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Measurement of the neutrino mixing angle $\theta_{13}$ with the Double Chooz detector

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Abstract. The $\theta_{13}$ parameter of the PMNS mixing matrix remained unknown until first hints and estimates by both Double Chooz and beam experiments in 2011. The Double Chooz reactor antineutrino experiment aims for a precise measurement of this parameter. Located at the Chooz nuclear power plant in France, it relies on a two identical detector measurement, canceling most of systematic uncertainties related to neutrino flux emission and detection. The near detector, located at a few hundred meters from the two reactor cores, aims to monitor the $\bar{\nu}_e$ flux from the cores. The far detector, located at a distance of about one kilometer from the reactor cores near the expected first maximum of the oscillation, measures an energy dependent deficit in the electron antineutrino spectrum. Different approaches are used to extract $\theta_{13}$: A combined rate and spectral shape analysis as well as a background-model-independent analysis based on reactor power variations. A unique feature of the Double Chooz experiment is that it was able to take data during a time period with both reactors off. This provides access to the background only measurement, allowing to crosscheck the background models used in the oscillation analysis. A new analysis based on 467.90 live days with 66.5 GW-ton-years of exposure with far detector only, leads to a value of $\sin^2 2\theta_{13} = 0.090^{+0.032}_{-0.029}$. Data taking in the near detector has started end of 2014, enabling a significant reduction of both reactor and detector related systematics uncertainties in a near future.

1. Introduction
In the standard three-flavour framework, neutrino oscillations are described by three mixing angles, three mass-squared differences (only two are independent) and one CP-violating phase. Beside the CP-violating phase and the mass hierarchy of neutrinos, all other parameters have been measured with high precision [1]. $\theta_{13}$ was recently measured by $\bar{\nu}_e$ disappearance in short base-line reactor experiments [2, 3, 4, 5, 6] and $\nu_\mu \rightarrow \nu_e$ appearance in long-baseline accelerator experiments [7, 8]. Without the CP-violating phase the oscillation formula for the survival probability of an electron antineutrino is:

$$P_{\bar{\nu}_e \rightarrow \bar{\nu}_e} = 1 - \sin^2 (2\theta_{13}) \left( c_{12}^2 s_{13}^2 \frac{\Delta m_{31}^2 L}{4E} + s_{12}^2 s_{23}^2 \frac{\Delta m_{32}^2 L}{4E} - c_{13}^4 \sin^2 (2\theta_{12}) \sin^2 \left( \frac{\Delta m_{21}^2 L}{4E} \right) \right)$$

with $s_{ij} = \sin \theta_{ij}$ and $c_{ij} = \cos \theta_{ij}$

One can see, that the oscillation amplitude is driven by the mixing angles and the length of the oscillation by the mass-squared differences. Since one mass-squared difference is much smaller than the other one, the only important oscillation for the case of reactor neutrinos is the one
driven by $\Delta m^2_{13}$. This allows to simplify equation (1):

$$P_{\bar{\nu}_e \rightarrow \nu_e} = 1 - \sin^2(2\theta_{13}) \sin^2 \left( \frac{1.27 \Delta m^2_{13} [eV^2] \cdot L [m]}{E [MeV]} \right)$$

This provides a robust measurement of $\theta_{13}$, because there is no degeneracy with other parameters of the mixing framework. The only input is $\Delta m^2_{13} = 2.44^{+0.09}_{-0.10} \cdot 10^{-3}$ eV$^2$ [7], which is the best known value at the moment and is used in the current analysis (assuming normal hierarchy).

Electron antineutrinos from nuclear power reactors can be detected through the inverse $\beta$-decay (IBD) reaction, with high efficiency and well known cross section: $\bar{\nu}_e + p \rightarrow e^+ + n$. IBD on protons is possible for neutrino energies above 1.8 MeV and provides a robust coincidence measurement. The first signal comes from positron-electron annihilation and provides information about the neutrino energy via $E_{\text{signal}} \approx E_\nu - 0.8$ MeV. In the Double Chooz detector, the second signal comes from capturing the neutron on H or Gd in the liquid scintillator. Gd captures occur after thermalization of the neutron, with a mean time of $\sim 30$ $\mu$s and emit a few $\gamma$’s with a total energy of 8 MeV. This is well above natural radioactivity and provides a powerful background suppression. The same process is possible with captures on H, leading to the emission of a single 2.2 MeV $\gamma$. Double Chooz was the first reactor neutrino experiment providing a $\theta_{13}$ measurement with H capture [3]. After the delayed coincidence is required, remaining backgrounds are mostly induced by cosmic muons, including long-lived cosmogenic isotopes, proton recoils by muon-induced spallation neutrons and stopping muons.

The analysis with only the far detector, which is shown here, is limited by the systematic uncertainties of the flux prediction. In the near future, together with the near detector, uncertainties on the background become more relevant. Therefore the new developed analysis methods [9] are crucial to enhance the sensitivity of future Double Chooz measurements because they also provide significant reduction to the background contributions.

2. The Double Chooz Experiment

The Double Chooz (DC) experiment was built at the site of the Chooz nuclear power plant in France. The two 4.25 GW thermal power pressurized water reactors are operated by EDF (Electricité de France). The far detector is located at an average distance of 1050 m from the two reactor cores, with a 300 meters water equivalent (m.w.e.) rock overburden. The near detector has an average baseline of 400 m and 120 m.w.e. rock overburden. All data in this paper was taken with the far detector only; the near detector started in the end of 2014 and will be taken into account in future analysis.

Since only data of the far detector is addressed here an accurate reactor flux simulation was needed to obtain a $\bar{\nu}_e$ prediction. The location and composition of reactor fuel as well as the instantaneous thermal power for each reactor is provided by EDF. The evolution of both fission rates and fuel composition, including their uncertainties,
Figure 2. Measured and expected neutrino rate for the data taking period from April 2011 to January 2013. In total this corresponds to 66.5 GW-tons of exposure and 17351 IBD candidates. Unique among all reactor neutrino experiments are 7.24 days with both reactors off.

is done with MURE [10, 11] code. The reference $\bar{\nu}_e$ spectra for $^{235}\text{U}$, $^{239}\text{Pu}$ and $^{241}\text{Pu}$ are computed from their $\beta$-spectrum [12, 13, 14], while the $^{238}\text{U}$ spectrum [15] is used for the first time. To improve the suppression of normalization uncertainties in the $\bar{\nu}_e$ prediction, Double Chooz uses the $\bar{\nu}_e$ rate measurement from Bugey4 [16]. The systematic uncertainty on the IBD signal rate associated with the flux prediction is evaluated to be 1.7 % of which the dominant component is an uncertainty of 1.4 % in the Bugey4 measurement. Figure 2 shows expected $\nu$ rate and measured IBD candidate rate for the whole data taking period from April 2011 to January 2013.

The Double Chooz detector is a calorimetric liquid scintillator detector, consisting of 4 concentric cylindrical vessels (see figure 1). The $\nu$-target (NT) is the innermost vessel, built out of 8 mm thick acrylics, and is filled with 10 m$^3$ Gd-loaded liquid scintillator. NT is surrounded by 22.5 m$^3$ Gd-free liquid scintillator with a thickness of 55 cm, called the $\gamma$-catcher (GC). For the analysis with neutron captures on Gd, the NT is the fiducial volume and the $\gamma$-rays with a total energy of 8 MeV are detected both in NT and GC. For the analysis with neutron captures on hydrogen, NT and GC together with a total volume of $\sim$ 33 m$^3$ are used as fiducial volume. To shield the inner part of the detector against natural radioactivity from the surroundings, a 105 cm thick layer of non-scintillating mineral oil, the buffer (BF), follows. The BF vessel is made of stainless steel and supports 390 low background 10-inch photomultiplier tubes (PMTs) [17, 18]. The inner three regions of the detector, NT, GC and BF, are collectively referred to as the inner detector (ID). The ID is surrounded by a 50 cm thick layer of liquid scintillator, the inner veto (IV), optically separated from the ID. The IV is equipped with 78 8-inch PMTs and serves as active veto against cosmic ray muons as well for fast neutrons coming from outside the detector. For a further reduction of $\gamma$-rays coming from the outside, IV and ID are shielded with a 15 cm thick layer of demagnetized steel. To cover the chimney region, which runs through all volumes, and provide tracking information, a second active veto, the outer veto (OV), is installed above the detector and under the ceiling of the laboratory. For calibration and probing the detector, there are several calibration systems, like a light injection system with optical fibers, a guide tube for radioactive sources in the GC and a z-axis deployment system in the NT and its chimney.

Digitized signal waveforms are recorded with a dead-time free data acquisition (DAQ) system.
The trigger threshold is set to 350 keV, well below the minimum energy of the prompt signal at 1.02 MeV. The energy threshold is 400 keV with 100% efficiency and negligible uncertainty.

3. Event reconstruction and detection efficiency

The reconstruction of events begins with pulse reconstruction. Signal charge and time for each PMT are extracted from the digitized waveform recorded by the flash-ADCs. Charge and time are also extracted for a Monte Carlo (MC) simulation by a readout simulation following the same procedure as that for data. The spatial vertex reconstruction is based on a maximum likelihood algorithm, which uses information from charge and timing of the events, assuming a point-like light source. Visible energy $E_{\text{vis}}$ is reconstructed from the total number of photoelectrons $N_{\text{pe}}$ as:

$$E_{\text{vis}} = N_{\text{pe}} \times f_{\text{u}}(\rho, z) \times f_{\text{MeV}} \times f_{\text{s}}(E_{\text{vis}}^0, t)$$

for the data

and

$$E_{\text{vis}} = N_{\text{pe}} \times f_{\text{u}}^{\text{MC}}(\rho, z) \times f_{\text{MeV}}^{\text{MC}} \times f_{\text{nl}}(E_{\text{vis}}^0)$$

for the MC.

In a linearized PE calibration the number of photoelectrons $N_{\text{pe}}$ is computed from the charge of every single PMT signal, including a charge and time dependent conversion factor. Corrections for the uniformity in the detector $f_{\text{u}}(\rho, z)$, with $\rho$ the radial distance from the central vertical axis and $z$ the vertical coordinate, has shown to have a value up to 5% in the NT. A similar pattern is seen in the correction map for the MC. An absolute energy scale $1/f_{\text{MeV}} = 186.2$ PE/MeV (data only) is determined using a $^{252}$Cf neutron source and the capture on hydrogen at 2.223 MeV. A stability correction $f_{\text{s}}(E_{\text{vis}}^0, t)$, to account for remaining time variations, is obtained by monitoring the evolution over time of the hydrogen capture peak. The time variation over both NT and GC is determined to be $+0.30\%$/year. An additional correction factor $f_{\text{nl}}(E_{\text{vis}}^0)$ is applied to the MC simulation because of non-linear discrepancies between data and MC. One last correction handling remaining non-linearities concerning readout and charge integration is taken into account for both data and MC. These non-linearities arise from scintillator modeling, parameters like quenching factor and light yield.

Figure 3 shows good agreement between MC and data over the full energy range. Both energy scales and energy resolution for different energies are matching perfectly. In total, a systematic uncertainty of 0.74% is achieved.

4. Neutrino candidate selection

The first step is the rejection of events occurring within 1 ms after the last muon and removal of events induced by spontaneous light emission from some PMT bases (light noise). Events which satisfy at least one of the following criteria are discarded as light noise:

(i) $q_{\text{max}}/q_{\text{tot}} > 0.12$, where $q_{\text{max}}$ and $q_{\text{tot}}$ are the maximum charge recorded by a PMT and the total charge in the event, respectively;

(ii) $\sigma_t > 36$ ns and $\sigma_q > (464 - 8\sigma_t)$ CU (charge unit), where $\sigma_t$ and $\sigma_q$ are the standard deviation of the PMTs hit time and integrated charge distributions, respectively;

(iii) $Q_{\text{dev}} > 3 \times 10^4$ CU where $Q_{\text{dev}}$ is defined as: $Q_{\text{dev}} = 1/N \times \sum_{i=1}^{N} (q_{\text{max}} - q_i)^2/q_i$, where $N$ is the number of PMTs within a sphere of 1 m radius centered at the PMT with maximum charge.

Neutrino candidates are selected from the remaining dataset requiring the following criteria:

(i) visible energy of the prompt signal should satisfy $0.5 < E_{\text{vis}} < 20$ MeV;

(ii) the delayed signal should satisfy $4 < E_{\text{vis}} < 10$ MeV;
Figure 3. Comparison of the visible energy of the data and MC simulation. Horizontal axis shows the peak energy obtained by a fit and vertical axis shows the energy resolution. Black circles show the data taken with calibration sources at the center of NT and black squares show the peak energy and resolution of neutron captures on Gd in the NT and captures on C distributed over the GC. Red circles and squares show those from the MC simulation.

(iii) the time correlation between the prompt and delayed signals should be in the $0.5 < \Delta T < 150 \mu s$ time window;
(iv) the distance between the vertex positions of the prompt and delayed signals should be within $\Delta R < 100$ cm;
(v) there are no additional events except for the delayed signal found within 200 $\mu s$ before and 600 $\mu s$ after the prompt signal (multiplicity cut).

5. Background contributions
Inverse $\beta$-decay is a coincidence signal, which therefore allows good background suppression. But however, there is still remaining background mostly induced by cosmic muons, which has to be taken into account. In the last publication [9], Double Chooz introduced new powerful tools to suppress this background, e.g. long-lived cosmogenic isotopes, proton recoils by spallation neutrons (referred to as fast neutrons) and stopping muons. In the following, some, but not all, contributions to background and their impact will be discussed. The different background contributions can be separated into two categories: 1) accidental background events, which are uncorrelated events on a random basis 2) correlated background events, mostly induced by high energetic particles, which have the same signature as an IBD signal.

5.1. Cosmogenic isotopes
Figure 4, left shows a typical correlated background event, induced by a cosmic muon. The high energetic muon passes the detector and produces a short-lived radioactive nucleus in a spallation process. These $\beta$-n-emitters cannot be distinguished from IBD, since they have the same coincidence signal: The $\beta$-decay mimics the prompt signal and the neutron capture after thermalization the delayed signal. The main contribution comes from $^9$Li and $^8$He, which have a lifetime of 257 ms and 172 ms respectively. This lifetime is much longer than the applied
muon veto of 1 ms. After the correction for inefficiency, the total cosmogenic background rate is determined to be $2.20^{+0.35}_{-0.27}$ events/day. In the standard neutrino candidates selection, Li candidates are rejected by a Li+He veto. After subtracting Li events rejected by the Li+He veto, the final cosmogenic isotope background rate is estimated to be $0.97^{+0.41}_{-0.16}$ events/day. The visible energy spectrum for $^9$Li can be seen in figure 4, on the right.

5.2. Fast neutrons and stopping muons
For this background contribution, one can imagine two processes (see figure 5, left). First possibility is a muon entering the chimney, therefore not detected by the muon veto, and stopping in the detector. This provides a signal for the prompt event and afterwards a Michel-electron mimics the delayed signal of a IBD signature. The second possibility is a cosmic muon passing by near the detector. On its way it can create fast neutrons through spallation processes in the surrounding rock. When the fast neutron enters the detector, it is possible to get a prompt signal from a proton recoil and the delayed signal from neutron capture after thermalization. Again, this looks the same as an IBD candidate. A new method, so called $F_V$ veto, is able to suppress stopping muons significantly. $F_V$ becomes large for events which have a different hit pattern than a point-like source in the NT and GC, and can be evaluated accordingly.

The background spectrum shape is measured using events, referred to as IV-tagged events, which pass the IBD selections, but would have been rejected by the IV veto. As the fast neutrons and stopping muons often deposit energy in the IV, IV tagging favorably selects correlated background events. Figure 5, right shows the prompt energy spectrum of three samples: 1) IBD candidates; 2) IV-tagged events; and 3) coincidence signals above 20 MeV which are selected by the standard IBD selection but for which the muon veto condition is shifted to higher energies. The correlated background rate is estimated to be $0.604 \pm 0.051$ events/day.
Figure 5. Prompt energy spectrum of three data samples: IBD candidates (black filled points); IV tagged events (red points); and coincident signals above 20 MeV (black empty circles). The red line shows the best fit of a linear function to the IV tagged events with a slope of $-0.02 \pm 0.11$ events/MeV$^2$. IV-tagged events below 1 MeV are not used in the fit to avoid contamination from Compton scattering of $\gamma$’s in the IV and ID.

Figure 6. Decay scheme of $^{214}$Bi and $^{212}$Bi. The $\gamma$ from Bi and the following $\alpha$ decay of Po provide a fast coincidence signal for detection. BiPo coincidences provide access to the radiopurity of the detector.

5.3. BiPo coincidences
Events coming from the decay of $^{214}$Bi and $^{212}$Bi followed by the $\alpha$-decay of $^{214}$Po and $^{212}$Po, referred to as BiPo coincidences, provide a fast coincidence signal between $\beta^-$ and $\alpha$ signal, which is also spatially correlated (see figure 6).

It can be easily distinguished from background and is therefore no contribution to the background of the neutrino candidate selection. But, it provides tagging of the number of decays within the U decay chain (or, at least, of Radon and it’s daughters) and the Th decay chain. This provides a tool to prove the radiopurity of the Double Chooz Detector.

5.4. Accidental background
Accidental background is the random occasion of two uncorrelated signal satisfying the selection criteria for neutrino candidates. This can be for example two $\gamma$’s coming from natural
radioactivity forming a random coincidence. Or the random coincidence between a $\gamma$ from natural radioactivity as prompt signal and a fast neutron capture as delayed signal (see figure 7, left).

Because of its random nature, accidental background can be studied with high precision, using the off-time window method. In this method the standard IBD selection criteria are used, but the time window for the delayed coincidence is shifted more than 1 sec after the prompt signal. A multiple number of successive windows are used to accumulate statistics. The background rate in the off-time windows is measured to be $0.070 \pm 0.003$ events/day, in which corrections for the different dead time from the standard IBD selection and the associated systematic uncertainties on the correction are accounted for. The prompt energy spectrum of the measured accidental background is shown in figure 7, right.

6. Analysis methods and results

During the data taking period, Double Chooz was able to collect 460.67 days of live-time, with at least one reactor on. In this time 17351 IBD candidates were observed, compared to the prediction without oscillation of 18290.3$^{+370}_{-330}$ events. This deficit is due to the non vanishing value of $\theta_{13}$ and the presence of neutrino oscillations. In addition, 7.24 days with both reactors off were collected, which is unique amongst all reactor neutrino experiments. 7 $\pm$ 2.6 (stat.) IBD candidates were found during the off-off period, whereas the prediction was $12.9^{+3.1}_{-1.4}$. This allows to put a constraint on the total background rate and provides a test for the background model.

To measure the value of $\theta_{13}$, Double Chooz uses several independent methods. The different analysis results are explained in the following. All results show good agreement and provide a robust and comparable measurement of $\theta_{13}$.

6.1. Reactor rate modulation

In the first analysis discussed here, we use the advantage of variations in the thermal power of both reactors, called reactor rate modulation (RRM) analysis. There is a linear correlation between observed and the expected neutrino candidate rate at different reactor power levels. In Double Chooz we have three well defined reactor configurations:

(i) both reactors on (referred to as 2-on)
(ii) one of the two reactors off (1-off)
(iii) both reactors off (2-off)

Here the data set was divided in seven bins of the reactor thermal power $P_{th}$: one bin for the 2-off period, three bins during 1-off and 2-on periods, respectively (see figure 8). The fit through the seven data points determines both $\sin^2 2\theta_{13}$ (slope of fit) and the total background rate $B$ (intercept). Fit function reads as

$$R_{obs} = B + R^{exp} = B + (1 - \alpha)R^{\nu}$$

with $R_{obs}$ the observed neutrino candidate rate, $R^{exp}$ the expected neutrino candidate rate, $R^{\nu}$ the neutrino reactor rate and $\alpha$ containing all oscillation variables. This provides an easy and robust measurement of $\theta_{13}$, independent from any background model and was used for the first time by Double Chooz amongst all reactor neutrino experiments.

A global scan is carried out on the $(\sin^2 2\theta_{13}, B)$ grid minimizing $\chi^2$ at each point with respect to the three systematic uncertainty parameters. The minimum $\chi^2$, $\chi^2_{min}/d.o.f. = 1.9/5$, is found at $\sin^2 2\theta_{13} = 0.060 \pm 0.039$ and $B = 0.93^{+0.43}_{-0.36}$ events/day. Next, the reactor-off term ($\chi^2_{off}$) is removed. This configuration tests the impact of the data in reactor-off running to the precision of $\theta_{13}$ measurement. The best fit without the 2-off data is obtained with $\sin^2 2\theta_{13} = 0.089 \pm 0.052$ and $B = 1.56 \pm 0.86$ events/day where $\chi^2_{min}/d.o.f. = 1.3/4$. Figure 9 shows the result of both fits. The allowed regions in the parameter space for several confidence levels are plotted. The high impact of the 2-off data included can be clearly seen by the reduction in parameter space by comparing the dashed lines (without 2-off) and the colored regions (together with 2-off).
6.2. Rate+Shape analysis

In the Rate+Shape analysis the measured energy spectrum of the IBD candidates is compared to the prediction coming from MC (see figure 10). The data set is divided into 40 energy bins between 0.5 and 20 MeV, which are suitably spaced to improve statistics on each bin. Compared to the previous Double Chooz publication [2], several improvements have been made. The treatment of the energy scale is much more detailed and is accounting for non-linearities as well as correction factors (see section 3). The measured energy spectrum from $^{238}$U [15] was used for the first time to get a more precise prediction on the reactor neutrino flux. And there is now an extra bin to take the time period with both detectors off into account. In table 1 the uncertainties of signal and background relative to the prediction are summarized.

A scan of $\chi^2$ is carried out over a wide range of $\sin^22\theta_{13}$, minimizing it with respect to eight fit parameters for each value of $\sin^22\theta_{13}$. The minimum $\chi^2$ value, $\chi^2_{\text{min}}/d.o.f. = 52.2/40$, is found at $\sin^22\theta_{13} = 0.090^{+0.032}_{-0.029}$, where the error is given as the range which gives $\chi^2 < \chi^2_{\text{min}} + 1.0$. Figure 10 shows the energy spectrum of the prompt signal superimposed on the best-fit prediction and the background components. Assuming the inverted hierarchy with $|\Delta m^2_{31}| = 2.38^{+0.09}_{-0.10} \times 10^{-3}\text{eV}^2$ [19], the best-fit is found at $\sin^22\theta_{13} = 0.092^{+0.033}_{-0.029}$ with $\chi^2_{\text{min}}/d.o.f. = 52.2/40$.

A cross-check of the rate+shape fit is carried out removing the constraint to fit parameters for the $^9$Li+$^8$He and correlated background rates. The minimum $\chi^2$, $\chi^2_{\text{min}}/d.o.f. = 46.9/38$, is found at $\sin^22\theta_{13} = 0.088^{+0.030}_{-0.031}$ with $^9$Li+$^8$He rate of $0.49^{+0.16}_{-0.14}$ events/day and correlated.
| Uncertainty (%) | Gd-III/Gd-II |
|-----------------|-------------|
| Reactor flux    | 1.7         | 1            |
| Detection efficiency | 0.6       | 0.6         |
| $^9$Li and $^8$He background | +1.1 / -0.4 | 0.5          |
| Fast-n, stopped-$\mu$ background | 0.1       | 0.2         |
| Statistics      | 0.8         | 0.7         |
| Total           | +2.3 / -2.0 | 0.8         |

Table 1. Signal and background normalization uncertainties relative to the signal prediction. The last column represents the relative reduction Gd-III/Gd-II, that means the current [9]/previous [2] publication.

background rate of $0.541^{+0.052}_{-0.048}$ events/day. The error for each parameter is defined as the range of $\chi^2 < \chi^2_{\text{min}} + 1.0$. A consistent value of $\sin^2 2\theta_{13}$ is thus obtained without the constraint to the background rates and the size of the errors are comparable after the fit. This indicates that the uncertainties on the background rates are strongly suppressed in the $R+S$ fit by the spectral shape information, and the output value of $\theta_{13}$ is robust with respect to the background estimation.

As a further cross-check, $\theta_{13}$ is found to be $\sin^2 2\theta_{13} = 0.090^{+0.036}_{-0.037}$ by a comparison of the total observed rate to the prediction (Rate-only fit). Observed rates in the reactor-on and reactor-off periods are separately used in the fit.

Figure 11 shows a more detailed view of the data compared to the null oscillation hypothesis. An energy dependent deficit below 4 MeV, coming from neutrino oscillation, can be clearly seen. Besides this deficit, a distortion of the energy spectrum is observed around 5 MeV. After checking this distortion carefully, we can say that it has no impact on the measurement of $\theta_{13}$. The possible causes for this effect will be discussed in section 7.

6.3. Hydrogen analysis

The Rate+Shape analysis described above uses the neutron capture on Gd as delayed coincidence signal. The same analysis is possible with neutron capture on hydrogen [3]. The disadvantage for the hydrogen analysis is the higher background contribution because of the lower delayed energy around 2.2 MeV. The Gd analysis was dominated by the correlated background, whereas the hydrogen analysis is dominated by accidental background. The advantage is the larger fiducial volume, both NT and GC can be used for the analysis, which means a factor three more target mass, yielding an exposure of 113.1 GW-ton-years. Thus, the hydrogen analysis provides an independent analysis besides the Gd analysis. The data sample used in this analysis is distinct from that of the Gd analysis, and the systematic uncertainties are also largely independent, with some exceptions, such as the reactor neutrino flux prediction. A combined rate- and energy-dependent fit finds $\sin^2 2\theta_{13} = 0.097 \pm 0.034 \text{ (stat.)} \pm 0.034 \text{ (syst.)}$, excluding the no-oscillation hypothesis at 2.0 $\sigma$ in good agreement with the Gd analysis.

7. Spectrum distortion

In figure 11 one can see a spectral distortion, which was found above 5 MeV and shows an excess of events in this region, compared to the non oscillation hypothesis. Although this excess has no effect on the $\theta_{13}$ measurement, a further investigation is shortly described here.

The energy scale in the region has been evaluated carefully with different methods. Furthermore both energy scale and resolution agree very well between data and MC. First
question is, if the excess comes from an unknown background contribution or not. If it is background, it should be independent of the reactor power. It was possible to show, that this is not the case and also the 2-off results disfavour an additional background contribution. The next possibility is a correlation to the reactor neutrino flux. A strong correlation between the rate of the excess and the overall reactor power was found and implicates an origin from the reactor flux prediction. The significance of the correlation becomes stronger by adding the IBD candidates with neutrons captured on H based on the same data set used in this paper. Further investigations and possible explanations are currently under review.

The significance of the excess between 4.25 and 6 MeV including the uncertainty of the flux prediction is evaluated to be 3.0 $\sigma$ assuming only standard IBD interactions. In addition to the excess, a deficit is found between 6 and 8 MeV with a significance of 1.6 $\sigma$.

8. Conclusion
A new precise measurement of $\theta_{13}$, based on several independent analysis methods, has been performed by Double Chooz. Based on the data of 467.90 days live time, a best-fit to the observed rate and energy spectrum gives $\sin^2 2\theta_{13} = 0.090^{+0.032}_{-0.029}$. A consistent value of $\sin^2 2\theta_{13} = 0.060 \pm 0.039$ is obtained by a fit to the observed rates in different reactor power conditions.

A spectrum distortion is observed at a high energy above 5 MeV but its impact on the $\theta_{13}$ measurement is evaluated to be insignificant. A strong correlation between the excess rate and the reactor power is observed.
For a more detailed explanation of the discussed topics, please refer to the latest Double Chooz publication [9].

References
[1] J. Beringer et al., Phys. Rev. D86, 010001 (2012) and 2013 partial update for the 2014 edition.
[2] Y. Abe et al., Phys. Rev. D86, 052008 (2012).
[3] Y. Abe et al., Phys. Lett. B723, 66 (2013).
[4] Y. Abe et al., Phys. Lett. B735, 51 (2014).
[5] F. P. An et al., Phys. Rev. Lett. 112, 061801 (2014).
[6] J. K. Ahn et al., Phys. Rev. Lett. 108, 191802 (2012).
[7] P. Adamson et al., Phys. Rev. Lett. 110, 171801 (2013).
[8] K. Abe et al., Phys. Rev. Lett. 112, 061802 (2014).
[9] Y. Abe et al., JHEP 10, 086 (2014).
[10] O. Meplan et al., in ENC 2005: European Nuclear Conference; Nuclear power for the XXIst century: from basic research to high-tech industry (2005).
[11] NEA-1845/01 (2009) http://www.oecd-nea.org/tools/abstract/detail/nea-1845
[12] K. Schreckenbach, G. Colvin, F. von Feilitzsch, Phys. Lett. B160, 325 (1985).
[13] F. von Feilitzsch, K. Schreckenbach, Phys. Lett. B118, 162 (1982).
[14] A. Hahn et al., Phys. Lett. B218, 365 (1989).
[15] N. Haag et al., Phys. Rev. Lett. 112, 122501 (2014).
[16] Y. Declais et al., Phys. Lett. B338, 383 (1994).
[17] T. Matsubara et al., Nucl. Instrum. Meth. A661, 16 (2011).
[18] C. Bauer et al., JINST 6, P06008 (2011).
[19] P. Adamson et al., Phys. Rev. Lett. 112, 191801 (2014).