Double Chooz double-detector results

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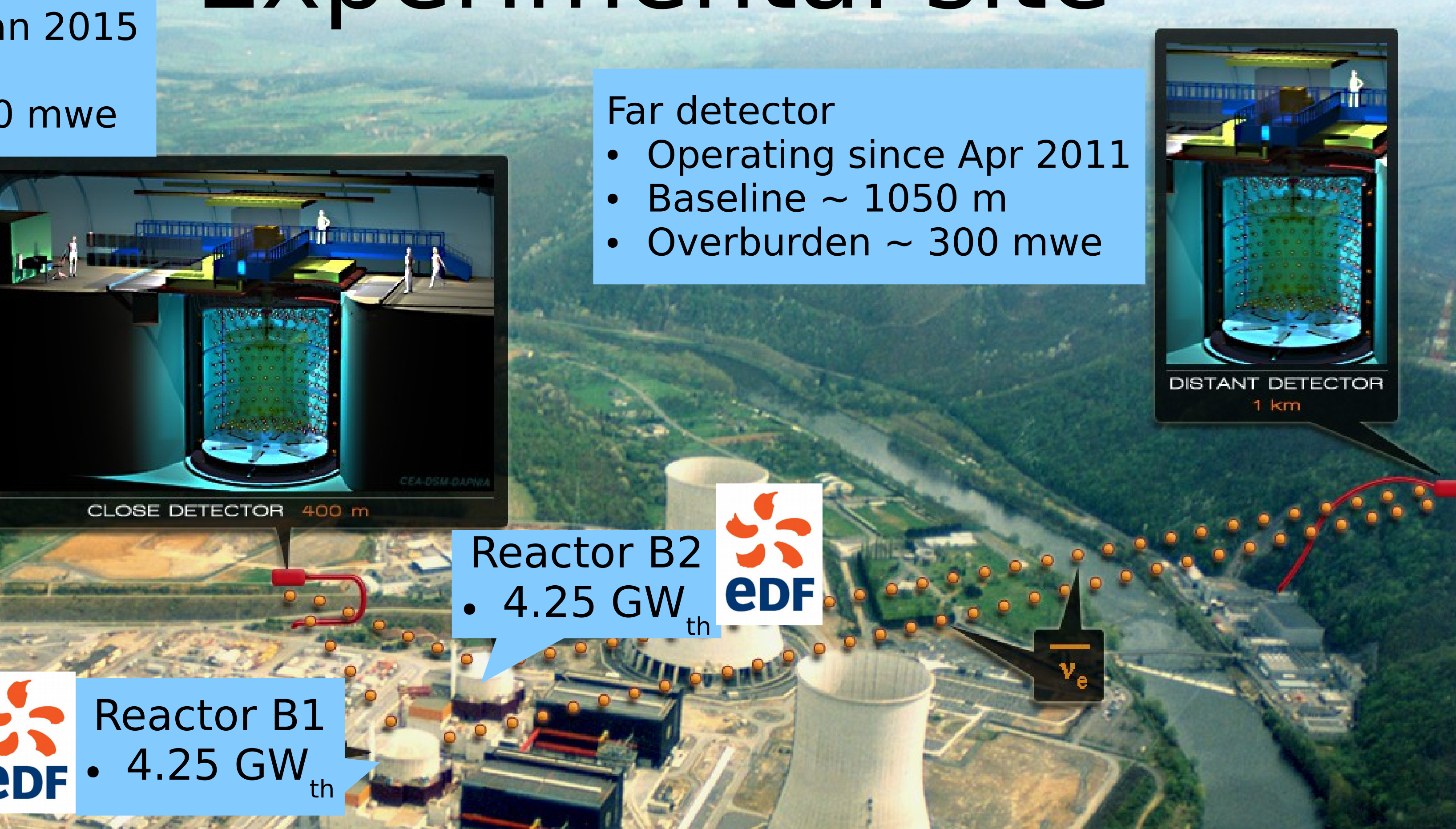
Experimental site

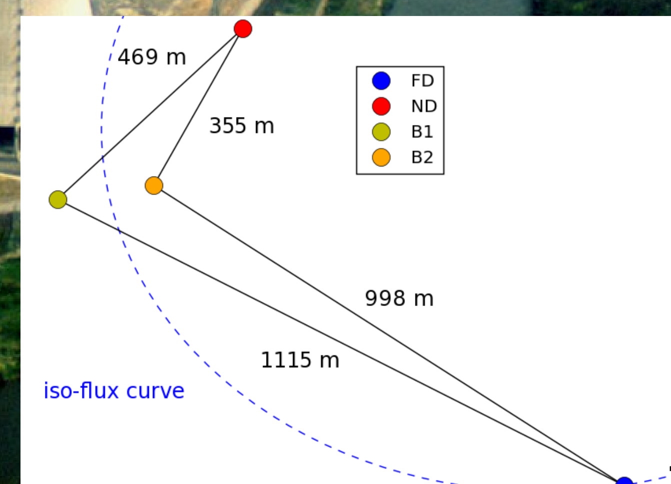
Near detector
- Operating since Jan 2015
- Baseline ~ 400 m
- Overburden ~ 120 mwe

Far detector
- Operating since Apr 2011
- Baseline ~ 1050 m
- Overburden ~ 300 mwe



Reactor B2
- 4.25 GW_{th}

Reactor B1
- 4.25 GW_{th}



θ_{13} Oscillations

$$P_{\bar{e}\to\bar{e}} \approx 1 - \sin^2(2\theta_{13}) \sin^2\left(\frac{\Delta m^2_{ee} L}{4E}\right)$$

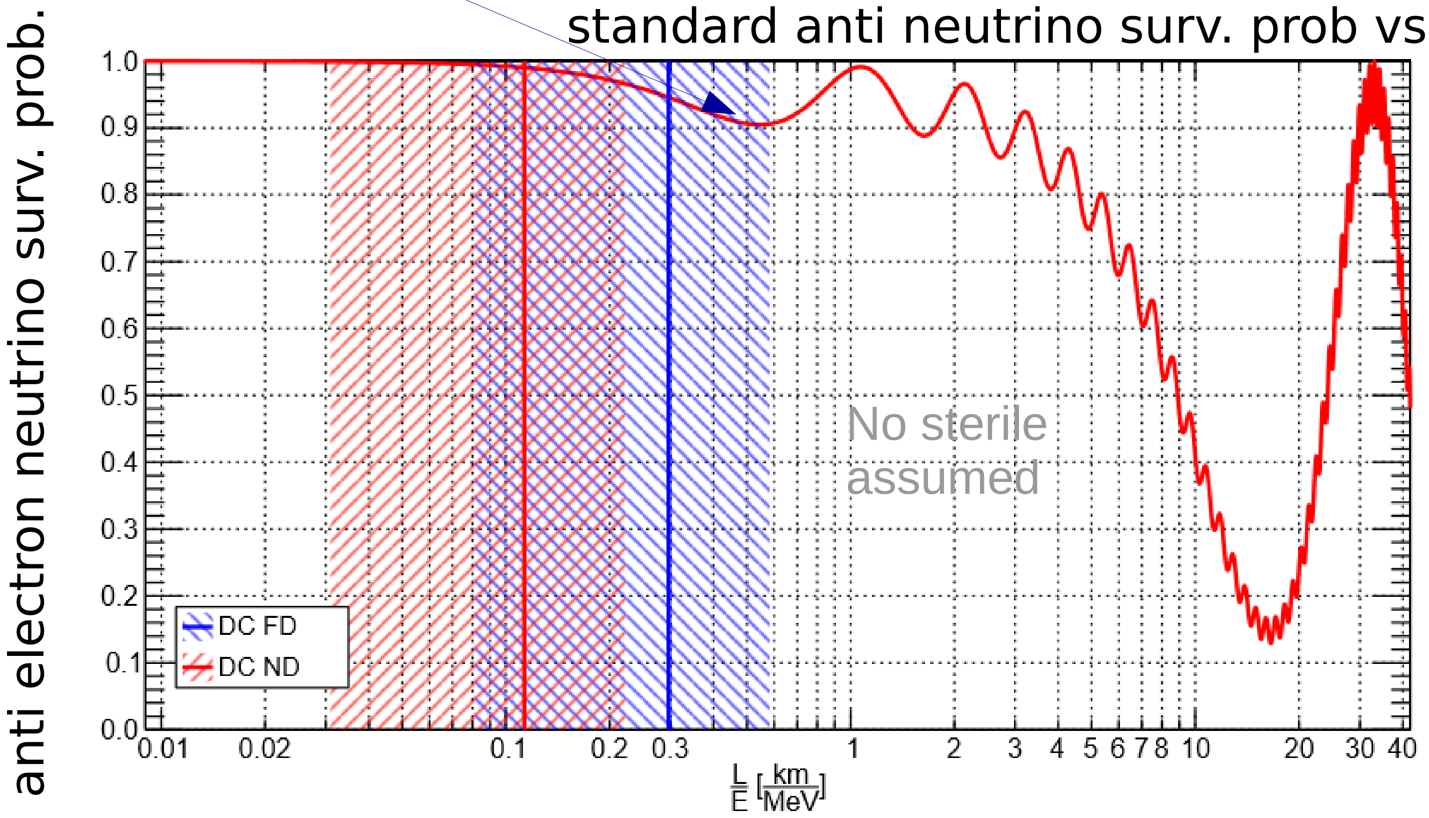
:= anti electron neutrino surv. prob.

$$\Delta m^2_{ee} = \cos^2\theta_{12} \cdot \Delta m^2_{31} + \sin^2\theta_{12} \cdot \Delta m^2_{32}$$

$$|\Delta m^2_{ee}| \approx |\Delta m^2_{31}| \approx |\Delta m^2_{32}|$$

matter effects safely negligible!

standard anti neutrino surv. prob vs. L/E



Double Chooz is optimized for θ_{13} measurement (Δm^2_{31})

θ_{13} Oscillations

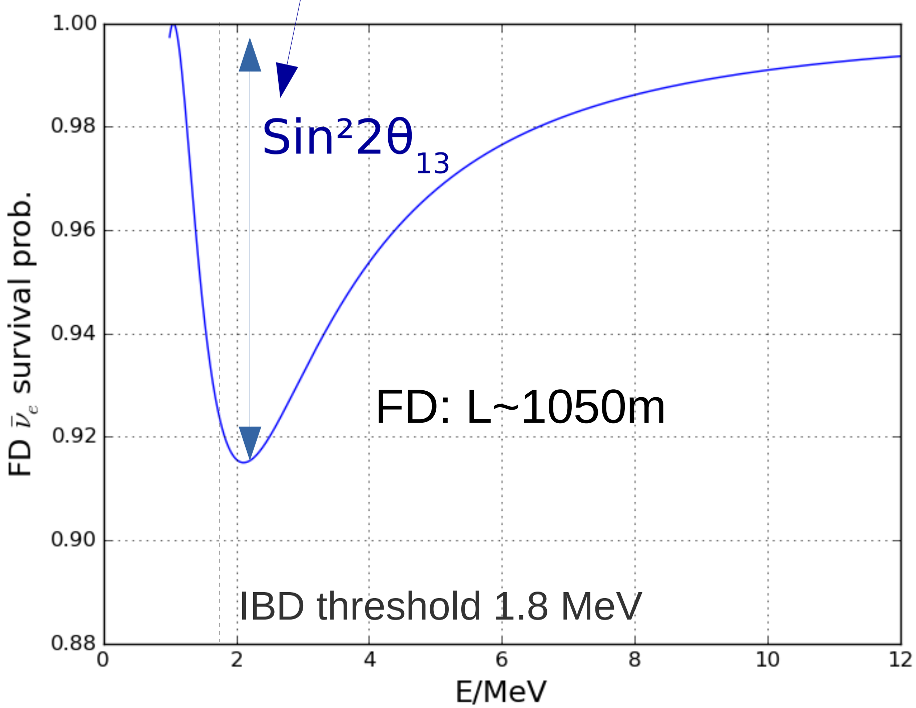
$$P_{\bar{e}\rightarrow\bar{e}} \approx 1 - \sin^2(2\theta_{13})\sin^2\left(\frac{\Delta m_{ee}^2 L}{4E}\right)$$

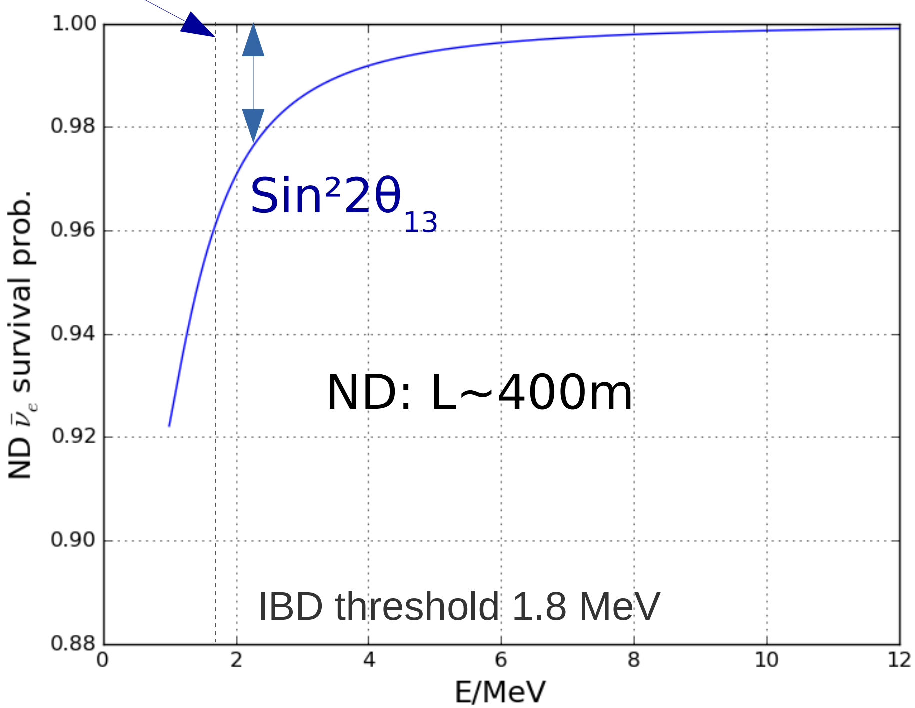
:= anti electron neutrino surv. prob.

$$\Delta m_{ee}^2 = \cos^2\theta_{12}\cdot\Delta m_{31}^2 + \sin^2\theta_{12}\cdot\Delta m_{32}^2$$

$$|\Delta m_{ee}^2| \approx |\Delta m_{31}^2| \approx |\Delta m_{32}^2|$$

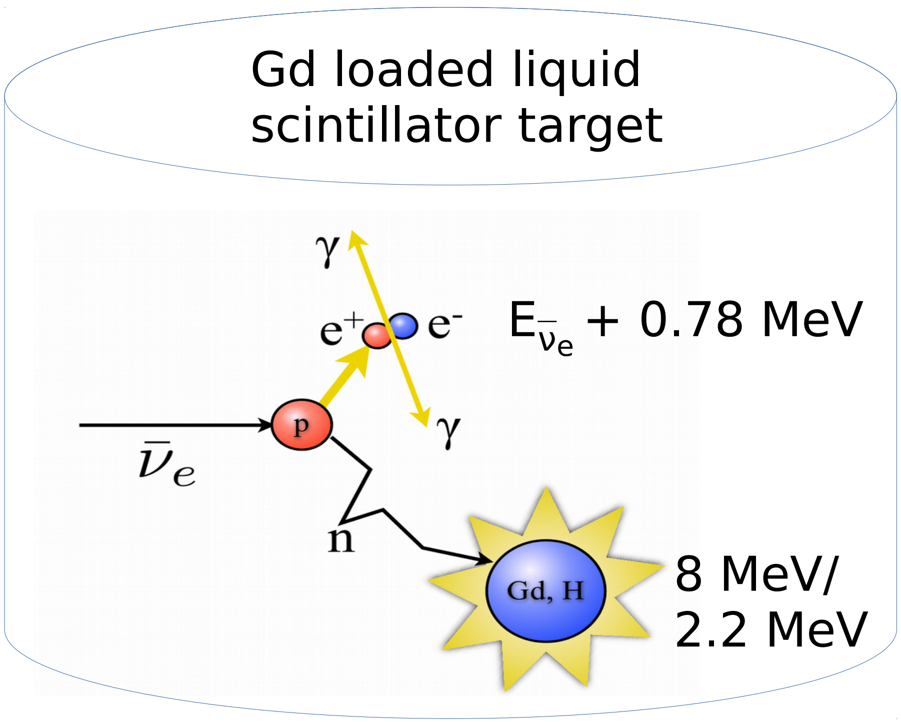
matter effects safely negligible!



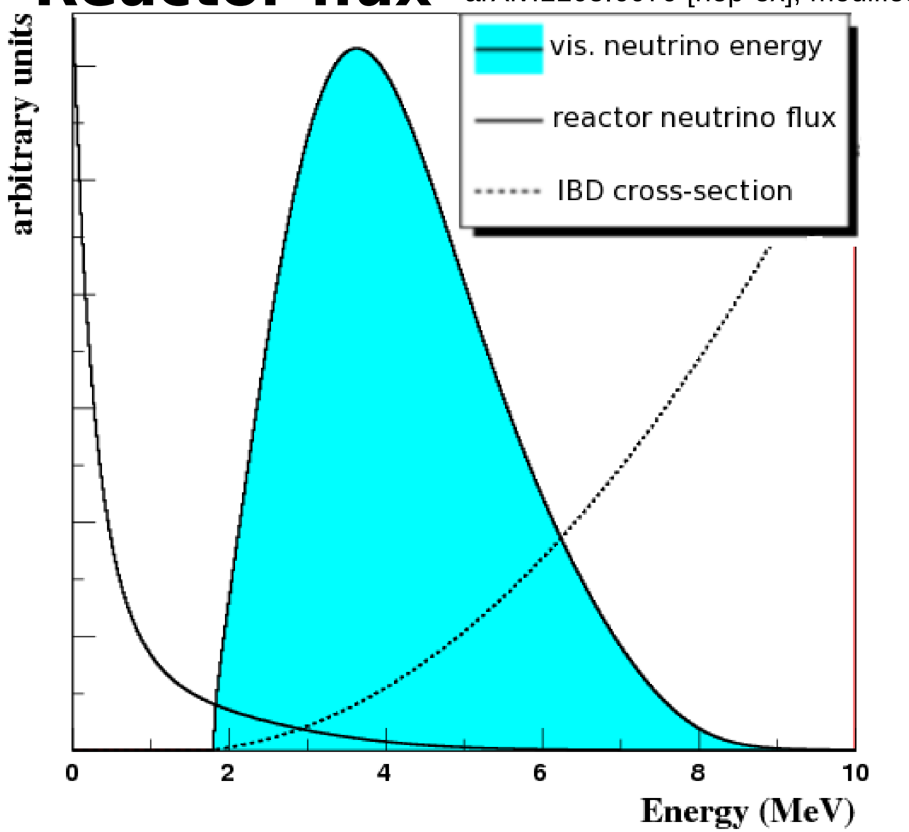


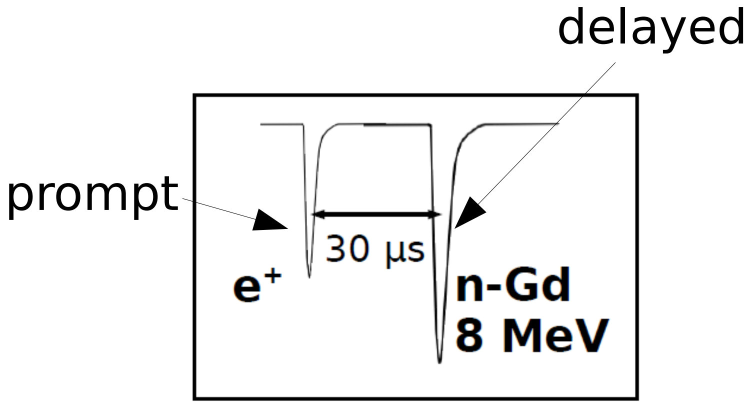
Neutrino Signal

Inverse beta decay IBD $p+\bar{\nu}_e \rightarrow e^+ + n$



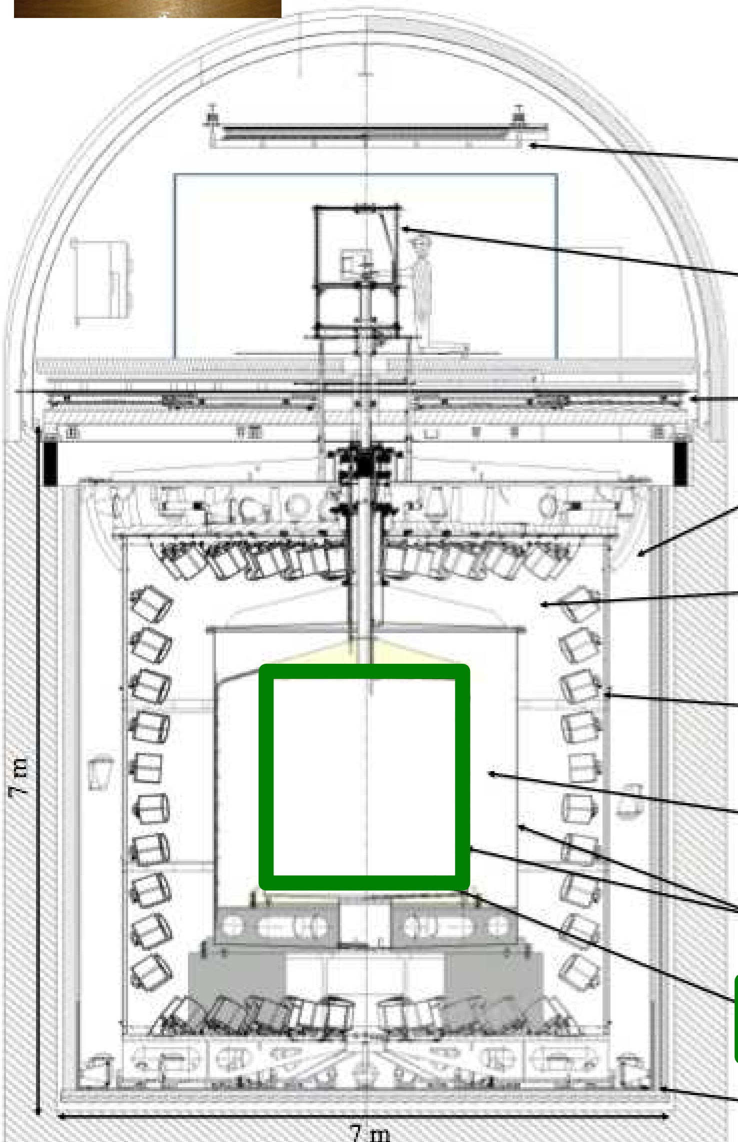
Reactor flux arXiv:1105.6079 [hep-ex], modified





- Two event coincidence:
  - i) prompt signal:
    - positron annihilation
  - ii) delayed signal:
    - n-capture on H or Gd after n-thermalization
    - characteristic energy deposit of 8.0 MeV (Gd)/ 2.2 MeV (H)
    - characteristic delay time ΔT~ 30 µs/ 220 µs

Detector

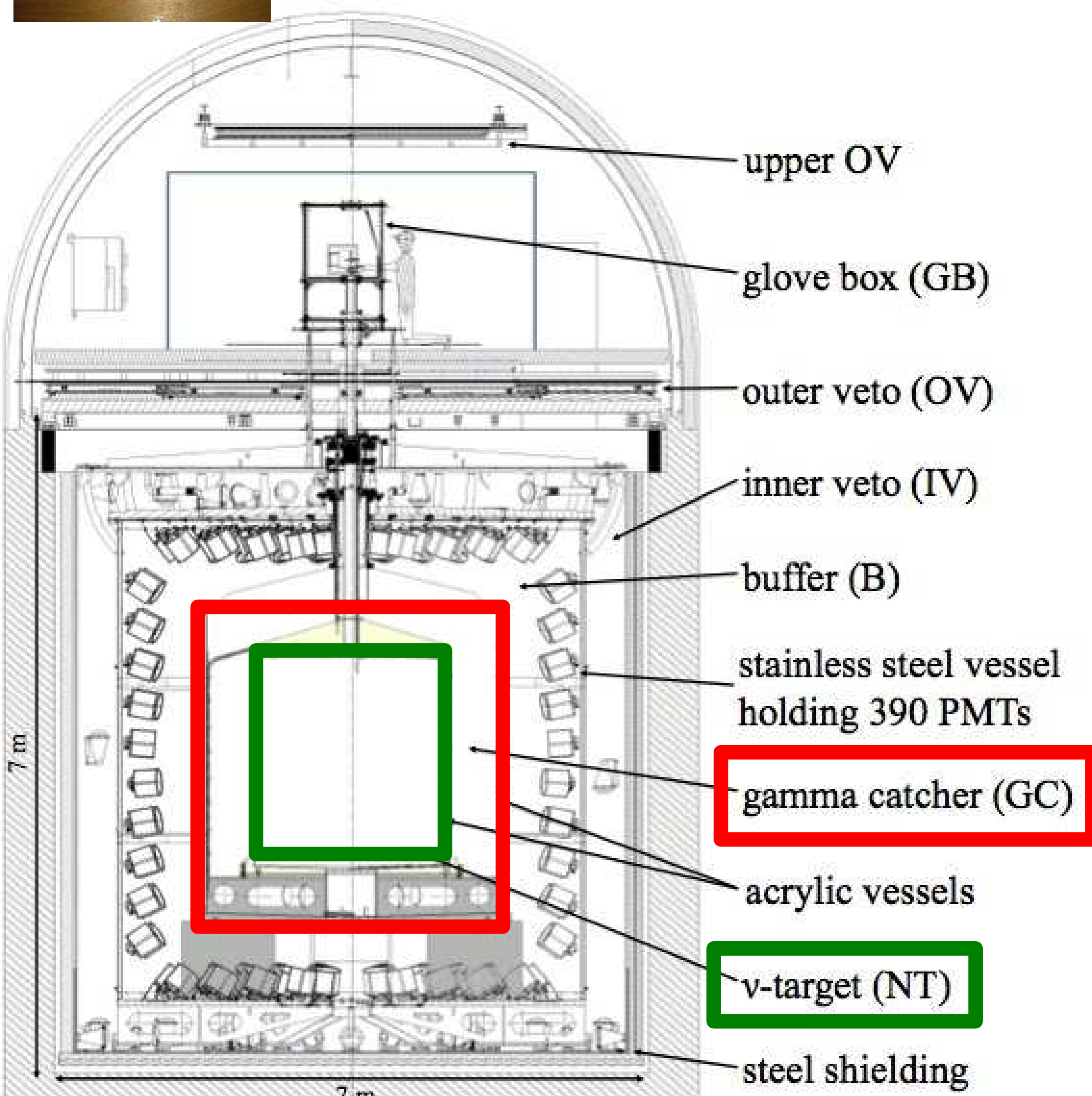


(Sketch of FD, ND almost identical)

(Nd: water shielding)

Neutrino Target (NT)
Gd loaded (1 g/l) liquid scint.
(10 m³)

Detector



Gamma Catcher (GC)
Liquid Scintillator (22 m^3)
Measures γ escaping the target

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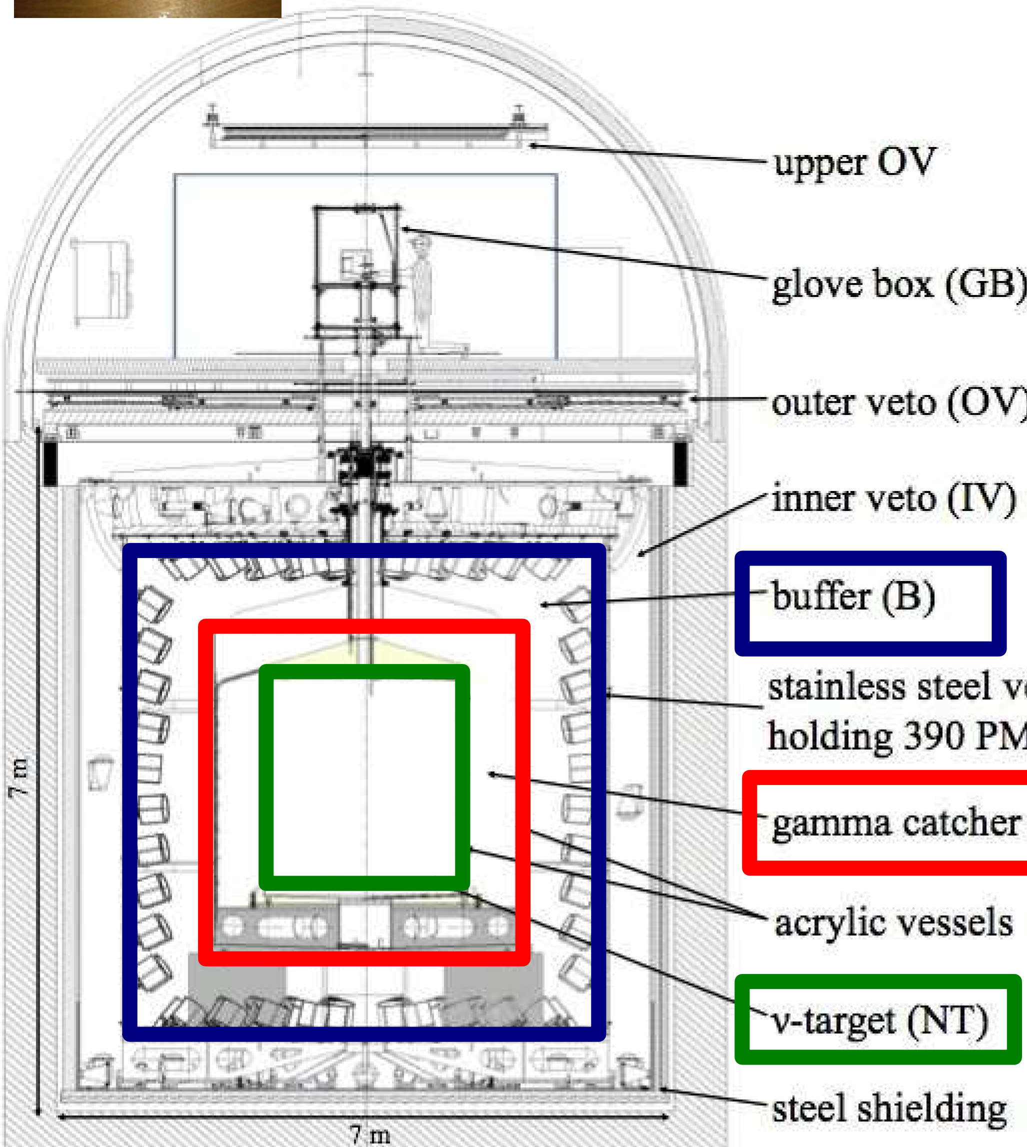

(Sketch of FD, ND almost identical)

(Nd: water shielding)

Buffer (B)
Non-scintillating mineral oil
(110 m³)
390 10" PMT
Shielding against external γ

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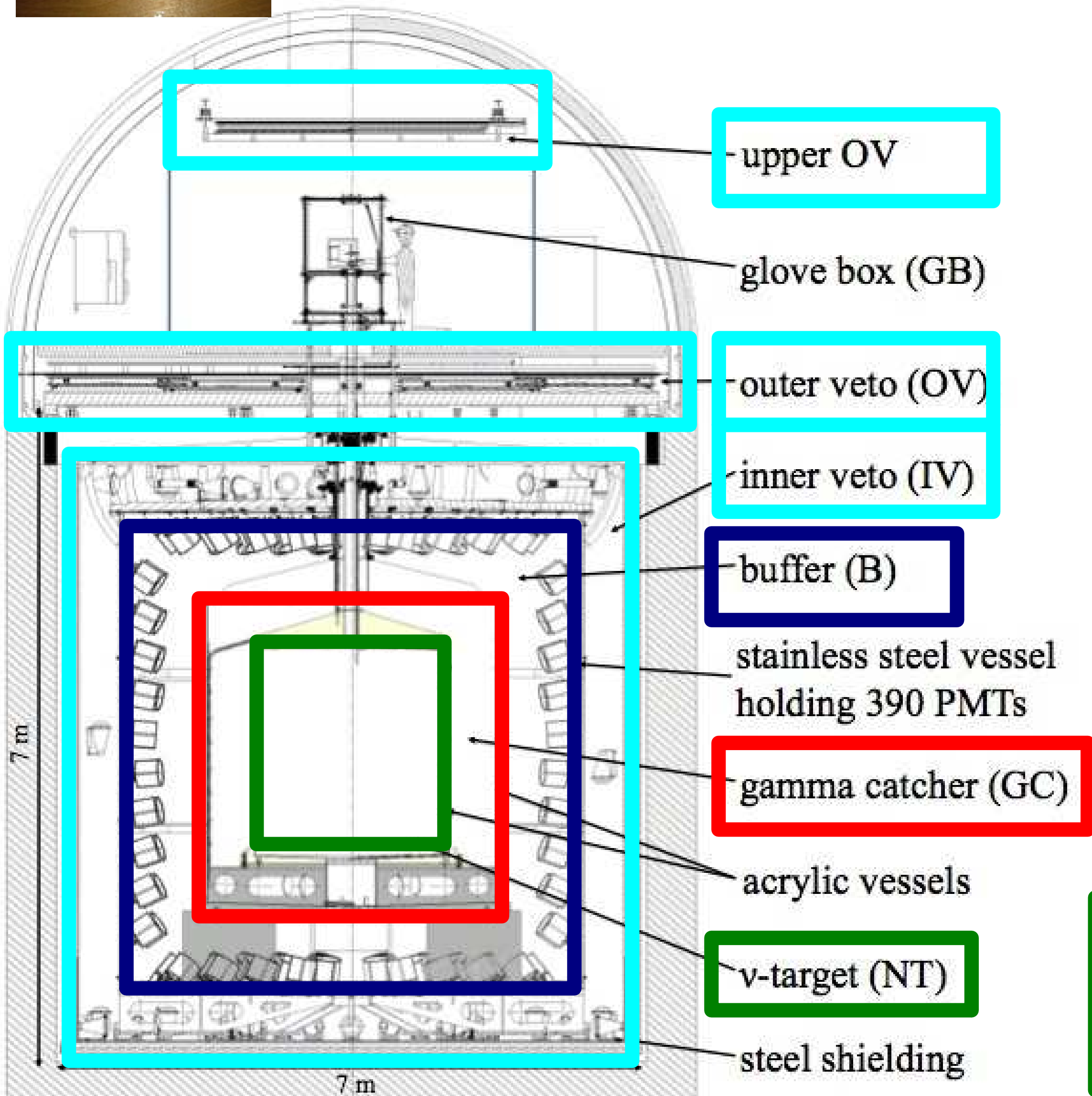

(Sketch of FD, ND almost identical)

(Nd: water shielding)

Outer Veto (OV)
Plastic scintillator strips
vetos atmospheric μ

Inner Veto (IV)
Liquid Scintillator (90 m³)
78 8" PMT
Vetos atmosperic μ and neutrons
Shielding

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Non-scintillating mineral oil
(110 m³)
390 10" PMT
Shielding against external γ

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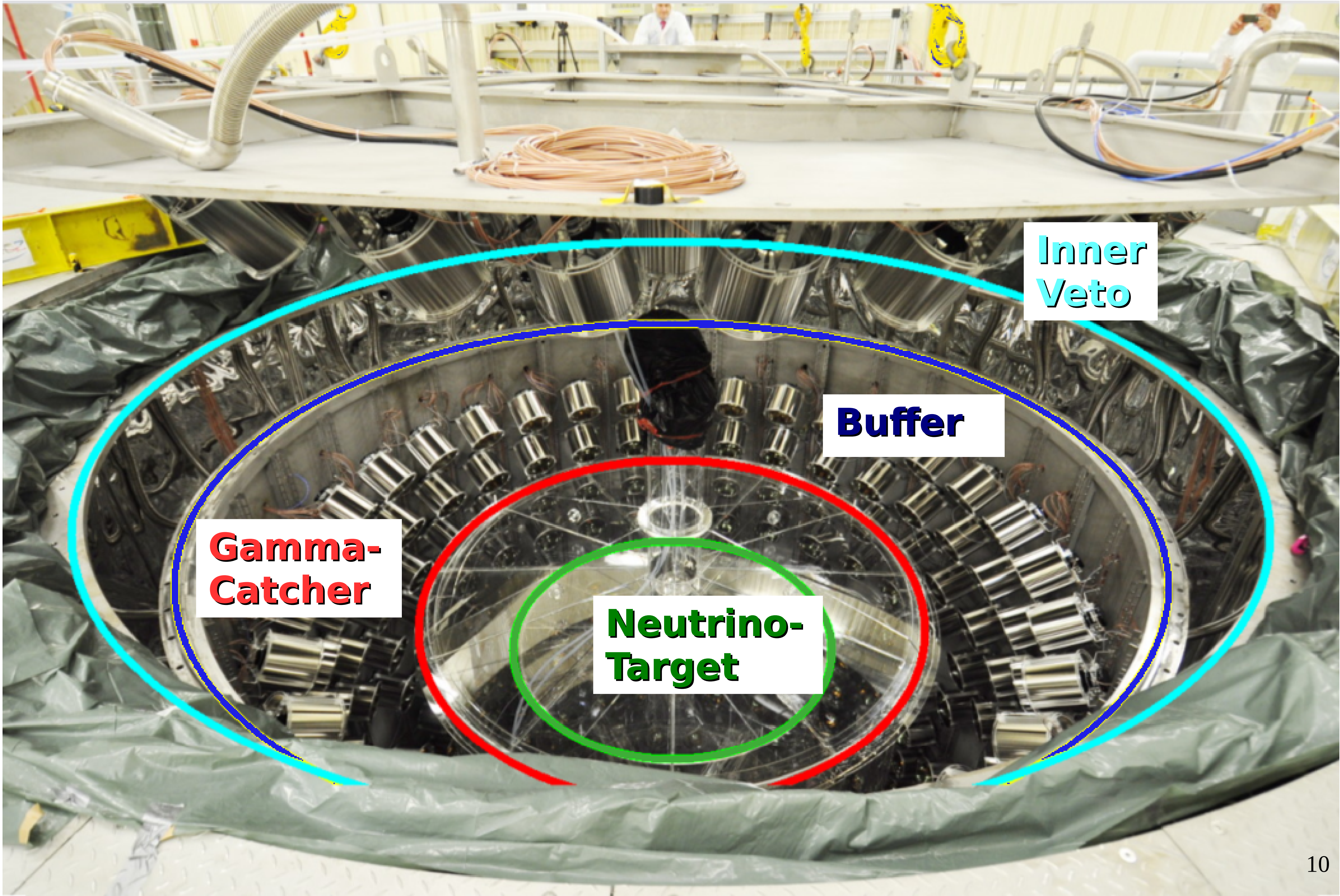
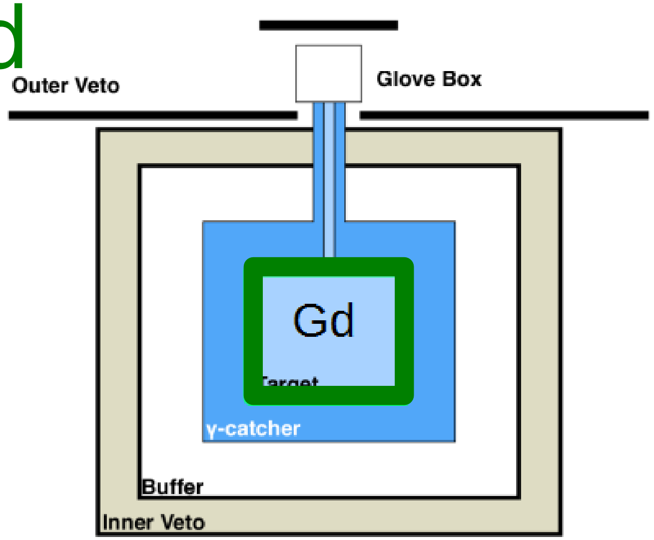
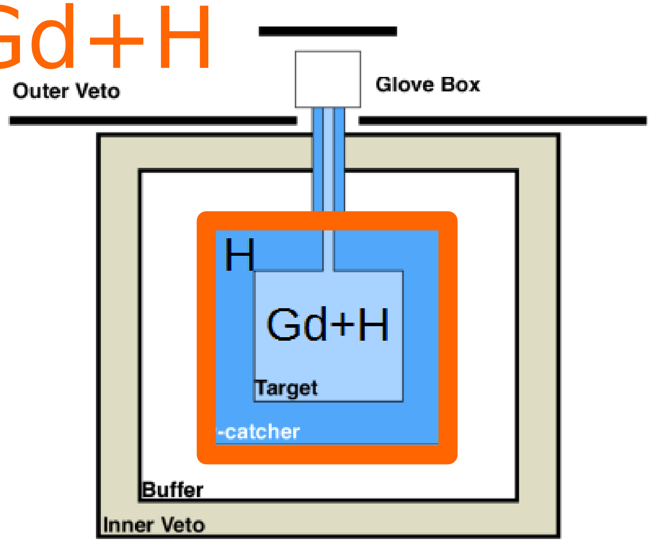


IBD Selection

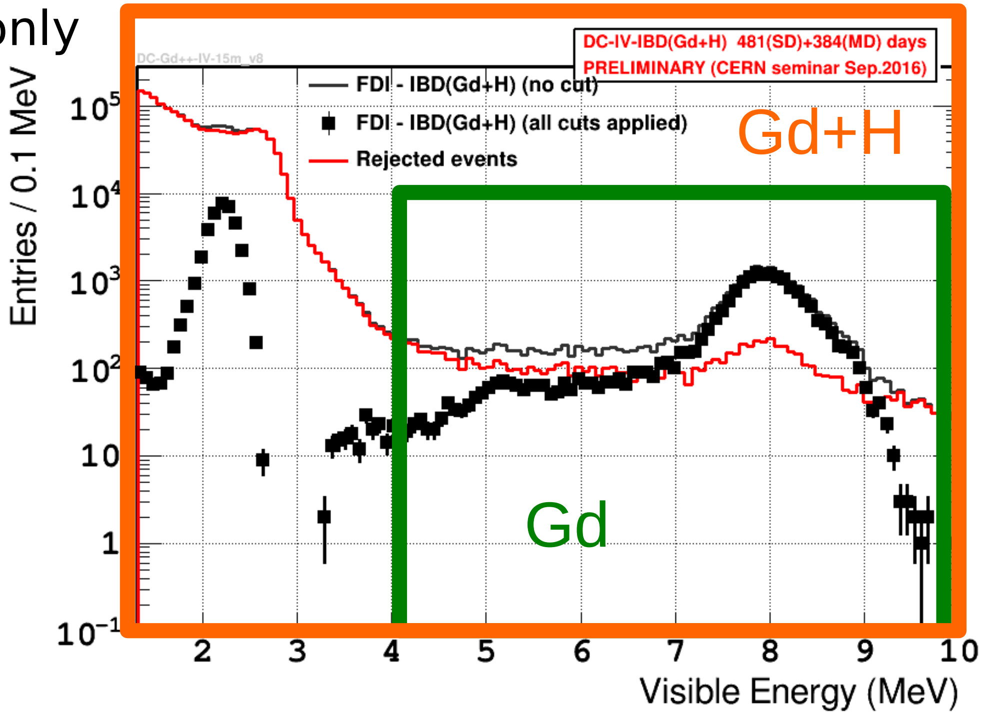
Gd



Gd+H



- Selecting **n-Gd** capture in **Neutrino Target** only

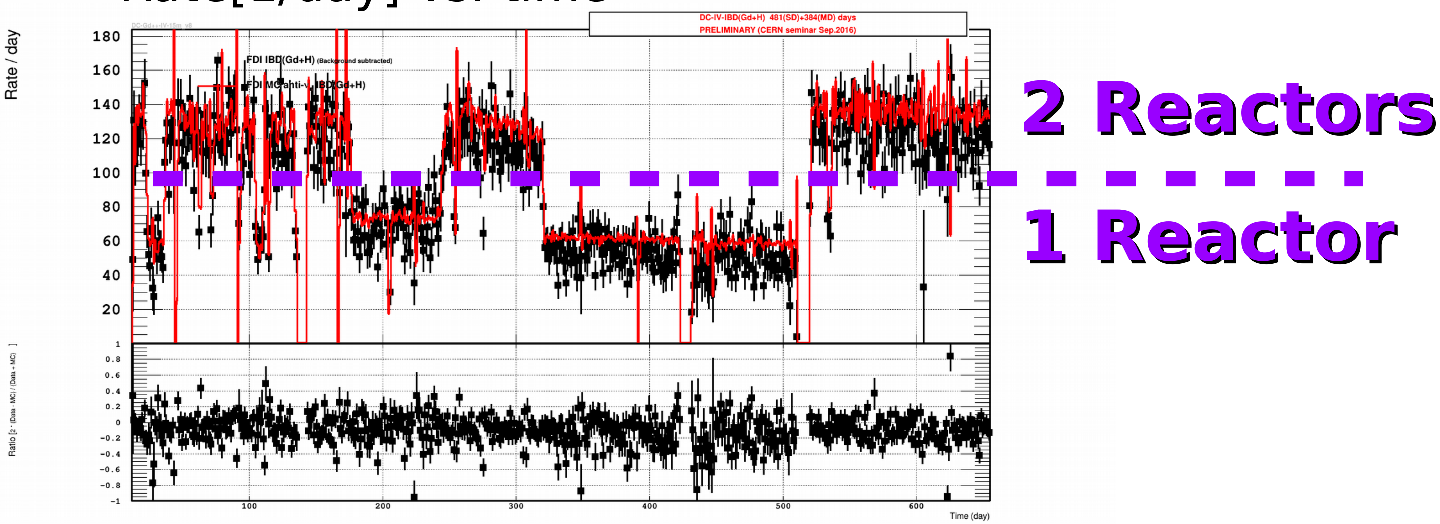


- Selecting **n-Gd and n-H** capture in **Neutrino Target and Gamma Catcher**
- **Statistics increase by ~2.5**
  - Immune to liquid exchange between ND Neutrino Target and Gamma-Catcher

Datasets

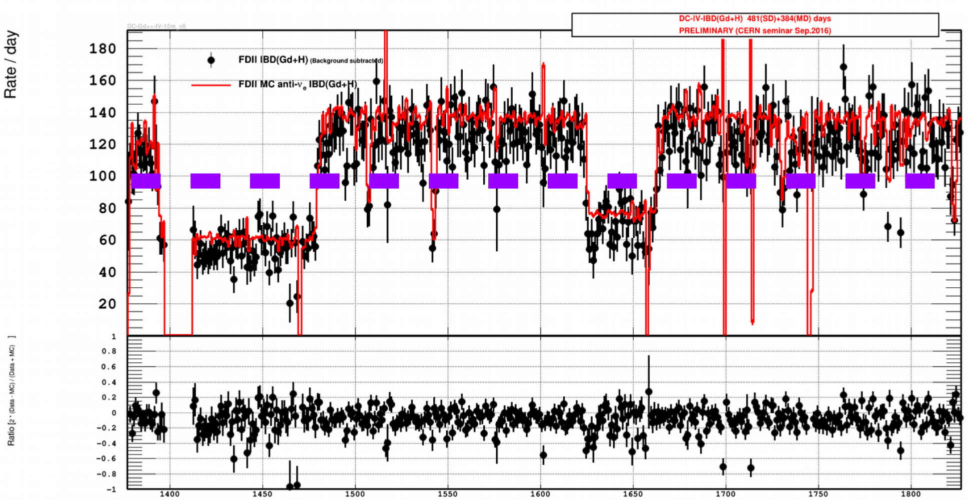
FDI (FD before ND existed) 455 days lifetime + 7 days lifetime reactor off

Rate[1/day] vs. time



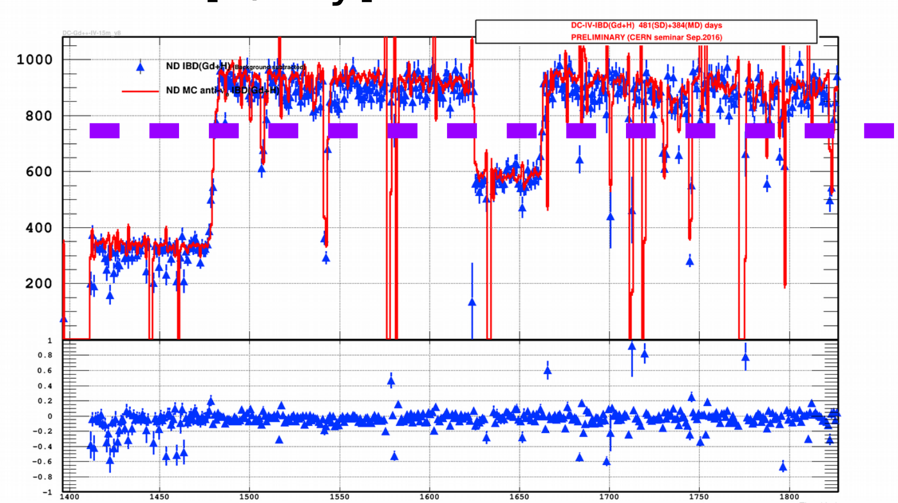
FDII (FD parallel to ND) 363 days lifetime

Rate[1/day] vs. time

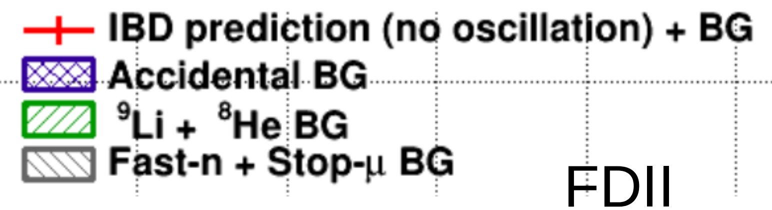


ND 258 days lifetime

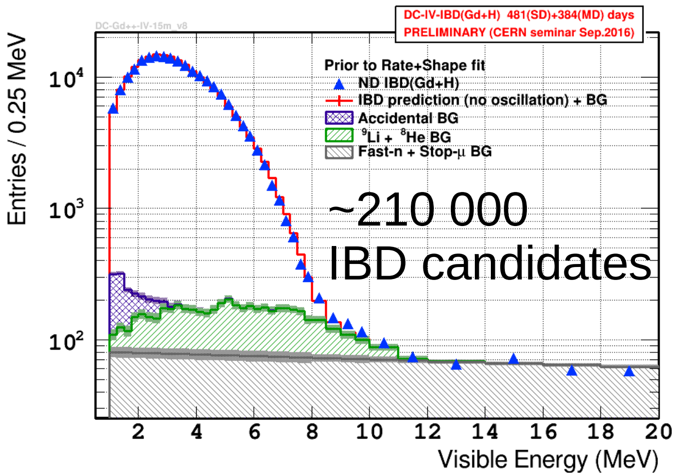
Rate[1/day] vs. time



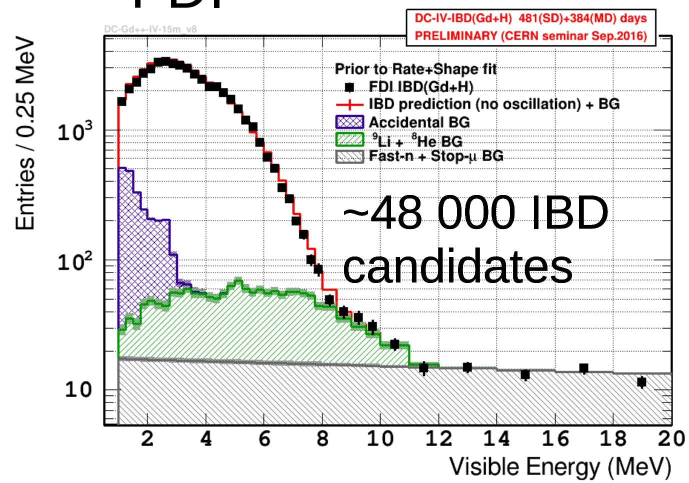
Datasets



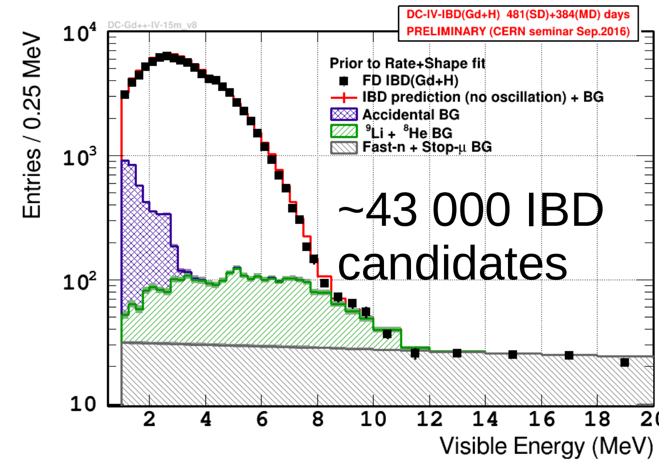
ND



FDI



FDII

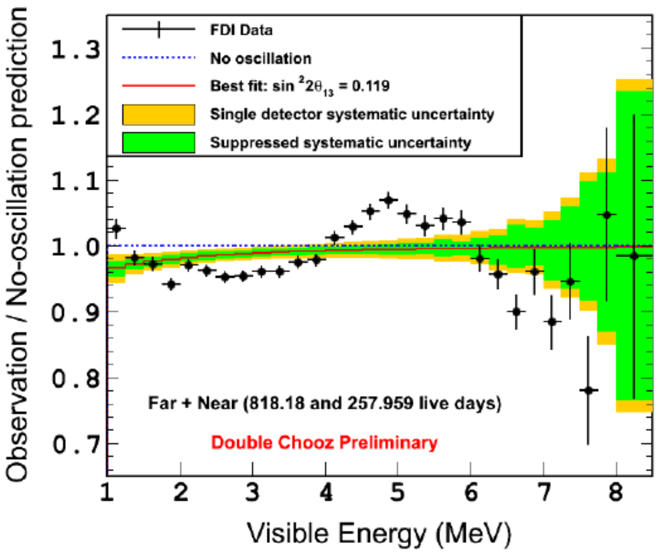


+ FDI Reactor-Off dataset
(highly constrainting backgrounds!!!)

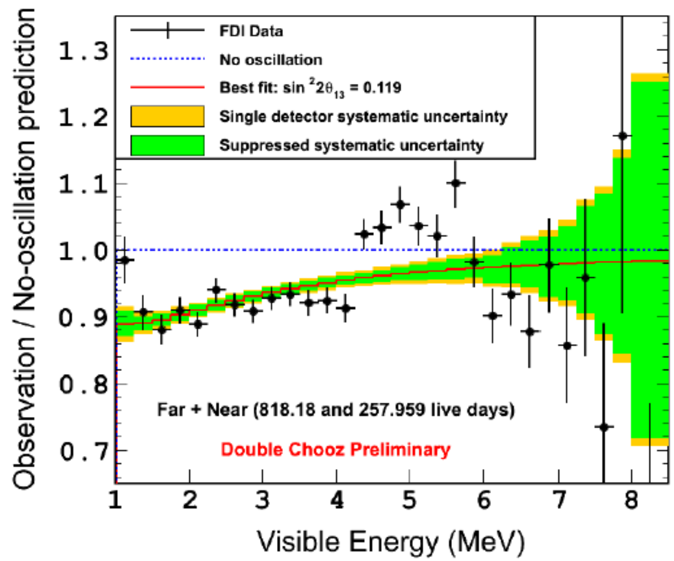
- Energy window on purpose extended to background dominated regions
  - Up to 8 MeV signal dominated
  - 8-12 MeV Lithium dominated
  - >12 MeV fast n + stopping μ dominated
- => background estimate for fit

Latest θ_{13} Results (Sep 2016)

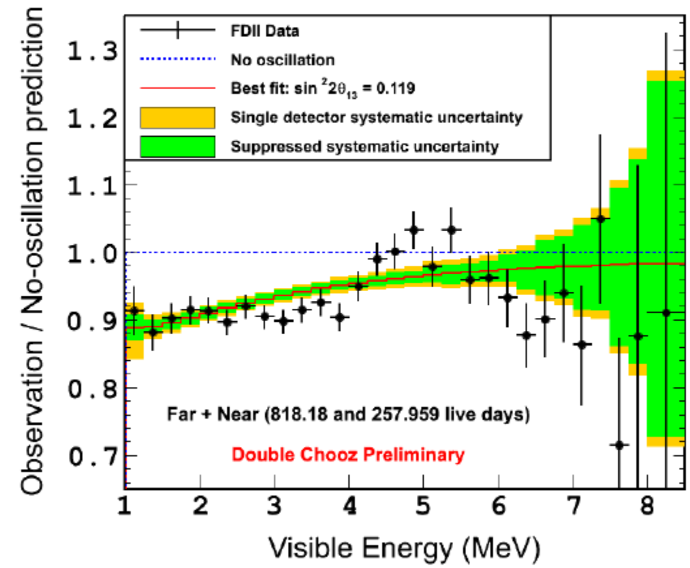
ND



FDI



FDII



Rate + Shape χ^2-fit of data to prediction:

$\sin^2(2\theta_{13}) = 0.119 \pm 0.016$ with χ^2 / ndf: 236.2 / 114

- Cross checked by Data-Data fit : $\sin^2(2\theta_{13}) = 0.123 \pm 0.023$
- Cross checked by three groups
- Not optimal χ^2 due to data-prediction mismatch observed with both detectors

Sterile Neutrino Signatures

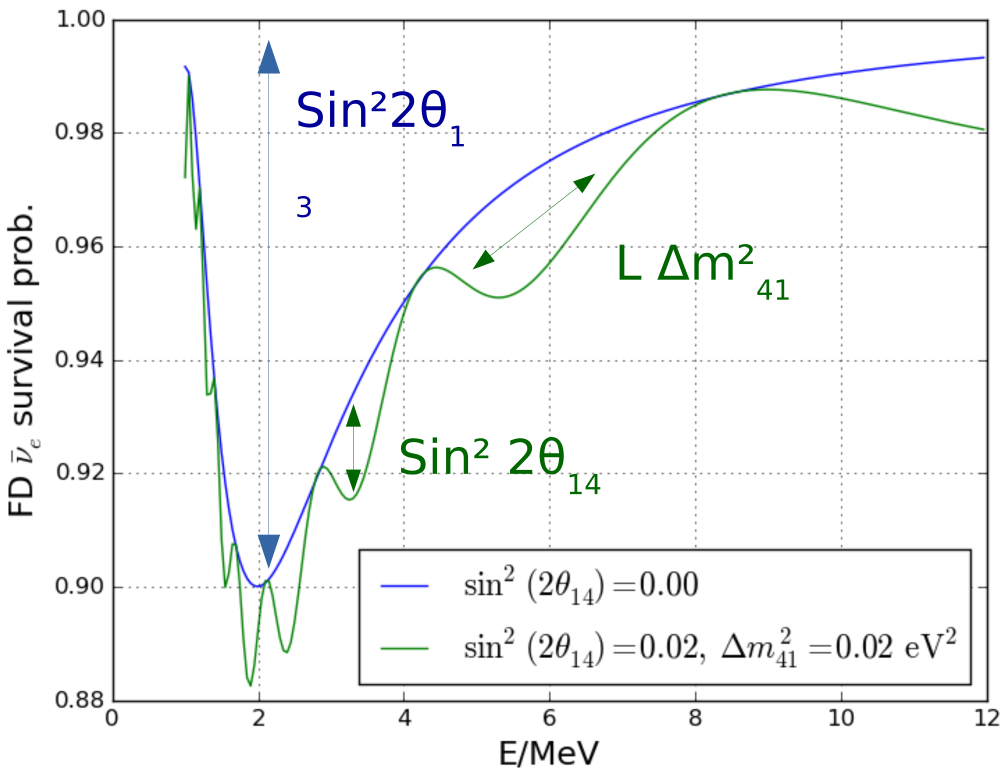
Standard part | sterile part

$$P_{\bar{e}\to\bar{e}} \approx 1-\sin^2(2\theta_{13})\sin^2\left(\frac{\Delta m^2_{ee} L}{4E}\right)-\sin^2(2\theta_{14})\sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

amplitude | frequency

:= anti electron neutrino surv. prob.

FD: L ≈ 1050m



- **Repeating signature, which is different for ND and FD**
  → hard to be matched by any single systematic effect

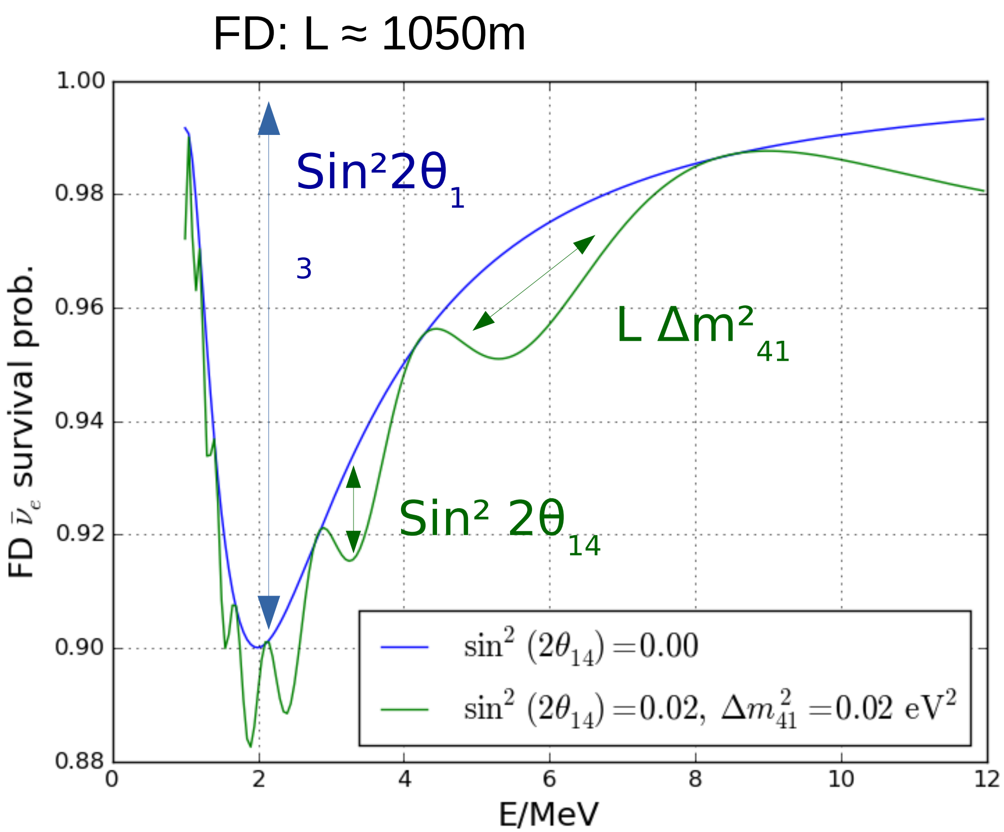
Sterile Neutrino Signatures

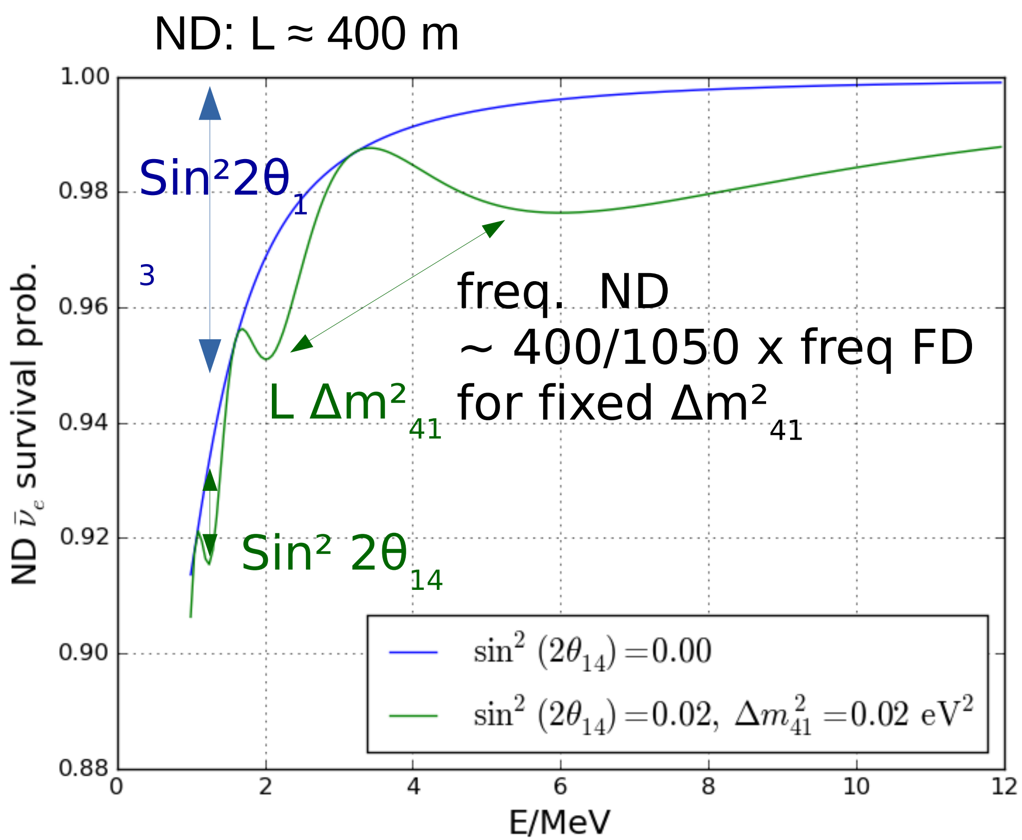
Standard part — sterile part

$$P_{\bar{e}\to\bar{e}} \approx 1-\sin^2(2\theta_{13})\sin^2\left(\frac{\Delta m^2_{ee} L}{4E}\right) - \sin^2(2\theta_{14})\sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$$

amplitude — frequency

:= anti electron neutrino surv. prob.

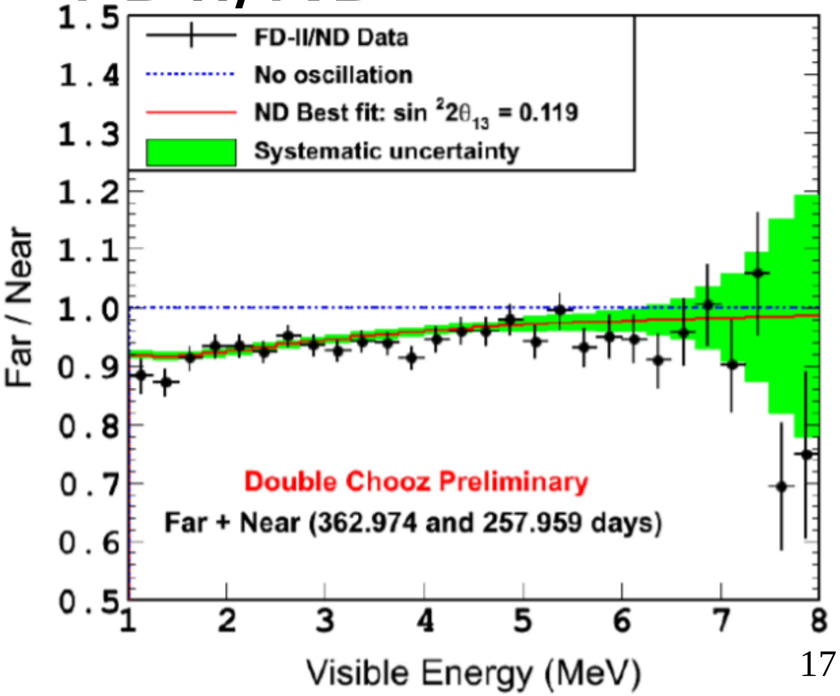




- **Repeating signature, which is different for ND and FD**
  → hard to be matched by any single systematic effect

Spectral Distortion

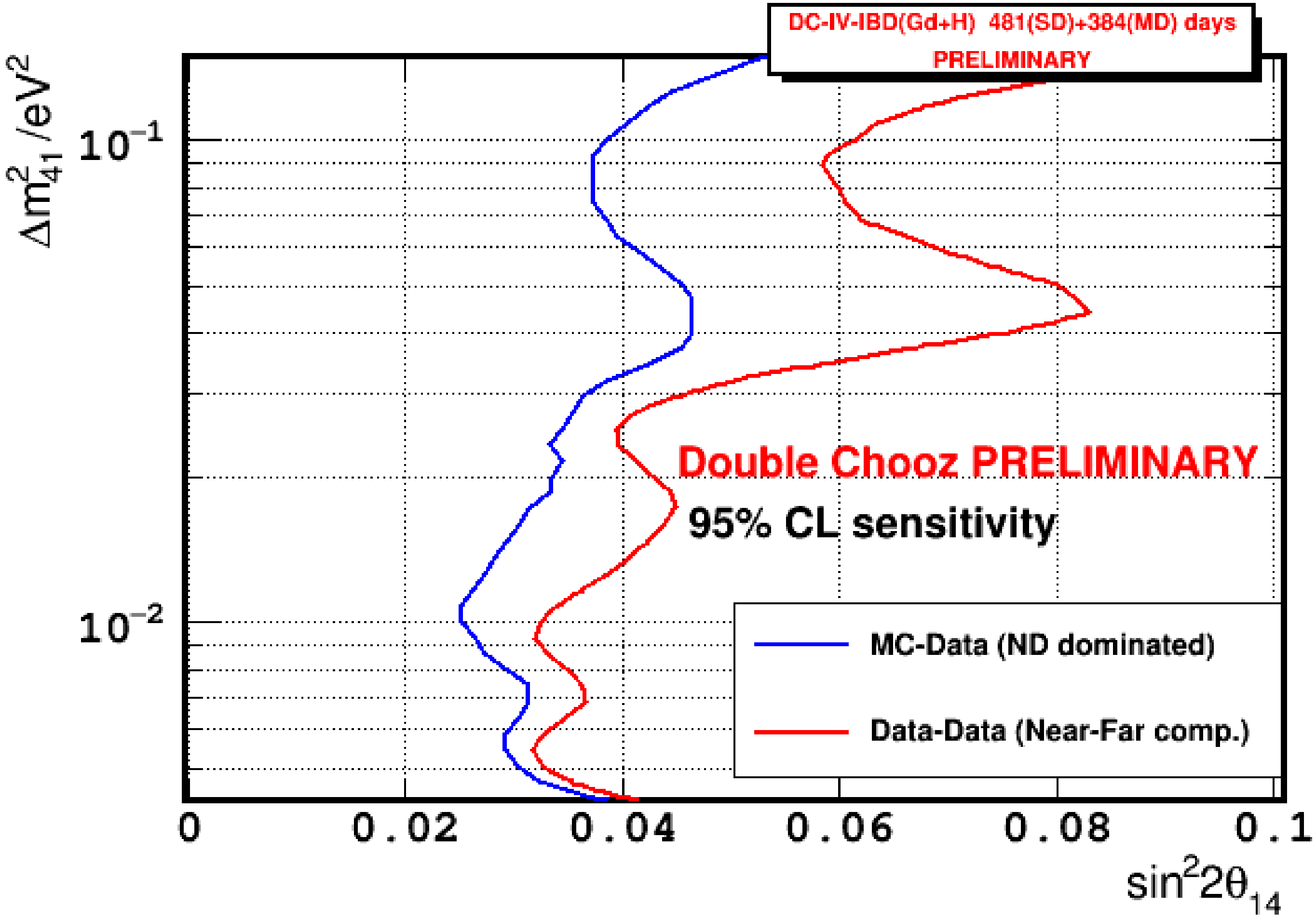
FDII/ND



Spectral distortion cancels out in FD/ND ratio

=> can not be explained by sterile neutrinos

Sensitivity to θ_{14}



- Current situation allows for Data-Data approach only
- Sterile analysis is statistically limited
- Results expected soon

Summary

- Reactor neutrino IBD detection using n-Gd and n-H capture
- Sensitivity to θ_{13} and θ_{14}
- Latest result: $\sin^2(2\theta_{13}) = 0.119 \pm 0.016$
- Precise measurement of detector volume during decommissioning
  - Dominant uncertainty on relative near/far signal normalization: now: 0.7% uncorrelated near/far
  - Dominating uncertainty in θ_{13} fit
  - Not important for sterile analysis
- Double Chooz is sensitive to light sterile neutrino ($|\Delta m^2_{41}| \sim 0.005\text{-}0.1\ \mathrm{eV}^2$)

Double Chooz Collaboration

Brazil	France	Germany	Japan	Russia	Spain	USA
CBPF UNICAMP UFABC	CEA/DSM/IRFU: SPP,SPhN,SEDI, SIS,SENAC. CNRS/IN2P3: APC,Subatech, IPHC	EKU Tübingen MPIK Heidelberg RWTH Aachen TU München U. Hamburg	Tohoku U. Tokyo Inst. Tech. Tokyo Metro. U. Niigata U. Kobe U. Tohoku Gakuin U. Hiroshima Inst. Tech.	INR RAS IPC RAS RRC Kurchatov	CIEMAT Madrid	U. Alabama ANL U. Chicago Columbia U. UC Davis Drexel U. U. Hawaii IIT KSU LLNL MIT U. Notre Dame U. Tennessee

Thanks for your attention!

About 150 scientistis in 7 countries

Spokesperson: Anatael Cabrera (CNRS/IN2P3 - APC)
Project Manager: Christian Veyssière (CEA Saclay)

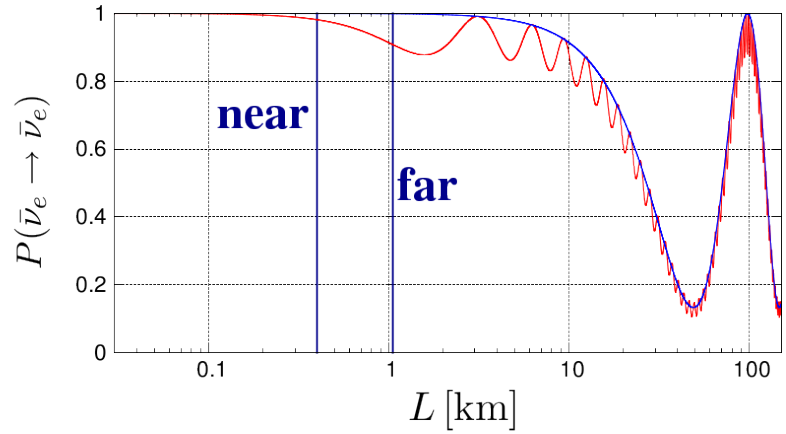
Backup

Reactor Neutrino θ_{13} Experiments

- Systematic uncertainties below 1% required to measure small θ_{13} oscillation
- Can not use reactor flux prediction only

➜ **Several identical detectors at different distances**

- Near detector measures unosillated flux
- Far detector measures energy dependent deficit due to disappearance
- Identical detector design cancels systematics!

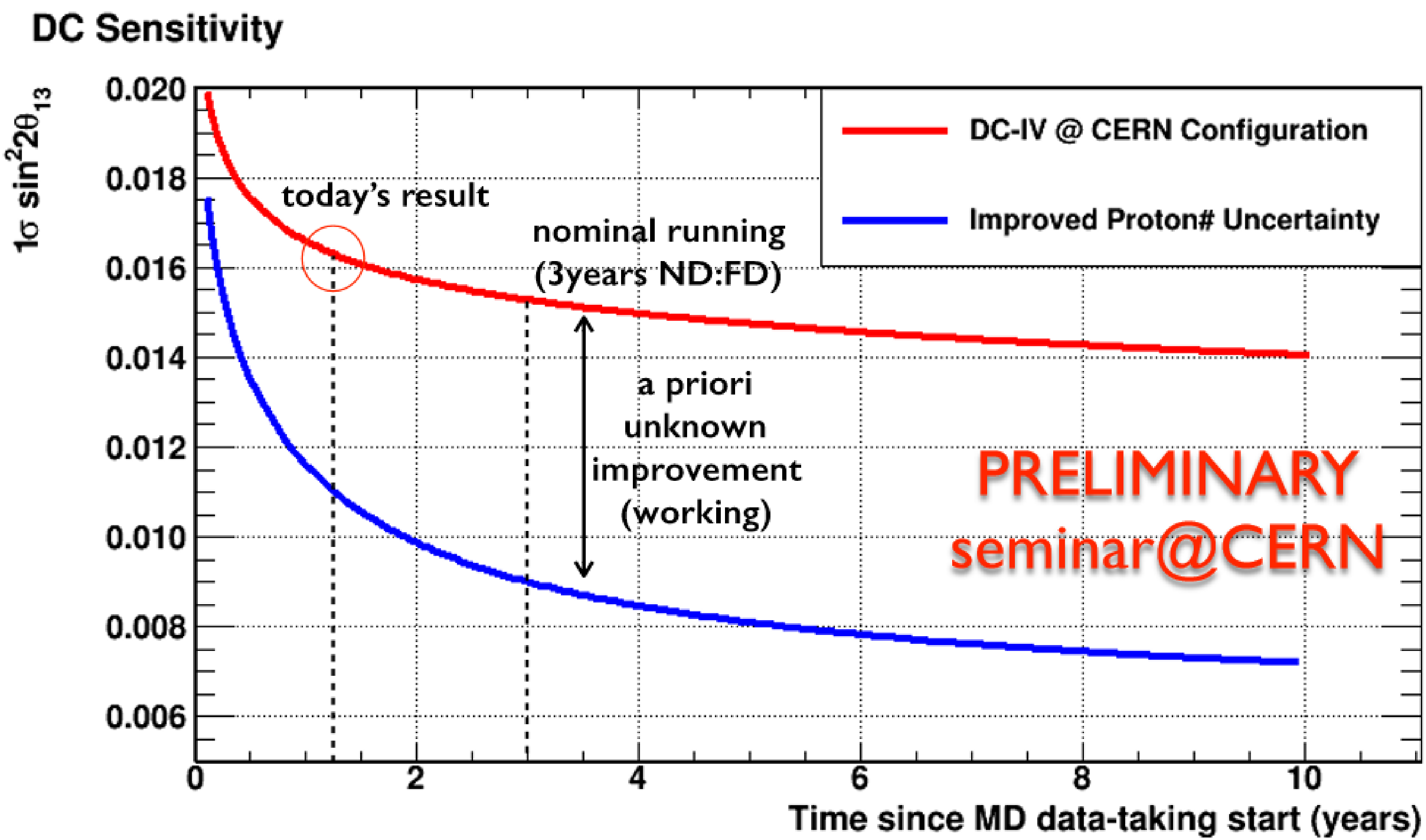


Three major experiment: Double Chooz, RENO, Daya Bay

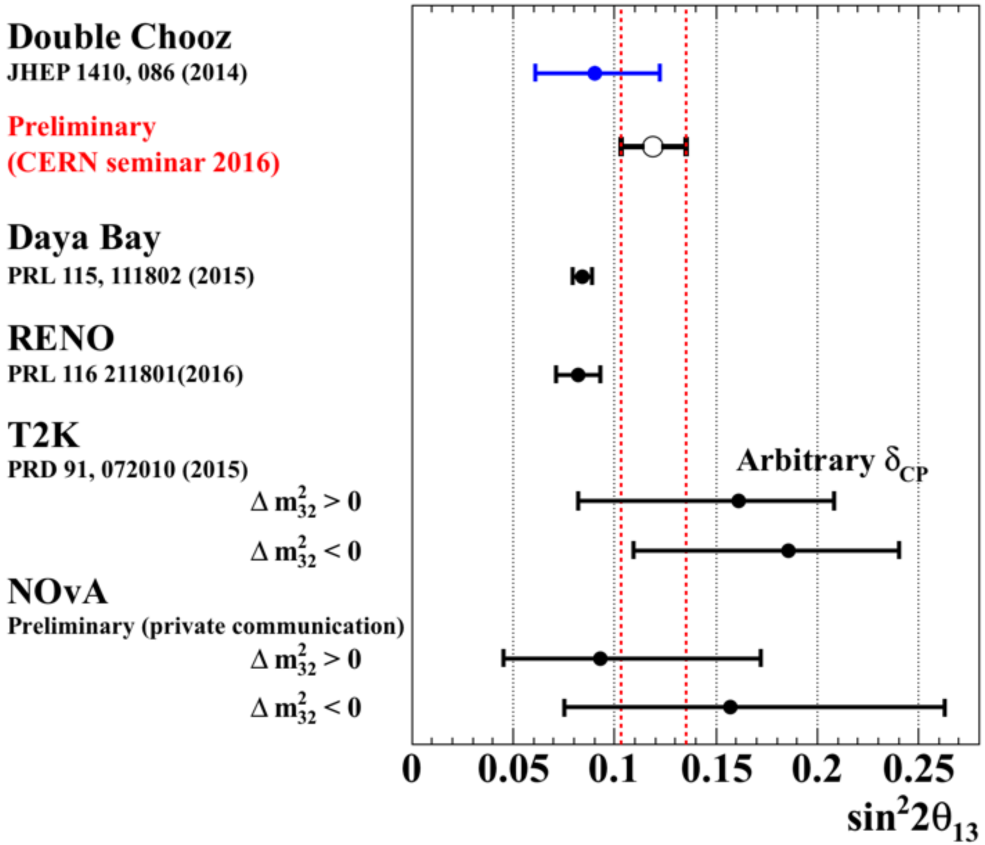
Chooz reactors
France /Ardenne

YonGwang reactors
South Korea

Daya Bay reactors
South China (close Hong Kong)


DC Sensitivity
1σ sin²2θ13
0.020
0.018
0.016
0.014
0.012
0.010
0.008
0.006
0
2
4
6
8
10
Time since MD data-taking start (years)
DC-IV @ CERN Configuration
Improved Proton# Uncertainty
today's result
nominal running
(3years ND:FD)
a priori
unknown
improvement
(working)
PRELIMINARY
seminar@CERN

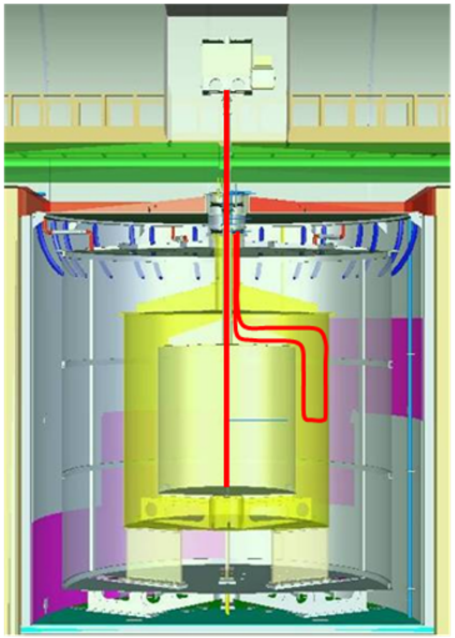
Latest θ_{13} Results (Sep 2016)



Difference to Daya Bay 2.2 σ

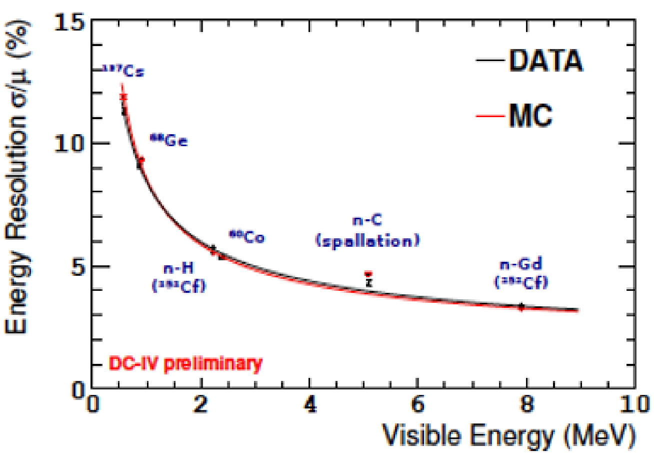
Difference to RENO 1.8 σ

Calibration

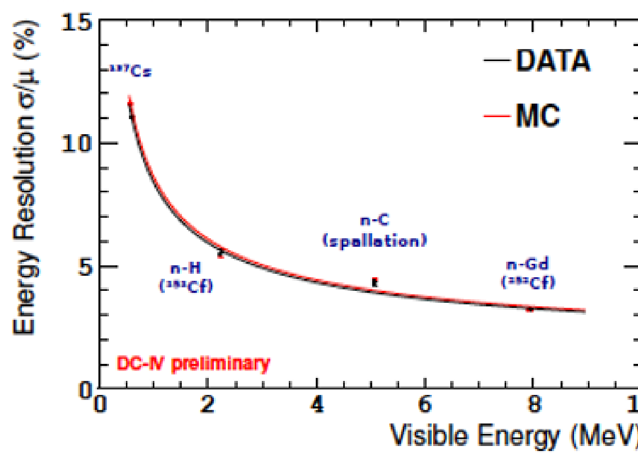


- two systems for calibration source deployment in the GC/ along the z-axis
- 252-Cf used as neutron source
- Characteristic energy deposit of n-Gd and n-H capture during source deploiment used to set energy scale
- Two light injection systems for regular monitoring of PMTs/scintillators

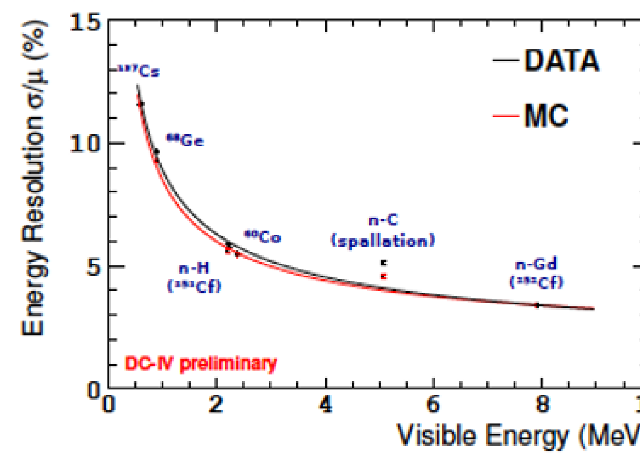
FAR DETECTOR I



FAR DETECTOR II



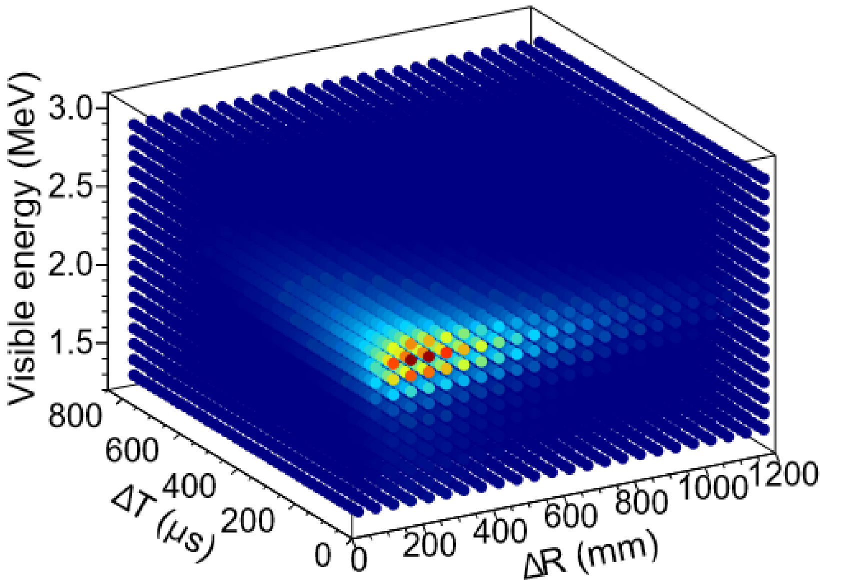
NEAR DETECTOR



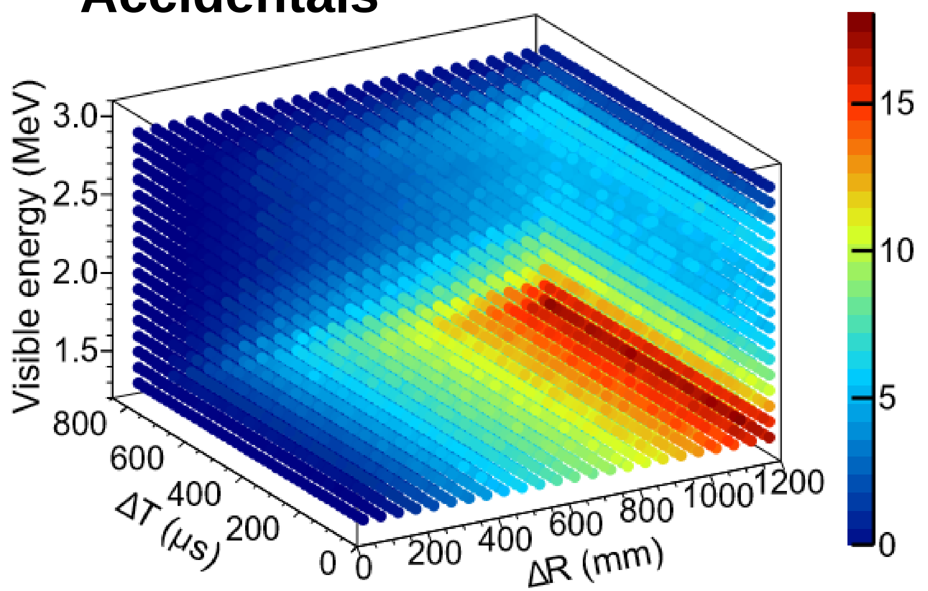
Accidental rejection

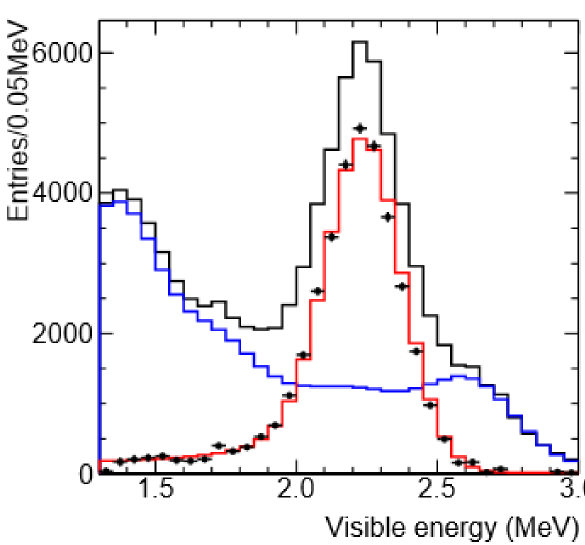
- Artificial neuronal network (ANN) using time and space difference and visible delayed energy => signal to background ratio increase > 7 on H data (arXiv:1510.08937)

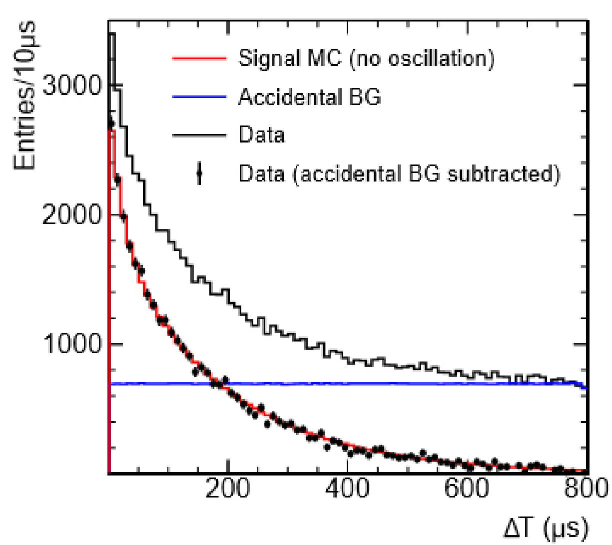
Neutrino IBD MC

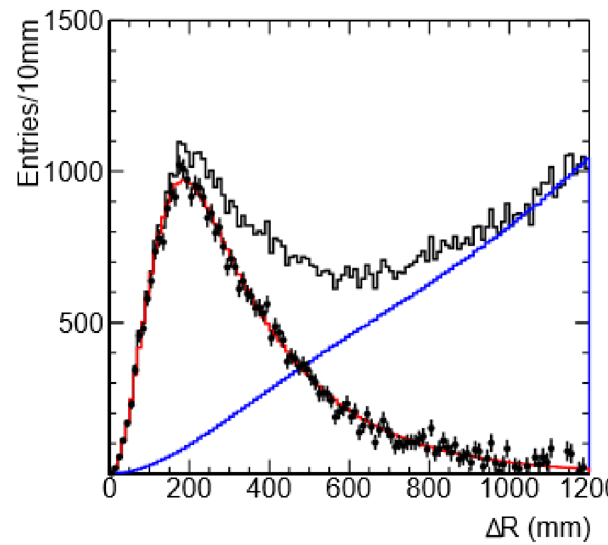


Accidentals

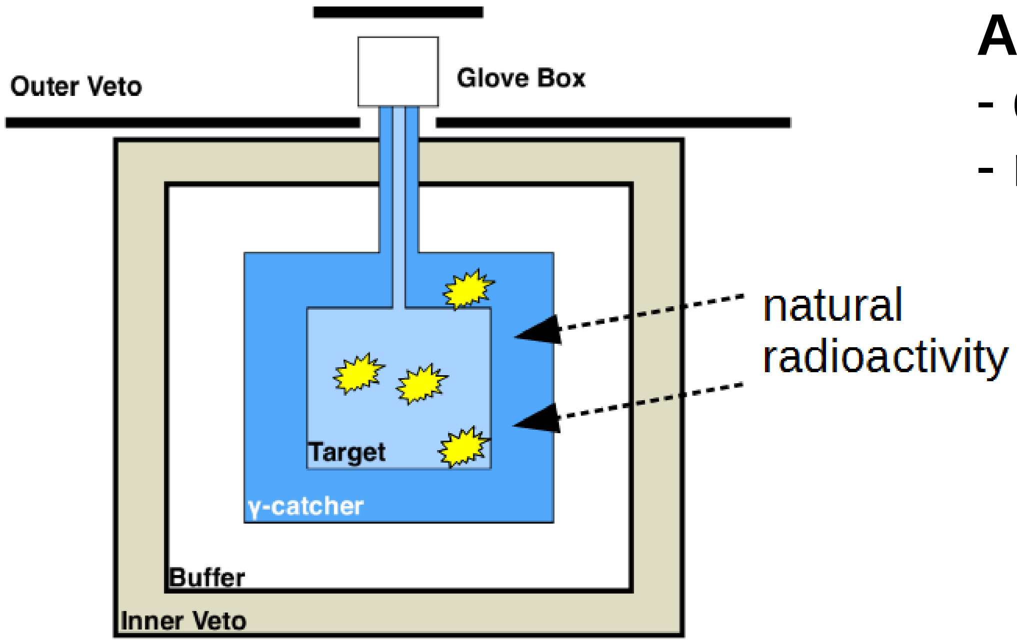




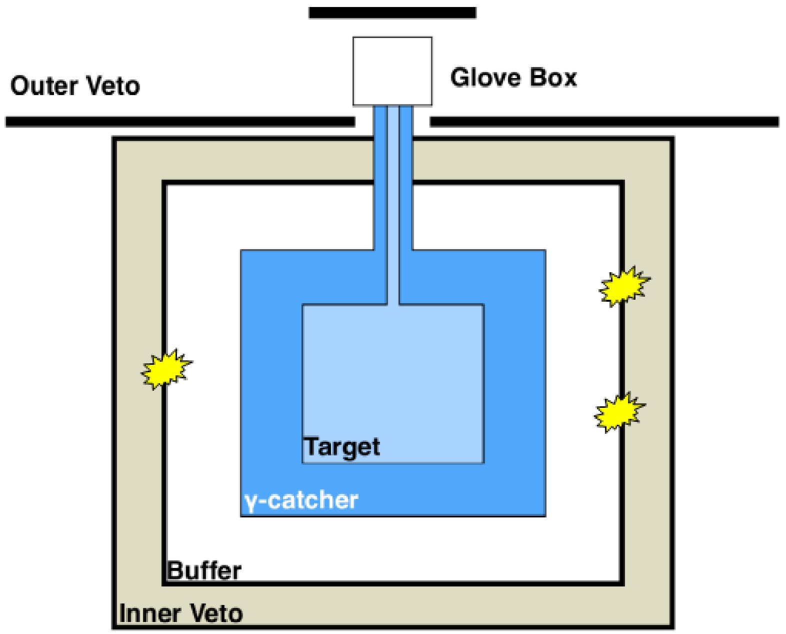




Uncorrelated Backgrounds

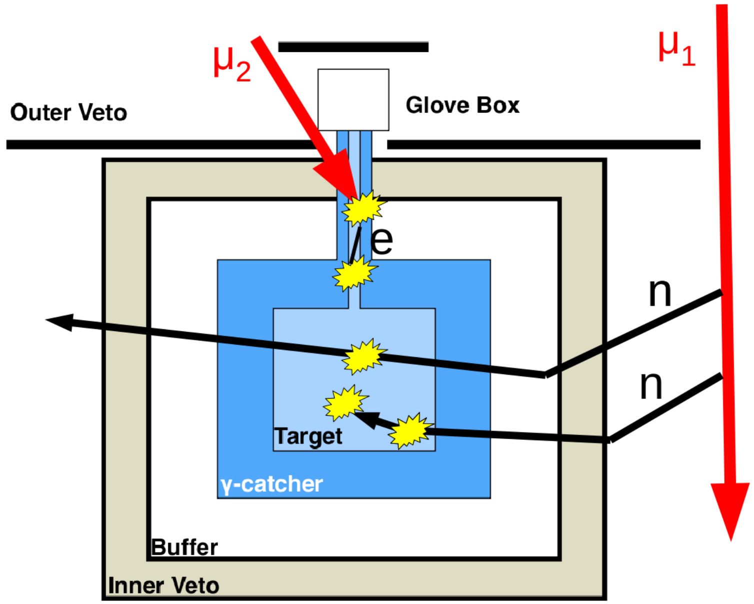


Accidentals
- due to natural radioactivity
- random coincidence



Light Noise
- Light emission by the PMTs themselves
- PMTs mostly light up themselves
  => easy to reject

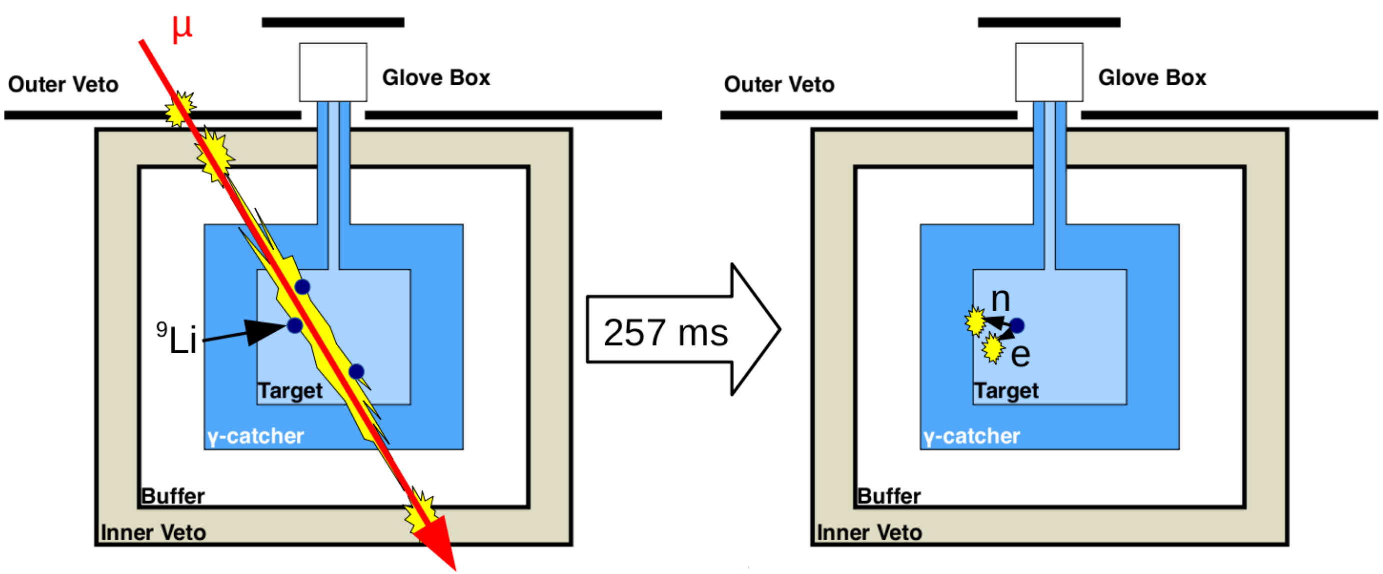
Muon induced Backgrounds



Crossing muon
- large energy deposit => efficiently rejected

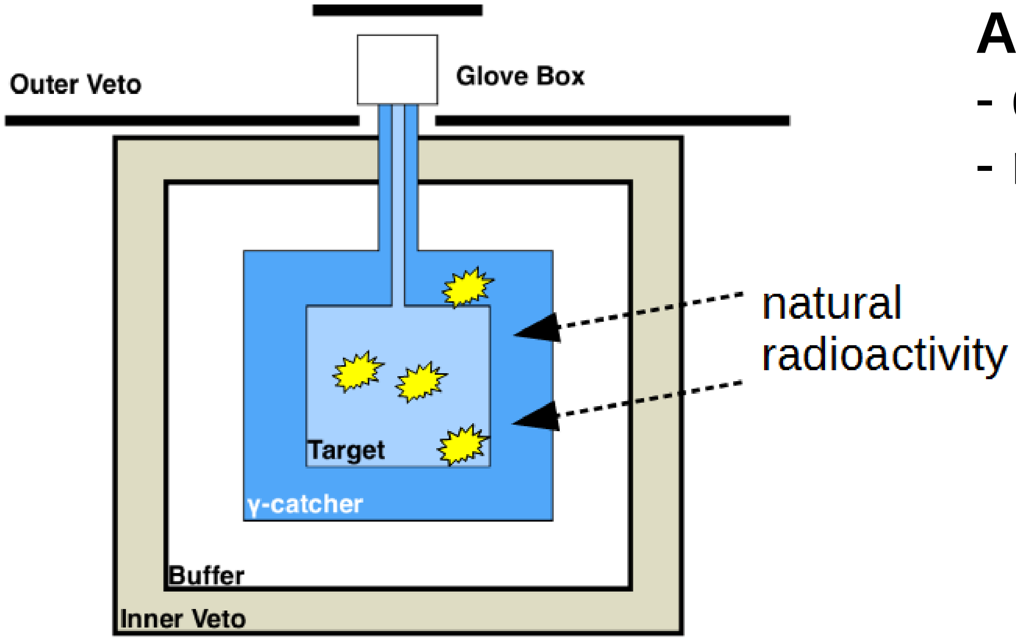
Fast neutrons (FN)
- induced by spallation due to atm. μ (cf. μ_1)
- protein recoil and n-capture may mimic IBD signal

Stopping Muons (SM)
- May enter in particular throught the chimney (cf. μ_2)
- end off the μ-track mimics prompt event
- Michel electron minimcs delayes event



Lithium (Li)
- atm. μ produce long lived β-n decay isotopes ^{9}Li, ^{8}He (257 ms resp. 172 ms mean live time)
- electrons cannot be distinguished from positrons

Backgrounds



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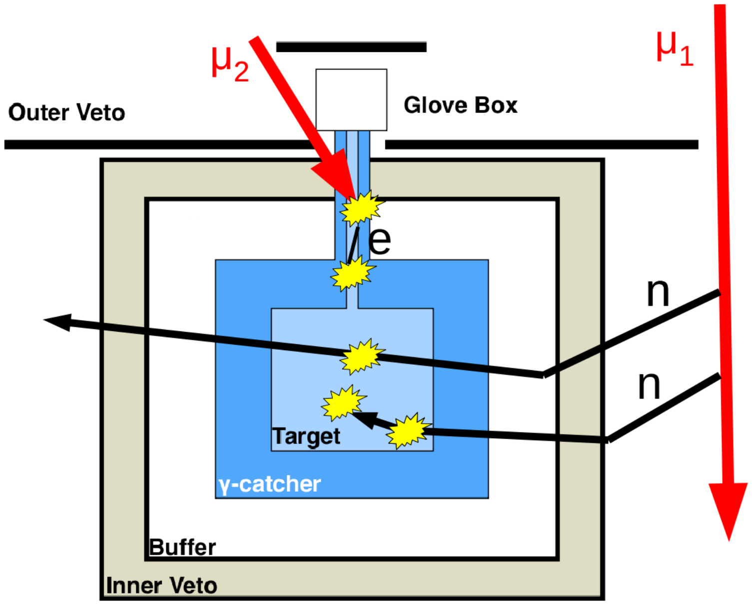

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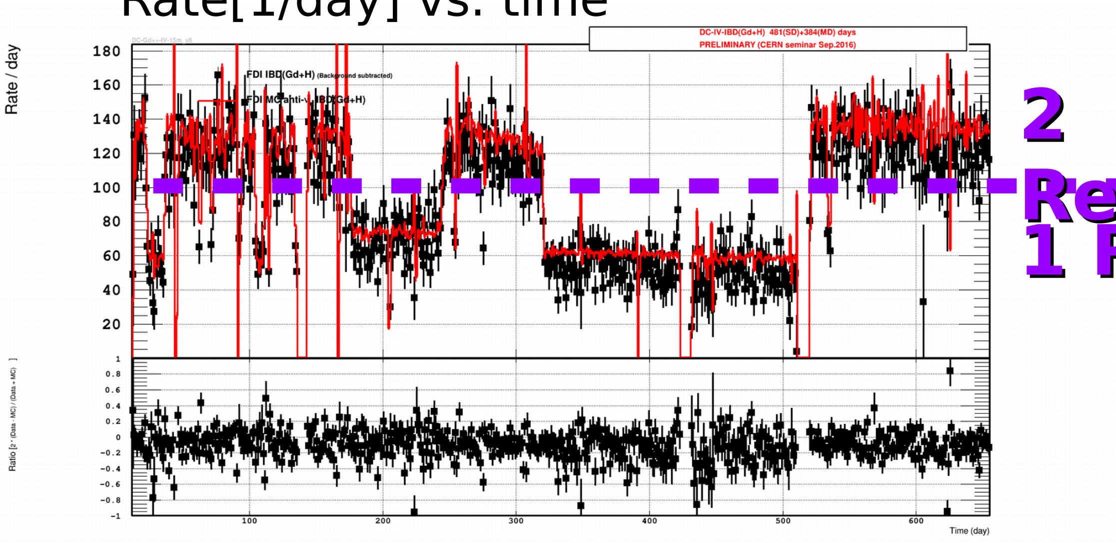
Stopping Muons (SM)

- May enter in particular throught the chimney (cf. μ_2)
- end off the μ-track mimics prompt event
- Michel electron mimics delayed event

Datasets

FDI (FD before ND existed) 455 days lifetime + 7 days lifetime reactor off

Rate[1/day] vs. time

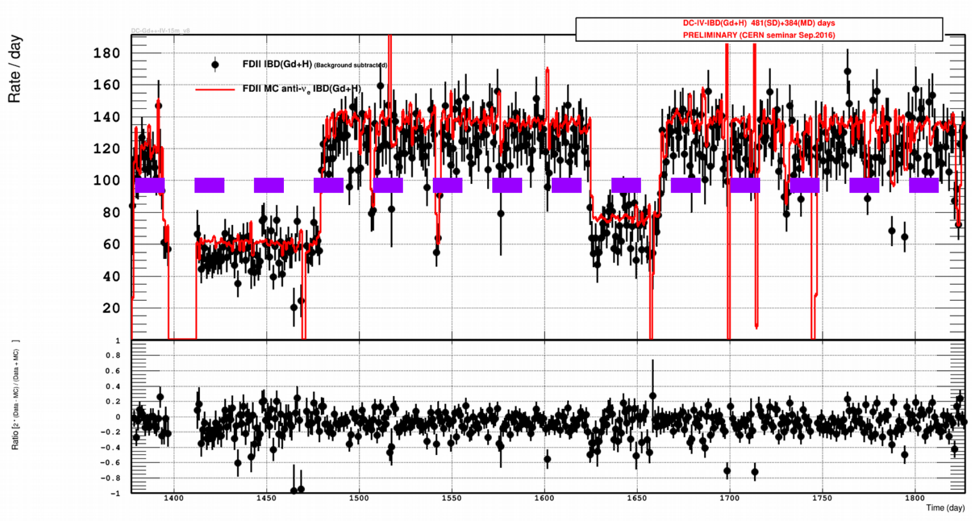


2 Reactors

1 Reactor

FDII (FD parallel to ND) 363 days lifetime

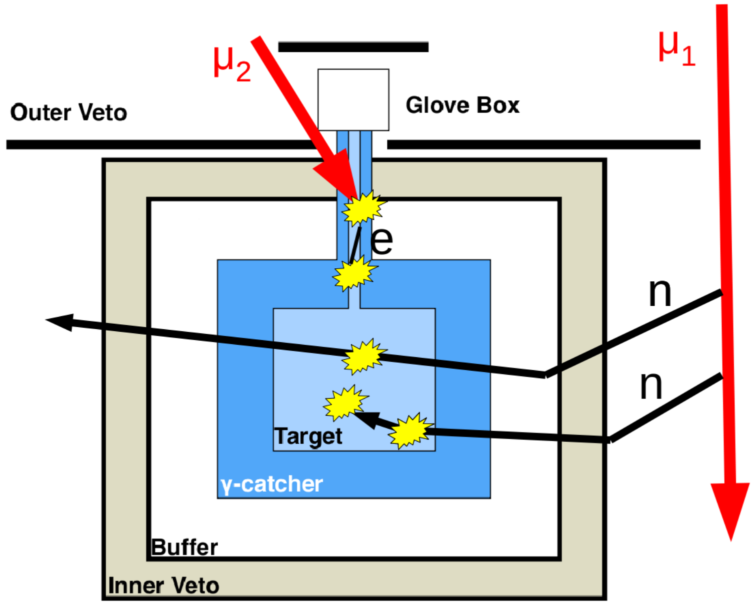
Rate[1/day] vs. time



ND 258 days lifetime

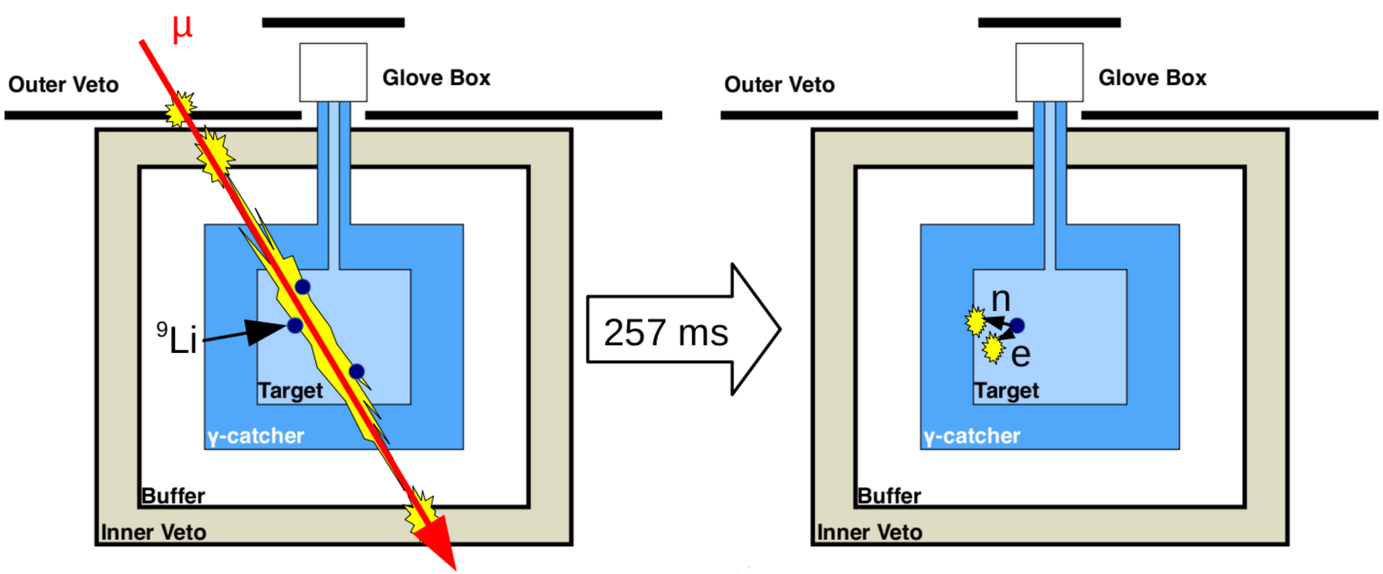
Rate[1/day] vs. time

Backgrounds



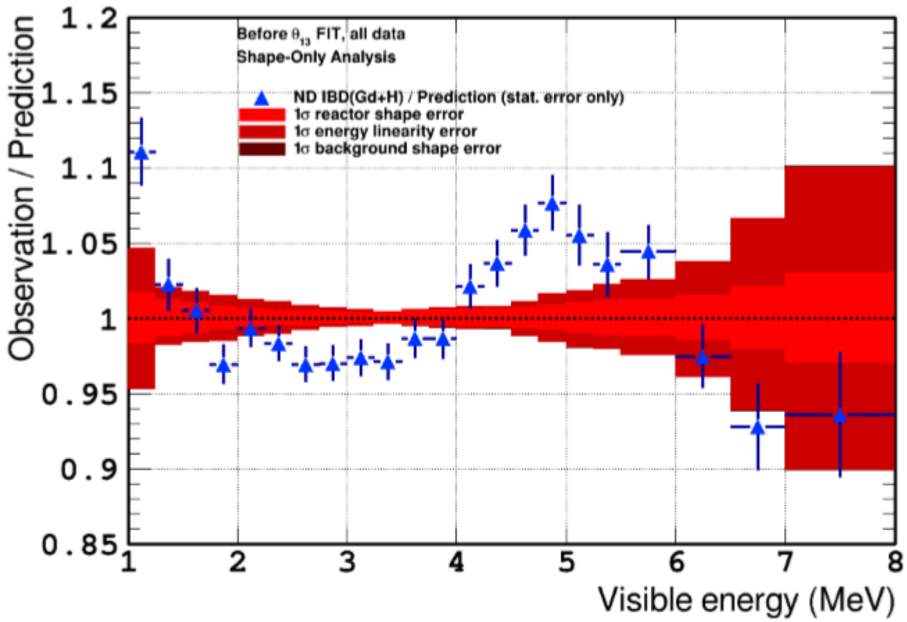
Fast neutrons (FN)
- induced by spallation due to atm. μ (cf. μ_1)
- protein recoil and n-capture may mimic IBD signal

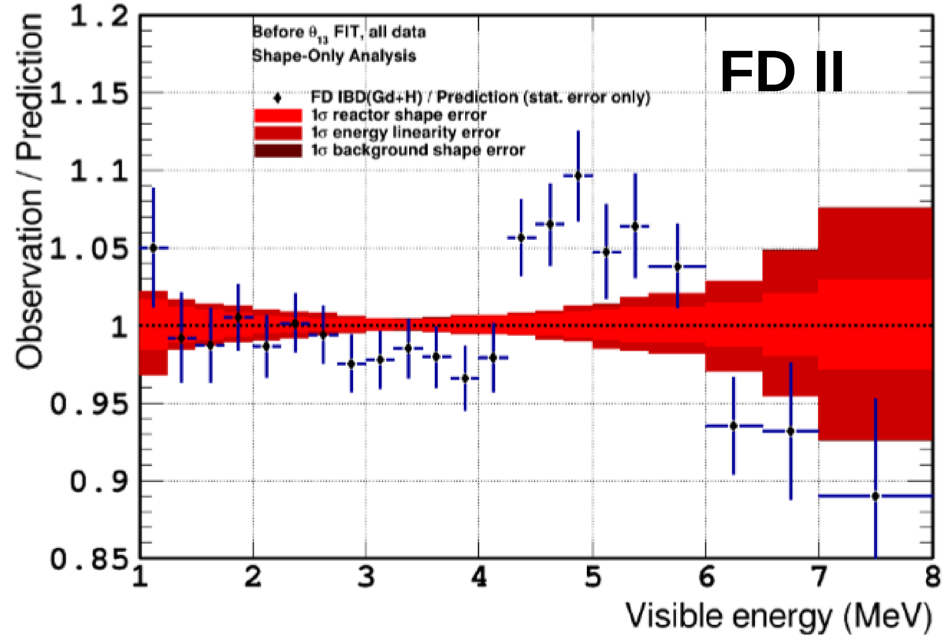
Stopping Muons (SM)
- May enter in particular throught the chimney (cf. μ_2)
- end off the μ-track mimics prompt event
- Michel electron mimics delayed event

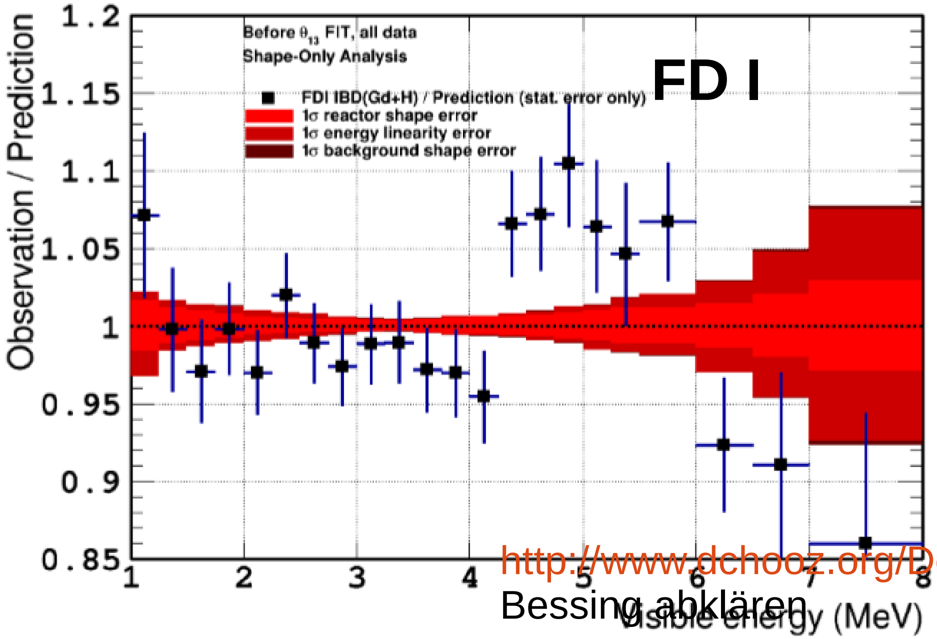


Lithium (Li)
- atm. μ produce long lived β-n decay isotopes ^9Li, ^8He (257 ms resp. 172 ms mean live time)
- electrons cannot be distinguished from positrons

Spectral distortion vs. baseline







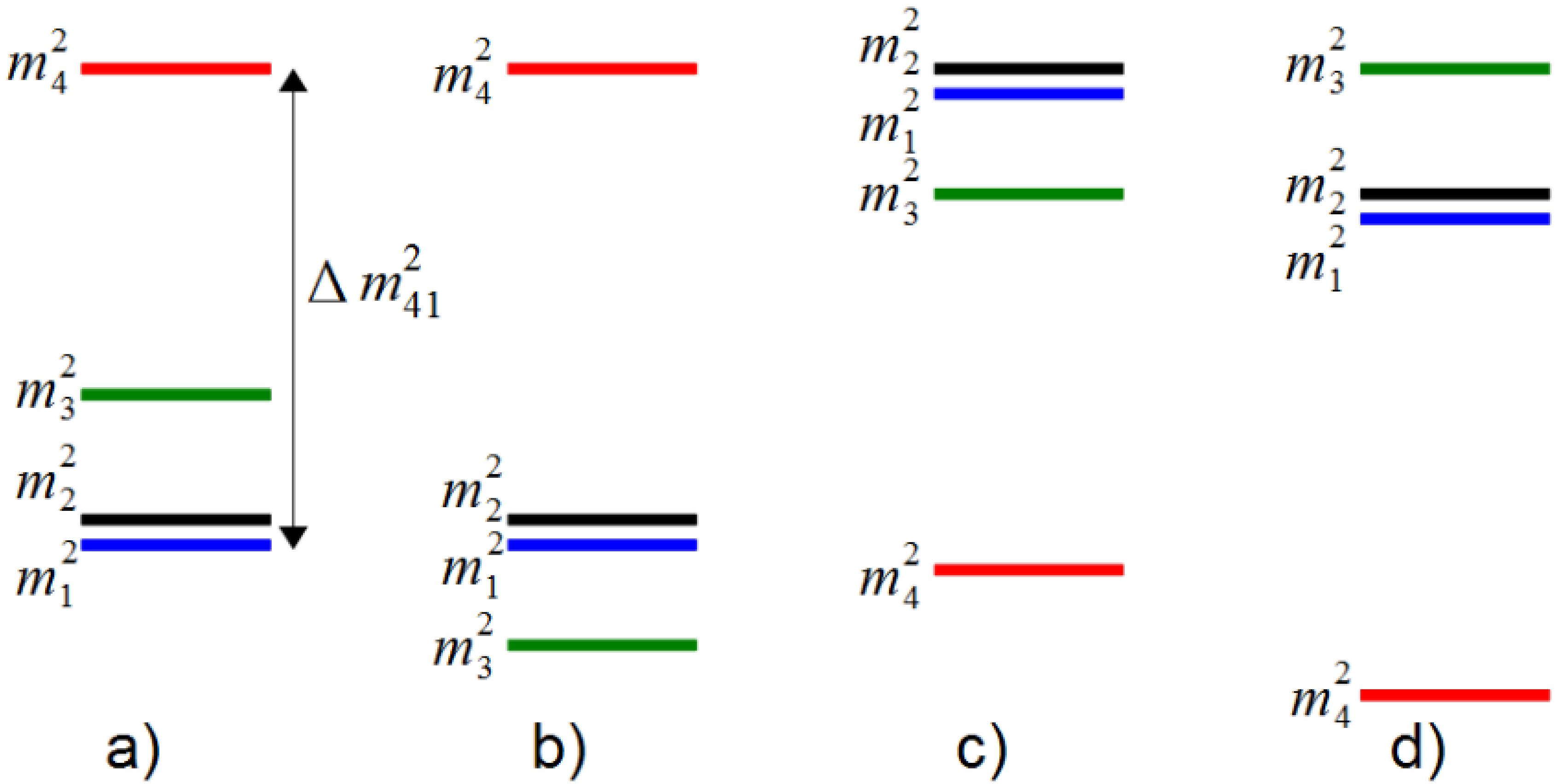
Spectral distortion observed in both detectors

=> very unlikely to be a sterile signature

http://www.dchooz.org/DocDB/0069/006919/006/nshape_brugiere_update7.pdf

Bessing abklären

Mass orderings



PMNS Matrix

$$\mathrm{U} = \mathrm{R}_{34}\mathrm{R}_{24}\mathrm{R}_{23}\mathrm{R}_{14}\mathrm{R}_{13}\mathrm{R}_{12}$$

$$U_{e1} = \cos\theta_{14}\cos\theta_{13}\cos\theta_{12}$$

$$U_{e2} = \cos\theta_{14}\cos\theta_{13}\sin\theta_{12} ,$$

$$U_{e3} = \cos\theta_{14}\sin\theta_{13} ,$$

$$U_{e4} = \sin\theta_{14} ,$$

$$P_{ee} = 1 - \sum_{i<j} 4|U_{ei}|^2|U_{ej}|^2 \sin^2\left(\frac{\Delta m_{ij}^2 L}{4E_\nu}\right)$$

IBD selection

Single event selection

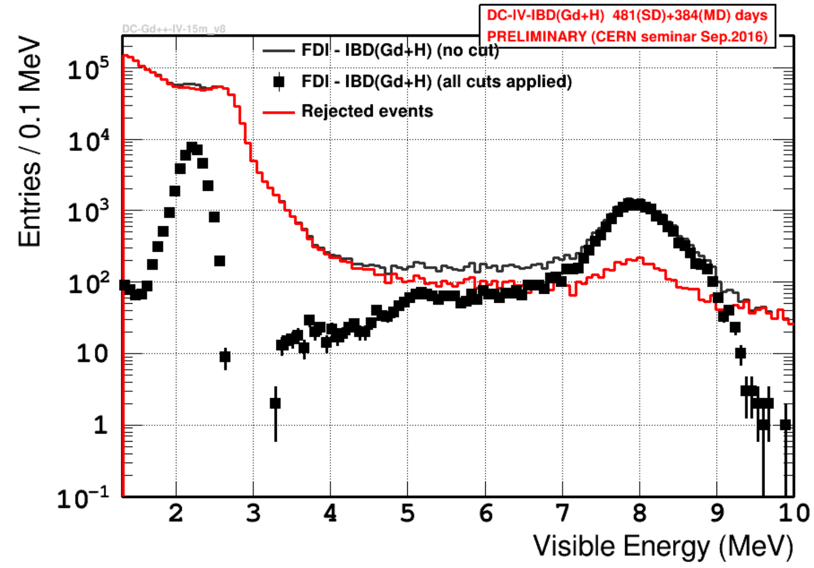
- Not light noise, muon, or random trigger
- Not within 1.25 ms after a muon

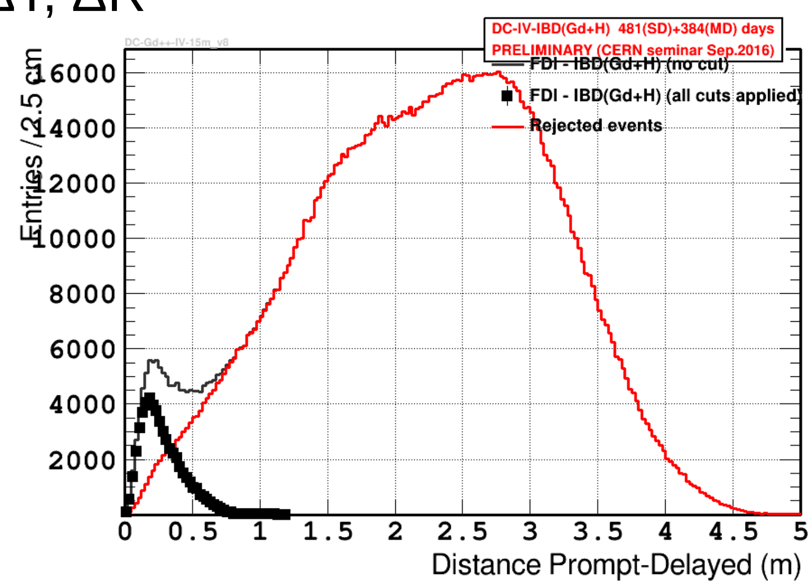
IBD prompt-delayed pair selection

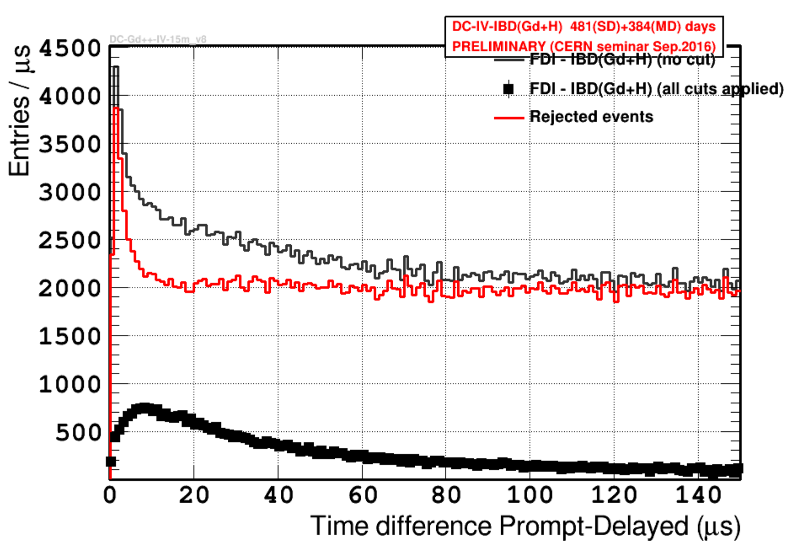
- E_{prompt} , $E_{delayed}$, ΔT, ΔR

Background rejection:

- Multiplicity cut
- No IV, OV coincidence
- Artificial neuronal network (ANN) using $E_{delayed}$, ΔT, ΔR
- Stopping μ veto cut
- Lithium veto cut







IBD selection

Single event selection

- Not light noise, muon, or random trigger
- Not within 1.25 ms after a muon

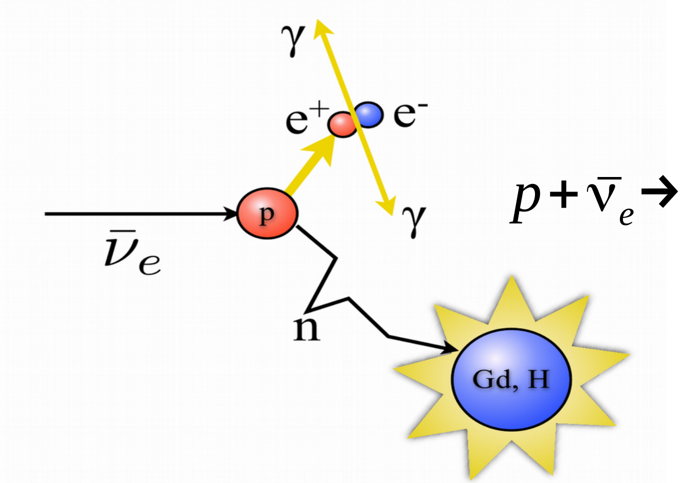
IBD prompt-delayed pair selection

- E_{prompt} , $E_{delayed}$, ΔT, ΔR

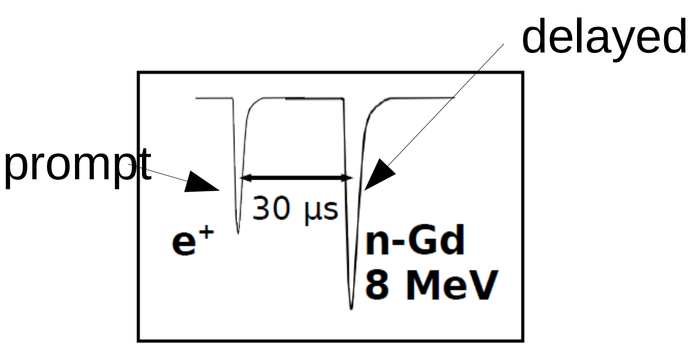
Background rejection:

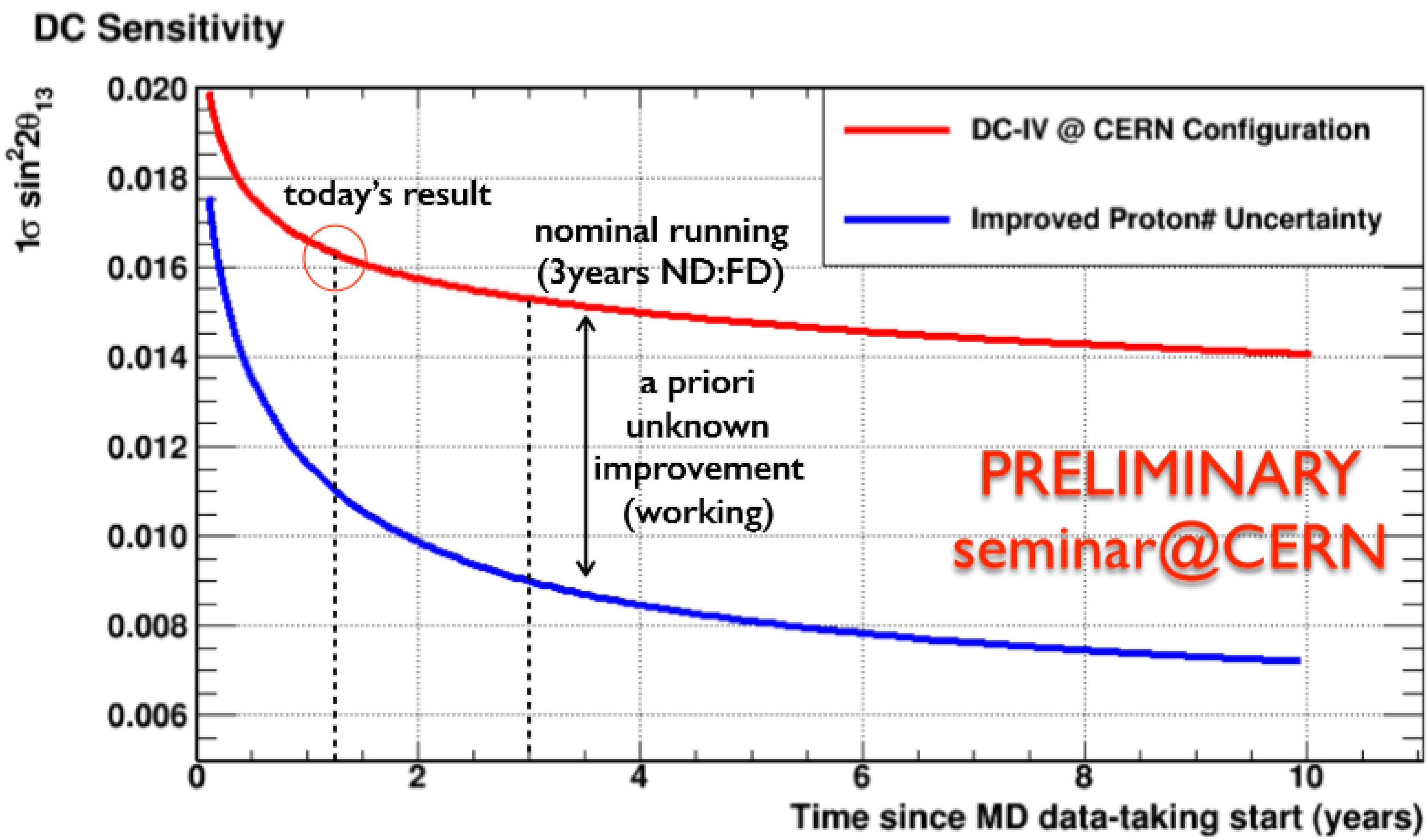
- Multiplicity cut
- No IV, OV coincidence
- Artificial neuronal network (ANN) using $E_{delayed}$, ΔT, ΔR
- Stopping μ veto cut
- Lithium veto cut

Inverse beta decay IBD



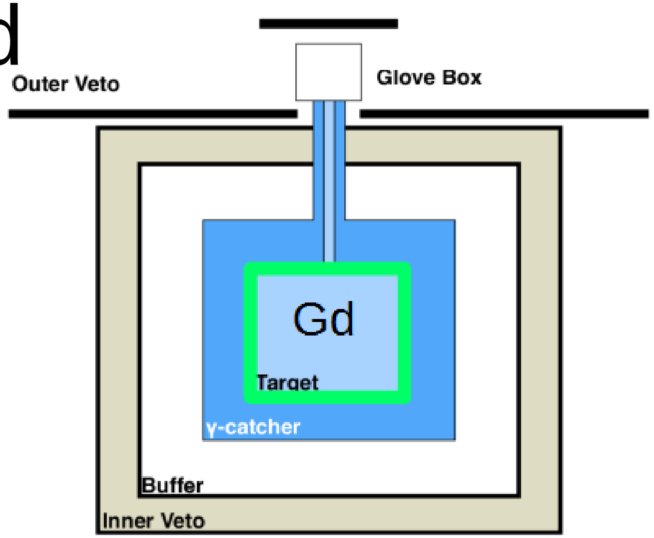
$$p+\bar{\nu}_e \rightarrow e^+ + n$$



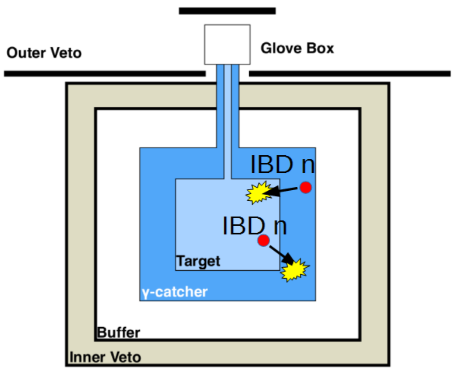

DC Sensitivity
$1\sigma\ \sin^2 2\theta_{13}$
0.020
0.018
0.016
0.014
0.012
0.010
0.008
0.006
0
2
4
6
8
10
Time since MD data-taking start (years)
DC-IV @ CERN Configuration
Improved Proton# Uncertainty
today's result
nominal running
(3years ND:FD)
a priori
unknown
improvement
(working)
PRELIMINARY
seminar@CERN

IBD Selection

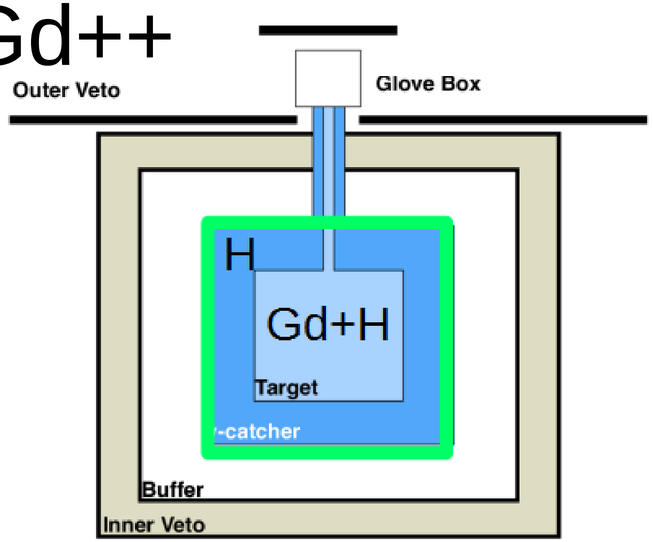
Gd



- Selecting **n-Gd** capture in **Neutrino Target** only
- less statistics
+ less background
- spilling relevant



Gd++

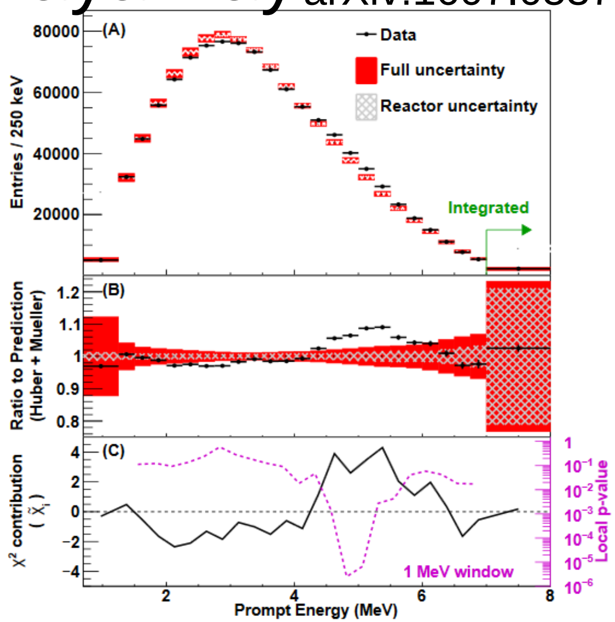


- Selecting **n-Gd and n-H** capture in **Neutrino Target and Gamma Catcher**

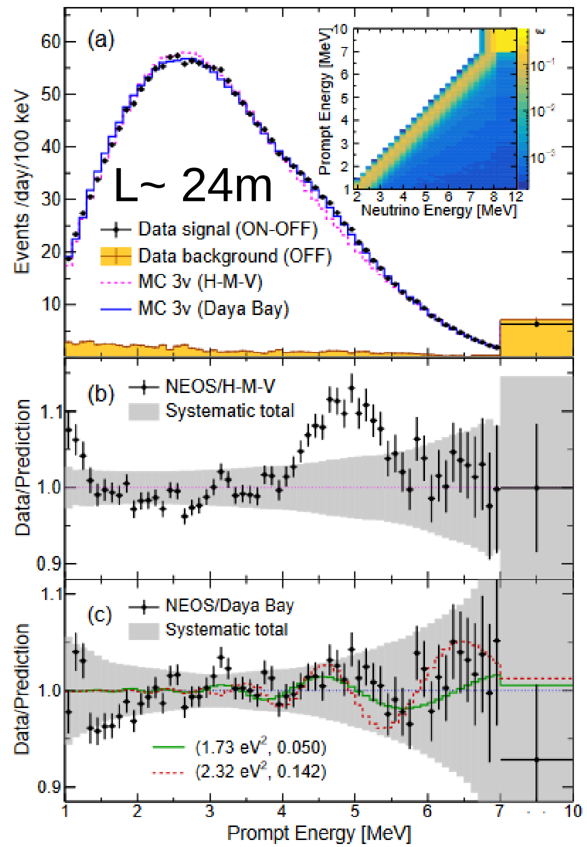
+ more statistics
- more background
+ spilling irrelevant

Spectral Distortion Seen by Other Experiments

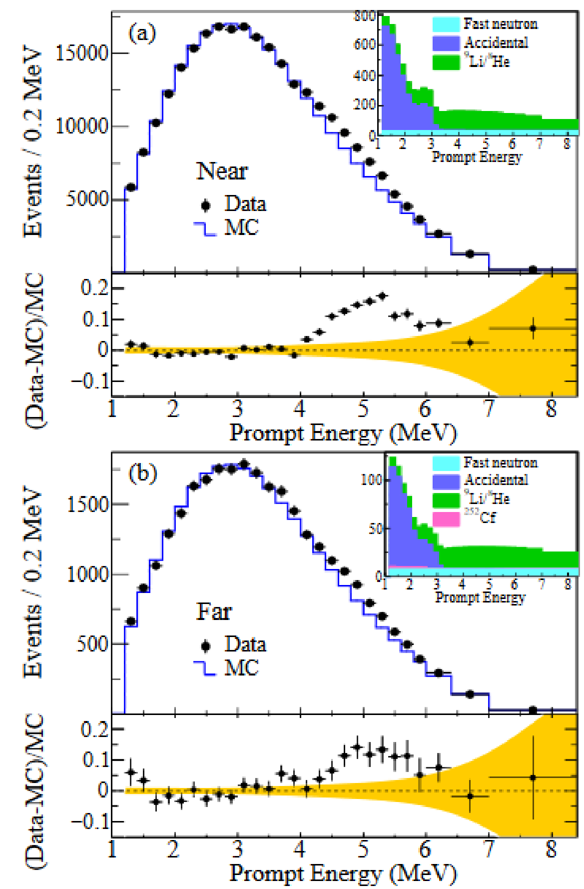
Daya Bay arXiv:1607.05378



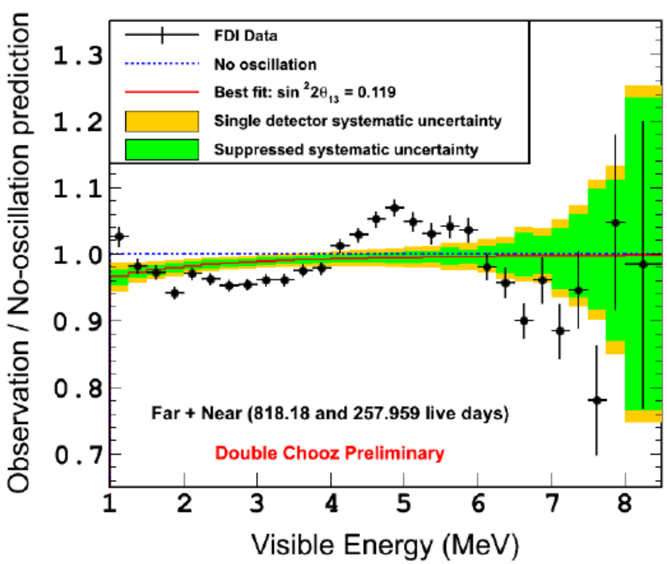
NEOS arXiv:1610.05134



Reno arXiv:1610.04326

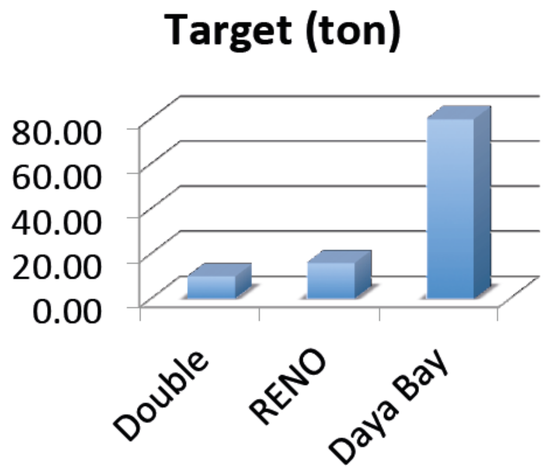


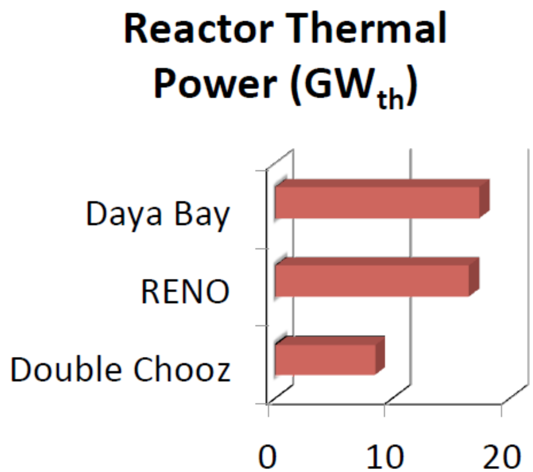
Double Chooz

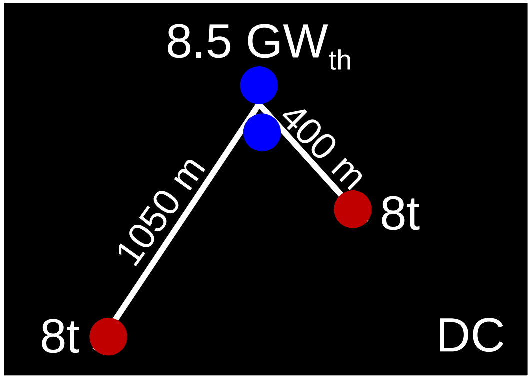


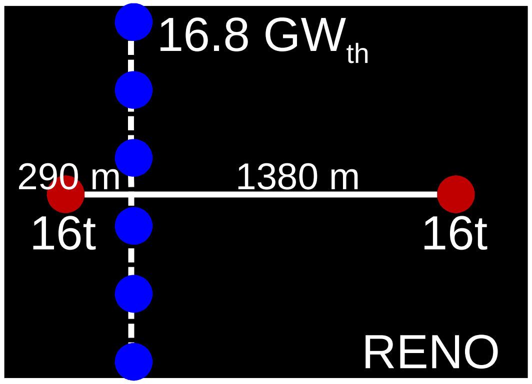
Spectral distortion seen by several experiments

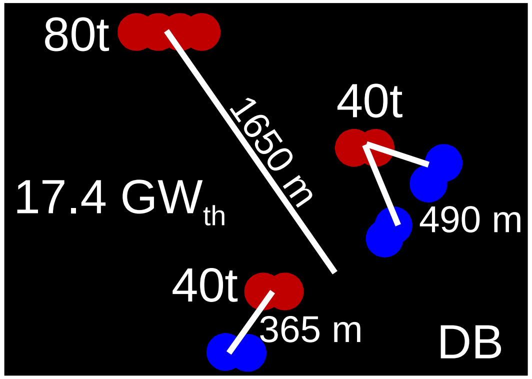
Comparision of Experiments











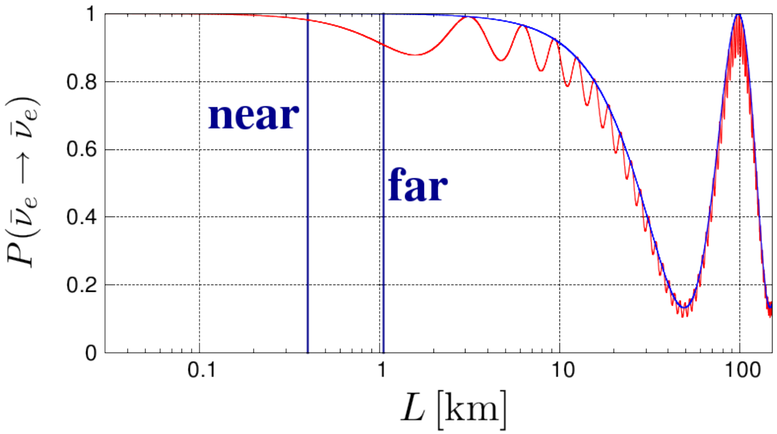
Experiment	Thermal Power (GW)	Distance Near/Far (m)	Depth Near/Far (mwe)	Target mass (ton)
Double Chooz	8,5	400/1050	120/300	8/8
RENO	16,8	290/1380	120/450	16/16
Daya Bay	17,4	360(500)/ 1985(1613)	260/860	40x2/80

- Very similar design

Reactor Neutrino θ_{13} Experiments

- Systematic uncertainties below 1% required to measure small θ_{13} oscillation
- Can not use reactor flux prediction only

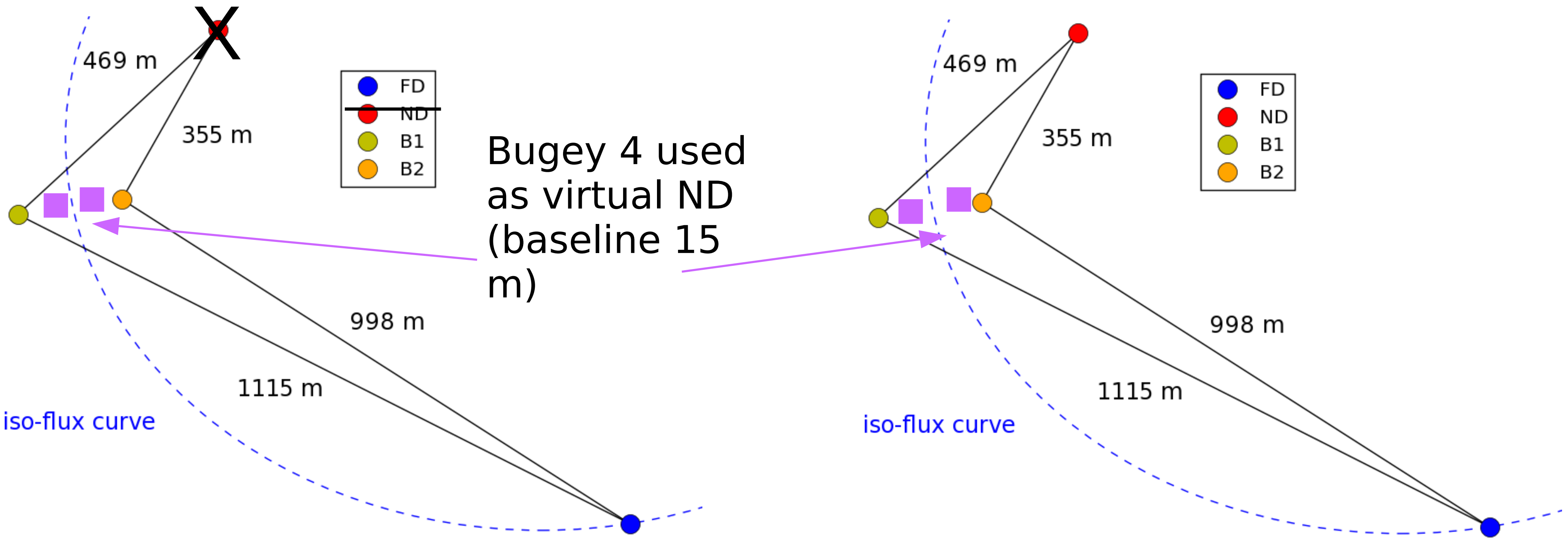
➜ **Several identical detectors at different distance**
- Near detector measures oscillated flux
- Far detector measures energy dependent deficit due to disappearance
- Identical detector design cancels systematics!



Three major experiment: Double Chooz, RENO, Daya Bay

Datasets

Before 2015 **Since 2015**



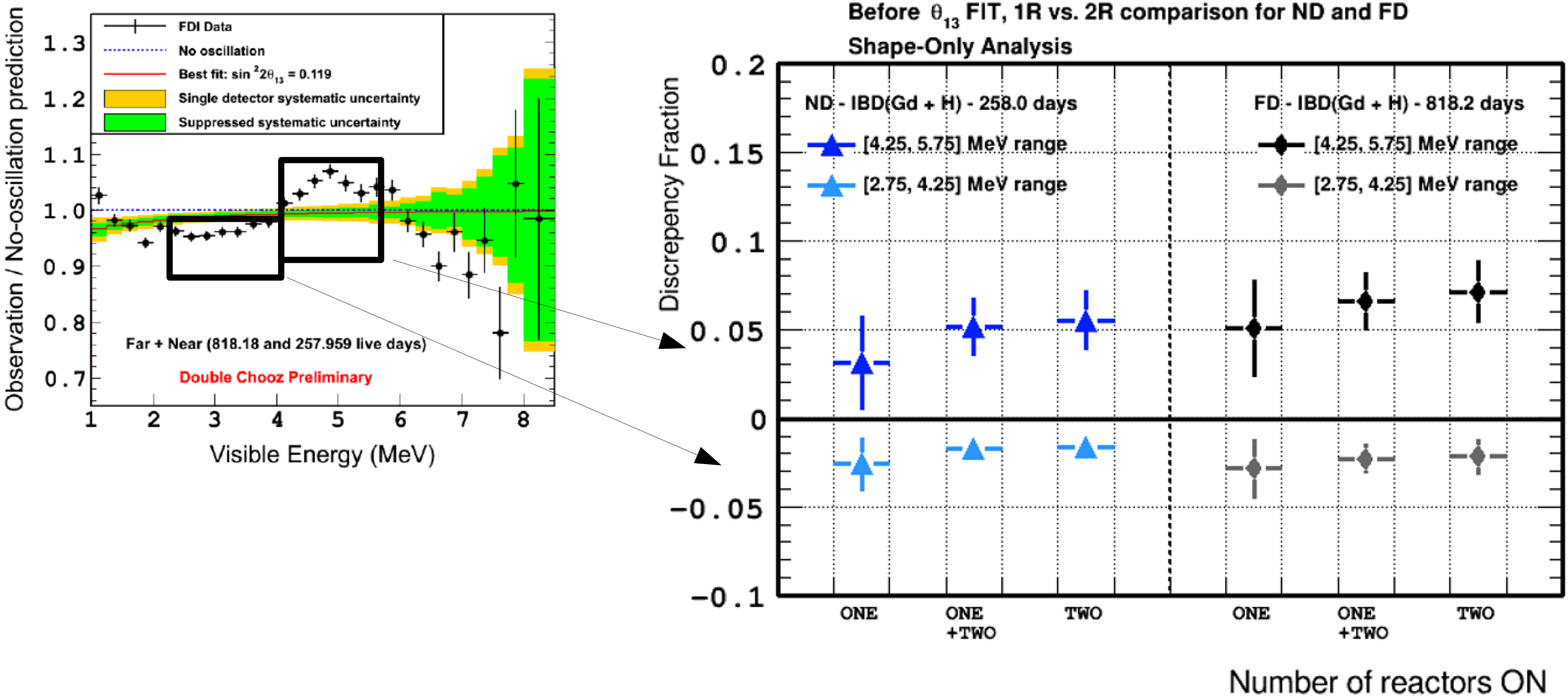
FDI 455 days lifetime
+ 7 days lifetime reactor off

ND 258 days lifetime
FDII 363 days lifetime

Double Chooz has been operated 3 years in full configuration (detectors still running)

Datasets can be combined!

Spectral Distortion vs. Reactor Power



Excess/deficit is consistent to be proportional to reactor power

Full oscillation prob.

$$P_{ee} = P_{\bar{e}\bar{e}} = 1 - 4\sum_{i<j} |U_{ei}|^2 |U_{ej}|^2 \sin^2\left(\frac{\Delta m_{ji}^2 L}{4E_\nu}\right)$$

$$U_{e1} = \cos\theta_{14}\cos\theta_{13}\cos\theta_{12}$$
$$U_{e2} = \cos\theta_{14}\cos\theta_{13}\sin\theta_{12}$$
$$U_{e3} = \cos\theta_{14}\sin\theta_{13}$$
$$U_{e4} = \sin\theta_{14}$$

$$P_{ee} = 1 - c_{14}^4 s_{12}^2 \sin^2 2\theta_{13}\sin^2\Delta_{32} - c_{14}^4 c_{12}^2 \sin^2 2\theta_{13}\sin^2\Delta_{31} - c_{14}^4 c_{13}^4 \sin^2 2\theta_{12}\sin^2\Delta_{12} \quad (1.7)$$

$$-s_{13}^2 \sin^2 2\theta_{14}\sin^2\Delta_{43} - c_{13}^2 s_{12}^2 \sin^2 2\theta_{14}\sin^2\Delta_{42} - c_{13}^2 c_{12}^2 \sin^2 2\theta_{14}\sin^2\Delta_{41} \quad (1.8)$$

Small anyway