Latest Results of the Double Chooz Experiment

Philipp Soldin

III. Physikalisches Institut B
RWTH Aachen University
Germany

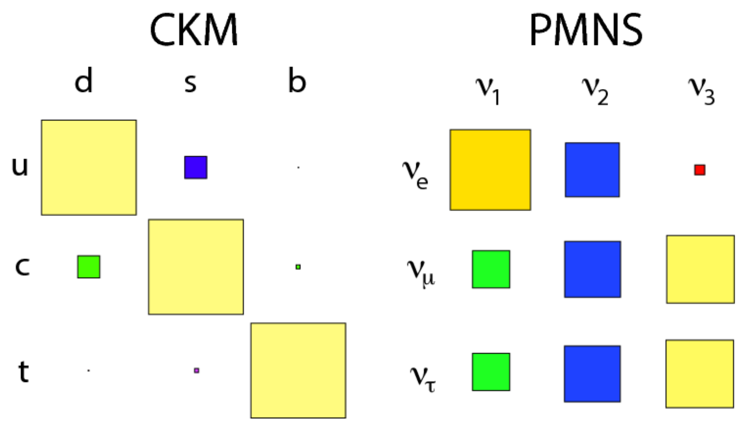
on behalf of the Double Chooz collaboration

CIPANP 2018 @ Palm Springs

May 30, 2018

Double Chooz wants to perform a precise measurement of the neutrino mixing angle θ_{13}

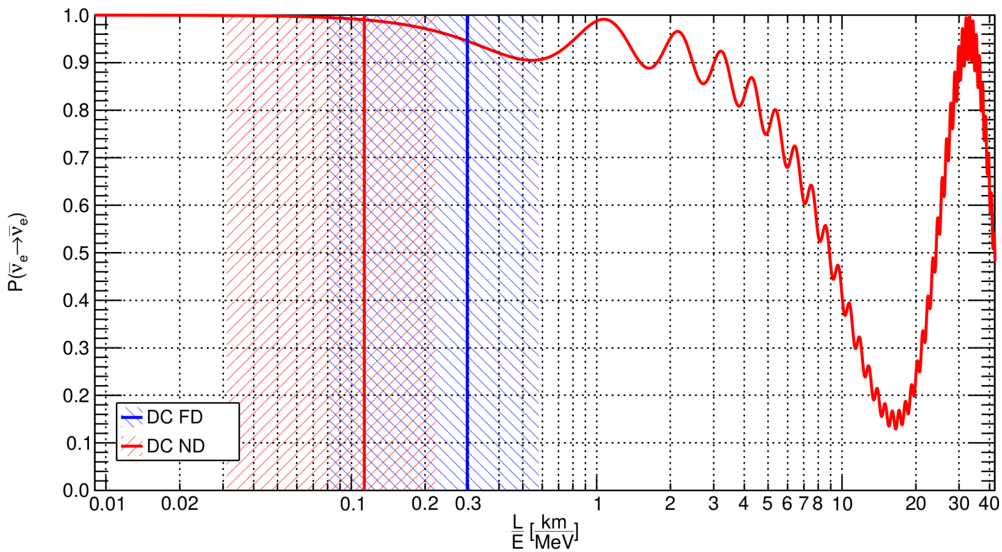
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \overbrace{\underbrace{\overbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}^{\substack{\text{atmospheric} \\ P(\nu_\mu\to\nu_\mu)}}}_{\theta_{23}\sim45^\circ} \underbrace{\overbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix}}^{\substack{\text{reactor \& accelerator} \\ P(\nu_e\to\nu_e)\,\&\,P(\nu_\mu\to\nu_e)}}}_{\theta_{13}\,\&\,\delta_{\mathrm{CP}}} \underbrace{\overbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}^{\substack{\text{solar} \\ P(\nu_e\to\nu_x)}}}_{\theta_{12}\sim33^\circ}}^{U_{\mathrm{PMNS}}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



Double Chooz wants to perform a precise measurement of the neutrino mixing angle θ_{13}

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

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



Two flavour oscillation formula is valid at $L \sim 1$ km

Double Chooz collaboration

Brazil	France	Germany	Japan	Russia	Spain	USA
CBPF UNICAMP	APC (IN2P3) CEA/IRFU: SPP SPhN SEDI SIS SENAC CENBG (IN2P3) LNCA (IN2P3/CEA) Subatech (IN2P3)	EKU Tübingen MPIK Heidelberg RWTH Aachen TU München	Tohoku U. Tokyo Inst. Tech. Tokyo Metro. U. Tokyo U. Science Kitasato U. Kobe U.	INR RAS RRC Kurchatov	CIEMAT-Madrid	Alabama U. ANL Chicago U. Drexel U. Hawaii U. Notre Dame U. Virginia Tech.

Spokesperson:
A. Cabrera (IN2P3/CNRS)

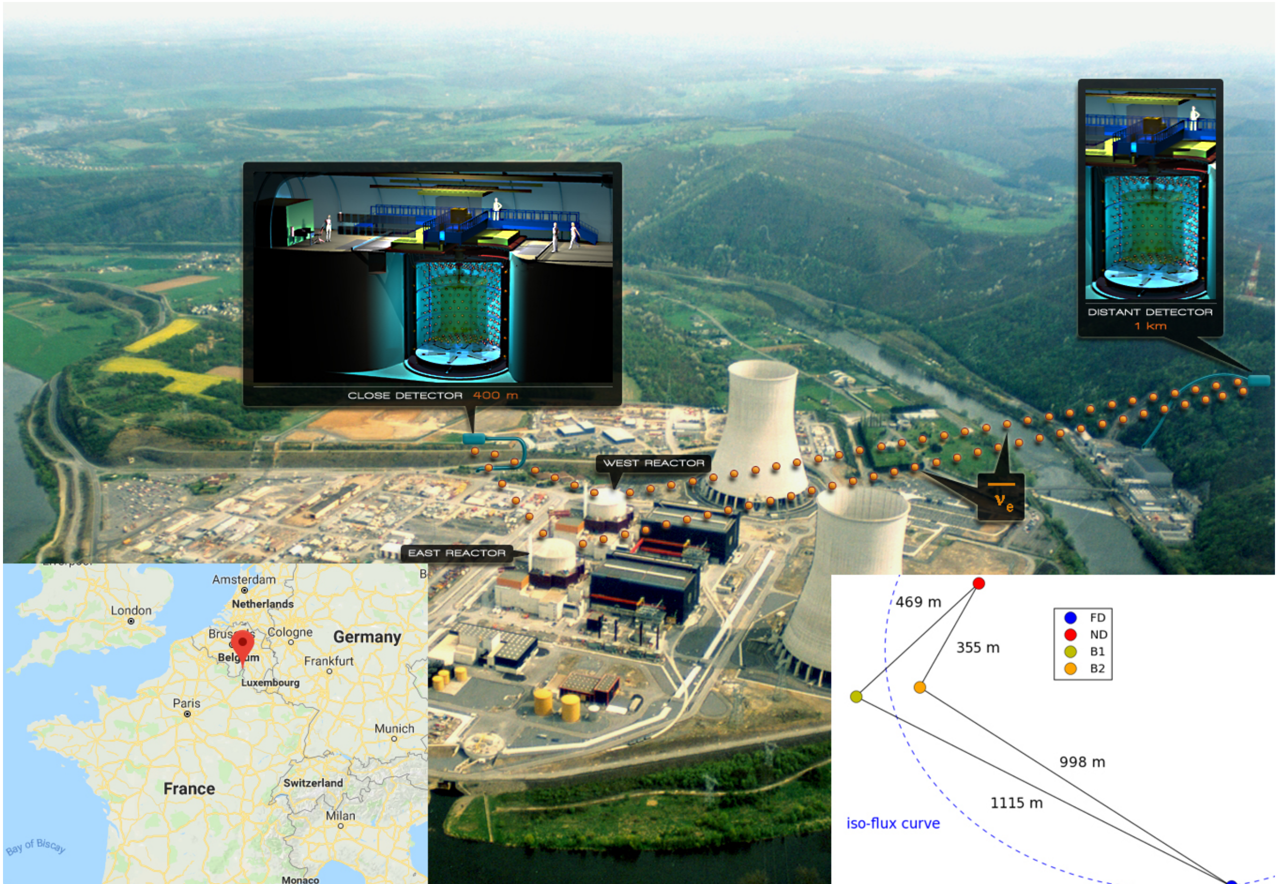
Project Manager:
Ch. Veyssière (CEA)

97 scientists 25 institutions (Americas, Asia, Europe)

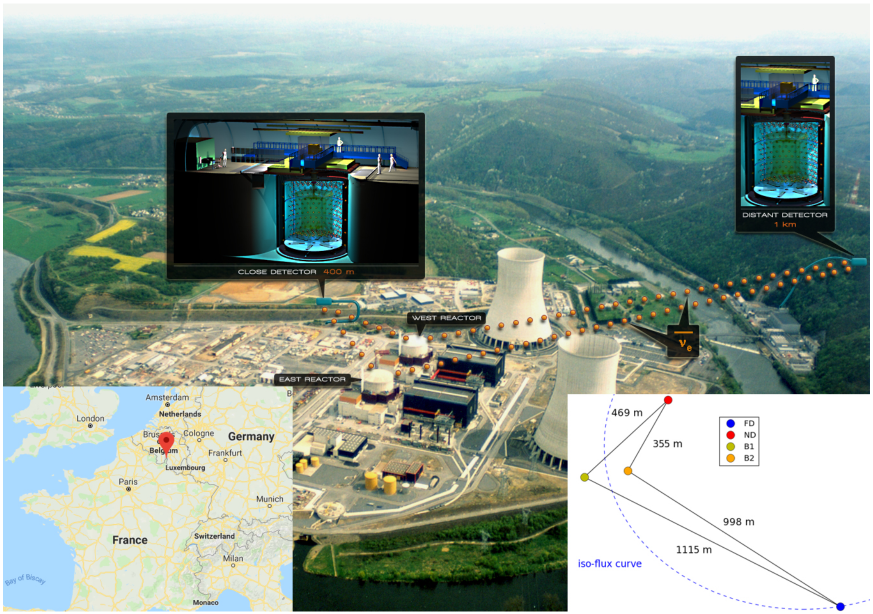
doublechooz.in2p3.fr

Detector Setup in Chooz

Detector Setup in Chooz

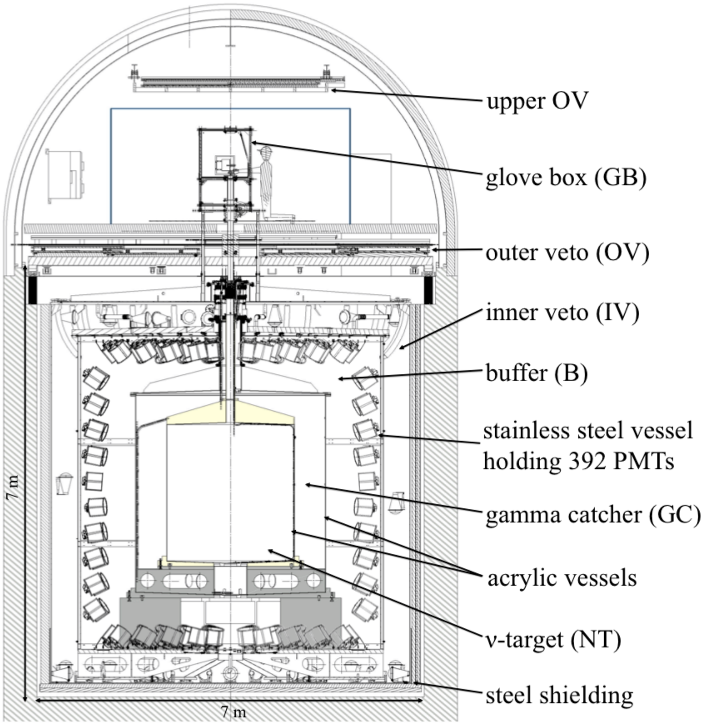


Detector Setup in Chooz

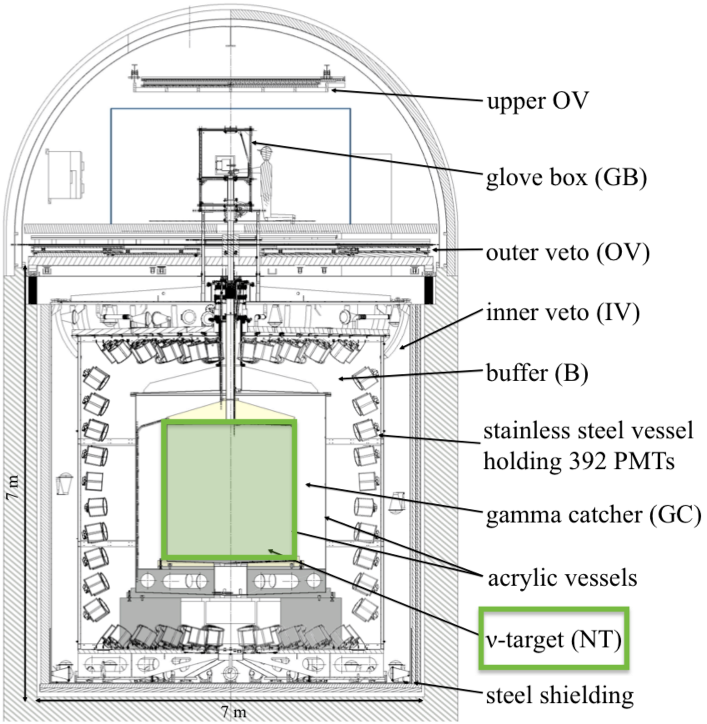


- Two reactor cores with a thermal output of 4.27 GW
- Near detector with a baseline of $\sim 400\,\text{m}$
- Far detector with a baseline of $\sim 1\,\text{km}$
- Near detector was installed in 2015
- Far detector only dataset is referred to as FD-1, past sets are called FD-2 and ND

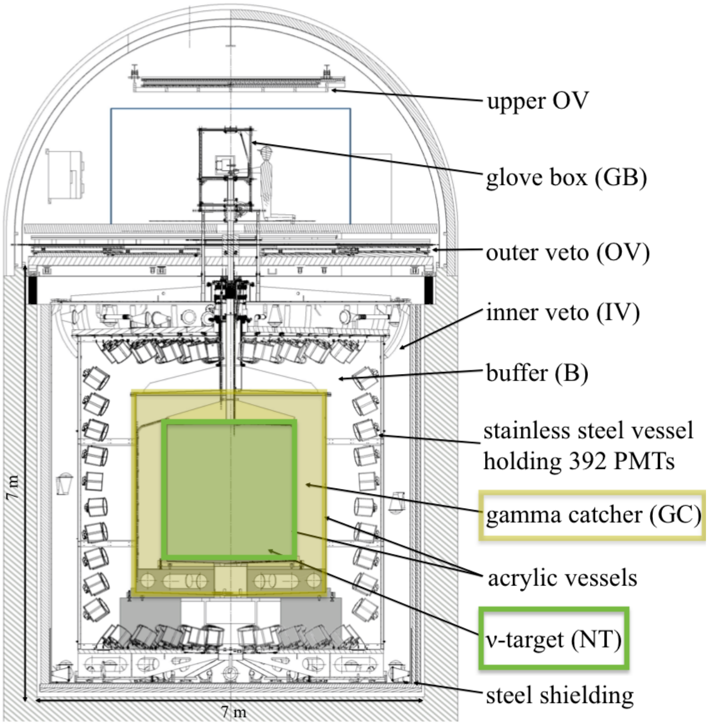
Detector Setup in Chooz



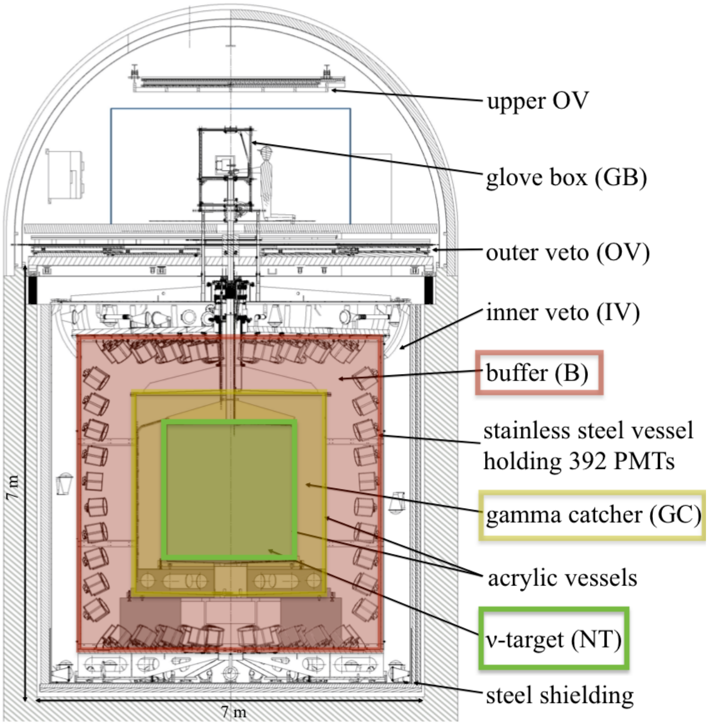
- Detector is build up like an onion or Russian doll



- Detector is build up like an onion or Russian doll
- **Neutrino Target (NT)**
  - $1\,\mathrm{g\,l^{-1}}$ Gd loaded LS ($10\,\mathrm{m^3}$)

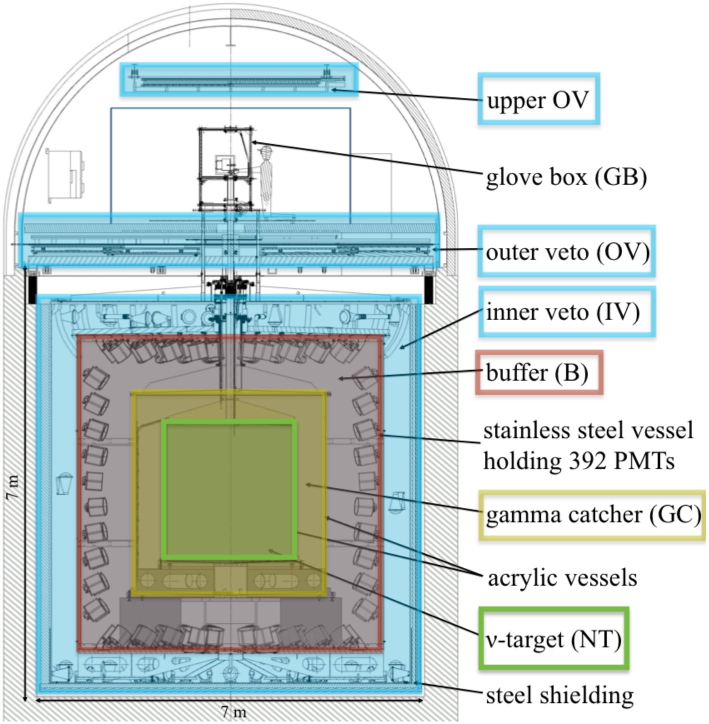


- Detector is build up like an onion or Russian doll
- **Neutrino Target (NT)**
  - $1\,\mathrm{g\,l^{-1}}$ Gd loaded LS ($10\,\mathrm{m}^3$)
- **Gamma Catcher**
  - Unloaded LS ($22\,\mathrm{m}^3$)
  - Measures γs escaping the NT



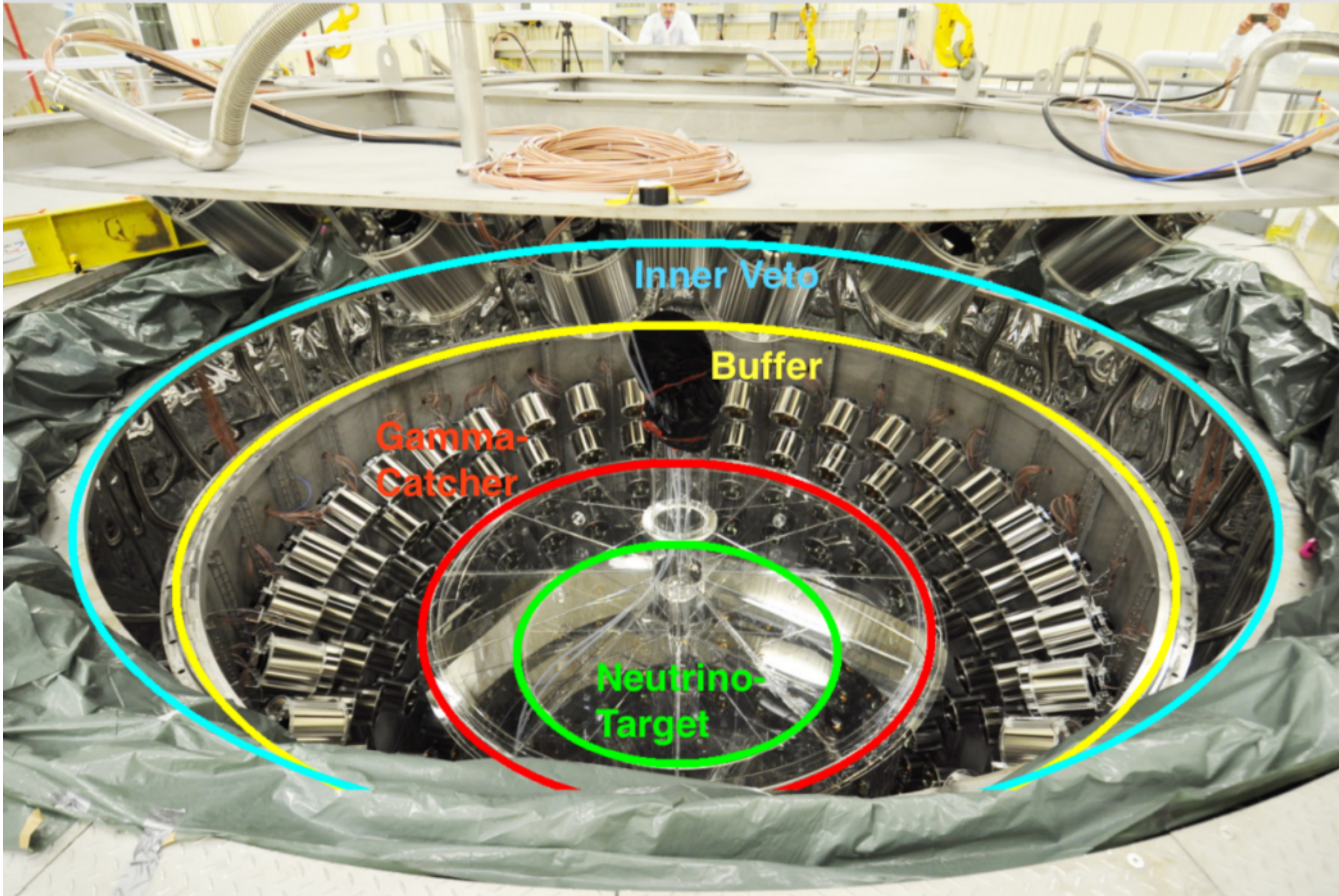
- Detector is build up like an onion or Russian doll
- **Neutrino Target (NT)**
  - $1\,\mathrm{g\,l^{-1}}$ Gd loaded LS ($10\,\mathrm{m^3}$)
- **Gamma Catcher**
  - Unloaded LS ($22\,\mathrm{m^3}$)
  - Measures γs escaping the NT
- **Buffer**
  - Non-scintillating mineral oil ($110\,\mathrm{m^3}$)
  - 390 10“ PMTs

Detector Setup in Chooz



- Detector is build up like an onion or Russian doll
- **Neutrino Target (NT)**
  - $1\,\mathrm{g\,l^{-1}}$ Gd loaded LS ($10\,\mathrm{m}^3$)
- **Gamma Catcher**
  - Unloaded LS ($22\,\mathrm{m}^3$)
  - Measures γs escaping the NT
- **Buffer**
  - Non-scintillating mineral oil ($110\,\mathrm{m}^3$)
  - 390 10" PMTs
- **Inner Veto**
  - Shielded $90\,\mathrm{m}^3$ LS with 78 8" PMTs for atm. μ and neutron veto
- **Outer Veto**
  - Plastic scintillators to veto atm. μ

Detector Setup in Chooz

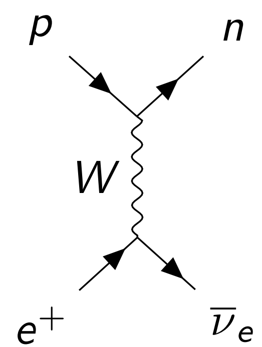


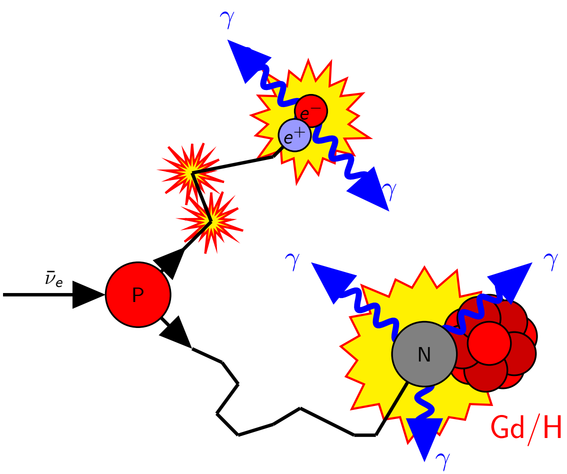
Inverse Beta Decay Signature

- Neutrinos are detected via the signature of the **I**nverse **B**eta **D**ecay (**IBD**)

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

- This signature consists of a prompt positron annihilation signal and a delayed neutron capture signal
- The neutron can be captured by Gadolinium (8 MeV, ν-Target) or Hydrogen (2.2 MeV, γ-Catcher)



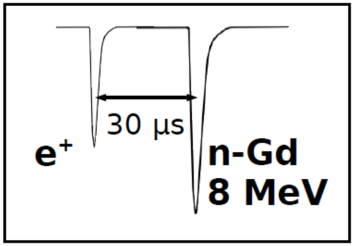


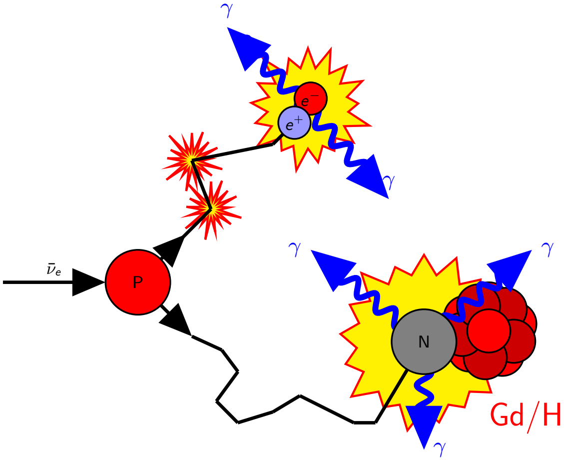
- Neutrinos are detected via the signature of the **I**nverse **B**eta **D**ecay (**IBD**)

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

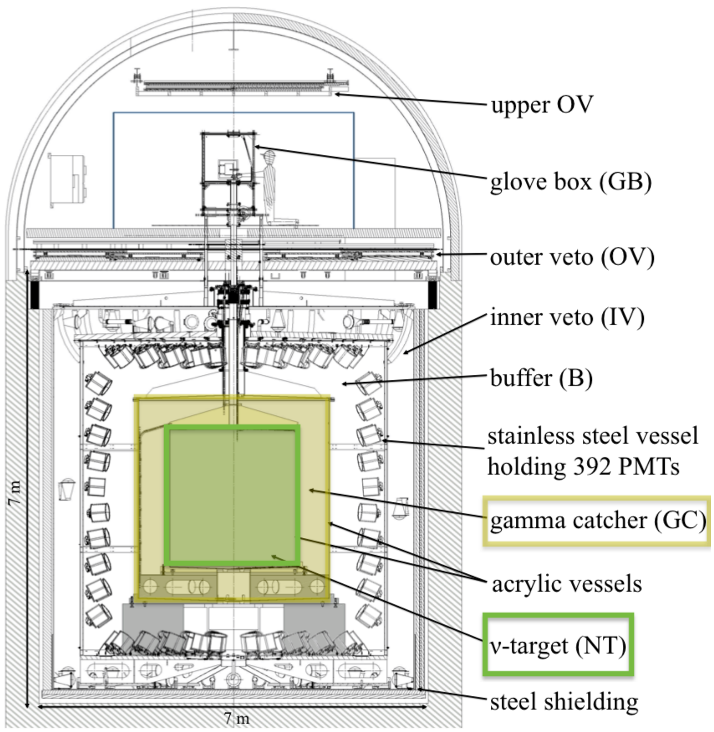
- This signature consists of a prompt positron annihilation signal and a delayed neutron capture signal
- The neutron can be captured by Gadolinium (8 MeV, ν-Target) or Hydrogen (2.2 MeV, γ-Catcher)

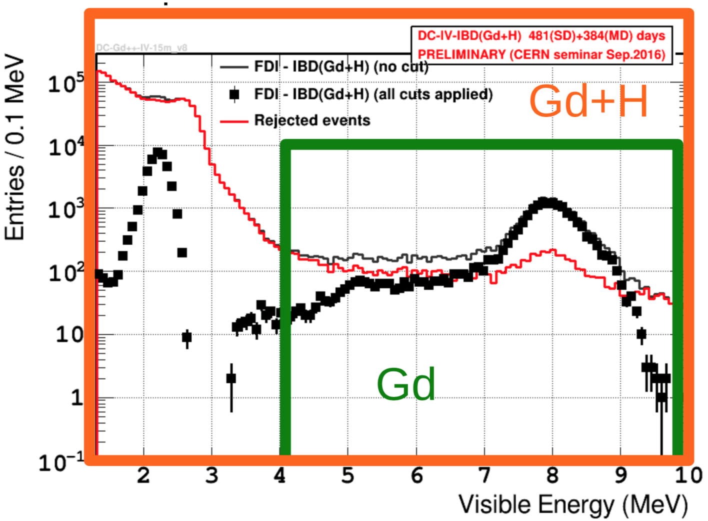
Time difference between prompt and delayed signal





IBD Selection

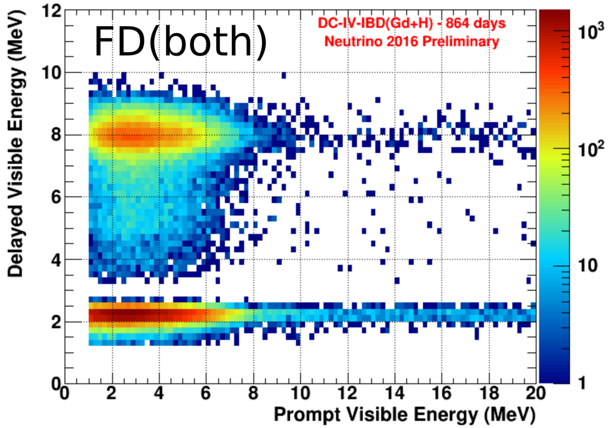




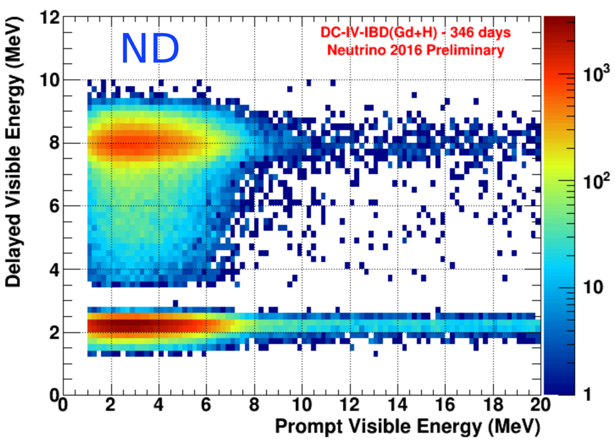
- Selecting n-Gd **and** n-H capture in Neutrino Target **and** Gamma Catcher
- Statistics increased by a factor of about 2.5
- Immune to liquid exchange between ND Neutrino Target and Gamma Catcher
- $\sim 30\,$t target (largest single θ_{13} detector target)

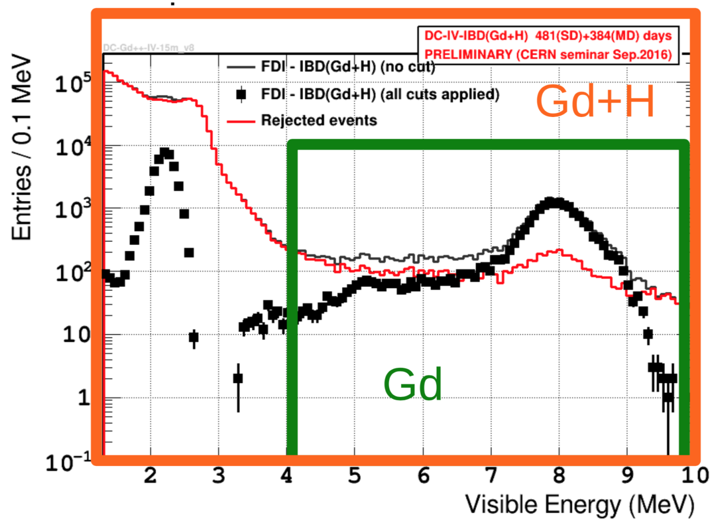
IBD Selection

Far Detector



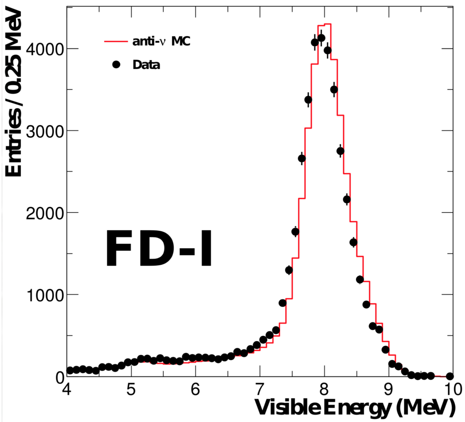
Near Detector



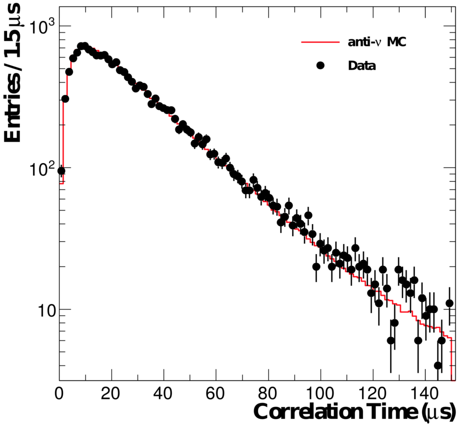


- Selecting n-Gd **and** n-H capture in Neutrino Target **and** Gamma Catcher
- Statistics increased by a factor of about 2.5
- Immune to liquid exchange between ND Neutrino Target and Gamma Catcher
- $\sim 30\,\mathrm{t}$ target (largest single θ_{13} detector target)

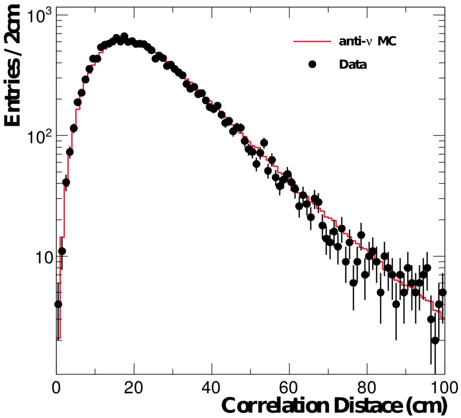
Delayed signal energy
$4 < E_{vis} < 10\,\mathrm{MeV}$



Correlated time
$0.5 < \Delta T < 150\,\mu s$



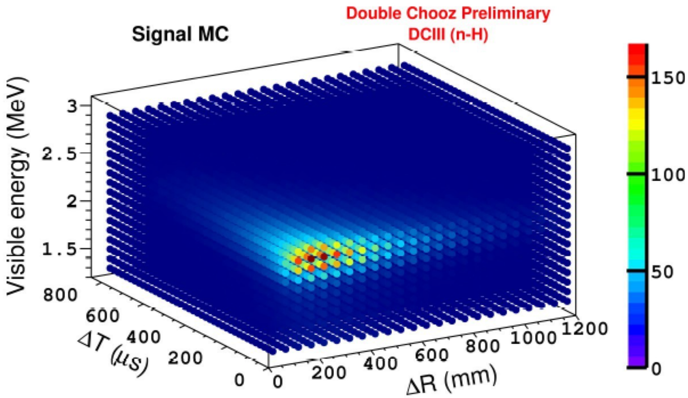
Correlation distance
$\Delta R < 100\,\mathrm{cm}$



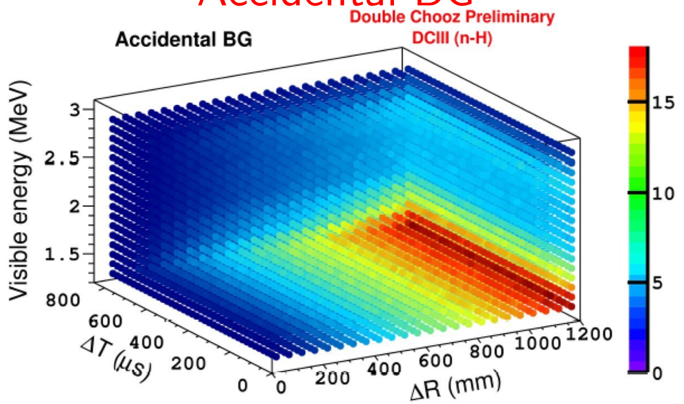
Remaining background for prompt and delayed events

- Cosmogenic β-n emitter: $^{9}\mathrm{Li} \rightarrow \alpha + \alpha + e + \nu + n$
- Fast neutron: $n + p \rightarrow p + n$
- Stopping μ: $\mu + e + \nu + \nu$
- Accidental coincidence: e.g. γ + spallation n

IBD-Signal



Accidental BG

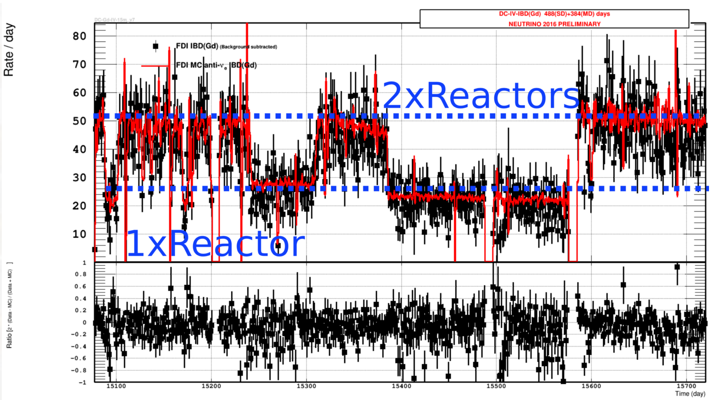


- Accidental background is dominant
- IBD selection through **A**rtificial **N**eural **N**etwork (ANN)
- ANN cut is based on three uncorrelated variables ΔR, ΔT and E of delayed event

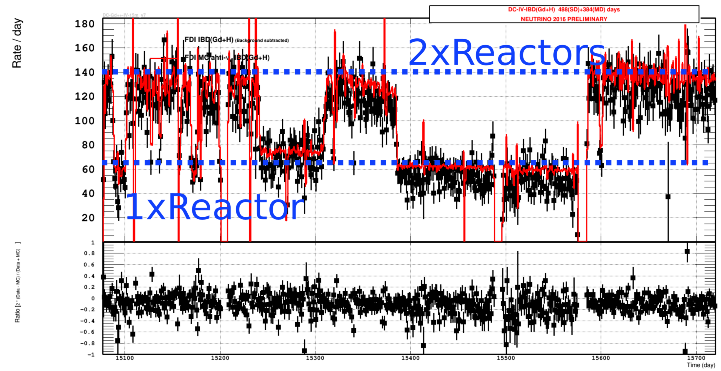
E_{prompt}	$1 - 20$ MeV
E_{delayed}	$1.3 - 10$ MeV
Δt	$0.5 - 800$ μs
ΔR	< 1.2 m
Isolation window (prompt)	$[-800, +900]$ μs
Δt after muon	> 1250 μs

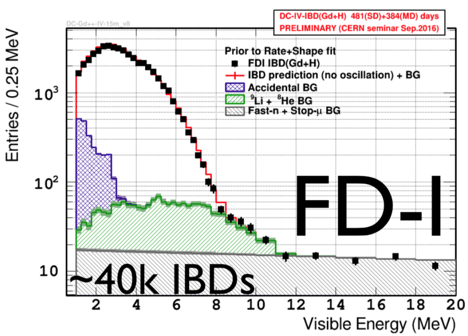
- **More** than a factor of 10 reduction of accidental background

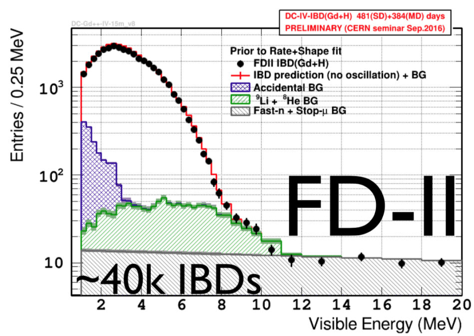
IBD (Gd) $\sim 50\,\mathrm{d}^{-1}$ with $\sigma^{\mathrm{stat}} = 0.56\,\%$

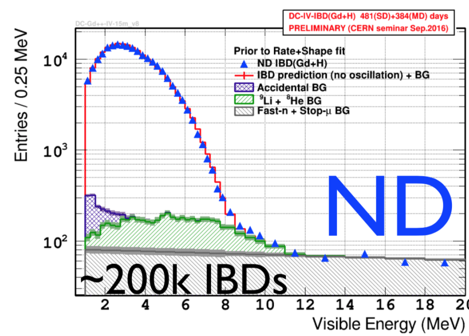


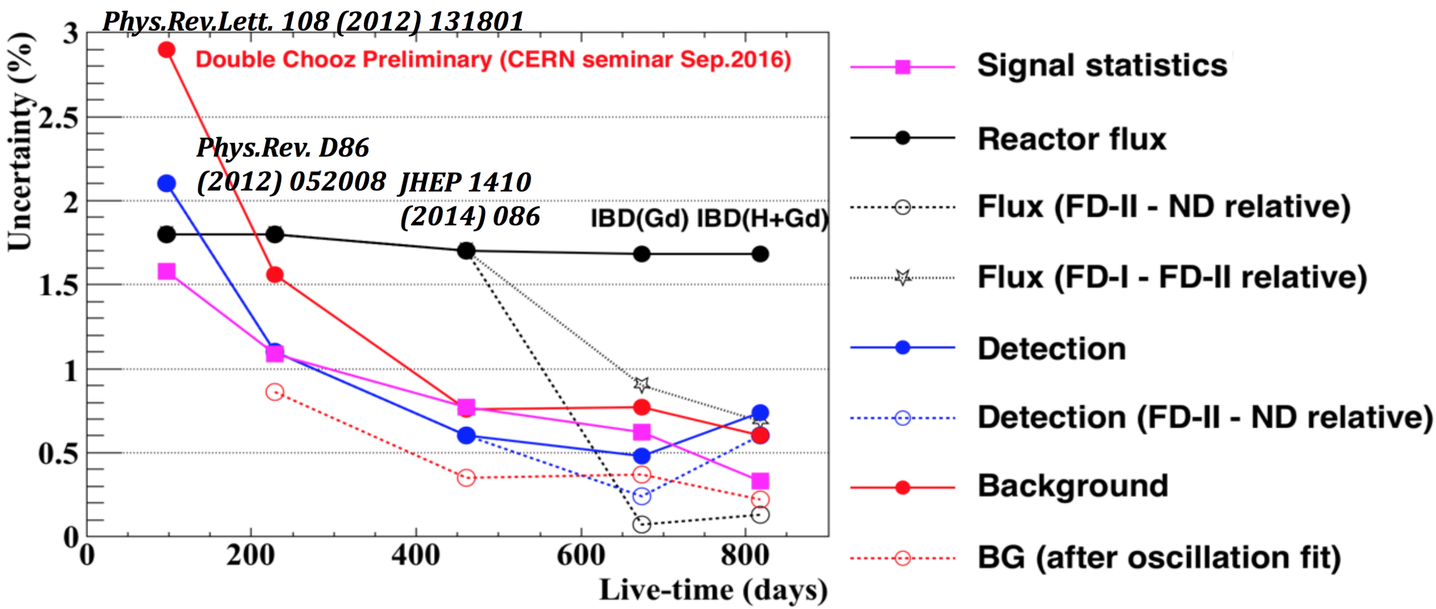
IBD (Gd+H) $\sim 140\,\mathrm{d}^{-1}$ with $\sigma^{\mathrm{stat}} = 0.35\,\%$



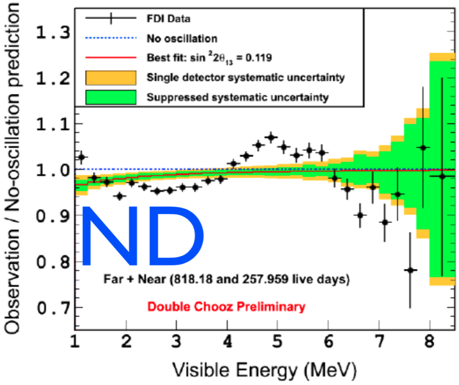


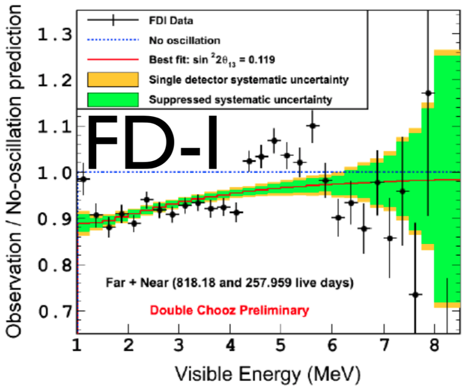


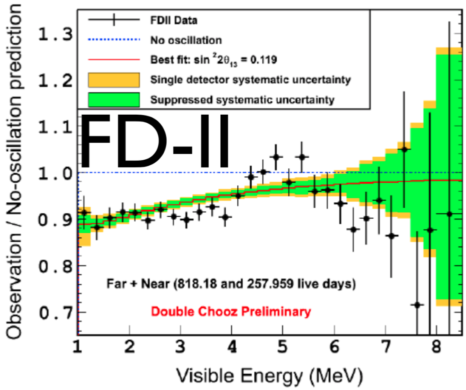




- Detection error due to uncertainty of the proton number in GC, limited sensitivity in Gd+H
  - Full volume: 0.53 %(uncorrolated) / 0.76 % (total)
  - Neutrino Target: 0.1 %(uncorrolated) / 0.3 % (total)
- The background (^{9}Li) rate is not used for the rate + shape fit (constrained in the fit)



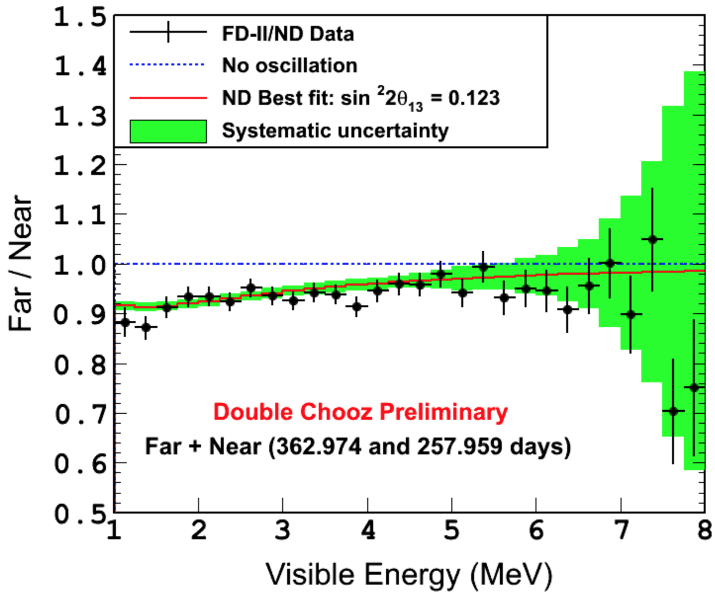




$$\sin^2(2\theta_{13})^{R+S} = 0.119 \pm 0.016$$

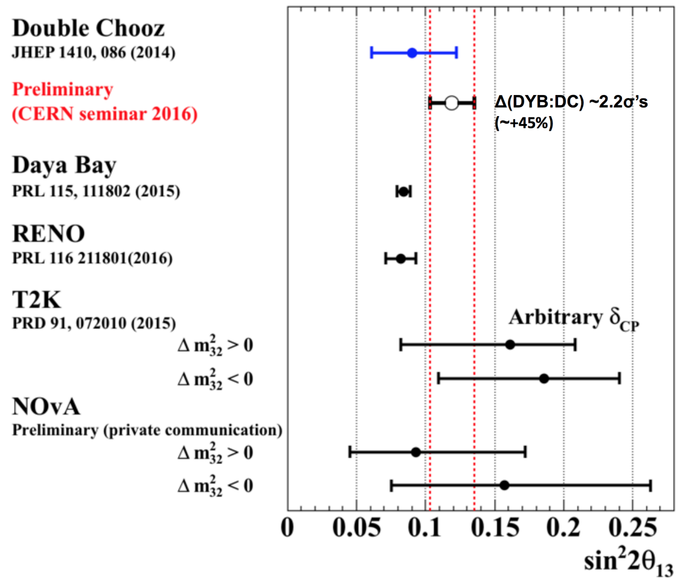
with $\chi^2/\text{ndf} = 236.2/114$ and marginalised over $\left(\Delta m^2 = (2.44 \pm 0.09)\,\text{eV}^2\right)$[1]

[1] Park et al. **arXiv**:1601.07464



- Ratio of FD-2:ND data not affected by distortion at [4,6] MeV (cancels out)
- $\sin^2(2\theta_{13}) = 0.123 \pm 0.023$
    - $\chi^2/\text{ndf} = 10.6/38$

Double Chooz results in comparison



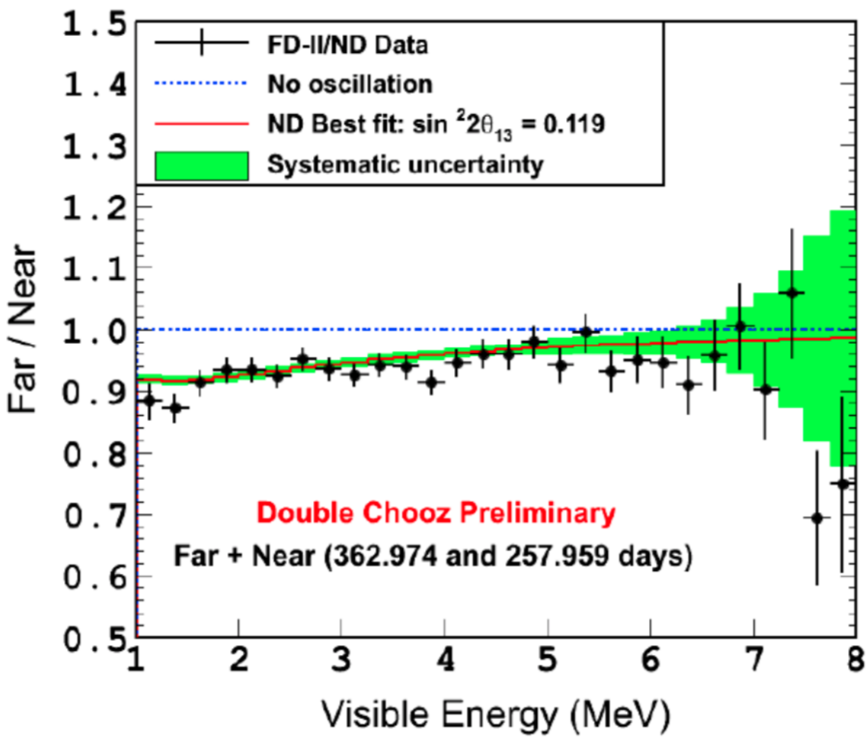
- Double Chooz and beam experiments favour higher θ_{13} values than reactor average
- Reactor θ_{13} is key parameter to solve CP-violation and mass hierarchy
- Difference to Daya Bay 2.2 σ
- Difference to RENO 1.8 σ

Summary & Outlook

- Reactor neutrino IBD detection using n-Gd and n-H capture
- Latest results: $\sin^2(2\theta_{13}) = 0.119 \pm 0.016$
- Precise measurement of detector volume during decommissioning
  - Dominant uncertainty on relative near/far signal normalisation (now 0.7 % uncorr. near/far)
  - Dominant uncertainty in θ_{13} fit
- New Double Chooz results will be published in one week at the Neutrino Conference

- New developments in GPUs lead to the possibility to run the gradient descent calculations and event by event oscillations in parallel, which would reduce a single fit runtime to about 30 seconds
- This new technology can also help with the development of an unbinned likelihood approach

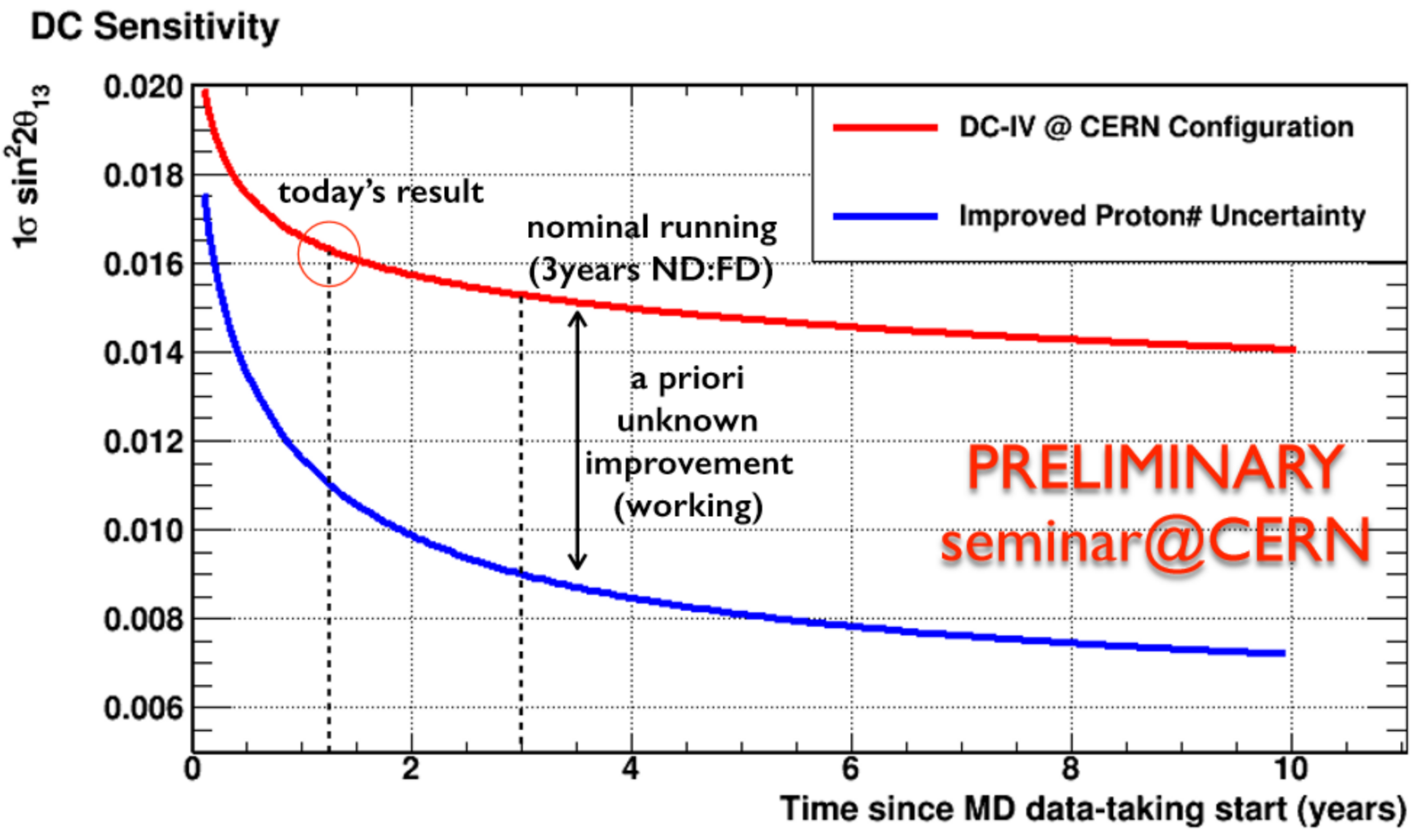
Backup



The spectral distortion cancels out in FD/ND ratio ⇒ This also means that it cannot be explained by sterile neutrinos

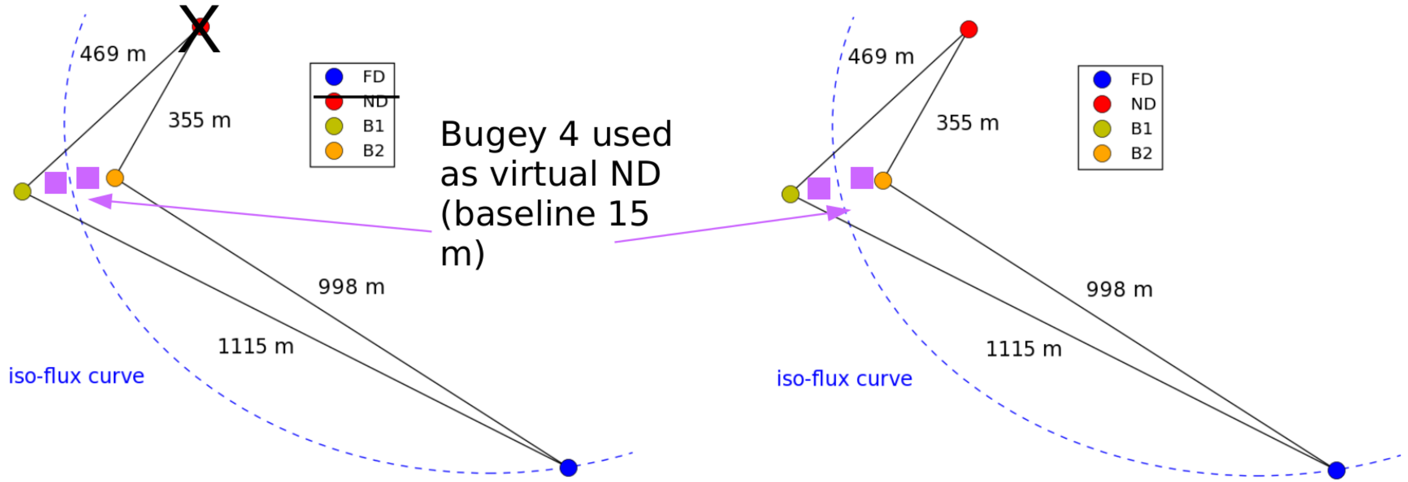
$$
\begin{aligned}
P(\bar{\nu}_e \to \bar{\nu}_e) = 1 &- 4\sin^2(\theta_{13})\cos^2(\theta_{13})\sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) \\
&- \cos^3(\theta_{13})\sin^2(2\theta_{12})\sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right) \\
&+ 2\sin^2(\theta_{13})\cos^2(\theta_{13})\sin^2(\theta_{12})\left(\cos\left(\frac{\Delta m^2_{31} L}{2E} - \frac{\Delta m^2_{21} L}{2E}\right) - \cos\left(\frac{\Delta m^2_{31} L}{2E}\right)\right)
\end{aligned}
$$

Sensitivity



Setup

Before 2015 **Since 2015**

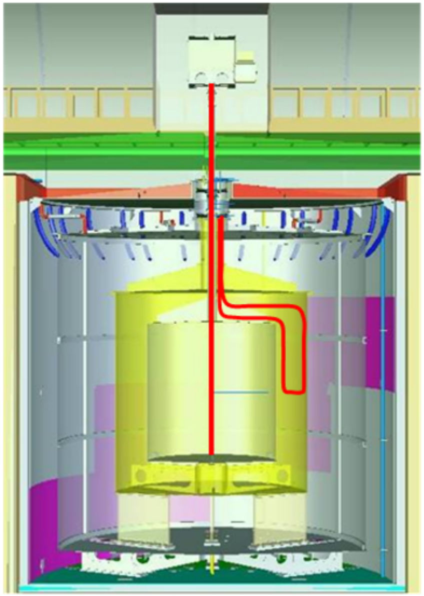


FDI 455 days lifetime
+ 7 days lifetime reactor off

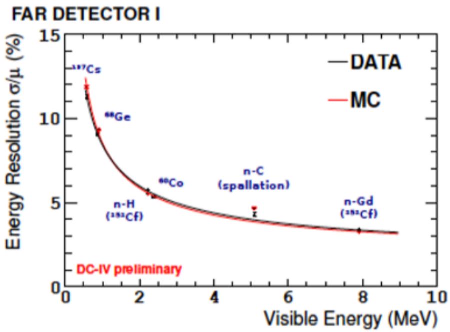
ND 258 days lifetime
FDII 363 days lifetime

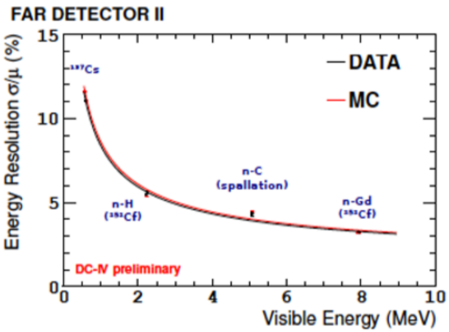
Full Likelihood Function

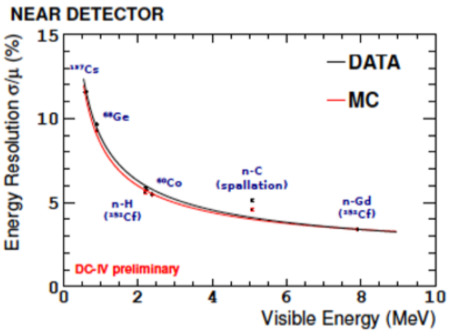
$$
\begin{aligned}
-2\ln(\mathcal{L}) = \sum_{d\in\{FD1,FD2,ND\}} \Bigg[& -2\cdot\sum_{i=1}^{40}\Big\{(n_i^{meas})_d\cdot\ln\Big[\Big((R_i^{\bar{\nu}_e})_d+(R_i^{bkgrd})_d\Big)\cdot(t_{On}^{live})_d\Big] \\
& -\Big[\Big((R_i^{\bar{\nu}_e})_d+(R_i^{bkgrd})_d\Big)\cdot(t_{On}^{live})_d\Big]\Big\} \\
& +\left(\frac{(b_{acc}^{rate})_d-(b_{acc}^{rate})_d^{CV}}{\sigma_{(b_{acc}^{rate})_d}}\right)^2+\sum_{k=1}^{40}\left(\frac{(b_{acc}^{shape})_{d,k}-0}{1}\right)^2 \\
& +\begin{pmatrix}(e_0)_d-(e_0)_d^{CV}\\(e_1)_d-(e_1)_d^{CV}\\(e_2)_d-(e_2)_d^{CV}\end{pmatrix}^{\mathrm{T}}\times\left(COV\left[\begin{pmatrix}(e_0)_d\\(e_1)_d\\(e_2)_d\end{pmatrix}\right]\right)^{-1}\times\begin{pmatrix}(e_0)_d-(e_0)_d^{CV}\\(e_1)_d-(e_1)_d^{CV}\\(e_2)_d-(e_2)_d^{CV}\end{pmatrix}\Bigg] \\
& +\sum_{m\in\{FD,ND\}}\left[\left(\frac{(b_{corr}^{rate})_m-(b_{corr}^{rate})_m^{CV}}{\sigma_{(b_{corr}^{rate})_m}}\right)^2\right]+\sum_{l=1}^{40}\left(\frac{(b_{LiHe}^{shape})_l-0}{1}\right)^2 \\
& +\left(\frac{\Delta m_{ee}^2-(\Delta m_{ee}^2)^{CV}}{\sigma_{\Delta m_{ee}^2}}\right)^2+\left(\frac{(\nu_{Off}^{rate})_{FD1}-(\nu_{Off}^{rate})_{FD1}^{CV}}{\sigma_{(\nu_{Off}^{rate})_{FD1}}}\right)^2 \\
& +\left(\frac{\nu^{norm}-0}{1}\right)^2+\sum_{j=1}^{80}\left(\frac{(\nu^{r+s})_j-0}{1}\right)^2 \\
& +\sum_{c\in\{FarFar,NearFar\}}\left[\left(\frac{(\nu_{split}^{norm})_c-0}{1}\right)^2+\left(\frac{(\nu_{split}^{r+s})_c-0}{1}\right)^2\right] \\
& -2\cdot\Big\{(n_{Off}^{meas})_{FD1}\cdot\ln\Big[\Big((R_{Off}^{\bar{\nu}_e})_{FD1}+(R^{bkgrd})_{FD1}\Big)\cdot(t_{Off}^{live})_{FD1}\Big] \\
& -\Big[((R_{Off}^{\bar{\nu}_e})_{FD1}+(R^{bkgrd})_{FD1})\cdot(t_{Off}^{live})_{FD1}\Big]\Big\}
\end{aligned}
$$



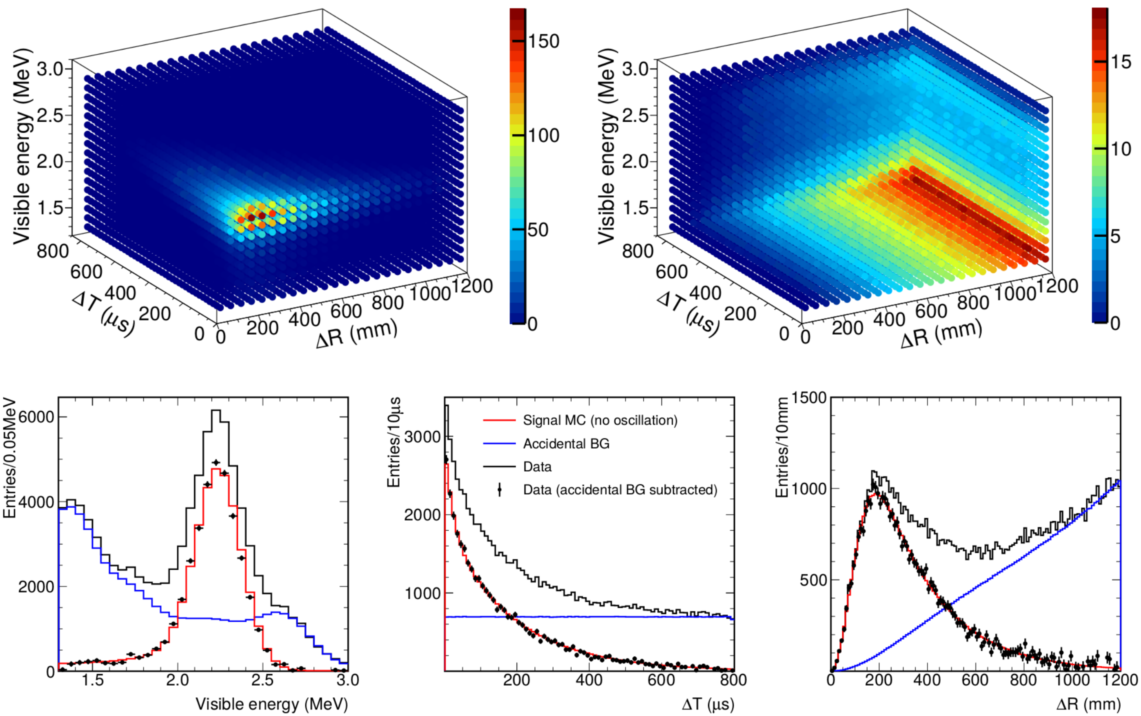
- Two systems for calibration source deployment in the GC/along the Z-axis
- 252-Cf used as neutron source
- Characteristic energy deposit of n-Gd and n-H capture during source deployment used to set energy scale
- Two light injection systems for regular monitoring of PMTs/scintillators







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



Double Chooz Likelihood Function

This is the likelihood we use for the minimisation process and hand it over to ROOT.

$$-2\ln\left(\mathcal{L}\left(\vec{n}_{\text{meas}}|\vec{a}\right)\right) = \sum_d \left[\left(-2\sum_{i=1}^{38} n_i^{\text{meas}} \cdot \ln\left(n_i^{\text{exp}}(\vec{a})\right) - n_i^{\text{exp}}(\vec{a})\right)\right]$$

$$+\sum_{i=1}^{38} n_{\text{OffOff,i}}^{\text{meas}} \cdot \ln\left(n_{\text{OffOff,i}}^{\text{exp}}\left(\vec{a}\right)\right) - n_{\text{OffOff,i}}^{\text{exp}}\left(\vec{a}\right)$$

$$+\sum_j \begin{cases} g_c\left(j\right) & j \text{ vector of correlated par.} \\ g\left(j\right) & j \text{ single par. (uncorrelated)} \end{cases}$$

The function consists in principle out of three parts. The Shape, OffOff and Pull part.

A **pull** is a gaussian prior added to the total likelihood to constrain (i.e Δm^2) certain parameters to a predefined value range.

$$-2\ln\left(\mathcal{L}\left(\vec{n}_{\text{meas}}|\vec{a}\right)\right) = \sum_{d}\left[\left(-2\sum_{i=1}^{38} n_i^{\text{meas}}\cdot\ln\left(n_i^{\text{exp}}(\vec{a})\right) - n_i^{\text{exp}}(\vec{a})\right)\right]$$

$$+\sum_{i=1}^{38} n_{\text{OffOff,i}}^{\text{meas}}\cdot\ln\left(n_{\text{OffOff,i}}^{\text{exp}}\left(\vec{a}\right)\right) - n_{\text{OffOff,i}}^{\text{exp}}\left(\vec{a}\right)$$

$$+\sum_{j}\begin{cases} g_c(j) & j \text{ vector of correlated par.} \\ g(j) & j \text{ single par. (uncorrelated)} \end{cases}$$

Pull

$$g\left(j\right) = \left(\frac{x_j - \langle x\rangle_j}{\sigma_j}\right)^2$$

Correlated Pull

$$g_c\left(j\right) = \left(\vec{j} - \langle\vec{j}\rangle\right)^T \cdot V_j^{-1} \cdot \left(\vec{j} - \langle\vec{j}\rangle\right)$$

Shape and OffOff are based on the poissonian likelihood function.

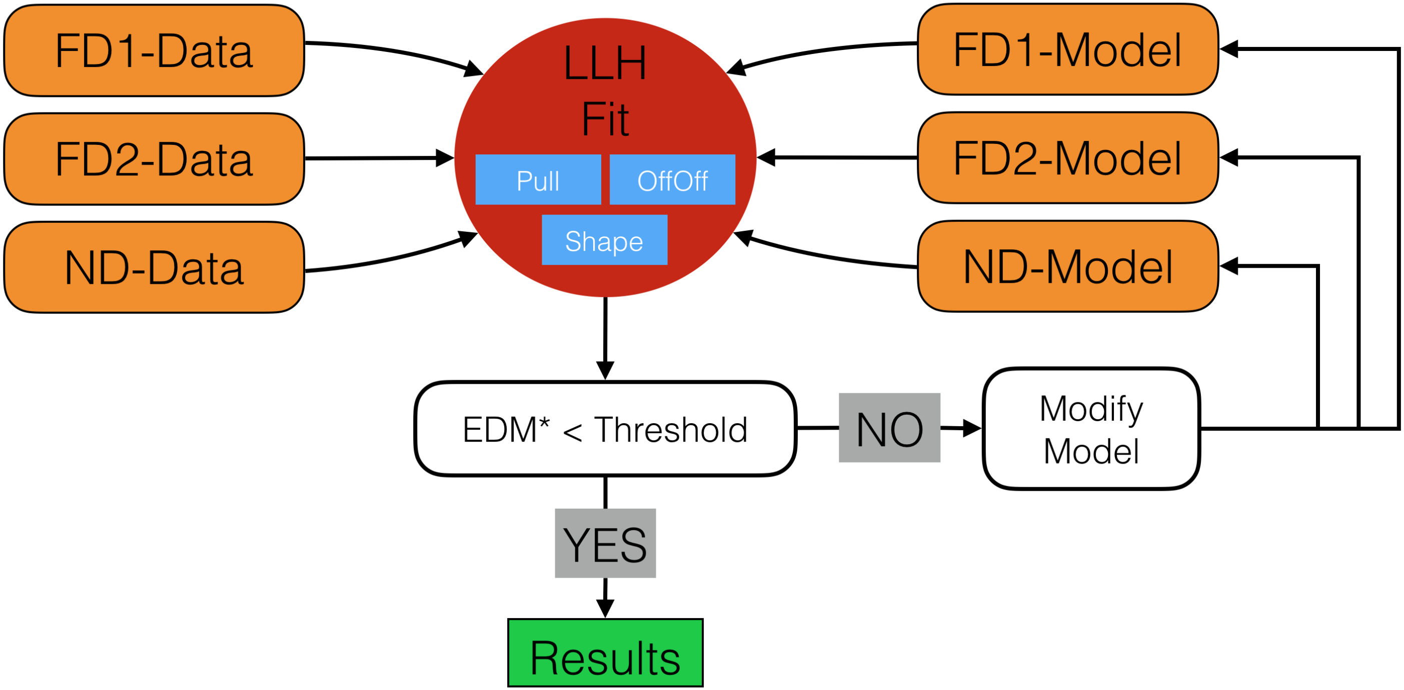
$$-2\ln\left(\mathcal{L}\left(\vec{n}_{\text{meas}}|\vec{a}\right)\right) = \sum_{d}\left[\left(-2\sum_{i=1}^{38} n_i^{\text{meas}}\cdot\ln\left(n_i^{\text{exp}}(\vec{a})\right) - n_i^{\text{exp}}(\vec{a})\right)\right]$$

$$+\sum_{i=1}^{38} n_{\text{OffOff,i}}^{\text{meas}}\cdot\ln\left(n_{\text{OffOff,i}}^{\text{exp}}(\vec{a})\right) - n_{\text{OffOff,i}}^{\text{exp}}(\vec{a})$$

$$+\sum_{j}\begin{cases} g_c(j) & j \text{ vector of correlated par.} \\ g(j) & j \text{ single par. (uncorrelated)} \end{cases}$$

Poissonian likelihood function

$$L(\lambda; x) = \prod_{i=1}^{n}\frac{\lambda^{x_i}e^{-\lambda}}{x_i!} \Rightarrow l(\lambda; x) = \sum_{i=1}^{n} x_i \log\lambda - n\lambda$$



***EDM** ≡ **E**stimated **D**istance to **M**inimum

Arbitrary initial reactor flux

Linear Spline Interpolation

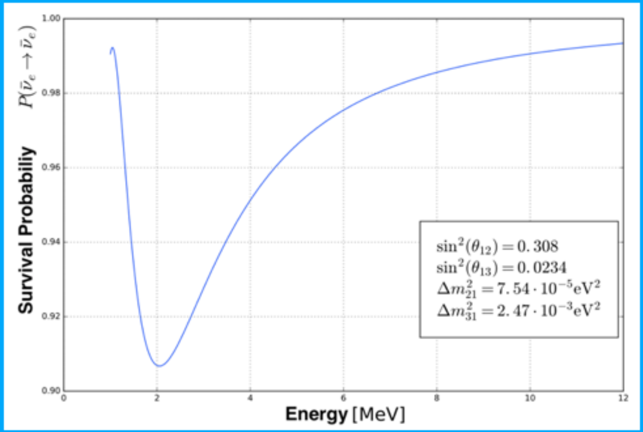
Apply Energy correction

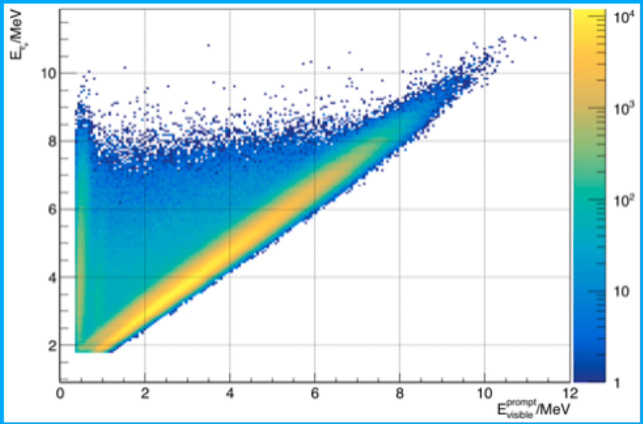
$E = a + b \cdot E' + c \cdot E'^2$

Linear Spline Interpolation

Apply normalisation with detection unc.
proton number, selection efficiency Gd/H capture fraction, Veto efficiency, boundary effects

Model construction finished





Likelihood Scan of MC generated $\sin^2(2\theta_{13}) \equiv 0.1$