The Double Chooz experiment

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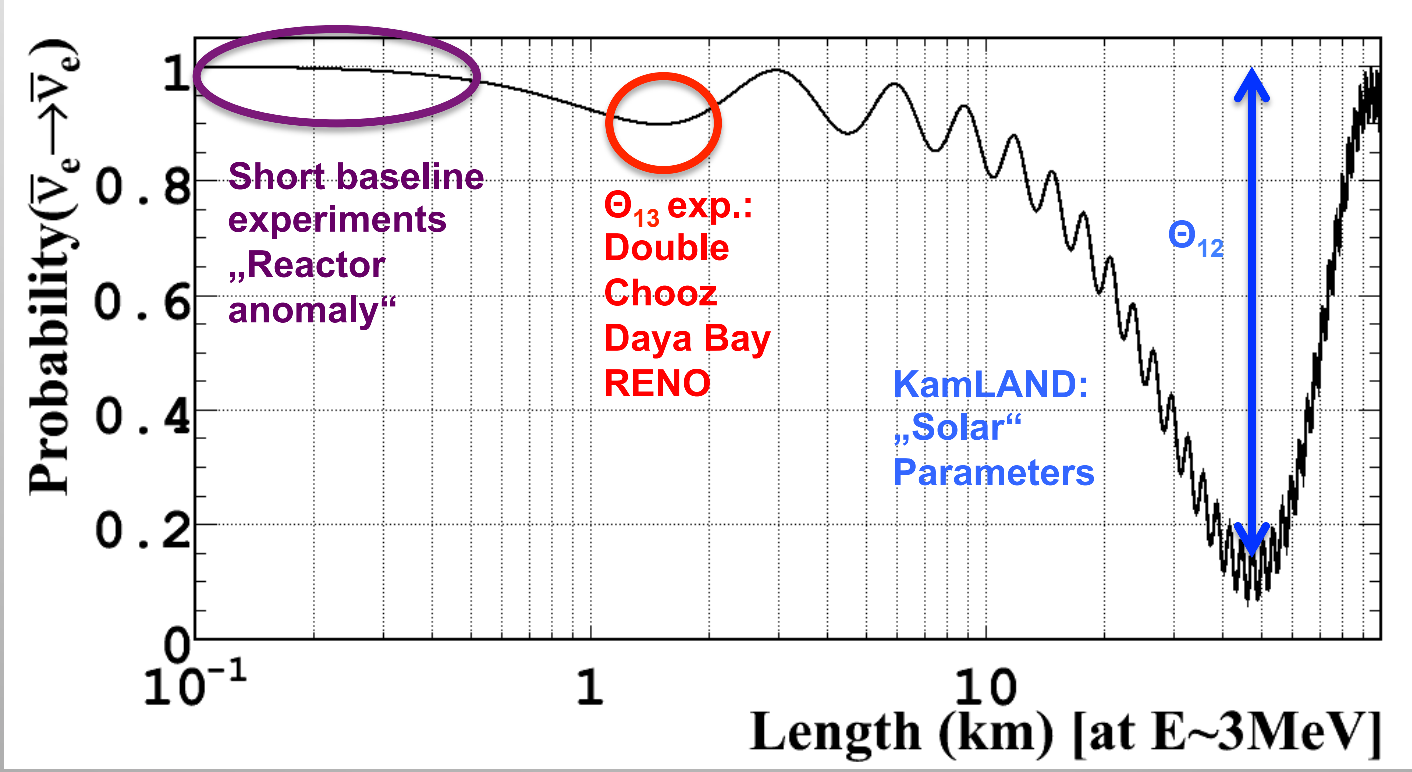
on behalf of the Double Chooz Collaboration

Neutrino Telescopes, Venice
March, 3rd 2015

Neutrino mixing at reactors

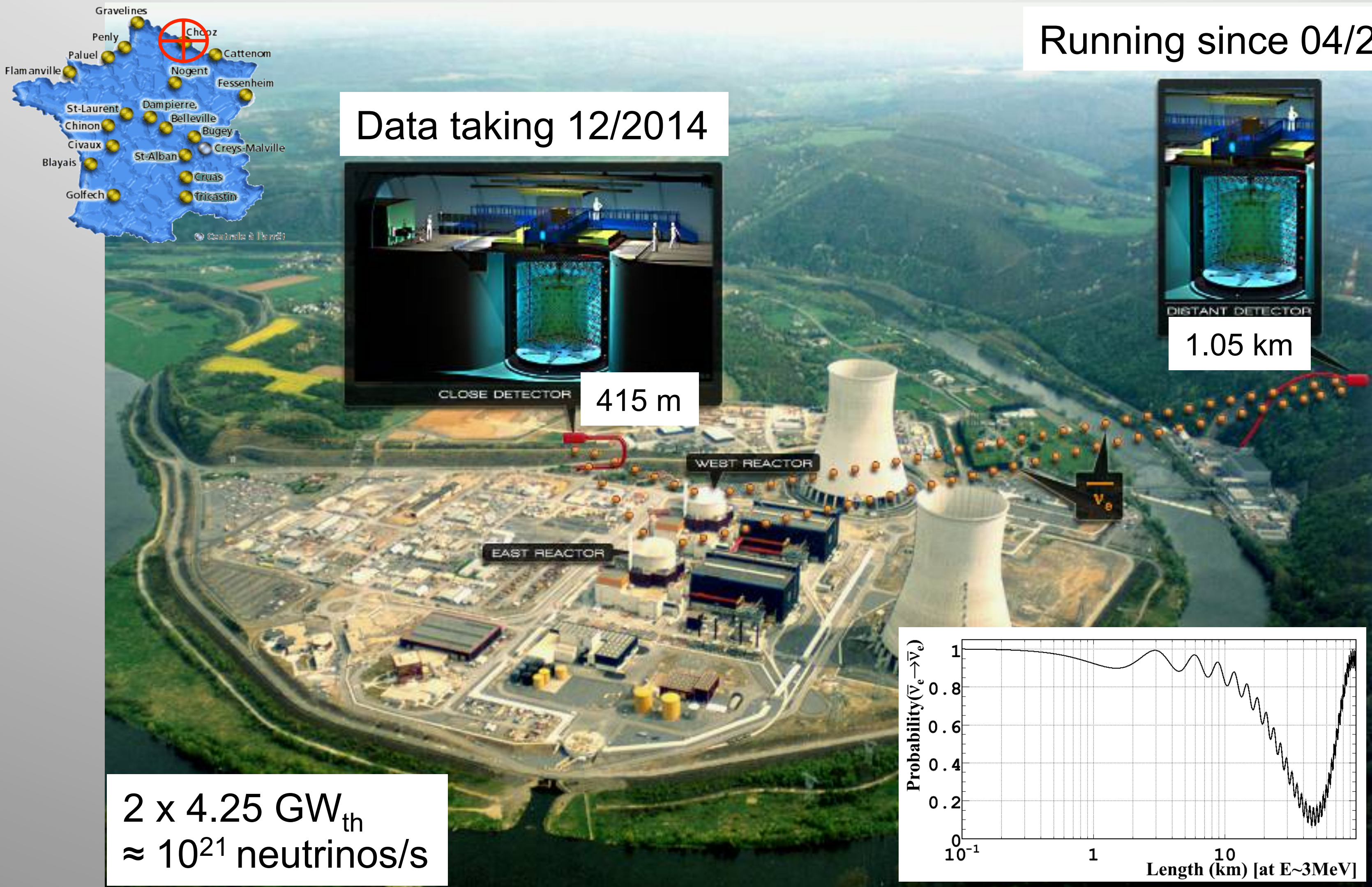
Reactors: Strong and pure source of MeV e-antineutrinos



$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - \sin^2 2\Theta_{13} \sin^2\left(1.27 \frac{\Delta m_{13}^2 (eV^2) L(m)}{E_\nu (MeV)}\right)$$

No parameter degeneracy!

Double Chooz site



Running since 04/2011

Data taking 12/2014

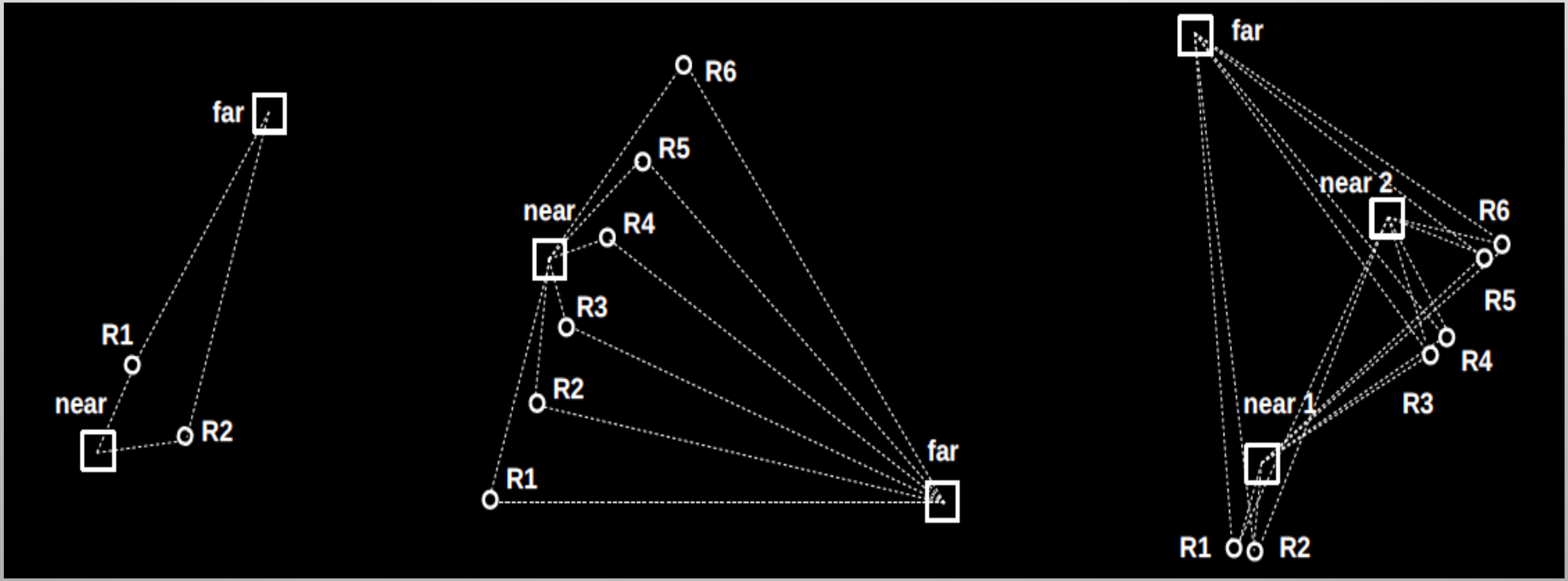
1.05 km

415 m

2 x 4.25 GW_{th}
≈ 10^{21} neutrinos/s

Site configurations

Double Chooz *RENO* *Daya Bay*



Double Chooz: „Only“ two reactors, but almost iso-flux

➔Low statistics, but good for systematics!

« Reactor Neutrino Flux Uncertainty Suppression on Multiple Detector Experiments »
arXiv:1501.0356

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

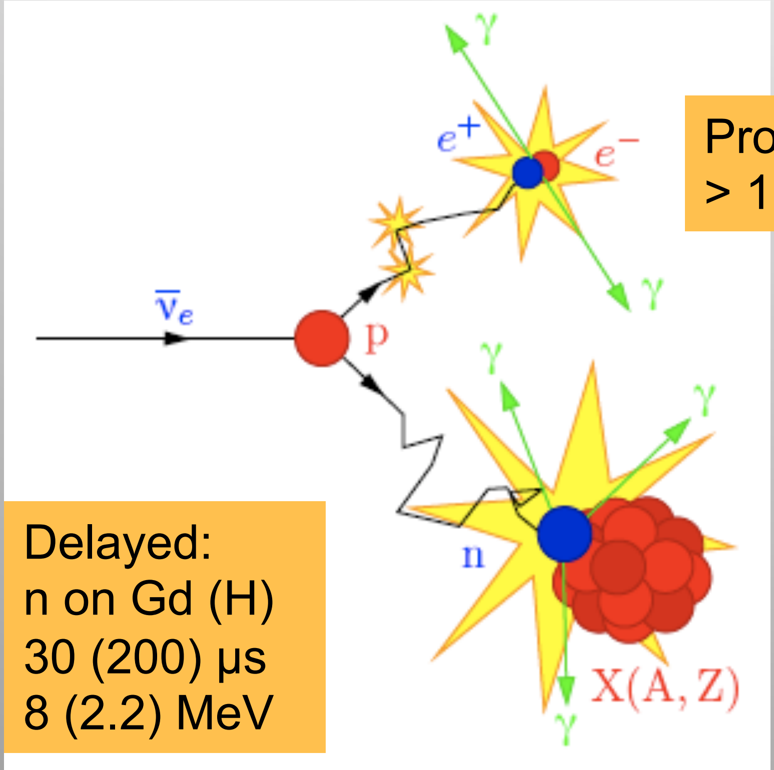
Spain
- CIEMAT-Madrid

USA
- U. Alabama
- ANL,U. Chicago
- Columbia U.
- UC Davis
- Drexel U.
- IIT, KSU, MIT,
- U. Notre Dame
- U. Tennessee
- Virginia Tech

Neutrino production / detection

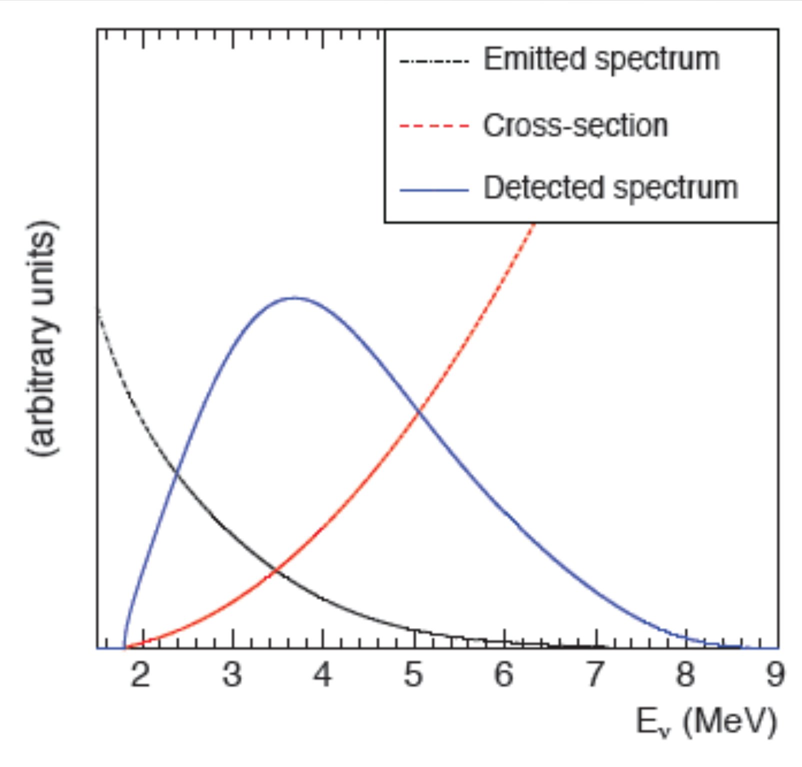
$$N_{\nu}^{\exp}(t) = \frac{\varepsilon N_p}{4\pi L^2} \times \frac{P_{th}(t)}{\langle E_f \rangle} \times \langle \sigma_f \rangle$$

→ Mean cross section per fission (Bugey anchor point!)



Prompt:
> 1MeV

Delayed:
n on Gd (H)
30 (200) µs
8 (2.2) MeV



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

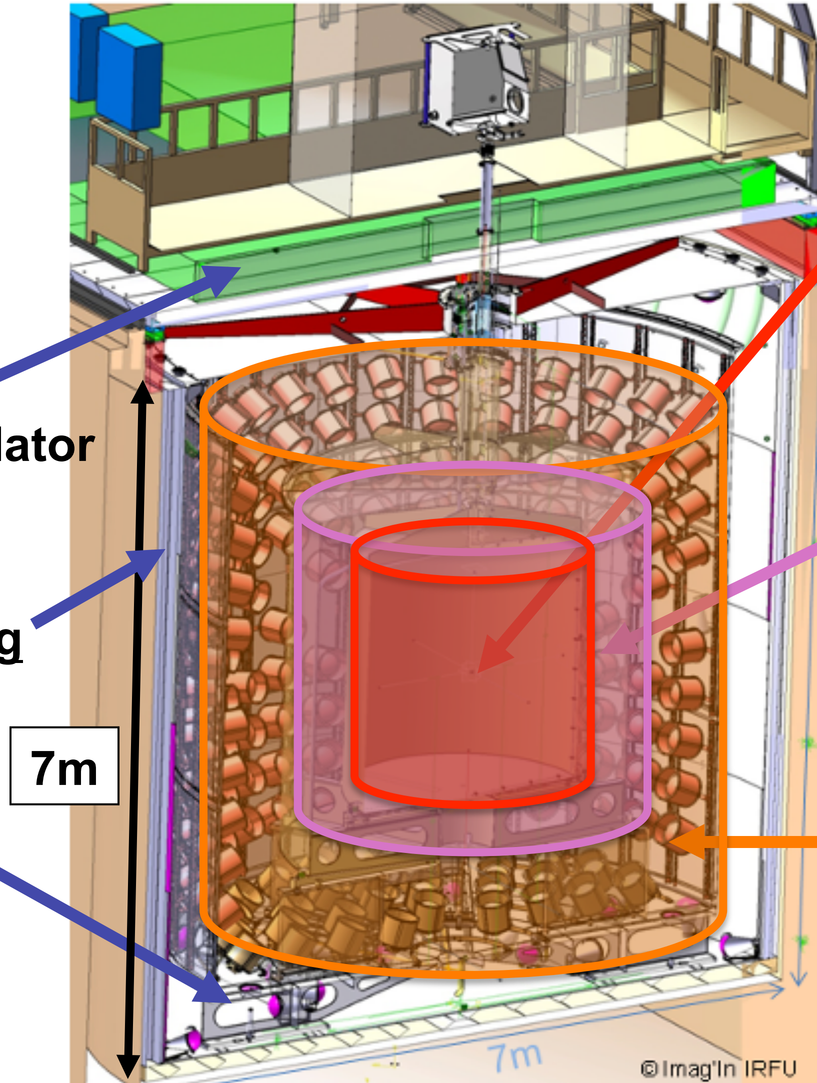
$$E_{vis} = E_\nu - 0.8MeV$$

Detector Design

Outer Veto:
Plastic scintillator

Steel shielding
(15 cm)

Inner Veto:
- Steel (8 mm)
- 70 tons LS
(LAB based)
78 PMTs (8")



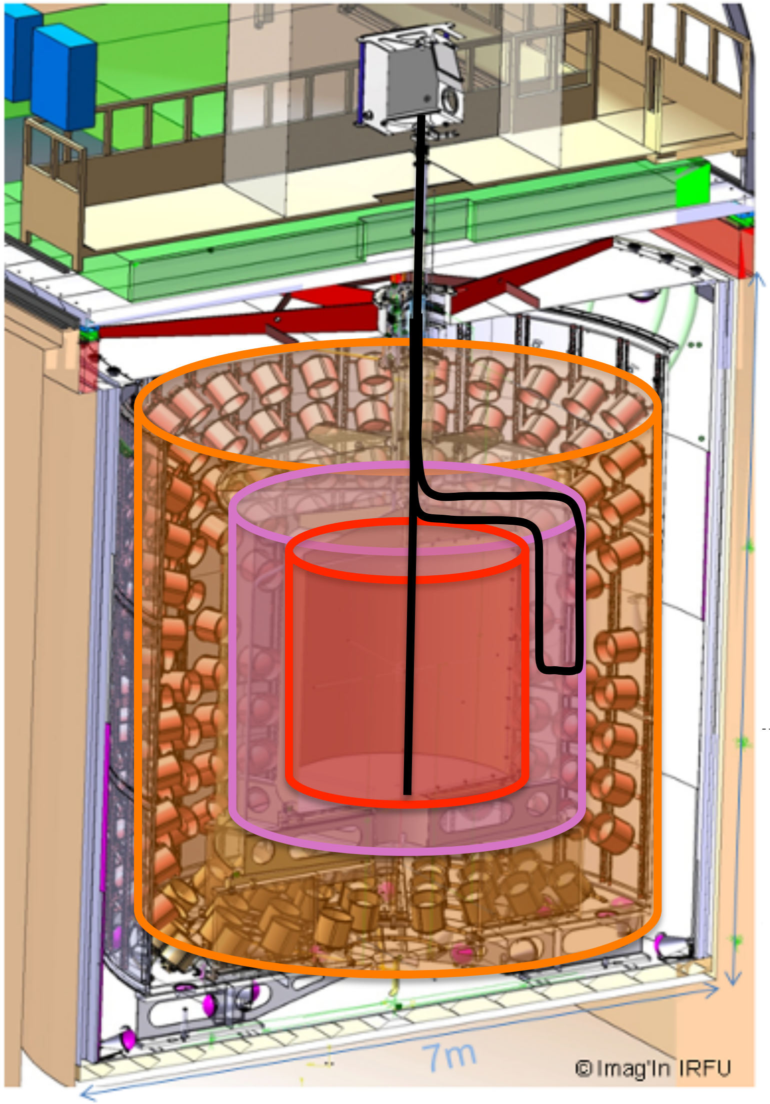
Inner detector:

Target (r = 1.2 m):
- Acrylic vessel (8 mm)
- 8.3 tons Gd-scintillator
(1 g/l Gd, o-PXE based)

Gamma Catcher (0.55 m):
- Acrylic vessel (12 mm)
- 18.1 tons liquid scint.
(o-PXE based)

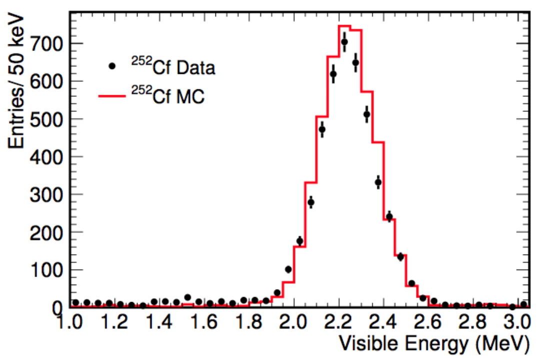
Buffer (1.05 m):
- Steel (3 mm)
- 80 tons "oil"
390 PMTs (10")

Calibration

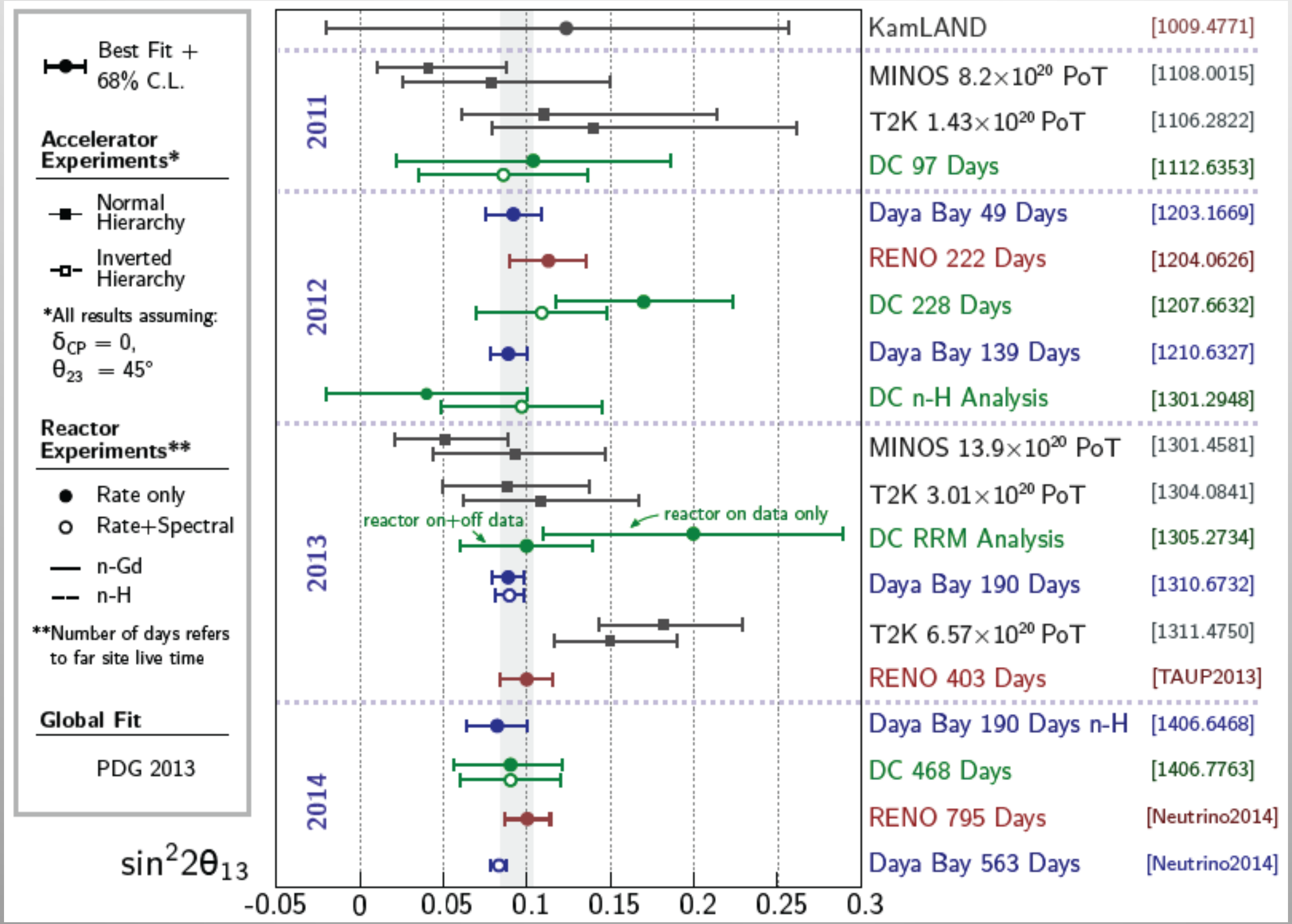


Calibration systems:

- **LED light injection (multi wavelengths)**
- **Vertical z-axis (radioactive sources, laser ball)**
- **GC guide tube (radioactive sources)**
- **Natural sources (spallation neutrons)**



Double Chooz milestones



2011: Start data taking (far only) and first results

2012: First analysis with n captures on H

2013: RRM (rate) analysis and near lab delivery

2014: Spectral distortion and near det. data taking

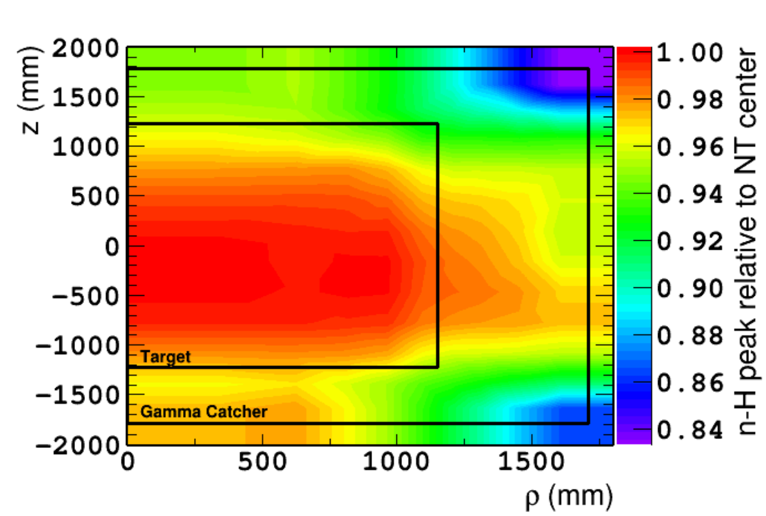
„Gd-III“ publication: Double Chooz Collaboration, JHEP10(2014)086

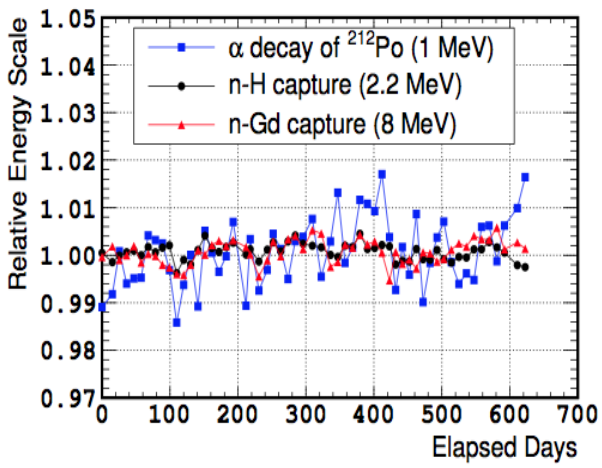
Energy scale

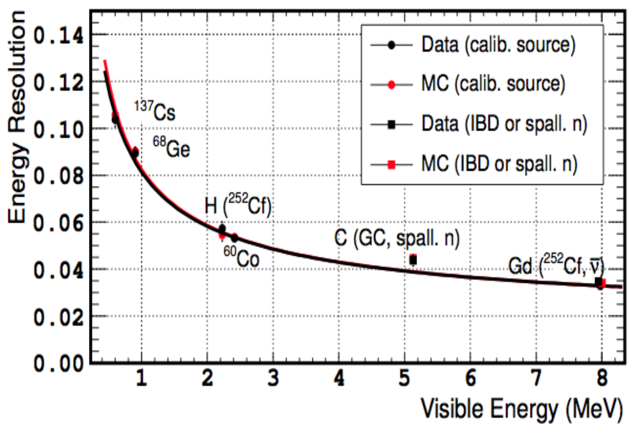
Visible energy reconstruction

- ➢ Detector uniformity
- ➢ Time stability
- ➢ Non-linearities

➔ Total uncertainty of 0.74 %







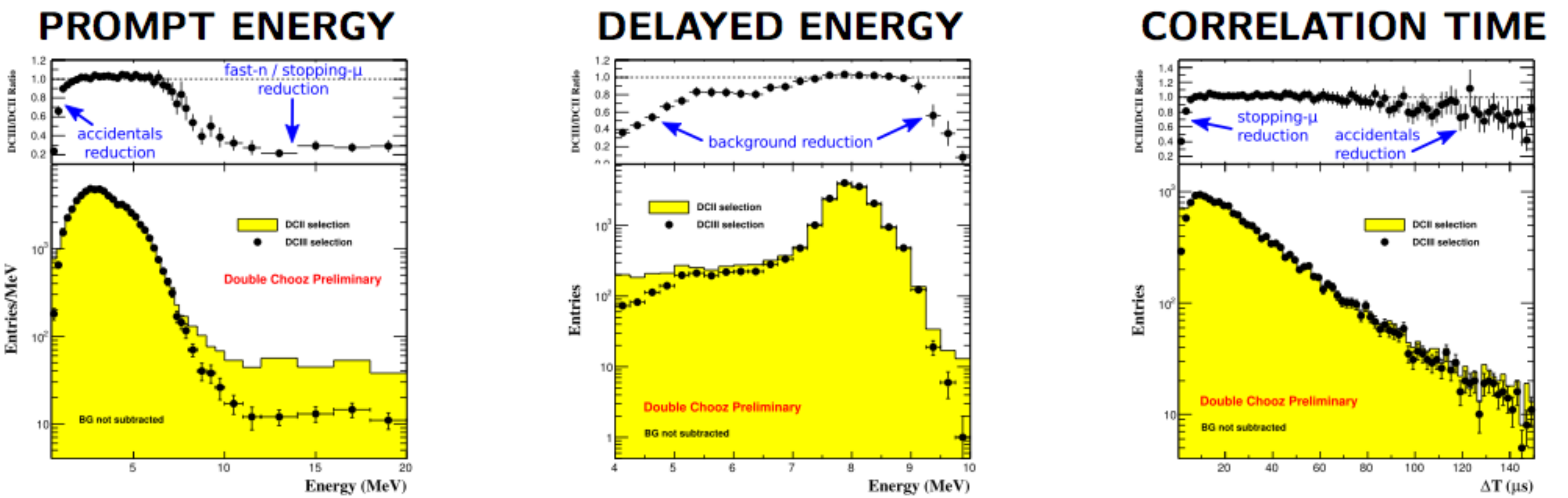
Neutrino selection (Gd)

Modified selection for optimized S/B ratio (> 20)

Modification to previous Gd publication (2012)

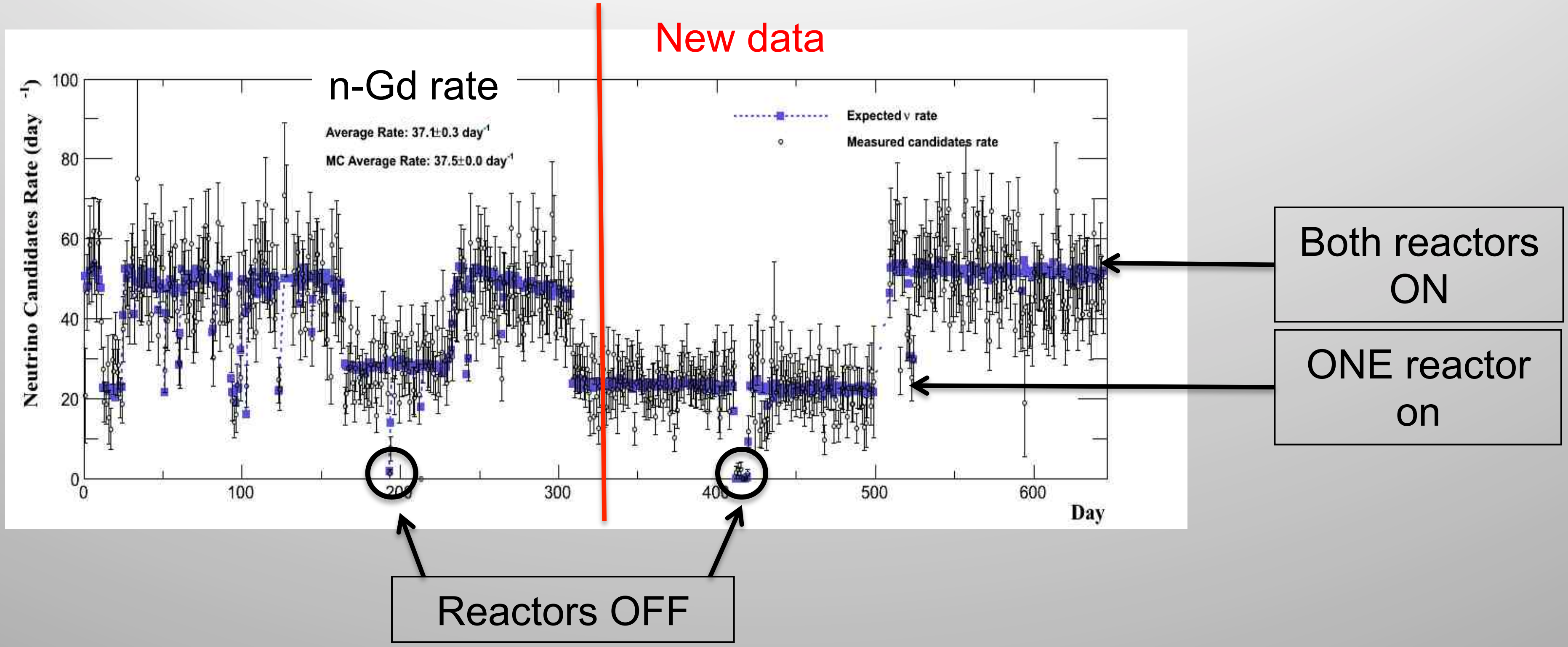
Muon veto	**> 1 ms**	
„Light noise“	Uniform (space) and simult. (time)	Optimized
Correlated Back-ground reduction	Use Inner/Outer veto and vertex reconstruction information	New
ΔR	< 1 m	New
Prompt energy	0.5 – 20 MeV	Wider range
Delayed energy	4 – 10 MeV	Wider range
ΔT	0.5 – 150 µs	Wider range
Isolation window	(-200, + 600) µs	Wider range

Selection improvements



Improvements compared to 2012 analysis („Gd-II“ publication) clearly visible in energy spectra and correlation time distribution

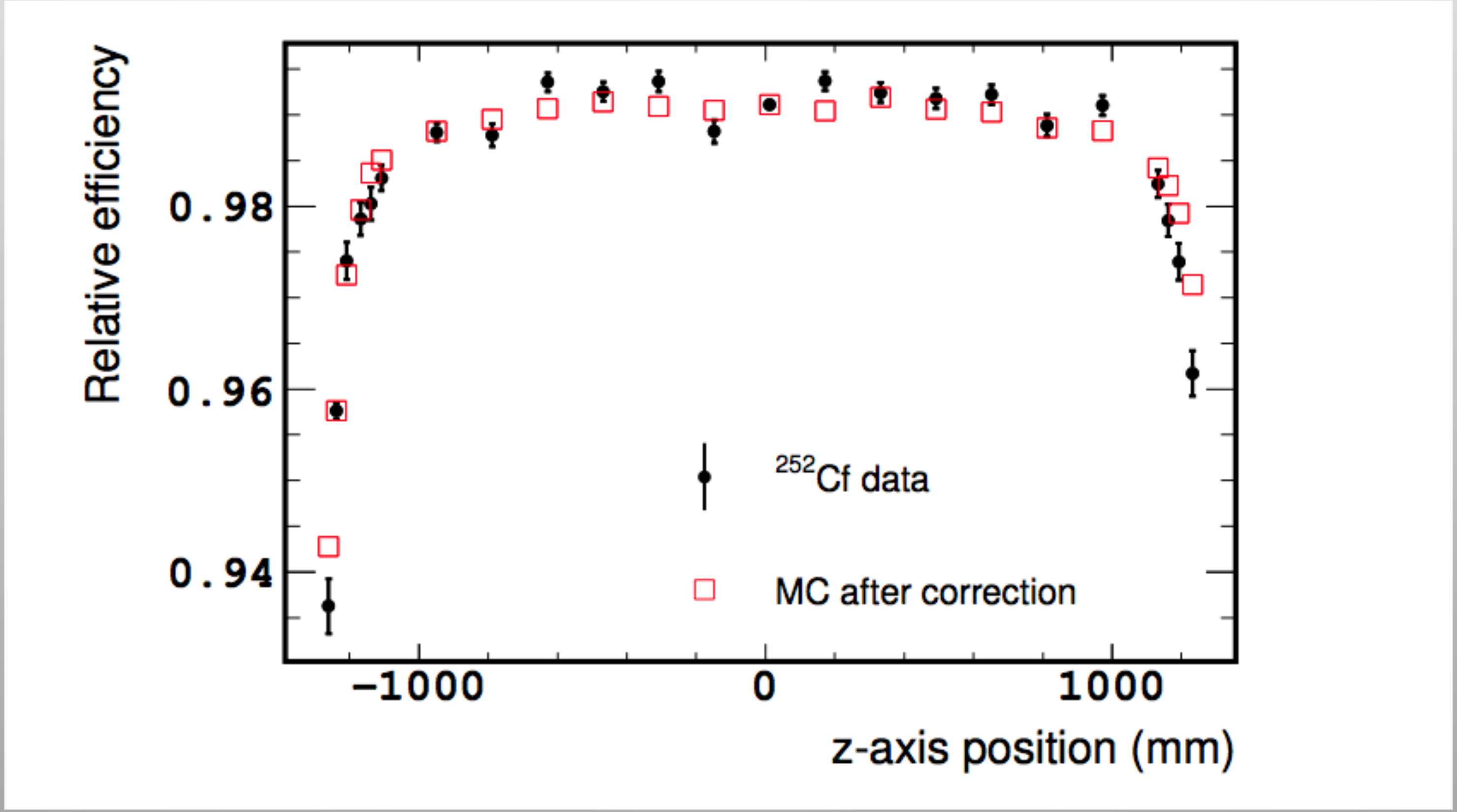
Neutrino candidates



- Data from Apr 2011 – Jan 2013 (live-time: 460.7 days)
- 17351 neutrino candidates (doubled statistics)
- 18290 predicted events (no oscillation)

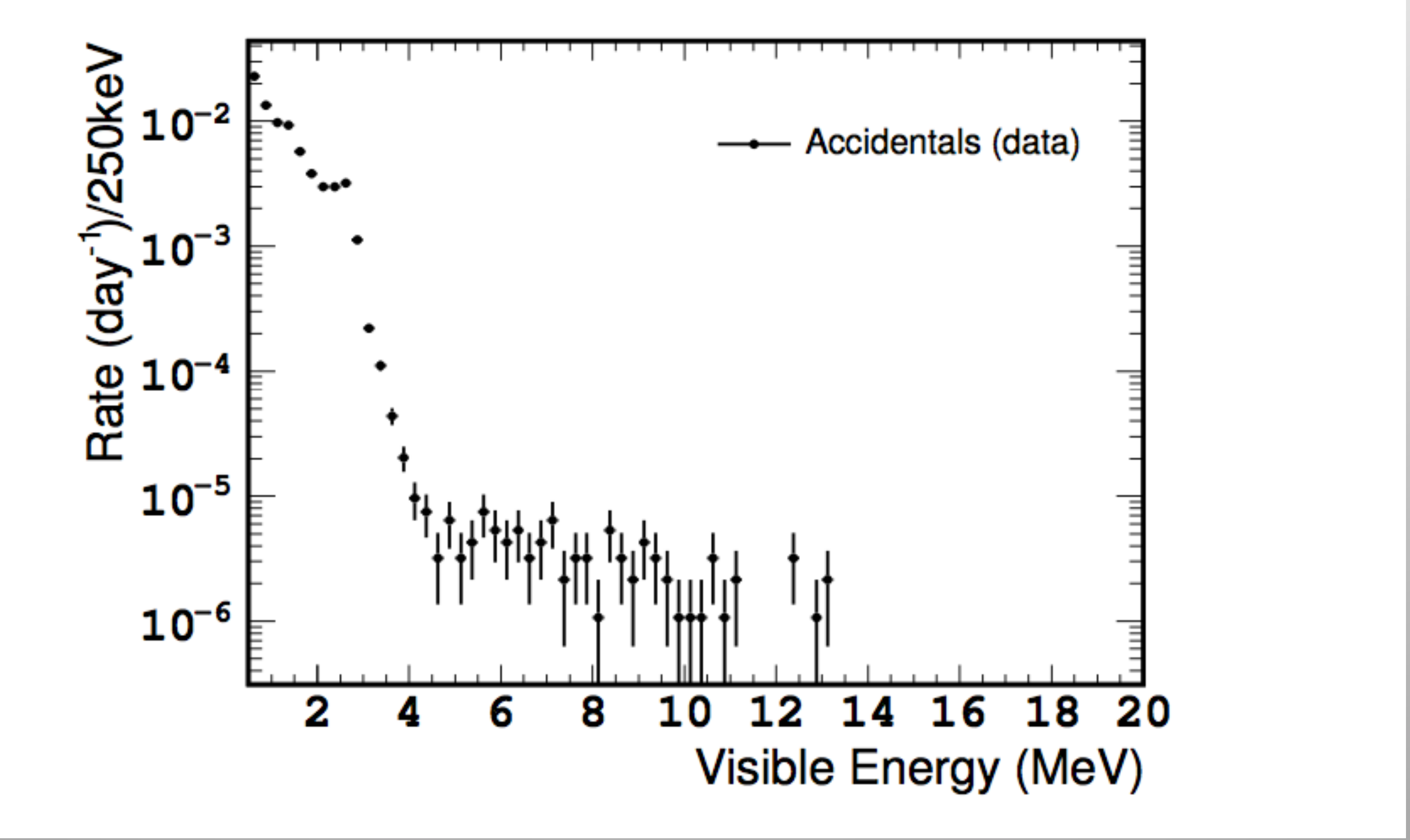
Detection efficiency

Evaluation of detection uncertainty using Cf data and IBD cand.



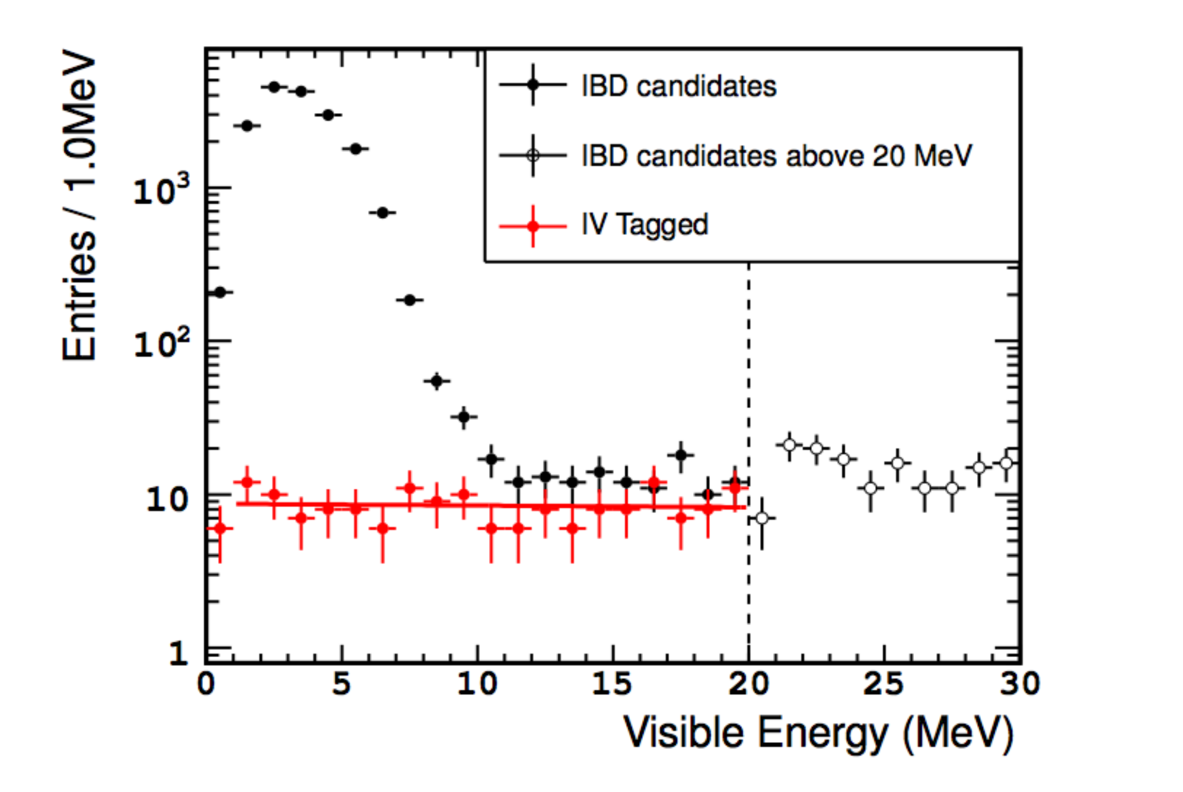
Total uncertainty: 0.6 % (dominated by Gd fraction)

Accidental background



Random coincidences determined by off-time window method
Constant rate of **0.070 ± 0.003 events / day**

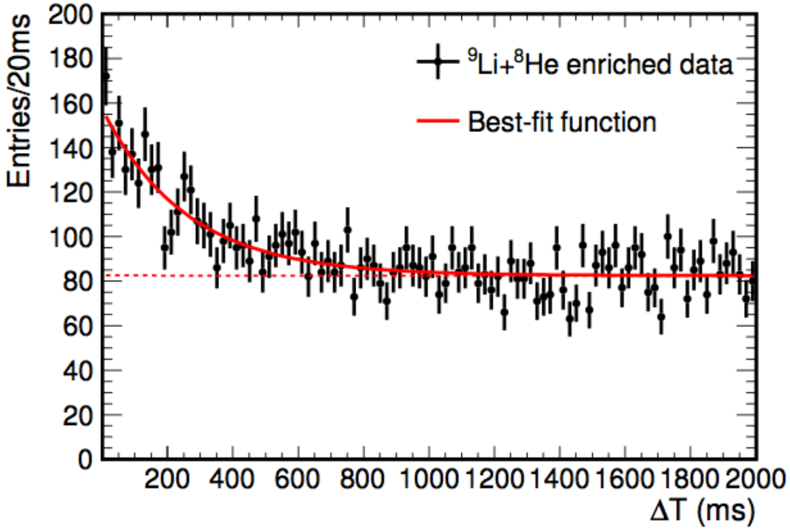
Fast neutrons and stopping muons

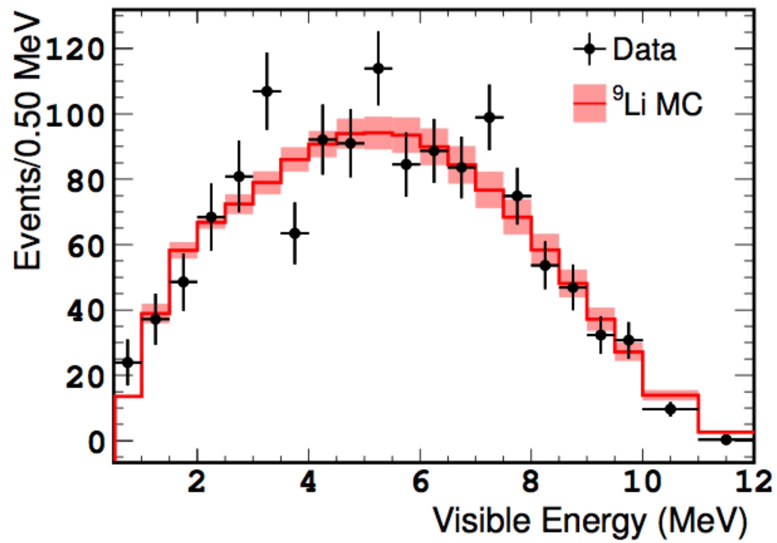


- Stopping muons effectively identified by PMT hit pattern
- Fast neutrons reduced using Inner Veto coincidences
- Rate extrapolated from high energies (flat spectrum):

0.60 ± 0.05 events / day

Cosmogenic isotopes



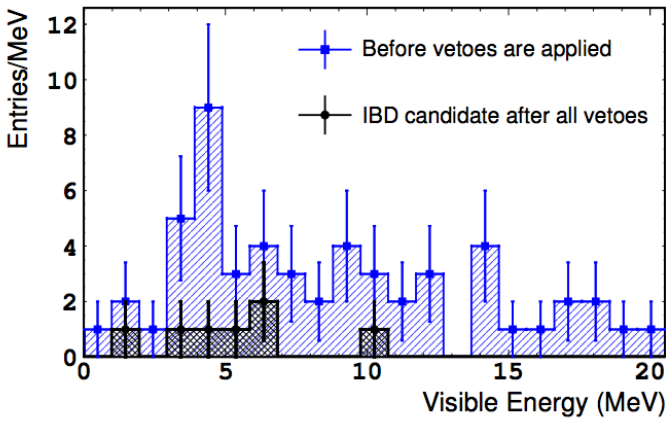


- Long-lived β-n emitters (^{9}Li and ^{8}He) produced by spallation interactions of muons in the detector
- Fit time correlation of IBD candidate and previous muon
- 55% rejection by *Li+He veto* (distance to μ track, #n after μ)
- Rate after subtraction of rejected Li candidates

$0.97^{+0.41}_{-0.16}$ events / day

Both reactors off data

- Unique for Double Chooz!
- Two periods: 7.24 days total
- Residual neutrinos (simul.): 1.57 ± 0.47 events
- Observed events:
  - 57 candidates selected
  - 7 remain after vetoes
- Constrains background in Θ_{13} fit



Normalization uncertainties

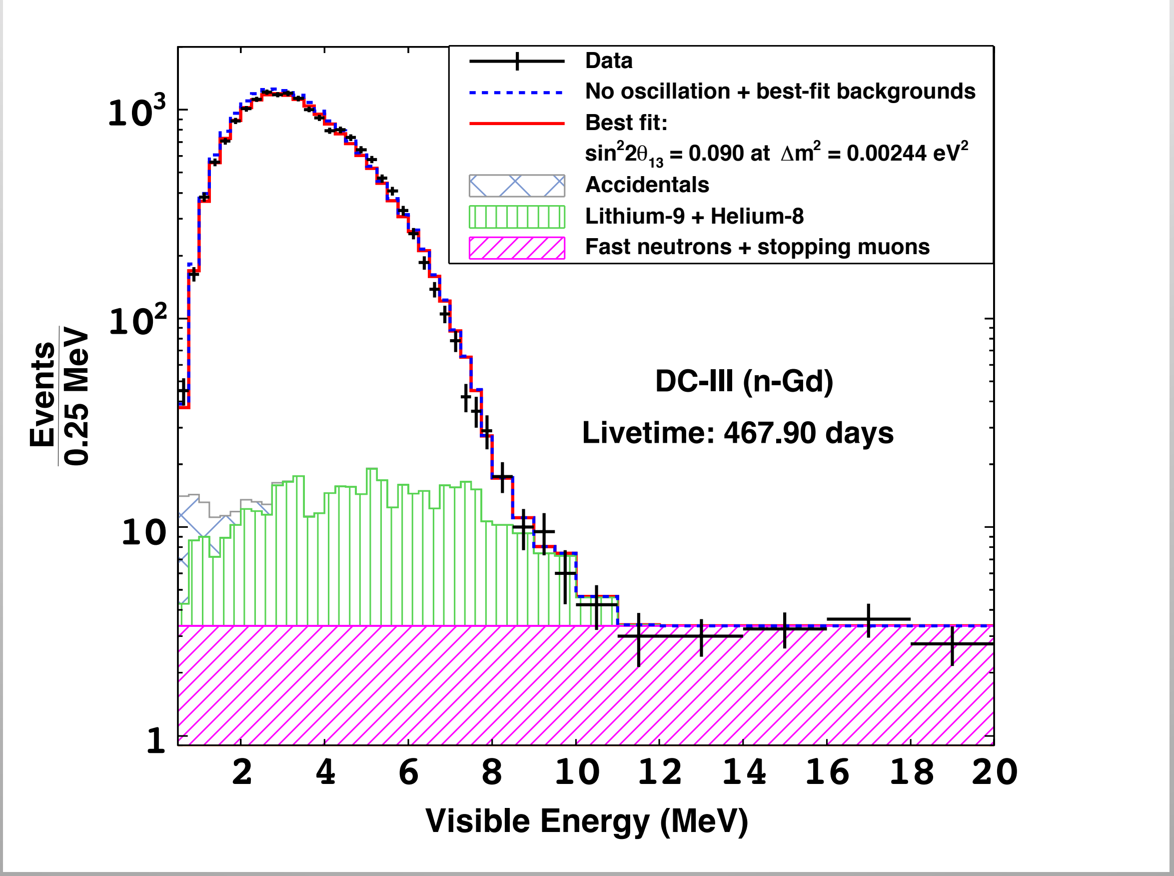
Uncertainties relative to signal prediction

Flux	1.7%
Detection efficiency	0.6%
Background (Li + He)	+1.1 / -0.4%
Other systematics	≤0.1%
Statistics	0.8%
Total	**+2.3 / - 2.0%**

Background errors further reduced by rate + shape fit

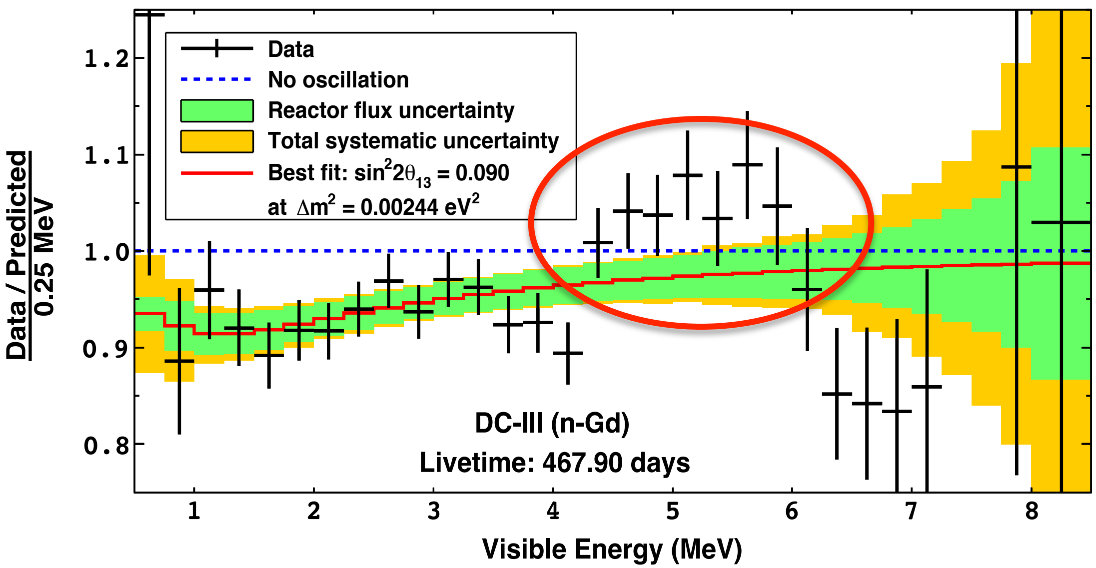
Θ_{13}: rate + shape result

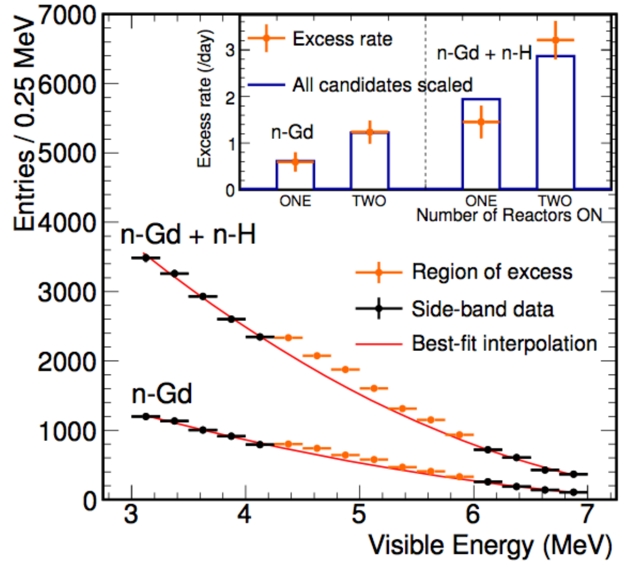
Gd analysis (467.9 live days) in Far Detector:



$$\sin^2 2\Theta_{13} = 0.090^{+0.032}_{-0.029}$$

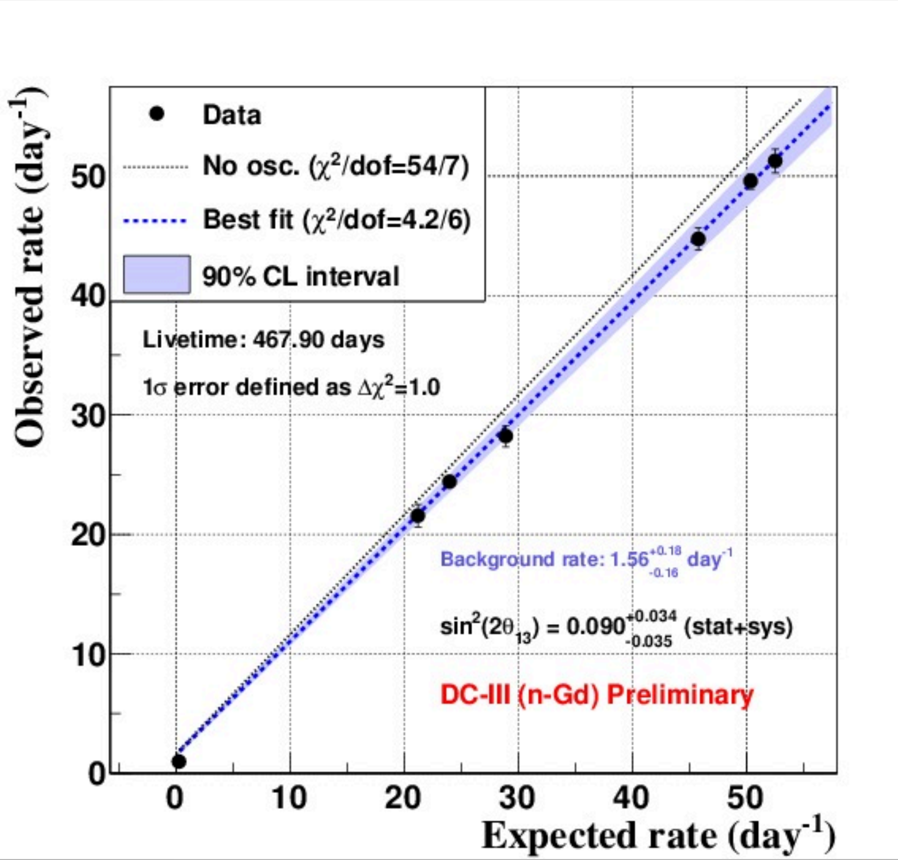
Spectral distortion





- Excess events in 4 – 6 MeV region (Gd and H)
- Background? Excess reactor flux correlated ➔ not favored
- Energy scale? Confirmed by n on C and ^{12}B ➔ not favored
- Flux prediction? Under investigation
- No significant impact on Θ_{13} measurement

Reactor rate modulation



- Compare obs. vs exp. rate for different reactor power cond.
- Rate only → spectrum and background model independent
- Extract Θ_{13} and background rate from linear correlation

RRM results

	Free BG	off-off	BG constr.
$\sin^2 2\Theta_{13}$	0.089 ± 0.052	0.060 ± 0.039	$0.090^{+0.034}_{-0.035}$
BG rate (ev/day)	1.56 ± 0.86	$0.093^{+0.43}_{-0.36}$	$1.56^{+0.18}_{-0.16}$

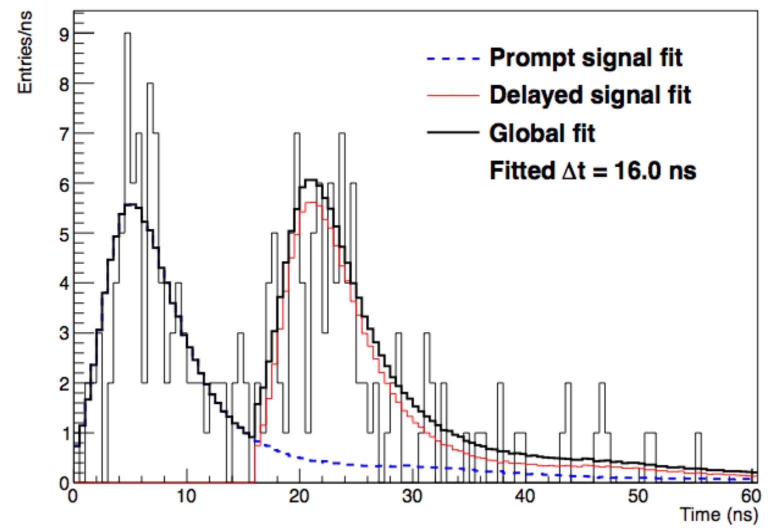
Comparison with rate + shape analysis:

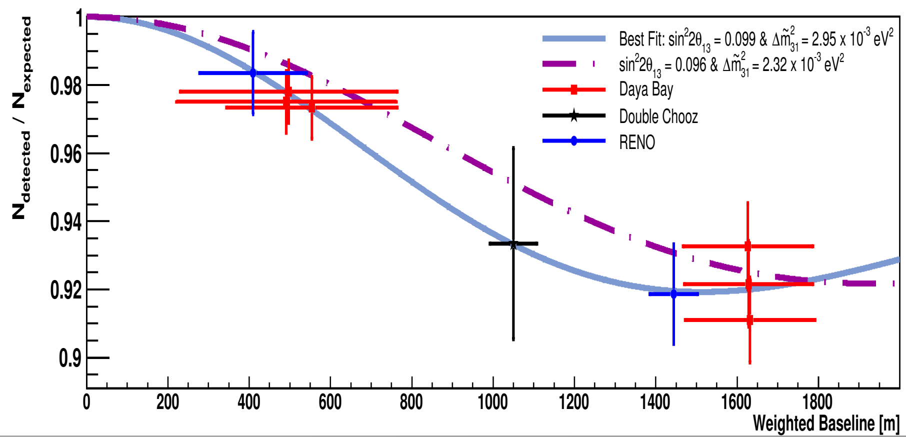
$$\sin^2 2\theta_{13} = 0.090^{+0.032}_{-0.029}$$

$$BG(ev / day) = 1.64^{+0.41}_{-0.17}$$

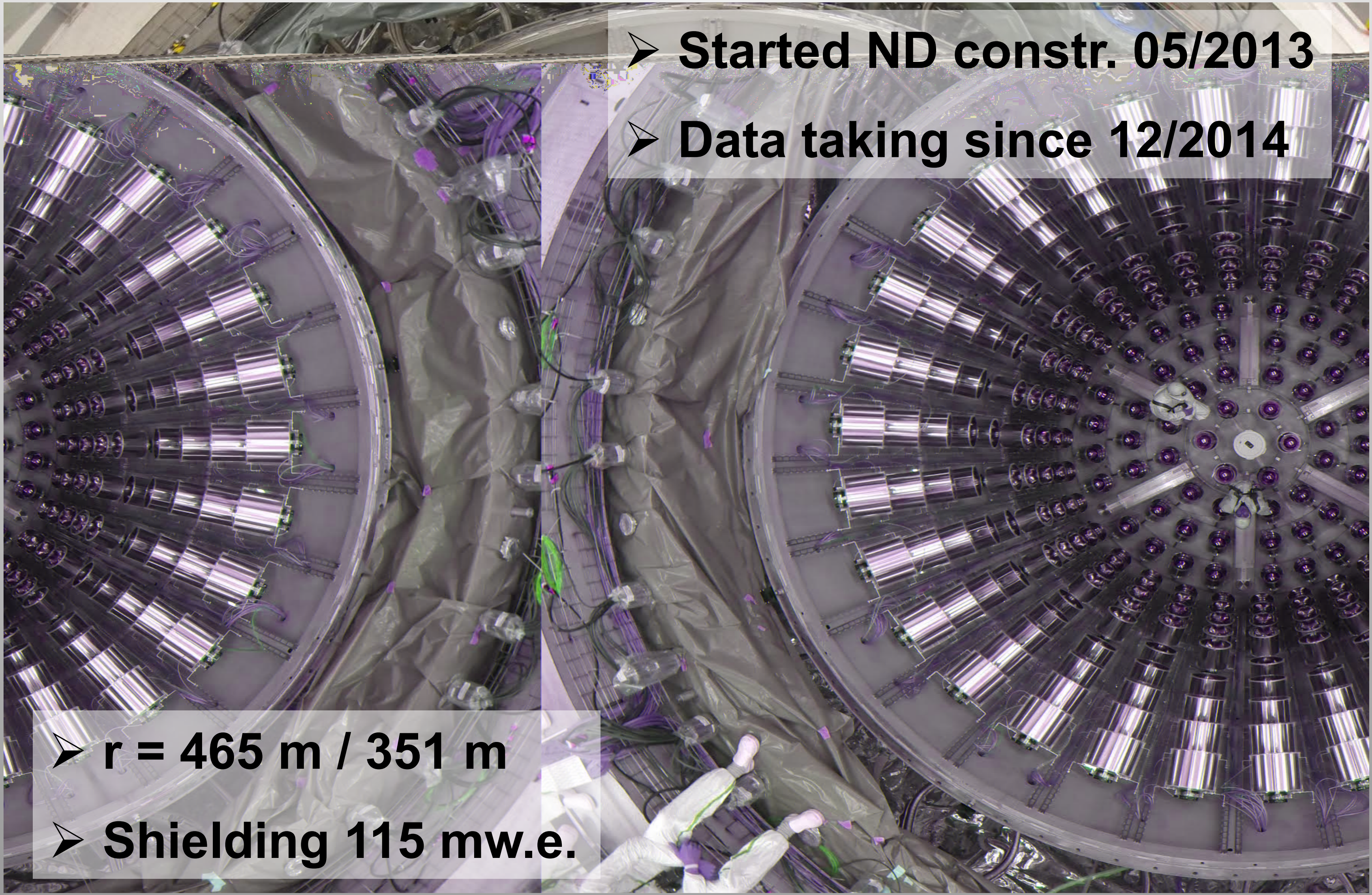
Physics beyond θ_{13}

- **Ortho-positronium**
  (DC, JHEP 10 (2014) 032)
- **Sensitivity to Δm_{13}^2**
  (Phys.Lett.B725 (2013) 271-276)
- **Neutrino directionality**
  (arXiv:1208.3628)
- **Sterile neutrino**
  (PRD 83 (2011) 073006)
- **Background studies**
  (DC, PRD 87 (2013) 011102(R))
- **Lorentz violation**
  (DC, PRD 86, 112009, 2012)

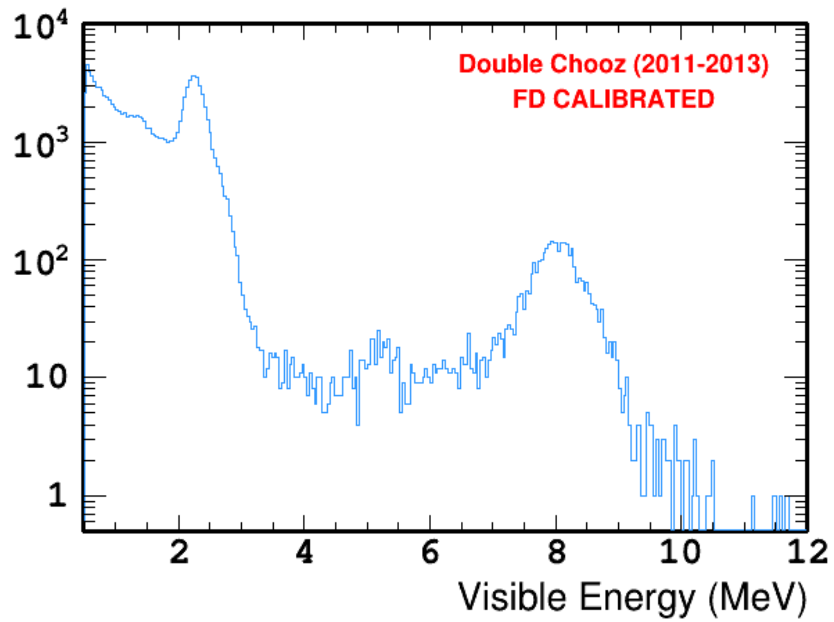


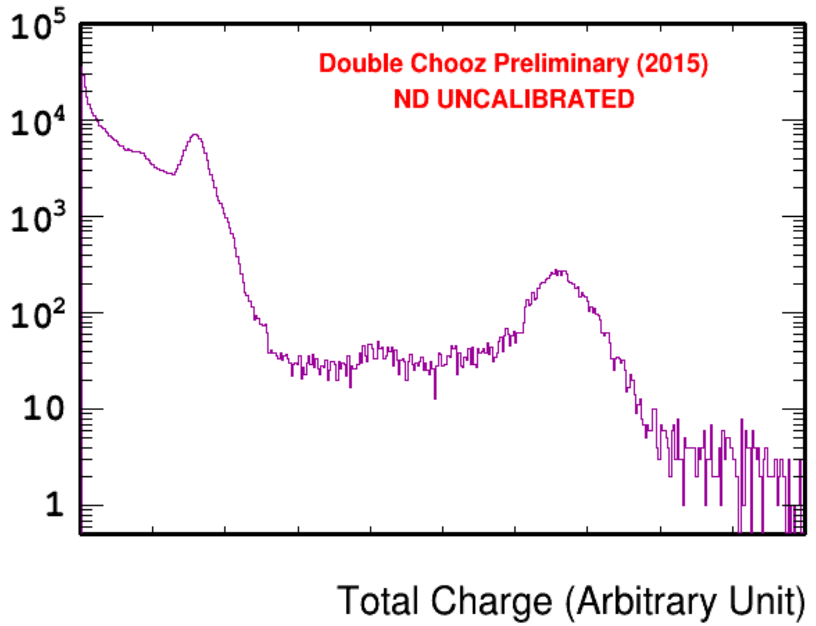


Near detector



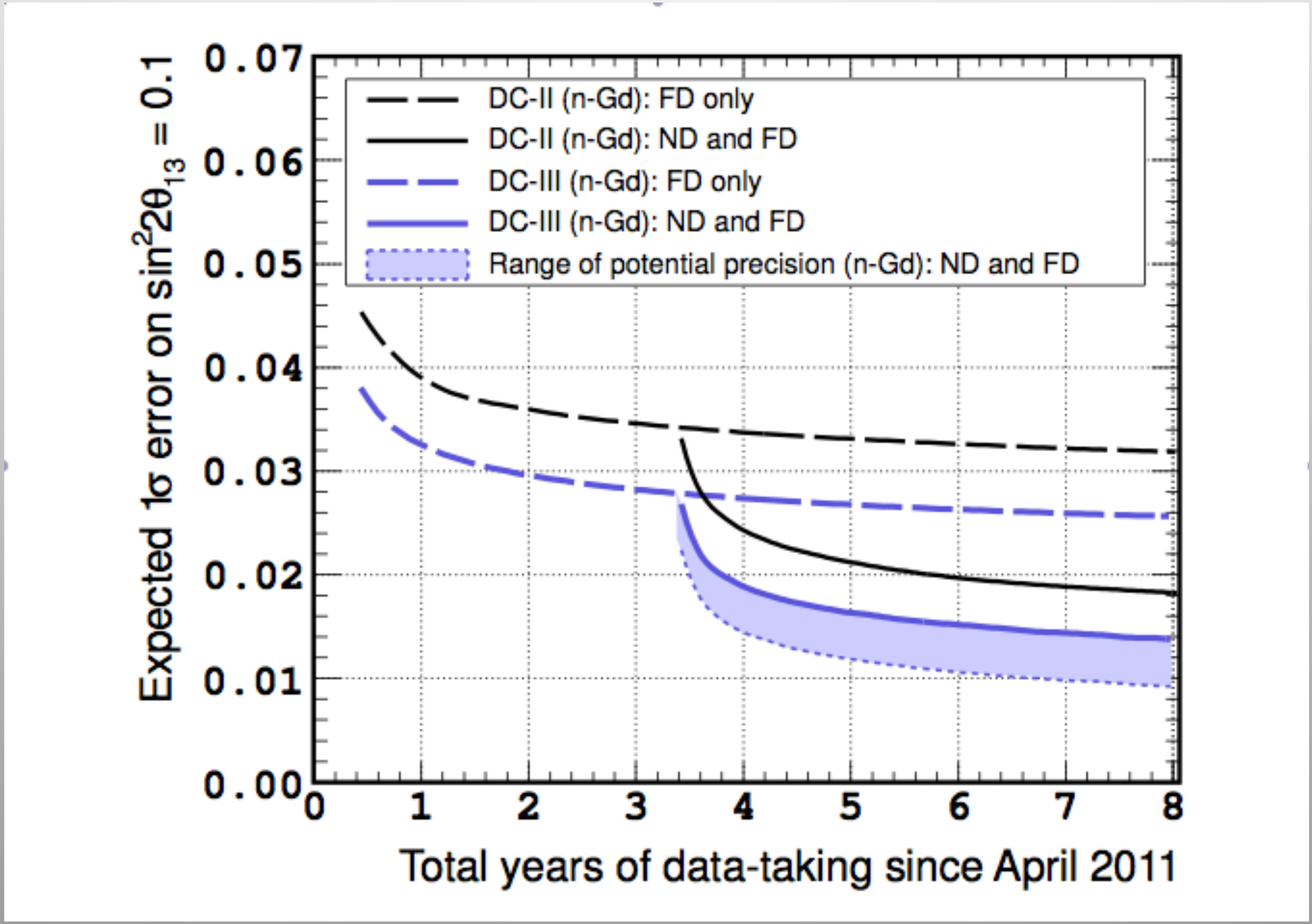
Near detector performance





- Spallation n captures Far (calib.) vs Near Detector (uncalib.)
  ➔ feasibilty of IBD measurement
- Preliminary study of ND singles indicates similar rate as in FD
  ➔ radiopurity and shielding goals achieved

Double Chooz sensitivity



Summary

- Recent analysis improvements with Far Detector
  - Improve accuracy of energy reconstruction
  - Optimized selection, reduce detection systematics
  - New background tagging and rejection techniques
  - Include reactor off-off data in fit
- Result rate + shape analysis: $\sin^2 2\Theta_{13} = 0.090^{+0.032}_{-0.029}$
- Independent cross-check analysis:
  - Neutron captures on Hydrogen
  - Reactor rate modulation analysis
- Near detector data taking started

Backup

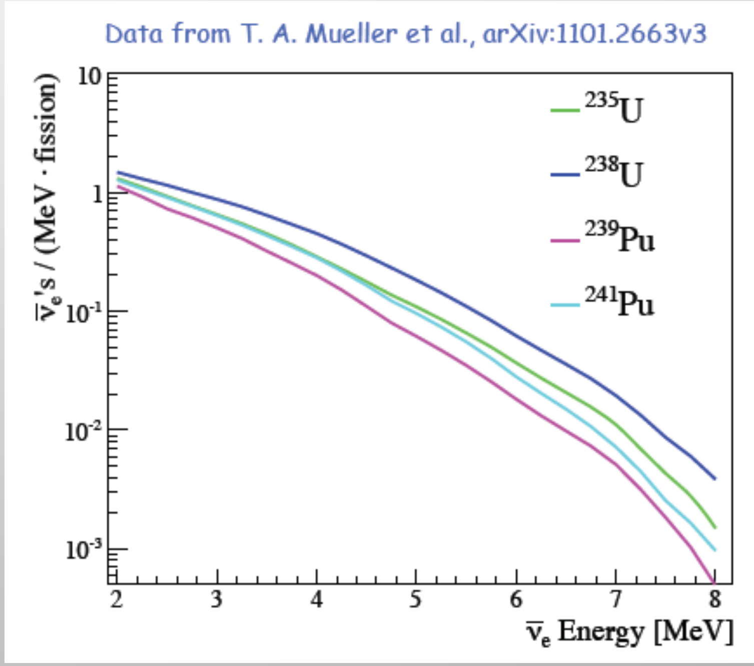
Reactor spectrum

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

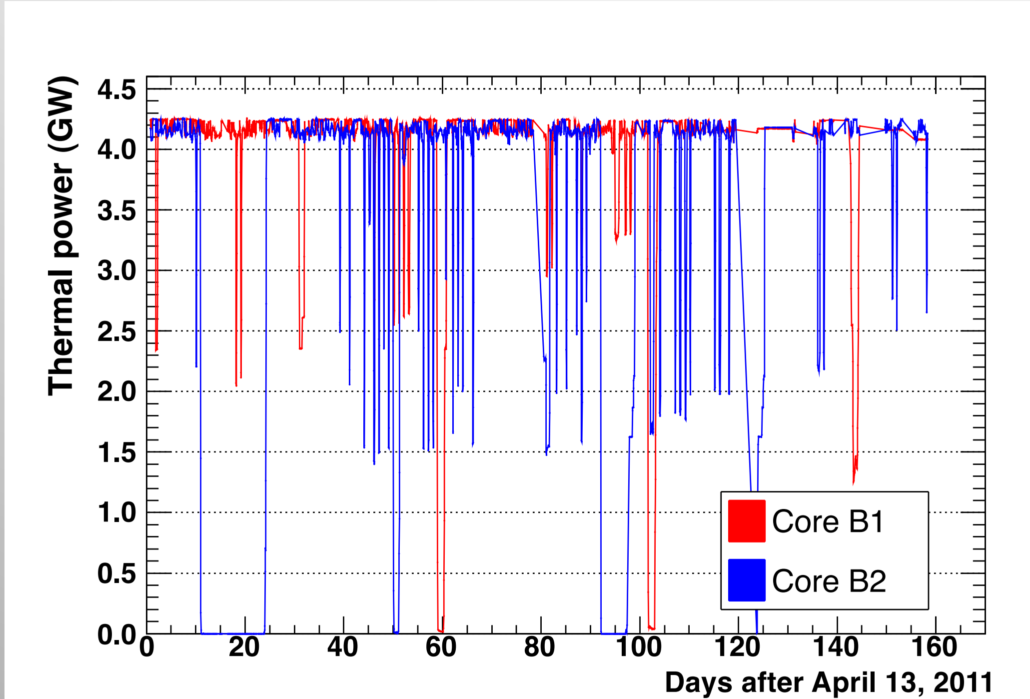
$$\langle \sigma_f \rangle = \langle \sigma_f \rangle^{Bugey} + \sum_k \left(\alpha_k^{DC}(t) - \alpha_k^{Bugey} \right) \langle \sigma_f \rangle_k$$

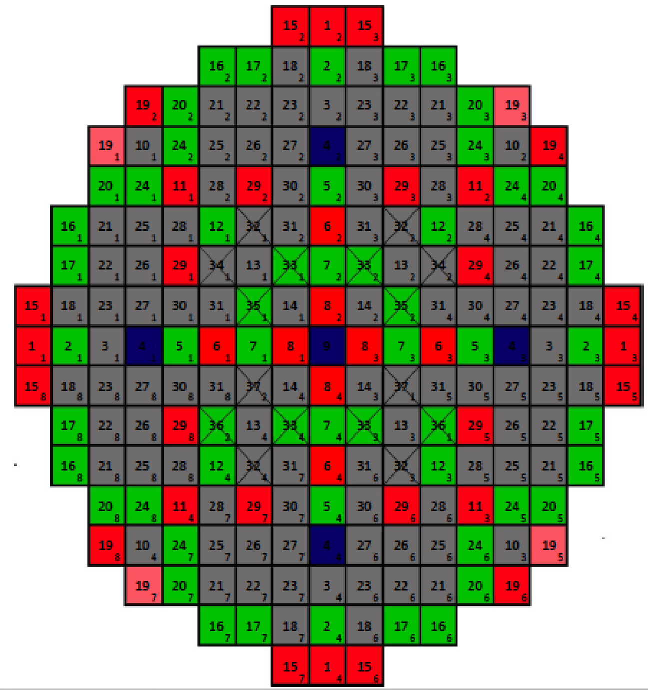
Bugey4 measurement as anchor point

Fission fraction in Chooz core



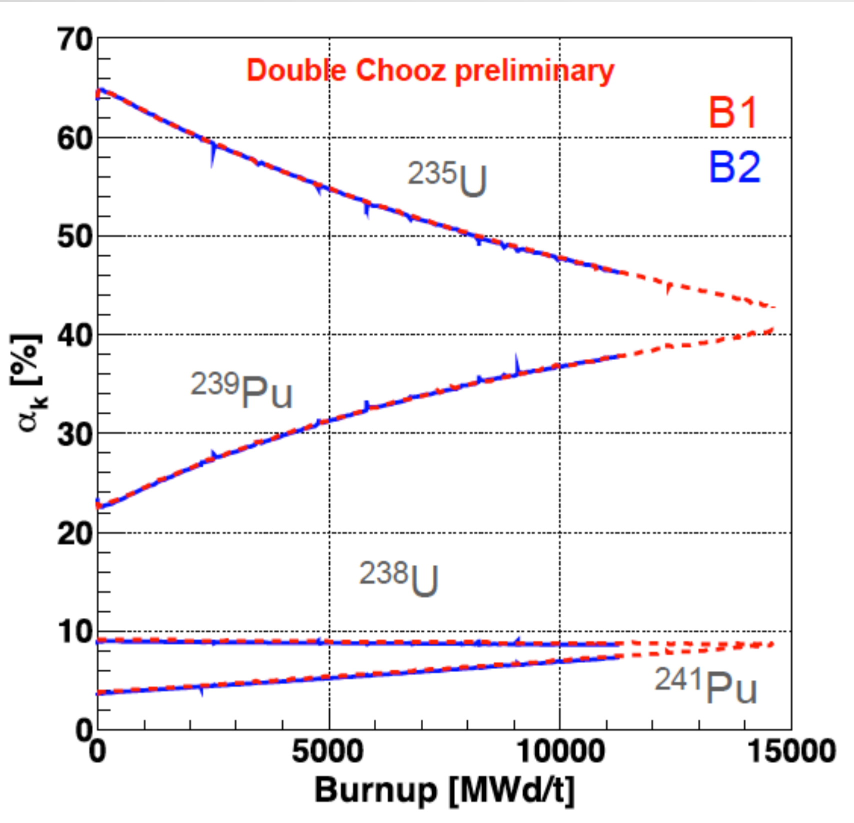
Reactor simulation

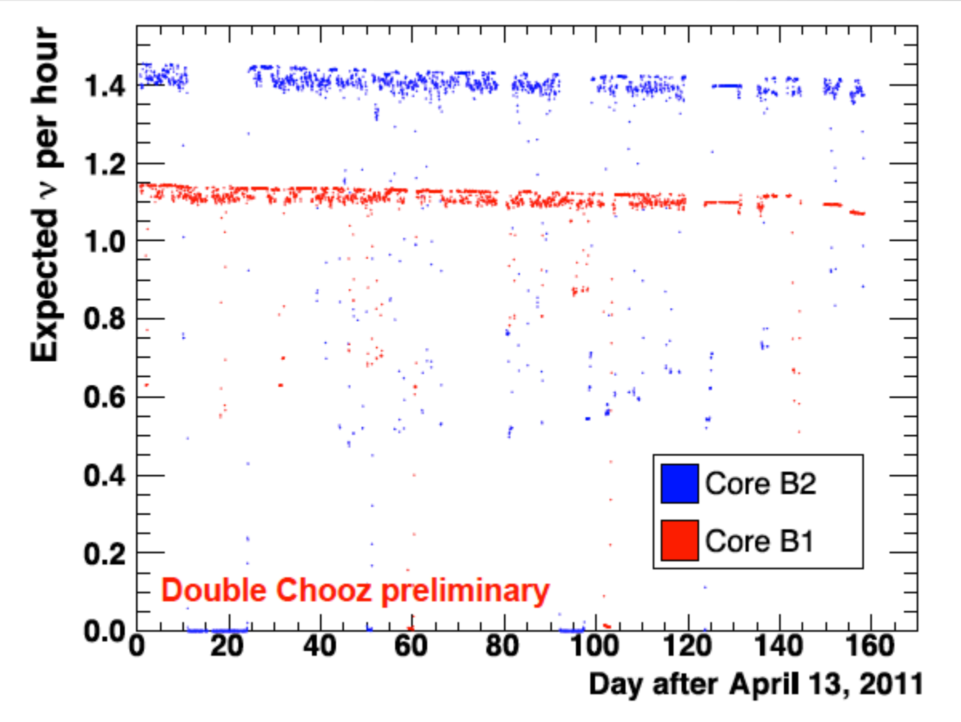




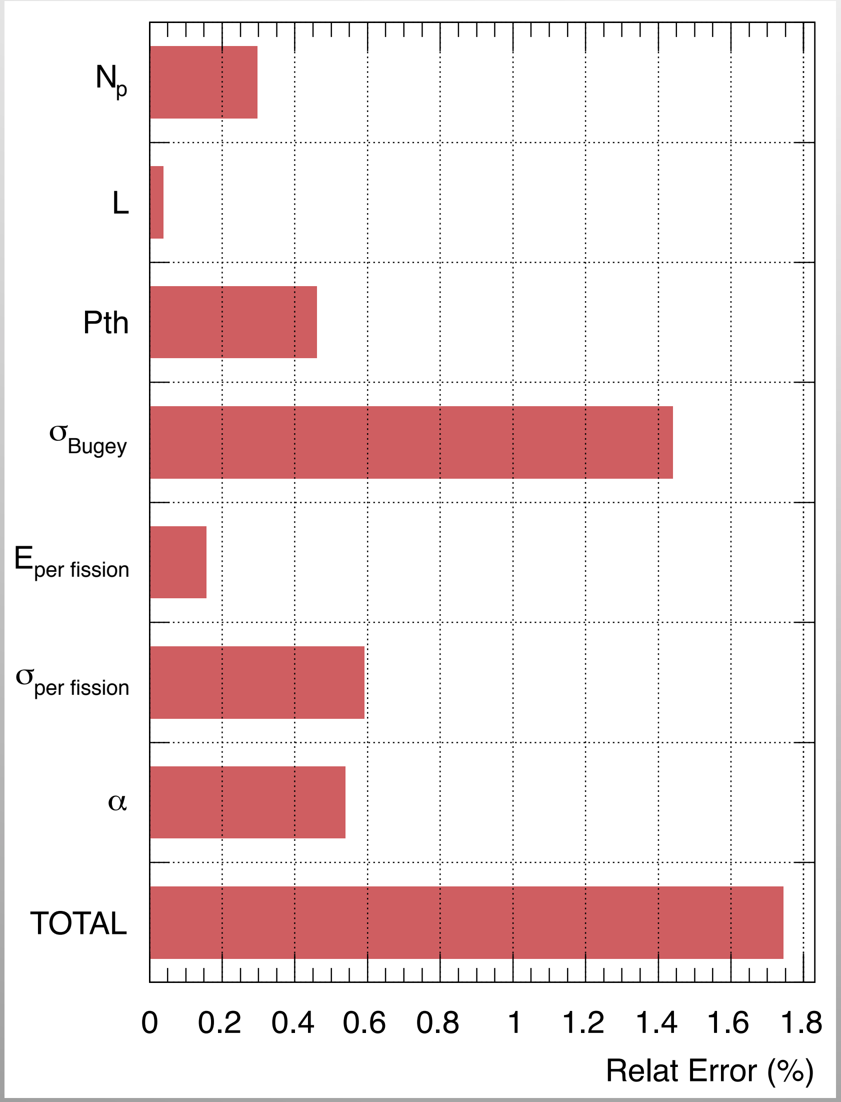
- Regular monitorintg of thermal power (T in primary loop every minute, weekly measurement of steam generator enthalpy balance)
- Fractional fission rates from U and Pu isotopes (burnup curves)
  - EDF inputs (fuel loading, geometry, power history,…)
  - Reactor simulations: MURE, Dragon

Reactor burnup



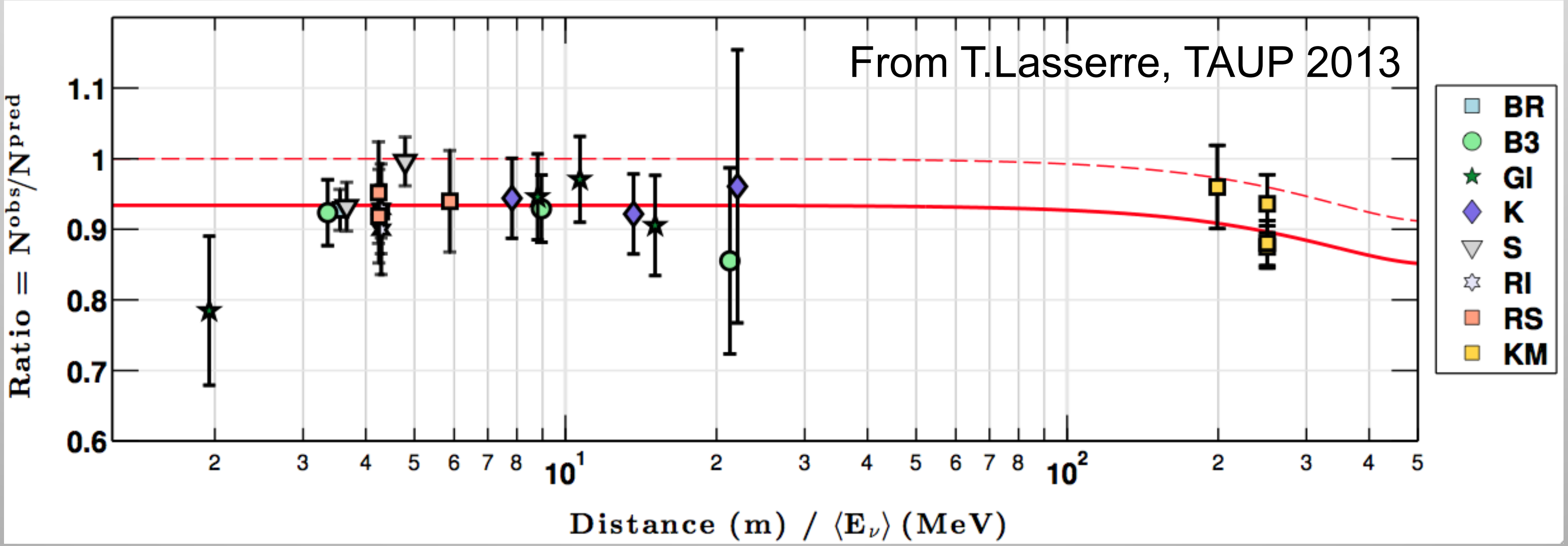


Uncertainty on reactor predictions



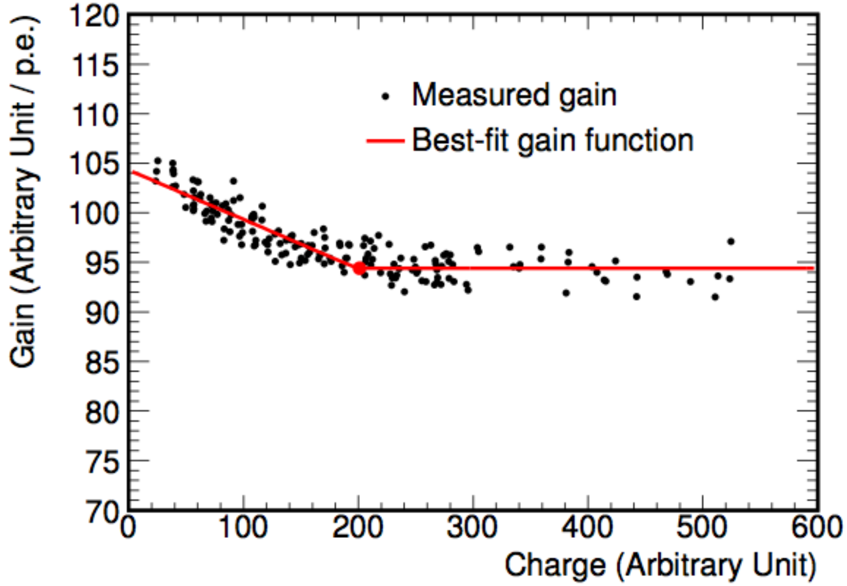
Total: 1.7 %
(2.7% without Bugey anchor point)

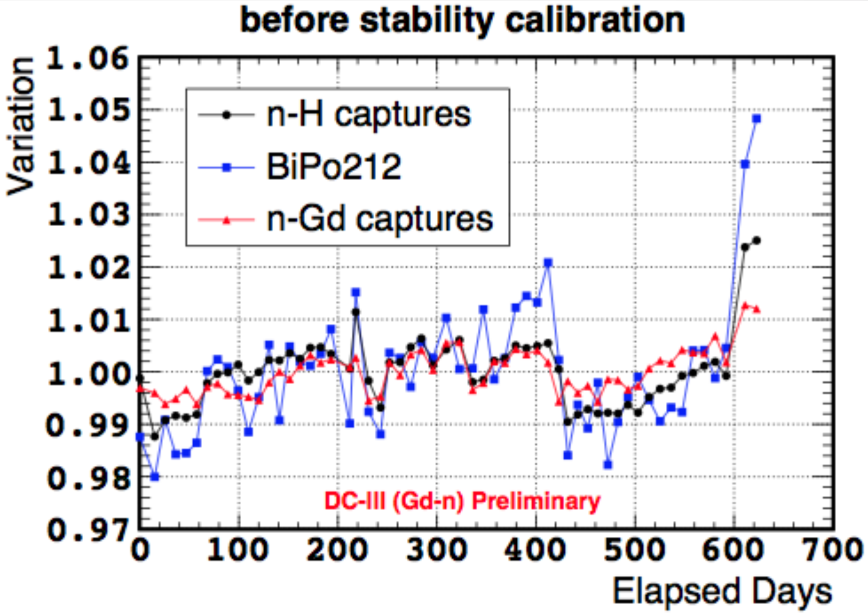
Reactor anomaly

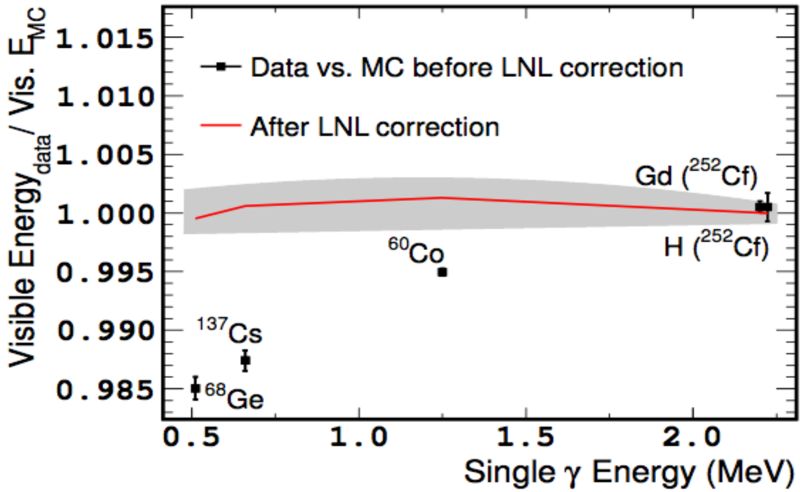


R = 0.936 ± 0.024 (2.7σ deviation from unity)

More on energy scale

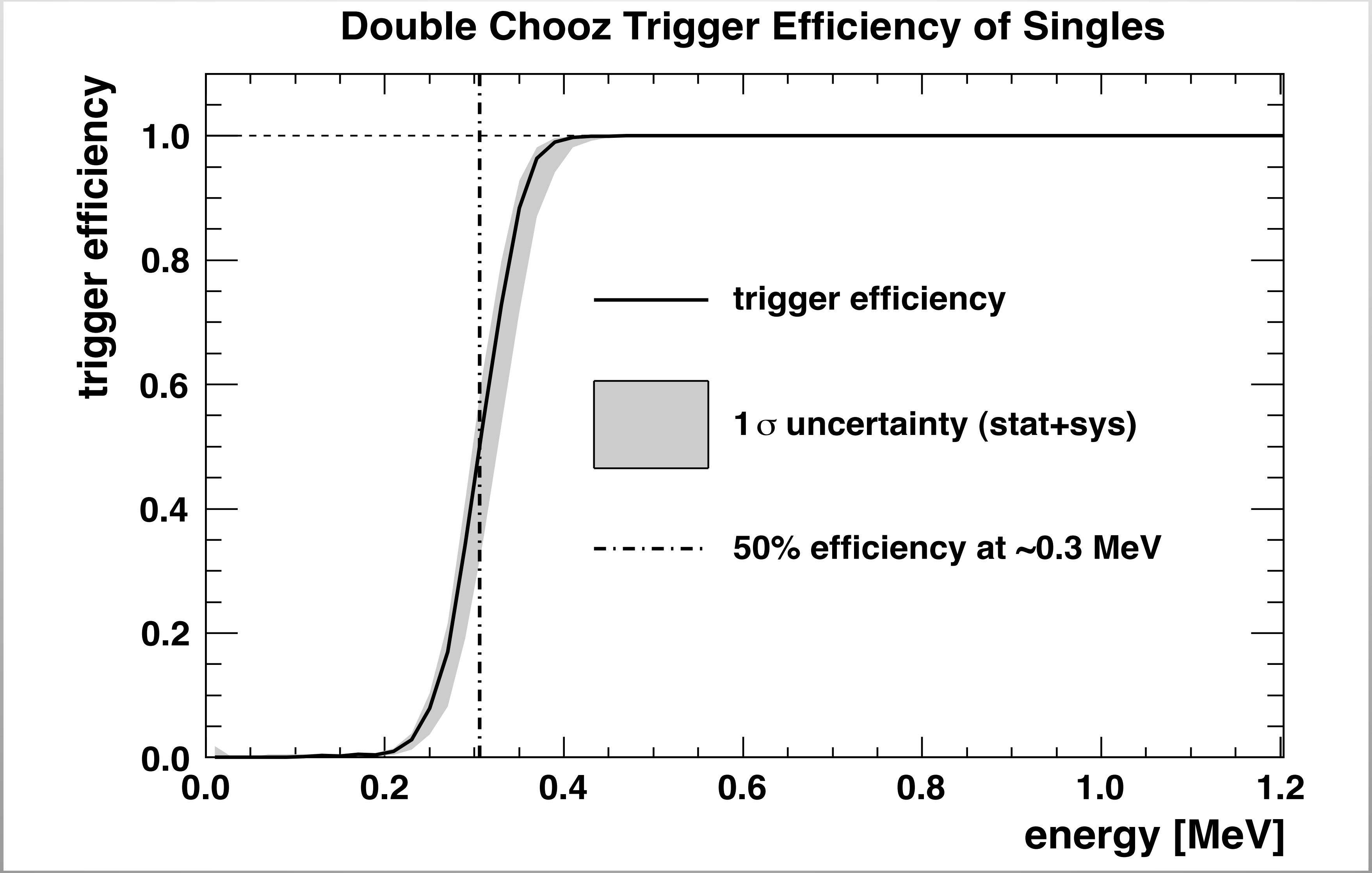






Source	Uncertainty (%)	Gd-III/Gd-II
Non-uniformity	0.36	0.84
Instability	0.50	0.82
Non-linearity	0.35	0.41
Total	0.74	0.65

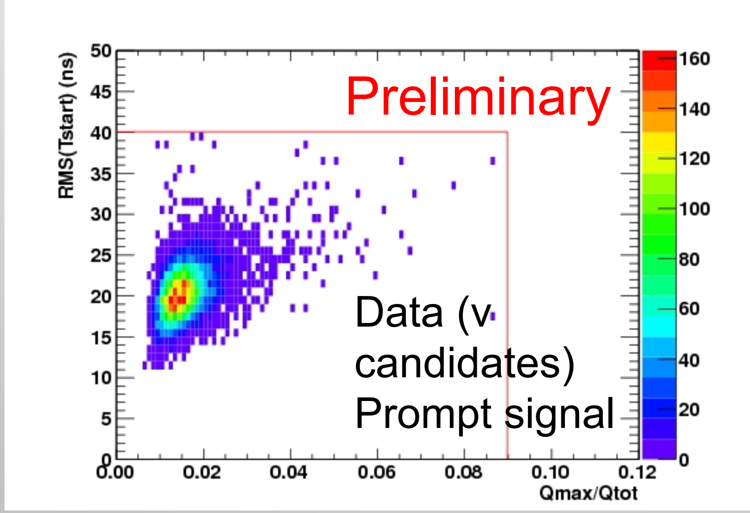
Trigger efficiency

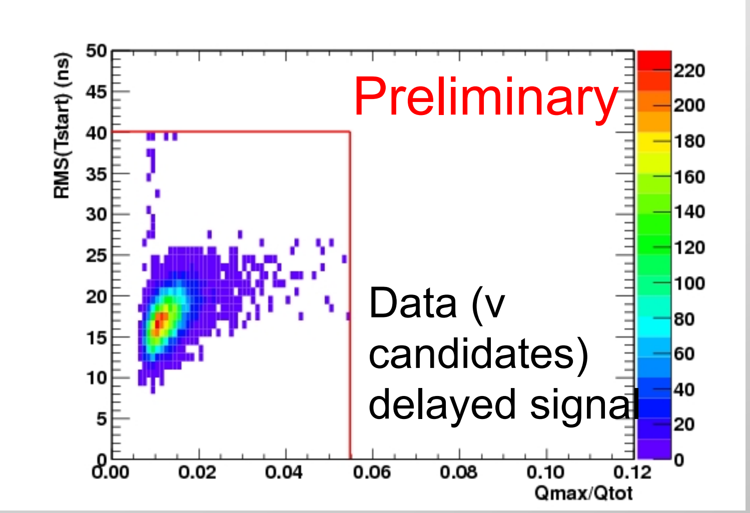


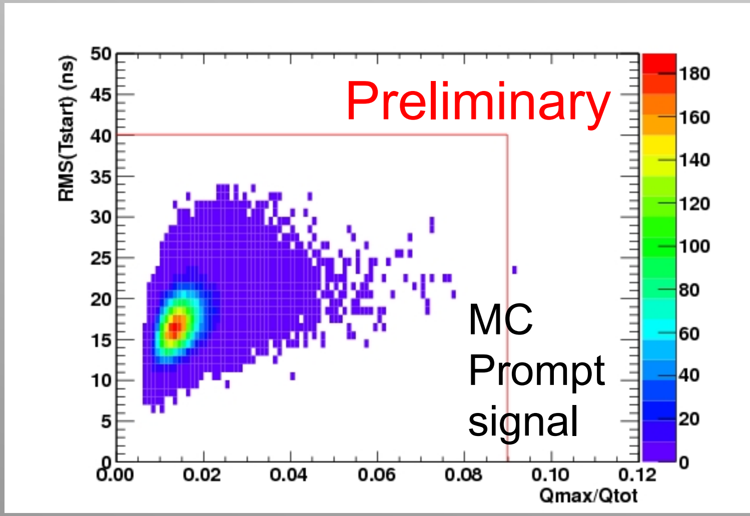
MC correction

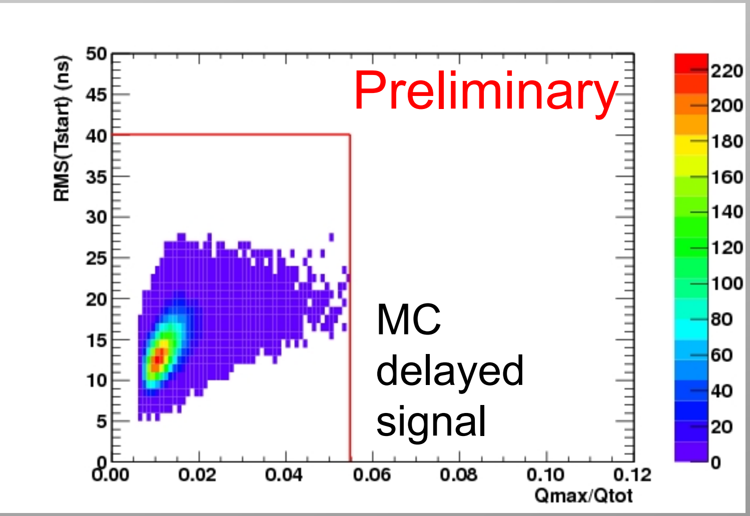
Correction source	MC Correction	Uncertainty (%)
DAQ & Trigger	1.000	< 0.1
Veto for 1 ms after muon	0.955	< 0.1
IBD selection	0.989	0.2
FV, OV, IV, Li+He veto	0.993	0.1
Scintillator proton number	1.000	0.3
Gd fraction	0.975	0.4
Spill in/out	1.000	0.3
Total	0.915	0.6

Light noise

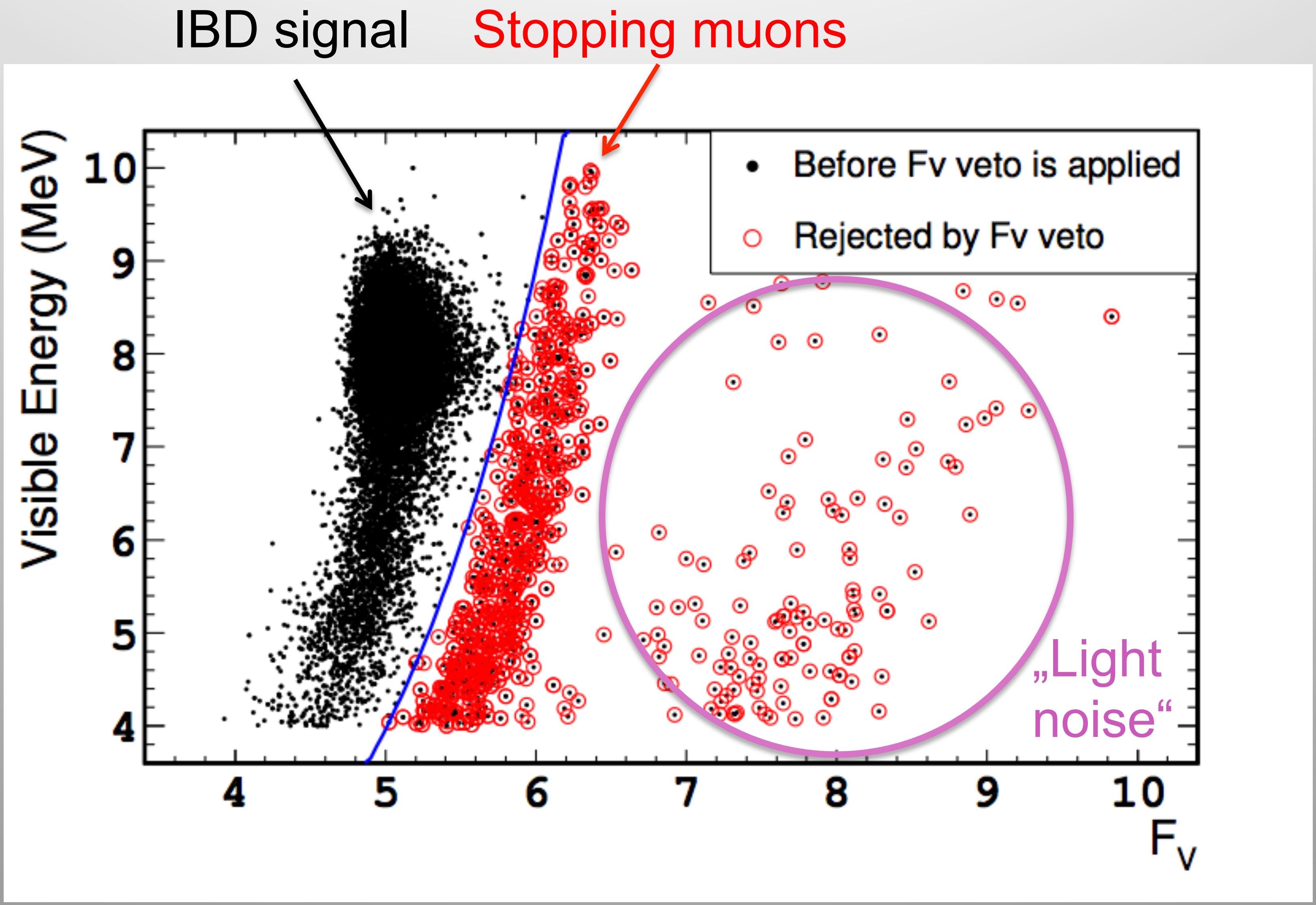

Preliminary
Data (ν candidates) Prompt signal
RMS(Tstart) (ns)
Qmax/Qtot


Preliminary
Data (ν candidates) delayed signal
RMS(Tstart) (ns)
Qmax/Qtot


Preliminary
MC Prompt signal
RMS(Tstart) (ns)
Qmax/Qtot

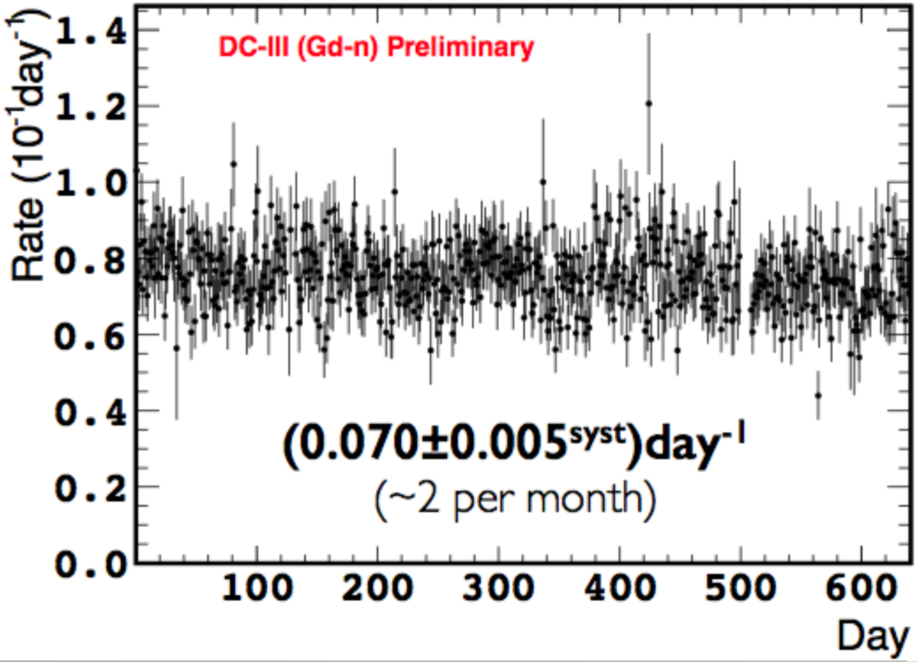

Preliminary
MC delayed signal
RMS(Tstart) (ns)
Qmax/Qtot

FV veto (delayed signal)

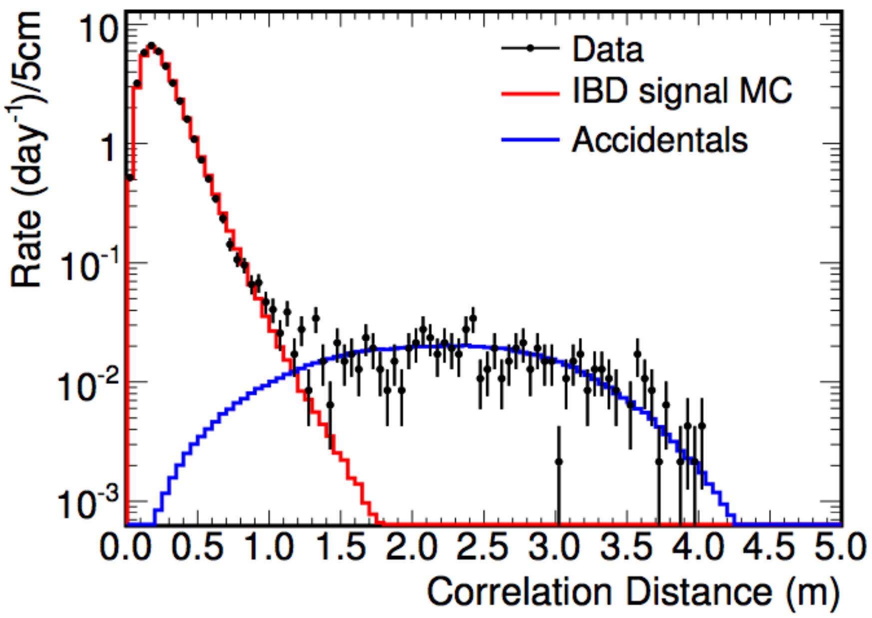


Details accidentals

Rate stability

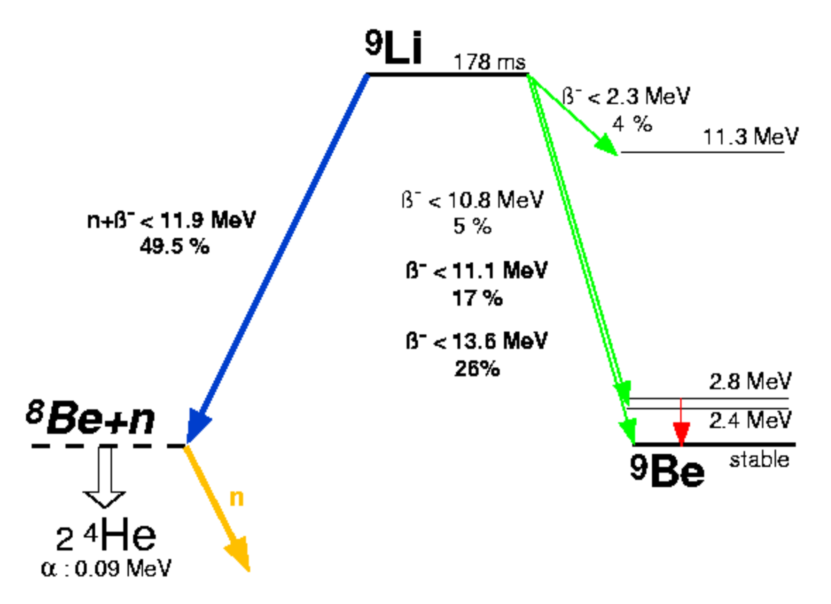


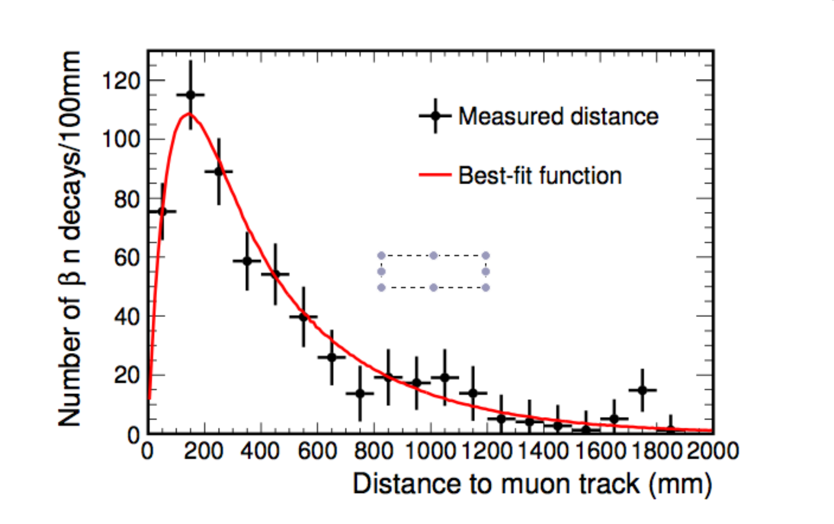
Distance vertex positions

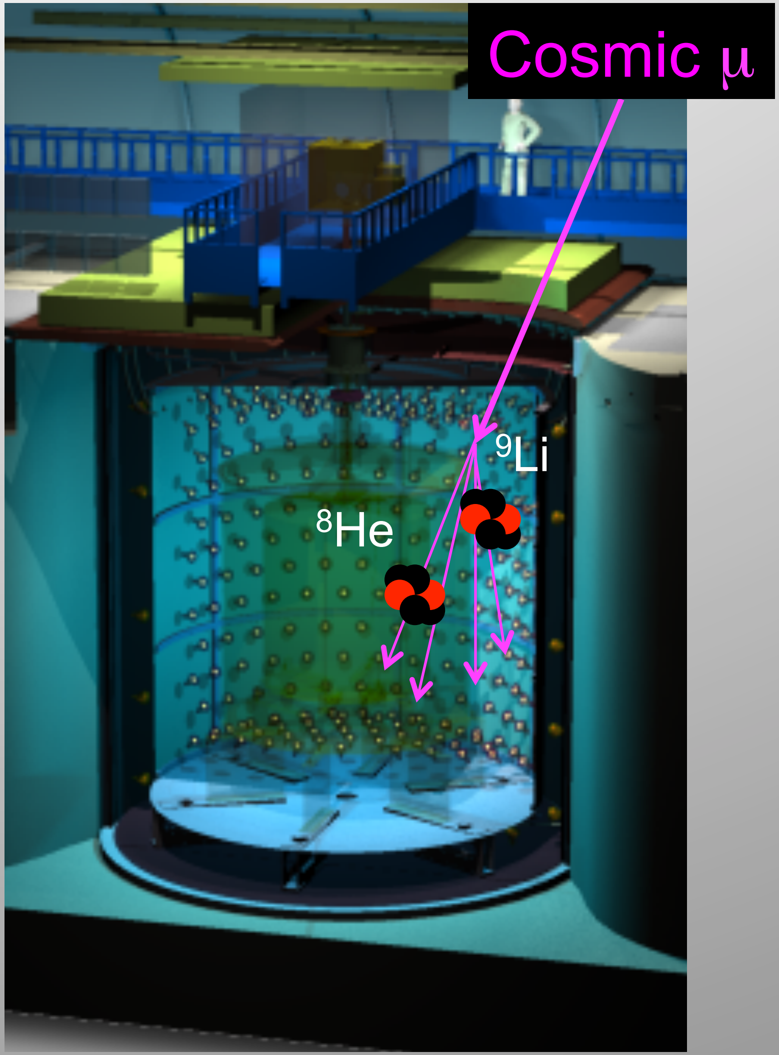


IBD signal inefficiency by ΔR cut: 0.3%

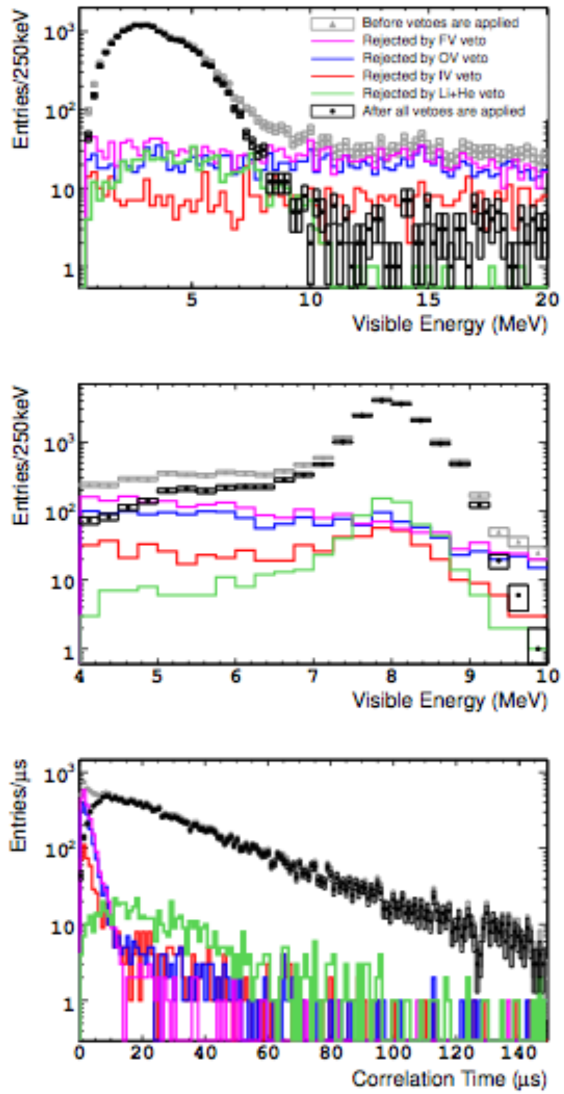
^{9}Li background





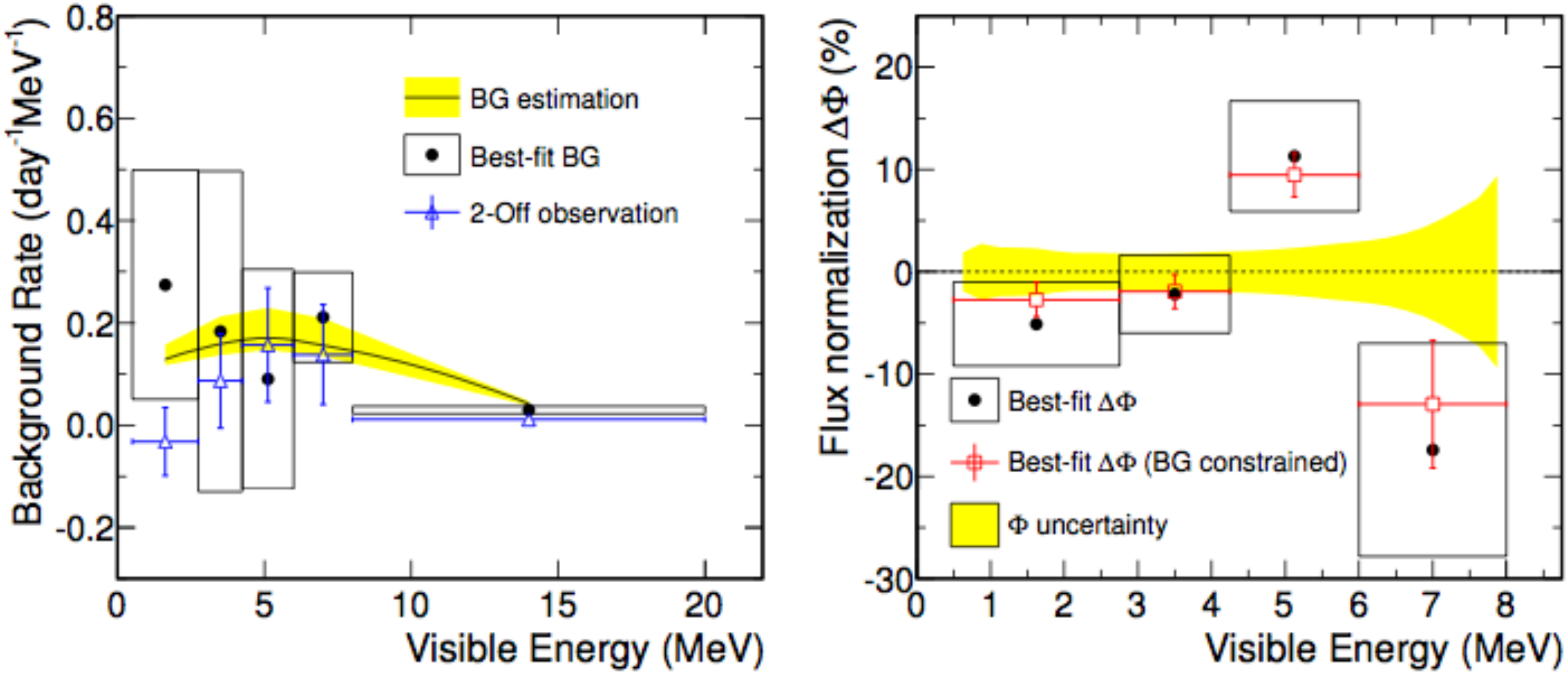


Vetoes



Before vetoes are applied
Rejected by FV veto
Rejected by OV veto
Rejected by IV veto
Rejected by Li+He veto
After all vetoes are applied
Entries/250keV
Visible Energy (MeV)
Entries/250keV
Visible Energy (MeV)
Entries/µs
Correlation Time (µs)

eRRM

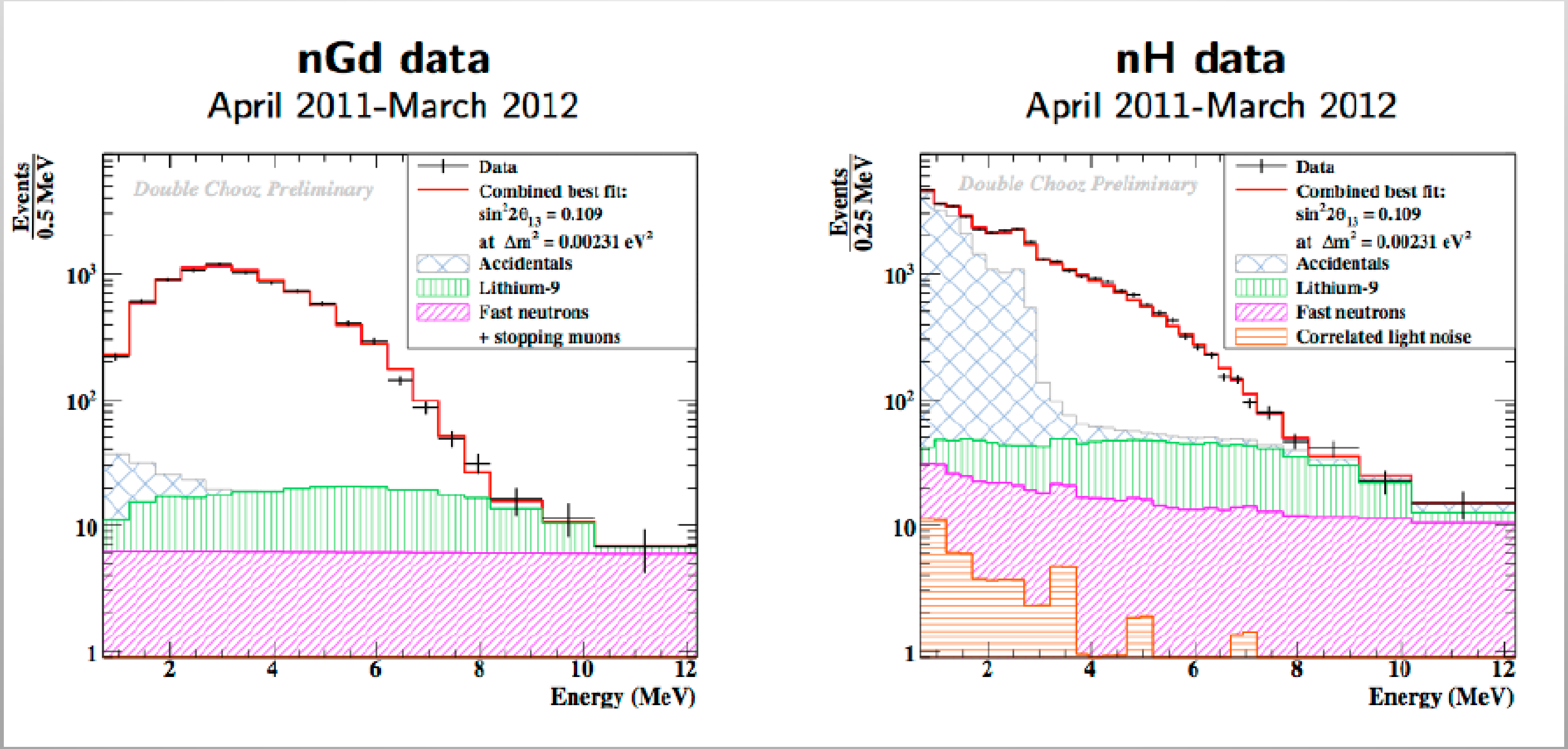


BG estimation
Best-fit BG
2-Off observation
Background Rate (day^{-1}MeV^{-1})
Visible Energy (MeV)
Best-fit ΔΦ
Best-fit ΔΦ (BG constrained)
Φ uncertainty
Flux normalization ΔΦ (%)
Visible Energy (MeV)

Fit parameters

Fit Parameter	Input Value	Best-Fit Value
Li+He bkg. (d^{-1})	$0.97^{+0.41}_{-0.16}$	0.74 ± 0.13
Fast-n + stop-μ bkg. (d^{-1})	0.604 ± 0.051	$0.568^{+0.038}_{-0.037}$
Accidental bkg. (d^{-1})	0.0701 ± 0.0026	0.0703 ± 0.0026
Residual $\bar{\nu}_e$	1.57 ± 0.47	1.48 ± 0.47
Δm^2 $(10^{-3}\,\mathrm{eV}^2)$	$2.44^{+0.09}_{-0.10}$	$2.44^{+0.09}_{-0.10}$
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	$-0.0005^{+0.0007}_{-0.0005}$

Spectra including background (DC-II)



Combined fit