Observation of Electron-antineutrino Disappearance at Daya Bay

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Outline

- Introduction
- Construction of Daya Bay Experiment
- Data Analysis
  - Calibrations
  - IBD Selections
  - Background
  - Oscillation Analysis

Inside Daya Bay Anti-neutrino Detector

Inside of Outer Water Shield
Neutrino mixing matrix (PMNS):

\[
V = \begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix}
\begin{pmatrix}
c_{13} & 0 & s_{13} \\
0 & e^{-i\delta} & 0 \\
-s_{13} & 0 & c_{13}
\end{pmatrix}
\begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
e^{i\rho} & 0 & 0 \\
0 & e^{i\sigma} & 0 \\
0 & 0 & 1
\end{pmatrix}
\]

Unknown mixing parameters: \( \theta_{13}, \delta + 2 \text{ Majorana phases} \)

Sizable \( \theta_{13} \) could open the door to answer the questions of CP violation, matter and anti-matter asymmetry, neutrino mass hierarchy

Goal: search for a new oscillation mode \( \theta_{13} \)?

\( \theta_{12} \) solar neutrino oscillation

\( \theta_{23} \) atmospheric neutrino oscillation

Ongoing programs:
- Reactor: Daya Bay Double-Chooz, Reno
- Accelerator: NOVA, T2K
Indications of nonzero $\theta_{13}$ in 2011, Observation in 2012

2011 has given many hints:

- Solar + KamLAND: G.L.Fogli et al., PRD 84, 053007 (2011)
- MINOS: P. Adamson et al., PRL. 107, 181802 (2011)
- T2K: K. Abe et al., PRL. 107 041801 (2011)
- Double CHOOZ: Y. Abe et al., PRL. 108, 131801 (2012)

No result $>2.5\sigma$ from $\theta_{13} = 0$

Daya Bay excludes $\theta_{13}= 0$ at $5.2\sigma$ – Mar. 8

$\sin^2 2\theta_{13} = 0.092 \pm 0.016$ (stat) $\pm 0.005$ (syst)


Reno confirms – Apr. 3

$\sin^2 2\theta_{13} = 0.113 \pm 0.013$ (stat) $\pm 0.019$ (syst)

Why measure $\theta_{13}$ with Reactor Experiments?

**reactor**

\[
P_{ee} \approx 1 - \sin^2 2 \theta_{13} \sin^2 \left( \frac{\Delta m_{31}^2 L}{4 E_\nu} \right) - \cos^4 \theta_{13} \sin^2 2 \theta_{12} \sin^2 \left( \frac{\Delta m_{21}^2 L}{4 E_\nu} \right)
\]

- Disappearance measurement
- Clean measurement of $\theta_{13}$
- No matter effects

**accelerator**

\[
P(\nu_\mu \to \nu_e) = 4 c_{13}^2 s_{13}^2 s_{23}^2 \sin^2 \Delta_{31} \\
+ 8 c_{13}^2 s_{13} s_{23} c_{23} s_{12} c_{12} \sin \Delta_{31} \left[ \cos \Delta_{32} \cos \delta - \sin \Delta_{32} \sin \delta \right] \sin \Delta_{21} \\
- 8 c_{13}^2 s_{13}^2 s_{23}^2 s_{12} \cos \Delta_{32} \sin \Delta_{31} \sin \Delta_{21} \\
+ 4 c_{13}^2 s_{12}^2 \left[ c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2 c_{12} c_{23} s_{12}^2 s_{23} s_{13} \cos \delta \right] \sin^2 \Delta_{21} \\
- 8 c_{13}^2 s_{13}^2 s_{23}^2 (1 - 2 s_{13}^2) \frac{aL}{4 E_\nu} \sin \Delta_{31} \left[ \cos \Delta_{32} - \frac{\sin \Delta_{31}}{\Delta_{31}} \right].
\]
The Daya Bay Collaboration

North America (16)
BNL, Caltech, LBNL, Iowa State Univ., Illinois Inst. Tech., Princeton, RPI,
UC-Berkeley, UCLA, Univ. of Cincinnati, Univ. of Houston, Univ. of Wisconsin,
William & Mary, Virginia Tech., Univ. of Illinois-Urbana-Champaign, Siena

~250 Collaborators

Europe (2)
JINR, Dubna, Russia
Charles University, Czech Republic

Asia (20)
The Daya Bay Site

45 km

55 km

Shenzhen

Daya Bay

Hong Kong

Guangdong
Daya Bay Nuclear Power Complex

- Three-pair reactor cores: $2.95 \times 6 = 17.7\text{GWth}$
- Each core produces $6 \times 10^{20}$ anti-$\nu_e$'s/s
- Mountains near by
Determining $\theta_{13}$ With Reactor $\nu_e$

Looking for non-$1/r^2$ behavior of $\bar{\nu}_e$ interaction rate

$$\frac{N_{\text{obs}}}{N_{\text{exp}}} = 1 - \sin^2 2\theta_{13} \sin^2 (1.27 \Delta m_{13}^2 \frac{L}{E}) - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 (1.27 \Delta m_{12}^2 \frac{L}{E})$$

- Absolute reactor flux is the largest uncertainty in previous measurements
- Relative measurement removes absolute uncertainties!

First proposed by L. A. Mikaelyan and V.V. Sinev, Phys. Atomic Nucl. 63 1002 (2000)

- Identical near and far detector

$\sin^2 2\theta_{13}$

\[
\frac{N_f}{N_n} = \left(\frac{N_{p,f}}{N_{p,n}}\right) \left(\frac{L_n}{L_f}\right)^2 \left(\frac{\varepsilon_f}{\varepsilon_n}\right) \frac{P_{\text{survival}}(E, L_f)}{P_{\text{survival}}(E, L_n)}
\]

far/near $\nu_e$ ratio, target mass, distances, efficiency, oscillation deficit
Underground Labs

<table>
<thead>
<tr>
<th>Location</th>
<th>Overburden (MWE)</th>
<th>$R_\mu$ (Hz/m²)</th>
<th>$E_\mu$ (GeV)</th>
<th>D1,2 (m)</th>
<th>L1,2 (m)</th>
<th>L3,4 (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EH1</td>
<td>250</td>
<td>1.27</td>
<td>57</td>
<td>364</td>
<td>857</td>
<td>1307</td>
</tr>
<tr>
<td>EH2</td>
<td>265</td>
<td>0.95</td>
<td>58</td>
<td>1348</td>
<td>480</td>
<td>528</td>
</tr>
<tr>
<td>EH3</td>
<td>860</td>
<td>0.056</td>
<td>137</td>
<td>1912</td>
<td>1540</td>
<td>1548</td>
</tr>
</tbody>
</table>
Neutrino Detection: Gd-loaded Liquid Scintillator

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

$$\tau \approx 28 \mu s (0.1\% \text{ Gd})$$

$$n + p \rightarrow d + \gamma (2.2 \text{ MeV})$$

$$n + \text{Gd} \rightarrow \text{Gd}^* + \gamma (8 \text{ MeV})$$

Neutrino Event: coincidence in time, space and energy

**Neutrino energy:**

$$E_{\bar{\nu}} \approx \left( T_{e^+} \right) + T_n + (M_n - M_p) + m_{e^+}$$

10-40 keV  \hspace{1cm} 1.8 MeV: Threshold
Anti-neutrino Detector (AD)

- Three zones modular structure:
  I. target: Gd-loaded scintillator
  II. γ-catcher: normal scintillator
  III. buffer shielding: oil

- 192 8” PMTs/module

- Two optical reflectors at the top and the bottom, photocathode coverage increased from 5.6% to 12%

Target: 20 t, 1.6m
γ-catcher: 20t, 45cm
Buffer: 40t, 45cm
Total weight: ~110 t
Gd-loaded Liquid Scintillator

- Liquid production, QA, storage and filling at Hall 5
  - 185t Gd-LS, ~180t LS, ~320t oil
- LAB+Gd (TMHA)$_3$+PPO+BisMSB
- Stable over time
  - Light yield: ~163 PE/MeV
Automatic Calibration System

- **Three Z axis:**
  - One at the center
    - For time evolution, energy scale, non-linearity…
  - One at the edge
    - For efficiency, space response
  - One in the $\gamma$-catcher
    - For efficiency, space response

- **3 sources for each z axis:**
  - LED
    - for $T_0$, gain and relative QE
  - $^{68}$Ge ($2 \times 0.511$ MeV $\gamma$’s)
    - for positron threshold & non-linearity…
  - $^{241}$Am-$^{13}$C + $^{60}$Co (1.17+1.33 MeV $\gamma$’s)
    - For neutron capture time, …
    - For energy scale, response function, …

- **Once every week:**
  - 3 axis, 5 points in Z, 3 sources
Muon Veto Detector

Dual tagging systems: 2.5 meter thick two-section water shield and RPCs

- **Water Cerenkov detector**
  - High purity de-ionized water in pools also for shielding
  - First stage water production in hall 4
  - Local water re-circulation & purification

- **RPCs**
  - 4 layers/module
  - 54 modules/near hall, 81 modules/far hall
  - 2 telescope modules/hall

- **Water Cerenkov detector**
  - Two layers, separated by Tyvek/PE/Tyvek film
  - 288 8” PMTs for near halls; 384 8” PMTs for the far hall

Goal efficiency: > 99.5% with <0.25% uncertainty
Two ADs Installed in Hall 1
Hall 1(two ADs) Started the Operation on Aug. 15, 2011
One AD installed in Hall 2
Physics Data Taking Started on Nov. 5, 2011
Three ADs installed in Hall 3
Physics Data Taking Started on Dec.24, 2011
Data Periods

A. Two Detector Comparison: arXiv:1202:6181
- Side-by-side comparison of 2 detectors in Hall 1
- Demonstrated detector systematics better than requirements.
- Soon published in Nucl. Inst. and Meth.

- All 3 halls (6 ADs) operating
- First observation of $\bar{\nu}_e$ disappearance

C. June Oscillation Result Update:
Neutrino 2012
- More than 2.5 x the previous data set
Trigger Performance

- **Threshold for a hit:**
  - AD & pool: $\frac{1}{4}$ PE

- **Trigger thresholds:**
  - AD: $\sim N_{\text{HIT}} = 45$, $E_{\text{tot}} = \sim 0.4$ MeV
  - Inner pool: $N_{\text{HIT}} = 6$
  - Outer pool: $N_{\text{HIT}} = 7$ (8 for far hall)
  - RPC: 3/4 layers in each module

- **Trigger rate (EH1)**
  - AD singles rate:
    - $>0.4\text{MeV}$, $\sim 280\text{Hz}$
    - $>0.7\text{MeV}$, $\sim 60\text{Hz}$
  - Inner pool rate: $\sim 170\text{ Hz}$
  - Outer pool rate: $\sim 230\text{ Hz}$
Flashers: Imperfect PMTs

- Spontaneous light emission by PMT
- Topology: a hot PMT + near-by PMTs and opposite PMTs
- \(~5\%\) of PMT, \(5\%\) of event
- Rejection: pattern of fired PMTs

\[
\log_{10} \left( \left( \frac{\text{Quadrant}}{1.} \right)^2 + \left( \frac{\text{MaxQ}}{0.45} \right)^2 \right) < 0
\]

Quadrant = Q3/(Q2+Q4)
MaxQ = maxQ/sumQ

Inefficiency to neutrinos: \(0.024\% \pm 0.006\%\) (stat)
Contamination: < 0.01\%
Single Rate

After PMT flasher remove

Muon remove with:
1µs < Pool muon <200µs

- Single rate contribution:
  - ~ 5 Hz from SSV
  - ~ 10 Hz from LS
  - ~ 25 Hz from PMT
  - ~ 5 Hz from rock
PMT Calibration:

- **PMT gain stability**
- **Energy calibration**
- **Energy in different ADs**

**Fit to one PMT SPE distribution**
- Data showing the distribution of entries over ADC values.

**60Co at center**
- Graph showing energy distribution with peak at 1.275 MeV.

**neutron capture**
- Graph showing neutron capture energy distribution with peaks at different energies for AD1 and AD2.
IBD event selection

Prompt + Delayed Selection  \( \bar{\nu}_e + p \rightarrow e^+ + n \)

- Reject Flashers
- Muon Veto:
  - Pool Muon: Reject 0.6ms
  - AD Muon (>20 MeV): Reject 1ms
  - AD Shower Muon (>2.5GeV): Reject 1s
- Multiplicity:
  - No other signal > 0.7 MeV in -200 µs to 200 µs of IBD.
- Prompt Positron: 0.7 MeV < \( E_p \) < 12 MeV
- Delayed Neutron: 6.0 MeV < \( E_d \) < 12 MeV
- Capture time: 1 µs < \( \Delta t \) < 200 µs
**Backgrounds**

- **Low background experiment**
  - Total backgrounds are 5% (2%) in far(near) halls
  - Background uncertainties are 0.3% (0.2%) in far (near) halls

- **The backgrounds are all estimated using data-driven methods:**
  - The largest source of background can be measured to ~1%

<table>
<thead>
<tr>
<th></th>
<th>Near Halls</th>
<th>Far Hall</th>
</tr>
</thead>
<tbody>
<tr>
<td>B/S %</td>
<td>σ_B/S %</td>
<td>B/S %</td>
</tr>
<tr>
<td>Accidentals</td>
<td>1.5</td>
<td>4.0</td>
</tr>
<tr>
<td>Fast neutrons</td>
<td>0.12</td>
<td>0.07</td>
</tr>
<tr>
<td>$^9$Li/$^8$He</td>
<td>0.4</td>
<td>0.3</td>
</tr>
<tr>
<td>$^{241}$Am-$^{13}$C</td>
<td>0.03</td>
<td>0.3</td>
</tr>
<tr>
<td>$^{13}$C(α, n)$^{16}$O</td>
<td>0.01</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Constrain fast-n rate using IBD-like signals in 10-50 MeV

Estimate $^9$Li rate using time-correlation with muon

$E_{\mu}>4$ GeV (visible)
Neutron Capture Time

Consistent IBD capture time measured in all detectors

Capture time in each detector constrains H/Gd capture ratio

Capture time cut:
1μs to 200μs

Relative detector efficiency estimated within 0.01% by considering possible variations in Gd concentration.

Measurement of Am-C source neutron capture time distributions constrain uncertainty in relative H/Gd capture efficiency to < 0.1% between detectors.
## Daya Bay Data Set Summary

### ~200k near and ~30k far detector antineutrino interactions

<table>
<thead>
<tr>
<th></th>
<th>AD1</th>
<th>AD2</th>
<th>AD3</th>
<th>AD4</th>
<th>AD5</th>
<th>AD6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antineutrino candidates</td>
<td>69121</td>
<td>69714</td>
<td>66473</td>
<td>9788</td>
<td>9669</td>
<td>9452</td>
</tr>
<tr>
<td>DAQ live time (day)</td>
<td>127.5470</td>
<td>127.3763</td>
<td>126.2646</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Efficiency</td>
<td>0.8015</td>
<td>0.7986</td>
<td>0.8364</td>
<td>0.9555</td>
<td>0.9552</td>
<td>0.9547</td>
</tr>
<tr>
<td>Accidentals (/day)</td>
<td>9.73 ± 0.10</td>
<td>9.61 ± 0.10</td>
<td>7.55 ± 0.08</td>
<td>3.05 ± 0.04</td>
<td>3.04 ± 0.04</td>
<td>2.93 ± 0.03</td>
</tr>
<tr>
<td>Fast neutron (/day)</td>
<td>0.77 ± 0.24</td>
<td>0.77 ± 0.24</td>
<td>0.58 ± 0.33</td>
<td>0.05 ± 0.02</td>
<td>0.05 ± 0.02</td>
<td>0.05 ± 0.02</td>
</tr>
<tr>
<td>$^8$He/$^9$Li (/day)</td>
<td>2.9 ± 1.5</td>
<td>2.0 ± 1.1</td>
<td></td>
<td>0.22 ± 0.12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Am-C corr. (/day)</td>
<td></td>
<td></td>
<td></td>
<td>0.2 ± 0.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{13}$C($\alpha$, n)$^{16}$O (/day)</td>
<td>0.08 ± 0.04</td>
<td>0.07 ± 0.04</td>
<td>0.05 ± 0.03</td>
<td>0.04 ± 0.02</td>
<td>0.04 ± 0.02</td>
<td>0.04 ± 0.02</td>
</tr>
<tr>
<td>Antineutrino rate (/day)</td>
<td>662.47 ± 3.00</td>
<td>670.87 ± 3.01</td>
<td>613.53 ± 2.69</td>
<td>77.57 ± 0.85</td>
<td>76.62 ± 0.85</td>
<td>74.97 ± 0.84</td>
</tr>
</tbody>
</table>

Uncertainty still dominated by statistics
Reactor Neutrinos

- Reactor neutrino spectrum

\[ S(E_\nu) = \frac{W_{th}}{\sum_i (f_i/F)e_i} \sum_i (f_i/F)S_i(E_\nu) \]

- Thermal power, \( W_{th} \), measured by KIT system, calibrated by KME method
- Fission fraction, \( f_i \), determined by reactor core simulation
- Neutrino spectrum of fission isotopes \( S_i(E_\nu) \) from measurements
- Energy released per fission \( e_i \)

<table>
<thead>
<tr>
<th>Isotope</th>
<th>( E_{fi}, \text{MeV/fission} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{235}\text{U})</td>
<td>201.92 ± 0.46</td>
</tr>
<tr>
<td>(^{238}\text{U})</td>
<td>205.52 ± 0.96</td>
</tr>
<tr>
<td>(^{239}\text{Pu})</td>
<td>209.99 ± 0.60</td>
</tr>
<tr>
<td>(^{241}\text{Pu})</td>
<td>213.60 ± 0.65</td>
</tr>
</tbody>
</table>


Relative measurement ➔ independent from the neutrino spectrum prediction
Baseline

- Various measurements: GPS, Total Station, laser tracker, level instruments, …
- Compared with design values, and NPP coordinates
- Data processing by three independent software
- Final baseline uncertainty is 28 mm
Uncertainty Summary

<table>
<thead>
<tr>
<th>Detector</th>
<th>Efficiency</th>
<th>Correlated</th>
<th>Uncorrelated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target Protons</td>
<td>0.47%</td>
<td></td>
<td>0.03%</td>
</tr>
<tr>
<td>Flasher cut</td>
<td>99.98%</td>
<td>0.01%</td>
<td>0.01%</td>
</tr>
<tr>
<td>Delayed energy cut</td>
<td>90.9%</td>
<td>0.6%</td>
<td>0.12%</td>
</tr>
<tr>
<td>Prompt energy cut</td>
<td>99.88%</td>
<td>0.10%</td>
<td>0.01%</td>
</tr>
<tr>
<td>Multiplicity cut</td>
<td>0.02%</td>
<td></td>
<td>&lt;0.01%</td>
</tr>
<tr>
<td>Capture time cut</td>
<td>98.6%</td>
<td>0.12%</td>
<td>0.01%</td>
</tr>
<tr>
<td>Gd capture ratio</td>
<td>83.8%</td>
<td>0.8%</td>
<td>&lt;0.1%</td>
</tr>
<tr>
<td>Spill-in</td>
<td>105.0%</td>
<td>1.5%</td>
<td>0.02%</td>
</tr>
<tr>
<td>Livetime</td>
<td>100.0%</td>
<td>0.002%</td>
<td>&lt;0.01%</td>
</tr>
<tr>
<td>Combined</td>
<td>78.8%</td>
<td>1.9%</td>
<td>0.2%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Reactor</th>
<th>Correlated</th>
<th>Uncorrelated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy/fission</td>
<td>0.2%</td>
<td>0.5%</td>
</tr>
<tr>
<td>$\bar{\nu}_e$/fission</td>
<td>3%</td>
<td>Fission fraction 0.6%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Spent fuel 0.3%</td>
</tr>
<tr>
<td>Combined</td>
<td>3%</td>
<td>Combined 0.8%</td>
</tr>
</tbody>
</table>

For near/far oscillation, only uncorrelated uncertainties are used.

Largest systematics are smaller than far site statistics (~1%)

Influence of uncorrelated reactor systematics (0.8%) is reduced to 0.04% detector systematics uncertainty by far vs near measurement.
Rate Only Oscillation Analysis

Estimate $\theta_{13}$ using measured rates in each detector.

$\sin^2 2\theta_{13} = 0.089 \pm 0.010 \text{ (stat)} \pm 0.005 \text{ (syst)}$

Most precise measurement of $\sin^2 2\theta_{13}$ to date.

Uses standard $\chi^2$ approach.

Far vs. near relative measurement.

[Absolute rate is not constrained.]
Clear observation of far site deficit.

Spectral distortion consistent with oscillation.*

\[ R = \frac{F_{\text{measured}}}{F_{\text{expected}}} = \frac{M_4 + M_5 + M_6}{\sum_{i=4}^{6}(\alpha_i(M_1 + M_2) + \beta_iM_3)} \]

\( M_n \) are the measured rates in each detector. Weights \( \alpha_i, \beta_i \) are determined from baselines and reactor fluxes.

\[ R = 0.944 \pm 0.007 \text{ (stat)} \pm 0.003 \text{ (syst)} \]

*Caveat: Spectral systematics not fully studied; \( \theta_{13} \) value from shape analysis is not recommended.
Global $\theta_{13}$ Situation

Double Chooz update

M. Ishitsuka Neutrino 2012

![Graphical data from Double Chooz experiment]

Preliminary

$\sin^2 2\theta_{13} = 0.170 \pm 0.035\text{(stat)} \pm 0.040\text{(syst)}$

$\sin^2 2\theta_{13} = 0.109 \pm 0.030\text{(stat)} \pm 0.025\text{(syst)}$

Reno

![Graphical data from Reno experiment]

$\sin^2 2\theta_{13} = 0.113 \pm 0.013\text{(stat.)} \pm 0.019\text{(syst.)}$
Measurement of $\theta_{13}$ opens an exciting future.
Daya Bay Summary

Daya Bay has made an unambiguous observation of electron-antineutrino disappearance at ~2km and measured a far/near ratio of

\[ R = 0.944 \pm 0.007 \text{ (stat)} \pm 0.003 \text{ (syst)} \]

previous: \[ R = 0.940 \pm 0.011 \text{ (stat)} \pm 0.004 \text{ (syst)} \]

Interpretation of disappearance as neutrino oscillation rules out \( \sin^2 2\theta_{13} = 0 \) at 7.7\( \sigma \)

Daya Bay precision surpasses all existing measurements.

\[ \sin^2 2\theta_{13} = 0.089 \pm 0.010 \text{ (stat)} \pm 0.005 \text{ (syst)} \]

previous: \[ \sin^2 2\theta_{13} = 0.092 \pm 0.016 \text{ (stat)} \pm 0.005 \text{ (syst)} \]

Last two detectors will be installed this year

Expect more statistics and improvements in analysis.

Daya Bay will continue to have the best sensitivity to \( \theta_{13} \) among all the other experiments in operation or in construction.
Backup
Event Signature and Backgrounds

**Signature:** \( \bar{\nu}_e + p \rightarrow e^+ + n \)

- **Prompt:** \( e^+ \), \( E: 1-10 \text{ MeV} \),
- **Delayed:** \( n \), \( E: 2.2 \text{ MeV} @ H, 8 \text{ MeV} @ Gd \)
- **Capture time:** 28 \( \mu \text{s} \) in 0.1\% Gd-LS

**Backgrounds**

- **Uncorrelated:** random coincidence of \( \gamma \gamma, \gamma n \) & \( nn \)
  - \( \gamma \) from U/Th/K/Rn/Co… in LS, SS, PMT, Rock, …
  - \( n \) from \( \alpha\)–\( n \), \( \mu\)-capture, \( \mu\)-spallation in LS, water & rock
- **Correlated:**
  - Fast neutrons: prompt—\( n \) scattering, delayed—\( n \) capture
  - \( 8\text{He}/9\text{Li} \): prompt—\( \beta \) decay, delayed—\( n \) capture
  - Am-C source: prompt—\( \gamma \) rays, delayed—\( n \) capture
  - \( \alpha\)-\( n \): \(^{13}\text{C}(\alpha,n)^{16}\text{O} \)
Background: Accidentals

Accidentals: Two uncorrelated events ‘accidentally’ passing the cuts and mimic IBD event.

Rate and spectrum can be accurately predicted from singles data.

Multiple analyses/methods estimate consistent rates.

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<thead>
<tr>
<th></th>
<th>EH1-AD1</th>
<th>EH1-AD2</th>
<th>EH2-AD1</th>
<th>EH3-AD1</th>
<th>EH3-AD2</th>
<th>EH3-AD3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accidental rate(/day)</td>
<td>9.82±0.06</td>
<td>9.88±0.06</td>
<td>7.67±0.05</td>
<td>3.29±0.03</td>
<td>3.33±0.03</td>
<td>3.12±0.03</td>
</tr>
<tr>
<td>B/S</td>
<td>1.37%</td>
<td>1.38%</td>
<td>1.44%</td>
<td>4.58%</td>
<td>4.77%</td>
<td>4.43%</td>
</tr>
</tbody>
</table>
Background: Fast neutrons

Correlated events mimic IBD events

Fast Neutrons
Energetic neutrons produced by cosmic rays (inside and outside of muon veto system)

Mimics antineutrino (IBD) signal
Prompt: Neutron collides/stops in target
Delayed: Neutron captures on Gd

Validate with fast-n events tagged by muon veto.
Projected errors - assuming $1/\sqrt{N}$ rate only

$1 \sigma$ Uncertainty vs. time assuming $\sqrt{N}$ statistics

Mar 26: End of RENO 229d data

Feb 17: End of DYB 55d data

May 17: End of present Daya Bay data set

~ Aug 1: 90 day shutdown

6 AD

8 AD

sys unc = 0.019

Reno potential with 0.010 sys

M. McFarlane

Rate-only PRLs

DYB 6ADs

DYB 8ADs

RENO