First Results from the Double Chooz Experiment

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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
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Japan

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Tokyo Inst. Tech.
Tokyo Metro. U.
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Kobe U.
Tohoku Gakuin U.
Hiroshima Inst Tech.

Russia

INR RAS
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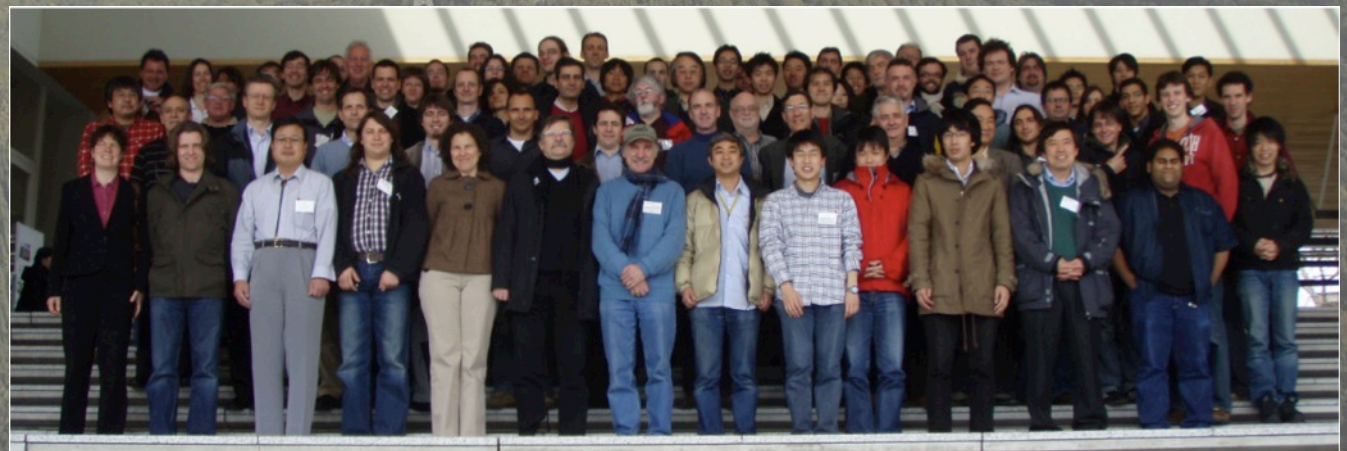
Sandia National Laboratories
U. Tennessee

Spokesperson: H. de Kerret (IN2P3)
Project Manager: Ch. Veyssière (CEA-Saclay)

Web Site: www.doublechooz.org/



Outline

- **Neutrino Oscillation**
- Detector Design and Construction
- Reactors
- Backgrounds
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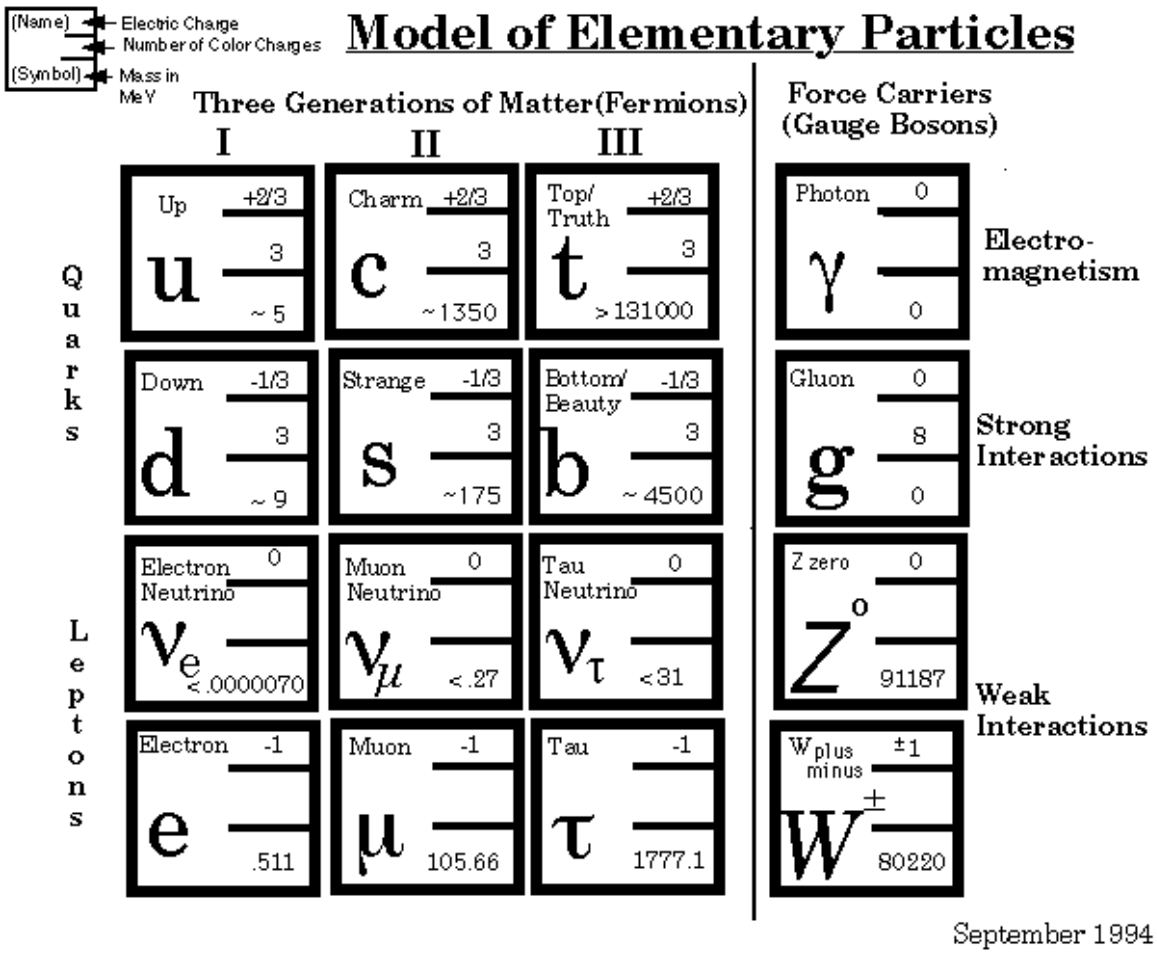
All Results Preliminary!

Neutrinos



- Nearly massless: but we know at least some of the neutrinos have mass.
- Only interact through the weak force.
- Extremely low interaction cross section (~10^{-38} cm^{-2})
- Have a flavor which is associated with a charged lepton.

Neutrino Oscillation

$$s_{ij} = \sin\theta_{ij}, \quad c_{ij} = \cos\theta_{ij}$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Atmospheric

$\nu_\mu \rightarrow \nu_\mu$

Super-K+K2K+MINOS

$$\sin^2\vartheta_{23} = 0.50^{+0.08}_{-0.07}$$
$$\Delta m^2_{23} = \left(2.5^{+0.20}_{-0.25}\right)\times 10^{-3}\,eV^2$$

Reactor etc.

CHOOZ
$\sin^2(2\theta_{13})<0.15$

+

Recent T2K, MINOS results

Solar

$\nu_e \rightarrow \nu_x$

Solar+KamLAND

$$\sin^2\vartheta_{12} = 0.30^{+0.02}_{-0.03}$$
$$\Delta m^2_{12} = (7.9 \pm 0.3)\times 10^{-5}\,eV^2$$

- Remaining parameters ➔ θ_{13} , CP-violating phase δ, Mass hierarchy

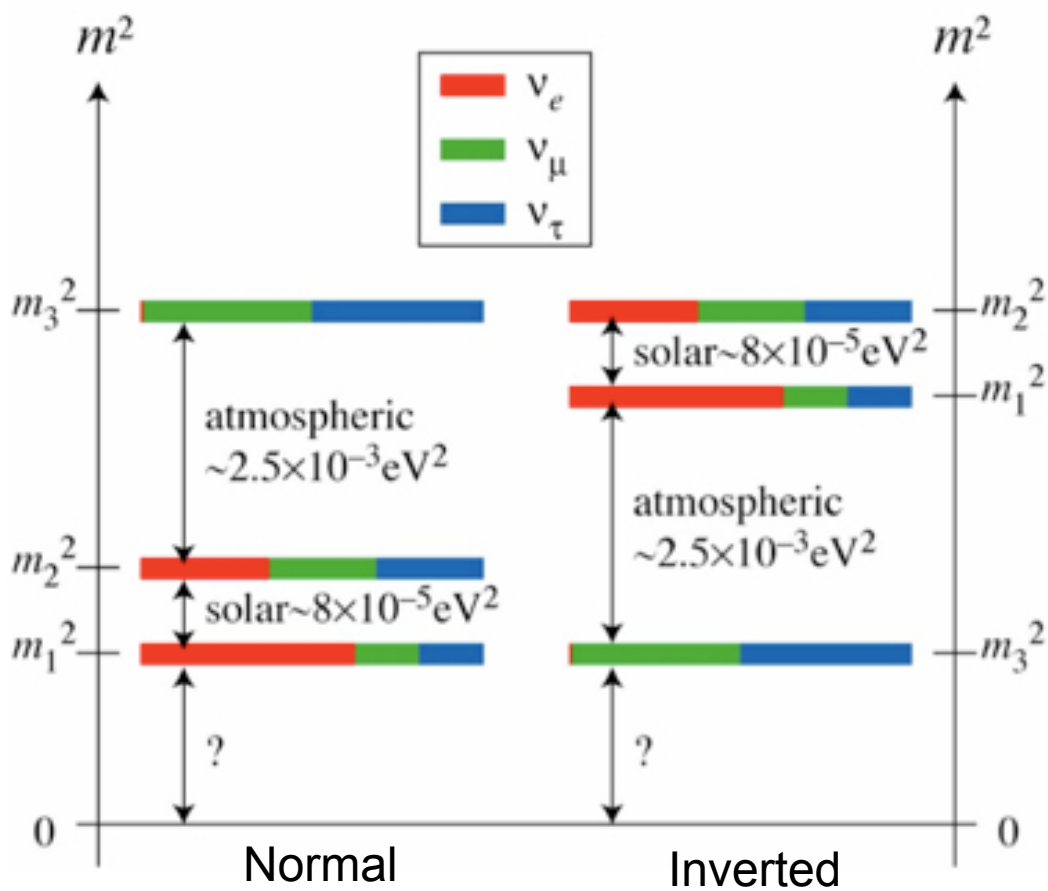
Current Understanding

Mass Squared Differences
- $\Delta m_{21}^2 \sim 7.9\times10^{-5}$ eV^2
- $|\Delta m_{32}^2| \sim |\Delta m_{31}^2| \sim 2.5\times10^{-3}$ eV^2

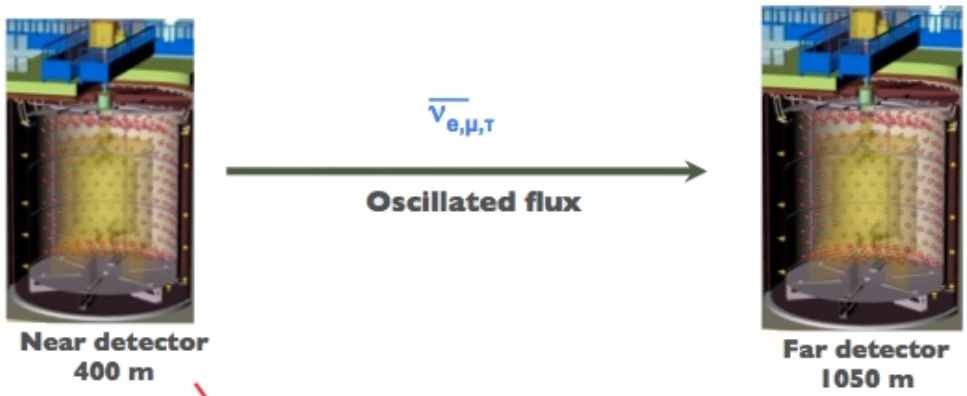
Mixing Angles
- $\theta_{12} \sim 34^o$
- $\theta_{23} \sim 45^o$
- $\theta_{13} < 12^o$ ($\sin^2 2\theta_{13} < 0.15$)

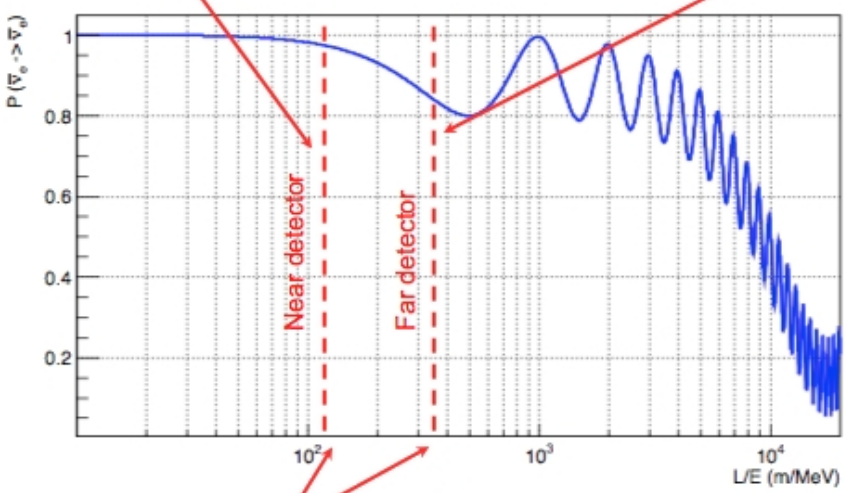
δ_{cp} unknown
Mass heirarchy unknown
Absolute mass scale unknown

$$P_{\bar{\nu}_e \to \bar{\nu}_e}(L) \simeq 1 - \sin^2(2\theta_{13})\sin^2\left(\frac{\Delta m_{13} L}{4E}\right)$$



Multiple Detectors

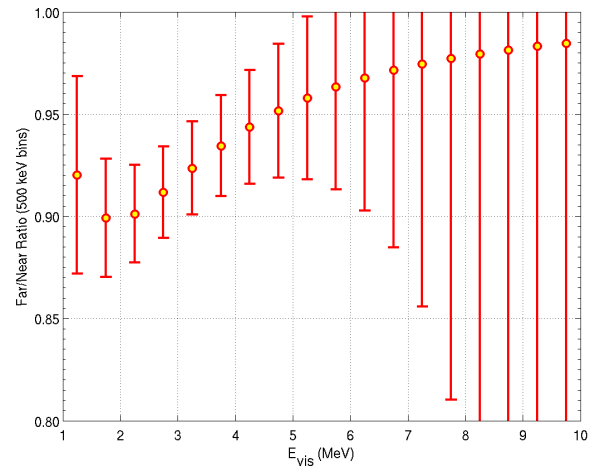




For <E> = 3 MeV

$\Delta m^2_{12}=7\times10^{-5}$ eV^2 $\sin^2(2\theta_{13})=0.2$

$\Delta m^2_{23}=2.5\times10^{-3}$ eV^2 $\cos^2(\theta_{12})=0.7$

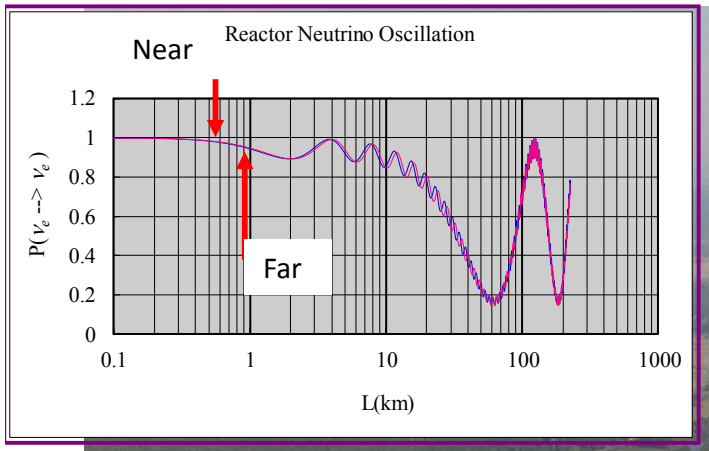


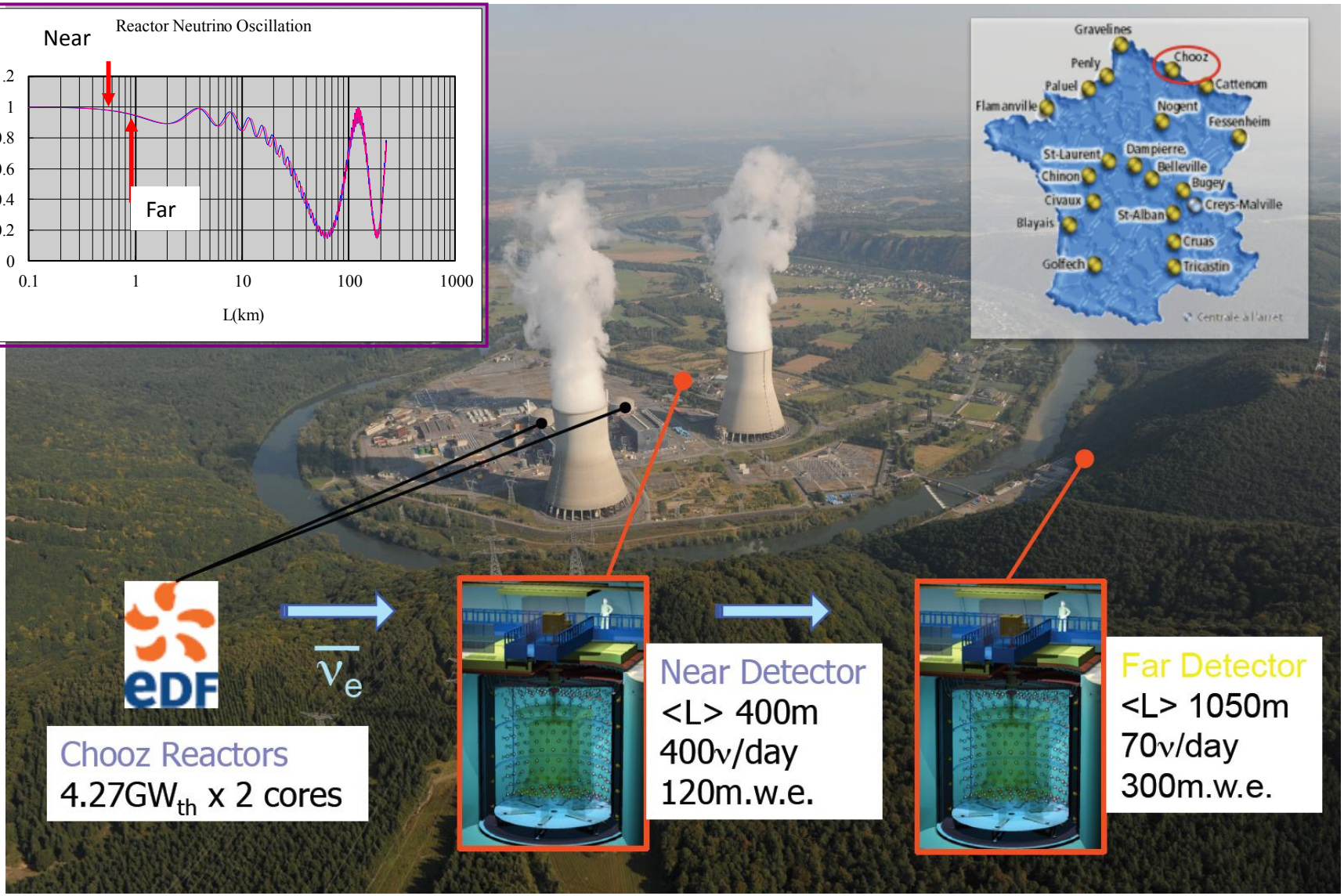
Oscillation Signature

$$P_{\bar{\nu}_e \to \bar{\nu}_e}(L) \simeq 1 - \sin^2(2\theta_{13})\sin^2\left(\frac{\Delta m_{13} L}{4E}\right)$$

Multi-detector approach is independent of δ and significantly reduces reactor based systematic errors

Double Chooz





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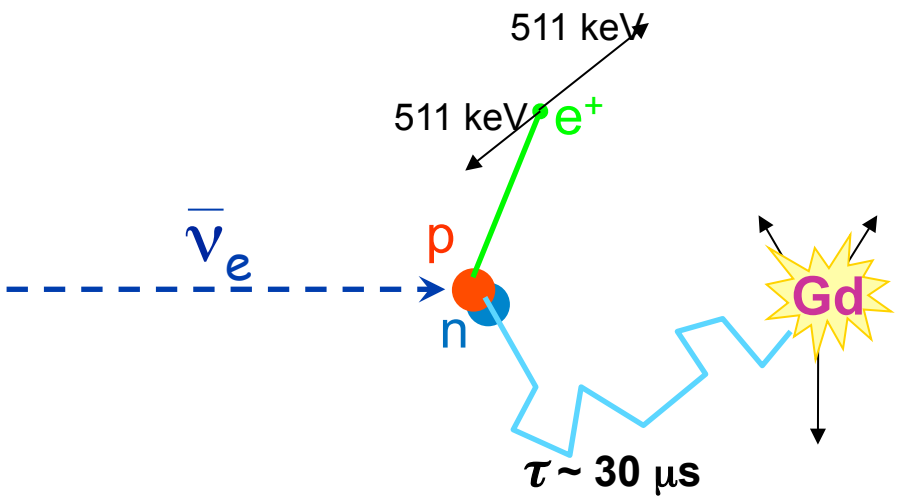
Goals

- The primary goal of the experiment is to measure or further constrain the neutrino mixing angle θ_{13} using the two detector approach to reduce the reactor based errors.
- Additionally the neutrino flux and spectrum measurements performed by the near detector will be used to further the use of neutrino detectors as reactor monitoring tools for non-proliferation.

Detecting Neutrinos: Inverse Beta Decay

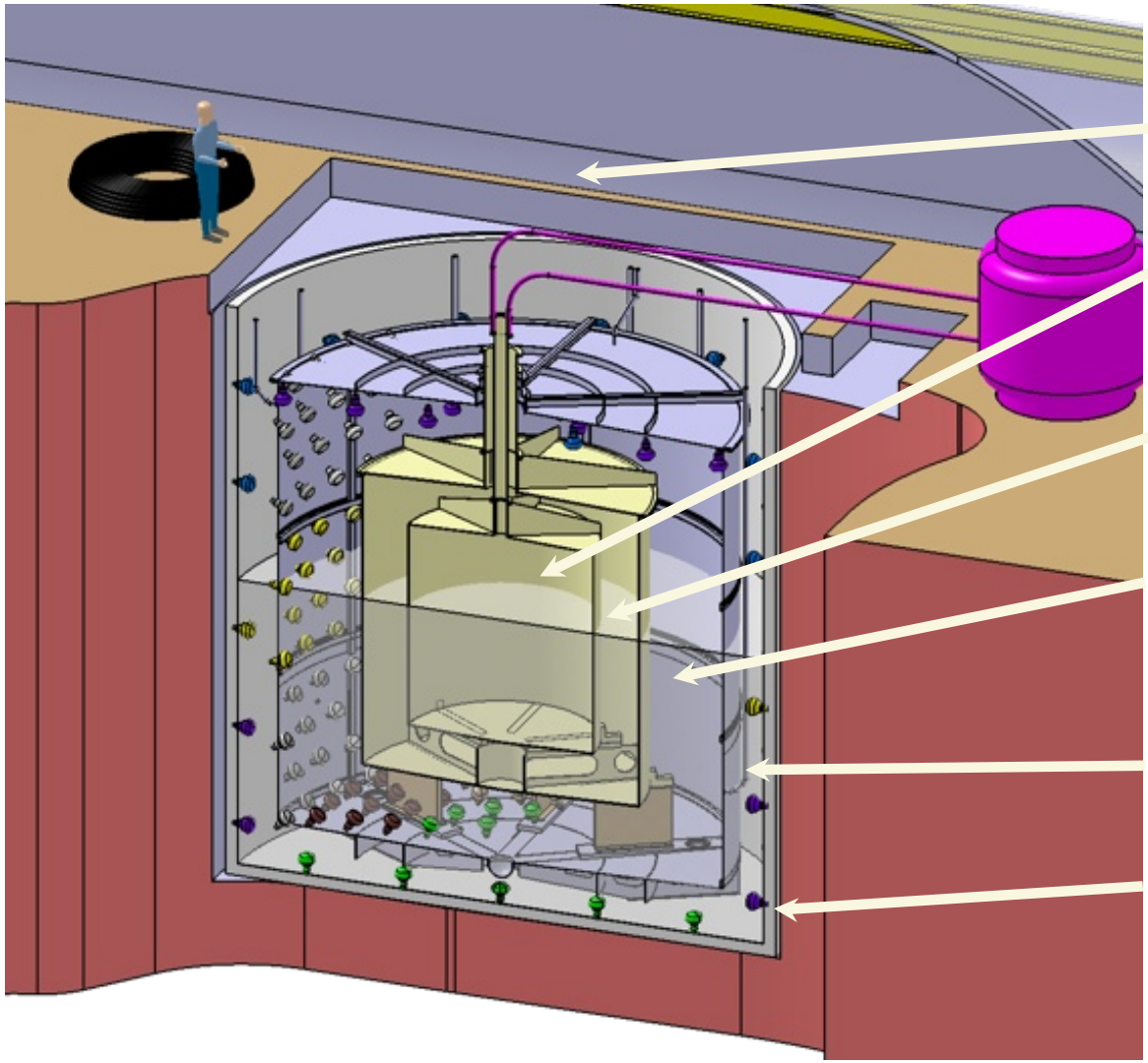


$$\nu_e + p \rightarrow n + e^+$$

- Positron
  - Immediate
  - 1- 8 MeV (incl 511 keV γs)
- Neutron
  - Delayed (τ = 28 μs for Gd)
  - 8 - 8.5 MeV γ cascade

- Inverse beta decay provides a good means of separating the neutrino signal from background.
- The energy deposits associated with the positron and neutron occur close to each other in time and space.
- By using a specific neutron capture agent (e.g. Gd) you can further restrict the energy of the delayed (neutron) event.

Detector Construction



Outer Veto: plastic scintillator strips

ν-Target: 10.3 m^3 of organic liquid scintillator, Gd-doped, in acrylic vessel (8 mm).

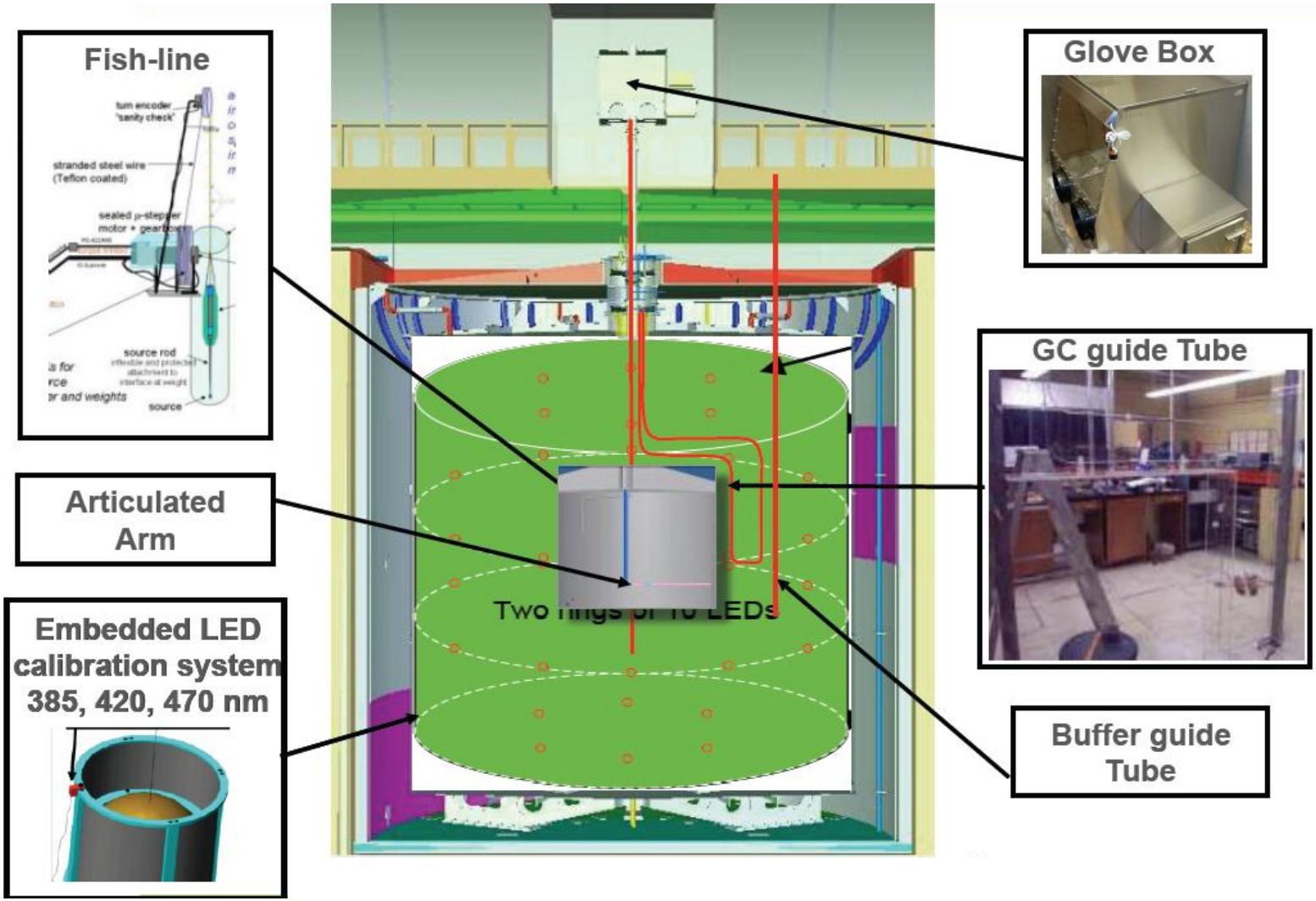
γ-Catcher: Liquid scintillator, no Gd, in acrylic (12 mm).

Buffer: Non-scintillating liquid, 390 PMTs (10”), stainless steel vessel.

Inner Veto: Scintillator in steel vessel. 78 PMTs (8”).

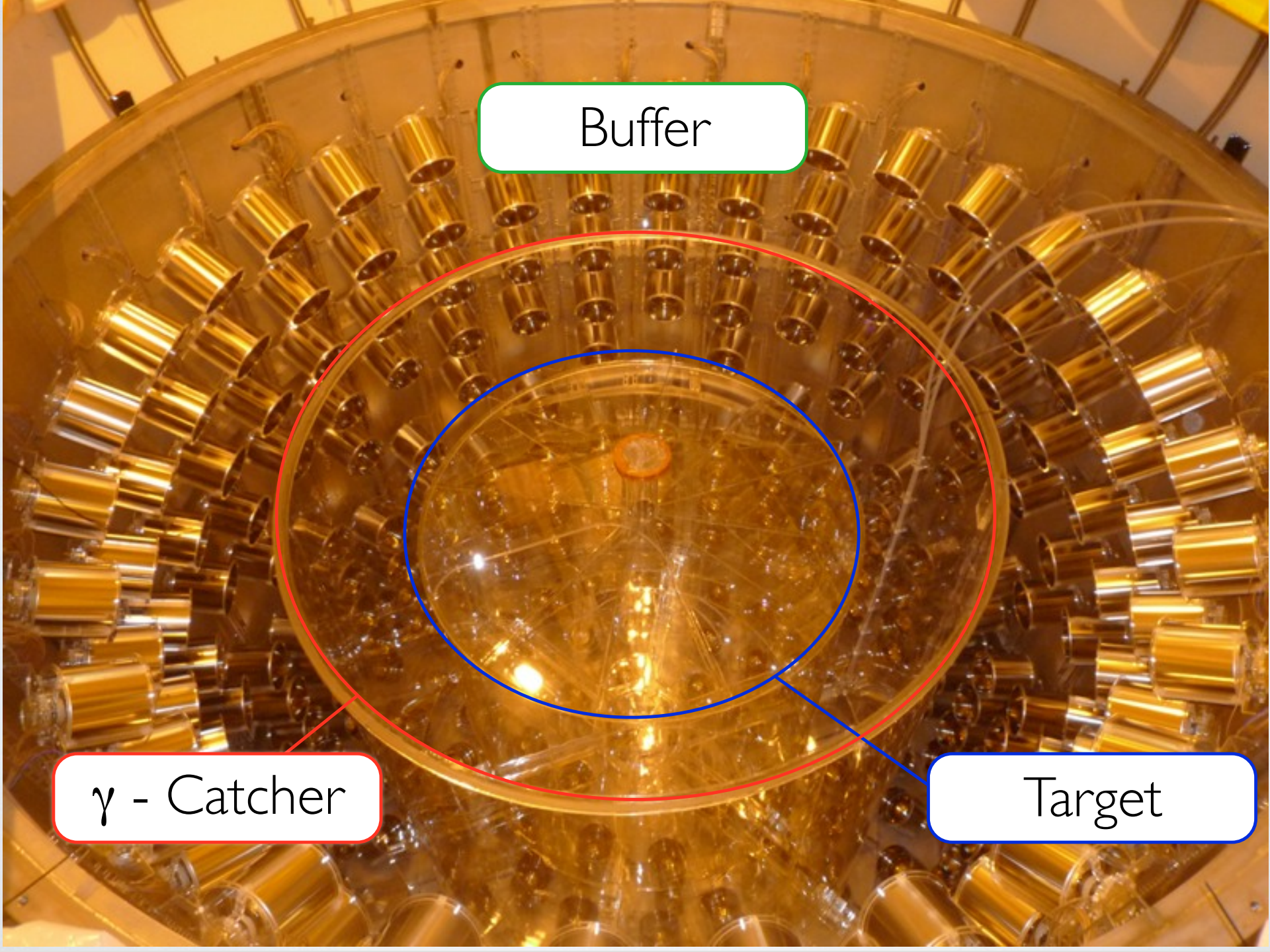
Shielding: about 250t steel shielding ~150 mm thick

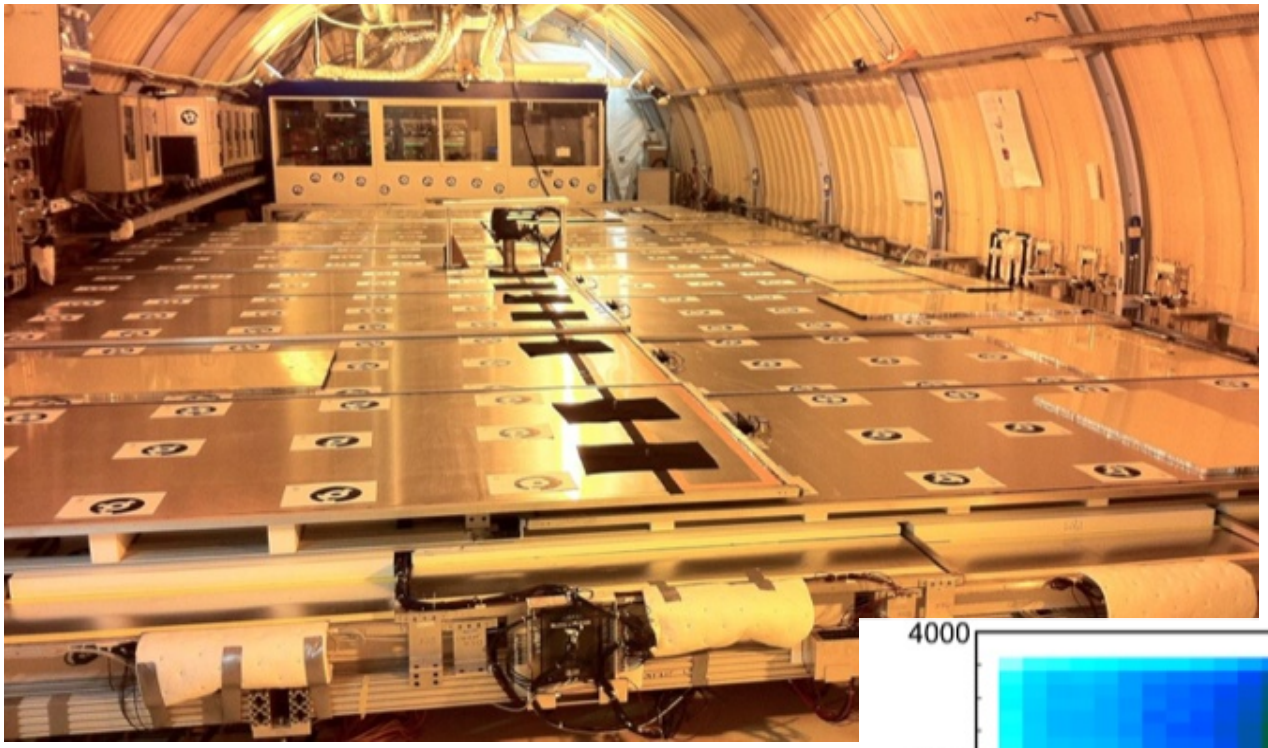
Calibration Systems



Milestones

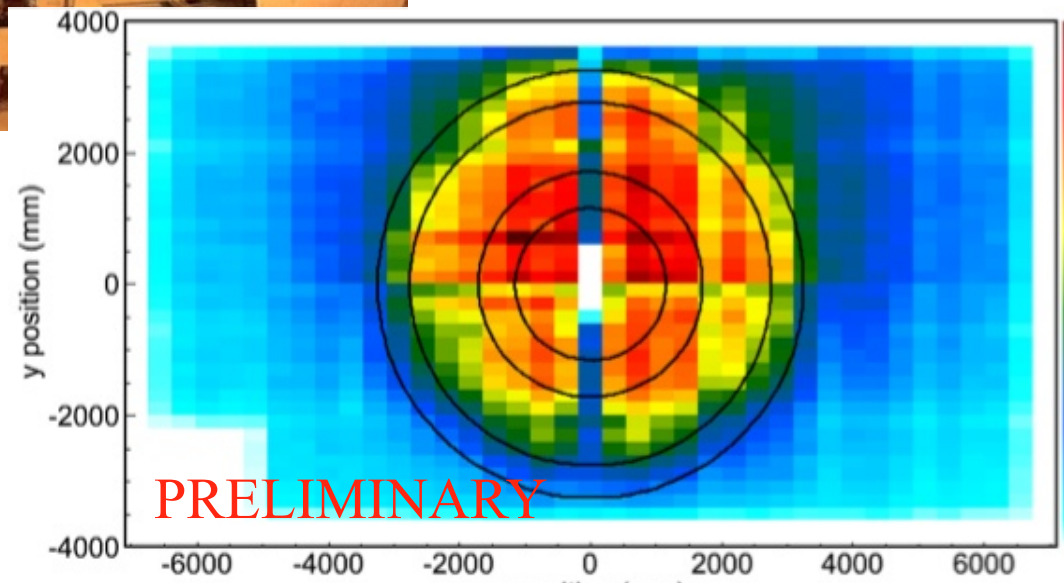
- May 2008 – October 2010: Far Detector construction
- December 2010: Far Detector filling complete
- April 2011
  - Far Detector commisioned
  - Far Detector data taking started
  - Near Lab construction begun
- July 2011: Outer Veto commisioned
- November 2011: First results


Buffer
γ - Catcher
Target



Outer Veto

Muons seen by both Outer-Veto and Neutrino Detector ("shadow")



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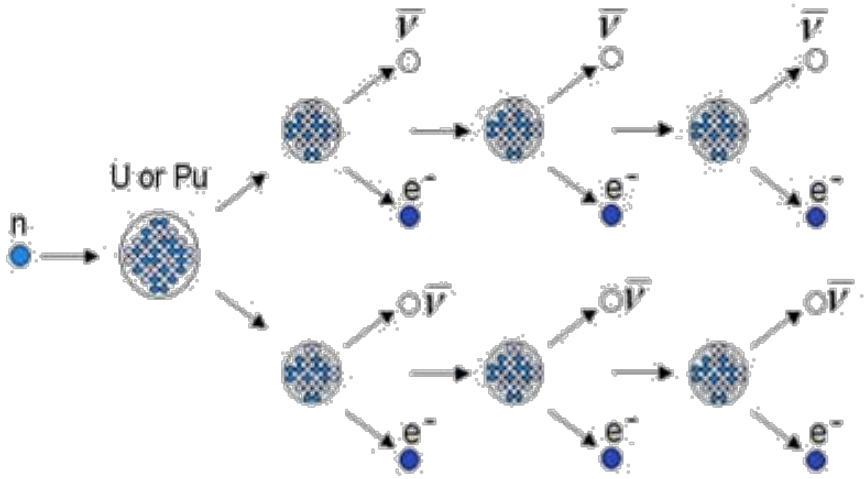
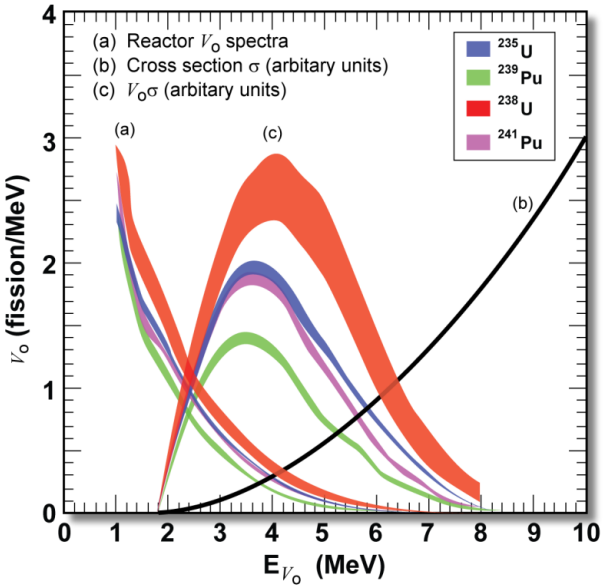
Reactors Produce Antineutrinos in Large Numbers



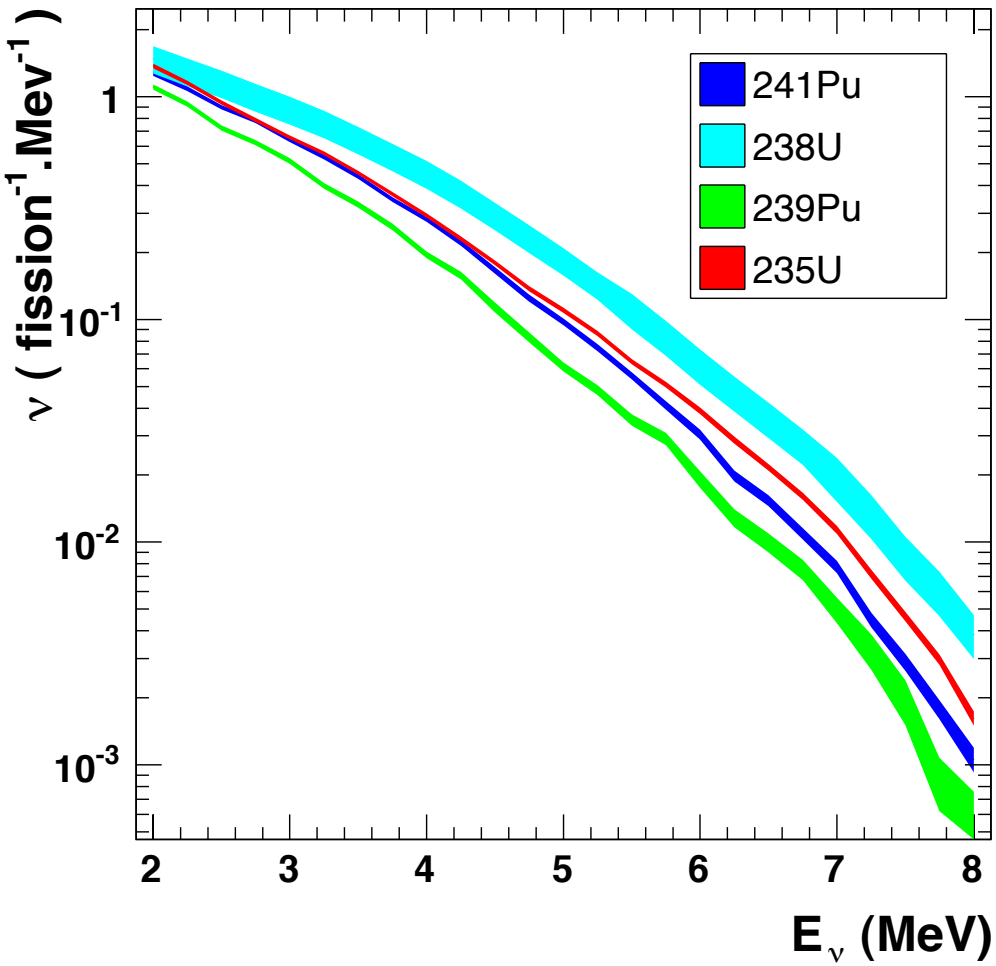


- Several antineutrinos are produced by each fission:

$$\Rightarrow N_{\bar{\nu}} \propto P_{th}$$

- Antineutrino emission rate and energy spectrum are sensitive to the isotopic composition of the core due to difference in emissions from fissions of different isotopes

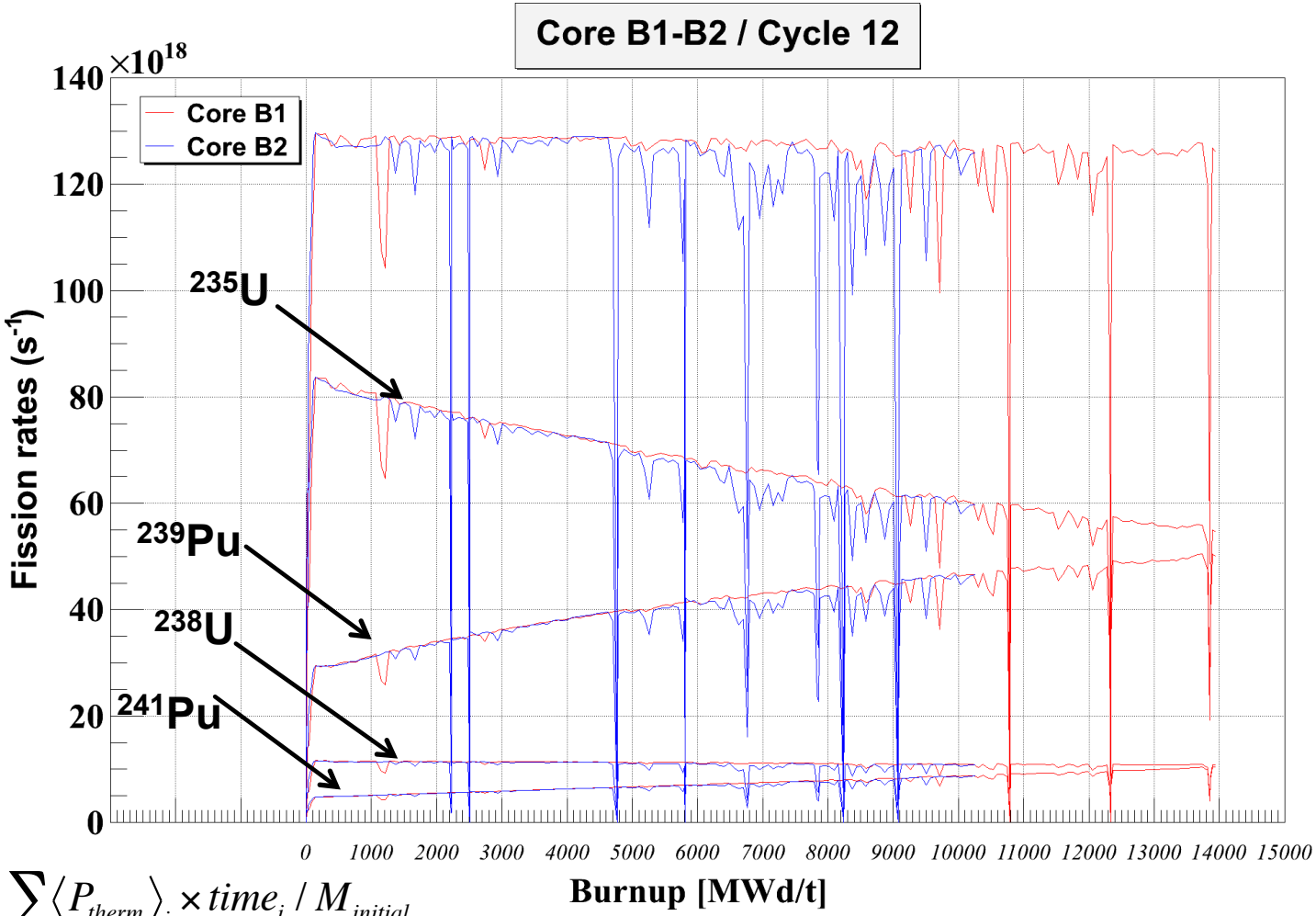
Reference ν Spectra



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

- Off-equilibrium corrections included
- Use Bugey4 as an anchoring point for the far detector only phase

Fission Rates



$$Burnup = \sum_i \langle P_{therm} \rangle_i \times time_i \,/\, M_{initial}$$

$\langle P_{therm} \rangle_i$: average thermal power for the ith interval [MW]

$time_i$: length [day] $M_{initial}$: initial mass of heavy nuclei (tons)

Predicted Neutrino Rate

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

$$\langle E_f \rangle = \sum_k \alpha_k(t) \langle E_f \rangle_k$$

Bugey4 anchor point

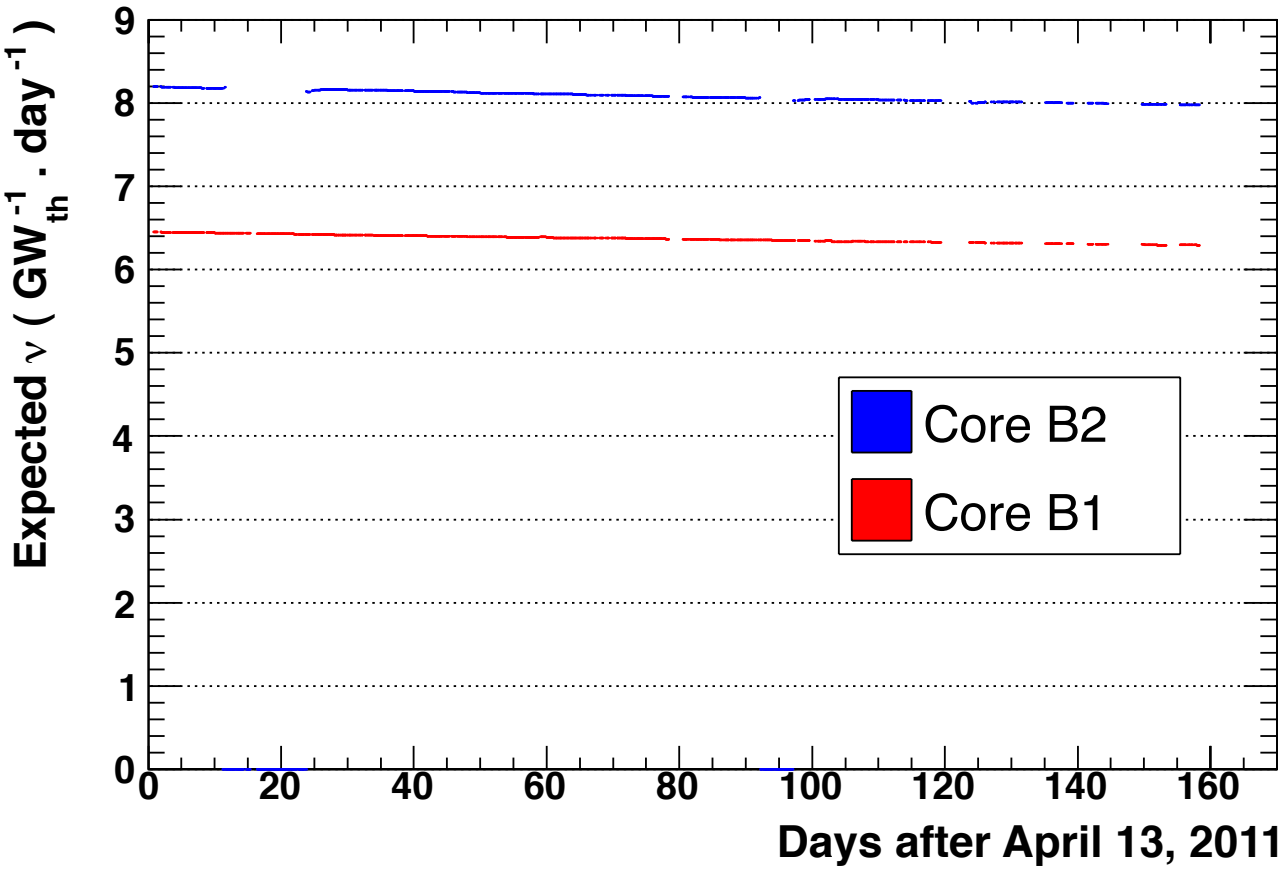
$$\langle \sigma_f \rangle = \langle \sigma_f \rangle^{Bugey} + \sum_k \left(\alpha_k^{DC}(t) - \alpha_k^{Bugey}(t) \right) \langle \sigma_f \rangle_k$$

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

Includes latest neutron life time

τ_n = 881.4 s, PDG2011

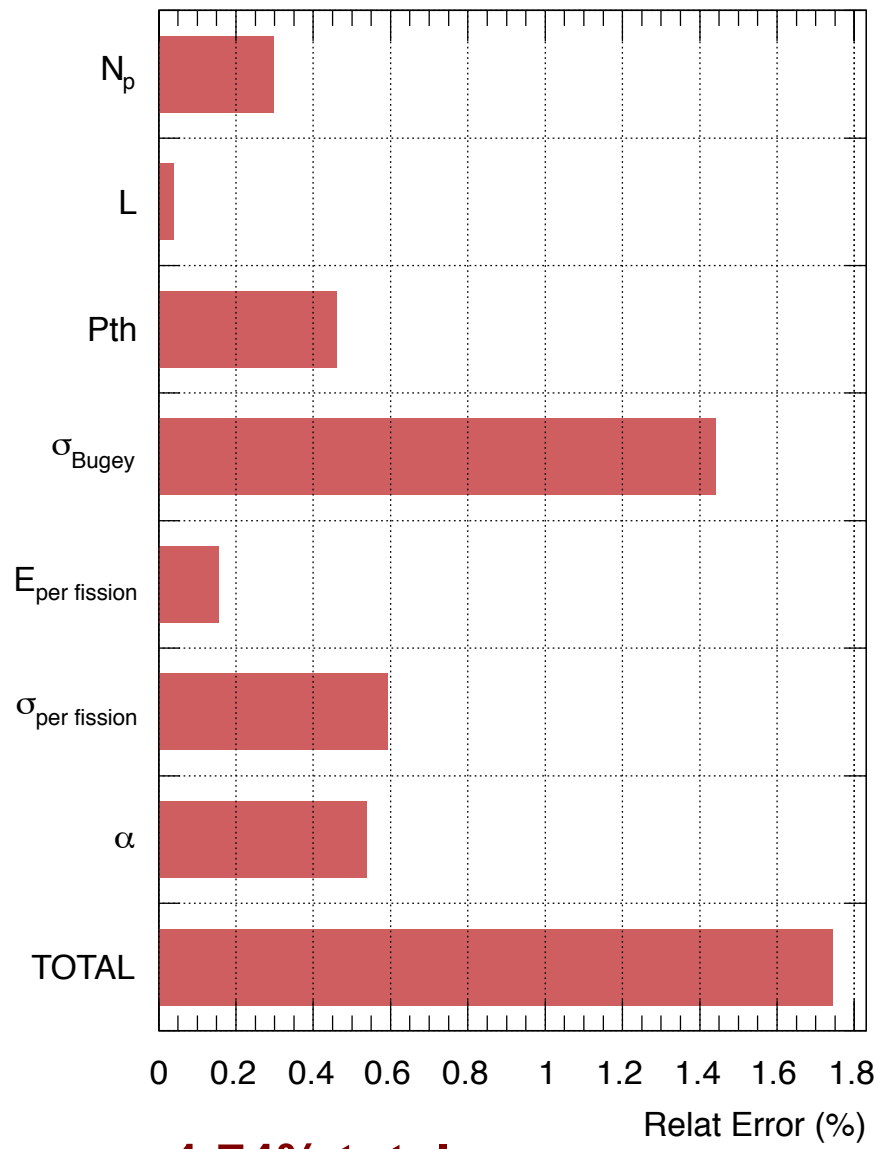
Predicted Neutrino Rate



~2.5% reduction of neutrino rate during data taking due to accumulation of ^{239}Pu in the core

Errors of Reactor Predictions

- Anchor point of 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.



1.74% total error

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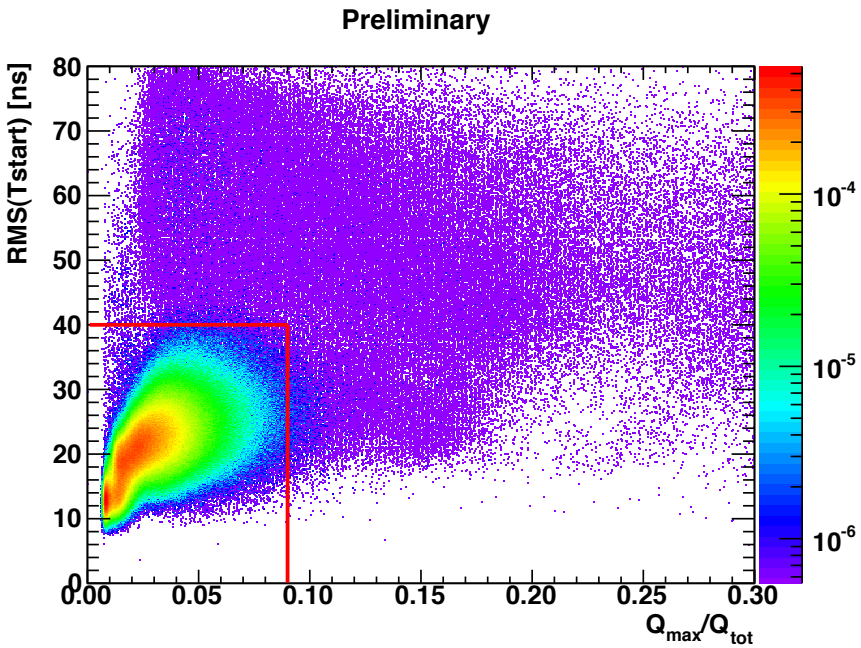
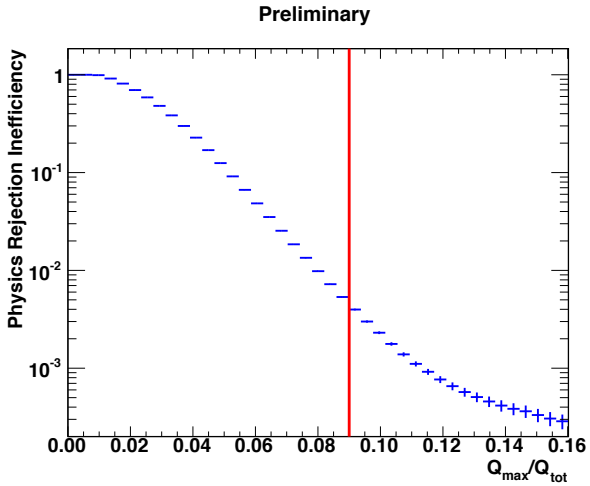
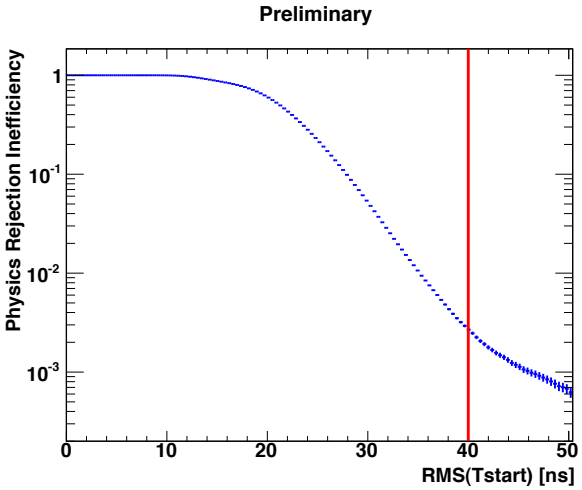
Light Noise

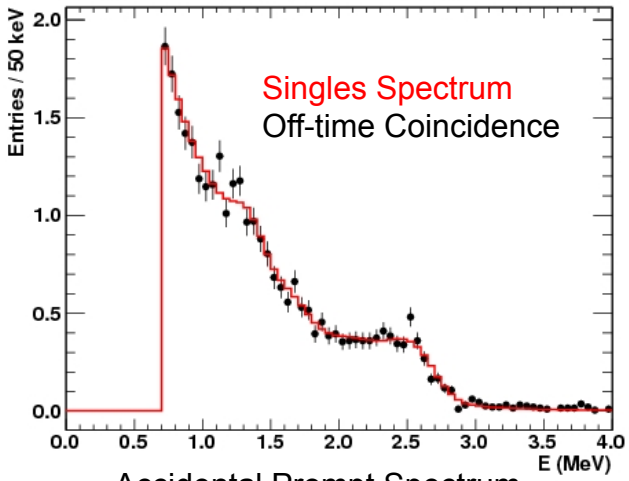
- Light created within the PMT bases observable due to transparent PMT potting.



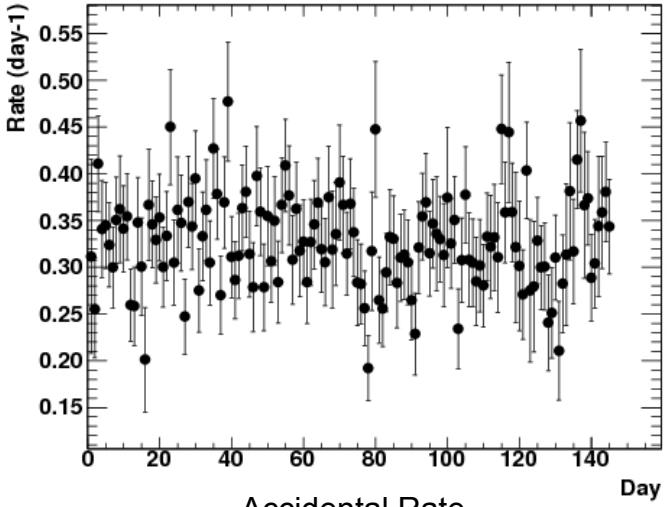




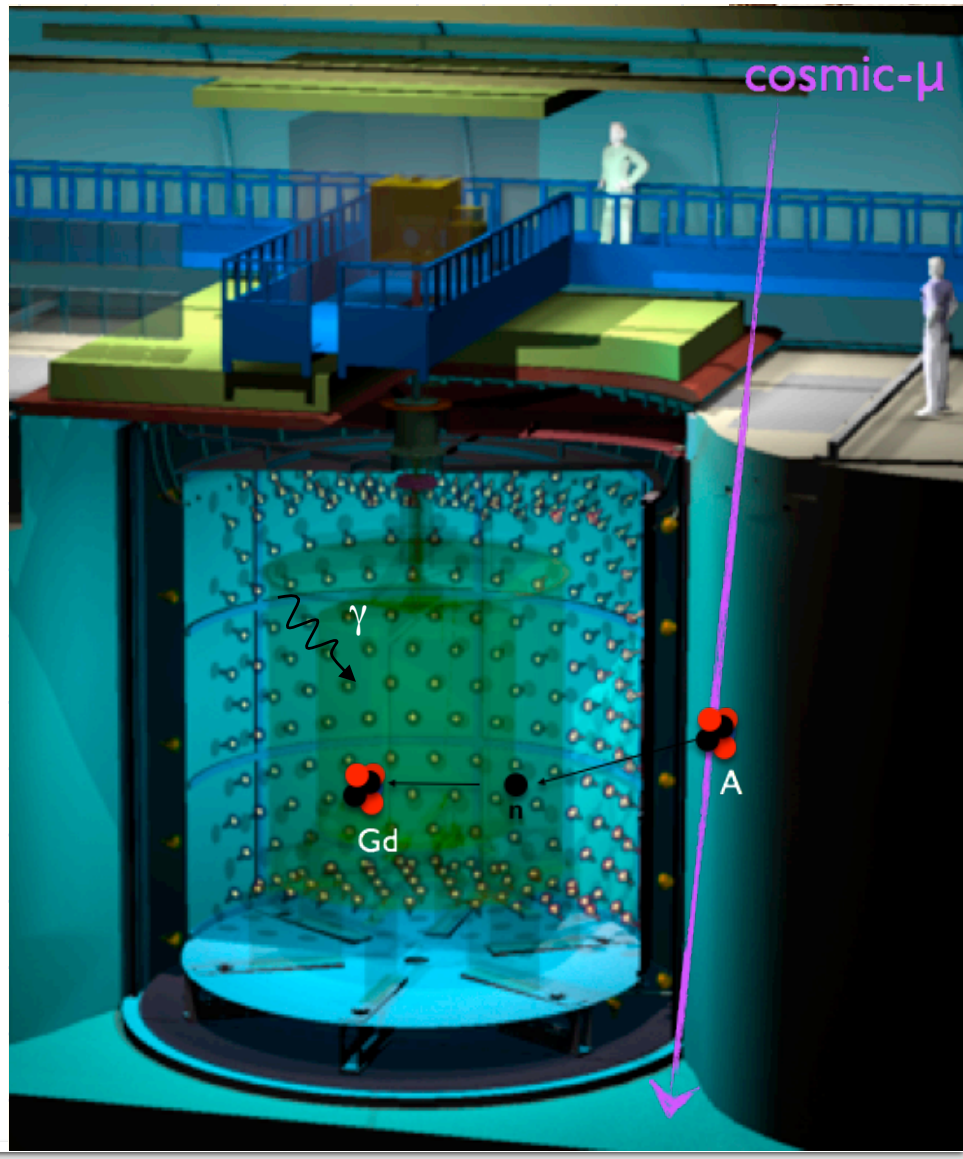
Accidental background



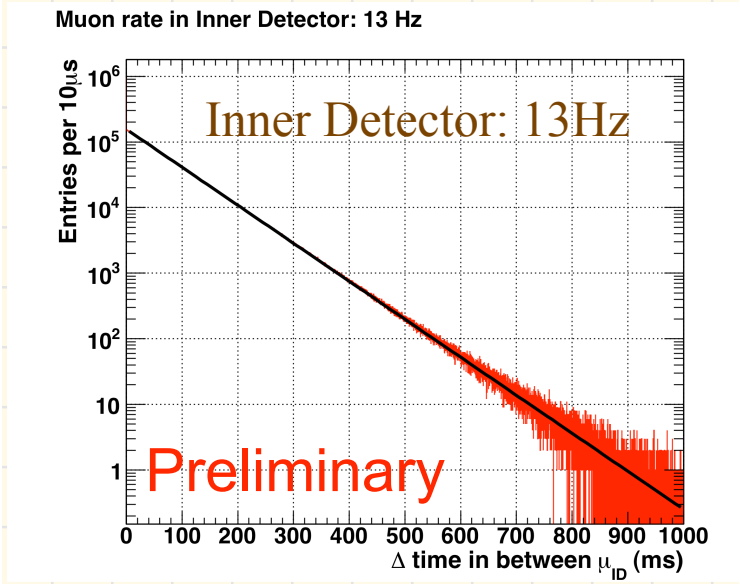
Accidental Prompt Spectrum

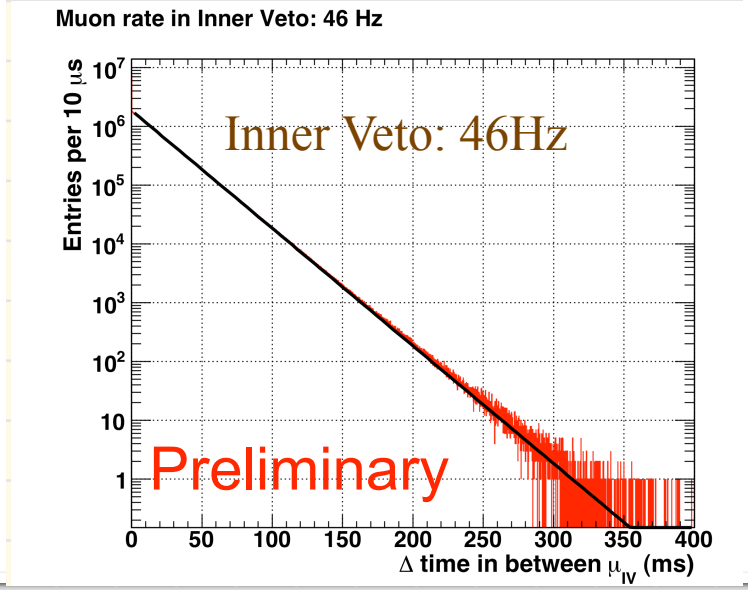


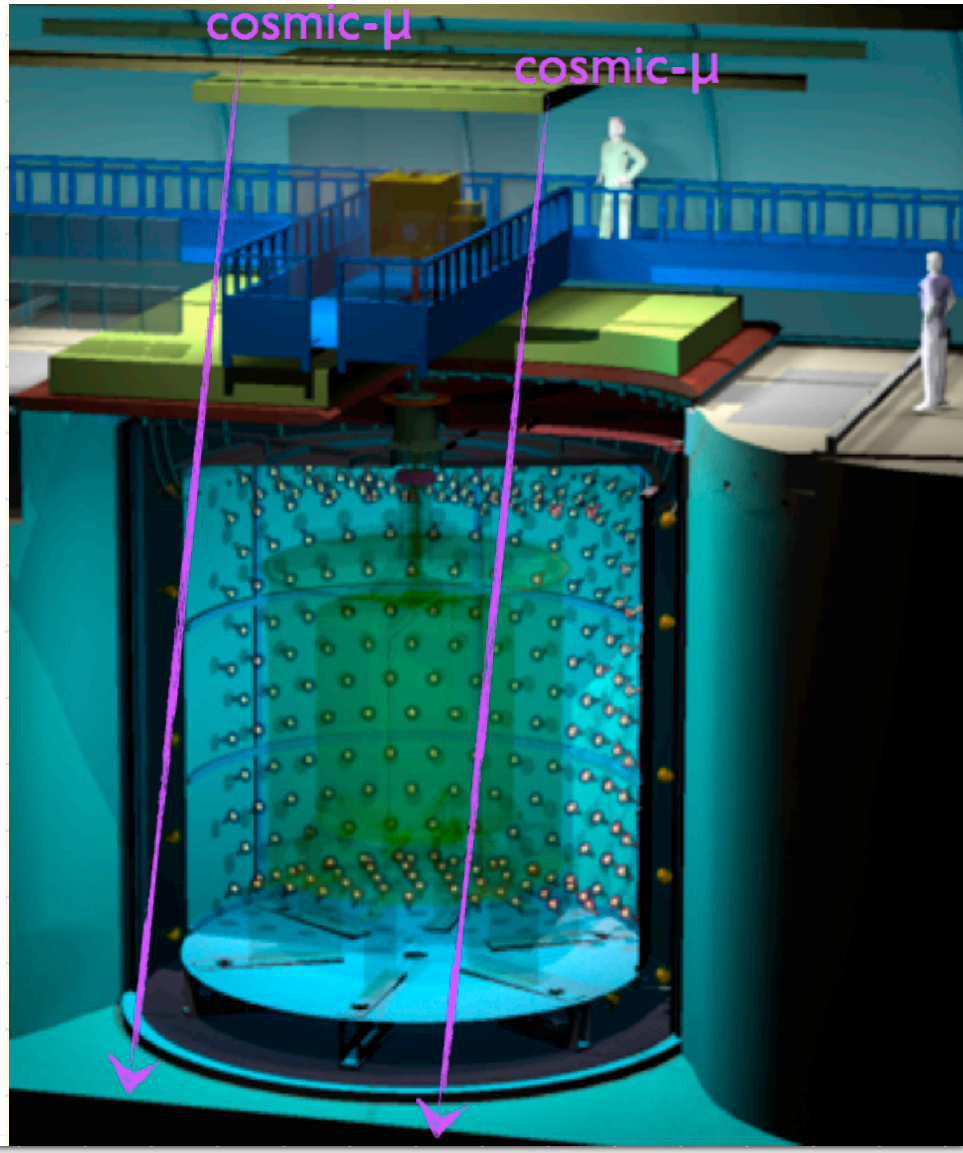
Accidental Rate



Cosmic Muon Rate



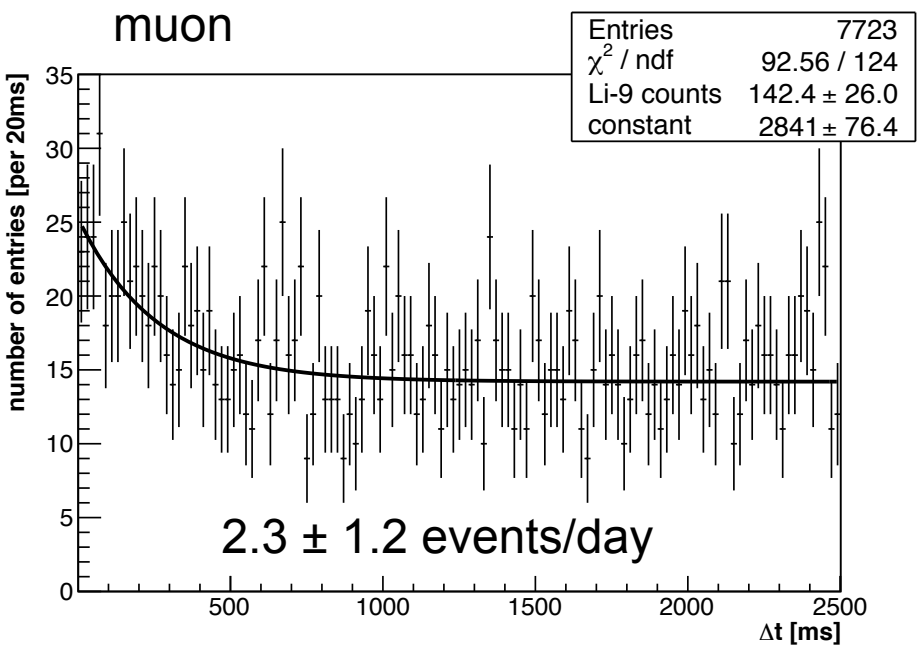


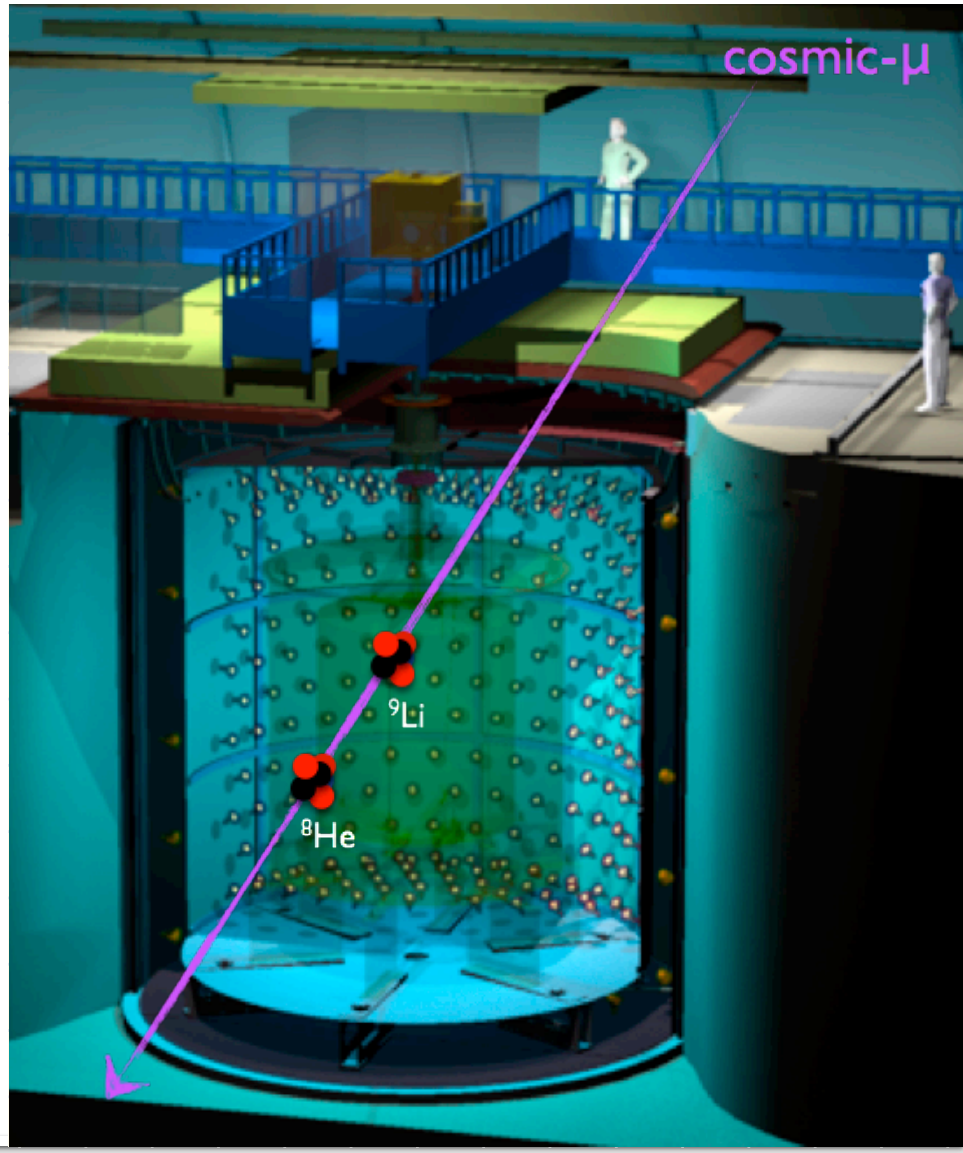


Cosmogenic Background

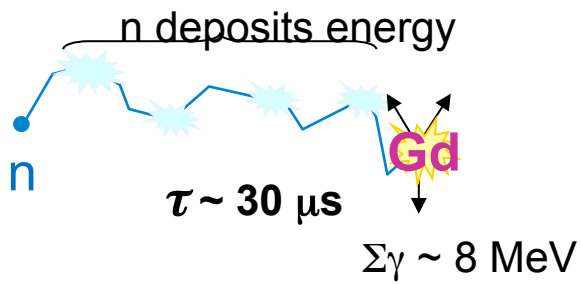
9Li, 8He: n+β with a half-life of 178, 119 ms and Q-value 11.9, 8.6 MeV can mimic the neutrino signal

Number of events estimated from time correlation with a showering muon

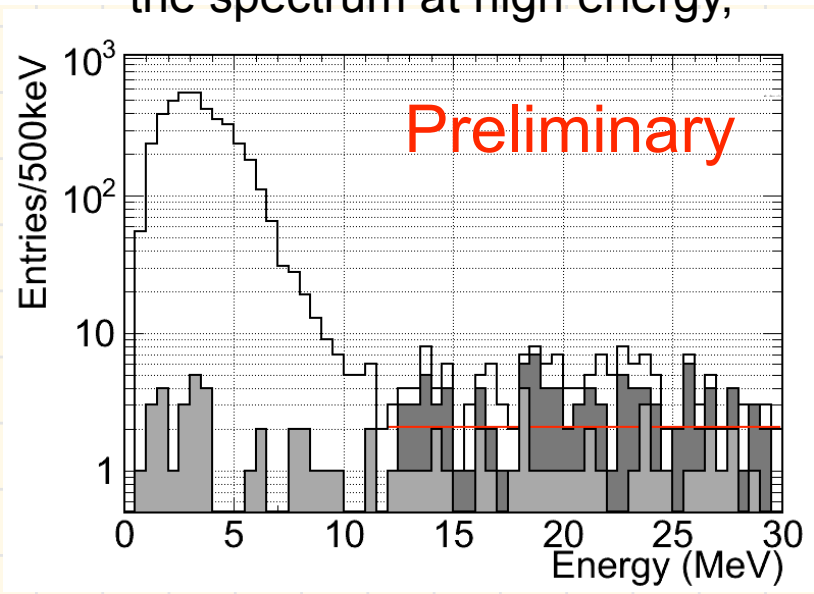




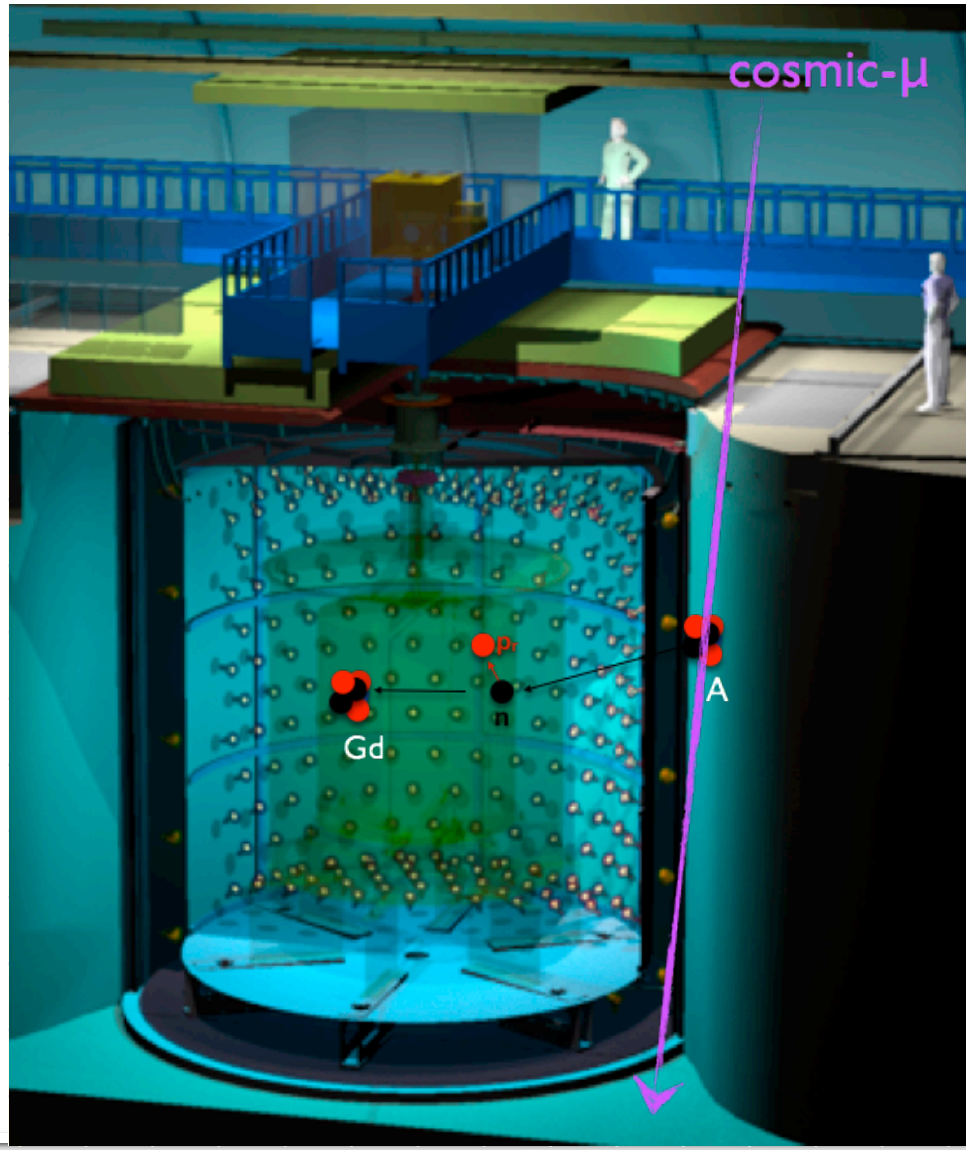
Fast Neutron Background



Events are estimated from the spectrum at high energy,



Rate 0.7 ± 0.5 events/day



Reactor Off Data

- One day of data was taken with both reactors off
- 3 events passed the neutrino selection criteria below 30 MeV
  - 1) E_{prompt} = 9.8 MeV, Δt = 201 ms from a showering muon (E_{muon} > 600 MeV), vertex 15 cm from the muon track.
  - 2) E_{prompt} = 4.8 MeV, Δt = 241 ms from a showering muon, 28 cm from the muon track.
  - 1) E_{prompt} = 26.5 MeV), no showering muon within 5 s
- The number of observed events are consistent with the background calculations.

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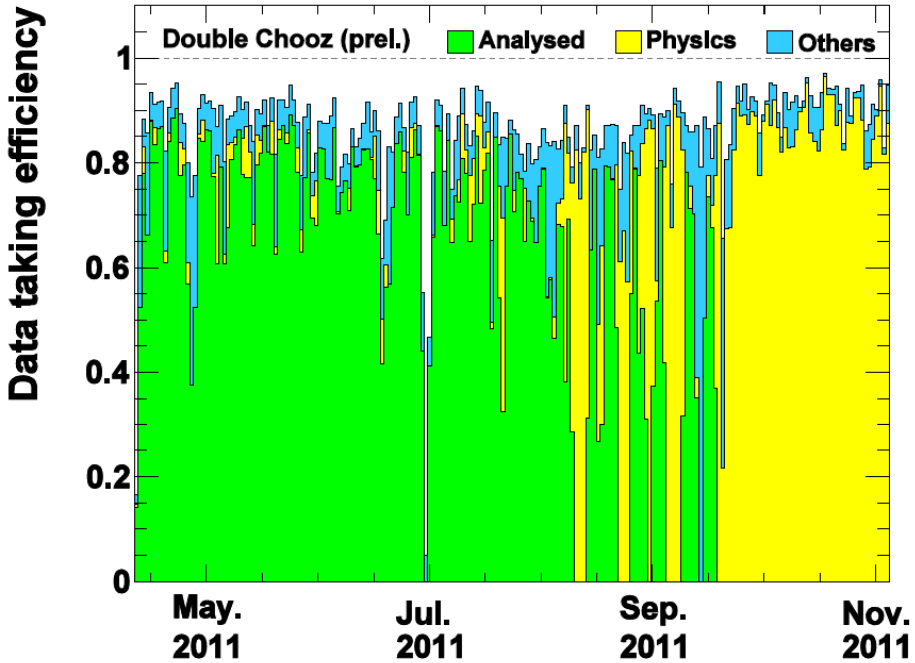
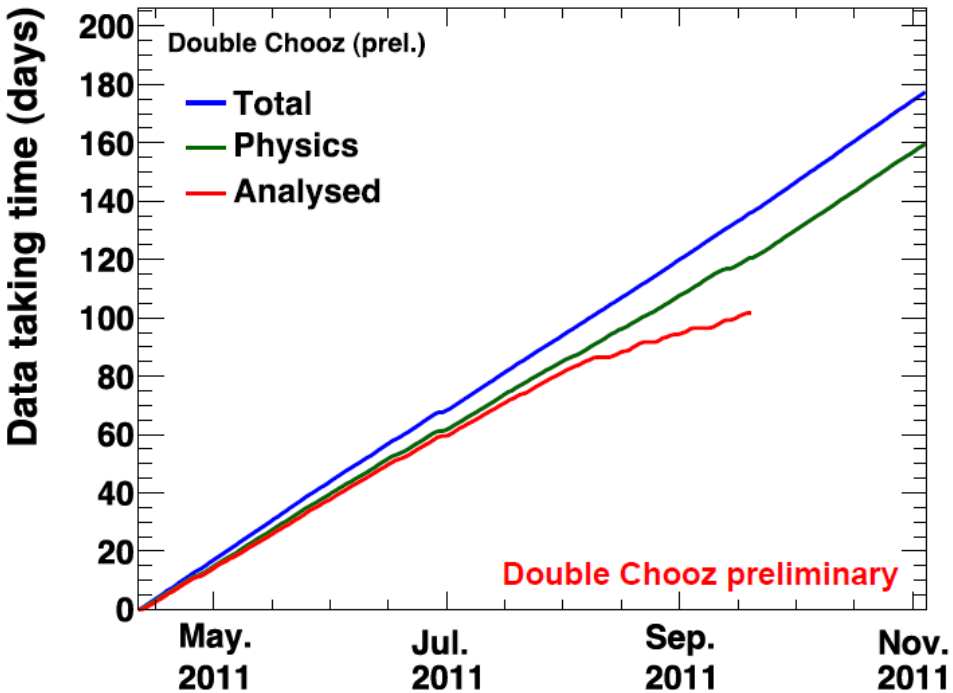
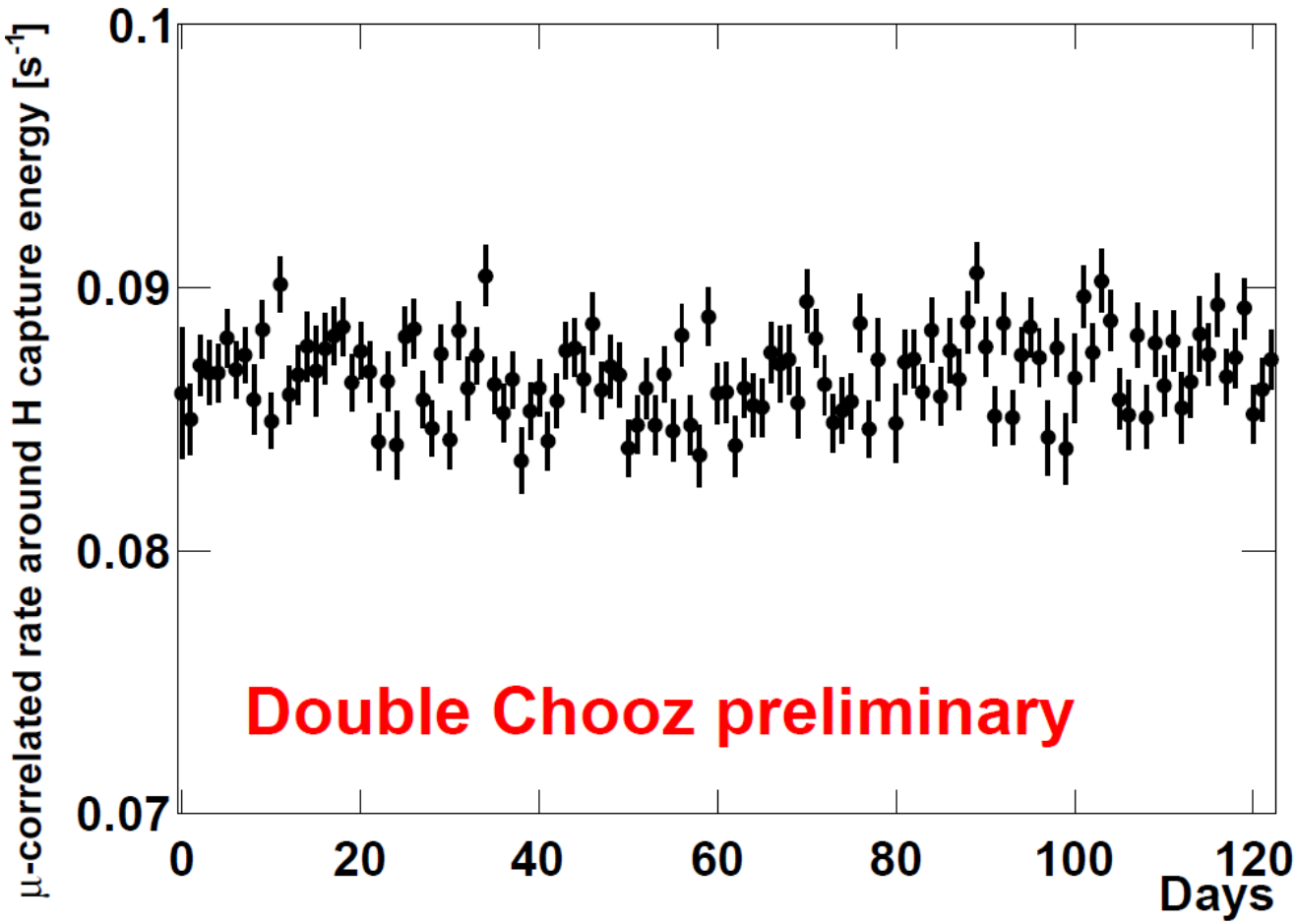
Data Taking Efficiency





- ✓ Number of data taking days : **206 days**
- ✓ Integrated data taking time in total : **177.4 days**
- ✓ Integrated data taking time for physics : **159.6 days**
- ✓ Data taking efficiency in total : **86.2 %**
- ✓ Data taking efficiency for physics : **77.5 %**

Detector Stability

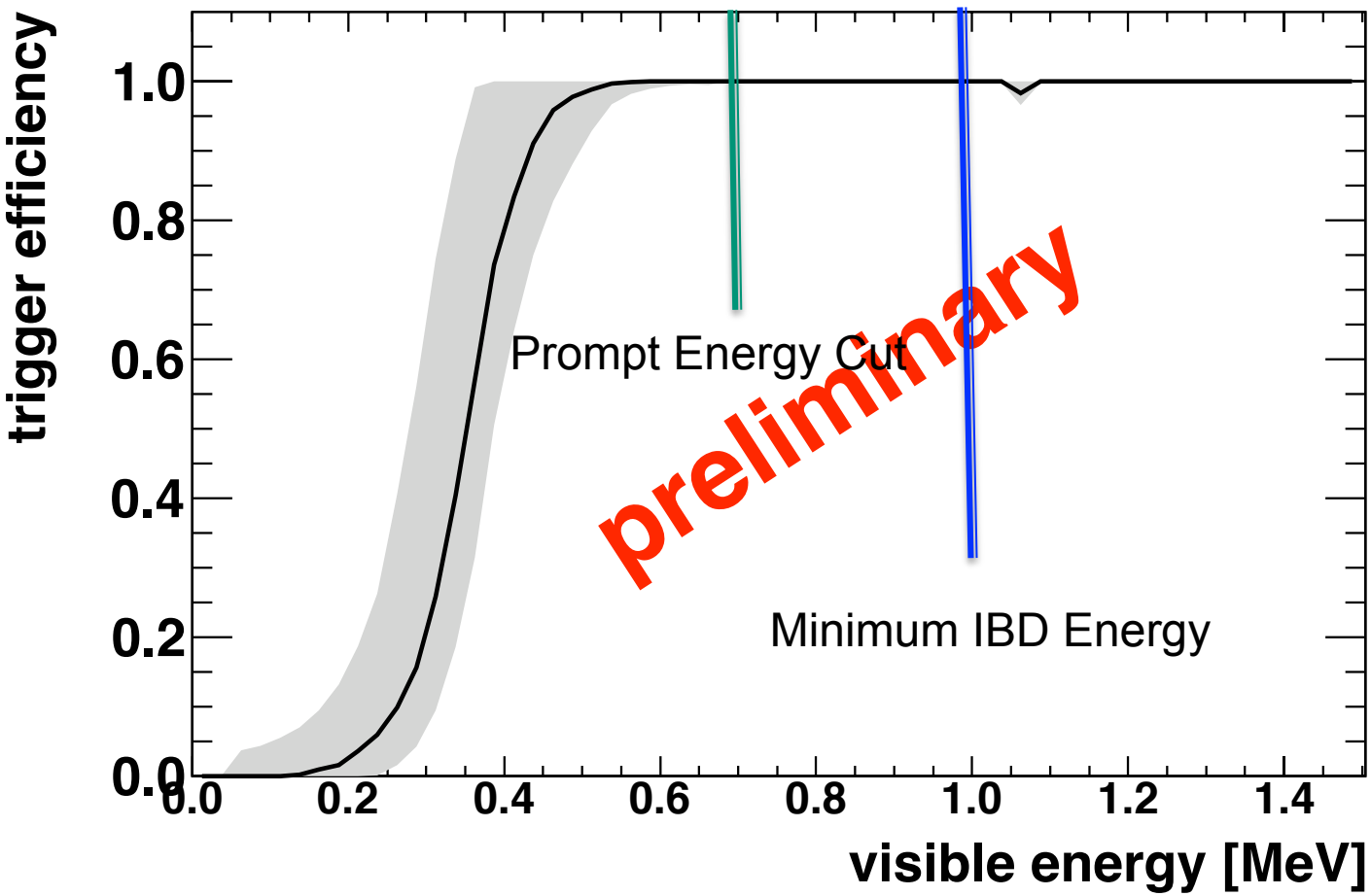


- neutron capture on proton after muon

Neutrino Candidate Selection

- Veto Detector for 1 ms after each muon
- Reject PMT light emission events
- Prompt signal within [0.7, 12] MeV
- Delayed signal within [6, 12] MeV
- Coincidence window between [2,100] μs
- Multiplicity Conditions
  - No trigger (E>0.5 MeV) 100 μs before prompt
  - Only one trigger (E>0.5 MeV) 400 μs after prompt

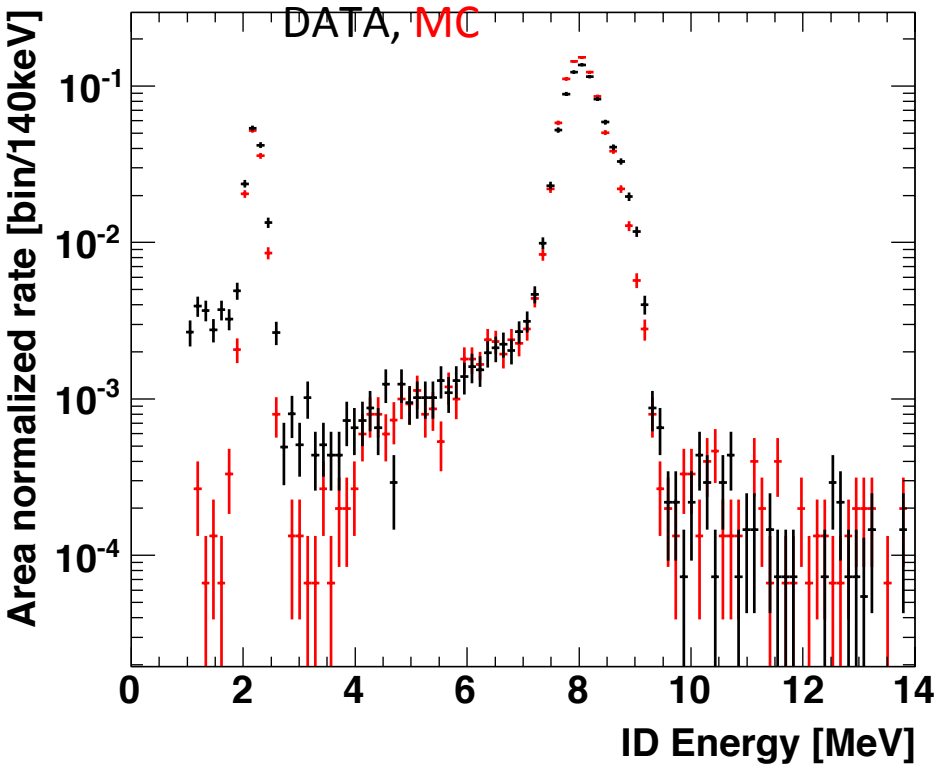
Trigger Threshold



Prompt energy cut efficiency > 99%

Cf Data delayed energy distribution

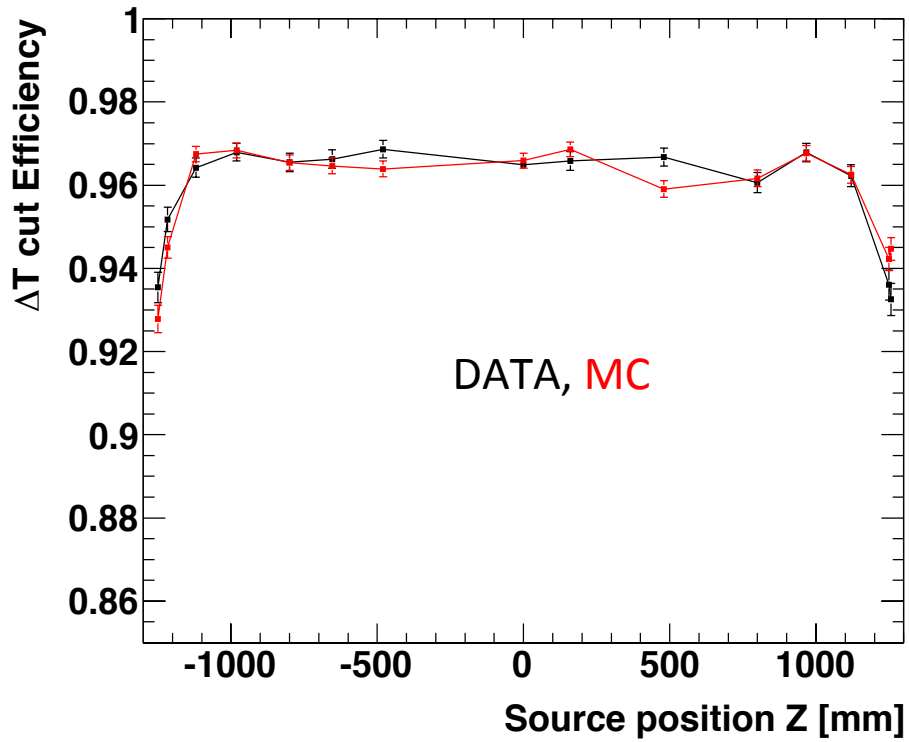
-Cf data and MC in the center:
-Delayed E distribution



Cuts:
BG subtraction for data with Physics Run
Before coincidence: dTmu > 1[ms] & Qratio < 0.09
Selection criteria for delayed coincience:
Prompt : dT > 1 [ms] & 7 < E < 30 [MeV] (tight cut)
Delayed : dT from Prompt < 1[ms] & 0.7 < E < 25 [MeV]
H capture : 1 < E < 3 [MeV]
Gd capture : 4 < E < 25 [MeV]

Neutron Capture efficiency

ΔT efficiency 2<ΔT<100 μs
Cf data and MC along Z-axis.



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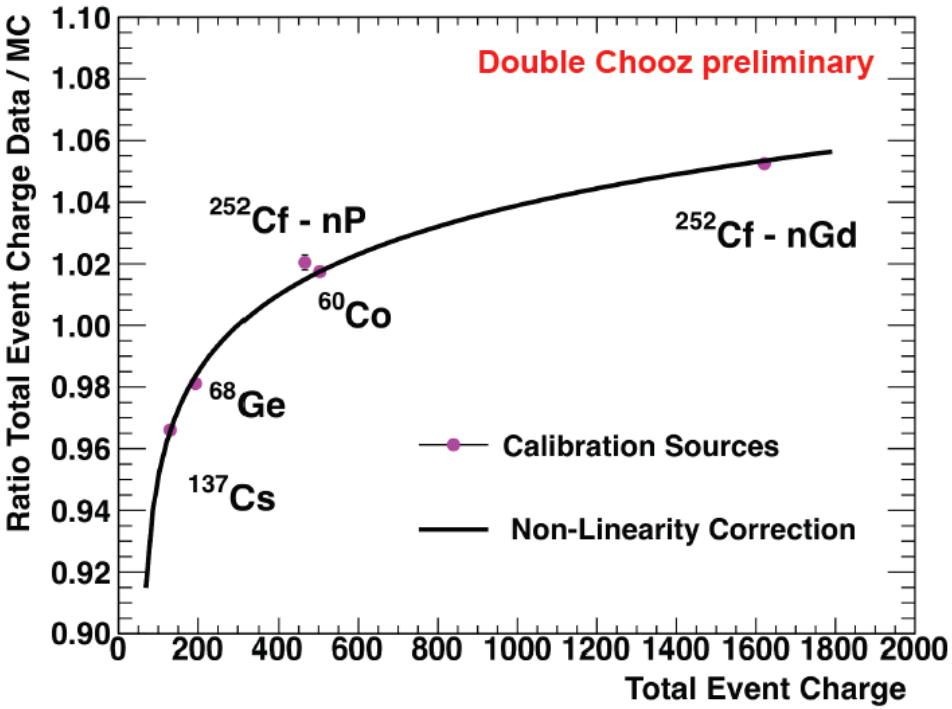
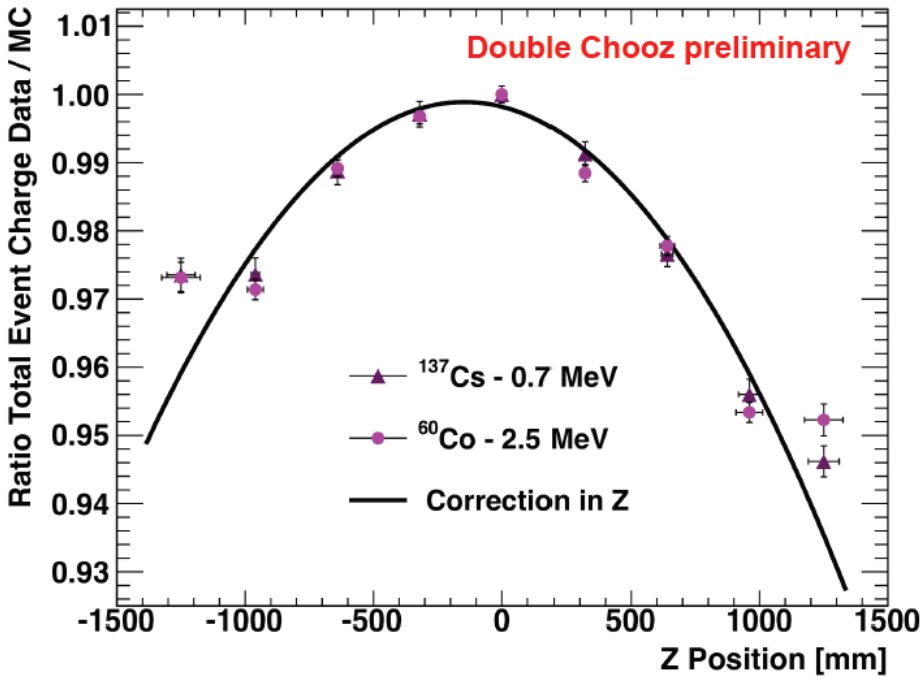
Relative difference: ≤ 0.5%

Charge / Position correction



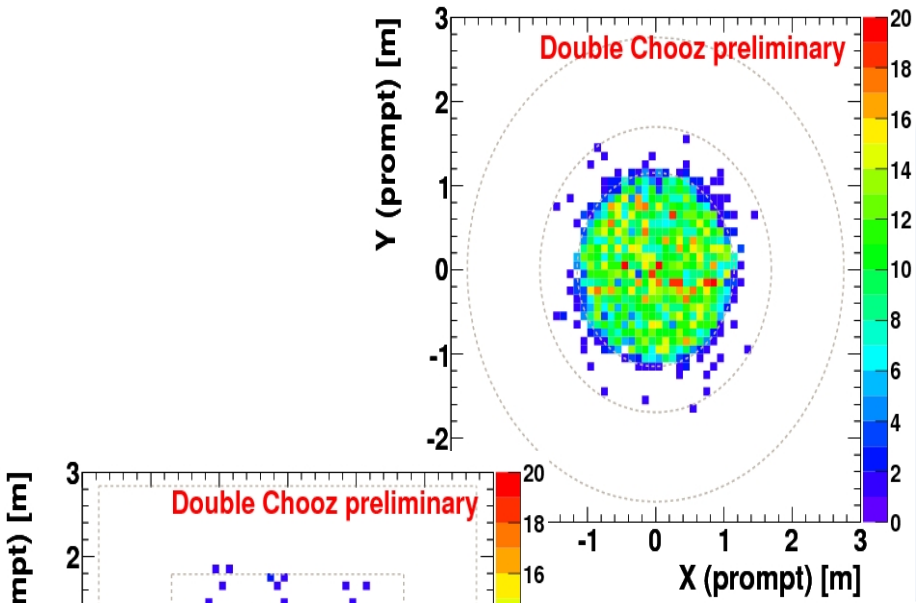


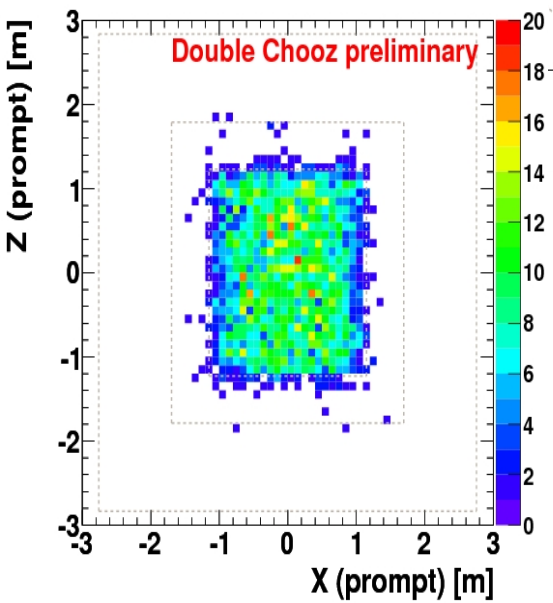
- Calibrate the non-linearity due to single photoelectron efficiency and electronics and Q-reconstruction effects.
- Calibration of the z-bias.
- Residuals in the correction included in the detector covariance matrix.

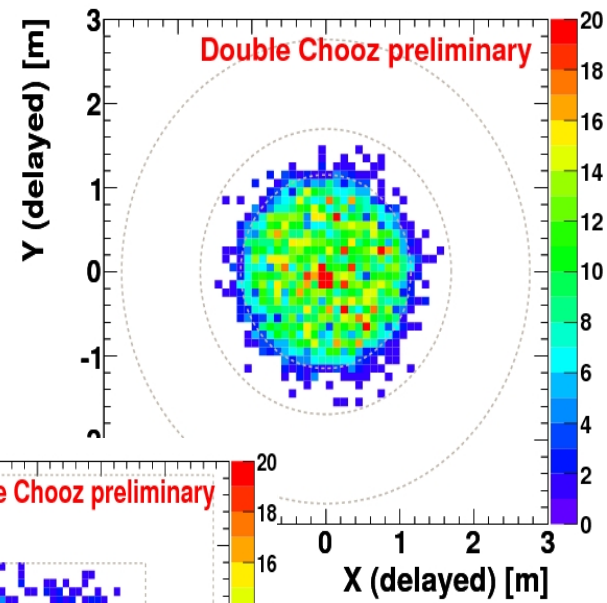
Additional Systematic Uncertainties

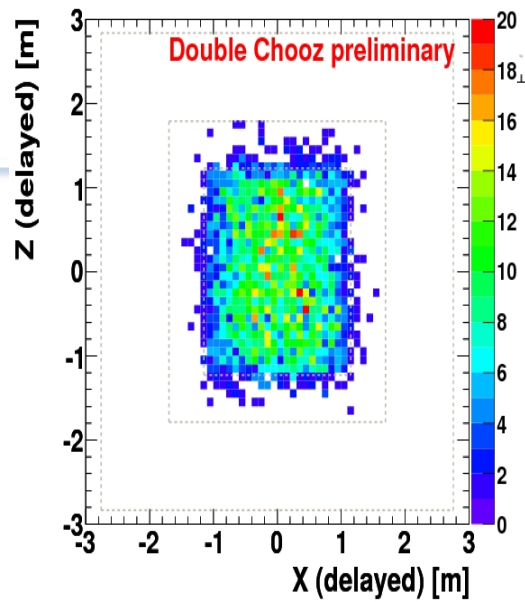
Source	Efficiency	Uncertainty
Target Proton measurement		+/- 0.3%
Trigger Efficiency		+/- 0.4%
Muon Dead Time	0.955	Negligible
Multiplicity cut	0.995	Negligible
Gd fraction	0.98	0.6%
Spill-in/out	0.993	0.4%

Reconstructed Candidate Position



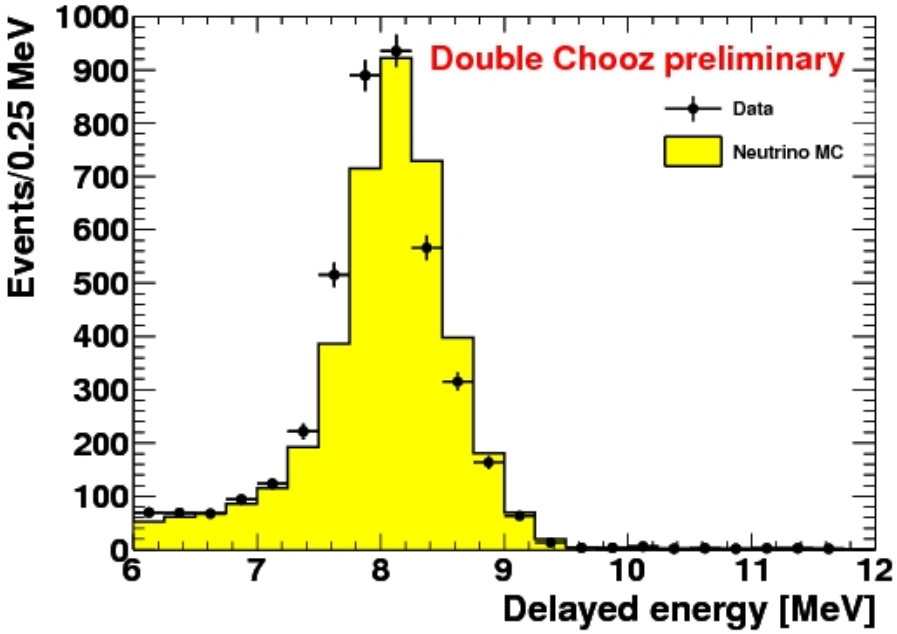


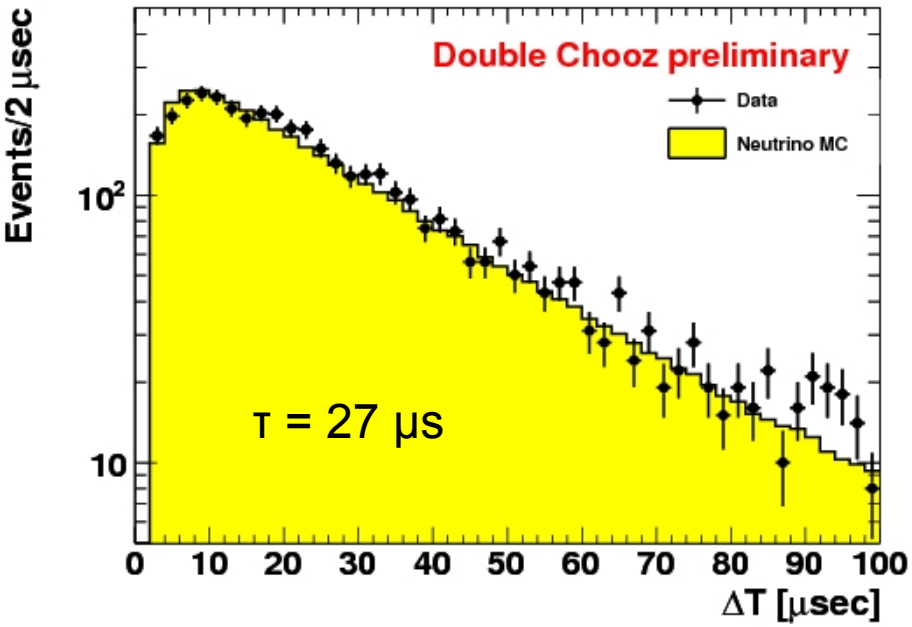




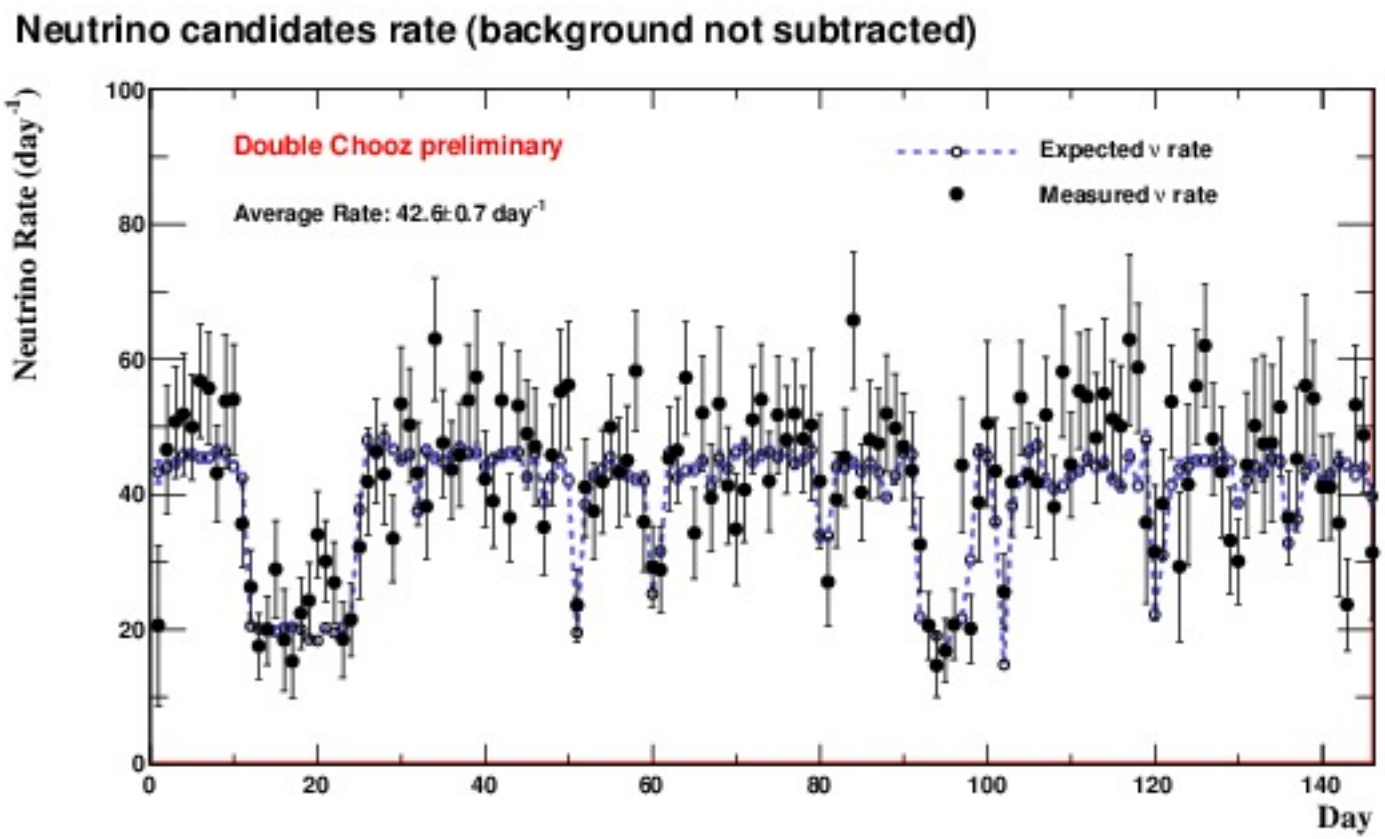
Neutrino Candidates

- ✓ Selection of Neutron Capture on Gd only
  - ➔ Allow to define the fiducial volume by the mass of Gd-loaded LS
  - ➔ Delayed Energy Cut Efficiency : 0.86 +/- 0.6%.
- ✓ The efficiency within [2,100] μs is 0.965 ± 0.5%





Candidates vs Time



Backgrounds NOT subtracted from candidates sample

Outline

- Neutrino Oscillation
- Detector Design and Construction
- Reactors
- Backgrounds
- Analysis
- **Results**

Oscillation Analysis

$$\chi^2 = \left(N_i - \left(\sum_R^{\text{Reactors}} N_i^{\nu,R} + \sum_b N_i^b(P_b)\right)\right) \times \left(M_{ij}^{\text{signal}} + M_{ij}^{\text{detector}} + M_{ij}^{\text{stat}} + \sum_b^{\text{bkgnds.}} M_{ij}^{\text{b}}\right)^{-1}$$
$$\times \left(N_j - \left(\sum_R^{\text{Reactors}} N_j^{\nu,R} + \sum_b N_j^b(P_b)\right)\right)^{\text{T}}$$
$$+ \sum_R^{\text{Reactors}} \frac{(P_R)^2}{\sigma_R^2}$$
$$+ \sum_b^{\text{bkgnds.}} \frac{(P_b)^2}{\sigma_b^2}$$

M_{ij}^{signal}: Signal covariance matrix.

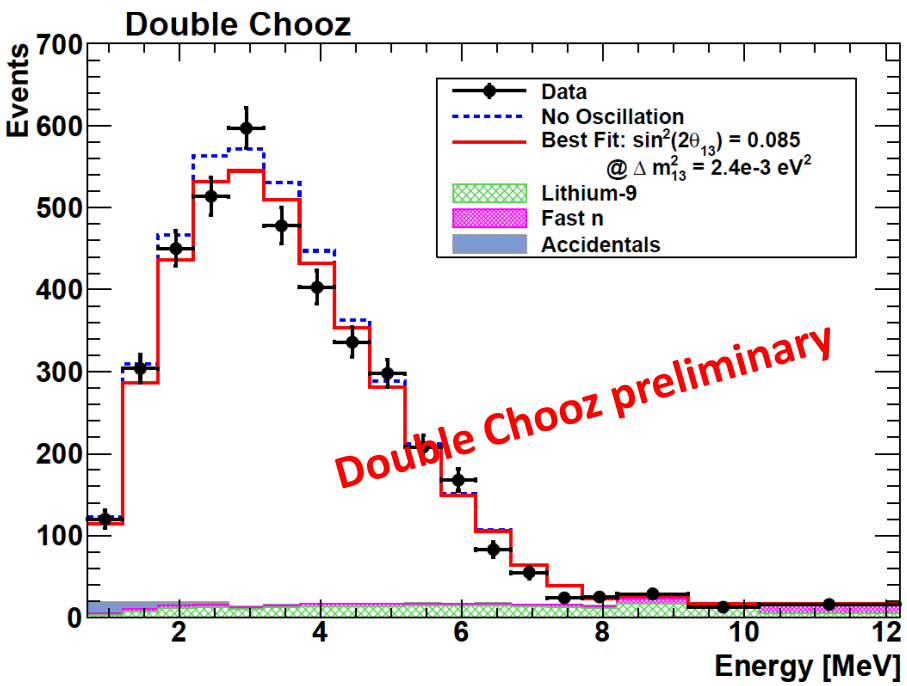
M_{ij}^{detector}: Detector covariance matrix.

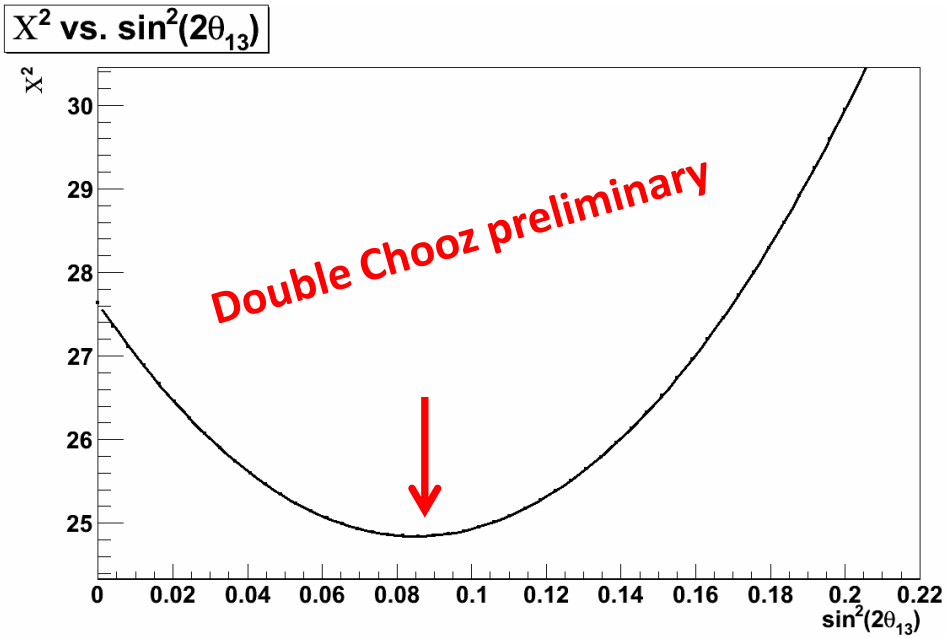
M_{ij}^{stat}: Statistical covariance matrix.

M_{ij}^{b}: Covariance matrix for background

- MC Events & Data flow handles in parallel
- Correction for MC/Data differences

Oscillation Analysis





θ_{13} Preliminary Results

- **Rate + Shape Analysis:**

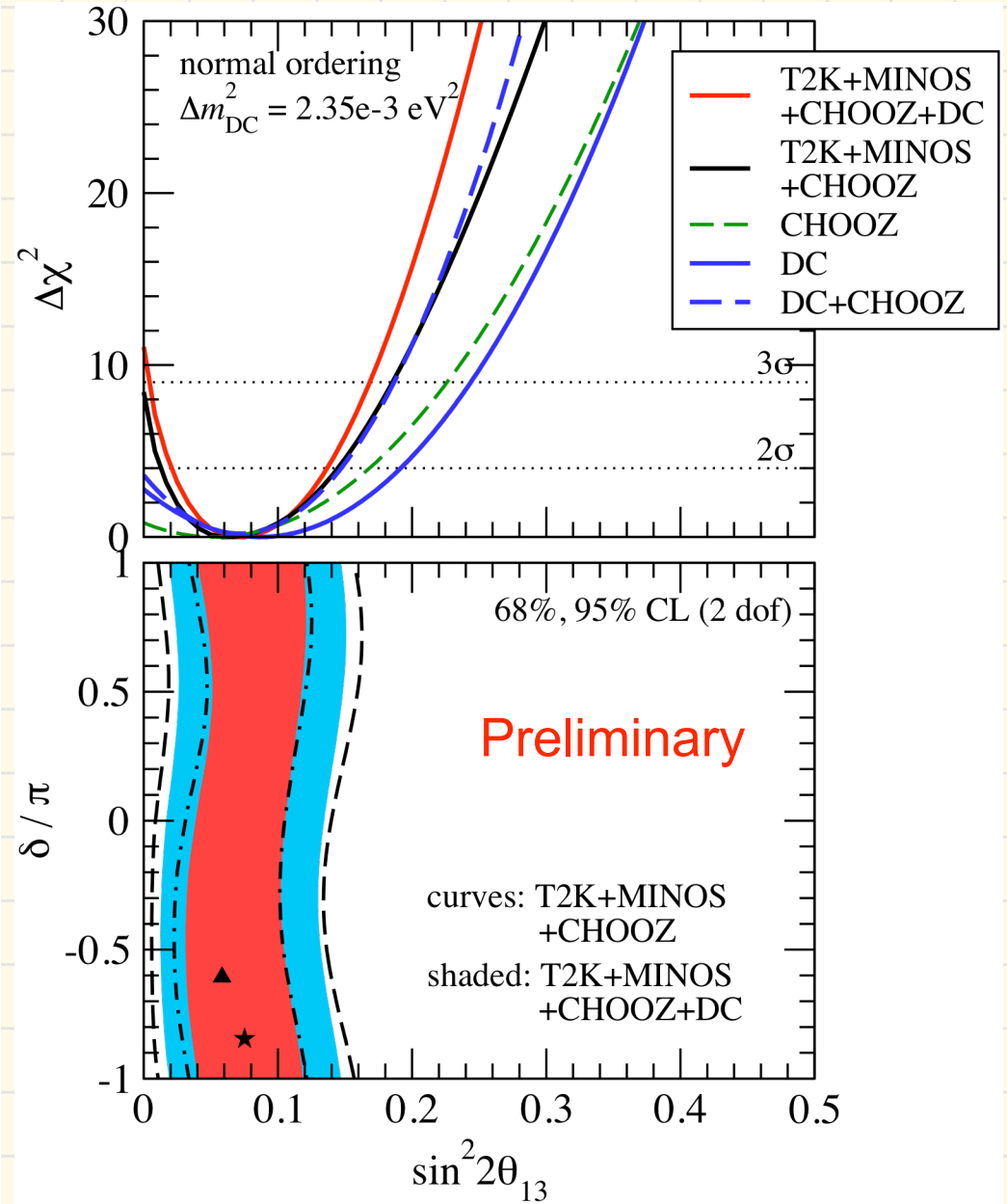
  sin2(2θ13) = 0.085±0.029(stat)±0.042(syst)

- **Rate Only:**

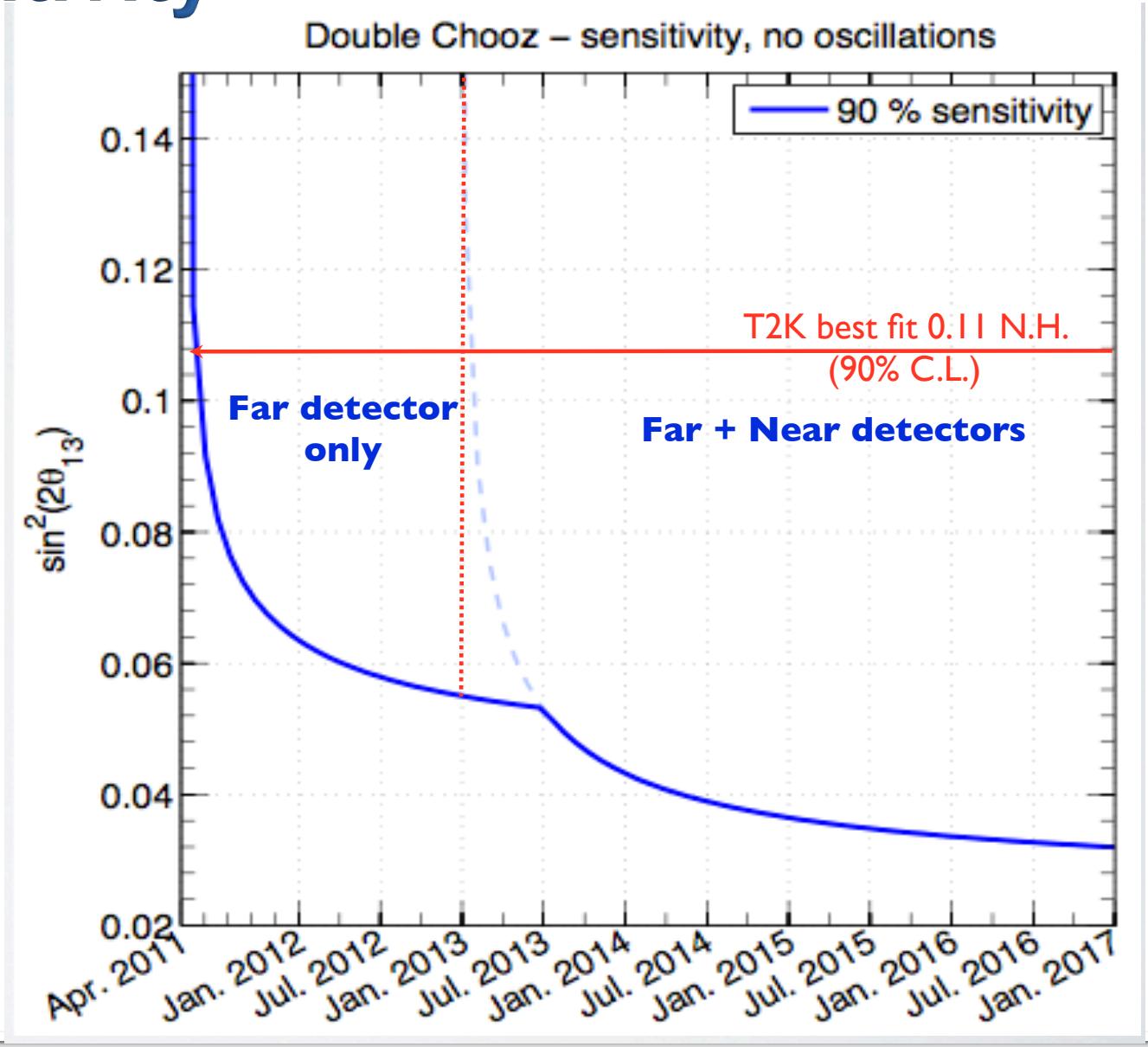
  sin2(2θ13) = 0.093±0.029(stat)±0.073(syst)

Global Data

- The Double Chooz Far Detector only results are consistent with previous results.
- A combined fit excludes $\theta_{13} = 0$ at 3σ



Sensitivity



Conclusion

- The Double Chooz far detector has been taking data since April 2011
- 5 months of data have been analyzed
- $\mathrm{Sin}^2 2\theta_{13} = 0.085 \pm 0.029(\mathrm{stat}) \pm 0.042(\mathrm{syst})$ @ 68% conf
- The near detector will be operational early 2013
- Double Chooz will reach a final sensitivity to $\mathrm{Sin}^2 2\theta_{13}$ of 0.03