Latest results of the Double Chooz reactor neutrino experiment

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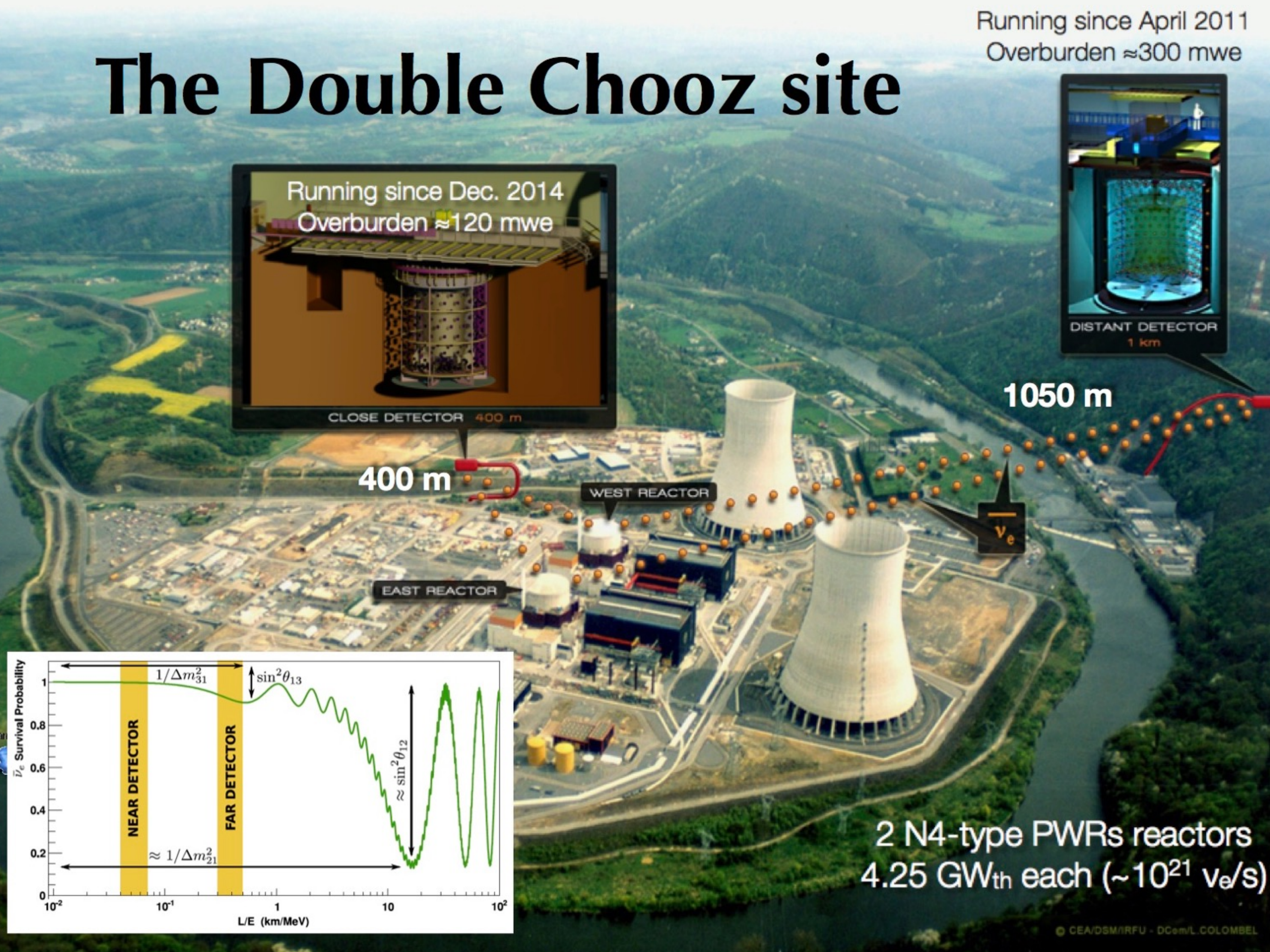
Rencontres du Vietnam 2017, Quy Nhon

The Double Chooz site



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

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

RUSSIA
INR RAS
IPC RAS
RRC Kurchatov

SPAIN
CIEMAT-Madrid

USA
U. Alabama
ANL
U. Chicago
Columbia U.
UC Davis
Drexel U.
IIT
KSU
MIT
U. Notre Dame
U. Tennessee

150 scientists from 7 countries

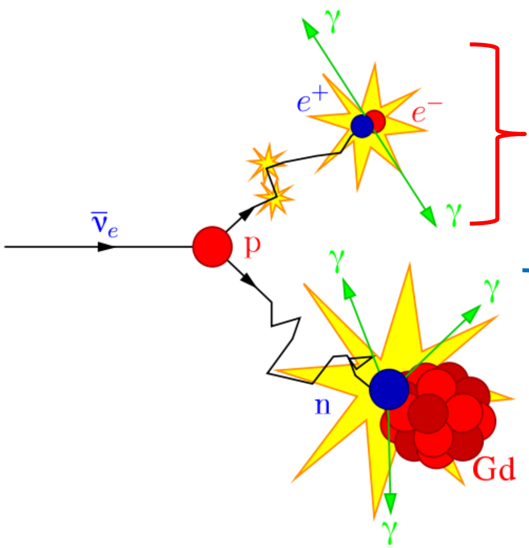
Spokesperson: Hervé de Kerret (CNRS/IN2P3)
Project manager: Christian Veyssière (CEA Saclay)

Detection of antineutrinos

- Detection of antineutrinos through inverse beta decay (IBD) reaction:

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

The golden channel…



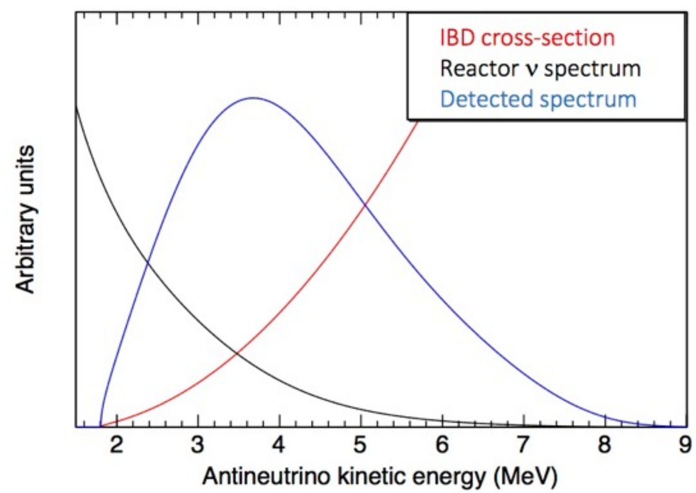
<u>Prompt</u> e^+ energy deposition: ionization + e^+/e^- annihilation $E_{vis} \approx E(\nu_e) - 0.782$ MeV

<u>Delayed</u> energy deposition: 8 MeV (resp. 2.2 MeV) γ-ray cascade from neutron capture on Gd (resp. H)

<u>Time/space correlation:</u>

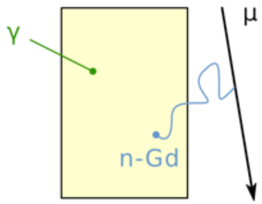
n-Gd: $\Delta t \approx 30\ \mu s$
n-H: $\Delta t \approx 200\ \mu s$

- Threshold reaction: $E_\nu \geq 1.8$ MeV
- Relatively high cross-section ($\sigma_{IBD} \approx 10^{-42}\ E_\nu^2\ cm^2$) compared to other detection channels
- Time/space coincidence between e^+ and neutron signal allows a strong suppression of backgrounds



Backgrounds

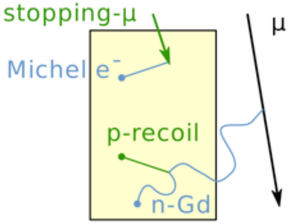
Accidental coincidences



Random coincidences between prompt-like & delayed-like energy depositions:

- Prompt: gammas from radioactivity in surrounding materials & rock
- Delay: neutrons from cosmic muons spallation, β decay of cosmogenic isotopes

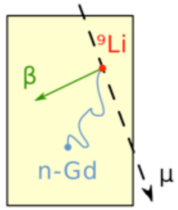
Correlated events



Muon-induced fast neutrons and stopping muons:

- Prompt: recoil proton from fast neutron scattering or muon track
- Delay: neutron capture or Michel e^-

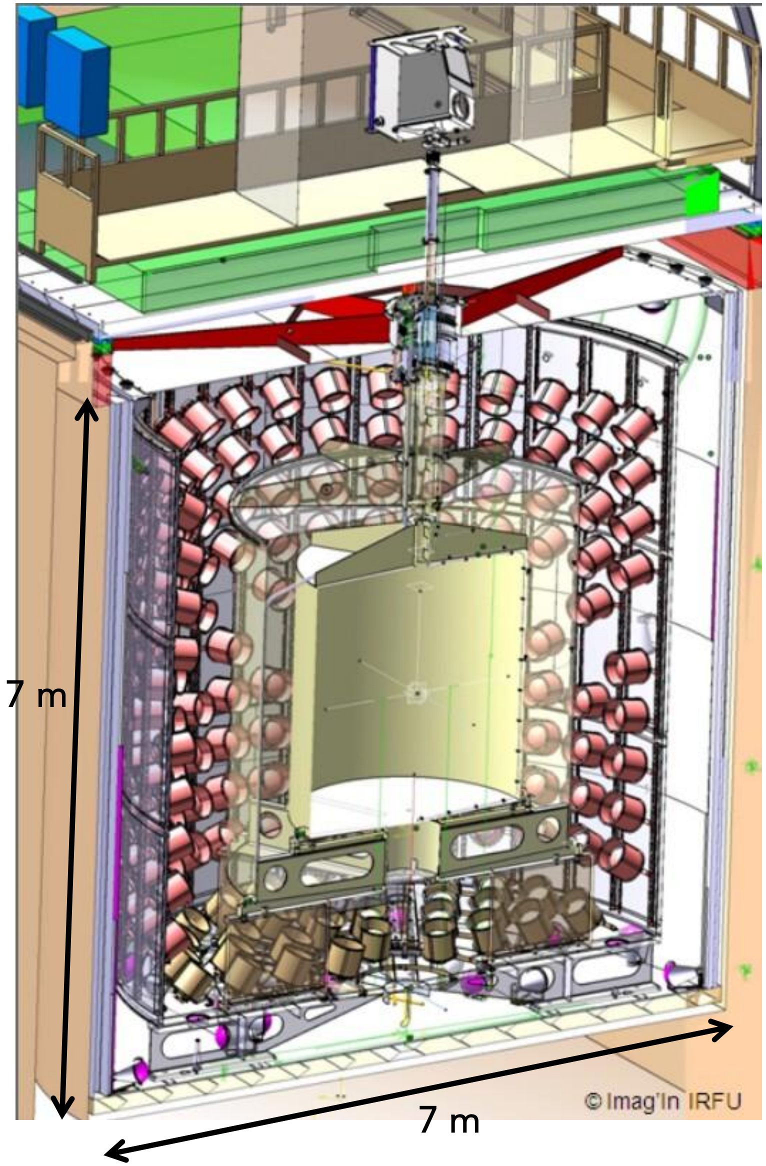
Cosmogenic isotopes



β-n emitters produced by muon spallation (^{9}Li or ^{8}He):

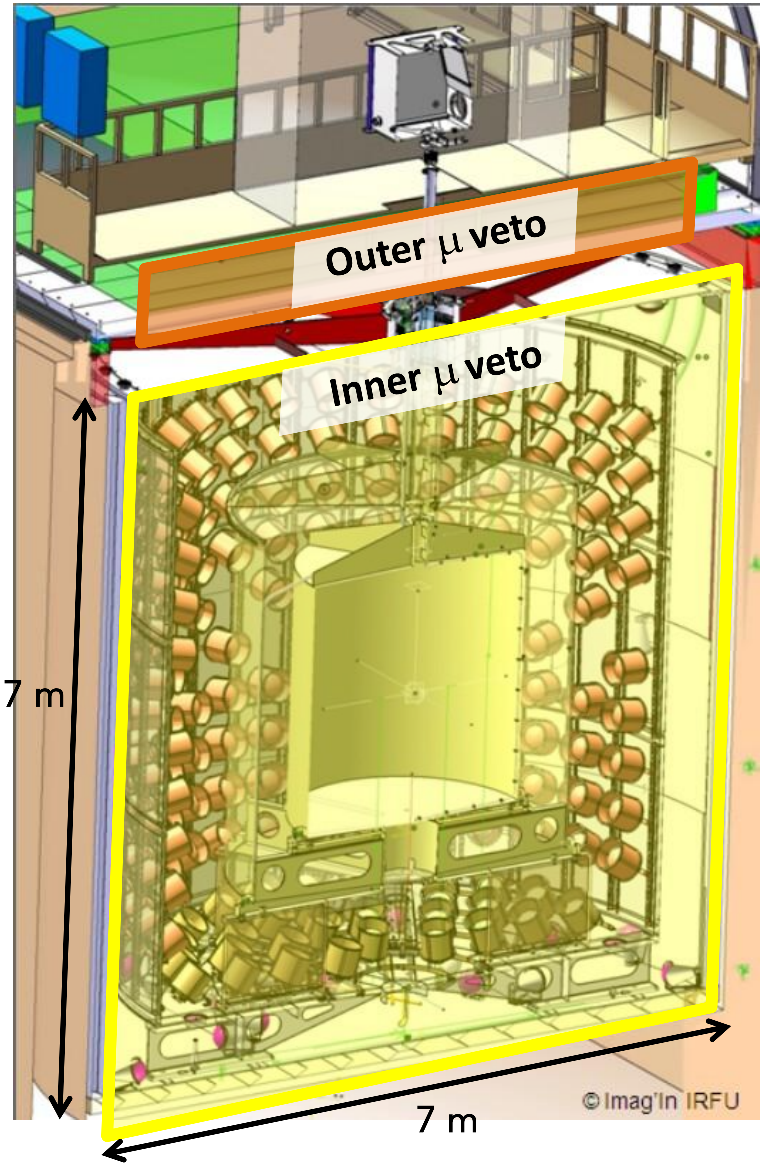
- Prompt: β particle
- Delay: neutron capture

Double Chooz detectors



A concentric arrangement of cylindrical sub-detectors…

Double Chooz detectors

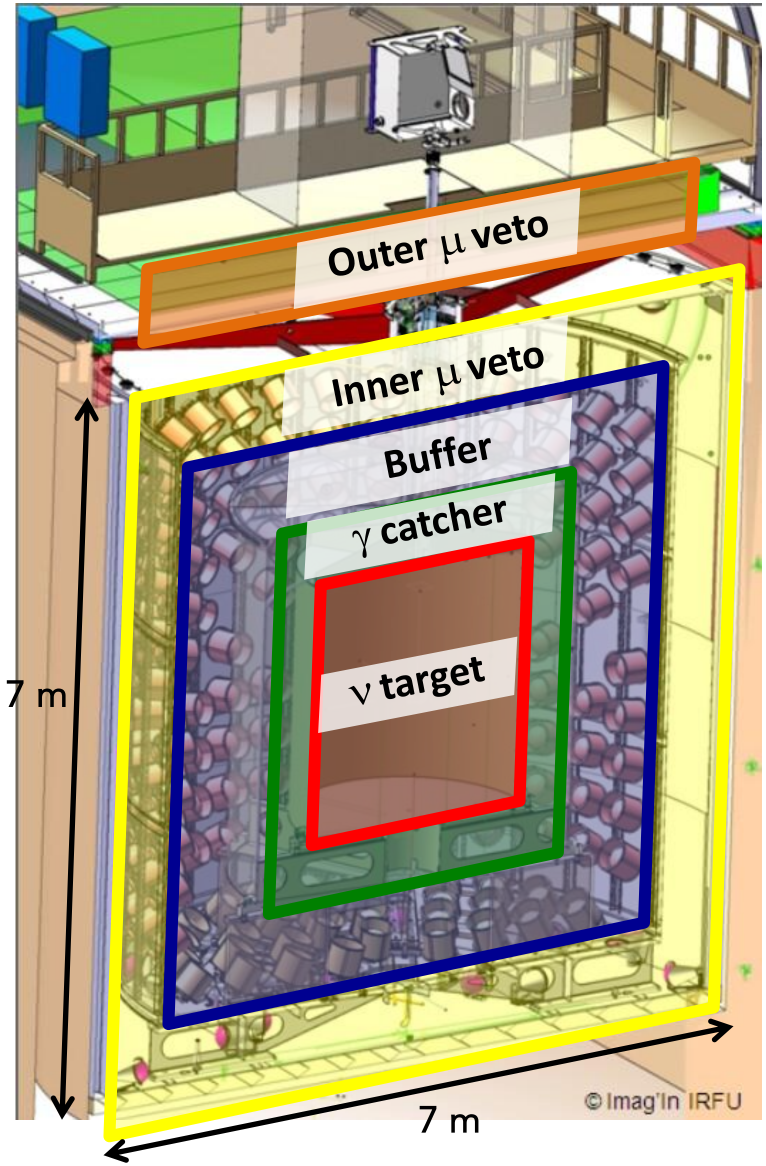


A concentric arrangement of cylindrical sub-detectors…

μ vetoes

- **Outer μ veto:** **plastic scintillator strips**
- **Inner μ veto:** **90 m^3 of LAB scintillator (50 cm thick) in a stainless steel tank equipped with 78 8' PMTs**

Double Chooz detectors



A concentric arrangement of cylindrical sub-detectors…

μ vetoes

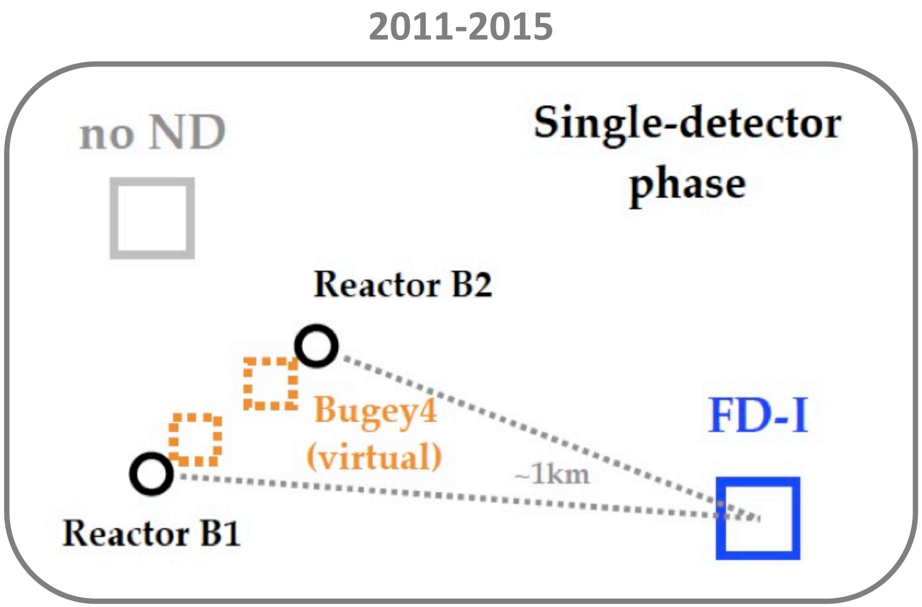
- **Outer μ veto: plastic scintillator strips**
- **Inner μ veto: 90 m³ of LAB scintillator (50 cm thick) in a stainless steel tank equipped with 78 8' PMTs**

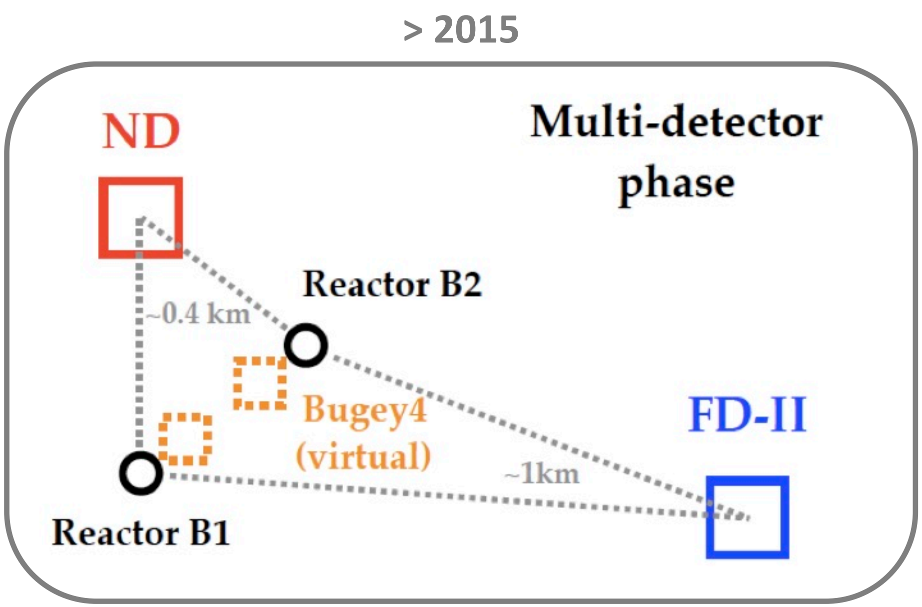
Inner detector (IV)

- **Buffer volume: 100 m³ of transparent mineral oil (105 cm thick) in a stainless steel tank, equipped with 390 low background 10' PMTs**
- **γ catcher: 55 cm thick Gd-free LS (PXE) layer contained in a transparent acrylic vessel**
- **ν target: 10 m³ of Gd-doped LS (PXE + 1 g/L of Gd)**

+ central chimney connected to all layers for calibration source insertion
+ fast readout electronics
+ laser system for PMT gain calibration
+ etc …

Double Chooz configurations

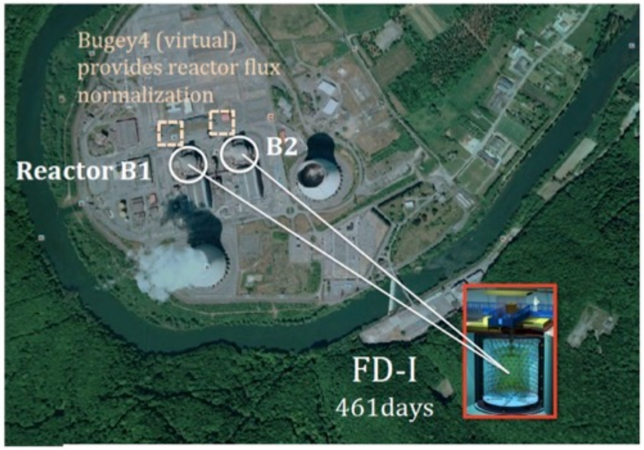




- Two reactors & two detectors
- DC unique features:
  - Nearly isoflux configuration: relative ν flux uncertainties between ND & FD are almost entirely cancelled
  - 7 days of reactor OFF data
- Two phases:
  - Single-detector (SD): ~ 480 days (FD-I only)
  - Multiple-detector (MD): ~ 350 days (FD-II +ND)
- Bugey-4 anchor: Bugey-4 experimental result is used as a virtual ND

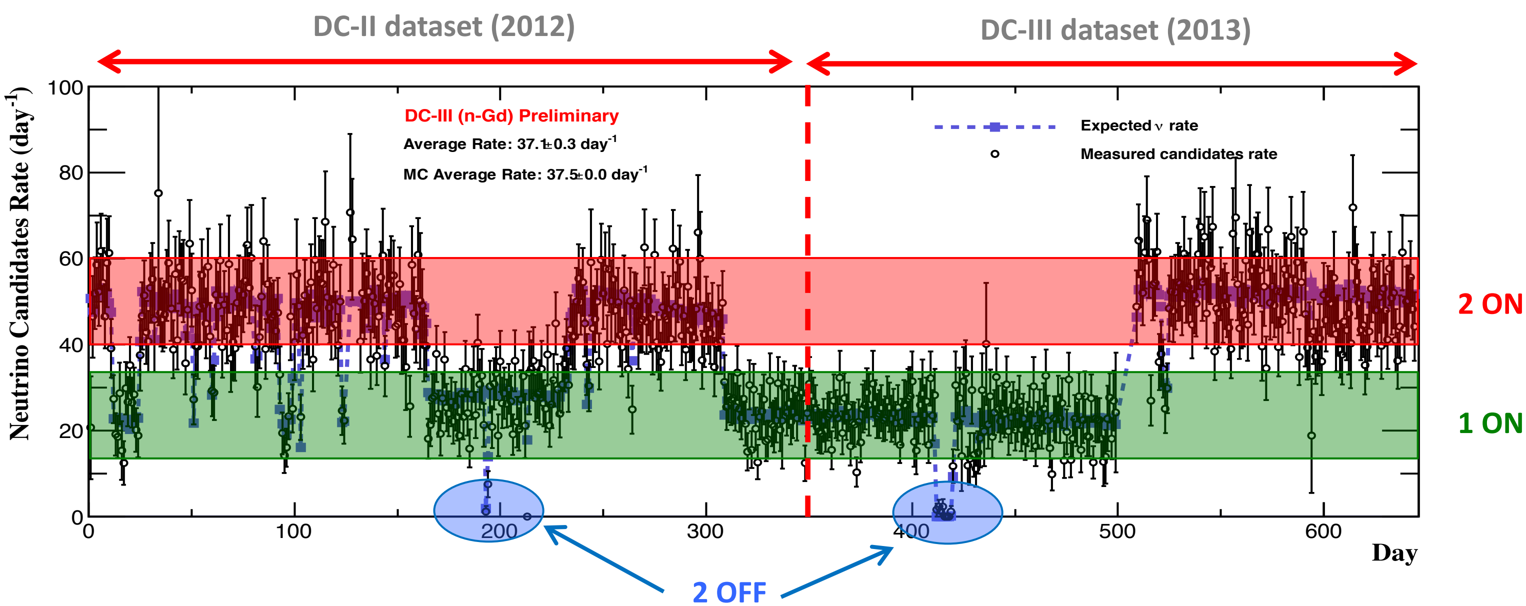
Single-detector analysis

Single detector analysis



n-Gd	Reactor ON (April 2011 – Jan 2013)	Reactor OFF (2011 & 2012)
Live-time (days)	460.67	7.24
Neutrino candidates	17351	7
Total prediction* (bck included)	18290^{+370}_{-330}	$12.9^{+3.1}_{-1.4}$

* Neutrino oscillation not included in the prediction



Two neutrino detection channels

Gadolinium analysis

- Standard analysis
- High cross-section for neutron capture
- Low (accidental) background

Hydrogen analysis

- Factor 2 more statistics (include GC volume)
- Different systematics & backgrounds
- High (accidental) background

DC-III	Gd analysis	H analysis
Muon veto	Δt > 1 ms	Δt > 1.25 ms
Light noise rejection	Q_{max}/Q_{tot} & $RMS(Q_{start})$ conditions	
E_{prompt}	0.5 – 20.0 MeV	1.0 – 20.0 MeV
$E_{delayed}$	4.0 – 10.0 MeV	1.3 – 3.0 MeV
Δt	0.5 – 150 μs	0.5 – 800 μs
ΔR	< 1 m	< 1.2 m
ANN	-	≥ -0.23
Multiplicity	No additional trigger around signal	
Vetoes	OV veto, FV veto, Li veto, IV veto	
Signal/Bck	~ 23	~ 10

Two neutrino detection channels

Gadolinium analysis

- Standard analysis
- High cross-section for neutron capture
- Low (accidental) background

Hydrogen analysis

- Factor 2 more statistics (include GC volume)
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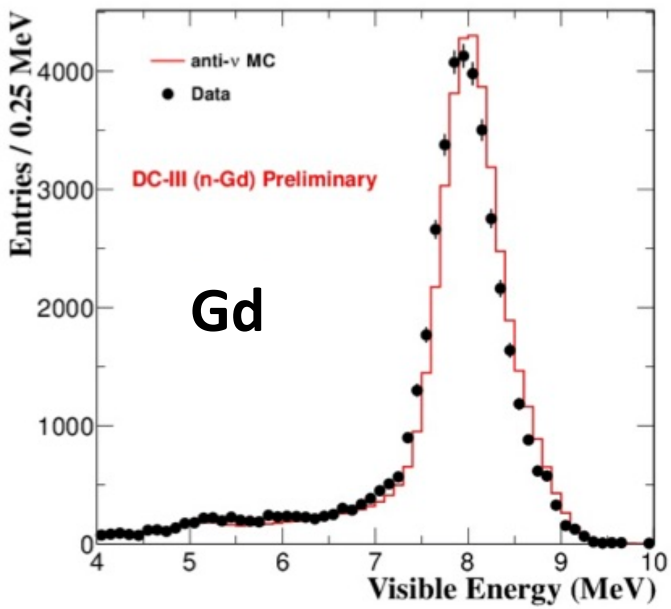
Complementary analyses



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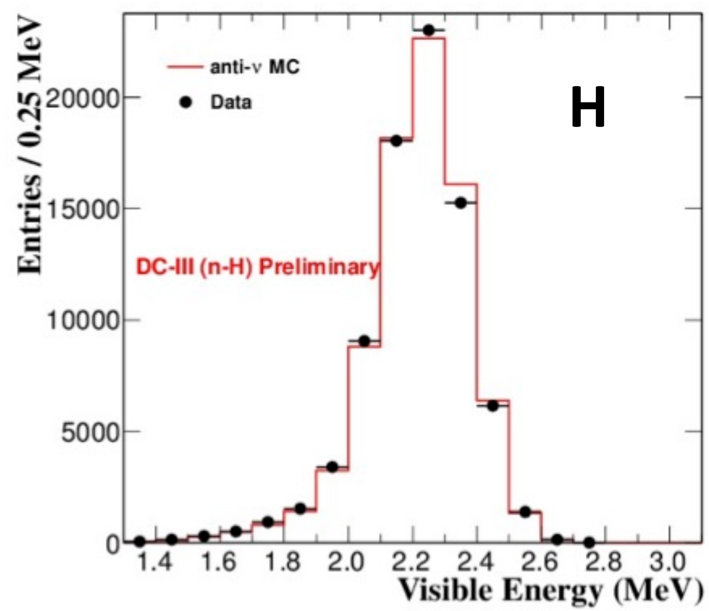

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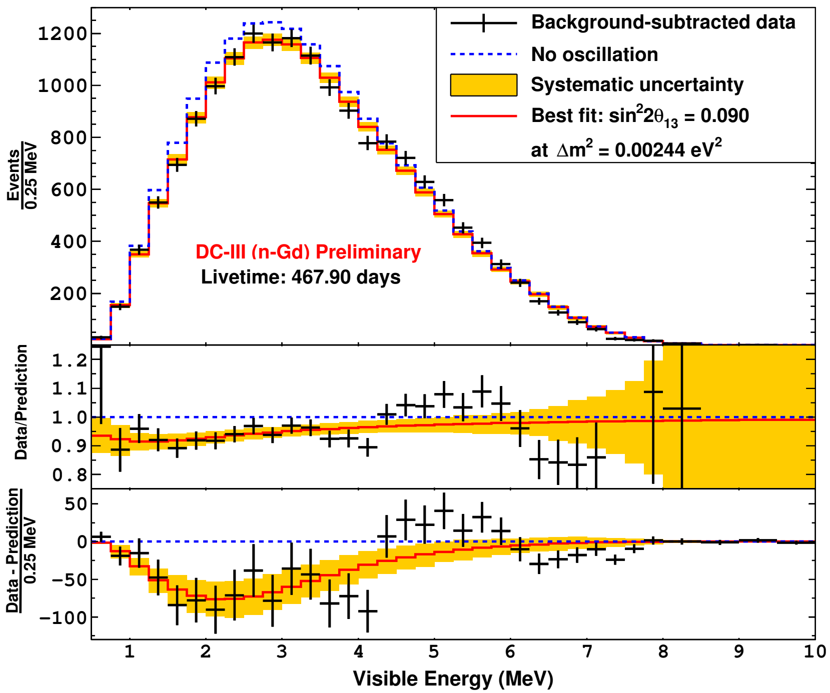
Single-detector results

Gadolinium analysis

Rate + shape fit to n-Gd IBD spectrum



$\sin^2(2\theta_{13}) = 0.090^{+0.032}_{-0.029}$ (stat. + syst.)
$\chi^2_{min}/n_{dof} = 52.2/40$

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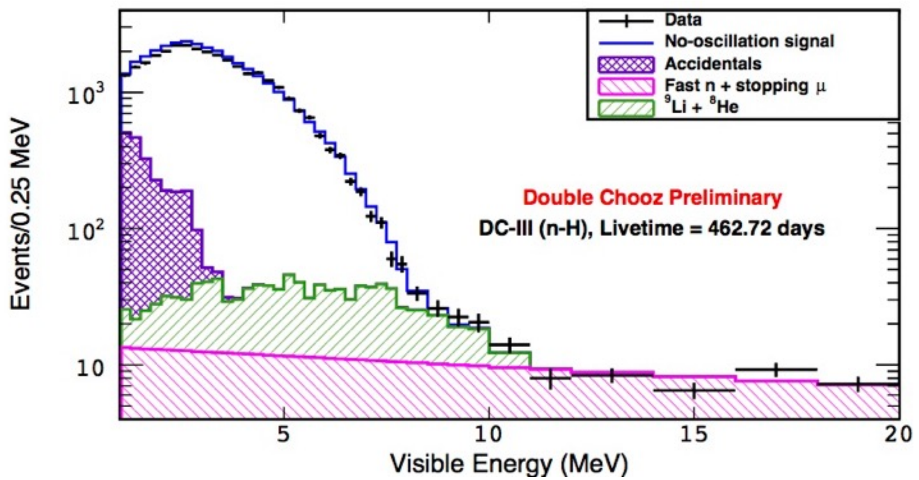
Hydrogen analysis

Rate + shape fit to n-H IBD spectrum



$\sin^2(2\theta_{13}) = 0.124^{+0.030}_{-0.039}$ (stat. + syst.)
$\chi^2_{min}/n_{dof} = 69.4/38$

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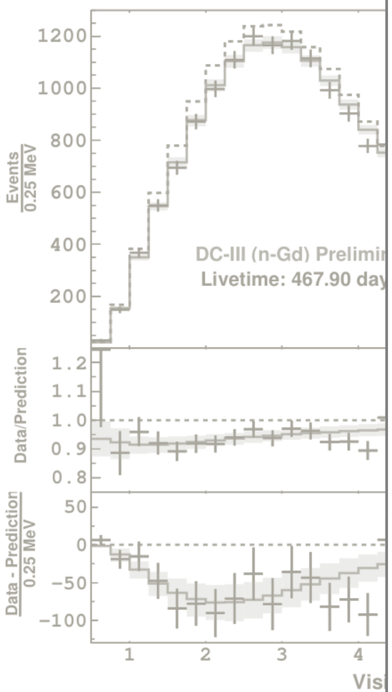
Single-detector results

Gadolinium analysis

Hydrogen analysis

Rate + shape fit t



$\sin^2(2\theta_{13})$ = 0.

χ^2_{mi}

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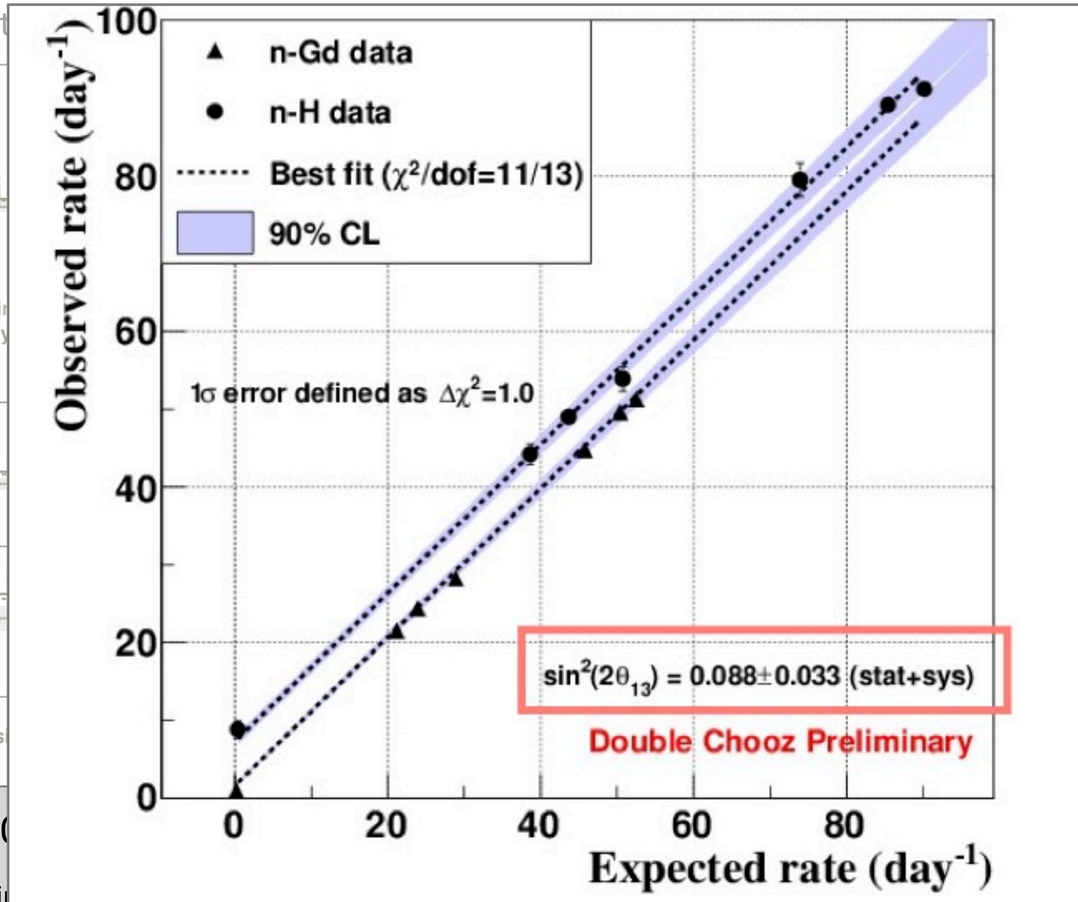
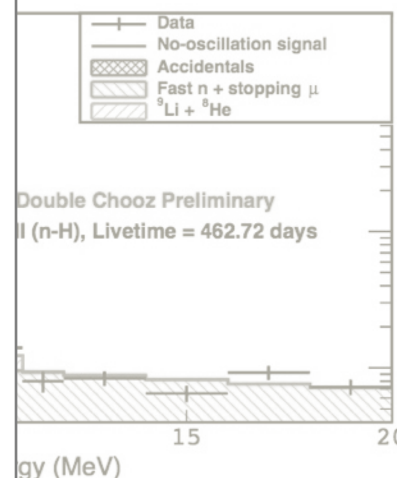
Reactor rate modulation analysis



Gd IBD spectrum



$.030_{-0.039}$ (stat. + syst.)

= 69.4/38

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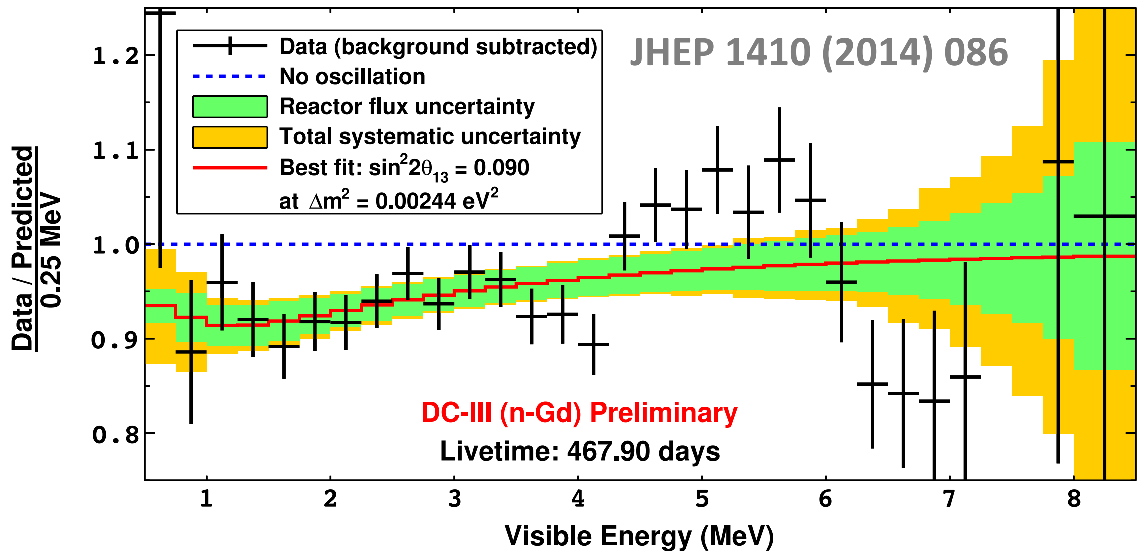
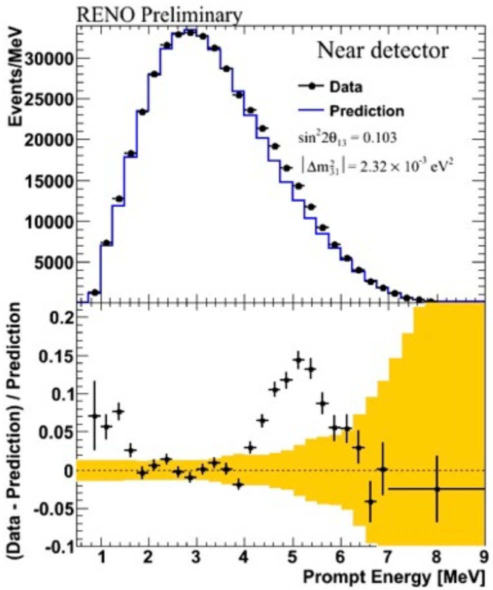
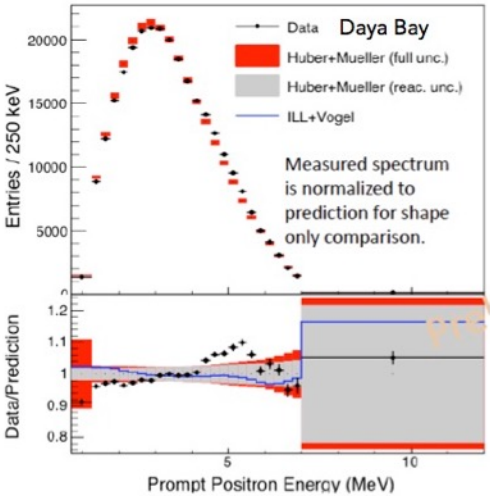
Reactor antineutrino spectrum distortion







- Spectral distortion observed in the 4-6 MeV region (3σ deviation w.r.t. reactor predictions)
- Several cross-checks have shown:
  - θ_{13} not affected by the distortion
  - No correlation with backgrounds
  - Strong correlation with reactor power
- Observed by other reactor experiments

DC legacy with one detector…

- **First** indication of reactor neutrino disappearance (non-zero θ_{13}), 101 days

  Phys. Rev. Lett. 108 (2012) 131801

- **First** measurement of θ_{13} using neutron capture on H, 240.1 days ***Phys. Lett. B 723 (2013) 66-70***

- Direct measurement of backgrounds using **reactor OFF** data ***Phys. Rev. D 87 (2013) 0111012R***

- **Novel backgrounds** reduction techniques & observation of **spectral distortion** at 4-6 MeV

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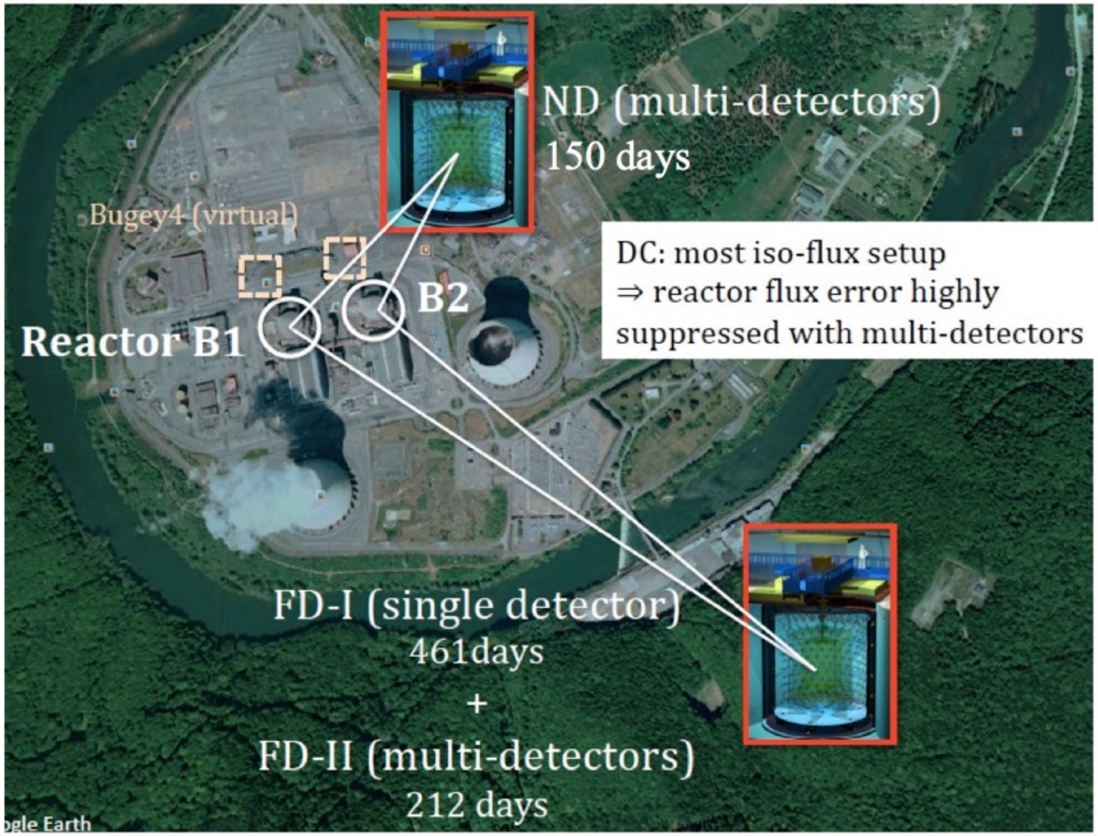
- **Various measurements of θ_{13}** with the far detector:
  - ***Phys. Rev. D 8 (2012) 052008, JHEP 1410 (2014) 086, Phys. Lett. B 735 (2014) 51-56***
  - High purity IBD selection
  - Well understood systematics at the per mil level (detection, energy & backgrounds)
  - Bugey-4 as an anchor for reactor flux normalization

First multi-detector data

Multi detector analysis



- ND running since Dec. 2014
- Live time:
  - **FD-I + FD-II: 673.14 days**
  - **ND: 150.76 days**
- MD results presented for the 1st time at Moriond 2016

“Enlarging” the neutrino target…

IBD n-Gd

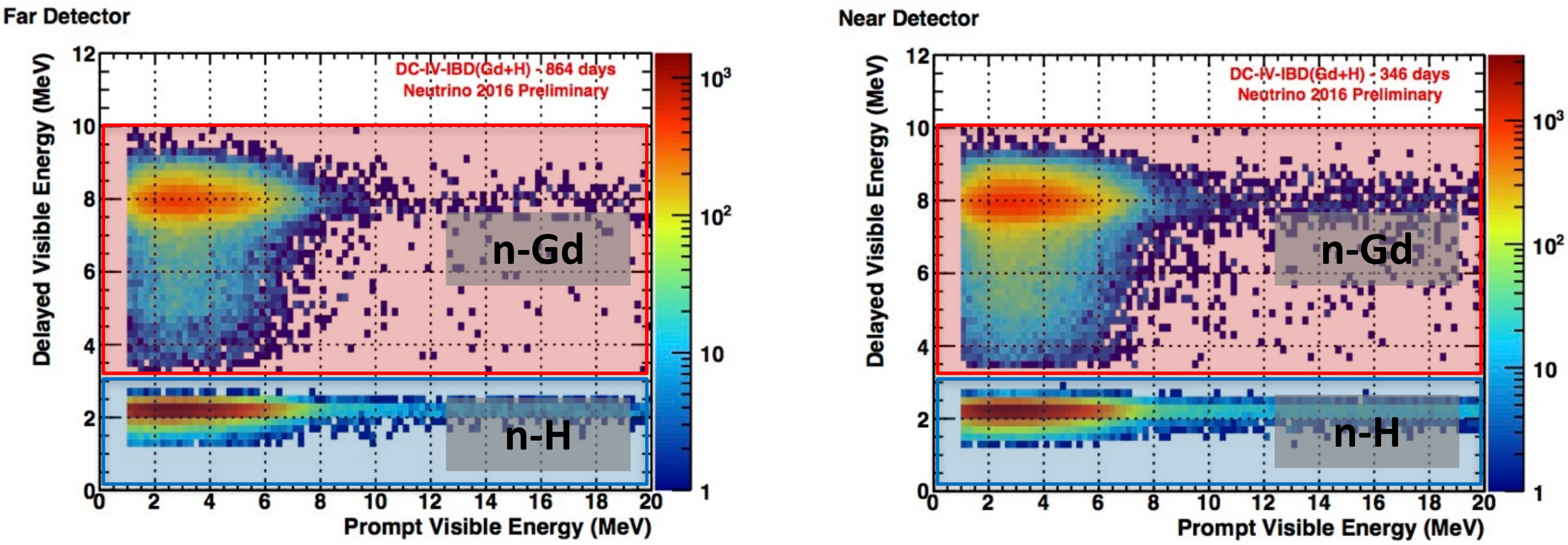
Total target ~ 8 t:
the smallest θ_{13} single neutrino target…

IBD n-(Gd+H)

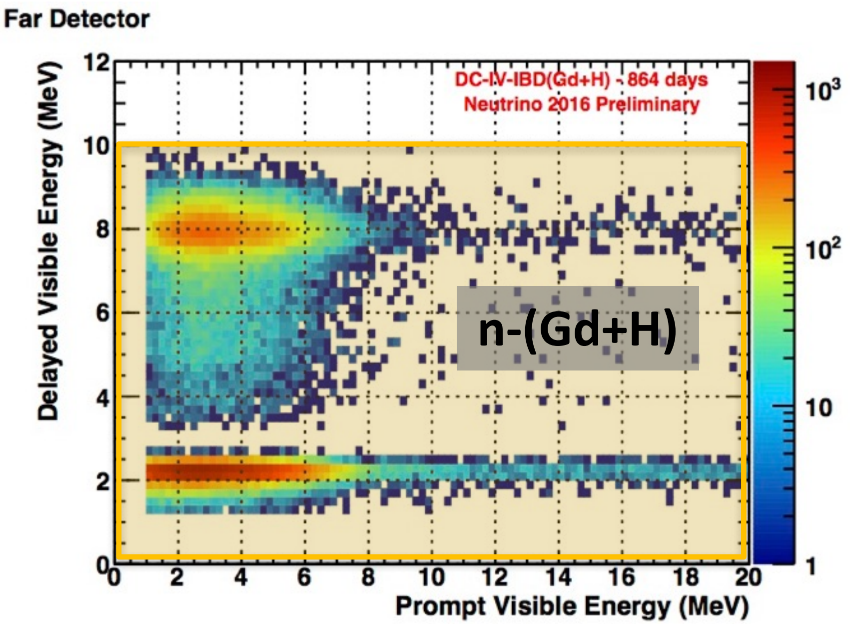
Total target ~ 26 t:
the largest θ_{13} single neutrino target…

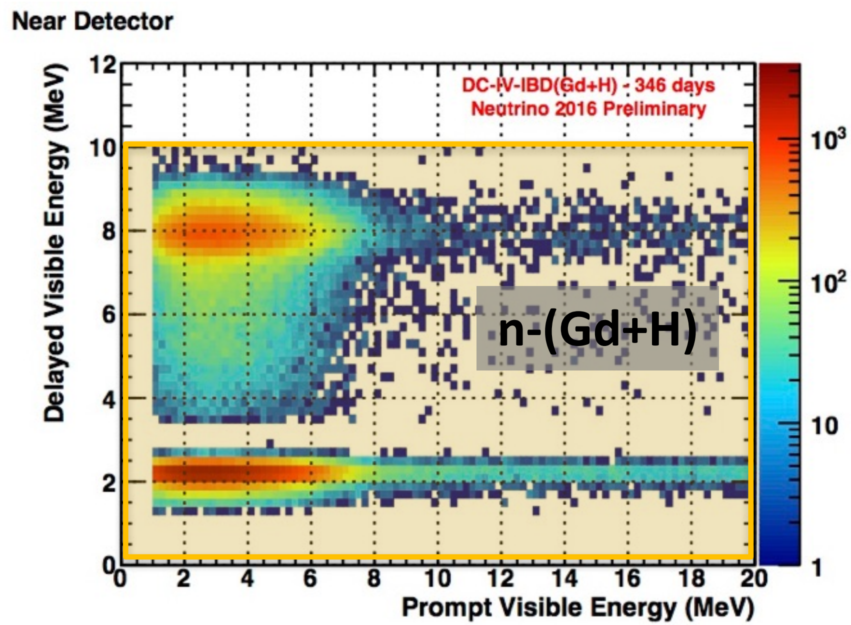
Statistics enhanced by almost a factor 3…

IBD candidate selection



IBD candidate selection

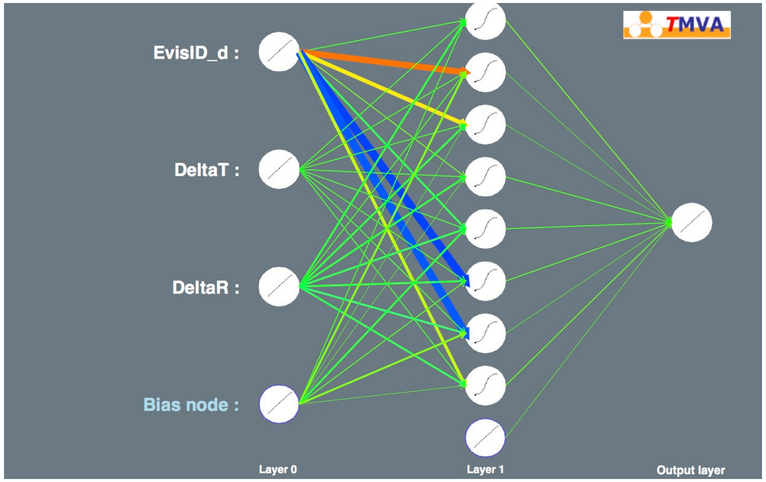


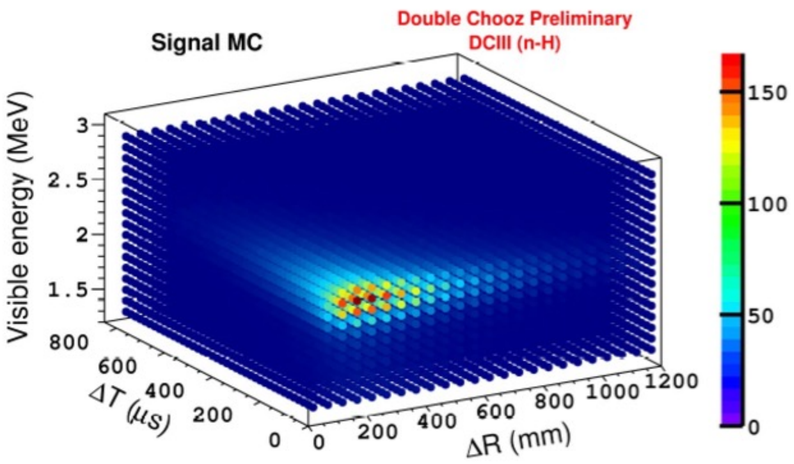


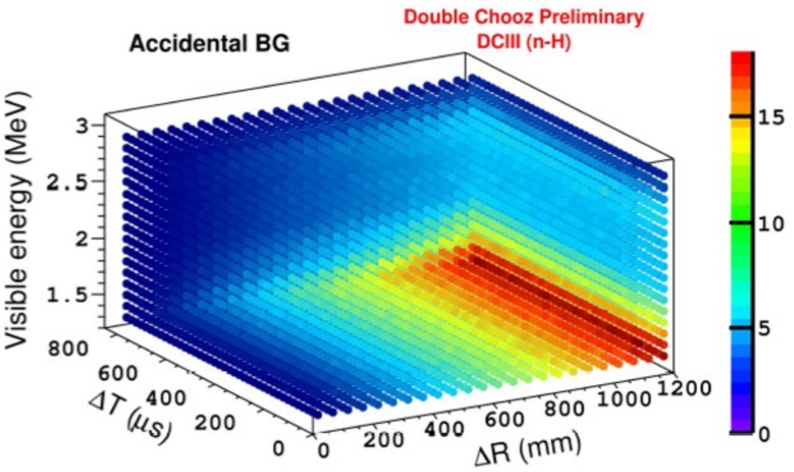
- The new IBD candidate selection integrates over all captures inclusively: cuts wide open!
  - The 8 MeV n-Gd capture associated events have low background contamination
  - The 2.2 MeV n-H capture events are highly contaminated by accidental background
- New analysis technique developed: **Artificial Neural Network analysis**
  - Highly efficient IBD selection in the full delayed energy range
  - Efficient background discrimination, especially in the n-H peak region
- Evaluating systematic uncertainties from this new analysis scheme is challenging

ANN construction

- ANN cut definition based upon 3 variables
  - **E** (delay)
  - **Δt** (prompt-delay)
  - **ΔR** (prompt-delay)
- Training with accurate MC for IBD signal and data for accidental background

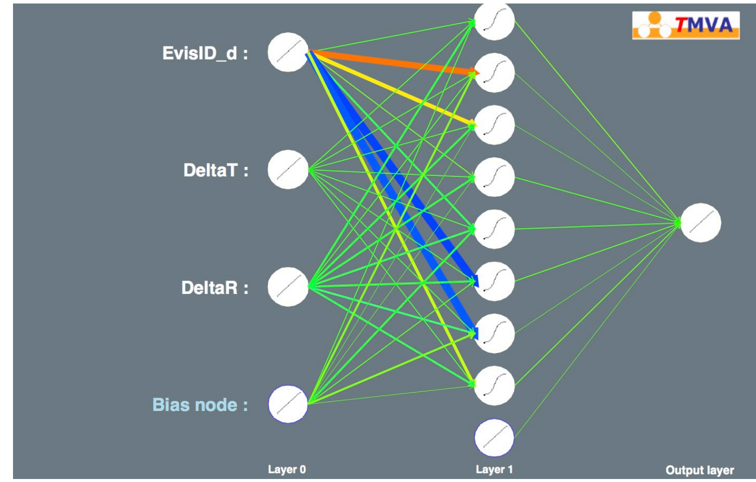




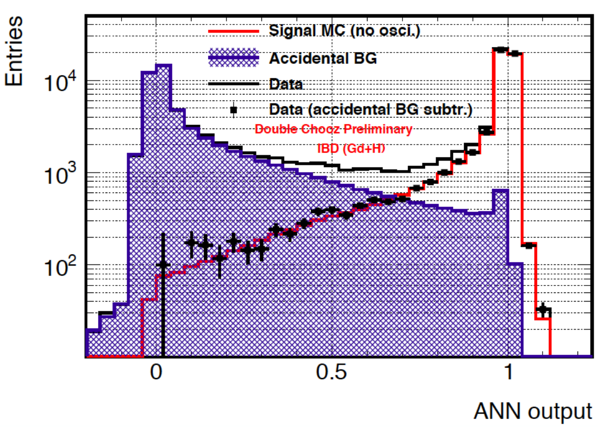


ANN construction

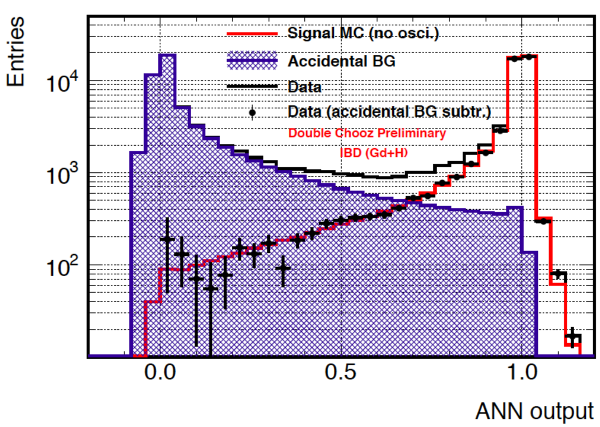
- ANN cut definition based upon 3 variables
  - **E** (delay)
  - **Δt** (prompt-delay)
  - **ΔR** (prompt-delay)
- Training with accurate MC for IBD signal and data for accidental background
- Cuts defined upon ANN outputs:



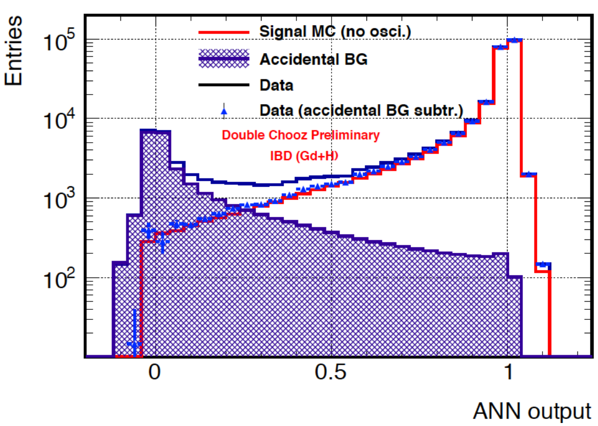
FD-I



FD-II

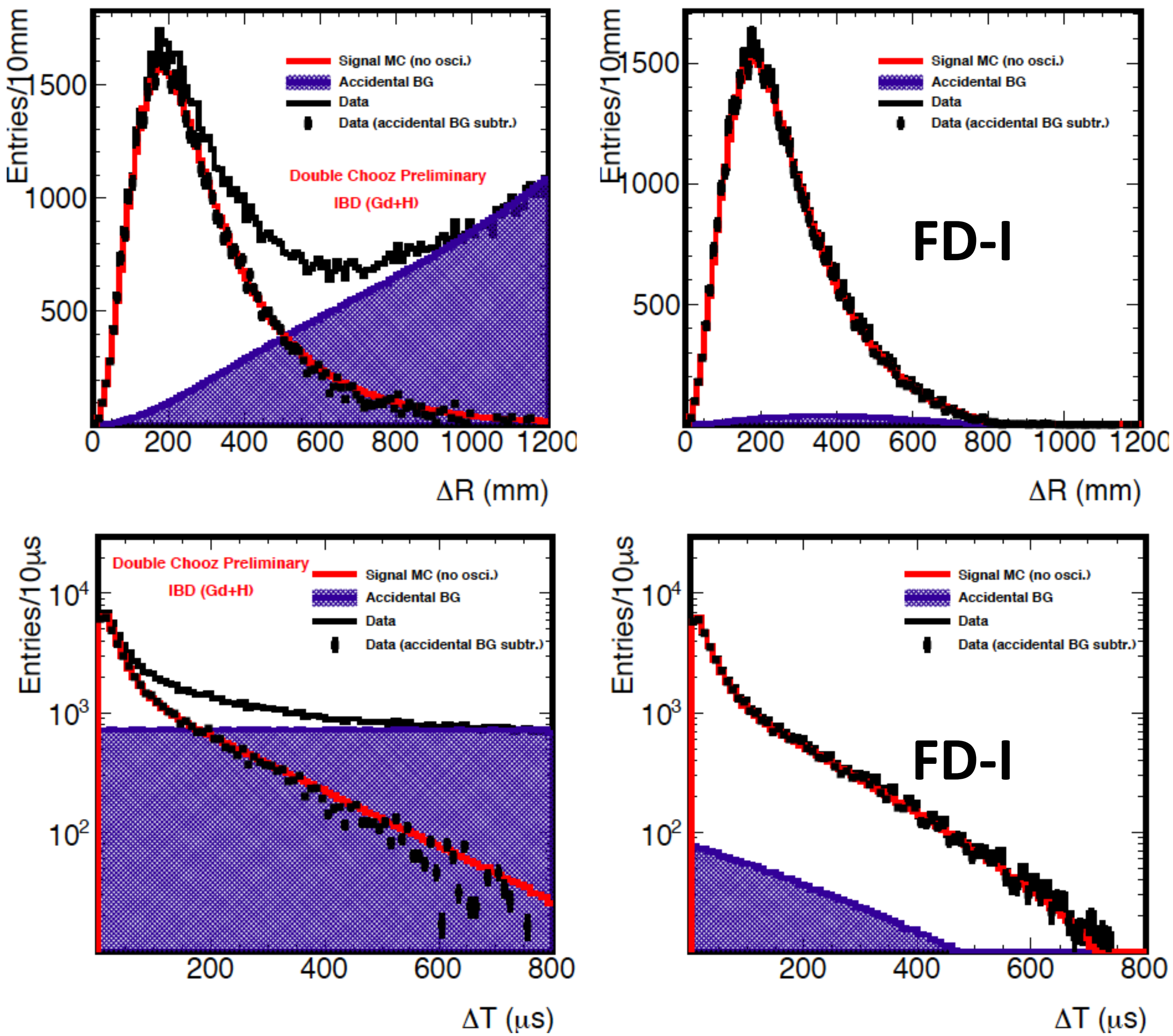


ND



ANN performances

Before ANN cut | **After ANN cut**

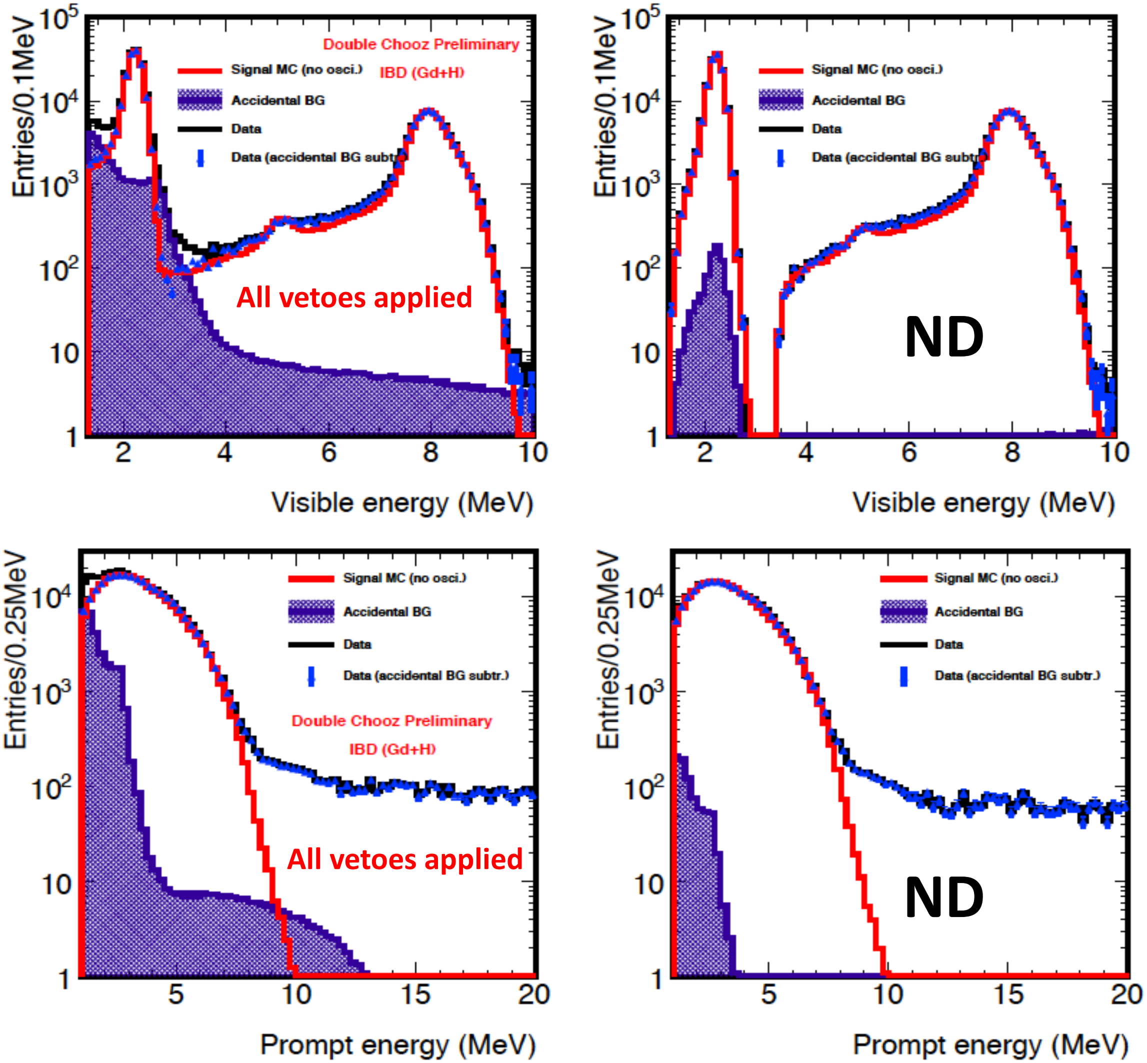


ΔR (prompt-delay)

Δt (prompt-delay)

ANN performances

Before ANN cut / After ANN cut

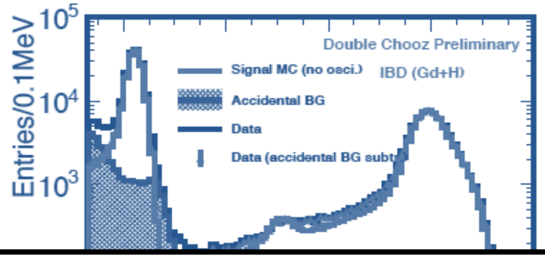


Delayed energy spectrum

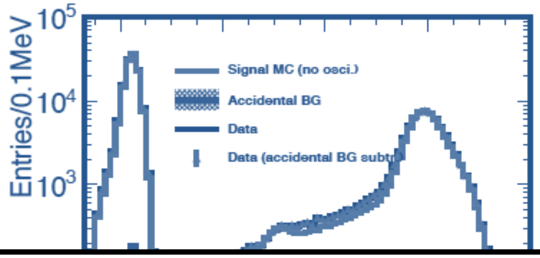
Prompt energy spectrum

ANN performances

Before ANN cut



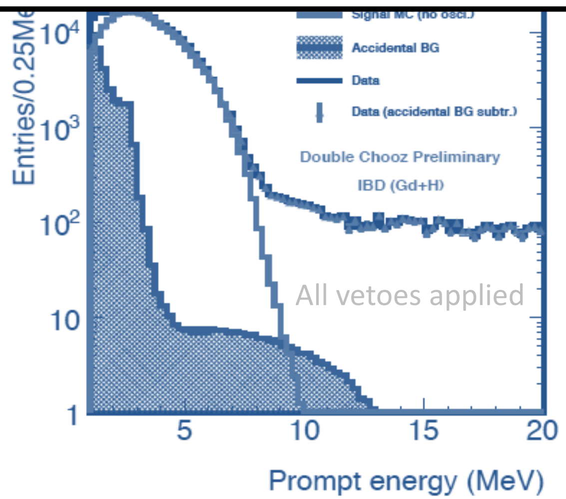
After ANN cut

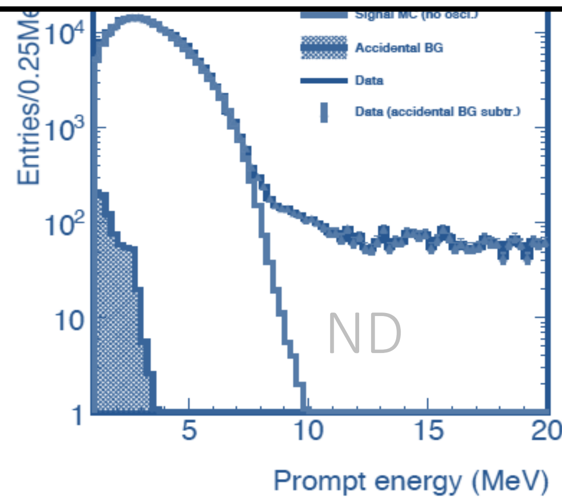


Delayed energy spectrum

- Accidental background dramatically reduced: ~ **4/day**
- n-(Gd+H) analysis gives × 2.5 increase in statistics wrt n-Gd analysis:

R_{IBD}: ~ **140/day @ FD**; **~800/day @ ND** (after all vetoes)

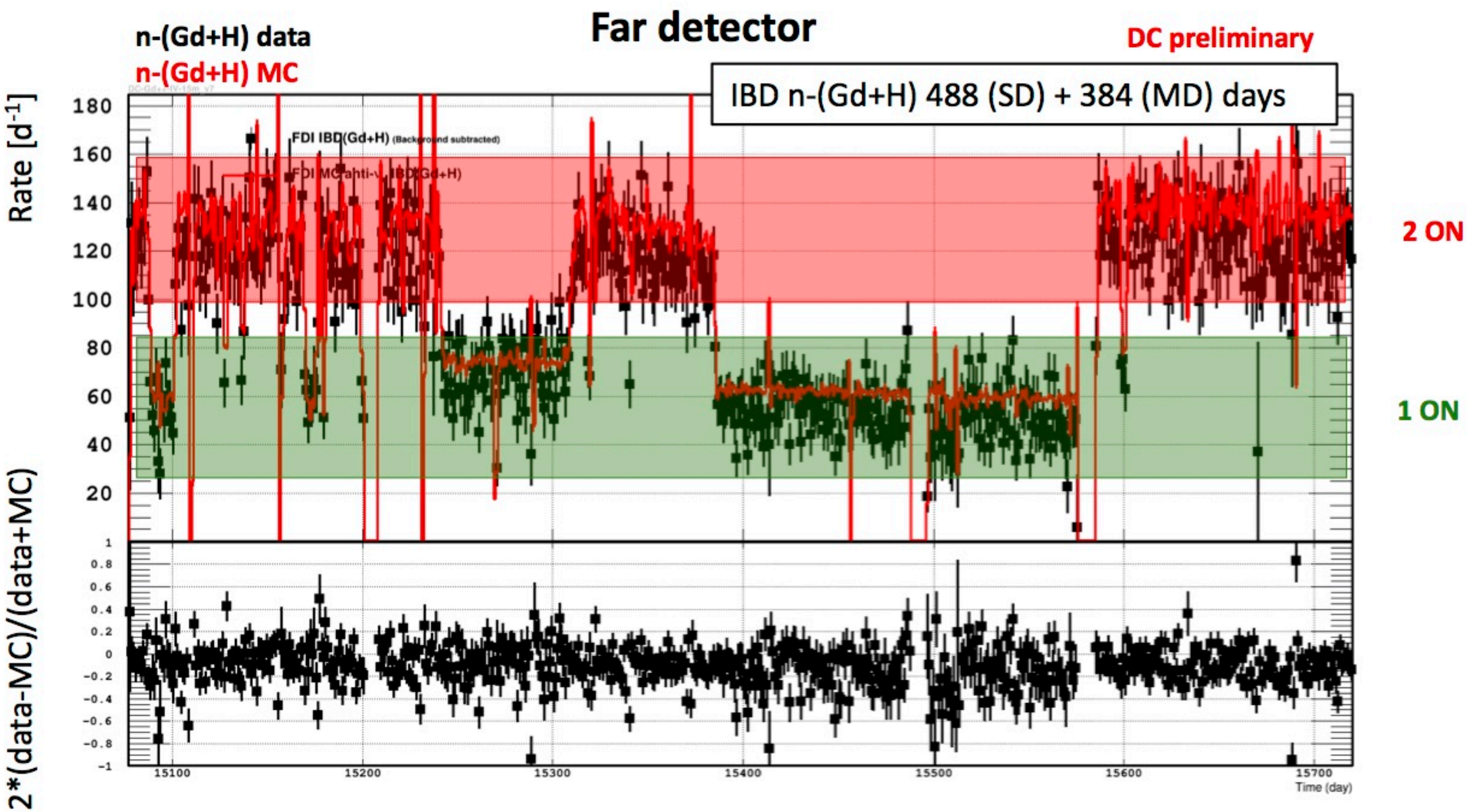




Prompt energy spectrum

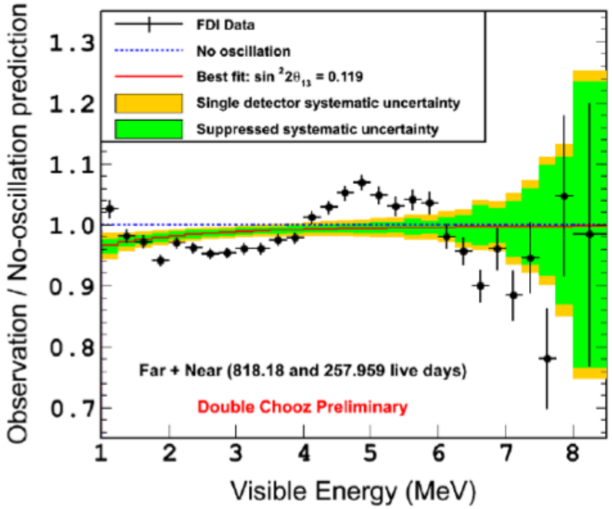
θ_{13} results

- Results presented at CERN in Sept 2016
- Data analyzed: FD-I & reactor-off data in SD mode, FD-II & ND data in MD mode

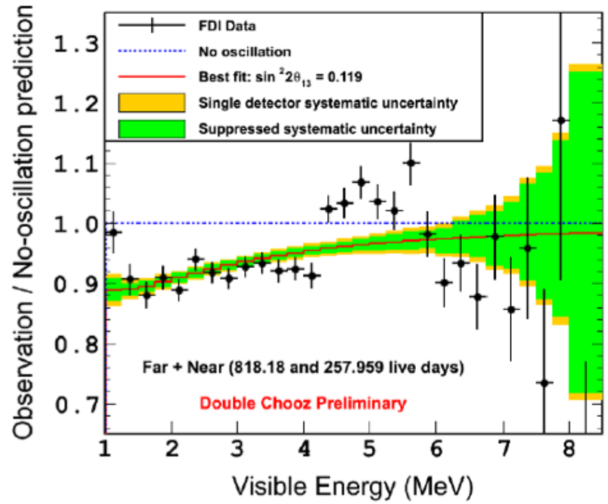


Rate + shape fit results

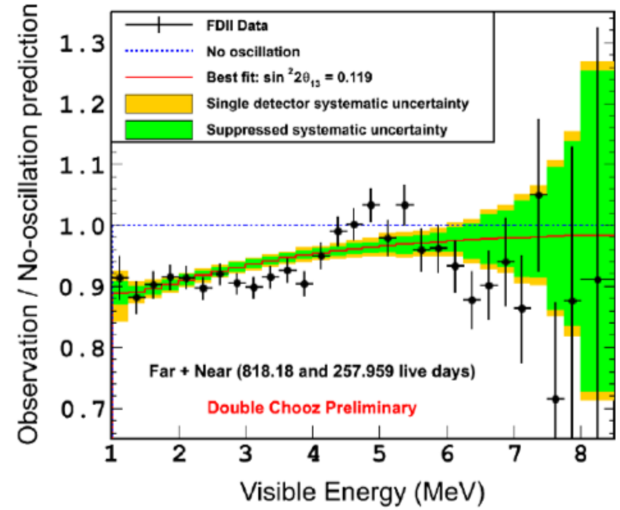
ND



FD-I



FD-II

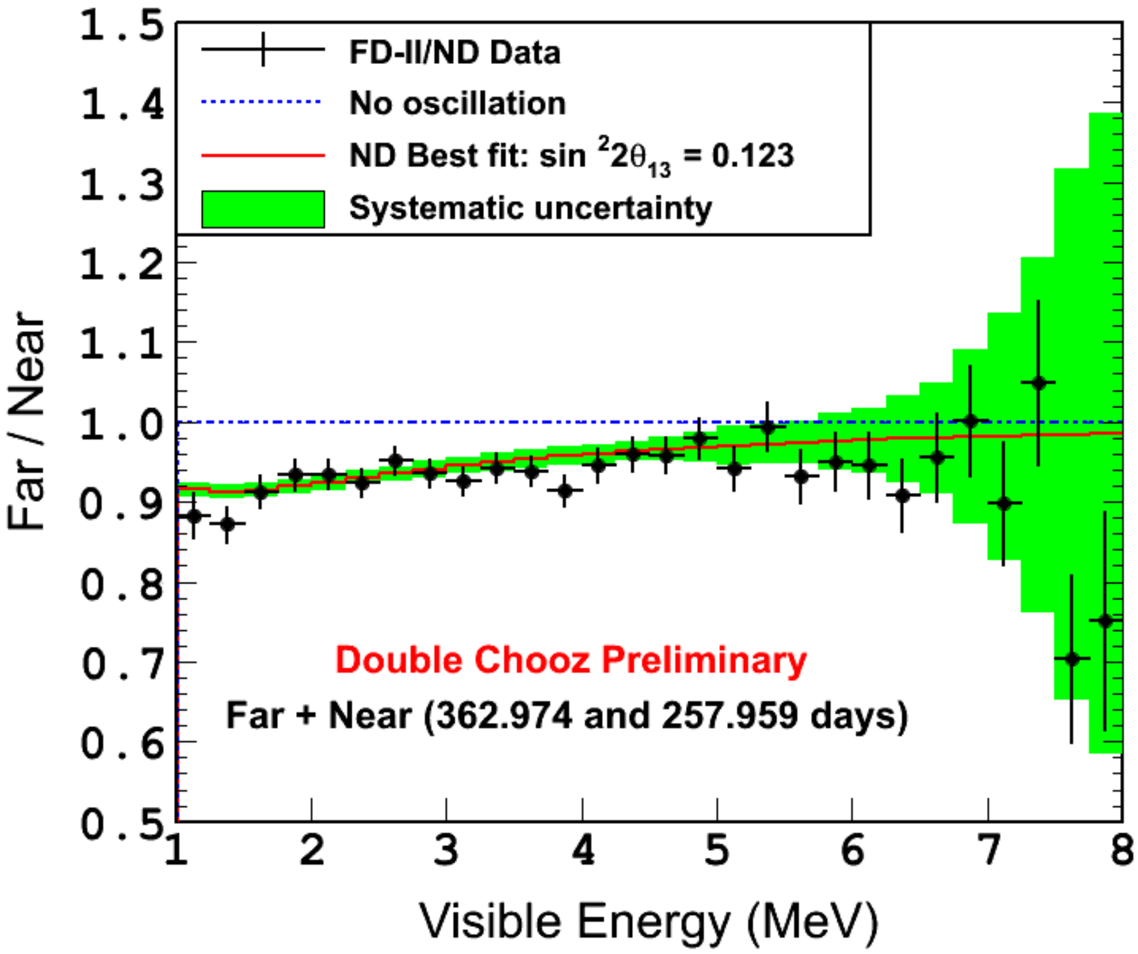


$\sin^2(2\theta_{13}) = 0.119 \pm 0.016$ (stat. + syst.)

$\chi^2_{min}/n_{dof} = 236.2/114$

Backgrounds	FD estimate	FD fit output	ND estimate	ND fit output
^9Li	$2.59 \pm 0.61\ d^{-1}$	$2.55 \pm 0.23\ d^{-1}$	$11.11 \pm 2.96\ d^{-1}$	$14.4 \pm 1.2\ d^{-1}$
Fast neutrons	$2.54 \pm 0.07\ d^{-1}$	$2.51 \pm 0.05\ d^{-1}$	$20.77 \pm 0.43\ d^{-1}$	$20.85 \pm 0.31\ d^{-1}$

Data to data fit



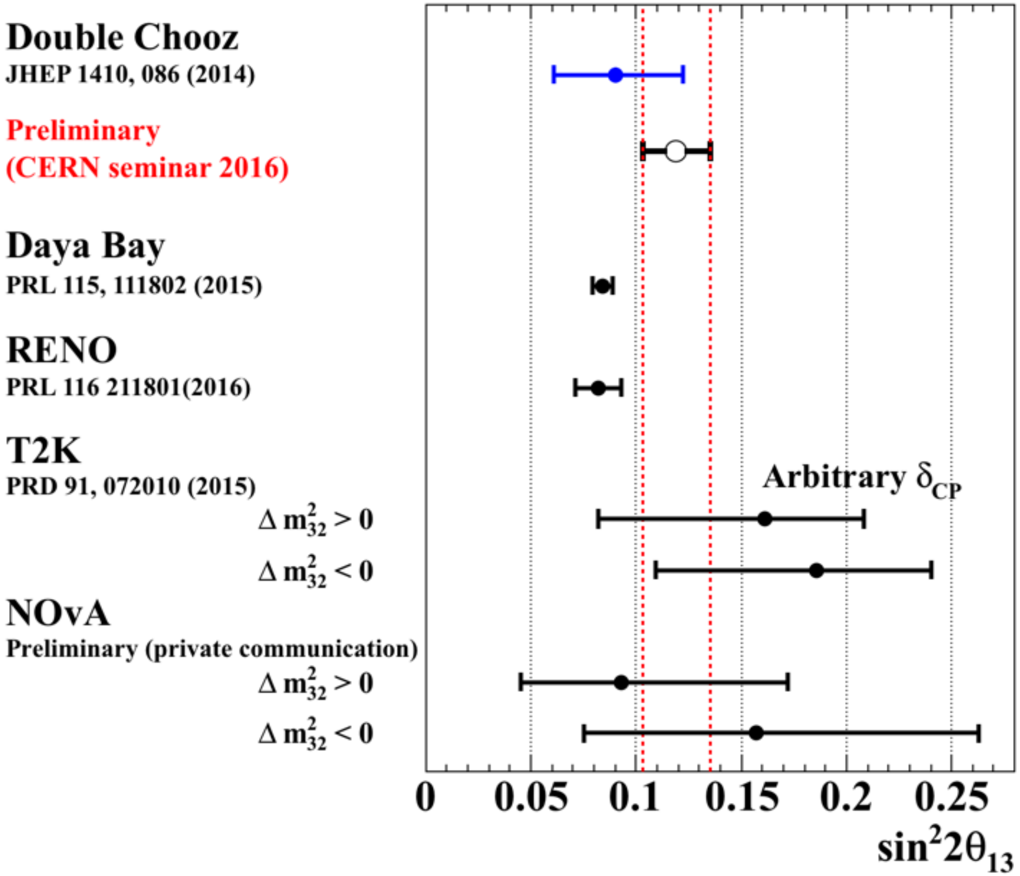
FD-II/ND

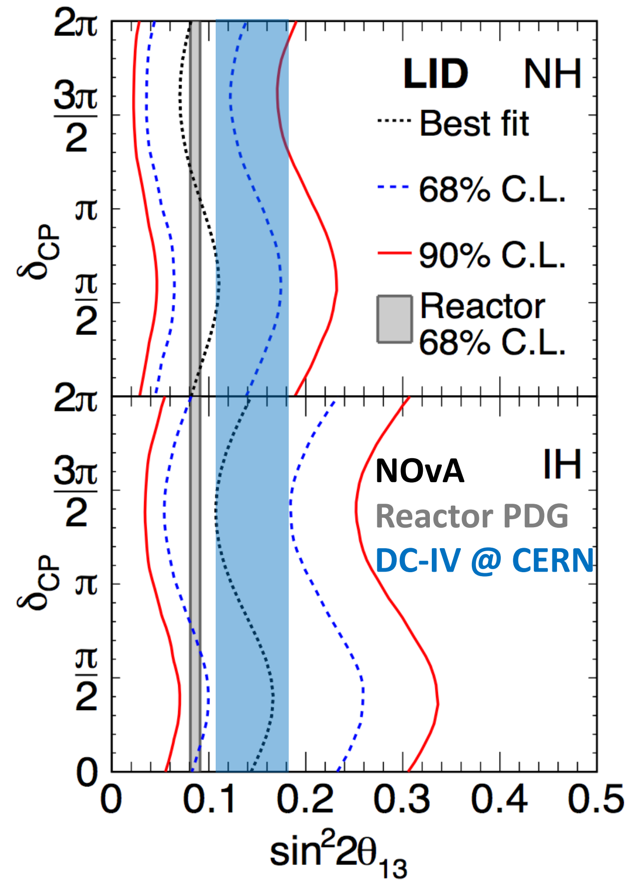
$\sin^2(2\theta_{13}) = 0.123 \pm 0.023$ (stat. + syst.)

$\chi^2_{min}/n_{dof} = 10.6/38$

θ_{13} result not affected by spectral distortion

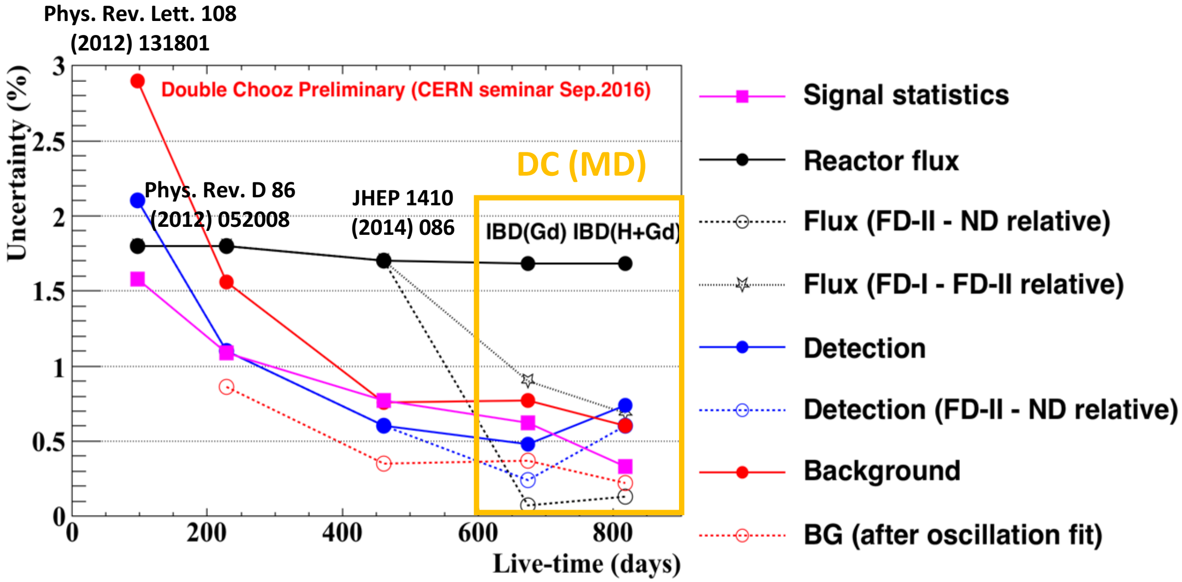
Comparison with other experiments



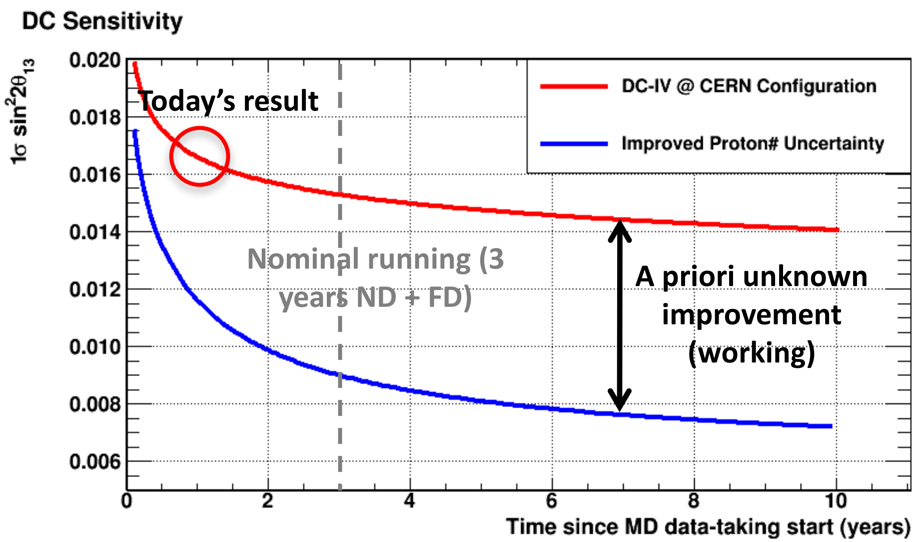


- DC θ_{13} (and accelerators) higher than other θ_{13} values (2.2σ tension with DB)
- Redundancy between reactor experiments is **fundamental**: θ_{13} is a key parameter for future δ_{CP} measurements

DC θ_{13} prospects



- Not limited anymore by statistics with MD analysis
- **Proton number** (in the full NT+GC volume) is the largest systematic uncertainty (embedded in detection systematics)
  - **NT+GC: 0.76 %** relative near/far
  - **NT: 0.1 %** relative near/far



- DC largely dominated by proton # uncertainty
  - Most conservative assumptions were adopted here
  - Possibility to improve proton # knowledge (analysis & hardware)

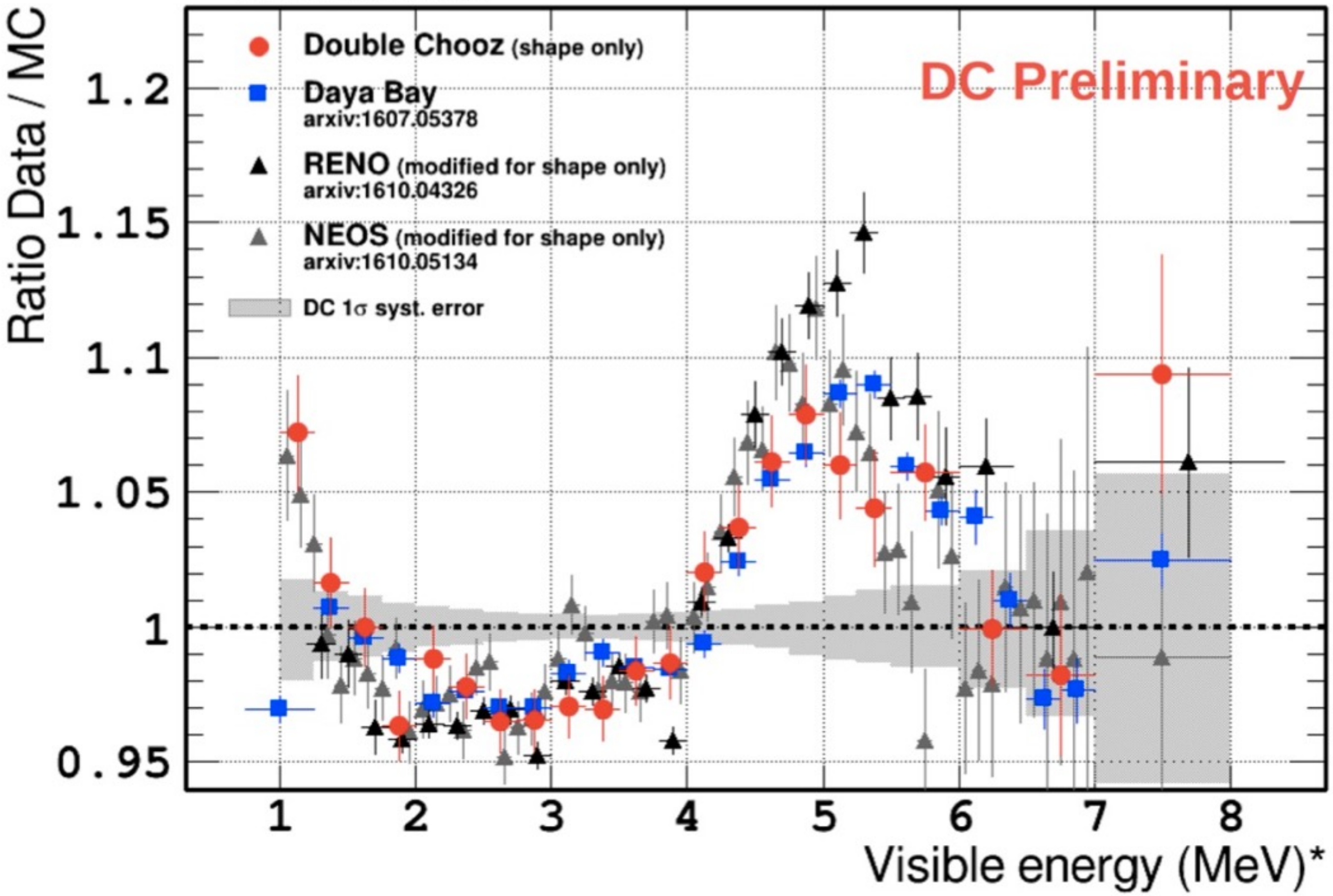
Near detector shape comparison

DC: 210 000 events / DB: 1.2 million events / RENO: 280 000 events

DATA/MC ratio comparison

→ ^{238}U neutrino flux spectra different in DC (Haag) and DB/Reno (Huber)

→ different reactor fuels



* can slightly differ from one experiment to another due to detector effects

Conclusions

- DC results with two detector and new IBD selection strategy (n-(Gd+H)):
  - Now largest θ_{13} single-detector target
  - Innovative analysis techniques (**ANN**) to efficiently reduce backgrounds and maximize detection efficiency
  - Reactor flux uncertainties almost fully cancelled thanks to DC isoflux configuration
  - Adopted conservative scenario in the evaluation & treatment of systematic uncertainties
- DC best value: $\mathbf{\sin^2 2\theta_{13} = 0.119 \pm 0.016}$
  - Dominated by proton # uncertainty
  - Work in progress to achieve $\sin^2 2\theta_{13}$ precision < 0.01