New measurements of reactor $\bar{\nu}_e$ disappearance with the Double Chooz far detector

Rachel Carr, Columbia University
on behalf of the Double Chooz collaboration

DPF | UC Santa Cruz | August 16, 2013
Outline

I. Experiment overview

II. Latest Double Chooz results
   ▶ Reactor-off background measurements
   ▶ First combined Gd+H fit
   ▶ Reactor rate modulation analysis

III. Future of Double Chooz
I. Experiment overview

II. Latest Double Chooz results
   ▶ Reactor-off background measurements
   ▶ First combined Gd+H fit
   ▶ Reactor rate modulation analysis

III. Future of Double Chooz
I. EXPERIMENT OVERVIEW

Double Chooz collaboration

Spokesperson: H. de Kerret (IN2P3)  Project manager: Ch. Veyssière (CEA-Saclay)
Website: www.doublechooz.org

Rachel Carr  (Columbia University)  Double Chooz for DPF 2013
I. EXPERIMENT OVERVIEW

Double Chooz experiment

Chooz, France

Designed to measure $\sin^2 2\theta_{13}$ via reactor $\bar{\nu}_e$ disappearance:

$$P_{\bar{\nu}_e \rightarrow \bar{\nu}_e} = 1 - \sin^2 2\theta_{13} \sin^2 (1.27 \Delta m_{31}^2 L/E)$$

$[\Delta m_{31}^2] = eV^2$, $[L] = m$, $[E] = MeV$
I. EXPERIMENT OVERVIEW

Site layout

**Near detector**
Overburden $\approx 120$ mwe
Ready in mid-2014

**Reactors**
Two N4-type PWRs, $4.25\;GW_{th}$ each

**Far detector**
Overburden $\approx 300$ mwe
Operating since April 2011
I. EXPERIMENT OVERVIEW

Inverse $\beta$ decay signal

**Prompt signal:**

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

$E_{prompt} \approx E_{\bar{\nu}_e} - 0.8\ MeV$

**Delayed signal:**

- n capture on Gd
  $\leftrightarrow \gamma$ cascade
  $E_{delayed} \approx 8\ MeV$
  $\Delta T \approx 30\ \mu s$

- n capture on H
  $\leftrightarrow$ single $\gamma$
  $E_{delayed} = 2.2\ MeV$
  $\Delta T \approx 200\ \mu s$

Unique to Double Chooz!
Detector design

Inner detector:

**Neutrino target**

Gd-doped liquid scintillator (8.3 tons)
Detector design

**Inner detector:**

**Neutrino target**
Gd-doped liquid scintillator (8.3 tons)

**Gamma catcher**
Undoped liquid scintillator (18 tons)
I. EXPERIMENT OVERVIEW

Detector design

Inner detector:

Neutrino target
Gd-doped liquid scintillator (8.3 tons)

Gamma catcher
Undoped liquid scintillator (18 tons)

Buffer
Non-scintillating mineral oil (80 tons)

390 PMTs
installed on stainless steel tank
I. EXPERIMENT OVERVIEW

Detector design

Cosmic ray veto systems:

**Inner veto**
Undoped liquid scintillator (70 tons) + 78 PMTs
I. EXPERIMENT OVERVIEW

Detector design

Cosmic ray veto systems:

**Inner veto**
Undoped liquid scintillator (70 tons) + 78 PMTs

**Outer veto**
Array of plastic scintillator strips
13 m × 7 m
I. EXPERIMENT OVERVIEW

Calibration

- **Source deployments:** $^{137}$Cs, $^{68}$Ge, $^{60}$Co, $^{252}$Cf
  - Z-axis
  - Guide tube
  - Fall 2013: Articulated arm

- **Spallation neutrons**
  generated by cosmic rays

- **LED injection system**
I. EXPERIMENT OVERVIEW

Energy reconstruction

- $q \rightarrow \text{PE}$, correcting for gain nonlinearity
- $\text{PE} \rightarrow \text{MeV}$, using H capture peak

- Correction for time instability, using Gd capture peak variation

- Correction for detector inhomogeneity, using H capture map

... Final energy scale uncertainty: 1-2%
## Signal selection

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Gd selection</th>
<th>H selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{\text{prompt}}$</td>
<td>$0.7 - 12.2$ MeV</td>
<td>$0.7 - 12.2$ MeV</td>
</tr>
<tr>
<td>$E_{\text{delayed}}$</td>
<td>$6.0 - 12.0$ MeV</td>
<td>$1.5 - 3.0$ MeV</td>
</tr>
<tr>
<td>$\Delta T$</td>
<td>$2 - 100$ $\mu s$</td>
<td>$10 - 600$ $\mu s$</td>
</tr>
<tr>
<td>$\Delta R$</td>
<td>$&lt; 90$ cm</td>
<td></td>
</tr>
</tbody>
</table>

### Further requirements for background reduction:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Gd selection</th>
<th>H selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multiplicity</td>
<td>No additional triggers in $500$ $\mu s$ surrounding prompt</td>
<td>No additional triggers in $1600$ $\mu s$ surrounding prompt</td>
</tr>
<tr>
<td>Muon veto</td>
<td>No muon in ID or IV in $1$ ms before prompt</td>
<td></td>
</tr>
<tr>
<td>Showering muon veto</td>
<td>No muon depositing $&gt; 600$ MeV in $0.5$ s before prompt</td>
<td>---</td>
</tr>
<tr>
<td>OV veto</td>
<td>No OV hit coincident with prompt</td>
<td></td>
</tr>
<tr>
<td>Light noise rejection</td>
<td>Passes cuts on PMT charge isotropy and pulse simultaneity</td>
<td></td>
</tr>
</tbody>
</table>

**Predicted no-oscillation signal in April 2011–March 2012 dataset:**

- **Gd selection:** 8,440
- **H selection:** 17,690
I. EXPERIMENT OVERVIEW

IBD candidates

**Gd selection**
April 2011 – March 2012

Live time: 227.9 days
Candidates: 8,249

**H selection**
April 2011 – March 2012

Live time: 240.1 days
Candidates: 36,284
I. EXPERIMENT OVERVIEW

Backgrounds

- **Accidentals**
  - Gd: $0.3 \, d^{-1}$ (error $\ll 0.1 \, d^{-1}$)
  - H: $73.5 \pm 0.2 \, d^{-1}$
I. EXPERIMENT OVERVIEW

Backgrounds

- **Accidentals**
  - Gd: $0.3 \text{ d}^{-1}$ (error $\ll 0.1 \text{ d}^{-1}$)
  - H: $73.5 \pm 0.2 \text{ d}^{-1}$

- **Fast neutrons + stopping muons**
  - Gd: $0.7 \pm 0.2 \text{ d}^{-1}$
  - H: $2.5 \pm 0.5 \text{ d}^{-1}$ (all fast n)
I. EXPERIMENT OVERVIEW

**Backgrounds**

- **Accidentals**
  - Gd: 0.3 d\(^{-1}\) (error \(< 0.1\) d\(^{-1}\))
  - H: 73.5 \(\pm\) 0.2 d\(^{-1}\)

- **Fast neutrons + stopping muons**
  - Gd: 0.7 \(\pm\) 0.2 d\(^{-1}\)
  - H: 2.5 \(\pm\) 0.5 d\(^{-1}\) (all fast n)
I. EXPERIMENT OVERVIEW

Backgrounds

- **Accidentals**
  - Gd: 0.3 d\(^{-1}\) (error \(\ll 0.1\) d\(^{-1}\))
  - H: 73.5 ± 0.2 d\(^{-1}\)

- **Fast neutrons + stopping muons**
  - Gd: 0.7 ± 0.2 d\(^{-1}\)
  - H: 2.5 ± 0.5 d\(^{-1}\) (all fast n)

- **Cosmogenic isotopes, mainly \(^9\)Li**
  - Gd: 1.3 ± 0.5 d\(^{-1}\)
  - H: 2.8 ± 1.2 d\(^{-1}\)

Rates of \(^9\)Li and FN + SM are further constrained in final fit.
Far detector-only analyses rely on $\bar{\nu}_e$ rate prediction:

$$N = \frac{\epsilon N_p}{4\pi} \sum_{R=1,2} \frac{1}{L_R^2} \frac{P_{th}^R}{\langle E_f \rangle_R^R} \langle \sigma_f \rangle_R$$

- $\epsilon$ = detection efficiency
- $N_p$ = number of protons in fiducial volume
- $L_R$ = distance between reactor and far detector
- $P_{th}^R$ = thermal power of reactor (time-dependent)
- $\langle E_f \rangle_R$ = average energy per fission (time-dependent)
- $\langle \sigma_f \rangle_R$ = average cross section per fission (time-dependent), “anchored” to Bugey4 measurement at $L = 15$ m
Uncertainties

Normalization uncertainties (relative to signal):

<table>
<thead>
<tr>
<th>Source</th>
<th>Gd selection</th>
<th>H selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor $\bar{\nu}_e$ flux</td>
<td>1.8%</td>
<td>1.8%</td>
</tr>
<tr>
<td>Efficiency</td>
<td>1.0%</td>
<td>1.6%</td>
</tr>
<tr>
<td>$^9$Li rate</td>
<td>1.5%</td>
<td>1.6%</td>
</tr>
<tr>
<td>Fast n + stopping $\mu$ rate</td>
<td>0.5%</td>
<td>0.6%</td>
</tr>
<tr>
<td>Accidentals rate</td>
<td>&lt;0.1%</td>
<td>0.2%</td>
</tr>
<tr>
<td>Total statistical error</td>
<td>1.1%</td>
<td>1.1%</td>
</tr>
</tbody>
</table>

Spectrum shape uncertainties:

- Reactor $\bar{\nu}_e$ spectrum
- Energy scale
- $^9$Li spectrum
- Fast n + stopping $\mu$ spectrum
I. EXPERIMENT OVERVIEW

Rate+Shape fit

Unique Double Chooz fit strategy:
- Improves upon rate-based analysis by adding spectrum information
- Constrains backgrounds
- Fits data with specific oscillation shape

\[ \chi^2_{Rate+Shape} = \sum_{i,j}^{B} \left( N_{i}^{obs} - N_{i}^{pred} \right) M_{ij}^{-1} \left( N_{j}^{obs} - N_{j}^{pred} \right)^T + \text{pull terms} \]

\( B = \text{number of energy bins} = \begin{cases} 18, & \text{for Gd} \\ 31, & \text{for H} \end{cases} \)

\( M = \text{covariance matrix, including spectrum shape uncertainties} \)

Pull terms on \(^9\text{Li} \text{ rate, FN + SM rate, energy scale, } \Delta m^2\)
I. EXPERIMENT OVERVIEW

Published Rate+Shape fits

**Gd analysis, June 2012**
*Phys. Rev. D 86 (2012)*

- Background-subtracted signal
- No oscillation
- Best fit: $\sin^2(2\theta_{13}) = 0.109$ at $\Delta m^2_{31} = 0.00232 \text{ eV}^2$ (χ²/d.o.f. = 42.1/35)
- Systematic error

**H analysis, December 2012**

- Background-subtracted signal
- No oscillation
- Best fit: $\sin^2(2\theta_{13}) = 0.097$ at $\Delta m^2_{31} = 0.00231 \text{ eV}^2$ (χ²/d.o.f. = 38.9/30)
- Systematic error

$\sin^2 2\theta_{13} = 0.109 \pm 0.039$

*Shown with all backgrounds subtracted. Gd uses two integration periods, yielding d.o.f. = 2 × 18 − 1*
Rate+Shape constraints

- **Rate+Shape fit constrains backgrounds:**

<table>
<thead>
<tr>
<th></th>
<th>Input (relative uncertainty)</th>
<th>Fit output (rel. unc.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gd</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^9$Li rate</td>
<td>$1.3 \pm 0.5 \text{ d}^{-1} \ (40%)$</td>
<td>$1.0 \pm 0.3 \text{ d}^{-1} \ (30%)$</td>
</tr>
<tr>
<td>FN + SM rate</td>
<td>$0.7 \pm 0.2 \text{ d}^{-1} \ (30%)$</td>
<td>$0.6 \pm 0.1 \text{ d}^{-1} \ (20%)$</td>
</tr>
<tr>
<td>H</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^9$Li rate</td>
<td>$2.8 \pm 1.2 \text{ d}^{-1} \ (40%)$</td>
<td>$3.9 \pm 0.6 \text{ d}^{-1} \ (15%)$</td>
</tr>
<tr>
<td>FN + SM rate</td>
<td>$2.5 \pm 0.5 \text{ d}^{-1} \ (20%)$</td>
<td>$2.6 \pm 0.4 \text{ d}^{-1} \ (15%)$</td>
</tr>
</tbody>
</table>

- Also adjusts energy scale and $\Delta m^2$ to reach best fit.
I. Experiment overview

II. Latest Double Chooz results
   ▶ Reactor-off background measurements
   ▶ First combined Gd+H fit
   ▶ Reactor rate modulation analysis

III. Future of Double Chooz
Reactor-off background measurements

Analyzed 7.5 days of data with both reactors off.

*Phys. Rev. D. 87 (2013)*

- Unique Double Chooz capability
- Rate consistent with predictions:
  - Gd selection: $1.0 \pm 0.4 \text{ day}^{-1}$
    - with residual $\bar{\nu}_e$ subtracted
    - (expected $2.0 \pm 0.6 \text{ day}^{-1}$)
  - H selection: $11.3 \pm 3.4 \text{ day}^{-1}$
    - with residual $\bar{\nu}_e$ and accidentals subtracted
    - (expected $5.8 \pm 1.3 \text{ day}^{-1}$)
- New constraint for oscillation fits
First combined Gd+H fit

Combining published Gd and H analyses:

- Data set covers April 2011-March 2012
- Fit includes correlation of systematic errors
- Backgrounds constrained by reactor-off measurements
## Combined Gd+H fit results

**PRELIMINARY:**

<table>
<thead>
<tr>
<th></th>
<th>Rate+Shape: $\sin^2 2\theta_{13} = 0.109 \pm 0.035$</th>
<th>Rate-Only: $\sin^2 2\theta_{13} = 0.107 \pm 0.045$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>($\chi^2$/d.o.f. = 61.2/50)</td>
<td>($\chi^2$/d.o.f. = 6.1/3)</td>
</tr>
</tbody>
</table>

Compare to Gd-only analysis of same dataset (June 2012):

<table>
<thead>
<tr>
<th></th>
<th>Rate+Shape: $\sin^2 2\theta_{13} = 0.109 \pm 0.039$</th>
<th>Rate-Only: $\sin^2 2\theta_{13} = 0.170 \pm 0.052$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>($\chi^2$/d.o.f. = 42.1/35)</td>
<td>($\chi^2$/d.o.f. = 0.5/1)</td>
</tr>
</tbody>
</table>
Reactor rate modulation analysis

**Fit observed rates for** $\sin^2 2\theta_{13}$ **and total background rate, B:**

$$R^{obs} = B + (1 - \sin^2 2\theta_{13} \langle \sin^2 (1.27 \Delta m^2 L/E) \rangle) \; R^{exp, \; no \; osc}$$

**Valuable features:**
- No *a priori* background model
- Combines Gd and H selections
- Leverage from reactor-off data
II. LATEST DOUBLE CHOOZ RESULTS

Reactor rate modulation results

Best fit: $\sin^2 2\theta_{13} = 0.097 \pm 0.035$
I. Experiment overview

II. Latest Double Chooz results
   ▶ Reactor-off background measurements
   ▶ First combined Gd+H fit
   ▶ Reactor rate modulation analysis

III. Future of Double Chooz
Near detector

Construction ongoing!

Near detector expected to begin taking data in spring of 2014.
Future $\theta_{13}$ results

Expanded far detector-only analysis (end of 2013)
- $\sim 2 \times$ more statistics + optimized selection
- Reduced systematic errors
- Projected precision: $\sigma \approx 0.03$

Two-detector analysis (2014)
- Reactor uncertainties nearly drop out
- Projected final precision: $\sigma \approx 0.01$
- Ultimately background-limited (especially $^9$Li)
- Rich, unique program with far detector
  - Two signal channels: Gd, H
  - Two oscillation analyses: R+S, RRM
  - Reactor-off background measurements
Rich, unique program with far detector
- Two signal channels: Gd, H
- Two oscillation analyses: R+S, RRM
- Reactor-off background measurements

New results
- Gd+H Rate+Shape fit: $\sin^2 2\theta_{13} = 0.109 \pm 0.035$
- Reactor rate modulation: $\sin^2 2\theta_{13} = 0.097 \pm 0.035$
Summary

- **Rich, unique program with far detector**
  - Two signal channels: Gd, H
  - Two oscillation analyses: R+S, RRM
  - Reactor-off background measurements

- **New results**
  - Gd+H Rate+Shape fit: \( \sin^2 2\theta_{13} = 0.109 \pm 0.035 \)
  - Reactor rate modulation: \( \sin^2 2\theta_{13} = 0.097 \pm 0.035 \)

- **Future prospects**
  - Improved single-detector analysis
  - First two-detector analysis
Additional plots
Summary of Double Chooz results

DC $\sin^2(2\theta_{13})$ Measurements (data set II)

- **Gd+H (Jul.13@EPS)**
  - Rate+Shape (OFF)
  - Preliminary

- **Gd-II (Jun.12@Kyoto)**
  - Rate+Shape

- **H-II (Dec.12@Paris)**
  - Rate+Shape

- **RRM (Mar.13@Moriond)**
  - Gd (OFF)

- **RRM (Jul.13@EPS)**
  - H (OFF)

- **Rate+Shape 68%CL**
  - Reactor Rate Modulation 68%CL
## Gd, H, and combined fit results

### Rate+Shape:

<table>
<thead>
<tr>
<th>Fit parameter</th>
<th>Individual fit results</th>
<th>Combined fit, Jul. 2013</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy scale</td>
<td>0.99 ± 0.01</td>
<td>0.99 ± 0.01</td>
</tr>
<tr>
<td>FN+SM rate (d⁻¹)</td>
<td>0.6 ± 0.1</td>
<td>2.6 ± 0.4</td>
</tr>
<tr>
<td>Li-9 rate (d⁻¹)</td>
<td>1.0 ± 0.3</td>
<td>3.9 ± 0.6</td>
</tr>
<tr>
<td>$\Delta m^2$ (10⁻³eV²)</td>
<td>2.32 ± 0.12</td>
<td>2.32 ± 0.12</td>
</tr>
<tr>
<td>$\sin^2 2\theta_{13}$</td>
<td>0.109 ± 0.039</td>
<td>0.097 ± 0.048</td>
</tr>
<tr>
<td>$\chi^2$/d.o.f.</td>
<td>42.1/35</td>
<td>38.9/30</td>
</tr>
</tbody>
</table>

### Rate-Only:

<table>
<thead>
<tr>
<th>Fit parameter</th>
<th>Individual fit results</th>
<th>Combined fit, Jul. 2013</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy scale</td>
<td>1.00 ± 0.01</td>
<td>1.00 ± 0.02</td>
</tr>
<tr>
<td>FN+SM rate (d⁻¹)</td>
<td>0.7 ± 0.2</td>
<td>2.5 ± 0.5</td>
</tr>
<tr>
<td>Li-9 rate (d⁻¹)</td>
<td>1.4 ± 0.5</td>
<td>2.8 ± 1.2</td>
</tr>
<tr>
<td>$\Delta m^2$ (10⁻³eV²)</td>
<td>2.32 ± 0.12</td>
<td>2.32 ± 0.12</td>
</tr>
<tr>
<td>$\sin^2 2\theta_{13}$</td>
<td>0.170 ± 0.052</td>
<td>0.044 ± 0.061</td>
</tr>
<tr>
<td>$\chi^2$/d.o.f.</td>
<td>0.5/1</td>
<td>0/0</td>
</tr>
</tbody>
</table>

*Reactor-off information is not included in individual fits.*
Combined Gd+H Rate+Shape fit

**Gd selection**

![Background-subtracted data](image1)

- No oscillation
- Combined best fit:
  - $\sin^2 2\theta_{13} = 0.109$
  - at $\Delta m^2 = 0.00231$ eV$^2$
- Systematic error

**H selection**

![Background-subtracted data](image2)

- No oscillation
- Combined best fit:
  - $\sin^2 2\theta_{13} = 0.109$
  - at $\Delta m^2 = 0.00231$ eV$^2$
- Systematic error

All backgrounds subtracted at best-fit rates.
Gd and H prompt spectra, with backgrounds

Gd selection

Red line is combined Gd+H Rate+Shape best fit. Backgrounds shown at best-fit rates.
Correlations between Gd and H analyses

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$\rho_{Gd,H}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accidental rate</td>
<td>0</td>
</tr>
<tr>
<td>Correlated light noise</td>
<td>0</td>
</tr>
<tr>
<td>Fast $n +$ stopping $\mu$ rate</td>
<td>0</td>
</tr>
<tr>
<td>$^{9}$Li rate</td>
<td>0.003</td>
</tr>
<tr>
<td>$^{9}$Li shape</td>
<td>1</td>
</tr>
<tr>
<td>Efficiency</td>
<td>0.09</td>
</tr>
<tr>
<td>Energy scale</td>
<td>0.4</td>
</tr>
<tr>
<td>Reactor</td>
<td>1</td>
</tr>
</tbody>
</table>
Candidates from Gd selection
Candidates from H selection

- Energy (MeV)
- $\Delta T$ (µs)
- $\Delta R$ (mm)
- $\rho^2$ (m$^2$)

Rachel Carr (Columbia University) Double Chooz for DPF 2013
\[ \chi^2_{Rate+Shape} = \sum_{i, j} \left( N_{ij}^{obs} - N_{ij}^{pred} \right) M_{ij}^{-1} \left( N_{ij}^{obs} - N_{ij}^{pred} \right)^T \]

\[ + \frac{(\alpha_{Li} - 1)^2}{\sigma_{Li}^2} + \frac{(\alpha_{FNSM} - 1)^2}{\sigma_{FNSM}^2} + \frac{(\alpha_E - 1)^2}{\sigma_E^2} \]

\[ + \frac{(\Delta m^2 - \Delta m^2_{MINOS})^2}{\sigma_{MINOS}^2} \]

with covariance matrix:

\[ M = M_{stat} + M_{reactor} + M_{acc} + M_{corr \ LN} + M_{Li \ shape} + M_{FNSM \ shape} \]
$\chi^2$ definition for combined Gd+H fit

$$\chi^2 = \sum_{i,j} \frac{(N_{i}^{\text{obs}} - N_{i}^{\text{pred}})(M_{ij}^{-1} (N_{j}^{\text{obs}} - N_{j}^{\text{pred}}))}{\sigma_{ij}^2}$$

$$\chi^2 = B \sum_{i,j} (N_{i}^{\text{obs}} - N_{i}^{\text{pred}}) M_{ij}^{-1} (N_{j}^{\text{obs}} - N_{j}^{\text{pred}})$$

$$+ \frac{(\Delta m^2 - \Delta m^2_{\text{MINOS}})^2}{\sigma_{\text{MINOS}}^2}$$

$$+ \left[ (\alpha_{H}^{Gd} - 1), (\alpha_{H}^{Gd} - 1), (\alpha_{e}^{Gd} - 1), (\alpha_{H}^{H} - 1), (\alpha_{e}^{H} - 1) \right]$$

$$\times \left[ \begin{array}{cccccc} (\sigma_{li}^{Gd})^2 & 0 & 0 & \rho_{li} \sigma_{li}^{Gd} \sigma_{li}^{H} & 0 & 0 \\ 0 & (\sigma_{fn}^{Gd})^2 & 0 & 0 & \rho_{fn} \sigma_{fn}^{Gd} \sigma_{fn}^{H} & 0 \\ 0 & 0 & (\sigma_{li}^{H})^2 & 0 & 0 & \rho_{li} \sigma_{li}^{H} \sigma_{li}^{Gd} \\ 0 & 0 & 0 & (\sigma_{fn}^{H})^2 & 0 & \rho_{fn} \sigma_{fn}^{H} \sigma_{fn}^{Gd} \\ 0 & 0 & 0 & 0 & (\sigma_{li}^{Gd})^2 & \rho_{li} \sigma_{li}^{Gd} \sigma_{li}^{H} \\ 0 & 0 & 0 & 0 & 0 & (\sigma_{fn}^{H})^2 \end{array} \right]^{-1}$$

$$+ \left[ (\alpha_{H}^{Gd} - 1), (\alpha_{H}^{Gd} - 1), (\alpha_{e}^{Gd} - 1), (\alpha_{H}^{H} - 1), (\alpha_{e}^{H} - 1) \right]^T$$

$$+ \left[ (\alpha_{H}^{Gd} R_{H}^{Gd}, \text{pred} + \alpha_{Gd} R_{Gd}^{Gd}, \text{pred - R}_{Gd}^{Gd}, \text{off} ), (\alpha_{H}^{H} R_{H}^{H}, \text{pred} + \alpha_{H}^{H} R_{H}^{H}, \text{pred} - R_{H}^{H}, \text{off}) \right]$$

$$\times \left[ \begin{array}{cccccc} (\sigma_{li}^{Gd})^2 & \rho_{li} \sigma_{li}^{Gd} \sigma_{li}^{H} & 0 & 0 & 0 & 0 \\ \rho_{li} \sigma_{li}^{H} \sigma_{li}^{Gd} & (\sigma_{li}^{H})^2 & 0 & 0 & 0 & 0 \\ 0 & 0 & (\sigma_{fn}^{Gd})^2 & \rho_{fn} \sigma_{fn}^{Gd} \sigma_{fn}^{H} & 0 & 0 \\ 0 & 0 & 0 & (\sigma_{fn}^{H})^2 & \rho_{fn} \sigma_{fn}^{H} \sigma_{fn}^{Gd} & 0 \\ 0 & 0 & 0 & 0 & (\sigma_{li}^{Gd})^2 & \rho_{li} \sigma_{li}^{Gd} \sigma_{li}^{H} \\ 0 & 0 & 0 & 0 & 0 & (\sigma_{li}^{H})^2 \end{array} \right]^{-1} \times \left[ \begin{array}{cccccc} (\alpha_{H}^{Gd} R_{H}^{Gd}, \text{pred} + \alpha_{Gd} R_{Gd}^{Gd}, \text{pred - R}_{Gd}^{Gd}, \text{off} ), (\alpha_{H}^{H} R_{H}^{H}, \text{pred} + \alpha_{H}^{H} R_{H}^{H}, \text{pred} - R_{H}^{H}, \text{off}) \end{array} \right]$$

Inner product with covariance matrix, as defined on previous slide

Mass splitting pull term

Correlated pull terms on background rates and energy scale

Reactor-off rate constraints
Predicted $\bar{\nu}_e$ spectrum

$$N_i = \frac{\epsilon N_p}{4\pi} \sum_R \frac{1}{L_R^2} \frac{P_{th}^R}{\langle E_f \rangle_R} \left( \frac{\langle \sigma_f \rangle_R}{\sum_k \alpha_k^R \langle \sigma_f \rangle_k} \sum_k \alpha_k^R \langle \sigma_f \rangle_i^k \right)$$

**Bugey4 “anchor”:** $\langle \sigma_f \rangle_R = \langle \sigma_f \rangle_{Bugey} + \sum_k (\alpha_k - \alpha_k^{Bugey}) \langle \sigma_f \rangle_k$

... scales predicted $\langle \sigma_f \rangle$ to match $\langle \sigma_f \rangle$ measured at $L = 15$ m, removing sensitivity to $\Delta m^2 \sim 1$ eV$^2$ oscillations

- $R, k = \{\text{Reactor 1, Reactor 2}\}$
- $\epsilon = \text{detection efficiency}$
- $N_p = \text{number of protons in fiducial volume}$
- $L_R = \text{distance between } R^{th} \text{ reactor and far detector}$
- $P_{th}^R = \text{thermal power of } R^{th} \text{ reactor (time-dependent)}$
- $\langle E_f \rangle_R = \text{mean energy per fission in } R^{th} \text{ reactor (time-dependent)}$
- $\langle \sigma_f \rangle_R = \text{mean cross section per fission in } R^{th} \text{ reactor (time-dependent)}$
- $\alpha_k^R = \text{fission fraction for } k^{th} \text{ isotope in } R^{th} \text{ reactor (time-dependent)}$
- $\langle \sigma_f \rangle_k = \text{mean cross section per fission of } k^{th} \text{ isotope}$
- $\langle \sigma_f \rangle_i^k = \text{mean cross section per fission of } k^{th} \text{ isotope in } i^{th} \text{ energy bin}$
$^9$Li measurement

Rate derived from $\Delta t_\mu = t - t_{\text{previous } \mu}$ for IBD candidates:

- $\Delta t_\mu$ fit with $\tau(^9\text{Li}) = 257$ ms
  
  (sample plot show for $E_\mu > 600$ MeV)

- Purity increased with $\Delta R_\mu\text{ track}$ cuts

- Consistent rates found for Gd and H

Spectrum shape predicted from MC:

- Spectrum uncertainties from uncertainty on $^9$Li branching ratios

- Data consistent with predicted shape
Fast n + stopping $\mu$ measurement

Rough estimate:
- Extrapolate from $E_p \in [12, 30]$ MeV

Refined measurement:
- Pure selection from IV/OV-tagging (+ additional cuts, background subtraction)
- Fit with linear/exponential model
- Rate from integrating spectrum fit

All stopping $\mu$ removed from H selection with $\Delta T < 10 \mu$s cut.
**Light noise**

**Cuts remove almost all light noise,** with negligible signal inefficiency:

- **Charge isotropy:** $\frac{Q_{\text{max}}}{Q_{\text{tot}}} < \begin{cases} 0.09 & \text{H, Gd prompt} \\ 0.06 & \text{Gd delayed} \end{cases}$

  - $Q_{\text{max}} = \text{maximum charge seen by single PMT}$
  - $Q_{\text{tot}} = \text{total charge seen by all PMTs}$

- **Pulse simultaneity:** $T^{\text{RMS}}_{\text{start}} < 40 \text{ ns}$

  - $T^{\text{RMS}}_{\text{start}} = \text{RMS of pulse start times, over all PMTs recording pulses}$

Time-correlated light noise remains in H selection: $0.3 \pm 0.1 \text{ d}^{-1}$

(included in H fit, but impact is negligible)