Determination of the detection systematics in the Double Chooz experiment

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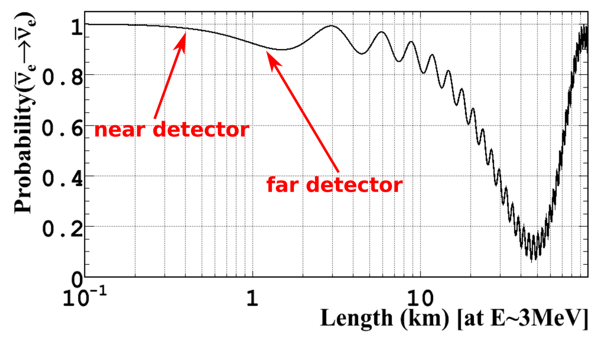
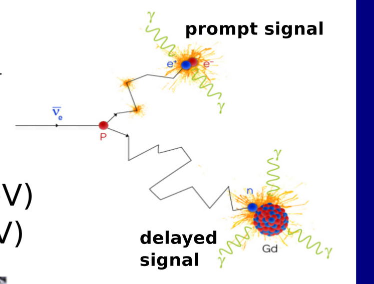
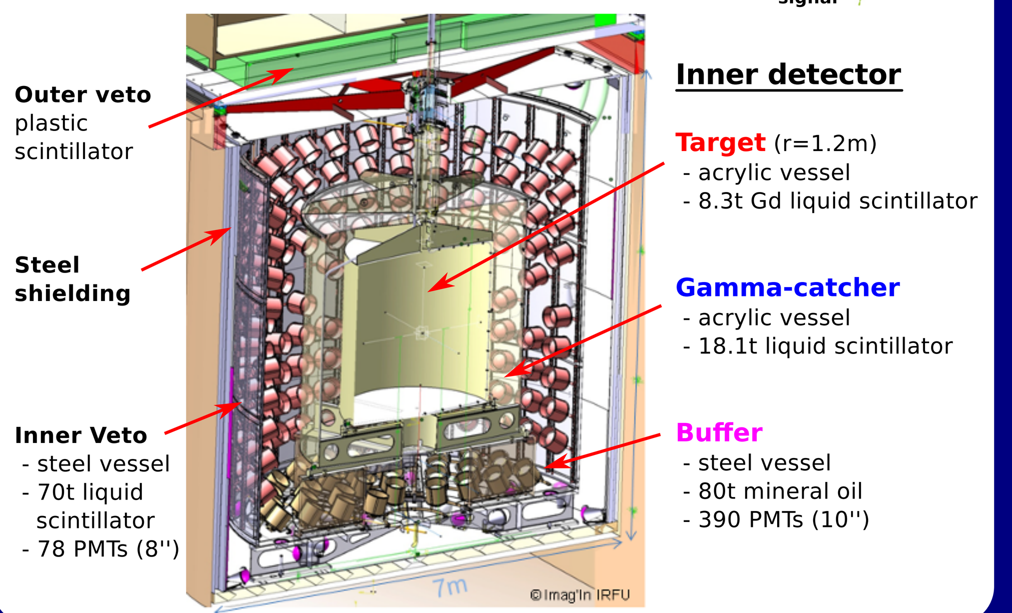
THE DOUBLE CHOOZ EXPERIMENT



- Reactor $\bar{\nu}_e$ disappearance is directly related to θ_{13}
- Relative measurement with two identical detectors
- Clean and precise measurement

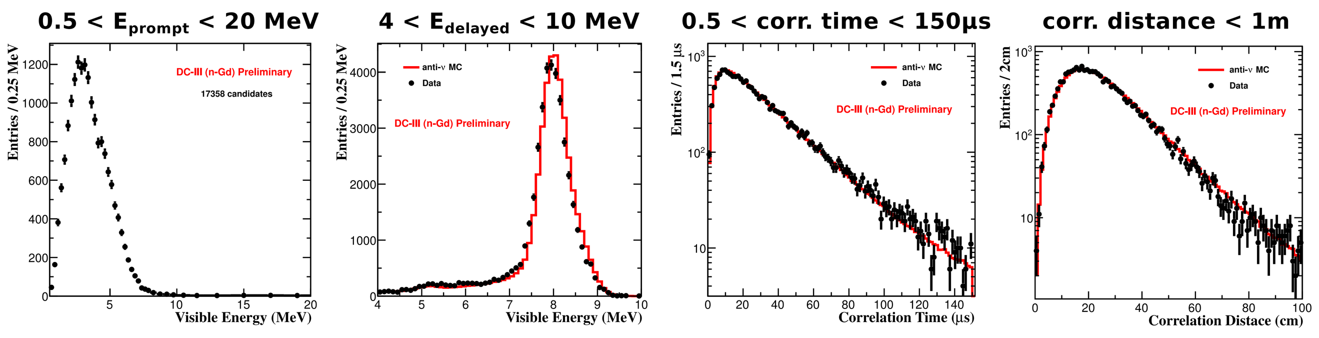


- Neutrino interactions detected through inverse beta decays: $\bar{\nu}_e + H^+ \rightarrow n + e^+$
- Coincidence signal in Gd-loaded liquid scintillator: n capture time ~30µs
- Prompt signal: e^+ energy deposit (1-8MeV)
- Delayed signal: n capture on Gd (~8MeV)



DETECTION SYSTEMATICS IN DOUBLE CHOOZ

- The inverse beta decay (IBD) events constitute the sought signal
- Selection cuts are optimized so that the efficiency of IBD detection is high while the background contamination remains at a low level



- Vetoes and background rejection cuts are added to this minimal selection
- As a consequence, the contributions to the **0.63%** detection systematics consist of

Contribution	MC normalization	Uncertainty
Delayed event selection **(presented in this poster)**	0.9750	0.54 %
Prompt event selection (i.e. trigger, electronics, DAQ)	1.000	negligible
Number of protons (IBD target)	1.000	0.30 %
Active background rejection cuts & livetime	0.9388	0.12 %

Monte Carlo normalization factors

- The current θ_{13} analysis derives the predicted $\bar{\nu}_e$ flux from simulation
- A Monte Carlo (MC) normalization factor in combination with an uncertainty ensures the detection dependent accuracy of the MC wrt. data
- This normalization is defined as the ratio of data to MC detection efficiency: $c = \frac{\varepsilon_{\rm Data}}{\varepsilon_{\rm MC}}$
- The delayed detection efficiency consists of three contributions:
  - a selection cut dependent efficiency $\varepsilon_{\rm cut}$
  - an inherent efficiency $f_{\rm Gd}$ of inverse beta decay neutrons to be captured on Gd
  - a neutron mobility related detection uncertainty
- The combined total MC normalization factor is then defined as product of the selection dependent and the inherent Gd capture fraction MC normalization:

$$c_{\rm total} = c_{\rm cut} \cdot c_{\rm Gd}$$

NEUTRON SOURCES

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 (inherits all improvements)
- Only non-neutron delayed events are background to this analysis:
  - 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: 5 hours of data at the detector center
- Fission event signature:
  - Prompt fission gammas with $\langle E_\gamma \rangle$~7 MeV
  - Delayed neutron capture (τ~30µs) with $\langle E_n^{\rm kin} \rangle$~2 MeV and multiplicity m~4
- Background-reduced event selection:
  - Prompt energy cut $E_{\rm prompt}$ > 4MeV
  - Accidental background measurement and subtraction by off-time selection
  - Correlated background reduction by requiring a delayed multiplicity of m≥2

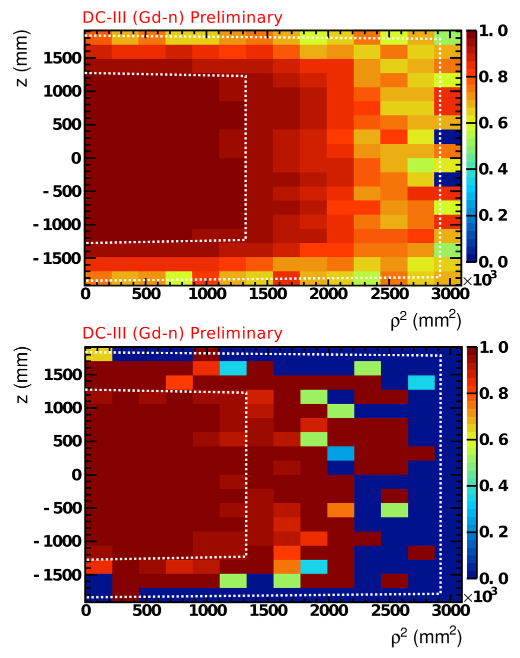
Muon spallation neutrons

- Event selection in the time range 50 < Δt < 150 µs after a muon with E_μ>50 MeV
- Background reduction:
  - Muon event isolation (±5 ms to next muon)
  - Accidental background subtraction by off-time selection
  - Delayed event multiplicity of m≥2
  - Fiducial volume cut (-0.5m < z < 0.2m, ρ < 0.5m)

VOLUME-WIDE DETECTION SYSTEMATIC UNCERTAINTY

- The volume-wide MC normalization factor ensures that the cut dependent detection efficiency in the MC reproduces the one in data
- The normalization factor is determined as the ratio of efficiencies (relative normalizations) computed for data and MC
- The efficiencies are computed for the whole target volume to include the reduction in their values when approaching the borders
- Each efficiency consists of a:
  - Numerator: events passing the delayed energy, correlation time and correlation distance cuts devised for the oscillation analysis
  - Denominator: events passing looser cuts on the same variables
- All the 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:

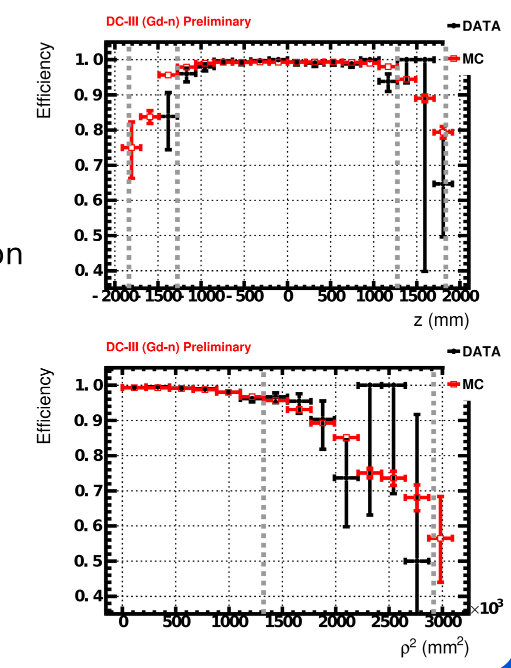
$$\varepsilon_{\rm cut} = \frac{N(0.5 < \Delta t < 150\,\mu{\rm s} \cap 4 < E_{\rm d} < 10\,{\rm MeV} \cap \Delta R < 1\,{\rm m})}{N(0.25 < \Delta t < 200\,\mu{\rm s} \cap 3.5 < E_{\rm d} < 10\,{\rm MeV} \cap \Delta R < 1.7\,{\rm m})}$$

- The integration is done in the target volume (innermost dashed line in the efficiency maps):

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

- Limited statistics are compensated by the efficient selection
- Systematics were estimated from the difference to the central value $c_{\rm cut}$ 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 an statistically independent MC
  - Use of a MC with the Gd-fraction altered by ± 3%
- 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).



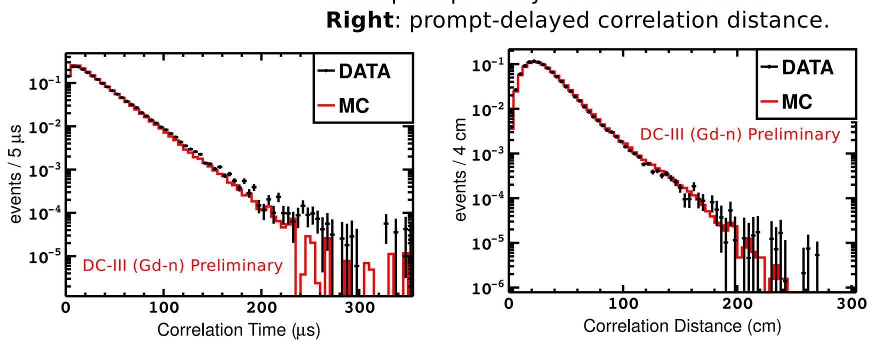
^{252}Cf fission neutron volume-wide uncertainty estimation

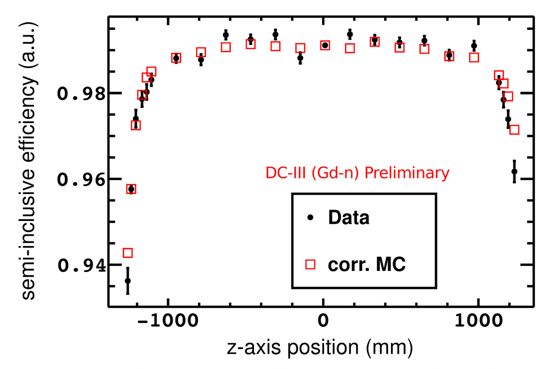
- The ^{252}Cf selection is very clean wrt background, the cut dependent efficiency is therefore estimated with wide cuts in the denominator:

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

- A volume-wide efficiency estimate is computed by extrapolation of the efficiencies along the symmetry axis z 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.



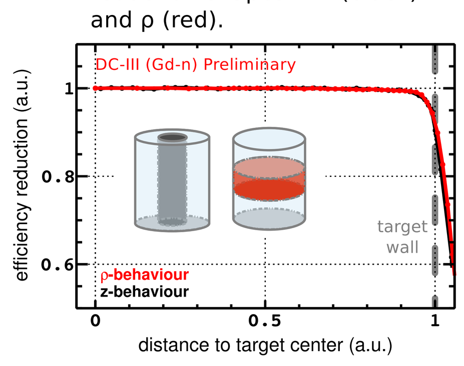


▲ Cut dependent efficiency as a function of the deployment position along the symmetry axis z. Black dots are data, red boxes corrected MC.

- The systematic uncertainty main contributions:
  1) Stability wrt. variations in the computation of $\varepsilon_{\rm cut}$:
     - Variation of the cuts of the denominator and numerator selections
     - Variation of the ^{252}Cf prompt energy and delayed multiplicity cut
     - Using only top or bottom volume data
     - Tested for variations in the result for position shifts of the deployment locations
  2) A method dependent uncertainty ⟶ dominant contribution
- Consistent results for different calibration campaigns
- ^{252}Cf result of the cut dependent volume-wide MC normalization:

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

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



GADOLINIUM-FRACTION SYSTEMATIC UNCERTAINTY

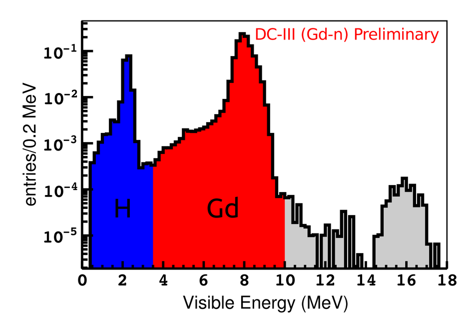
- The Gadolinium-fraction $f_{\rm Gd}$ represents the proportion of radiative neutron captures on Gadolinium (Gd) nuclei
- It is estimated via the ratio of events counted in the Gd-peak and H-peak energy region of the delayed energy spectrum:

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

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

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

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

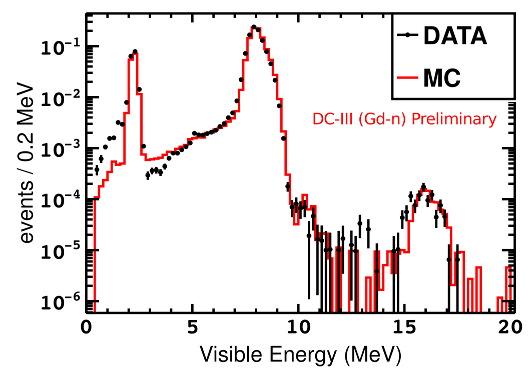


▲ Integration of the delayed energy spectrum to estimate the Gd-fraction.

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

- The central value of $c_{\rm Gd}$ is measured at the target center with large statistics (~5 hours of data taking)
- The systematic uncertainty is estimated by variation of both the sample selection and the $c_{\rm Gd}$ estimation method:
  - Negligible variation (<0.1%) when prompt energy cut or prompt-delayed correlation time is varied ⟶ validation of the background reduction
  - Variation of the estimation method (integrated energy region) induces discrepancies of ~0.3-0.4%
- The largest systematic deviation was found when varying the lower energy threshold to $E_{\rm th} = 1.5\,{\rm MeV}$
- Stability: in agreement with an earlier calibration result
- The Gd-fraction MC normalization was computed to be

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



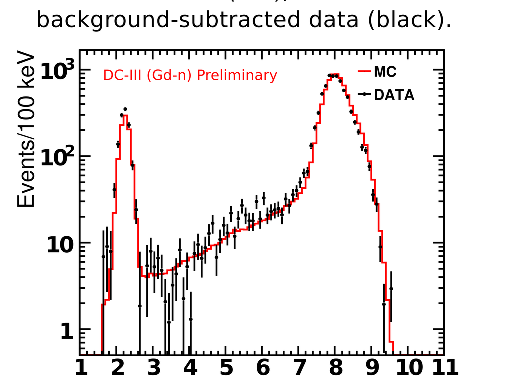
▲ ^{252}Cf energy spectrum: visible energy of the delayed events normalized in the region from 7-10 MeV. The black bullets are data points, the red line MC. The peak at 2.2 MeV represents the radiative neutron capture events on H nuclei, the peak at 8 MeV on Gd. Double captures in one DAQ window are visible at 10.2 MeV and 16 MeV.

IBD neutron Gd-fraction crosscheck

- Minimize stopping muon contribution below H-peak:
  - Using 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
- Systematics estimated by varying integration range and the fiducial volume
- Result:

$$c_{\rm Gd}^{\bar{\nu}} = 0.9794 \pm 0.0040({\rm stat}) \pm 0.0044({\rm syst})$$

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

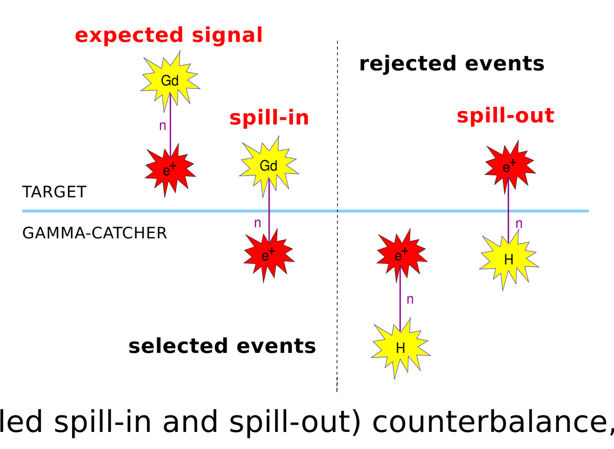


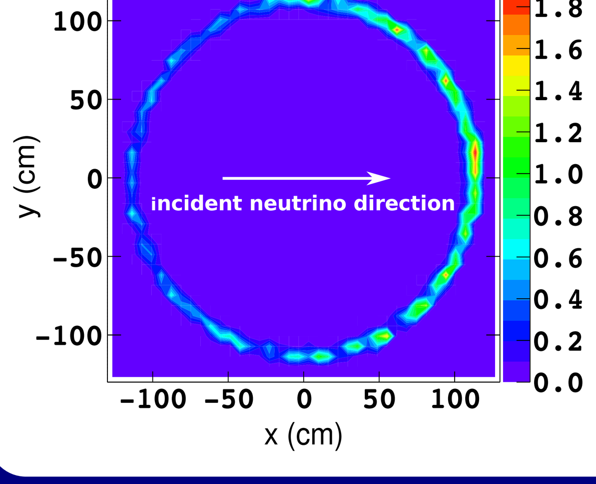
Spallation neutron Gd-fraction crosscheck

- Higher neutron kinetic energies than for IBD or 252Cf neutrons ⟶ important cross-check
- Compute a $c_{\rm Gd}^{\rm spall}$ by comparison of the spallation neutron Gd-fraction to the antineutrino MC Gd-fraction
- The results of $c_{\rm Gd}^{\rm Cf\text{-}252}$ and $c_{\rm Gd}^{\rm spall}$ are in agreement within **<0.4%**

NEUTRON MIGRATION SYSTEMATIC UNCERTAINTY

- The target constitutes the fiducial analysis volume in which the occurring IBD events are selected
- Nevertheless, due to neutron migrations between the different detector volumes, additional IBDs occurring in other volumes are detected whereas some target events are lost:
  - an IBD neutron emitted in the target may escape the volume and be captured outside, leading to a loss of expected detected events
  - an IBD neutron emitted outside the target may enter this volume and be captured on Gd, leading thus to an increase of detected events





- These two effects (respectively called spill-in and spill-out) counterbalance, yet do not cancel each other out
- The fraction of spill cannot be measured in the data and is thus estimated in the Monte Carlo simulation
- The spill estimation is known to be sensitive to the low energy neutron physics modeling, especially to the bonds between hydrogen and other atoms
- The Geant4 simulation developed in the DC collaboration includes an analytical modeling of the impact of molecular bonds on low energy neutrons
- The systematic uncertainty associated to the Geant4 evaluated spill fraction is given by the comparison with an other simulation code known for the reliability of its low energy neutron physics modeling (Tripoli4), resulting in

$$\text{net spill fraction} = (2.08 \pm 0.27)\,\%$$

SUMMARY

- The summary of all delayed detection MC normalization factors and their uncertainties are given by the table on the right

Delayed detection uncertainty contribution	MC normalization	uncertainty (stat+syst)
Gd-fraction	0.9750	0.43%
Cut dependent	1.0000	0.20%
Spill-in/out	1.0000	0.27%
total	0.9750	0.54%

- The cut dependent and volume-wide normalization factor was measured by two independent analyses using IBD and ^{252}Cf fission neutrons to be in agreement within 1 ⟶ revised selection criteria for DC-III analysis led to a good data to MC agreement
- The cut dependent normalization uncertainty was computed using the combined IBD and ^{252}Cf result
- The Gd-fraction MC normalizaton was found to be the dominant contribution to the total MC normalization central value and uncertainty of the delayed detection
- Cross-check measurements using IBD and spallation neutrons could confirm the Gd-fraction normalization result
- The neutron migration systematic uncertainty has been evaluated by MC to MC comparison
- Since the Gd-fraction as well as the neutron migration MC normalization and uncertainty are created by a MC simulation mismatch, these contributions will be strongly reduced in a two detector measurement of θ_{13}

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