Double Chooz: Latest results

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(on behalf of the Double Chooz collaboration)

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NOW 2014
Outline

• Double Chooz concept
• Antineutrino detection
• Reactor flux
• Detector
• Energy reconstruction
• Backgrounds
• New analysis
• Conclusion
**Double Chooz collaboration**

**Brazil**
- CBPF
- UNICAMP
- UFABC

**France**
- APC
- CEA/DSM/IRFU: SPP, SPhN, SEDI, SIS
- SENAC
- CNRS/IN2P3: Subatech, IPHC, ULB/VUB

**Germany**
- EKU Tübingen
- MPIK Heidelberg
- RWTH Aachen
- TU München
- U. Hamburg

**Japan**
- Tohoku U.
- Tokyo Inst. Tech.
- Tokyo Metro. U.
- Niigata U.
- Kobe U.
- Tohoku Gakuin U.
- Hiroshima Inst. Tech.

**Russia**
- INR RAS
- IPC RAS
- RRC Kurchatov

**Spain**
- CIERMAT Madrid

**USA**
- U. Alabama
- ANL
- U. Chicago
- Columbia U.
- UC Davis
- Drexel U.
- U. Hawaii
- IIT
- KSU
- LLNL
- MIT
- U. Notre Dame
- U. Tennessee
- Virginia Tech

**Website**
www.doublechooz.org

**Spokesperson**
Hervé de Kerret (IN2P3)

**Project manager**
C. Veyssière (CEA-Saclay)
Double Chooz: a 2-detector experiment

Near Detector
- L ~ 400 m
- ~ 300 v/day
- 120 mwe
- Fall 2014

Far Detector
- L ~ 1050 m
- ~ 40 v/day
- 300 mwe
- April 2011

EDF’s Chooz nuclear power plant (Ardennes, France)

Chooz-B reactors
- PWR N4s
- 2 × 4.27 GWth
- ~ 10^{21} v/s
- 100% anti-ν_e

Direct measurement

\[ P_{\nu_e \rightarrow \nu_x} \cong 1 - \sin^2(2\theta_{13}) \sin^2 \left( 1.27 \frac{\Delta m^2_{12}[eV^2] \cdot L[m]}{E_e[MeV]} \right) \]

~ Probability(ν_x)

- ND
- FD

Solar Δm_{21}^2 Dominated

Atmospheric Δm_{23}^2 Dominated
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Antineutrino detection

- Inverse Beta Decay (IBD):
  \[ \bar{\nu}_e + p \rightarrow e^+ + n \]
  - Reaction threshold: \( E_\nu \geq 1.806 \text{ MeV} \).
  - Disappearance experiment.
  - Well known cross-section.

- Coincidence of 2 signals: background suppression.

**Prompt signal:**
- Positron kinetic energy + \( \gamma \)'s from annihilation.
- \( E \sim 1 - 8 \text{ MeV} \)
  - \( E_{\text{vis}} \approx E_\nu - 0.8 \text{ MeV} \)

**Delayed signal:**
- \( \gamma \)'s from n capture on Gd (H).
- \( E \sim 8 \text{ MeV}, \Delta t \sim 30 \mu s \) (\( E \sim 2.2 \text{ MeV}, \Delta t \sim 200 \mu s \)).
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Reactor flux prediction

Expected antineutrino spectrum:

\[ N_v^{\text{exp}}(E,t) = \frac{N_p \varepsilon}{4\pi L^2} \times P_{th}(t) \times \langle \sigma_f \rangle \]

Mean energy per fission:

\[ \langle E_f \rangle = \sum_k \alpha_k(t) \langle E_f \rangle_k \]

Fission fractions

Mean cross-section per fission:

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

Reference spectra

Mean cross-section per nuclide:

\[ \langle \sigma_f \rangle_k = \int dE S_k(E) \sigma_{IBD}(E) \]

New $^{238}$U: PRL 112 (2014) 122501

MURE (NEA-1845/01 (2009))

DRAGON (PRD 86 (2012) 012001)
Reactor flux uncertainty

- Bugey4 (L ~ 15 m) total cross-section per fission measurement:
  - Used as effective Near Detector in the MC simulation.
  - Reduction of ~30% flux uncertainty (still dominant).
- Major cancellation of flux uncertainty once Near Detector is operative.
  - Double Chooz almost isoflux configuration will allow to exploit the cancellation.
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The Double Chooz detector

Inner detector:
- **Neutrino target:** acrylic vessel (8 mm) with 10.3 m³ Gd-loaded (1 g/l) liquid scintillator.
- **Gamma-catcher:** acrylic (12 mm) vessel with 22.3 m³ of liquid scintillator.
- **Buffer:** stainless steel (3 mm) vessel supporting 390 10” PMTs, with 110 m³ of non-scintillating mineral oil.

Outer detector:
- **Inner veto:** steel (10 mm) vessel supporting 78 8” PMTs, with 90 m³ of liquid scintillator.
- **Shielding:** 15 cm steel.
- **Outer veto:** plastic scintillator strips.
Calibration systems

- **Light injection** in Inner Detector and Inner Veto:
  - Multi-wavelength LED-fiber system.
- **Deployable**: radioactive sources ($^{137}$Cs, $^{68}$Ge, $^{60}$Co, $^{252}$Cf) and laser.
  - Z-Axis.
  - Guide Tube.
- **Natural**: muon spallation neutrons, IBD neutrons, $^{212}$Bi – $^{212}$Po.
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Energy reconstruction

- Applied to DATA and MC in parallel.

- **PE calibration:**
  - Correct for gain non-linearity at low charge.
  - Computed for each channel per power-cycle.
  - Using LED light-injection calibration system.

- **Uniformity calibration:**
  - Correct for spatial dependence of PE.
  - Maps using n-H captures: spallation-n (DATA), antineutrinos-n (MC).

- **MeV calibration:**
  - Conversion from PE to MeV.
  - $^{252}$Cf source at the center.
Energy reconstruction

- **Stability calibration (only DATA):**
  - Correct for time dependence of MeV.
  - Computed using spallation-n captures on H and Gd, and $^{212}\text{Bi} - ^{212}\text{Po}$.

- **Charge non-linearity (only MC):**
  - Correct for remaining energy non-linearity due to readout effects.
  - Using ratio of $^{252}\text{Cf}$-n captures in H and Gd.

- **Light non-linearity (only MC):**
  - Correct for scintillator model (quenching, light yield).
  - Implemented in the rate + shape fit.
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Backgrounds

\(^9\text{Li}\) and \(^8\text{He}\):
- Produced by muon-spallation.
- \(\beta\)-n emitters, mimic the antineutrino signal.
- Long lifetime \(\sim\)250 ms. Veto not feasible.

Correlated background
  - Fast neutrons
  - Stopping muons

Accidental background
Backgrounds

$^9$Li and $^8$He

**Correlated background:**

- **Fast neutrons:**
  - Nearby muon-spallation.
  - Prompt: proton recoil
  - Delayed: neutron capture

- **Stopping muons**

**Accidental background**
Backgrounds

$^9$Li and $^8$He

**Correlated background:**

- Fast neutrons

**Stopping muons:**

- Muons decaying in the detector.
- Acceptance hole in chimney.
- Prompt: muon track.
- Delayed: Michel electron.

**Accidental background**
Backgrounds

$^9\text{Li}$ and $^8\text{He}$

Correlated background:
- Fast neutrons
- Stopping muons

Accidental background:
- Random coincidence (uncorrelated):
  - Radioactivity from PMTs, rock, materials, ...
  - Neutron-like signal produced by high energy depositions ($\beta$-emitters, n-capture, ...).
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Double Chooz previous $\theta_{13}$ results

Gd
- 1st reactor experiment to provide indication of non-null $\theta_{13}$:
  \[ \text{Gd-I: } \sin^2(2\theta_{13}) = 0.086 \pm 0.051 \]  
  (Phys. Rev. Lett. 108 (2012) 131801)
- Previous Gd result published:
  \[ \text{Gd-II: } \sin^2(2\theta_{13}) = 0.109 \pm 0.039 \]  
  (Phys. Rev. D86 (2012) 052008)
- Gd-III: New Gd result!

H
- 1st reactor experiment to use neutron captures in H:
  \[ \sin^2(2\theta_{13}) = 0.097 \pm 0.048 \]  
  (Phys. Lett. B 723 (2013) 66-70)

Gd + H
- 1st reactor experiment to combine neutron captures in Gd and H:
  \[ \sin^2(2\theta_{13}) = 0.109 \pm 0.035 \]  
  (EPS HEP 2013)

RRM fit
- Unique experiment with a background model-independent fit:
  \[ \text{Gd: } \sin^2(2\theta_{13}) = 0.107 \pm 0.049 \]
  \[ \text{H: } \sin^2(2\theta_{13}) = 0.091 \pm 0.078 \]
  \[ \text{Gd + H: } \sin^2(2\theta_{13}) = 0.102 \pm 0.043 \]  
  (Phys. Lett. B 735 (2014) 51-56)
Motivation for a new analysis

- We have been dominated by the reactor flux uncertainty (1.7%).
- But this is about to change with our Near Detector.
- New analysis: prototyping the 2-detector analysis.
  - More accurate energy.
  - Wider and more efficient selection: $\times 2$ improvement on detection unc.
  - New background vetoes: $\times 3$ improvement on background unc.
  - Increased S/B: 15.6 → 22.
- More statistics ($\times 2$): 227.9 days → 467.9 days.
New selection

Muon veto

New
• $\mu$-tag: $\text{Energy(ID)} \geq 20$ MeV or $\text{Charge(IV)} \geq 30$ k (a.u.)
• Veto after-$\mu$: 1ms

Light noise cuts

New
• $(\text{Max. charge})/(\text{Total charge}) \leq 0.12$
• $\text{RMS}(\text{Time}_{\text{start}}) - \text{RMS}(\text{Charge})$: 2-D cut
• Charge difference to neighbor PMTs $< 30$ k (a.u.)

IBD selection

New
• Isolation window (around prompt): $[-200 \, \mu\text{s}, 600 \, \mu\text{s}]$
• $0.5$ MeV $< \text{Prompt energy} < 20$ MeV
• $4$ MeV $< \text{Delayed energy} < 10$ MeV
• $0.5 \, \mu\text{s} < \text{Correlation time} < 150 \, \mu\text{s}$
• Correlation distance $< 1$ m

New Background rejection
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$^{9}\text{Li}/^{8}\text{He}$ background measurement

- Likelihood built from information after $\mu$ (distance to track, neutron multiplicity).
- Likelihood cut: rejects 50% of $^{9}\text{Li}/^{8}\text{He}$ with $<0.5\%$ dead-time.
- Rate estimated from time correlation to last $\mu$.
  - 2 samples for upper/lower limits.
- Spectrum extracted from DATA (vetoed candidates).

![Rate: $0.97^{+0.41}_{-0.16}\text{ day}^{-1}$](image1)

![Prompt spectrum](image2)
Correlated background measurement & vetoes

- **OV veto**: veto prompt events coincident with an OV trigger.
  - Useful for passing nearby $\mu$ which do not penetrate the detector, but produce fast-\(n\).
- **FV veto**: veto delayed events not consistent with a reconstructed point-like vertex.
  - Useful for stopping muons/Michel $e^-$ and remaining light noise.
- **IV veto**: veto prompt events which show correlated activity in the IV.
  - Useful for fast-\(n\) and stopping muons.
- OV, FV and IV veto together reject 90% of events with $E > 12$ MeV.
- IV-vetoed events used for measuring rate ($0.60 \pm 0.05$ day\(^{-1}\)) and spectrum (flat).
Accidental background measurement

- Correlation distance < 1m: more than $\times 10$ accidental rejection
- Rate and spectrum measured using same selection cuts except correlation time:
  - Virtual prompt event shifted $1s + N \times 0.8$ ms, where $N = \{0, \ldots, 1999\}$

Rate: $0.070 \pm 0.003 \text{ day}^{-1}$
### Background uncertainties: summary

| Background          | Rate (day⁻¹) | Spectrum shape                  | Prompt energy range (MeV) | Suppression wrt previous Gd |
|---------------------|--------------|---------------------------------|---------------------------|-----------------------------|
| $^{9}$Li/$^{8}$He   | 0.97 +0.41 -0.16 | DATA (likelihood tagged)        | (0, 12)                   | 1.3                         |
| Correlated background | 0.60 ± 0.05    | DATA (IV tagged)                | (0, 20)                   | 1.9                         |
| Accidental          | 0.070 ± 0.003  | DATA (off-time)                 | (0, 4)                    | 3.7                         |
Reactors OFF

- **Unique from Double Chooz.** (Phys. Rev. D87 (2013) 011102)
- Only **7.24 days**: not enough for spectral information, mainly rate.
- Agreement between OFF-DATA and background model:
  - Inclusive OFF measurement (7 events)
  < $\sum$ exclusive backgrounds (12.9$^{+3.1}_{-1.4}$ events)
  - Additional unknown background is disfavored.
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Detection uncertainties

- **MC normalization** must be corrected to account for effects not simulated.
- Dominant uncertainty: **neutron detection**.
  - Reduced from 0.96% (Gd-II) to 0.54%

### Detection uncertainties

| Correction source                              | MC correction factor | Relative uncertainty |
|------------------------------------------------|----------------------|----------------------|
| Veto for 1ms after muon                        | 0.955                | negligible           |
| FV, OV, IV, Li+ He veto inefficiency           | 0.993                | 0.1%                 |
| Isolation cut inefficiency                     | 0.989                | negligible           |
| Neutron detection                              | 0.975                | 0.5%                 |
| \( N_{\text{proton}} \)                        | 1.000                | 0.3%                 |
| Electronic, trigger, DAQ inefficiency          | 1.000                | negligible           |
| Total                                          | 0.915                | 0.6%                 |

| Detection source                              | MC correction factor | Relative uncertainty |
|------------------------------------------------|----------------------|----------------------|
| Gd/H fraction                                 | 0.9750               | 0.43%                |
| Volume-wide neutron detection efficiency      | 1.000                | 0.19%                |
| Spill-in/out                                   | 1.000                | 0.27%                |
| Total                                          | 0.9750               | 0.54%                |
Detection uncertainties

- Dominant contribution: neutron detection (uncertainty 0.54%).
  - Gd/H fraction uncertainty: 0.43% (dominant).
    - Ratio of neutron captures in Gd to H.
    - Measured using $^{252}$Cf neutrons, IBD-neutrons and spallation-neutrons.
  - Volume-wide neutron detection efficiency uncertainty: 0.19%
  - Spill-in/out current uncertainty: 0.27%
Detection uncertainties

- Dominant contribution: neutron detection (uncertainty 0.54%).
  - Gd/H fraction uncertainty: 0.43% (dominant).
  - Volume-wide neutron detection efficiency uncertainty: 0.19%
    - Selection efficiency in the detector volume.
    - Measured using IBD-neutrons and $^{252}$Cf neutrons.
  - Spill-in/out current uncertainty: 0.27%
Dominant contribution: neutron detection (uncertainty 0.54%).

- Gd/H fraction uncertainty: 0.43% (dominant).
- Volume-wide neutron detection efficiency uncertainty: 0.19%

- Spill-in/out current uncertainty: 0.27%
  - Neutron migration between detector volumes.
  - Measured comparing MC (customized Geant4 vs. Tripoli4).
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Normalisation uncertainty summary

Uncertainty relative to signal prediction

| Systematic source | Uncertainty (%) | Improvement wrt old analysis |
|-------------------|-----------------|-----------------------------|
| Reactor flux      | 1.7             | -                           |
| Detection         | 0.6             | -40%                        |
| Background        | 0.8             | -50%                        |

- Successful reduction of background and detection systematics.
- Backgrounds: not only uncertainties, but also rates have been reduced.
- The Near Detector will cancel most of the reactor systematic and reduce the detection one further.
- Statistics doubled:
  - Livetime: 227.9 d → 467.9 d
  - IBD candidates: 8249 → 17358
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• Conclusion
• Measure \( \theta_{13} \) from the reactor power variations.
• Compare observed rate to expected rate in absence of oscillation.
• Determine \( \theta_{13} \) (slope) and background rate (intercept) simultaneously.
  - Background model independent:
    \[
    \sin^2(2\theta_{13}) = 0.060 \pm 0.039; \quad \text{bkg rate} = 0.93^{+0.43}_{-0.36} \text{ day}^{-1}
    \]
    Bkg model = 1.46^{+0.41}_{-0.17} \text{ day}^{-1} (agreement in < 1.5\sigma).
• Background estimation can be included to get the most precise result:
  \[
  \sin^2(2\theta_{13}) = 0.090^{+0.034}_{-0.035}; \quad \text{bkg} = 1.56^{+0.18}_{-0.16} \text{ day}^{-1}
  \]
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Rate + Shape fit

- Measure $\theta_{13}$ using the rate and spectrum shape.

New features:
- Finer binning.
- Range extended.
- Background shape data-driven.
- New energy model.
- Reactor OFF data included.

$\Delta m^2$ from MINOS: $(2.44^{+0.09}_{-0.10}) \times 10^{-3}$ eV$^2$

$\sin^2(2\theta_{13}) = 0.090^{+0.032}_{-0.029}$

$\chi^2$/ndf = 52.2/40

Bkg rate after fit = $1.38 \pm 0.14$ day$^{-1}$

Previous: $\sin^2(2\theta_{13}) = 0.109 \pm 0.039$

→ Precision improved 5.3%

Rate-only fit: $\sin^2(2\theta_{13}) = 0.090^{+0.036}_{-0.037}$
Considering only IBD interaction ($\overline{\nu}_e + p \rightarrow e^+ + n$), $P(\overline{\nu}_e \rightarrow \overline{\nu}_e)$ structure consistent with an unaccounted $\overline{\nu}_e$ reactor flux effect.

- $3\sigma$ significance wrt flux prediction when including the background constraint from our estimation.
- (Other hypotheses disfavored by consistency and tension).
Structure at > 4 MeV

- No correlation found to any background-sensitive variable.
- Strong correlation with reactor power. More data (H) makes it stronger.
- It does NOT affect significantly the $\theta_{13}$ value (many tests showed it is very robust).
- The nature of the structure at > 4 MeV is still under investigation.
  - The high statistics of the Near Detector will help.

Considering only IBD interaction ($\bar{\nu}_e + p \rightarrow e^+ + n$), $P(\bar{\nu}_e \rightarrow \bar{\nu}_e)$ structure consistent with an unaccounted $\bar{\nu}_e$ reactor flux effect.
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The Near Detector
Near Detector schedule

- Detector integration: finished.
- Filling: September - October.
- Data-taking commissioning: Fall 2014.
Expected sensitivity

- Assumptions:
  - Flux uncertainty = 0.1% (isoflux suppression).
  - Detection uncertainty = 0.2% (identical detectors).
  - Background in ND scaled from FD accounting for larger $\mu$ flux.

- Band: Our systematics will improve with more statistics:
  - 10 – 15% precision after 3 years.
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Conclusions

• **New analysis: a major improvement** with respect to previous Gd:
  – New selection: Higher signal efficiency, less background (active rejection).
  – Detection uncertainty reduced.
  – Background uncertainty reduced. Data-driven background estimations.
  – Better energy reconstruction (non-linearities calibrated).
  – Statistics doubled.

• **New \( \theta_{13} \) results (arXiv:1406.7763):**
  – Rate + Shape: \( \sin^2(2\theta_{13}) = 0.090^{+0.032}_{-0.029} \)
  – Reactor Rate Modulation (w/ background model): \( \sin^2(2\theta_{13}) = 0.090^{+0.034}_{-0.035} \)

• **Spectrum distortion at > 4 MeV: unaccounted reactor flux effect favored.**

• **New analysis ready for Near Detector.** More improvements to come.

• **Near Detector** running this fall.
  – **Major systematic cancellation** → Uncertainty on \( \sin^2(2\theta_{13}) \geq 0.01 \) (1\( \sigma \)).
Extra slides
θ_{13} compilation

- **Best Fit + 68% C.L.**
- **Accelerator Experiments**
  - Normal Hierarchy
  - Inverted Hierarchy
  *All results assuming:
  \( \delta_{CP} = 0 \),
  \( \theta_{23} = 45^\circ \)
- **Reactor Experiments**
  - Rate only
  - Rate+Spectral
  - n-Gd
  - n-H
  **Number of days refers to far site live time**
- **Global Fit**
  PDG 2013

\[
\sin^2 2\theta_{13}
\]

- KamLAND
  [1009.4771]
- MINOS 8.2\times 10^{39} \text{ PoT}
  [1108.0016]
- T2K 1.43\times 10^{39} \text{ PoT}
  [1106.2822]
- DC 97 Days
  [1112.6353]
- Daya Bay 49 Days
  [1203.1669]
- RENO 222 Days
  [1204.0626]
- DC 228 Days
  [1207.6632]
- Daya Bay 139 Days
  [1210.6327]
- DC n-H Analysis
  [1301.2948]
- MINOS 13.9\times 10^{20} \text{ PoT}
  [1301.4581]
- T2K 3.01\times 10^{20} \text{ PoT}
  [1304.0841]
- DC RRM Analysis
  [1305.2734]
- Daya Bay 190 Days
  [1310.6732]
- T2K 6.57\times 10^{20} \text{ PoT}
  [1311.4750]
- RENO 403 Days
  [TAUP2013]
- Daya Bay 190 Days n-H
  [1406.6468]
- DC 468 Days
  [1406.7763]
- RENO 795 Days
  [Neutrino2014]
- Daya Bay 563 Days
  [Neutrino2014]
New energy

\[ \frac{\sigma}{E_{\text{vis}}^2} = \sqrt{\frac{a^2}{E_{\text{vis}}^2} + b^2 + \frac{c^2}{E_{\text{vis}}^2}} \]

- a: statistical term
- b: constant term
- c: e.g. electric noise

**Data**
- \( a = 0.0773\pm 0.0025 \)
- \( b = 0.0182\pm 0.0014 \)
- \( c = 0.0174\pm 0.0107 \)

**MC**
- \( a = 0.0770\pm 0.0018 \)
- \( b = 0.0183\pm 0.0011 \)
- \( c = 0.0235\pm 0.0061 \)
Energy scale at 4 – 6 MeV

- n-C peak in Gamma-Catcher with $\Delta$(data,MC) < 0.5%
Structure at $> 4$ MeV

\[ R^{\text{obs}} = B + R^{\text{exp}} = B + \left( 1 - \sin^2(2\theta_{13})\eta_{\text{osc}} \right) R^\nu \]
Spectrum distortion at 3 experiments

**Double Chooz @ LAL (Orsay, May 2014)**

![Double Chooz spectrum graph]

**RENO @ Neutrino 2014 (Boston, June 2014)**

![RENO spectrum graphs]

**Daya Bay @ ICHEP 2014 (Valencia, July 2014)**

![Daya Bay spectrum graph]
# Rate + Shape fit parameters

| Fit Parameter                             | Input Value       | Best-Fit Value      |
|-------------------------------------------|-------------------|---------------------|
| Li+He bkg. (d\(^{-1}\))                  | 0.97\(\pm\)0.41  | 0.74 \(\pm\) 0.13  |
| Fast-n + stop-\(\mu\) bkg. (d\(^{-1}\)) | 0.604 \(\pm\) 0.051 | 0.568 \(\pm\) 0.038 |
| Accidental bkg. (d\(^{-1}\))             | 0.0701 \(\pm\) 0.0026 | 0.0703 \(\pm\) 0.0026 |
| Residual \(\bar{\nu}_e\)                 | 1.57 \(\pm\) 0.47 | 1.48 \(\pm\) 0.47  |
| \(\Delta m^2\) (10\(^{-3}\) eV\(^2\))  | 2.44 \(\pm\) 0.09 | 2.44 \(\pm\) 0.09  |
| E-scale \(\epsilon_a\)                   | 0 \(\pm\) 0.006   | 0.001 \(\pm\) 0.006 |
| E-scale \(\epsilon_b\)                   | 0 \(\pm\) 0.008   | \(-0.001\) \(\pm\) 0.004 |
| E-scale \(\epsilon_c\)                   | 0 \(\pm\) 0.0006  | \(-0.0005\) \(\pm\) 0.0007 |
Rate + Shape fit

\[ \chi^2 = \sum_{i=1}^{40} \sum_{j=1}^{40} (N_{i}^{\text{obs}} - N_{i}^{\exp}) M_{ij}^{-1} (N_{j}^{\text{obs}} - N_{j}^{\exp}) + \sum_{k=1}^{5} \frac{\xi_k^2}{\sigma_k^2} \]

\[ + (\epsilon_a, \epsilon_b, \epsilon_c) \left( \begin{array}{ccc} \sigma_a^2 & \rho_{ab}\sigma_a\sigma_b & \rho_{ac}\sigma_a\sigma_c \\ \rho_{ab}\sigma_a\sigma_b & \sigma_b^2 & \rho_{bc}\sigma_b\sigma_c \\ \rho_{ac}\sigma_a\sigma_c & \rho_{bc}\sigma_b\sigma_c & \sigma_c^2 \end{array} \right)^{-1} \left( \begin{array}{c} \epsilon_a \\ \epsilon_b \\ \epsilon_c \end{array} \right) \]

\[ + 2 \left[ N_{\text{off}}^{\text{obs}} \cdot \ln \left( \frac{N_{\text{off}}^{\text{obs}}}{N_{\text{off}}^{\exp}} \right) + N_{\text{off}}^{\exp} - N_{\text{off}}^{\text{obs}} \right] . \]

\[ M_{ij} = M_{ij}^{\text{stat}} + M_{ij}^{\text{flux}} + M_{ij}^{\text{eff}} + M_{ij}^{\text{Li/He(shape)}} + M_{ij}^{\text{acc(stat)}} \]
RRM fit

\[ \chi^2 = \chi_{\text{on}}^2 + \chi_{\text{off}}^2 + \chi_{\text{bg}}^2 + \frac{\epsilon_d^2}{\sigma_d^2} + \frac{\epsilon_r^2}{\sigma_r^2} + \frac{\epsilon_{\nu}^2}{\sigma_{\nu}^2} \]

\[ \chi_{\text{on}}^2 = \sum_{i=1}^{6} \frac{(R_i^{\text{obs}} - R_i^{\text{exp}} - B)^2}{(\sigma_i^{\text{stat}})^2} \]

\[ \chi_{\text{off}}^2 = 2 \left[ N_{\text{off}}^{\text{obs}} \ln \left( \frac{N_{\text{off}}^{\text{obs}}}{N_{\text{off}}^{\text{exp}}} \right) + N_{\text{off}}^{\text{exp}} - N_{\text{off}}^{\text{obs}} \right] \]

\[ \chi_{\text{bg}}^2 = \frac{(B - B^{\text{exp}})^2}{\sigma_{\text{bg}}^2} \]
$^9$Li/$^8$He veto
FV veto