DC V:
Double Chooz Latest and Last Results

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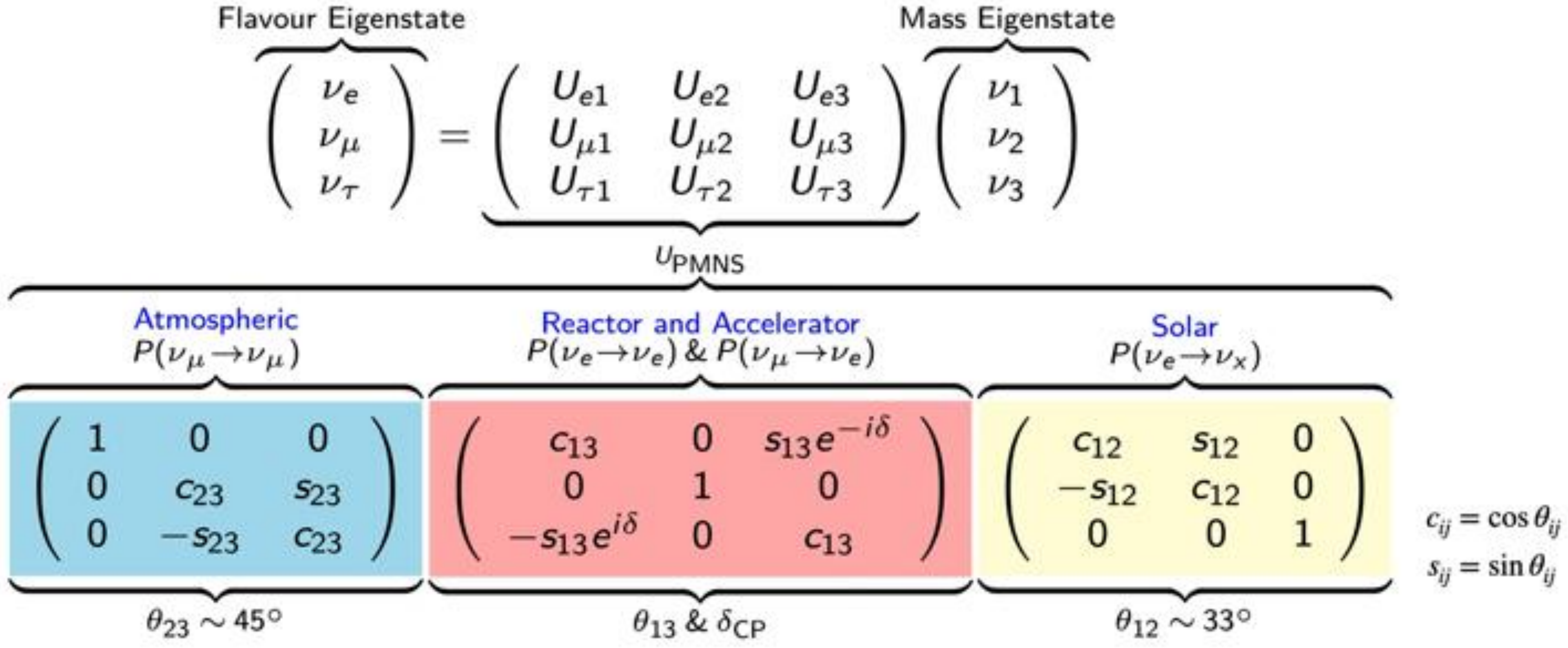
for the Double Chooz Collaboration

NATIONAL RESEARCH CENTER
"KURCHATOV INSTITUTE"

TWENTY-SECOND LOMONOSOV
CONFERENCE August, 21-27, 2025
ON ELEMENTARY PARTICLE PHYSICS
MOSCOW STATE UNIVERSITY

Neutrino Oscillation

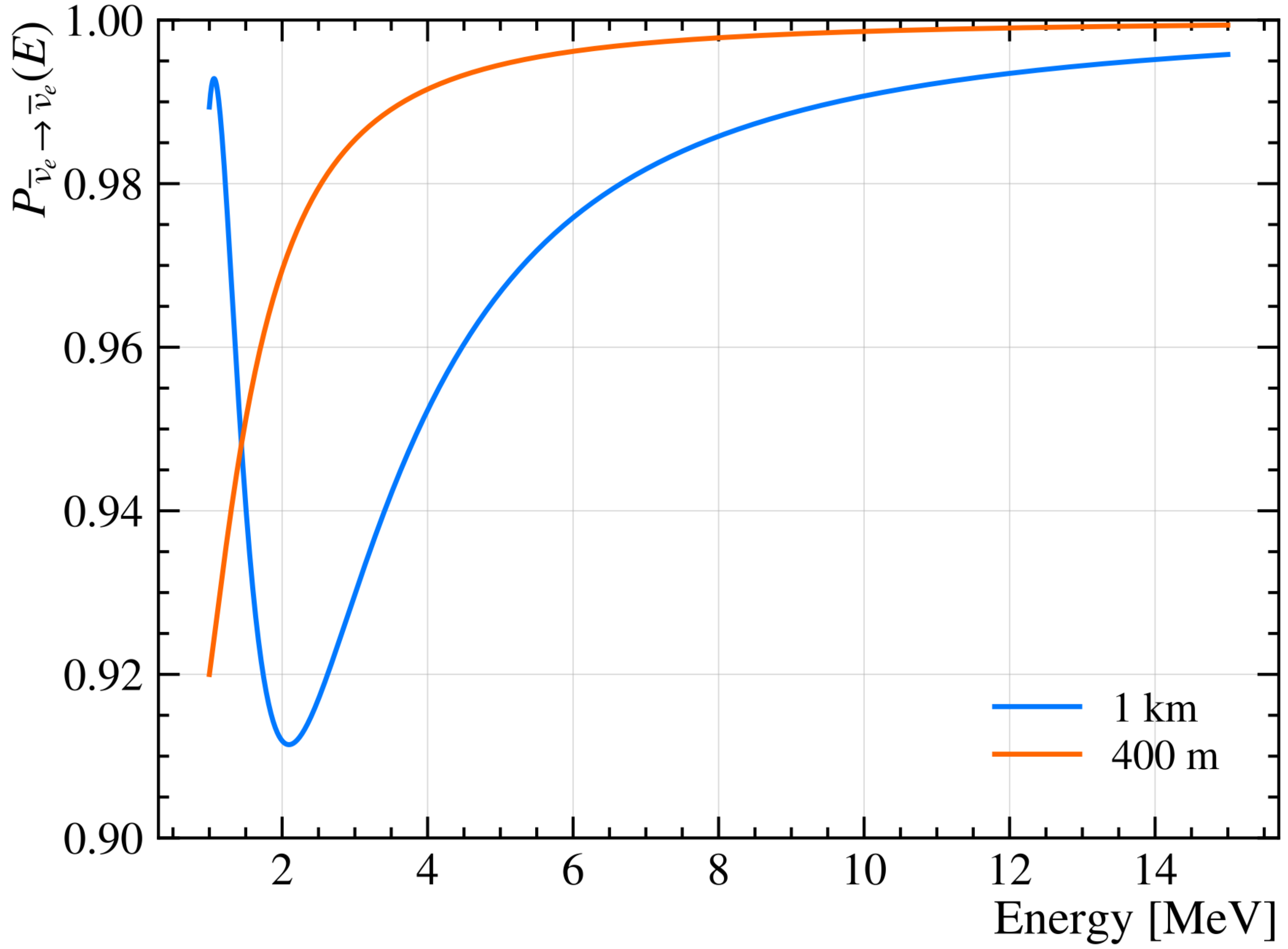


$$P(\overline{\nu}_e \to \overline{\nu}_e) = |\langle \overline{\nu}_e | \overline{\nu}_e \rangle|^2 = \left| \sum_i U_{ei}^* U_{ei} \exp\left(-i \frac{m_i^2 L}{2E}\right) \right|^2 = \ldots$$

$$\approx 1 - \sin^2(2\theta_{13}) \sin^2\Delta_{ee} - \cos^4\theta_{13} \sin^2(2\theta_{12}) \sin^2\Delta_{21}$$

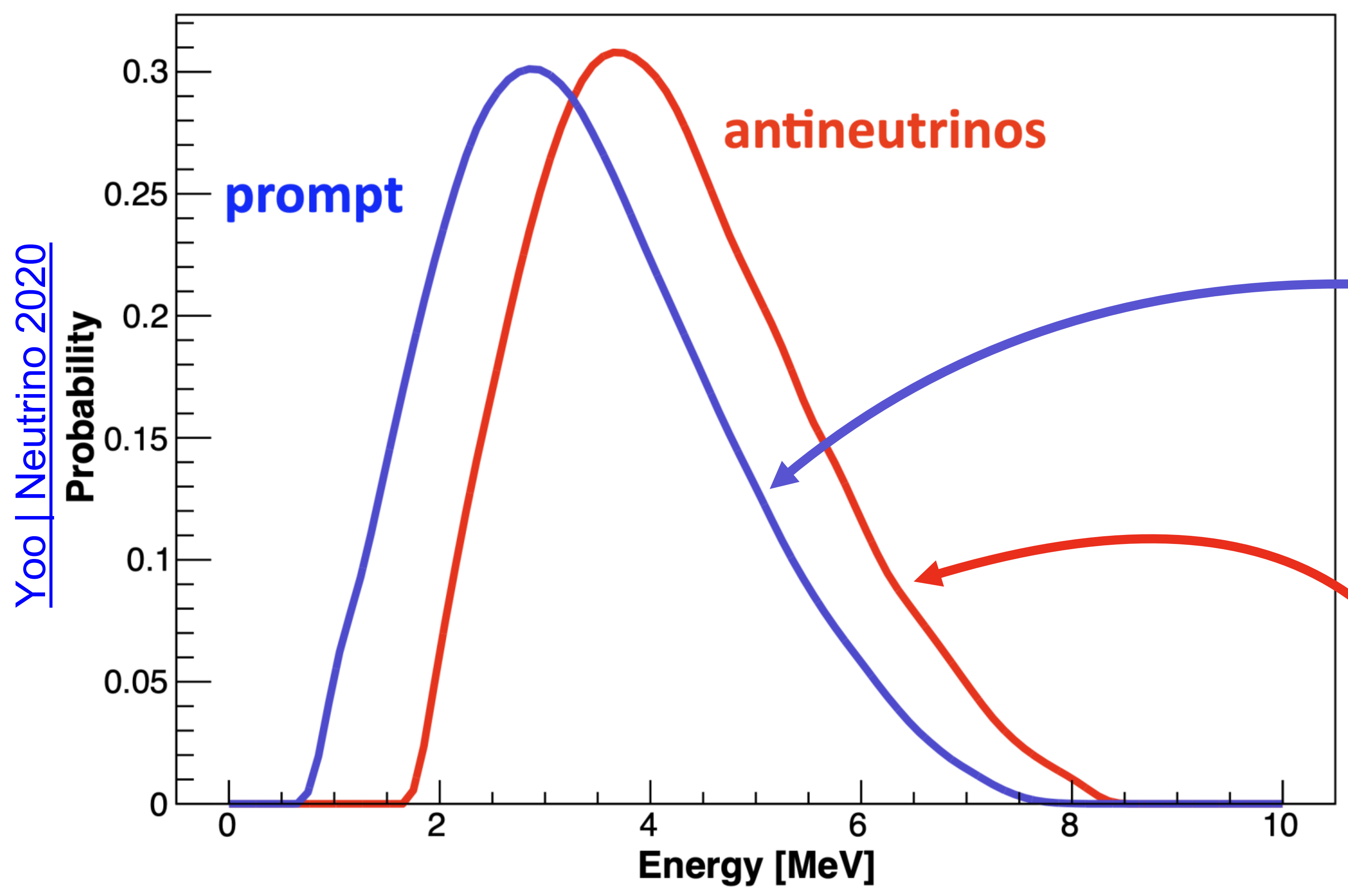
$$\Delta m_{ee}^2 \equiv \cos^2\theta_{12} \Delta m_{31}^2 + \sin^2\theta_{12} \Delta m_{32}^2$$

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

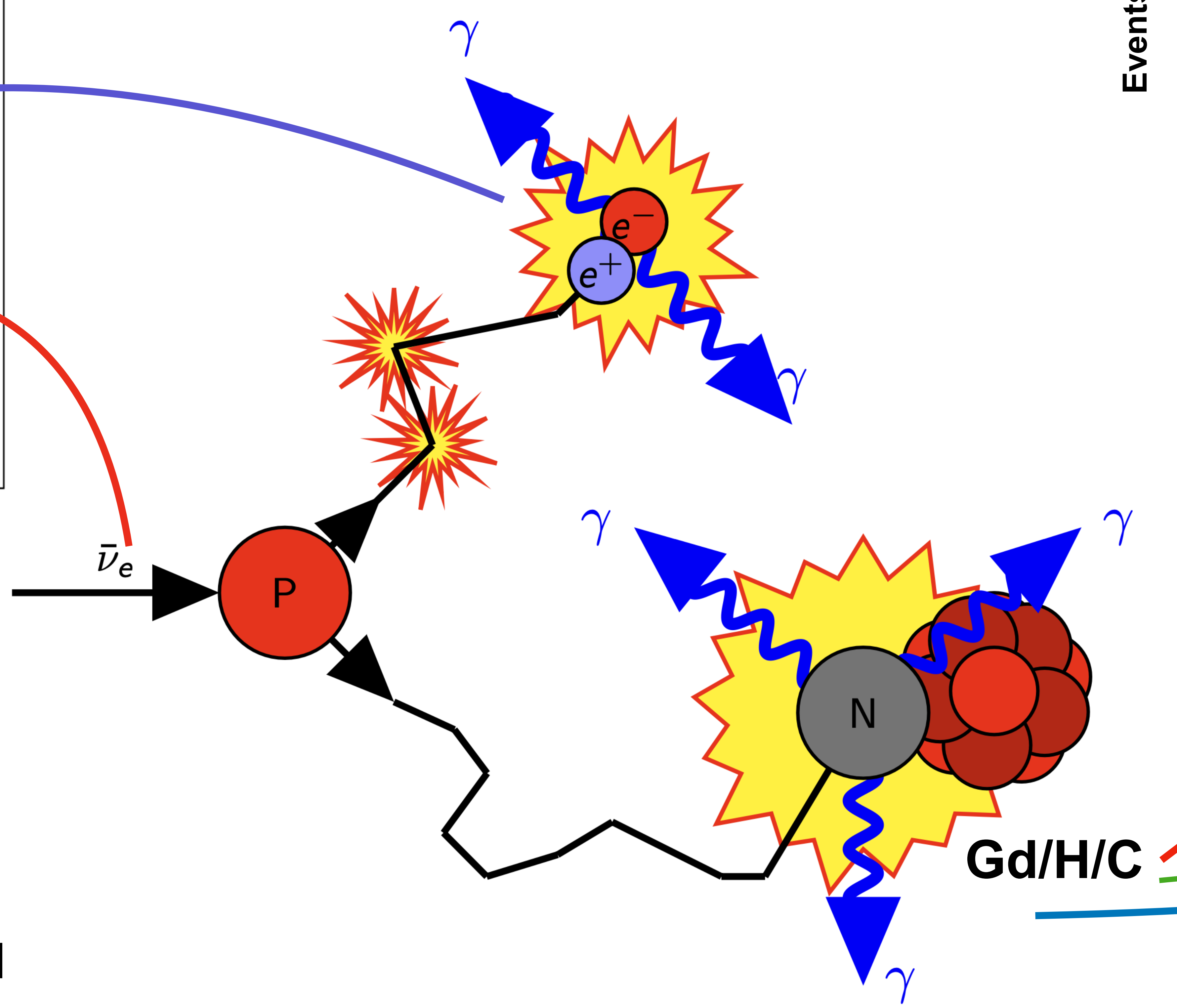


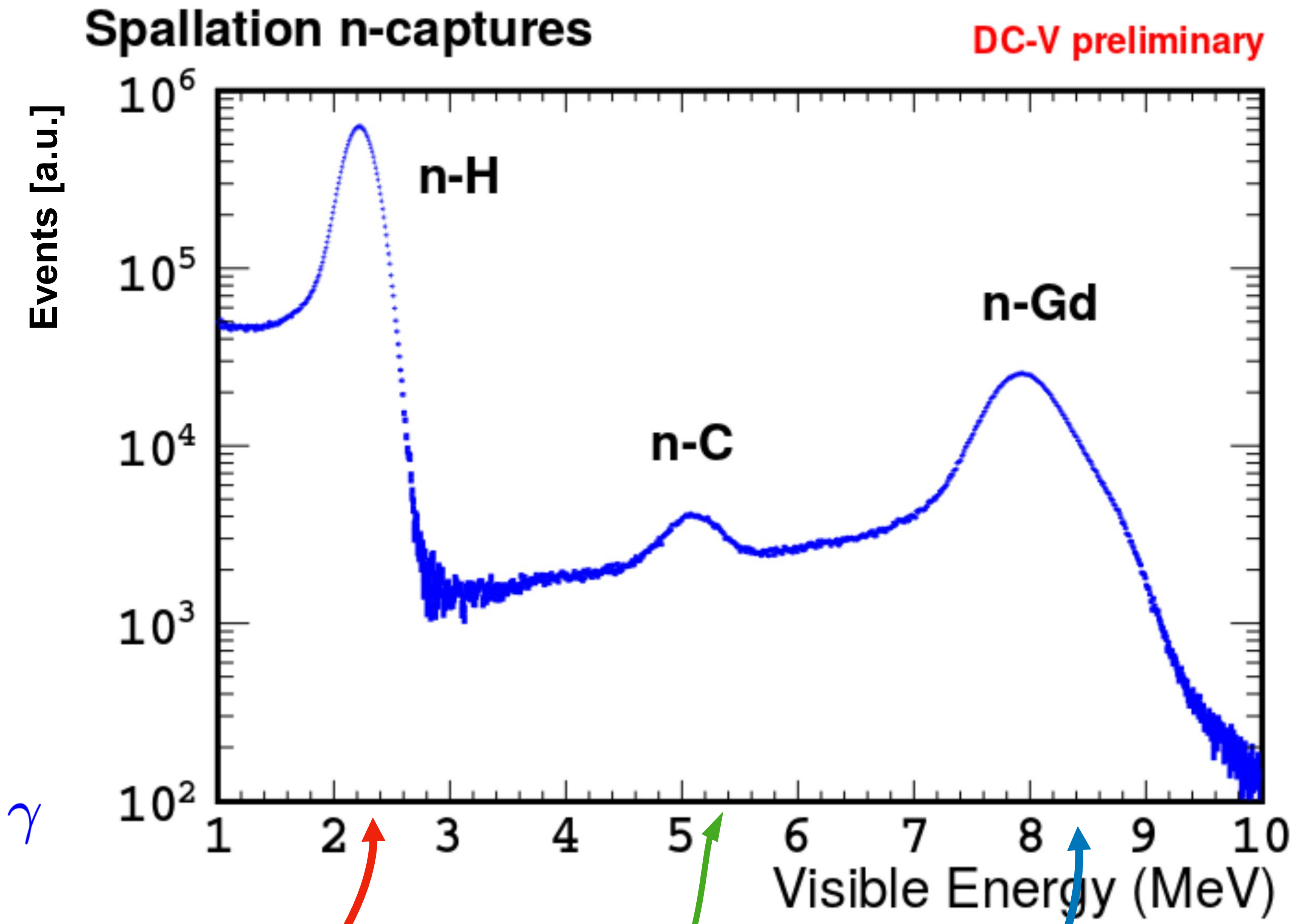
- Neutrinos *oscillate* as a function of distance and energy;
- For a single flavour ($\overline{\nu}_e$) source the energy spectrum changes for different distances;
- For fixed distances the effect is observable as a systematic deficit of measured neutrinos.

Neutrino Detection via Inverse Beta Decay



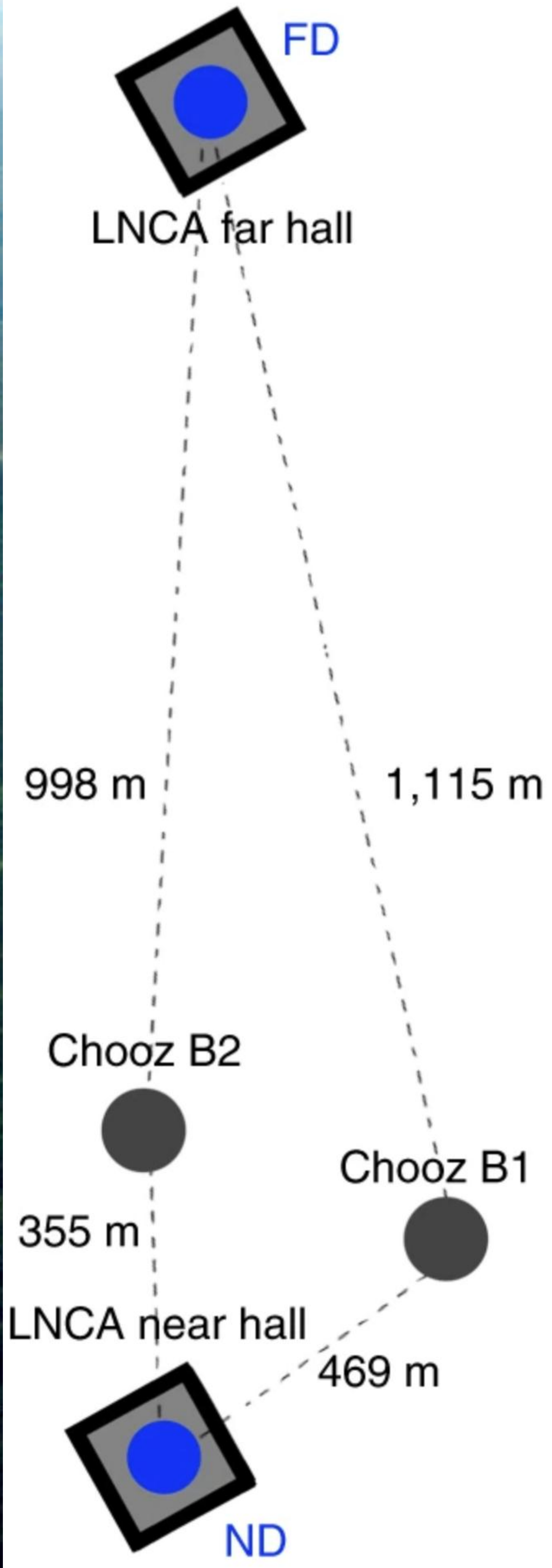
$$\bar{\nu}_e + p \rightarrow n + e^+$$



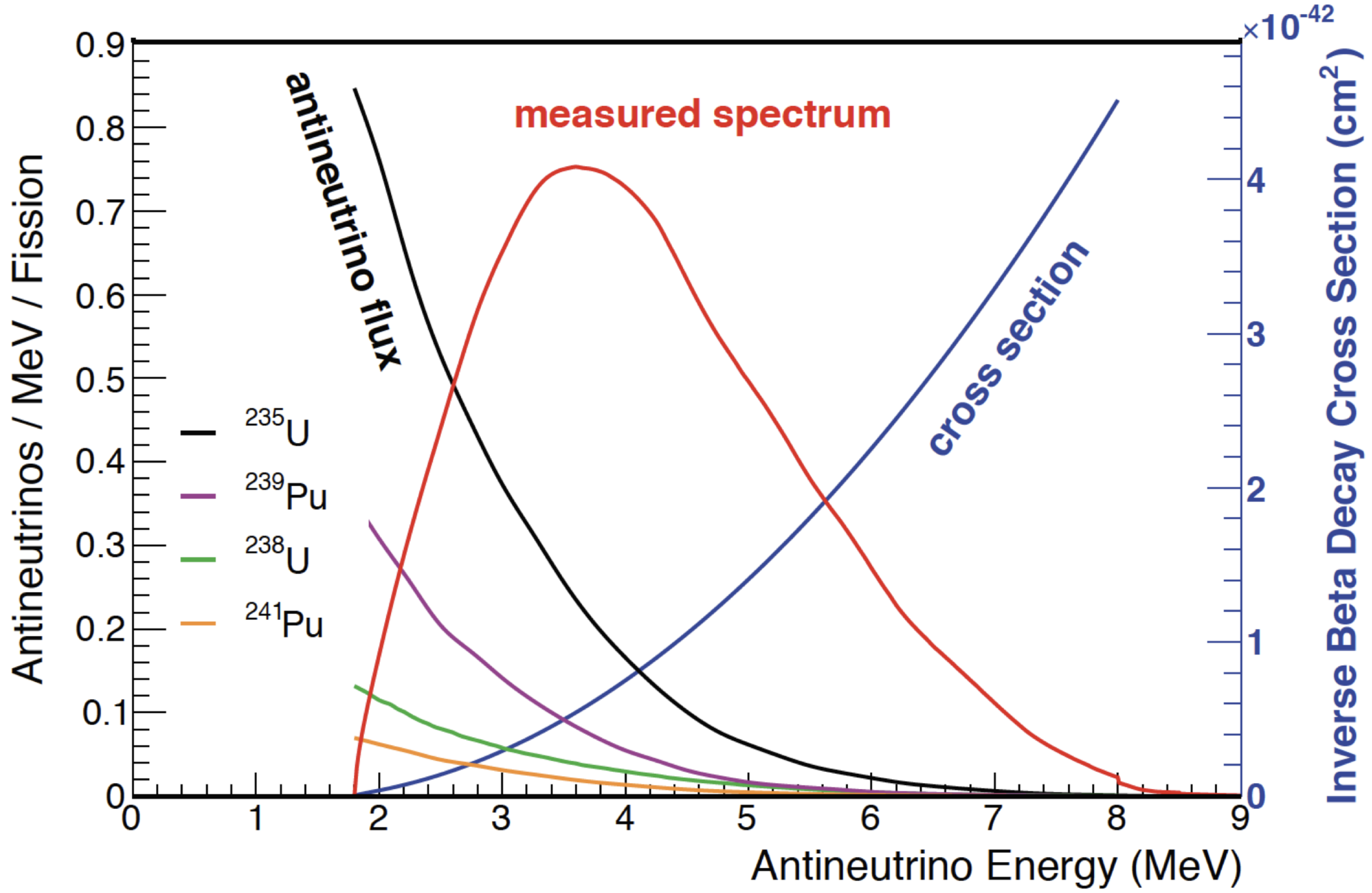


- $1.8\mathrm{MeV}$ threshold for IBD process
  - $E_{\text{prompt}} \approx E_\nu - 0.8\mathrm{MeV}$
- Distinct double event signature
- Low background due to double signal
- Relatively high cross section

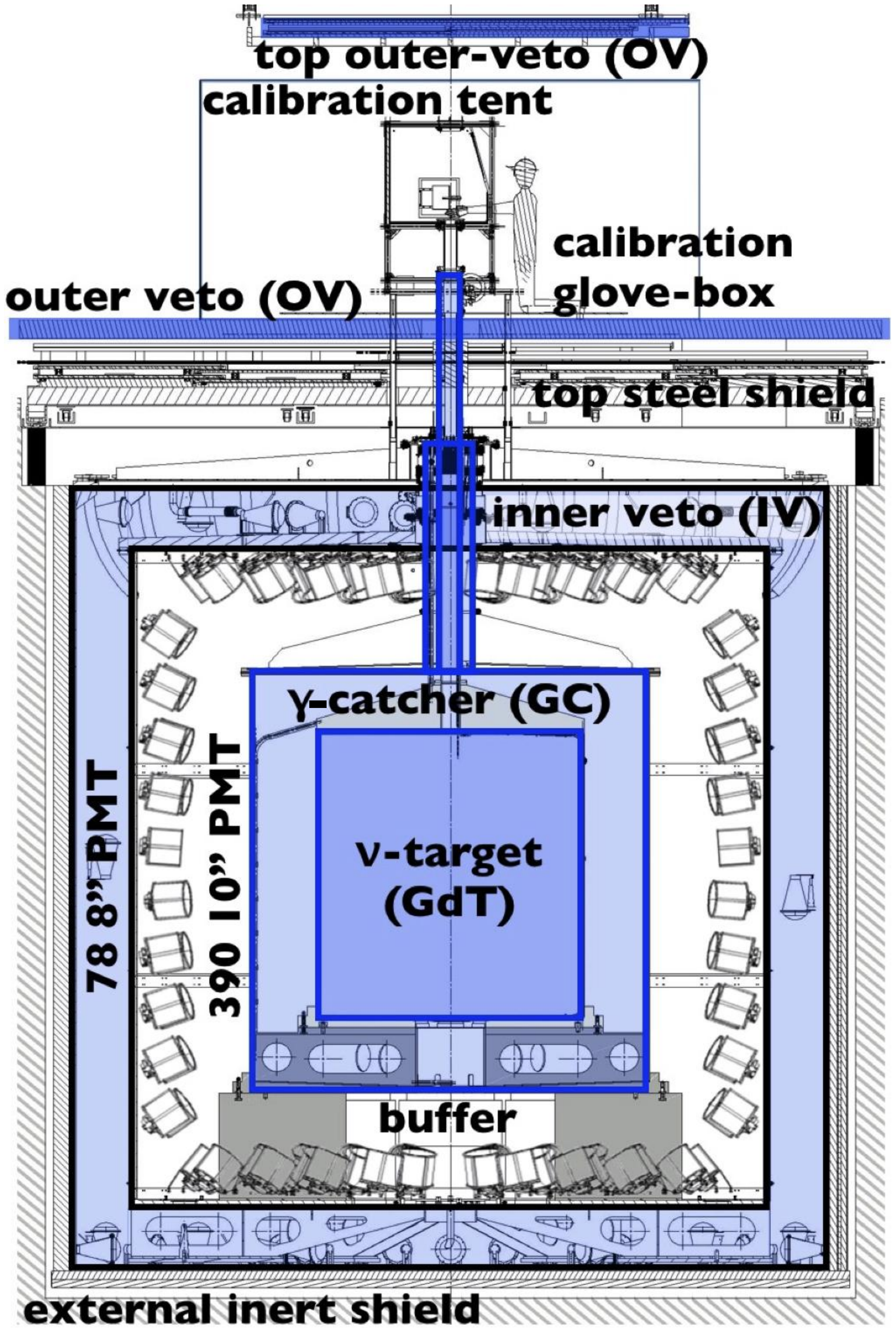
Experimental Setup



- Nuclear Reactors are a strong neutrino source
  - $\sim 6\, \overline{\nu}_e$ per fission
  - $\sim 10^{21}\, \overline{\nu}_e\, [s^{-1} GW^{-1}]$
- Use strong reactors in Chooz, France with a power of $8.5 GW_{th}$
- Almost iso-flux configuration.
- Three dataset (FDI, FDII, ND);



Double Chooz Detector

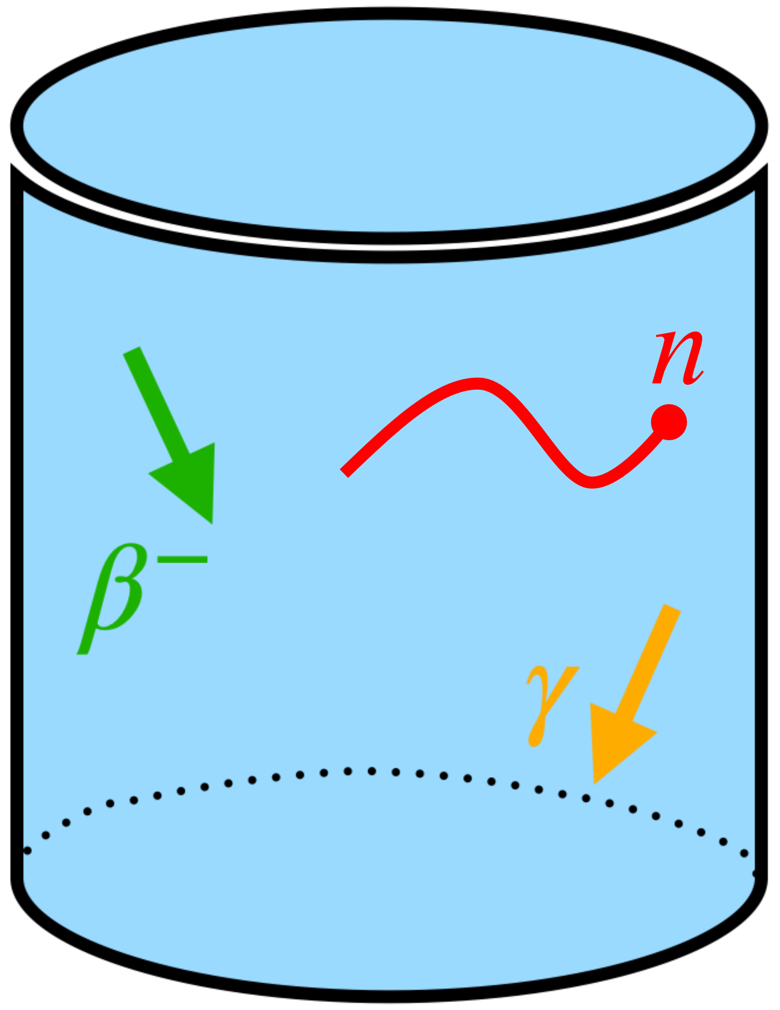


- Identical design for both detectors
- Detector is built in an onion like structure
- **ν - target**
  - $1 \mathrm{gl}^{-1}$ Gd doped Liquid Scintillator
- **γ - catcher**
  - Undoped Liquid Scintillator
- **buffer**
  - Non scintillating mineral oil
  - 390 10-inch PMTs
- **inner veto**
  - Shielded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

Background Model

Uncorrelated

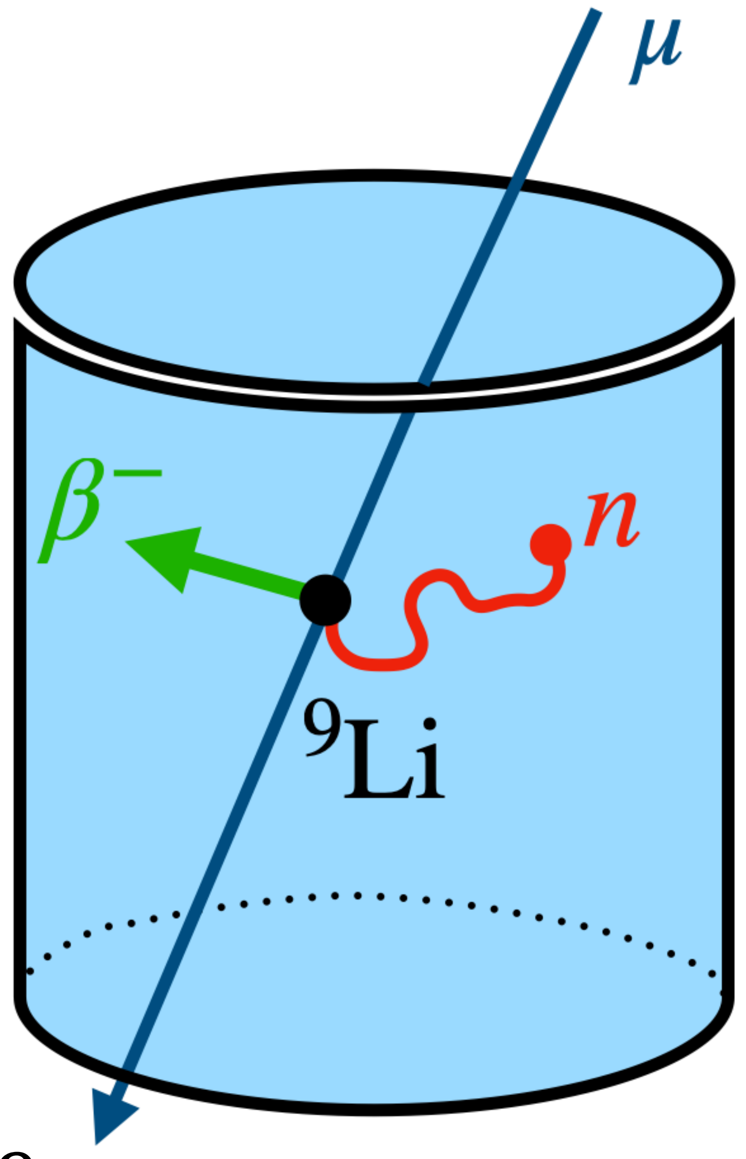
Accidental



Random coincidences between uncorrelated events

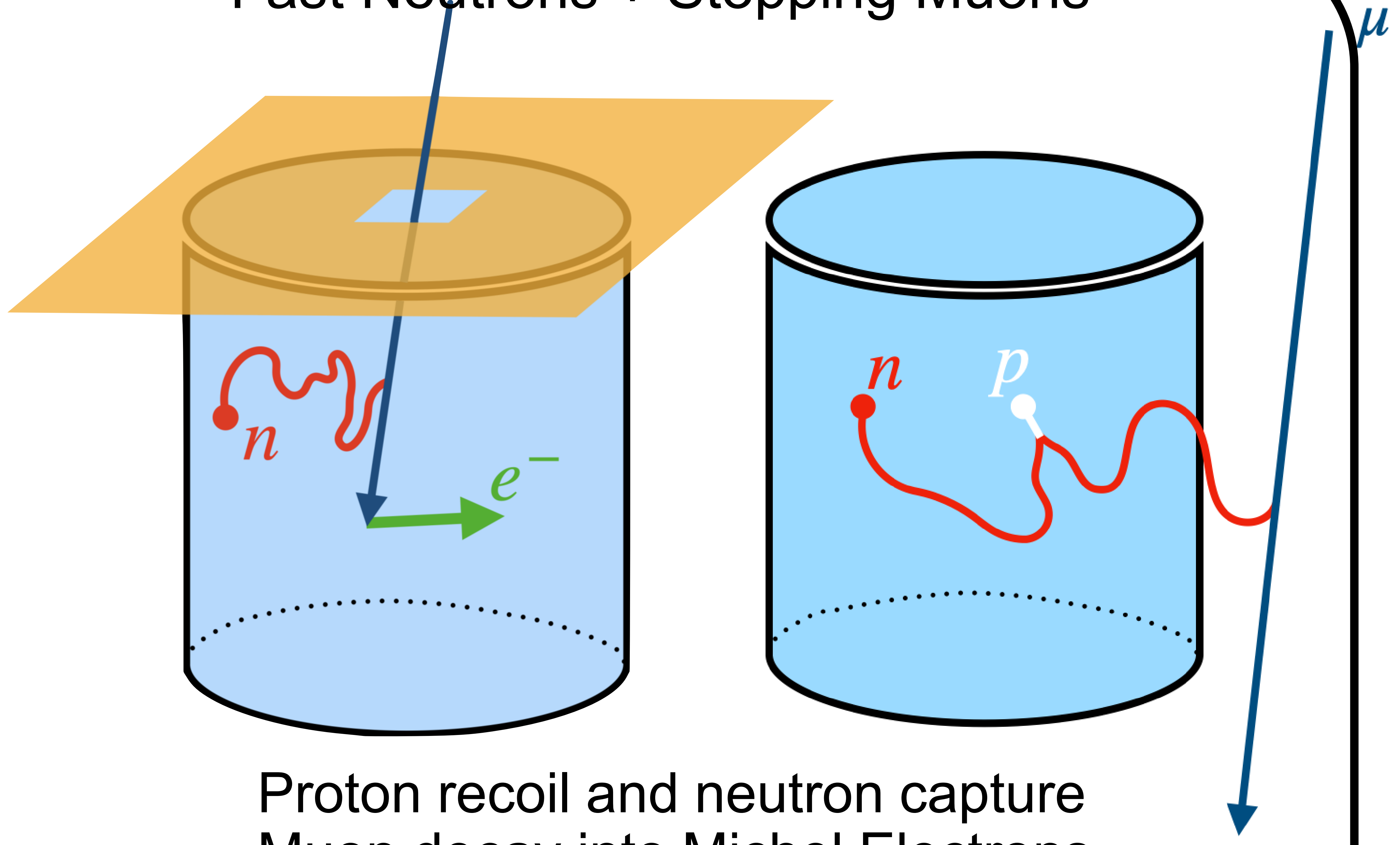
Correlated from cosmic Muon

Cosmogenic



$^9\mathrm{Li}/^8\mathrm{He}\ \beta^-$ decay after carbon spallation by an cosmic muon

Fast Neutrons + Stopping Muons



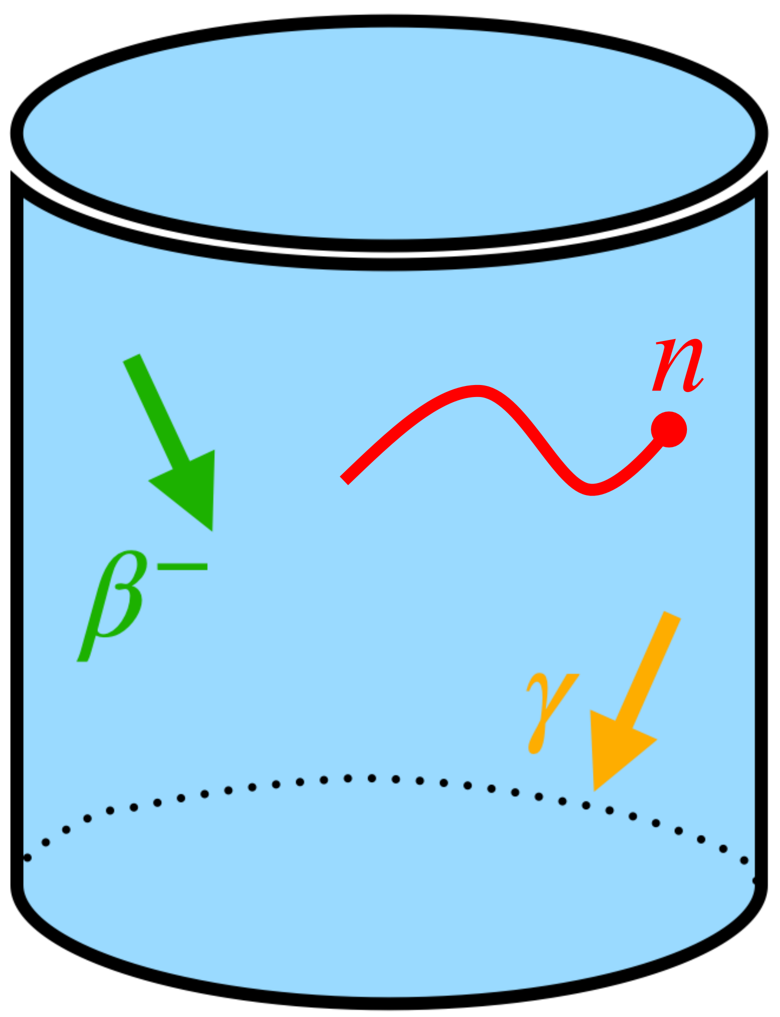
Proton recoil and neutron capture
Muon decay into Michel Electrons

B.Roskovec PIC 2019

Background Model

Uncorrelated

Accidental

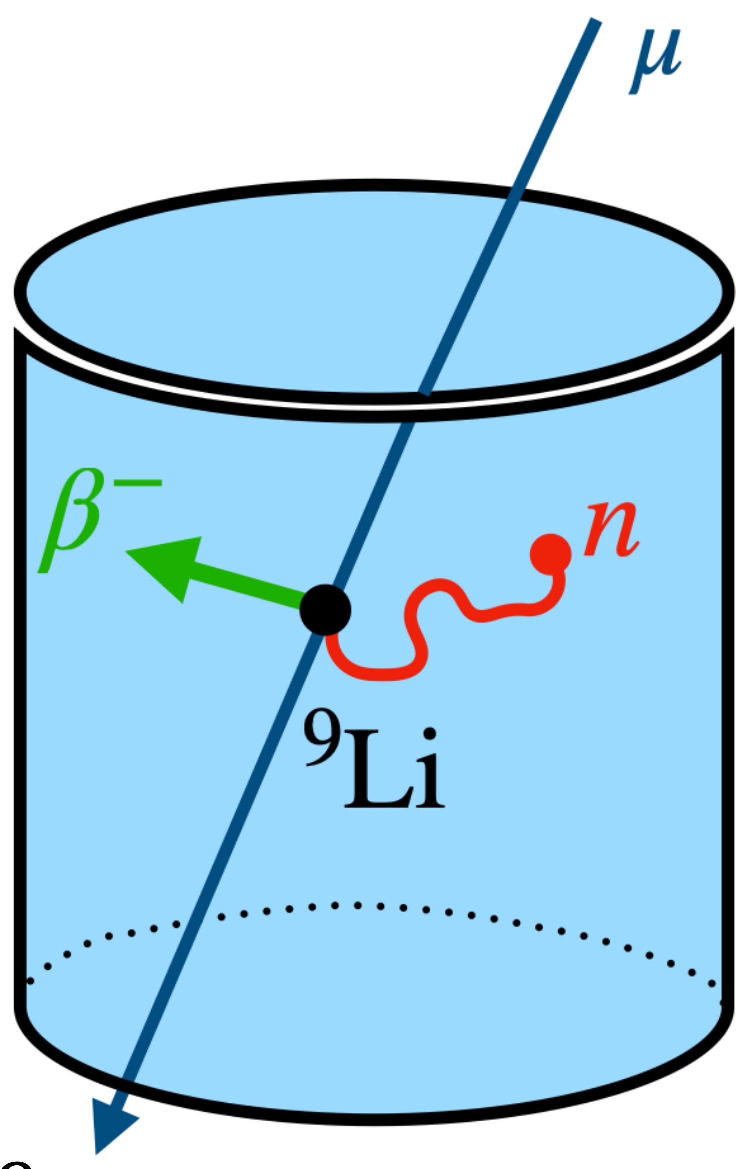


Random coincidences between uncorrelated events

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

Correlated from cosmic Muon

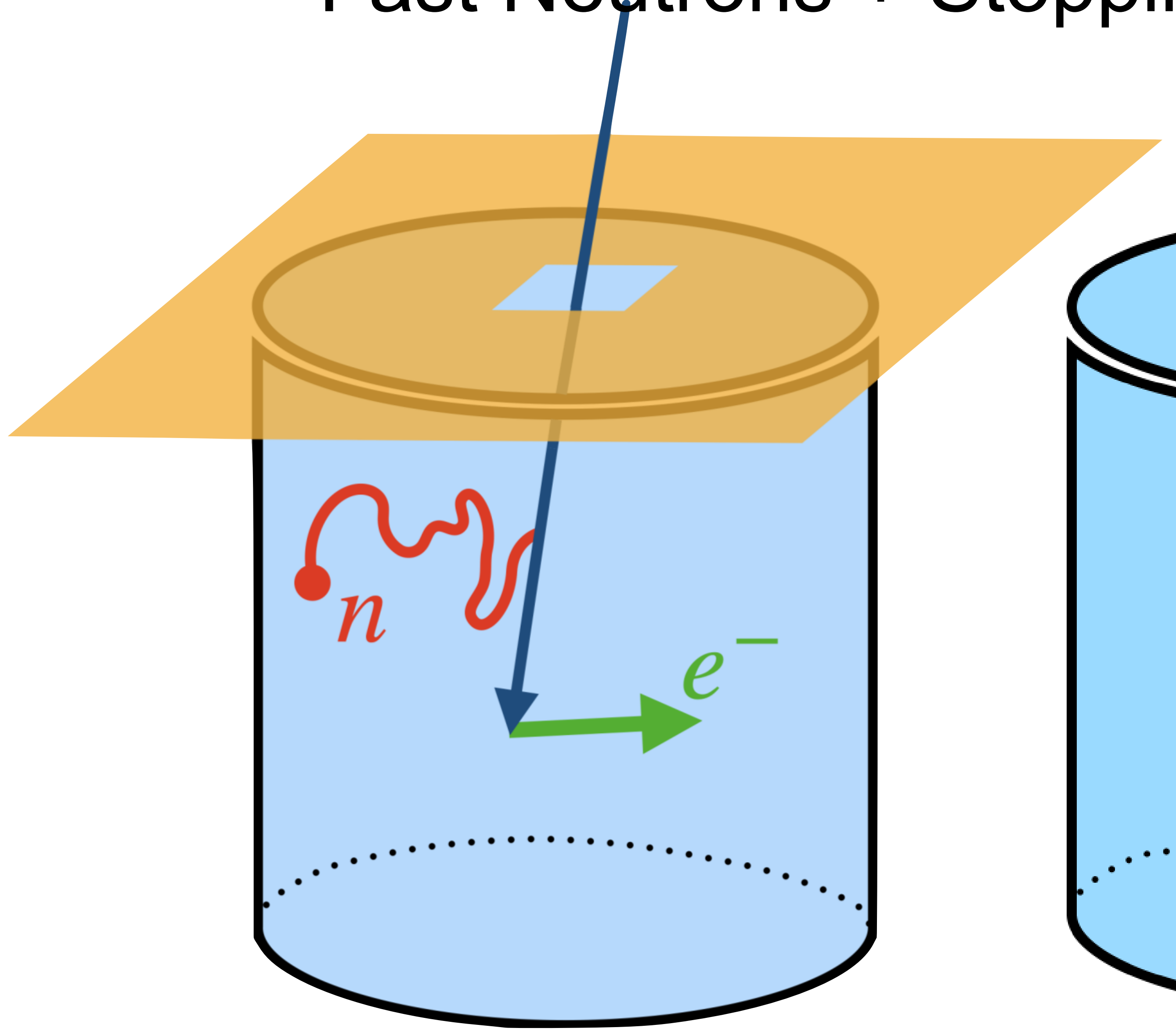
Cosmogenic

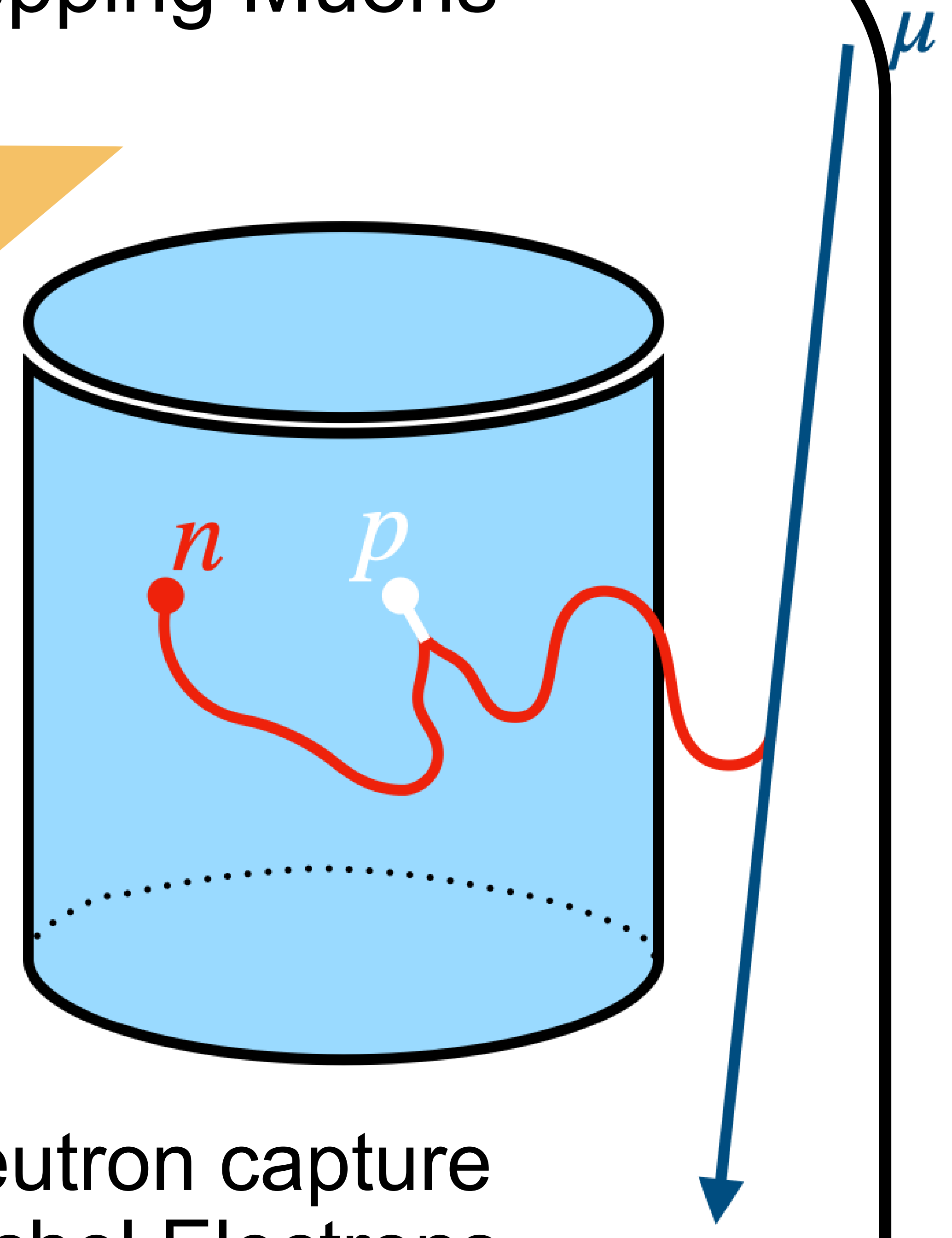


$^9\mathrm{Li}/^8\mathrm{He}\ \beta^-$ decay after carbon spallation by an cosmic muon

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

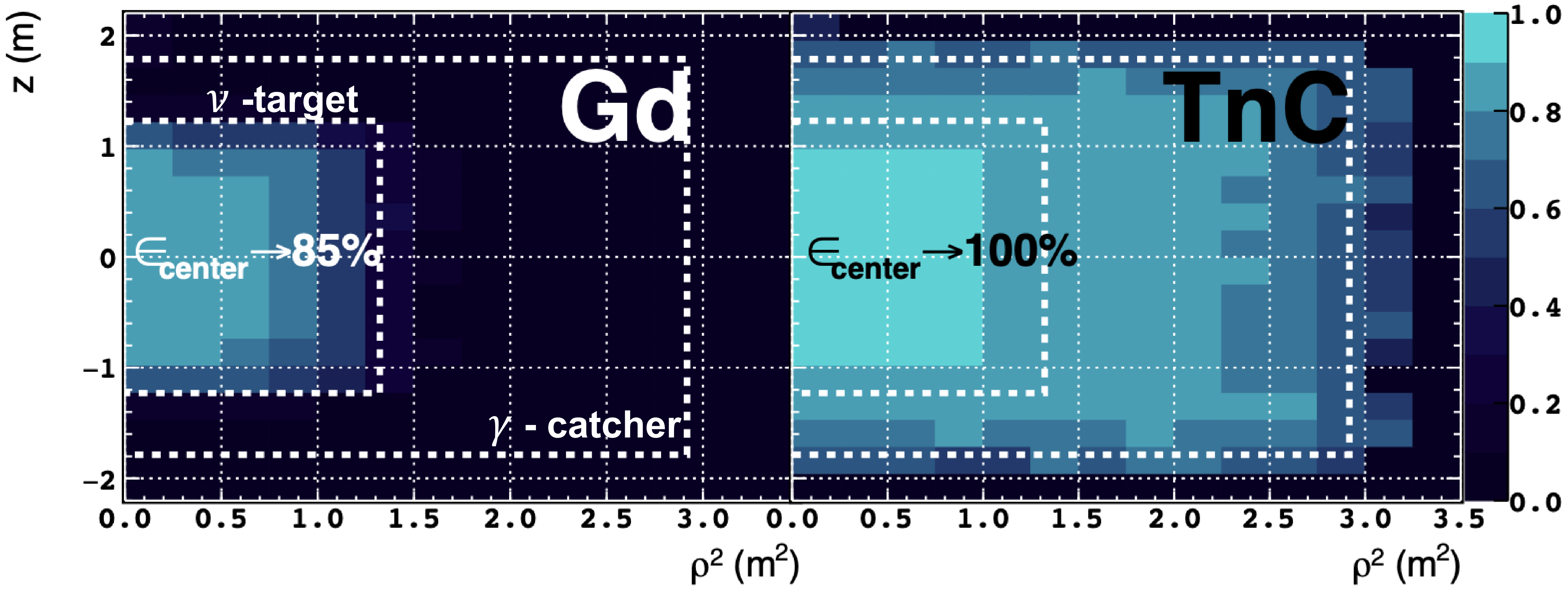
FD	$6.05 \pm 0.10\ \mathrm{day}^{-1}$
ND	$45.56 \pm 0.36\ \mathrm{day}^{-1}$

FD ~300 m.w.e overburden
ND ~120 m.w.e overburden

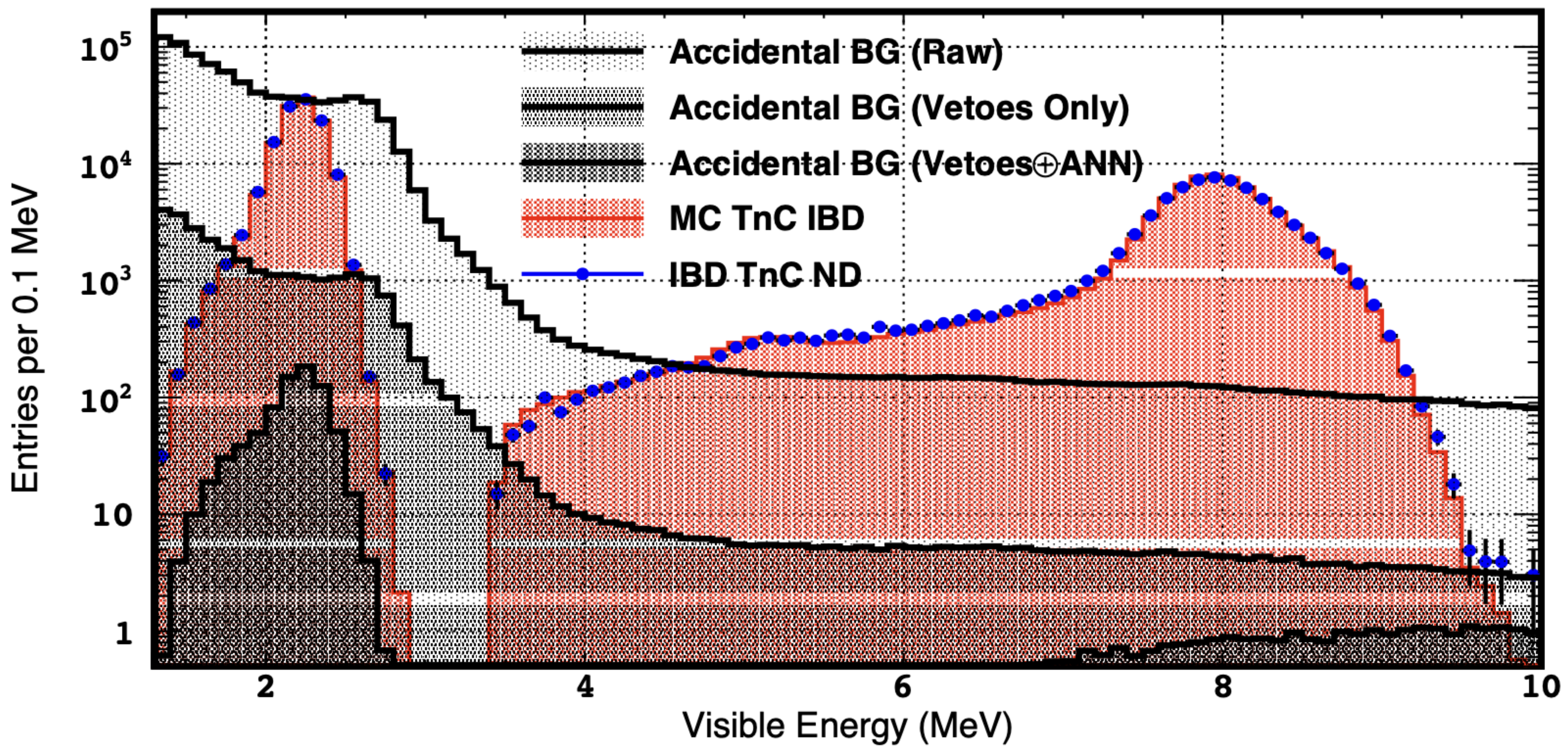
B.Roskovec PIC 2019

Background Reduction

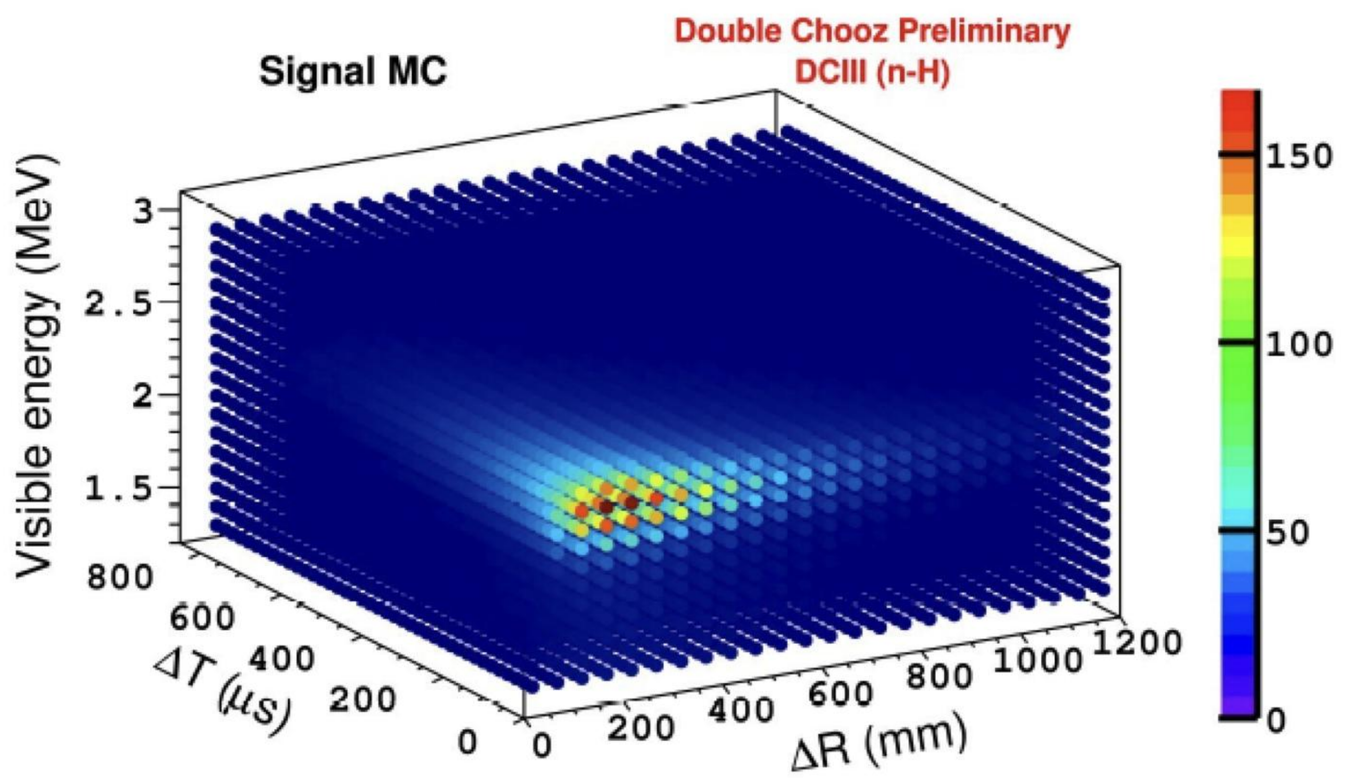
DC IV, Nat. Phys. 16, 558-564 (2020)

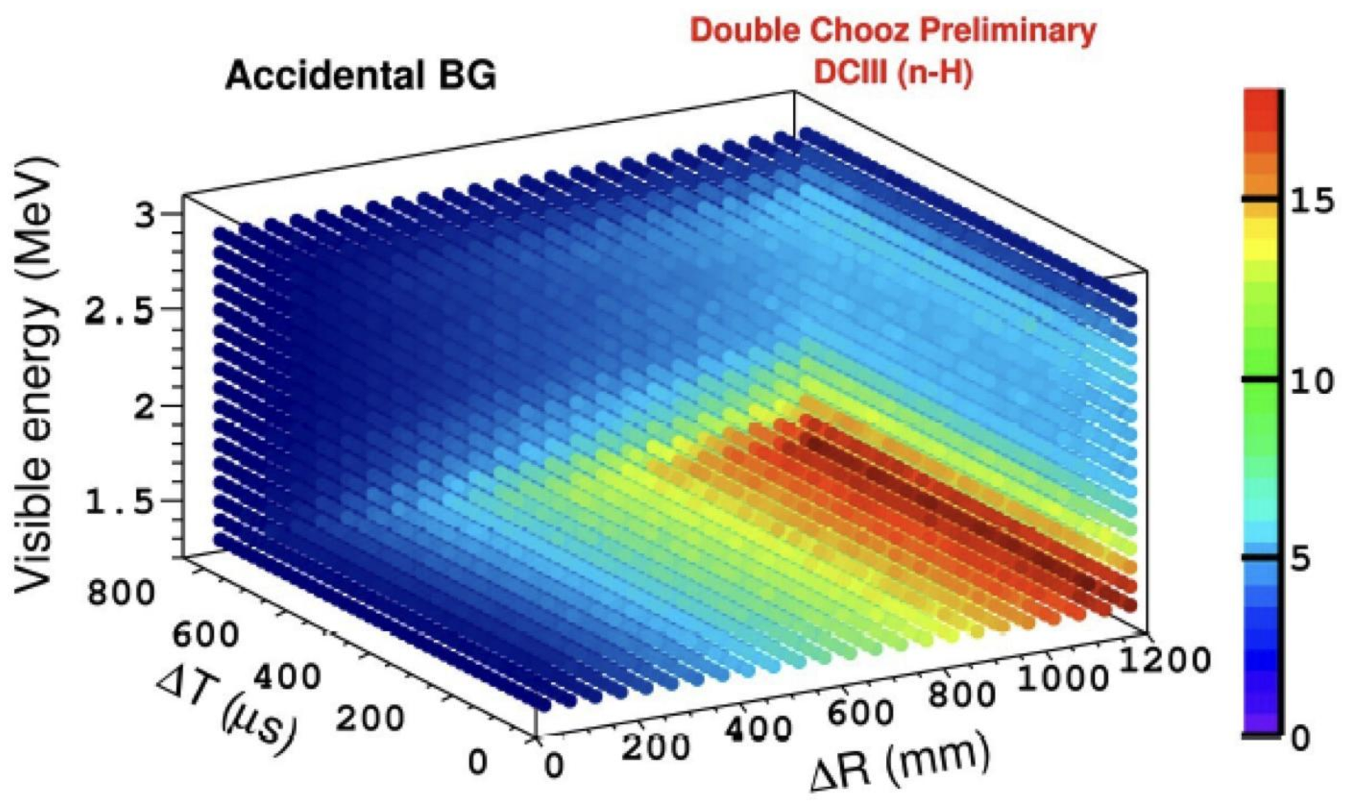


DC IV, Nat. Phys. 16, 558-564 (2020)

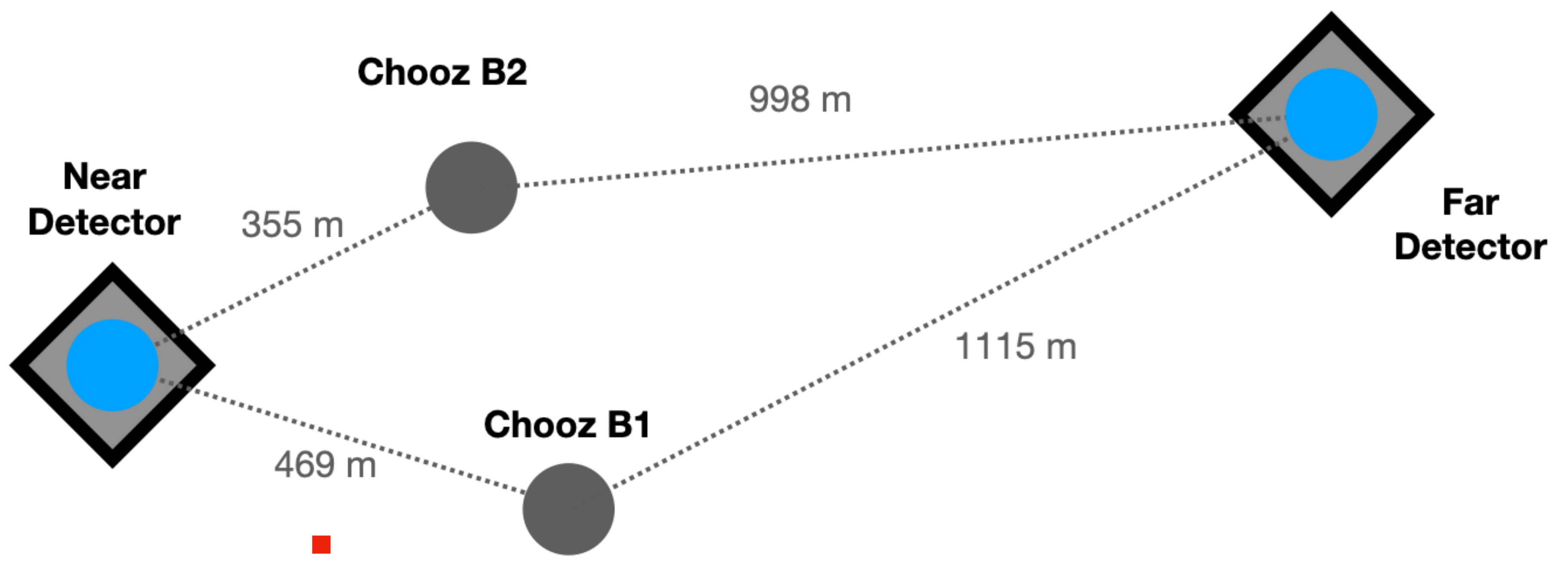


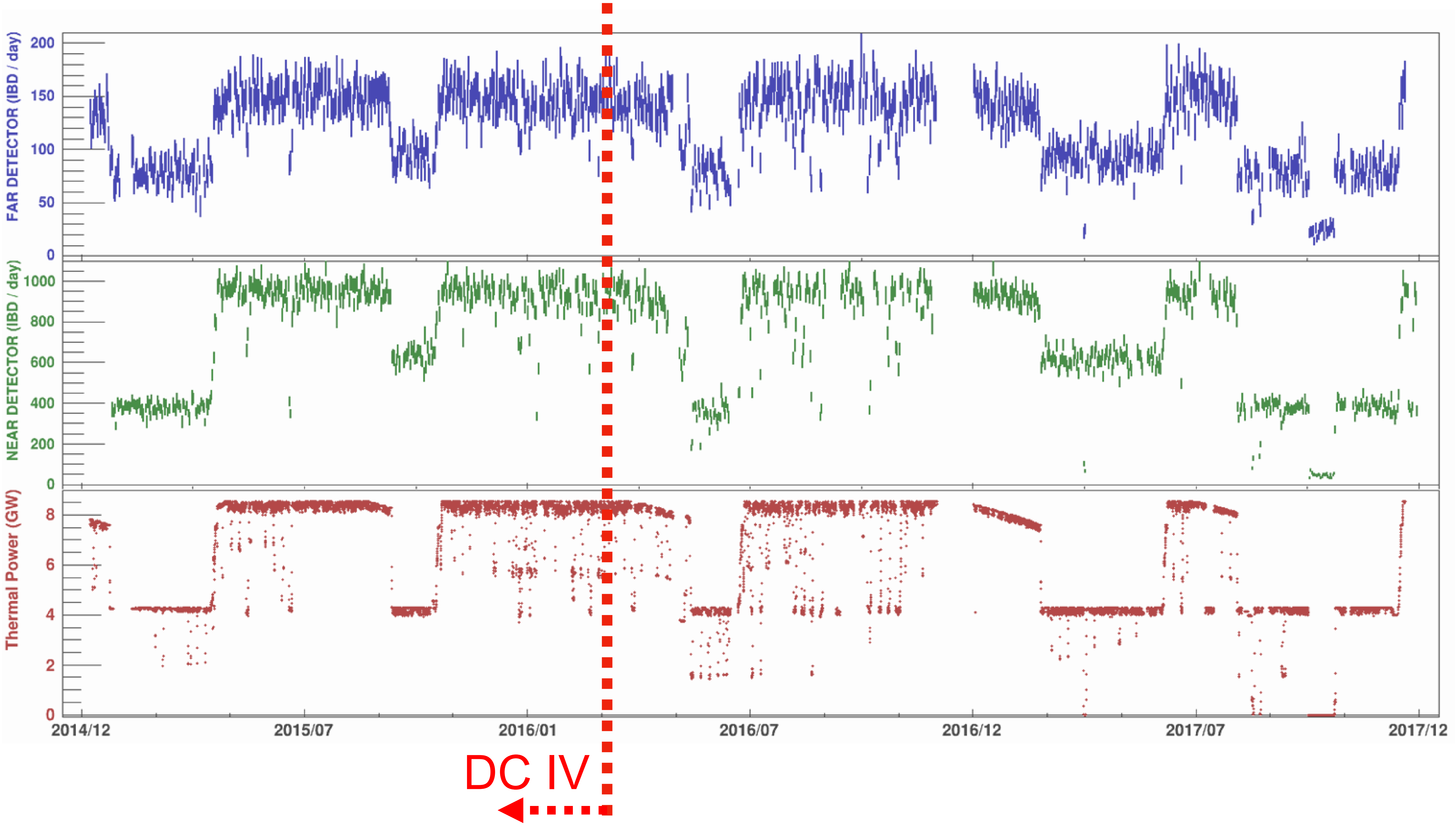
- The Total-neutron-Capture (TnC) integrates over all n-capturing elements available (Gd, H, C);
- The γ-Catcher is a detection volume;
- The statistics increased by a factor of ~ 2.5;
- ANN (Coincidence of ΔT, $E_{delayed}$, ΔR).





Reactor Modulation

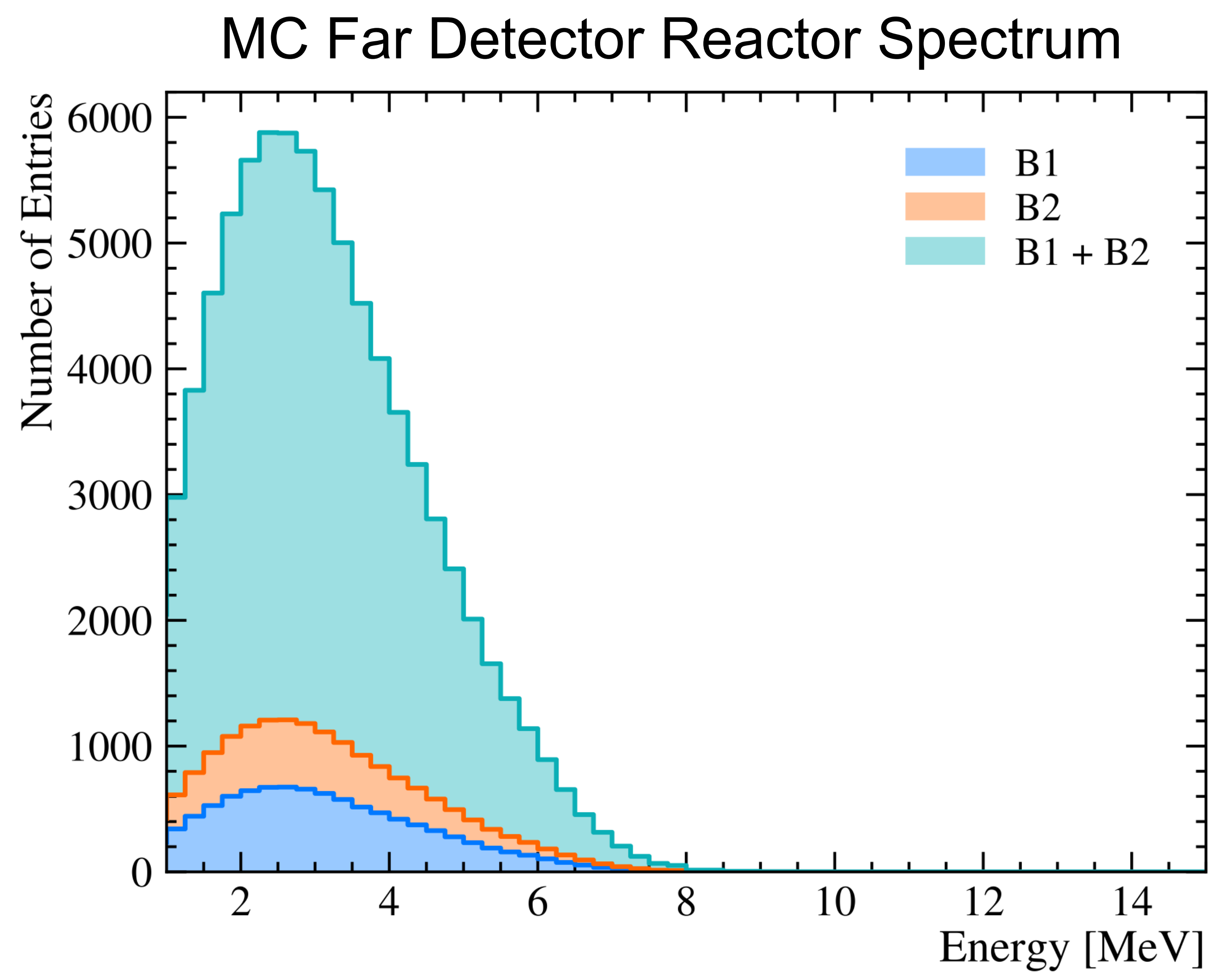




Far Detector

Near Detector

Reactor Thermal Power



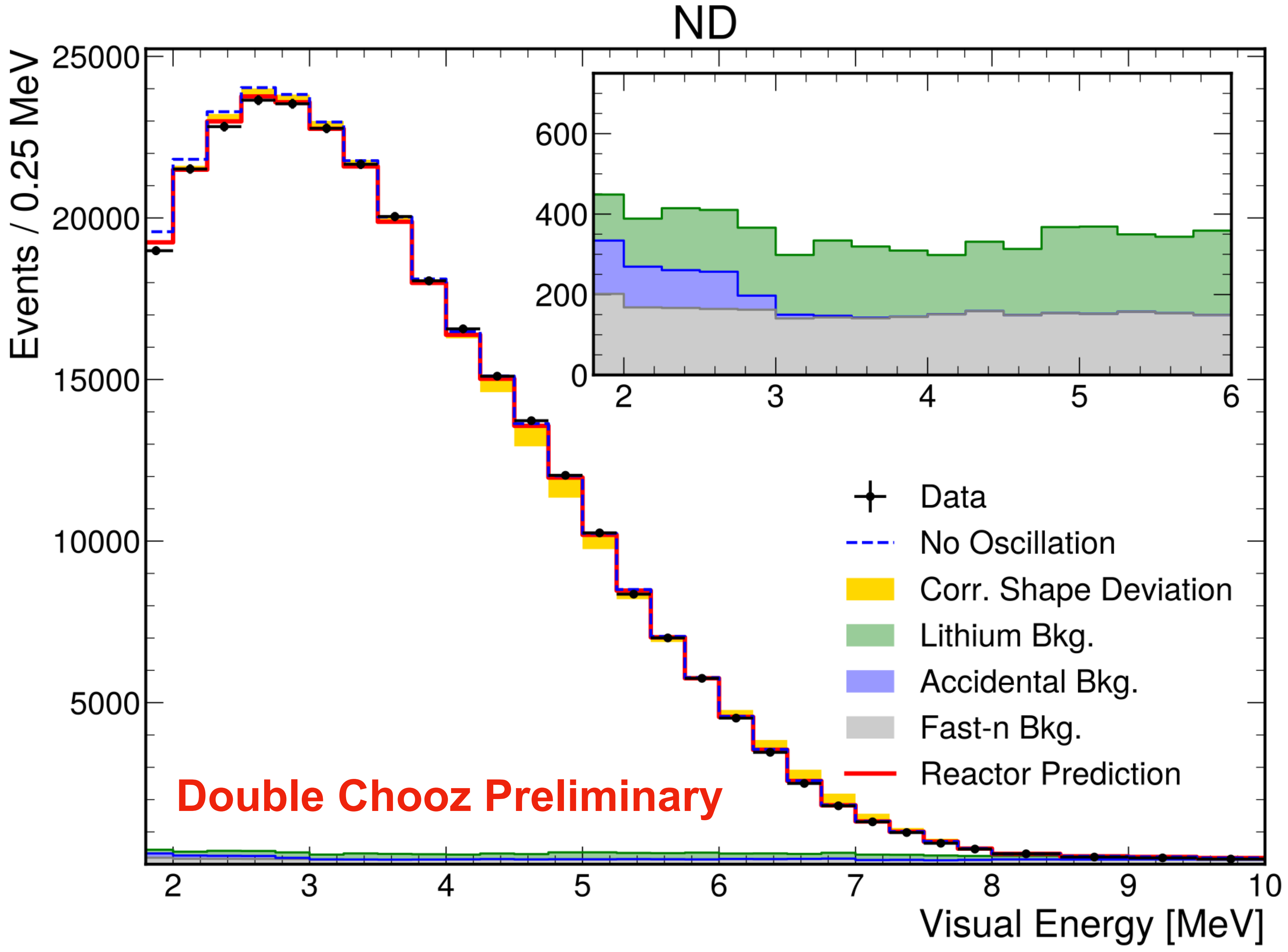
- ~×2.3 of Statistics;
- Reactor split helps better constraint the θ_{13};
- Combines DC RRM[1] and DC II[2] Methods

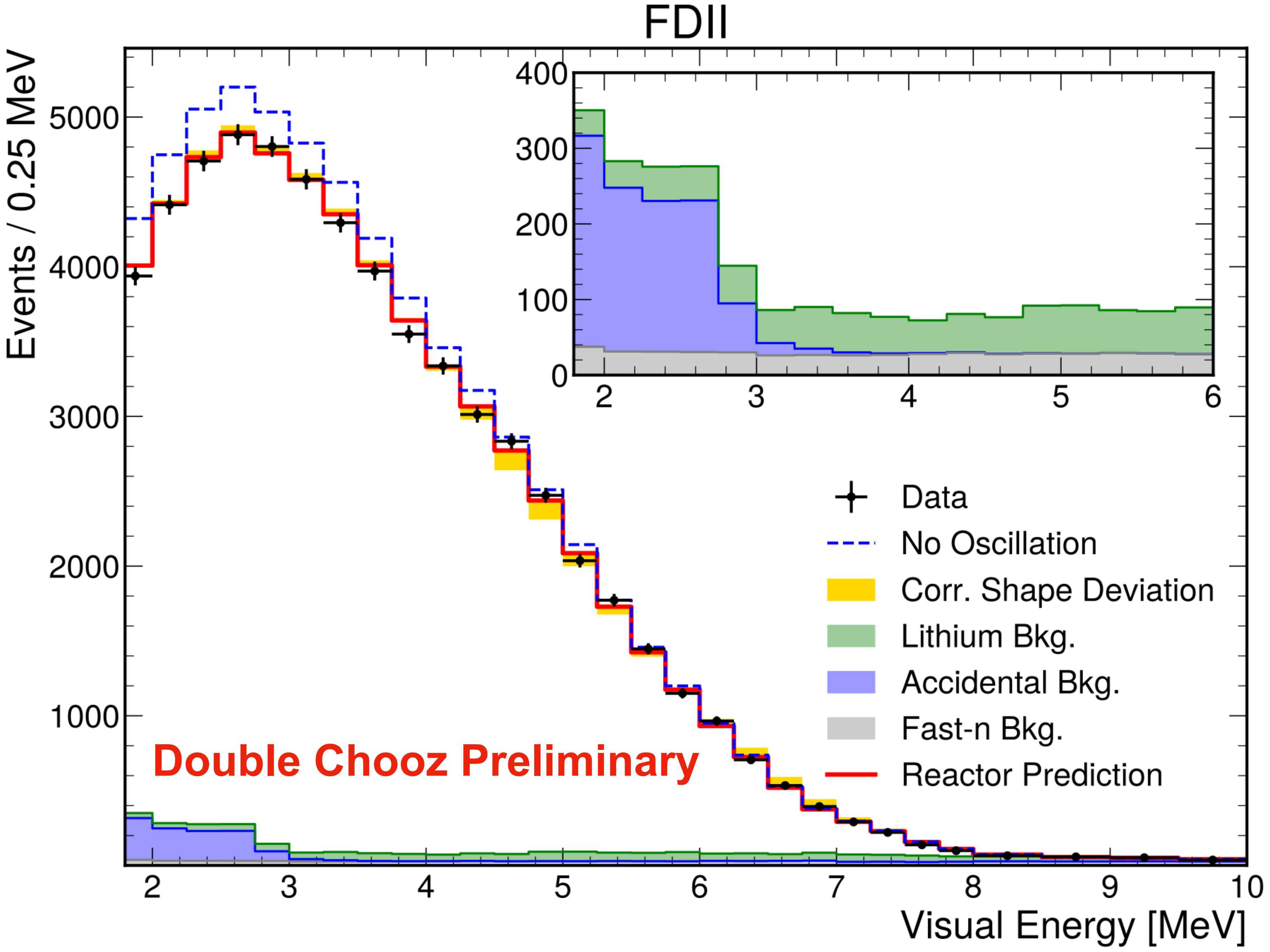
[1]. *J. High Energ. Phys.* **2021**, 190 (2021)
[2]. *Phys. Rev. D 86, 052008 (2012)*

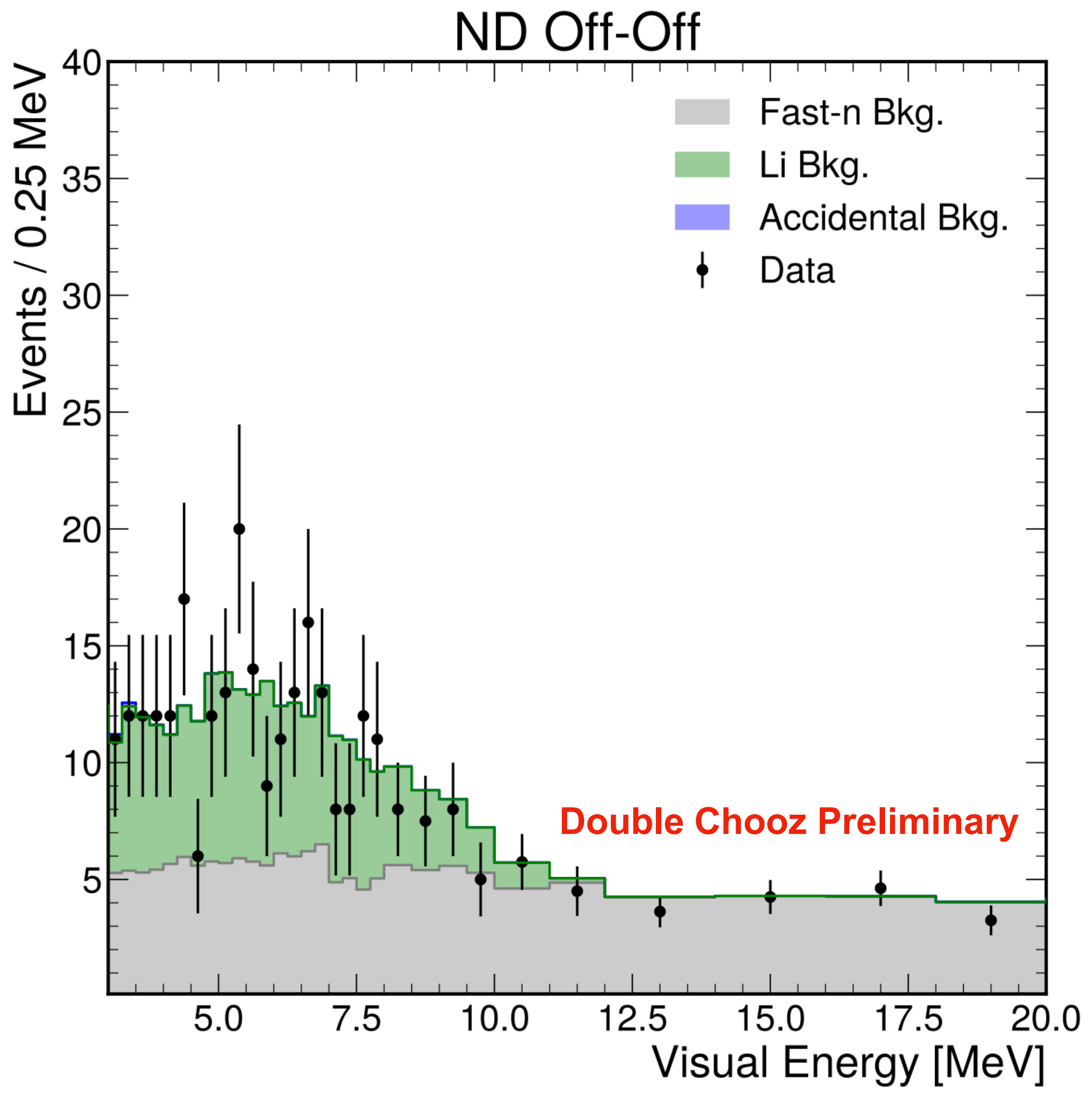
Prompt Energy Spectra

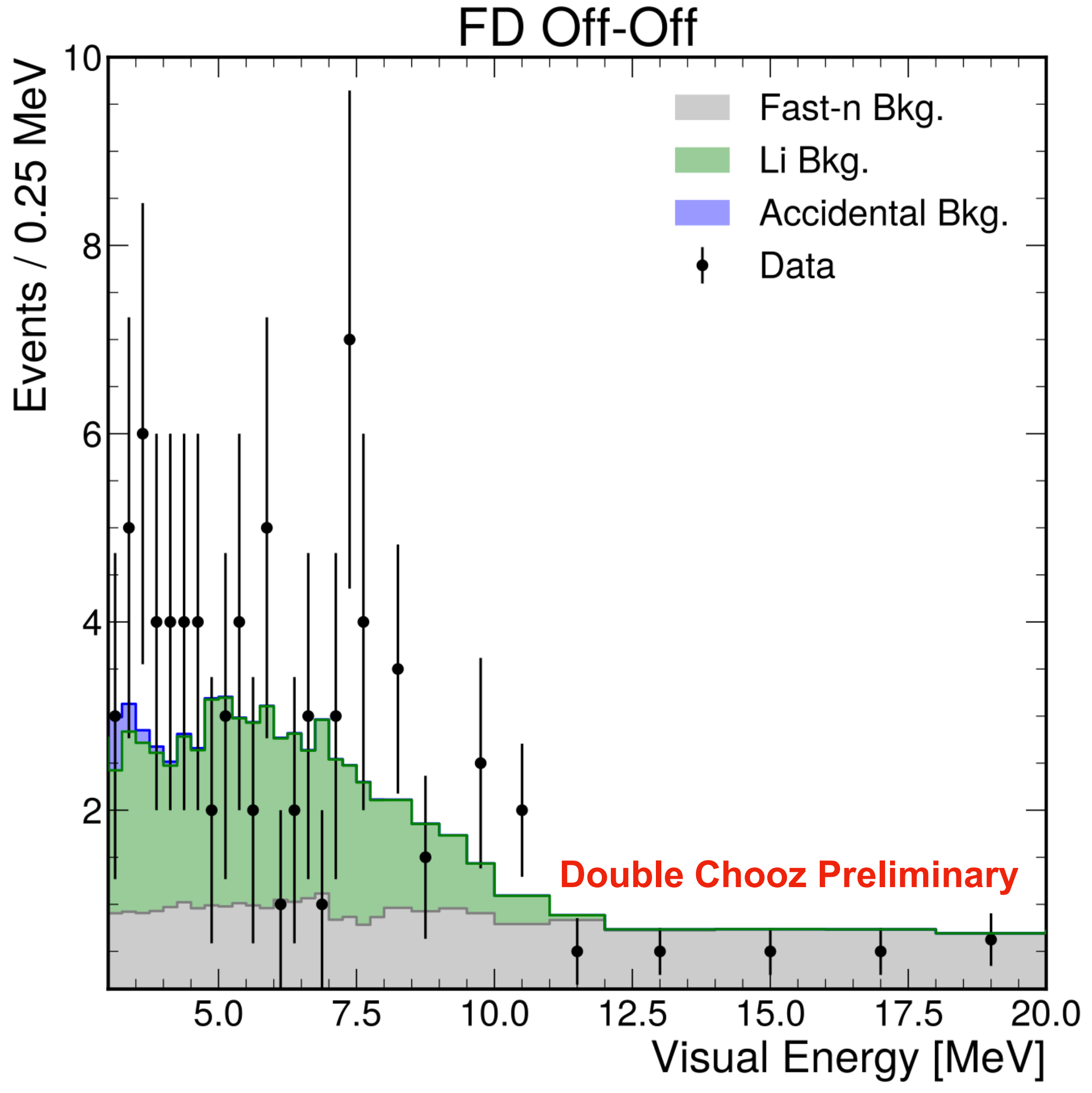
OFF-time

ON-time





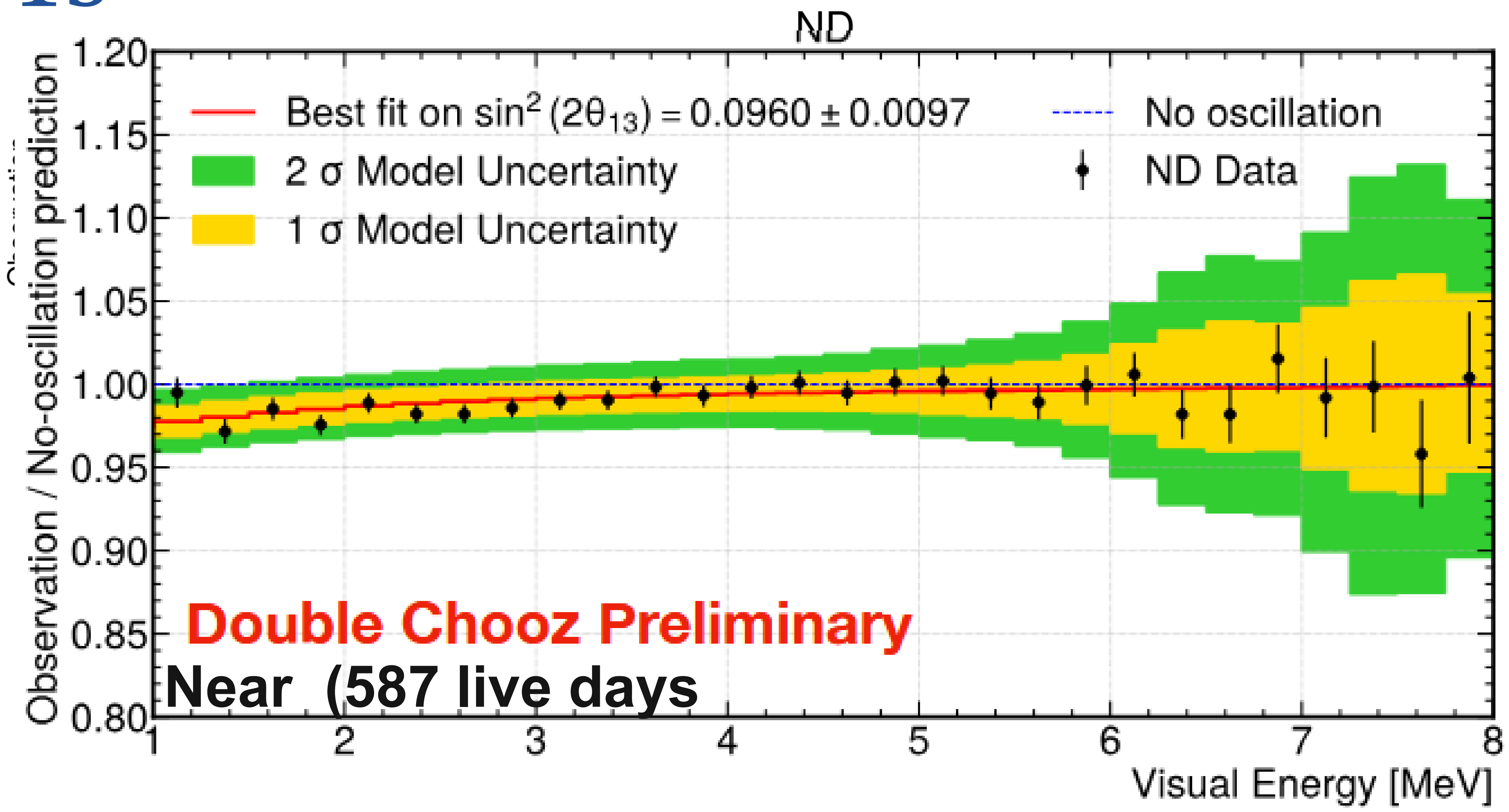


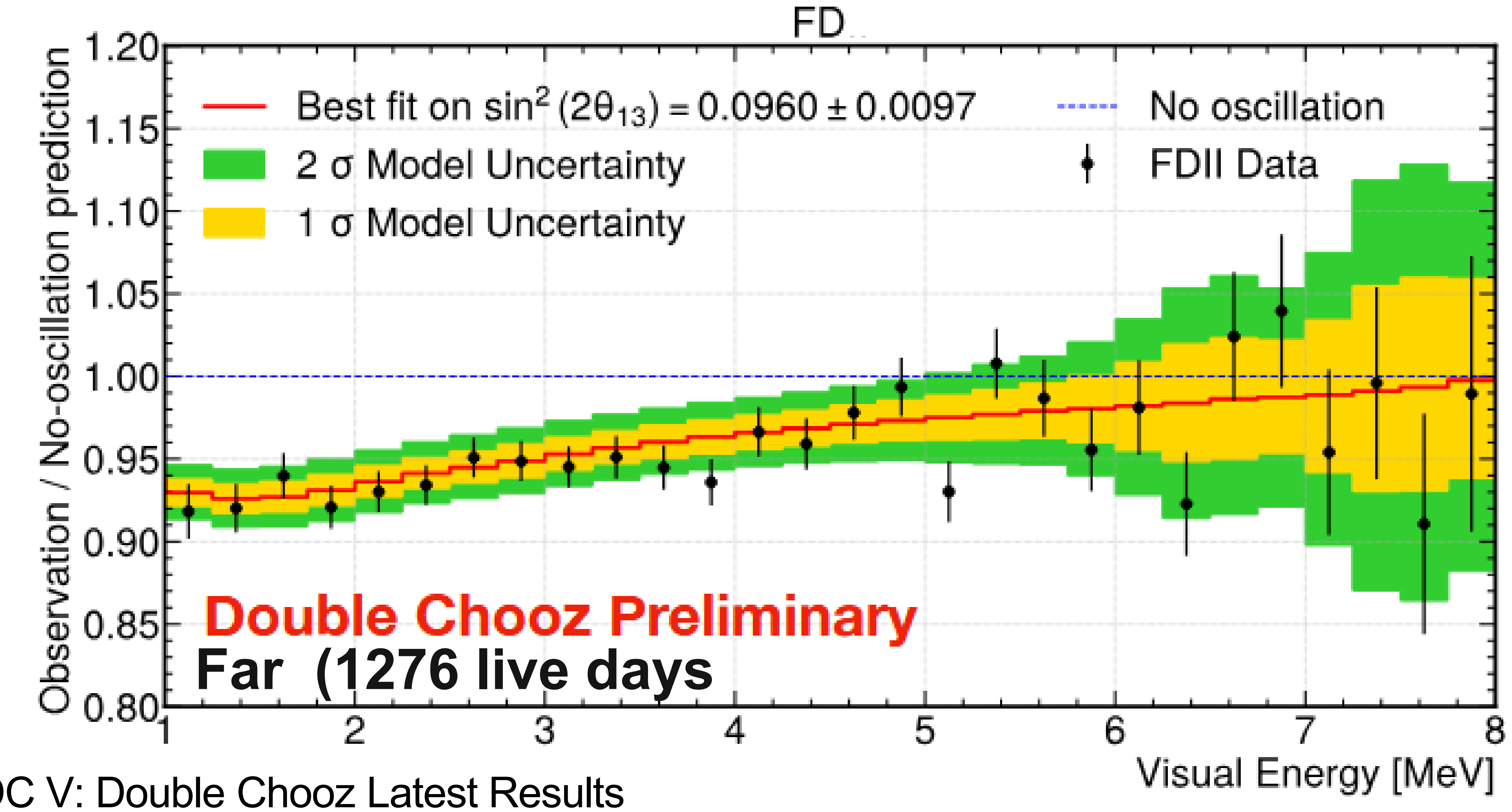


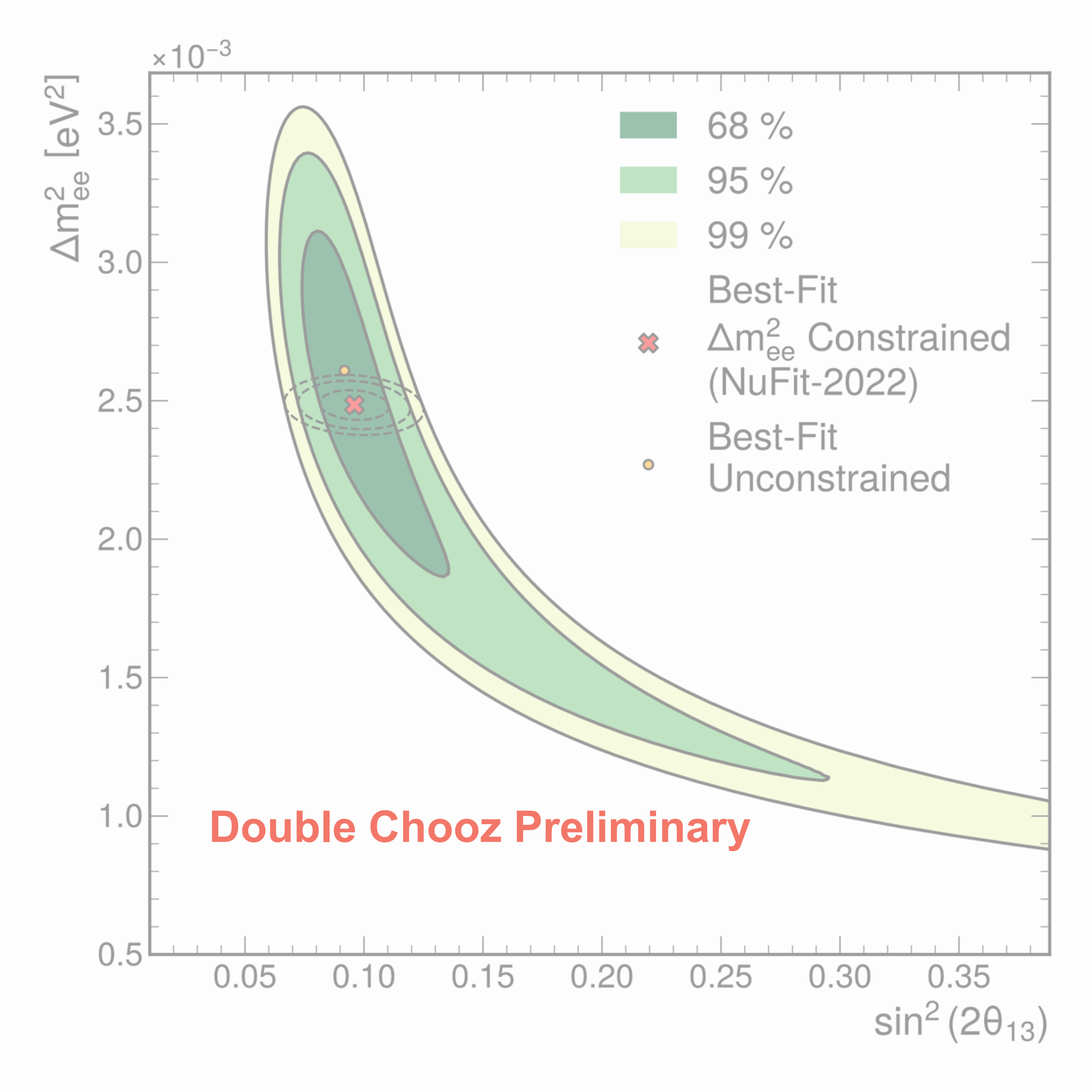
- Good agreement between the data and the reactor model;
- Clearly visible θ_{13} effect;
- Reactor-Off phases can be used to constrain the backgrounds $> 3\text{MeV}$

S/B

θ_{13} Fit Results

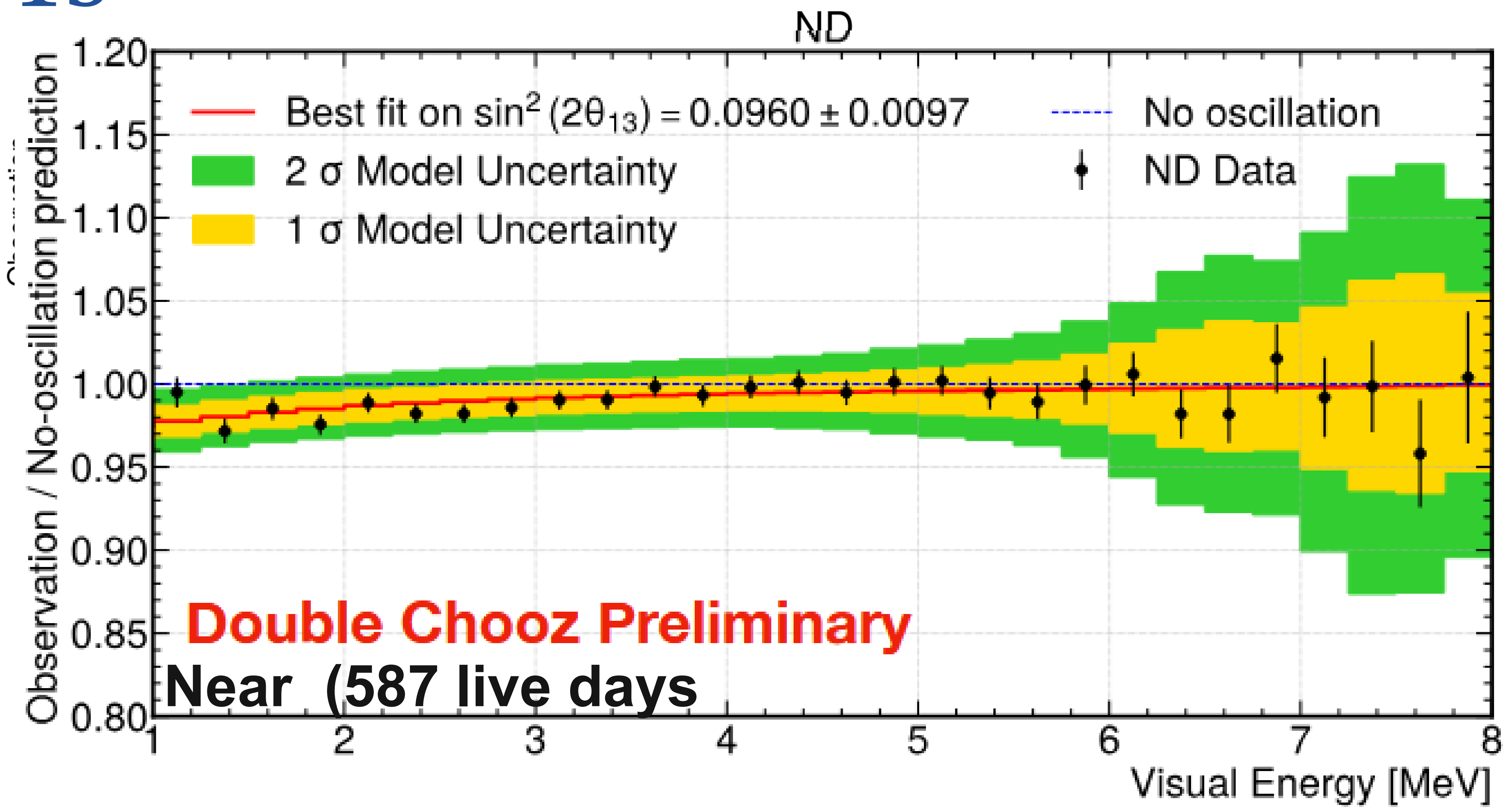


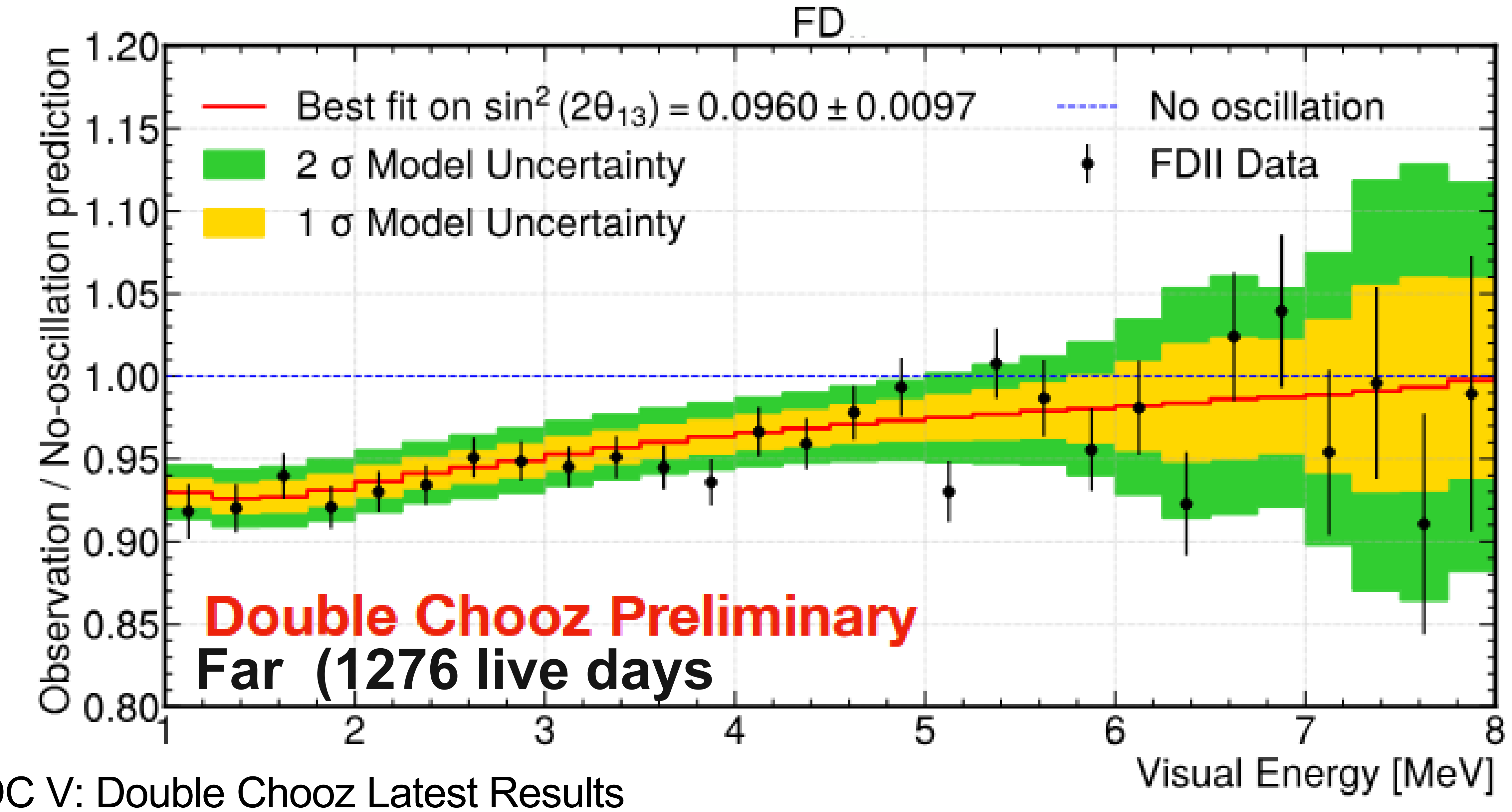


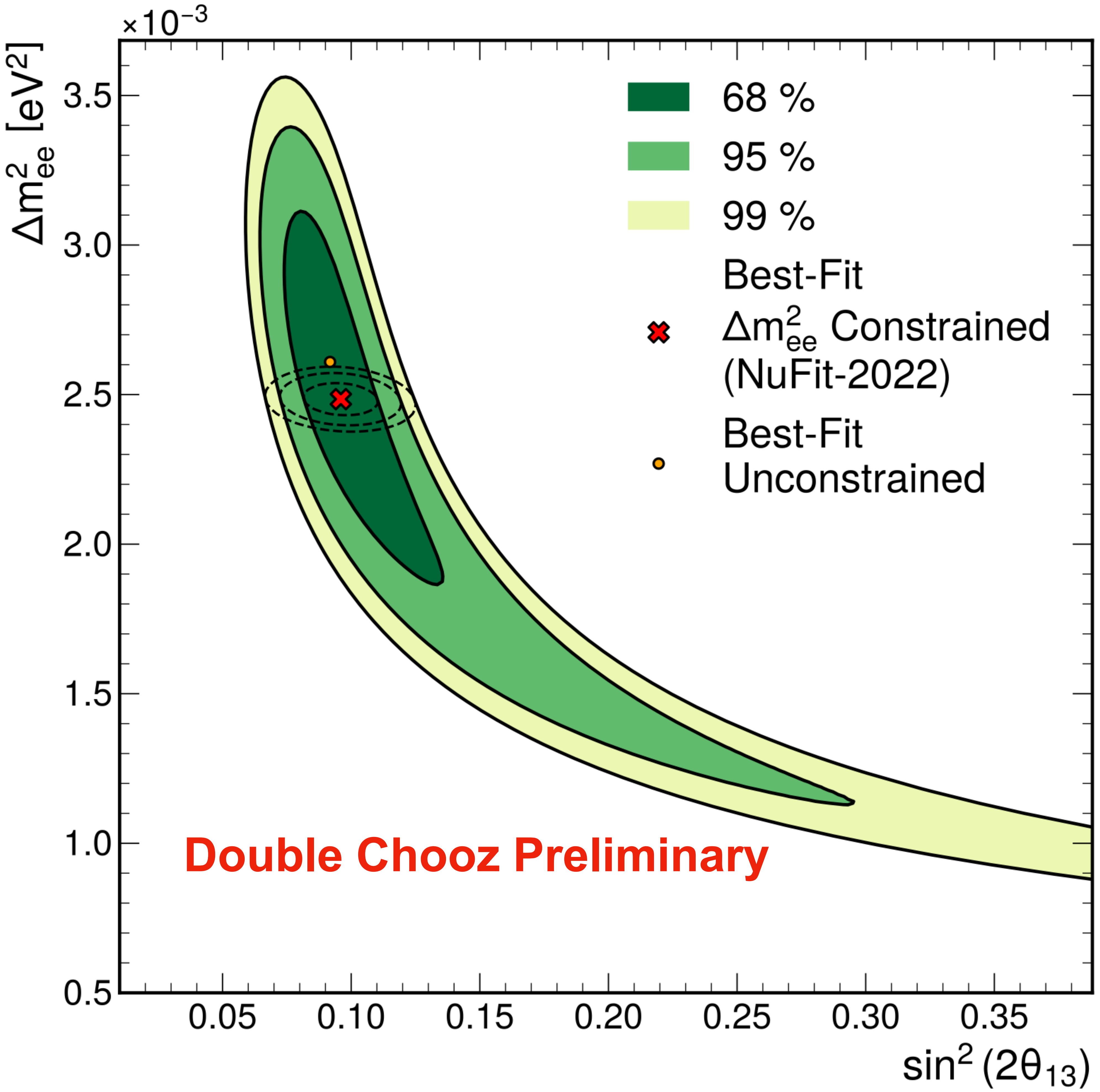


Newest Result: $\sin^2(2\theta_{13}) = 0.0960 \pm 0.0086(\text{syst.}) \pm 0.0044(\text{stat.})$

θ_{13} Fit Results



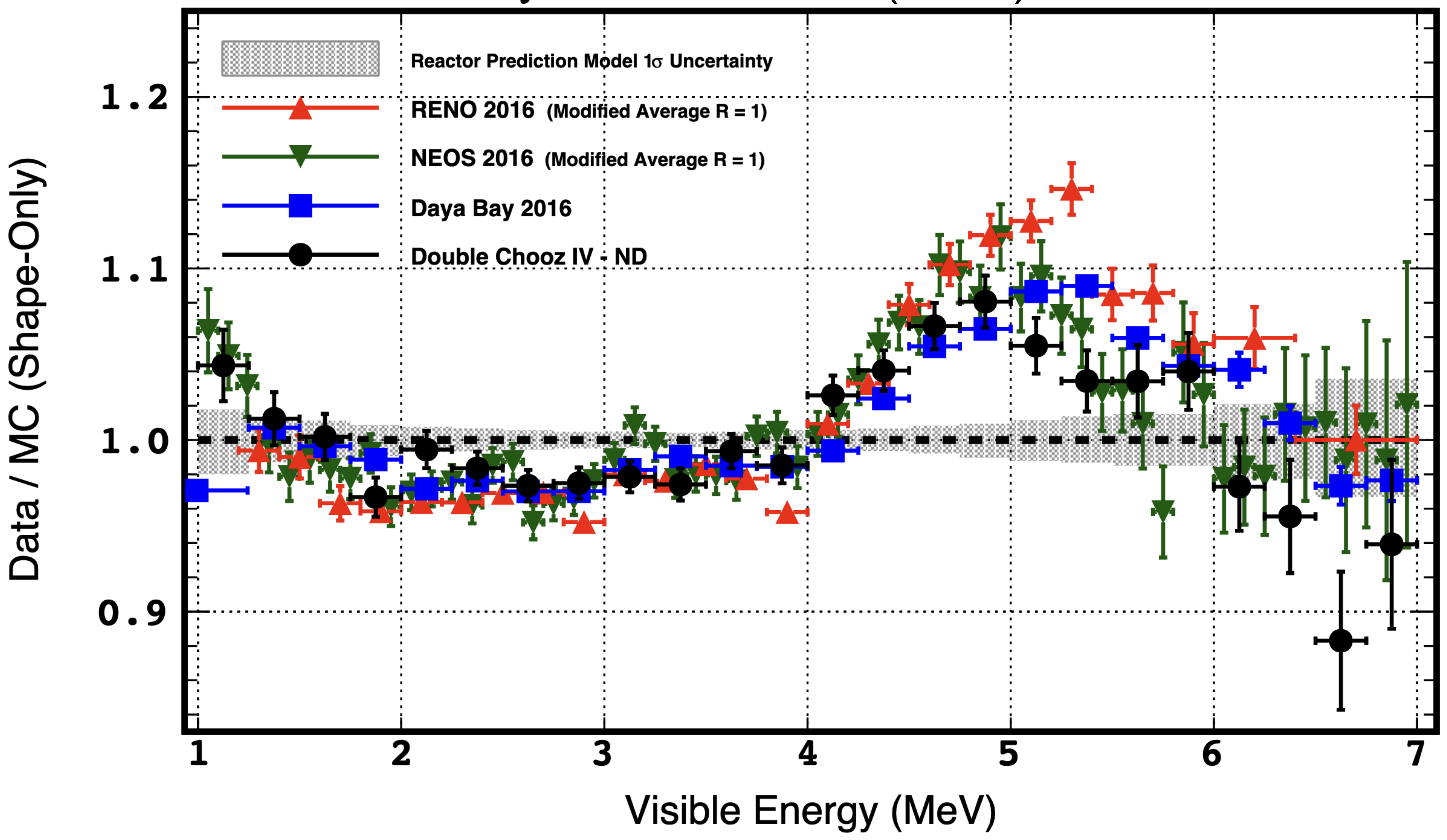


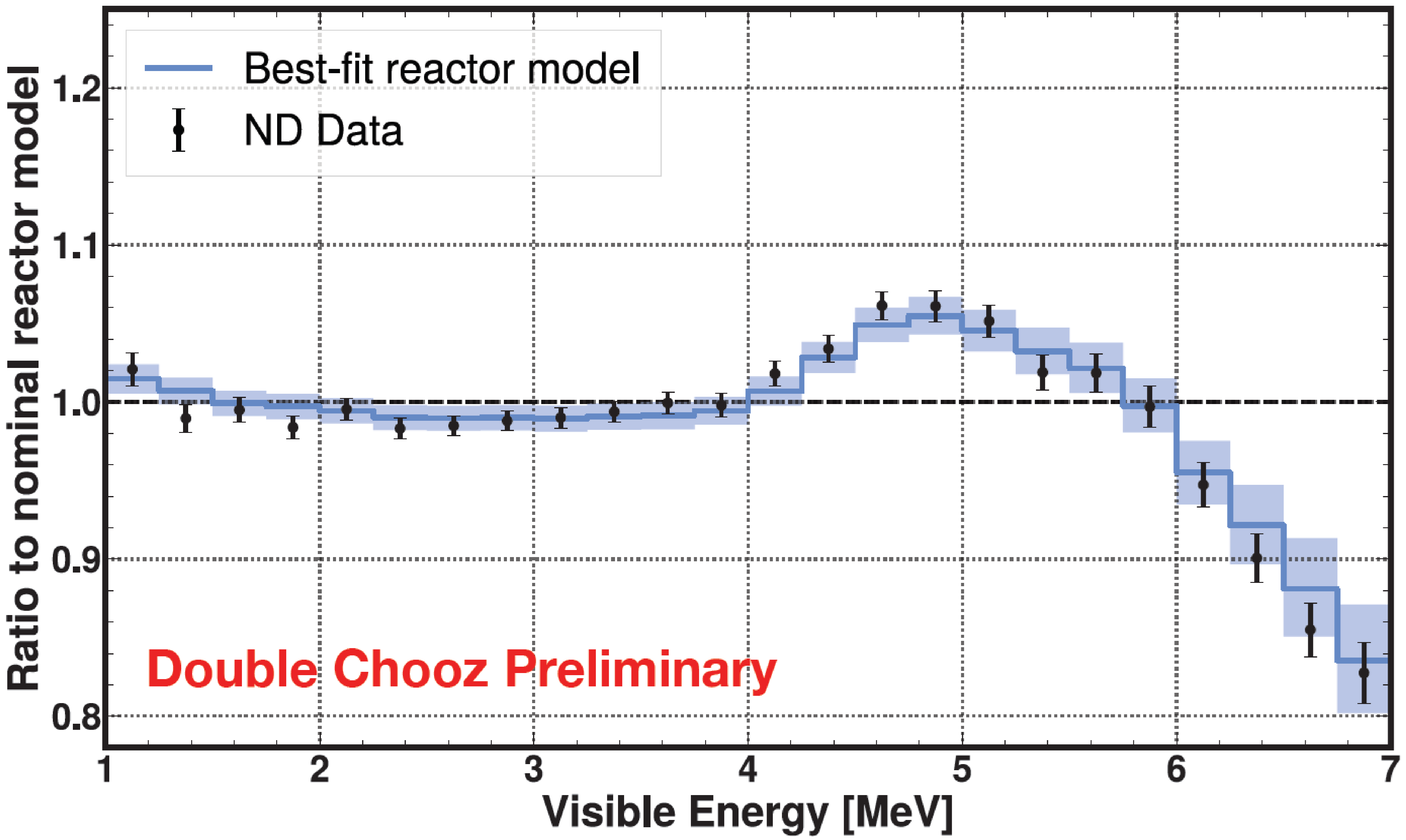


Newest Result: $\sin^2(2\theta_{13}) = 0.0960 \pm 0.0086(\text{syst.}) \pm 0.0044(\text{stat.})$

Spectral Distortion Extraction

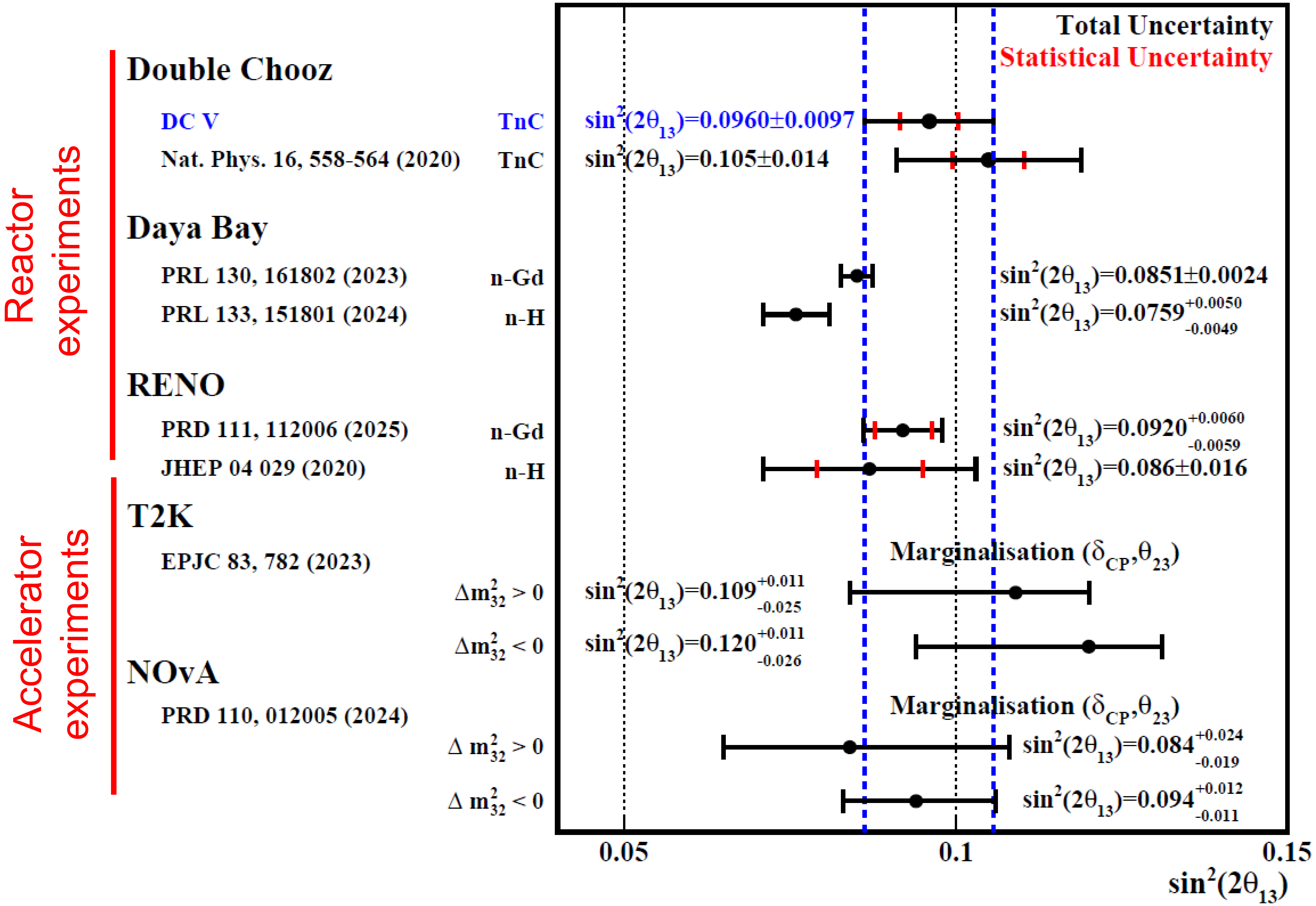
DC IV, Nat. Phys. 16, 558-564 (2020)

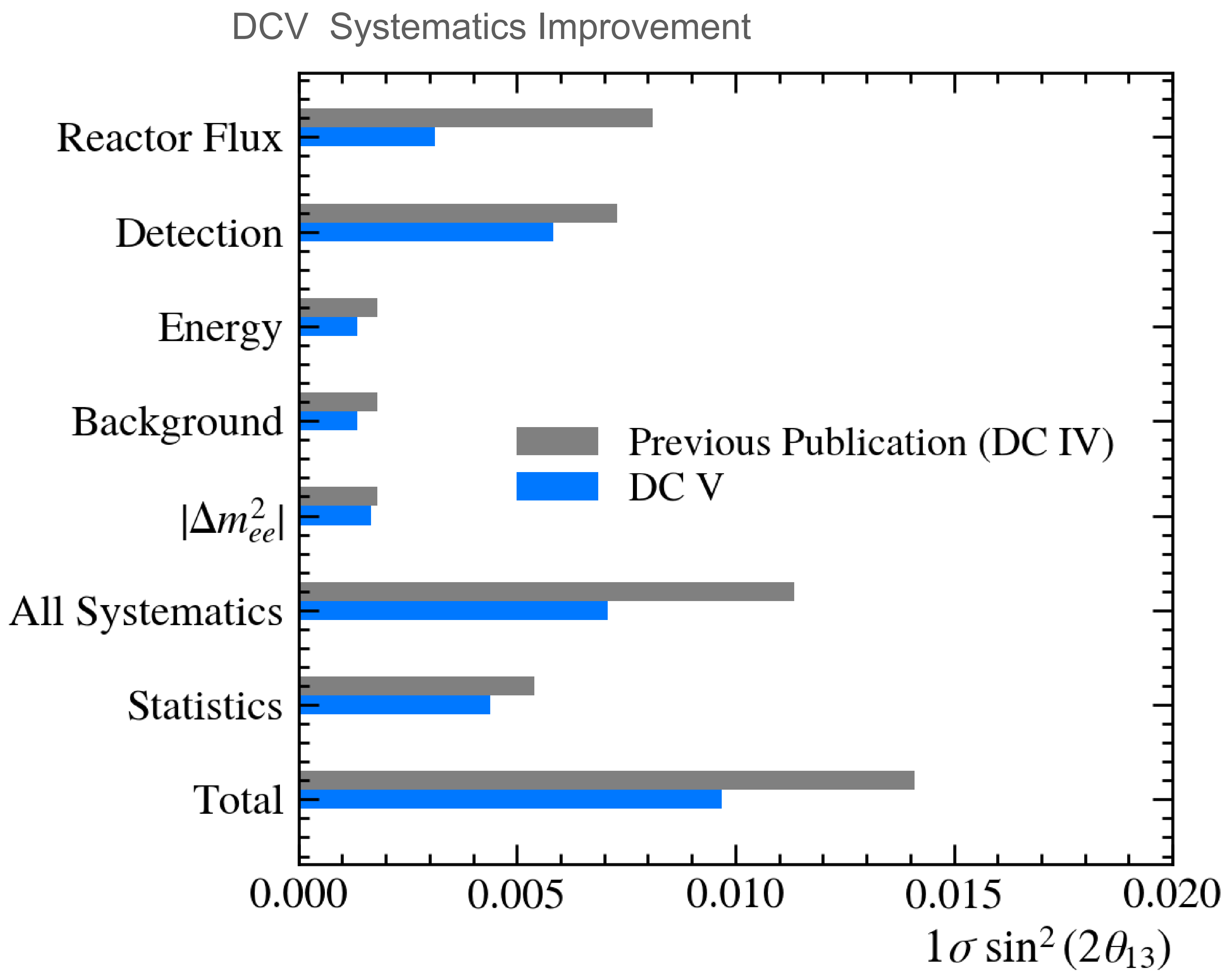




- Visible deviation can be seen by almost all reactor neutrino experiments
- Utilizing the extracted correlated shape deviations, the shape deviation can be observed

θ_{13} Agreement Worldwide





- Reactor Flux: iso-flux & reactor modulation;
- Detection: proton# (both NT &GC);
- Energy: improved energy model;
- Background : reactor-OFF & reactor modulation

DC V: Double Chooz Latest Results

Reactor Absolute Flux

Fission fraction of k-isotope

Mean Cross Section per Fission (MCSpF):

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

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

IBD cross-section

MCSpF for k-isotope

Counting approach

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

- The resulting value is

$$\langle\sigma_f^{DC\ IV}\rangle = (5.71 \pm 0.06) * 10^{-43}\ \frac{cm^2}{fission}$$ [1]

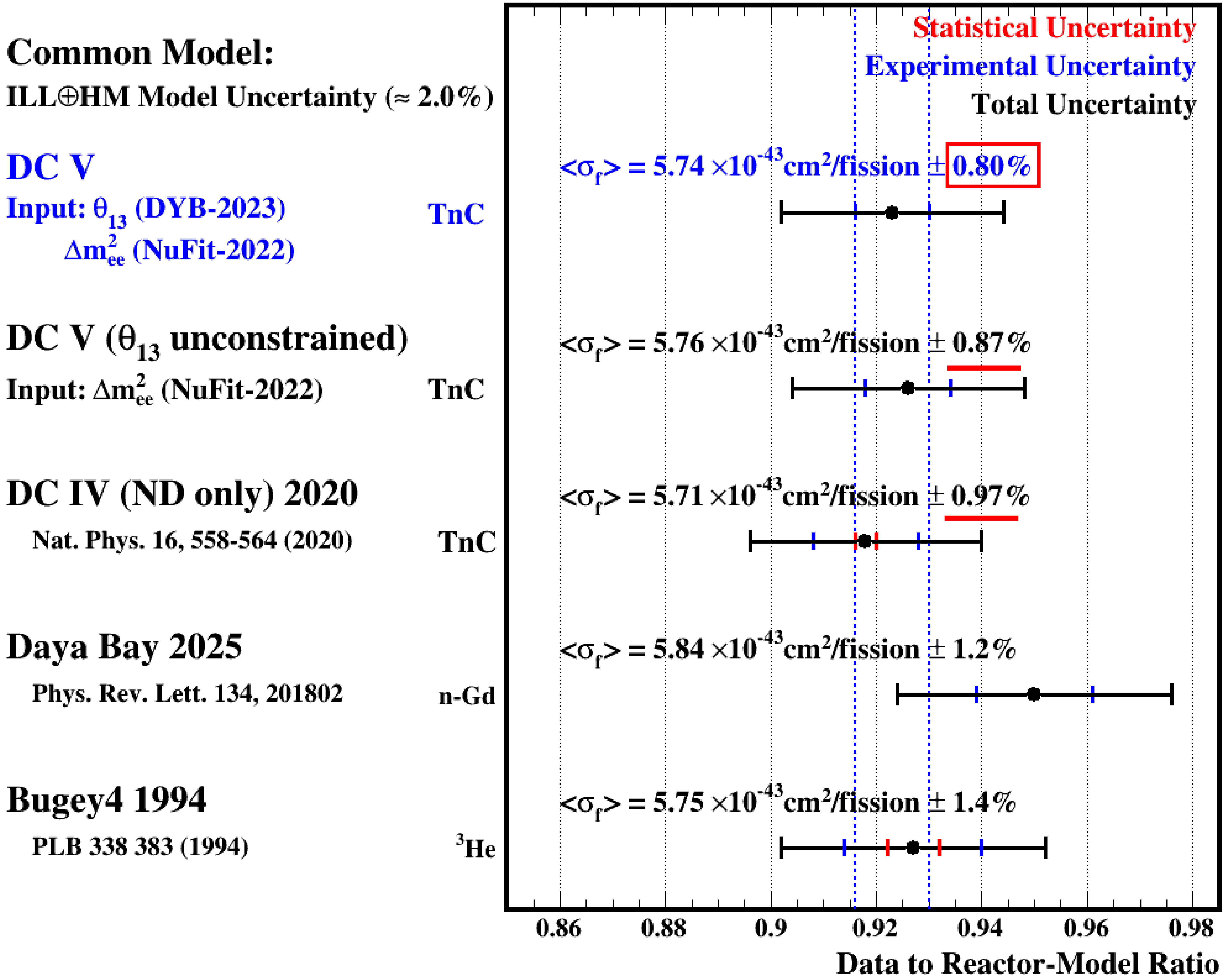
- The relative uncertainty is 0.97%;

Fit approach

- Through the common normalization parameter of the fit;
- Simultaneously with θ_{13} estimation;
- **Full (FD+ND)** DC-statistics;
- Possible to benefit from other experiments via nuisance parameters.

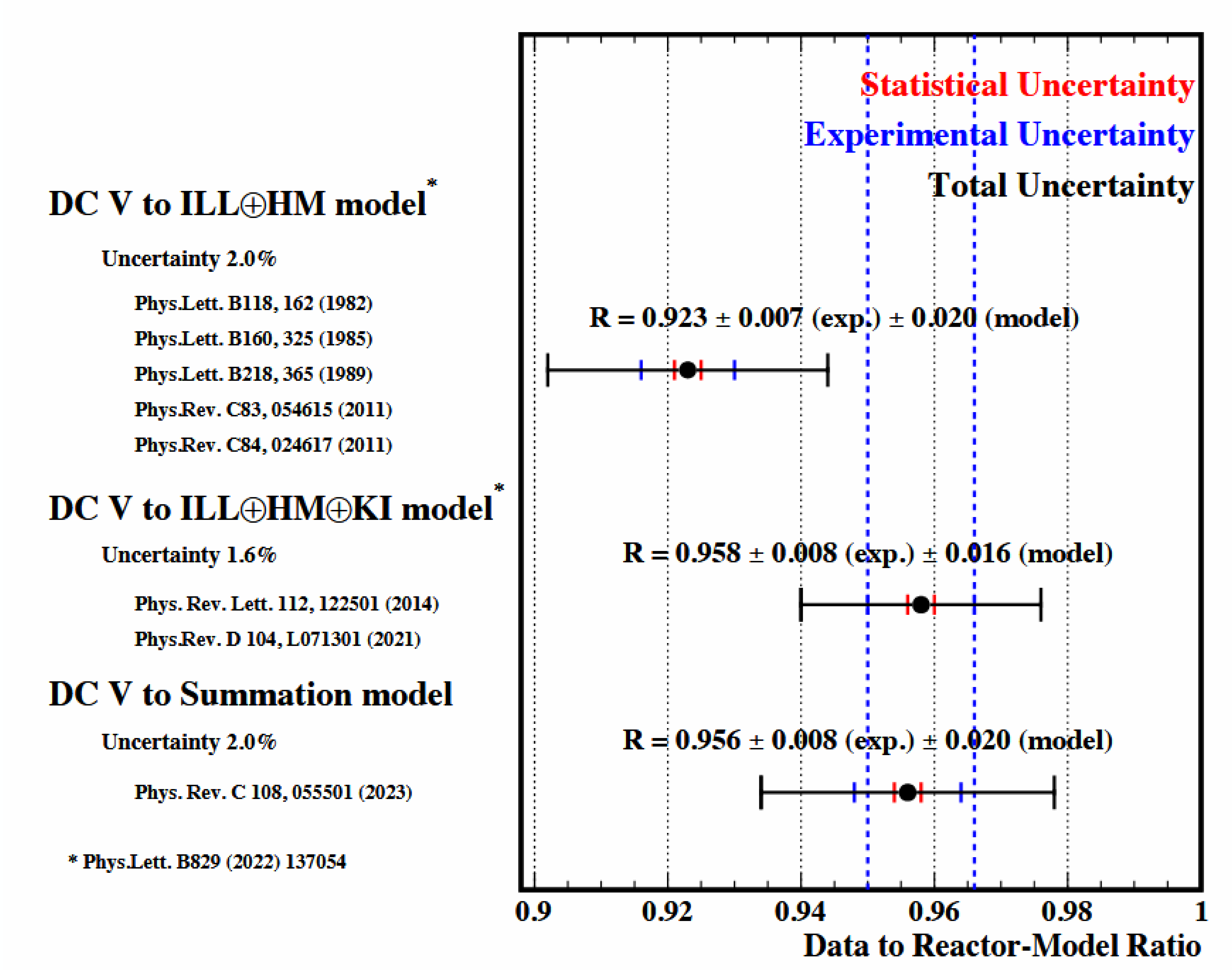
[1]. DC IV, Nat. Phys. 16, 558-564 (2020)

MCSpF Results



DC V: Double Chooz Latest Results

MCSpF Model Comparison



3.7σ

$\sim 2\sigma$

$\sim 2\sigma$

DC V: Double Chooz Latest Results

DOUBLE CHOOZ COLLABORATION

Many people contributed to the experiment

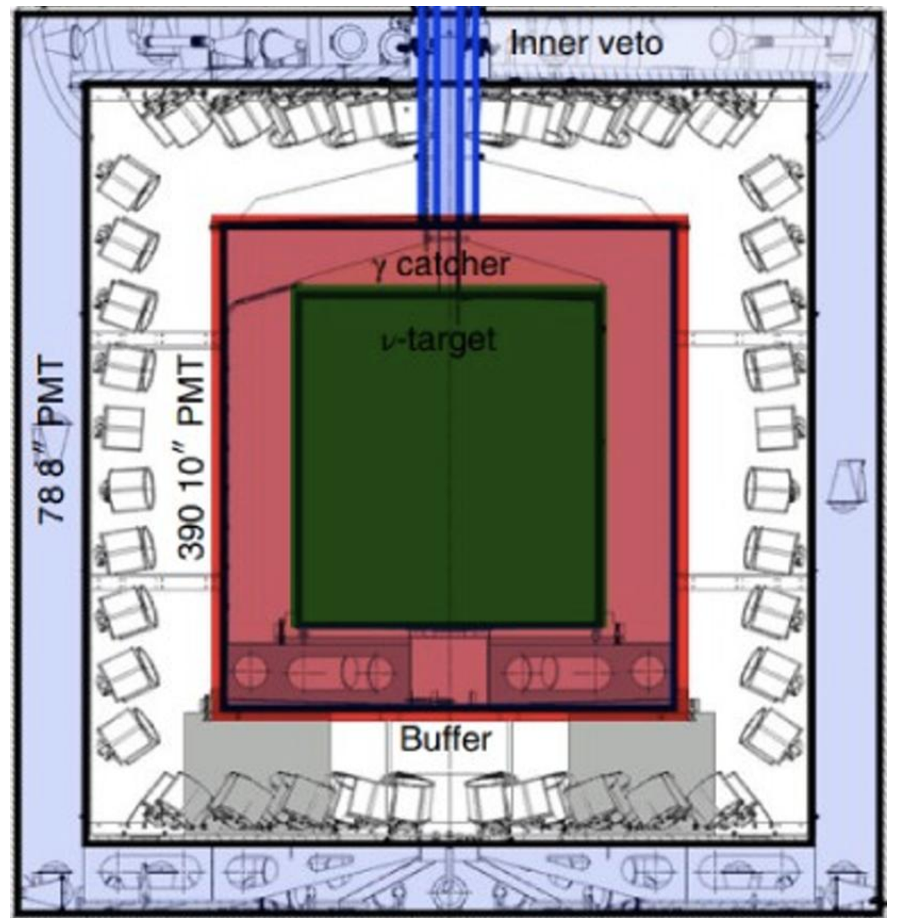
Thanks for all the hard work!

Conclusion

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

Backup

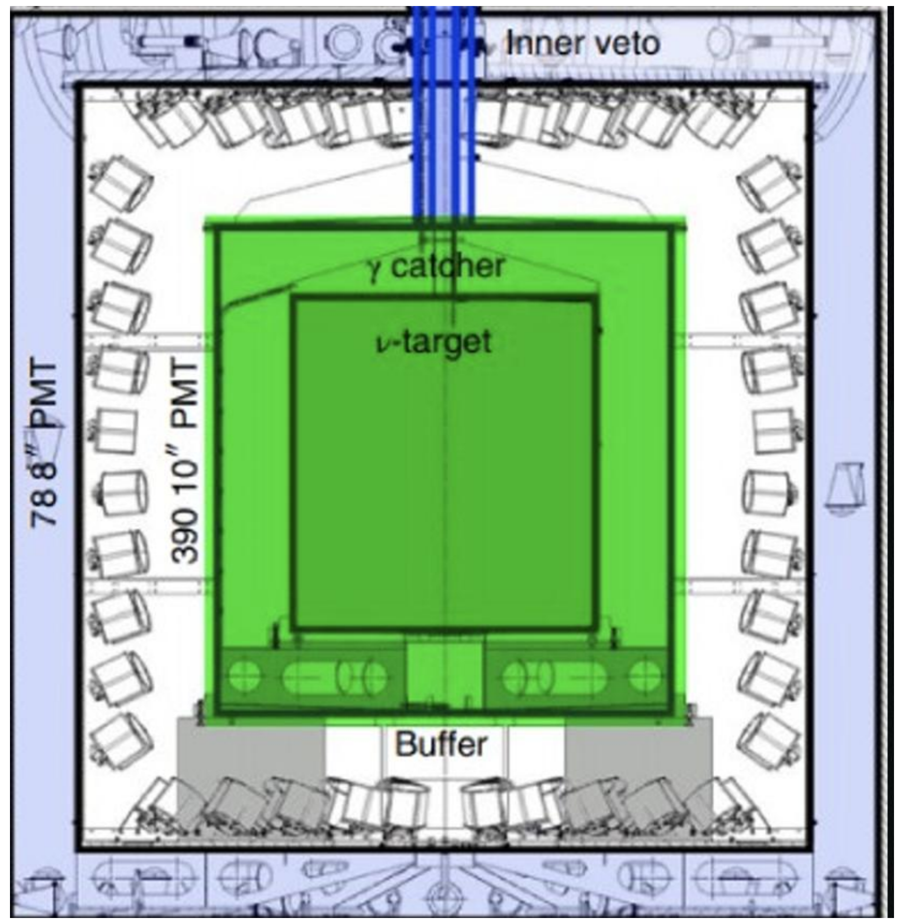
Detector Dismantling



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

0.012

0.0099



- During dismantling NEW GC mass measurements;
- Based on 3D Laser technique (LEICA RTC 360 – 2 mm precision);
- M_{liquid} uncertainty for GC has reduced ~50%;