

θ_{13} oscillation analysis in Double Chooz with two detectors

Pietro Chimenti, Denise Hellwig, Philipp Kampmann, Tsunayuki Matsubara, Pau Novella, Stenfan Schoppmann, Guang Yang^{†*}

[†]*E-mail:* gyang@nngroup.physics.sunysb.edu

The Double Chooz experiment is a reactor neutrino disappearance experiment located at the Chooz nuclear power plant in France. The primary goal of the Double Chooz experiment is to precisely measure the neutrino mixing angle θ_{13} , a neutrino oscillation parameter. In this paper, oscillation analysis methods and configurations are shown. The systematics budget and the oscillation fit results are described.

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*Speaker.

1. Introduction

Double Chooz was built to measure the neutrino mixing angle θ_{13} . The experiment consists of two identical liquid scintillator detectors and measures the electron-antineutrino flux of the two nuclear reactors. The 1 km distant far detector started operation in 2011. The 400 m distant near detector started operation at the end of 2014. The reactor neutrinos are detected by the signature of an inverse beta decay (IBD). Inverse beta decay provides a unique prompt-delayed coincident signal to identify the electron antineutrinos from the reactors. The high correlation between the near and the far detector can significantly suppress the systematics for oscillation measurements. The neutrino energy spectrum is extracted from the spectrum of the IBD-produced positrons. The IBD-produced neutrons can be captured by Gadolinium or Hydrogen, which provides two independent data samples. Both samples allow the utilisation of the neutrino rate and energy spectral shape information in a combined fit. The parameter θ_{13} is extracted by a simultaneous fit to the data observed in the two detectors. To validate the measurement, multiple statistical methods as well as multiple fit configurations using the two detectors have been developed in Double Chooz. They are complementary to each other to deliver a precise θ_{13} value.

The far detector took data alone for 3 years and the two detectors took data together for 1 year. Therefore, three data samples are used, one for the far detector alone period, FDI and the other two for the simultaneous data taking period, FDII and ND. Figure 1 shows the locations of the two detectors as well as the three data samples. We also uses the Bugey 4 measurement [1] as a

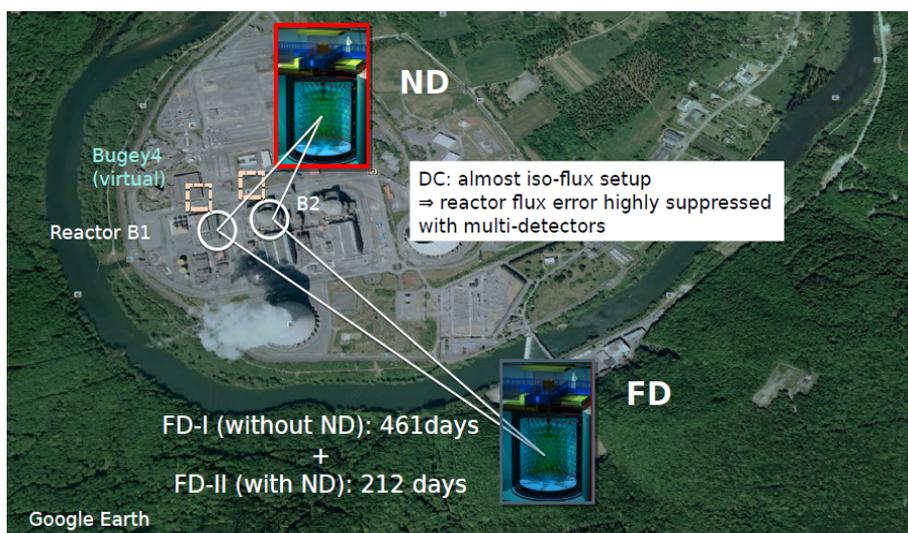


Figure 1: Locations of the reactors and detectors. Three data samples are also highlighted.

constraint on the cross section per fission, which is the dominant systematic uncertainty for a single detector. The method that uses both the rate deficit caused by θ_{13} and energy shape information (Rate + Shape) is described here.

2. Systematic uncertainties

There are three dominant systematic uncertainty sources: reactor flux, energy scale and detec-

tion systematics. For the reactor flux systematics, three dominant sources are the cross section per fission (Bugey 4 constraint), thermal power and fission fraction. For the FDI–FDII correlation, the cross section per fission is correlated and since the data taking periods are different, the thermal power and fission fraction are uncorrelated. For the FDII–ND correlation, again, the cross section per fission is correlated. The thermal power and fission fraction uncertainties from the same reactor to the two detectors are correlated and from different reactors to the two detectors are uncorrelated.

With above treatment, the reactor flux is reduced from 1.4% down to less than 0.1% with two detectors, so energy scale and detection systematics are dominant in the two detector oscillation analysis. The detection systematics in both detectors are partially correlated. The reduced systematics is $\sim 0.2\%$ in the data samples. The energy scale systematics is assumed to be uncorrelated across the three data samples. This is the most conservative treatment.

3. Data-MC simultaneous fit

The method that uses the comparison between MC and data for all the three samples is called the MC-based fit. Figures 2 shows the data and MC comparisons for the three data samples. The

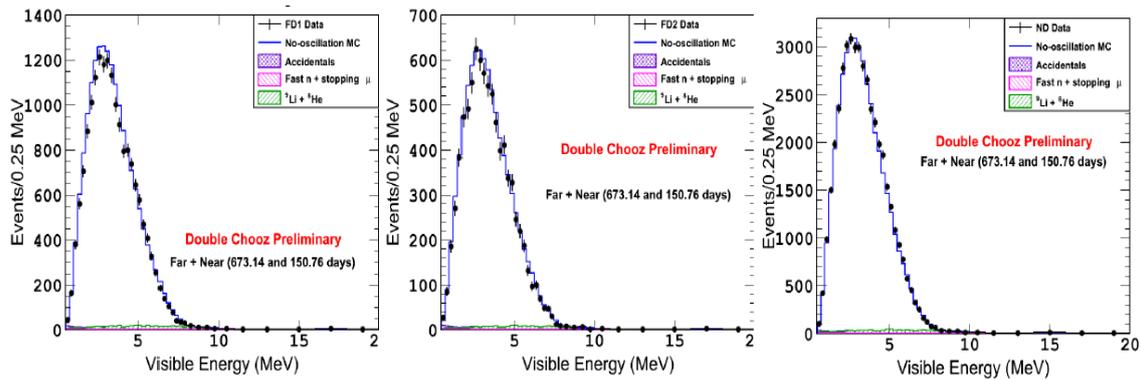


Figure 2: Data and MC comparisons for the three data samples. The blue histograms show the non-oscillation MC and the black points are the data.

deficit due to the oscillation appear in the FDI and FDII samples but not in the ND. To see the background components clearly, fig. 3 shows the same plots using log scales. The visible energy we fit ranges from 0.5 MeV to 20 MeV. Most of the bins have a 0.25 MeV width. Three dominant background appear in this energy region: accidental background, cosmogenic Li/He events and fast neutrons. Details of the backgrounds can be found in ref. [2]. The energy range 10–20 MeV is dominated by the fast neutrons and the energy range 8–10 MeV is dominated by the Li/He events. So the rate + shape fit has a strong ability to constrain the background rates. We free the Li/He background rate and let the fitter constrain that. Figure 4 shows the Li/He rate uncertainty from the fitter with different energy ranges. The Li/He rate is highly constrained by the fitter in the 8–10 MeV region.

We use a least squares fit structure to construct the data and MC comparison. This χ^2 method assumes events in each energy bin are distributed as a Gaussian. Since the oscillation signal is apparent in Double Chooz, this method can simply give us a precise θ_{13} measurement. Systematic

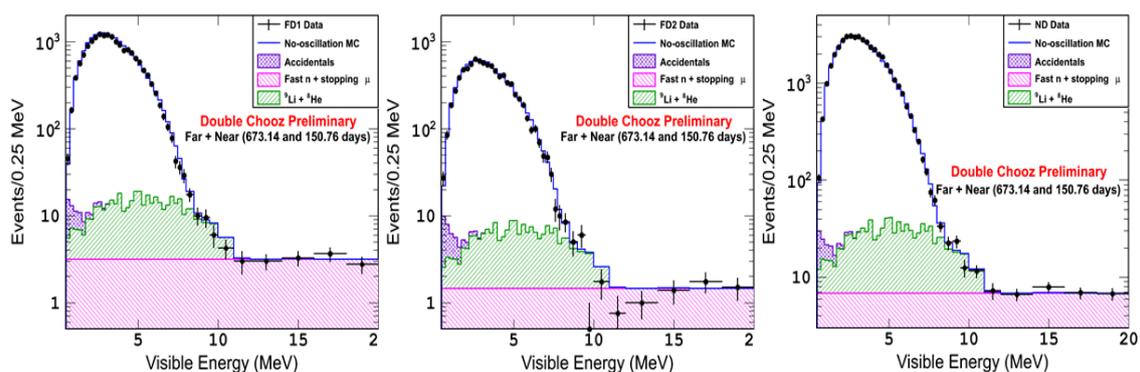


Figure 3: Data and MC comparisons in log scales. The blue histograms show the non-oscillation MC and the black points are the data. The three background components are also shown.

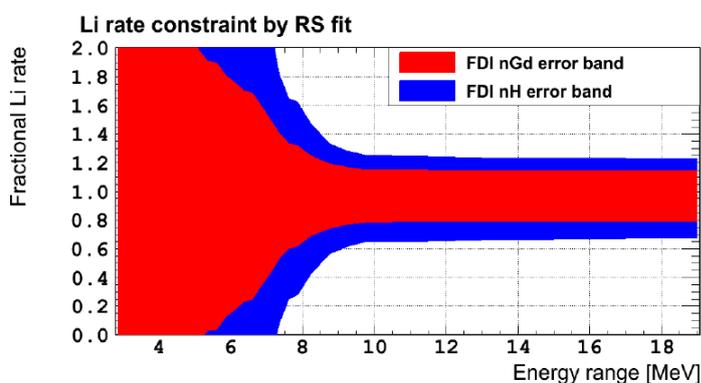


Figure 4: Uncertainty of the Li/He rate per day vs. fitting range in MeV. Red band is for the nGd analysis and blue band is for the nH analysis.

uncertainties can be treated as either a covariance matrix or a pull term in this oscillation fit. The energy scale parameters, background rates and Δm_{ee}^2 are treated as pull terms. Since the baseline of the Double Chooz far detector does not reach the first oscillation minimum, the value of Δm_{ee}^2 is constrained by external measurements [3, 4]. Other systematic uncertainties are all treated as covariance matrices. Figures 5 shows the data and MC comparisons for the three data samples. The oscillation best fit lines are also shown in the plots. The oscillation effect is obvious in the FD but not in the ND. Our best fit result is $\sin^2 2\theta_{13} = 0.111 \pm 0.018$. The non-zero θ_{13} observation is at the 5.8σ confidence level. For the FD, the output rate for the Li/He background is 0.75 ± 0.14 per day and that for the fast neutron background is 0.535 ± 0.035 per day. Those numbers for the ND are 4.89 ± 0.78 per day and 3.53 ± 0.16 per day.

4. Cross-checks

Double Chooz has multiple cross checks on the primary oscillation analysis results. All cross checks provide consistent results. We briefly introduce four kinds of cross check here.

First, we can ignore the energy shape information. By doing so, the energy scale systematics can be ignored. Then the neutrino rates in the data and non-oscillation MC are compared and the

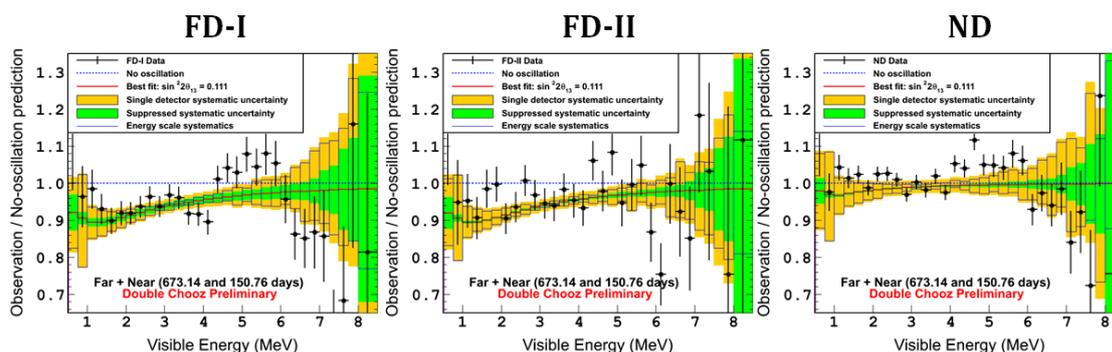


Figure 5: Ratios of data to non-oscillation MC. Red lines are the best fit curves. Yellow bands are the systematics for the single detector and green bands are the reduced systematics for the two detectors.

θ_{13} can be obtained by the rate deficit in the data. The other three kinds of cross check use both rate and shape information. The second cross check uses the FD data comparing to the ND data directly and the value θ_{13} is extracted from the FD neutrino deficit. In this framework, the sensitivity to θ_{13} is worse than the MC-based fit due to statistics in the data and lack of constraints on background rates. Third, we use a log-likelihood fit framework instead of least squares framework. We still compare the data to the non-oscillation MC but we assume in each energy bin that the event distribution is Poisson. The last cross check is a Bayesian framework. We insert priors to the fitter. We assume θ_{13} is flat distributed between 0 and 1 and other pull parameters (background rates and Δm^2) are Gaussian distributed and constrained by the external measurements.

5. Conclusion

Double Chooz has its first two detector oscillation analysis result in 2016. The best fit value is $\sin^2 2\theta_{13} = 0.111 \pm 0.018$. The systematic contribution is only 0.005. As statistics is dominant for the current sensitivity, we aim to combine the nGd and nH channels to obtain more statistics. Our preliminary estimate of the non-zero $\sin^2 2\theta_{13}$ sensitivity with a combination of the two channels is at $\sim 10 \sigma$ confidence level.

References

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