Double Chooz

Results towards the ND phase

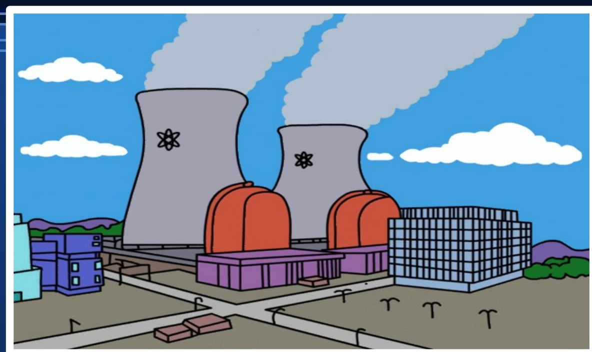
Pau Novella (CNRS/APC)

On behalf of the DC collaboration

Overview

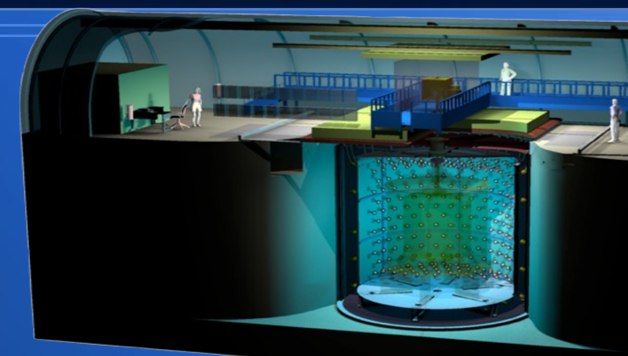
- Reactor neutrinos and θ_{13}
- The Double Chooz experiment
- n-Gd and n-H R+S oscillation results
- Reactor Rate Modulation analysis
- Towards the ND+FD phase
- Summary and conclusions

Reactor neutrinos and θ_{13}



L ~ 1 km

$P(\bar{\nu}_e \to \bar{\nu}_x)$



- In contrast to accelerator experiments...

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

- No parameter correlations
- Pure $\bar{\nu}_e$ beam
- Low energy
- No matter effects
- Cheap, as source exists
- High flux and large x-section

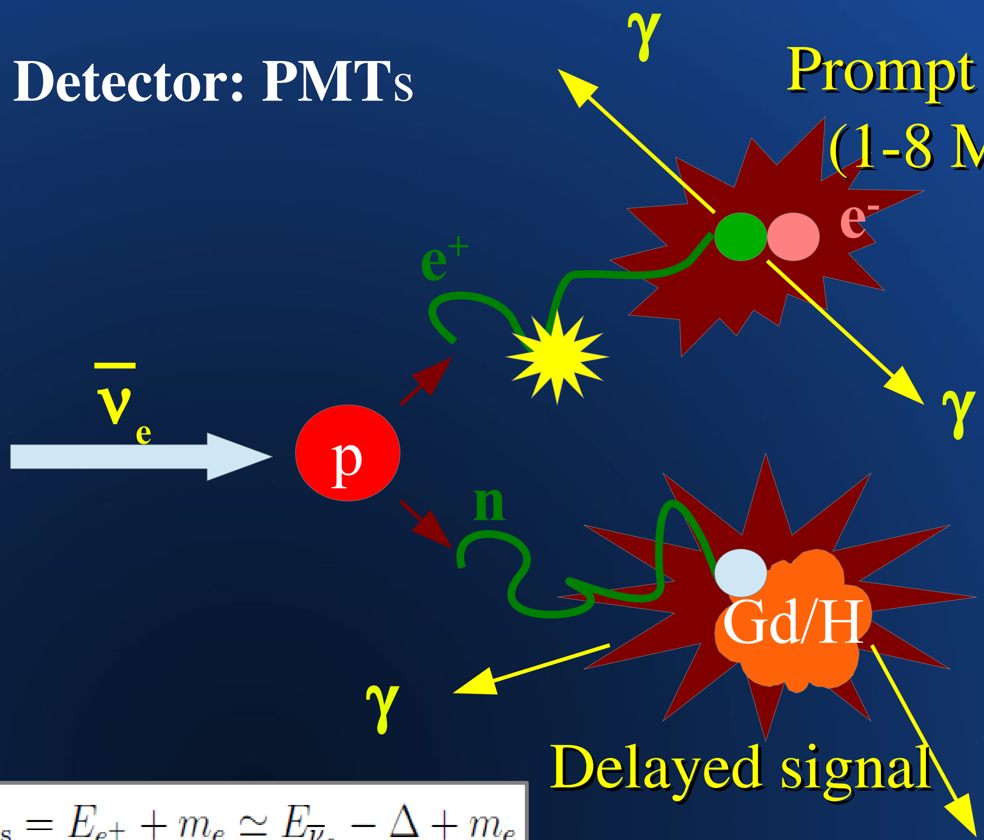
2014: θ_{13} measured by DC, DB and RENO → precision phase!

Detecting reactor neutrinos

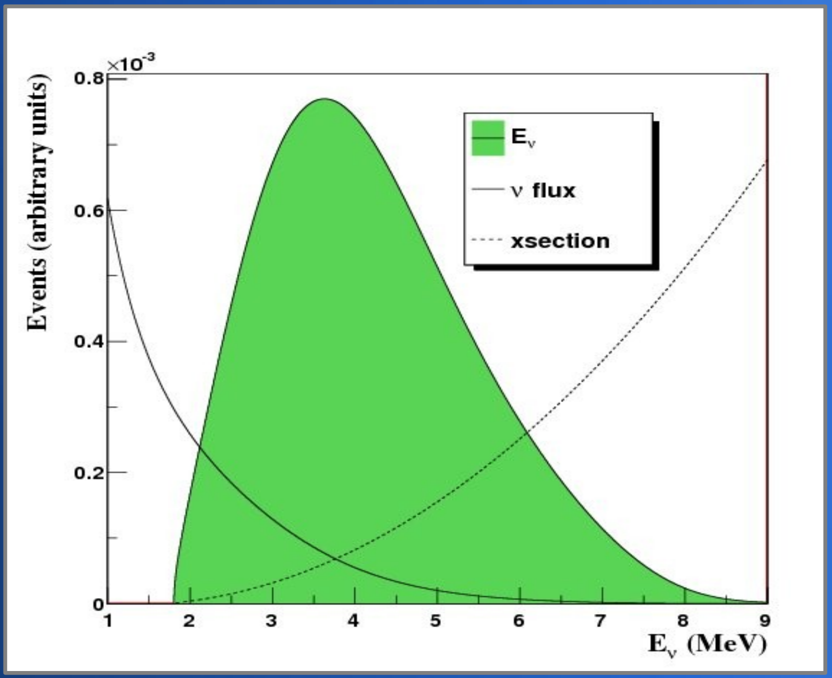
IBD: $\overline{\nu}_e + p \rightarrow e^+ + n$

Th: 1.8 MeV. Disappearance!

- **Target: scintillator + n-catcher (Gd)**
- **Detector: PMTs**



E_ν spectrum

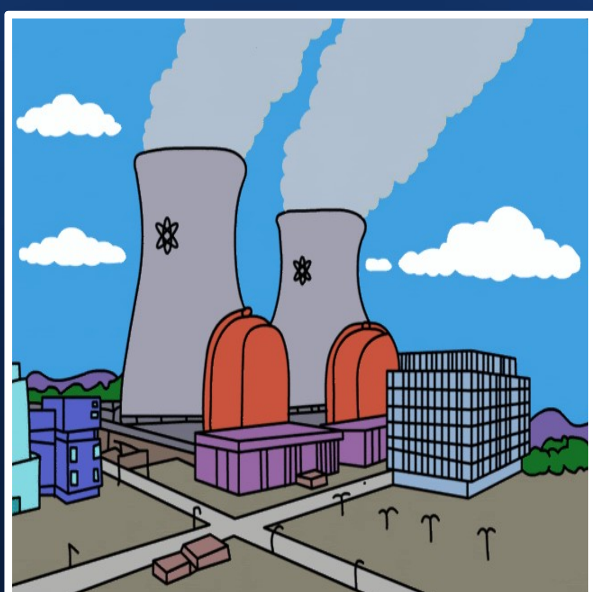


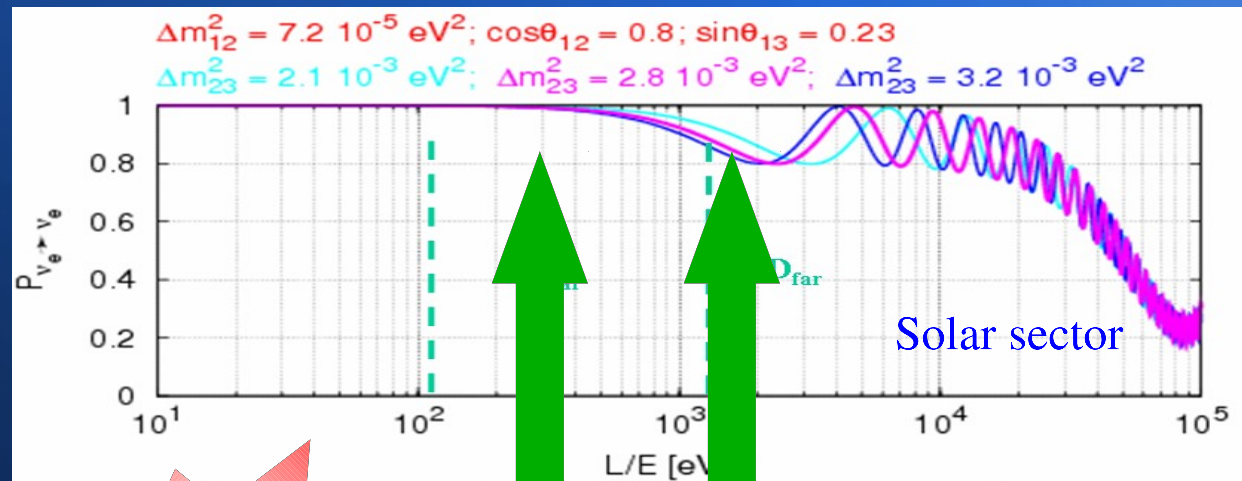
$$E_{\text{vis}} = E_{e^+} + m_e \simeq E_{\overline{\nu}_e} - \Delta + m_e$$

Setting up the experiments

Reactor neutrinos:

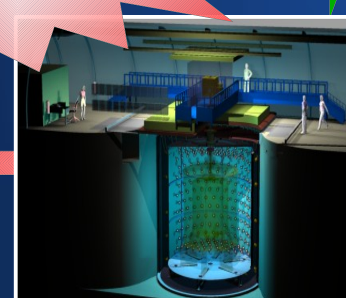
$<E_\nu> \sim 4$ MeV

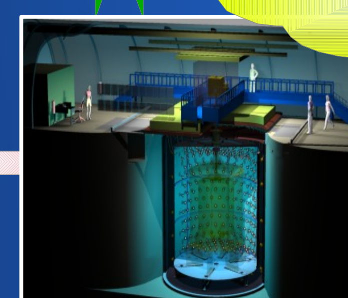




Systematics!

Oscillation!





~100 m

~1 km

The Double Chooz Experiment

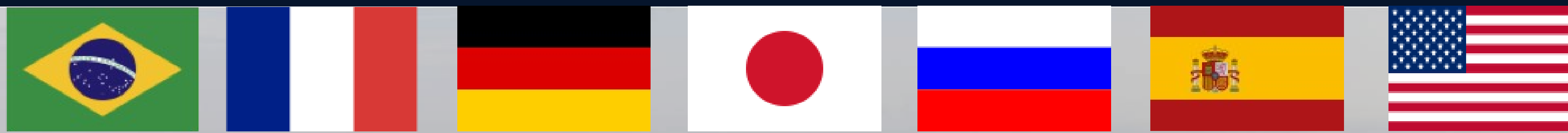
Near Detector
L = 400m
$10m^3$ target
120 m.w.e.
Summer 2014

Far Detector
L = 1050m
$10m^3$ target
300 m.w.e.
April 2011 ~

Chooz Reactors
$4.27GW_{th}$ x 2 cores

- Pioneered reactor experiments after CHOOZ:
    - Experimental concept of using two detectors
    - New detector structure: 4 layers detector
    - Low background (S/N ~ 20, proven by reactor OFF)
    - Stable Gd loaded LS developed

The DC Collaboration



Brazil
- CBPF
- UNICAMP
- UFABC

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

Germany
- EKU Tübingen
- MPIK Heidelberg
- RWTH Aachen
- TU München
- U. Hamburg

Japan
- Tohoku U.
- Tokyo Inst. Tech.
- Tokyo Metro. U.
- Niigata U.
- Kobe U.
- Tohoku Gakuin U.
- Hiroshima Inst. Tech.

Russia
- INR RAS
- IPC RAS
- RRC Kurchatov

Spain
- CIEMAT-Madrid

USA
- U. Alabama
- ANL
- U. Chicago
- Columbia U.
- 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 Detectors

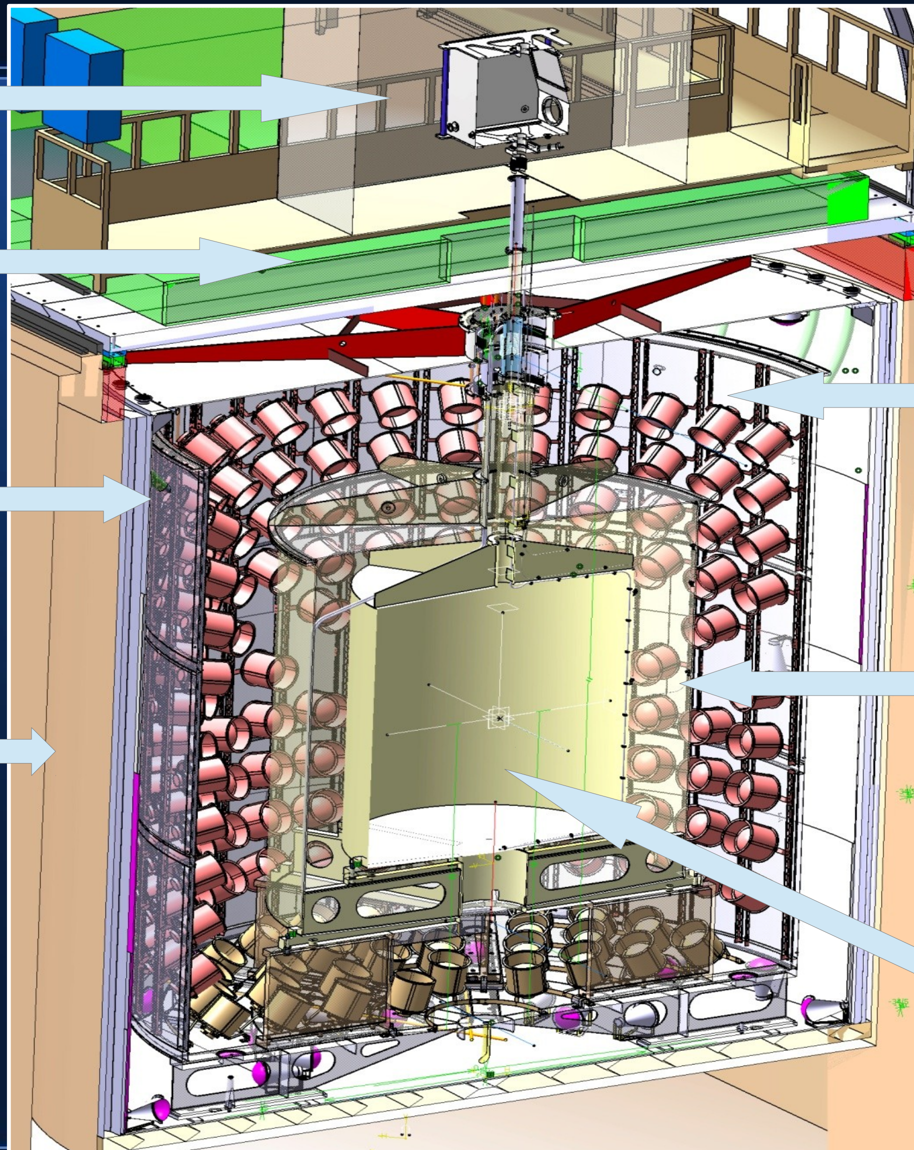
Glove box

μ Outer Veto
Plastic scint. strips

Inner Veto
Scint. (LAB)
78 8” PMTs

Iron Shield

Inner
ND and FD
are identical



Inner Detector
Steel buffer
2 acrylic vessels

Buffer
Mineral oil
390 10” PMT

Gamma Catcher
Scintillator (PXE)

Target
Scintillator (PXE)
doped with Gd

Detector Calibration

- 3 Calibration sources:

Radiactive sources

^{137}Cs, ^{68}Ge, ^{60}Co, ^{252}Cf

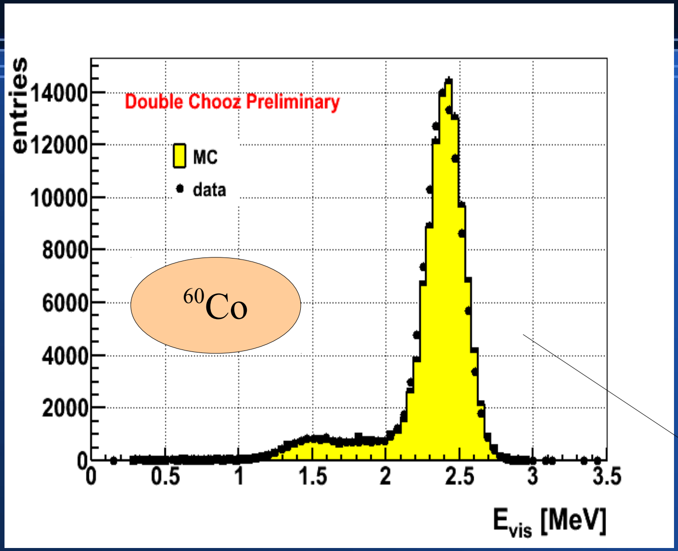
***Natural* sources**

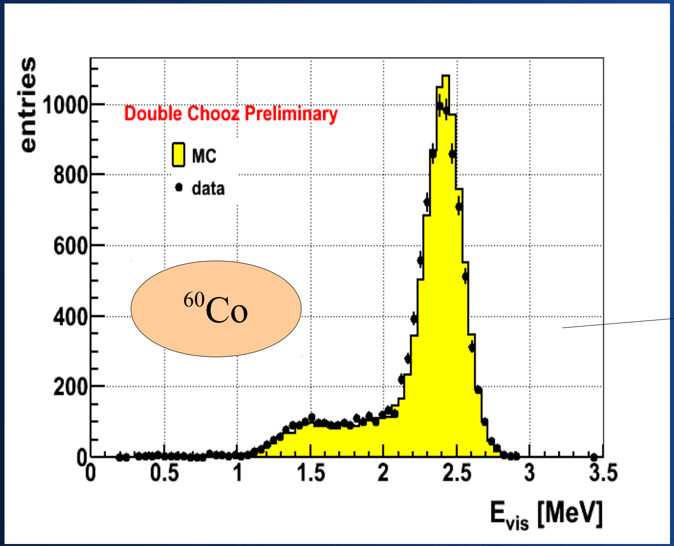
n-H captures, BiPo

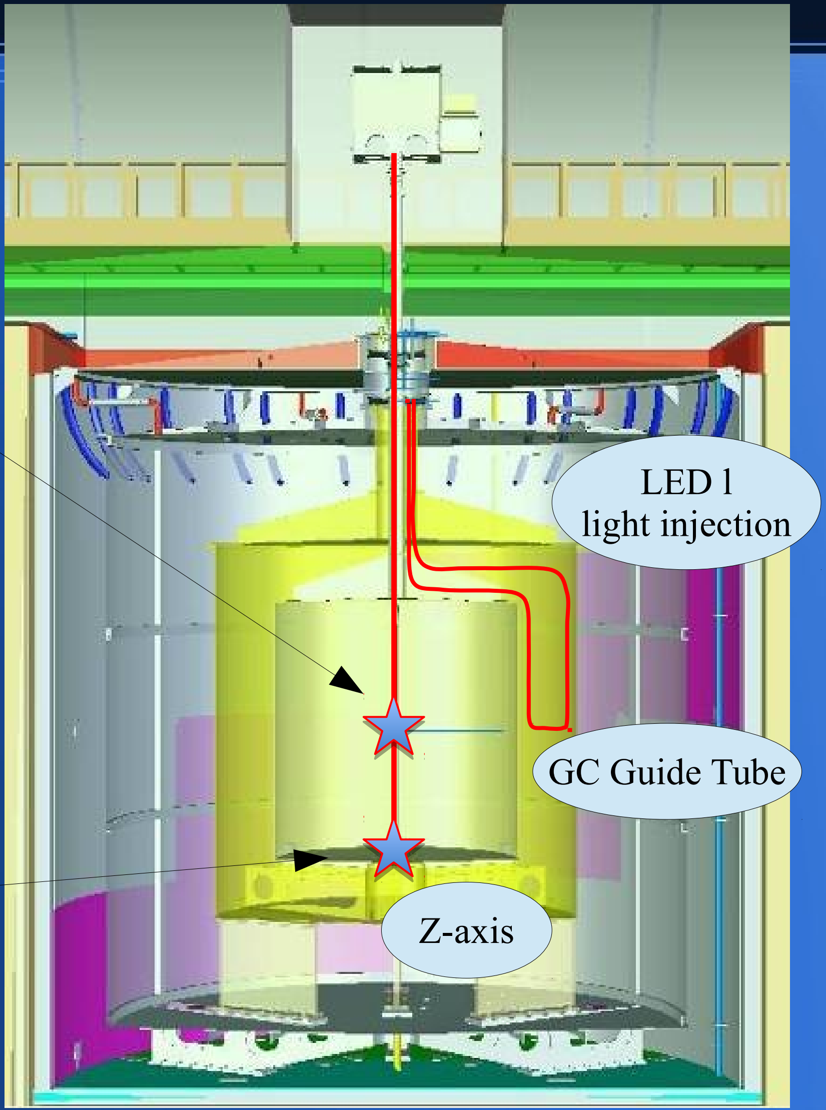
LED light injection

Energy Scale

PE non-linearity
Detector uniformity
Time stability







Neutrino Candidates Selection

n from IBD can be captured either in Gd or H

n-Gd

- High x-section
- $\Delta T \sim 30\mu s$
- $E_{delay} \sim 8$ MeV

n-H

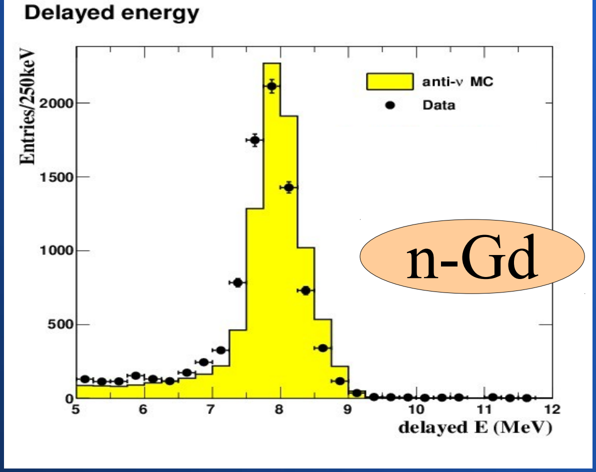
- High stats **(TG+GC)**
- $\Delta T \sim 200\mu s$
- $E_{delay} \sim 2.2$MeV

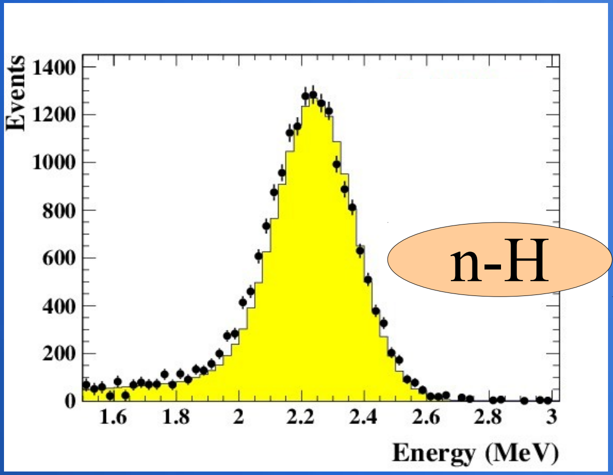
Independent statistical samples:

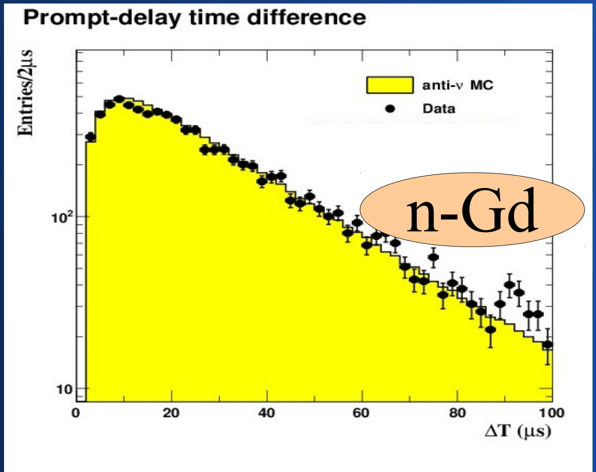
1) x-check on θ_{13}

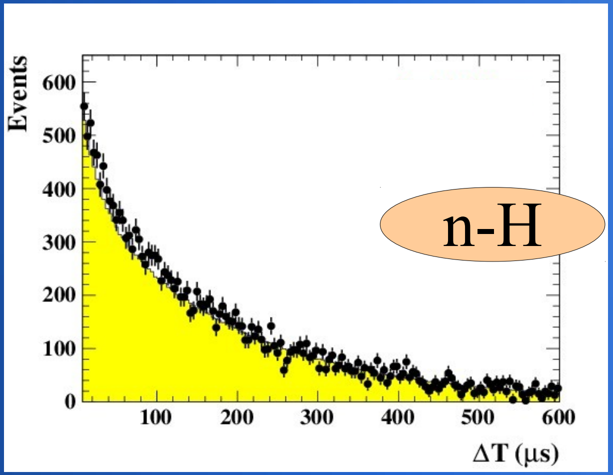
2) Boost statistics

Characteristic p-d correlation: Background reduction



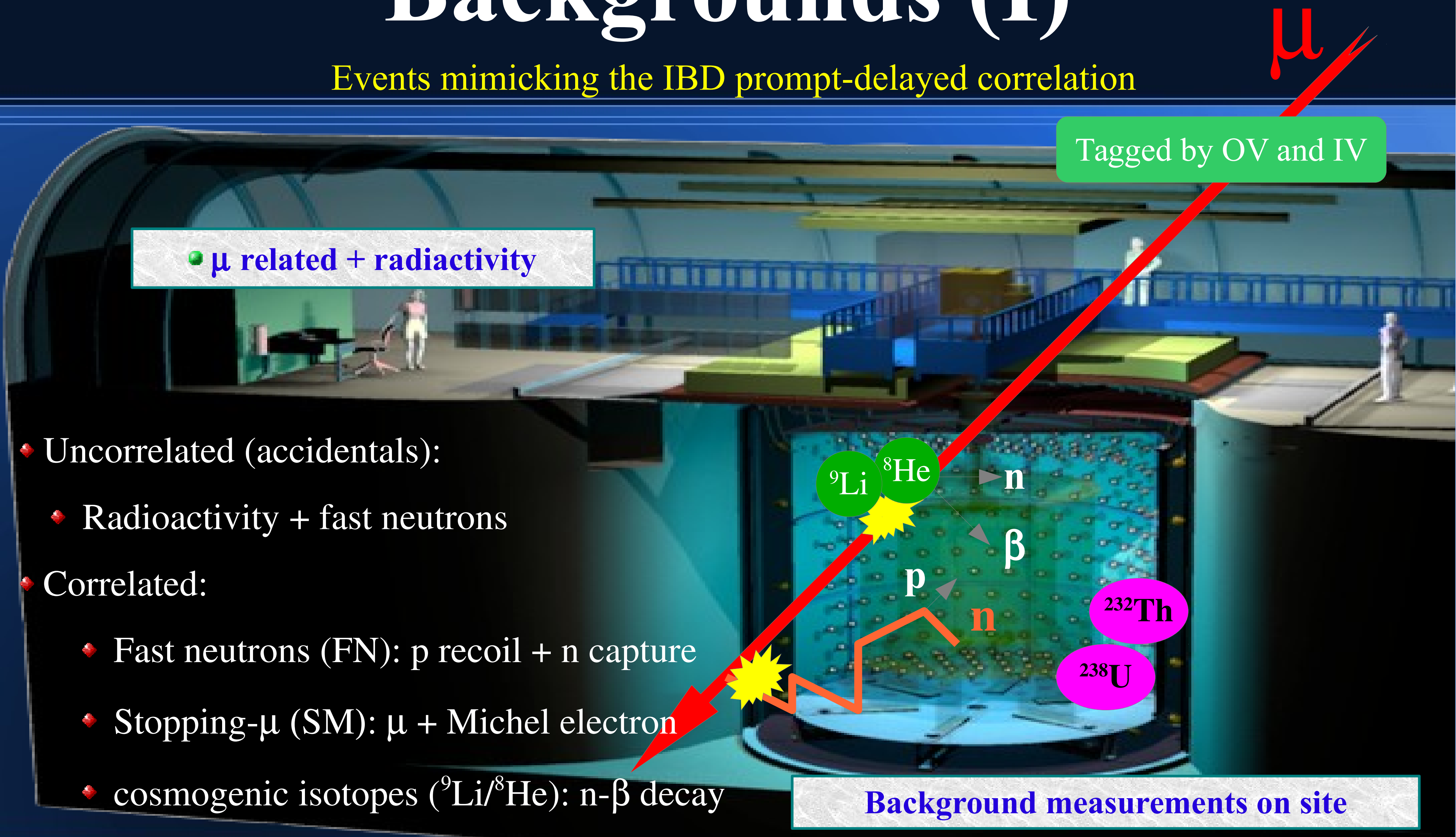






Backgrounds (I)

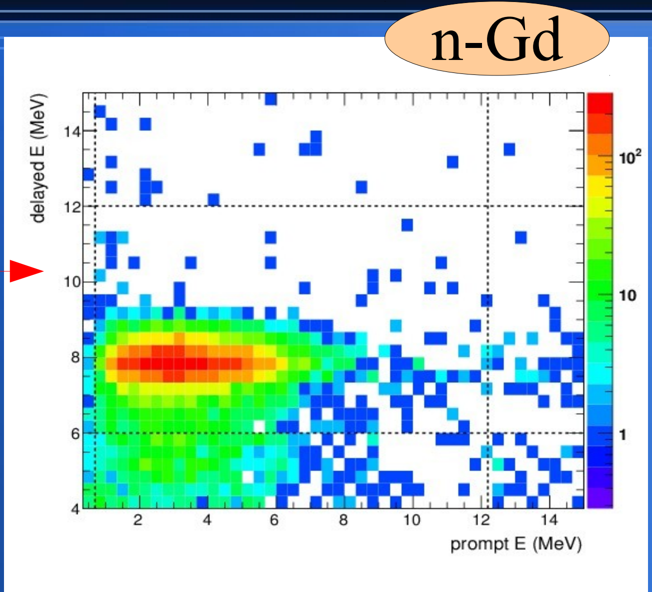
Events mimicking the IBD prompt-delayed correlation



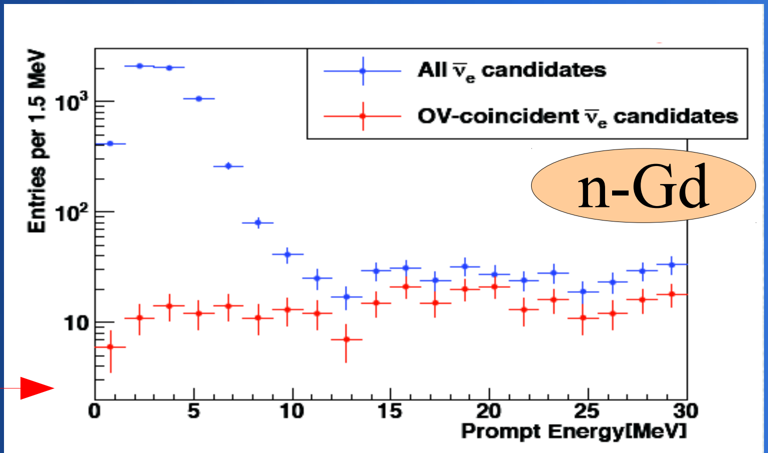
- Uncorrelated (accidentals):
  - Radioactivity + fast neutrons
- Correlated:
  - Fast neutrons (FN): p recoil + n capture
  - Stopping-μ (SM): μ + Michel electron
  - cosmogenic isotopes ($^{9}Li/^{8}He$): n-β decay

Candidates Selection (II)

p-d correlation	n-Gd	n-H
E prompt	0.7-12.2 MeV	0.7-12.2 MeV
E delayed	6.0-12.0 MeV	1.5-3.0 MeV
ΔT	2-100 μs	10-600 μs
ΔR	--	<0.9 m

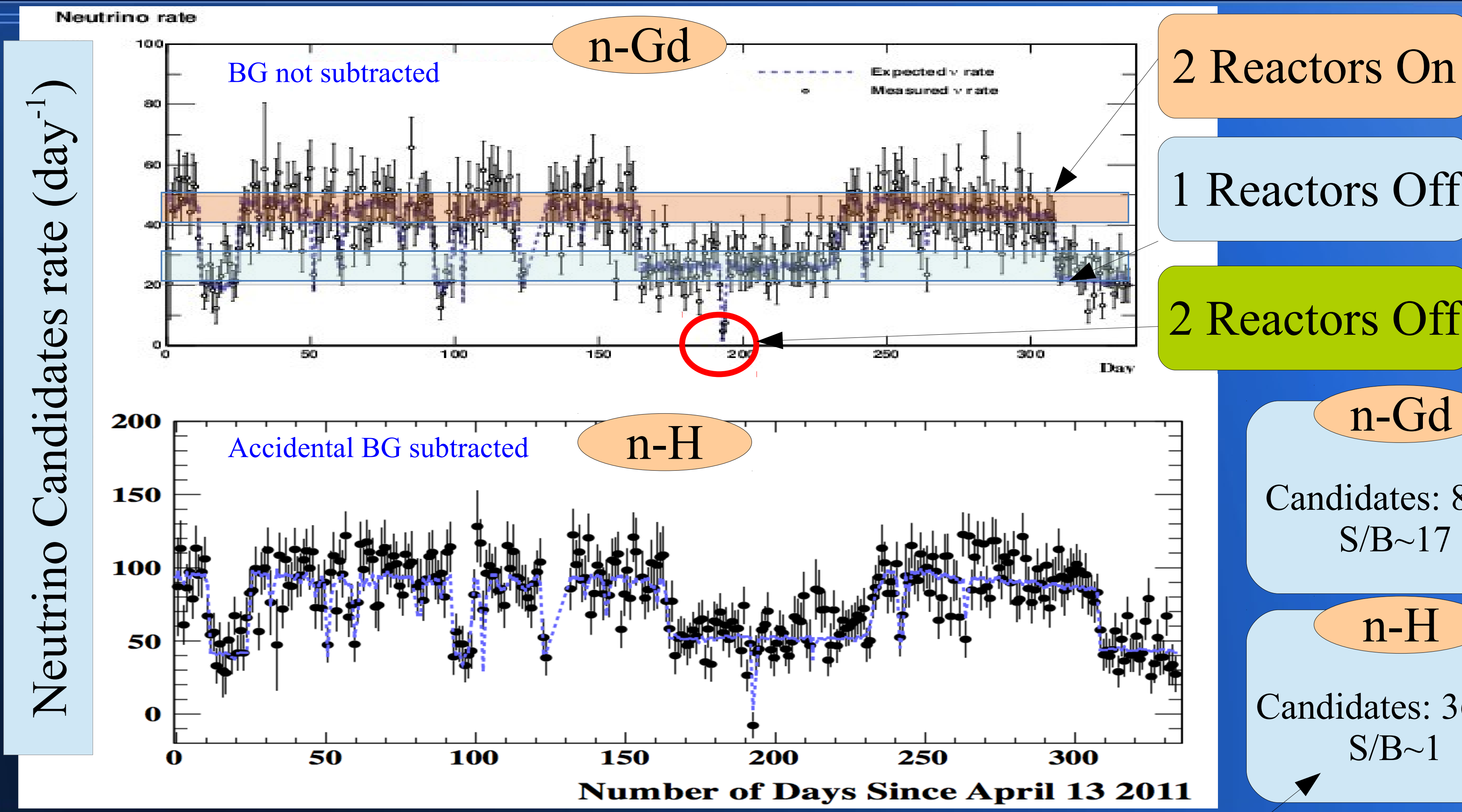


BG reduction	n-Gd	n-H
μ veto	ΔT > 1ms	
Showering–μ	E_μ > 600 MeV, ΔT>0.5s	--
isolation	500 μs	1600 μs
OV veto	Prompt not coincident with OV	



Neutrino Candidates Rate

Run Time: 251.3 day



n-Gd

Candidates: 8249
S/B~17

n-H

Candidates: 36284
S/B~1

Acc. BG

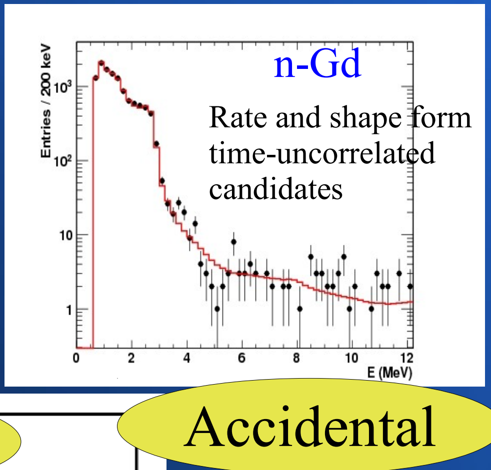
Backgrounds (II)

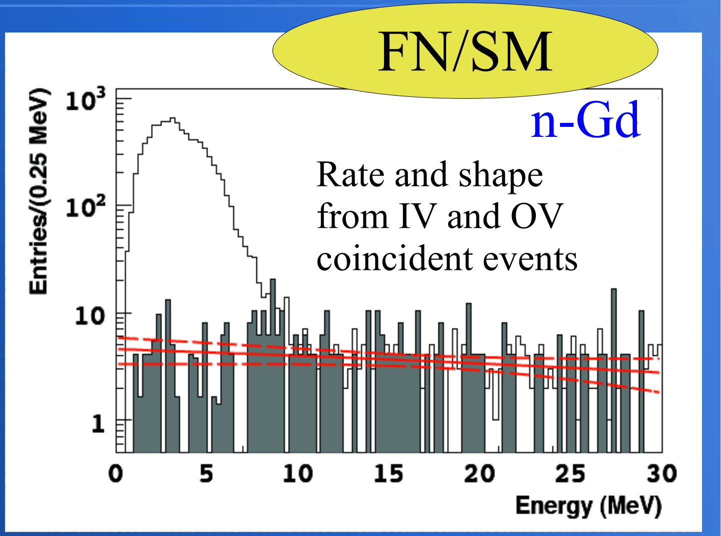
n-Gd

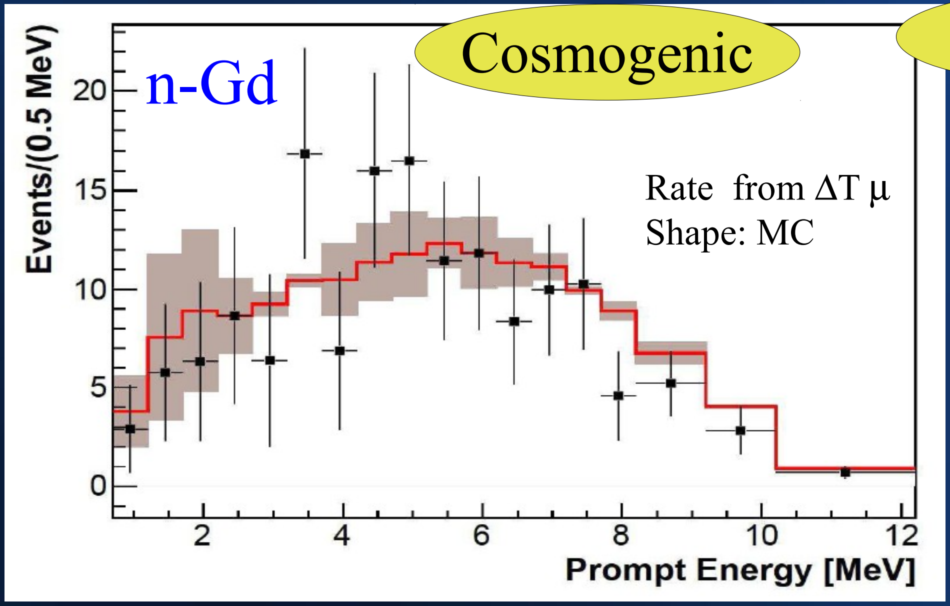
Accidentals: 0.261±0.002 / day

Fast-n/Stop-μ: 0.67±0.20 / day

Cosmo. $^{9}Li/^{8}He$: 1.25±0.54 /day







n-H

Accidentals: 73.45±0.16 / day

Fast-n/Stop-μ: 2.50±0.47 / day

Cosmo. $^{9}Li/^{8}He$: 2.8±1.2 /day

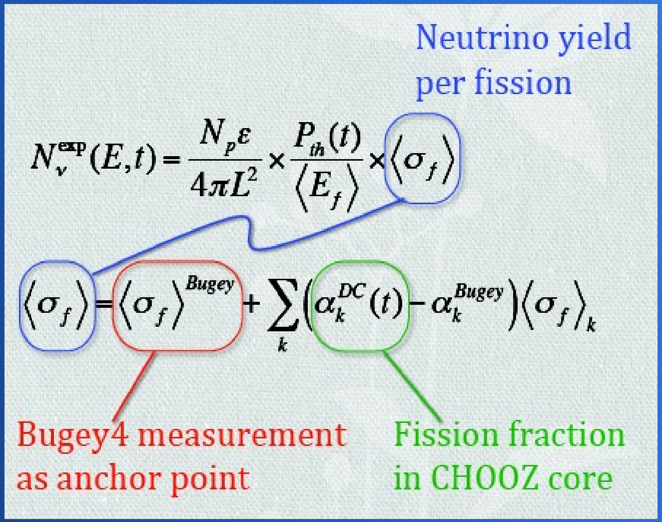
Systematic Uncertainties

Rate Error (%)	n-Gd	n-H
statistics	1.1	1.1
Flux prediction	1.7	1.7
det. efficiency	1.0	1.6
background	1.6	1.7
Total	2.7	3.1

Shape uncertainties

- Reactor spectrum
- Energy scale
- ^{9}Li spectrum
- FN/SM spectrum

- Dominated by flux error:
  - to be canceled by the ND

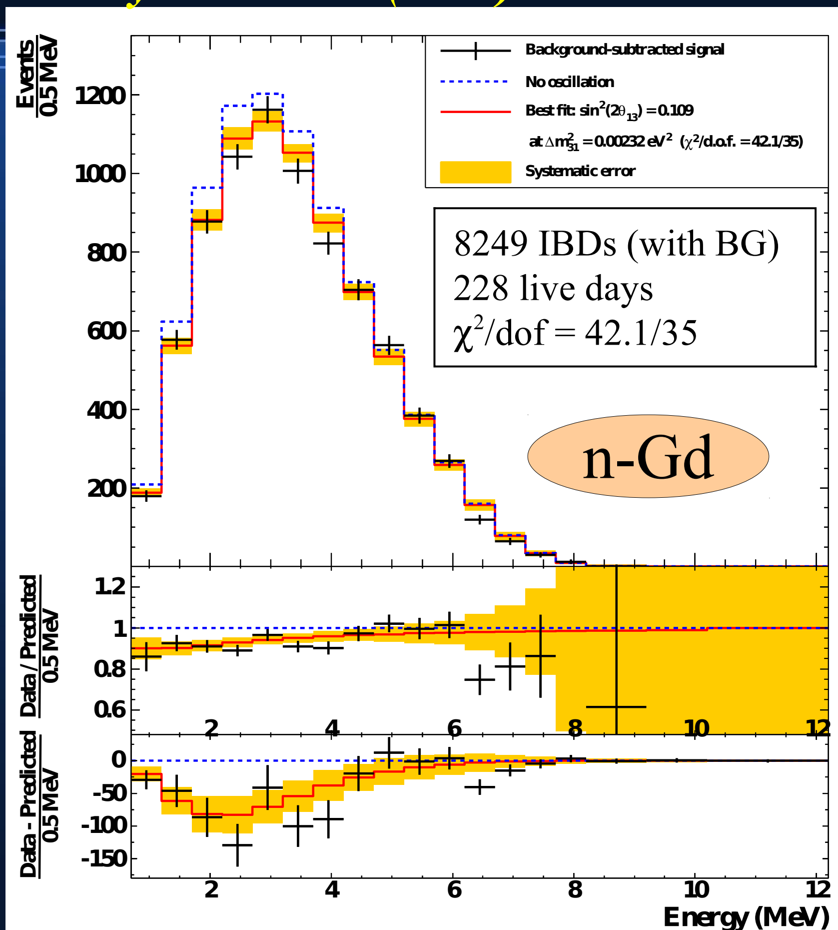


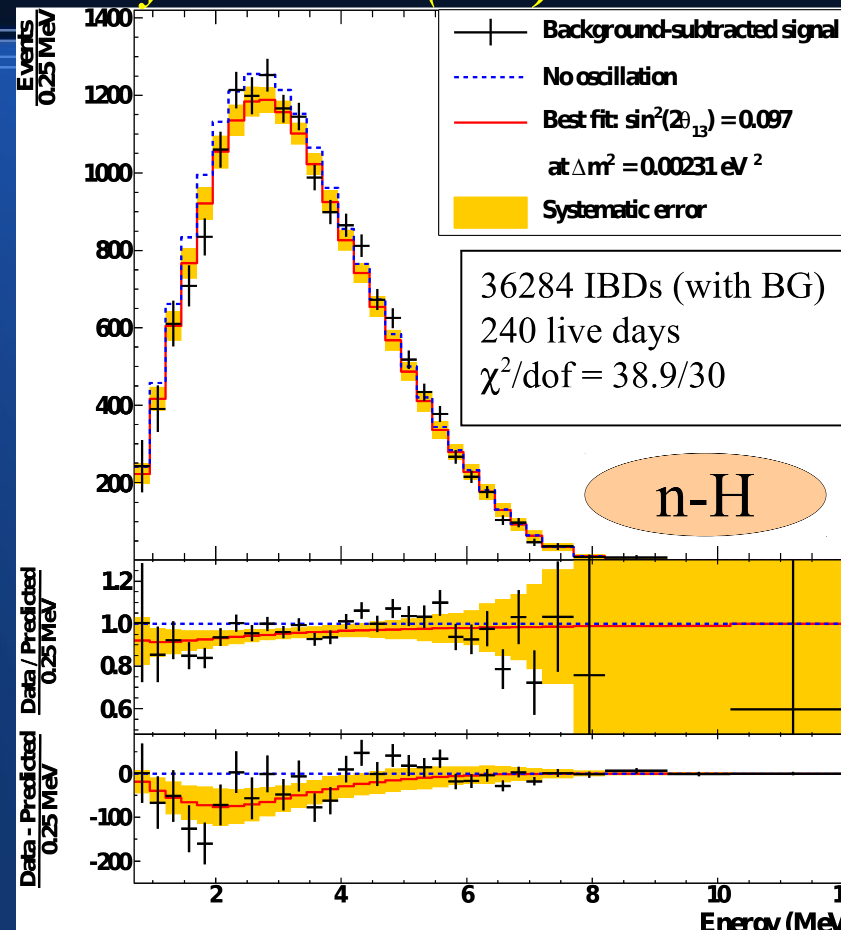
- $^{9}Li/^{8}He$ dominates the BG error
  - 1.5% for n-Gd, 1.6% for n-H
  - To be reduced with larger stats

R+S Oscillation Results

Phys. Rev. D86 (2012) 052008

Phys. Lett. B723 (2013) 66-70



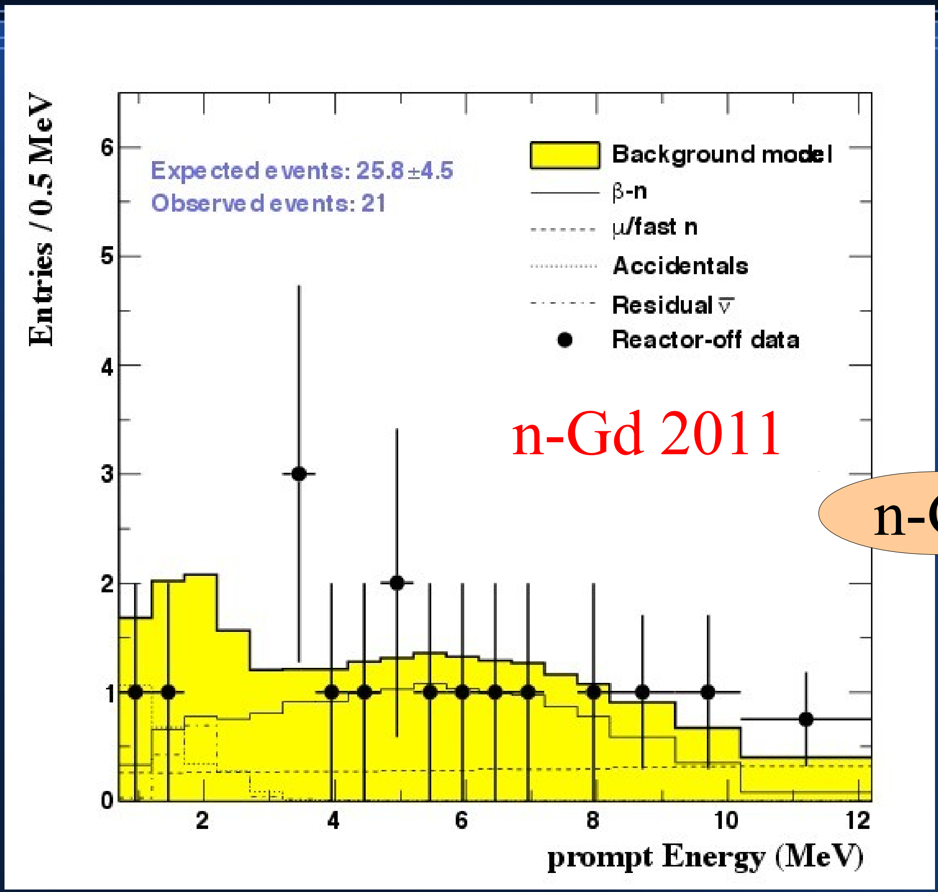


DC-II(Gd): $\sin^2 2\theta_{13} = 0.109 \pm 0.039\ [0.030^{stat} \pm 0.025^{syst}]$

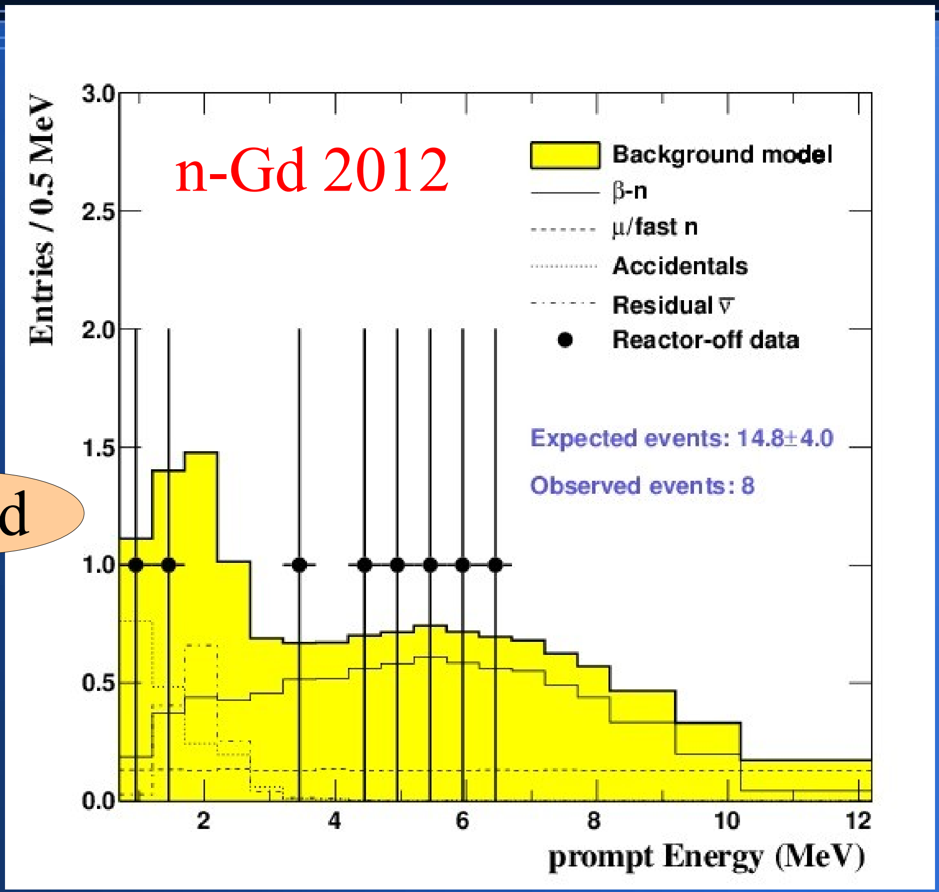
DC-II(H): $\sin^2 2\theta_{13} = 0.097 \pm 0.048\ [0.034^{stat} \pm 0.034^{syst}]$

Reactor-Off: BG measurement

2011 and 2012 reactor-off samples: 7.53 days



n-Gd



Phys.Rev. D87 (2013) 011102

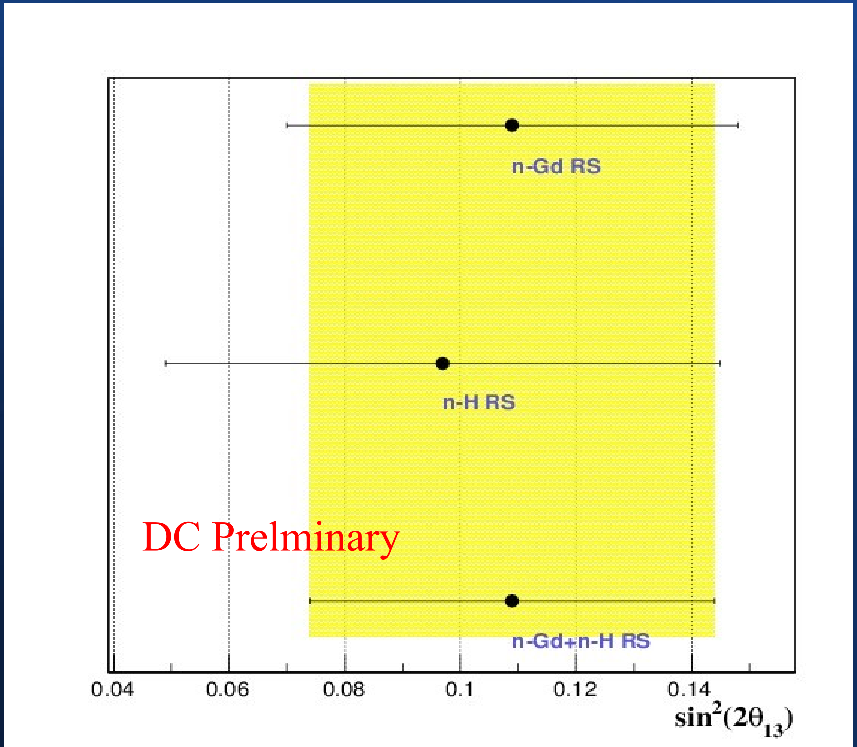
- n-Gd selection: R_{BG}=1.0±0.4 events/day
- n-H selection: R_{BG}=10.8±3.4 events/day (acc. sub.)

Consistent with BG model used in R+S fit

Gd-H Combined Result

New since Moriond 2013

- Taking the most from DC: n-Gd + n-H + Reactor-Off:



Rate+Shape: $\sin^2 2\theta_{13}=0.109\pm0.035$

Rate-Only: $\sin^2 2\theta_{13}=0.107\pm0.045$

- To be compared with n-Gd *"only"*:

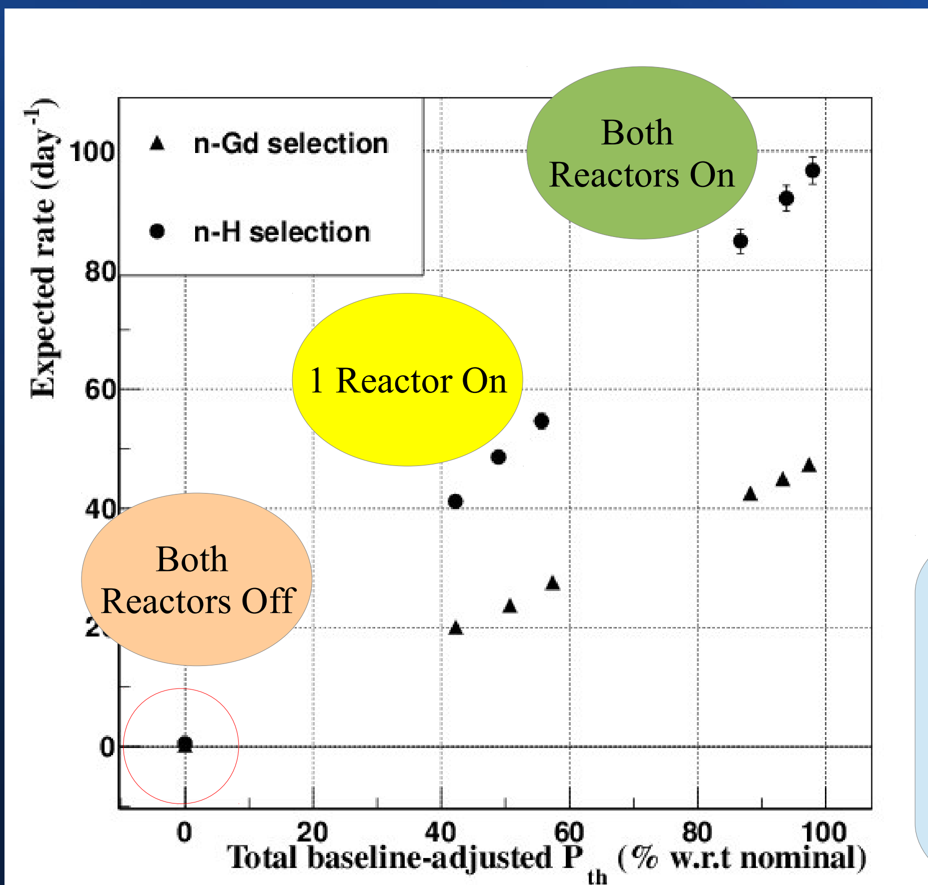
Rate+Shape: $\sin^2 2\theta_{13}=0.109\pm0.039$

Rate-Only: $\sin^2 2\theta_{13}=0.170\pm0.052$

- n-H will be a powerful handle to improve the θ_{13} results

Reactor Rate Modulation

New since Moriond 2013



- New θ_{13}/BG analysis
  - Different reactor powers (2-Off!)
- No background model assumed

1) BG-independent θ_{13} measurement

2) cross-check of the BG model

- RRM unique in DC:
- 2 reactors only
- Reactor-Off data
- n-Gd and n-H samples

n-Gd RRM Analysis

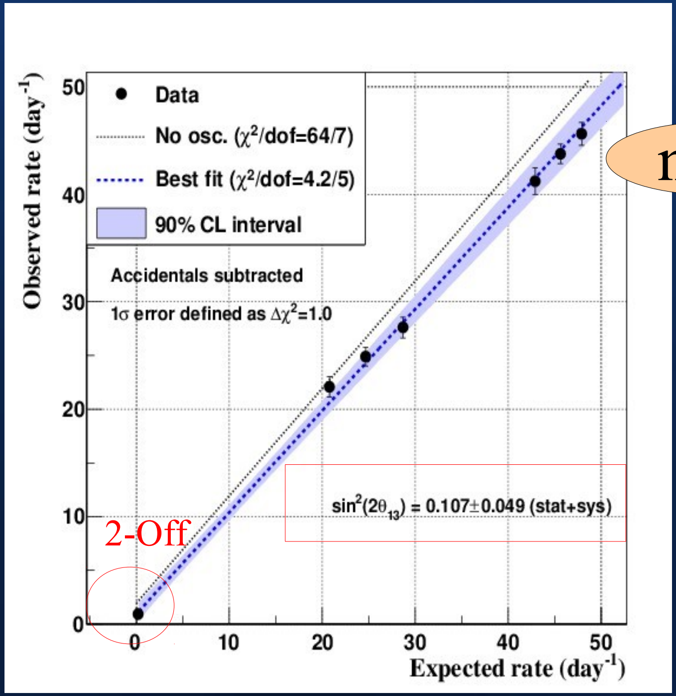
ArXiv:1401.5981, submitted to PLB

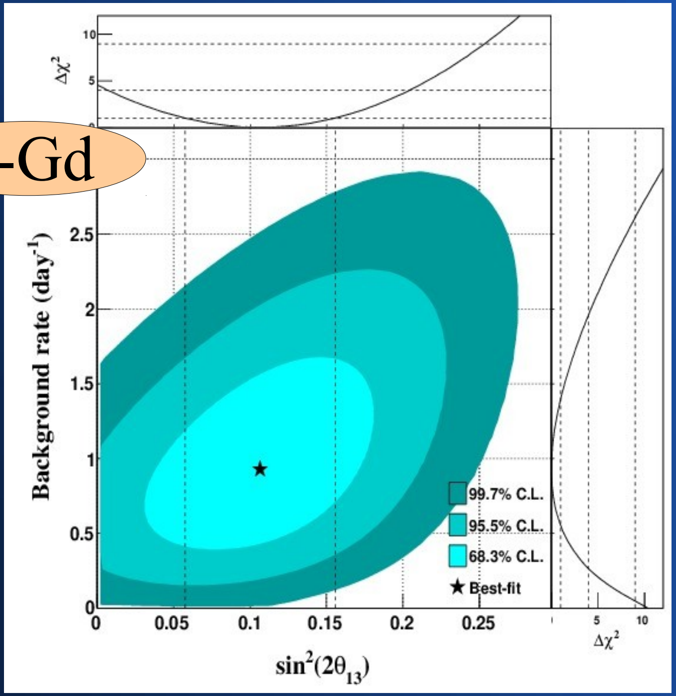
New since Moriond 2013

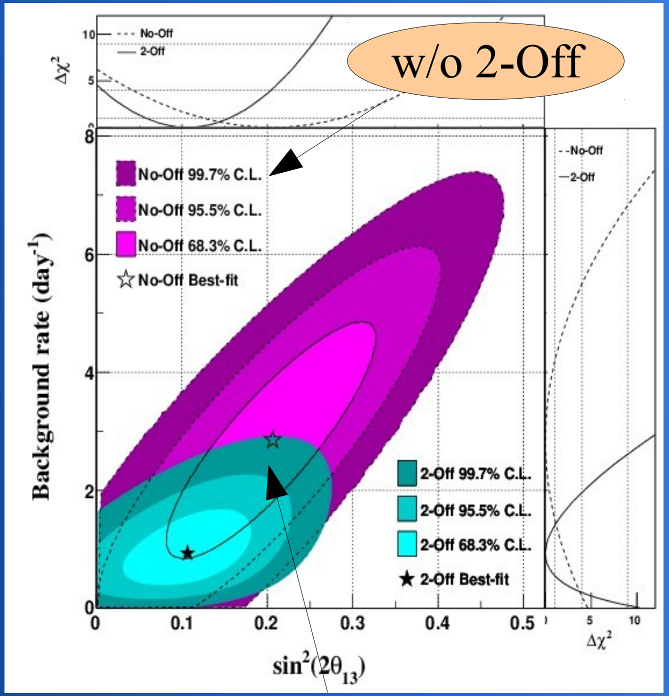
$$R^{\text{obs}} = B + R^{\text{exp}} = B + \left(1 - \sin^2(2\theta_{13})\eta_{\text{osc}}\right) R^{\nu}$$

$$\eta_{\text{osc}} = \langle \sin^2(\Delta m^2 L/4E) \rangle$$

- θ_{13} from the slope, while BG from extrapolation to 0 power







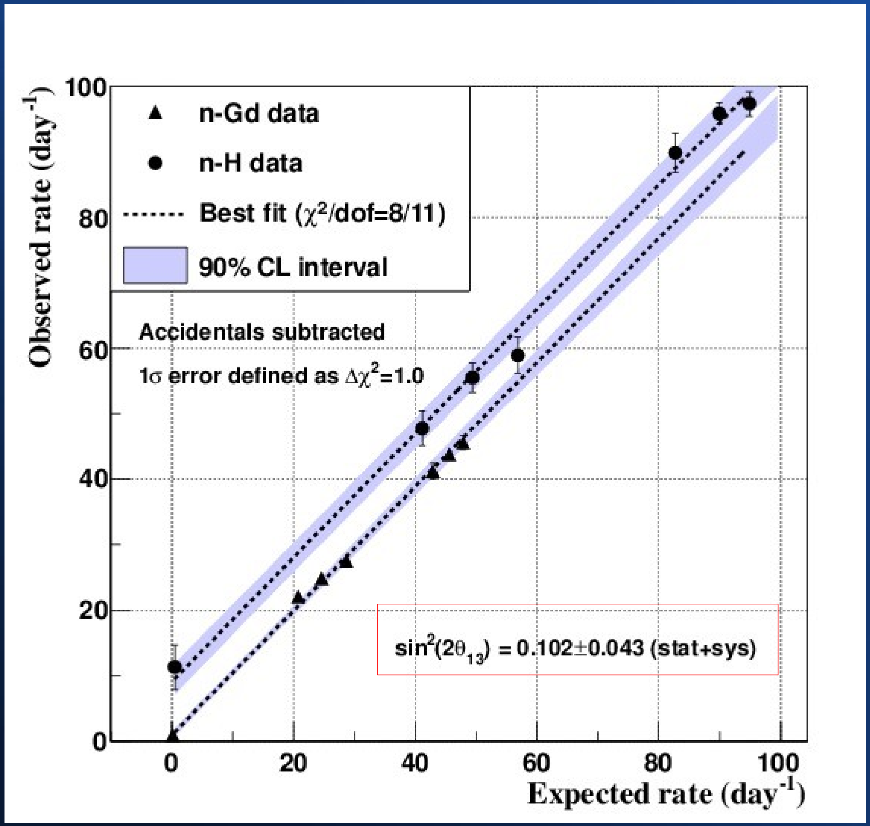
Independent BG measurement

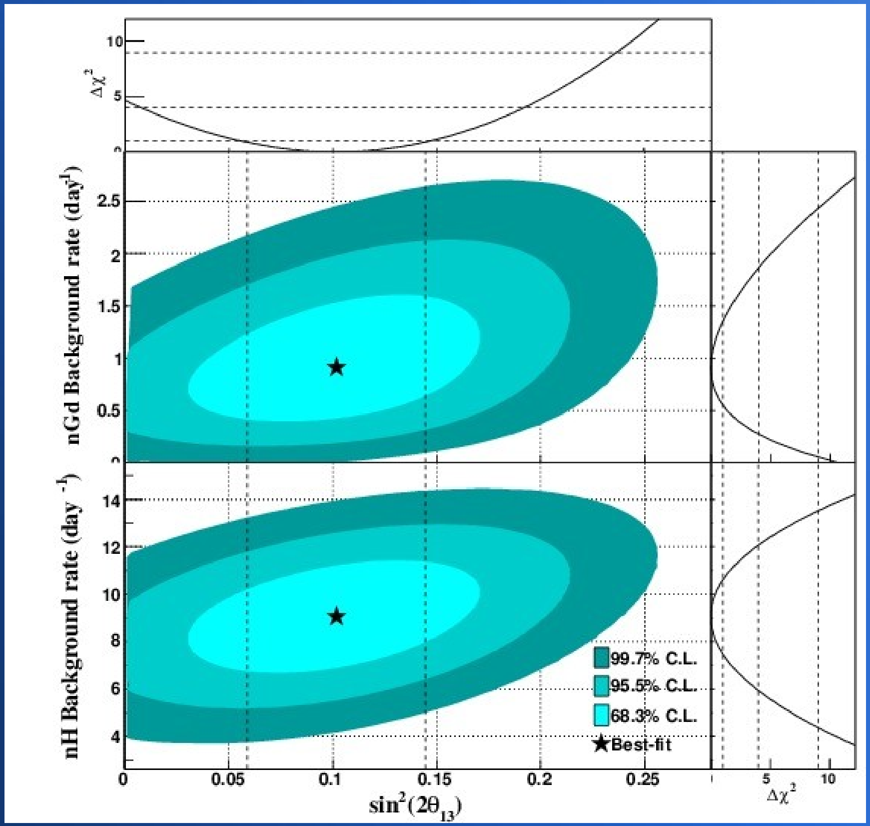
Gd-H Combined RRM Result

ArXiv:1401.5981, submitted to PLB

New since Moriond 2013

- Taking the most from DC: n-Gd + n-H + Reactor-Off:

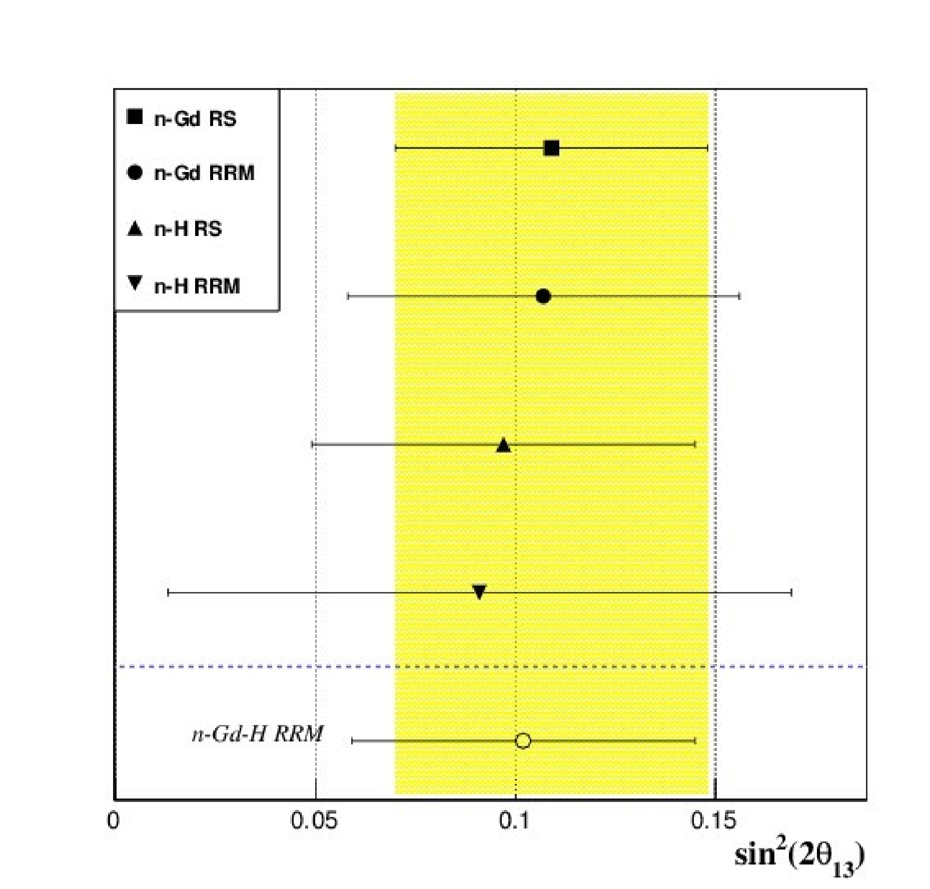




- θ_{13} consistent with R+S fit, BG consistent with BG model used in R+S fit

Summary of DC Results

ArXiv:1401.5981, submitted to PLB

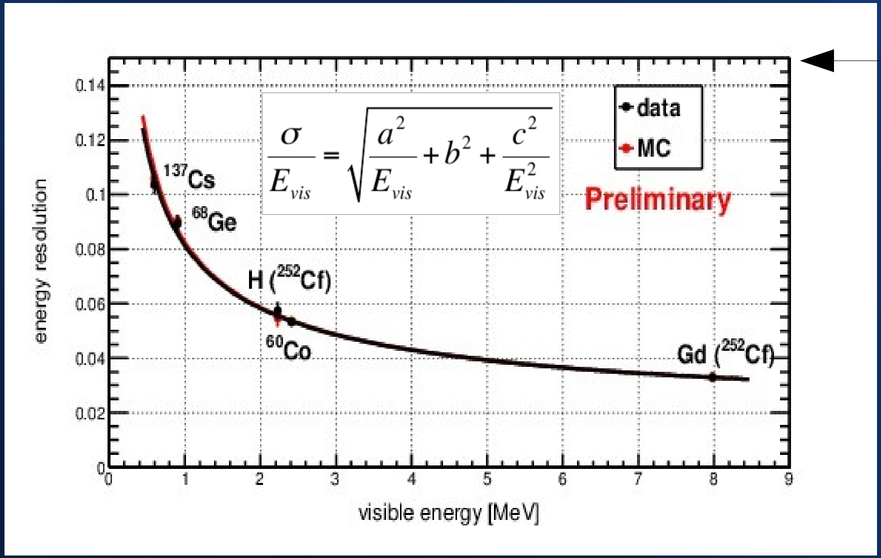


- 4 different θ_{13} analysis:
  - 2 samples: nGd and nH
  - 2 methods: R+S and RRM
    - RS: BG-model dependent
    - RRM: BG-model independent
- 2 combined results:
  - R+S with nGd + nH
  - RRM with nGd and nH
- θ_{13} consistent within 1σ
- BG model consistent 2-Off and RRM

ND+FD Analysis Ongoing

New since Moriond 2013!

- Precision on θ_{13} is limited by reactor systematics (1.8%): ~3σ
- New analysis: reduction of all other systematics with FD only (x2 stats)
  - exploit DC capabilities in the ND+FD phase (reactor sys canceled!)



New Energy
Calibration improved

New Selection
Reduced BG
Increased signal

Reduced systematics
BG, detection efficiency, E_{scale}

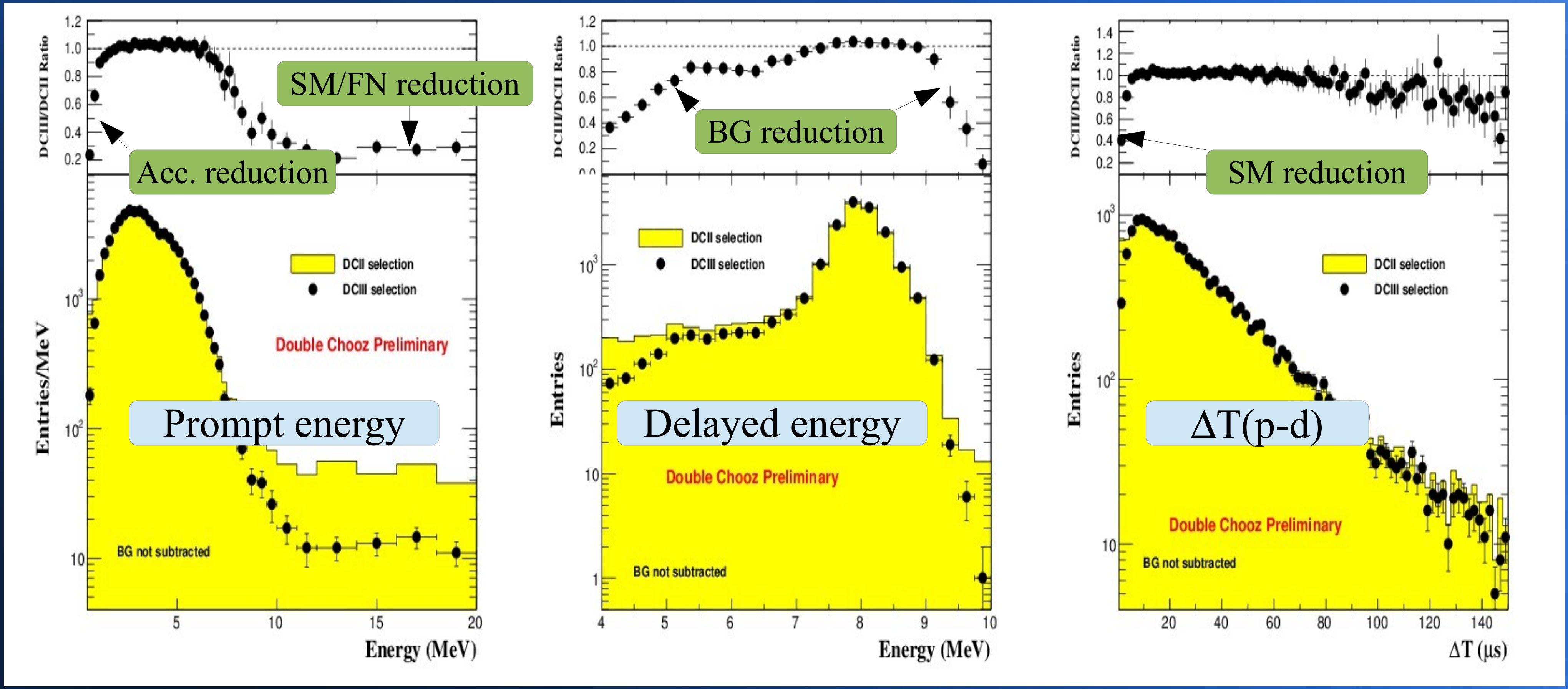
ND+FD θ_{13} precision goal: ~10%

Towards a New Selection

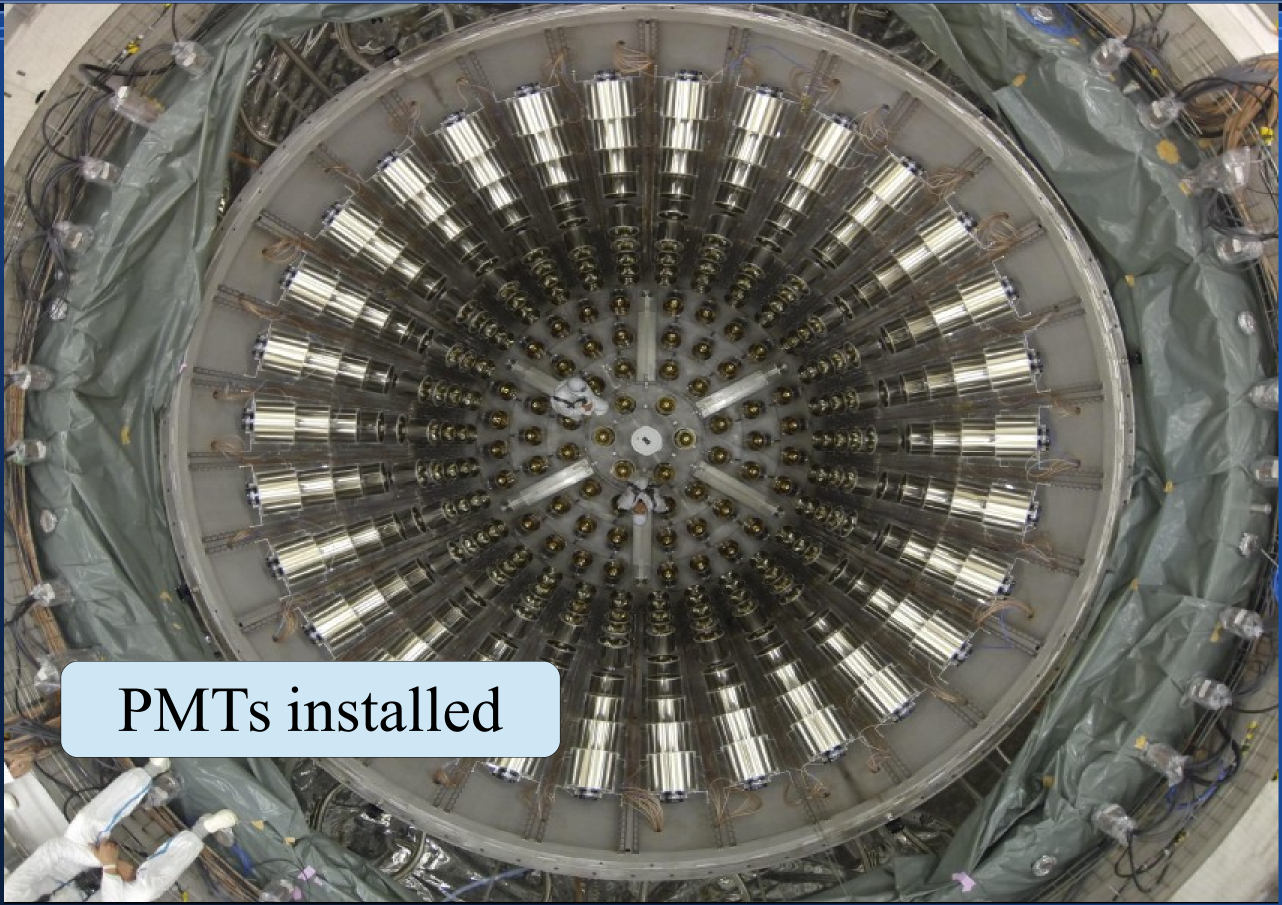
x2 stats, new energy reconstruction

New since Moriond 2013!

- Open cuts + new BG vetoes: boosted S/B → reduced detection and BG sys



Near Detector



- Data taking starting in summer 2014

Physics beyond θ_{13}

- 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)
- Reactor physics (future ND data)

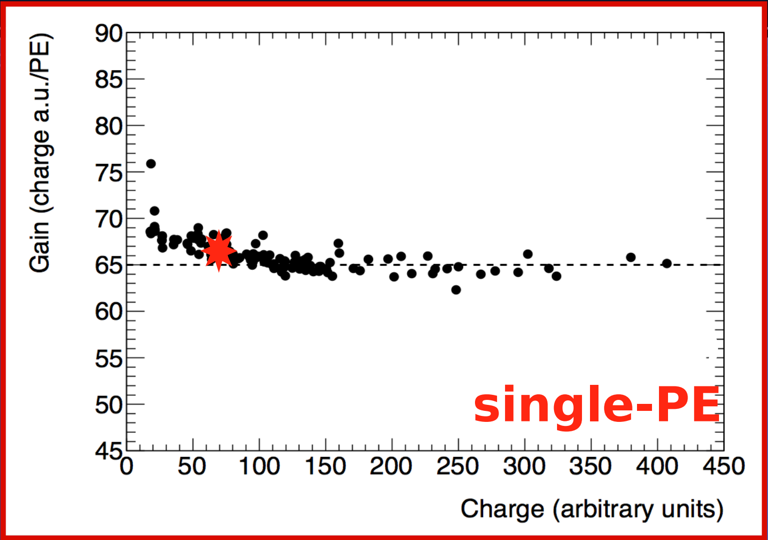
Summary and Conclusions

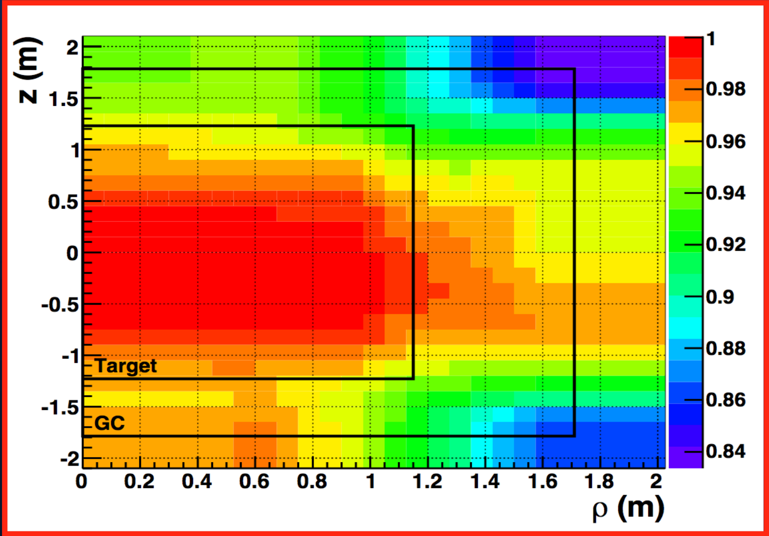
- Successful FD-Only phase (almost completed): limited by reactor sys
  - 4 θ_{13} measurements: nGd and nH with R+S and RRM
  - 3 independent BG measurements: Reactor-On, Reactor-Off and RRM
    - New result: R+S nGd-nH combined: $\sin^2 2\theta_{13}=0.109\pm0.035$
  - New RRM analysis: BG model-independent measurement of θ_{13}
    - nGd: $\sin^2 2\theta_{13}=0.107\pm0.049$. nGd+nH: $\sin^2 2\theta_{13}=0.102\pm0.043$
- ND+FD phase to be started: ~10% θ_{13} measurement expected
  - ND will start operation by summer 2014
  - ND+FD analysis "*already ongoing*": better S/B, reduced systematics
- Rich physics program beyond θ_{13}

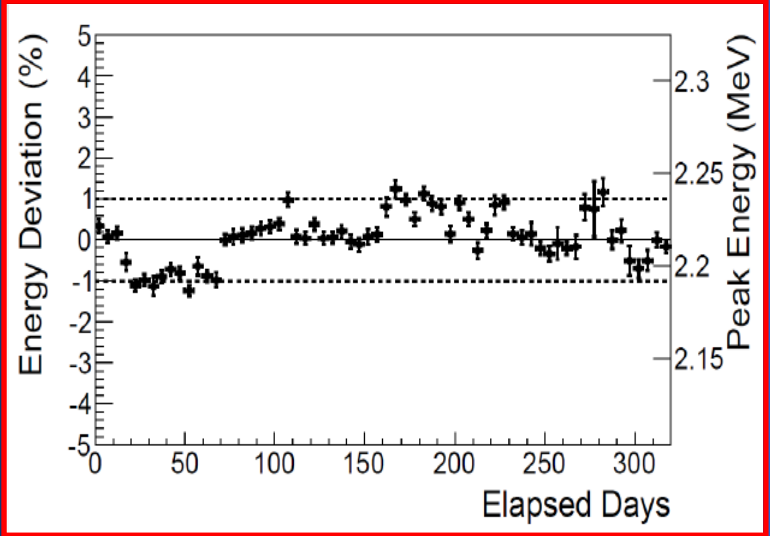

Thank you!
Photo: Lola Garrido

Energy Scale

- PE nonlinearity: LED system
- Detector uniformity: nH captures map
- Time stability: nH captures







Statistical Analysis

- Standard χ^2 minimization: $\chi^2 = \chi^2_{on} + \chi^2_{off} + \chi^2_{pull}$
  - Distinguish between Reactor-On and Reactor-Off periods
    - Different systematics

$$\chi^2_{pull} = (\frac{\alpha^d}{\sigma_d})^2 + \sum_i^N (\frac{\alpha_i^r}{\sigma_i^r})^2 + (\frac{\alpha^\nu}{\sigma_\nu})^2$$

$$\chi^2_{on} = \sum_i^N \frac{\left(R_i^{obs} - f(R_i^{exp}) \cdot [1 + \alpha^d + \alpha_i^r + w_i \cdot \alpha_i^\nu]\right)^2}{\sigma^2_{stat}}$$

- α^d pull for detection sys
- α^r pull for reactor-on sys
- α^ν pull for res-ν sys
- w: fraction of res-ν

$$\chi^2_{off} = \frac{\left(R^{obs} - K \cdot [1 + \alpha^d + w_i \cdot \alpha^\nu]\right)^2}{\sigma^2_{stat}}$$

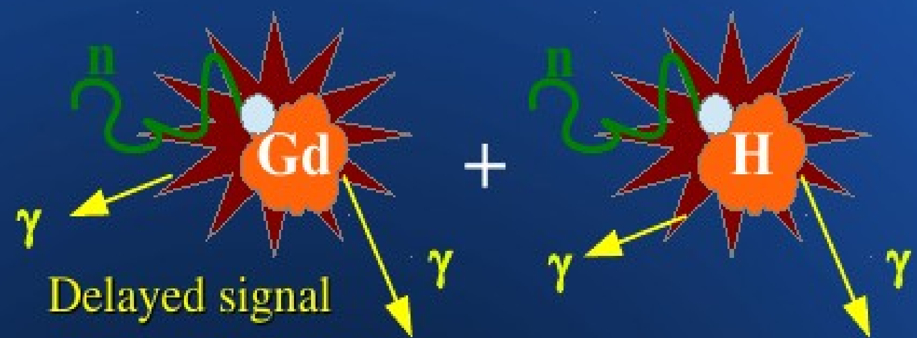
nH: gauss

$$\chi^2_{off} = 2\left(R^{obs} \cdot T_{off} \cdot \ln \frac{R^{obs} \cdot T_{off}}{K \cdot [1 + \alpha^d + w_i \cdot \alpha^\nu]} + K \cdot [1 + \alpha^d + w_i \cdot \alpha^\nu] - R^{obs} \cdot T_{off}\right)$$

nGd: poisson

RRM Gd-H Combined Fit

- Boost stats: n-Gd + n-H candidates



Systematics	n-Gd	n-H
Reactor-On	1.7%	1.7%
Reactor-Off	30%	30%
Efficiency	1.0%	1.6%

- Global fit to θ_{13}, B_{Gd} and B_H

$$\chi^2 = \chi^2_{Gd} + \chi^2_H + \chi^2_{pull}$$

- Systematic sources:
  - Residual ν: fully correlated
  - Reactor power: fully correlated
    - If common binning
  - Detection efficiency:
    - $\rho = 0.09$: $\sigma^{unc} + \sigma^{cor}$

$$\chi^2_{pull} = \left(\frac{\alpha^d_{Gd-un}}{\sigma^d_{Gd-un}}\right)^2 + \left(\frac{\alpha^d_{H-un}}{\sigma^d_{H-un}}\right)^2 + \left(\frac{\alpha^d_{cor}}{\sigma^d_{cor}}\right)^2 + \sum\left(\frac{\alpha^r_i}{\sigma^r_i}\right)^2 + \left(\frac{\alpha^\nu}{\sigma_\nu}\right)^2$$