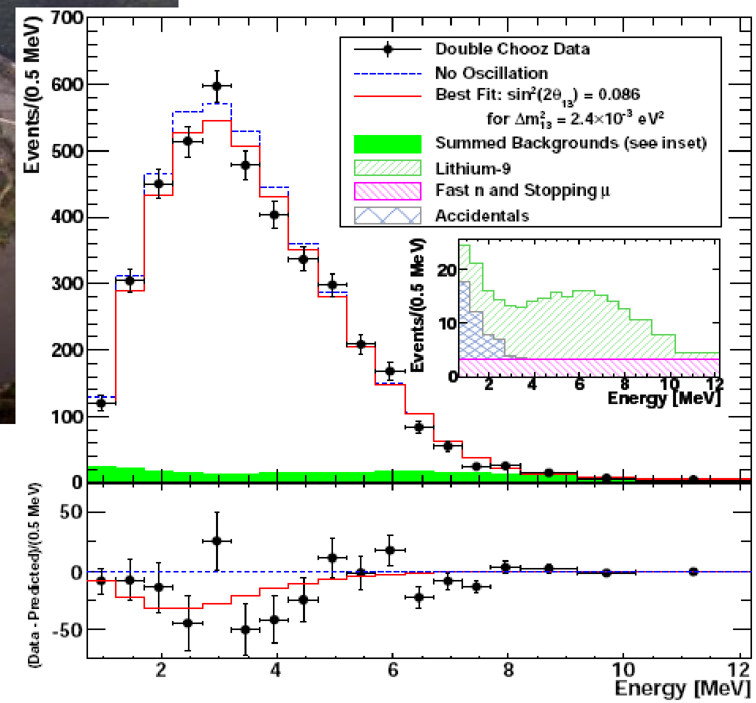
First Results on θ_{13} from the Reactor Antineutrino Experiment Double Chooz

arxiv hep-ex 1112.6353 submitted to PRL



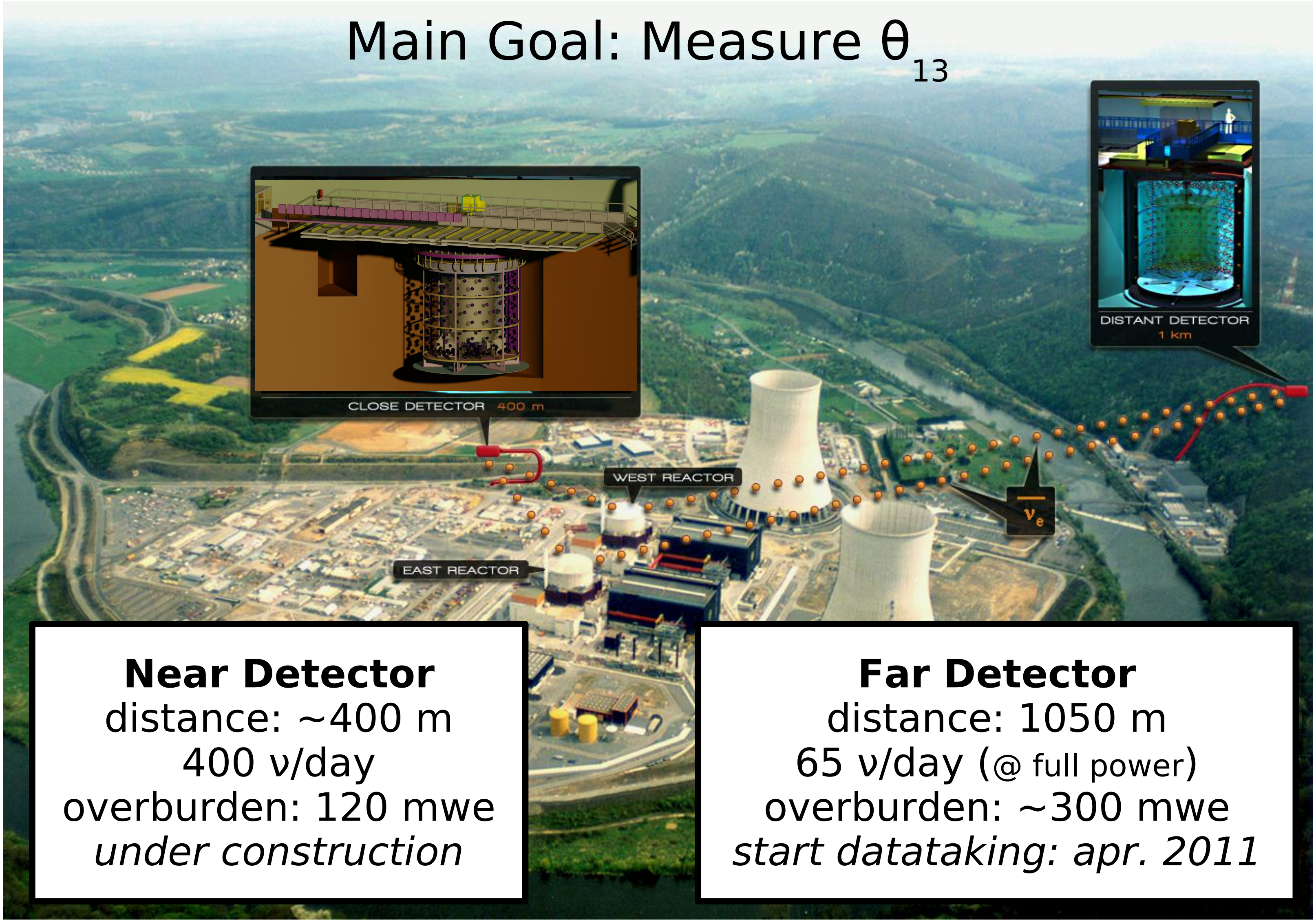
Bernd Reinhold (MPIK Heidelberg)
for the Double Chooz collaboration

La Thuile, Feb 28th, 2012

Double Chooz collab.

Double Chooz Overview

Main Goal: Measure θ_{13}

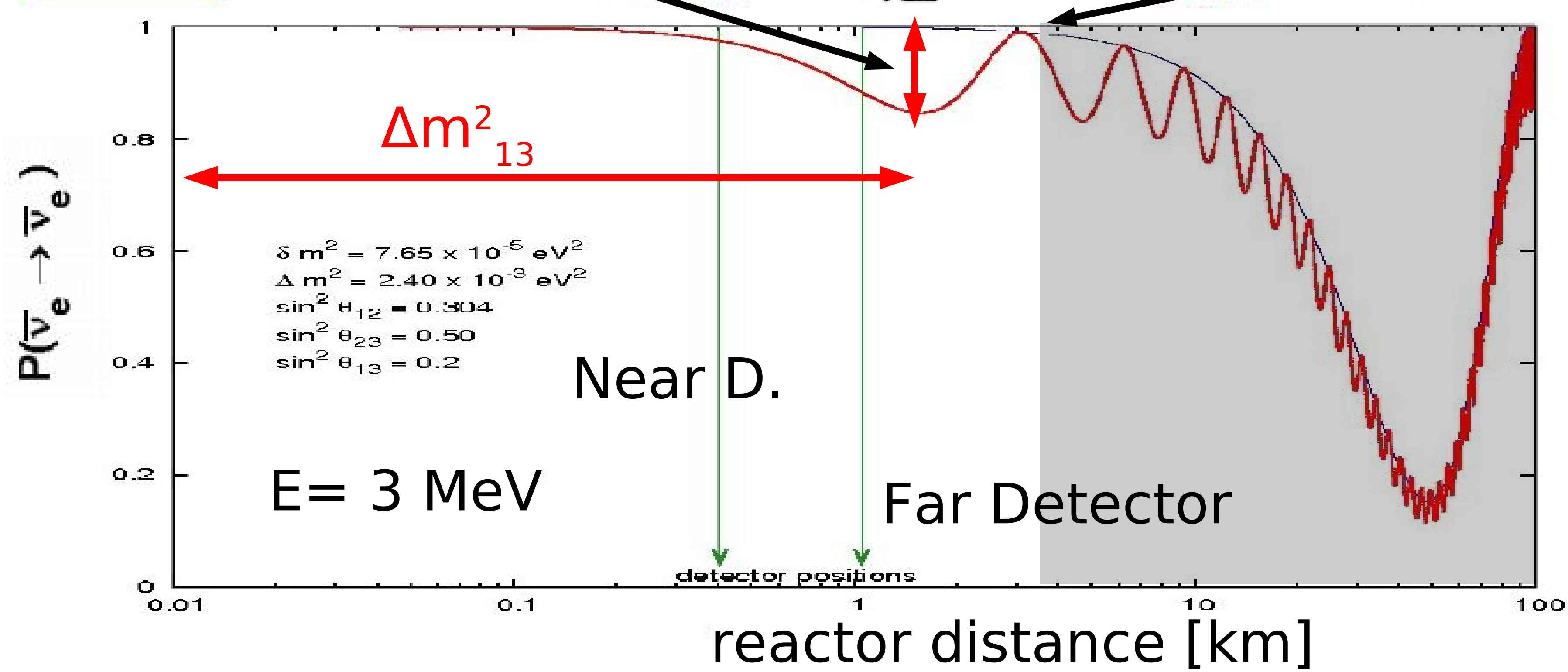


Near Detector
distance: ~400 m
400 ν/day
overburden: 120 mwe
under construction

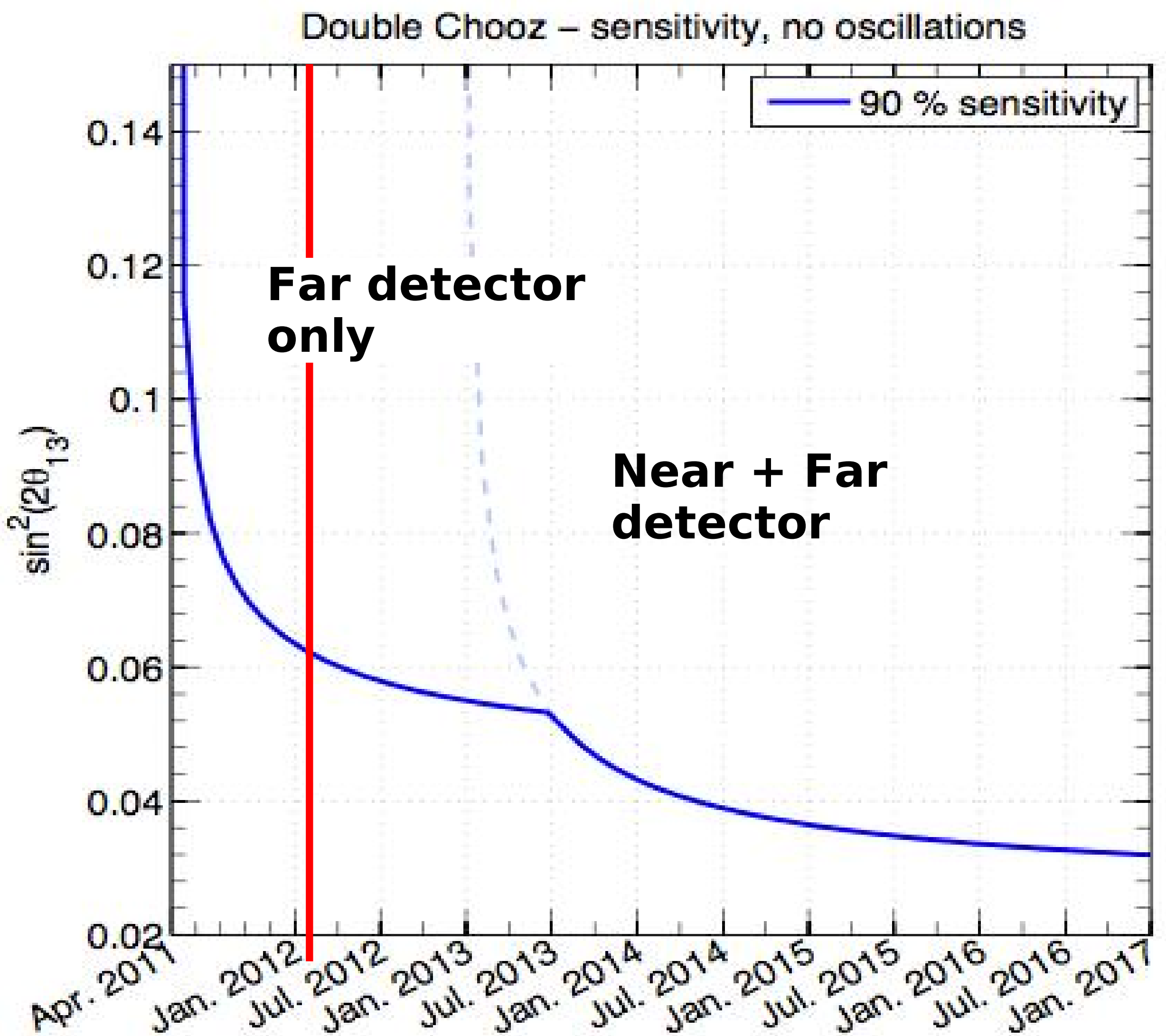
Far Detector
distance: 1050 m
65 ν/day (@ full power)
overburden: ~300 mwe
start datataking: apr. 2011

Disappearance Probability

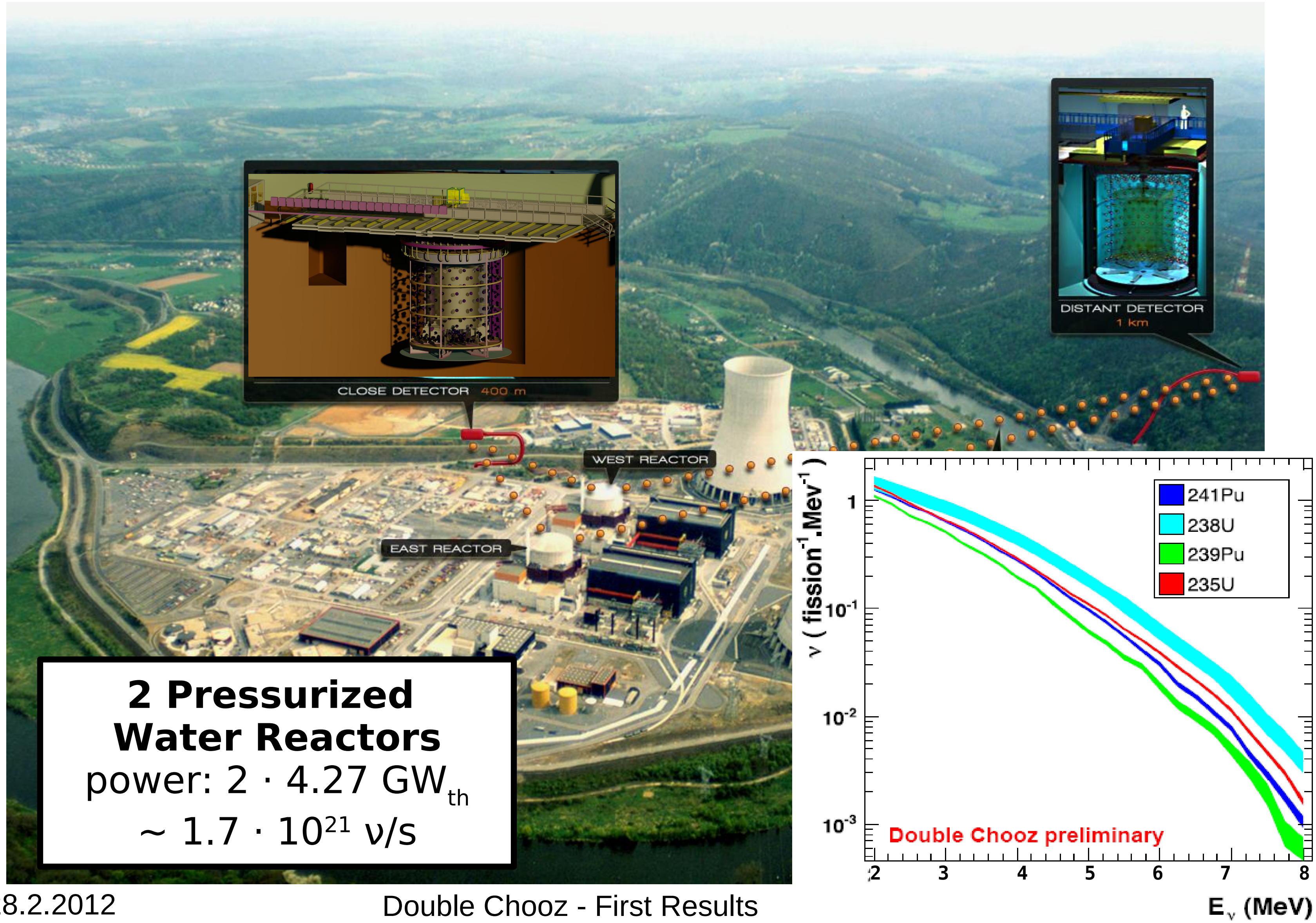
$$P_{\bar{\nu}_e \to \bar{\nu}_e} \approx 1 - \sin^2 2\theta_{13} \cdot \sin^2\left(\frac{\Delta m^2_{13} \cdot L}{4E}\right) + \text{[small corr.]}$$



DC Sensitivity



ν-source: Reactors



2 Pressurized Water Reactors

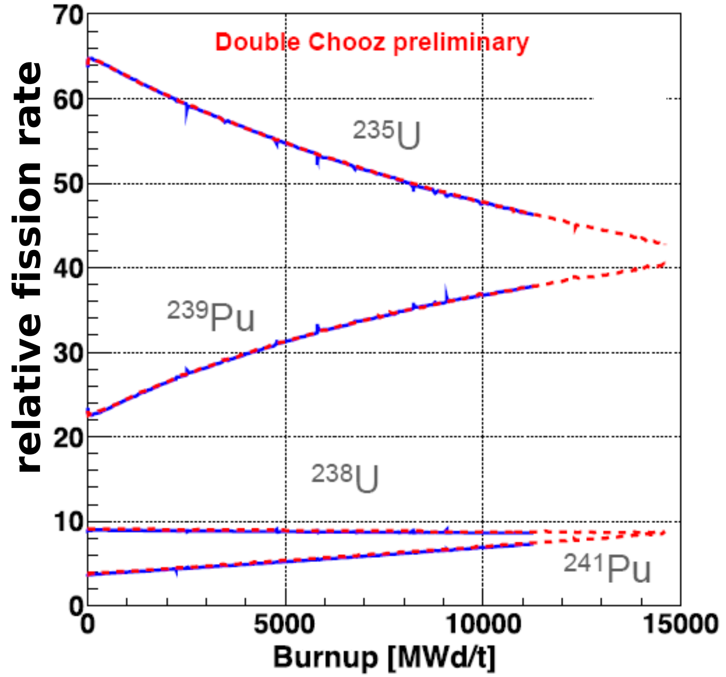
power: $2 \cdot 4.27\ \mathrm{GW_{th}}$

$\sim 1.7 \cdot 10^{21}\ \nu/\mathrm{s}$

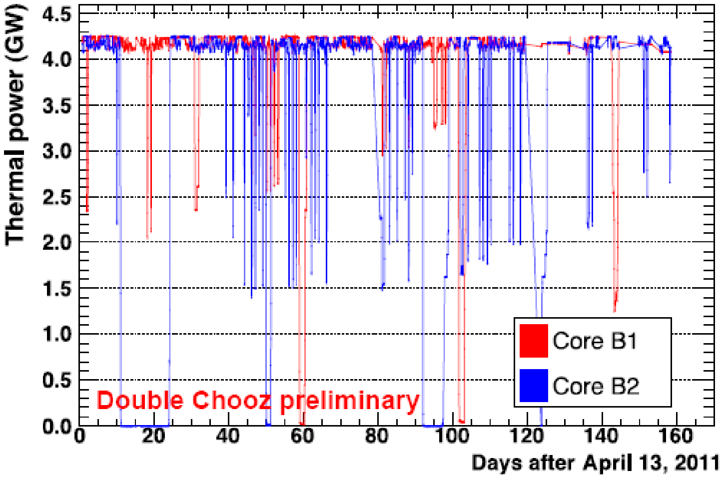
Reactor Antineutrino Flux

Antineutrino flux: $N_\nu \sim P_{th} \cdot (1+k)$

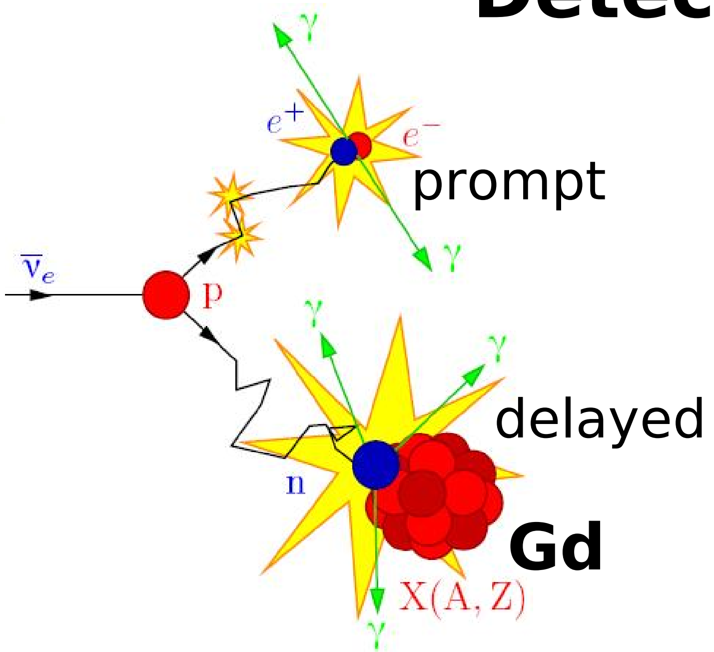
- P_{th} thermal power
- k fuel evolution correction ("burn-up")



- detailed simulation of core evolution (MURE & Dragon)
- P_{th} extracted continuously from reactor data
- normalisation to Bugey-4 σ_ν-measurement (use as "DC near detector", same for CHOOZ experiment)

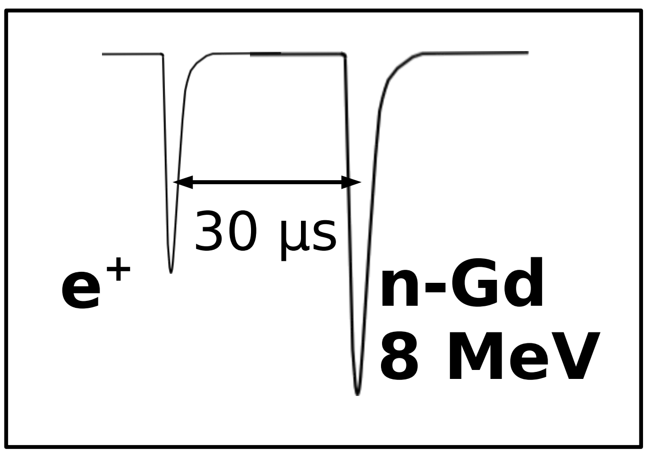


Detection Principle

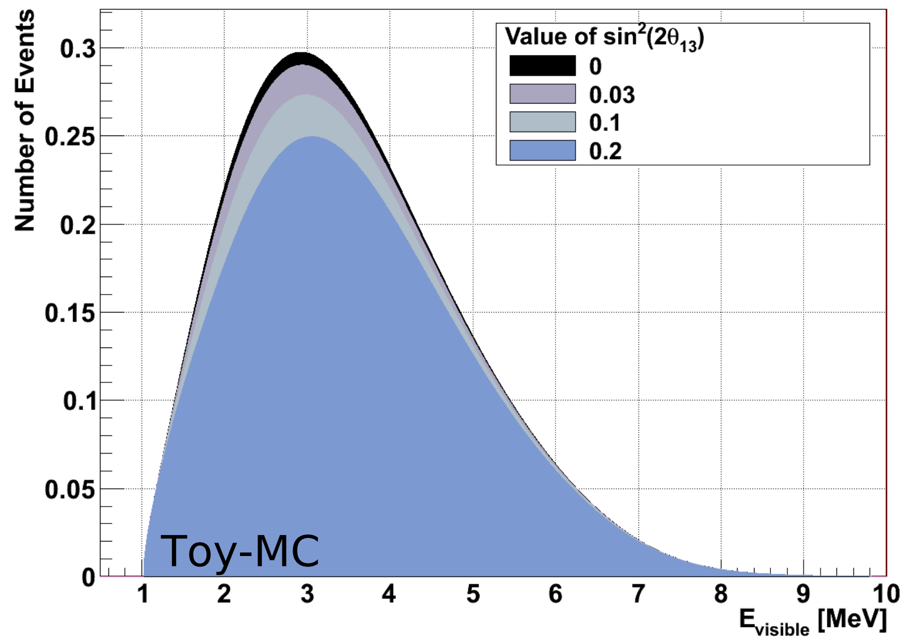


inverse beta decay:

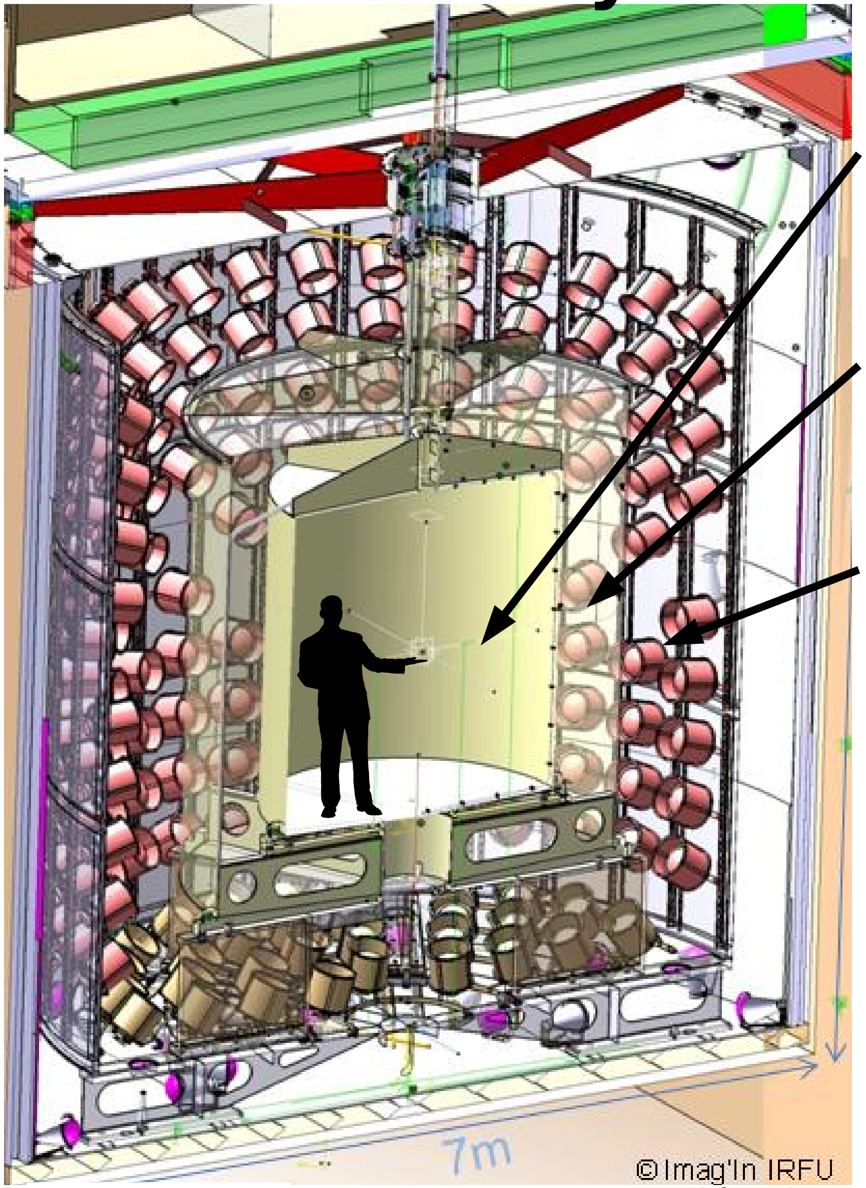
$$\bar{\nu}_e + p \rightarrow e^+ + n$$



prompt $E_{visible} \cong E_\nu$ - 0.78 MeV



4-Layer Detector Concept



Inner Target (10 m³):

- Gd-loaded liquid scint. (1g/l Gd)
- *ν-Target, Fiducial Volume*

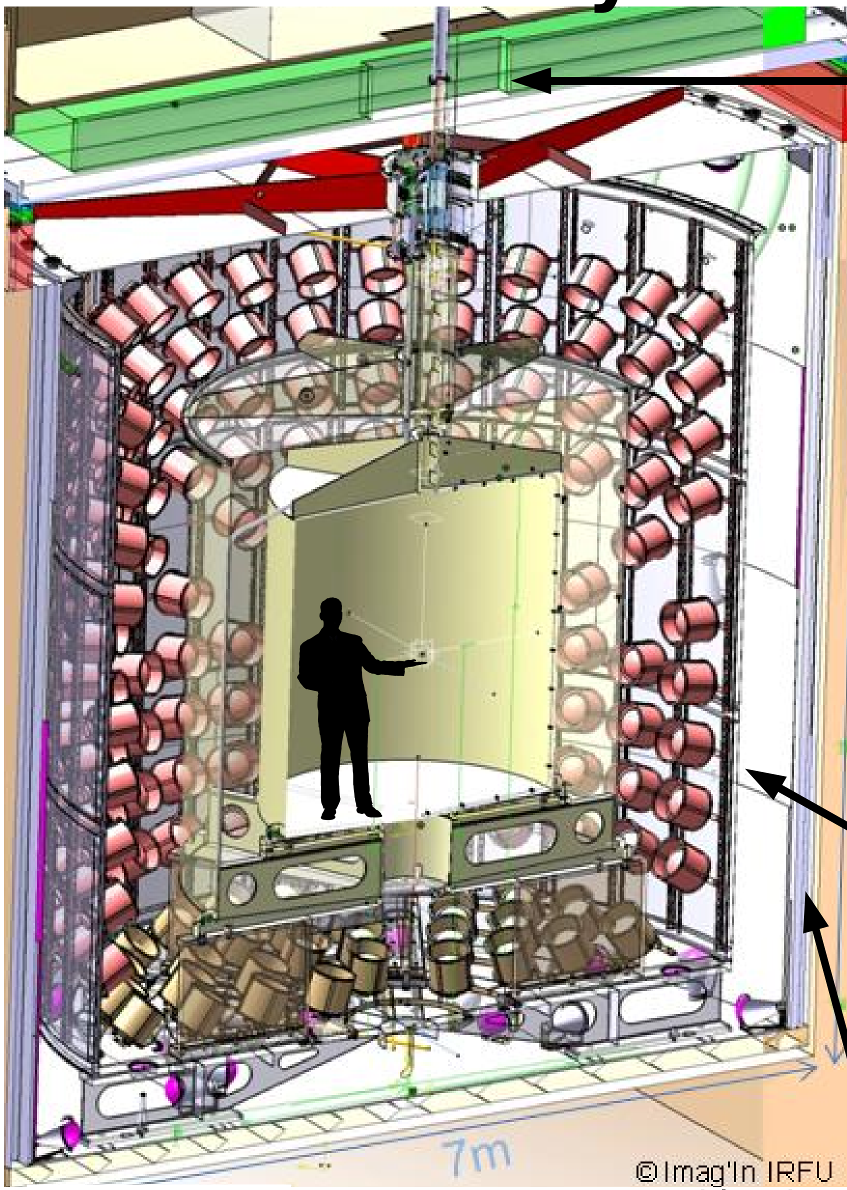
Gamma Catcher (22 m³):

- unloaded liquid scint. (C_xH_y)
- *energy containment*

Buffer (114 m³):

- 390 PMTs (10”)
- non-scintillating mineral oil
- *protection against radioactivity*

4-Layer Detector Concept



Outer Veto (plastic scintillator strips)

Inner Target (10 m^3):
- Gd-loaded liquid scint. (1g/l Gd)
- *ν-Target, Fiducial Volume*

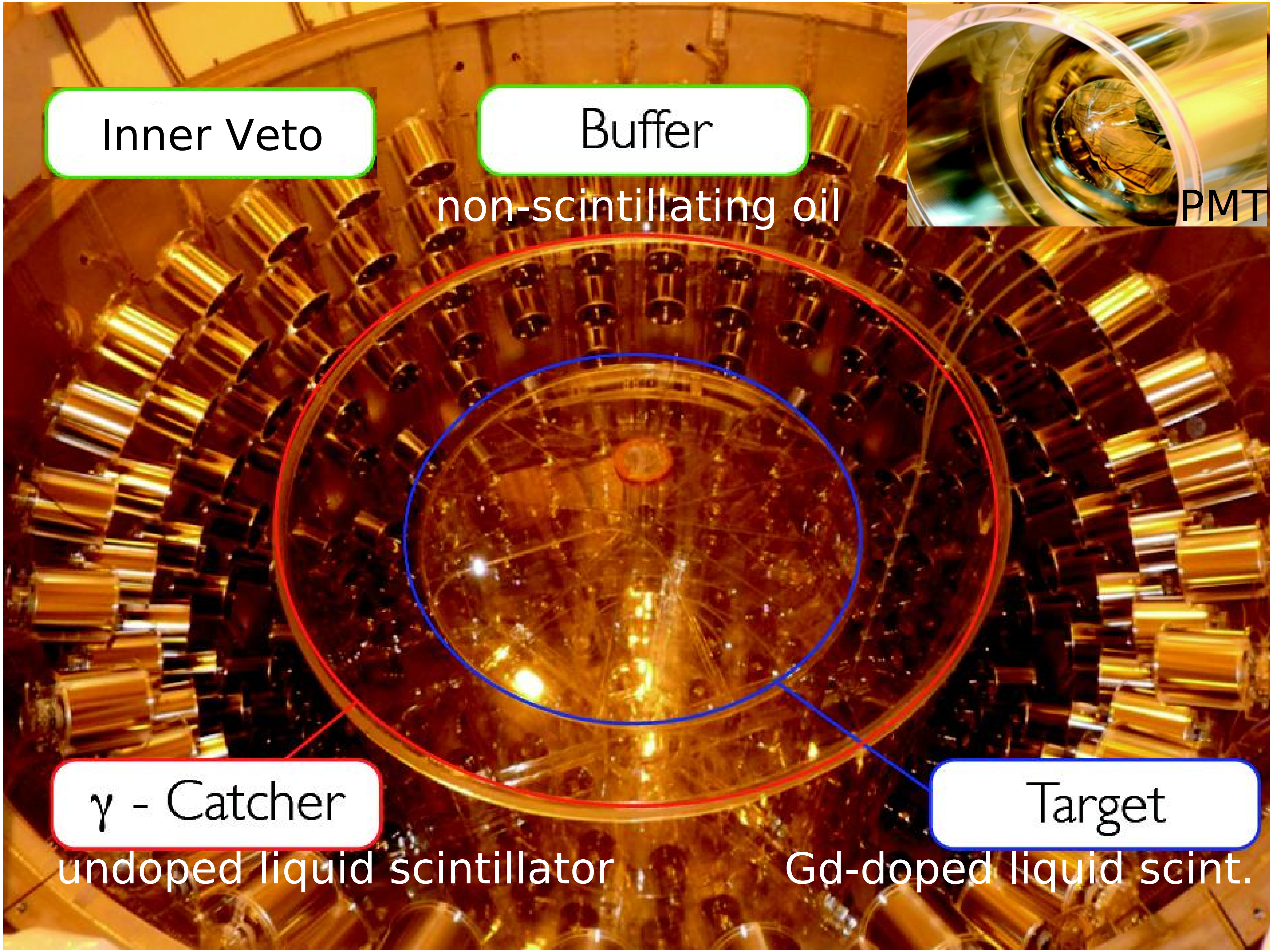
Gamma Catcher (22 m^3):
- unloaded liquid scint. (C_xH_y)
- *energy containment*

Buffer (114 m^3):
- 390 PMTs (10”)
- non-scintillating mineral oil
- *protection against radioactivity*

optically separated

Inner Veto: (90 m^3)
- 78 PMTs (8”)
- LAB (scintillating oil)
- *active muon tagging*

passive 15 cm Steel Shielding


Inner Veto
Buffer
non-scintillating oil
PMT
γ - Catcher
undoped liquid scintillator
Target
Gd-doped liquid scint.

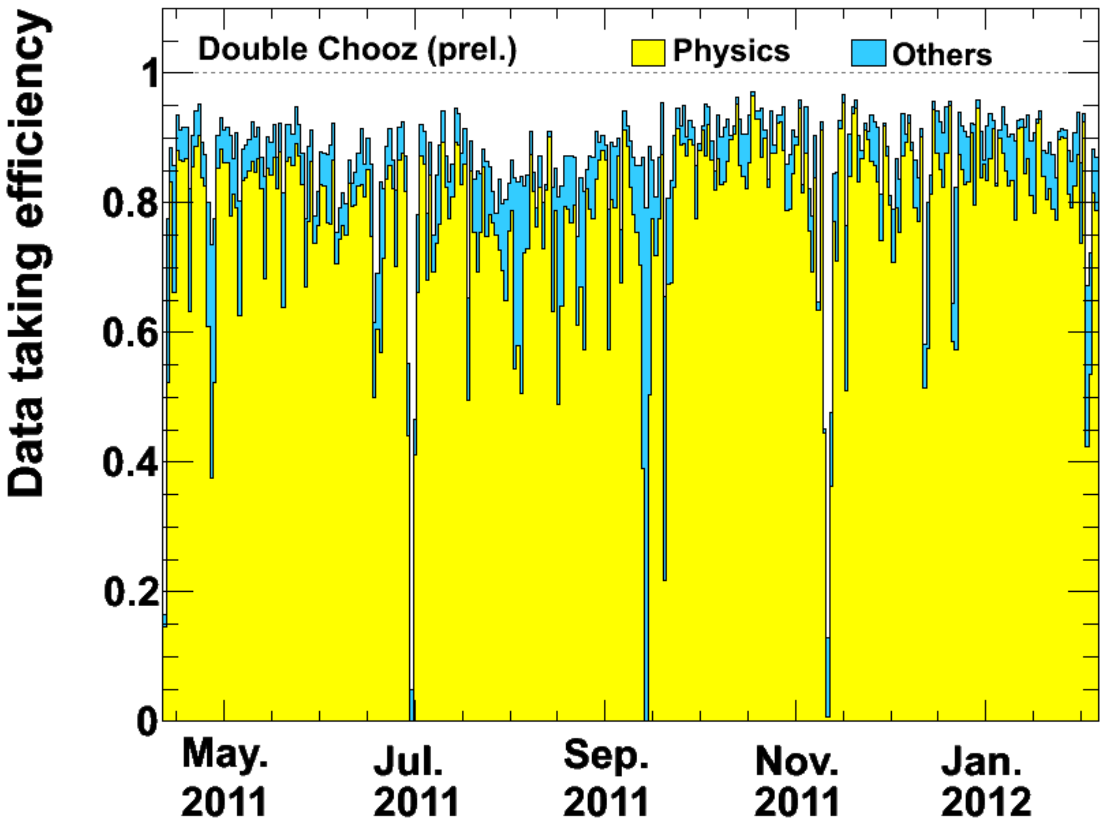
Milestones

- May 2008 - October 2010 → Far detector construction.
- December 2010 → Far detector filling completed.
- April 2011 → Far detector commissioned.

- April 2011 → Start physics data taking with far detector.
- April 2011 → Near laboratory construction started.
- July 2011 → Outer Veto commissioned.

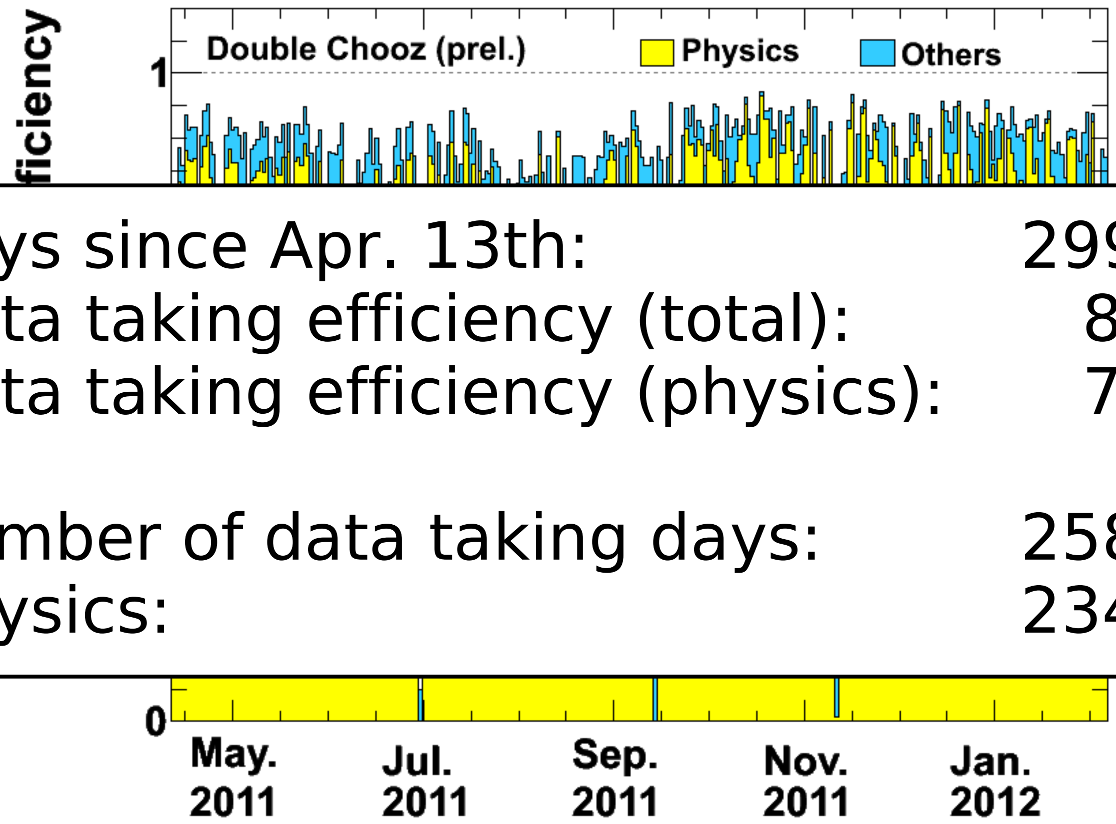
- November 2011 → First result @ LowNu 2011
- Dec 2011 → *Paper on arxiv:1112.6353*
  submitted to PRL

Data Taking
(as of Feb, 5th 2012)



start:
Apr. 13th 2011

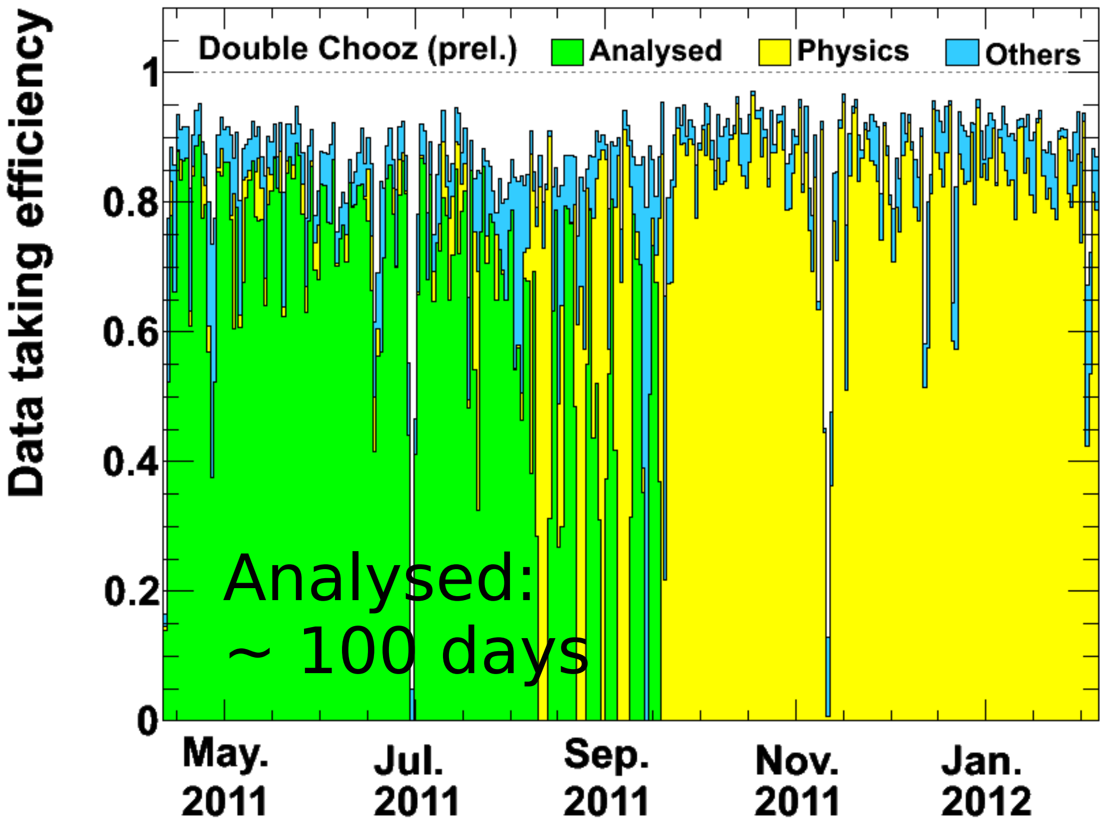
Data Taking
(as of Feb, 5th 2012)



• days since Apr. 13th:	299 days
• Data taking efficiency (total):	86.3 %
• Data taking efficiency (physics):	78.4 %
• number of data taking days:	258 days
• physics:	234 days

start:
Apr. 13th 2011

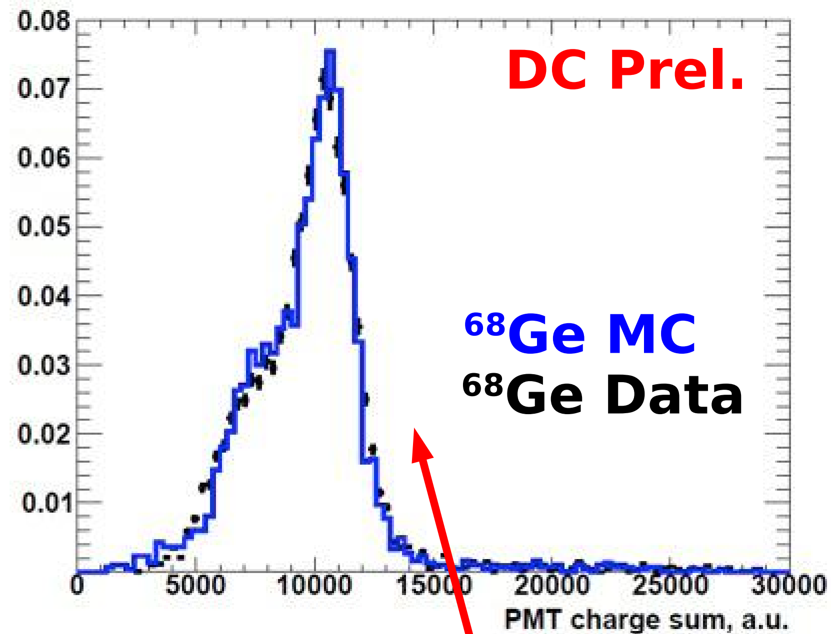
Data Taking
(as of Feb, 5th 2012)

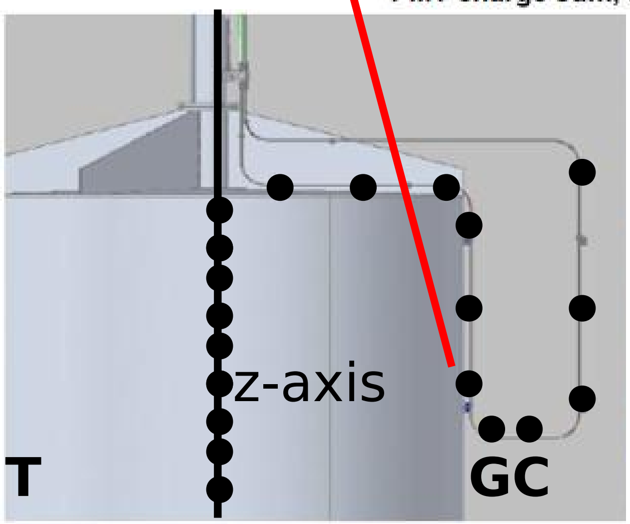


start:
Apr. 13th 2011

Calibration

- LED light injection system (Inner Detector/ Inner Veto)
- deployment of radioactive sources (^{137}Cs, ^{68}Ge, ^{60}Co, ^{252}Cf)
    - in Gamma Catcher volume
    - in Target volume on z-axis
- µ-induced calib. sources: e.g. ^{12}B, spallation neutrons





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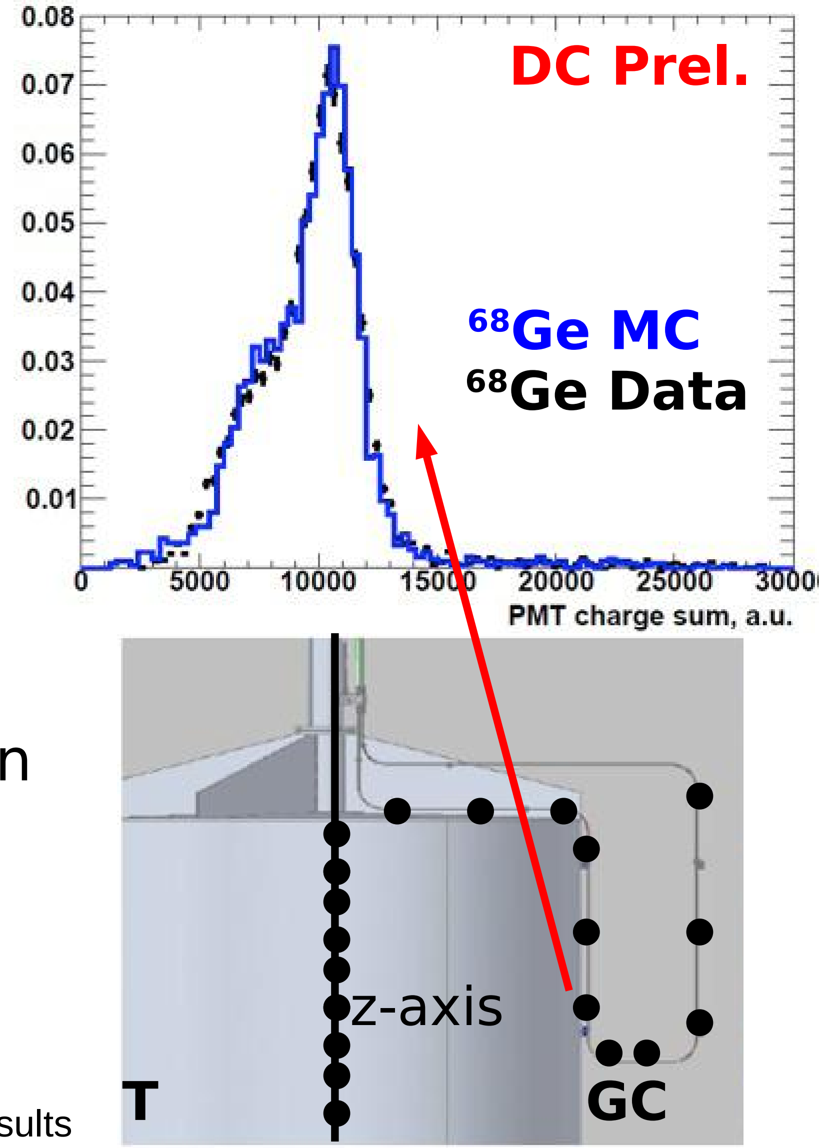
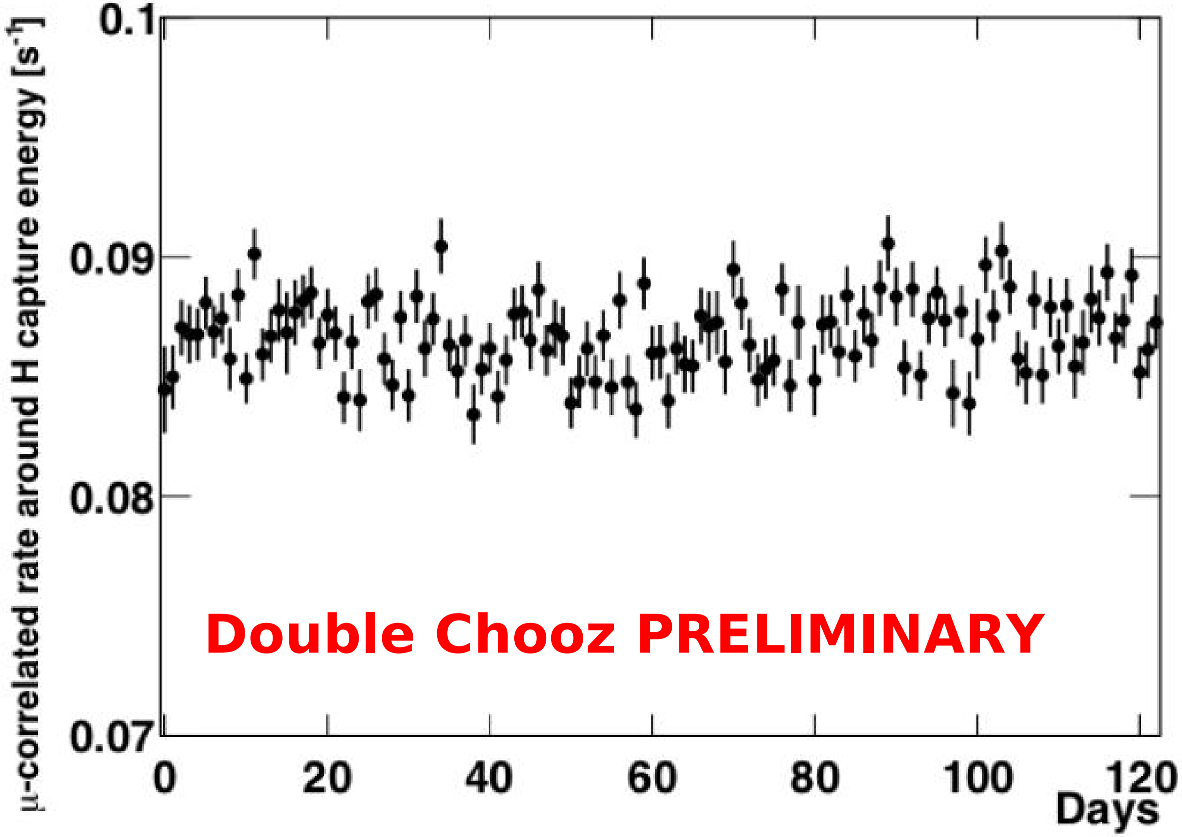


- reconstruction performance
- detector response (e.g. position dependency)
- quenching and Cerenkov (scintillator non-linearities)
- MC tuning

Detector Stability

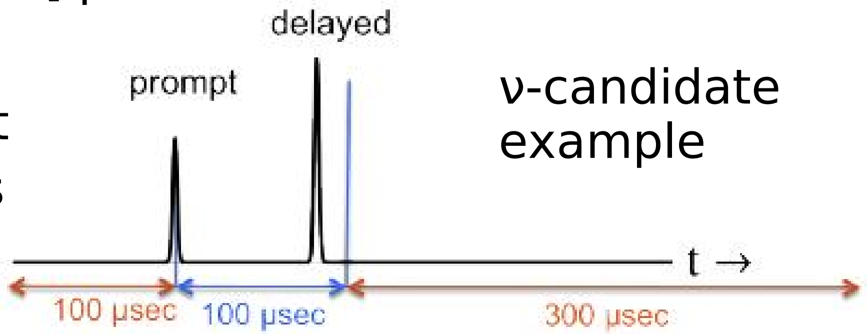
rate around n-H capture energy (~ 7000/ day)



scintillator+electronics stable during analysed period

Neutrino candidate selection

- PMT spontaneous light emission rejection cuts (14 PMTs switched off):
  - ensure homogenously distributed light: $maxQ_{onePMT}/totQ_{allPMTs}$
  - require small spread in start times: $rms(T_{start})$
- *Muon Veto*: discard all triggers within 1ms after a muon
- *Inverse Beta Decay*:
  - Prompt signal within [0.7,12] MeV
  - Delayed signal within [6,12] MeV (*Gd-only*)
  - Coincidence time window: [2, 100] μs
- *Multiplicity condition*
  - No trigger 100 μs before prompt
  - Exactly one trigger in [2,400] μs after the prompt

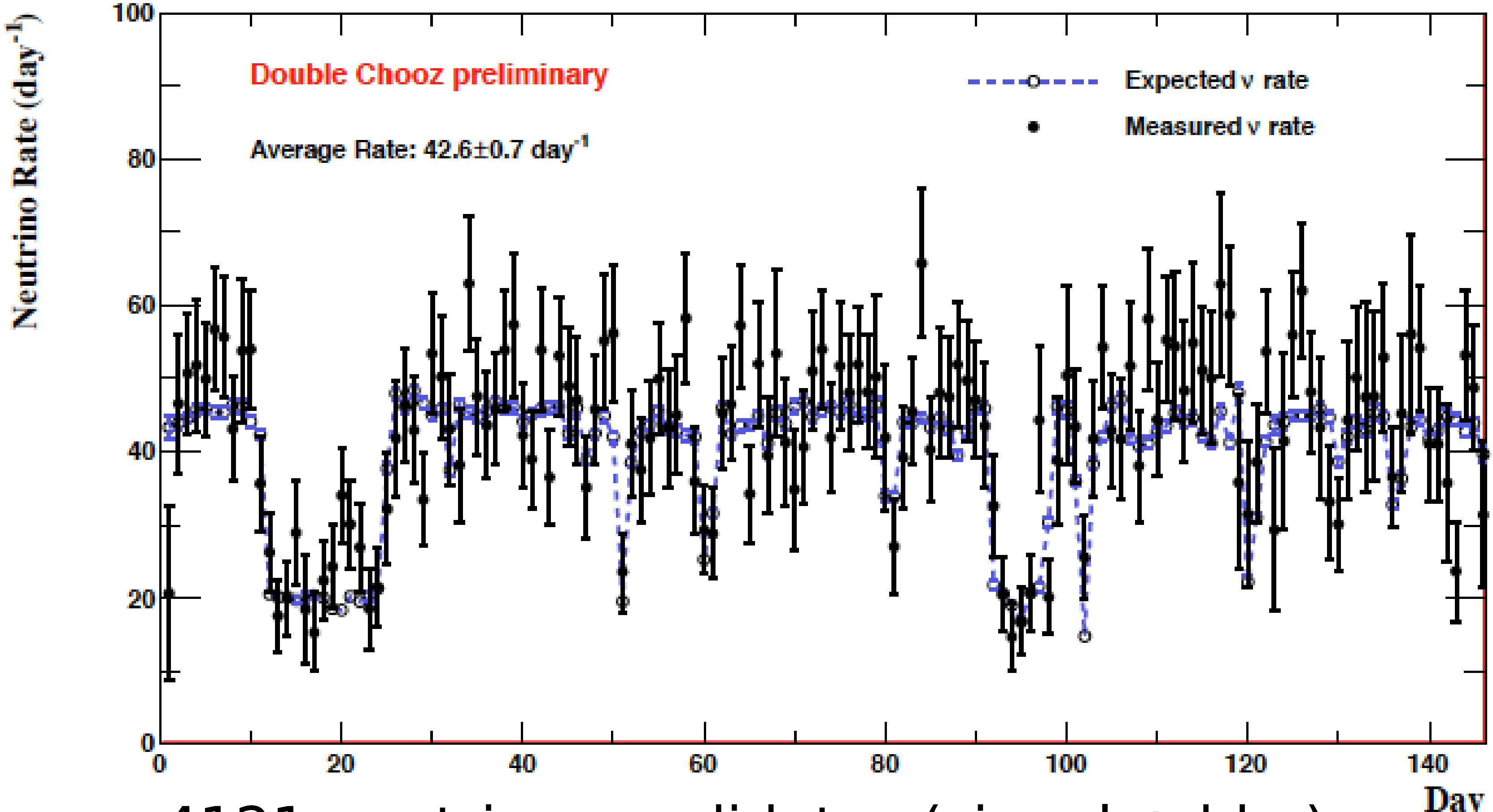


ν-candidate example

Candidates vs. Time

Neutrino candidates rate

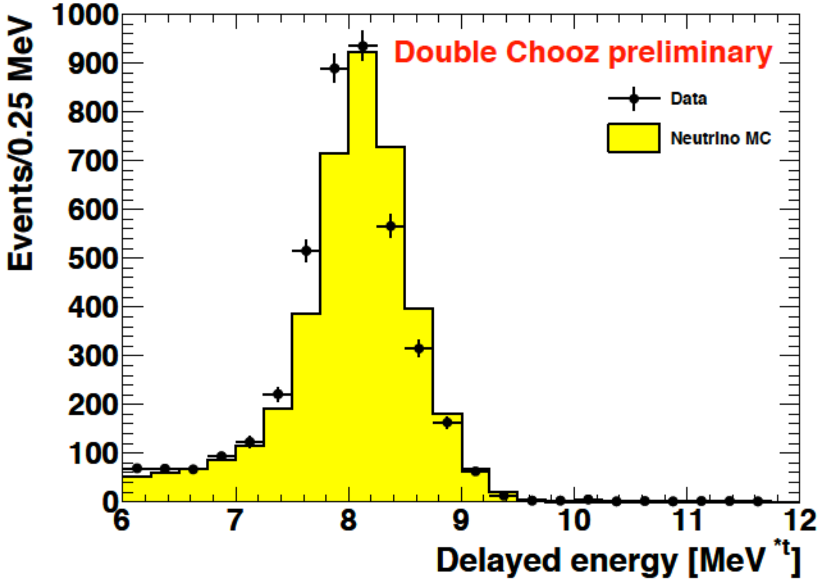
no background subtracted



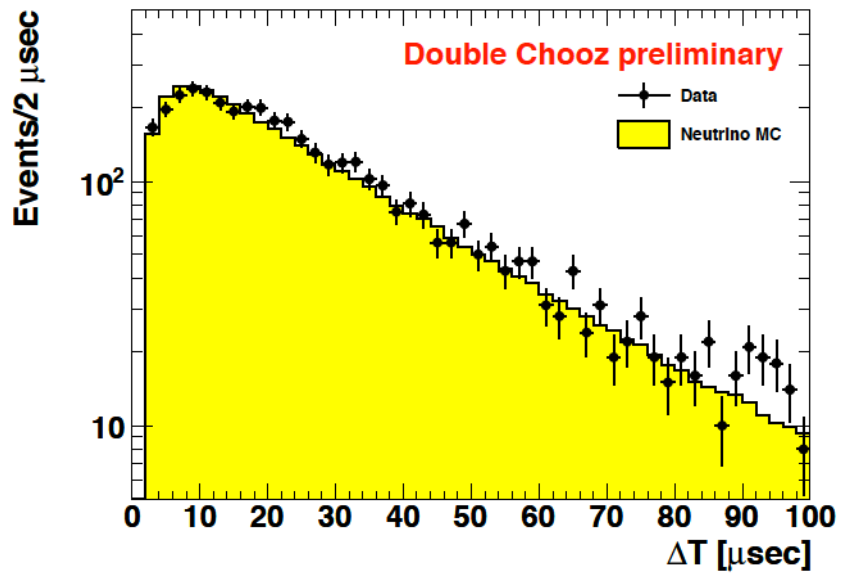
4121 neutrino candidates (signal + bkg)

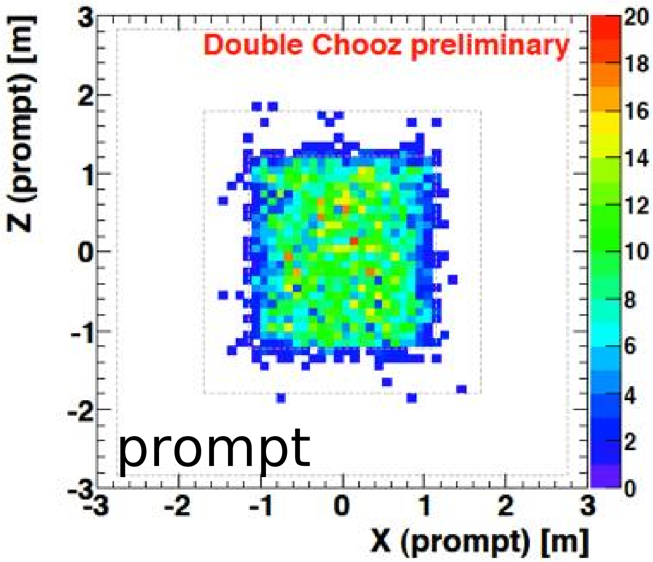
Example Distributions

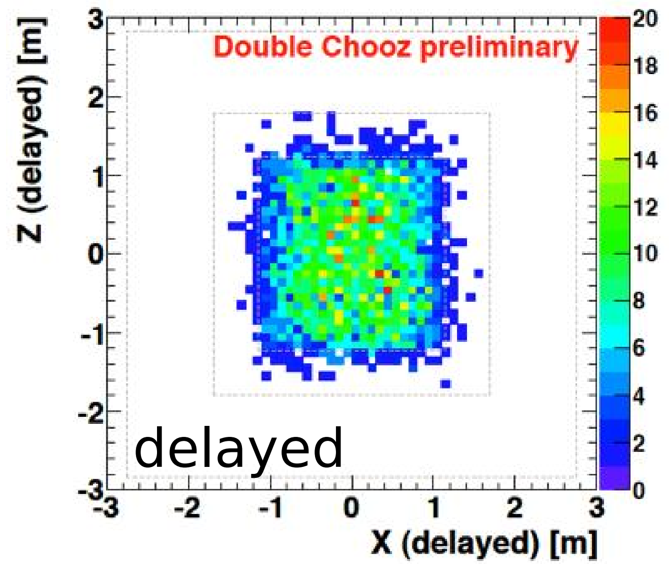
delayed energy



Δt (prompt-delayed)







Cut Efficiencies & MC Lifetime Correction

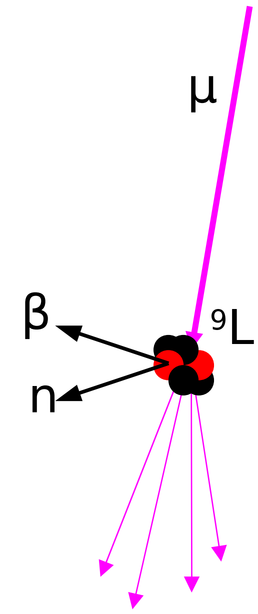
Parameter	Value [%]	Uncertainty [%]	Comment
Trigger efficiency	100	$^{+0}_{-0.4}$	readout threshold 0.7 MeV
Gd fraction	86.0	$\pm$ 0.6	^{252}Cf: $\frac{Gd}{Gd+H}$
Δt window	96.5	$\pm$ 0.5	^{252}Cf: data/MC residual
ΔE window	94.5	$\pm$ 0.6	^{252}Cf: data/MC residual
Total	78.3	$\pm$ 1.0	

- uncertainties estimated from data/MC remaining discrepancies
- MC lifetime corrections 92.5 % overall, dominantly: muon veto dead time (4.5 %)

Backgrounds

- 3 classes of *correlated* background, all muon induced:
  - ^{9}Li
  - fast neutrons
  - stopping muons entering through the chimney
- *accidental* background:
  - in-situ measurement with offtime windows
  - rate: $0.33 \pm 0.03\ d^{-1}$

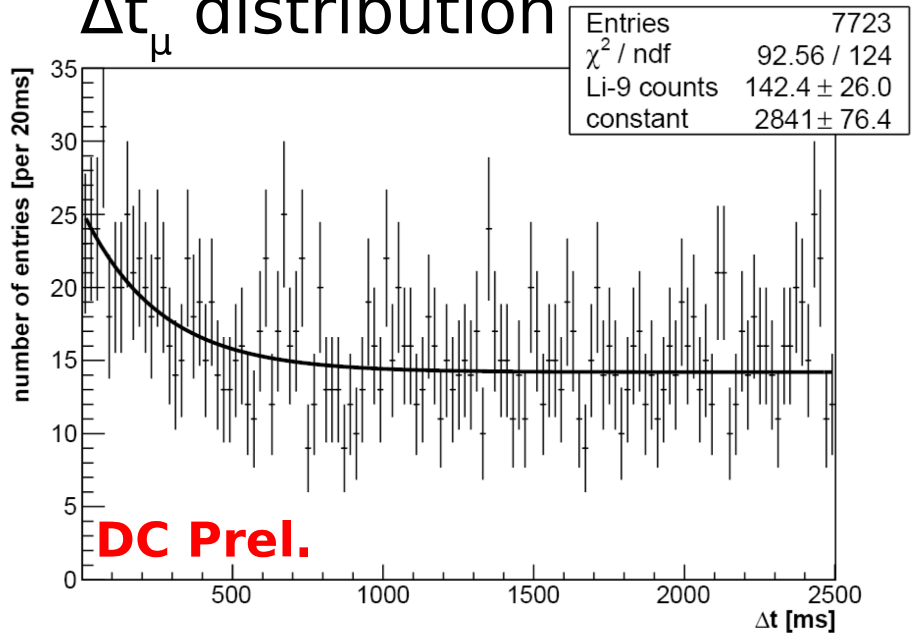
^{9}Li Background



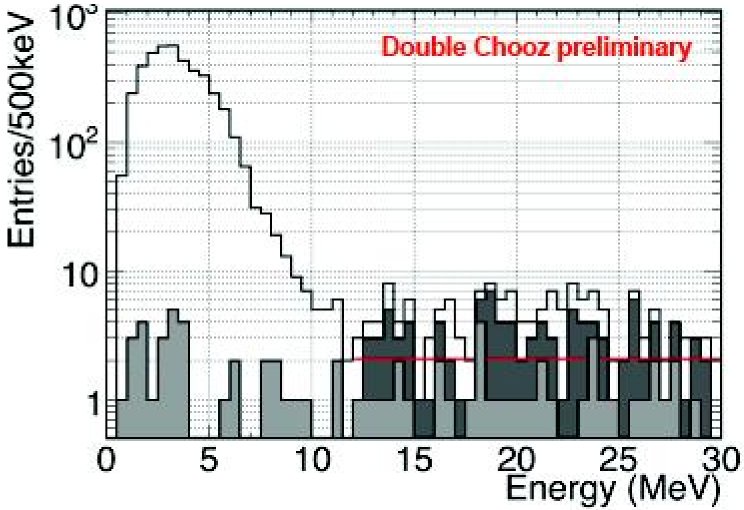
- ^{9}Li production by muons mainly during high energy deposition
- β-n emitter, halflife: 178 ms for ^{9}Li
- search for triple coincidence:
  HE muon (>600 MeV)-prompt-delayed

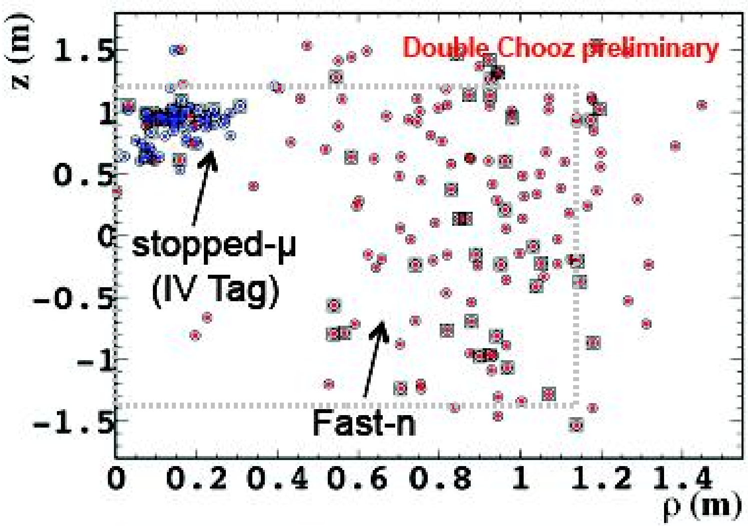
- fit constant + exponential (^{9}Li halflife)
- rate: $2.3 \pm 1.2\ d^{-1}$

Δt_{μ} distribution



Fast Neutrons & Stopping Muons



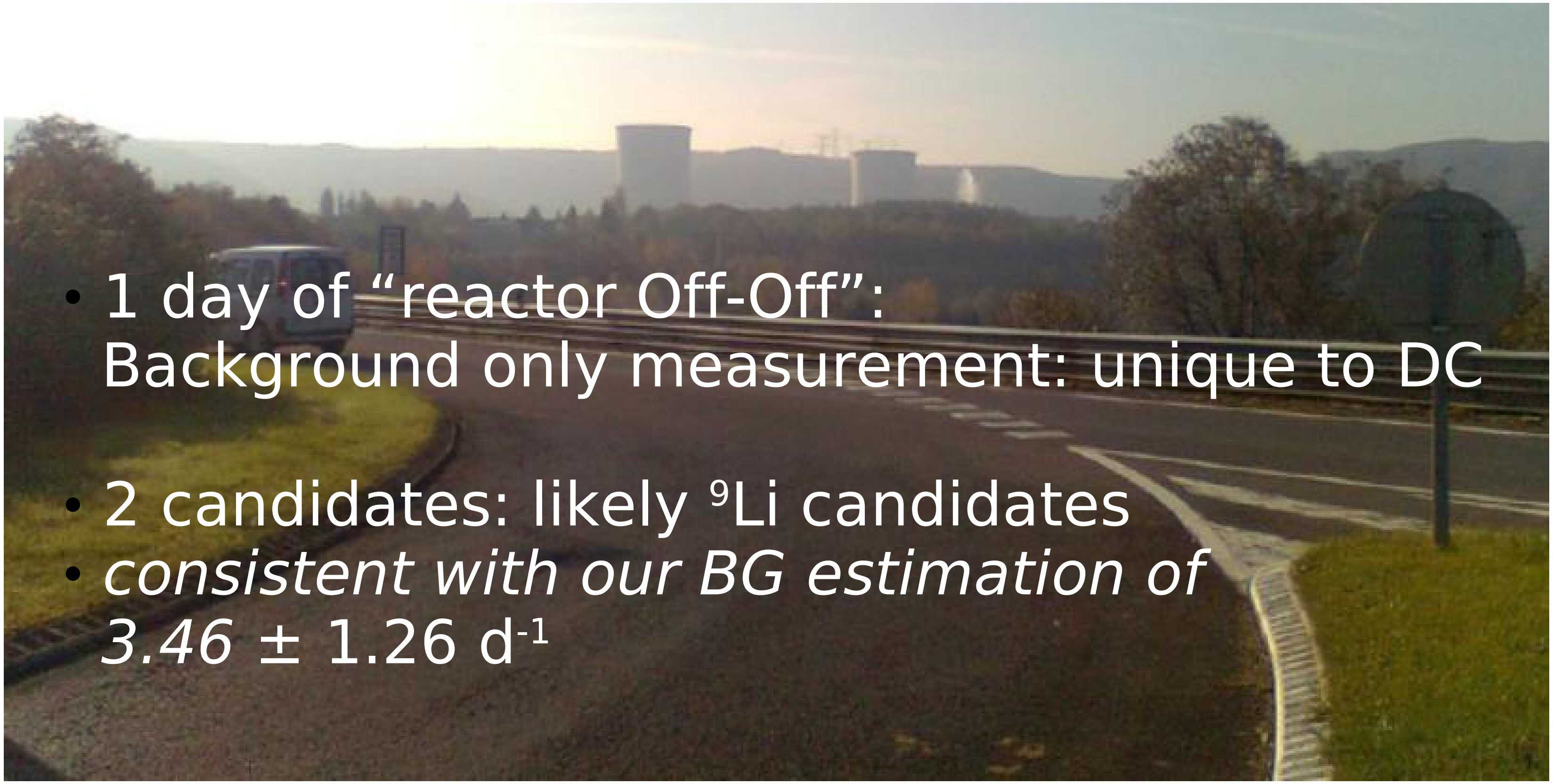


- Neutrino search extended to 30 MeV for prompt
- > 12 MeV: pure BG sample (dark grey)

- extrapolation into neutrino energy [0.7, 12] MeV assuming flat spectrum (validated, using *IV tagged* events, light grey)
- rate: 0.83 ± 0.38 d^{-1}

vertex distribution
boxed events: IV tagged

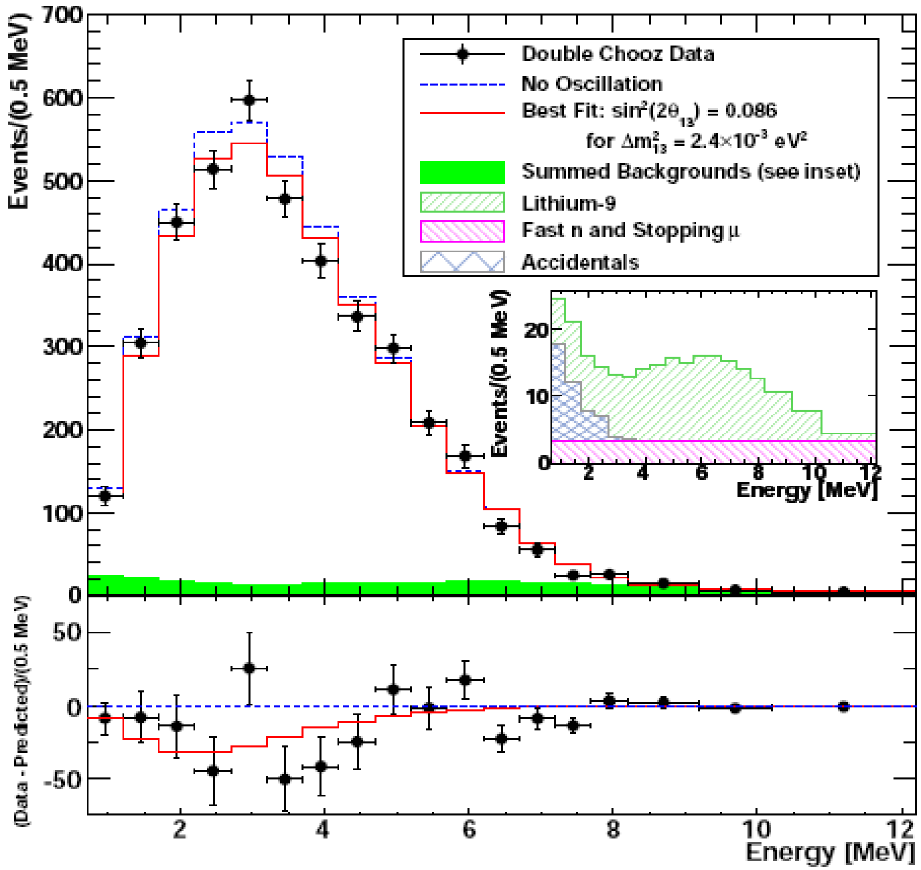
Both Reactors Off



- 1 day of "reactor Off-Off":
  Background only measurement: unique to DC

- 2 candidates: likely ^{9}Li candidates
- *consistent with our BG estimation of 3.46* ± 1.26 d^{-1}

Rate + Shape fit

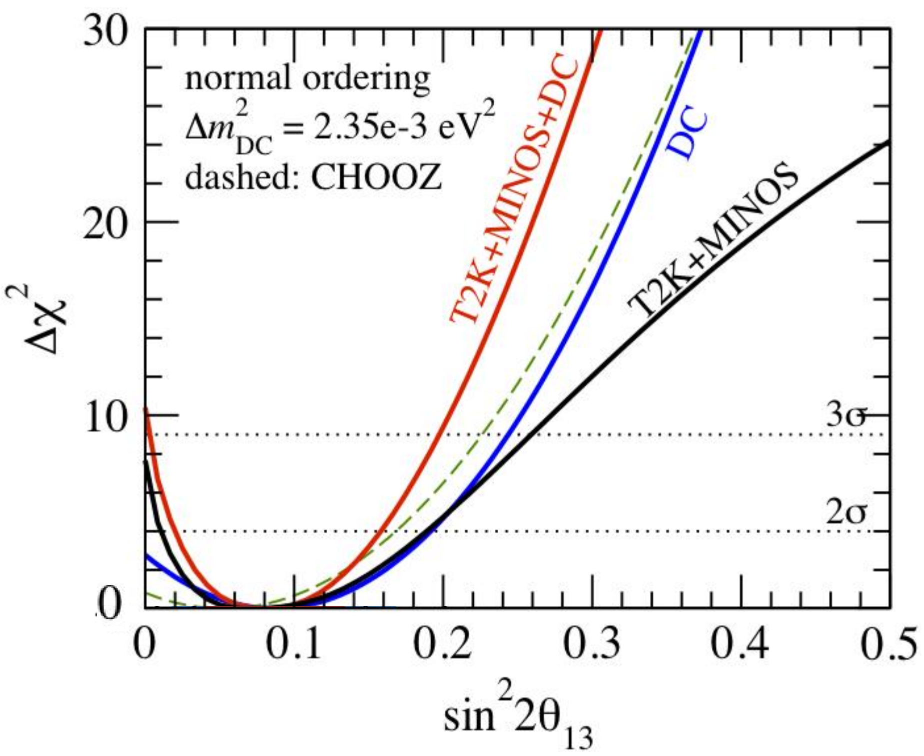


best fit:

$\sin^2(2\theta_{13}) = 0.086 \pm 0.041$ (stat) $\pm\ 0.030$ (syst)

no-oscillation hypothesis excluded at 94.6 % C.L.

Global θ_{13} Search



- consistent best fit values of T2K+MINOS and DC
- fit including T2K+MINOS+DC excludes $\theta_{13}=0$ by more than 3σ

Summary & Outlook

- Far Detector is stable, data taking is continuing as planned

- DC has analysed 100 days of data, first results on rate+shape analysis of θ_{13} have been published: $\sin^2(2\theta_{13}) = 0.086 \pm 0.041$ (stat) ± 0.030 (syst)

- Promising analysis improvements underway
- 2 times statistics already available for analysis

- Near detector is under construction, operational end of 2012

Thank you!

General Formula

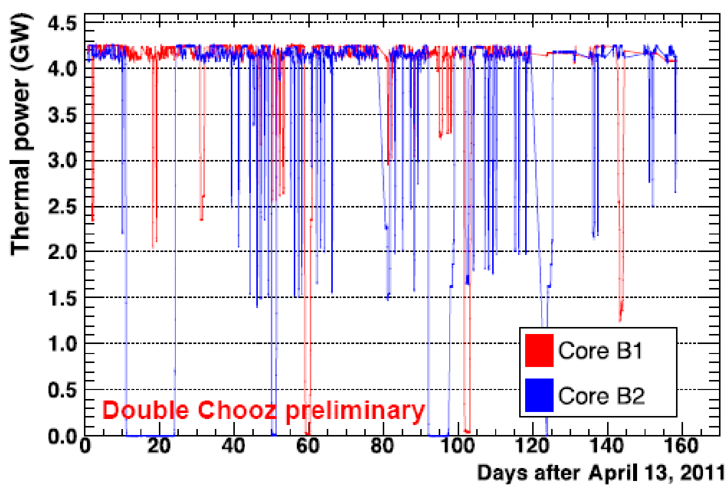
$$\mathcal{P}_{ee} \simeq 1 \; - \; 4\sin^2\theta_{13}\cos^2\theta_{13}\sin^2\Delta_{31}$$
$$- \; \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$
$$+ \; 2\sin^2\theta_{13}\cos^2\theta_{13}\sin^2\theta_{12}(\cos(\Delta_{31}-\Delta_{21})-\cos\Delta_{31})$$

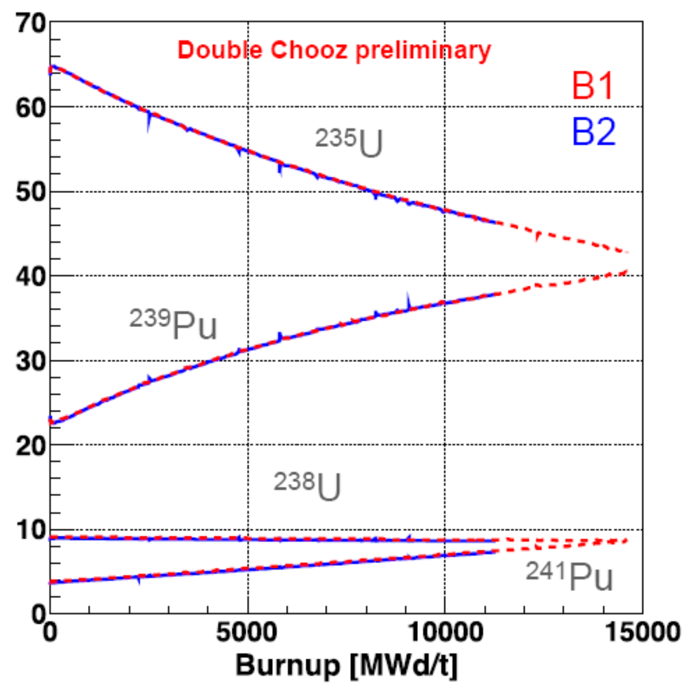
where $\Delta_{ij} := \Delta m^2_{ij}\frac{L}{4E}$ and $i, j \in 1, 2, 3.$

Reactor Flux

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

- $P_{th}(t)$: thermal power vs. time
- E_f: takes into account fuel evolution ("burn-up")



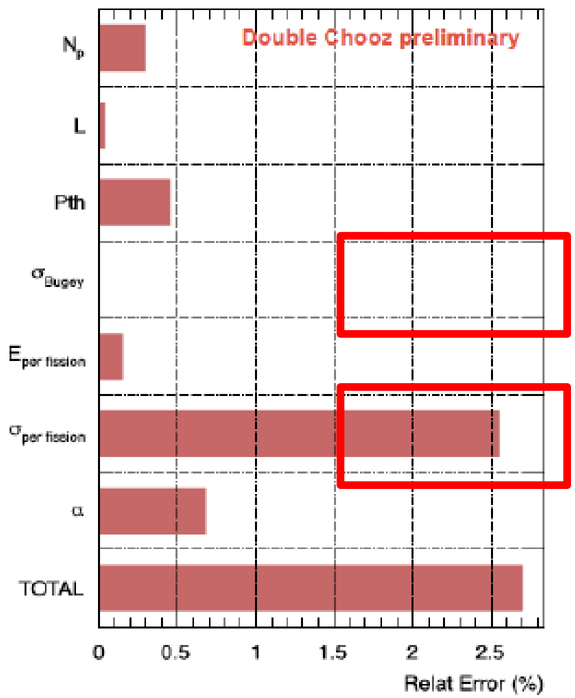


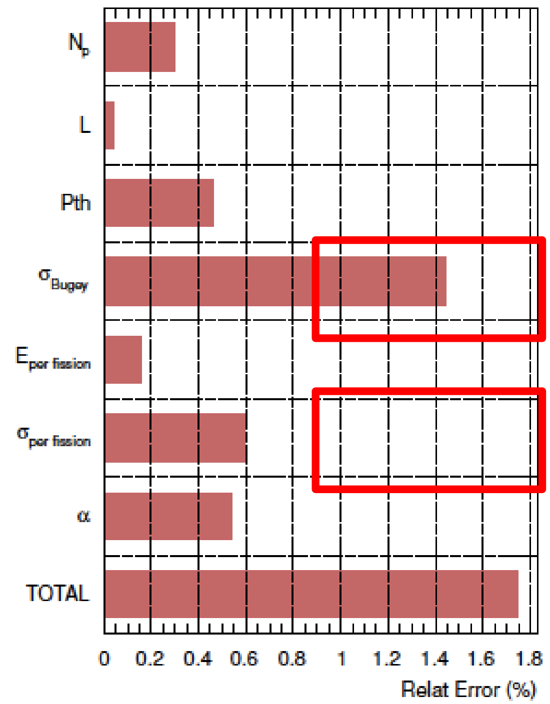
Bugey 4 anchor point

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

σ_{Bugey}

$\sigma_{per\ fission}$



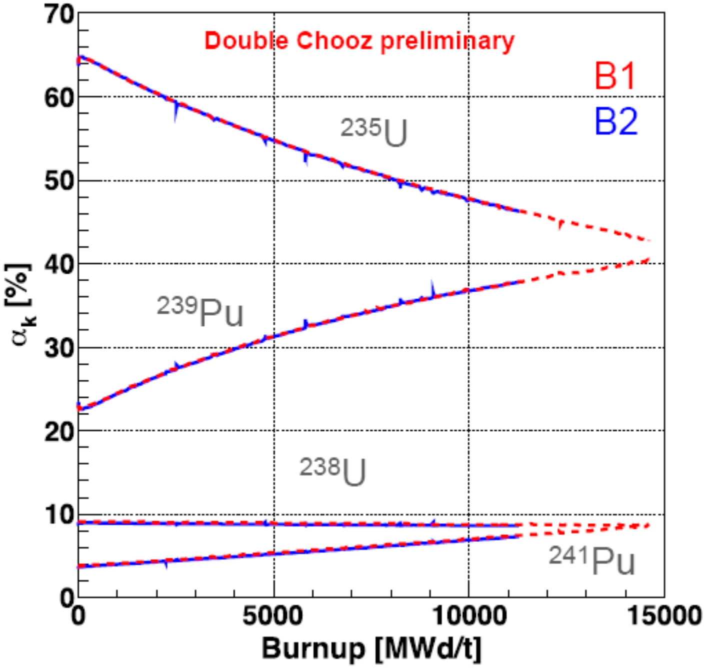


without Bugey 4 anchor:
uncertainty 2.7 %

with Bugey 4 anchor:
uncertainty 1.7 %

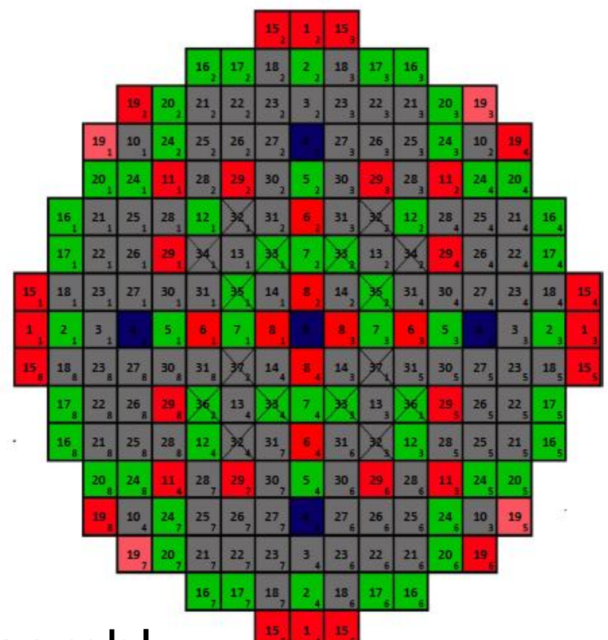
Burn Up

fraction fission rate



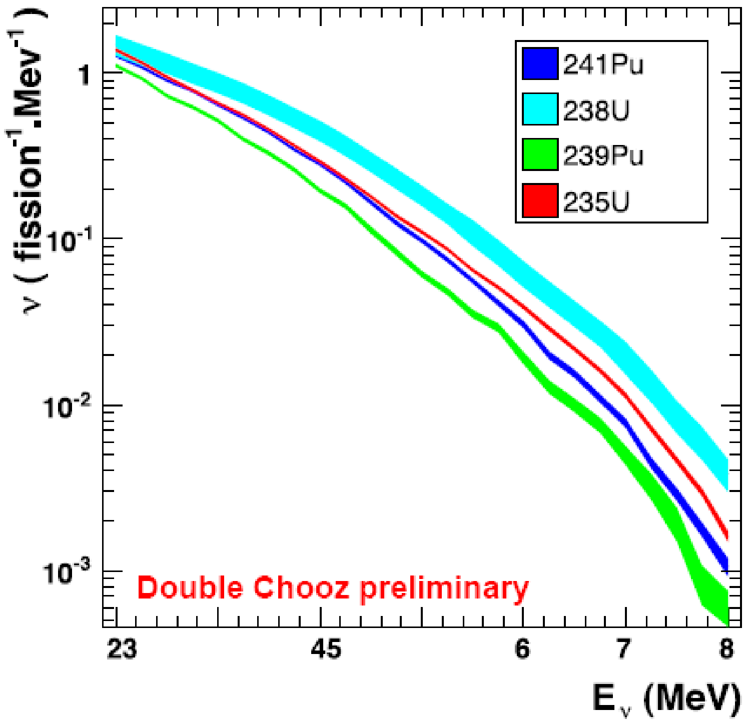
reactor core evolution was simulated in detail with MURE (Subatech Nantes), DRAGON (US)

reactor neutrino flux uncertainty: 1.7 %
(without Bugey anchor point: 2.7 %)



core assembly

Signal: Neutrino Flux



▪Recent re-evaluations of fissile isotopes by

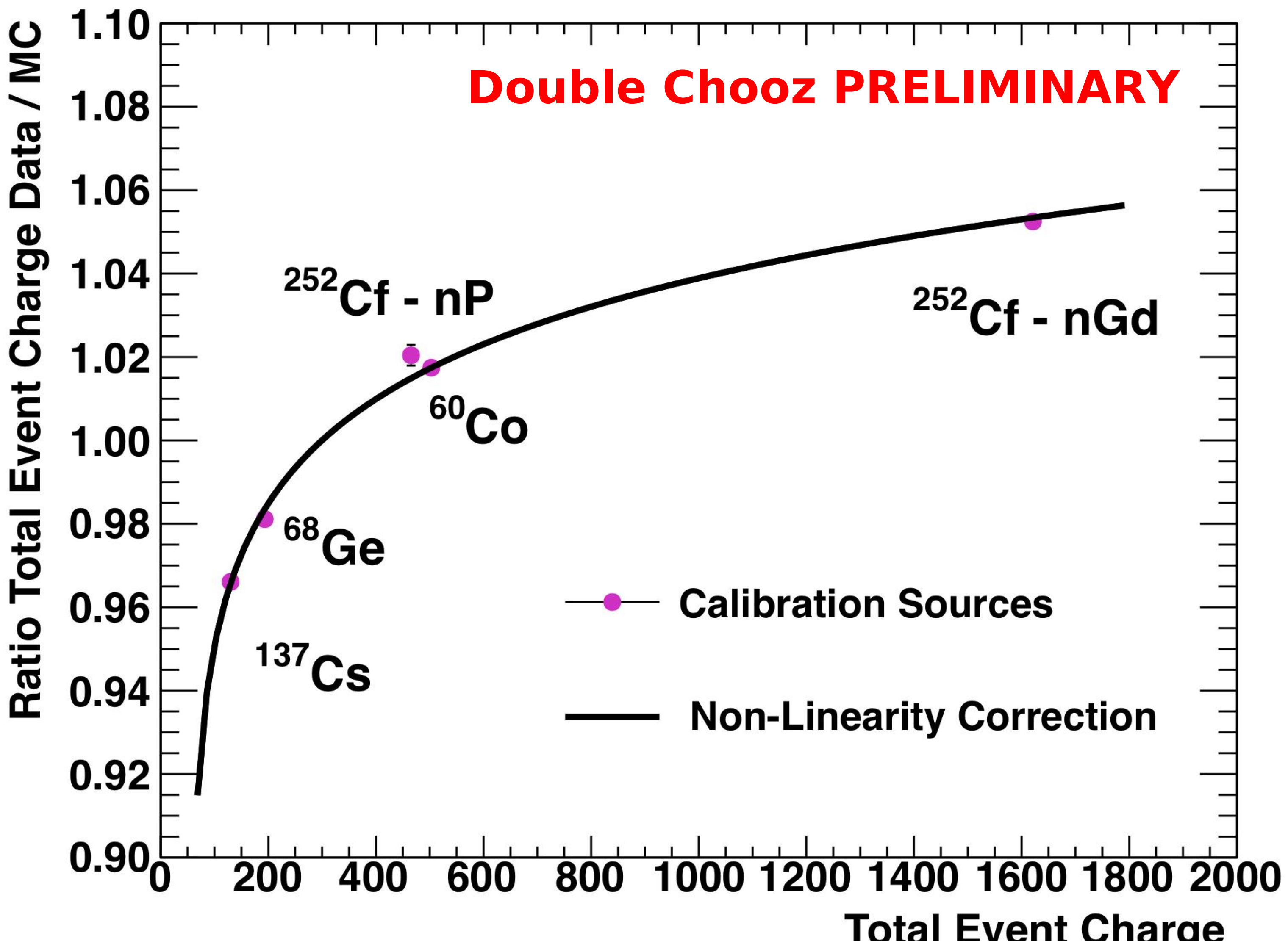
-Th. A. Mueller et al, Phys.Rev. C83(2011) 054615

-P. Huber, Phys.Rev. C84 (2011) 024617

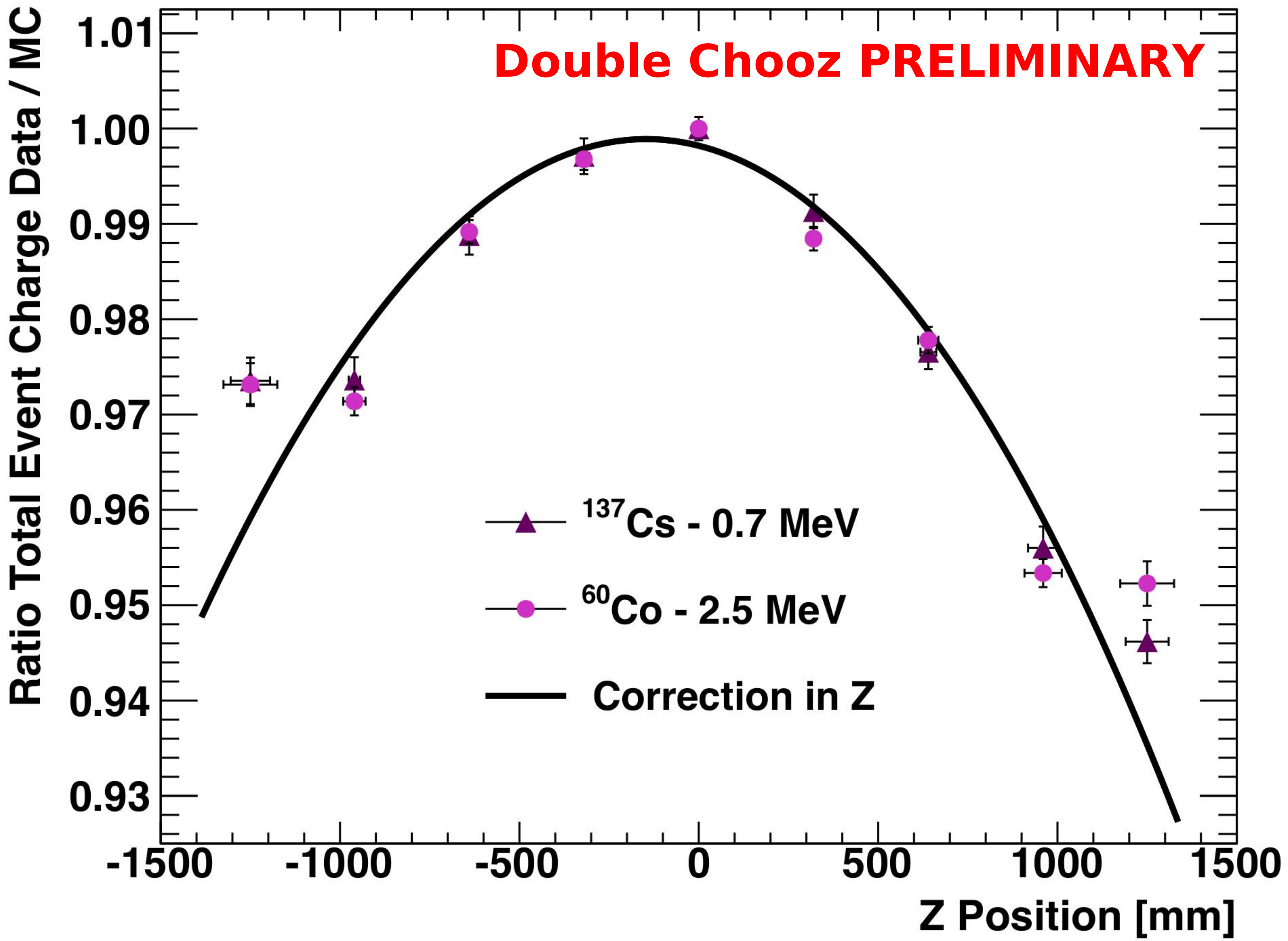
▪ Ab initio calculation of ^{238}U at Irfu and Subatech-Nantes.

- flux reevalution +3 % compared to previous reference
- DC 1 detector phase: use Bugey-4 cross section *measurement* (1990) as anchor point for flux normalisation (like CHOOZ)

Calibration

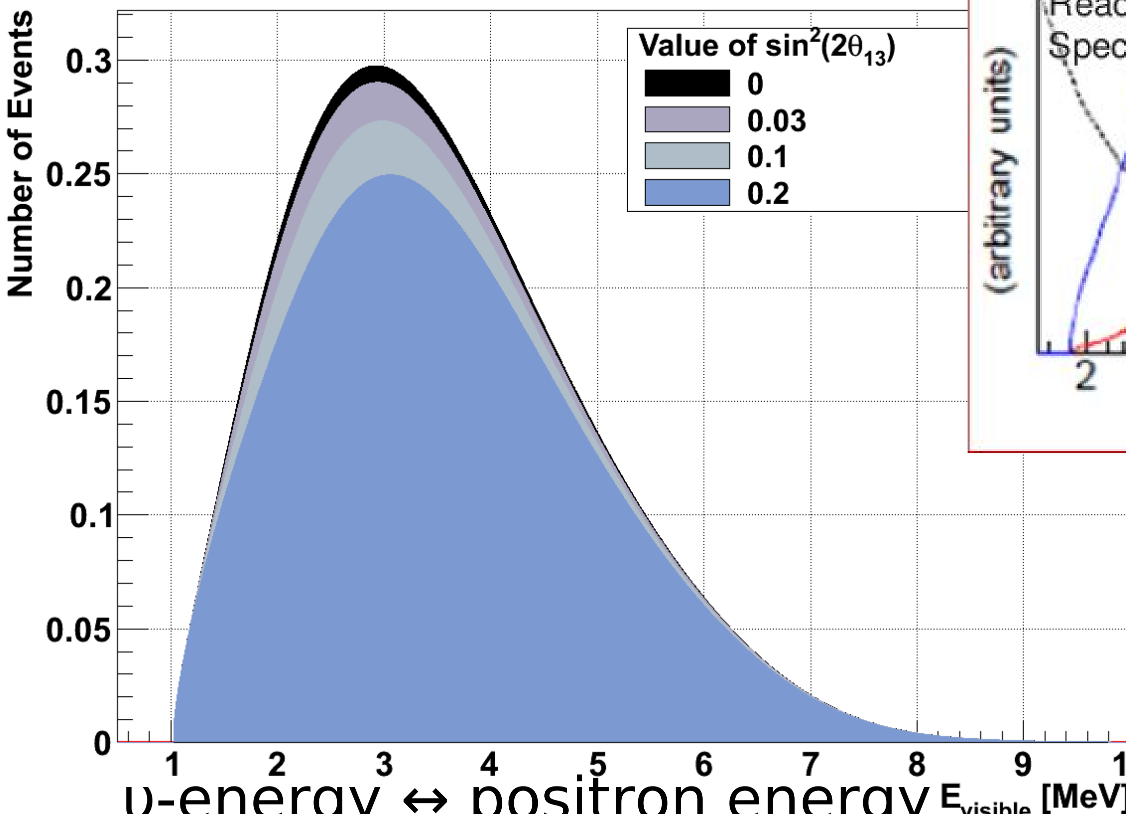


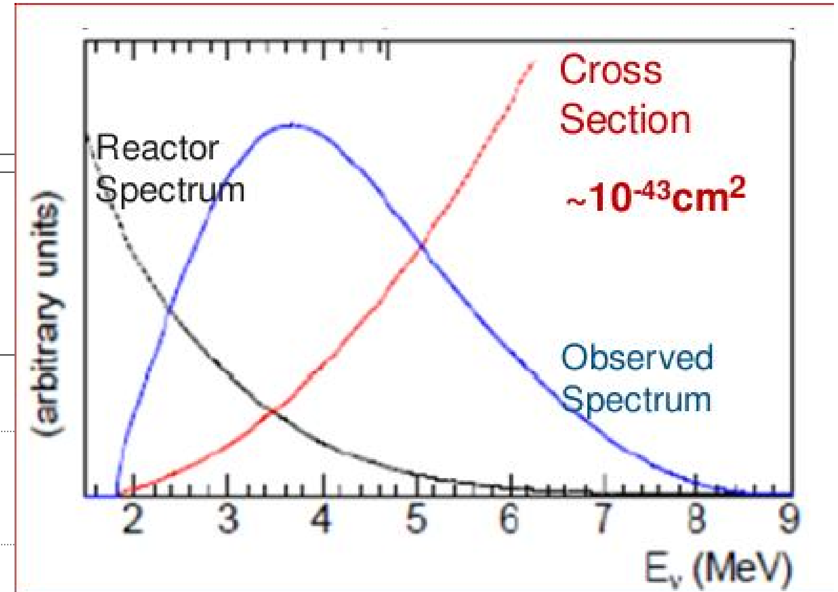
Calibration



Prompt Energy Spectrum

Inverse Beta Decay





υ-Energy Spectrum

υ-energy ↔ positron energy

↔ prompt visible energy

spectral distortion due to θ_{13}

θ_{13} analysis:

- rate information

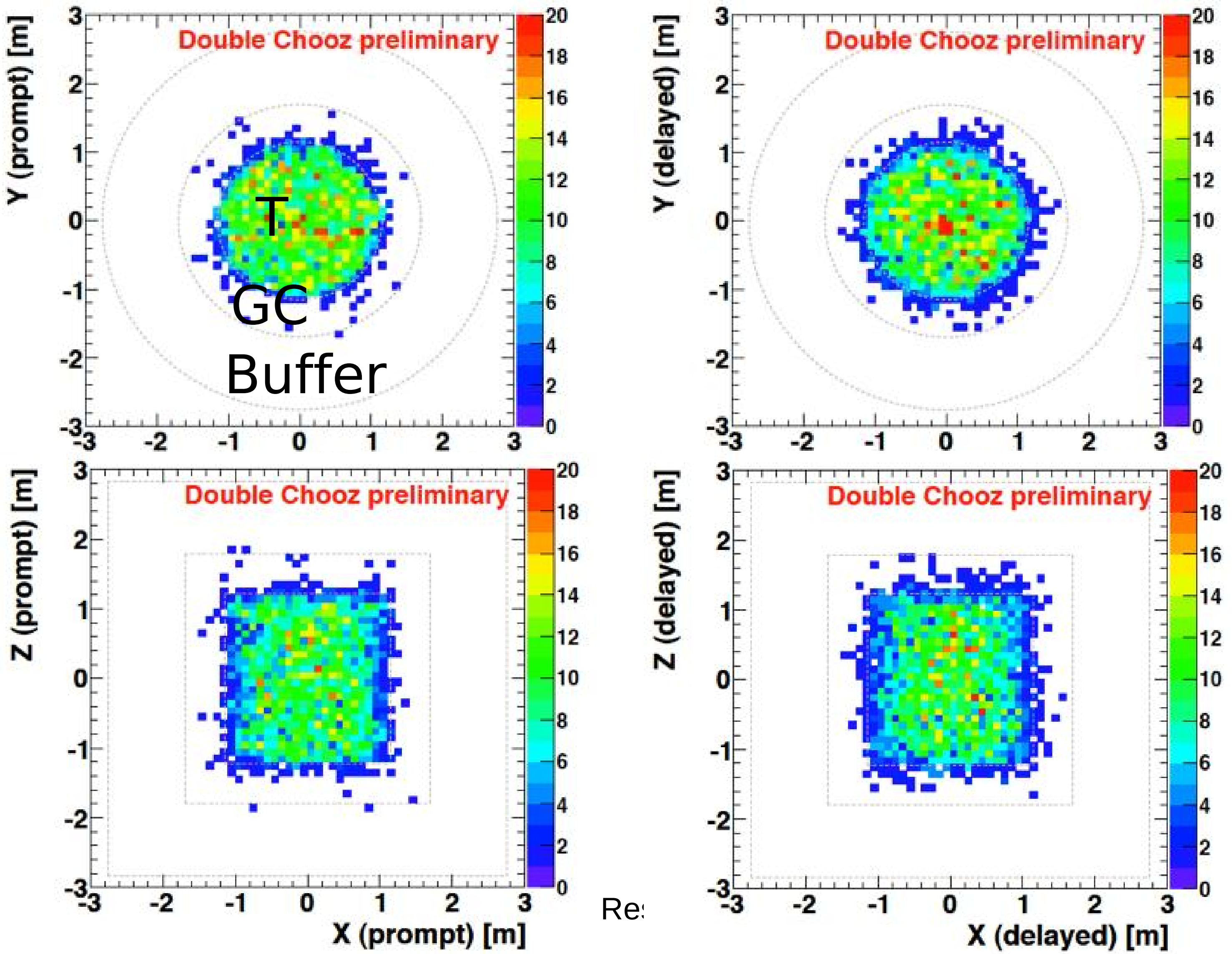
- shape information

→ different systematic uncertainties

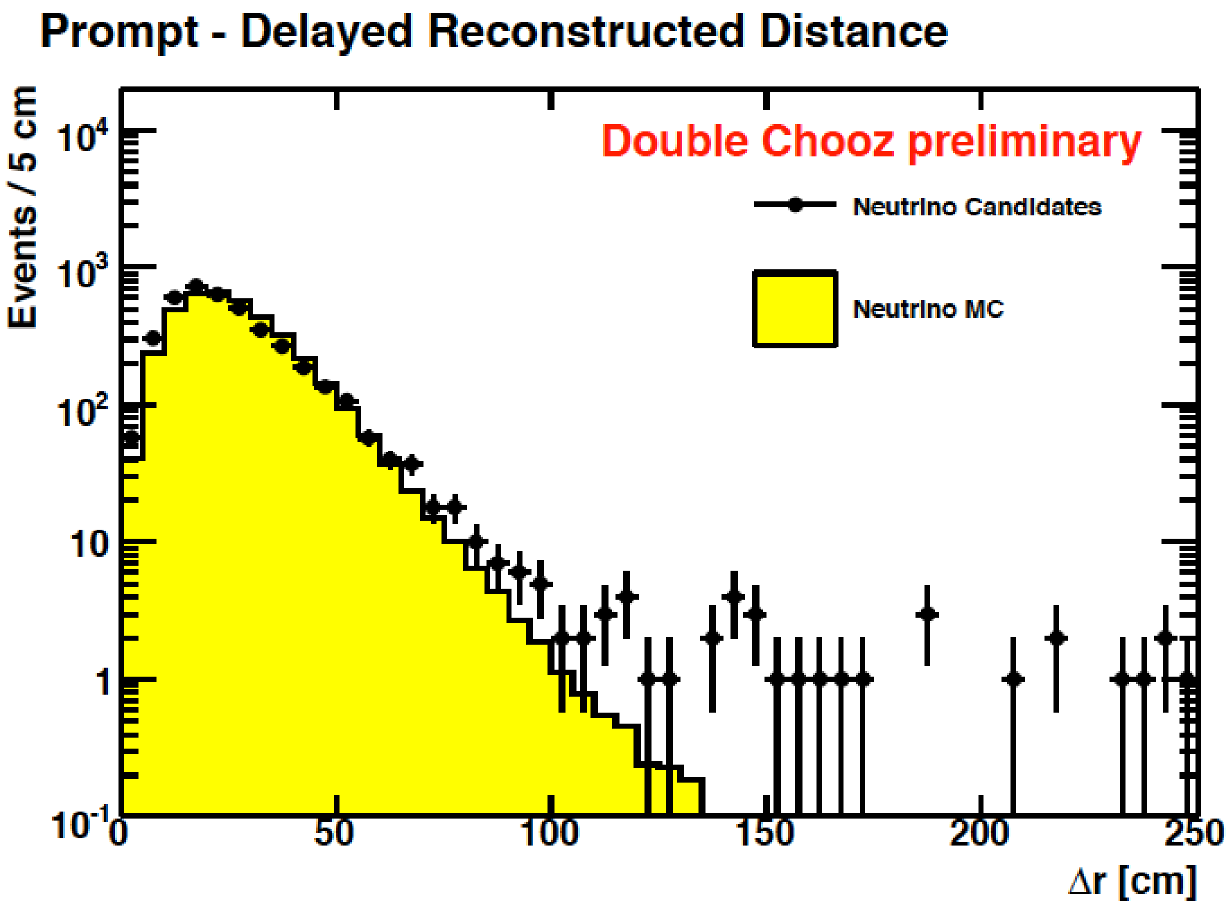
Candidate Vertex Distributions

Prompt **Delayed**

no analysis cut on Fiducial Volume



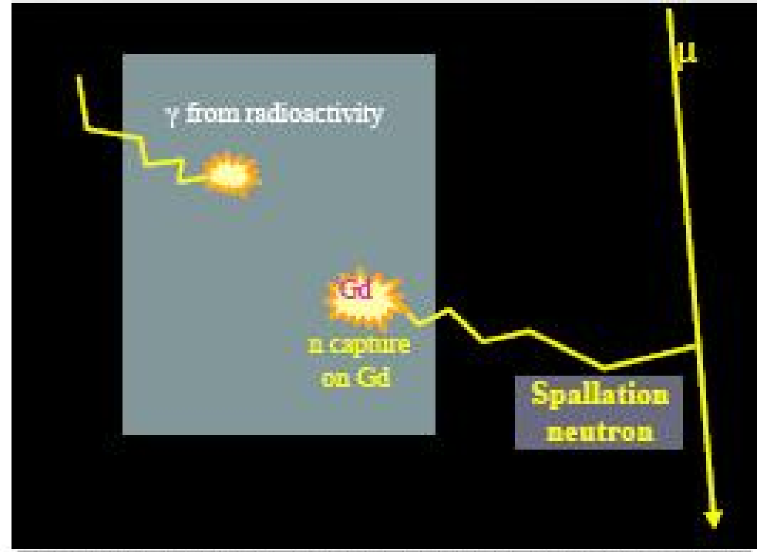
Prompt-Delayed Distance

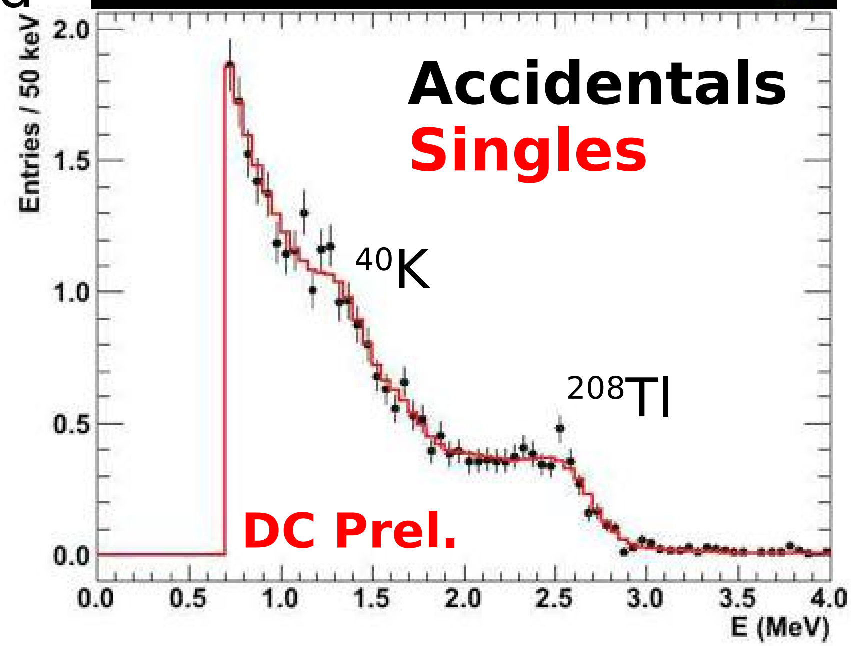


- MC contains no background
- no analysis cut on distance

Accidental Background

- Prompt: radioactivity (ambient rock, PMTs, other materials)
- Delayed: mainly muon induced n capturing on Gd
- Accidental spectrum extracted using neutrino selection conditions from offtime windows [1,100] ms
- Rate: $0.33 \pm 0.03\ d^{-1}$

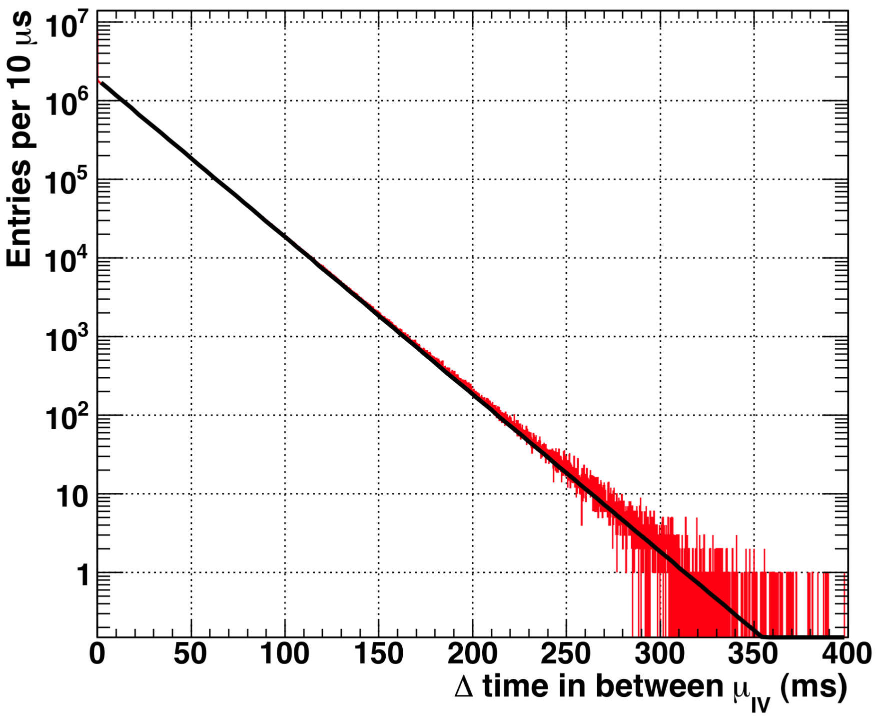




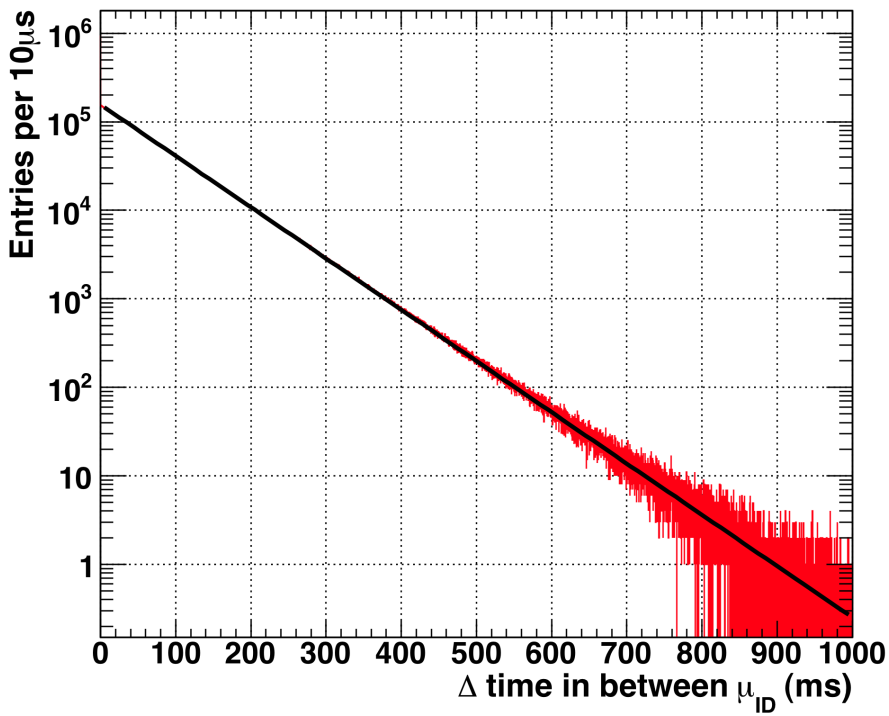
Muons

- Inner Veto muon rate: 46 Hz
- Inner Detector (T+GC): 13 Hz
- ν-search: software muon cut:
  discard all events within 1 ms after a muon (IV muons)

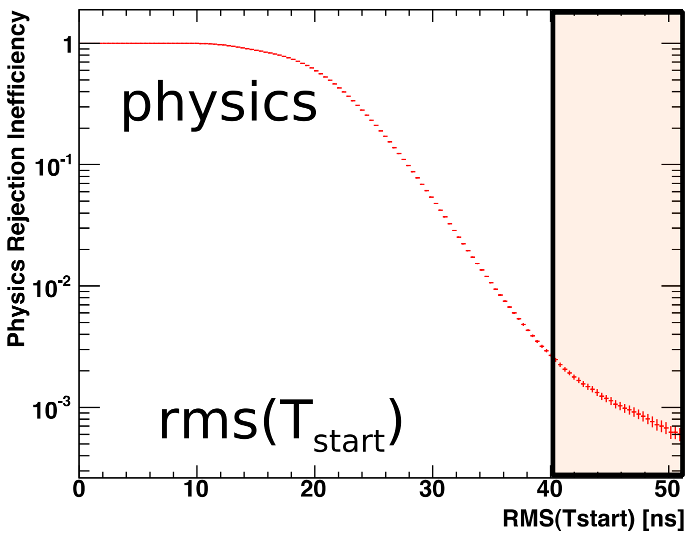
Muon rate in Inner Veto: 46 Hz

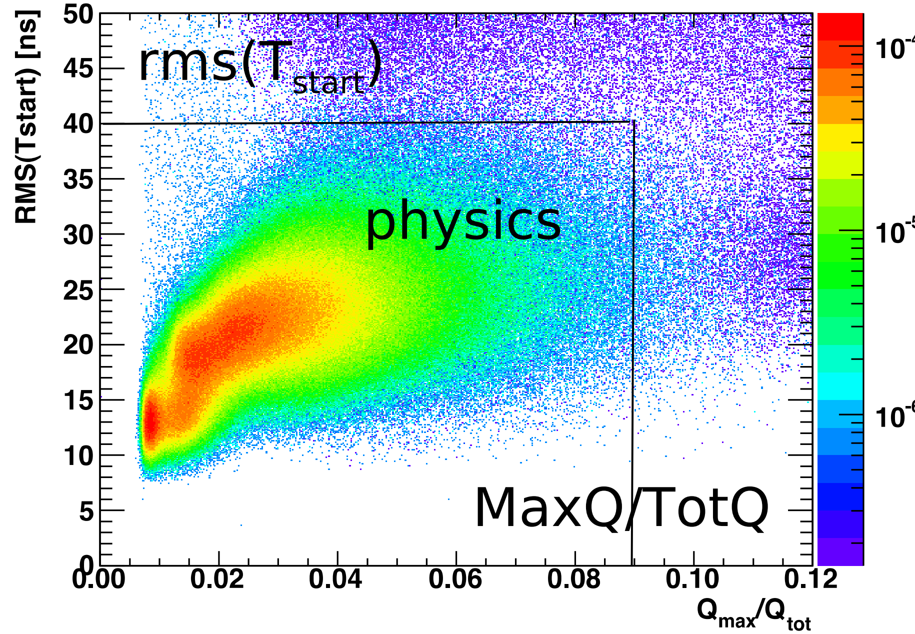


Muon rate in Inner Detector: 13 Hz

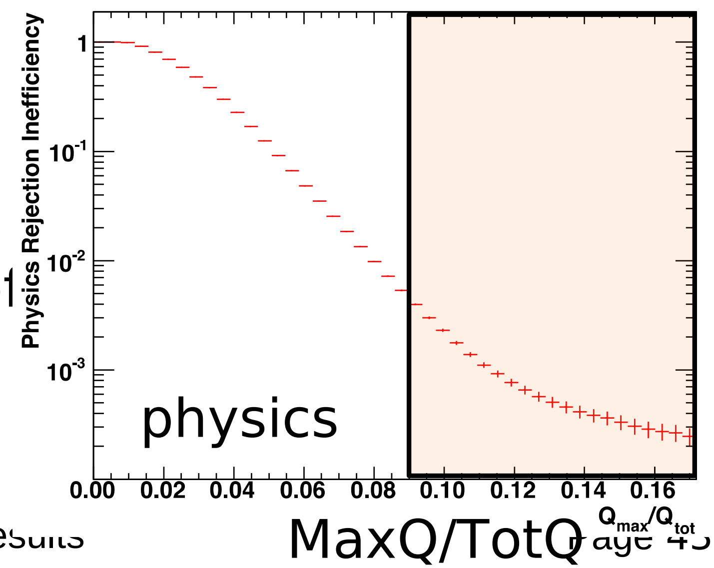


Background: Light Noise



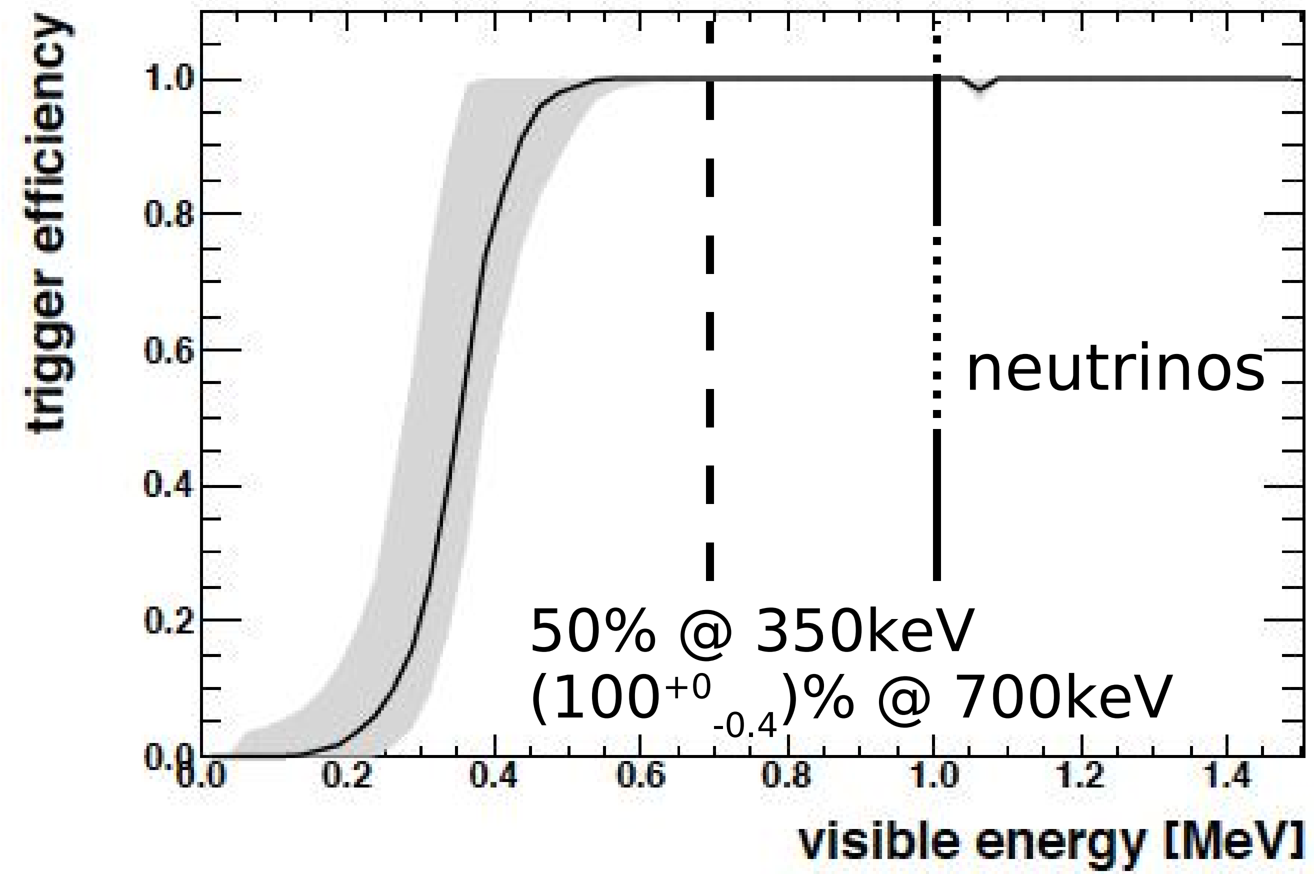


- light emissions from some PMT bases: 14 PMTs turned off
- rejection variables based on
  - anisotropic light emission/ collection: $maxQ_{onePMT}/totQ_{allPMTs}$
  - Large dispersion of start time of PMT signals for light noise → RMS(T_{start})



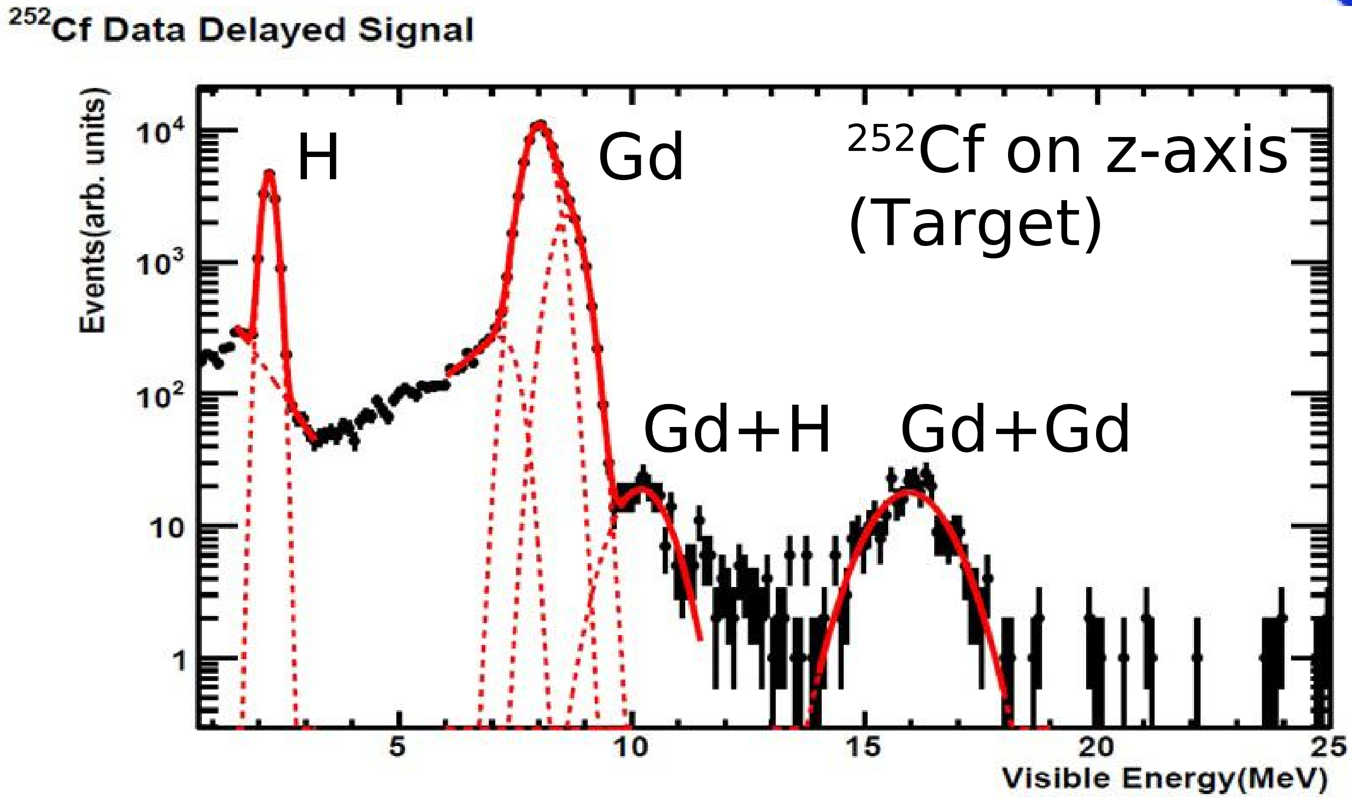
Efficiencies &
Towards Final Fit

Readout Threshold



Cut efficiency 100 % at neutrino prompt threshold

Gd fraction



- Gd fraction [Gd/(Gd+H)] in Target (data): 86 ± 0.6 % (uncertainty estimated from data-MC comparison)

Cut Efficiencies

Parameter	Value [%]	Uncertainty [%]	Comment
Trigger efficiency	100	$^{+0}_{-0.4}$	readout threshold 0.7 MeV
Gd fraction	86.0	$\pm$ 0.6	^{252}Cf: $\frac{Gd}{Gd+H}$
Δt window	96.5	$\pm$ 0.5	^{252}Cf: data/MC residual
ΔE window	94.5	$\pm$ 0.6	^{252}Cf: data/MC residual
Total	78.3	$\pm$ 1.0	

MC Lifetime Correction

Parameter	Value [%]	Uncertainty [%]	Comment
μ veto deadtime	95.5	negligible	
Multiplicity	99.5	negligible	rejection via accidentals
Gd to H fraction	98.0	$\pm$ 0.6	MC/data mean difference
Target H	100	$\pm$0.3	
Spill In/Out	99.2	$\pm$ 0.4	MC estimated
Total	92.5	$\pm$ 0.78	

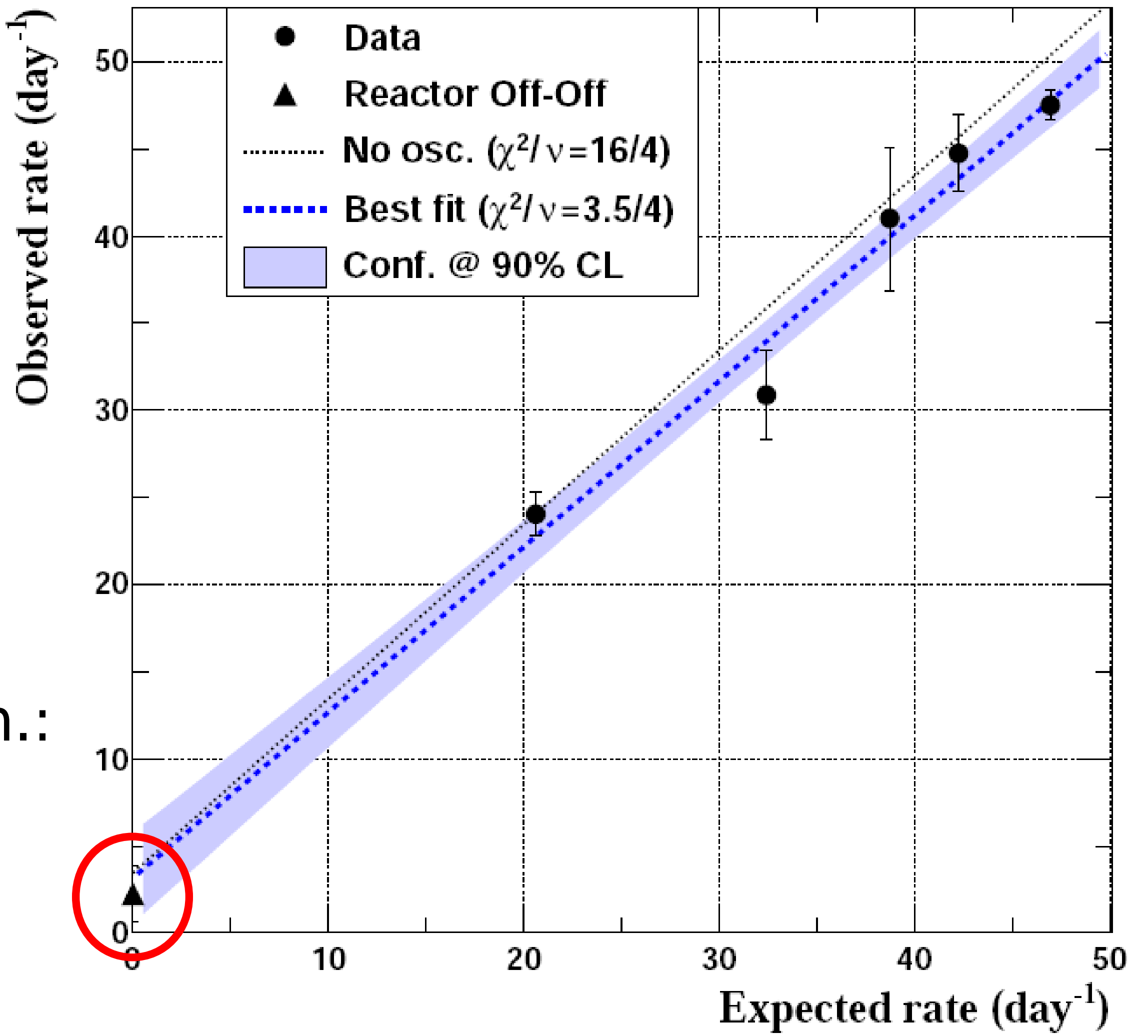
Observed Rate vs. Expected Rate

observed/ measured rate vs. expected rate (from reactor information)

intercept at 0:
BG rate: 3.2±1.3 d^{-1}
including reactor OFF-OFF

independent BG estim.: 3.46±1.26 d^{-1}

→ consistent



Oscillation Analysis

$$\chi^2 = \left(N_i - \sum_R^{\text{Reactors}} N_i^{\nu,R}\right) \times \left(M_{ij}^{\text{Reactors}} + M_{ij}^{\text{detector}} + M_{ij}^{\text{stat}} + \sum_b^{\text{bkgnds.}} M_{ij}^{\text{b}}\right)^{-1} \times \left(N_j - \sum_R^{\text{Reactors}} N_j^{\nu,R}\right)^{\text{T}}$$

Rate Only Analysis:

$R_{DC} = 0.944 \pm 0.016$ (stat) ± 0.040 (syst)

$\sin^2(2\theta_{13}) = 0.104 \pm 0.030$ (stat) ± 0.076 (syst)

Rate+Shape (18 bins):

$\sin^2(2\theta_{13}) = 0.086 \pm 0.041$ (stat) ± 0.030 (syst)

for $\Delta m^2_{13} = 2.32 \cdot 10^{-3}\ \text{eV}^2$

Table of Uncertainties

TABLE II. Contributions of the detector and reactor errors to the absolute normalization systematic uncertainty.

Detector		Reactor	
Energy response	1.7%	Bugey4 measurement	1.4%
E_{delay} Containment	0.6%	Fuel Composition	0.9%
Gd Fraction	0.6%	Thermal Power	0.5%
Δt_{e+n}	0.5%	Reference Spectra	0.5%
Spill in/out	0.4%	Energy per Fission	0.2%
Trigger Efficiency	0.4%	IBD Cross Section	0.2%
Target H	0.3%	Baseline	0.2%
Total	2.1 %	Total	1.8%

Backgrounds

TABLE I. The breakdown of the estimated background rate. Additional shape uncertainties are described in the text.

Background	Rate/day	Syst. Uncertainty (% of signal)
Accidental	0.33 ± 0.03	< 0.1
Fast neutron	0.83 ± 0.38	0.9
^{9}Li	2.3 ± 1.2	2.8

Near Detector

Dezember 2011

Double Chooz
related

Reactor Antineutrino Anomaly

arXiv:1101.2755

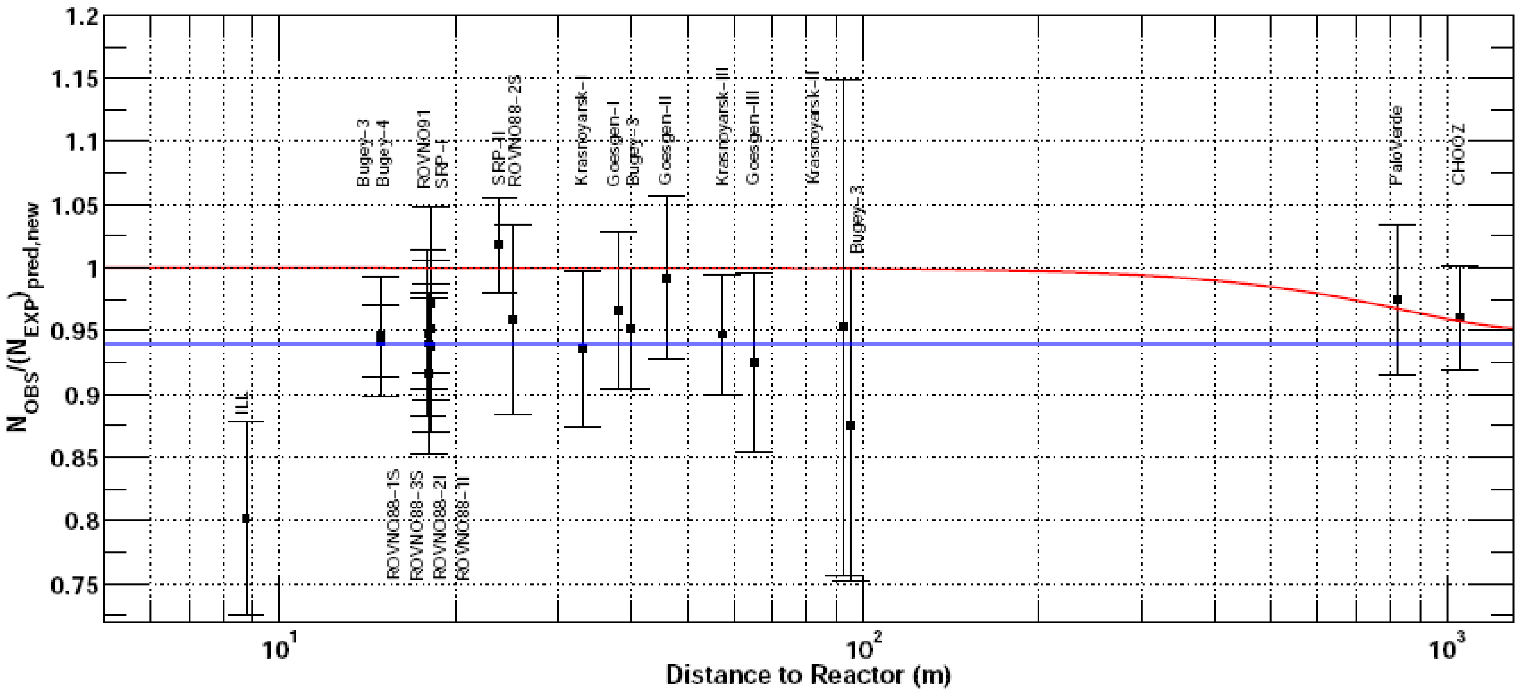


FIG. 5. Illustration of the short baseline reactor antineutrino anomaly. The experimental results are compared to the prediction without oscillation, taking into account the new antineutrino spectra, the corrections of the neutron mean lifetime, and the off-equilibrium effects. Published experimental errors and antineutrino spectra errors are added in quadrature. The mean averaged ratio including possible correlations is 0.943 ± 0.023. The red line shows a possible 3 active neutrino mixing solution, with $\sin^2(2\theta_{13}) = 0.06$. The blue line displays a solution including a new neutrino mass state, such as $|\Delta m^2_{\mathrm{new,R}}| \gg 1\ \mathrm{eV}^2$ and $\sin^2(2\theta_{\mathrm{new,R}}) = 0.12$ (for illustration purpose only).

Non-Proliferation

- worldwide effort (Fr, US, Brazil, Japan, ...)
- IAEA interest (Nonproliferation of Nuclear Weapons)
- monitor ^{239}Pu (weapons-grade) vs. ^{235}U, ^{238}U from different neutrino spectra
- distance: of a few tens of meters,
- "small" detectors of the order of few cubic meters in size, shallow depth: Nucifer (Fr), SONGS (US)
- papers:
    - arxiv:0704.0891, M. Cribier, 5 pages ("Neutrinos for peace")
    - arxiv:0908.4338, A. Bernstein et al., 84 pages