Latest results of the Double Chooz reactor neutrino experiment

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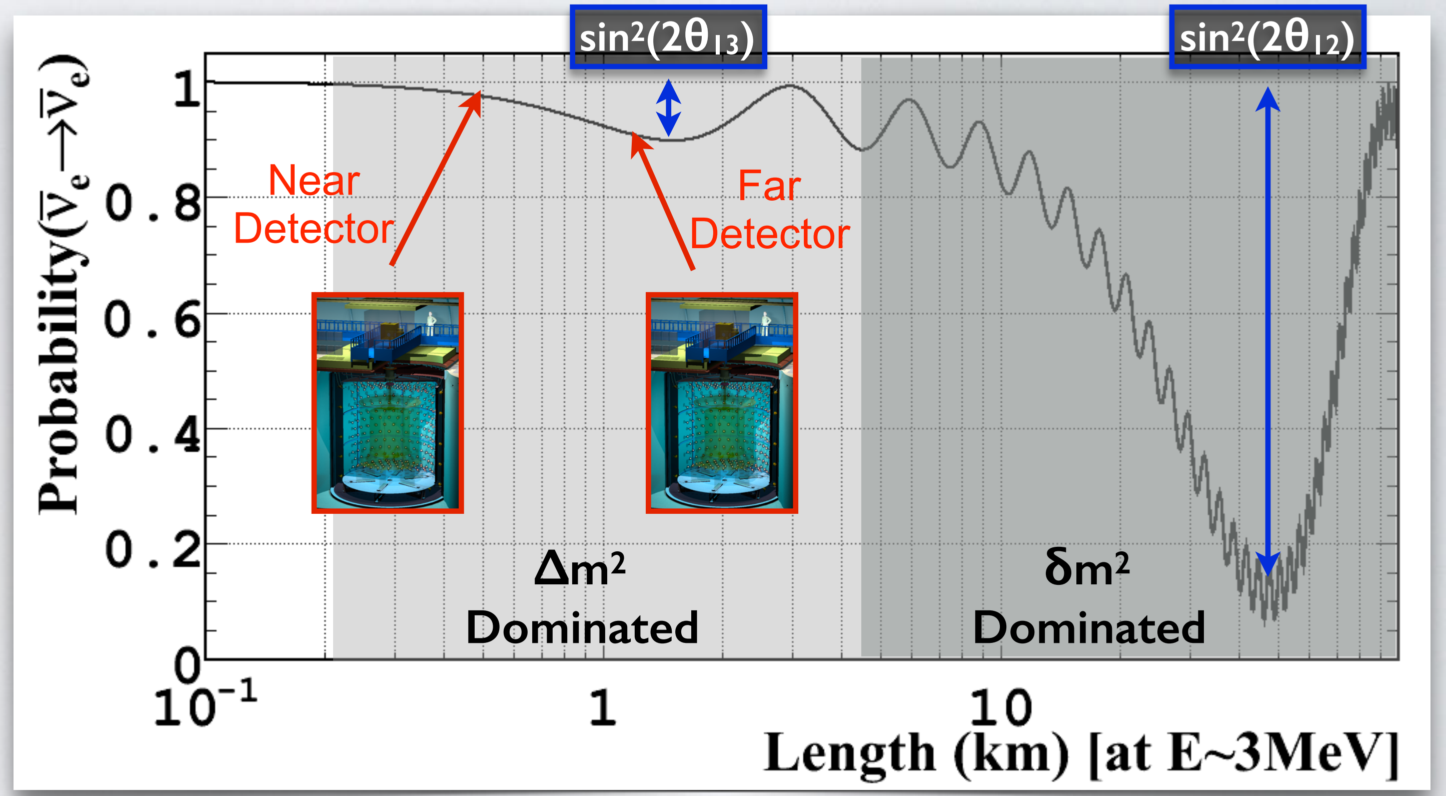
INTRODUCTION

- Reactor oscillation experiments aim at the measurement of θ_{13} through the observation of $\bar{\nu}_e \rightarrow \bar{\nu}_e$ transition according to the oscillation probability:

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \simeq 1 - \sin^2(2\theta_{13}) \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)$$

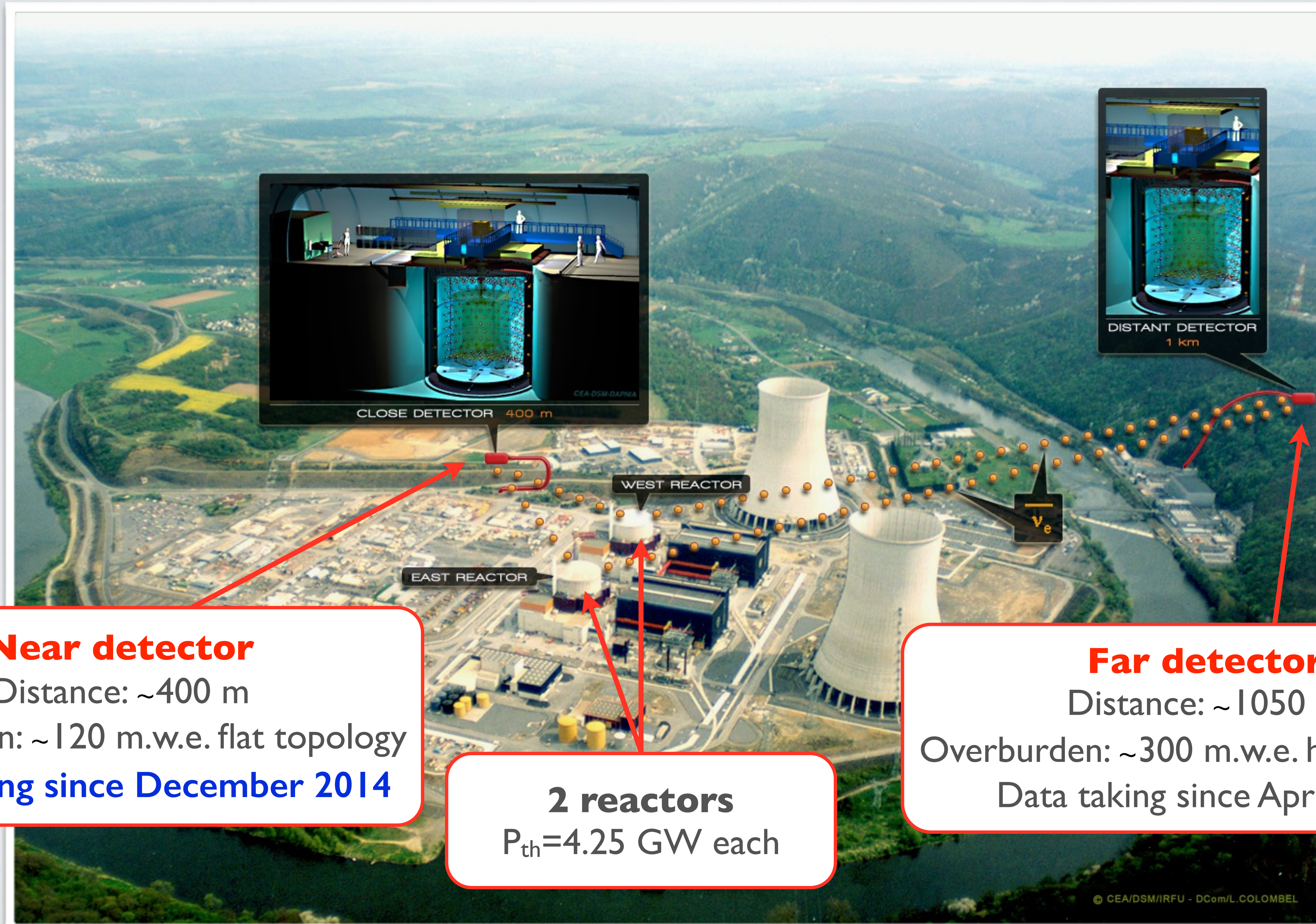
- The use of two detectors allows to measure the flux before and after the oscillation to cancel out the associated systematics.



- The advantages of this measurement with respect to long baseline oscillation experiments is a ***clean measurement*** of θ_{13} since:

  1. It is a disappearance experiment, therefore insensitive to the value of the δ-CP phase.
  2. It has a short baseline (order of 1 km) and it is therefore insensitive to matter effects.
  3. The dependence on Δm^2_{21} is very weak : O ($\Delta m^2_{21}/\Delta m^2_{31}$).

Double Chooz OVERVIEW

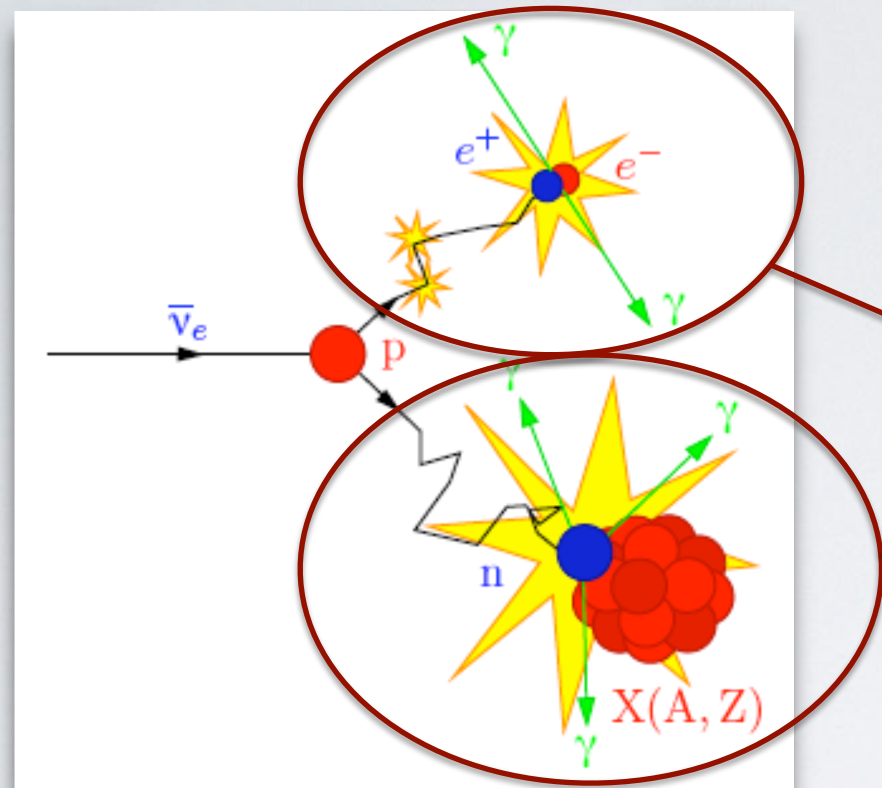


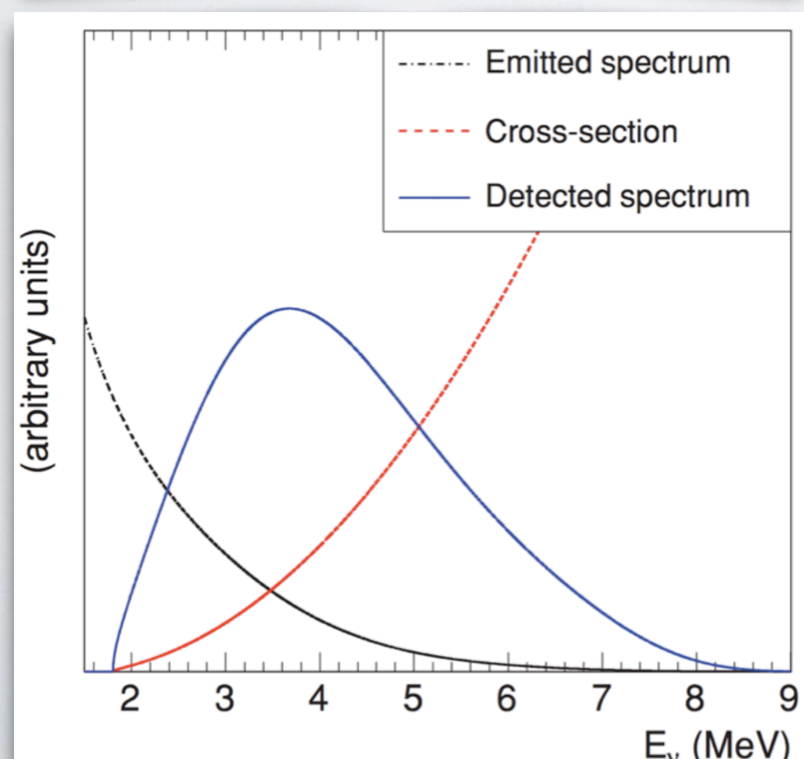
Near detector
Distance: ~400 m
Overburden: ~120 m.w.e. flat topology
Data taking since December 2014

2 reactors
P_{th}=4.25 GW each

Far detector
Distance: ~1050 m
Overburden: ~300 m.w.e. hill topology
Data taking since April 2011

NEUTRINO DETECTION





- Neutrinos are observed via Inverse Beta Decay (IBD):

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

- The signal signature is given by a **twofold coincidence**:

  1. Prompt photons from e^+ ionisation and annihilation (1-8 MeV).
  2. Delayed photons from n capture on Gadolinium (~8 MeV) or H (2.2 MeV).
  3. Time correlation: $\Delta t \sim 30\ \mu s$ for Gd and $\Delta t \sim 200\ \mu s$ for H.
  4. Space correlation (< 1m).

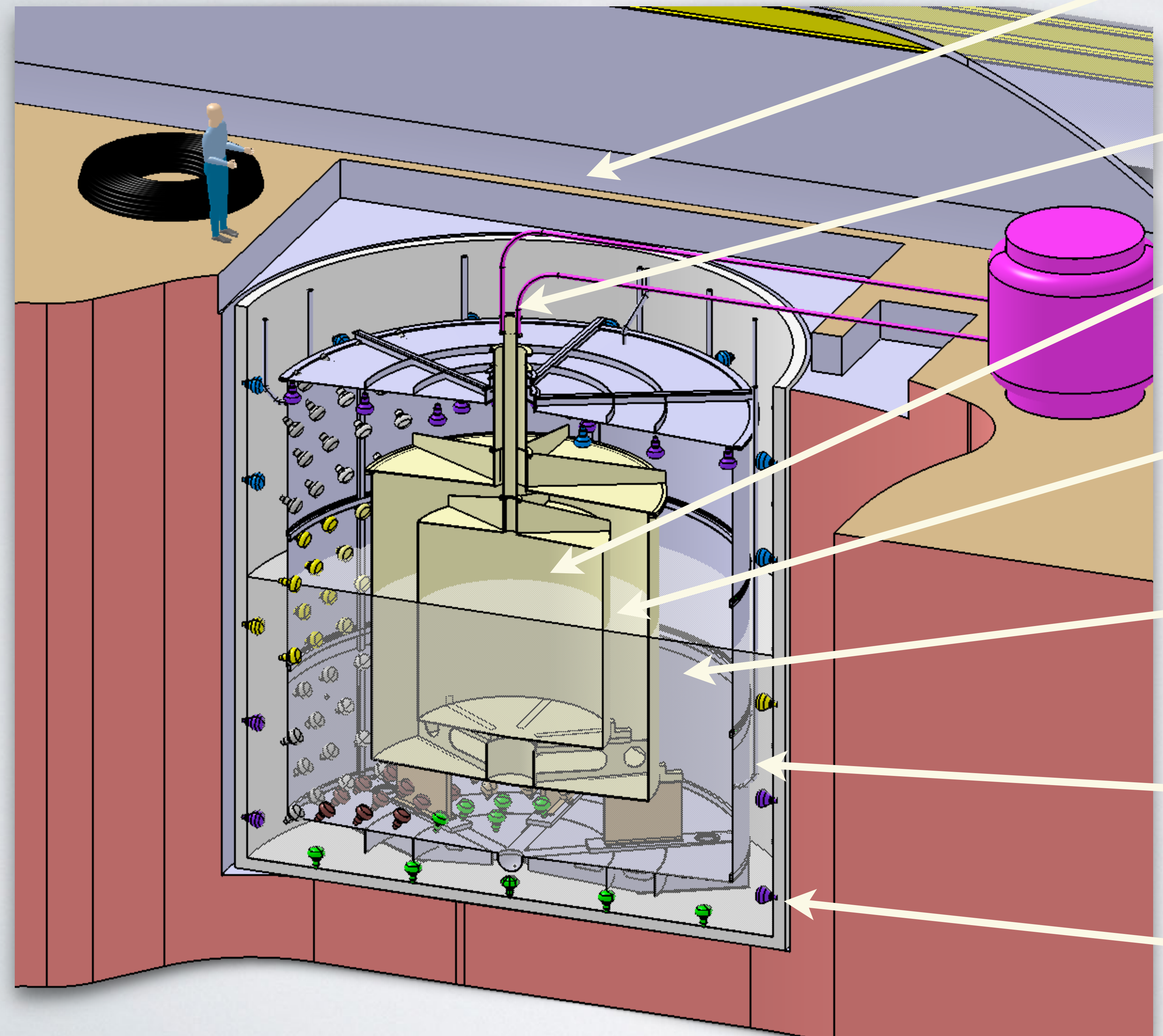
- The energy spectrum is a convolution of flux and cross section (threshold at 1.8 MeV).

- The prompt energy is related to $\overline{\nu}_e$ energy:

$$E_{prompt} = E_\nu - T_n - 0.8\ \text{MeV}$$

- The survival probability depends on E_ν therefore we have a measurement of θ_{13} using rate and spectral deformation.

DETECTOR DESIGN



Outer Veto: plastic scintillator strips

Chimney: deployment of radioactive source for calibration in the ν-Target and γ-Catcher.

ν-Target: 10.3 m^3 scintillator (PXE based) doped with 1g/l of Gd in an acrylic vessel (8 mm)

γ-Catcher: 22.5 m^3 scintillator (PXE based) in an acrylic vessel (12 mm)

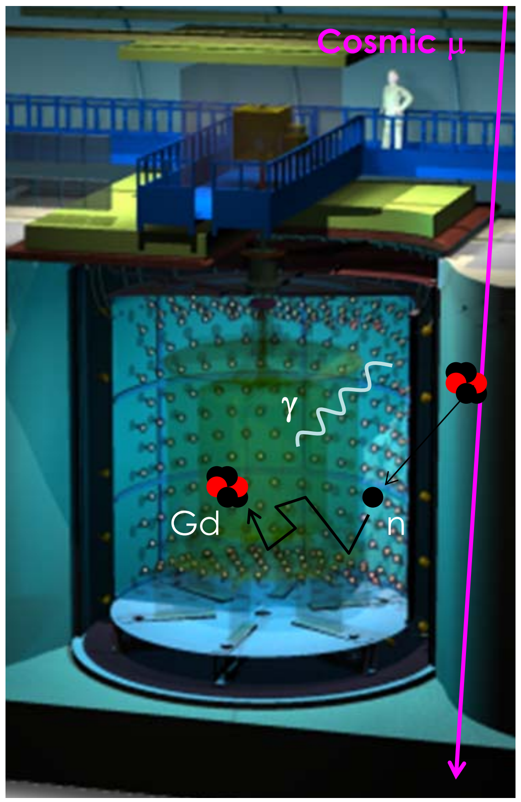
Buffer: 100 m^3 of mineral oil in a stainless steel vessel (3 mm) viewed by 390 PMTs (10 inches)

Inner Veto: 90 m^3 of scintillator (LAB based) in a steel vessel (10 mm) equipped with 78 PMTs (8 inches)

Shielding: about 250 t steel shielding (150 mm) (FD) / 1 m water (ND)

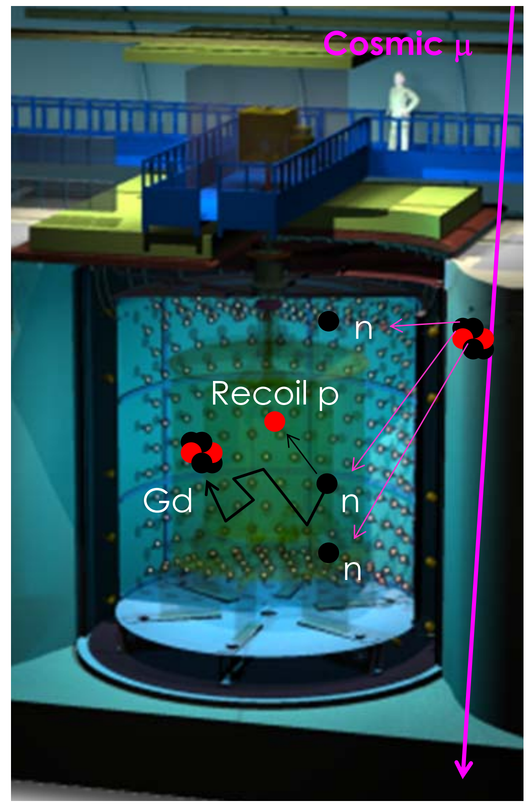
BACKGROUND

Accidental BG

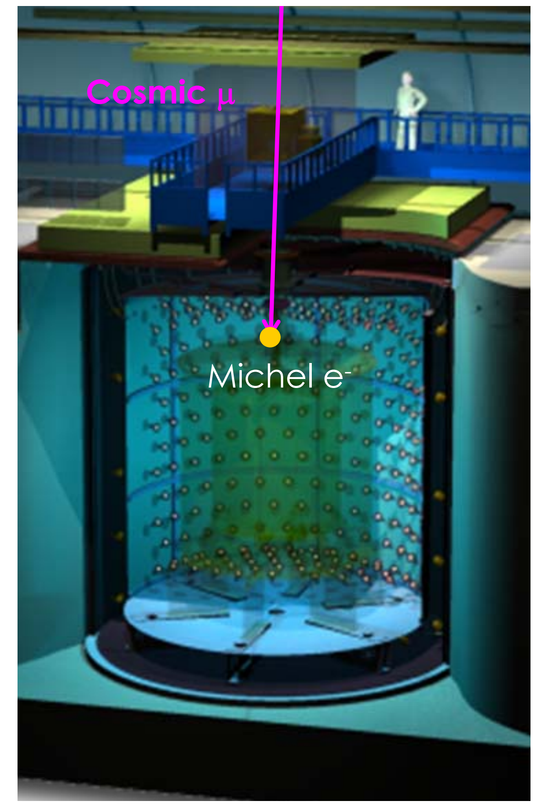


Correlated BG

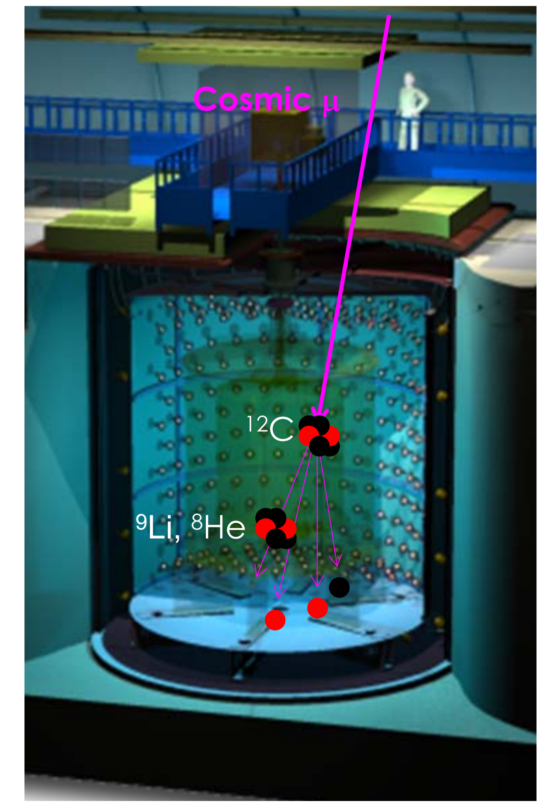
Fast neutrons



Stopping μ



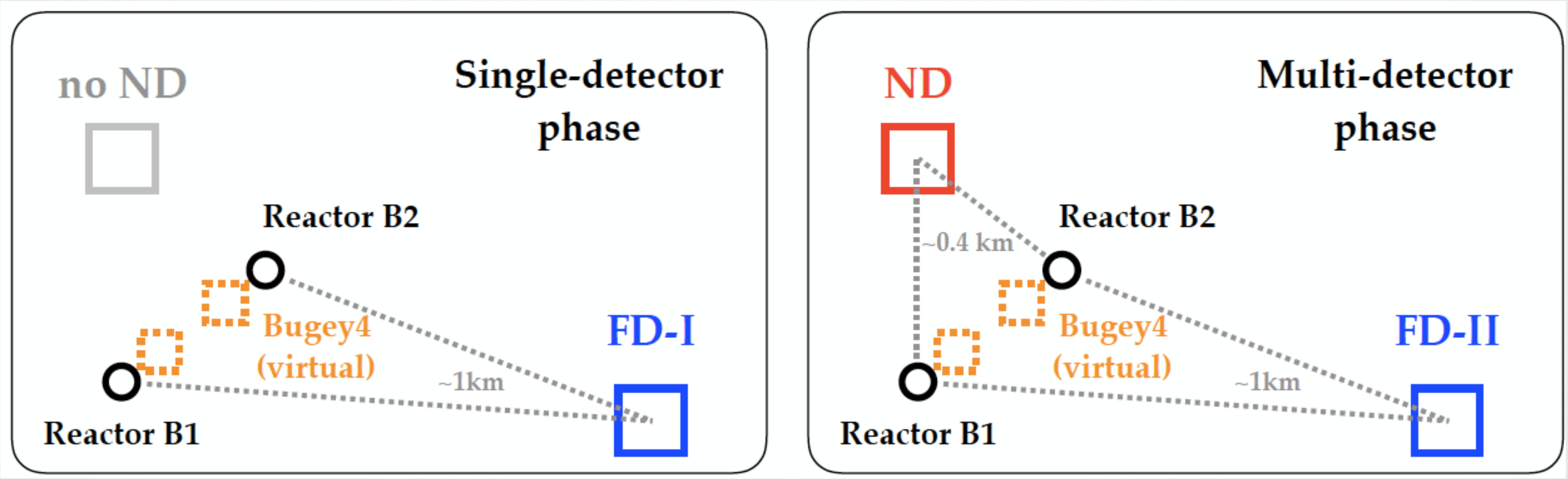
Cosmogenics



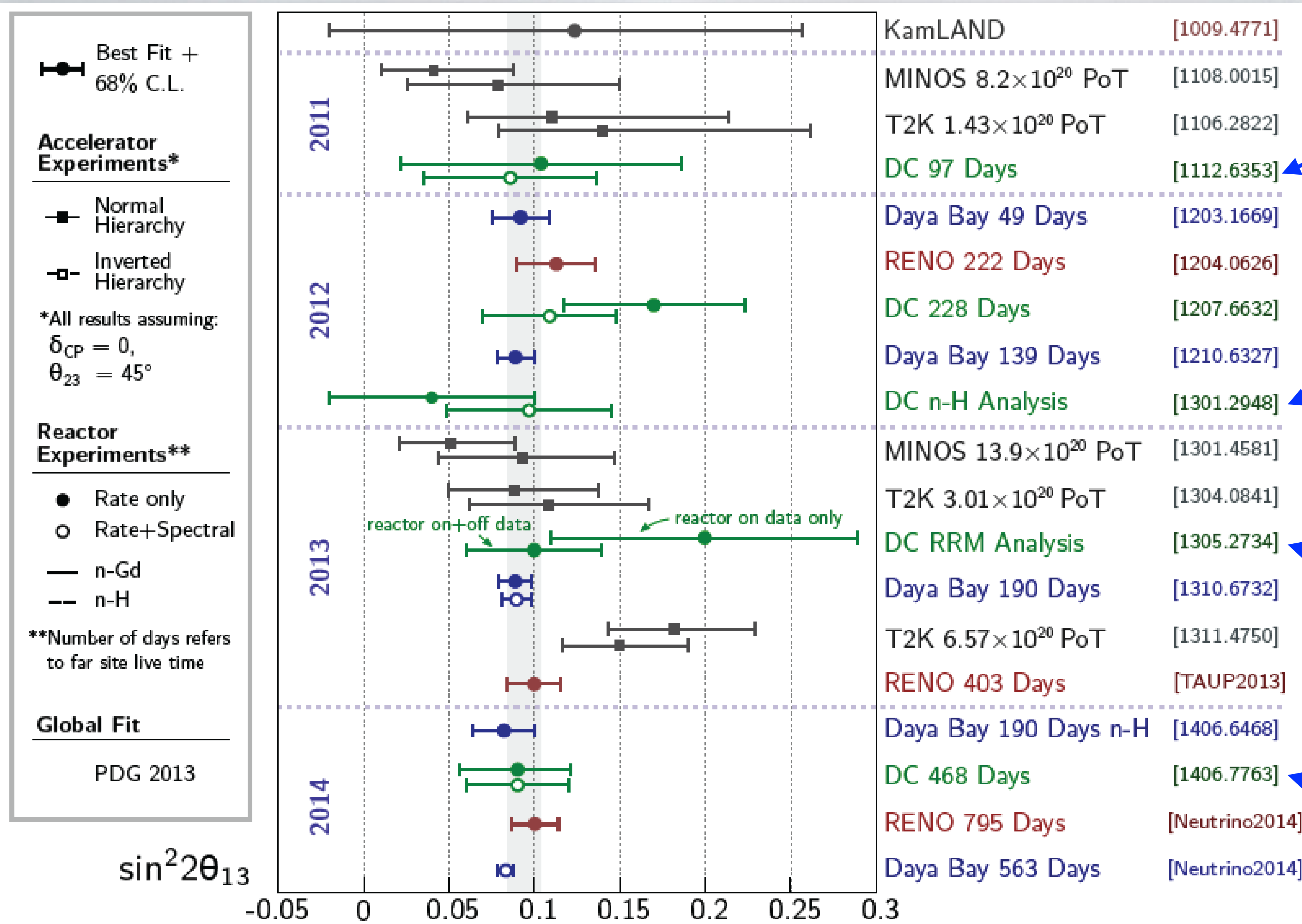
	Accidental BG	Fast neutrons	Stopping μ	Cosmogenics
Prompt	Radioactivity from materials, PMTs, surrounding rock (^{208}Tl).	Neutrons from cosmic μ spallation gives recoil protons (low energy).	Cosmic μ entering from the chimney.	Electrons from $^{9}Li/^{8}He$ β + n decays.
Delay	Neutrons from cosmic μ spallation captured on Gd/H, or γ like prompt fake signal in case of H analysis.	Neutrons from cosmic μ spallation captured on Gd/H, or γ like prompt fake signal in case of H analysis.	Michel electrons.	Neutrons from $^{9}Li/^{8}He$ β + n decays captured on Gd/H.

Double Chooz SETUPS

- 2 reactor cores and 2 detectors.
- Unique DC features: almost iso-flux setup, reactor-off data (~ 7 days).
- 2 phases:
  - Single Detector (SD) period: ~480 days (FD1-only ~2011)
  - Multi Detector (MD) period: ~350 days (FDII +ND ~ 2015)
- Bugey4 anchor: Bugey4 experimental result is used as virtual ND.



Double Chooz MILESTONES (single detector)



First indication of non-zero θ_{13} and rate+shape analysis
Phys.Rev.Lett. 108 (2012) 131801

First n-H capture analysis
Phys.Lett. B723 (2013) 66-70

First (and only) Reactor Rate Modulation (RRM) analysis
Phys.Lett. B735 (2014) 51-56

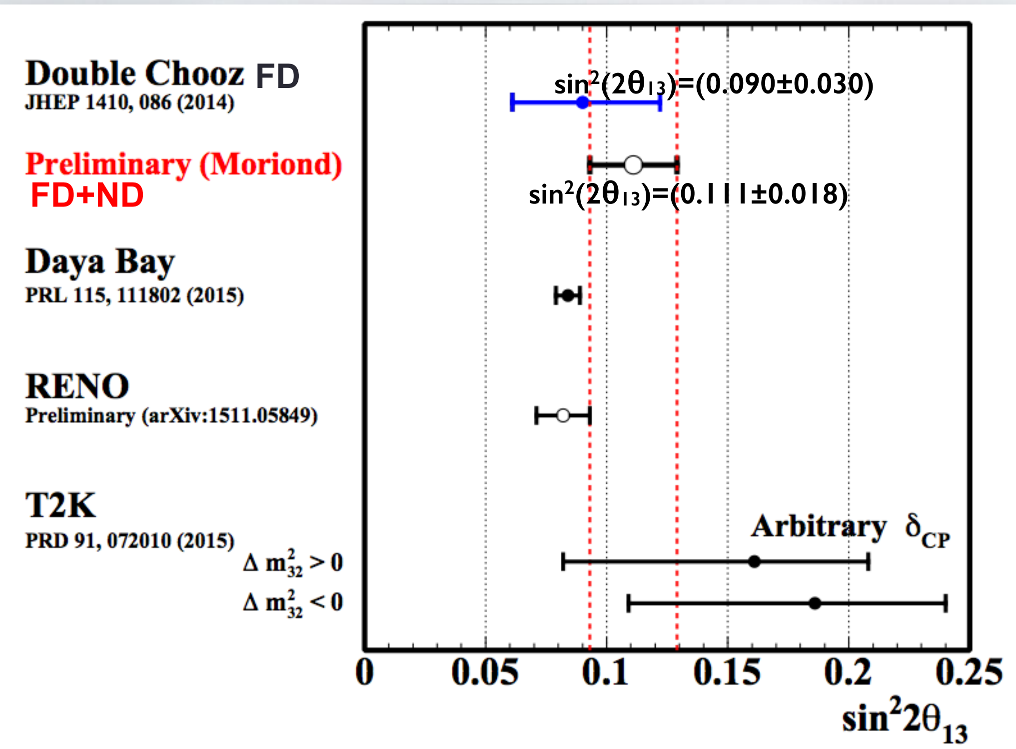
First publication on "5 MeV distortion"
JHEP 1410 (2014) 86

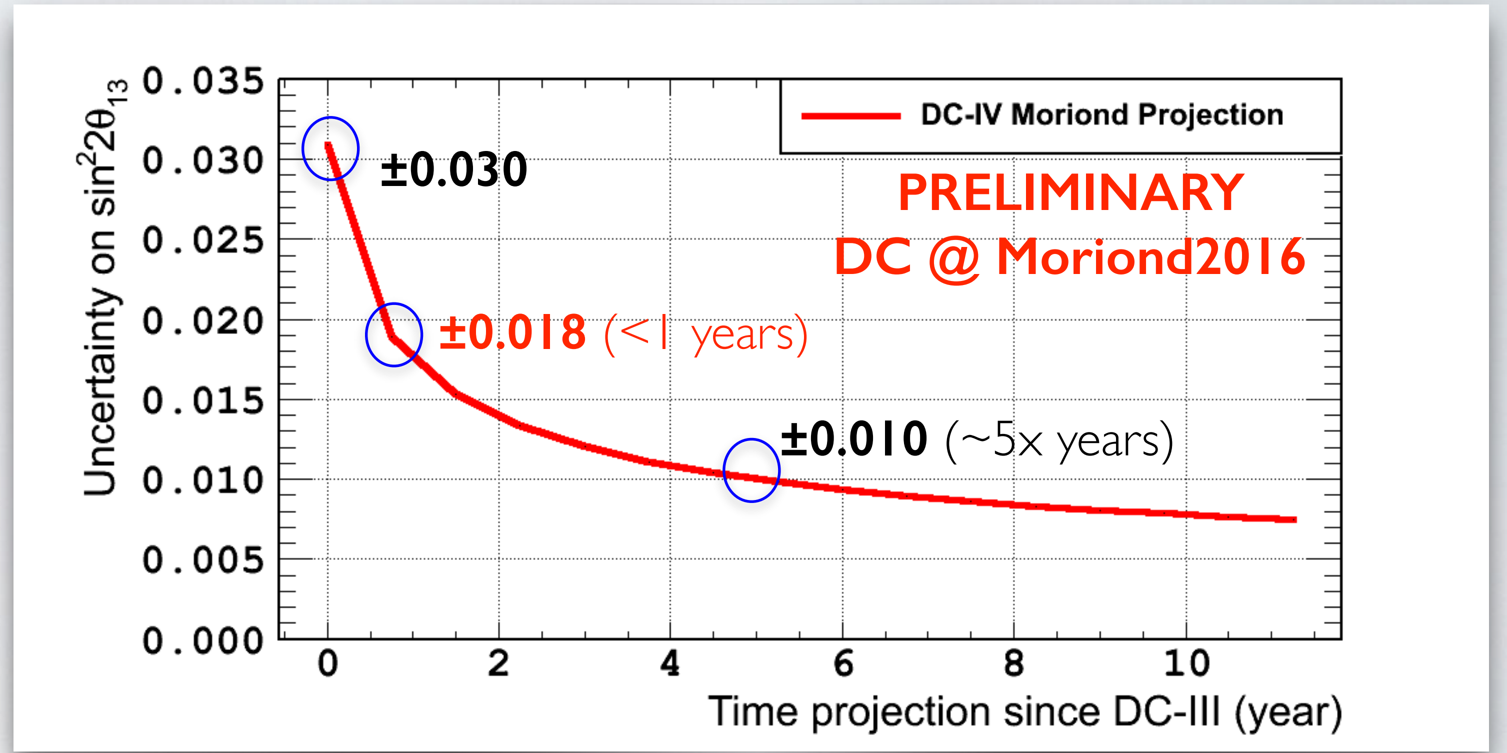
Multi-detector results:

- First multi-detector results on n+Gd released at Moriond 2016.
- New results with higher statistics and larger neutrino target released in September 2016.

STATISTICS: AN ISSUE?

- The result presented at Moriond 2016 were dominated by the statistic.
- The projection of the uncertainty on θ_{13} shows that **statistics is the limiting factor for about 10 years**.



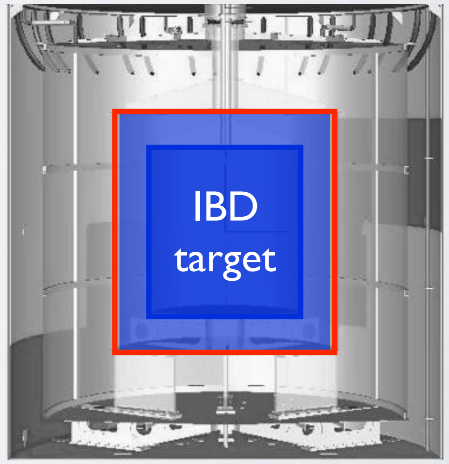


- Exploiting the Gamma Catcher as neutrino target, Double Chooz is no longer dominated by the statistics.

IBD (Gd)

target: ~8t
(smallest θ_{13} target)

IBD (Gd+H+C)

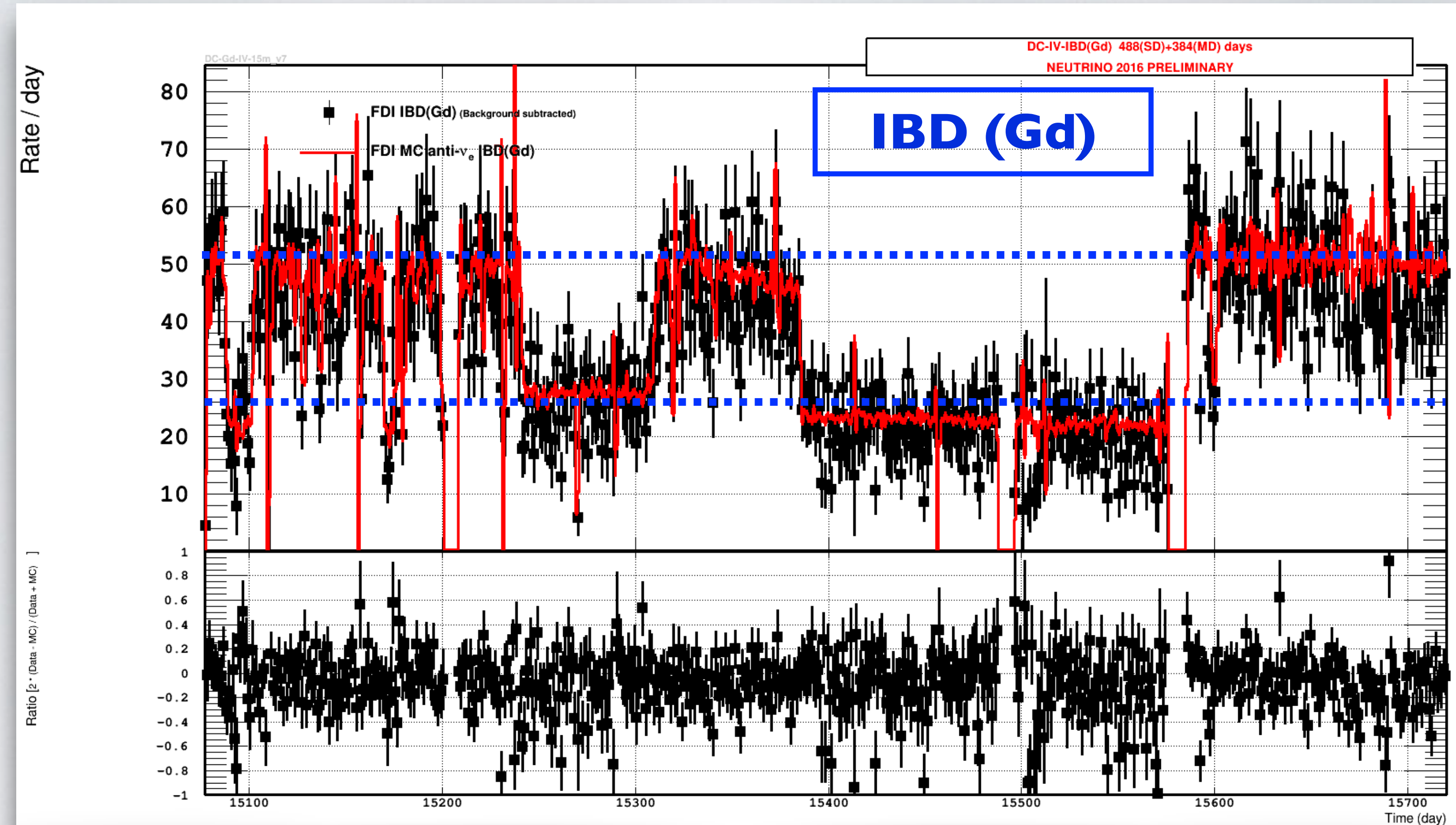


target: ~30t
(largest θ_{13} single detector target)

RATES

50 events per day at FD

σ_{stat} = 0.56%

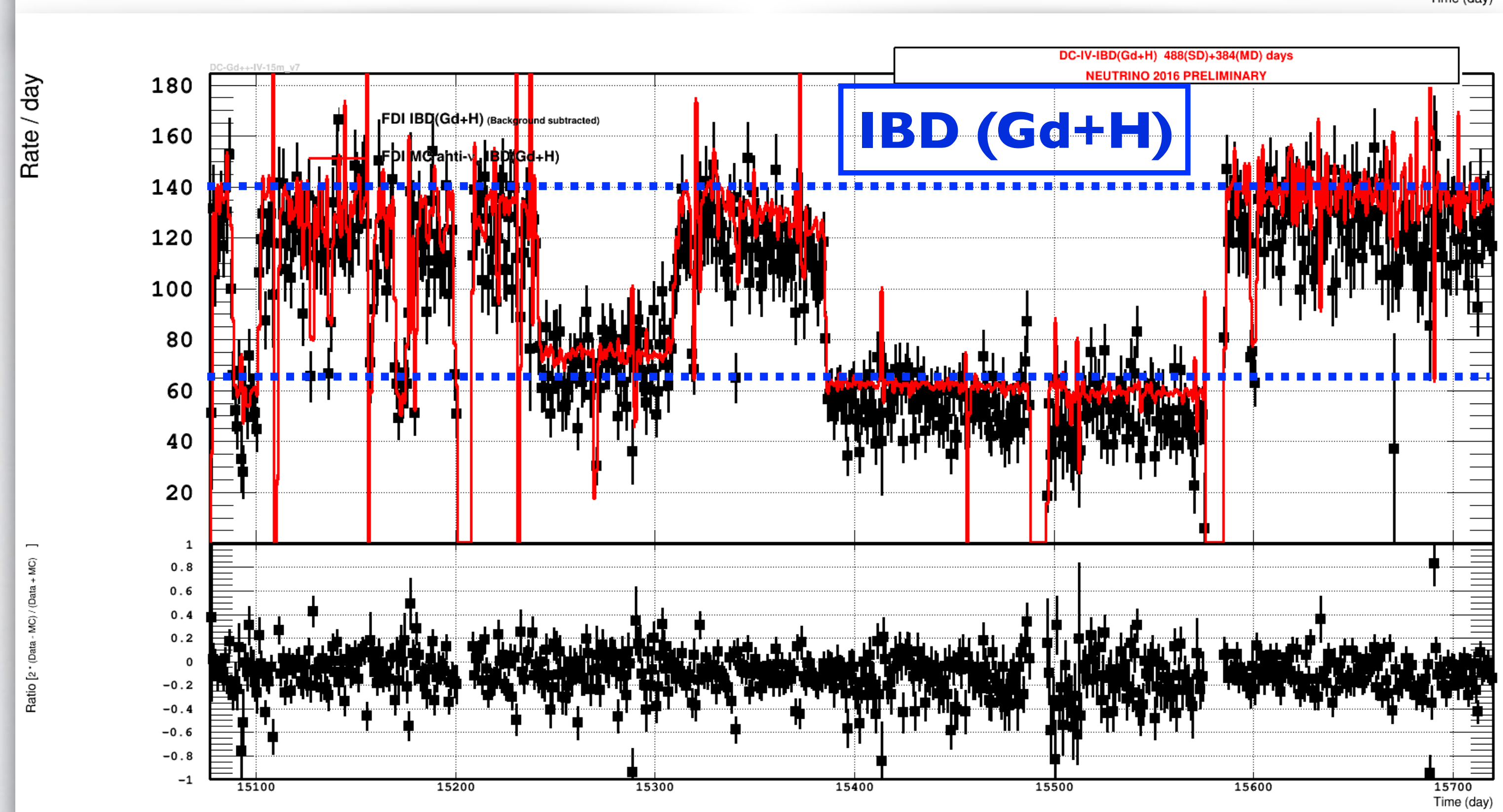


2 Reactors

1 Reactor

140 events per day at FD

σ_{stat} = 0.35%



2 Reactors

1 Reactor

SELECTION

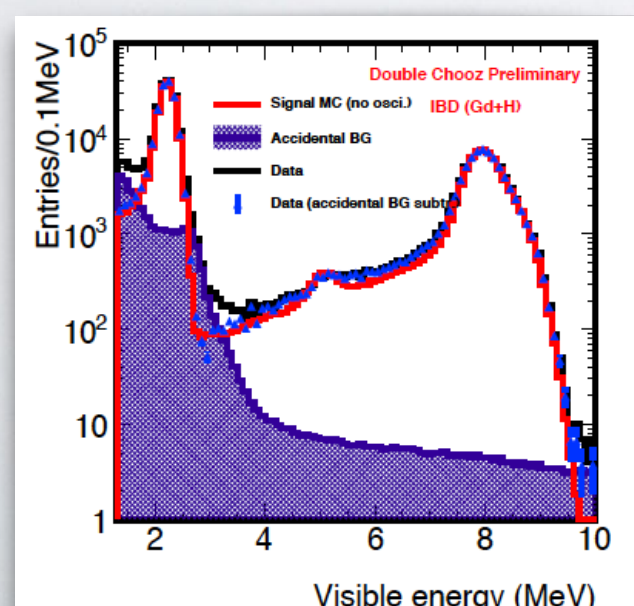
- The signal selection follows the same strategy as for Gd analysis but the background rejection is more demanding.
- A Neural Network (ANN), based on ΔR, Δt and on the delayed energy, is used to reduce the accidental background.

Neutrino candidates selection

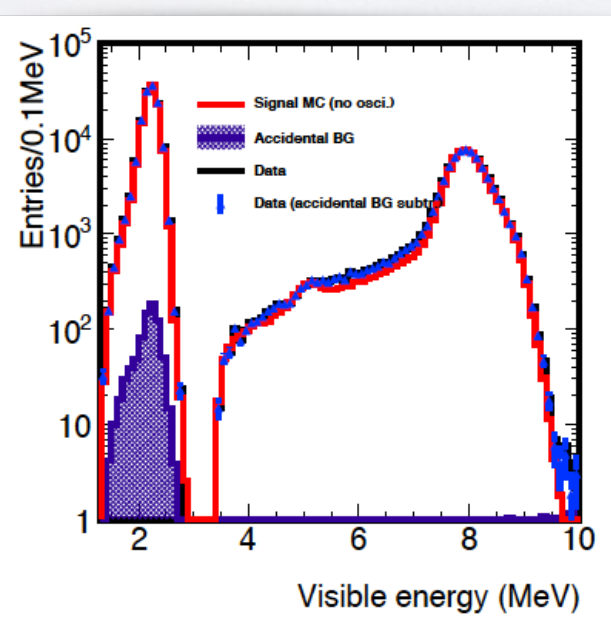
Prompt Energy	1 - 20 MeV
Delayed Energy	1.3 -10 MeV
Δt	0.5 - 800 μs
ΔR	< 1.2 m
Isolation window (prompt)	[-800, +900] μs
Δt after a muon	> 1250 μs

ND delayed

Before ANN

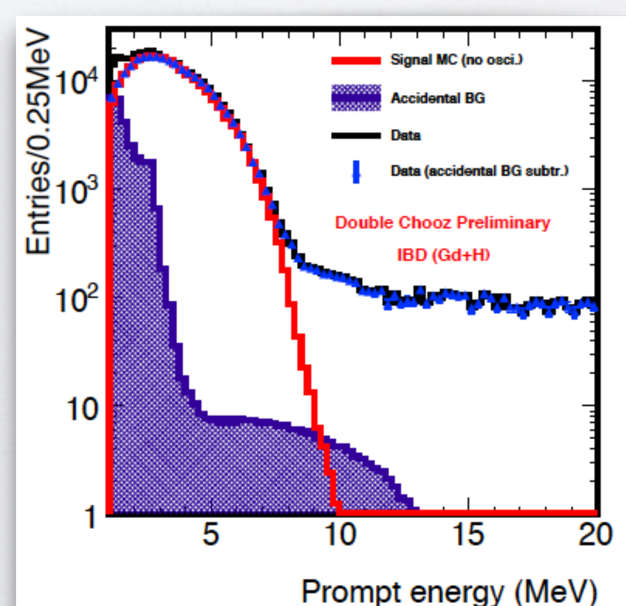


After ANN

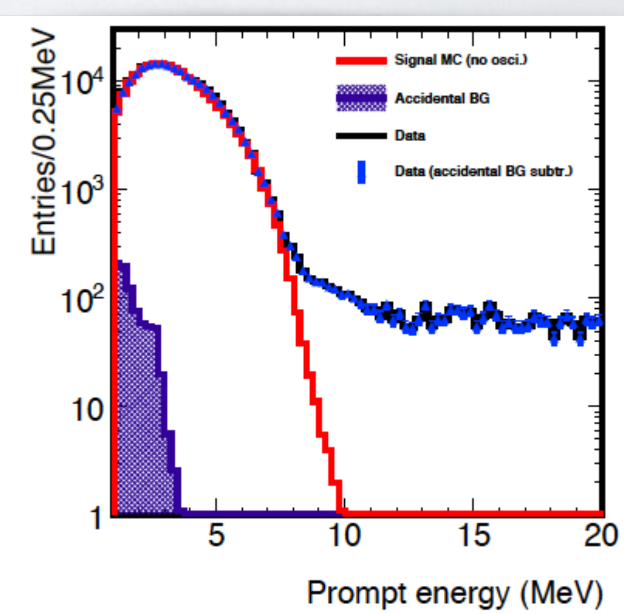


ND prompt

Before ANN

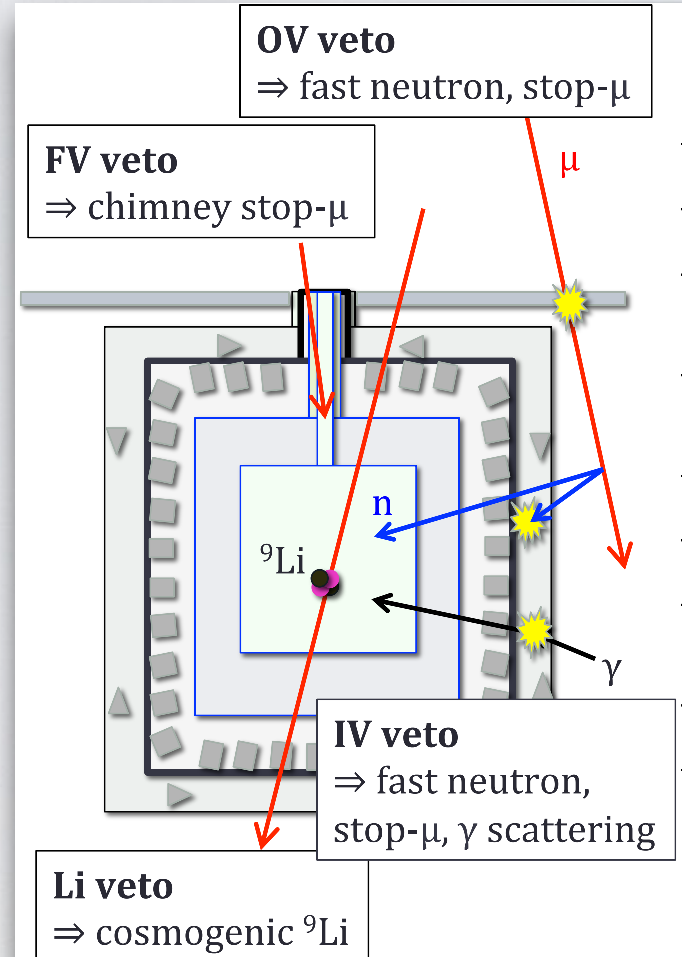


After ANN



BACKGROUND REJECTION

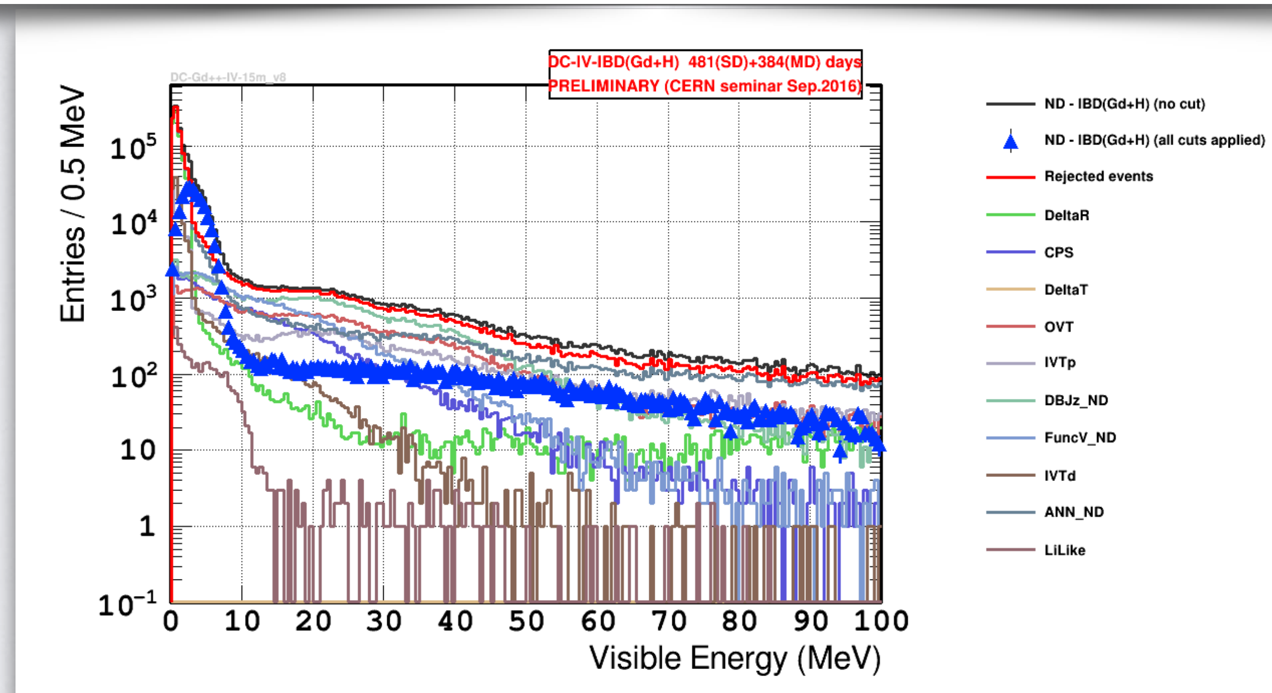
- In the IBD selection there are background contributions which are efficiently removed by the use of several vetoes.



Cut	Information used	BG removed
μ veto	1.25ms veto after μ	μ, cosmogenic
Multiplicity	e^{+}/n signals isolated	multiple-n
FV veto	vertex reconst. likelihood	chimney stop-μ
IV veto	IV – ID signal coincidence	fast n, stop-μ, γ scattering
OV veto	OV activity	fast n, stop-μ
Li veto	Li-likelihood	^{9}Li, ^{12}B
LN cut	PMT hit pattern & time	light emission from PMT
(CPS veto)	chimney likelihood	stop-μ

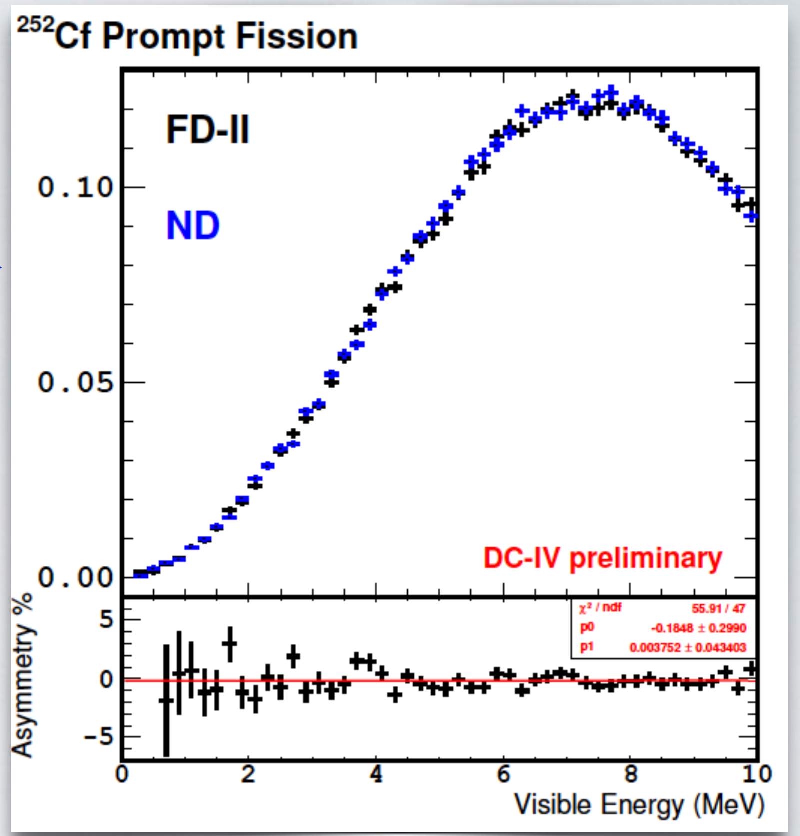
BG after all vetoes [0.5,20] MeV

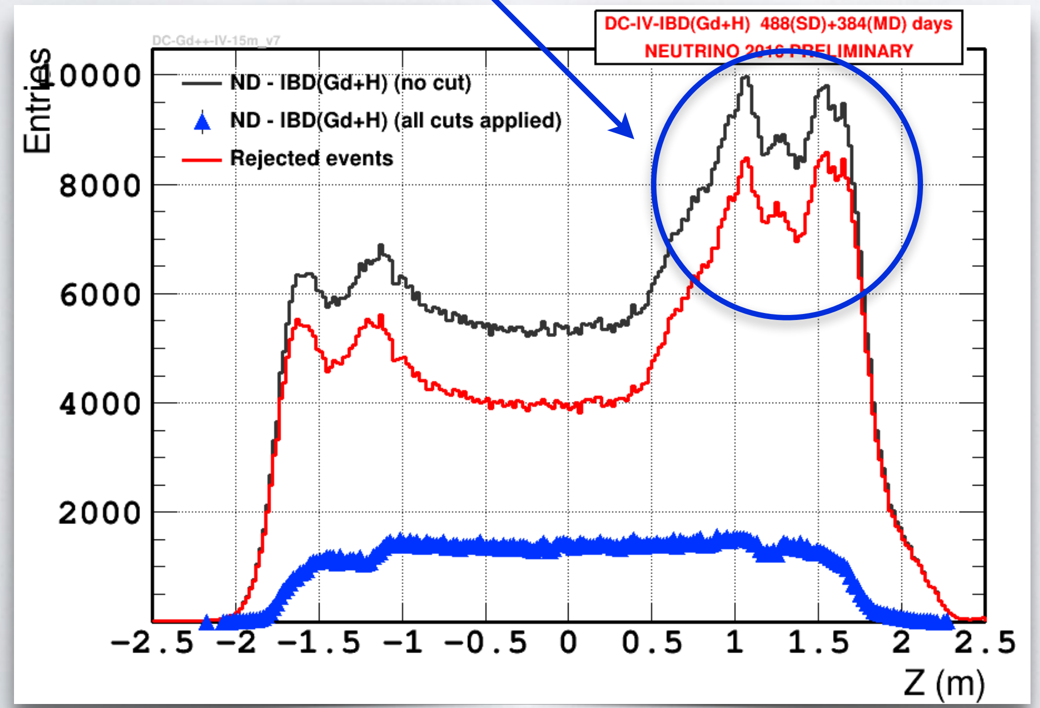
	FD	ND
IBD prediction (day^{-1})	~110	~780
^{9}Li (day^{-1})	~2.5	~11
Correlatet BG (day^{-1})	~2.5	~21
Accidental BG (day^{-1})	~4	~3



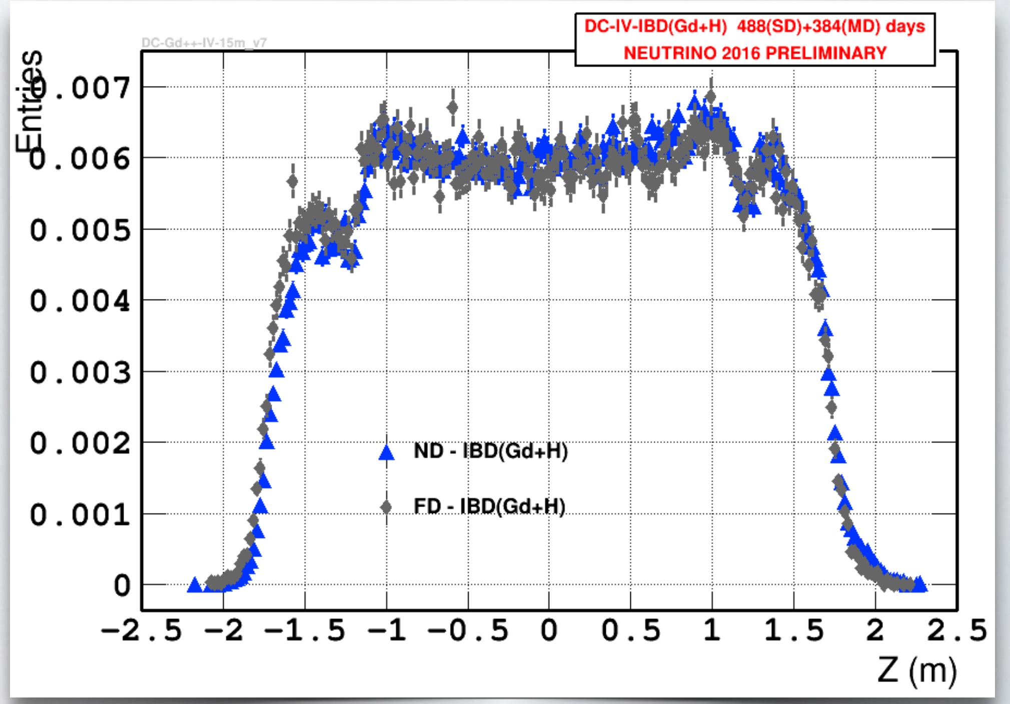
ND PERFORMANCE

- The ND response is very similar to the FD one and fulfils the expectations.
- For example in the Cf calibration campaign (same source for the two detectors) we obtained a relative response linearity ≤ 0.3% within [1,10] MeV.
- **However** we had a **leak** issue: some Gd in Gamma Catcher and some scintillator in Buffer.
- Gd in the GC is **not an issue** in the Gd+H analysis (self compensating).
- The scintillator in the Buffer is an issue for stopping muons which are already a factor of 100 higher in ND with respect to FD.

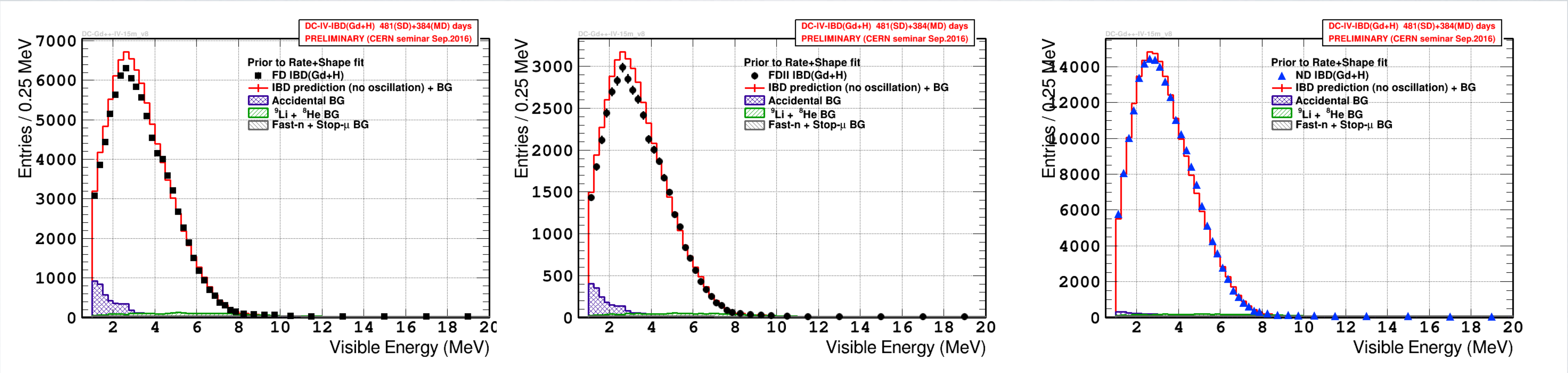




Not an issue after background rejection



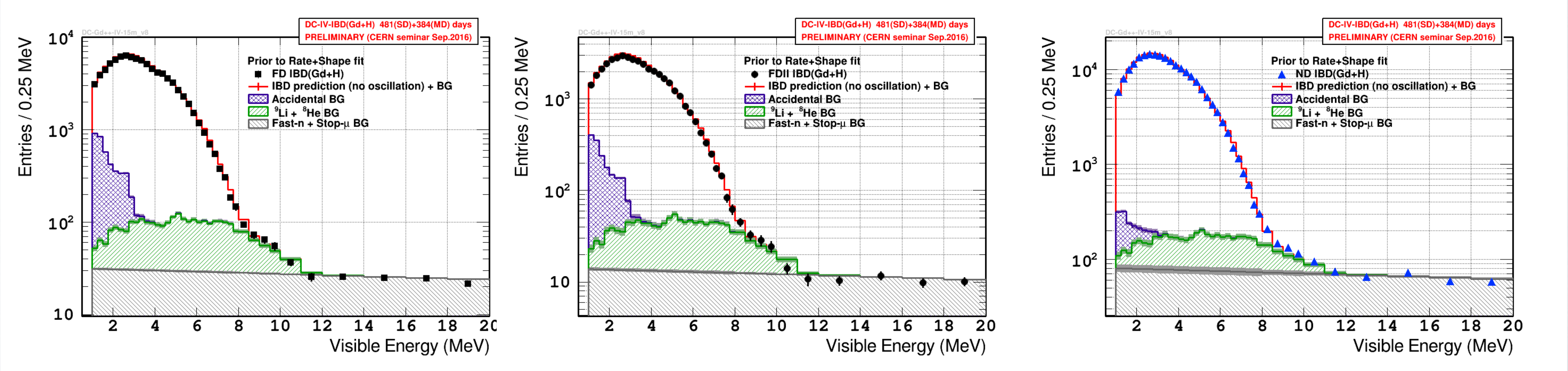
ENERGY SPECTRA



FD-I
~ 40k IBD

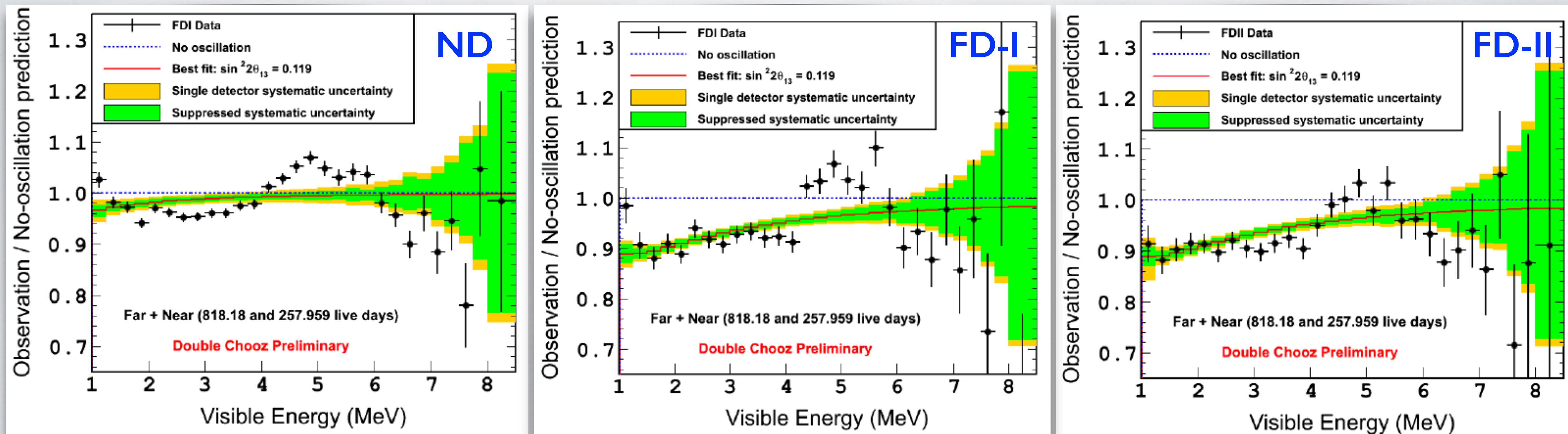
FD-II
~ 40k IBD

ND
~ 200k IBD



FIT AND RESULT

- The fit is done comparing FD-I, FD-II and ND data to the Monte Carlo (prediction + BG).
- Correlation of systematics errors are included in the fit as well as energy non linearities.
- BG rate and shapes are estimated by data (Li BG rate is not constrained in the fit and only shape information is used)



$\sin^2(2\theta_{13}) = 0.119 \pm 0.016$ (stat.+syst.) (χ^2/dof = 236.2/114)

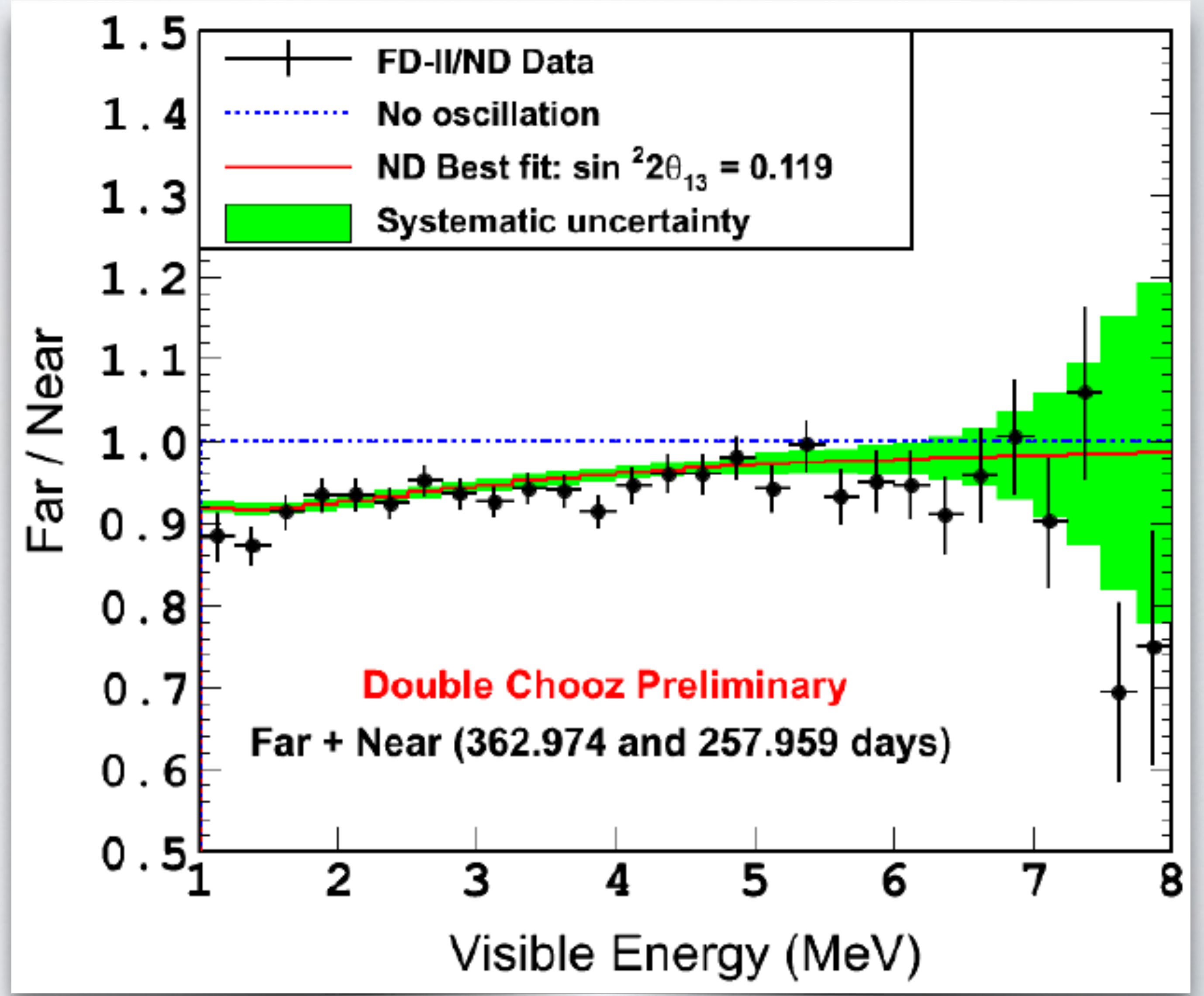
Background	Estimation FD	Fit output FD	Estimation ND	Fit output ND
^{9}Li (β-n)	2.59 ± 0.61	2.55 ± 0.23	11.11 ± 2.96	14.4 ± 1.2
Correlated	2.54 ± 0.10	2.51 ± 0.05	20.77 ± 0.43	20.85 ± 0.31

CROSS CHECK

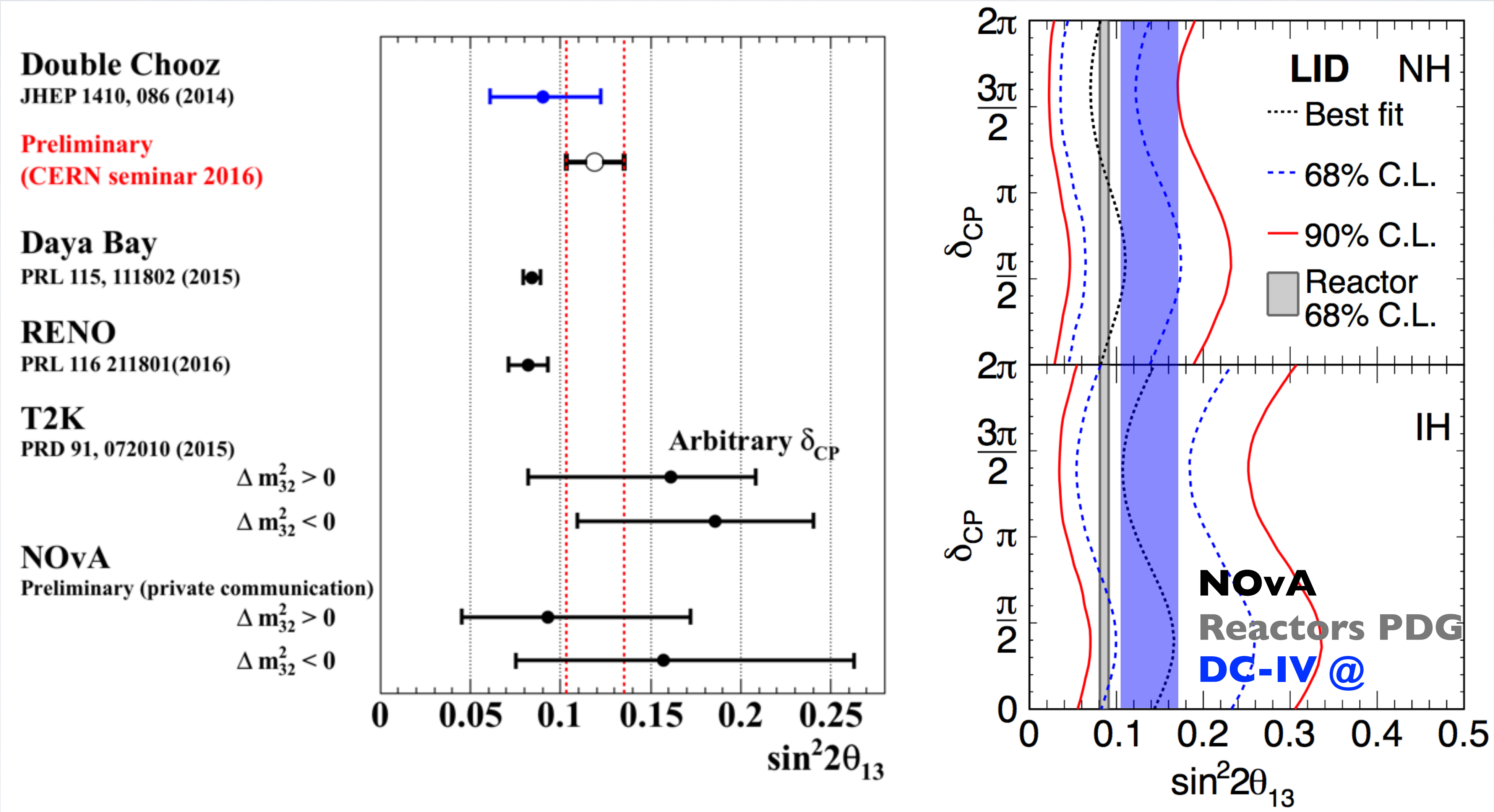
- As a cross check we performed a data-data fit using ND and FD-II.
- This is not affected by the MC spectrum distortion between [4,6] MeV.
- The obtained result is in agreement with the one from the data/MC fit using all the available statistics.

$$\sin^2(2\theta_{13})^{R+S} = (0.123 \pm 0.023)$$

$$\chi^2 / \text{ndf: } 10.6 / 38$$



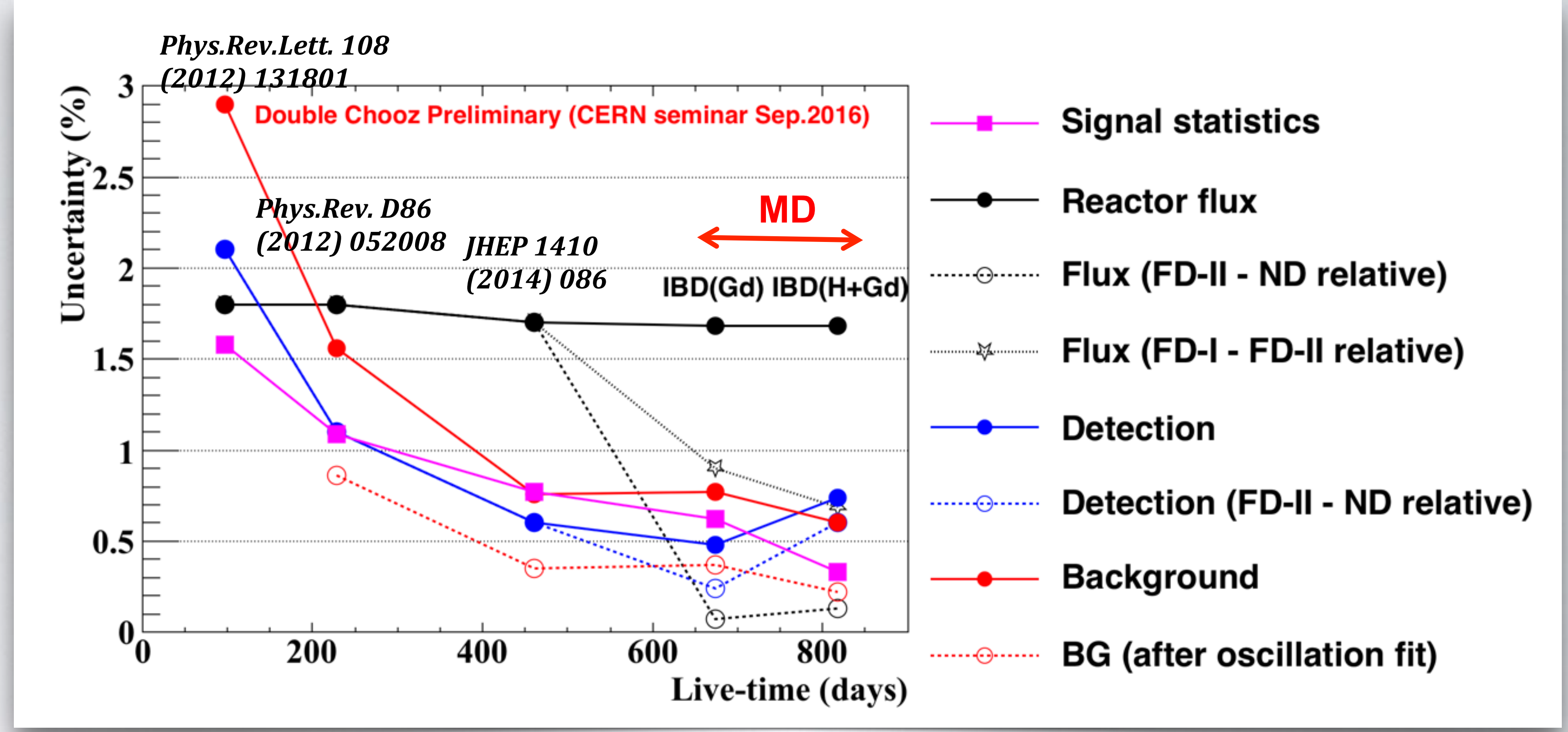
COMPARISON WITH OTHER EXPERIMENTS

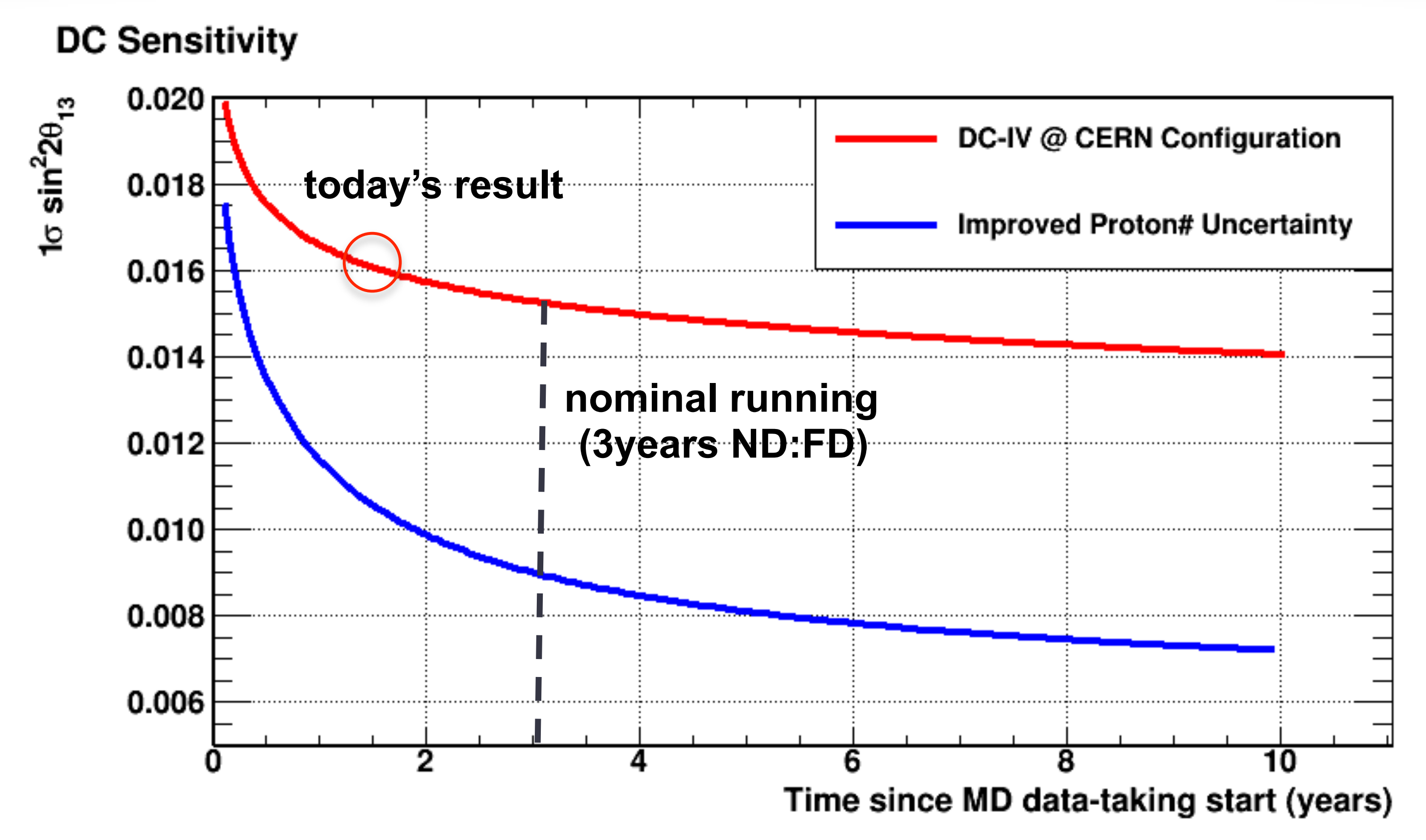


- DC θ_{13} is higher than other θ_{13} reactor values (by ~2.2σ wrt Data Bay).
- The θ_{13} value is a key parameter for future CP-violation and mass hierarchy experiments.

EXTRAPOLATION

- With the multi detector analysis (Gd+H) the statistics is no more a limiting factor.
- The **largest systematics** comes from detection systematics: the uncertainty on the **proton number in the GC** limits the sensitivity to 0.76% whereas if we consider only the neutrino target the detection systematics is 0.3%.
- With a reduction on the proton number uncertainty **we could reach a sensitivity ≤ 0.01** (work in progress).





CONCLUSIONS

- Double Chooz has released a measurement of mixing angle θ_{13} exploiting the multi detector analysis: **$\sin^2(2\theta_{13})=0.119 \pm 0.016$**.

- The use of all neutron captured (Gd+H) allowed for an increase of statistics (statistical error reduce by 40%) which was the limiting factor.

- The new analysis allowed to correctly take into account the (tiny) leak between Target and Gamma Catcher.

- The reactor flux uncertainty is strongly suppressed thanks to the almost iso-flux geometry (<0.1%).

- We are today dominated by the proton number uncertainty: work is in progress to reduce it and a **final sensitivity better than 0.01** on $\sin^2(2\theta_{13})$ could be achieved.

THE COLLABORATION

- **France:**
  CEA/IRFU SPP & SPhN & SEDI & SIS & SENAC Saclay, APC Paris, Subatech Nantes, IPHC Strasbourg
- **Germany:**
  MPIK Heidelberg, TU München, EKU Tübingen, RWTH Aachen
- **Japan:**
  Tohoku U., Niigata U., Tokyo Metropolitan U., Tokyo Inst.Tech., Kobe U., Tohoku Gakuin U., Hiroshima I Inst.Tech.

Russia:
RAS, Kurchatov Institute (Moscow)

Spain:
CIEMAT Madrid

- **USA:**
  Alabama, ANL, Chicago, Columbia, Drexel, Kansas State, MIT, Notre Dame, Tennessee, IIT, U.C. Davis, Virginia Tech
- **Brazil:**
  CBPF, UNICAMP, UFABC