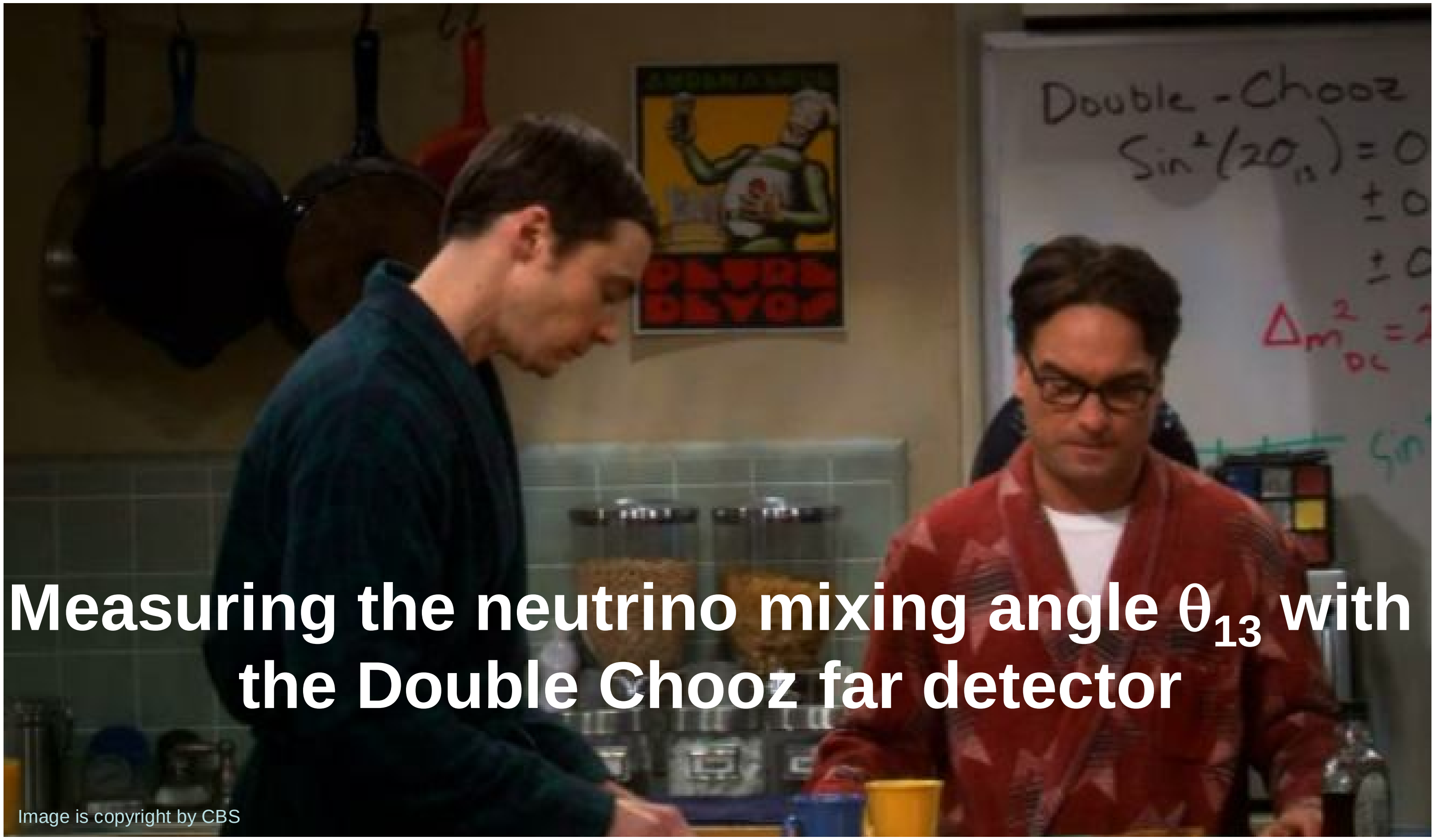


Measuring the neutrino mixing angle θ_{13} with the Double Chooz far detector

Igor Ostrovskiy

Outline

- Introduction
- First Double Chooz measurement
  - Data set
  - Backgrounds
  - Detector response
  - Efficiency
- Final analysis
- Results

Introduction: Neutrino

- Results from a number of different experiments – solar, reactor, atmospheric, and accelerator, can be consistently explained assuming that the neutrino has a nonzero mass, and different flavors can mix (neutrino oscillation)

Neutrino	
Composition:	Elementary particle
Family:	Fermion
Group:	Lepton
Interaction:	weak interaction and gravitation
Antiparticle:	Antineutrino (possibly identical to the neutrino)
Theorized:	1930 by Wolfgang Pauli
Discovered:	1956 by Clyde Cowan, Frederick Reines, F. B. Harrison, H. W. Kruse, and A. D. McGuire.
Symbol:	ν_e, ν_μ^0, ν_τ^0
No. of types:	3 – electron, muon and tau
Mass:	Nonzero, see Mass below
Electric charge:	0
Color charge:	0
Spin:	½

from Wikipedia

Introduction: Neutrino oscillation

The idea is that neutrinos are observed as flavor eigenstates (ν_l), but propagate as mass eigenstates (ν_i):

$$\nu_l = \sum_i U_{li} \nu_i$$

Maki-Nakagawa-Sakata-Pontecorvo matrix

$$\begin{array}{c} \\ e \\ \mu \\ \tau \end{array} \begin{array}{c} \begin{array}{ccc} 1 & 2 & 3 \end{array} \\ \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{13}s_{23}c_{12}e^{i\delta} & c_{23}c_{12} - s_{13}s_{23}s_{12}e^{i\delta} & c_{13}s_{23} \\ s_{23}s_{12} - s_{13}c_{23}c_{12}e^{i\delta} & -s_{23}c_{12} - s_{13}c_{23}s_{12}e^{i\delta} & c_{13}c_{23} \end{pmatrix} \end{array}$$

If neutrino masses are different from each other, the relative phases of the mass wave functions will periodically change with time, resulting in observable oscillation in flavor

$$P_{ee} = 1 - c_{13}^4 sin^2(2\theta_{12}) sin^2(1.266\frac{\Delta m_{21}^2 L}{E}) - c_{12}^2 sin^2(2\theta_{13}) sin^2(1.266\frac{\Delta m_{31}^2 L}{E}) - s_{12}^2 sin^2(2\theta_{13}) sin^2(1.266\frac{\Delta m_{32}^2 L}{E})$$

Introduction: Oscillation Parameters

Oscillations depend on the mass squared differences and the mixing angles

The CP violating phase (δ) is unknown.
θ_{13} :
Upper limit (CHOOZ, Palo Verde) **$\sin^2(2\theta_{13})$ ~< 0.15 90% C.L. CHOOZ**
Hints of non-zero value from global analyses **$\sin^2(2\theta_{13}) = 0.036^{0.051}_{0.028}$ (KamLAND, Oct'10)**
Further evidence from recent appearance results: e.g. **$0.03(0.04)<\sin^2(2\theta_{13})<0.28(0.34)$ (T2K Jun'11)**

$$U_{MNSP} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}} \overbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}$$

Atmospheric oscillations
Measured by K2K, SK, Minos.
$|\Delta m^2_{31}|=(2.43\pm0.13)\cdot10^{-3}$ eV^2,
$\sin^2(2\theta_{23})>0.95$

Solar oscillations
Measured by solar experiments (Homestake, SAGE, GALLEX/GNO, SNO) and KamLAND
$\Delta m^2_{21}=(7.59\pm0.21)\cdot10^{-5}$ eV^2,
$\tan^2(\theta_{12})=0.457^{+0.04}_{-0.029}$

θ_{13}

- It is important to improve our knowledge of θ_{13}
  - to complete our understanding of neutrino oscillations
  - to see if we can measure CP violation in the foreseeable future
- Increasing sensitivity for θ_{13} is possible using reactor neutrinos and accelerator neutrino beams
- The reactor measurement has the following advantages over the accelerator beams:
  - no ambiguity from matter and CP violation effects
  - smaller costs

Introduction: Double Chooz concept

1. The Chooz-B nuclear power plant (France) emits ~ 10^{21} electron antineutrinos per second
2. Detect the neutrinos with *two* detectors through the inverse β-decay reaction:

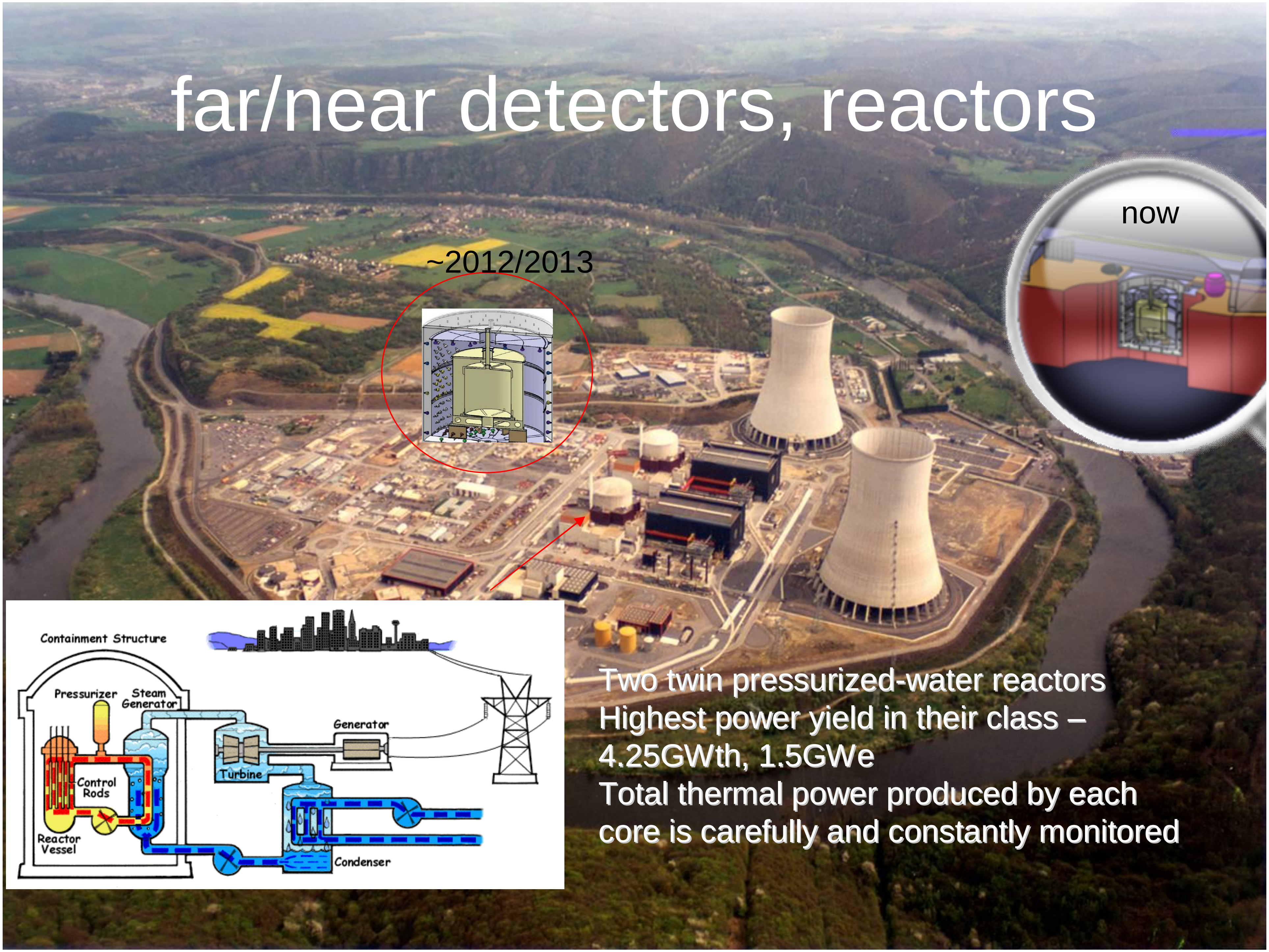
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

3. Instead of comparing measured rate/spectrum with calculated ones, based on reactor information (CHOOZ approach), compare the data between the Far and the Near detector
4. Search for possible deficit of neutrinos in the far detector

$$P_{ee} = 1 - sin^2(2\theta_{13}) sin^2(1.266 \frac{\Delta m^2_{atm} L}{E})$$

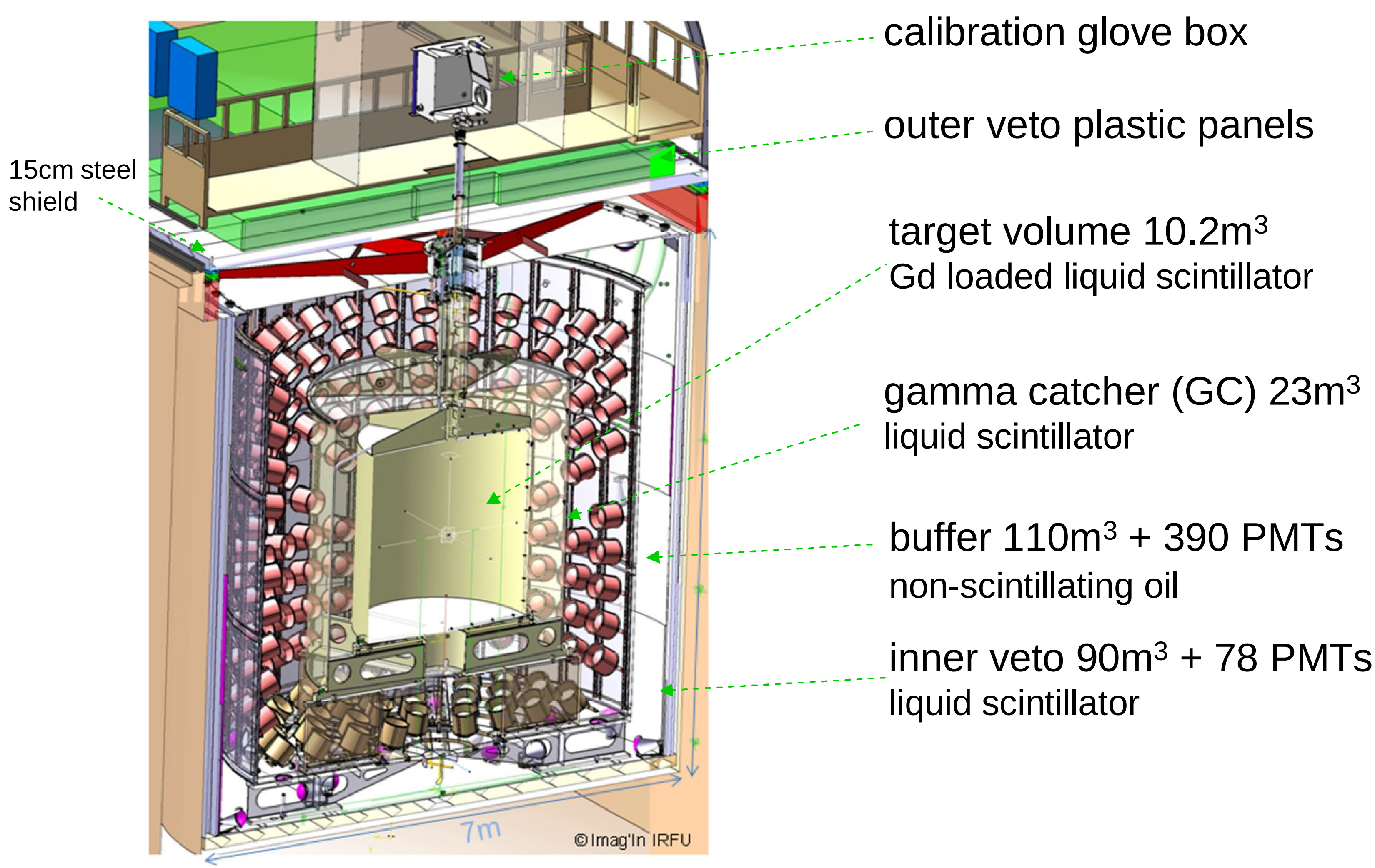
After 3 years of data taking, the sensitivity down to $\sin^2(2\theta_{13})<0.03$ can be achieved

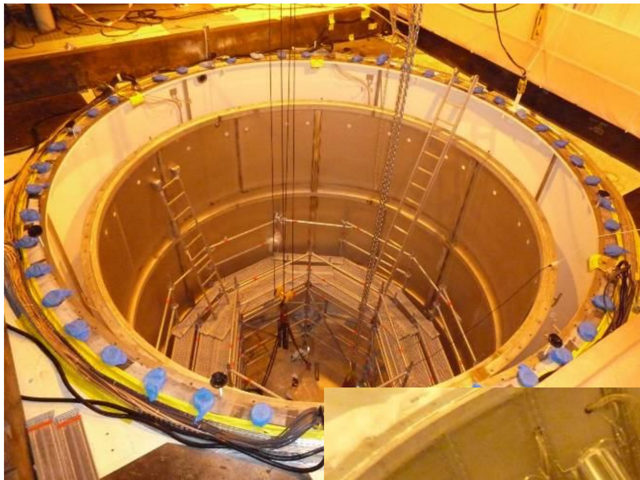
far/near detectors, reactors



Two twin pressurized-water reactors
Highest power yield in their class – 4.25GWth, 1.5GWe
Total thermal power produced by each core is carefully and constantly monitored

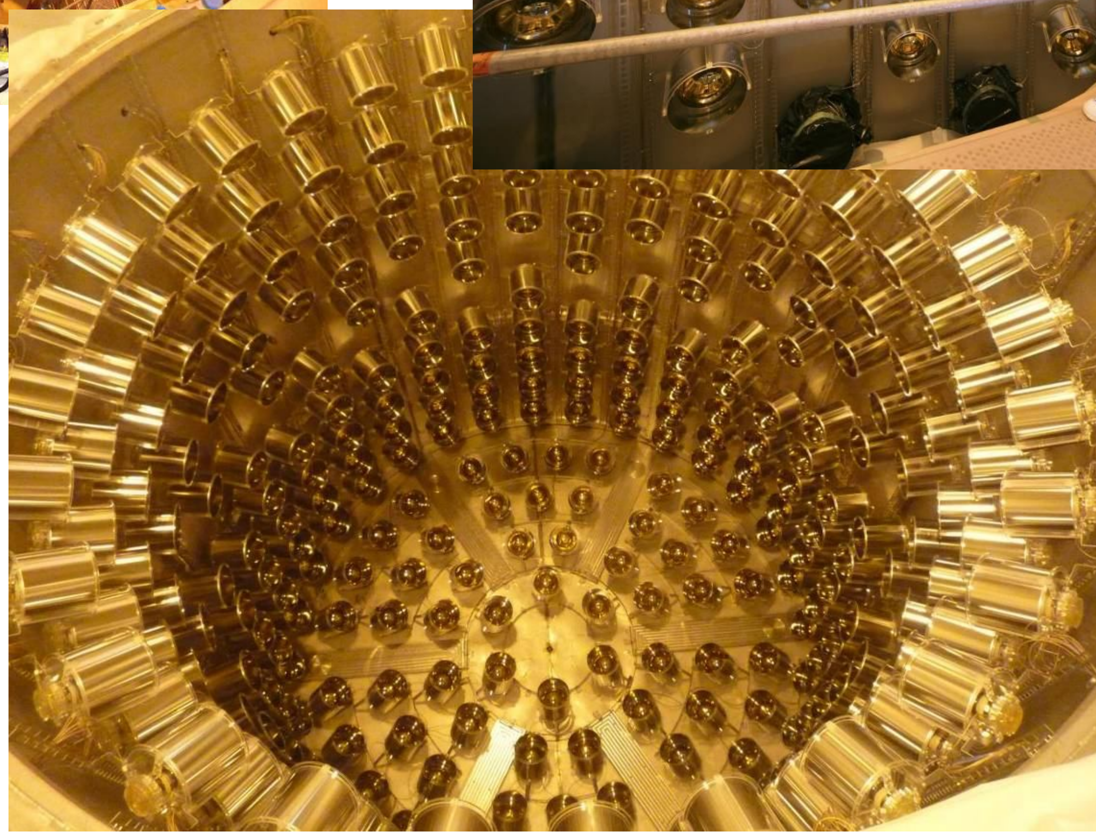
Detector Design





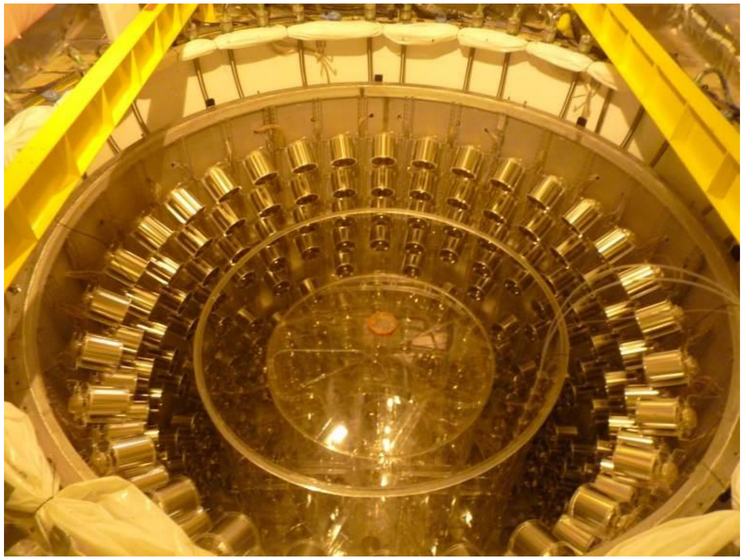
June-July 2009

Buffer vessel
and ID PMTs



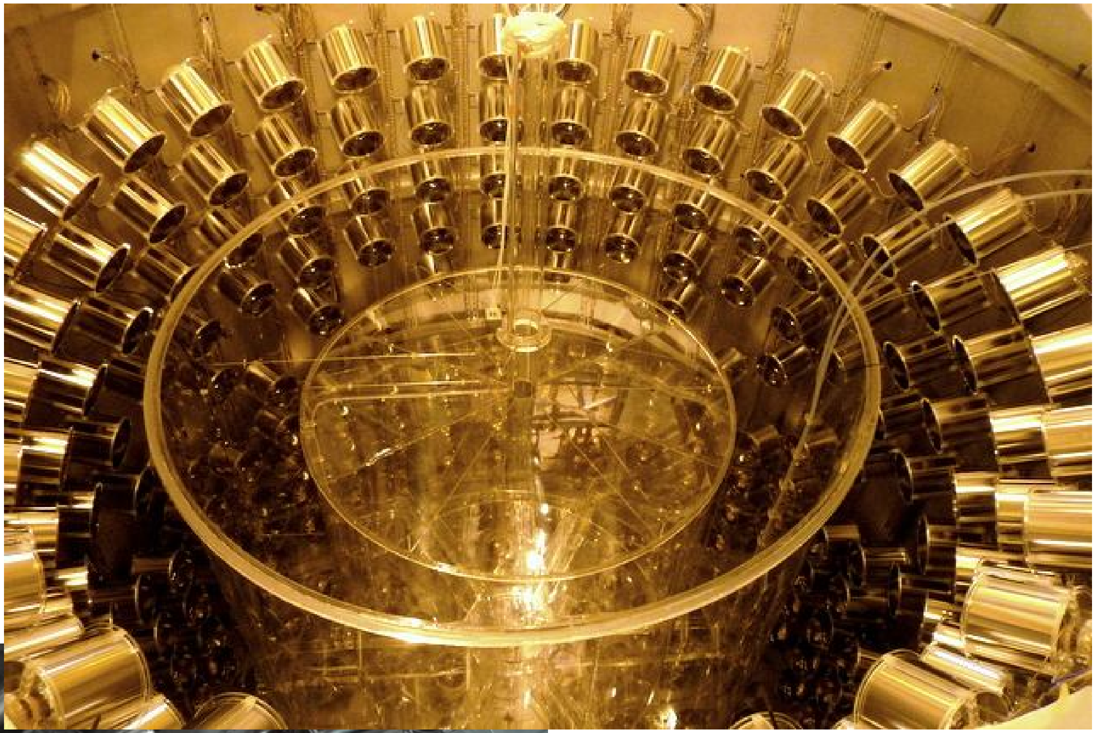
Gamma-Catcher

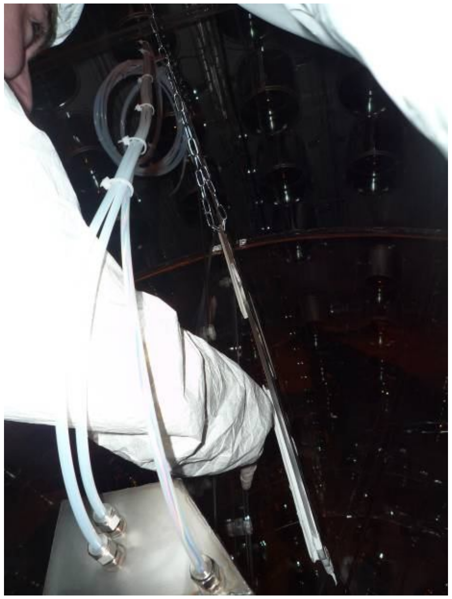
Gamma-catcher integration. Fall 2009



Target installed

Guide tube integrated



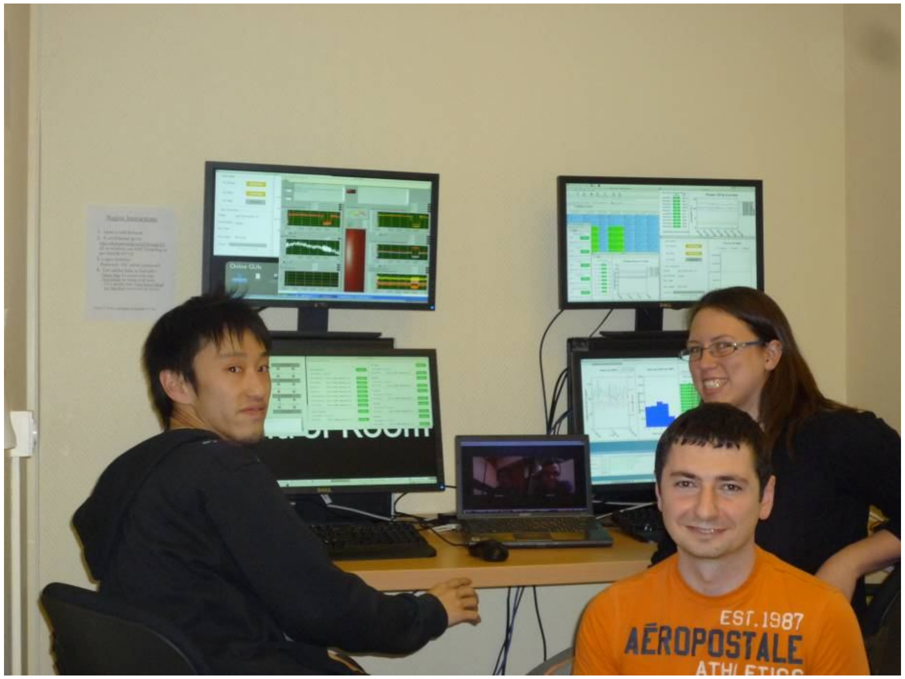


Inner veto closed

Top shielding installed. Dec 2010

Far detector closed and filled end of 2010

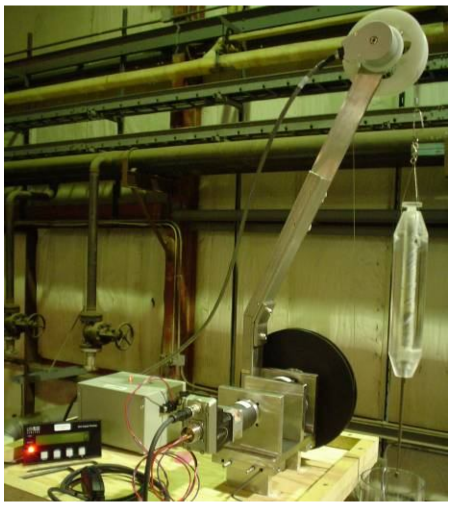
Far detector is On-line



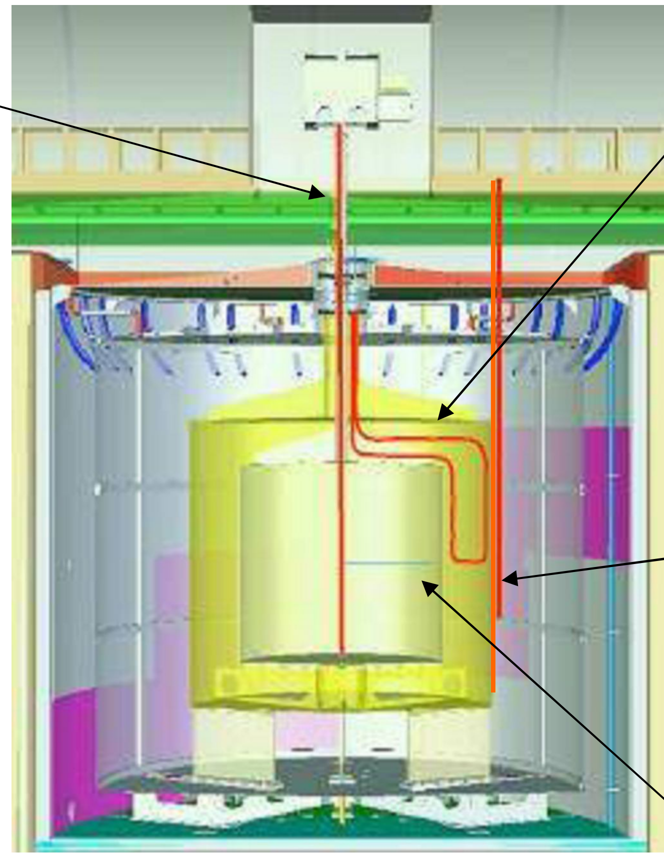
"DC is now officially running and accumulating neutrinos as we speak
Our first run...
Date: 18:00 13/4/2011.
RunNumber 11000.
Shifters: Herve, Masaki, Anatael, Junpei, Igor, Erica.
Comment: First Neutrino Physics Run of DC ..."

Calibration systems

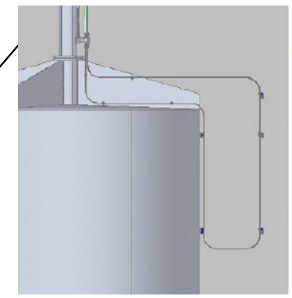
Z-axis fish line

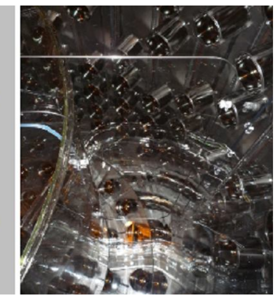


Target volume
• Tagged Cf-252 and untagged gamma and neutron sources
• Laser ball and LED flasher



Gamma-catcher guide tube

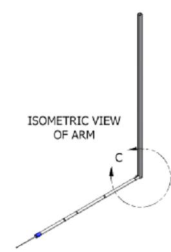




• Untagged gamma and neutron sources

Buffer tube

Articulated arm

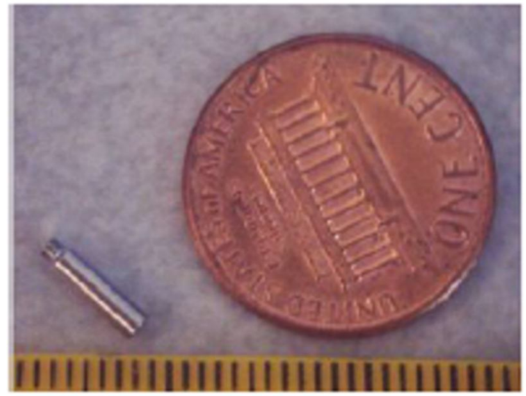


Also: Embedded LED systems in Buffer and Inner Veto

Untagged sources

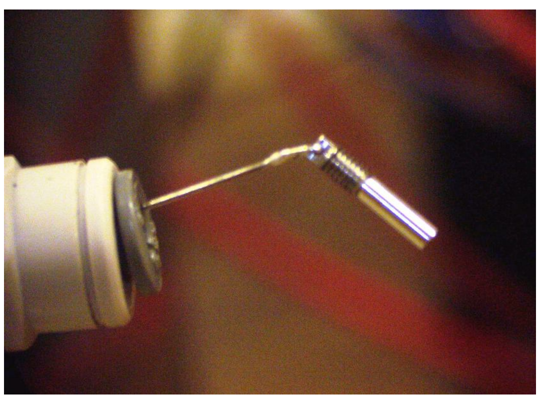
- Double encapsulated
- Leak-tested to ISO standards
- 2mm diameter outer capsule
- Same source can be deployed with any system in both detectors

- The following sources used for the first calibration: Cs-137, Ge-68, Co-60, Cf-252

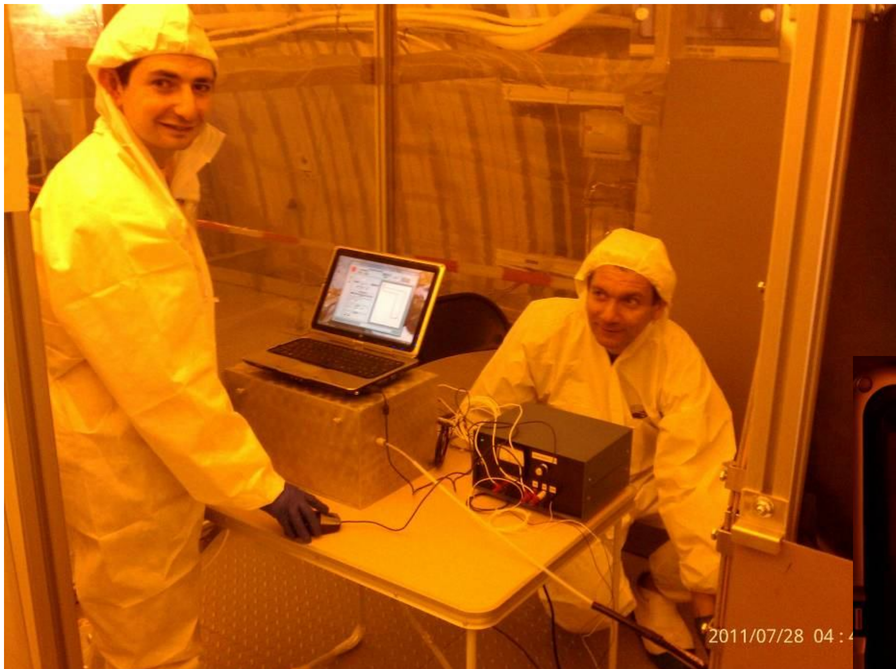


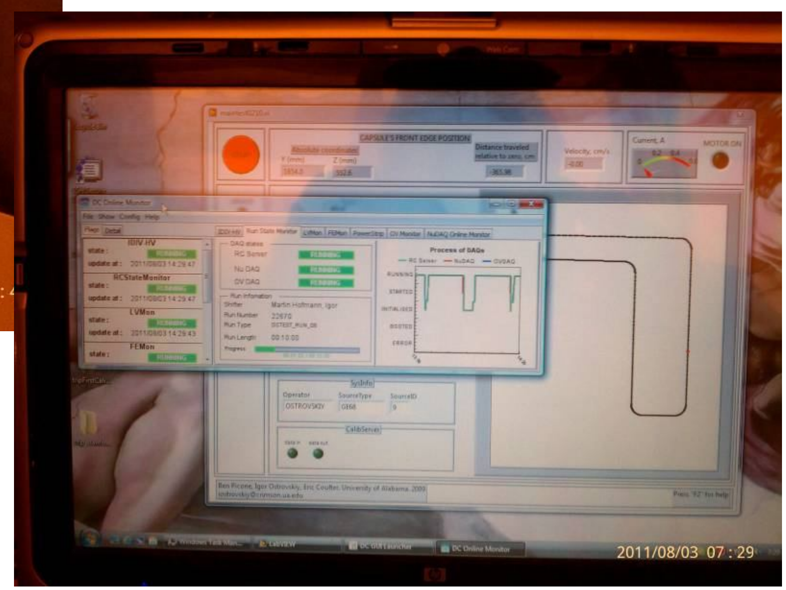
DC untagged source
ruler notches are mm

AmBe inner capsule (tungsten)



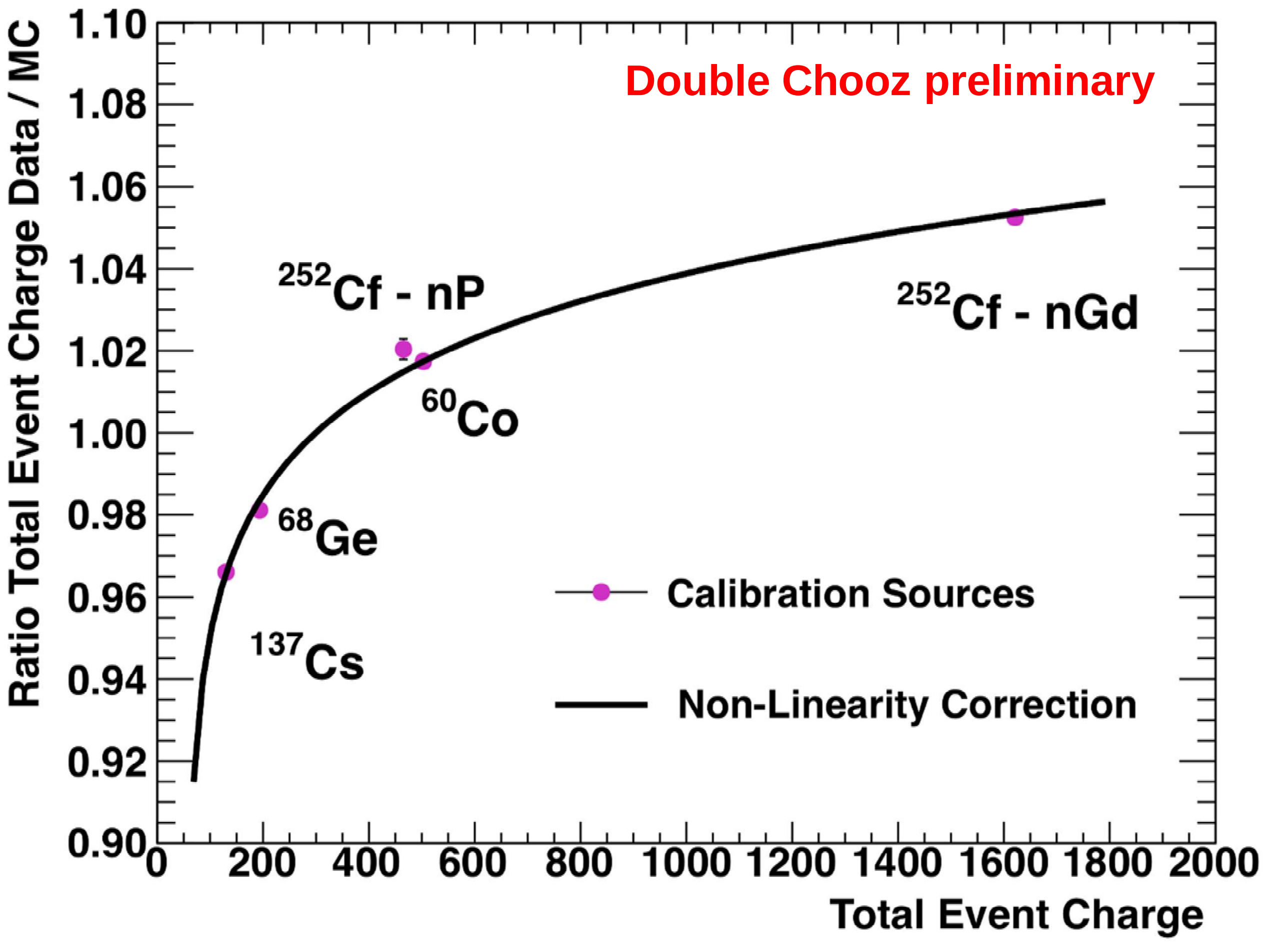
First deployment of radioactive sources in Double Chooz





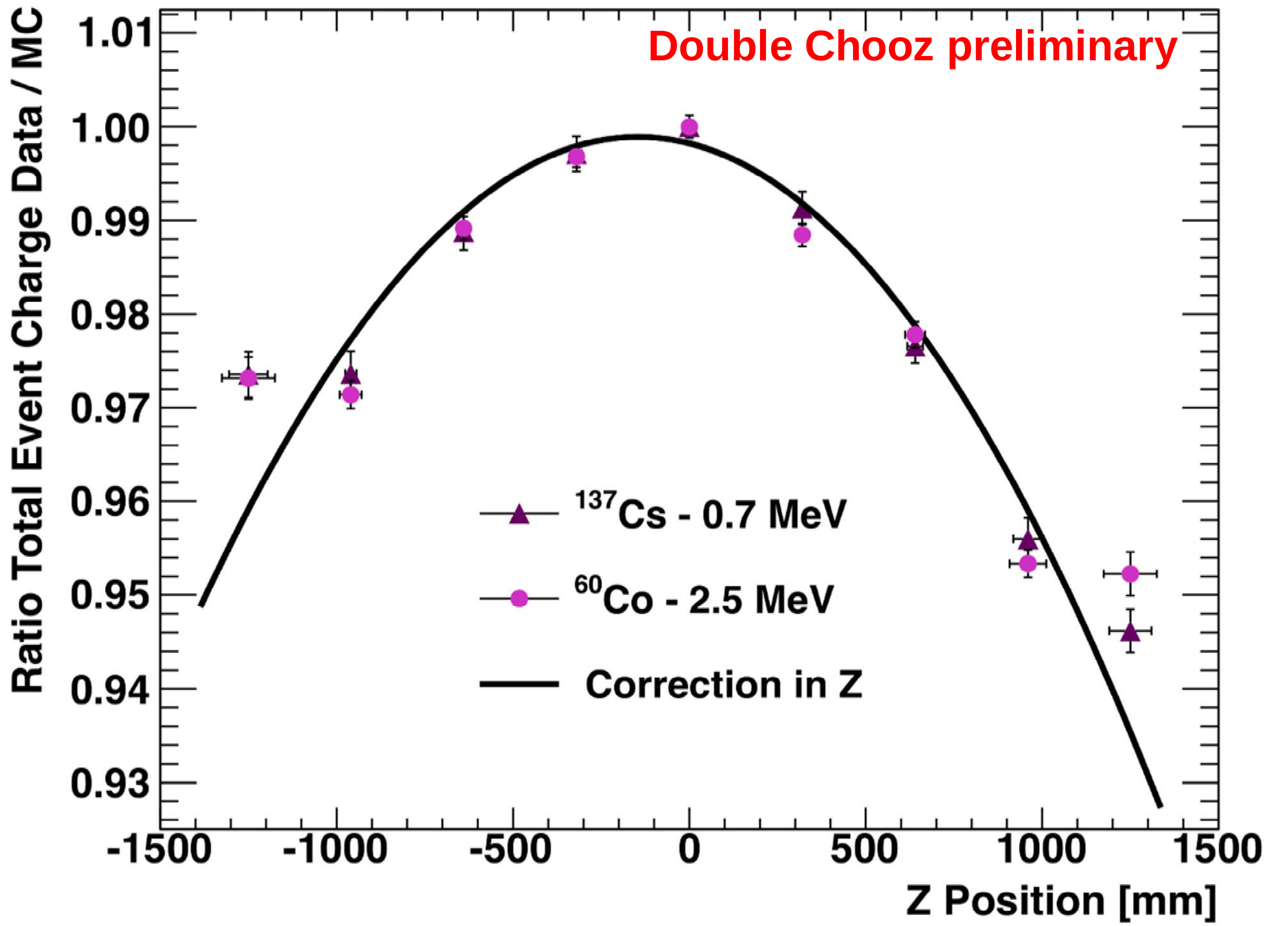
MC/data: energy response

Calibrate the non-linearity due to single photoelectron inefficiency, electronics, and Q-reconstruction effects.

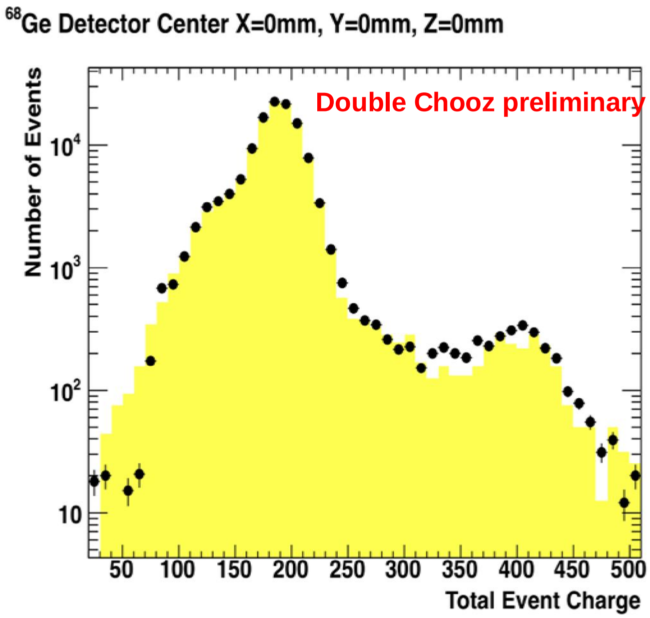


MC/data: Position dependence of the energy response

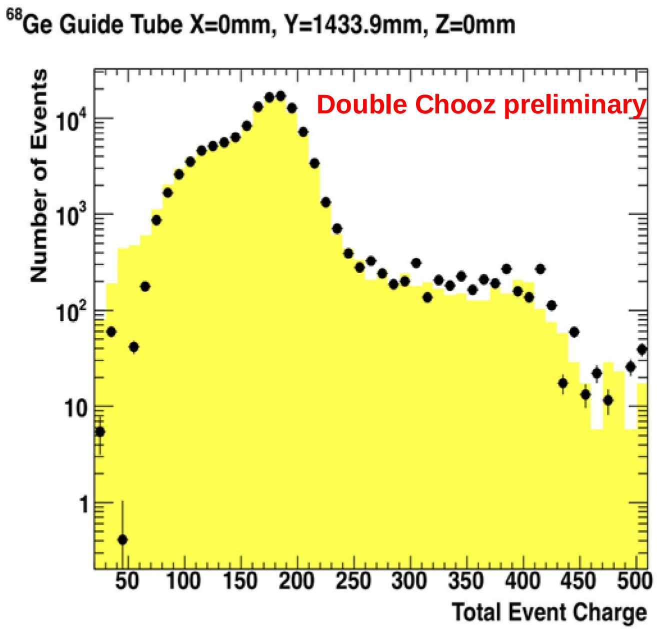
Calibration of the z-bias. Residuals in the correction will be included in the detector covariance matrix.



MC/data: Source spectra examples



Ge-68 at the target center

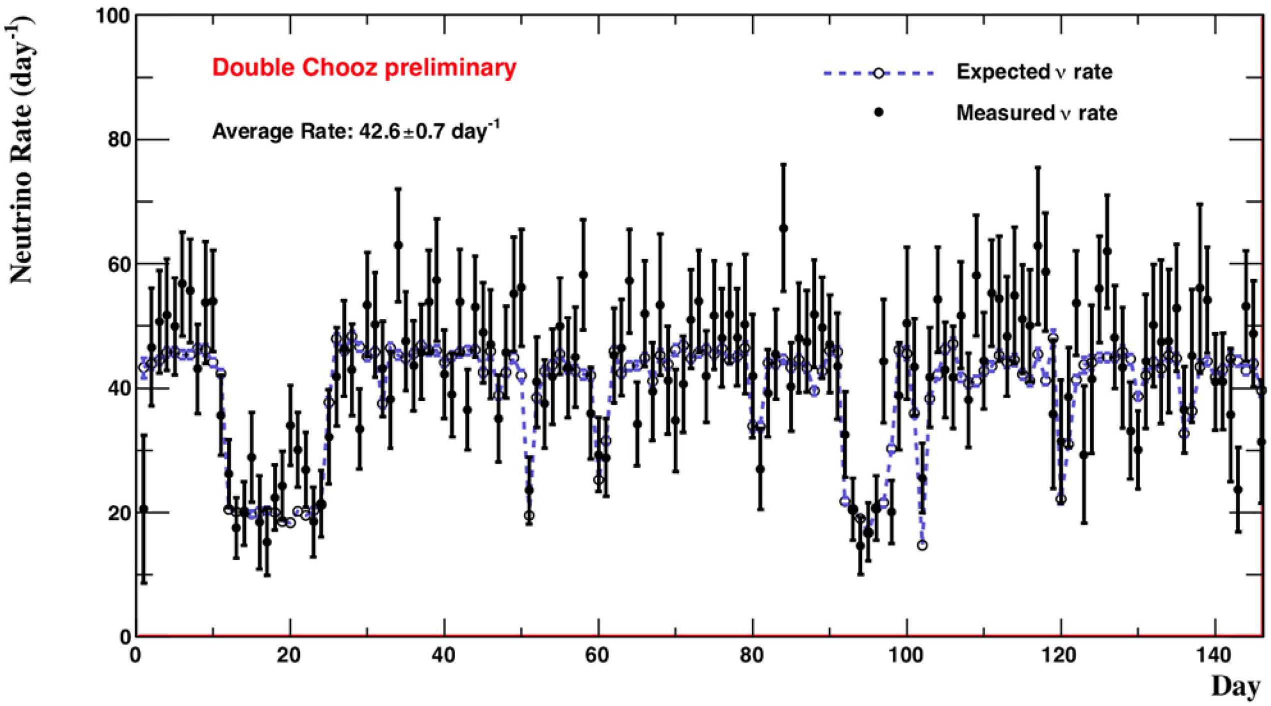


^{68}Ge in the Guide Tube, midway between target and gamma catcher walls

overall, ~1-1.5% agreement between neutron capture peaks in the neutrino dataset

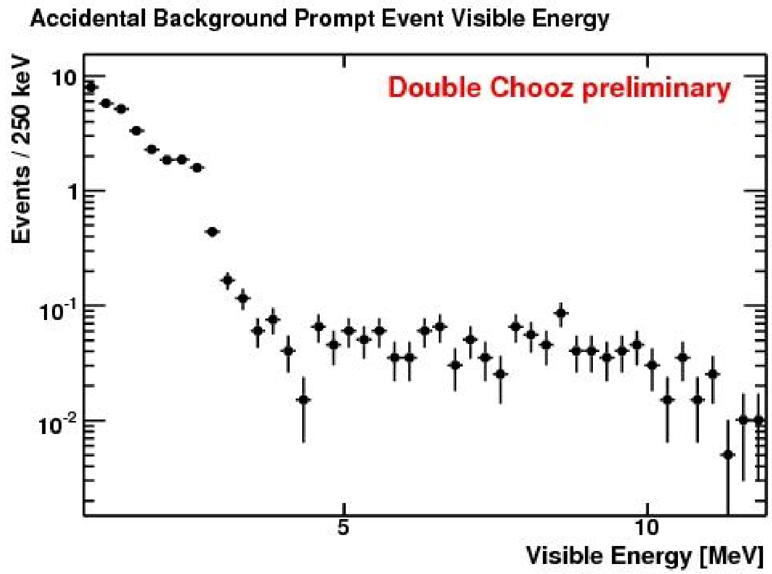
Measurement

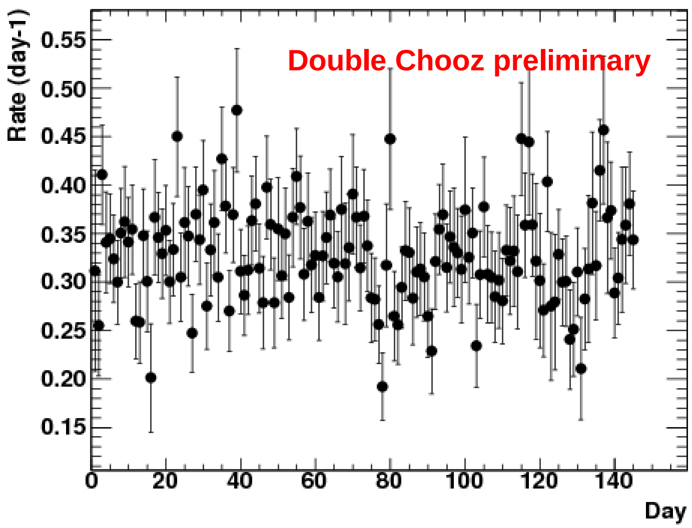
- ~100 days of data used for the first analysis
- Prompt-delayed coincidence selection results in 4121 anti-neutrino candidates



Note: expected rate does not include **backgrounds**

Accidental backgrounds



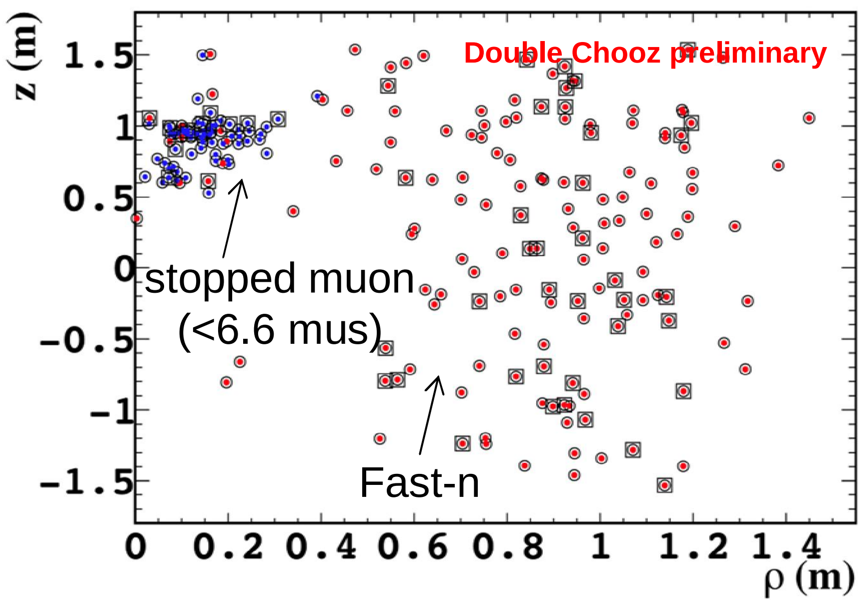


- Same as for neutrino search but delayed event uncorrelated in a delayed time window (1 ms)

- Rate:
    - **0.33 +-0.03 per Day**
    - Lower than in the proposal
    - Stable in time

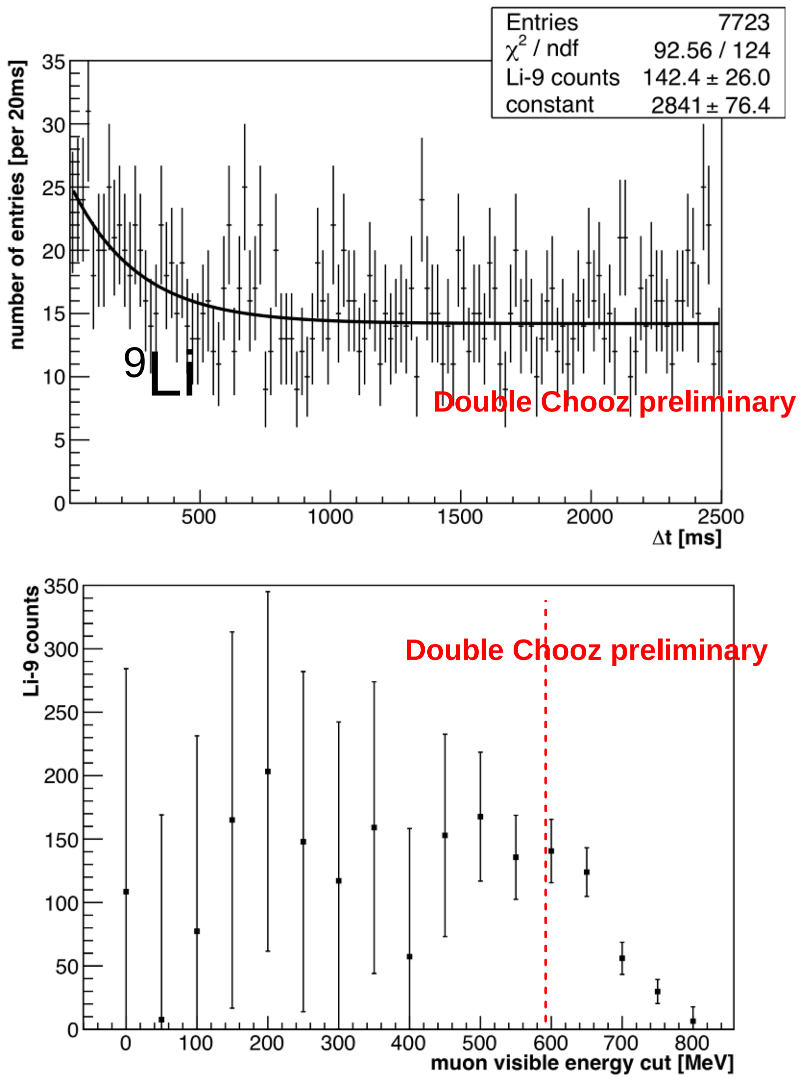
- Spectrum: compatible with singles events

Fast neutrons



- Neutrino selection with prompt energy extended to 30 MeV
- Two populations:
  - Fast-n
  - Stopping-muon
- Rate:
  - Extrapolation from high Energies to lower ones
  - **0.83 -0.38 +0.38 per Day**
- Spectrum:
  - Flat
  - Stopped Mu Shape Unc.

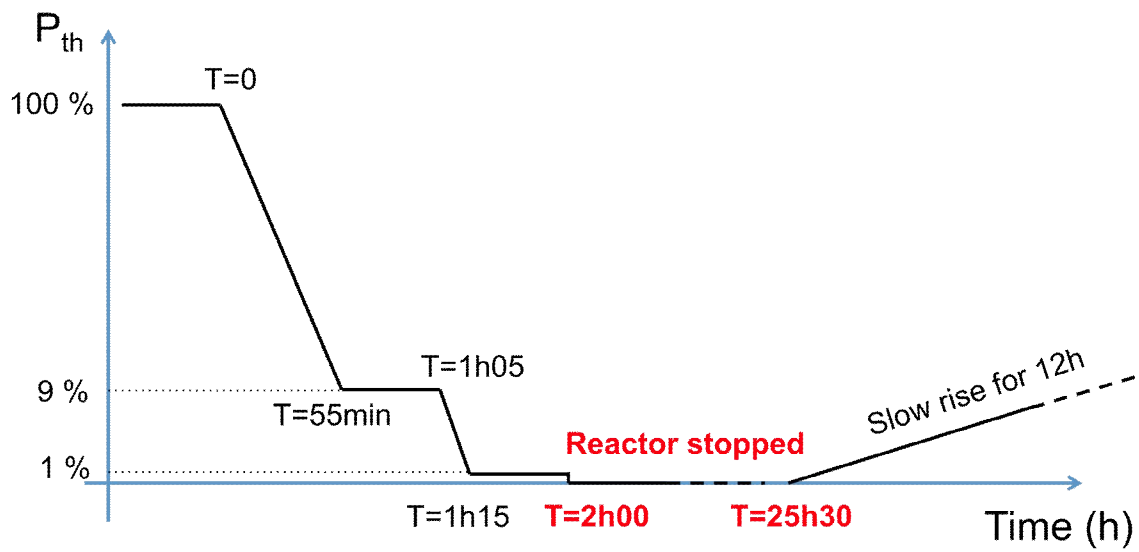
Li-9



- ^{9}Li events selection:
  - Search for a triple delayed coincidence between showering muon and neutrino-like coincidence
- Showering muon : E>600 MeV
- deltaT between showering muon and prompt event is given by the ^{9}Li-like life time (257ms).
- **Rate: 2.3 -1.2 +1.2 per Day**

1 day of Reactor Off-Off data

- 22.5 hours when both reactors were off (<0.3 expected anti-neutrino events)
- Good opportunity for an independent cross-check of the background estimate
- 2 events pass IBD selection cuts
  - time-since-muon and prompt energy consistent with Li-9



Prediction

- Anti-neutrino prediction is generated using actual time-dependent information provided by EdF
  - Spectrum parameterizations, $S_k(E)$, based on the recent re-evaluation of the conversion procedure (Th. A. Mueller et al, Phys.Rev. C83(2011) 054615, P. Huber, Phys.Rev. C84 (2011) 024617)

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

$$\langle E_k \rangle = \sum_k \alpha_k(t) \langle E_k \rangle$$

k = ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu

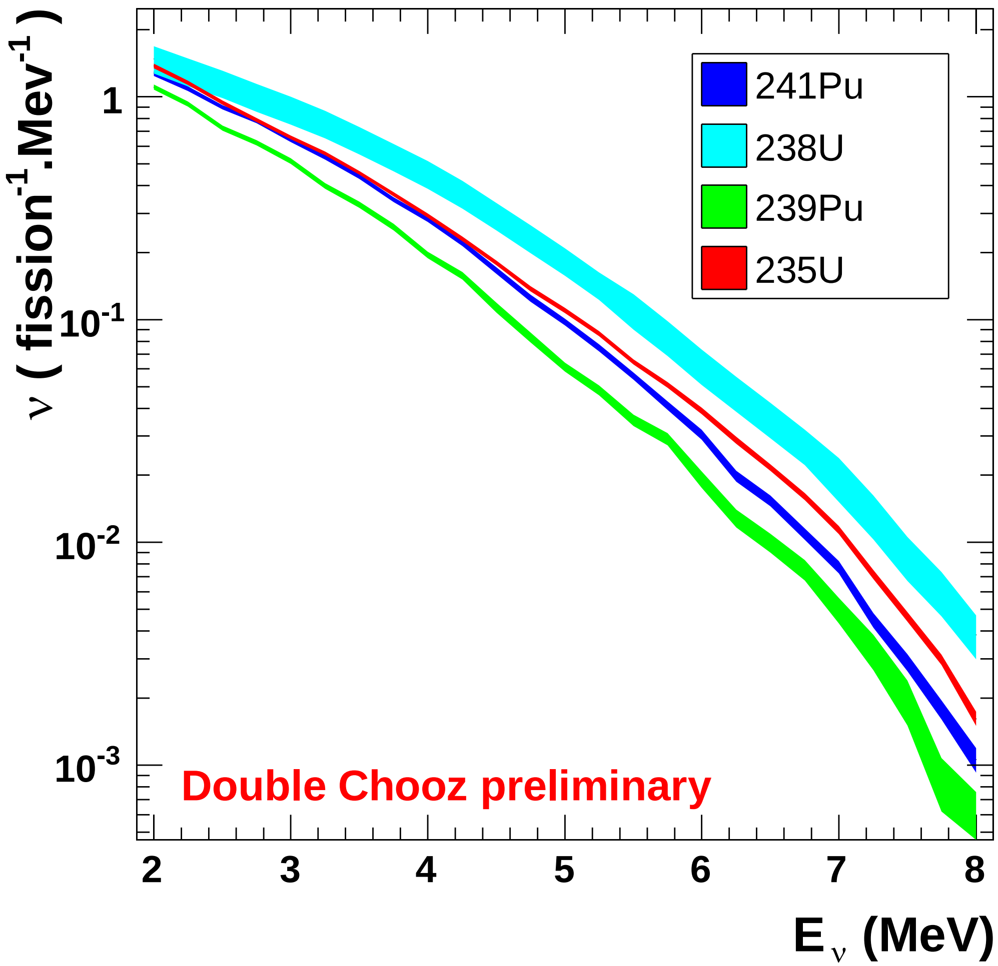
α_k : fractional fission rate

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

mean cross-section per fission

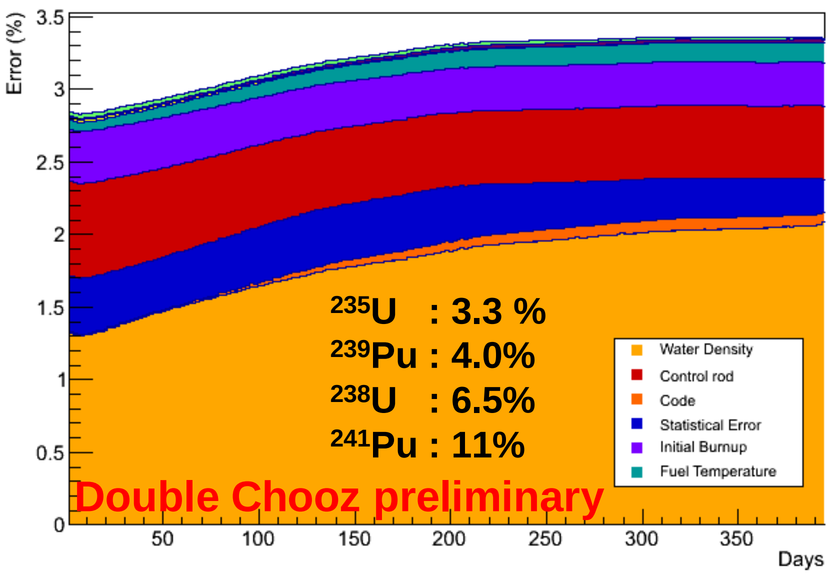
$$\langle \sigma_f \rangle_k = \int_0^{\infty} dE\ S_k(E)\, \sigma_{IBD}(E)$$

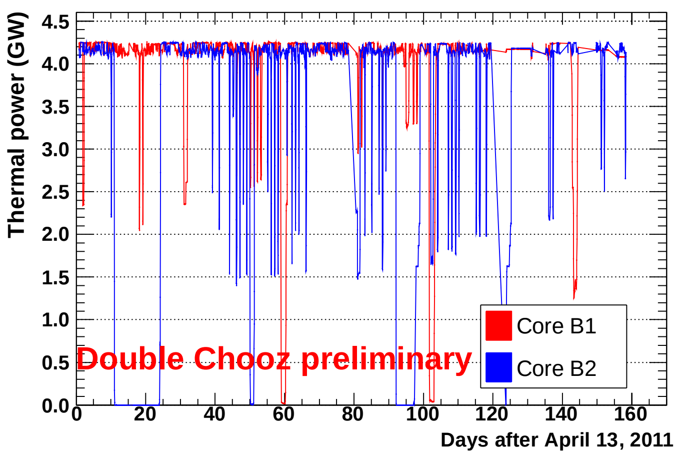
normalization “anchored” to Bugey-4 measurement



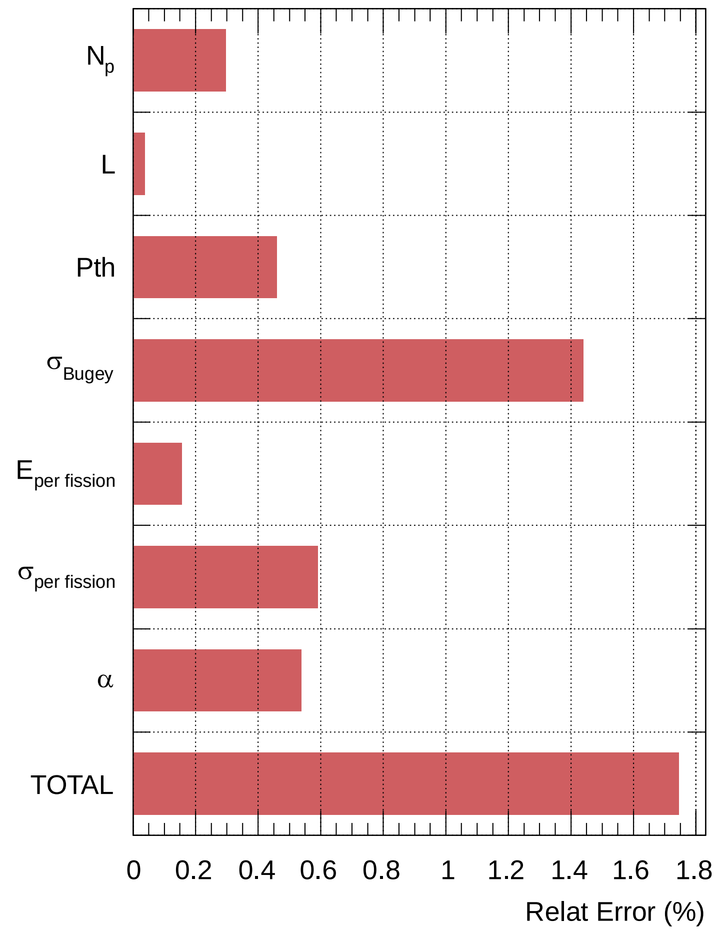
- Recent re-evaluations of fissile isotopes by
- Th. A. Mueller et al, Phys.Rev. C83(2011) 054615
- P. Huber, Phys.Rev. C84 (2011) 024617
- Ab initio calculation of ^{238}U at IRFU and Subatech-Nantes

Prediction errors





$\delta P_{th}/P_{th}$ = 0.46%
(1 sigma)

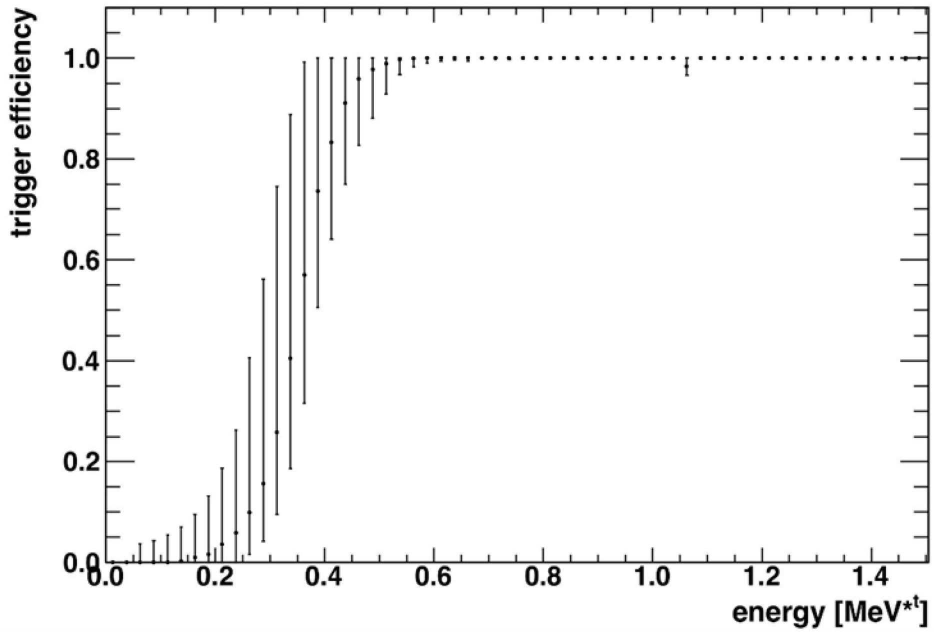


Efficiency: Trigger

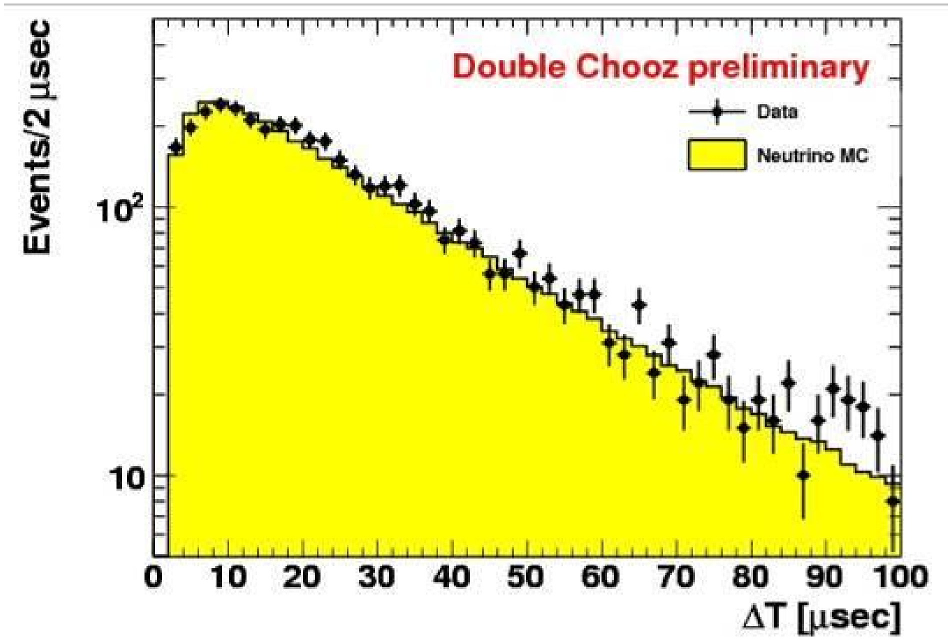
- Minimum anti-neutrino signal in the detector: 2x511 keV gammas

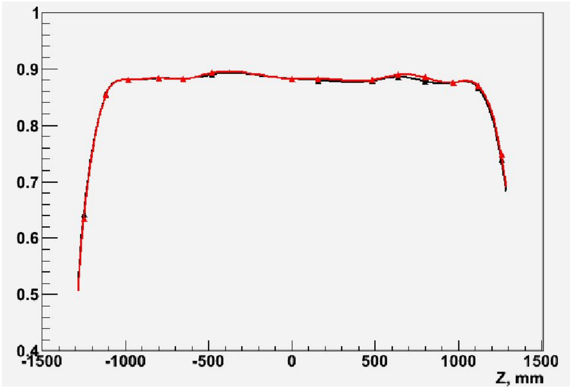
- Trigger threshold should be small enough to accept all anti-neutrinos

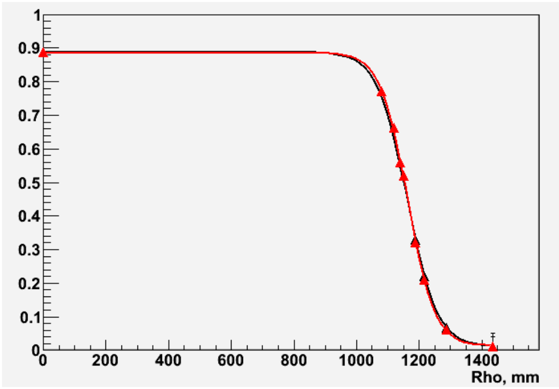
- Prompt analysis cut (0.7 MeV) efficiency is >99.9% with 0.4% error



Efficiency: Inter-event cut

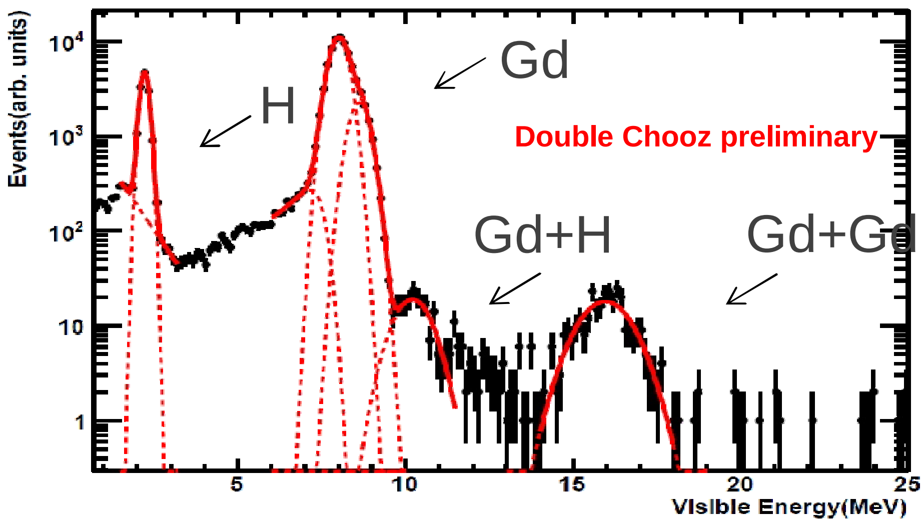


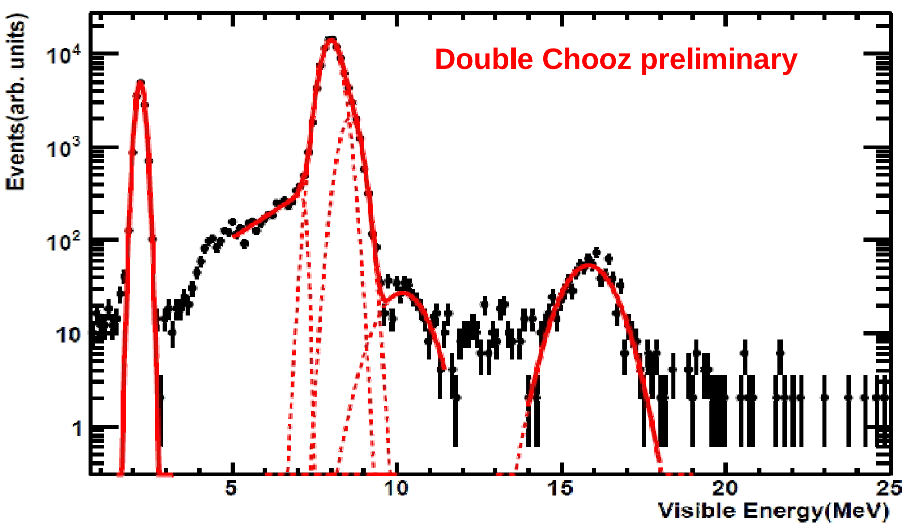




The efficiency within [2,100] μs is 0.965 ± 0.5%

Efficiency: fraction of captures on Gd



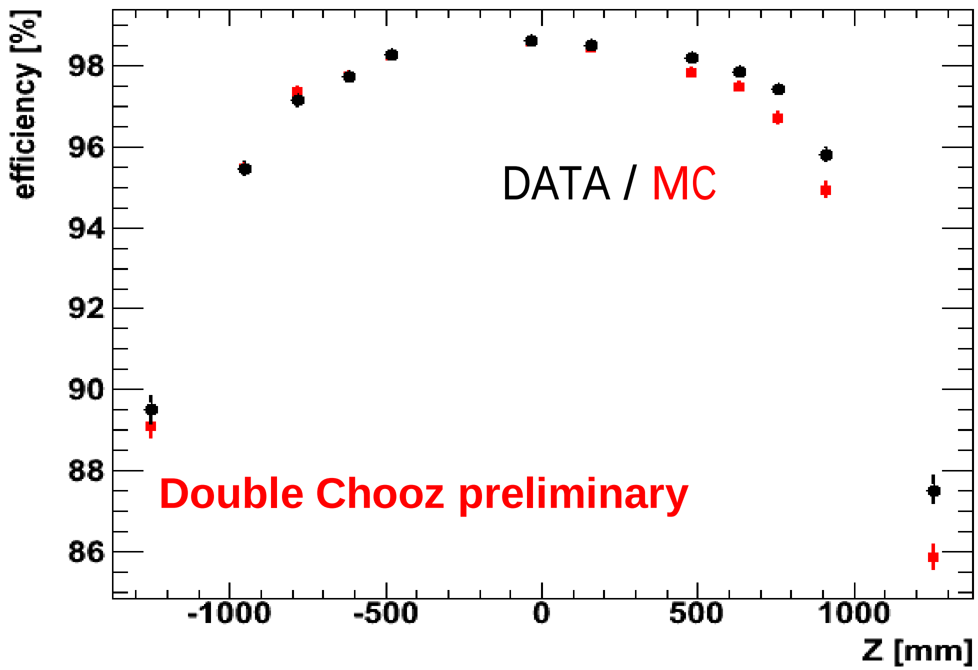


- Deployment along the z-axis
- Compute Gd/(H+Gd) capture rate
- 2% correction between data & MC
- The 6 Mev cut efficiency is 0.86 ± 0.6%

Efficiency: delayed energy containment

• Some Gd gamma's can escape sensitive volume resulting in less than 6 MeV deposited energy total

• # captures **[6,12]** MeV / # captures **[4,12] MeV = 94.5%**



Averaged (Data-MC)/Data relative difference: 0.6%

Putting it all together

$$\chi^2 = \sum_{ij}(Data_i - (\sum_{R}^{Reactors} N_i^{\nu,R} + \sum_{b}^{Backgrounds} N_i^b))\times$$

$$(M_{ij}^{Reactor} + M_{ij}^{Detector} + M_{ij}^{Stat} + \sum_b^{Backgrounds} M_{ij}^b + M_{ij}^{Efficiency})^{-1} \times$$

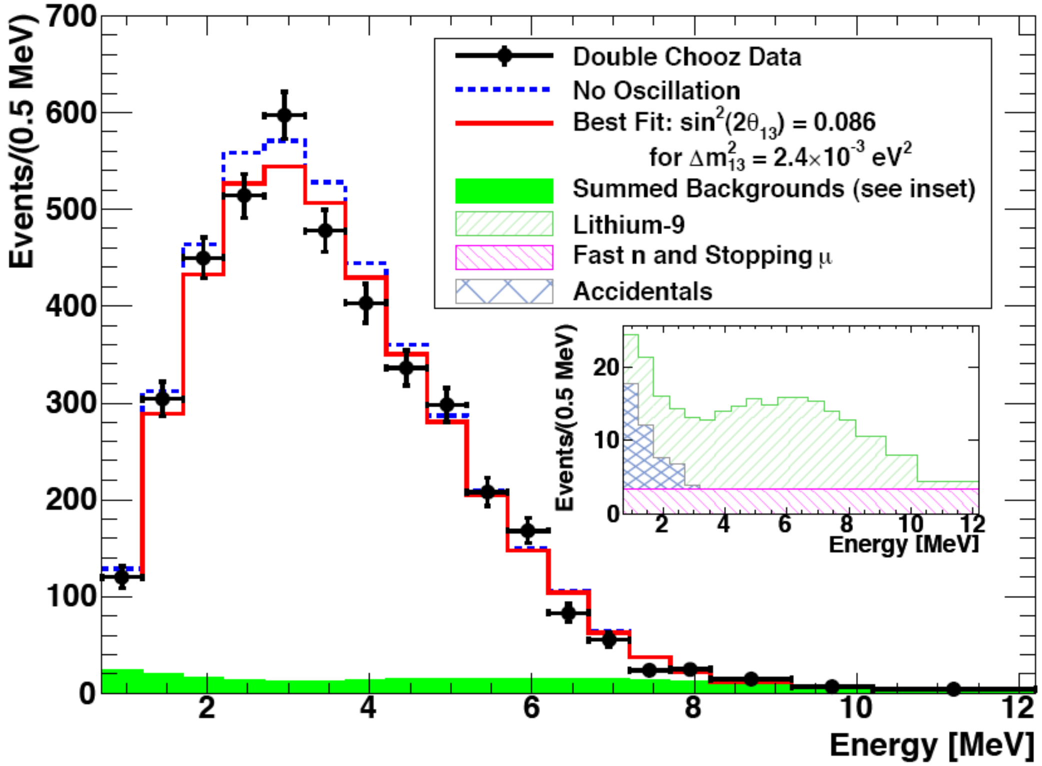
$$(Data_j - (\sum_R^{Reactors} N_j^{\nu,R} + \sum_b^{Backgrounds} N_j^b))$$

normalization systematics

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%

in practice, all errors (including shape errors) included as covariance matrices

Fit results



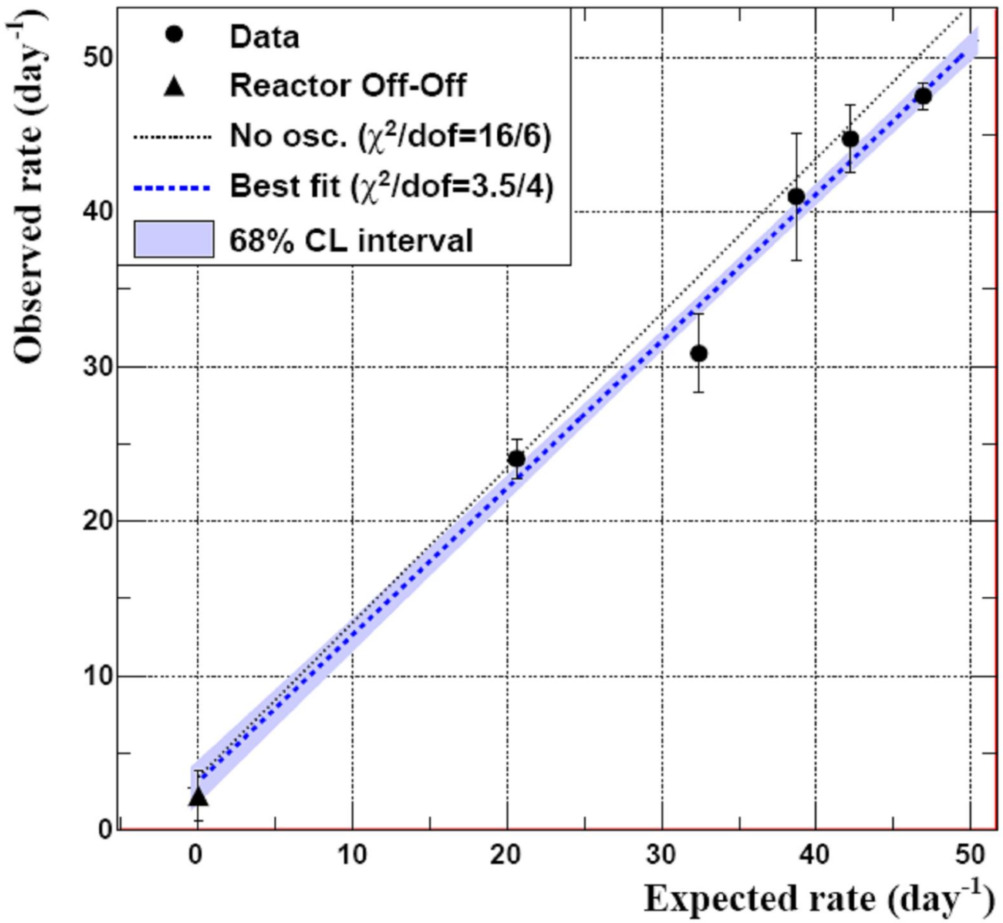
χ^2 = 23.17/17d.o.f.

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

Frequentist studies

- $\Delta\chi^2$ as test statistic
- 94.6% of toy experiments with true value of $\sin^2 2\theta_{13}=0$ have test statistic smaller than the data
- 90% C.L. interval:

$$0.015 < \sin^2 2\theta_{13} < 0.16$$



Daily number of detected candidates vs. the expected number. The dotted line is the expectation in the no-oscillation scenario. The triangle indicates the measurement with both reactors off.

Concluding remarks

- First Double-Chooz analysis found 4121 electron anti-neutrino candidates when 4344±165 were expected for no-oscillation
- Rate+Shape fit suggests

$$\mathbf{\sin^2(2\theta_{13}) = 0.086 \pm 0.051}$$

- "No oscillation" is excluded at **94.6% C.L.**
- 90% C.L. frequentist interval

$$\mathbf{\sin^2(2\theta_{13}) \sim [0.015, 0.16]}$$

- Combining DC results with T2K and Minos excludes no-oscillation at **>3 sigma** [arXiv:1111.3330v1]

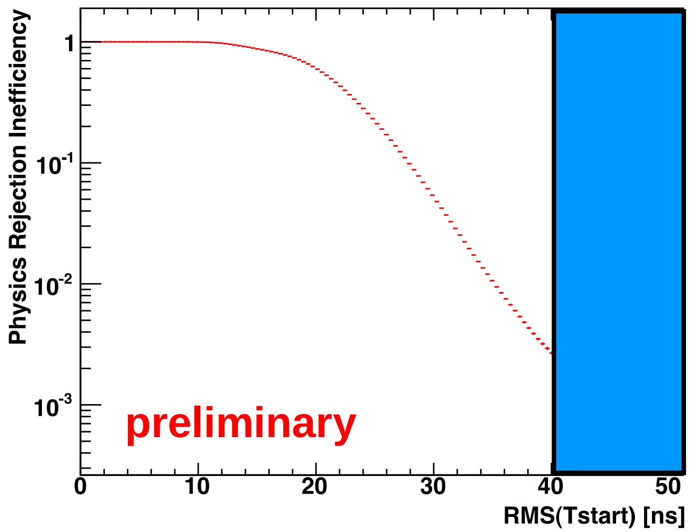
- More coming soon
  - Doubling data set as we speak
  - Refining the backgrounds measurements
  - Refining the detector response with additional calibrations
  - Near detector in ~1 year

Brazil	France	Germany	Japan	Russia	Spain	UK	USA
CBPF UNICAMP UFABC	APC CEA/DSM/IRFU: SPP SPhN SEDI SIS SENAC CNRS/IN2P3: Subatech IPHC ULB/VUB	EKU Tübingen MPIK Heidelberg RWTH Aachen TU München U. Hamburg	Tohoku U. Tokyo Inst. Tech. Tokyo Metro. U. Niigata U. Kobe U. Tohoku Gakuin U. Hiroshima Inst Tech.	INR RAS IPC RAS RRC Kurchatov	CIEMAT-Madrid	Sussex	U. Alabama ANL U. Chicago Columbia U. UCDavis Drexel U. IIT KSU LLNL MIT U. Notre Dame Sandia National Laboratories U. Tennessee

Spokesperson: H. de Kerret (IN2P3)
Project Manager: Ch. Veyssière (CEA-Saclay)

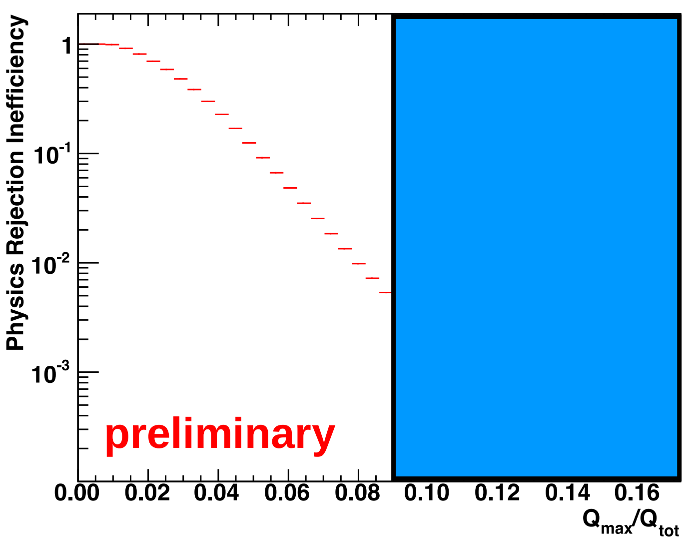
Web Site: www.doublechooz.org/

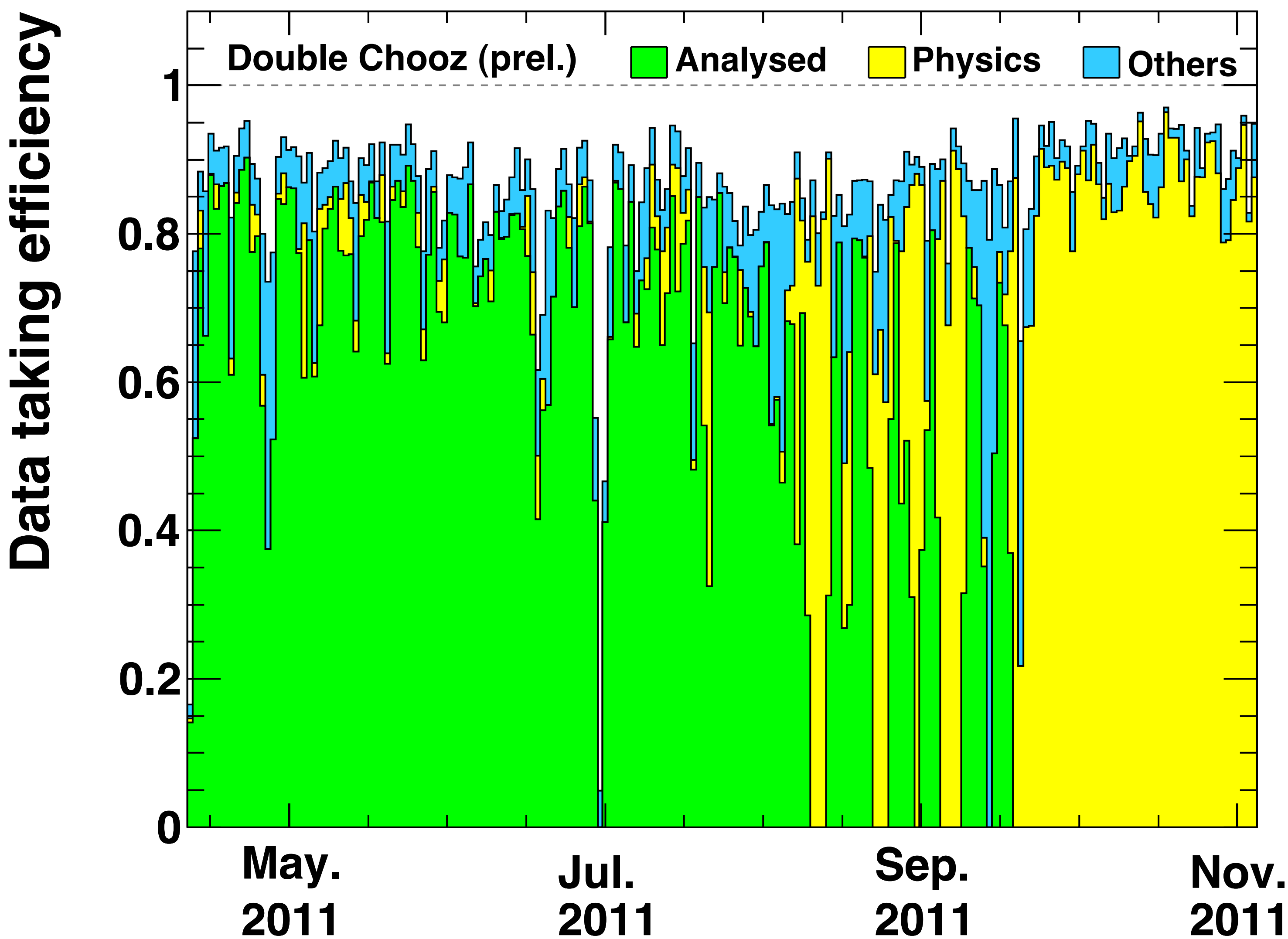
Light noise



Parasitic light emitted by some PMTs. 14 PMTs turned off + effective rejection based on anisotropic light collection:

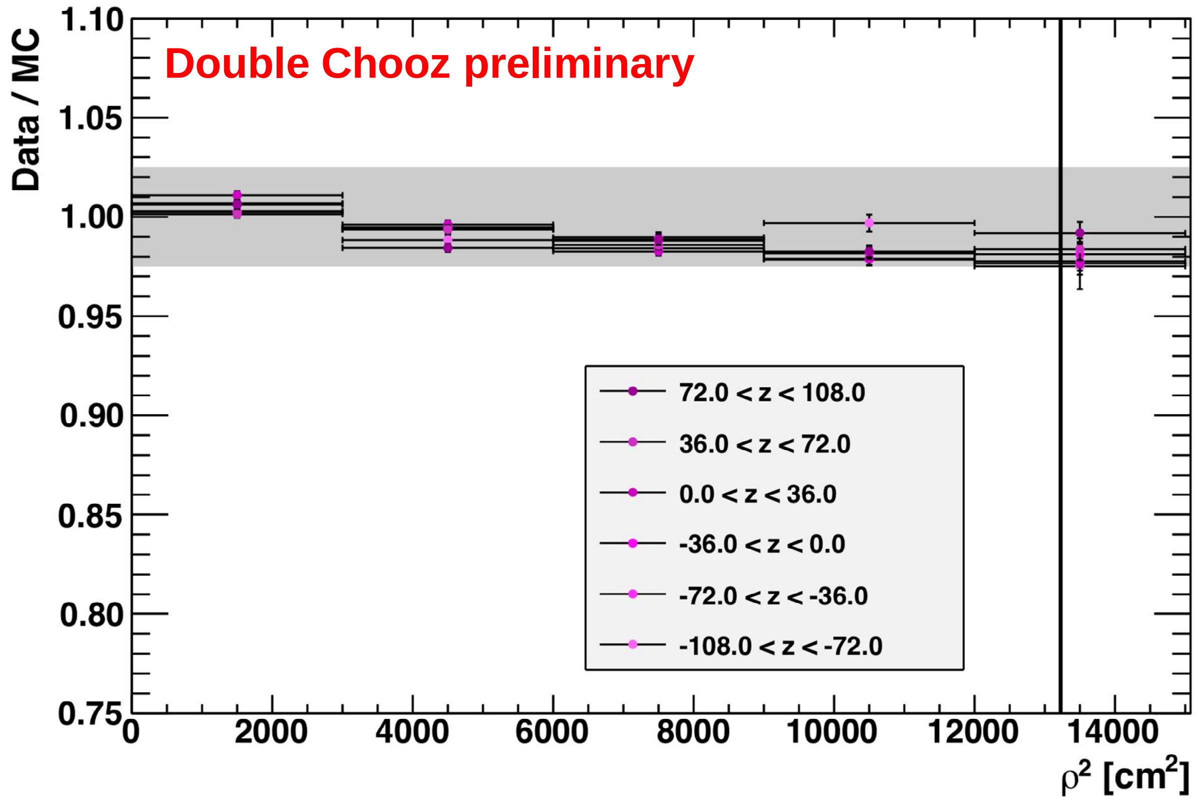
- PMT sees its own light
  → Qmax/Qtot
- Large dispersion of start time of PMT signals → rms(T_{start})

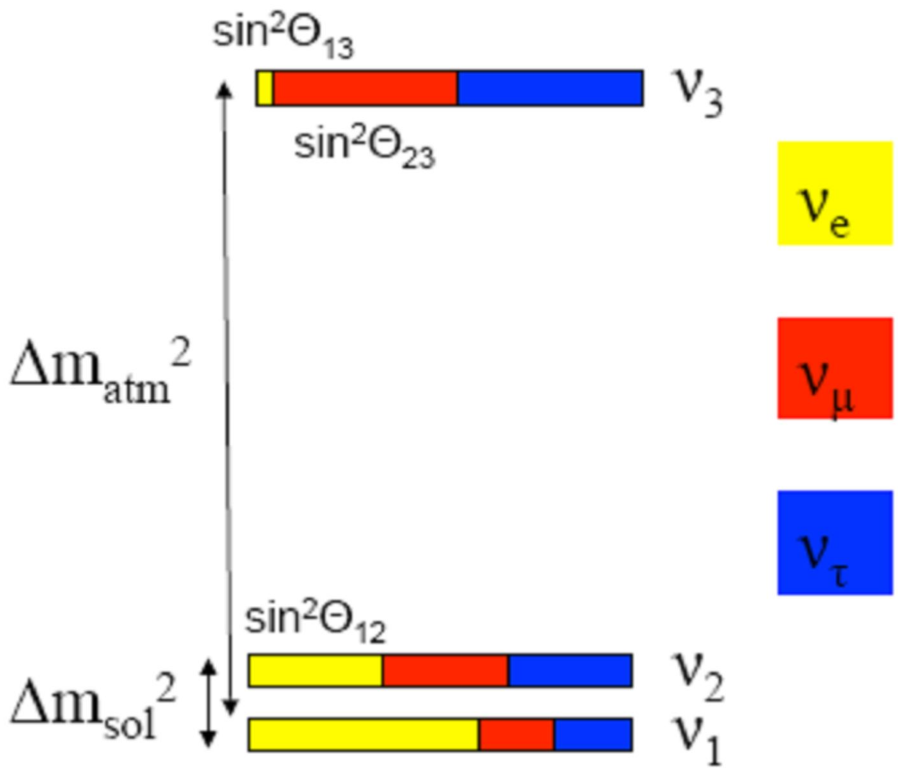



Data taking efficiency
Double Chooz (prel.)
Analysed
Physics
Others
1
0.8
0.6
0.4
0.2
0
May.
2011
Jul.
2011
Sep.
2011
Nov.
2011

	Best-Fit	**68%CL**	**90%CL**	χ^2@**Best − Fit**
Rate Only	0.1044(0.1045)	0.0813(0.0816)	0.1338(0.1343)	n.a.
Shape Only	0.1078(0.1436)	0.1680(0.1704)	0.2766(0.2802)	23.85(23.55)
Rate + Shape	0.0856(0.0854)	0.0502(0.0502)	0.0826(0.0826)	23.71(23.70)

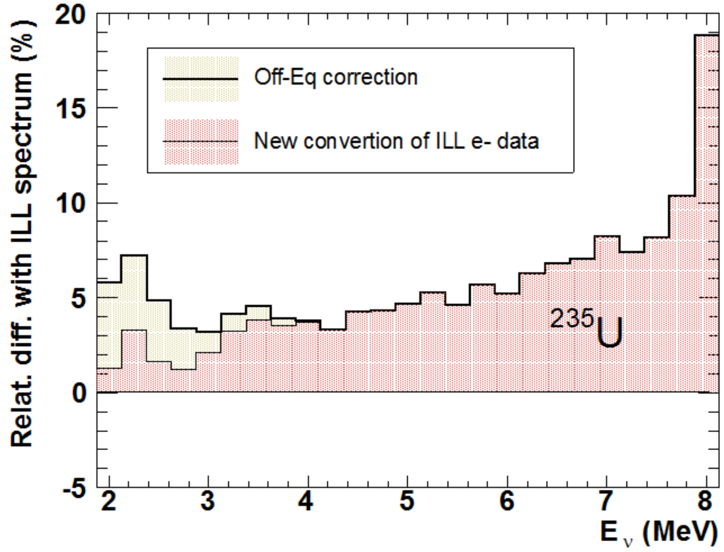
- Evaluation of the (Q,Z) correction in all volumes
- Study of spallation neutrons in $\rho^2 = x^2+y^2$ in slices of z
- Gd n capture peak
- Except for the extremes of the GC all is within +/-2.5%.

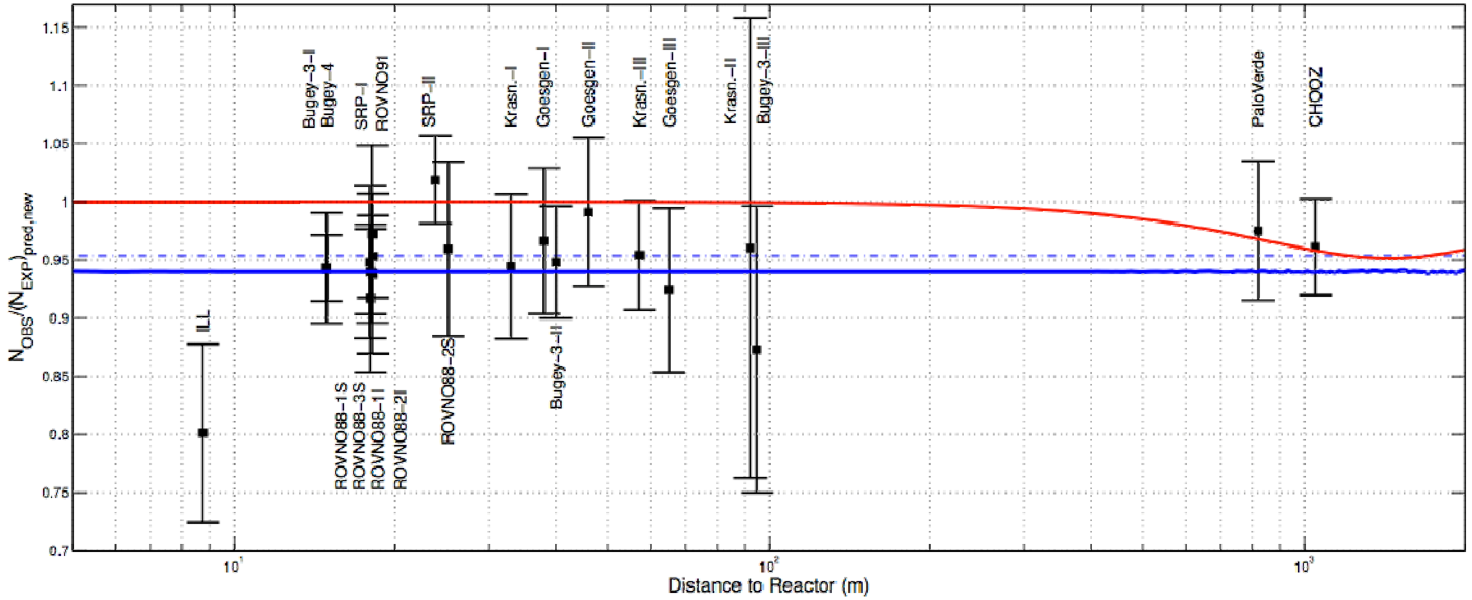



$\sin^2\Theta_{13}$
ν_3
$\sin^2\Theta_{23}$
ν_e
Δm_{atm}^2
ν_μ
ν_τ
$\sin^2\Theta_{12}$
ν_2
Δm_{sol}^2
ν_1

- **Prompt Event:**
  - No Inner Veto Energy Deposition
  - $Q_{max}/Q_{tot} < 0.09$ & $rms(T_{start})<40$ ns
  - E in [0.7 ; 12] MeV
- **Delayed Event:**
  - No Inner Veto Energy Deposition
  - $Q_{max}/Q_{tot} < 0.06$ & $rms(T_{start})<40$ ns
  - E in [6 ; 12] MeV
- **Coincidence:**
  - No Space Coincidence Cut
  - Time Coincidence: 2 μs < Δt < 100μs
- **Multiplicity:**
  - No valid triggers allowed in the 100 μs preceding the prompt
  - The time window from 2 μs to 100 μs following the prompt can contain only one valid trigger: the delayed candidate
  - No valid triggers allowed in the time window 100 μs through 400 μs after the prompt

Th. A. Mueller et al, Phys.Rev. C83(2011) 054615, P. Huber, Phys.Rev. C84 (2011) 024617





G. Mention et al., The Reactor Antineutrino Anomaly. arXiv:1101.2755v4, 23 March 2011