Double Chooz: 100 jours de données

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pour le groupe Double Chooz du CEA / Irfu

energie atomique • energies alternatives

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

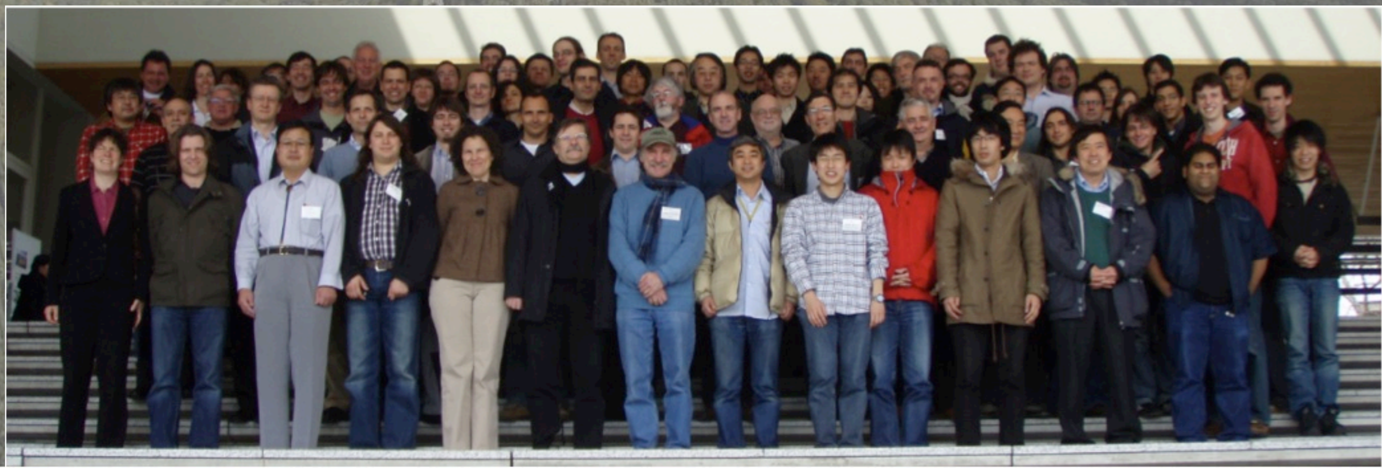
Spain
CIEMAT-Madrid

UK
Sussex

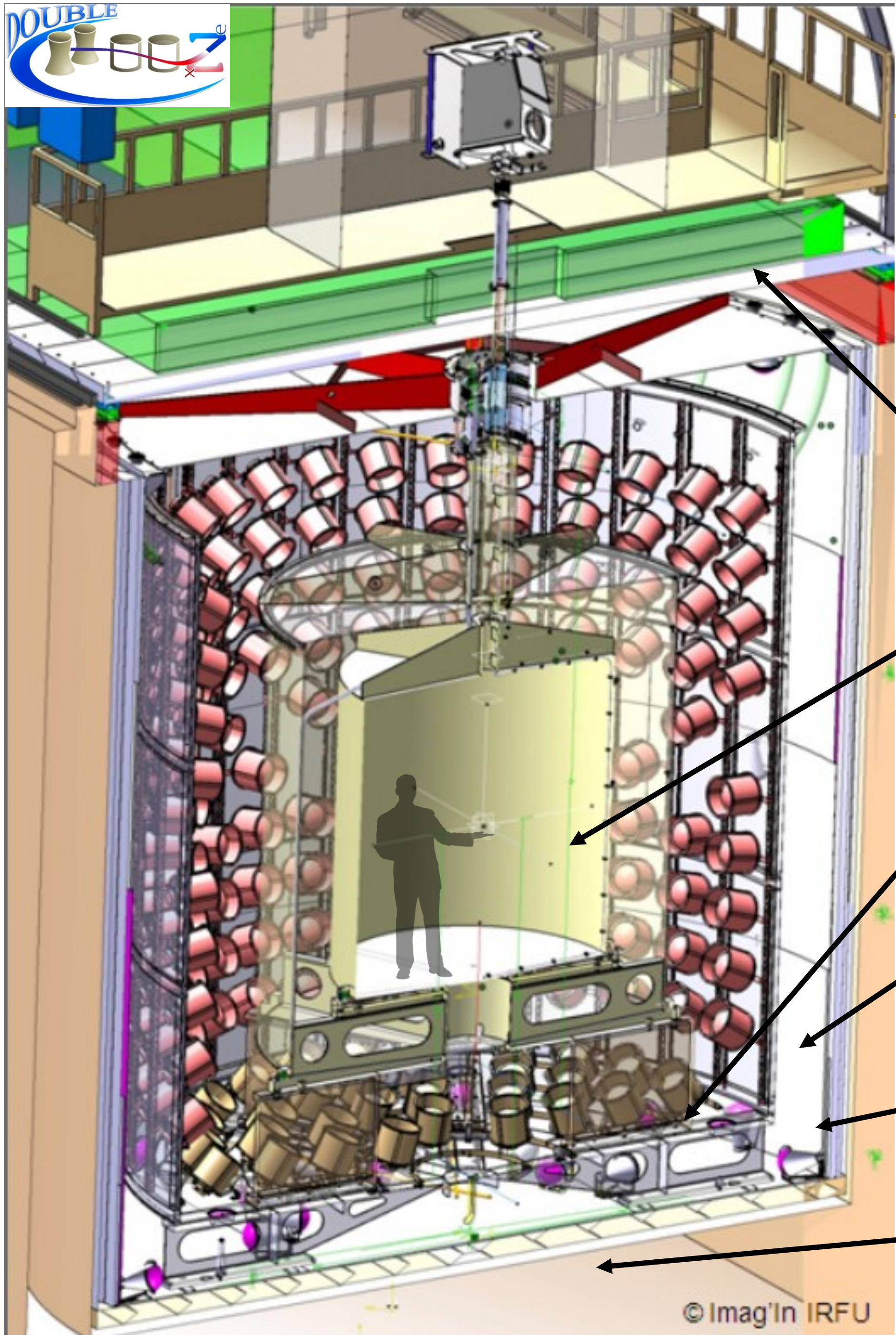
USA
U. Alabama
ANL
U. Chicago
Columbia U.
UCDavis
Drexel U.
IIT
KSU
LLNL
MIT
U. Notre Dame
Sandia National Laboratories
U. Tennessee

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

Web Site: www.doublechooz.org/



Similar Detector Designs



New 4-region large detector concept from Double Chooz Coll. (2003)

http://bama.ua.edu/~busenitz/rnu2003_talks/lasserre1.doc
http://bama.ua.edu/~busenitz/rnu2003_talks/suekane1.pdf

Outer Veto: plastic scintillator strips (400 mm)

ν-Target: 10,3 m^3 scintillator doped with 1g/l of Gd compound in an acryclic vessel (8 mm)

γ-Catcher: 22,3 m^3 scintillator in an acrylic vessel (12 mm)

Buffer: 110 m^3 of mineral oil in a stainless steel vessel (3 mm) viewed by 390 PMTs

Inner Veto: 90m^3 of scintillator in a steel vessel equipped with 78 PMTs

Veto Vessel (10mm) & Steel Shielding (150 mm)

Far Detector Construction 2008-10

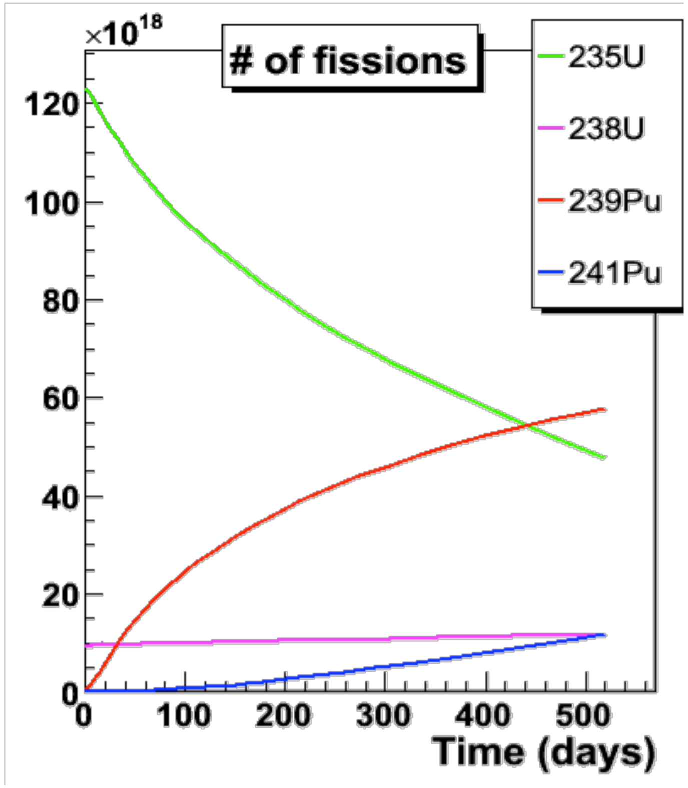
Challenging “4-layer vessel” detector concept,
invented by Double Chooz in 2002 has proved to be possible

Physics Principles

Reactor Neutrino Overview

energie atomique • energies alternatives

- **Electron antineutrinos emitted through Decays of Fission Products of ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu**



- **Nuclear reactors** : $1\ \mathrm{GW_{th}} \Leftrightarrow 2\ 10^{20}\ \bar{\nu}/\mathrm{s}$

- **Neutrino Luminosity** : $N_{\bar{\nu}} = \gamma(1+k)P_{\mathrm{th}}$

  γ: reactor constant

  k : fuel evolution correction up to 10%

- **Common Detection**
  - Inverse Beta-Decay reaction (xsec: $\sigma_{V\text{-}A}$)

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

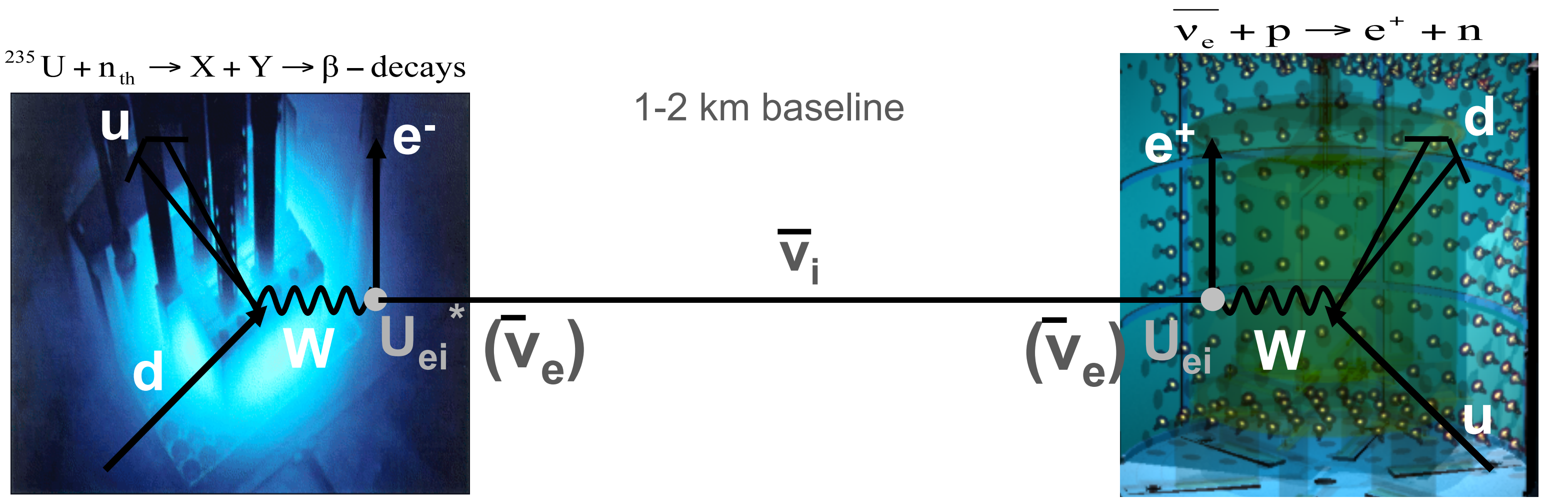
  - Threshold 1.8 MeV. E_ν extend to 10 MeV
  - Measure anti-ν_e of interaction rate

$$n_\nu = \frac{1}{4\pi R^2}\frac{P_{\mathrm{th}}}{\langle E_f\rangle}N_p\varepsilon\sigma_f \longrightarrow \sigma_f^{\mathrm{meas.}} = \frac{4\pi R^2 n_\nu^{\mathrm{meas.}}}{N_p\varepsilon}\frac{\langle E_f\rangle}{P_{\mathrm{th}}}$$

  - Comparison of σ_f to prediction

$$\sigma_f^{\mathrm{pred.}} = \int_0^\infty \phi_f^{\mathrm{pred.}}(E_\nu)\sigma_{\mathrm{V\text{-}A}}(E_\nu)\mathrm{d}E_\nu$$

Reactor Neutrino Oscillation Physics (θ_{13})



Reactor core

Target free H

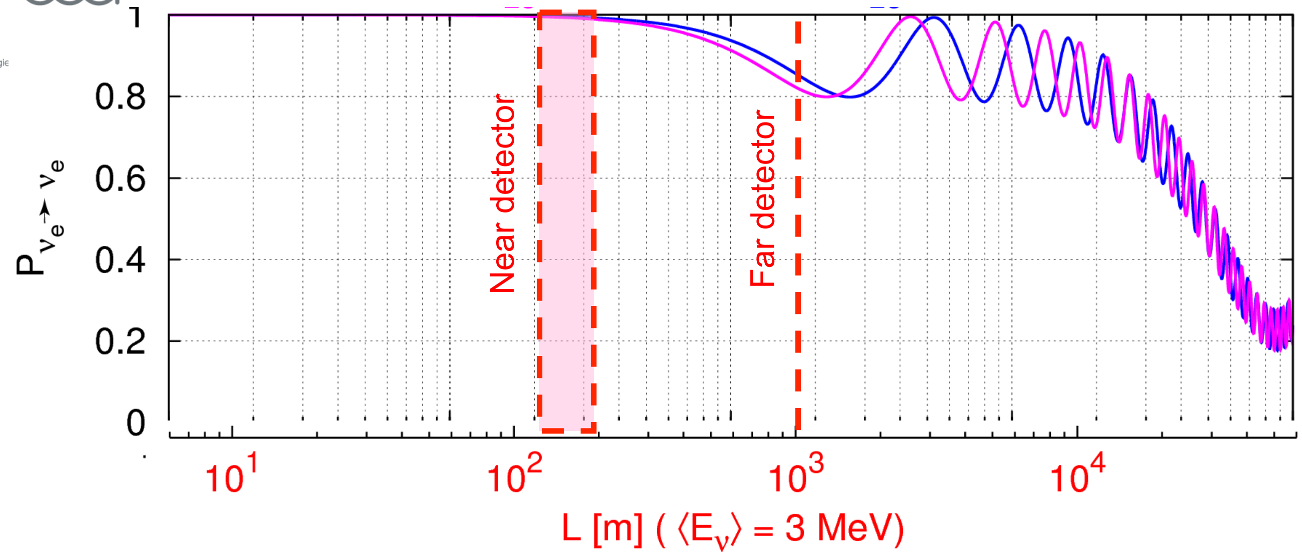
$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2(2\theta_{13}) \left[\sin\left(1.27 \frac{\Delta m^2_{atm}\ (eV^2) L\ (m)}{E\ (MeV)}\right) + O\left(\frac{\Delta m^2_{sol}}{\Delta m^2_{atm}}\right) \right]$$

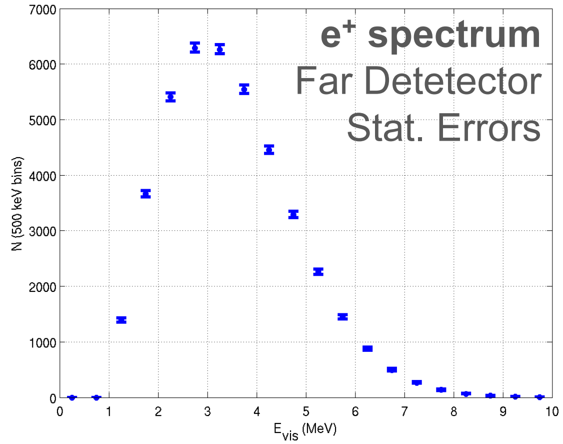
- **Straightforward oscillation formula** : weak dependence on Δm_{sol}^2
- MeV electron antineutrinos : only **disappearance** experiments
- $\sin^2(2\theta_{13})$ measurement **independent of δ-CP**
- $\sin^2(2\theta_{13})$ measurement **independent of sign(Δm^2_{13})**

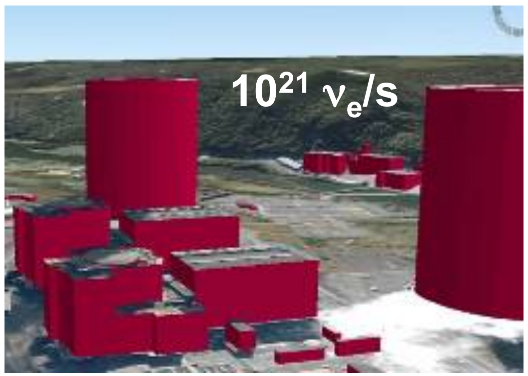
} **'clean'** information on θ_{13}

The concept from Lev Mikaelyan (Kurchatov, 2000)

$$P(\nu_e \rightarrow \nu_e) = 1 - \sin^2(2\theta_{13})\sin^2(\Delta m^2_{31} L/4E)$$

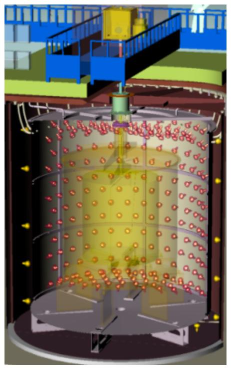






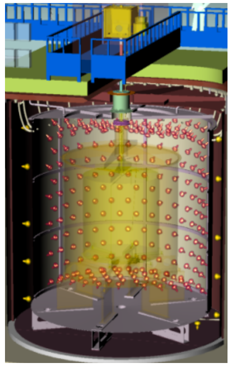
Chooz Nuclear Power Station
2 cores of 4.3 GW_{th} each

$\bar{\nu}_e$



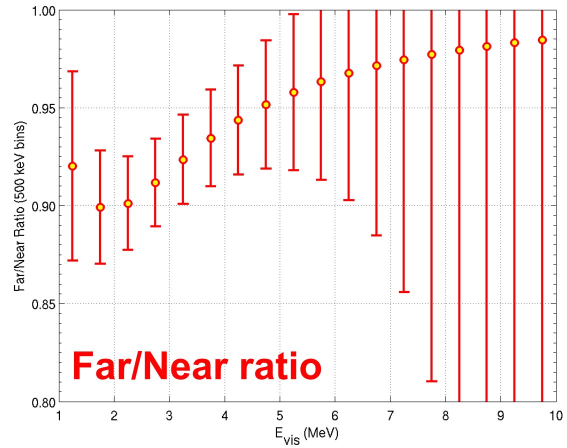
Near detector
400 m

$\bar{\nu}_{e,\mu,\tau}$



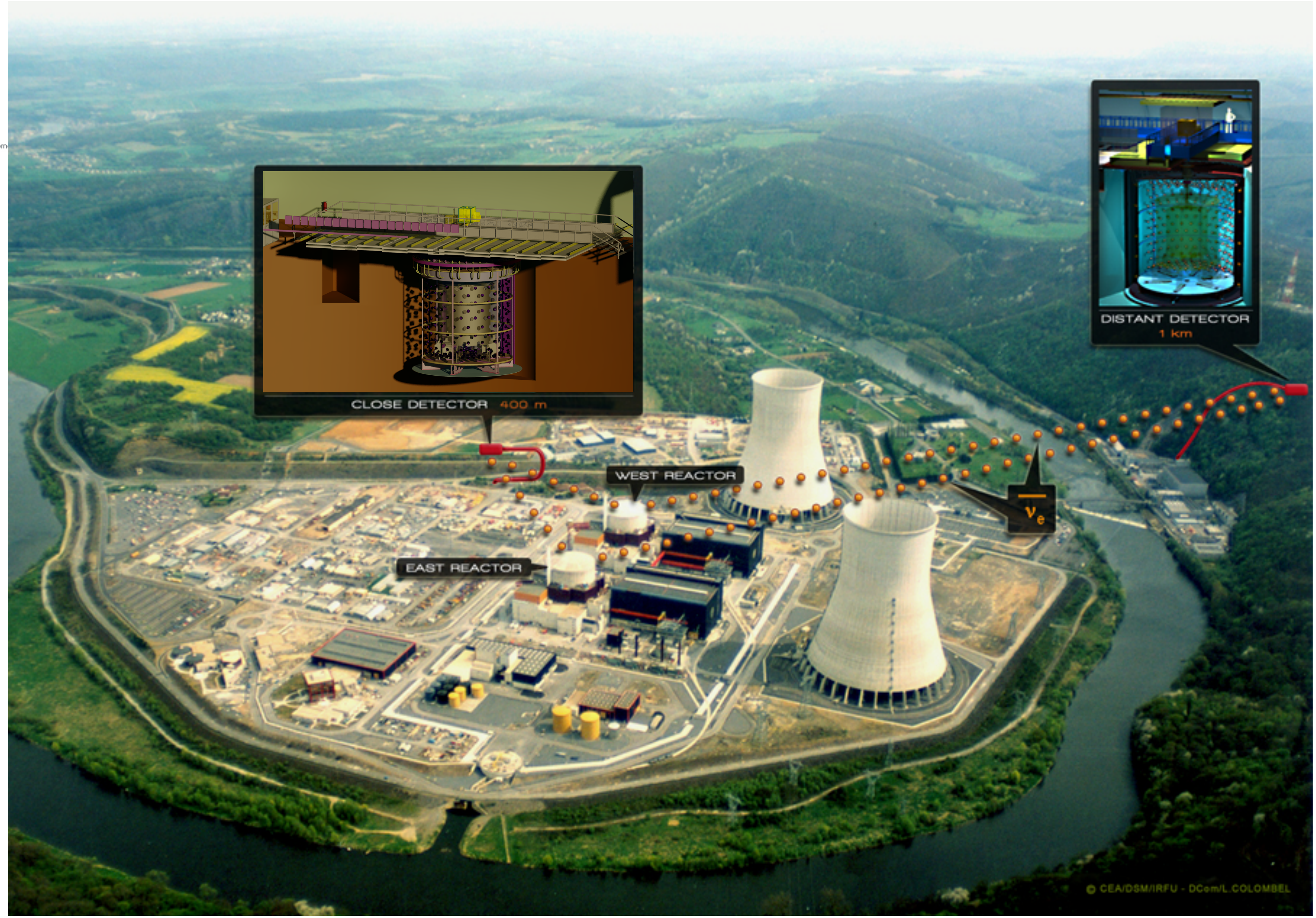
Far detector
1050 m

$\sin^2(2\theta_{13})=0.12$



Site & Detector

Double Chooz Sites (France)



Near Laboratory Excavation

- Started Apr. 2011
- Lab delivery Apr. 2012
- Early 2012
- Baseline ~ 400 m
- Overburden ~120 mwe

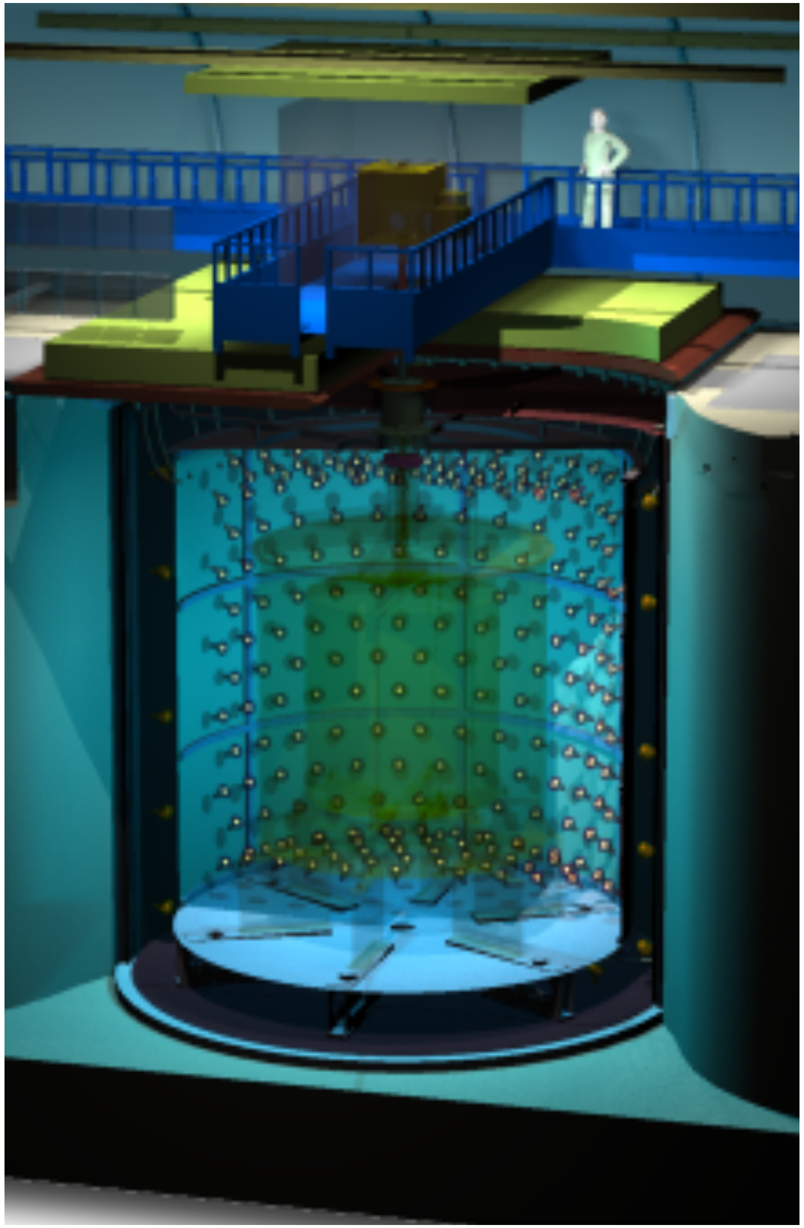
Backgrounds

Background

- Target volume protected by several concentric layers.

- Radiopurity

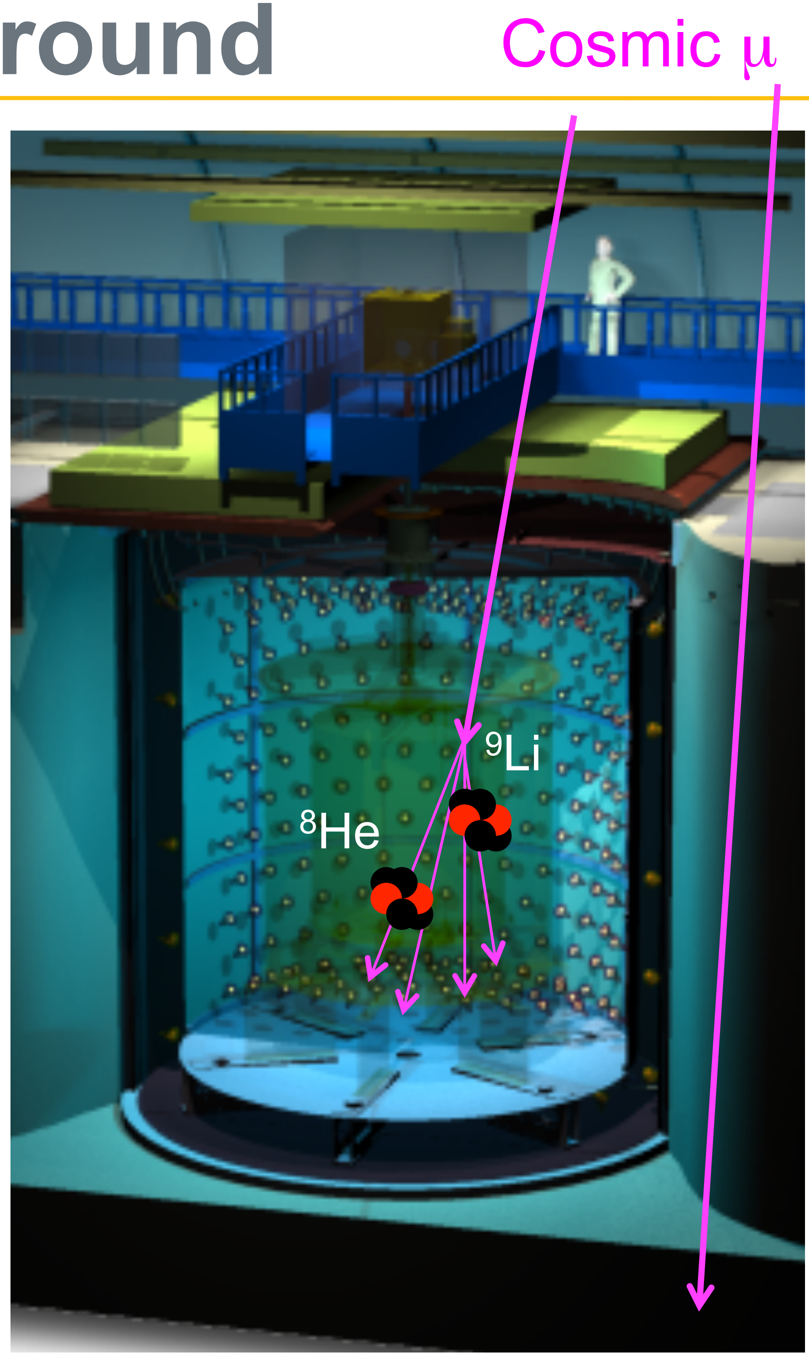
- Efficient muon tagging by inner and outer veto.



Background

- Correlated:

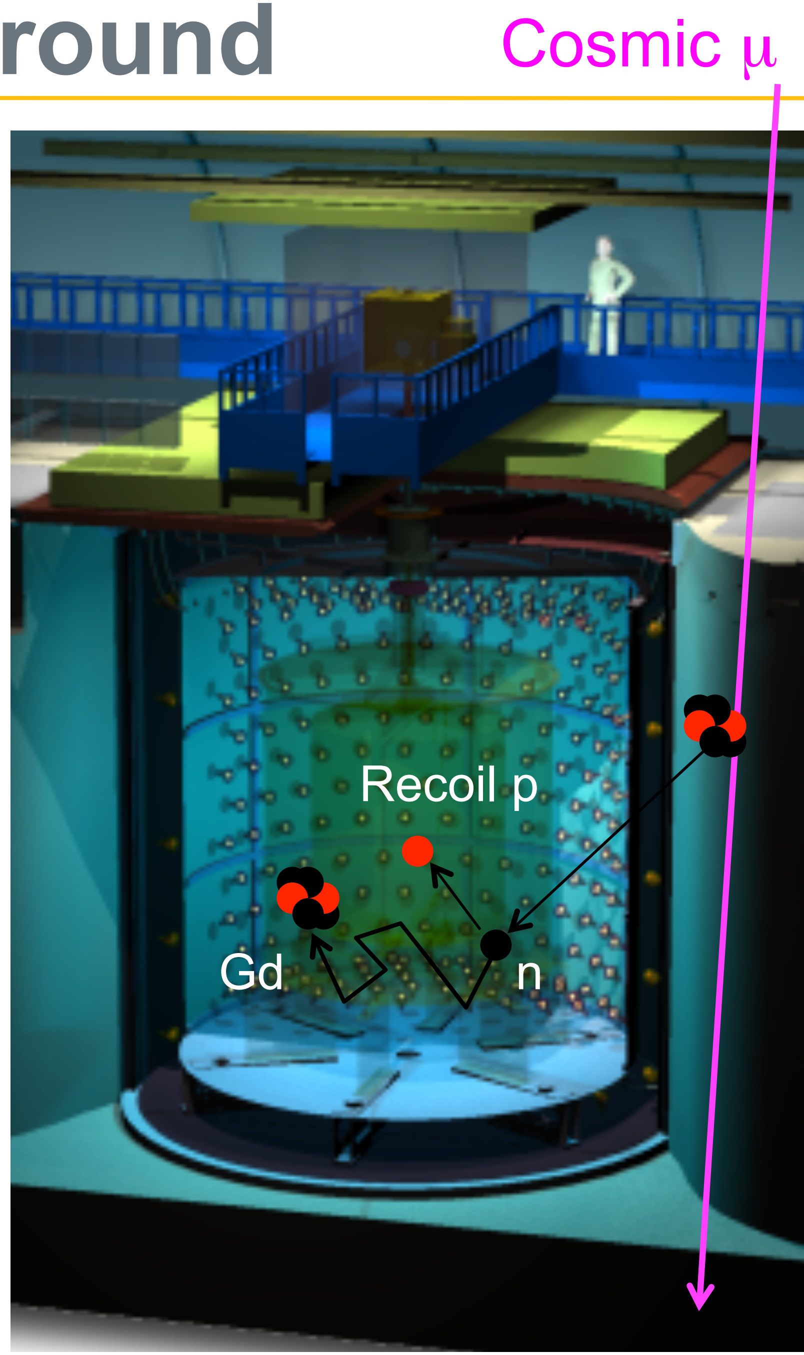
- ^{9}Li and ^{8}He can be produced by μ-induced spallation processes
- β-n emitters, perfectly mimic the ν signal.
- Life time ~250 ms, can't veto it completely because of excessive dead time.
- Proposal : 1.4 +/- 0.5 / day



Background

- Correlated:

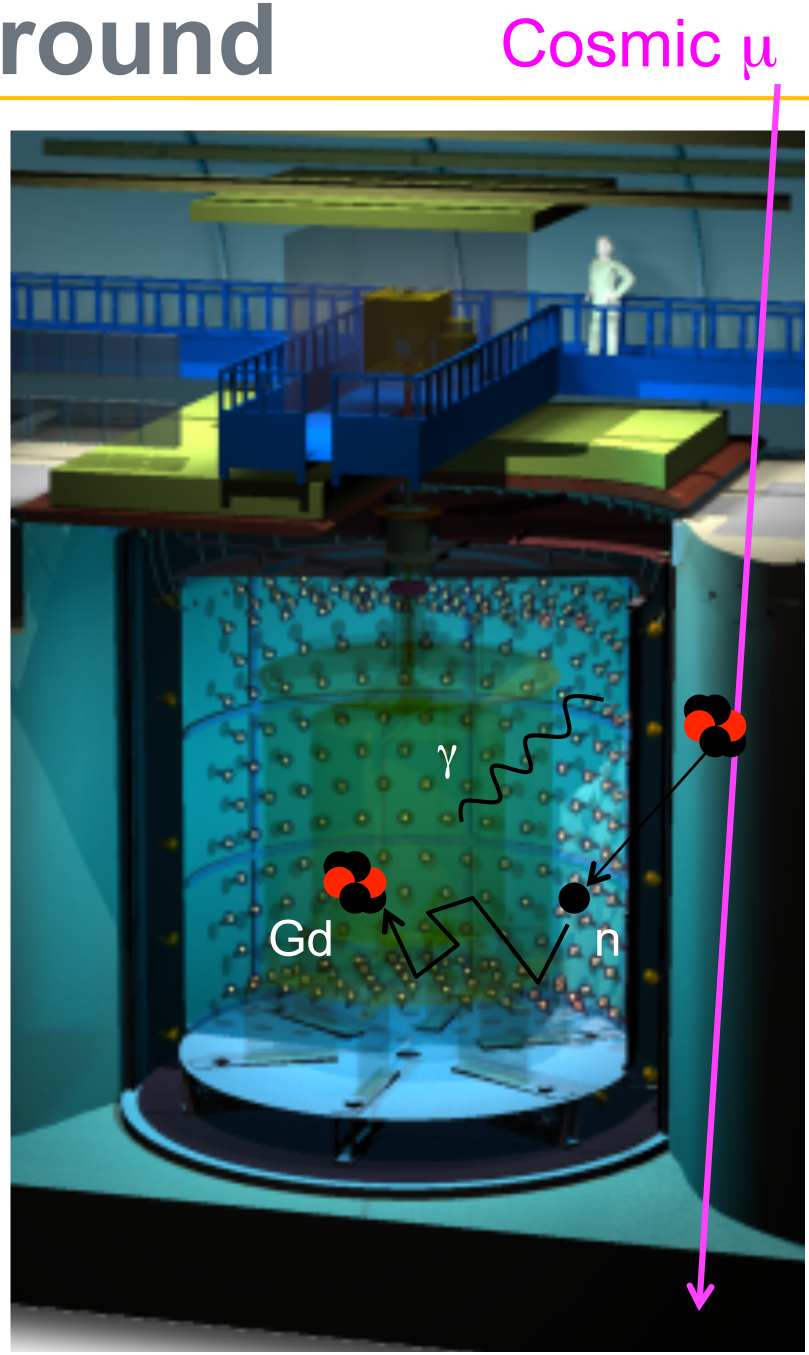
- μ-induced fast neutron
- Prompt = recoil proton
- Delayed = neutron capture on Gd.
- Proposal : 0.2 +/- 0.2 /day



Background

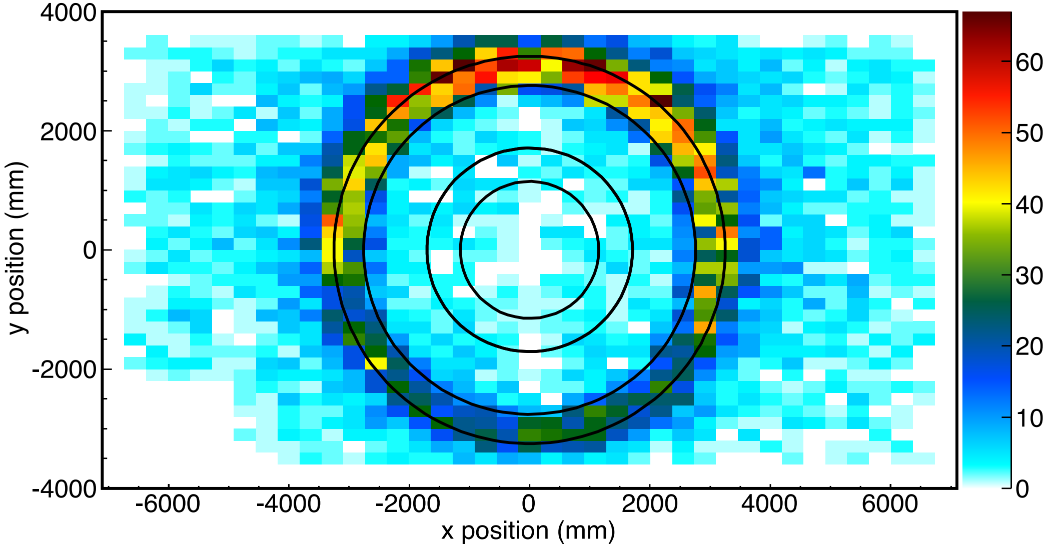
- Accidentals:

- μ-induced fast neutron
- Prompt = recoil proton
- Delayed = neutron capture on Gd.
- Proposal: 2.0 +/- 0.9 / day



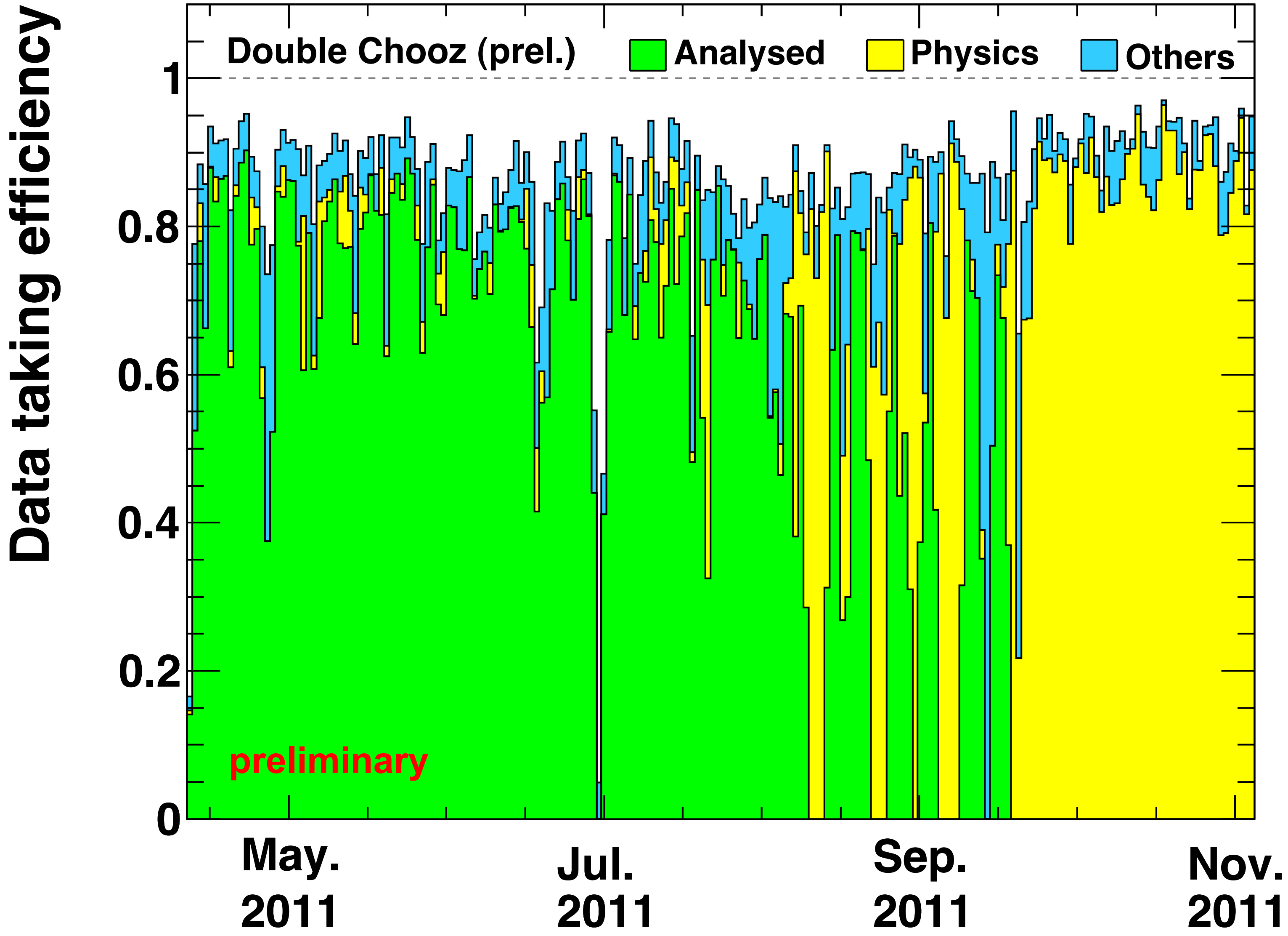
Outer Veto / Inner Veto

- Very large charge required in inner veto
→ selecting vertical μ going
 through all inner veto height.

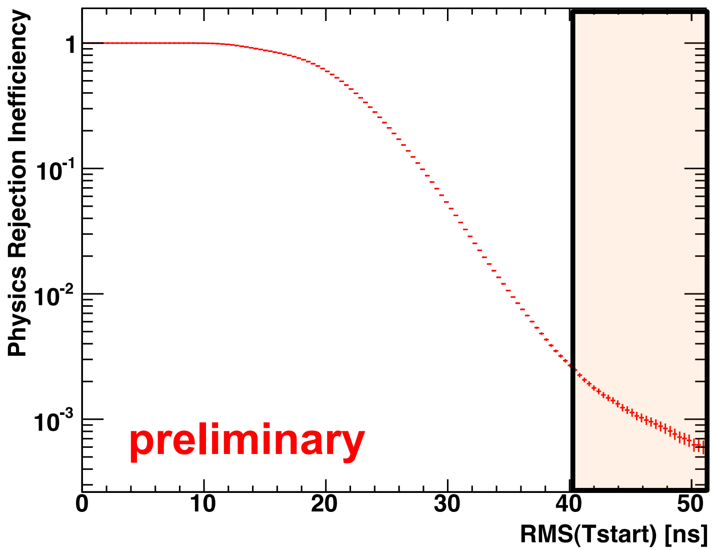


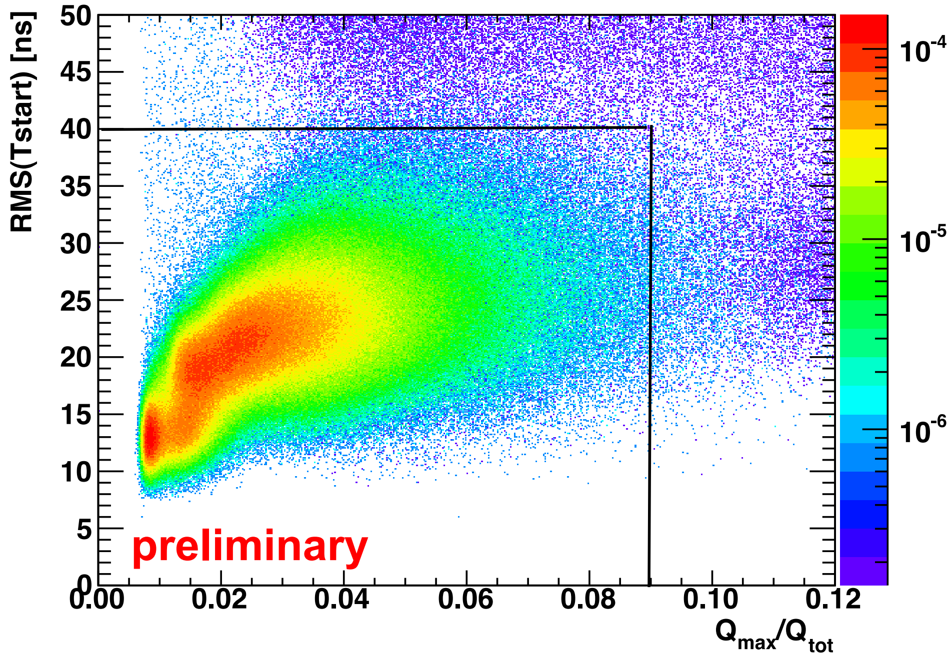
Data Taking

Data Taking Efficiency



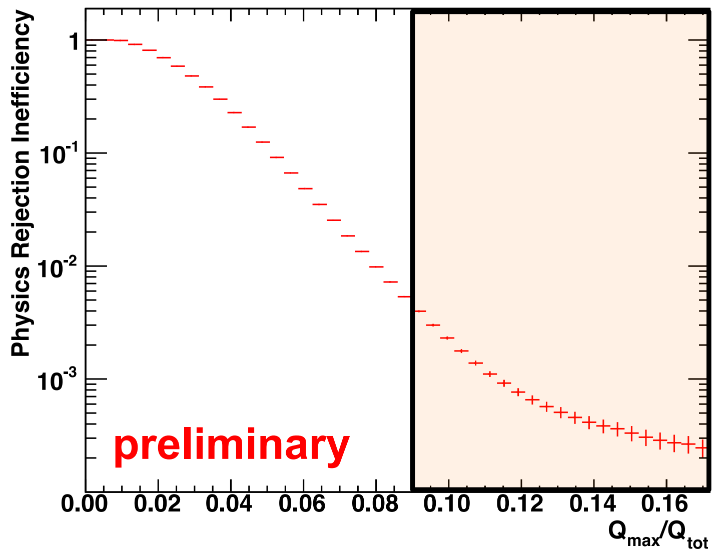
Light Noise : Q_{max}/Q_{tot} VS rms(T_{start})



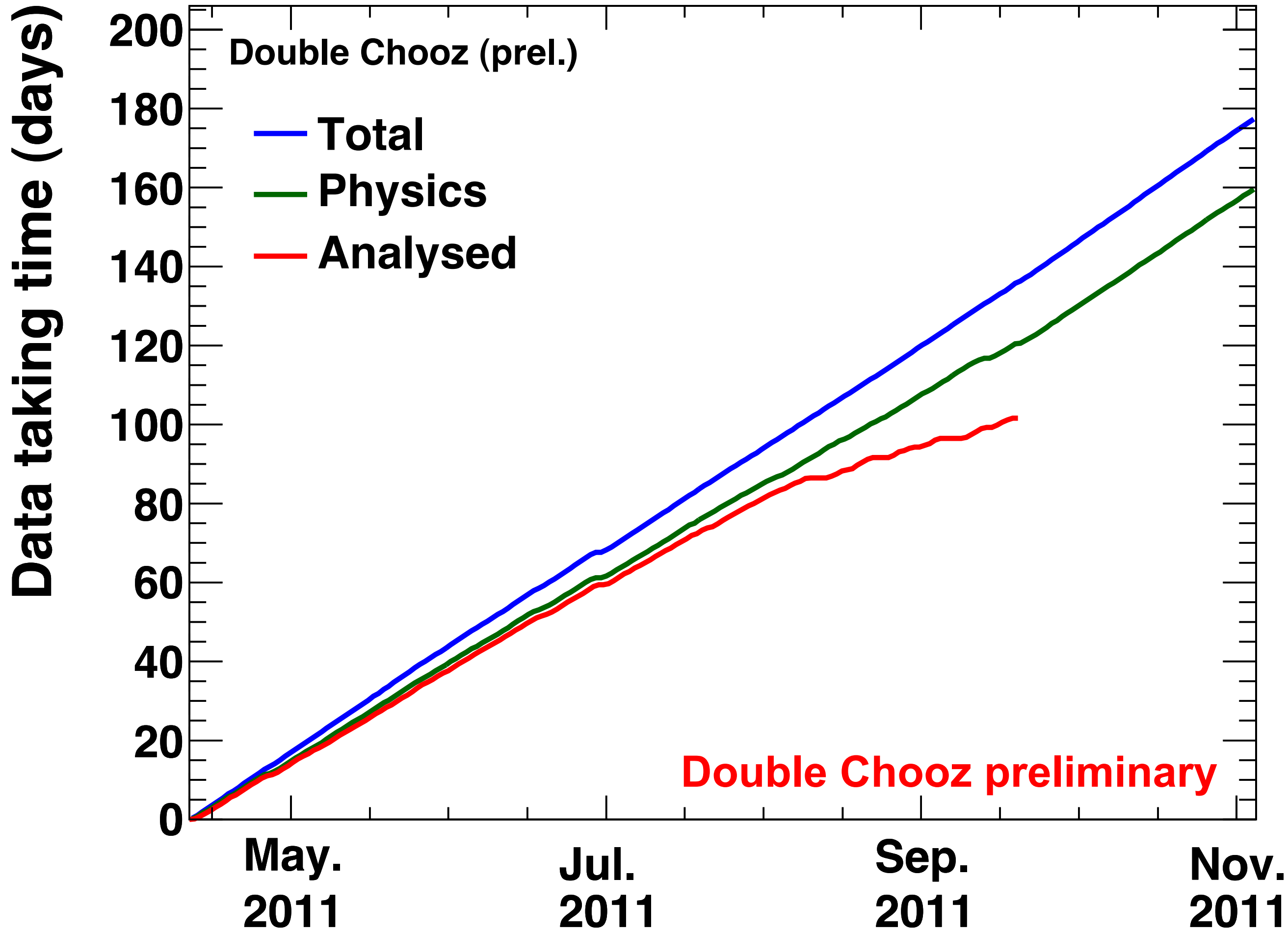


Parasitic light emitted by some PMTs.
15 PMTs turned off + effective rejection based on anisotropic light collection:

- PMT sees its own light
  → Qmax/Qtot
- Large dispersion of start time of PMT signals → rms(T_{start})



Integrated Data Taking



– Integrated data taking time for physics : **159.6 days**
– Data taking efficiency in total : **86.2 %**
– Data taking efficiency for physics : **77.5 %**

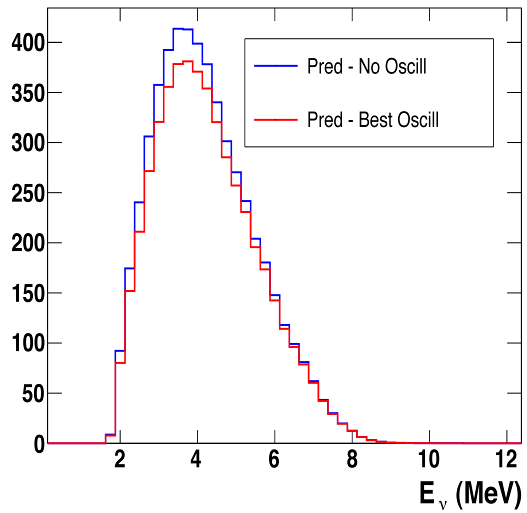
Oscillation Analysis

Reactor | Detector

$N_{predicted}$ ⟷ $N_{observed}$

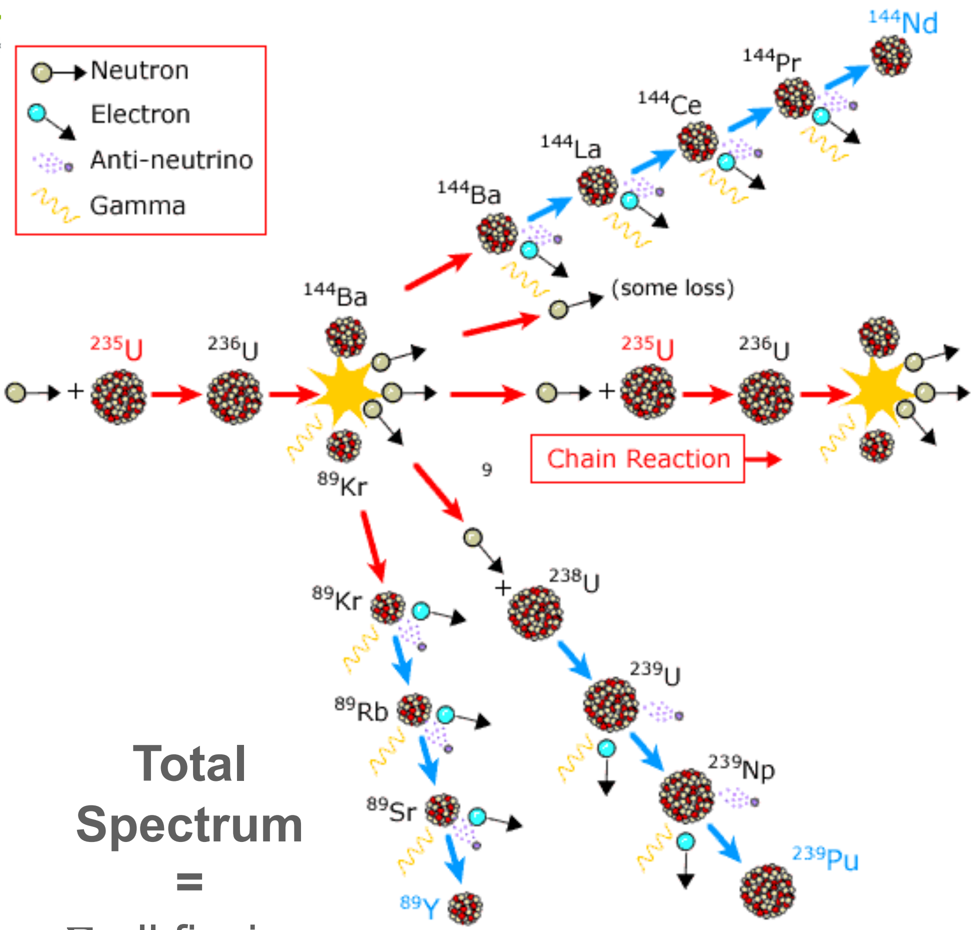
- Rate only: $N_{observed} = N_{predicted} \times \left\langle P_{ee}(\sin^2(2\theta_{13})) \right\rangle$

- Rate + Shape:



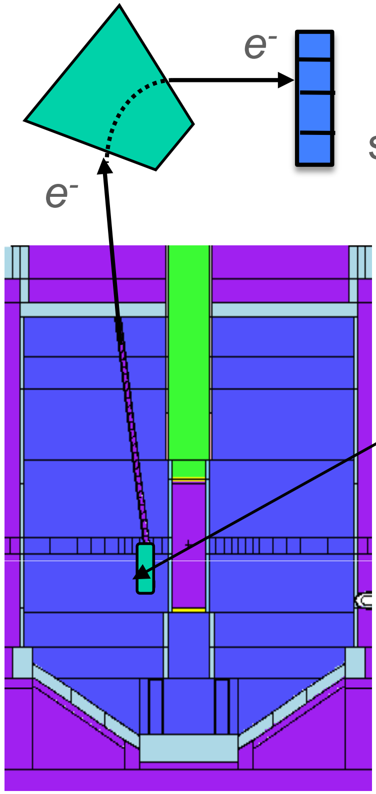
Reactor Neutrino Signal

Reactor Neutrinos



Total Spectrum
=
Σ all fission products

Accurate total electron spectra from the β-decays of ^{235}U, ^{239}Pu and ^{241}Pu fission products.



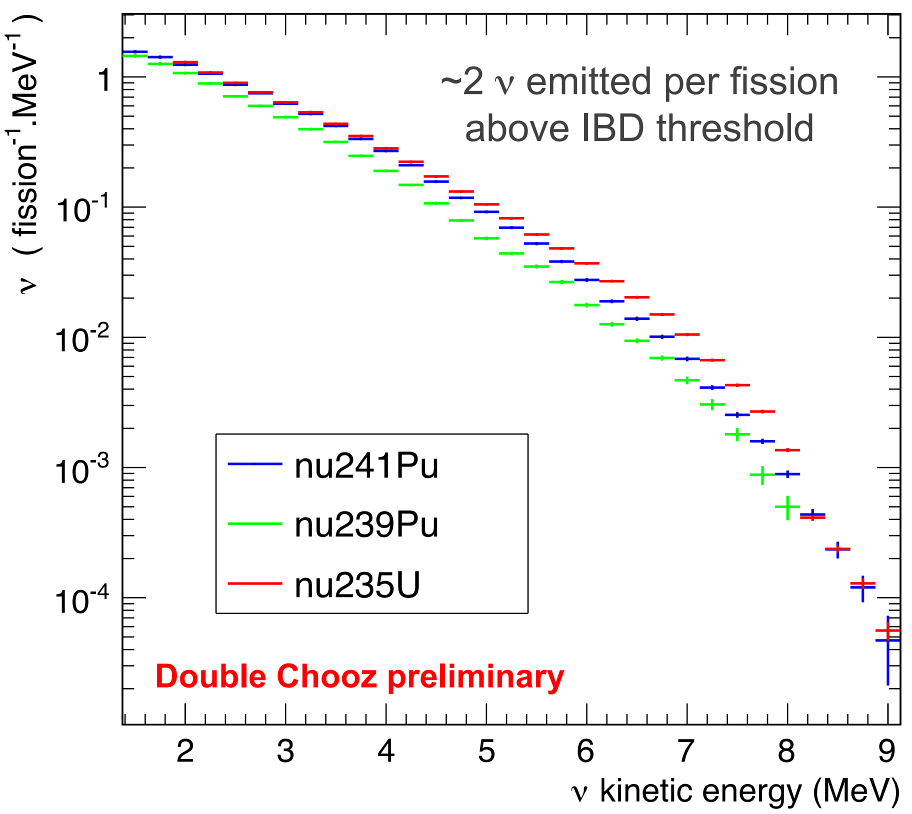
High resolution spectrometer

Target foil (^{235}U, ^{239}Pu, ^{241}Pu) in thermal n flux

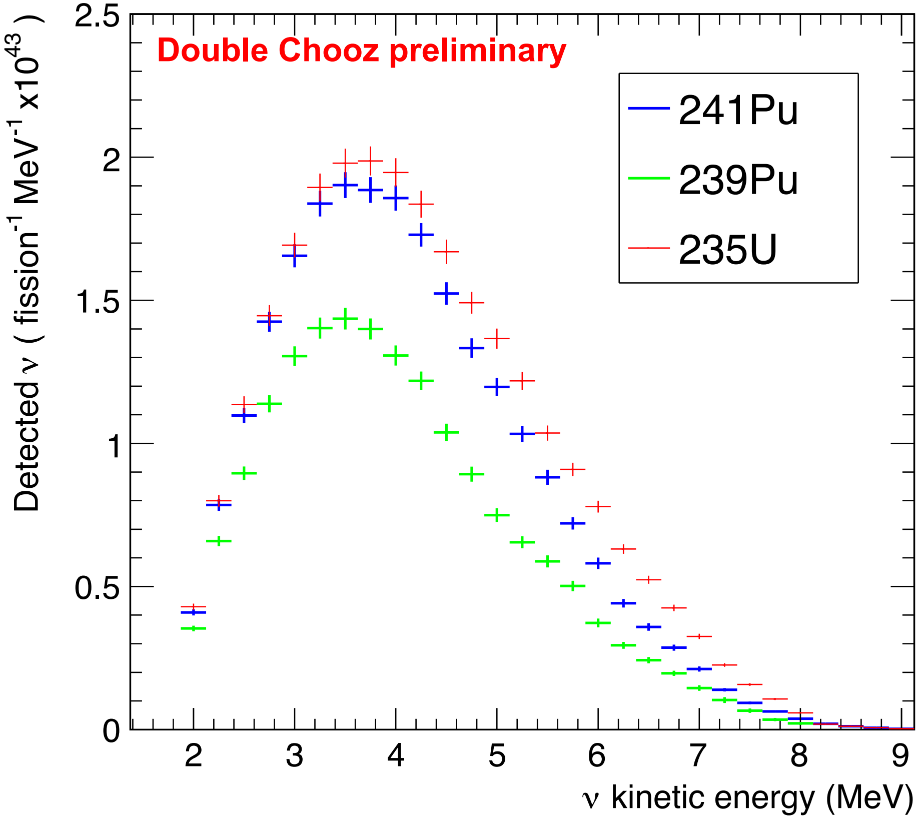
ILL research reactor (Grenoble, France)

ILL ν spectra

Emitted

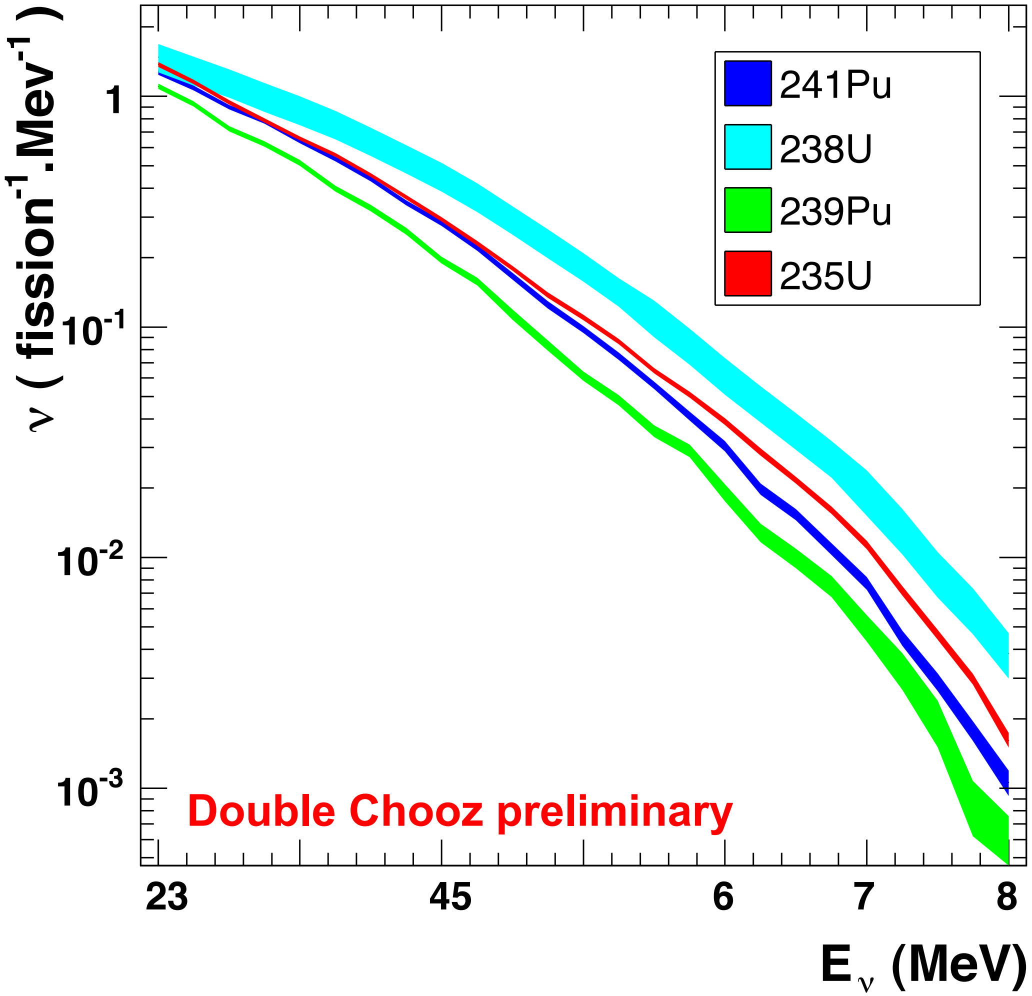


Interacting via IBD



- Reference spectra over the last 25 years

New Reference ν Spectra



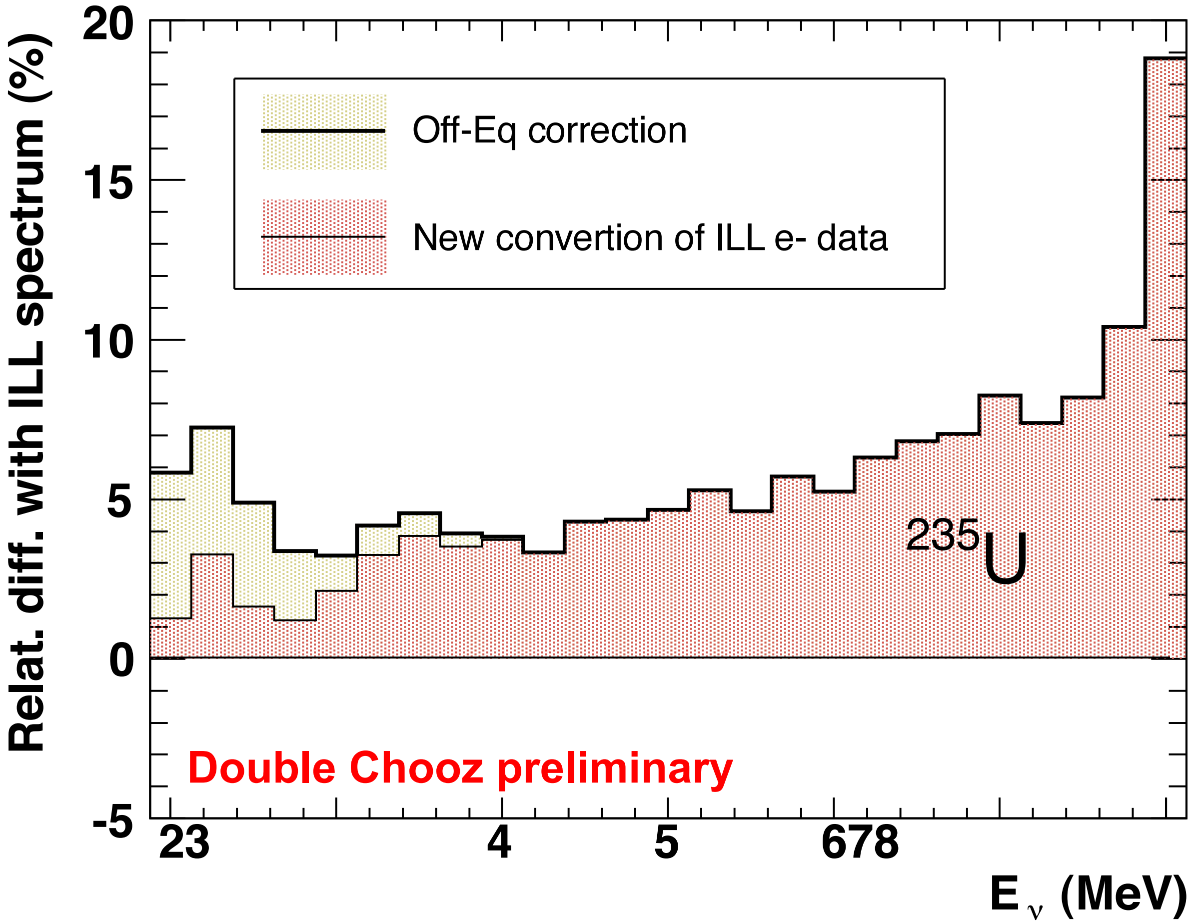
- Recent re-evaluations of fissile isotopes by

-Th. A. Mueller et al,
Phys.Rev. C83(2011) 054615

-P. Huber,
Phys.Rev. C84 (2011) 024617

- Ab initio calculation of ^{238}U at Irfu and Subatech-Nantes.

Comparison with ILL reference



+2.4% in emitted flux

+3.7% in detected flux

Off-Eq

+4.9% in emitted flux

+3.7% in detected flux

Reactor Antineutrino Anomaly

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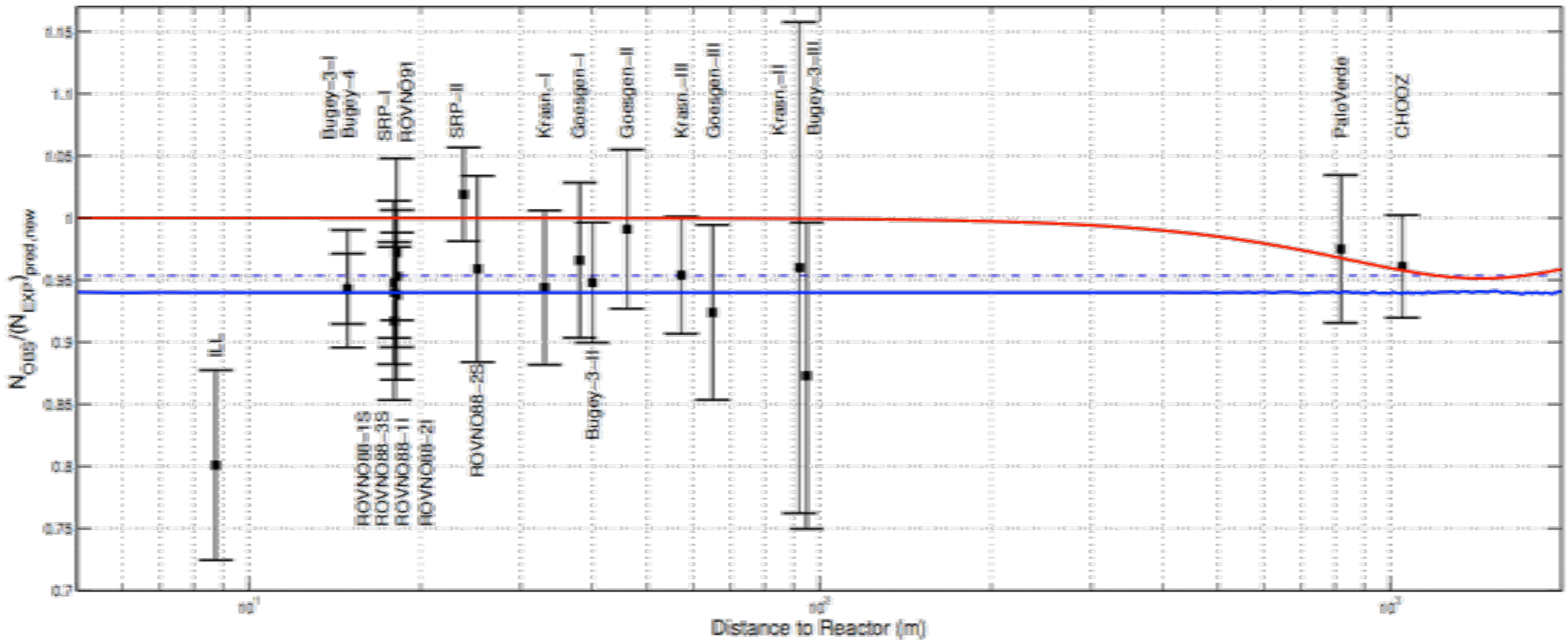


- Use accurate experimental mean value at short distances as an absolute normalization.
- Includes all interpretations of the anomaly.

Predicted Neutrino Rate

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

- Mean energy per fission:

$$\langle E_k \rangle = \sum_k \alpha_k(t) \langle E_k \rangle$$

k = ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu

α_k : fractional fission rate

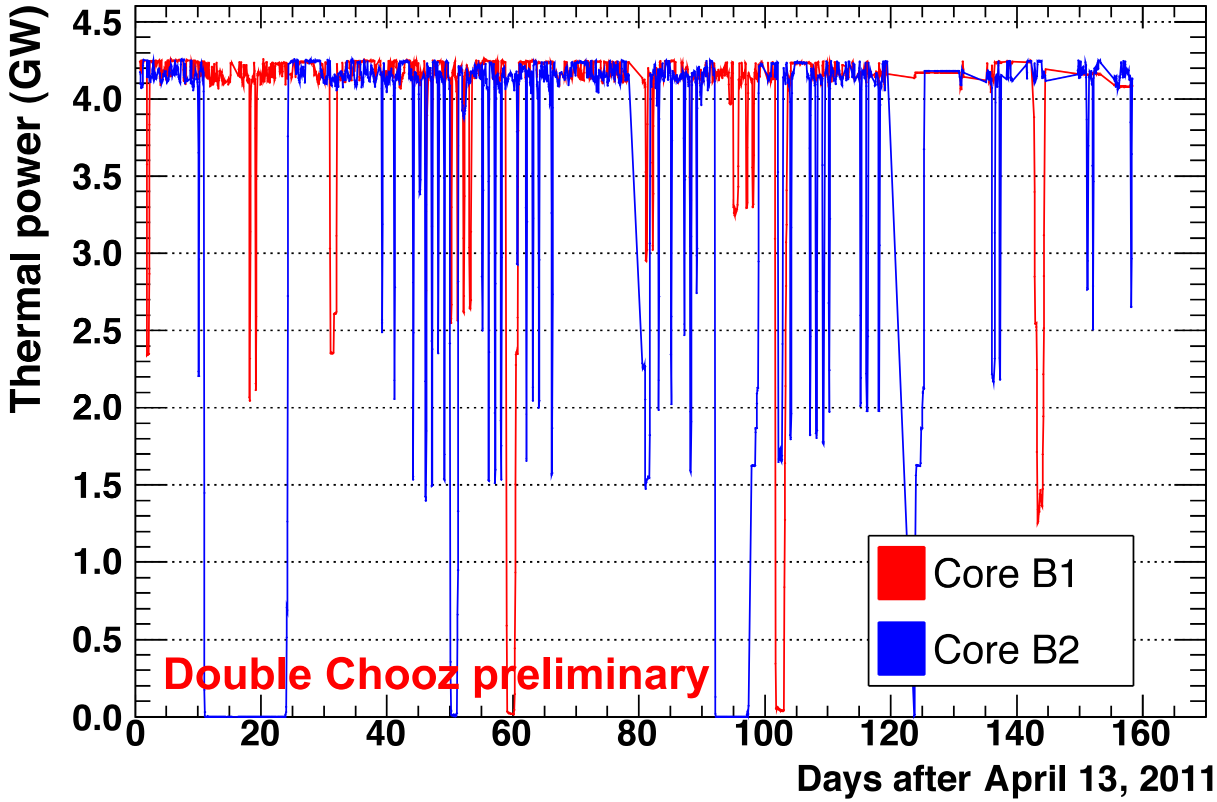
- Mean cross-section per fission:

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

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

Bugey4 anchor point

Monitoring of Thermal Power



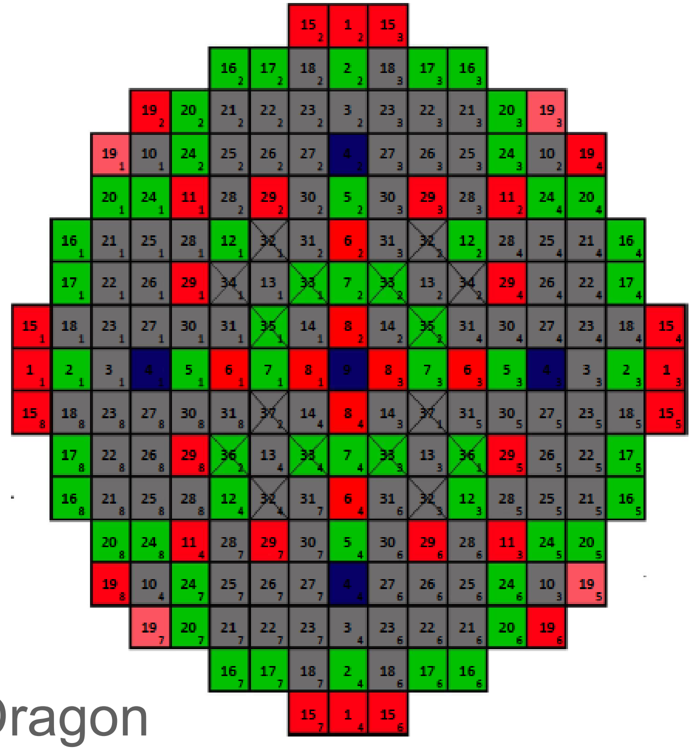
$\delta P_{th}/P_{th} = 0.46\%$

(1 sigma)

- Precise weekly anchor points by enthalpic balance at steam generators.
- Monitoring every minute, based on temperature in primary loop.
- Full error treatment in EDF note (HP1C-2011-2007-FR, Y. Caffari, J.M. Favennec)

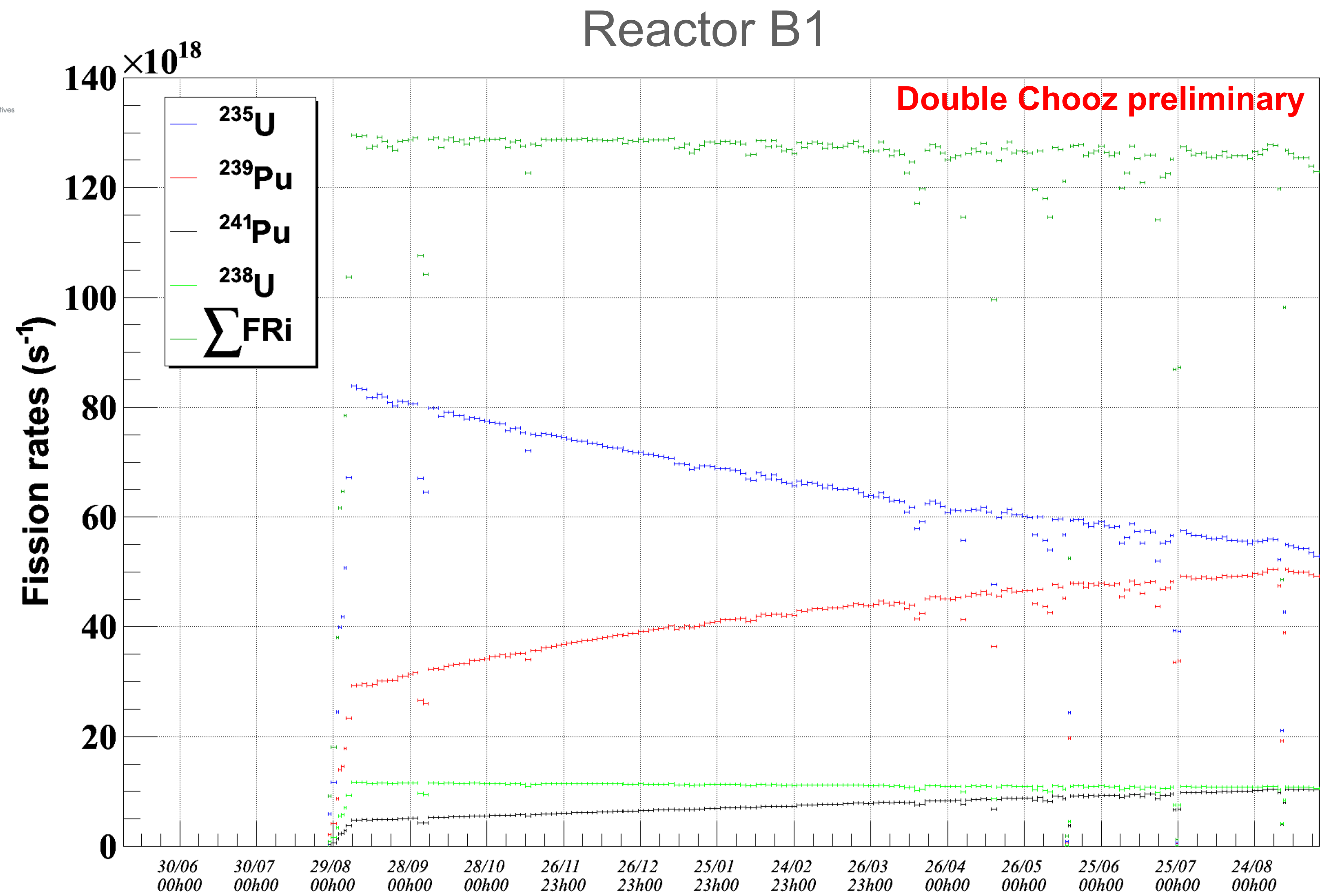
Reactor Evolution Code

Development of full core simulation with MURE Code (Subatech).

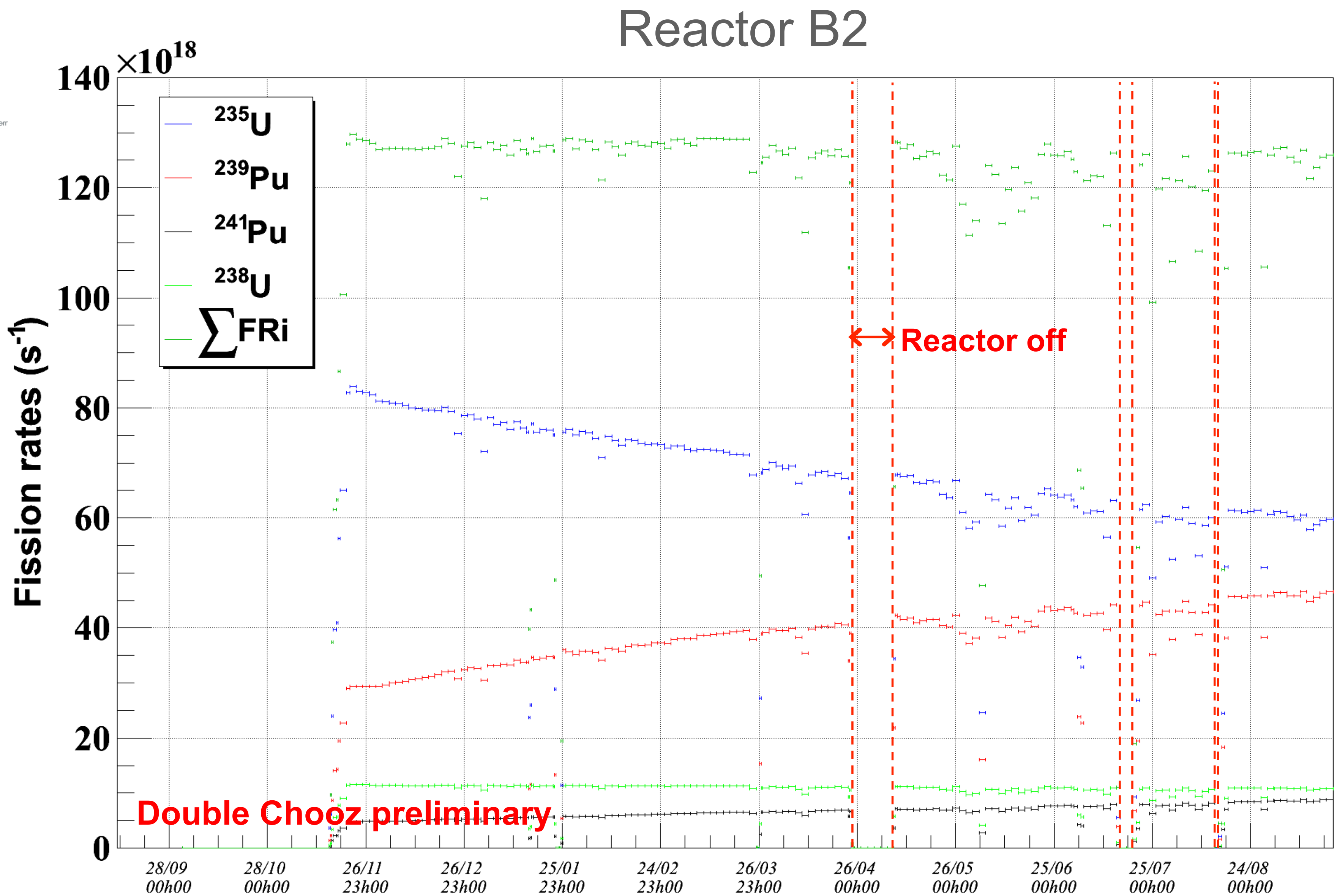


- A lot of EDF inputs (initial fuel loading, geometry, power history,…)
- Validation with independent calculation (Dragon code, EDF calculations, Takahama benchmark).
- Complete error budget based on uncertainty on reactor parameters, code comparison, nuclear database inputs.

Fission Rates

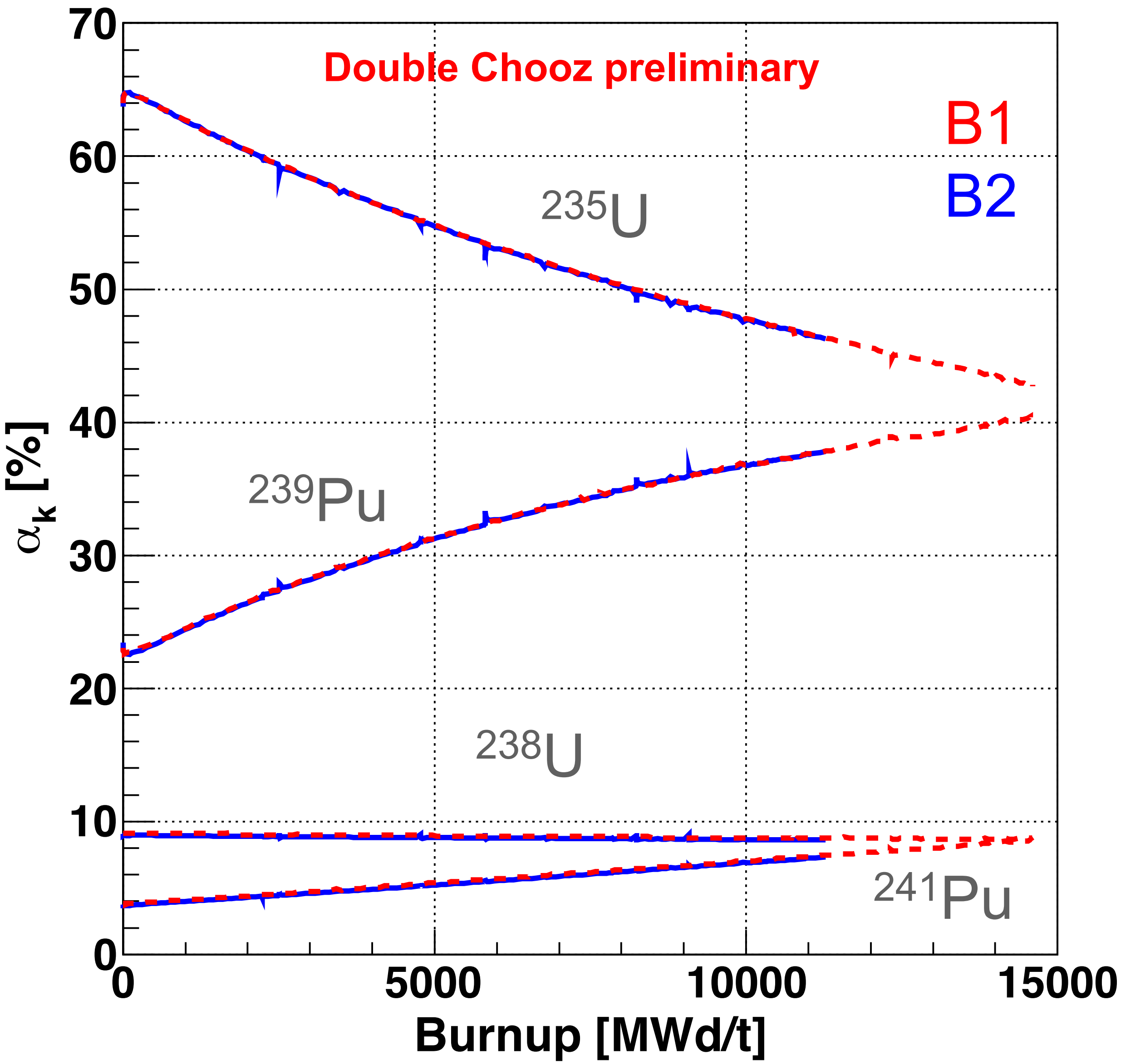


Fission Rates



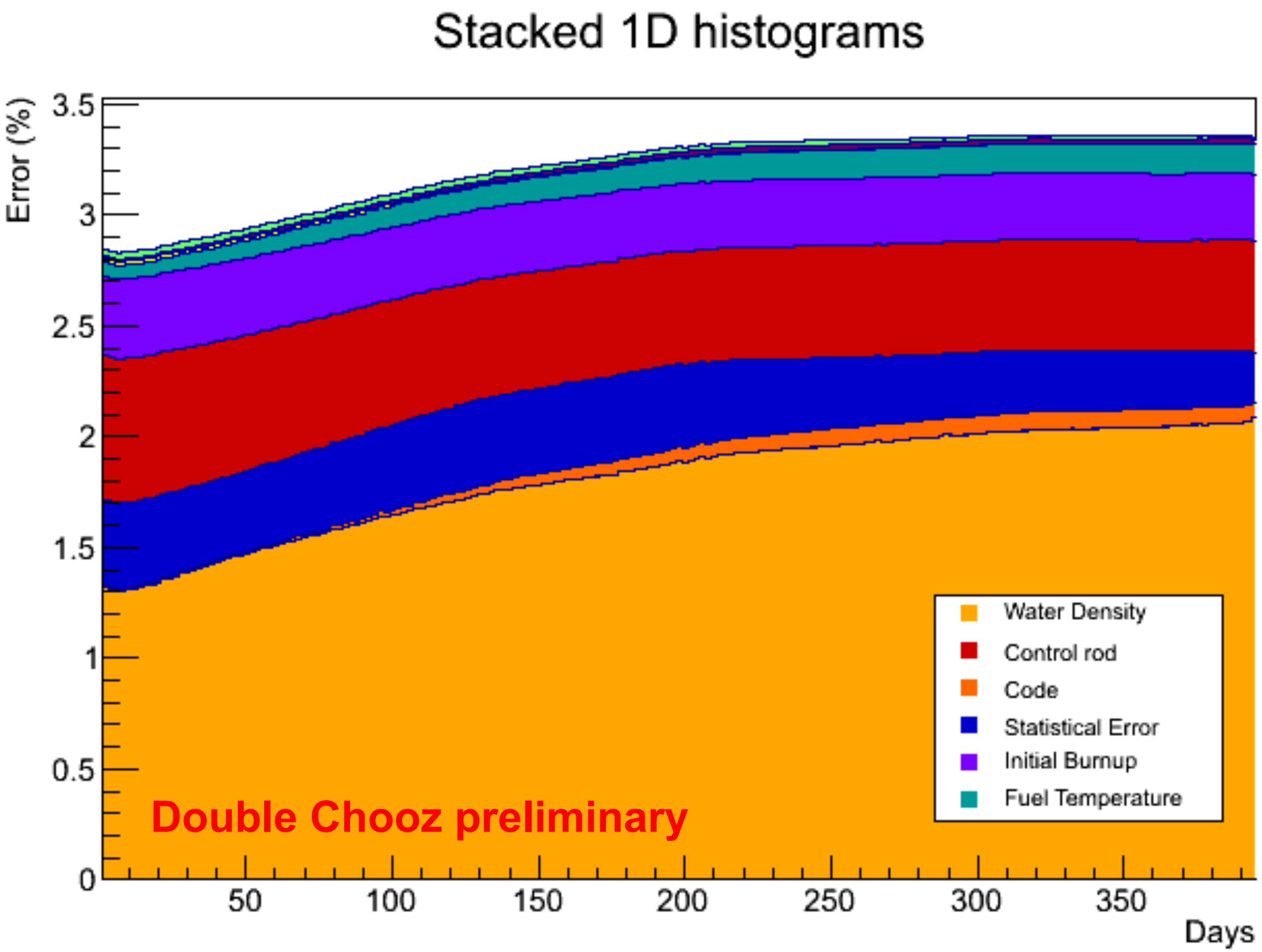
F. Ardellier, Ch. Veyssière, Th. Lasserre, D. Lhuillier, CEA-Saclay, Nov. 09th 2011

Fractional Fission Rates



Perfect agreement of burnup curves

Fission Rate Error Breakdown



Mean relative errors:

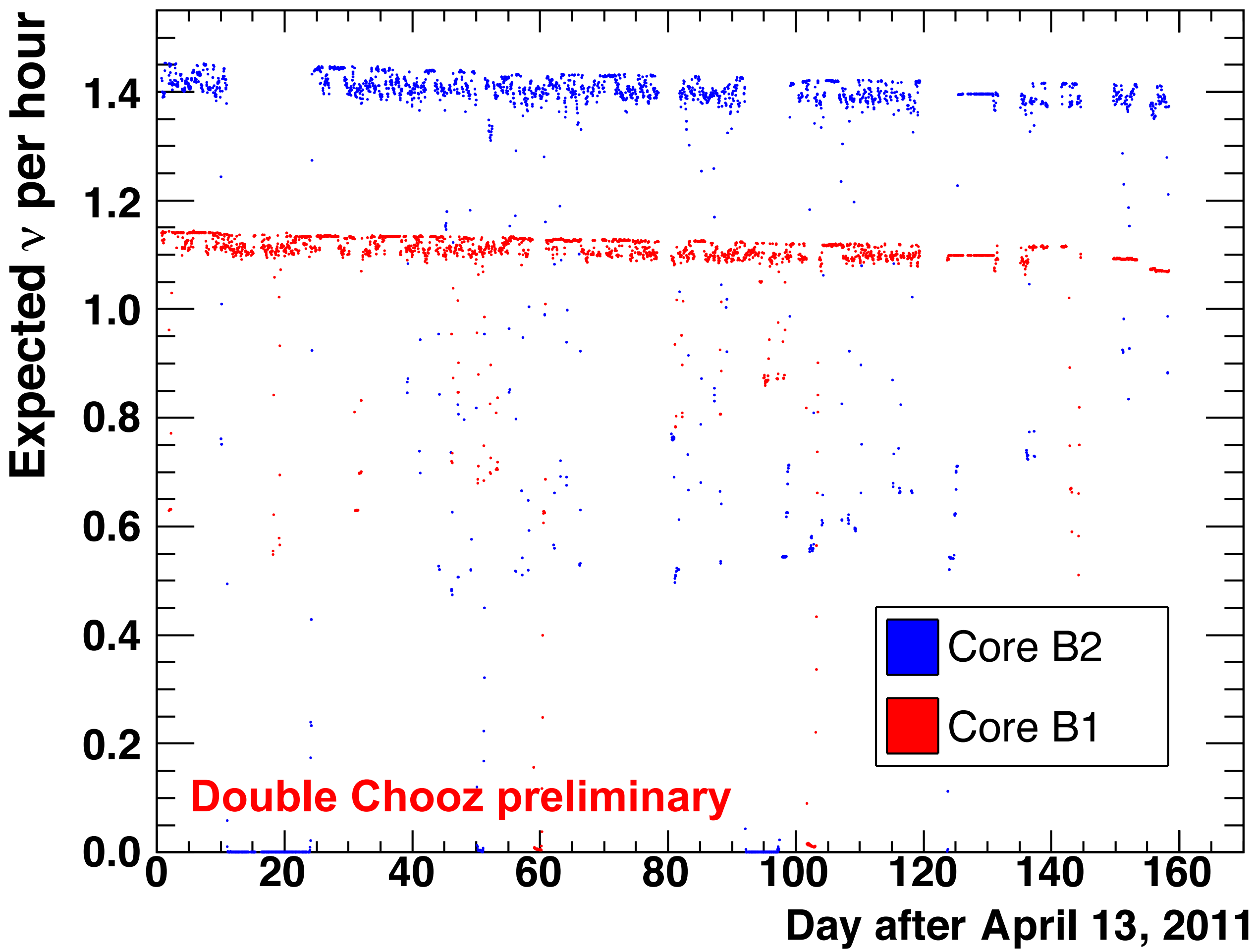
^{235}U : 3.3 %

^{239}Pu : 4.0%

^{238}U : 6.5%

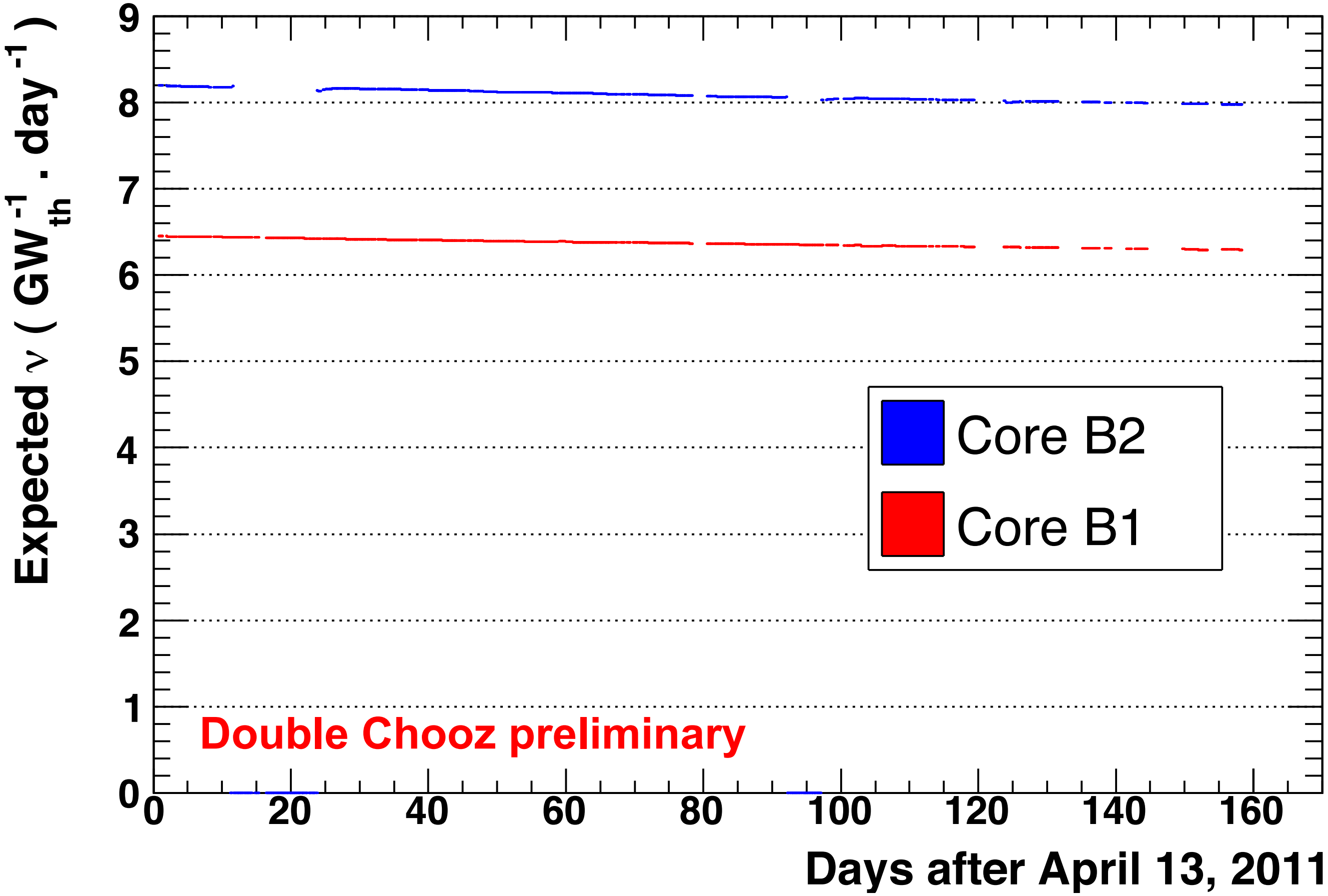
^{241}Pu : 11%

Predicted Neutrino Rate



2594 runs, ~ 1h long

Predicted Neutrino Rate



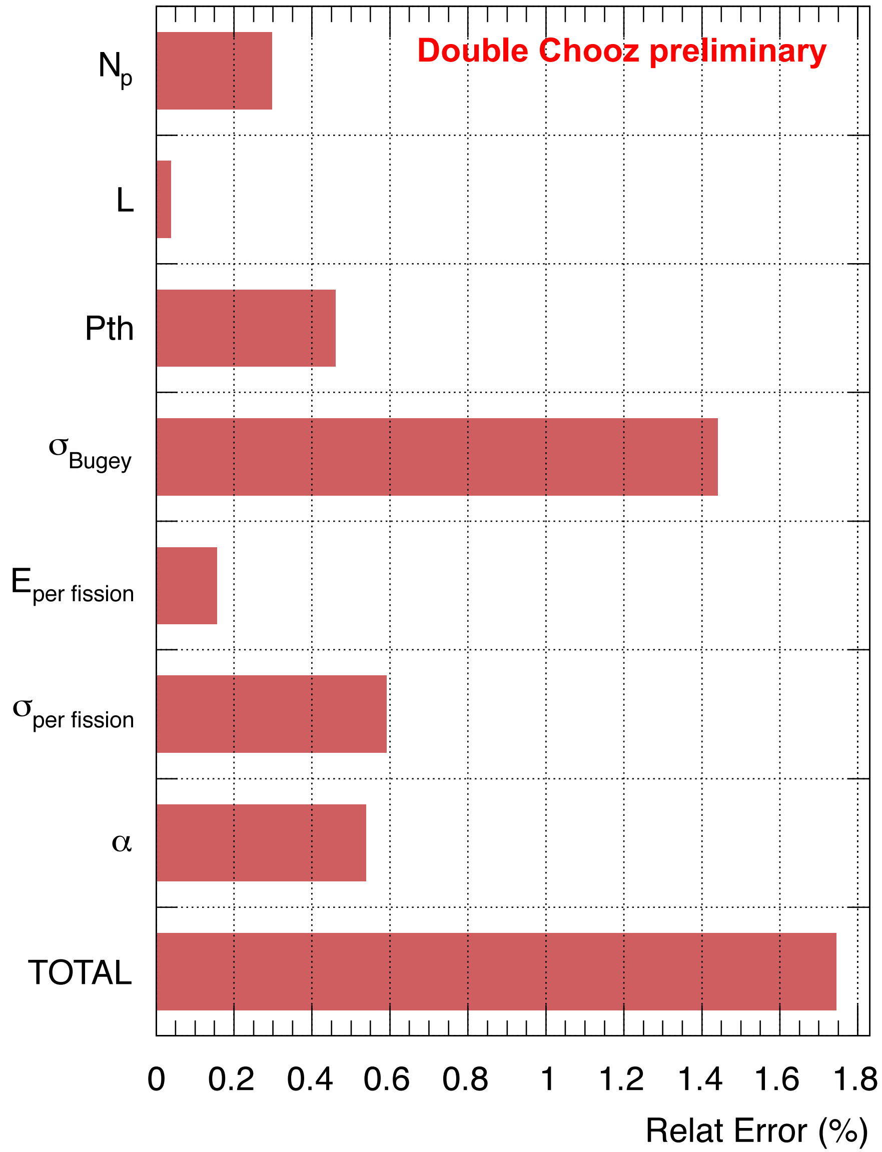
- ~2.5% reduction of neutrino rate during data taking due to accumulation of ^{239}Pu in the core

Error on Reactor Predictions

- Anchor point of Bugey4 measurement suppresses sensitivity to reference spectra ($\sigma_{per\ fission}$)
- Accurate reactor simulation with MURE keep contribution of the uncertainty on fission rates low.

1.7% total error

(2.7% if no Bugey4 anchor)



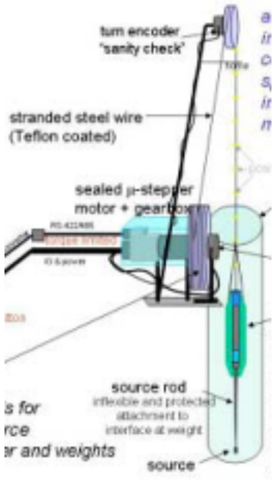
Predicted Number of Neutrinos

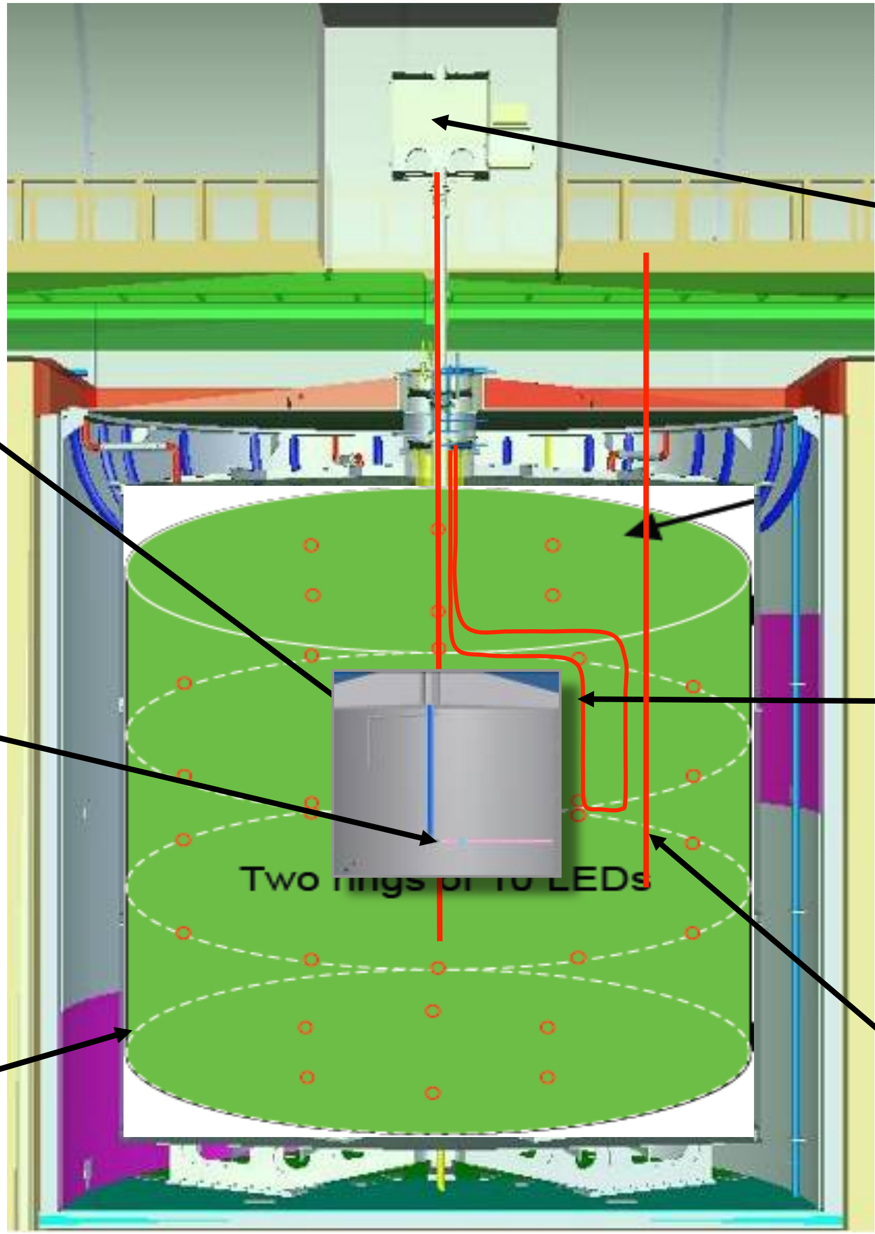
Reactor B1		2583.5
	+	
Reactor B2		2751.2
	=	
Total		**5334.7 ± 93** (1.74%)

Detector Calibration

Calibration Systems

Fish-line





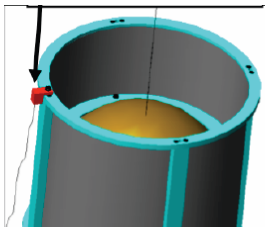
Glove Box

GC guide Tube

Articulated Arm

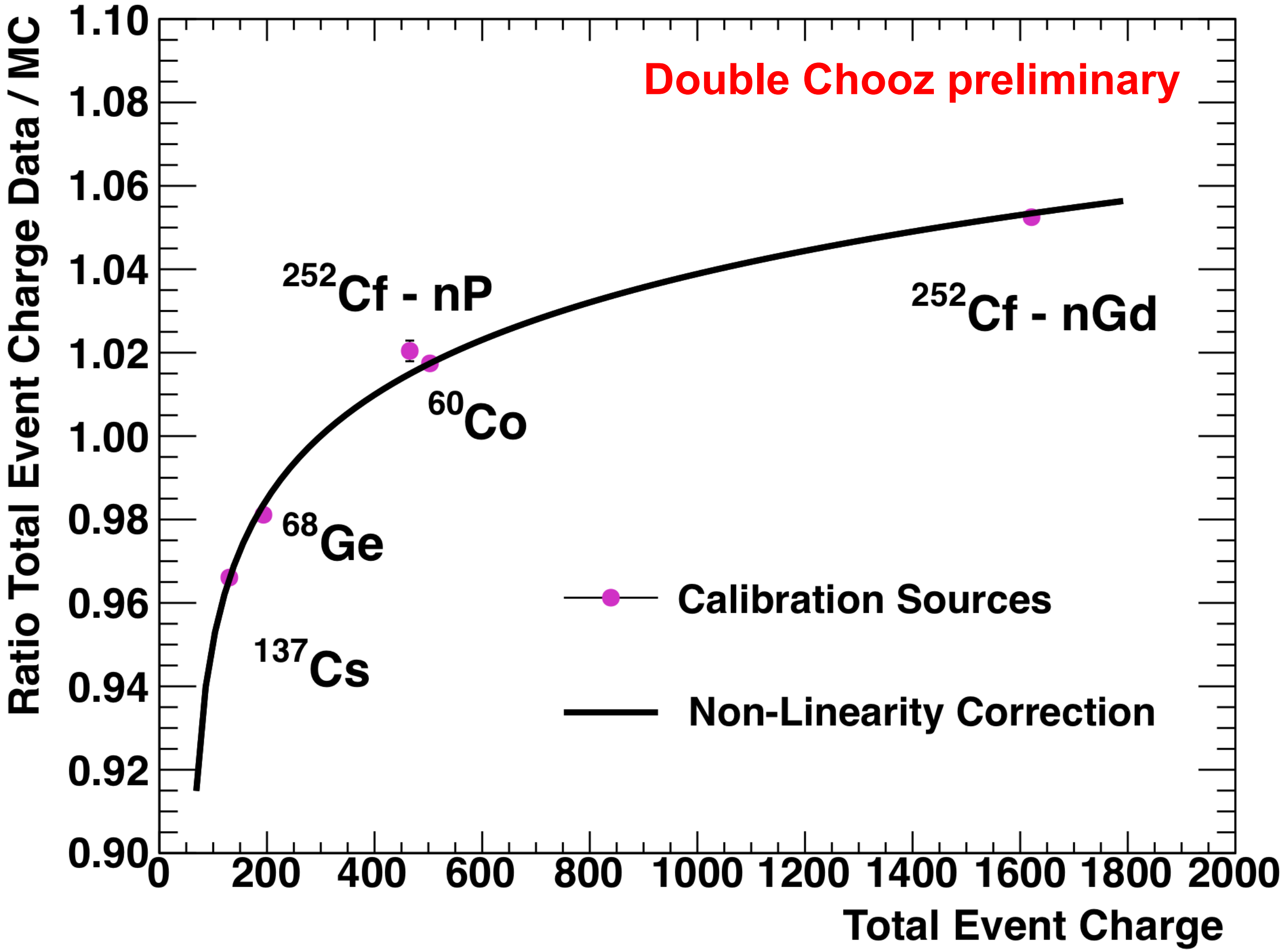
Buffer guide Tube

Embedded LED calibration system 385, 420, 470 nm



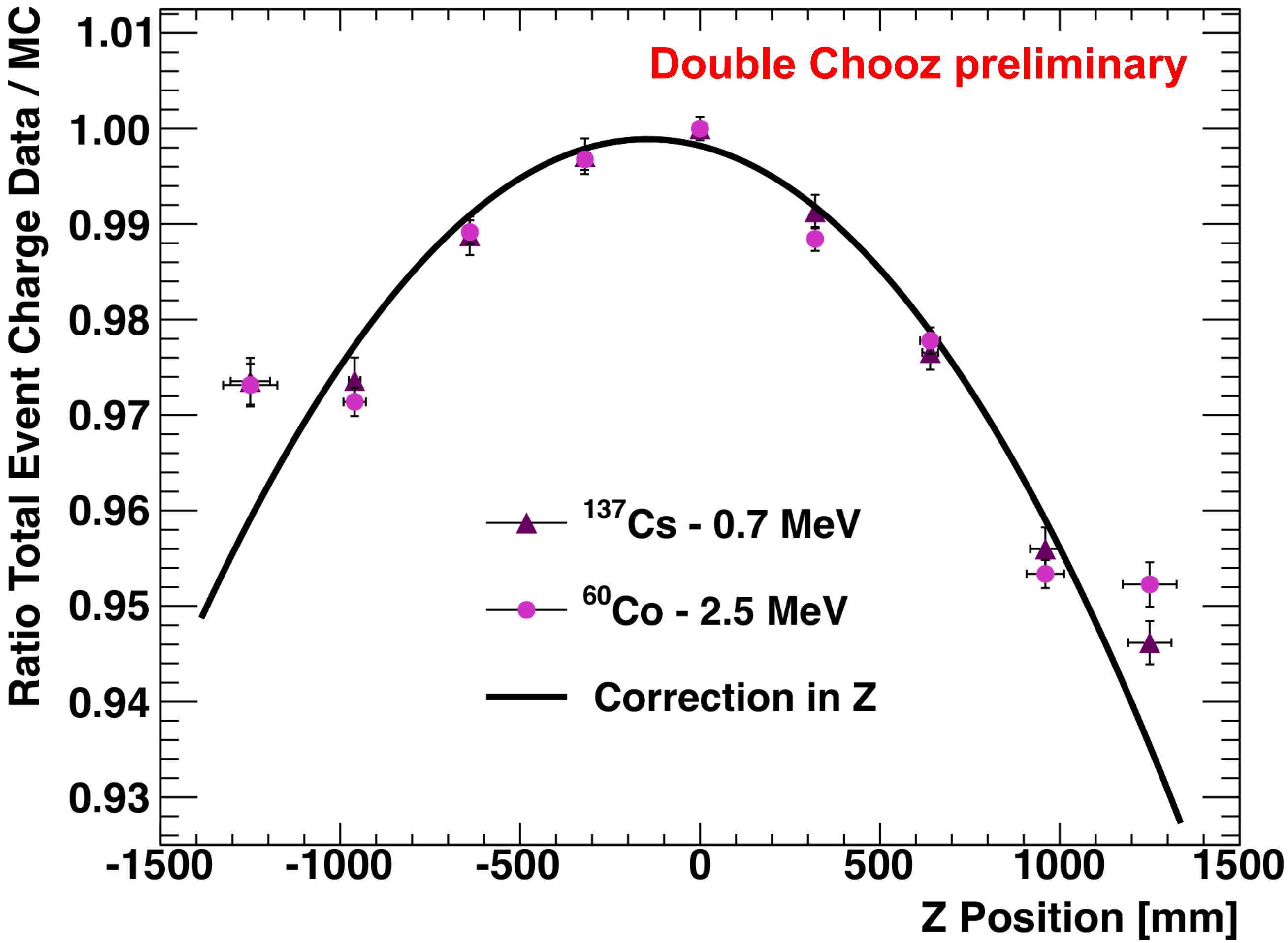
Charge Correction

Calibrate the non-linearity due to single photoelectron efficiency and electronics and Q-reconstruction effects.



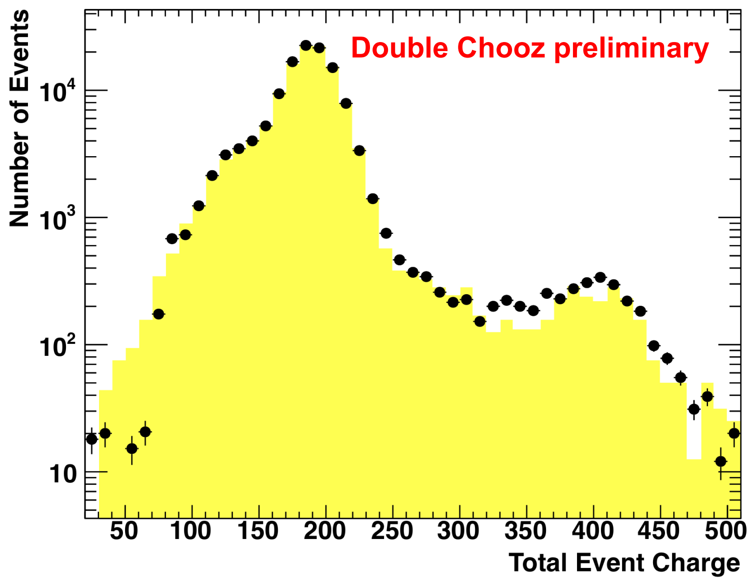
Z-correction

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



Energy Calibration

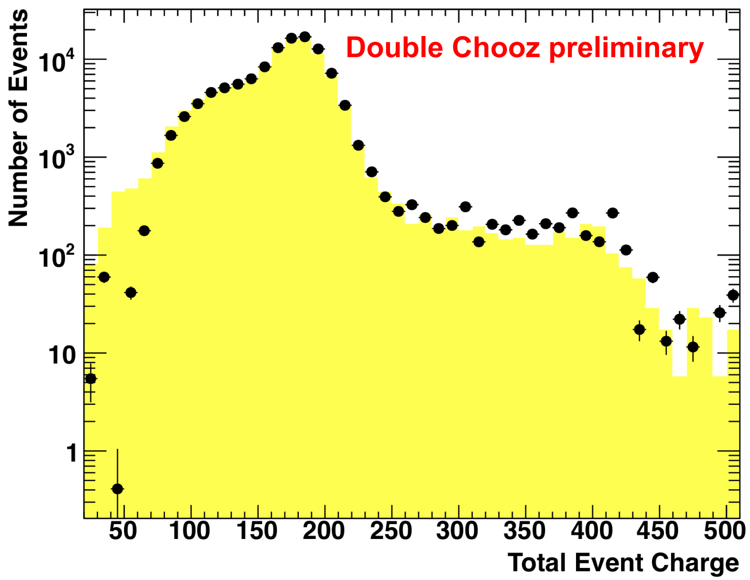
^{68}Ge Detector Center X=0mm, Y=0mm, Z=0mm



^{68}Ge at the Center of the Target

- Positron source
- The spectrum is well modeled
- Verification of the energy threshold

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

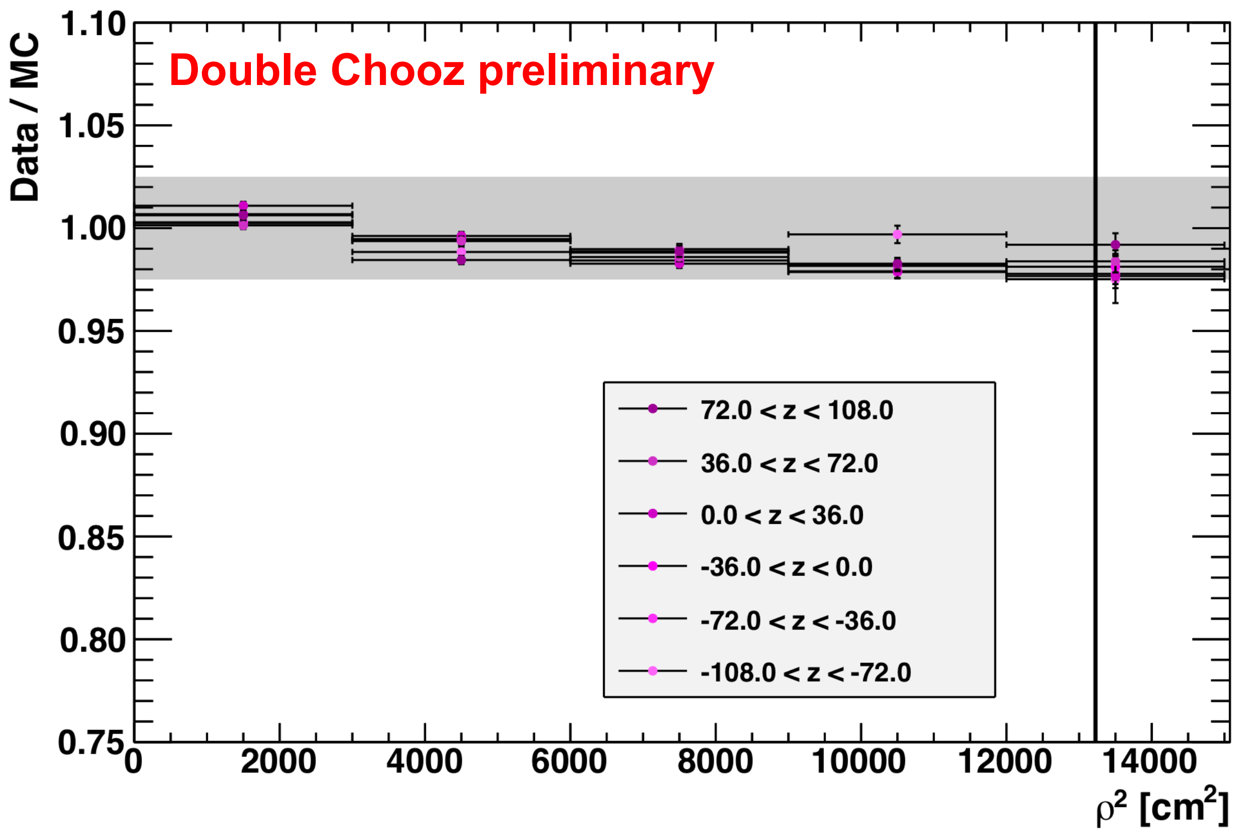


^{68}Ge in the Guide Tube

- Correction work also in the Gamma Catcher

Spallation Neutrons

- Evaluation of the (Q,Z) correction in all volumes
- Study of spallation neutrons in $\rho^2 = x^2+y^2$ in slices of z
- Capture on Gd peak
- Except for the extremes of the GC all is within +/-2.5%.

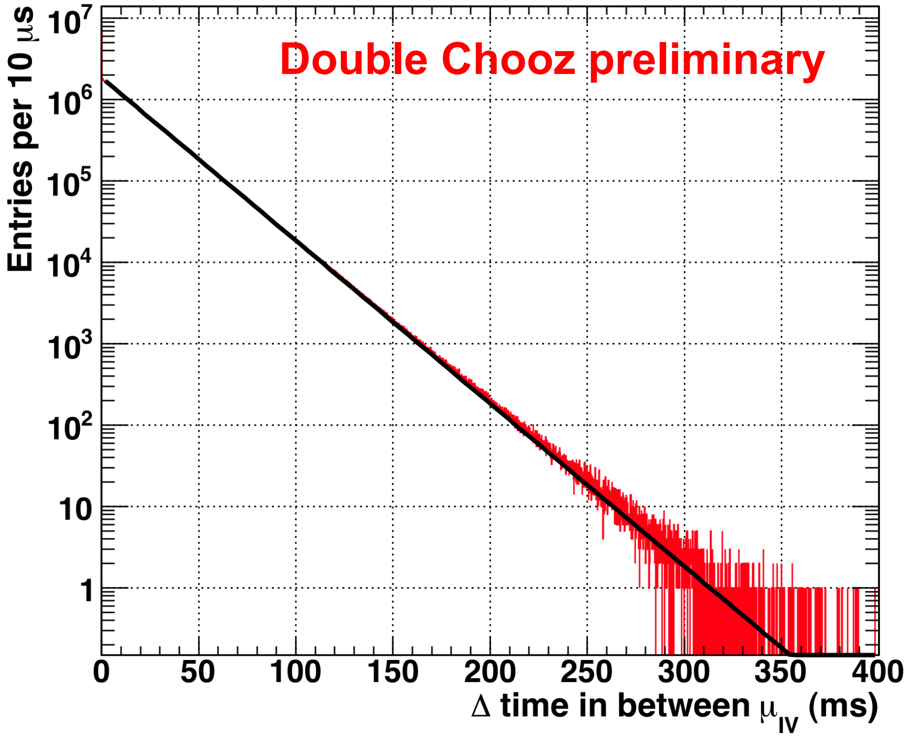


Neutrino Search

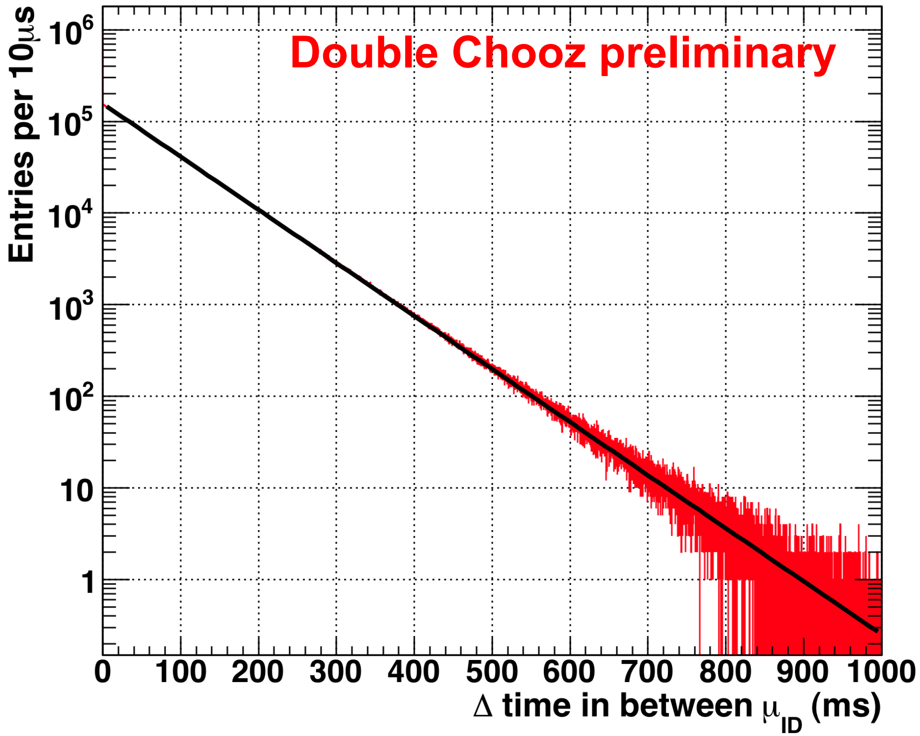
Muons

- Far Detector is located 150 m under a hill
- Inner Veto Muon Rate: **46 Hz**
- Inner Detector Muon Rate: **13 Hz**
- ν-search: Software Muon Veto of **1 ms** after Each Muon

Muon rate in Inner Veto: 46 Hz



Muon rate in Inner Detector: 13 Hz

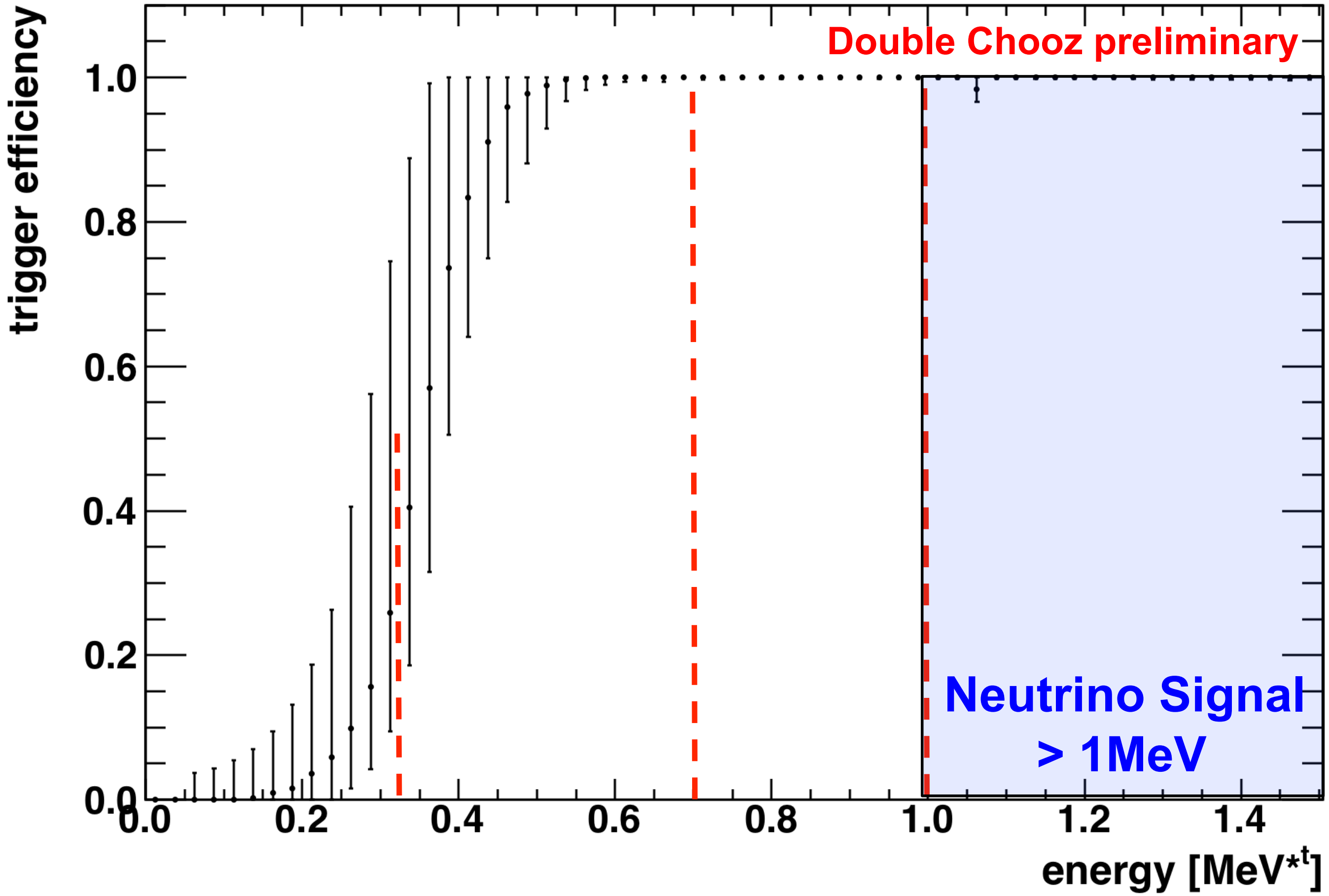


Neutrino Selection Criteria

- **Prompt Event:**
  - No Inner Veto Energy Deposition
  - $Q_{max}/Q_{tot} < 0.09$ & rms(T_{start})<40 ns
  - E in [0.7 ; 12] MeV
- **Delayed Event:**
  - No Inner Veto Energy Deposition
  - $Q_{max}/Q_{tot} < 0.06$ & rms(T_{start})<40 ns
  - E in [6 ; 12] MeV
- **Coincidence:**
  - No Space Coincidence Cut
  - Time Coincidence: 2 μs < Δt < 100μs
- **Multiplicity:**
  - No valid triggers allowed in the 100 μs preceding the prompt
  - The time window from 2 μs to 100 μs following the prompt can contain only one valid trigger: the delayed candidate
  - No valid triggers allowed in the time window 100 μs through 400 μs after the prompt

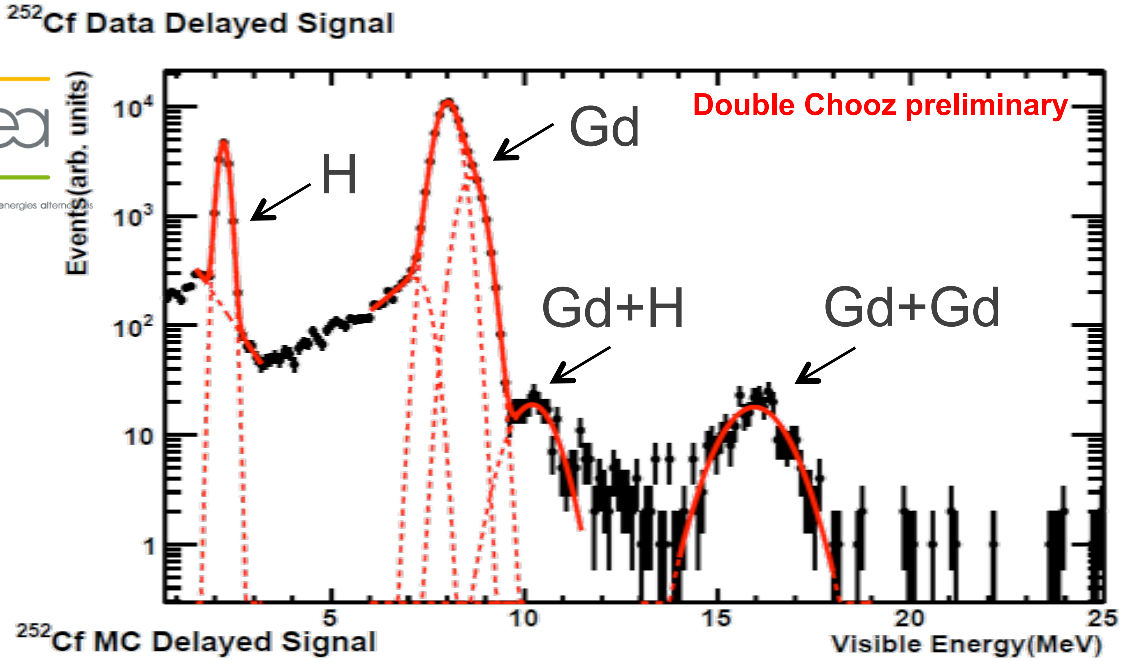
E_{prompt} & Trigger Efficiency

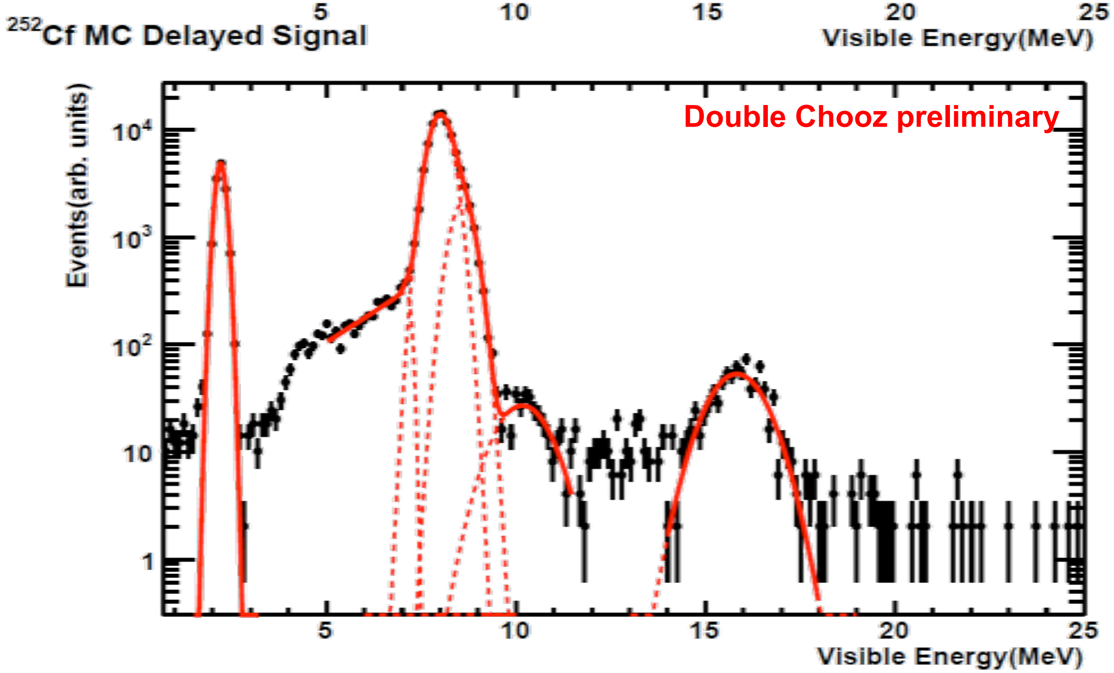
- Trigger threshold (50% efficiency) : 350 keV
- Trigger efficiency :100% +0/-0.4% for E>700 keV



- Prompt Energy Cut Efficiency : > 99.9%

Fraction of Gd Capture

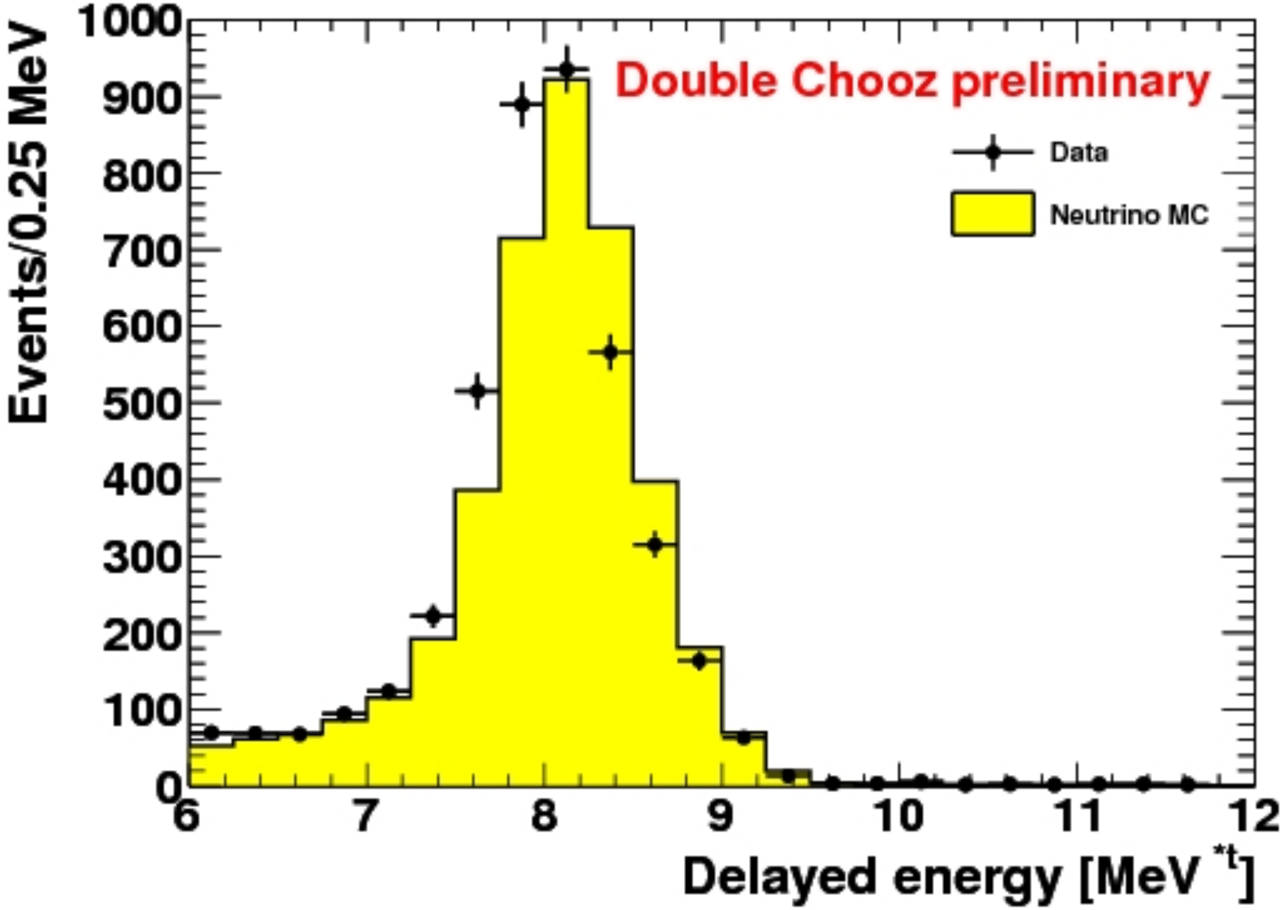




- Calibration with a ^{252}Cf source in the central target region
- Deployment along the z-axis (7 positions)
- Compute Gd/(H+Gd) capture rate
- 2% correction between data & MC
- The 6 Mev cut efficiency is 0.86 ± 0.6%

Delayed energy Spectrum

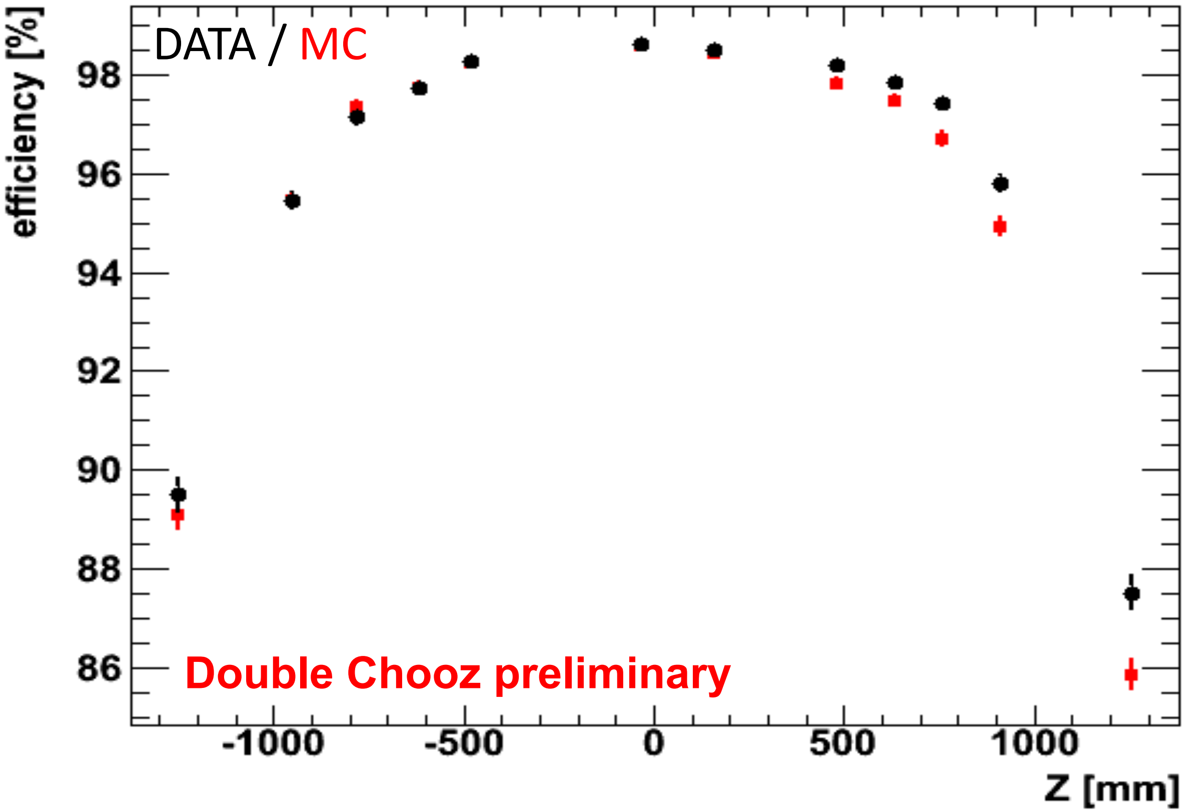
- Selection of Neutron Capture on Gd only
- Allow to define the fiducial volume by the mass of Gd-loaded LS



- Delayed Energy Cut Efficiency : 0.86 +/- 0.6%

Delayed Event Energy Containment

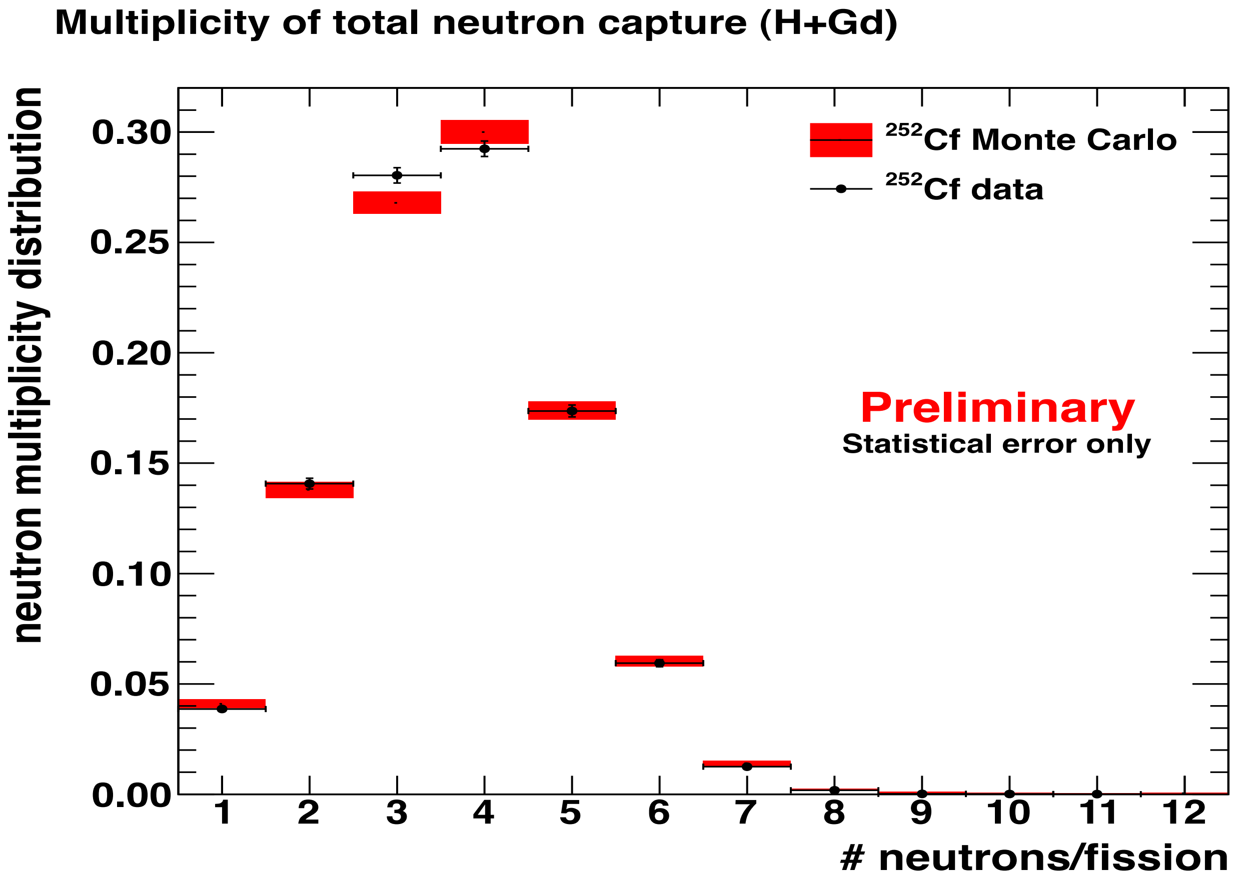
- Part of the Gd-capture gamma's escape the Target + G-Catcher
- Deployment of ^{252}Cf along the Target z-axis
- Eff. (CHOOZ) = # capture **[6,12]** MeV / # capture **[4,12] MeV**



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

^{252}Cf Neutron Multiplicity

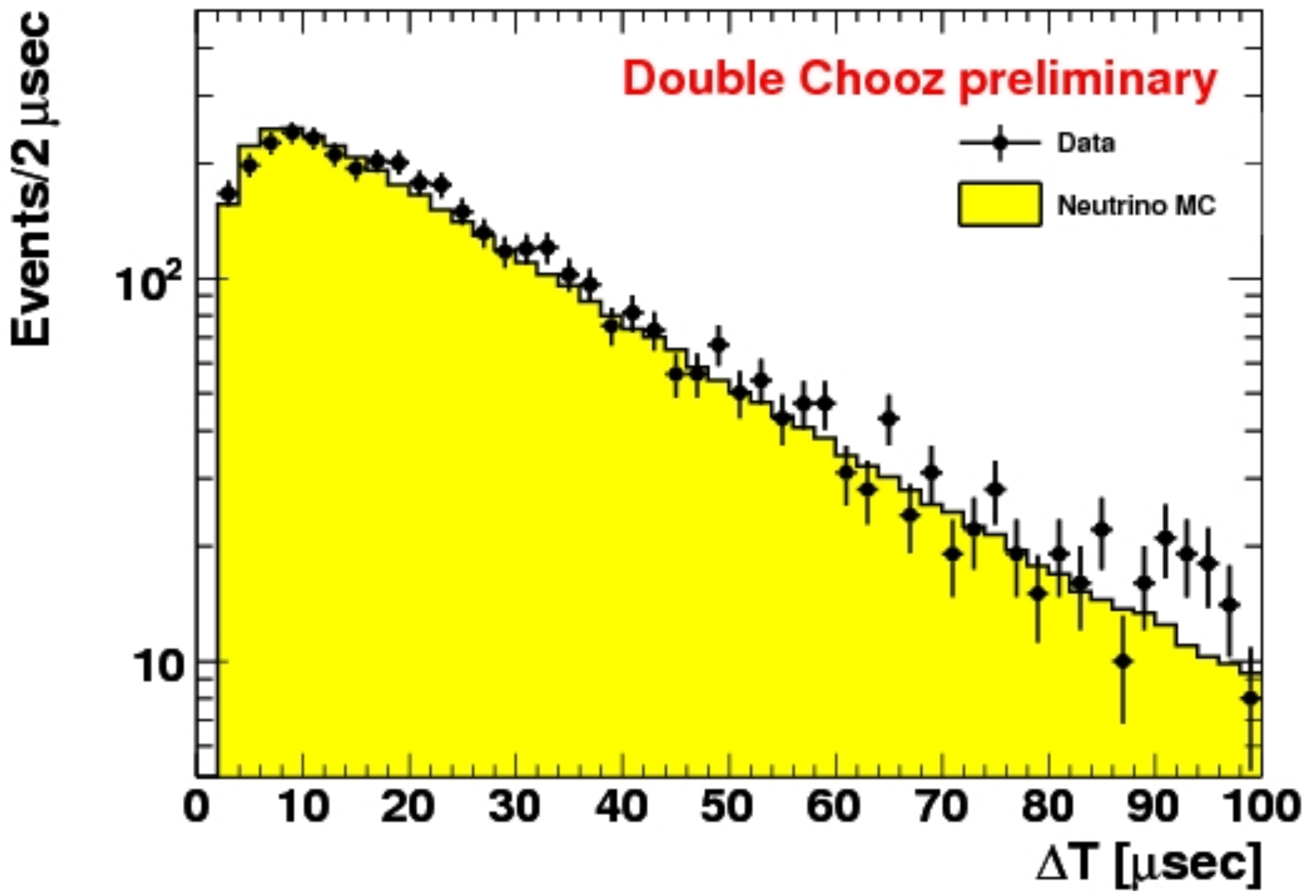
- Important verification of the neutron detection efficiency



- Using the first 8 neutron per fission only:
- Average neutron multiplicity **data: 3.659 +/- 0.008 (stat)**
- Average neutron multiplicity **MC : 3.677 +/- 0.013 (stat)**

Prompt – Delayed Δt

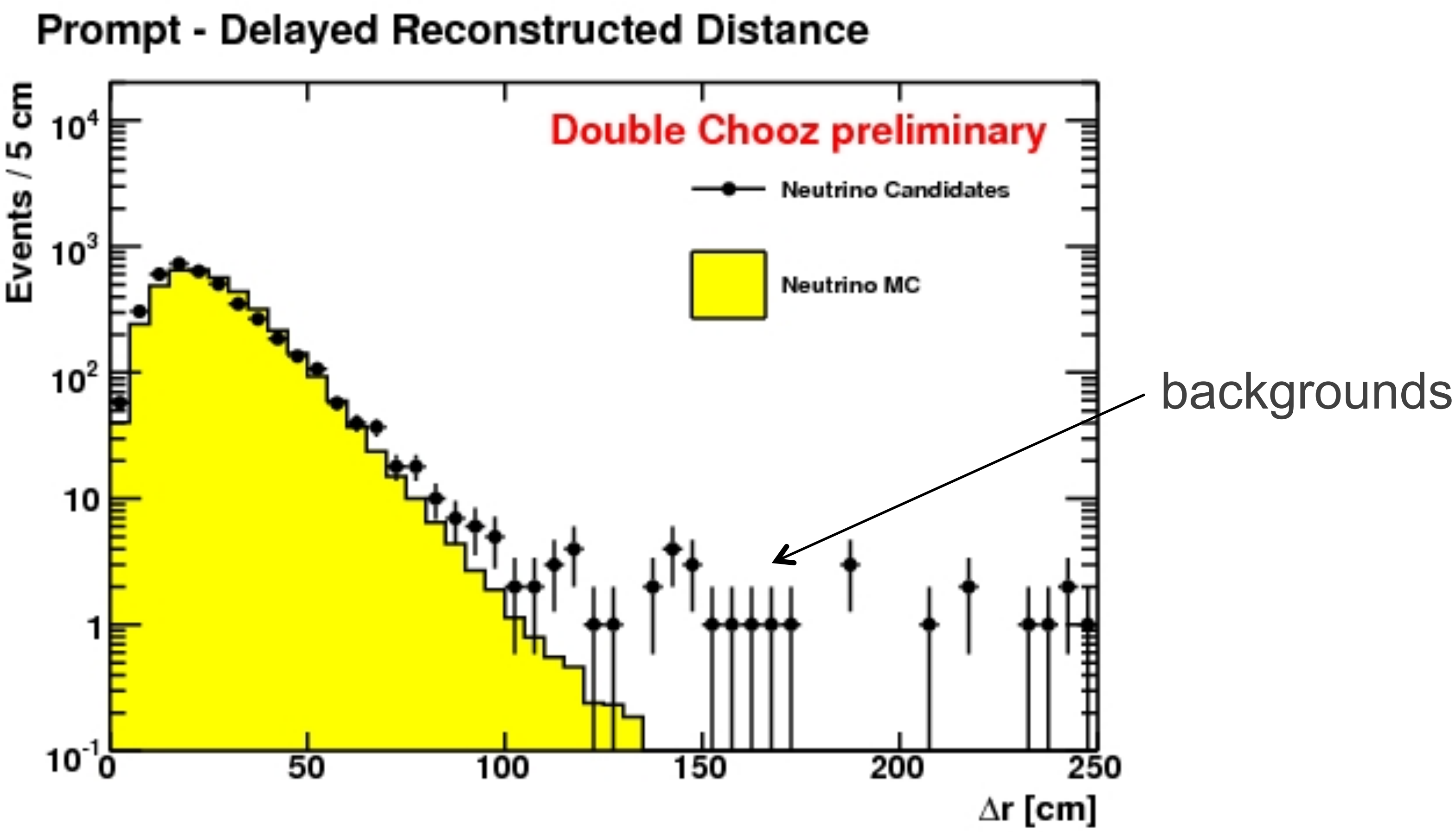
- KeV neutrons thermalize within a few μs
- Then neutrons get captured on Gd with τ = 27μs
- Good agreement with the MC expectation



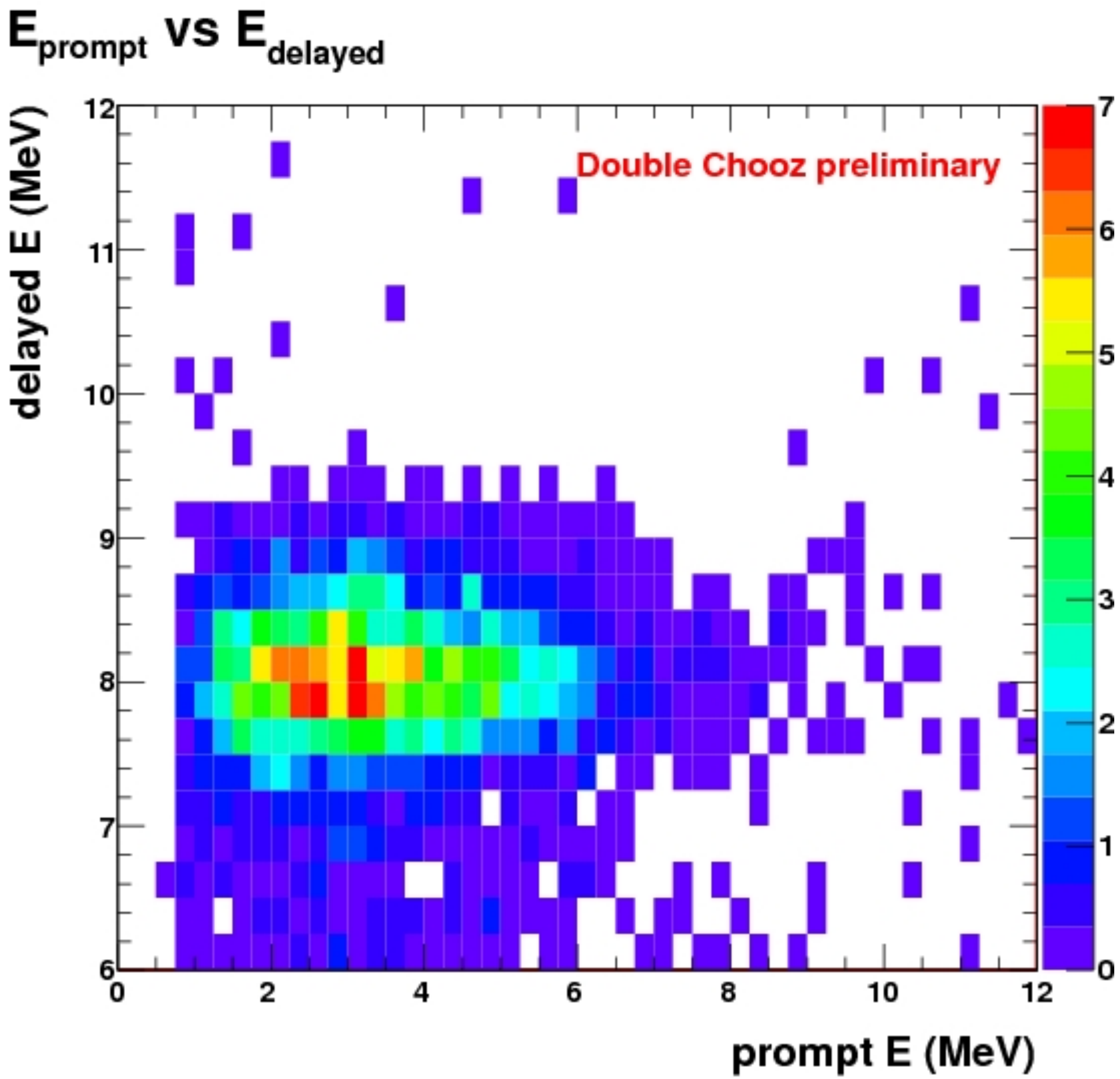
The efficiency within [2,100] μs is 0.965 ± 0.5%

Prompt – Delayed ΔR

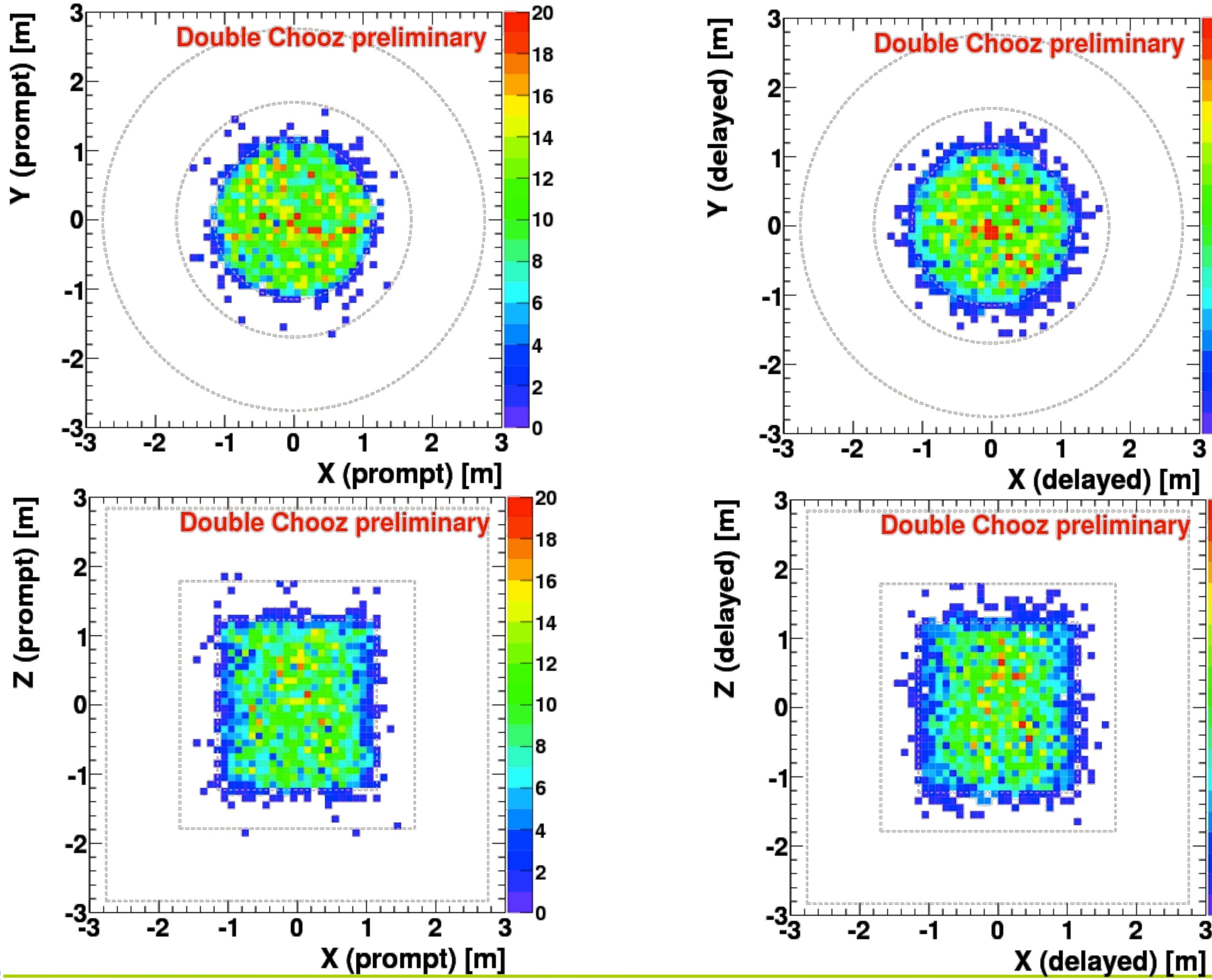
- Low level of accidental background
- No Need for ΔR Cut as designed in the proposal



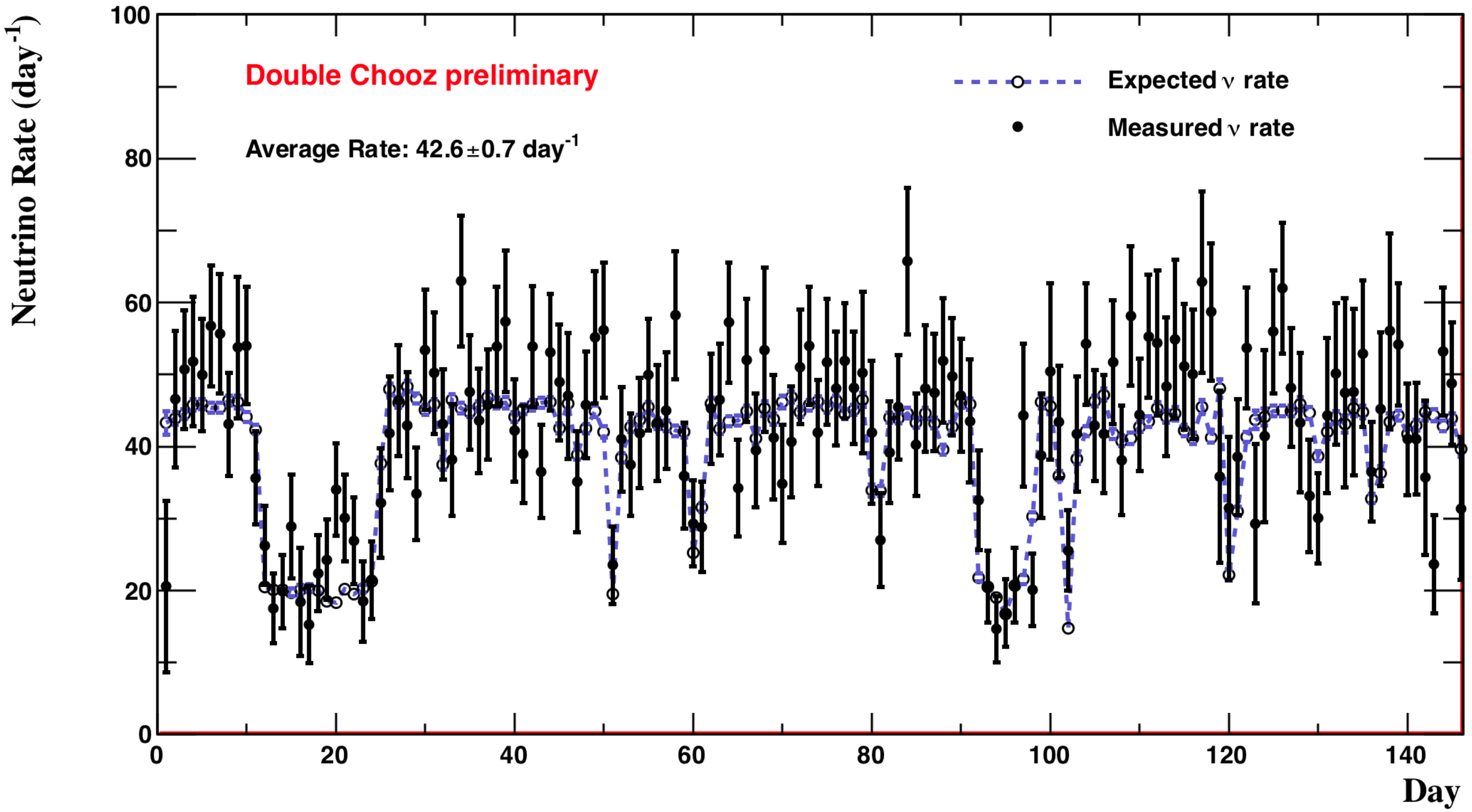
E_{prompt} VS $E_{delayed}$



Prompt & Delayed Vertex Reconstruction



Neutrino Candidate Rate



Backgrounds NOT subtracted from candidates sample

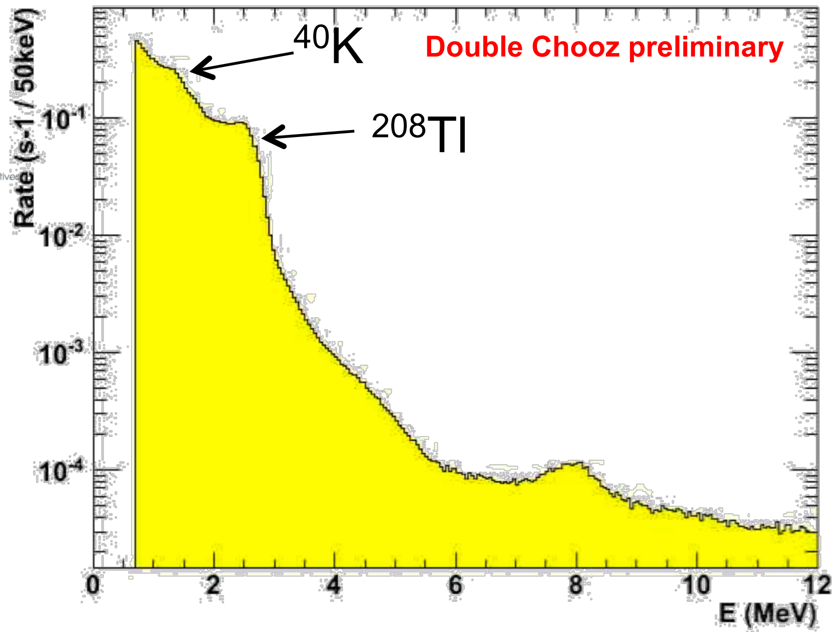
Low Background Detector !

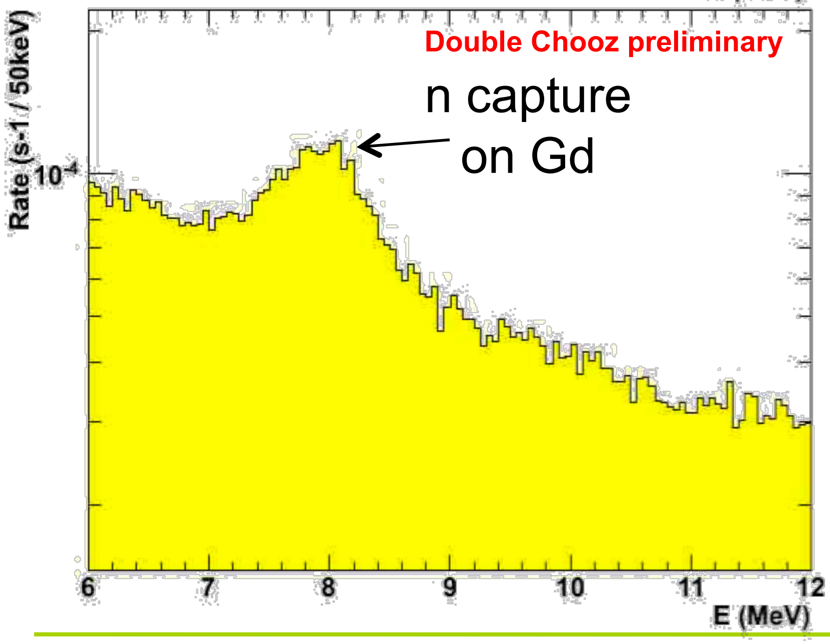
4121

Neutrinos Candidates

Backgrounds

Singles : Rate & Spectrum

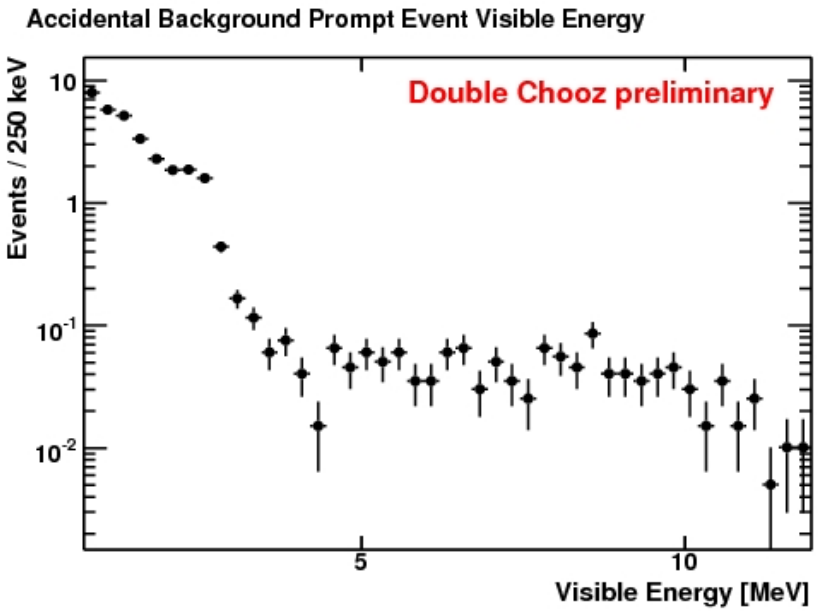


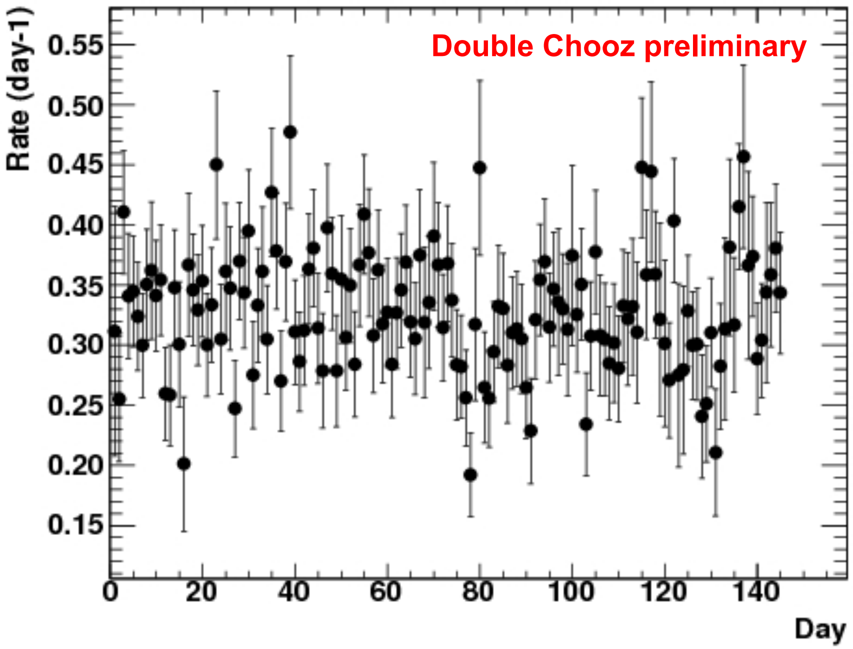


- **[0.7,12] MeV: radioactivity**
- Proposal: 10 Hz
- DC (E>700 keV): 7.625±0.001/s

- **[6,12] MeV : thermal neutrons**
- Proposal : 100 n/h
- DC: 20 n/h

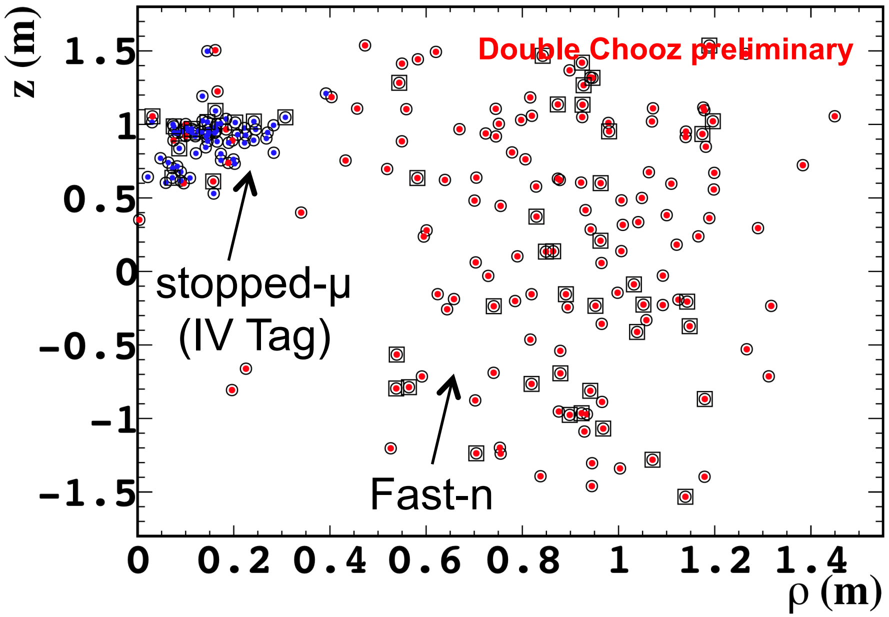
Accidentals Background

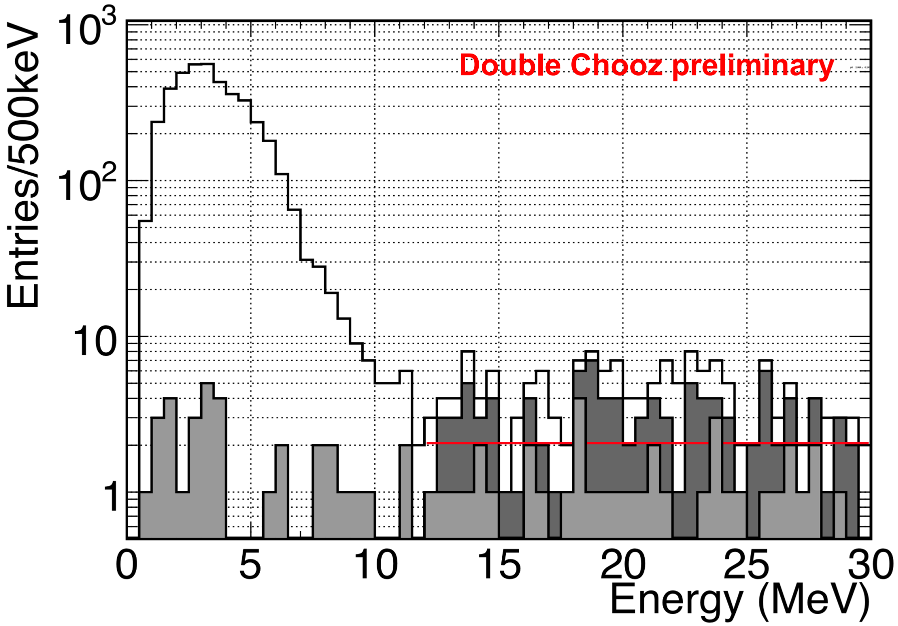




- Same as for neutrino search but delayed event uncorrelated in a delayed time window (1 ms)
- Multiplicity cuts applied method
- Rate:
  - **0.332 +-0.004 per Day**
  - 5 times lower than in the proposal !
  - Stable in time
- Spectrum: compatible with 'singles'

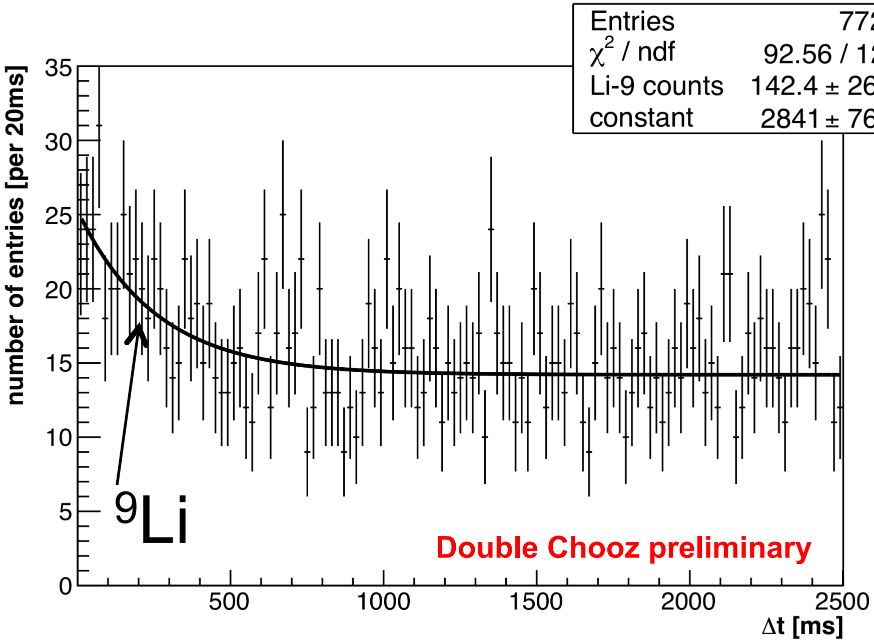
Correlated Bkg: Fast Neutrons

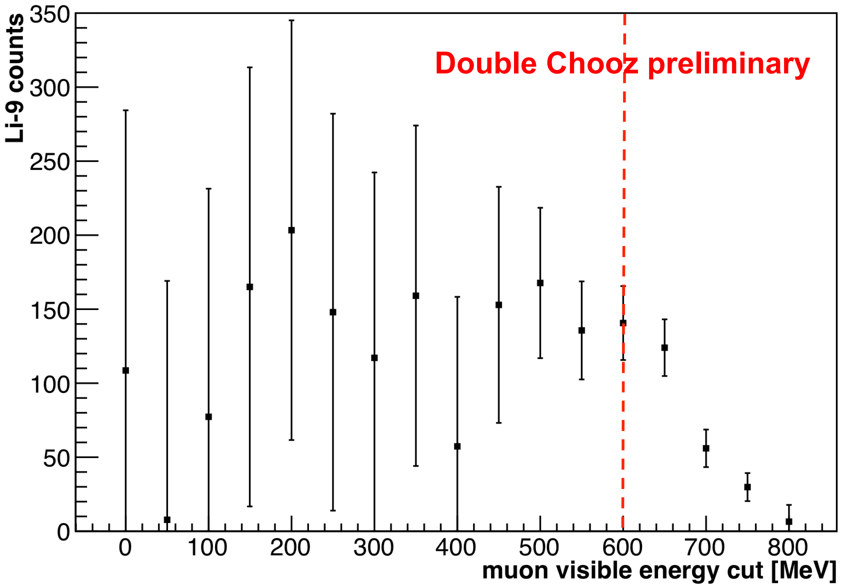




- Neutrino Analysis with prompt energy extended to 30 MeV
- Two populations:
  - Fast-n
  - Stopping-muon
- Rate:
  - Extrapolation from high Energies to lower ones
  - **0.7 -0.5 +0.5 per Day**
- Spectrum:
  - Flat
  - + Stopped Mu Shape Unc.

Correlated Bkg: ^{9}Li

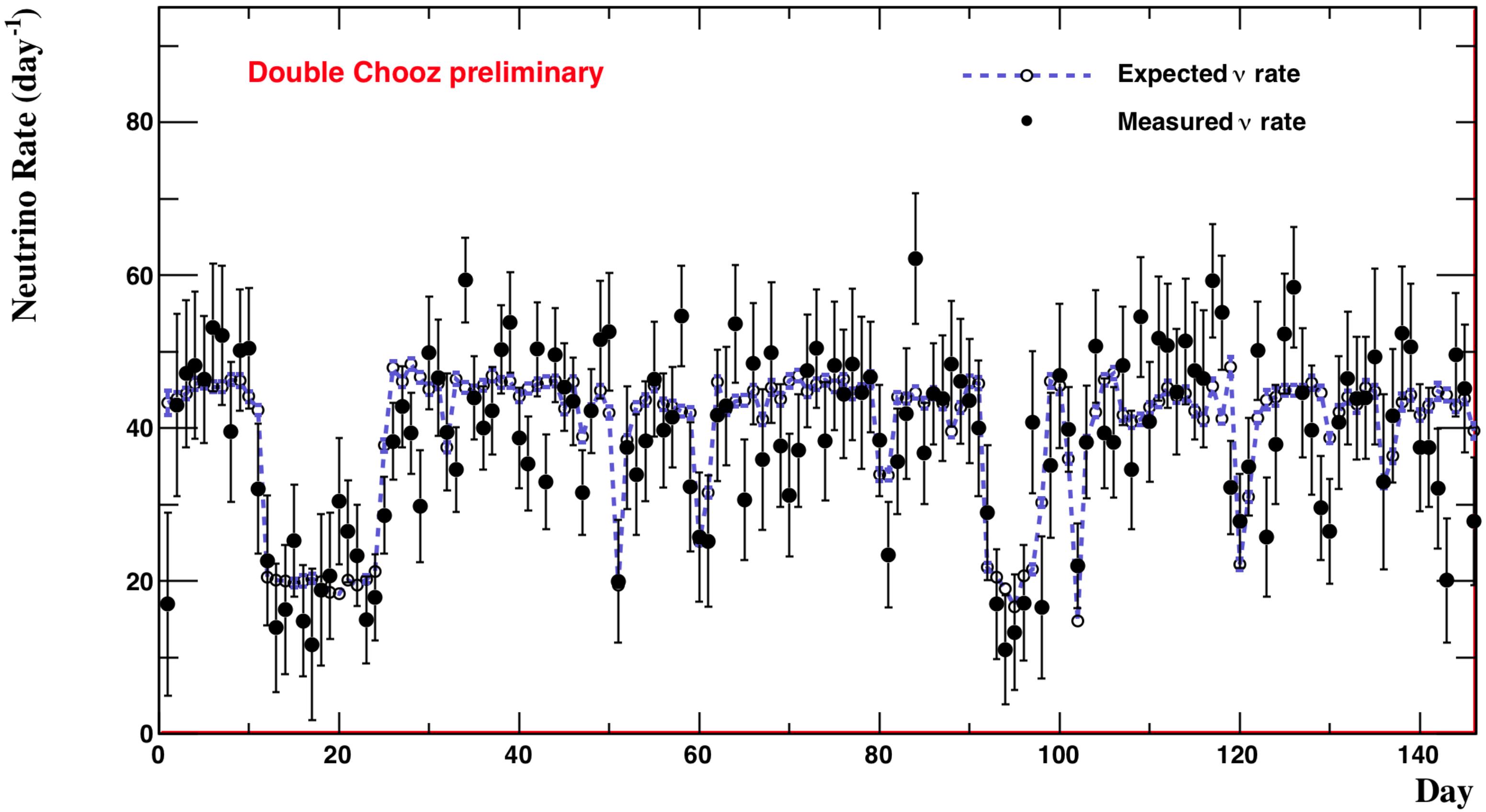




- ^{9}Li events selection:
  - Statistical
  - Search for a triple delayed coincidence between showering muon and neutrino-like coincidence
- Showering muon : E>600 MeV
- Δt between showering muon and prompt event is given by the ^{9}Li-like life time (257ms).
- **Rate: 2.3 -1.2 +1.2 per Day**
- Spectrum: nuclear database

Neutrino Rate vs Day

Type	#Evts	Rate/Day	σ/Day
Neutrino Candidates	4121	42.6	0.7
- Expected Accidentals	31.60	0.32	0.06
- Expected ^{9}Li	227.3	2.3	1.2
- Expected Fast-n	69.2	0.7	0.5

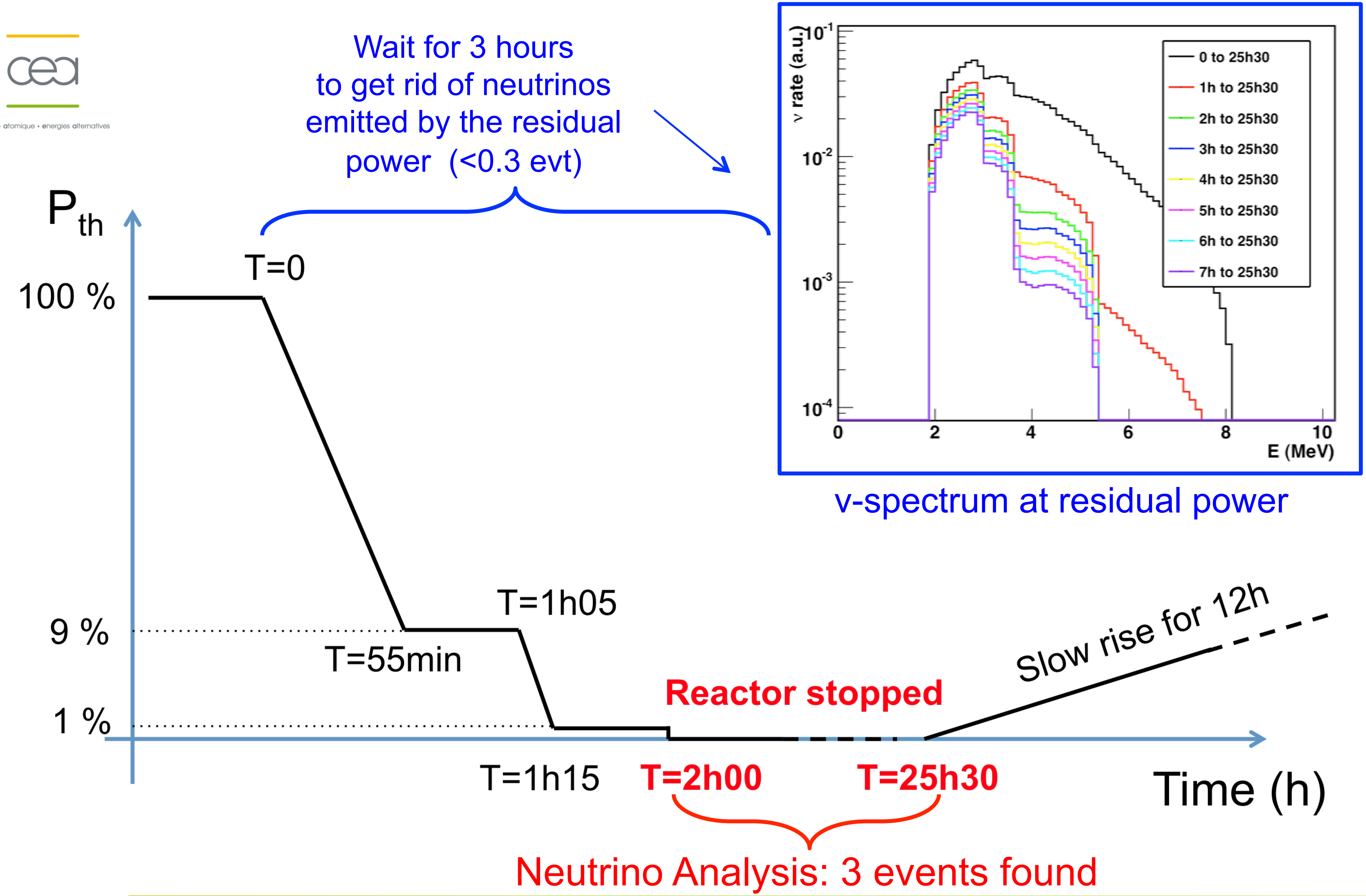


Reactor Off-Off

Reactor 1 stopped for 2 months (refueling)
Reactor 2 stopped for 1 day for servicing

In Situ Background Measurements
(Unique Capability of Double Chooz)
3 events within [0,7 – 30] MeV
1 event in [0,7-8 MeV]

1 Day Reactor Off-Off



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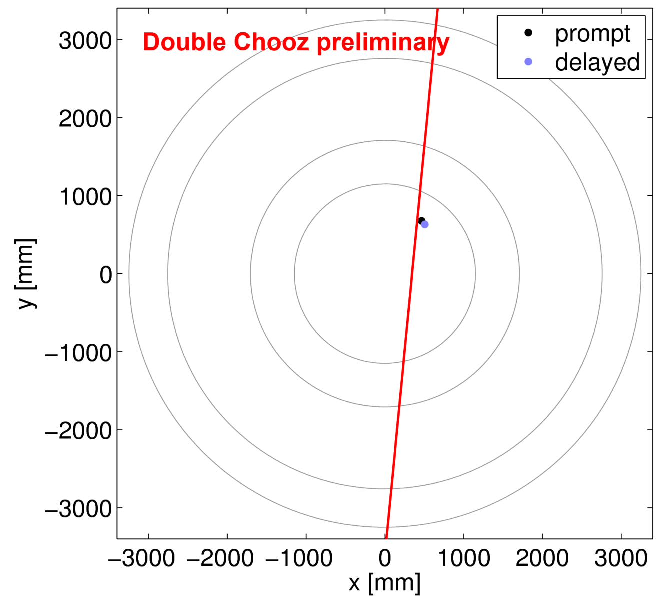
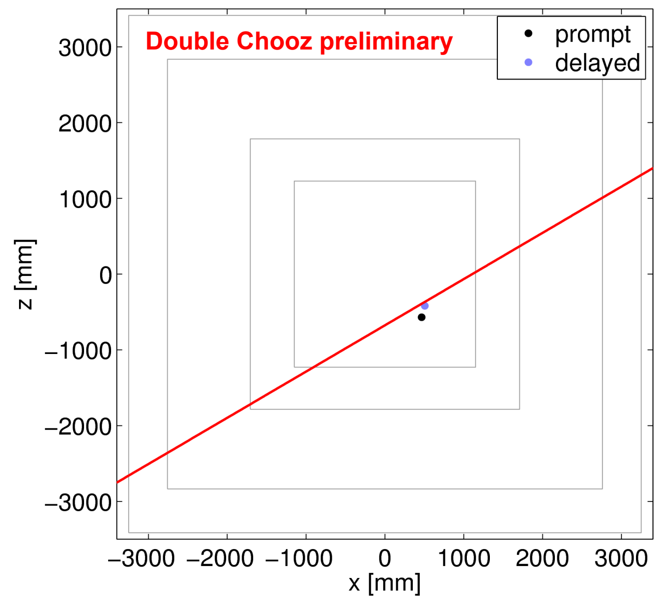
1 Day Reactor Off-Off: Event I

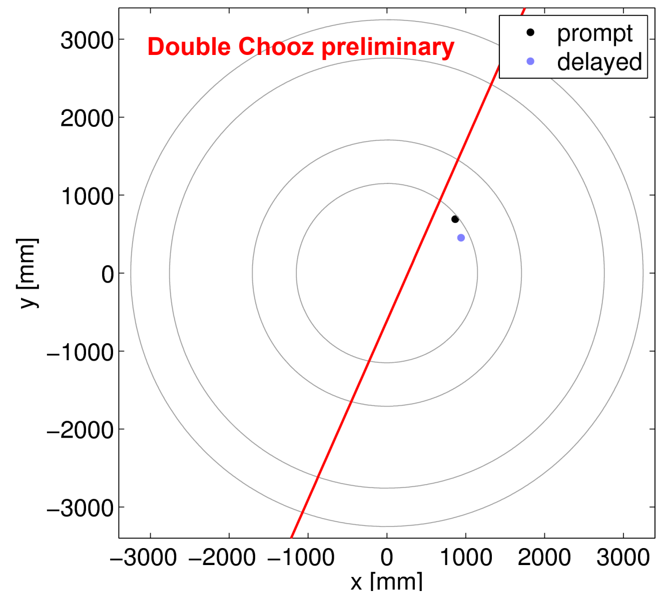
- ^{9}Li Event Candidate
- **Prompt event**
  - Inner Detector energy: 9.8 MeV
- **Delayed event**
  - Inner Detector energy 8.0 MeV
- **Coincidence characteristics**
  - Distance 16.4 cm
  - Δt: 4 ms
- **Muon$_{(> 600\ \mathrm{MeV})}$**
  - Inner Detector energy 739 MeV
  - Distance to prompt: 15.4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

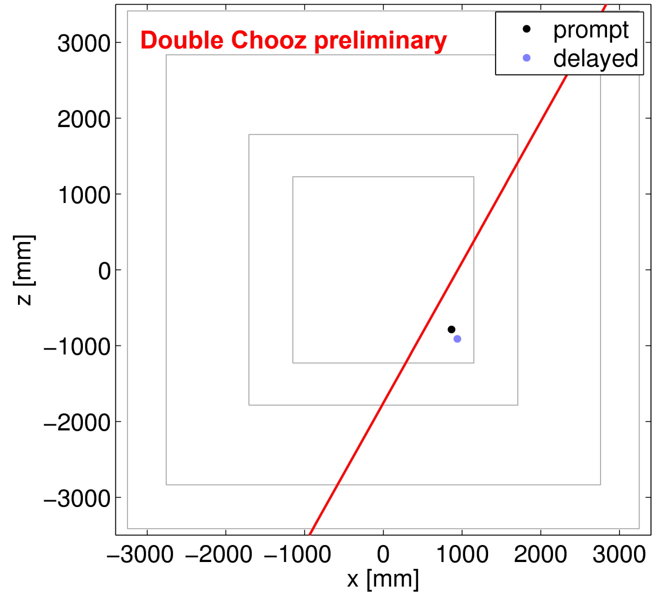




1 Day Reactor Off-Off: Event II

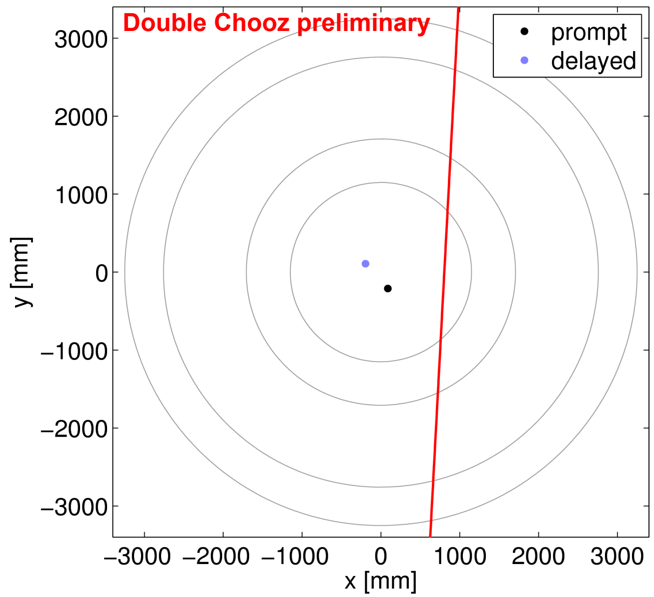
- ^{9}Li Event Candidate
- **Prompt event**
  - Inner Detector energy: 4.8 MeV
- **Delayed event**
  - Inner Detector energy 8.6 MeV
- **Coincidence characteristics**
  - Distance 27.9 cm
  - Δt: 26 ms
- **Muon$_{(> 600\ MeV)}$**
  - Inner Detector energy 627 MeV
  - Distance to prompt: 30.8 cm
  - Δt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

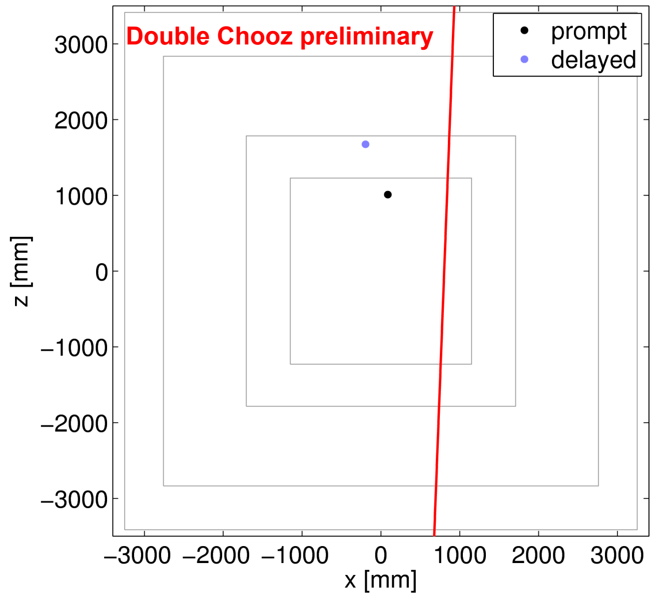




1 Day Reactor Off-Off: Event III

- **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 ms
- **Muon$_{(> 600\ \mathrm{MeV})}$**
  - Closest one 17 s prior to prompt
  - shown track is m with highest energy deposition (523 MeV) within 5 s, with 206 ms, 103 cm distance to prompt





Oscillation Search

Efficiency, Live Time Correction, Systematics

Source	Uncertainty
Target Free H	+/- 0.3 %
Trigger Efficiency	+/- 0.5 %

Source	Efficiency	Uncertainty
Prompt Event	99.9 %	+/- 0
Delayed Event	86.0 %	+/- 0.6 %
Δt Cut	96.5 %	+/- 0.5 %
ΔE Cut	94.5 %	+/- 0.6 %

78 %

Source	MC Live Time Correction	Uncertainty
Muon Deadtime	0.955	+/- 0
Multiplicity	0.995	+/- 0
Gd Fraction	0.98	+/- 0.6 %
Spill in/out	0.993	+/- 0.4 %

92.4%

Back Of The Envelop Estimation

- Data (Neutrino Candidates) : 4121 (+ bkg = 328)
- MC (Expected Signal) : 5339

- Neutrinos_{obs} = (4121 – 328) = 3793
- Neutrinos_{pred} = 5339 . 0.757 = 4041

$$\sin^2(2\theta_{13}) = \frac{\left(1 - \frac{N_{obs}}{N_{pred}}\right)}{1 - 0.54} \approx 0.13$$

Oscillation Fit Strategy

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

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

$$\times \left(N_j - \left(\sum_R^{\text{Reactors}} N_j^{\nu,R} + \sum_b N_j^b(P_b)\right)\right)^{\text{T}}$$

$$+ \sum_R^{\text{Reactors}} \frac{(P_R)^2}{\sigma_R^2}$$

$$+ \sum_b^{\text{bkgnds.}} \frac{(P_b)^2}{\sigma_b^2}$$

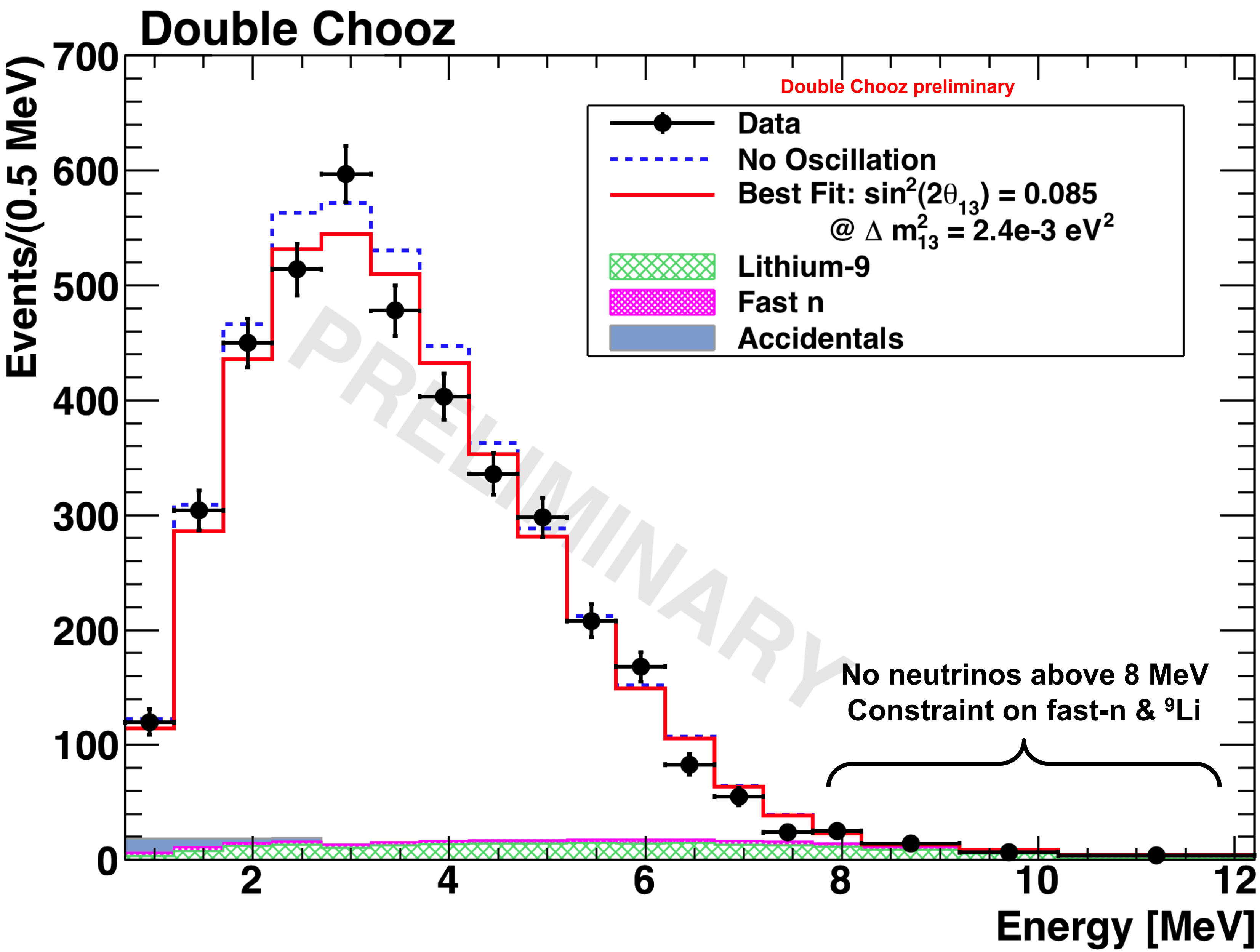
M_{ij}^{signal}: Signal covariance matrix.

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

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

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

Rate & Shape Oscillation Analysis



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Summary of the Results

Rate Only :

- $\sin^2(2\theta_{13}) = 0.096 +/- 0.029(stat) +/- 0.073(syst)$

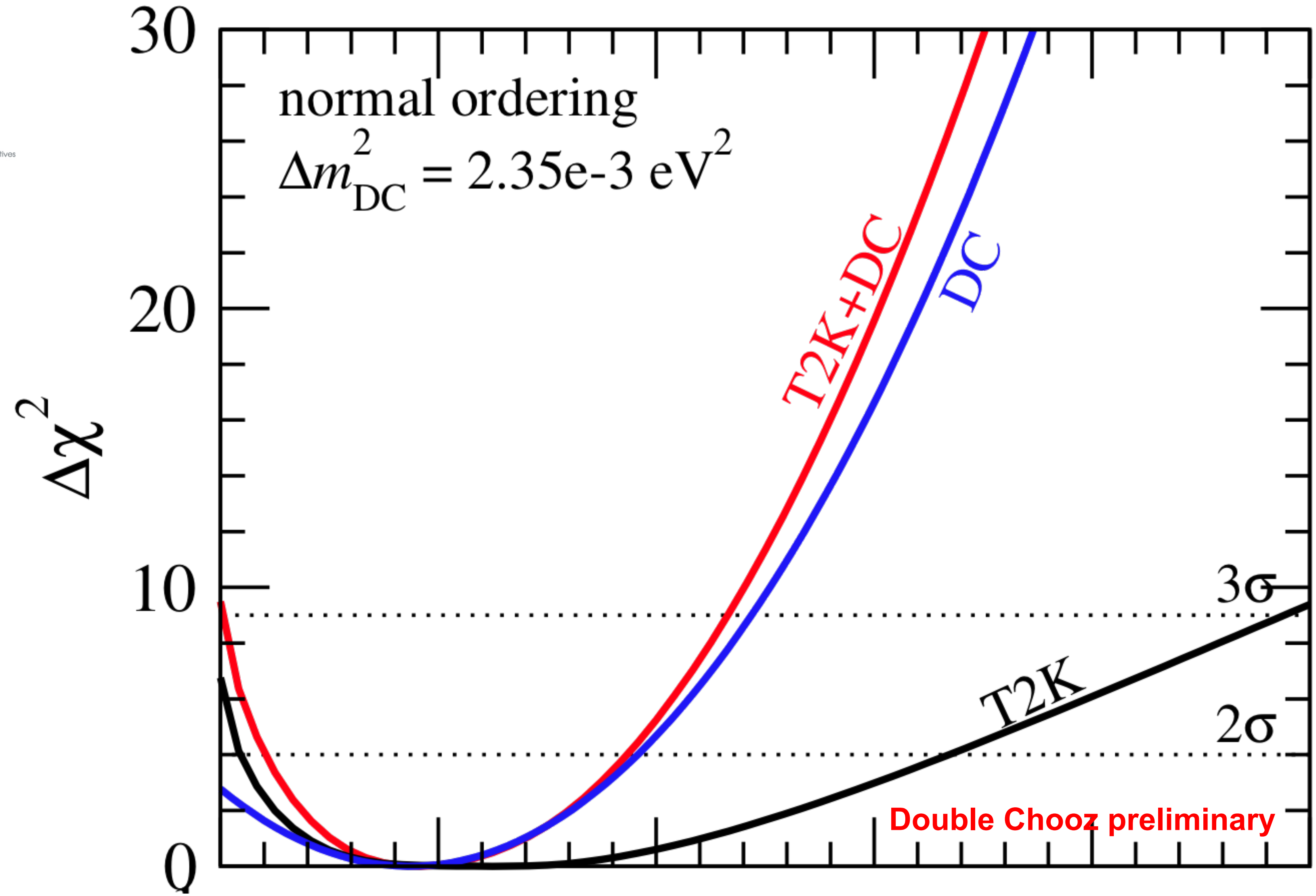
Shape Only :

- $\sin^2(2\theta_{13}) = 0.044 +/- 0.157$

Rate & Shape :

- $\sin^2(2\theta_{13}) = 0.086 +/- 0.029(stat) +/- 0.042(syst)$
- No-Oscillation Excluded at 92.9 %

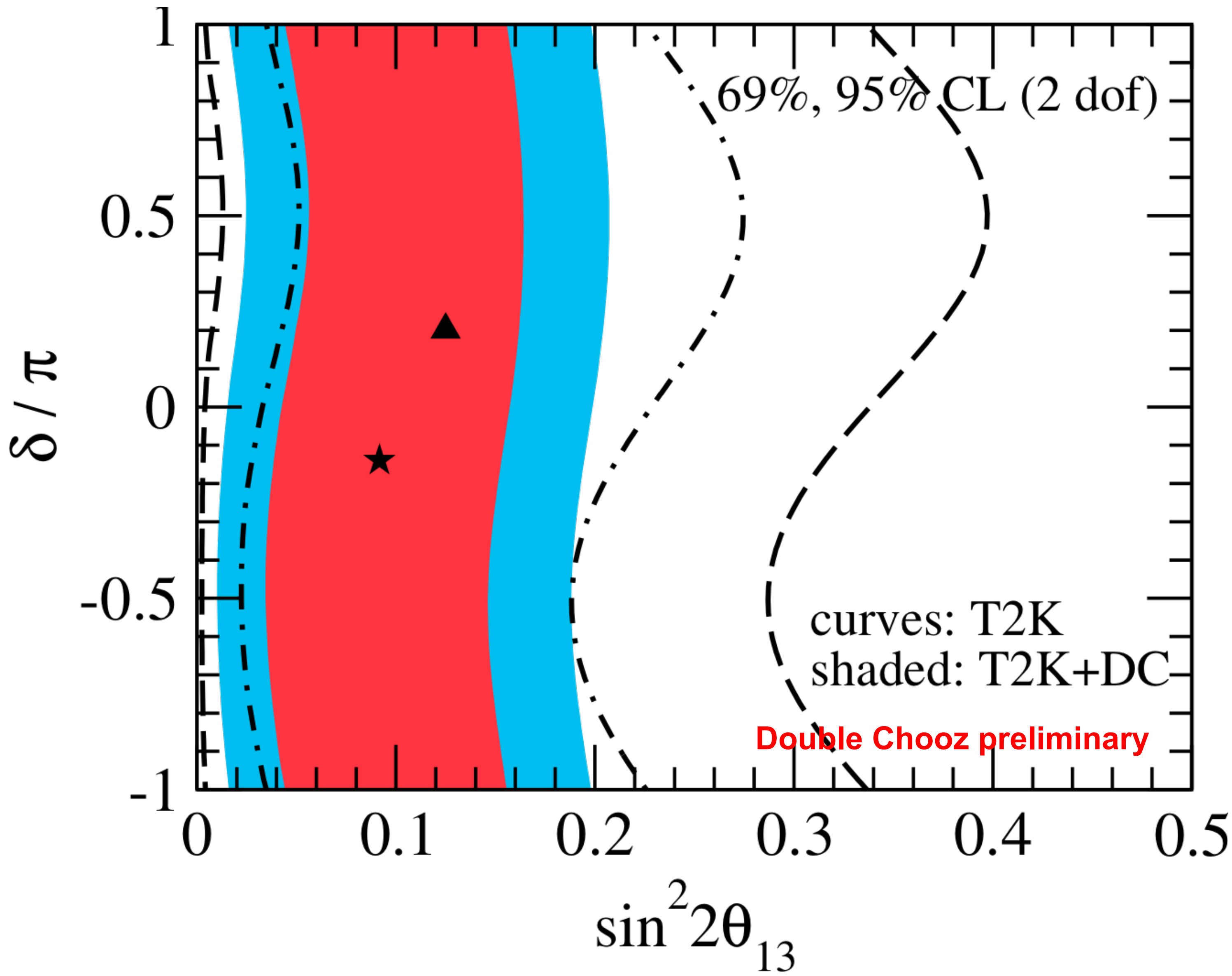
Double Chooz / T2K Combination



Combined best fit point is at 0.092

θ_{13} = 0 is excluded at 3 sigma from T2K+DC

Double Chooz / T2K Combination



Conclusions

- Double Chooz is running as designed

- Report of Analysis of 5 months of data. Hint for positive value of θ_{13}
  - $\sin^2(2\theta_{13})$ = 0.086 +/- 0.029(stat) +/- 0.042(syst)
  - No-Oscillation excluded at 92.1% CL

- The near detector will be operational by early 2013

- Great prospect towards the most precise measurement θ_{13} with 2 nuclear cores

  - Simple site configuration. Reactor Off-Off periods for in-situ bkg measurement

  - Comprehensive set of Calibration Systems

A la mémoire d'Alain & de Dario