The Visible Energy of the Double Chooz Experiment

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on behalf of the Double Chooz Collaboration
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1 Introduction

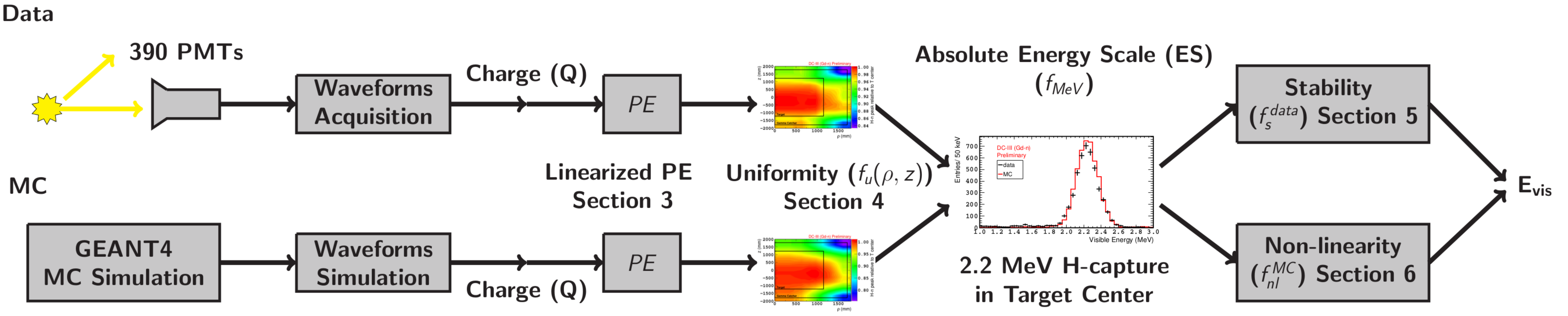
- Double Chooz (DC) is a neutrino experiment aiming to measure θ_{13} with high precision using both the deficit and the spectral distortion of the positron spectrum expected [1].
- Energy uncertainties have a direct impact on the sensitivity to θ_{13}. However, the largest impact on the sensitivity in the final phase of the experiment after two-detector systematic cancellation is expected to arise from the cosmogenic backgrounds.
- When measuring θ_{13}, the combined rate and full background shape information can be used to further constrain background systematics leading to a significant improvement of the overall precision of the result.
- DC analysis requires an excellent control of the e^+ energy scale systematics, otherwise deteriorating both rate and shape information on θ_{13}.

2 Visible Energy Definition

- The DC visible energy is based on photoelectrons (PE) and is calculated and calibrated independently for data and Monte Carlo (MC) following the same sequence of steps, as shown in the scheme below, treating the MC like a second detector:

$$\mathbf{E^0_{vis} = PE \times f_u(\rho, z) \times f_{MeV}} \begin{cases} \mathbf{E^{data}_{vis} = E^{0,\,data}_{vis} \times f^{data}_s(E^{0,\,data}_{vis}, t)} & (1) \\ \mathbf{E^{MC}_{vis} = E^{0,\,MC}_{vis} \times f^{MC}_{nl}(E^{0,\,MC}_{vis})} & (2) \end{cases}$$

- Same reconstruction algorithms are applied for data and MC, but with a dedicated calibration.
- Systematic uncertainties are estimated from residual data-MC discrepancies and propagated into the θ_{13}-fit algorithms as part of an energy model (section 8) [1].



Data

390 PMTs

Waveforms Acquisition

Charge (Q)

PE

MC

GEANT4 MC Simulation

Waveforms Simulation

Charge (Q)

PE

Linearized PE Section 3

Uniformity ($f_u(\rho, z)$) Section 4

Absolute Energy Scale (ES) (f_{MeV})

2.2 MeV H-capture in Target Center

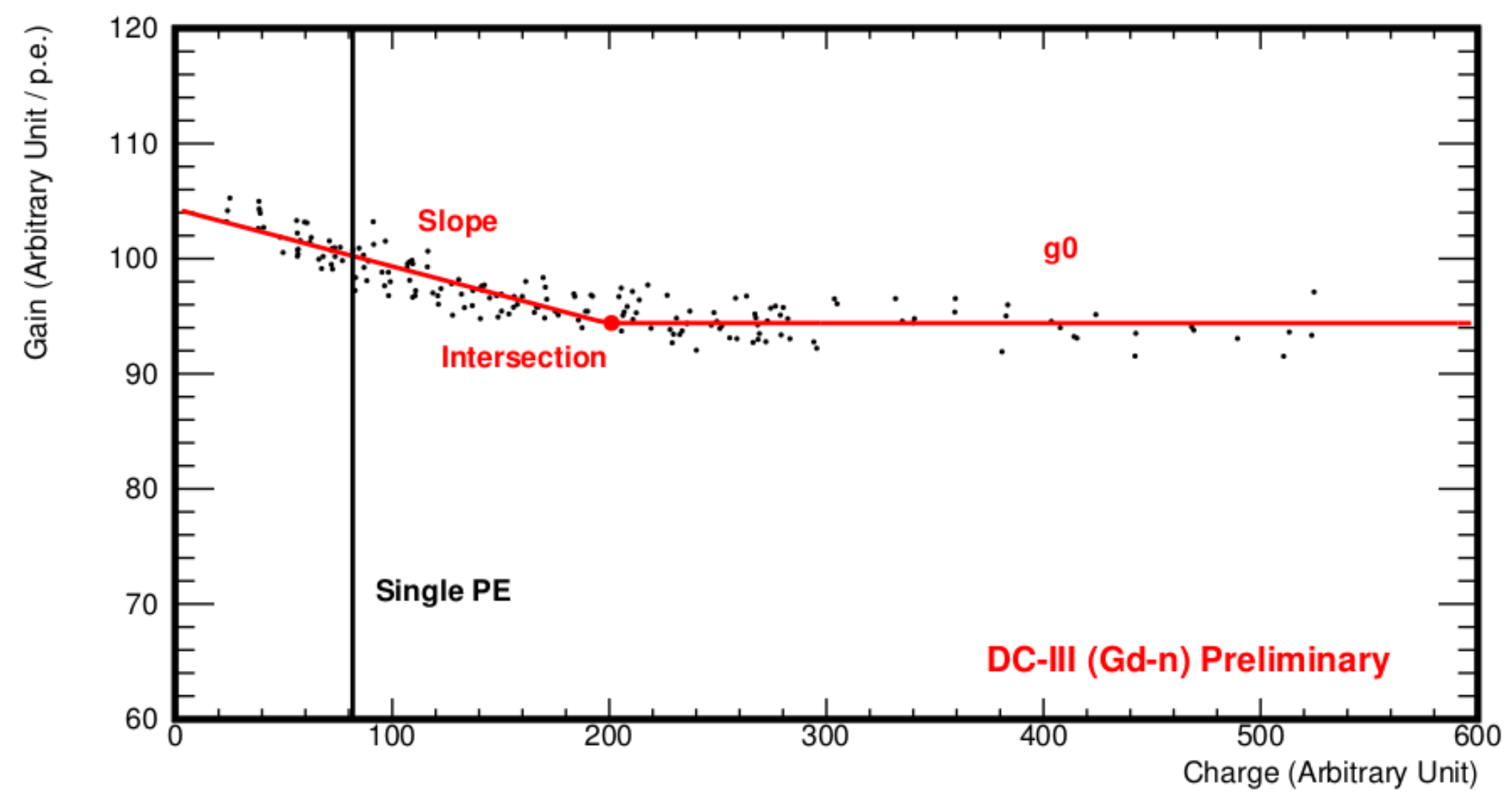
Stability (f^{data}_s) Section 5

Non-linearity (f^{MC}_{nl}) Section 6

$\mathbf{E_{vis}}$

3 Linearized PE calibration

- The linearized PE calibration is a gain calibration, which give the total number of photo electrons as: $\mathbf{PE = \sum_i PE_i = \alpha \times \sum_i Q_i / gain_i(Q_i, t)}$, where i loops through all PMT signals and the gain is a function of the charge itself as is illustrated with a typical readout channel in the figure below.

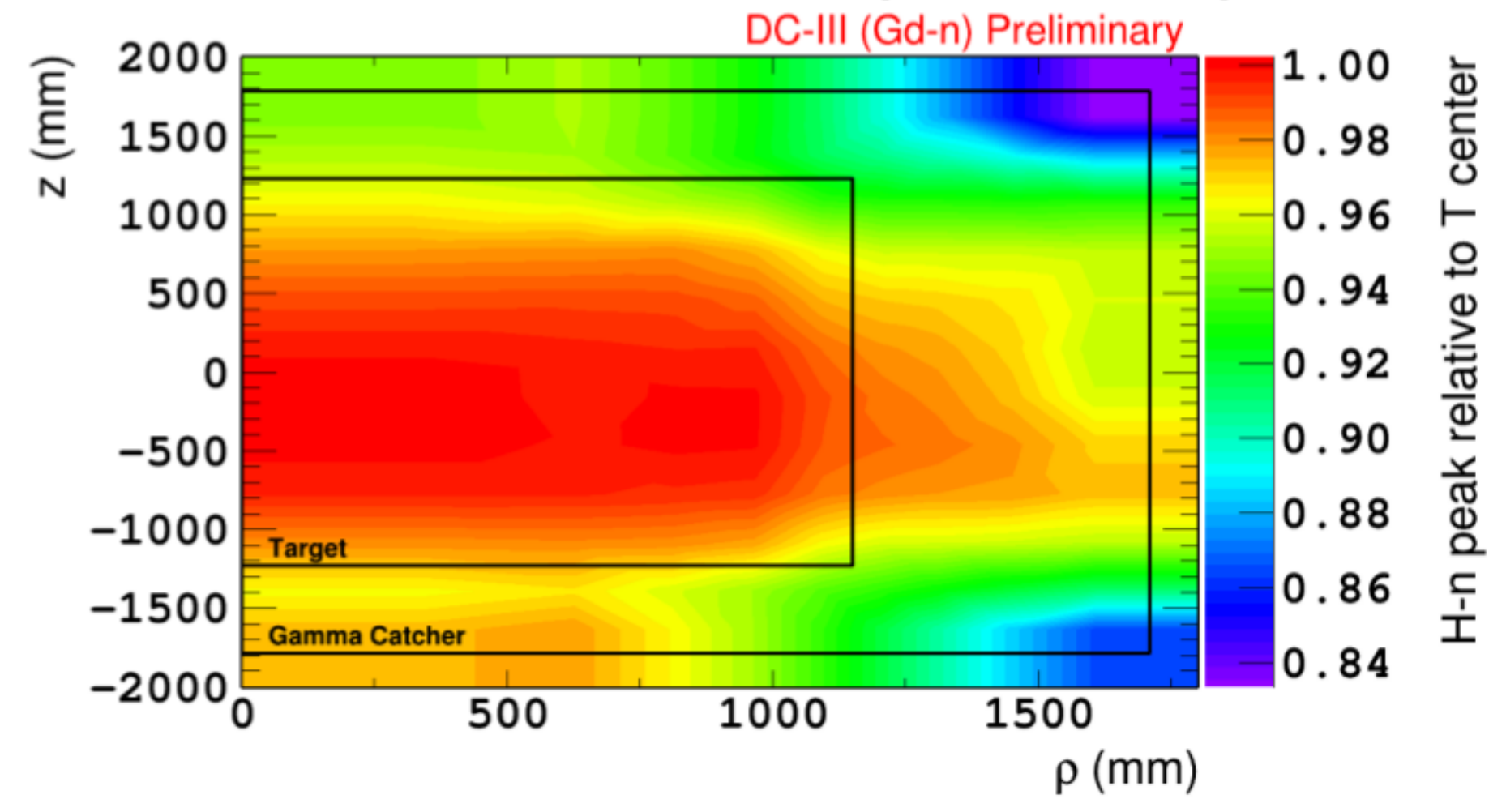


- In many experiments, the PMT gains are extracted by measuring single PEs, which in our case is in the nonlinear regime. Instead, in DC the PMT gains are measured in a wider PE range using a light injection calibration system several times per week [2].
- Thereby the charge non-linearity, as well as its time dependency, is fully characterized on a per-channel basis. This is one of the major improvements in data-MC agreement over a previously adopted SPE calibration. The MC is calibrated in the same way.
- α is a normalizing constant calculated as $\alpha = \mathbf{n/PE}$ where n is the Poisson corrected number of hit PMTs, thereby anchoring the PE scale to the count of PMT hits, which is more robust against time variations in electronics gain and baseline estimation than PE.

4 Uniformity calibration

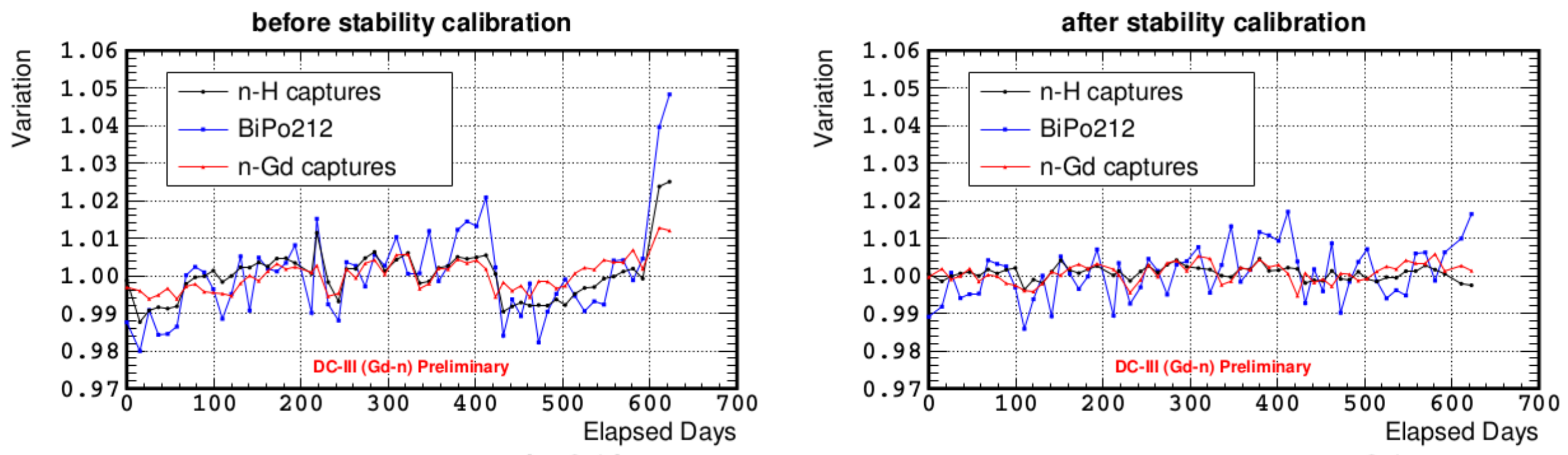
- Uniformity correction $f_u(\rho, z)$ is applied separately to data and MC, where (ρ, z) are the cylindrical detector coordinates.
- The 2.2 MeV Hydrogen capture peak from neutrons is used to produce a (ρ, z) detector response map. In data these neutrons come from muons spallating on Carbon in the scintillator, and in MC come from $\overline{\nu}$ IBD.
- The detector response in PE, i.e. before uniformity calibration, agrees between data and MC within few % in the target and in the surrounding γ-catcher region.

Data Detector Response Map



5 Energy-dependent stability calibration

- The time stability of the detector response has been studied over the full positron energy range from 1 to 8 MeV.
- A positive drift (0.3% per year) common to all energies is calibrated out, as well as an energy-dependent time variation of the detector response.

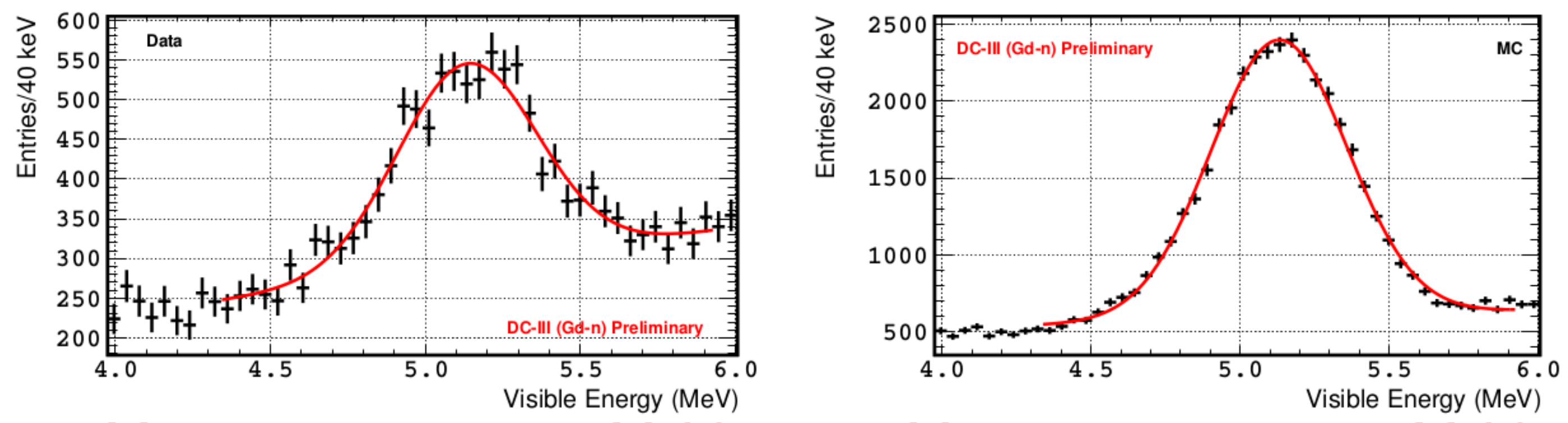


$\sigma_{stability} = O(1\%) \quad \rightarrow \quad \sigma_{stability} = 0.5\%$

6 Non-linearity calibration

- A residual energy dependent data-MC discrepancy at the 1% level found in calibration data in the Target center has been corrected.
- This non-linearity between data and MC has a particle and position independent nature, stemming from the interplay between MC readout modeling and charge reconstruction.
- With this correction the C-capture data-MC comparison shows an agreement at the permill level in a completely different subdetector.

Data and MC Carbon peak from neutron capture in γ-catcher



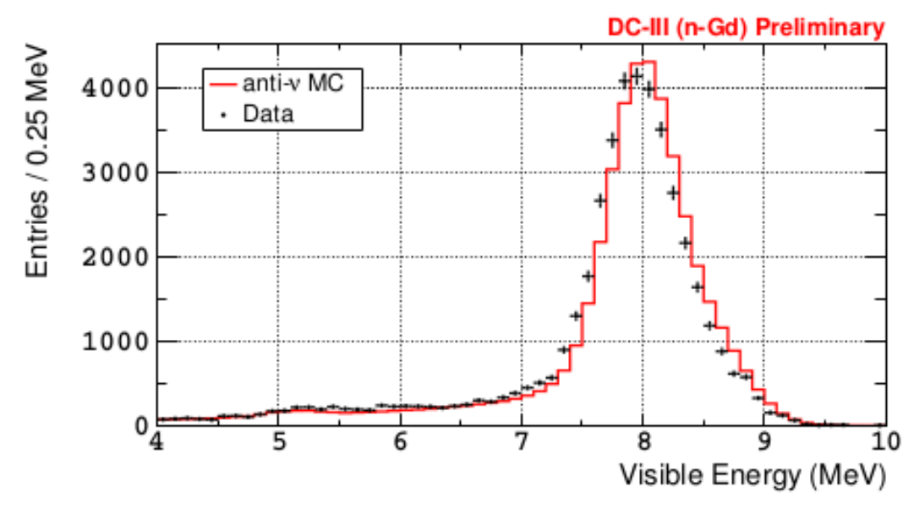
Mean: 5.135 ± 0.01 MeV
Frac. Width: 4.38%

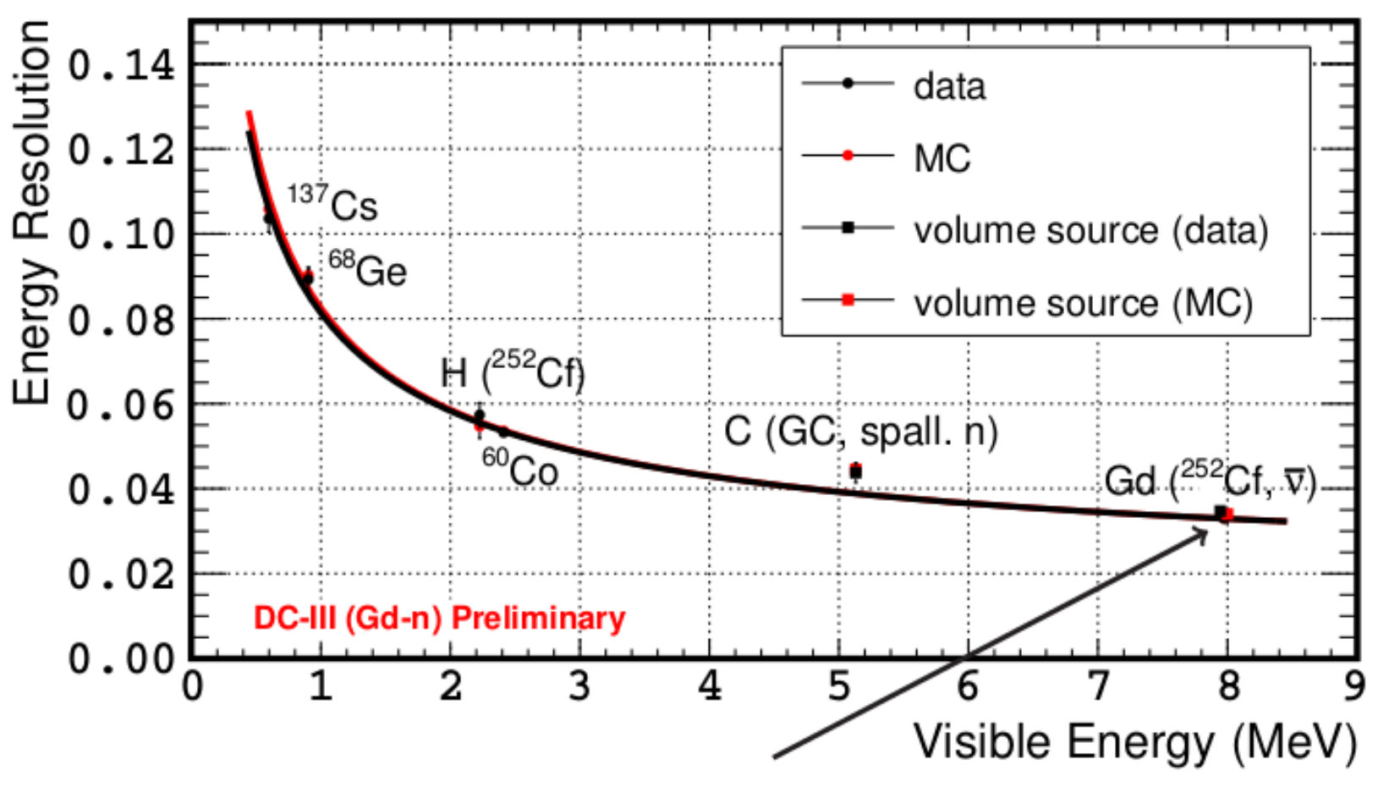
Mean: 5.13 ± 0.001 MeV
Frac. Width: 4.46%

7 Validation

- Two example plots demonstrate the good data-MC agreement of our E_{vis}:
  - ▷ The delayed n-Gd peak of our $\overline{\nu}$ signal agrees within 1σ of our energy scale uncertainty.
  - ▷ The energy resolution as a function of visible energy shows very good data-MC agreement in the Target center with calibration data, in the Target volume ($\overline{\nu}$) and in the γ-catcher (n capture on ^{12}C).

    Thanks to our uniformity and stability calibration $\overline{\nu}$ interactions in the full target region over a period of $\sim$ 600 days behave as if interacting in the target center during one day.





The resolution of the $\overline{\nu}$ capturing on Gd is very close to the Gd-capture peak from ^{252}Cf deployed in the Target center.

8 Energy Model in the θ_{13} Fit

- To account for energy scale uncertainties in the θ_{13} fit a 3 parameters model is implemented: $\mathbf{E^{MC}_{vis} \rightarrow a + b \times E^{MC}_{vis} + c \times (E^{MC}_{vis})^2}$. Pull parameters a, b, c, their uncertainties and correlations are computed:
  - ▷ From dedicated stability, uniformity and non-linearity systematics studies.
  - ▷ A remaining data-MC discrepancy in the modeling of the scintillator (quenching and Cerenkov) was also included in the energy model of the fit of the positron spectrum.
- A weighted average of the energy fit model's uncertainties gives an uncertainty of 0.74 % *before* the θ_{13} fit. In exploiting the positron spectral shape the θ_{13} fit constrains uncertainties even more stringently, among them e.g. the Li^9+He^8 background uncertainty as well as ES uncertainties [1].

[1] Carr, Lucht, Novella, « New results and future capabilities of the Double Chooz reactor antineutrino experiment », Neutrino 2014 poster
[2] Chauveau, Pronost, Rybolt, « Status of the Double Chooz detectors », Neutrino 2014 poster

Poster presented at **NEUTRINO 2014**, Boston

Acknowledgments: