First results on the θ_{13} mixing angle with the Double Chooz reactor experiment

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15 December 2011

GOBIERNO
DE ESPAÑA

MINISTERIO
DE CIENCIA
E INNOVACIÓN

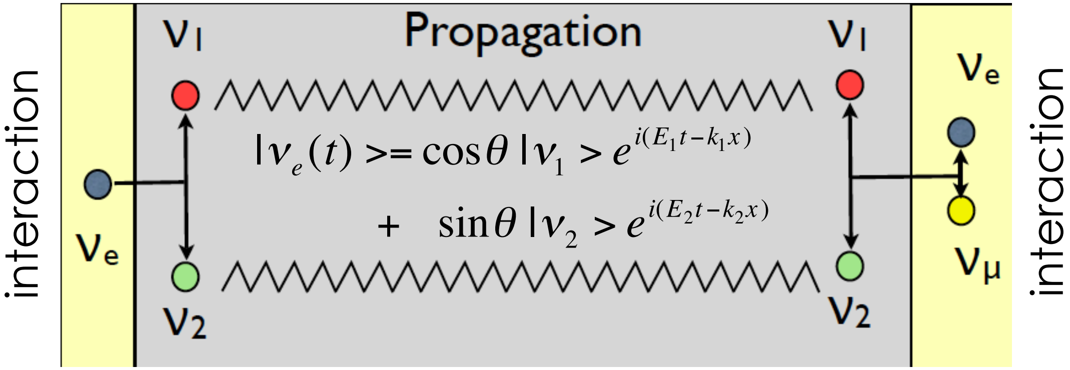
Ciemat
Centro de Investigaciones
Energéticas, Medioambientales
y Tecnológicas

Overview

- Neutrino oscillations status
    - The search for the θ_{13} mixing angle
- Neutrino oscillations at nuclear reactors
    - Neutrino detection and backgrounds
- The Double Chooz experimental setup
- CIEMAT contribution
- Physics results
    - Detector performance
    - Neutrino selection and backgrounds
    - Oscillation analysis
- Prospects
- Conclusions

Neutrino oscillations status

Neutrino oscillations

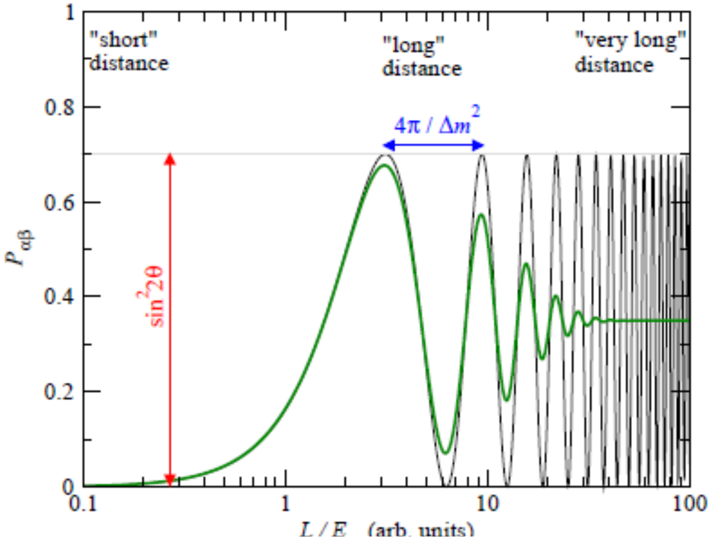


$$|\nu_e(t)> = \cos\theta\,|\nu_1>e^{i(E_1t-k_1x)} + \sin\theta\,|\nu_2>e^{i(E_2t-k_2x)}$$

$$|\nu_e(0)> = \cos\theta\,|\nu_1> + \sin\theta\,|\nu_2>$$

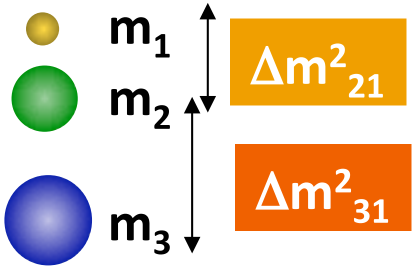
$$P(\nu_e \xrightarrow{osc} \nu_\mu) = |<\nu_\mu(0)|\nu_e(t)>|^2$$

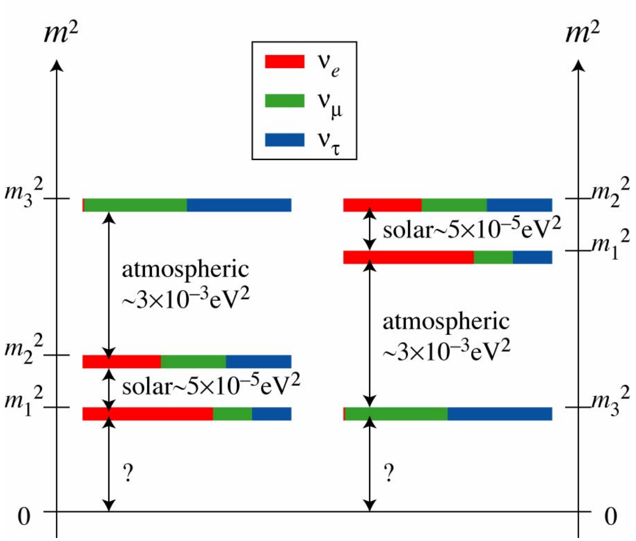
- Quantum mechanical phenomenon
- **Flavor transitions** due to:
  - Finite mass
  - Neutrino mixing
- For two families: $P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \, \sin^2\left(\frac{\Delta m^2 \cdot L}{4 \cdot E_\nu}\right)$



Global analysis of oscillation data

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \underbrace{\overbrace{\begin{pmatrix}1&0&0\\0&c_{23}&s_{23}\\0&-s_{23}&c_{23}\end{pmatrix}}^{\text{Atmosph + LBL}}}_{\theta_{atm}}\underbrace{\overbrace{\begin{pmatrix}c_{13}&0&s_{13}e^{-i\delta}\\0&1&0\\-s_{13}e^{i\delta}&0&c_{13}\end{pmatrix}}^{\text{CHOOZ + LBL}}}_{\theta_{13},\ \delta_{CP}\ ??}\underbrace{\overbrace{\begin{pmatrix}c_{12}&s_{12}&0\\-s_{12}&c_{12}&0\\0&0&1\end{pmatrix}}^{\text{Solar + KamLAND}}}_{\theta_{sol}}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$





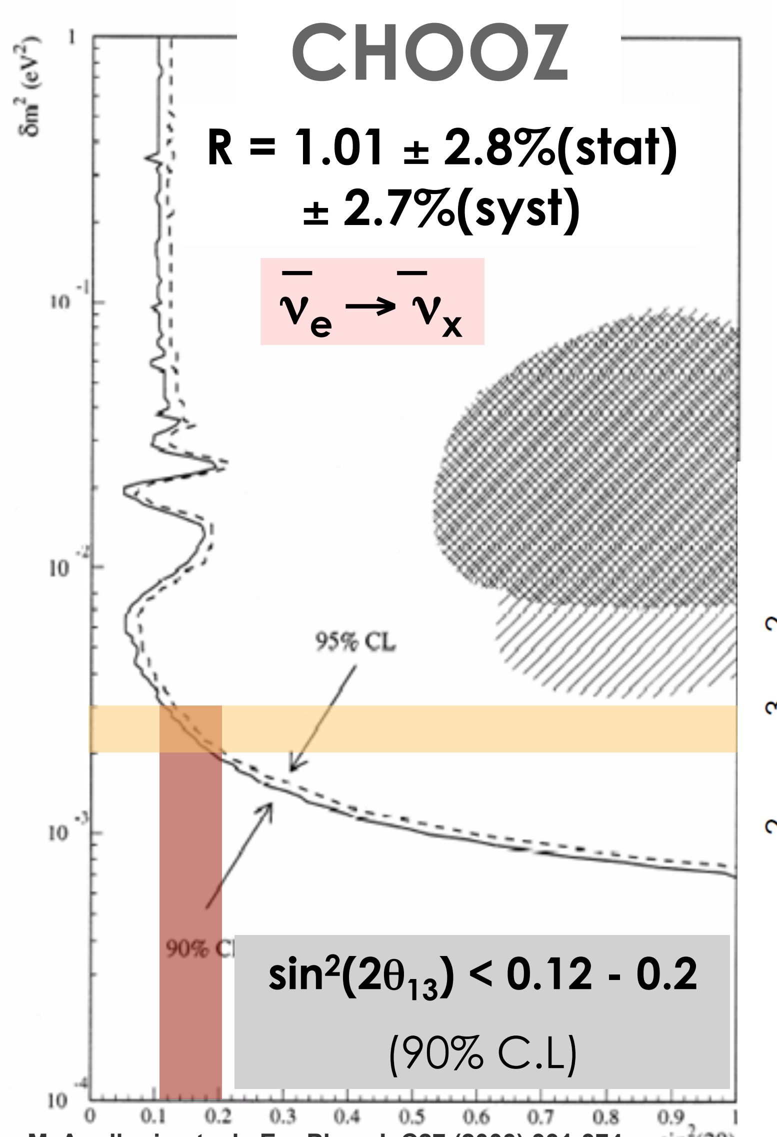
Experimental measurements

parameter	best fit	2σ	3σ
Δm^2_{21} $[10^{-5}\mathrm{eV}^2]$	$7.65^{+0.23}_{-0.20}$	7.25–8.11	7.05–8.34
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\mathrm{eV}^2]$	$2.40^{+0.12}_{-0.11}$	2.18–2.64	2.07–2.75
$\sin^2\theta_{12}$	$0.304^{+0.022}_{-0.016}$	0.27–0.35	0.25–0.37
$\sin^2\theta_{23}$	$0.50^{+0.07}_{-0.06}$	0.39–0.63	0.36–0.67
$\sin^2\theta_{13}$	$0.01^{+0.016}_{-0.011}$	≤ 0.040	≤ 0.056

T. Schwetz et al.,
New J.Phys.10:113011,2008

θ_{13}, δ_{CP}, sign Δm^2_{31}, θ_{23} maximal??

The θ_{13} mixing angle



CHOOZ

R = 1.01 ± 2.8%(stat) ± 2.7%(syst)

$\bar{\nu}_e \rightarrow \bar{\nu}_x$

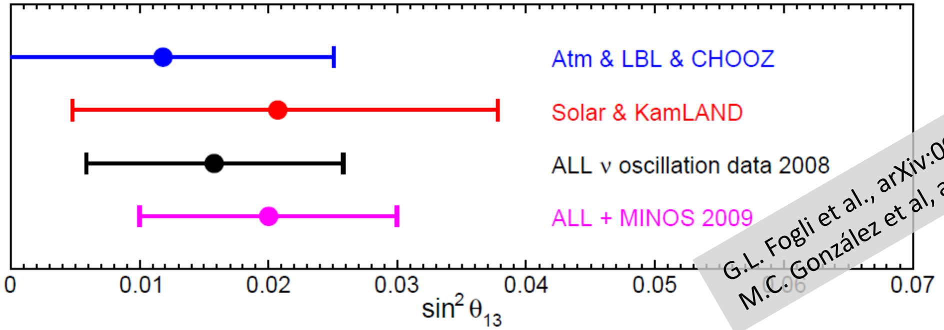
$\sin^2(2\theta_{13}) < 0.12 - 0.2$

(90% C.L)

M. Apollonio et. al., Eur.Phys.J. C27 (2003) 331-374

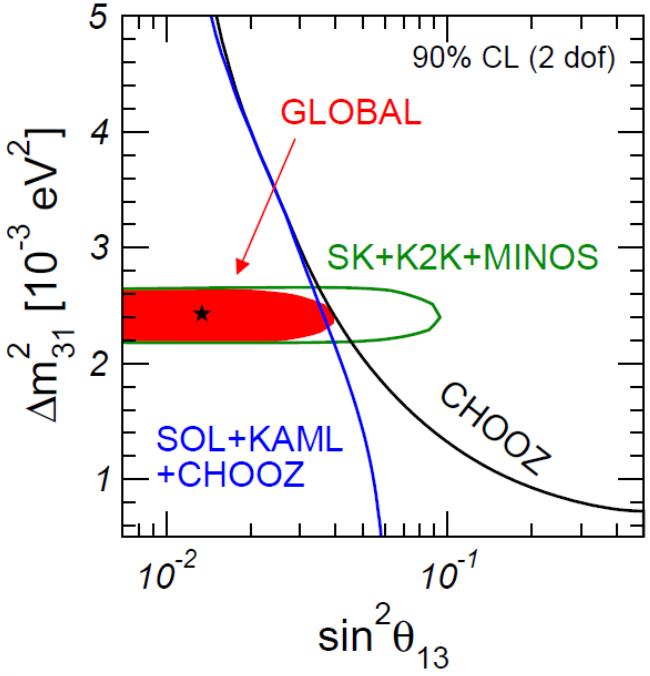
Hints for $\theta_{13} > 0$

$\sin^2\theta_{13} = 0.01 - 0.02\ (1\sigma)$



G.L. Fogli et al., arXiv:0905.3549
M.C. González et al, arXiv: 1001.4524

+ T2K



Best global limit on θ_{13}

M. Mezzeto & T. Schwetz
arXiv:1003.5800

Global (90% CL)
$\sin^2\theta_{13} \leq 0.031$

Two approaches for measuring θ_{13}

ACCELERATOR

- ***Appearance*** experiments
- **$P(\nu_\mu \rightarrow \nu_e)$** depends on $\sin^2(2\theta_{13})$, $\sin^2(\theta_{23})$, $\text{sign}(\Delta m^2_{31})$, δ_{CP} phase
  - Parameter degeneracies and correlations
  - Matter effects sensitive
- Possible measurement of CP and $\text{sign}(\Delta m^2_{31})$
- EXP. **CHALLENGES**: ν beam intensity, ν beam flavor contamination, ν flux properties, ν-N interactions

REACTOR

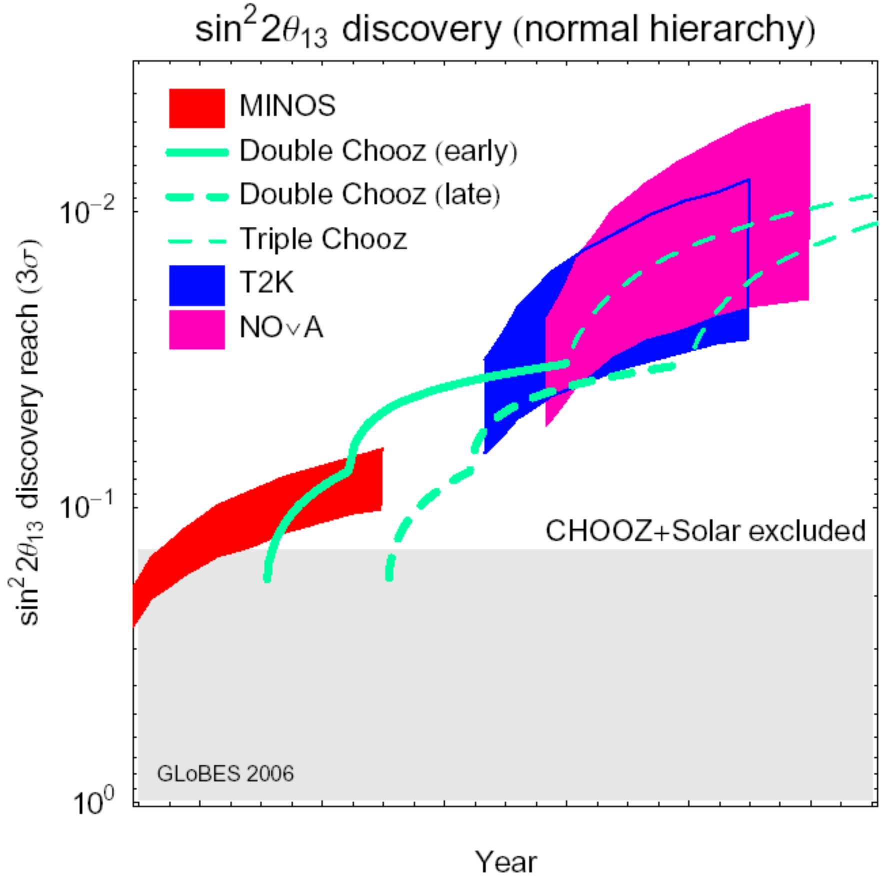
- ***Disappearance*** experiments
- **$P(\bar{\nu}_e \rightarrow \bar{\nu}_e)$** depends on $\sin^2(2\theta_{13})$
- **Unambiguous determination of θ_{13}**
  - no dependence on δ_{CP}
  - no dependence on mass hierarchy
  - weak dependence on Δm^2_{12}
- Resolve θ_{23} degeneracy combined with accelerator experiments
- EXP. **CHALLENGES**: backgrounds, systematic uncertainties

Both type of experiments provide independent and complementary information on θ_{13}

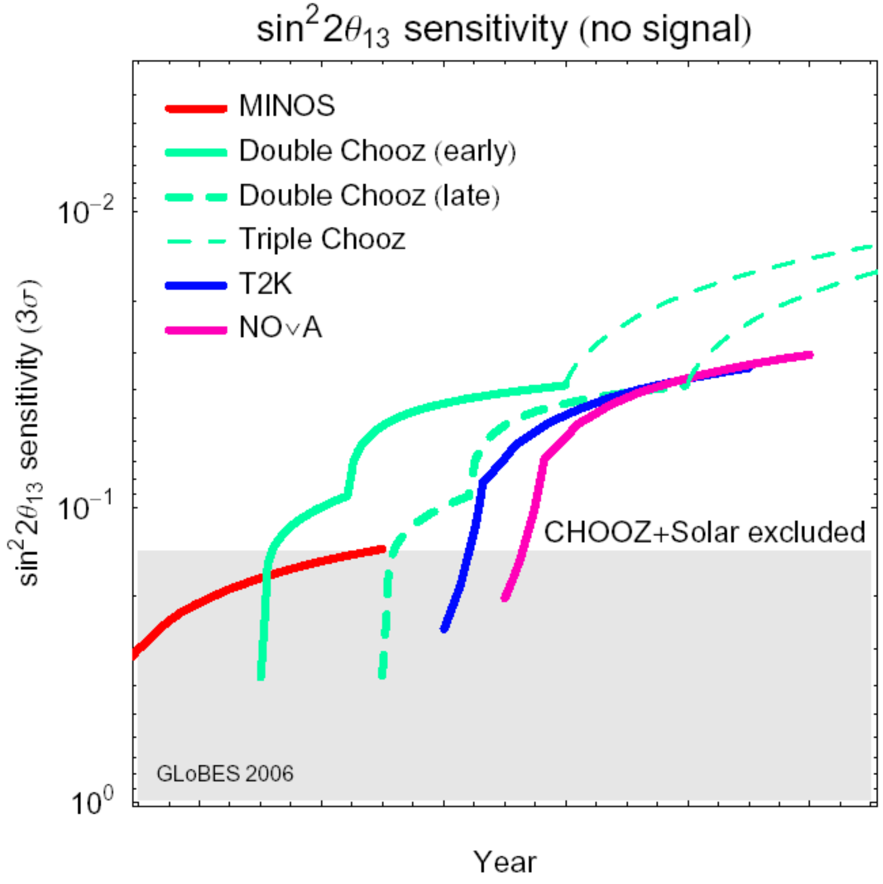
Evolution of the 3σ discovery and sensitivity

hep-ph/0601266

3σ discovery potential



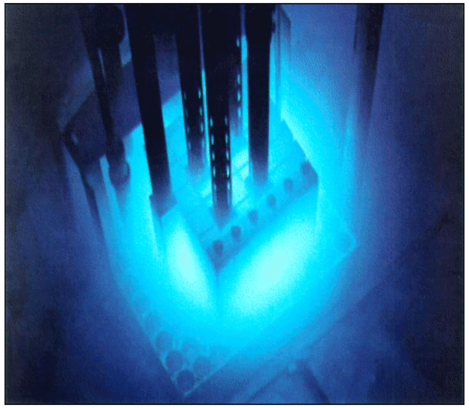
3σ sensitivity (no signal)

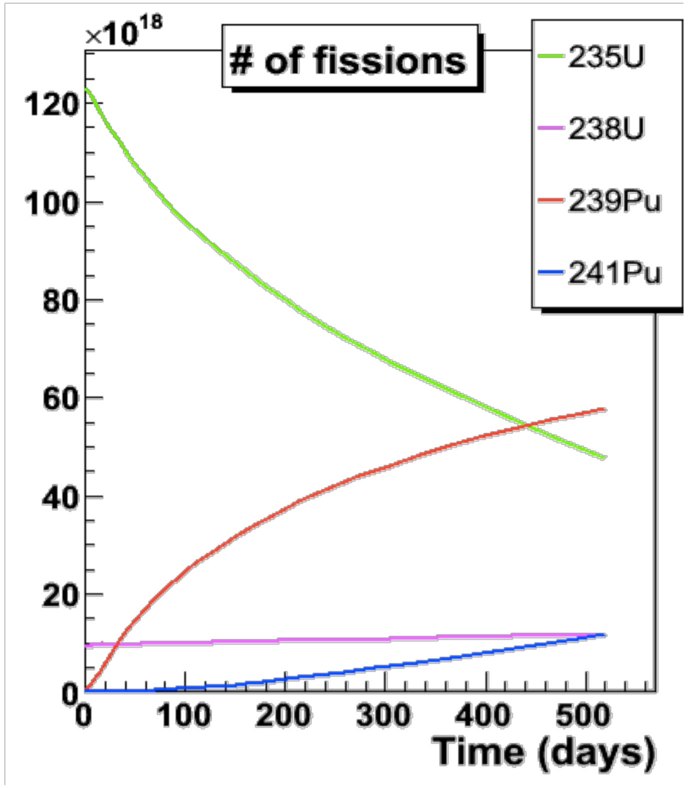


Neutrino oscillations at nuclear reactors

Nuclear reactors

- Electron antineutrinos emitted through decays of fission products of ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu
- Nuclear reactors: 1 GW$_{th}$ ≅ 2 × 10^{20} $\bar{\nu}$/s
- Neutrino luminosity: $N_{\bar{\nu}} = \gamma(1+k)P_{\mathrm{th}}$
  - γ: reactor constant
  - *k*: fuel evolution correction up to 10%
- ~200 MeV/fission is released
- ~6 antineutrinos/fission





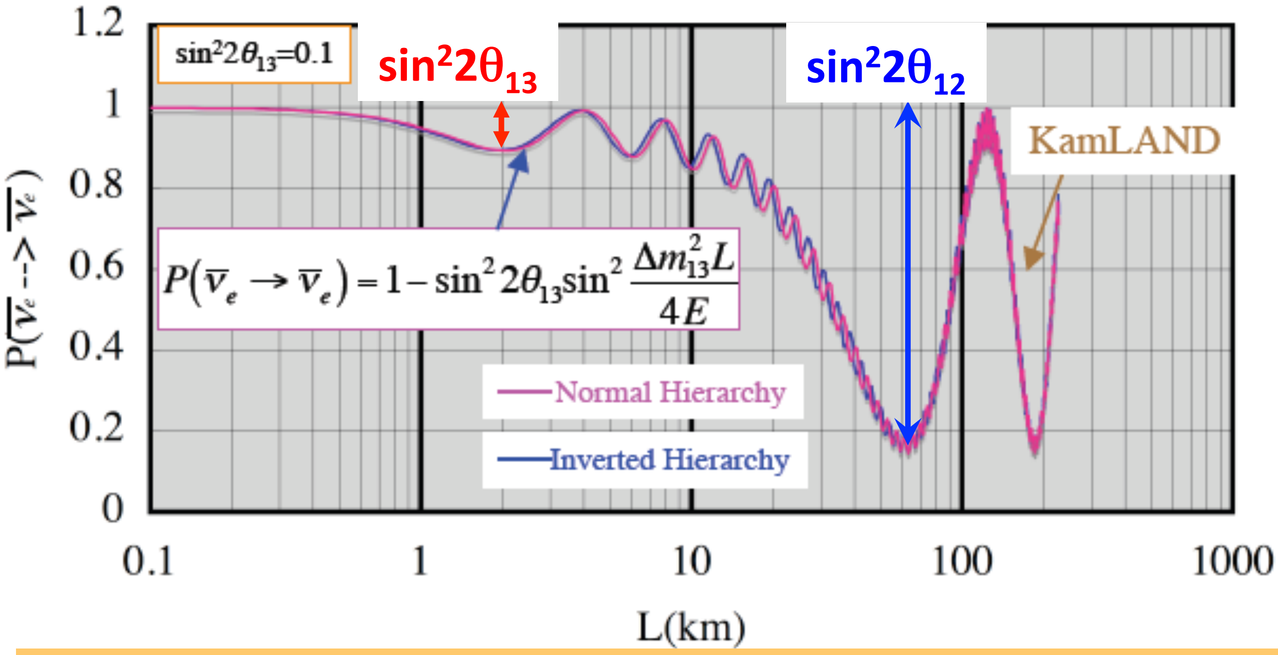
Neutrino oscillations at nuclear reactors

$\bar{\nu}_e$ survival probability

Clean measurement

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{13}{}^2 L}{4E_\nu}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}{}^2 L}{4E_\nu}\right)$$

MeV neutrinos: only *disappearance* experiments



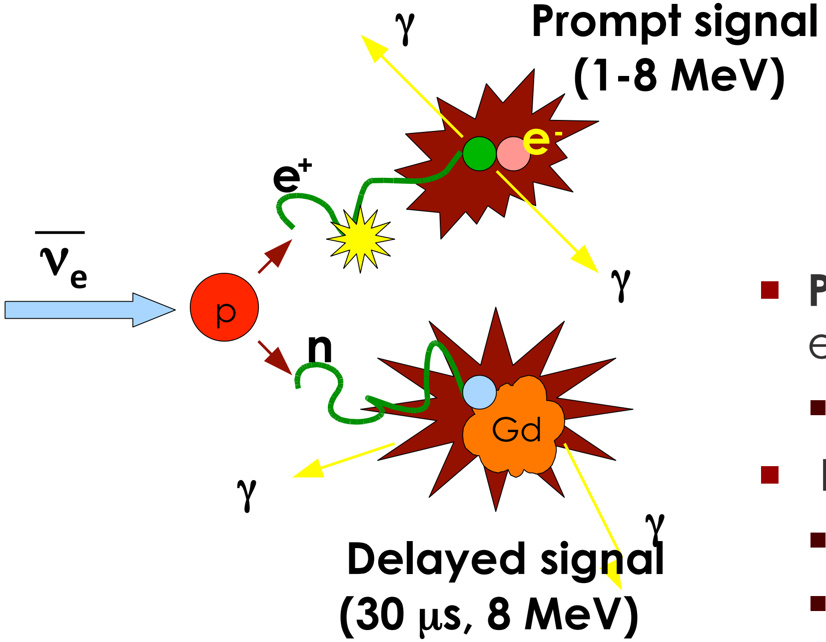
Small deficit (= $\sin^2 2\theta_{13}$) ➲ high precision is necessary

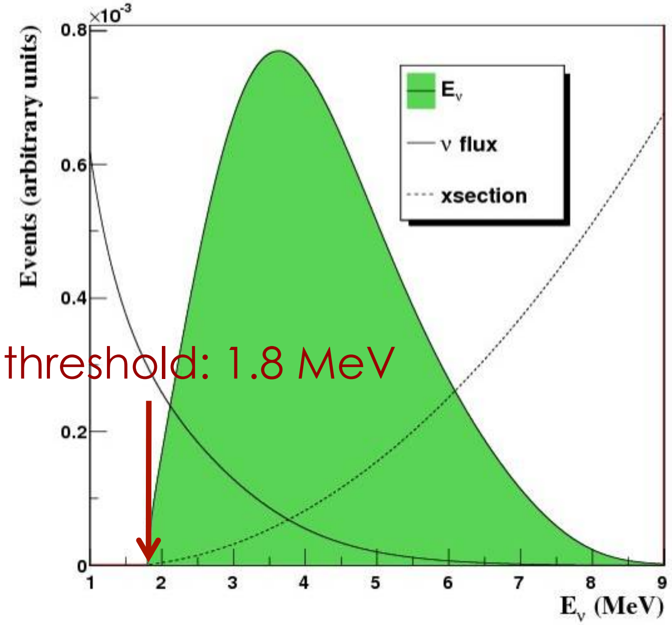
Antineutrino detection

$\bar{\nu}_e$ detection: inverse beta decay

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

$$n + Gd \rightarrow 8\ \text{MeV}\ \gamma$$



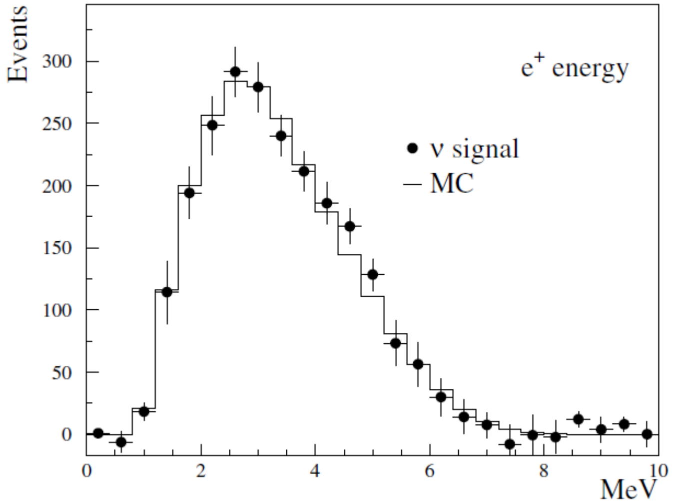


Reaction threshold: 1.8 MeV

- **Prompt signal:** e^+ kinetic energy + photons from e^+ annihilation:
  - $E_{VIS} \approx E_\nu - (m_n - m_p) + m_e \approx \mathbf{E_\nu - 0.8\ MeV}$
- **Delayed signal:** photons from n capture
  - on H : Δt ~200 µs, E~2 MeV
  - on dedicated nuclei (Gd): **Δt ~30 µs, E ~8 MeV**

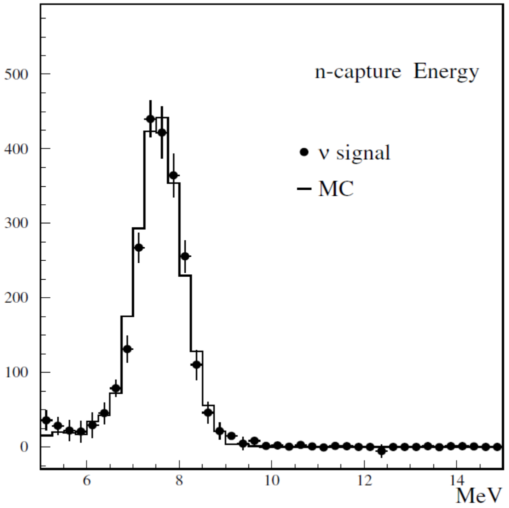
Main selection observables (CHOOZ data plots)

Prompt energy spectrum



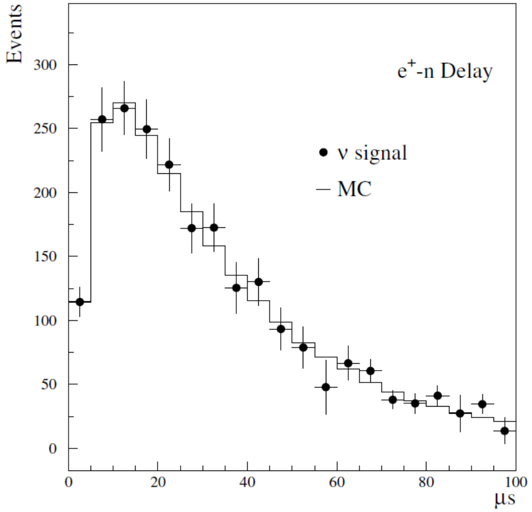
$E_{e+} \approx [1\text{-}8]$ MeV

Delay energy spectrum



$E_n \approx [6\text{-}12]$ MeV

Time delay distribution



$\Delta t \approx [2\text{-}100]$ μs

- In addition in CHOOZ: fiducial cut, spatial distance between e^+ and n, neutron multiplicity

The Double Chooz experimental setup

Double Chooz collaboration

Brazil

- CBPF
- UNICAMP
- UFABC

France

- APC
- CEA/DSM/IRFU:
  - SPP
  - SPhN
  - SEDI
  - SIS
  - SENAC
- CNRS/IN2P3:
  - Subatech
  - IPHC
- ULB/VUB

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

UK

- Sussex

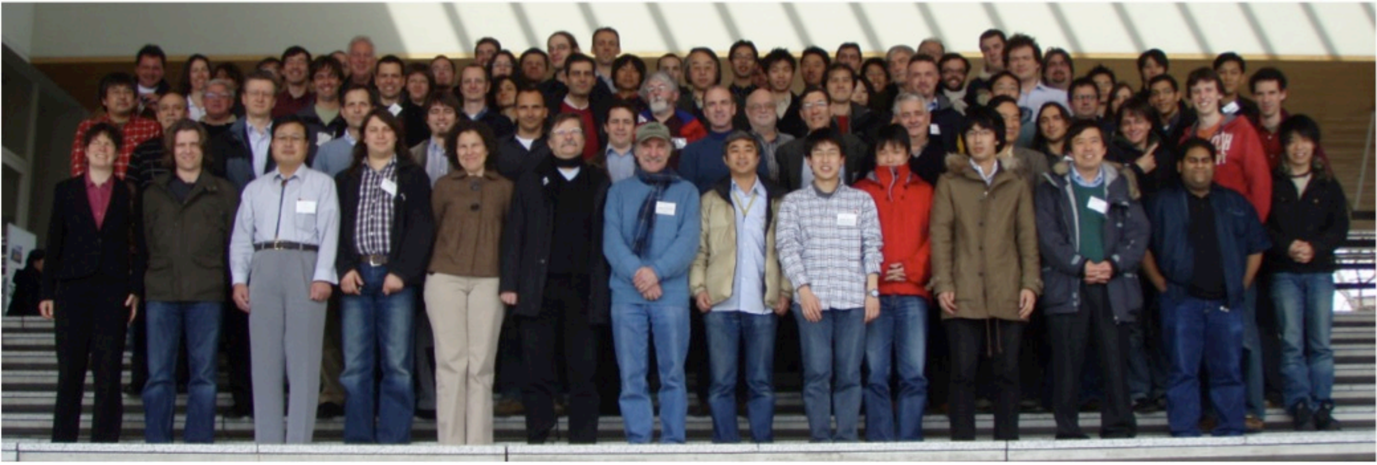
USA

- U. Alabama
- ANL
- U. Chicago
- Columbia U.
- UCDavis
- Drexel U.
- IIT
- KSU
- LLNL
- MIT
- U. Notre Dame
- Sandia National Laboratories
- U. Tennessee

Spokesperson: H. de Kerret (IN2P3)

Project Manager: Ch. Veyssière (CEA-Saclay)

Web Site: www.doublechooz.org/



The Double Chooz concept

Near detector (400 m)
115 m.w.e.

400 ν/day

50 ν/day

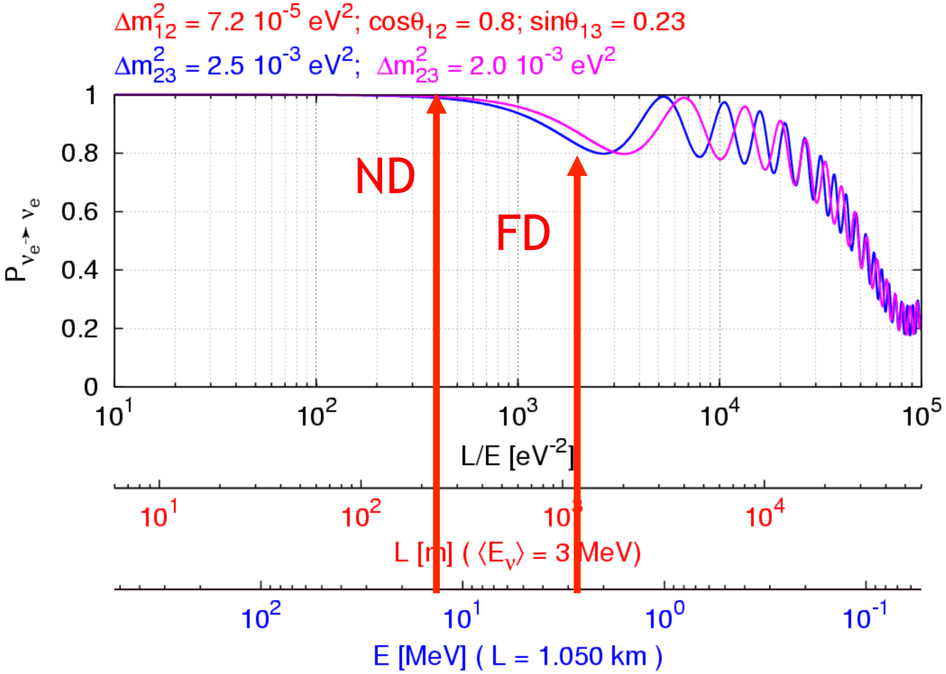
Far detector (1050 m)
300 m.w.e.

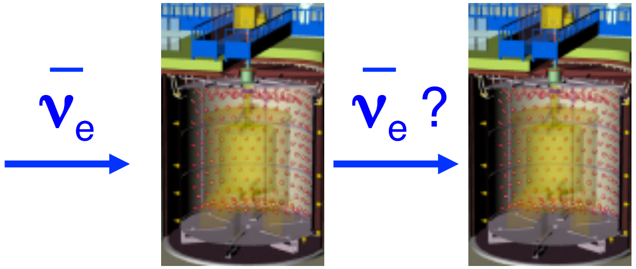
2 Chooz reactors
Power: 8.5 GW_{th} ($\sim10^{21}\ \bar{\nu}_e/s$)

Chooz-B nuclear power plant
Ardennes, France

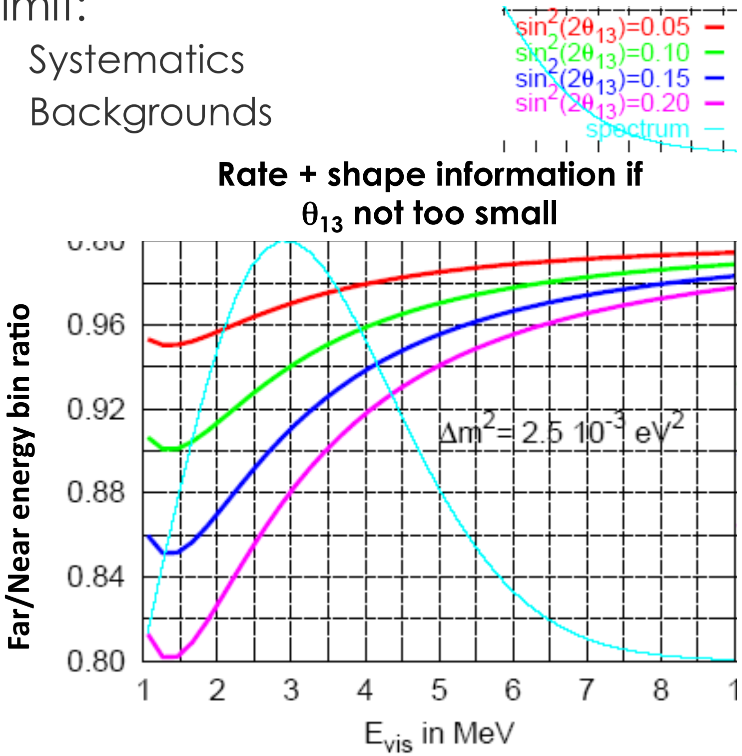
© CEA/DSM/IRFU - DCom/L.COLOMBEL

Reactor measurement principle



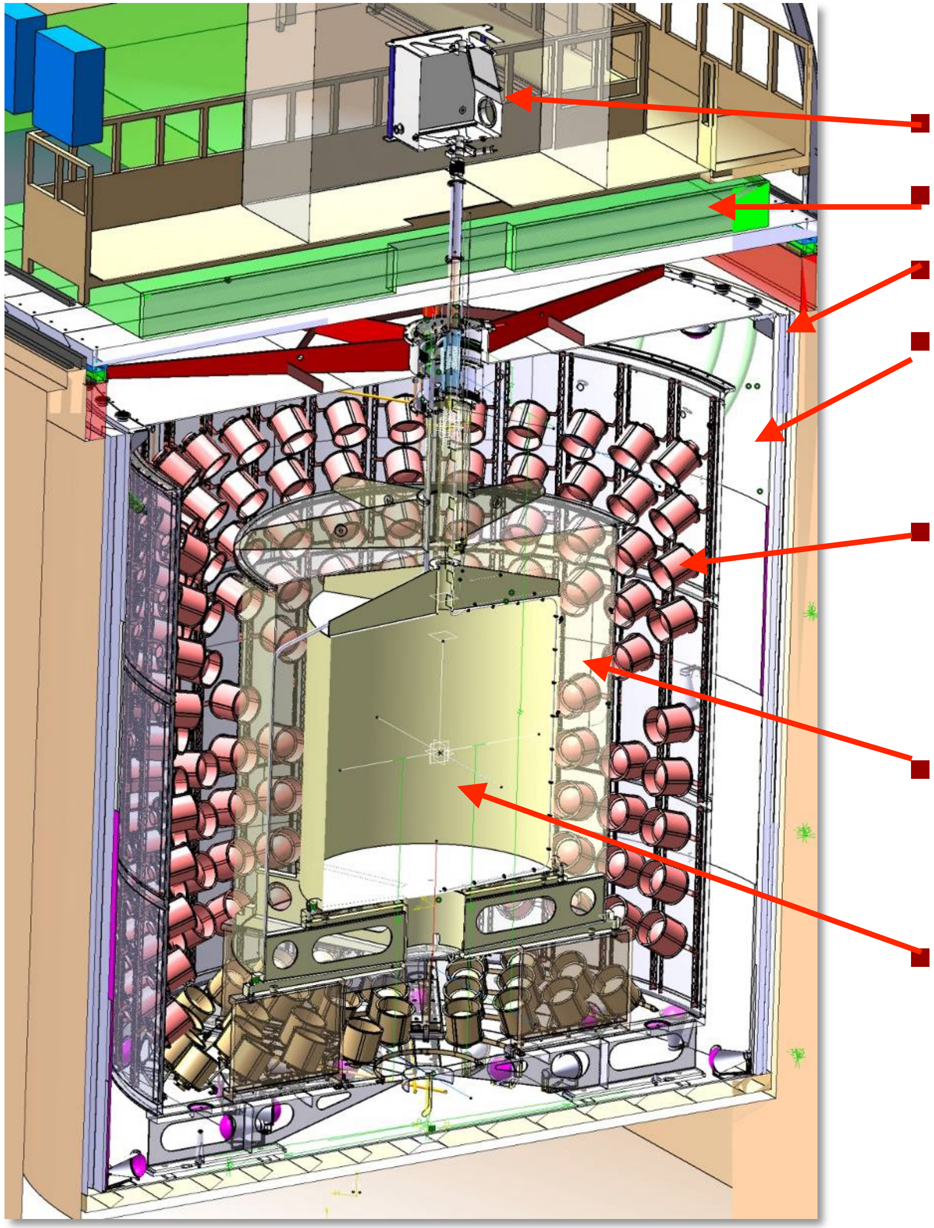


- 2 “identical” detectors
- Rate comparison
- Spectral distortion
- Limit:
  - Systematics
  - Backgrounds



Rate + shape information if θ_{13} not too small

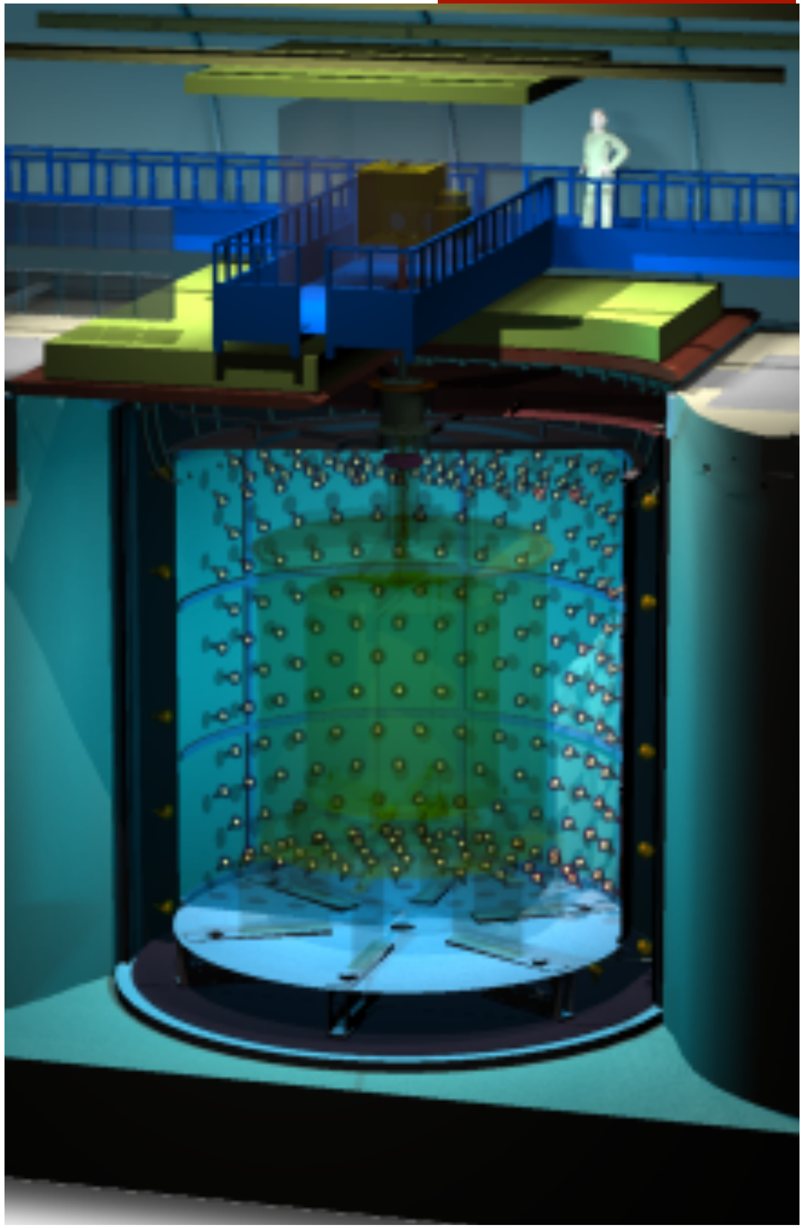
Detector design



- **Calibration glove box**
- **Outer veto**: plastic scintillator strips
- **Shielding**: 15 cm steel
- **Inner veto**:
  - 90 m^3 of liquid scintillator & 78 8" PMTs in a steel vessel (10 mm)
- **Buffer**:
  - 110 m^3 of non scintillating mineral oil & 390 10" PMTs in a stainless steel vessel (3 mm)
- **Gamma-catcher**:
  - 22.3 m^3 of liquid scintillator in an acrylic vessel (12 mm)
- **Target**:
  - 10.3 m^3 of liquid scintillator doped with 1 g/L of Gd in an acrylic vessel (8 mm)

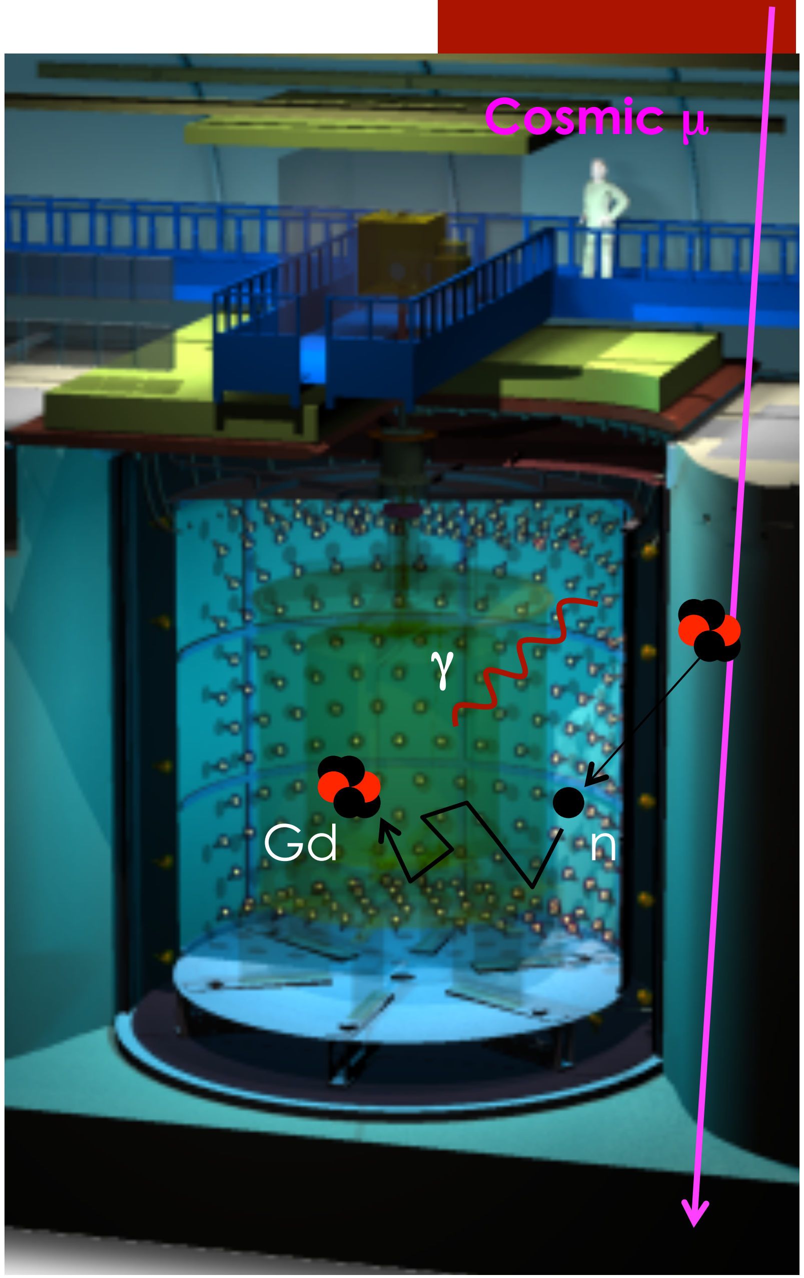
Expected backgrounds

- Will be reduced with respect to CHOOZ
- Target volume protected by several concentric layers
- Radiopurity requirements for detector materials and during installation
- Efficient muon tagging by inner and outer veto



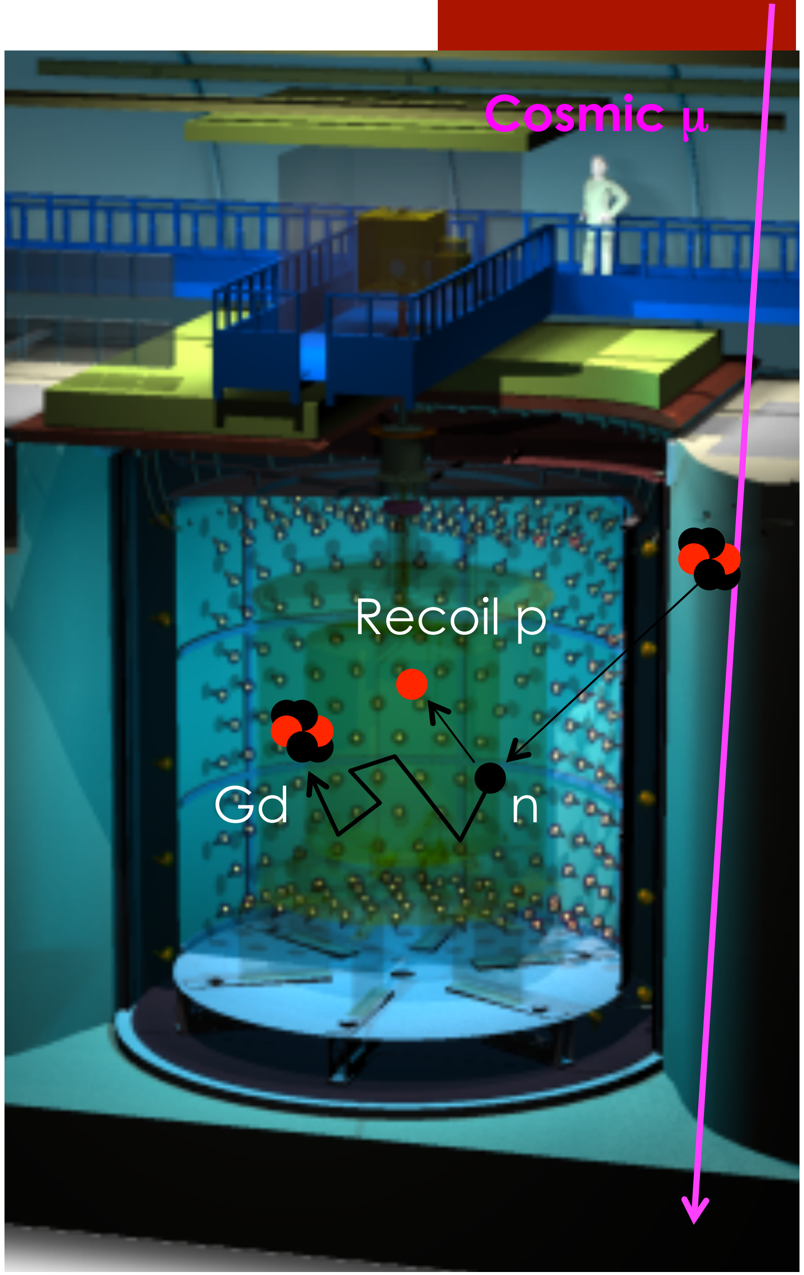
Expected background

- **Accidental coincidences:**
  - Prompt = radioactivity from materials, rock
  - Delayed = neutron from cosmic muon captured on Gd
  - **Proposal : 2.0 ± 0.9 / day**



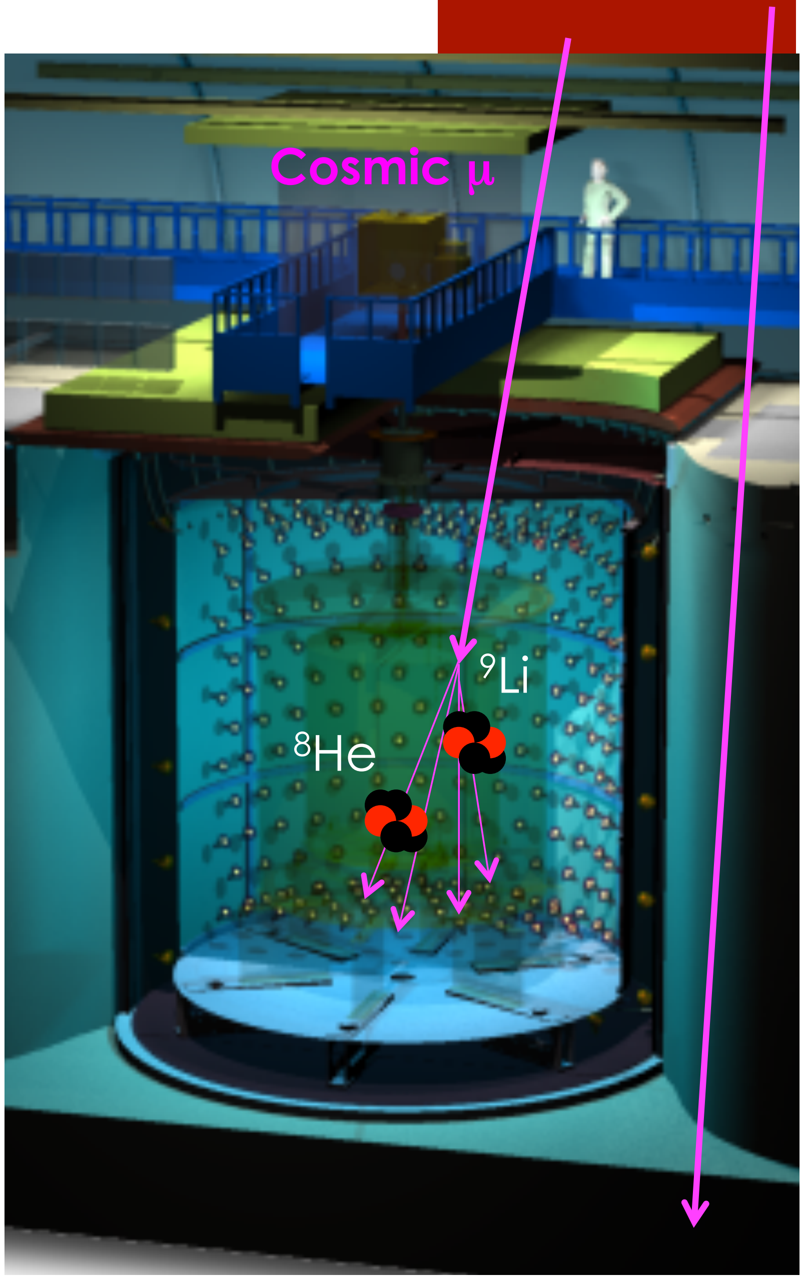
Expected background

- **Correlated fast neutrons:**
  - μ-induced
  - Prompt = recoil proton
  - Delayed = neutron capture on Gd
  - **Proposal : 0.2 ± 0.2 / day**



Expected background

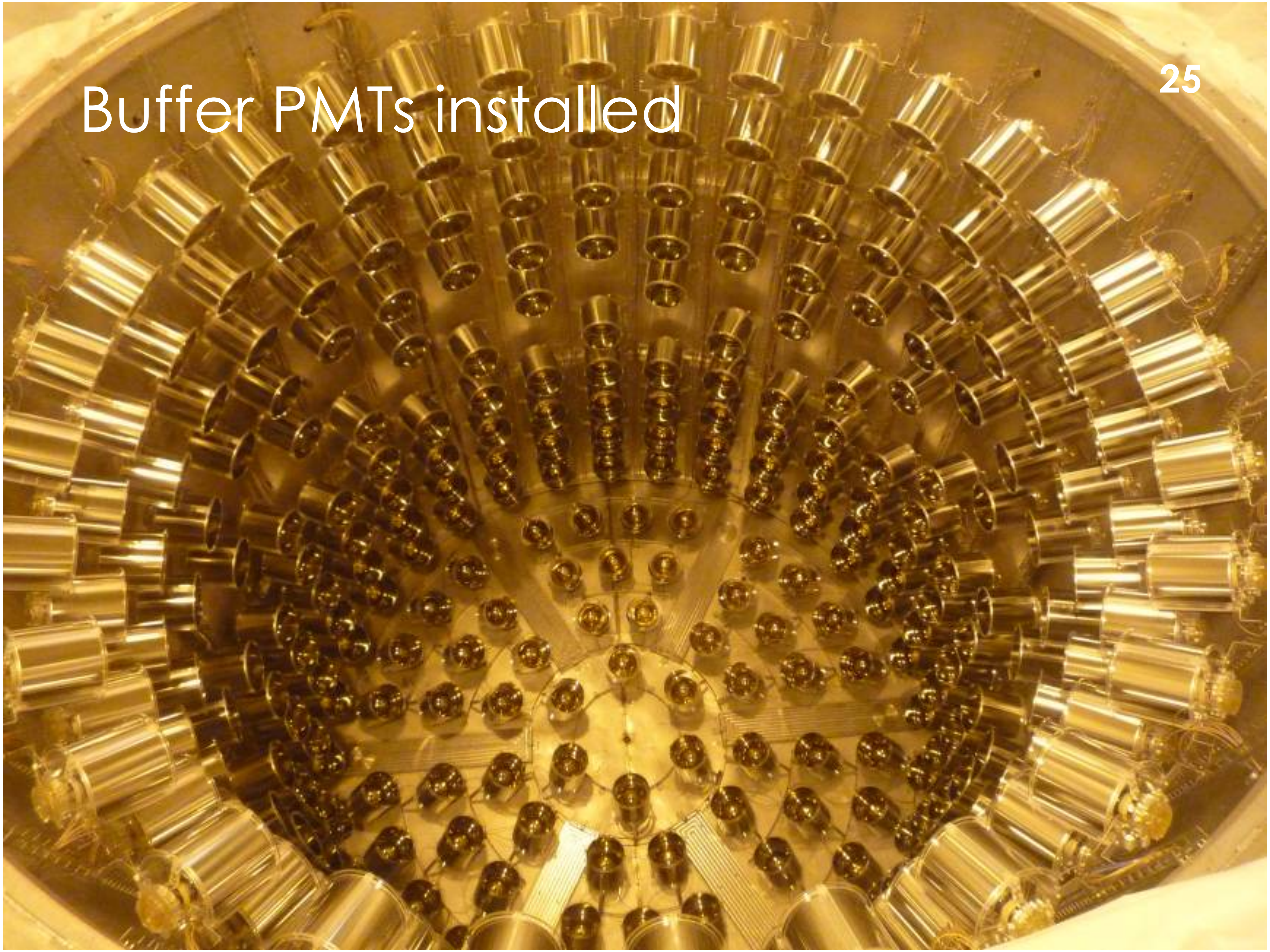
- **Correlated ^{9}Li and ^{8}He:**
  - Produced by μ-induced spallation processes
  - β-n emitters, perfectly mimic the ν signal.
  - Long life time ~250 ms, difficult to veto completely because of excessive dead time
  - **Proposal : 1.4 ± 0.5 / day**



Far detector construction (2008-2010)

Inner veto PMTs installed

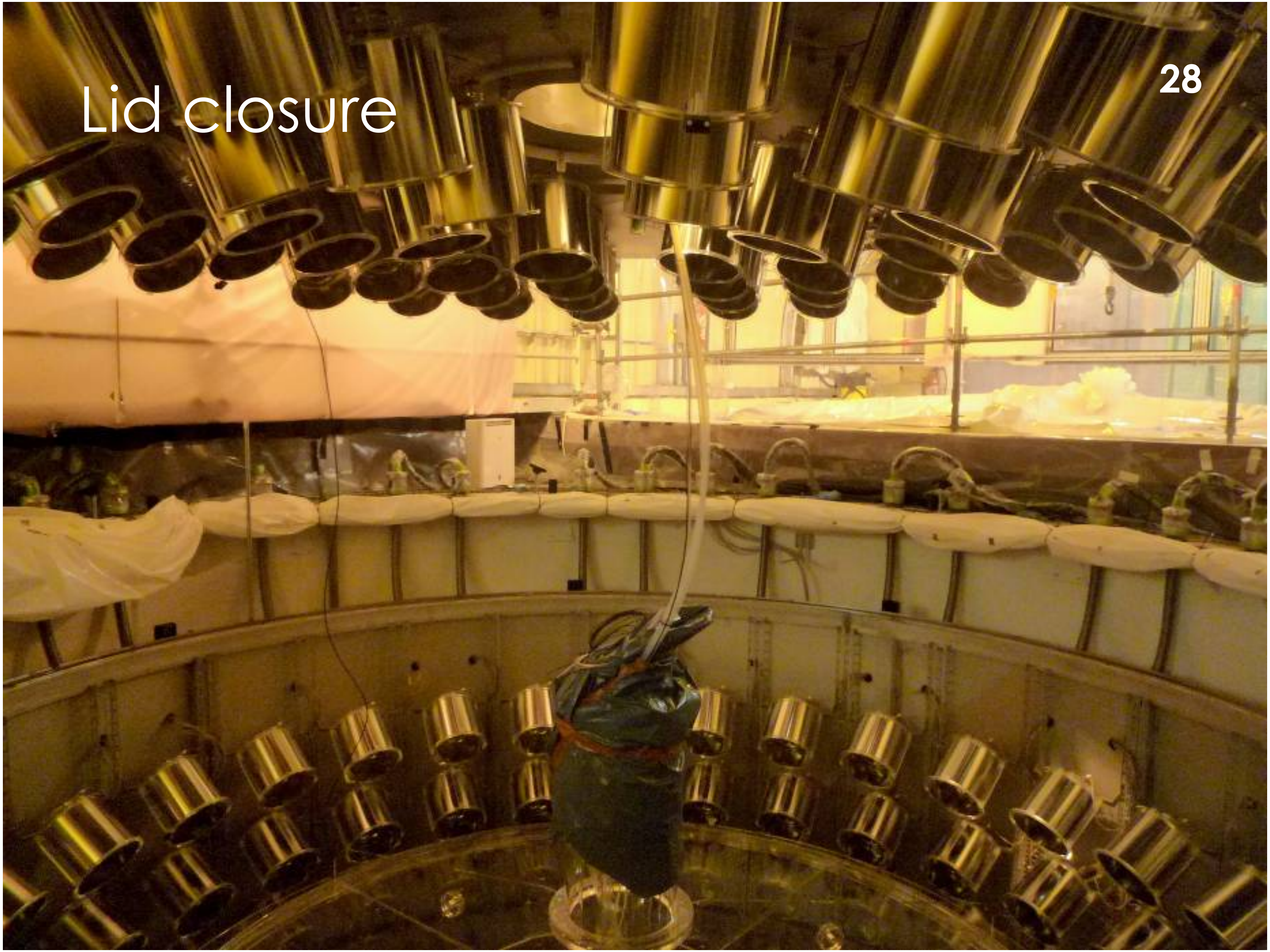
Buffer PMTs installed



Installation of acrylic vessels

Acrylic vessels and PMTs installed

Lid closure



Buffer PMT volume closed

Steel shield installed

Outer veto installation completed

Milestones

- May 2008 – October 2010: far detector construction
- December 2010: far detector filling completed
- April 2011: far detector commissioned
- **April 2011: start physics data with far detector**
- July 2011: Outer veto commissioned
- July 2011: Glove box installed
- August 2011: First campaign of calibration
- **November 2011: First release of physics results**
- June 2012: Expected delivery of near lab
- End 2012: Expected near detector completion
- Beg. 2013: Start data taking with far and near detectors

Near detector lab civil construction

- Started April 2011
- Delivery June 2012
- Detector construction until end 2012
- Overburden: 120 mwe

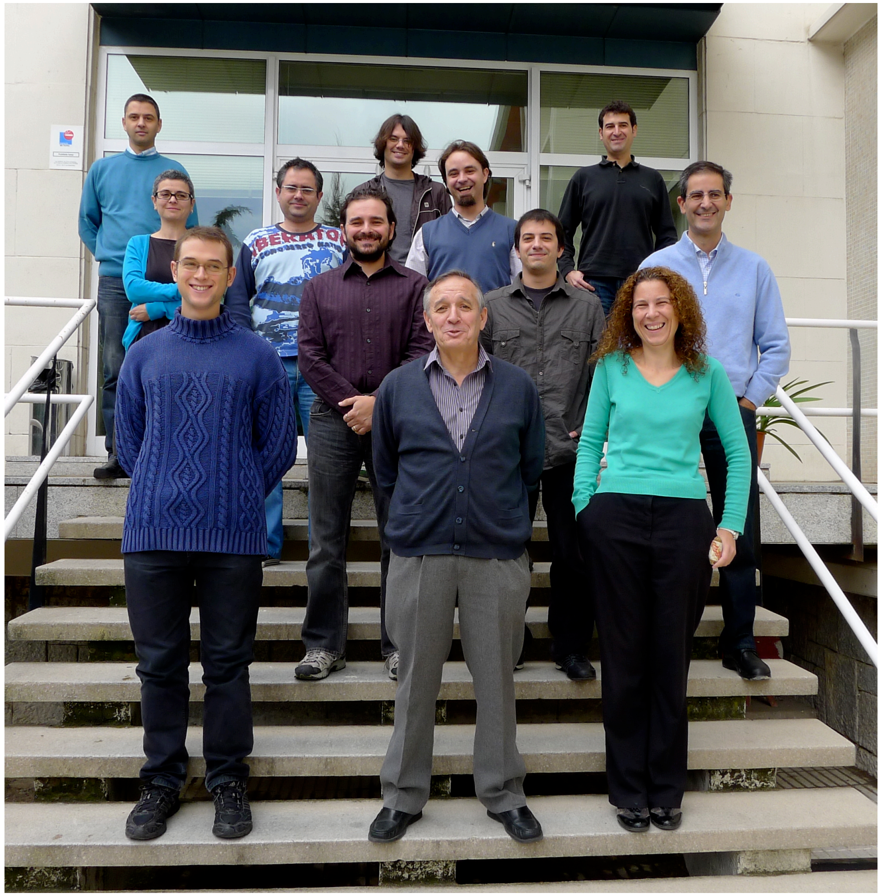
CIEMAT contribution

Experimental neutrino group at CIEMAT

RESEARCHERS	
I. Gil Botella	(I. P.) Permanent
M. Cerrada	Permanent
C. Palomares	Permanent
P. Novella	Postdoc
R. Santorelli	Postdoc
J. Crespo	PhD student
M. López	PhD student

ENGINEERS	
E. Calvo	Mechanical E.
S. Jiménez	Electronic E.
A. Verdugo	Electronic E.

TECHNICAL STAFF	
J.M. Ahijado	Permanent
F. García	Permanent
CIEMAT mechanical workshop	



Spanish contributions to Double Chooz

DETECTOR MECHANICS

- Design and construction of special tools for acrylics installation
- Design, construction and assembly of PMT mechanical supports
- Installation of PMTs in the detectors

PHOTODETECTION SYSTEM

- PMT functionality tests
- PMT characterization under magnetic field
- Design, tests, production and assembly of PMT magnetic shields
- PMT light noise characterization

COMMON FUND

- Filling system
- Buffer and veto liquids
- Safety systems
- Running costs

ELECTRONICS

- Design, tests, production and installation of PMT HV splitters

ONLINE SYSTEM

- DAQ Event Builder development

SIMULATION, DATA RECONSTR. AND PHYSICS ANALYSIS

- Detector simulation software
- Data reconstruction algorithms
- Background simulation and analysis
- Neutrino selection
- Analysis tools for sys. and sensit. estimation
- Coordination of the European cluster

Mechanical tools for acrylics installation

- 3 mechanical tools for construction and transportation of *target acrylic vessels*
- 1 mechanical tools for construction, transportation and installation of *gamma catcher vessel*
- Tools designed in collaboration with Saclay
- **Manufactured at CIEMAT workshop in 2008**
- Successful acrylic vessel installation at Chooz in 2009

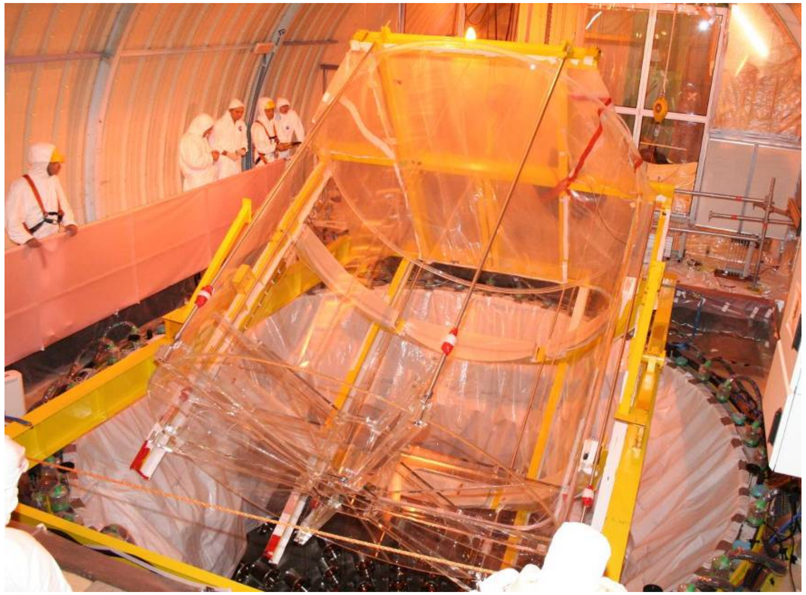

Tools for target vessels

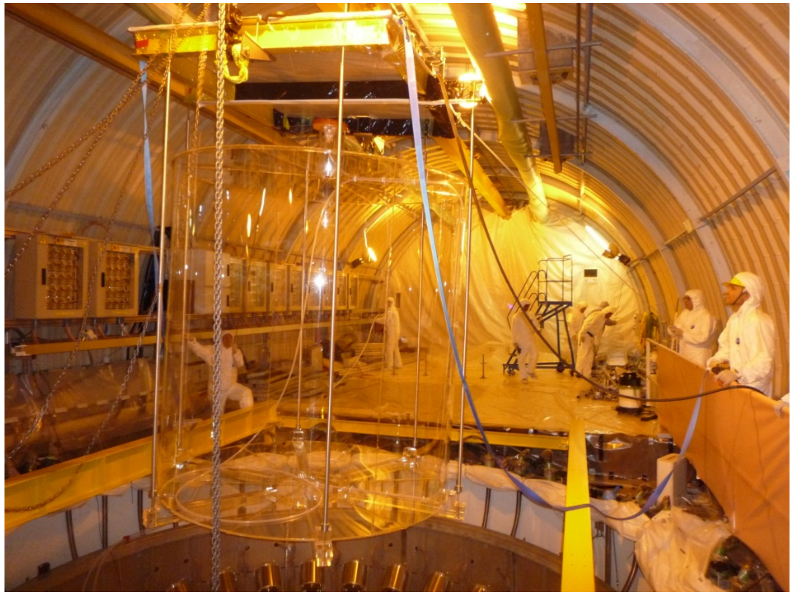

Tool for gamma catcher vessel

Successful installation at Chooz

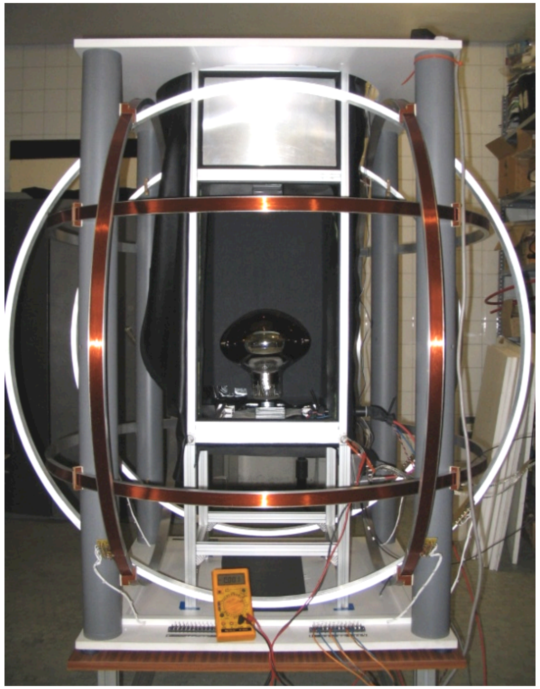
Gamma catcher vessel installation

Target vessel installation





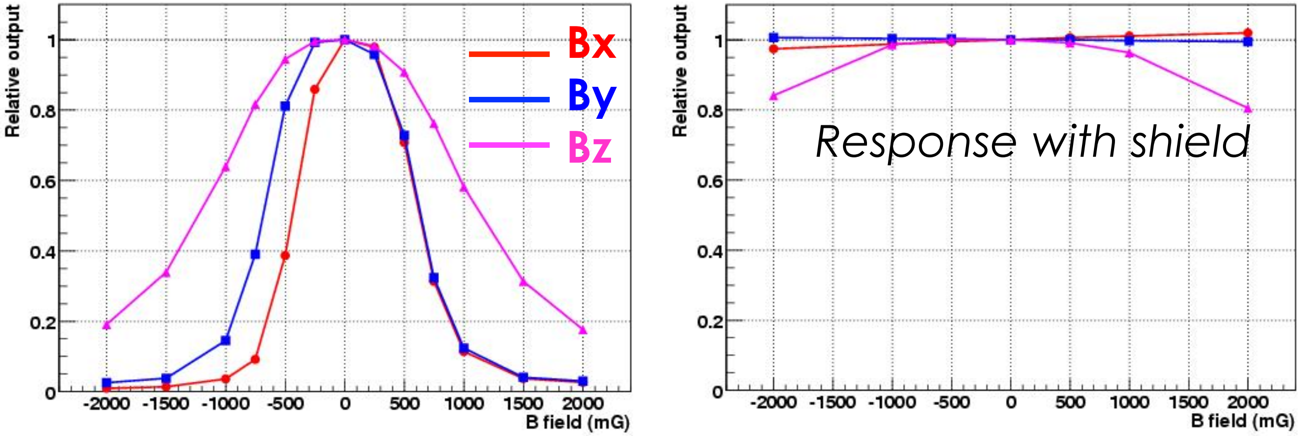
PMT magnetic characterization & magnetic shields



- Hamamatsu 10” R7081 **tests at CIEMAT**:
  - Main characteristics
  - Response under low B-field (for the first time)
  - Uniformity measurements
- **Design and production** of *800 magnetic shields* keeping >95% of signal for B-fields up to 1G in any direction
- **Quality tests** of final production shields before their assembly
- **2 NIM papers published**

Quality tests of shields

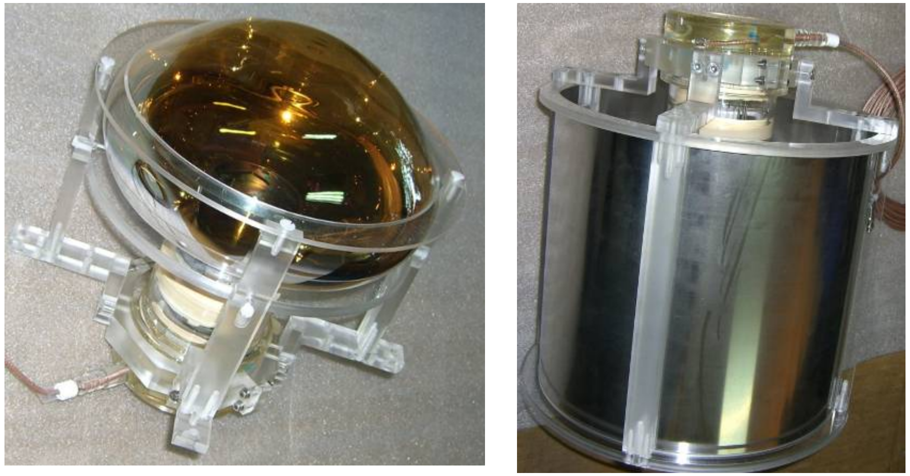
Relative response



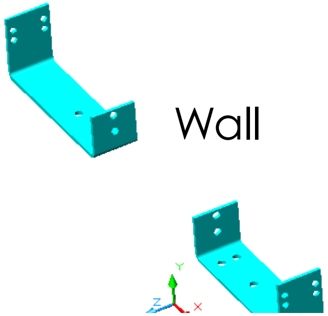
PMT mechanics: design and fabrication

- **Complete design of PMT mechanical supports** for Double Chooz
- Mechanical and pressure tests at CIEMAT
- Design and production of **fixing system to the buffer wall**
- **Production of all mechanical pieces** (~10,000 pieces) **at CIEMAT workshop**
  - 8 technicians during 8 months (only for FD production)
  - **Production also finished for near detector**
- **Quality control**, **cleanliness** procedure and **thermal treatment** of acrylics, nylon and stainless steel components at CIEMAT by our technicians (~8 months)

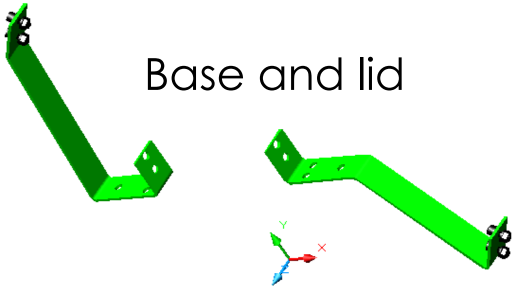
Acrylics (18 pieces per PMT)



Stainless steel

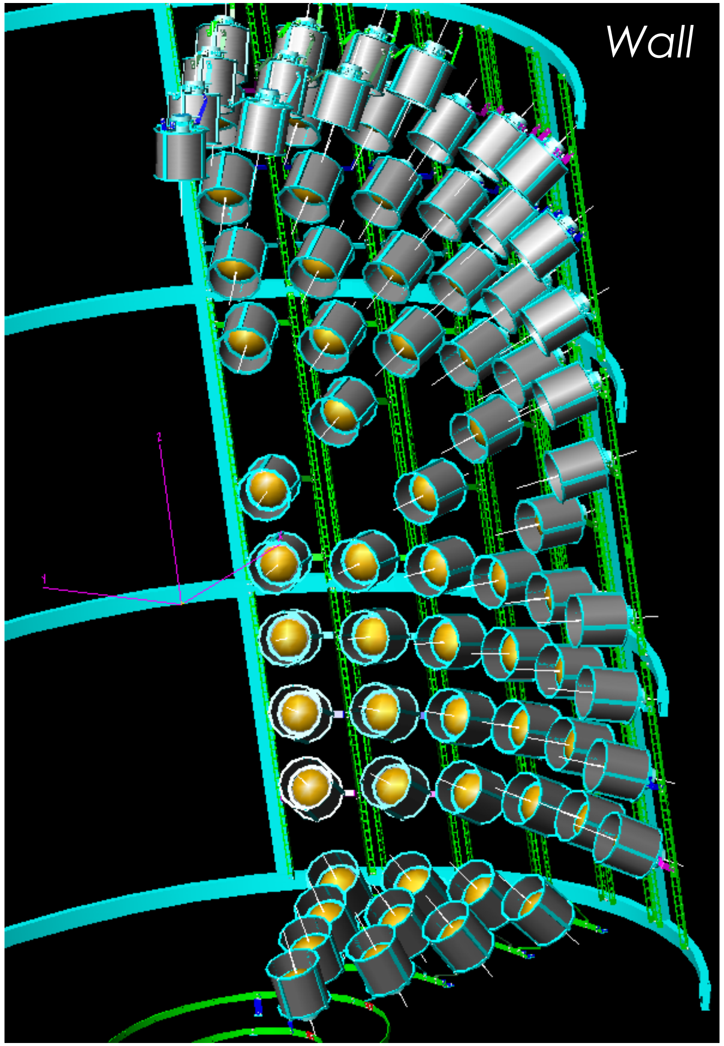


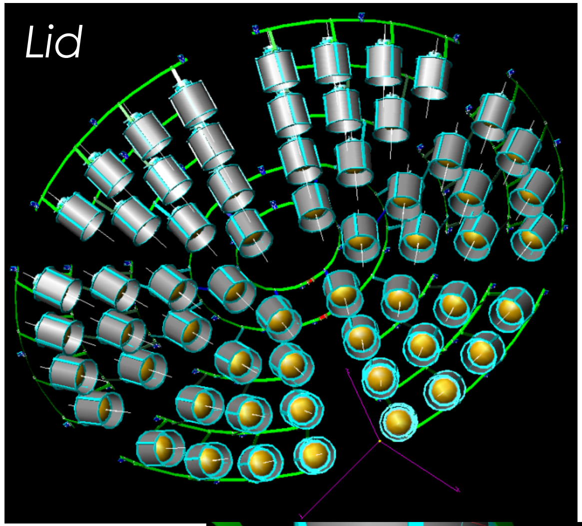
Wall

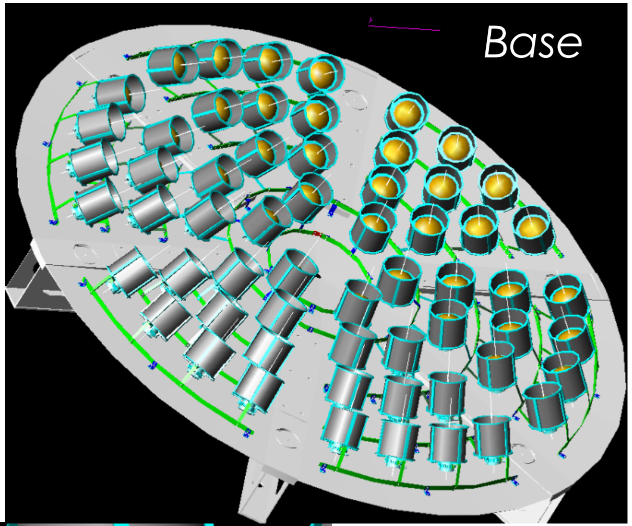


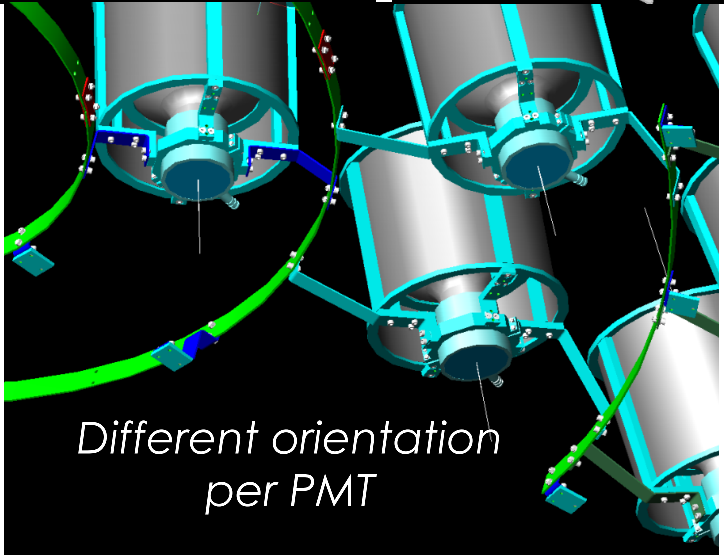
Base and lid

PMT mechanics: distribution and fixing system to the buffer


Wall


Lid

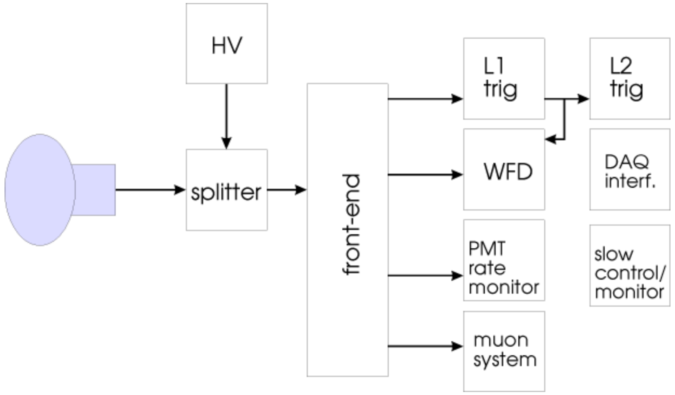

Base


Different orientation per PMT

PMT mechanics: assembly

- **7 weeks** of work for far detector in MPIK Heidelberg
- **4 technicians** from CIEMAT
- Preparation of special tools
- Clean room environment
- 3 CIEMAT technicians **currently assembling near detector PMTs**

PMT HV splitters



HV

splitter

front-end

L1 trig

WFD

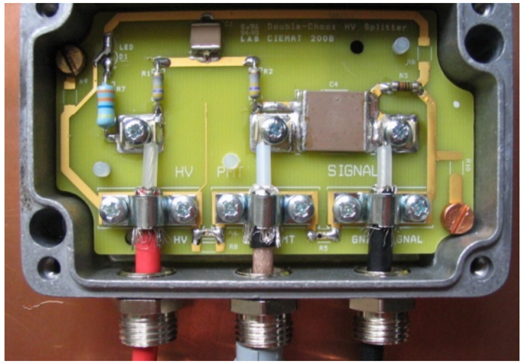
PMT rate monitor

muon system

L2 trig

DAQ interf.

slow control/ monitor



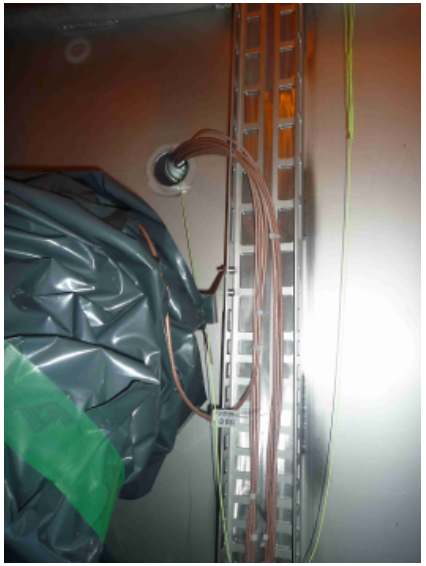
- Divide PMT signal (~10 mVpp) and HV (~1500 V) and filter power supply noise (~300 mVpp) and EMI noise induced in HV cables
- **Design, tests and manufacturing of 480 HV splitters for far detector at CIEMAT labs**
  - 10 modules – 48 HV splitters each
- **HV cables manufactured and tested at CIEMAT**
- Successful installation at Chooz in 2009
- **Currently working in the production for near detector**

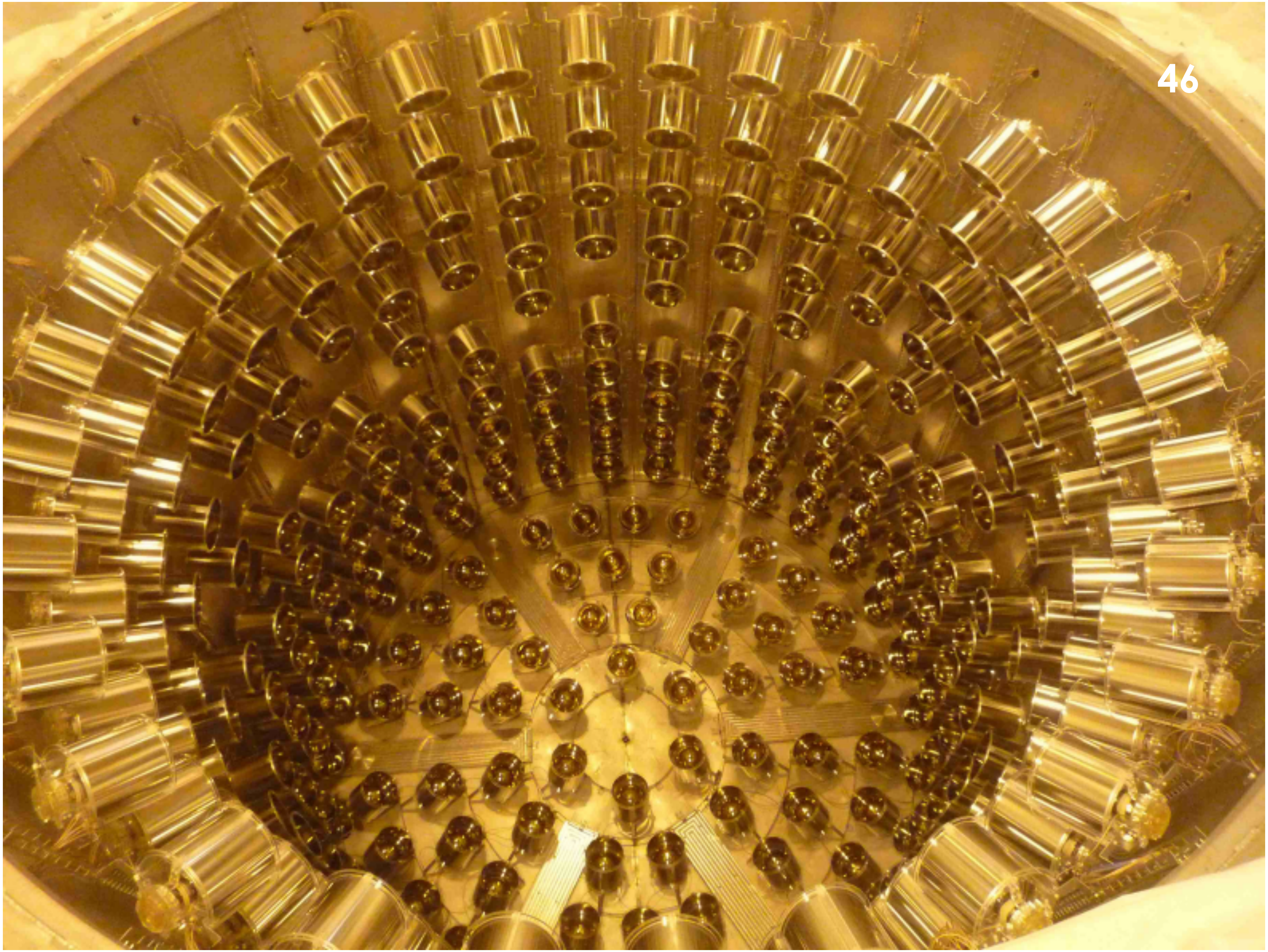
PMT installation inside the pit

- **Detailed procedure** (phase I: bottom and wall, phase II: lid)
- Performed during **2 months by a team of 10 people** (2 technicians from CIEMAT inside the pit + 1 technician for cabling + our engineers)

PMT cabling

- Cabling strategy inside & outside the detector designed by our engineers and technicians





PMT installation on the lid

- One more week for installing 60 PMTs on the lid

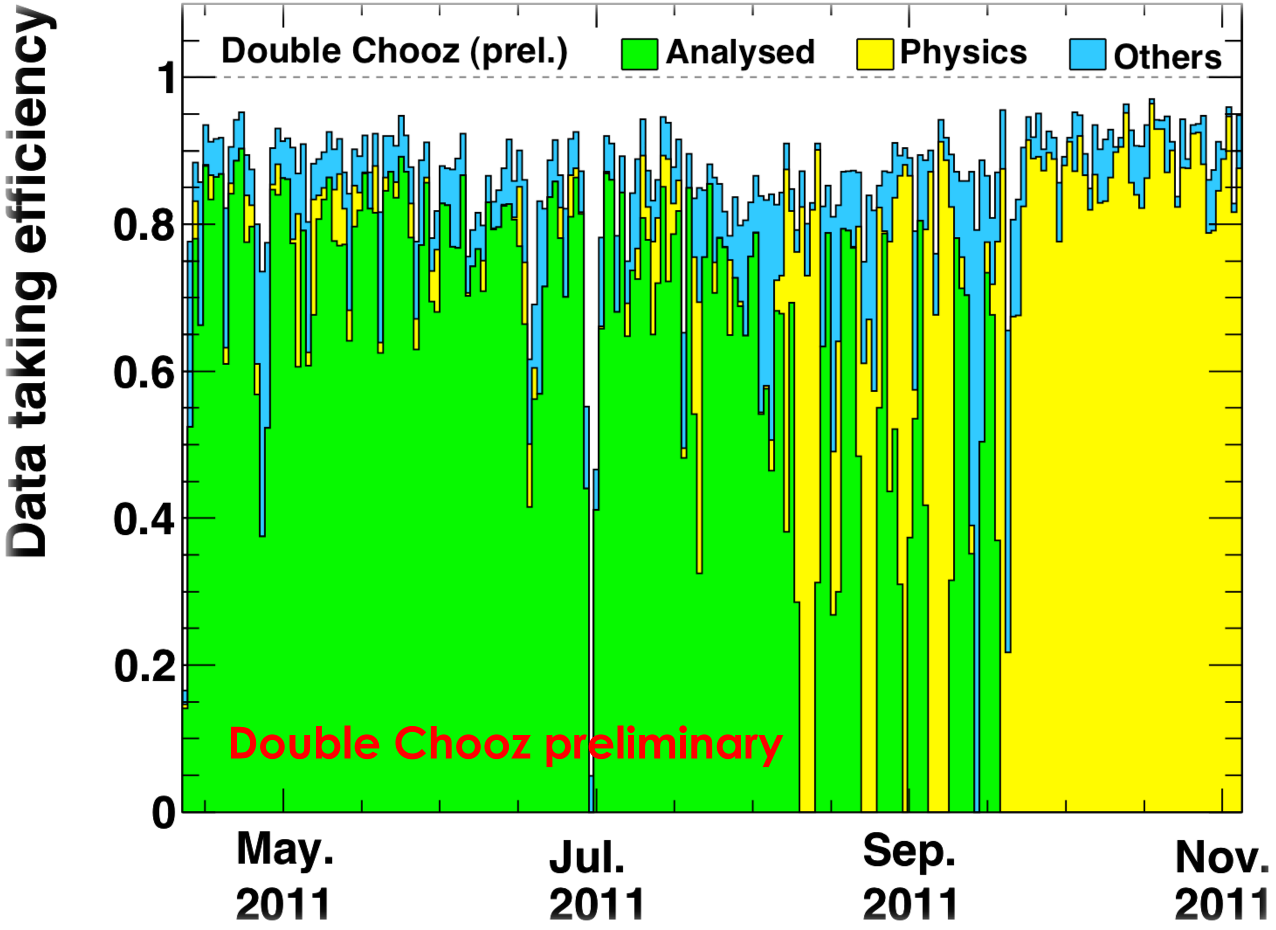
First physics results

Presented in LowNu 2011 Korea

November 2011

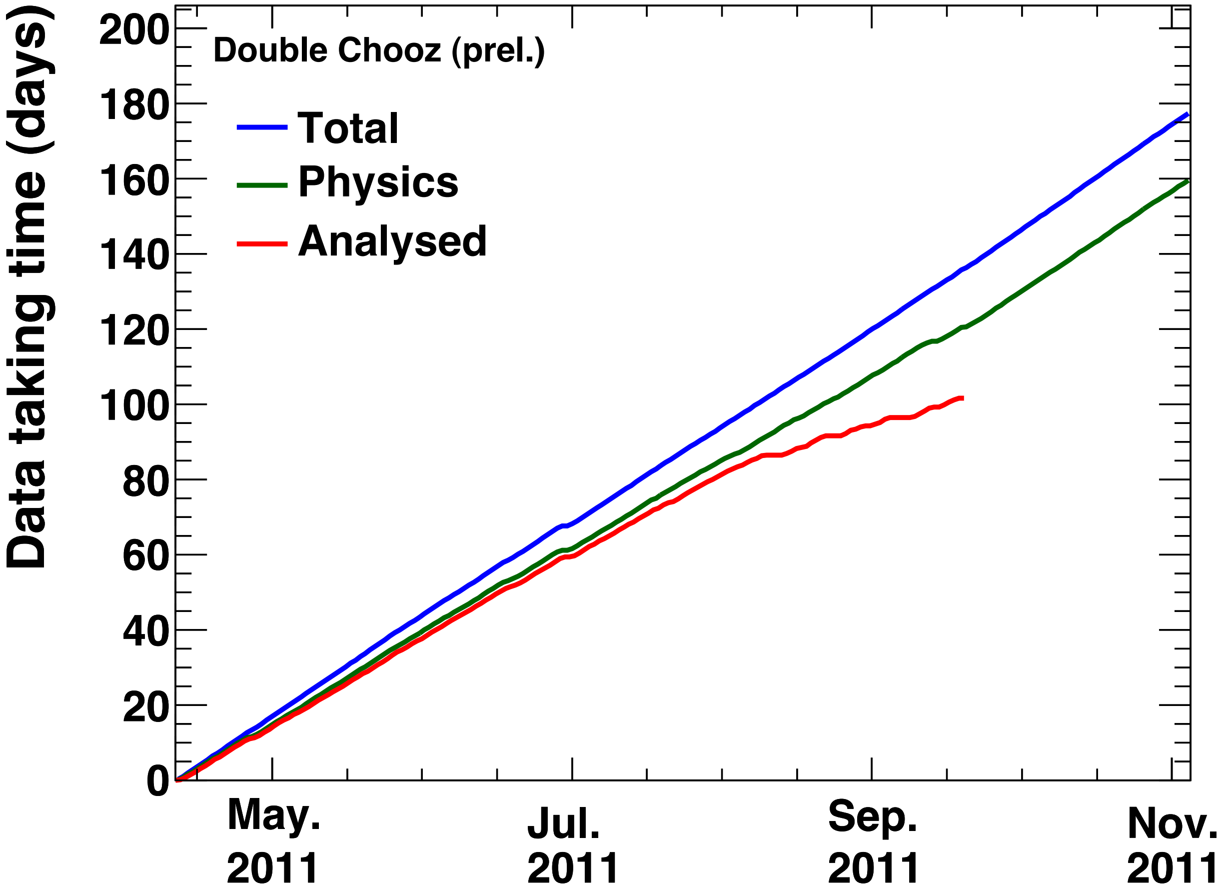
Detector performance

Data taking efficiency



- Taking physics data since **April, 13th 2011**
- Averaged data taking efficiency: **86.2 %**
- **77.5 %** of physics data efficiency
- 10% of calibration runs
- Trigger rate ~120 Hz
- Trigger threshold < 0.6 MeV

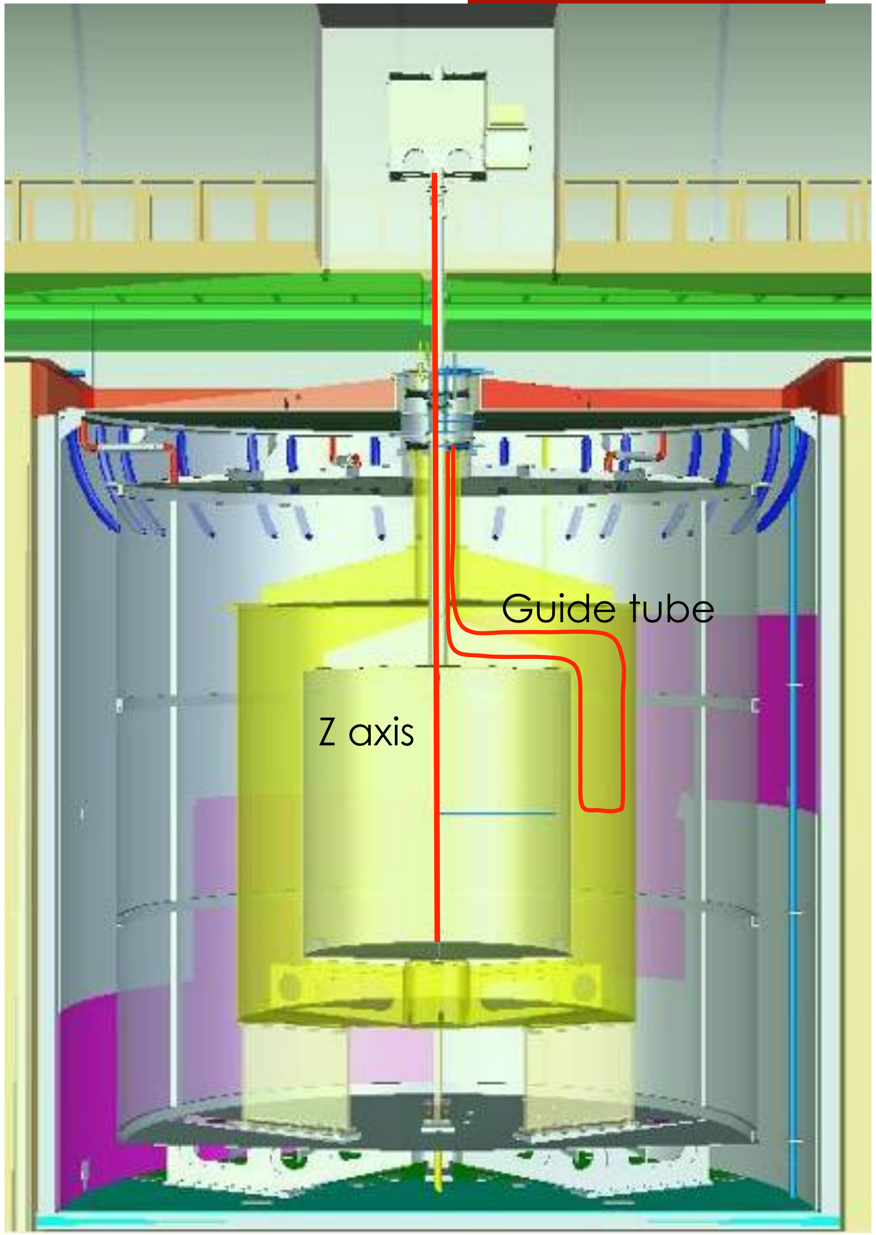
Integrated data taking



- Integrated data taking time for physics (till 4th Nov): **159.6 days**
- Integrated data taking time analyzed: **100 days**
- Run time: 101.5234 days (to Sept 18th)
- Live-time: 96.823 days (1ms muon veto)

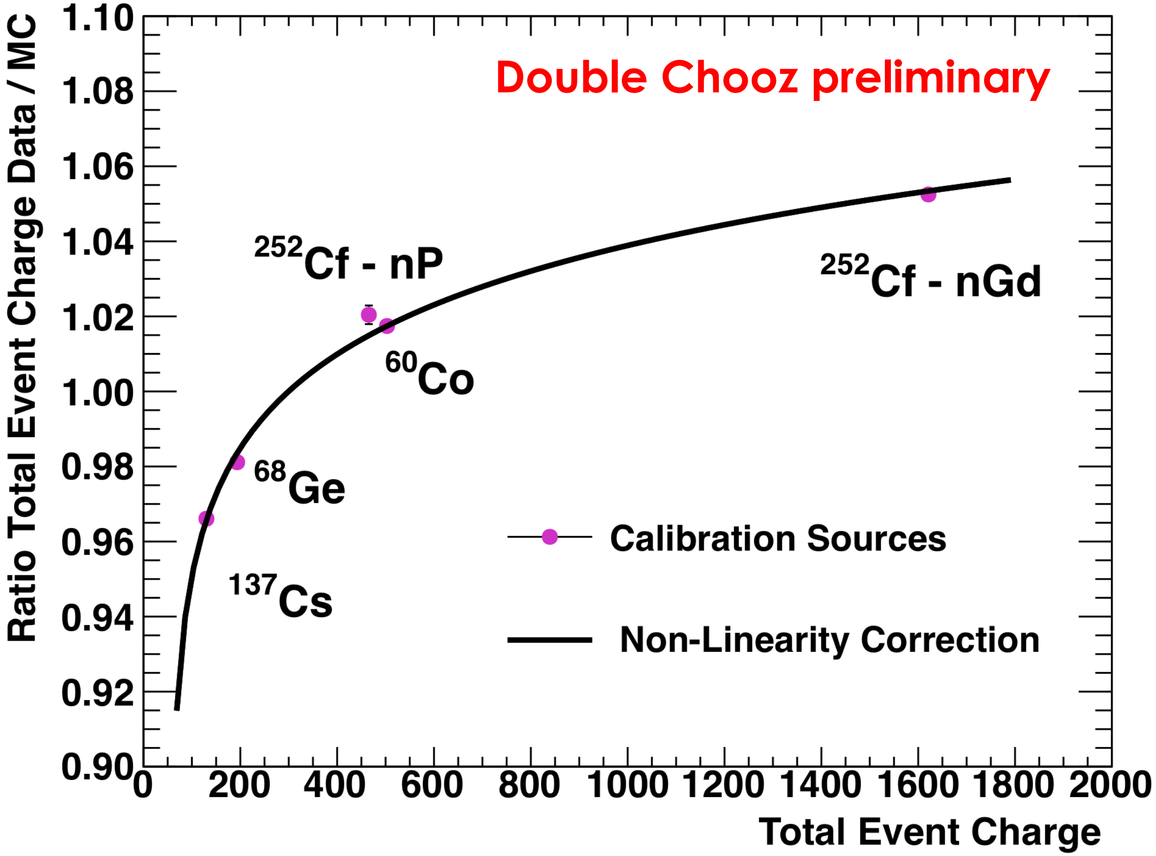
Detector calibration

- Multiple calibration methods:
  - **Light injection** in ID and IV
    - Monitor stability of readout (timing, gain) and scintillator
  - **Radioactive sources** deployment
    - Across most energy scale
- Sources deployed in **Z axis** in target and **guide tube** in GC:
  - ^{68}Ge, ^{137}Cs, ^{60}Co, ^{252}Cf (n source)
    - Linearity and energy calibration
    - Z-correction
    - Neutron detection efficiency



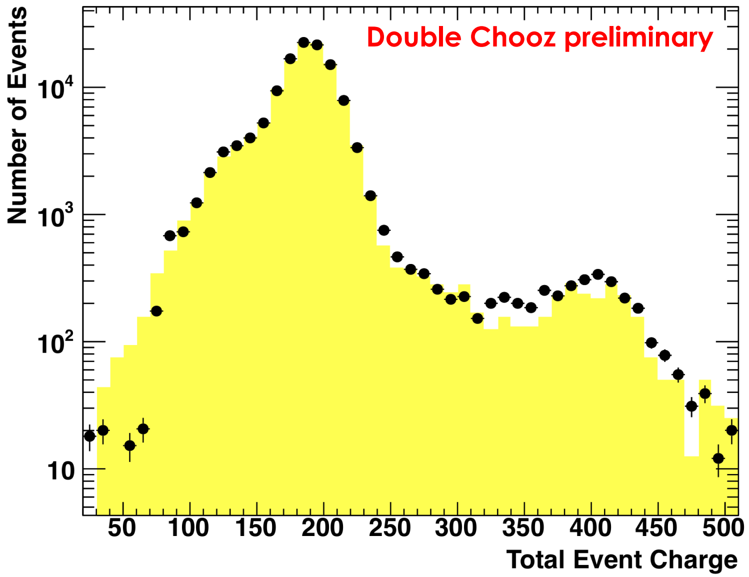
Charge correction

- Calibrate non-linearity due to single photoelectron efficiency, charge reconstruction and electronics effects

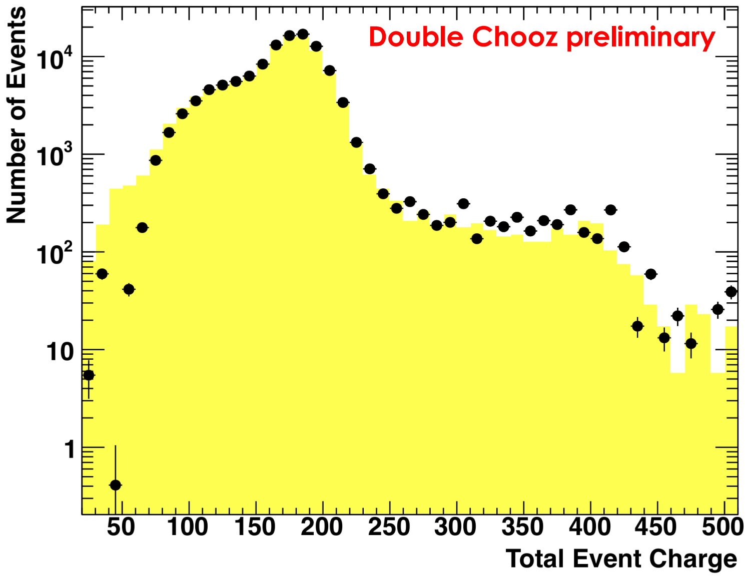


Energy calibration

^{68}Ge Detector Center X=0mm, Y=0mm, Z=0mm



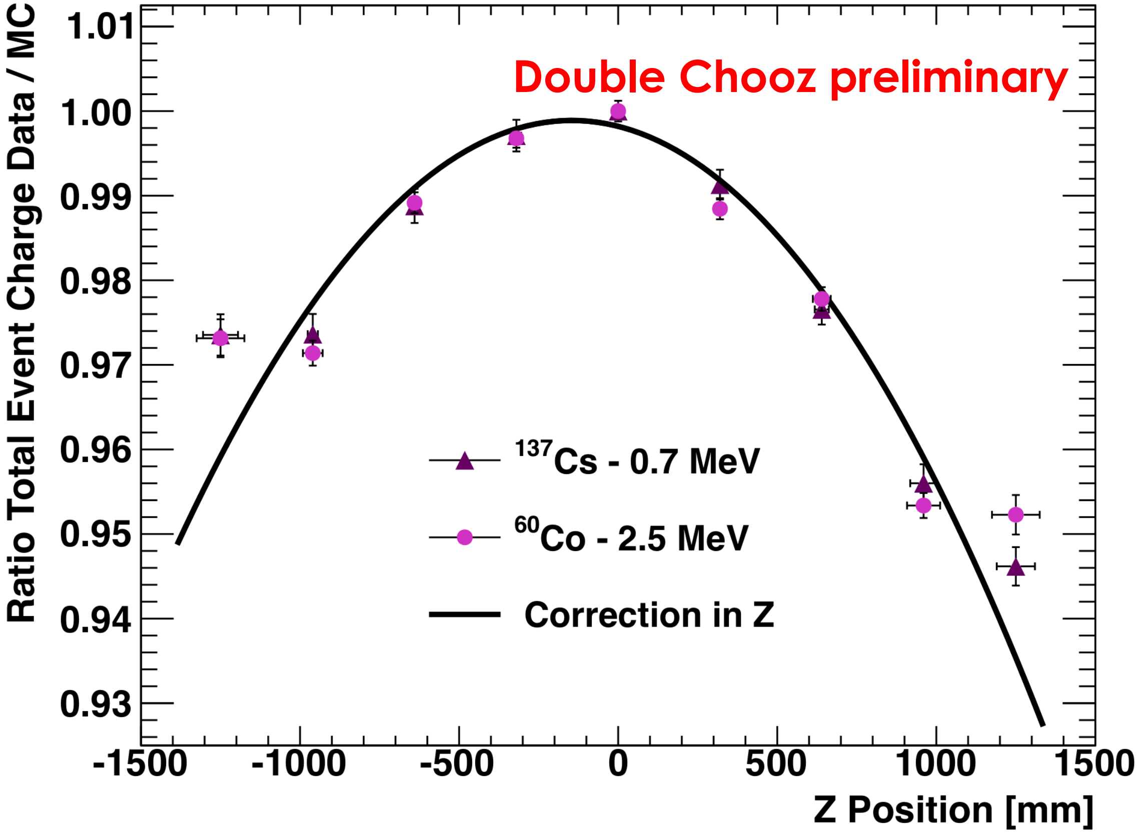
^{68}Ge Guide Tube X=0mm, Y=1433.9mm, Z=0mm



- **^{68}Ge at the center of the target**
  - Positron source
  - The spectrum is well modeled
  - Verification of the energy threshold
- **^{68}Ge in the guide tube**
  - Correction work also in the Gamma Catcher

Z correction

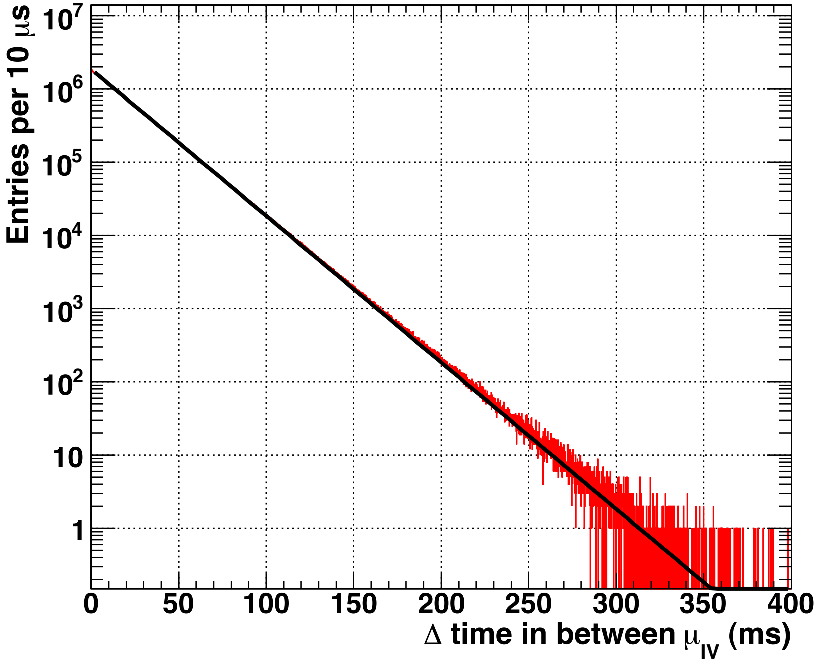
- Calibration of the Z-bias
  - Residuals in the correction will be included in the detector covariance matrix



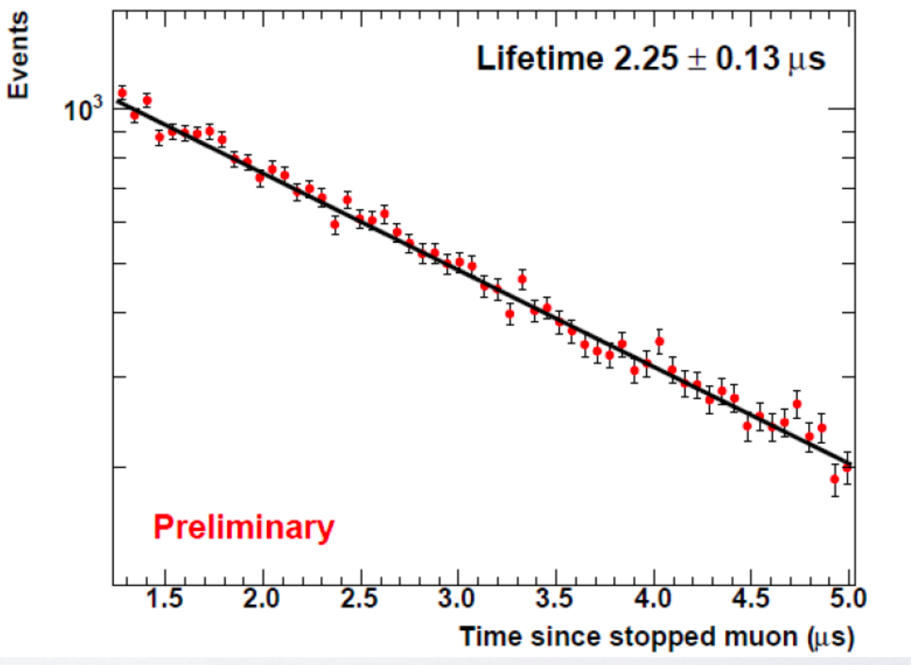
Muon detection

- Rate of muons in IV: 46 Hz
- Rate of muons in ID: 13 Hz
- Stopping muons can also be tagged and the Michel electron is clearly seen
- Michel electrons: $\tau = 2.25 \pm 0.13\ \mu s$ (stat error only)

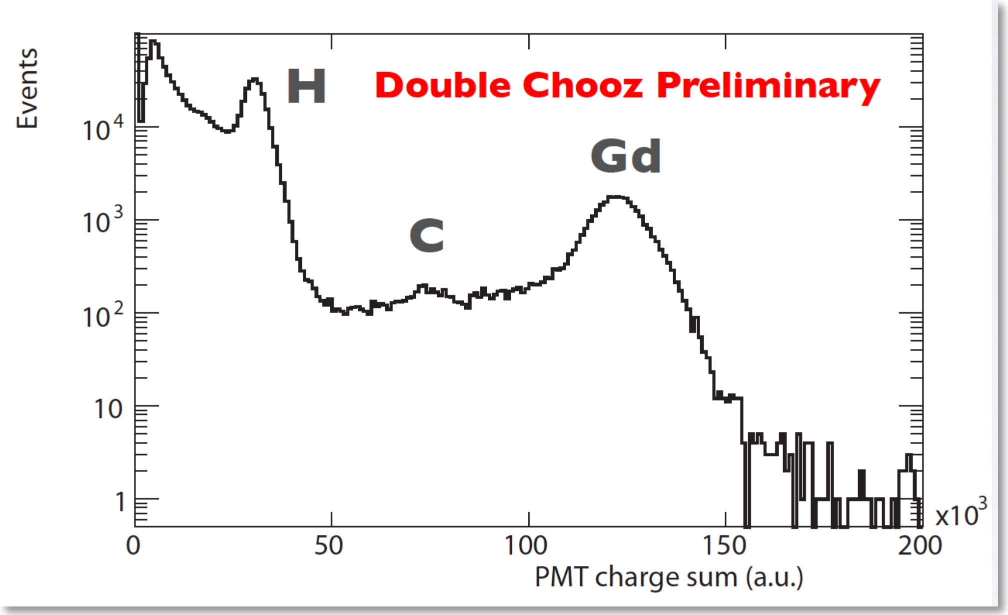
Muon rate in Inner Veto: 46 Hz

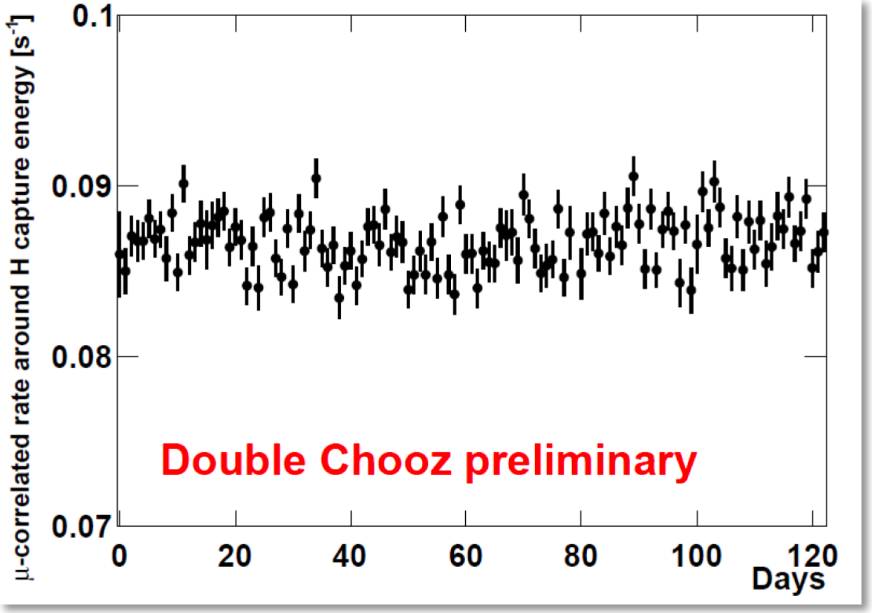


Michel electron timing distribution



Muon correlated physics





Preliminary energy reconstruction only

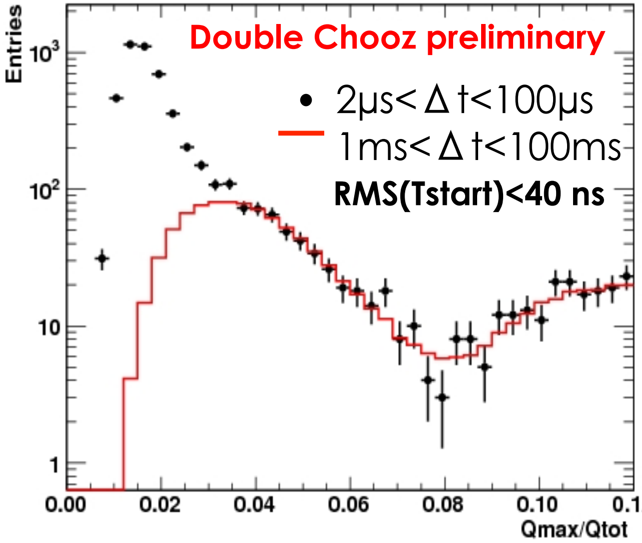
Muon induced neutron capture in H energy window (1.9 – 2.5 MeV)
Rate < 0.1 Hz stable for 120 days

Neutrino selection

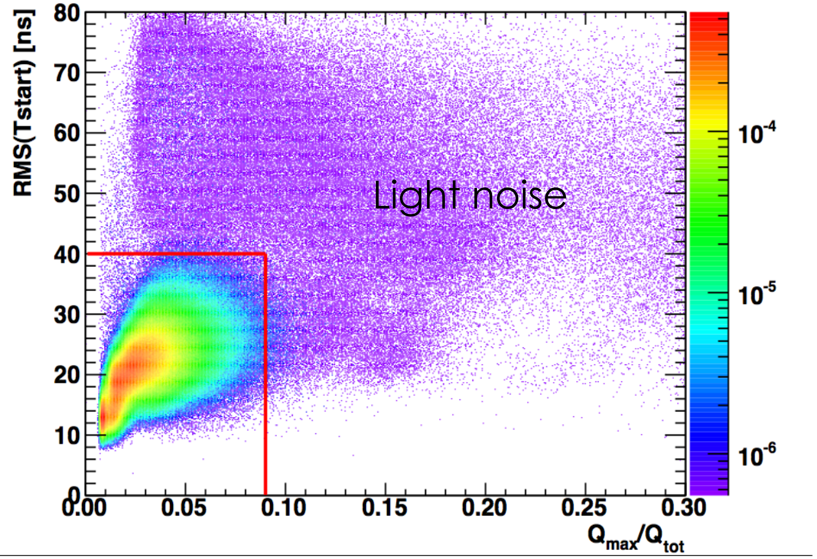
$$\bar{\nu}_e + p \longrightarrow e^+ + n$$

Muon veto and light noise rejection

- **Muon veto**
  - 1 ms veto after each muon (large energy deposition in IV or ID)
- **Instrumental PMT light noise rejection**
  - 15 PMTs turned off (large emitters)
  - Q_{max}/Q_{tot}: emitter PMT sees its own light
  - RMS(T_{start}): light spread in time across all PMTs

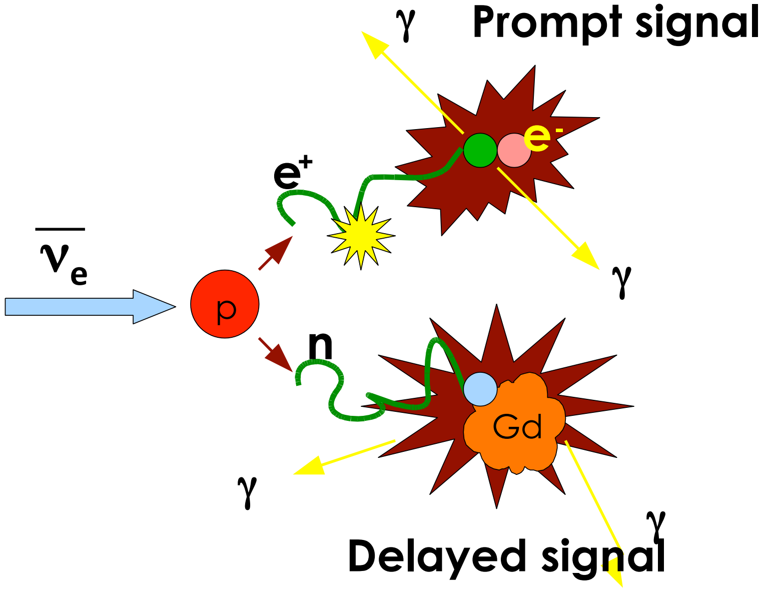


Calibration data

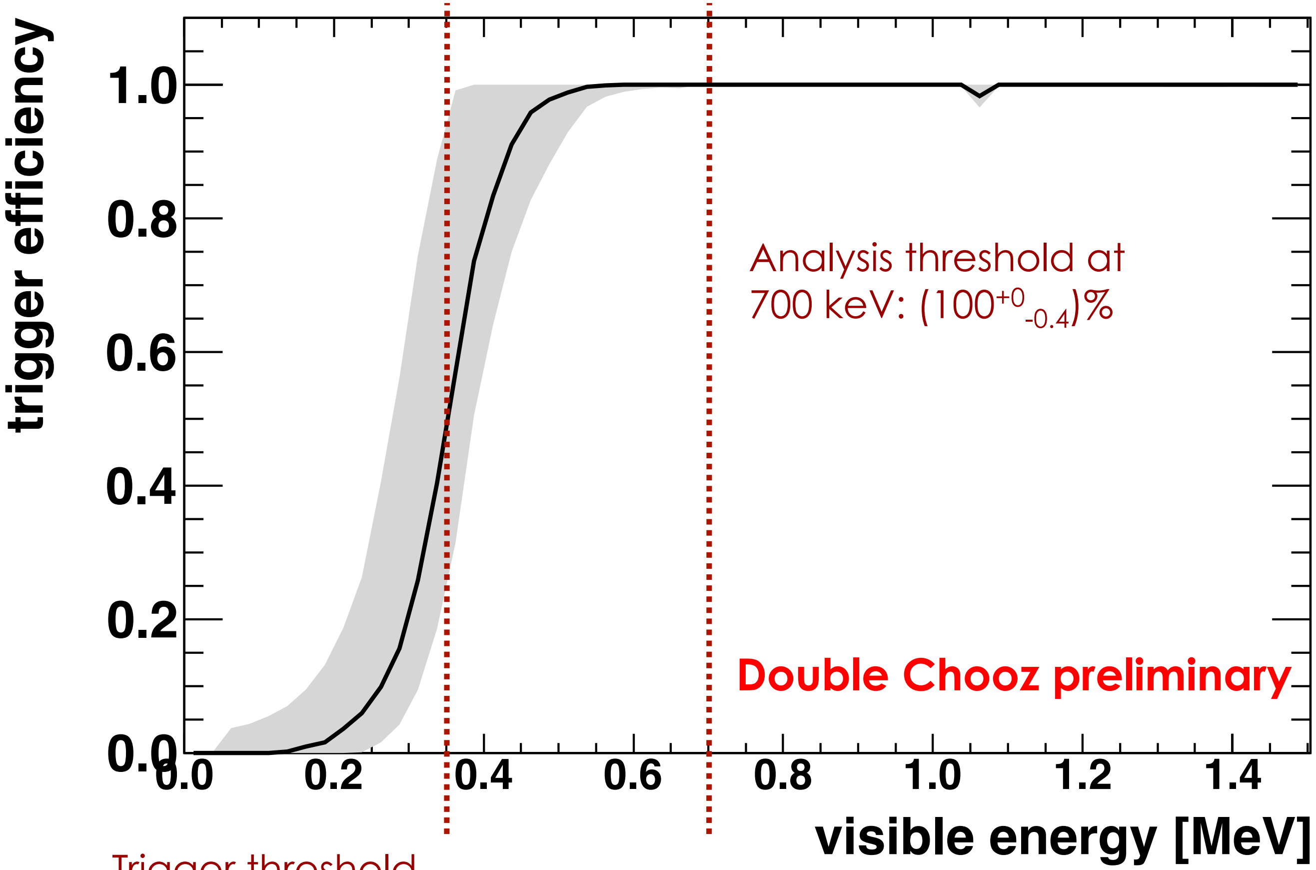


Neutrino selection criteria

- **Prompt signal:**
  - $Q_{max}/Q_{tot} < 0.09$ & $RMS(T_{start}) < 40$ ns
  - **0.7 < E < 12 MeV**
- **Delayed signal:**
  - $Q_{max}/Q_{tot} < 0.06$ & $RMS(T_{start}) < 40$ ns
  - **6 < E < 12 MeV**
- **Coincidence:**
  - Time coincidence: **$2 < \Delta t < 100$ μs**
  - No space coincidence cut
- **Multiplicity:**
  - No events within 100 μs before the prompt
  - Only one delayed event allowed within 400 μs after the prompt



Trigger efficiency

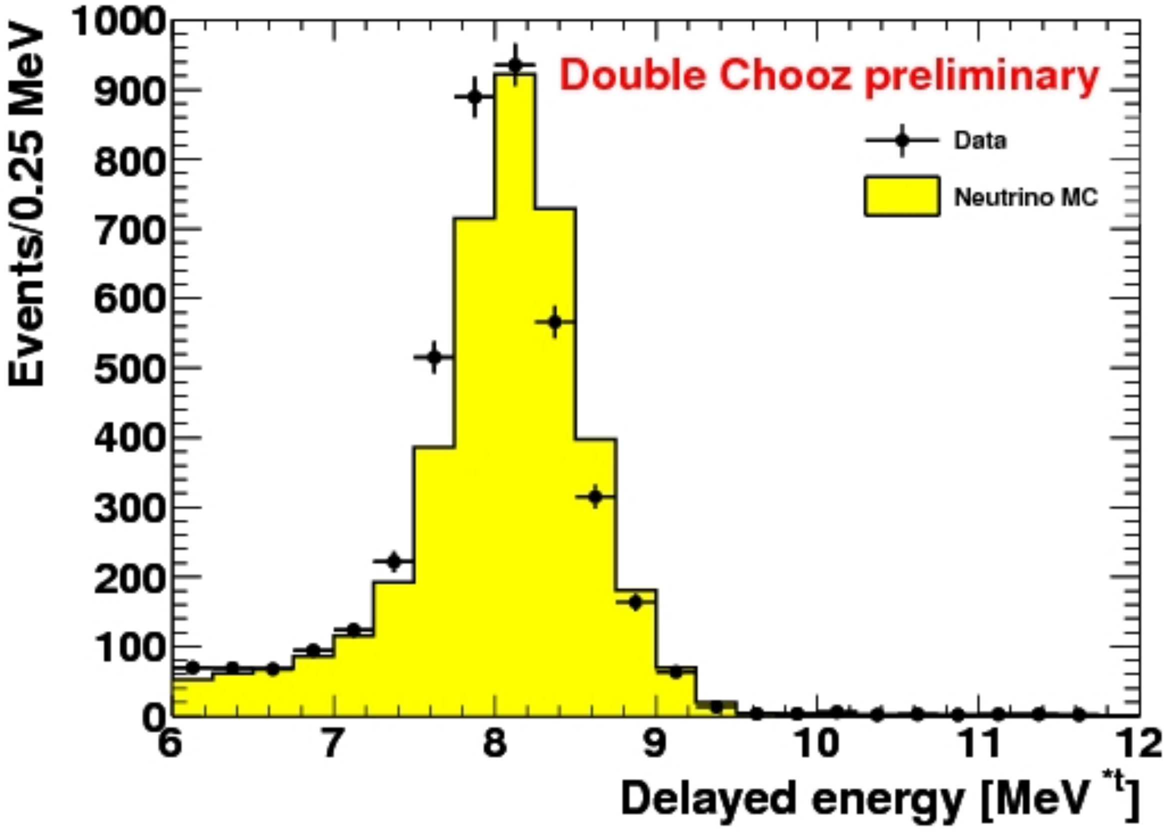


Analysis threshold at 700 keV: $(100^{+0}_{-0.4})$%

Trigger threshold
(50% efficiency)
at 350 keV

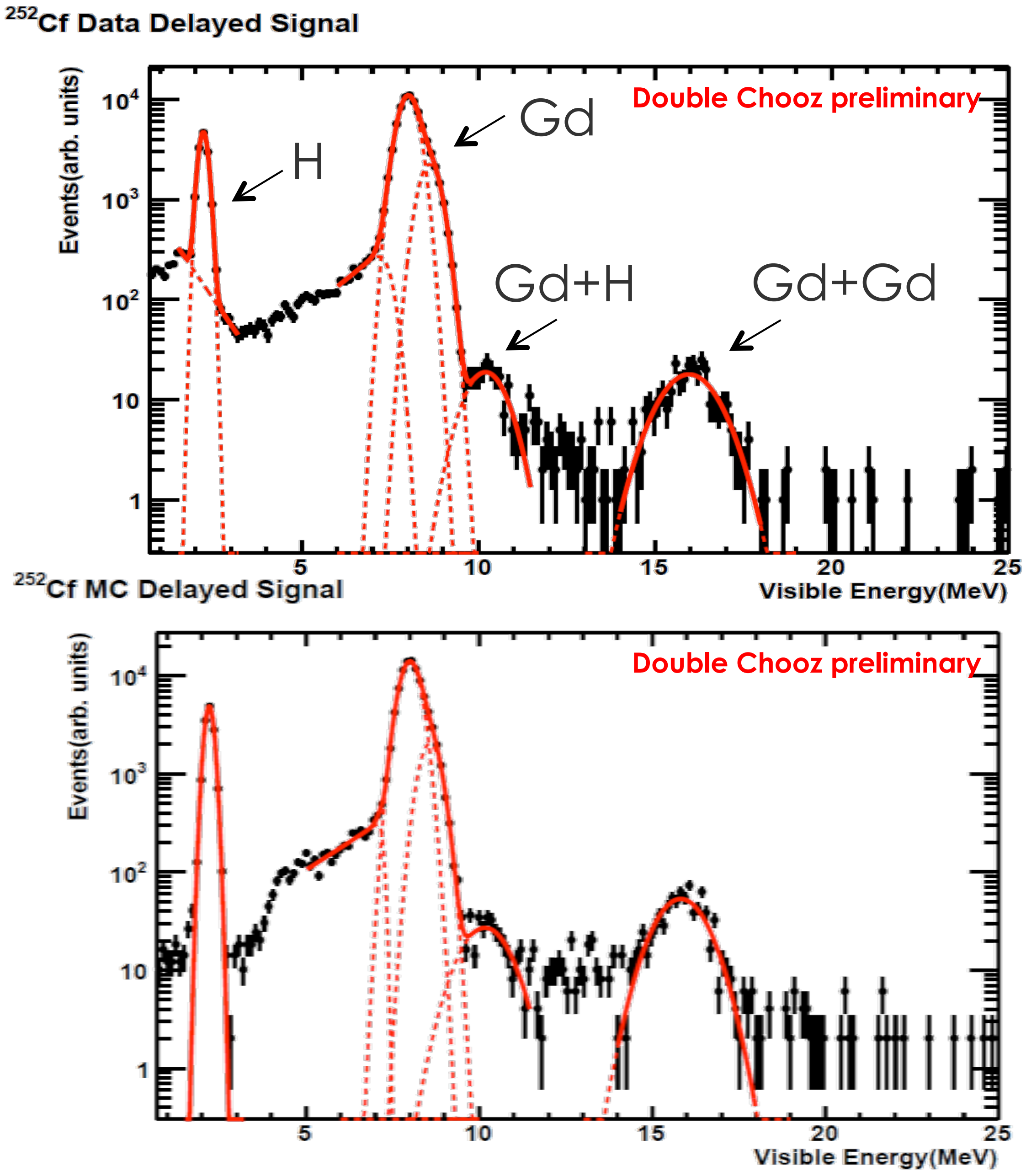
Prompt energy cut efficiency > 99.9 %

Delayed energy spectrum



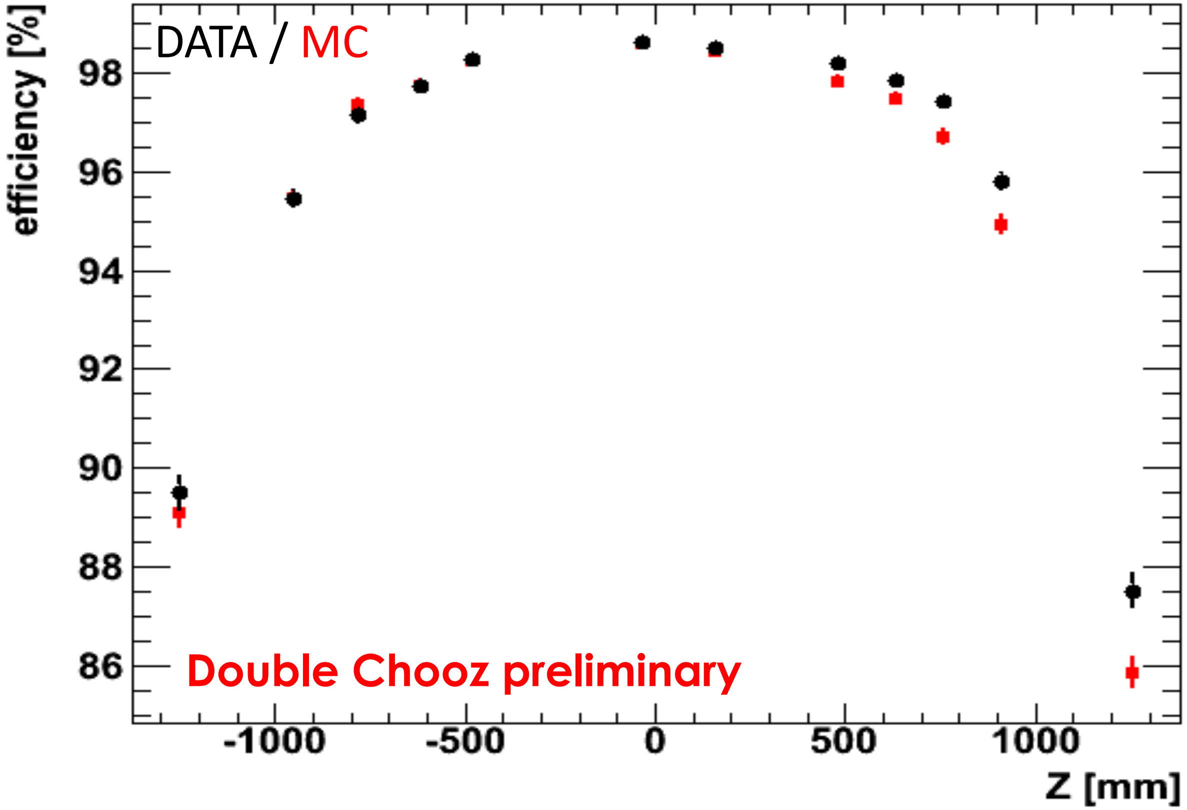
- Fiducial volume is defined by the target

Fraction of Gd capture



- Calibration with a ^{252}Cf source in the central target region
- Deployment along the Z-axis (7 positions)
- Compute Gd/(H+Gd) capture rate
- 2% correction between data & MC
- Gd capture efficiency is 86.0 ± 0.6%

Delayed event energy containment

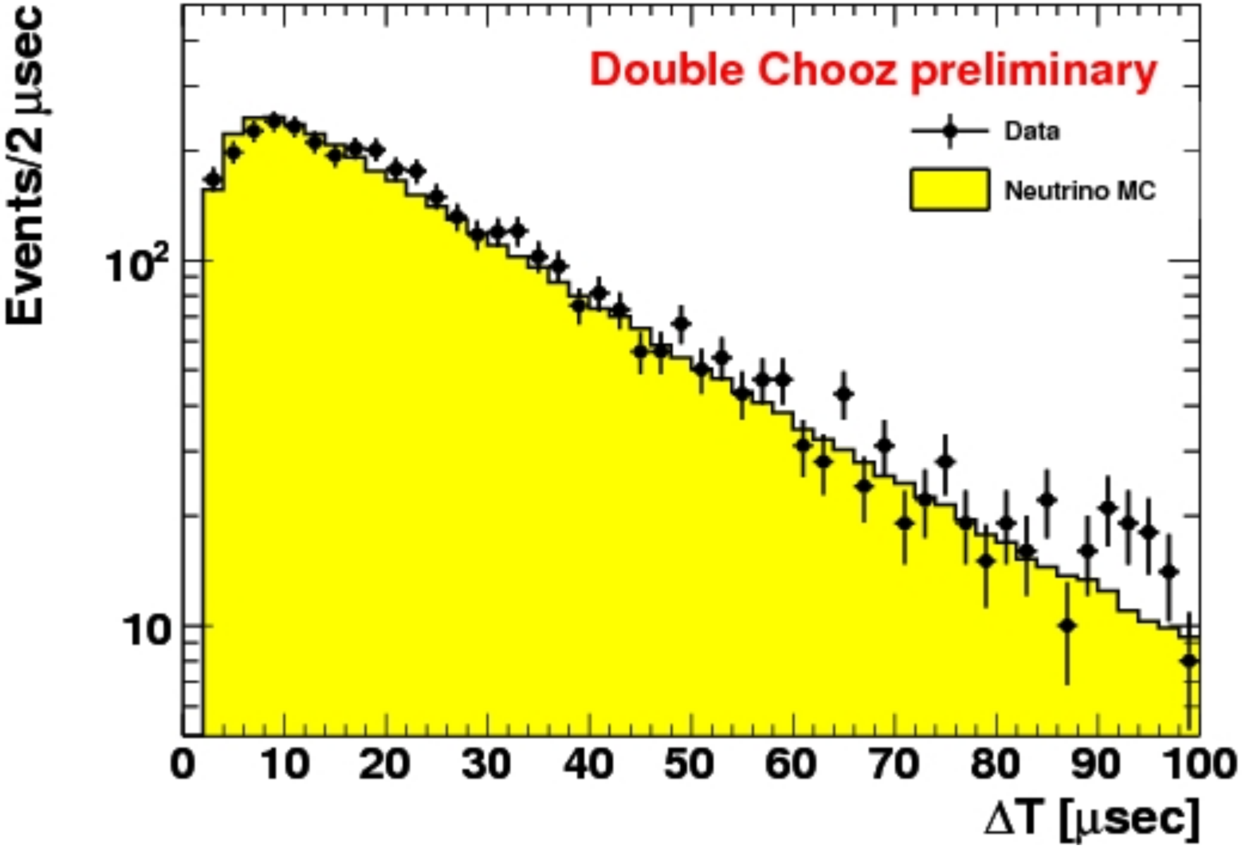


- Part of the Gd-capture gamma's escape the Target + G-Catcher
- Deployment of ^{252}Cf along the Target z-axis
- Eff. (CHOOZ) = # capture [6,12] MeV / # capture [4,12] MeV

ΔE cut efficiency: 94.5 ± 0.6 %

Averaged (Data-MC)/Data relative difference: ≤ 0.6%

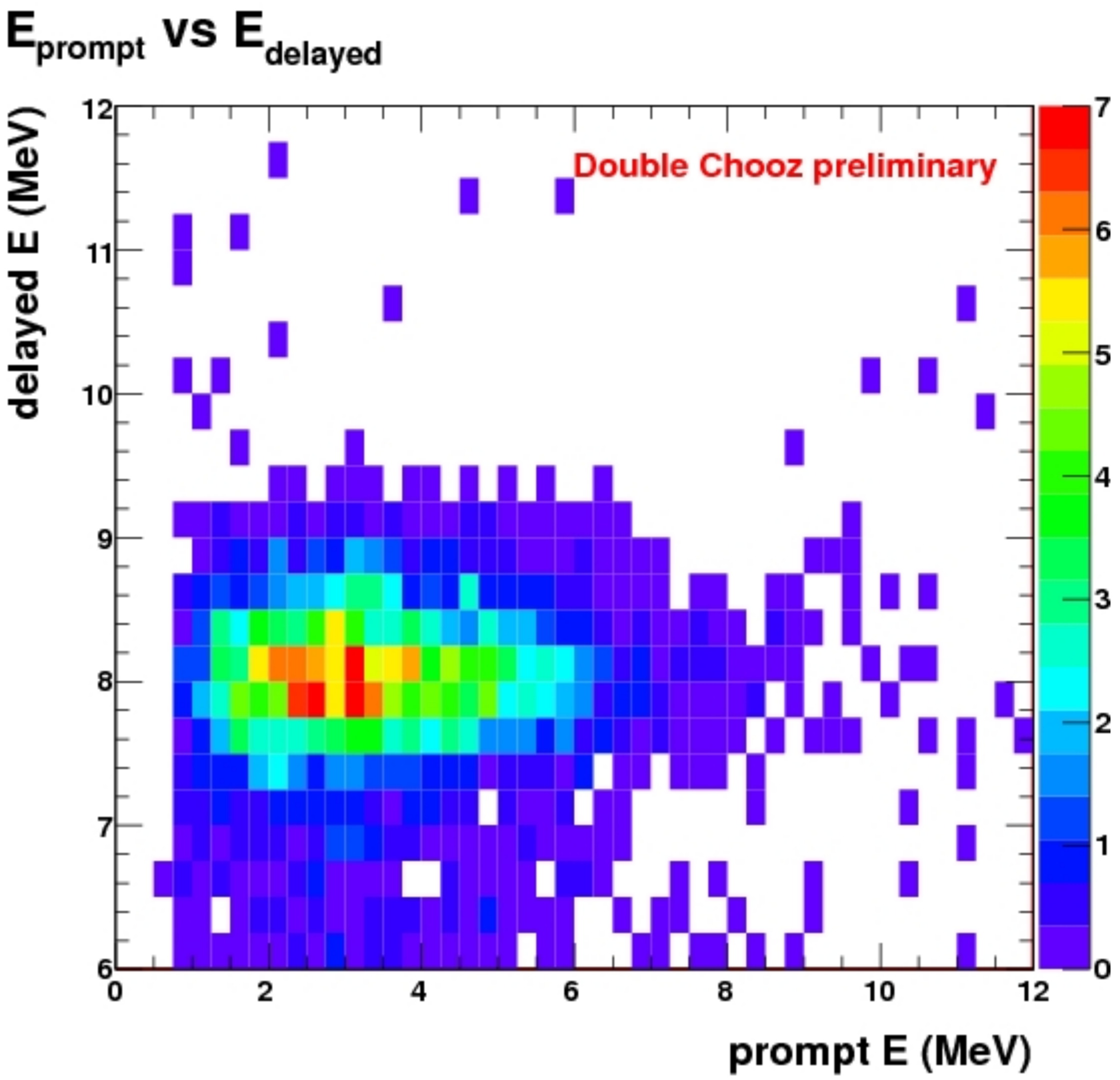
Time coincidence



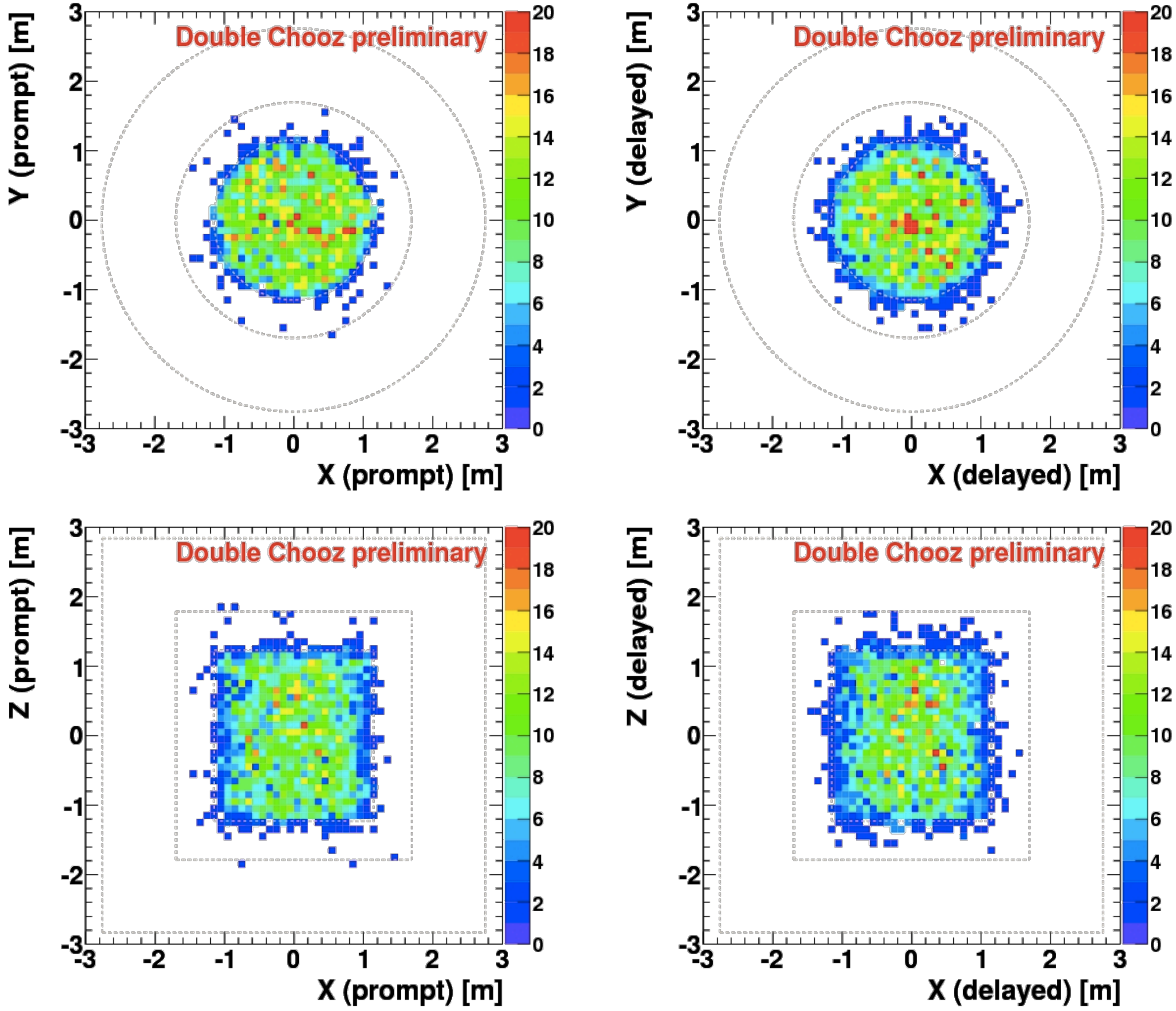
- keV neutrons thermalize within a few µs
- Neutrons are captured on Gd with τ ~ 27 µs

ΔT cut efficiency within [2,100] µs: 96.5 ± 0.5 %

Prompt vs delayed energy

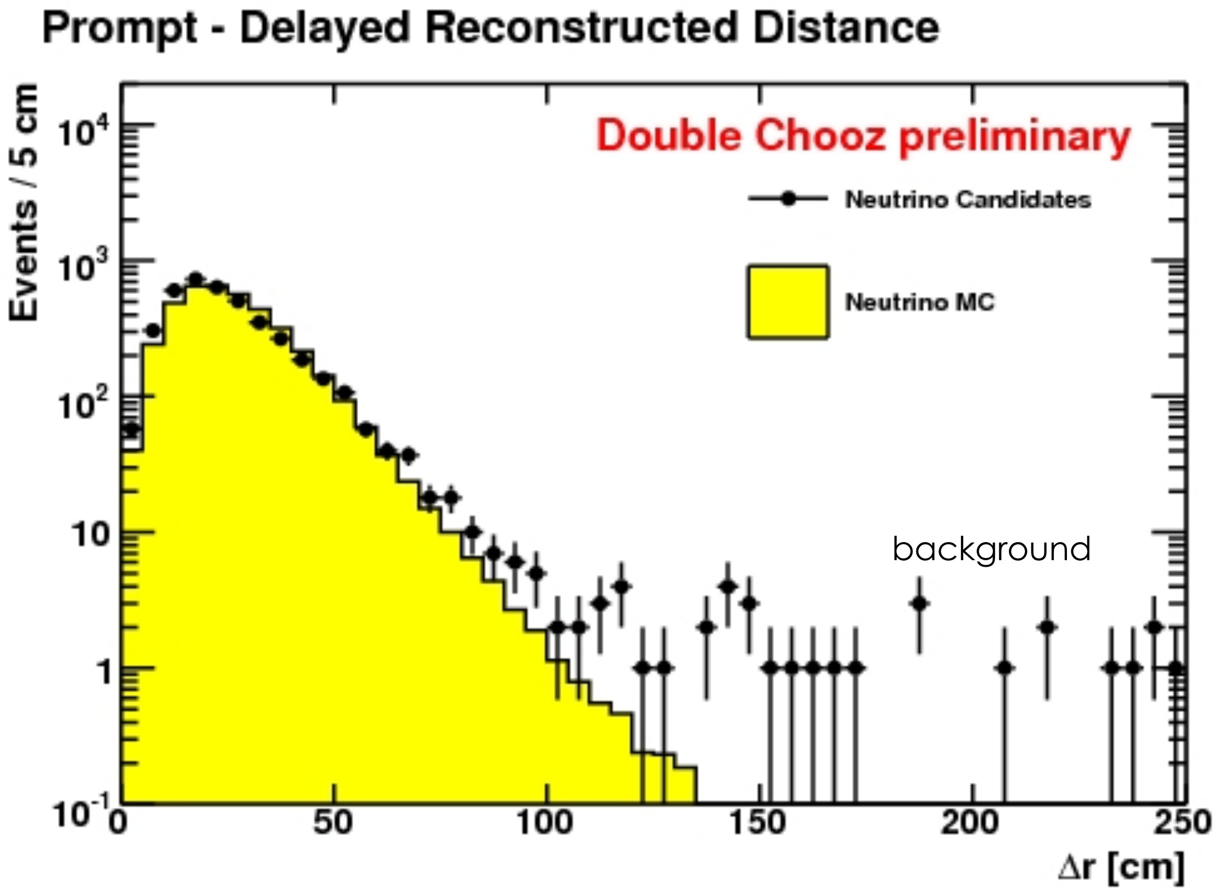


Reconstructed vertex positions



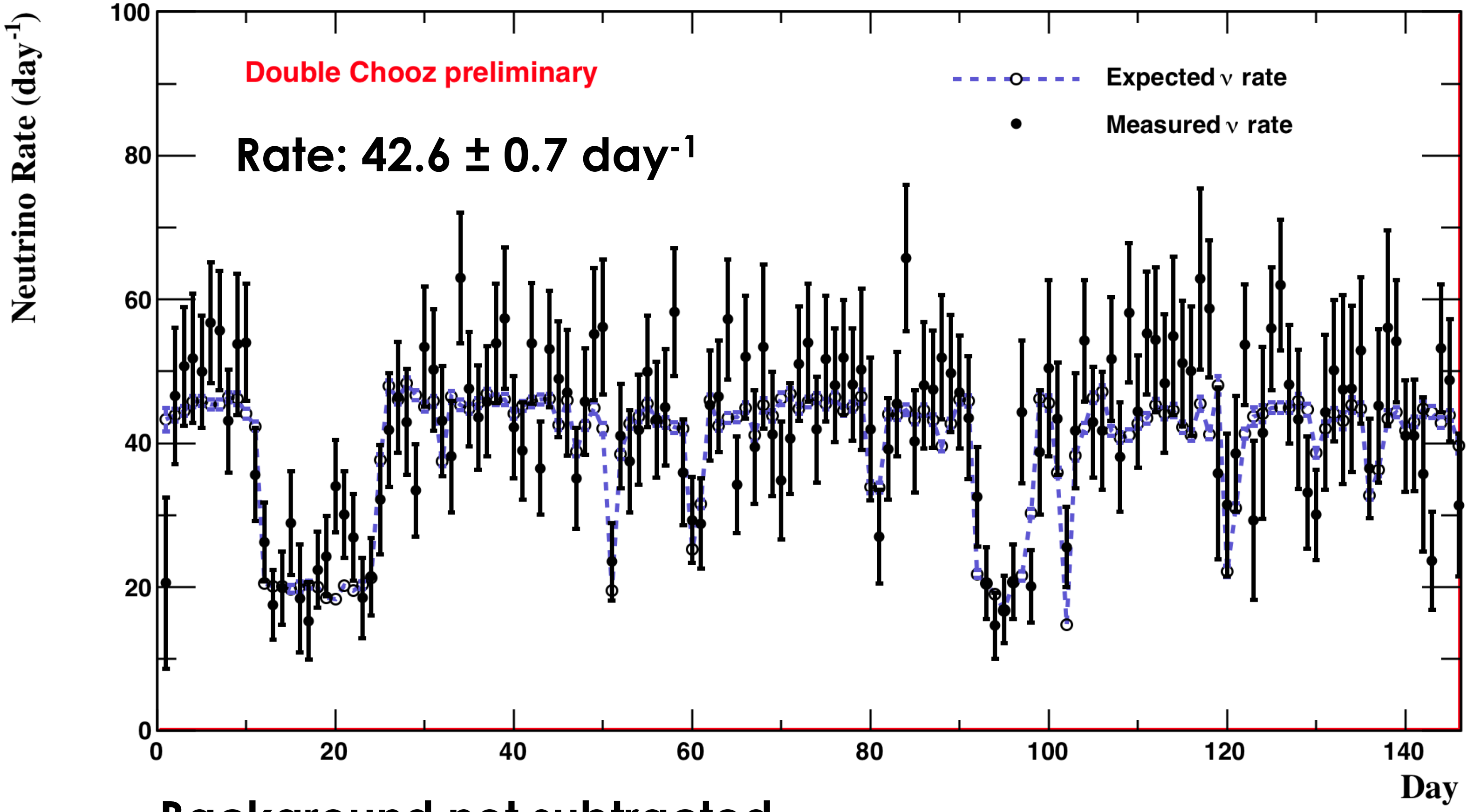
No analysis fiducial cut

Prompt-delayed distance



- Only signal MC
- No need for Δr cut as designed in the proposal

Neutrino candidate rate



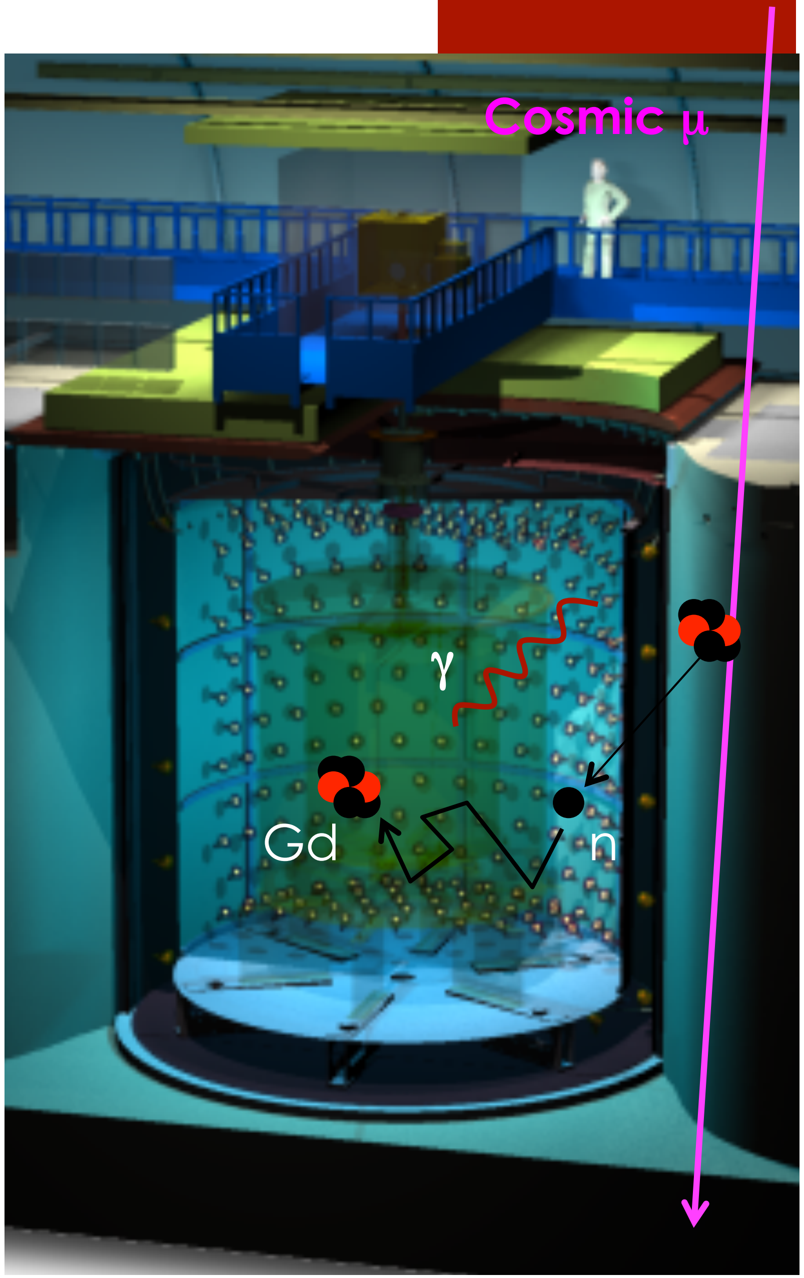
Background not subtracted

➡ low background level !

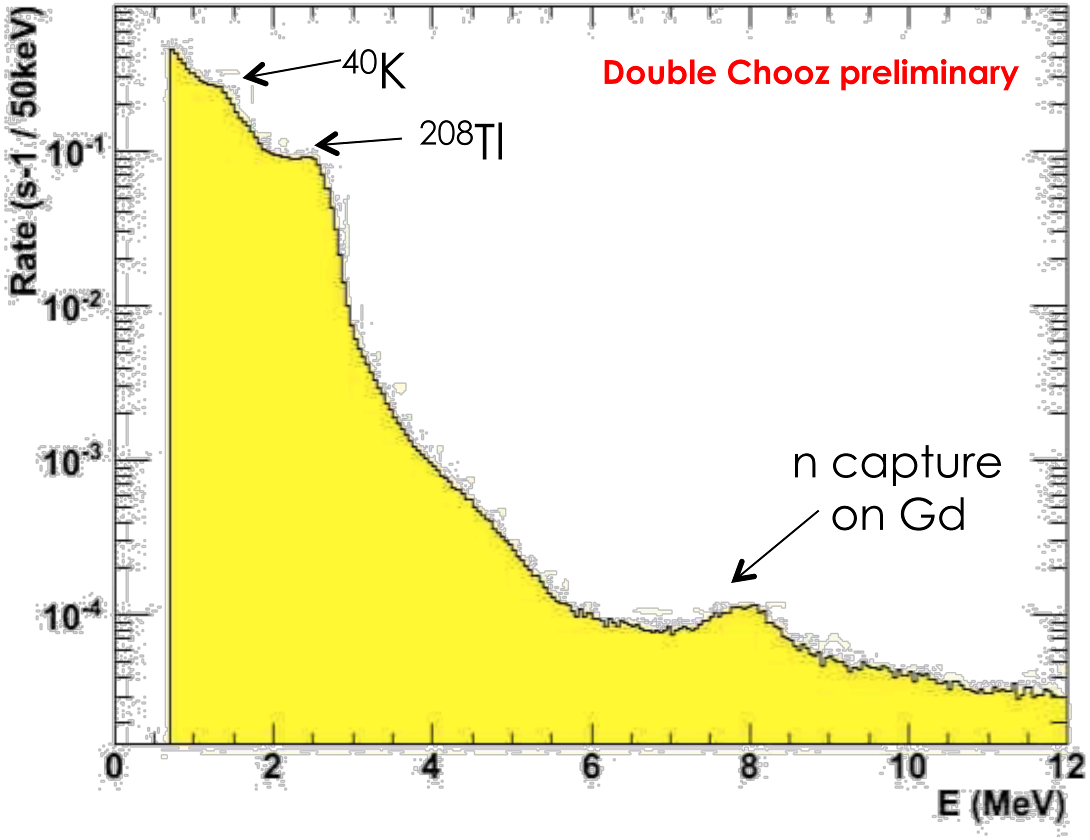
4121 neutrino candidates

Backgrounds

Accidental BG

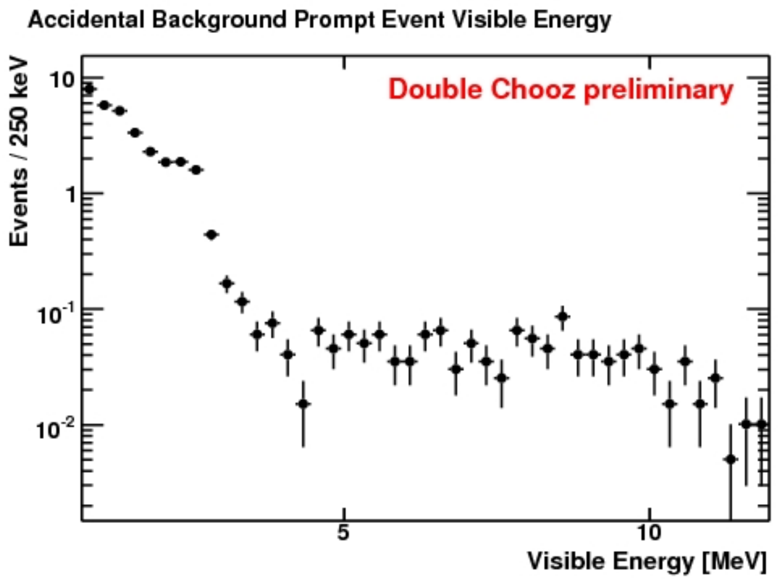


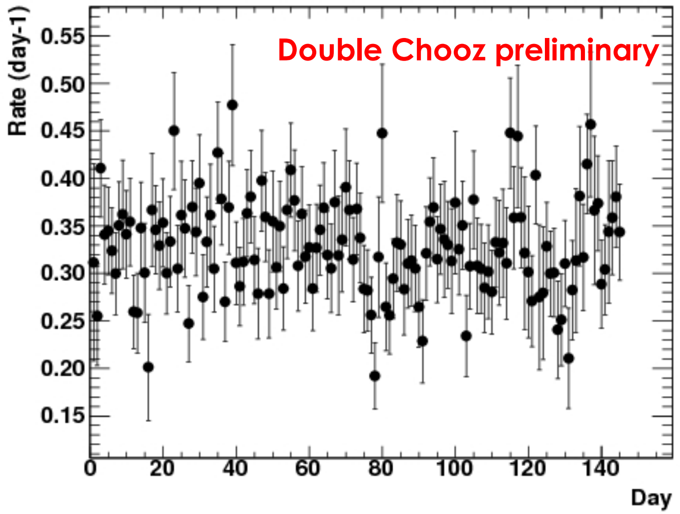
Singles: rate & spectrum



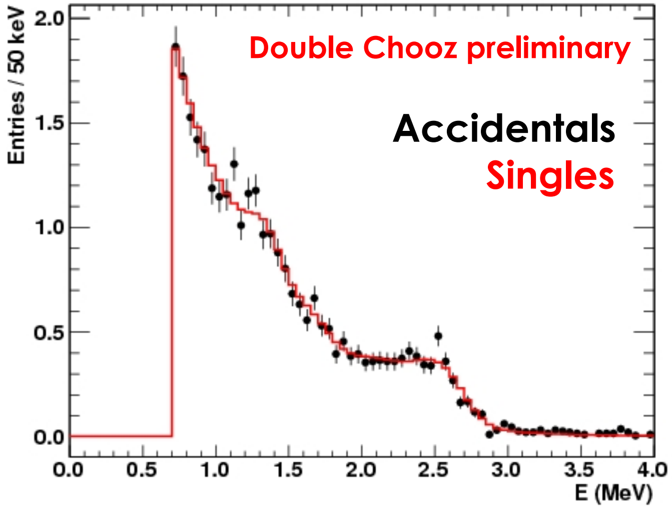
- [0.7,12] MeV
- DC proposal: 10 Hz
- DC (E > 700 keV) = **7.625 ± 0.001 Hz**

Accidental background

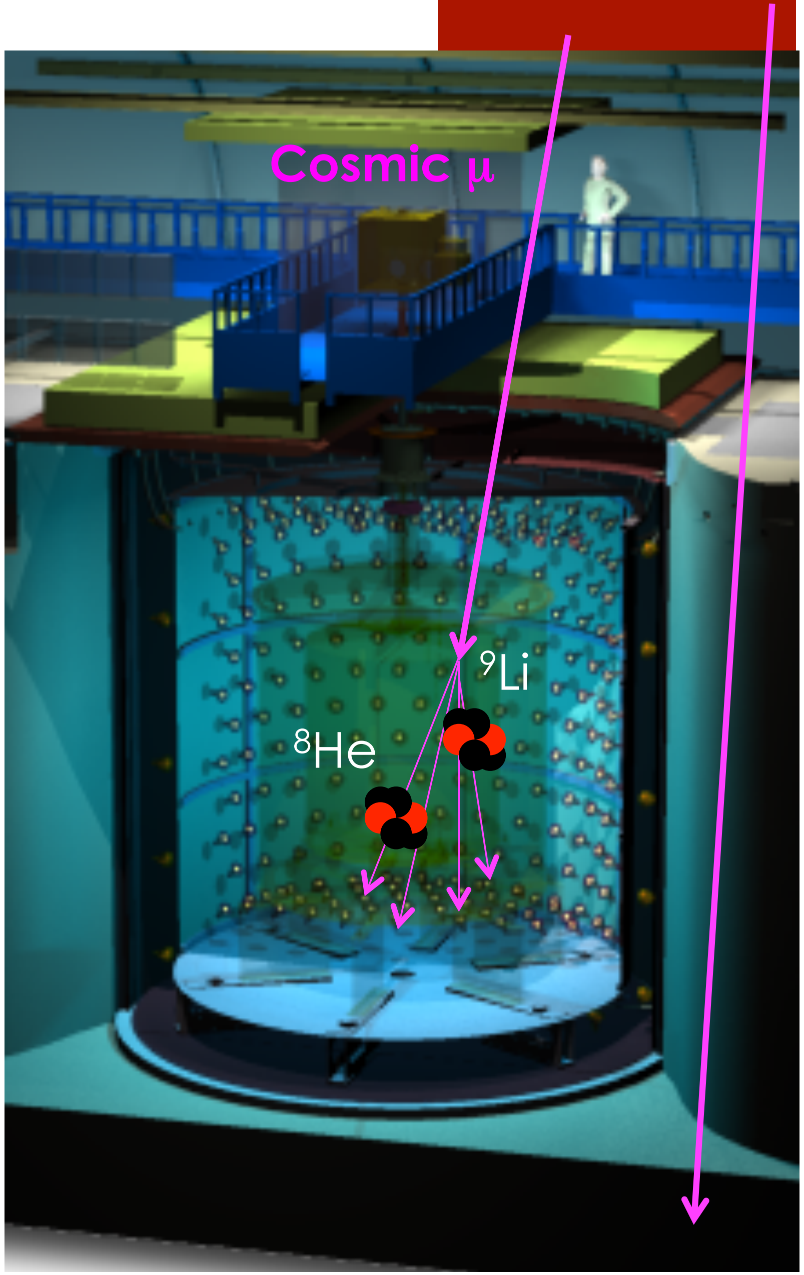




- Prompt energy in off-time window [1,100] ms away from neutrino candidates
- Very low rate: **R = (0.332 ± 0.004) day^{-1}**
  - Dominant background for < 2 MeV (oscillation signal)
  - **Stable in time**
- Spectrum dominated by singles (natural radioactivity)

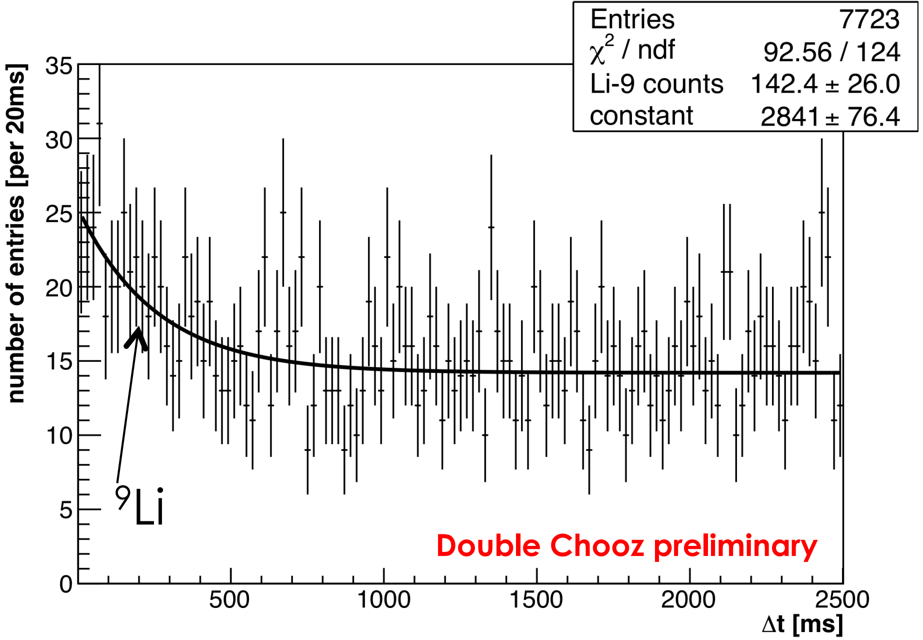


Cosmogenic BG: ^{9}Li & ^{8}He

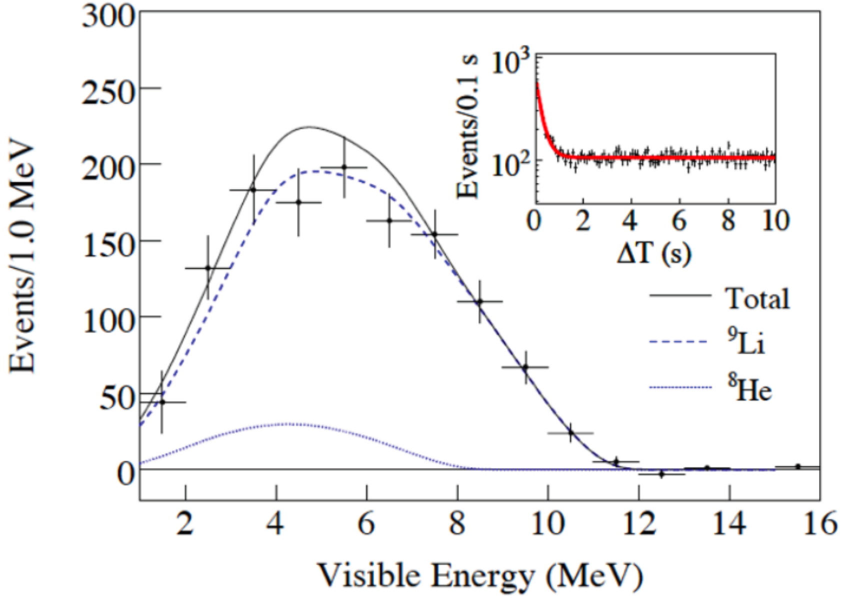


Cosmogenic BG: ^{9}Li & ^{8}He

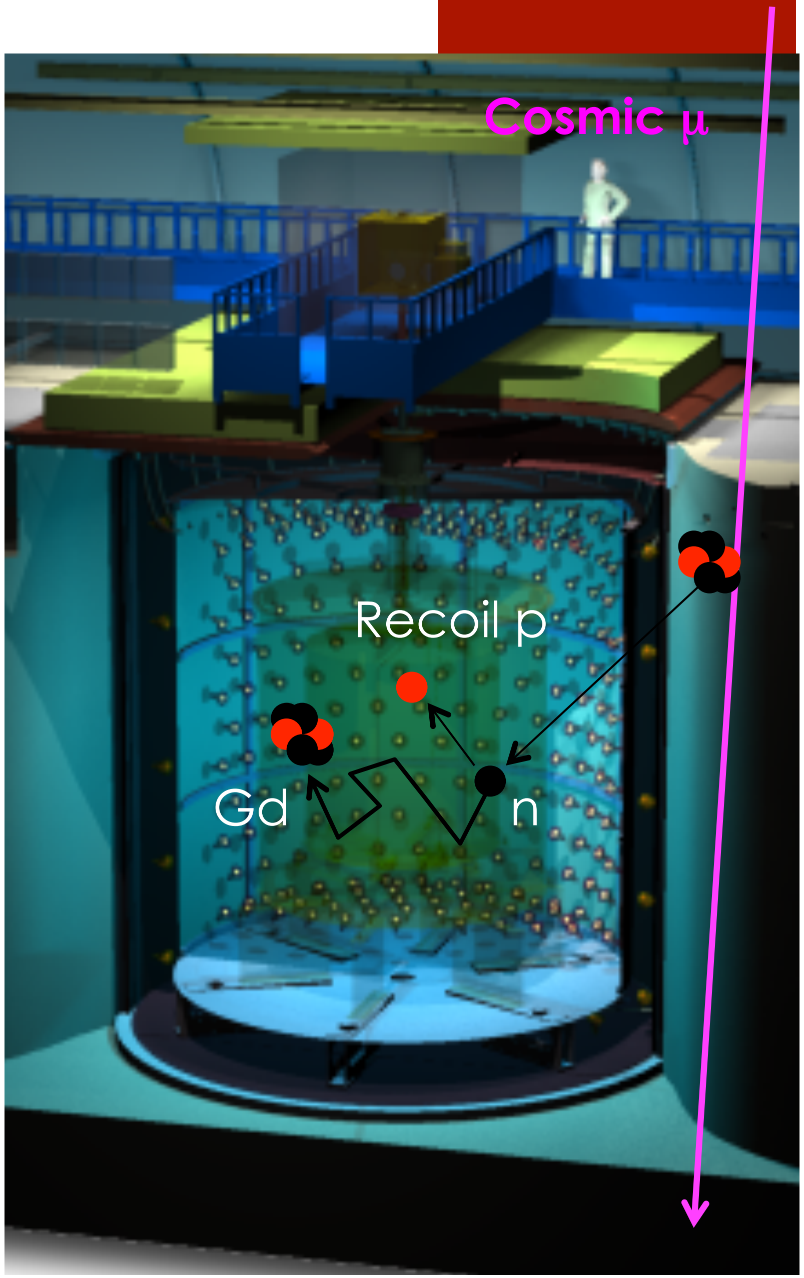
- ^{9}Li selection:
  - Production measured statistically
  - Search for triple delayed coincidence between showering muon and neutrino-like coincidence
- Δt between showering muon and prompt event is given by the ^{9}Li-like life time (257 ms)
- Rate: **(2.3 ± 1.2) day^{-1}**
- Energy spectrum from KamLAND via MC



Correlation to last-muon with E_{dep} > 600 MeV

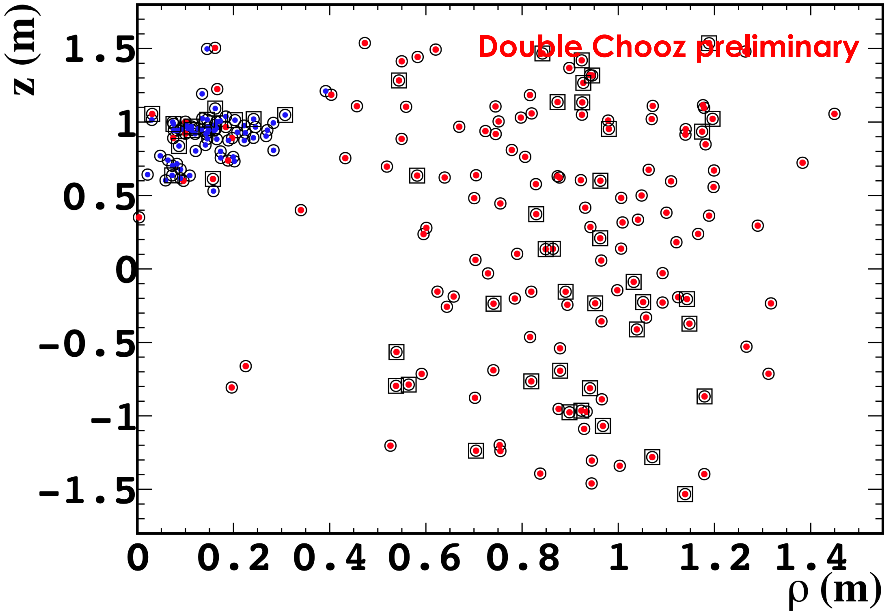


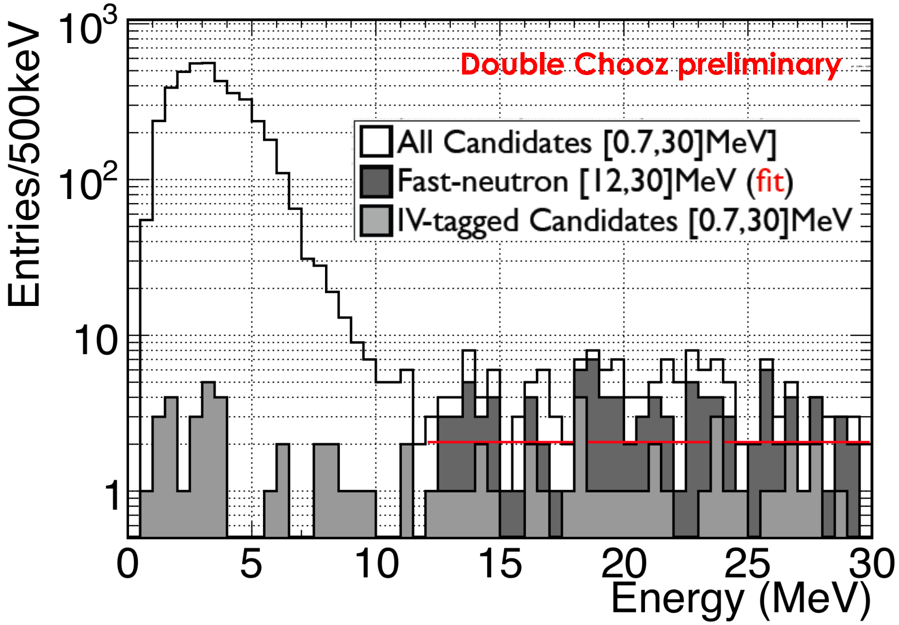
Fast-neutron BG



Fast-neutron BG

- Neutrino analysis with prompt energy extended up to 30 MeV
- Two main sources identified:
  - **Fast-n**: scatter in periphery of detector (top/sides predominantly)
    - Delay is captured on Gd (τ ~27 μs)
  - **Stopping muon**: sneaking through the chimney
    - Delay is Michel-e upon muon decay @ rest (Δt ~2.2 μs)
- Rate: extrapolation from high to low energies
  - **Rate = (0.7 ± 0.5) day^{-1}**
- Spectrum: flat hypothesis with uncertainty due to the stopping muon shape





Summary of backgrounds

Type	R (day^{-1})	δR (day^{-1})	δR/R	R/total (42.6 day^{-1})	Spectrum
Candidates	42.6	0.7	0.016		
Accidental	0.332	0.004	0.012	0.008	Measured
Li/He	2.3	1.2	0.522	0.054	From MC
Fast-n	0.7	0.5	0.714	0.016	Flat + shape uncertainty

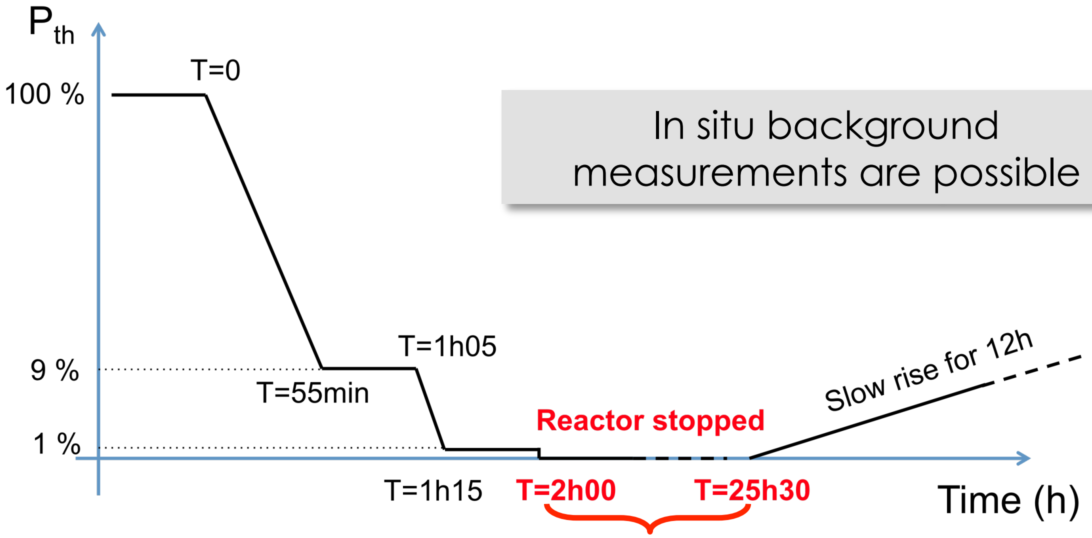
4121 neutrino candidates

328 expected background events

in 96.82 days

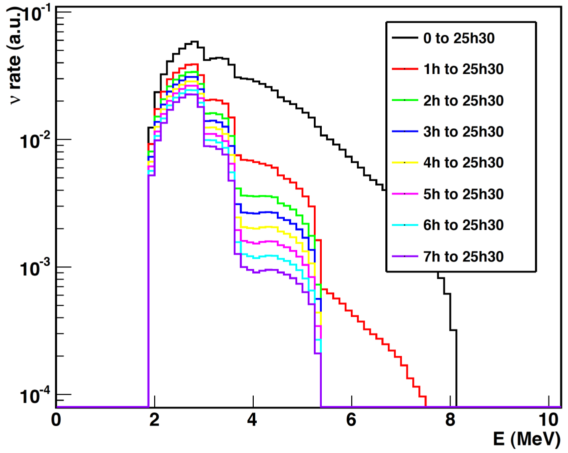
Both reactors OFF for 1 day

- Reactor 1 was OFF for 2 months (new data not analyzed yet)
- Reactor 2 was OFF for 1 day



In situ background measurements are possible

ν -spectrum at residual power



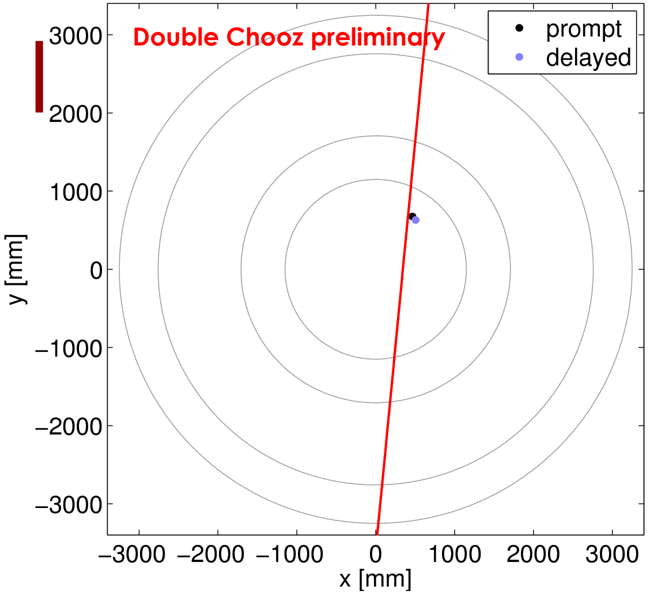
Neutrino Analysis: **3 events found** (< 30 MeV)

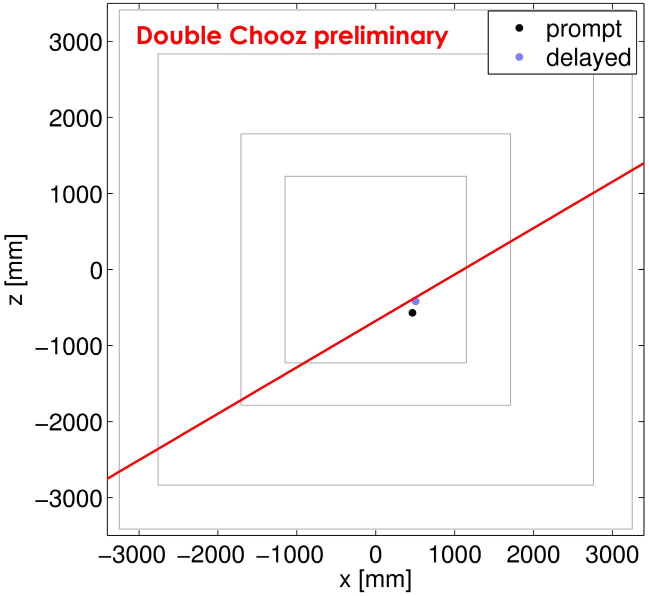
- 2 candidates within [0.7, 12] MeV
  - Li/He candidates
- 1 candidate > 12 MeV
  - Stopping muon (sneaking through the chimney)

Number of background events consistent with estimated number of BG events

Both reactors OFF: Event I

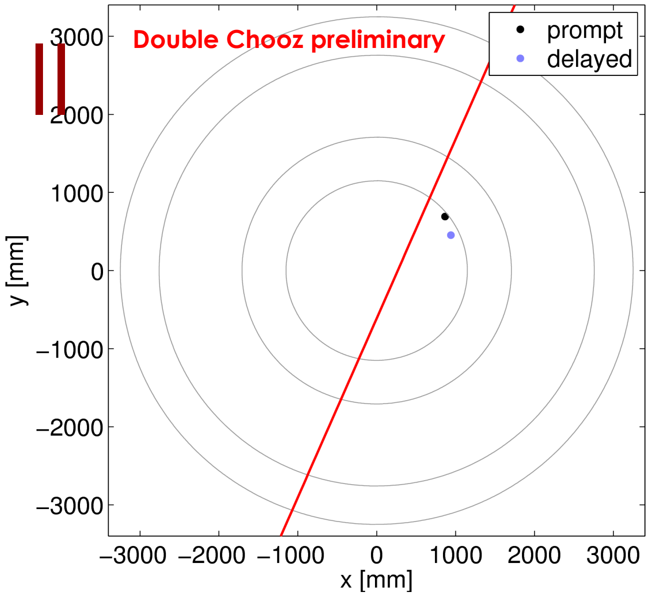
- **^{9}Li event candidate**
- Prompt event
  - Inner Detector energy: 9.8 MeV
- Delayed event
  - Inner Detector energy 8.0 MeV
- Coincidence characteristics
  - Distance 16.4 cm
  - Δt: 4 μs
- Muon(> 600 MeV)
  - Inner Detector energy 739 MeV
  - Distance to prompt: 15.4 cm
  - Δt to prompt: 201 ms

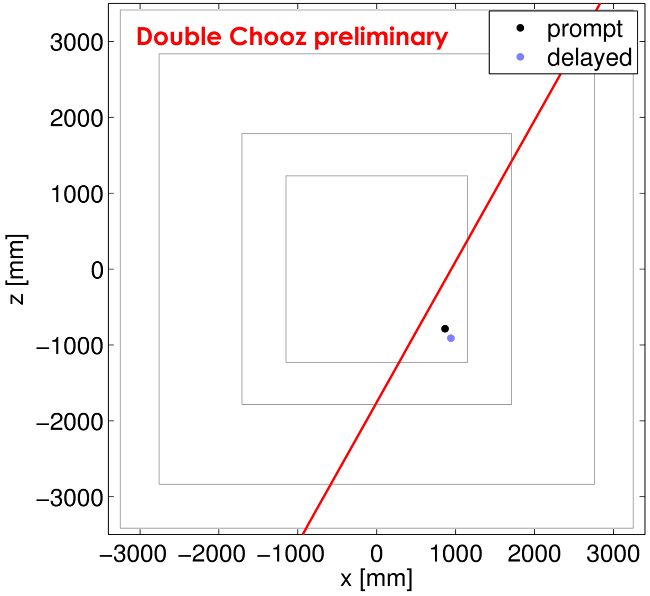




Both reactors OFF: Event II

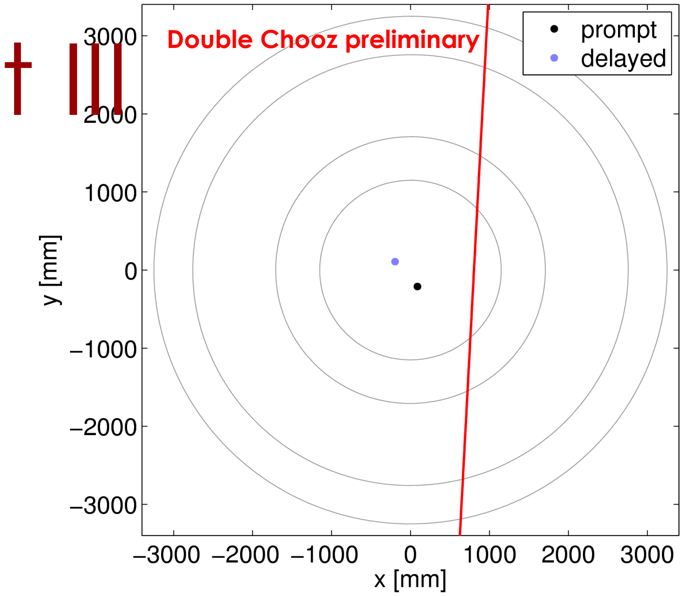
- **^{9}Li event candidate**
- Prompt event
  - Inner Detector energy: 4.8 MeV
- Delayed event
  - Inner Detector energy 8.6 MeV
- Coincidence characteristics
  - Distance 27.9 cm
  - Δt: 26 μs
- Muon(> 600 MeV)
  - Inner Detector energy 627 MeV
  - Distance to prompt: 30.8 cm
  - Δt to prompt: 241 ms

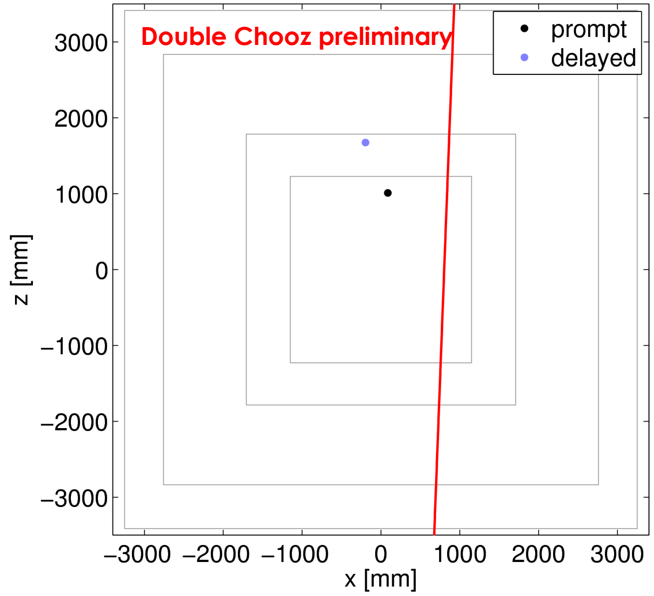




Both reactors OFF: Event III

- **Stop muon chimney event candidate**
- Prompt event
  - Inner Detector energy: 26.5 MeV
- Delayed event
  - Inner Detector energy 7.6 MeV
- Coincidence characteristics
  - Distance 79 cm
  - Δt: 2.2 μs
- Muon(> 600 MeV)
  - Closest one 17 s prior to prompt
  - Shown track is μ with highest energy deposition (523 MeV) within 5 s, with 206 ms, 103 cm distance to prompt



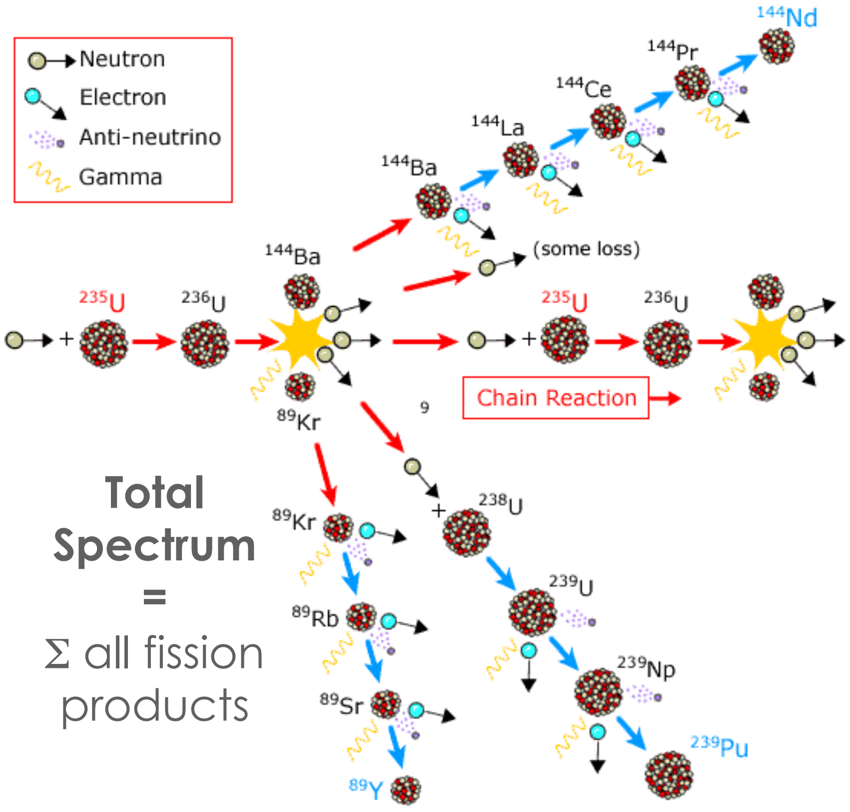


Oscillation analysis

Blinded analysis

- The analysis up to here was **blinded**
  - No access to the reactor power and fission rate data
- Only a few elected people had reactor information to develop the corresponding simulations and provide the expected neutrino spectrum

Reactor neutrino flux calculation



Total Spectrum
=
Σ all fission products

Expected neutrino flux

$$N_\nu^{\exp}(t) = \frac{N_p\,\varepsilon}{4\pi L^2} \times \frac{\boxed{P_{th}(t)}}{\langle E_f \rangle} \times \langle \sigma_f \rangle$$

- Mean energy per fission (k = ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu):

from EdF & simulations

$$\langle E_f \rangle = \sum_k \boxed{\alpha_k(t)} \langle E_k \rangle$$

α_k : fractional fission rate

- Mean cross-section per fission:

from simulations & measurements

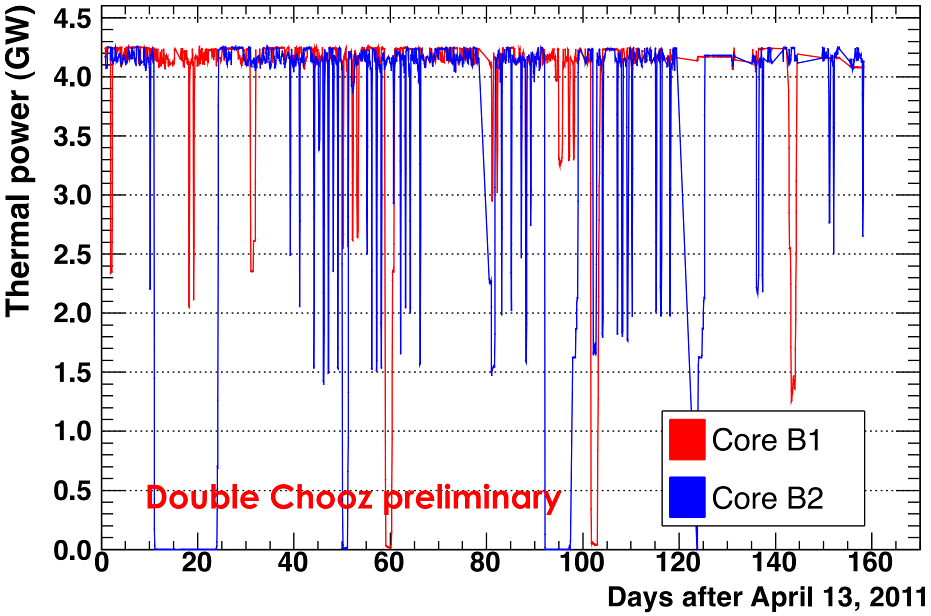
$$\langle \sigma_f \rangle = \langle \sigma_f \rangle^{Bugey} + \sum_k \left(\alpha_k^{DC}(t) - \alpha_k^{Bugey}(t) \right) \boxed{\langle \sigma_f \rangle_k}$$

$$\langle \sigma_f \rangle_k = \int_0^\infty dE\; S_k(E)\, \sigma_{IBD}(E)$$

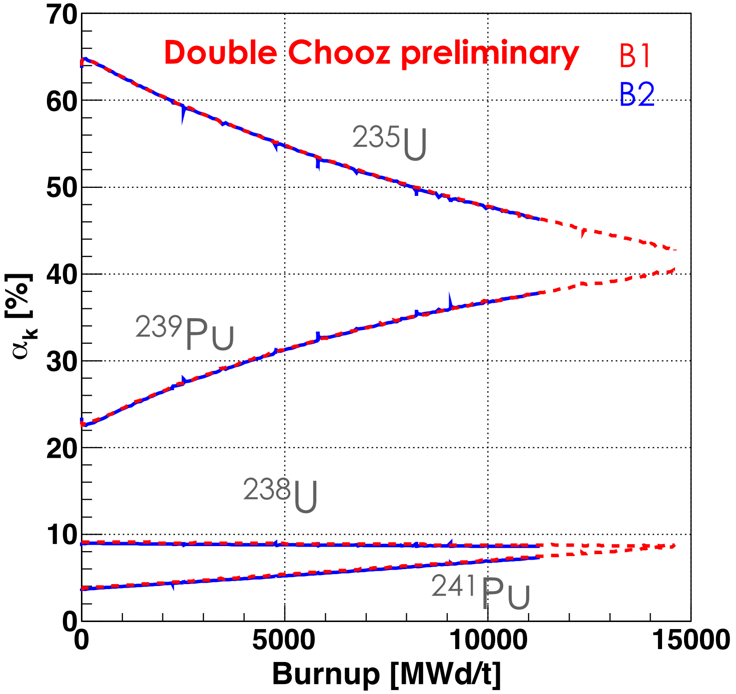
Based on Bugey 4 measurement with correction to DC

Reactor information and simulations

Monitoring of thermal power



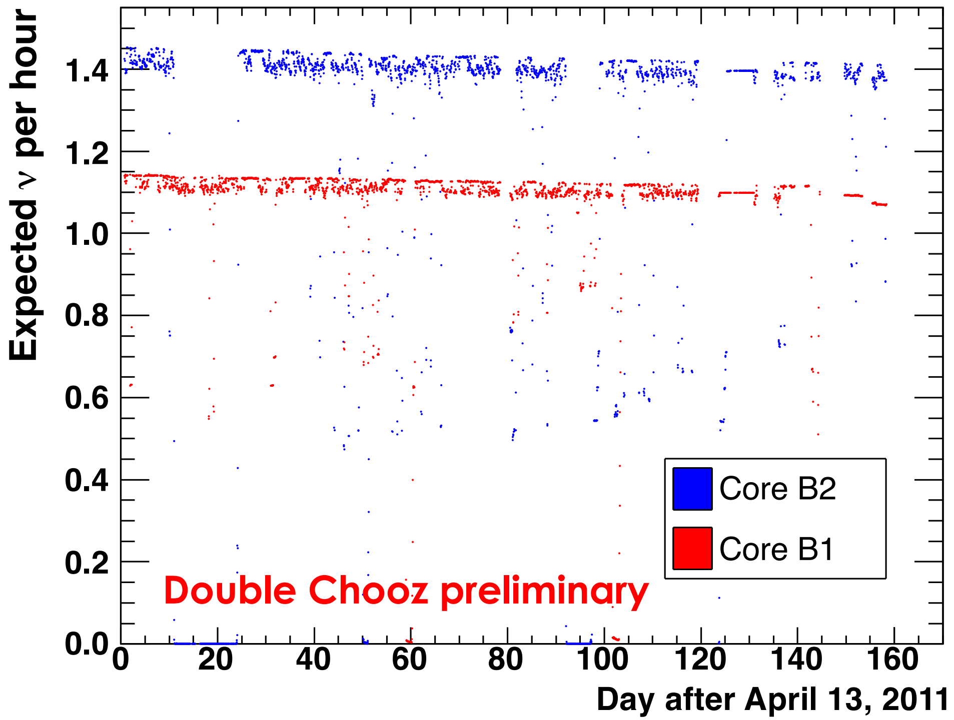
Fractional fission rates



- Monitoring P_{th} every minute ($\delta P_{th}/P_{th} = 0.46\%$)
- Reactor core evolution
  - Complete core simulation (EdF inputs, validation with independent calculations)
  - Error budget based on uncertainty on reactor parameters, code comparison, nuclear database inputs…

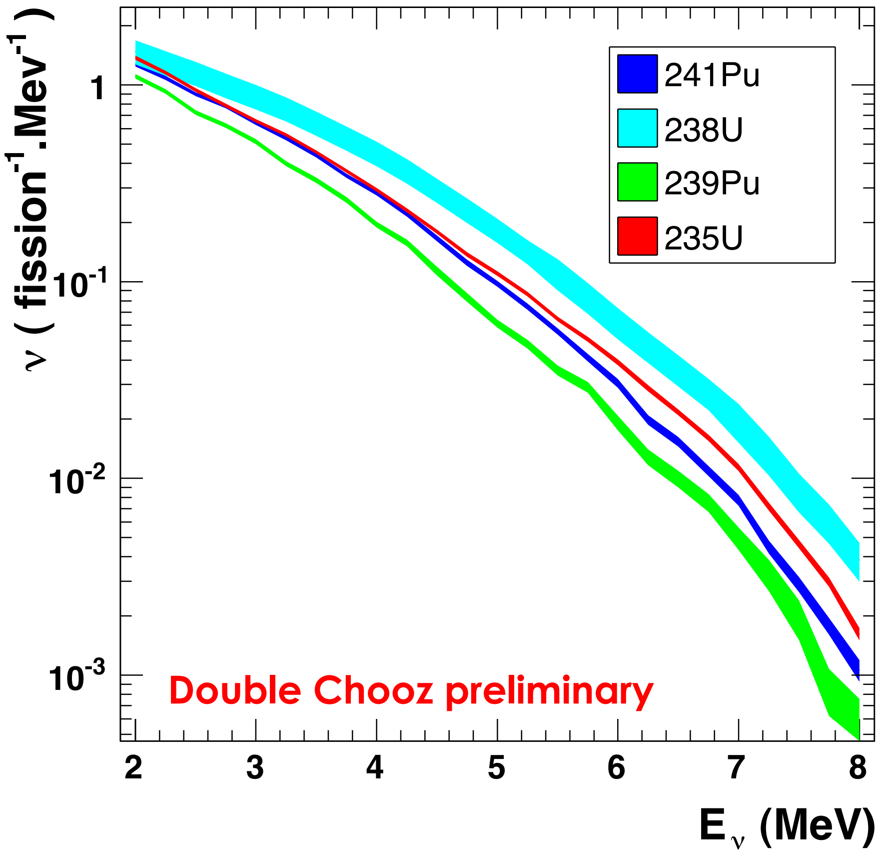
Predicted neutrino spectrum

Predicted neutrino rate at FD



New reference neutrino spectrum

Recent re-evaluations of fissile isotopes by:
Th. A. Mueller et al, Phys.Rev. C83 (2011) 054615
P. Huber, Phys. Rev. C84 (2011) 024617

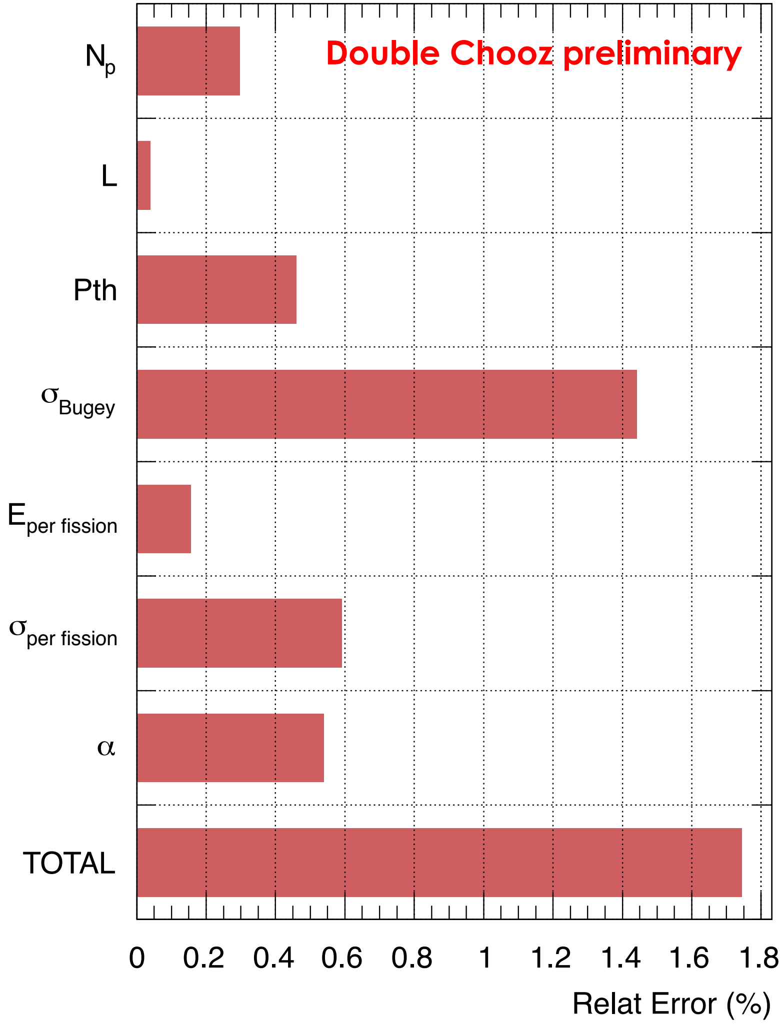


Total relative error on the predicted neutrino rate

- Bugey4 measurement suppresses sensitivity to reference spectra ($\sigma_{\text{per fission}}$)
- Accurate reactor simulation with MURE keep contribution of the uncertainty on fission rates low
- **TOTAL = 1.7% of total error**

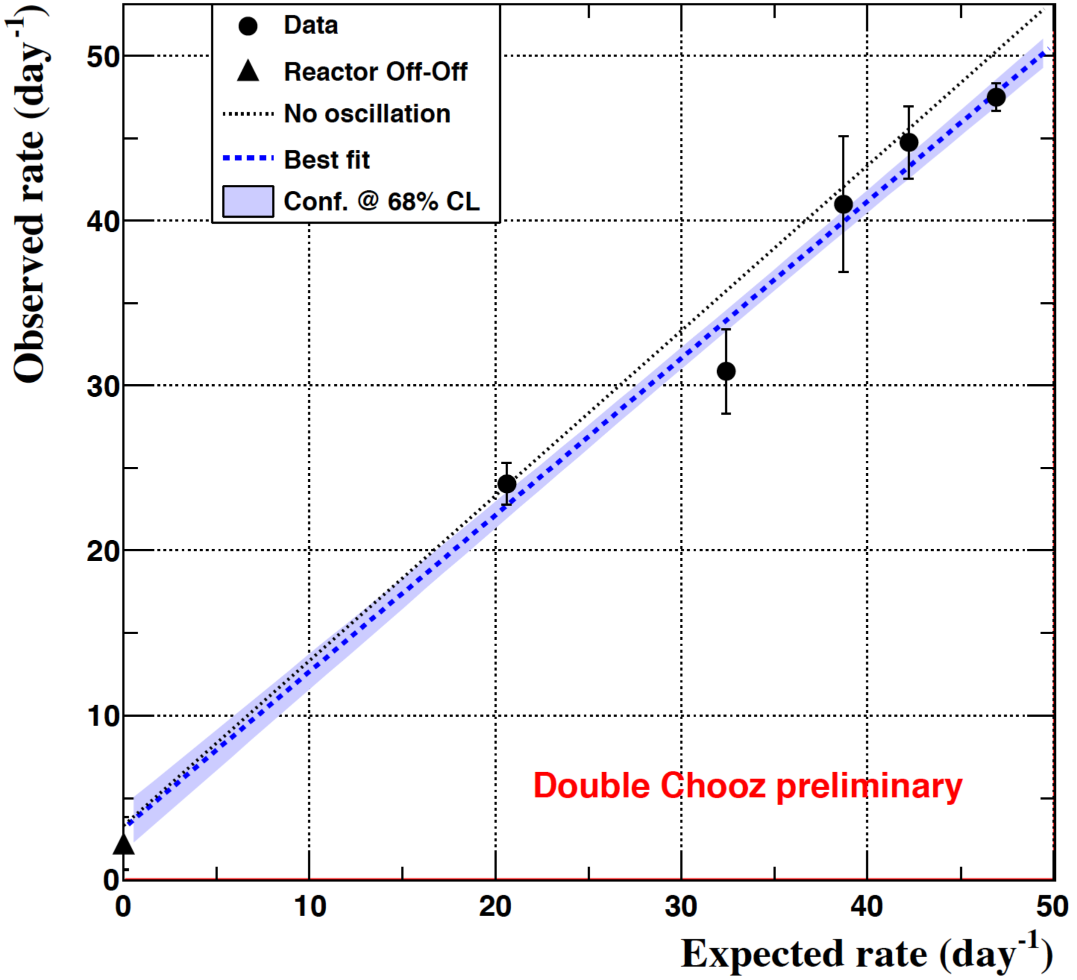
Predicted number of neutrinos = 5334.7 ± 93

(4121 candidates observed)



Observed vs expected rate

- Background not subtracted
- Reactor OFF-OFF point:
  - 2 candidates
- Background can be measured from fit
  - Without reactor OFF-OFF: BG = 5.0 ± 2.3 day^{-1}
  - With reactor OFF-OFF: BG = **3.2 ± 1.3 day^{-1}**
- Estimated background from analysis: **3.33 ± 1.32 day^{-1}**
- Slope:
  - $\sin^2(2\theta_{13})$ 0.093 ± 0.065



Fit strategy

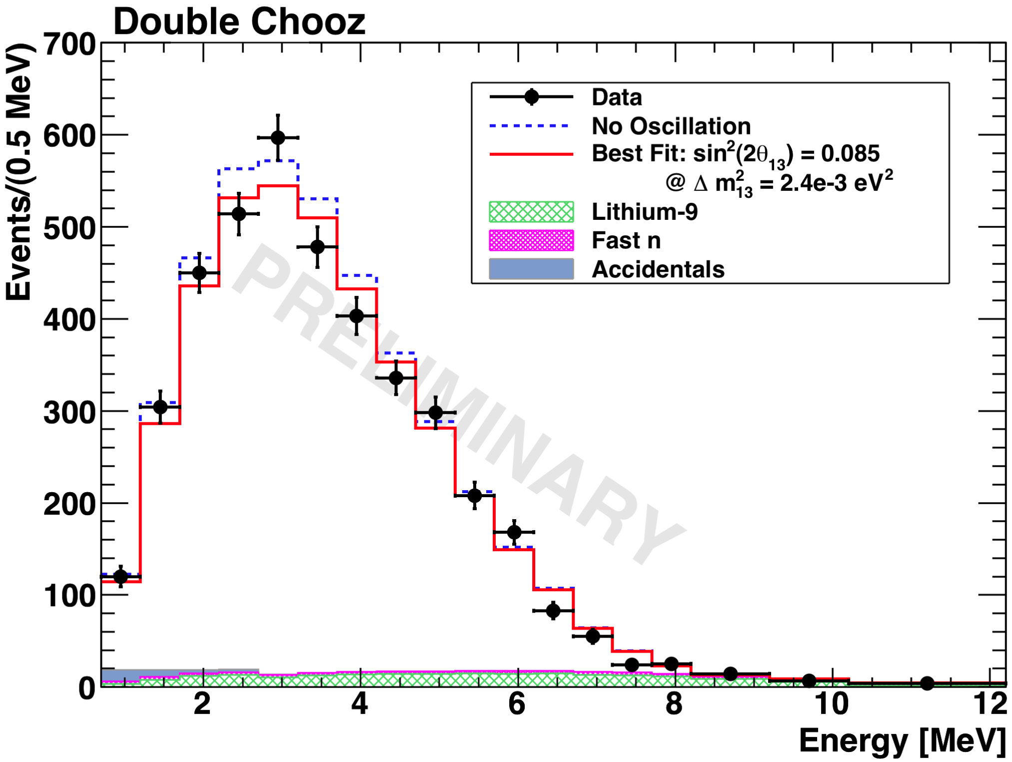
$$
\begin{aligned}
\chi^2 \;=\; & \left(N_i - \left(\sum_{R}^{\text{Reactors}} N_i^{\nu,R} + \sum_b N_i^b(P_b)\right)\right) \times \underbrace{\left(M_{ij}^{\text{signal}} + M_{ij}^{\text{detector}} + M_{ij}^{\text{stat}} + \sum_{b}^{\text{bkgnds.}} M_{ij}^{\text{b}}\right)}_{\text{Covariance matrices}}{}^{-1} \\
\times \; & \left(N_j - \left(\sum_{R}^{\text{Reactors}} N_j^{\nu,R} + \sum_b N_j^b(P_b)\right)\right)^{\mathrm{T}} \\
& \left.\begin{aligned}
+ \; & \sum_{R}^{\text{Reactors}} \frac{(P_R)^2}{\sigma_R^2} \\
+ \; & \sum_{b}^{\text{bkgnds.}} \frac{(P_b)^2}{\sigma_b^2}
\end{aligned}\right\} \text{Pull terms (rate uncertainties)}
\end{aligned}
$$

- M^{signal}: signal covariance matrix (uncertainties on neutrino signal from reactor, conversion to reconstructed positron energy)
- M^{detector}: efficiencies uncertainties, data/MC discrepancy, energy scale uncertainty and other detector effects
- M^{stat}: statistical covariance matrix
- M^{backg}: relative spectral uncertainties

Efficiencies and MC correction

SOURCE	VALUE	UNCERTAINTY
DETECTION EFFICIENCY		
Target free H	100 %	± 0.3 %
Prompt efficiency	100 %	Negligible
Delay efficiency	86.0 %	± 0.6 %
Δt cut	96.5 %	± 0.5 %
ΔE (delay) cut	94.5 %	± 0.6 %
MC CORRECTION		
Muon veto deadtime	95.5 %	Negligible
Multiplicity	99.5 %	Negligible
Gd to H fraction	98.0%	± 0.6 %
Spill in/out	99.3 %	± 0.4 %

Rate and shape oscillation analysis

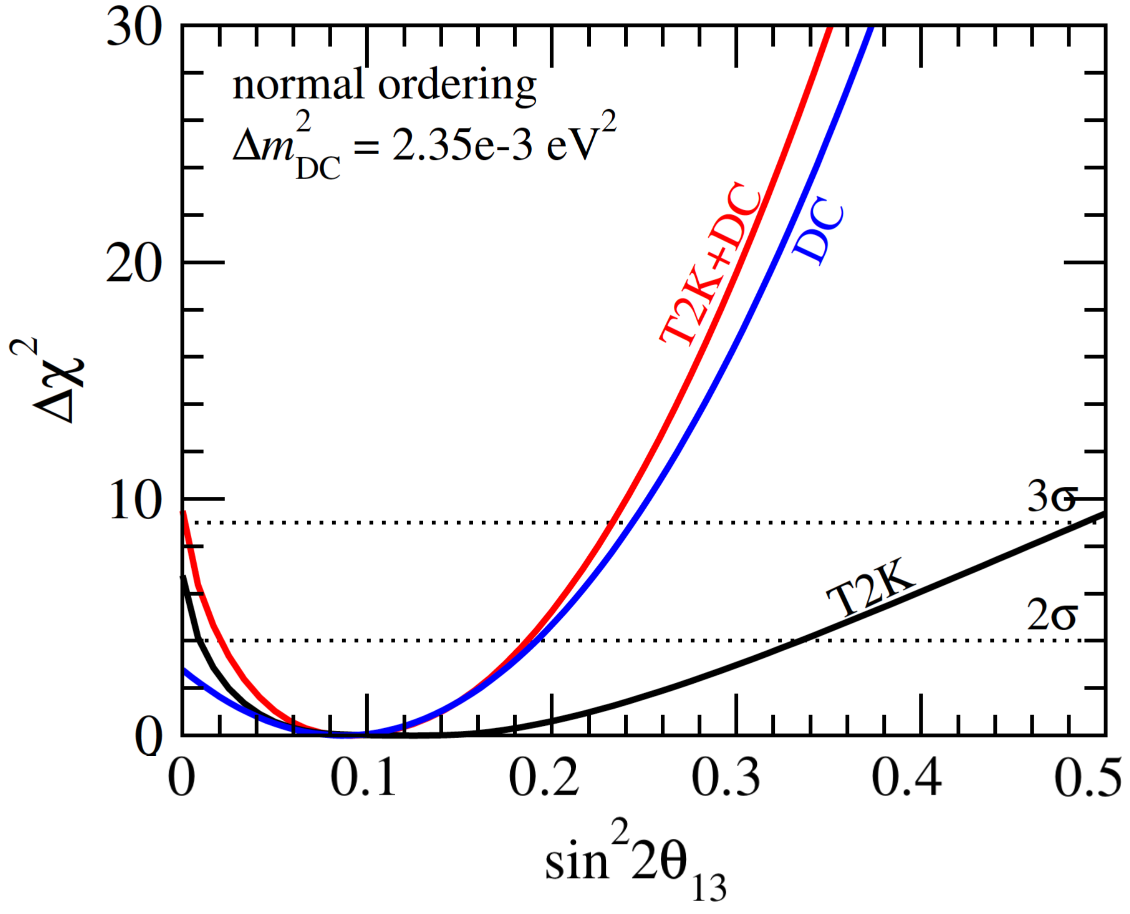


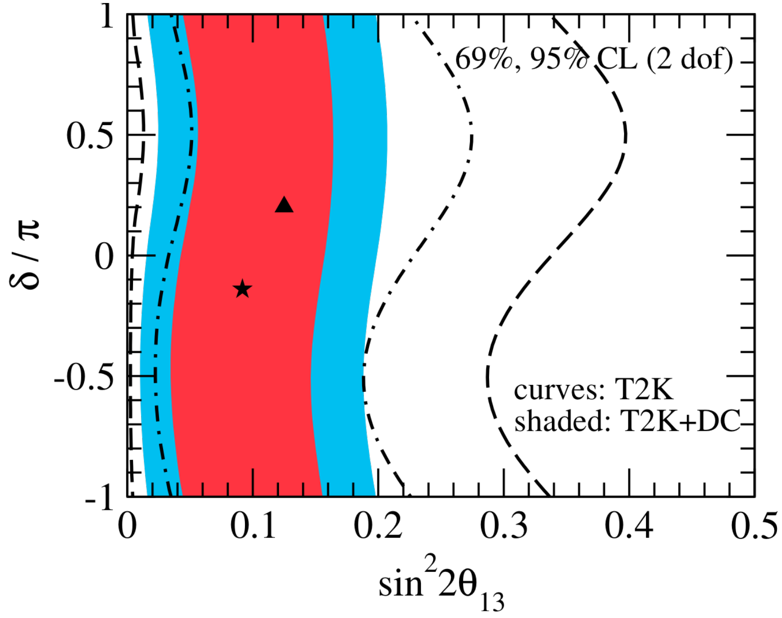
- **Rate only:**
  - $\sin^2(2\theta_{13}) = 0.096 \pm 0.029$ (stat) ± 0.073 (sys)
- **Shape only:**
  - $\sin^2(2\theta_{13}) = 0.044 \pm 0.157$
- **Rate + shape:**
  - $\sin^2(2\theta_{13}) = 0.085 \pm 0.029$ (stat) ± 0.042 (sys) at 68% CL
  - No oscillation excluded at 92.9%

Total uncertainties

UNCERTAINTY SOURCE	VARIANCE
Statistical	**1.56 %**
Reactor flux	1.71 %
Detection efficiency	1.10 %
Detector response	1.20 %
Accidental backg	0.01 %
Fast neutron backg	1.14 %
Lithium-9 backg	2.73 %
Systematic total	**3.78 %**

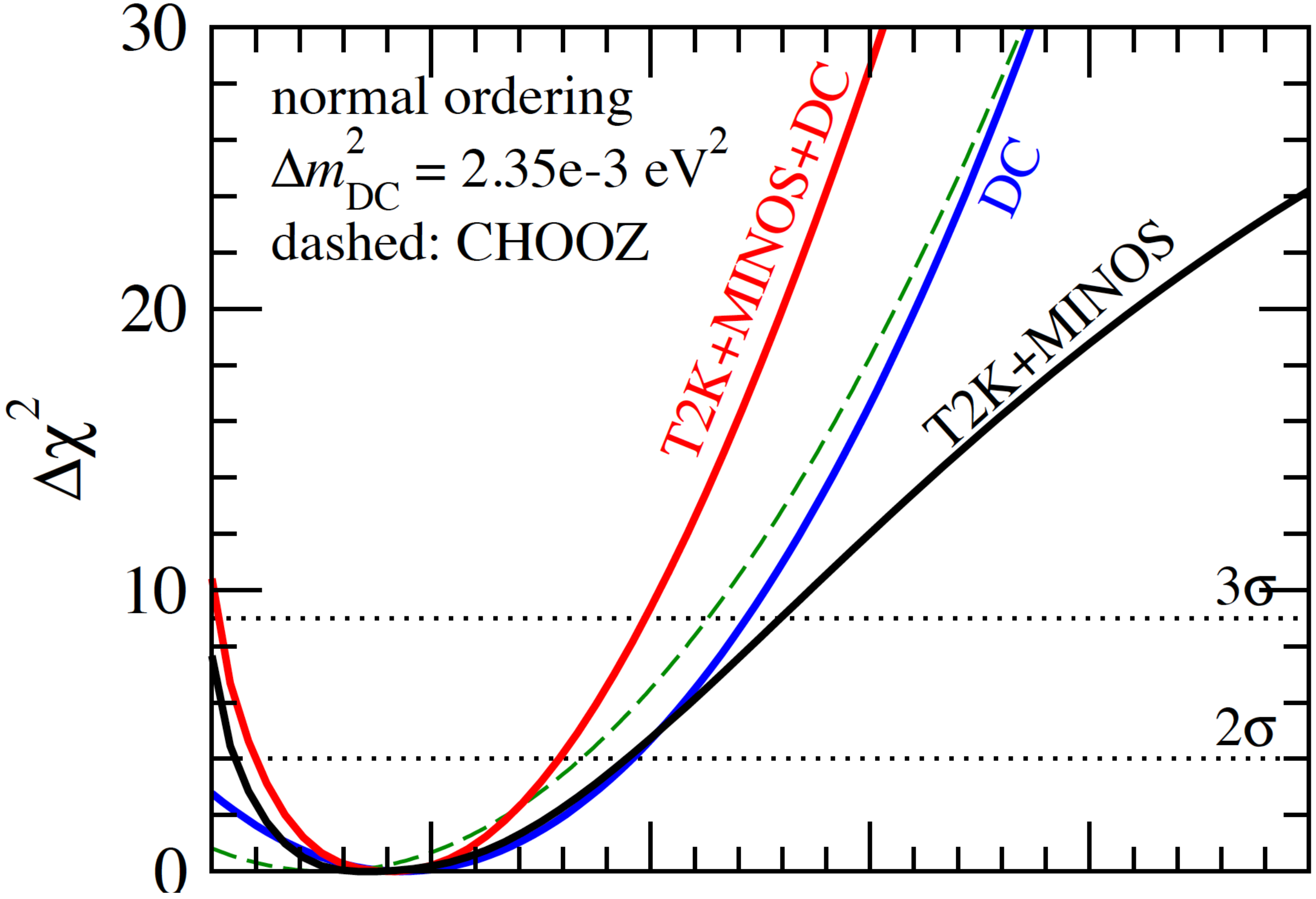
Double Chooz+T2K combination



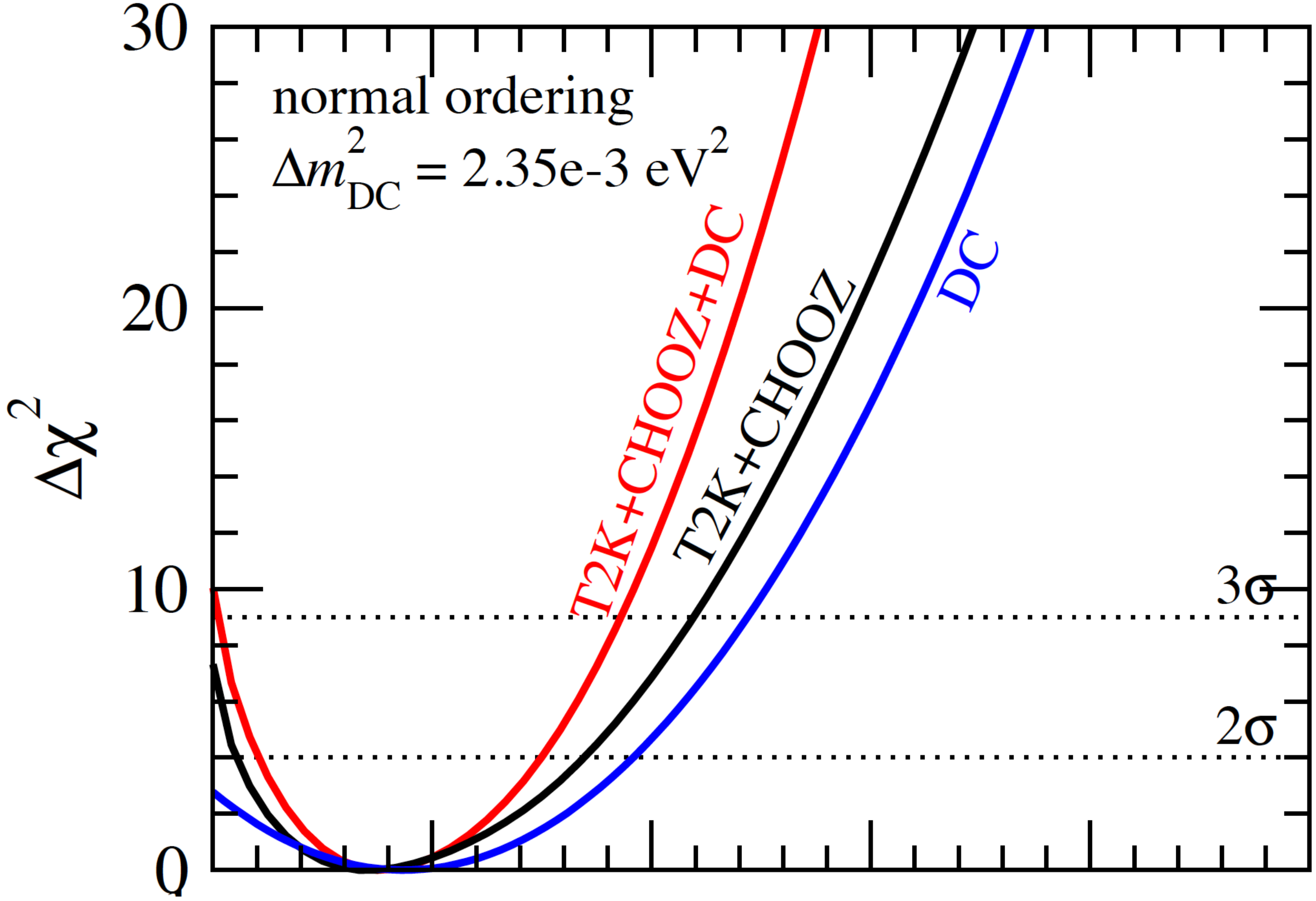


- Best fit point is 0.092
- **θ_{13} = 0 is excluded at 3σ** from DC and T2K
  - Lower limit dominated by T2K
  - Upper limit dominated by DC

Combination DC+T2K +MINOS



Combination DC+T2K +CHOOZ



Prospects

Statistical and systematic errors

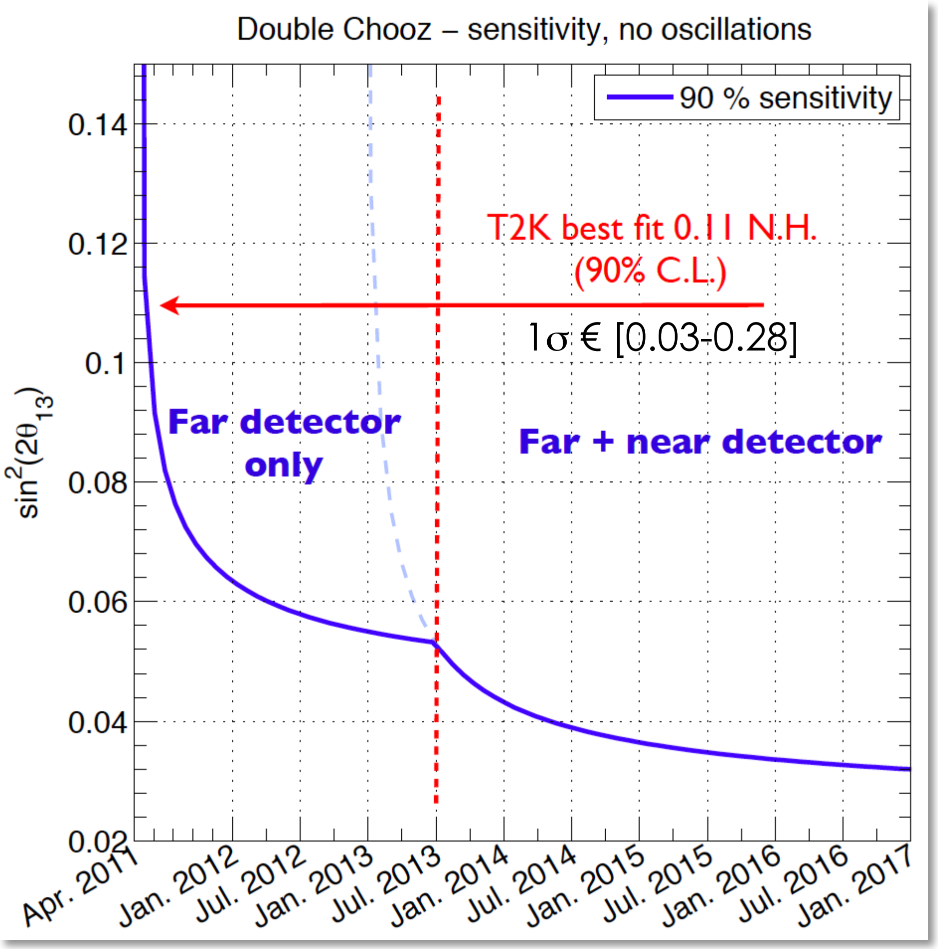
CHOOZ: $N_{obs} / N_{exp} = 1.01 \pm 2.8\% \text{ (stat.)} \pm 2.7\% \text{ (sys.)}$

	CHOOZ	Double Chooz
Target volume	5.55 m^3	10.3 m^3
Data taking period	few months	3-5 years
Event rate	2700	far: 20.000/y near: 150.000/y
Statistical error	2.8 %	0.5 %

	CHOOZ	Double Chooz
Reactor uncertainties (ν flux and reactor power)	2.1 %	< 0.1 %
Number of protons	0.8 %	< 0.2 %
Detector efficiency	1.5%	< 0.5 %
Systematic error	2.7%	< 0.5 %

Double Chooz sensitivity

- Normalization to Bugey-4 cross section (with FD) to be independent from the flux prediction
- **Phase I (FD only)**: 10 x more statistics than CHOOZ
  - Limited by rate and shape reactor flux uncertainties (2.8% total)
- **Phase II (FD + ND):** more robust
  - Limited by inter-detector normalization systematic uncertainties (0.6 %)
- With 3 years of data taking (2 detectors):
  - the sensitivity of the experiment is **$\sin^2(2\theta_{13}) < 0.03$** at 90% CL and
  - the **discovery potential is $\sin^2(2\theta_{13}) > 0.05$** at 3σ C.L.



Conclusions

- Double Chooz started physics data taking since April 2011
  - Measuring neutrinos with low backgrounds
- The first preliminary data release at LowNu conference (November, 2011)
  - Oscillation analysis (rate + shape): **$\sin^2(2\theta_{13}) = 0.085 \pm 0.029 \pm 0.042$ (68% CL)**
  - **No-oscillation excluded** at 92.1% CL
- **First publication is almost ready**
- **Data taking continues without stop**
- Near detector operational by early 2013
- Great prospects towards very precise θ_{13} measurement
  - Final sensitivity **$\sin^2(2\theta_{13}) < 0.03$ (90% CL)**

More DC information on "The Big Bang Theory" show


OUT OF ORDER
CAUTION
CBS