Measurement of the detection systematic uncertainty in the Double Chooz experiment

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on behalf of the Double Chooz Collaboration

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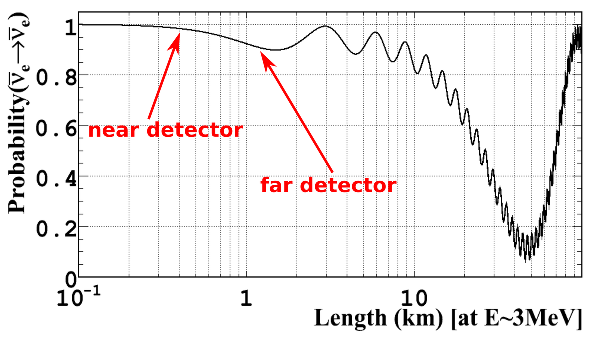
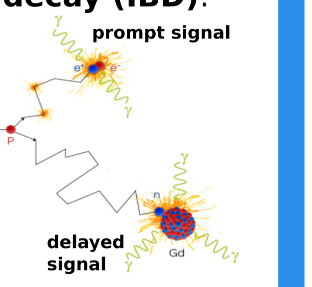
The Double Chooz experiment

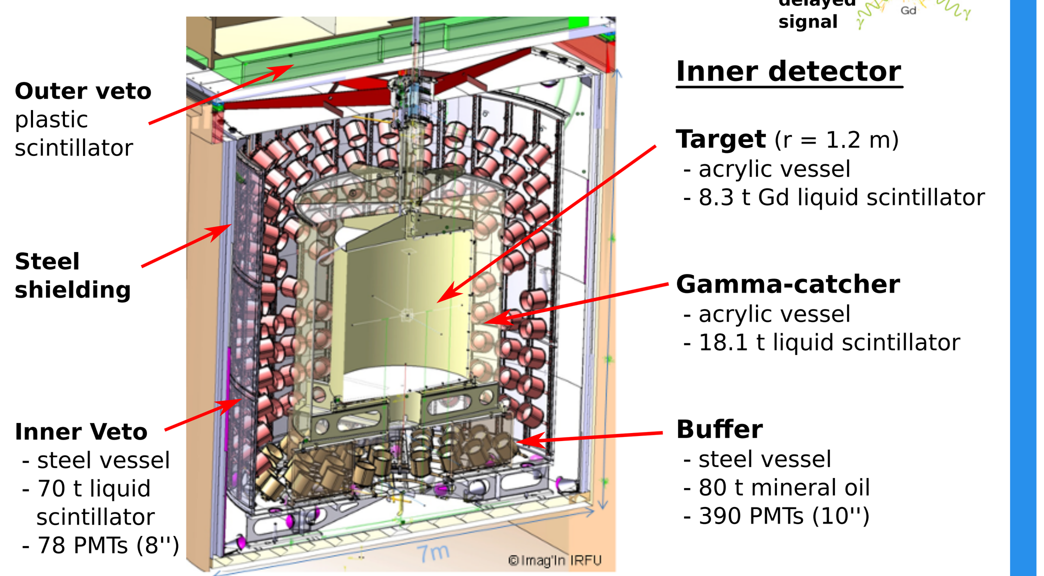


- Reactor $\bar{\nu}_e$ **disappearance** is directly related to the mixing angle **θ_{13}**.
- Relative measurement with **two identical detectors**.
- **Clean and precise** measurement.
- Antineutrinos detected through **inverse beta decay (IBD)**:

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

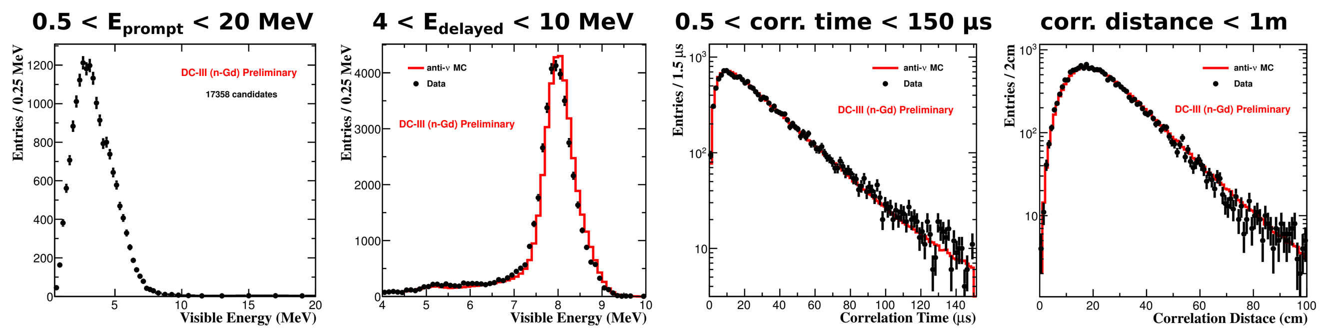
- Coincidence signal in Gd-loaded liquid scintillator: n capture time ~ 30 µs.
- **Prompt** signal: e⁺ energy deposit (1 - 8 MeV).
- **Delayed** signal: n capture on Gd (~ 8 MeV).





Detection systematic uncertainty in Double Chooz

- **New selection** is optimized: high efficiency of IBD detection and low background.



- Vetoes and background rejection cuts are added to this minimal selection.
- The current θ_{13} analysis derives the **predicted antineutrino flux from simulation**.
- A **Monte Carlo normalization factor** ensures the detection dependent accuracy of the simulation wrt. data.
- This factor is defined as the ratio of data to MC detection efficiency: $c = \frac{\varepsilon_{\text{Data}}}{\varepsilon_{\text{MC}}}$
- The **detection systematic uncertainty** represents the uncertainty in the anti-neutrino normalization due to detection related effects.

Contribution	MC normalization	Uncertainty
Delayed event selection (presented in this poster)	**0.9750**	**0.54%**
Prompt event selection (i.e. trigger, electronics, DAQ)	1.0000	negligible
Number of protons (IBD target)	1.0000	0.30%
Active background rejection cuts & livetime	0.9388	0.11%
Total	**0.9153**	**0.63%**

- The **delayed detection efficiency** consists of three contributions:
  - a selection cut dependent efficiency ε_{cut}.
  - an inherent efficiency f_{Gd} of neutrons to be captured on Gd.
  - a neutron mobility related detection uncertainty.
- The **delayed MC normalization factor** is defined as the product of three MC normalization factors arising from the three contributions above:

$$c_{\text{delayed}} = c_{\text{cut}} \cdot c_{\text{Gd}} \cdot c_{\text{spill}}$$

Neutron sources used in this analysis

Inverse beta decay (IBD) neutrons

- **Antineutrinos** are regarded as a **neutron source** through IBD.
- **Homogeneously** distributed in the detector.
- Same **neutron physics** as the oscillation signal.
- Selection similar to the one for oscillation analysis.
- Only non-neutron delayed events are background:
  - Stopping muon greatly reduced: reconstruction likelihood cut (prompt and delayed) + IV-veto (prompt) + OV-veto (prompt).
  - Accidental background is subtracted using an off-time selection.

^{252}Cf delayed fission neutrons

- Point-like **fission source** with ~ 13 neutrons per second.
- Deployed at positions along the **Target symmetry axis**.
- **Calibration campaign** in the middle of the $\bar{\nu}_e$ data taking period.
- **High statistics**.
- **Fission event signature**:
  - Prompt: fission gammas with ⟨E$_\gamma$⟩ ~ 7 MeV.
  - Delayed: neutron capture (τ ~ 30 µs) with ⟨E$_{kin}$⟩ ~ 2 MeV and multiplicity m ~ 4.
- Background-reduced event selection:
  - Prompt energy cut + accidental background subtraction by off-time selection.
  - Correlated background reduction by requiring a delayed multiplicity of m ≥ 2.

Muon spallation neutrons

- Neutrons originated from **spallation of nuclei by cosmic muons**:
  - Selection: 50 < Δt < 150 µs after a muon with E$_\mu$ > 50 MeV.
  - Accidental background subtraction by off-time selection.
  - Delayed event multiplicity of m ≥ 2.
  - Fiducial volume cut.

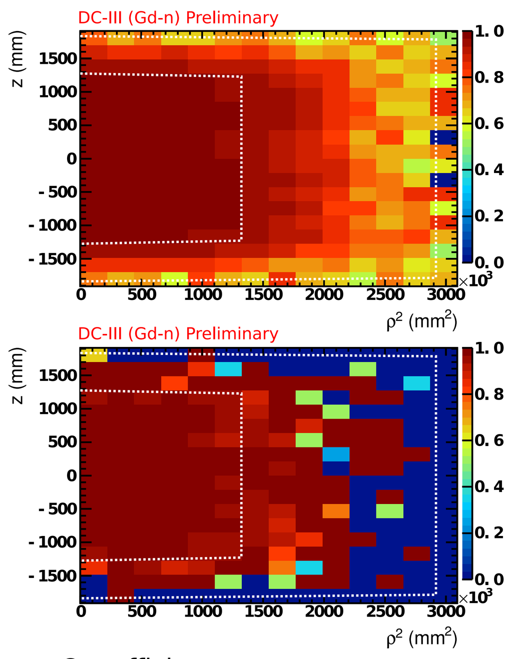
Volume-wide detection systematic uncertainty

- **Volume-wide** MC normalization factor: ratio of **selection cut dependent** efficiencies for data and MC.
- The efficiencies are computed for the **whole Target** volume to include the reduction when approaching the borders.

efficiency = $\frac{\text{events passing the delayed energy, correlation time and correlation distance cuts for the oscillation analysis}}{\text{events passing looser cuts on the same variables}}$

- Cuts are evaluated simultaneously in an **inclusive** way to account for any possible correlation between them.

IBD neutron volume-wide uncertainty estimation



▲ Cut efficiency maps. **Top**: MC. **Bottom**: data (accidental background-subtracted).

- **Direct measurement** of volume-wide efficiency.
- The efficiency definition used for IBD neutrons is:

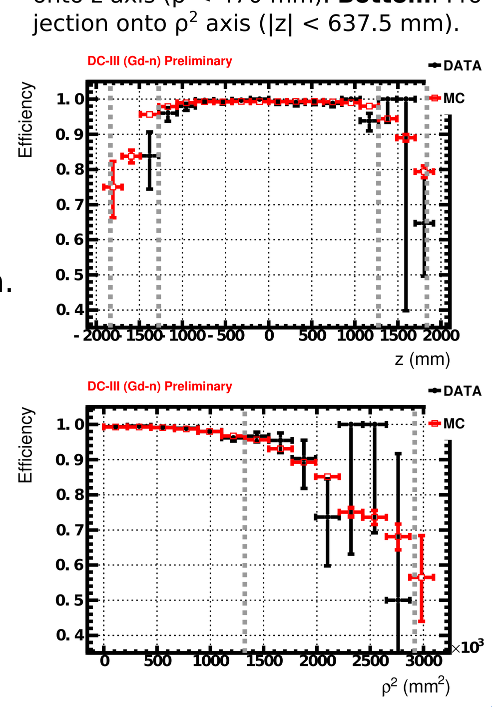
$$\varepsilon_{\text{cut}} = \frac{N(0.5 < \Delta t < 150\,\mu\text{s} \cap 4 < E_d < 10\,\text{MeV} \cap \Delta R < 1\,\text{m})}{N(0.25 < \Delta t < 200\,\mu\text{s} \cap 3.5 < E_d < 10\,\text{MeV} \cap \Delta R < 1.7\,\text{m})}$$

- The integration is done in the Target volume:

$$c_{\text{cut}} = 0.9996 \pm 0.0021\,(\text{stat} + \text{syst})$$

- Limited statistics are compensated by the efficient selection.
- **Systematics** were estimated from the difference to the value of c_{cut} using only the **bottom half of the Target** (to suppress the stopping muon background).
- The result passed successfully several checks:
  - Variation in the selection/efficiency definition.
  - The fiducial volume for integration was varied.
  - Use of alternative MCs.
- An **exclusive** definition of the efficiency (one cut evaluated at each time) yielded the same result.

▼ Cut efficiency map projections. Data (black) has the accidental background subtracted. **Top**: Projection onto z axis (ρ < 470 mm). **Bottom**: Projection onto ρ² axis (|z| < 637.5 mm).



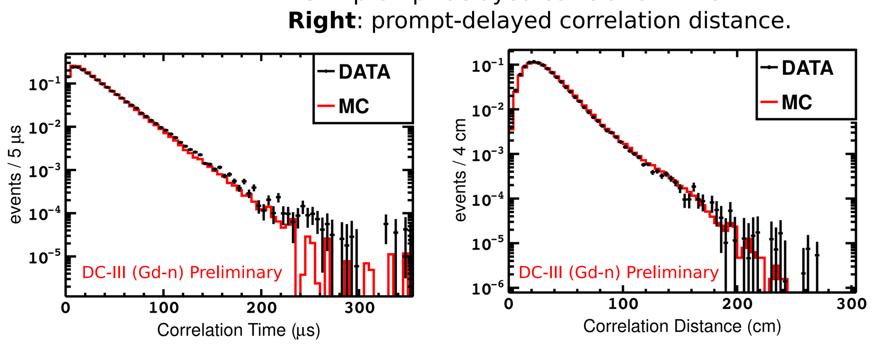
^{252}Cf fission neutron volume-wide uncertainty estimation

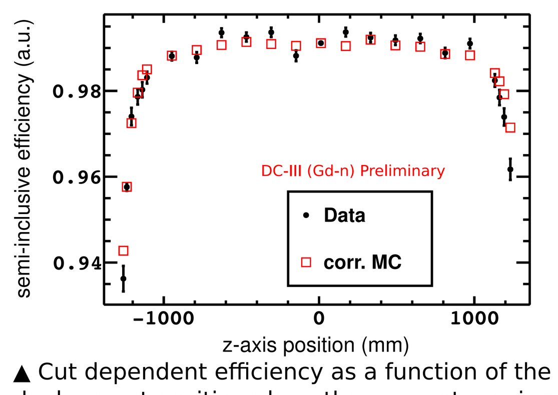
- The ^{252}Cf selection is **very clean wrt. background**, allowing wide cuts in the denominator:

$$\varepsilon_{\text{cut}} = \frac{N(0.5 < \Delta t < 150\,\mu\text{s} \cap 4 < E_d < 10\,\text{MeV} \cap \Delta R < 1\,\text{m})}{N(0.25 < \Delta t < 1000\,\mu\text{s} \cap 3.5 < E_d < 10\,\text{MeV})}$$

- A volume-wide efficiency estimate is computed by **extrapolation** of the efficiencies along the symmetry **z-axis to the full volume**.
- Antineutrino MC was used to validate the accuracy and systematic uncertainty of this method.

▼ ^{252}Cf data (black) and MC (red) spectra. **Left**: prompt-delayed correlation time. **Right**: prompt-delayed correlation distance.



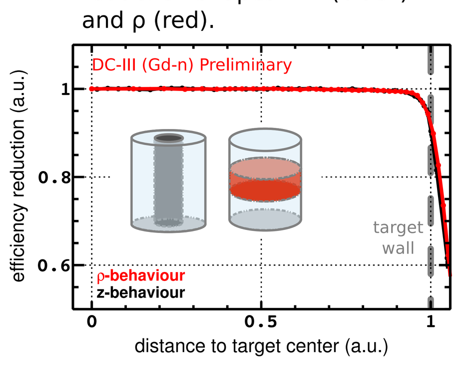


▲ Cut dependent efficiency as a function of the deployment position along the symmetry axis z. Black dots are data, red boxes corrected MC.

- The **systematic uncertainty** main contributions:
  1) Stability wrt. variations in the computation of ε_{cut}:
     - Variation in the selection/efficiency definition.
     - Using only top or bottom volume data.
     - Variations in the position of the deployment locations.
  2) A **method-dependent uncertainty** → **dominant contribution**.
- Consistent results for different calibration campaigns
- ^{252}Cf result:

$$c_{\text{cut}} = 1.0003 \pm 0.0032\,(\text{stat} + \text{syst})$$

▼ Antineutrino MC efficiency reduction shapes in z (black) and ρ (red).



Gadolinium-fraction systematic uncertainty

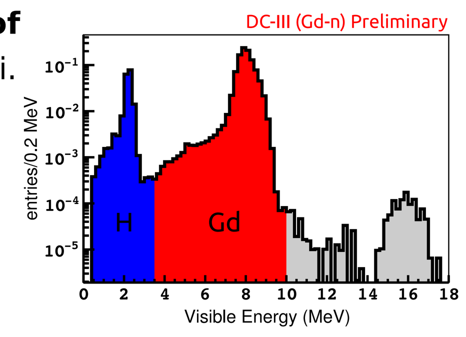
- The Gadolinium-fraction f_{Gd} represents the **proportion of radiative neutron captures on Gadolinium** (Gd) nuclei.
- It is estimated via the ratio of events in the Gd and H peaks in the delayed energy spectrum:

$$f_{\text{Gd}} = \frac{N(\text{Gd})}{N(\text{H+Gd})} = \frac{N(3.5 < E_{\text{delayed}} < 10\,\text{MeV})}{N(E_{\text{th}} < E_{\text{delayed}} < 10\,\text{MeV})}$$

with energy threshold $E_{\text{th}} = 0.5\,\text{MeV}$.

- The Gd-fraction MC normalization is defined as the ratio:

$$c_{\text{Gd}} = f_{\text{Gd}}^{\text{Data}} / f_{\text{Gd}}^{\text{MC}}$$



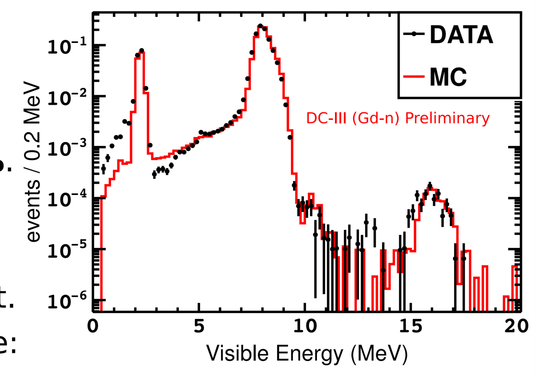
▲ Integration of the delayed energy spectrum to estimate the Gd-fraction.

^{252}Cf fission-n Gd-fraction normalization

- The central value of c_{Gd} is measured at the target center with **large statistics** (~ 5 hours of data taking).
- The **systematic uncertainty** is estimated by varying:
  - **Sample selection: negligible** impact (< 0.1%).
    → validation of the background reduction.
  - c_{Gd} **estimation**: variations in the integrated energy region induce discrepancies of **~ 0.3 - 0.4%**.
    → largest systematic deviation when varying the **lower energy threshold** to: $E_{\text{th}} = 1.5\,\text{MeV}$
- **Stable**: in agreement with an earlier calibration result.
- The Gd-fraction MC normalization was computed to be:

$$c_{\text{Gd}} = 0.9750 \pm 0.0011(\text{stat}) \pm 0.0041(\text{syst})$$

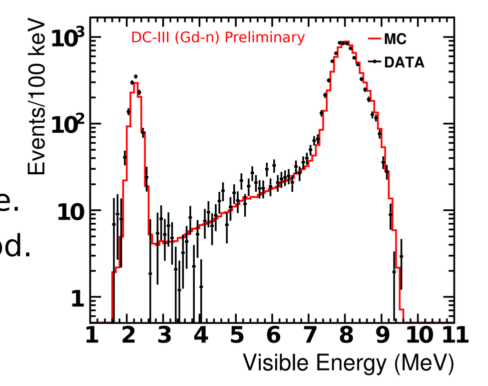
▼ ^{252}Cf energy spectrum: visible energy of the delayed events normalized in the region from 7 - 10 MeV. Black circles are data, red line is MC.



IBD neutron Gd-fraction crosscheck

- **Result**: $c_{\text{Gd}}^{\bar{\nu}} = 0.9794 \pm 0.0040(\text{stat}) \pm 0.0044(\text{syst})$
- In **agreement with the ^{252}Cf result**.
- **Systematics** estimated by varying integration range and the fiducial volume.
- Minimized stopping muon contribution in H-peak:
  - Used only data in which the Outer Veto was operative.
  - Additional cut on the delayed reconstruction likelihood.
- Fiducial volume cut in prompt and delayed vertices to ensure only Target events are counted.

▼ IBD delayed energy spectra in the fiducial volume, normalized in the region from 7 to 10 MeV. MC (red), accidental background-subtracted data (black).

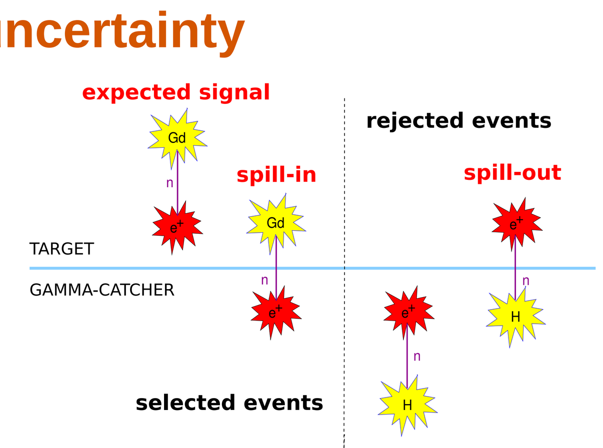


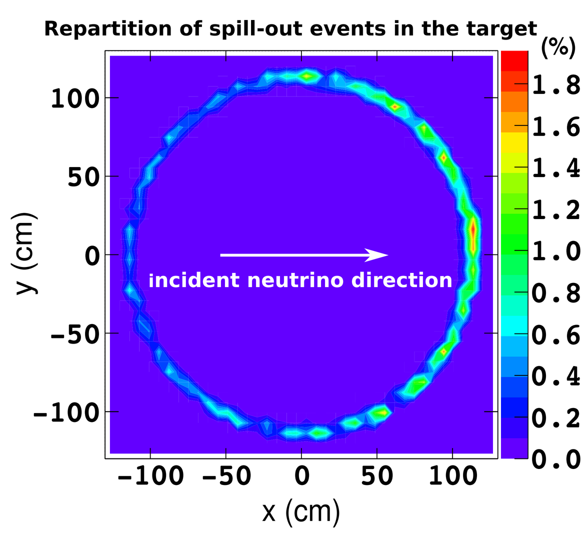
Spallation neutron Gd-fraction crosscheck

- **Higher neutron energies** than IBD or ^{252}Cf neutrons → important cross-check.
- Compute $c_{\text{Gd}}^{\text{spall}}$ using the spallation neutron and the antineutrino MC Gd-fractions.
- The results of $c_{\text{Gd}}^{\text{Cf-252}}$ and $c_{\text{Gd}}^{\text{spall}}$ are in **agreement within < 0.4%**.

Neutron migration systematic uncertainty

- The Target acts as a fiducial volume in which the IBD events are selected.
- **Neutron migration** effects between detector volumes:
  - **Spill-out**: an IBD neutron emitted in the Target escapes the volume and is captured outside ⇒ **loss** of expected detected events.
  - **Spill-in**: an IBD neutron emitted outside the Target enters this volume and is captured on Gd ⇒ **increase** of detected events.





- These two effects counterbalance, yet do not cancel out.
- The fraction of spill cannot be measured in the data. It is estimated in MC.
- The spill is sensitive to the **low energy neutron physics** modeling, especially to the **molecular bonds** between H and other atoms.
- The **Geant4 simulation developed in DC** includes an analytical modeling of the impact of molecular bonds on low energy neutrons.
- The **systematic uncertainty** of the Geant4 spill fraction is given by the comparison with another simulation code (**Tripoli4**, known for the reliability of its low energy neutron physics modeling), resulting in:

$$c_{\text{spill}} = 1.0000 \pm 0.0027$$

Summary

Delayed detection contribution	MC normalization	Uncertainty (stat. + syst.)
Gd-fraction	0.9750	0.43%
Selection cut dependent	1.0000	0.19%
Neutron migration	1.0000	0.27%
Delayed detection total	**0.9750**	**0.54%**

- The **volume-wide selection cut dependent normalization factor** and its uncertainty were computed using the **combined IBD and ^{252}Cf results**:

$$c_{\text{cut}} = 1.0000 \pm 0.0019(\text{stat} + \text{syst})$$

New selection leads to a good data to MC agreement.
- The **Gd-fraction normalization is the dominant contribution** to the total MC normalization factor and to its uncertainty.
- **Cross-check** measurements using **IBD and spallation neutrons are in agreement with the ^{252}Cf Gd-fraction** result.
- The **neutron migration** systematic uncertainty has been evaluated by **MC to MC comparison**.
- Since the Gd-fraction and the neutron migration uncertainties are created by a MC simulation mismatch, these **uncertainties will be strongly reduced in the two detector measurement of θ_{13}**.

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