Double Chooz double-detector results

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Content

- θ_{13} Experiments
- Double Chooz Detectors
  - Setup
  - Selection
  - Datasets
- Latest θ_{13} result
- Beyond θ_{13}
- Summary/Outlook

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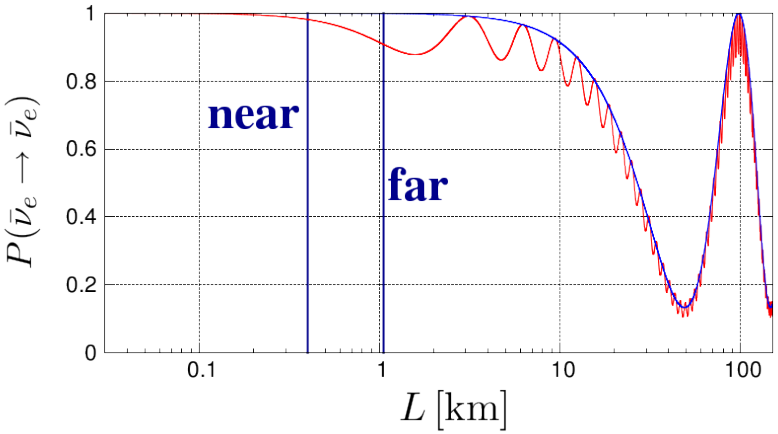
Reactor Neutrino θ_{13} Experiments

- 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!



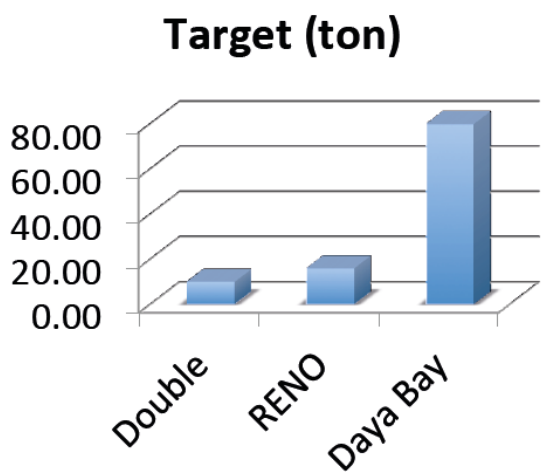
Three major experiment: Double Chooz, RENO, Daya Bay

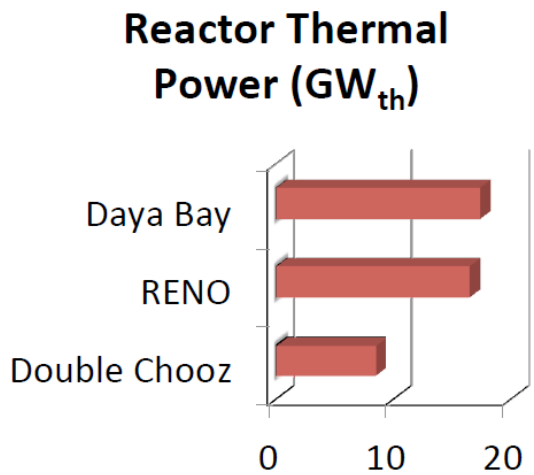
Chooz reactors
France /Ardenne

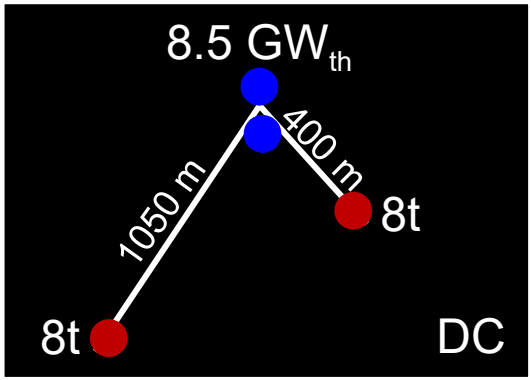
YonGwang reactors
South Korea

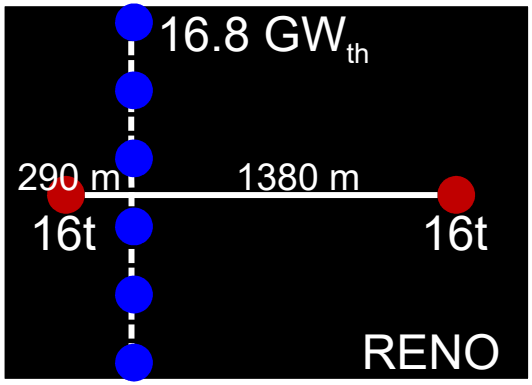
Daya Bay reactors
South China (close Hong Kong)

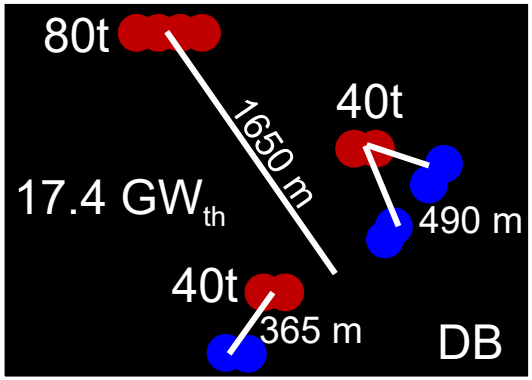
Comparision of Experiments











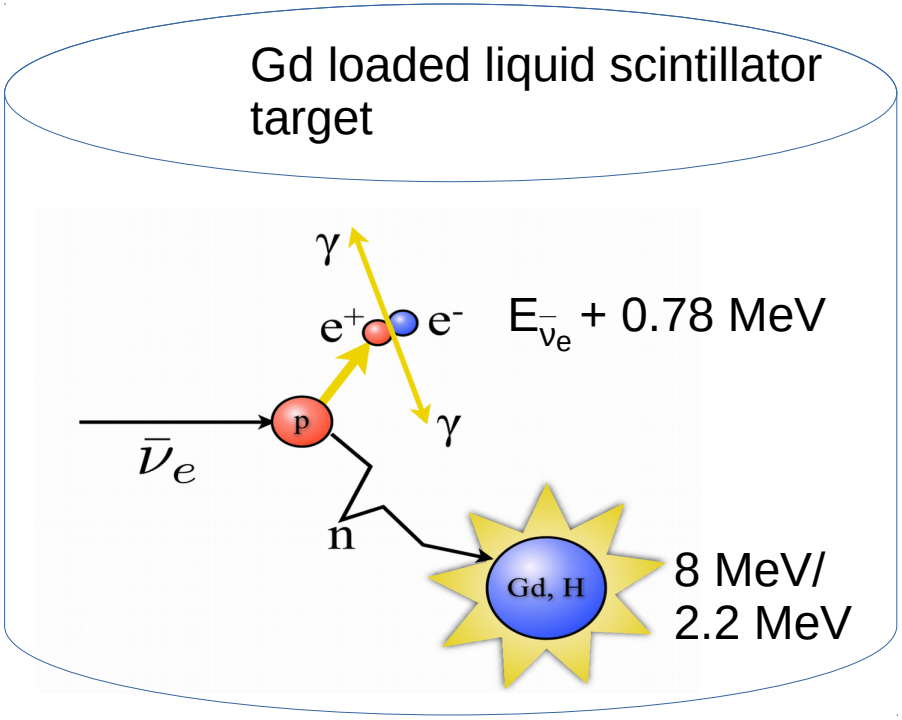
Experiment	Thermal Power (GW)	Distance Near/Far (m)	Depth Near/Far (mwe)	Target mass (ton)
Double Chooz	8,5	400/1050	120/300	8/8
RENO	16,8	290/1380	120/450	16/16
Daya Bay	17,4	360(500) /1985(1613)	260/860	40x2/80

Very similar design
Highest statistics for Daya Bay (by far)
Note, at the end of the day the systematics is limiting

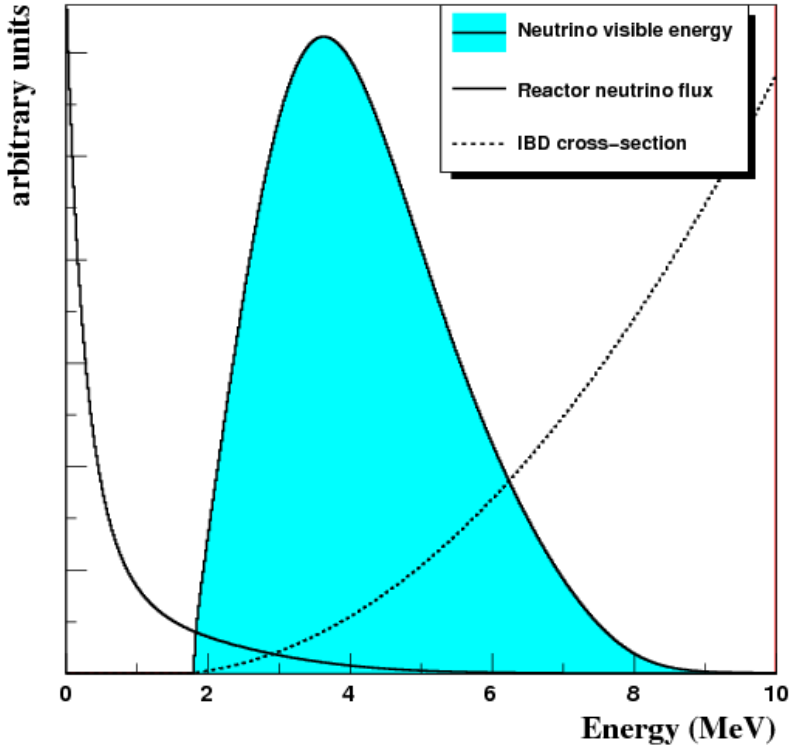
Neutrino Signal

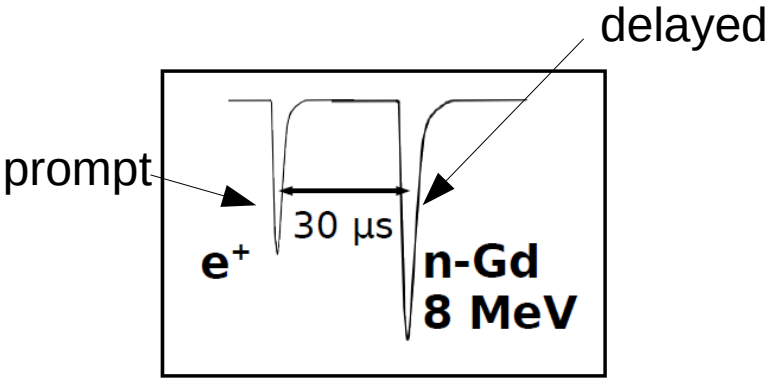
Inverse beta decay IBD

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



Reactor flux





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

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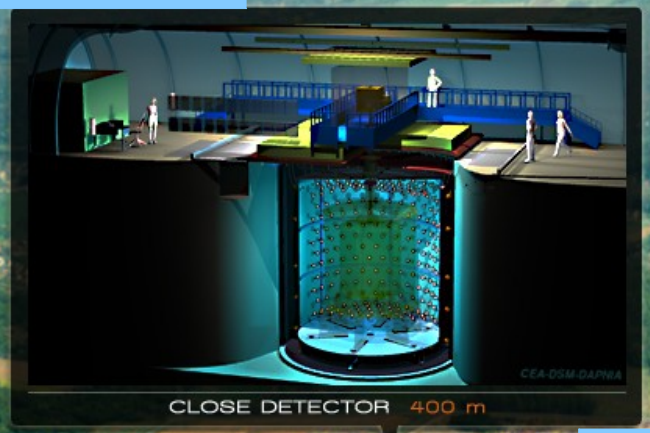
Experimental site

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

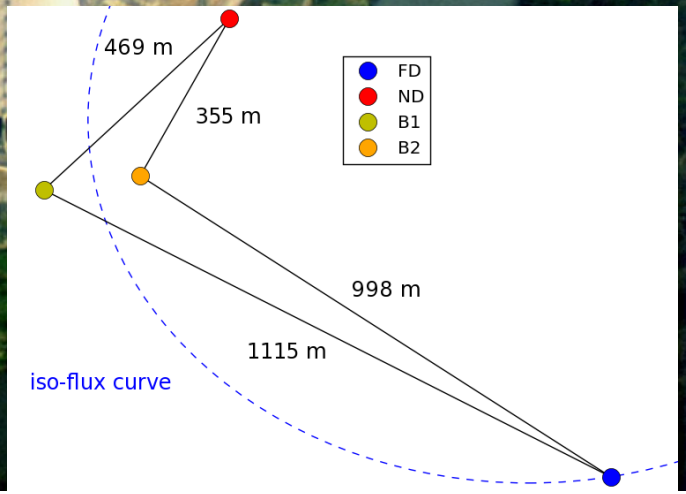
Far detector
- Operating since Apr 2011
- Baseline ~ 1050 m
- Overburden ~ 300 mwe



Reactor B2
- 4.27 GW_{th}

Reactor B1
- 4.27 GW_{th}

$\bar{\nu}_e$



θ_{13} Oscillations

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

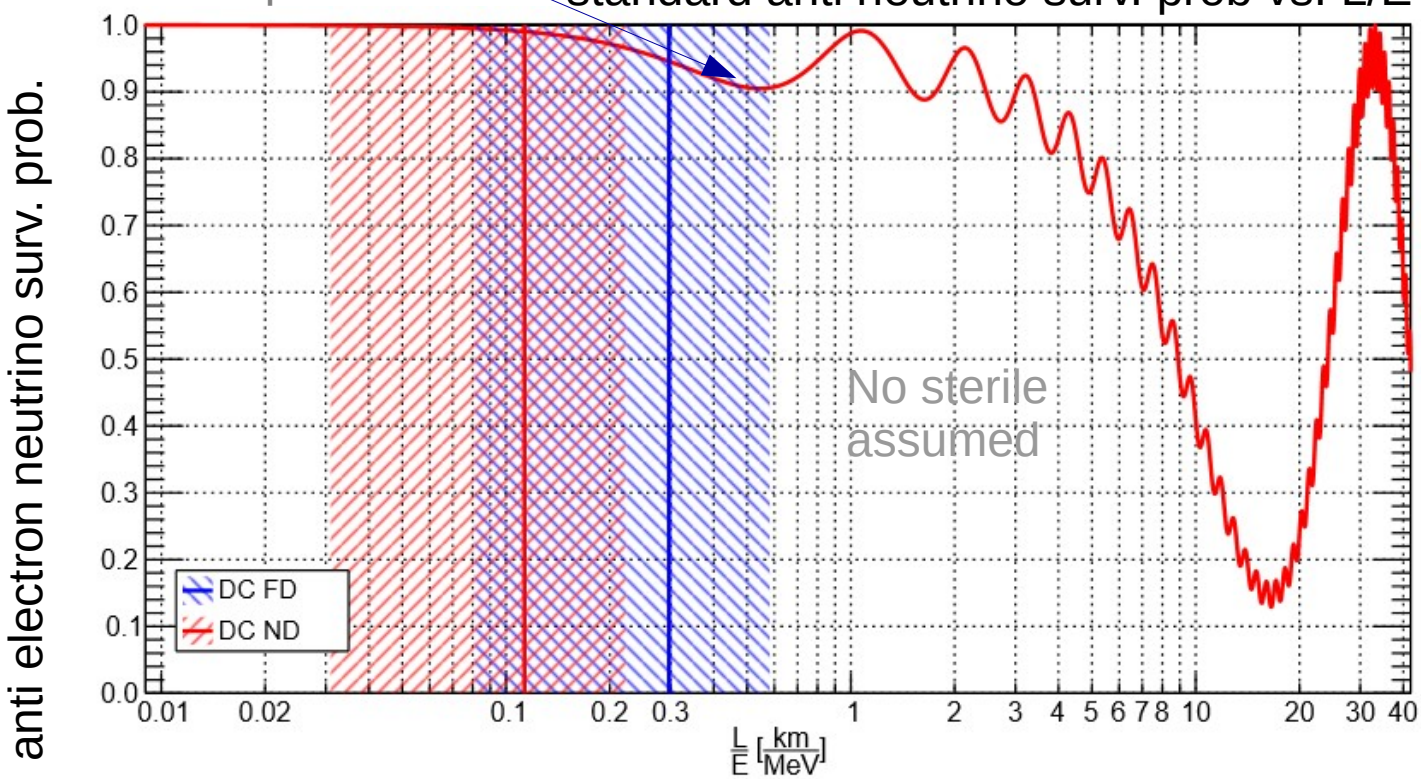
:= anti electron neutrino surv. prob.

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

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

matter effects safely negligible!

standard anti neutrino surv. prob vs. L/E



Double Chooz is optimized for θ_{13} measurment (Δm_{31})

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.

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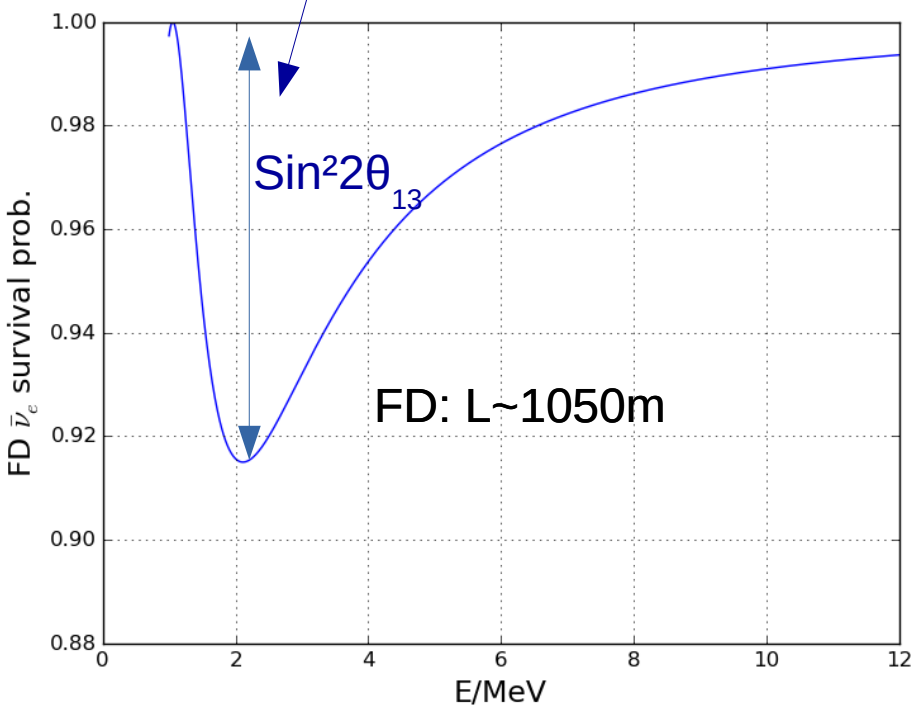
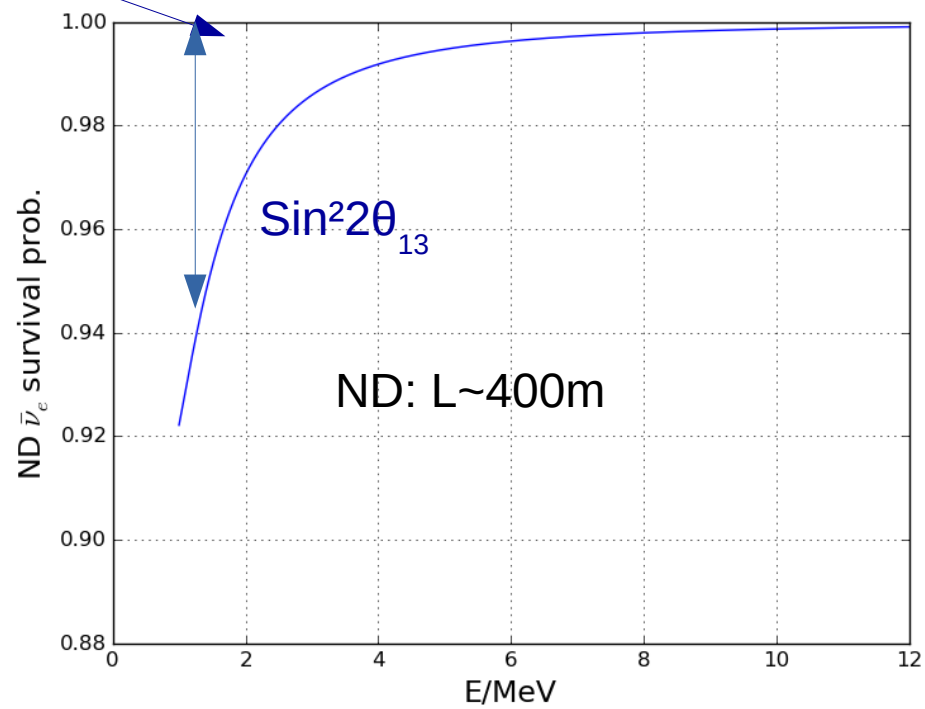
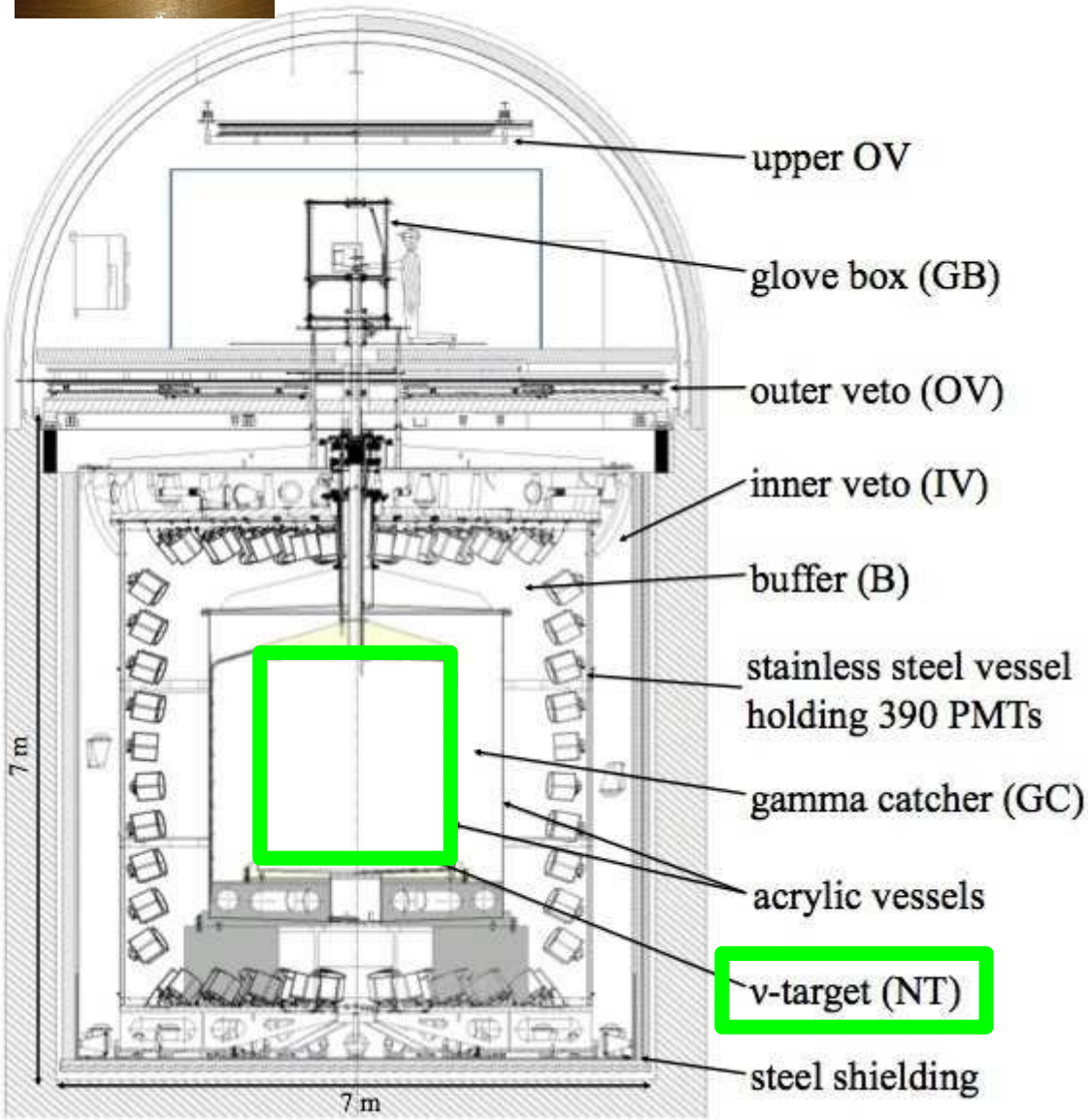


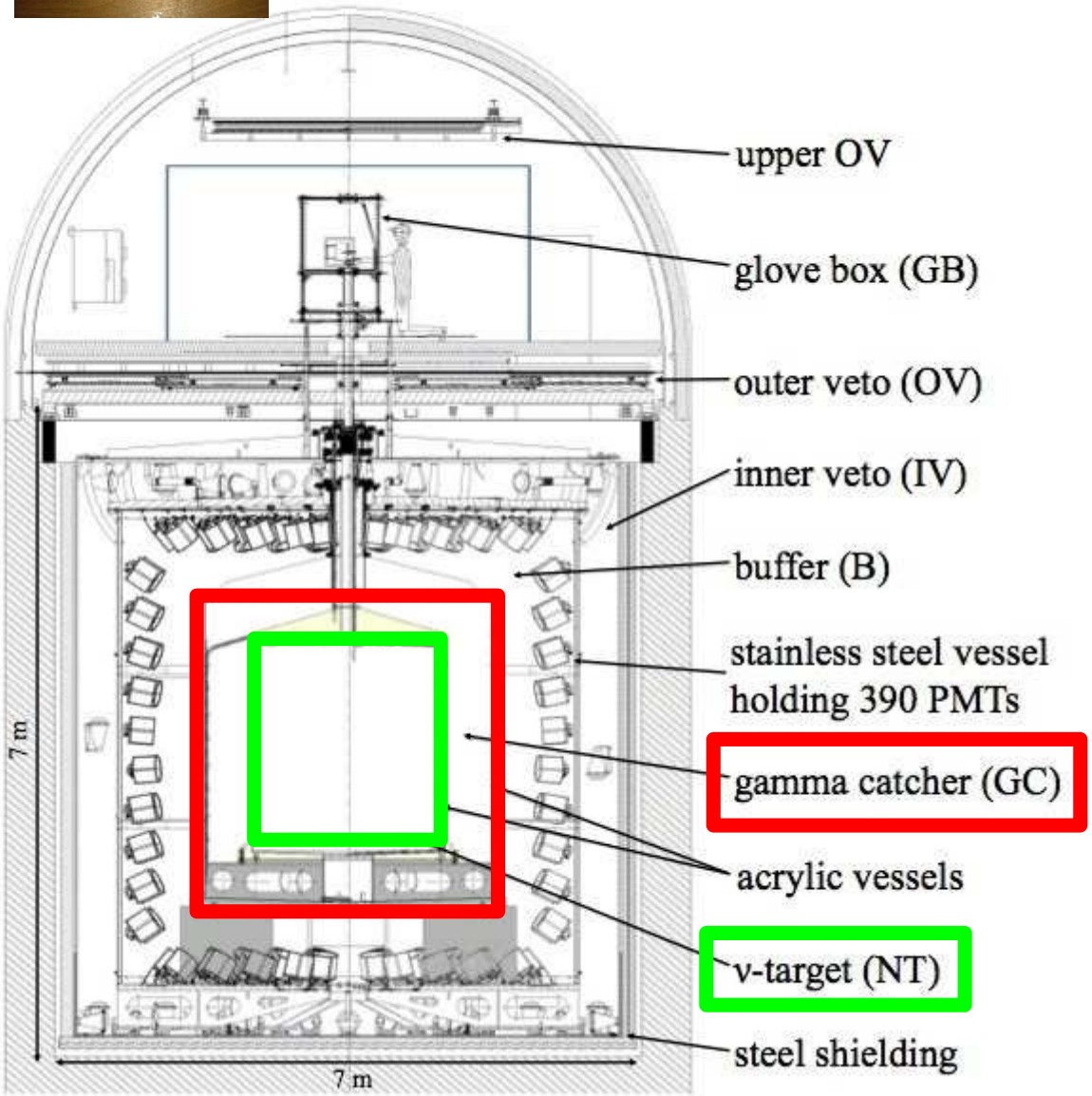


Detector



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

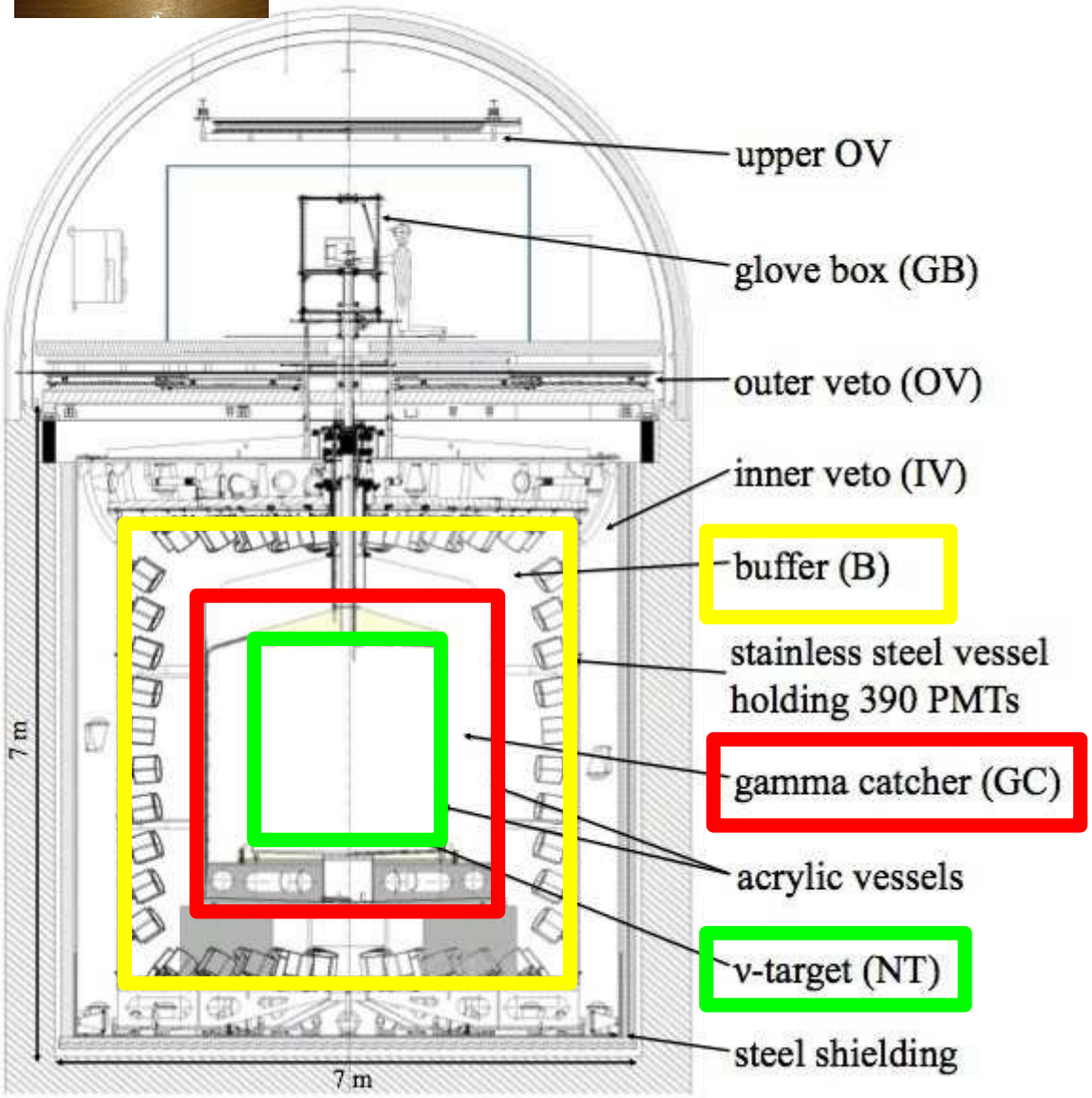
Detector



Gamma Catcher (GC)
Liquid Scintillator (22 m³)
Measures γ escaping the target

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

Detector

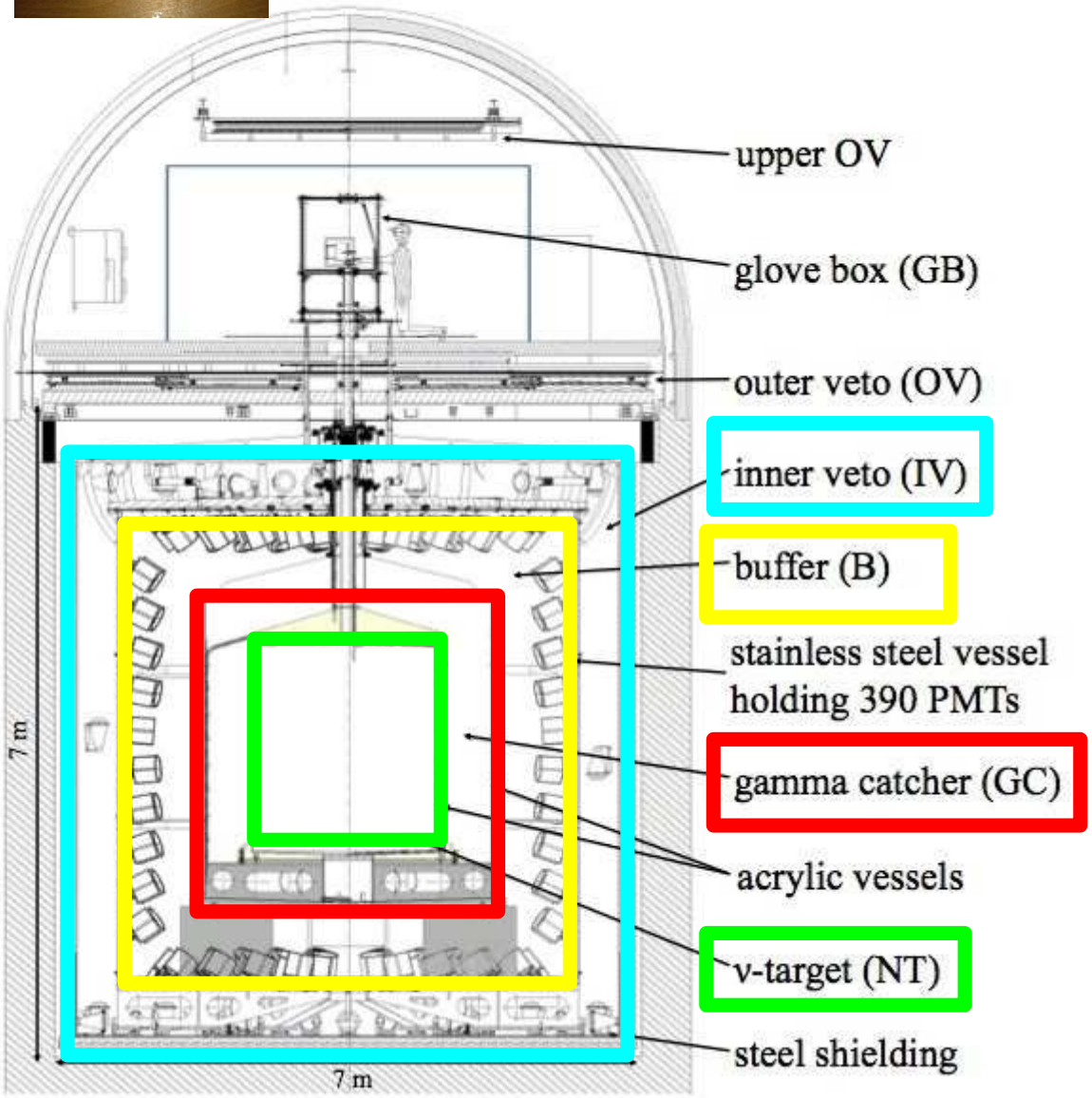


Buffer (B)
Non-scintillating mineral oil (110m³)
390 10" PMT
Shieling against external γ

Gamma Catcher (GC)
Liquid Scintillator (22 m³)
Measures γ escaping the target

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

Detector



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

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

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Liquid Scintillator (22 m³)
Measures γ escaping the target

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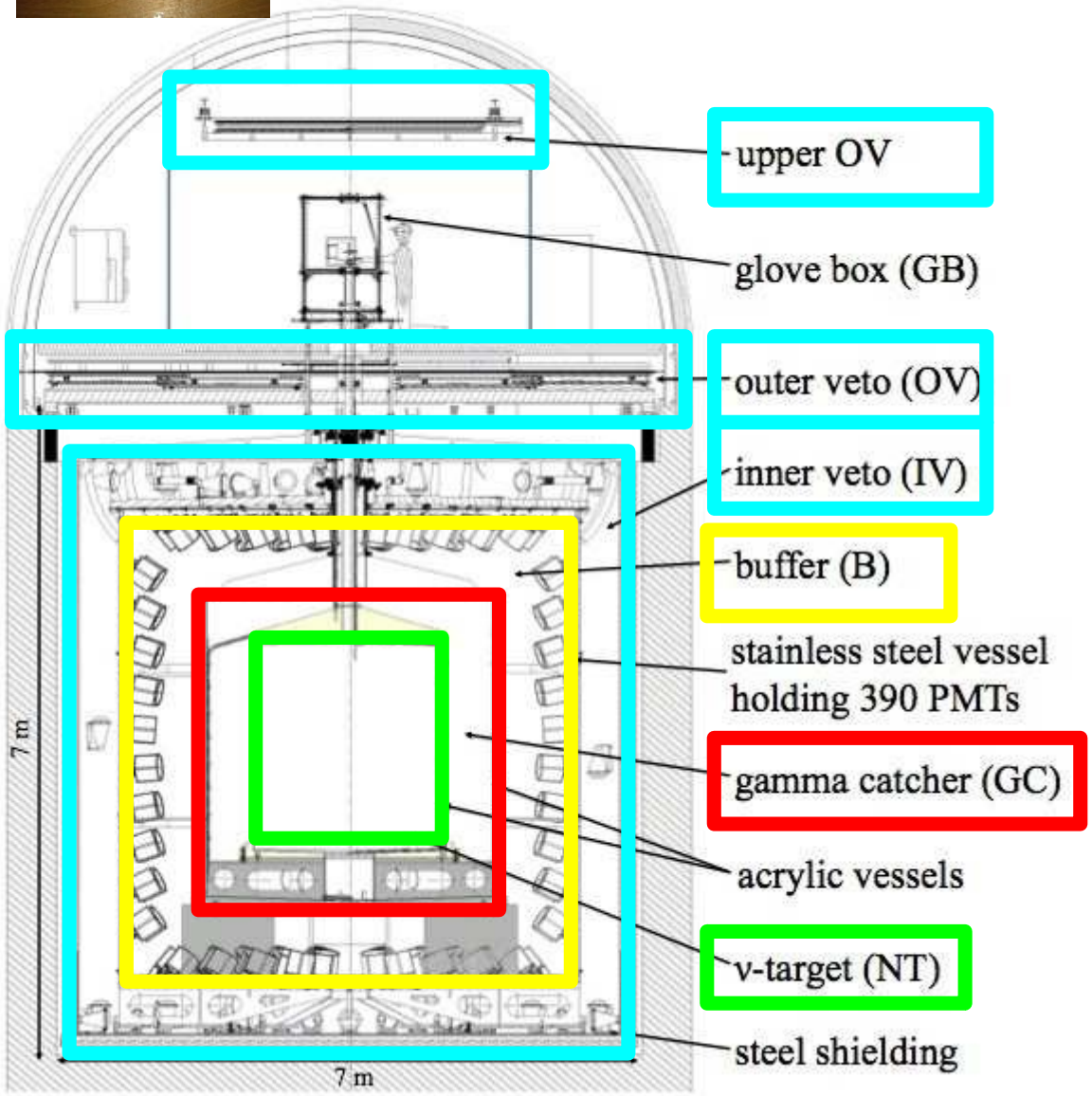
Gd loaded (1 g/l) liquid scint. (10 m³)
IBD interactions on Gd capture

Detector



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

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

Gamma Catcher (GC)
Liquid Scintillator (22 m³)
Measures γ escaping the target

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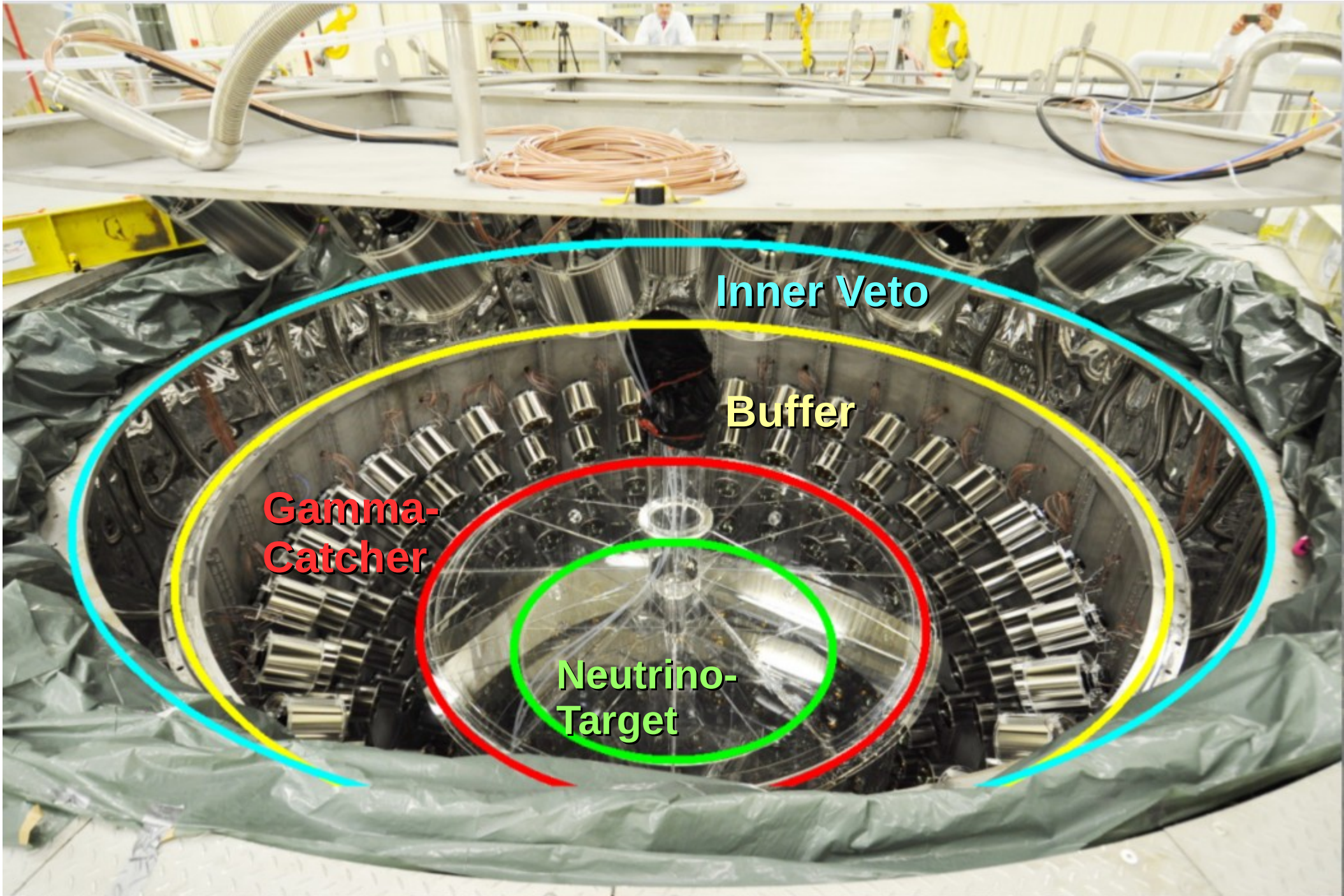
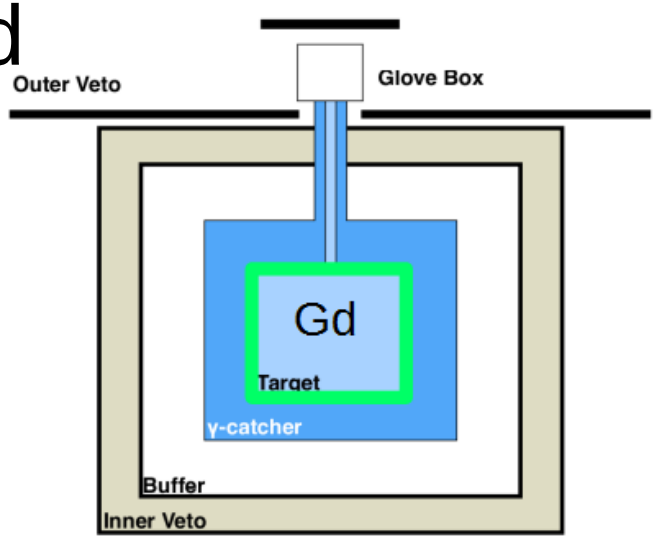
Gd loaded (1 g/l) liquid scint. (10 m³)
IBD interactions on Gd capture

Detector

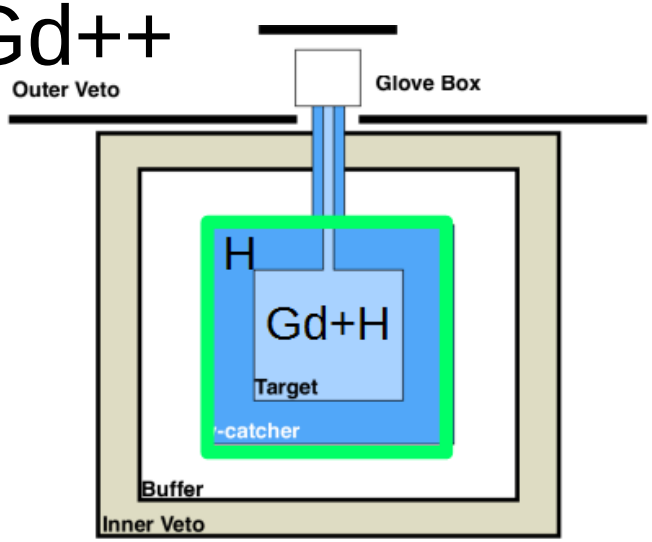


IBD Selection

Gd

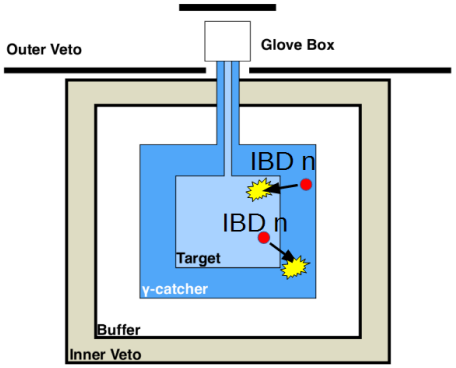


Gd++



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

- less statistics
+ less background
- spilling relevant

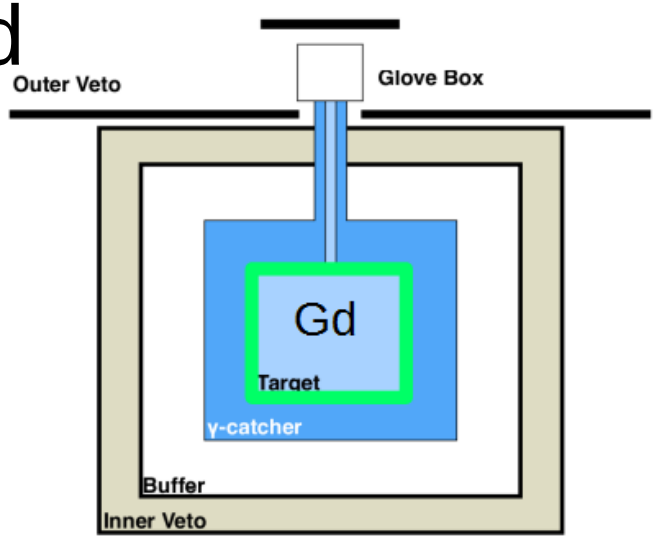


- Selecting **n-Gd and n-H** capture in **Neutrino Target and Gamma Catcher**

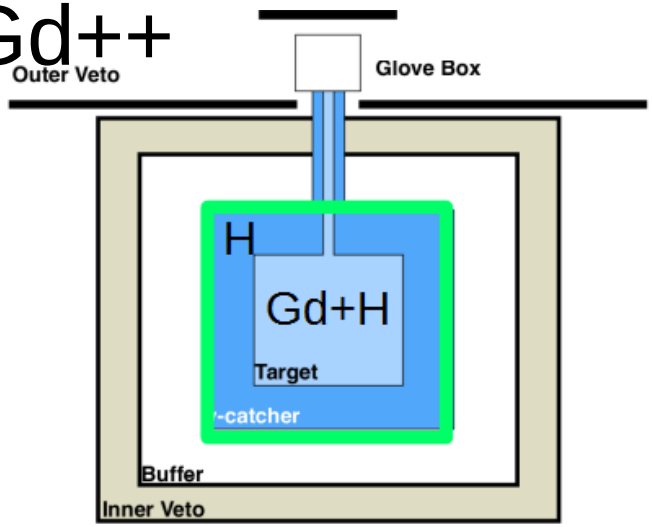
+ more statistics
- more background
+ spilling irrelevant

IBD Selection

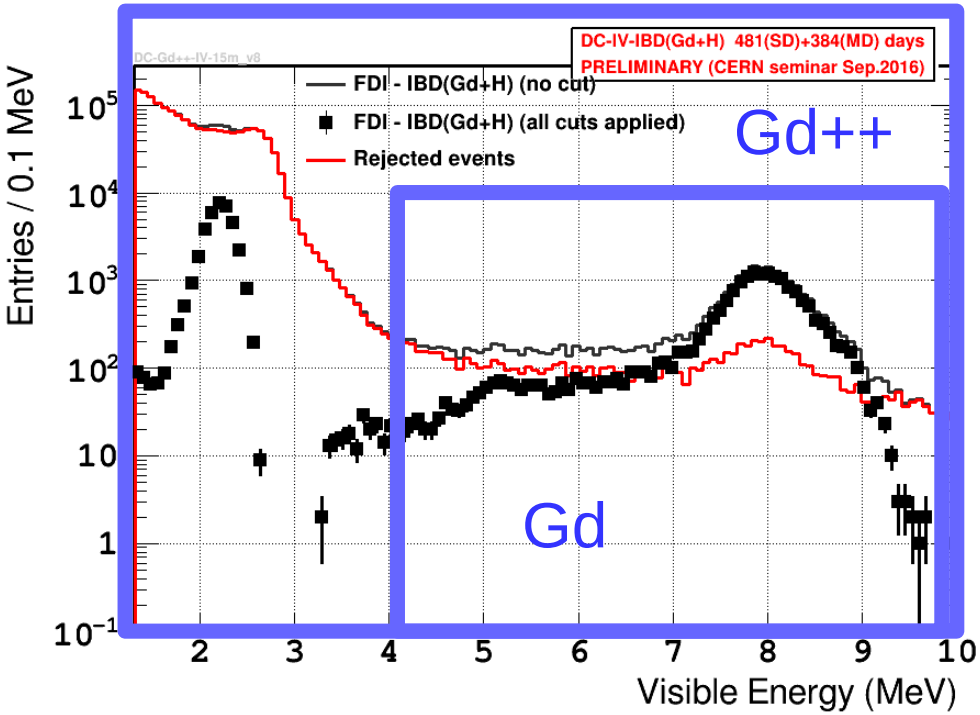
Gd



Gd++

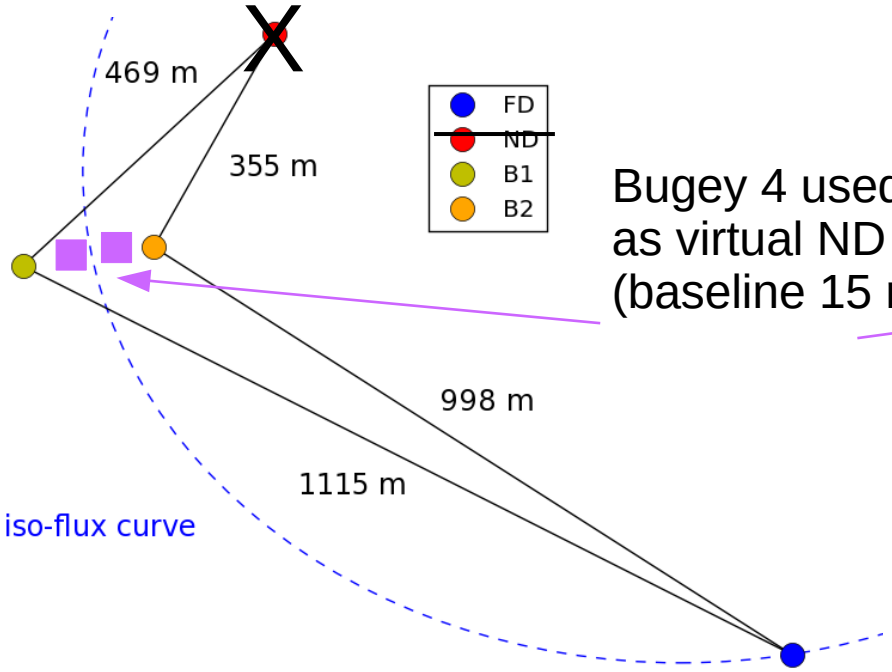


- Selecting **n-Gd** capture in **Neutrino Target** only
- Selecting **n-Gd and n-H** capture in **Neutrino Target and Gamma Catcher**



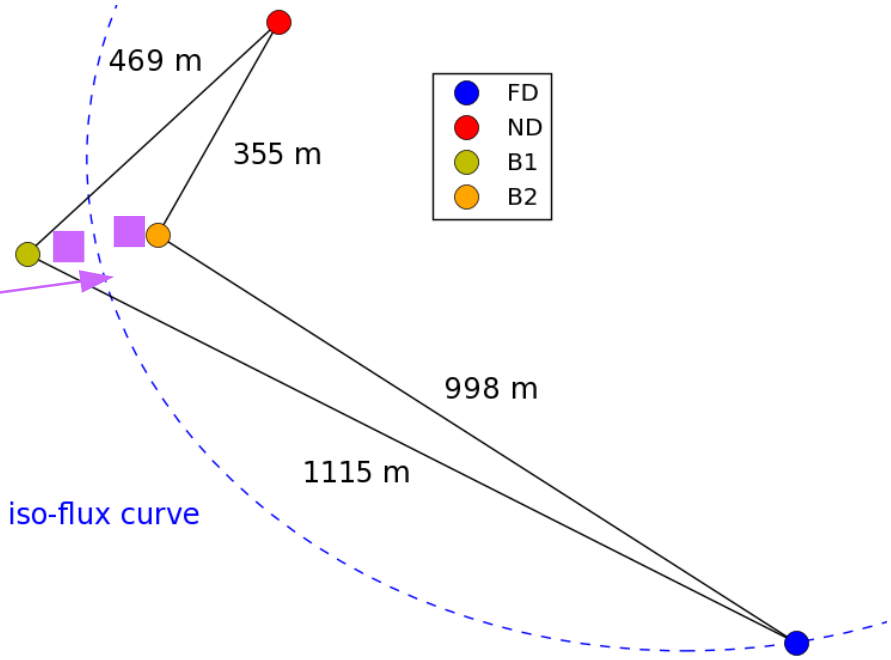
Datasets

Before 2015



Bugey 4 used
as virtual ND
(baseline 15 m)

Since 2015



FDI 455 days lifetime
+ 7 days lifetime reactor off

ND 258 days lifetime
FDII 363 days lifetime

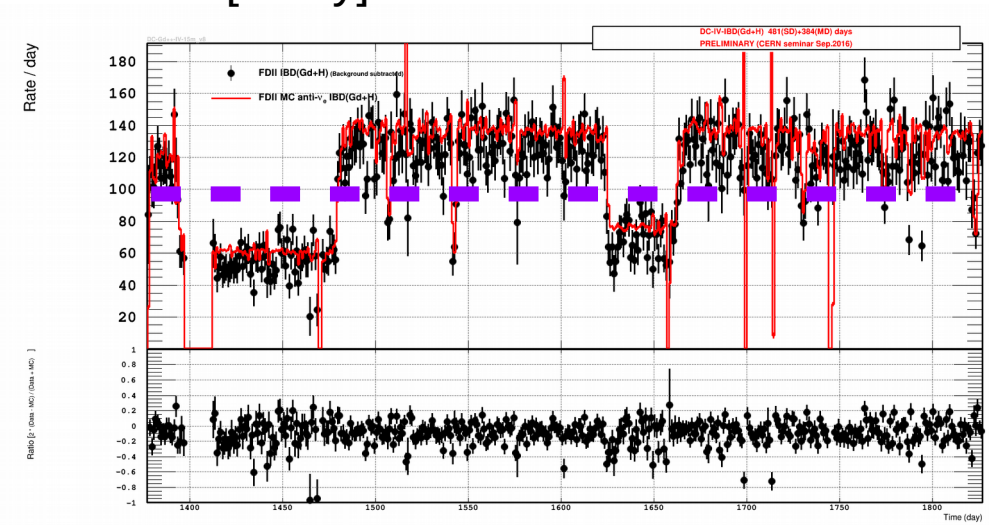
Double Chooz is expected to operate 3 years in full configuration until end 2017

Datasets can be combined!

Datasets

FDII (FD parallel to ND) 363 days lifetime

Rate[1/day] vs. time

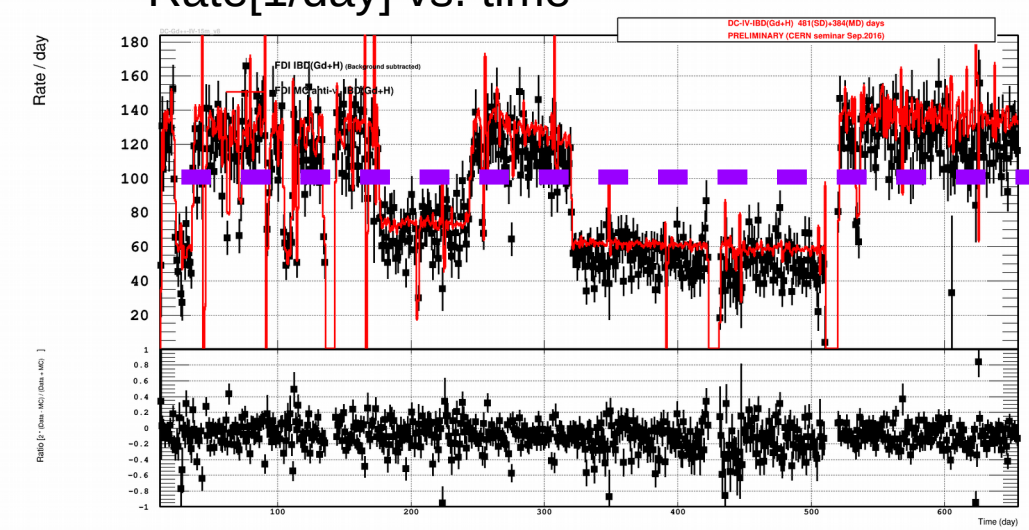


ND 258 days lifetime

Rate[1/day] vs. time

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

Rate[1/day] vs. time



2 Reactors

1 Reactor

Rates with 2 reactors on:

ND: ~ 900/ day
FD: ~ 130/ day

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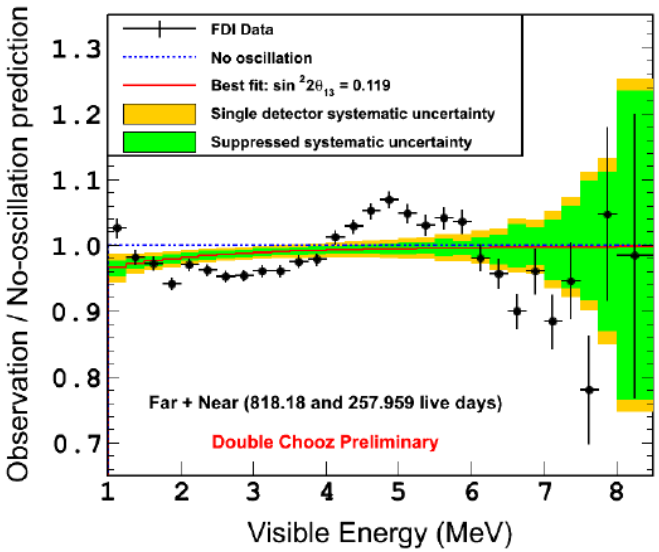
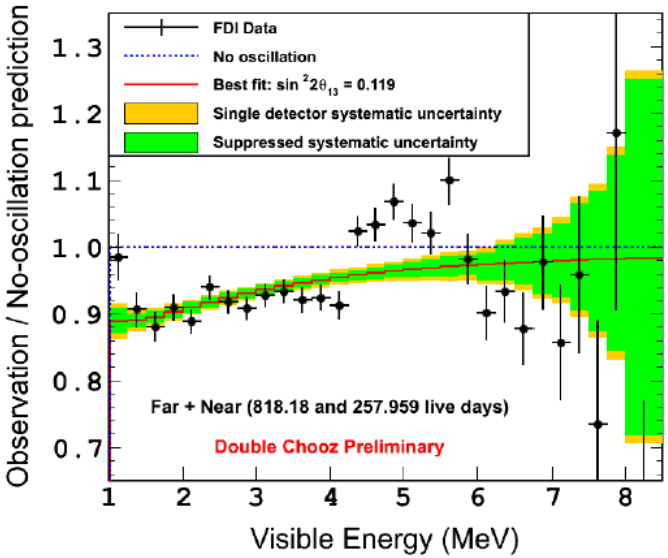
Latest θ_{13} Results (Sep 2016)

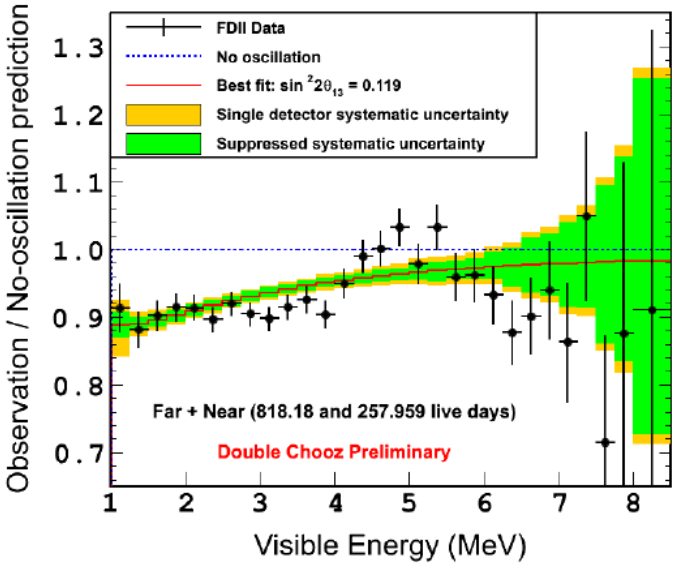
ND



FDI



FDII

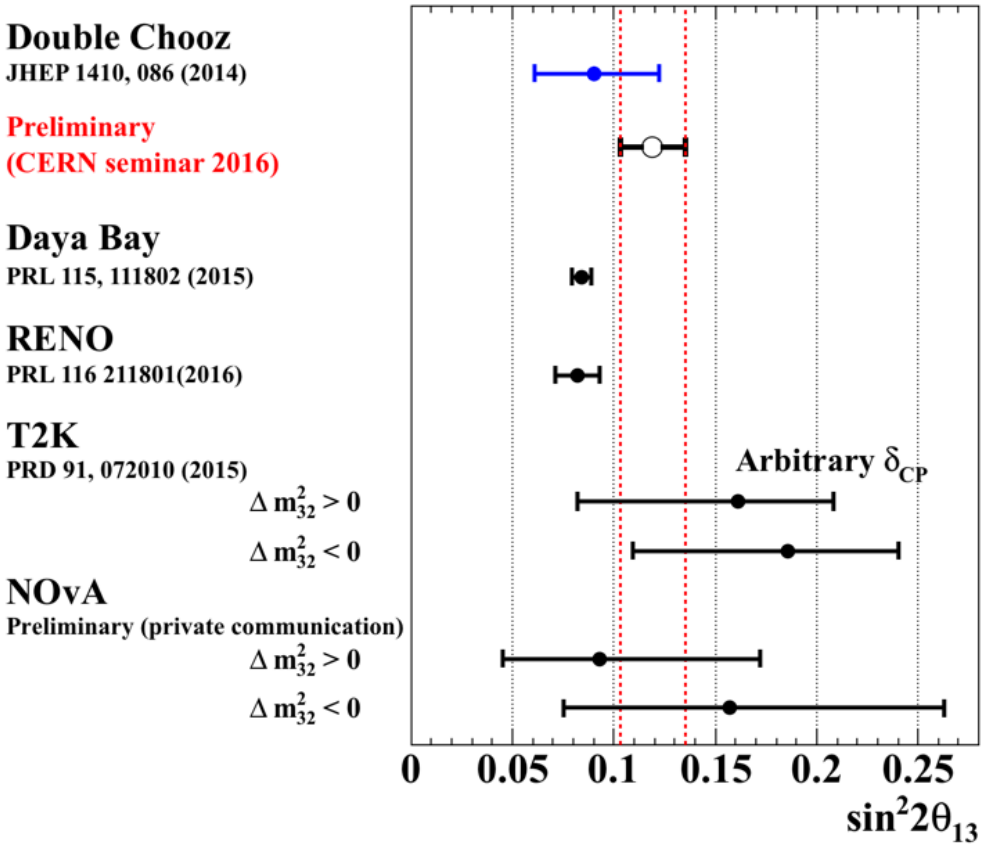


Rate+ Shape χ^2-fit of data to prediction:

$\sin^2(2\theta_{13})$=(0.119±0.016) with $\chi2$ / ndf: 236.2 / 114

- Cross checked by Data-Data fits
- Cross checked by three groups
- Not optimal $\chi2$ due to data-prediction mismatch observed with both detectors

Latest θ_{13} Results (Sep 2016)



Difference to Daya Bay 2.2 σ

Difference to RENO 1.8 σ

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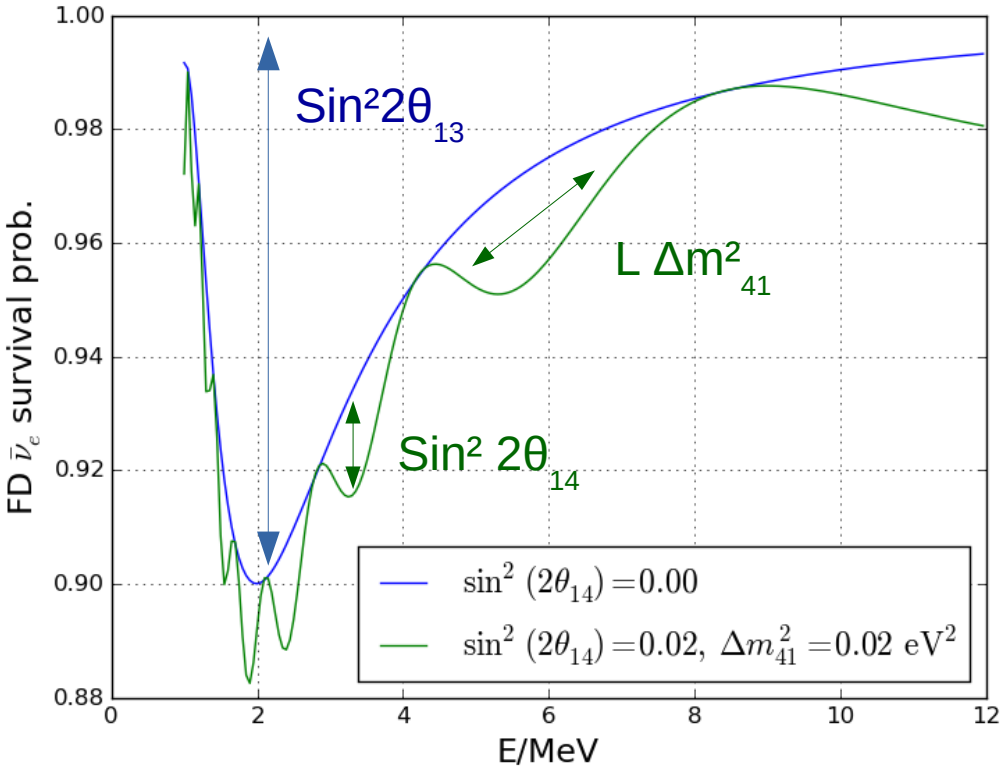
Sterile Signatures

Standard part — sterile part

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

:= anti electron neutrino surv. prob.

FD: L ≈ 1050m



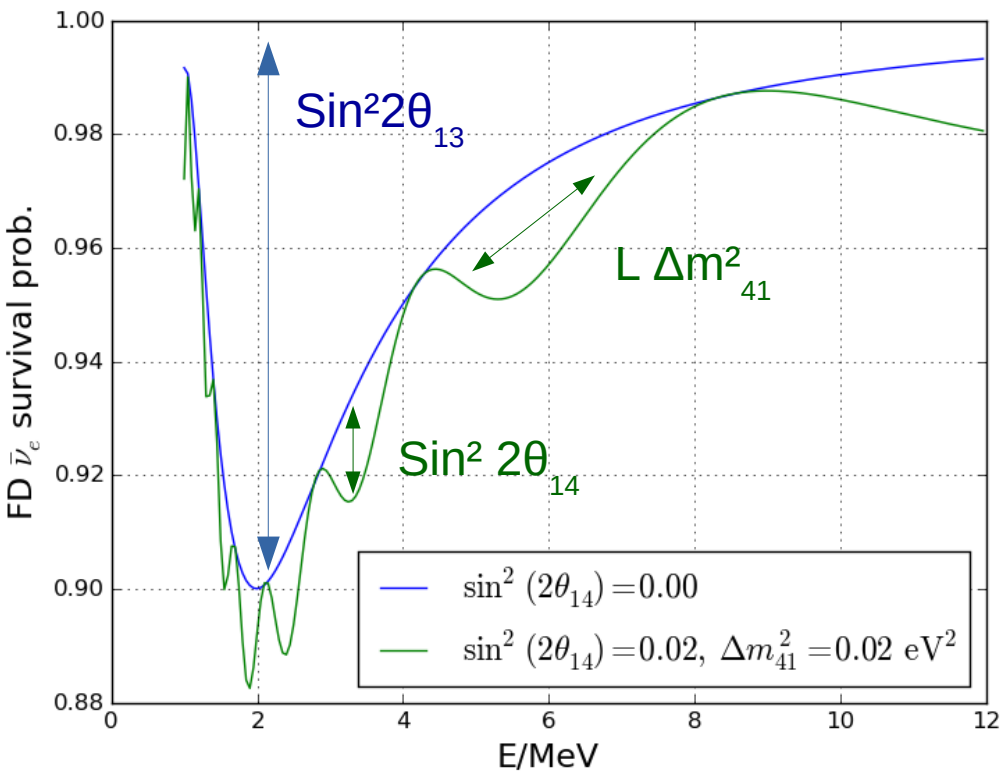
Sterile Signatures

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

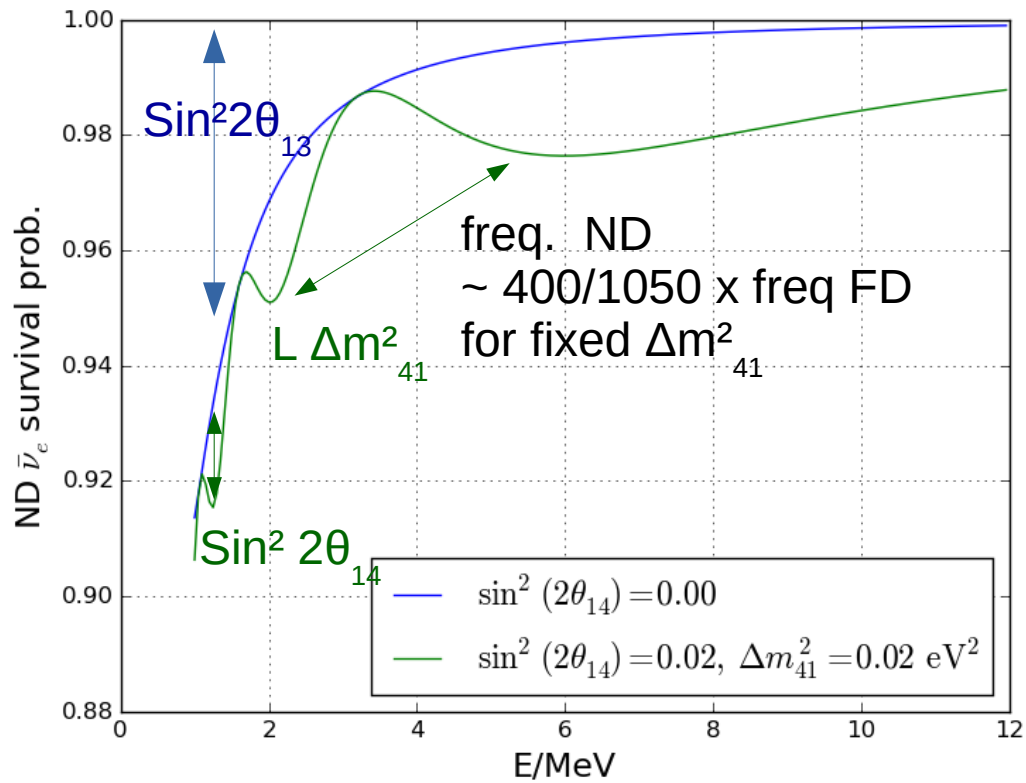
sterile part

:= anti electron neutrino surv. prob.

FD: L ≈ 1050m



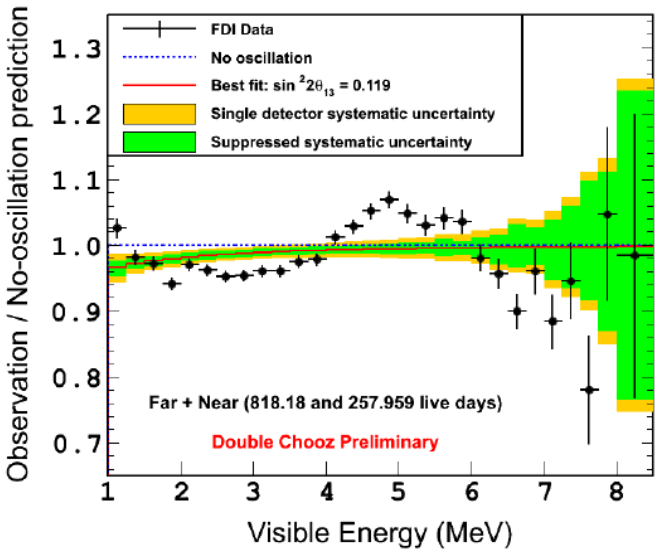
ND: L ≈ 400 m



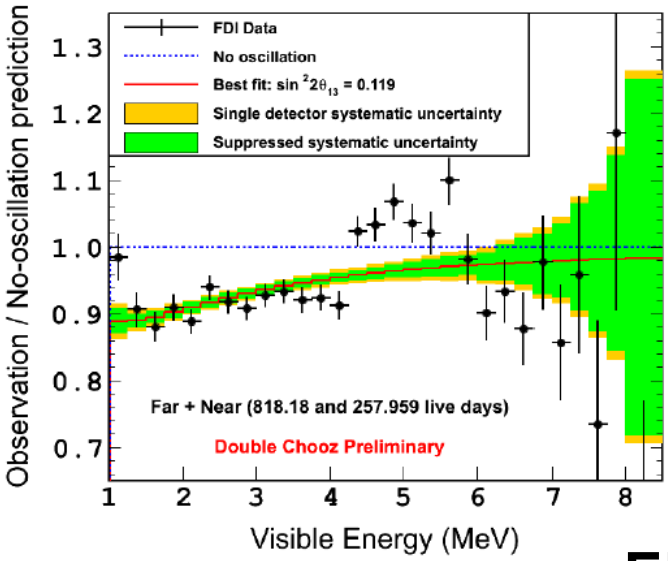
- **Repeating signature, which is different for ND and FD**
  → hard to be matched by any single systematic effect

Spectral Distortion

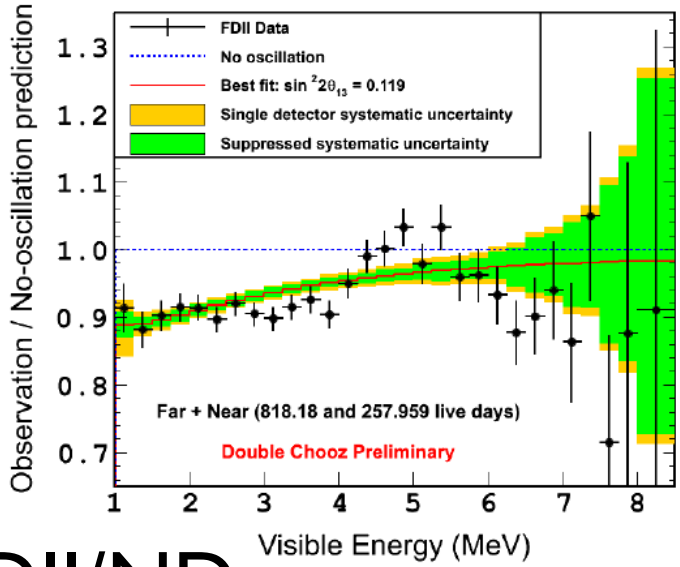
ND



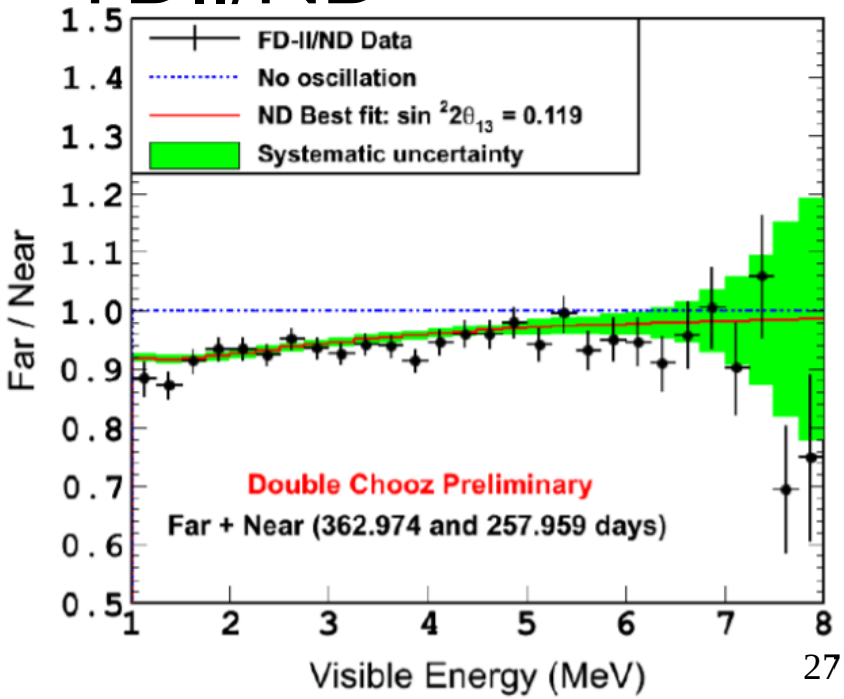
FDI



FDII



FDII/ND



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

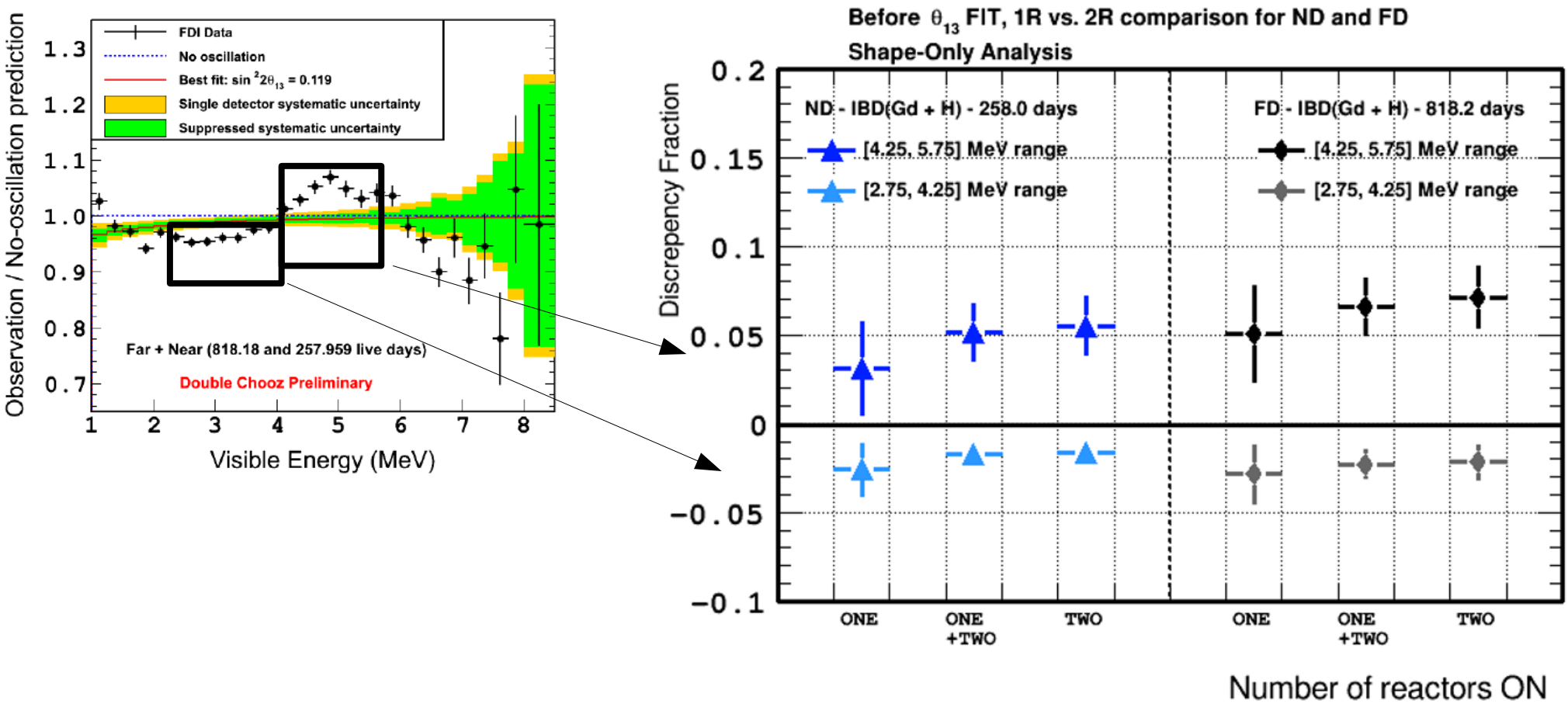
$\sin^2(2\theta_{13})=(0.119\pm0.016)$

with $\chi2$ / ndf: 236.2 / 114

Spectral distortion cancels out in FD/ND ratio

=> can not be explained by sterile neutrinos

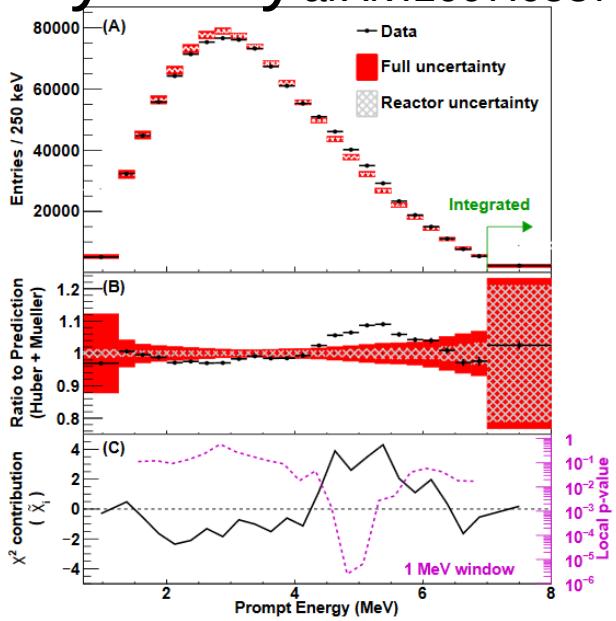
Spectral Distorion vs. Reactor Power



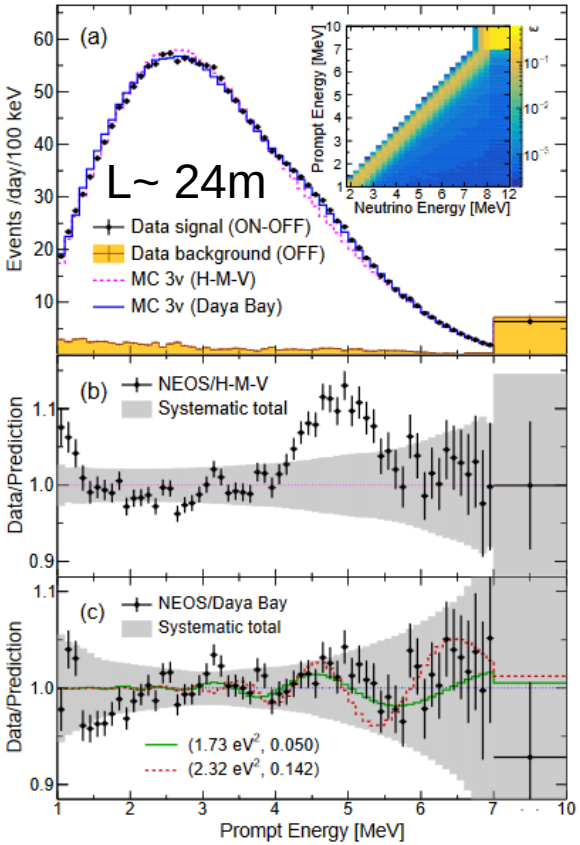
Excess/deficit is consistent to be proportional to reactor power

Spectral Distortion Seen by Other Experiments

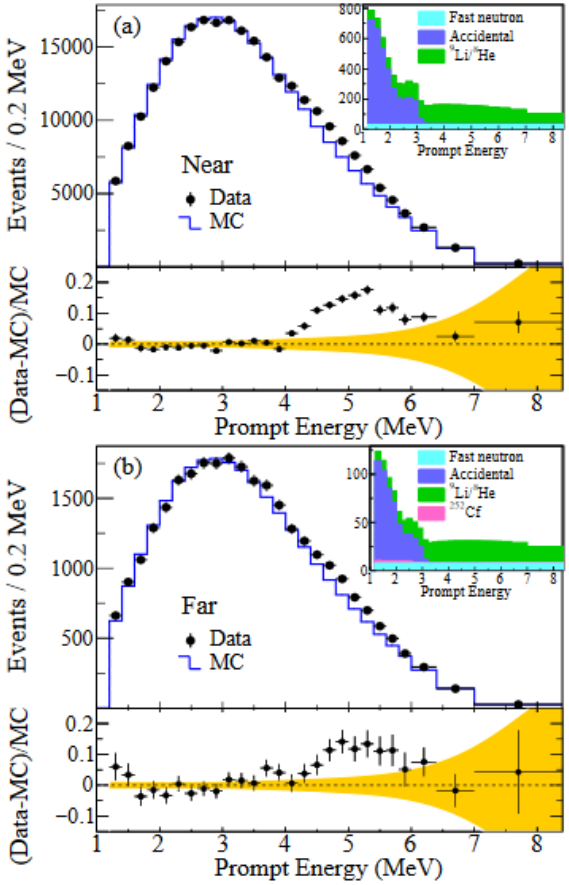
Daya Bay arXiv:1607.05378



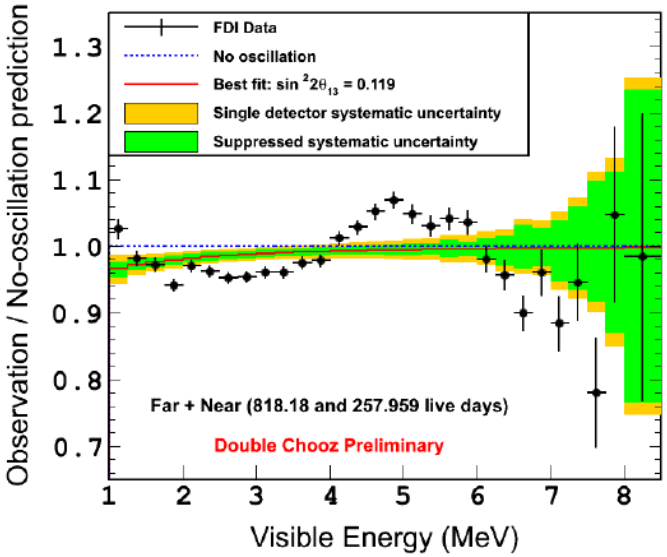
NEOS arXiv:1610.05134



Reno arXiv:1610.04326



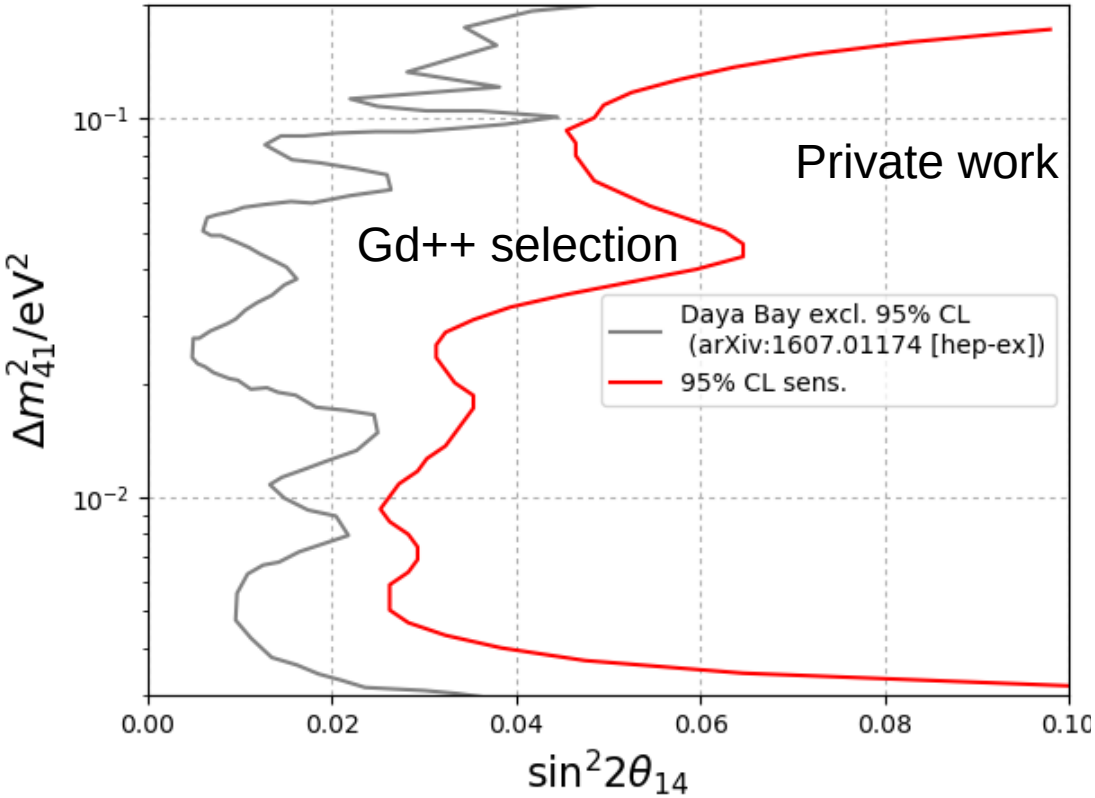
Double Chooz



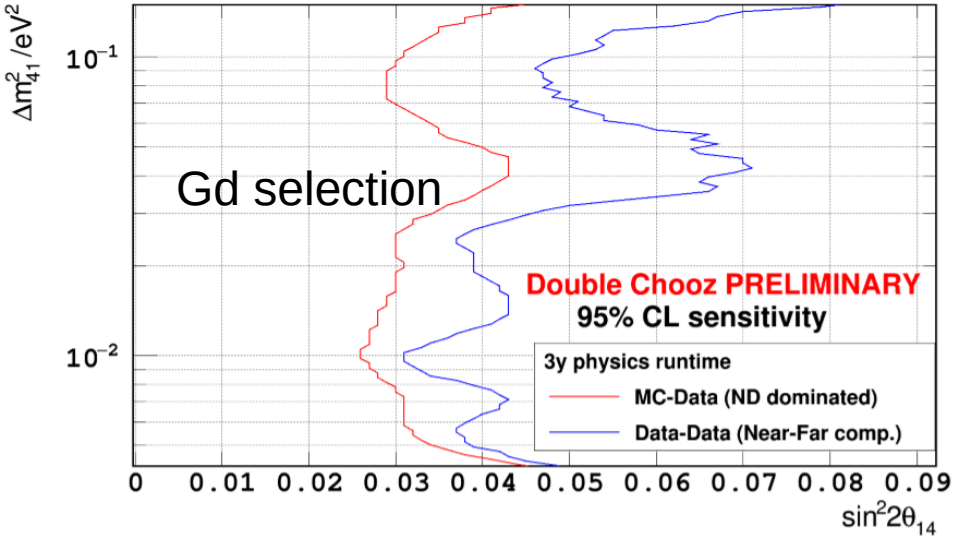
Spectral distortion seen by several experiments

Sensitivity to θ_{14}

Sensitivity with CERN data set
(15 month GD++ selection)



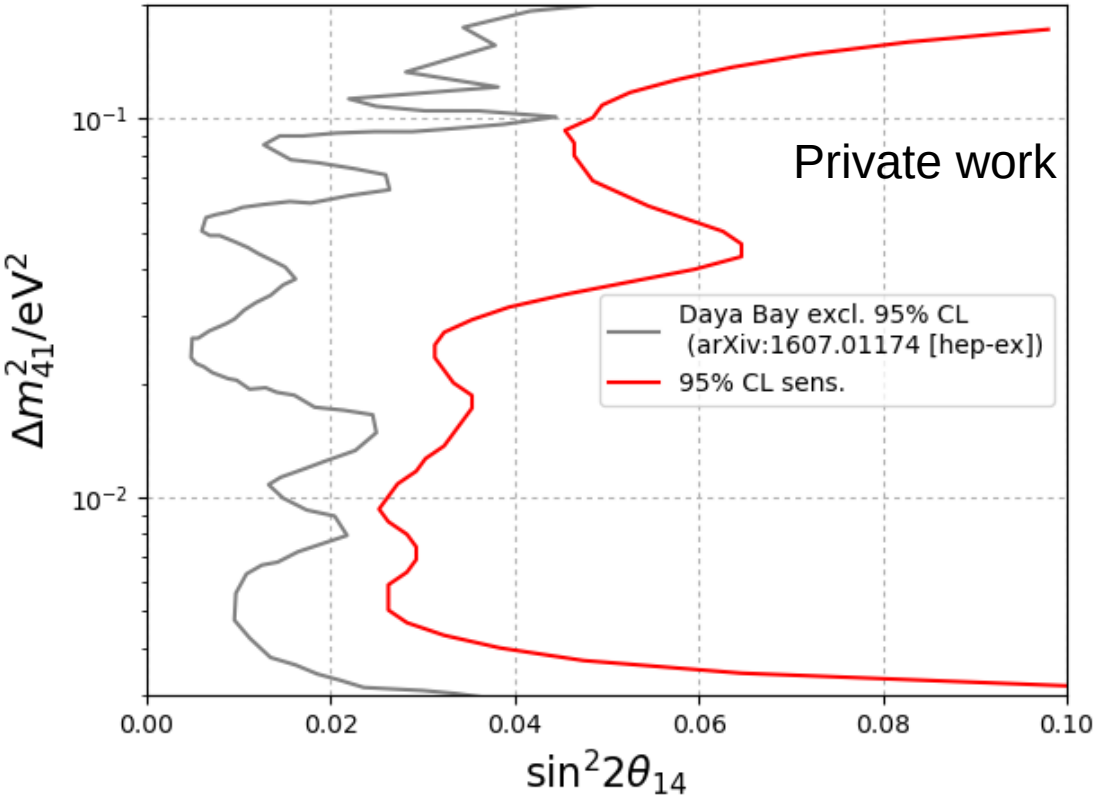
Officially presented @NEUTRINO
3 years Gd selction data

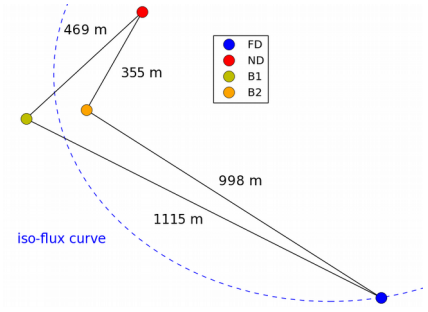


- Sensitivity with Gd++ selection much better than with Gd selection
- Sensitivity valley around 4×10^{-2} eV² due to canceling of oscillation signatures of neutrino flux from reactor B1 and B2

Sensitivity to θ_{14}

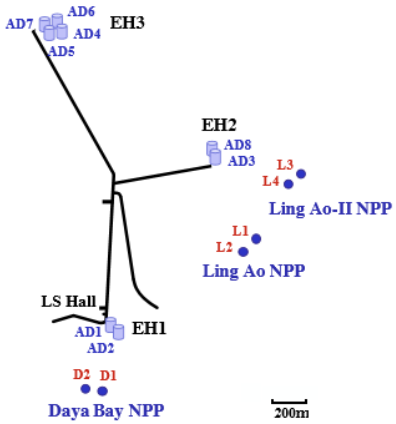
Sensitivity with CERN data set
(15 month GD++ selection)





Double Chooz

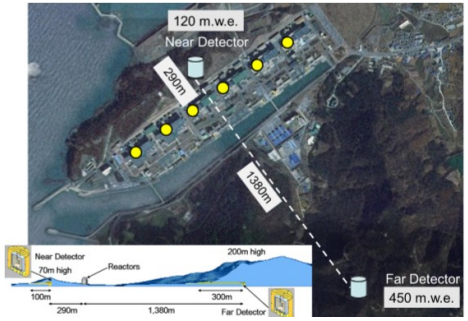
2 reactors
8.5 GW_{th}
2 det.
8T (30t) each



Daya Bay

6 reactors
17.4 GW_{th}
8 det.
20t each

- Statistics in final Double Chooz dataset is going to be higher (x2)



Reno
6 reactors
16.8 GW_{th}
2 det.
16t (45t) each

Summary

- Reactor neutrino IBD detection using n-Gd and n-H capture
- Sensitivity to θ_{13} and θ_{14}
- Latest result: $\sin^2(2\theta_{13})=0.119\pm0.016$
- Energy shape distortion between 4-6 MeV observed by reactor neutrino experiments
- Biggest uncertainty (proton number) is most likely going to tp be reduced
- Double Chooz is sensitive to light sterile neutrino ($|\Delta m^2_{41}|\sim 0.005\text{-}0.1\ eV^2$)

Double Chooz Collaboration

Brazil

CBPF
UNICAMP
UFABC

France

CEA/DSM/IRFU:
SPP,SPhN,SEDI,
SIS,SENAC.
CNRS/IN2P3:
APC,Subatech, IPHC

Germany

EKU Tübingen
MPIK Heidelberg
RWTH Aachen
TU München
U. Hamburg

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

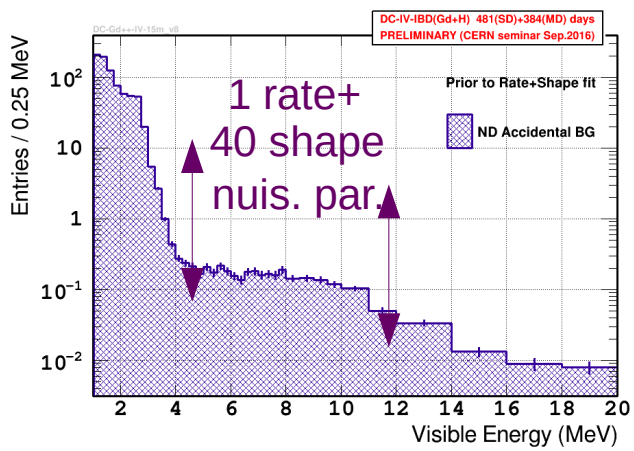
U. Alabama
ANL
U. Chicago
Columbia U.
UC Davis
Drexel U.
U. Hawaii
IIT
KSU
LLNL
MIT
U. Notre Dame
U. Tennessee

Thanks for your attention!

Backup

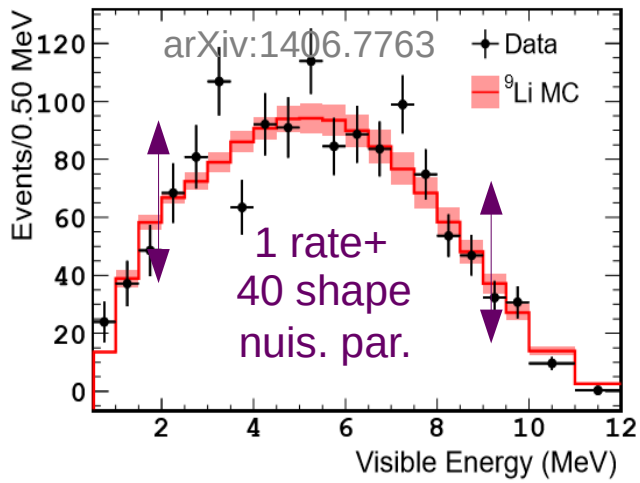
Background Model

Accidental



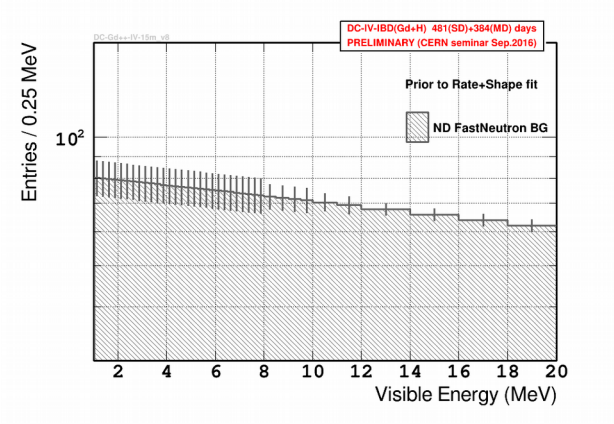
- Rate and shape measured with offtime method
- Rate and shape constraint in fit using cov. matrix from measurement

Lithium



- Lithium likelihood based on distance between vertex and next μ track and number of neutron candidates within 1ms after that μ
- Rate unconstrained in fit
- Shape constraint in fit using cov. matrix from measurement

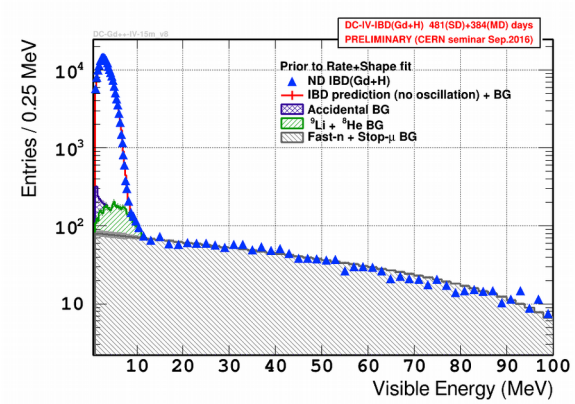
Fast n + stopping μ



- Empirical function

$$f(E_{vis}) = p_0 \cdot \exp(p_1 \cdot E_{vis}) + p_2 + p_3 \cdot E_{vis}$$

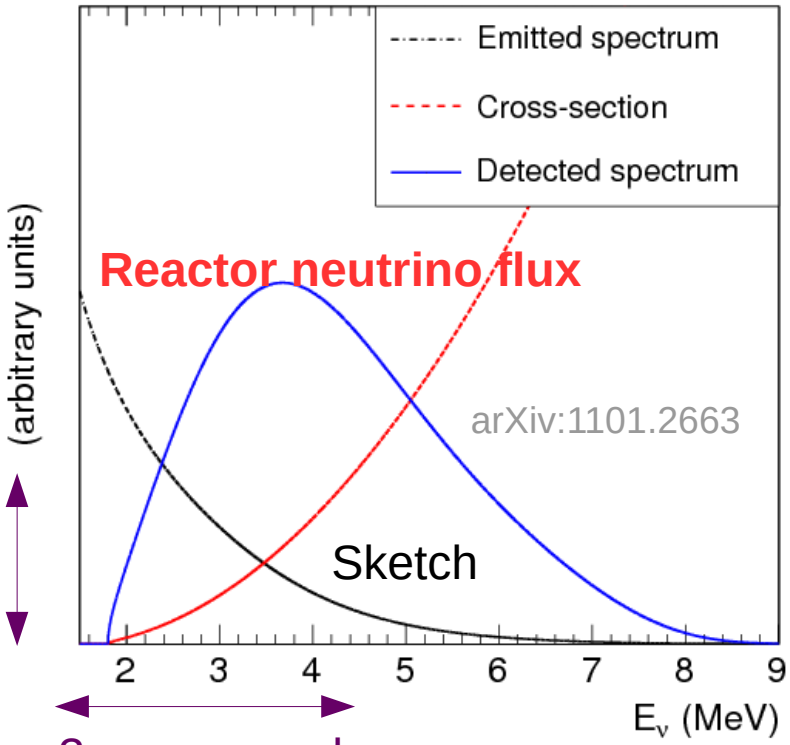
- Sample from IV tagged events
- Dominant at high energies
- Rate estimated using 20-100 MeV prompt energy window



All backgrounds constraint with reactor off sample

Inputs

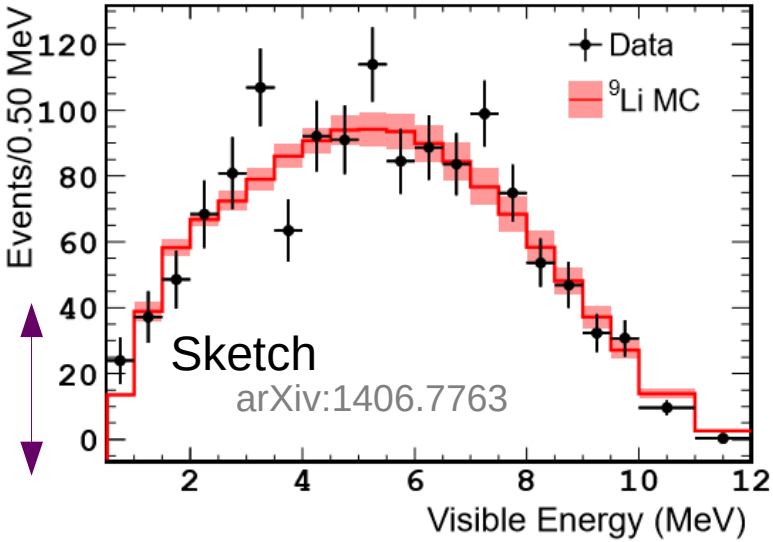
1 rate+
43 eff. free
shape par.
+
osc. par.



3 energy scale par.

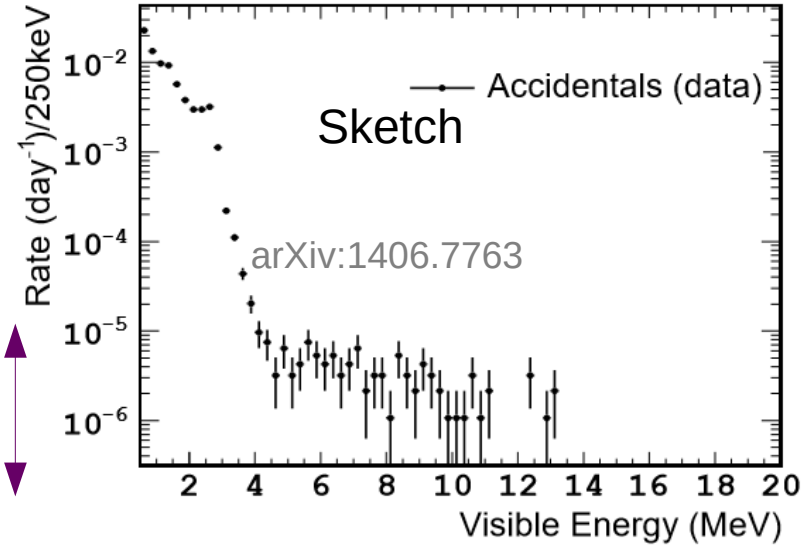
Li9 backgr.

1 rate
+
40 shape
nuis. par.



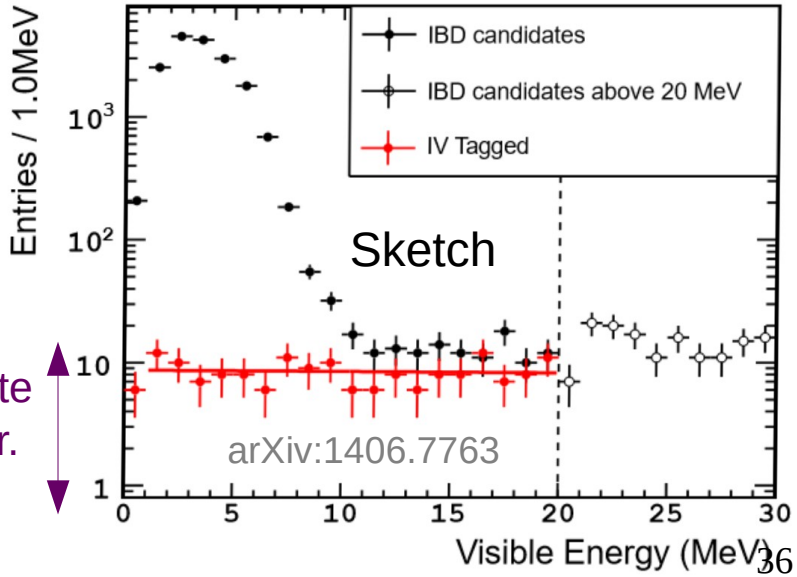
Accidental backgr.

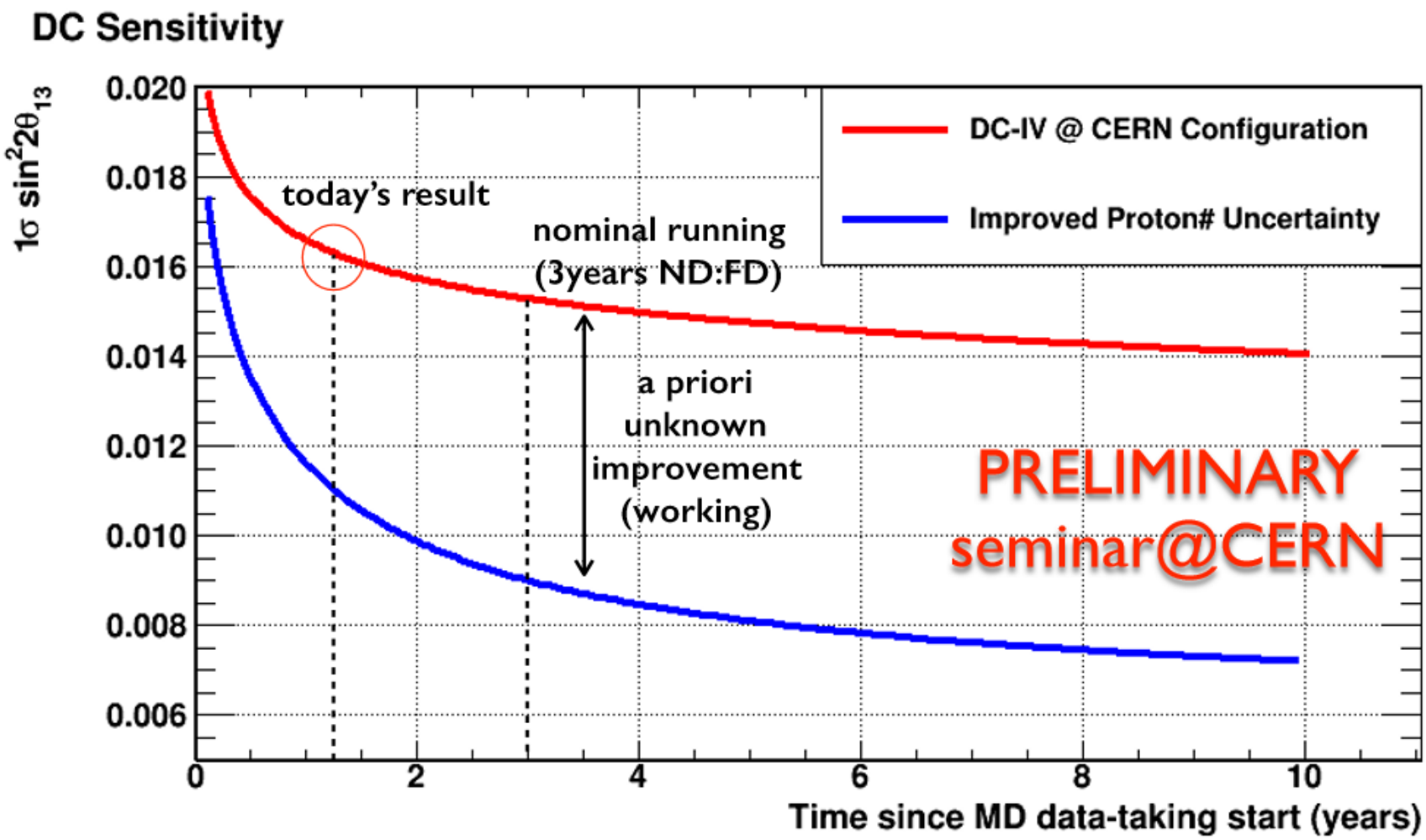
1 rate
+40
shape
nuis.
par.



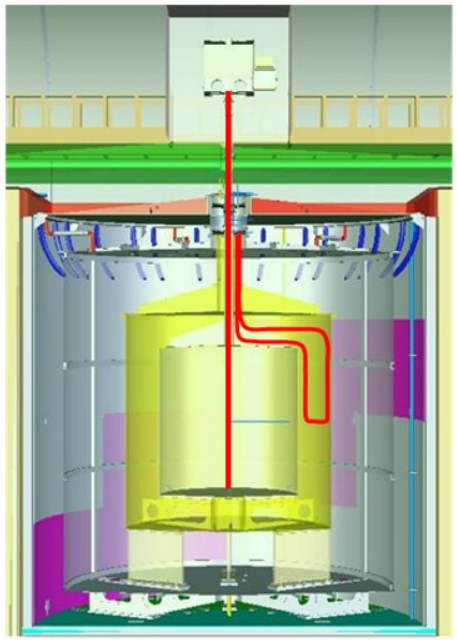
Fast neutron + stopping muon bckgr.

1 rate
nuis. par.

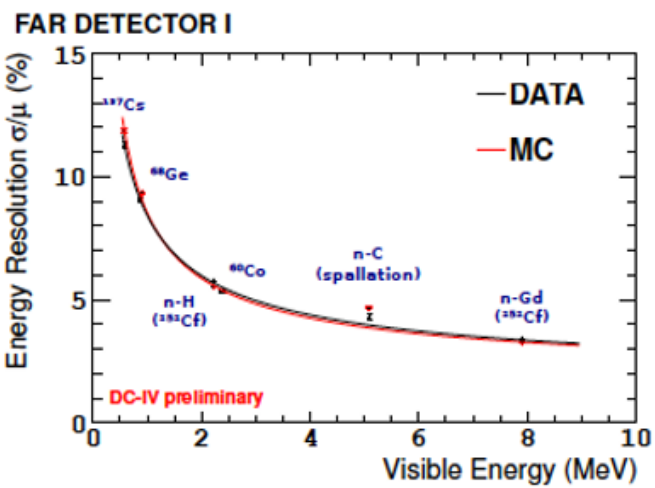


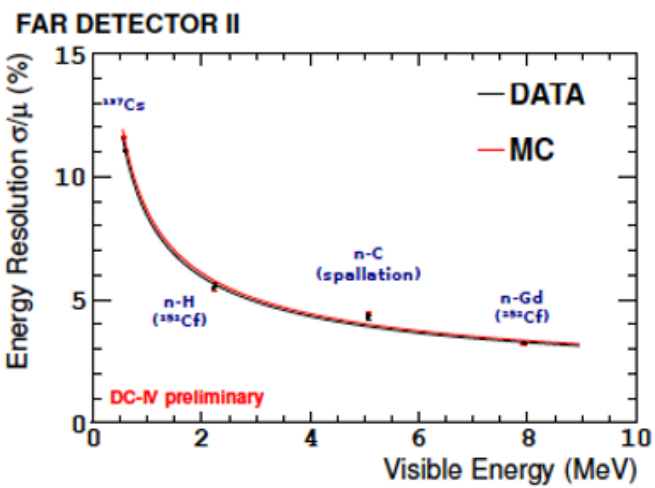

DC Sensitivity
$1\sigma \sin^2 2\theta_{13}$
0.020
0.018
0.016
0.014
0.012
0.010
0.008
0.006
0
2
4
6
8
10
Time since MD data-taking start (years)
DC-IV @ CERN Configuration
Improved Proton# Uncertainty
today's result
nominal running
(3years ND:FD)
a priori
unknown
improvement
(working)
PRELIMINARY
seminar@CERN

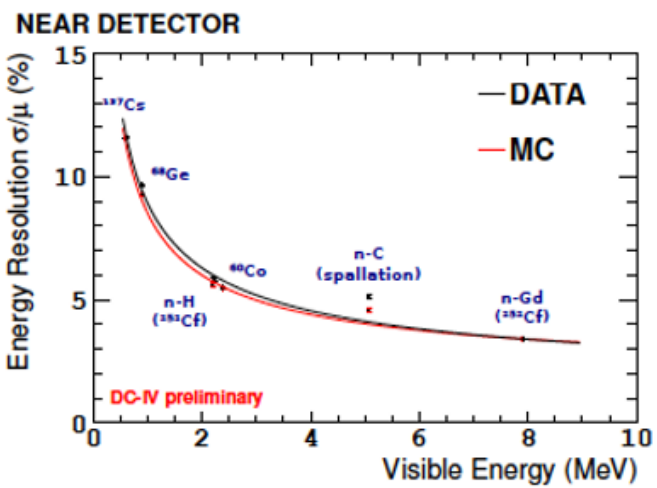
Calibration



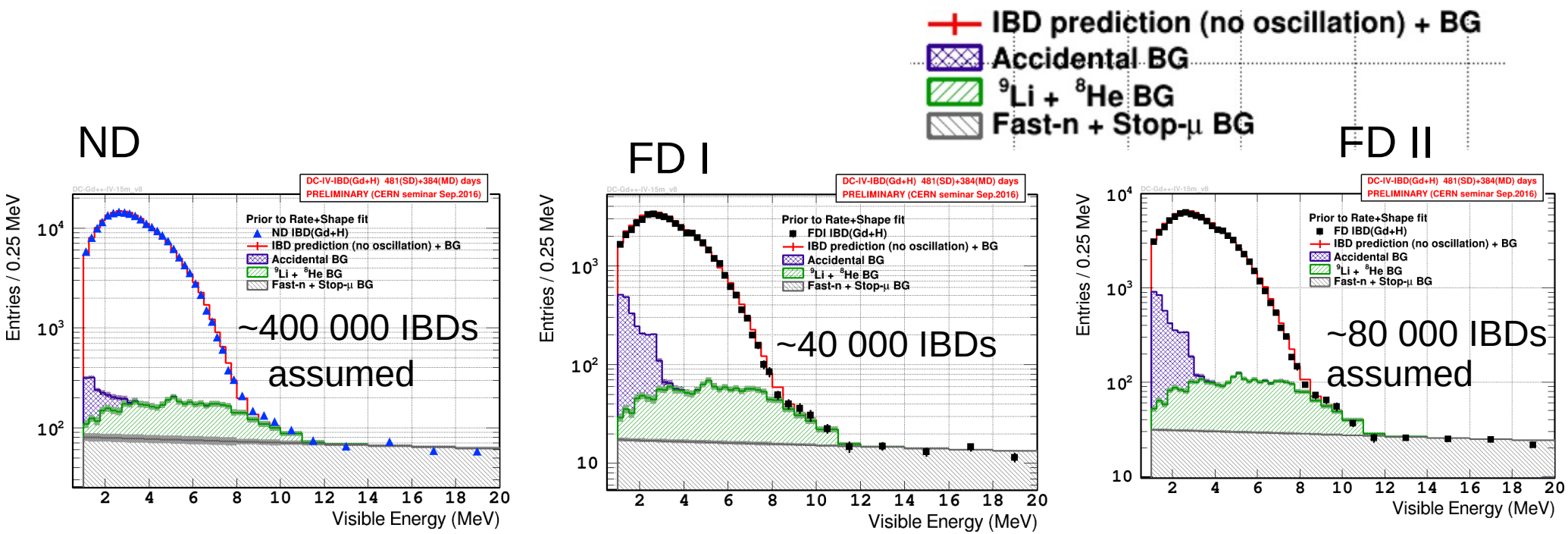
- two systems for calibration source deployment in the GC/ along the z-axis
- 252-Cf used as neutron source
- Characteristic energy deposit of n-Gd and n-H capture during source deploiment used to set energy scale
- Two light injection systems for regular monitoring of PMTs/scintillators







Gd++ Dataset



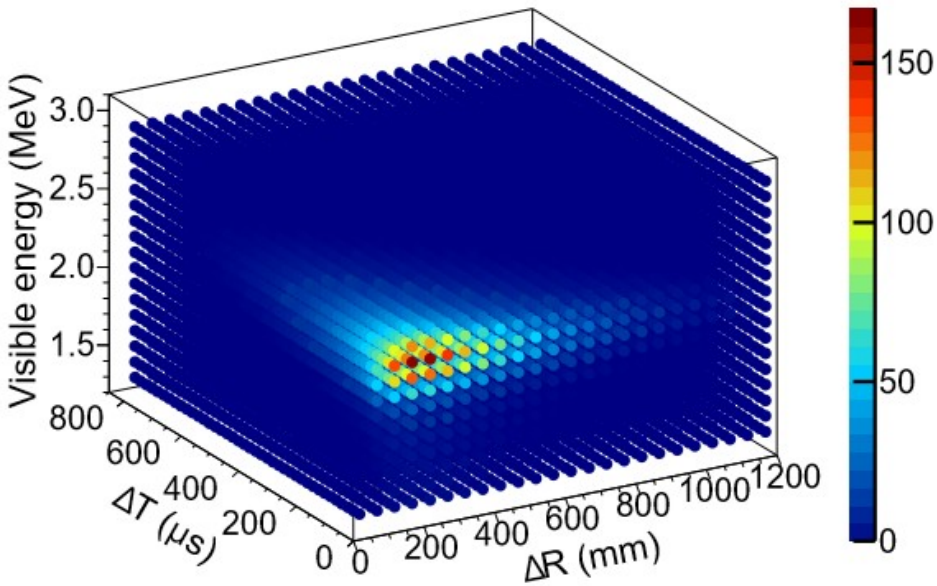
Gd ++ selection yields ~ 2.5 times more IBDs than Gd selection

- Accidental contamination at low energies (1 order of magnitude more than Gd)
- 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

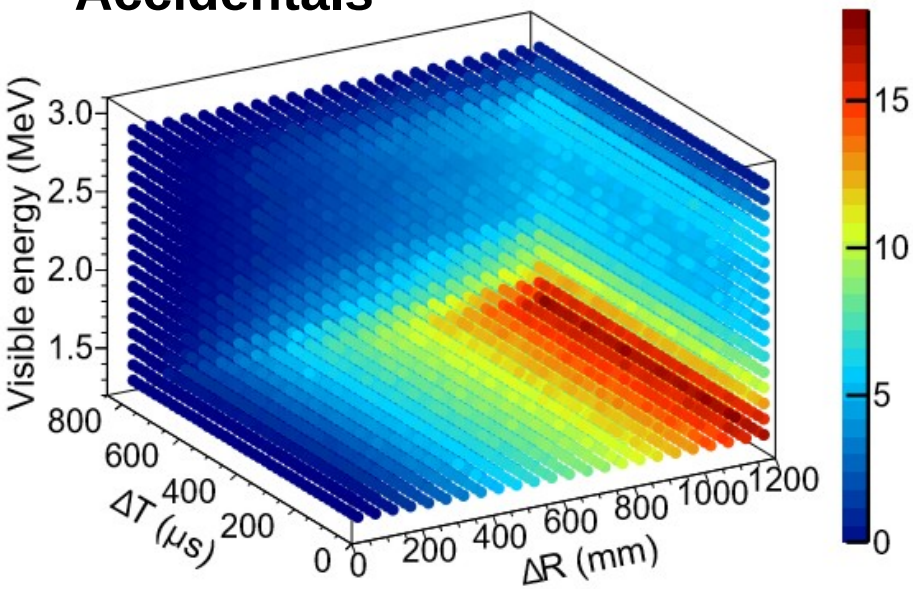
Accidental rejection

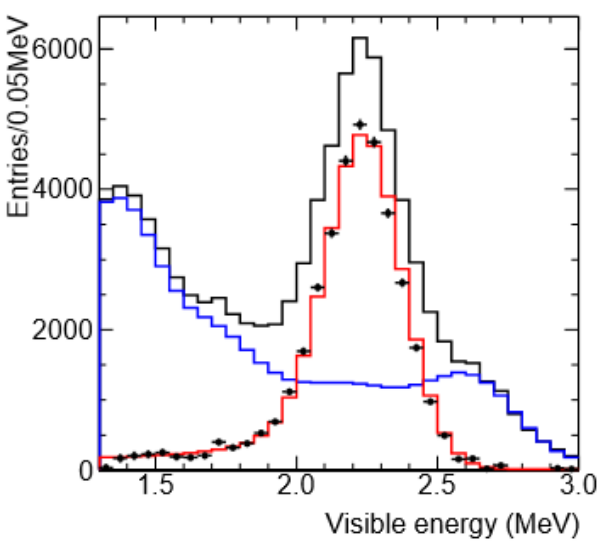
- Artificial neuronal network (ANN) using time and space difference and visible delayed energy => signal to background ratio increase > 7 on H data (arXiv:1510.08937)

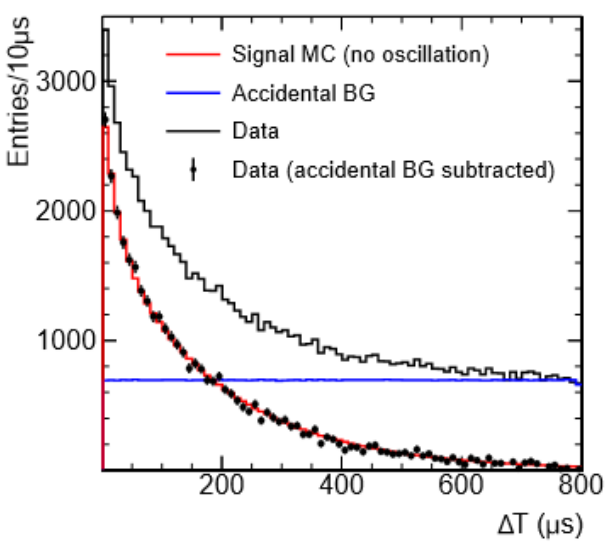
Neutrino IBD MC

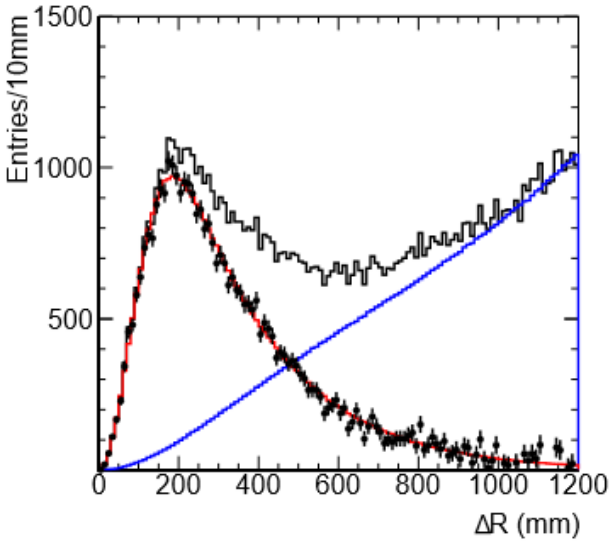


Accidentals

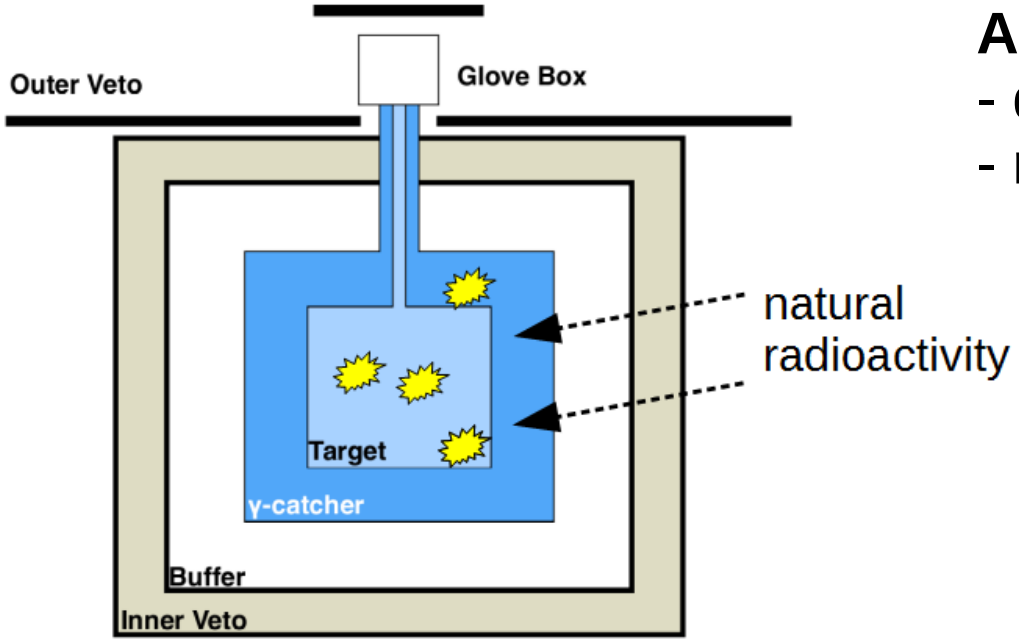




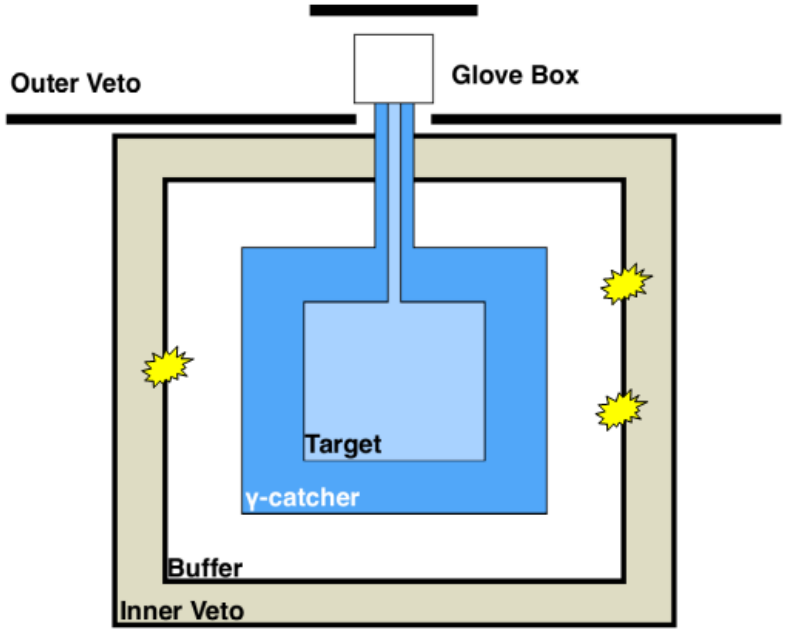




Uncorrelated Backgrounds

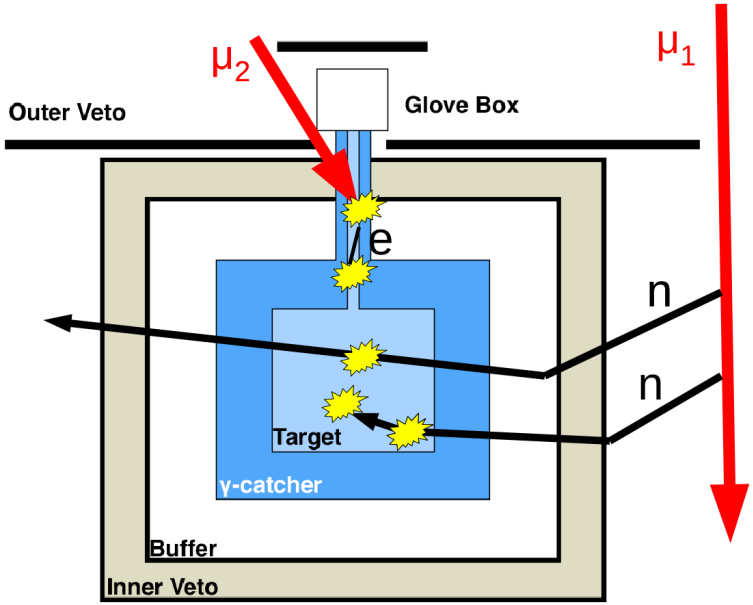


Accidentals
- due to natural radioactivity
- random coincidence



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

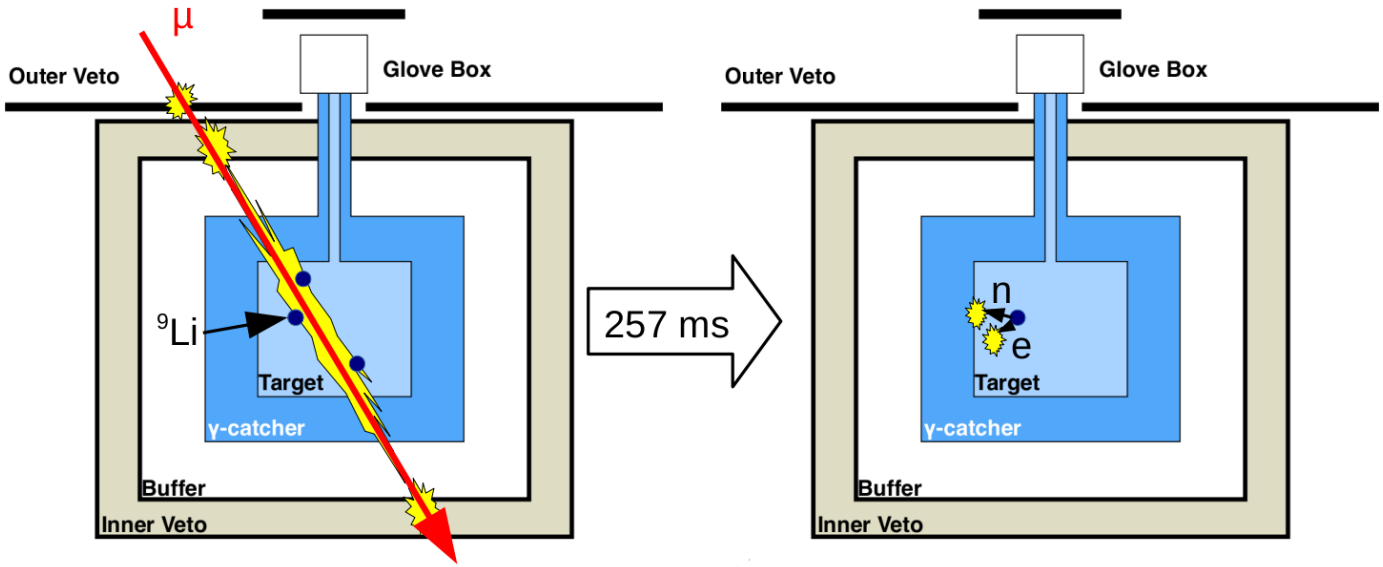
Muon induced Backgrounds



Crossing muon
- large energy deposit => efficiently rejected

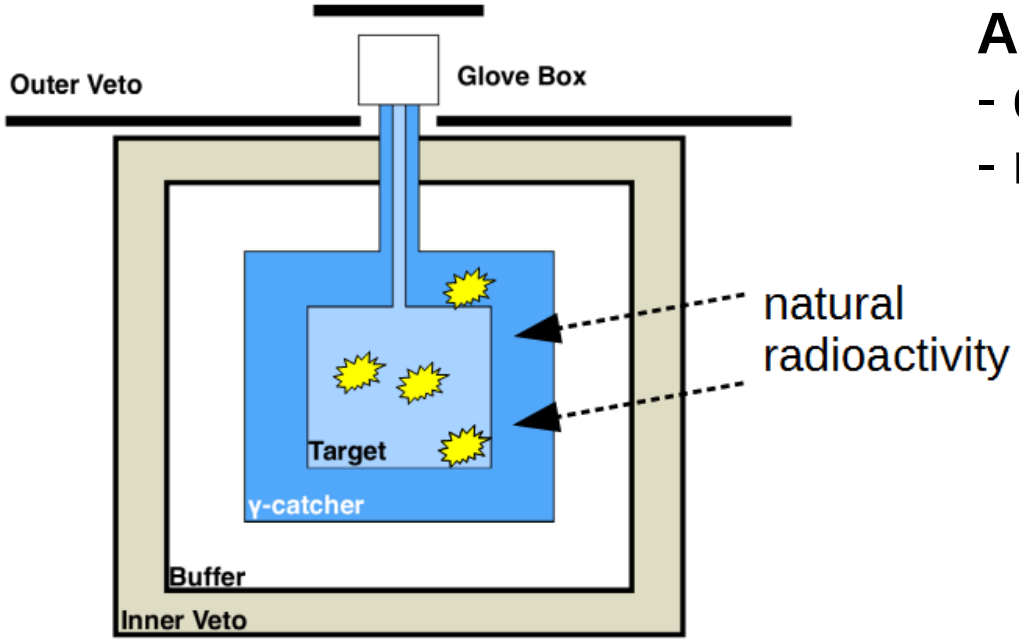
Fast neutrons (FN)
- induced by spallation due to atm. μ (cf. μ_1)
- protein recoil and n-capture may mimic IBD signal

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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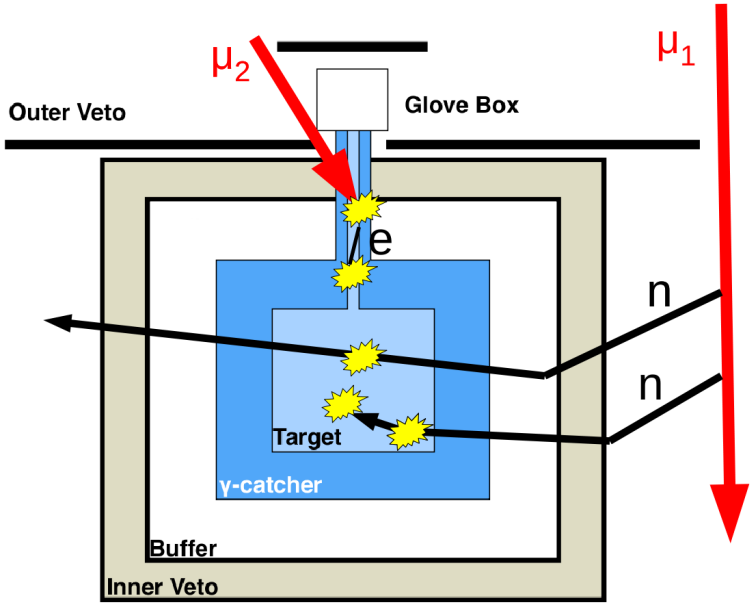

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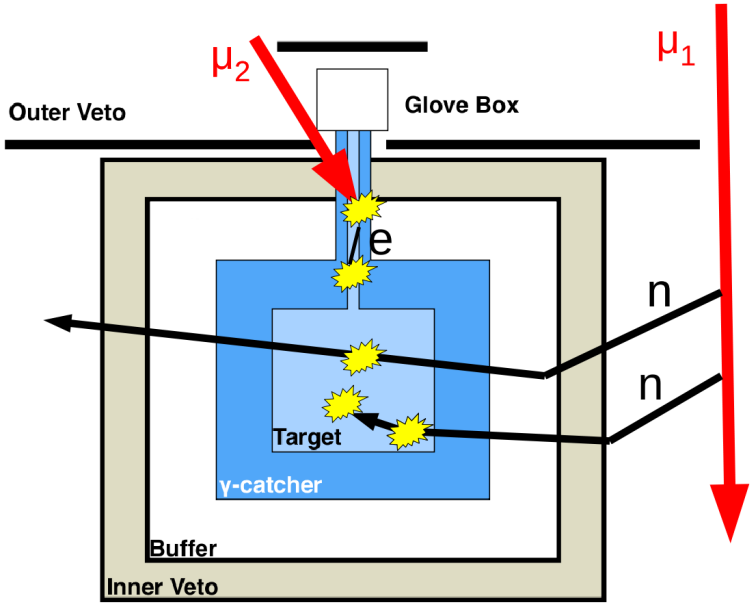

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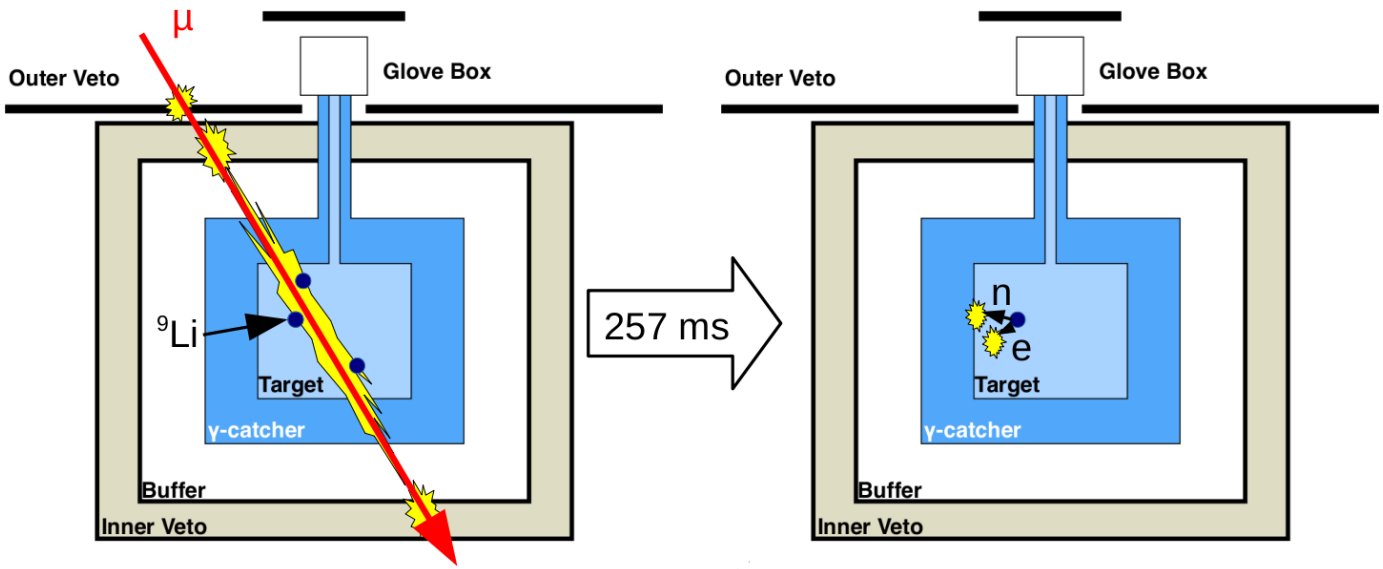

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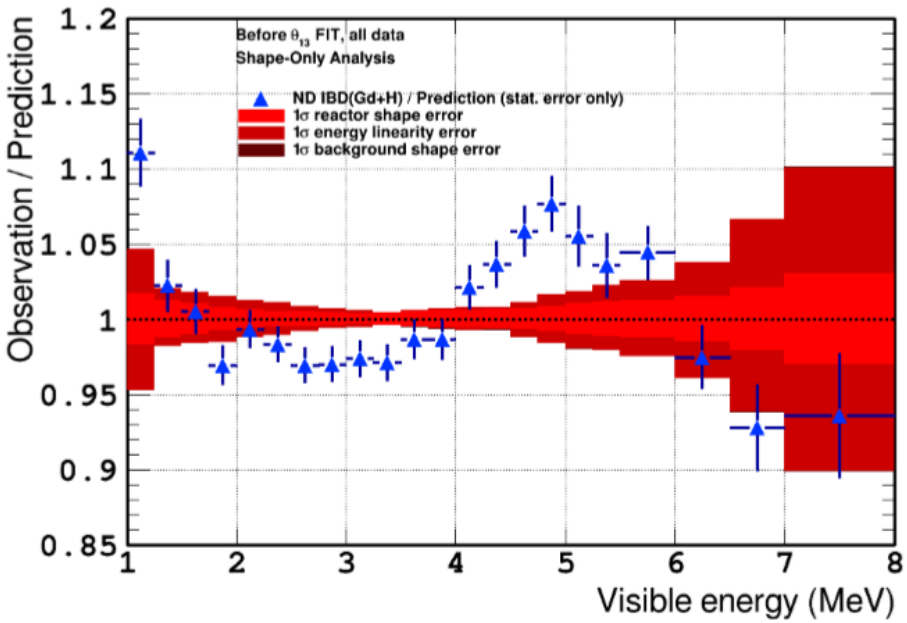
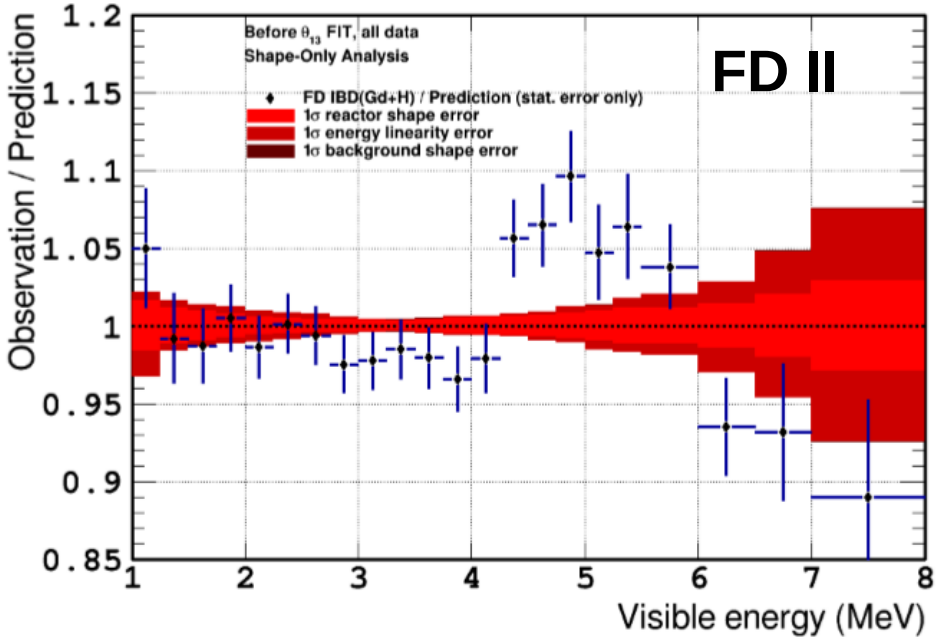
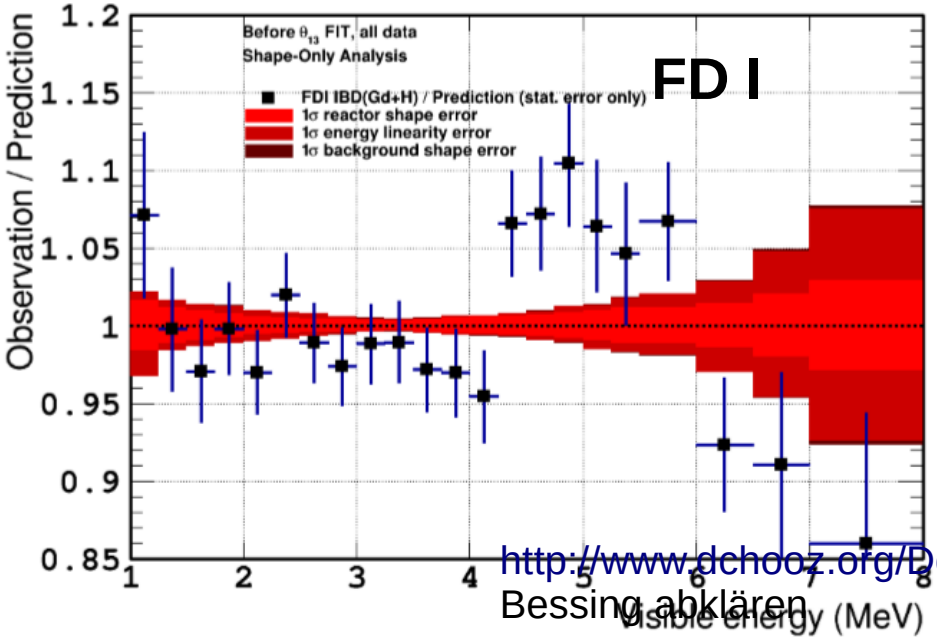
- electrons cannot be distinguished from positrons

Spectral distortion vs. baseline



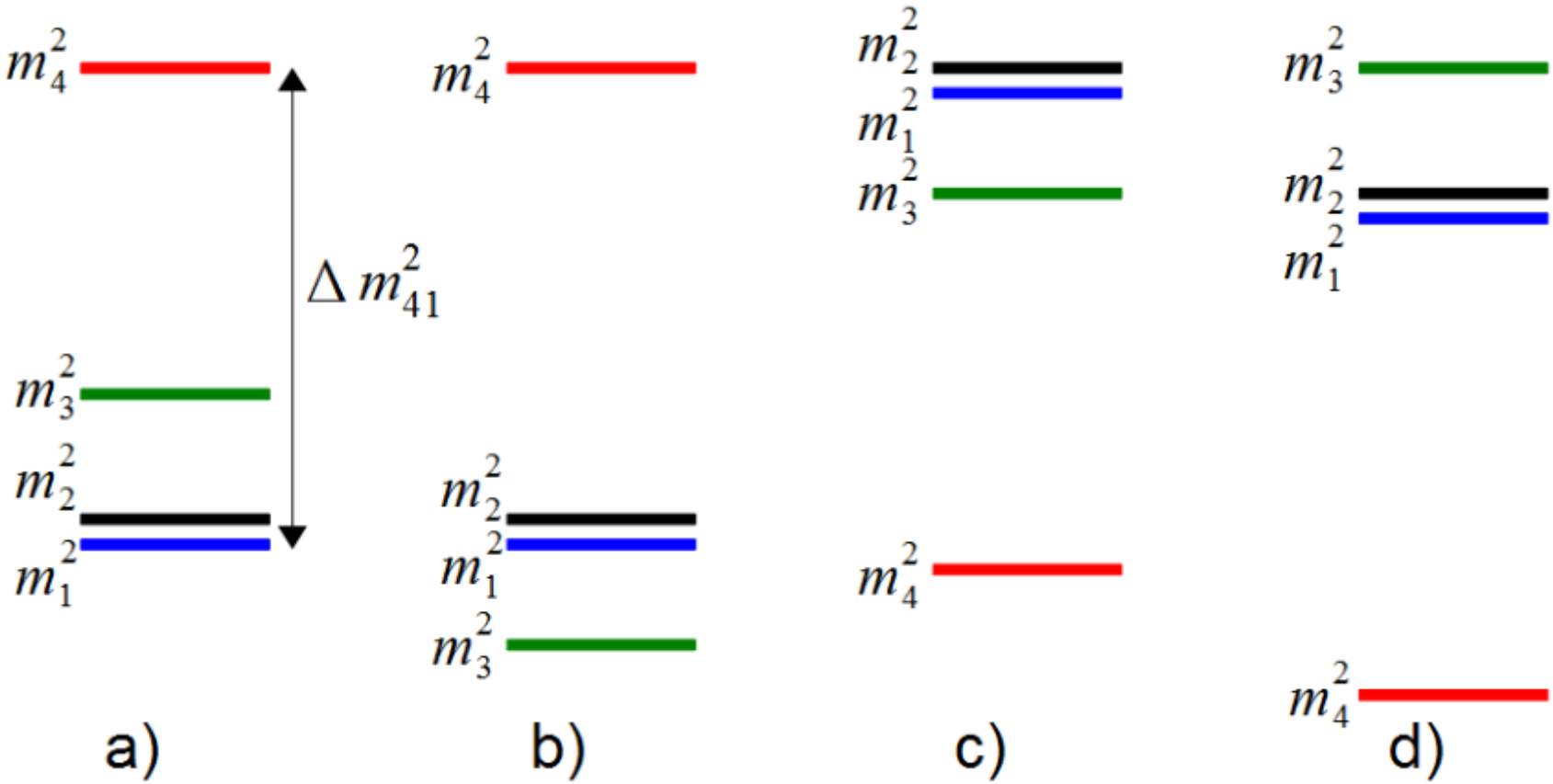




Spectral distortion observed in both detectors
=> very unlikely to be a sterile signature

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

Mass orderings



PMNS Matrix

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

$$\begin{aligned}
U_{e1} &= \cos\theta_{14}\cos\theta_{13}\cos\theta_{12} \\
U_{e2} &= \cos\theta_{14}\cos\theta_{13}\sin\theta_{12}\,; \\
U_{e3} &= \cos\theta_{14}\sin\theta_{13}\,, \\
U_{e4} &= \sin\theta_{14}\,,
\end{aligned}$$

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

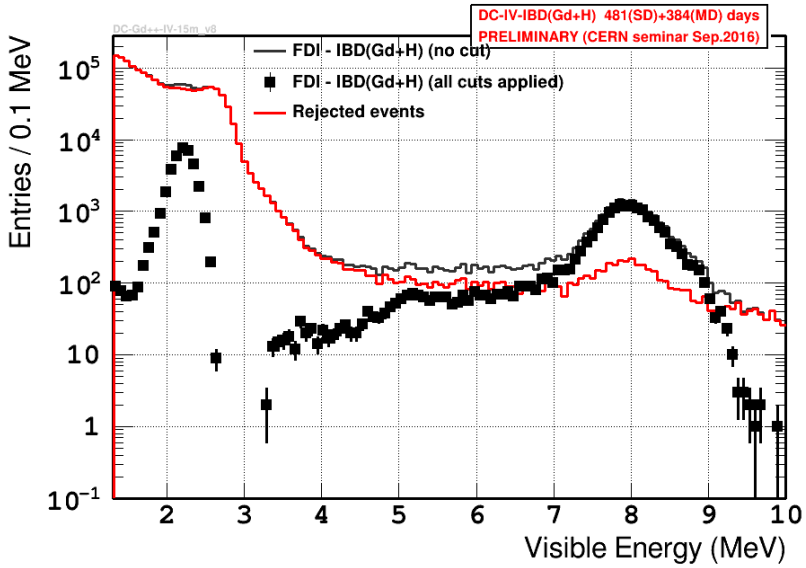
IBD selection

Single event selection

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

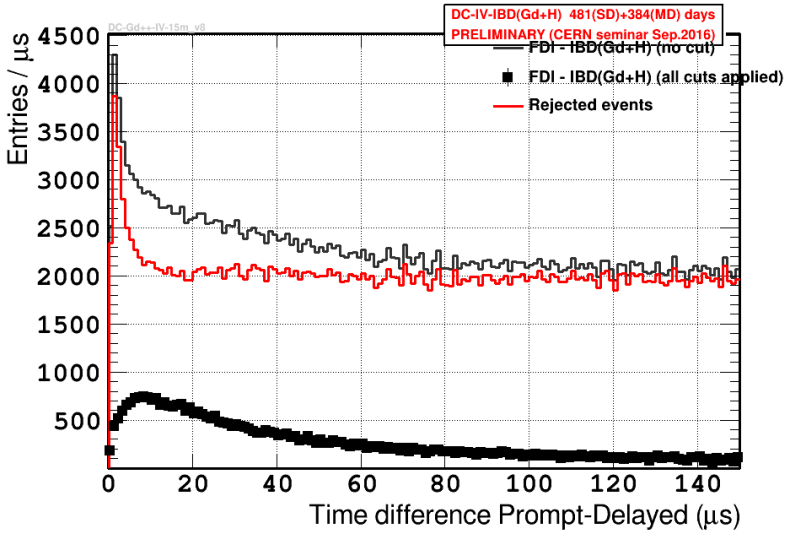
IBD prompt-delayed pair selection

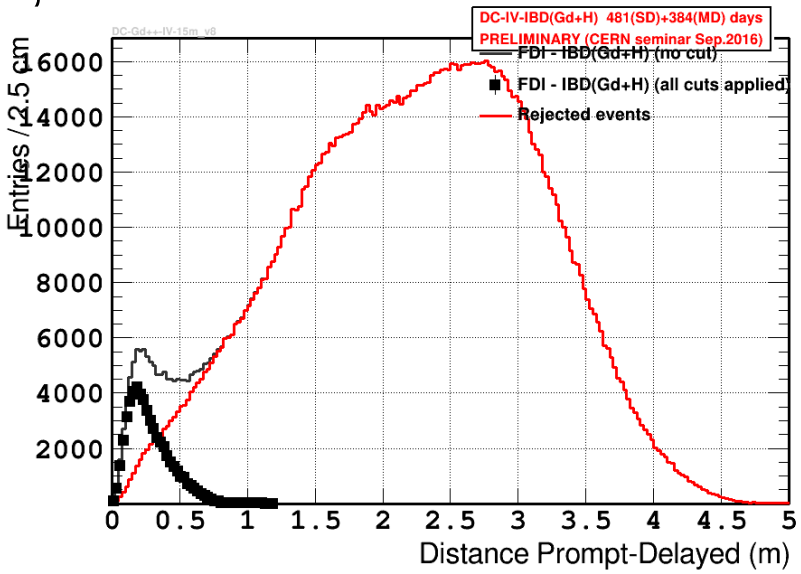
- E_{prompt} , $E_{delayed}$, ΔT, ΔR



Background rejection:

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





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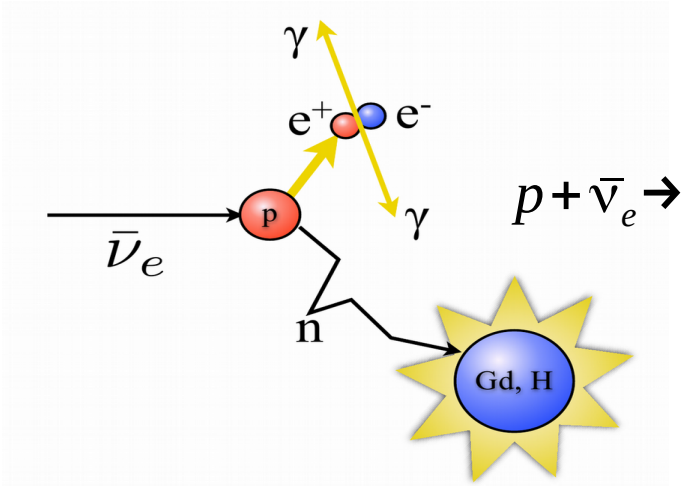
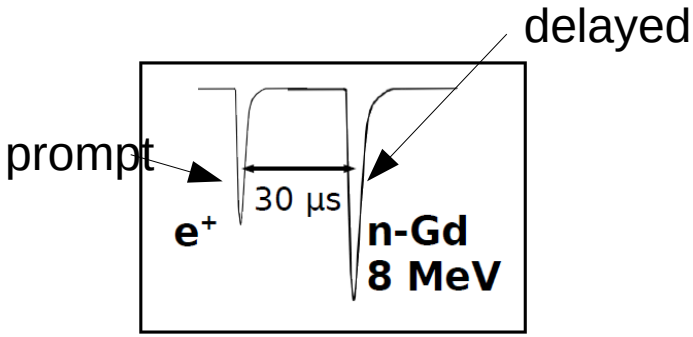
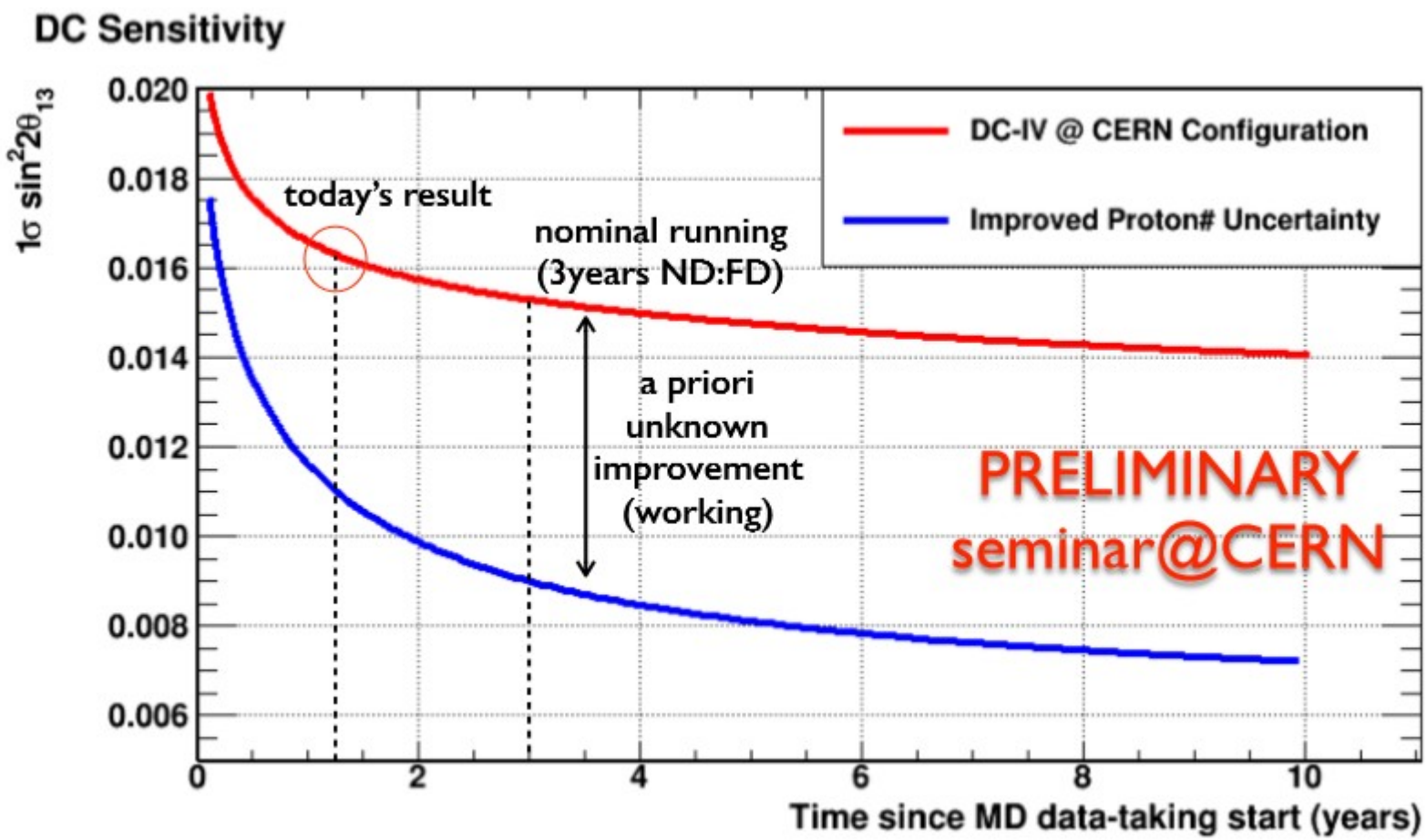
Inverse beta decay IBD



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




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

Full oscillation prob.

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

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

$$P_{ee} = 1 - c^4_{14} s^2_{12} \sin^2 2\theta_{13} \sin^2 \Delta_{32} - c^4_{14} c^2_{12} \sin^2 2\theta_{13} \sin^2 \Delta_{31} - c^4_{14} c^4_{13} \sin^2 2\theta_{12} \sin^2 \Delta_{12} \tag{1.7}$$

$$-s^2_{13} \sin^2 2\theta_{14} \sin^2 \Delta_{43} - c^2_{13} s^2_{12} \sin^2 2\theta_{14} \sin^2 \Delta_{42} - c^2_{13} c^2_{12} \sin^2 2\theta_{14} \sin^2 \Delta_{41} \tag{1.8}$$

Small anyway