New results from the hydrogen channel in Double Chooz

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on behalf of the Double Chooz collaboration
BNL HEP seminar | July 23, 2015

Outline

- Measuring $\sin^2 2\theta_{13}$ in Double Chooz
- New techniques and results
  from the H-based analysis
- Outlook for future measurements

Measuring $\sin^2 2\theta_{13}$ in Double Chooz

Targeting θ_{13}

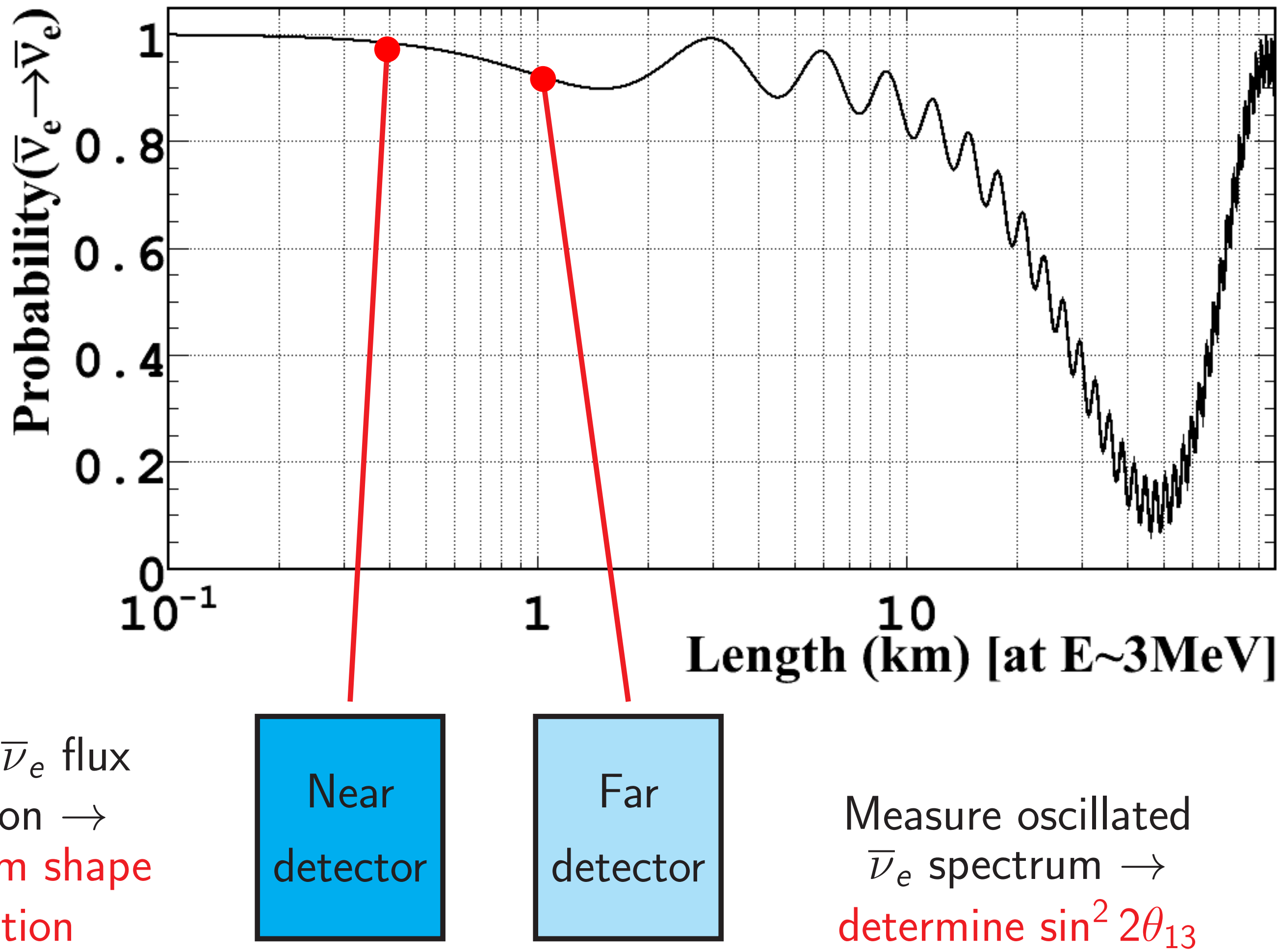
Neutrino oscillations:

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U^*_{\alpha i}|\nu_i\rangle$$

$$\mathbf{U} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \cdot \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{+i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \cdot \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- Goal of Double Chooz, Daya Bay, RENO: **precisely measure $\sin^2 2\theta_{13}$**
  - May help to explain flavor structure
  - Prerequisite for determining ν mass hierarchy
  - Needed for measuring CP violation in ν oscillations

$$P(\overline{\nu}_e \to \overline{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2(\frac{\Delta m^2_{31} L}{4E}) - \sin^2 \theta_{12} \cos^4(\theta_{13}) \sin^2\left(\frac{\Delta m^2_{12} L}{4E}\right)$$



Measure reactor $\overline{\nu}_e$ flux **before** oscillation $\to$ Constrain spectrum shape and normalization

Measure oscillated $\overline{\nu}_e$ spectrum $\to$ determine $\sin^2 2\theta_{13}$

Double Chooz collaboration

Brazil
CBPF
UNICAMP
UFABC

France
APC
CEA/DSM/IRFU
- SPP
- SphN
- SEDI
- SIS
- SENAC

CNRS/IN2P3
- SUBATECH
- IPHC

Germany
EKU Tübingen
MPIK
Heidelberg
RWTH Aachen
TU München
U. Hamburg

Japan
Tohoku U.
Tokyo Inst. Tech.
Tokyo Metro. U.
Niigata U.
Kobe U.
Tohoku Gakuin U.
Hiroshima Inst. Tech.

Russia
INR RAS
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Kurchatov

Spain
CIEMAT-Madrid

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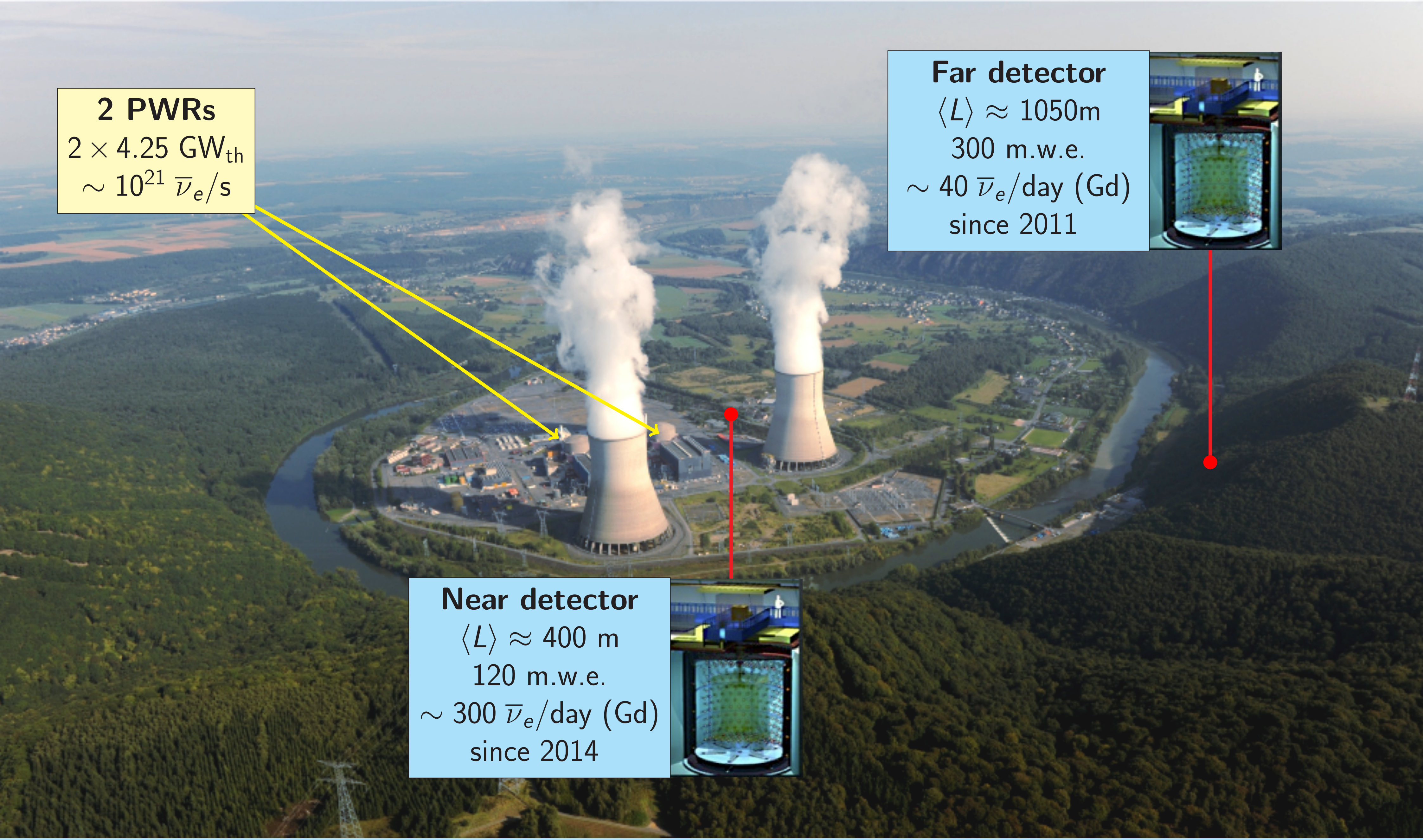
U. Chicago
Columbia U.
UCDavis
Drexel U.
IIT
KSU
LLNL
MIT
U. Notre Dame
U. Tennessee

Spokesperson: H. de Kerret (IN2P3) Project Manager: Ch. Veyssière (CEA-Saclay) Web Site: www.doublechooz.org

Experiment layout

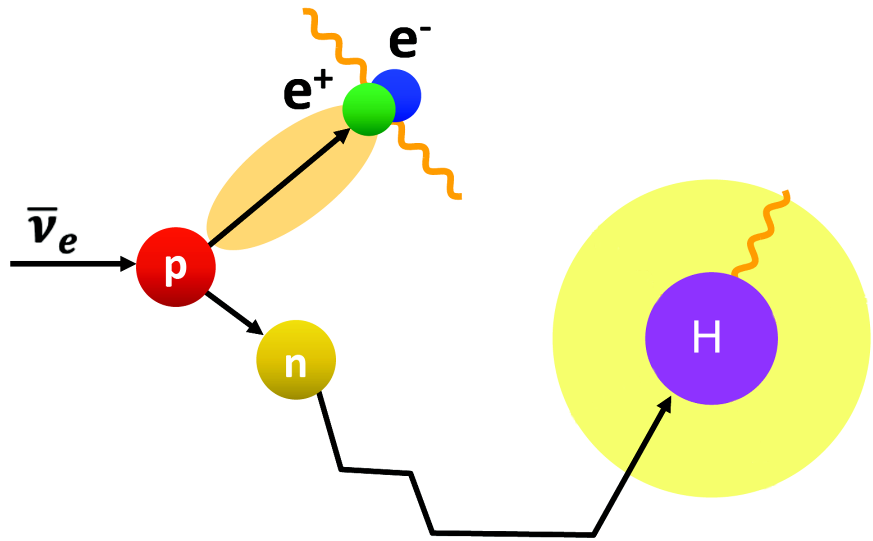


Inverse beta decay detection

- Inverse beta decay (IBD):

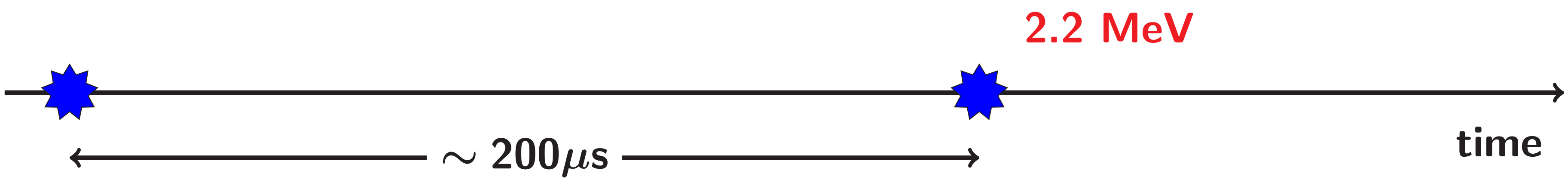
  $\overline{\nu}_e + p \rightarrow n + e^+$

- **Prompt signal**: e^+ ionization + annihilation, $E_{vis} \approx E_\nu - 0.8$ MeV
- **Delayed signal**: n capture on Gd or H

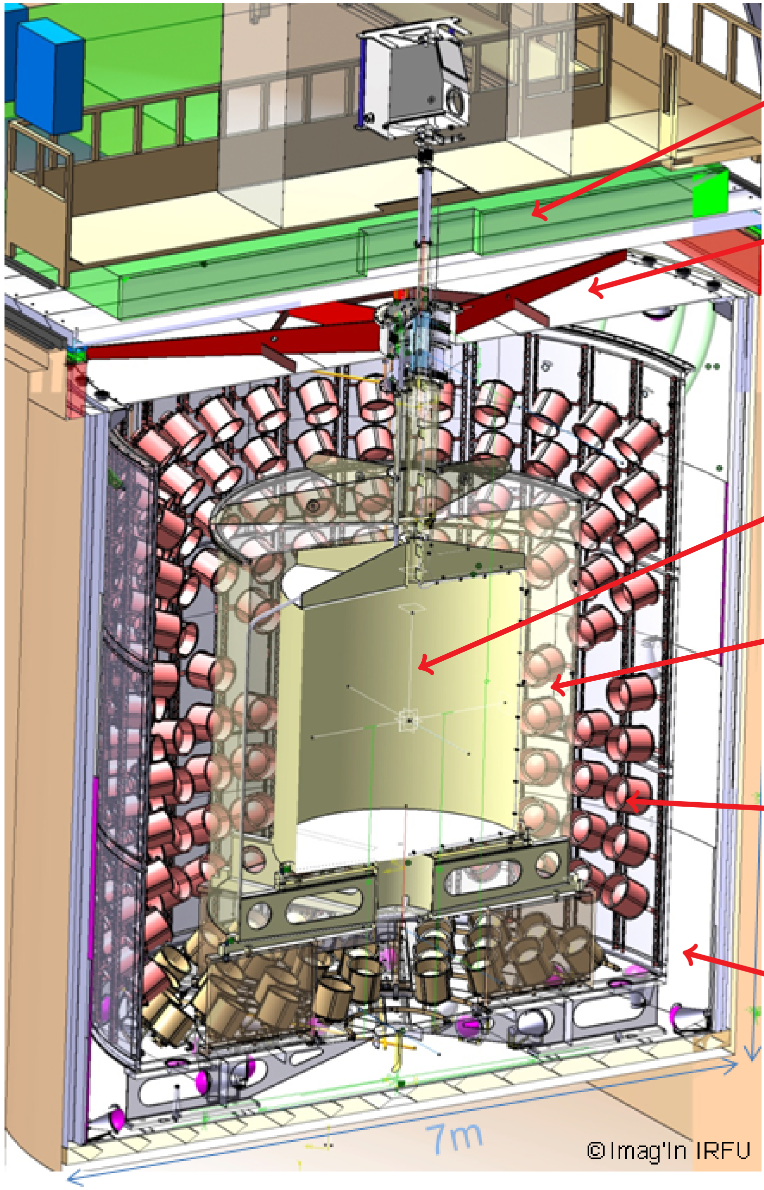


Gd channel

H channel



Detector design



Outer Veto (OV): Array of plastic scintillator strips

Wide-area cosmic μ detection

Steel shield (15 cm thick)

Inner Detector (ID)

Neutrino target: $10.3\,m^3$ Gd-loaded scintillator

IBD sensitive region (Gd)

Gamma catcher: $22.3\,m^3$ scintillator

Escaping γ measurement (Gd)

IBD sensitive region (H)

Buffer + PMTs: $110\,m^3$ mineral oil, 390 PMTs

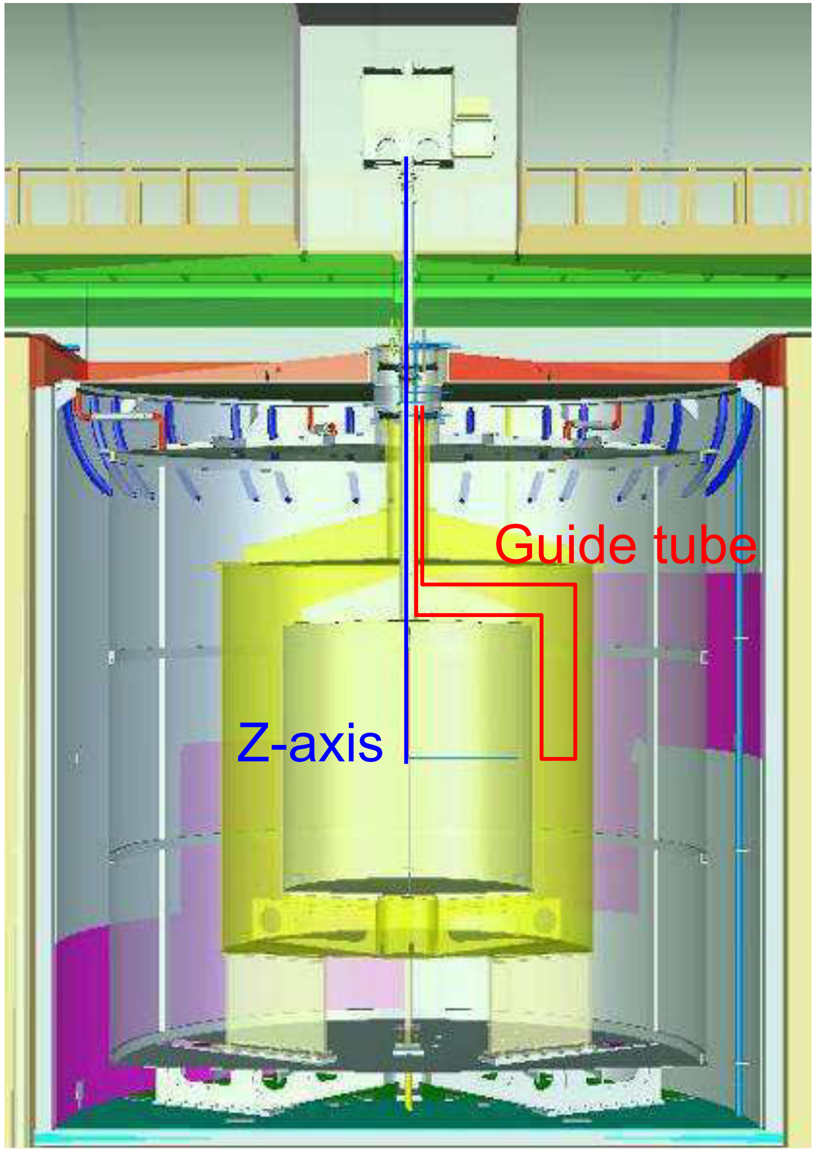
Passive radioactivity shielding.

Inner Veto (IV): $90\,m^3$ liquid scintillator, 78 PMTs

Cosmic μ, fast neutron, and external γ detection

Calibration systems

- **LED light injection**
  - PMT gains and time offsets
- **Source deployment systems**
  - z-axis in Target
  - Guide tube in GC (limited coverage)
  - Radioactive sources
    - γ (^{60}Co, ^{137}Cs, ^{68}Ge)
    - n (^{252}Cf)
  - Laser diffuser ball
- **Natural radioactivity**
  - Spallation n captures on Gd, H, C
  - α particles from Bi-Po decays



Why the H channel?

Benefits

- Double the statistics of standard Gd channel
- Somewhat independent systematics

  $\Rightarrow$ Validate and enhance Gd-based results

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- Somewhat independent systematics

$\Rightarrow$ Validate and enhance Gd-based results

Challenges

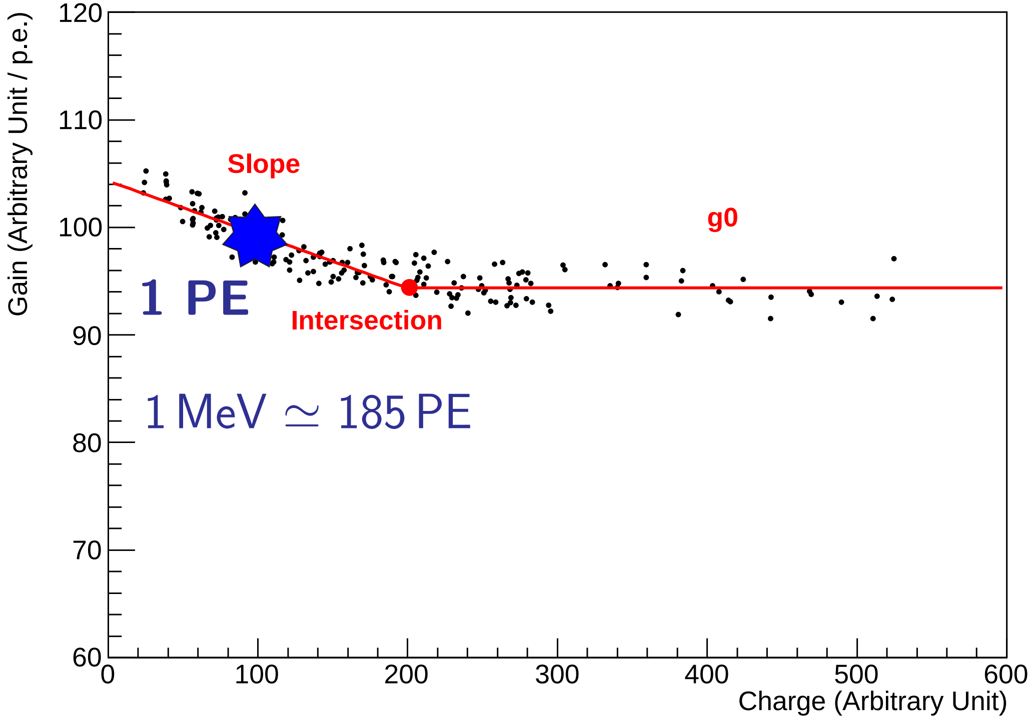
- Potentially huge accidental coincidence background
- GC volume not as well characterized

$\Rightarrow$ **Need new techniques beyond Gd analysis**

Energy reconstruction

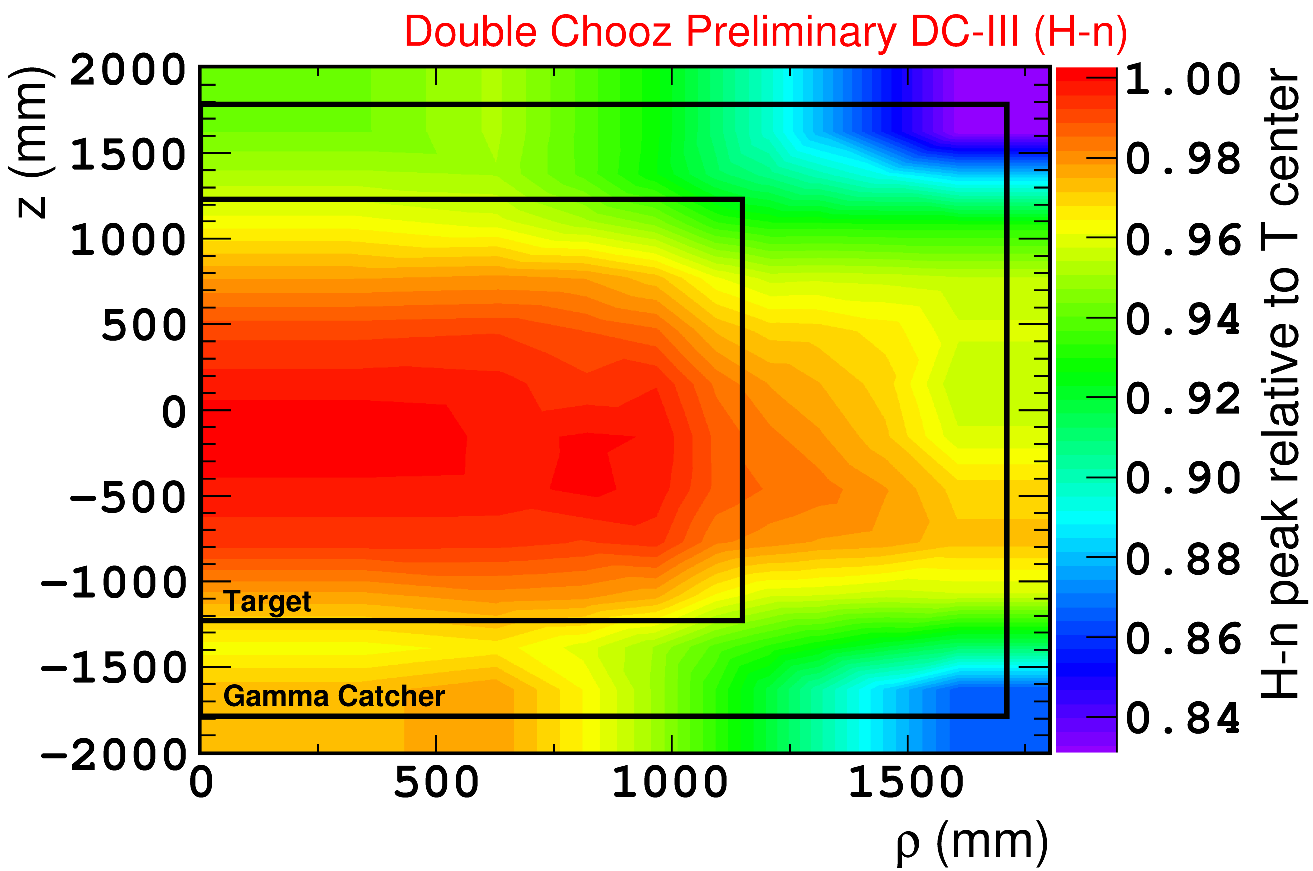
$$E_{vis} = \boxed{N_{pe}} \times f_u(\rho, z) \times f_{PE/MeV} \times f_s^{data}(E_{vis}^0, t) \times f_{nl}^{MC}$$

Raw charge → PE conversion performed with **nonlinear gain function** developed from light injection data



$$E_{vis} = N_{pe} \times \boxed{f_u(\rho, z)} \times f_{PE/MeV} \times f_s^{data}(E^0_{vis}, t) \times f_{nl}^{MC}$$

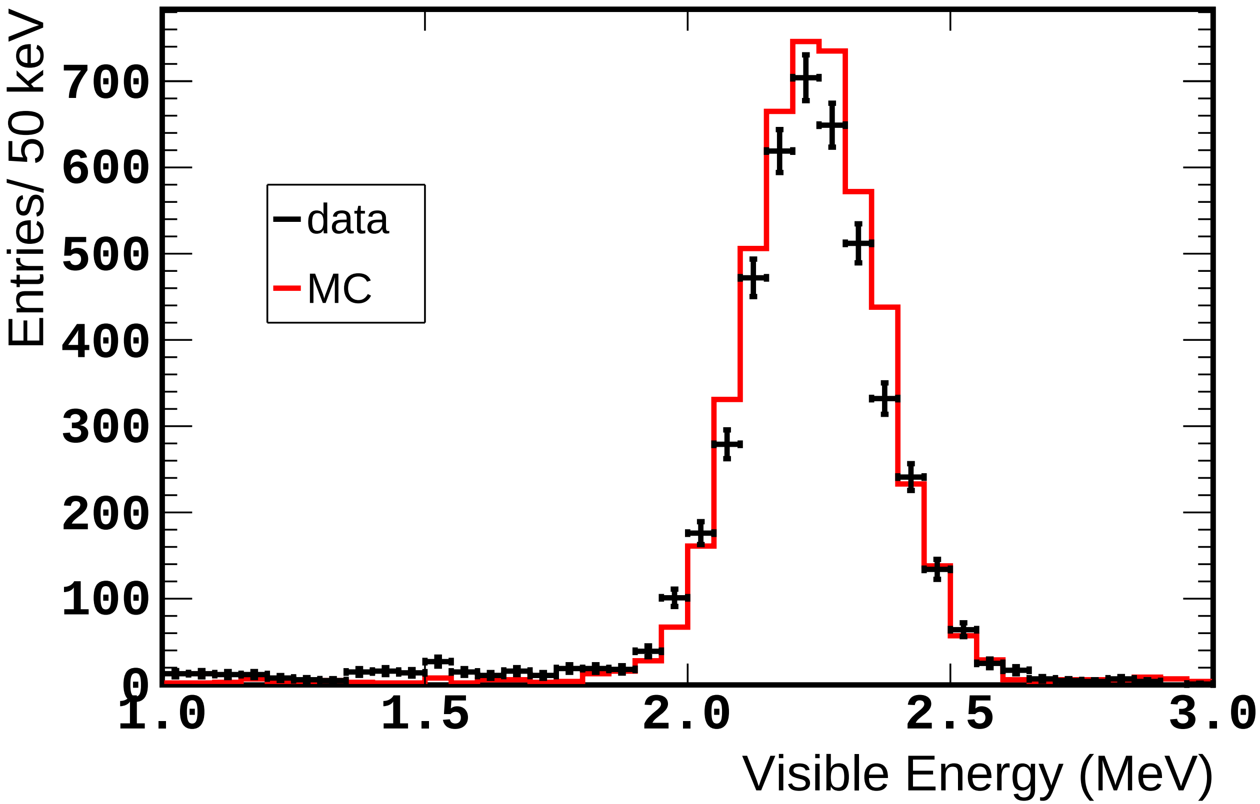
Position dependence greatly reduced using "map" from spallation n captures on H



Energy reconstruction

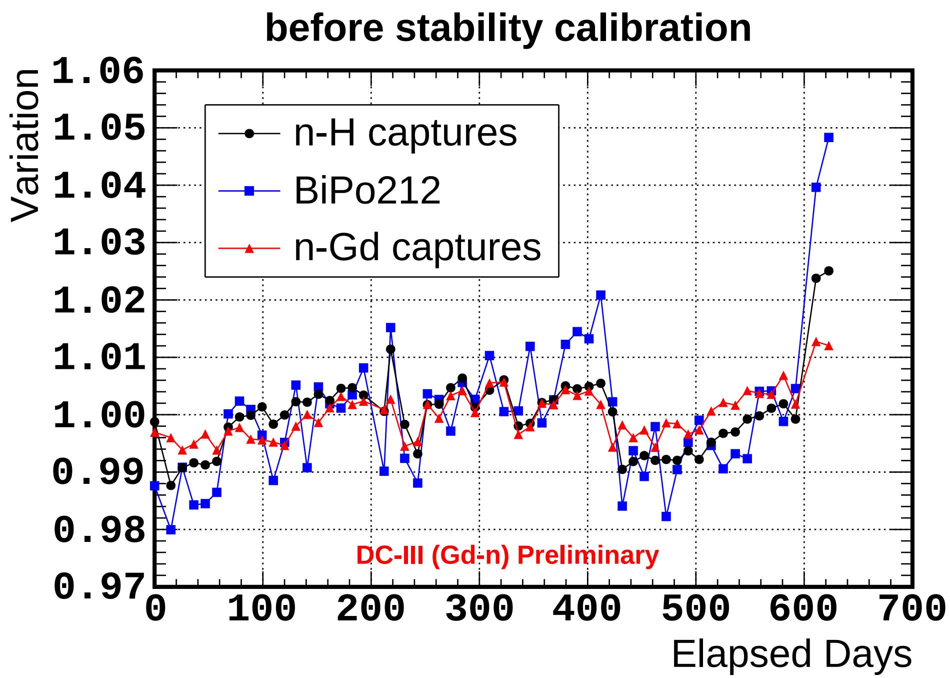
$$E_{vis} = N_{pe} \times f_u(\rho, z) \times \boxed{f_{PE/MeV}} \times f_s^{data}(E^0_{vis}, t) \times f_{nl}^{MC}$$

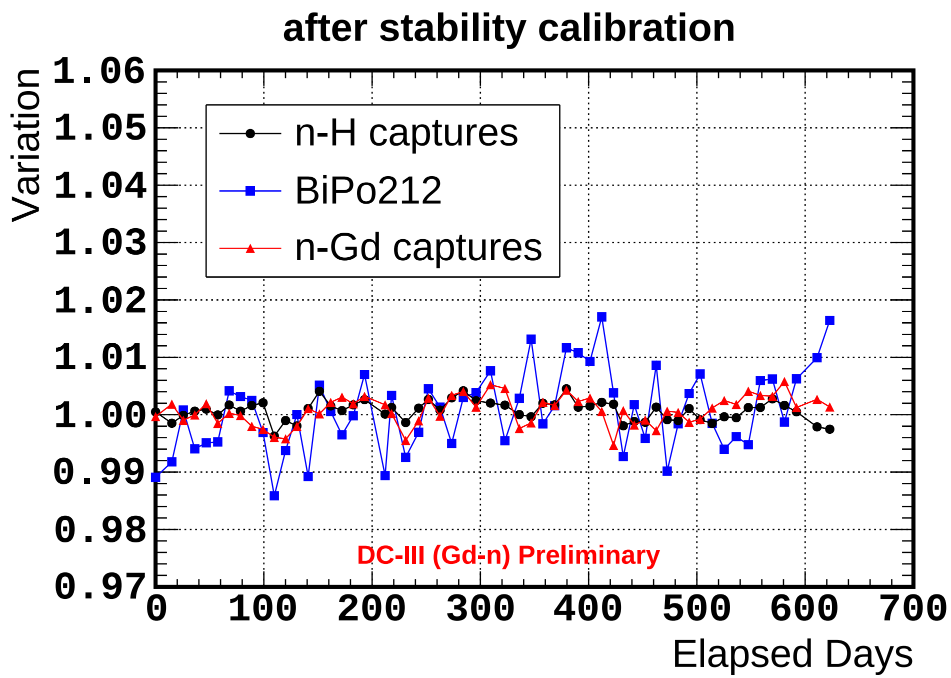
PE $\rightarrow$ MeV conversion performed with **absolute energy scale** defined by n captures from ^{252}Cf source at center (2.223 MeV)

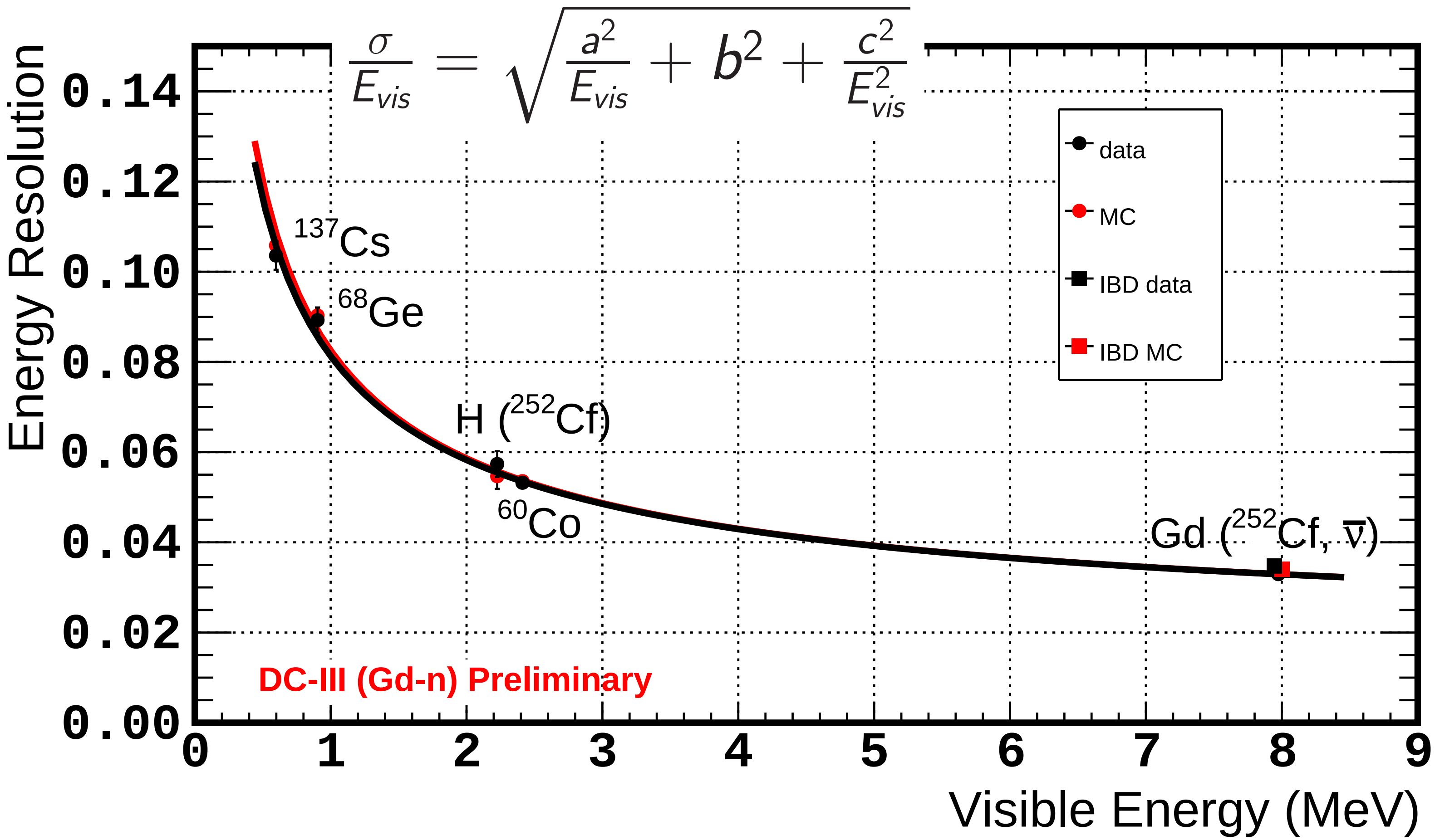


$$E_{vis} = N_{pe} \times f_u(\rho, z) \times f_{PE/MeV} \times \boxed{f_s^{data}(E^0_{vis}, t)} \times f_{nl}^{MC}$$

Time variations, due to scintillator aging and electronics effects, corrected using multiple cosmogenic/ambient sources







Fit to data:
$a = 0.0773 \pm 0.0025$
$b = 0.0182 \pm 0.0014$
$c = 0.0174 \pm 0.0107$

Fit to MC:
$a = 0.0770 \pm 0.0018$
$b = 0.0183 \pm 0.0011$
$c = 0.0235 \pm 0.0061$

Excellent data-MC agreement in energy scale and resolution

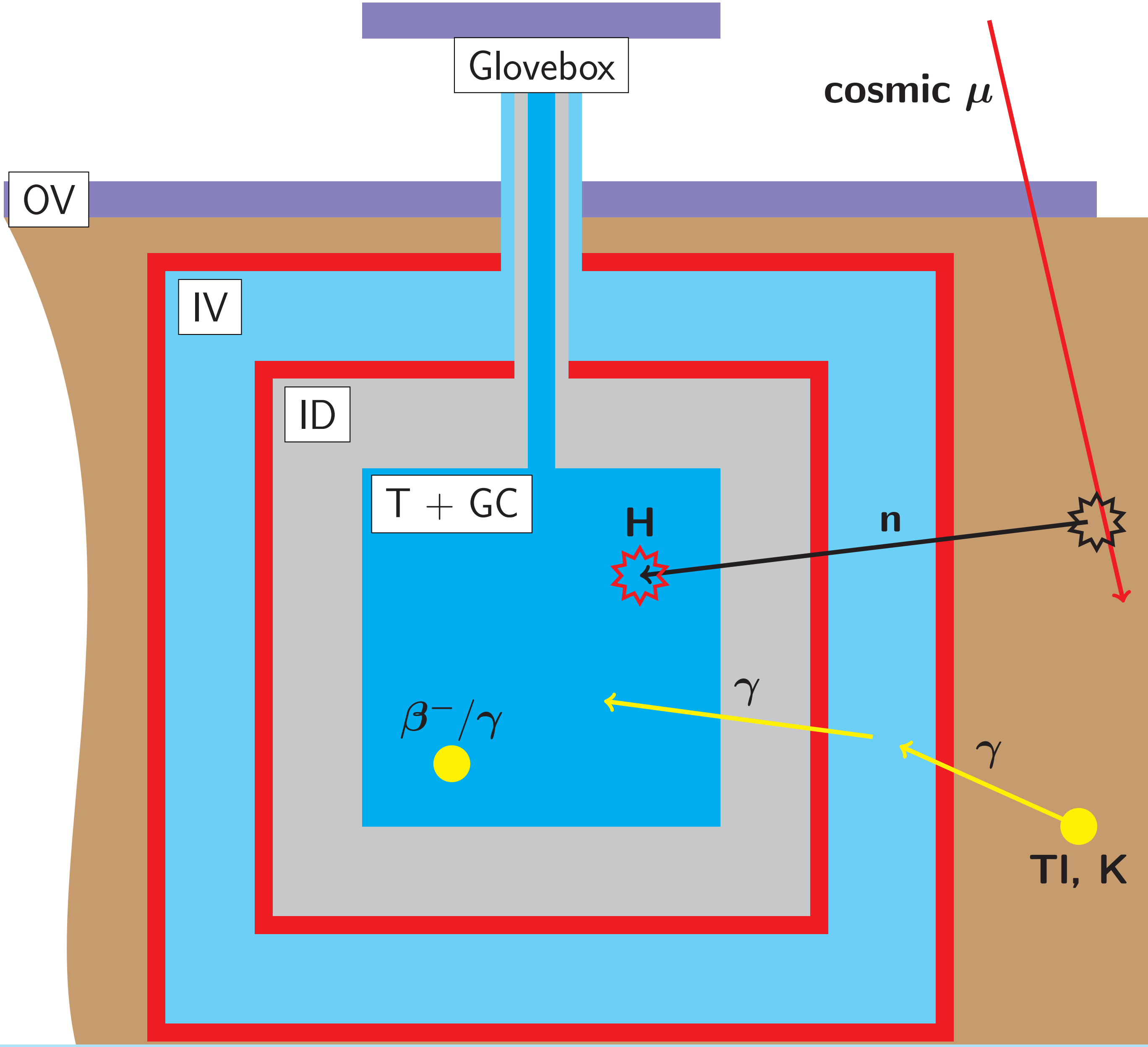
Backgrounds in Double Chooz

Accidental coincidences

Prompt/delayed signals:

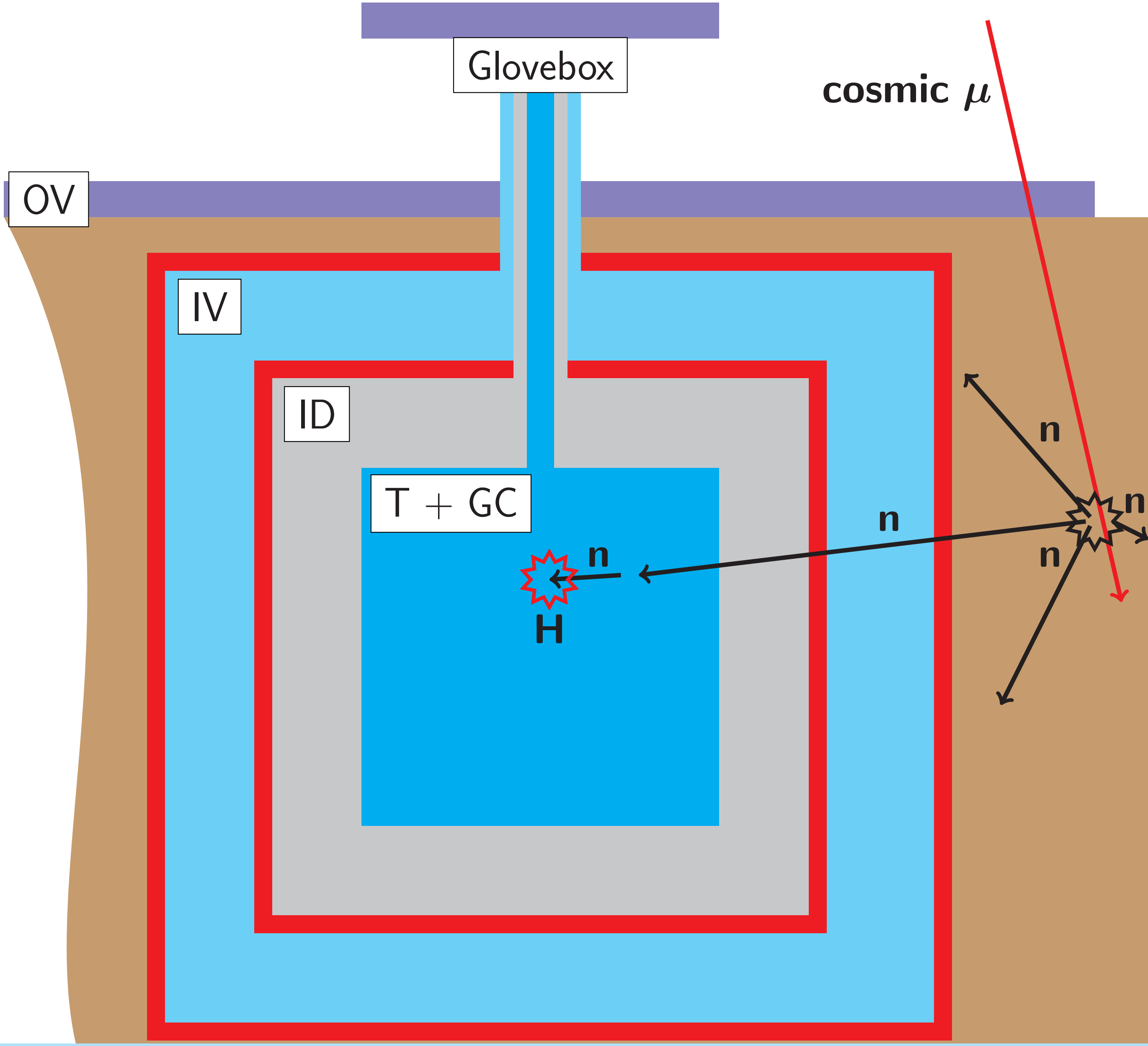
- Primordial radionuclide γ
  - ^{40}K : 1.3 $\sim$ 1.4 MeV
  - ^{208}Tl : 2.6 MeV
- Spallation *n* captures
- Decays of cosmogenic isotopes

Largest background in previous H analysis!



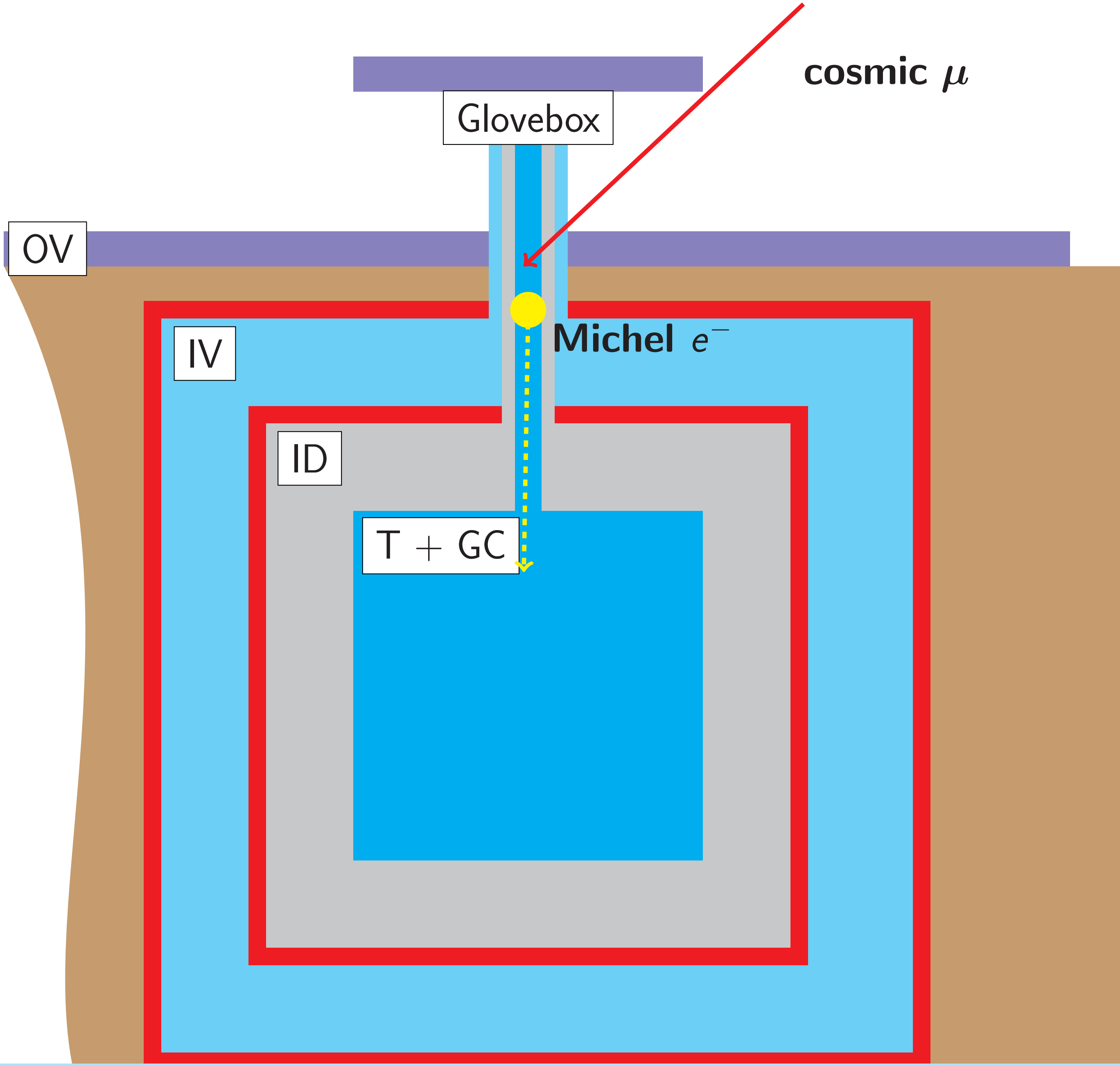
Signals

- Prompt: p recoil
- Delayed n capture



Signals:

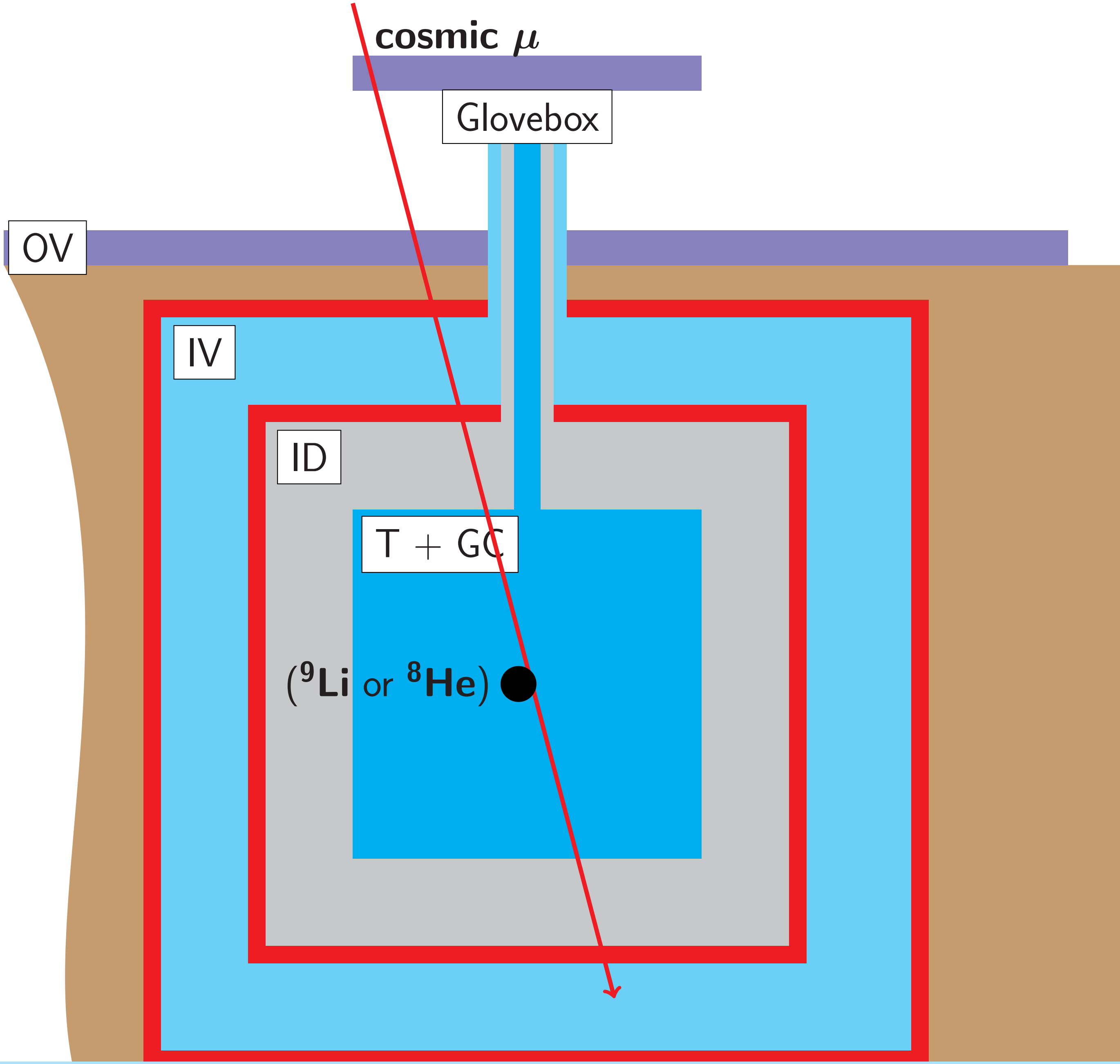
- Prompt: track cosmic μ entering through acceptance hole
- Delayed: Michel $e^{\pm}$



Decays of cosmogenic ^{9}Li and ^{8}He

Signals:

- Cosmic μ–induced ^{9}Li, ^{8}He production
- Long lifetimes ($\sim$ 200 ms)
- $\beta - n$ decay mimics IBD



Signal selection

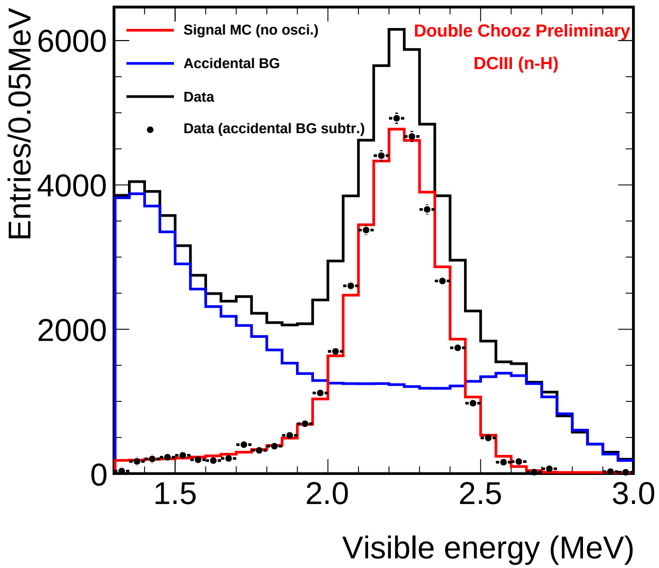
Selection cuts

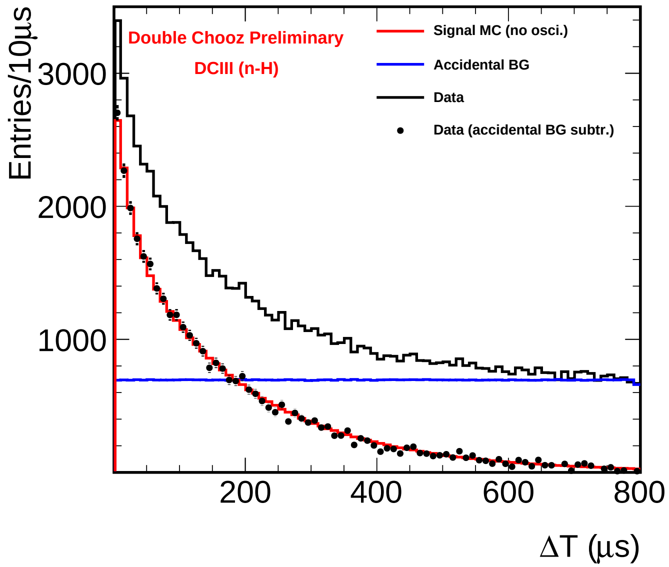
Cut **(new)**	**Rejects**
Basic background rejection	
Muon veto (1.25 ms)	μ and decay products
Light noise cut	Spontaneous light emission
OV veto	Fast neutrons, stopped μ
Multiplicity cut	Multiple spallation *n*
IBD selection	
Delayed coincidence	Accidental coincidences
Advanced background vetoes	
Vertex quality veto	Stopped μ, spontaneous light emission
IV veto (prompt)	Fast neutrons, stopped μ, external γ
IV veto (delayed)	Fast neutrons, external γ
Li+He veto	Cosmogenic radionuclide decays
Pulse shape–based veto	Fast neutrons

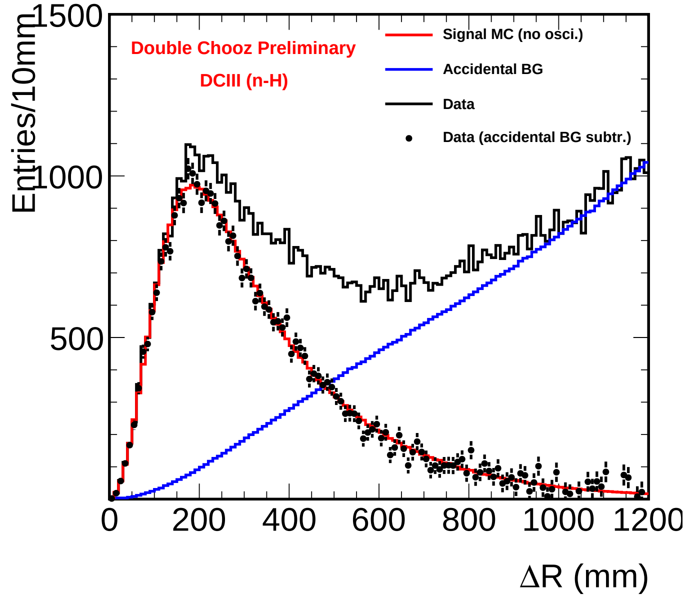
Delayed coincidence selection

- Delayed energy
- Prompt-delayed time separation
- Prompt-delayed space separation

} Previously, cut-based approach
Now: **multivariate approach**



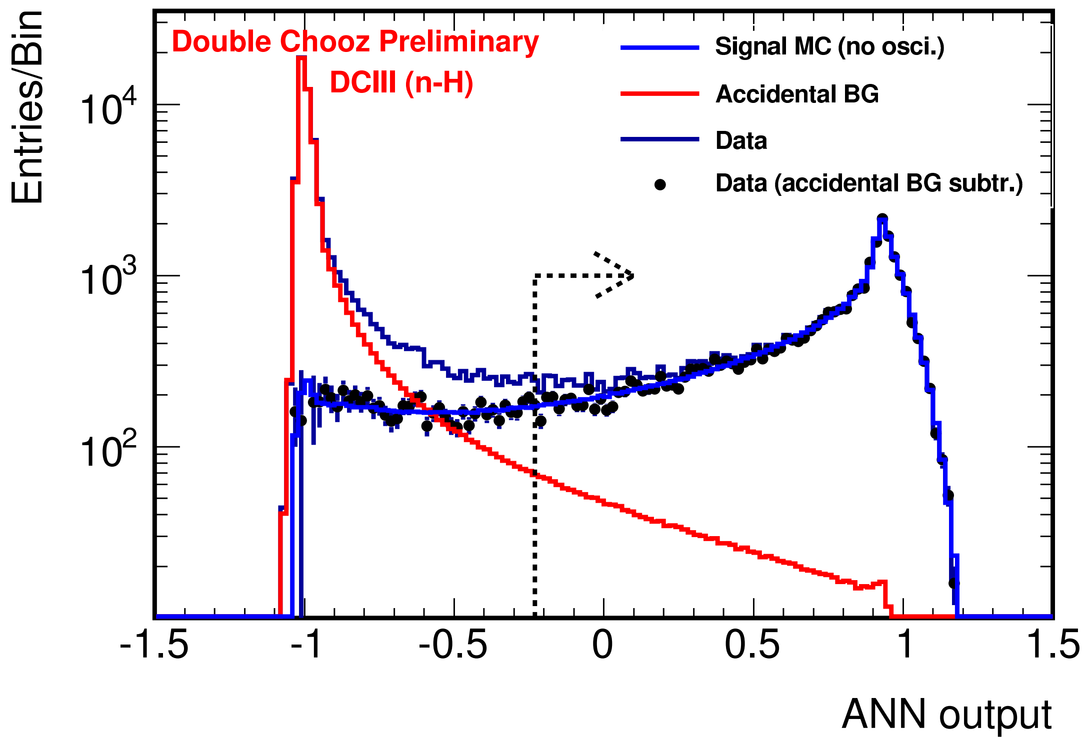




Colors in above plots: accidentals, measured from data; signal MC; IBD candidates from data; points = accidentals-subtracted IBD candidates

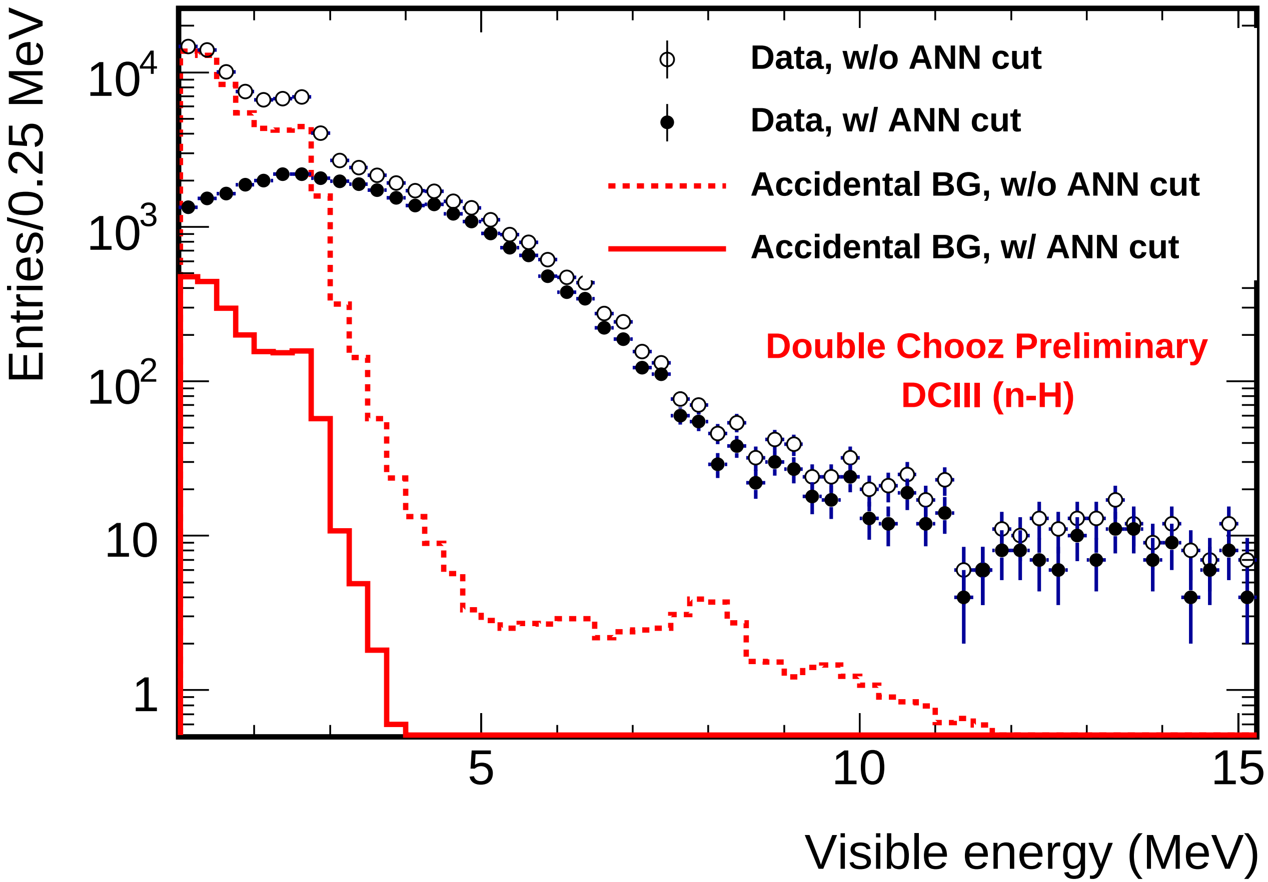
ANN-based multivariate tool

- Inputs: correlation time, correlation distance, delayed energy
- Trained with data-derived accidentals sample, signal MC
- Very good data-MC agreement



$\Rightarrow$ Signal to BG ratio **10$\times$ better** than previous H analysis

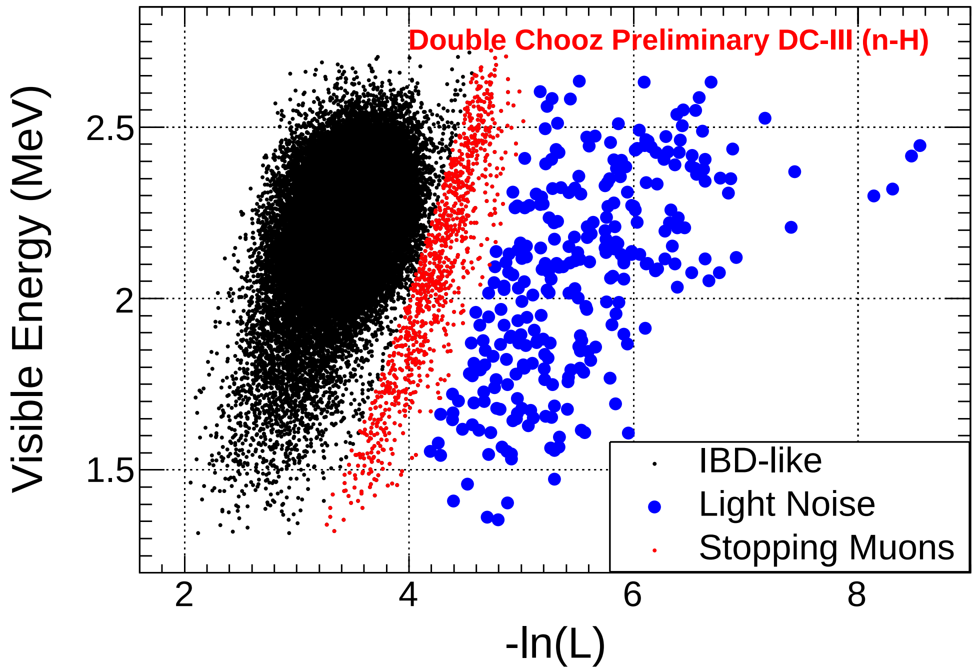
Artificial Neural Network algorithm

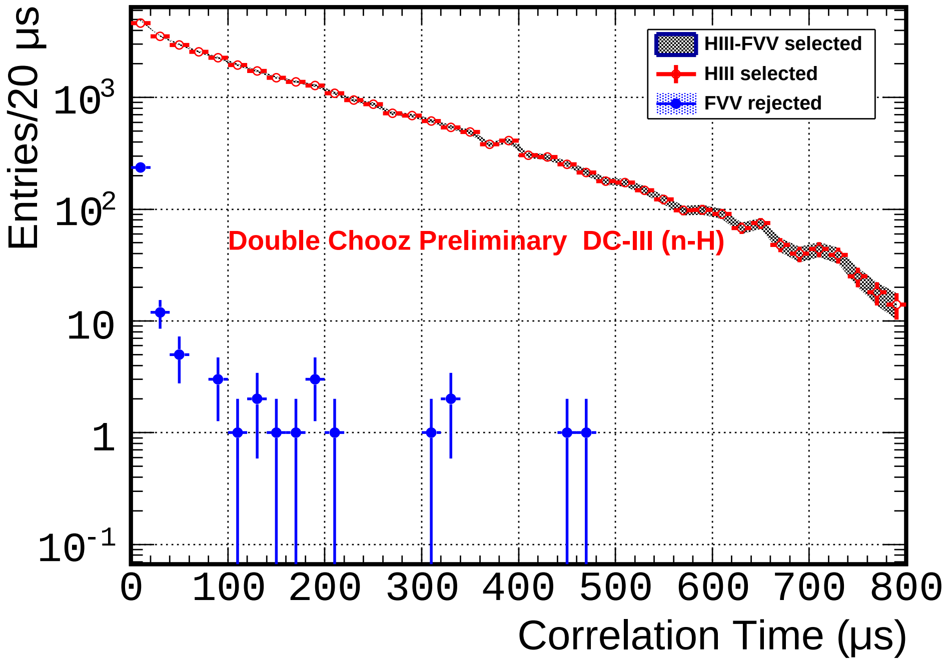


IBD spectrum clearly visible after reduction of accidental BG

Vertex quality veto

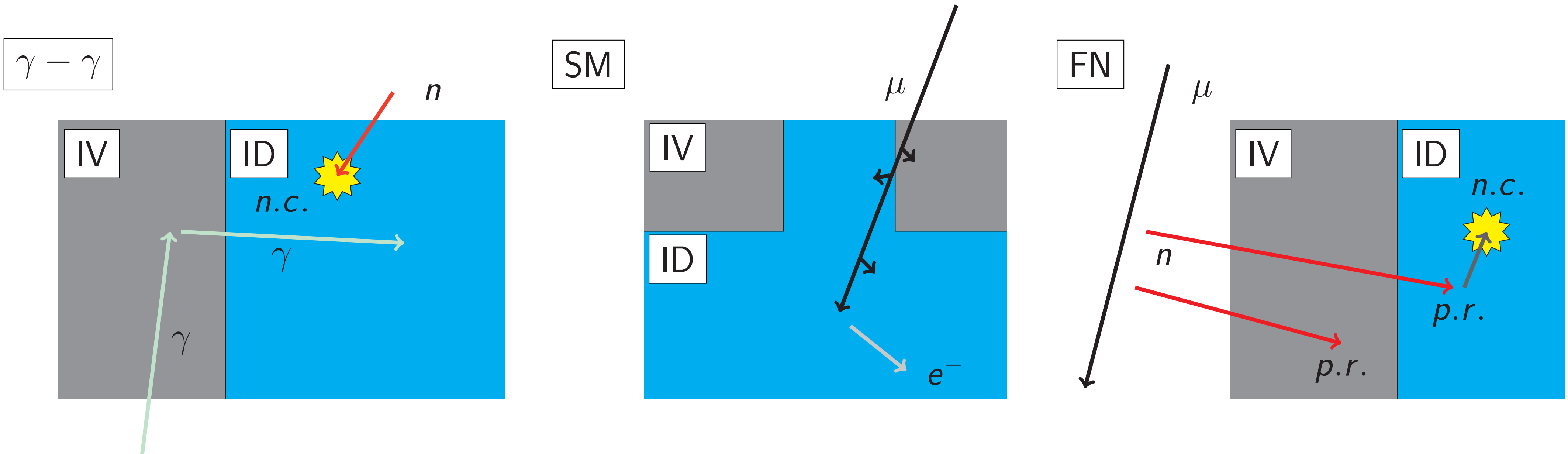
- Cut on **vertex reconstruction likelihood** (FV)
  - Vertex reconstruction assumes point light sources
  - Michel e^- in chimney have large FN from event topology/geometry
  - Require: $E_{\text{vis}} \geq 0.2755 \times e^{(FV/2.0125)}$





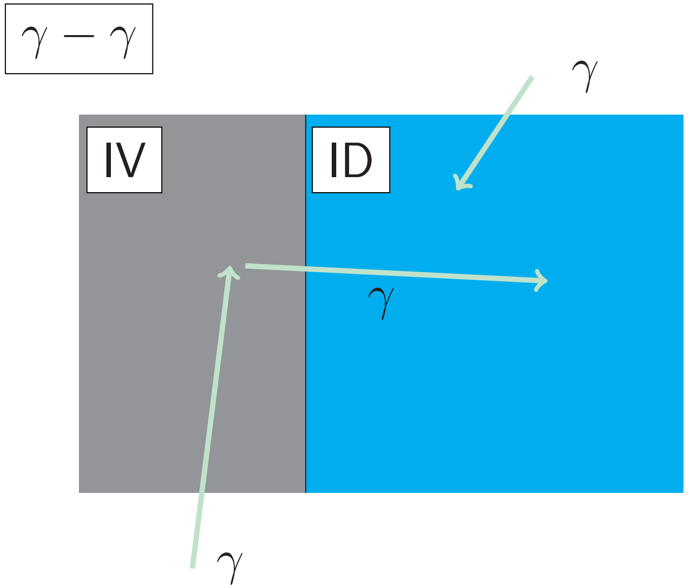
IV veto (prompt)

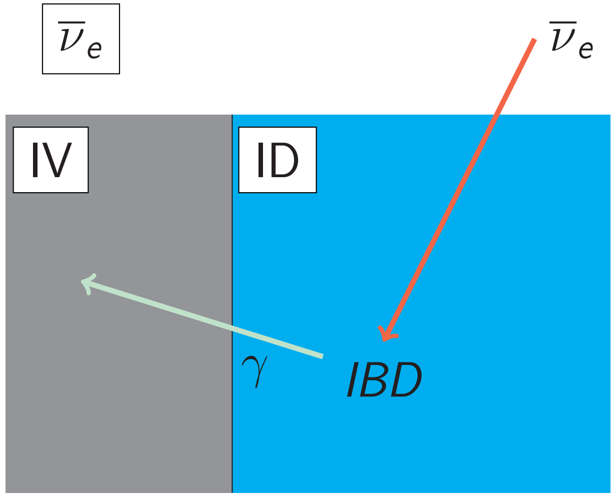
- Original IV use: μ veto, *n* shield
- Also tags fast neutron & **Compton** γ **(new)**
  - Reject IV-ID coincident activity (w/in 80 ns, 4 m) ($\geq$ 2 PMT hits & charge $\geq$ 0.2 MeV required)
  - IVV (prompt) rejects $\sim$ **15%** of accidental BG



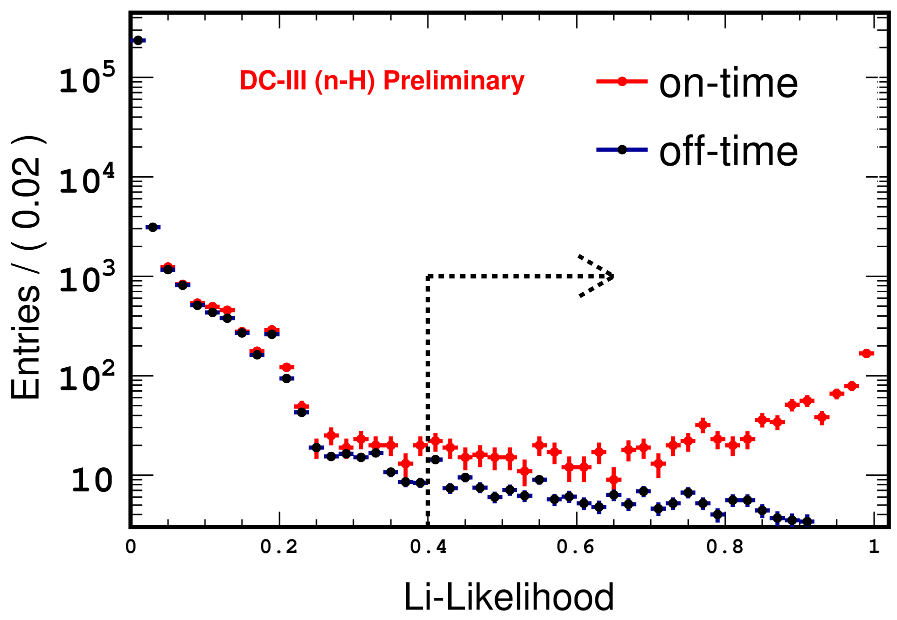
IV veto (delayed) (new)

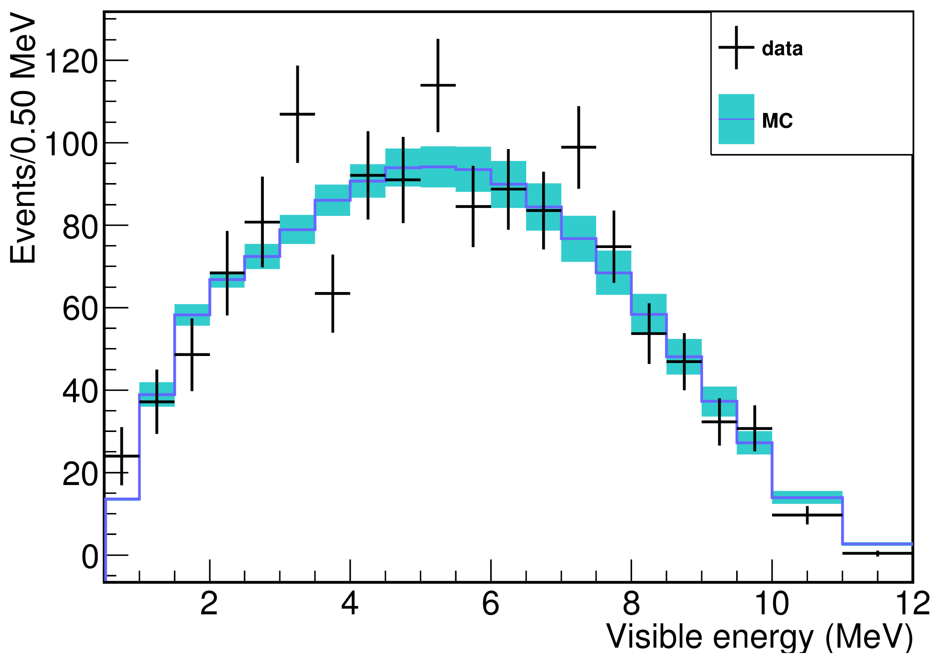
- Not used in Gd analysis to avoid IBD inefficiency
- Valuable in H analysis to reduce ^{208}Tl γ (peak at 2.6 MeV)
  - Time coincidence cut tuned to avoid IBD rejection
  - Same condition as IVV (prompt)
  - IVV (p + d) rejects $\sim$ **27**% of accidentals after ANN (IVV (d) alone: $\sim$ 15%)





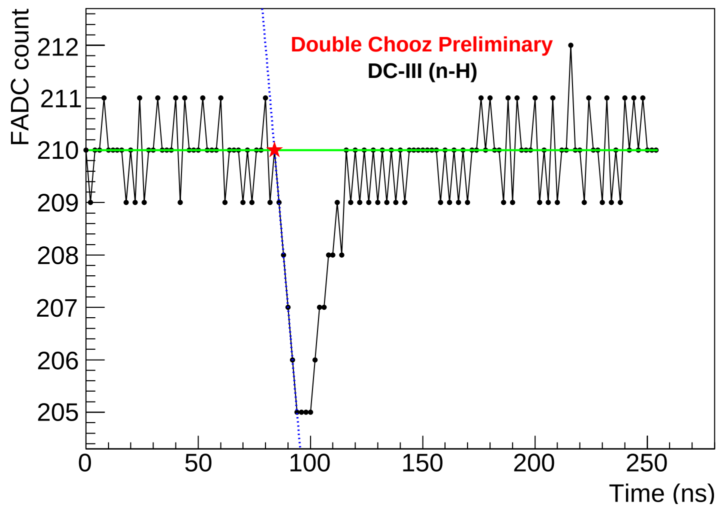
- **^{9}Li and ^{8}He likelihood cut**
  - $\mathcal{L}_{Li}$ built from number of n after μ, distance from IBD prompt to μ track
  - Events with $\mathcal{L}_{Li} > 0.4$ rejected
  - Rejects $\sim$ **55**% of cosmogenic BG

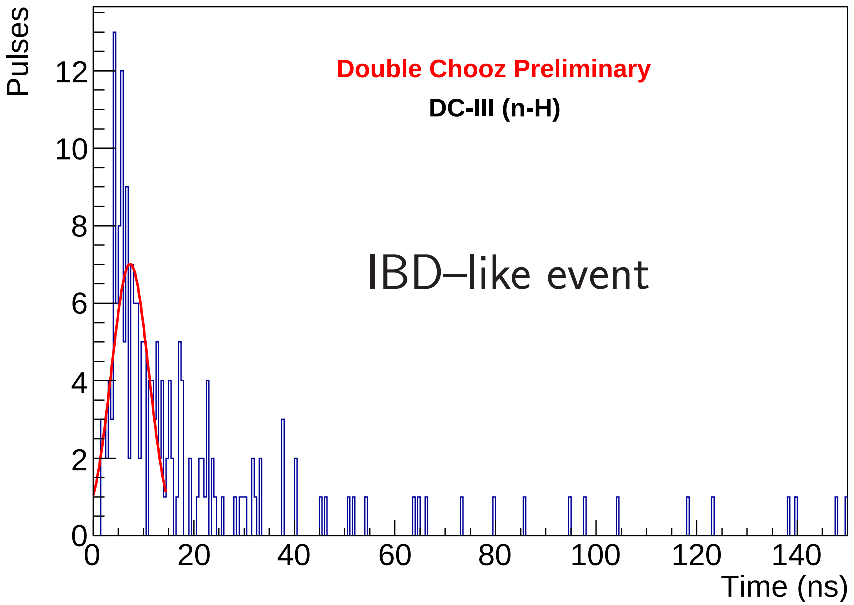


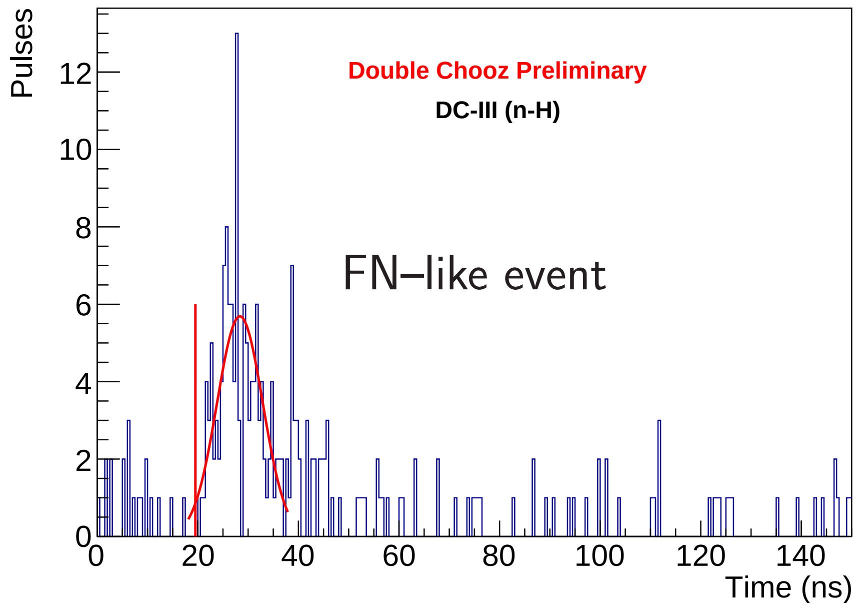


Pulse shape–based veto (new)

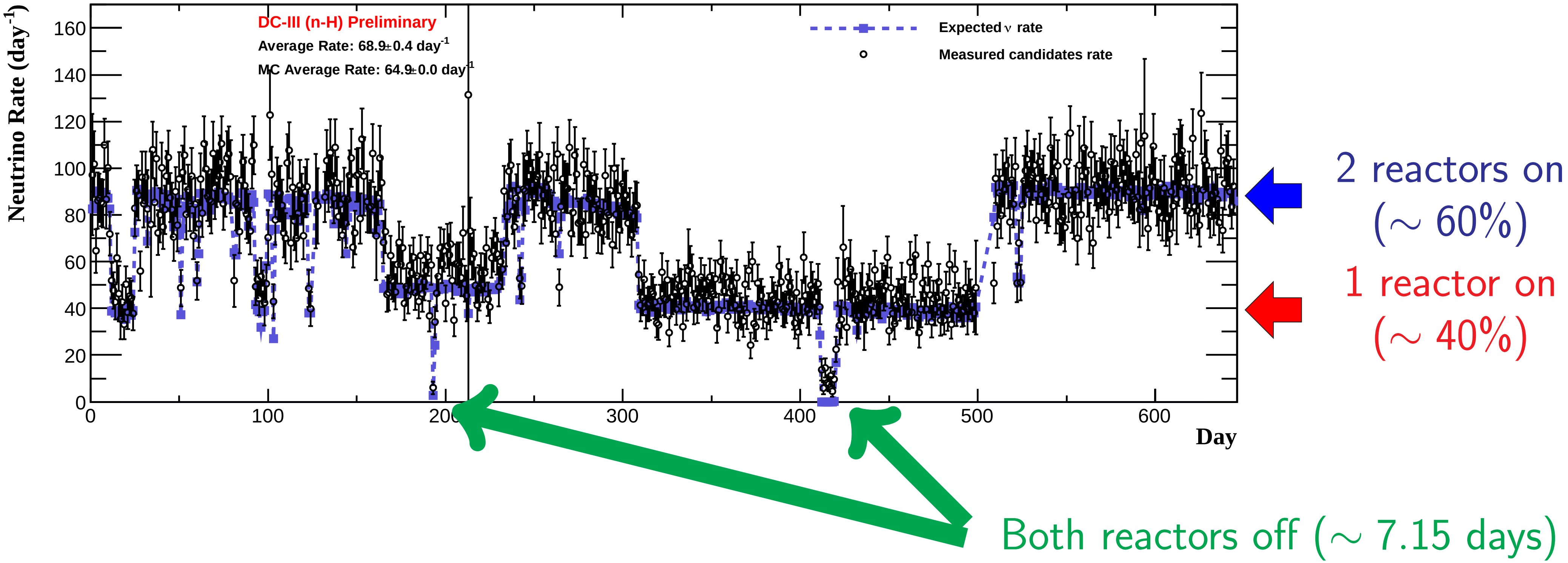
- Fast neutron showers produced from μ spallation
  - Major proton recoil proton $\Rightarrow$ prompt signal
  - Smaller recoils within 256 ns recorded in same event $\Rightarrow$ earlier PMT pulses
- Veto rejects $\sim$ **25%** of fast neutron BG







IBD candidates



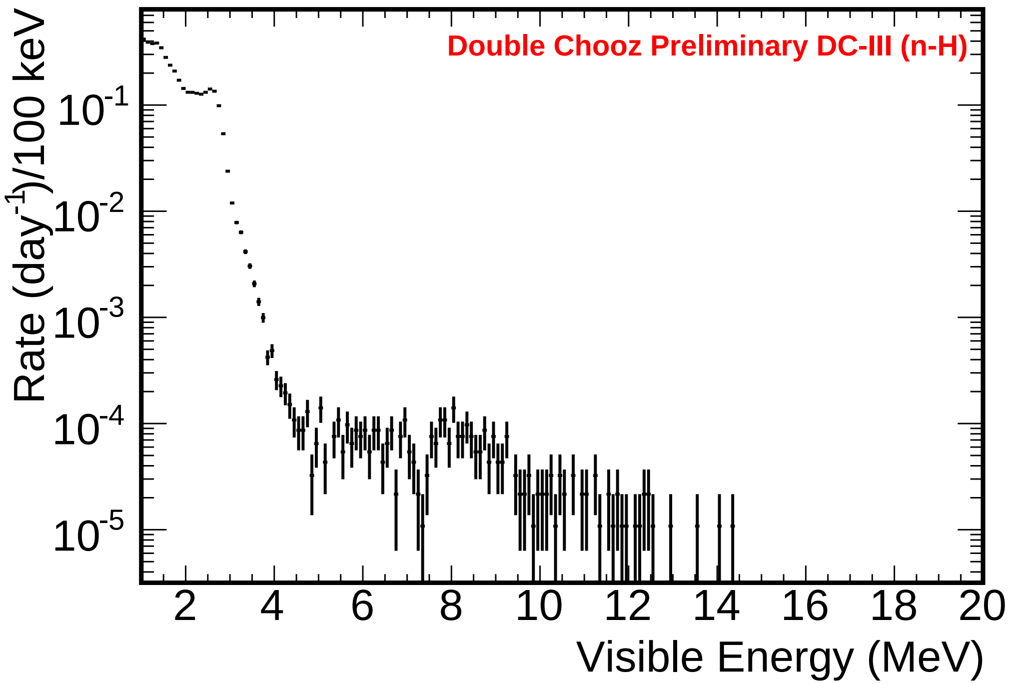
BG-subtracted IBD candidate rate / MC expectation (no osciillation):

(H): **62.1** day^{-1} / 64.9 day^{-1}

c.f. (Gd) (JHEP 10(2014) 086): **35.5** day^{-1} / 37.5 day^{-1}

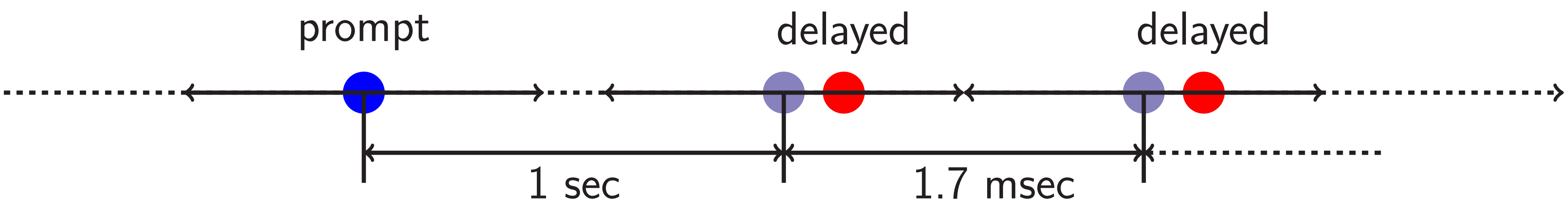
Remaining backgrounds

Remaining accidental background

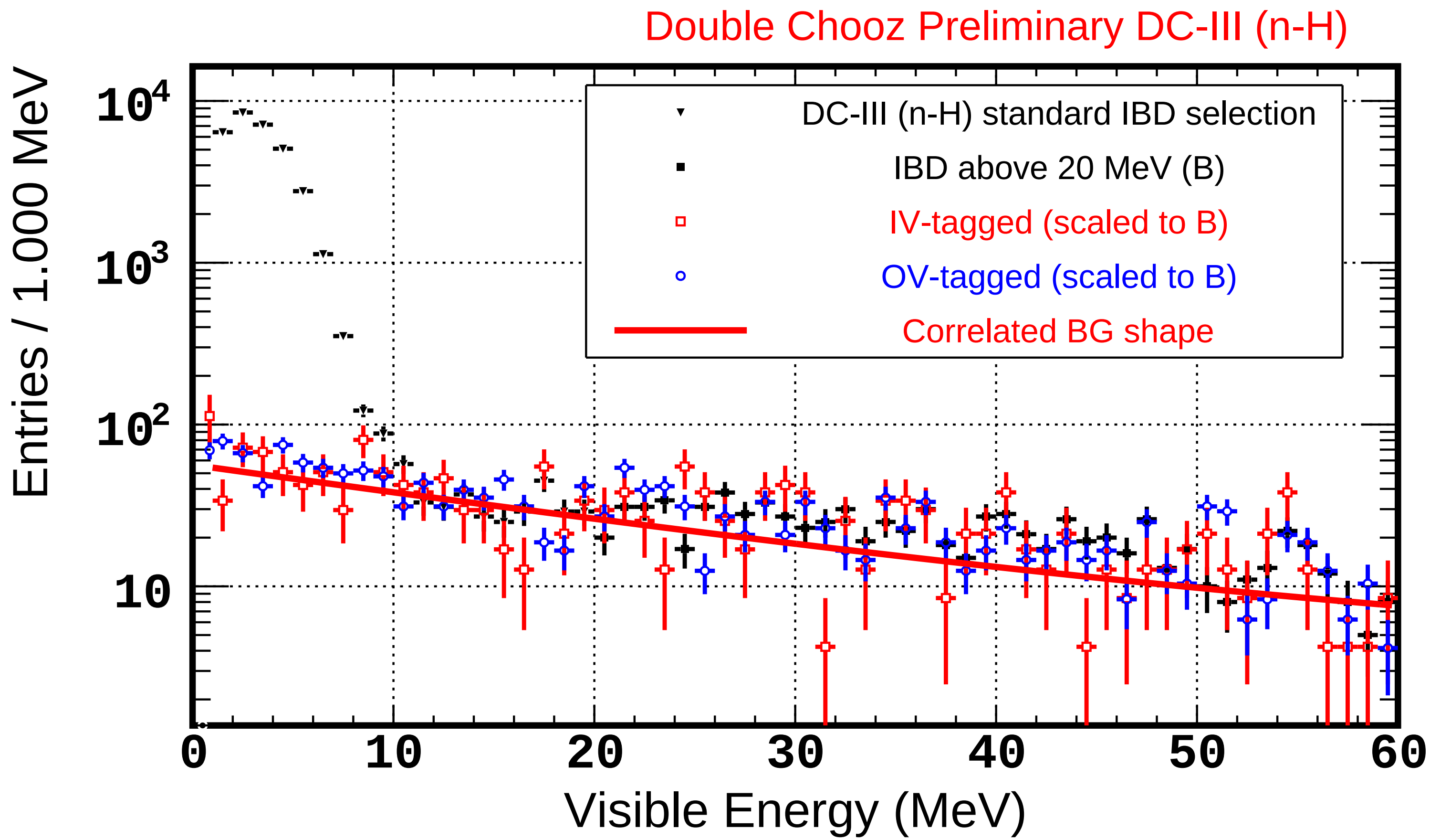


- Rate $= 4.334 \pm 0.011$ per day
- Minor impact on θ_{13} precision
  $\rightarrow$ **Major achievement** of this analysis

Measurement method: Off-time windows

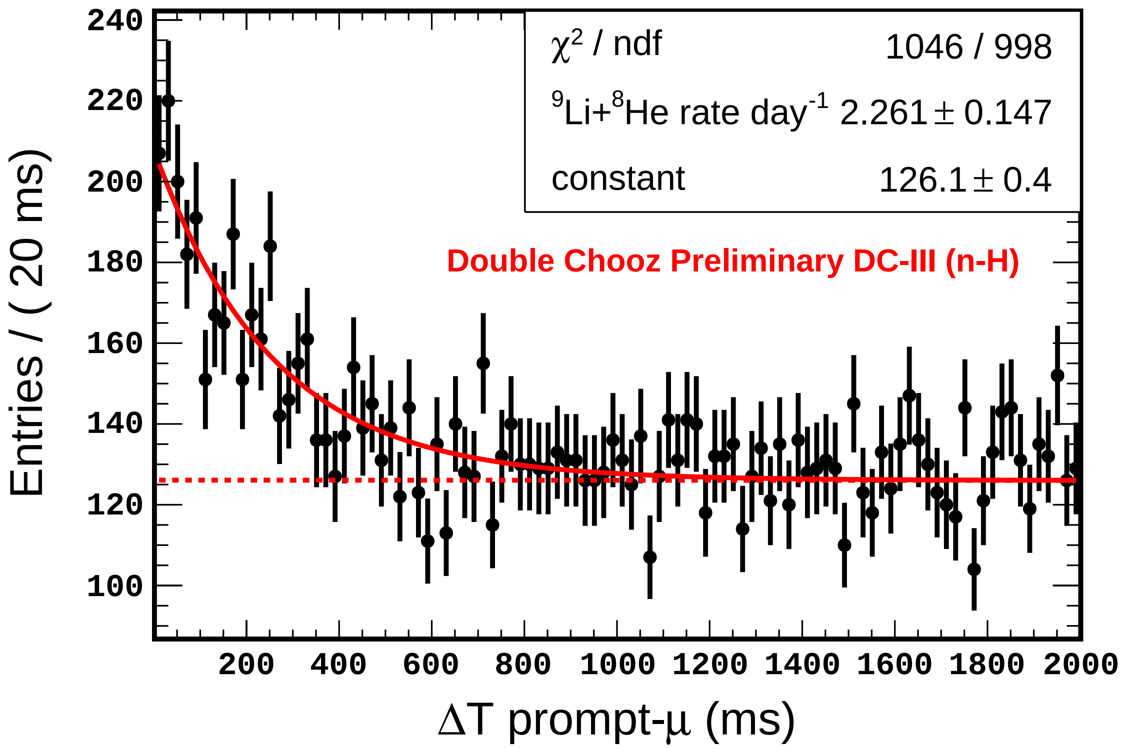


Remaining fast neutrons + stopping muons



- Shape measured from IV-tagged candidates
- Rate estimated using normalization > 20 MeV
- Mostly FN; SM $\sim$ 0.02 per day

Remaining ^{9}Li + ^{8}He backgrounds



- Divide IBD candidates according to energy deposited by possible progenitor μ
- If needed, enhance purity with $\Delta R_{prompt-\mu}$ cut (find efficiency from MC)
- Fit $\Delta T_{prompt-\mu}$ distributions $\rightarrow$ Li+He component

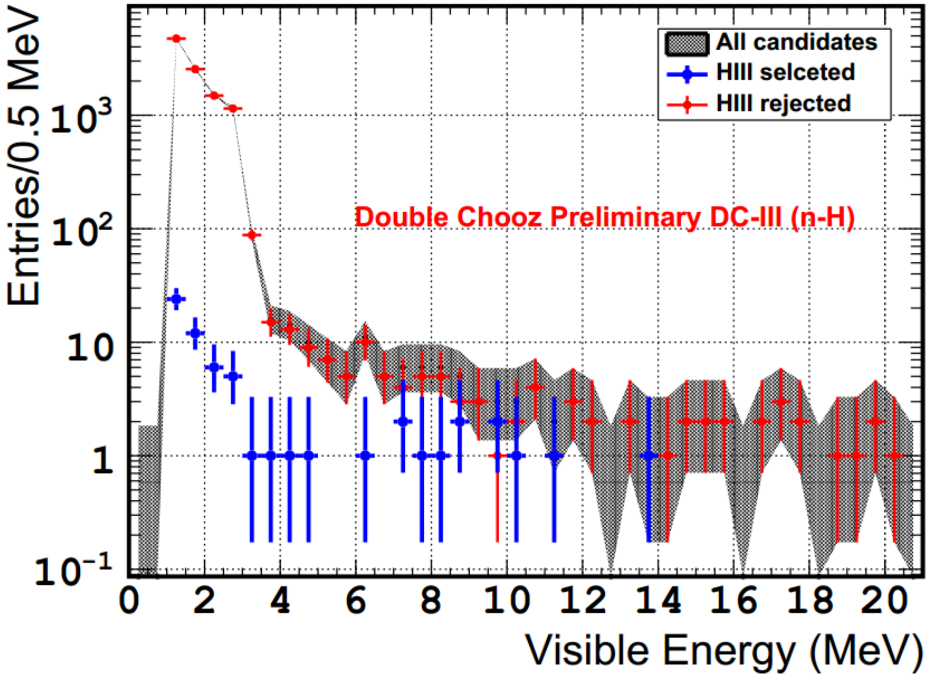
Summary of remaining backgrounds

BG	Rate (event/day)	Shape	Suppression w.r.t previous H analysis	Gd rate (event/day)
Accidental	4.334 ± 0.011	data (off-time)	$\times 16.9$	0.070 ± 0.003
Fast n + stopped μ	1.55 ± 0.15	data (IV tag)	$\times 2.0$	0.604 ± 0.051
^{9}Li + ^{8}He	$0.95^{+0.57}_{-0.33}$	data (Li+He tag)	$\times 2.9$	$0.97^{+0.41}_{-0.16}$

- ^{9}Li+^{8}He rate uncertainty dominates BG systematics
- Accidentals well controlled and well measured

Reactors-off data

- **Unique feature** of Double Chooz



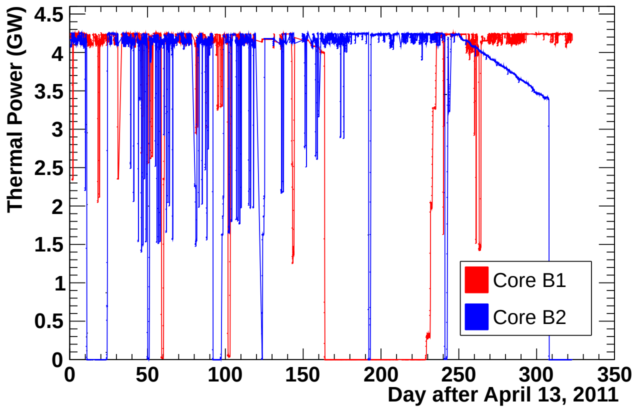
Number of events	All	$E > 12MeV$ (Correlated BG)
Before Vetos	10185	23
After Vetos	63	1
Rejection	$\sim 160\times$	$\sim 23\times$

- Expected rate: $7.05^{+0.6}_{-0.4}$ events/day (including 0.33 ± 0.10 residual $\overline{\nu}_e$/day)
- Measured rate: 8.8 ± 1.1 events/day

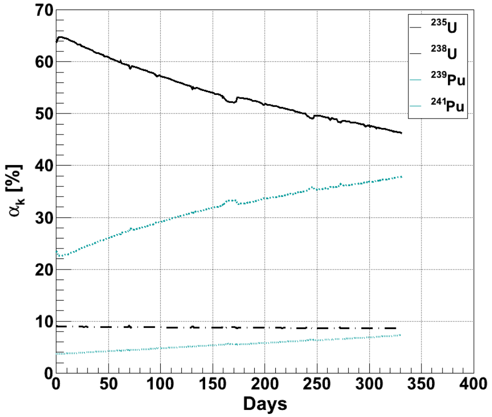
- Validates background model
- Constrains background rates in oscillation fits

Reactor simulation

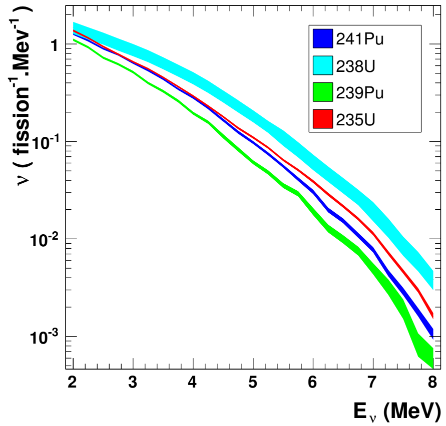
Reactor flux prediction



Thermal power, P_{th}**, from** reactor operation data



Simulated **fission fractions,** α_k**,** and **mean energy,** $\langle \mathbf{E_f} \rangle$



Semi-empirical **mean cross section per fission,** $\langle \sigma_f \rangle$
(following Huber/Mention et al., 2011)

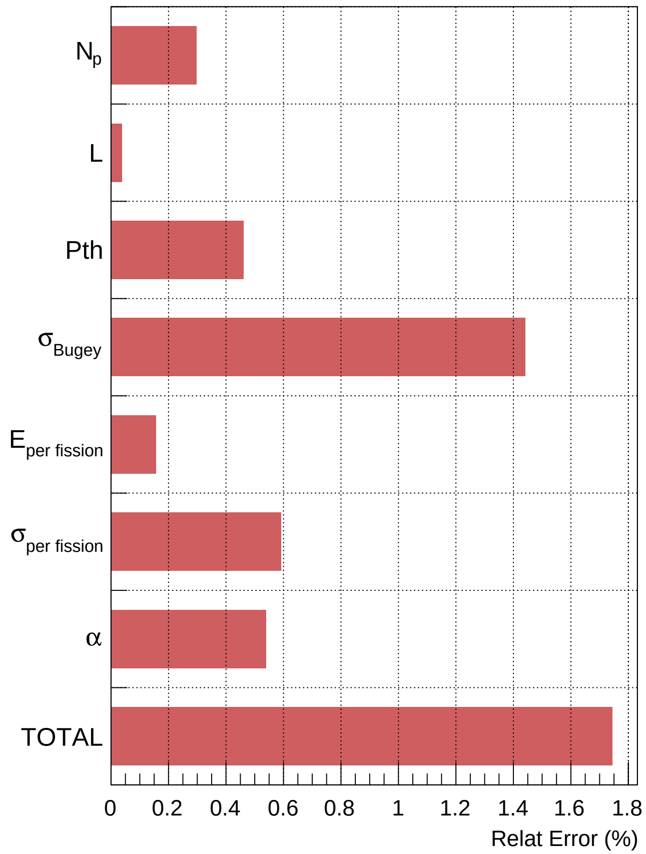
$$N_i = \frac{\epsilon N_p}{4\pi} \sum_R \frac{1}{L_R^2} \frac{\mathbf{P_{th}^R}}{\langle \mathbf{E_f} \rangle_\mathbf{R}} \left(\frac{\langle \boldsymbol{\sigma}_\mathbf{f} \rangle_\mathbf{R}}{\sum_\mathbf{k} \boldsymbol{\alpha}_\mathbf{k}^\mathbf{R} \langle \boldsymbol{\sigma}_\mathbf{f} \rangle_\mathbf{k}} \sum_k \boldsymbol{\alpha}_\mathbf{k}^\mathbf{R} \langle \boldsymbol{\sigma}_\mathbf{f} \rangle_\mathbf{k,i} \right)$$

Bugey4 "anchor": $\langle \sigma_f \rangle_R = \langle \sigma_f \rangle_{Bugey} + \sum_k \left(\alpha_k - \alpha_k^{Bugey} \right) \langle \sigma_f \rangle_k$

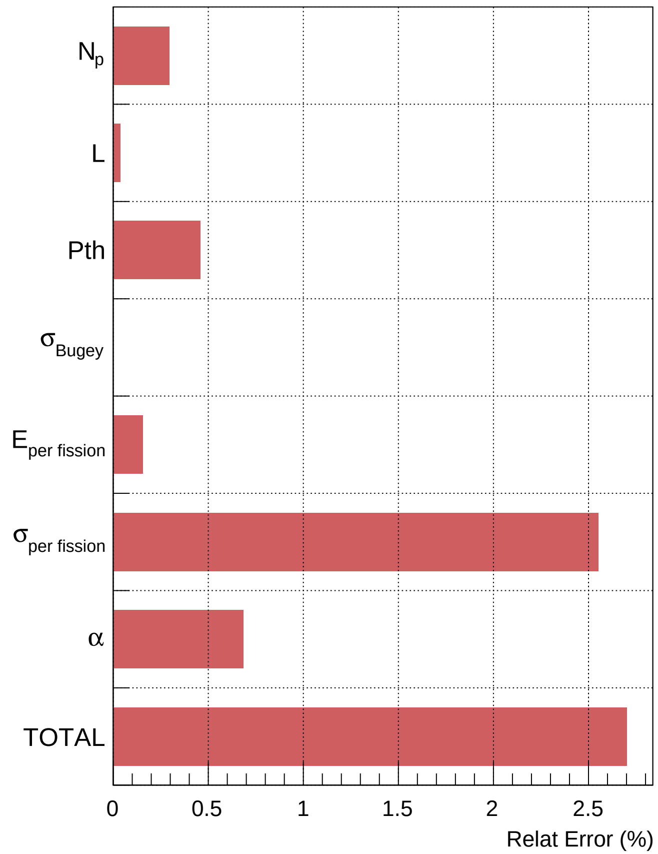
i = energy bin index, R = {Reactor 1, Reactor 2}, k = {^{235}**U,** ^{238}**U,** ^{239}**P,** ^{241}**P}**

ϵ **= detection efficiency,** N_p **= number of protons in fiducial volume,** L_R **= distance between** R^{th} **reactor and detector**

Reactor flux systematics



With Bugey4 (1.7%)



Without Bugey4 (2.7%)

Bugey4 used as **"virtual near detector"**

$\Rightarrow$ flux normalization uncertainty: 1.7% ($\sim$ 30% less than w/o Bugey4)

Systematic uncertainties

Detection systematics

- δ(detection) = uncertainty on all MC correction factors, including:
  - **Proton number**: $\sim 0.91\%$ (dominant)
    - Includes Target, GC, acrylics
    - GC liquid weighed less precisely than Target
  - **Spill uncertainty**: $\sim 0.29\%$
  - **Hydrogen fraction**: $\sim 0.21\%$
  - **Selection efficiency:** $\sim 0.22\%$
- $\boldsymbol{\delta}$**(detection) = 1.0%**
- Comparable to Gd, except proton number

Uncertainties in fits

Normalization uncertainties:

Source of uncertainty	First H analysis (2013)	Current H analysis (2015)	Latest Gd analysis (2014)
Reactor flux	1.7%	**1.7%**	1.7%
Signal detection efficiency	1.6%	**1.0%**	0.6%
^{9}Li+^{8}He background	1.6%	$^{+0.9\%}_{-0.5\%}$	$^{+1.1\%}_{-0.4\%}$
Fast n + stopping μ	0.6%	**0.2%**	0.1%
Accidental background	0.2%	$<$ **0.1%**	$<$ 0.1%
Statistics	1.1%	**0.6%**	0.8%

Shape uncertainties, for Rate+Shape fit:

- Reactor spectrum
- Background spectra
- Energy scale

$\sin^2 2\theta_{13}$ measurements

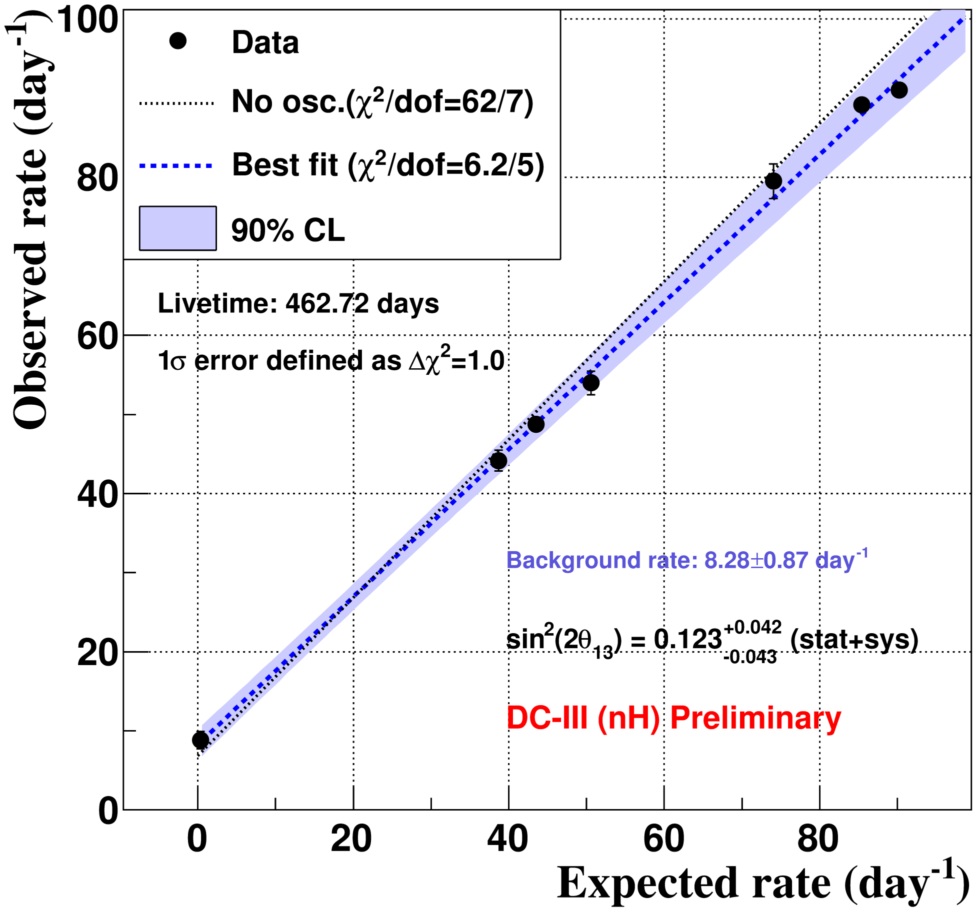
Reactor Rate Modulation (RRM) analysis

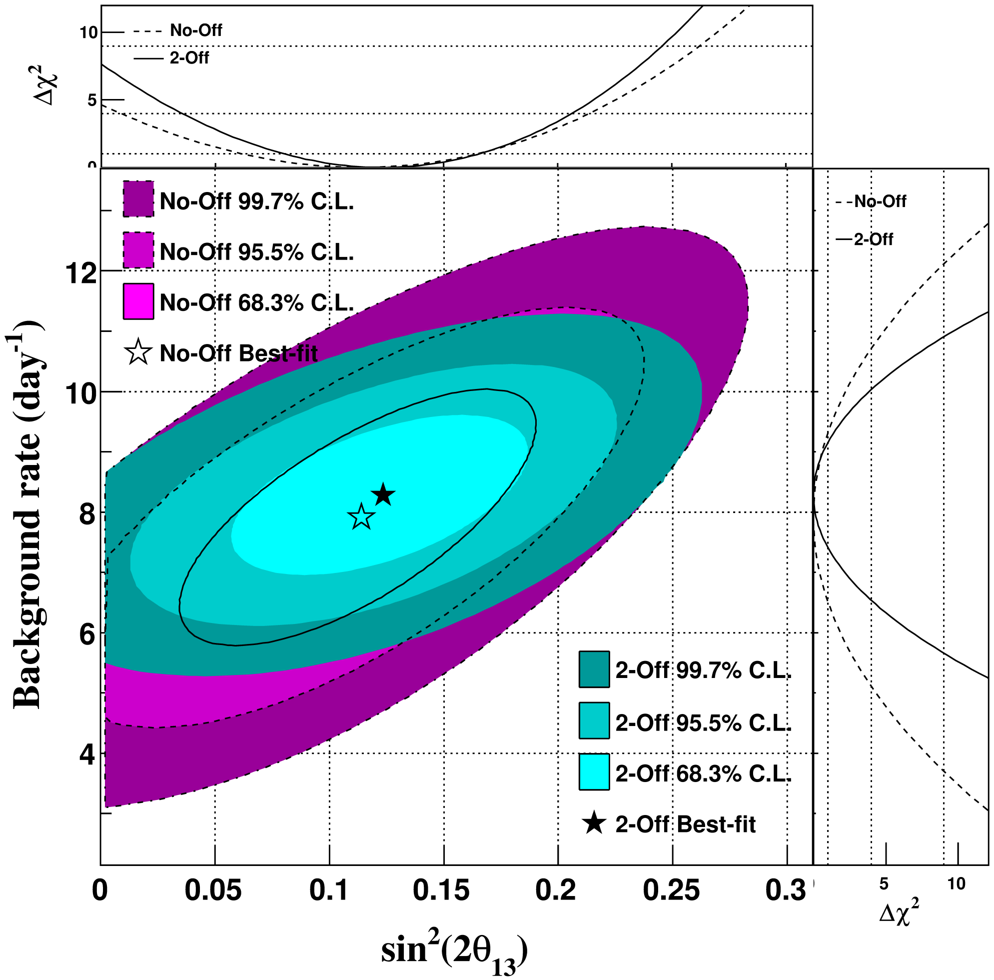
- Compare observed and expected IBD rates in different reactor power bins ($i = 1, ..., N$), fitting for **$\sin^2 2\theta_{13}$** and **total background rate, B**:

$$R_i^{obs} = \mathbf{B} + \left(1 - \boldsymbol{\sin^2 2\theta_{13}} \left\langle \sin^2 \frac{1.27 \Delta m^2 L}{E_\nu} \right\rangle \right) R_i^{exp,\, no\ osc}$$

- Independent of model for reactor spectrum shape
- Gains leverage from unique reactor-off data
- Optional use of *a priori* background model

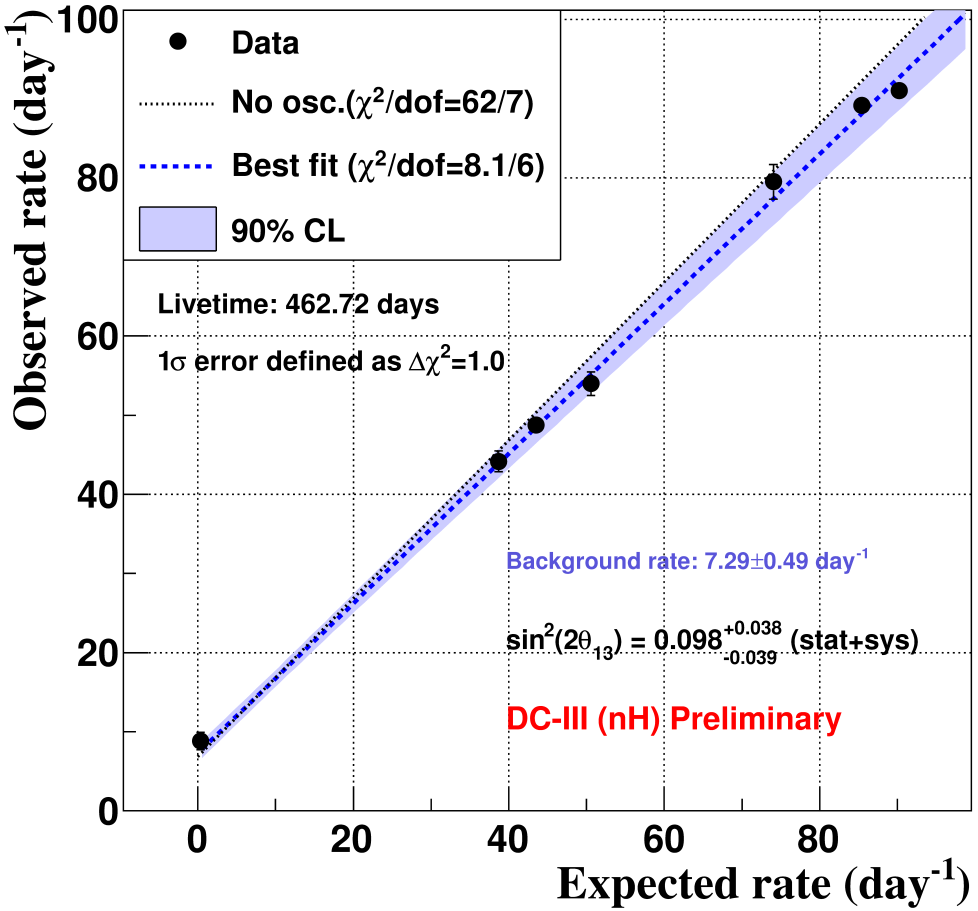
No *a priori* background model ... a unique Double Chooz analysis!

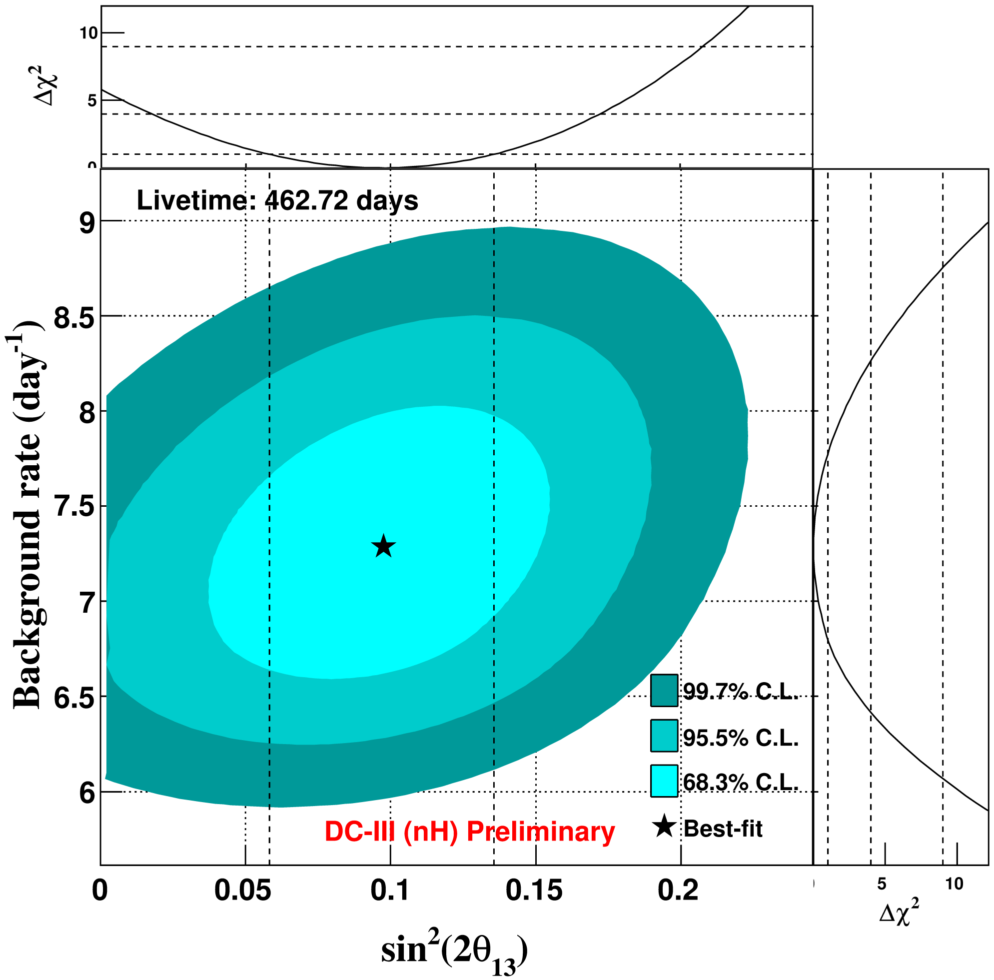




$$\sin^2 2\theta_{13} = 0.123^{+0.042}_{-0.043}$$

Constrain with *a priori* background model $\rightarrow$ increase $\sin^2 2\theta_{13}$ precision

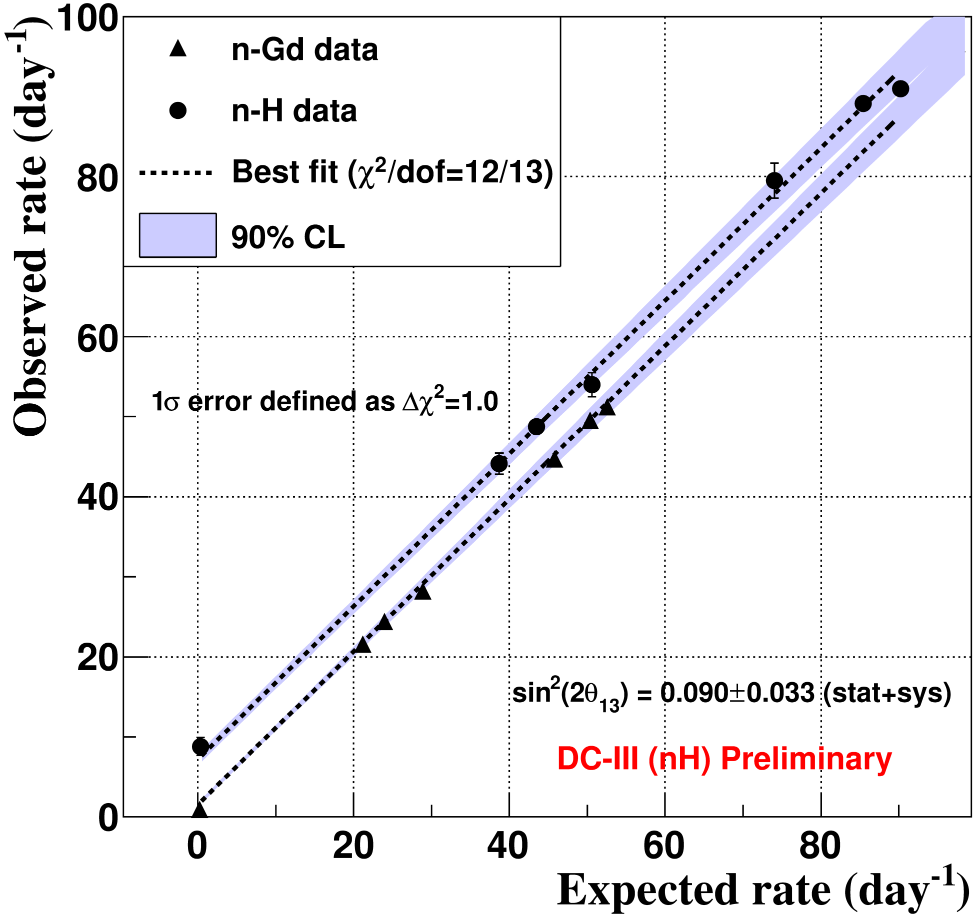


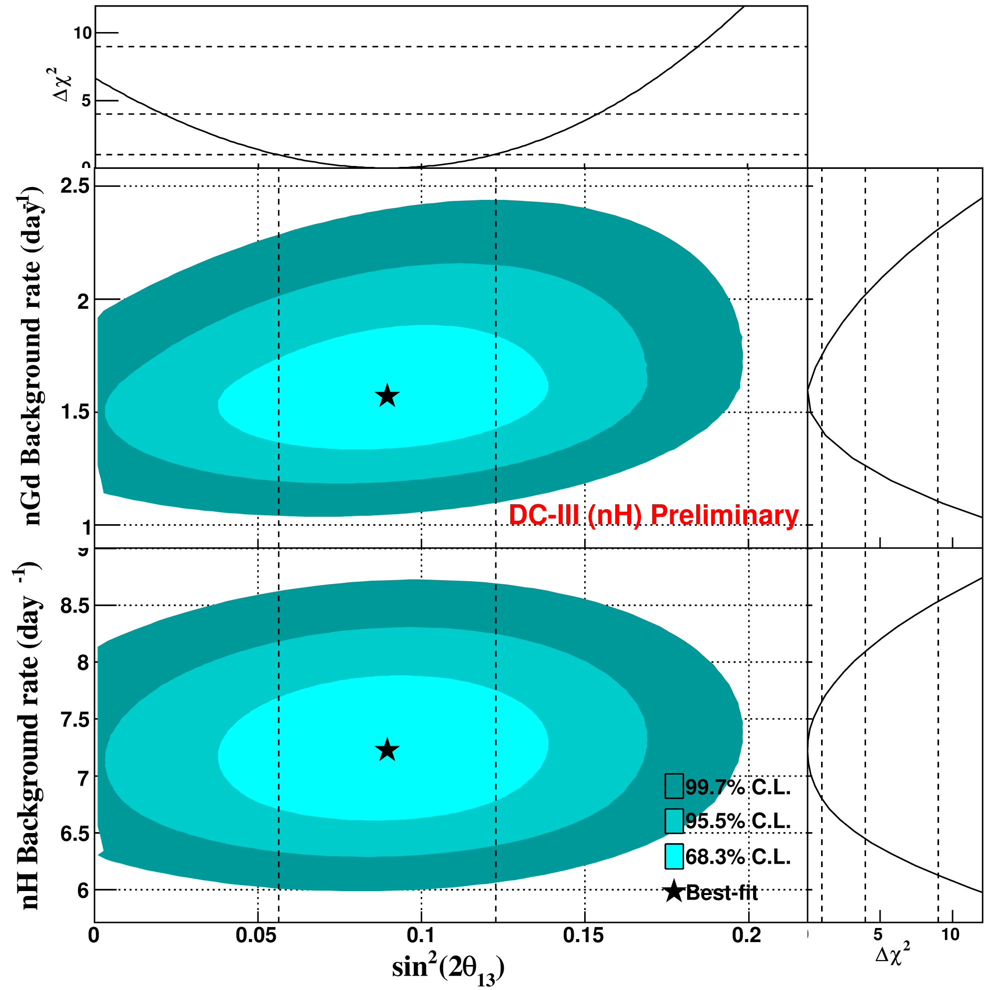


$$\sin^2 2\theta_{13} = 0.098^{+0.038}_{-0.039}$$

RRM: Gd+H combination, with background model

Combining this H-based result with latest Gd-based result (2014):

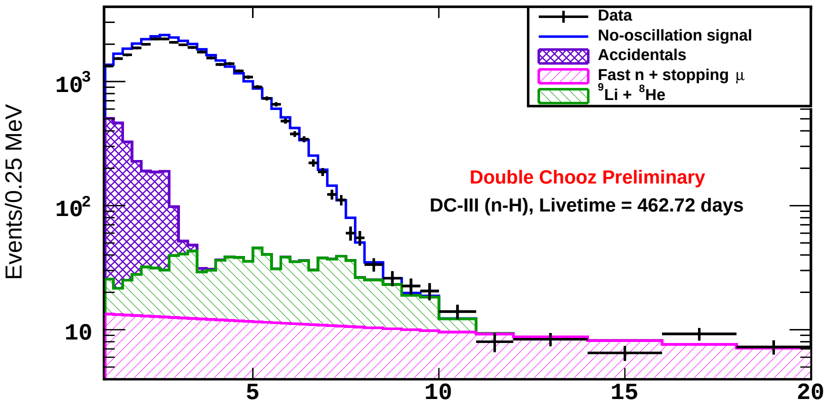


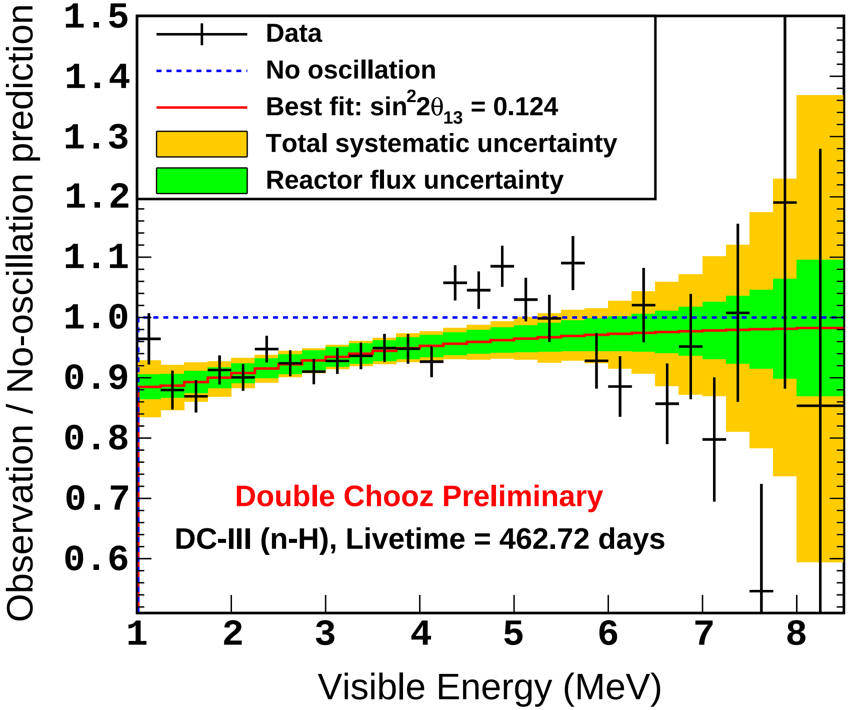


$$\sin^2 2\theta_{13} = 0.090 \pm 0.033$$

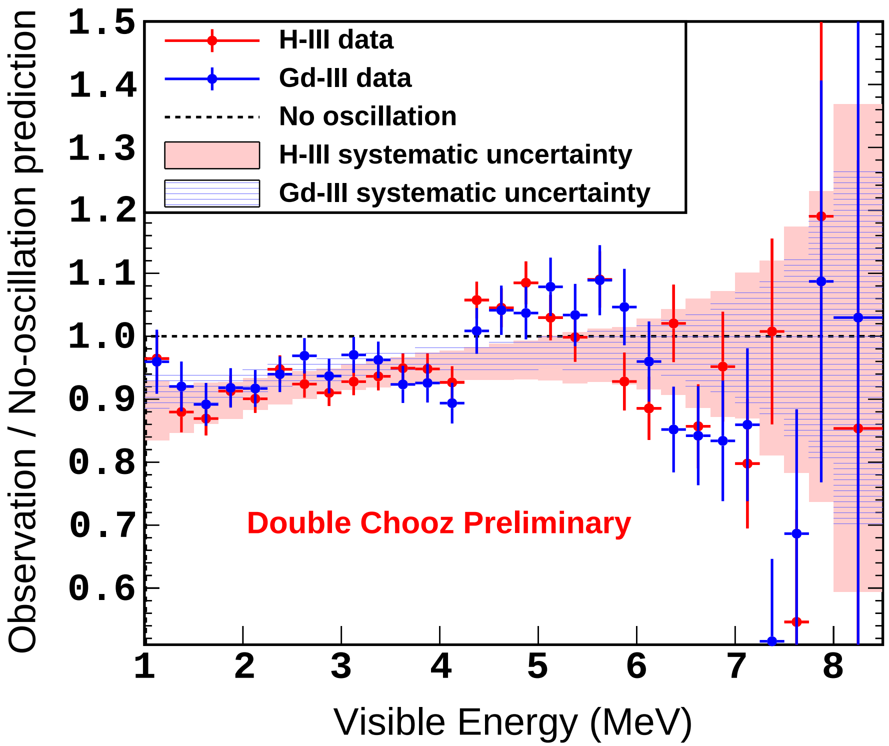
H only: $\sin^2 2\theta_{13} = 0.098^{+0.038}_{-0.039}$, Gd only: $\sin^2 2\theta_{13} = 0.090^{+0.034}_{-0.035}$

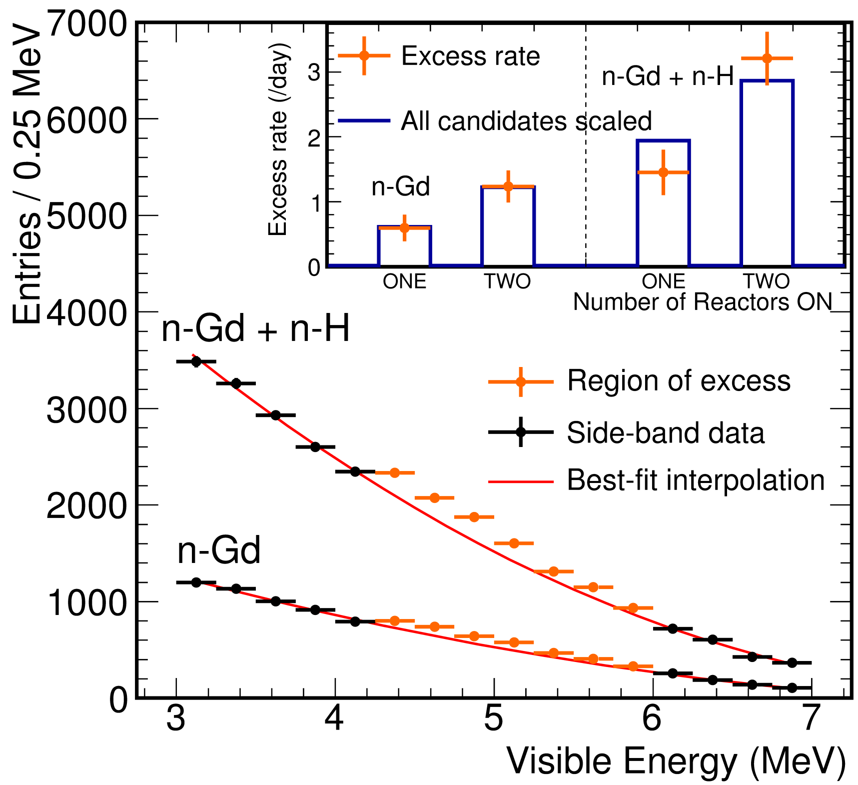
Rate+Shape fit





- Uses **prompt energy spectrum,** with single reactor power bin
- Able to constrain backgrounds $\rightarrow$ better $\sin^2 2\theta_{13}$ precision
- $\sin^2 2\theta_{13} = 0.124^{+0.030}_{-0.039}$
- Large χ^2 in $\sim$ 4-6 MeV, region of spectrum distortion observed in latest Gd analysis





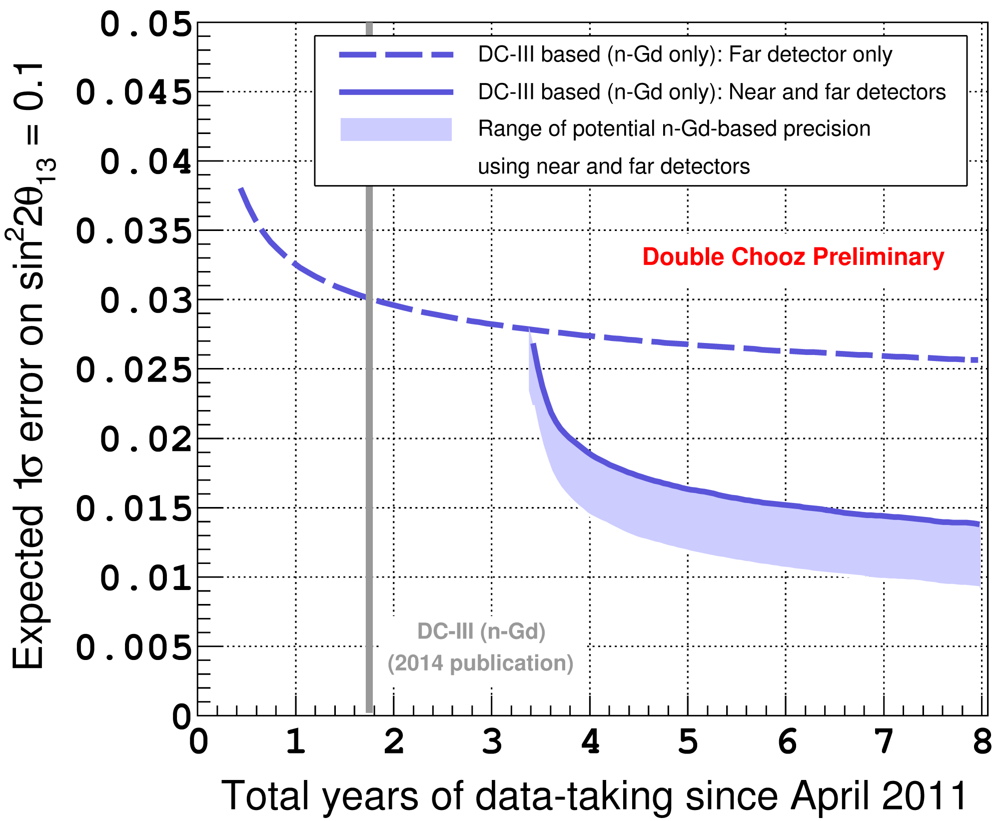
- **Consistent features** observed in Gd and H channels
- Excess in 4-6 MeV region is correlated with reactor power
- Ongoing investigations in neutrino and reactor communities

(Plot on right, from Gd 2014 analysis, uses a simplified n-H selection.)

Looking forward

Future precision, including near detector

Projected precision $\sin^2 2\theta_{13}$, using *only Gd captures*:



Adding H capture data → better precision in shorter timescale.

Conclusions and outlook

- New H results **validate and enhance** Gd results:
  - New H analysis (RRM): $\mathbf{sin^2 2\theta_{13} = 0.098^{+0.038}_{-0.039}}$
  - $[4, 6]$ MeV spectrum distortion measurement
  - Combined Gd+H: $\mathbf{sin^2 2\theta_{13} = 0.090 \pm 0.033}$

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  - New background rejection methods: ANN, pulse shape, IV veto
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- Paving the way for **two-detector analyses:**
  - Already taken 6 months of data
  - Working now on a two-detector $\sin^2 2\theta_{13}$ analysis
  - Also planned: sterile neutrino analyses, reactor spectrum measurements