Final Measurements of the Double Chooz Experiment

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for the Double Chooz Collaboration

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Physics Institute III B

Neutrino Oscillation

Flavour Eigenstate / Mass Eigenstate

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}}_{U_{\mathrm{PMNS}}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Atmospheric $P(\nu_\mu \to \nu_\mu)$ | Reactor and Accelerator $P(\nu_e \to \nu_e)$ & $P(\nu_\mu \to \nu_e)$ | Solar $P(\nu_e \to \nu_x)$

$$\underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\theta_{23} \sim 45^\circ} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix}}_{\theta_{13}\ \&\ \delta_{\mathrm{CP}}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\theta_{12} \sim 33^\circ}$$

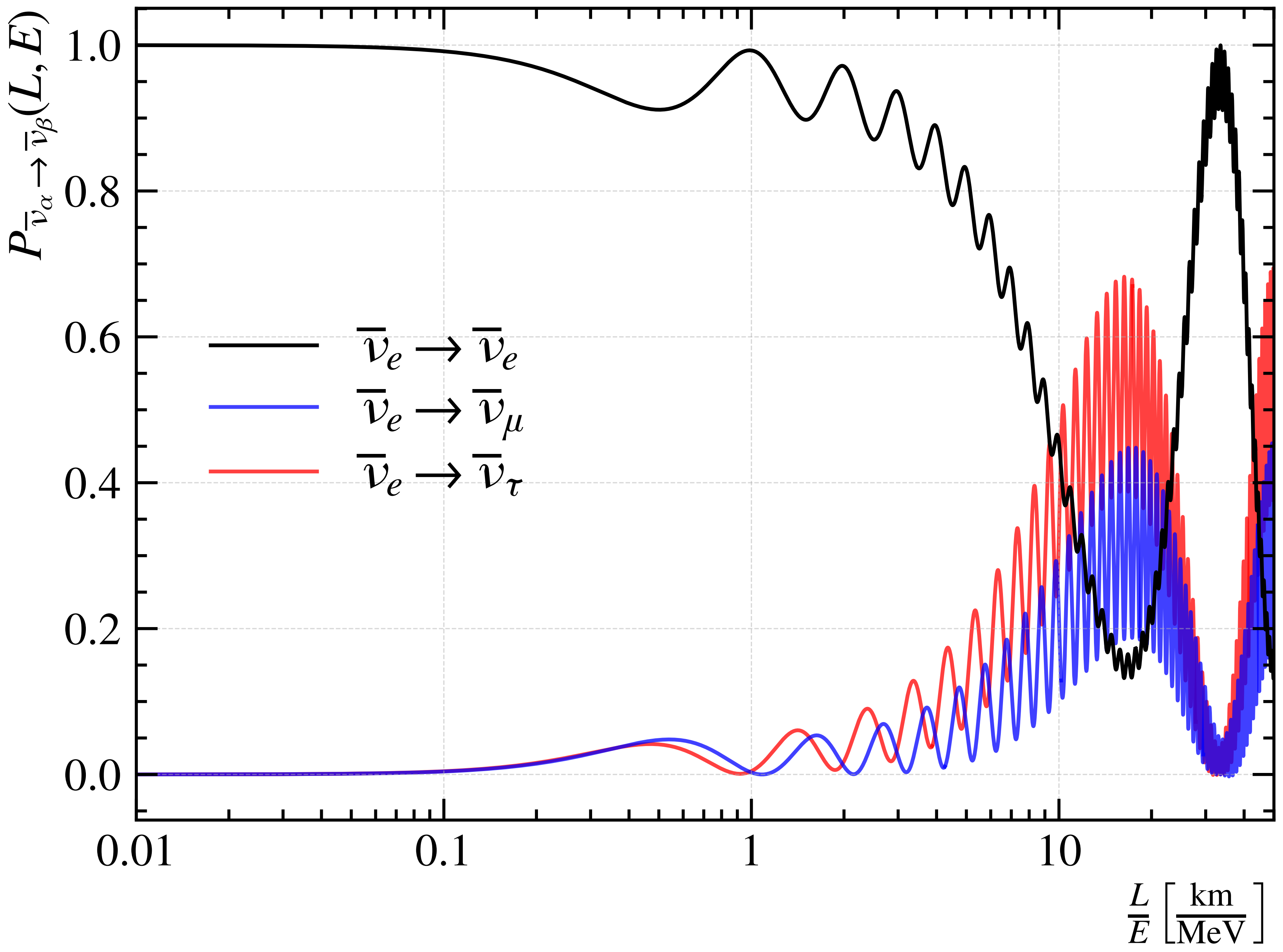
$c_{ij} = \cos\theta_{ij}$

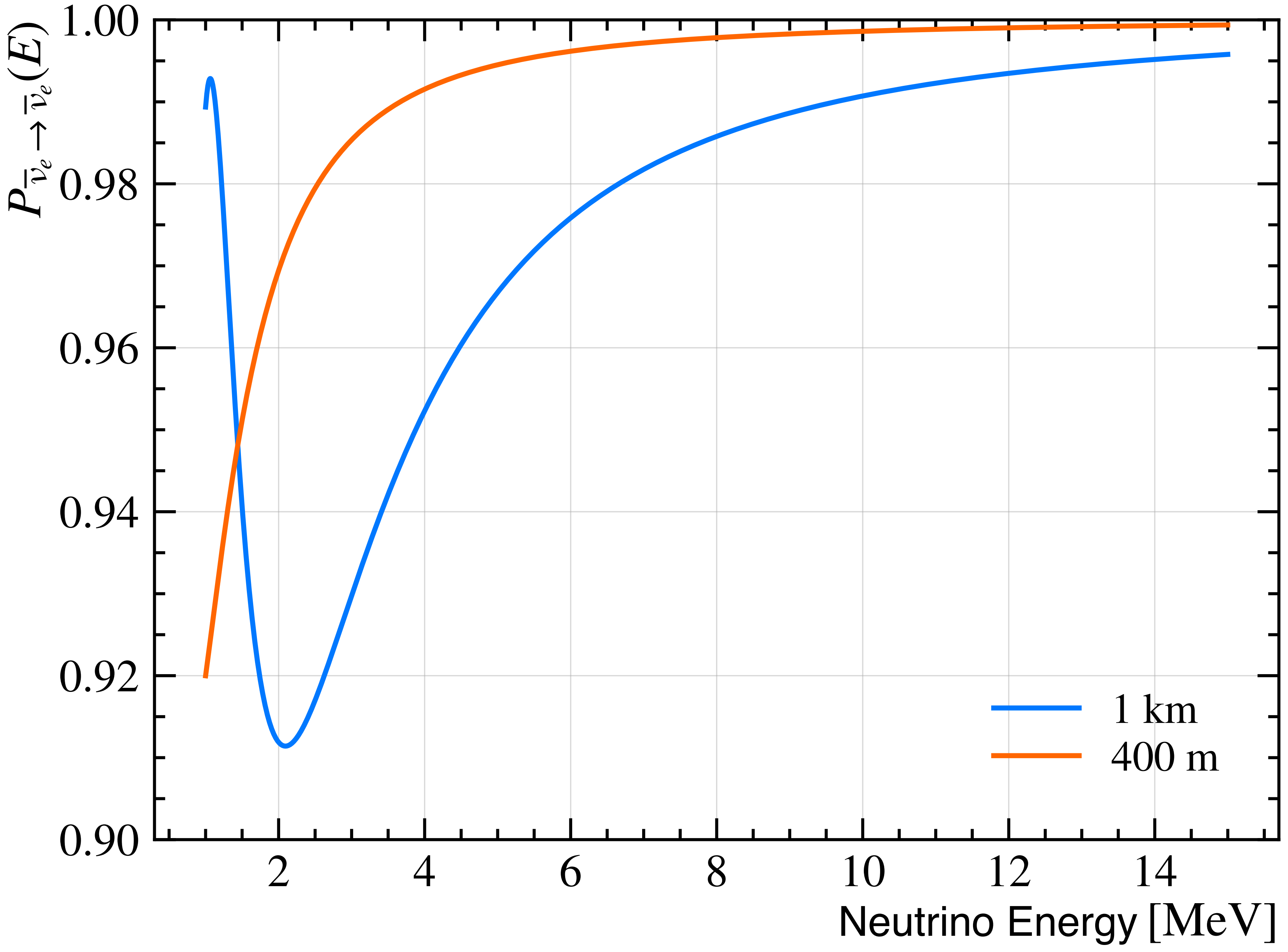
$s_{ij} = \sin\theta_{ij}$

$$P(\bar{\nu}_e \to \bar{\nu}_e) = \ldots \approx 1 - \sin^2(2\theta_{13})\sin^2\Delta_{ee} - \cos^4\theta_{13}\sin^2(2\theta_{12})\sin^2\Delta_{21}$$

$$\Delta m^2_{ee} \equiv \cos^2\theta_{12}\Delta m^2_{31} + \sin^2\theta_{12}\Delta m^2_{32}$$

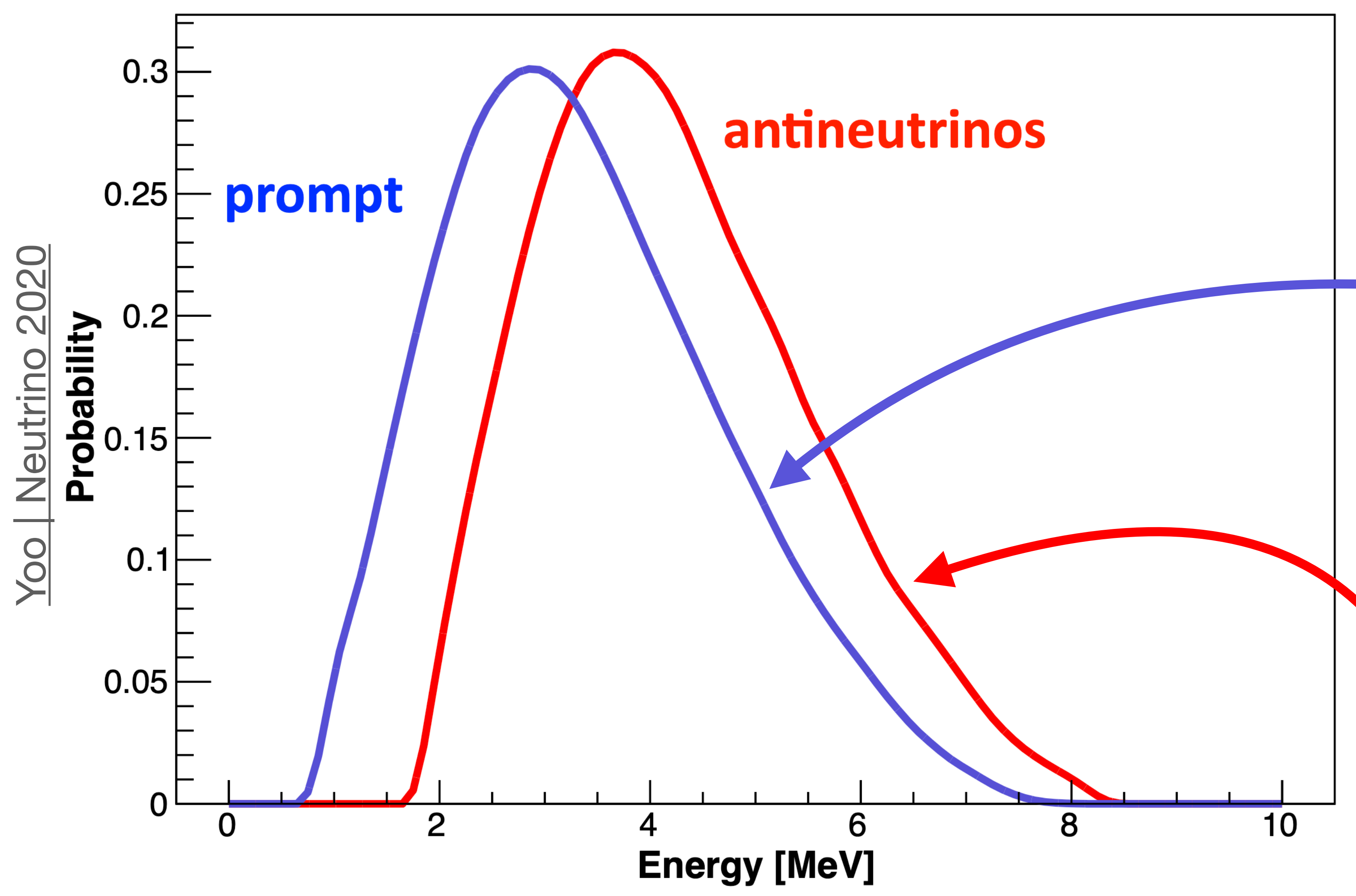
$$\Delta_{ij} \equiv \Delta m^2_{ij}\frac{L}{4E}$$

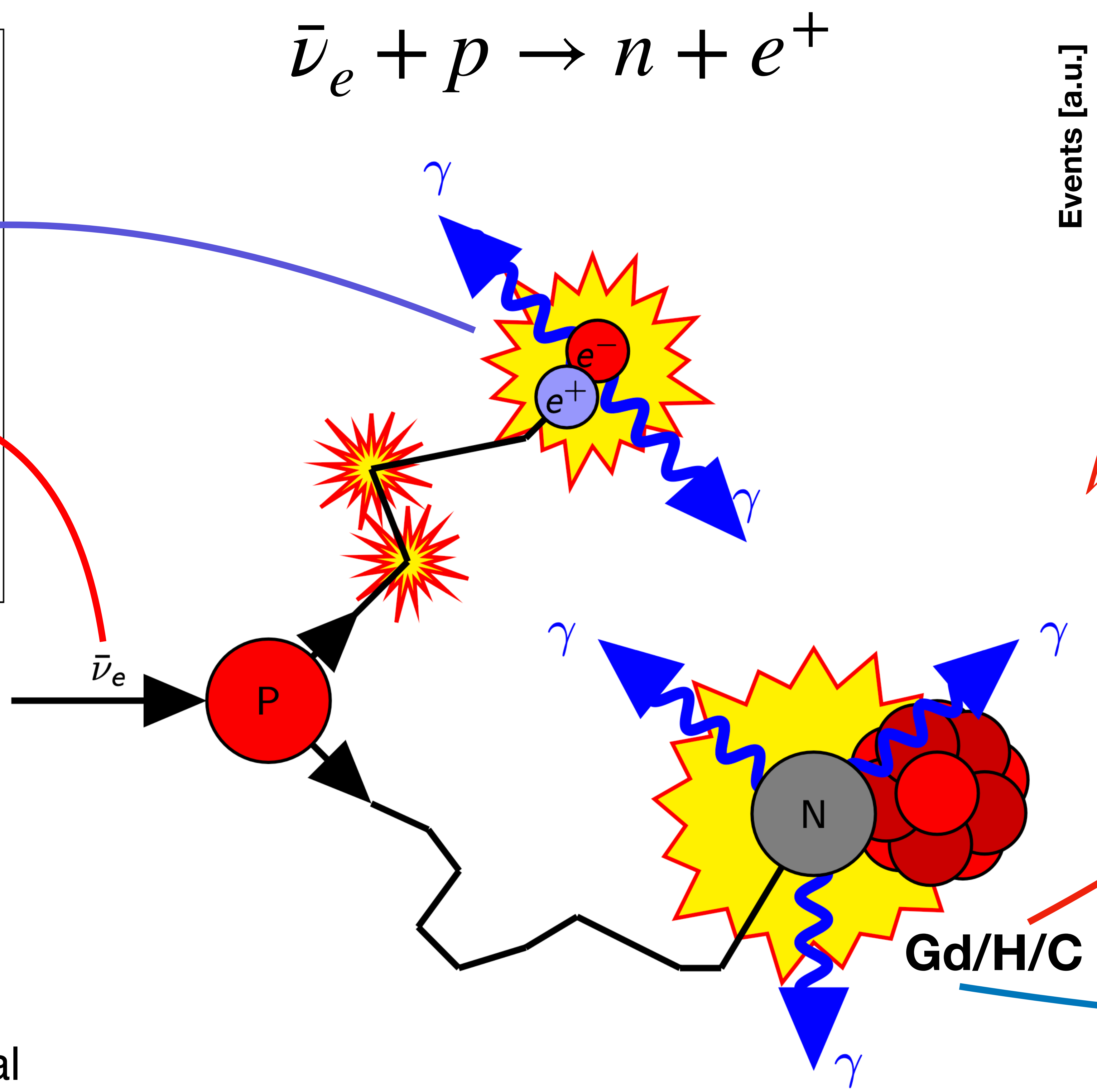


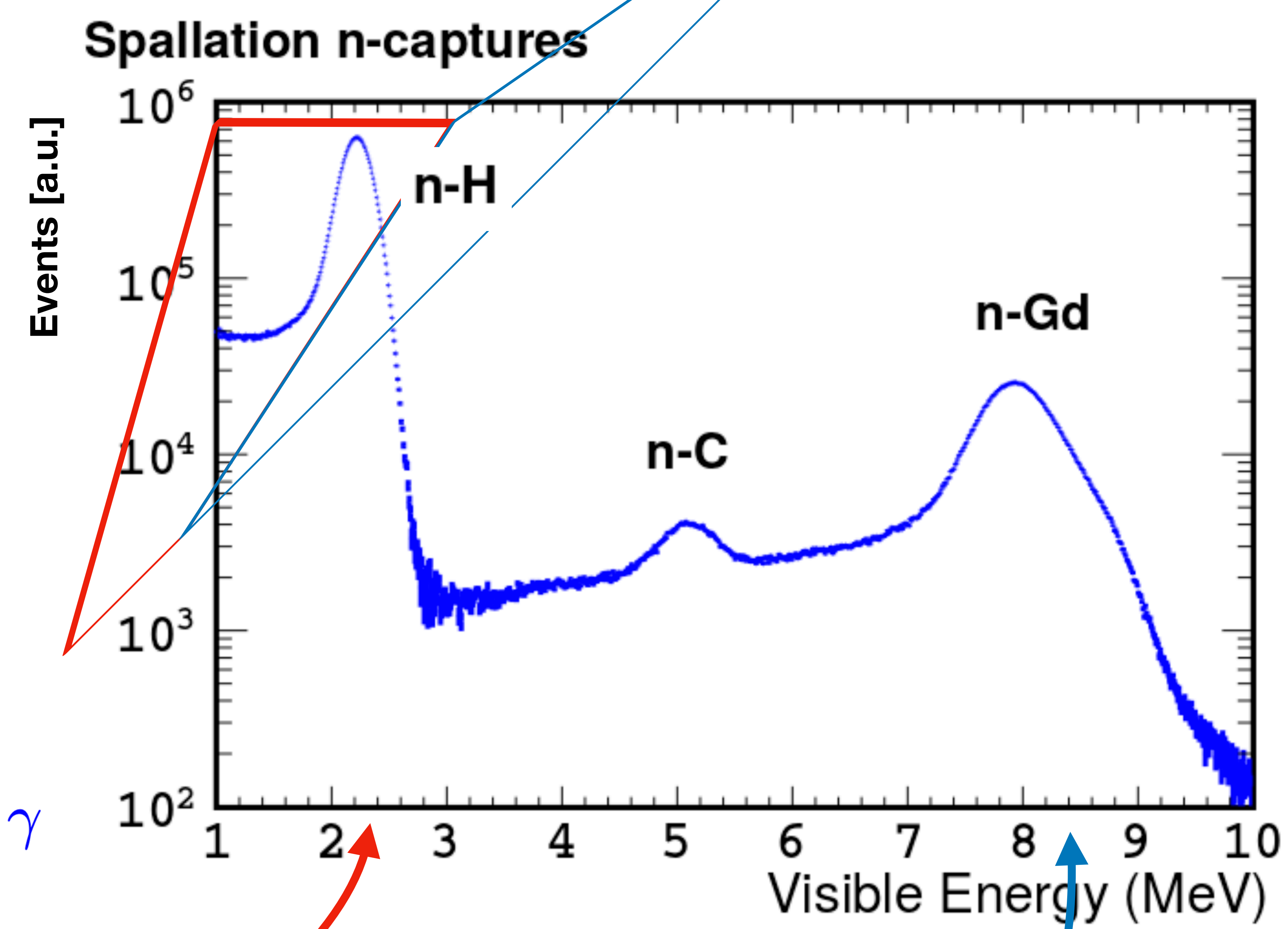


- Neutrinos *oscillate* as a function of distance and energy
- For a single flavor ($\bar{\nu}_e$) source the energy spectrum changes for different distances
- For fixed distances the effect is observable as a systematic deficit of measured neutrinos

Neutrino Detection via Inverse Beta Decay

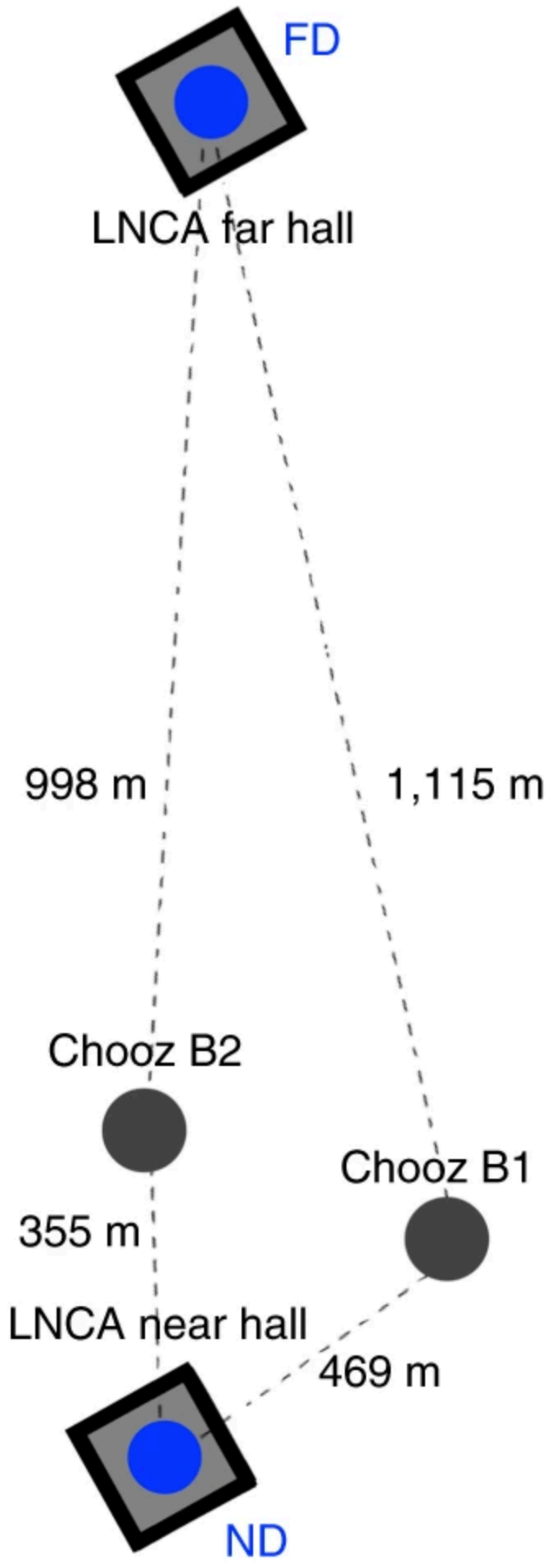




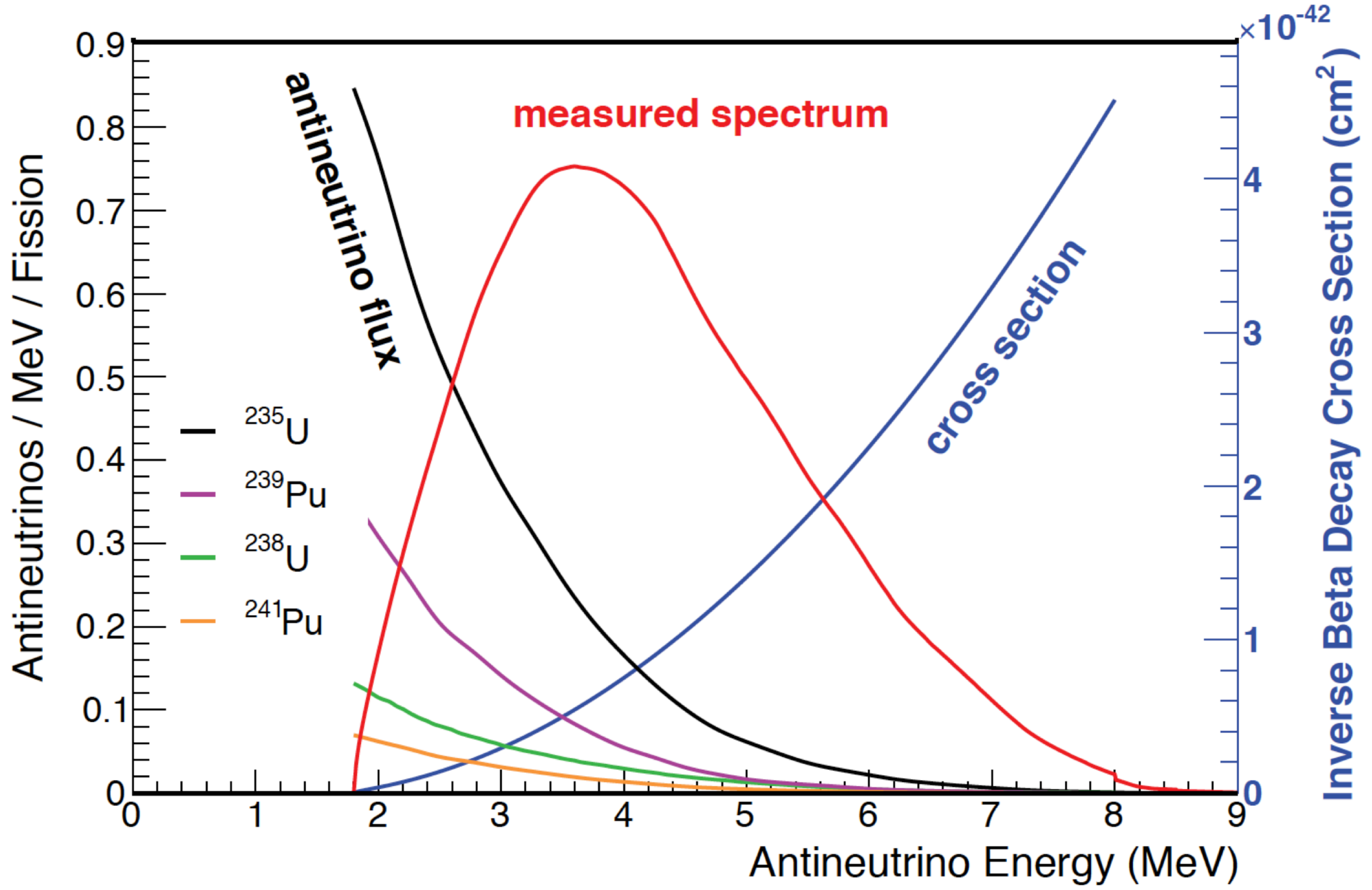


- 1.8 MeV threshold for IBD process
  - $E_{\text{prompt}} \approx E_\nu - 0.8$ MeV
- Distinct double event signature
- Low background due to double signal
- Relatively high cross section

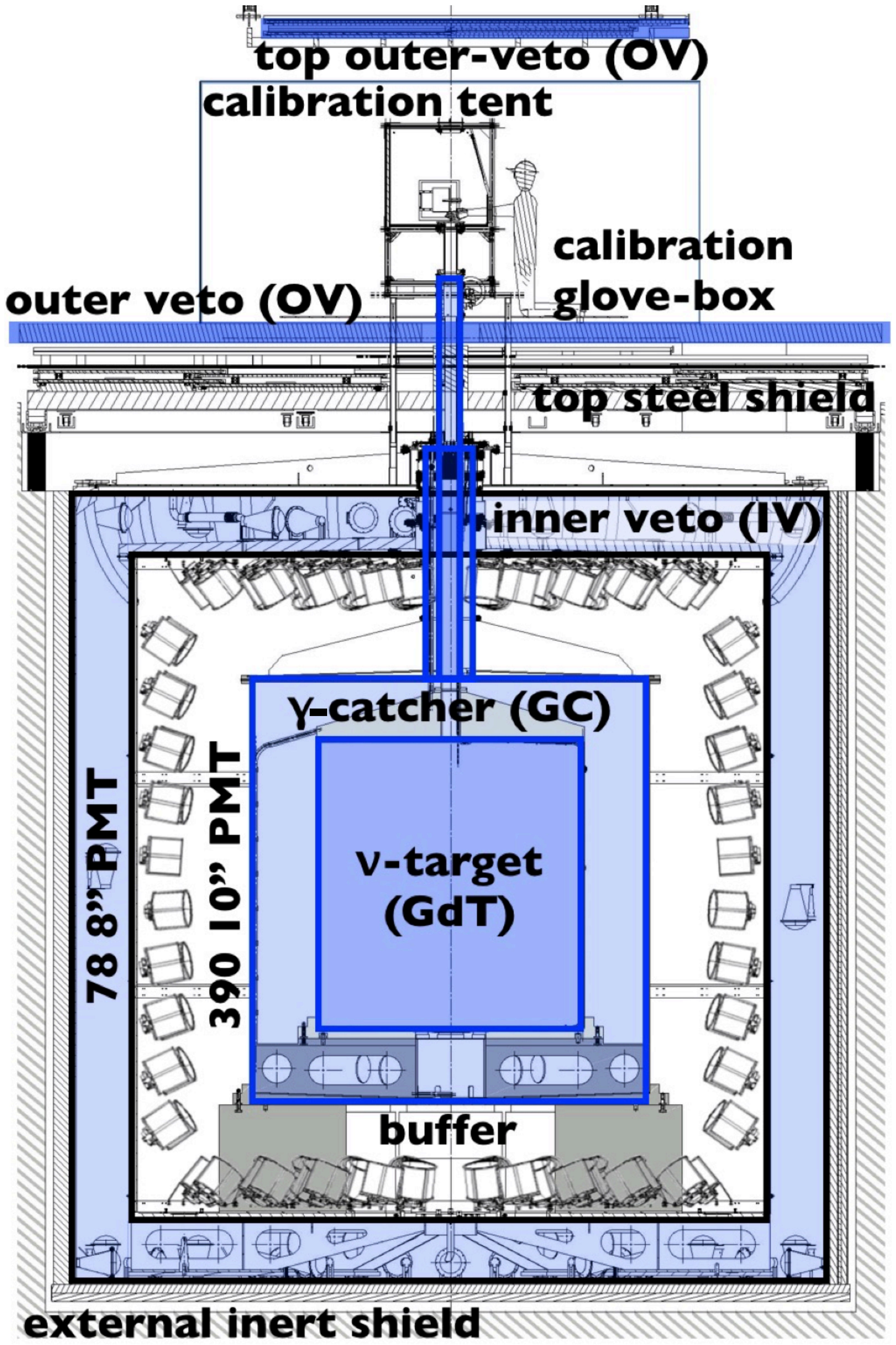
Experimental Setup



- Nuclear Reactors are a strong neutrino source
  - $\sim 6\,\bar{\nu}_e$ per fission
  - $2 \cdot 10^{20}\,\bar{\nu}_e\,\mathrm{s}^{-1}\mathrm{GW}^{-1}$
- Strong reactors in Chooz, France with a power of $8.5\,\mathrm{GW_{th}}$
- Data taking from 2011 - 2018
- Near detector assembled in 2015
  - Close to Iso-flux
- Three data sets (FDI, FDII, ND)



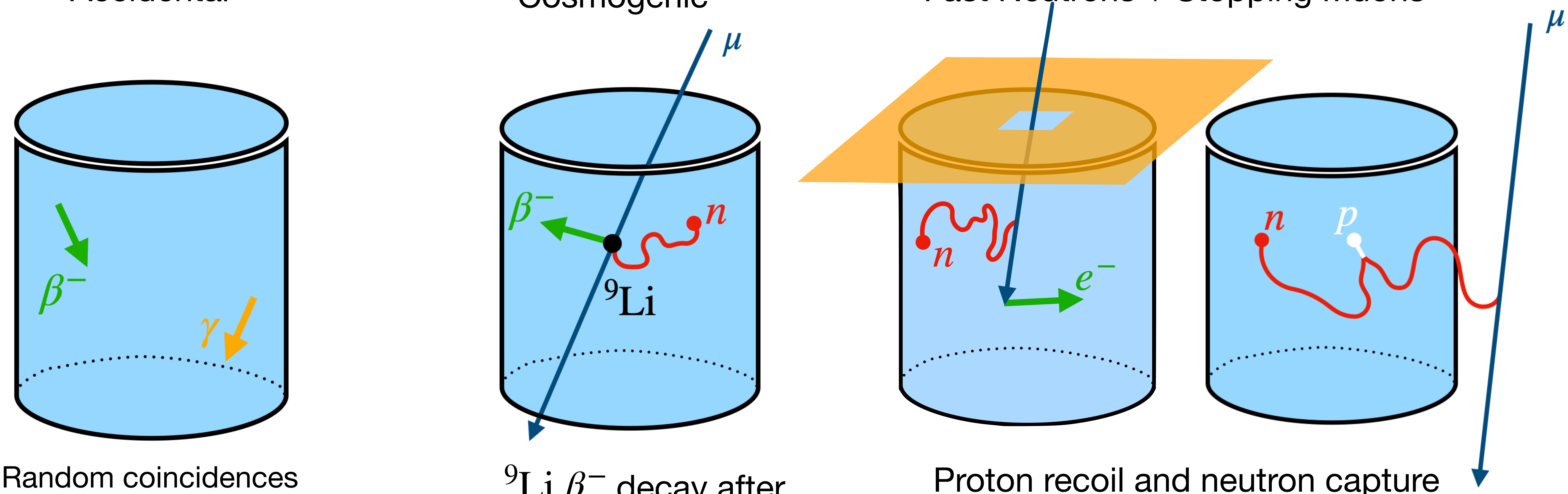
Double Chooz Detector



- Identical near and far detector design
- Detector is build in an onion like structure
- **ν - target**
  - $1\,\mathrm{g}\,\mathrm{l}^{-1}$ Gd doped Liquid Scintillator
- **γ - catcher**
  - Undoped Liquid Scintillator
- **buffer**
  - Non scintillating mineral oil
  - 390 10-inch PMTs
- **inner veto**
  - Shielded Liquid Scintillator for atm. μ and neutron veto
  - 78 8-inch PMTs
- **outer veto**
  - Plastic Scintillator strips above

IBD Backgrounds

Accidental	Cosmogenic	Fast Neutrons + Stopping Muons

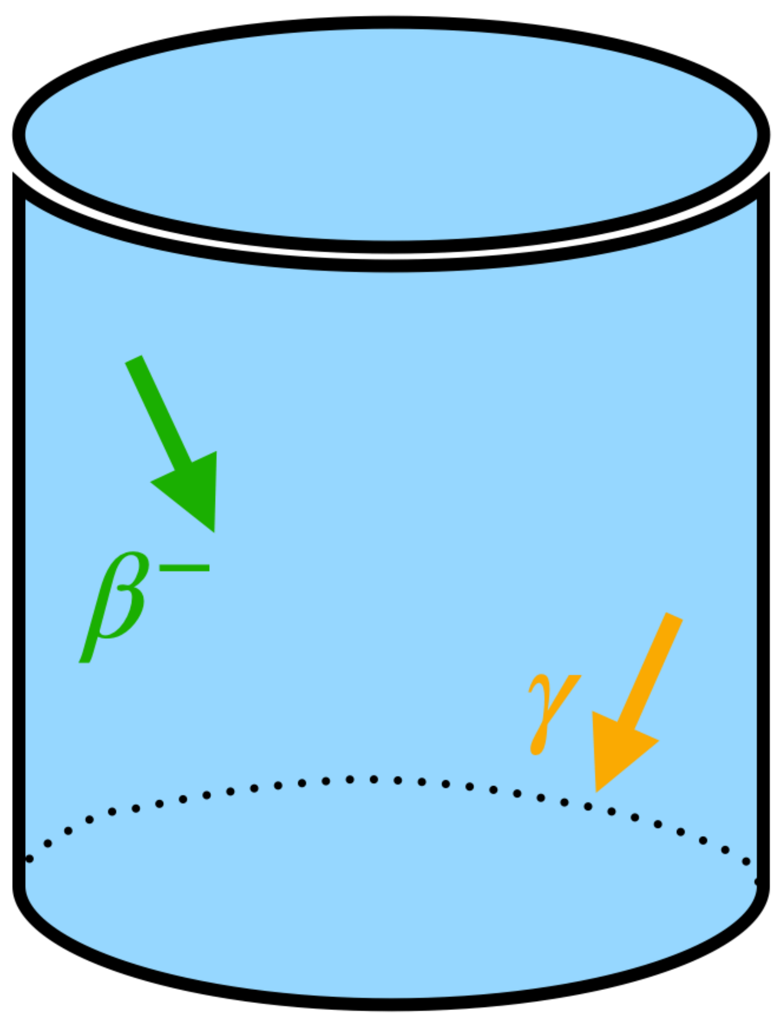


Random coincidences between uncorrelated events	^{9}Li β^- decay after carbon spallation by an cosmic muon	Proton recoil and neutron capture Muon decay into Michel Electrons

B.Roskovec PIC 2019

IBD Backgrounds

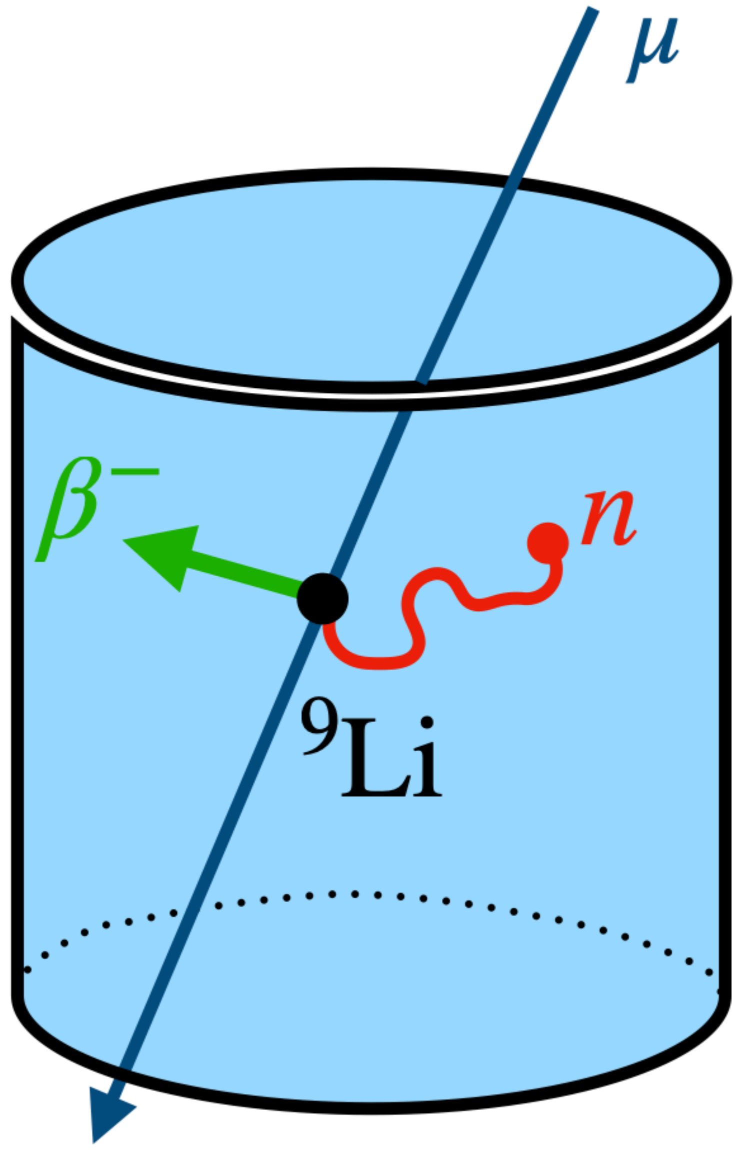
Accidental



Random coincidences between uncorrelated events

FD: $4.360 \pm 0.010\ \mathrm{day}^{-1}$
ND: $3.066 \pm 0.001\ \mathrm{day}^{-1}$

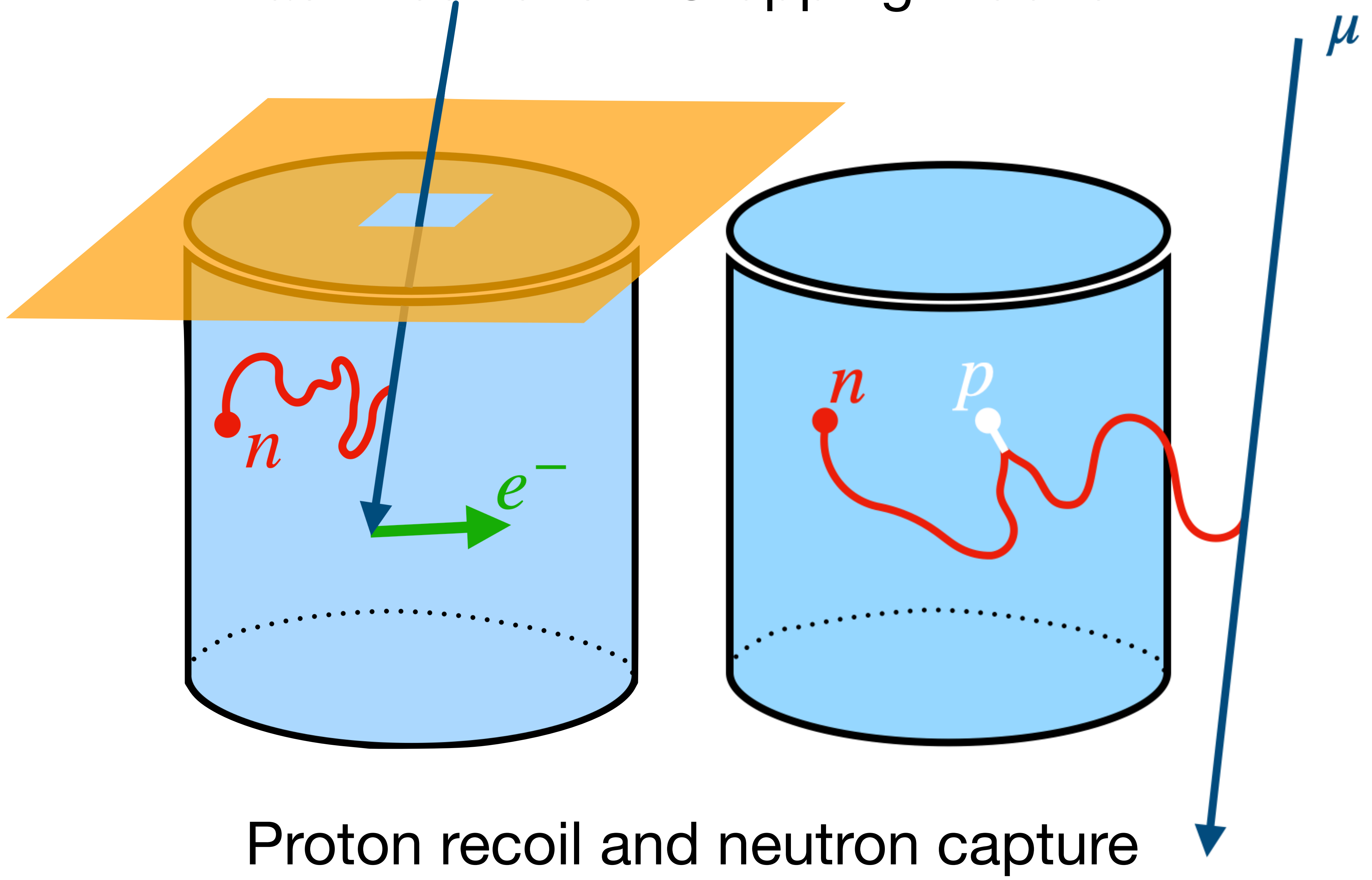
Cosmogenic



$^9\mathrm{Li}\ \beta^-$ decay after carbon spallation by an cosmic muon

FD: $2.40 \pm 0.21\ \mathrm{day}^{-1}$
ND: $11.38 \pm 0.95\ \mathrm{day}^{-1}$

Fast Neutrons + Stopping Muons



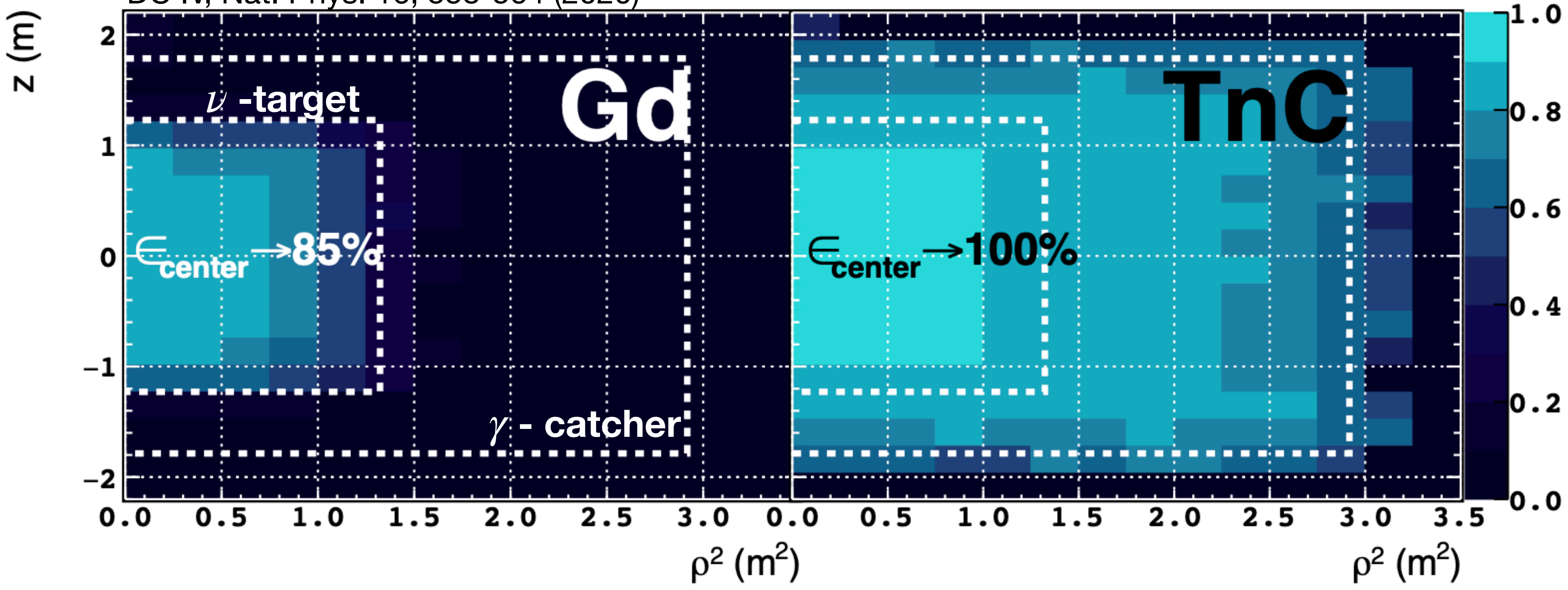
Proton recoil and neutron capture
Muon decay into Michel Electrons

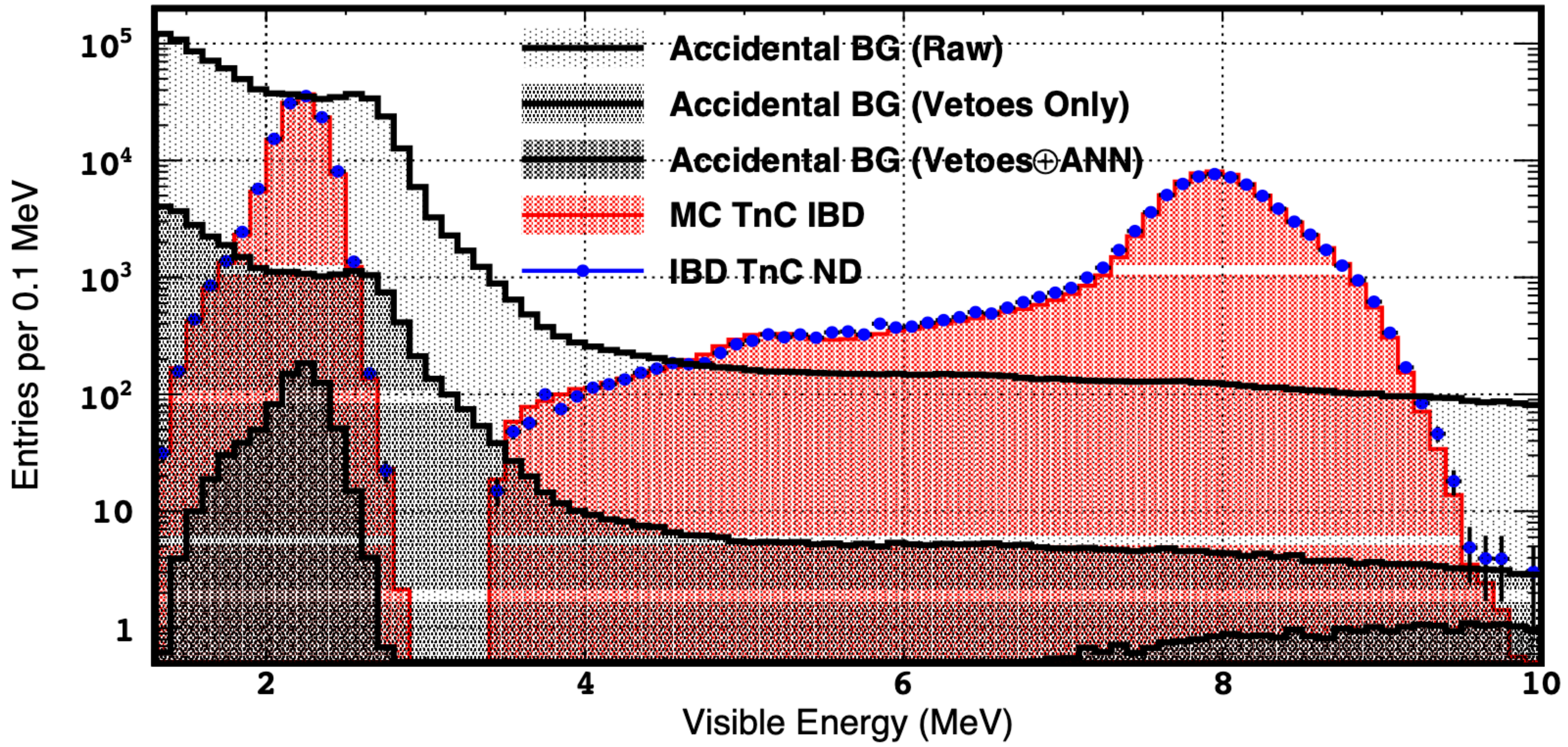
FD: $6.05 \pm 0.10\ \mathrm{day}^{-1}$
ND: $45.56 \pm 0.36\ \mathrm{day}^{-1}$

B.Roskovec PIC 2019

Background Reduction

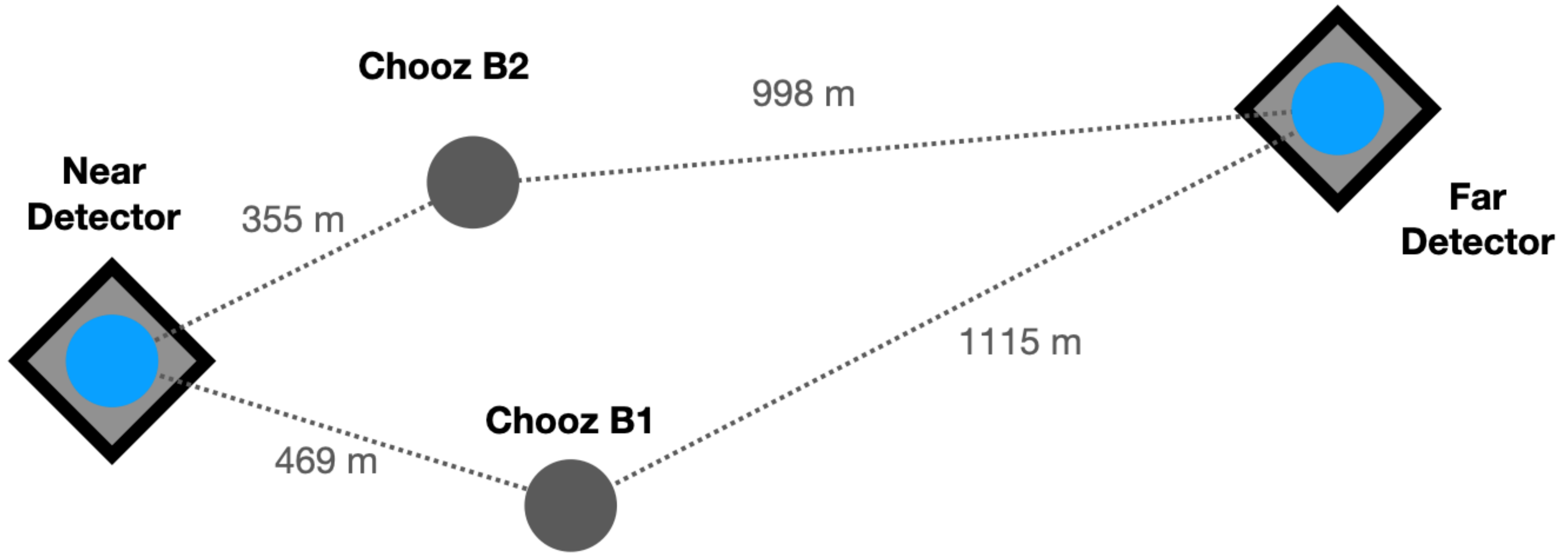
DC IV, Nat. Phys. 16, 558-564 (2020)

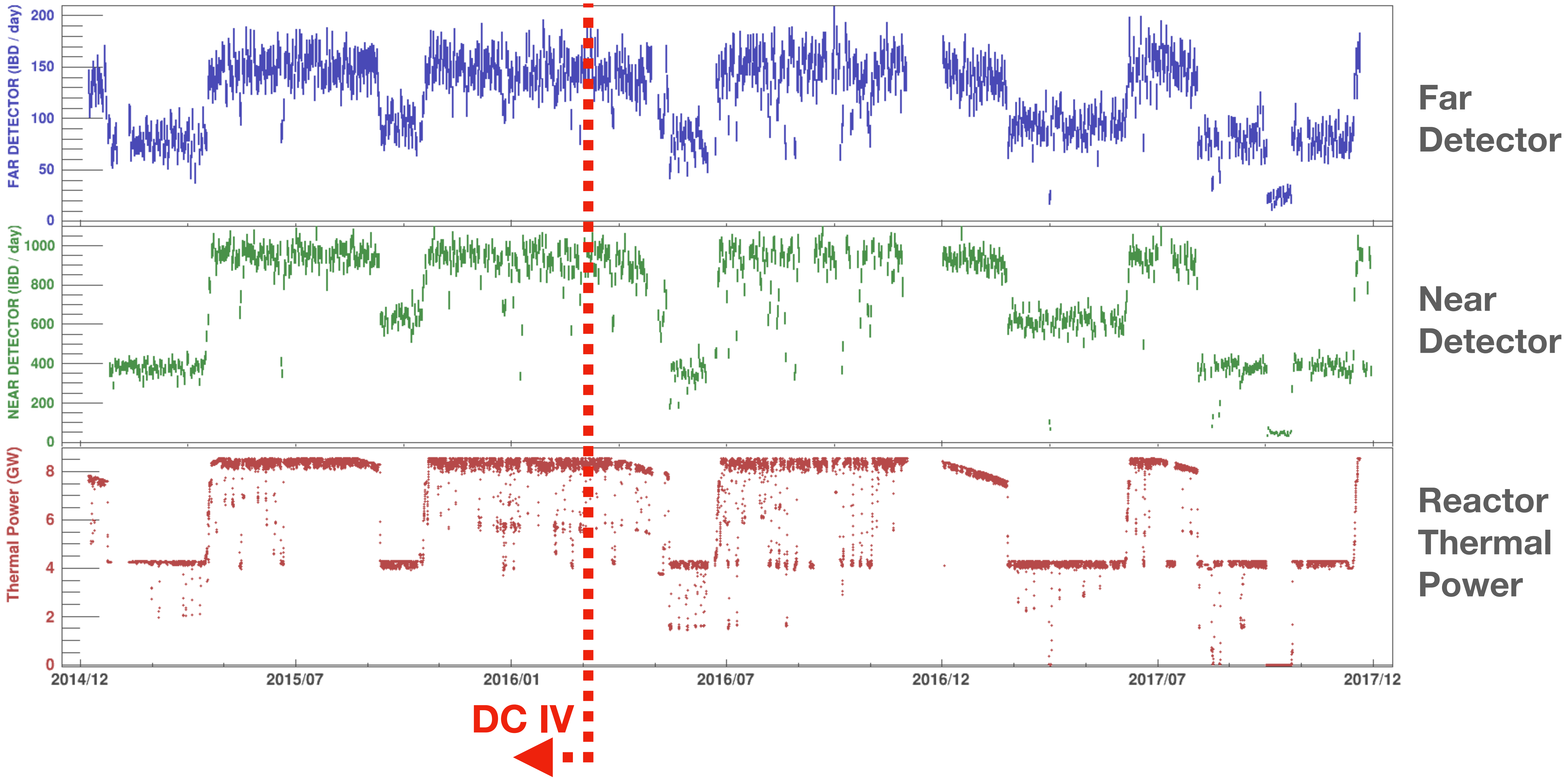




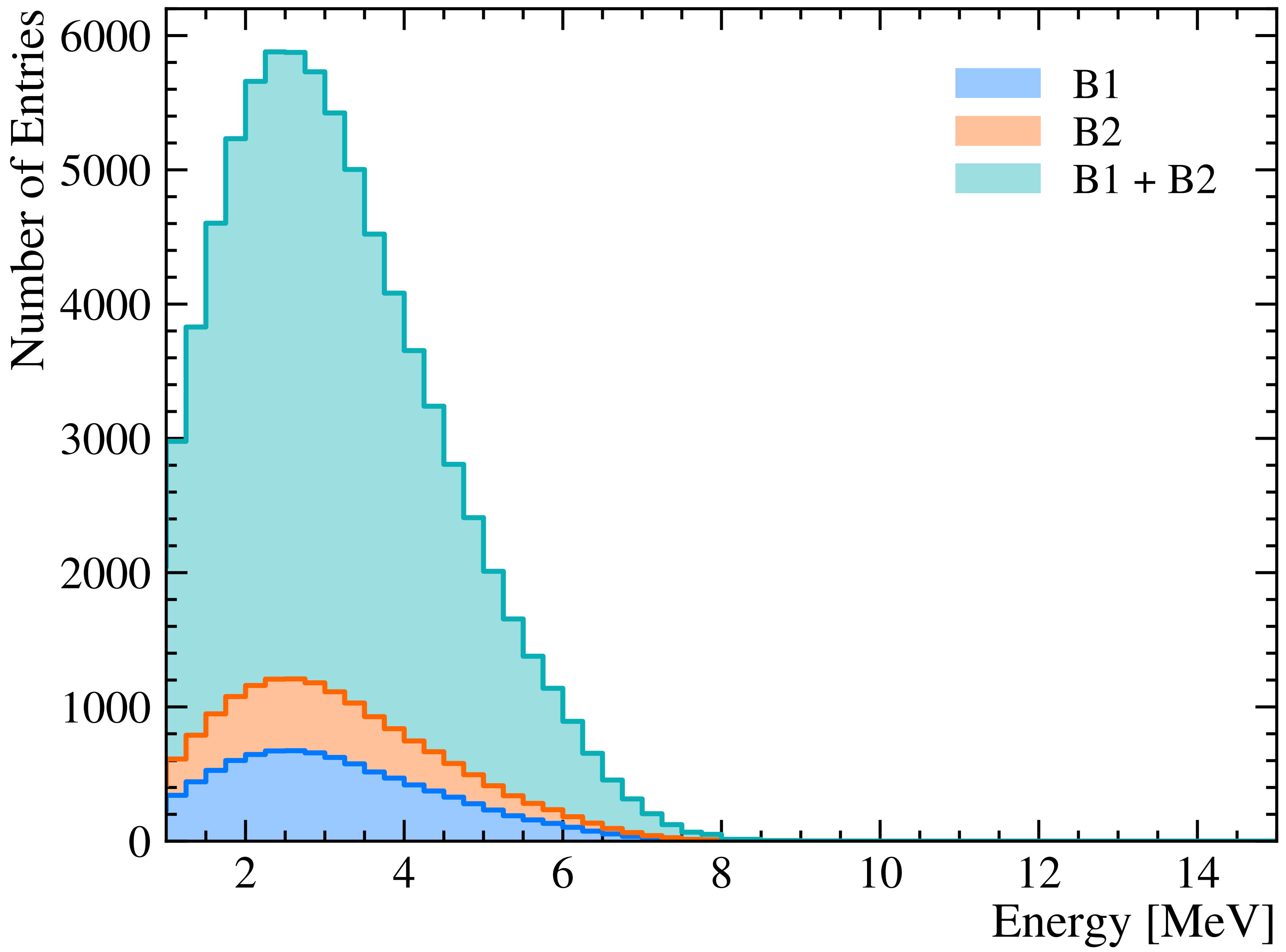
- By including Hydrogen in the event selection, all neutron capture channels can be utilized (Gd + H + C) in Total Neutron Capture (TnC) (DC IV)
- The γ-Catcher can be used as fiducial volume. In total this increases the statistics by a factor ~ 2.5
- This requires a significant background reduction
  - Use of NN that uses ΔR, Δt and E_{delayed}

Reactor Split





MC Far Detector Reactor Spectrum



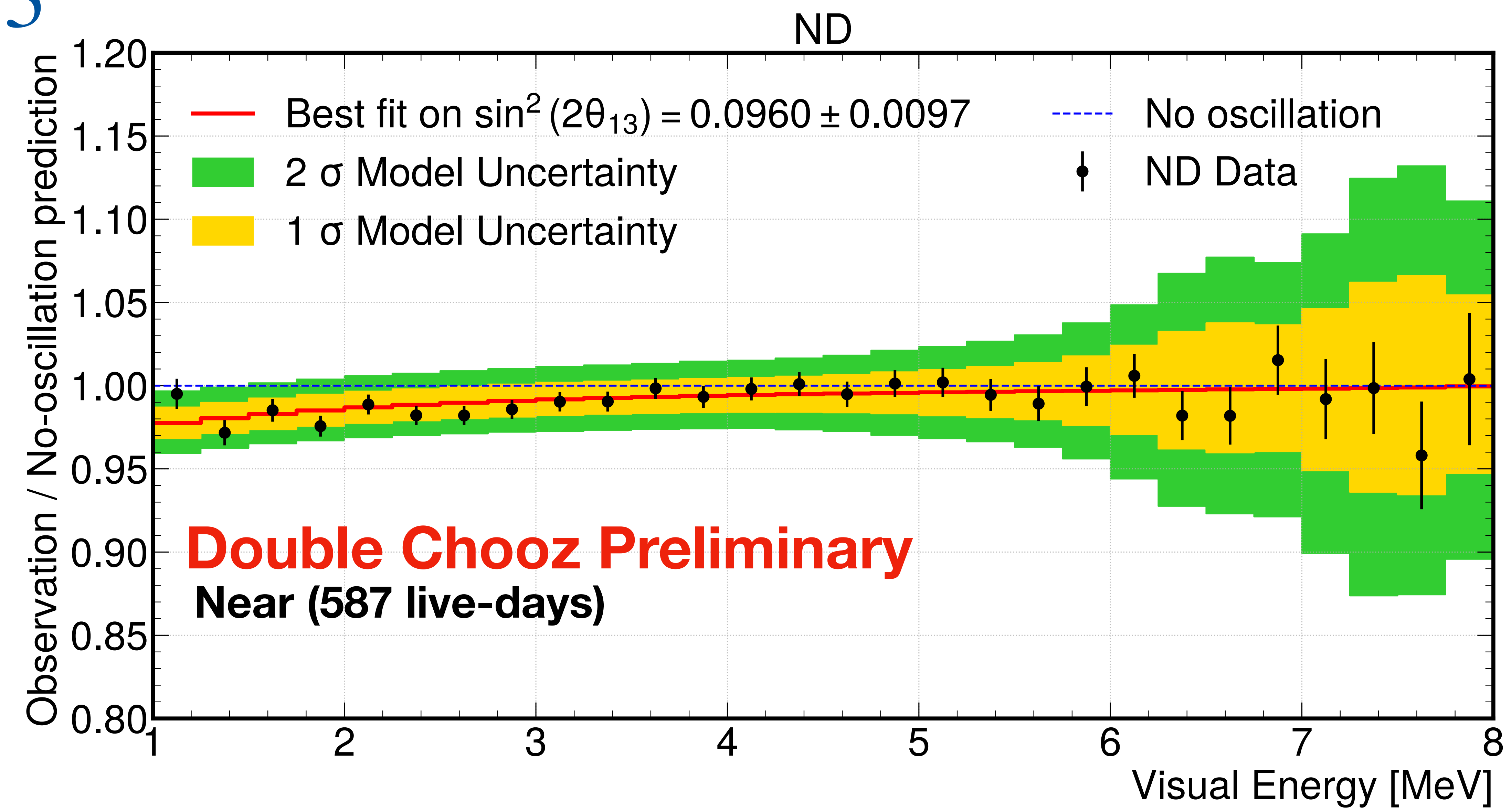
- The current implementation uses all reactor run-times simultaneously
- Separating the individual reactor run-times, utilizes distance dependency more effectively
- Combines DC RRM and DC II Methods *J. High Energ. Phys.* 2021, 190 (2021)

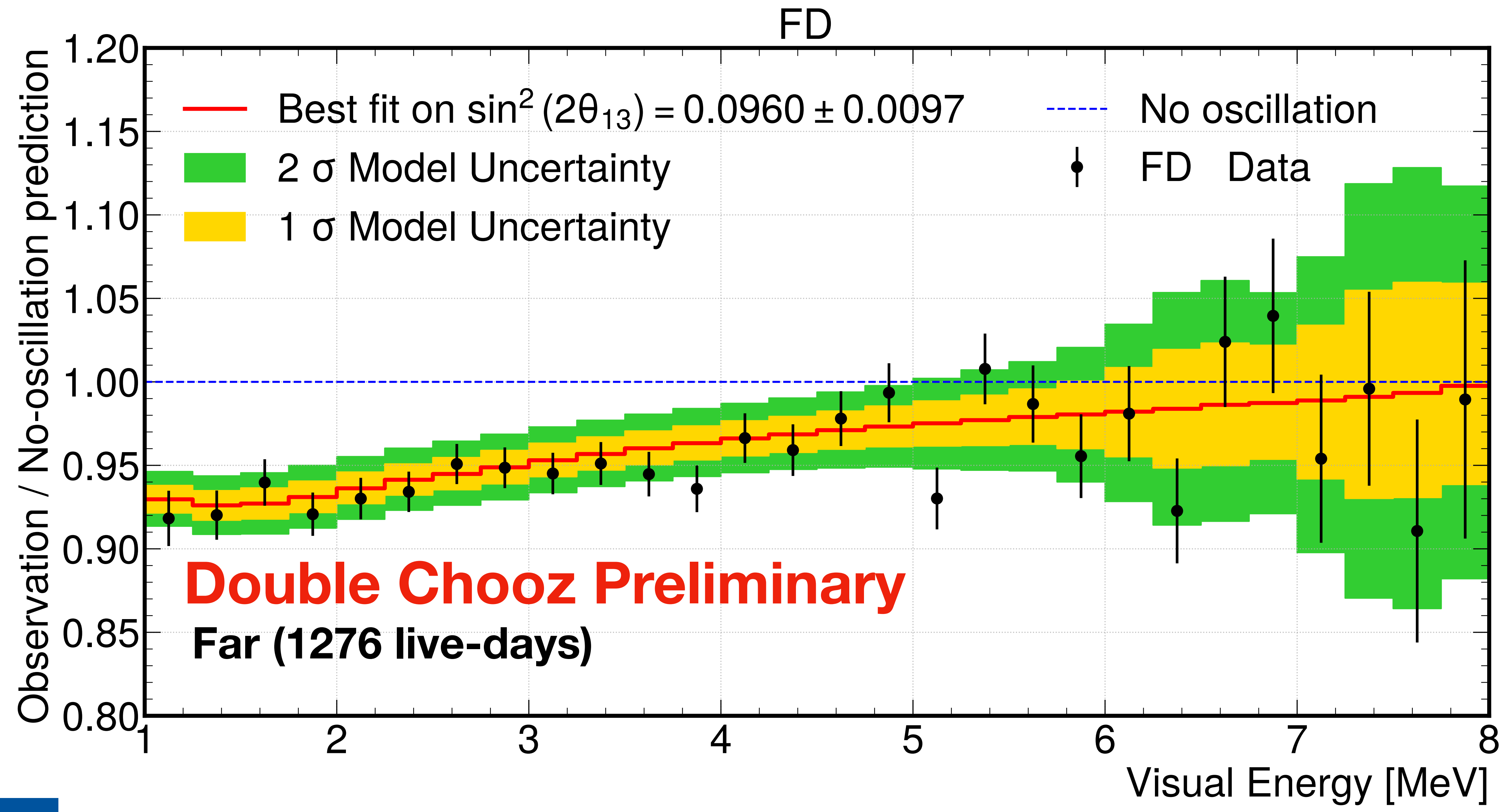
DC II, PHYSICAL REVIEW D 86, 052008 (2012)

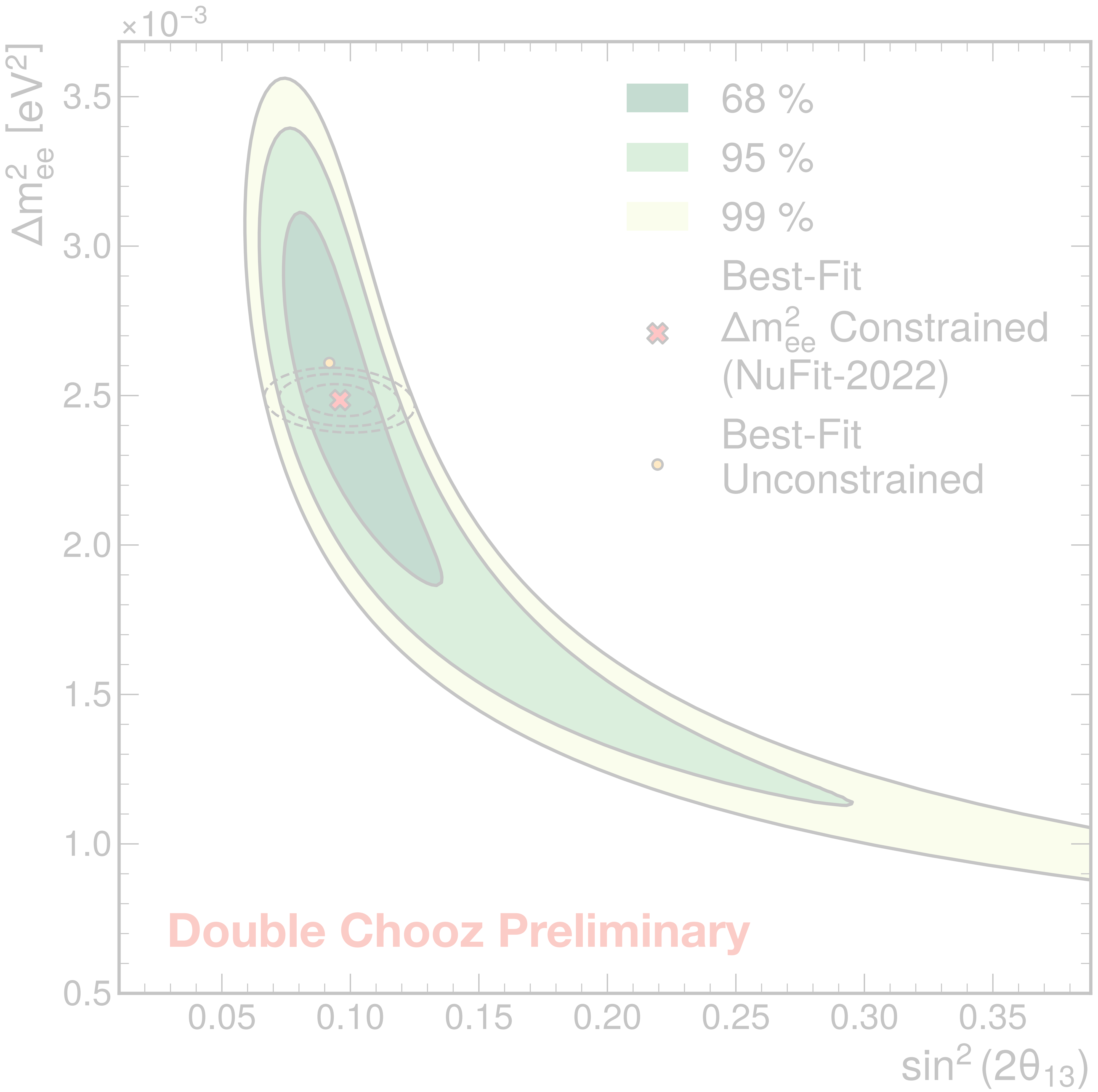
Data, Signal & Background

- Reactor-Off phases can be used to constrain the backgrounds $> 3\,\mathrm{MeV}$
- Corr. Shape deviations illustrate the difference to the assumed reactor model

θ_{13} Fit Results



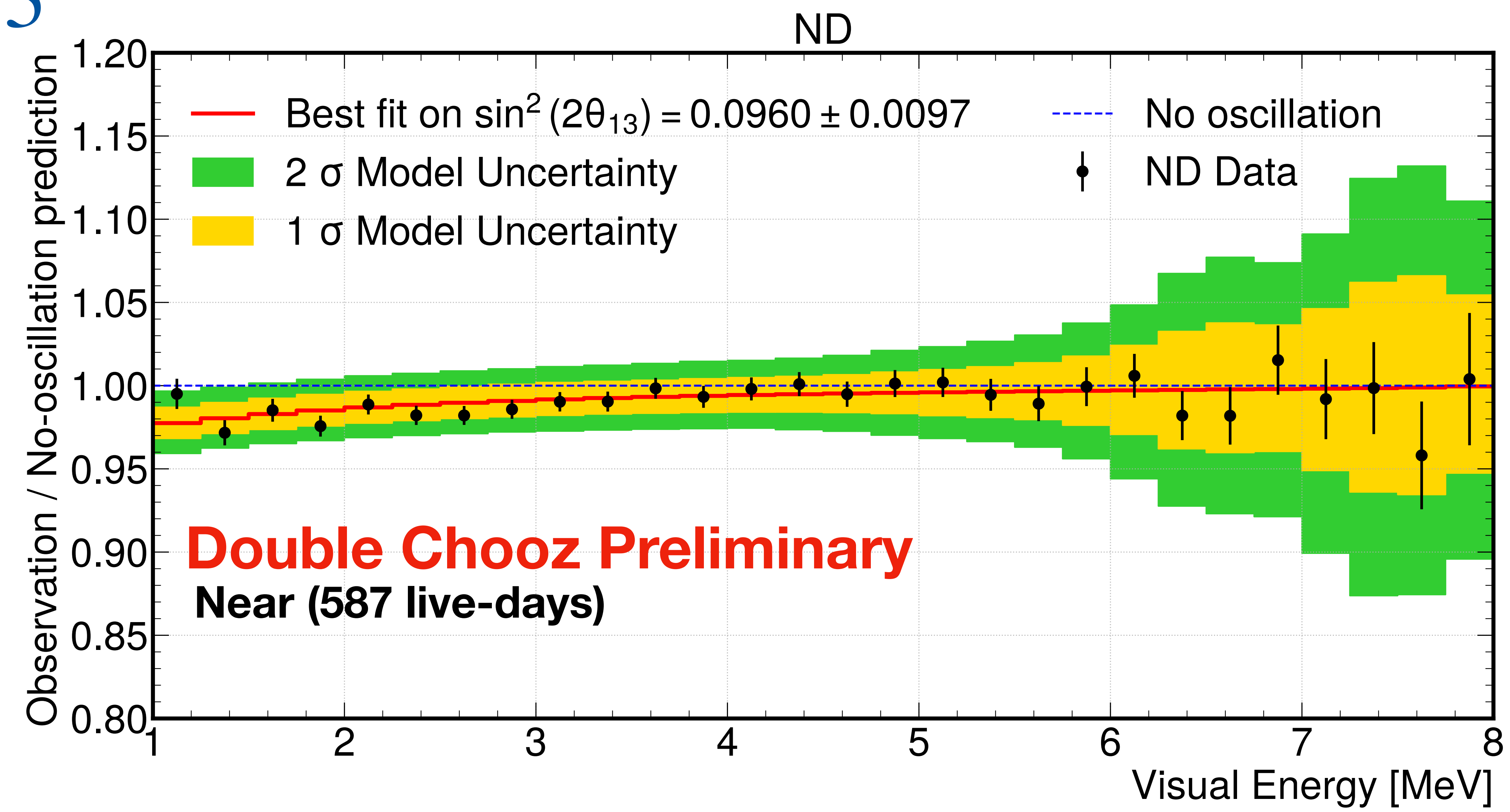


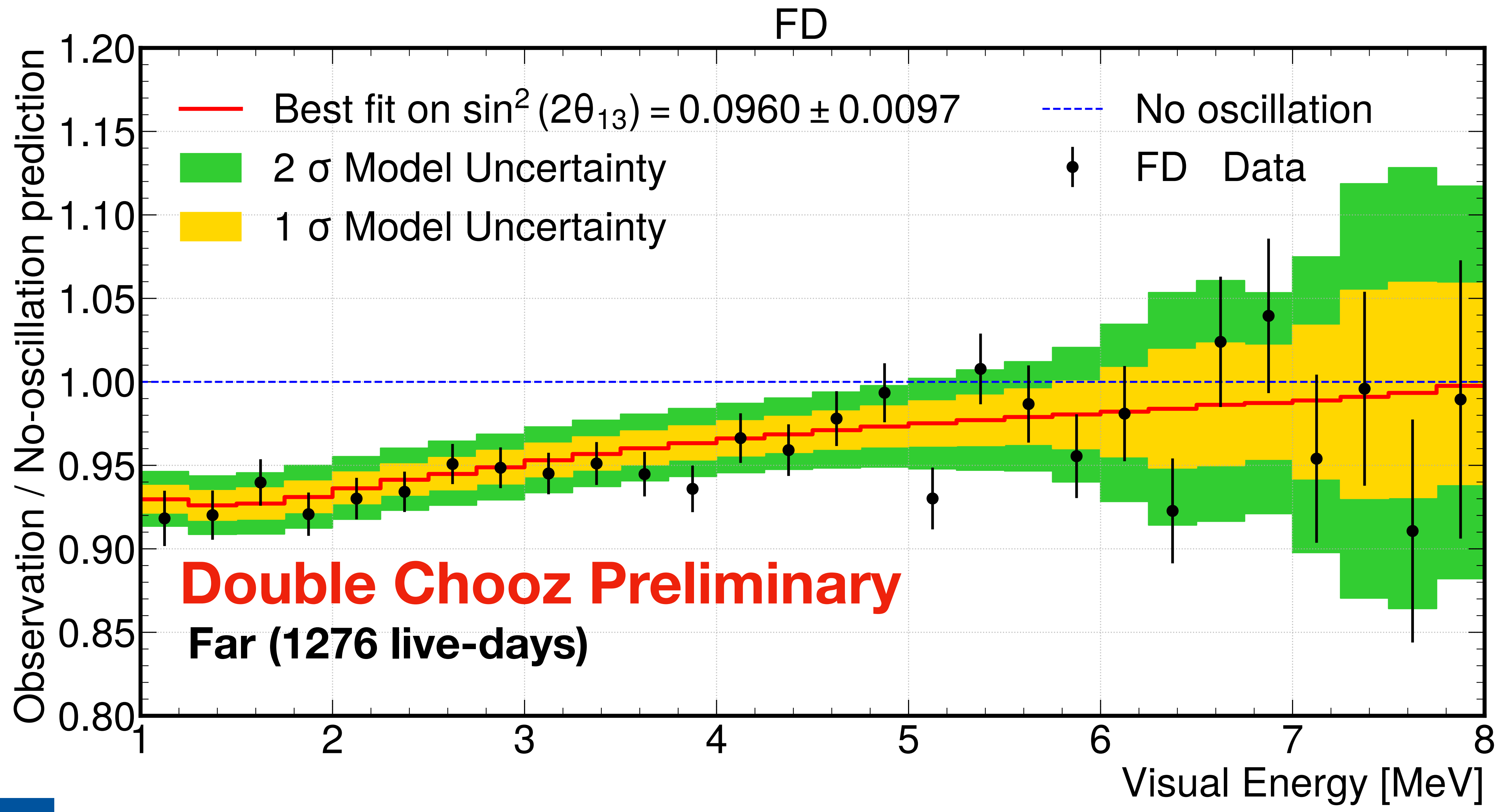


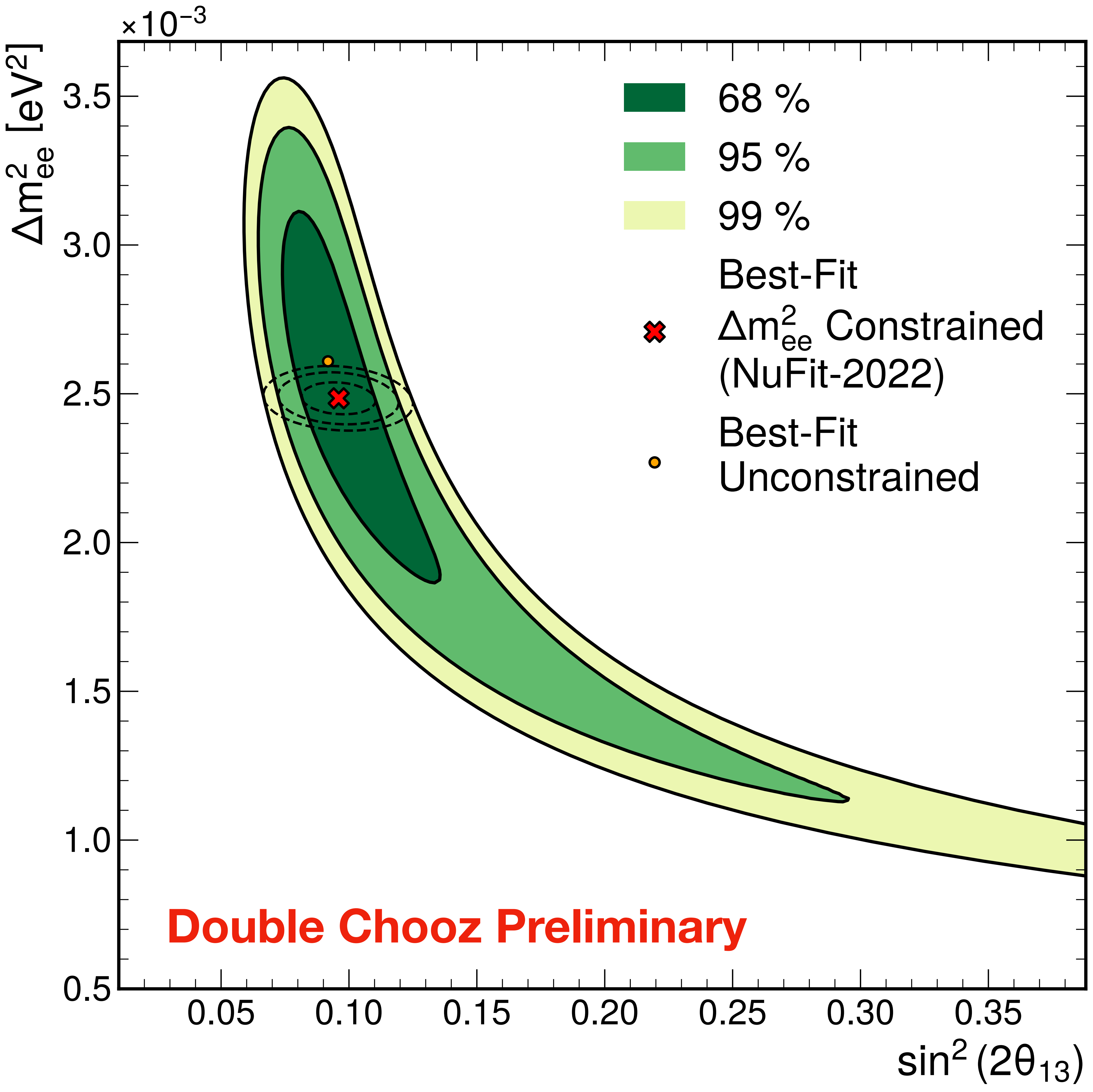
Newest Result:

$$\sin^2(2\theta_{13}) = 0.0960 \pm 0.0086\,(\text{syst.}) \pm 0.0044\,(\text{stat.})$$

θ_{13} Fit Results





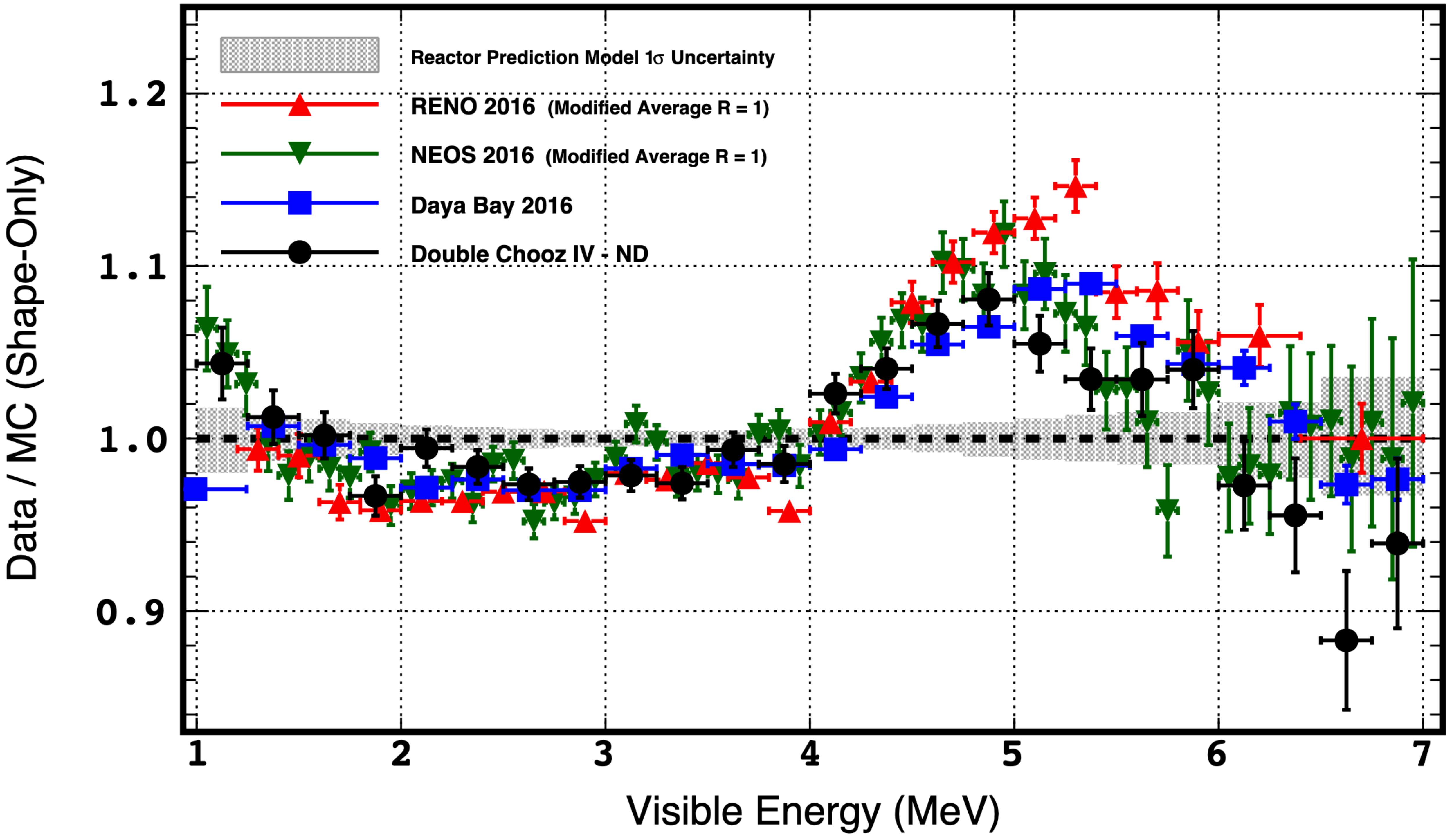


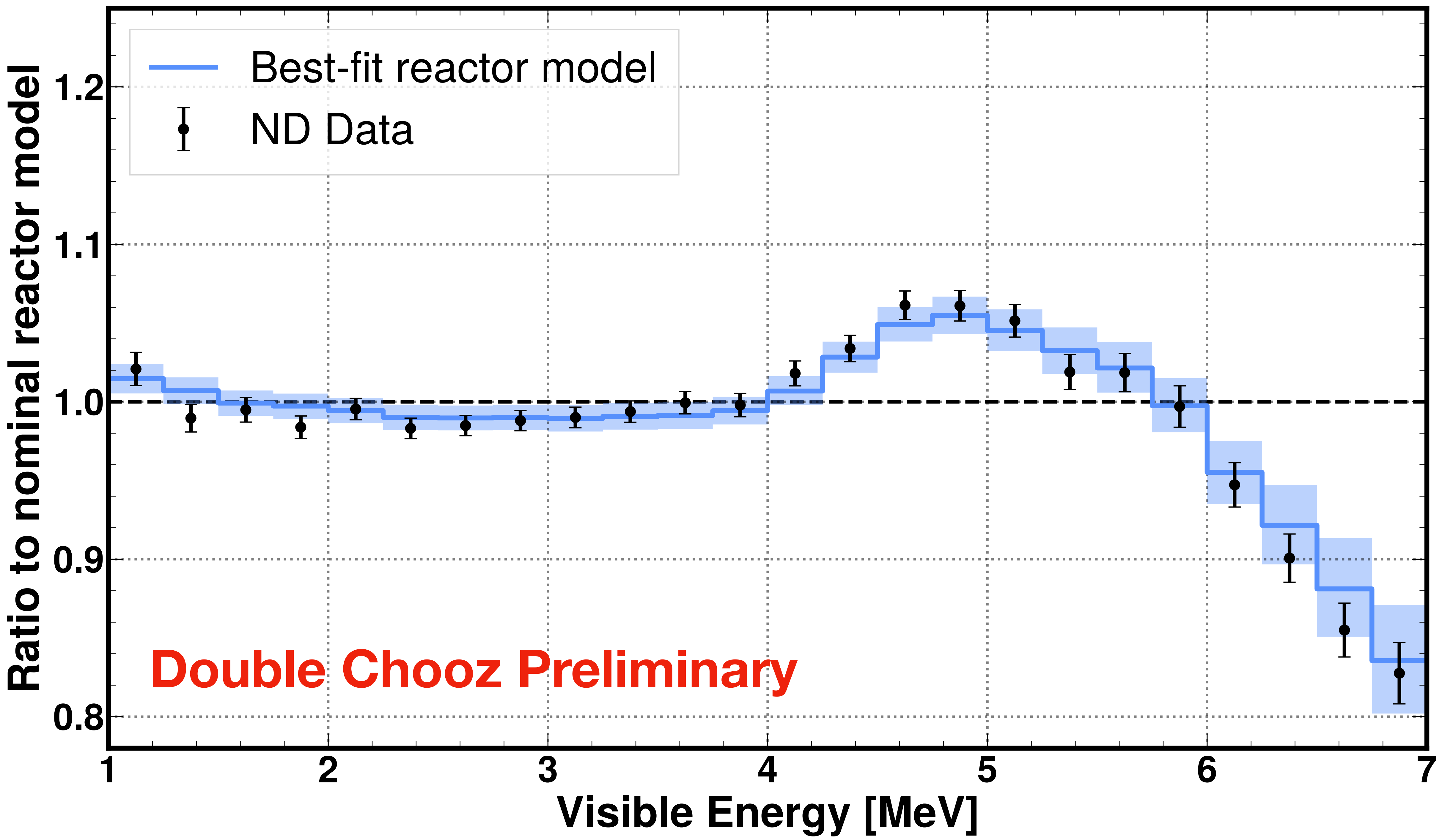
Newest Result:

$$\sin^2(2\theta_{13}) = 0.0960 \pm 0.0086\,(\text{syst.}) \pm 0.0044\,(\text{stat.})$$

Spectral Distortion Extraction

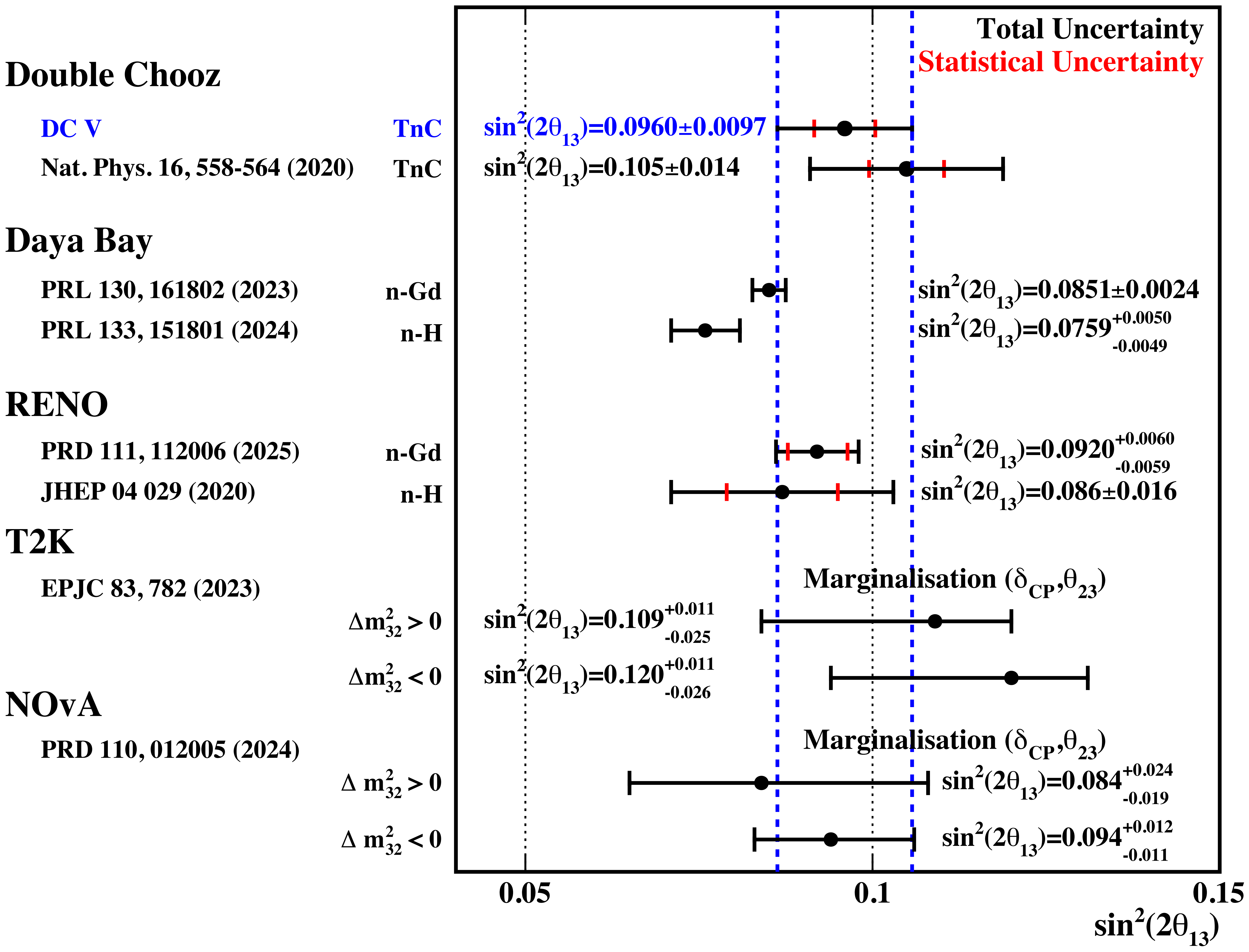
DC IV, Nat. Phys. 16, 558-564 (2020)

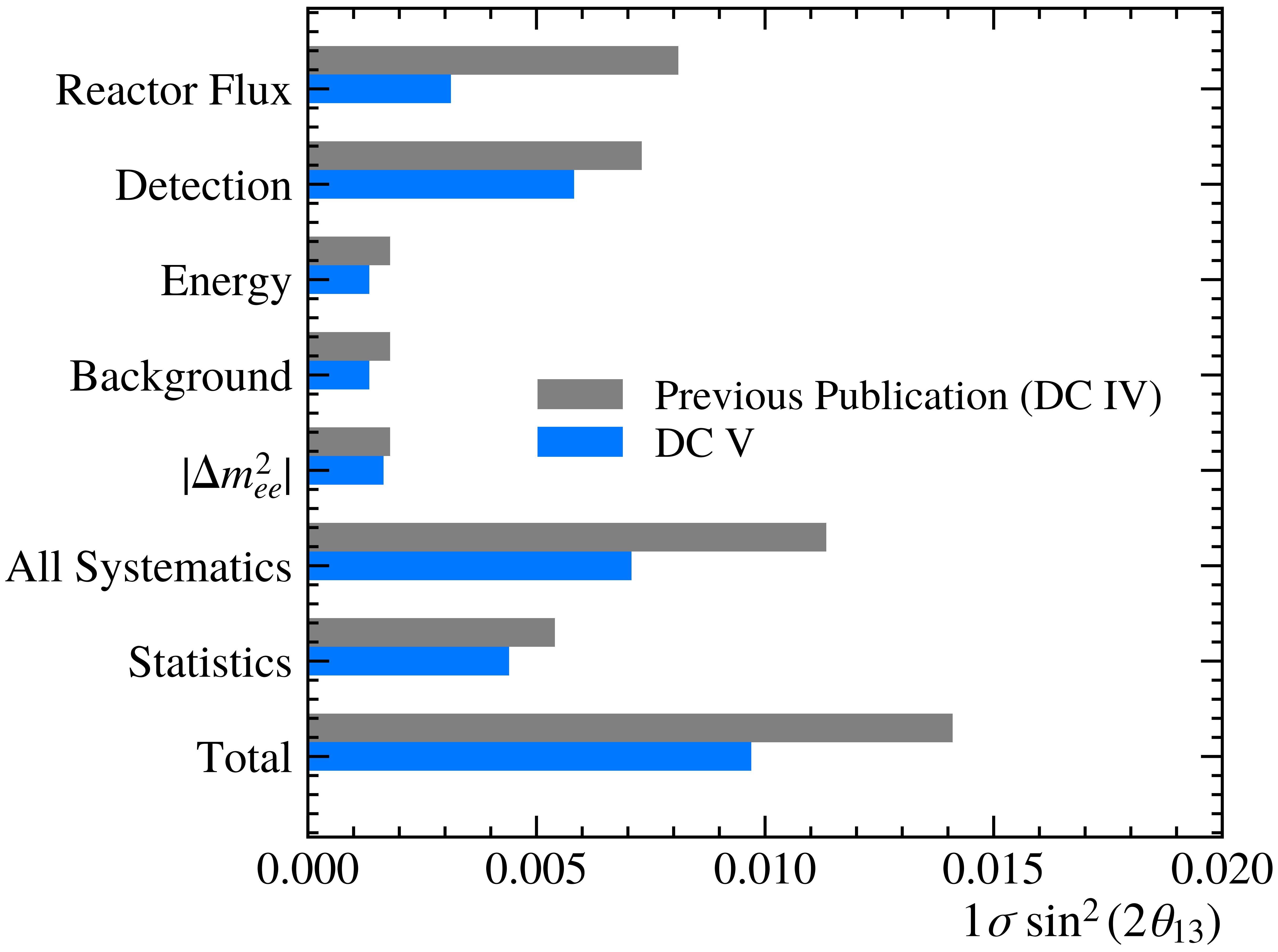




- Visible deviation can be seen by almost all reactor neutrino experiments
- Utilizing the extracted correlated shape deviations, the shape deviation can be observed

θ_{13} Comparison & Systematics Breakdown





- Reactor Flux: Statistics with Iso-flux Setup & Reactor Split
- Detection: Improved Proton# measurement
- Energy: Improved energy model
- Background: Reactor-OFF data

Mean Cross Section per Fission Results (MCSpF)

Fission fraction of k-isotopes

$$\langle \sigma_f \rangle (t) = \sum_k \alpha_k \int S_k(E) \sigma_{\mathrm{IBD}}(E) \mathrm{d}E = \sum_k \alpha_k \langle \sigma_k \rangle$$

MCSpF for k-isotope

Reactor $\bar{\nu}_e$ spectrum from k-isotope

Reactor $\bar{\nu}_e$ spectrum from k-isotope

Counting Approach

$$\langle \sigma_f \rangle = \frac{N(\bar{\nu}_e)}{N_p \epsilon} \left(\sum_{r=\mathrm{B1,B2}} \frac{\langle P_{\mathrm{th}} \rangle_r}{4\pi L_r^2 \langle E_f \rangle_r} \right)^{-1} \frac{\mathrm{cm}^2}{\mathrm{fission}}$$

- Based on ND statistics only
- The resulting value is: DC IV, Nat. Phys. 16, 558-564 (2020)

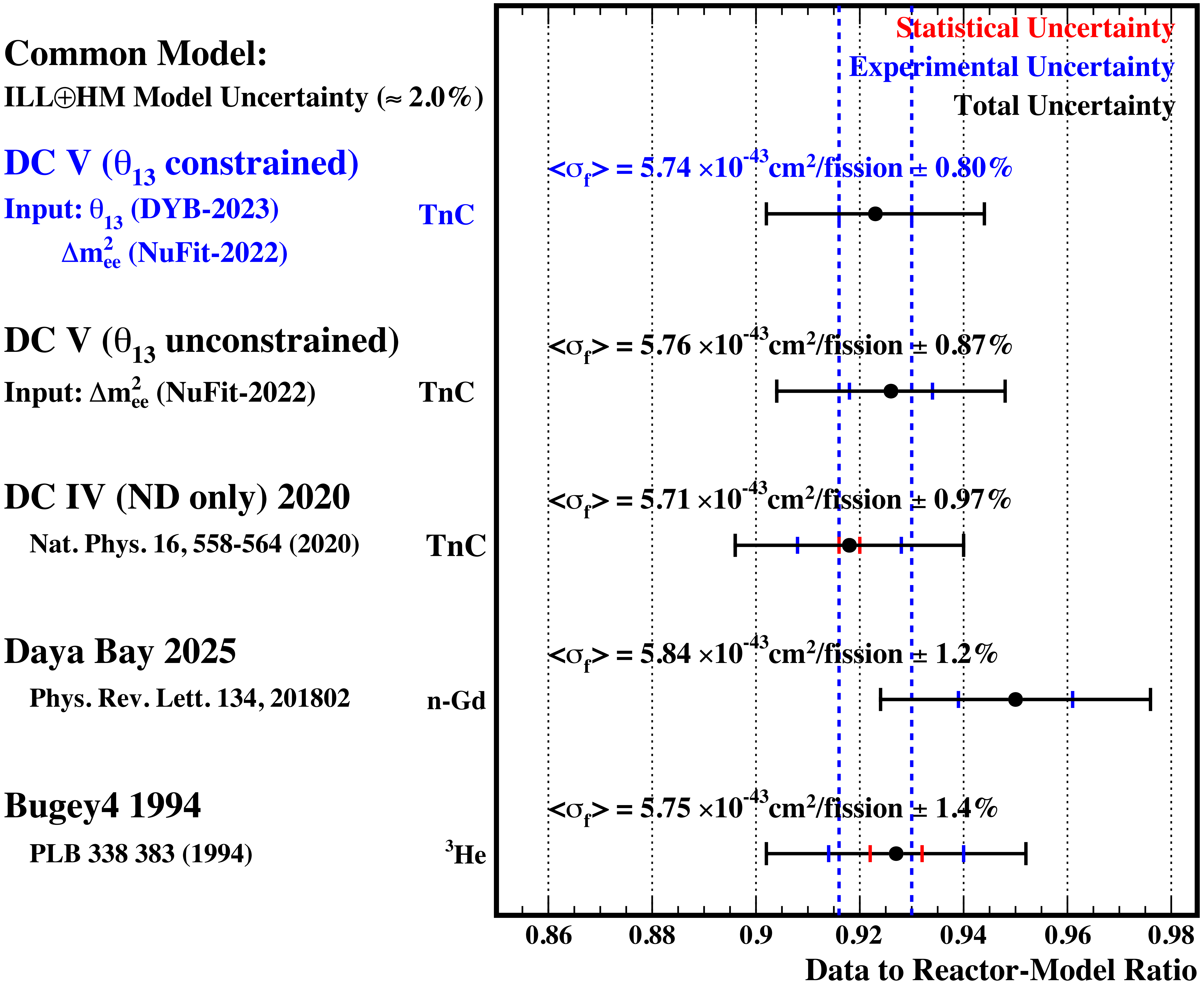
$$\langle \sigma_f^{\mathrm{ND}} \rangle = (5.71 \pm 0.06) \cdot 10^{-43} \frac{\mathrm{cm}^2}{\mathrm{fission}}$$

- Relative Uncertainty of $0.97\,\%$

Fit Approach

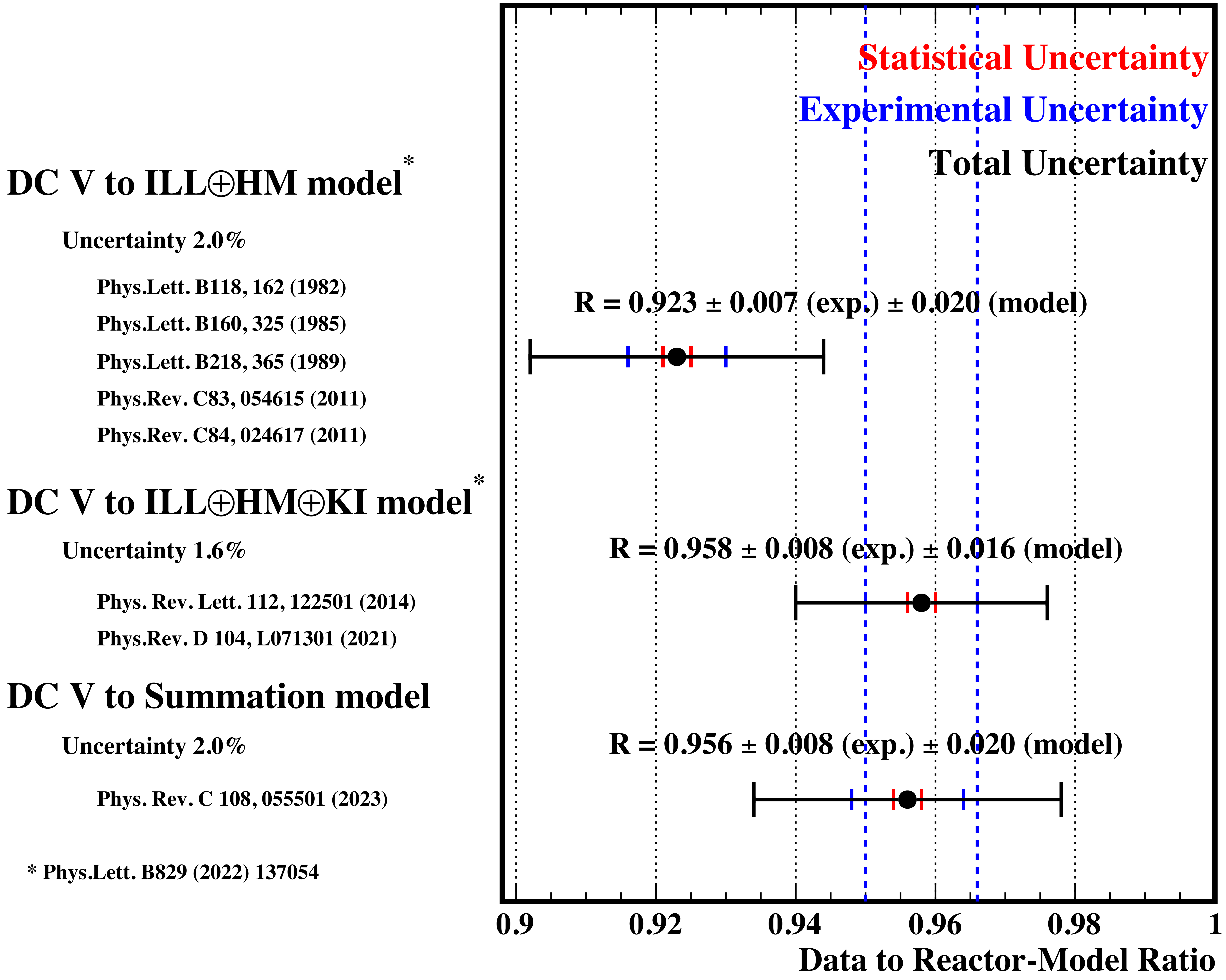
- Through common normalization parameter of θ_{13} fit in all detectors
- **Full** DC-statistics
- Can be constrained with information from other experiments via nuisance parameters
- Single detector systematics improved due to proton#

Mean Cross Section per Fission Results (MCSpF)



- Most precise MCSpF uncertainty of $0.8\ \%$
- DC alone gives $0.87\ \%$
- In agreement with other experiments
- Still inconsistency between experiments and ILL+HM model

MCSpF Model Comparison



- Additionally compared to summation model and Kurchatov Institute model
- Kurchatov Institute (KI) model and Summation model are in better agreement with data
- Indication that ILL+HM is underestimating the U235 normalization

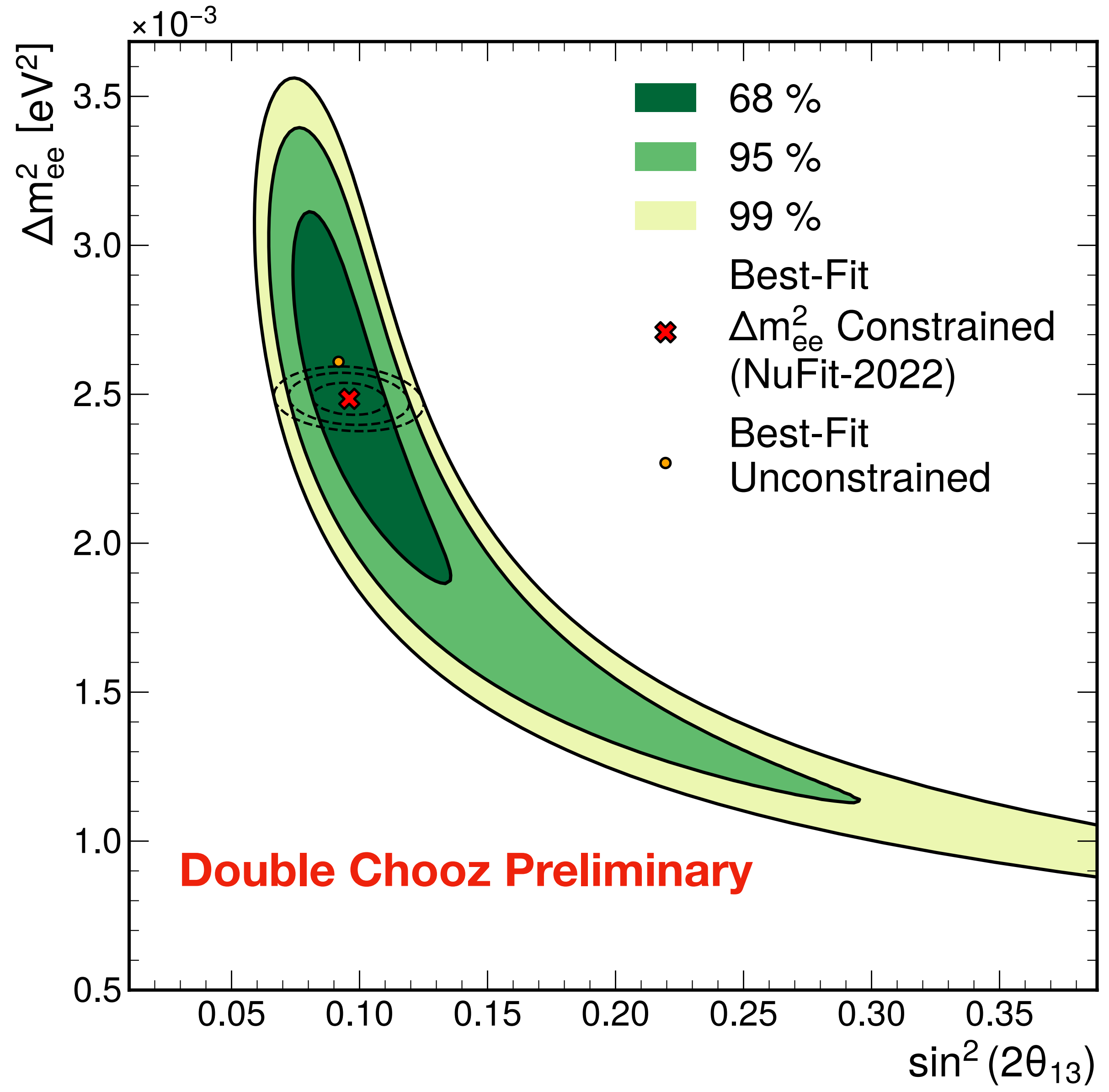
DOUBLE CHOOZ COLLABORATION

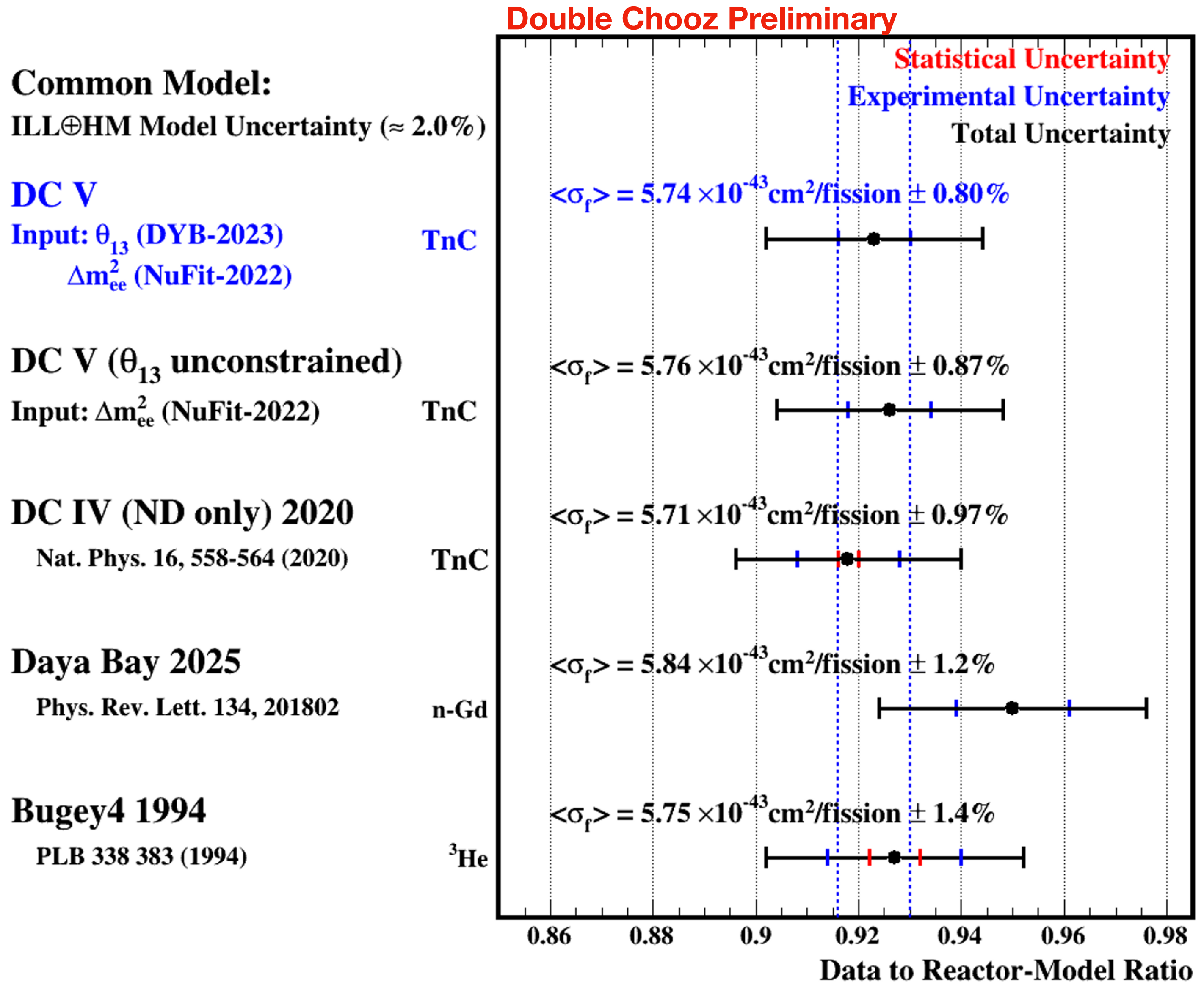
Many people contributed to the experiment

Thanks for all the hard work!

Conclusion

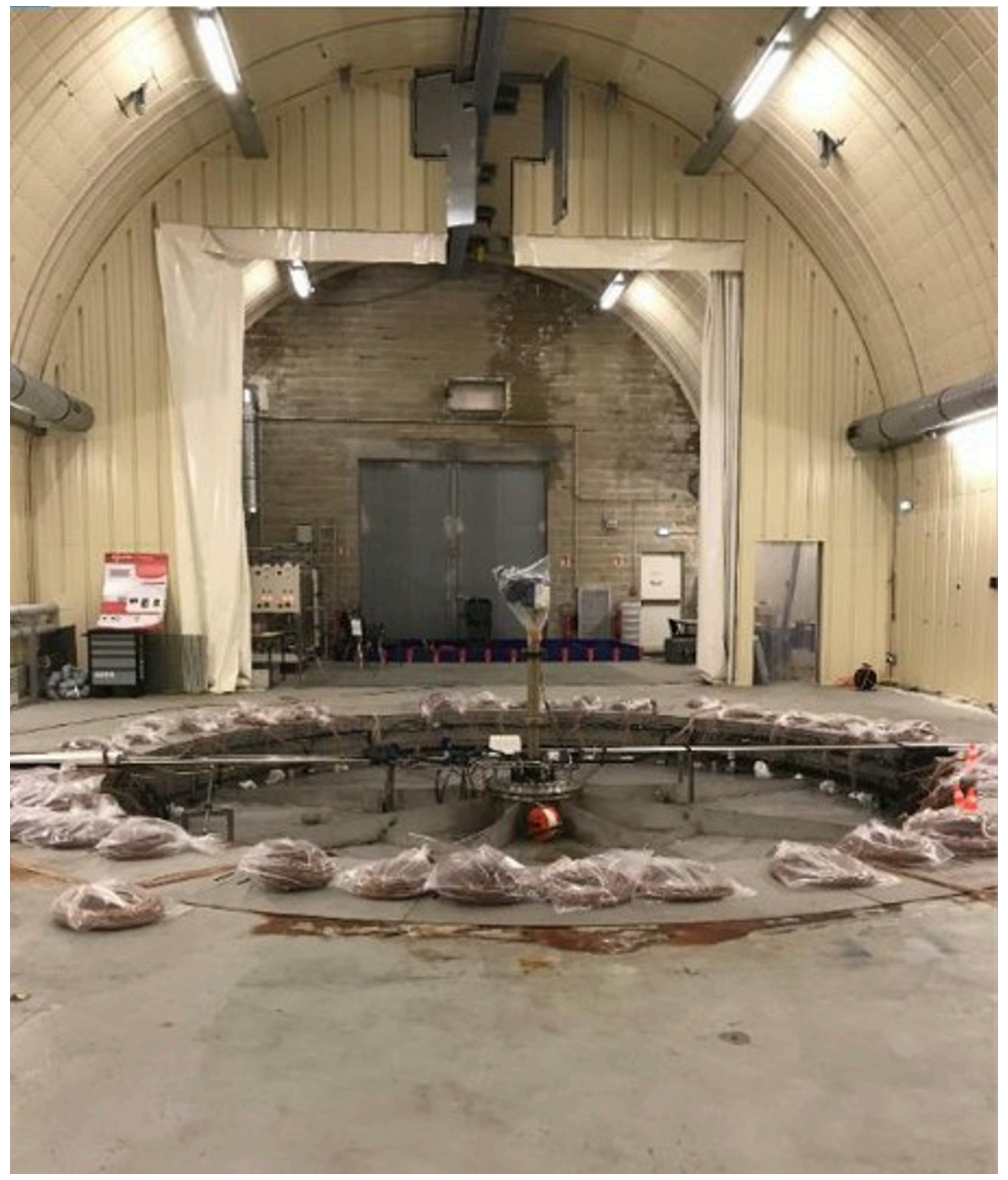
- Double Chooz is a reactor neutrino disappearance experiment
- Double Chooz detectors have been dismantled
- Final best fit: $\sin^2(2\theta_{13}) = 0.0960 \pm 0.0086\,(\text{syst.}) \pm 0.0044\,(\text{stat.})$
- Best $\langle\sigma_F\rangle = (5.74 \pm 0.80\%) \times 10^{-43}$ cm²/fission measurement
- Final publication is on its way!
- First Measurement of Neutrino Emissions from Spent Nuclear Fuel publication on the way

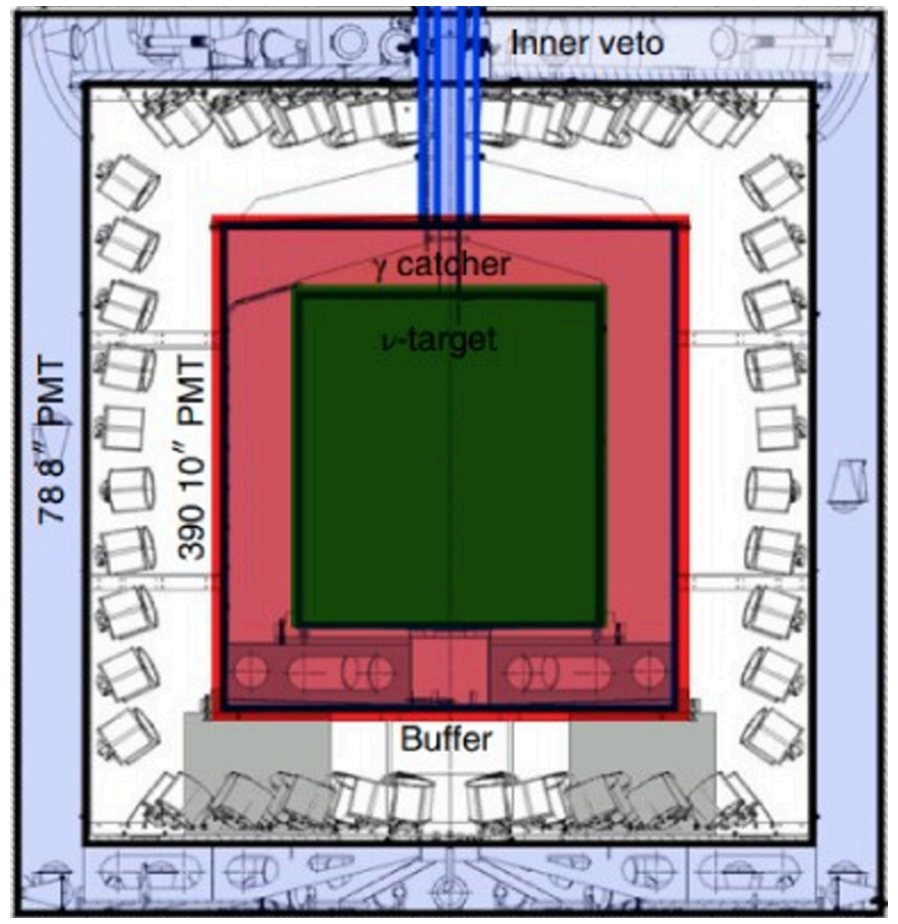




Backup

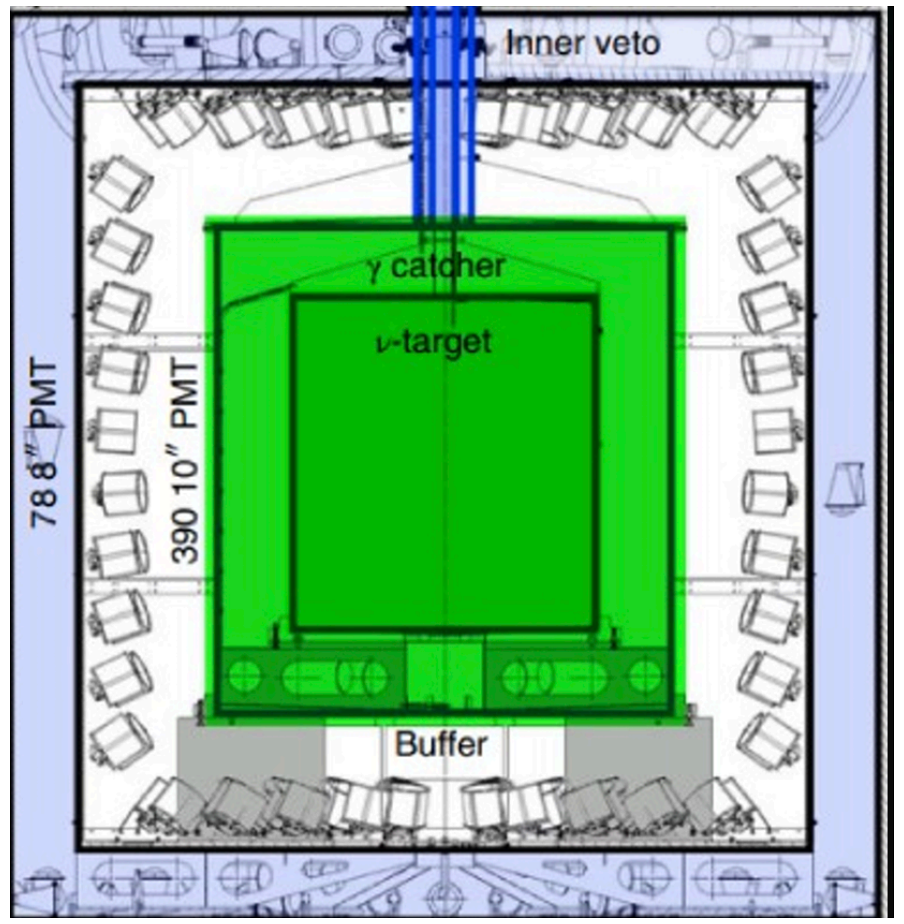
Detector Dismantling



$1\,\sigma\,\sin^2(2\theta_{13})$

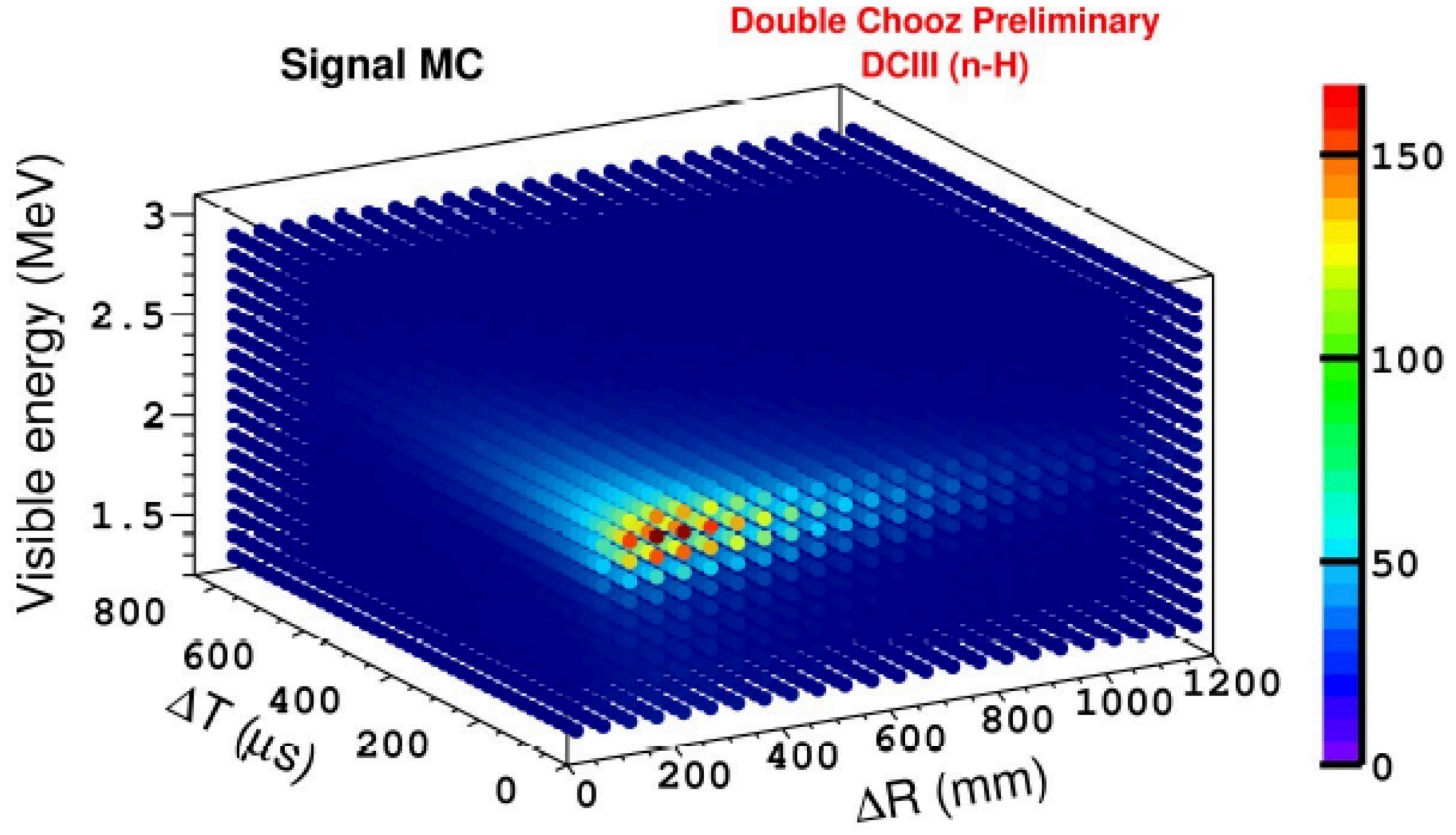
0.012

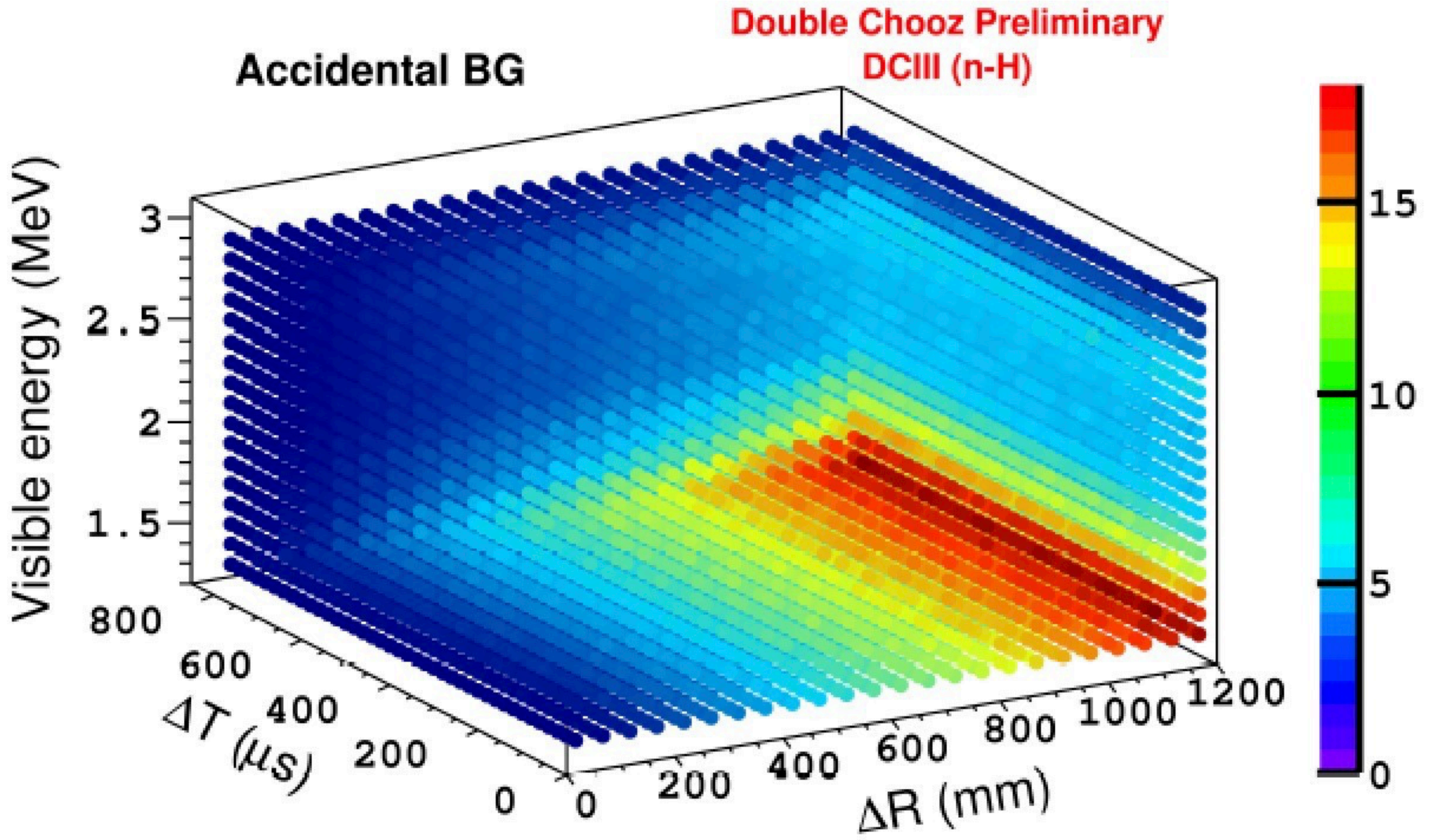


0.0099

- Double Chooz Detector has beed dismantled
- During dismantling new γ-catcher mass measurement
- Based on 3D Laser technique (LEICA RTC 360 - 2mm precision)
- M_{liquid} uncertainty reduced by $50\,\%$
- Detection efficiency improvement and more precise measurement of Mean Cross Section per Fission (MCSpF)

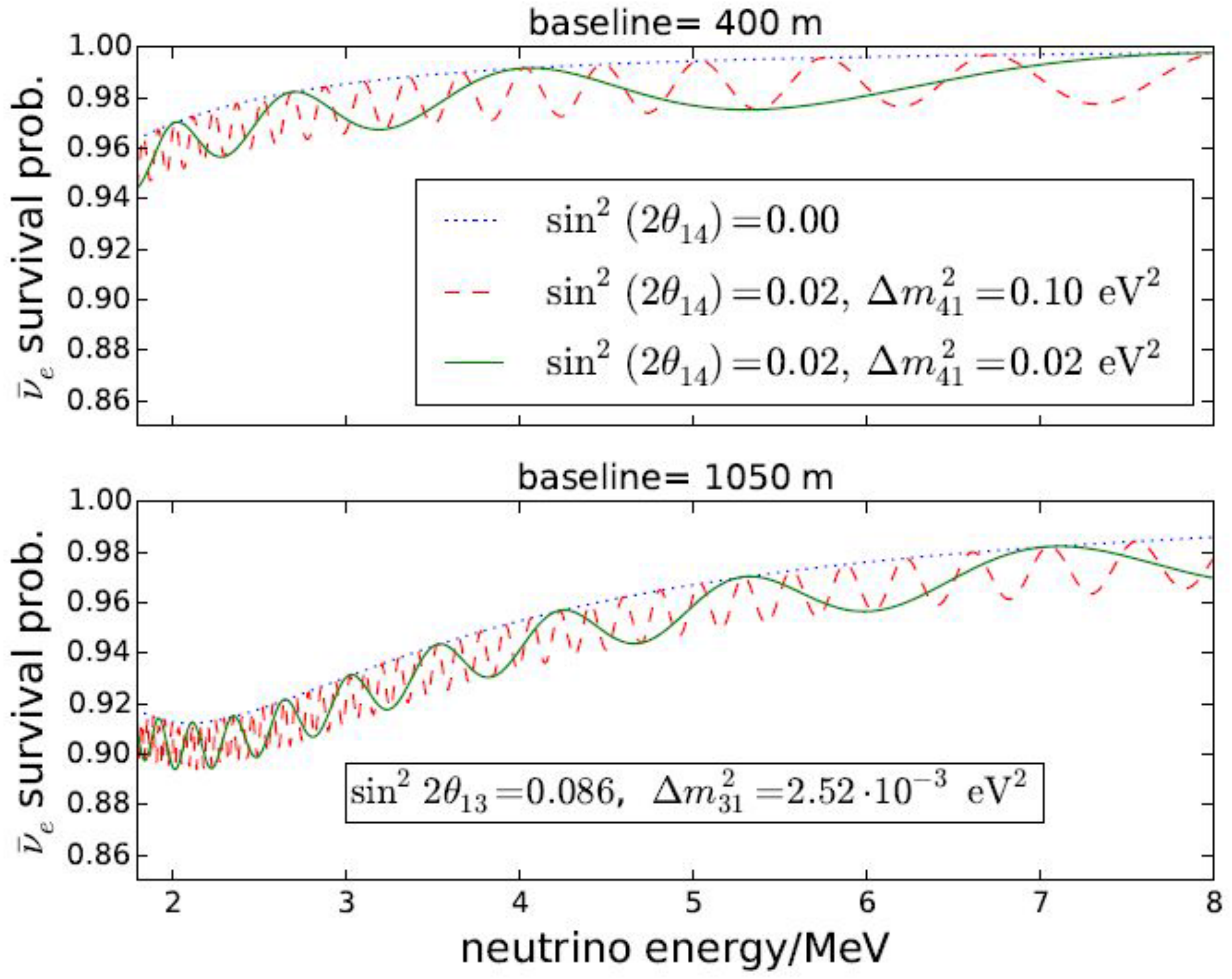
Accidental Background ANN Variables

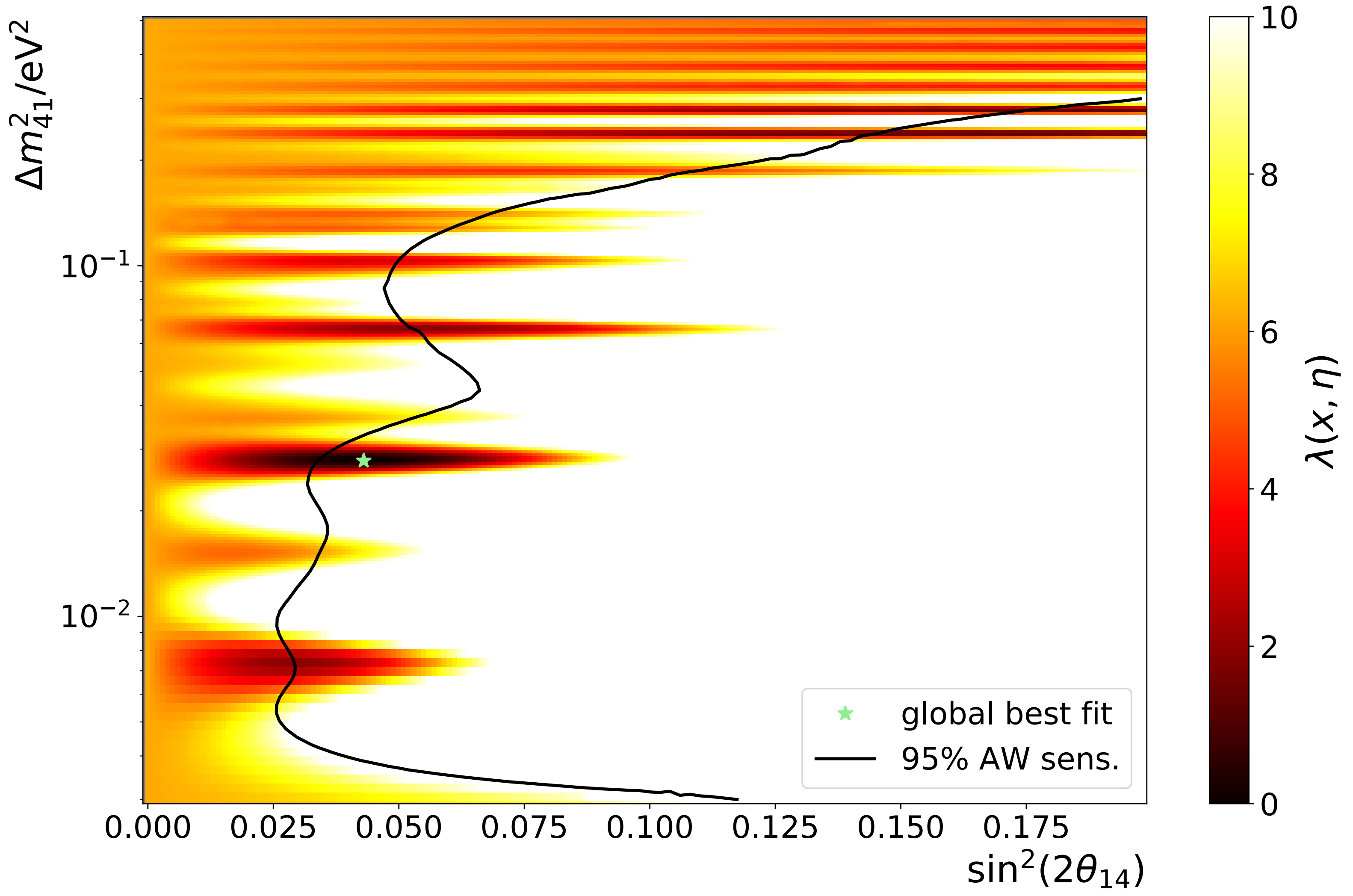


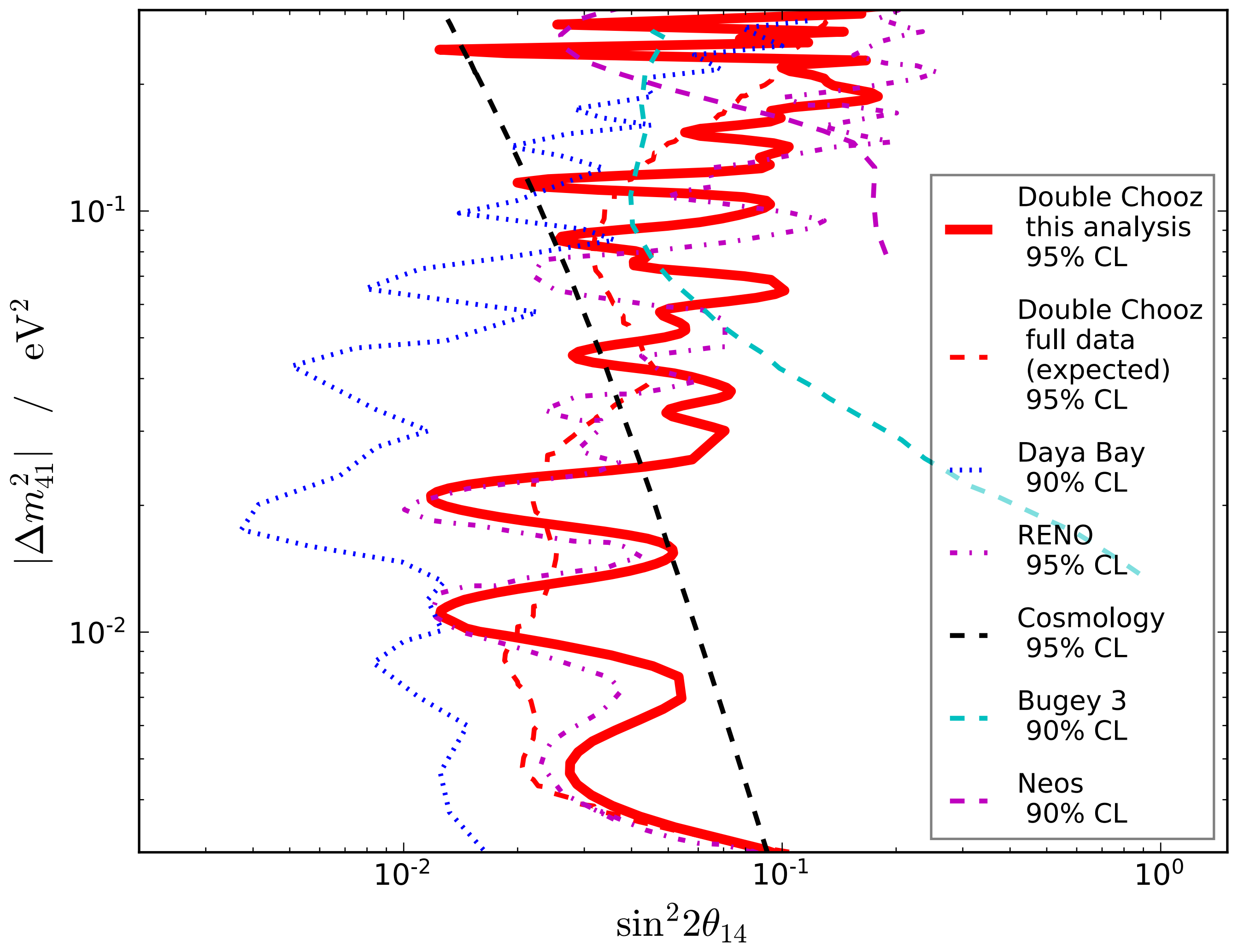


Sterile Neutrinos

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - \sin^2(2\theta_{13})\sin^2\left(\frac{\Delta m^2_{ee}L}{4E}\right) - \sin^2(2\theta_{14})\sin^2\left(\frac{\Delta m^2_{41}L}{4E}\right)$$







- Double Chooz did also perform a search for sterile neutrinos
- The signal would manifest in a systematic deficit of the θ_{13} oscillation
- $95\ \%$ confidence level for the measurement data is given

1D Profile Likelihood Scan