

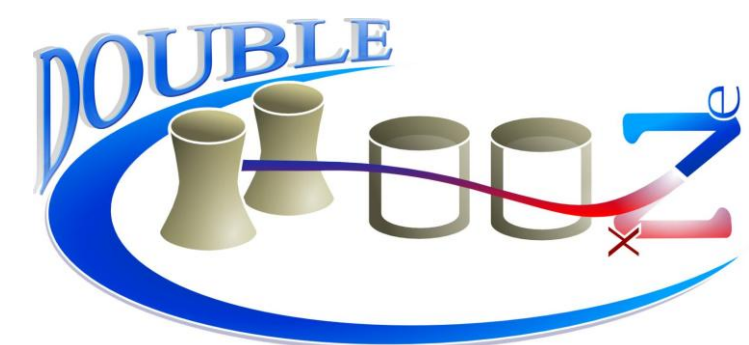
DC V: Double Chooz Latest and Last Results

Aldiyar Oralbaev

for the Double Chooz Collaboration



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



Neutrino Oscillation

$$\begin{array}{c}
 \text{Flavour Eigenstate} \\
 \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}}_{U_{\text{PMNS}}} \underbrace{\begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}}_{\text{Mass Eigenstate}}
 \end{array}$$

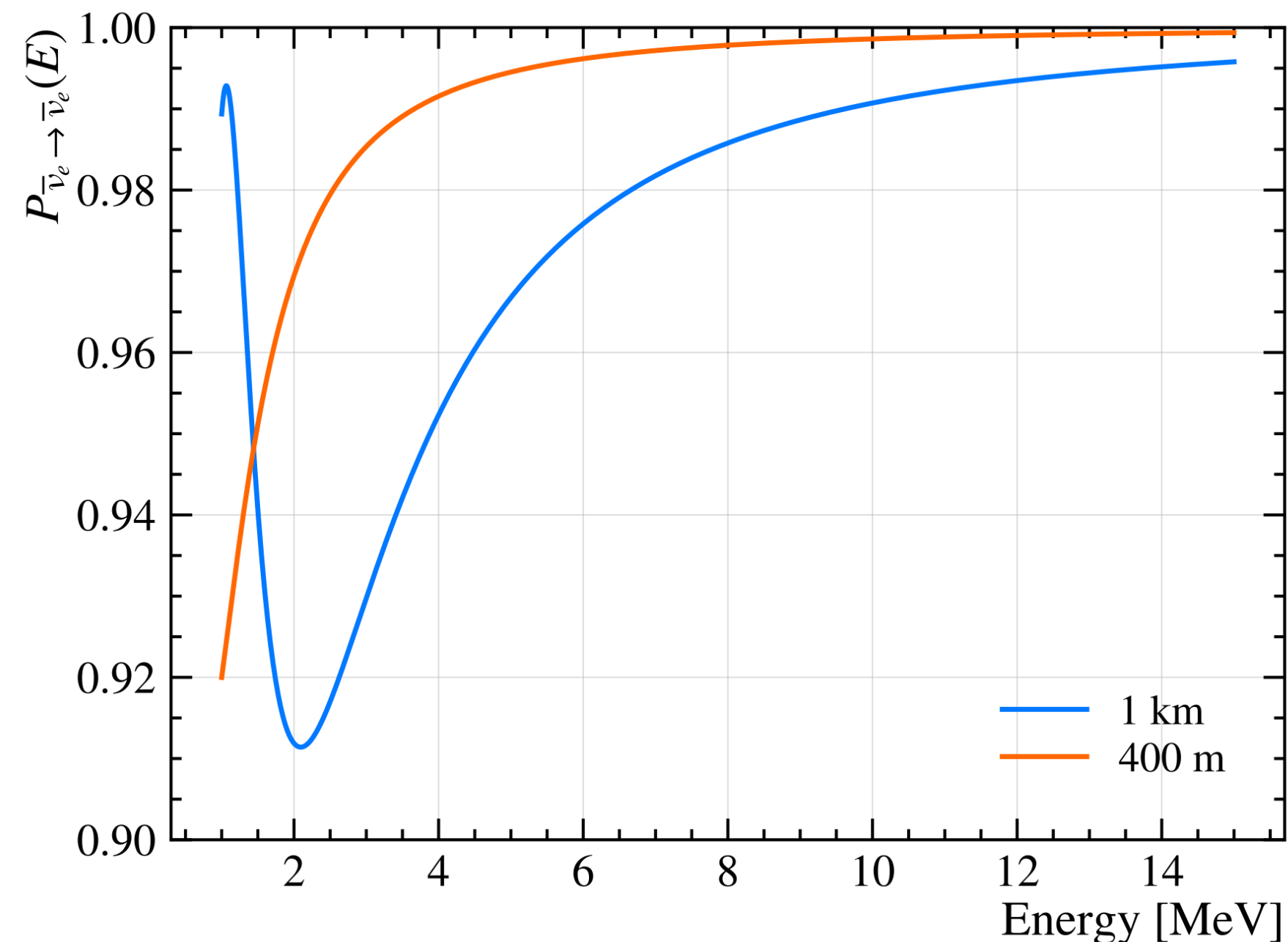
Atmospheric $P(\nu_\mu \rightarrow \nu_\mu)$	Reactor and Accelerator $P(\nu_e \rightarrow \nu_e) \text{ \& } P(\nu_\mu \rightarrow \nu_e)$	Solar $P(\nu_e \rightarrow \nu_x)$
$\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}$	$\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix}$	$\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$
$\theta_{23} \sim 45^\circ$	$\theta_{13} \text{ \& } \delta_{\text{CP}}$	$\theta_{12} \sim 33^\circ$

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

$$\begin{aligned}
 P(\bar{\nu}_e \rightarrow \bar{\nu}_e) &= |\langle \bar{\nu}_e | \bar{\nu}_e \rangle|^2 = \left| \sum_i U_{ei}^* U_{ei} \exp\left(-i \frac{m_i^2 L}{2E}\right) \right|^2 = \dots \\
 &\approx 1 - \sin^2(2\theta_{13}) \sin^2 \Delta_{ee} - \cos^4 \theta_{13} \sin^2(2\theta_{12}) \sin^2 \Delta_{21}
 \end{aligned}$$

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

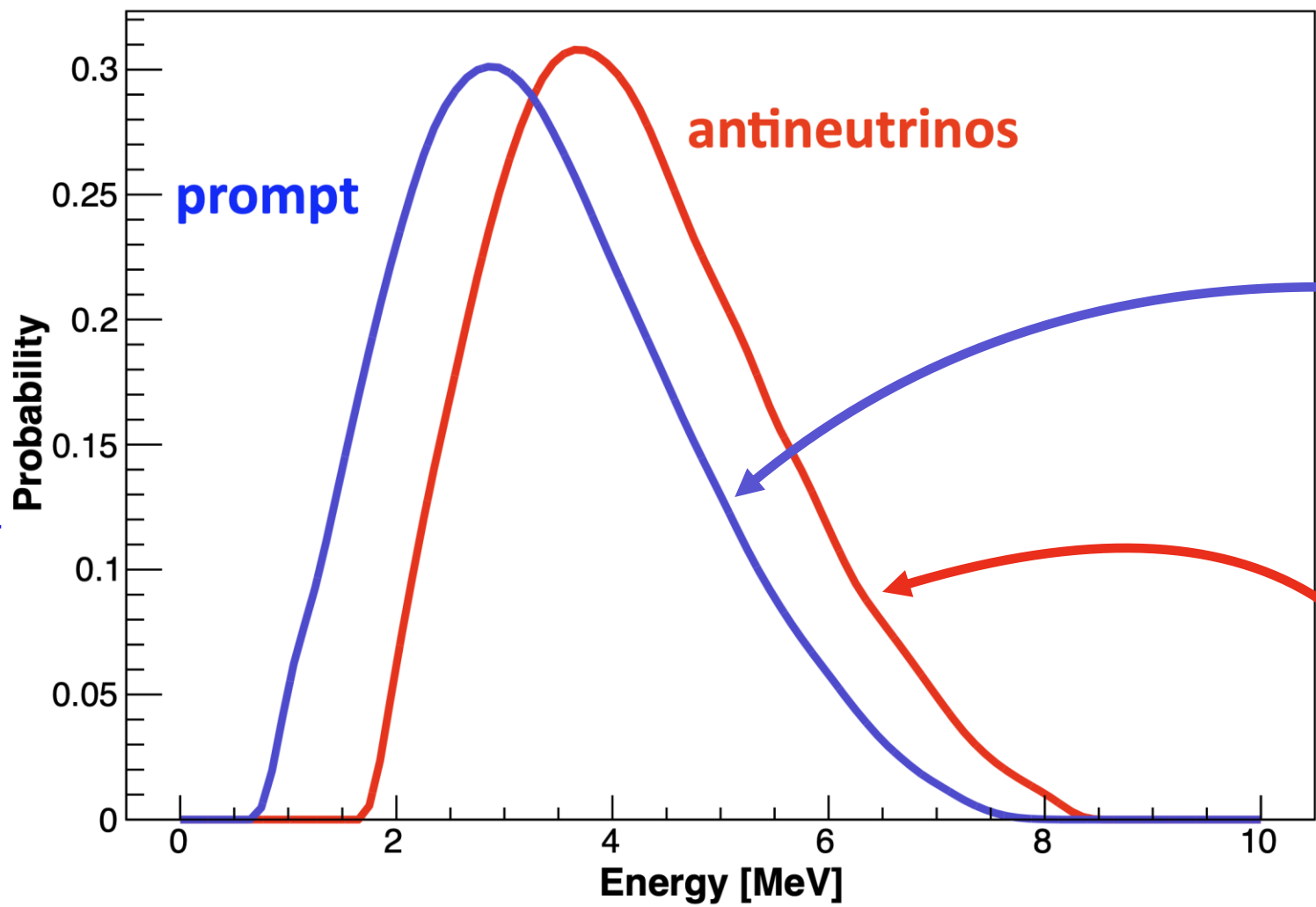
$$\Delta_{ij} \equiv \Delta m_{ij}^2 \frac{L}{4E}$$



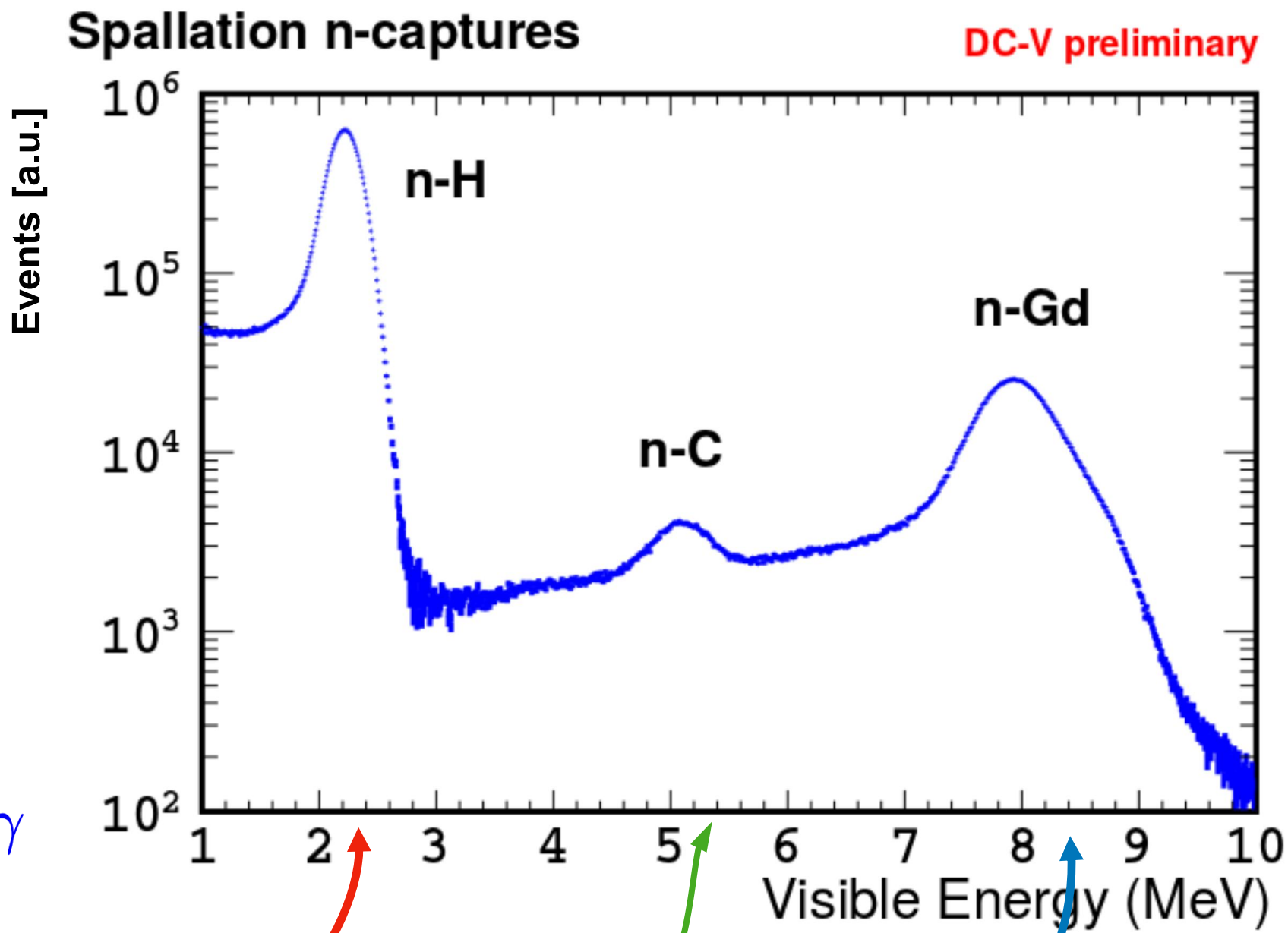
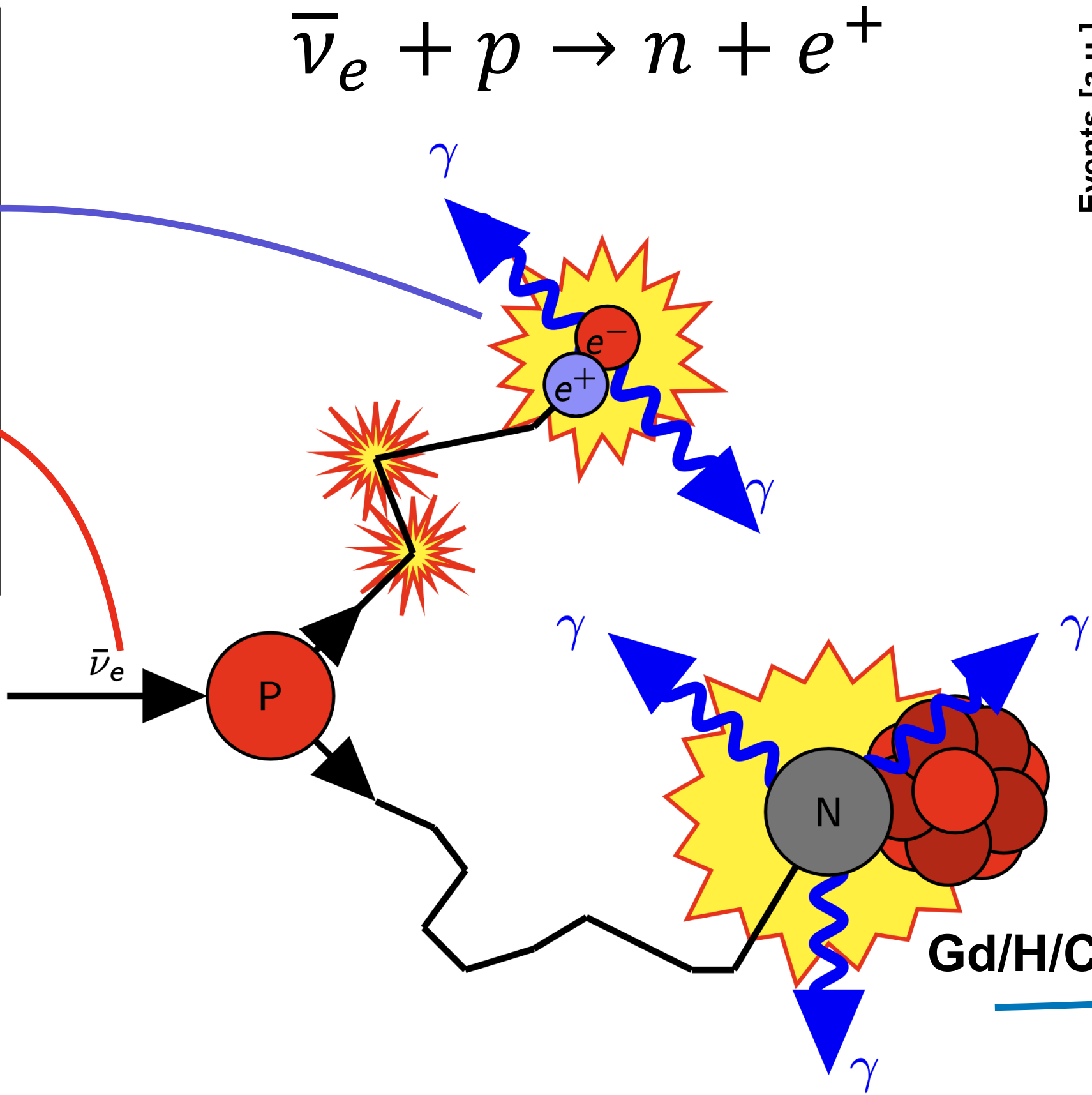
- Neutrinos *oscillate* as a function of distance and energy;
- For a single flavour ($\bar{\nu}_e$) source the energy spectrum changes for different distances;
- For fixed distances the effect is observable as a systematic deficit of measured neutrinos.

Neutrino Detection via Inverse Beta Decay

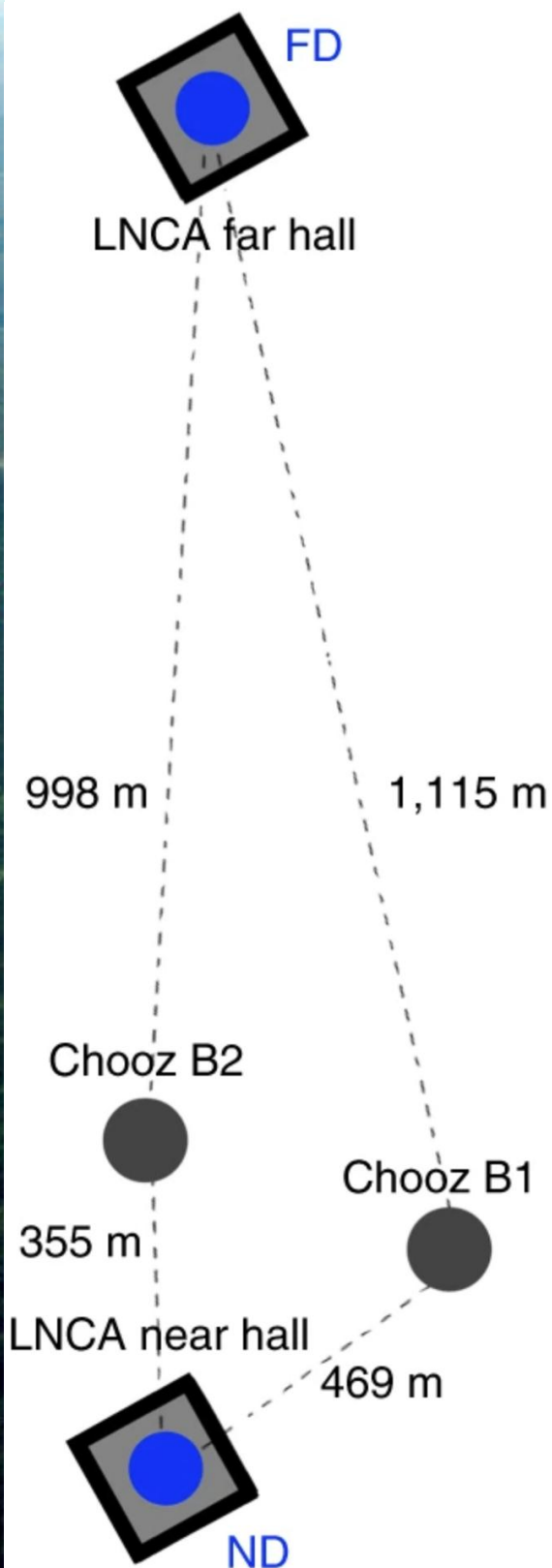
Yoo | Neutrino 2020



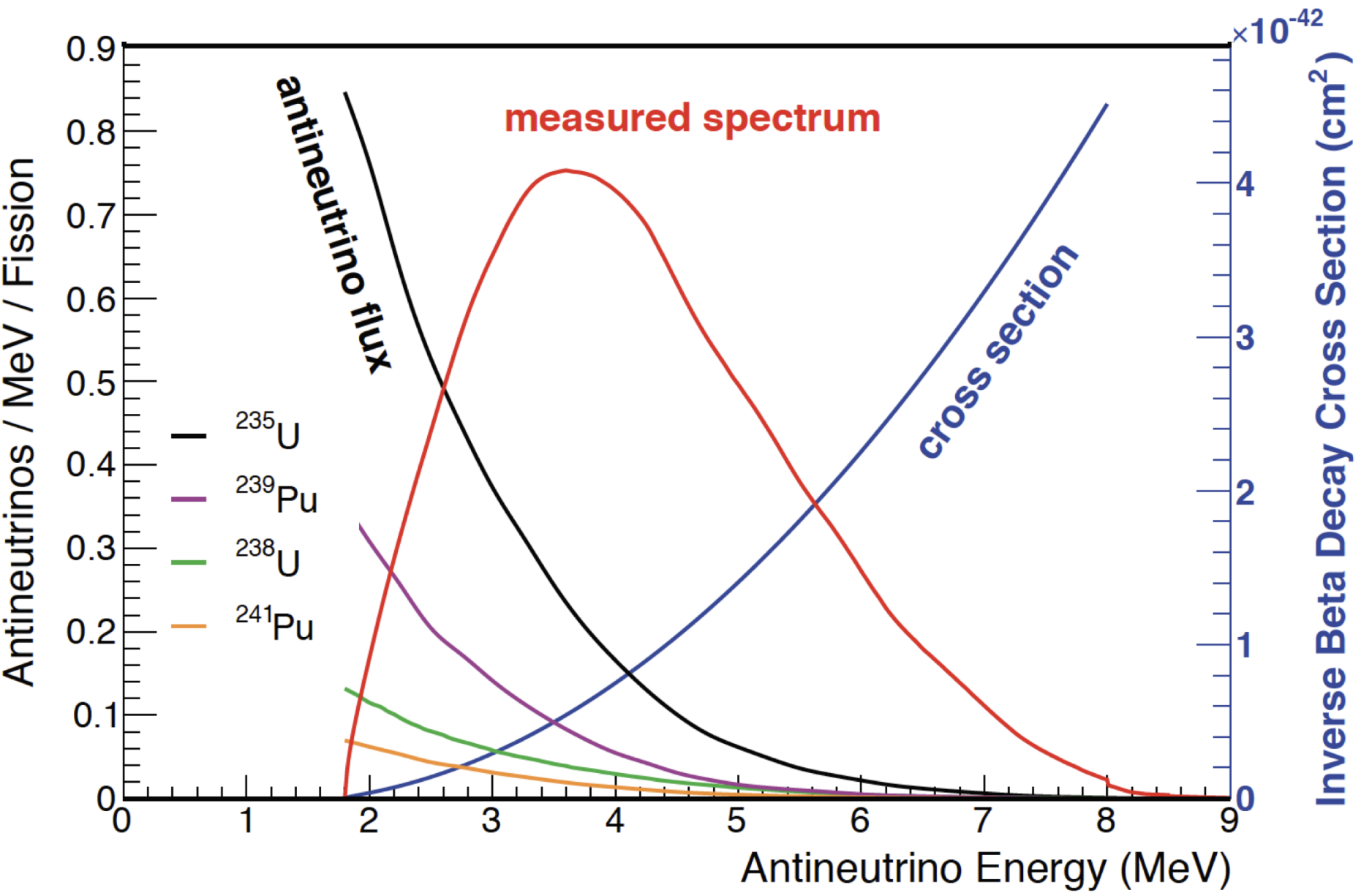
- 1.8MeV threshold for IBD process
 - $E_{\text{prompt}} \approx E_{\nu} - 0.8\text{MeV}$
- Distinct double event signature
- Low background due to double signal
- Relatively high cross section



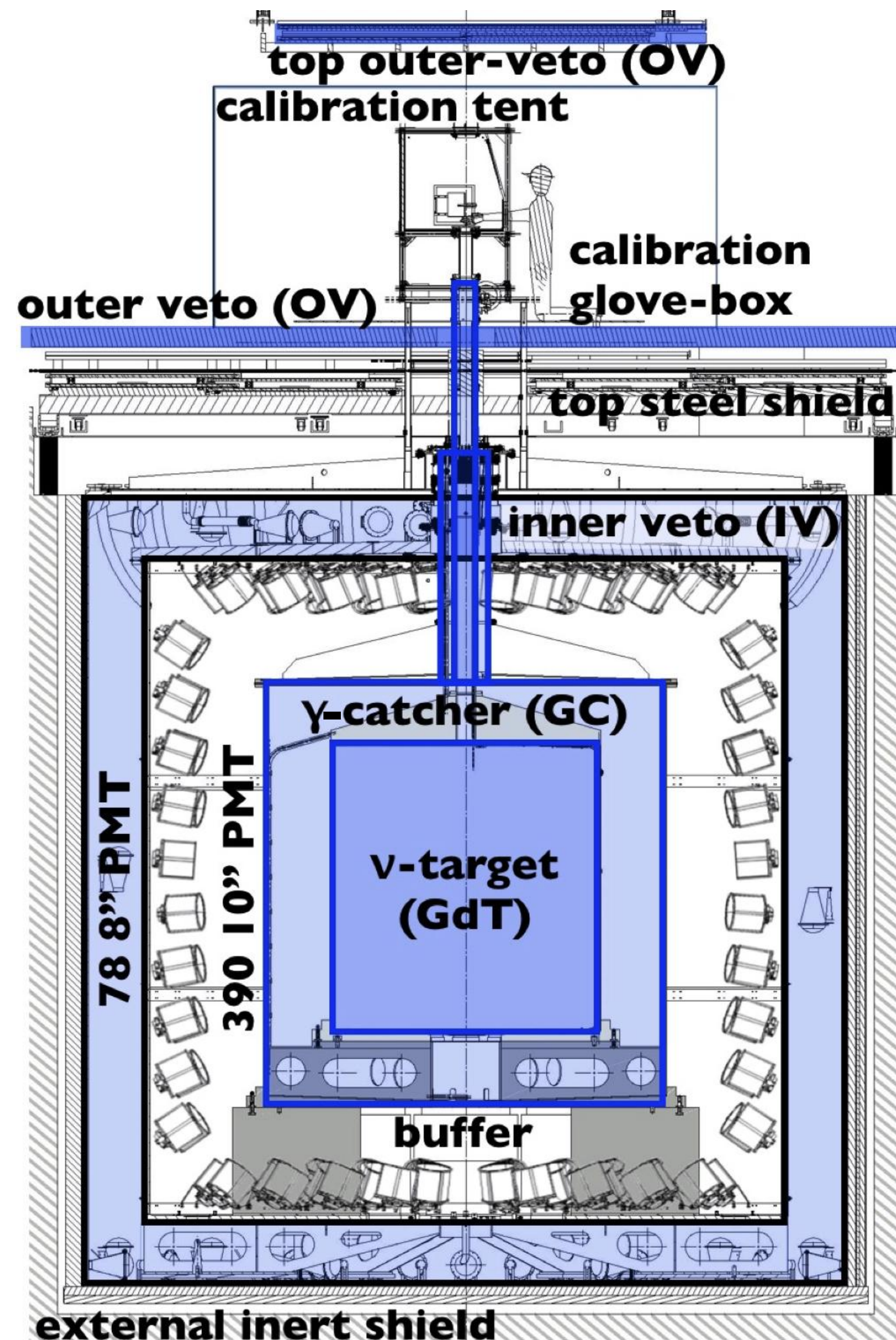
Experimental Setup



- Nuclear Reactors are a strong neutrino source
 - $\sim 6 \bar{\nu}_e$ per fission
 - $\sim 10^{21} \bar{\nu}_e [s^{-1} GW^{-1}]$
- 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

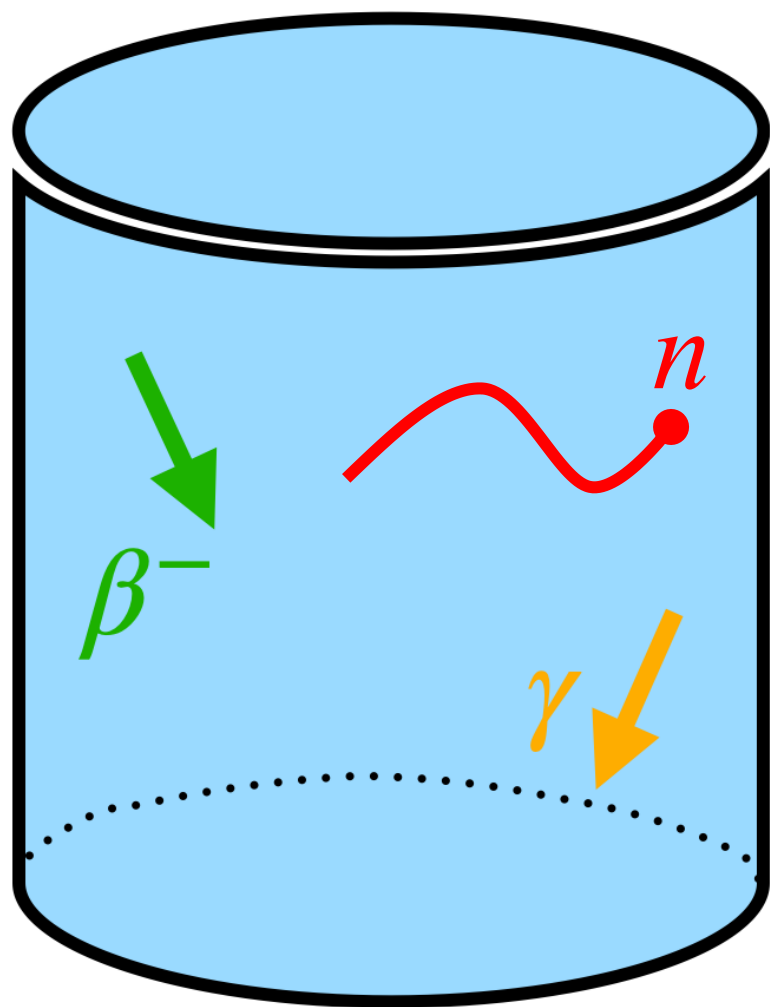


- Identical design for both detectors
- Detector is built in an onion like structure
- ν - target
 - 1gl^{-1} Gd doped Liquid Scintillator
- γ - catcher
 - Undoped Liquid Scintillator
- buffer
 - Non scintillating mineral oil
 - 390 10-inch PMTs
- inner veto
 - Shielded Liquid Scintillator for atm. μ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

Background Model

Uncorrelated

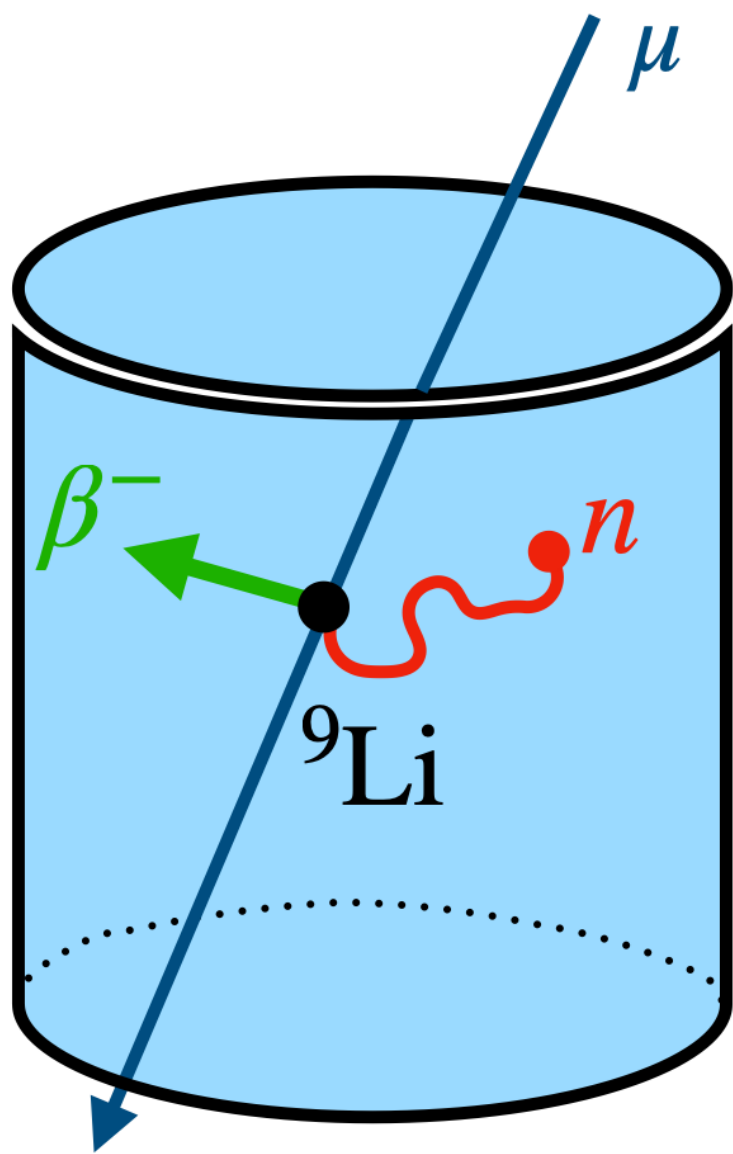
Accidental



Random coincidences
between uncorrelated
events

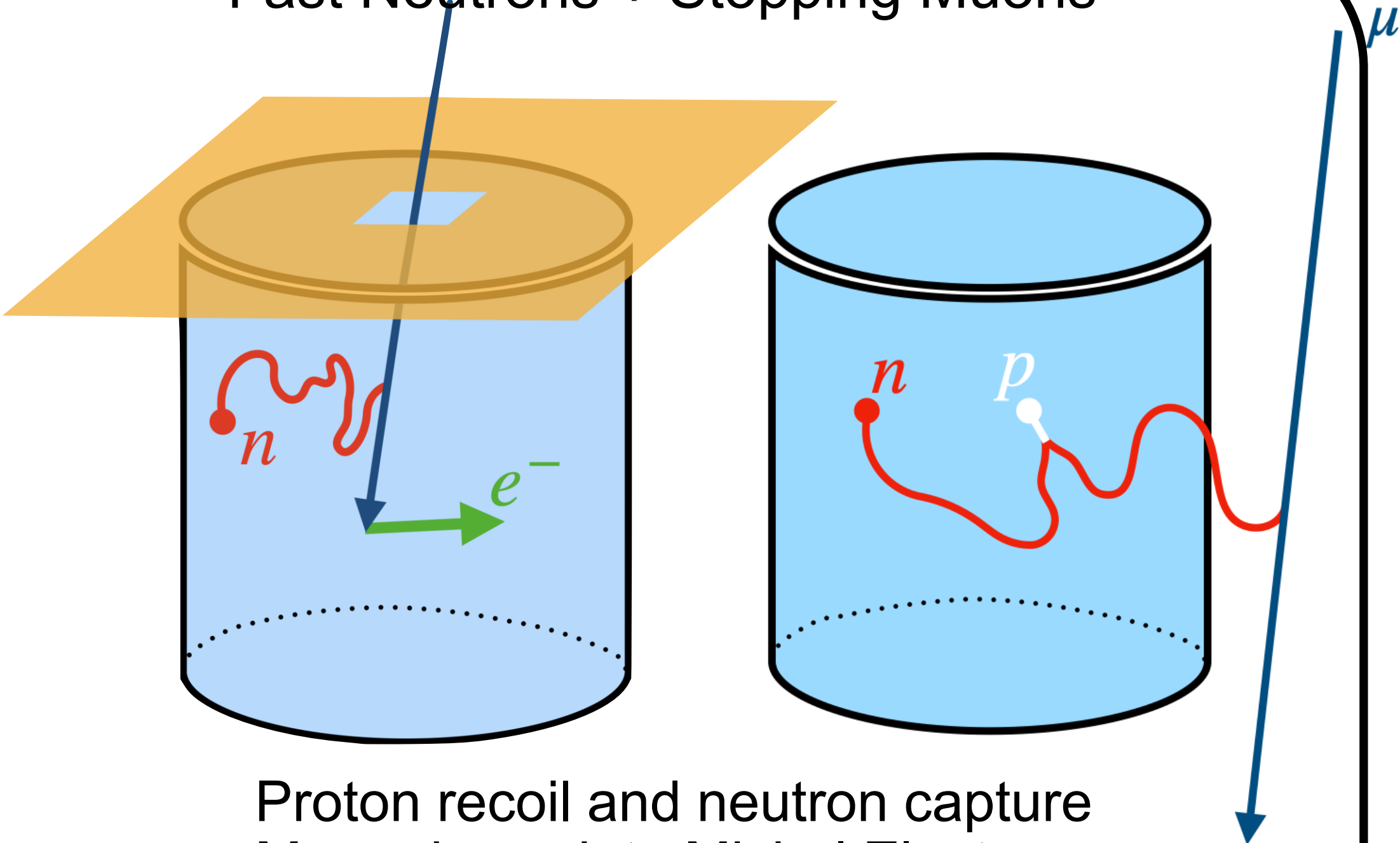
Correlated from cosmic Muon

Cosmogenic



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

Fast Neutrons + Stopping Muons

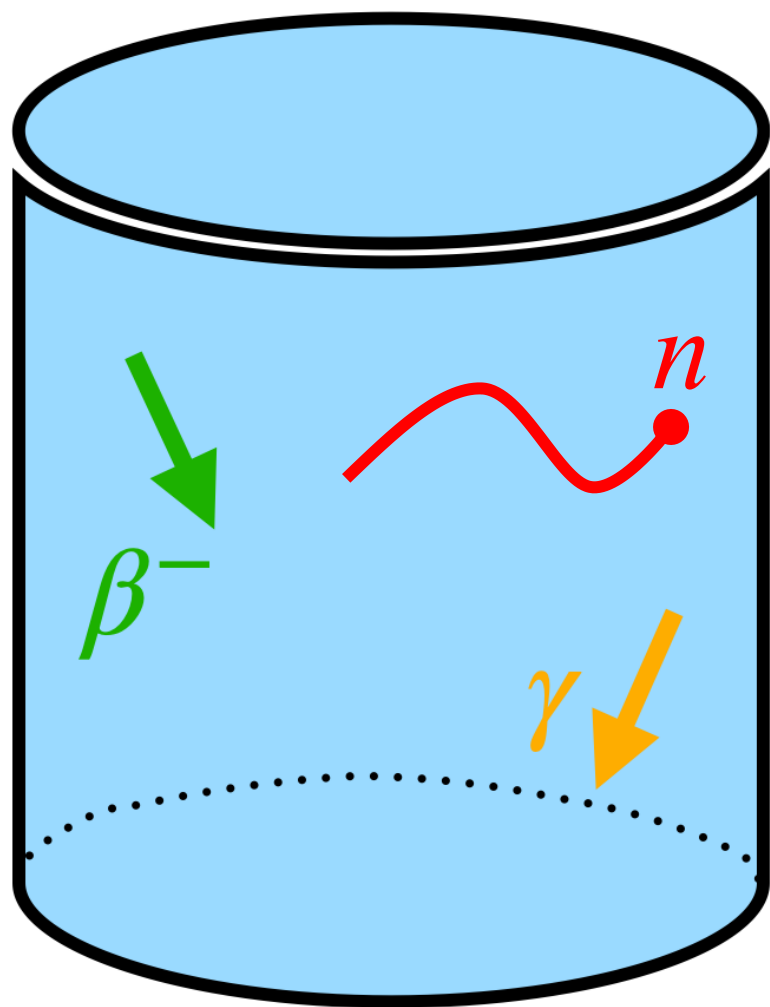


Proton recoil and neutron capture
Muon decay into Michel Electrons

Background Model

Uncorrelated

Accidental

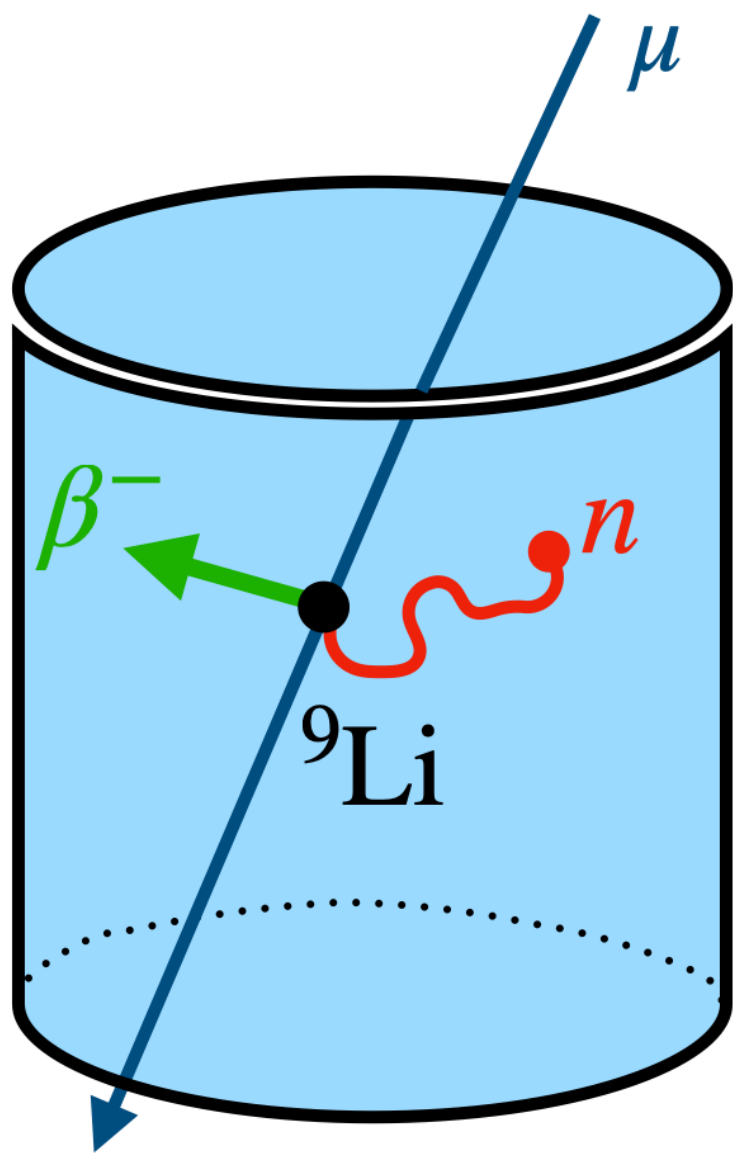


Random coincidences
between uncorrelated
events

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

Correlated from cosmic Muon

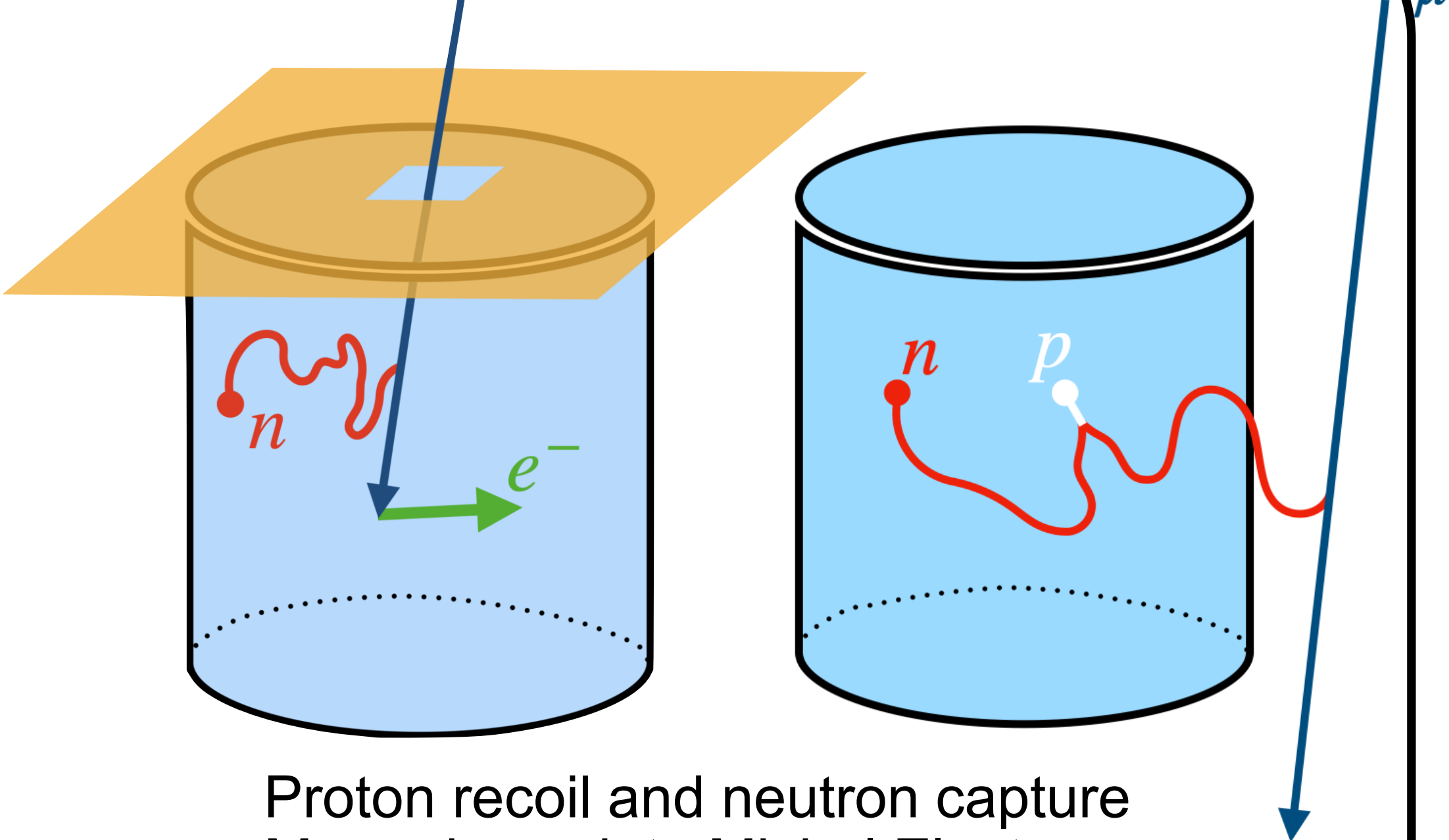
Cosmogenic



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

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

Fast Neutrons + Stopping Muons



Proton recoil and neutron capture
Muon decay into Michel Electrons

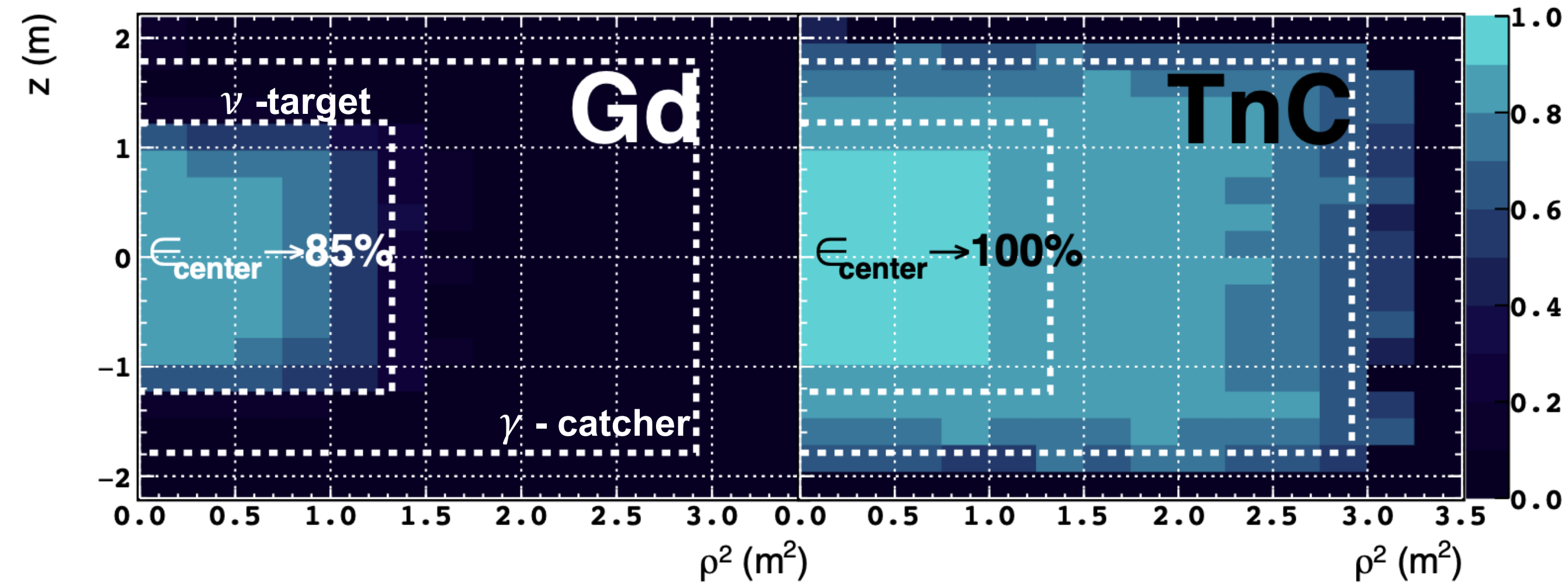
FD	$6.05 \pm 0.10 \text{ day}^{-1}$
ND	$45.56 \pm 0.36 \text{ day}^{-1}$

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

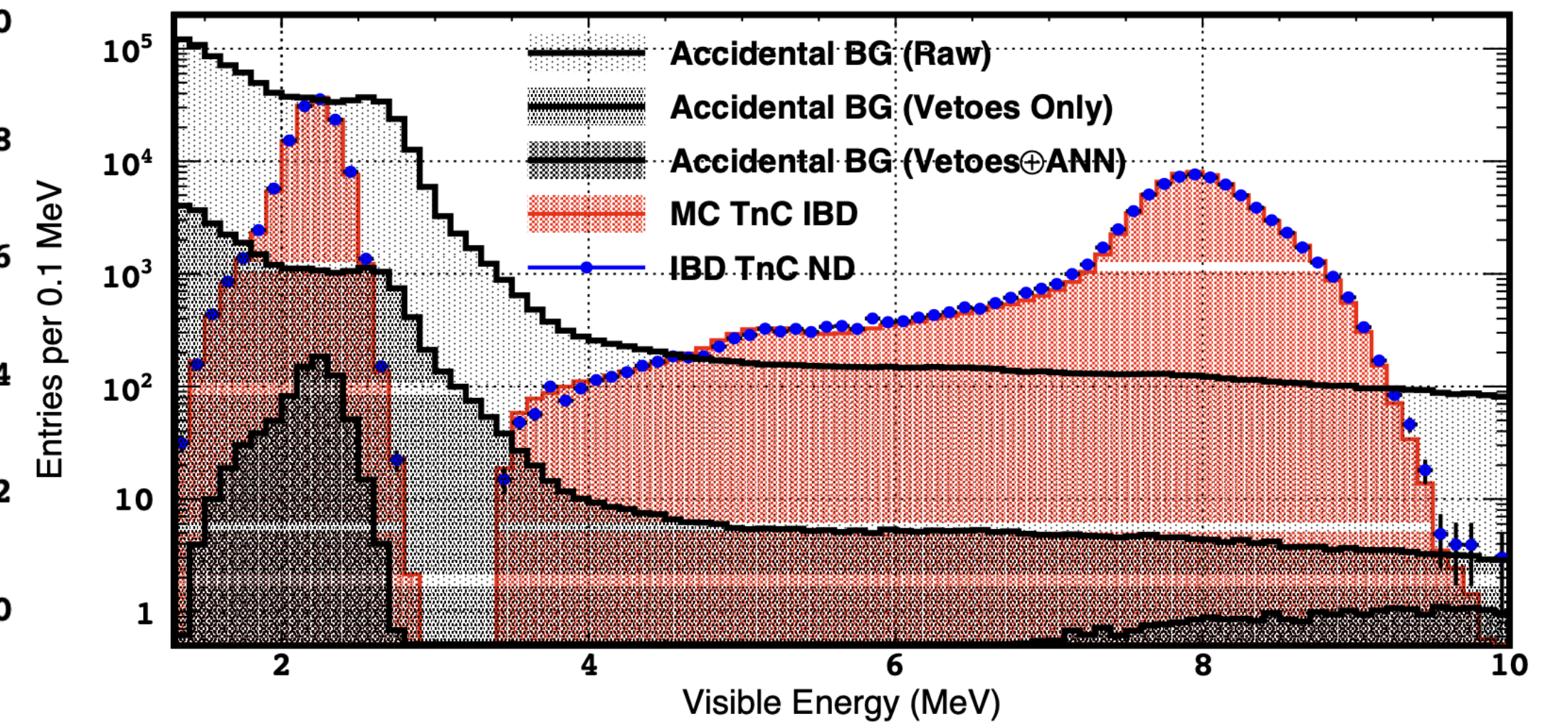
B.Roskovets PIC 2019

Background Reduction

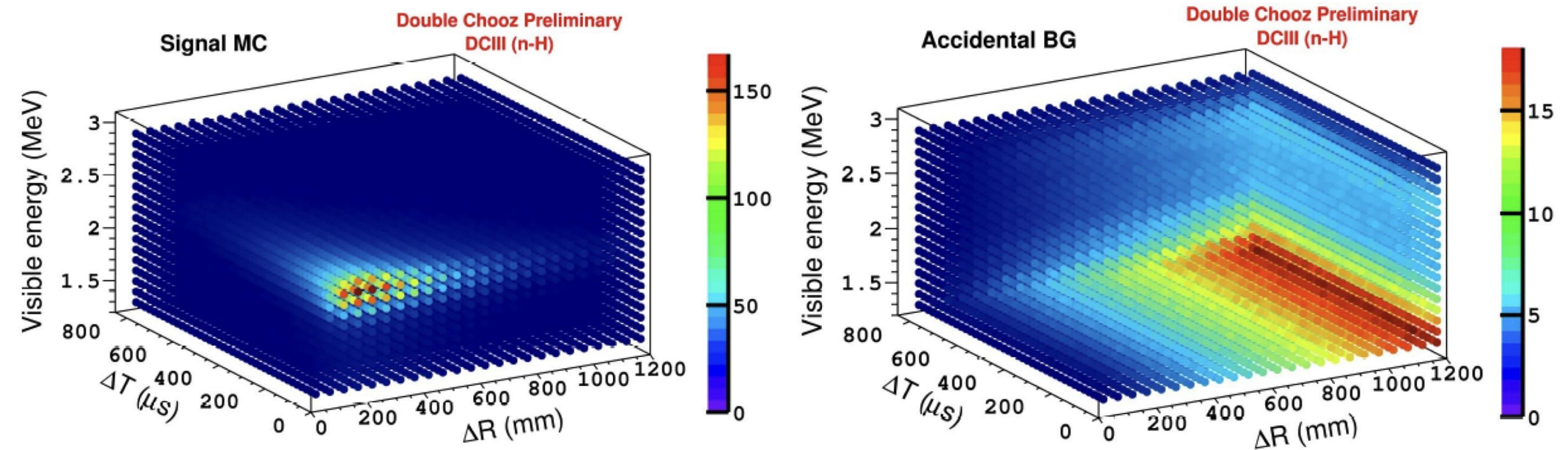
DC IV, Nat. Phys. 16, 558-564 (2020)



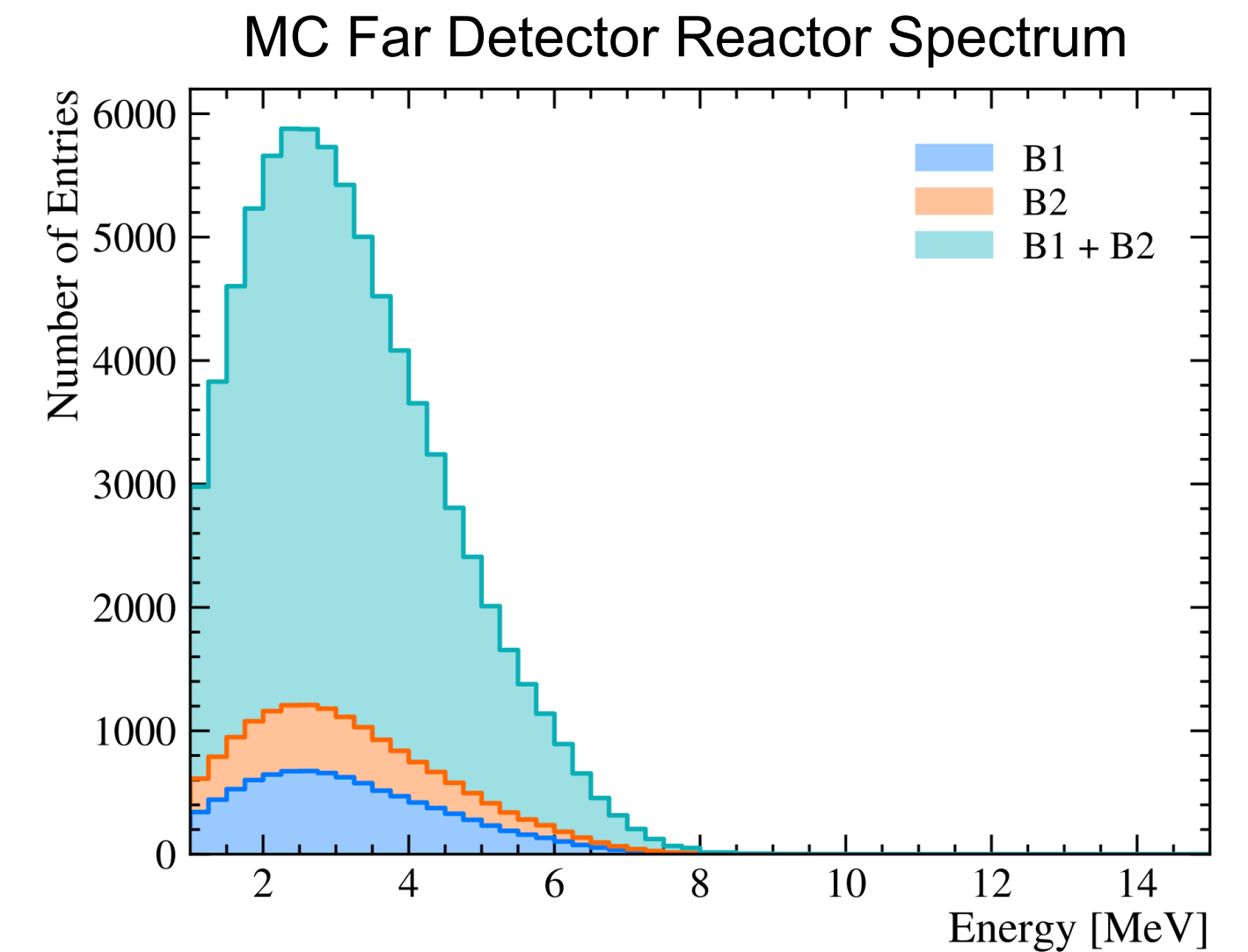
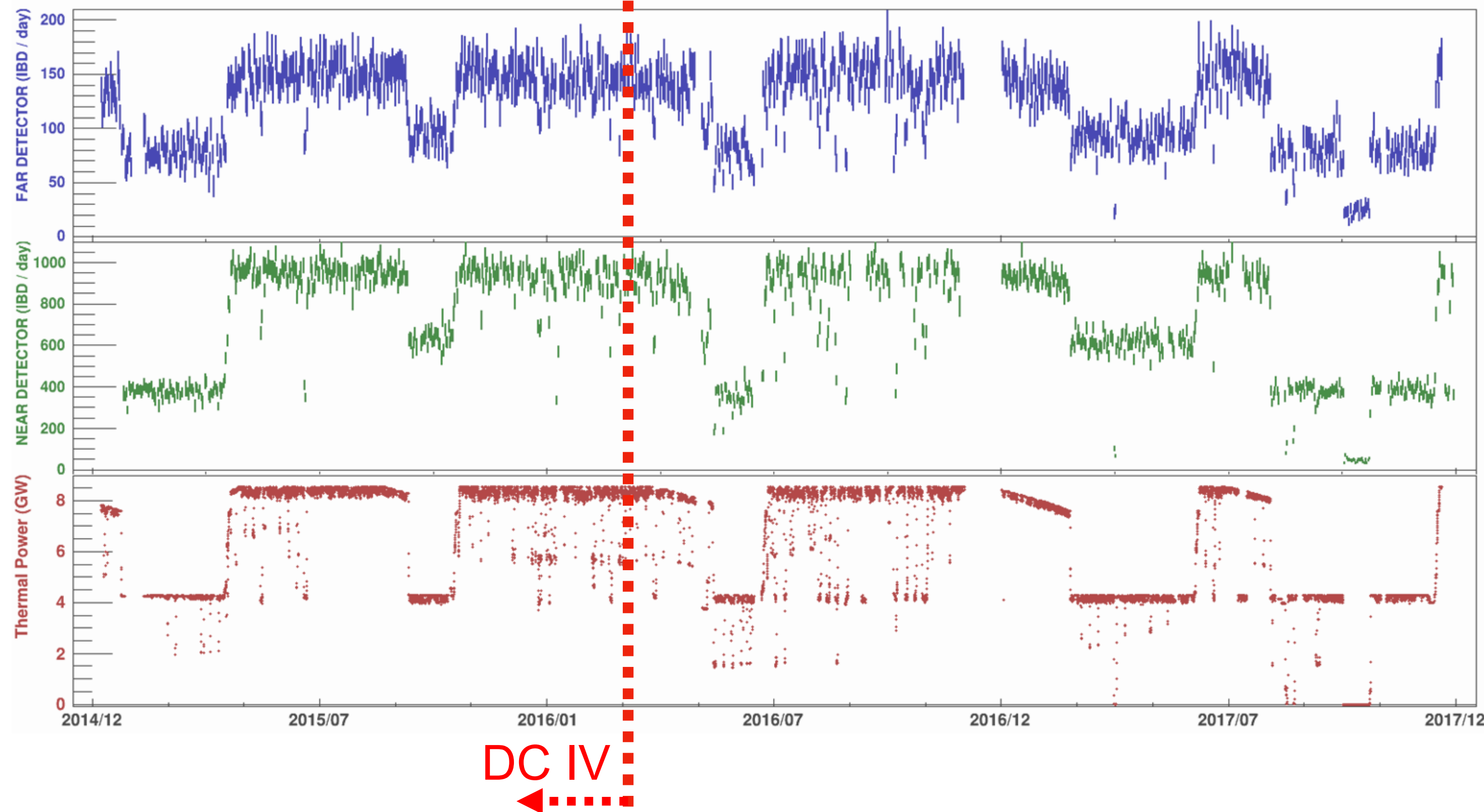
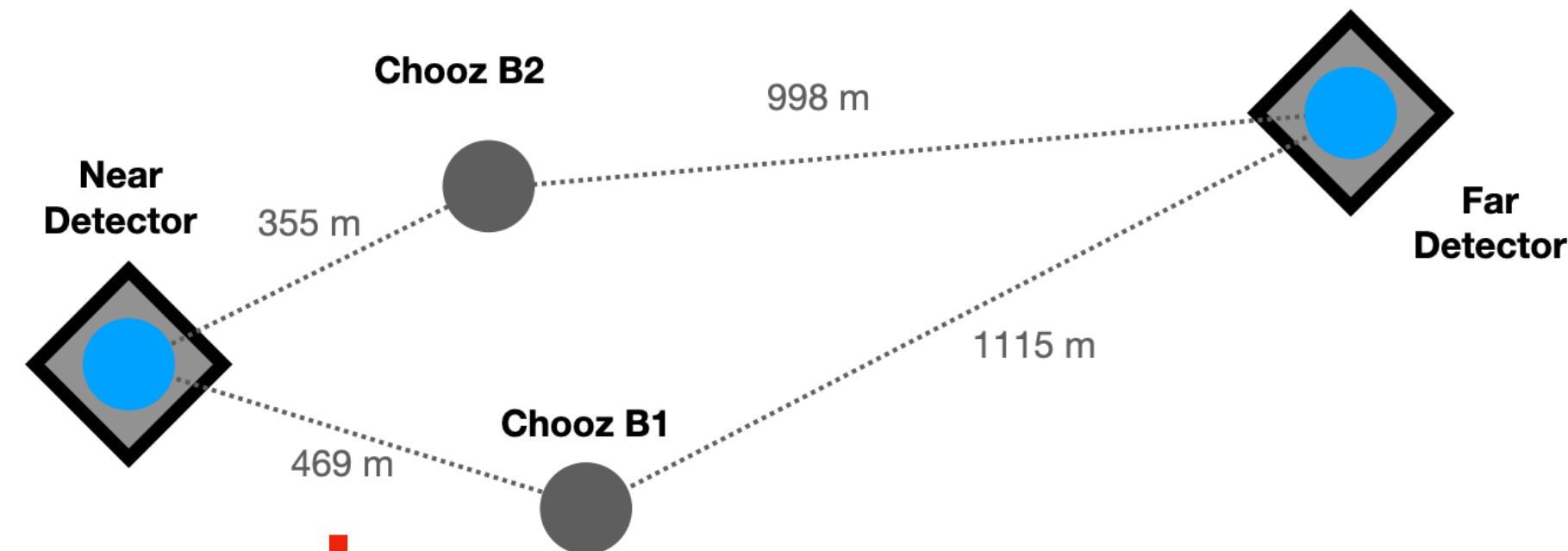
DC IV, Nat. Phys. 16, 558-564 (2020)



- 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

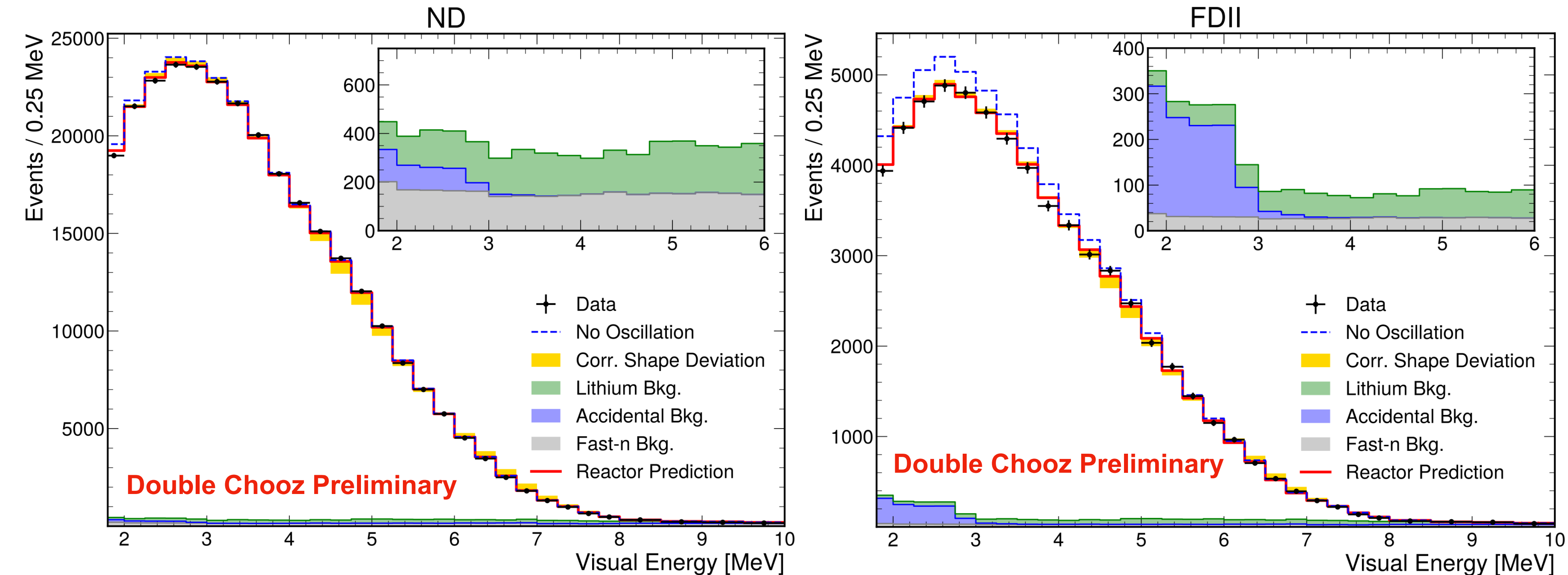
Near
Detector

Reactor
Thermal
Power

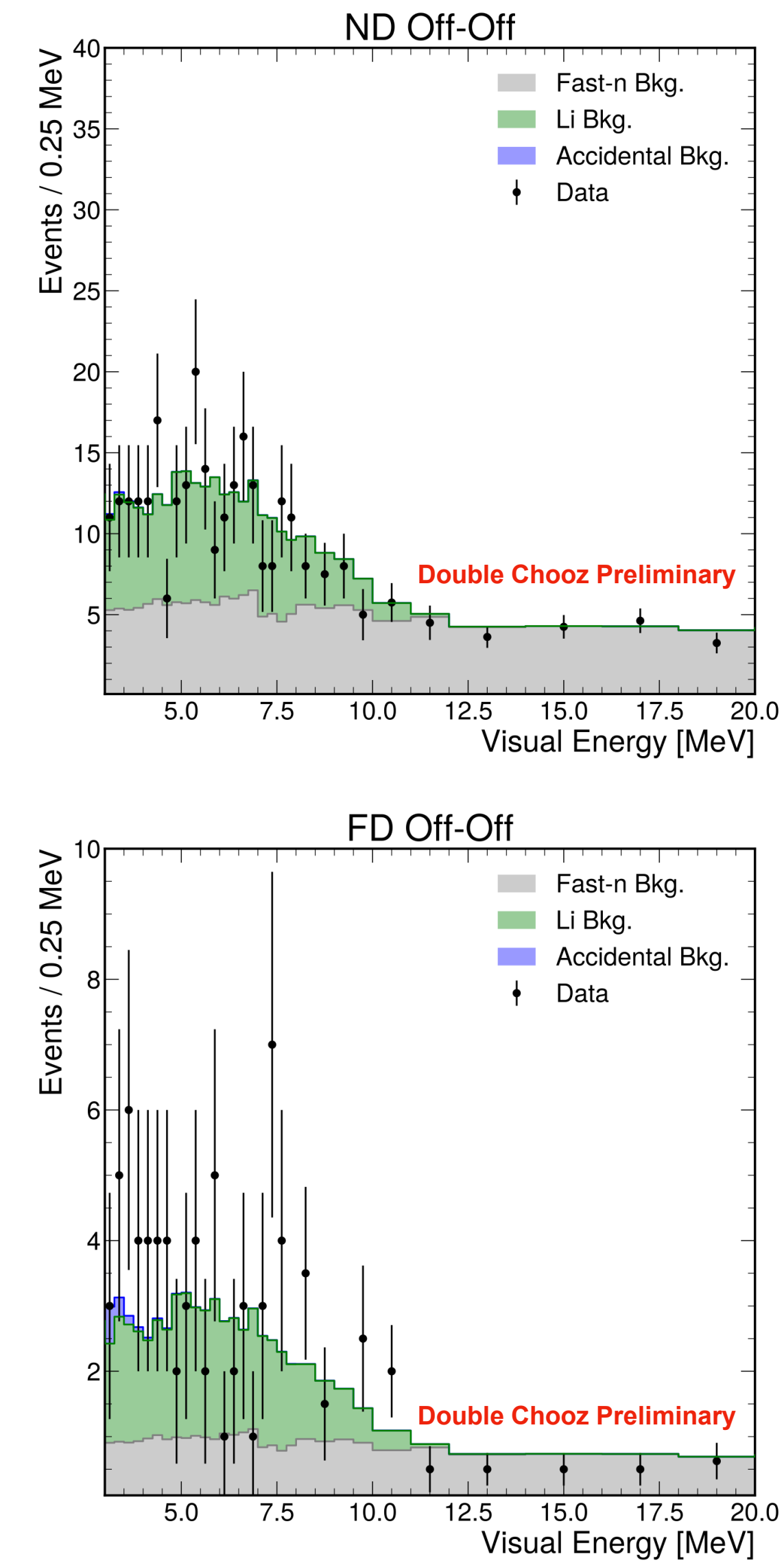
- $\sim \times 2.3$ of Statistics;
- Reactor split helps better constraint the θ_{13} ;
- Combines DC RRM^[1] and DC II^[2] Methods

Prompt Energy Spectra

ON-time

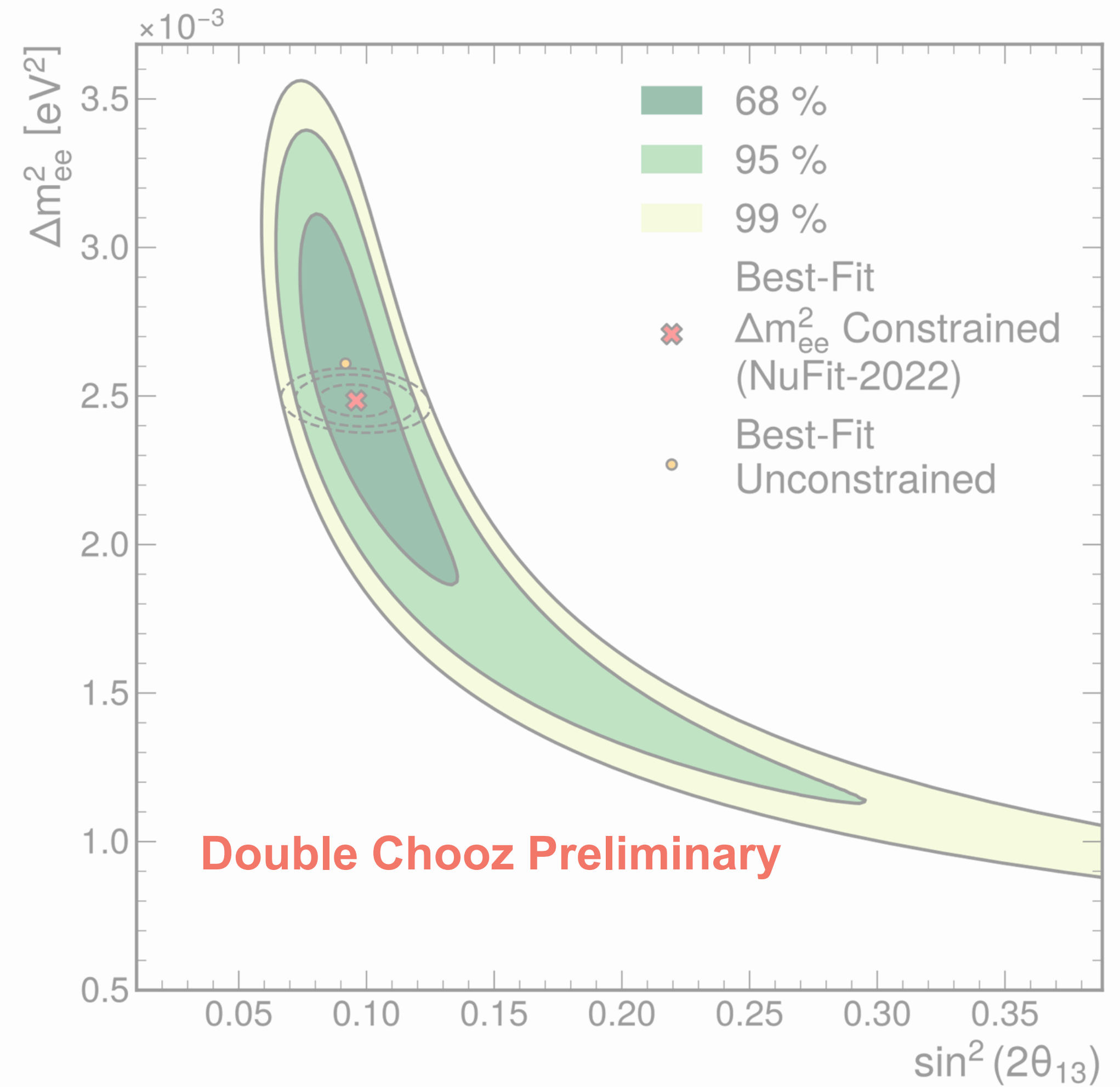
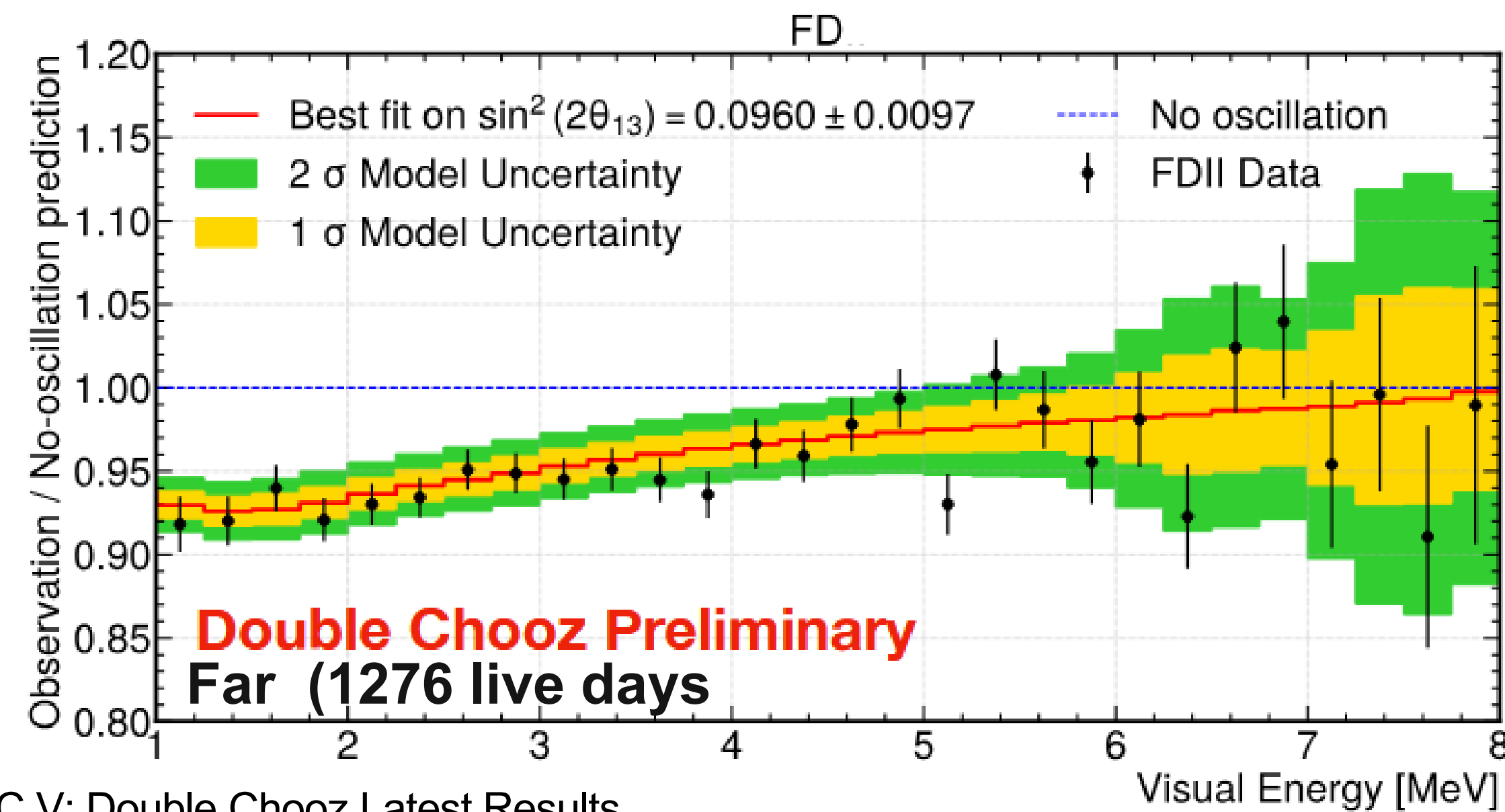
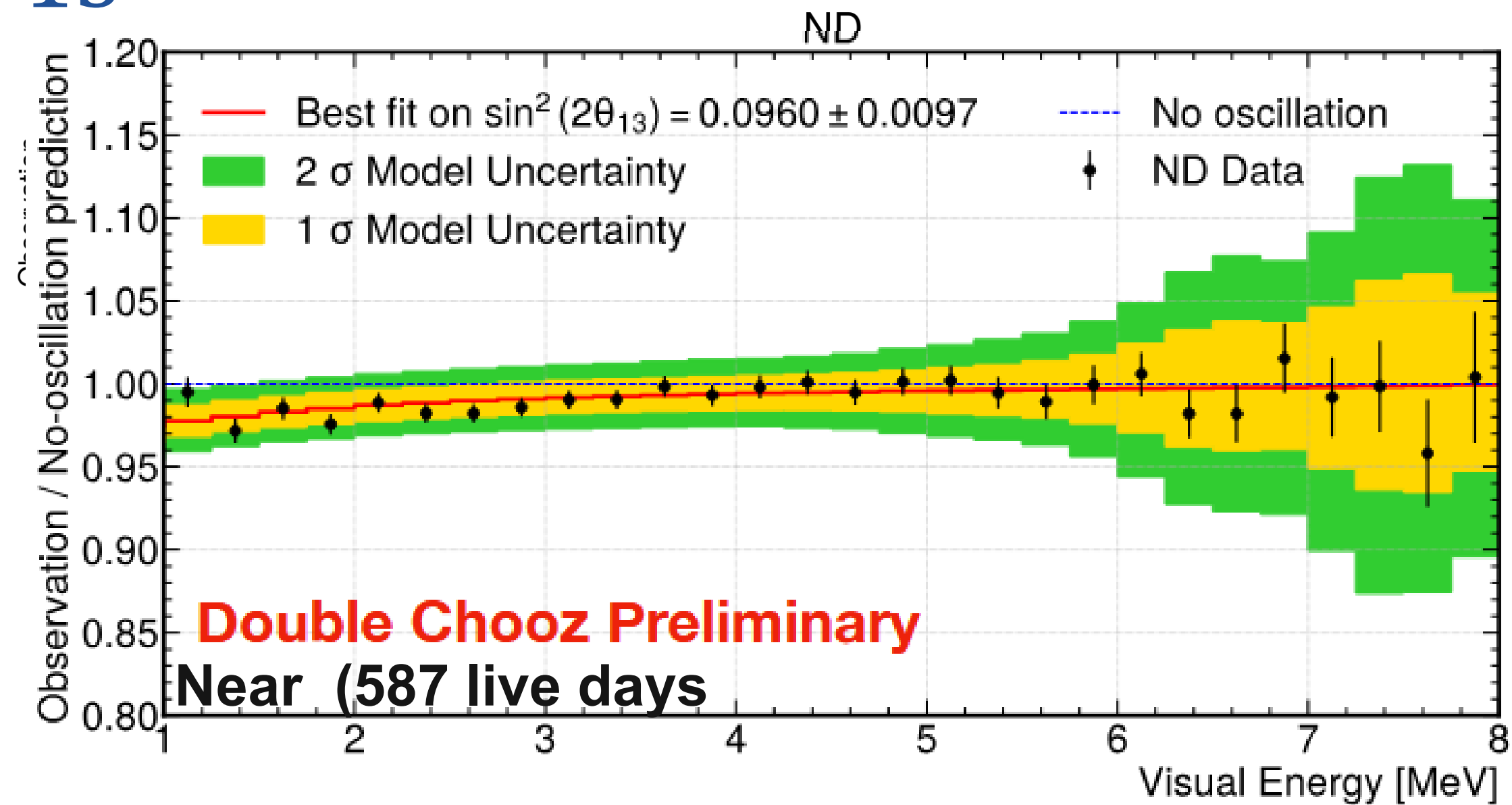


OFF-time



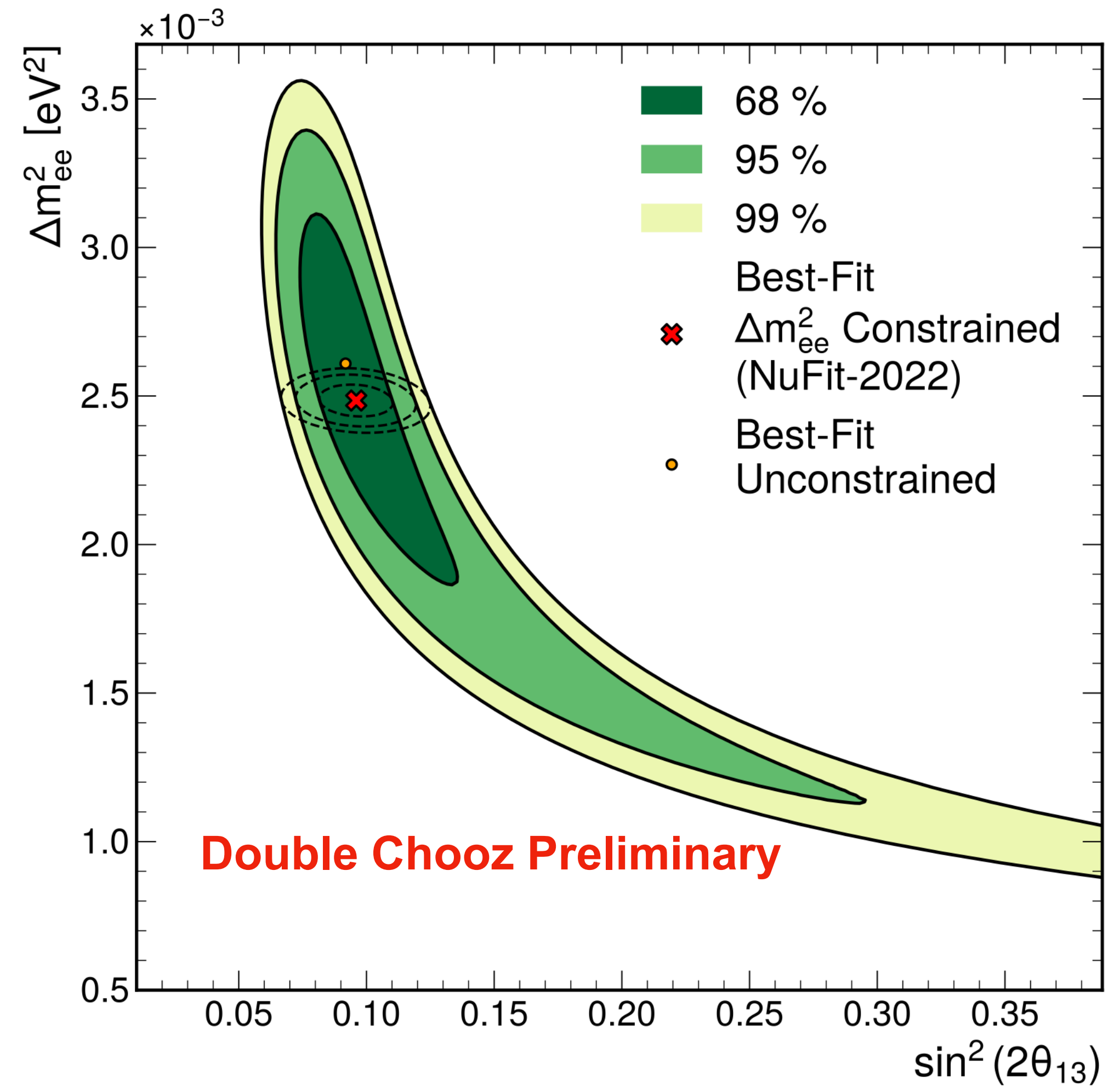
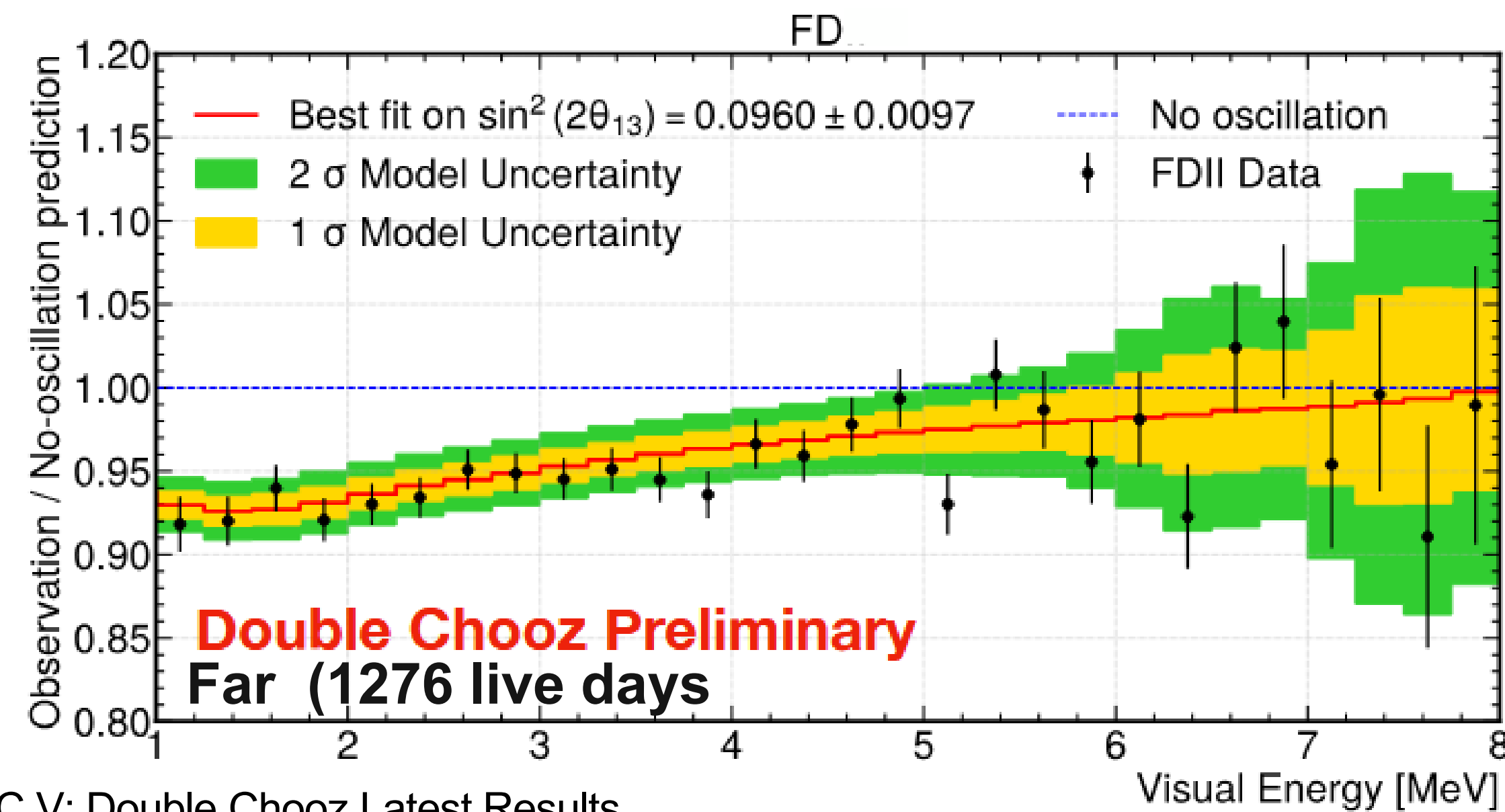
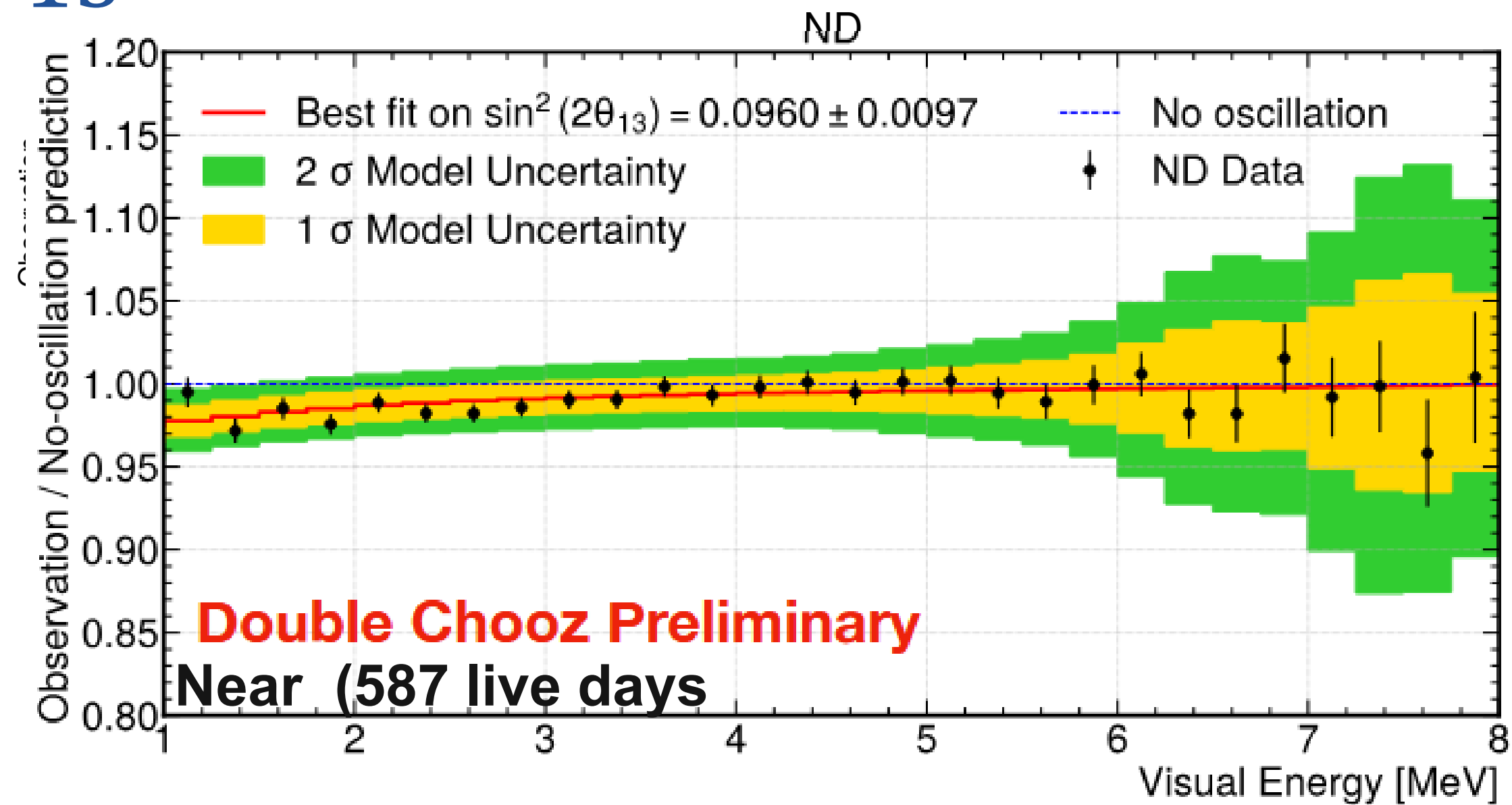
- Good agreement between the data and the reactor model;
- Clearly visible θ_{13} effect;
- Reactor-Off phases can be used to constrain the backgrounds $> 3\text{MeV}$

θ_{13} Fit Results



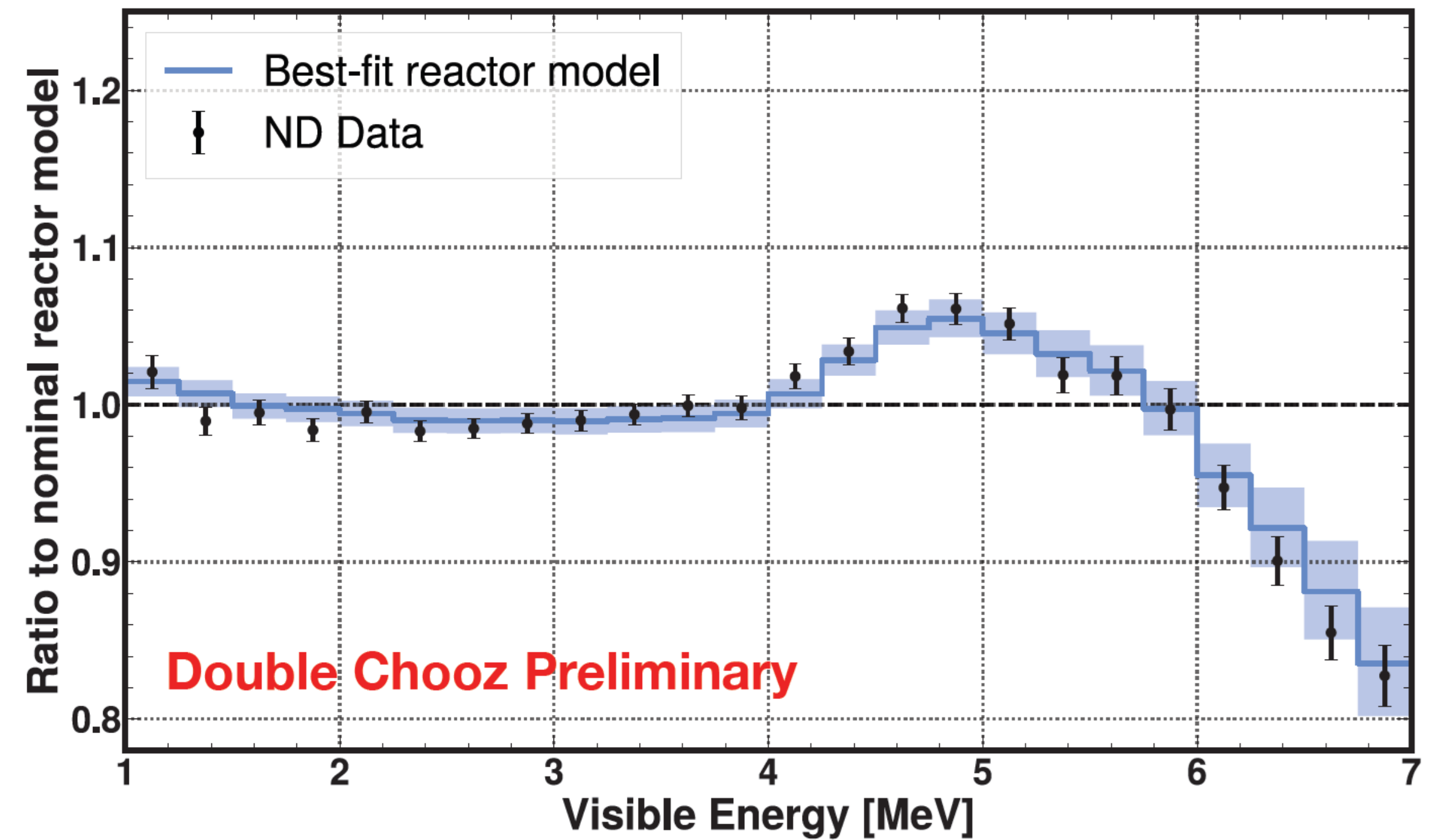
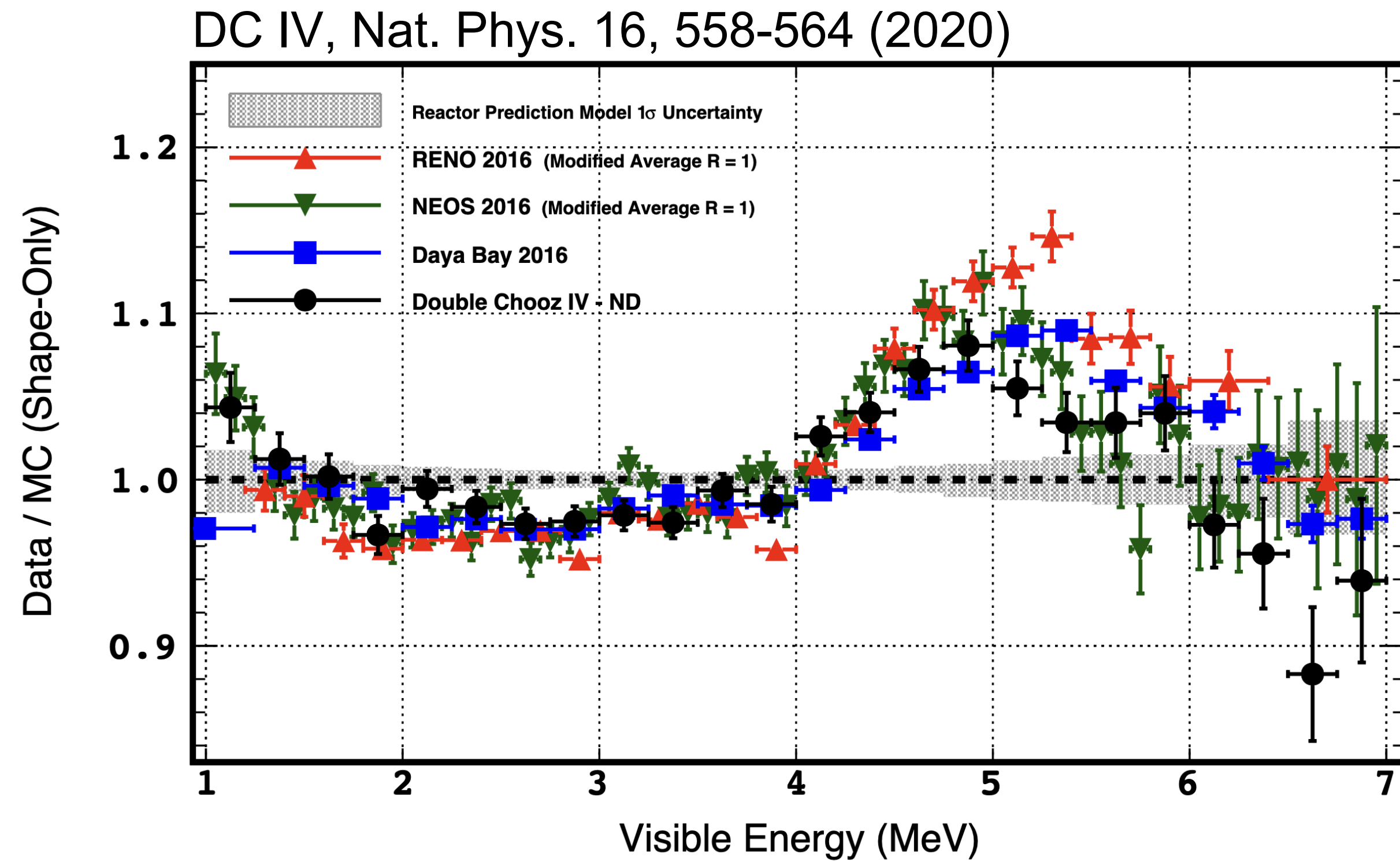
**Newest Result: $\sin^2(2\theta_{13}) = 0.0960$
 $\pm 0.0086(\text{syst.}) \pm 0.0044(\text{stat.})$**

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

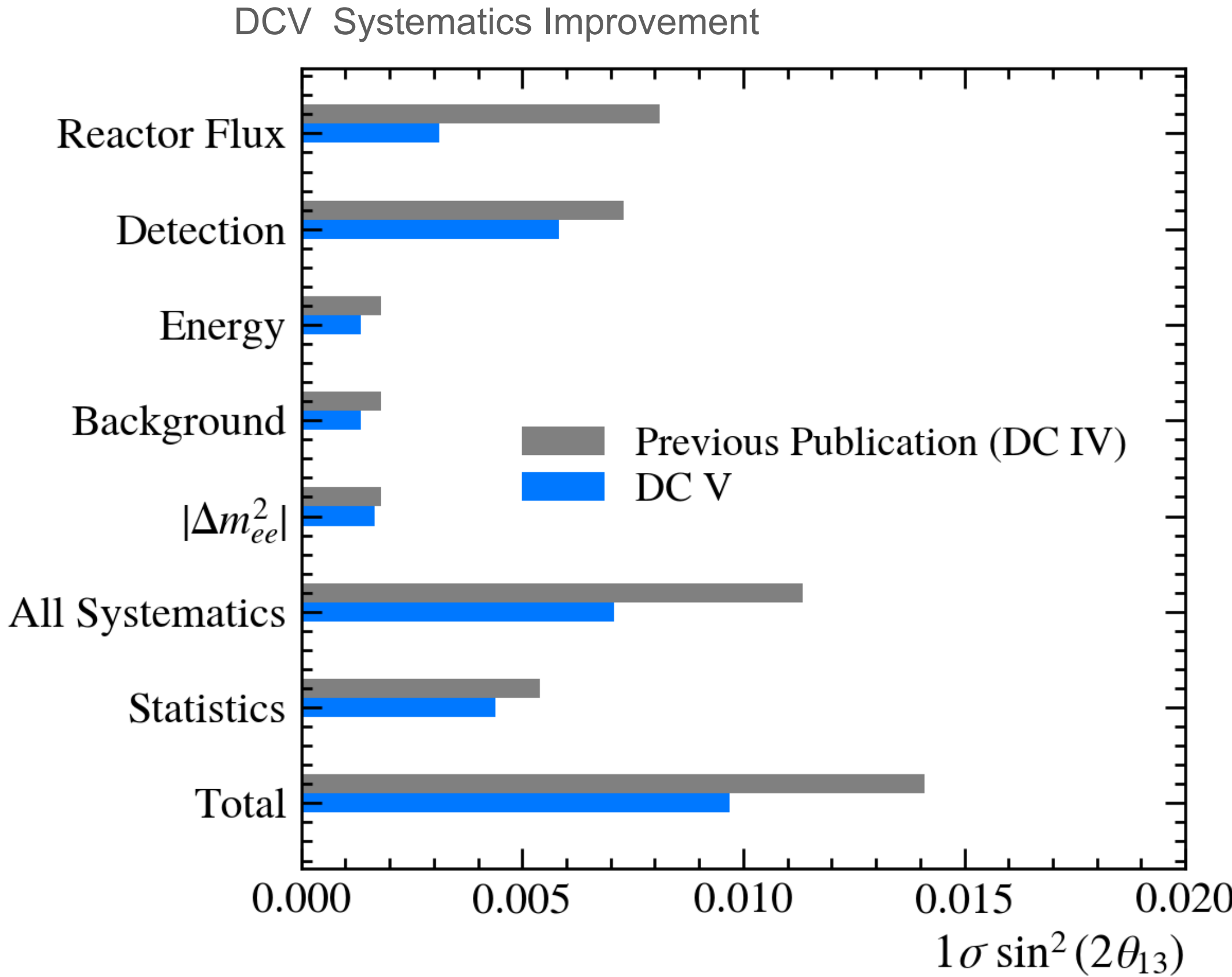
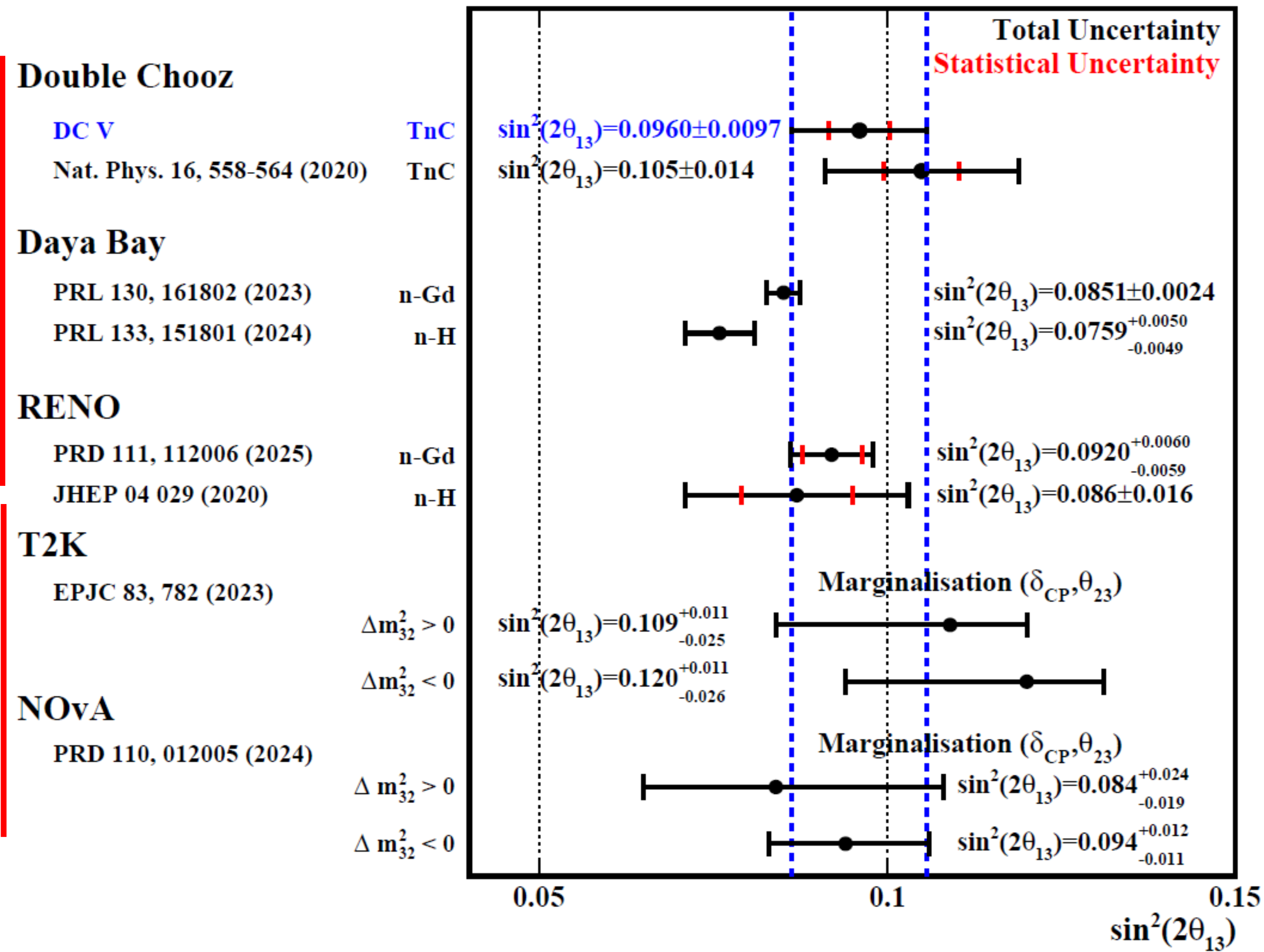


- Visible deviation can be seen by almost all reactor neutrino experiments
- Utilizing the extracted correlated shape deviations, the shape deviation can be observed

θ_{13} Agreement Worldwide

Reactor experiments

Accelerator experiments



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

Reactor Absolute Flux

Mean Cross Section per Fission
(MCSpF):

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

Fission fraction of k-isotope
Reactor $\bar{\nu}_e$ spectrum from k-isotope
IBD cross-section
MCSpF for k-isotope

Counting approach

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

- 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.

MCSpF Results

Common Model:

ILL⊕HM Model Uncertainty ($\approx 2.0\%$)

DC V

Input: θ_{13} (DYB-2023)
 Δm_{ee}^2 (NuFit-2022)

TnC

DC V (θ_{13} unconstrained)

Input: Δm_{ee}^2 (NuFit-2022)

TnC

DC IV (ND only) 2020

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

TnC

Daya Bay 2025

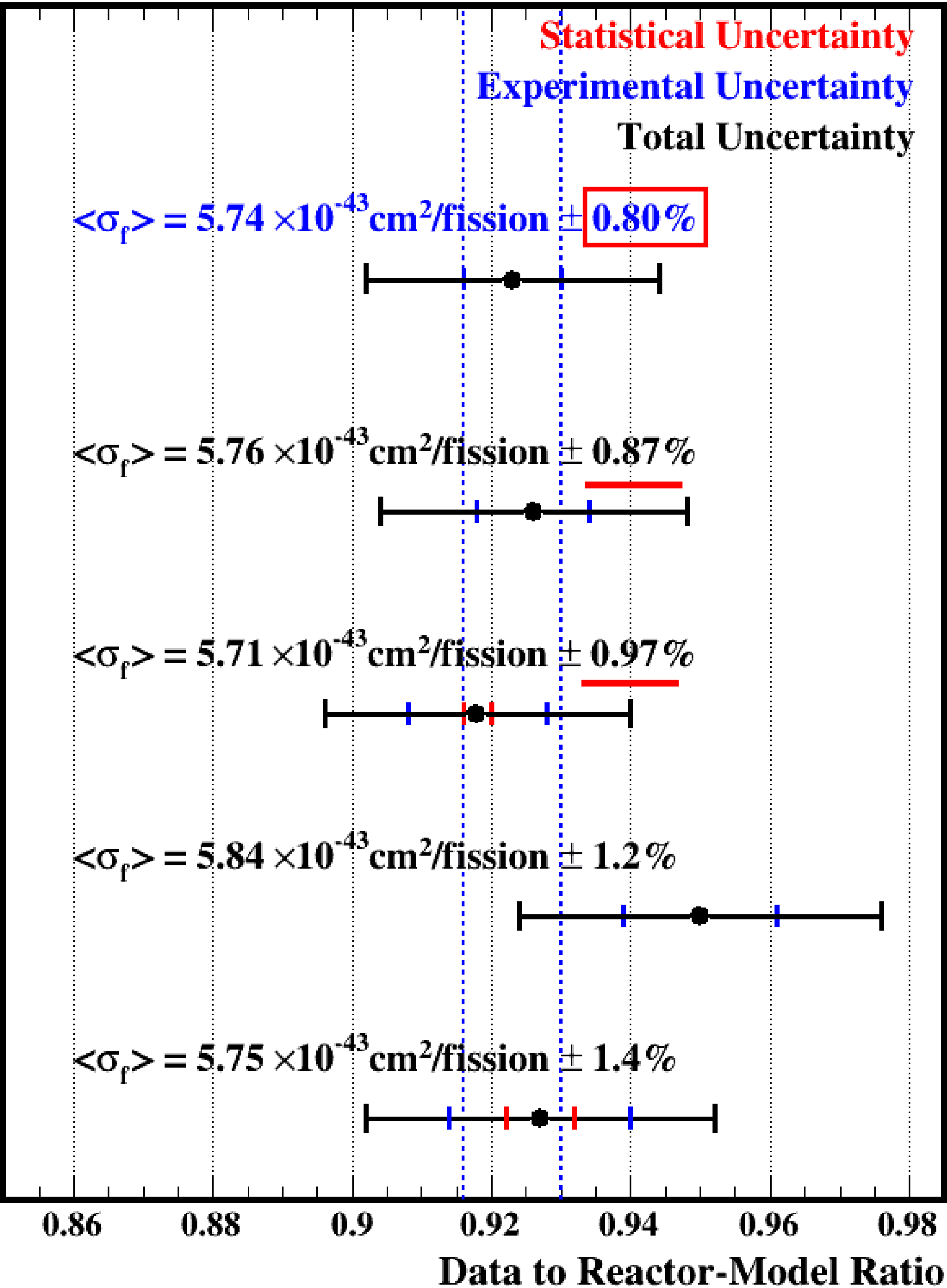
Phys. Rev. Lett. 134, 201802

n-Gd

Bugey4 1994

PLB 338 383 (1994)

^3He



MCSpF Model Comparison

DC V to $ILL \oplus HM$ model^{*}

Uncertainty 2.0 %

Phys.Lett. B118, 162 (1982)

Phys.Lett. B160, 325 (1985)

Phys.Lett. B218, 365 (1989)

Phys.Rev. C83, 054615 (2011)

Phys.Rev. C84, 024617 (2011)

DC V to $ILL \oplus HM \oplus KI$ model^{*}

Uncertainty 1.6 %

Phys. Rev. Lett. 112, 122501 (2014)

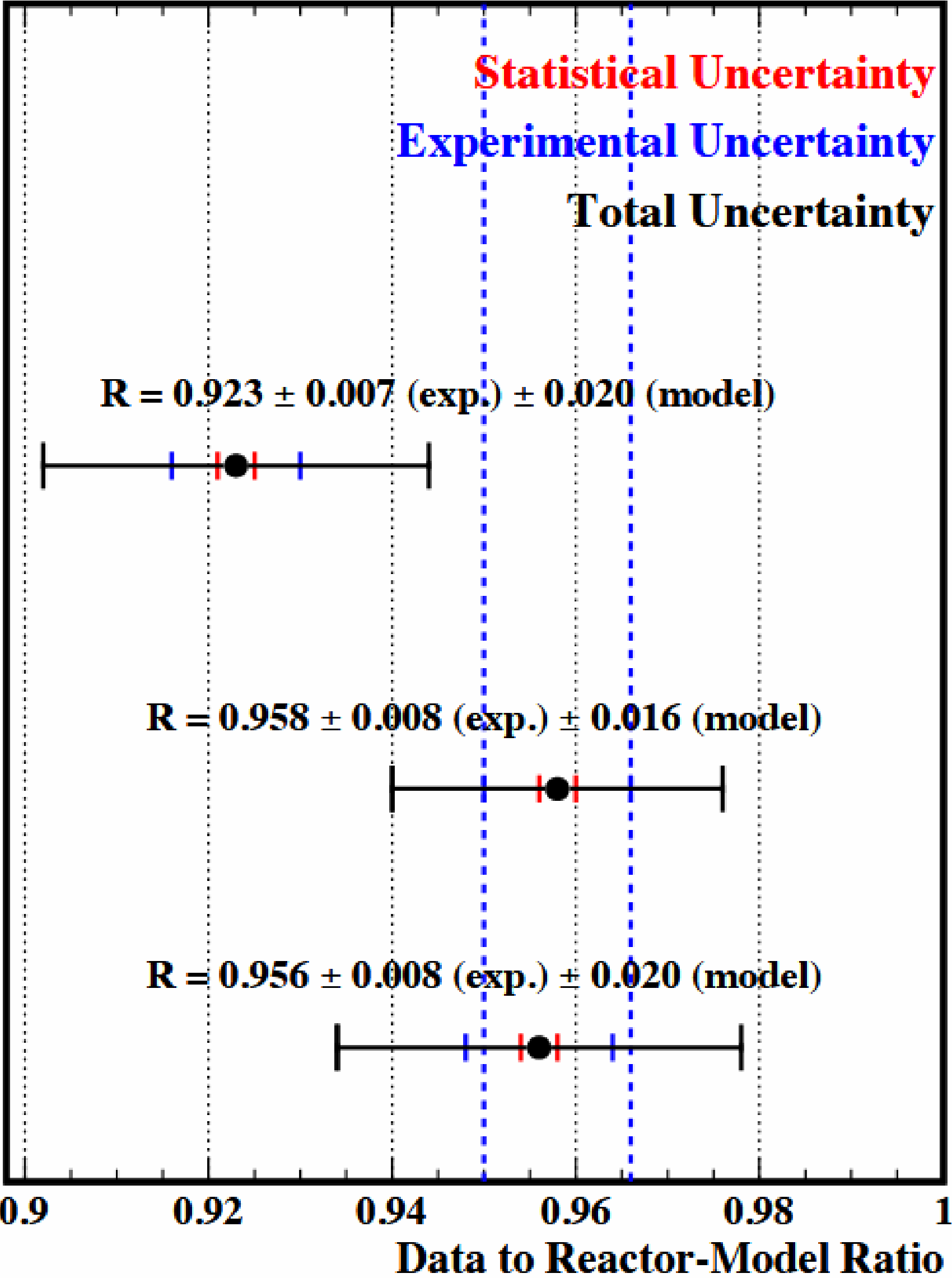
Phys.Rev. D 104, L071301 (2021)

DC V to Summation model

Uncertainty 2.0 %

Phys. Rev. C 108, 055501 (2023)

^{*} Phys.Lett. B829 (2022) 137054

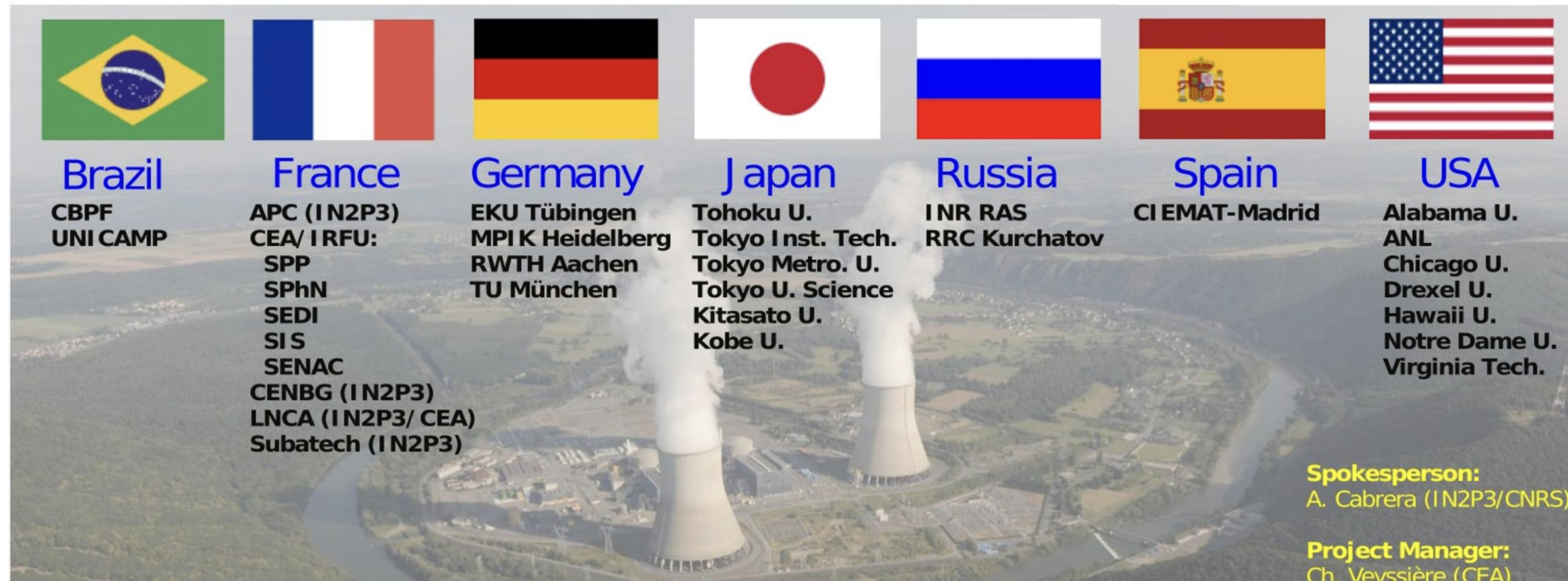


3.7σ

$\sim 2\sigma$

$\sim 2\sigma$

DOUBLE CHOOZ COLLABORATION



Brazil
CBPF
UNI CAMP

France
APC (IN2P3)
CEA/IRFU:
SPP
SPhN
SEDI
SIS
SENAC
CENBG (IN2P3)
LNCA (IN2P3/CEA)
Subatech (IN2P3)

Germany
EKU Tübingen
MPI K Heidelberg
RWTH Aachen
TU München

Japan
Tohoku U.
Tokyo Inst. Tech.
Tokyo Metro. U.
Tokyo U. Science
Kitasato U.
Kobe U.

Russia
INR RAS
RRC Kurchatov

Spain
CIEMAT-Madrid

USA
Alabama U.
ANL
Chicago U.
Drexel U.
Hawaii U.
Notre Dame U.
Virginia Tech.

Spokesperson:
A. Cabrera (IN2P3/CNRS)

Project Manager:
Ch. Veyssière (CEA)

97 scientists 25 institutions (Americas, Asia, Europe)



doublechooz.in2p3.fr

Many people contributed to the experiment
Thanks for all the hard work!

Conclusion

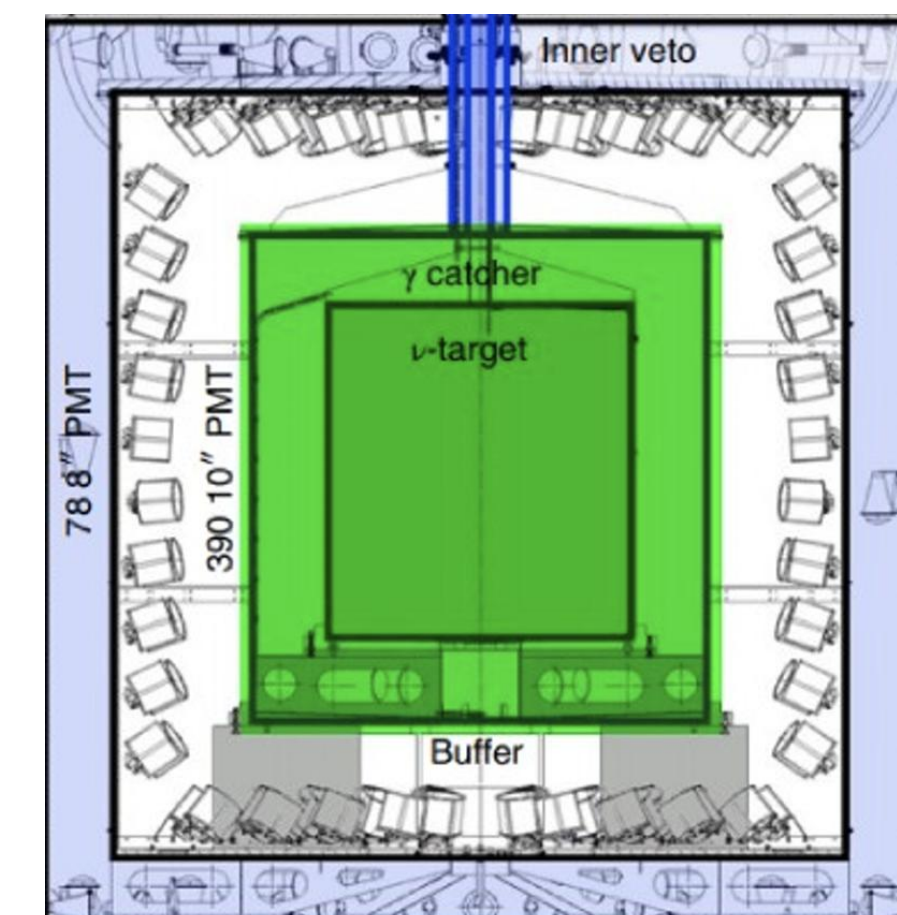
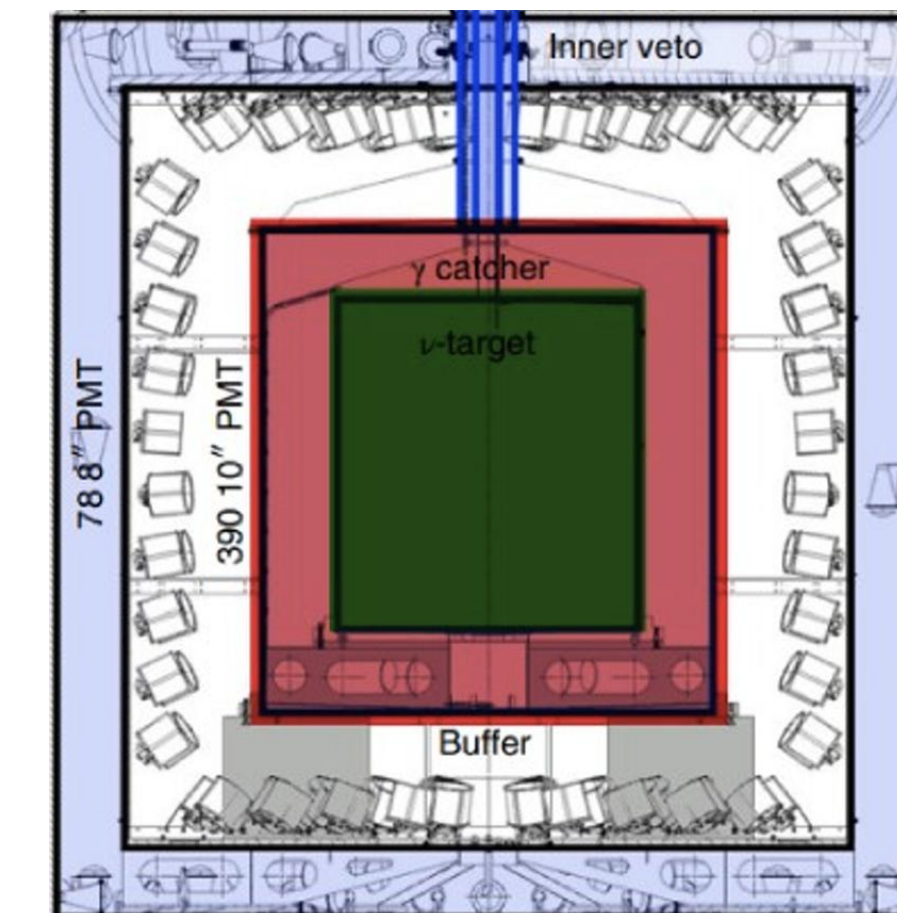
- Double Chooz is a reactor neutrino disappearance experiment;
- Double Chooz detectors have been dismantled;
- Final best fit: $\sin^2(2\theta_{13}) = 0.0960 \pm 0.0086(\text{syst.}) \pm 0.0044(\text{stat.})$;
- The Best $\langle \sigma_f \rangle = (5.74 \pm 0.80\%) \times 10^{-43} \text{cm}^2/\text{fission}$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

Backup

Detector Dismantling



- 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%;



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

$$0.012$$

$$0.0099$$