First result from the Double Chooz reactor-neutrino experiment

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on behalf of the Double Chooz collaboration

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TOKYO METROPOLITAN UNIVERSITY
首都大学東京

Outline

- Double Chooz experiment to measure θ_{13}

- Neutrino prediction

- Neutrino selection and backgrounds

- Oscillation analysis and conclusion

Neutrino oscillation

Neutrino oscillation occurs as a consequence of non-zero mass and mixing of mass eigenstates and flavor eigenstates as :

$(*)\ c_{ij} = cos\theta_{ij},\ s_{ij} = sin\theta_{ij}$

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

θ_{23} : $P(\nu_\mu \to \nu_\mu)$ by Atoms. ν and ν beam

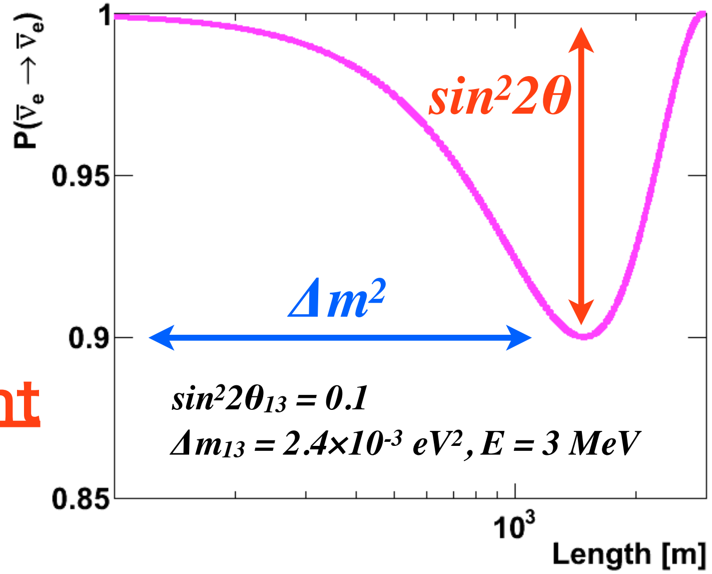
θ_{13}: $P(\nu_e \to \nu_e)$ by Reactor ν
θ_{13} & δ: $P(\nu_\mu \to \nu_e)$ by ν beam

θ_{12} : $P(\nu_e \to \nu_e)$ by Reactor and solar ν

Neutrino oscillation in two flavor scheme :

$$P(\nu_\alpha \to \nu_\alpha) = 1 - \sin^2 2\theta \sin^2\left(\frac{1.27 \times \Delta m^2\ [\mathrm{eV}^2] \times L\ [\mathrm{m}]}{E\ [\mathrm{MeV}]}\right)$$

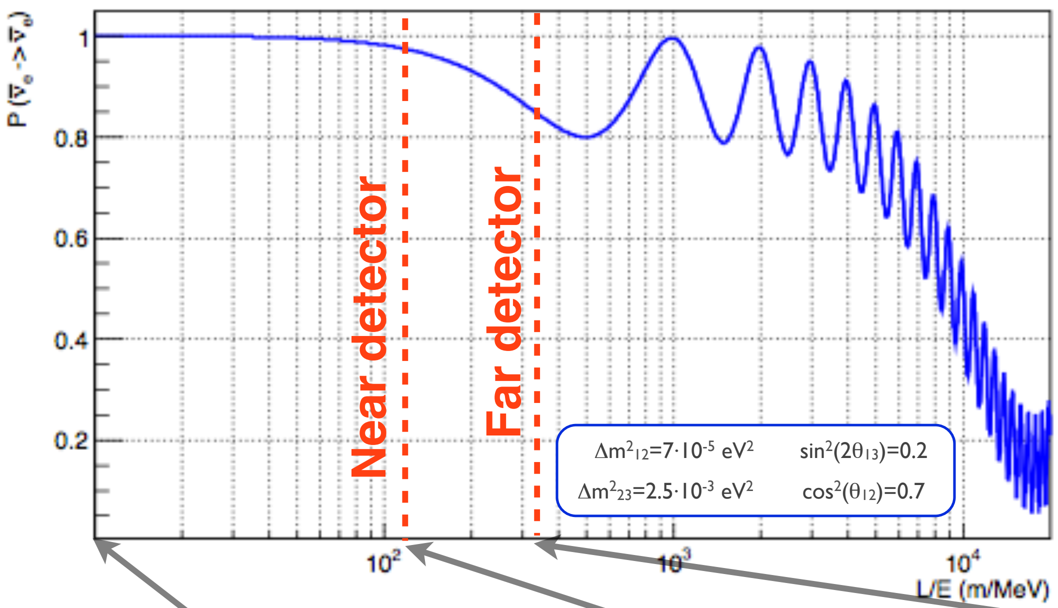
Survival probability



Double Chooz reactor-neutrino experiment aims to measure the unknown θ_{13}

Experimental concept

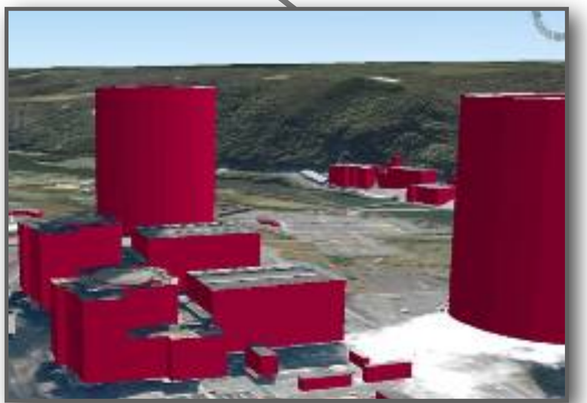
Survival probability of anti-electron neutrinos



$$P\left[\overline{\nu_e} \to \overline{\nu_e}\right] \cong 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) + O(10^{-3})$$

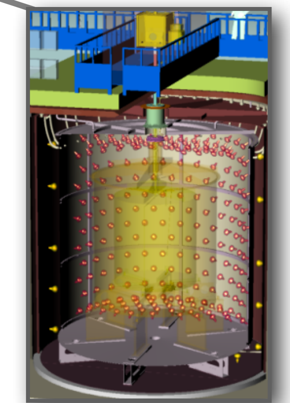
Systematics uncertainty on
- Neutrino flux
- Interaction cross-section
- Number of target proton
- Detection efficiency

are canceled by two detectors.



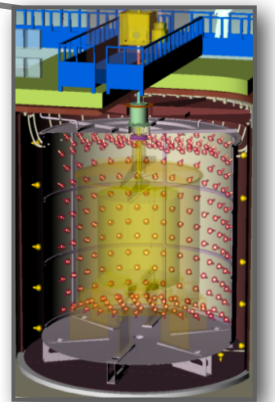
Chooz-reactor power plant

Total flux →



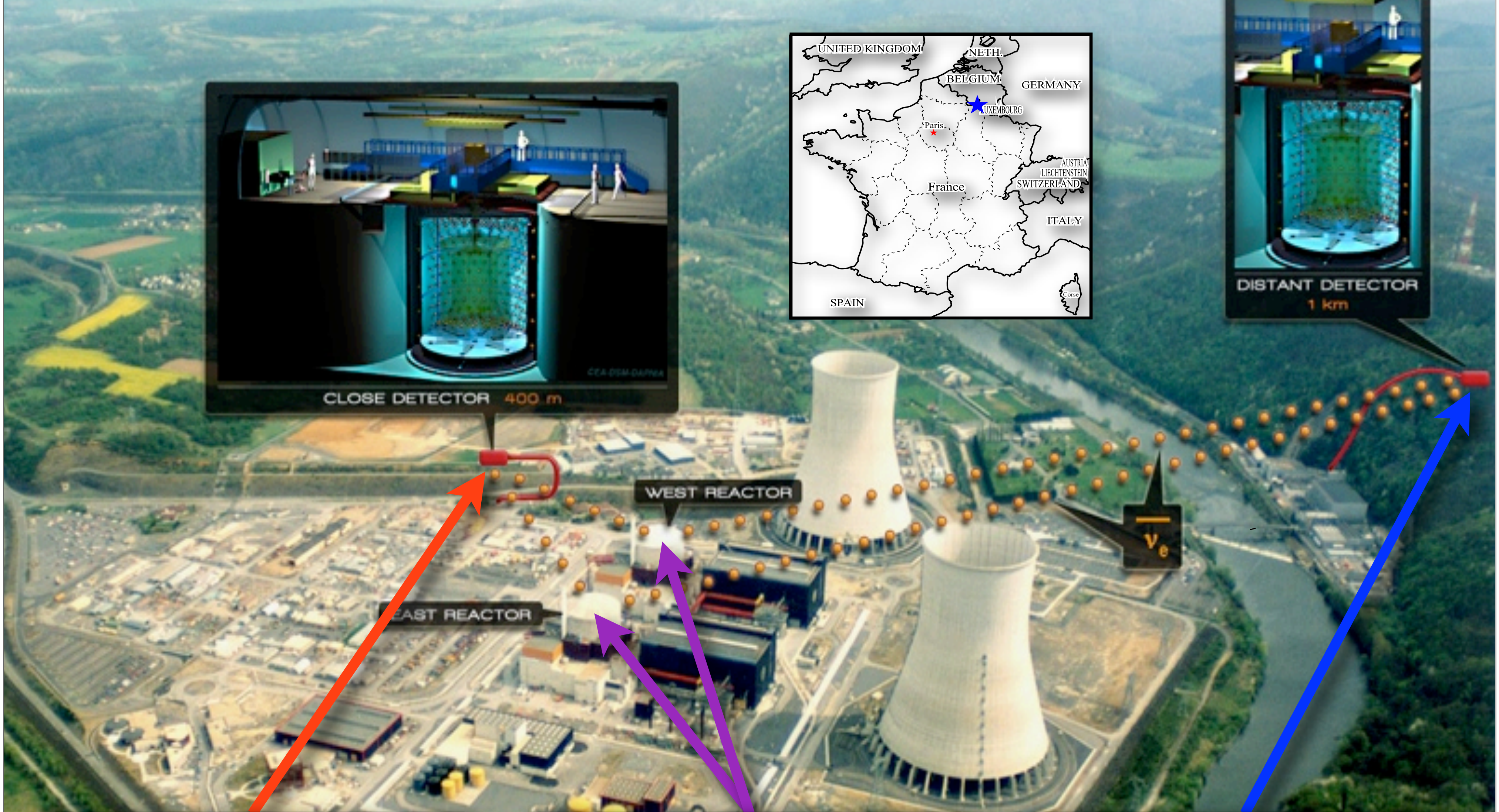
Near detector (400 m)

Oscillated flux →



Far detector (1050 m)

Experimental site



Near detector
Distance: ~ 400 m
Overburden: ~120 m.w.e.

Reactor
Two reactor cores
4.27 GWth for each core

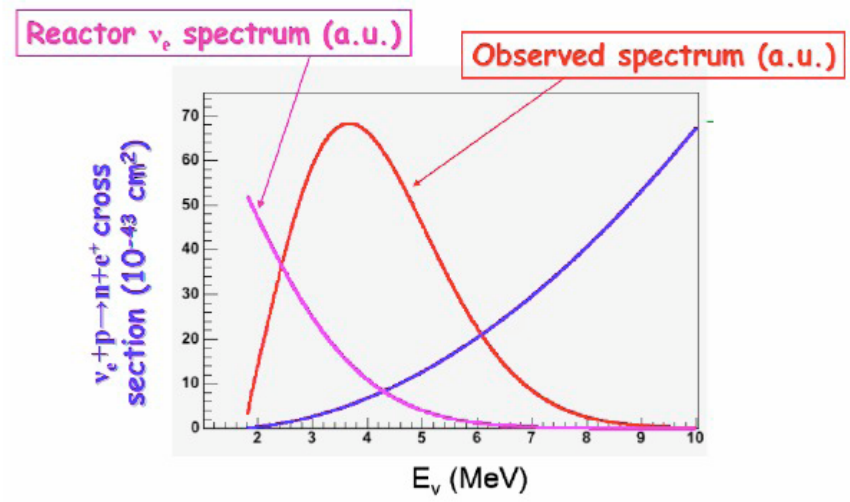
Far detector
Distance: ~ 1050 m
Overburden: ~300 m.w.e.

Neutrino detection principle

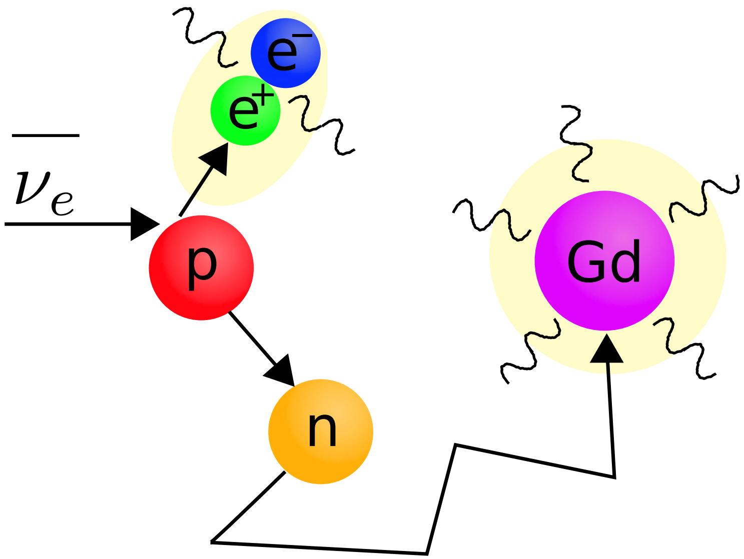
Inverse beta decay (IBD) reaction :

$$\overline{\nu_e} + p \rightarrow e^+ + n$$

$$\left(E_{\bar{\nu}_e}^{Threshold} = \frac{m_{e^+}^2 + m_n^2 - m_p^2}{2m_p} \simeq 1.806\,\mathrm{MeV.}\right)$$



Neutrino-signal signature is given by :



(1) Prompt signal from e^+ ionization and annihilation (1~8 MeV).

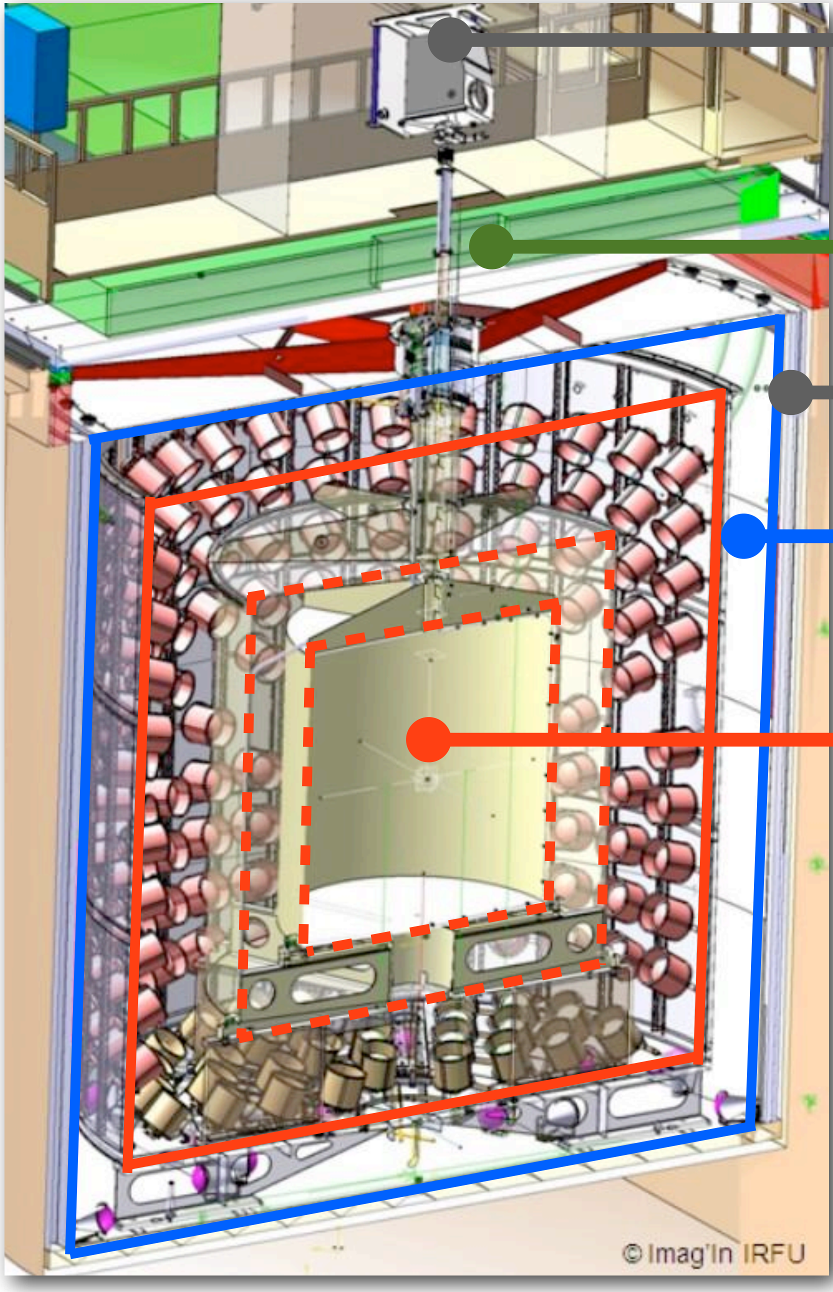
(2) Delayed signal from neutron capture on Gadolinium (~8 MeV).

(3) Coincidence (τ ~ 30 μsec).

In this IBD process, prompt energy is expected with neutrino energy:

$$E_{vis} = E(kin)_{e^+} + 2m_e \simeq E_{\bar{\nu}_e} - (M_n - M_p) + m_e \simeq E_{\bar{\nu}_e} - 0.782\,\mathrm{MeV}$$

The Double Chooz detector



Glove box

- Source deployment with GC-guide tube, Z-axis system and Articulated arm (in future).

Outer Veto

- Plastic scintillator strip + WLS fiber + MAPMT.

Shielding

- ~250 tons of steel shielding (150 mm).

Inner Veto

- 90 m^3 liquid scintillator in a steel vessel (10 mm) equipped with 78 PMTs (8 inch).

Inner Detector (three layers)

ν-target region

- 10.3 m^3 liquid scintillator doped with 1 g/l of Gd composed in acrylic vessel (8 mm).

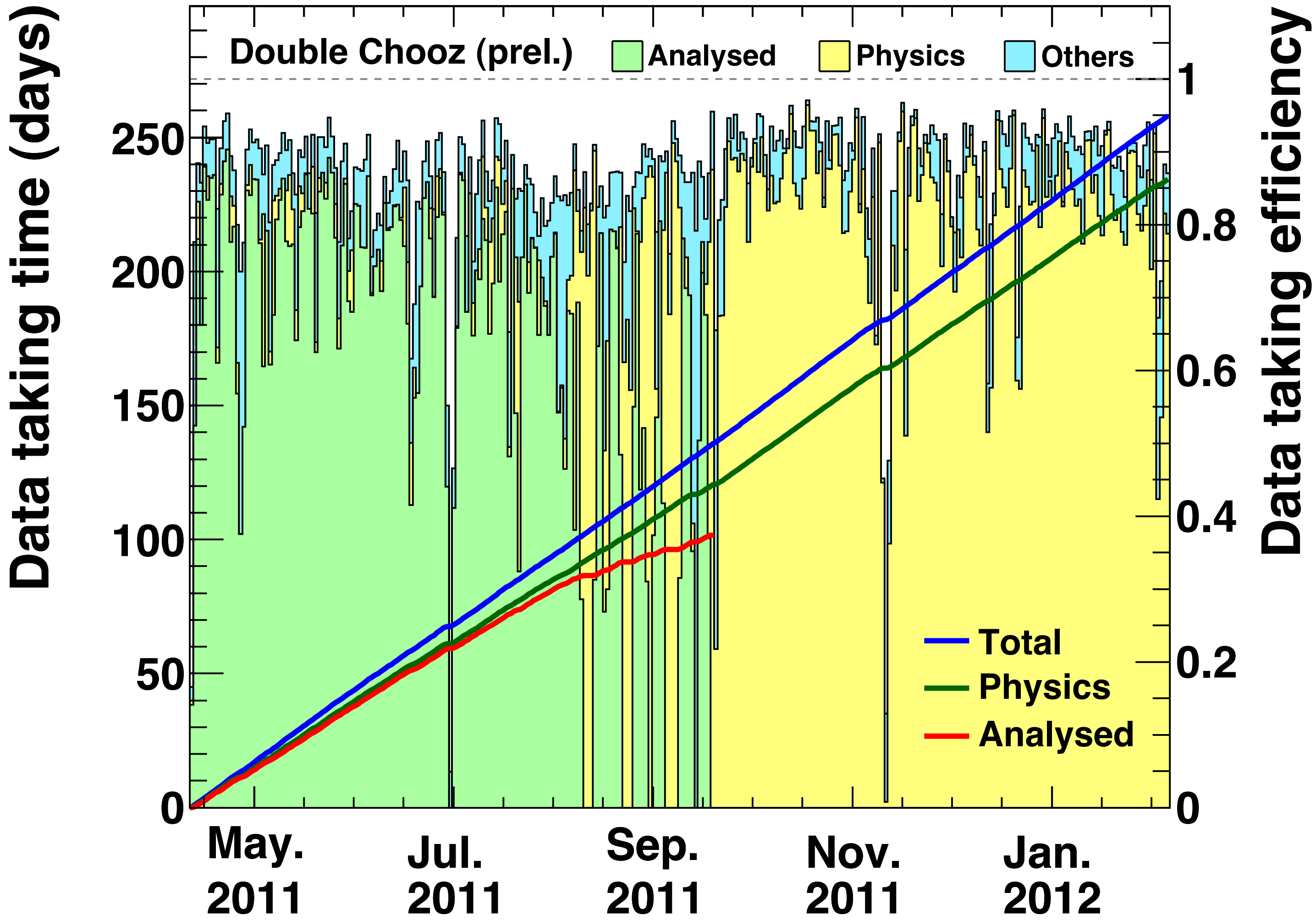
γ-catcher region

- 22.3 m^3 liquid scintillator in acrylic vessel (12 mm).

Buffer region

- 110 m^3 mineral oil in a stainless steel vessel (3 mm) viewed by 390 low-BG PMTs (10 inch).

Data taking



Integrated data taking time for physics : 234.4 days

Analyzed run time : 101.5 days

Analyzed live time : 96.8 days (due to 1 ms muon veto)

- Double Chooz experiment to measure θ_{13}

- **Neutrino prediction**

- Neutrino selection and backgrounds

- Oscillation analysis and conclusion

Reactor neutrino flux

Expected number of neutrinos

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

N_p ... Number of protons in the detector

$P_{th}(t)$ ... Thermal power of reactor

$\langle E_f \rangle$ ... Mean energy per fission

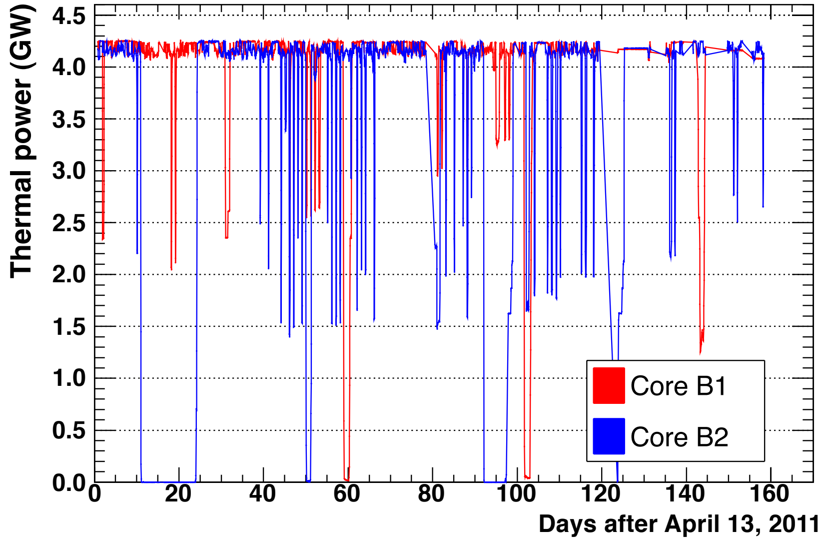
$\langle \sigma_f \rangle$ ... Mean cross section per fission

Neutrino prediction

Expected number of neutrinos

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

Thermal power

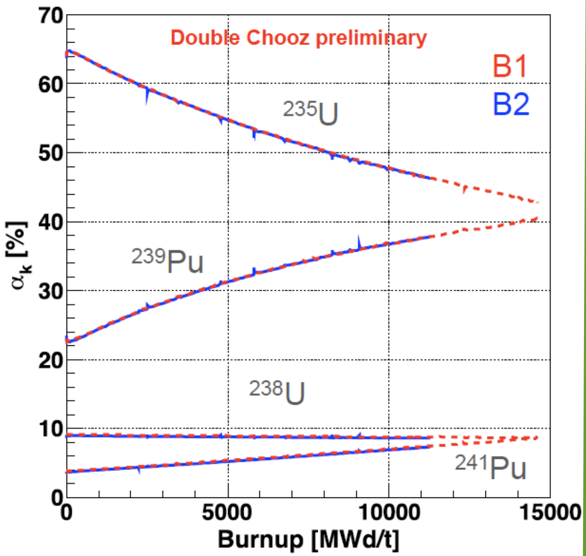


Mean energy per fission

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

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

Fuel evolution in reactor core



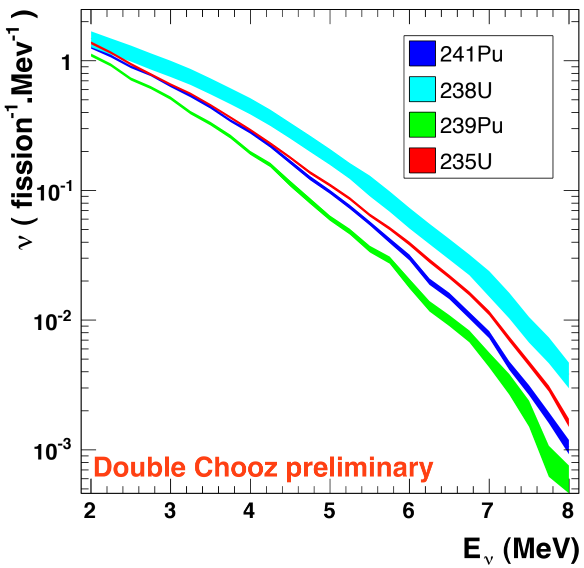
Mean cross-section per fission

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

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

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

Reference spectra



- Th. A. Mueller et al, Phys.Rev.C83(2011)054615 | |
- P. Huber, Phys.Rev.C84(2011)024617

Systematic uncertainty on flux prediction

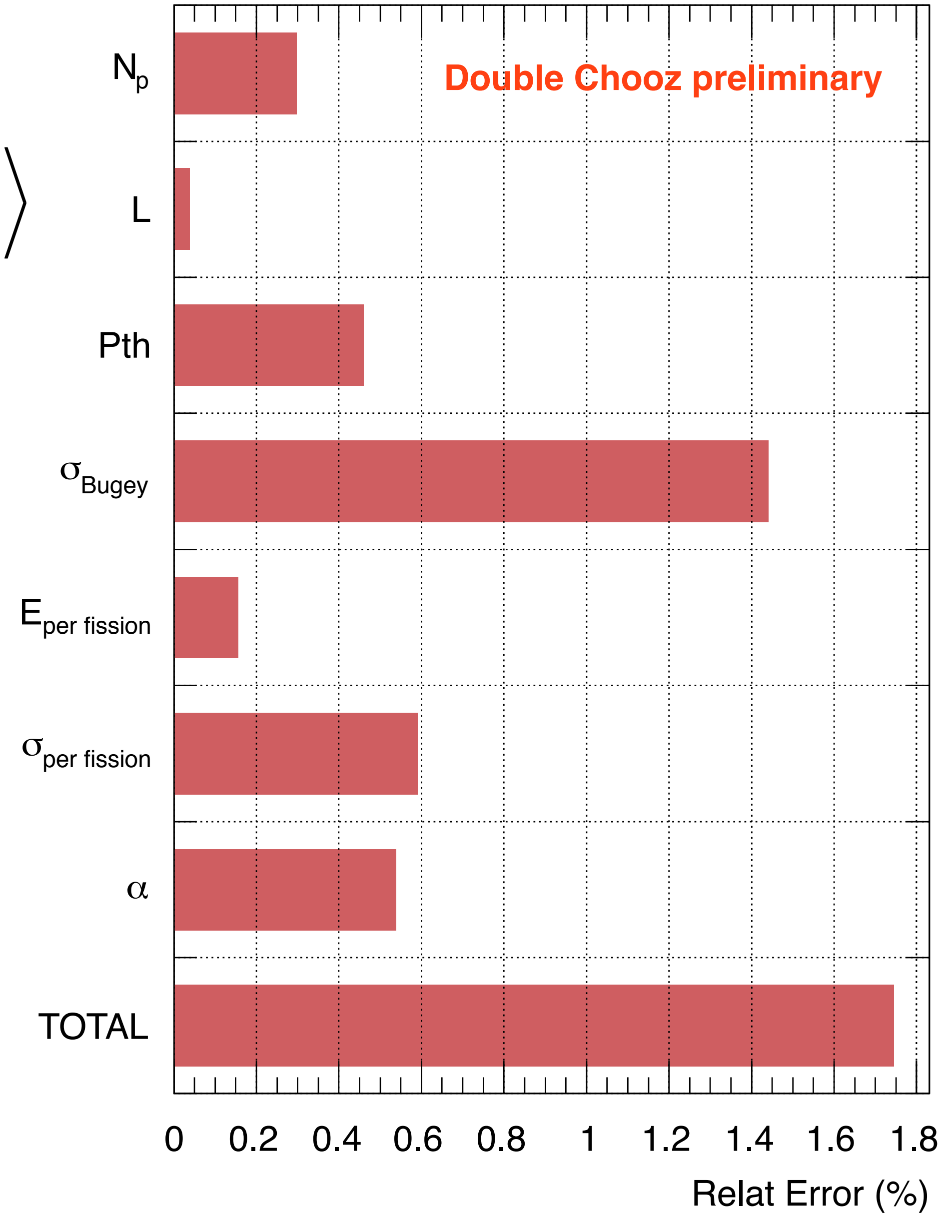
Expected number of neutrinos

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

Neutrino prediction is based on Bugey4 measurement with correction to Chooz reactor.

(fission rates for each isotope etc.)

Total systematic uncert. : 1.7 %



- Double Chooz experiment to measure θ_{13}

- Neutrino prediction

- Neutrino selection and backgrounds

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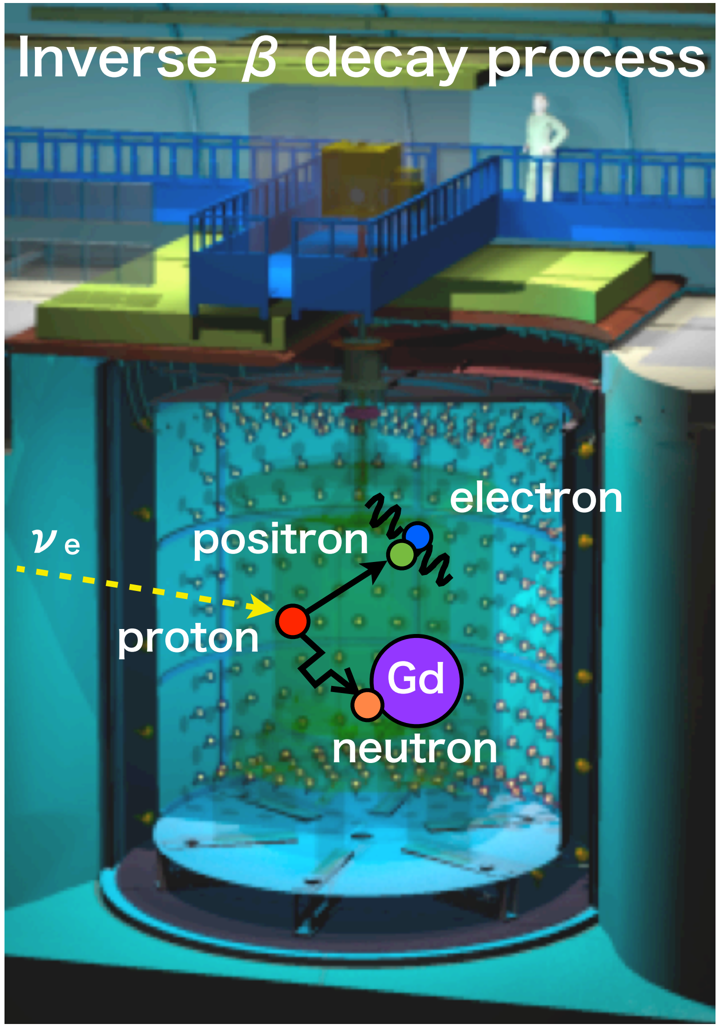
Neutrino selection



Muon veto :

- $\Delta T_\mu > 1$ ms

Prompt event :

- No energy deposition in Inner veto
- Qmax/Qtotal < 0.09 & RMS_{Tstart} < 40 ns
- 0.7 < E < 12 MeV

Delayed event :

- No energy deposition in Inner veto
- Q_{max}/Q_{total} < 0.06 & RMS_{Tstart} < 40 ns
- 6 < E < 12 MeV

Coincidence :

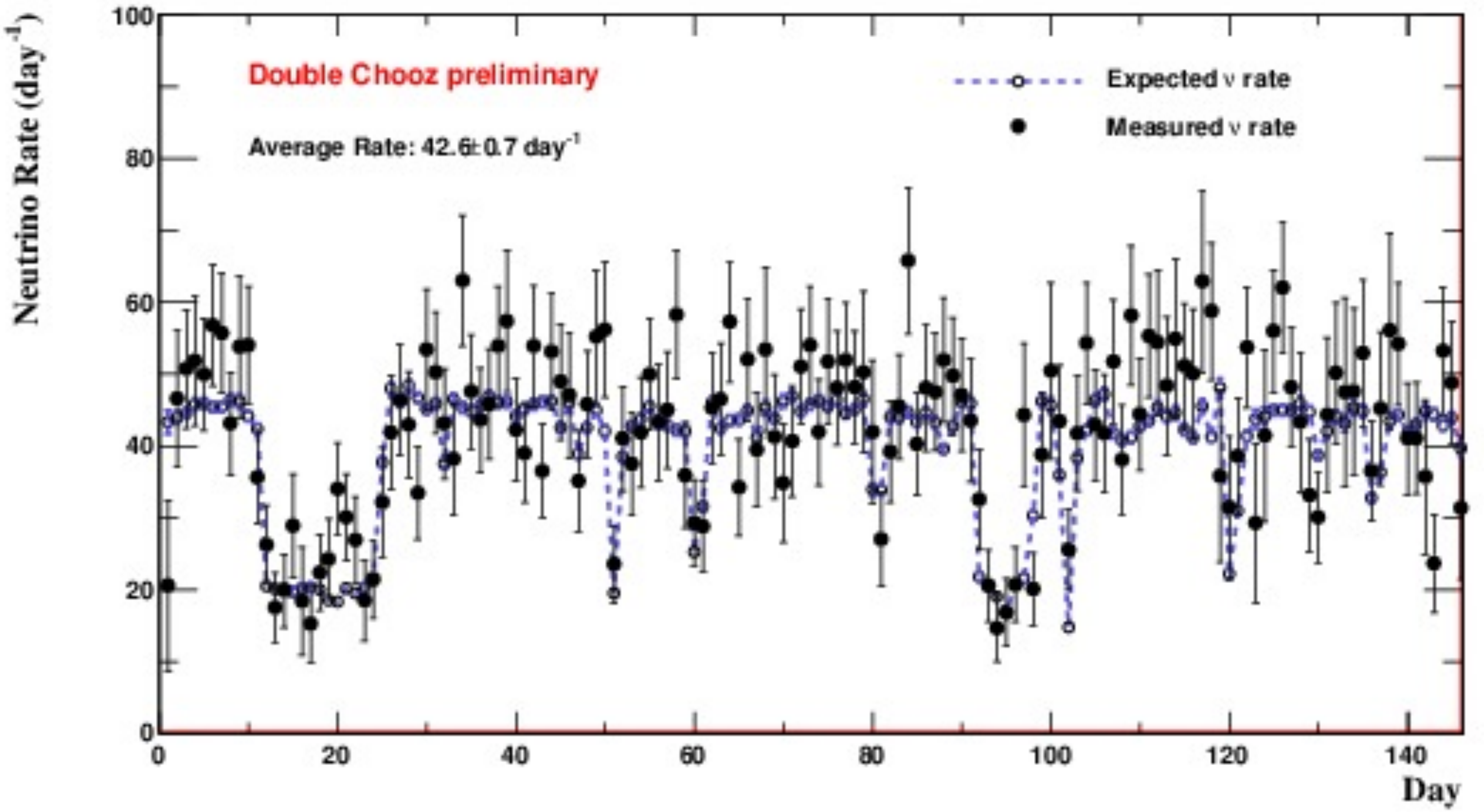
- 2 < ΔT < 100 μs

Multiplicity :

- No trigger (> 500 keV) within 100 μs before prompt.
- Only one trigger (> 500 keV) within 400 μs after prompt.

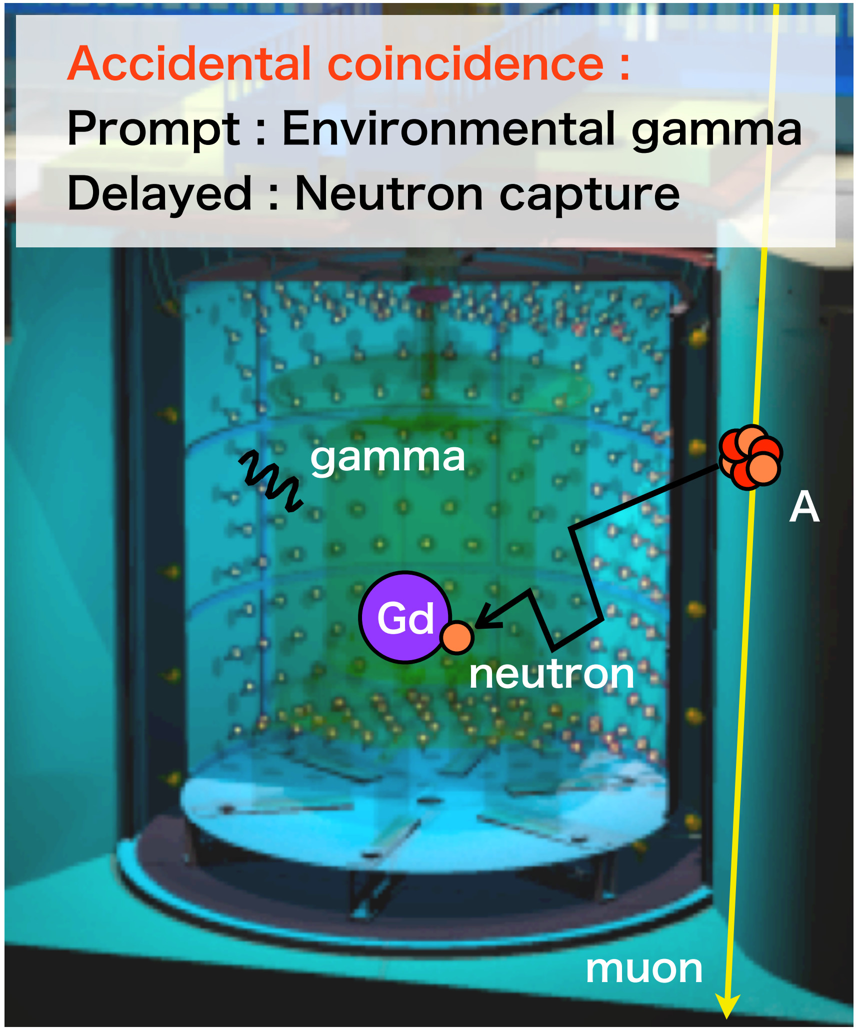
Neutrino candidates

Neutrino candidates rate (background not subtracted)



Total 4121 (42.6 /day) neutrino candidates.

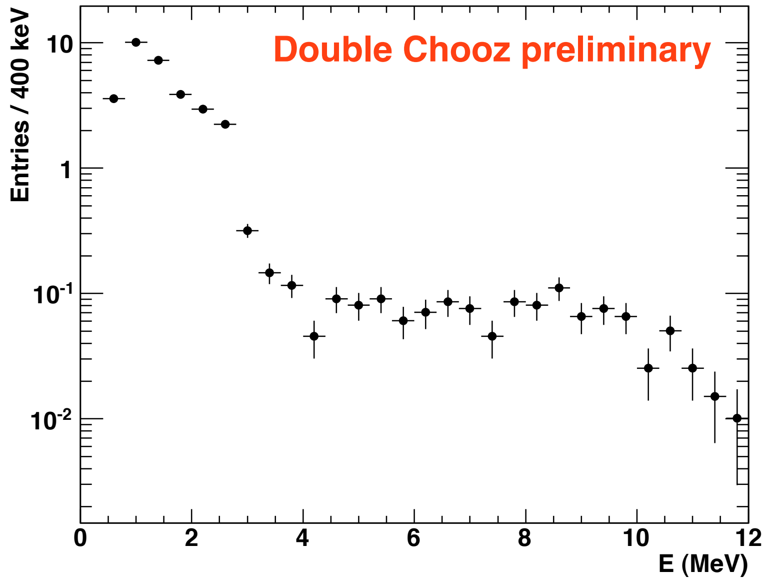
Accidental background



Estimation method

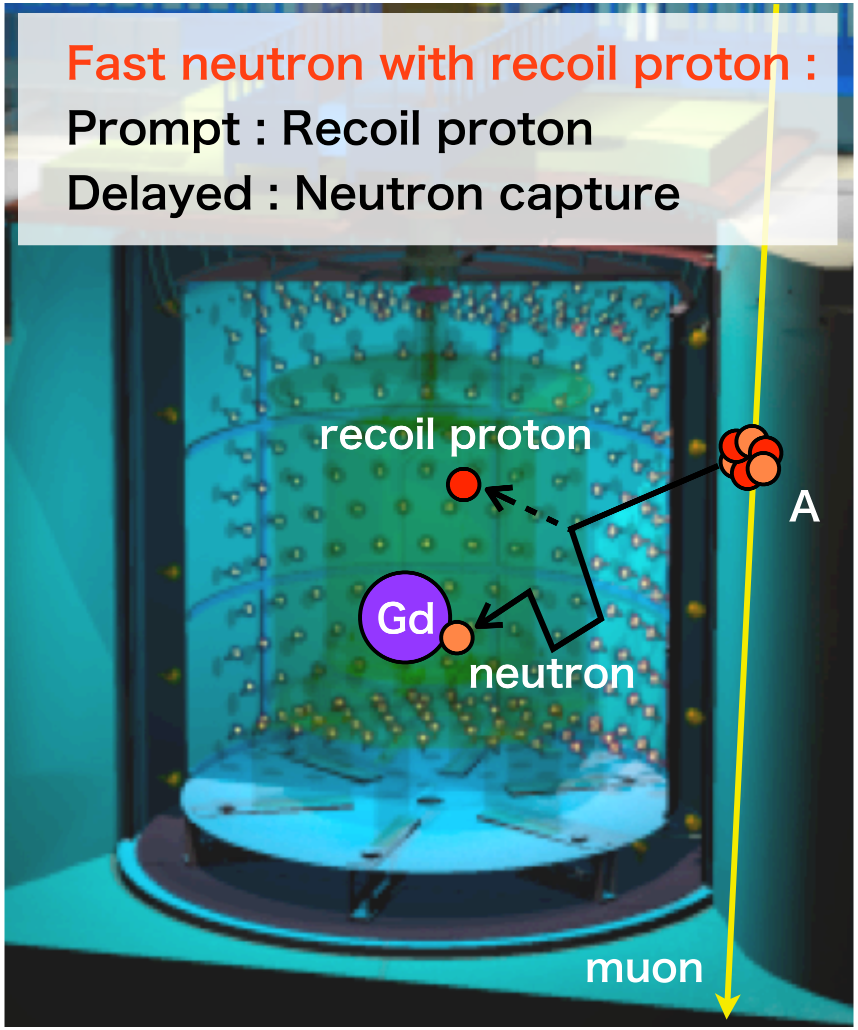
Off-time window from [1,100] msec is used including multiplicity condition. (On-time window is [2, 100] μsec)

Energy spectrum of accidental BG



Accidental BG rate = 0.332 ± 0.03 events/day.

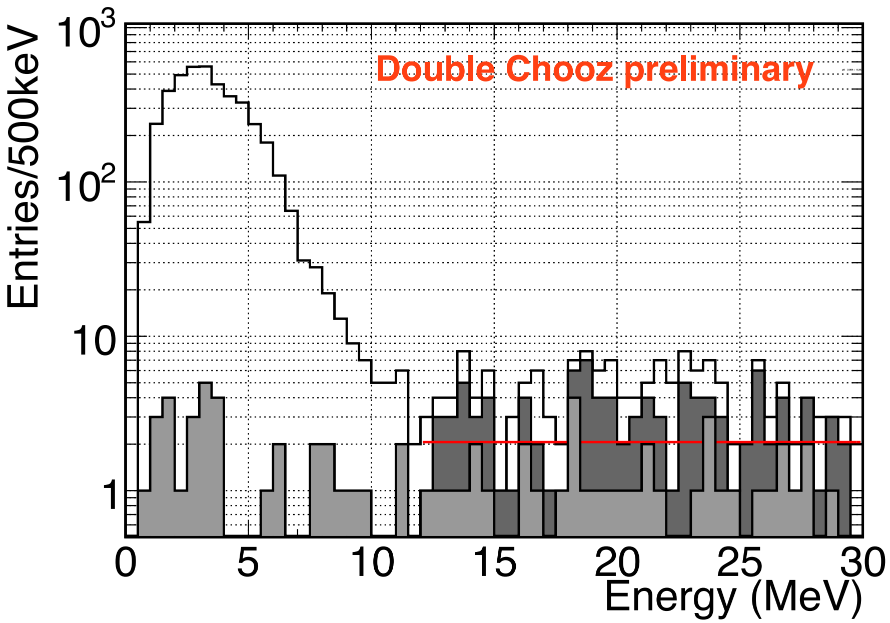
Fast neutron background



Estimation method

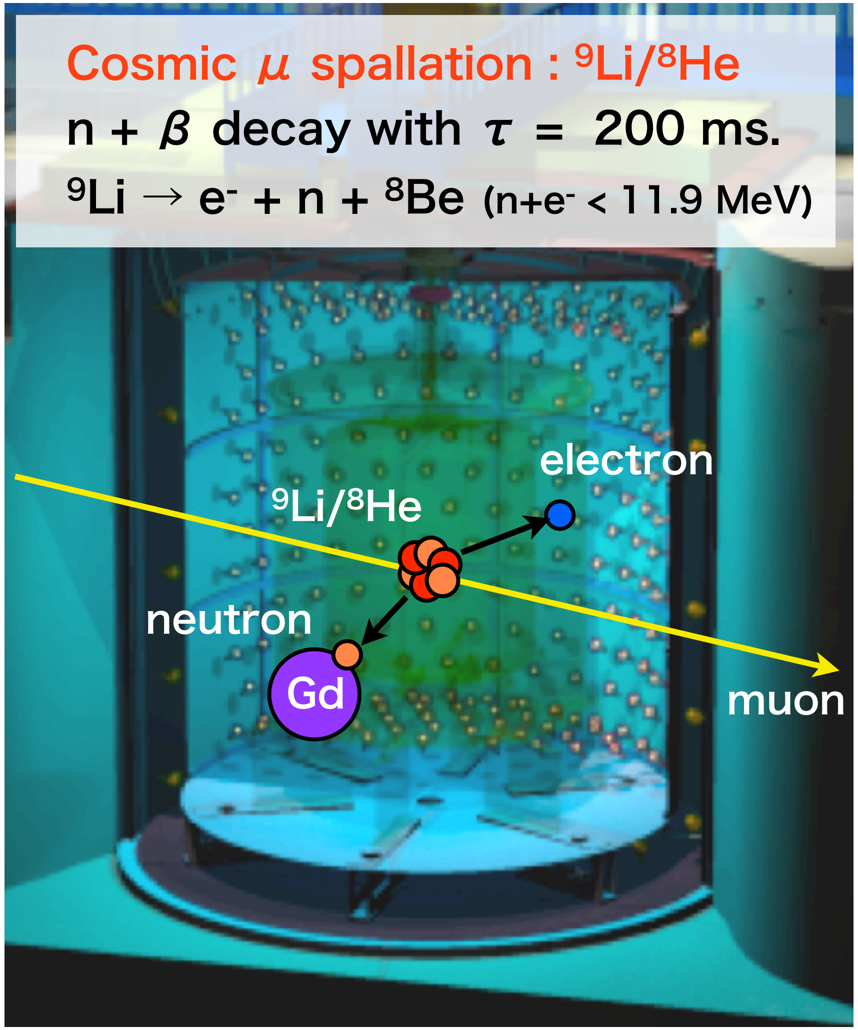
Number of BG events estimated from the spectrum at high energy.

Energy spectrum at high energy



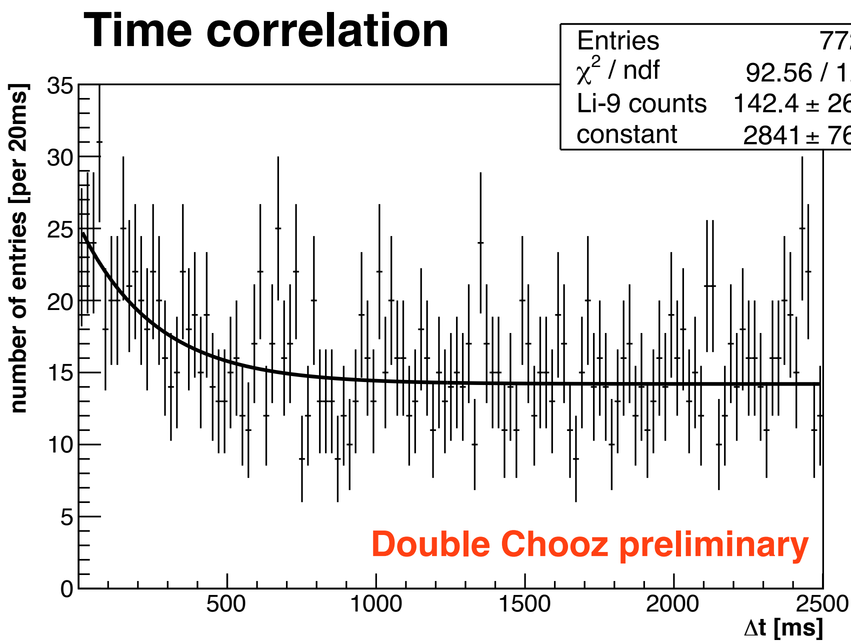
Fast neutron BG rate = 0.8 ± 0.4 events/day.

Cosmogenic background



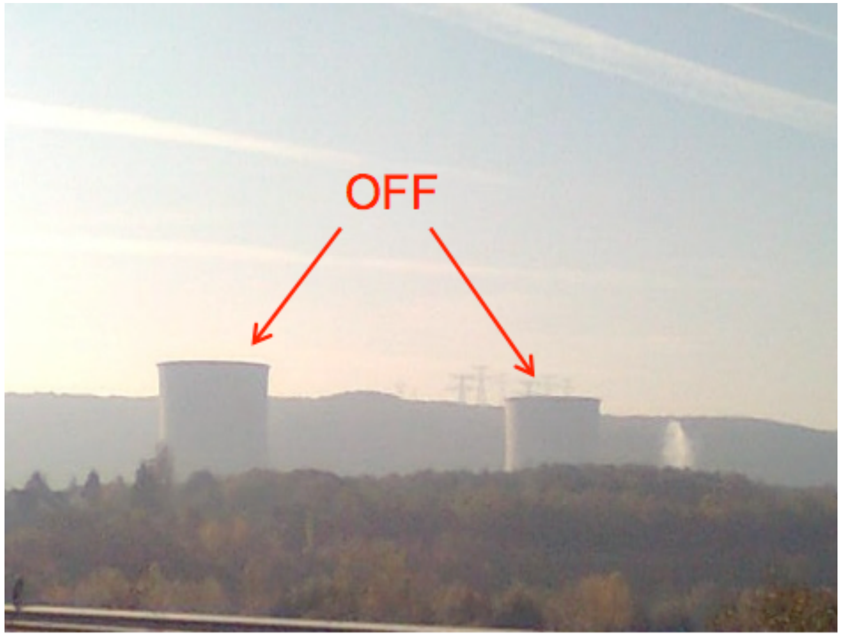
Estimation method

Time correlation with showering muon from the selected neutrino candidates.
Consistent with reactor-off measurement.



Cosmogenic BG rate = 2.3 ± 1.2 events/day.

Reactor-off data



Both reactor off for ~24 hours;
Unique opportunity to validate our background estimation.

Two candidates in neutrino energy window following high energy muon → Candidates of ^{9}Li background.

Consistent with the estimated number of BG events (3.46 ± 1.26 events/day).

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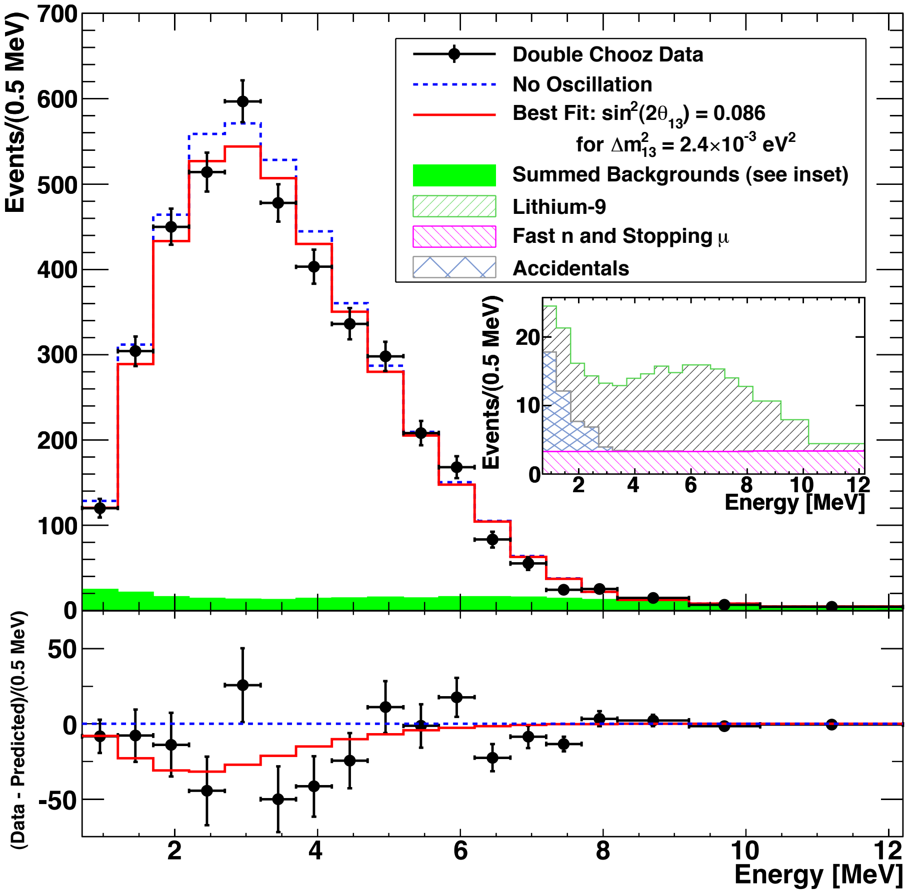
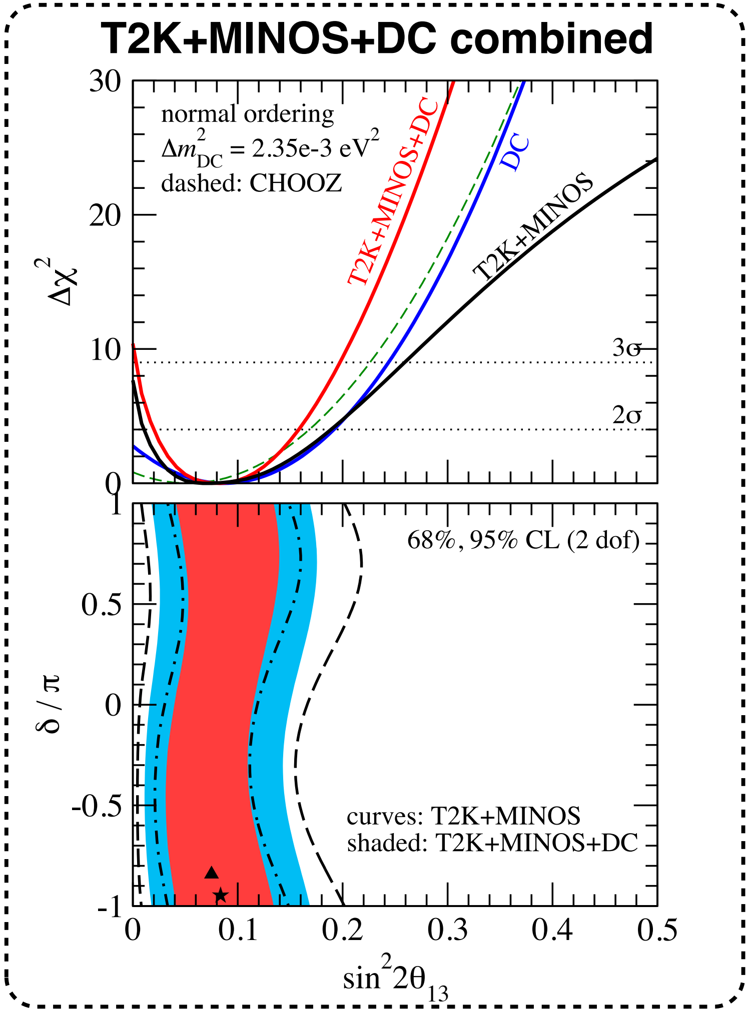
Summary of uncertainties

Source		Uncertainty w.r.t signal	
Statistics		1.6%	
Reactor	Bugey4 measurement	1.4%	1.8%
	Fuel composition	0.9%	
	Thermal power	0.5%	
	Reference spectra	0.5%	
	Energy per fission	0.2%	
	IBD cross section	0.2%	
	Baseline	0.2%	
Detector	Energy response	1.7%	2.1%
	E_{delay} containment	0.6%	
	Gd fraction	0.6%	
	Δt_{e+n}	0.5%	
	Spill in/out	0.4%	
	Trigger efficiency	0.4%	
	Target H	0.3%	
Background	Accidental	< 0.1%	3.0%
	Fast neutron	0.9%	
	^{9}Li	2.8%	

Fit results

(hep-ex) arXiv:1112.6353 / Submitted to PRL



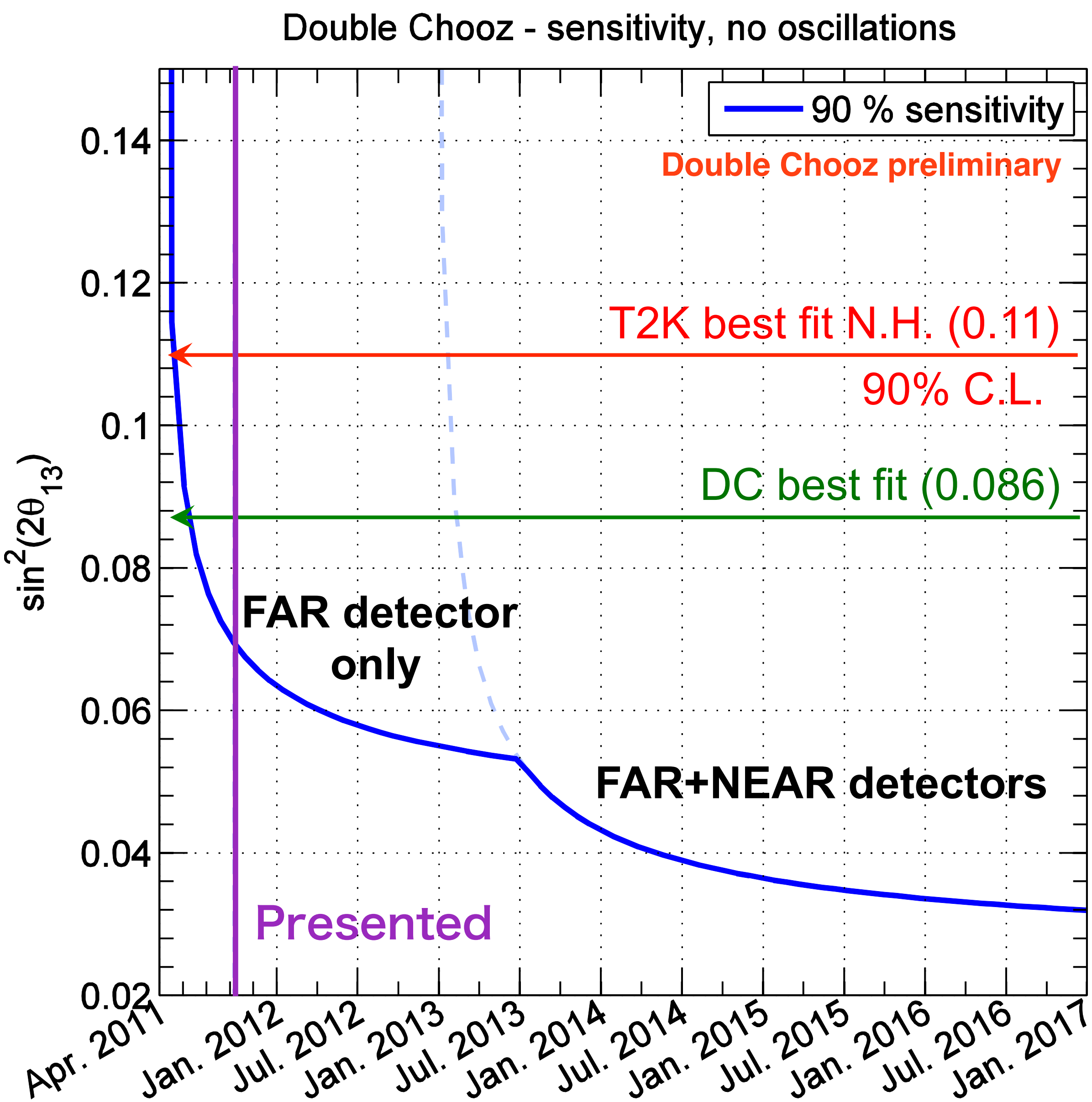


Rate-only fit : $\sin^2 2\theta_{13}$ = 0.104 ± 0.030(stat.) ± 0.076(syst.)

Rate+shape fit : $\sin^2 2\theta_{13}$ = 0.086 ± 0.041(stat.) ± 0.030(syst.)

→ No oscillation excluded by 94.6% C.L.

Sensitivity prospects



(*) Data taking efficiency is considered.

Conclusion

Double Chooz started physics data taking since April 2011.

First neutrino oscillation analysis result are presented.

Rate+shape analysis:

$\sin^2 2\theta_{13} = 0.086 \pm 0.041(\text{stat.}) \pm 0.030(\text{syst.})$

Rate only analysis:

$\sin^2 2\theta_{13} = 0.104 \pm 0.030(\text{stat.}) \pm 0.076(\text{syst.})$

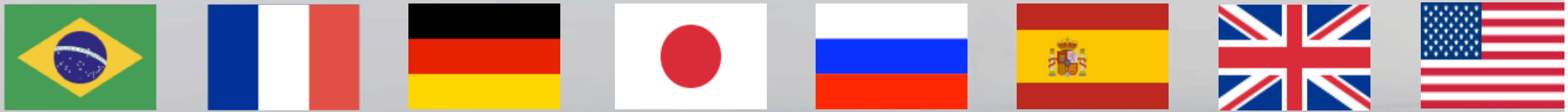
→ No oscillation excluded by 94.6% C.L.

Near detector will be operated by 2013.

→ Precise measurement of θ_{13}.

Backup slides

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
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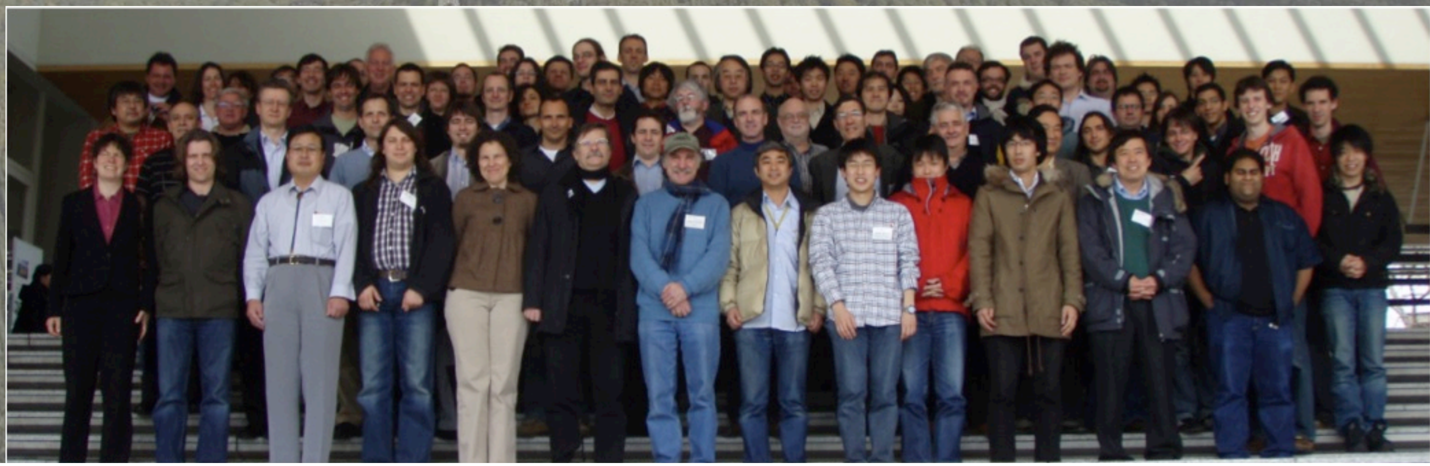
Spain
- CIEMAT-Madrid

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/



Current understandings

Mass difference scales :

$|\Delta m_{12}|^2 \sim 8 \times 10^{-5}\ eV^2$

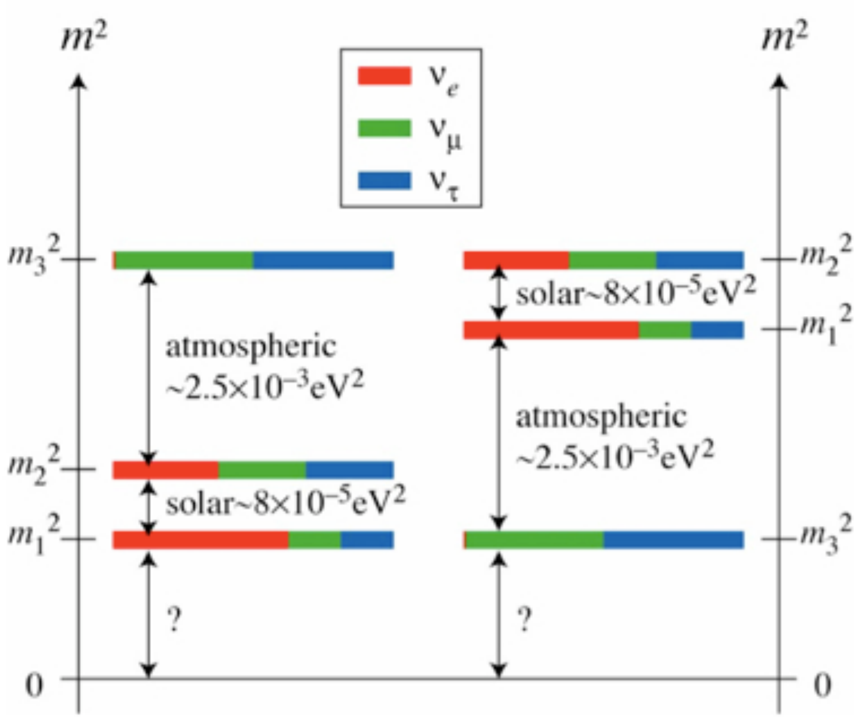
$|\Delta m_{23}|^2 \sim |\Delta m_{13}|^2 \sim 2.4 \times 10^{-3}\ eV^2$

Mixing angles :

$\theta_{12} \sim 34°$

$\theta_{23} \sim 45°$

$\theta_{13} < 12°$ ($\sin^2 2\theta_{13} < 0.15$)



δ → Unknown

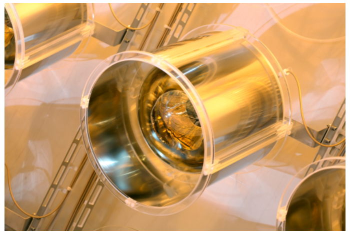
Mass hierarchy → Unknown

} Measurement of θ_{13} is essential.

Absolute mass scale → Unknown

Electronics and Flash-ADC signal

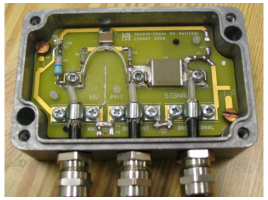
Photo-multiplier tubes
ID : 390 PMTs (R7081MOD)
IV : 78 PMTs (R1408)



HV

Signal

HV/sig. splitter
Custom (by CIEMAT)

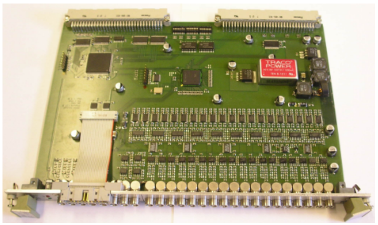


HV

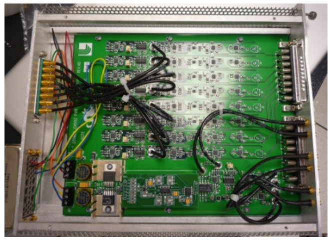
HV supply
SY1527LC & A1535P (CAEN)

Signal

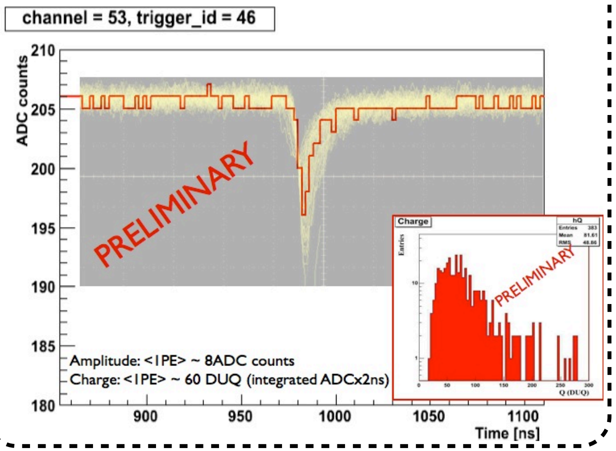
Trigger & clock
Custom (by RWTH-Aachen)



Front-end electronics
Custom (by Drexel Univ. & LLNL)



Flash-ADC signal example



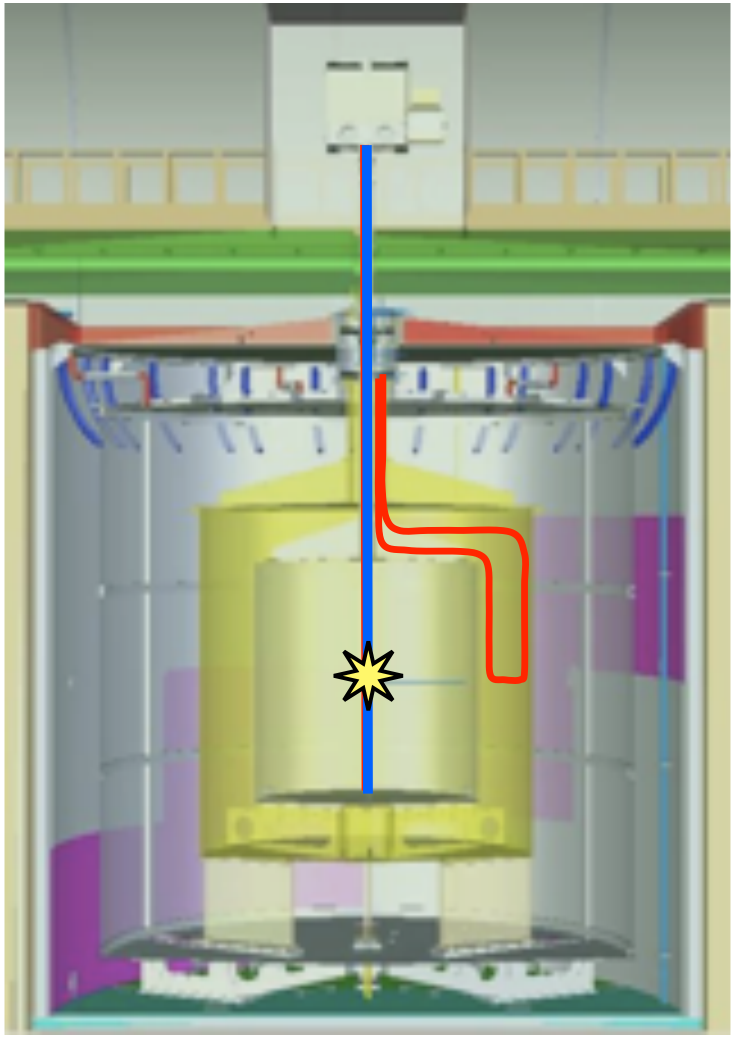
Trigger pattern
& clock (T=16 ns)

ν-FADC VX1721 (by CAEN & APC)
μ-FADC Custom (by CBPF)

ν-DUQ
MVME3100 (by Emerson)
implemented in Ada

Source deployment system - 1

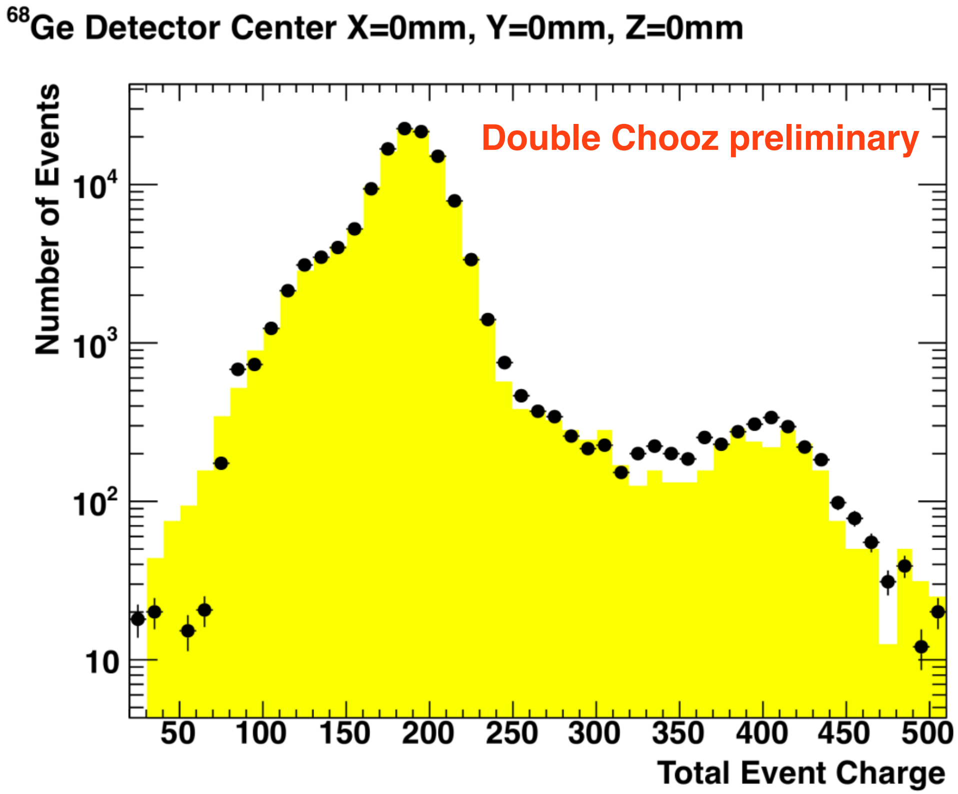
Radioactive source is deployed by Z-axis system.



e.g.) ^{68}Ge positron source in target volume.

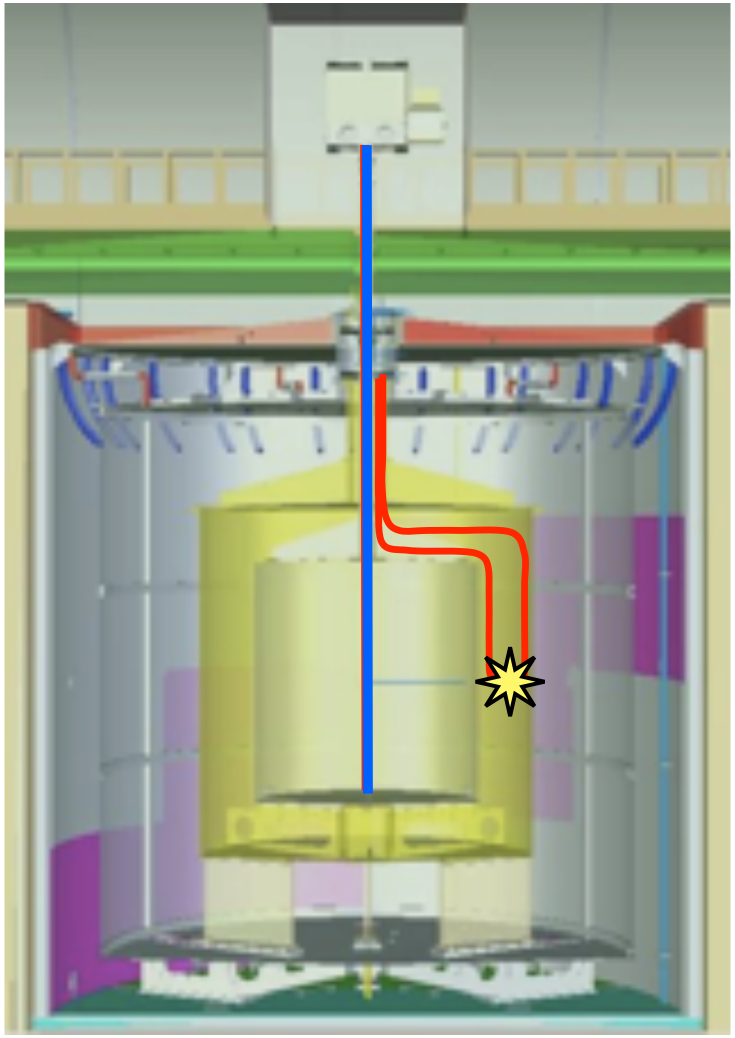
Total 1.02 MeV γ's from annihilation.

(corresponds to the minimum energy from inverse β-decay reaction)



Source deployment system - 2

Radioactive source is deployed by GC-guide tube system.



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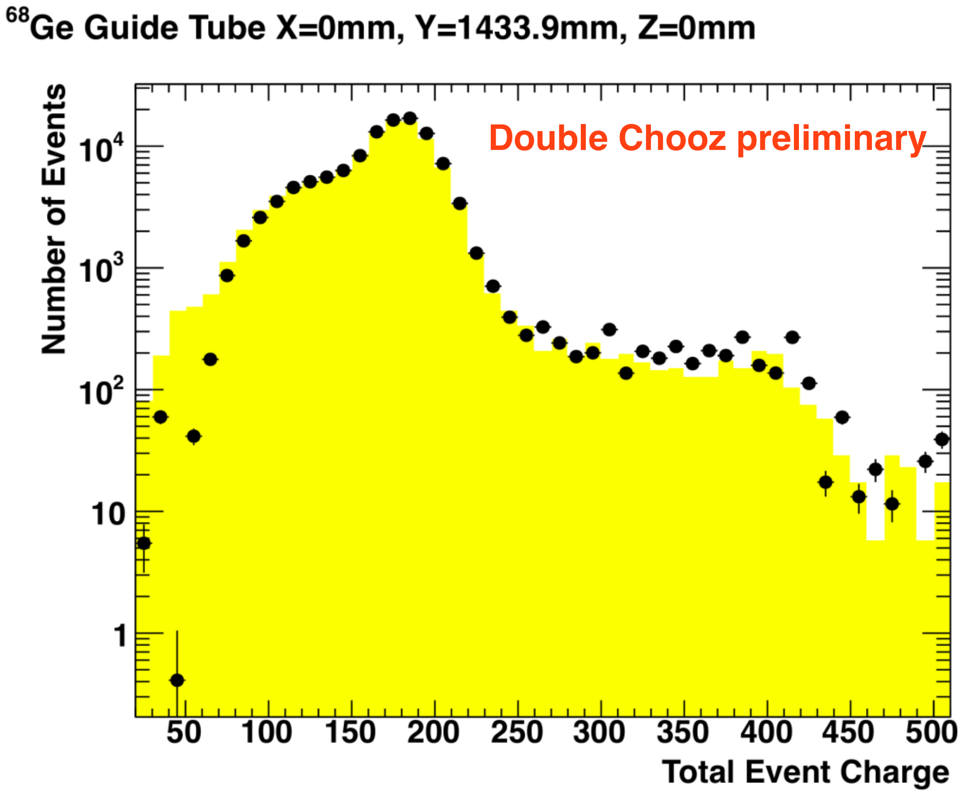
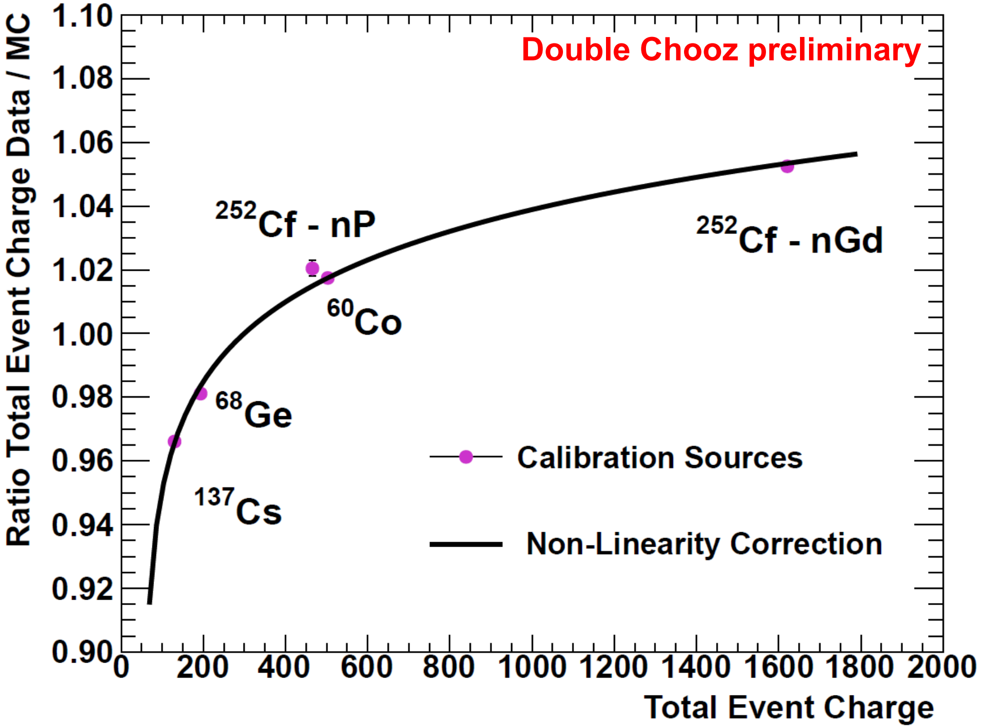
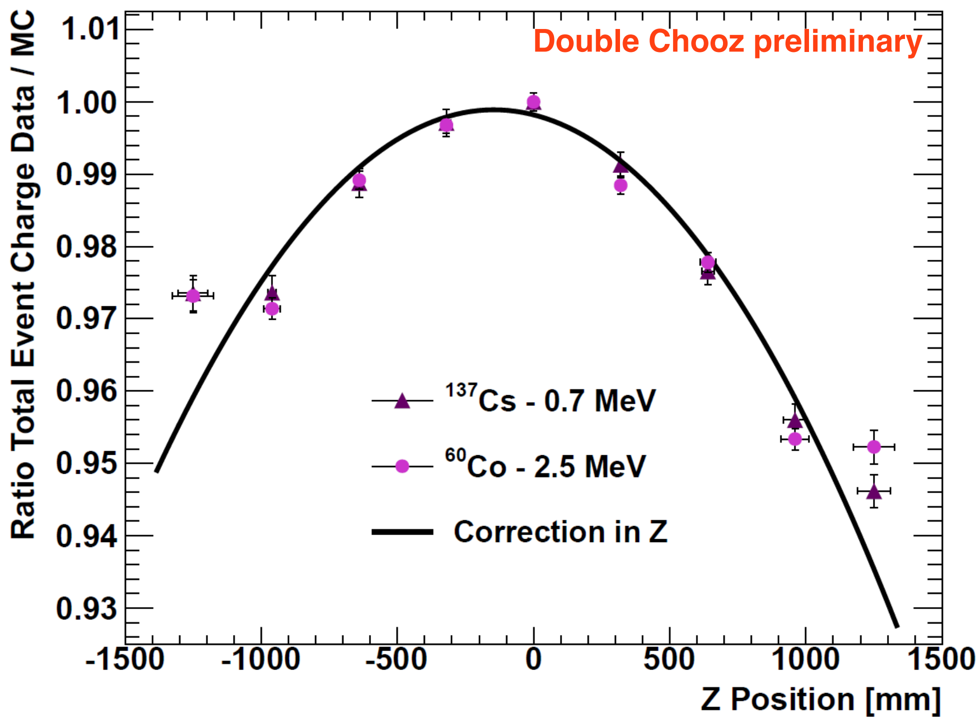


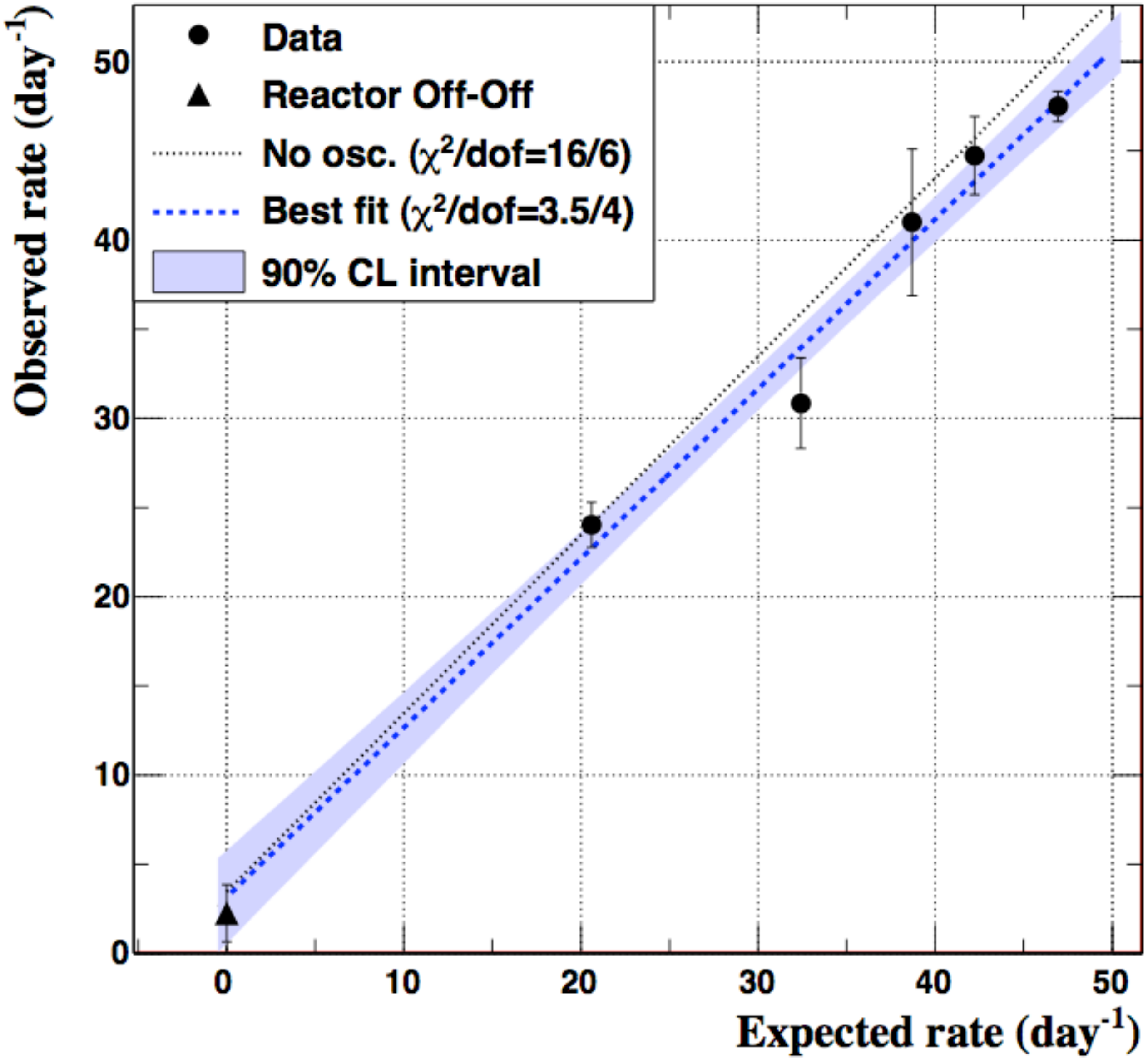
Energy scale uncertainties

Corrected DATA/MC disagreement of energy scale based on source calibration. Energy scale uncertainty was also estimated and applied in the oscillation analysis.



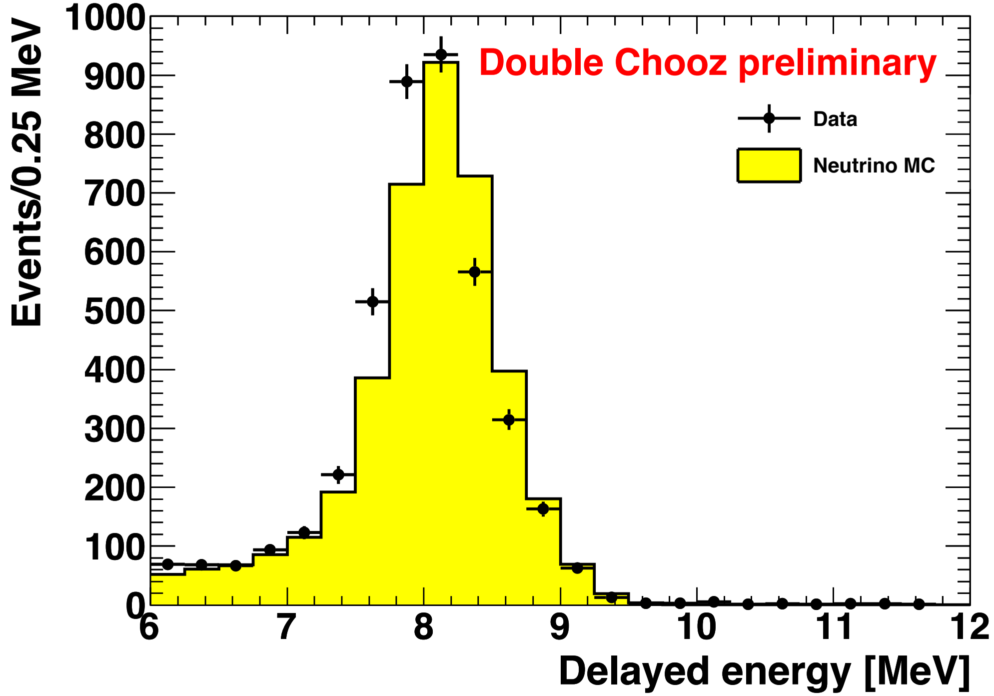


Observed vs expected neutrino rate

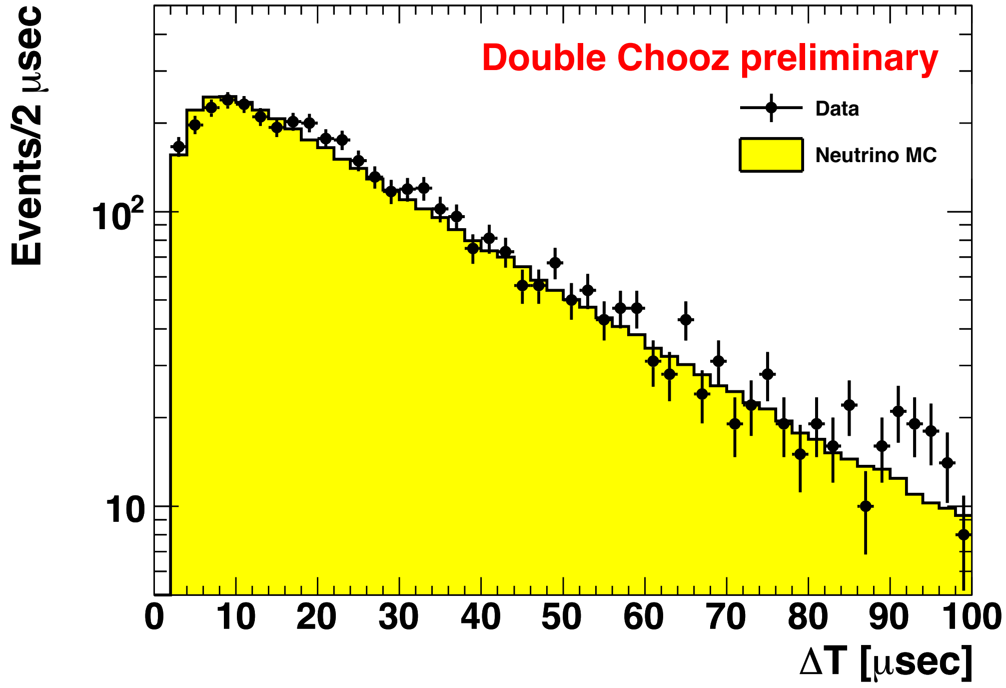


Delayed energy and ΔT distributions

Delayed energy distribution



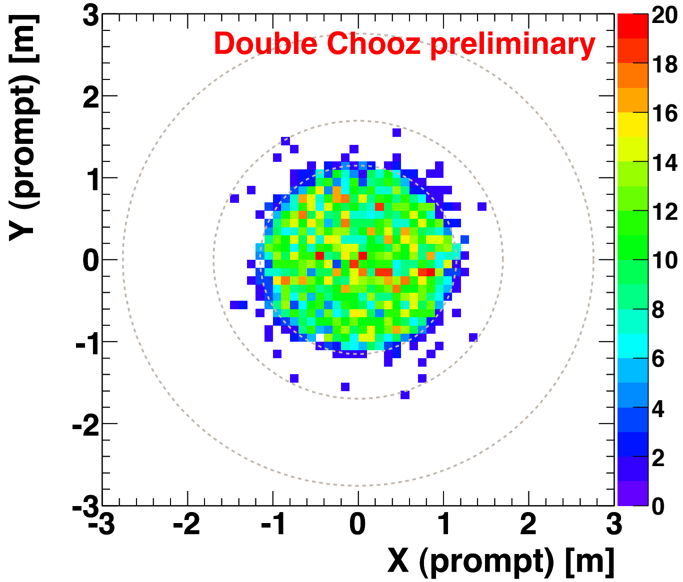
ΔT distribution



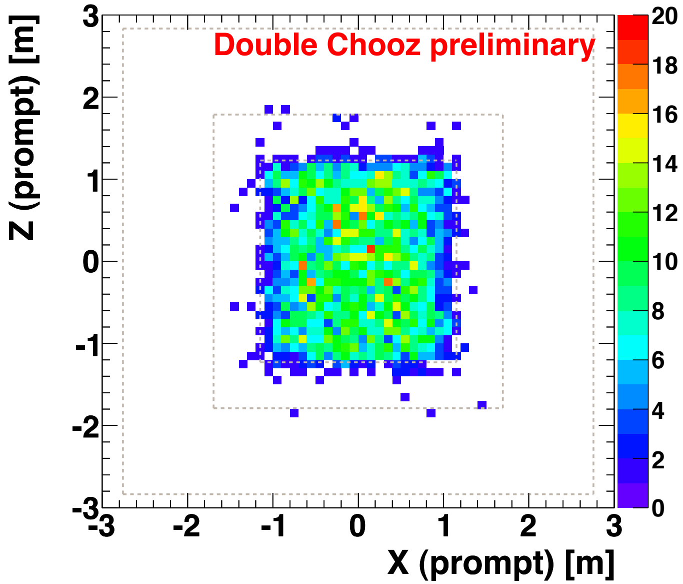
- Reasonable agreements with MC prediction.
- Delayed energy cut efficiency : 86.0 ± 0.6 %.
- Time coincidence efficiency : 96.5 ± 0.5 %

Validation : Vertex distribution

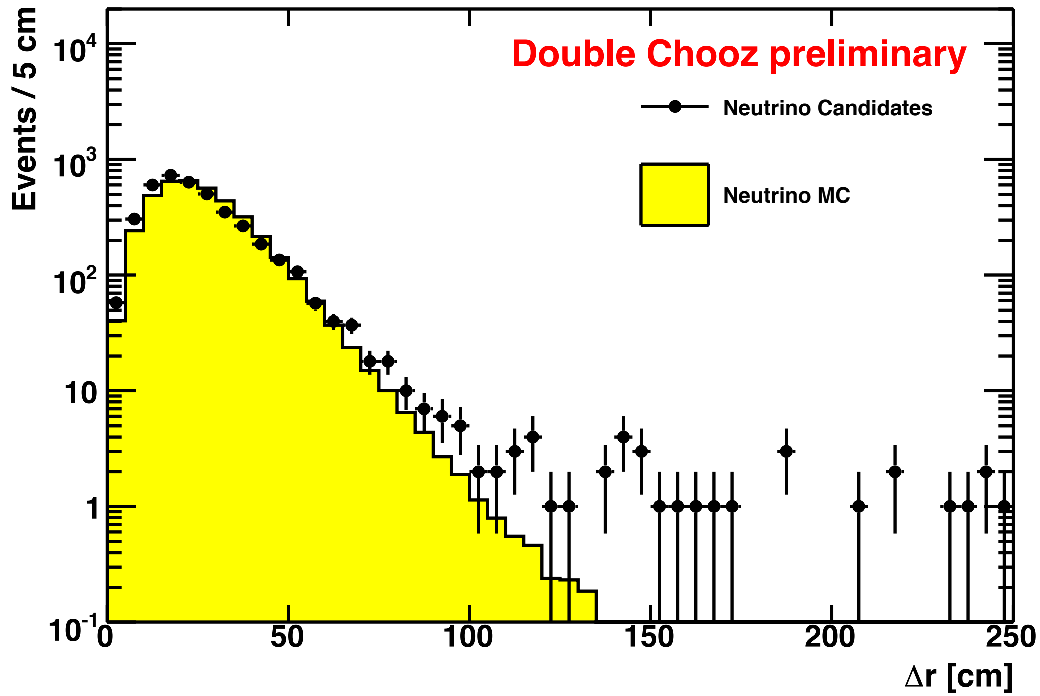
Vertex position in X-Y plane



Vertex position in X-Z plane



Prompt - Delayed Reconstructed Distance



- Not used for analysis cut.
- Almost all neutrino candidates are in target volumes.
- Vertex distance between prompt and delayed signals are in good agreement with MC prediction.

Reactor-off data

- One day data was taken with both reactor OFF.

- 3 events pass neutrino selection with E_{prompt} < 30 MeV.

1. E_{prompt} = 9.8 MeV, ΔT = 201 msec from showing muon (> 600 MeV), Vertex close to muon track (15 cm).
2. E_{prompt} = 4.8 MeV, ΔT = 241 msec from showing muon, Vertex close to muon track (28 cm).
3. E_{prompt} = 26.5 MeV, no showing muon within 5 sec.

- Number of events observed under reactor OFF condition was consistent with the estimated number of BG event.

Oscillation analysis method

Definition of χ^2 test with covariance matrices and pull terms :

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

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

$$+ \sum_R^{\text{Reactors}} \frac{(P_R)^2}{\sigma_R^2} + \sum_b^{\text{Bkgs}} \frac{(P_b)^2}{\sigma_b^2}$$

P_R : Pull parameter varying the total rate of neutrinos from reactor *R*

P_b : Pull parameter varying the total rate of of background *b*

M_{ij}^{signal} : Signal covariance matrix (reactor ν flux etc.)

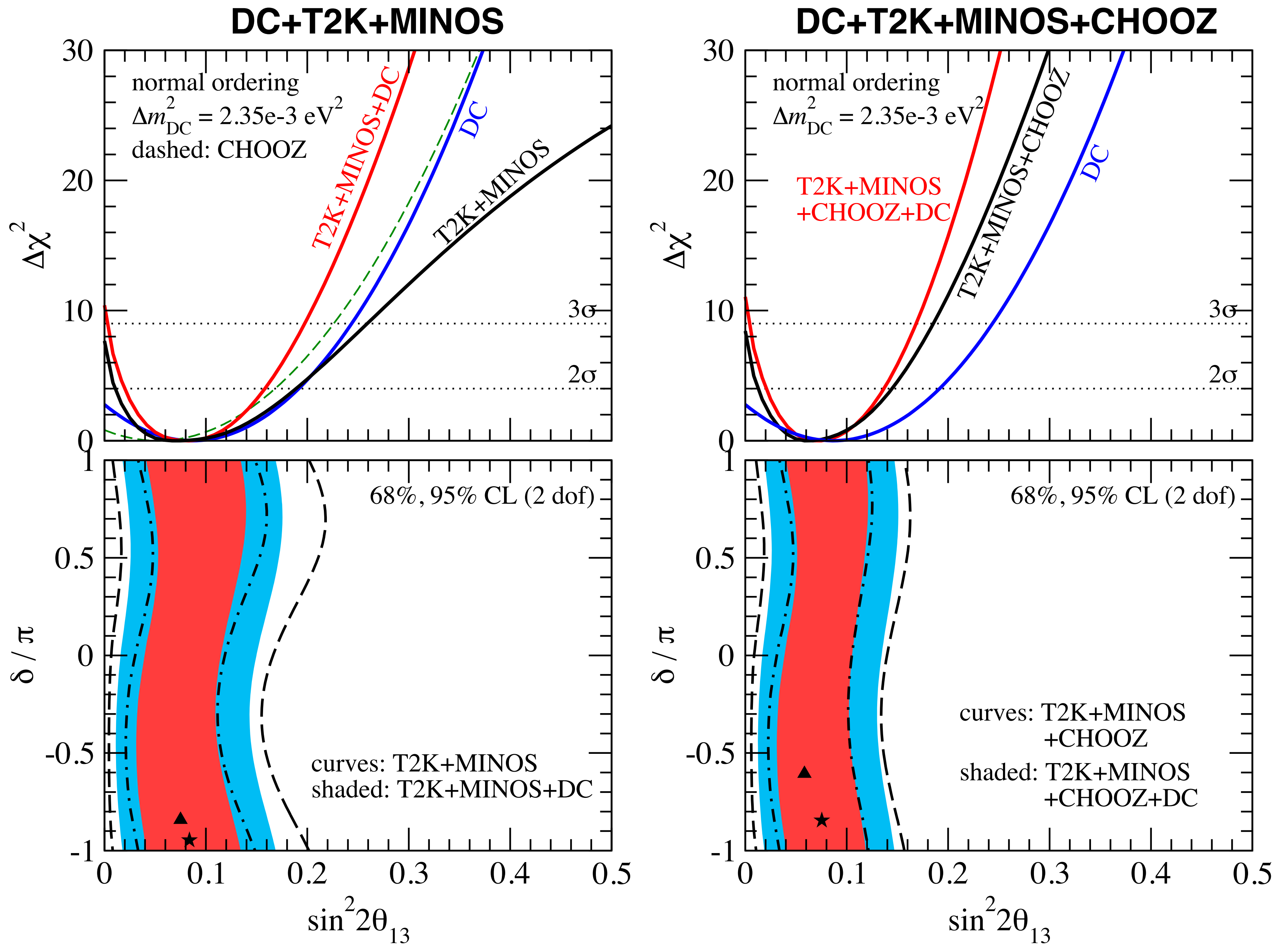
M_{ij}^{detector} : Detector covariance matrix (E scale etc.)

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

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

Used blind analysis. Reactor prediction was blinded until the selection cuts were frozen.

Combined analysis



Reactor experiment results