reactor $\theta_{13}$
(the ultimate measurement?)

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CNRS / IN2P3
Double Chooz @ APC (Paris)
will the reactor-$\Theta$13 be the ultimate measurement?

the best for long time…

(so must get it right!)

this seminar: tell you how we are doing that…
le menu...

• les apéritives...
  • neutrino oscillation (a fast reminder)
  • neutrino oscillation status
  • global impact of $\theta_{13}$ (a few examples)

• les plats…
  • reactor neutrinos: (a fast) why?
  • review on reactor $\theta_{13}$ experiments results

• le dessert…
  • today & tomorrow on reactor $\theta_{13}$ systematics

• conclusions?
neutrino oscillations…
(very fast reminder)
Let's take $\nu_\mu$ (a good example) to start with…

"propagation" in vacuum/matter

\[\nu_\mu \rightarrow \nu_\mu \]
“mixing”: a common phenomenon in Nature

\[ V_\alpha = 0.5 \cdot V_1 + 0.5 \cdot V_2 \]
Mixing in the leptonic sector \((\theta)\rightarrow\text{PMNS matrix (à la CKM)}\)

Non-degenerate mass spectrum \((\Delta m^2)\rightarrow\text{macroscopic (i.e. over km’s!!) quantum interference}\)

\(L,E\) to be tuned (i.e. experimental setup) \(\rightarrow\) measure \(P(L_0,\Delta E)\)

solution for 2\(\nu\)'s…
ν-oscillations knowledge...
\( (\nu_e, \nu_\mu, \nu_\tau)^T = U (\nu_1, \nu_2, \nu_3)^T \), where \( U \) looks like

\[
U = \begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix}
\]

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

\[
= \begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\]

“atmospheric” \( \theta_{23} \sim 45^\circ \)

\( \Delta m^2_{31} \)

Sub-leading

“solar” \( \theta_{12} \sim 33^\circ \)

\( \Delta m^2_{21} \)

Sub-leading

Chooz + LBL (app)

\( P(\nu_e \rightarrow \nu_e) \) & \( P(\nu_\mu \rightarrow \nu_e) \)

atmos + LBL (dis)

\( P(\nu_\mu \rightarrow \nu_\mu) \)

\[ P(\nu_\mu \rightarrow \nu_e) \]

Knowledge on \( \theta_{13} \) & \( \delta_{CP} \) [later]

Fogli et al, arXiv:1106.6028
**Numerical 1σ, 2σ, 3σ ranges:**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Best fit</th>
<th>1σ range</th>
<th>2σ range</th>
<th>3σ range</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta m^2/10^{-5}$ eV$^2$ (NH or IH)</td>
<td>7.54</td>
<td>7.32 – 7.80</td>
<td>7.15 – 8.00</td>
<td>6.99 – 8.18</td>
</tr>
<tr>
<td>$\sin^2 \theta_{12}$/10$^{-1}$ (NH or IH)</td>
<td>3.07</td>
<td>2.91 – 3.25</td>
<td>2.75 – 3.42</td>
<td>2.59 – 3.59</td>
</tr>
<tr>
<td>$\Delta m^2/10^{-5}$ eV$^2$ (NH)</td>
<td>2.43</td>
<td>2.33 – 2.49</td>
<td>2.27 – 2.55</td>
<td>2.19 – 2.62</td>
</tr>
<tr>
<td>$\Delta m^2/10^{-3}$ eV$^2$ (IH)</td>
<td>2.42</td>
<td>2.31 – 2.49</td>
<td>2.26 – 2.53</td>
<td>2.17 – 2.61</td>
</tr>
<tr>
<td>$\sin^2 \theta_{13}$/10$^{-2}$ (NH)</td>
<td>2.41</td>
<td>2.16 – 2.66</td>
<td>1.93 – 2.90</td>
<td>1.69 – 3.13</td>
</tr>
<tr>
<td>$\sin^2 \theta_{13}$/10$^{-2}$ (IH)</td>
<td>2.44</td>
<td>2.19 – 2.67</td>
<td>1.94 – 2.91</td>
<td>1.71 – 3.15</td>
</tr>
<tr>
<td>$\sin^2 \theta_{23}$/10$^{-2}$ (NH)</td>
<td>3.86</td>
<td>3.65 – 4.10</td>
<td>3.48 – 4.45</td>
<td>3.31 – 6.37</td>
</tr>
<tr>
<td>$\sin^2 \theta_{23}$/10$^{-2}$ (IH)</td>
<td>3.92</td>
<td>3.70 – 4.31</td>
<td>3.53 – 5.34 + 5.43 – 6.41</td>
<td>3.35 – 6.63</td>
</tr>
<tr>
<td>$\delta/\pi$ (NH)</td>
<td>1.08</td>
<td>0.77 – 1.36</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\delta/\pi$ (IH)</td>
<td>1.09</td>
<td>0.83 – 1.47</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Fractional 1σ accuracy** [defined as 1/6 of ±3σ range]

- $\delta m^2$: 2.6%
- $\Delta m^2$: 3.0%
- $\sin^2 \theta_{12}$: 5.4%
- $\sin^2 \theta_{13}$: 10%
- $\sin^2 \theta_{23}$: 14%

Note: above ranges obtained for “old” reactor fluxes. For “new” fluxes, ranges are shifted (by ~ 1/3 σ) for two parameters only: $\Delta \sin^2 \theta_{12}/10^{-1} = +0.05$ and $\Delta \sin^2 \theta_{13}/10^{-2} = +0.08$

**Hierarchy differences well below 1σ for various data combinations**
why $\theta_{13}$?

- $\theta_{13}$ **must be measured**
  - free parameter in SM (like in CKM $\rightarrow$ parameter constraints)
  - test $U_{PMNS}$ unitarity (hard) $\rightarrow$ sensitive to $\geq 3\nu$s (steriles?)
- a non-zero $\theta_{13}$ is necessary (but not sufficient) to measure $\delta_{CP}$
  - value important to measure the Mass Hierarchy (MH): $\pm \Delta m^2_{31}$
- $\theta_{13}$ helps to improve **our global knowledge** …
    - $\theta_{23}$ octant [example later]
    - $\delta_{CP}$ (Dirac phase) [example later]
- $\theta_{13}$ **oscillations observed** $\rightarrow$ validation of $3\nu$ oscillation model
  - confirms $3\nu$ families (like seeing the $\nu_\tau$ in 2000 by DONUT)
  - a “discovery”? [within a well established framework]
    - “solar” & “atmospheric” $\rightarrow$ main channels for oscillations so far
- $\theta_{13}$ $\rightarrow$ **discriminate flavour unification models** …
  - $U_{PMNS} + U_{CKM}$ $\rightarrow$ quark-lepton unification flavour model
  - example: Barr et al ([hep-ph/1208.6546](https://arxiv.org/abs/1208.6546)), etc…
global $\theta$ 13

impact...
• consistent reactor-θ13 result (all reactor experiments)
  • good knowledge ➞ high precision
  • constraint 3ν model & discriminate against predictions
  • good agreement ➞ high accuracy (relevant when high precision)
  • constraint 3ν model & discriminate against predictions
• observe E/L distortion
  • flux normalisation ➞ flux(DB or RENO) < flux(DC) [FD only]
• consistency between reactor and beam θ13 too…
  • beam-θ13 less precise (other observables) ➞ (still) it must be consistent
  • δCP rather insensitive to θ13 (but need a θ13 ≠ 0)
• mass hierarchy is more sensitive to θ13
  • atmospheric-νs ➞ INO, PINGU, ORCA, etc
  • reactor-νs ➞ Daya Bay II (amplitude of interference term)
• if inconsistency/tension found ➞ new physics/systematics? (exciting!)
combining baselines $\rightarrow$ $\Delta m_{23}^2$ measurement?

3 experiments $\rightarrow$ 3x $\theta_{13}$ measurements

- 3x difference baselines results on $\theta_{13}$
- combine results $\rightarrow$ **better constraint** $\Delta m_{23}^2$
- beams (i.e. MINOS) measure $\Delta m_{32}^2$ (complementary)
- important physics (even if less precision than MINOS)

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impact to the $\theta_{23}$ octant...
(\sin^2 \theta_{13}, \sin^2 \theta_{23}) \text{ from LBL app. + disapp. data plus solar + KamLAND data:}

Latest LBL disappearance data from T2K and MINOS favor nonmaximal \( \theta_{23} \)

From LBL appearance+disappear. data, two quasi-degenerate \( \theta_{23} \) solutions emerge, in anticorrelation with \( \theta_{13} \) (one slightly above and the other slightly below \( \sin^2 \theta_{13} \sim 0.02 \)). The two solutions merge above \( \sim 1\sigma \).

[It would be nice to see these plots in the official T2K and MINOS data analyses!]

Solar+KamLAND data happen to prefer just \( \sin^2 \theta_{13} \sim 0.02 \), and are unable to lift the octant degeneracy: the depth of the two minima differ by only \( \sim 0.3\sigma \).
Adding 2012 SK atmospheric neutrino data:

Further hints for $\theta_{23}$ in 1st octant. But no significant hierarchy discrimination.
impact to $\delta_{\text{CP}}$ info...
\((\sin^2 \theta_{13}, \delta)\) from LBL app. + disapp. data plus solar + KamLAND data:

\[ \delta \text{ is basically unconstrained at } \sim 1\sigma. \]

Fuzzy 1\(\sigma\) contours are a side effect of \(\theta_{23}\) degeneracy: the two \(\theta_{23}\) minima correspond to slightly different \(\theta_{13}\) ranges and thus to two slightly overlapping "wavy bands" in the plot. Minima flip easily from one band to the other.

Fuzziness disappear at higher CL (degeneracy just enlarges bands).
Adding 2012 SK atmospheric neutrino data:

We find a preference for $\delta \sim \pi$ (helps fitting sub-GeV e-like excess in SK)
why reactors are so cool?
• discovery of neutrinos (1956 → Nobel Prize 1995)
  • Pauli’s hypothesis (Nobel Prize)
• today’s best measurement of “solar” $\Delta m^2_{12}$ (KamLAND)
  • LMA solution & high precision “Solar-ν” physics
• best (ever?) measurement of $\theta_{13}$…
  • this talk → today’s status (+ my prospect) review
• very sensitive way to explore Sterile-ν existence…
  • very-short baseline experiments → “reactor anomaly”
  • ν industry → IAEA non-proliferation
• (future) best precision $\theta_{12}/\Delta m^2_{12}$ & Mass Hierarchy
  • Daya Bay II in preparation(?)
• complementary input in the neutrino oscillation quest…
  • NSI (short L), over-constraint 3ν-model, etc…
the most beautiful (to me) E/L so far...

\[ P_{\text{survival}} \approx 1 - \sin^2 2\theta \sin^2 \left( \frac{\Delta m^2}{4} \frac{L}{E_\nu} \right) \]
\[ P(\nu_e \rightarrow \nu_e) \sim 1 - \sin^2(2\theta_{13}) \sin^2(\Delta m^2_{32}L_0/E) \]

[plot: \( E = 3\text{MeV}, \sin^2(2\theta_{13}) = 0.1, \Delta m^2_{32} = 2.5 \times 10^{-3}\text{eV}^2 \)]

**ND** → reduce all correlated systematic uncertainties

**ND** → isolates from other physics (reactor anomaly → fast oscillation)
Backgrounds always ON (radio-activity & $\mu$-related)

$\rightarrow$ signal can be OFF (or significantly reduce)

[ask your solar-neutrino colleagues how cool this might be...]
reactor $\theta_{13}$ measurement...
• 3 experiments $\rightarrow$ Daya Bay (DB), Double Chooz (DC) & RENO

• $\theta_{13}$ best measurement worldwide from reactors
  • hard to improve (or re-trigger dedicated experimental activity)
  • $\theta_{13}$ measurement to $\sim$5% precision (eventually) $\rightarrow$ use by beams
    • high precision $\rightarrow$ due to multi-detector technique
    • high accuracy $\rightarrow$ due to several experiments (any bias?)
  • oscillation signature $\rightarrow$ $\theta_{13}$ measure via both rate + shape
    • rate-only = “any deficit” is numerically associated to $\theta_{13}$ (BG, etc)
    • results are rate driven $\rightarrow$ only DC uses shape to some extent

• beams to use the “reactor $\theta_{13}$” $\rightarrow$ further insight in neutrino oscillations
  • $\nu_e$ appearance: first appearance experiment (T2K $\rightarrow$ 5$\sigma$s soon!!)
    • rich physics…
      • O(1%) precision measurement of $\Delta m^2_{32}$, $\theta_{23}$ (T2K, NOvA)
      • further (with some luck) $\rightarrow$ $\delta$ and MH (also with atmospheric)
      • over-constraint 3$\nu$ oscillation scenario $\rightarrow$ NSI, sterile, exotic, etc
highlights on experiments...

• **RENO** (1204.0626)
  - **first multi-detector** running → **rate only analysis** (229 days)
  - remarkable effort/success by small (rather local) collaboration (Korea)

• **Double Chooz** (1112.6353, 1207.6632, 1210.3748, **today**)
  - the (slow) pioneer: **first detector design** (influenced the field)
  - **first result** (Nov. 11) after CHOOZ → $\theta_{13}$ large (rate+shape)
    - small detectors (8t target) & less overburden (still excellent BGs)
  - **FD+Bugey4** (“ND” via MC) → high precision absolute knowledge
  - **best 1 detector results ever** (wrt CHOOZ) → analysis quality
    - ND by spring 2014 but 5 publication (+3 preparation)

• **Daya Bay** (1203.1669, 1210.6327)
  - huge multi-detector complex → FD running since 25th Dec. 2011
    - largest $\theta_{13}$-detection complex → full configuration (Sept. 2012)
    - large detectors (20t) & deepest overburden (low cosmogenic BG)
  - most precise result today → **rate-only analysis** (139 days, 6 detectors)
    - fantastic first results within 55 days of data-taking
reactor-ν detection technology...
• Energy($\nu$) = Energy(e+) - 0.8MeV

• high & well known $\sigma_{IBD}$ [$T_{\text{neutron}} = (881.5\pm1.5)\text{s}$]

• $\nu$ manifests via two triggers:
  1$^{\text{st}}$ event (prompt): e+
  2$^{\text{nd}}$ event (delay): n-Gd capture (8MeV)

• both events are time/space correlated

• time/space coincidence $\rightarrow$ reduce BG!

NOTE: n can also capture on H (à la Reynnes, KamLAND)
a generic $\theta_{13}$-LAND...

**Outer $\mu$-Veto**
- **DC:** Plastic Scintillator
- **DB:** RPCs

**$\nu$-Target**
- Liquid-Scintillator + 0.1% of Gd

**$\gamma$-Catcher**
- Liquid-Scintillator

**Light Buffer**
- Oil (negligible Scintillation)

**Inner $\mu$-Veto**
- **DC:** Liquid-Scintillator
- **DB/RENO:** Water Cherenkov
4x Inner-Detectors = $\nu$-Target + $\gamma$-Catcher + Buffer

(common) $\mu$-veto: water Cherenkov pool
34 results...
latest Daya Bay (@ Nu2012)…

Entries / 0.25 MeV

Far hall
Near halls (weighted)

No oscillation
Best fit

Far / Near (weighted)

Prompt energy [MeV]

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latest RENO (@ Nu2012)...

Entries / 0.25MeV

Prompt energy [MeV]

Far / Near

Prompt energy [MeV]
latest $\text{DC}_{\text{Gd-II}}$ (@ Nu2012)...

- Background-subtracted signal
- No oscillation
- Best fit: $\sin^2(2\theta_{13}) = 0.109$
- at $\Delta m^2_{31} = 0.00232 \text{ eV}^2$ ($\chi^2$/d.o.f. = 42.1/35)
- Systematic error
new results by DC (now)
Remark:
For following figures 1, 2, 3, we will include a similar figure with an enlarged X-axis to show a distribution just outside the cut values. Due to time limitation, this could not be prepared for this meeting.

**Figure 1:** $\bar{\nu}_e$ candidates' delayed Energy distribution after subtracting the accidental backgrounds' spectrum. Yellow is MC and black dots are DATA. MC is normalized to expected number of $\bar{\nu}_e$ with no oscillation.

**Figure 2:** $\bar{\nu}_e$ candidates’ $\Delta R$ distribution after subtracting the accidental backgrounds' spectrum. Yellow is MC and black dots are DATA. MC is normalized to expected number of $\bar{\nu}_e$ with no oscillation. The mean of the distribution is shifted between the data and MC by about 1.3 cm. For the detection efficiency estimation, this is covered in $\Delta R$ systematic uncertainty after applying a MC correction factor.

**Figure 13:** Prompt energy distribution of accidental backgrounds from Off-Time selection (125 windows) shown in black data points. Error bars are weighted by number of windows.

**Figure 14:** Delayed energy distribution of accidental backgrounds from Off-Time selection (125 windows) shown in black data points. Error bars are weighted by number of windows.

**Gd-analysis:** S/BG~40

MC/data (energy) difference: <0.5%
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killing accidentals: cut on \( \Delta d(\text{prompt-delay}) \) ...

excellent precision on vertex-reco \( \rightarrow \text{narrow } \Delta d \) (correlated events)

small \( \Delta d \rightarrow \nu s \) (spatially correlated)

large \( \Delta d \) (spatially uncorrelated)

Double Chooz Preliminary

On-Time

Off-Time

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BG subtracted…

systematics budget…

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>n-H variance</th>
<th>n-Gd variance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total statistical error</td>
<td>1.05%</td>
<td>1.12%</td>
</tr>
<tr>
<td>Accidentals</td>
<td>0.21%</td>
<td>0.01%</td>
</tr>
<tr>
<td>Li-9</td>
<td>1.50%</td>
<td>1.46%</td>
</tr>
<tr>
<td>Fast neutrons</td>
<td>0.61%</td>
<td>0.54%</td>
</tr>
<tr>
<td>Correlated light noise</td>
<td>0.09%</td>
<td>N/A</td>
</tr>
<tr>
<td>Energy scale</td>
<td>0.34%</td>
<td>0.32%</td>
</tr>
<tr>
<td>Detection efficiency</td>
<td>1.57%</td>
<td>1.01%</td>
</tr>
<tr>
<td>Reactor</td>
<td>1.75%</td>
<td>1.76%</td>
</tr>
</tbody>
</table>

p on target: $6.75 \times 10^{29} \pm 0.3\% (T) + 1.58 \times 10^{30} \pm 1.0\% (GC)$

with BGs (huge accidentals)…

DC-II(Gd) and DC-II(H) compatible to (68-84)% (depending on correlation)
• amazing progress end-2011/2012…

• all results are consistent…
  • coherent picture: $\theta_{13}$ is LARGE
  • coherence test not tight (more precision)

• accuracy $\rightarrow$ most important with higher precision

• Daya Bay leads the way (for now)

• redundancy is a must (& on the way)

### Table of Results

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$\sin^2(2\theta_{13})$</th>
<th>Exposure (days)</th>
<th>arXiv</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{DC}_{\text{GdI}}$(rate+shape)</td>
<td>0.086±0.051 (0.041$^{\text{stat}}$±0.030$^{\text{sys}}$)</td>
<td>96.8</td>
<td>1112.6353</td>
</tr>
<tr>
<td>$\text{DB-I}$(rate)</td>
<td>0.092±0.017 (0.016$^{\text{stat}}$±0.005$^{\text{sys}}$)</td>
<td>55</td>
<td>1203.1669</td>
</tr>
<tr>
<td>$\text{RENO-I}$(rate)</td>
<td>0.113±0.023 (0.013$^{\text{stat}}$±0.019$^{\text{sys}}$)</td>
<td>229</td>
<td>1204.0626</td>
</tr>
<tr>
<td>$\text{DC}_{\text{GdII}}$(rate)</td>
<td>0.170±0.053 (0.035$^{\text{stat}}$±0.040$^{\text{sys}}$)</td>
<td>251</td>
<td>1207.6632</td>
</tr>
<tr>
<td>$\text{DC}_{\text{GdII}}$(rate+shape)</td>
<td>0.109±0.039 (0.030$^{\text{stat}}$±0.025$^{\text{sys}}$)</td>
<td>251</td>
<td>1207.6632</td>
</tr>
<tr>
<td>$\text{DB II}$(rate)</td>
<td>0.089±0.011 (0.010$^{\text{stat}}$±0.005$^{\text{sys}}$)</td>
<td>139</td>
<td>1210.6327</td>
</tr>
<tr>
<td>$\text{DC}_{\text{HII}}$(rate+shape)</td>
<td>0.097±0.048 (0.034$^{\text{stat}}$ ± 0.034$^{\text{sys}}$)</td>
<td>240</td>
<td>last monday</td>
</tr>
</tbody>
</table>
DC-II (Gd) (June’12)

\(<L>= 1050\text{m}\)
- short \(L\) → hard to see rise (low constrain in \(\Delta m^2\))
- rate+shape analysis (+ \(\theta_{13}\) below <6MeV)
- DC-II(H) → no structure @ 6MeV

DB (June’12)

\(<L>= 1648\text{m}\)
- L/E shape → more sensitive to \(\Delta m^2\)
- “healthy” shape but rate only (no p-value)

RENO (April’12)

\(<L>= 1383\text{m}\)
- shape: consistent with only \(\theta_{13}\)?
- rate-only analysis → all assumed to be \(\theta_{13}\)

strage behaviour (@ ~6MeV)? → rate+shape analysis a MUST!

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• **statistical uncertainty**
  - generally all experiments enough (DC a little too small)

• **δ(flux): flux uncertainty** (→impacts **mainly rate**)
  - ND critical → eliminates primary reactor flux and spectral shape uncertainties
  - issue: **uncorrelated reactor** systematics

• **δ(detection): detection uncertainty** (→impacts **mainly rate**)
  - ND critical → eliminates many inter-detector detection systematics
  - excellent detector understanding (**energy-reco** and **MC**)
  - issue: **uncorrelated inter-detector** systematics

• **δ(BG): backgrounds uncertainties** (→impact both **rate & shape**)
  - each site a different BG rate and shape (specially correlated BG)
    - ND more signal but also more BG → shapes can also be different
  - issue: **normalisation and shape of each BG** (with reactor ON → hard!)

• **warning:** **high-precision physics** (i.e. systematics @ “per-mil” level)
  - **first word** (fast) → impressive $\theta_{13}$ (large) measurement “overnight”
  - **final legacy** (slow) → cross-checks for best $\theta_{13}$ world knowledge
my goal: explain to you *how systematics are controlled*...

(please note *per-mil* systematics → very careful)

<table>
<thead>
<tr>
<th>FD+Bugey4 (as ND*): dominated $\delta$ (reactor flux) = 1.7%</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DC-II(Gd)</strong> rate+shape [2012 June &amp; Dec. via <strong>DC-II(H)</strong>]</td>
</tr>
<tr>
<td><strong>multi-detector systematics</strong>: dominated by what?</td>
</tr>
<tr>
<td><strong>RENO</strong> rate-only [April 2012]</td>
</tr>
<tr>
<td><strong>Daya Bay</strong> rate-only [June 2012]</td>
</tr>
</tbody>
</table>

Total Uncertainty

*Systematic Uncertainty*
reactor systematics...
reactors vs detectors interplay...

multi-detector: “kill” \( \delta(\text{flux}) \) totally? yes...? (proposals)

\[ \delta(\text{flux}): 0.8\% \, (\text{DB}), \, 0.9\% \, (\text{RENO}), \, ?(0.1 \sim 0.3)\% \, (\text{DC}) \]

("uncorrelated reactor flux uncertainty")

- **RENO/DB**: \( \sim 0.5\% \) (thermal power) & \( \sim 0.6\% \) (fission fractions)
- extremely hard to improve this (impossible?)
- geometry is critical…
  - "Rate(FD)/Rate(ND) per reactor and per ND?"
    - **DB** \( \rightarrow \, \delta(\text{flux}) = 0.8\%/\sqrt{6} \) (fit)
    - **RENO** \( \rightarrow \, \delta(\text{flux}) = 0.9\% \) (impossible to improve?)
    - **DC**: almost isoflux \( \rightarrow \, \delta(\text{flux}) \leq 0.3\% \) (under study)
- \( \delta(\text{flux}) \) dominant uncertainty for DB & RENO [\( \rightarrow \) not DC!]
reactor flux uncertainty...

- DC-II (FD+Bugey4) [1.67%] (one detector)
- DC(FD+ND) [my prospect: 0.1%]
- RENO [0.9%]
- Daya Bay [0.8%] (table)
- Daya Bay [0.8%/√6 = 0.33%] (fit)
BG systematics...
Neutrinos
Fast-Neutrons/μ-Capture
Cosmogenic (Li) [He dashed]
Accidentals

BG model (CHOOZ+KamLAND)...

is this the full story?
(so far, entirely assumed by all experiments)

“cartoon”
(not to scale)
individual measurement . . . (all experiments)
**best known BG...**

- $\delta_{BG/Signal} \rightarrow 0$ (i.e. no rate systematics)
- (if large) distort shape @ oscillation region

**accidental BG...**
decay $\beta$-n [$\tau \sim 100$ ms]

less known BG...
- $\delta$BG/Signal $\rightarrow$ largest (rate systematics)
- poorly known shape (MC $\rightarrow$ KamLAND)

cosmogenic BG... ($^9$Li and $^8$He)
IBD Candidates (with BG)
IV-tagged events
BG Spectrum (fit to tagged)

**most difficult BG...**
- shape varies per detector (acceptance & overburden) → shapes could mimics $\theta_{13}$
- poorly known shape (not easy to MC)

**correlated BG...**
(fast-n & stopping-$\mu$)
Correlated BG measurement

- proton-recoil spectrum @ low energies (very challenging)
  - neutron energy dependence $\rightarrow$ size of buffer and $\gamma$-catcher
  - proton quenching effects $\rightarrow$ difficult to MC (data-driven)
- must measure with data $\rightarrow$ (DC) IV & OV tagging mechanisms
- DB/RENO: extrapolate from high-energy (>14MeV): too naive?
  - DC: up to $\sim25\%$ bias in normalisation (rising shape @ low energies)
  - BG-spectrum resembles $\theta_{13}$ signature (slope-like) $\rightarrow$ bias $\theta_{13}$?
measuring & validating BG model...

• **BG measurement:** rate (much easier) & shape (statistics limited knowledge)
  • CHOOZ BG (reactor OFF: no need for a model) → Li (by KamLAND)
  • **BG improves with time:** ≤ 1 BG per day

• **1(all): measure each BG (sample) with reactor ON**
  • **cons:** sub-sample (different selection) & approximations/extrapolations
    • corrected/scaled (accuracy?) & complete (new BG?)

• **2(DC): fit θ13+BGs (shape analysis) with reactor ON**
  • **pro:** use knowledge a priori (method-1) → propagate to θ13 (correlations)
  • **cons:** interpretation of pull-info (degeneracies) & and lack of knowledge still

• **3(DC): reactor OFF direct measurement** (total rate validation)
  • **pro:** direct measurement (no assumptions) → **complete** (à la CHOOZ)
  • **cons:** stats very limited (DC: 1 week only) → no info on BG shape

• **4(DC): observed vs expected correlation**
  • **pro:** combined use of both reactor ON/OFF → **BG rate estimation**

• **5(DC): 2 Integration Periods** fit (à la “2-1 reactor” analysis)
  • **validation:** θ13 outcome is the same for 2IP~1IP (DC-II) → **BG robust!**
(DC) BG validation and direct measurement... (examples)
reactor OFF data (~1 week)...

**DC-I(Gd) Selection**  
(2x more BG)

**DC-II(Gd) Selection**  
(less BG → \(\mu_{\text{shower-veto}}\))

<table>
<thead>
<tr>
<th>Rate (day(^{-1}))</th>
<th>(\beta-n)</th>
<th>Accidental</th>
<th>(\mu/\text{fast n})</th>
<th>Total Est.</th>
<th>Total Obs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC-I</td>
<td>2.10±0.57</td>
<td>0.35±0.02</td>
<td>0.93±0.26</td>
<td>3.4±0.6</td>
<td>2.7±0.6</td>
</tr>
<tr>
<td>DC-II</td>
<td>1.25±0.54</td>
<td>0.26±0.02</td>
<td>0.44±0.20</td>
<td>2.0±0.6</td>
<td>1.0±0.4</td>
</tr>
</tbody>
</table>

validation with two BG-selections DC-I and DC-II (BG varies by ~2x)

\[ \text{BG(observed)} < \text{BG(expected)} \]

→ fluctuation? \(\sigma_{\text{stats}} < 1.5\sigma\), but same trend seen shape-fit!
rate+shape fit $\rightarrow \theta_{13} +$ BGs measure...

- **fit input:** full data + BGs rate&shape measurements (each)
- **fit output:** $\theta_{13}$ & (constraint) re-measurement of BGs (using shape)

- **BG(fit) <85% BG (rate-only) $\rightarrow$ less subtraction (smaller $\theta_{13}$?)**
  - BG(fit) in excellent agreement with direct reactor-OFF measurements
  - all other experiment rely on rate BG measurement $\rightarrow$ BG bias impact?
  - $\theta_{13}$ is approx. the same with 1 or 2 Integration Periods $\rightarrow$ result is BG robust

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(only validation) observed vs expected rate...

- **disappearance** (i.e. $\theta_{13} \neq 0$) $\rightarrow$ shallower slope
- **total BG measurement** is intercept (when expected rate $\rightarrow 0$)
  - Rate(BG) with and without reactor OFF data point $\rightarrow$ consistent
  - reactor-OFF data to constraint $\theta_{13} \rightarrow$ future (stay tuned)
• cosmo & correlated **BG knowledge is statistics dominated**

• **DB lowest cosmo BGs** (largest overburden and reduce Acc-BG)

• **DC** surprisingly (less overburden) **best BG/S** (excellent $\delta S/BG$) $\rightarrow$ high quality analysis (precise BG estimation & 4x validation/cross-checks)

<table>
<thead>
<tr>
<th>@FD</th>
<th>accidental [day$^{-1}$]</th>
<th>correlated [day$^{-1}$]</th>
<th>cosmo [day$^{-1}$]</th>
<th>“Am-C” [day$^{-1}$]</th>
<th>BG</th>
<th>$\delta$BG</th>
<th>$\delta$BG/BG (%)</th>
<th>BG/S (%)</th>
<th>$\delta$BG/S (%)</th>
<th>max. signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC-II</td>
<td>0.261±0.002</td>
<td>0.67±0.20</td>
<td>1.25±0.54</td>
<td>×</td>
<td>2.2</td>
<td>0.58</td>
<td>26.4</td>
<td>4.8</td>
<td>1.28</td>
<td>45</td>
</tr>
<tr>
<td>DC-II (fit)</td>
<td>0.261±0.002</td>
<td>0.64±0.13</td>
<td>1.00±0.29</td>
<td>×</td>
<td>1.9</td>
<td>0.32</td>
<td>16.7</td>
<td>4.2</td>
<td>0.71</td>
<td>45</td>
</tr>
<tr>
<td>DC-II (OFF)*</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>1.0</td>
<td>0.40</td>
<td>40.0</td>
<td>2.2</td>
<td>0.89</td>
<td>45</td>
</tr>
<tr>
<td>DC (H-n)*</td>
<td>73.45±0.16</td>
<td>2.50±0.47</td>
<td>3.00±1.00</td>
<td>×</td>
<td>79.0</td>
<td>1.12</td>
<td>1.4</td>
<td>79.0</td>
<td>1.12</td>
<td>100</td>
</tr>
<tr>
<td>RENO</td>
<td>0.68±0.03</td>
<td>0.97±0.06</td>
<td>2.59±0.75</td>
<td>×</td>
<td>4.2</td>
<td>0.75</td>
<td>17.8</td>
<td>5.3</td>
<td>0.94</td>
<td>80</td>
</tr>
<tr>
<td>DB (1xFD)</td>
<td>~3.30±0.03</td>
<td>~0.04±0.04</td>
<td>~0.16±0.11</td>
<td>0.2±0.2</td>
<td>3.7</td>
<td>0.23</td>
<td>6.3</td>
<td>5.3</td>
<td>0.33</td>
<td>70</td>
</tr>
<tr>
<td>DB (3xFD)</td>
<td>3x more</td>
<td>3x more</td>
<td>3x more</td>
<td>3x more</td>
<td>11.1</td>
<td>0.40</td>
<td>3.6</td>
<td>5.3</td>
<td>0.19</td>
<td>210</td>
</tr>
<tr>
<td>DB (4xFD)</td>
<td>4x more</td>
<td>4x more</td>
<td>4x more</td>
<td>4x more</td>
<td>14.8</td>
<td>0.47</td>
<td>3.2</td>
<td>5.3</td>
<td>0.17</td>
<td>280</td>
</tr>
</tbody>
</table>
• **the worst BGs…**
  - **Acc-BG: DB**, but will improve some (cut on $\Delta d$)
  - **Cor-BG: RENO**, but will improve little (no OV or scint-IV)
    - claimed measurement is suspicious (6% precision + extrapolation)
  - **Cosmo-BG: RENO**, but will improve with showering-$\mu$ vetoing
  - Surprising success **DC** $\rightarrow$ shallowest overburden ("deeper" via analysis)

• **the best BGs...**
  - **DC** lowest Acc BG ever ($\sim 10x$ better with cut on $\Delta r$)
  - **DB** lowest $\mu$-BGs (expected $\rightarrow$ deeper+vetoing+huge water pool)

• **the best understood BGs** (i.e. lowest $\delta$BG and $\delta$BG/BG)...
  - **DB & DC** $\rightarrow$ the best understood BG (lowest $\delta$BG and $\delta$BG/BG)

• **the best BG systematics...**
  - **DB** best rate BG knowledge ($\delta$BG/S) $\rightarrow$ huge signal and deep overburden
  - **DC** best shape BG knowledge (BG/S) $\rightarrow$ exploited in rate+shape analysis
  - **DC** powerful redundant BG $\rightarrow$ 4x methods (stat limited) to handle BG bias
BG systematics (rate-only analysis)...

- **DC-II rate-only** [1.59%]
- **DC-II rate+shape** [0.88%]
- **DC-X** [my prospect $\geq 0.3\%$]
- **RENO** [1.03%]
- **Daya Bay (3x FD)** [0.19%]
final precision on $\theta_{13}$...
## rate-driven uncertainties...

<table>
<thead>
<tr>
<th>uncertainty (%)</th>
<th>DC-I (rate)</th>
<th>DC-II (rate)</th>
<th>DC-II (r+s)</th>
<th>DC-II (OFF*)</th>
<th>RENO (abs &amp; relative)</th>
<th>DB (abs &amp; relative)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>flux</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>reactor</td>
<td>1.67</td>
<td>1.67</td>
<td><strong>1.67</strong></td>
<td>1.67</td>
<td><strong>2.00</strong></td>
<td><strong>0.90</strong></td>
</tr>
<tr>
<td>detection</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>efficiency</td>
<td>1.14</td>
<td>0.95</td>
<td><strong>0.95</strong></td>
<td>0.95</td>
<td><strong>1.50</strong></td>
<td><strong>0.20</strong></td>
</tr>
<tr>
<td>response</td>
<td>1.7</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>background for rate analysis (δBG/S)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>cosmogenic</td>
<td>2.82</td>
<td>1.49</td>
<td>0.80</td>
<td>X</td>
<td>1.03</td>
<td>1.03</td>
</tr>
<tr>
<td>correlated</td>
<td>0.89</td>
<td>0.55</td>
<td>0.36</td>
<td>X</td>
<td><strong>0.08</strong></td>
<td><strong>0.08</strong></td>
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<tr>
<td>accidental</td>
<td>0.07</td>
<td>0.01</td>
<td>0.01</td>
<td>X</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>“Am-C”</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>BG (∑)</td>
<td>2.96</td>
<td>1.59</td>
<td><strong>0.88</strong></td>
<td>1.10</td>
<td>1.03</td>
<td>1.03</td>
</tr>
<tr>
<td><strong>syst total</strong></td>
<td>3.58</td>
<td>2.49</td>
<td><strong>2.11</strong></td>
<td>2.22</td>
<td><strong>2.70</strong></td>
<td><strong>1.38</strong></td>
</tr>
<tr>
<td><strong>stat total</strong></td>
<td>1.56</td>
<td>1.10</td>
<td>1.10</td>
<td>1.10</td>
<td>0.76</td>
<td>0.76</td>
</tr>
</tbody>
</table>

*debatable numbers*

DB best multi-detector & DC best single detector

Anatael Cabrera (CNRS-IN2P3 & APC)

12年12月6日木曜日
reactor $\theta_{13}$ rate (ultimate?) knowledge...

**DC-II** rate+shape [June 2012]

**RENO** rate-only [April 2012]

**Daya Bay** rate-only [June 2012]

**Total Uncertainty (with stats)**

- **Systematic Uncertainty**
  - $\delta$(flux): 0.9% (→ 0.3%)
  - $\delta$(detection): 0.2%
  - $\delta$(BG): 1.0% (→ 0.5%)
  - $\delta$(syst.): 1.38% (1.05%)

- $\delta$(flux): 0.1% (→ 0.3%)
- $\delta$(detection): 0.2%
- $\delta$(BG): 0.3% (→ 0.5%)
- $\delta$(syst.): 0.36% (0.6%)

- $\delta$(flux): 0.6%
- $\delta$(detection): 0.2%
- $\delta$(BG): 1.0% (→ 0.5%)
- $\delta$(syst.): 1.1%

- $\delta$: 1.1%

- $\delta$: 1.4%

- $\delta$: 0.43% (0.40%)
sin^2(2\theta_{13}) systematics breakdown

- DC-II(r+s)
- RENO
- DB(0.8%)
- DB(0.8%/\sqrt{6})
- DC-X

**Systematic Uncertainty (%)**

- \(\delta(\text{flux})\)
- \(\delta(\text{detection})\)
- \(\delta(\Sigma\text{BG})\)

**only 2 experiments <10% precision → test accuracy**

(\text{validate systematics})
what to remember?
what to remember?

- **θ₁₃ measured** by reactor experiments (➞ **dominate for long!**)
  - **sure!** → precise rate-only (DB) & clean rate+shape (DC)
  - **high precision** (uncertainty) & **high accuracy** (what’s the true value?)
    - to measure/constrain 3ν oscillation model

- **high precision on θ₁₃** → final ~5% **uncertainty** expected
  - multi-detector → cancellation of all correlated uncertainties

- **high accuracy on θ₁₃** → unbiassed measurements?
  - **rate+shape analysis** (E/L & BGs) to measure θ₁₃ → a **must**!
  - **cross-check** among all experiments → on-going effort (transparent)
    - different sites/BGs/systematics/baselines, etc → the **ONLY** way!

- regardless **θ₁₃ is LARGE**
  - …if you were waiting for this, **please go ahead! :-)**
  - combined θ₁₃ (a few years time) → **best θ₁₃ for very long!**