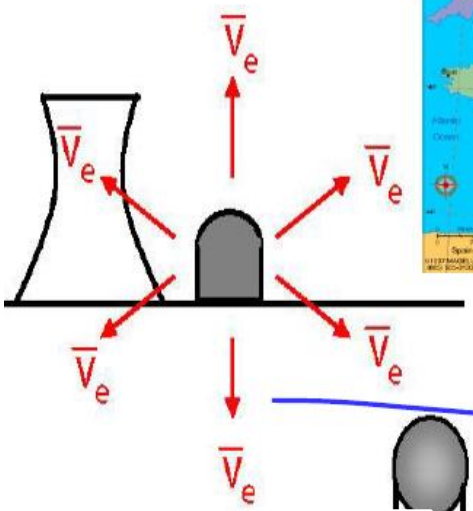
Spokesperson:
H. de Kerret (IN2P3)

Project Manager:
Ch. Veyssière (CEA-Saclay)

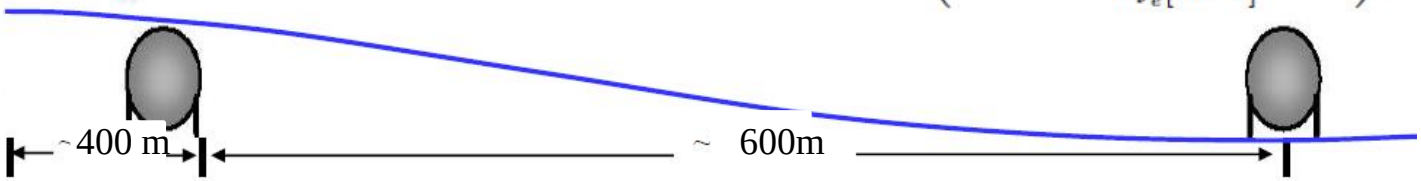
Web Site:
www.doublechooz.org/

Double Chooz Experiment





$$P_{ee}(E_{\overline{\nu}_e}, L, \Delta m^2_{31}, \theta_{13}) = 1 - \sin^2(2\theta_{13})\sin^2\left(1.27\frac{\Delta m^2_{31}[10^{-3}\ \mathrm{eV}^2]L[\mathrm{km}]}{E_{\overline{\nu}_e}[\mathrm{MeV}]}\right)$$



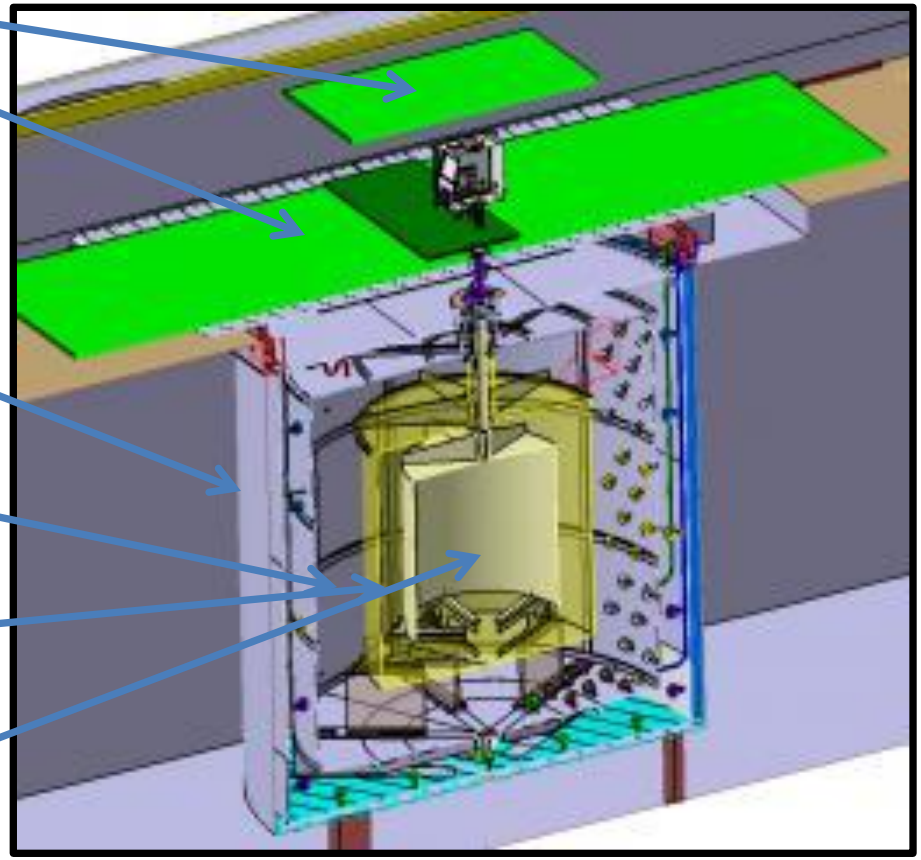
Double Chooz Detector

Outer Veto (OV)
Plastic scintillator strips

Inner Veto (IV)
90 m^3 of scintillator in a steel Vessel (10 mm) equipped with 78 PMTs (8 inches)

Buffer
110 m^3 of mineral oil in a steel Vessel. (3mm) equipped with 390 low-background PMTs (10 in.)

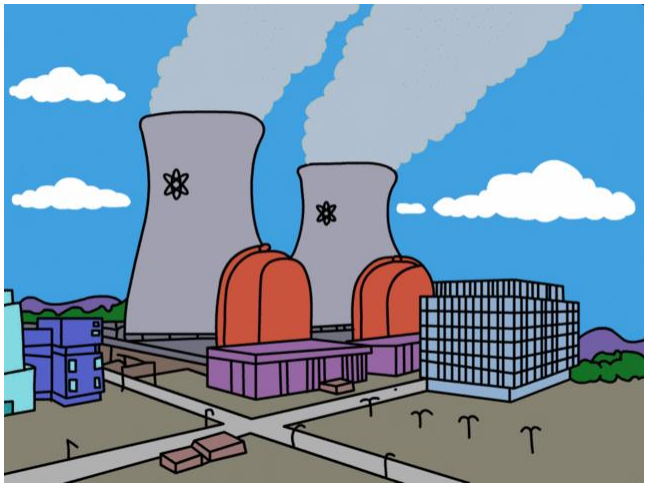
Gamma Catcher (GC)
22.3 m^3 scintillator in an acrylic Vessel (12 mm)

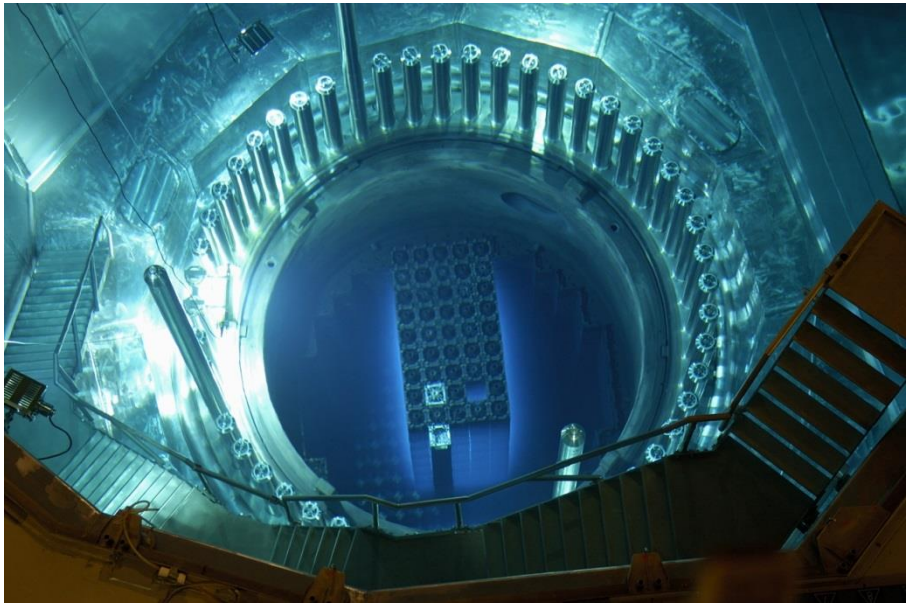


Target
10.3 m^3 schintillator doped with 1 g/l of Gd in acrylic vessel (8 mm)

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

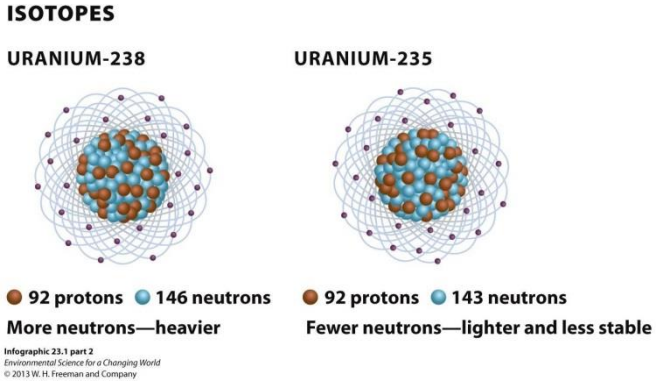
Double Chooz Experiment





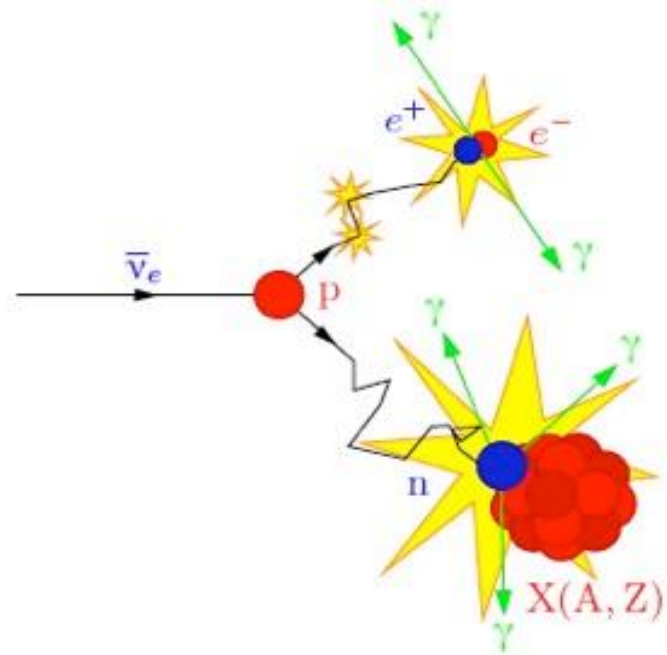
Antineutrino intensity: 2X 10^{17} per MW.
DC reactor cores: 8.6 GW ~ 1.7 x 10^{21} / s

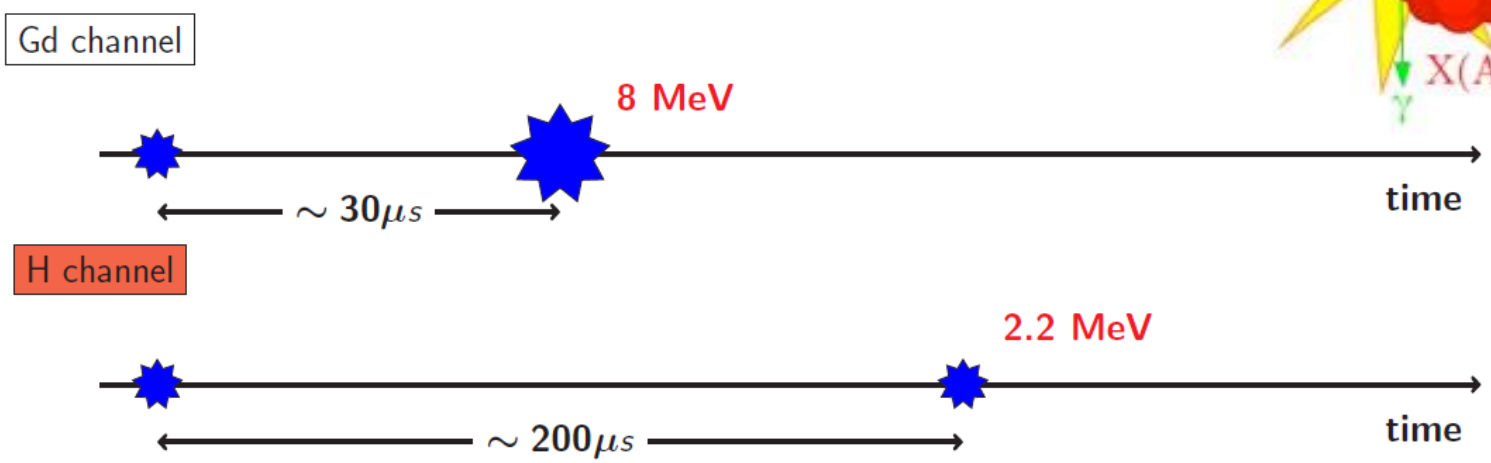
Isotopes: ^{235}U, ^{238}U, ^{241}Pu, ^{239}Pu



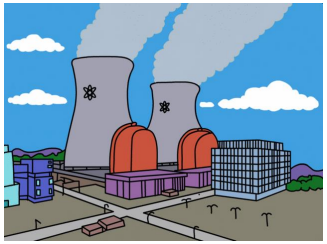
Double Chooz Experiment

- **Inverse Beta Decay (IBD)**:
  - $\overline{\nu}_e + p \rightarrow n + e^+$
- **Prompt signal**: positron energy + annihilation γ's (1 $\sim$ 9 MeV)
- **Delayed signal**: γ's from neutron capture on Gd or H
- **Delayed coincidence**

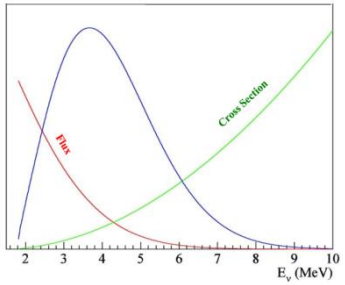




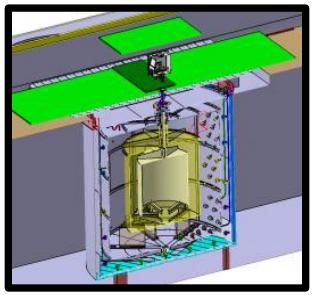
Antineutrino detection

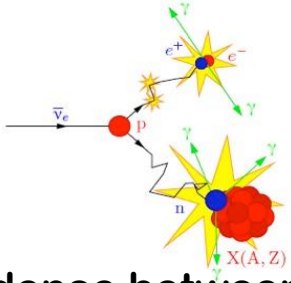


1.7 x 10^{21} / s

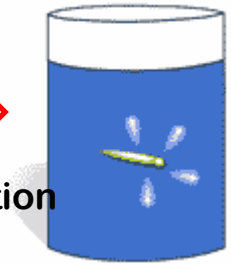


IBD

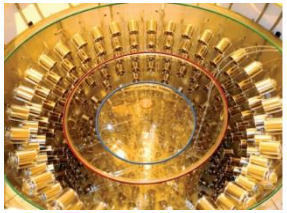


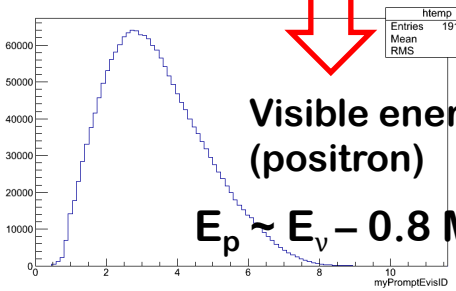


Scintillation



PMT

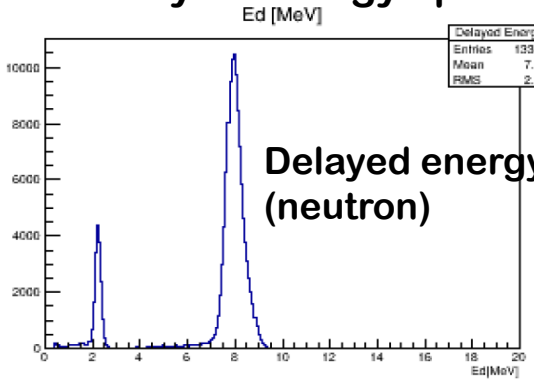




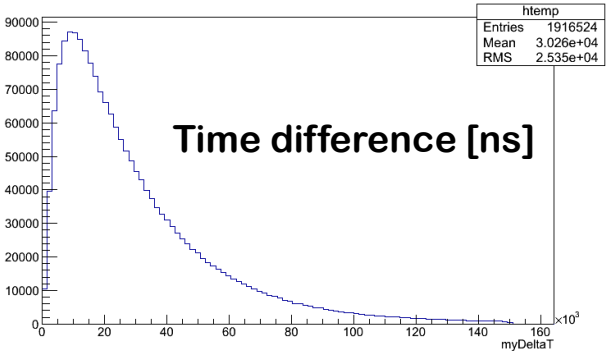
Visible energy (positron)

$E_p \sim E_\nu - 0.8$ MeV

We use the delayed coincidence between the positron and the neutron to identify antineutrinos. Delayed energy spectrum and time difference:



Delayed energy [MeV] (neutron)

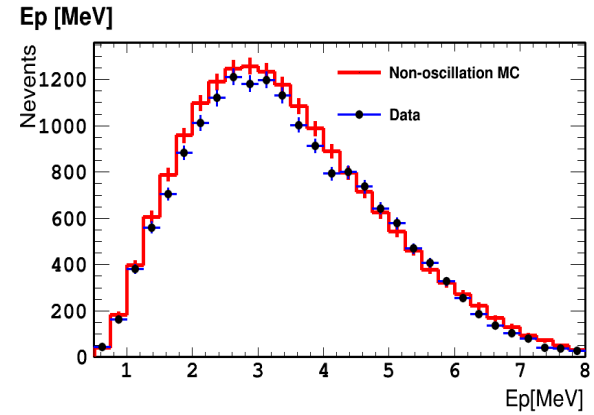


Time difference [ns]

Argonne's tasks in Double Chooz:

- Calibration tool installation
- Energy reconstruction
- Detection efficiency evaluation
- Low background radioactivity study
- Oscillation analysis
- Extended physics searches

nGd Rate + Shape fit



$$
\begin{aligned}
\chi^2 = & \sum_i^B \sum_j^B (N_i^{pred} - N_i^{obs})\, M_{ij}^{-1}\, (N_j^{pred} - N_j^{obs}) \\
& + \frac{(\alpha_{Li+He} - 1)^2}{(\sigma_{Li+He})^2} + \frac{(\alpha_{acc\ (syst)} - 1)^2}{(\sigma_{acc\ (syst)})^2} + \frac{(\alpha_{FN+SM} - 1)^2}{(\sigma_{FN+SM})^2} \\
& + \frac{(\Delta m^2 - \Delta m^2_{ee})^2}{\sigma^2_{ee}} + \frac{(\alpha_{residual} - 1)^2}{\sigma^2_{residual}} \\
& + \left[(a' - a'_{CV}), (b' - b'_{CV}), (c' - c'_{CV})\right] \\
& \times \begin{bmatrix} (\sigma_{a'})^2 & \rho_{a'b'}(\sigma_{a'}\sigma_{b'}) & \rho_{a'c'}(\sigma_{a'}\sigma_{c'}) \\ \rho_{b'a'}(\sigma_{b'}\sigma_{a'}) & (\sigma_{b'})^2 & \rho_{b'c'}(\sigma_{b'}\sigma_{c'}) \\ \rho_{c'a'}(\sigma_{c'}\sigma_{a'}) & \rho_{c'b'}(\sigma_{c'}\sigma_{b'}) & (\sigma_{c'})^2 \end{bmatrix}^{-1} \times \begin{bmatrix} (a' - a'_{CV}) \\ (b' - b'_{CV}) \\ (c' - c'_{CV}) \end{bmatrix} \\
& + 2\left(N_{off}^{obs} \cdot \ln\left[\frac{N_{off}^{obs}}{N_{off}^{pred}}\right] + N_{off}^{pred} - N_{off}^{obs} \right)
\end{aligned}
$$

where:

$B = 40$ for Rate+Shape, $B = 1$ for Rate-Only

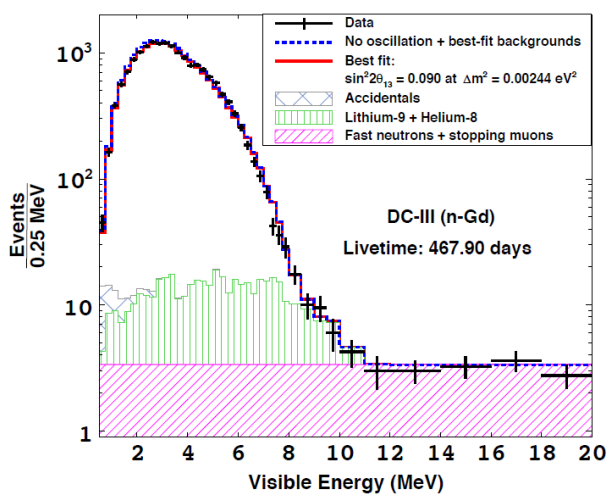
$M = M_{stat} + M_{reactor} + M_{eff} + M_{Li+He\ shape} + M_{acc\ (stat)}$

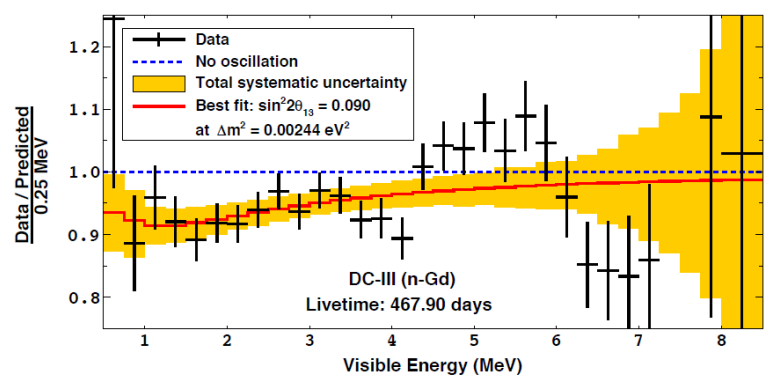
$N_{off}^{pred} = \left(\alpha_{Li+He} R_{Li+He} + \alpha_{FN+SM} R_{FN+SM} + \alpha_{acc\ (syst)} R_{acc}\right) \cdot T_{off} + \alpha_{residual} N_{residual}^{pred}$

$N_{residual}^{pred}$ is a function of $\sin^2 2\theta_{13}$, and N_i^{pred} is a function of $\sin^2 2\theta_{13}$ and all pull terms.

nGd Rate + Shape fit

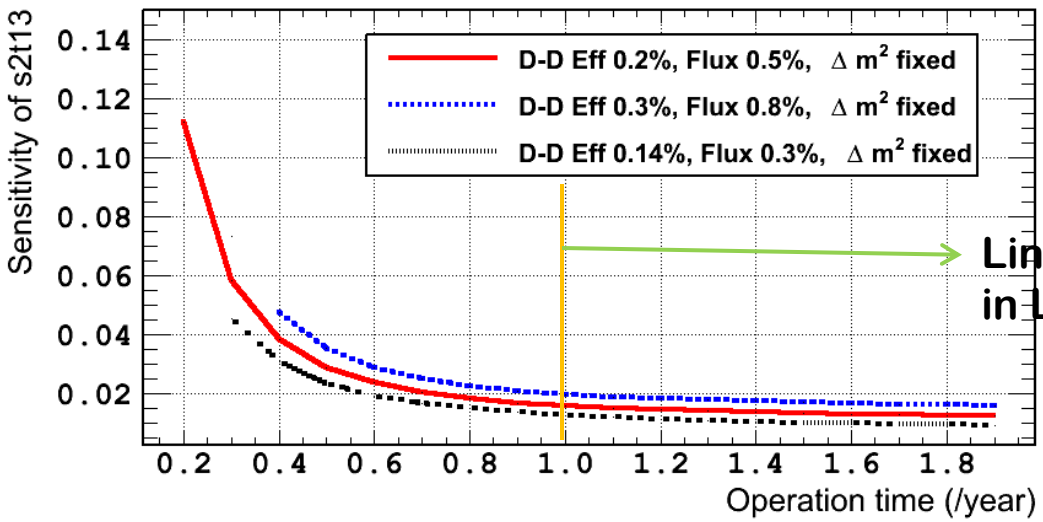
Parameter	Input C.V.	Input Error	Output C.V.	Output Error
E-scale a'	-0.027	0.006	-0.026	$+0.006, -0.005$
E-scale b'	1.012	0.008	1.011	$+0.004, -0.006$
E-scale c'	-0.0001	0.0006	-0.0006	$+0.0007, -0.0005$
FN+SM rate (d^{-1})	0.604	0.051	0.568	$+0.038, -0.037$
Li+He rate (d^{-1})	0.97	$+0.41, -0.16$	0.74	0.13
Accidentals rate (d^{-1})	0.0701	0.0026	0.0703	0.0026
Residual $\bar{\nu}_e$	1.57	0.47	1.48	0.47
Δm^2 (10^{-3} eV^2)	2.44	$+0.09, -0.10$	2.44	$+0.09, -0.10$
$\sin^2 2\theta_{13}$	—	—	0.090	$+0.032, -0.029$
χ^2/d.o.f.	—	—	52.2/40	—





Near detector + Far detector fit

- Now we have the near detector, the systematics, especially reactor flux, can be reduced significantly.
- In addition, the statistics can be increased significantly and more background events can make corresponding measurements more precise.



Line for Nu-2016 in London.

- Operation time from ND+FD (beginning of 2015).
- My thesis goal is to measure θ_{13} at 5 sigma level by this summer, which is the end of my PhD.

Summary

- Double Chooz has best single detector θ_{13} sensitivity in the world.
- With two detectors, θ_{13} sensitivity in Double Chooz is competitive to other reactor antineutrino experiments.
- Other physics topics can be tested in Double Chooz.
- As Zelimir's graduate student, I will finish the topics in Double Chooz. In addition, other tasks have been/will be done.
- After graduating in this summer, I intend to stay in the neutrino physics field due to these exciting and thrilling results!

Thank you !

Photo taken in 2005, we achieve a lot in this decade!

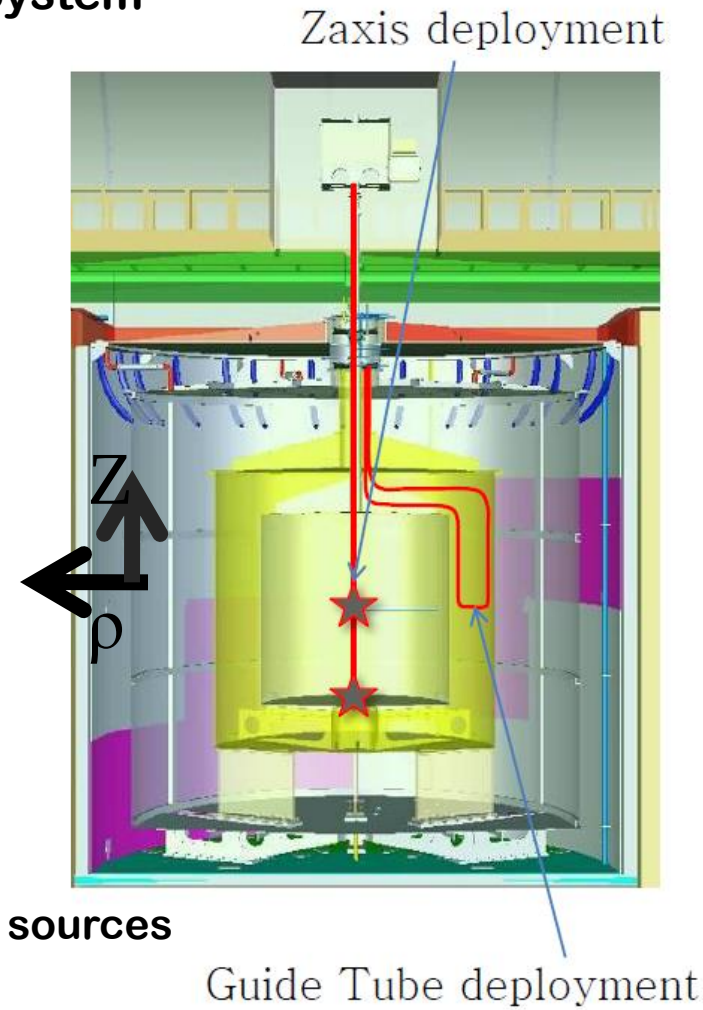
Double Chooz Calibration System

-Embedded LEDs inside inner detector and inner veto
- routinely used to monitor detector stability and PMT gains

-Laser (UV and green)

- Calibration source deployment devices:
  - Z-axis system (in target)
  - Guide Tubes (in gamma catcher)
  - Articulated Arm

- Radioactive sources used:
  a) Radioactive sources deployed so far:
  Cs-137, Co-60, Ge-68, Cf-252
  b) spallation neutrons and natural radioactive sources



Physics goals in Double Chooz Experiment

- Measure the mixing angle θ_{13}
  - Reactor modeling
  - Energy reconstruction
  - Detection efficiency
  - Background estimation

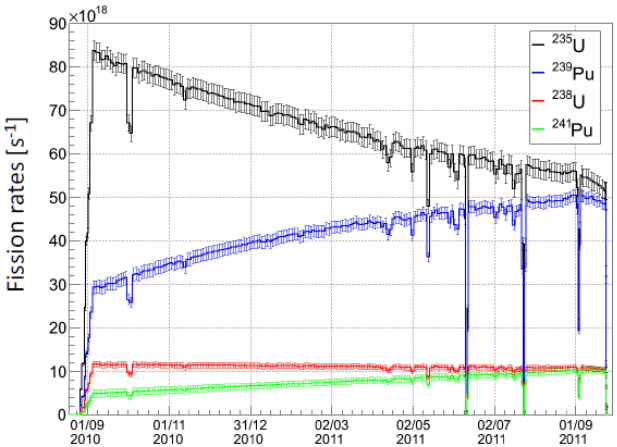
→ Oscillation analysis

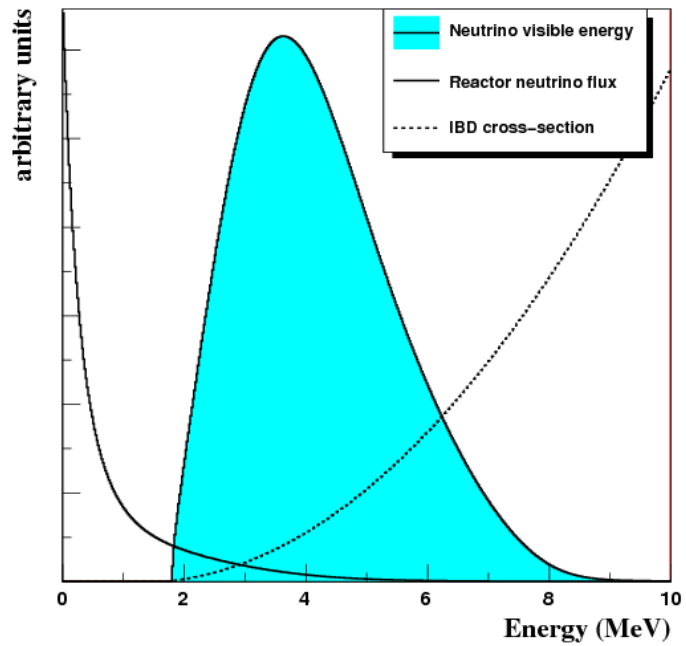
- Reactor flux measurement
- Lorentz violation test
- Muon physics
- Δm^2_{31} measurement
- Sterile neutrino search
- Cf source characterization study

Reactor modeling

Reactor modeling

- Double Chooz ran with single detector for few years, so precise reactor prediction is needed.
- Four isotopes in the reactor core: ^{235}U, ^{238}U, ^{241}Pu, ^{239}Pu.





	B1-C12	B1-C13	B1-C14	B2-C12	B2-C13	Integrated α_k (B2/C12)
235U	**-0.33**	**0.41**	**0.15**	**-0.34**	**0.33**	**0.521**
238U	-0.20	0.13	-0.31	0.17	-0.50	0.087
239Pu	**0.37**	**-0.50**	**0.13**	**0.24**	**0.09**	**0.332**
241Pu	1.17	-0.96	-2.11	1.27	-2.64	0.060

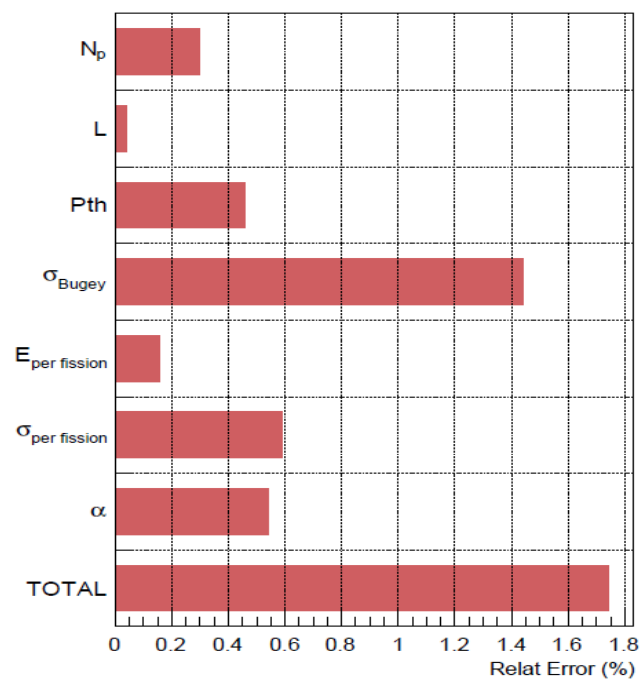
Reactor modeling

Predicted antineutrino spectrum:

$$N_\nu^{exp}(s^{-1}) \;=\; \frac{1}{4\pi L^2} N_p\, \epsilon\, \frac{P_{th}}{\langle E_f \rangle} \langle \sigma_f \rangle$$

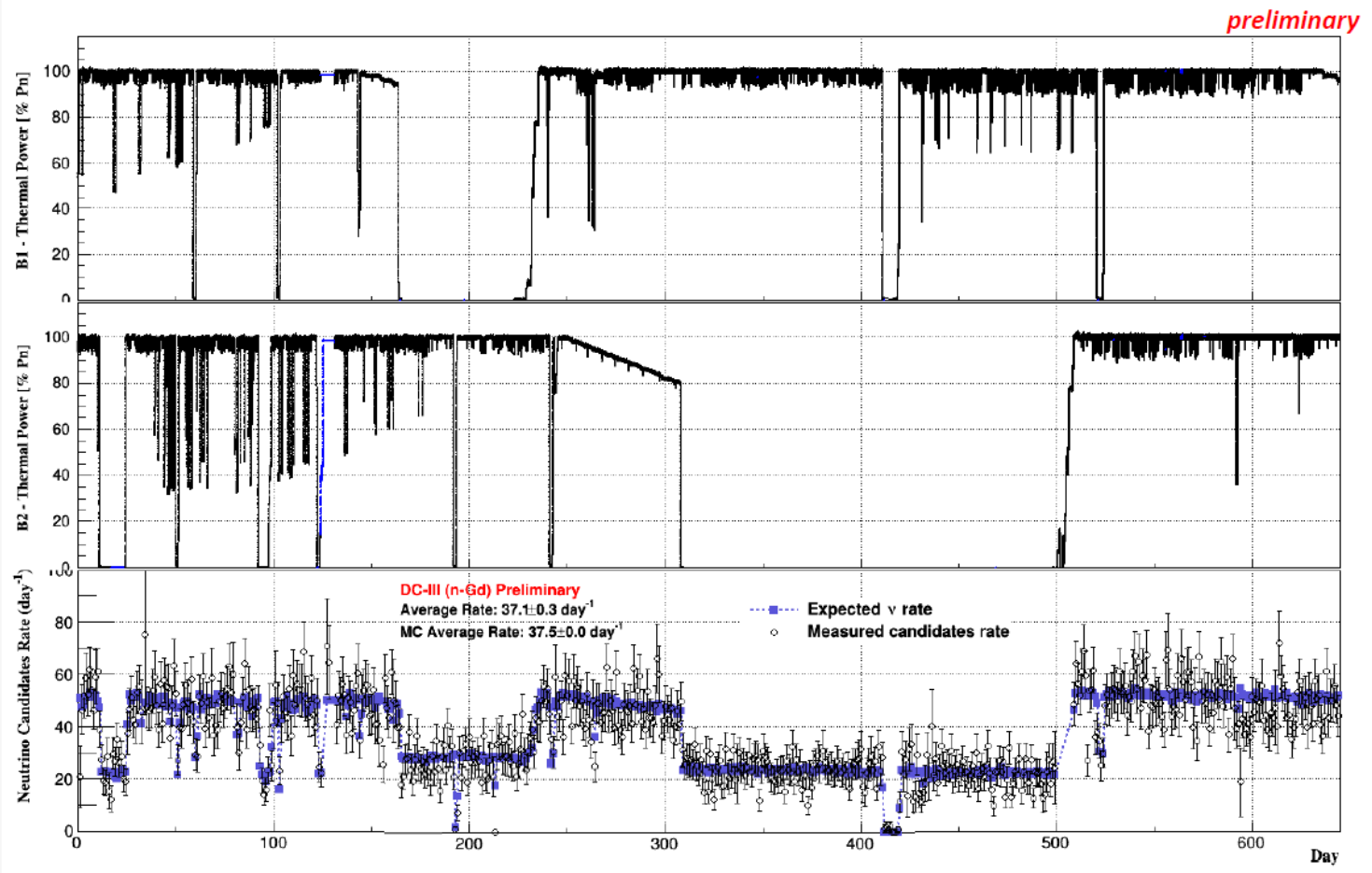
$$\langle \sigma_f \rangle_R = \langle \sigma_f \rangle^{Bugey} + \sum_k (\alpha_k^R - \alpha_k^{Bugey}) \langle \sigma_f \rangle_k$$

$$\langle \sigma_f \rangle = \sum_k \alpha_k \langle \sigma_f \rangle_k = \sum_k \alpha_k \int_0^\infty dE\, S_k(E)\, \sigma_{IBD}(E)$$



- Bugey measurement is used as an anchor point.
- α is the fission fraction for each isotope.
- S(E) is the reference spectrum for each isotope.

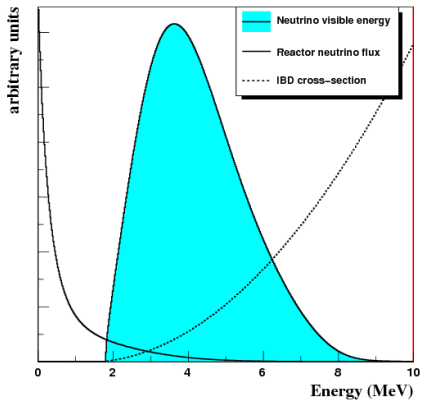
Thermal power and neutrino rate

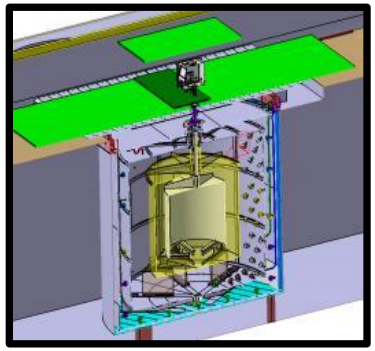


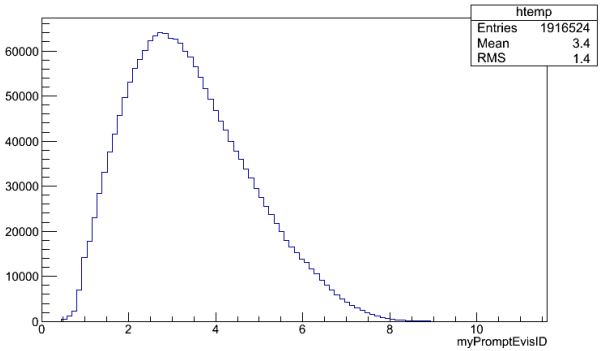
DC reactor thermal power and neutrino rate for DC-III (n-Gd)

Energy reconstruction

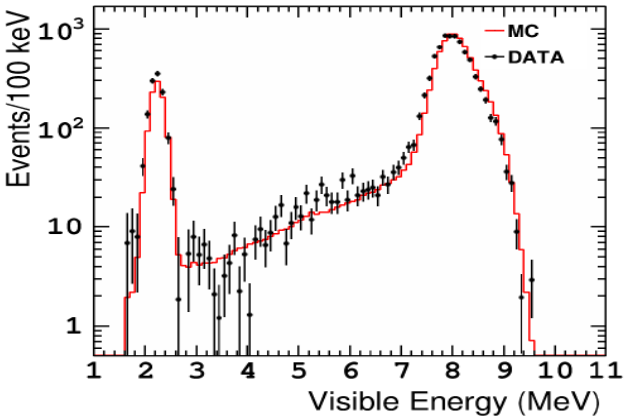
- Neutrino oscillates in its true energy and detected in visible energy from the scintillation light.

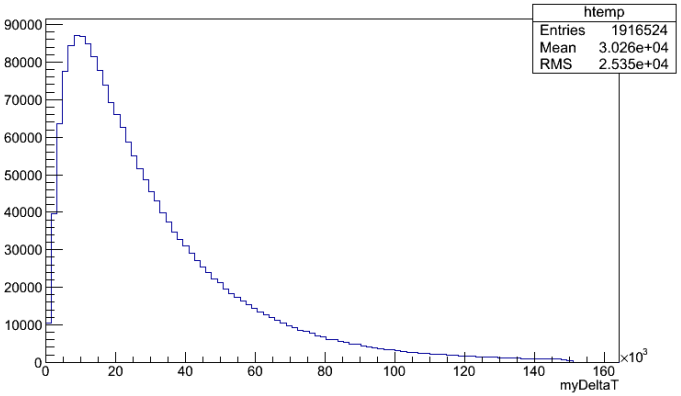






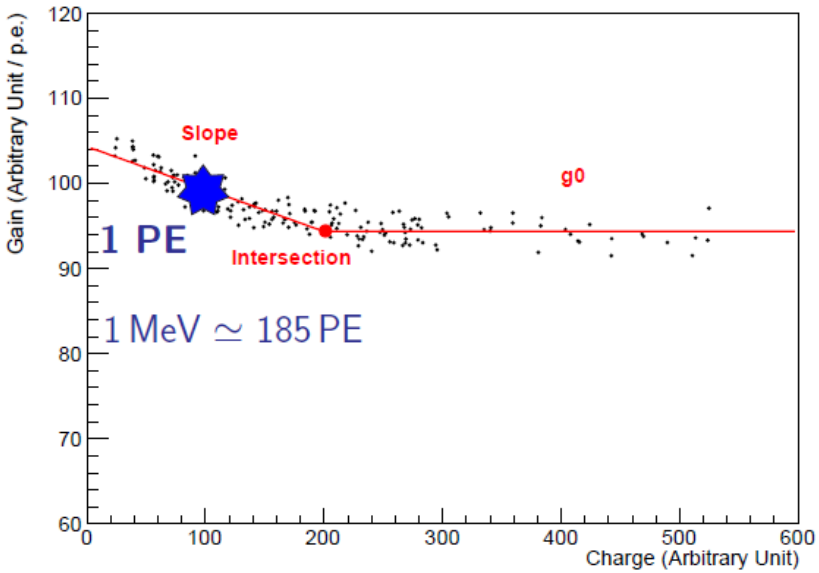
Delayed energy and time difference :





PE Calibration

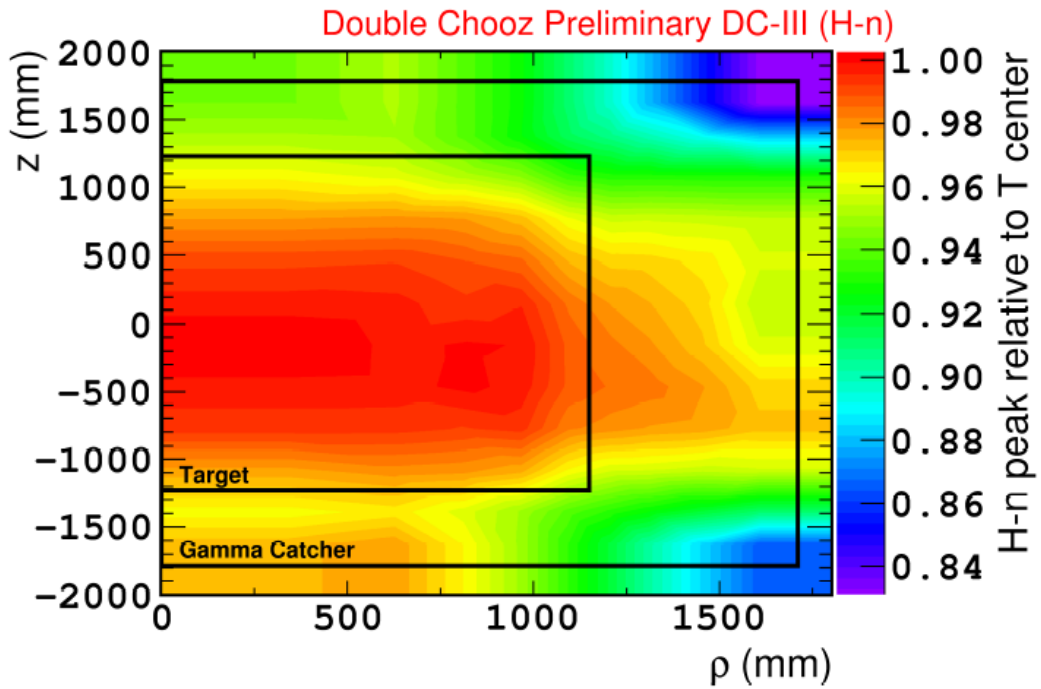
$$E_{vis} = \boxed{N_{pe}} \times f_u(\rho, z) \times f_{PE/MeV} \times f_s^{data}(E_{vis}^0, t) \times f_{nl}^{MC}$$



- Charge to PE non-linearity correction (using light injection system) correct for non-linear effects due to electronics response

Uniformity

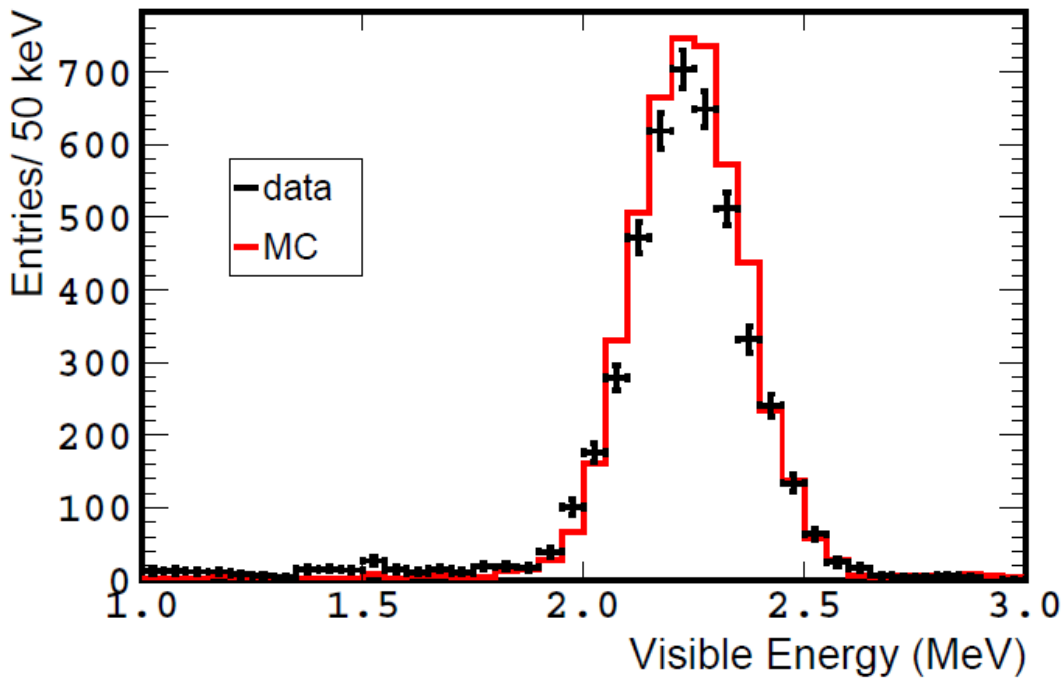
$$E_{vis} = N_{pe} \times \boxed{f_u(\rho, z)} \times f_{PE/MeV} \times f_s^{data}(E_{vis}^0, t) \times f_{nl}^{MC}$$



- Energy non-uniformity correction (using spallation n captures on H) correct for detector response position dependence

PE2MeV calibration

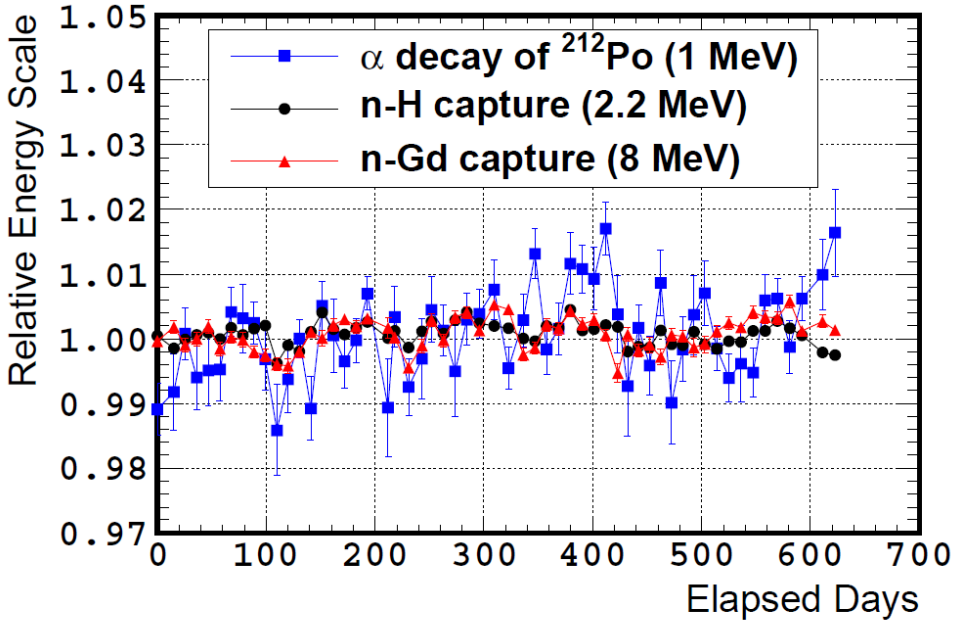
$$E_{vis} = N_{pe} \times f_u(\rho, z) \times \boxed{f_{PE/MeV}} \times f_s^{data}(E_{vis}^0, t) \times f_{nl}^{MC}$$



Absolute energy scale determination (using ^{252}Cf source at detector center)
Determine PE to MeV conversion factor from (H-n) captures

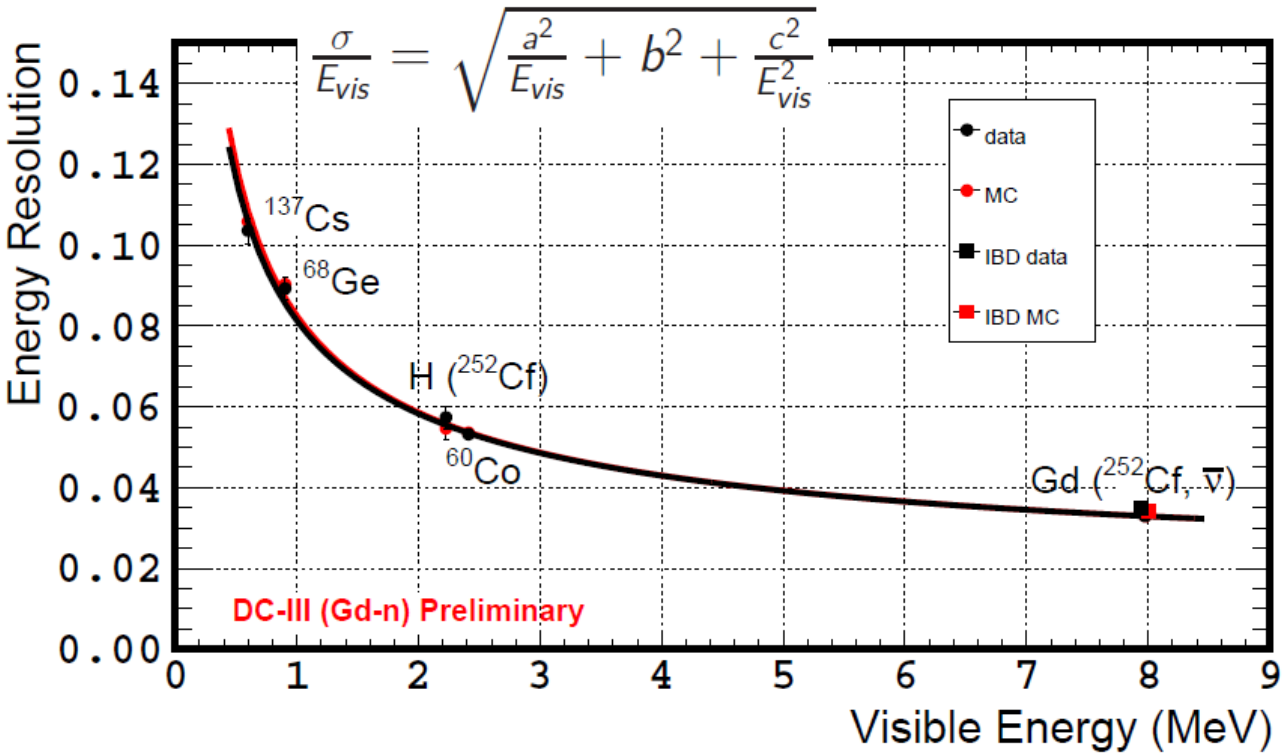
Stability

$$E_{vis} = N_{pe} \times f_u(\rho, z) \times f_{PE/MeV} \times f_s^{data}(E_{vis}^0, t) \times f_{nl}^{MC}$$



- Energy time stability correction (using natural radioactivity sources) correct time fluctuations due to electronics response and liquid scintillator deterioration

Energy resolution



data:
$a = 0.0773 \pm 0.0025$
$b = 0.0182 \pm 0.0014$
$c = 0.0174 \pm 0.0107$

MC:
$a = 0.0770 \pm 0.0018$
$b = 0.0183 \pm 0.0011$
$c = 0.0235 \pm 0.0061$

- Very good agreement data to MC over the whole energy range.

Detection efficiency

Detection efficiency

- Neutron detection efficiency may be determined as $\xi_{neutron} = \xi_{Gd} \times \xi_{\Delta t} \times \xi_{\Delta E}$
  - ξ_{Gd} is the graction of neutron captures on gadolinium.
  - $\xi_{\Delta t}$ is the fraction of neutron captures within desired time interval.
  - $\xi_{\Delta E}$ is the fraction of neutron captures within certain energy range.

- Sets overall normalization for the signal prediction in absence of the near detector data.

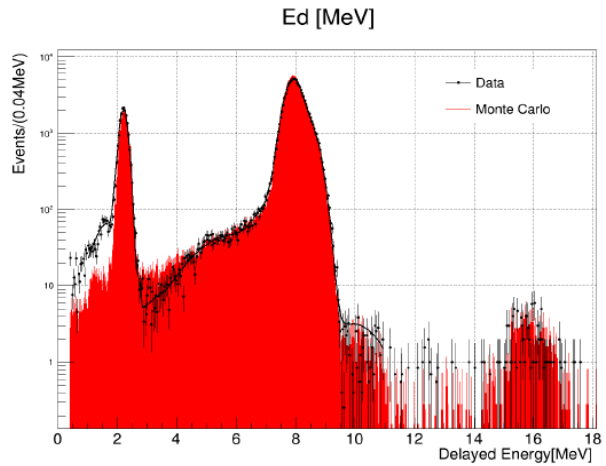
- Neutron detection efficiency may be different between data and MC, if so, need to apply a MC correction due to this difference.

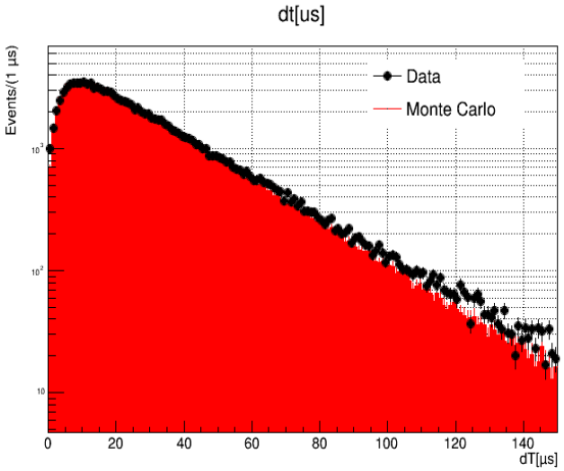
- ^{252}Cf fission emits gammas as prompt signal and neutrons as delayed signal, which can mimic the antineutrino signals. We can use ^{252}Cf to calculate the neutron detection efficiency.

Semi-inclusive efficiency

$$\text{Gd fraction} = \frac{N_{event}\ dE[4\text{-}10MeV]}{N_{event}\ dE[1\text{-}10MeV]}$$

$$\text{Semi-inclusive efficiency} = \frac{N_{event}\ dT[0.5\text{-}150\ \mu s] \times N_{event}\ dE[4\text{-}10MeV]}{N_{event}\ dT[0.\text{-}1000\ \mu s] \times N_{event}\ dE[3.5\text{-}10MeV]}$$





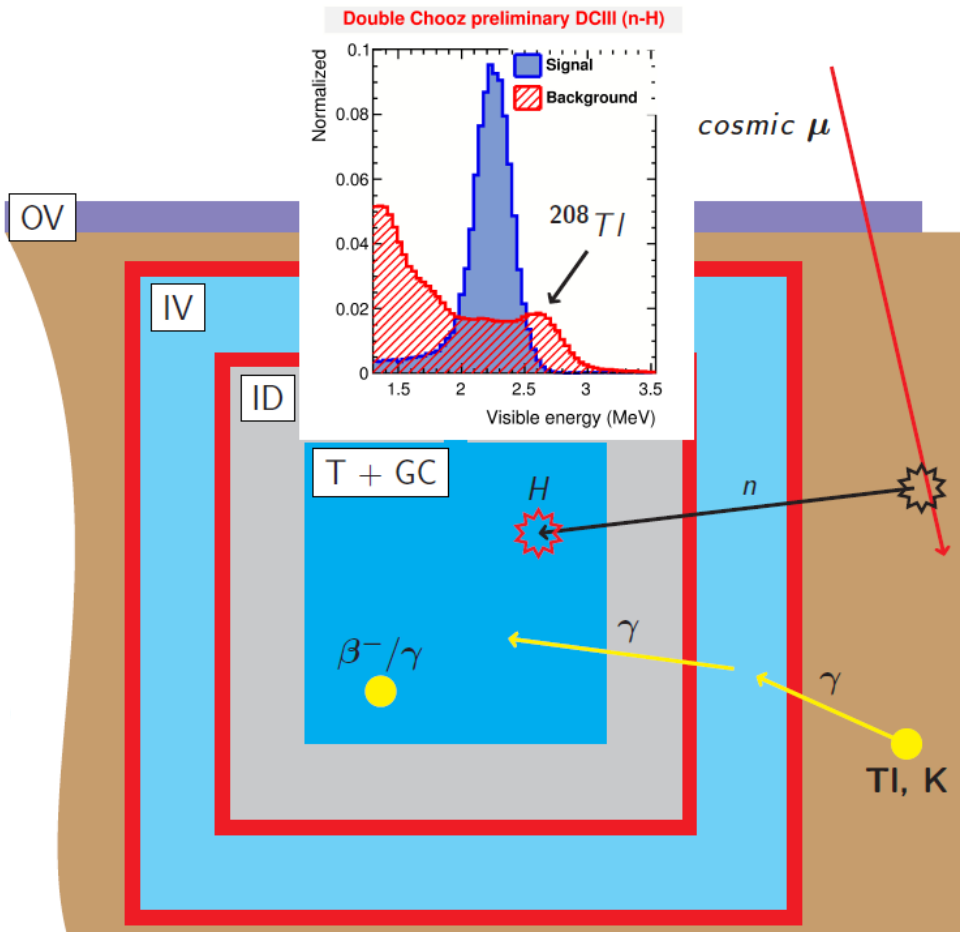
Total neutron detection efficiency = Gd fraction × semi-inclusive.

With $0.5 < dT < 150\mu s$: 0.960 ± 0.0106 (stat.+syst.)

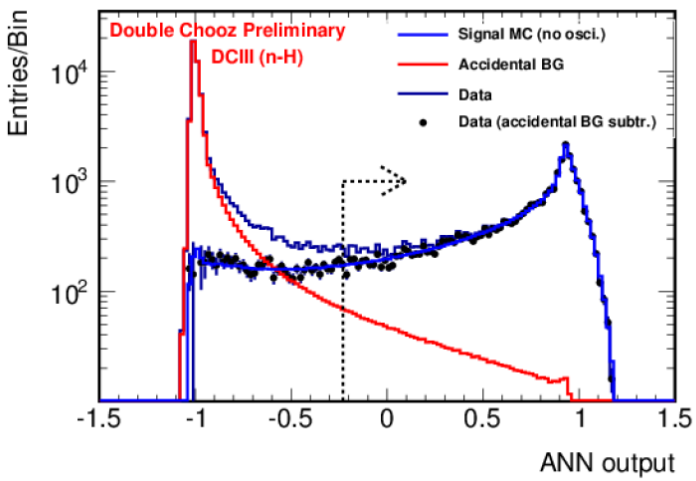
-The number is the MC correction and the error goes to the detection systematics.

Background estimation

Accidentals

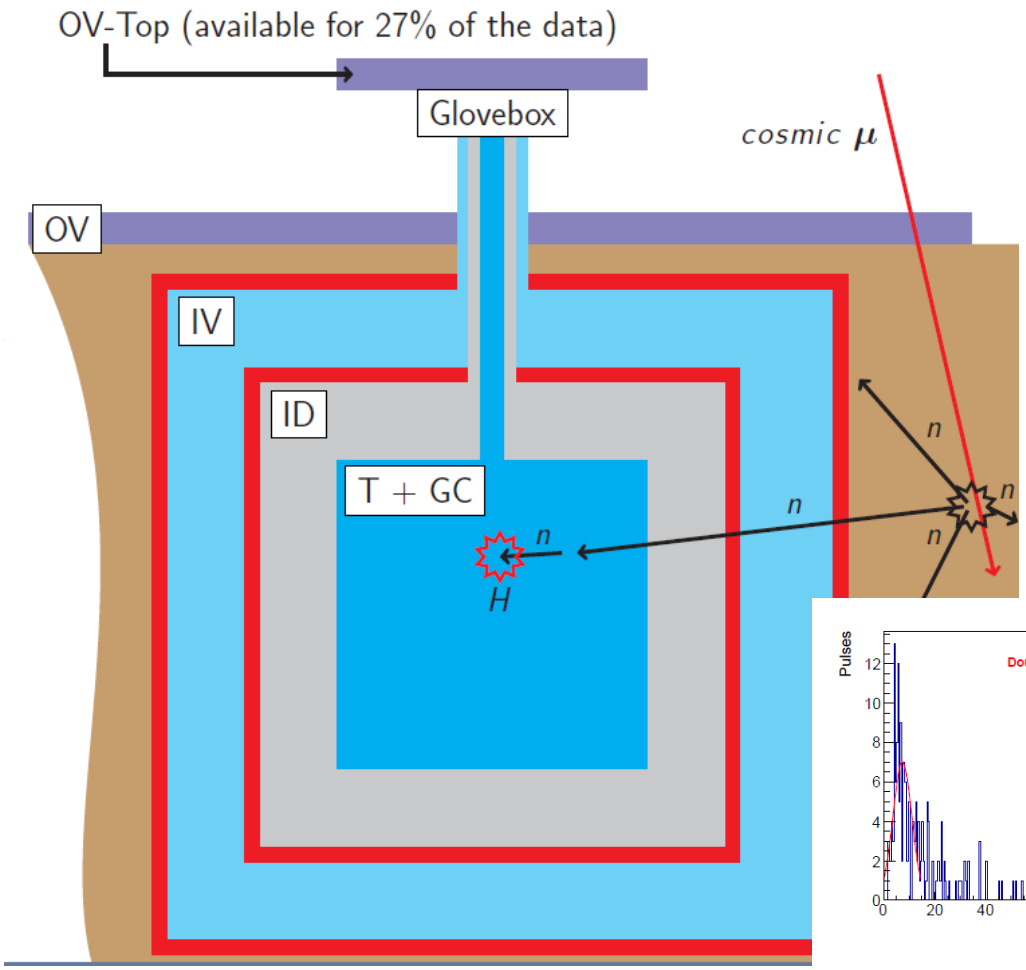


Neural network



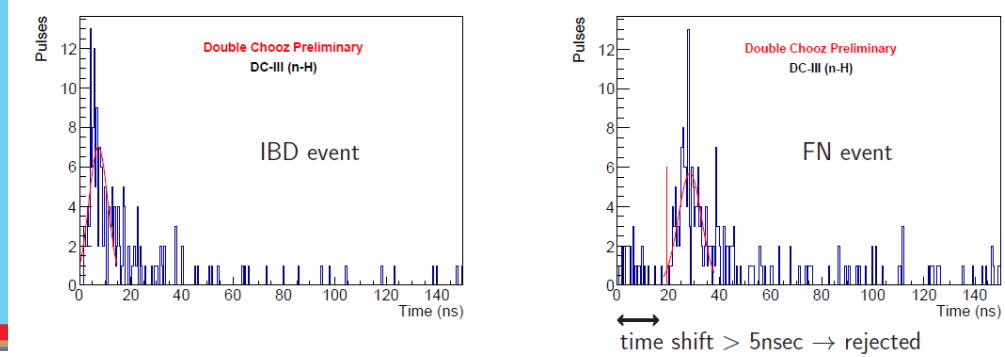
- The random association of a prompt trigger from natural radioactivity and a later neutron-like candidate.
- Accidental background is stable over time.
- Can be measured in the off-time window.

Fast Neutrons



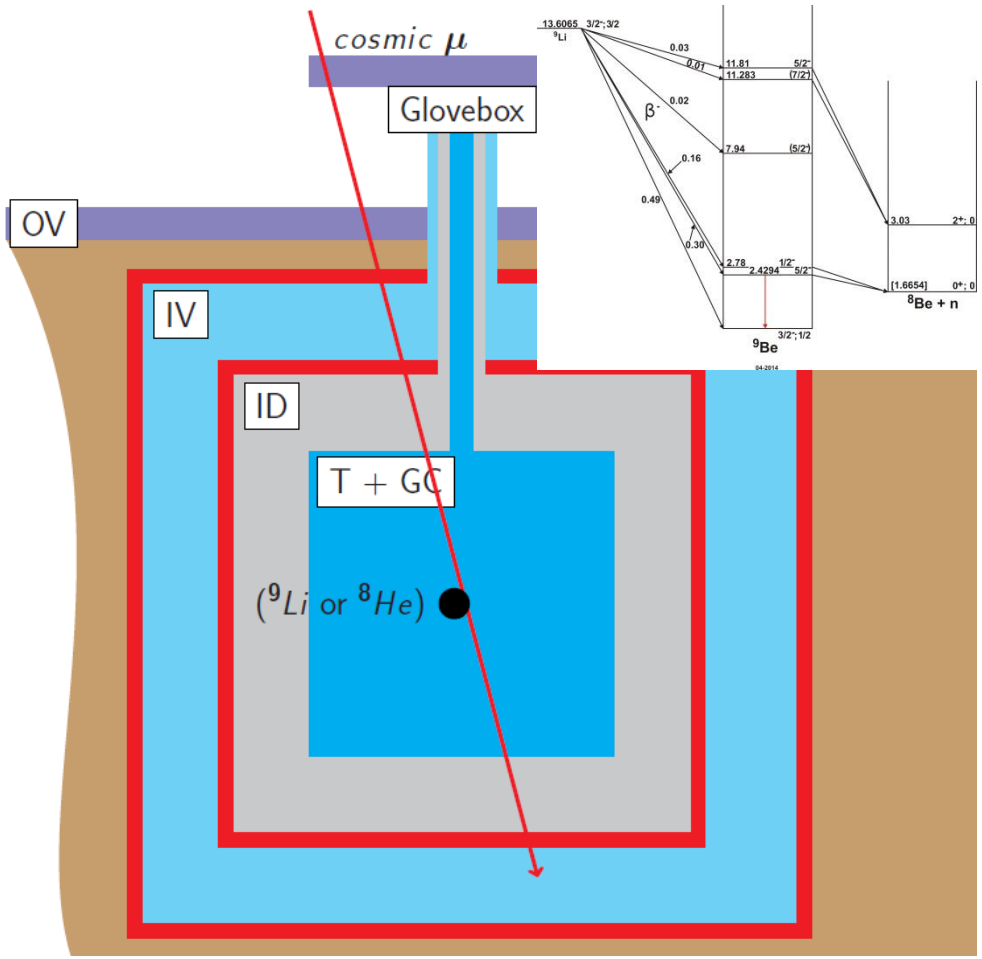
- Neutrons produced by muons around the detector and muons entering the inner detector from the chimney area on the top of the detector.
- Extend the prompt energy window, we can see these background.
- Only rate , not the shape of FN/SM will be considered in the final fit.

Pulses shape



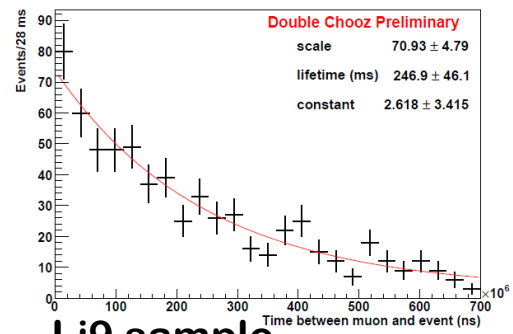
- There is still small amount of contributions from the stopping muons taken into account.

^{9}Li / ^{8}He

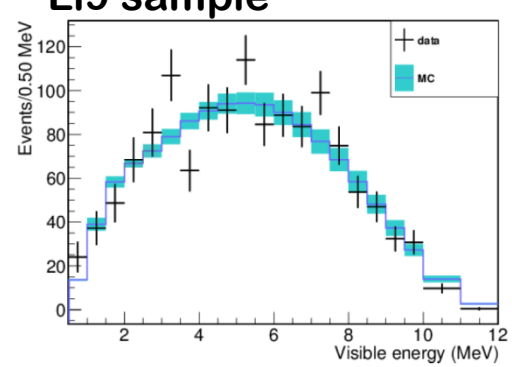


- Generated when a cosmogenic muon crosses the scintillator volume and is captured by ^{12}C.
- can be identified by studying the time and space correlation of its parent muons.

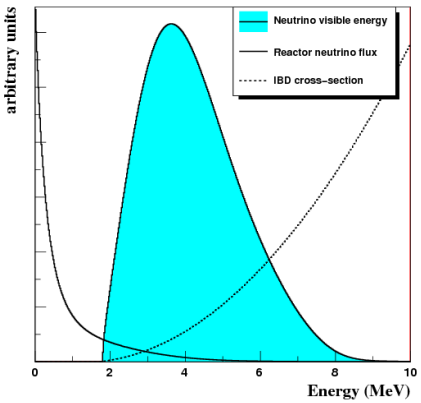
Time from Muons

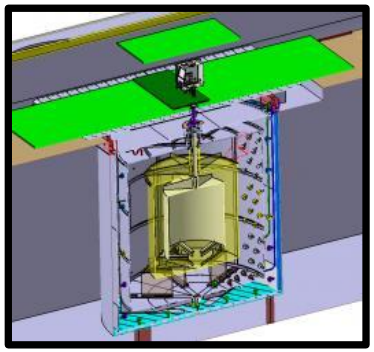


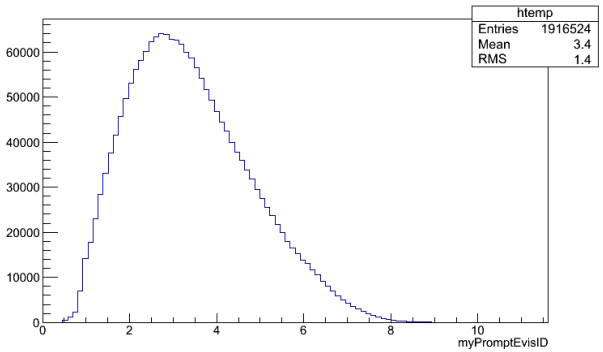
Li9 sample



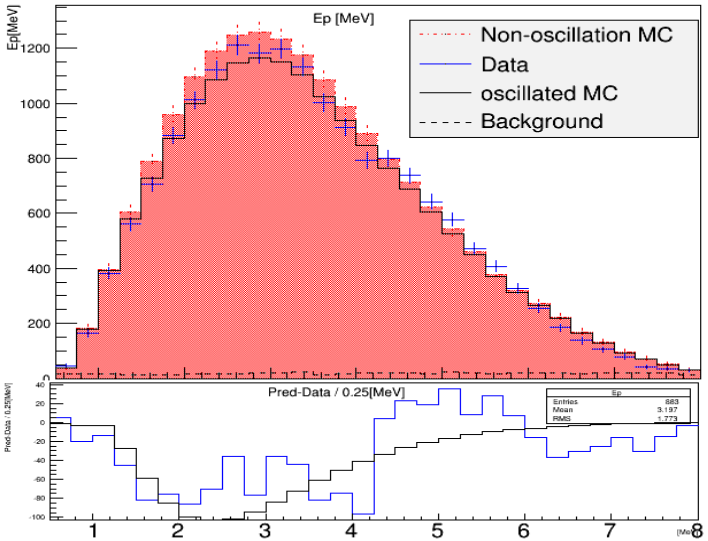
Oscillation analysis



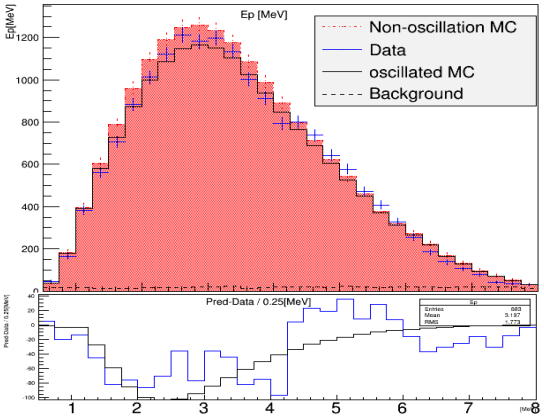




Add oscillation to the predicted spectrum,
Then compare to data to extract
Best θ_{13} value.



nGd Rate + Shape fit



$$
\begin{aligned}
\chi^2 = & \sum_i^B \sum_j^B (N_i^{pred} - N_i^{obs})\, M_{ij}^{-1}\, (N_j^{pred} - N_j^{obs}) \\
& + \frac{(\alpha_{Li+He} - 1)^2}{(\sigma_{Li+He})^2} + \frac{(\alpha_{acc\ (syst)} - 1)^2}{(\sigma_{acc\ (syst)})^2} + \frac{(\alpha_{FN+SM} - 1)^2}{(\sigma_{FN+SM})^2} \\
& + \frac{(\Delta m^2 - \Delta m^2_{ee})^2}{\sigma^2_{ee}} + \frac{(\alpha_{residual} - 1)^2}{\sigma^2_{residual}} \\
& + \left[(a' - a'_{CV}), (b' - b'_{CV}), (c' - c'_{CV})\right] \\
& \times \begin{bmatrix} (\sigma_{a'})^2 & \rho_{a'b'}(\sigma_{a'}\sigma_{b'}) & \rho_{a'c'}(\sigma_{a'}\sigma_{c'}) \\ \rho_{b'a'}(\sigma_{b'}\sigma_{a'}) & (\sigma_{b'})^2 & \rho_{b'c'}(\sigma_{b'}\sigma_{c'}) \\ \rho_{c'a'}(\sigma_{c'}\sigma_{a'}) & \rho_{c'b'}(\sigma_{c'}\sigma_{b'}) & (\sigma_{c'})^2 \end{bmatrix}^{-1} \times \begin{bmatrix} (a' - a'_{CV}) \\ (b' - b'_{CV}) \\ (c' - c'_{CV}) \end{bmatrix} \\
& + 2\left(N_{off}^{obs} \cdot \ln\left[\frac{N_{off}^{obs}}{N_{off}^{pred}}\right] + N_{off}^{pred} - N_{off}^{obs} \right)
\end{aligned}
$$

where:

$B = 40$ for Rate+Shape, $B = 1$ for Rate-Only

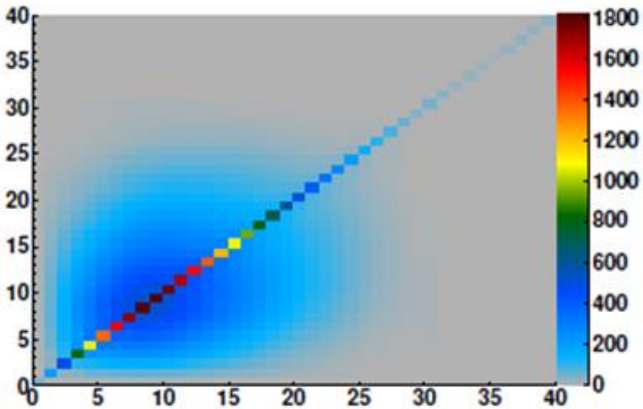
$M = M_{stat} + M_{reactor} + M_{eff} + M_{Li+He\ shape} + M_{acc\ (stat)}$

$N_{off}^{pred} = \left(\alpha_{Li+He} R_{Li+He} + \alpha_{FN+SM} R_{FN+SM} + \alpha_{acc\ (syst)} R_{acc}\right) \cdot T_{off} + \alpha_{residual} N_{residual}^{pred}$

$N_{residual}^{pred}$ is a function of $\sin^2 2\theta_{13}$, and N_i^{pred} is a function of $\sin^2 2\theta_{13}$ and all pull terms.

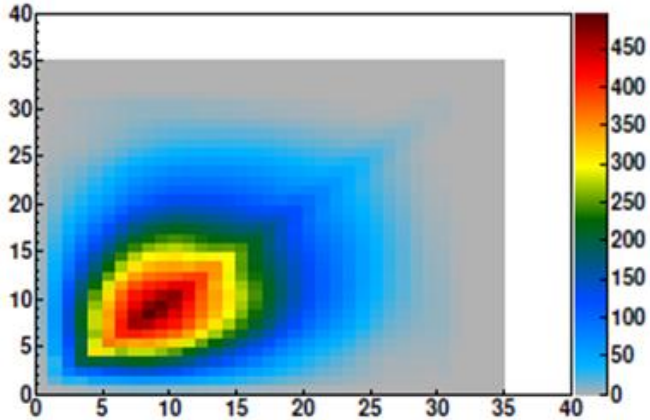
nGd Rate + Shape fit

Total



	Reactor On	Reactor Off
Live-time (days)	460.67	7.24
IBD Candidates	17351	7
Reactor $\bar{\nu}_e$	17530 ± 320	1.57 ± 0.47
Cosomogenic ^{9}Li/^{8}He	447^{+189}_{-74}	$7.0^{+3.0}_{-1.2}$
Fast-n and stop-μ	278 ± 23	3.83 ± 0.64
Accidental BG	32.3 ± 1.2	0.508 ± 0.019
Total Prediction	18290^{+370}_{-330}	$12.9^{+3.1}_{-1.4}$

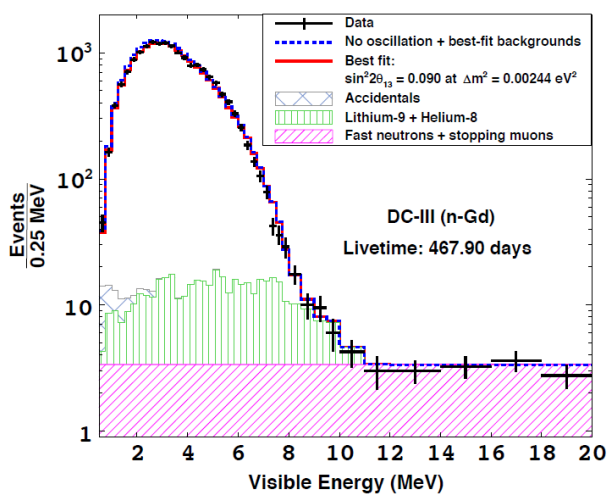
Reactor

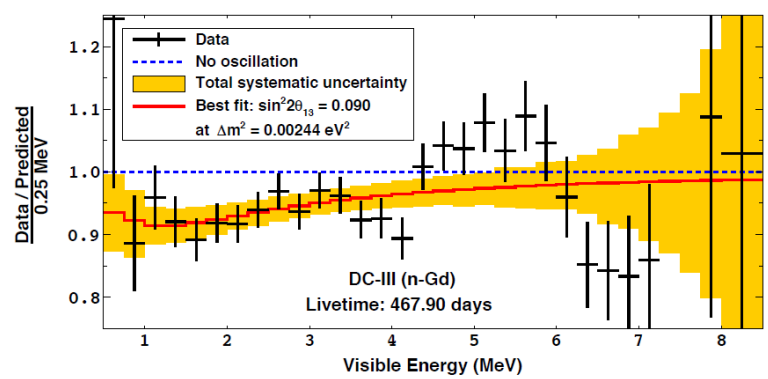


Source	Uncertainty (%)	Gd-III/Gd-II
Reactor flux	1.7	1.0
Detection efficiency	0.6	0.6
^{9}Li + ^{8}He BG	+1.1 / −0.4	0.5
Fast-n and stop-μ BG	0.1	0.2
Statistics	0.8	0.7
Total	+2.3 / −2.0	0.8

nGd Rate + Shape fit

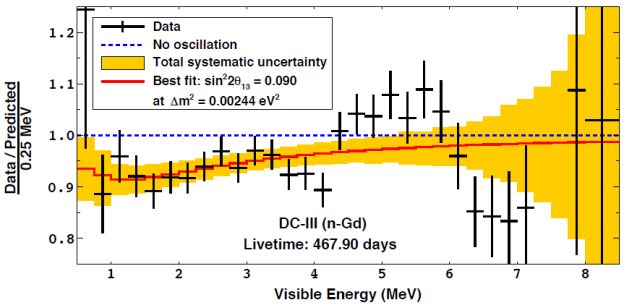
Parameter	Input C.V.	Input Error	Output C.V.	Output Error
E-scale a'	-0.027	0.006	-0.026	$+0.006, -0.005$
E-scale b'	1.012	0.008	1.011	$+0.004, -0.006$
E-scale c'	-0.0001	0.0006	-0.0006	$+0.0007, -0.0005$
FN+SM rate (d^{-1})	0.604	0.051	0.568	$+0.038, -0.037$
Li+He rate (d^{-1})	0.97	$+0.41, -0.16$	0.74	0.13
Accidentals rate (d^{-1})	0.0701	0.0026	0.0703	0.0026
Residual $\bar{\nu}_e$	1.57	0.47	1.48	0.47
Δm^2 (10^{-3} eV^2)	2.44	$+0.09, -0.10$	2.44	$+0.09, -0.10$
$\sin^2 2\theta_{13}$	—	—	0.090	$+0.032, -0.029$
χ^2/d.o.f.	—	—	52.2/40	—



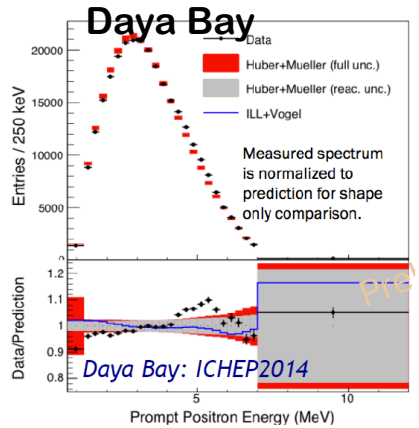


5 MeV bump

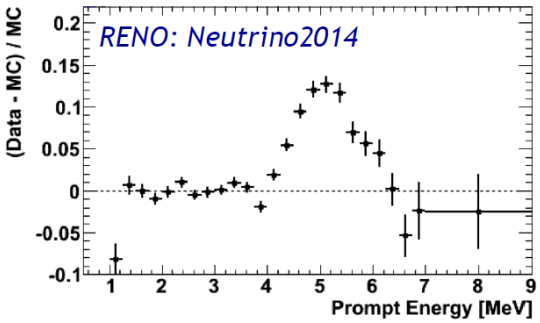
Double Chooz



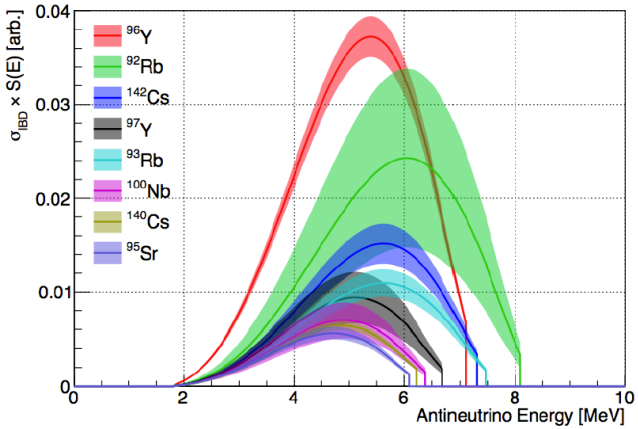
Daya Bay



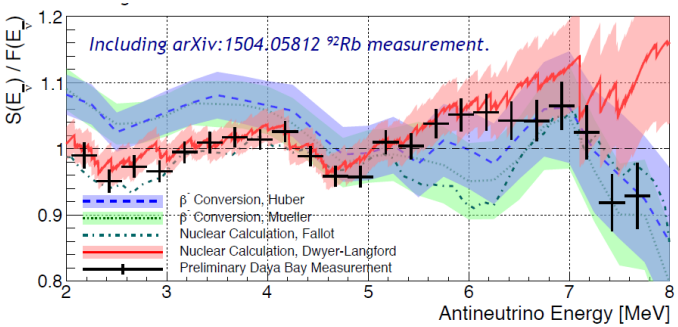
RENO



- Thousands of the beta decays from the reactor core contribute to the neutrino spectrum.
- Might come from the mismodeling of the isotopes that contribute to the 5 MeV region.

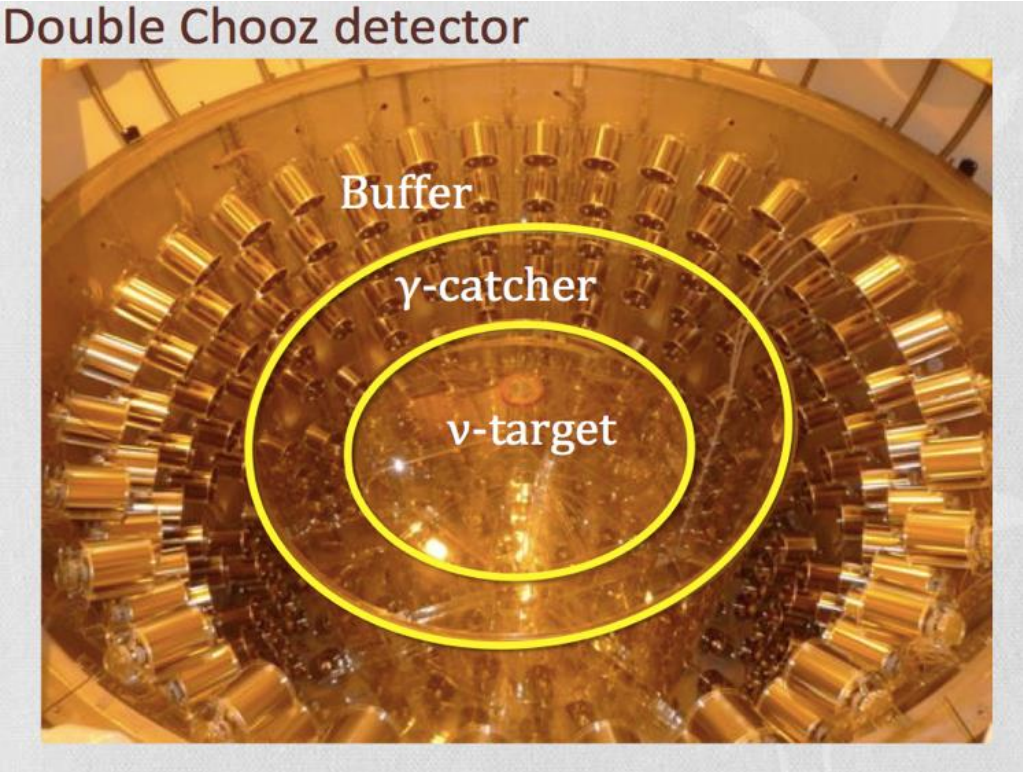


With new ^{92}Rb measurement



Dwyer, CIPANP 2015 talk

nH Rate + Shape fit



- Choose the delayed energy window of 1-4 MeV, instead of 4-10 MeV.
- Add gamma catcher region, which only contains hydrogen, without Gd.
- More backgrounds in low energy region.

nH Rate + Shape fit

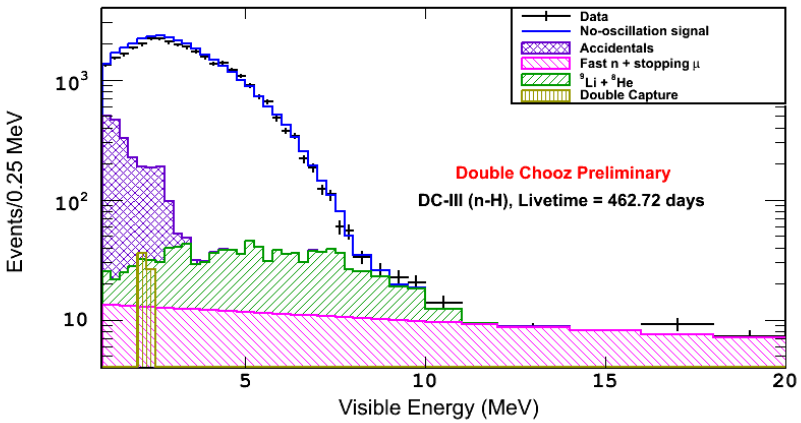
Parameter	Input C.V.	Input Error	Output C.V.	Output Error
E-scale a'	0	0.067	−0.008	+0.028, −0.020
E-scale b'	1.004	0.022	0.997	+0.007, −0.009
E-scale c'	−0.0001	0.0006	−0.0006	+0.0006, −0.0005
Li+He rate (d^{-1})	0.95	+0.57, −0.33	1.60	+0.22, −0.24
Accidentals rate (d^{-1})	4.334	0.007 (stat)	4.334	0.007 (stat)
		0.008 (syst)		0.008 (syst)
FN+SM rate (d^{-1})	1.55	0.15	1.62	0.10
FN+SM shape p_0	12.52	1.36	12.33	1.33
FN+SM shape p_1	0.042	0.015	0.037	+0.016, −0.009
FN+SM shape p_2	0.79	1.39	0.39	+1.49, −1.33
Residual $\bar{\nu}_e$	2.34	0.70	2.40	0.70
Δm^2 (10^{-3} eV^2)	2.44	+0.09, −0.10	2.44	+0.09, −0.10
$\sin^2 2\theta_{13}$	—	—	0.124	+0.030, −0.039
χ^2/d.o.f.	—	—	69.5 / 38 (Probability: 0.13%)	

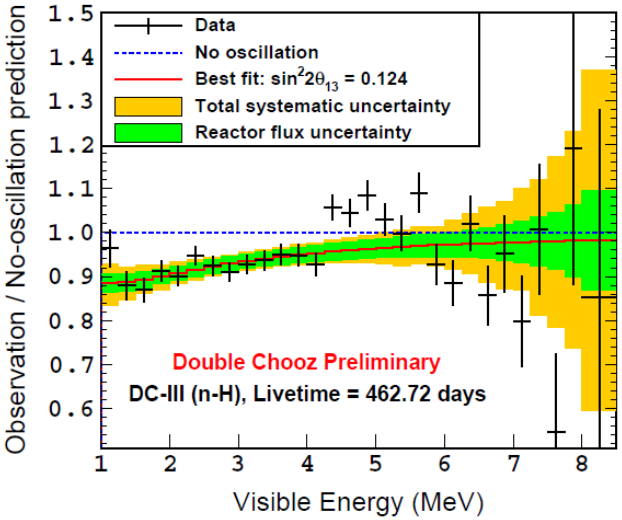
nGd result:

Δm^2 (10^{-3} eV^2)	2.44	+0.09, −0.10	2.44	+0.09, −0.10
$\sin^2 2\theta_{13}$	—	—	0.090	+0.032, −0.029
χ^2/d.o.f.	—	—	52.2/40	—

nH Rate + Shape fit

With the double neutron capture background





Handling the 5 MeV bump:

- Fit up to 4 MeV.
- Add a bump around 5 MeV.
- Increase the flux uncertainty on that region.

All of them give consistent results, which indicates that the bump does not exert significant effect to θ_{13}.

Reactor rate modulation fit

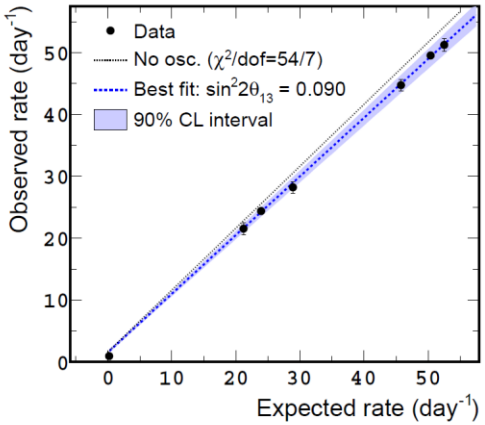
$$\chi^2 = \chi^2_{\rm on} + \chi^2_{\rm off} + \chi^2_{\rm bg} + \frac{\epsilon_{\rm d}^2}{\sigma_{\rm d}^2} + \frac{\epsilon_{\rm r}^2}{\sigma_{\rm r}^2} + \frac{\epsilon_\nu^2}{\sigma_\nu^2}$$

$$\chi^2_{\rm on} = \sum_{i=1}^{6} \frac{\left(R_i^{\rm obs} - R_i^{\rm exp} - B\right)^2}{(\sigma_i^{\rm stat})^2}$$

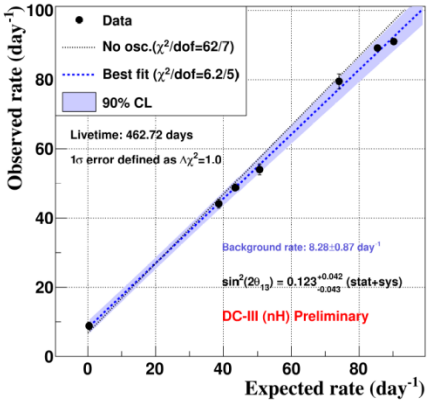
$$\chi^2_{\rm off} = 2\left[N_{\rm off}^{\rm obs} \ln\left(\frac{N_{\rm off}^{\rm obs}}{N_{\rm off}^{\rm exp}}\right) + N_{\rm off}^{\rm exp} - N_{\rm off}^{\rm obs}\right]$$

$$\chi^2_{\rm bg} = \frac{(B - B^{\rm exp})^2}{\sigma_{\rm bg}^2},$$

nGd channel



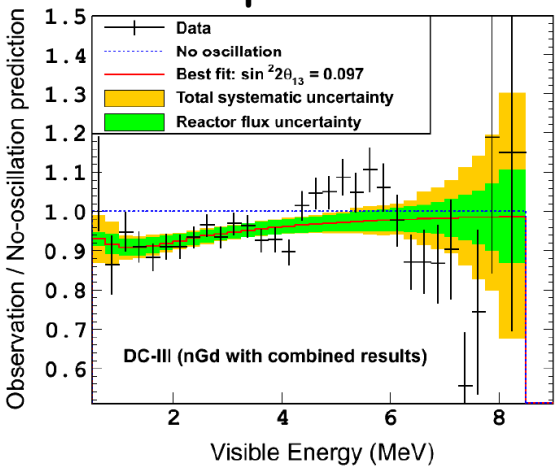
nH channel



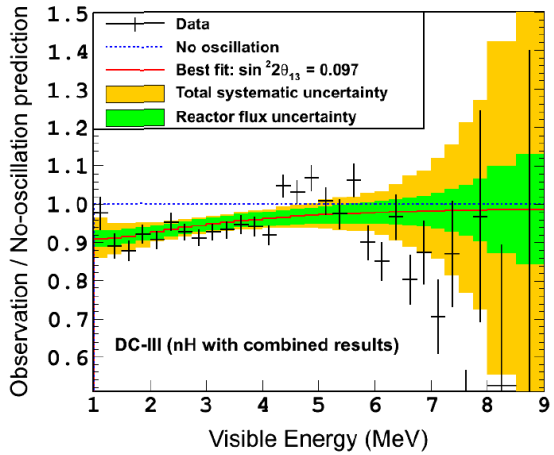
Combined Rate + Shape fit

	parameter	input	error	output	error
nGd	a'	-0.027	0.006	-0.026	0.006
	b'	1.012	0.008	1.007	0.006
	c'	-0.0001	0.0006	-0.0006	0.0006
	Li	0.97	+0.41, -0.16	0.7	0.14
	Residual $\overline{\nu}_e$	1.57	30%	1.50	30%
nH	a'	0	0.0345	-0.008	0.028
	b'	1.004	+0.57, -0.33	1.002	0.009
	c'	-0.0001	0.008	-0.0004	0.0006
	Li	0.95	0.15	1.9	0.34
	Residual $\overline{\nu}_e$	2.34	30%	2.4	30%
	$\sin^2 2\theta_{13}$			0.097	+0.032, -0.025
	χ^2/d.o.f			122.3/78	

Gd spectrum



H spectrum



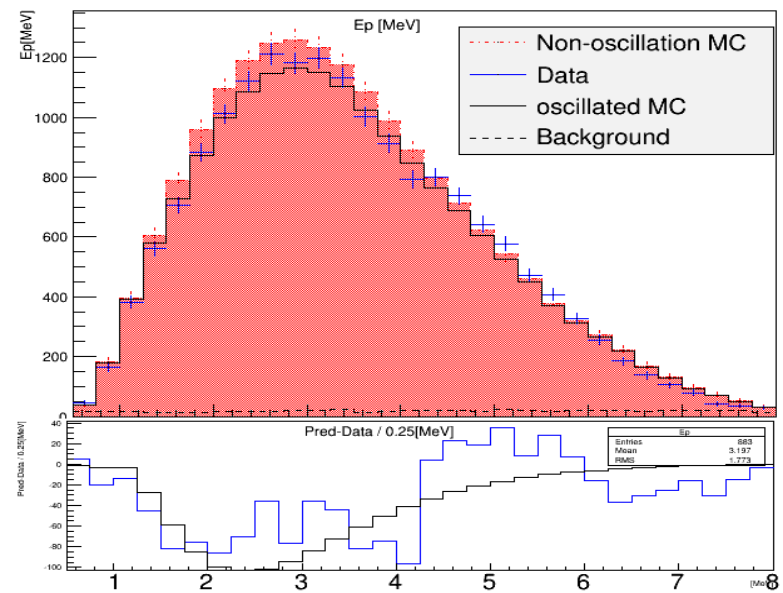
Near + Far fit

- Scale the near site data to directly compare to the far site data.
- The relative systematics and the visible-to-neutrino energy transformation should be carefully considered.
- Not heavily rely on the full MC chain.

$$\chi^2 = \sum_{i,j} (N_j^{\mathrm{f}} - w_j \cdot N_j^{\mathrm{n}})(V^{-1})_{ij}(N_i^{\mathrm{f}} - w_i \cdot N_i^{\mathrm{n}})$$

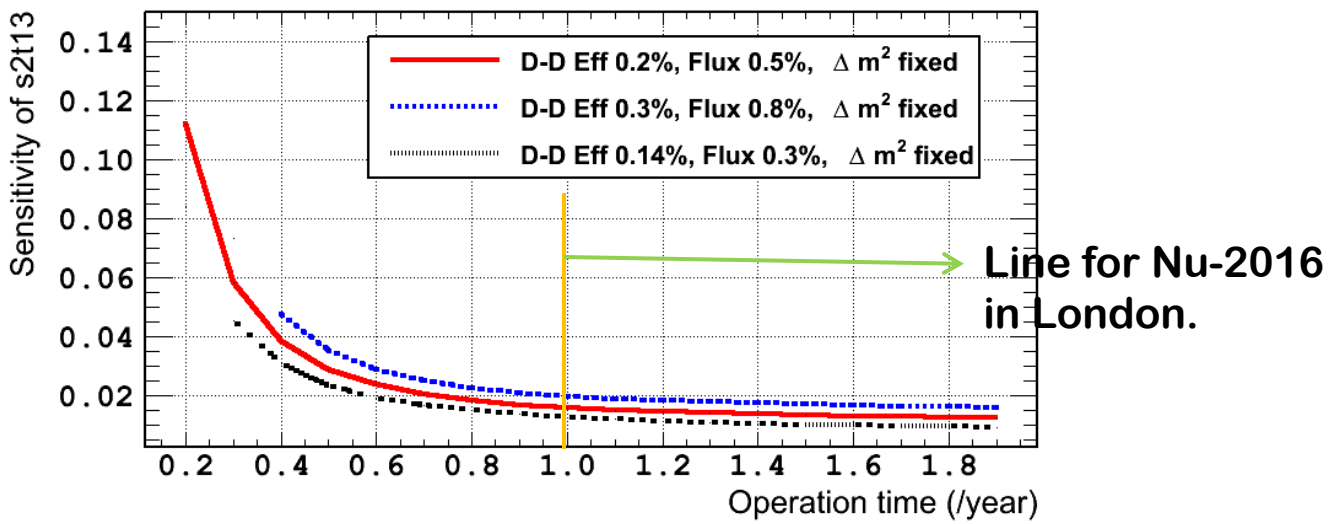
$$w_i^{\mathrm{SR}} = \frac{N_i^{\mathrm{f}}}{N_i^{\mathrm{n}}} = \left(\frac{T^{\mathrm{f}}}{T^{\mathrm{n}}}\right)\left(\frac{\epsilon^{\mathrm{f}}}{\epsilon^{\mathrm{n}}}\right)\left(\frac{L^{\mathrm{n}}}{L^{\mathrm{f}}}\right)^2\left(\frac{P_i^{\mathrm{f}}}{P_i^{\mathrm{n}}}\right)\left(\frac{\phi}{\phi}\right)$$

Here T is the number of target protons, ϵ is the efficiency, and L is the distance to the reactor for a given detector. P_i is the oscillation probability for the i-th reconstructed energy bin and ϕ the reactor antineutrino flux (which cancels from w_i).



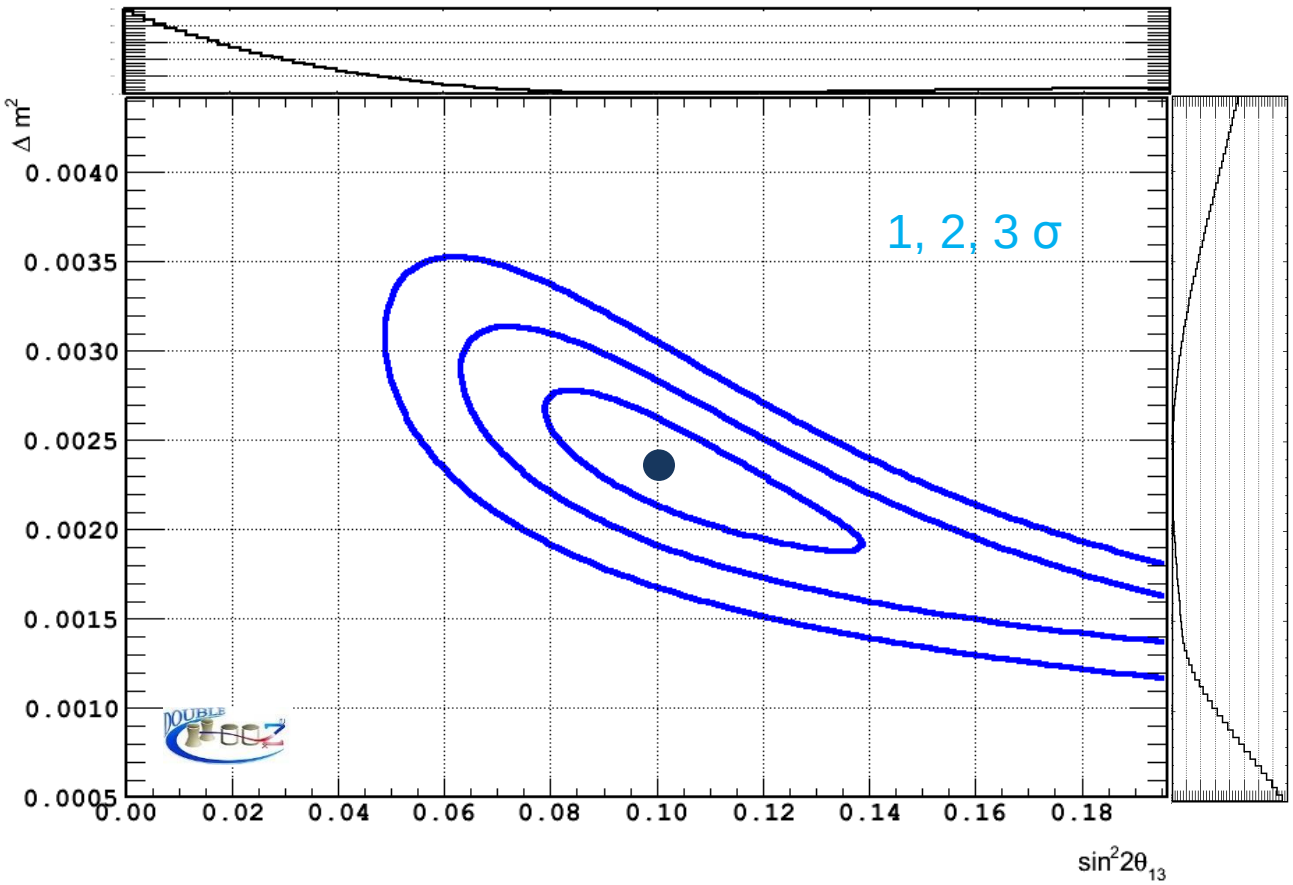
Near + Far fit

- With the near detector, the systematics, especially reactor flux, can be reduced significantly.
- In addition, the statistics can be increased significantly and more background events can make corresponding measurements more precise.



- Operation time from ND+FD (beginning of 2015). Always include the FD-only period.
- With the mass splitting fixed at the MINOS central value or having a pull with MINOS uncertainties.

Δm^2_{31} measure



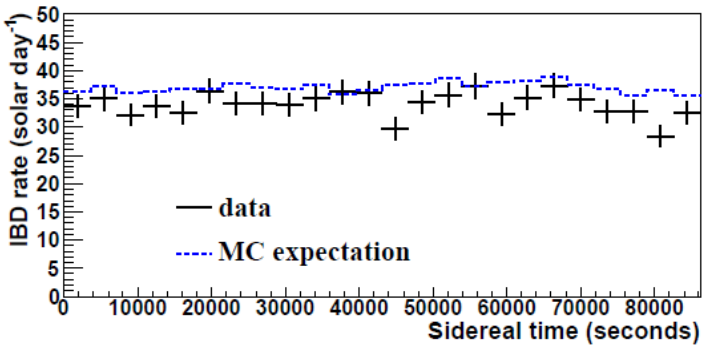
- Assume 0.14% Flux and 0.3% detection systematics with 1 year F+D run time.

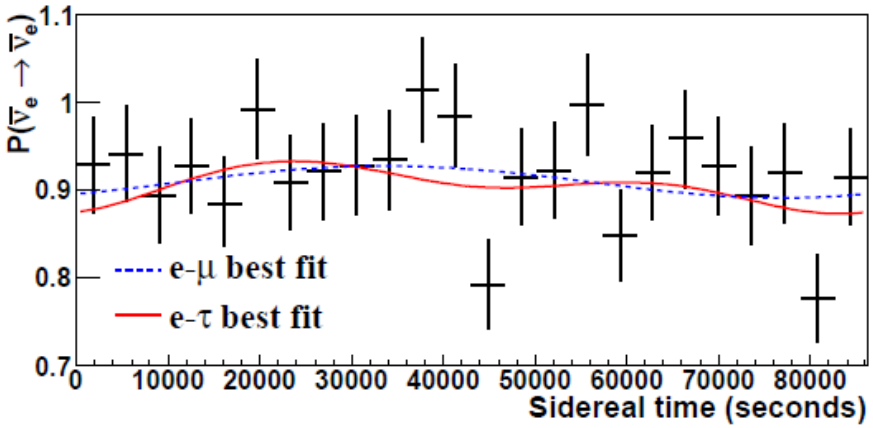
Other physics goals

Lorentz violation test

- From arXiv. 1209.5810:

We present a search for Lorentz violation with 8249 candidate electron antineutrino events taken by the Double Chooz experiment in 227.9 live days of running. This analysis, featuring a search for a sidereal time dependence of the events, is the first test of Lorentz invariance using a reactor-based antineutrino source. No sidereal variation is present in the data and the disappearance results are consistent with sidereal time independent oscillations. Under the Standard-Model Extension (SME), we set the first limits on fourteen Lorentz violating coefficients associated with transitions between electron and tau flavor, and set two competitive limits associated with transitions between electron and muon flavor.





- No sidereal variation found.
- Set limits to the SME coefficients.

Muon physics

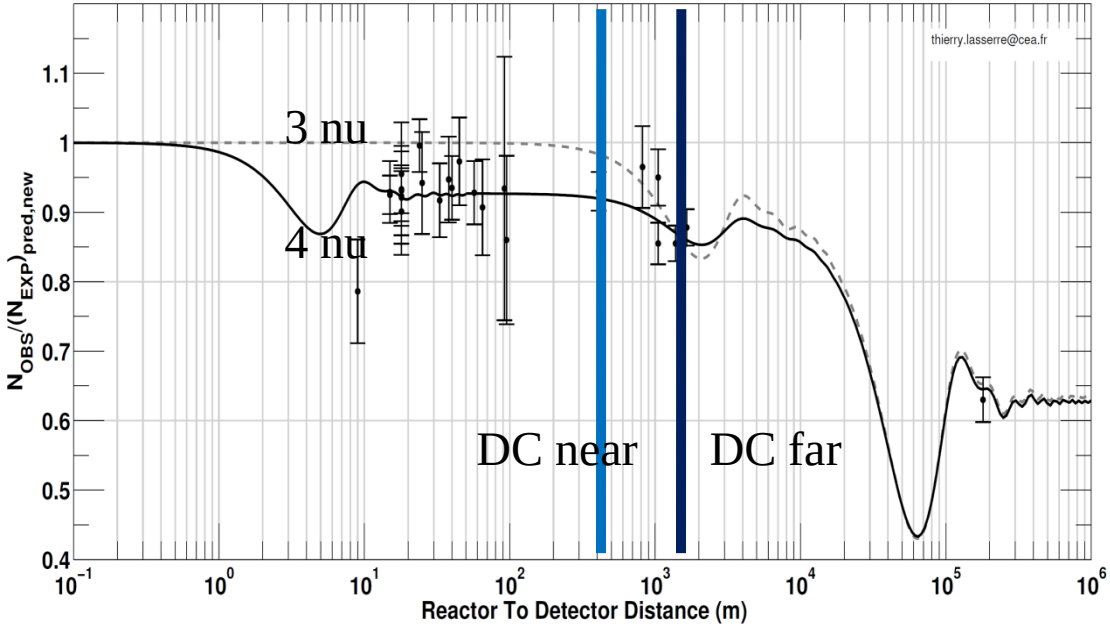
- **Muon reconstruction. arXiv.1405.6227.**

We describe a muon track reconstruction algorithm for the reactor anti-neutrino experiment Double Chooz. The Double Chooz detector consists of two optically isolated volumes of liquid scintillator viewed by PMTs, and an Outer Veto above these made of crossed scintillator strips. Muons are reconstructed by their Outer Veto hit positions along with timing information from the other two detector volumes. All muons are fit under the hypothesis that they are through-going and ultrarelativistic. If the energy depositions suggest that the muon may have stopped, the reconstruction fits also for this hypothesis and chooses between the two via the relative goodness-of-fit. In the ideal case of a through-going muon intersecting the center of the detector, the resolution is ~40 mm in each transverse dimension. High quality muon reconstruction is an important tool for reducing the impact of the cosmogenic isotope background in Double Chooz.

- **Muon capture rate measurements on ^{12}C, ^{13}C, ^{14}N and ^{16}O have been measured and will be published in a short time.**

- **Measurement of the yield rate for ^{9}Li, ^{8}He, ^{12}B, ^{12}N, ^{8}B and ^{8}Li is under preparation.**

Sterile neutrino search

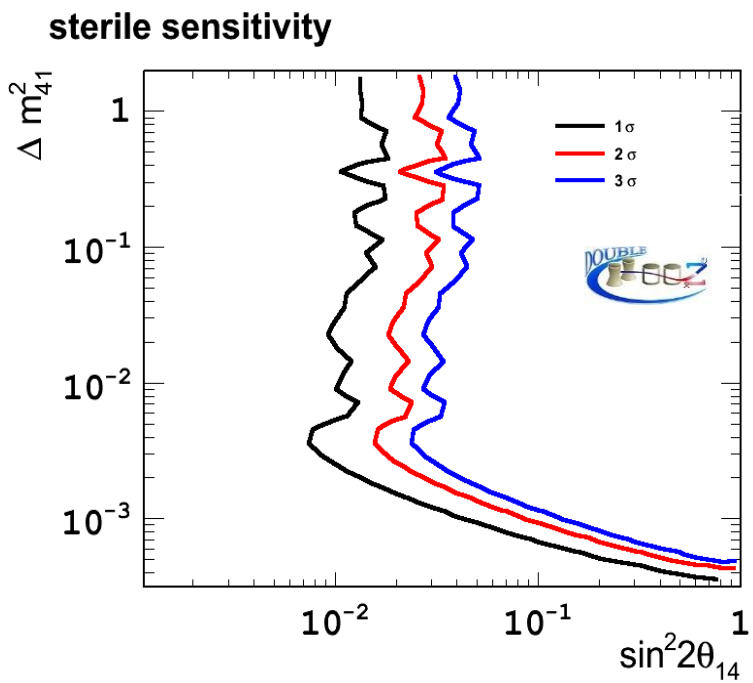


- For the Data-to-data comparison, we have good sensitivity to a light sterile neutrino.
- Formula used here:

$$
\begin{aligned}
P_{\mathrm{Th}}(\bar{\nu}_e \to \bar{\nu}_e) \;=\; & 1 - c_{14}^4 c_{13}^4 \sin^2 2\theta_{12} \sin^2(1.27\Delta m_{21}^2 \frac{L}{E}) \\
& - c_{14}^4 \sin^2 2\theta_{13} \sin^2(1.27\Delta m_{31}^2 \frac{L}{E}) \\
& - c_{13}^2 \sin^2 2\theta_{14} \sin^2(1.27\Delta m_{41}^2 \frac{L}{E}) \\
& - s_{13}^2 \sin^2 2\theta_{14} \sin^2(1.27\Delta m_{43}^2 \frac{L}{E})
\end{aligned}
$$

Sterile neutrino search

Data-to-data with conventional χ^2 method



- Assume 0.14% Flux and 0.3% detection systematics with 1 year F+D run time.

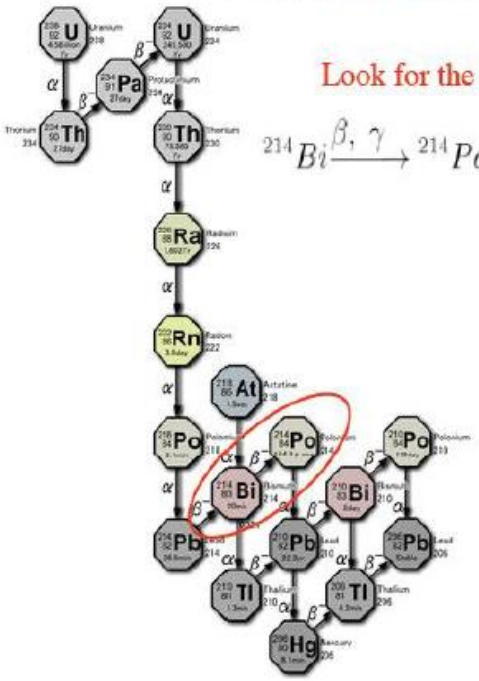
Conclusion

- Double Chooz is the first one that reported a non-zero θ_{13} value. (arXiv:1112.6353)
- Double Chooz nGd + nH combined fit gives $\sin^2 2\theta_{13} = 0.097^{+0.032}_{-0.025}$.
- Double Chooz is in the two-detector phase and will provide precise measurement of θ_{13} with major systematic error cancellation. It will have competitive results to Daya Bay and RENO. Double Chooz and Daya Bay are likely to have a combined result after the Nu-2014@London.
- Beyond that, Double Chooz is a playground for lots of other physics researches. We are entering a productive period.

Near and Far comparison

- With six months data, use radioactive chains:

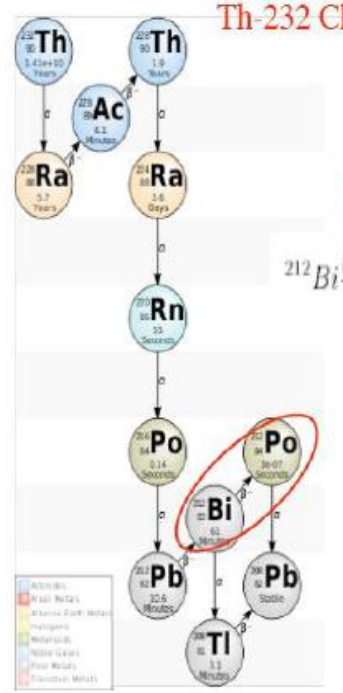
U-238 Chain Radioactive decays



Look for the coincidence:

$$^{214}Bi \xrightarrow{\beta,\ \gamma} {}^{214}Po(\tau = 236\ \mu s) \xrightarrow[7.687\ MeV]{\alpha} {}^{210}Pb.$$

Th-232 Chain Radioactive decays

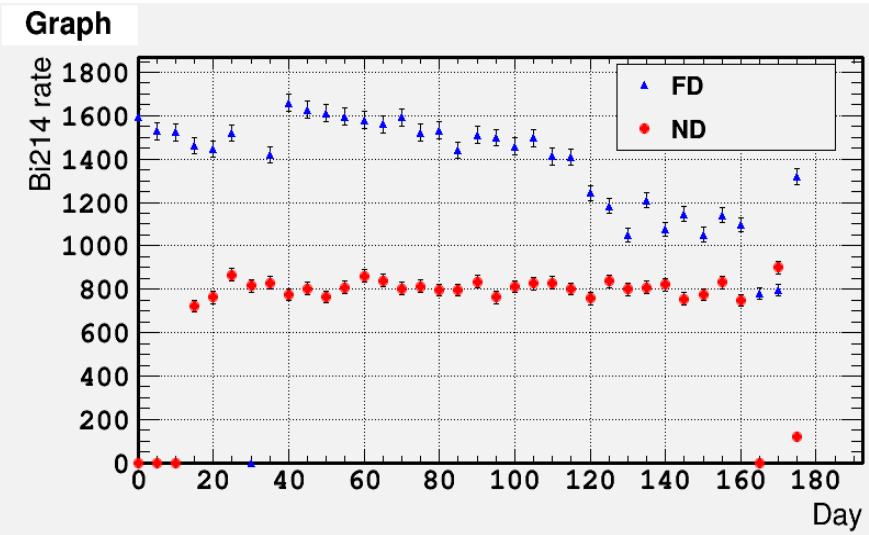


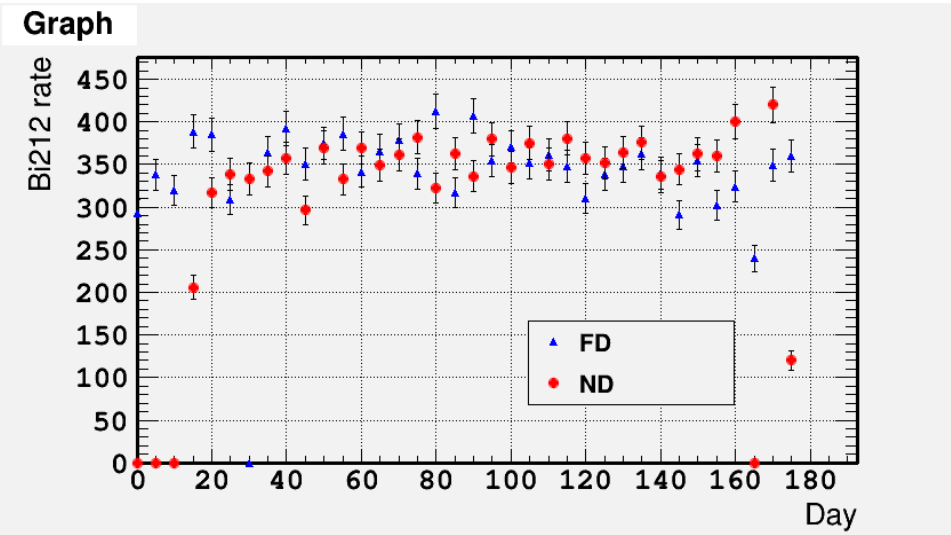
Look for the coincidence:

$$^{212}Bi \xrightarrow{\beta,\ \gamma} {}^{212}Po(\tau = 433\ ns) \xrightarrow[8.784\ MeV]{\alpha} {}^{208}Pb$$

Near and Far comparison

- Event rates for the near detector and far detector

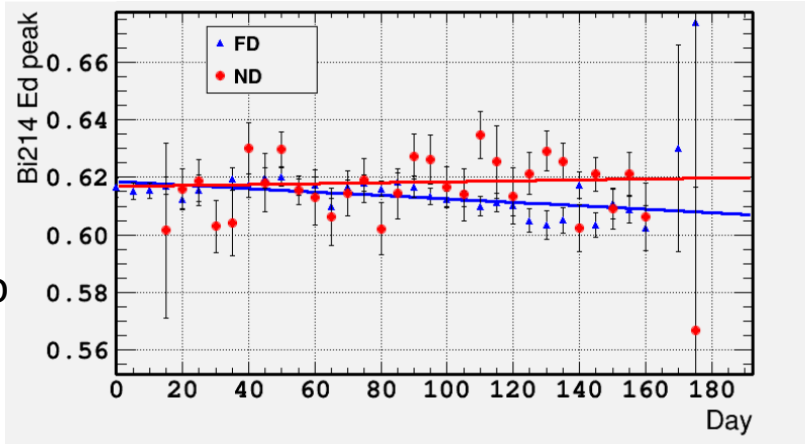




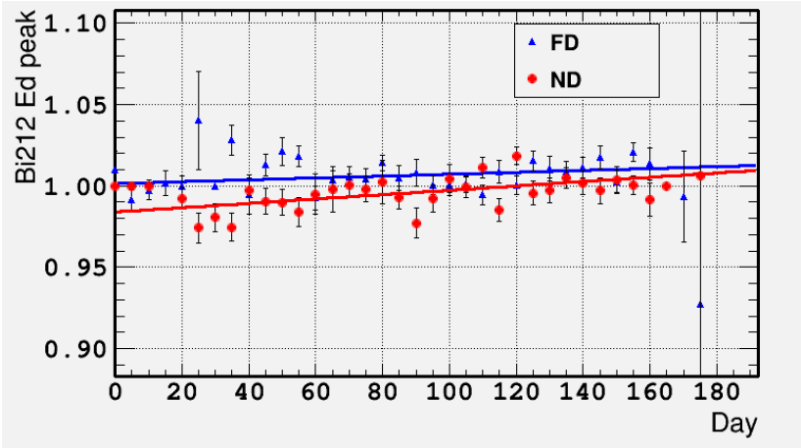
Near and Far comparison

delayed α energy

Po



Po



- From the α energy, we can postulate the quenching factor for different detector volumes.

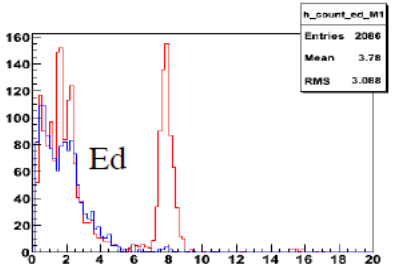
Quenching factor

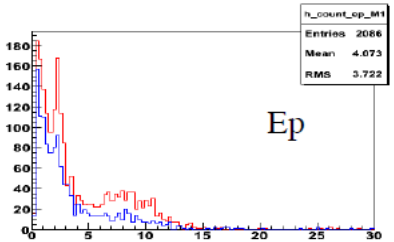
		Bi214		Bi212	
		Lab measure	our measure	Lab measure	our measure
FD	NT	9.8 +- 0.4	9.60 +- 0.04	\	8.74 +- 0.06
	GC	12.6 +- 0.6	12.32 +- 0.09	\	11.39 +- 0.07
ND	NT	9.8 +- 0.4	9.64 +- 0.04	\	8.78 +- 0.08
	GC	12.6 +- 0.6	12.20 +- 0.09	\	11.31 +- 0.07

-Red histogram is the on-time window. 0-1000 μs from prompt event.
-Blue histogram is the off-time window. 1000-2000 μs from prompt event.
- An average 3.75 neutrons will be generated after a prompt gamma in the Cf-252 decay.

Delayed energy | **Prompt energy**

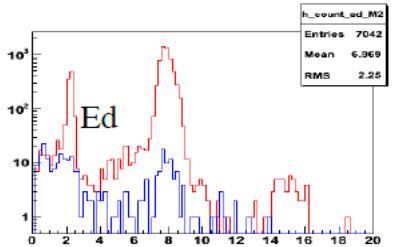
M=1

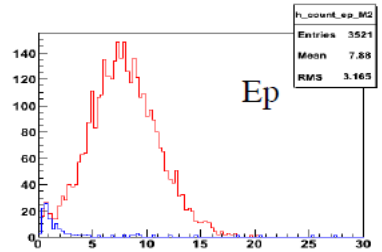




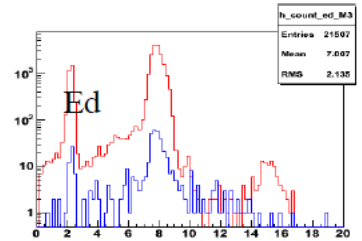
Expected M=3.75

M=2

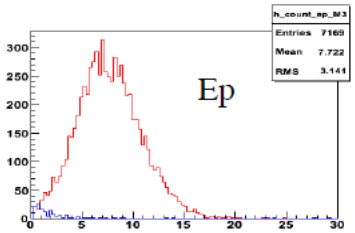




M=3



The red histogram: on-time window.
The blue histogram: off-time window

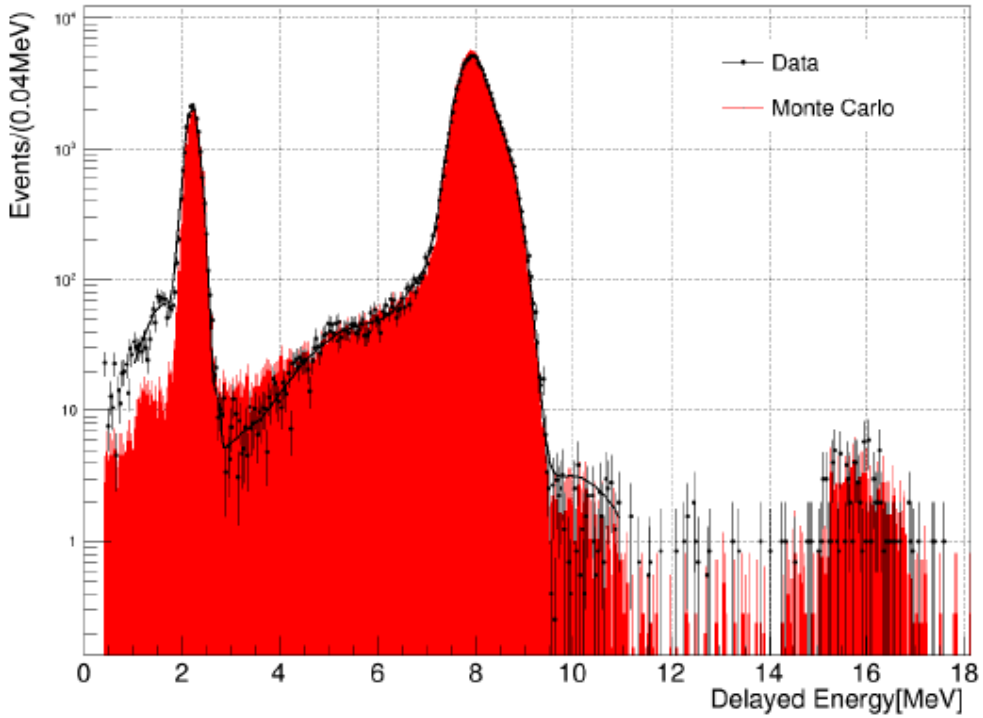


4

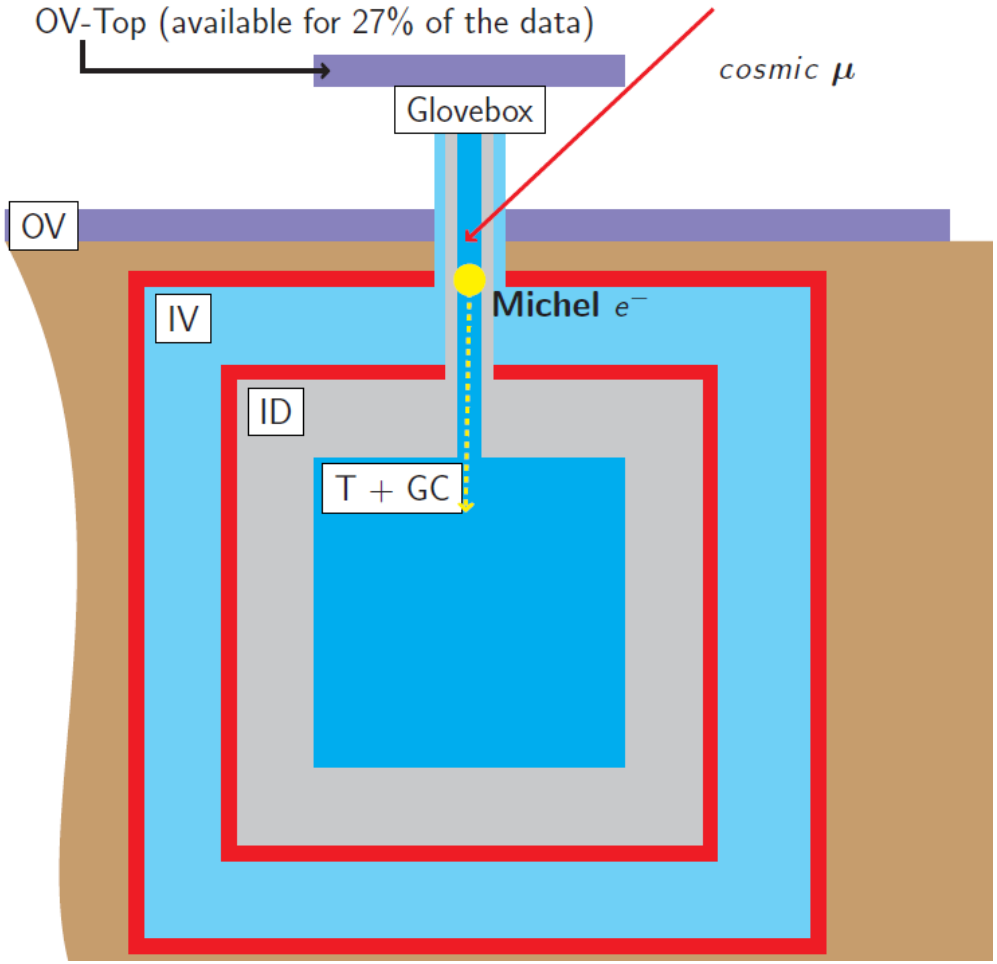
Gd/H fraction

$$Gd\ fraction = \frac{N_{event}[4 < Ed < 10MeV]}{N_{event}[1 < Ed < 10MeV]}$$

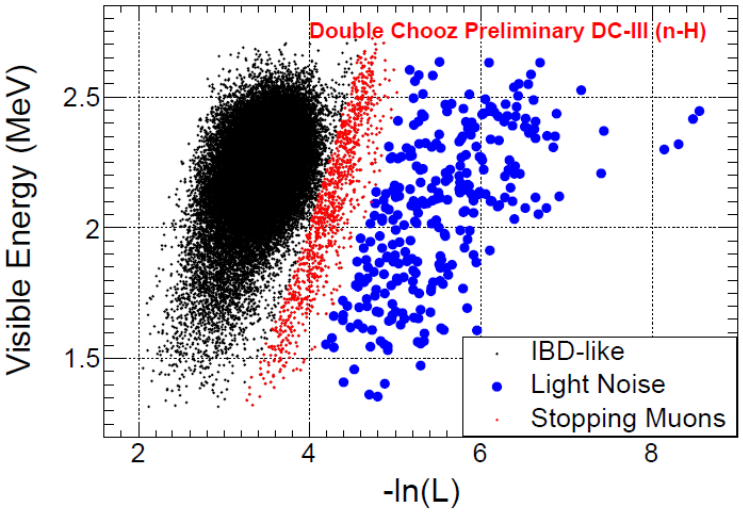
Ed [MeV]



Stopping muons



Point-like likelihood



nH Rate + Shape fit

- Differences to the nGd Rate + Shape fit:

  - Contains gamma catcher volume, so the MC corrections are different for different regions.
  - The fast neutrons are not exactly flat. It is described by an exponential function, so the shape parameters are also taken into account.
  - Increase the visible energy threshold.
  - Nonlinearity behaviors are opposite in the target and gamma catcher, so almost no constraints assigned for the energy scale parameters.
  - Potentially, Having a new background, double nH capture, has negligible impact on the fit results.

Combined Rate-only fit

$$\chi^2 = \left(N_{nGd}^{pred} - N_{nGd}^{obs}, N_{nH}^{pred} - N_{nH}^{obs}\right) M^{-1} \begin{pmatrix} N_{nGd}^{pred} - N_{nGd}^{obs} \\ N_{nH}^{pred} - N_{nH}^{obs} \end{pmatrix}$$

$$+\frac{(\Delta m^2 - \Delta m_{ee}^2)^2}{\sigma_{ee}^2}$$

$$+[(BG_{Gd} - BG_{GdCV}), (BG_H - BG_{HCV})]\times$$

$$\begin{pmatrix} (\sigma_{BG_{Gd}})^2 & \rho_{BG_{Gd}BG_H}(\sigma_{BG_{Gd}}\sigma_{BG_H}) \\ \rho_{BG_{Gd}BG_H}(\sigma_{BG_{Gd}}\sigma_{BG_H}) & (\sigma_{BG_H})^2 \end{pmatrix}^{-1}$$

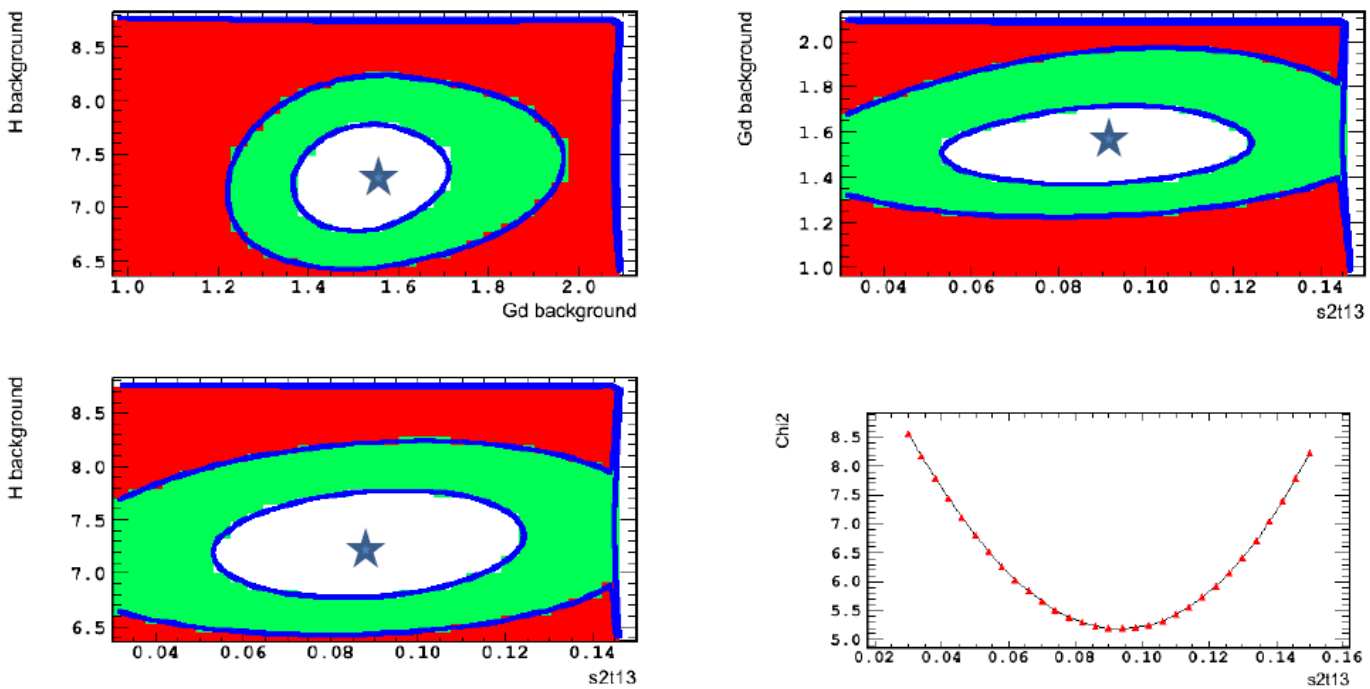
$$\times \begin{bmatrix} (BG_{Gd} - BG_{GdCV}) \\ (BG_H - BG_{HCV}) \end{bmatrix}$$

$$+ \sum_{Gd}^{H} 2\left(N_{off}^{obs} \cdot \ln\left[\frac{N_{off}^{obs}}{N_{off}^{pred}}\right] + N_{off}^{pred} - N_{off}^{obs}\right),$$

- Bullet natrual to combine

- **Since the baseline is degenerate, this can only add limited statistics. Therefore, we do not expect much improvement on the result.**

Combined Rate-only fit



$\sin^2 2\Theta_{13} = 0.092 +-0.034$ χ^2 / d.o.f = 5.2 / 3

- Here assume 0% correlation between the nGd background and nH background. However, adding up to 90% correlation, results are consistent.

Combined Rate + Shape fit

$$\chi^2 = \sum_i^B \sum_j^B (N_i^{pred} - N_i^{obs})\, M_{ij}^{-1}\, (N_j^{pred} - N_j^{obs}) + \frac{(\Delta m^2 - \Delta m^2_{ee})^2}{\sigma^2_{ee}} + \sum_{Gd}^{H} \frac{(b' - b'_{CV})^2}{\sigma^2_{b'}}$$

$$+(a', c' terms) + [(FN_{p0} - FN_{p0CV}), (FN_{p1} - FN_{p1CV}), (FN_{p2} - FN_{p2CV})] \times$$

$$\begin{pmatrix} (\sigma_{FN_{p0}})^2 & \rho_{FN_{p0}FN_{p1}}(\sigma_{FN_{p0}}\sigma_{FN_{p1}}) & \rho_{FN_{p0}FN_{p2}}(\sigma_{FN_{p0}}\sigma_{FN_{p2}}) \\ \rho_{FN_{p1}FN_{p0}}(\sigma_{FN_{p1}}\sigma_{FN_{p0}}) & (\sigma_{FN_{p1}})^2 & \rho_{FN_{p1}FN_{p2}}(\sigma_{FN_{p1}}\sigma_{FN_{p2}}) \\ \rho_{FN_{p2}FN_{p0}}(\sigma_{FN_{p2}}\sigma_{FN_{p0}}) & \rho_{FN_{p2}FN_{p1}}(\sigma_{FN_{p2}}\sigma_{FN_{p1}}) & (\sigma_{FN_{p2}})^2 \end{pmatrix}^{-1}$$

$$\times \begin{bmatrix} (FN_{p0} - FN_{p0CV}) \\ (FN_{p1} - FN_{p1CV}) \\ (FN_{p2} - FN_{p2CV}) \end{bmatrix}$$

$$+ \sum_{Li/He}^{FN/SM} [(BG_{Gd} - BG_{GdCV}), (BG_H - BG_{HCV})] \times$$

$$\begin{pmatrix} (\sigma_{BG_{Gd}})^2 & \rho_{BG_{Gd}BG_H}(\sigma_{BG_{Gd}}\sigma_{BG_H}) \\ \rho_{BG_{Gd}BG_H}(\sigma_{BG_{Gd}}\sigma_{BG_H}) & (\sigma_{BG_H})^2 \end{pmatrix}^{-1}$$

$$\times \begin{bmatrix} (BG_{Gd} - BG_{GdCV}) \\ (BG_H - BG_{HCV}) \end{bmatrix}$$

$$+ \sum_{Gd}^{H} 2 \left(N_{off}^{obs} \cdot \ln \left[\frac{N_{off}^{obs}}{N_{off}^{pred}} \right] + N_{off}^{pred} - N_{off}^{obs} \right).$$

BACKUP

- Spectrum contains Gd and H.
- For the nonlinear energy model, pulls for a' and c' are added to second line.
- FN shape for H only.
- Background rates are uncorrelated

Near + Far fit

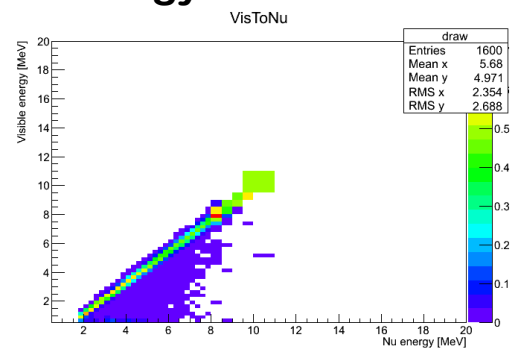
- Scale the near site data to directly compare to the far site data.
- The relative systematics and the visible-to-neutrino energy transformation should be carefully considered.
- Not heavily rely on the full MC chain.

$$\chi^2 = \sum_{i,j} (N_j^{\mathrm{f}} - w_j \cdot N_j^{\mathrm{n}})(V^{-1})_{ij}(N_i^{\mathrm{f}} - w_i \cdot N_i^{\mathrm{n}})$$

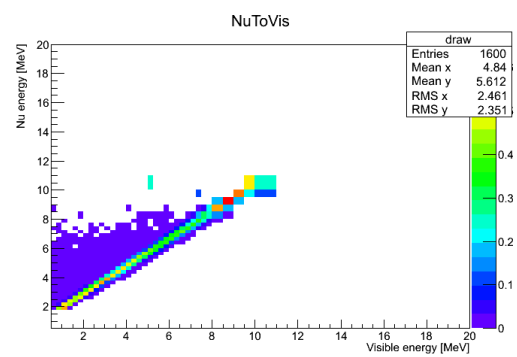
$$w_i^{\mathrm{SR}} = \frac{N_i^{\mathrm{f}}}{N_i^{\mathrm{n}}} = \left(\frac{T^{\mathrm{f}}}{T^{\mathrm{n}}}\right)\left(\frac{\epsilon^{\mathrm{f}}}{\epsilon^{\mathrm{n}}}\right)\left(\frac{L^{\mathrm{n}}}{L^{\mathrm{f}}}\right)^2\left(\frac{P_i^{\mathrm{f}}}{P_i^{\mathrm{n}}}\right)\left(\frac{\phi}{\phi}\right)$$

Here T is the number of target protons, ϵ is the efficiency, and L is the distance to the reactor for a given detector. P_i is the oscillation probability for the i-th reconstructed energy bin and ϕ the reactor antineutrino flux (which cancels from w_i).

Visible energy to Neutrino energy

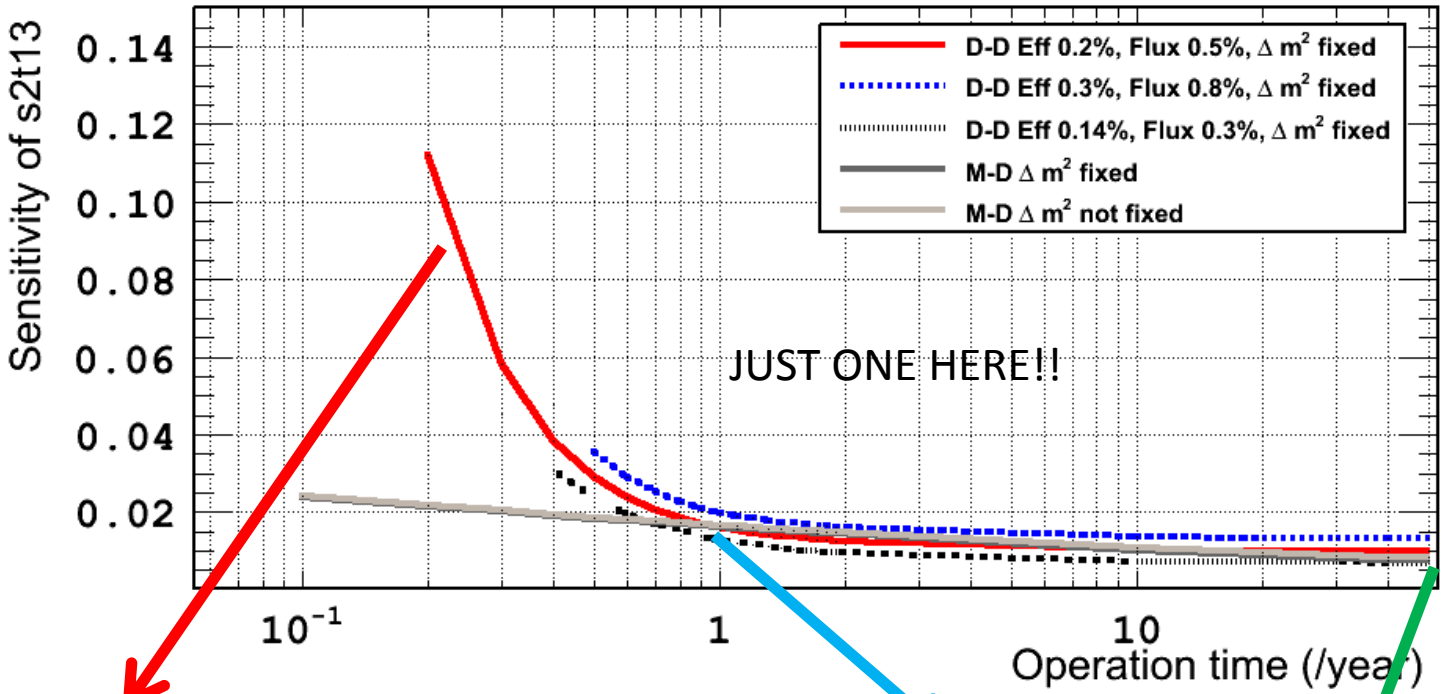


Neutrino energy to visible energy



Near + Far fit

-M-D: Assume ~80% correlated reactor flux and ~93% correlated detection systematics.



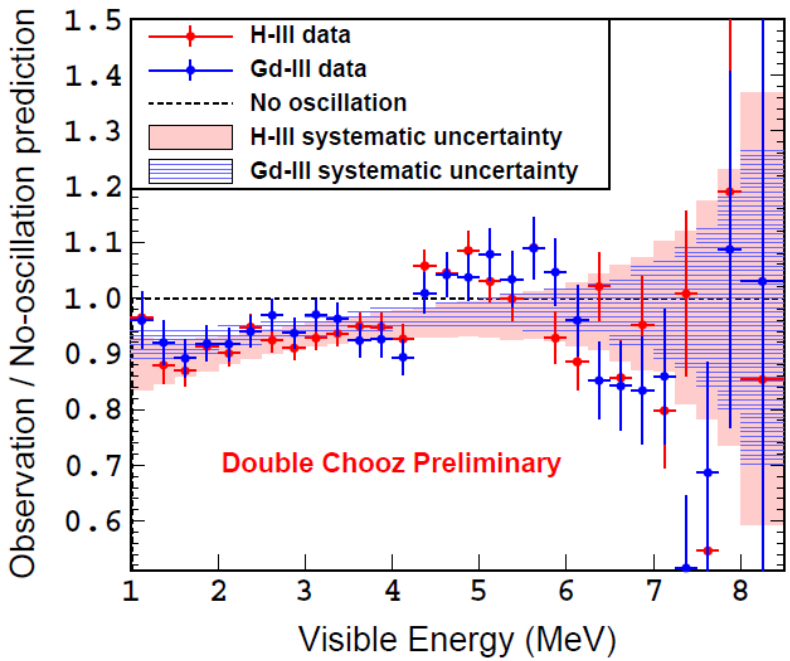
Statistics on the ND is too low, although normalized to the FD statistics, the bin contents are not precise to match the FD. so the sensitivity is bad initially.

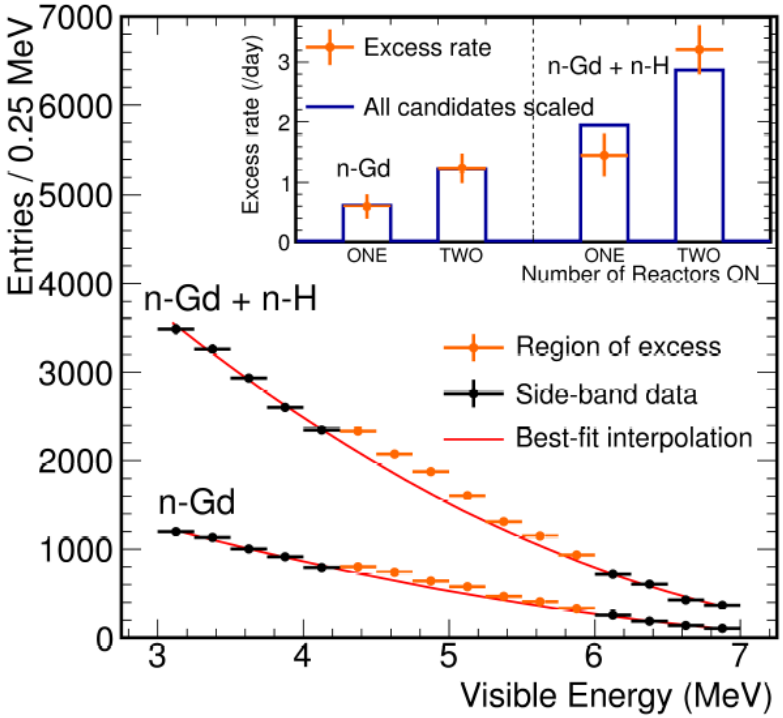
As the ND bin contents formed, the D-D case has better sensitivity because the ND takes advantage of the FD statistics.

Eventually they are equivalent.

Reactor flux measurement

BACKUP!!





- 5MeV bump is from the mismodelling of the reactor spectrum.
- Near detector is powerful to provide a precise reactor antineutrino spectrum.

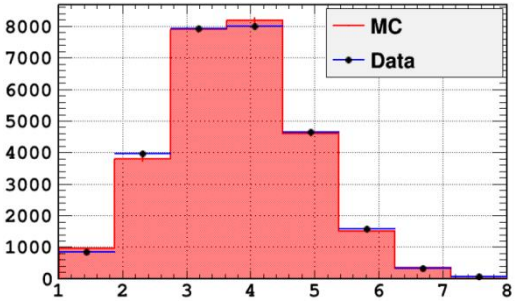
^{252}Cf spontaneous fission study

^{252}Cf neutron multiplicity

- ^{252}Cf spontaneous fission emits multiple gammas and multiple neutrons.
- The gammas are detected immediately but the neutrons scatter in the detector and are captured by H or Gd later.
- Our detector resolution is around 112ns. We cannot distinguish the gammas but we can see multiple neutron captures.
- We use the source deployed at the target center.

Neutron Multiplicity

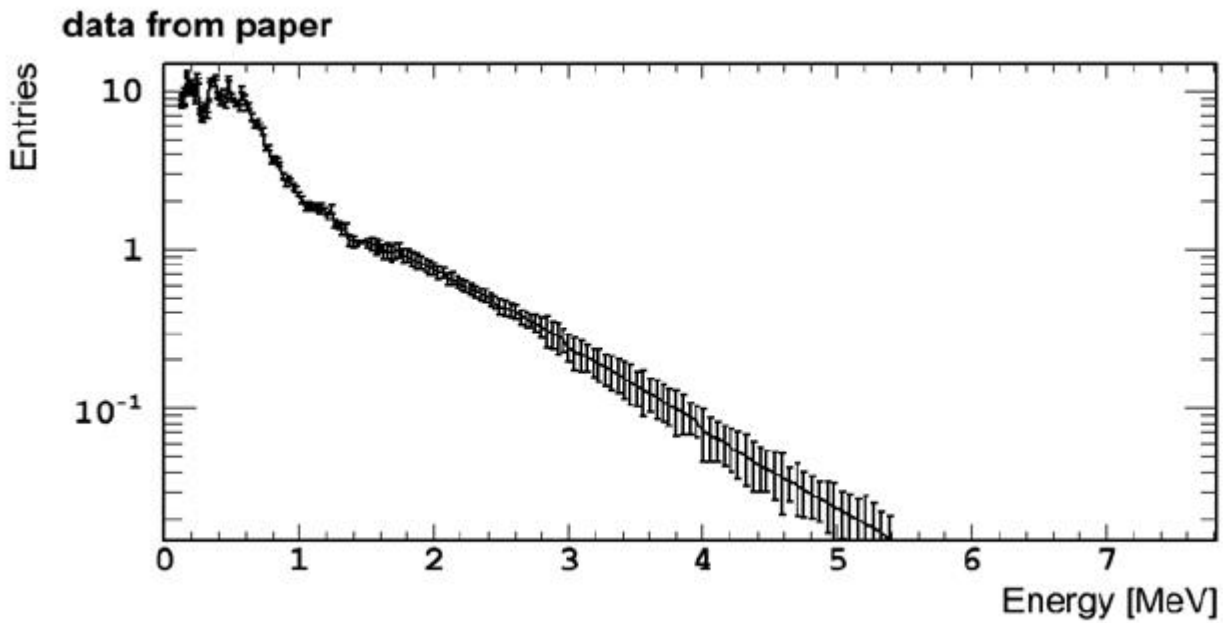
Multiplicity	1	2	3	4	5	6	7	8	ave.
250Cf	0.03654	0.1673	0.2945	0.2983	0.1451	0.0472	0.0040	0.0031	N/A
252Cf	0.0262	0.1262	0.2752	0.3018	0.1846	0.0668	0.0150	0.0021	N/A
combined	0.0274	0.1309	0.2774	0.3014	0.1800	0.0645	0.0137	0.0022	3.7281
Data									3.680



- Data has lower neutron multiplicity. It is because the merging of two neutrons. It is studied using MC.

^{252}Cf gamma prompt spectrum

- A combination of the single gamma energy and the gamma multiplicity
- Single gamma energy (R.Billnert, 2013.):



^{252}Cf gamma prompt spectrum

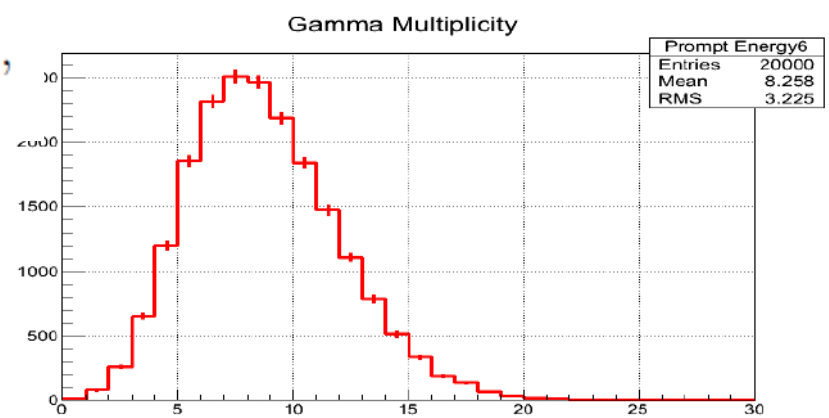
- **Gamma multiplicity:**

$$D(G) = C_1 \frac{C_2^G e^{-C_2}}{G} + (1 - C_1) \frac{C_3^G e^{-C_3}}{G},$$

- **C_1, C_2 and C_3 are free parameters, as we know the central values of the single gamma Energy and the total gamma energy, those parameters can be obtained from a fit:**

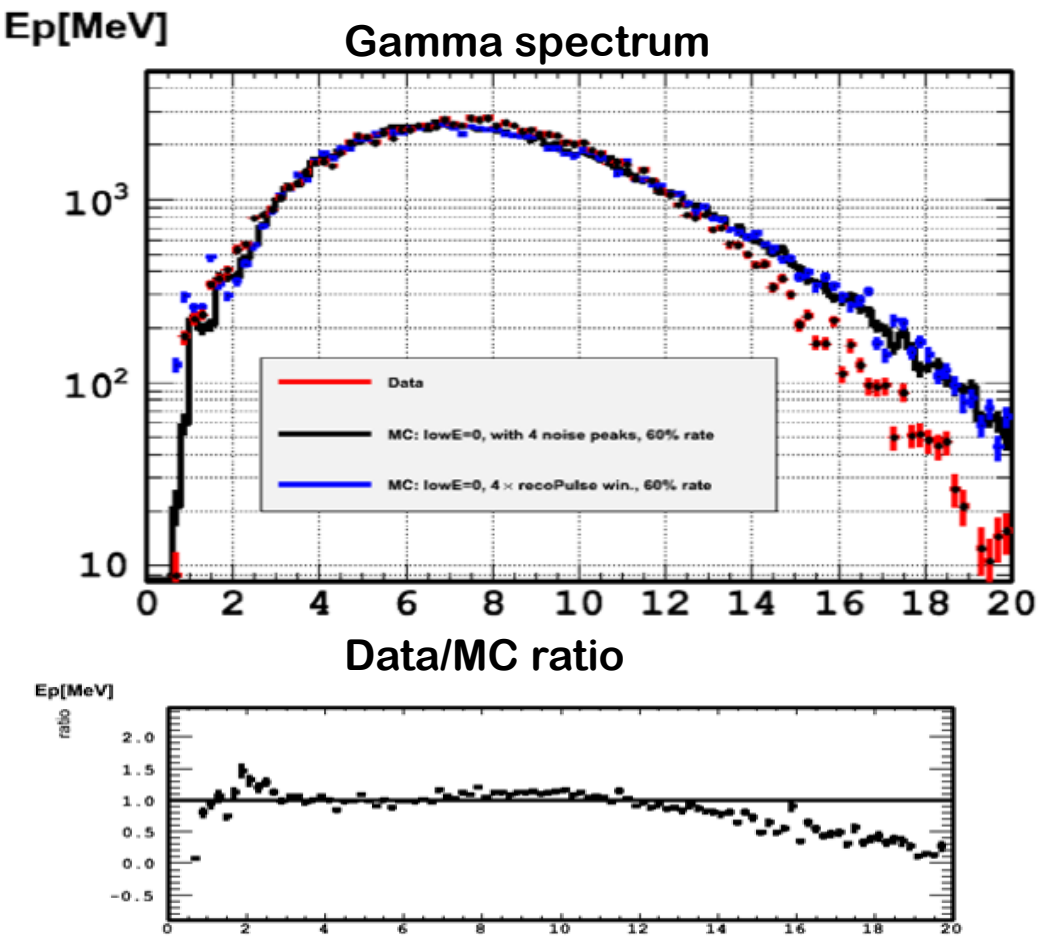
$$\chi^2 = \left(\frac{M_{single} - CV_{single}}{\sigma_{single}}\right)^2 + \left(\frac{M_{tot.} - CV_{tot.}}{\sigma_{tot.}}\right)^2,$$

	C_1	C_2	C_3
[3]	0.71	7.33	10.10



[3]: the central values are taken from R. Billnert, 2013

Prompt gamma spectrum



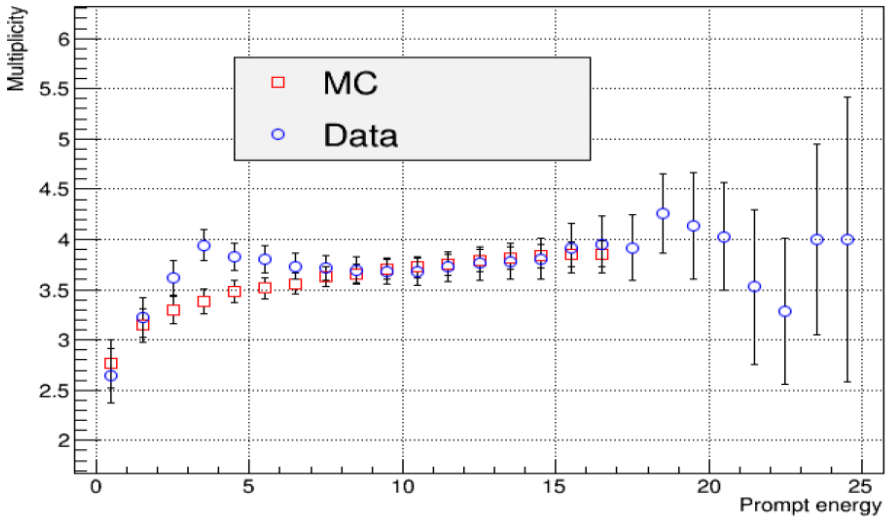
- Assume the energy of the single gamma below 0.2 MeV is 0.
- Add some low energy backgrounds to match the data at low energy region
- High energy discrepancy is under investigation.

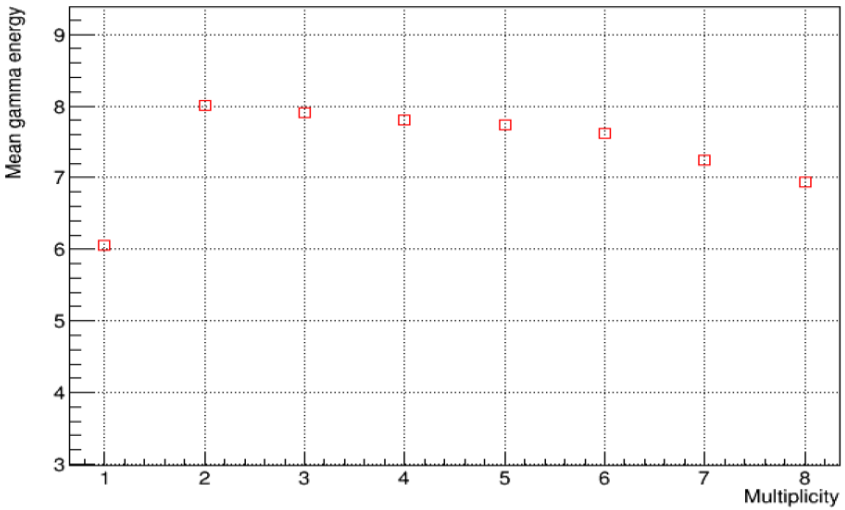
- Paper of T.E.Valentine ,1999 demonstrate that:

$$E_t(\nu) = 0.75\nu + 4.0,$$

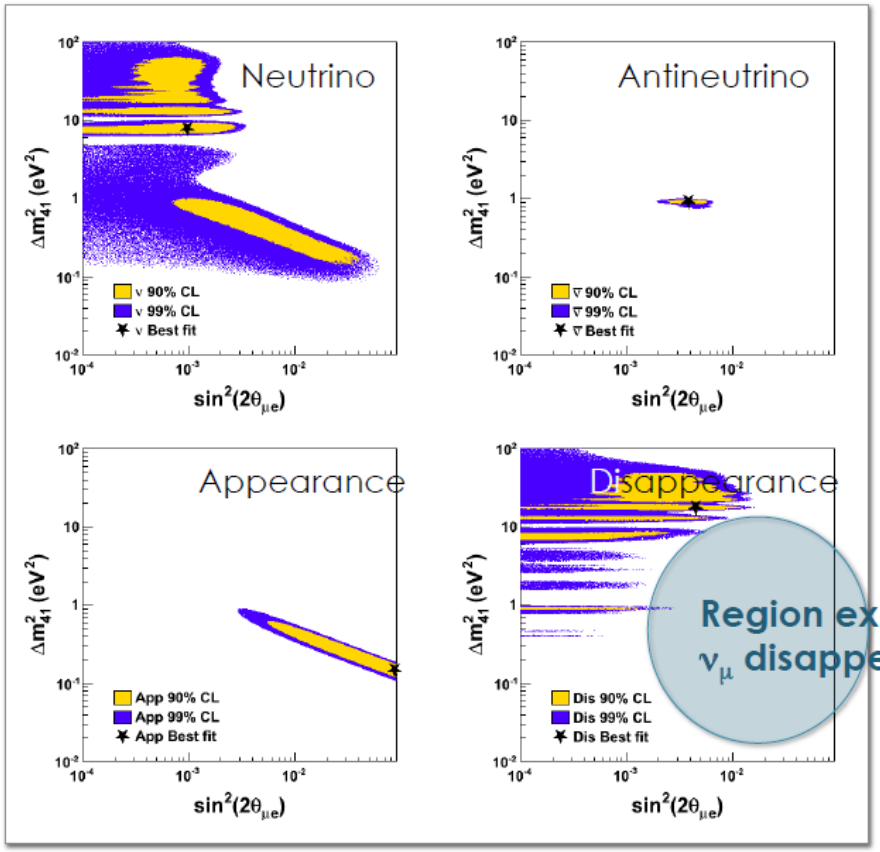
where E is gamma energy and ν is neutron multiplicity.

- In our data:





Sterile neutrino search



Compatibility $(\nu, \bar{\nu})$ = 0.14%

Compatibility (app, dis) = 0.013%

Region excluded from ν_μ disappearance experiments

[2] **slide from G. Karagiorgi presented at the Nu@Fermilab workshop.**

- All allowed region has been completely excluded for the 3+1 model.