Recent results from the Double Chooz experiment

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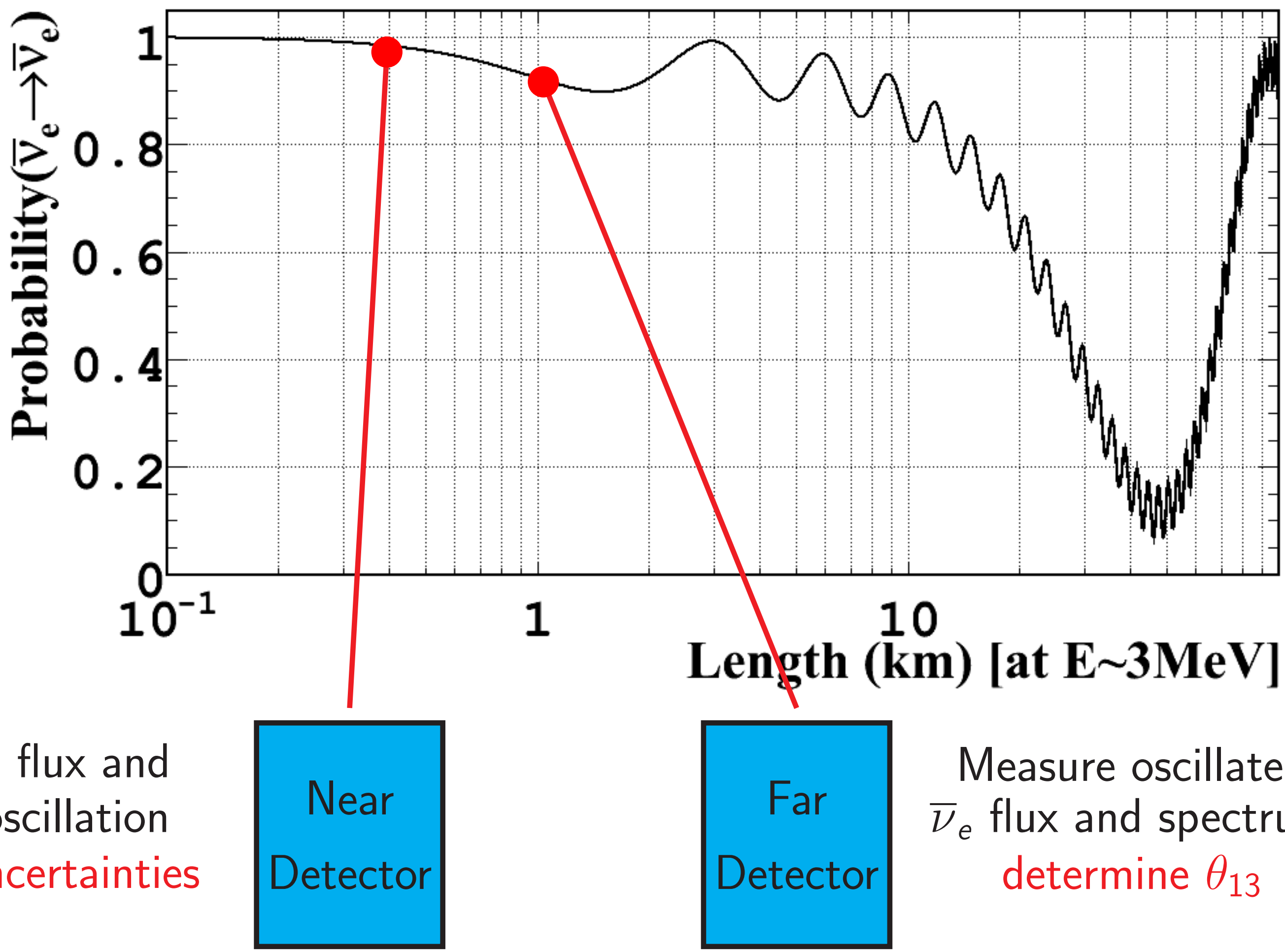
Survival probability:

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

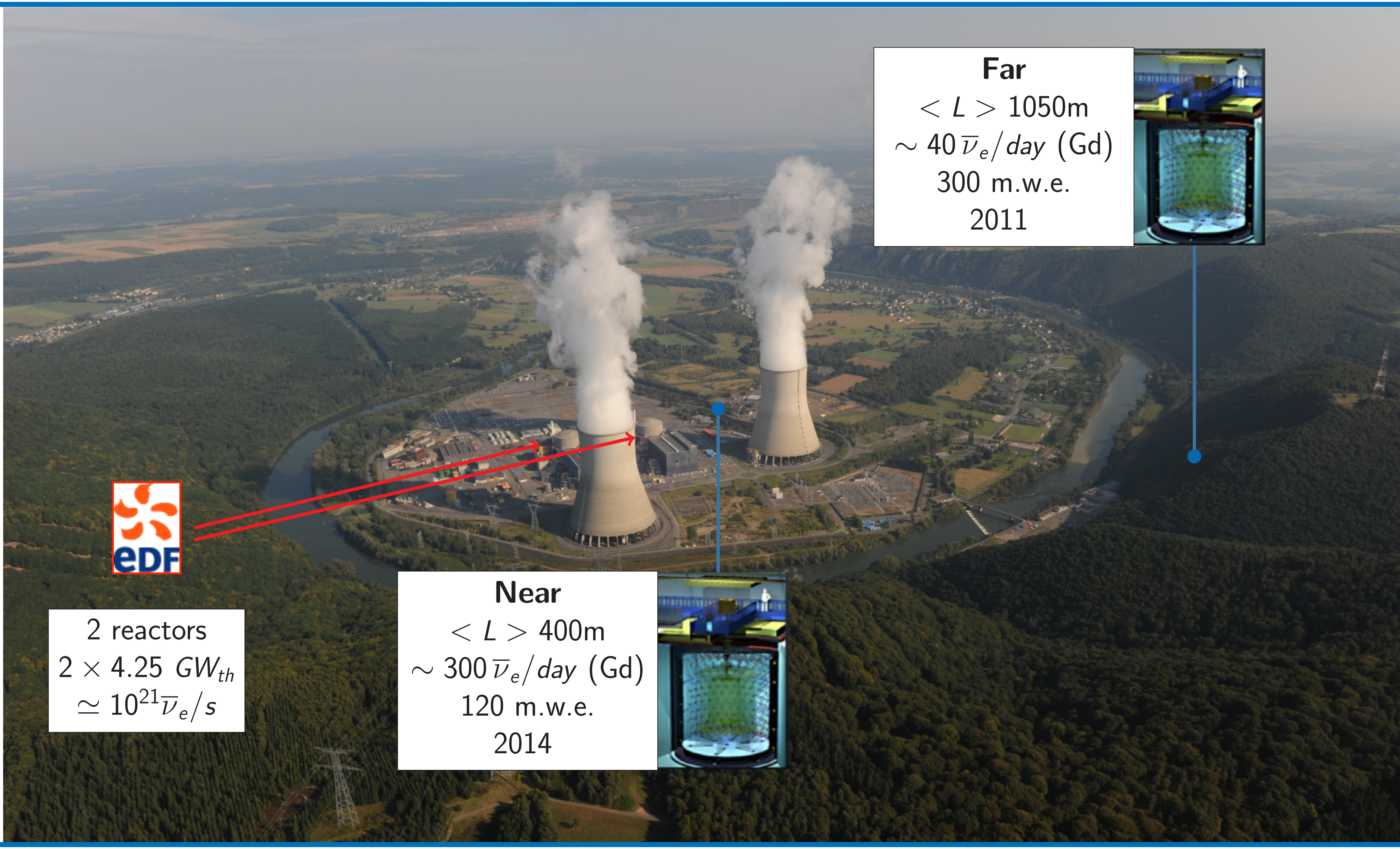


FD-only phase: Double Chooz uses Bugey4 as effective ND

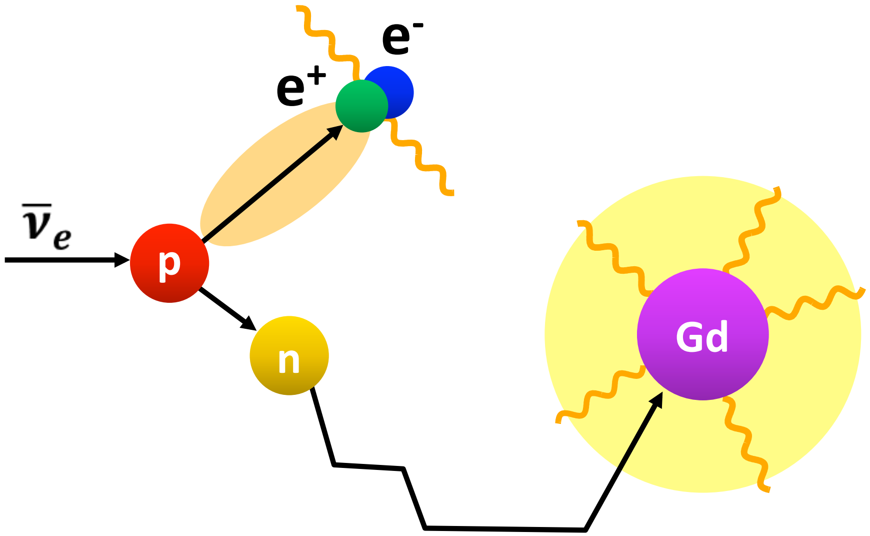
Measure reactor $\overline{\nu}_e$ flux and spectrum **before** oscillation
reduce systematic uncertainties

Measure oscillated $\overline{\nu}_e$ flux and spectrum
determine θ_{13}

The Double Chooz experiment

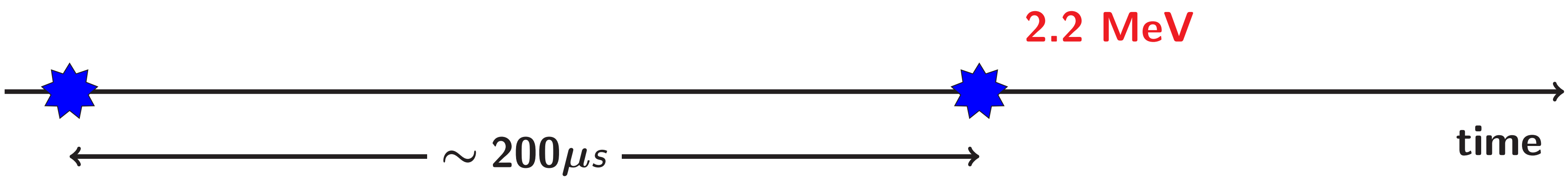


- **Inverse Beta Decay (IBD)**:
  - $\overline{\nu}_e + p \rightarrow n + e^+$
- **Prompt signal**: E_{e^+} + annihilation γ's ($1 \sim 9$ MeV, $E_{\rm vis} \simeq E_{\overline{\nu}_e} - 0.8\,{\rm MeV}$)
- **Delayed signal**: γ's from neutron capture on Gd or H
- **Delayed coincidence**

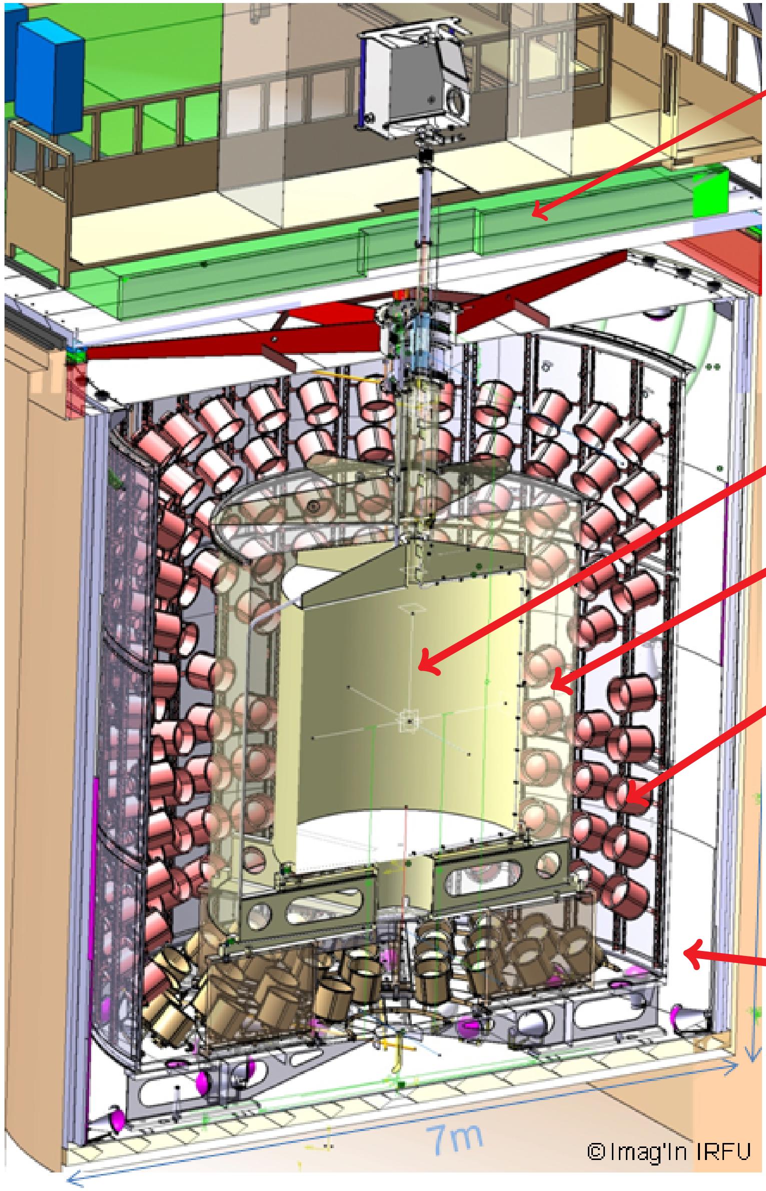


Gd channel

H channel



The Double Chooz detectors



Outer Veto (OV) : Plastic Scintillator Strips

Inner Detector (ID)

Gd channel

ν-**target**: 10.3 m^3 Liquid Scintillator Gd-loaded

γ-**catcher**: 22.3 m^3 Liquid Scintillator

H channel

Buffer : 110 m^3 Mineral Oil & 390 PMTs

Inner Veto (IV)

90 m^3 Liquid Scintillator & 78 PMTs

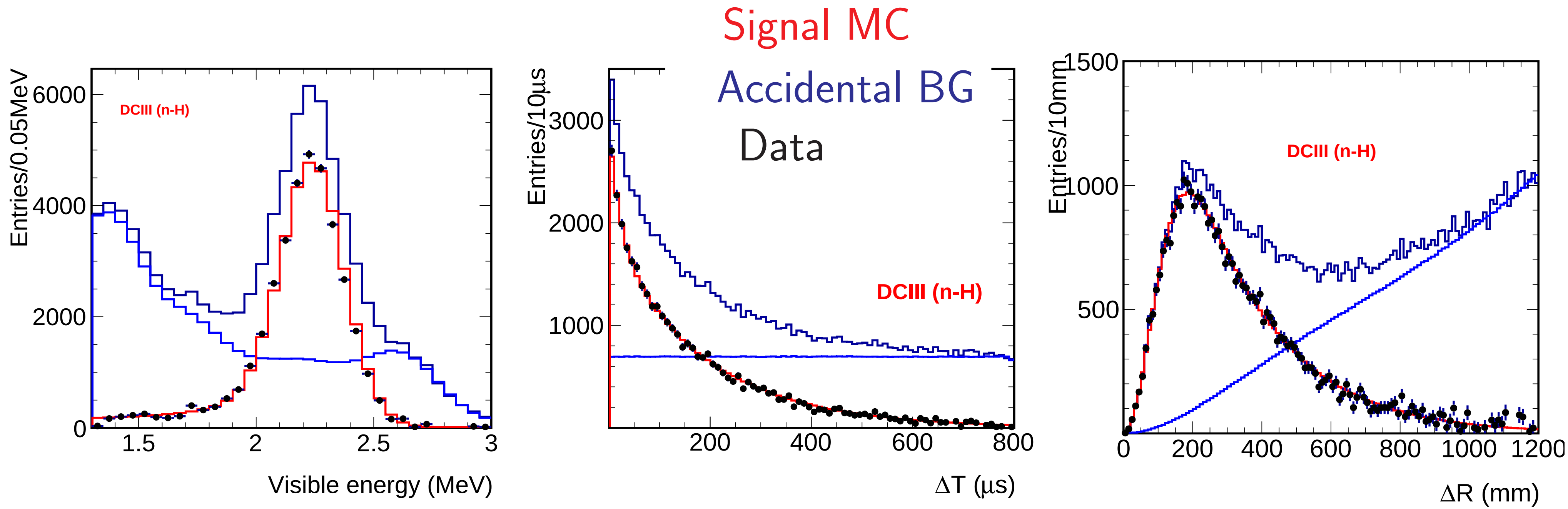
Signal selection

Cut	Purpose	
Muon veto	μ and decay products (if μ is tagged) rejection	*pre-selection*
Light noise cut	spontaneous light emission rejection	
Multiplicity cut	multiple spallation n scattering rejection	
Prompt energy & Delayed coinc.	**IBD selection** & random coincidences rejection	
Li+He veto	cosmogenic radioisotope rejection (^{9}Li, ^{8}He and ^{12}B)	
FV veto	stopped μ, spontaneous light emission rejection	*BG vetos*
IV veto (prompt)	fast neutrons, stopped μ, rock γ's rejection	
IV veto (delayed)	fast neutrons, rock γ's rejection	
MPS veto	fast neutrons rejection	
OV veto	fast neutrons, stopped μ rejection	

Signal selection

- Prompt candidate selection → by prompt energy
- Delayed coincidence → reject random coincidences (accidental BG)
  - prompt-delayed space correlation
  - prompt-delayed time correlation
  - delayed energy

} Gd-III: cut-based approach
H-III: **multivariate approach (ANN-based)**



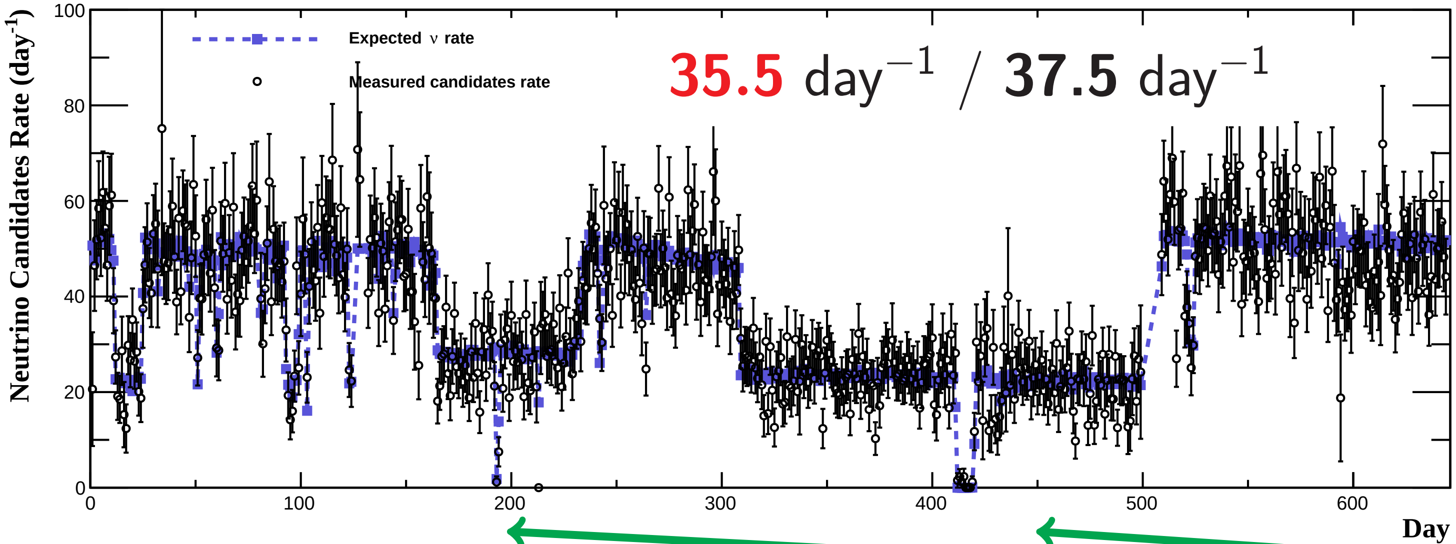
Remaining backgrounds

BG	H-III rate (event/day)	H-III signal MC (event/day)	Gd-III rate (event/day)	Gd-III signal MC (event/day)
Accidental	4.3 ± 0.01	**64.9**	$< 0.1 \pm 0.003$	**37.5**
Fast neutron stopped-μ	1.55 ± 0.15	**64.9**	0.60 ± 0.05	**37.5**
$^{9}Li + {}^{8}He$	$0.95^{+0.57}_{-0.33}$	**64.9**	$0.97^{+0.41}_{-0.16}$	**37.5**

$^{9}Li + ^{8}He$: dominates BG systematics budget by $> 50\%$

H-III: successfully reduced accidental background to a negligible level as for Gd-III (c.f. H-II (2013): signal MC/Accidental $= 1.1$)

IBD (BG subt) rate / MC (no osci) rate

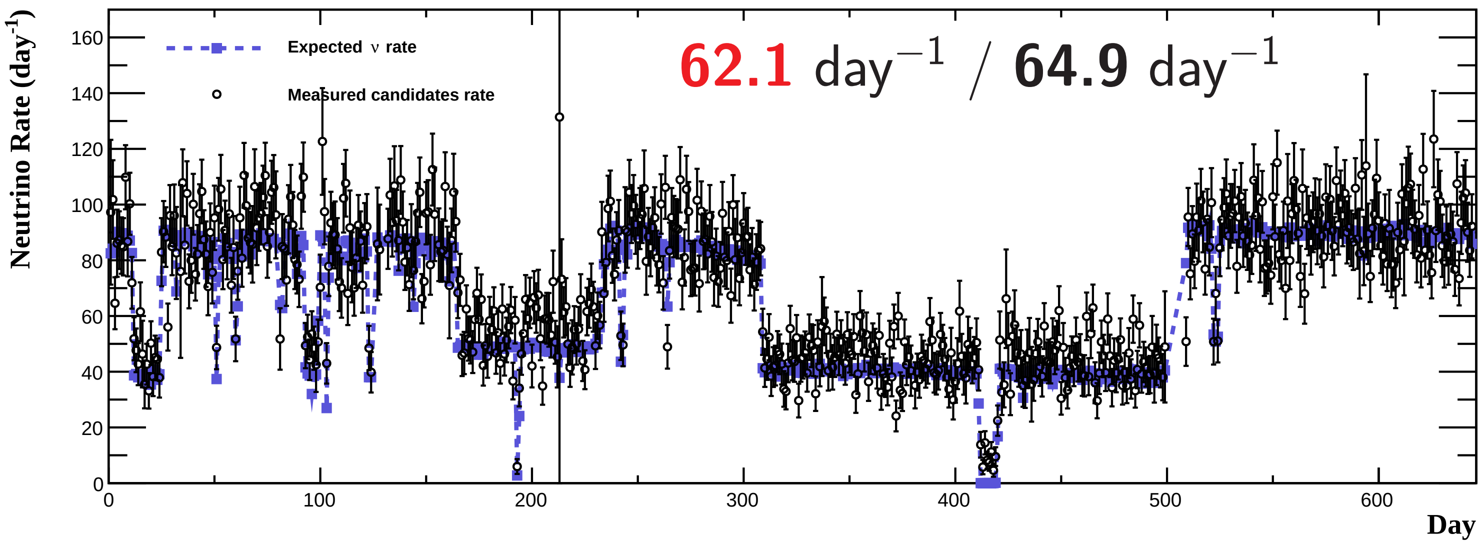


Gd-III JHEP 10(2014) 86

2 reactors on (∼ 60%)

1 reactor on (∼ 40%)

Both reactors off

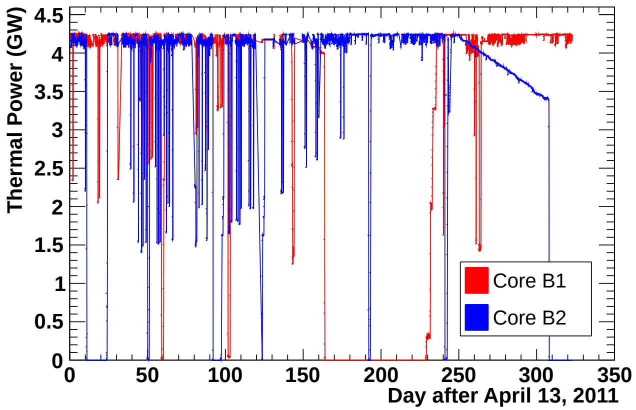


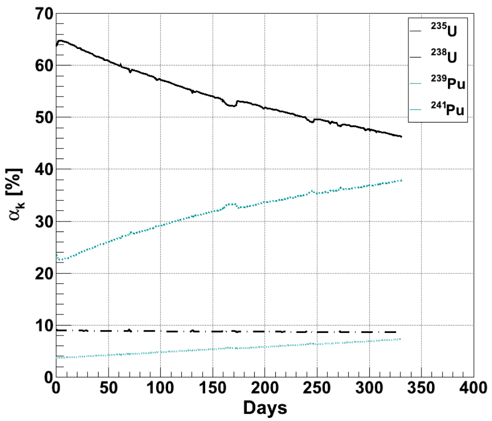
H-III (2015)

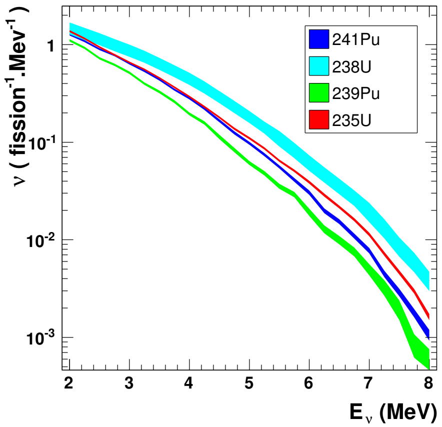
2 reactors on (∼ 60%)

1 reactor on (∼ 40%)

Reactor flux prediction







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

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

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

$$N_{\bar{\nu}}^{exp} = \frac{\epsilon N_p}{4\pi} \frac{1}{L^2} \frac{P_{th}(t)}{\langle E_f \rangle} \langle \sigma_f \rangle$$

$$\langle \sigma_f \rangle = \langle \sigma_f \rangle^{Bugey} + \sum_k \left(\alpha_k(t) - \alpha_k^{Bugey} \right) \langle \sigma_f \rangle_k$$

Flux uncertainty constrained w/ Bugey4 measurement 2.7% → 1.7%

In ND+FD analysis flux error mostly cancelled (due to isofluxness)

Uncertainties in fits

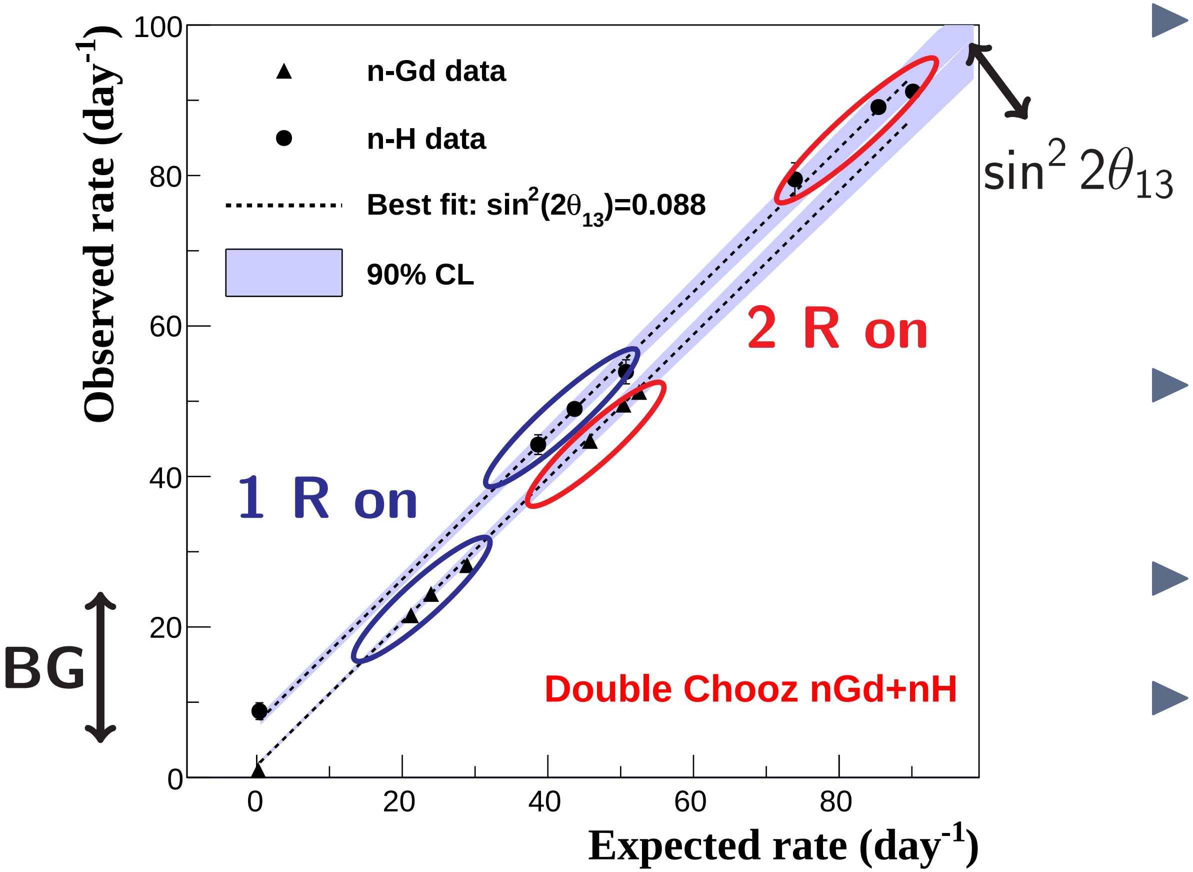
Normalization uncertainties:

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

Shape uncertainties, for Rate+Shape fit:

- Reactor spectrum
- Nonlinear energy scale
- Background spectra

Reactor Rate Modulation analysis:

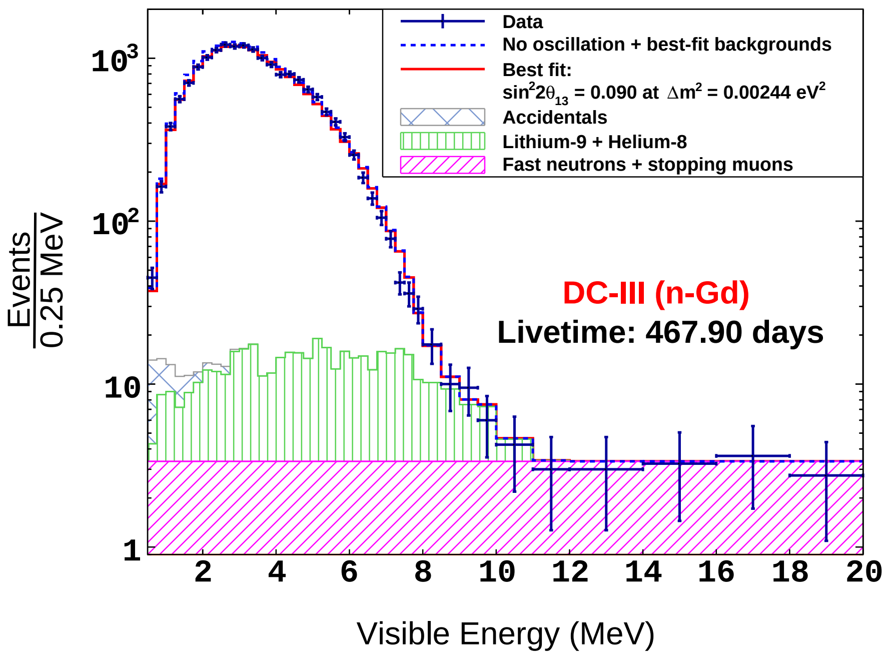


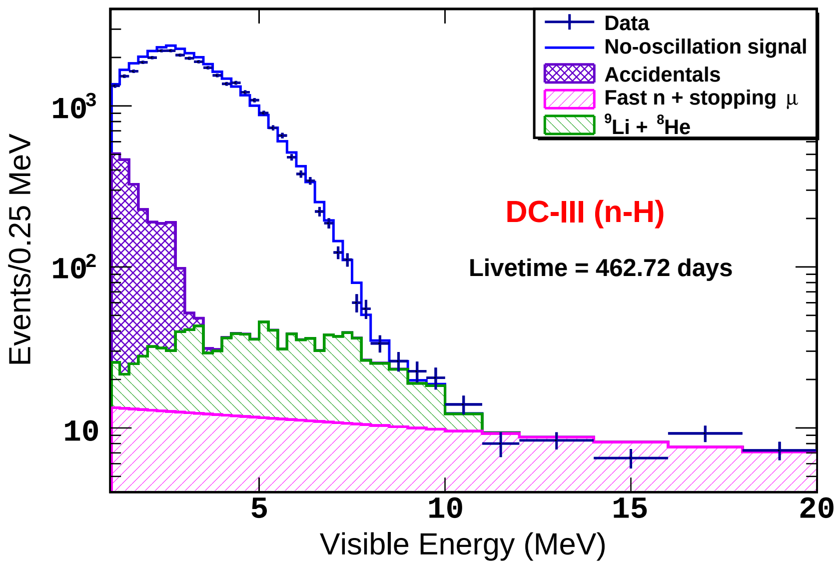
- Compares observed and expected IBD rates at different reactor powers, fitting for $\sin^2 2\theta_{13}$ and total background rate, B
- Independent of reactor spectrum shape model
- Leverage from unique reactor-off data
- Optional use of background model

$$\sin^2 \mathbf{2\theta_{13} = 0.088 \pm 0.033}$$

H only: $\sin^2 2\theta_{13} = 0.095^{+0.038}_{-0.039}$, Gd only: $\sin^2 2\theta_{13} = 0.090^{+0.034}_{-0.035}$

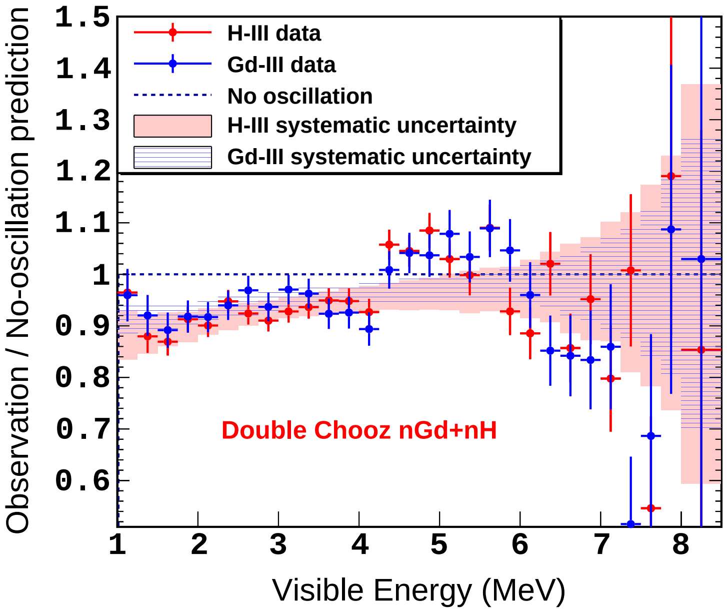
Rate+Shape fit

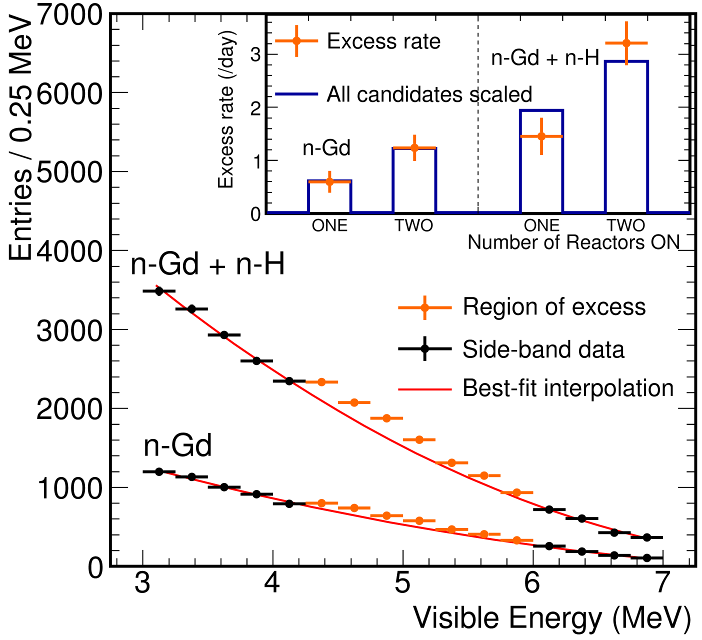




- Uses prompt energy spectrum, with single reactor power bin
- Able to constrain backgrounds → better $\sin^2 2\theta_{13}$ precision
- n-H: $\sin^2 2\theta_{13} = 0.124^{+0.030}_{-0.039}$
- n-Gd: $\sin^2 2\theta_{13} = 0.090^{+0.032}_{-0.029}$

Reactor spectrum features

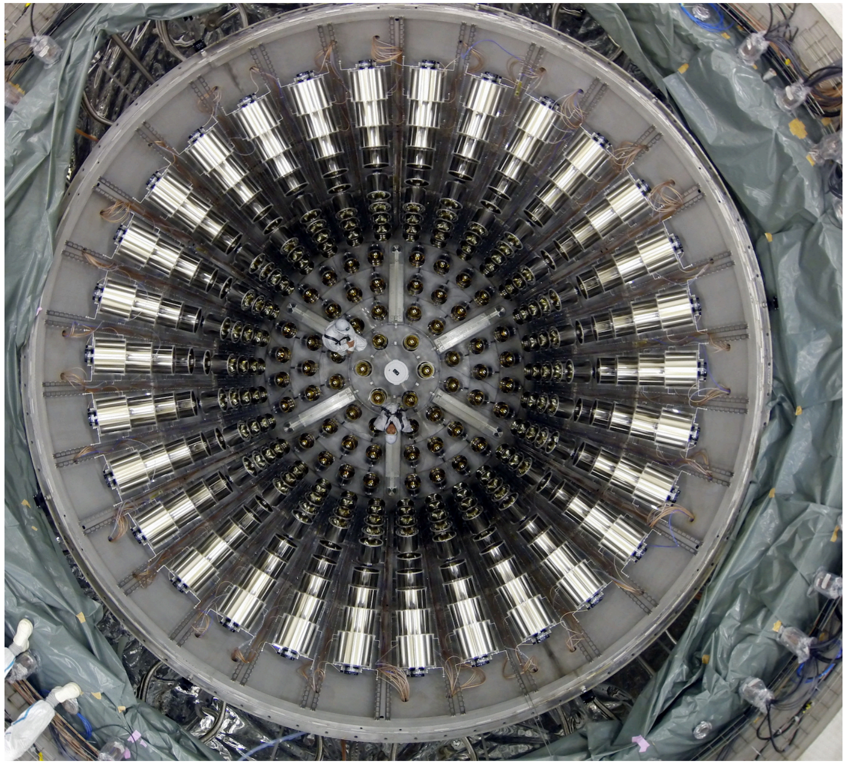


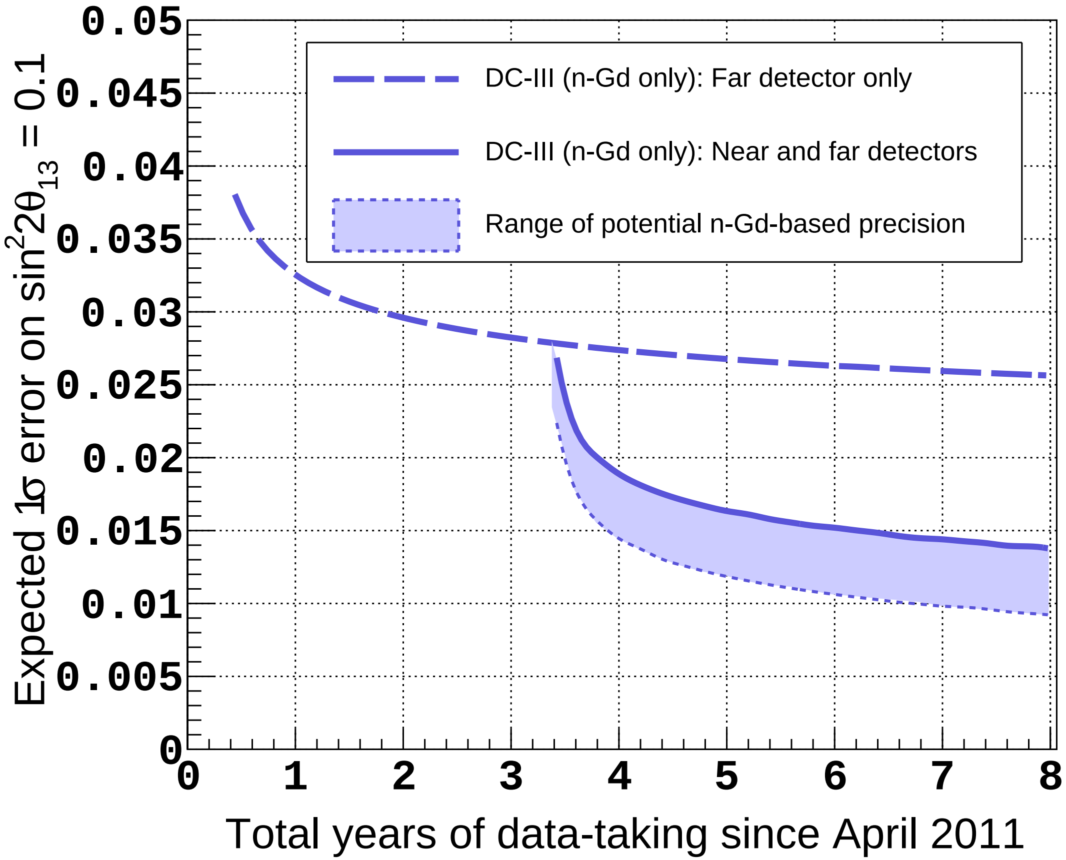


- Double Chooz reported prompt spectrum distortion in 4-6 MeV region
  - confirmed by RENO and Daya Bay
  - Excess also measured w/ independent nH sample
- Excess confirmed to be correlated w/ reactor power
  - strong indication it is due to reactor flux modelling
- Ongoing investigations in the community

Future precision, including near detector

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





Already taken more than 12 months of ND+FD data

Expect 10% **precision on** $\sin^2 2\theta_{13}$ **in 3 years of ND+FD datataking.**

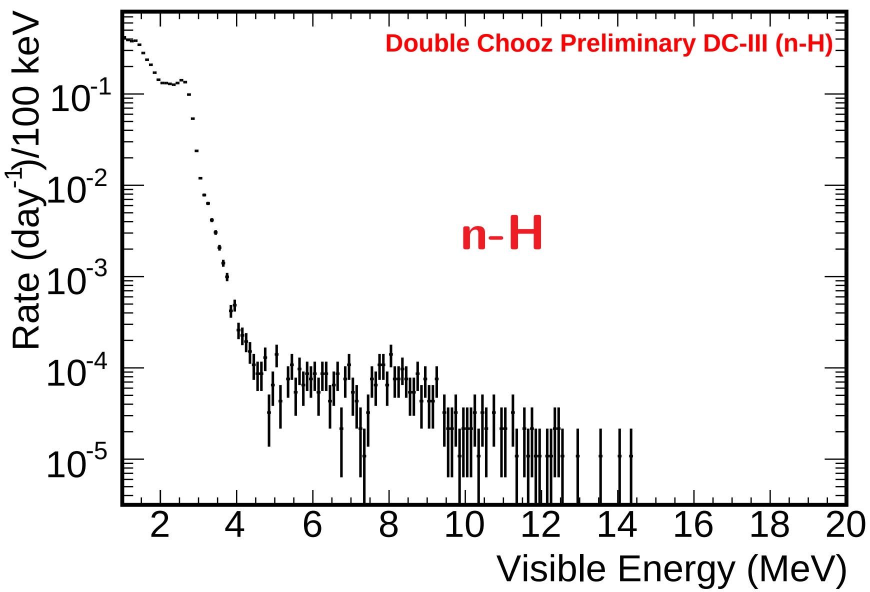
Conclusions and outlook

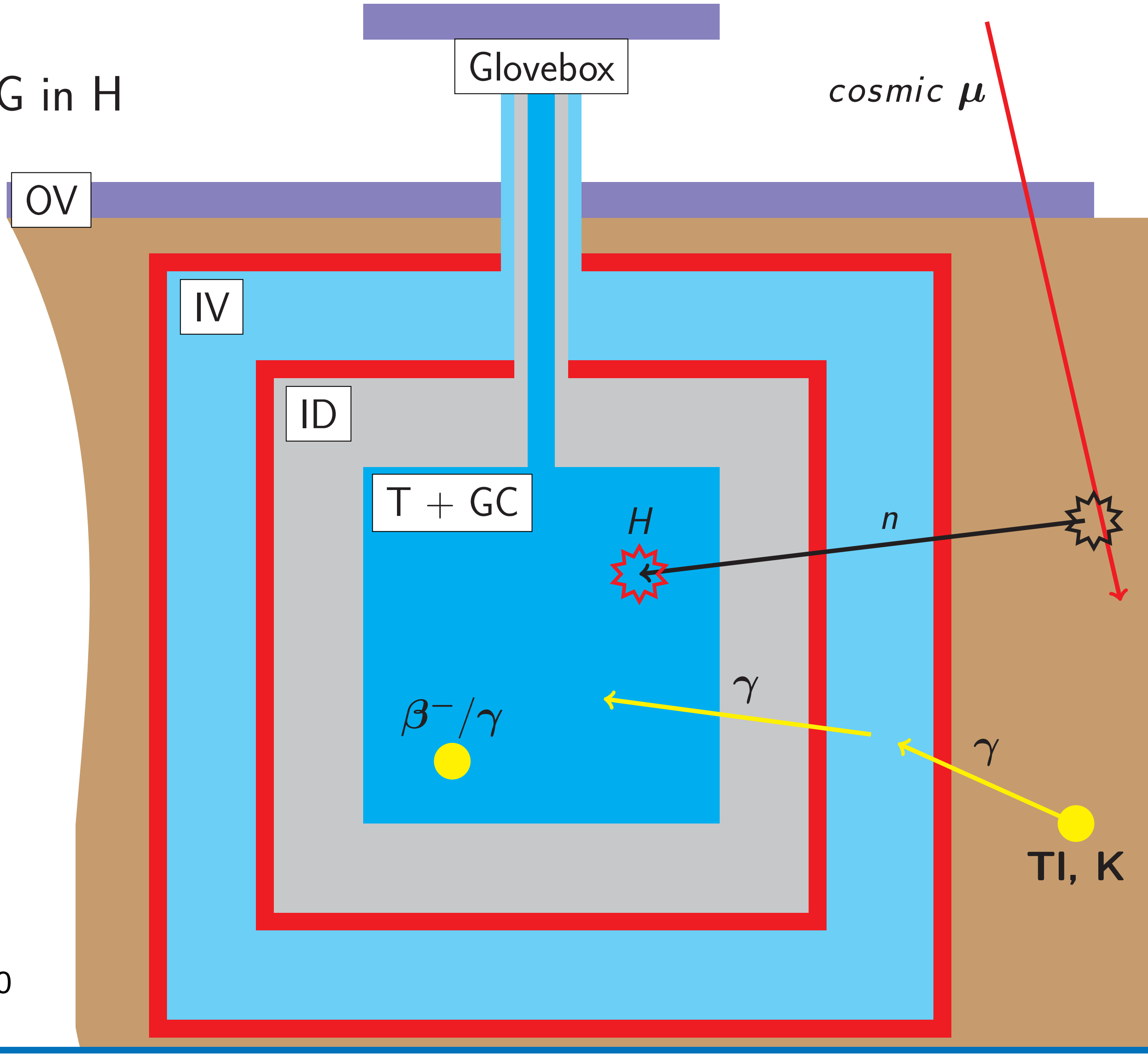
- High precisions physics:
  - Combined Gd+H (RRM): $\sin^2 2\theta_{13} = 0.090 \pm 0.033$
  - Rate+ Shape results:
    - Gd-III (2014): $\sin^2 2\theta_{13} = 0.90^{+0.032}_{-0.029}$
    - H-III (2015): $\sin^2 2\theta_{13} = 0.124^{+0.030}_{-0.039}$
  - Double Chooz reported prompt spectrum distortion around $[4, 6]$ MeV
    - distortion confirmed by RENO & Daya Bay
    - cross-checked w/ independent n-H sample
- Near detector operating
  - Already taken 12 months of data
  - Working now on a two-detector $\sin^2 2\theta_{13}$ analysis
  - Expect 10% precision after three years of running ND+FD

Backup

Accidental Background

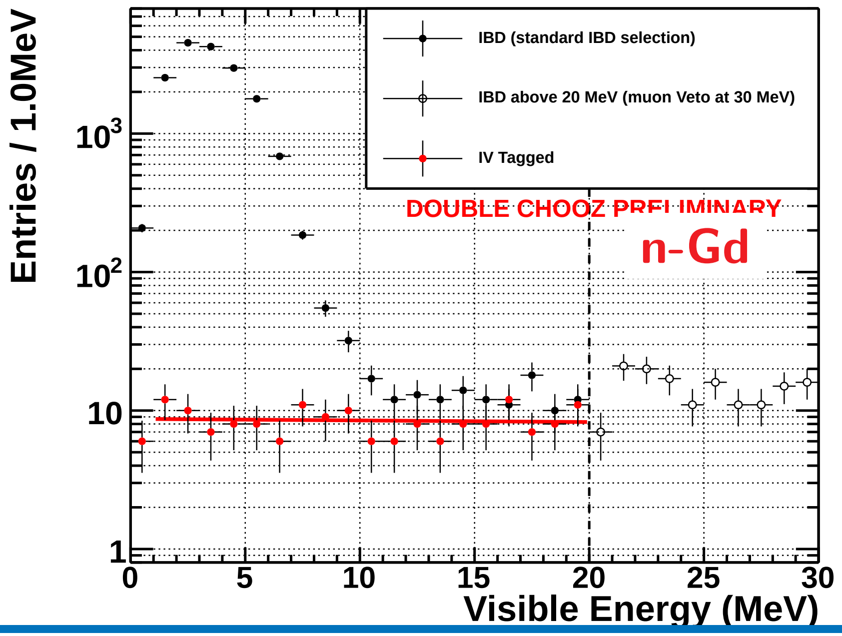
- Almost negligible in Gd, main BG in H
- By radioactivity and cosmogenic
- **Rejection**:
  - Space & time relations, delayed energy
  - Inner Veto (compton γ)

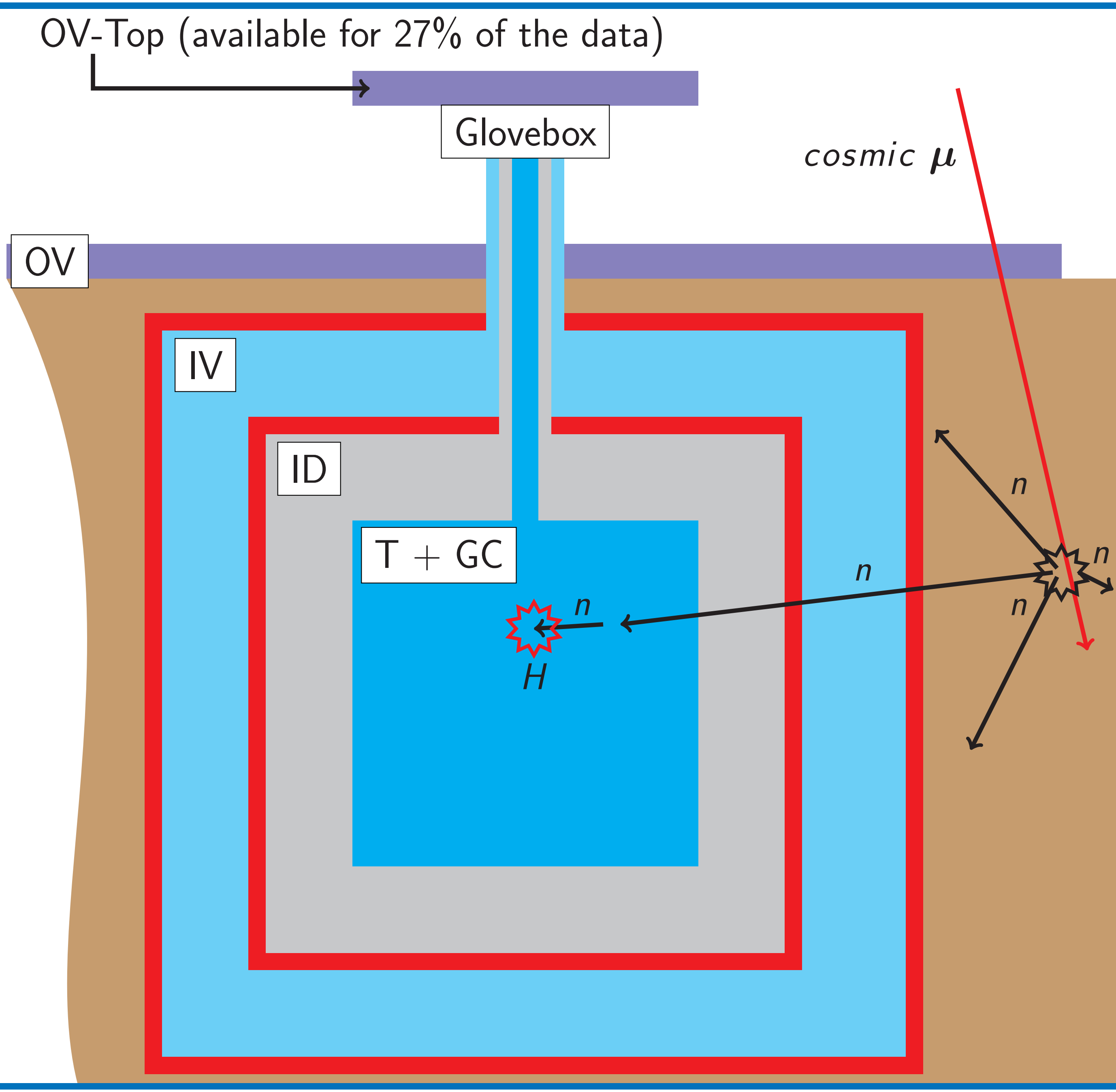




Fast Neutron Background

- By cosmic μ spallations in rock
- **Rejection**:
  - Tag with IV and OV
  - Tag with FADC waveform

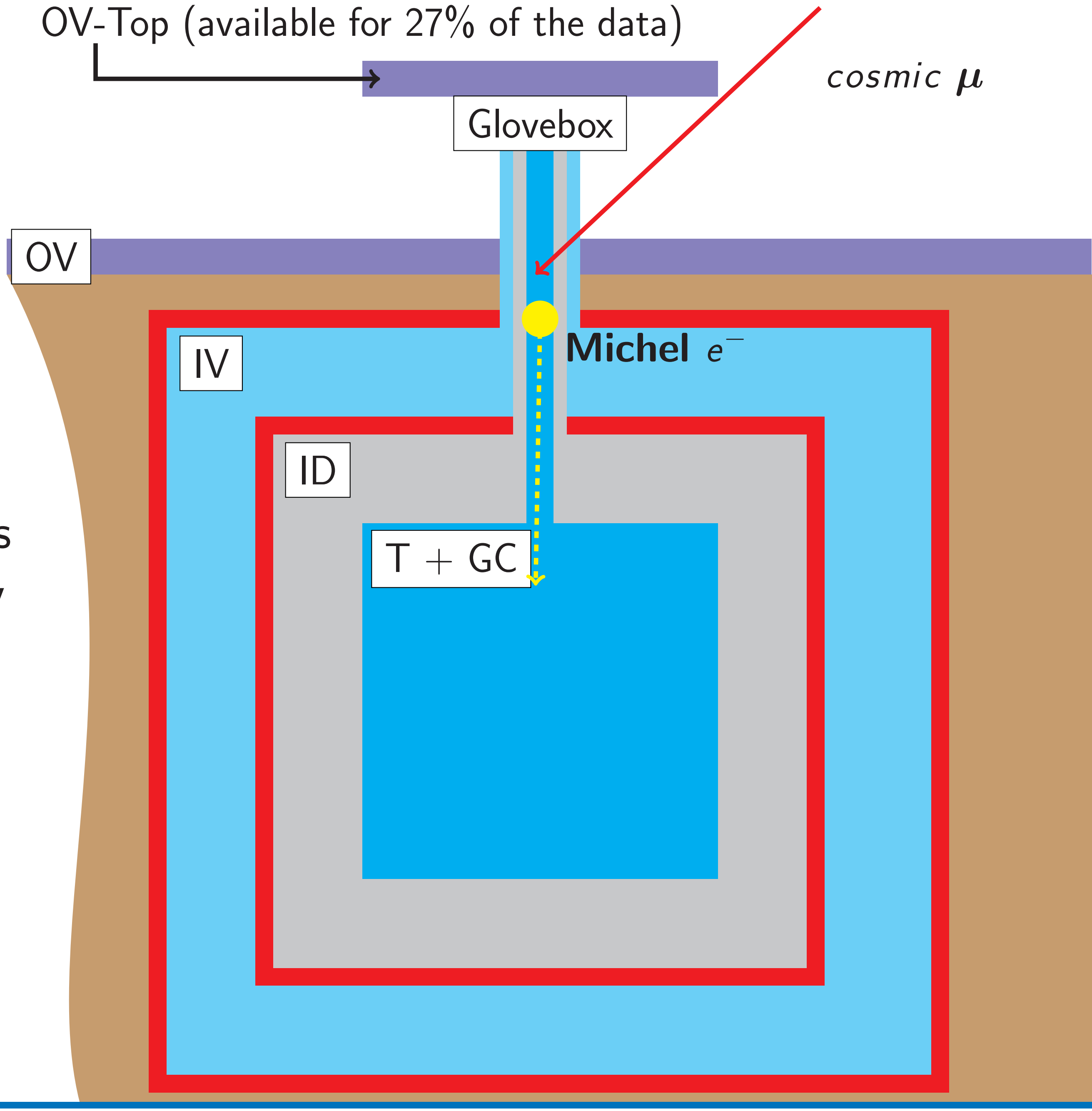




Backgrounds in Double Chooz

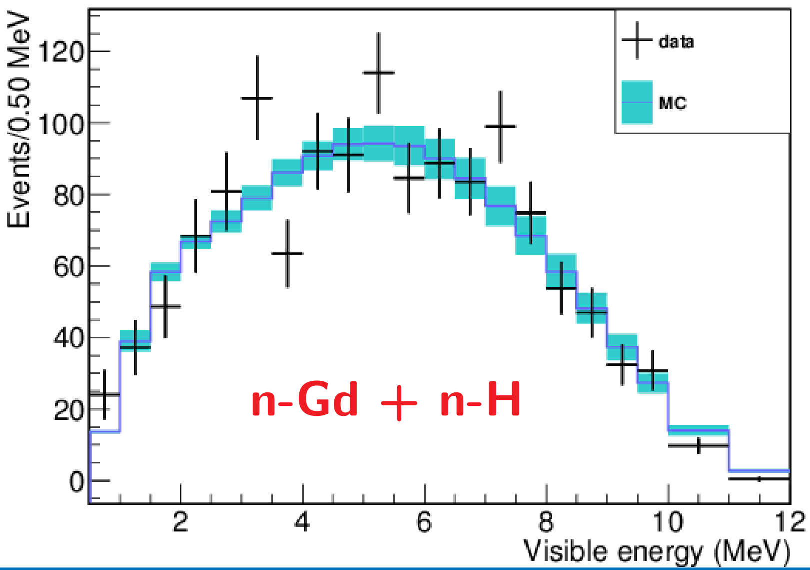
Stopped-μ Background

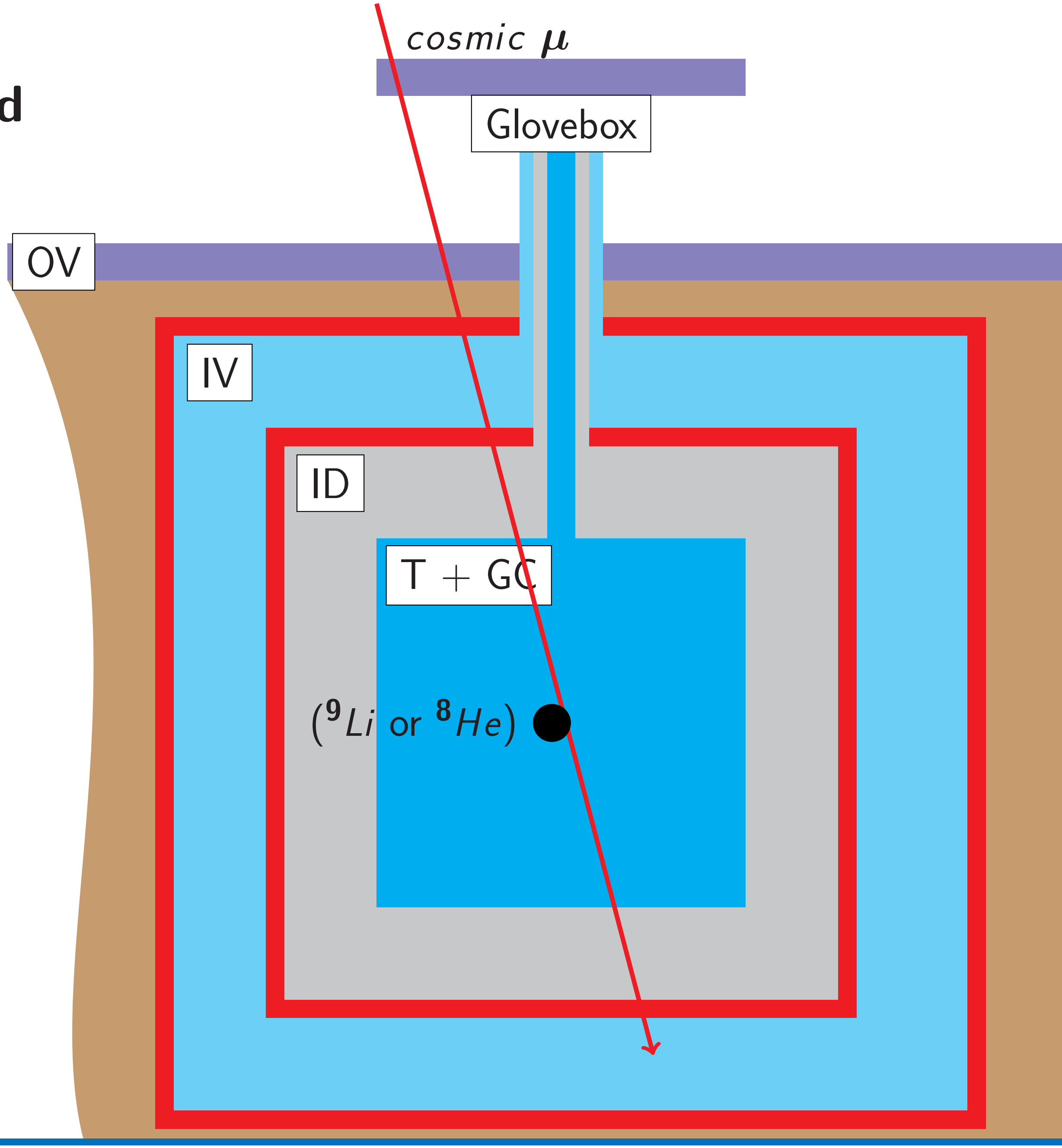
- By cosmic μ decays within detector
- Acceptance hole in chimney
  - Not-vetoed μ
- Michel e^-: Non-point like events due to reflections inside chimney
- **Rejection**:
  - Tag with IV and OV
  - Tag non-pointlike events using position reconstruction
  - Tag with FADC waveform



Cosmogenic nuclei Background

- By cosmic μ spallations producing ^{12}Be, ^{9}Li & ^{8}He
- Decay: $\beta - n$ (mimics IBD signal)
- **Rejection**:
  - Trace the progenitor μ and use time and space correlations



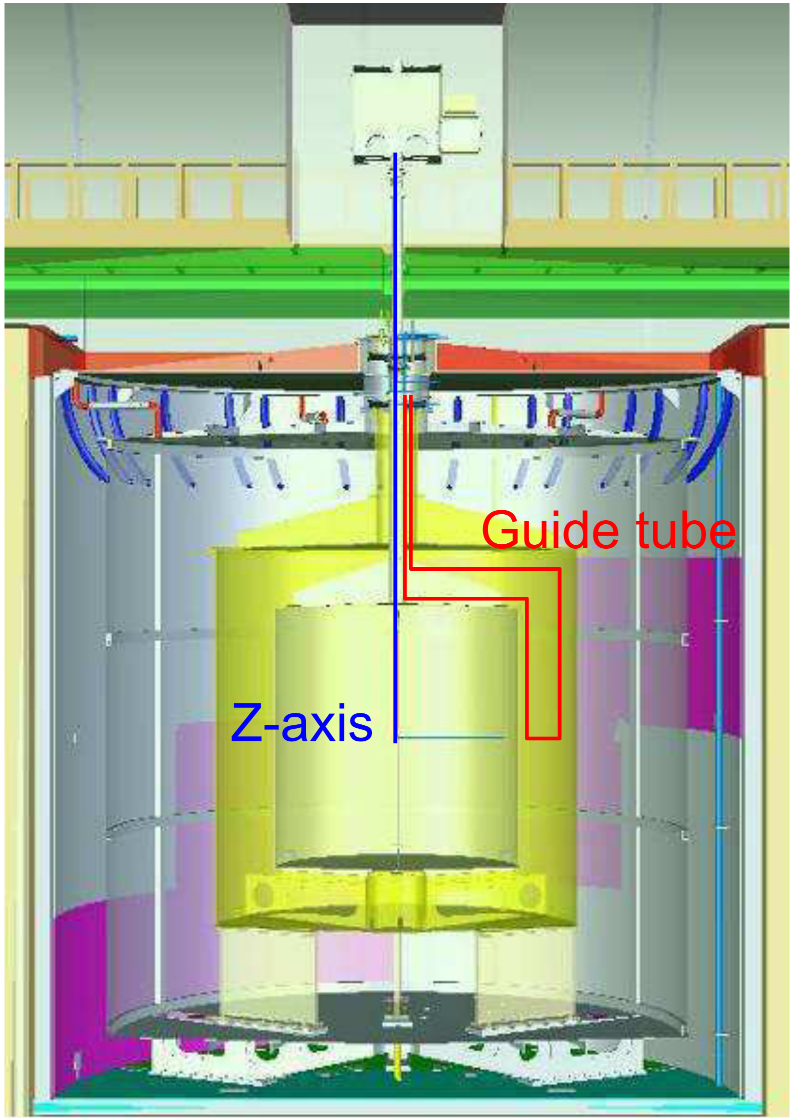


Detector calibration

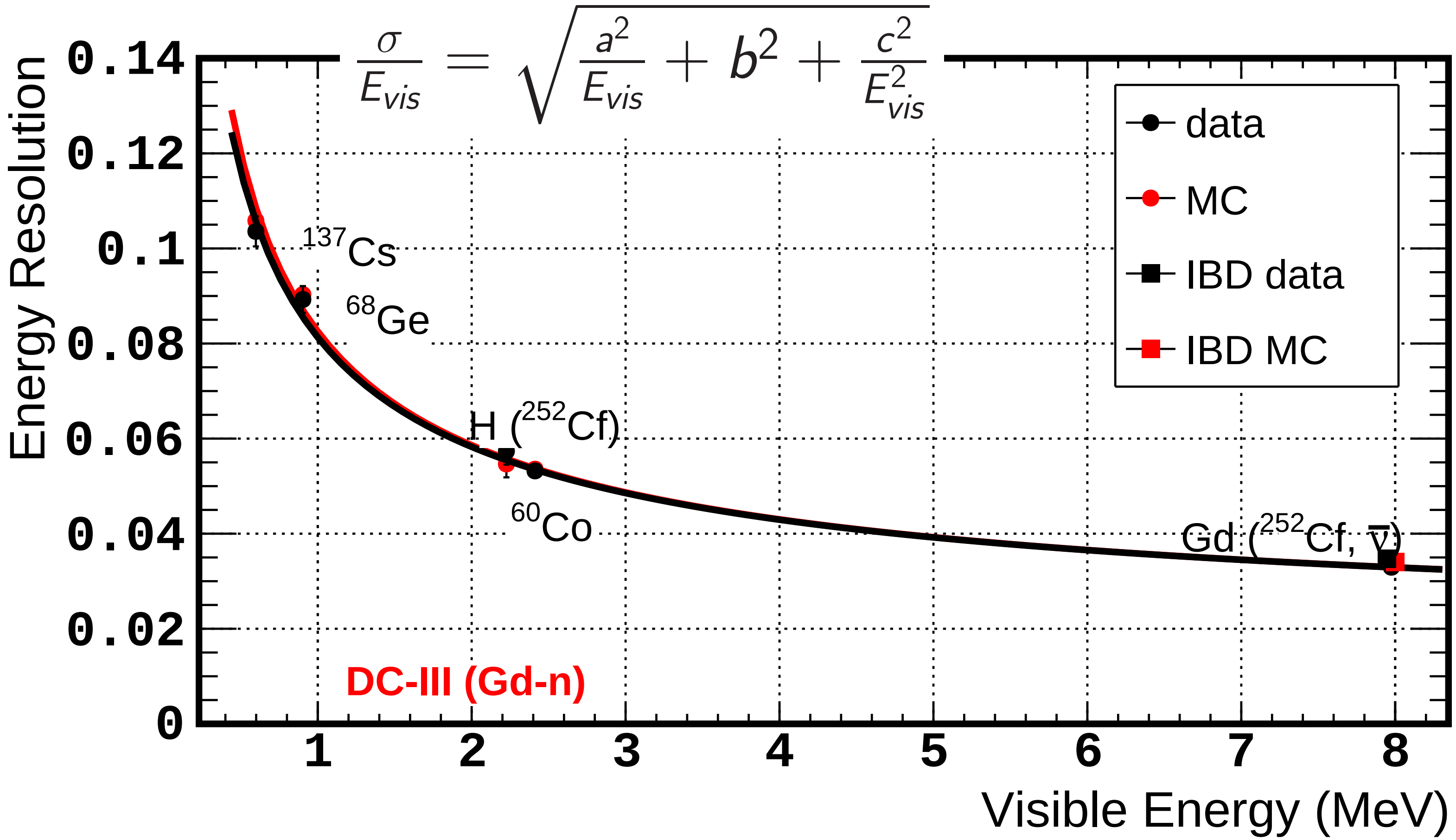
- LED light injection
  - gain & timing calibration
- Source deployment systems
  - Target & Gamma catcher
  - radioactive sources
    - γ (^{60}Co, ^{137}Cs, ^{68}Ge)
    - neutron (^{252}Cf)
  - laser diffuser ball

limited by design

- Natural radioactivity
  - spallation n captures on Gd, H, C
  - α's from ^{210}Po decays



Energy reconstruction



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

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

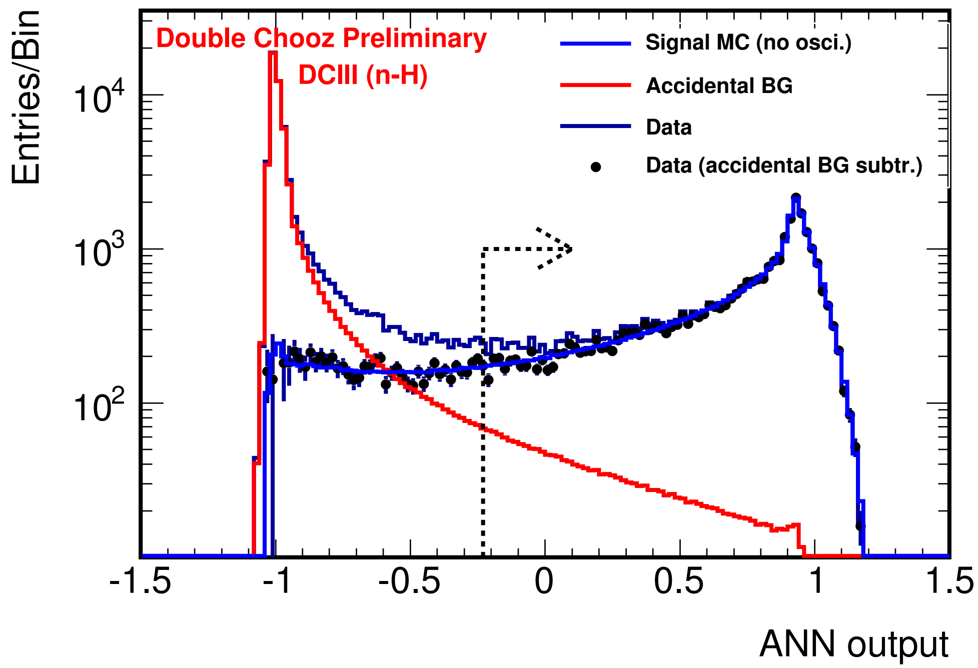
Very good agreement data to MC over whole energy range

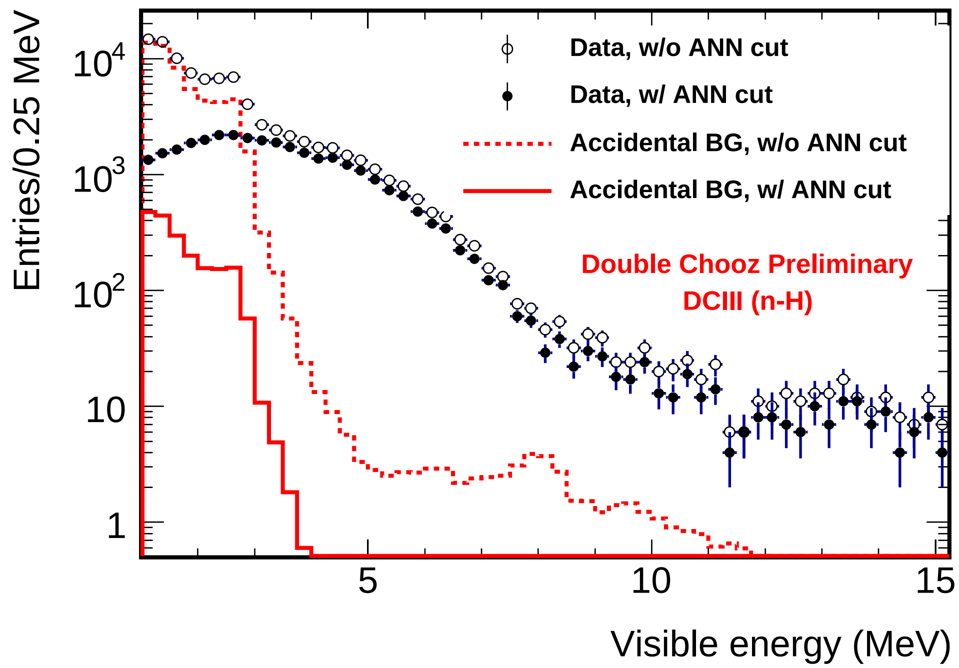
Constant term of resolution b $\sim$ 0.018

Signal selection

H-III: use ANN-based multivariate tool trained with correlation time, correlation distance and delayed energy as input

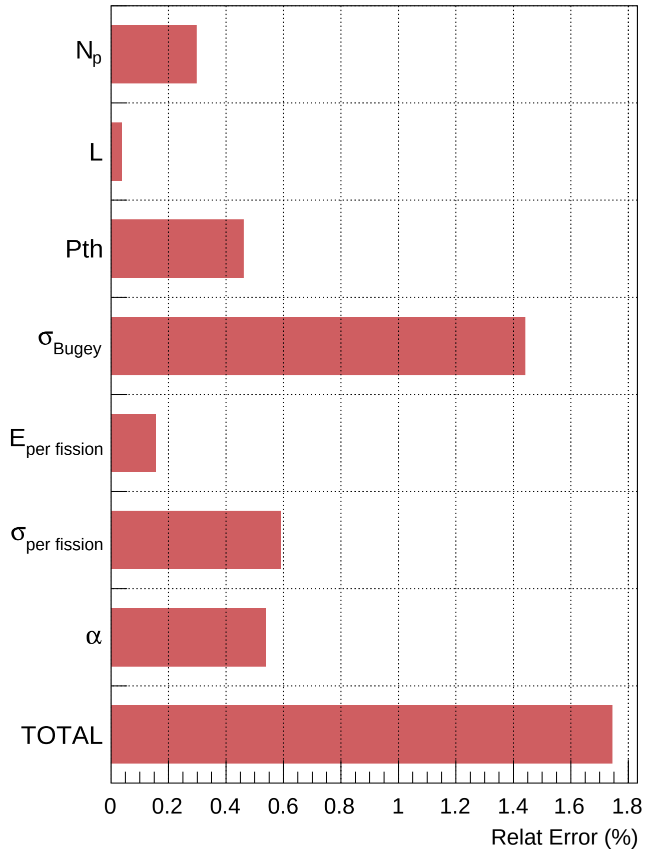
very good agreement data to MC



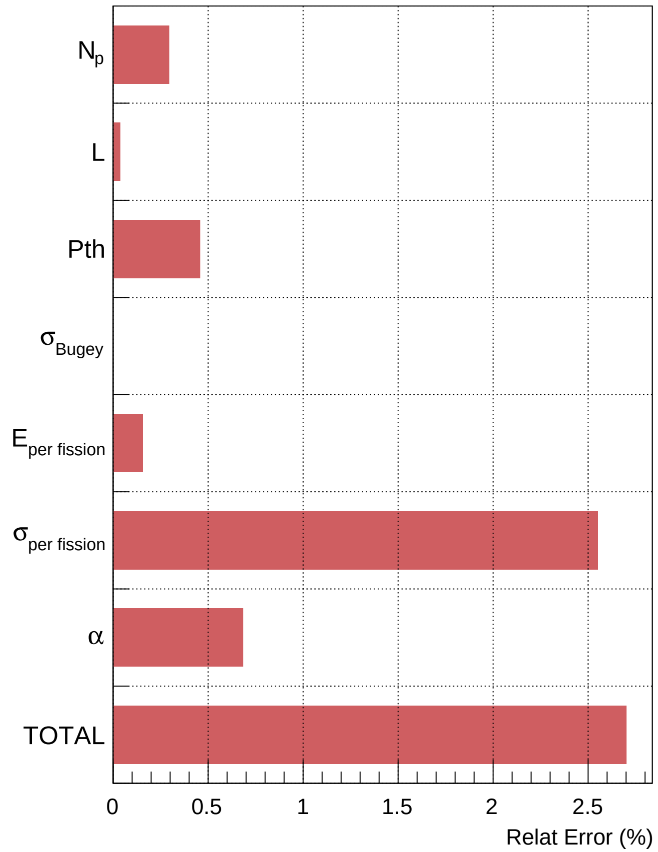


Signal to BG ratio improved by factor $> 7\times$ w.r.t. H-II

Flux Systematics



With Bugey4 (1.7%)



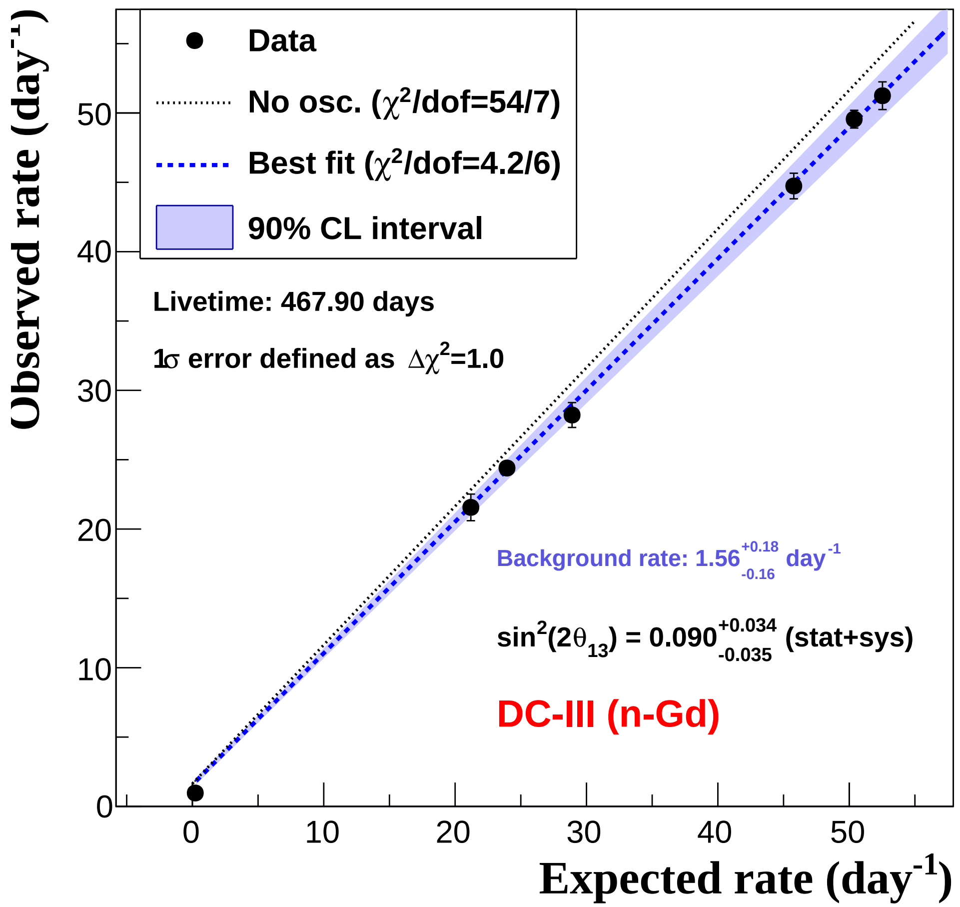
Without Bugey4 (2.7%)

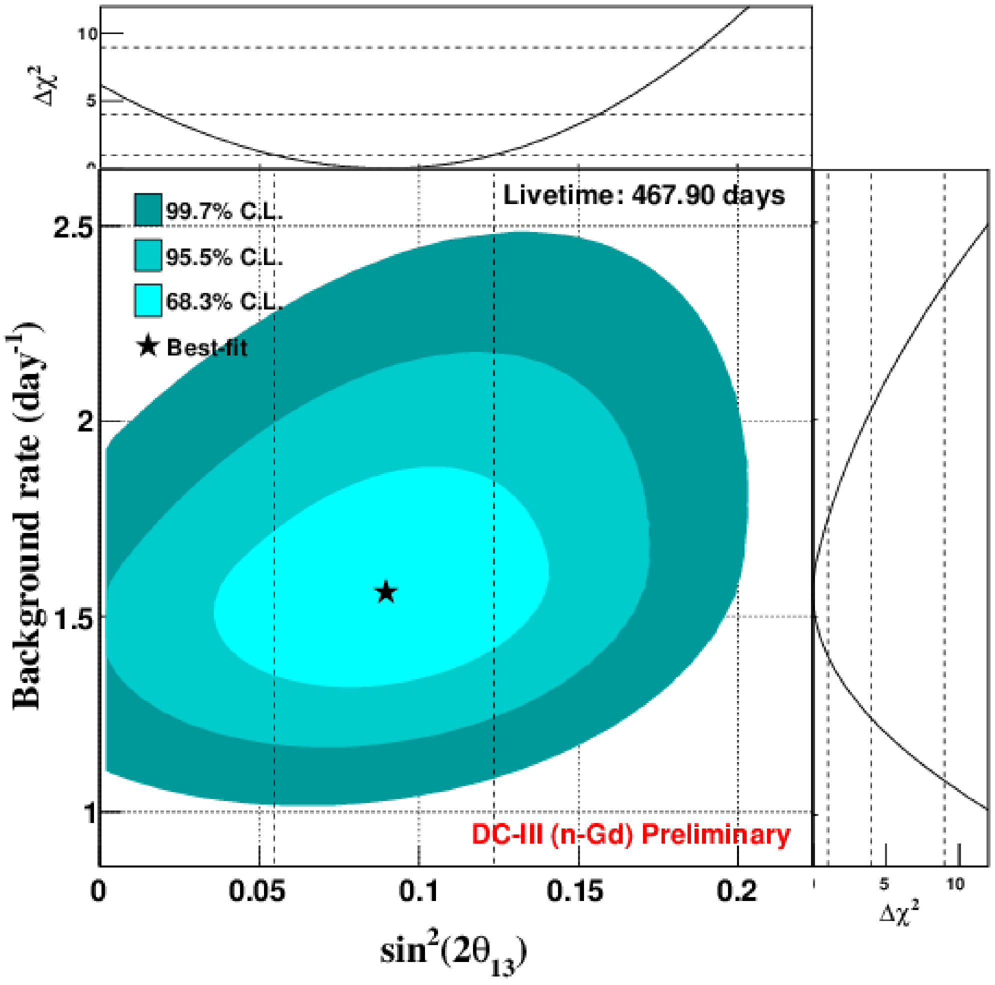
DC used Bugey4 as effective ND (via MC)

Leads to a flux error of 1.7% ($\sim$ 30% reduction)

RRM: n-Gd, with background model

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

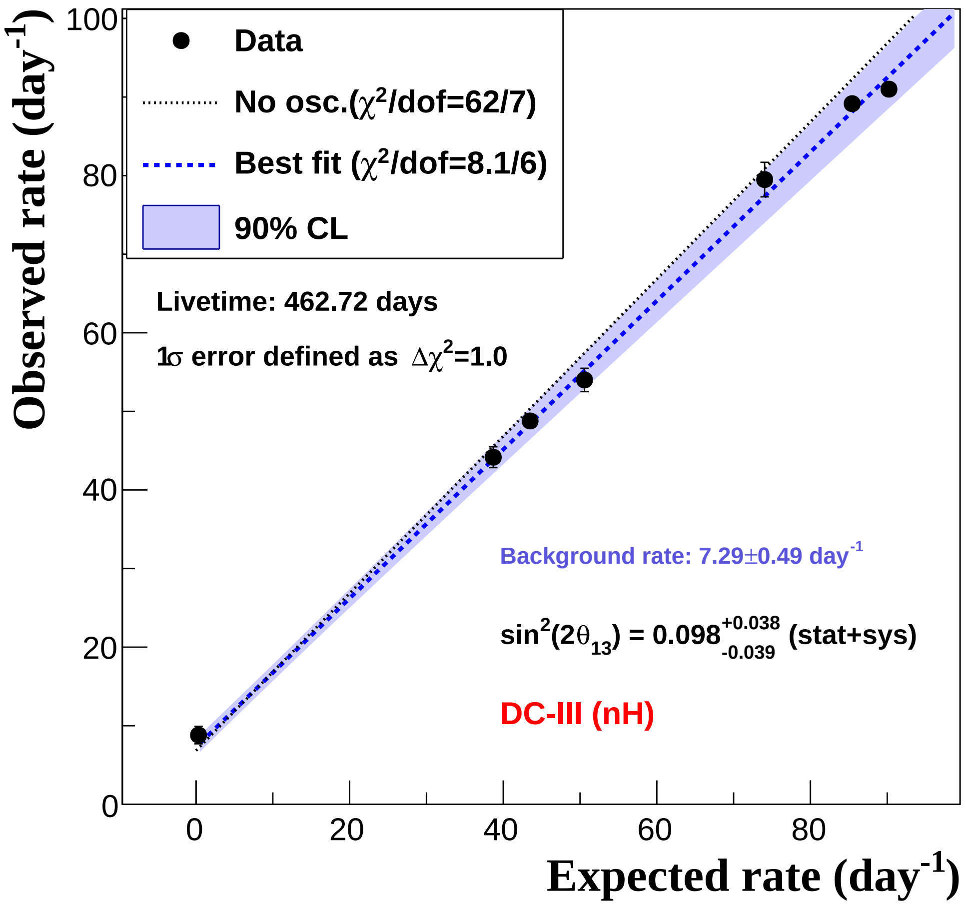


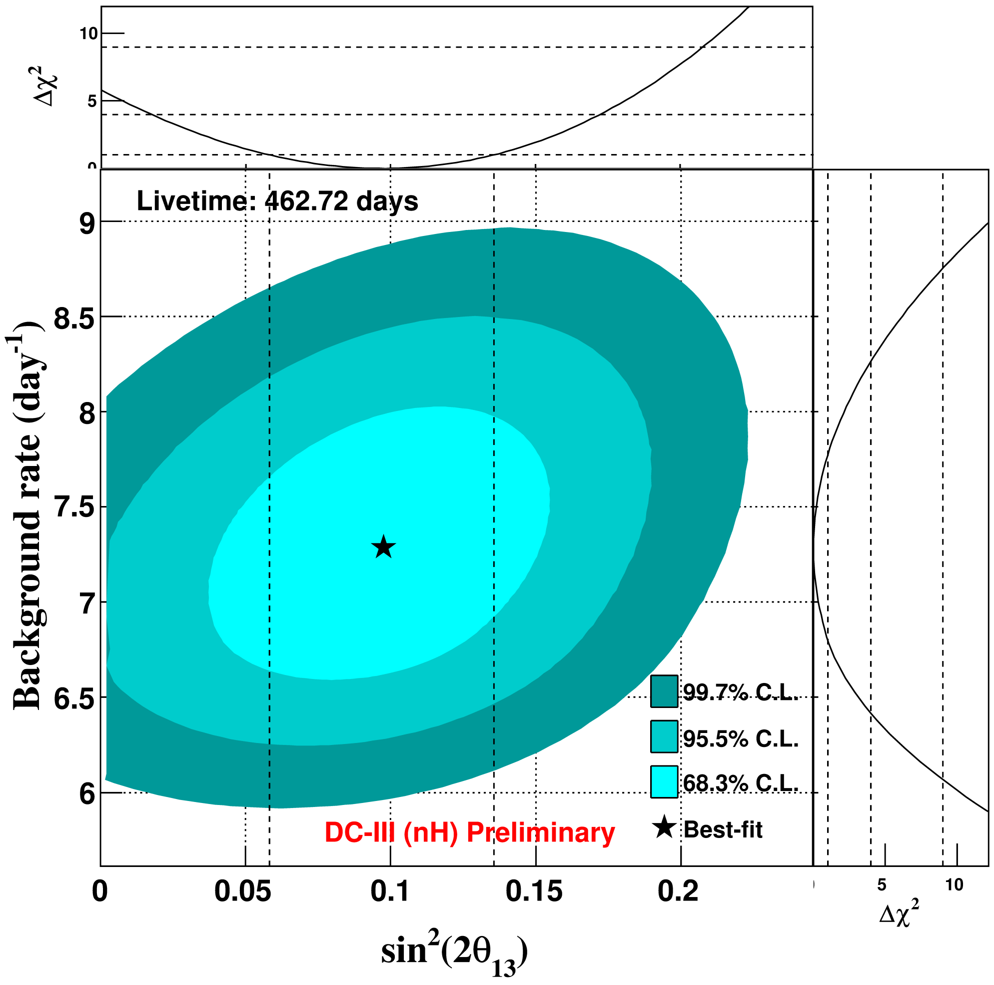


$$\sin^2 2\theta_{13} = 0.090^{+0.034}_{-0.035}$$

RRM: n-H, with background model

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





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