Recent Results from the Double Chooz Experiment

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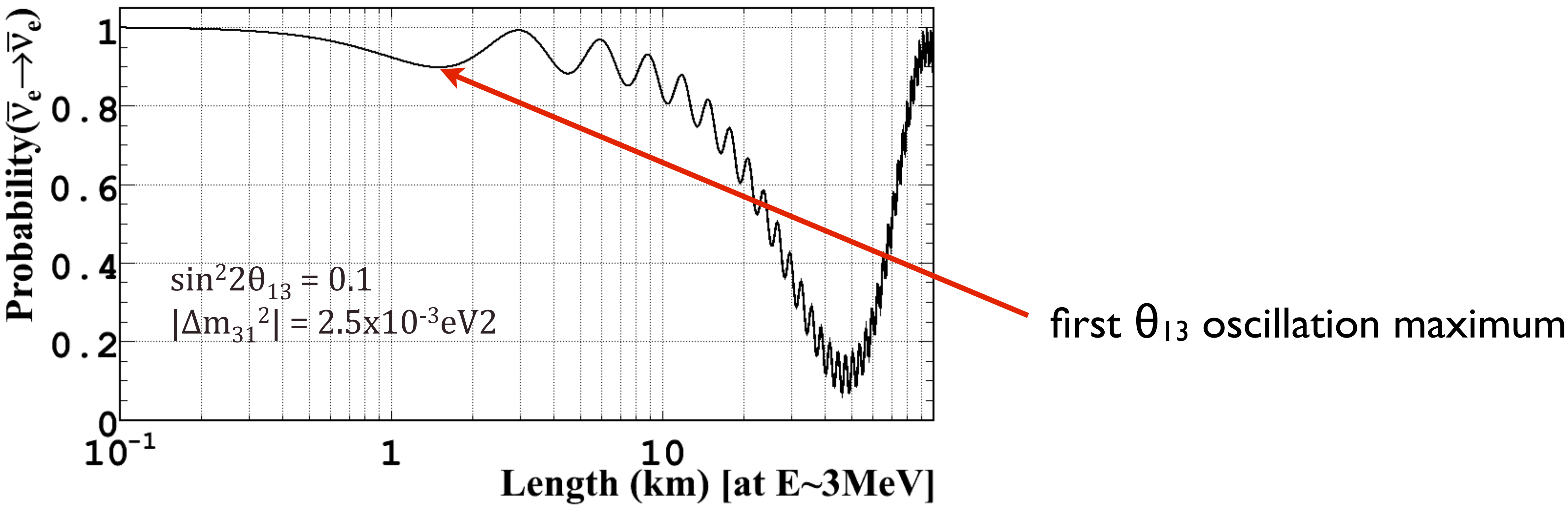
Motivation for θ_{13} measurments with reactor neutrinos

- Reactors: rich and free electron antineutrino sources
- Strong BG reduction by taking delayed coincidence (S/N~40)
- Pure θ_{13} measurement independent of CP-δ, θ_{23}, etc.

Motivation for θ_{13} measurements with reactor neutrinos

Survival probability

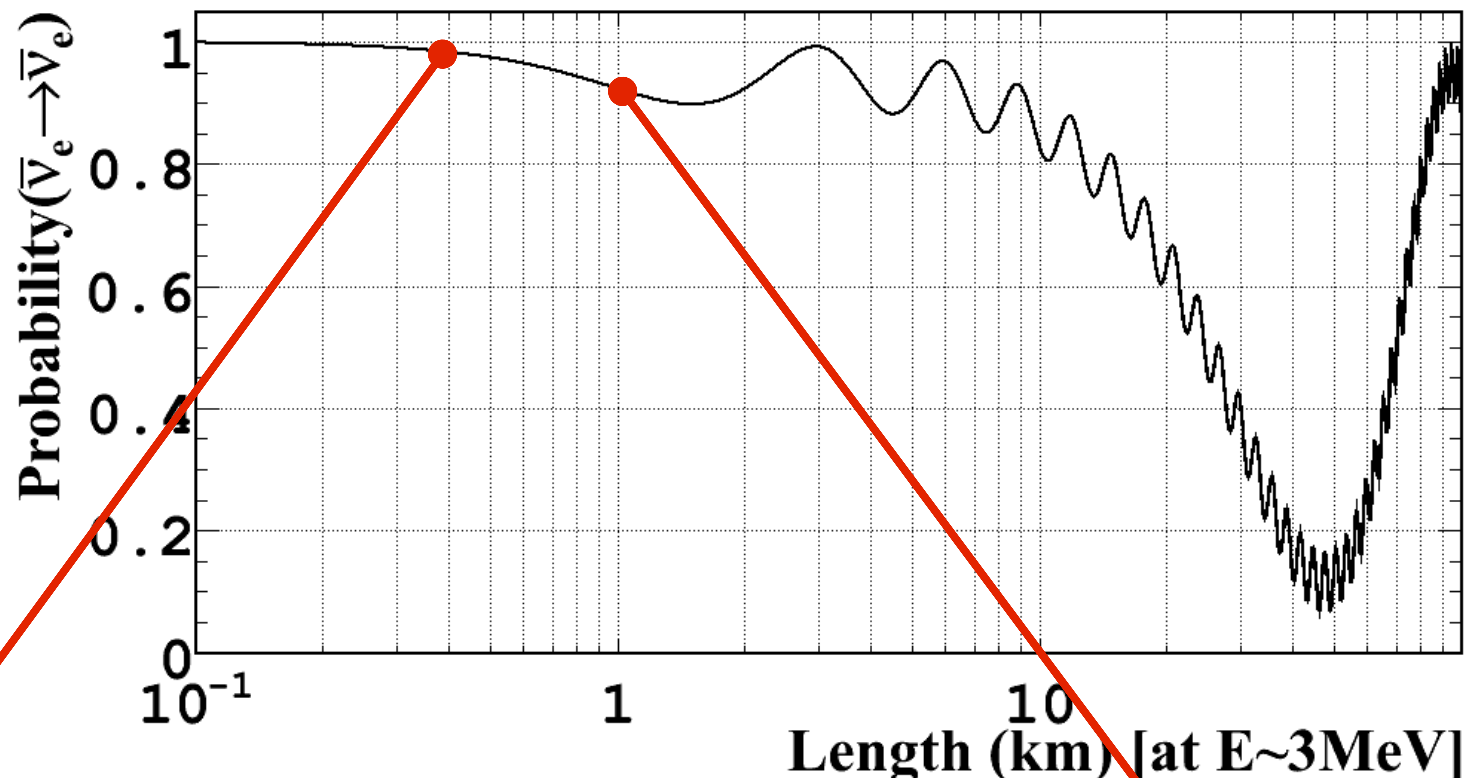


$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2(2\theta_{13}) \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right)$$

Simple 2-flavour oscillation formula is valid at L ~ 1km with no matter effect
→no parameter degeneracy

Motivation for θ_{13} measurements with reactor neutrinos

Survival probability



Near detector

Measure reactor
ν flux & spectrum
before oscillation

reduce systematic uncertainties

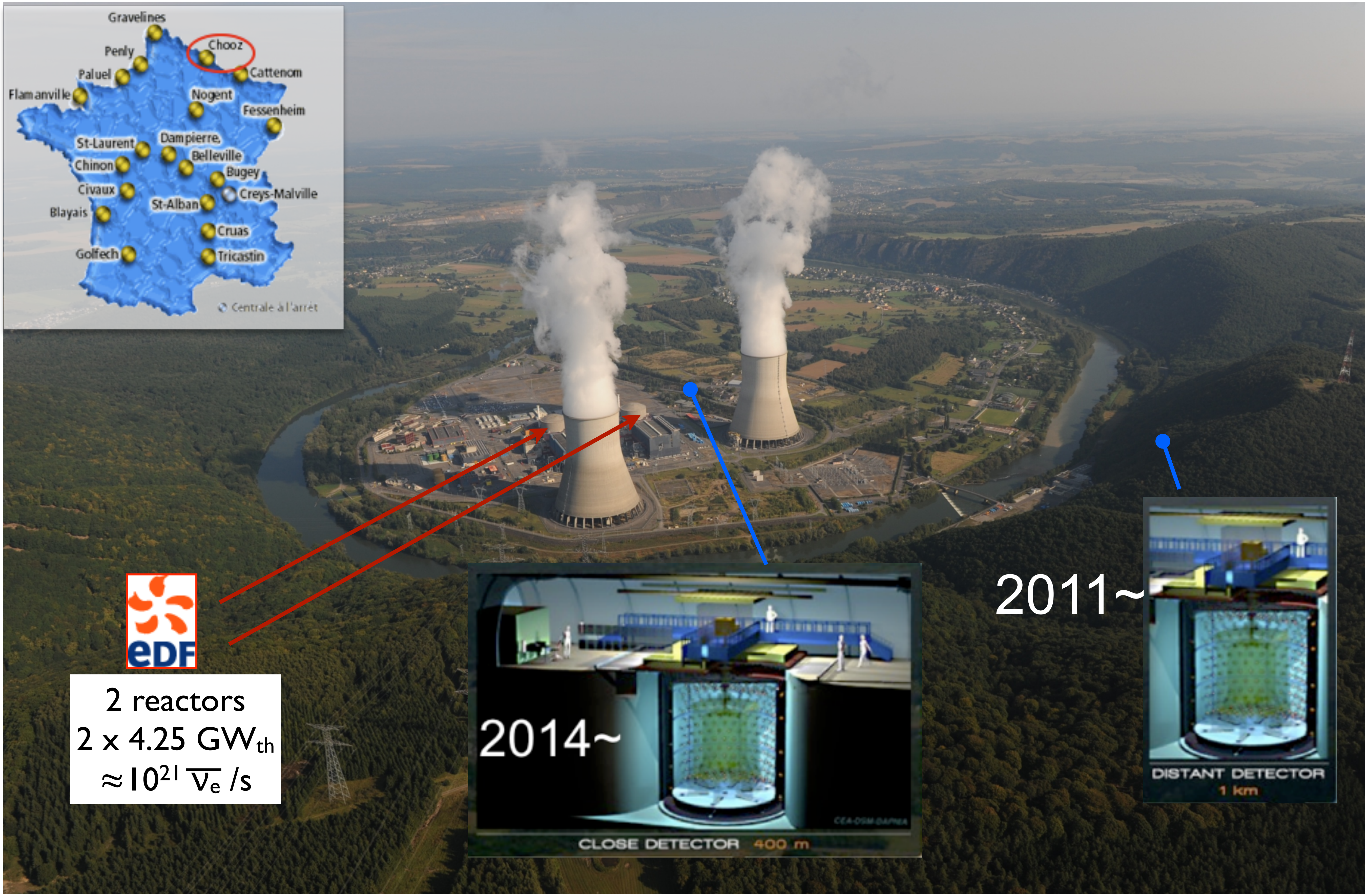
Far detector

Measure oscillated
ν flux & spectrum

determine θ_{13}

Same detector type

The 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
- U. Hamburg

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

Russia
- INR RAS
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Spain
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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)

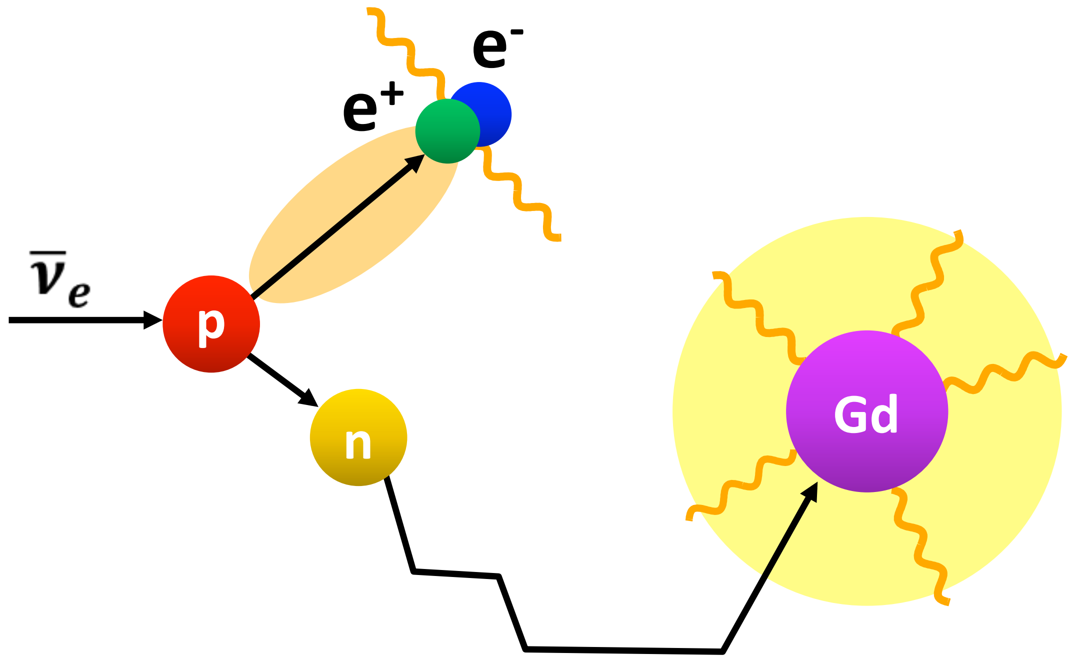
Project Manager:
Ch. Veyssière (CEA-Saclay)

Web Site:
www.doublechooz.org/

Neutrino detection

Inverse β-decay (IBD)

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

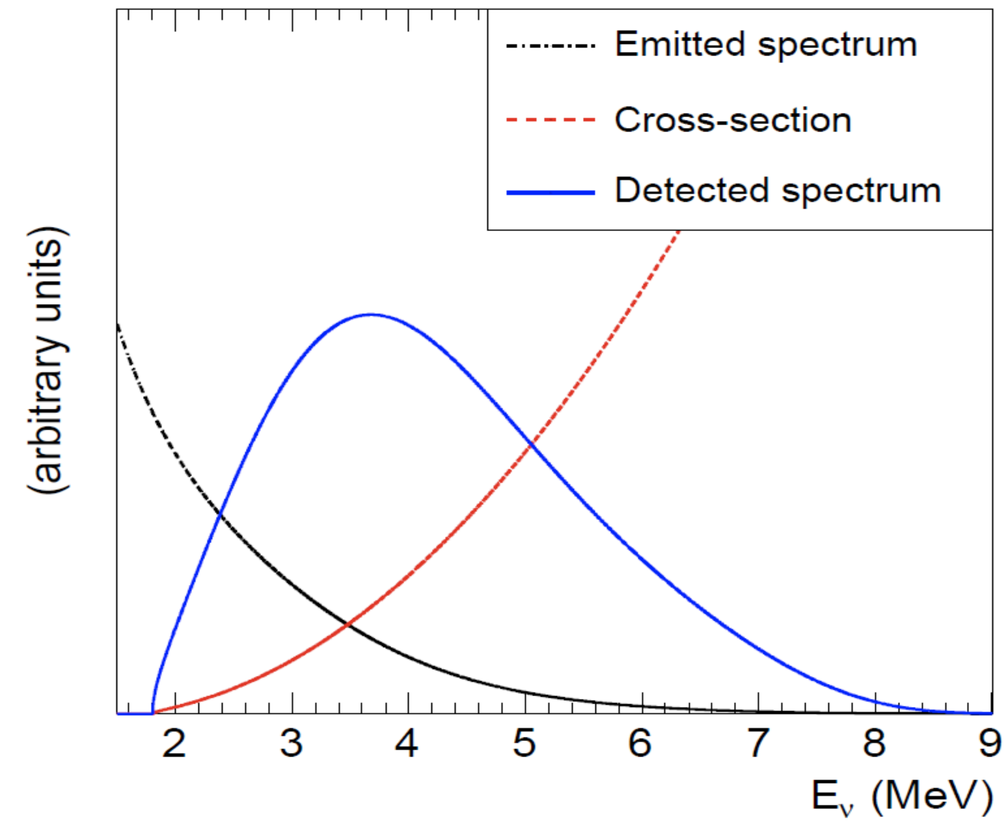


Delayed coincidence

Prompt signal: positron + annihilation γ's (1~9MeV)

Delayed signal: γ's from neutron capture on Gd (H)

Neutrino energy spectrum



Capture on Gd

ΔT~30μs

delayed signal: 8MeV

well above natural radioactivity

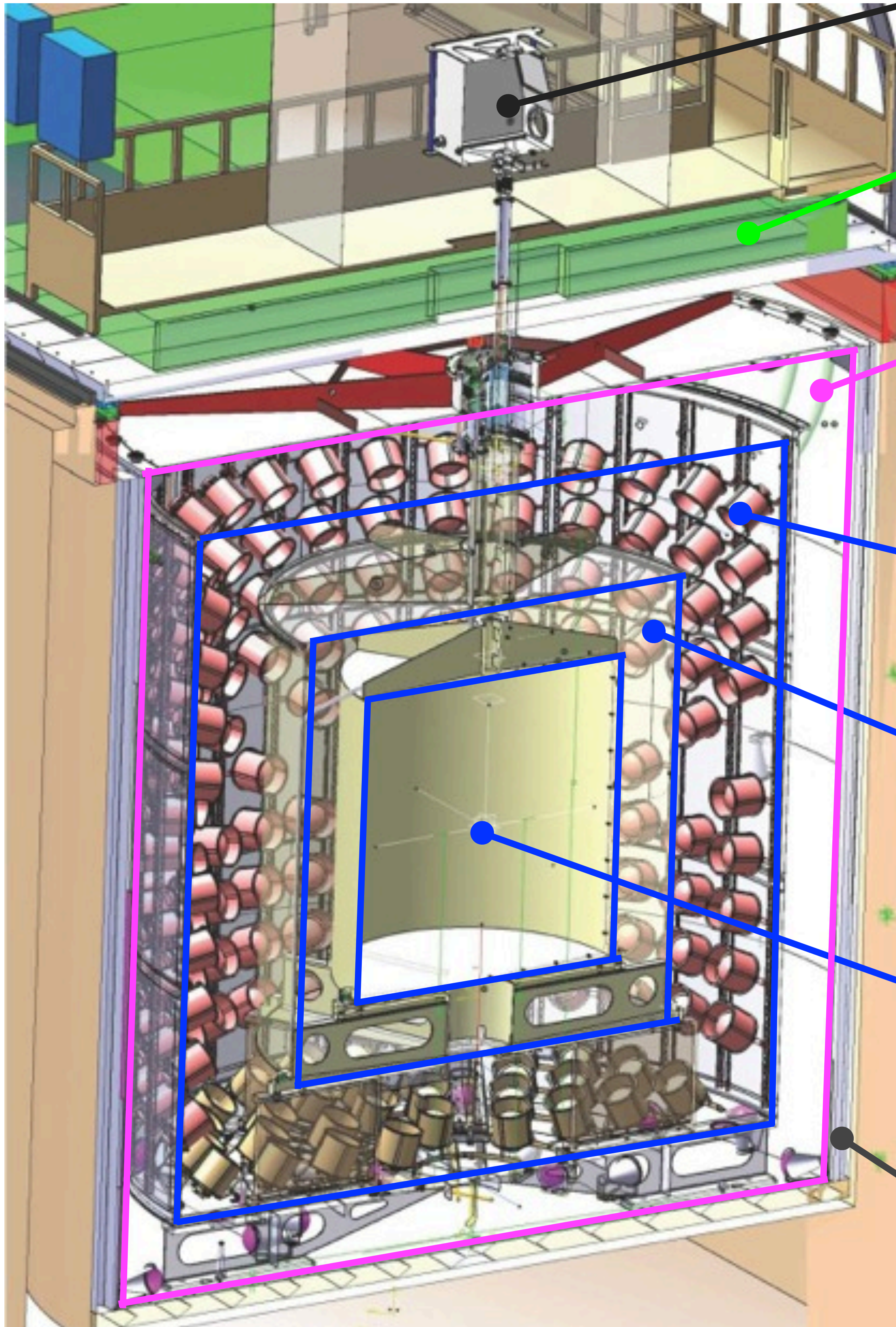
Capture on H

ΔT~200μs (out of Gd doped LS)

delayed signal: 2.2MeV

accidental BG is dominant

Detector design



Glove Box:
Calibration source deployment

Outer Veto:
Plastic scintillator

Inner Veto:
- Liquid scintillator (90 m^3) in a steel vessel (8mm)
- 78 PMTs (8")

Inner detector (3 layers)

Buffer:
- 110 m^3 mineral oil in a steel vessel (3mm)
- 390 low-BG PMTs (10")

γ-catcher:
- Liquid scintillator (22.3 m^3)
- Acrylic vessel (12mm)

ν-target:
- Gd-loaded liquid scintillator (10.3 m^3)
- Acrylic vessel (8mm)

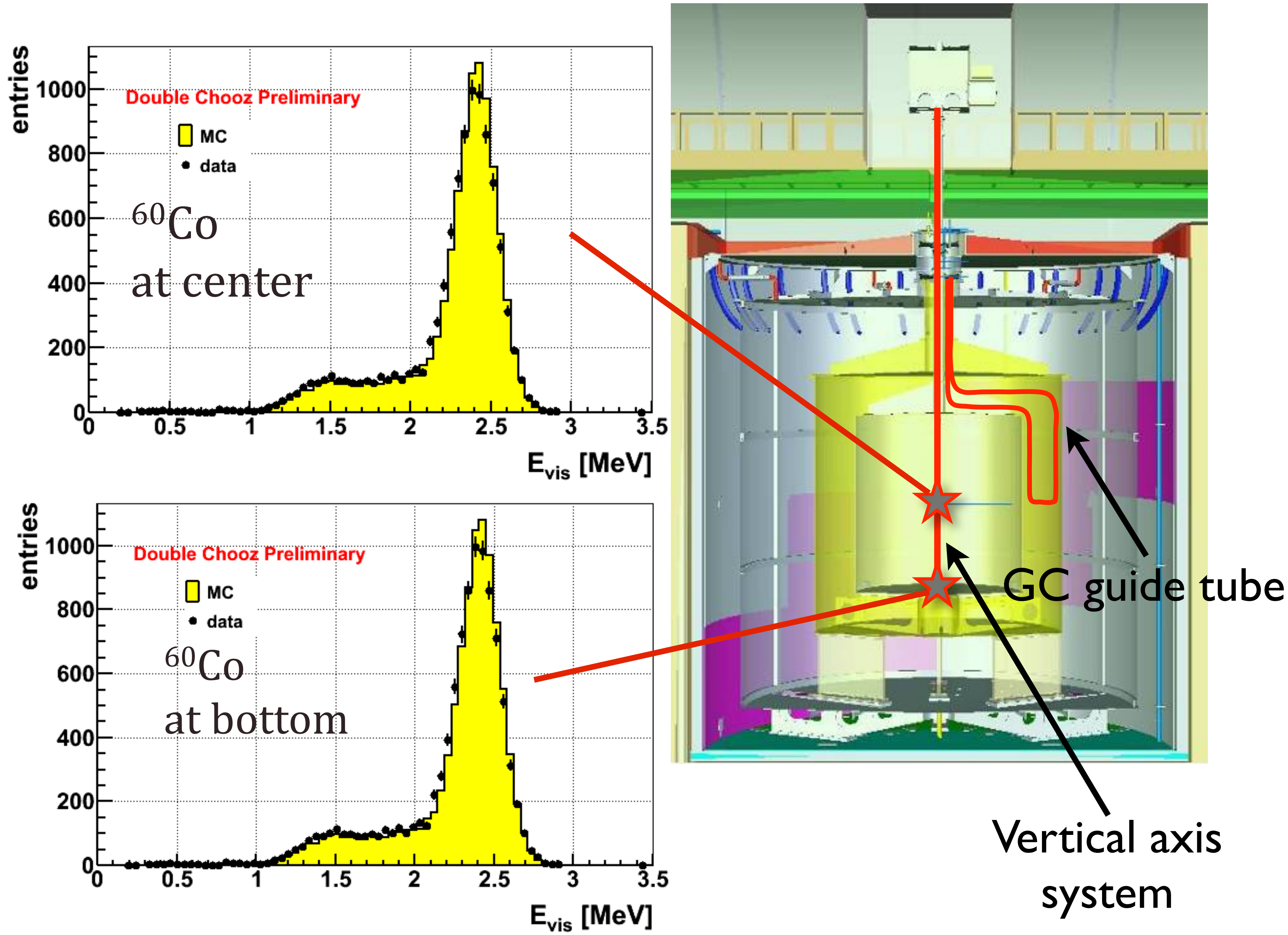
Steel shielding (150mm)

Calibration

1.Calibration of PMT & electronics gain non-linearity
•LED light injection system

2.Correction of position dependence & stability
•Spallation neutron captures on Gd and H

3.Energy scale
•Radioactive sources deployed into ν-target and γ-catcher



<u>Neutrino detection efficiency estimation</u>

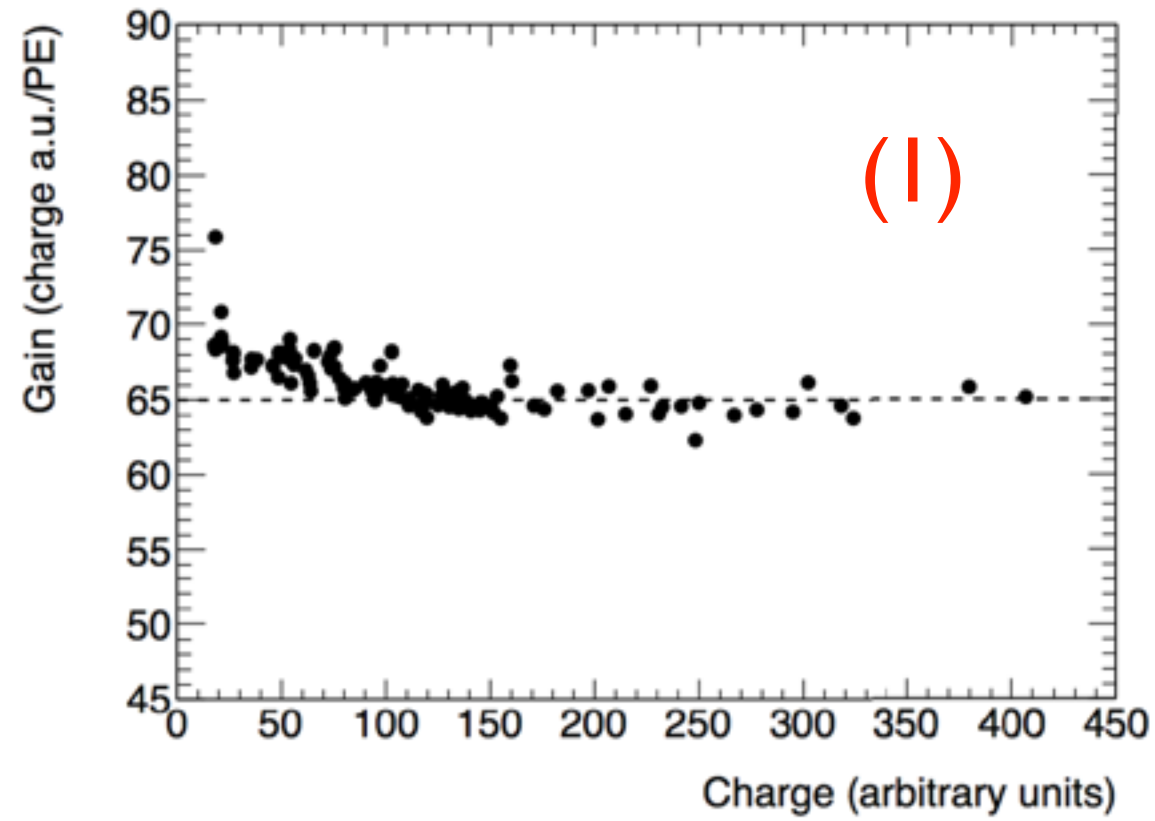
Energy & time window, Gd (H) fraction, spill in/out effects
•^{252}Cf source deployed into ν-target and γ-catcher

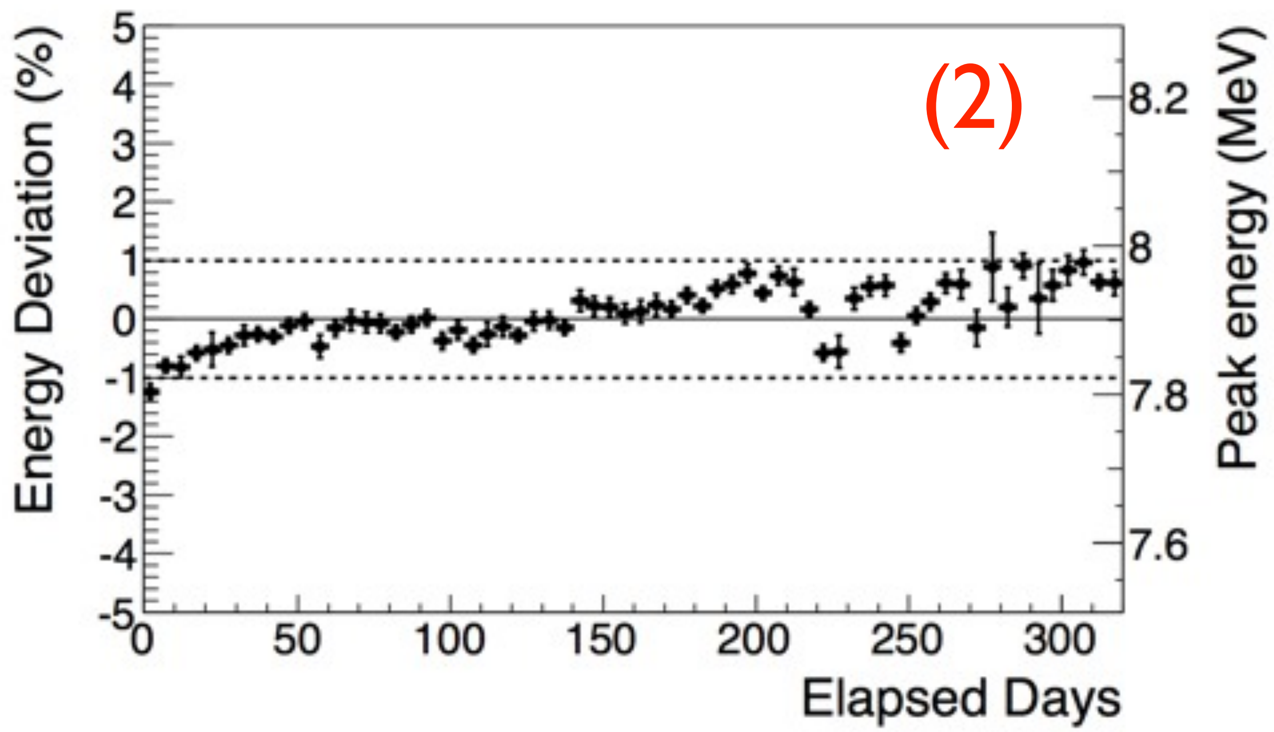
Calibration & energy reconstruction

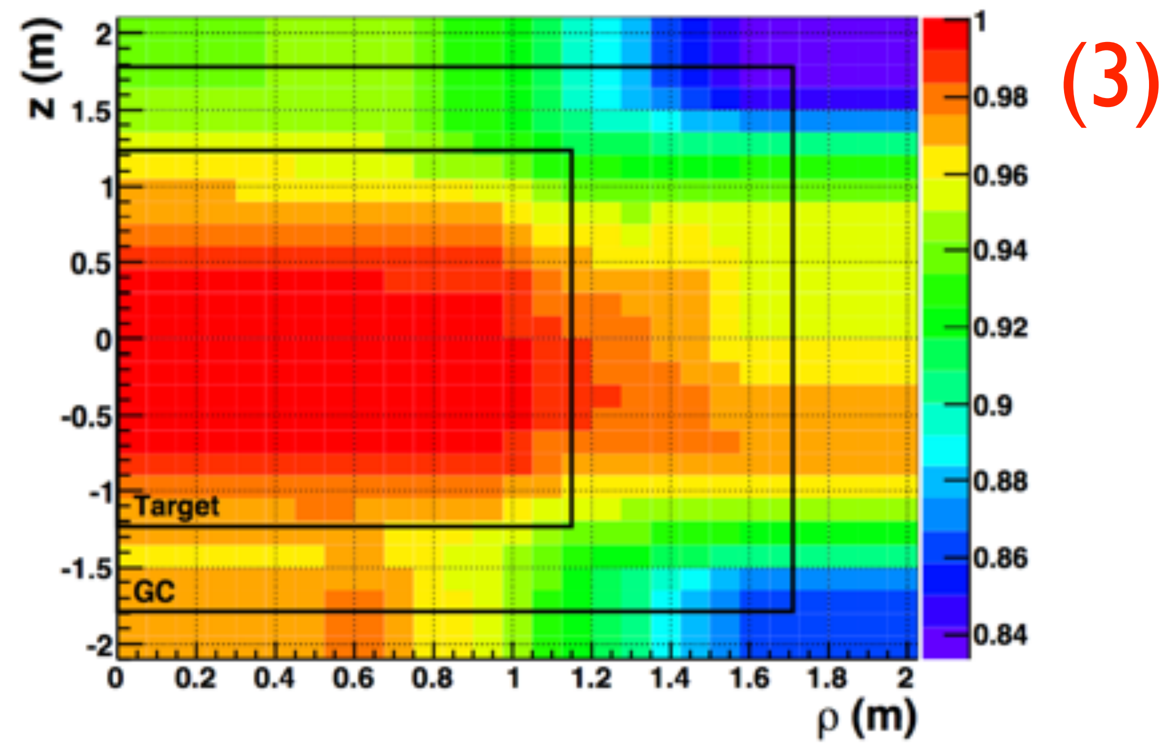
(1) Charge to PE nonlinearity correction

(2) Time stability
Gd captures at center

(3) Detector nonuniformity correction
H capture map







Flux prediction

Neutrino yield per fission

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

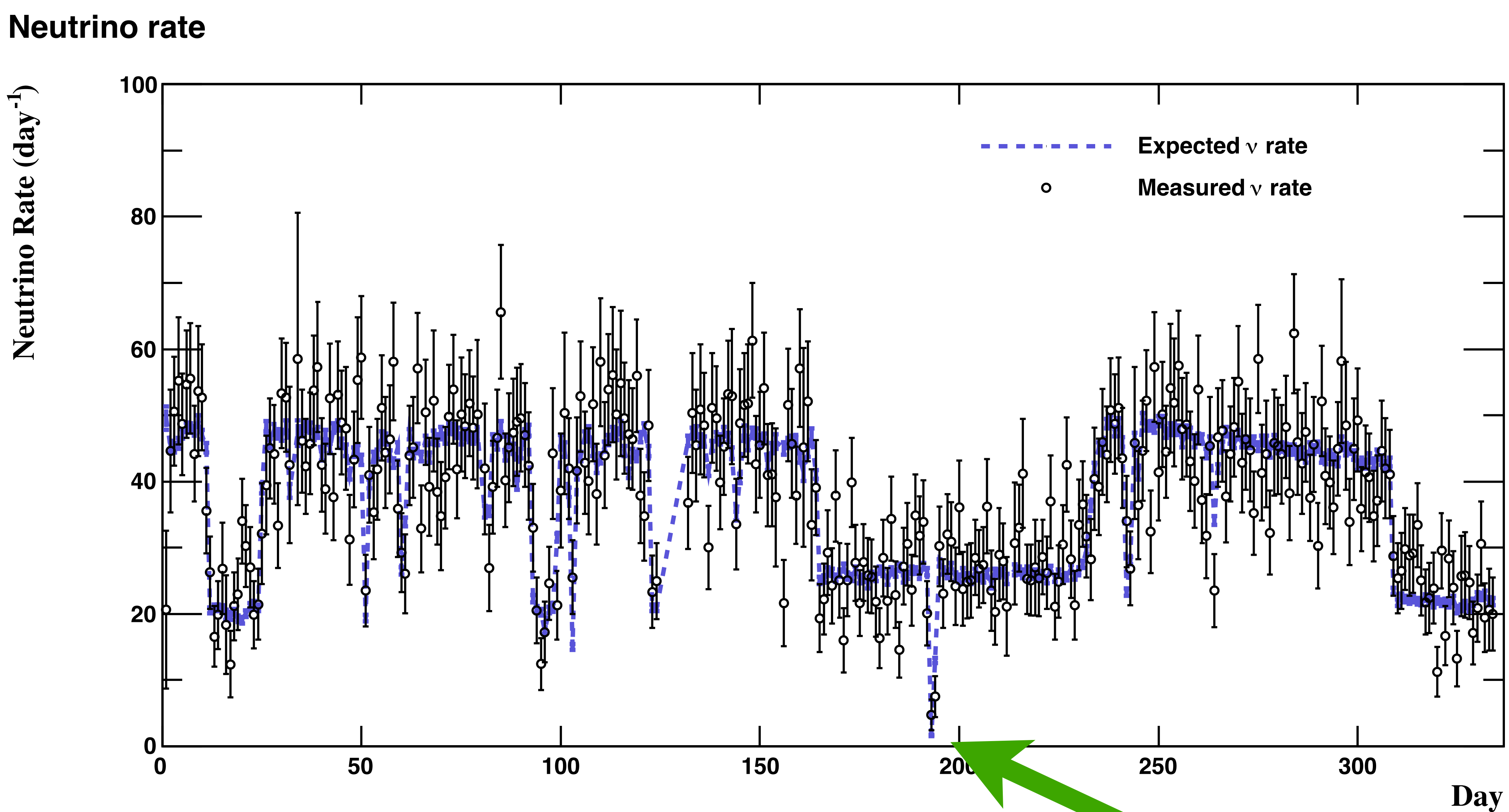
$$\langle \sigma_f \rangle = \langle \sigma_f \rangle^{Bugey} + \sum_k \left(\alpha_k^{DC}(t) - \alpha_k^{Bugey} \right) \langle \sigma_f \rangle_k$$

Bugey4 measurement as anchor point

Fission fraction in CHOOZ core

Flux prediction uncertainty is suppressed by using Bugey4 measurement: 2.7% → 1.8%

Time variation of neutrino candidates



2 reactors on (~60%)

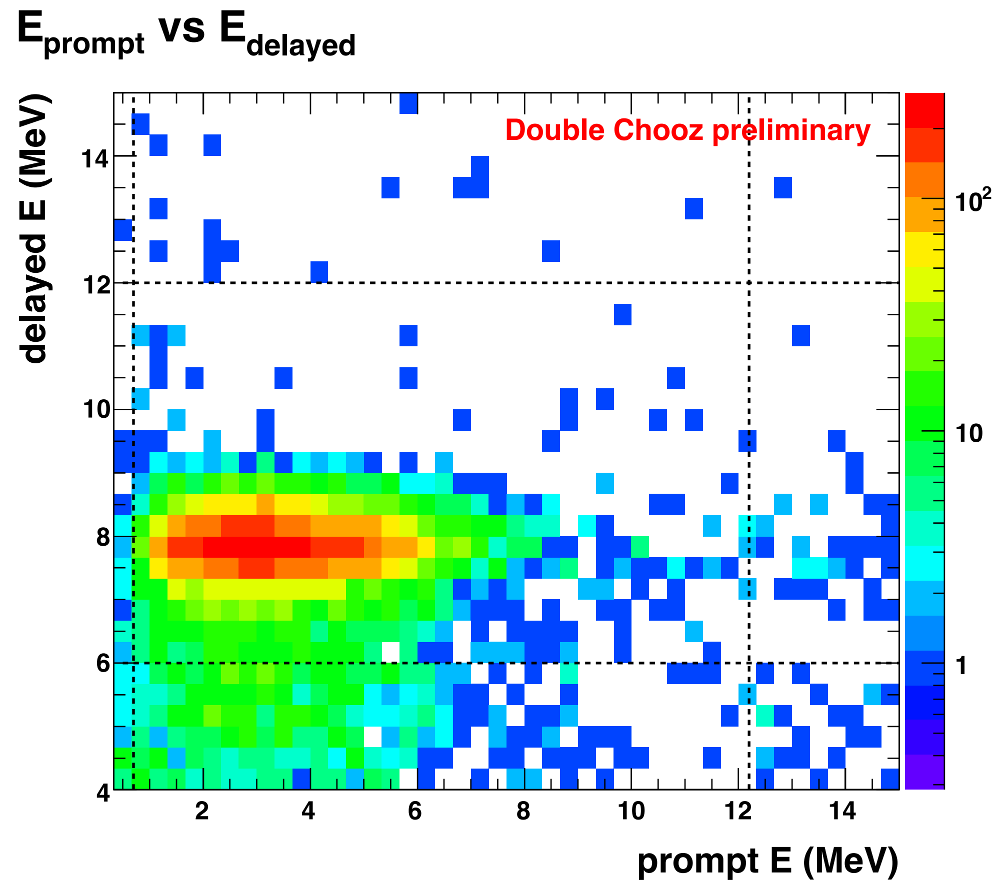
1 reactor on (~40%)

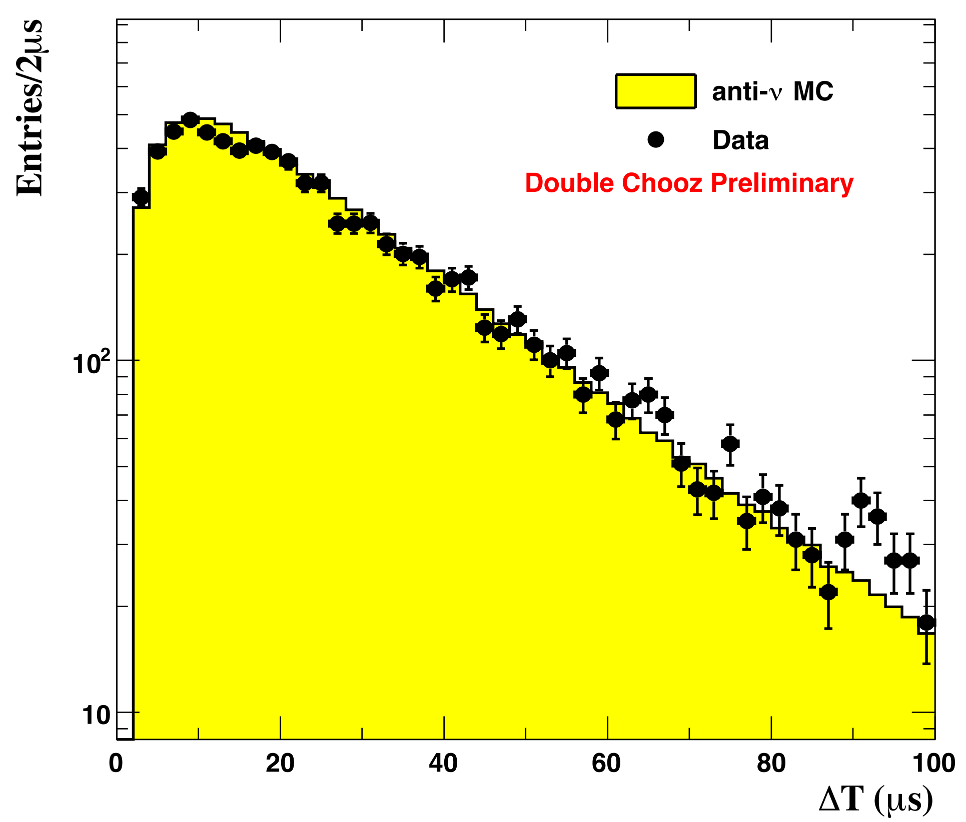
Both reactors off (~1 day)

Rate of Gd capture candidates

Neutrino selection (Gd analysis)

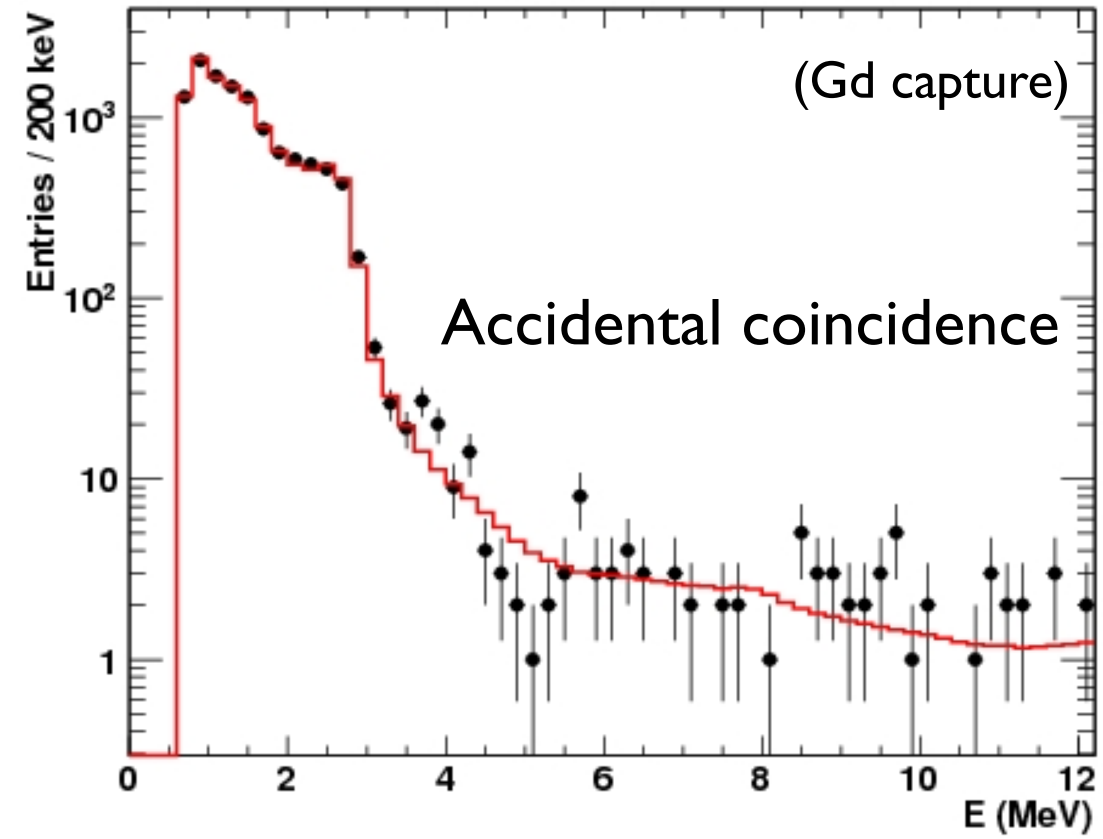
- Muon veto
  - no coincidence in IV
  - Δt_{μ} > 1msec
- PMT light noise cuts
- No coincidence signal in OV
- Prompt event
  - 0.7MeV < Evis < 12.2MeV
- Delayed event
  - 6MeV < Evis < 12MeV
- Delayed coincidence
  - 2μs < ΔT < 100μs
- Multiplicity cut
  - reject multiple n captures
- Further BG reduction
  - Δt_{μ} > 500msec (Eμ > 600MeV)

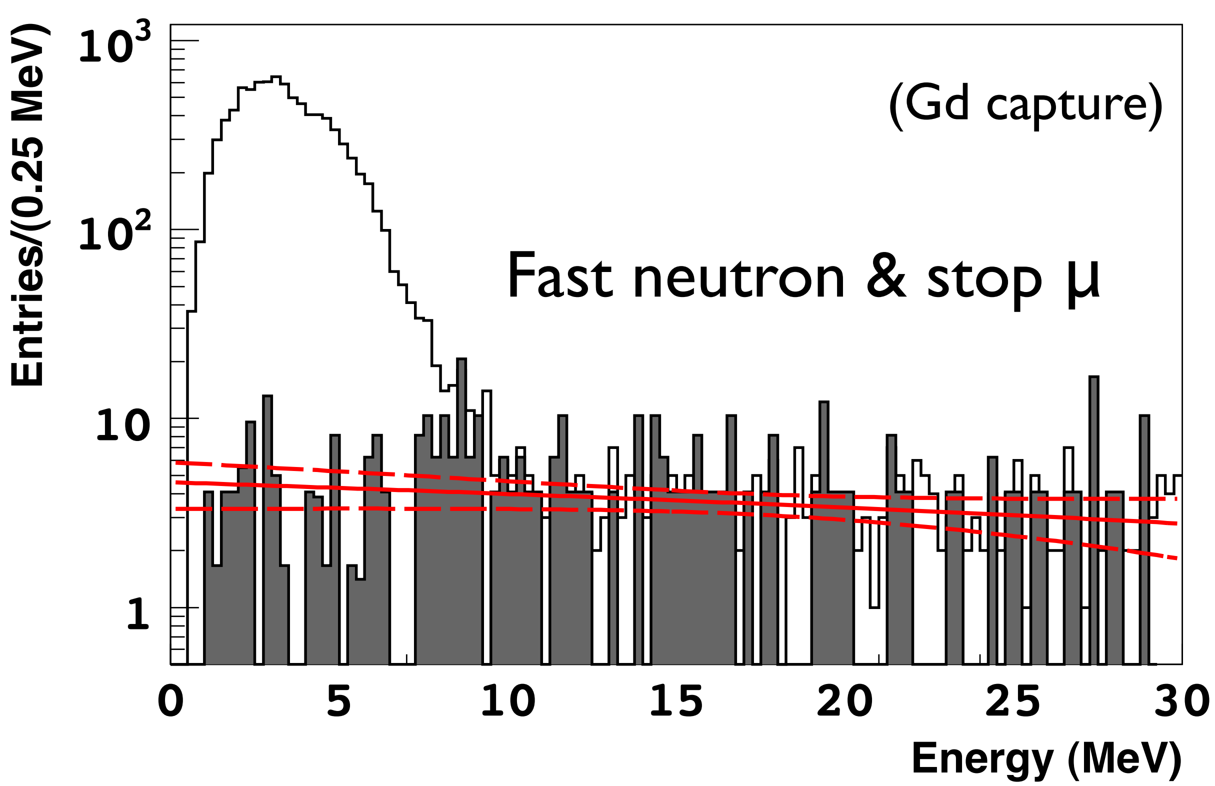


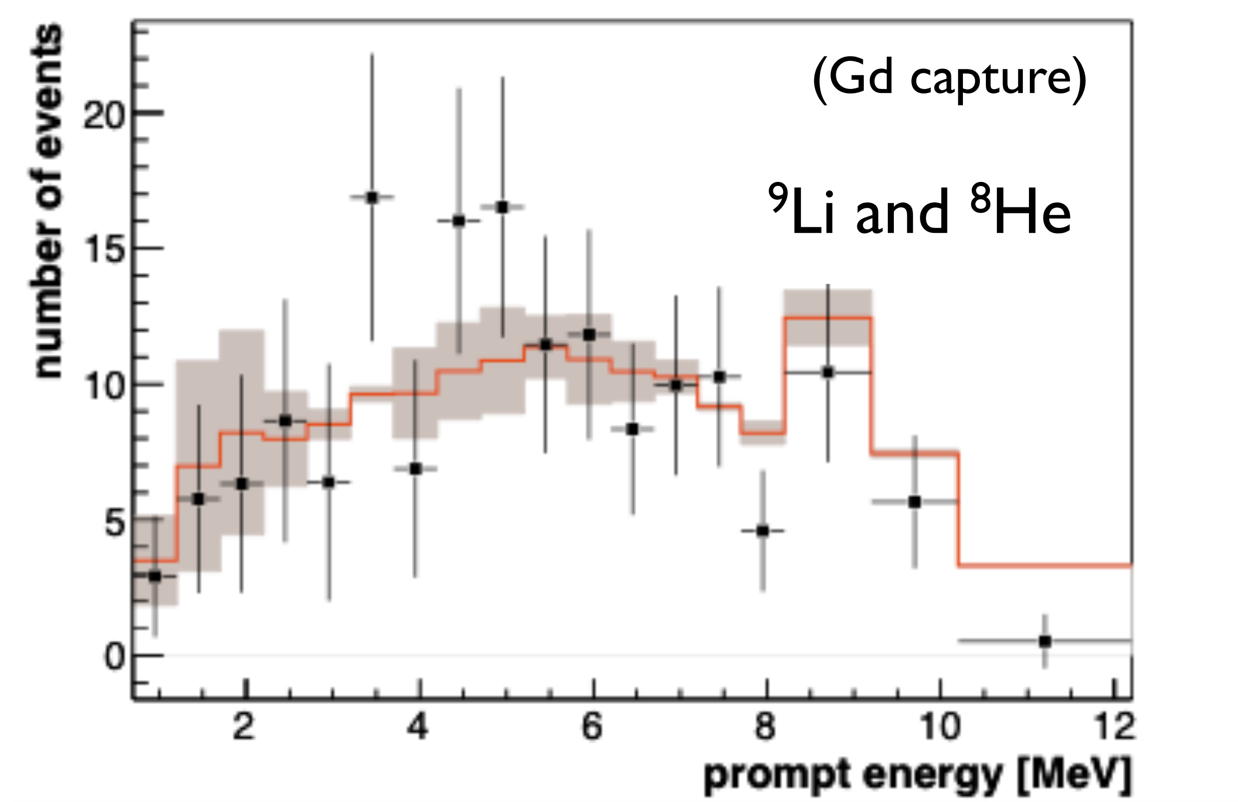


Backgrounds

BG rate (events/day)	Gd capture	H capture
Accidentals	0.261 ± 0.002	73.45 ± 0.16
^{9}Li	1.20 ± 0.54	2.84 ± 1.15
Fast neutrons and stopping μ	0.67 ± 0.20	2.50 ± 0.47
Light noise	negligible	0.32 ± 0.07





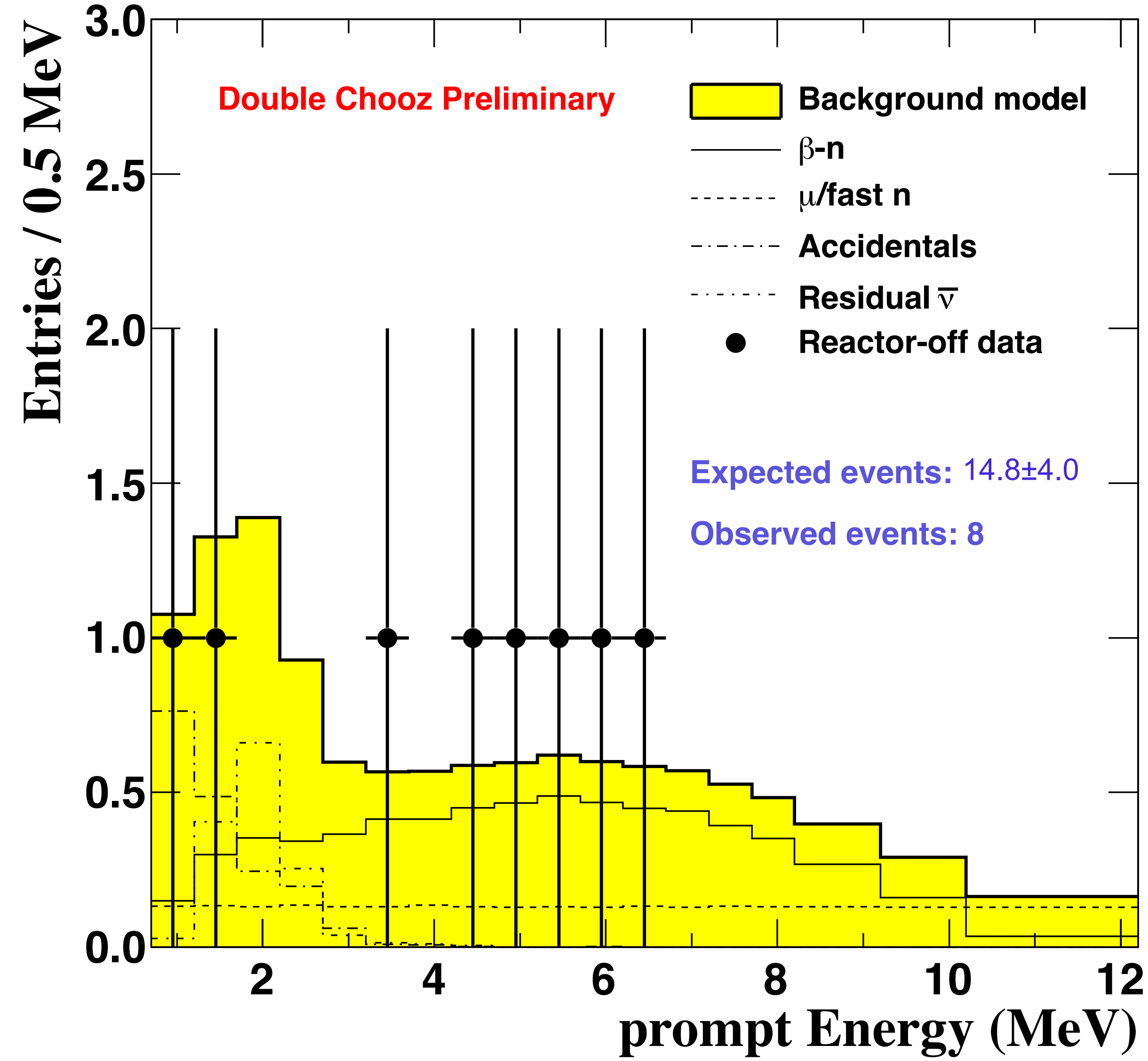


Data with both reactors off

- Unique for Double Chooz
- Direct BG measurement
- 7.53 days so far (6.84 after μ veto):
  - 0.84 days in October 2011
  - 6 days in June 2012
- Expected rate: 2.0±0.6 events/day
- Observed rate: 1.0±0.4 events/day

*Gd capture

Phys. Rev. D87 (2013) 011102



BG measurement consistent with estimations

Uncertainties

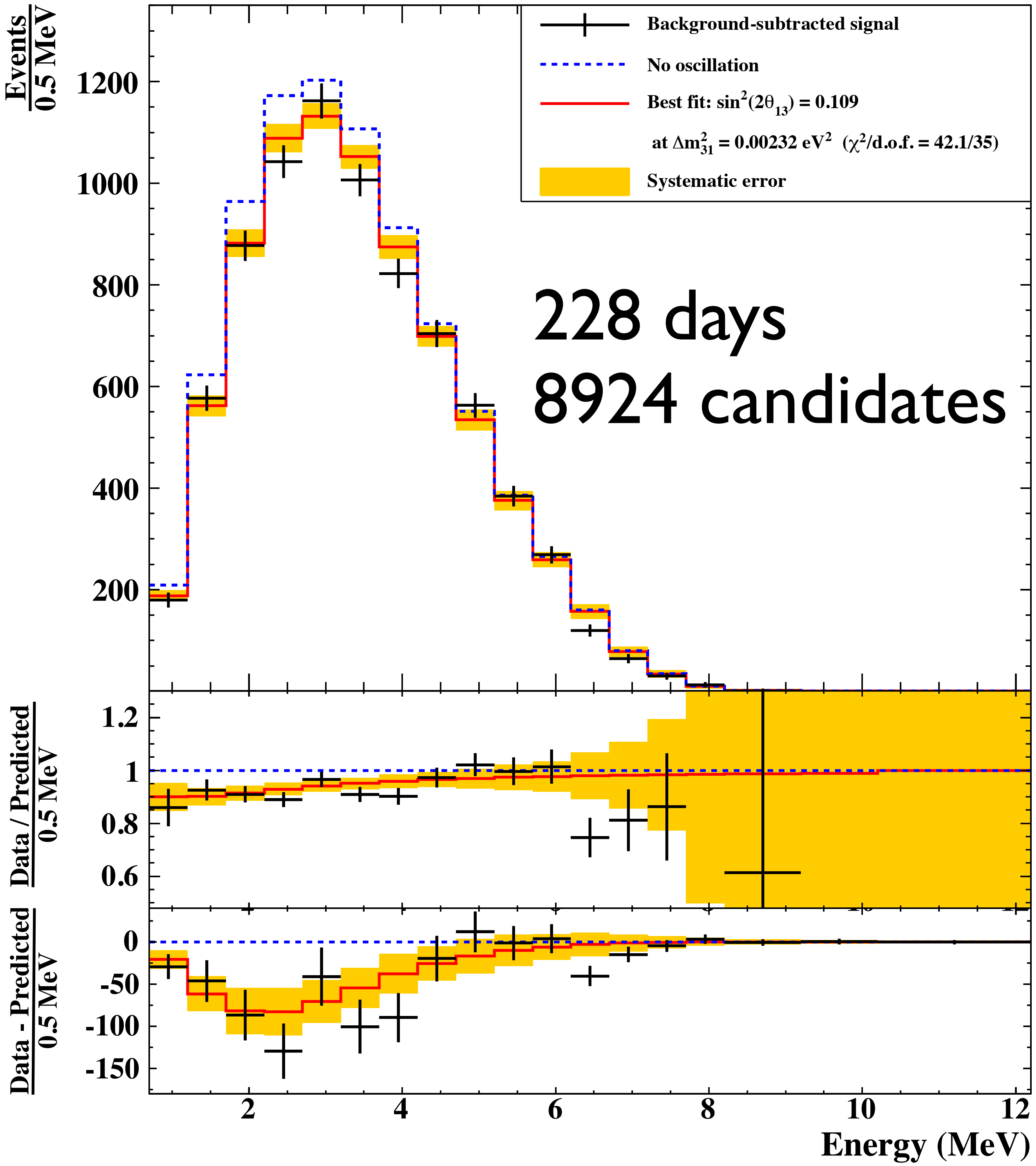
Rate uncertainties (w.r.t. signal)

Source	Gd capture	H capture
Statistical error	1.12%	1.08%
Reactor $\bar{\nu}_e$ flux	1.8%	1.8%
Detection efficiency	1.0%	1.6%
Accidental BG rate	< 0.1%	0.2%
^{9}Li rate	1.5%	1.6%
Fast n & stopping μ rate	0.5%	0.6%

<u>Energy scale uncertainties</u>:
Gd capture 1.1%
H capture 1.7%

Double Chooz results (Gd)

Phys. Rev. D86 (2012) 052008



- BG estimation is consistent with reactor off-off measurement
- BG is further constrained by spectrum shape

Rate only:

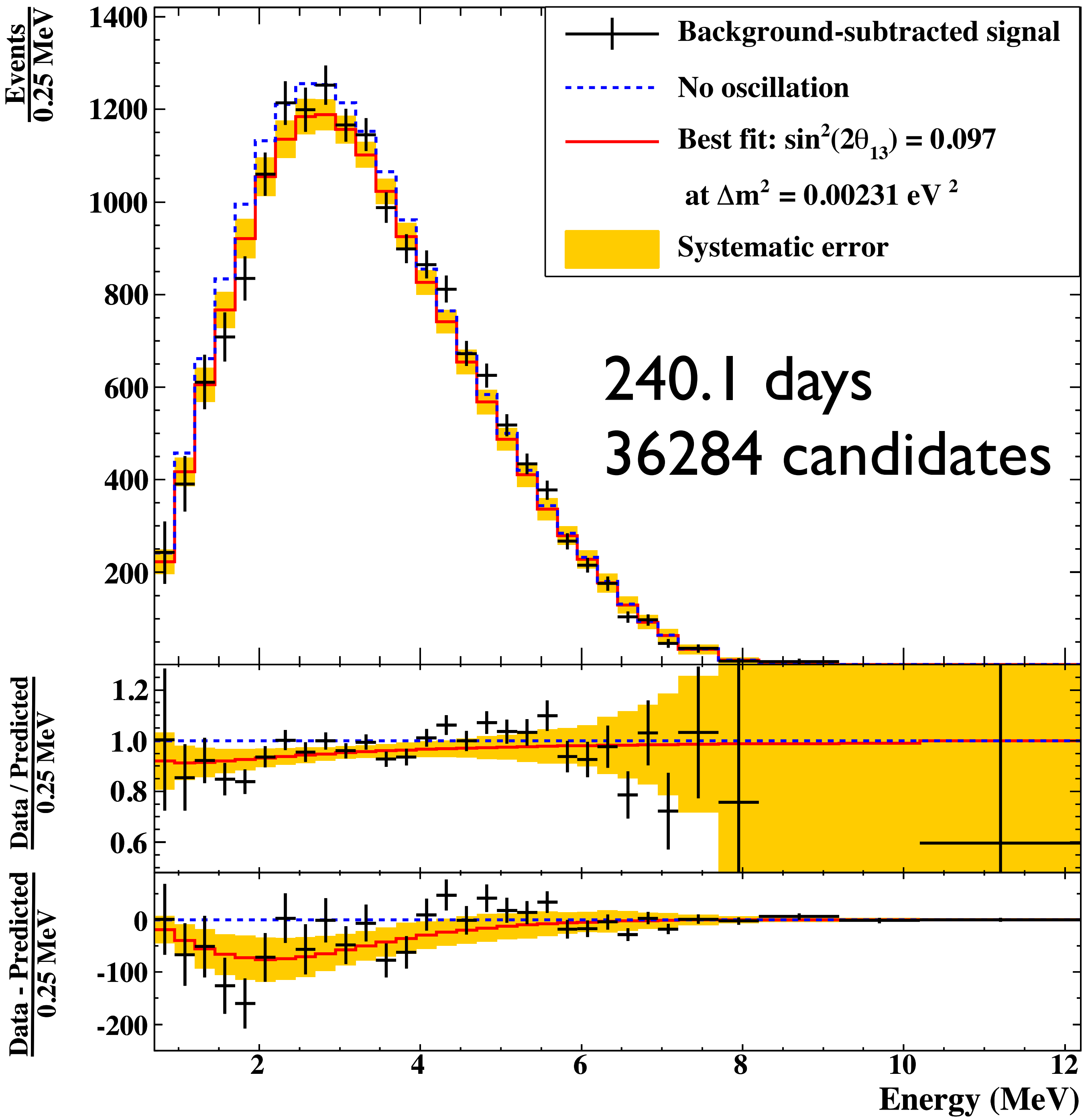
$\sin^2 2\theta_{13} = 0.170 \pm 0.035(\mathrm{stat}) \pm 0.040(\mathrm{syst})$

Rate+Shape:

$\sin^2 2\theta_{13} = 0.109 \pm 0.030(\mathrm{stat}) \pm 0.025(\mathrm{syst})$

Double Chooz results (H)

Phys. Lett. B723 (2013) 66–70



Statistically independent analysis

Rate+Shape:

$\sin^2 2\theta_{13}$ = 0.097 ± 0.034 (stat) ± 0.034 (syst)

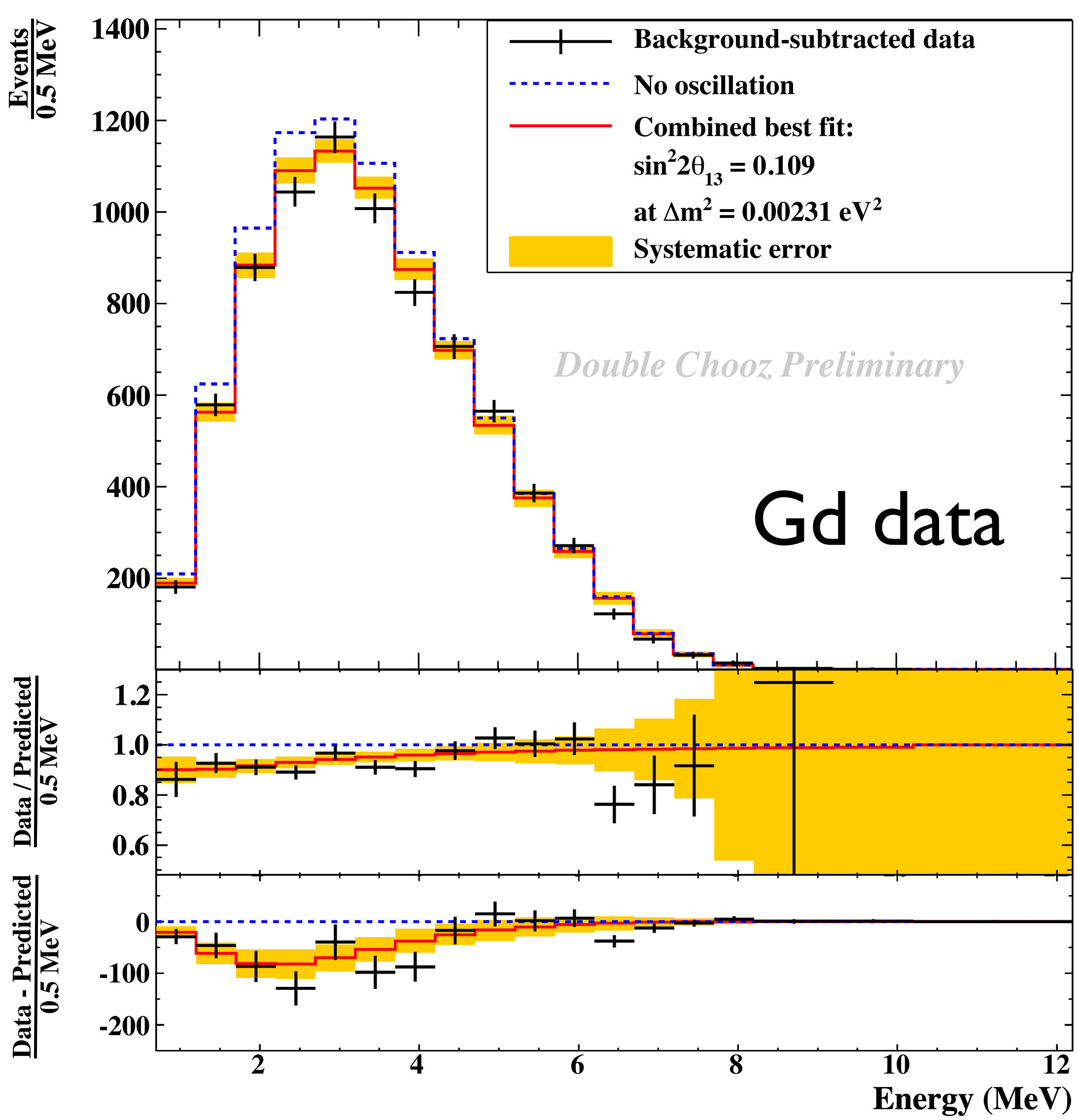
χ^2/DOF = 38.9/30

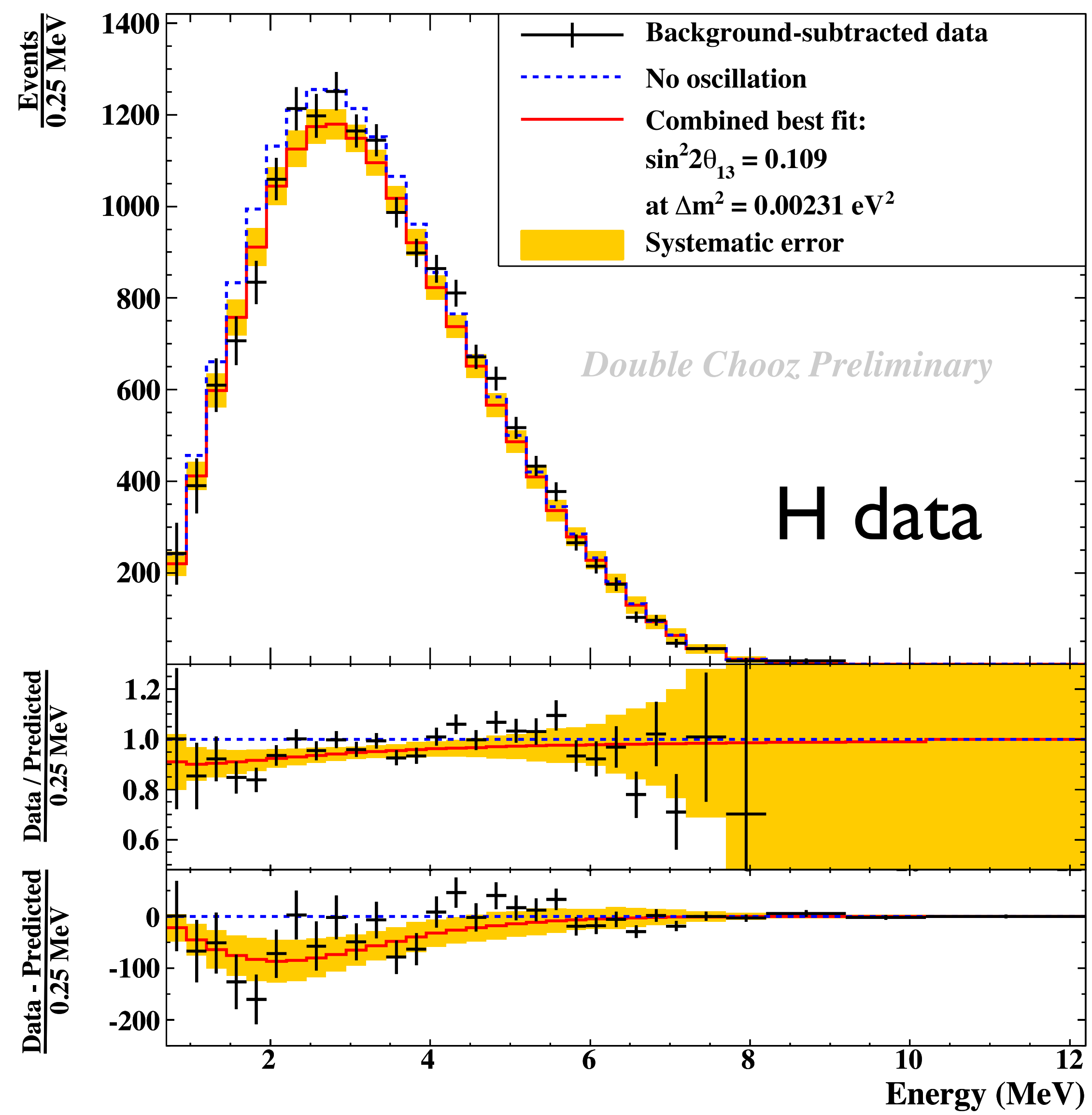
Gd capture and H capture results are consistent

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

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

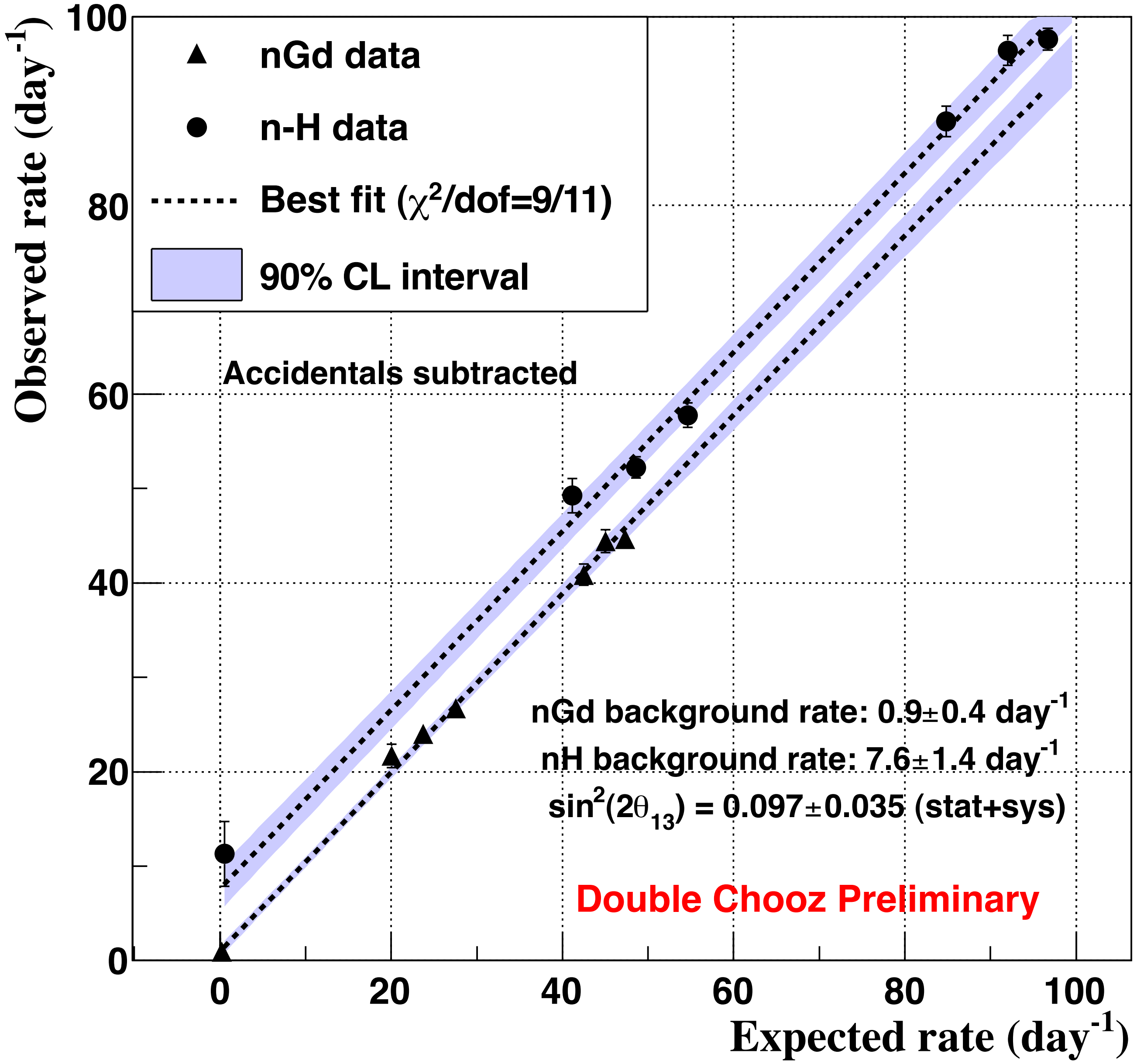
Combined Gd and H fit





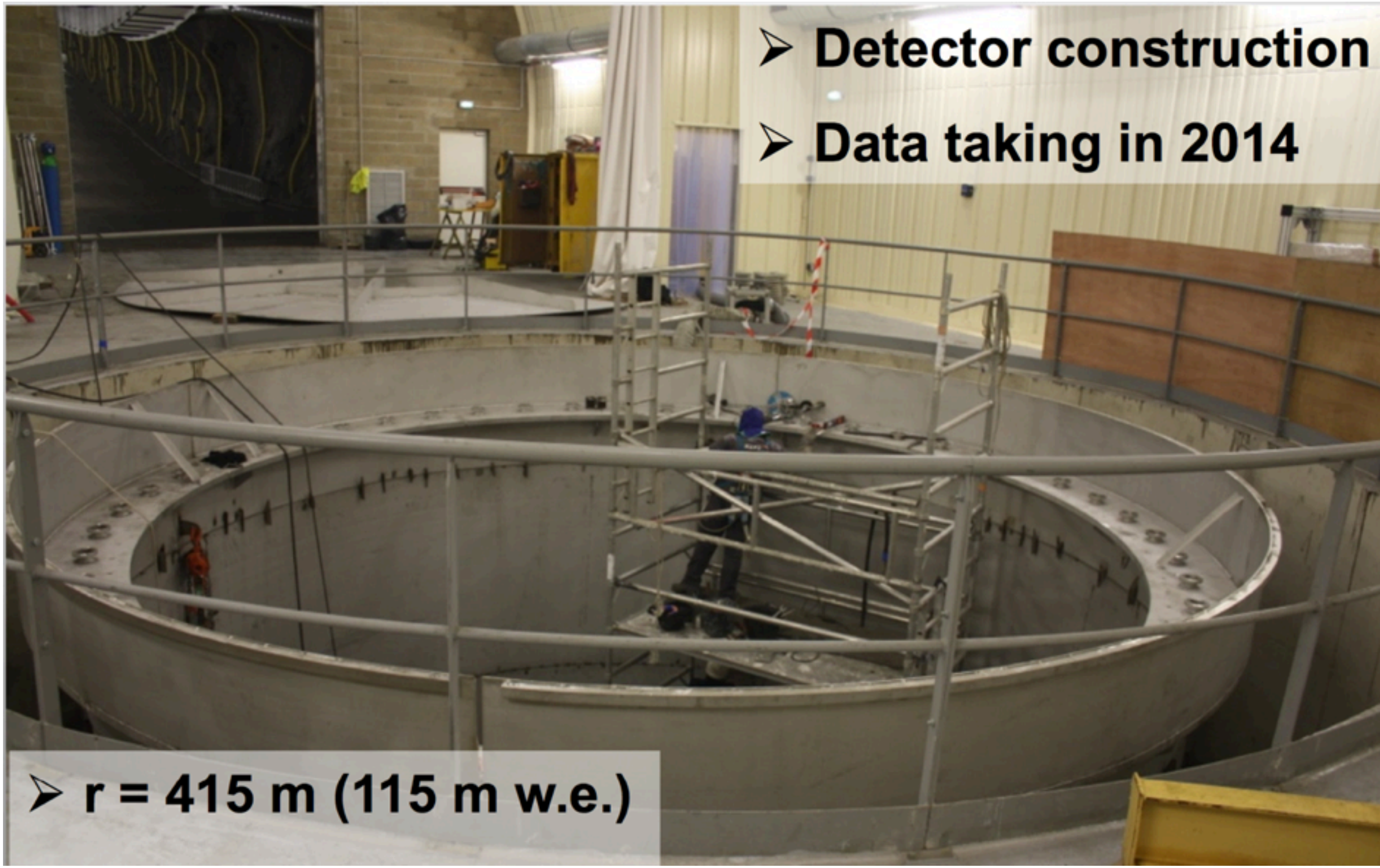
- Data set: April 2011- March 2012
- Correlations of systematic uncertainties are included in fit
- Reactor off-off data used to constrain BG
- Rate+Shape: $\sin^2 2\theta_{13} = 0.109 \pm 0.035$ cf. Gd analysis: $\sin^2 2\theta_{13} = 0.109 \pm 0.039$
- χ^2/DOF = 61.2/50

Reactor Rate Modulation Analysis (Gd and H combined)



- Data: April 2011- March 2012
- Using dependence of ν rate on reactor power
- Independent of BG estimation
- Best fit: $\sin^2 2\theta_{13} = 0.097 \pm 0.035$
- Consistent with Double Chooz rate+shape results

Near Detector

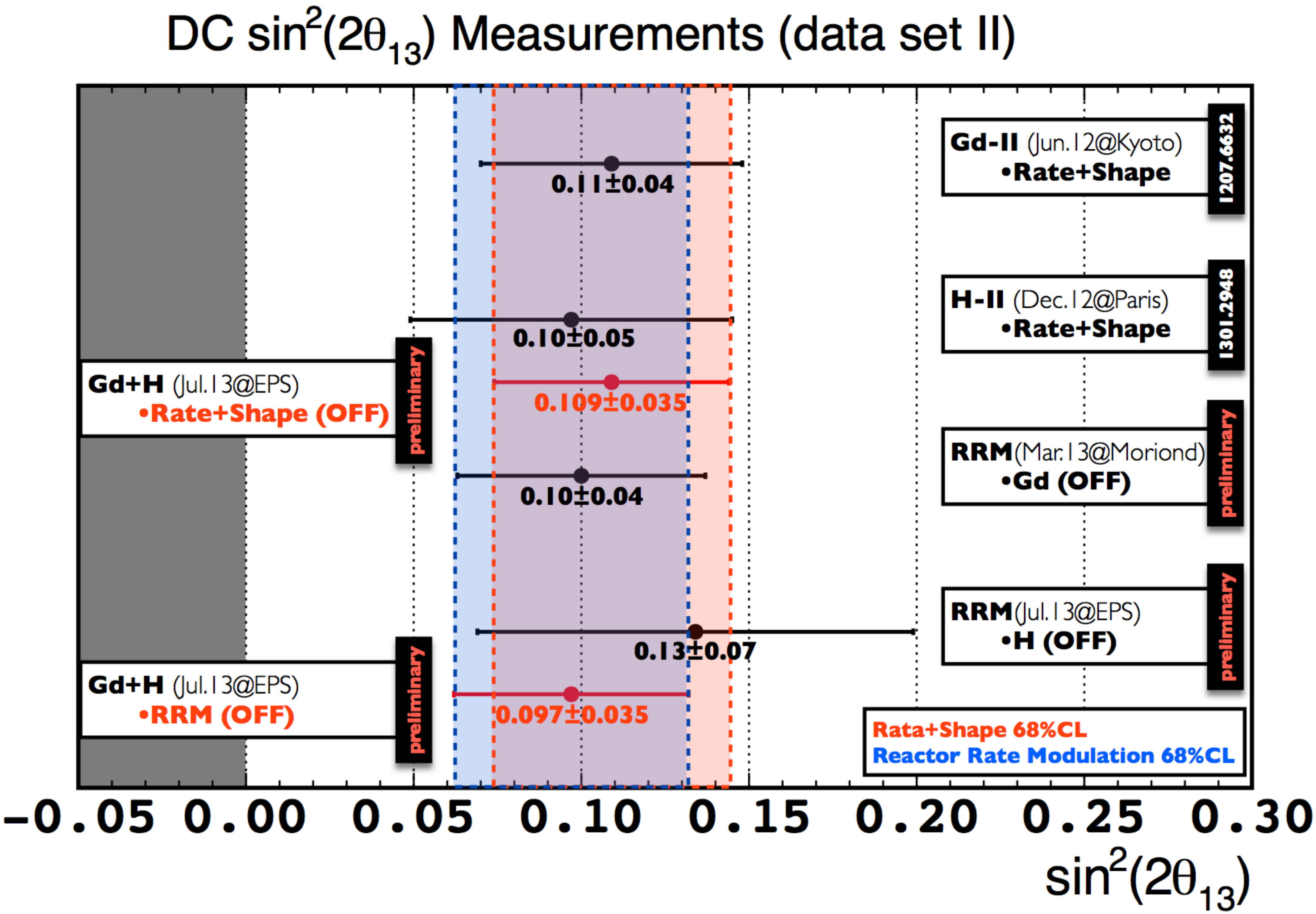


Summary

- Double Chooz θ_{13} measurements with Far detector
  - two different samples: n capture on Gd and H
  - two different approaches: rate+shape and reactor rate modulation
- All analyses showed consistent θ_{13}
  - Rate+Shape (combined): $\sin^2 2\theta_{13} = 0.109 \pm 0.035$
  - RRM (combined): $\sin^2 2\theta_{13} = 0.097 \pm 0.035$
- Several validations of BG estimation
  - BG estimation confirmed with reactor off measurement
  - BG constrained by rate+shape fit
  - RRM analysis measured consistent θ_{13} independent of BG estimation
- Future
  - We aim at 10% precision of $\sin^2 2\theta_{13}$ measurement with Near detector

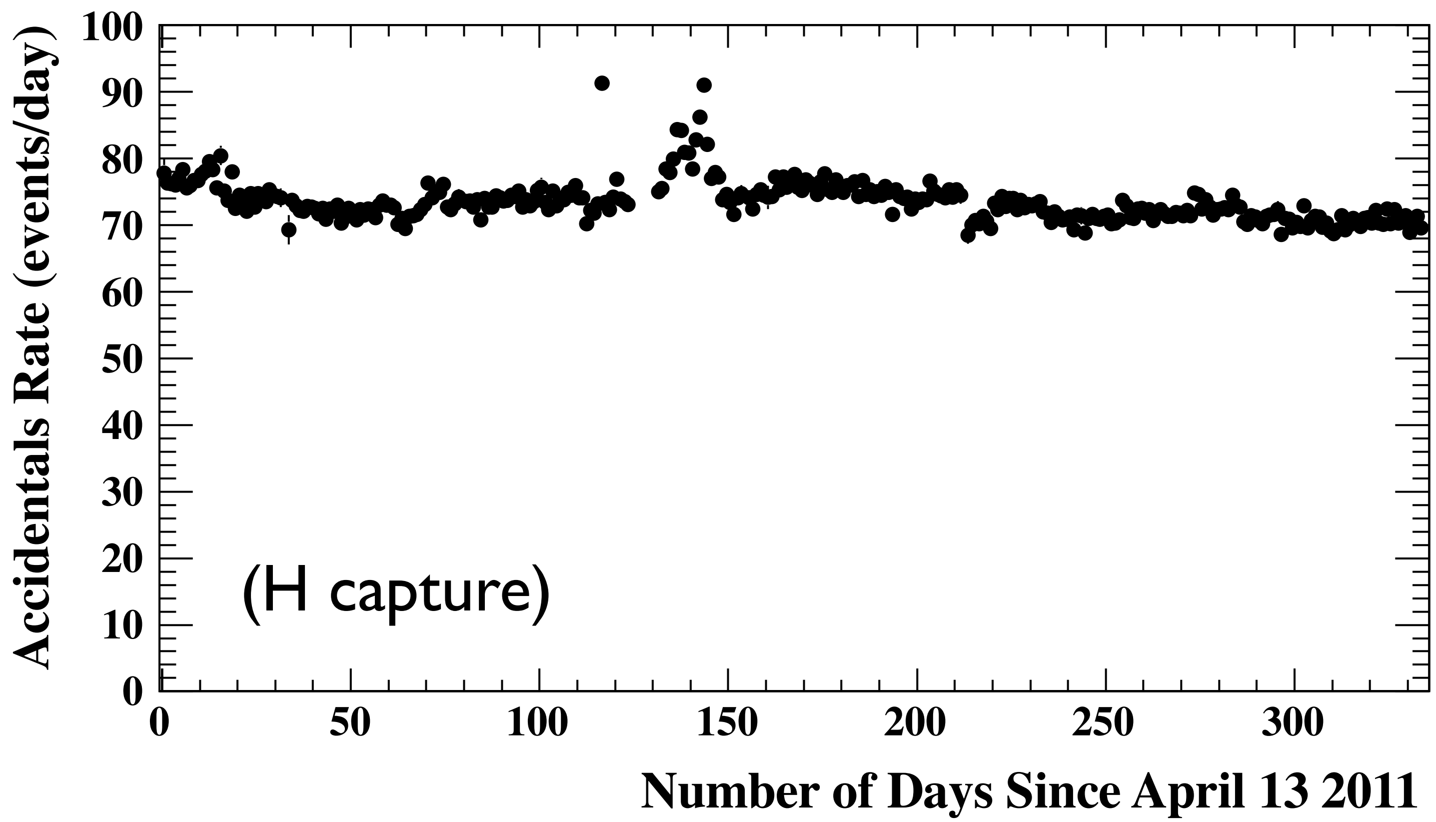
Backup

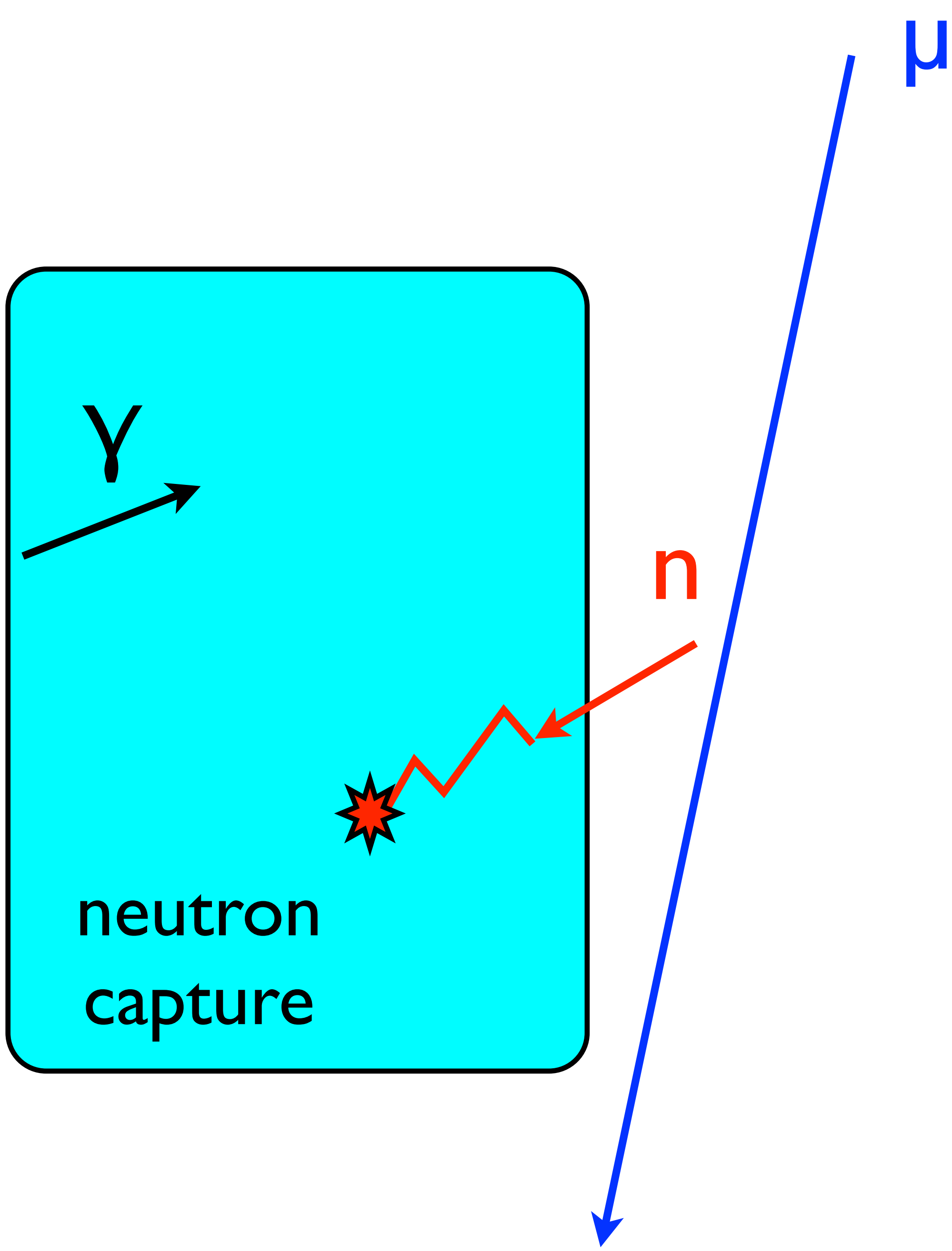
Summary of Double Chooz results



Accidental BG mechanism

<u>Prompt signal</u>:
γ from PMTs etc.
<u>Delayed signal</u>:
capture of spallation neutron





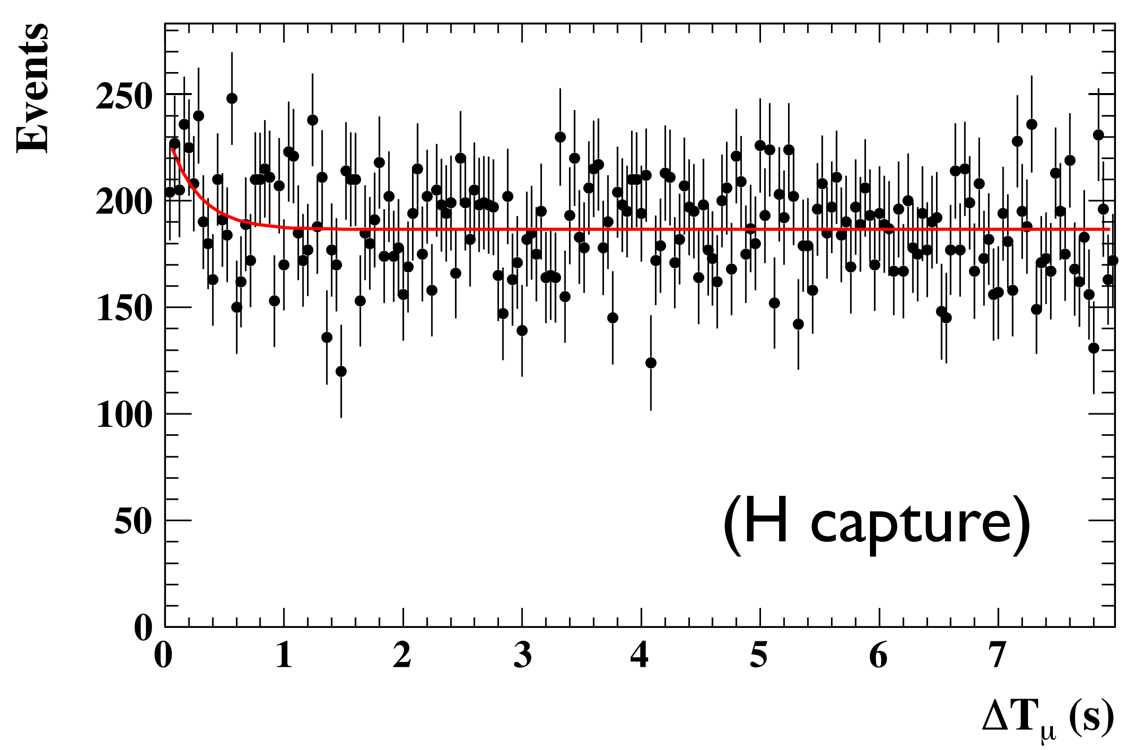
Cosmogenic isotopes (^{9}Li)

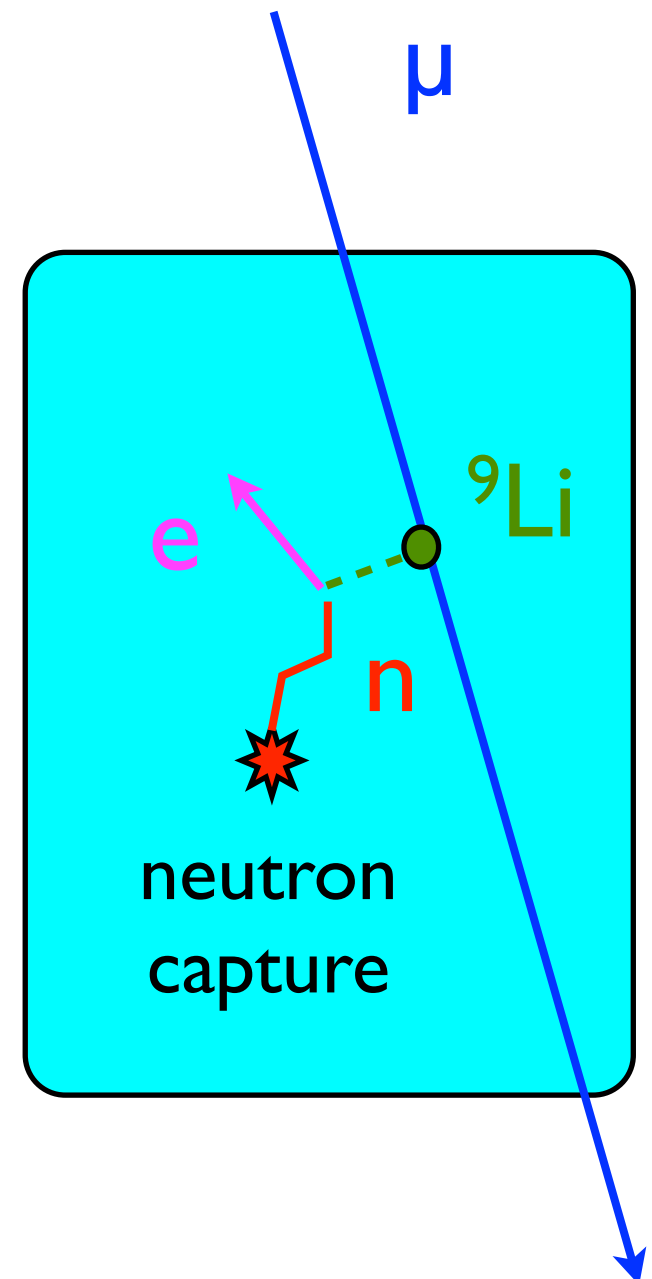
Spallation products from muon:

$$^9\text{Li} \rightarrow e^- + n + {}^8\text{Be}$$

$(\tau \sim 200\text{msec})$

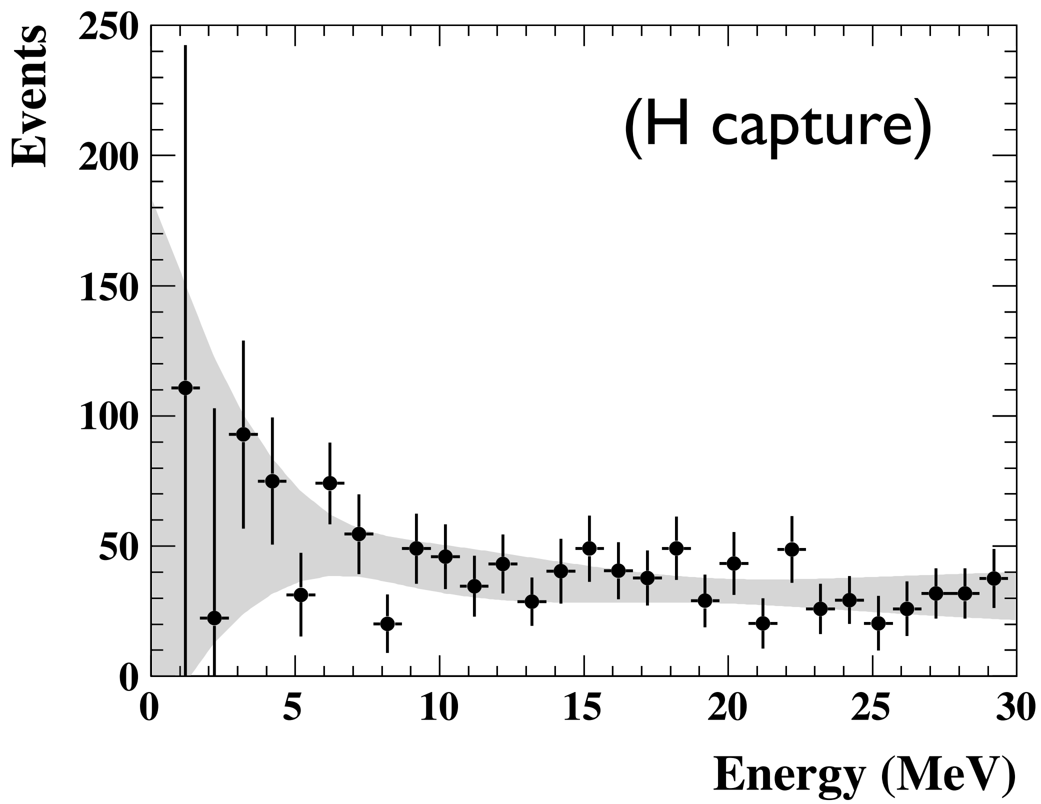
<u>Prompt signal</u>:
γ's from electron
<u>Delayed signal</u>:
neutron capture

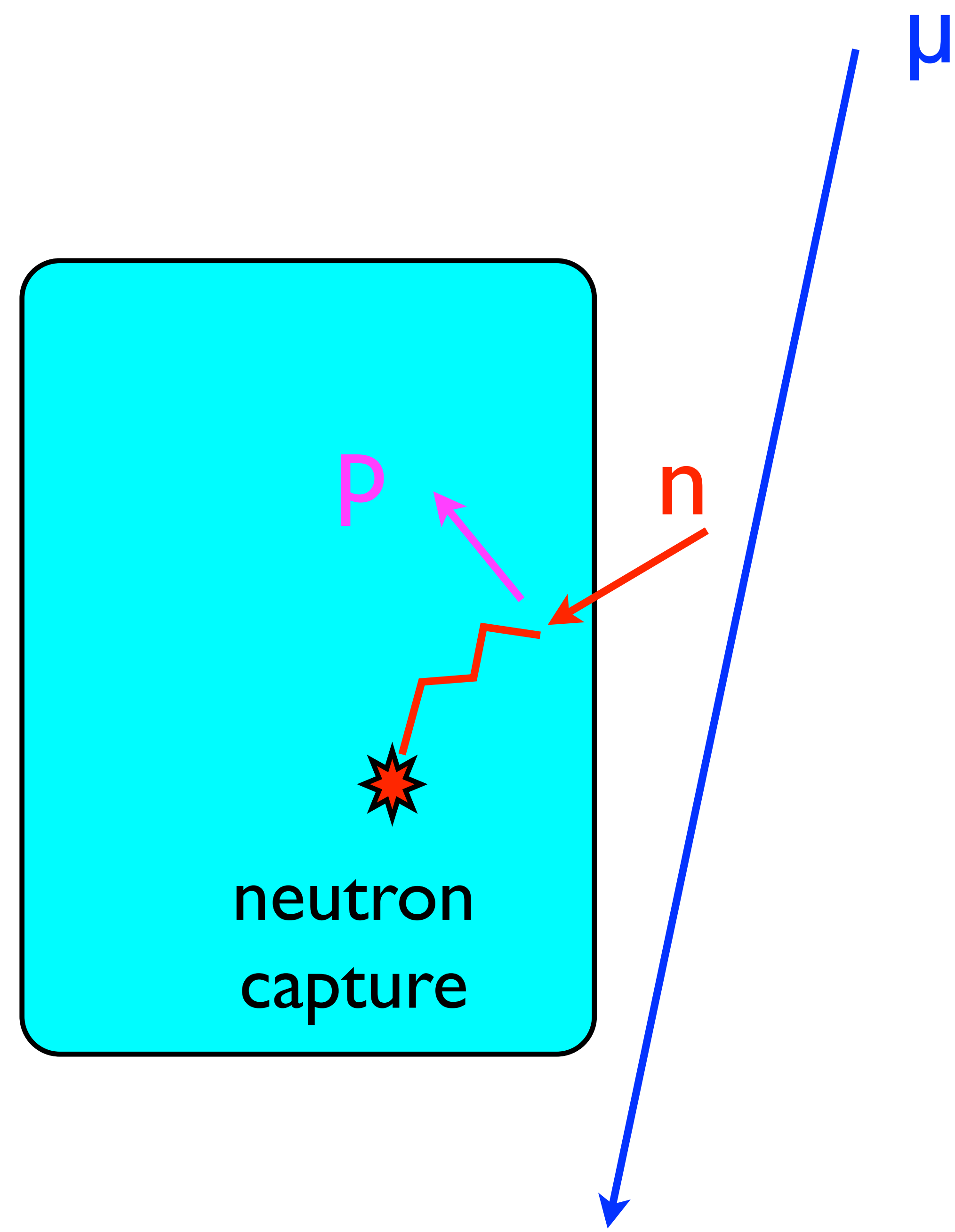




Fast neutrons

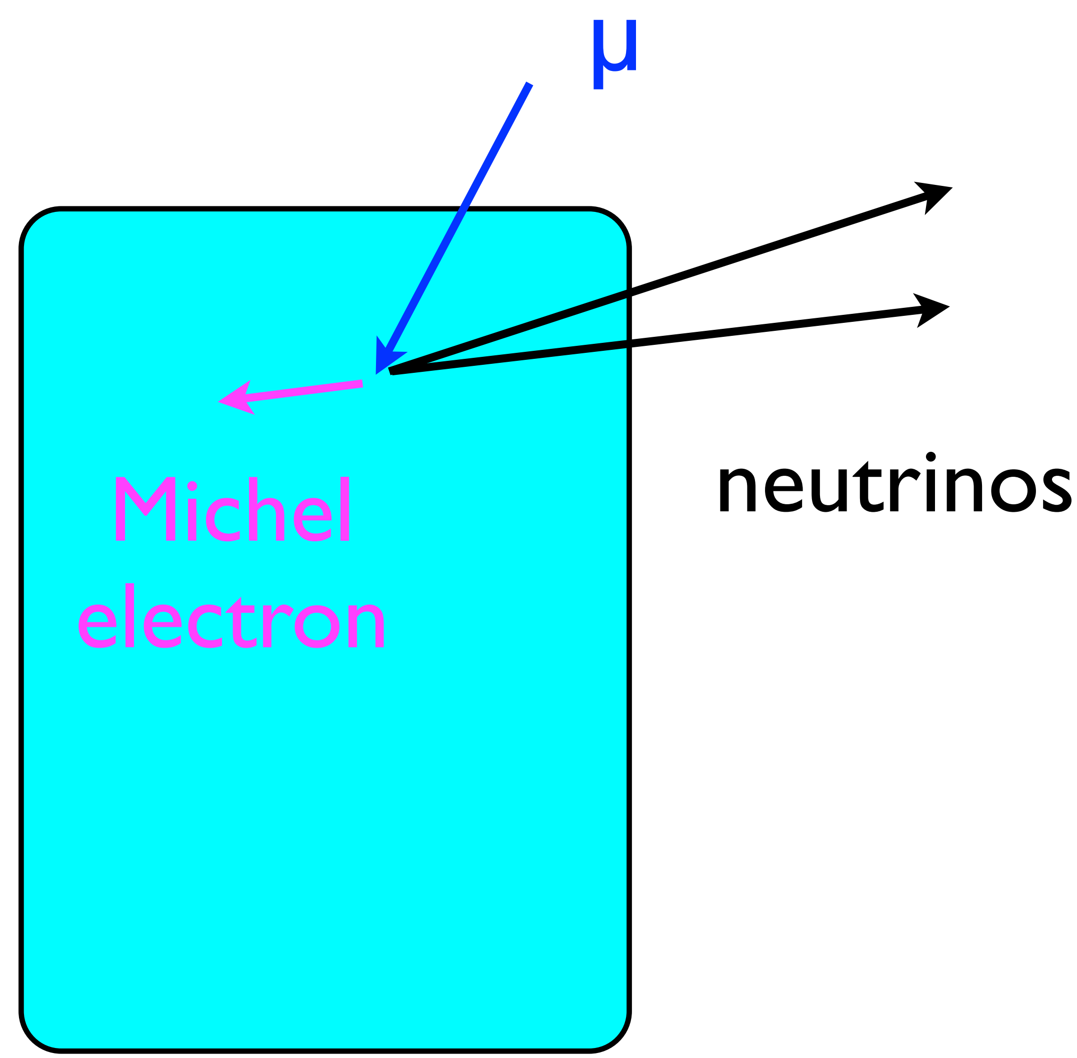
Prompt signal:
γ's from recoiled proton
Delayed signal:
capture of spallation neutron





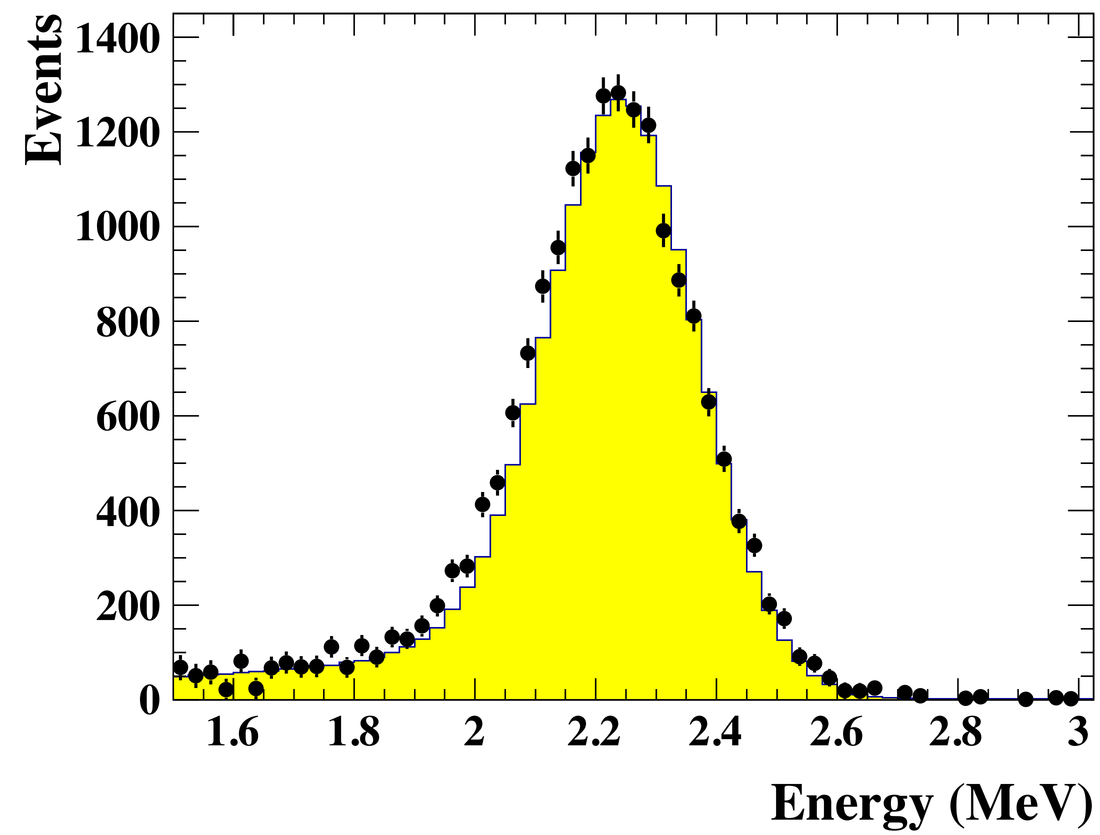
Stopping muons

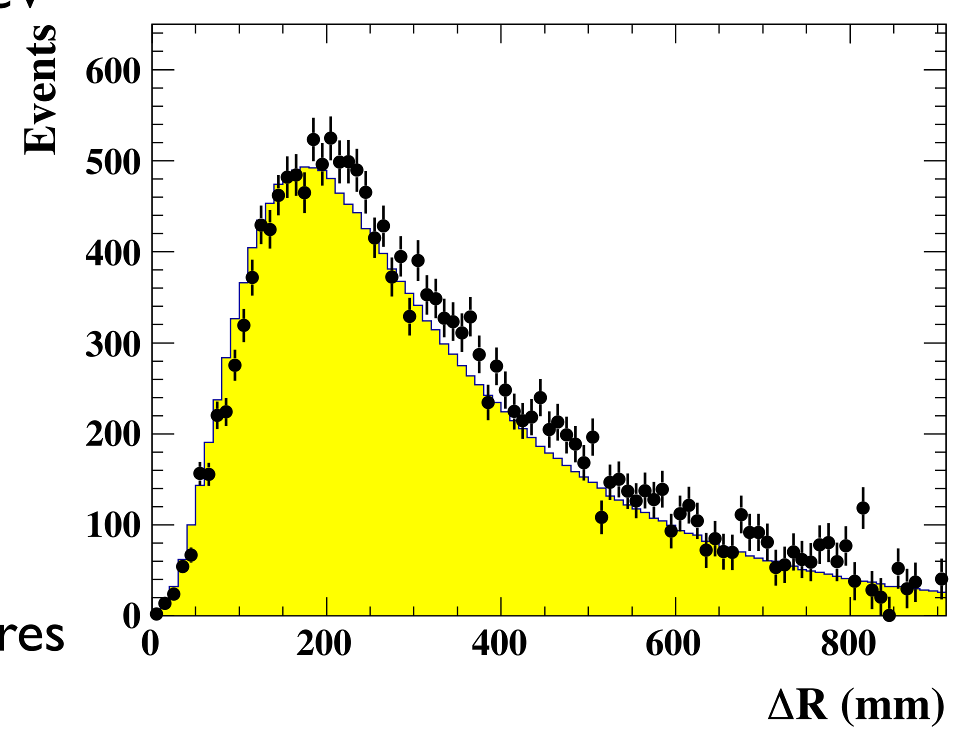
Prompt signal:
scintillation from μ
Delayed signal:
scintillation from Michel electron

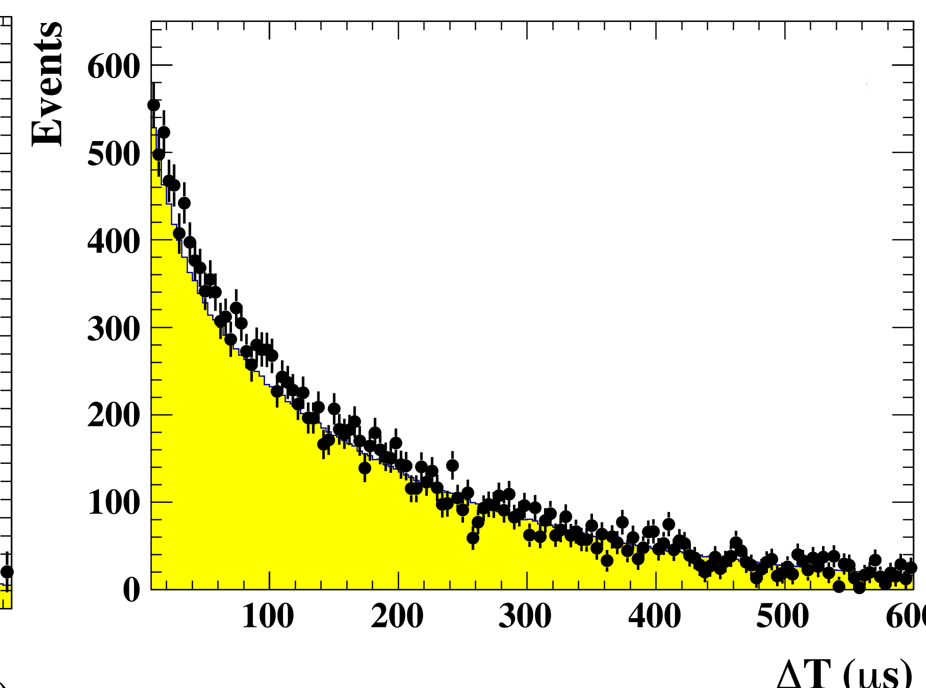


Neutrino selection (H analysis)

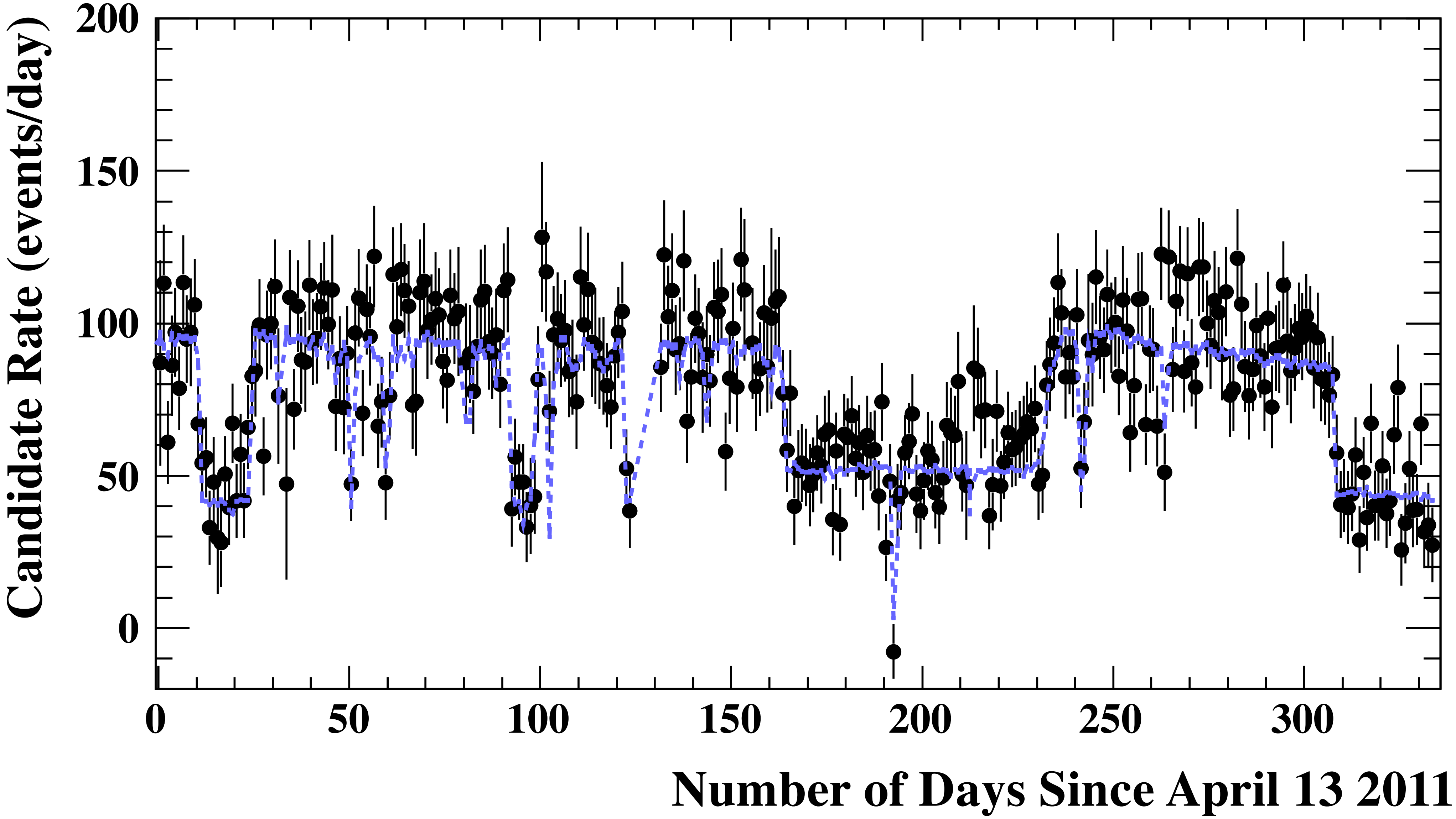
- Muon veto
  - no coincidence in IV
  - $\Delta t_{\mu} > 1$msec
- PMT light noise cuts
- No coincidence signal in OV
- Prompt event
  - 0.7MeV < Evis < 12.2MeV
- Delayed event
  - 1.5MeV < Evis < 3.0MeV
- Delayed coincidence
  - 10μs < ΔT < 600μs
  - ΔR < 900mm
- Multiplicity cut
  - reject multiple n captures







Time variation of H capture neutrino candidates



Individual fits and combined fit results

Preliminary

Rate+Shape

	Individual fit results		Combined fit results	
Fit parameter	nGd (PRD Sep. 2012)	nH (PhysLettB Jun. 2013)	nGd	nH
Energy scale	0.986 ± 0.007	0.99 ± 0.01	0.985 ± 0.006	0.993 ± 0.007
FN+SM rate (d^{-1})	0.64 ± 0.13	2.6 ± 0.4	0.61 ± 0.13	2.64 ± 0.35
Li-9 rate (d^{-1})	1.00 ± 0.29	3.9 ± 0.6	0.89 ± 0.24	3.93 ± 0.56
Δm^2 ($10^{-3}\mathrm{eV}^2$)	2.32 ± 0.12	2.32 ± 0.12	2.31 ± 0.12	
$\sin^2 2\theta_{13}$	0.109 ± 0.039	0.097 ± 0.048	0.109 ± 0.035	
χ^2/dof	42.1/35	38.9/30	61.2/50	

Rate only

	Individual fit results		Combined fit results	
Fit parameter	nGd (PRD Sep. 2012)	nH (PhysLettB Jun. 2013)	nGd	nH
Energy scale	0.998 ± 0.011	1.000 ± 0.017	0.998 ± 0.011	1.004 ± 0.017
FN+SM rate (d^{-1})	0.69 ± 0.20	2.5 ± 0.5	0.57 ± 0.19	2.74 ± 0.46
Li-9 rate (d^{-1})	1.40 ± 0.49	2.8 ± 1.2	0.76 ± 0.37	3.65 ± 0.96
Δm^2 ($10^{-3}\mathrm{eV}^2$)	2.32 ± 0.12	2.32 ± 0.12	2.32 ± 0.12	
$\sin^2 2\theta_{13}$	0.170 ± 0.052	0.044 ± 0.061	0.107 ± 0.045	
χ^2/dof	0.5/1	0/0	6.1/3	

*Individual fits do not use reactor off-off information

Correlations b/n Gd and H in combined fit

Correlation coefficients

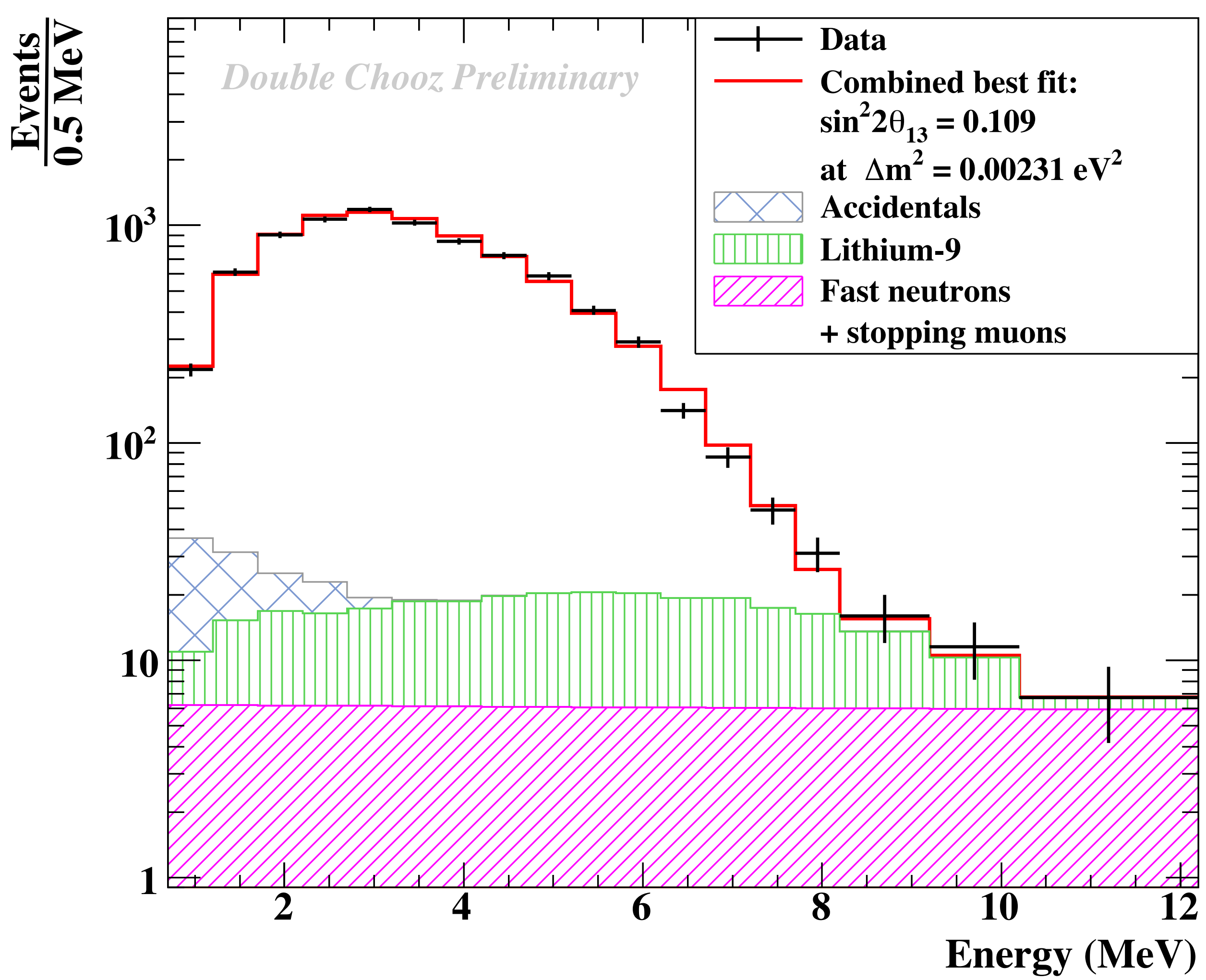
Preliminary

Parameter	$\rho_{\mathrm{Gd,H}}$
Accidental rate	0
Corr. light noise	0
FN/SM rate	0
^{9}Li rate	0.003
^{9}Li shape	1
Efficiency	0.09
Energy scale	0.4
Reactor	1

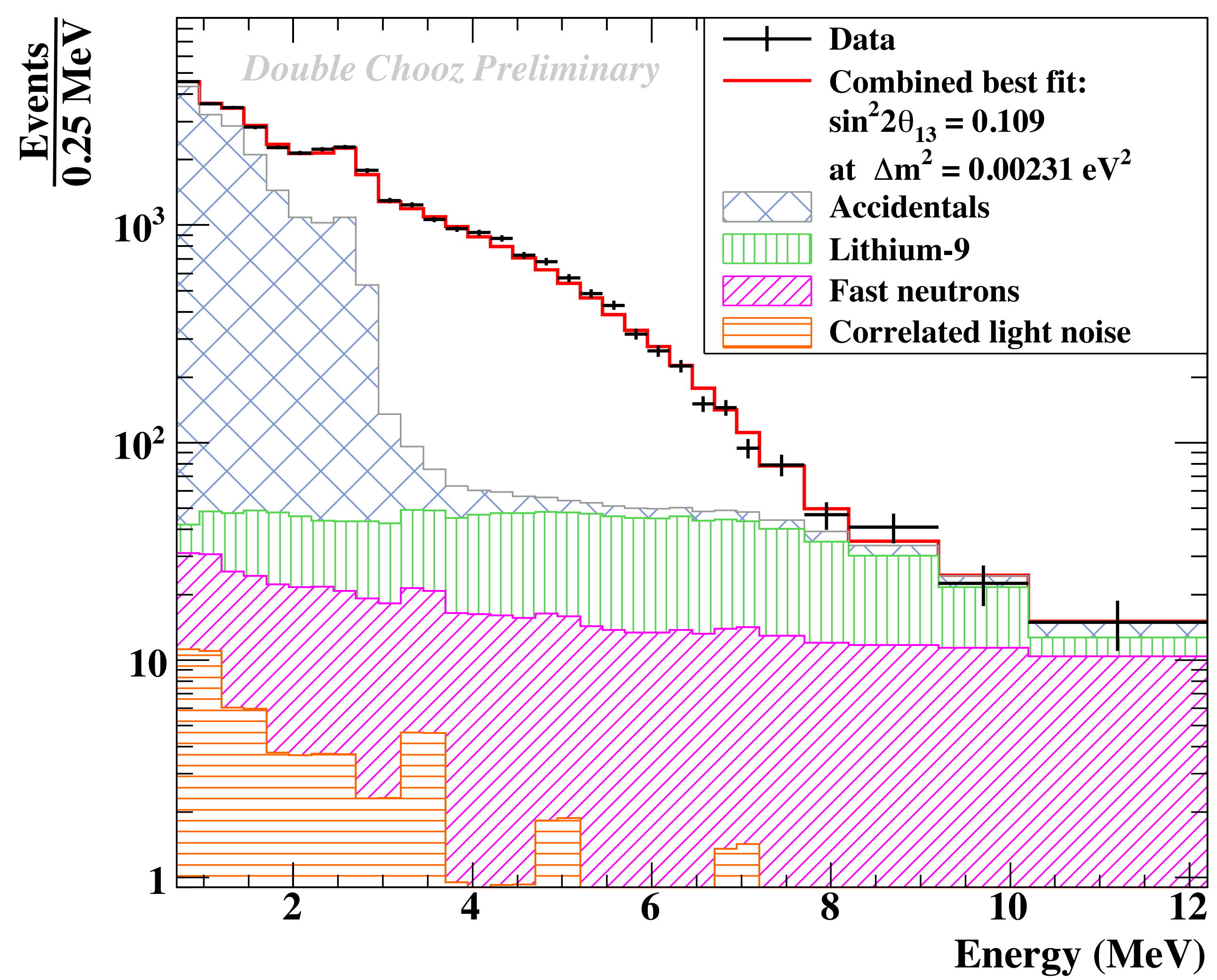
$$\rho_{x,y} \equiv \frac{\mathrm{Cov}\left[x,y\right]}{\sigma_x \sigma_y}$$

Gd capture and H capture $\overline{\nu}_e$ spectra with BG (April 2011~March 2012)

Gd capture



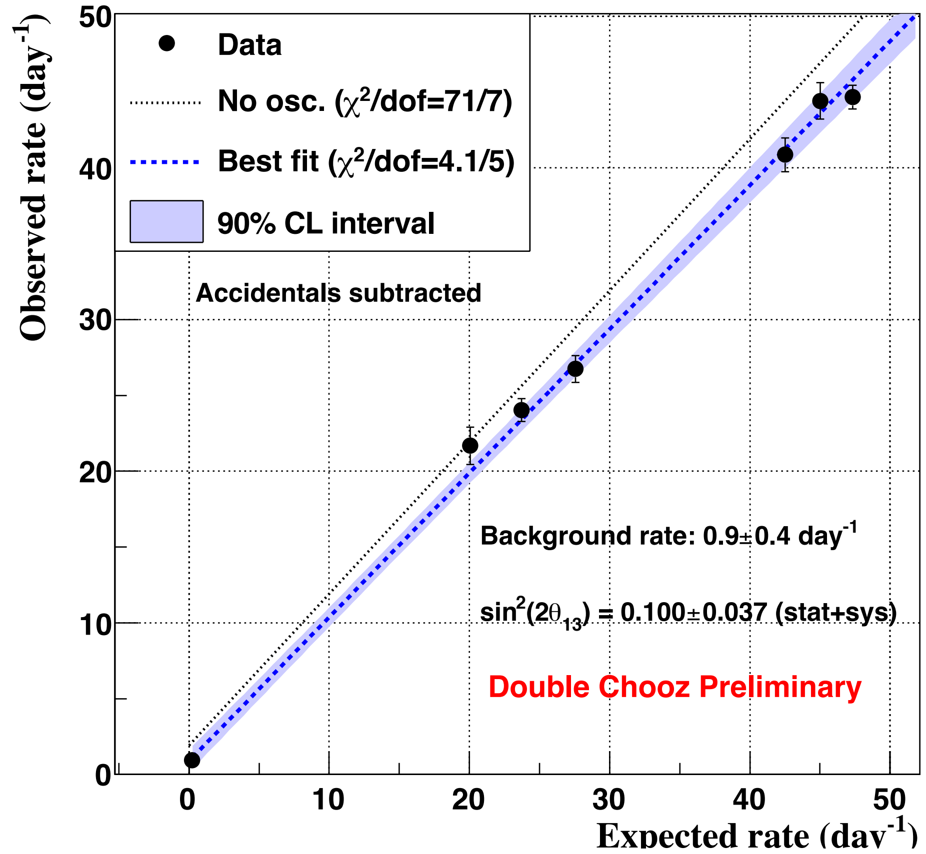
H capture

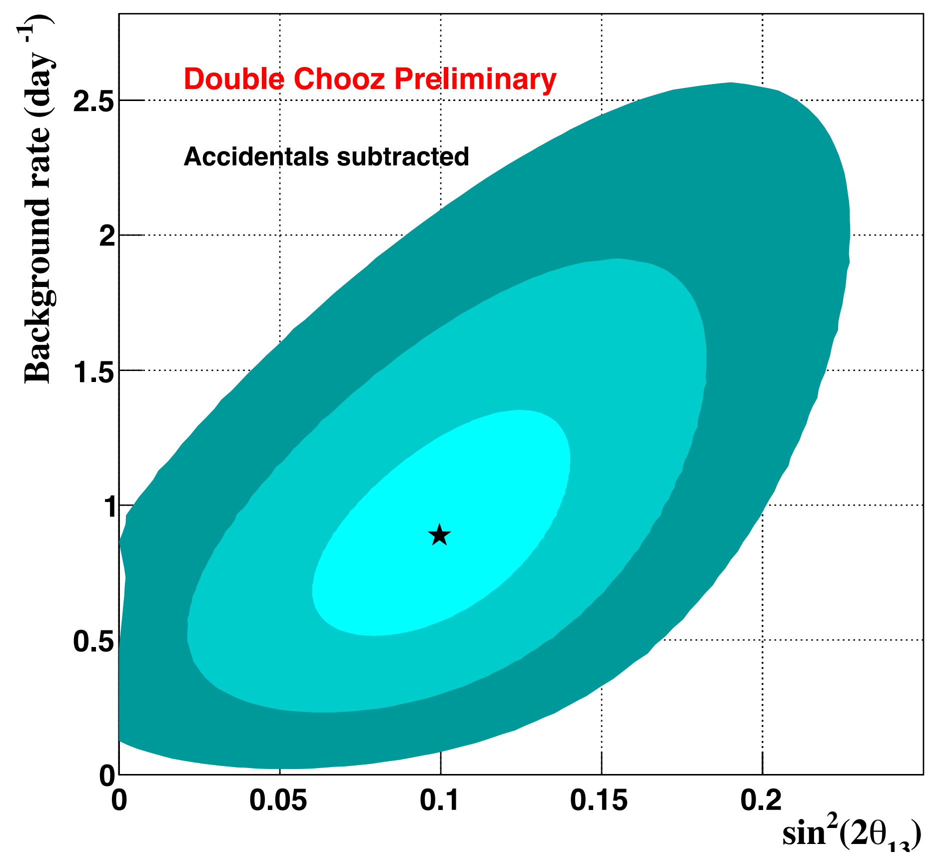


Red line shows best fit (combined analysis)

RRM individual results

Gd data





H data