LATEST DOUBLE CHOOZ RESULTS

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On behalf of the Double Chooz collaboration

DOUBLE CHOOZ

25th International Workshop on Weak Interactions and Neutrinos
June, 2015

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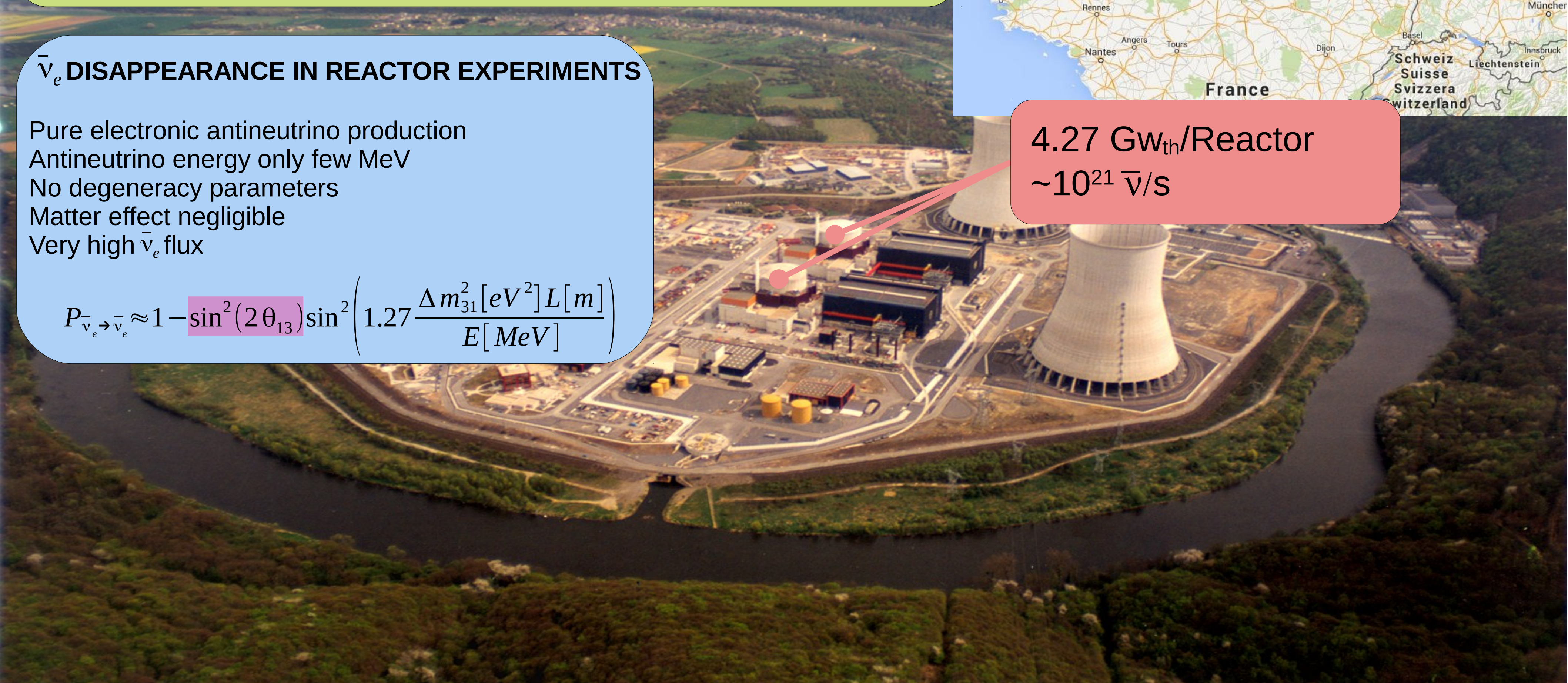
PMNS matrix

$$U=\begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{i\delta}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{-i\delta} & 0 & \cos\theta_{13}\end{pmatrix}\begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}$$

$\bar{\nu}_e$ DISAPPEARANCE IN REACTOR EXPERIMENTS

Pure electronic antineutrino production
Antineutrino energy only few MeV
No degeneracy parameters
Matter effect negligible
Very high $\bar{\nu}_e$ flux

$$P_{\bar{\nu}_e\rightarrow\bar{\nu}_e}\approx 1-\sin^2(2\theta_{13})\sin^2\left(1.27\frac{\Delta m^2_{31}[eV^2]L[m]}{E[MeV]}\right)$$



4.27 Gw_{th}/Reactor
~10^{21} $\bar{\nu}$/s

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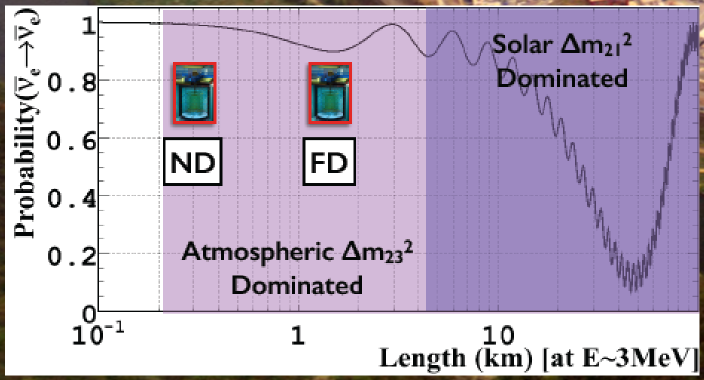


NEAR DETECTOR

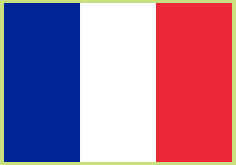
L ~ 400 m
~300 $\bar{\nu}_e$/day
Overburden 120 mwe
Started on December 2014

FAR DETECTOR

L ~ 1050 m
~ 50 $\bar{\nu}_e$/day
Overburden 300 mwe
Started on April 2011

DC COLLABORATION

CBPF
UNICAMP
UFABC



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- IPHC
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RWTH Aachen
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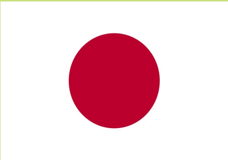
U. Hamburg



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Virginia Tech.

Spokeperson:
H. de Kerret (IN2P3)

Project manager:
Ch.Veyssière (CEA-Saclay)

Website:
www.doublechooz.org

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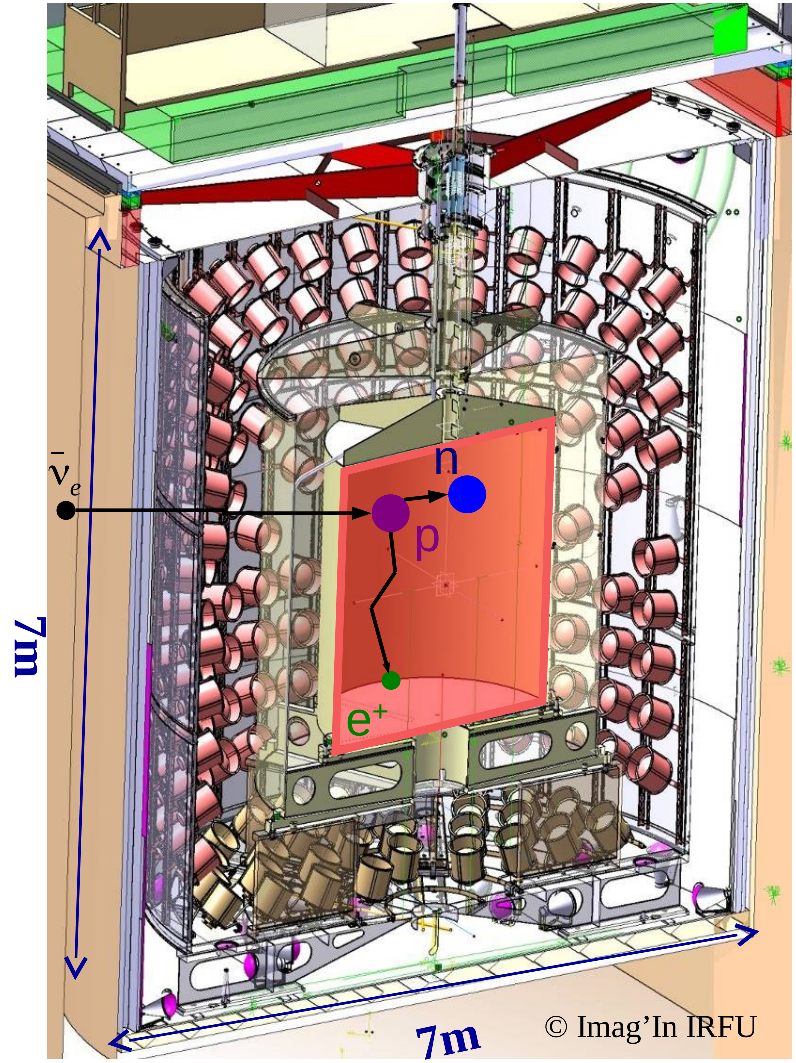
DOUBLE CHOOZ DETECTOR

INVERSE BETA DECAY:

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

ENERGY THRESHOLD: 1.8 MeV



INVERSE BETA DECAY:

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

ENERGY THRESHOLD: 1.8 MeV

PROMPT SIGNAL: POSITRON

Positron kinetic energy
+
Positron annihilation

$$E_e \approx E_\nu - 0.8\, MeV$$

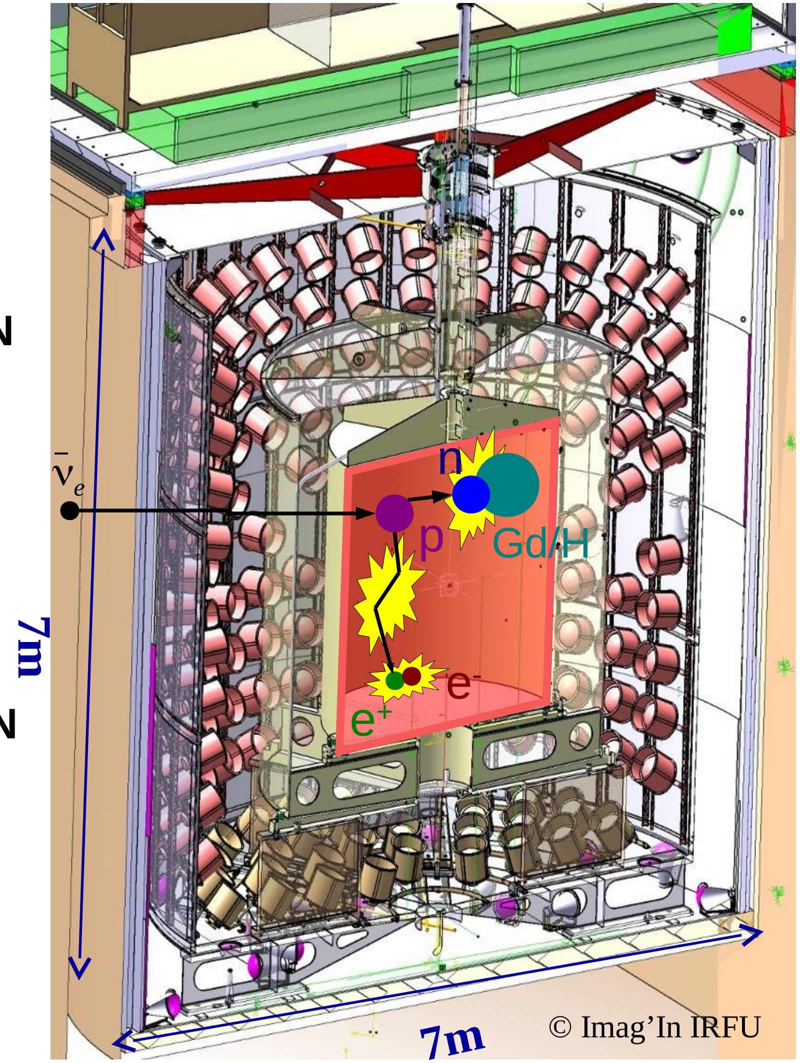
DELAYED SIGNAL: NEUTRON

1. Radiative neutron capture on Gd

   E ~ 8 MeV, ΔT ~ 30 μs

2. Radiative neutron capture on H

   E ~ 2.2 MeV, ΔT ~ 200 μs



Target: Gd-doped scintillator (10.3m³)

DOUBLE CHOOZ DETECTOR

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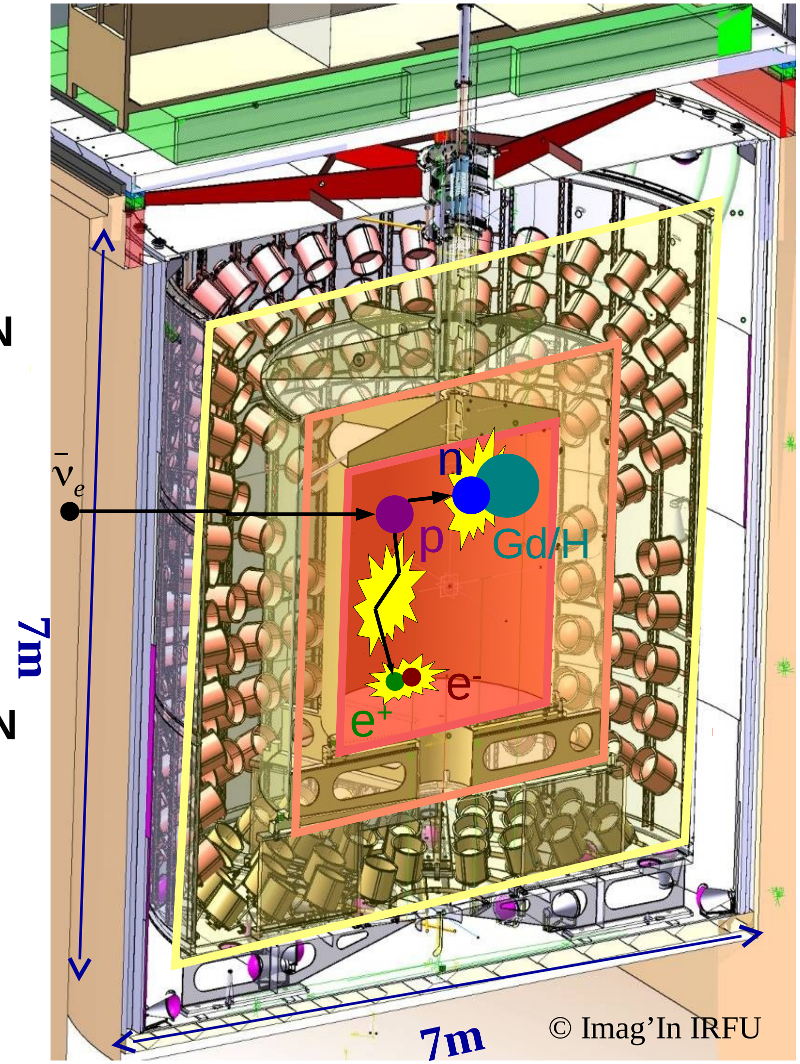

© Imag'In IRFU

Target: Gd-doped scintillator (10.3m³)

γ-catcher (GC): non-doped scintillator (22.6m³)

Buffer: Non-scintillator mineral oil (110m³)
Stainless steel vessel
390 10" PMTs in the inner wall

INNER DETECTOR

DOUBLE CHOOZ DETECTOR

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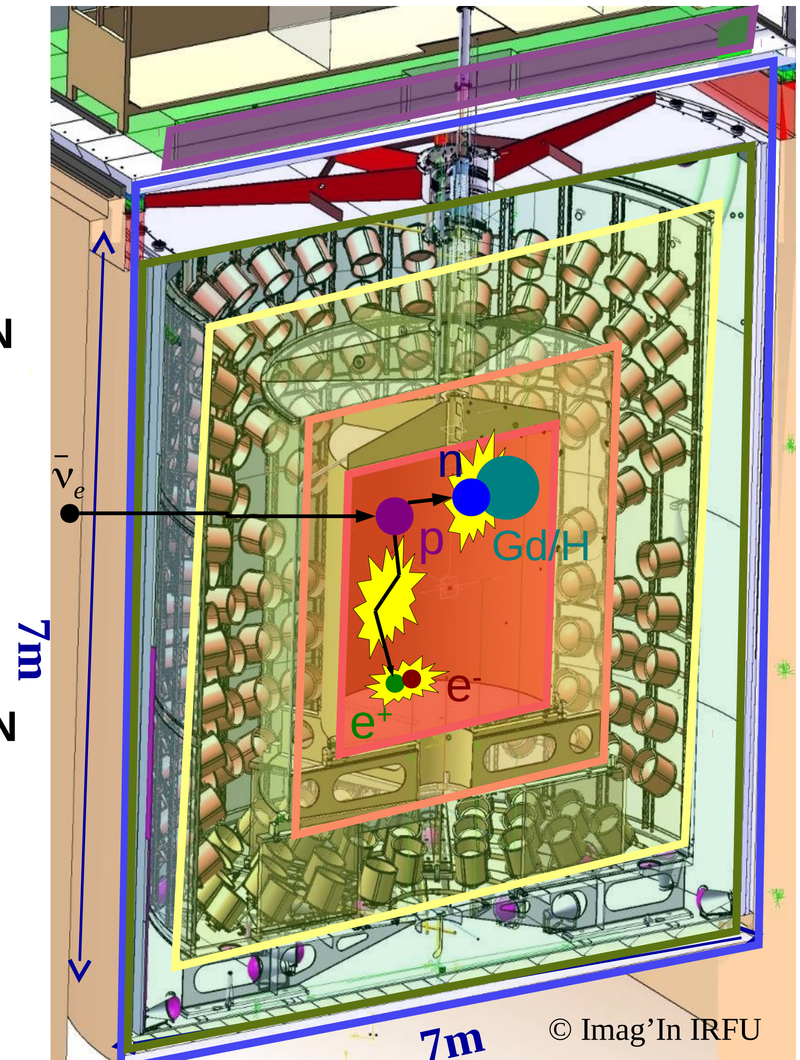

Target: Gd-doped scintillator ($10.3 m^3$)

γ-catcher (GC): non-doped scintillator ($22.6 m^3$)

Buffer: Non-scintillator mineral oil ($110 m^3$)
Stainless steel vessel
390 10" PMTs in the inner wall

Inner Muon Veto: non-doped scintillator ($90 m^3$)
Veto steel vessel
78 8" PMTs in the inner wall

Shielding
FD: 15 cm of steel
ND: 15 cm of steel in the top
1m of water around the rest

Outer Muon Veto:
Plastic scintillator strips (13 m x 7 m)

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ENERGY RECONSTRUCTION

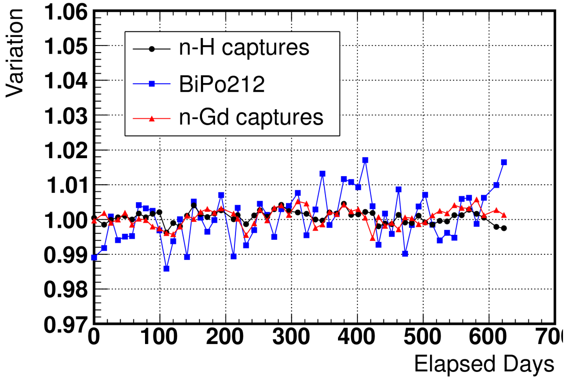
Charge ──► Photoelectron

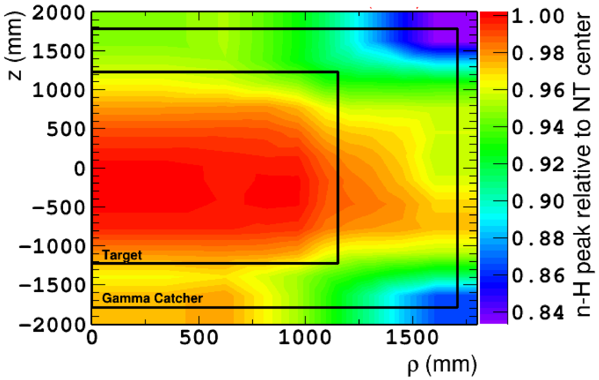
LED calibration system

Total photoelectron ──► Energy

Using n-H capture from ^{252}Cf calibration source

Corrections for time instability and detector inhomogeneity are applied





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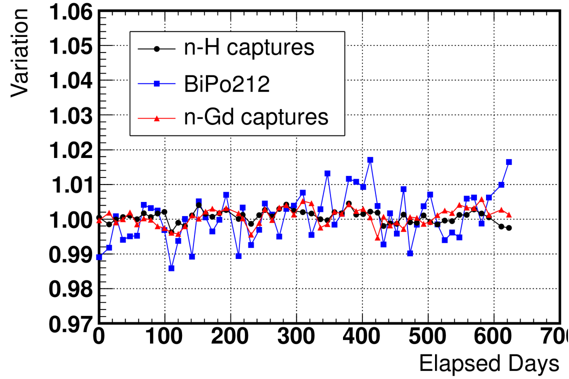

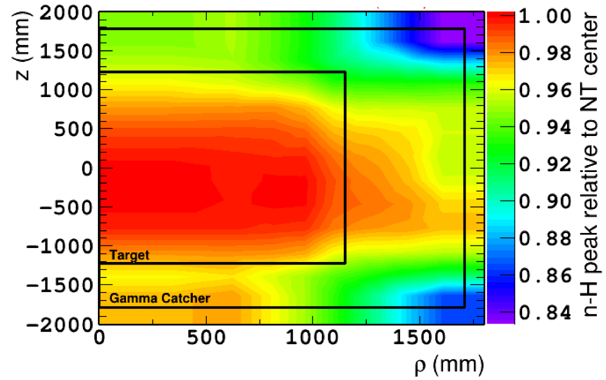

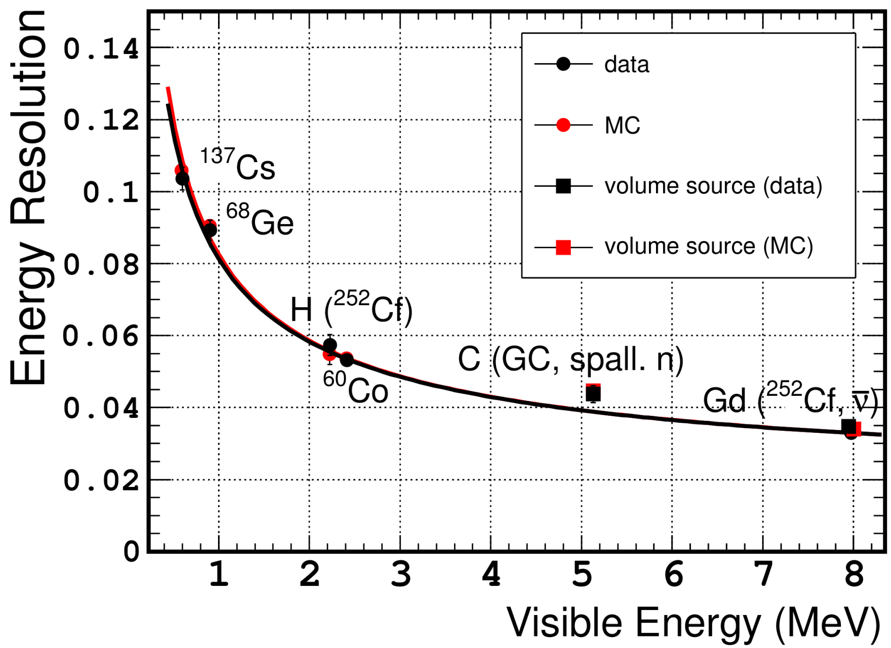

Energy uncertainty: 0.74%

PREVIOUS: 1.14%

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IBD SELECTION

MUON DEFINITION: E > 20 MeV or IV energy > 16 MeV

Variable	DCII	**DCIII (n-Gd)**
E_{prompt} (MeV)	[0.7,12.2]	**[0.5,20]**
E_{delay} (MeV)	[6,12]	**[4,10]**
ΔT (μs)	[2,100]	**[0.5,150]**
ΔR (m)	-	**< 1**
Multiplicity (μs)	[-100,400]	**[-200,600]**
Muon veto (ms)	$\Delta T\mu$-s > 1	**$\Delta T\mu$-s > 1**
Light-Noise	APPLIED	**Variable added**
OV veto	**No correlated with OV signal**	
new veto techniques	-	**APPLIED**

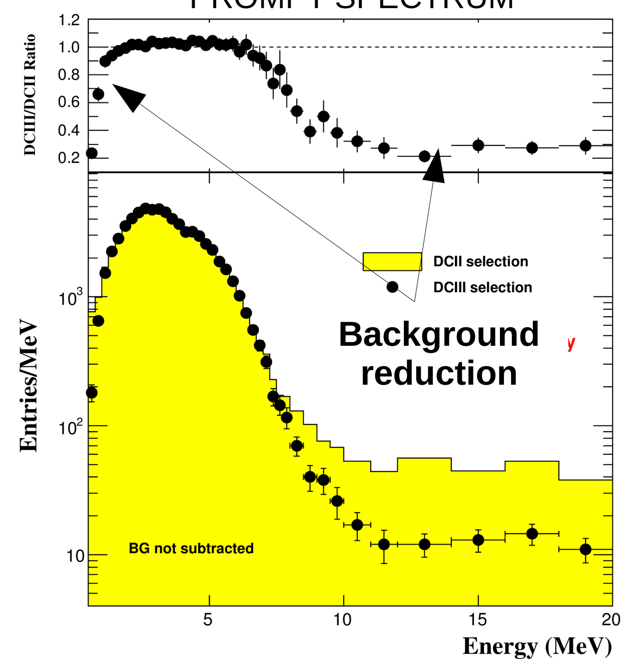
Wider selection

Background reduction

For example, removing the events with ID-IV correlation signals

- More data: 227.9 days to 467.9 days
- Background reduction improved with the new veto techniques
  - Wider selection
    - Reduced uncertainty on selection efficiency

PROMPT SPECTRUM



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IBD CANDIDATES

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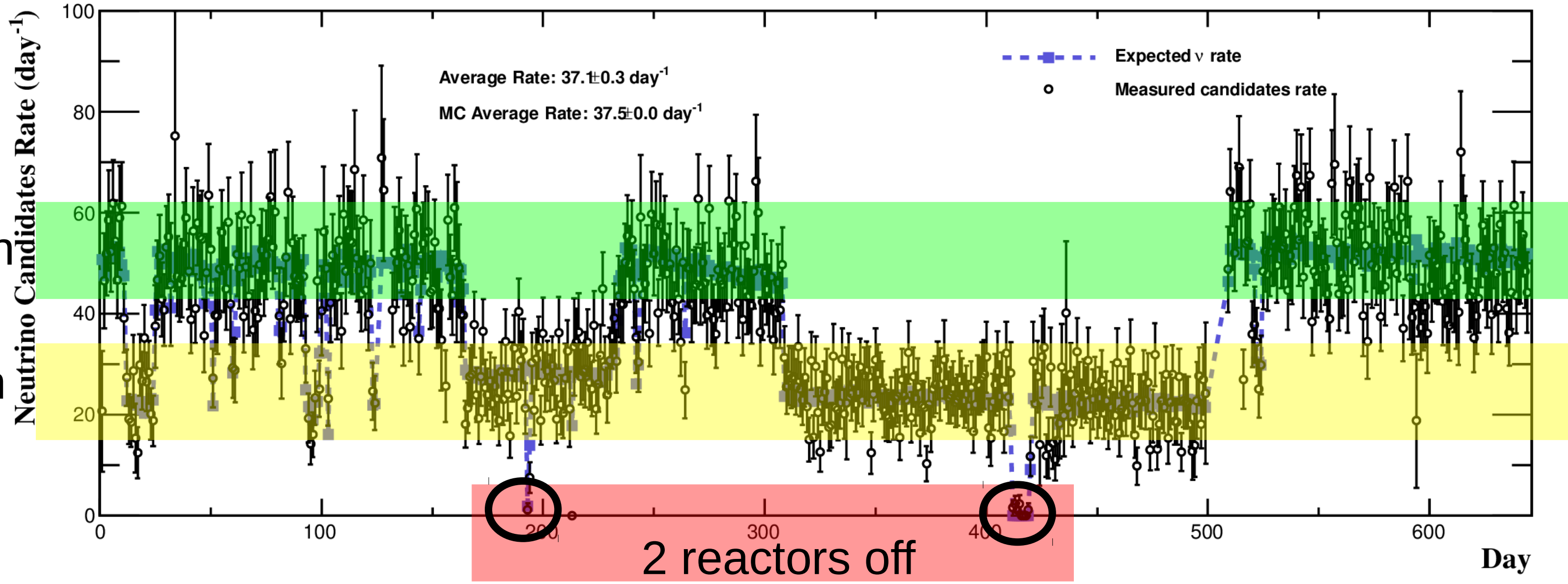
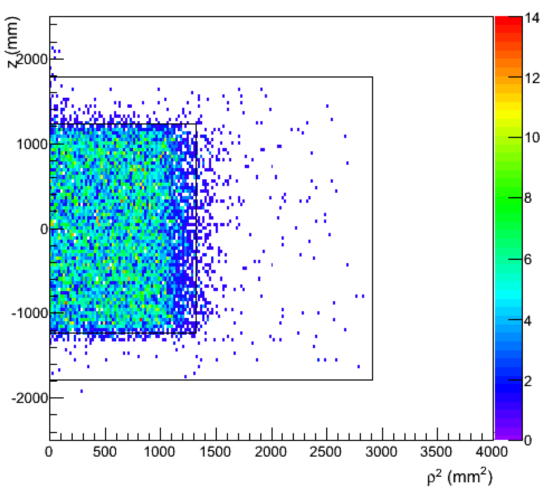
Live-time: 467.9 days

17351 $\bar{\nu}_e$ candidates

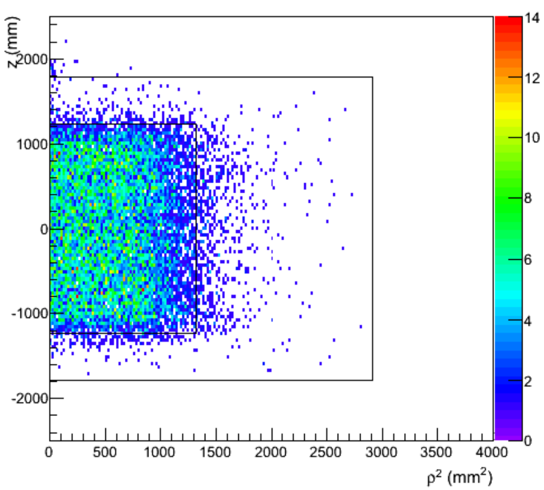
DAILY RATE



PROMPT VERTEX DISTRIBUTION



DELAYED VERTEX DISTRIBUTION



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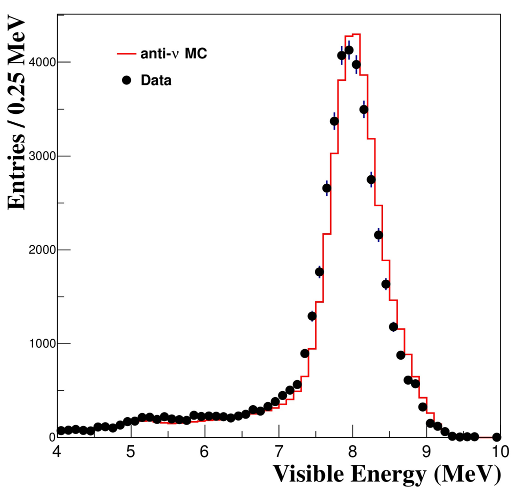

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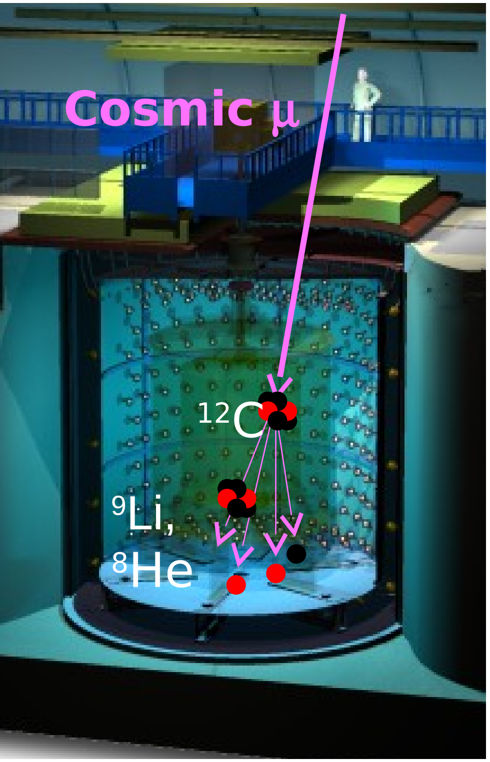
β-n LONG LIFE-TIME ISOTOPES



Correlated with cosmic muons

β-n unstable long life-time isotopes:

PROMPT: β
DELAYED: n capture

The muon veto is not feasible

^{8}He (172 ms)

^{9}Li (257 ms)

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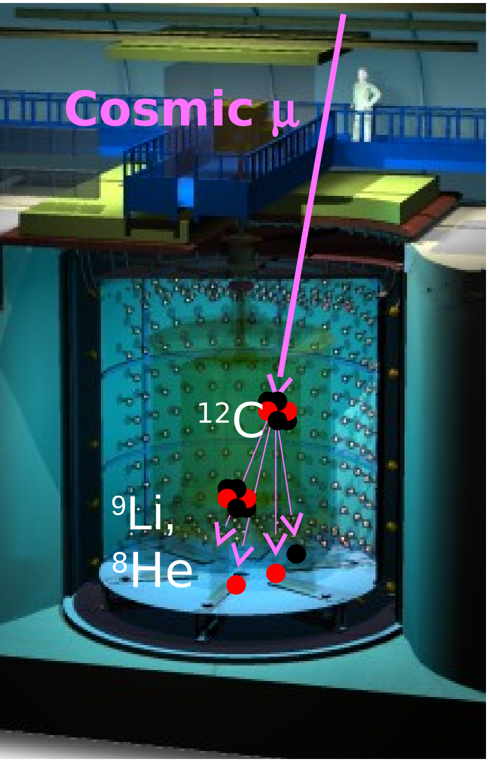

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Li+He veto: Likelihood based on the proximity to the μ and the association with other neutrons

Reduction: ~50%

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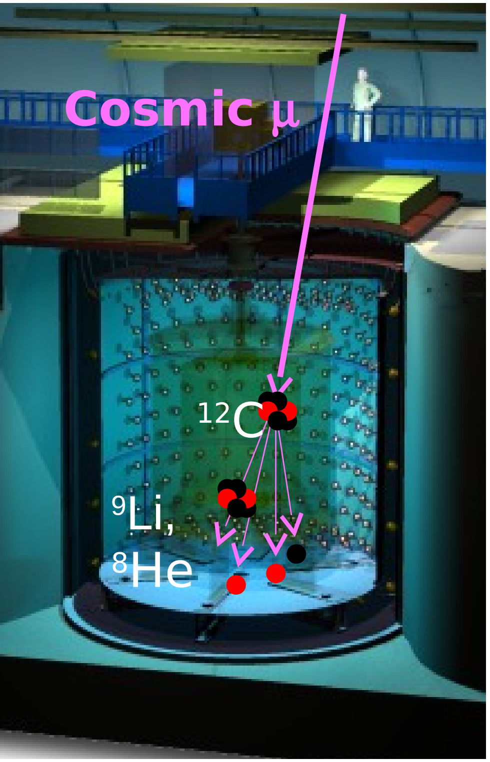

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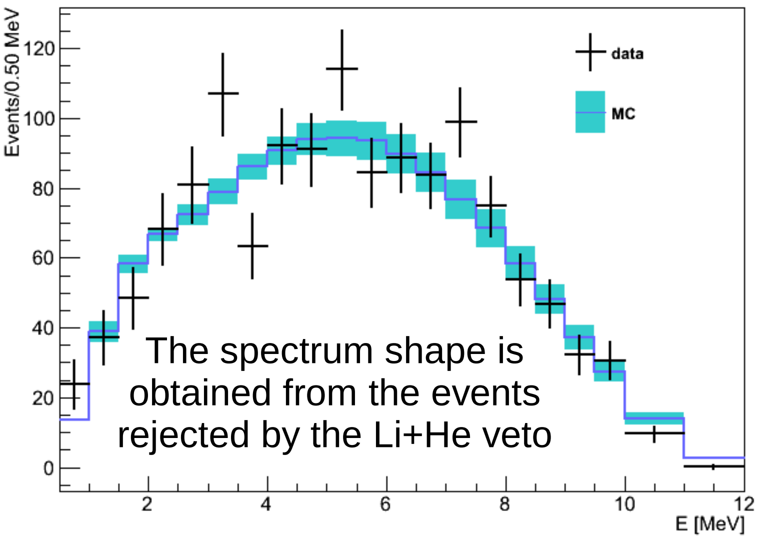

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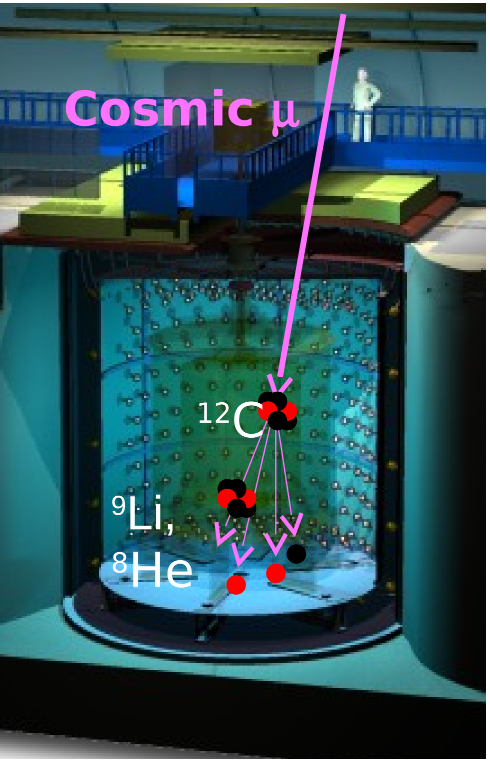

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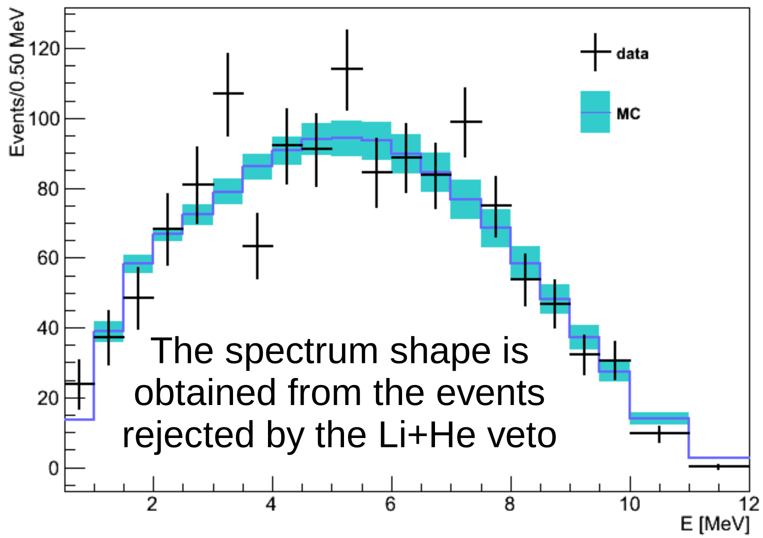

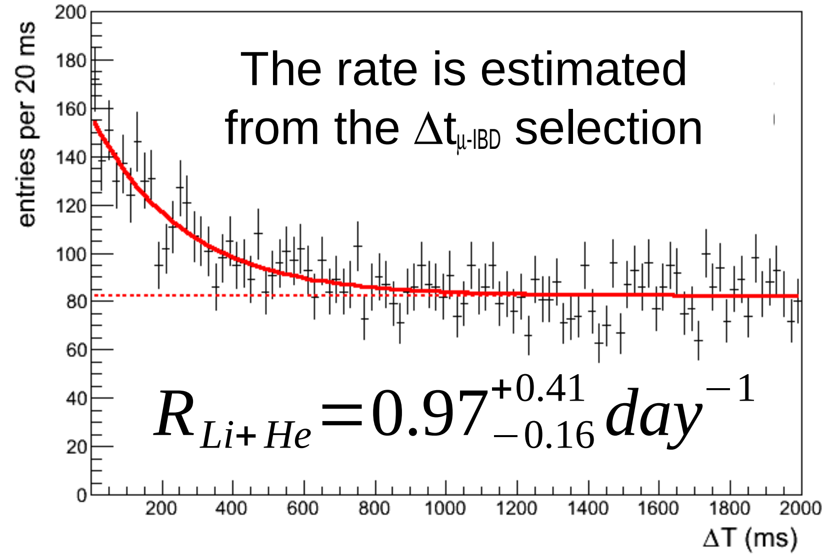

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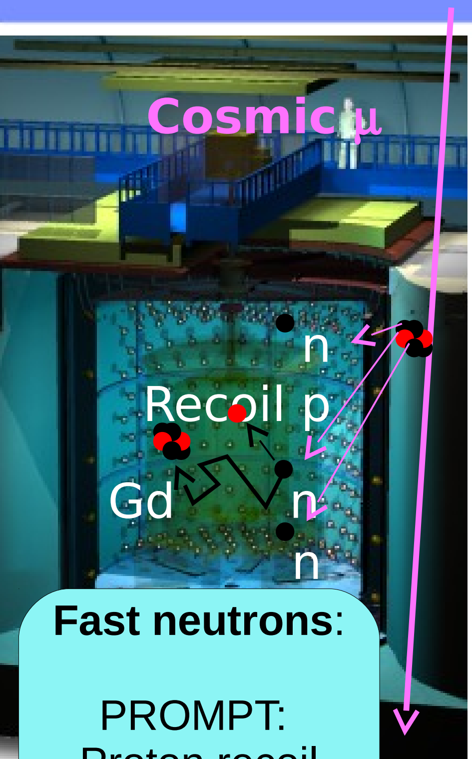
(OTHER) CORRELATED BACKGROUNDS



Fast neutrons:

PROMPT:
Proton recoil
DELAYED:
n capture

Stopping muon:

PROMPT:
Muon track
DELAYED:
Michel electron

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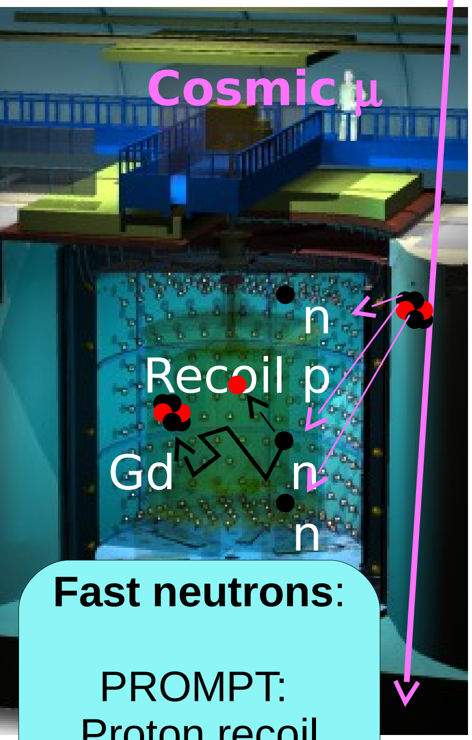
(OTHER) CORRELATED BACKGROUNDS



Fast neutrons:

PROMPT:
Proton recoil
DELAYED:
n capture

Acceptance hole

Stopping muon:

PROMPT:
Muon track
DELAYED:
Michel electron

IV veto: ID-IV correlation
Goodness reconstruction: Poor vertex reconstruction around the chimney

Reduction (+OV): ~90%

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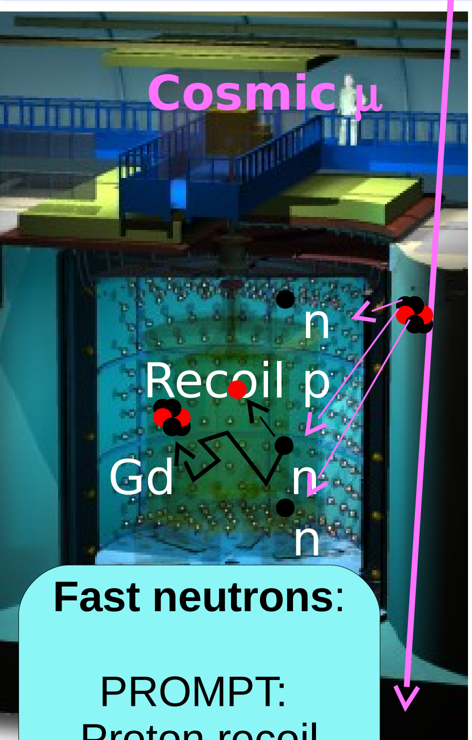

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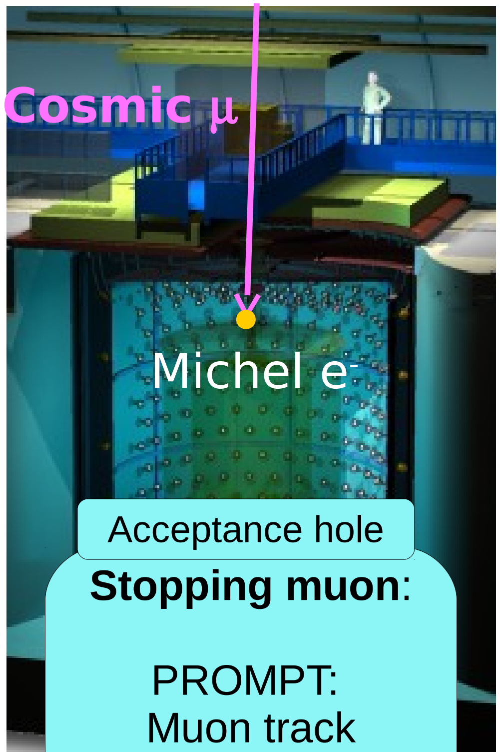

Stopping muon:

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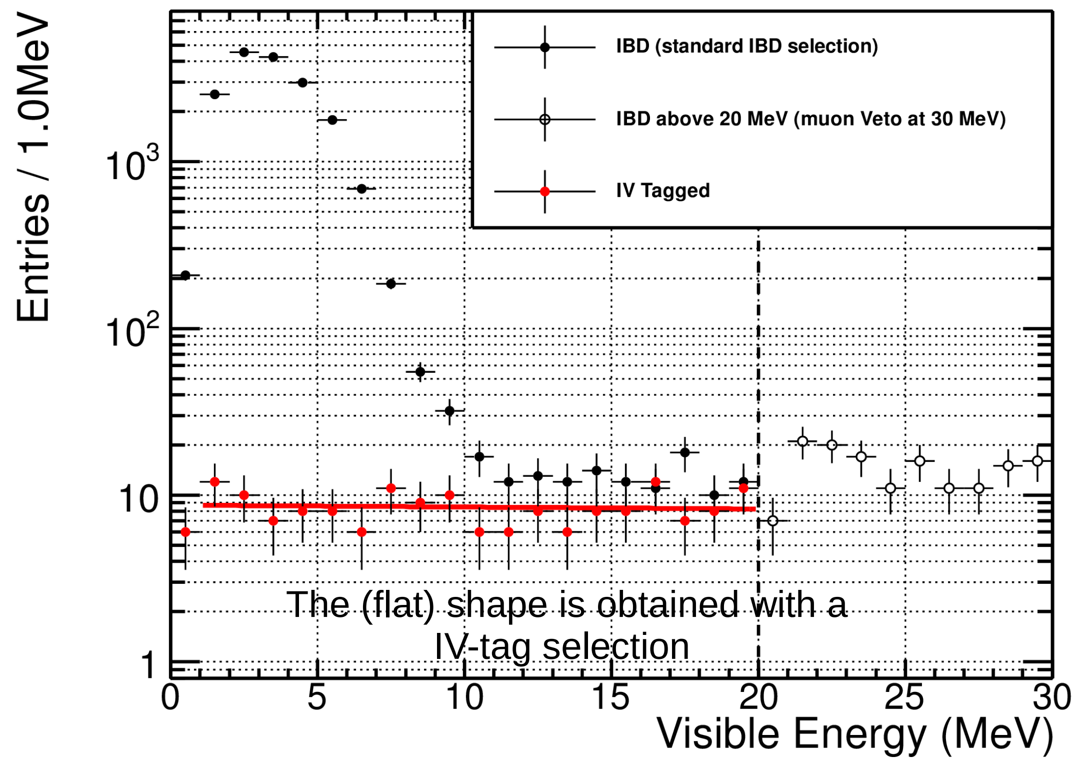

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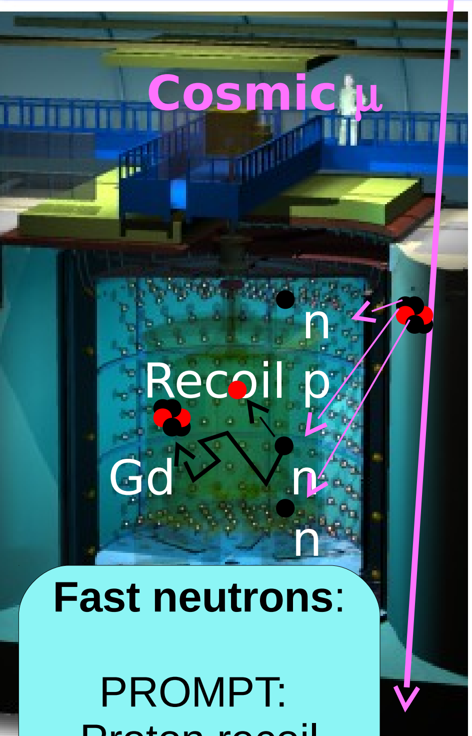

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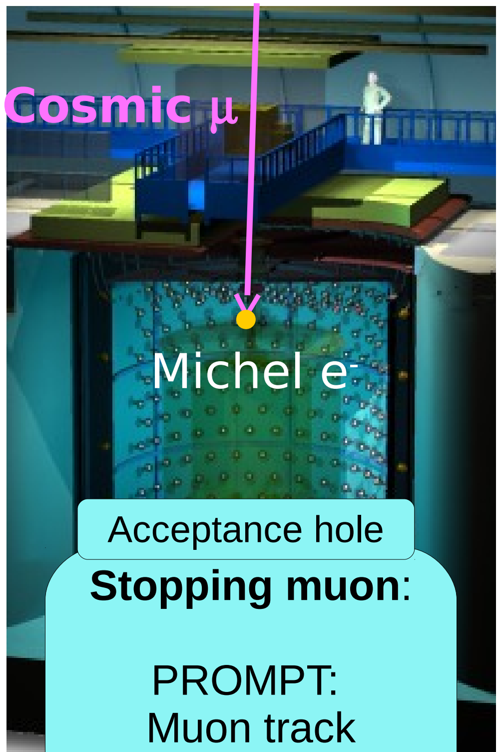

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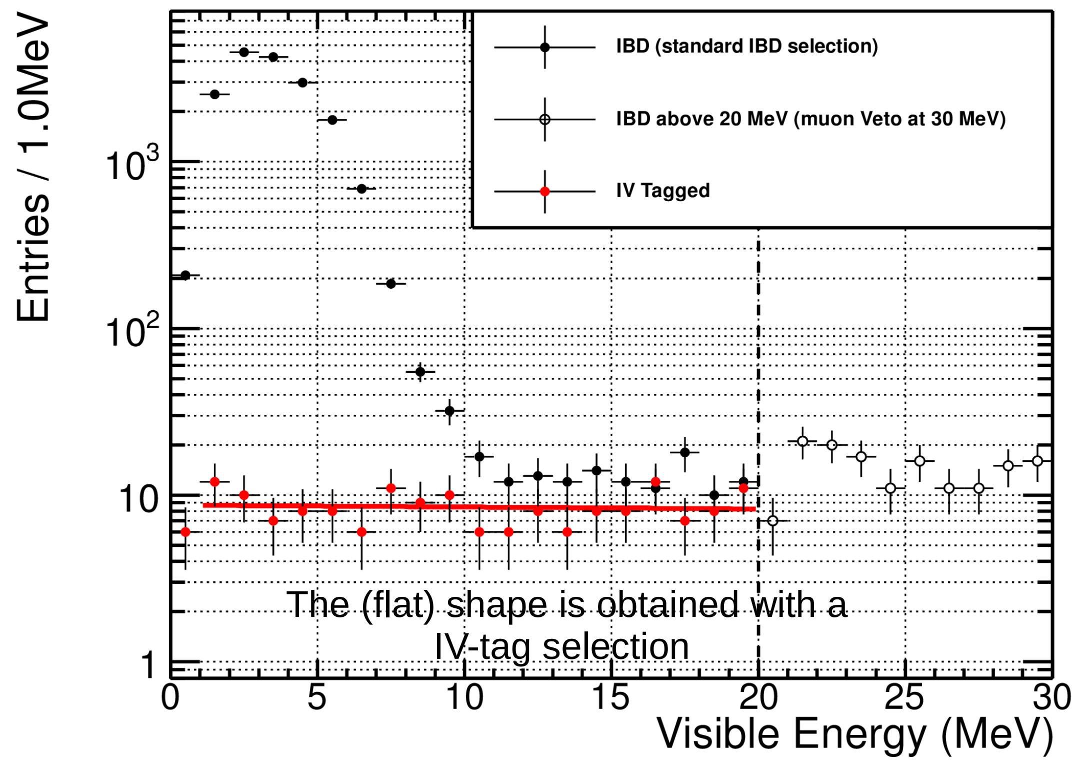

IV veto: ID-IV correlation
Goodness reconstruction: Poor vertex reconstruction around the chimney

Reduction (+OV): ~90%

The rate is estimated extrapolating from the rate between 20 and 30 MeV to low energy

$$R_{Corr} = 0.604 \pm 0.051\, day^{-1}$$

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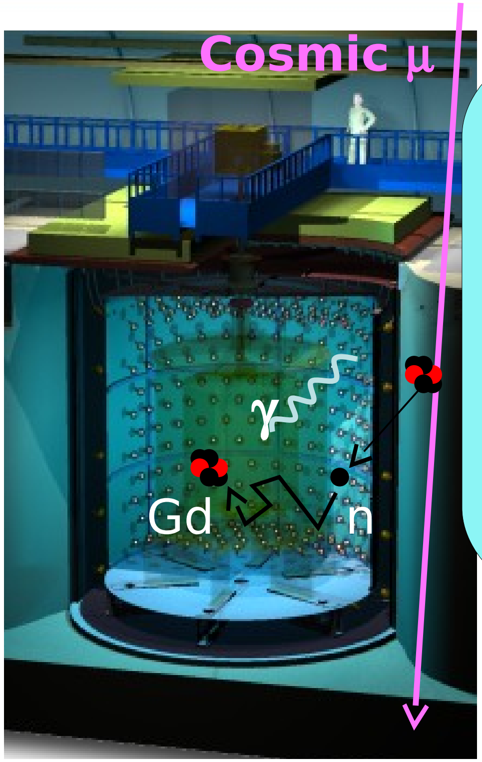
ACCIDENTAL BACKGROUND



Single accidental coincidences:

PROMPT: Natural radioactivity
DELAYED: High energy cosmogenic products

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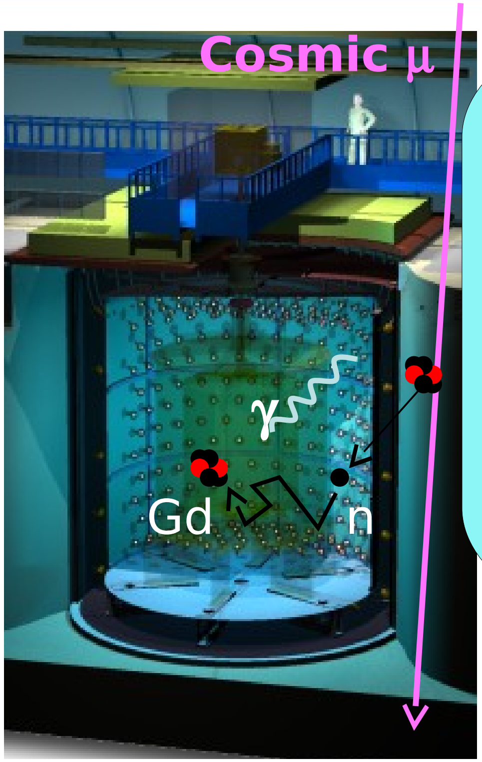

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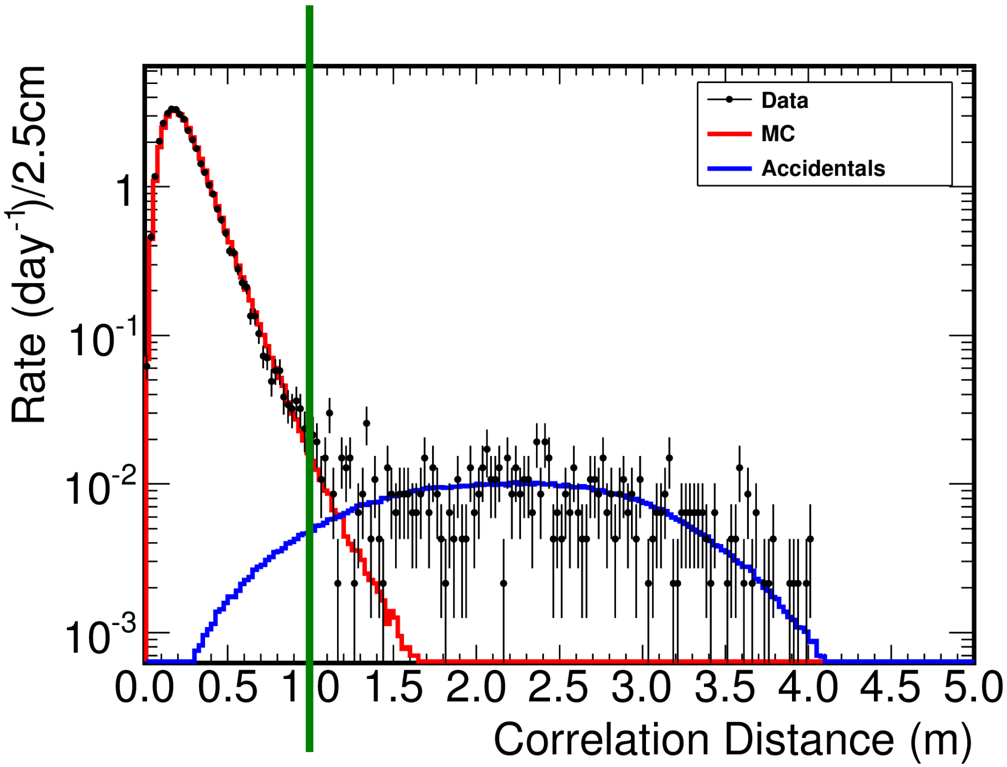

ΔR: Distance between prompt and delayed signal.

Reduction: ~85%

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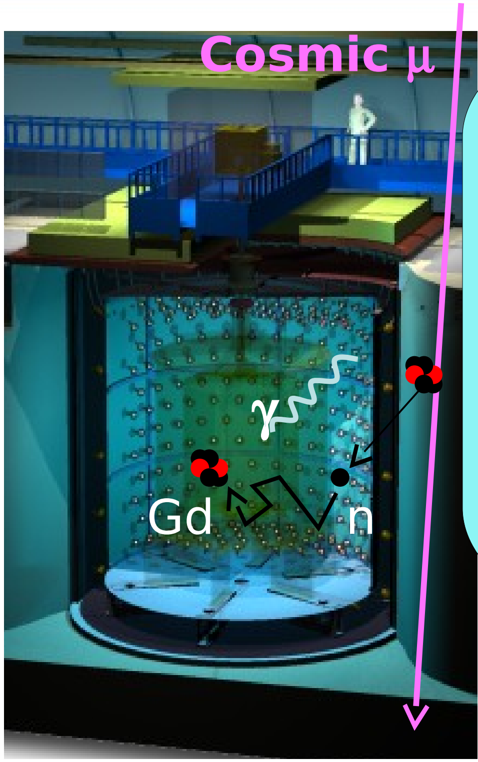

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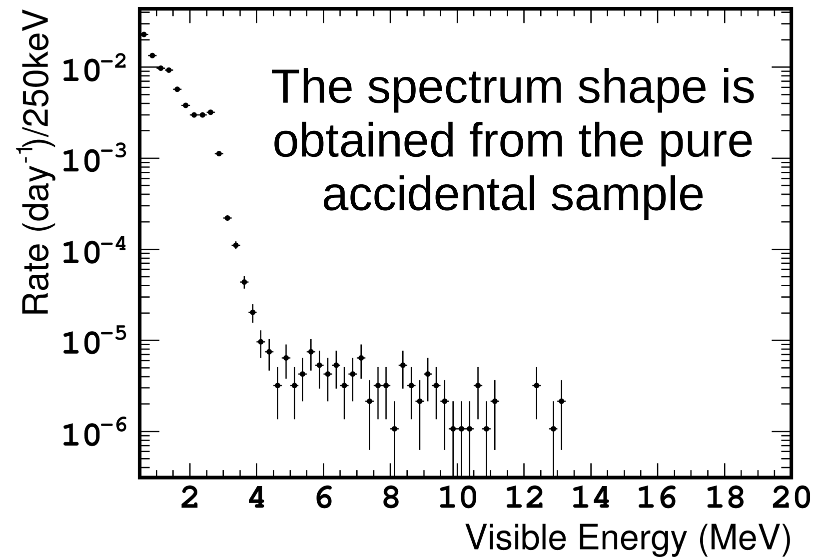

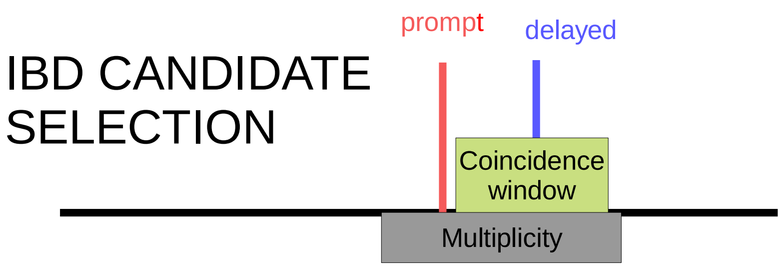

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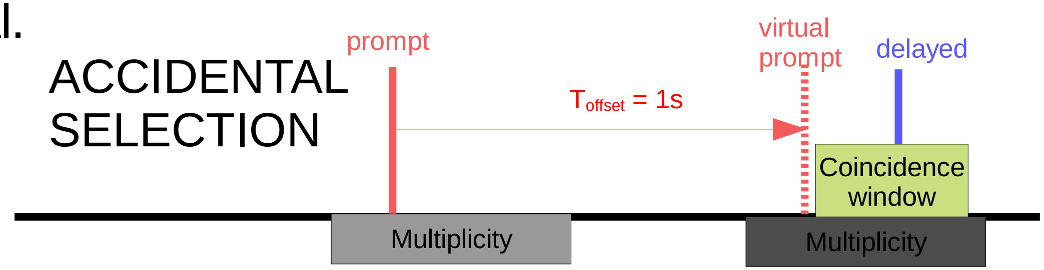

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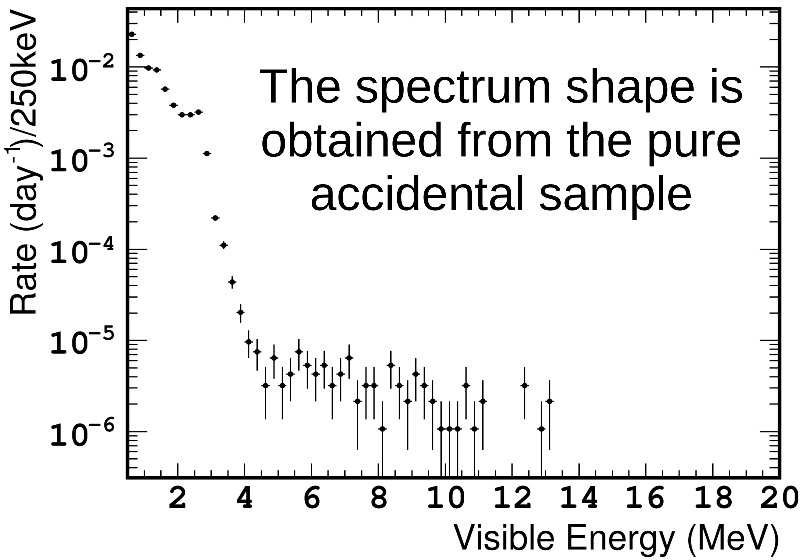

The rate is estimated from the pure accidental sample

$$R_{Acc} = 0.0701 \pm 0.0026\, day^{-1}$$

ΔR: Distance between prompt and delayed signal.

Reduction: ~85%

Corrections factors are applied to take into account the differences between the on-time (IBD) and off-time (accidental) samples: multiplicity cut, ...

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NEUTRINO OSCILLATION ANALYSIS

LIFETIME	467.9 days
	EVENTS
IBD CANDIDATES	17351
TOTAL EXPECTED	18290^{+370}_{-330}
REACTOR $\bar{\nu}_e$	17530 ± 320
COSMOGENIC $^9Li/^8He$	447^{+189}_{-74}
Fast-n and Stop-μ	278 ± 23
ACCIDENTAL BACKG.	32.3 ± 1.2

(IBD CANDIDATES vs. TOTAL EXPECTED: $\bar{\nu}_e$ disappearance)

NORMALIZATION UNCERTAINTIES:

Uncertainty source		DCIII (n-Gd) uncertainty*	
Reactor flux		1.7%	
Detection efficiency		0.6%	
Backgrounds	Accidental	<0.1%	$^{+1.1}_{-0.4}$%
	Correlated	0.1%	
	β-n isotopes	$^{+1.1}_{-0.4}$	
Statistics		0.8%	
TOTAL		$^{+2.3}_{-2.0}$%	

*with respect to the signal

SPECTRUM UNCERTAINTIES:

- Reactor $\bar{\nu}_e$ spectrum
- Energy scale
- Background spectrum shapes

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θ_{13} MEASUREMENTS

$\Delta m^2_{31} = 2.44 \times 10^{-3}\, eV^2$
(MINOS)

2 reactor off data
(7 events in 7.24 days)

2 methods: REACTOR RATE MODULATION

Comparing observed and expected ν rate for different reactor power

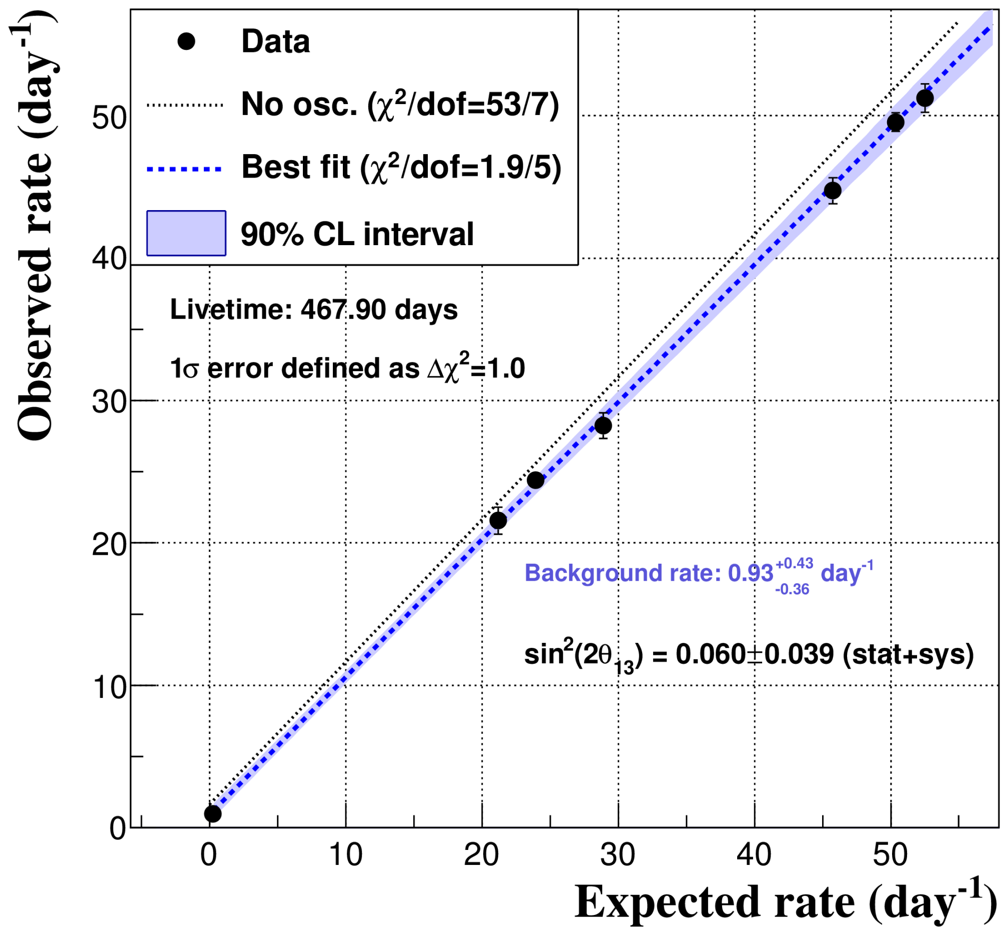
JHEP 1410 (2014) 86

Background model independent measurement

$$\sin^2(2\theta_{13}) = 0.060^{+0.039}_{-0.039}$$

Using backg. estimation

$$\sin^2(2\theta_{13}) = 0.090^{+0.034}_{-0.035}$$



θ_{13} MEASUREMENTS

Double Chooz | **n-Gd analysis: Oscillation** | On-going analyses | Conclusions

$\Delta m^2_{31} = 2.44 \times 10^{-3}\,eV^2$
(MINOS)

2 reactor off data
(7 events in 7.24 days)

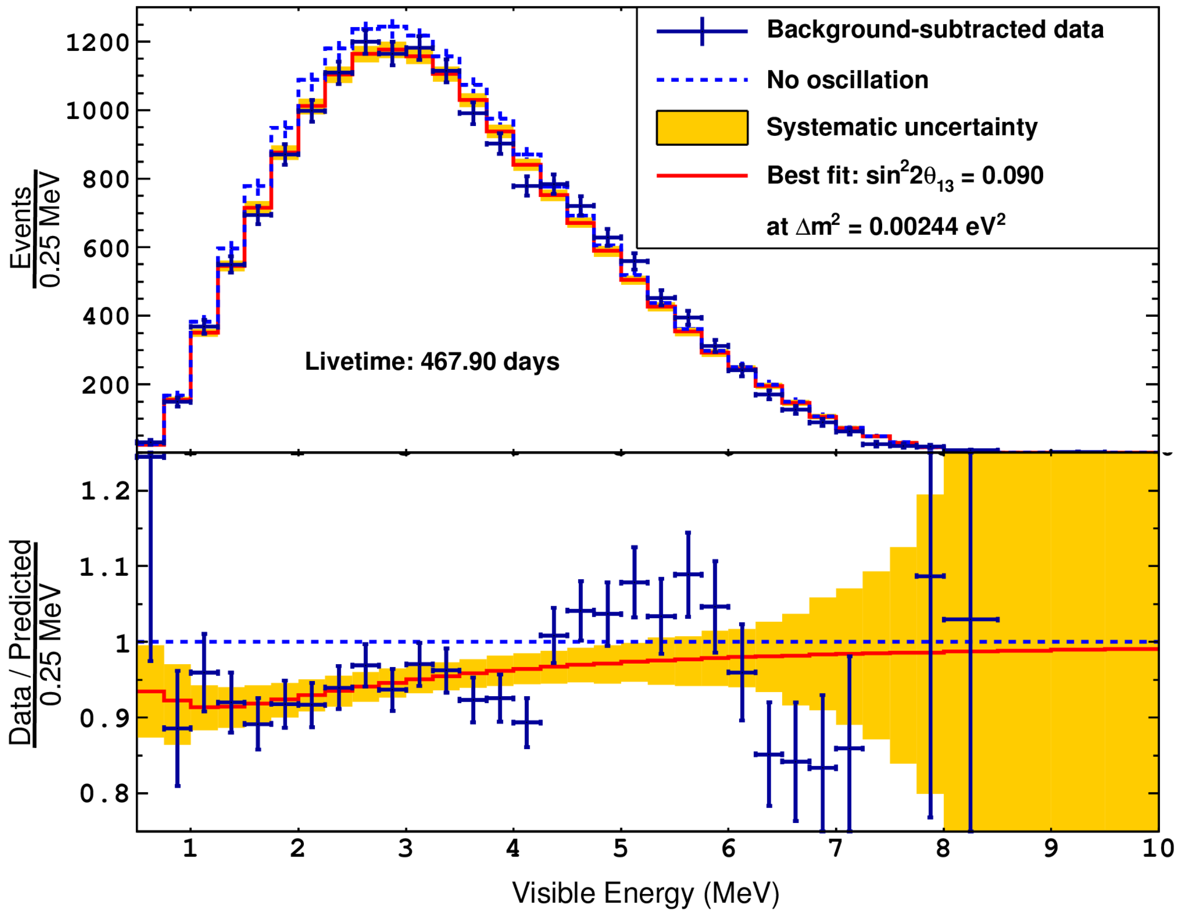
2 methods:
RATE + SHAPE

Prompt spectrum fit

JHEP 1410 (2014) 86

$$\sin^2(2\theta_{13}) = 0.090^{+0.032}_{-0.029}$$

$\chi^2/n_{dof} = 52.2/40$



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n-H ANALYSIS

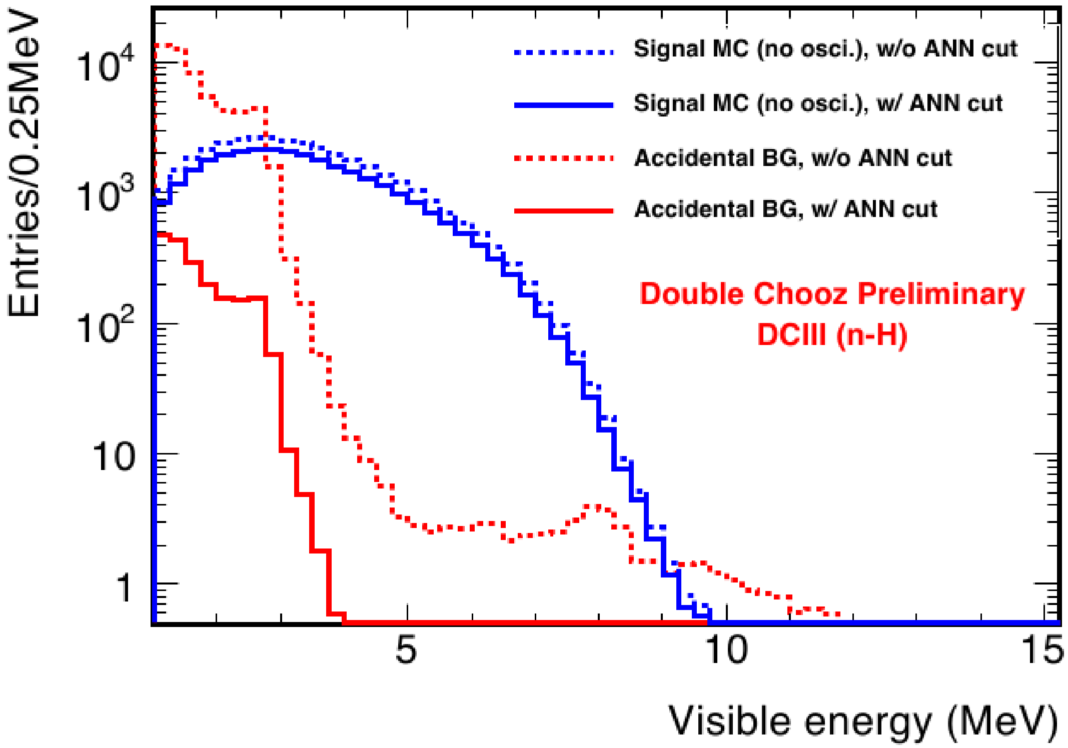
Double Chooz: 1st experiment that measured θ_{13} with the n-H capture: $\sin^2(2\theta_{13}) = 0.097 \pm 0.053$

PLB 723 (2013) 66

Most important background: Accidental background

New (DCIII) n-H analysis → DCIII Improvements + More statistics + Multivariable analysis

A neural network is used to reduce the accidental background in the sample



Double Chooz Preliminary
DCIII (n-H)

NEW RESULT: $\frac{S}{B} \approx 10$

FIRST RESULT: $\frac{S}{B} \approx 1$

A new publication about this analysis is almost ready

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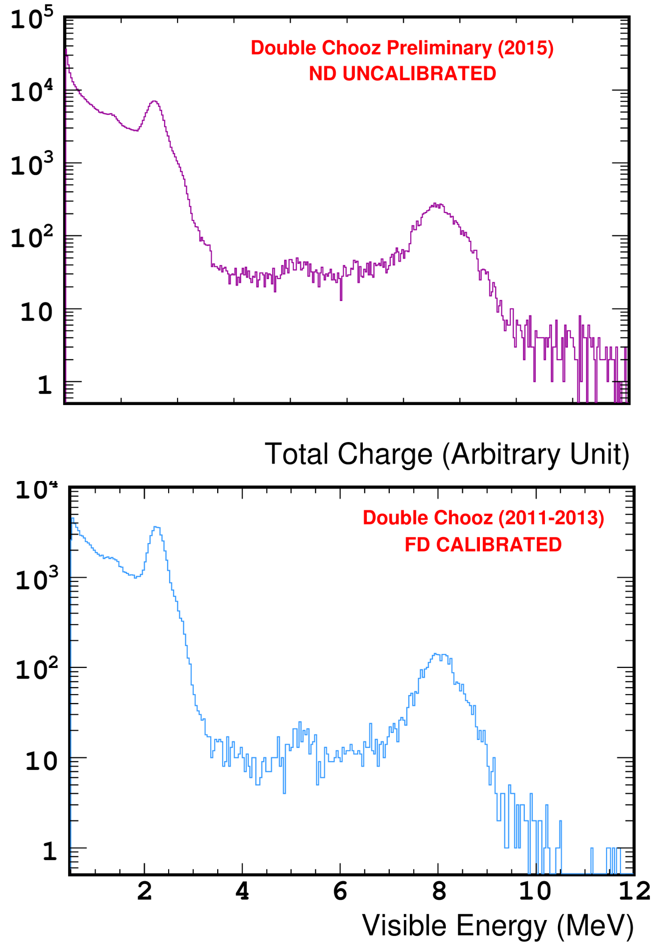
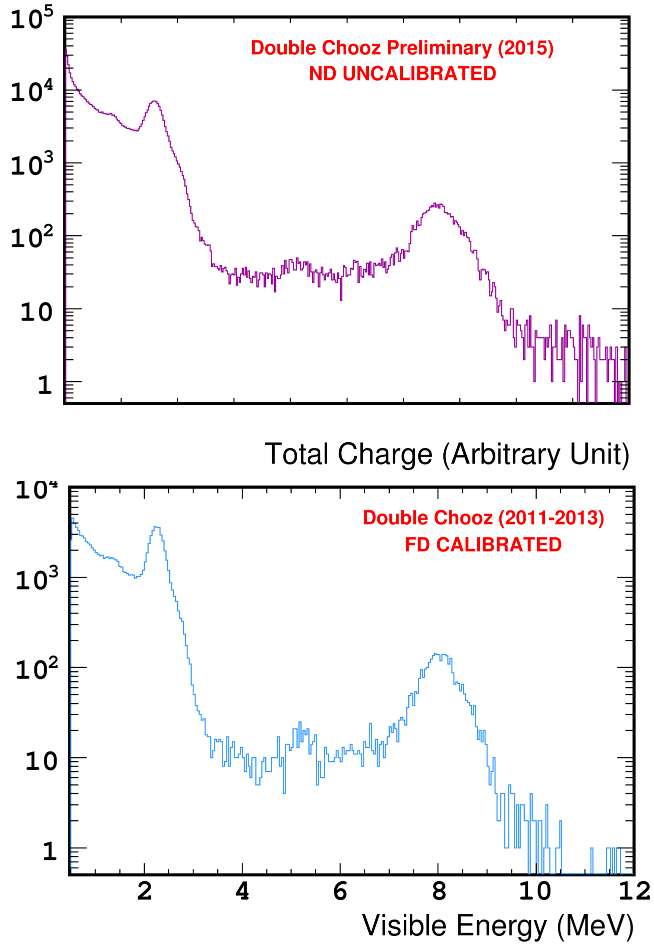
NEAR DETECTOR

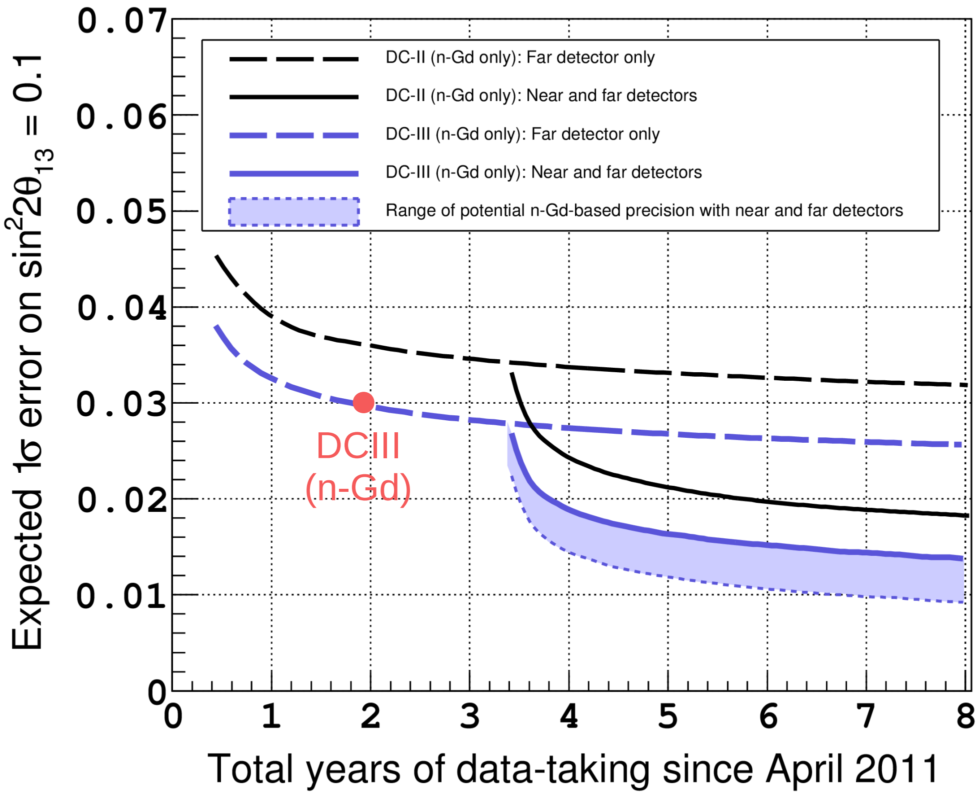


The single rate is similar in both detectors

Demonstrates the IBD capability detection of ND

NEAR DETECTOR





The single rate is similar in both detectors

Demonstrates the IBD capability detection of ND

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CONCLUSIONS

- Analysis improvements with FD only
  - More accurate energy reconstruction
  - Optimized selection that produces a reduced detection systematics
  - New veto background techniques that reduce strongly the background
  - 2 Reactors off included
- The latest θ_{13} value is: $\sin^2(2\theta_{13}) = 0.090^{+0.032}_{-0.029}$
  - An independent analysis (RRM) provides a compatible result

    $\sin^2(2\theta_{13}) = 0.090^{+0.034}_{-0.035}$
- New n-H analysis with more data and improved techniques is almost ready
- Far and near detectors are taking data from December 2014
- Two detectors analysis is in progress

PUBLICATIONS

THANK YOU VERY MUCH

θ_{13}

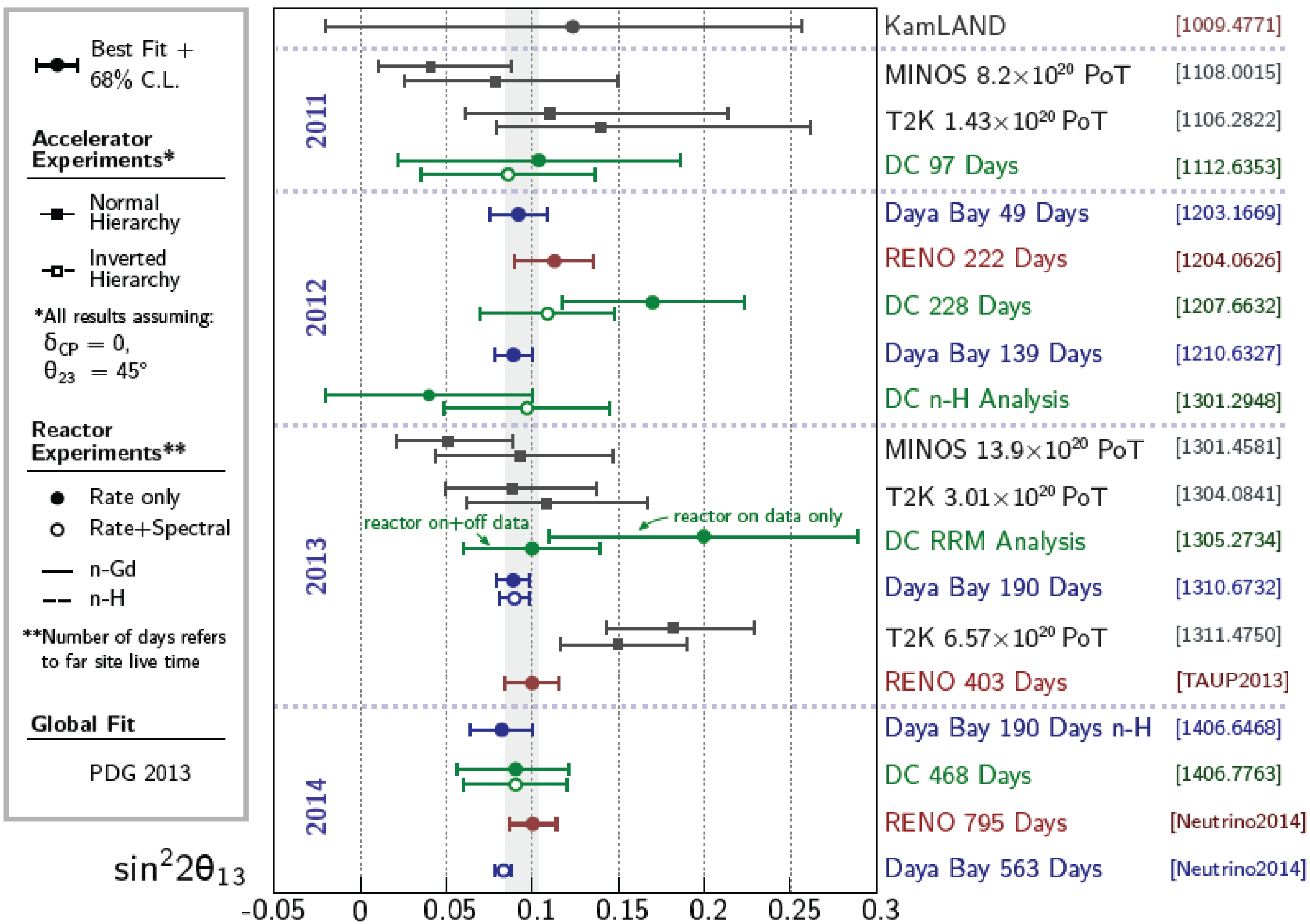
DCI n-Gd analysis (DC, PRL 108 (2012) 131801)
DCII n-Gd analysis (DC, PRD 86 (2012) 052008)
First n-H analysis (DC, PLB 723 (2013) 66)
DCII n-Gd background independent analysis (DC, PLB 735 (2014) 51)
DCIII n-Gd analysis (DC, JHEP 1410 (2014) 86)

Physics beyond θ_{13}

Sterile neutrino (PRD 83 (2011) 073006)
Lorentz violation (DC, PRD 86 (2012) 112009)
Neutrino directionality (arXiv:1208.3628)
Background studies (DC, PRD 87 (2013) 011102 (R))
Sensitivity to Δm^2_{13} (PLB 725 (2013) 271)
Ortho-positronium (DC, JHEP 10 (2014) 032)

EXTRA SLIDES

θ_{13} RESULTS



CALIBRATION

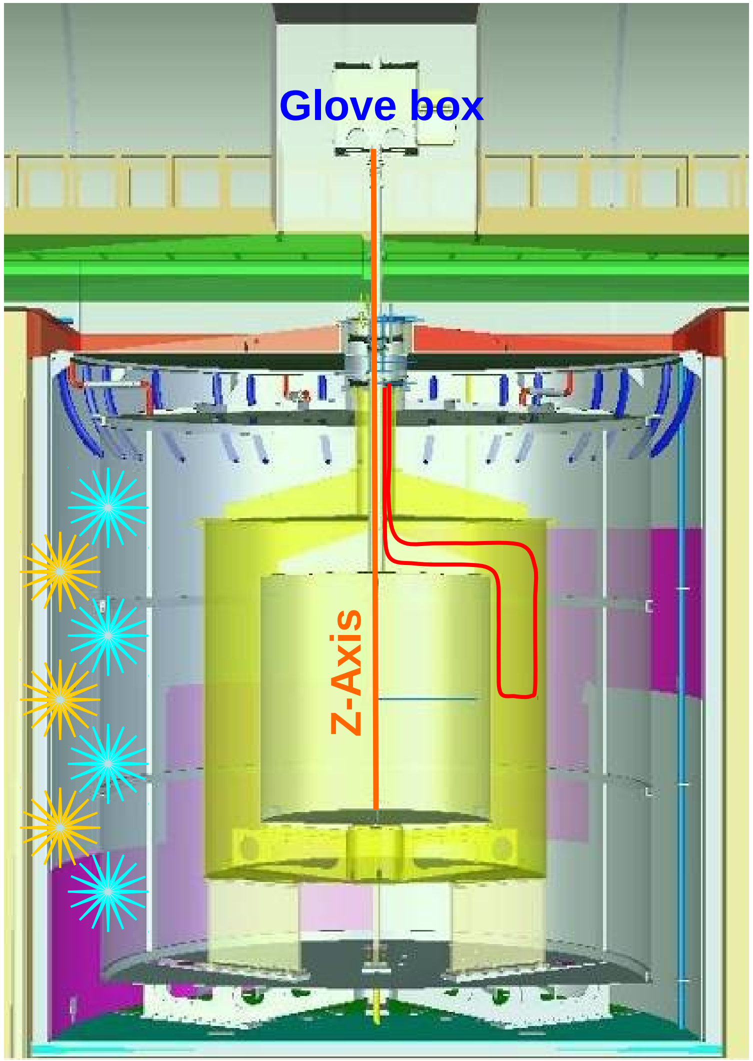
2 CALIBRATION SYSTEMS:

LED in inner-detector and inner-veto

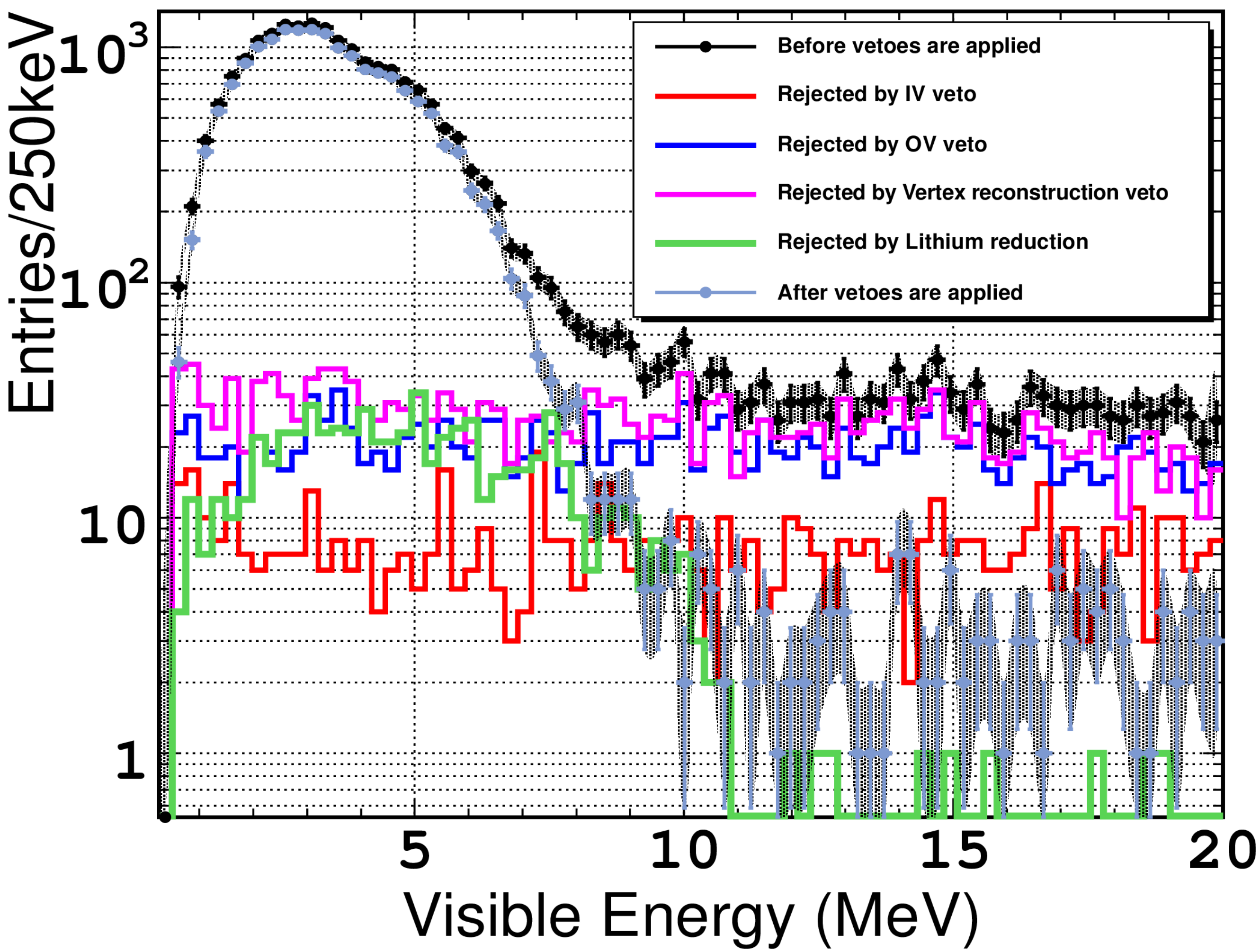
- PMT gain
- PMT timing
- Scintillator stability
- Scintillator attenuation

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

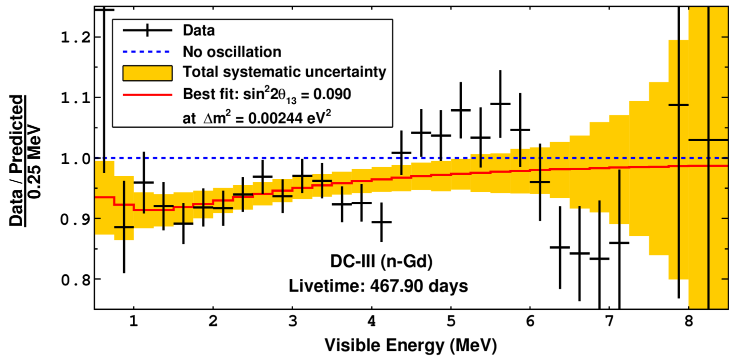
- Vertical axis (target)
- GC guide tube

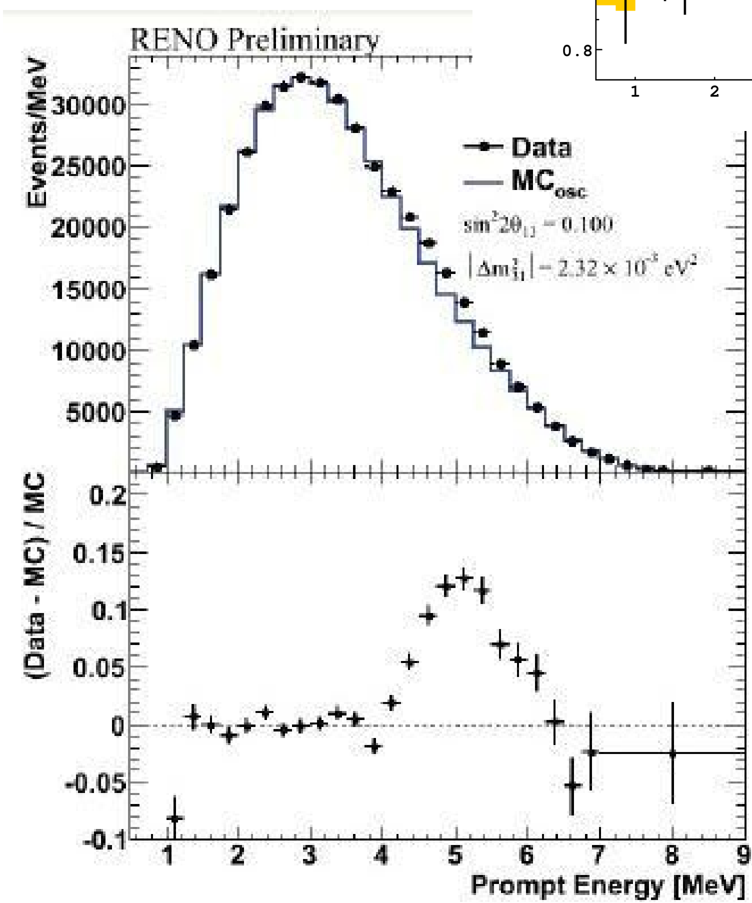


BACKGROUND REDUCTION

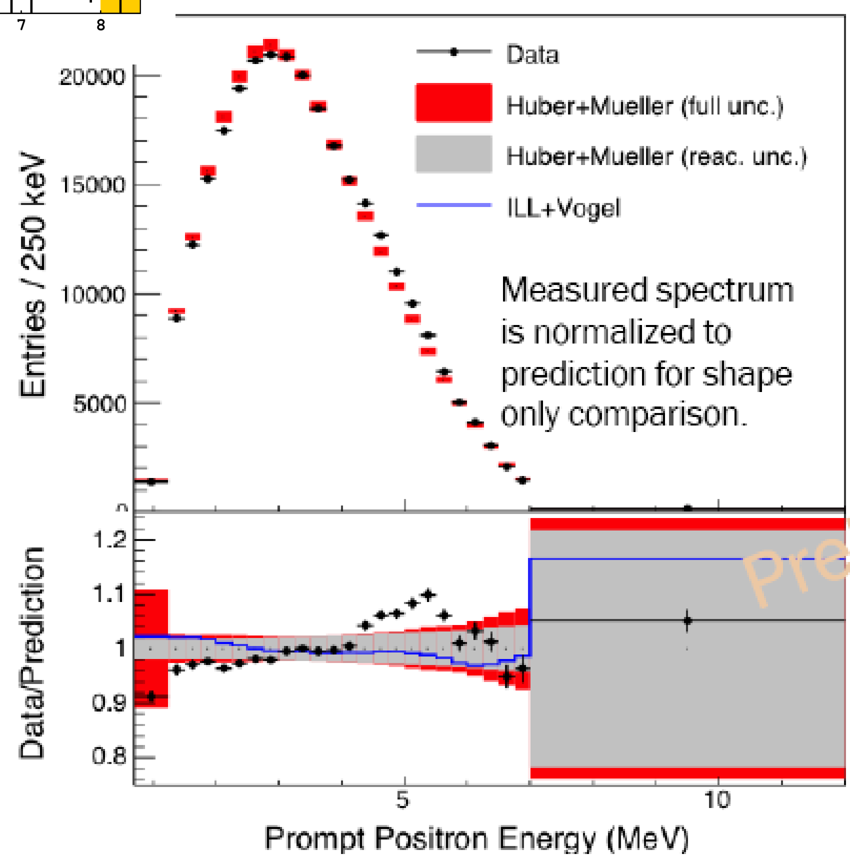


SPECTRUM DISTORTION





DAYA BAY



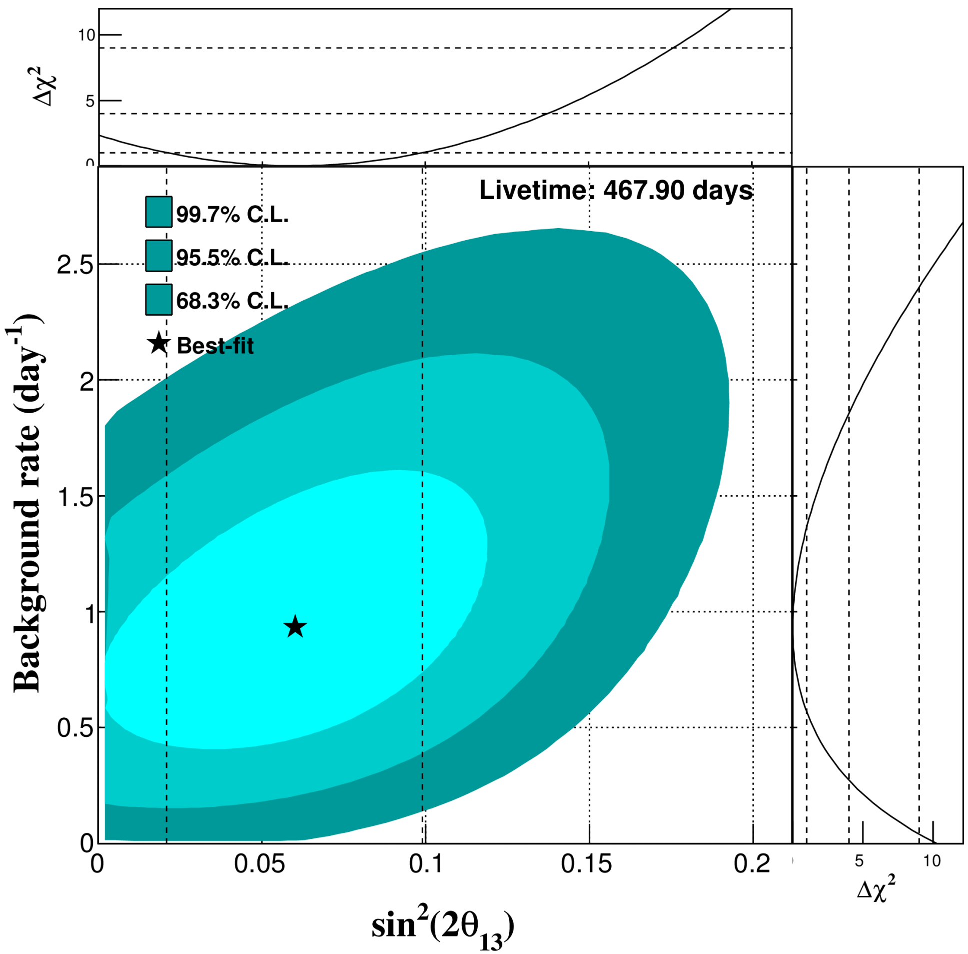
FIT: INPUTS & OUTPUTS

Fit parameter	Input value	Best-Fit value
Li+He background	$0.97^{+0.41}_{-0.16}$	0.74 ± 0.13
Fast-n + stop-μ backg.	0.604 ± 0.051	$0.568^{+0.038}_{-0.037}$
Accidental backg.	0.0701 ± 0.0026	0.0703 ± 0.0026
Residual $\bar{\nu}_e$	1.57 ± 0.47	1.48 ± 0.47
Δm^2_{13} (10^{-3} eV^2)	$2.44^{+0.09}_{-0.10}$	$2.44^{+0.09}_{-0.10}$
E-scale ε_a	0 ± 0.006	$0.001^{+0.006}_{-0-005}$
E-scale ε_b	0 ± 0.008	$-0.001^{+0.004}_{-0-006}$
E-scale ε_c	0 ± 0.0006	$-0.0005^{+0.0007}_{-0-0005}$

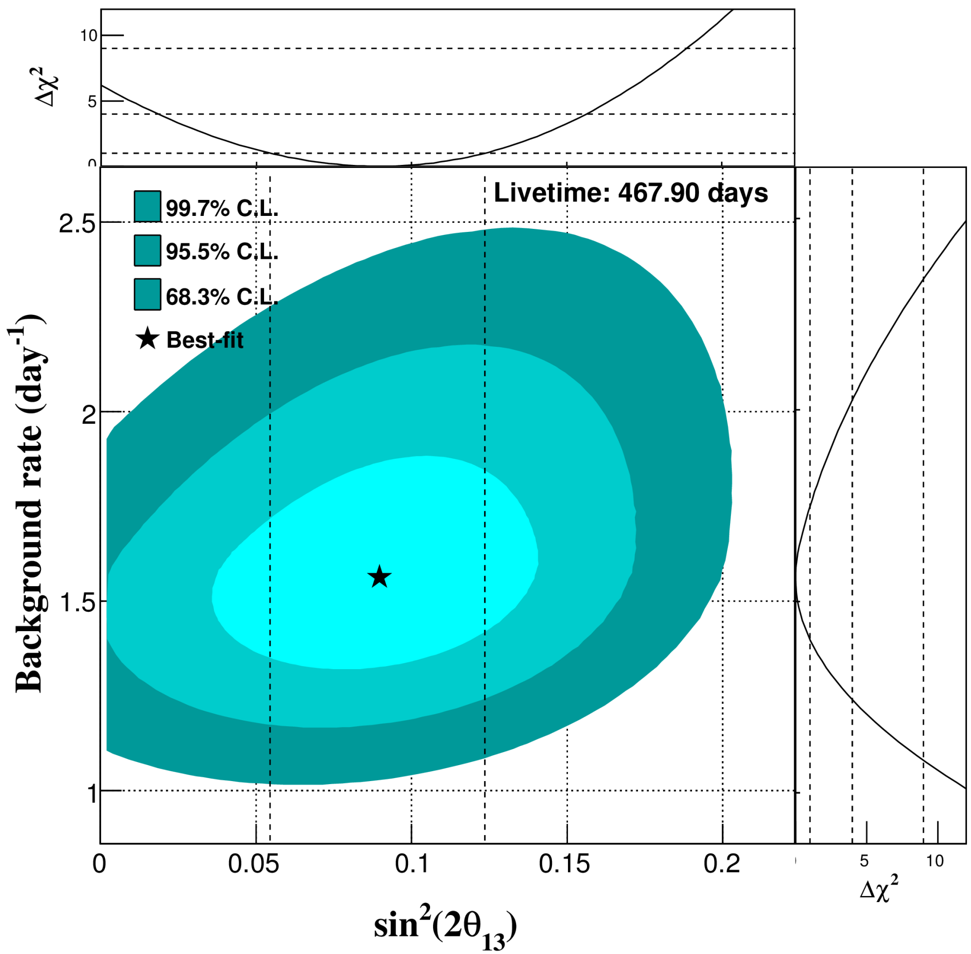
$$\delta E = \varepsilon_a + \varepsilon_b E + \varepsilon_c E^2$$

RRM

BACKGROUND MODEL INDEPENDENT



USING BACKGROUND ESTIMATION



REACTOR FLUX

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

Mean cross-section per fission:

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

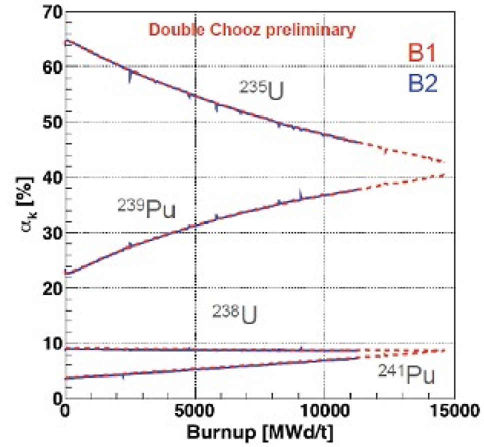
Mean cross-section per nuclide:

$$\langle\sigma_f\rangle_k = \int dE\, S_k(E)\,\sigma_{IBD}(E)$$

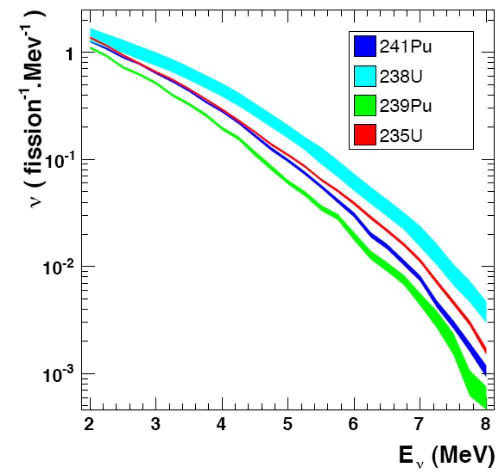
MURE (NEA-1845/01 (2009))

DRAGON (PRD 86 (2012) 012001)

Fission fractions

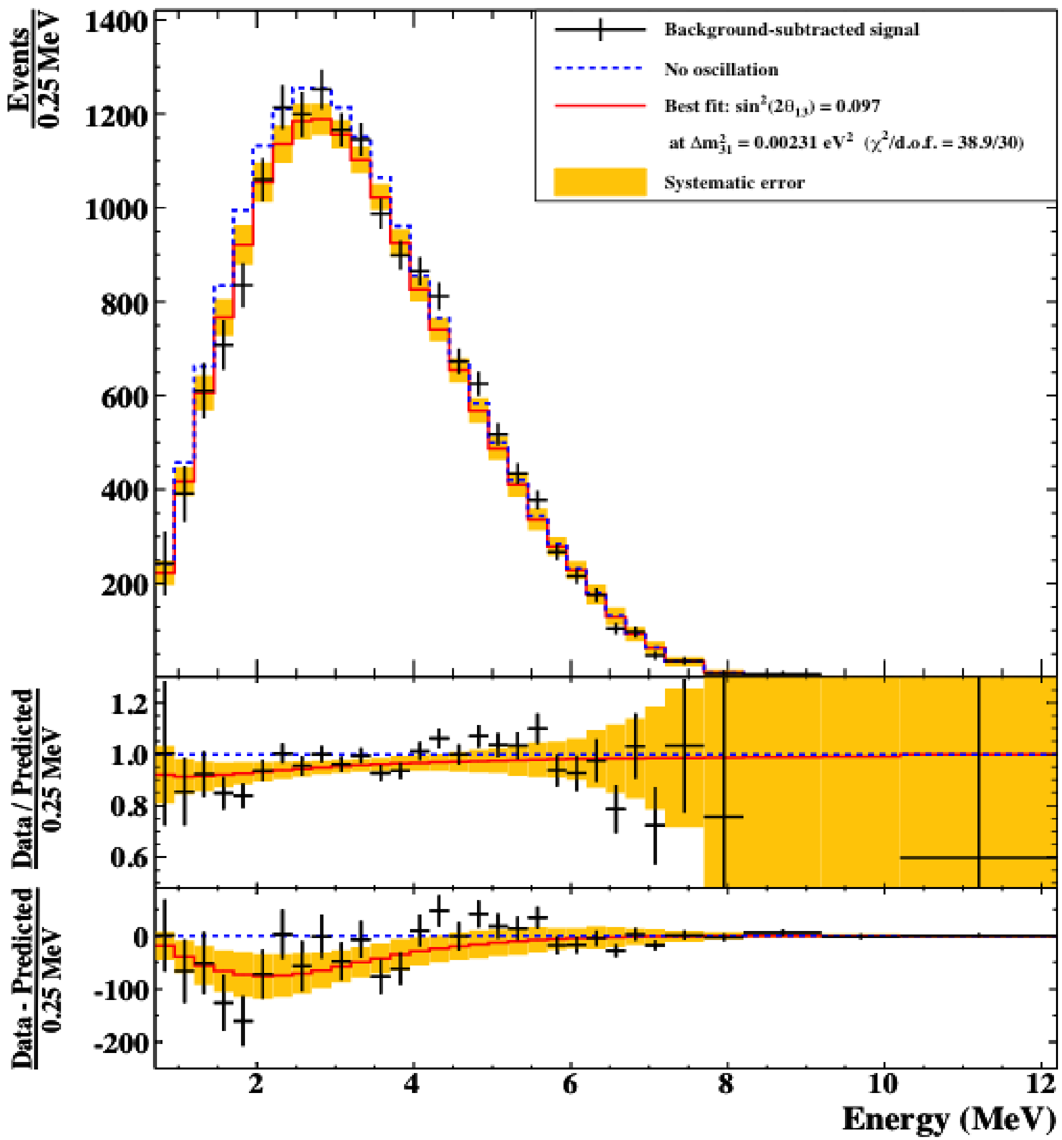


Reference spectra

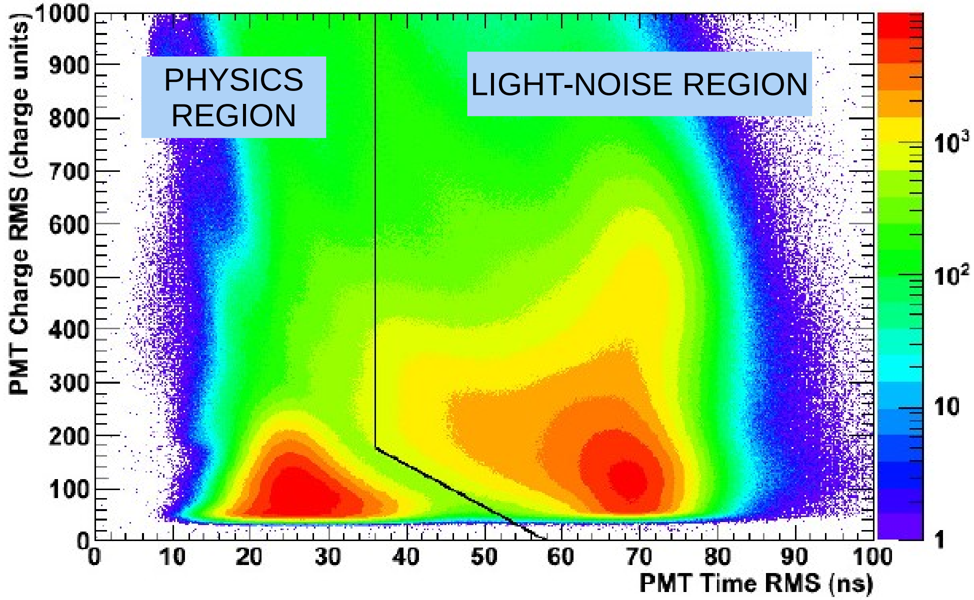


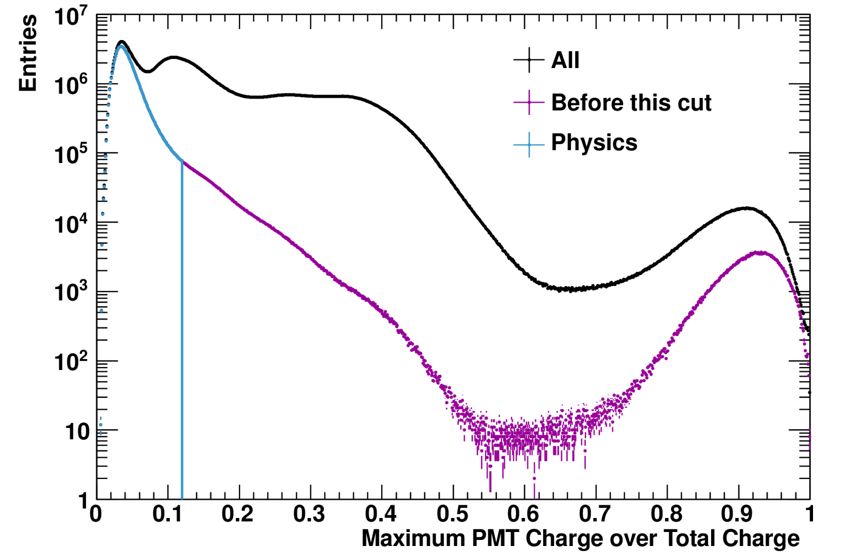
Error source	Uncertainty
Bugey4	1.4%
Isotope fission rate	0.8%
Thermal P.	0.5%
Energy per fission	0.2%
Cross section	0.2%
Baseline	< 0.1%
TOTAL	**1.7%**

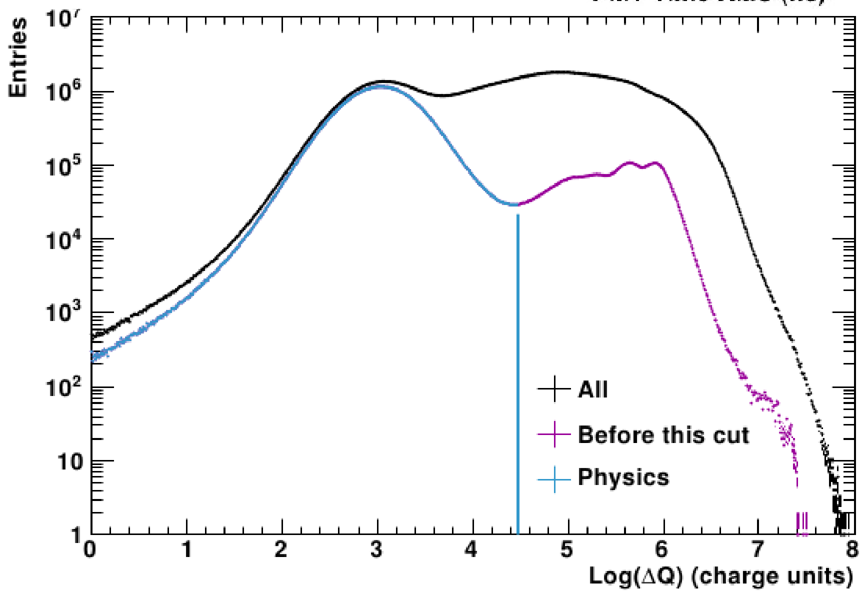
OLD n-H ANALYSIS

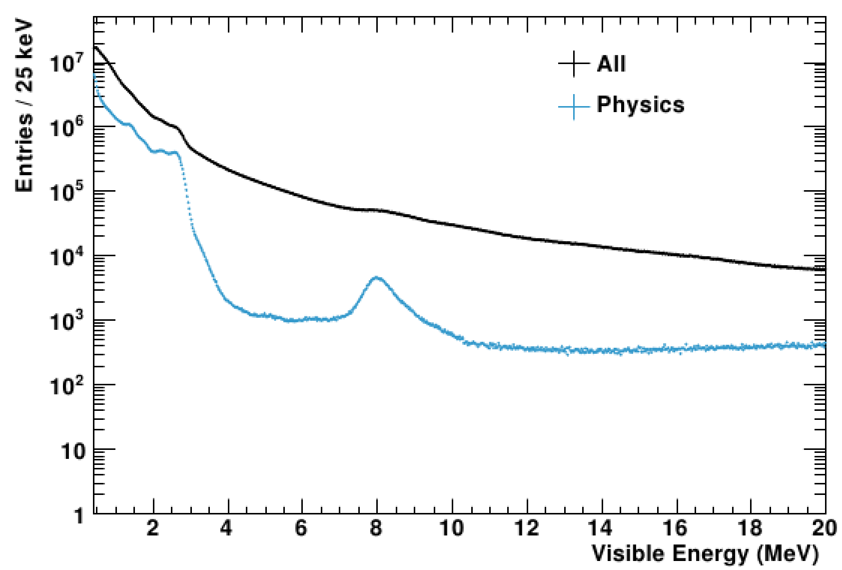


LIGHT-NOISE

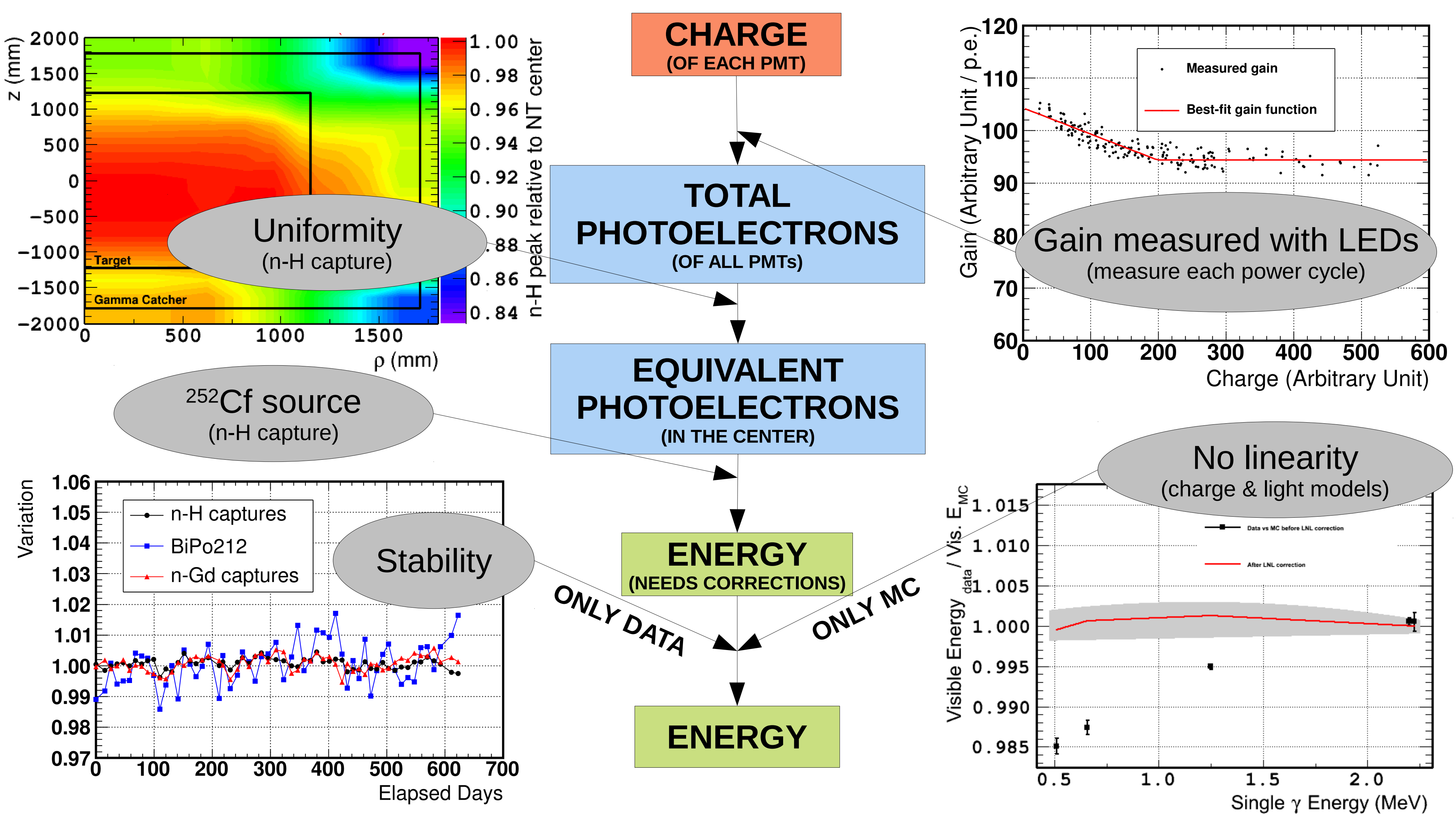

PHYSICS REGION
LIGHT-NOISE REGION
PMT Charge RMS (charge units)
PMT Time RMS (ns)


All
Before this cut
Physics
Entries
Maximum PMT Charge over Total Charge


All
Before this cut
Physics
Entries
Log(ΔQ) (charge units)

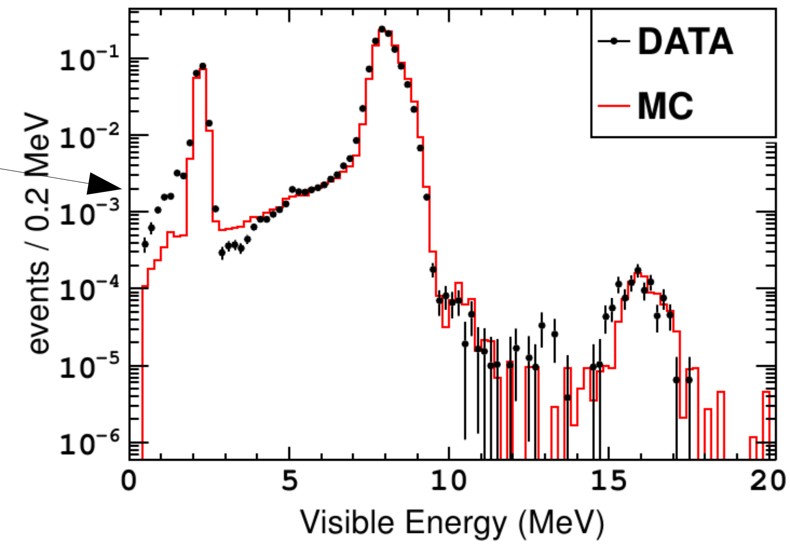

All
Physics
Entries / 25 keV
Visible Energy (MeV)

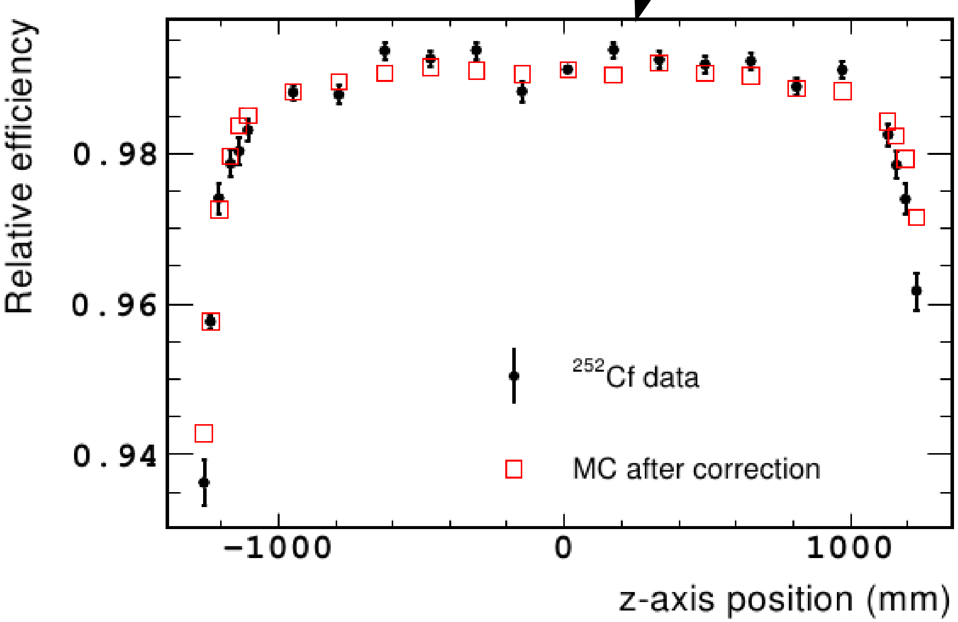
ENERGY RECONSTRUCTION

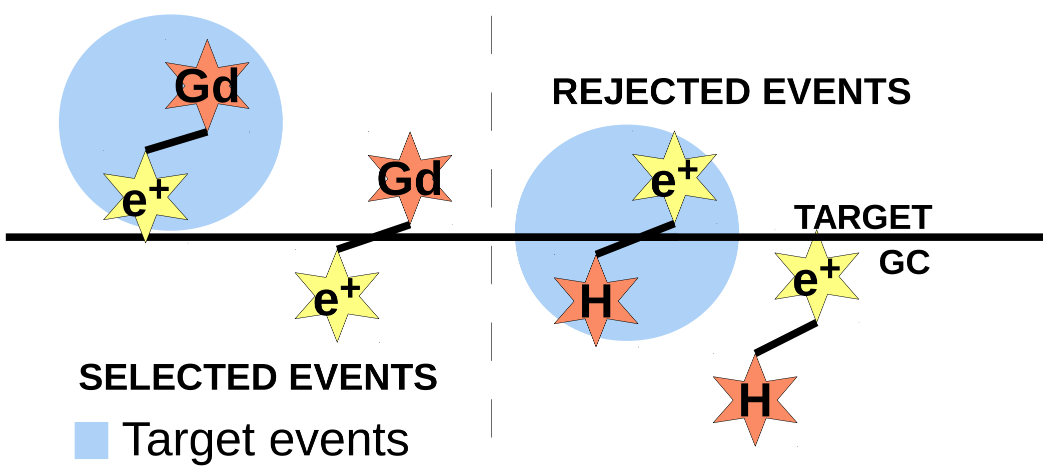


NEUTRON DETECTION EFF.

Contribution	Effic.	MC Normalization
Gd fraction	85.30%	0.975 ± 0.004
Selection	98.58%	1.000 ± 0.003
Spill	-	1.000 ± 0.003
TOTAL	84.09%	0.975 ± 0.006







2 REACTORS OFF

Only 7.24 days

EXPECTED BACKGROUND EVENTS: $11.3^{+2.7}_{-1.0}$
EXPECTED RESIDUAL $\bar{\nu}_e$: 1.57 ± 0.47
IBD CANDIDATES DURING 2 REACTORS OFF PERIOD: 7

Compatible within 1.7σ