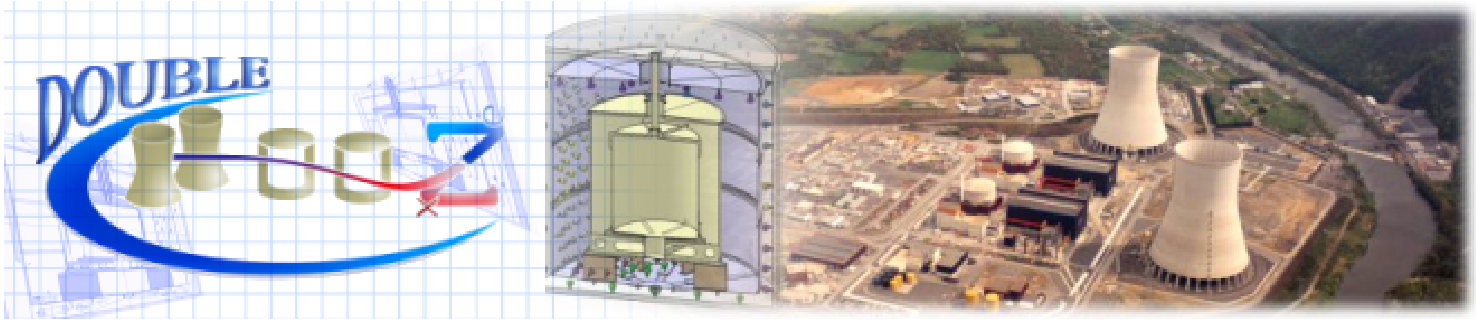


Last results from Double Chooz

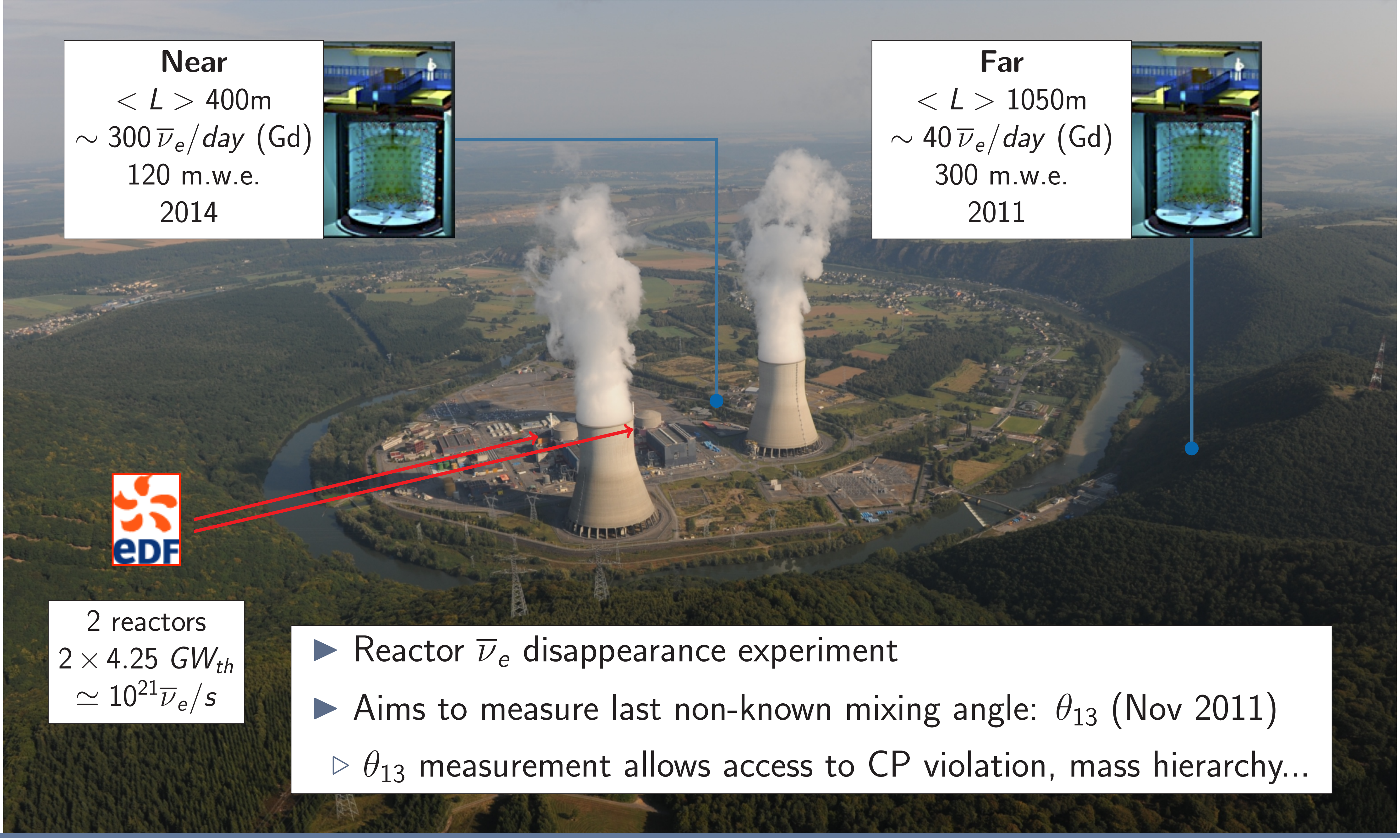
Guillaume Pronost

on behalf of the Double Chooz collaboration

NuFact 2015

The Double Chooz experiment

The Double Chooz experiment



Near
$< L >$ 400m
$\sim 300\,\overline{\nu}_e/day$ (Gd)
120 m.w.e.
2014

Far
$< L >$ 1050m
$\sim 40\,\overline{\nu}_e/day$ (Gd)
300 m.w.e.
2011

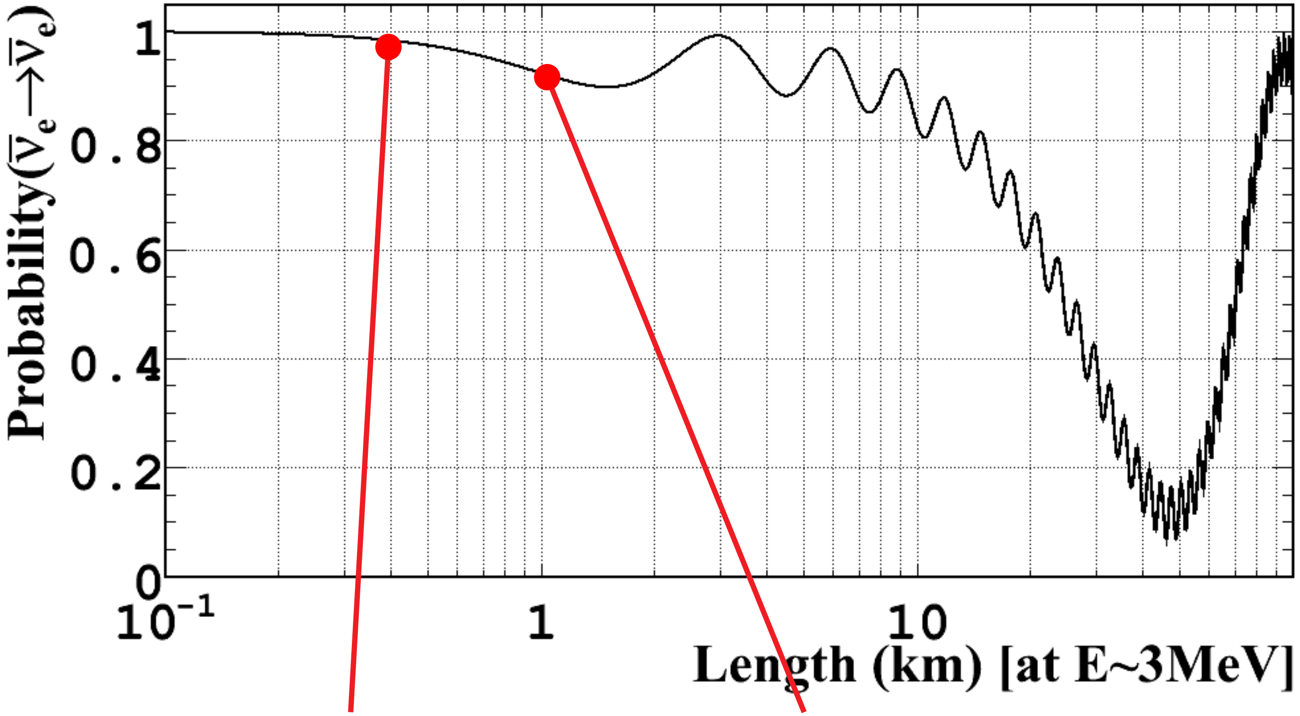
2 reactors
$2 \times 4.25\ GW_{th}$
$\simeq 10^{21}\overline{\nu}_e/s$

- Reactor $\overline{\nu}_e$ disappearance experiment
- Aims to measure last non-known mixing angle: θ_{13} (Nov 2011)
  - θ_{13} measurement allows access to CP violation, mass hierarchy...

A disappearance experiment

Survival probability:

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



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

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

reduce systematic uncertainties

Near Detector

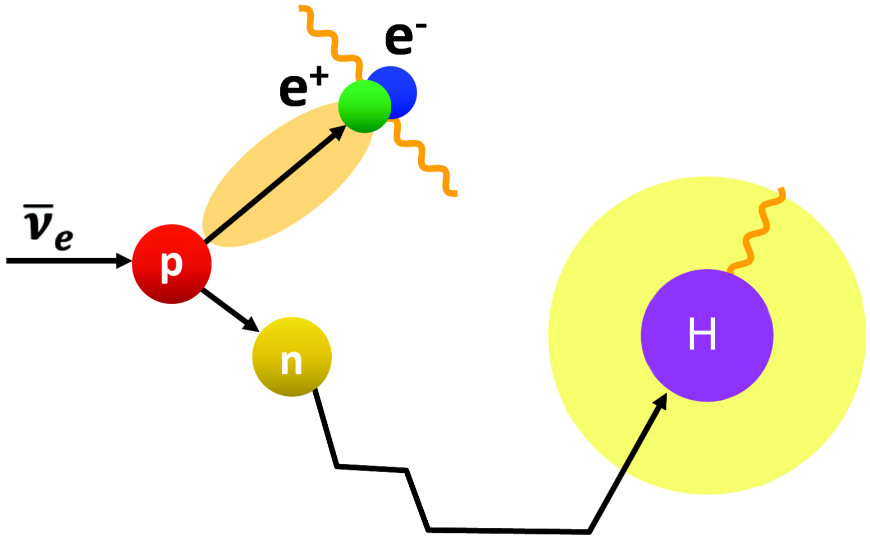
Far Detector

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

determine θ_{13}

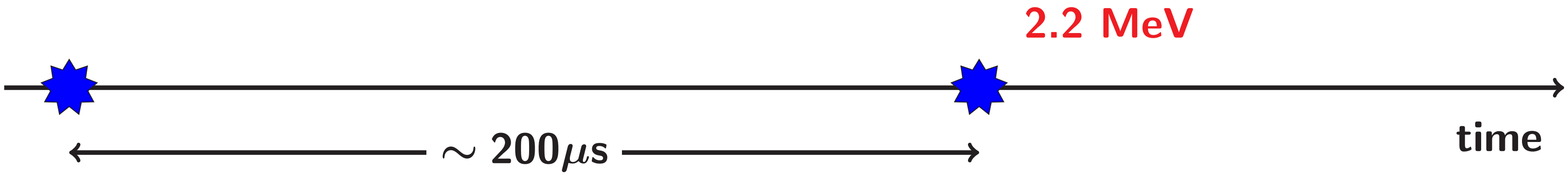
Neutrino detection

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

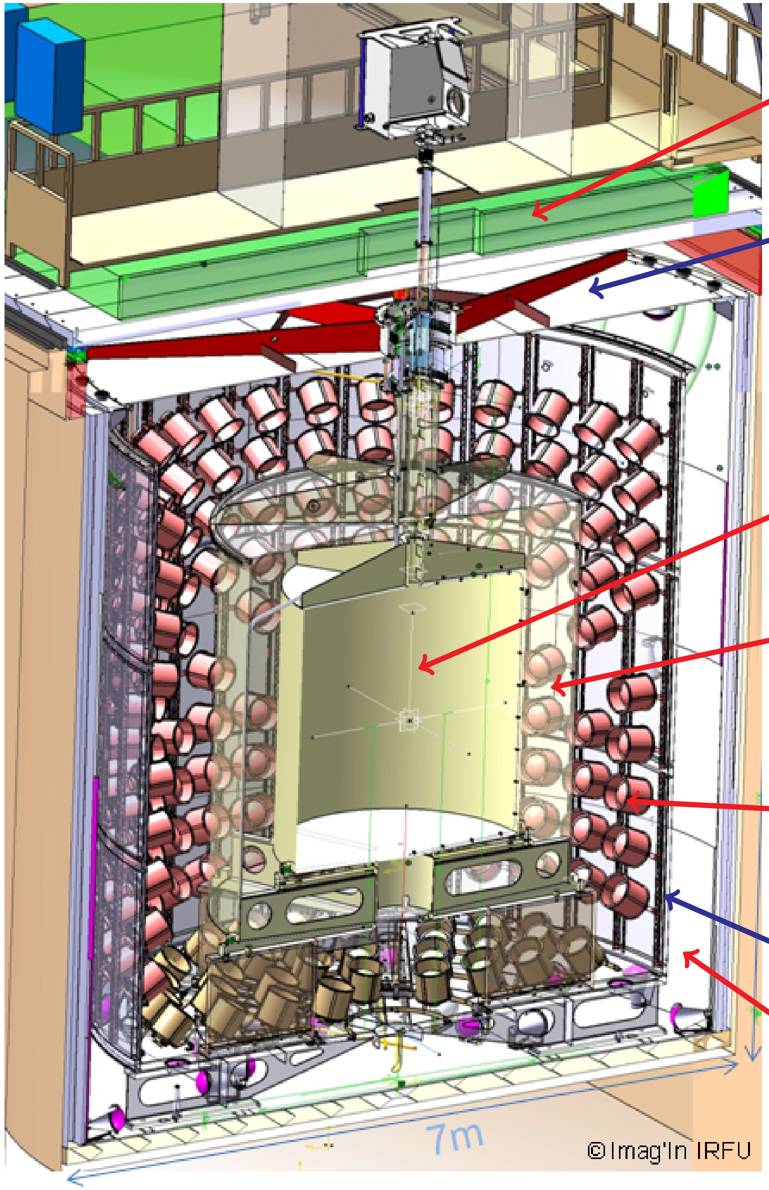


Gd channel

H channel



The Double Chooz detectors



Outer Veto (**OV**) : Plastic Scintillator 5 cm wide strips

Cosmic μ detection

Steel shield (15cm width)

Inner Detector (**ID**)

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

IBD sensitive region (Gd-n)

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

Escaping γ measurement (Gd-n)
IBD sensitive region (H-n)

Buffer : 110 m^3 Mineral Oil & 390 Photomultiplier

PMTs radioactivity shielding.

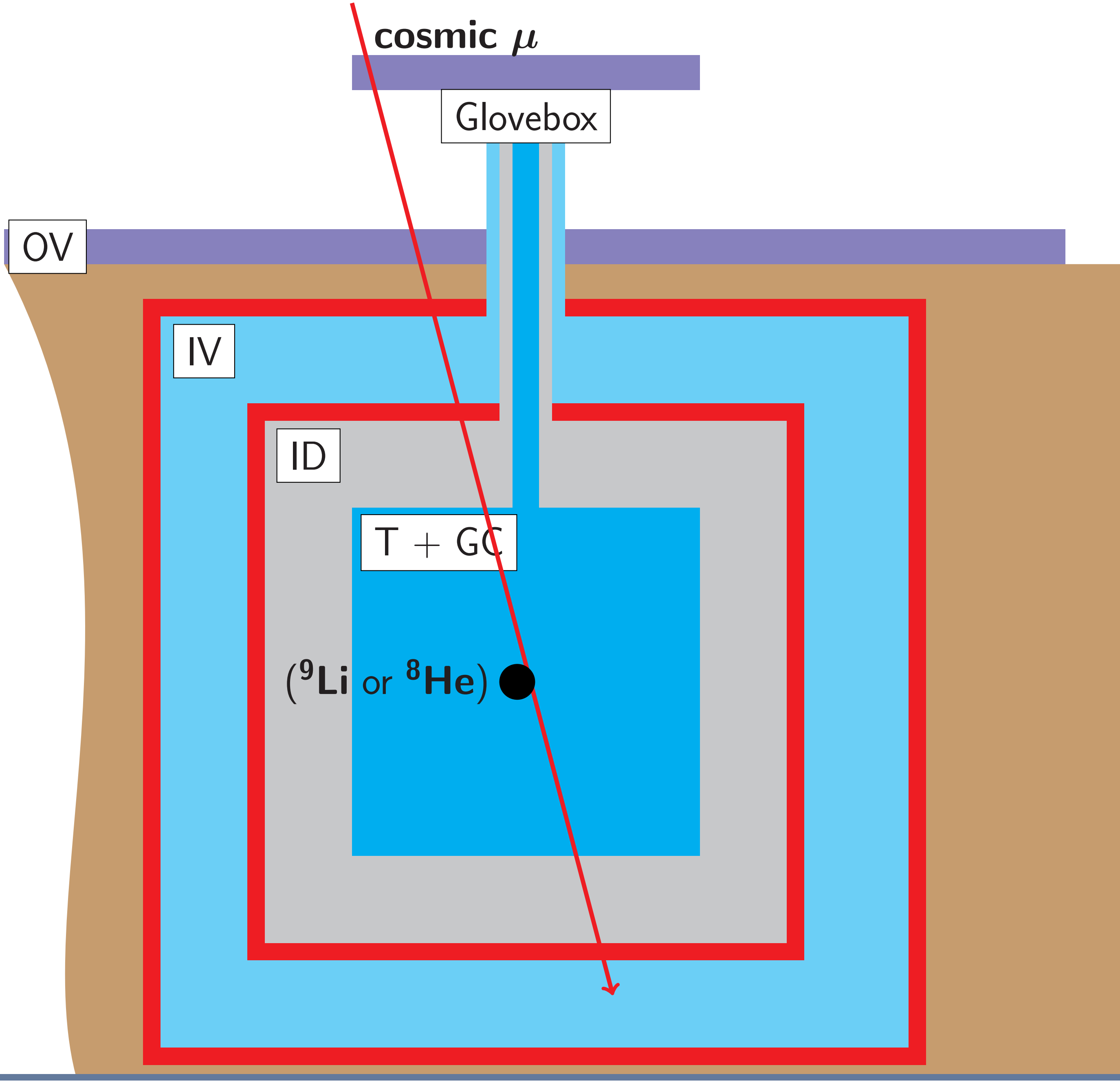
Steel tank (3mm width)

Inner Veto (**IV**) : 90 m^3 Liquid Scintillator & 78 PMTs

Cosmic μ, fast neutrons and rock γ's detection

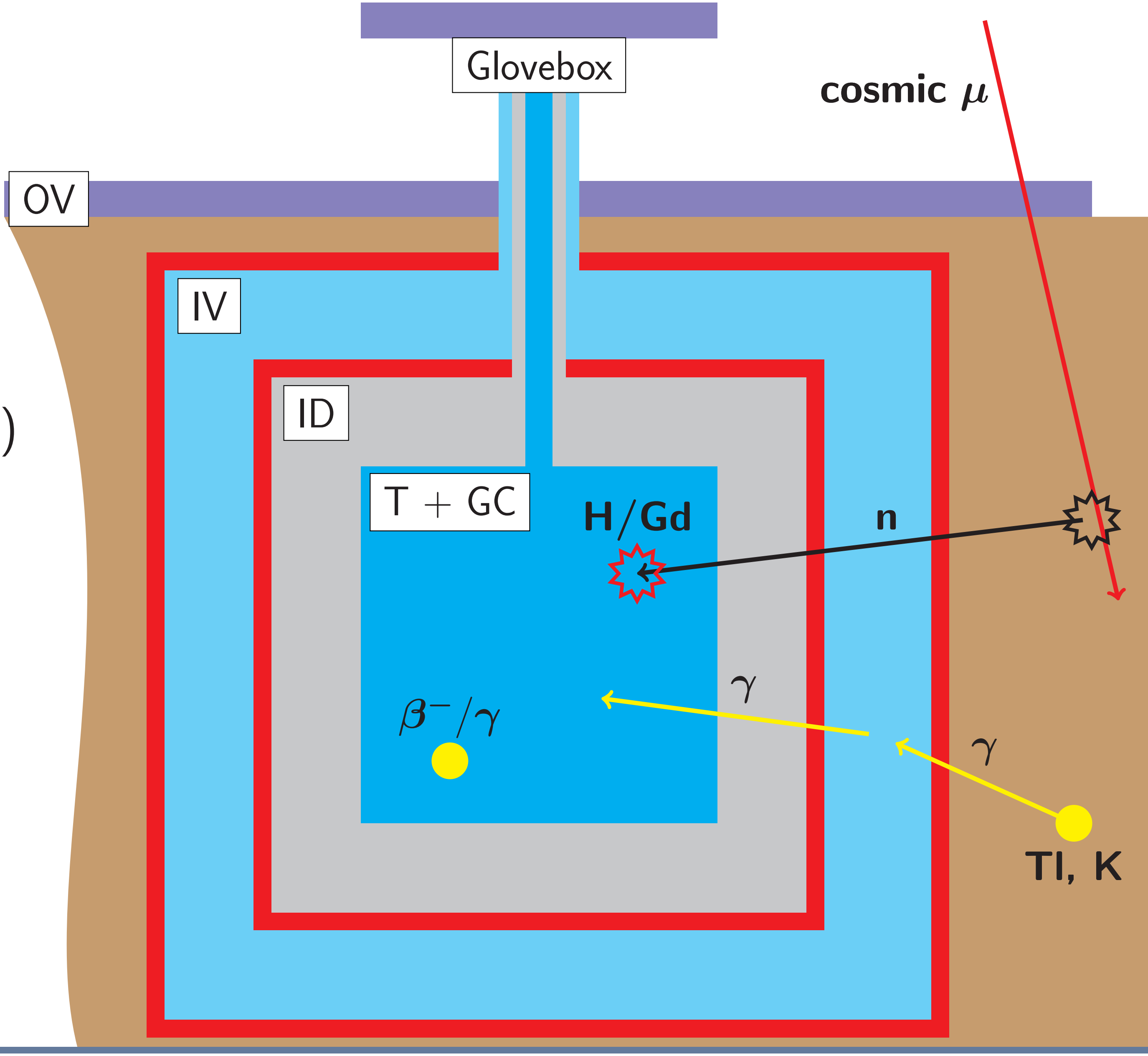
Backgrounds in Double Chooz

- **Cosmogenic nuclei BG**
  - Long lifetime β-n emitters
    Mainly ${}^{9}Li$ and ${}^{8}He$
  - Most dangerous BG for DC



Backgrounds in Double Chooz

- **Cosmogenic nuclei BG**
  - Long lifetime β-n emitters
    Mainly ^{9}Li and ^{8}He
  - Most dangerous BG for DC
- **Accidental BG**
  - Natural radioactivity (^{40}K,^{208}Tl)
  - Main BG in H-n



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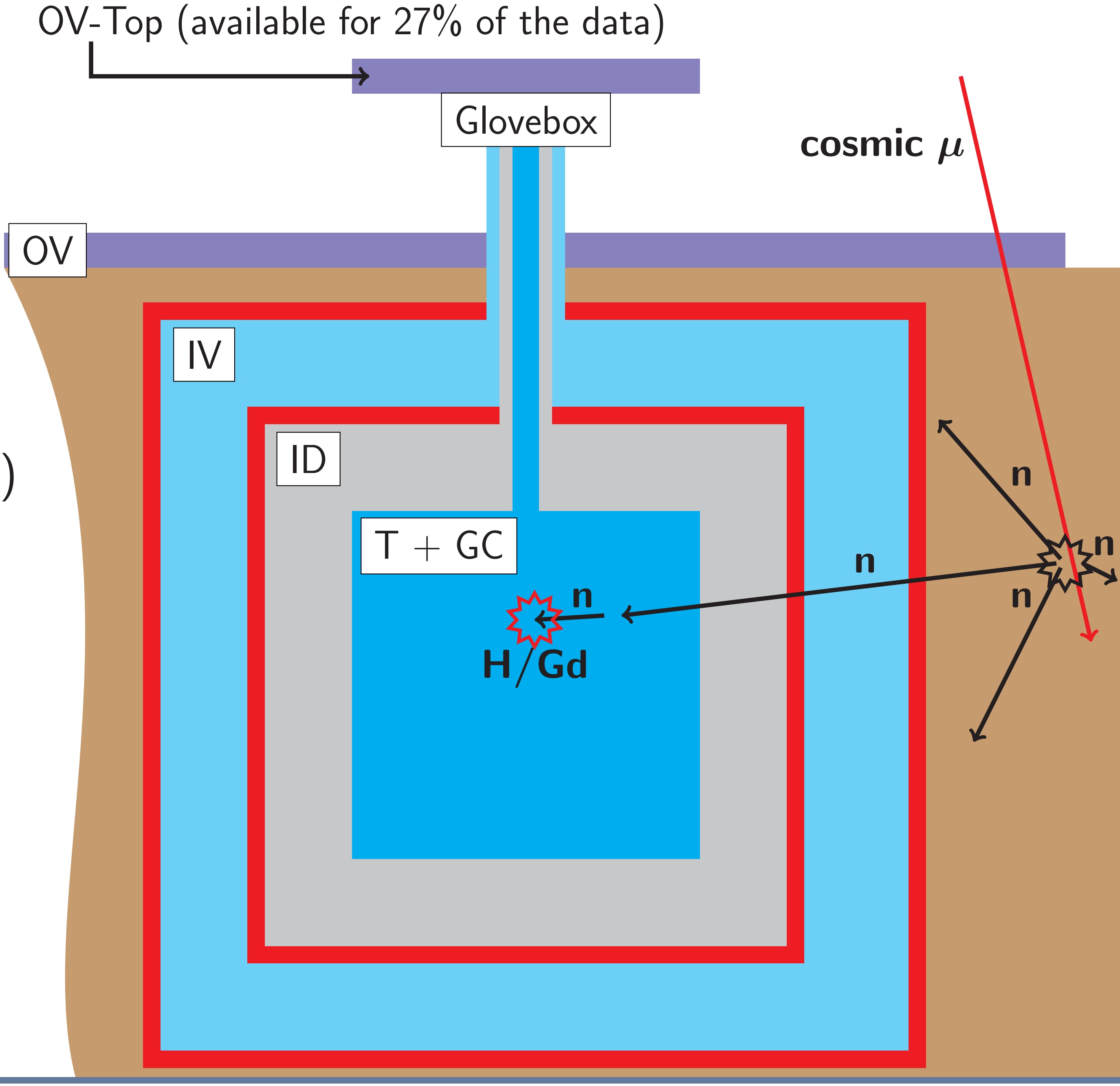
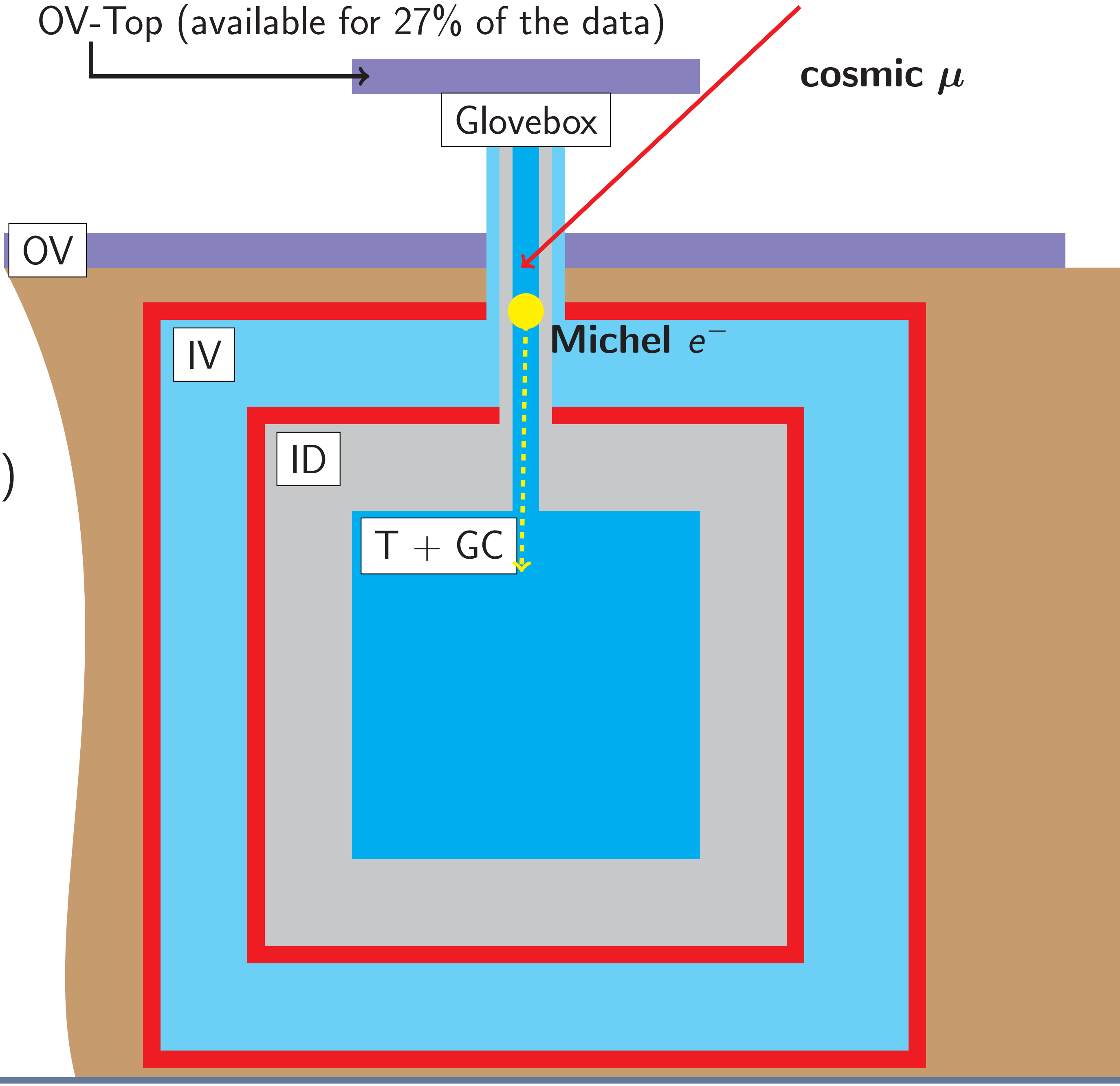
- **Fast Neutron BG**
  - From muon spallations in rocks



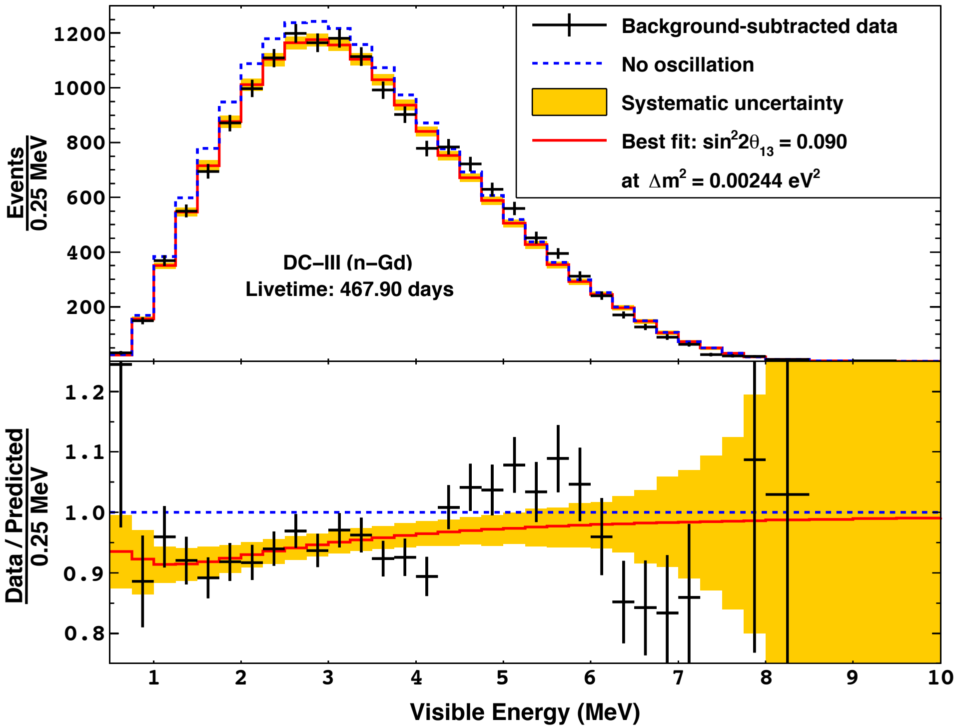
Backgrounds in Double Chooz

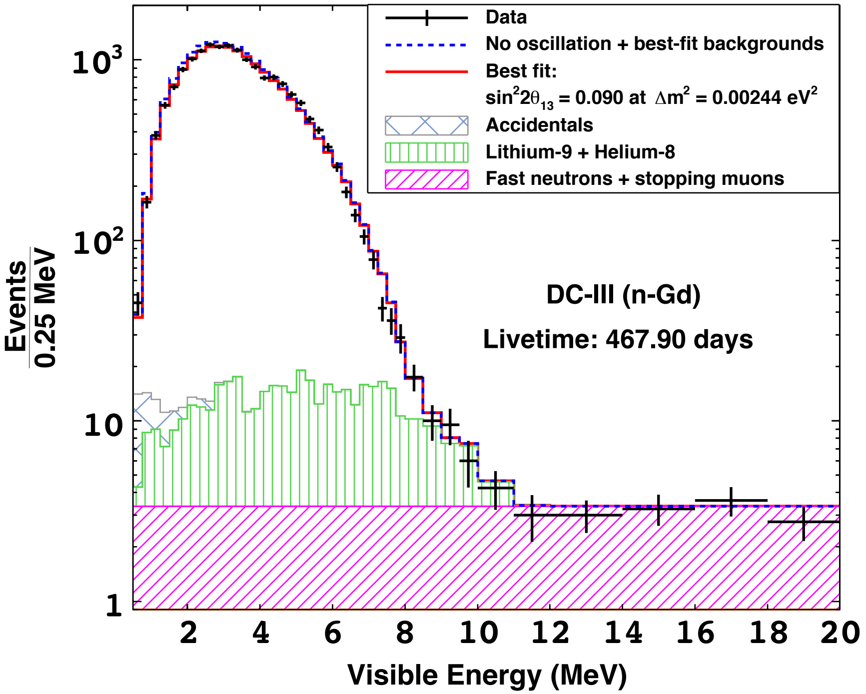
- **Cosmogenic nuclei BG**
  - Long lifetime β-n emitters Mainly ^9Li and ^8He
  - Most dangerous BG for DC
- **Accidental BG**
  - Natural radioactivity (^{40}K,^{208}Tl)
  - Main BG in H-n
- **Fast Neutron BG**
  - From muon spallations in rocks
- **Stopped-μ BG**
  - Low energy μ through chimney
  - Made negligible thanks to cuts



Double Chooz analysis

Last Gadolinium analysis: DC-III (Gd-n) (2014)





- New analysis using relaxed selection cuts and innovative BG rejection methods
- Rate+shape analysis allows to extract θ_{13} from [0.5,4] MeV distortion:

$$\sin^2(2\theta_{13}) = \mathbf{0.090^{+0.032}_{-0.029}}$$

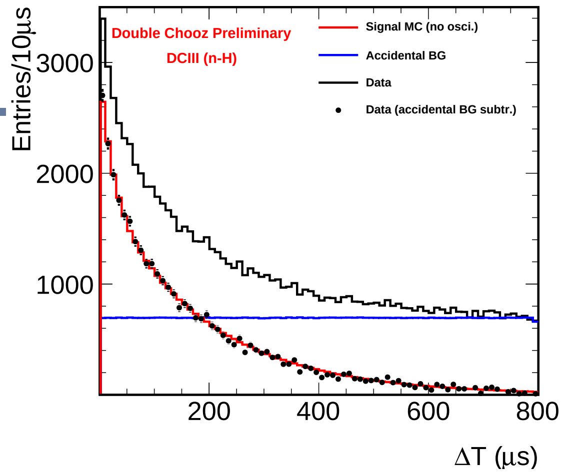
- First publication on the unexpected [4,6] MeV data/MC spectrum distortion [1]

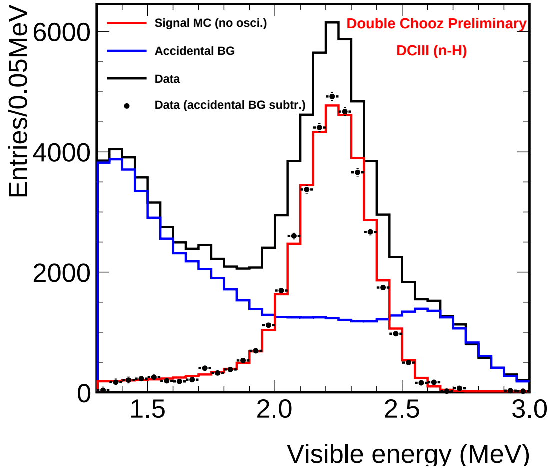
[1]: JHEP 10 (2014) 086 [Erratum ibid. 02 (2015) 074]

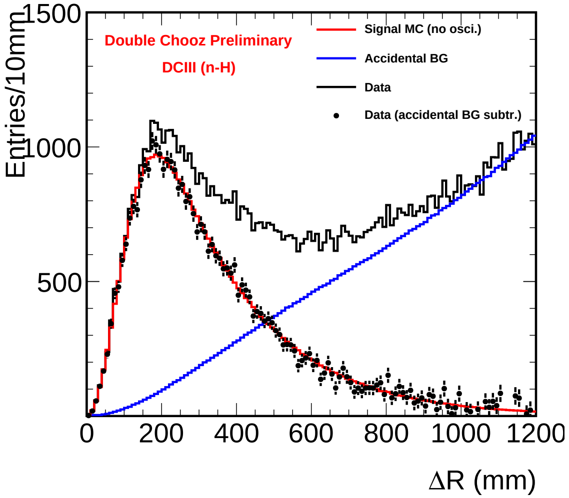
New Hydrogen analysis: DC-III (H-n)

μ veto μ dead time	$E_{vis}(\text{ID}) > 20$ MeV or Q(IV) $> 30k$ a.u. 1250 μs
light noise cut	yes
E_{vis} (prompt)	$[1, 20]$ MeV
Delayed coincidence	**Multivariate analysis** (**New**) Relaxed cuts: E_{vis} (delayed) $\in [1.3, 3]$ MeV Δt (e^+ - n) $\in [0.5, 800]$ μs and Δd (e^+ - n) < 1200 mm
Multiplicity cuts	$[-0.8, 0.9]$ ms (relative to prompt)
OV veto	yes
IV veto (prompt)	yes
IV veto (delayed)	**yes** (**New**)
FV veto	yes
Li+He veto	yes
MPS veto	**yes** (**New**)

- Huge improvements since first Hydrogen analysis (thanks to DC-III (Gd-n) analysis)
- Innovative methods developped since Gd analysis to deal with the huge background rate

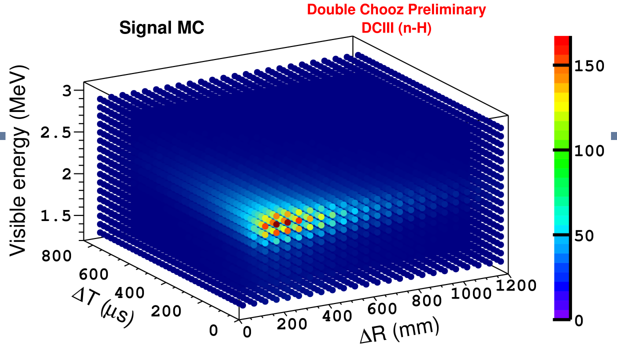


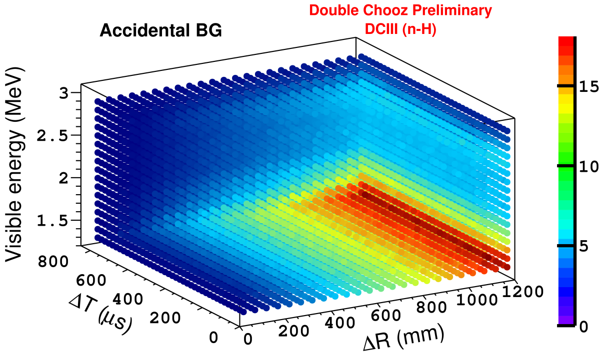




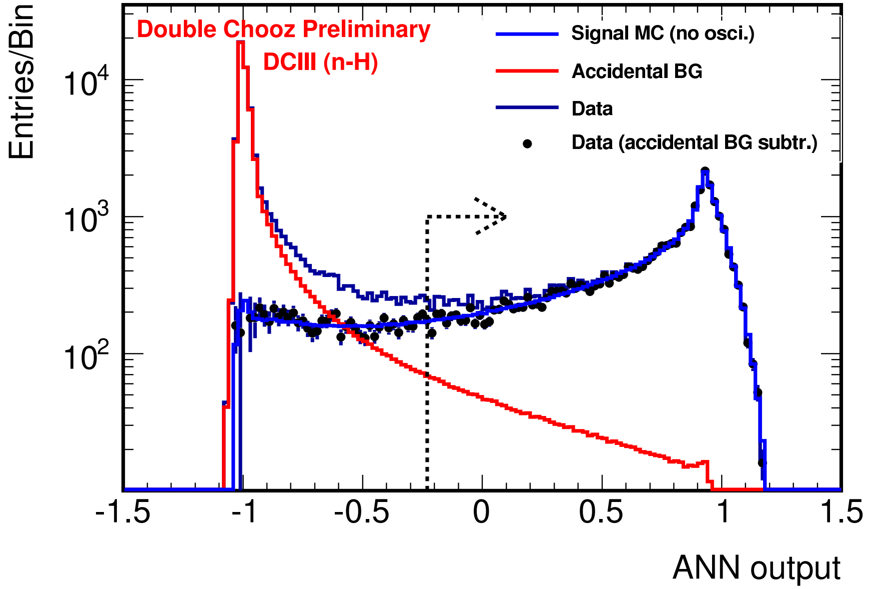
DC-III (H-n): Multivariate analysis

- Relations between Δd, Δt, and E_{vis}(delayed)
  - Different between IBD and accidental BG
- ANN-based multivariate analysis
- Major improvement:
  Signal to BG ratio by factor $> 10\times$ w.r.t. H-II

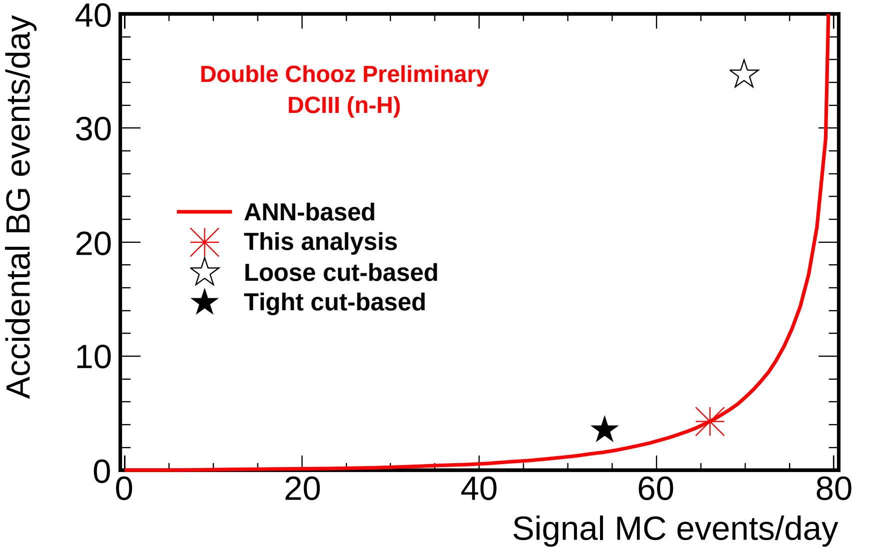




very good agreement data to MC

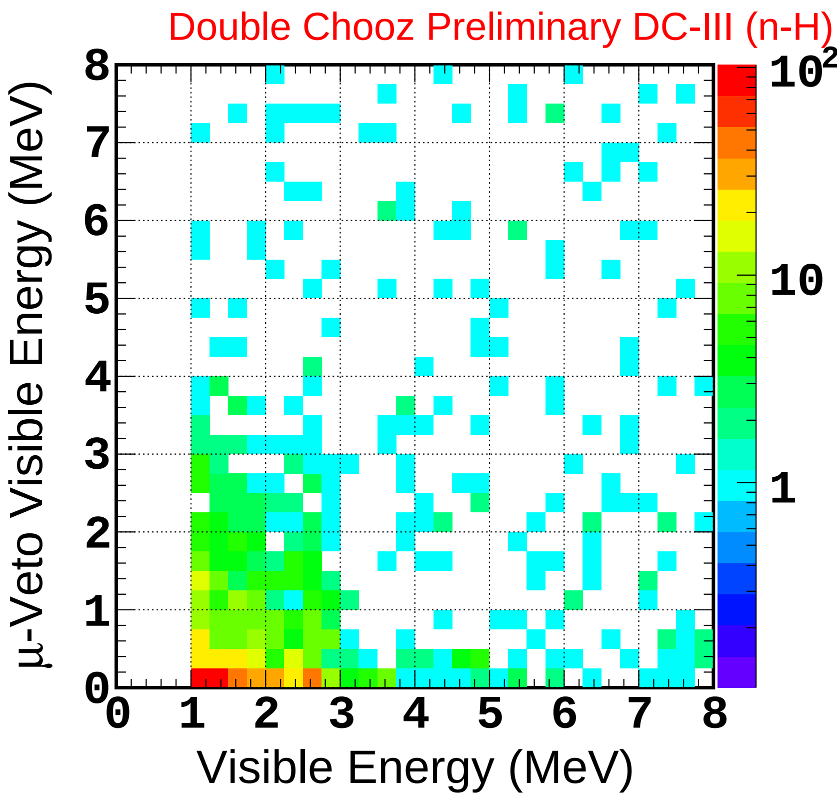


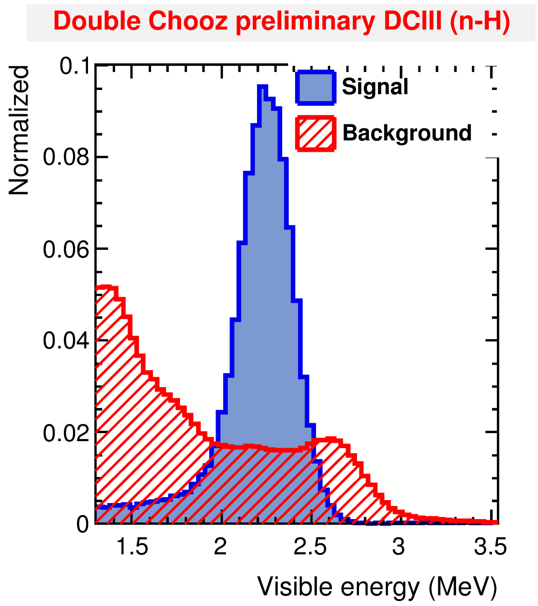
c.f. H-II: signal MC **73.7**, acc. BG **73.5** events/day

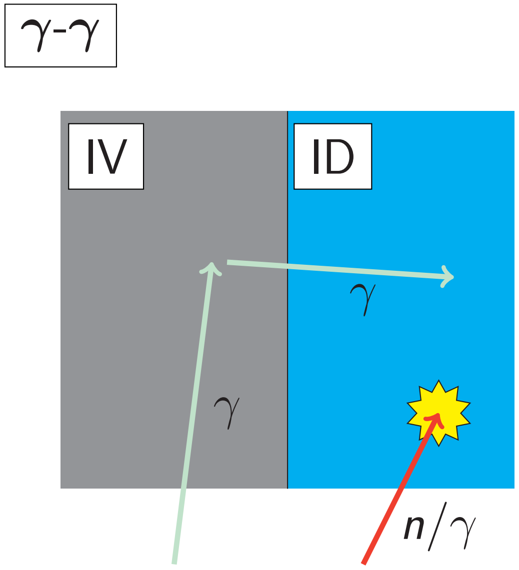


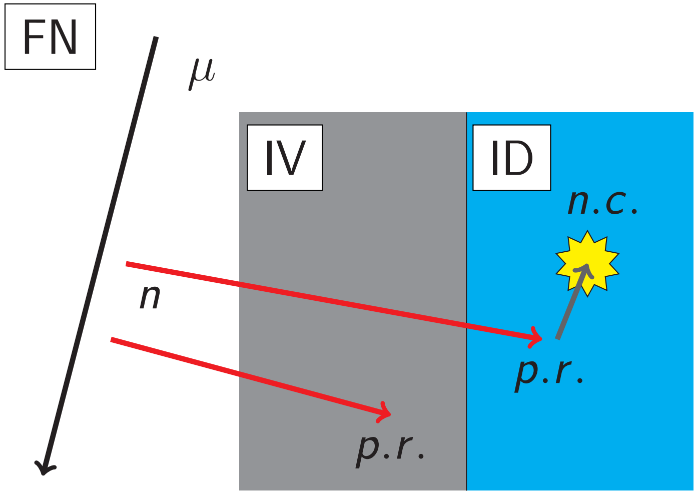
DC-III (H-n): IV veto

- IV originally equipped as active veto for muons & shield for fast neutrons
- Tags fast neutron (as for Gd) & **Compton γs** (new)
- Application on Delayed (new): mandatory due to ^{208}Tl γ comptons from rocks (peak at 2.6 MeV)
- IV veto rejects $\sim$ **27%** of remaining accidental BG



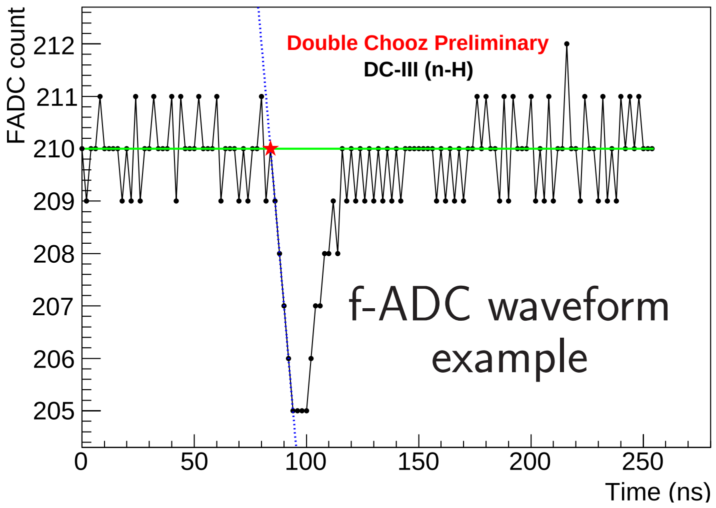


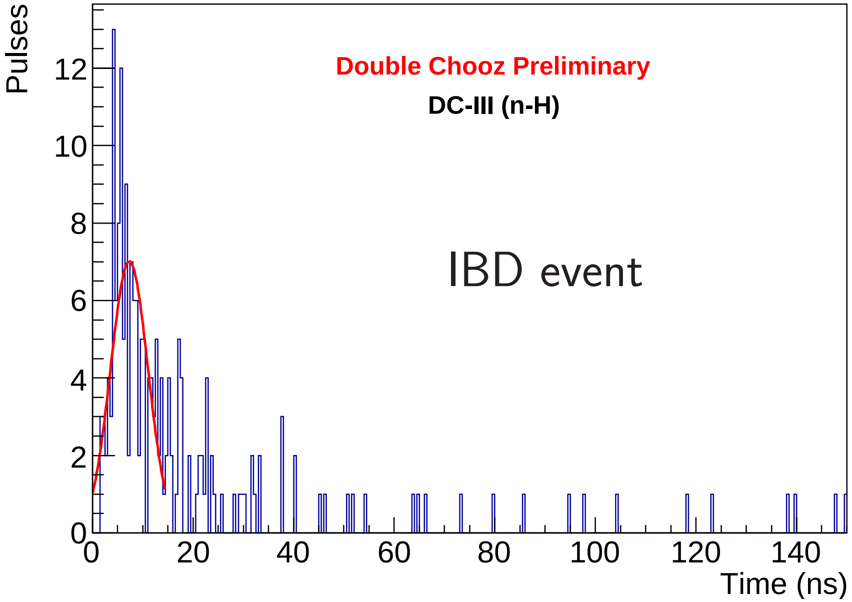


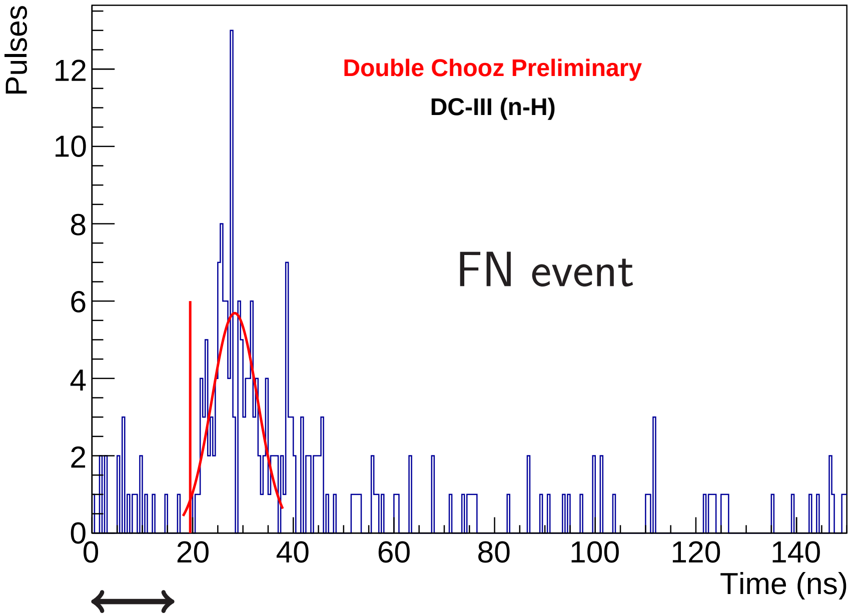


DC-III (H-n): MPS veto (Multiple Pulse Shapes)

- Multiple fast neutrons produced by μ spallations in rocks.
- Pulse Shape: Main pulse (proton recoil mimicking prompt signal) + Additional pulses (low energy proton recoils) within 256 ns recorded in same event
- Rejects ∼ **25**% of fast neutron BG

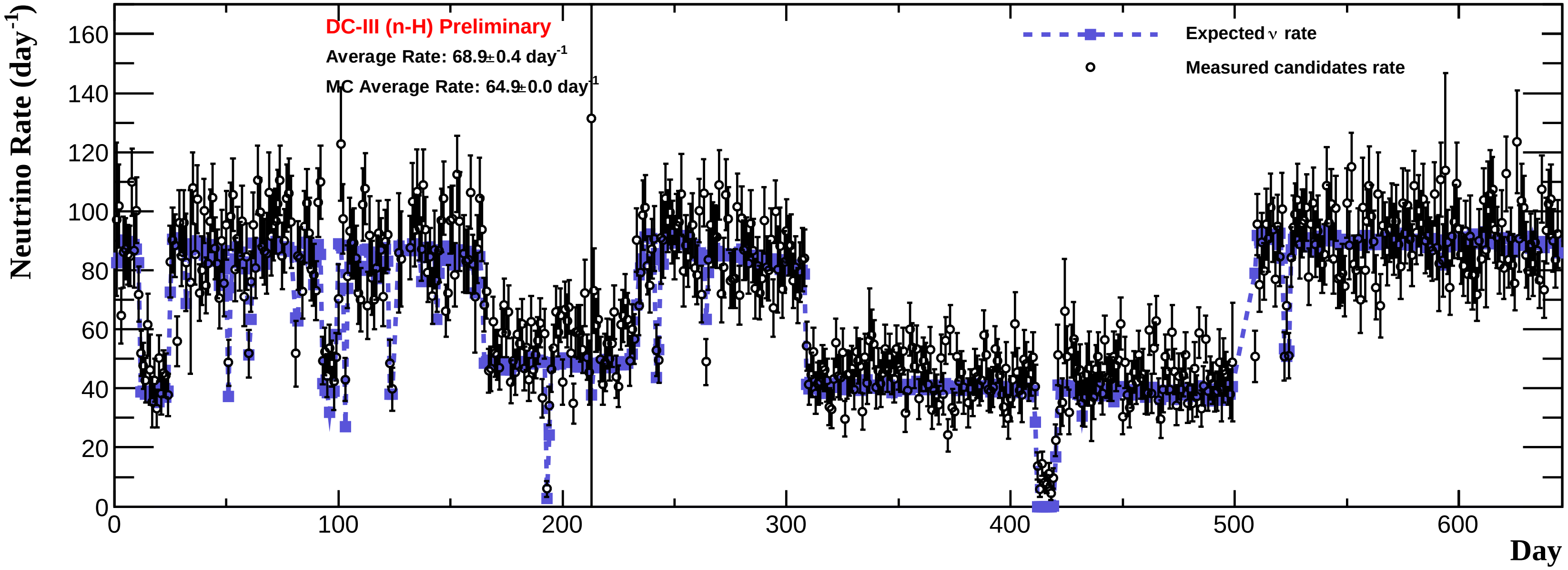






time shift > 5nsec → rejected

DC-III (H-n): IBD candidates

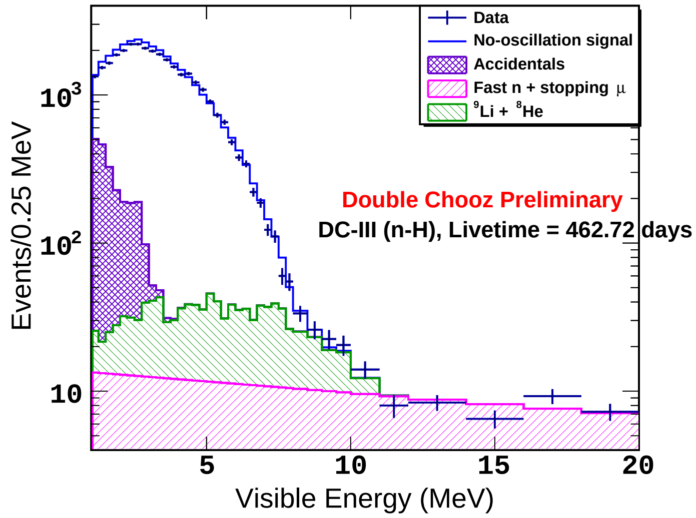


2 reactors on (∼ 60%)

1 reactor on (∼ 40%)

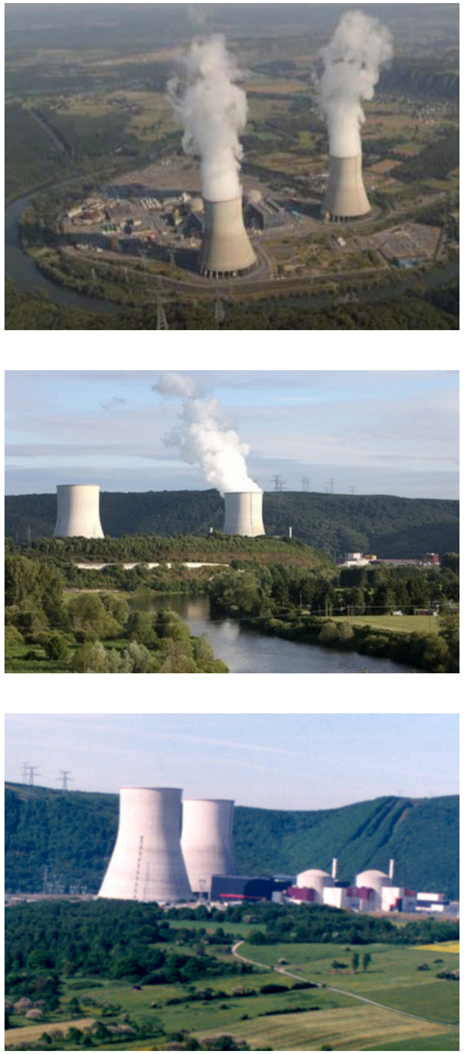
2 reactor off (∼ 7.15 days)

Rates (events/day)	DC-III (H-n)	(w.r.t. H-II)	DC-III (Gd-n)
IBD (BG-subtracted)	**62.1**		35.5
MC expectation (no osci.)	**64.9**		37.5
Accidental BG	4.334 ± 0.011	($16.9\times$ less)	0.070 ± 0.003
Fast neutron + stopped-μ BG	1.55 ± 0.15	($2.0\times$ less)	0.604 ± 0.051
$^{9}Li + {}^{8}He$ BG	$0.95^{+0.57}_{-0.33}$	($2.9\times$ less)	$0.97^{+0.41}_{-0.16}$

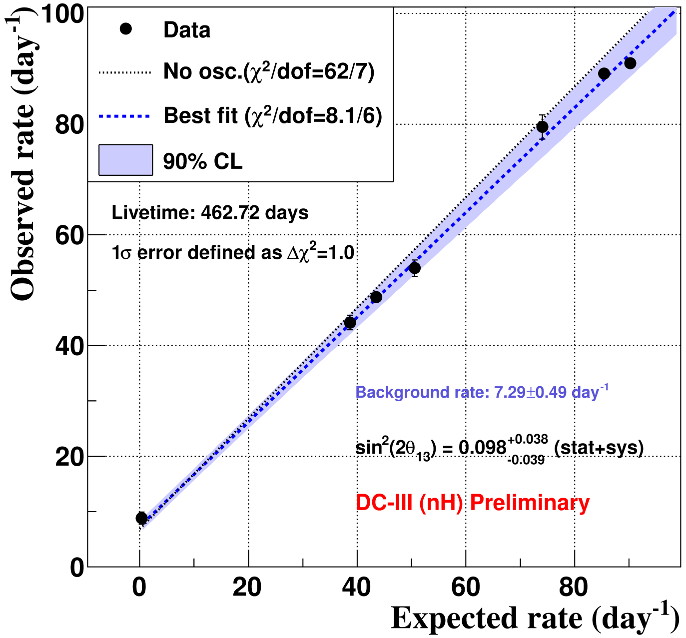


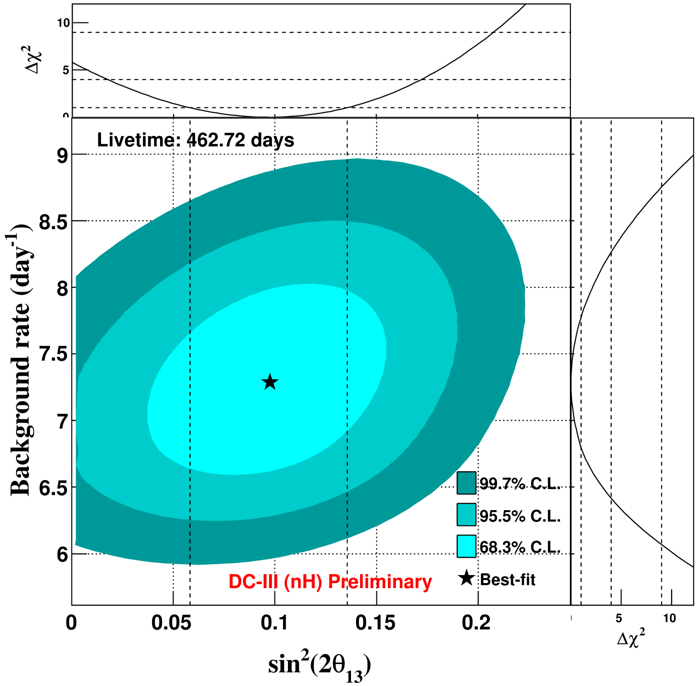
θ_{13} measurement

Reactor Rate Modulation (RRM) analysis



- Compares observed and expected IBD rates at different reactor powers.
  - Independent of model for reactor spectrum shape
  - Gains leverage from unique reactor-off data

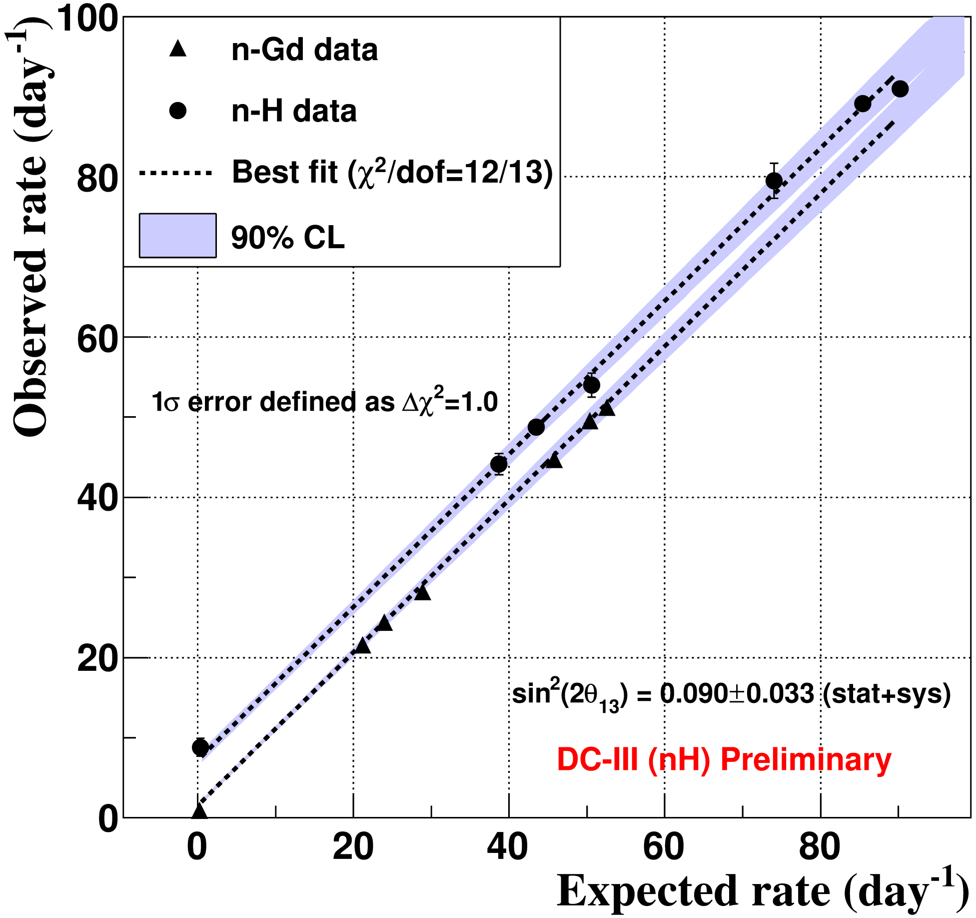


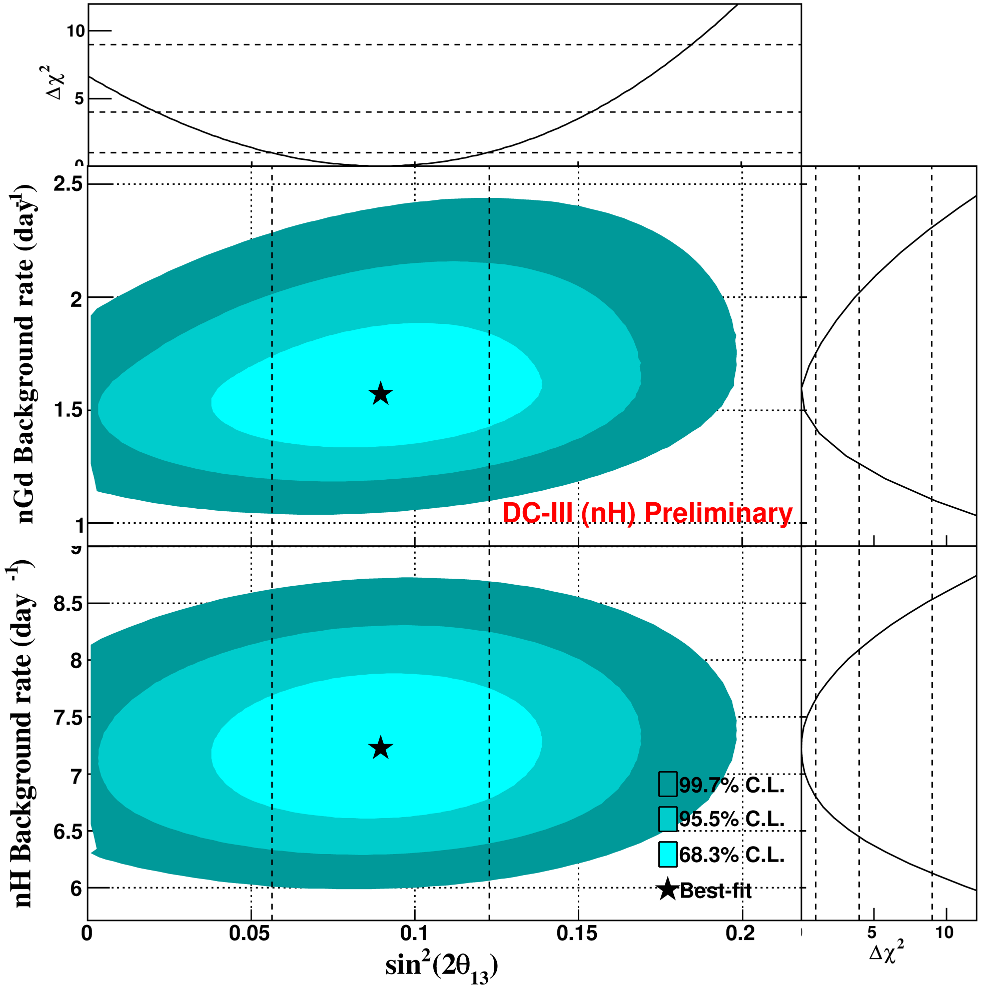


$$\sin^2 2\theta_{13} = 0.098^{+0.038}_{-0.039}$$

RRM: Gd+H combination

Combining the H (2015) and Gd-based (2014) results:



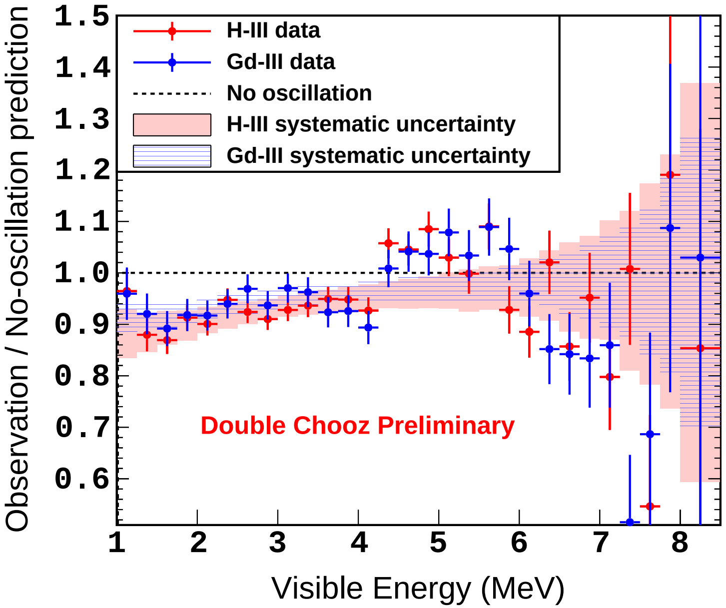


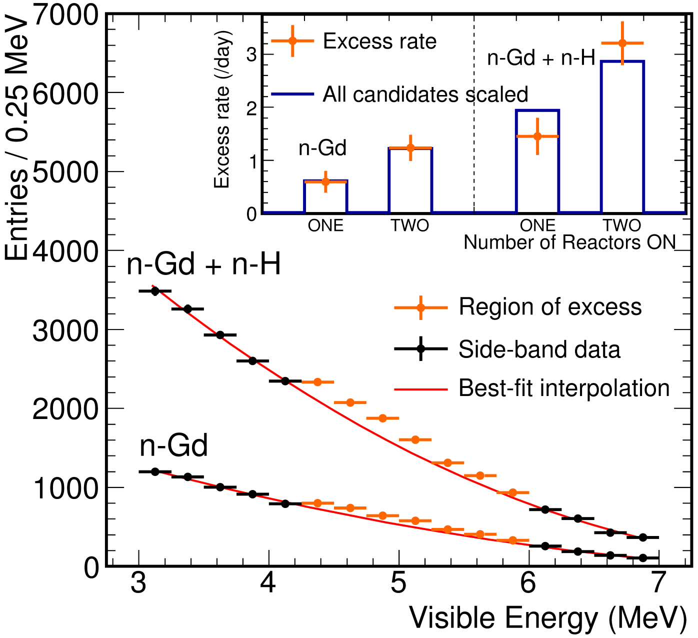
$$\sin^2 2\theta_{13} = \mathbf{0.090 \pm 0.033}$$

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

Correlations between Gd and H have minimal impact. This result assumes no correlation.

Reactor spectrum distortion at [4,6] MeV





- Consistent features observed in Gd and H channels
- Excess in 4-6 MeV region is correlated with reactor power
  - Gd excess: $\sim 3\sigma$, H excess: computation ongoing
- Origin: Ongoing research/discussion in the community

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

Conclusions and outlook

- New Hydrogen analysis using Far Detector only:
  - Validation and cross-check of Gd-n measurement
    - RRM: $\mathbf{sin^2 2\theta_{13} = 0.098^{+0.038}_{-0.039}}$
    - $[4, 6]$ MeV spectrum distortion measurement
  - Combination of Gd-n and H-n to increase statistical significance
    - RRM: $\mathbf{sin^2 2\theta_{13} = 0.090 \pm 0.033}$

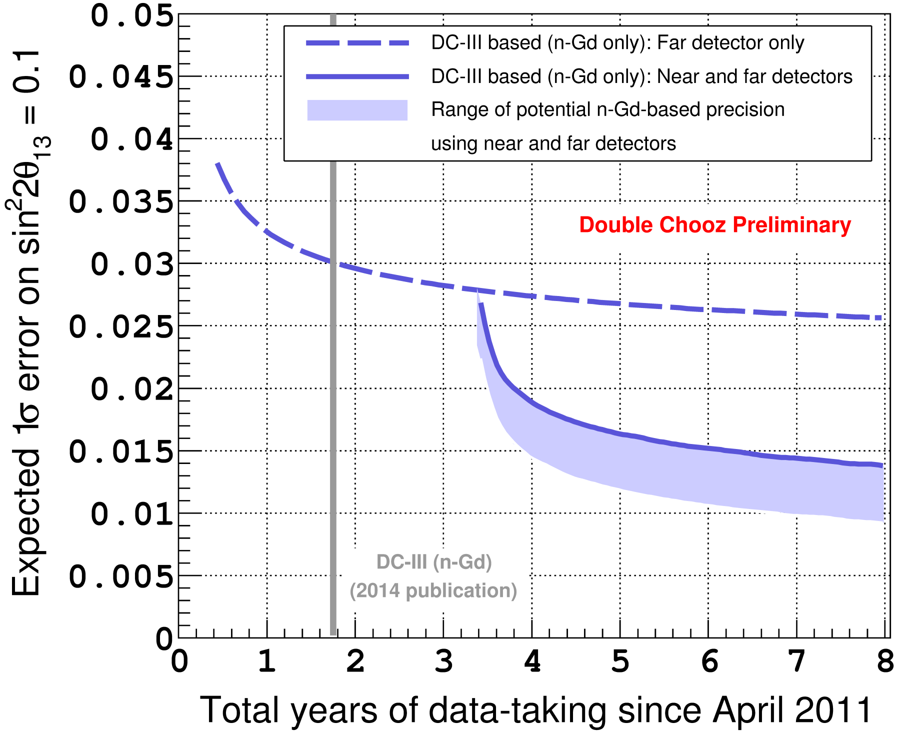
- Instrumentation:
  - Demonstration of powerful new techniques allowing low BG H-n IBD selection
  - Accidental BG reduction by $> 10\times$ & negligible impact to systematic and statistical resolutions (relative Gd-n)
  - Demonstration of the possibility to build DC-like H-n only experiments for precise reactor neutrinos measurement

Conclusions and outlook

- Near detector operating
  - Already taken 6 months of data
  - Working now on a two-detector $\sin^2 2\theta_{13}$ analysis

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

(*Adding H capture data* $\rightarrow$ *better precision in shorter timescale.*)



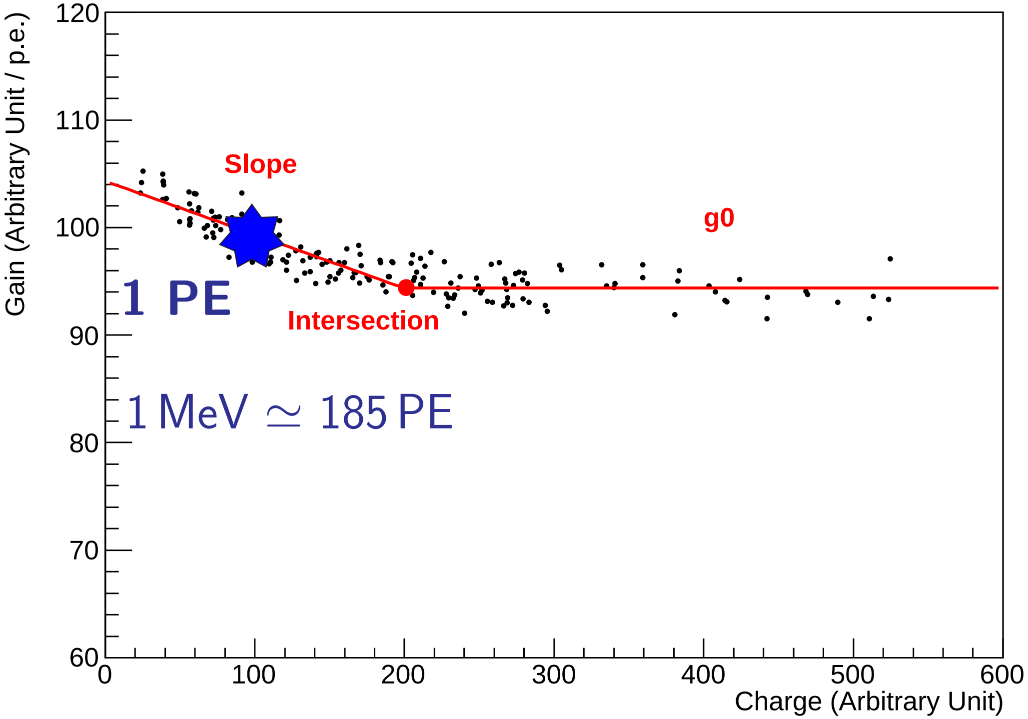
Backup

Backup

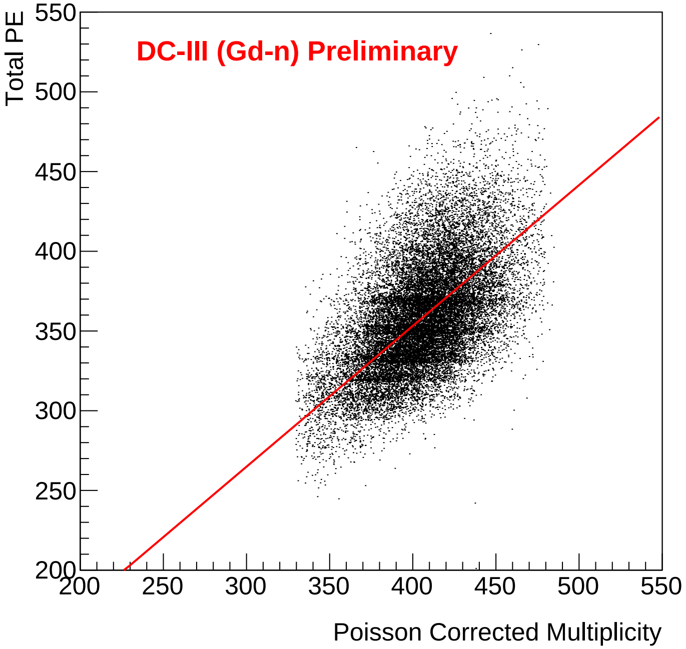
Energy reconstruction

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

(1) Charge to PE non-linearity correction (using light injection system)
correct for non-linear effects due to electronics response



1 MeV $\simeq$ 185 PE

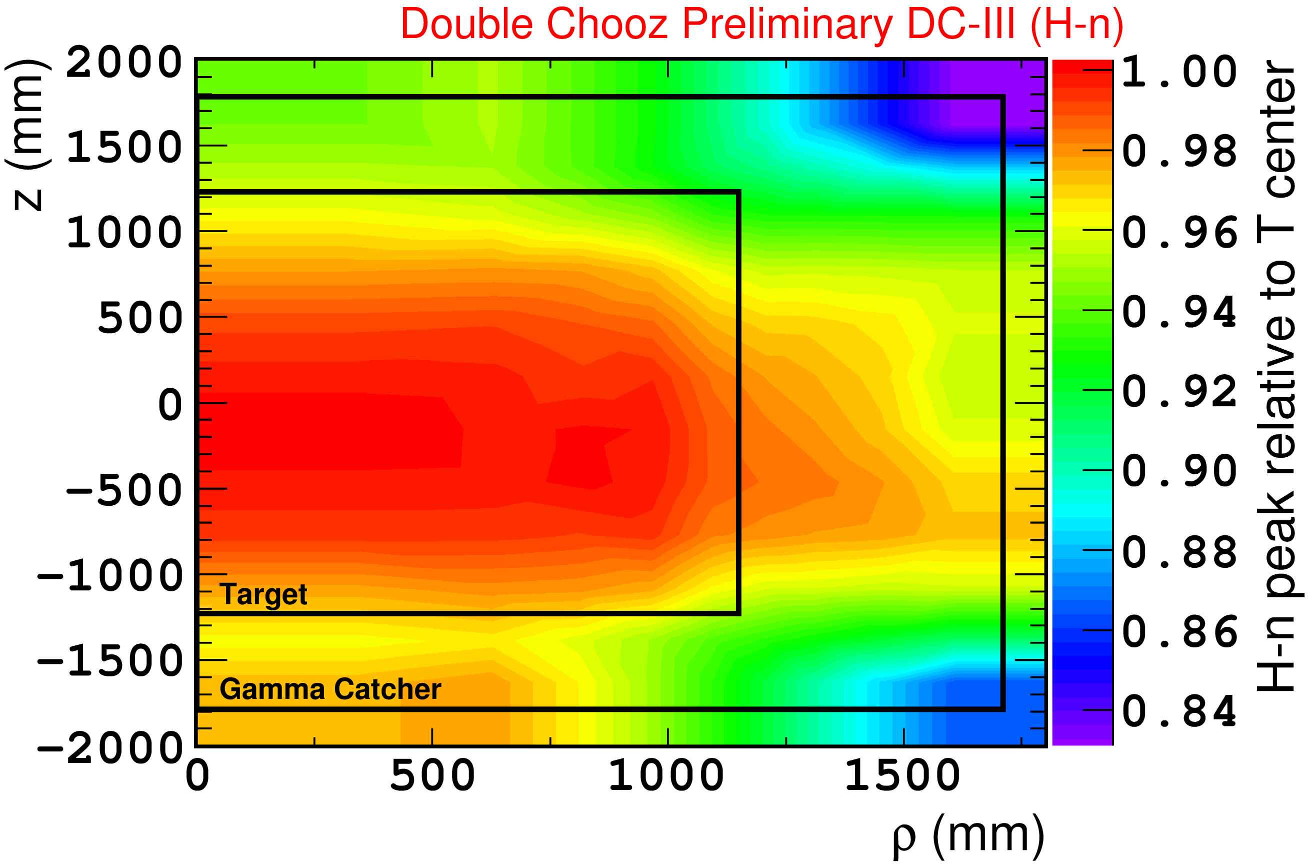


correct for "zero" hits

Energy reconstruction: Uniformity

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

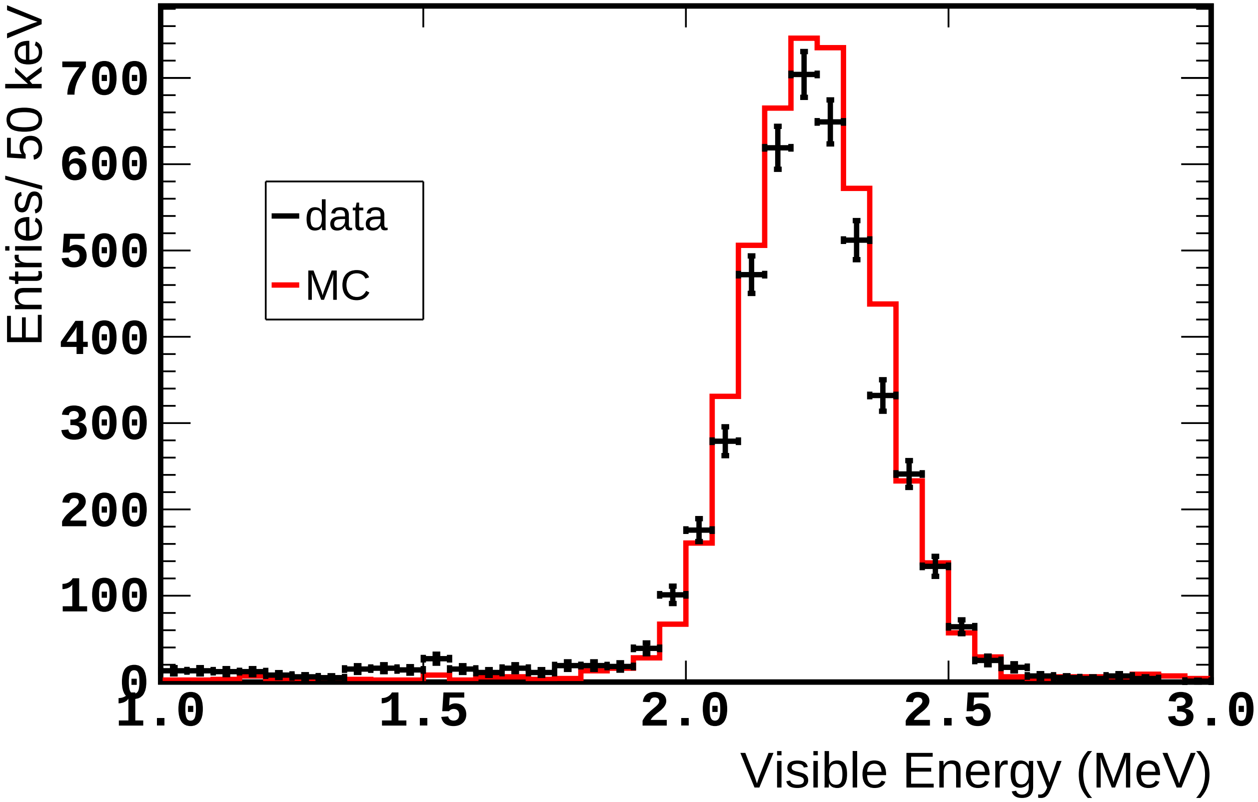
(2) Energy non-uniformity correction (using spallation n captures on H) correct for detector response position dependence



Energy reconstruction: Absolute Energy Scale

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

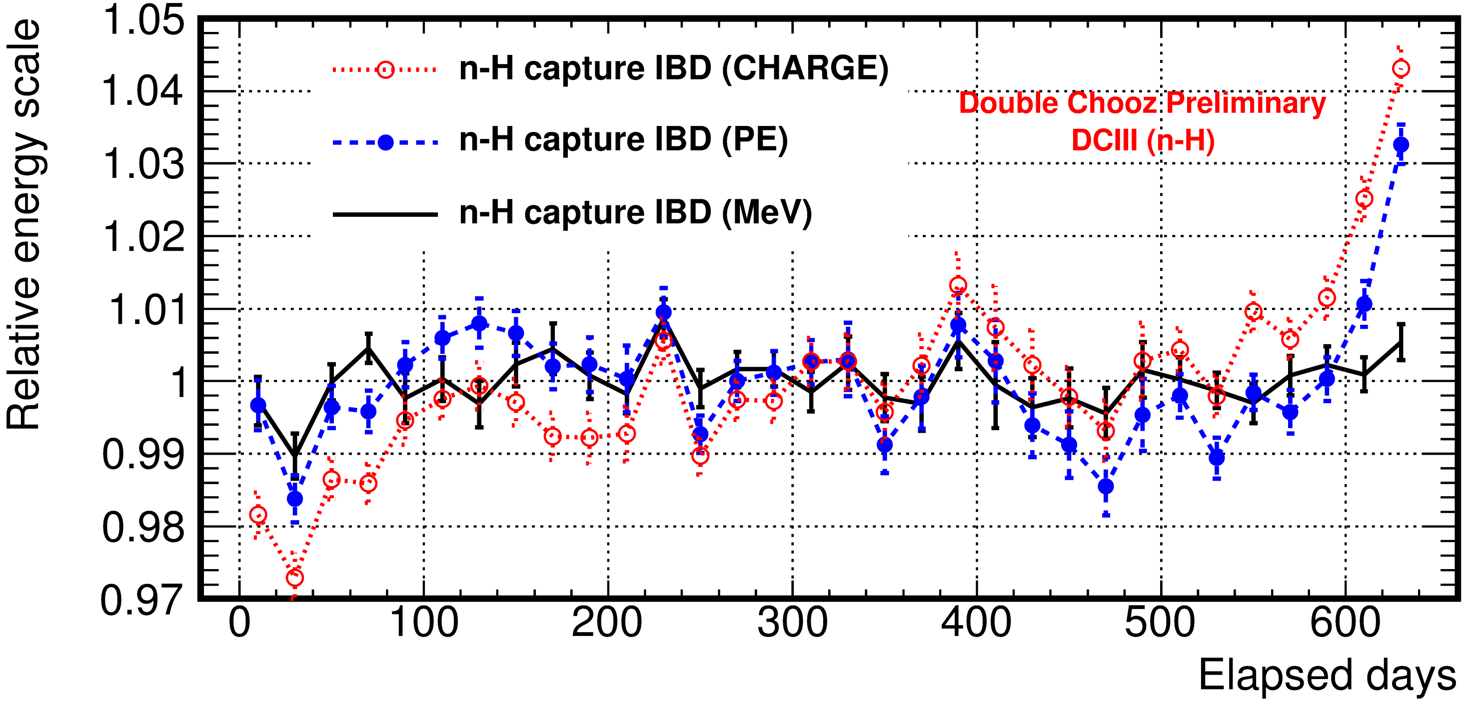
(3) Absolute energy scale determination (using ^{252}Cf source at detector center)
Determine PE to MeV conversion factor from (H-n) captures



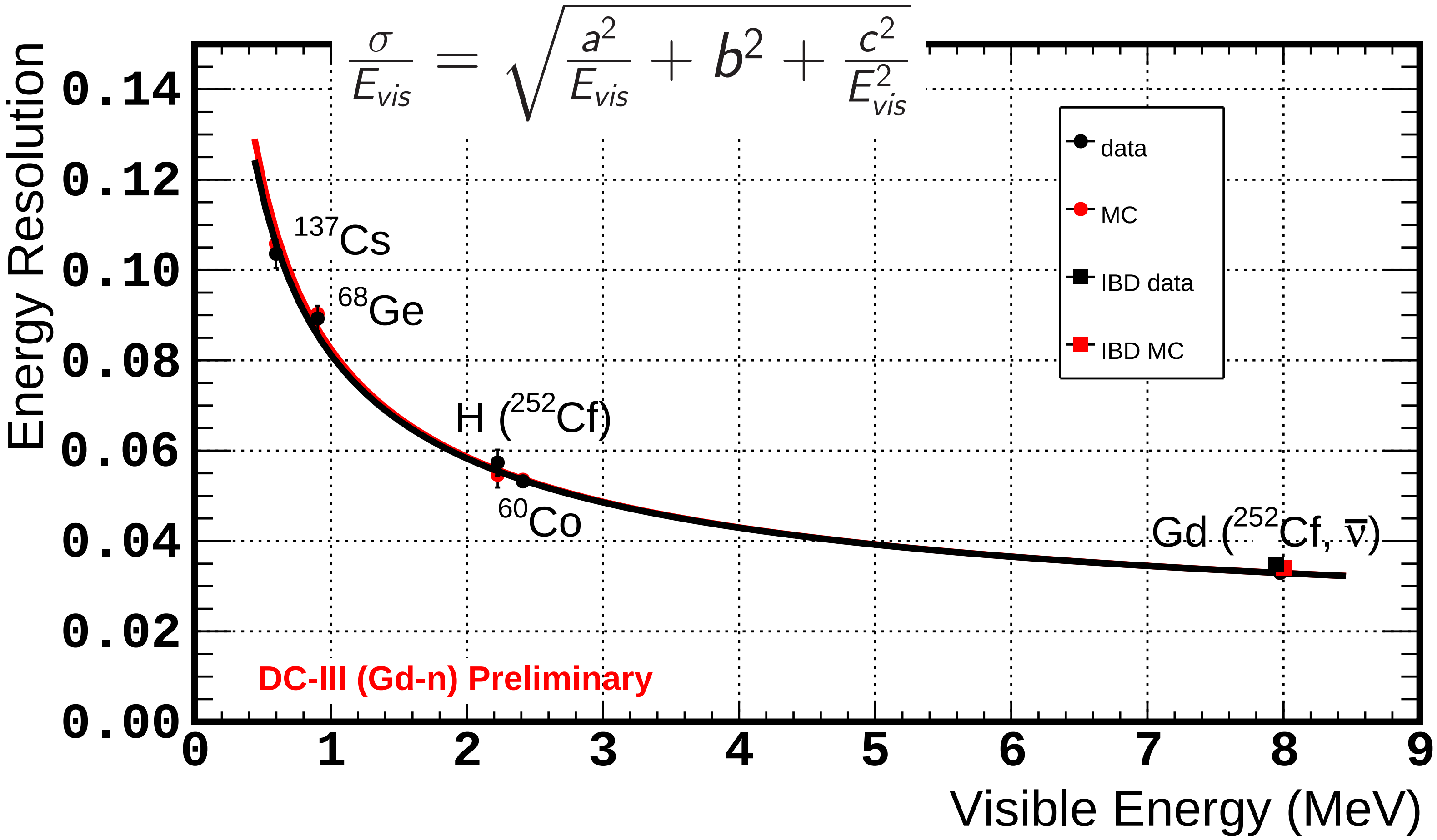
Energy reconstruction: Stability

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

(4) Energy time stability correction (using natural radioactivity sources) correct time fluctuations due to electronics response and liquid scintillator deterioration



Energy resolution



$$\frac{\sigma}{E_{vis}} = \sqrt{\frac{a^2}{E_{vis}} + b^2 + \frac{c^2}{E_{vis}^2}}$$

data:

$a = 0.0773 \pm 0.0025$

$b = 0.0182 \pm 0.0014$

$c = 0.0174 \pm 0.0107$

MC:

$a = 0.0770 \pm 0.0018$

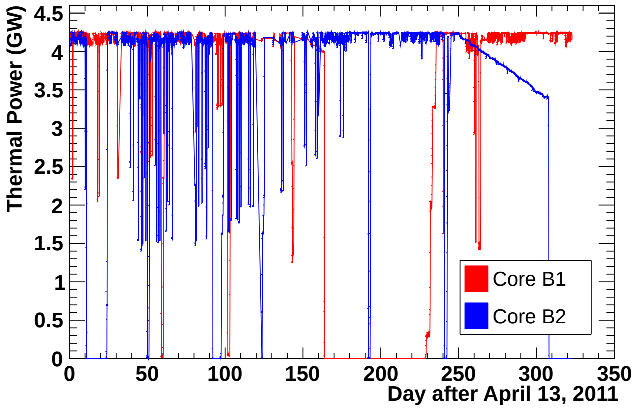
$b = 0.0183 \pm 0.0011$

$c = 0.0235 \pm 0.0061$

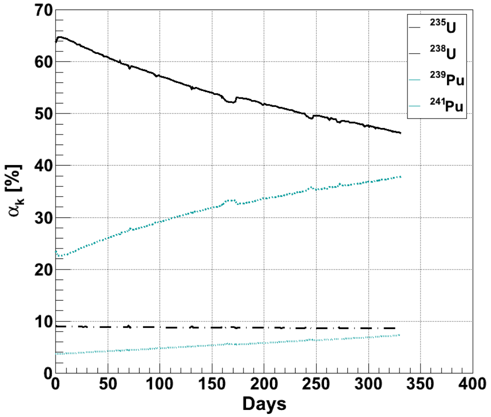
Very good agreement data to MC over whole energy range

Constant term of resolution b ~ 0.018

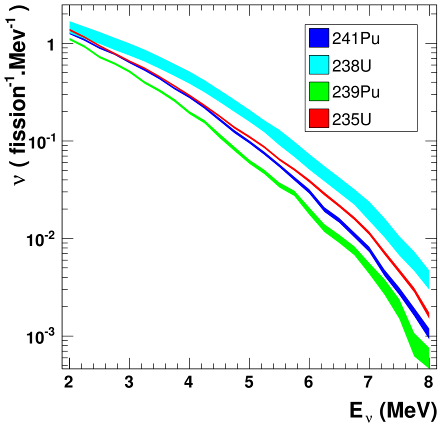
Reactor flux prediction



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)

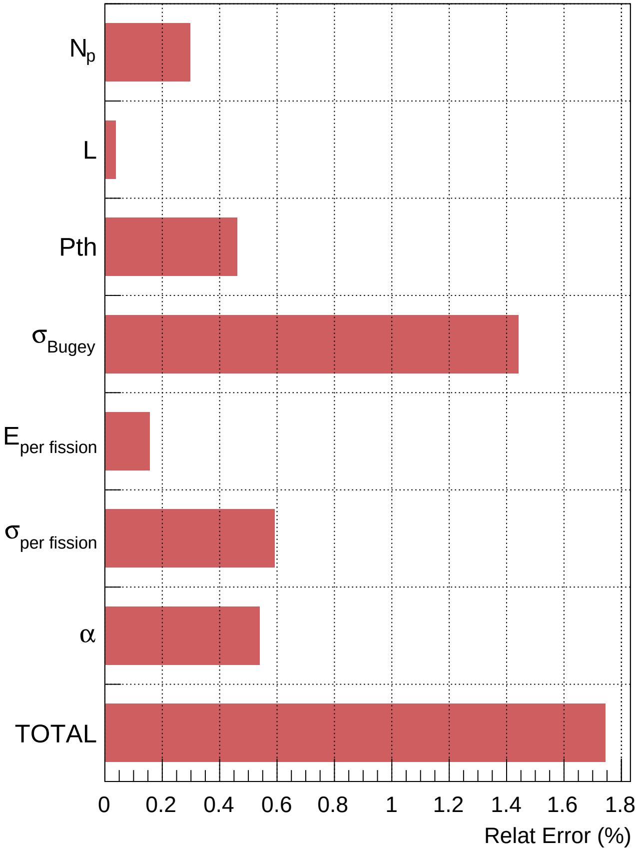
$$N_i = \frac{\epsilon N_p}{4\pi} \sum_R \frac{1}{L_R^2} \frac{\mathbf{P_{th}^R}}{\langle \mathbf{E_f} \rangle_\mathbf{R}} \left(\frac{\langle \boldsymbol{\sigma}_\mathbf{f} \rangle_\mathbf{R}}{\sum_\mathbf{k} \boldsymbol{\alpha}_\mathbf{k}^\mathbf{R} \langle \boldsymbol{\sigma}_\mathbf{f} \rangle_\mathbf{k}}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

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

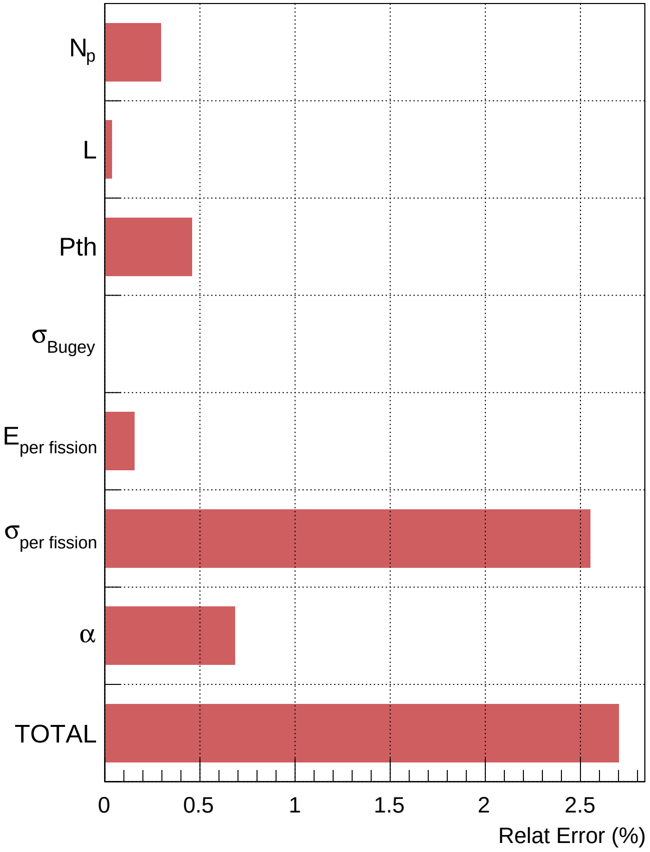
i = energy bin index, R = {Reactor 1, Reactor 2}, k = {^{235}U, ^{238}U, ^{239}P, ^{241}P}

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

Flux Systematics



With Bugey4 (1.7%)

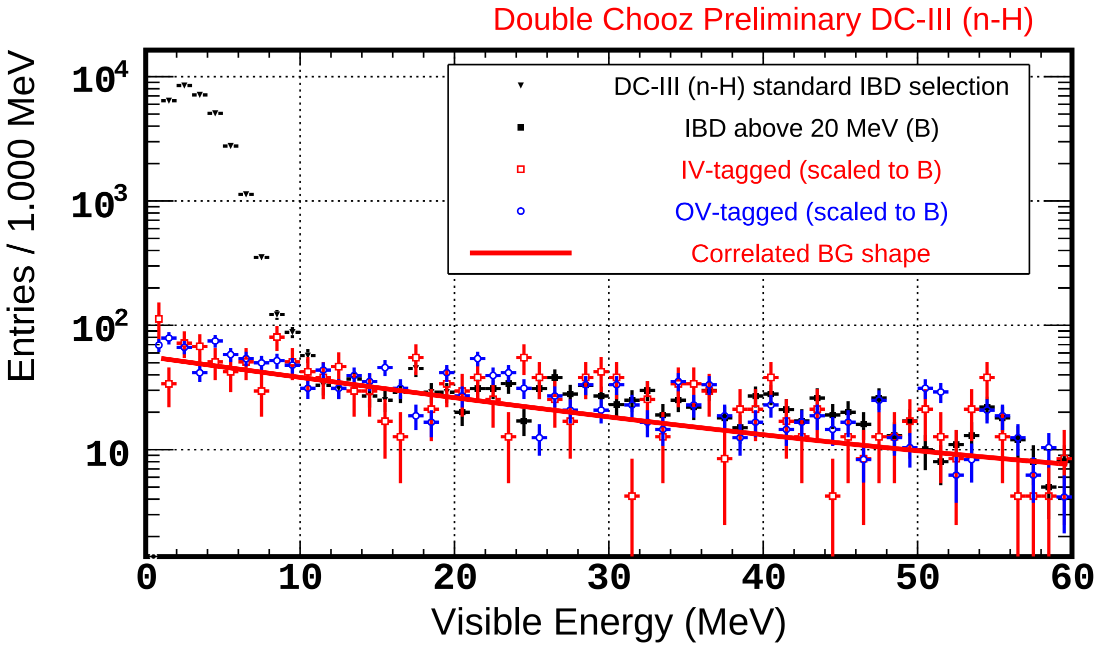


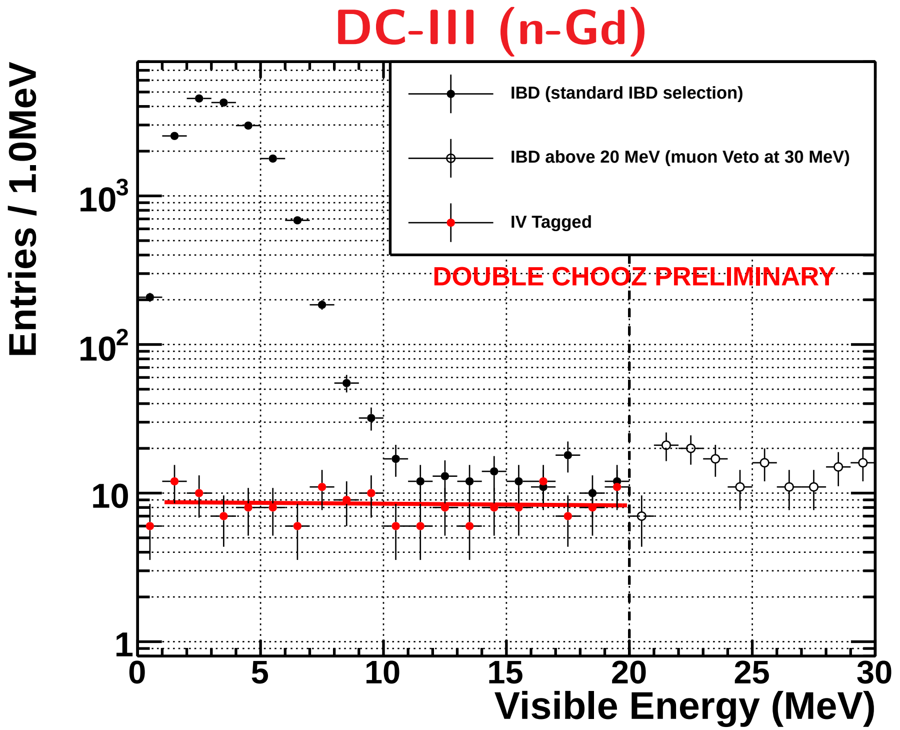
Without Bugey4 (2.7%)

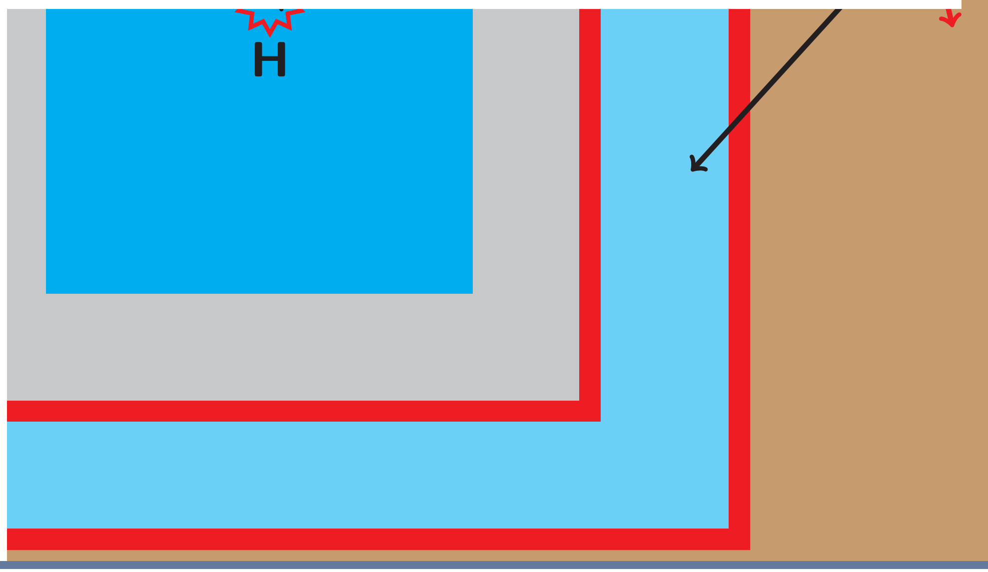
DC used Bugey4 as effective ND (via MC)

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

Remaining Correlated background



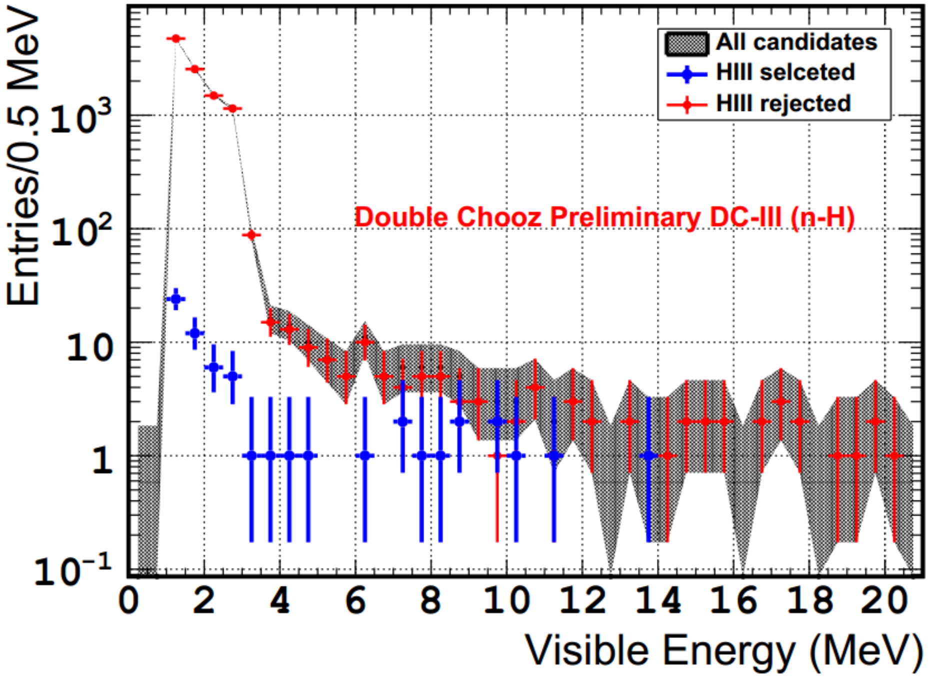




- **Measurement method**:
  - Tag with IV (or OV) allows to get shape in IBD region. Get norm. from region beyond IBD.
- **Exponential shape** (flat for Gd)
- Included the stopped muon contamination (negligible: ~ 0.02 cpd)

Reactor OFF-OFF

- A unique feature of Double Chooz



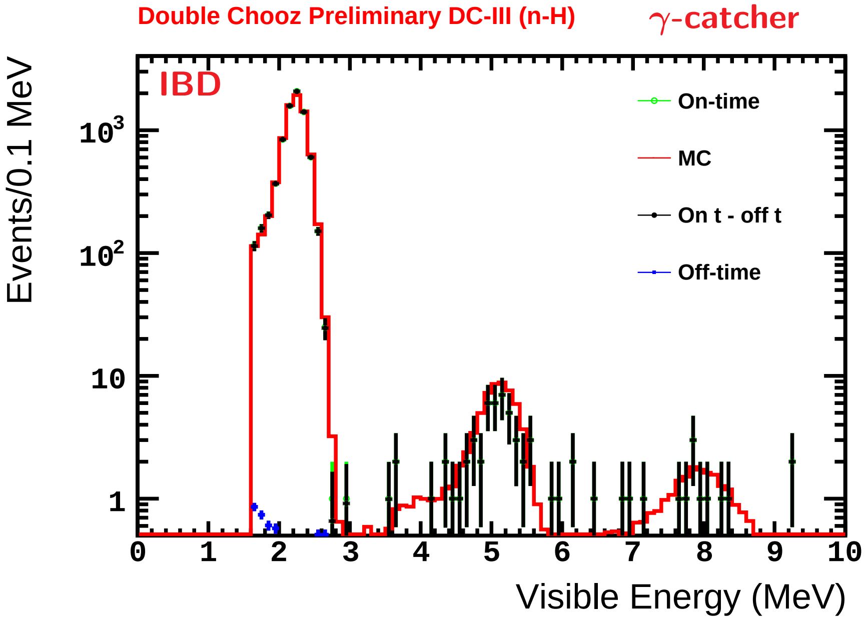
Number of events	All	$E > 12MeV$ (Correlated BG)
Before Vetos	10185	23
After Vetos	63	1
Rejection	$\sim 160\times$	$\sim 23\times$

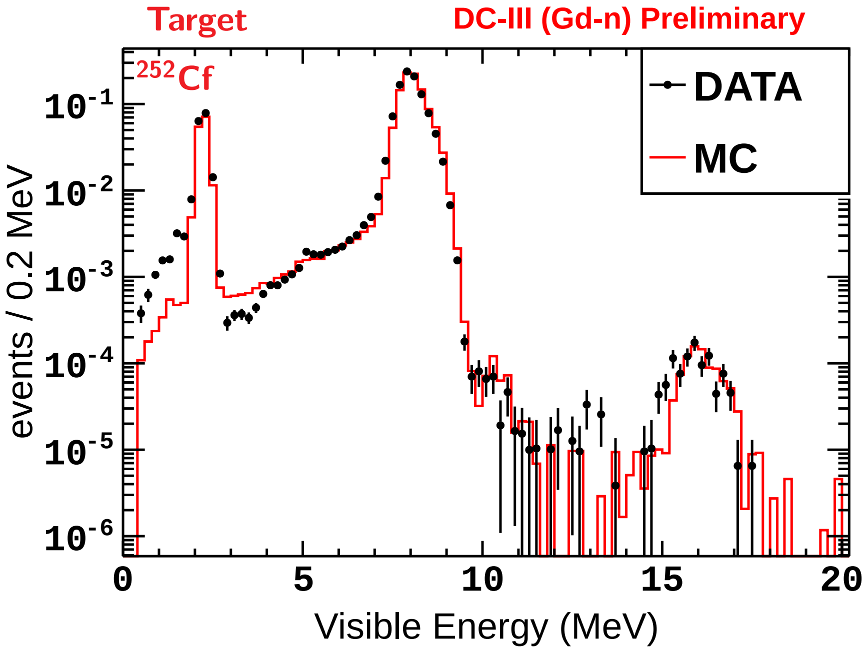
- Expected rate: $7.05^{+0.6}_{-0.4}$ events/day
- Measured rate: 8.8 ± 1.1 events/day

- Demonstration of the power of our selection
- Validation of our background model
- Rates includes residual neutrino: 0.33 ± 0.10 event/day

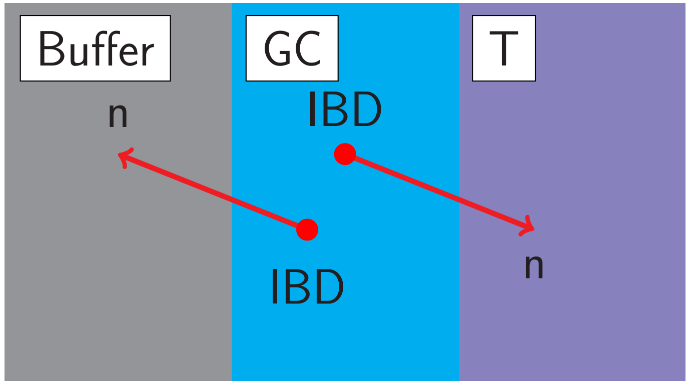
Detection Systematics

- $\delta(detection)$: error on all corrections
  - DATA/MC normalization from errors due to: Dead time, vetoes inefficiencies, etc.
  - MC corrections (w.r.t. FD)
- Contributions from MC corrections:
  - **Proton number**: $\sim 0.91\%$ (dominant)
    - Computed for γ-catcher (GC) and acrylics
    - GC was not designed to be used for high precision physics
  - **Spill uncertainty**: $\sim 0.29\%$
  - **Hydrogen fraction**: $\sim 0.21\%$ (T and GC)
- Selection efficiency: $\sim 0.22\%$
- $\boldsymbol{\delta}$**(detection)** $\simeq$ **1.0%** (all systematics comparable to Gd except proton number)





Spill effect and Selection efficiency

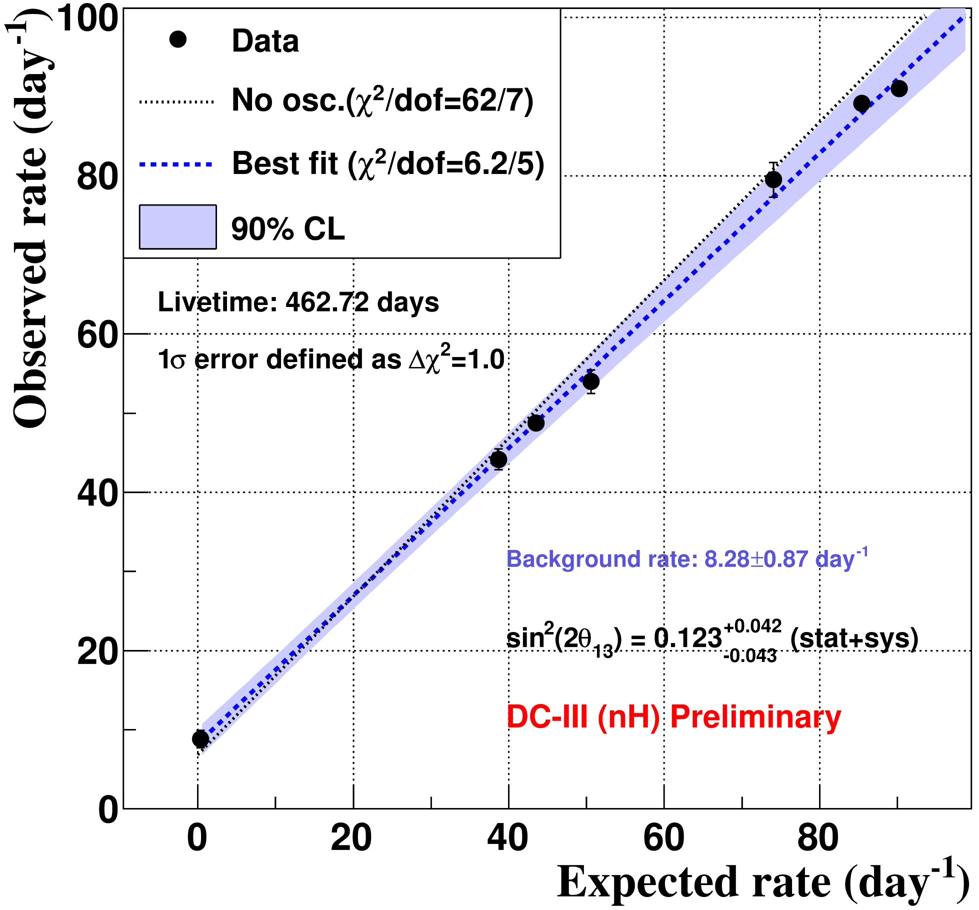


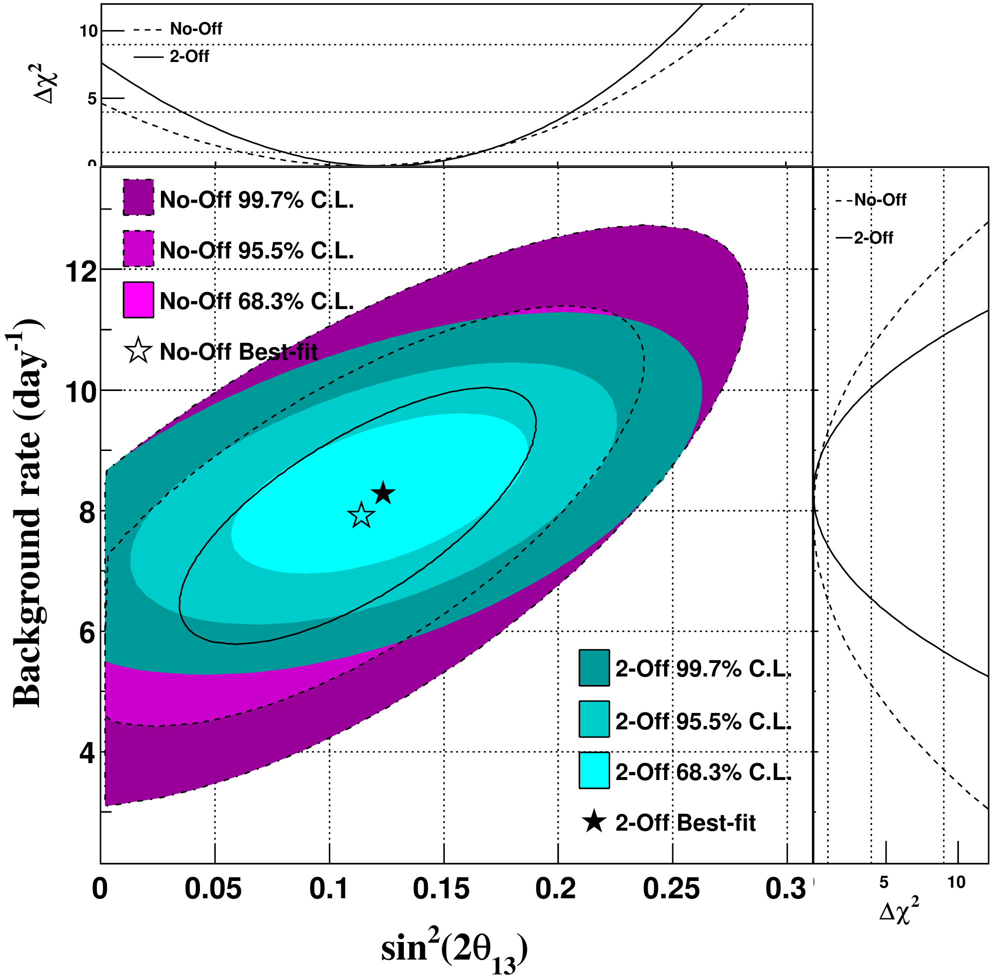
- **Spill**: Neutrons travel through different volumes
    - Captures can occur in a different volume than IBD
- High model dependency
- Comparison between Tripoli4 and an ad hoc Geant4 neutron model

- **Selection efficiency**:
- Computed on whole detection volume
- Neutron efficiency defined as $\varepsilon = \frac{\#\textit{Standard delayed cuts}}{\#\textit{Extended delayed cuts}}$
- Computed for data (taking BGs into account) and MC

RRM without background model

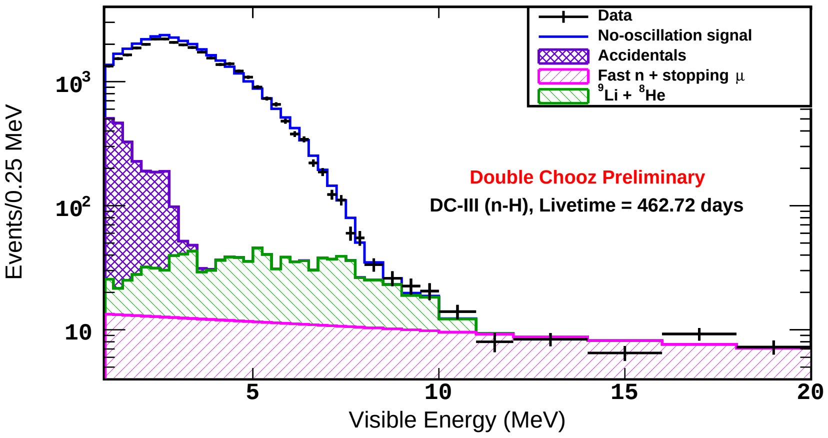
No *a priori* background model … a unique Double Chooz analysis!

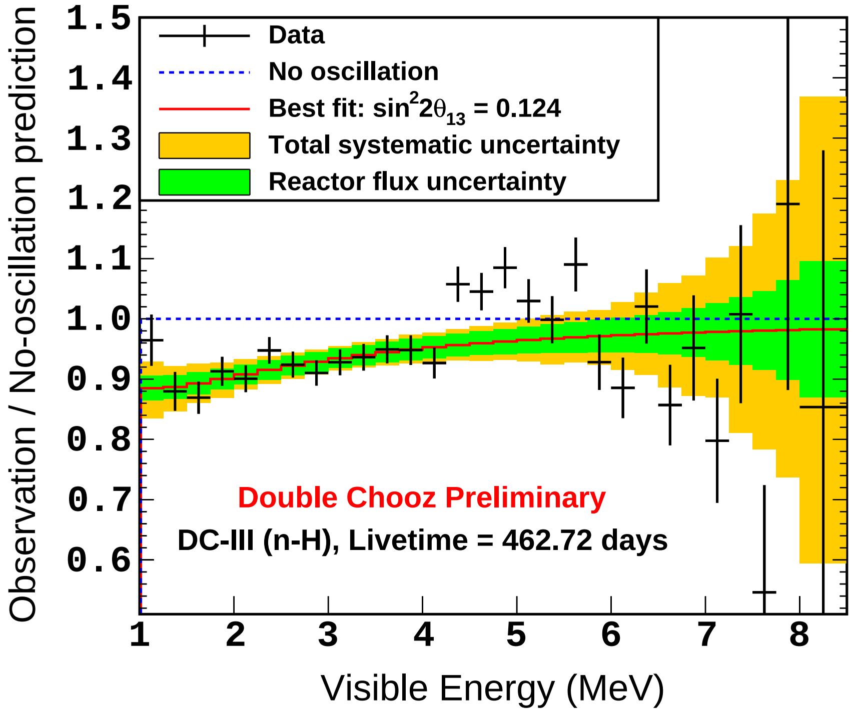




$$\sin^2 2\theta_{13} = \mathbf{0.123^{+0.042}_{-0.043}}$$

Rate+Shape fit





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