Double Chooz: Towards the near Detector Phase

Vulcano Workshop 2014

Lee Stokes for the Double Chooz Collaboration

Neutrino Oscillations

Neutrino oscillations occur as a result of **non-zero neutrino masses** and **mixing of flavour & mass eigenstates** as:

$$s_{ij} = \sin\theta_{ij}, c_{ij} = \cos\theta_{ij}$$

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

Flavour eigenstate	atmos. / acceler. $\nu_\mu \to \nu_\mu$	reactor / accelerator $\nu_e \to \nu_e$ / $\nu_\mu \to \nu_e$	solar $\nu_e \to \nu_e$	Mass eigenstate

Neutrino oscillation $\overline{\nu}_e$ survival probability, short baseline

Mixing Angle — Mass difference

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

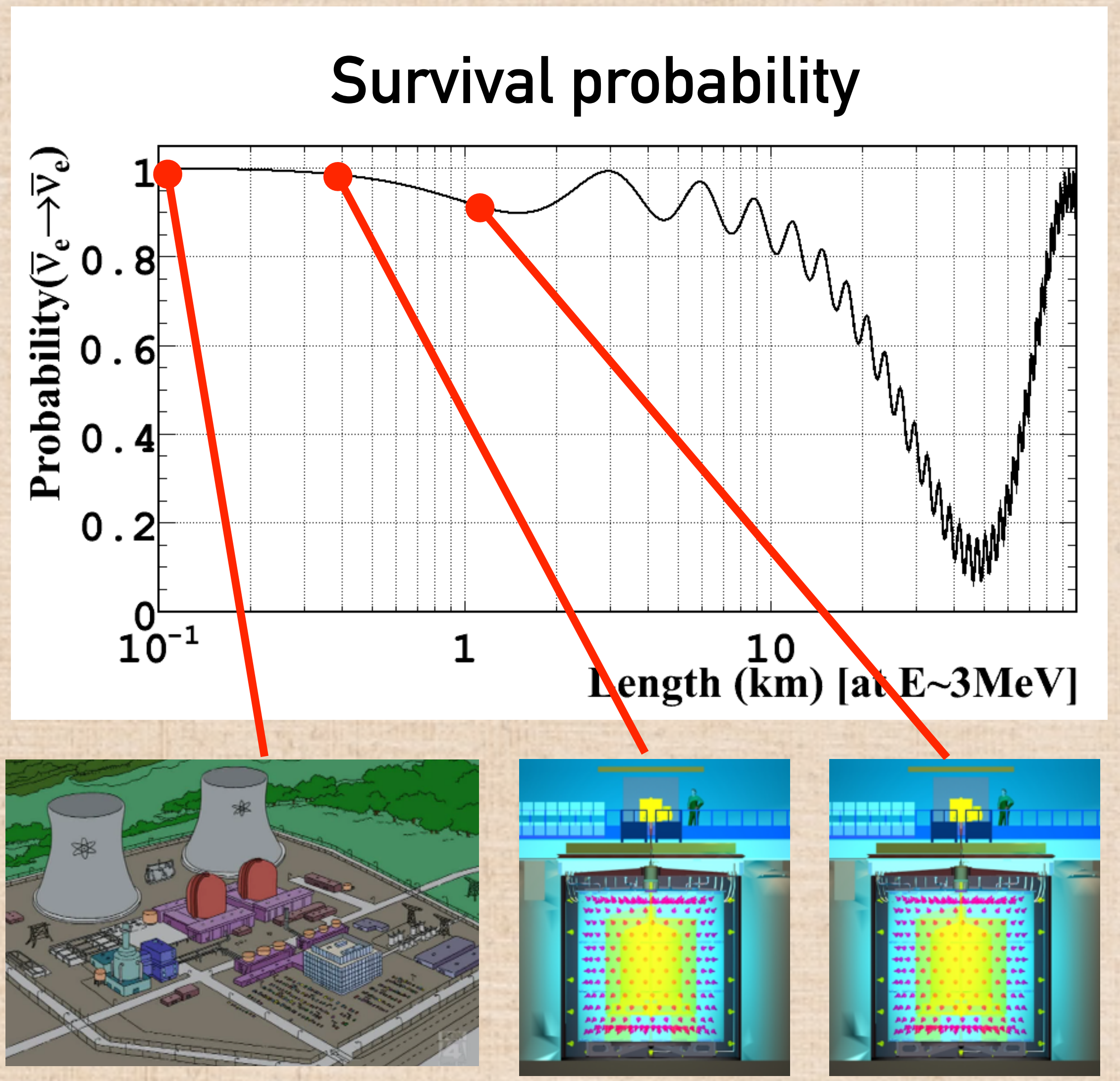
Until recently, θ_{13} was the only unknown mixing angle

- ➛ First result shown in 2011 by Double Chooz
- ➛ 2012 measured by Double Chooz, Daya Bay & Reno

θ_{13} needed to explore CP violation via the phase δ and mass hierarchy

θ_{13} from Reactor Anti-Neutrinos

- Reactors are a free & rich source of electron antineutrinos
- Direct measurement θ_{13} from $\overline{\nu}_e$ disappearance
- Reduction systematic uncertainties using two detectors at different baselines



Ratio	Ratio	Proton number	Baseline	Efficiency	Survival probability

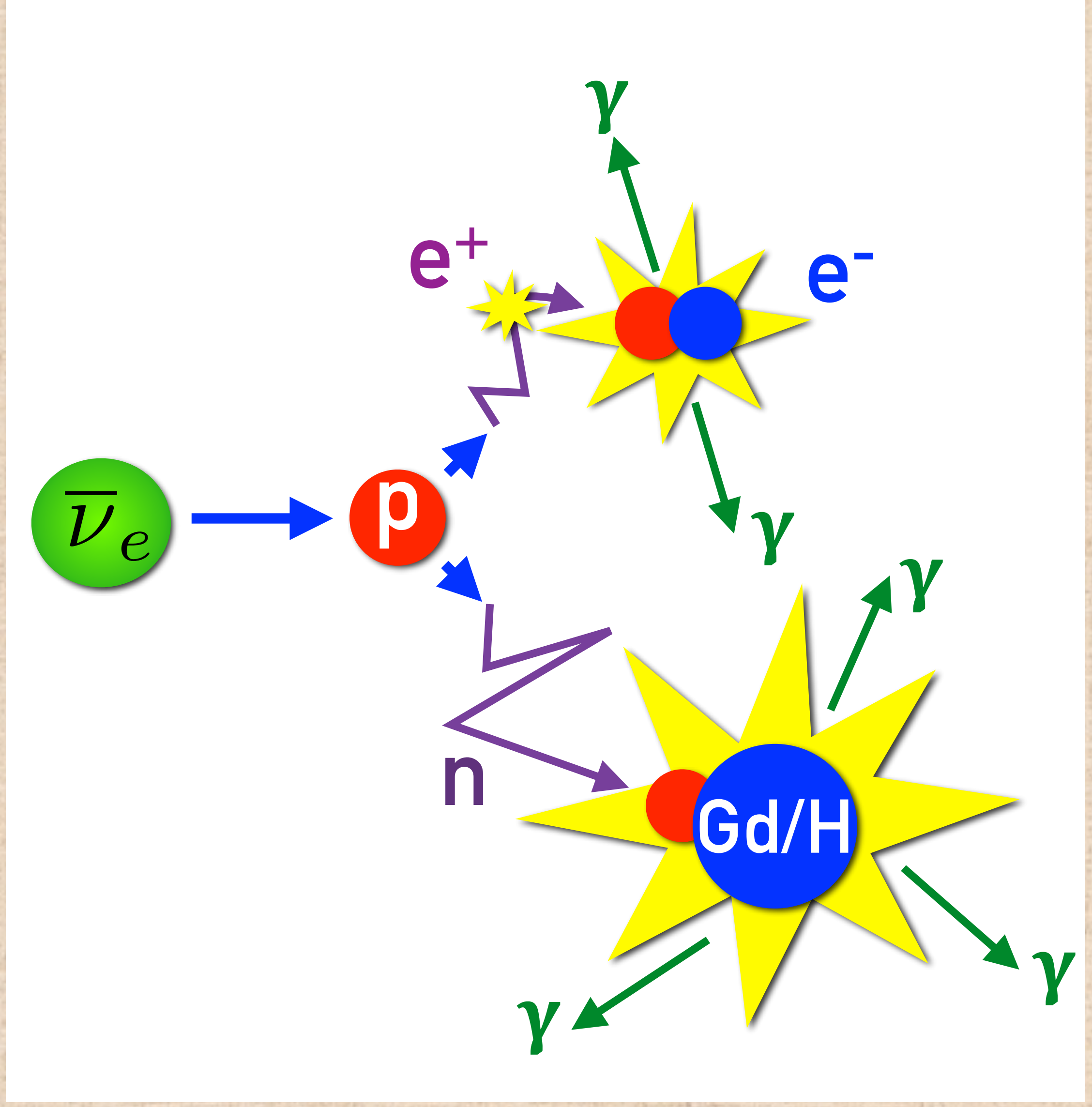
$$R(\sin^2 2\theta_{13}, \Delta m^2_{31}) = \left(\frac{N_{far}}{N_{near}}\right) = \left(\frac{N_{p,far}}{N_{p,near}}\right) \cdot \left(\frac{L_{near}}{L_{far}}\right)^2 \cdot \left(\frac{\epsilon_{far}}{\epsilon_{near}}\right) \cdot \left[\frac{P_{surv}(E,L)}{P_{surv}(E,L)}\right]$$

Detecting Reactor Anti-Neutrinos

Inverse Beta Decay:

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

Double Coincidence Signal
➡ Background suppression



Prompt signal:

positron + annihilation γs
1~8 MeV

Prompt Energy related to neutrino E

$$E_{vis} \simeq E_{\overline{\nu}_e} - 0.8MeV$$

Delayed signal:

γs from neutron capture
on Gd/H: 8 MeV/2.2 MeV

Time Difference:

Δt ~ 30μs (Gd)
Δt ~ 200μs (H)

Double Chooz Experiment

Double Chooz Collaboration

Brazil
- CBPF
- UNICAMP
- UFABC

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

Germany
- EKU Tübingen
- MPIK Heidelberg
- RWTH Aachen
- TU München

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

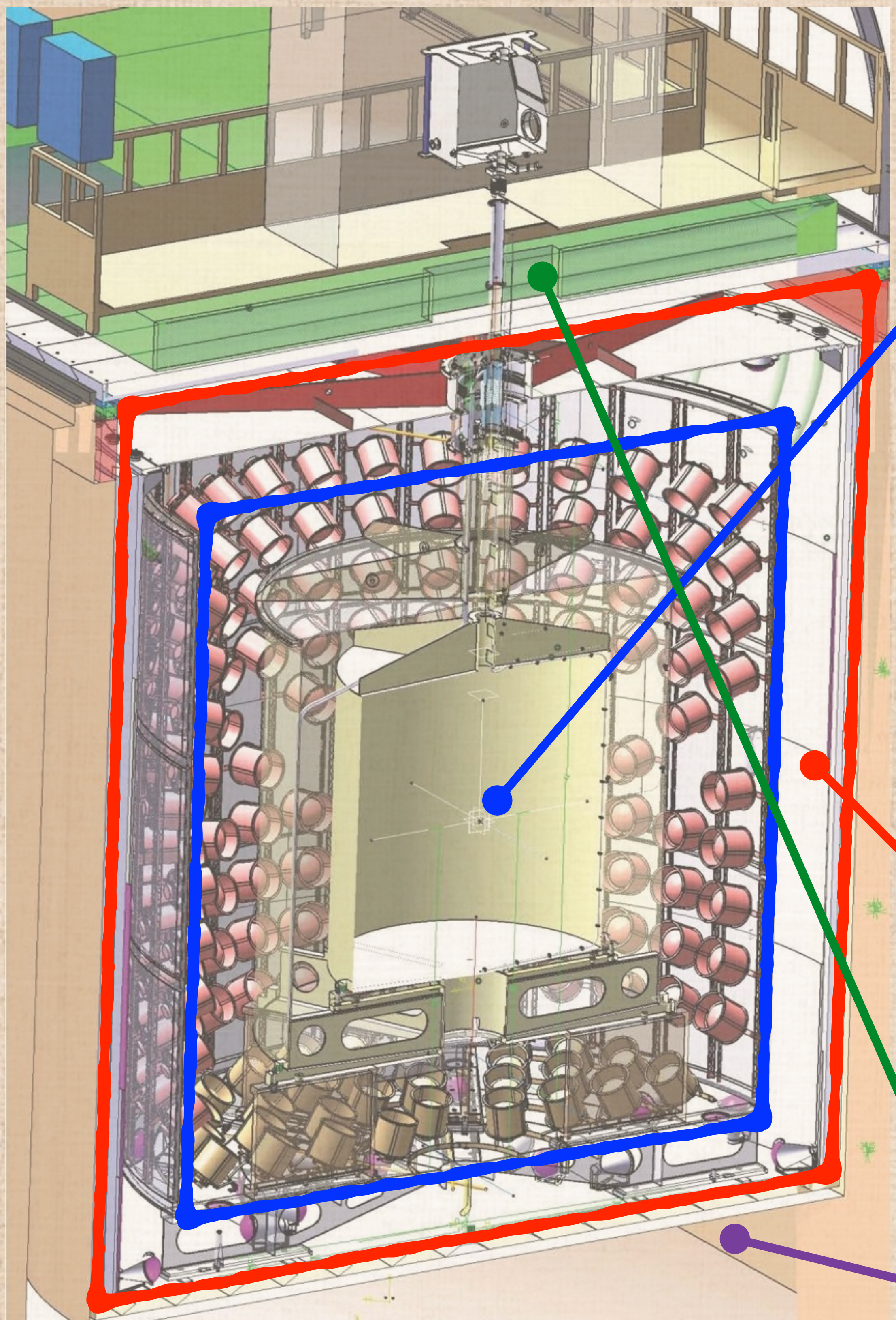
USA
- U. Alabama
- ANL
- U. Chicago
- Columbia U.
- UCDavis
- Drexel U.
- IIT
- KSU
- LLNL
- MIT
- U. Notre Dame
- U. Tennessee

Spokesperson:
H. de Kerret (IN2P3)

Project Manager:
Ch. Veyssiere (CEA-Saclay)

Website:
www.doublechooz.org

Detector Concept



Inner Detector (ID) - three cylindrical layers

ν_e - target

- Gd loaded (1g/L) liquid scintillator (10.3m^3)
- Target for neutrino interactions

----- Transparant acrylic vessel -----

γ - catcher

- Liquid scintillator (22.3 m^3)
- "Catch" γs from ν interactions in target

----- Transparant acrylic vessel -----

Buffer

- 110 m^3 mineral oil & 390 10" PMTs, non-scintillating
- Reduces BG

Inner Veto (IV)

- Liquid scintillator & 78 8" PMTs in steel tank
- Identify cosmic μs

Outer Veto (OV)

- Plastic scintillator strips

Steel Shielding

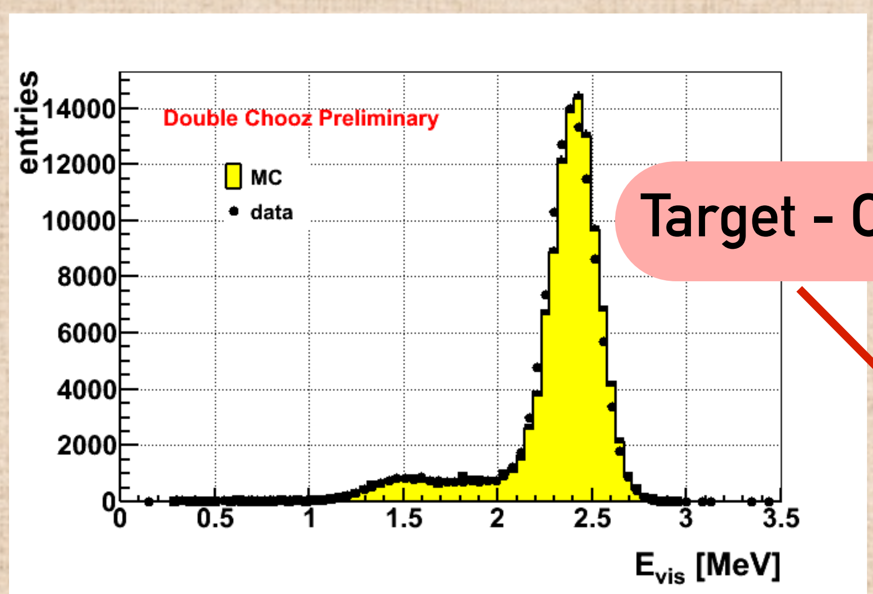
- 15 cm shielding

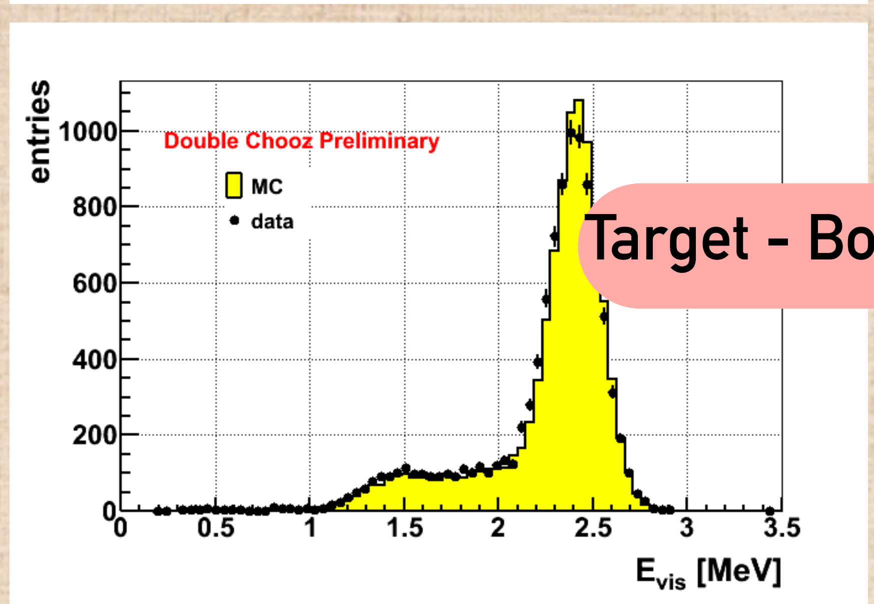
Detector Calibration

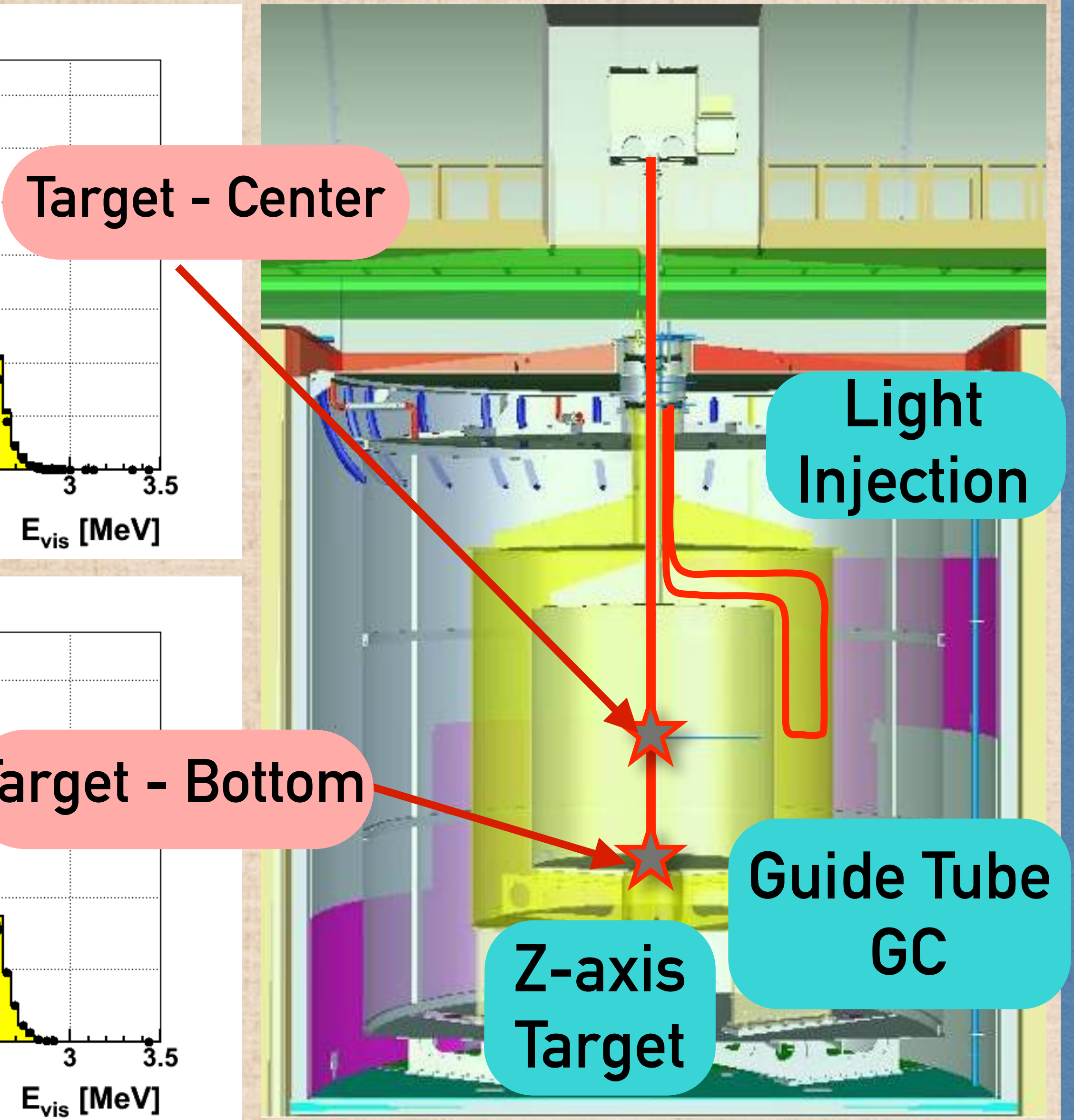
PMT & electronics gain non-linearity correction
LED light injection

Position and time variation correction
Spallation n-H & n-Gd capture

Energy scale
radioactive sources
^{137}Cs, ^{60}Co, ^{68}Ge, ^{252}Cf







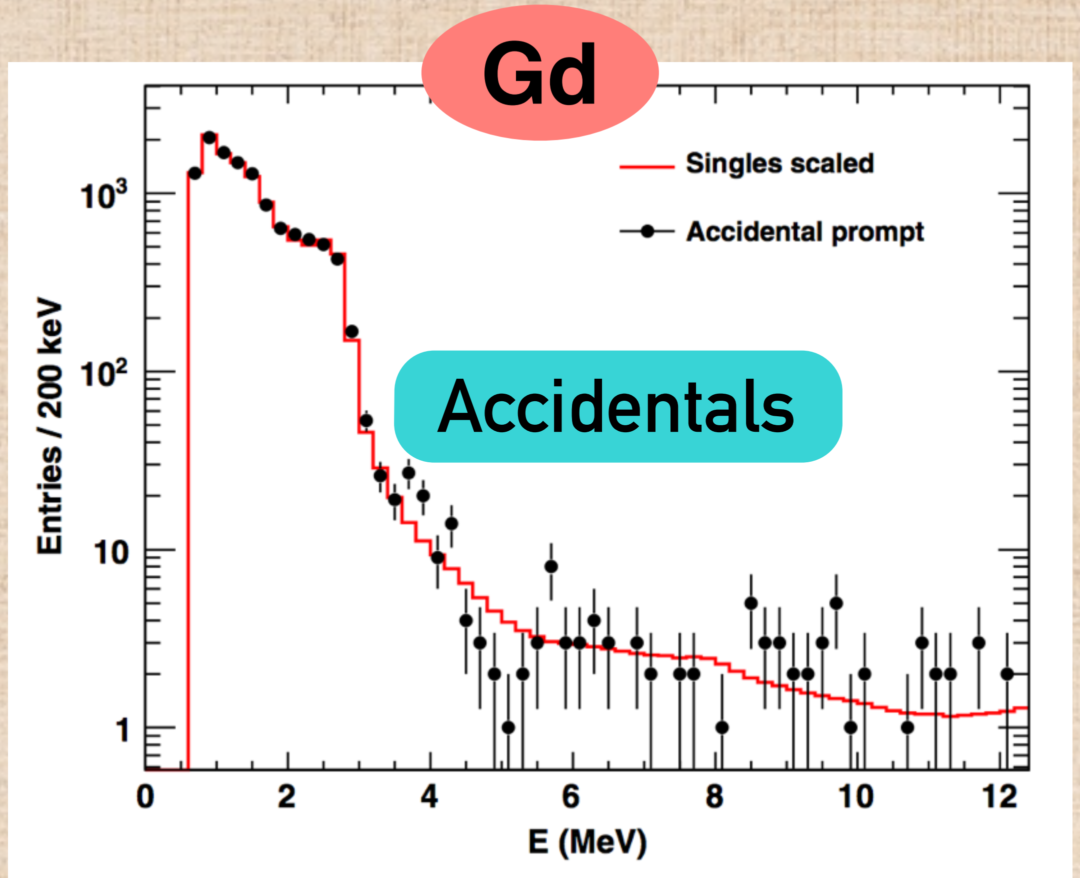
Backgrounds (I)

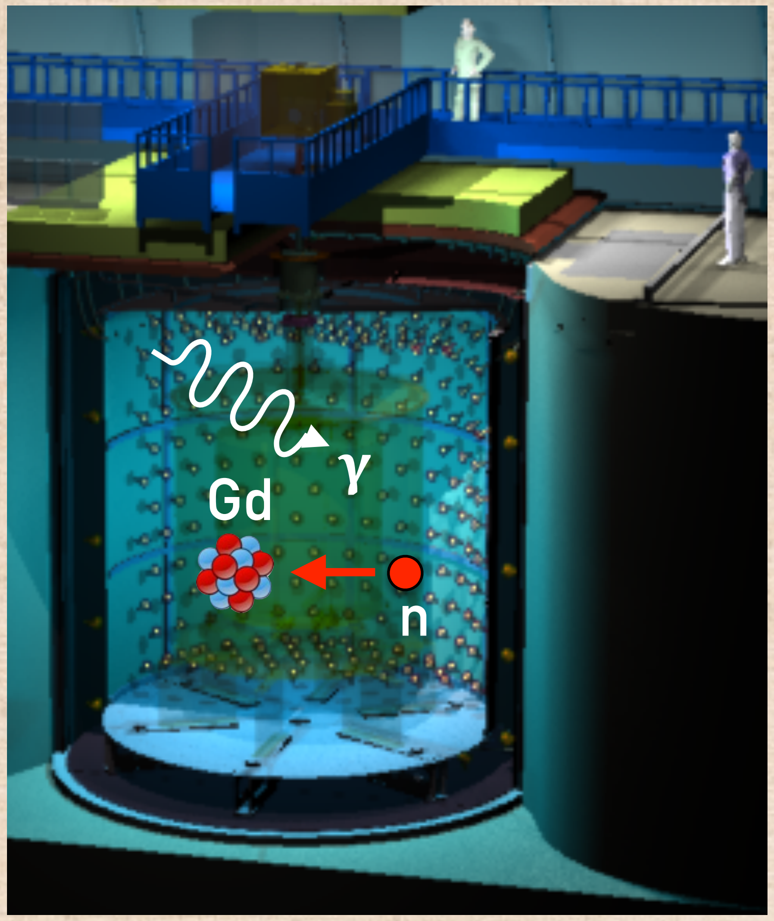
Accidental background
Accidental coincidences

Gd	0.261 ± 0.002 events/day
H	73.45 ± 0.16 events/day

Prompt: gammas from radioactive materials, rocks…

Delayed: neutron-like event





Backgrounds (II)

Correlated background
Muon induced fast neutrons & stopping muons

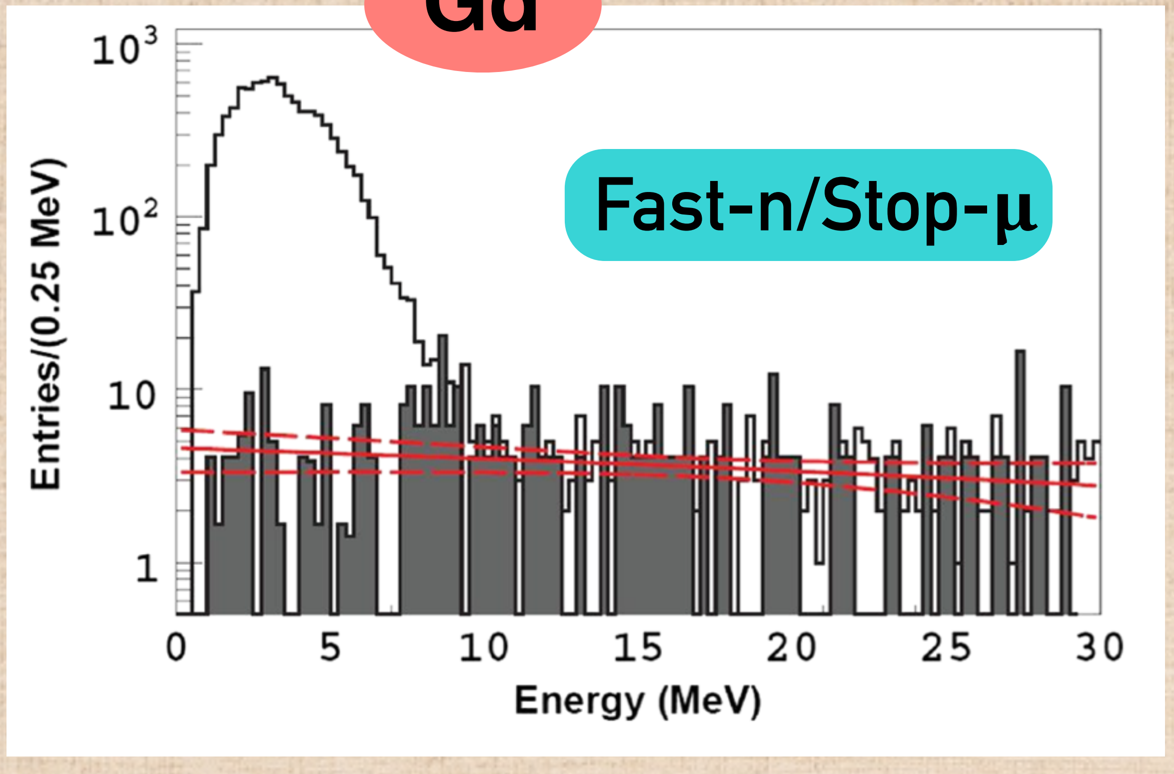
→

Prompt: recoil protons from neutrons or stopping muons

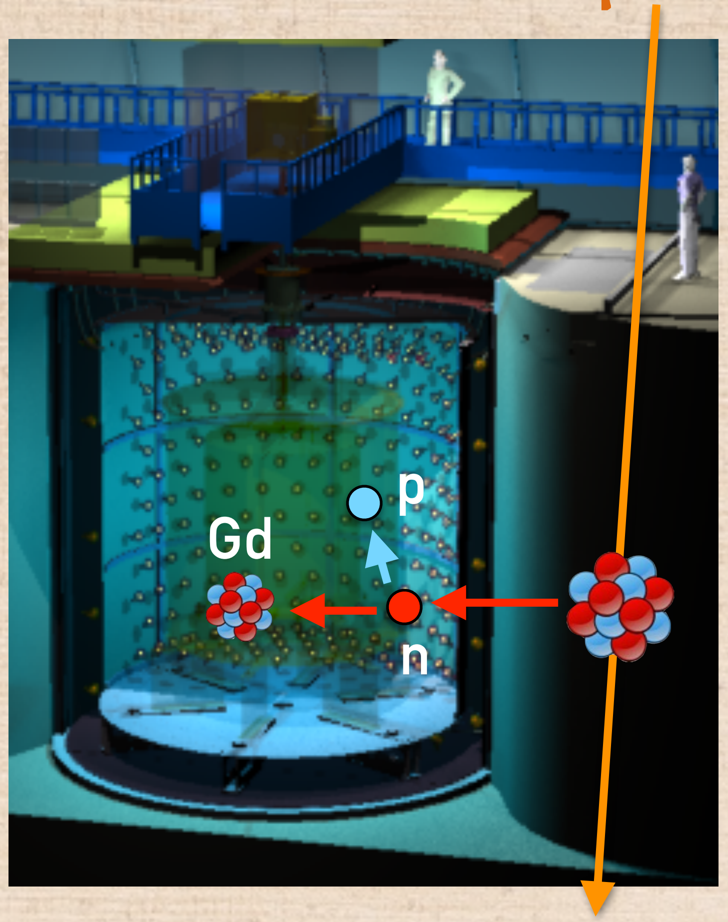
Delayed: fast neutrons or Michel electrons

Gd	0.67	± 0.20 events/day
H	2.50	± 0.47 events/day

Gd



Cosmic μ



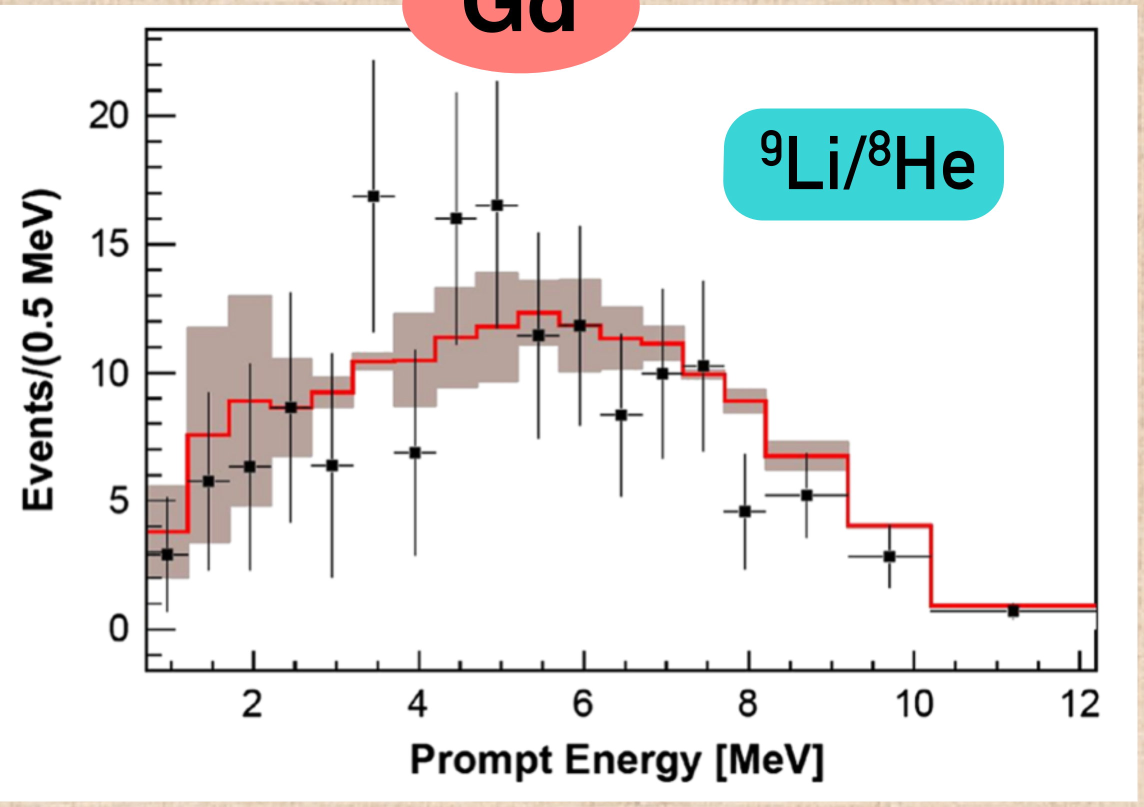
Backgrounds (III)

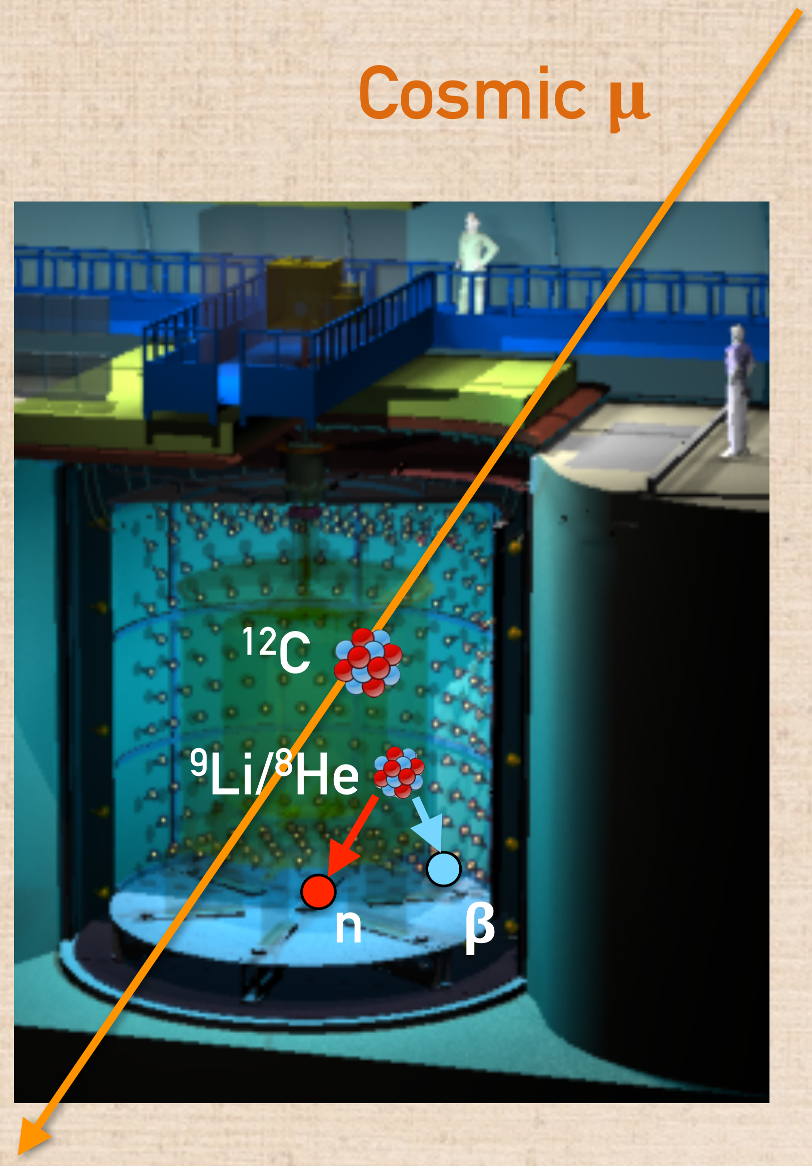
Cosmogenic bkg.
Long lived β-n emitters

→ **Prompt:** electron
Delayed: neutron

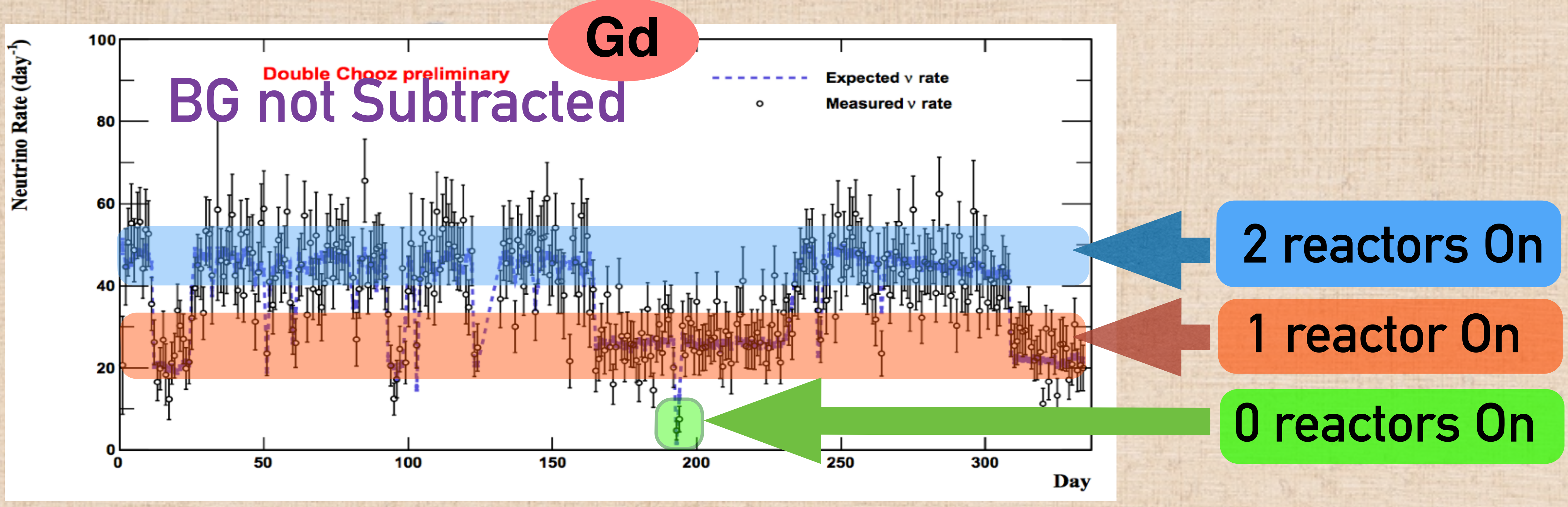
Gd	1.25	± 0.54 events/day
H	2.8	± 1.2 events/day

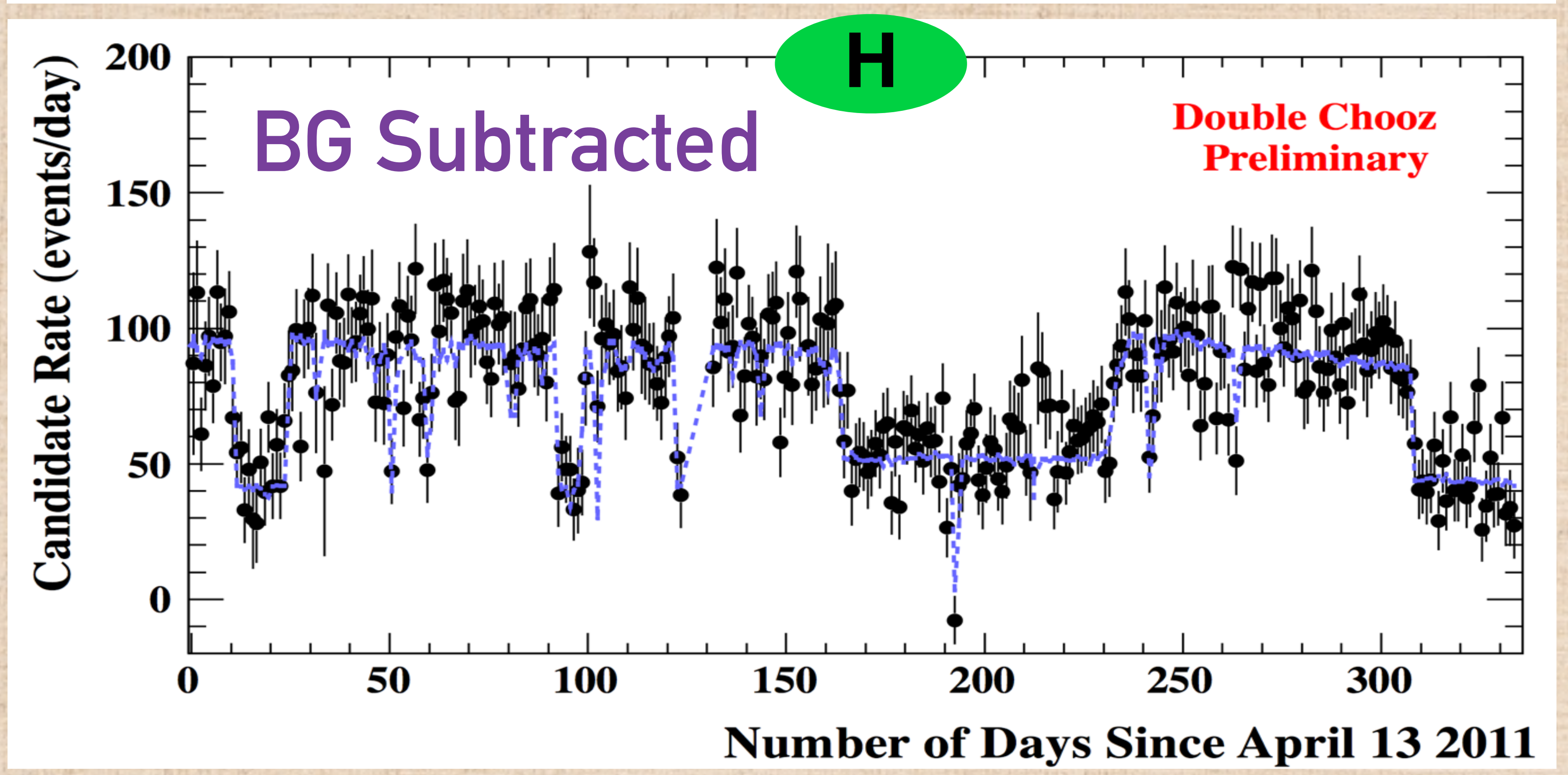
Gd





Neutrino Rate





Gd

Candidates: 8249

S/B ~ 17

H

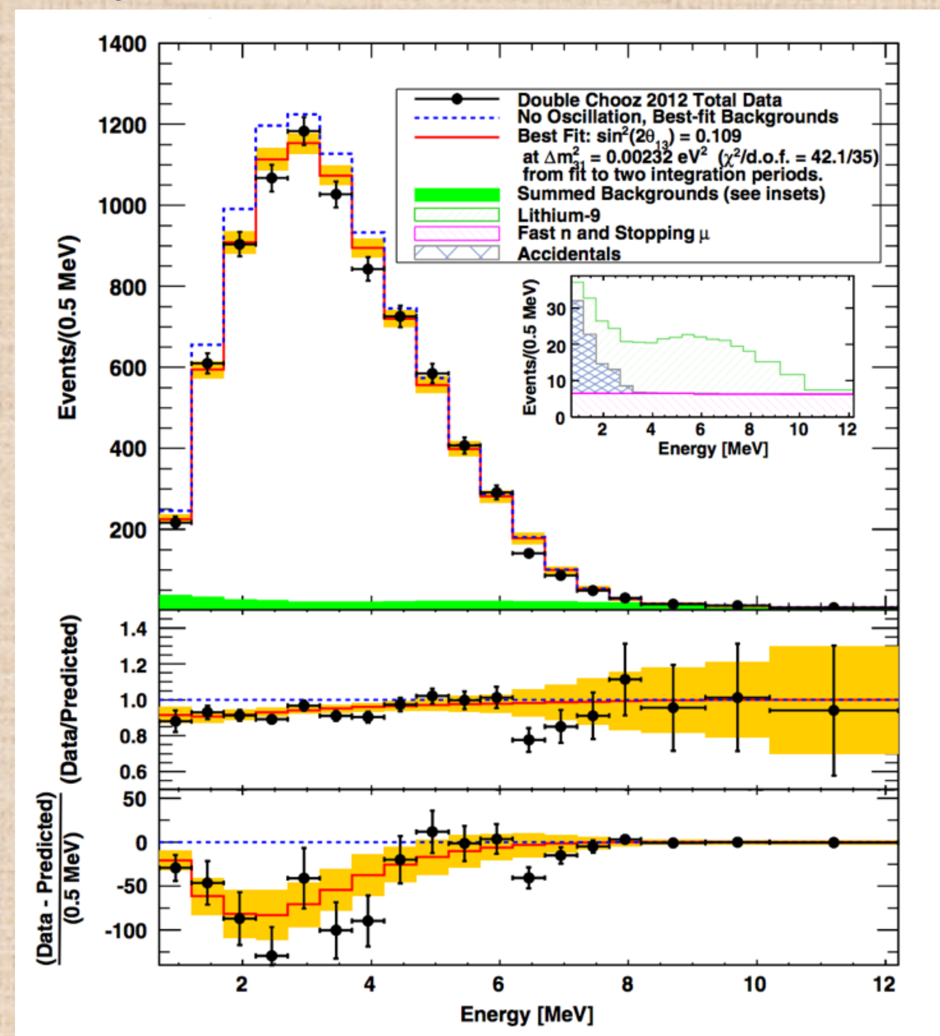
Candidates: 36284

S/B ~ 1

R+S Oscillation Results

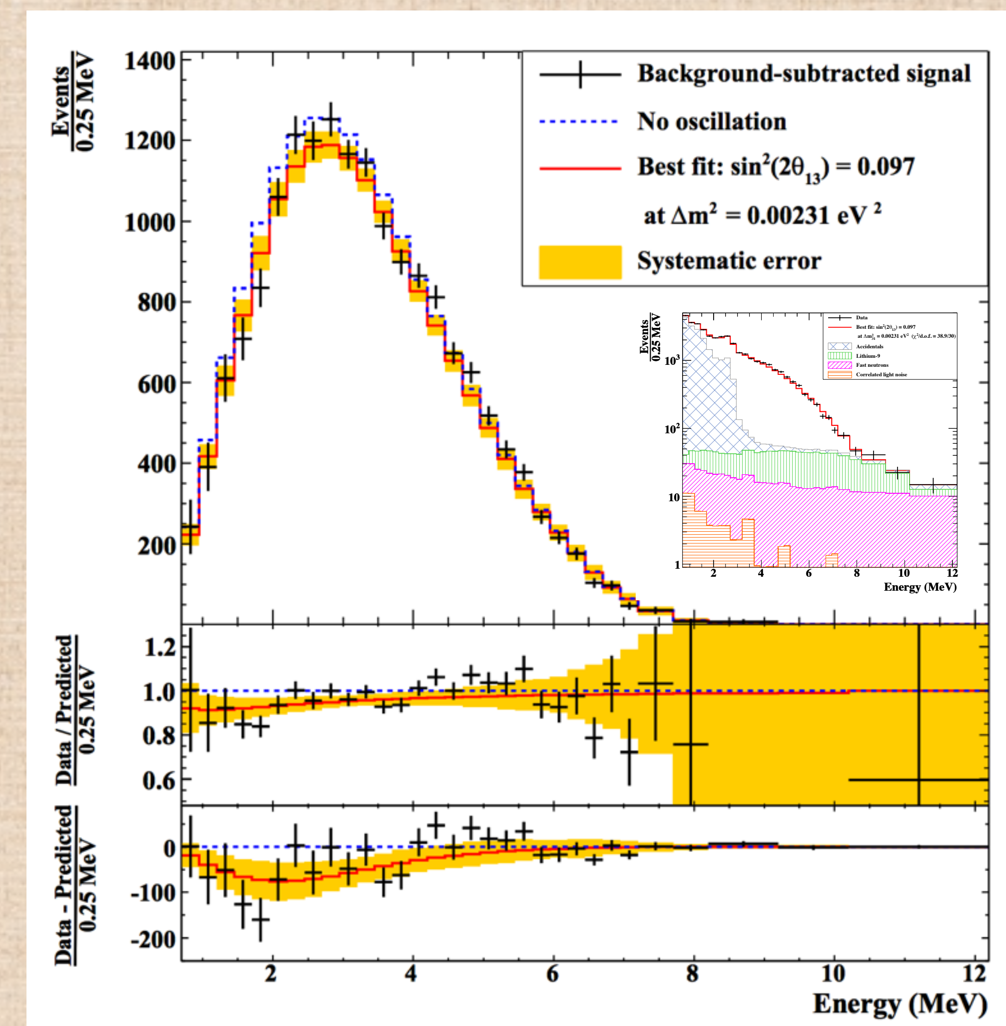
Gd-Analysis

Phys. Rev. D86 (2012) 052008



H-Analysis

Phys. Lett. B723 (2013) 66-70

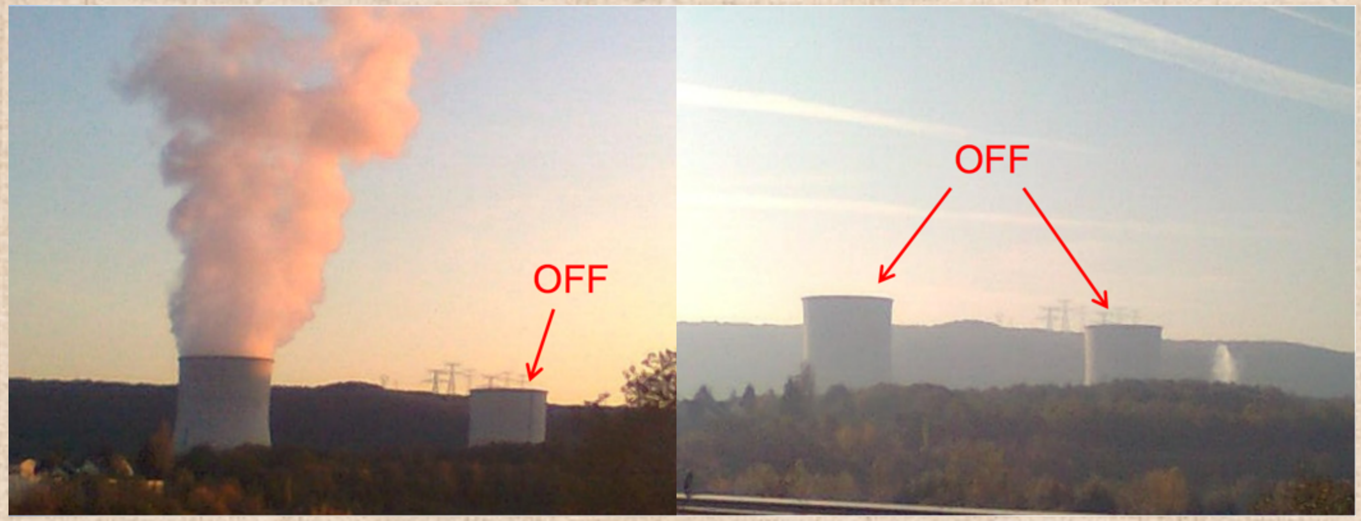


DC-II (Gd) : $\sin^2 2\theta_{13} = 0.109 \pm 0.039$

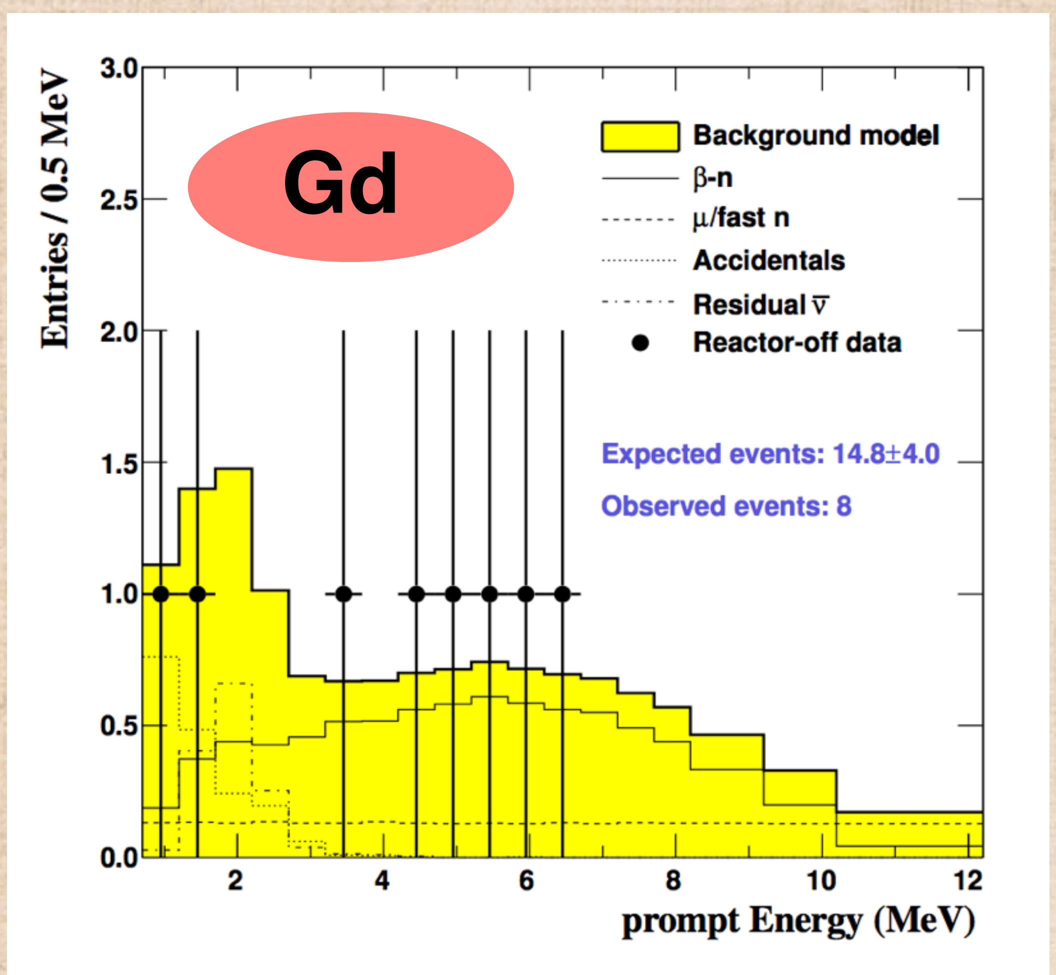
DC-II (H) : $\sin^2 2\theta_{13} = 0.097 \pm 0.048$

Combined (Gd+H) : $\sin^2 2\theta_{13} = 0.109 \pm 0.035$ (preliminary)

Reactor Off-Off



- Only experiment with 7.53 days all reactors off
- Unique opportunity to measure backgrounds
  - ➡ Expected: 2.0 ± 0.6 [day^{-1}]
  - ➡ Observed: 1.0 ± 0.4 [day^{-1}]

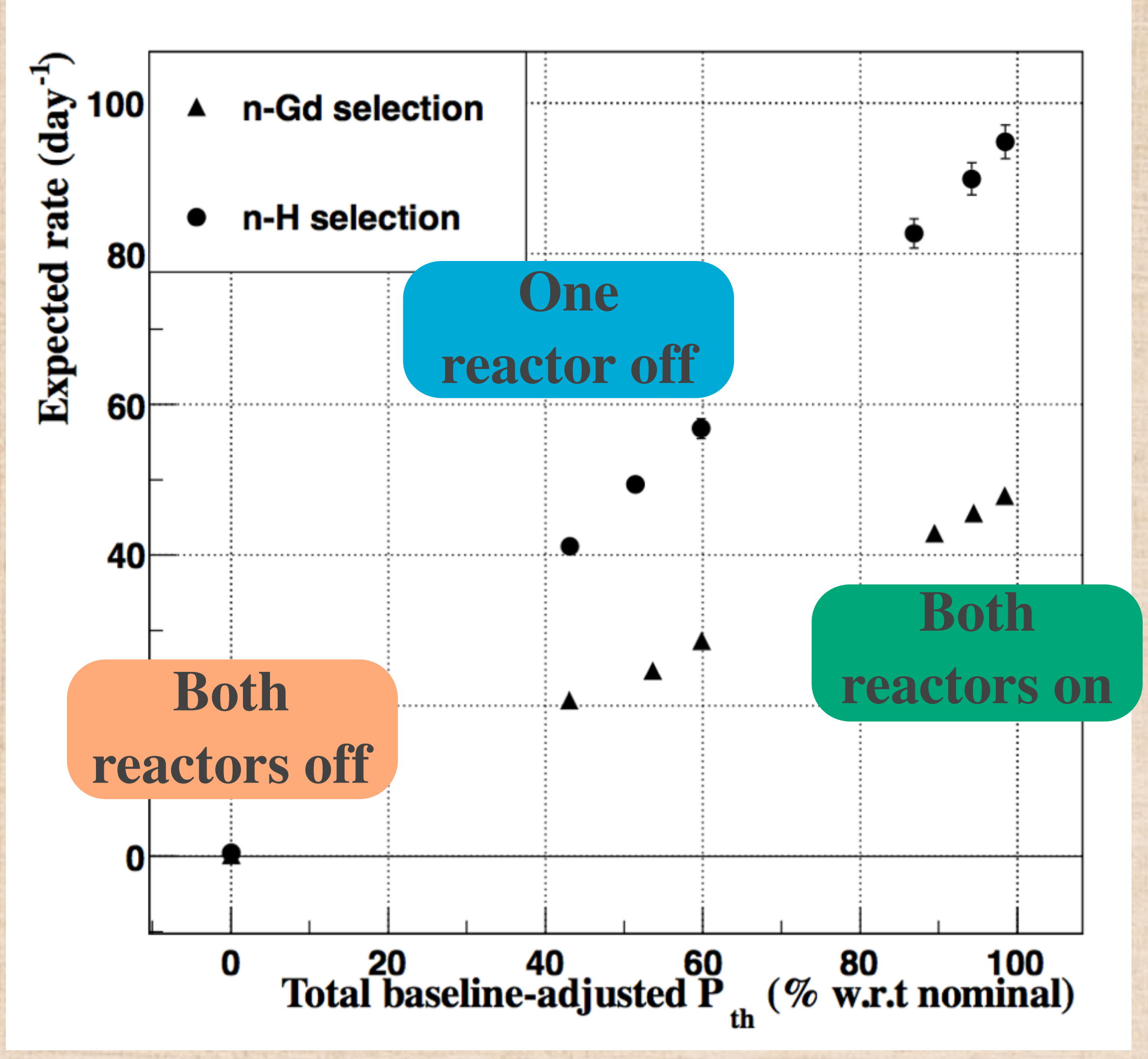


Phys. Rev. D87 (2013) 011102(R)

Reactor Rate Modulation (RRM)

New !!!

- New θ_{13}/BG analysis
- Rate only using different reactor powers
- No background model assumed
  - BG-independent θ_{13} measurement
  - Cross-check of BG model



ArXiv: 1401.5981

Reactor Rate Modulation (RRM) Analysis

$$R^{obs} = B + R^{exp} = B + (1 - \sin^2(2\theta_{13})\eta_{osc})R^{\nu}$$

$$\langle \sin^2(\Delta m^2 L/4E) \rangle$$

New !!!

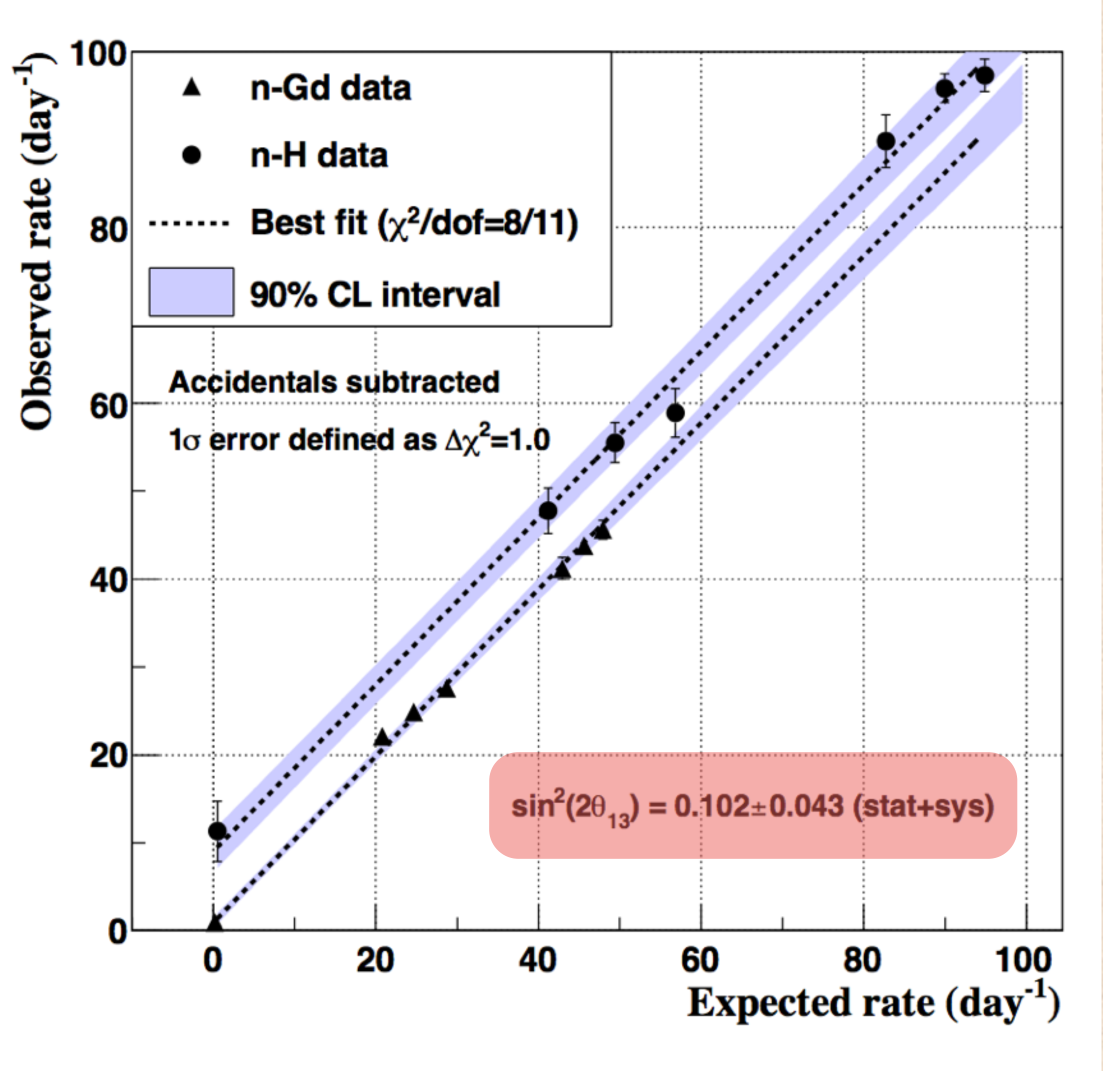
ArXiv: 1401.5981

- Observed vs Expected rate
- Fit provides $\sin^2 2\theta_{13}$ and background rate

Gd B = 0.9 ± 0.4 (W/O accid.)

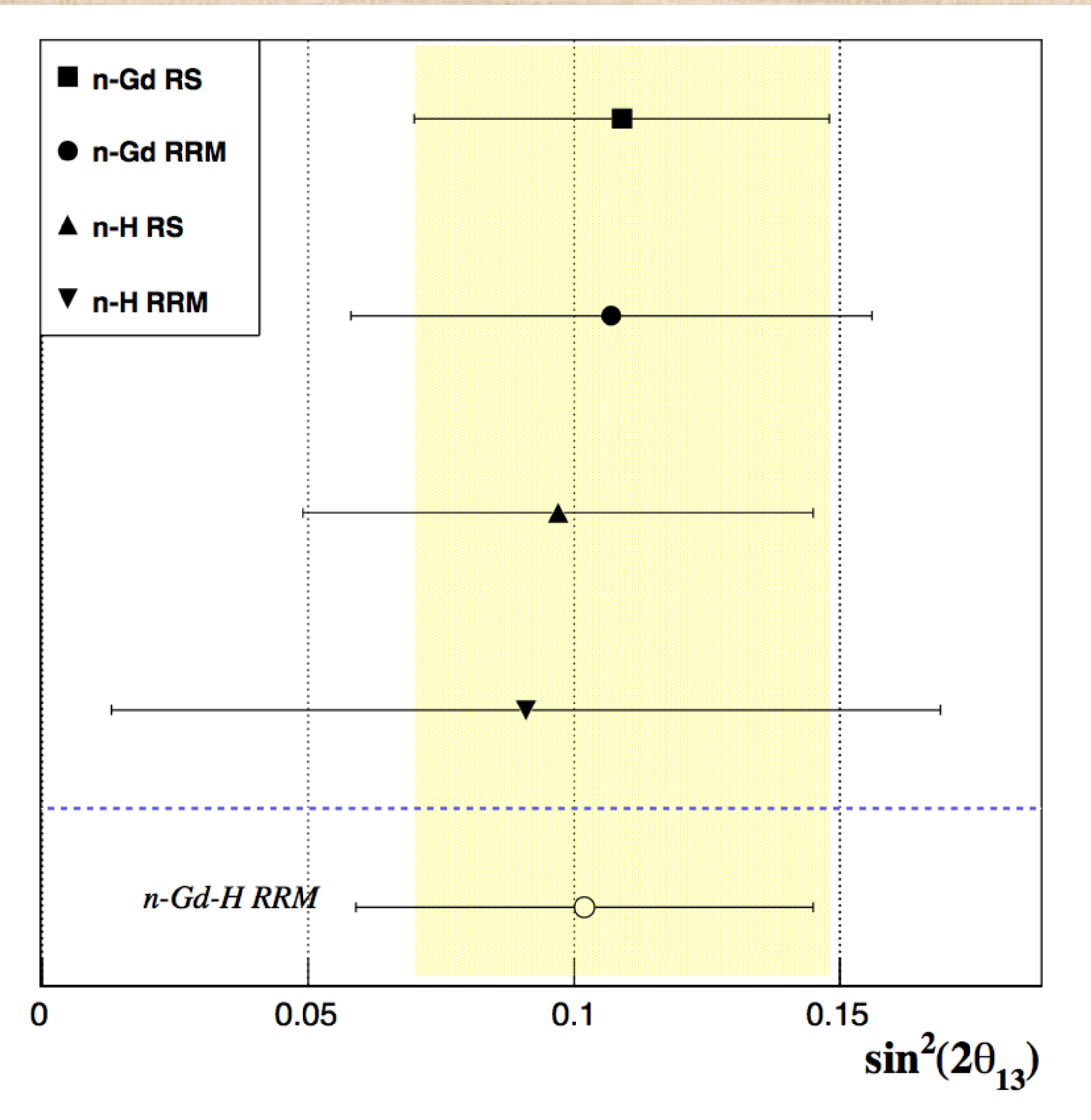
Combined (Gd + H):
$\sin^2 2\theta_{13} = 0.102 \pm 0.043$

In agreement with R+S analysis



Summary of DC results

ArXiv: 1401.5981

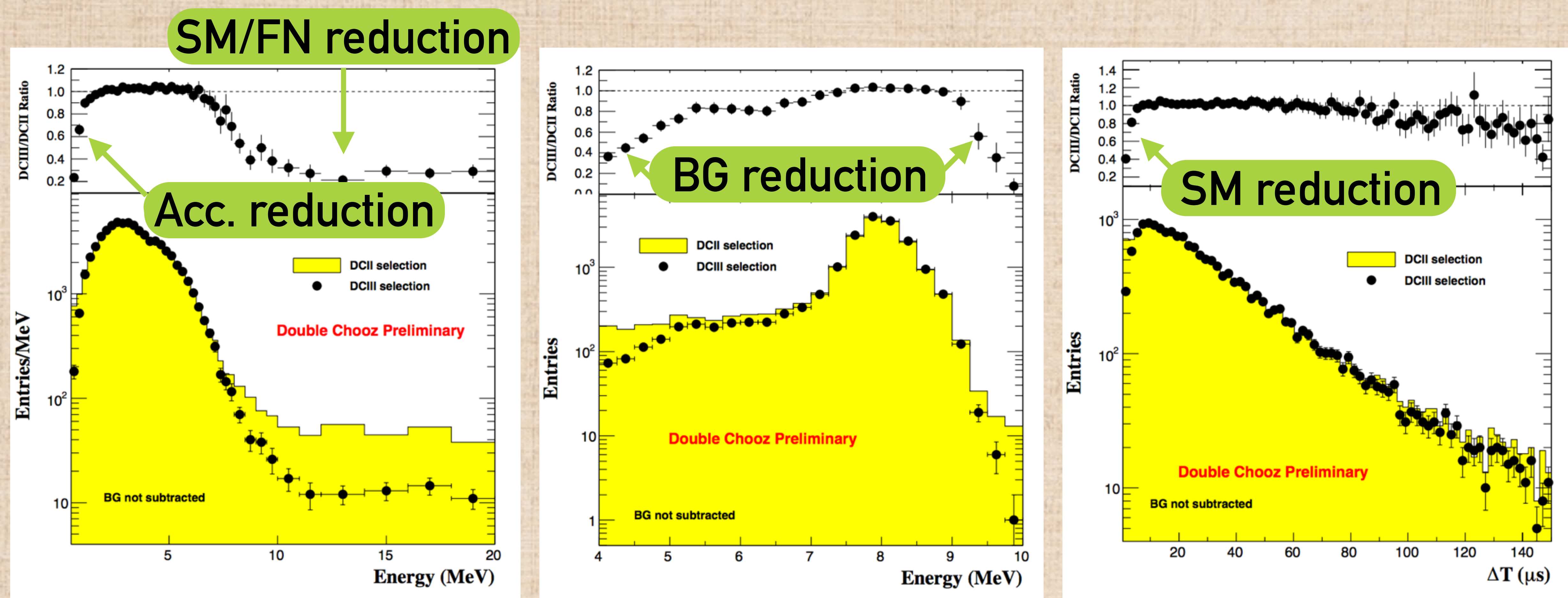


- 4 different $\sin^2 2\theta_{13}$ analyses
  - 2 separate samples: Gd / H
  - 2 separate methods: R+S/RRM
- 2 combined results
  - R+S with Gd + H
  - RRM with nGd + nH
- $\sin^2 2\theta_{13}$ consistent with 1σ
- BG model consistent between all

New !!!

Towards a new selection

- Open selection cuts + addition new BG vetoes
- Better S/BG



Prompt Energy [MeV] | Delayed Energy [MeV] | ΔT prompt-delayed [μs]

New !!!

Towards a new selection

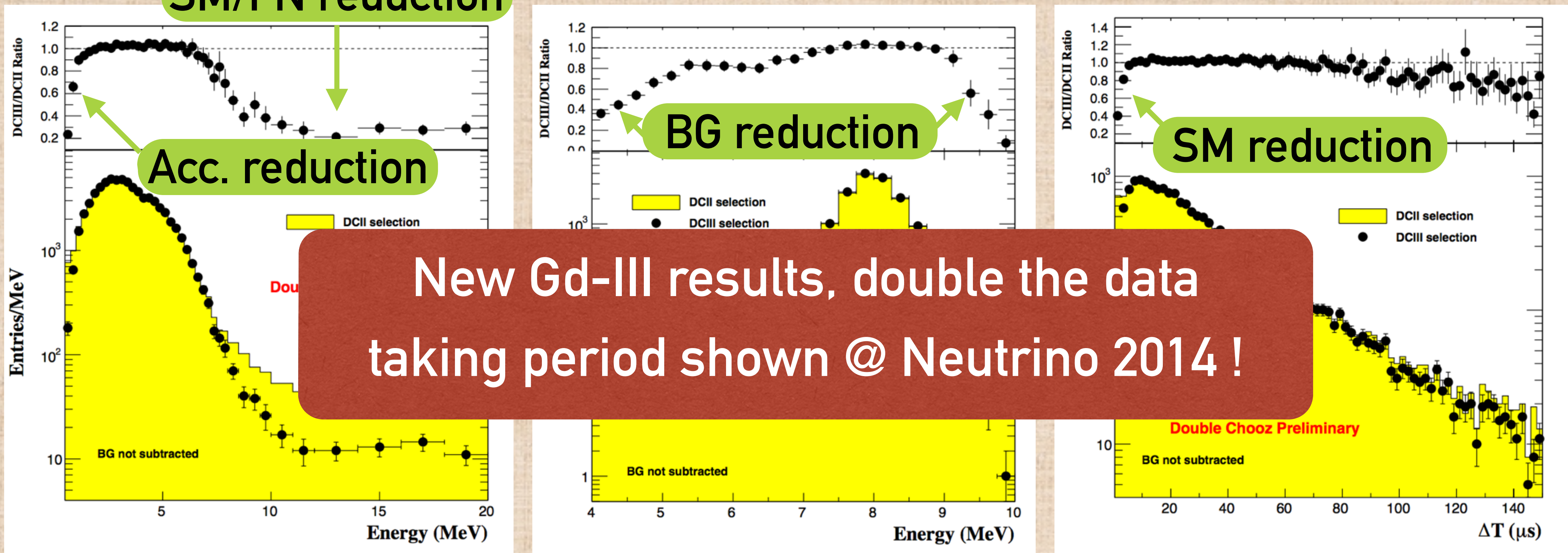
- Open selection cuts + addition new BG vetoes
- Better S/BG

SM/FN reduction

Acc. reduction

BG reduction

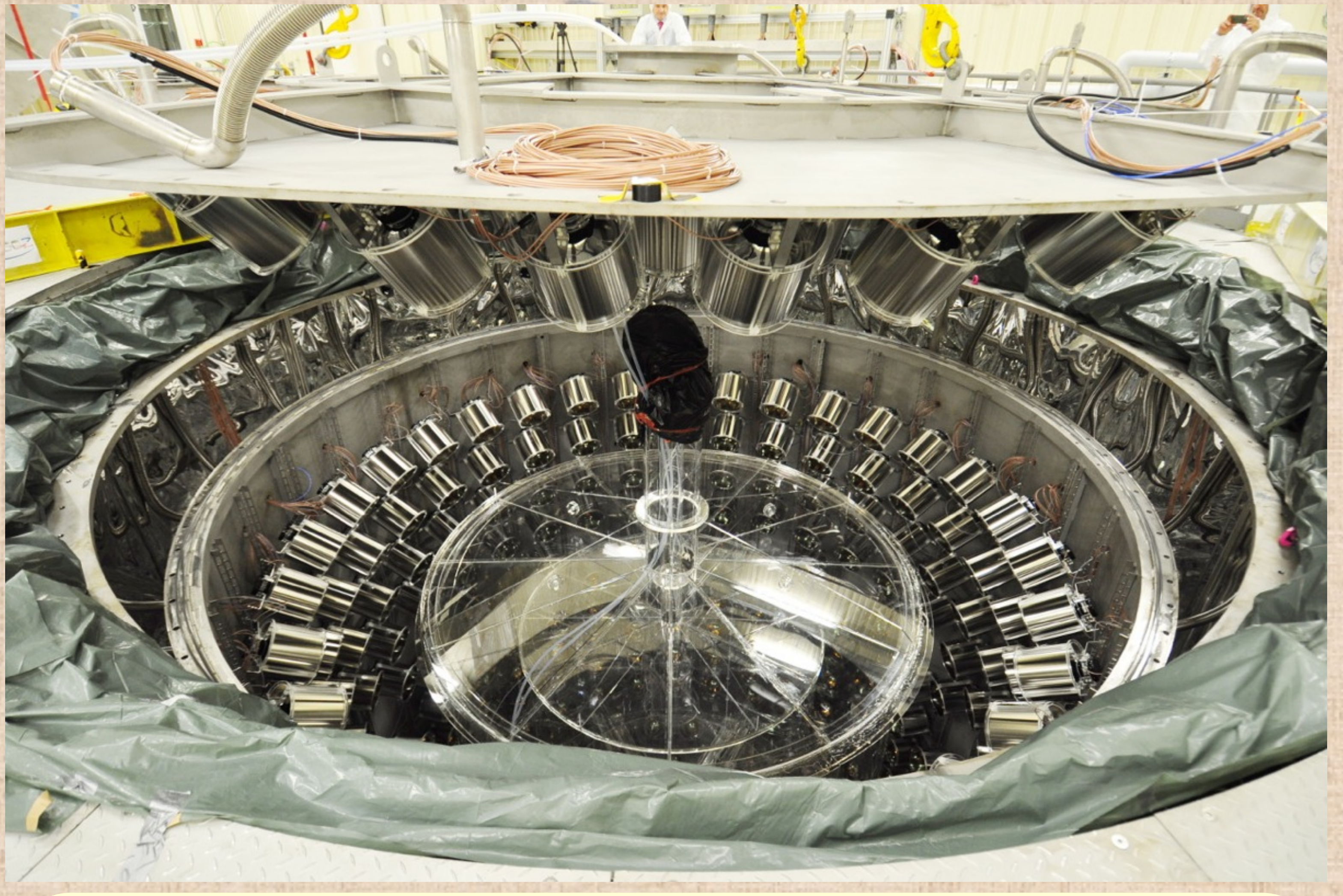
SM reduction



New Gd-III results, double the data taking period shown @ Neutrino 2014 !

Prompt Energy [MeV] | Delayed Energy [MeV] | ΔT prompt-delayed [μs]

Status Near Detector



Buffer Lid & PMTs installed

Installation Veto PMTs Last Week
- by me!

Start data taking - later this year!

Summary

- Successful FD phase : limited by reactor sys
- 4 θ_{13} measurements: nGd, nH (R+S) & RRM
  - ➡ RRM measurement Gd+H: $\sin^2\theta_{13} = 0.102 \pm 0.043$
  - ➡ Combined Gd+H (R+S): $\sin^2\theta_{13} = 0.109 \pm 0.035$
- 3 independent BG measurements: Rxtr On, Rxtr-Off & RRM
- ND+FD phase to start
  - ➡ ND start data taking later this year
  - ➡ Selection improvements for FD+ND "ongoing"
- Rich physics beyond θ_{13}

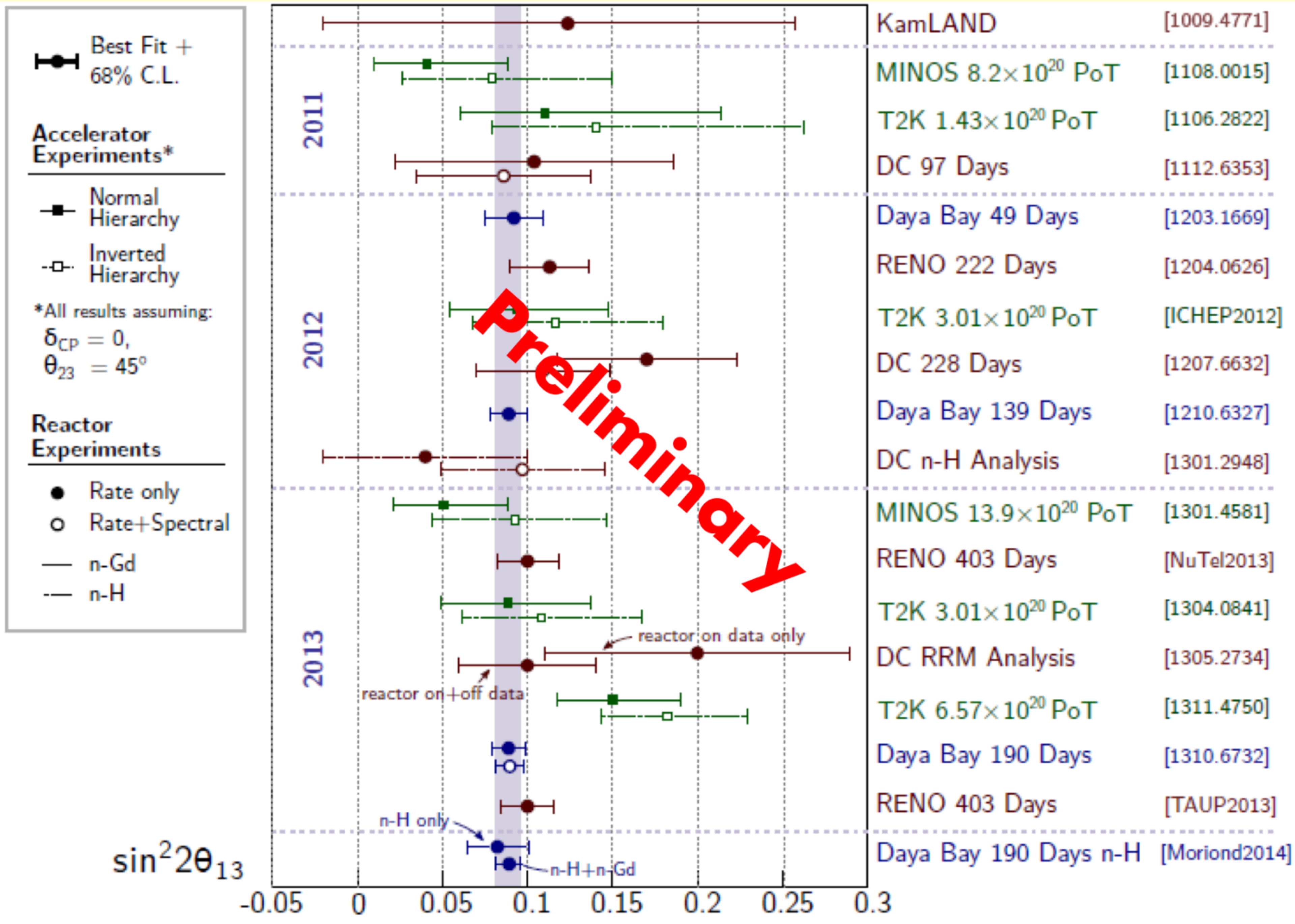
New Gd-III results (~ double the data) shown @ Neutrino 2014 !

Thank You!

Back-up Slides

Summary θ_{13} results

Taken from Daya Bay Talk @ Moriond 2014



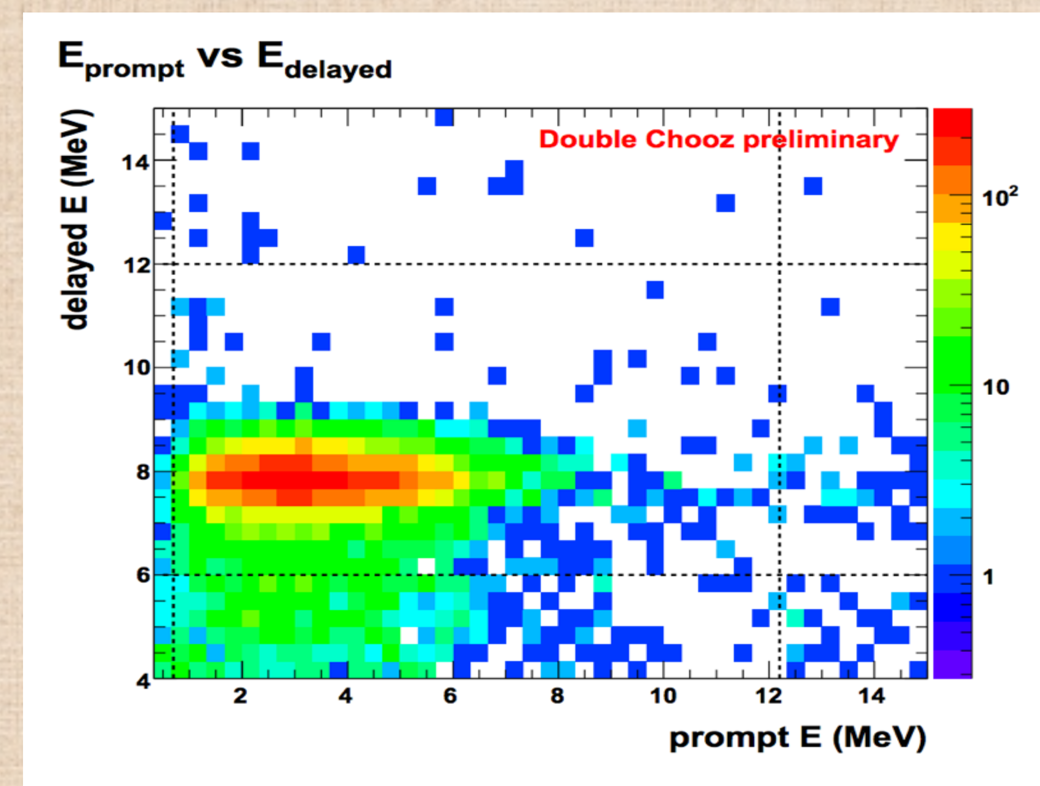
Anti-ν_e Selection Criteria

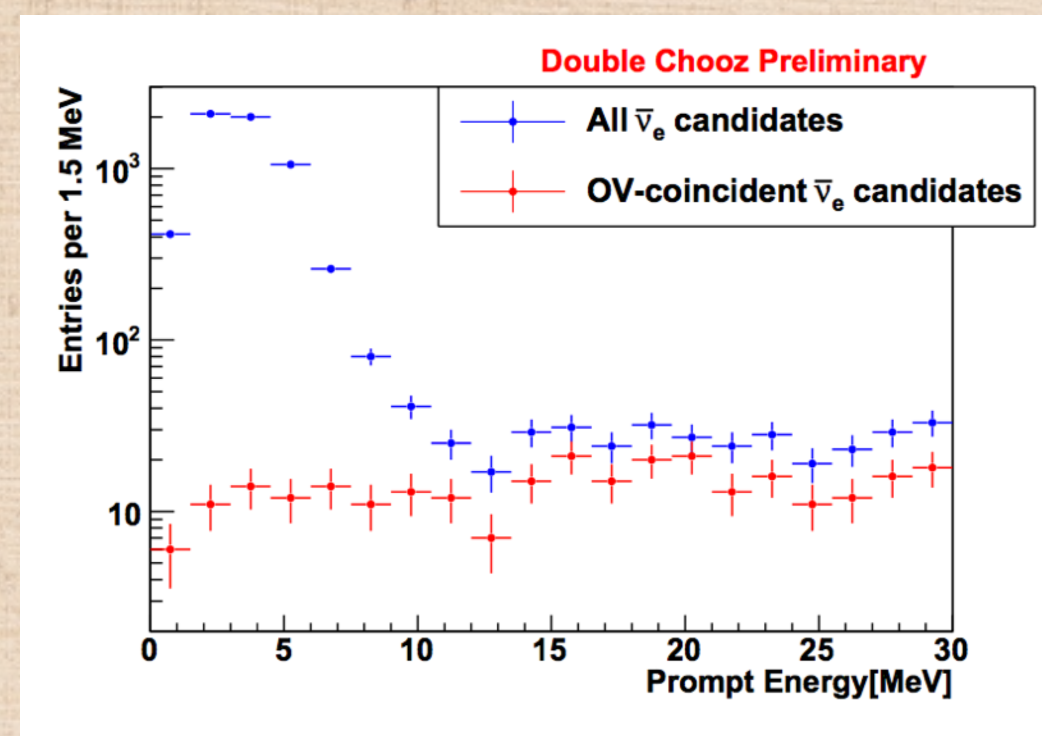
Selection Cuts

	Gd	H
Energy prompt	0.7-12.2 MeV	0.7-12.2 MeV
Energy delayed	6 - 12 MeV	1.5 - 3 MeV
ΔT	2 - 100 μs	10 - 600 μs
ΔR	—	< 0.9 m

BG Reduction

	Gd	H
μ veto	ΔT > 1 ms	
Showering μ	E_μ 0.5s	—
isolation	500 μs	1600 μs
OV veto	Prompt not coincident OV	

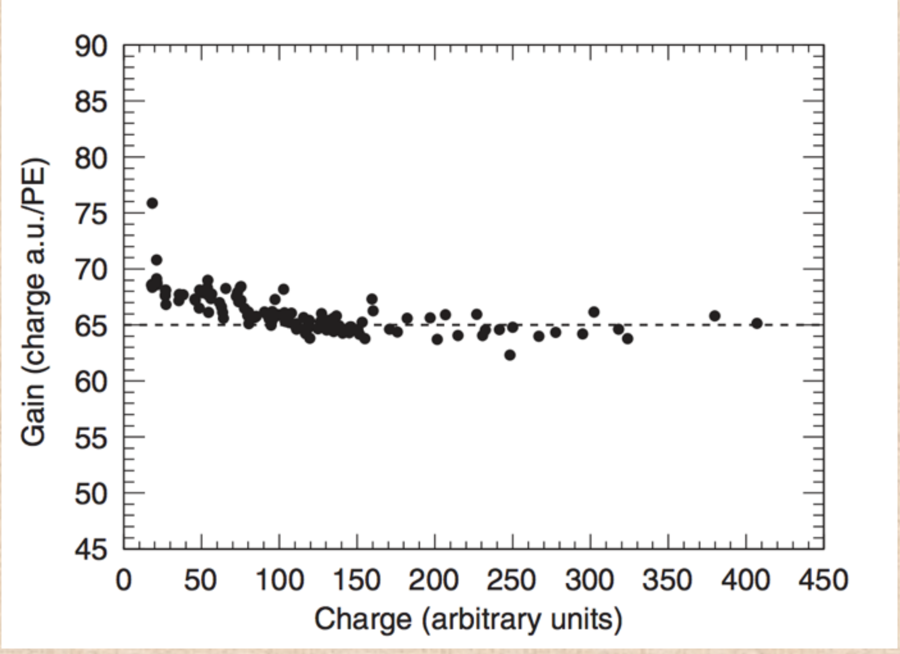




Energy Reconstruction

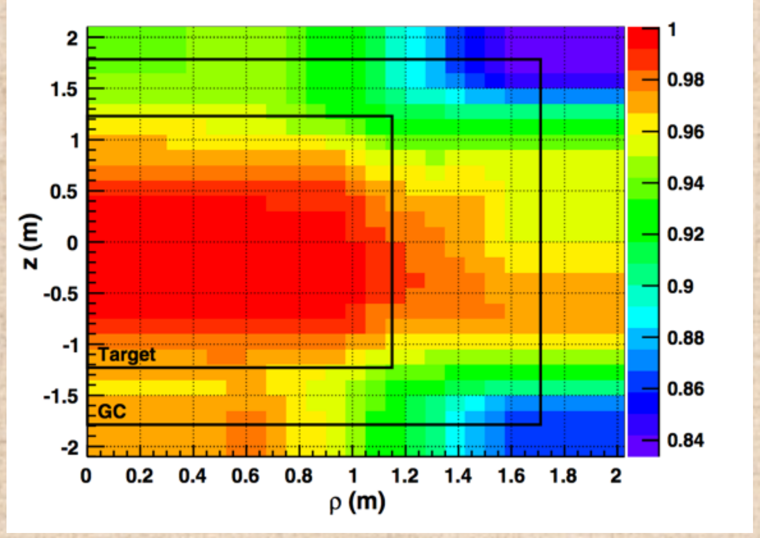
Gain non-linearity calibration:

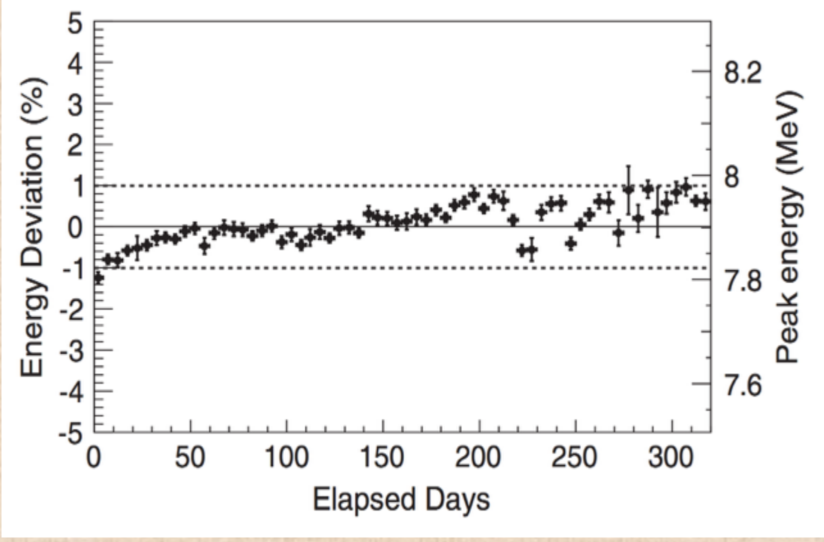
$$PE = \sum_i pe_i = \sum_i q_i/gain(q_i,t)$$

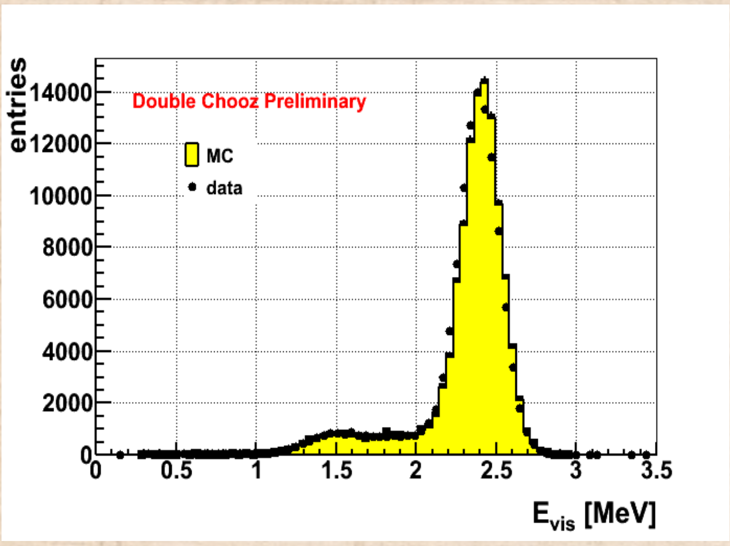


Energy definition:

$$E_{vis} = PE^{DATA,MC} \times f_u^{DATA,MC}(\rho,z) \times f_s^{DATA}(t) \times f_{MeV}^{DATA,MC}$$

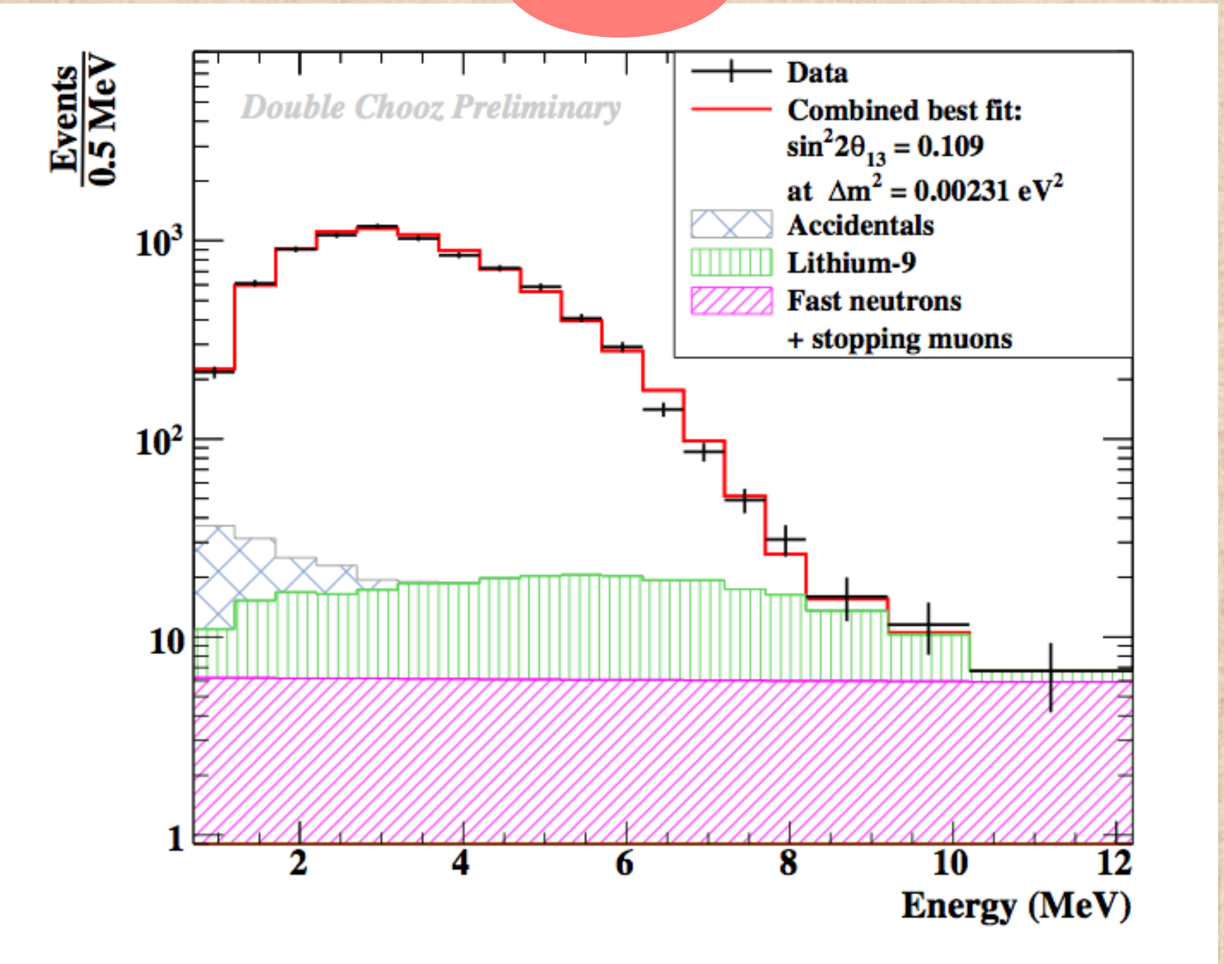




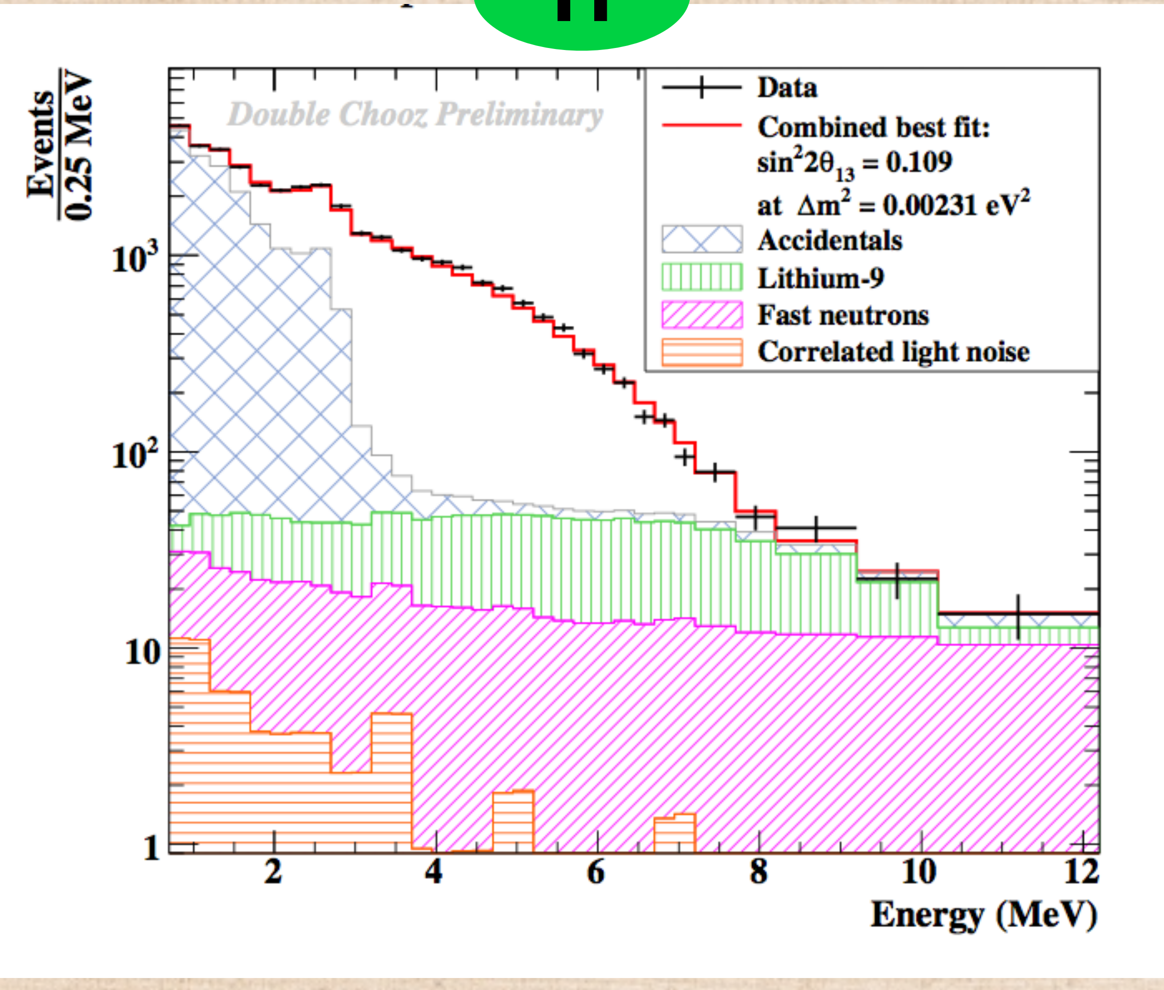


Backgrounds

Gd



H



Systematic Uncertainties

Rate Error (%)	Gd	H
Statistics	1.06	1.1
Reactor Flux	1.67	1.8
Det. Efficiency	0.95	1.6
Background	1.47	1.7
Total	**2.7**	**3.1**

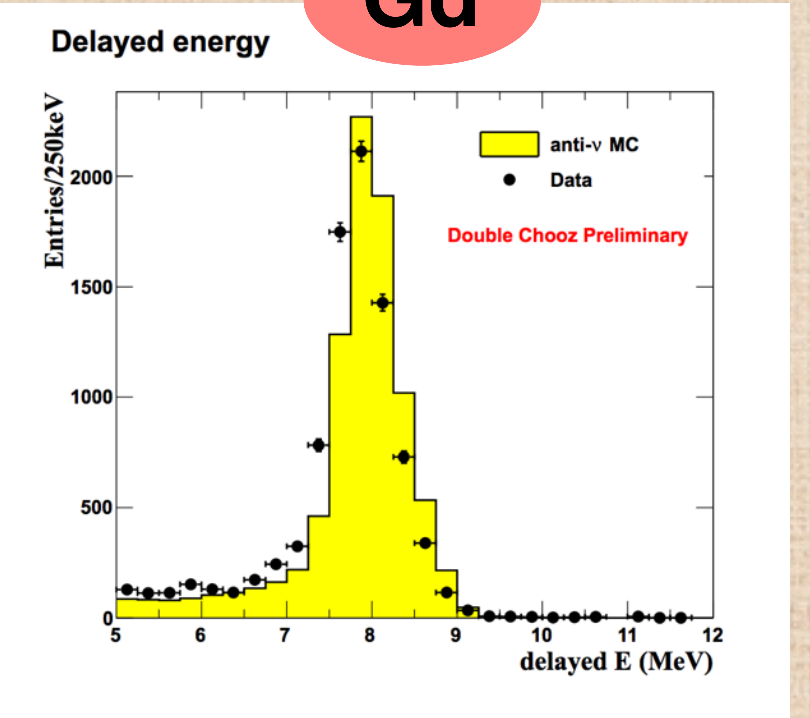
Rate Error (%)	Gd	H
^{9}	1.38	1.6
FN/SM	0.51	0.6
Accidentals	0.01	0.2
Light Noise	-	0.1
Total	**1.47**	**1.7**

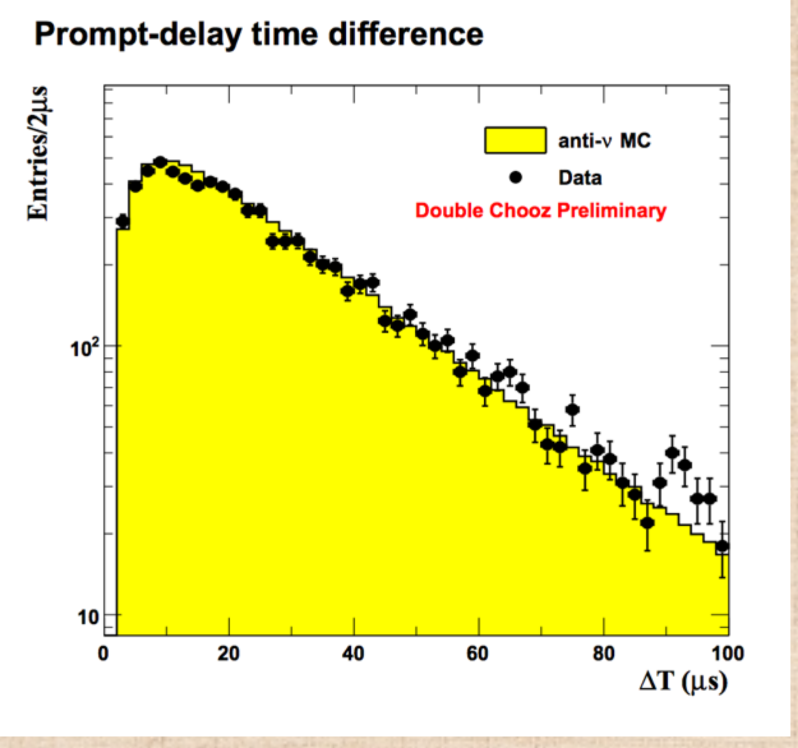
Shape uncertainties:

- Reactor anti-ν_e spectrum
- Energy Scale
- BG spectra

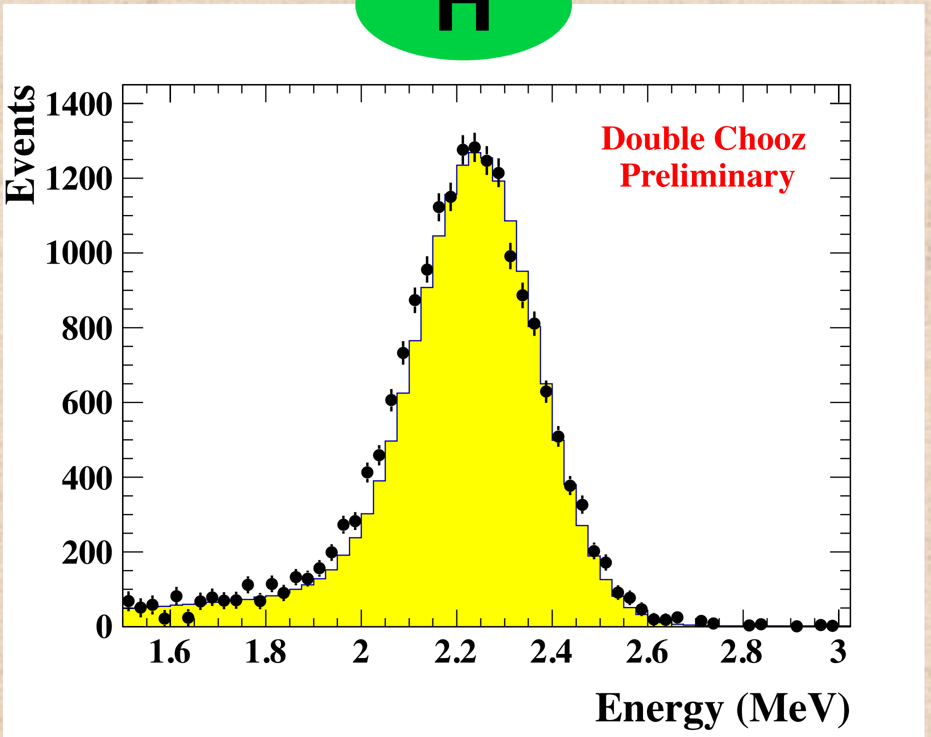
Antineutrino Candidate Attributes

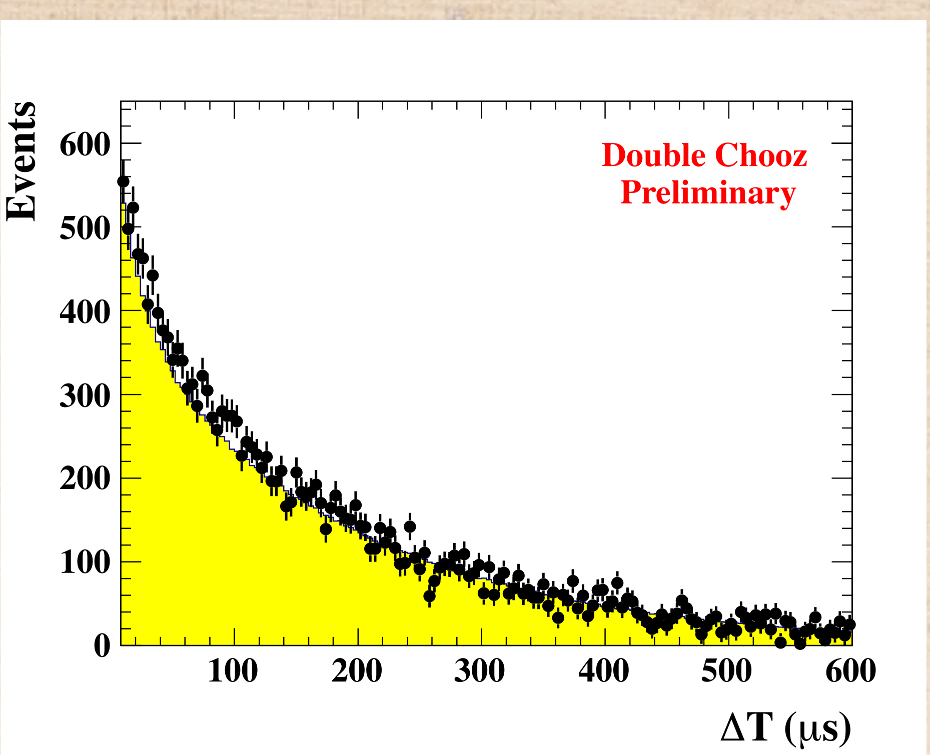
Gd





H





Reactor neutrino Prediction I

Predicted neutrino rate:

$$N_\nu^{exp}(E,t) = \frac{N_p \epsilon}{4\pi L^2} \times \frac{P_{th}(t)}{\langle E_f \rangle} \times \langle \sigma_f \rangle$$

$$\langle E_f \rangle = \sum_k \alpha_k(t) \langle E_k \rangle$$

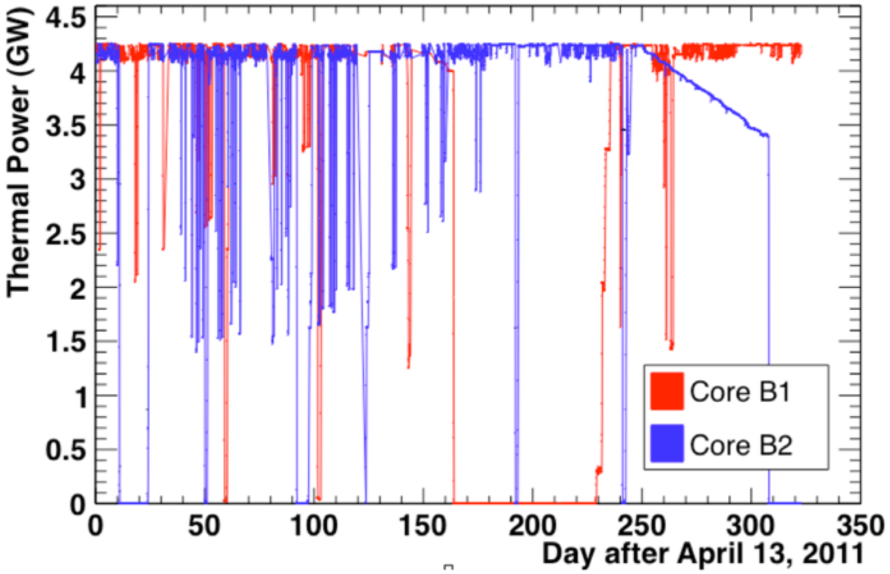
$$\langle \sigma_f \rangle = \langle \sigma_f \rangle^{Bugey} + \sum_k (\alpha_k^{DC}(t) - \alpha_k^{Bugey}(t)) \langle \sigma_f \rangle_k$$

$$\langle \sigma_f \rangle_k = \int_0^\infty S_k(E) \sigma_{IBD}(E) \mathrm{d}E$$

N_p	-	Number protons in detector
ϵ	-	Detection efficiency
L	-	Baseline
$P_{th}(t)$	-	Thermal power
$\langle \sigma_f \rangle$	-	Mean cross section
$\langle E_f \rangle$	-	Mean energy per fission
$S_k(E)\sigma_{IBD}(E)$	-	Reference spectra × IBD cross section
$\alpha_k(t)$	-	Fuel fraction evolution

Thermal Power

Electricité de France (EDF) provide thermal power of both cores, B1 & B2



Reactor neutrino Prediction II

Predicted neutrino rate:

$$N_\nu^{exp}(E,t) = \frac{N_p \epsilon}{4\pi L^2} \times \frac{P_{th}(t)}{\langle E_f \rangle} \times \langle \sigma_f \rangle$$

$$\langle E_f \rangle = \sum_k \alpha_k(t) \langle E_k \rangle$$

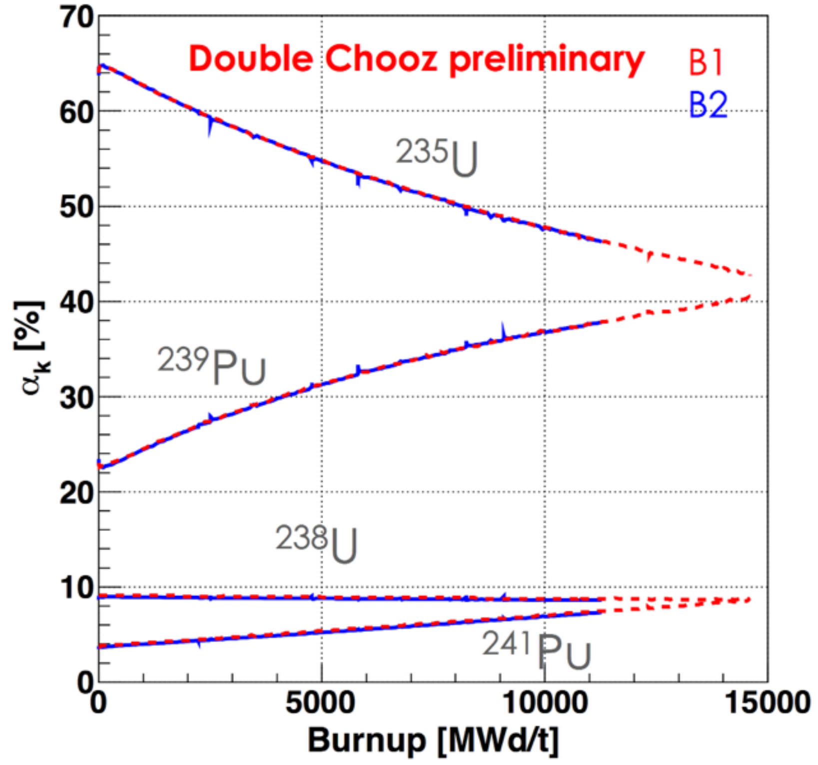
$$\langle \sigma_f \rangle = \langle \sigma_f \rangle^{Bugey} + \sum_k (\alpha_k^{DC}(t) - \alpha_k^{Bugey}(t)) \langle \sigma_f \rangle_k$$

$$\langle \sigma_f \rangle_k = \int_0^\infty S_k(E) \sigma_{IBD}(E) \mathrm{d}E$$

- N_p - Number protons in detector
- ϵ - Detection efficiency
- L - Baseline
- $P_{th}(t)$ - Thermal power
- $\langle \sigma_f \rangle$ - Mean cross section
- $\langle E_f \rangle$ - Mean energy per fission
- $S_k(E)\sigma_{IBD}(E)$ - Reference spectra × IBD cross section
- $\alpha_k(t)$ - Fission fraction evolution

Mean Energy per Fission

Fuel evolution in reactor cores simulated by MURE & Dragon



Reactor neutrino Prediction III

Predicted neutrino rate:

$$N_\nu^{exp}(E,t) = \frac{N_p \epsilon}{4\pi L^2} \times \frac{P_{th}(t)}{\langle E_f \rangle} \times \langle \sigma_f \rangle$$

$$\langle E_f \rangle = \sum_k \alpha_k(t) \langle E_k \rangle$$

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

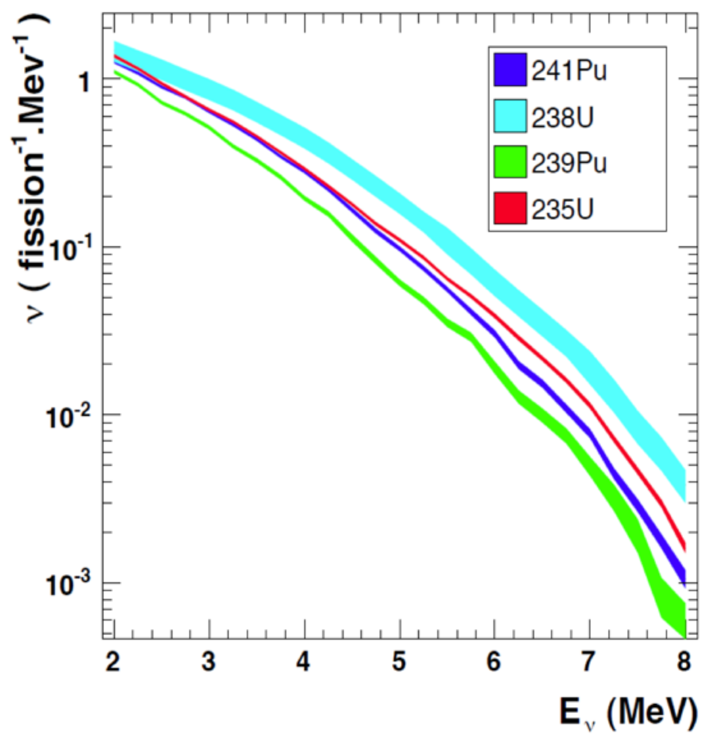
$$\langle \sigma_f \rangle_k = \int_0^\infty S_k(E) \sigma_{IBD}(E) \mathrm{d}E$$

- N_p - Number protons in detector
- ϵ - Detection efficiency
- L - Baseline
- $P_{th}(t)$ - Thermal power
- $\langle \sigma_f \rangle$ - Mean cross section
- $\langle E_f \rangle$ - Mean energy per fission
- $S_k(E)\sigma_{IBD}(E)$ - Reference spectra × IBD cross section
- $\alpha_k(t)$ - Fuel fraction evolution

Mean Cross Section

Used Bugey4 as anchor point

Reference spectra $S_k(E)$



Reactor neutrino Prediction IV

Predicted neutrino rate:

$$N_{\nu}^{exp}(E,t) = \frac{N_p \epsilon}{4\pi L^2} \times \frac{P_{th}(t)}{\langle E_f \rangle} \times \langle \sigma_f \rangle$$

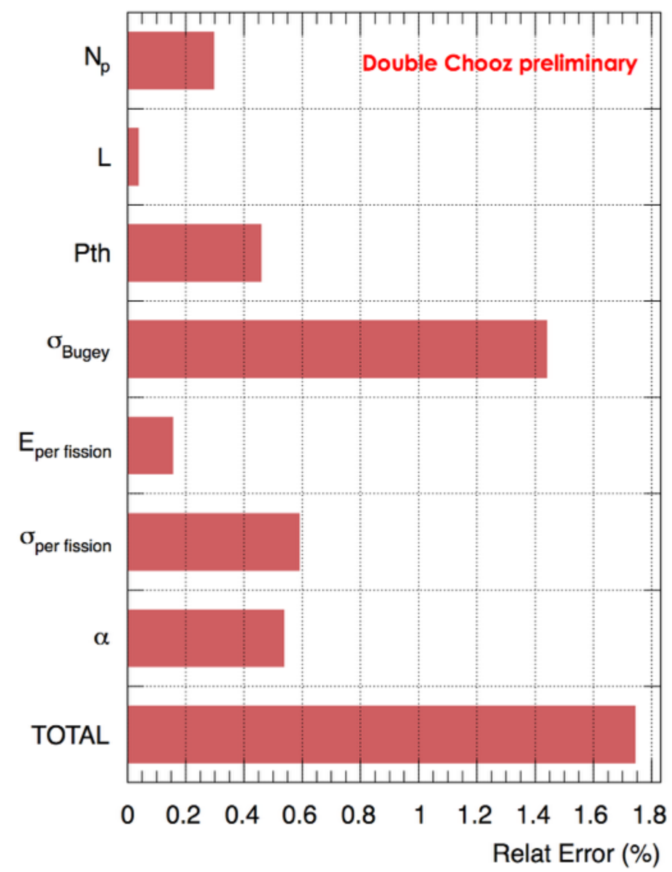
$$\langle E_f \rangle = \sum_k \alpha_k(t) \langle E_k \rangle$$

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

$$\langle \sigma_f \rangle_k = \int_0^{\infty} S_k(E) \sigma_{IBD}(E) \mathrm{d}E$$

N_p	-	Number protons in detector
ϵ	-	Detection efficiency
L	-	Baseline
$P_{th}(t)$	-	Thermal power
$\langle \sigma_f \rangle$	-	Mean cross section
$\langle E_f \rangle$	-	Mean energy per fission
$S_k(E)\sigma_{IBD}(E)$	-	Reference spectra × IBD cross section
$\alpha_k(t)$	-	Fuel fraction evolution

Reactor Related Uncertainty



Total uncertainty 1.75%

Reactor neutrino Prediction V

Predicted neutrino rate:

$$N_\nu^{exp}(E,t) = \frac{N_p \epsilon}{4\pi L^2} \times \frac{P_{th}(t)}{\langle E_f \rangle} \times \langle \sigma_f \rangle$$

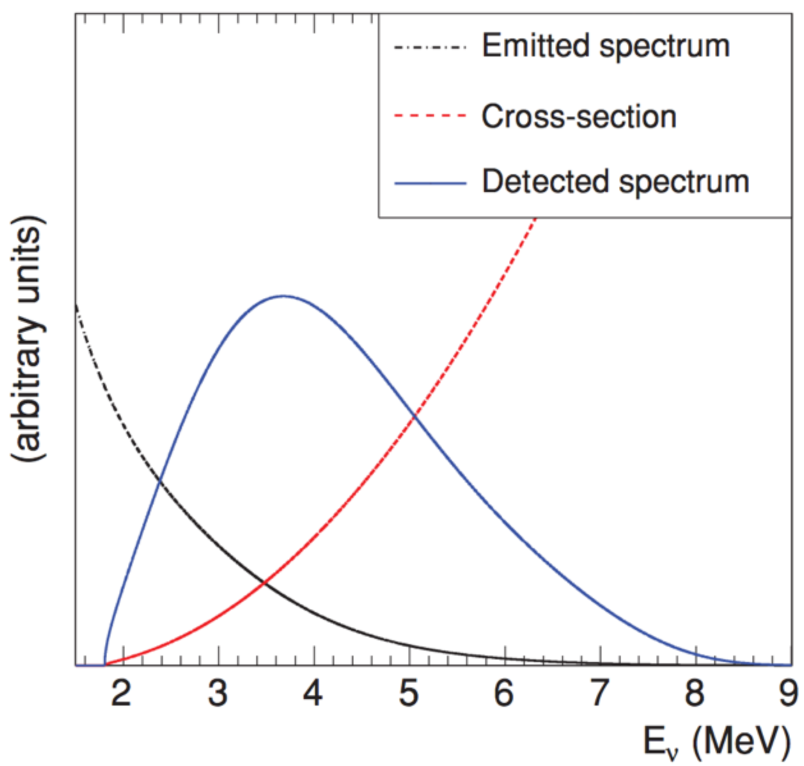
$$\langle E_f \rangle = \sum_k \alpha_k(t) \langle E_k \rangle$$

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

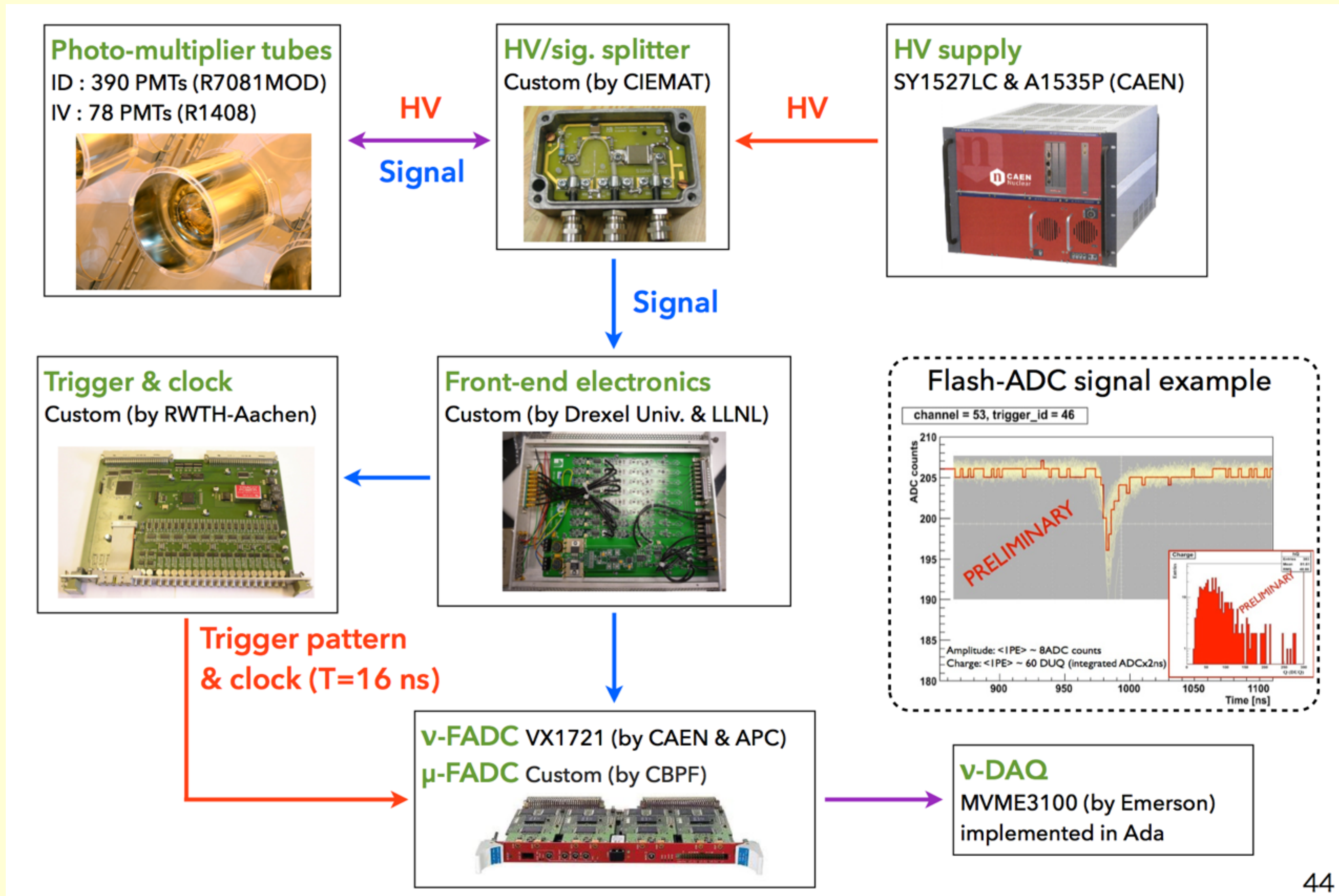
$$\langle \sigma_f \rangle_k = \int_0^\infty S_k(E) \sigma_{IBD}(E) \mathrm{d}E$$

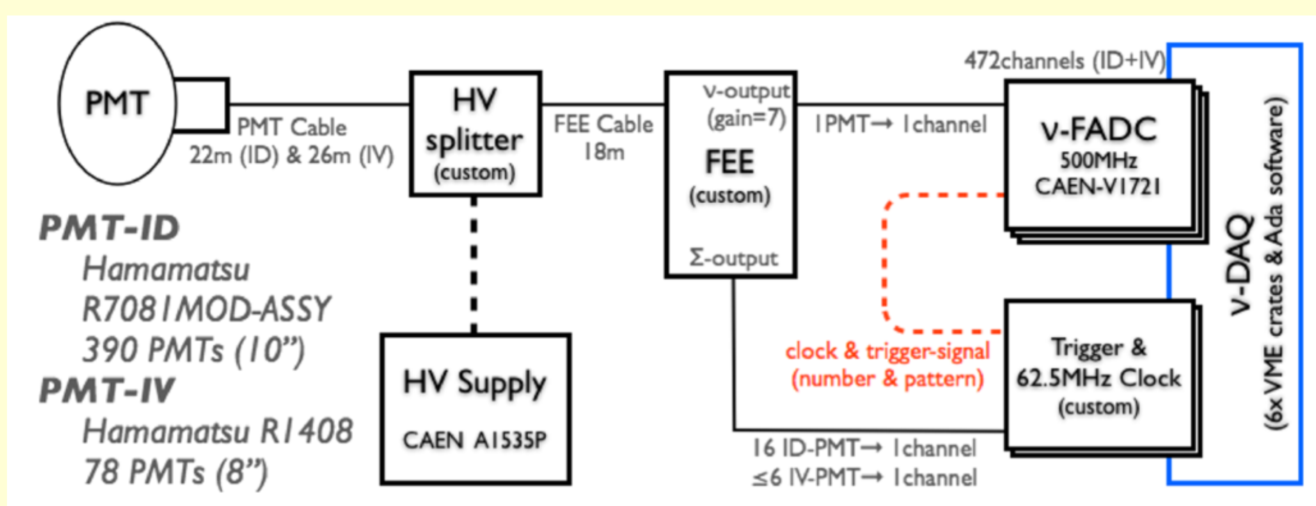
N_p	-	Number protons in detector
ϵ	-	Detection efficiency
L	-	Baseline
$P_{th}(t)$	-	Thermal power
$\langle \sigma_f \rangle$	-	Mean cross section
$\langle E_f \rangle$	-	Mean energy per fission
$S_k(E)\sigma_{IBD}(E)$	-	Reference spectra × IBD cross section
$\alpha_k(t)$	-	Fuel fraction evolution

Detected spectrum



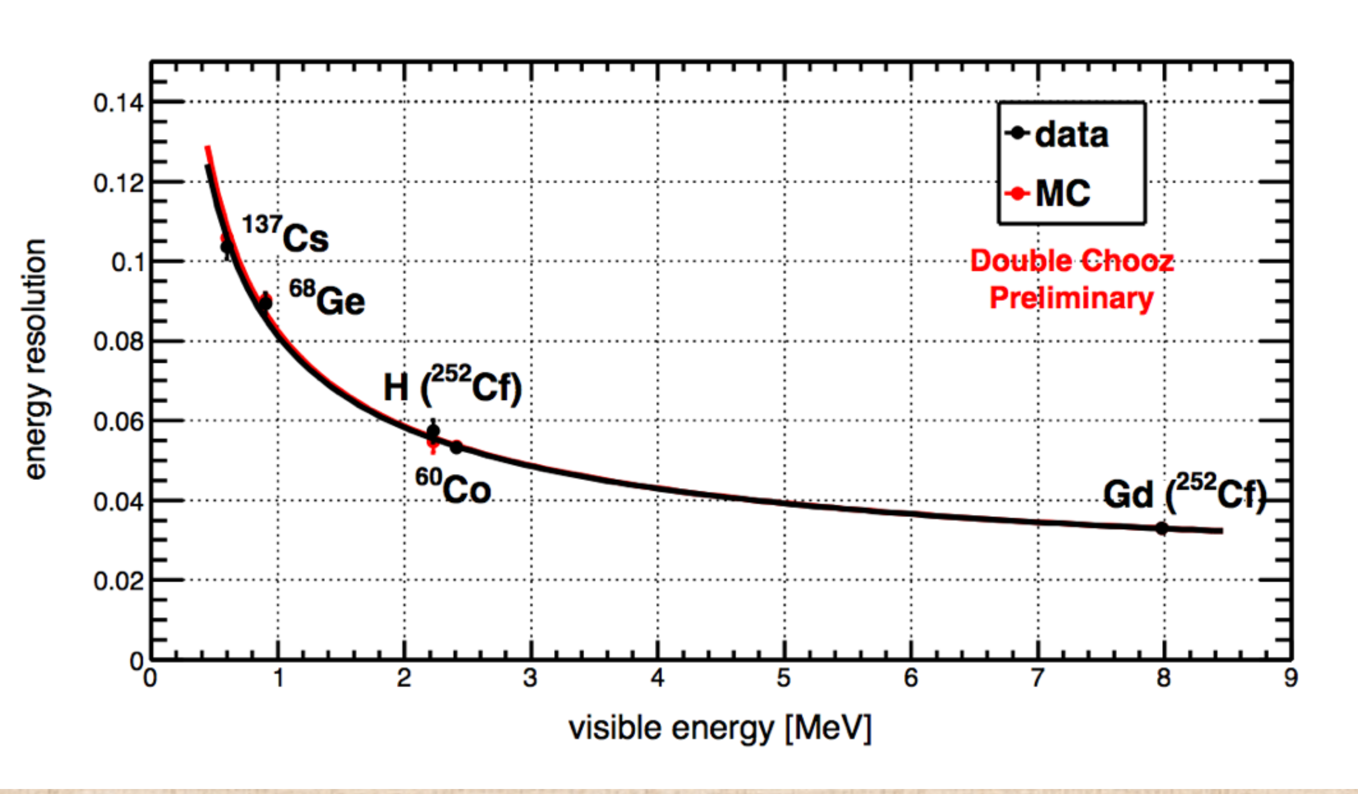
Electronics





Gd-III Energy Scale

- Source deployed detector Center
- Data & MC fit to extract peak (x-axis) & resolution (y-axis)



$$\frac{\sigma}{E_{vis}} = \sqrt{\frac{a^2}{E_{vis}} + b^2 + \frac{c^2}{E_{vis}^2}}$$

a: statistical term
b: constant term
c: e.g electrical noise

Data:	MC:
0.0773±0.0025	0.0770±0.0018
0.0182±0.0014	0.0183±0.0011
0.0174±0.0107	0.0235±0.0061

Further physics

- Background Studies (reactor off) (DC, PRD 87, 011102(R) 2013)
- Lorentz Violation (DC Coll., PRD 86, 112009, 2012)
- Neutrino Directionality (DC, arXiv: 1208.3628)
- Sensitivity to Δm_{13}^2 (arXiv: 1304.6259 [hep-ex])
- Sterile Neutrino (PRD 83, 073006, 2011)
- Muon physics (DC, paper in preparation)
- Orto-positronium observation (DC, La Thuile 2014)

Status Near Detector