

## **Last results from Double Chooz\***

Guillaume Pronost<sup>1,†</sup>

(for the Double Chooz collaboration)

<sup>1</sup>*SUBATECH, CNRS/IN2P3, Université de Nantes,  
Ecole des Mines de Nantes, 44307 Nantes, France*

(Dated: December 22, 2015)

## Abstract

The Double Chooz collaboration presents an updated measurement of  $\sin^2(2\theta_{13})$  using reactor  $\bar{\nu}_e$  detected through the inverse beta decay reaction in which the neutron is captured on hydrogen. This measurement is based on the far detector-only 2 years data-set, which contains about twice as much data as in the previous hydrogen analysis. The H-based sample allows for an independent data-set, additional to the Gd-based sample. This sample is normally contaminated by an overwhelming accidentals background due to radioactivity (hence the need for gadolinium) and is affected by different detector response systematics. Thanks to new methods for both background rejection and detection systematics, Double Chooz was able to measure  $\sin^2(2\theta_{13}) = 0.098^{+0.038}_{-0.039}$ , consistent with the value measured in the Gd-based sample:  $\sin^2(2\theta_{13}) = 0.090^{+0.032}_{-0.029}$ . This demonstrates that the H-based IBD analysis is as good as the Gd-based one for high precision physics. The H and Gd analyses were also combined in order to measure  $\sin^2(2\theta_{13})$  and the spectral distortion above 4 MeV observed in the Gd analysis.

## INTRODUCTION

The Double Chooz (DC) experiment aims at the measurement of the  $\theta_{13}$  mixing angle from the oscillation of reactor  $\bar{\nu}_e$ . It consists in two identical liquid-scintillator Gd-loaded detectors located at 400 m (Near detector (ND)) and 1050 m (Far detector (FD)) from the two reactor cores of the CHOOZ nuclear power plant (Ardenne, France). The design of both detectors is presented in FIG. 1.  $\theta_{13}$  can be extracted from the measurement of an  $\bar{\nu}_e$  deficit and of an energy distortion in the FD due to  $\nu$  oscillations.

Reactor neutrinos are detected by a delayed coincidence technique through the inverse  $\beta$ -decay (IBD) reaction on protons:  $\bar{\nu}_e + p \rightarrow e^+ + n$ . The positron is observed as the prompt signal with an energy related to the neutrino energy as:  $E_{signal} \simeq E_\nu - 0.8$  MeV. The neutron is captured after its thermalization, either on Gd or H in liquid scintillator with high efficiency. Gd captures occur after a mean time of  $\sim 30$   $\mu$ s and emit a few  $\gamma$ -rays with a total energy of 8 MeV, which is well above the energy of natural radioactivity. In addition, DC was the first experiment to publish a measurement of  $\theta_{13}$  using IBD neutron captures on H [1], in which the released  $\gamma$ -ray carries only 2.2 MeV, an energy well within the range of natural radioactivity thus leading to sizable background. Two IBD analyses are performed in DC, one with Gd neutron captures and the other with H neutron captures. Since the ND

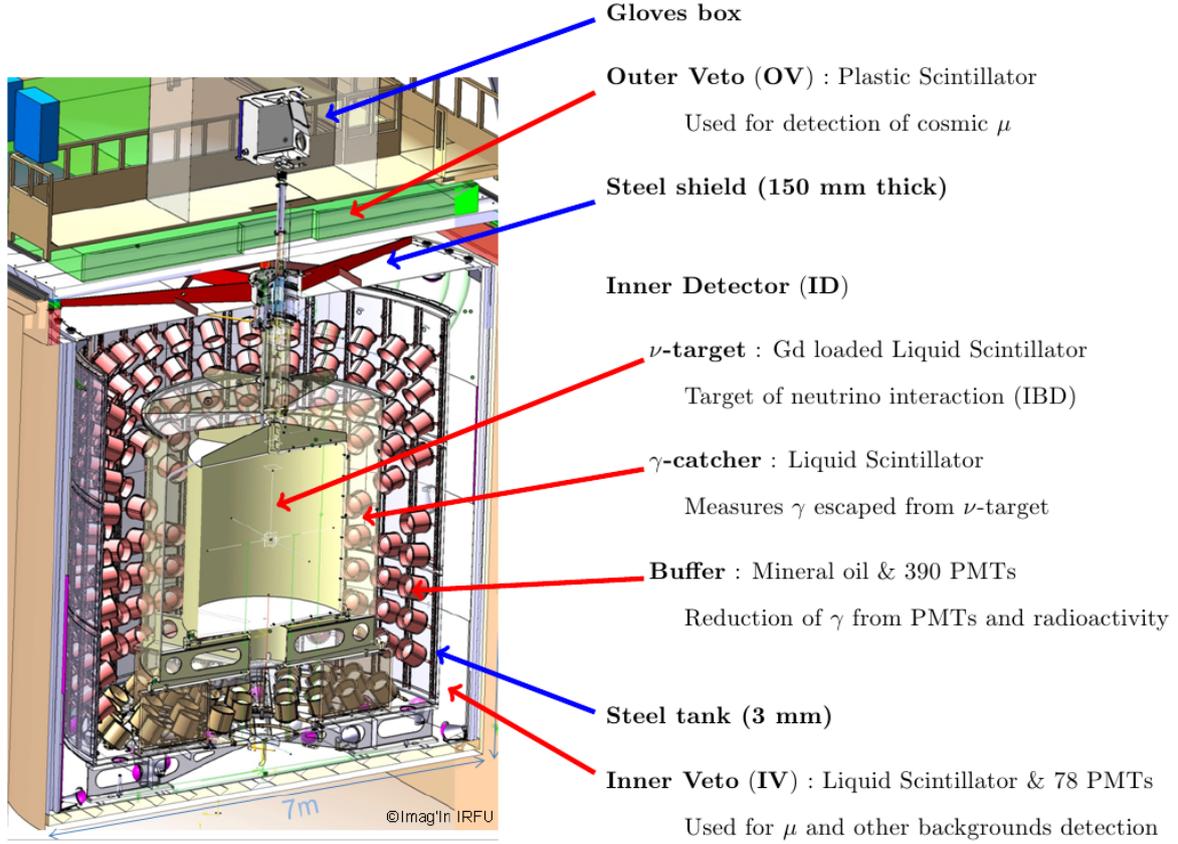


FIG. 1: Double Chooz detector design

was not completed for the last analyses,  $\theta_{13}$  was extracted from the comparison between the  $\bar{\nu}_e$  flux and spectrum from a MC simulation and from the FD.

The Gd analysis, published in [2], allowed to measure  $\sin^2(2\theta_{13}) = 0.090_{-0.029}^{+0.032}$  and showed a distortion in the ratio of the background-subtracted data to the prediction above a prompt signal energy of 4 MeV. The present H analysis has been performed in order to cross-check the results of the Gd analysis with an independent data-set, and demonstrates the capability of precise measurement of reactor  $\bar{\nu}_e$  without Gd loading.

## ENERGY RECONSTRUCTION

The Double Chooz visible energy ( $E_{vis}$ ) is computed from the number of photoelectrons (PE)  $N_{PE}$ . It is calculated and calibrated independently for data and Monte Carlo (MC),

following the same sequence of steps, and treating the MC like a second detector. The following equations show the relation between the  $E_{vis}$  and the total number of PE:

$$E_{vis}^{0,m} = N_{PE}^m \times f_u(\rho, z) \times f_{MeV} \quad (1)$$

$$E_{vis}^{data} = E_{vis}^{0,data} \times f_s^{data}(E_{vis}^{0,data}, t) \quad (2)$$

$$E_{vis}^{MC} = E_{vis}^{0,MC} \times f_{nl}^{MC}(E_{vis}^{0,MC}) \quad (3)$$

where  $E_{vis}^{0,m}$  is a notation for the visible energy before the application of the stability correction or of the non-linearity corrections.  $m$  refers to either *data* or *MC*,  $f_u(\rho, z)$  is the correction coming from the uniformity of the detector response, with  $(\rho, z)$  the reconstructed event position in the detector in cylindrical coordinates.  $f_{MeV}$  is the conversion factor from PE to MeV, extracted from the Hydrogen capture peak of neutron coming from a  $^{252}\text{Cf}$  source deployed at the center of the detector, during a long calibration run.  $f_s^{data}(E_{vis}^{0,data}, t)$  is the correction coming from the stability of the detector response, with  $t$  the reconstructed event's time. Finally,  $f_{nl}^{MC}(E_{vis}^{0,MC})$  is the correction coming from the non-linearities of the detector response. These non-linearities are the charge non-linearity (QNL), which is associated with the modeling of the readout system, and the light non-linearity (LNL), which arises from the scintillator modeling, which is particle dependent.

## NEUTRINO SELECTION

The selection of Hydrogen neutrino candidates is performed on an energy depositions data-set taken between April 2011 and January 2013. The single energy deposition data-set is obtained after application of a 1.25 ms muon veto and some cuts to reject spontaneous light emission from the photomultipliers (called *light noise*). The prompt and the delayed signals are selected with cuts on the energy, the multiplicity and the delayed coincidence. In order to reject the different backgrounds affecting the sample, several other cuts are applied. The different selection cuts applied in the H selection are listed in TAB. I.

Three different backgrounds contaminate the sample:  $\beta - n$  emitters, like  $^9\text{Li}$  and  $^8\text{He}$ , which are long live-time cosmogenic radio-isotope ; correlated energy deposition due to fast

$\mu$ veto	$E_{vis}(\text{ID}) > 20 \text{ MeV}$ or $Q(\text{IV}) > 30k \text{ a.u.}$
$\mu$ dead time	1250 $\mu\text{s}$
Light noise cut	yes
$E_{vis}$ (prompt)	[1, 20] MeV
Delayed coincidence	Multivariate analysis: ANN cut ( <b>New</b> ) Relaxed cuts: $E_{vis}$ (delayed) $\in [1.3, 3]$ MeV $\Delta t (e^+ - n) \in [0.5, 800]$ $\mu\text{s}$ and $\Delta d (e^+ - n) < 1200$ mm
Multiplicity cuts	[-0.8, 0.9] ms (relative to prompt)
OV veto	yes
IV veto (prompt)	yes
IV veto (delayed)	yes ( <b>New</b> )
FV veto	yes
Li+He veto	yes
MPS veto	yes ( <b>New</b> )

TABLE I: Selection cuts applied in the H analysis for neutrino candidates. The label (**New**) indicates the new methods developed for the H analysis.

neutrons proton-recoil and capture on H nuclei, and to stopping- $\mu$  decaying with the emission of a Michel electron ; and accidental background due to random coincidence between two single energy depositions, mainly due to natural radioactivity. In this H analysis, this last background is the dominant one since the delayed signal energy is well within the range of the natural radioactivity.

The delayed coincidence cuts were relaxed with respect to the previous H selection [1] in order to reduce the systematic uncertainties on the detection efficiency. This was allowed thanks to the development of new powerful background rejection methods which lead to an efficient rejection of background with a low inefficiency (i.e. low rejection of IBD events). These new rejection methods are the Artificial Neural Network cut (ANN cut), the Inner Veto veto (IV veto) and the Multiple Pulse Shape veto (MPS veto).

The ANN cut has been developed to reduce the accidental background by exploiting the different relations between the delayed energy, the space correlation,  $\Delta d$ , and the time

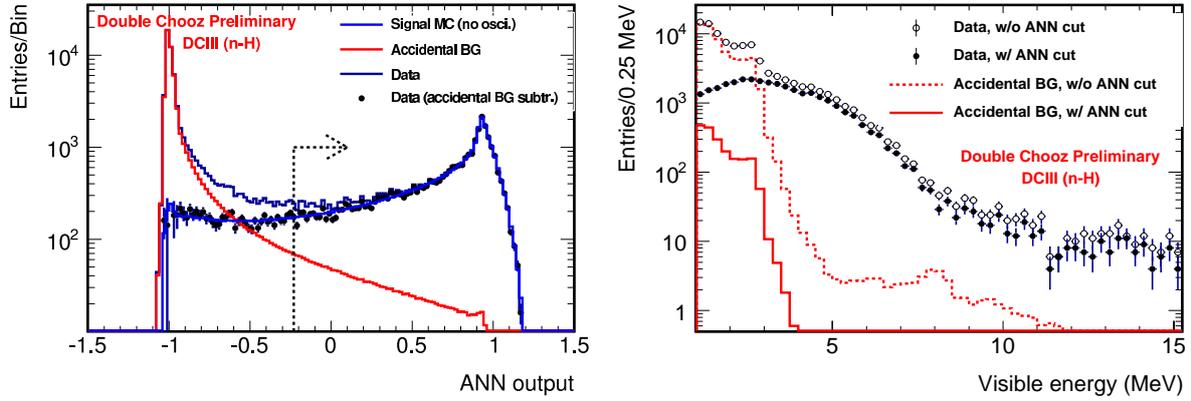


FIG. 2: *Left*: Output of ANN for H neutrino candidates (gray), accidental (blue), signal MC (red) and neutrino candidates after accidental BG subtraction (points). *Right*: Prompt energy spectrum of neutrino candidates (black) and accidental events (red) before and after application of ANN cut.

correlation,  $\Delta t$ , for the accidental background and the IBD events. A multivariate analysis has been performed using an Artificial Neural Network (ANN). FIG. 2 (left) illustrated the output of this ANN for on-time and off-time delayed coincidence data. With the application of this cut, the IBD efficiency only decreased by  $\sim 6\%$  whereas the signal to accidental background ratio has been improved by more than a factor of 10 with respect to the previous H analysis [1]. The data sample after application of the ANN cut, shown in FIG. 2 (right), clearly demonstrating its effectiveness.

The IV veto method tags and rejects events triggered by the ID energy deposition and exhibiting energy deposition in the IV detector within the same *flash*-ADC window (256 ns). In contrast to the last Gd analysis [2], where the main target of the IV veto was the fast neutron background, the IV veto main target in the H analysis is the accidental background which can be reduced by tagging multiple Compton scattering of  $\gamma$ s in the IV and ID. In this new analysis, the IV veto has been applied on both the prompt and the delayed signal, allowing to reject  $\sim 27\%$  of the remaining accidental background after the ANN cut, in addition to also reject fast neutron and stopping- $\mu$ .

The MPS cut method tags and rejects events triggered by their pulse shape distribution. Multiple fast neutrons are expected to be produced by  $\mu$  spallations. Therefore, multiple simultaneous fast neutron interactions in the detector can be expected. Looking at pulse shape composed by a main pulse and multiple additional pulses within a *flash*-ADC window,

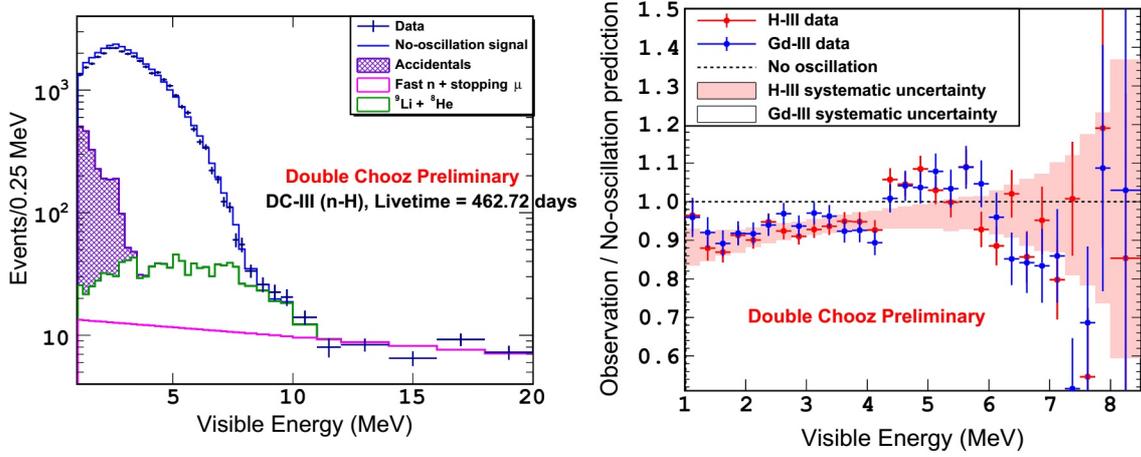


FIG. 3: *Left*: Prompt energy spectrum of neutrino candidates (black) with the the three stacked background components and non-oscillated prediction. *Right*: Ratio of the observation to the prediction for Gd (published in [2]) and H analysis.

MPS can tag and reject 25% of the fast neutron events.

## RESULTS

FIG. 3 (left) shows the prompt energy spectrum of the H IBD candidates, together with the measured background components and the expected spectrum in the non-oscillation hypothesis. 31898 IBD candidates have been obtained in the data sample, with estimated background rates of  $4.34 \pm 0.02$  accidental background events per day,  $1.55 \pm 0.15$  fast neutron and stopping- $\mu$  background events per day and  $0.95^{+0.57}_{-0.33}$   $^9\text{Li}$  and  $^8\text{He}$  background events per day. FIG. 3 (right) is the ratio of the background-subtracted data to the prediction. It demonstrates a clear spectral deficit of  $\bar{\nu}_e$  due to oscillations. In addition, a distortion between 4 and 6 MeV is present. This is a confirmation of the distortion already observed in the Gd analysis with an independent data sample of IBD events.

The  $\theta_{13}$  value was extracted using a reactor rate modulation method (RRM) [3] which consists in the comparison between the observed and the expected rate of IBD candidates for different reactor power. This method allows to measure an independent value of  $\theta_{13}$  and of the background rate. As shown on FIG. 4, the best-fit values are obtained for  $\sin^2(2\theta_{13}) = 0.098^{+0.038}_{-0.039}$  and  $7.29 \pm 0.49$  background events per day. Due to the observed,

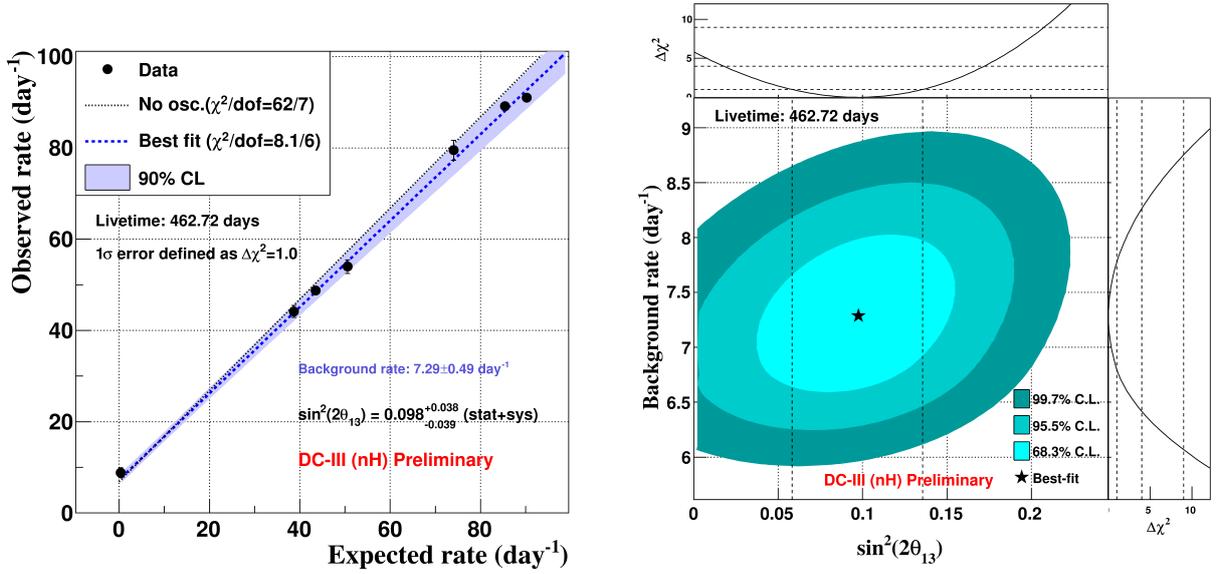


FIG. 4: Reactor rate modulation analysis in H channel: observed rate of neutrino candidates in function of expected rate from reactor flux (left) and best fit results on  $\sin^2(2\theta_{13})$  and background rate (right).

and not yet understood, distortion, this result is considered the main H result. A cross-check has been performed with a rate+shape method and gave  $\sin^2(2\theta_{13}) = 0.124^{+0.030}_{-0.039}$ . A combined RRM fit of the data samples from the last Gd analysis [2] and from this H analysis has also been performed. It gave a result of  $\sin^2(2\theta_{13}) = 0.90 \pm 0.033$ . Thanks to the higher statistics, this improved the Gd-only RRM result ( $\sin^2(2\theta_{13}) = 0.090^{+0.034}_{-0.035}$ ).

## CONCLUSIONS

A new measurement of  $\sin^2(2\theta_{13})$  has been released by the Double Chooz collaboration with a H analysis. Several novel background rejection methods have been developed for this analysis, allowing to reach a predicted signal to background ratio of 10.2, one order a magnitude larger than in the previous H analysis [1]. The RRM analysis of H IBD candidates measured a value of  $\sin^2(2\theta_{13}) = 0.098^{+0.038}_{-0.039}$ . This analysis is a demonstration of the capability of precise measurement of reactor  $\bar{\nu}_e$  without Gd loading. The spectral distortion between 4 and 6 MeV observed in the Gd analysis has been confirmed with this independent analysis. This analysis has been published in [4].

The near detector of Double Chooz started to take data since early 2015. The near

detector + far detector analysis would allow to reduce the current large uncertainties on the neutrino flux and detection efficiency to below 0.1%. Double Chooz is expected to reach a final precision of 10% on  $\sin^2(2\theta_{13})$  in this next phase.

---

\* *Presented at NuFact15, 10-15 Aug 2015, Rio de Janeiro, Brazil [C15-08-10.2]*

† `guillaume.pronost@subatech.in2p3.fr`

- [1] Y. Abe et al. (Double Chooz), Phys. Lett. **B723**, 66 (2013), 1301.2948.
- [2] Y. Abe et al. (Double Chooz), JHEP **10**, 086 (2014), [Erratum: JHEP02,074(2015)], 1406.7763.
- [3] Y. Abe et al. (Double Chooz), Phys. Lett. **B735**, 51 (2014), 1401.5981.
- [4] T. Abrahao et al. (Double Chooz) (2015), 1510.08937.