Status of Double Chooz experiment

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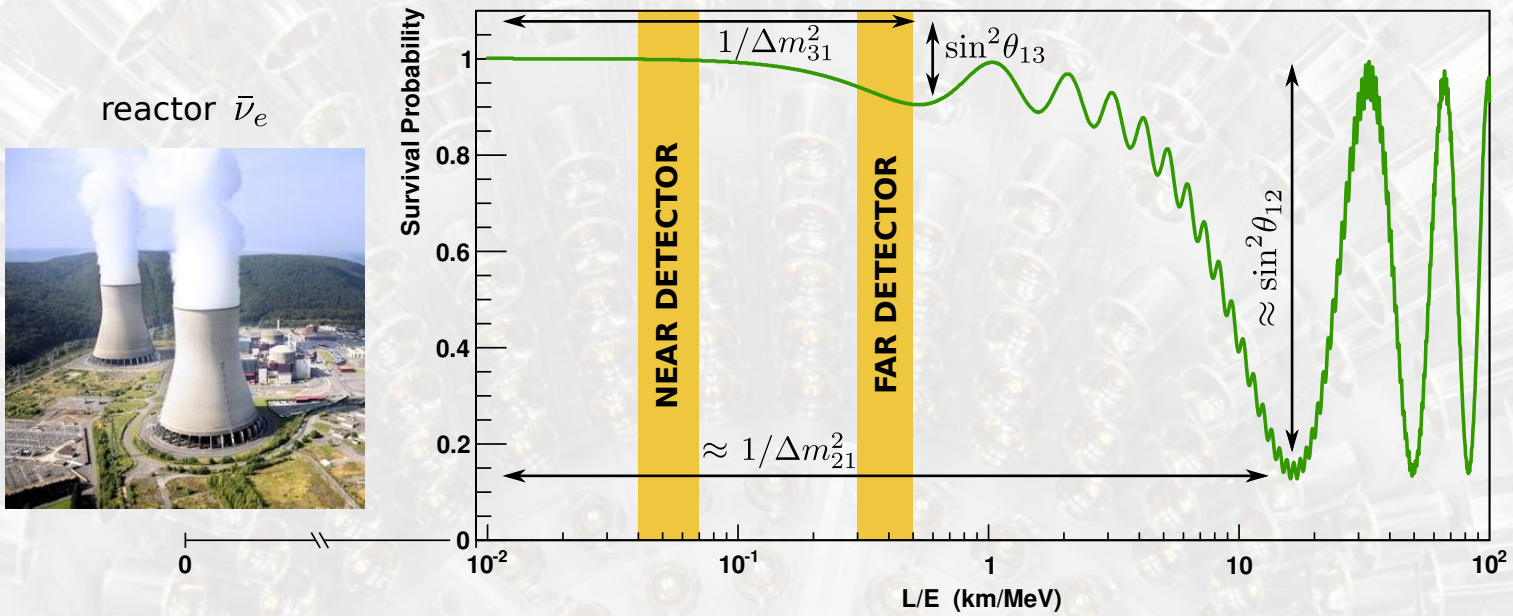
Measurement of θ_{13} with Double Chooz



- non vanishing last mixing angle θ_{13} (Nov. 2011)
  $\rightarrow$ input for next generation experiments: mass hierarchy, CP violation, etc.
- direct measurement of θ_{13} through disappearance $\bar{\nu}_e$ from nuclear reactors:

$$P_{\bar{\nu}_e \rightarrow \bar{\nu}_e} \approx 1 - \sin^2(2\theta_{13}) \sin^2\left(\frac{\Delta m^2_{31} \mathrm{L}}{4\ \mathrm{E}}\right) + O(10^{-3})$$

- 2 identical detectors for high precision (detection+flux systematics reduction)

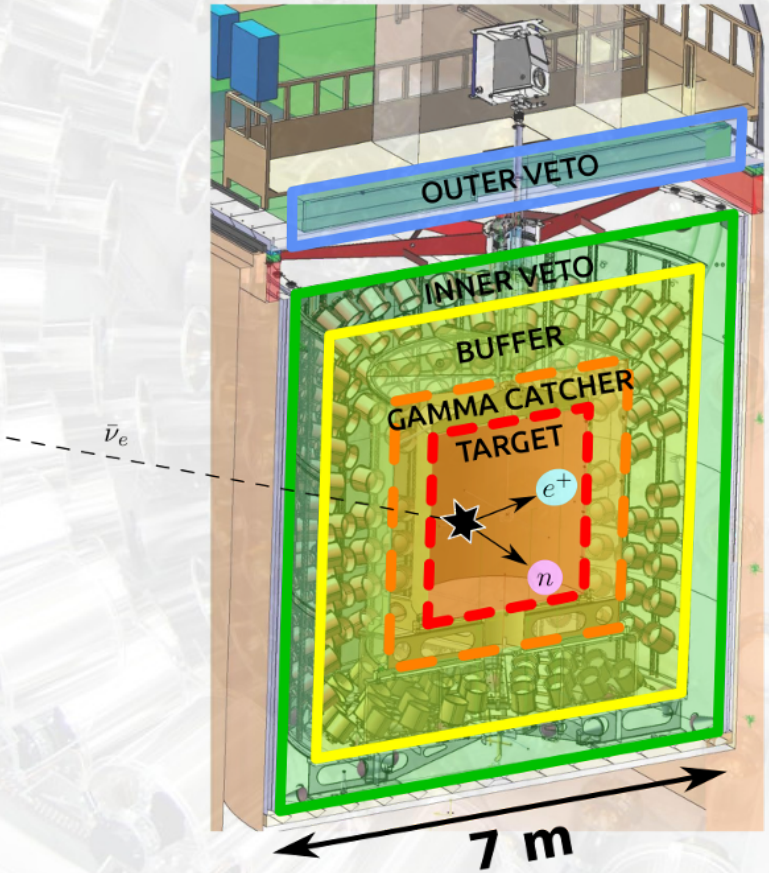
Double Chooz detectors layout

INVERSE BETA DECAY on proton (threshold > 1.8 MeV)

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

prompt signal: scintillation + e^+ annihilation
$E_{prompt} \approx E(\nu_e) - 0.8$ MeV

delayed signal: γ ray(s) from neutron capture
n-Gd $E_{delayed} \approx 8.0$ MeV $\Delta T \approx 30$ μs
or n-H $E_{delayed} \approx 2.2$ MeV $\Delta T \approx 200$ μs



Neutrino target:
liquid scintillator PXE + Gd

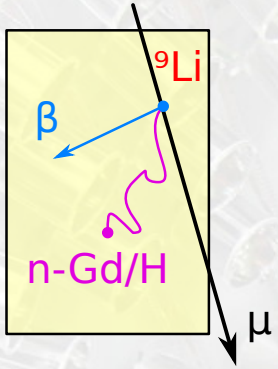
Gamma catcher:
liquid scintillator PXE (no Gd)

Buffer volume:
transparent mineral oil
with 390 x 10" PMTs assembly

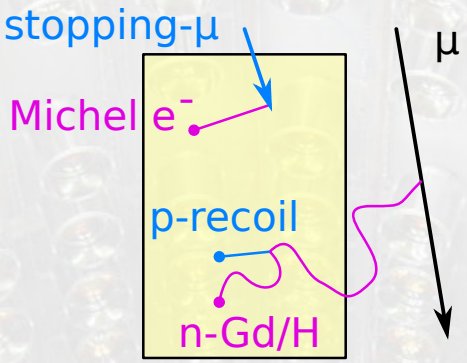
Inner Veto:
liquid scintillator (LAB)
with 78 x PMTs 8"

Outer Veto:
plastic scintillator strips

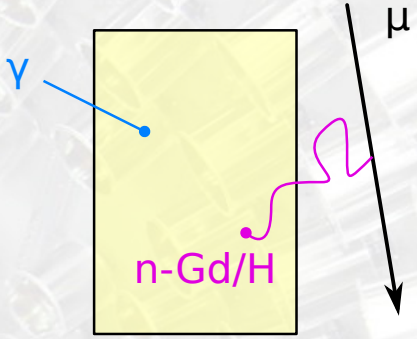
Background



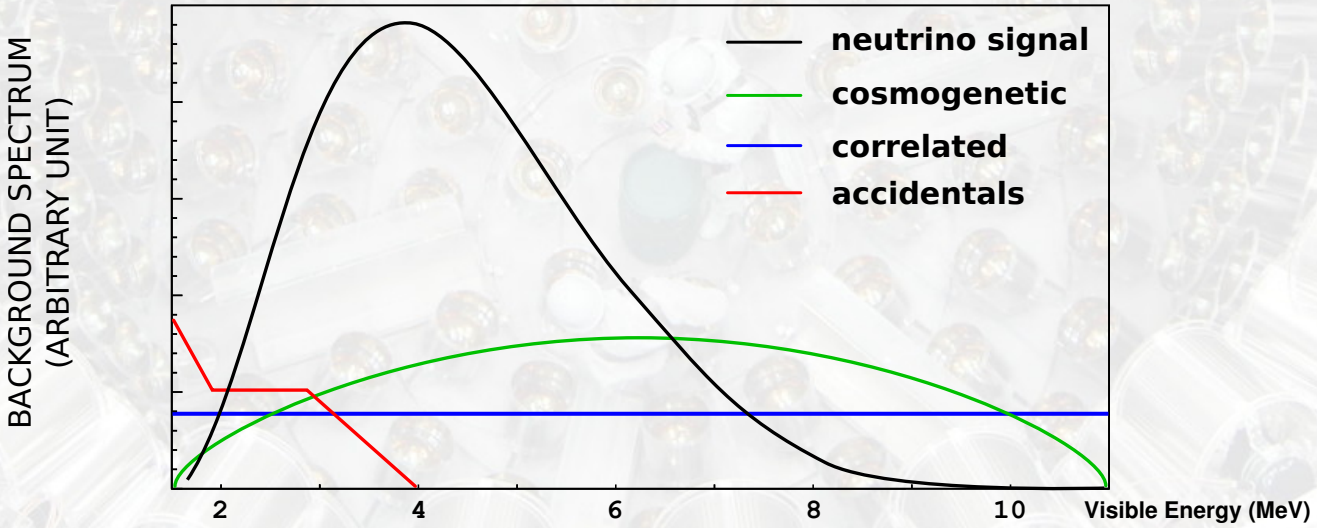
COSMOGENETIC
long lifetime β-n emitter
(mainly ^{9}Li)



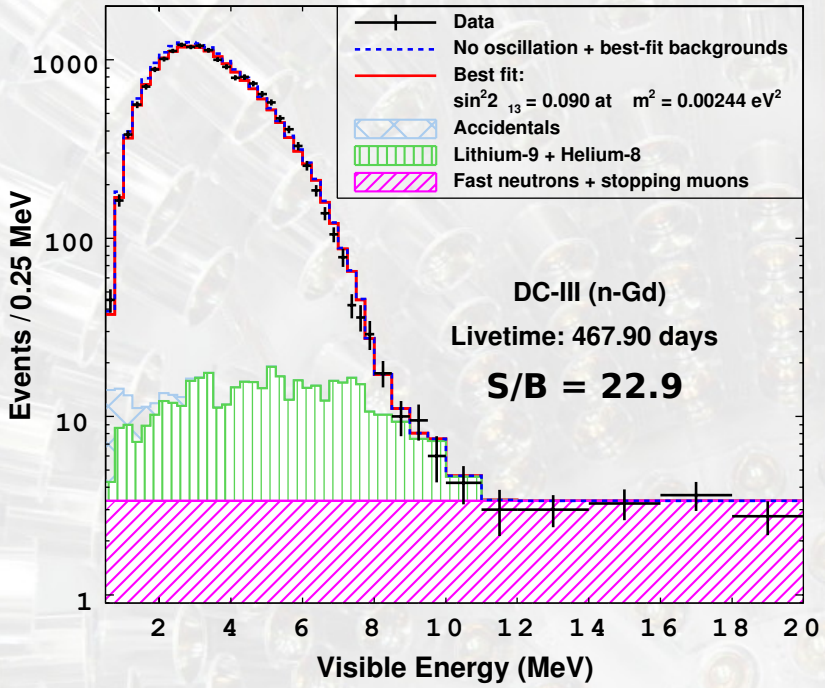
CORRELATED
fast neutrons from μ spallation,
stopping-μ (acceptance hole)

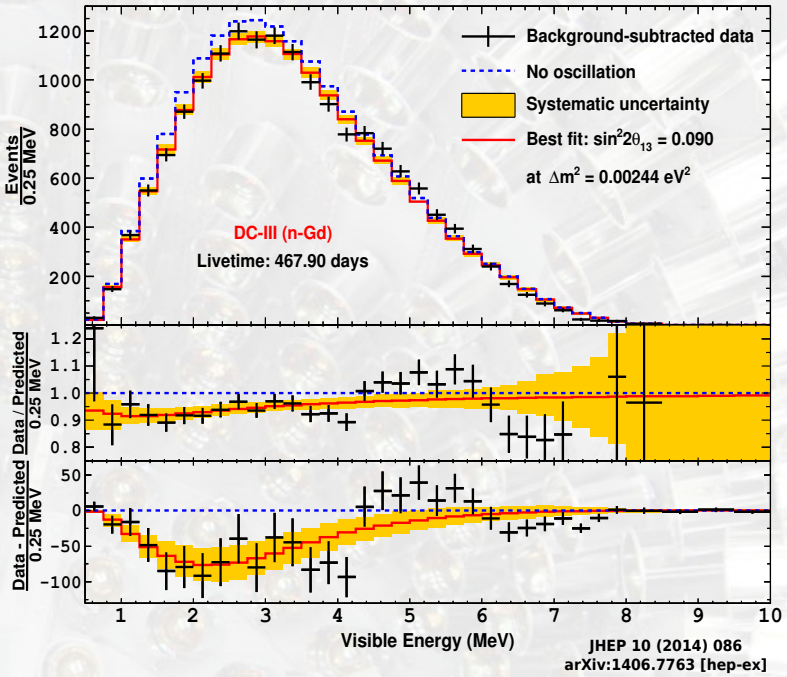


ACCIDENTALS
natural radioactivity: ^{40}K, ^{208}Tl
$\rightarrow$ dominant in H-analysis



Highlight of last Gd analysis (2014)





- new analysis with opened selection (more signal) + new vetos (less background)
- excellent spectral distortion in 0.5 – 4 MeV region constraining θ_{13} fit

  $\sin^2(2\theta_{13}) = 0.090\ ^{+0.032}_{-0.029}$ previous Gd results: 0.109 ± 0.039
- unexpected E/L structure > 4 MeV (only published experimental observation)

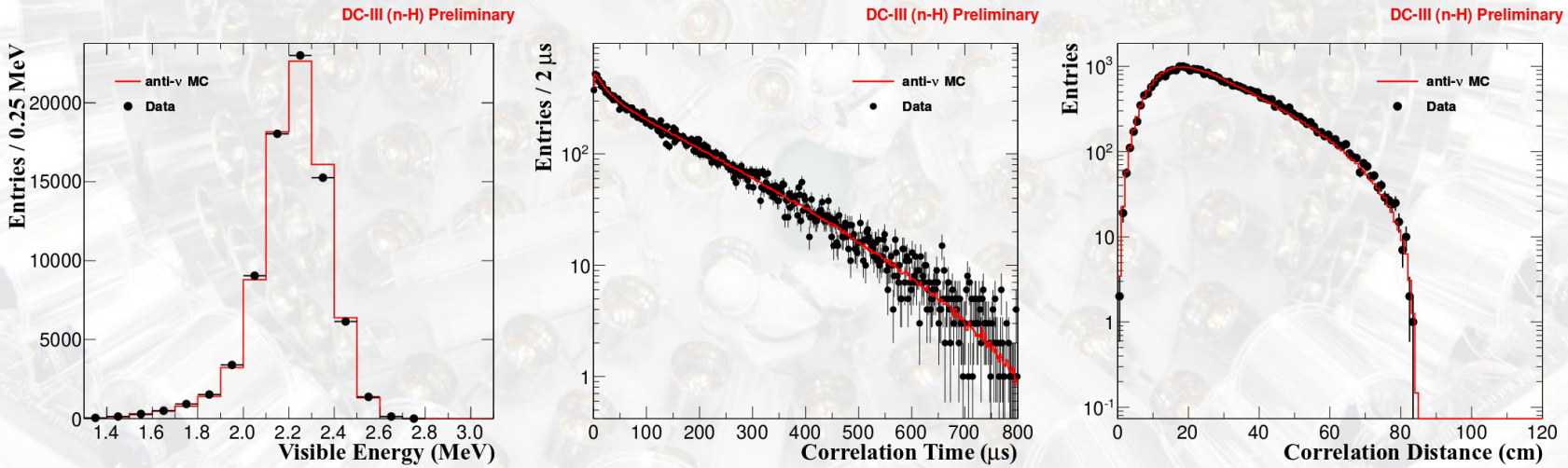
New H analysis "H-III" (2015)

Alternative channel to Gd (main) with independant data sample

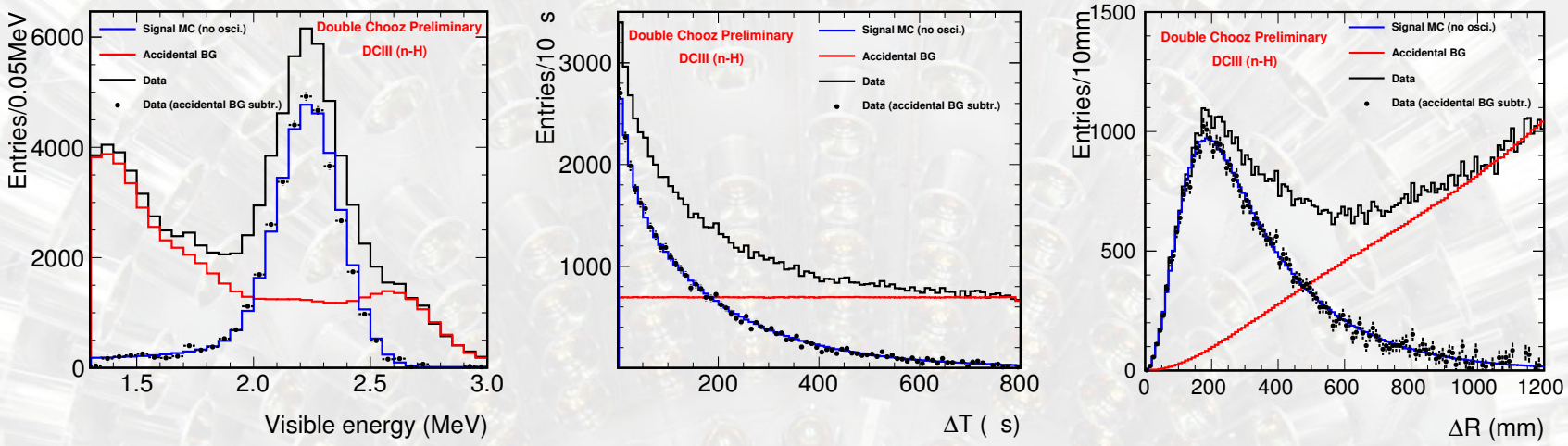
	H-II (2013)	H-III (2015)
Prompt Energy	0.7 – 12.2 MeV	1.0 – 20 MeV
Delayed Energy	1.5 – 3.0 MeV	1.3 – 3 MeV
Δ t	10 – 600 μs	0.5 – 800 μs
Δ R	$<$ 0.9 m	$<$ 1.2 m
isolation window	[-600, +1000] μs	[-800, +900] μs

- **muon veto:** $\Delta t_{last-\mu} > 1.25$ ms
- **OV veto:** no OV hit coincident with prompt
- **^{9}Li veto:** likelihood method trained with ^{12}B
- **"FV" veto:** reject stopping muons
- **IV veto:** reject fast-neutrons and accidentals
- **ANN:** reject accidentals ***NEW***
- **MPS veto:** reject fast-neutrons ***NEW***

H-III analysis benefits previous improvement from last Gd analysis (2014)

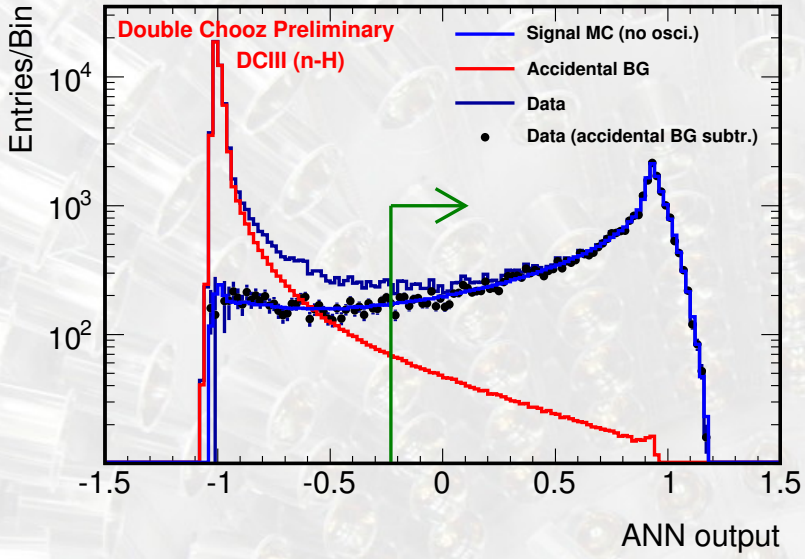


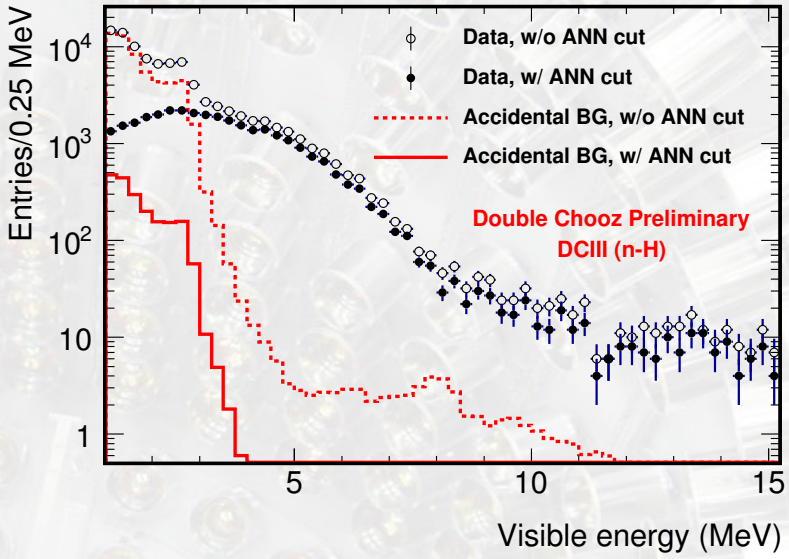
Neural Network for accidental background rejection (ANN)



- **multiple variable analysis** instead of cut-based approach
- input: delayed energy, time and space correlation
- maximise signal/background for unprecedented accidental reduction

Neural Network for accidental background rejection (ANN)



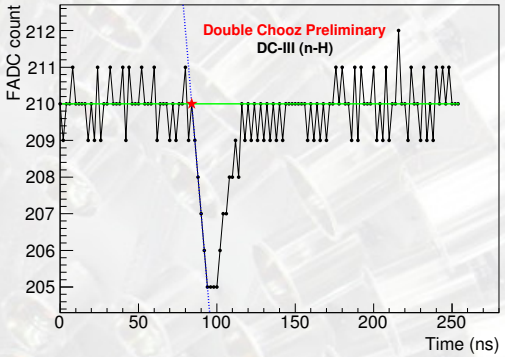


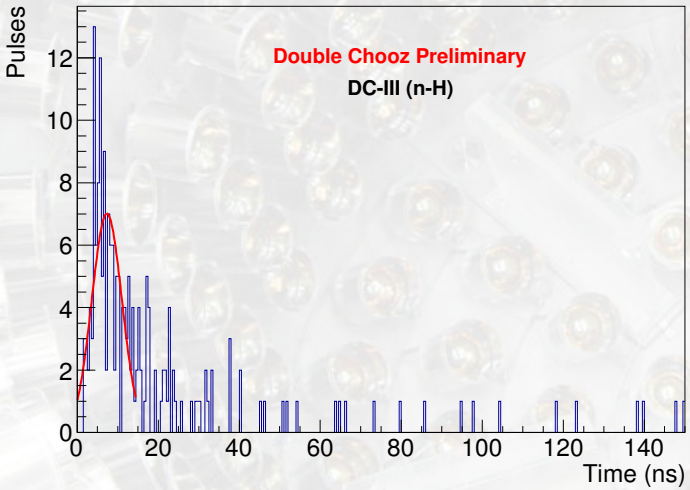
- **multiple variable analysis** instead of cut-based approach
- input: delayed energy, time and space correlation
- maximise signal/background for unprecedented accidental reduction

H-II: 73.45 $\pm$ 0.16 events/day
H-III: 4.334 $\pm$ 0.011 events/day (17x less)

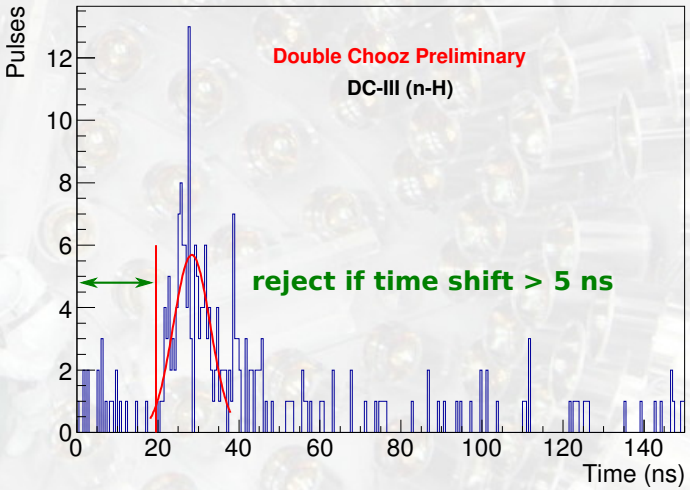
Multiplicity Pulse Shape veto (MPS)

- μ producing multiple fast-neutrons in rocks
- proton recoil mimics prompt signal
- additionnal pulses (low energy p-recoil) recorded within 256 ns $\rightarrow$ exploit power of FADC





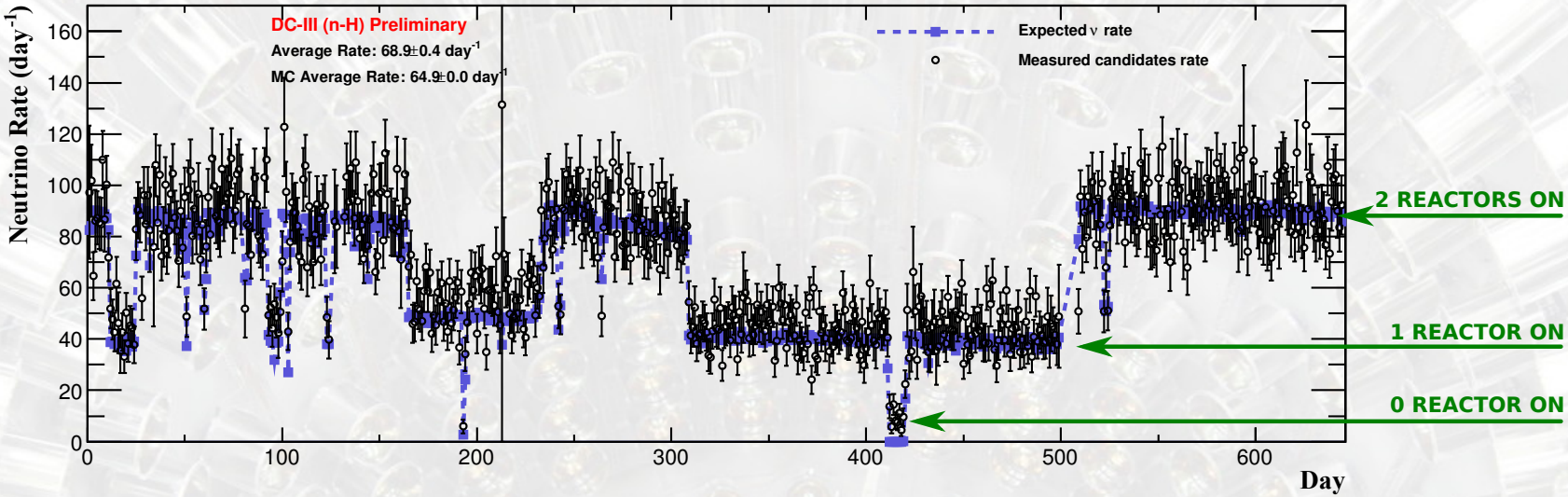
IBD event

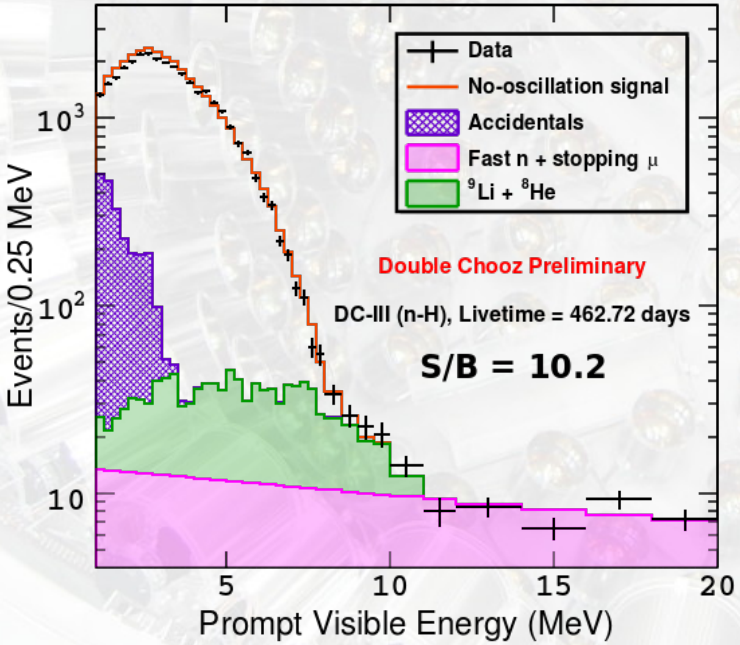


fast neutron event

MPS veto rejects $\sim$ 25 % of fast-neutron background

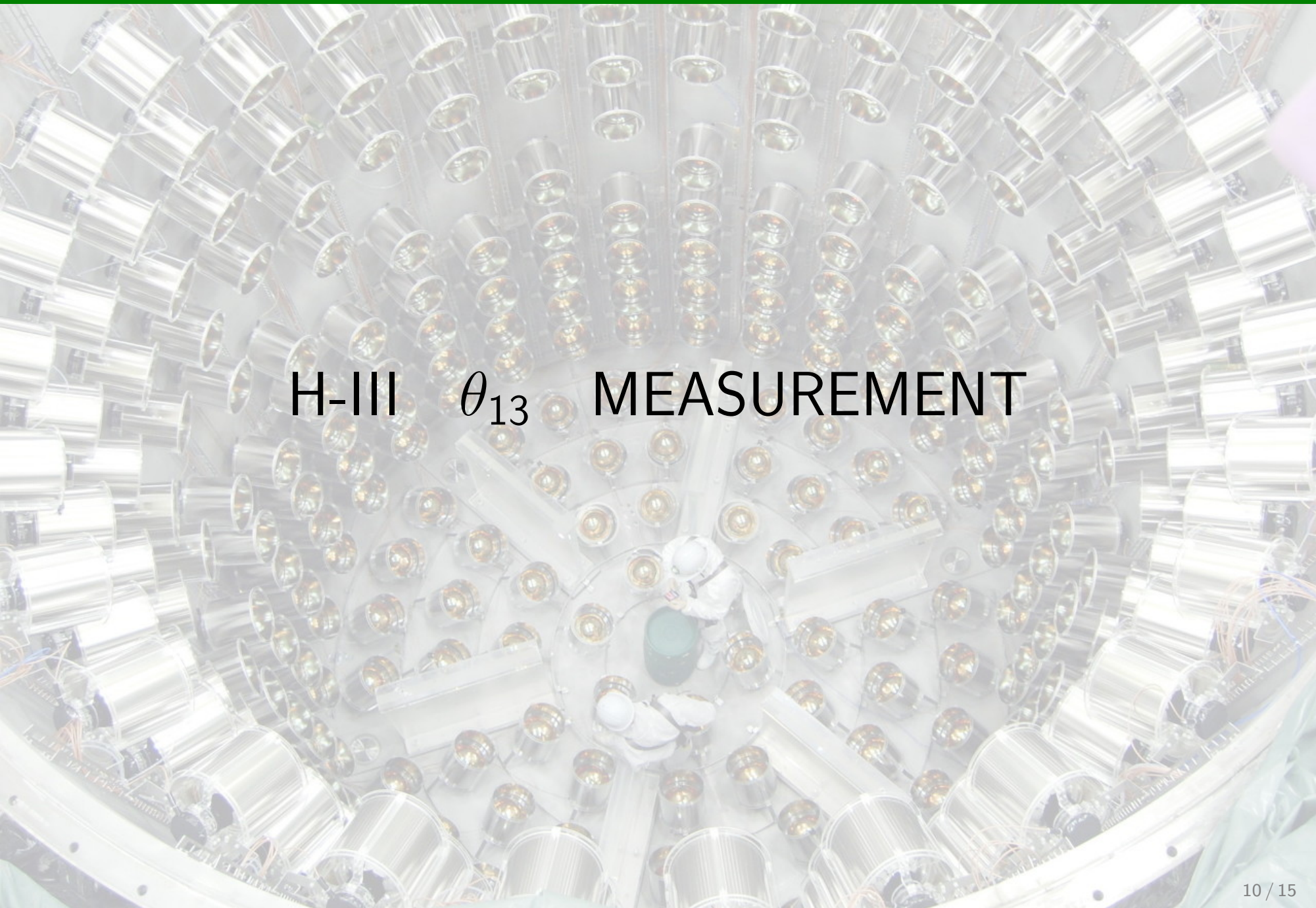
H-III neutrino candidates, background and systematics





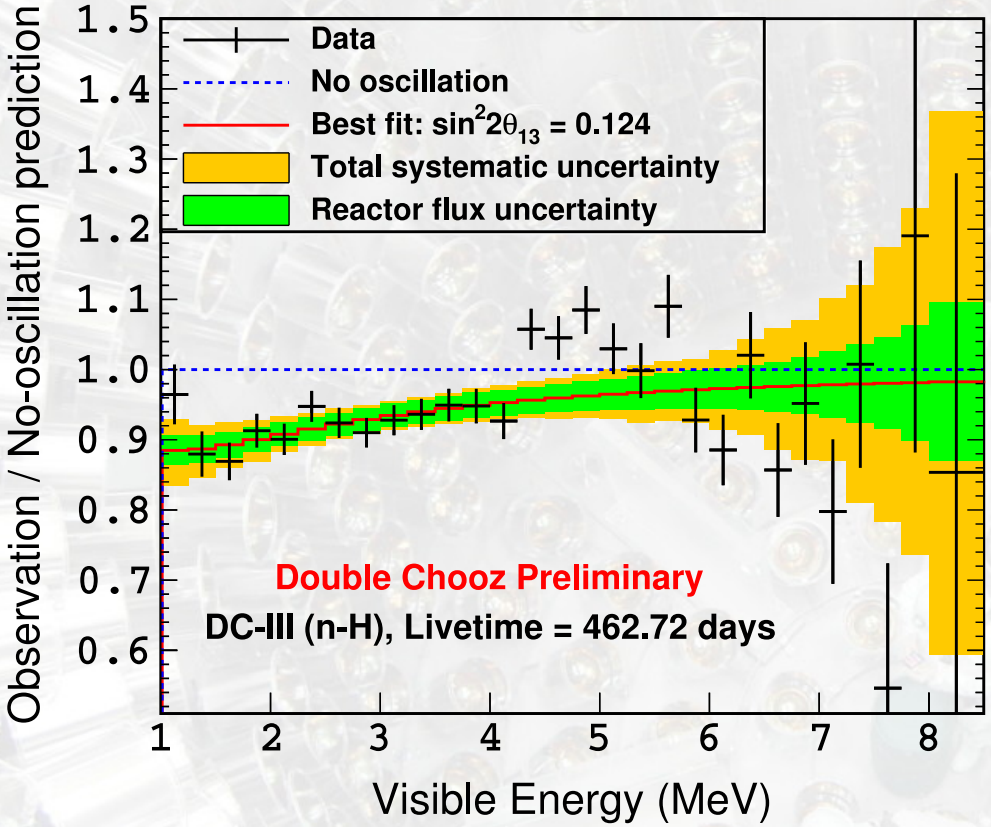
Background	H-II (d^{-1})	H-III (d^{-1})
Accidental	73.45 ± 0.16	4.33 ± 0.01
Cosmogenic ^{9}Li/^{8}He	2.8 ± 1.2	$0.95^{+0.57}_{-0.33}$
Fast-n + Stopping muons	3.17 ± 0.54	1.55 ± 0.15
Total	79.4±1.3	$6.83^{+0.59}_{-0.36}$

Source	Uncertainty
Reactor flux	1.73 %
Statistics	0.60 %
Detection efficiency	1.00 %
Accidental BG	0.02 %
^{9}Li + ^{8}He BG	+0.86 % / -0.50 %
Fast-n and stop-μ BG	0.23 %
Total	+2.28 % / -2.18 %



H-III θ_{13} MEASUREMENT

H-III rate + shape result



$$\sin^2(2\theta_{13}) = 0.124\ ^{+0.030}_{-0.039}$$

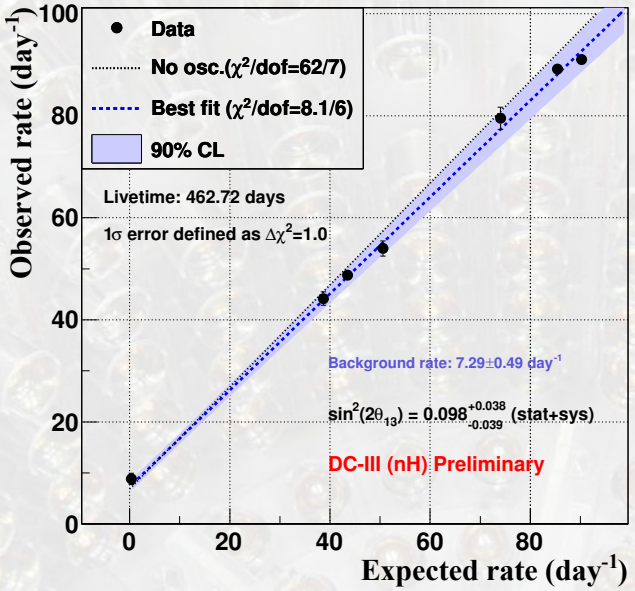
Gd-III: $0.090\ ^{+0.032}_{-0.029}$

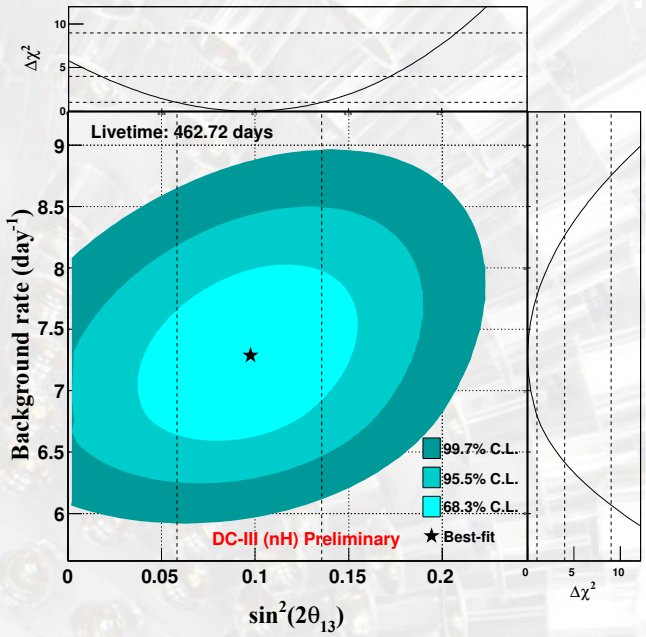
H-II: 0.097 ± 0.048

deviation in 4–6 MeV similair with the Gd-III one reported

(result for cross-check only)

H-III Reactor Rate Modulation (RRM) result





- independent measurement of θ_{13} (slope)
- constraint with background model to increase precision

$\sin^2(2\theta_{13}) = 0.098\ ^{+0.038}_{-0.039}$ background $= 7.29 \pm 0.49$ /day

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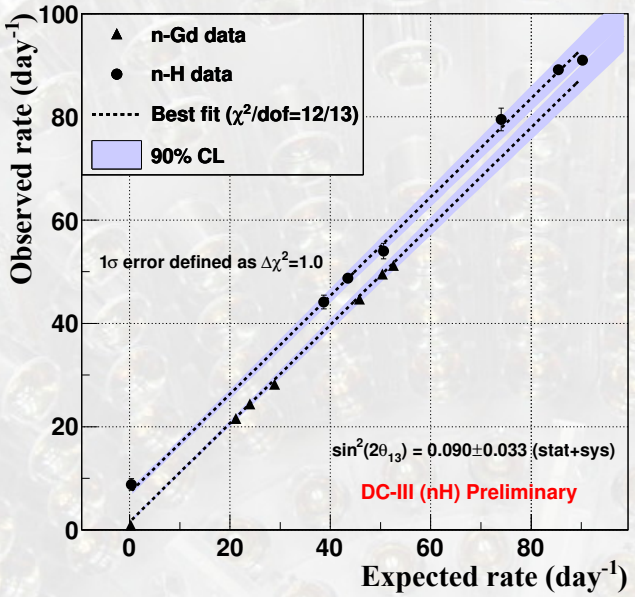
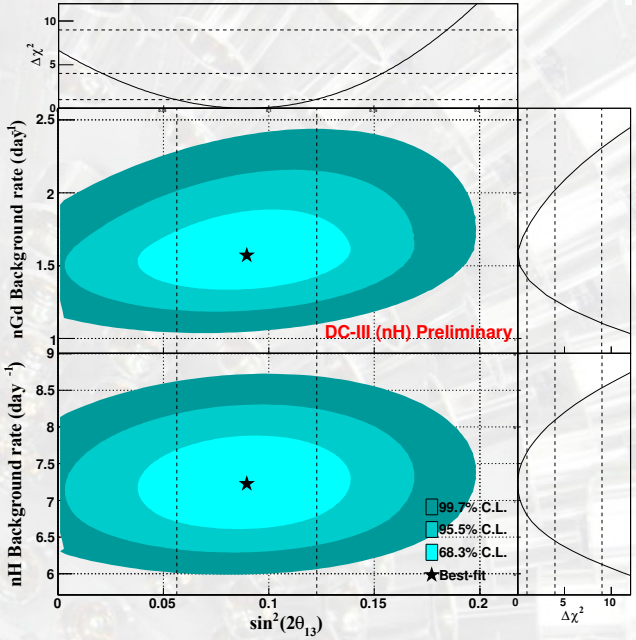




- independent measurement of θ_{13} (slope)
- constraint with background model to increase precision

$\sin^2(2\theta_{13}) = 0.098\ ^{+0.038}_{-0.039}$ background $= 7.29 \pm 0.49$ /day

- combination Gd-III + H-III: $\sin^2(2\theta_{13}) = 0.090 \pm 0.033$
  Gd-III only: $\sin^2(2\theta_{13}) = 0.090\ ^{+0.034}_{-0.035}$

Conclusion and outlook

New analysis with n-H channel (far detector only)

- validation and cross-check of Gd-III measurement (2014)
- RRM analysis: $\sin^2(2\theta_{13}) = 0.098\ ^{+0.038}_{-0.039}$
- combined fit Gd+H RRM: $\sin^2(2\theta_{13}) = 0.090 \pm 0.033$
- verification of E/L distortion with independent data set and detection volume

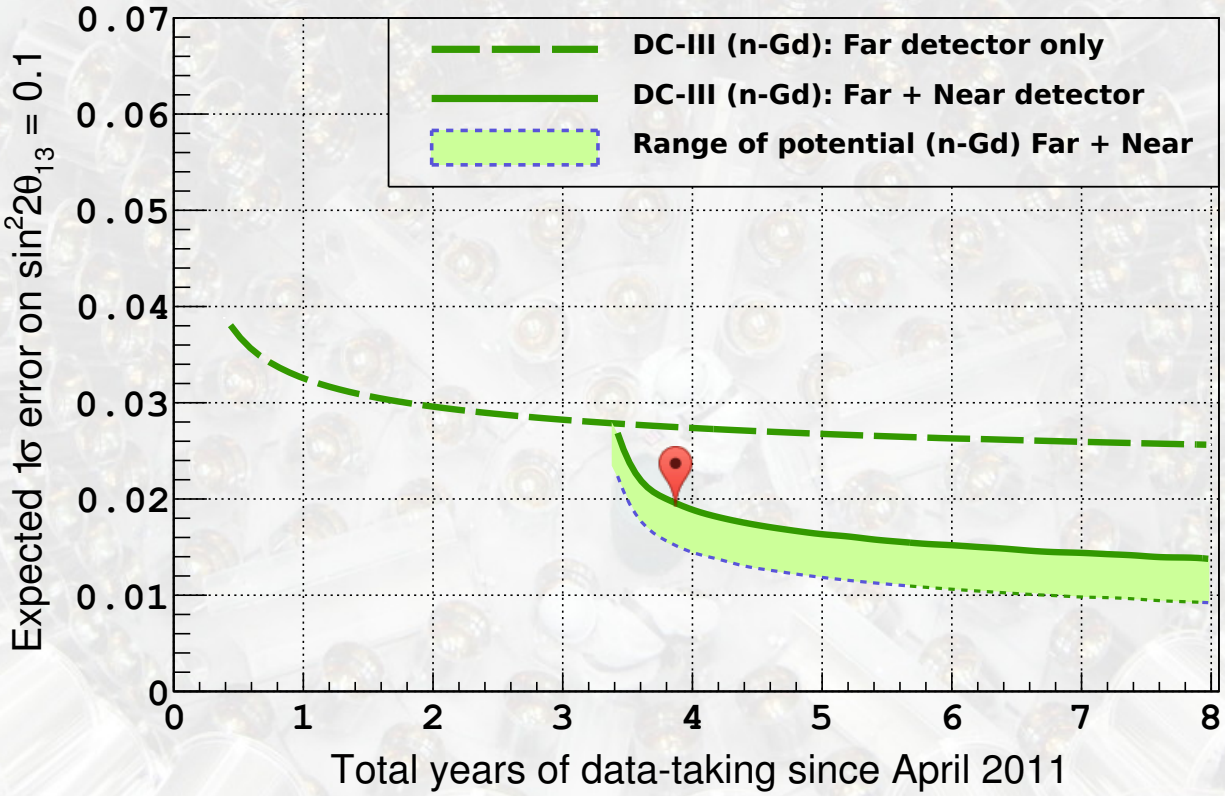
Instrumentation

- novel powerful techniques for low background IBD selection
- accidentals reduced by > 10x with negligible impact on syst. and stat. errors

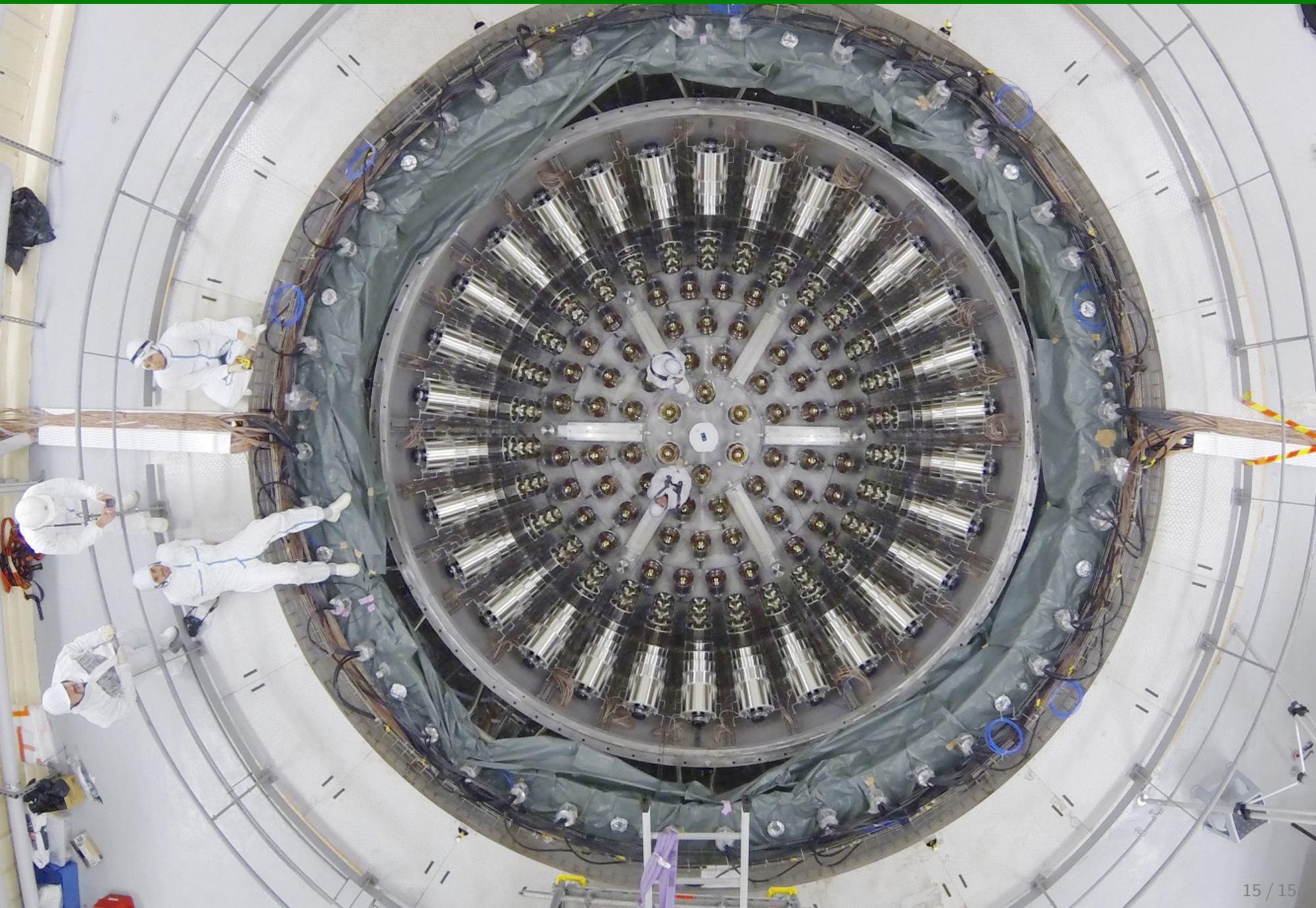
  $\rightarrow$ Double Chooz demonstrates capability of precision measurement of reactor neutrinos with Hydrogen and narrow overburden (Gd still better)

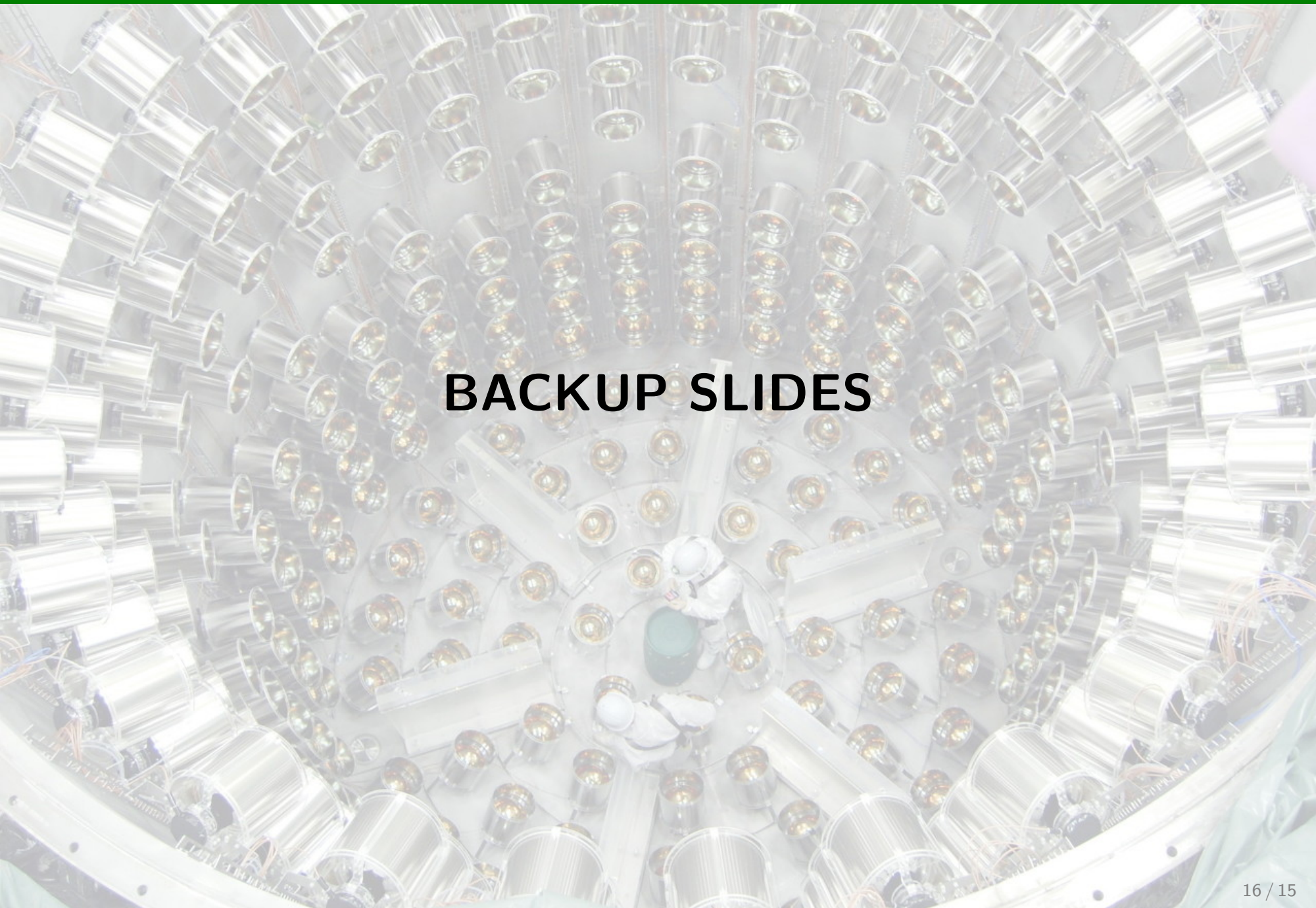
Conclusion and outlook

- Near detector operating since January 2015
- working on two detector analysis to challenge 10 % 1σ-error within $\sim$ 3 years
- more prospects with ND data: one reactor spectrum, cosmogenetic isotope, etc.



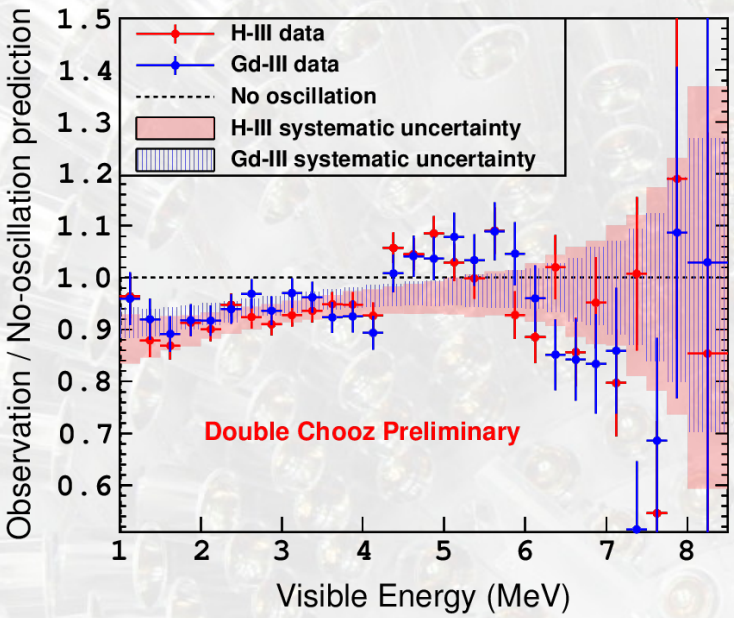
THANKS FOR YOUR ATTENTION

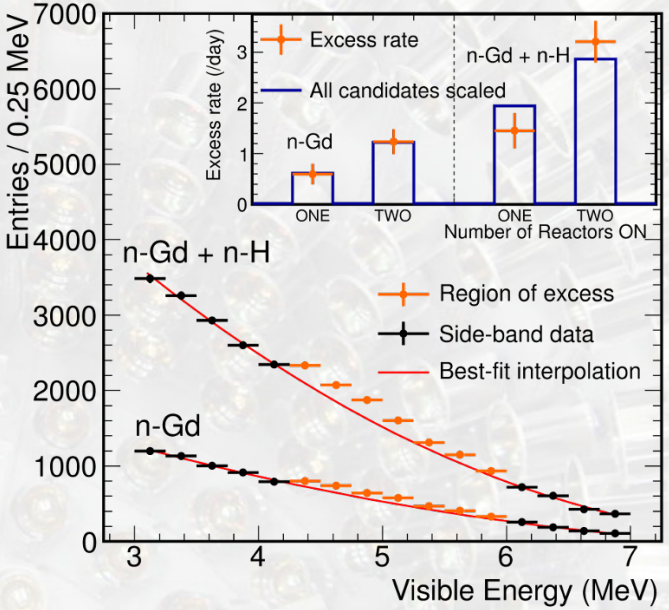




BACKUP SLIDES

4–6 MeV distortion

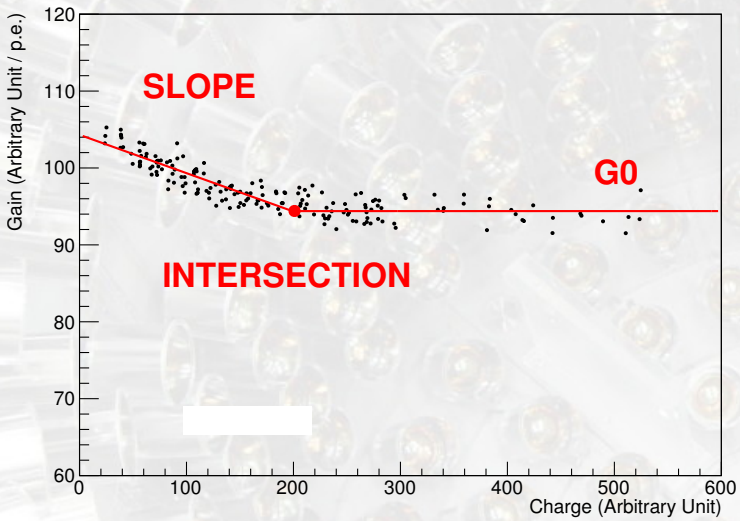




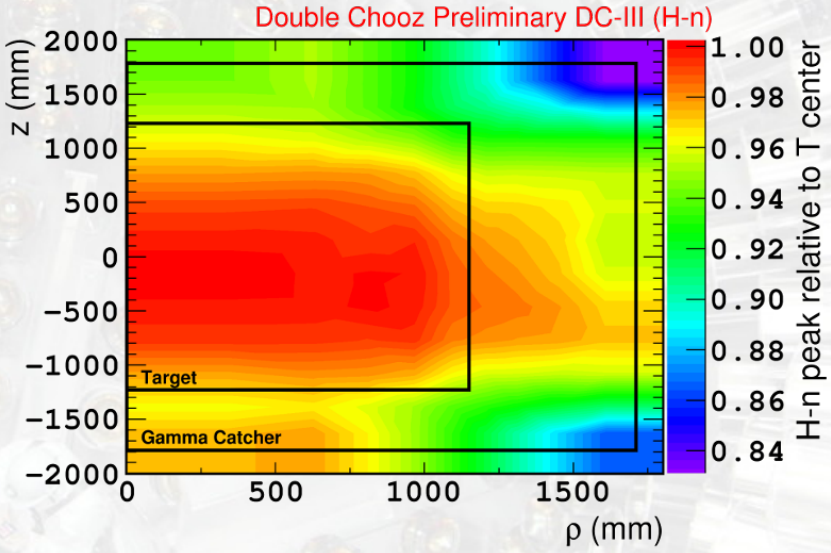
- consistent feature in Gd and H channels (different volume and background)
- excess in 4–6 MeV region correlated with reactor power
- ongoing research and discussion in the community

Energy reconstruction

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



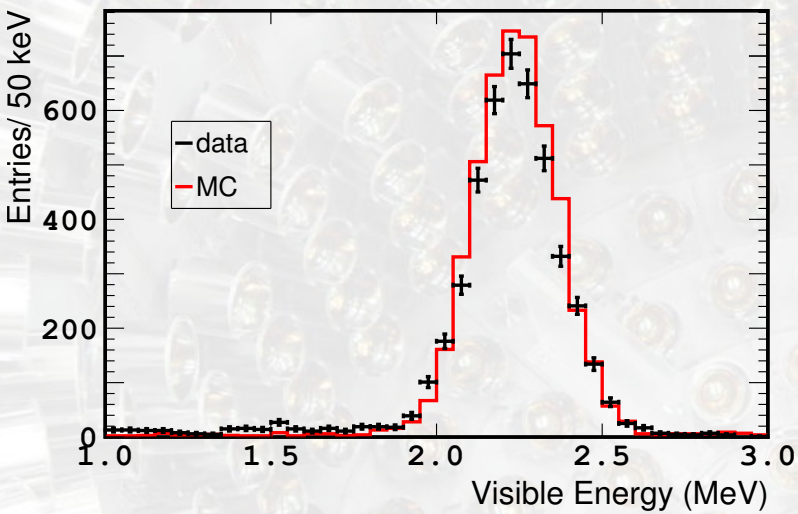
N_{pe} : Charge to PE
non linearity correction

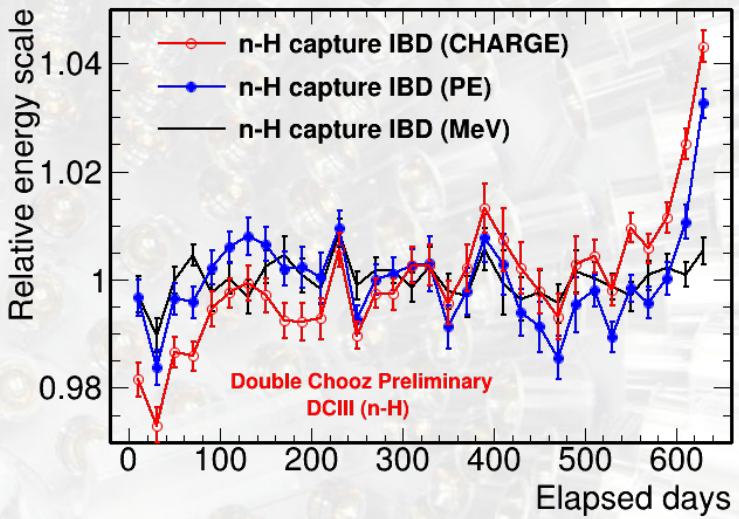


$f_u(\rho, z)$: non-uniformity correction

Energy reconstruction

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

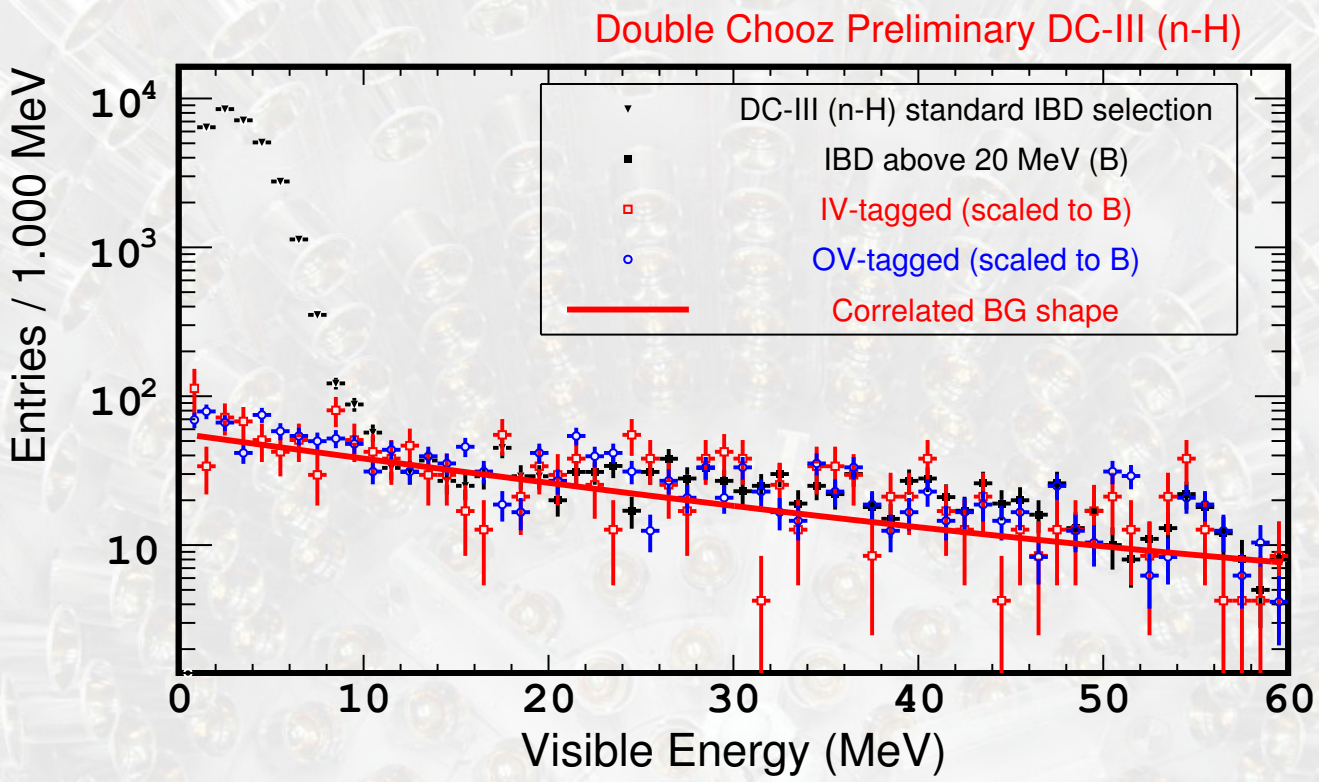




$f_{PE/MeV}$: absolute PE to MeV scale using ^{252}Cf @ center

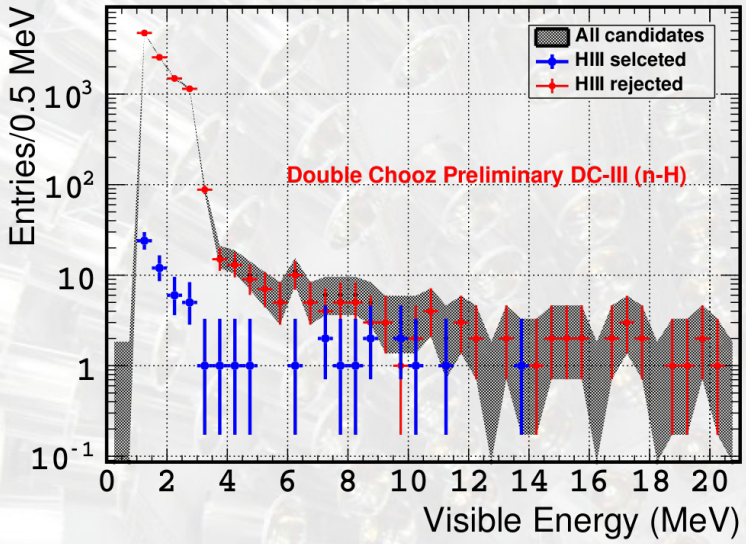
$f_s^{data}(E_{vis}, t)$: time stability correction

Correlated background



- data driven measurement
- exponentional shape in H channel (flat for Gd)
- includes a negligible proportion of stopping muons

H-III OFF-OFF data



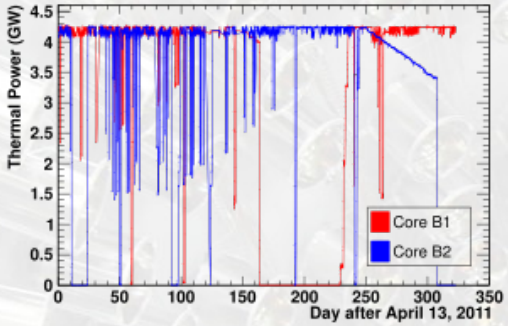
	all events	>12 MeV
before vetos	10185	23
after vetos	63	1
rejection	160x	23x

- expected rate: $7.05^{+0.6}_{-0.4}$ events/day (residual neutrino = 0.33 ± 0.10)
- measured rate: 8.8 ± 1.1 events/day

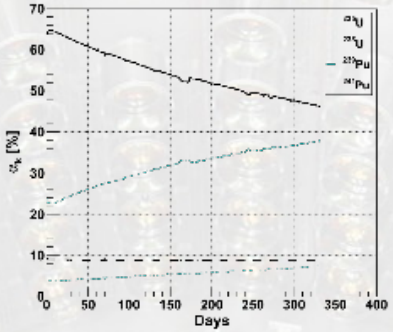
  → demonstration of the rejection of power of our selection

  → validation of our background model

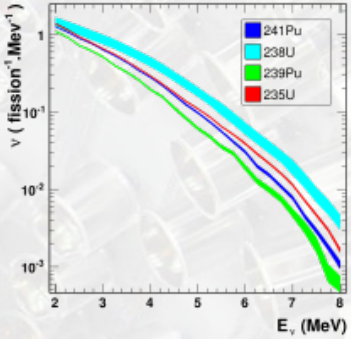
Reactor flux prediction



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)

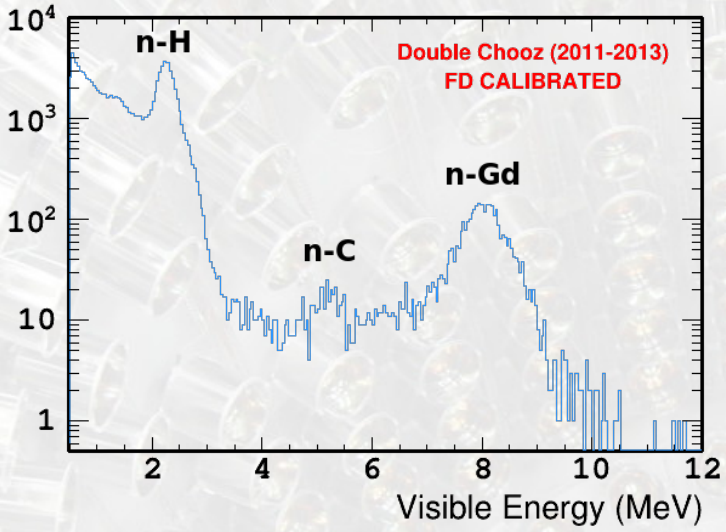
$$N_i = \frac{\epsilon N_p}{4\pi} \sum_R \frac{1}{L_R^2} \frac{\mathbf{P_{th}^R}}{\langle \mathbf{E_f} \rangle_\mathbf{R}} \left(\frac{\langle \boldsymbol{\sigma}_\mathbf{f} \rangle_\mathbf{R}}{\sum_\mathbf{k} \boldsymbol{\alpha}_\mathbf{k}^\mathbf{R} \langle \boldsymbol{\sigma}_\mathbf{f} \rangle_\mathbf{k}}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

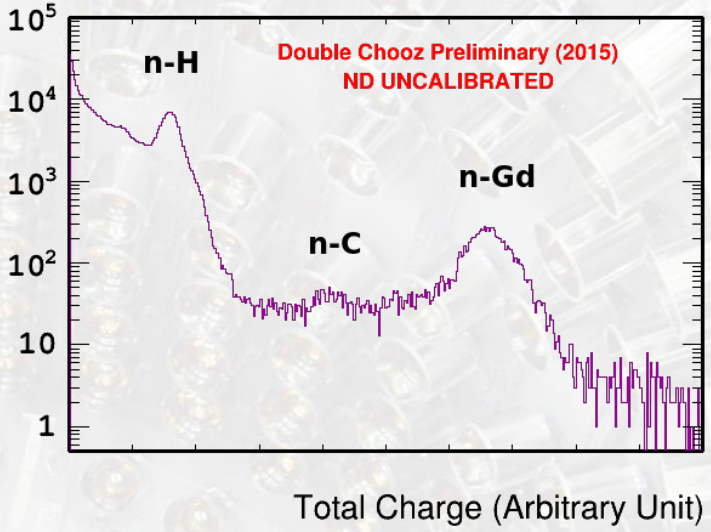
Bugey4 "anchor": $\langle \sigma_f \rangle_R = \langle \sigma_f \rangle_{Bugey} + \sum_k \left(\alpha_k - \alpha_k^{Bugey} \right) \langle \sigma_f \rangle_k$

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

First ND data





Spectrum of spallation neutron captures following crossing muons

Early uncalibrated ND data demonstrating:

- feasibility of IBD measurement and quality/similarities of the two detectors
- illustration of energy reconstruction (from ND to FD)
- preliminary study of singles in ND indicates a similar rate as in FD
  $\rightarrow$ goals in term of radiopurity and shielding are achieved