The Search for θ_{13} : First Results from Double Chooz

Jaime Dawson, APC

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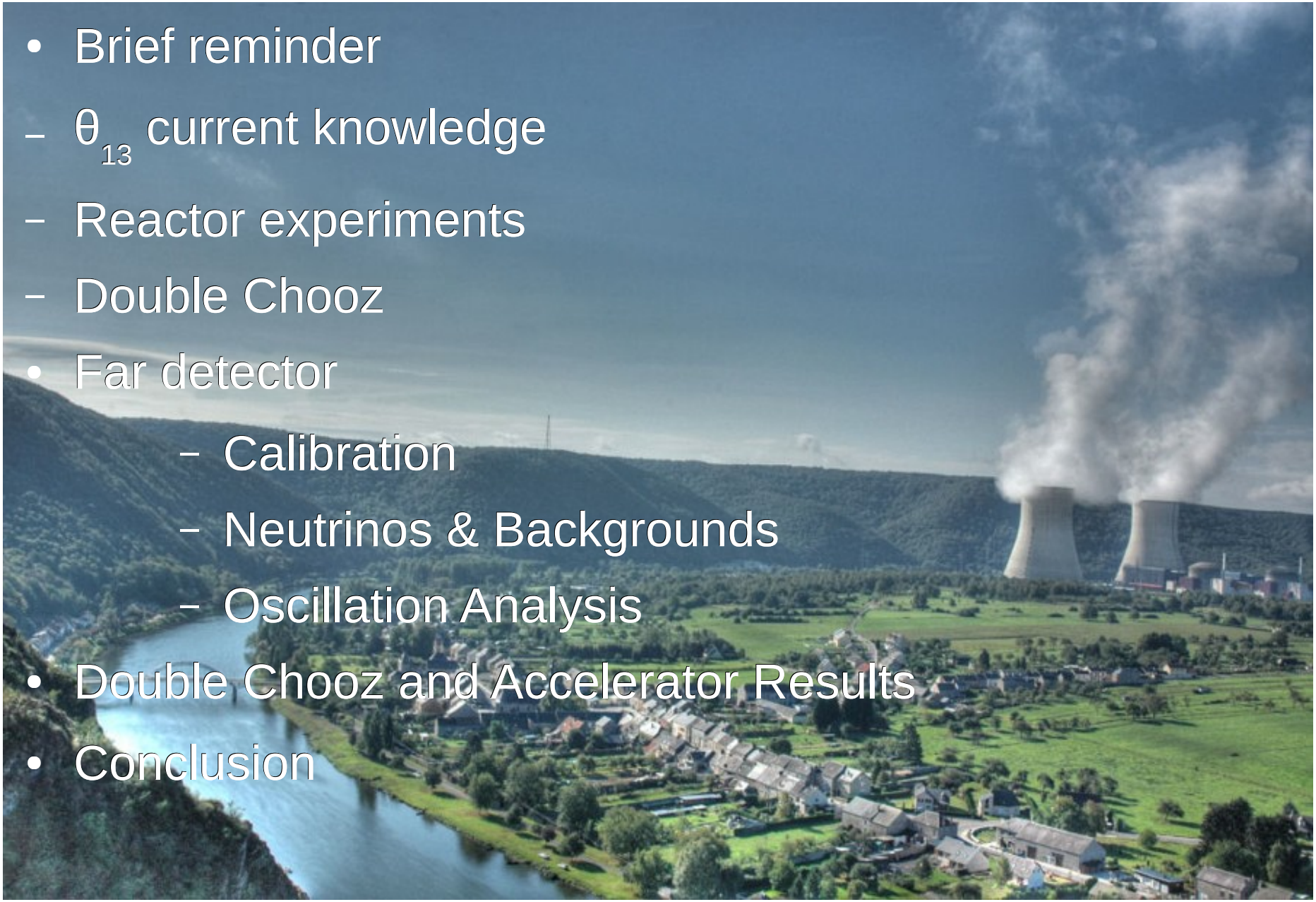


- Brief reminder
  - θ_{13} current knowledge
  - Reactor experiments
  - Double Chooz
- Far detector
  - Calibration
  - Neutrinos & Backgrounds
  - Oscillation Analysis
- Double Chooz and Accelerator Results
- Conclusion

Three Neutrino Mixing

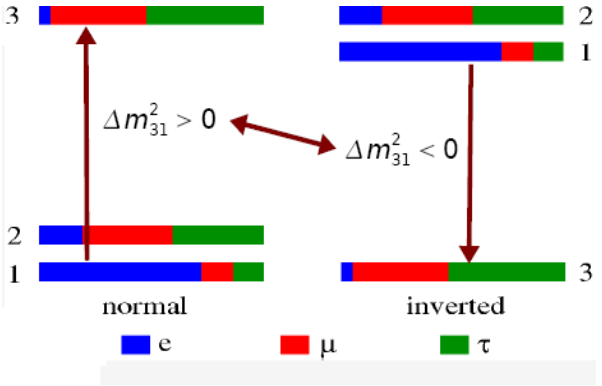
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Pontecorvo – Maki – Nakagawa – Sakata (PMNS) matrix

- 3 mixing angles
- 1 CP phase

$$U = \underbrace{\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{solar}} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}}_{\text{atmospheric}}$$

- 2 mass splittings Δm^2_{ij}
- We don't know θ_{13}, δ_{cp} and sign of Δm^2_{31}



Neutrino Oscillations

Global fit

arXiv:1108.1376, T. Schwetz et al

parameter	best fit $\pm 1\sigma$
Δm^2_{21} $[10^{-5}\mathrm{eV}^2]$	$7.59^{+0.20}_{-0.18}$
Δm^2_{31} $[10^{-3}\mathrm{eV}^2]$	$2.50^{+0.09}_{-0.16}$ $-(2.40^{+0.08}_{-0.09})$
$\sin^2\theta_{12}$	$0.312^{+0.017}_{-0.015}$
$\sin^2\theta_{23}$	$0.52^{+0.06}_{-0.07}$ 0.52 ± 0.06
$\sin^2\theta_{13}$	$0.013^{+0.007}_{-0.005}$ $0.016^{+0.008}_{-0.006}$
δ	$\left(-0.61^{+0.75}_{-0.65}\right)\pi$ $\left(-0.41^{+0.65}_{-0.70}\right)\pi$

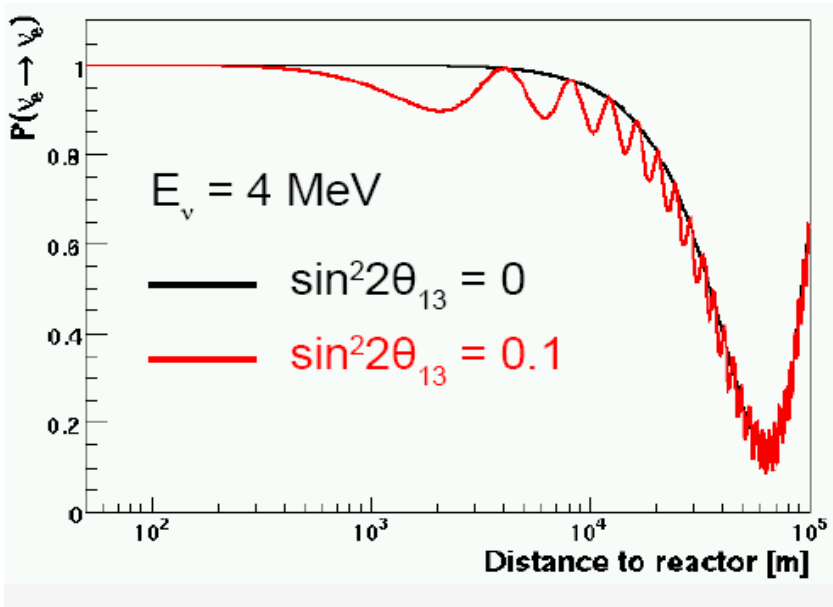
Before Double Chooz result!

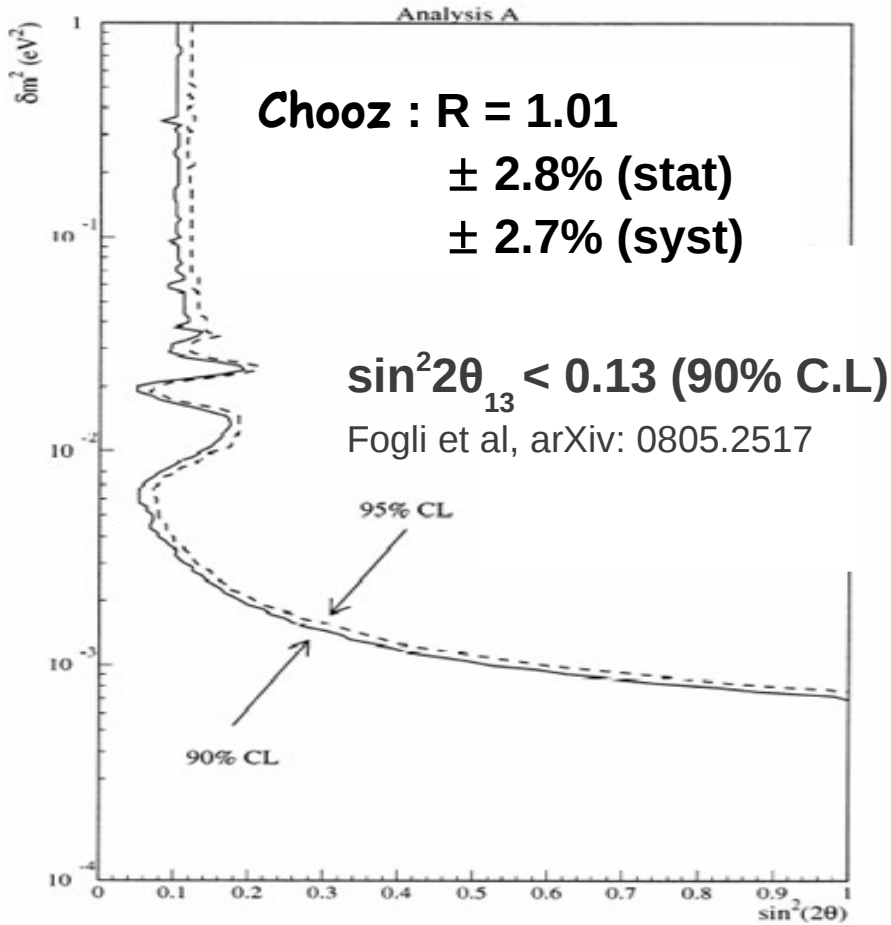
θ_{13} from long baseline accelerator experiments

$\nu_\mu \rightarrow \nu_e$ appearance - T2K and MINOS

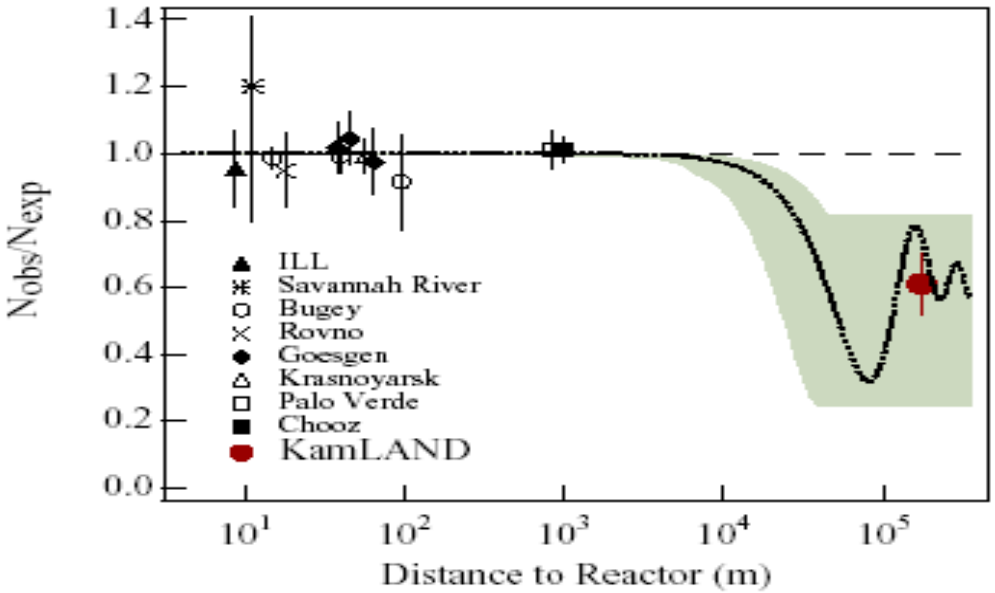
Reactor Experiments

$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{1.27\, L[km]\, \Delta m^2_{31}[10^{-3} eV^2]}{E[MeV]}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{1.27\, L[km]\, \Delta m^2_{21}[10^{-3} eV^2]}{E[MeV]}\right)$$





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



Reactor Experiments

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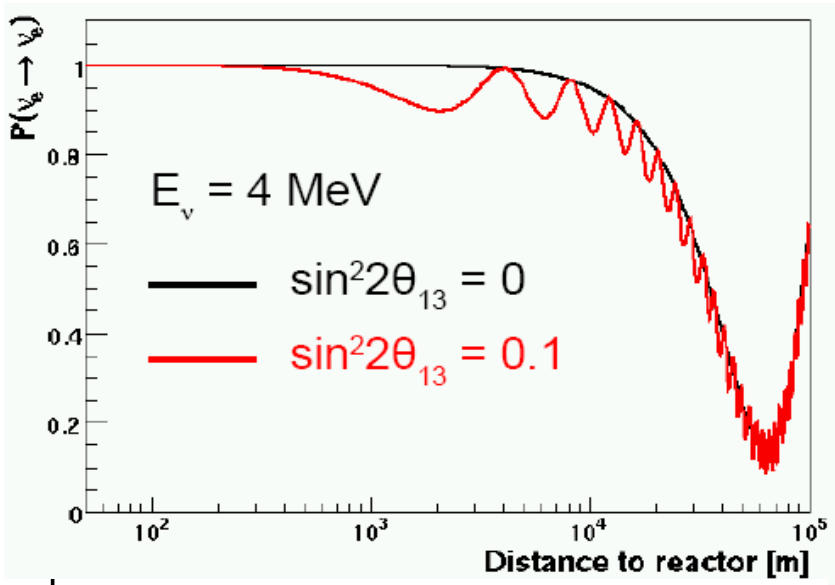
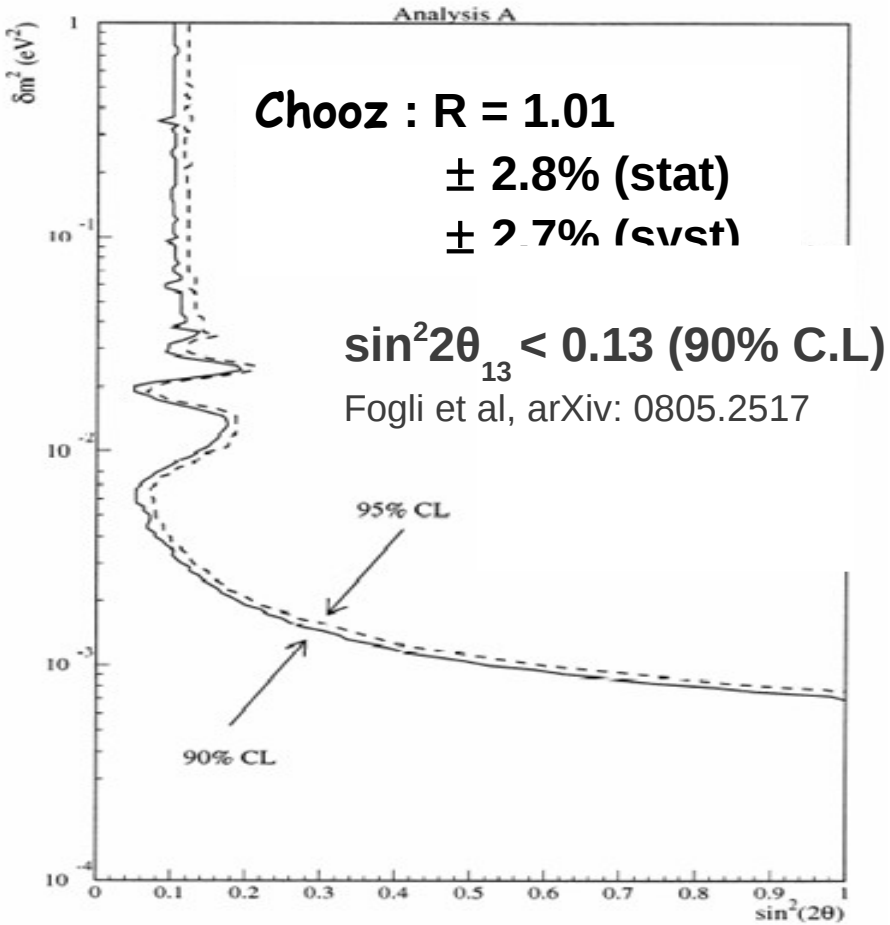


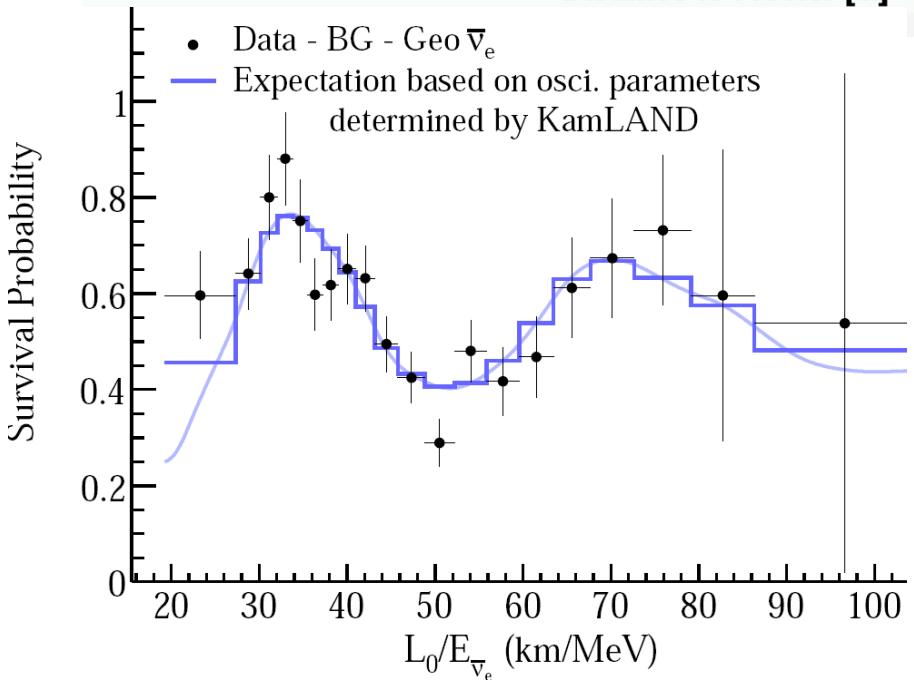


Chooz : R = 1.01
± 2.8% (stat)
± 2.7% (syst)

$\sin^2 2\theta_{13}$ < 0.13 (90% C.L)

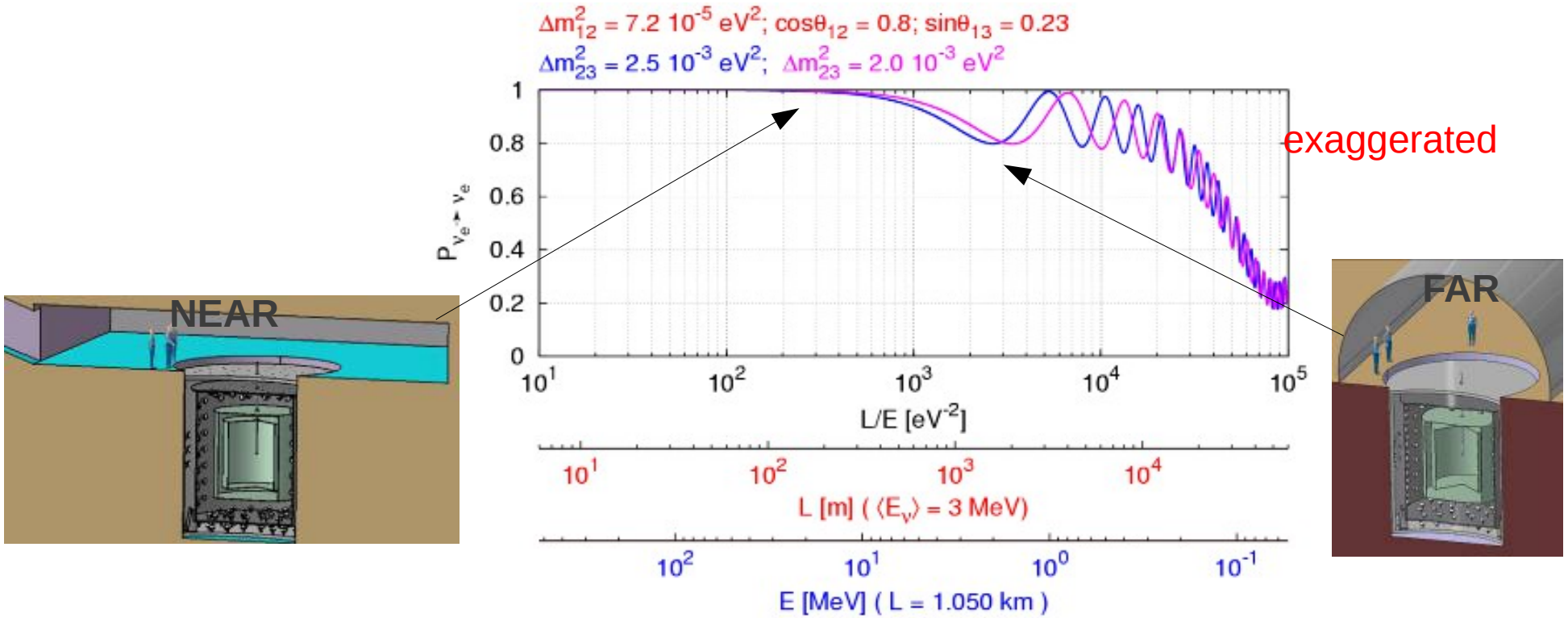
Fogli et al, arXiv: 0805.2517

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



Modern Reactor θ_{13} Experiments

- Disappearance of anti-neutrinos (independent of δ_{cp} and sign of Δm_{31}, weak dependence of Δm_{21})
- Short distances, ~MeV signals (no matter effects)



Double Chooz collaboration

Brazil

CBPF
UNICAMP
UFABC

France

APC
CEA/DSM/IRFU:
- SPP
- SPhN
- SEDI
- SIS
- SENAC

CNRS/IN2P3:
- Subatech
- IPHC

ULB

Germany

EKU Tübingen
MPIK Heidelberg
TU München
U. Aachen
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/

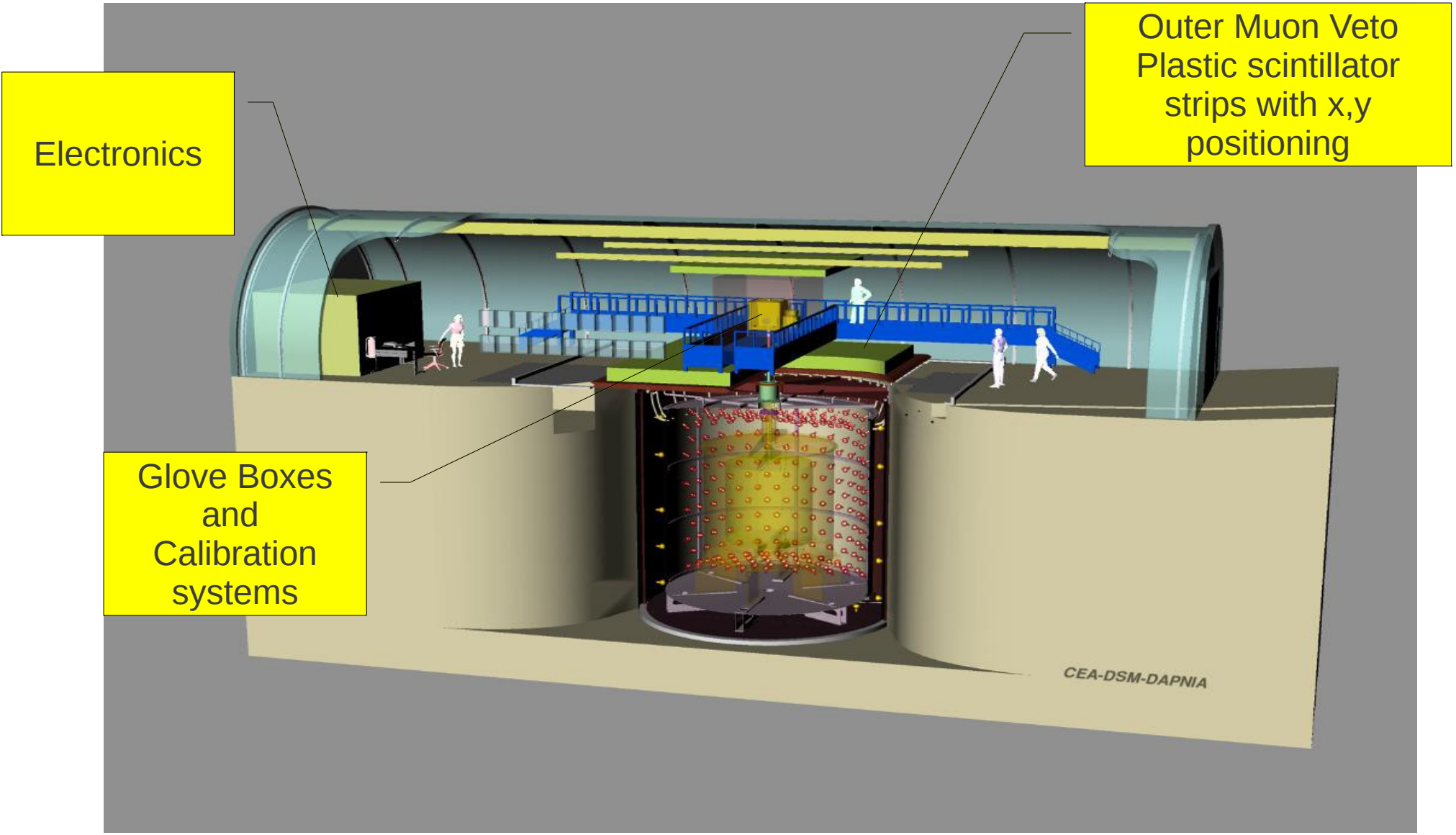
Concept

Chooz-B
2 x 4.27GW

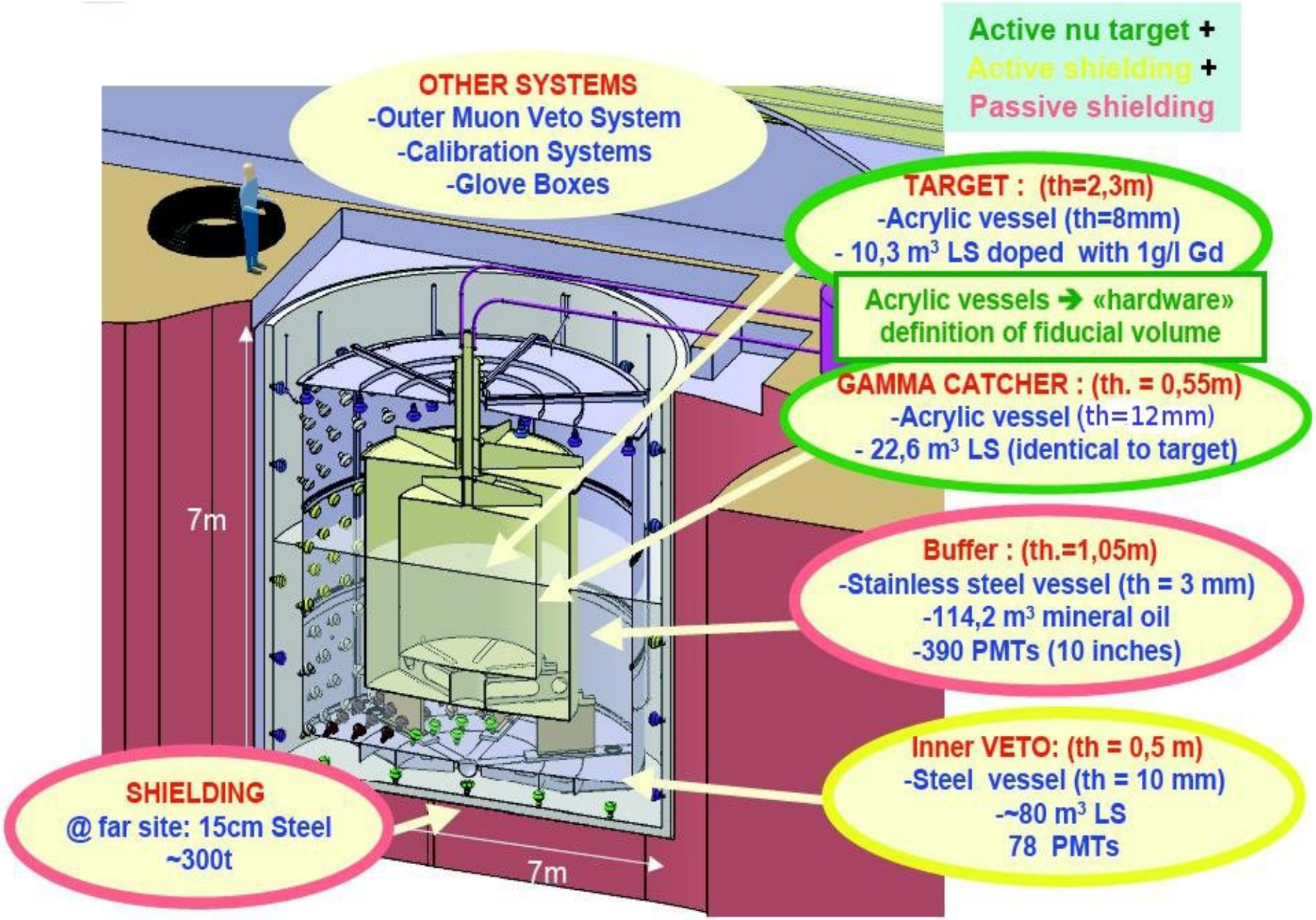
- 2 'identical' detectors
  - **Near**
    - 410 m
    - 115 m.w.e
    - ~500 ν/day
  - **Far**
    - 1050 m
    - 300 m.w.e
    - ~70 ν/day
- Systematics on reactor power, neutrino spectrum, cross-section and detection are insignificant for a relative measurement

Near Laboratory Construction

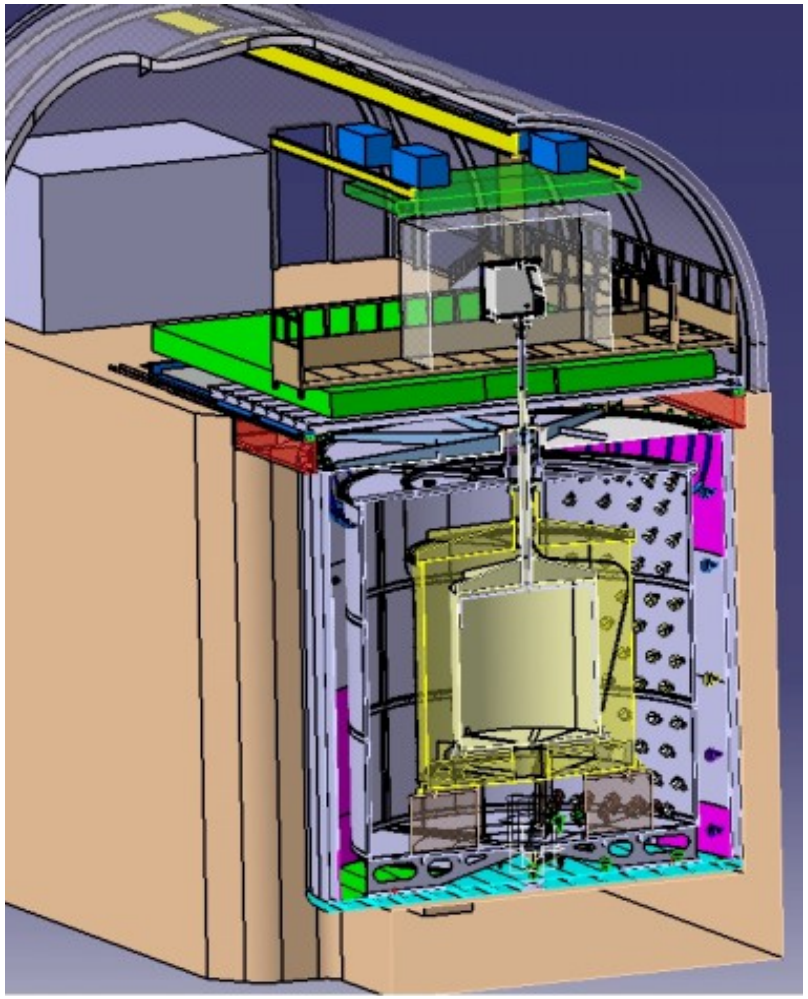
The Laboratories



The Detectors

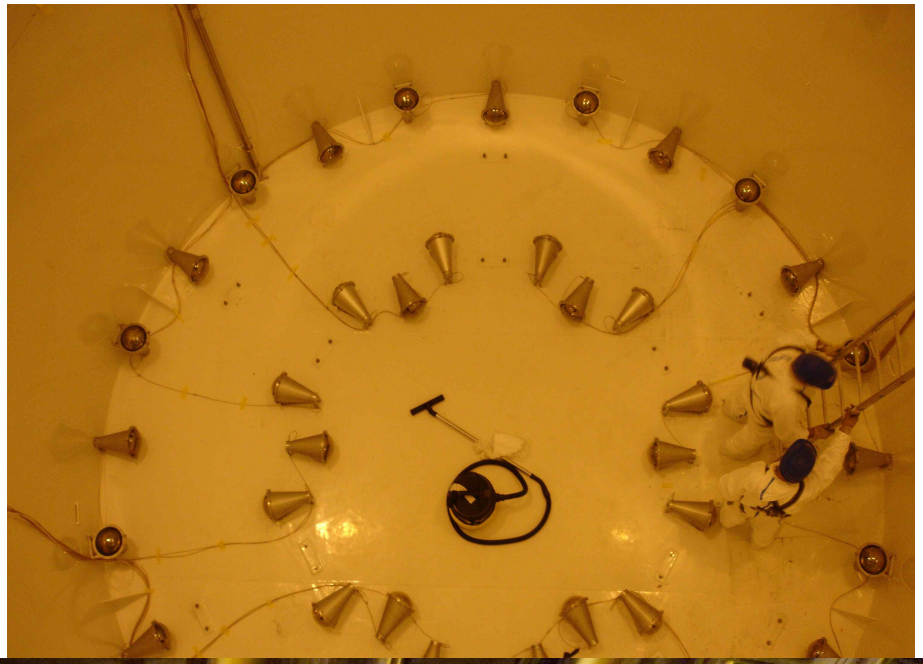


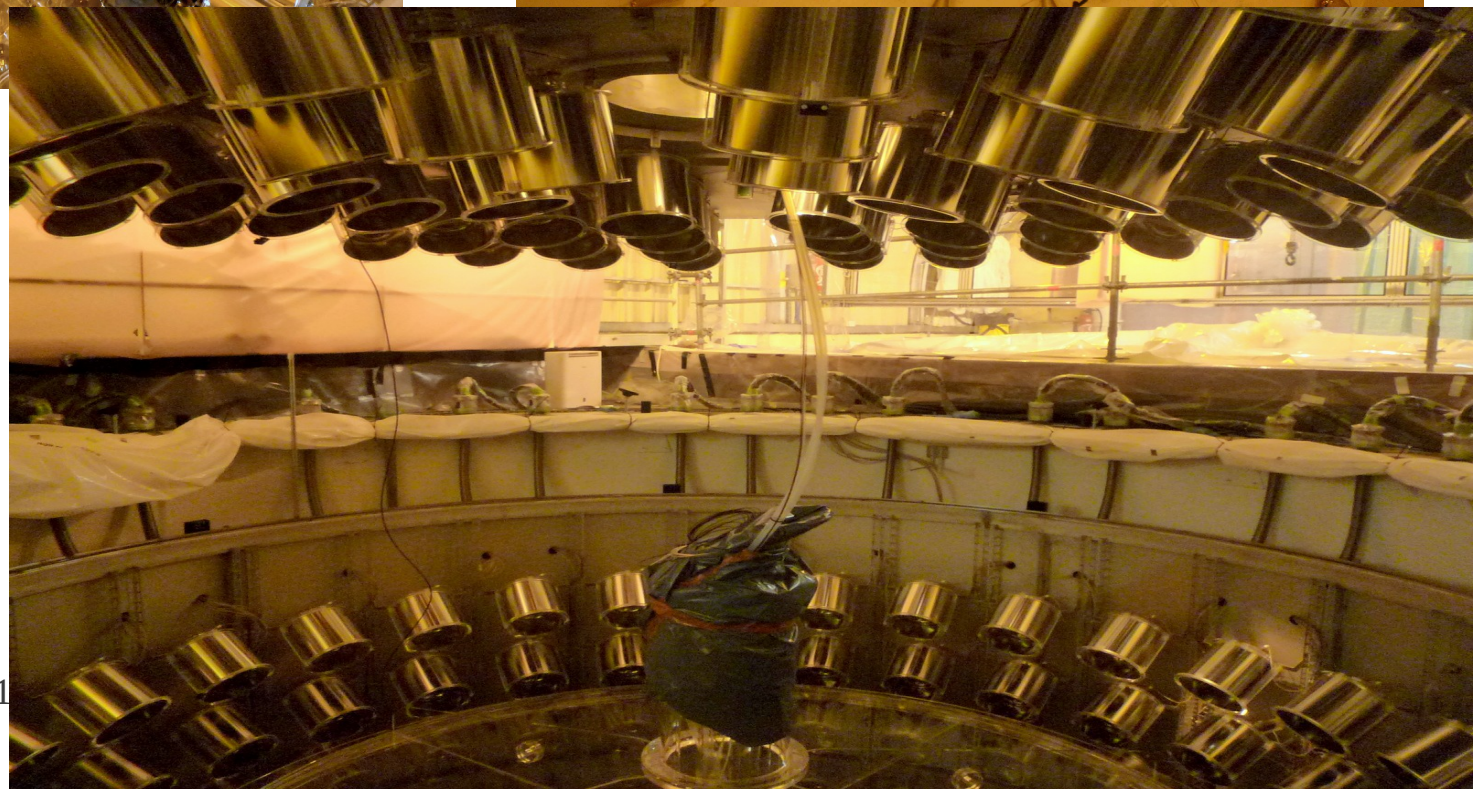
Muon Tracking



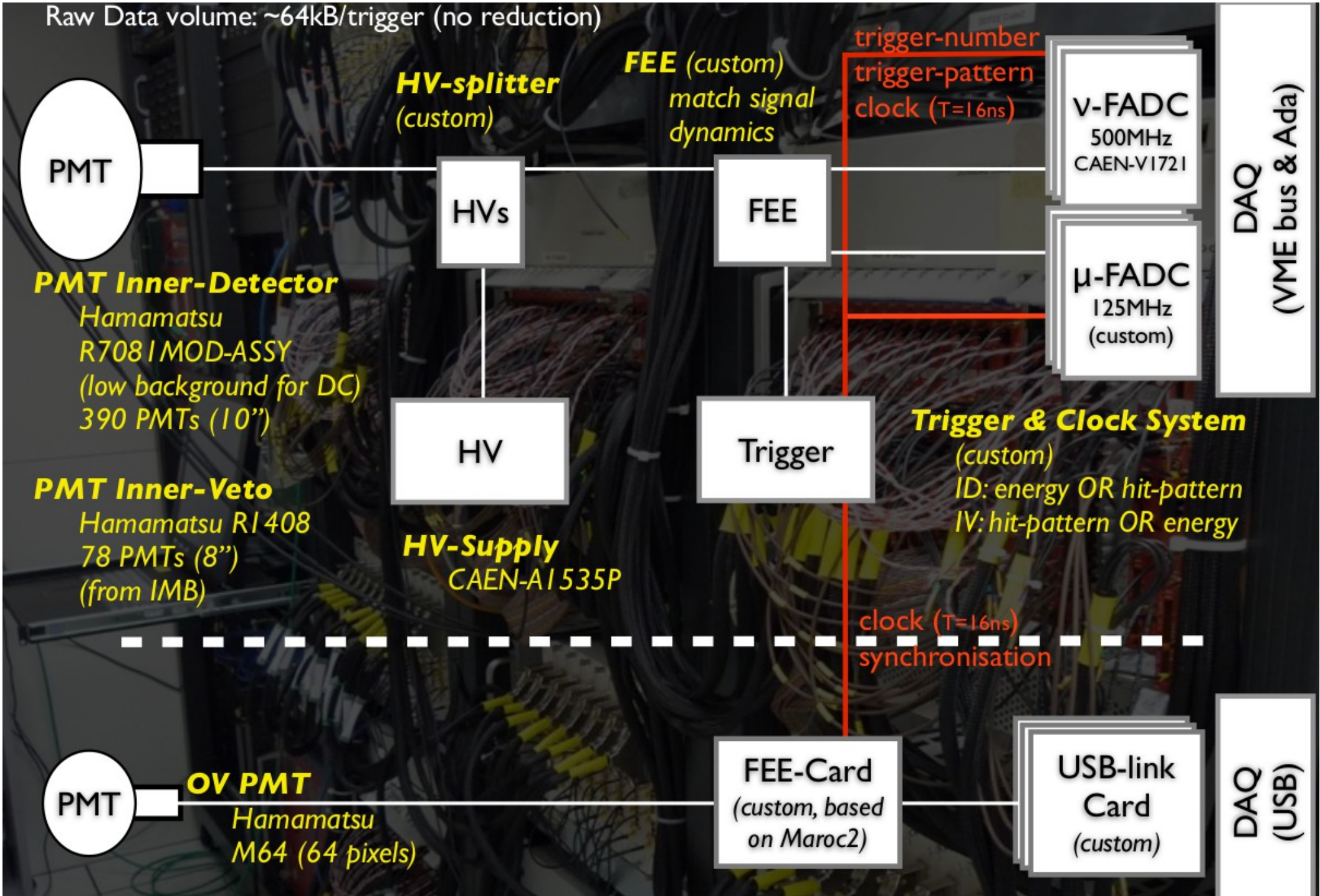
- Outer Veto
  - Tag near miss muons
  - Entry point of any muon
- Inner Veto
  - Efficient tag of muons and secondaries
  - Track muon
- Muon Electronics
  - Attenuated output of Inner Detector PMTs
  - Track muon

Inside the Far Detector

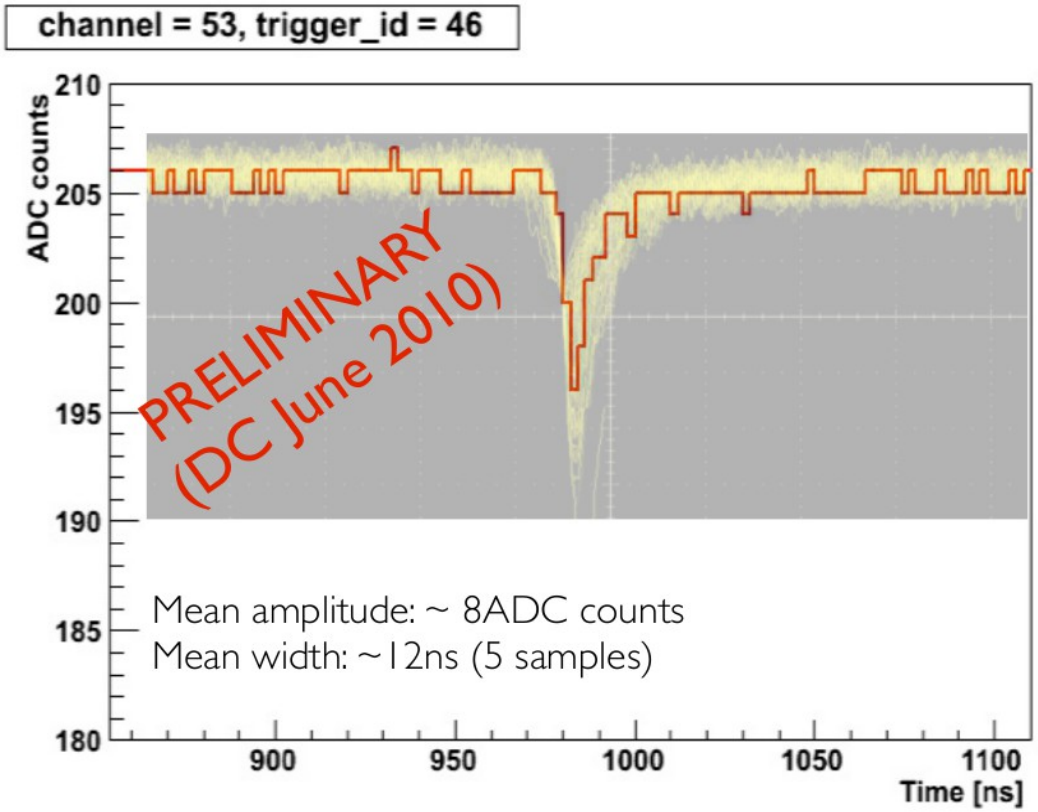




Electronics & ReadOut



Waveform Digitisers



Single photoelectrons as seen by the waveform digitisers

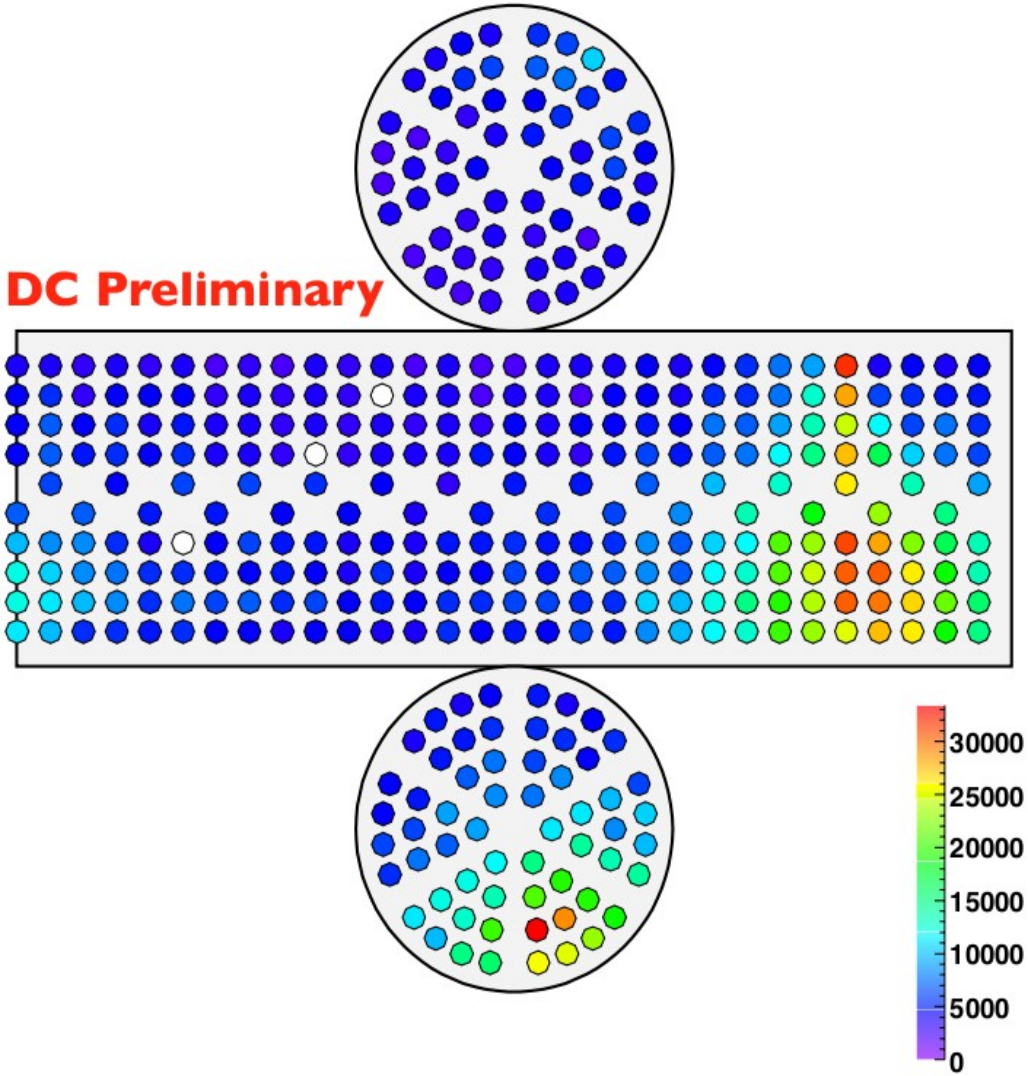
500 MHz 8-bit flash ADC (developed with Caen – V1721X)

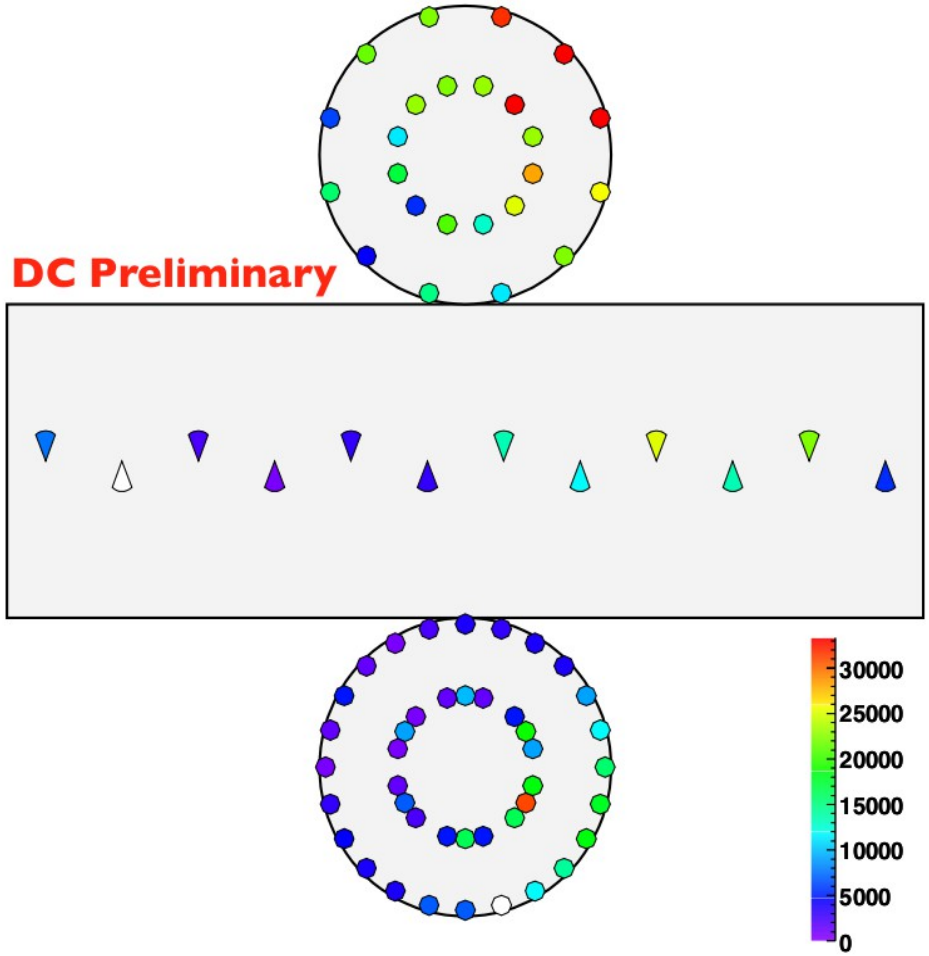
- Dead-time-less (for our event rate)
- In-house firmware allows choice of event size based on
  - Info from trigger
  - Time between consecutive events

Event Display

Muon in Inner Veto

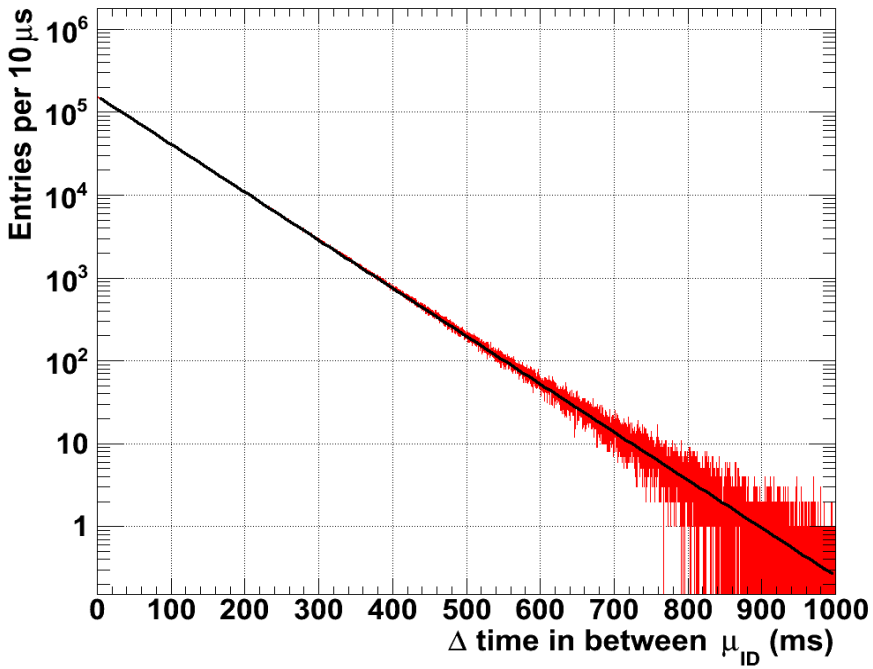
Muon in Inner Detector



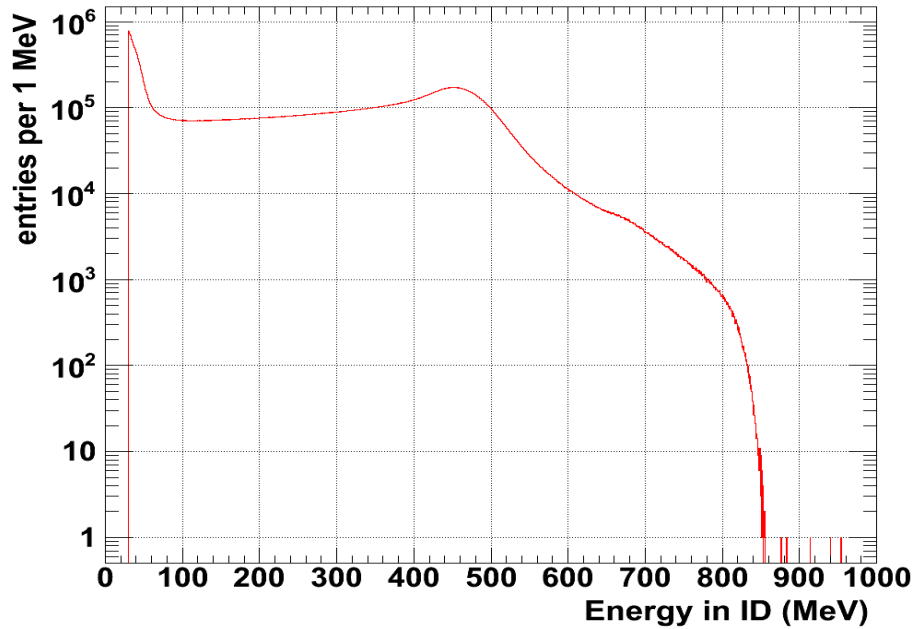


Muons

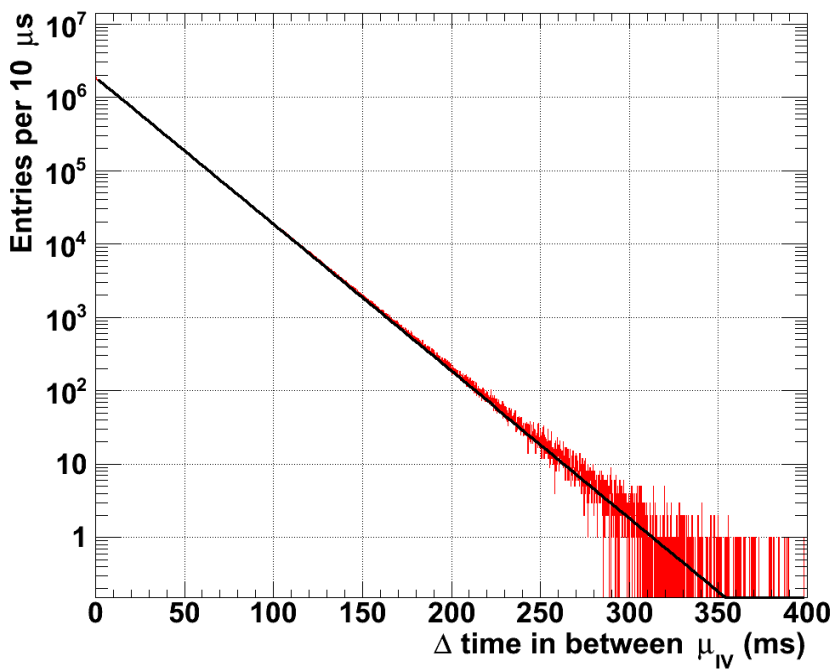
Muon rate in Inner Detector: 13 Hz



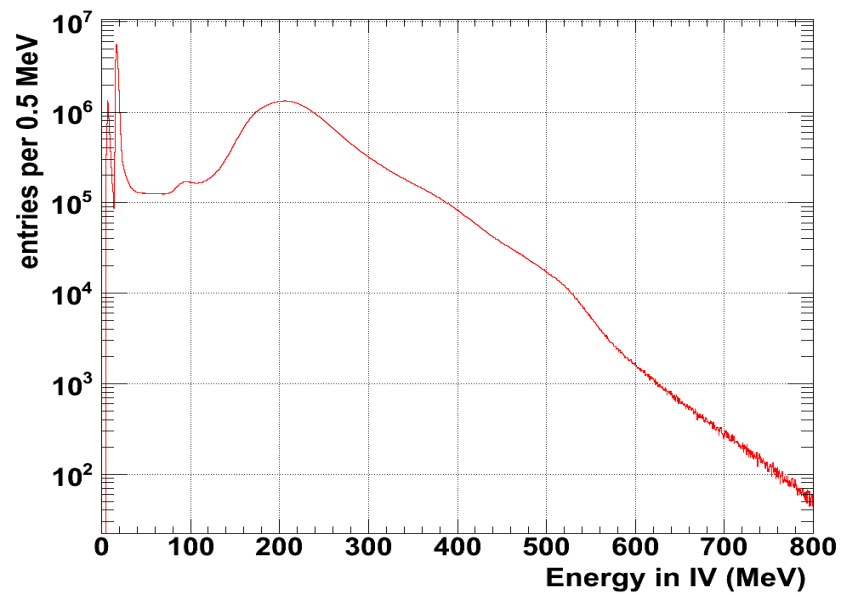
Energy spectrum for muon events in the Inner Detector



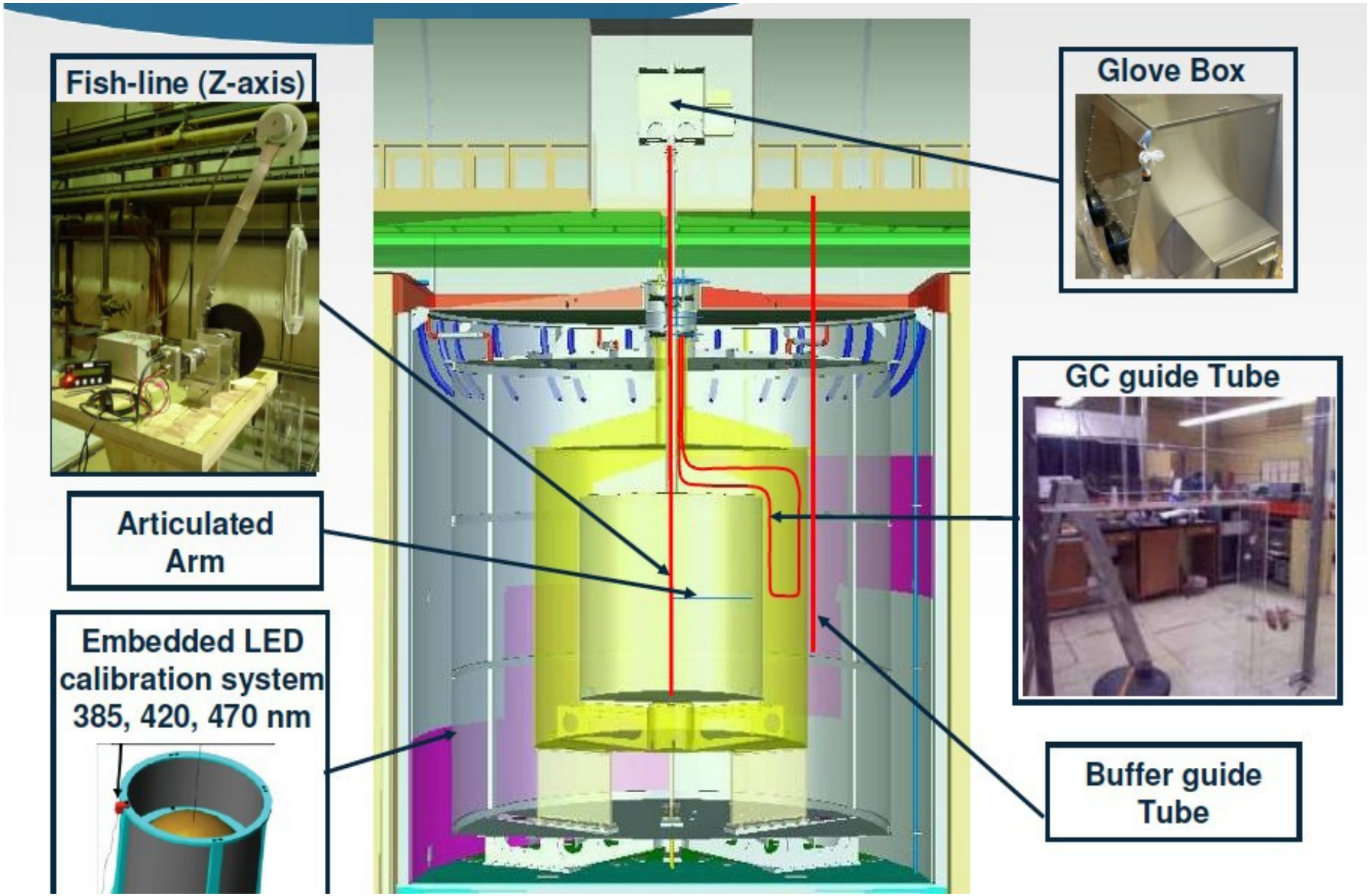
Muon rate in Inner Veto: 46 Hz



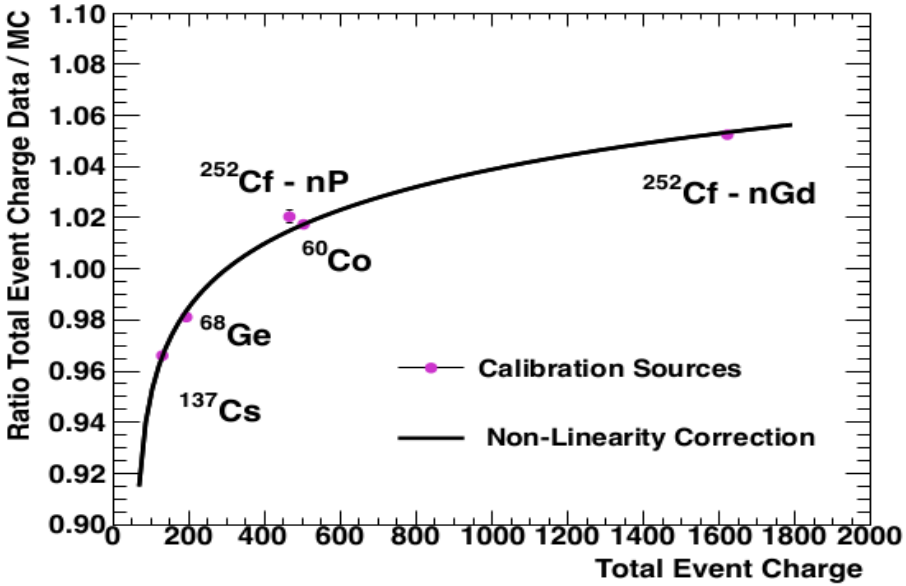
Energy spectrum for muon events in the Inner Veto



Calibration

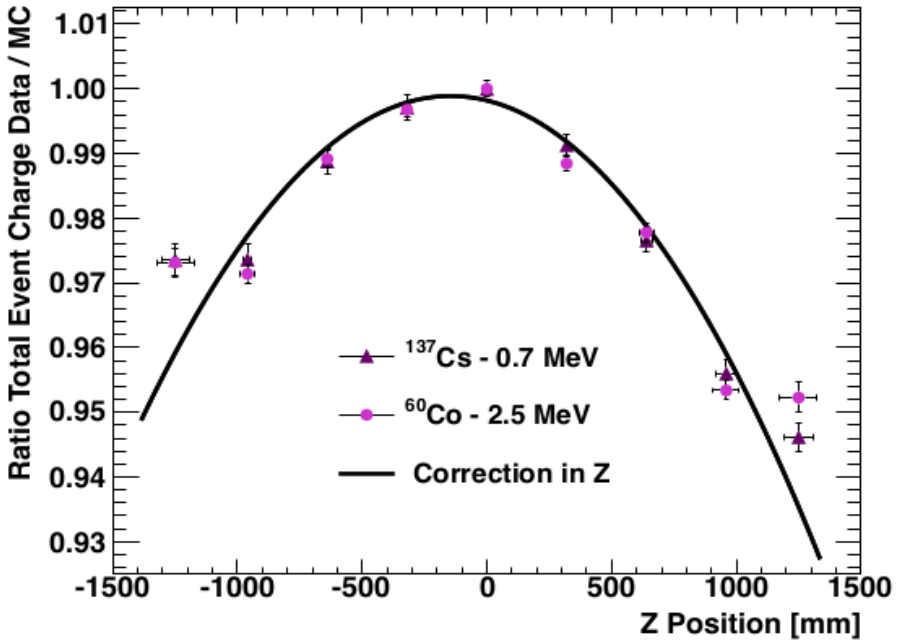


Calibration



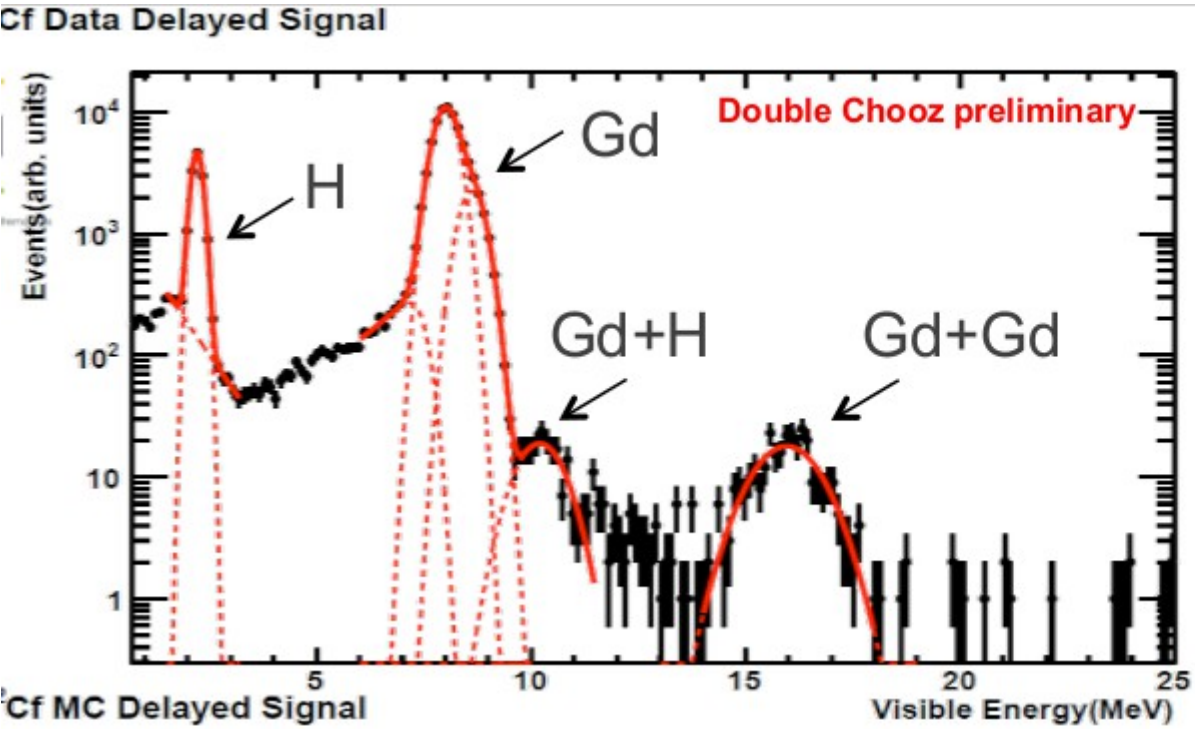
neutron, gamma and positron sources

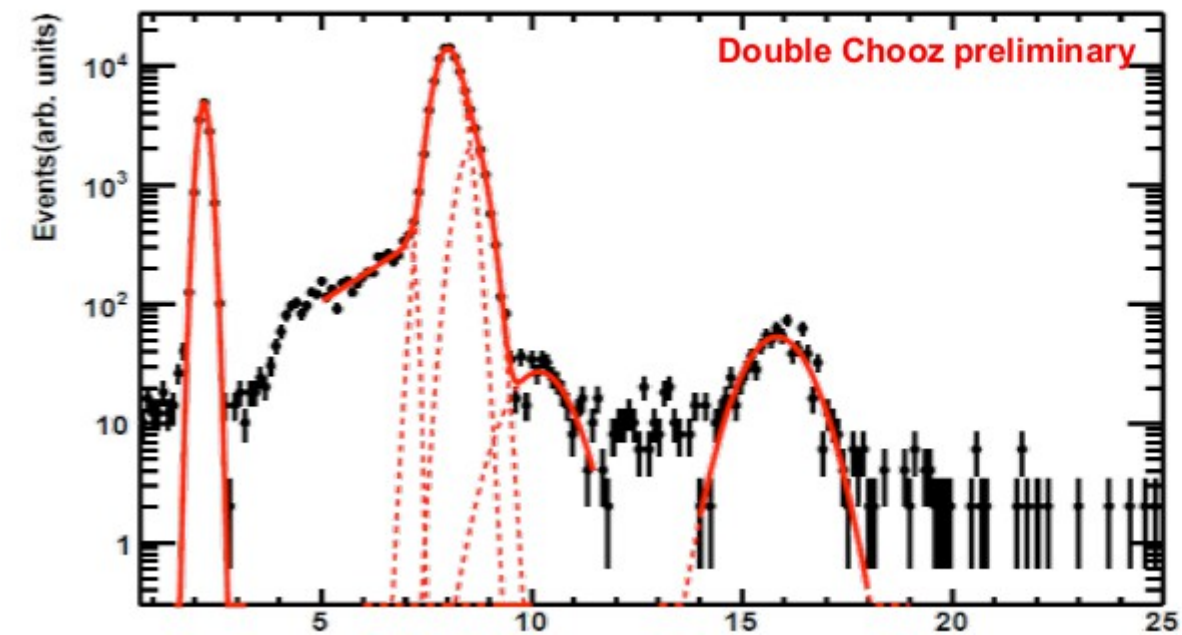
Non-linearity from
electronics & charge reconstruction



Charge bias in z-direction

Neutron Calibration

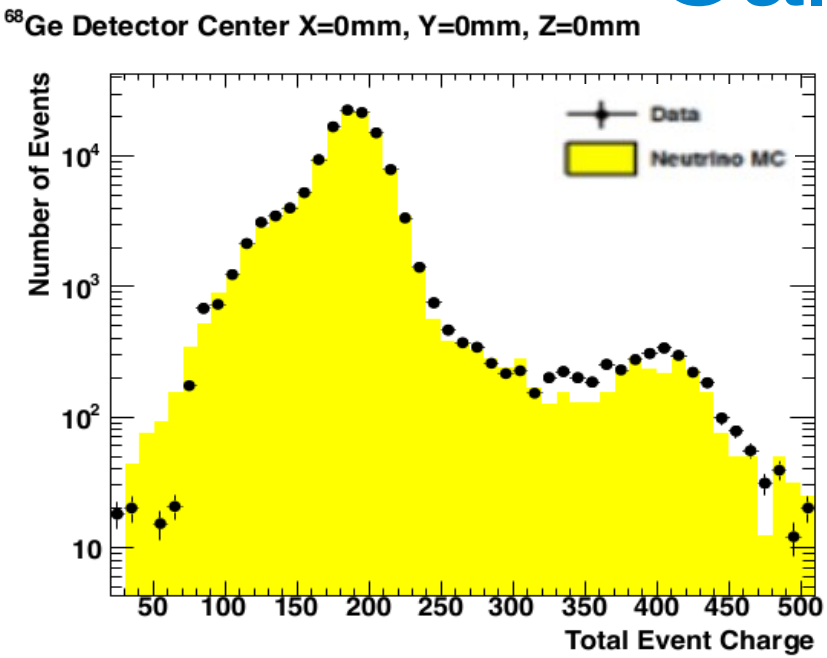


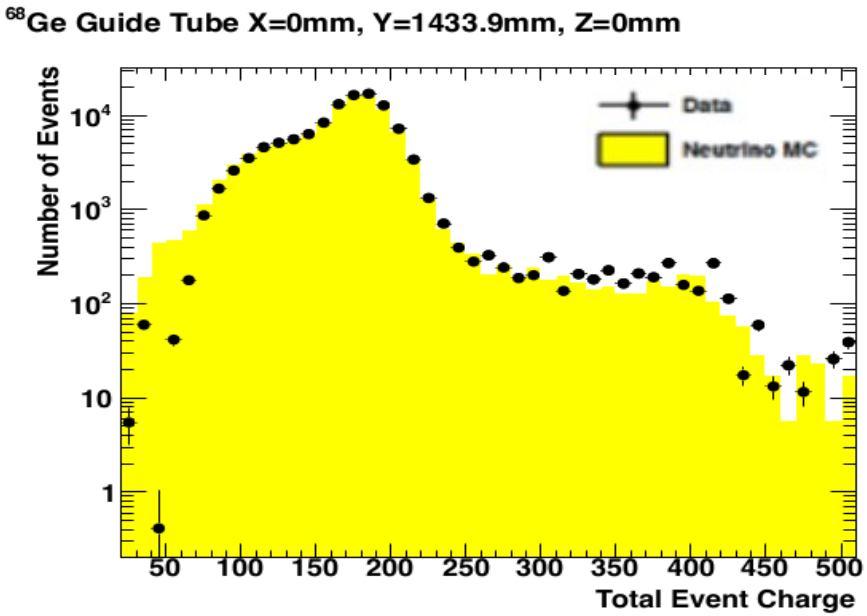


^{252}Cf source inside target,
Deployed along z-axis

Calculate neutron capture
Gd/(H+Gd)
Find 2% correction between data and MC

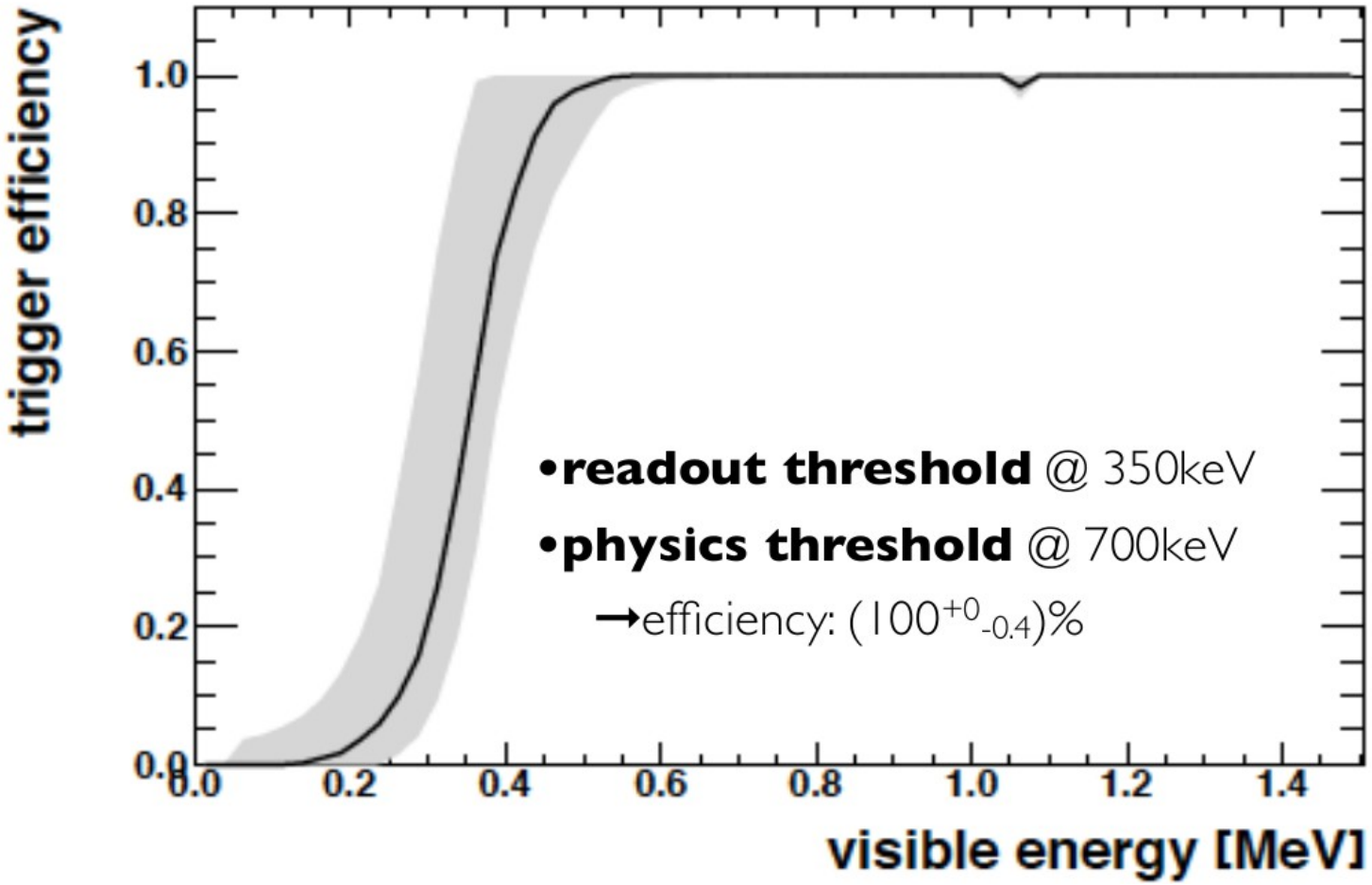
Calibration



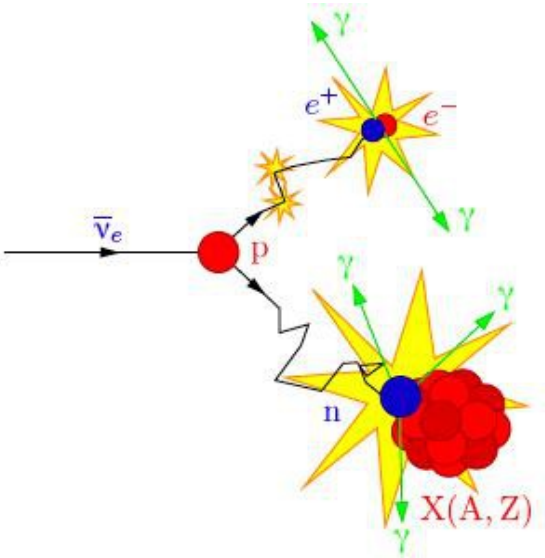


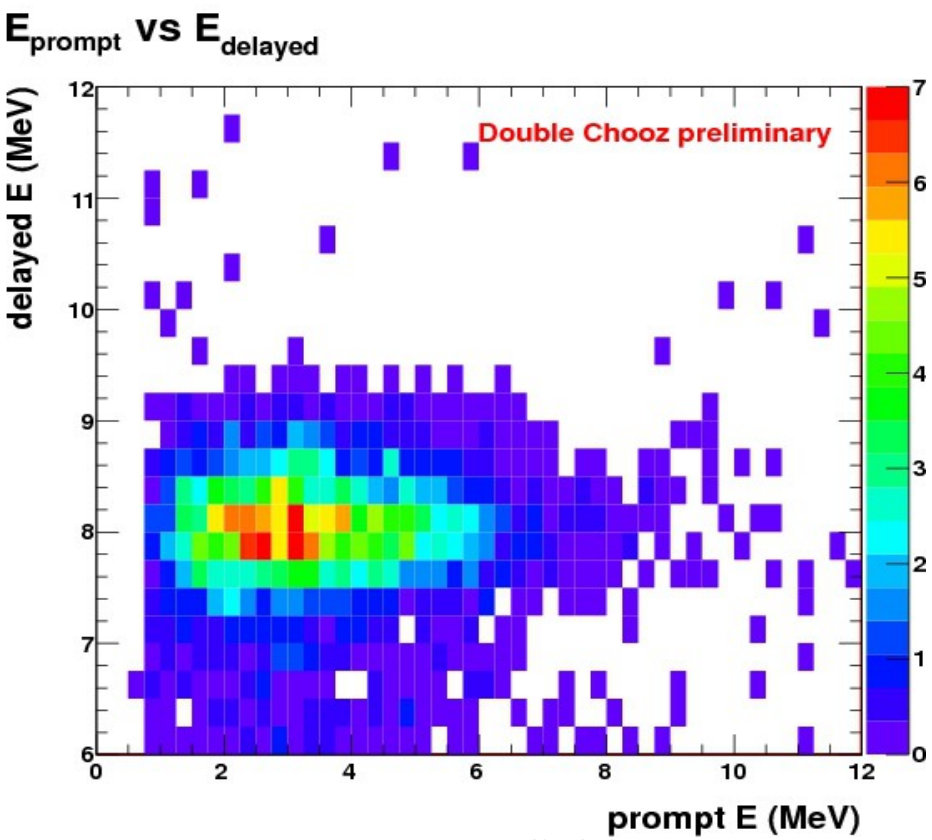
^{68}Ge (positron emitter) spectrum well modelled

Energy Threshold and Trigger



Detect Neutrinos





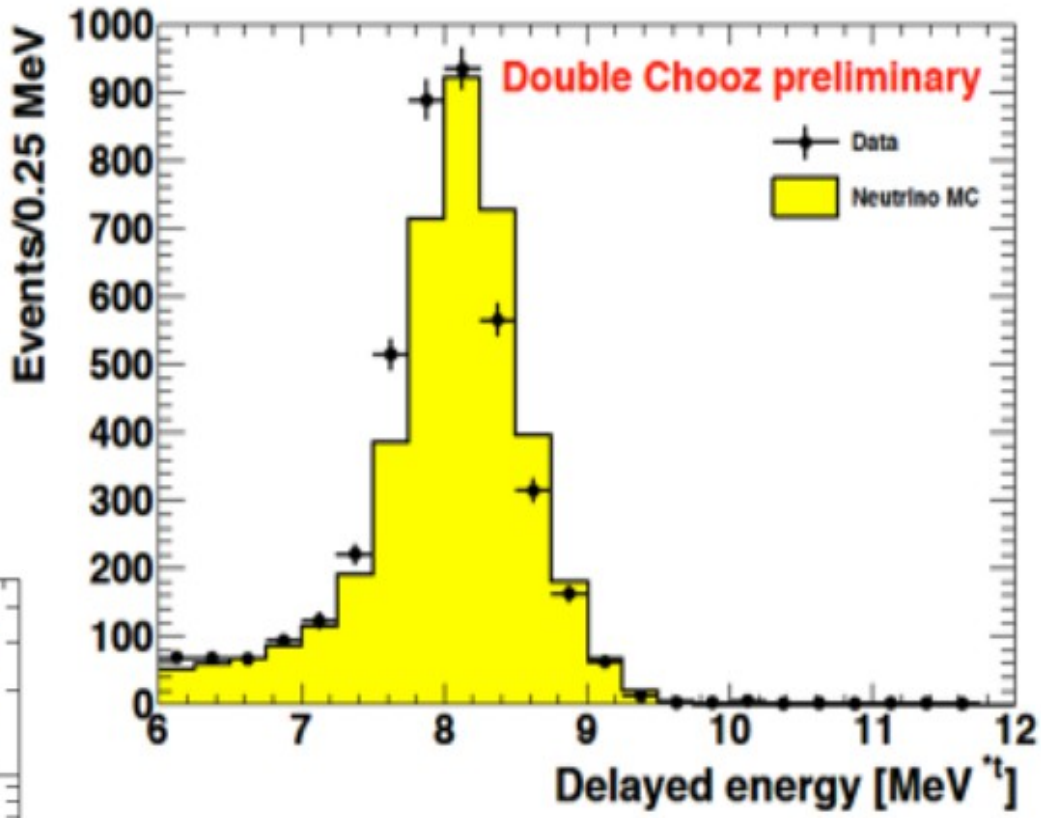
- Detect anti-neutrinos via inverse beta decay
  - $p + \bar{\nu} \rightarrow n + e^+$
- In Gd- loaded scintillator
  - Prompt e^+ signal 1-8MeV
  - Prompt e^+ e^- annihilation(2 x 511 keV)
    - $E_{vis} = E_\nu - (M_n - M_p) + m_e$
  - Delayed neutron capture on
    - Gd ~30 μs ~ 8 MeV (>80%)
    - H ~200 μs 2.2 MeV

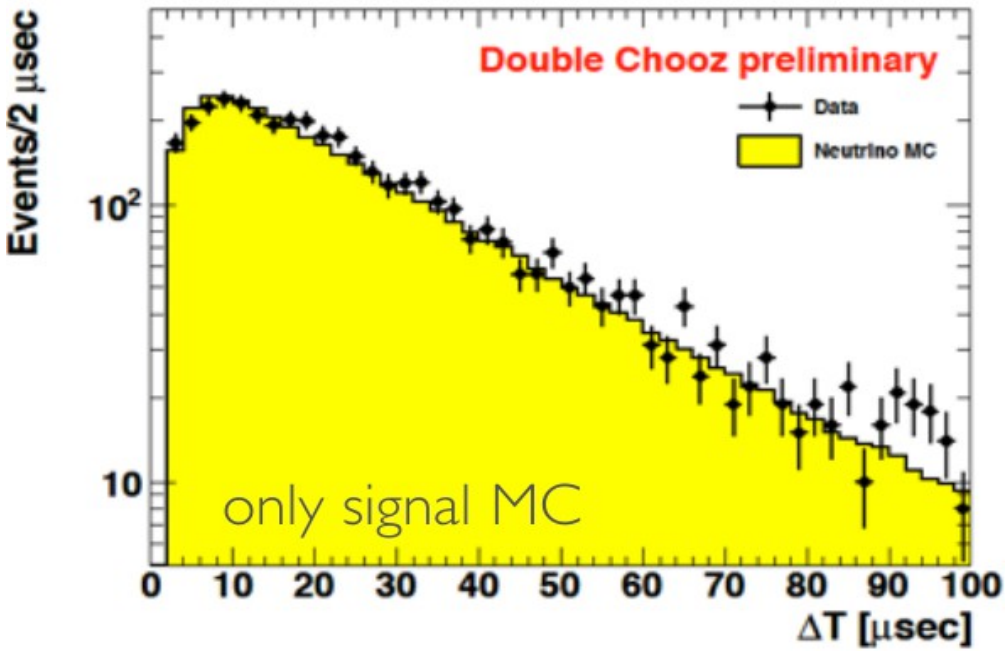
Neutrinos – delayed signal

Tag → helps define Neutrino event
- 8 MeV → less background
- Rapid capture time → less background

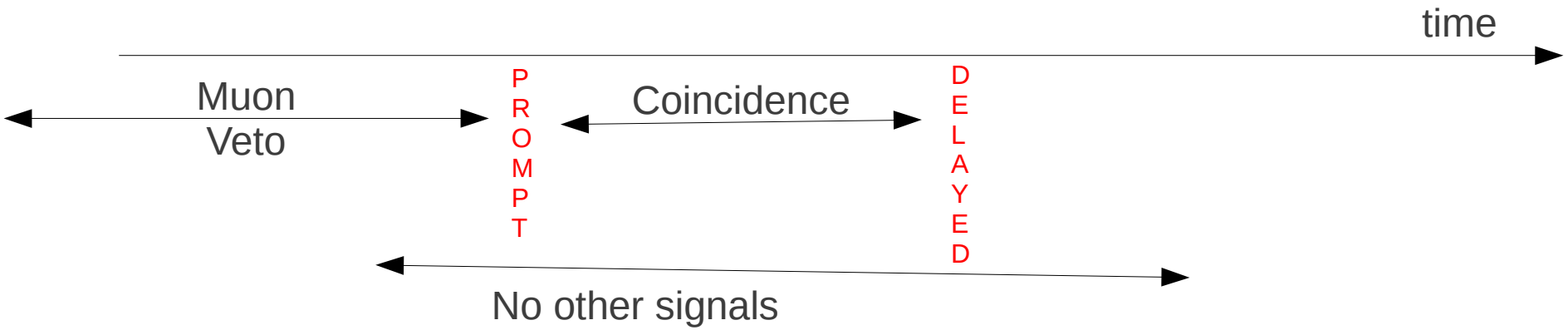
Fiducial volume → Gd only in target

Neutron capture on Gd





Neutrino Selection

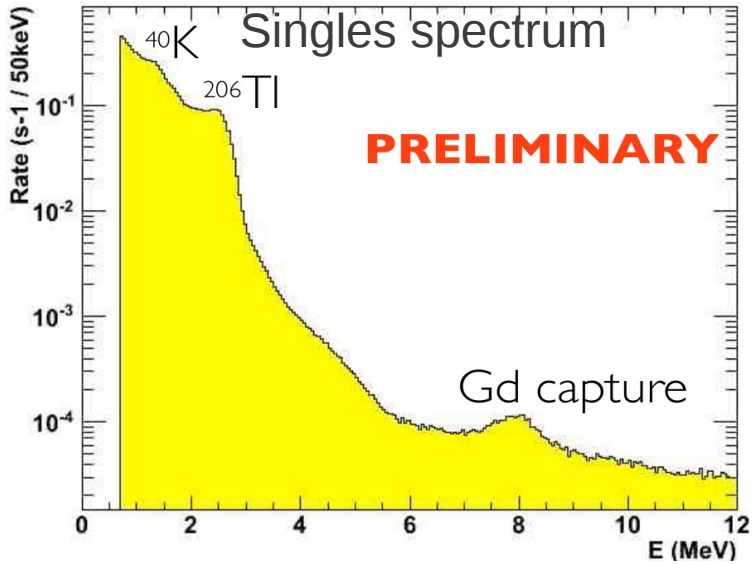


- Muon veto - No preceding muons (1 ms)
- No PMT light noise events. Real signals have
  - Homogeneous spread across PMTs
  - Small spread in arrival times
- Energy
  - Prompt [0.7, 12] MeV
  - Delayed [6, 12] MeV
- Coincidence [2, 100] μs
- No other signals [100 μs before prompt and 400 μs after]

Systematics

Detector	
Energy response	1.7%
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%
Total	2.1 %

Accidental Background

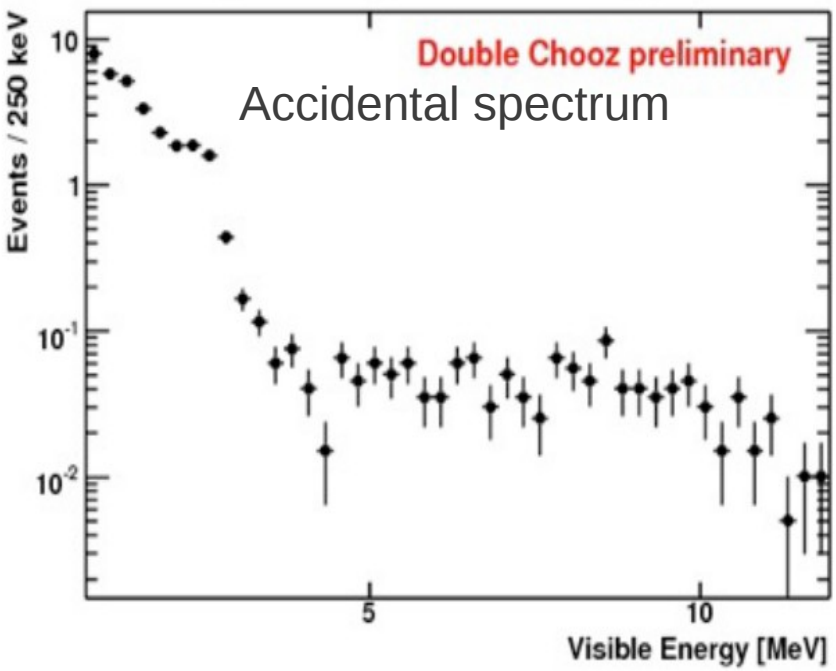


Dominant source of accidentals is

Radioactivity (from PMTs) - 7.6 Hz (>700keV)

Thermal neutrons - 20 n/hr

Shift coincidence time window [1,100]ms away from neutrino candidates



Background	Rate (D^{-1})	Syst. Uncertainty (% of signal)
Accidental	0.33 ± 0.03	< 0.1
Fast neutron	0.83 ± 0.38	0.9
^{9}Li	2.3 ± 1.2	2.8

Correlated Backgrounds

Cosmogenics (β-neutron): Li-9, He-8

- Main production mechanism → spallation on C
- Search for showering muons (e.g. Edep> 600 MeV)

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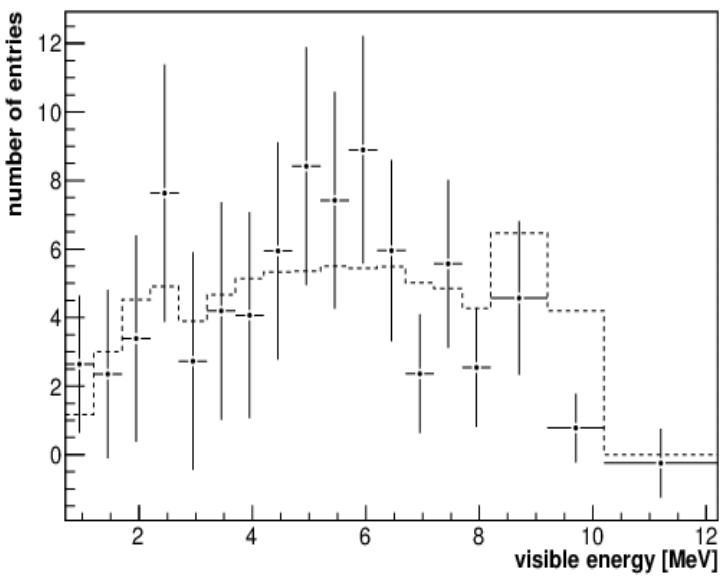
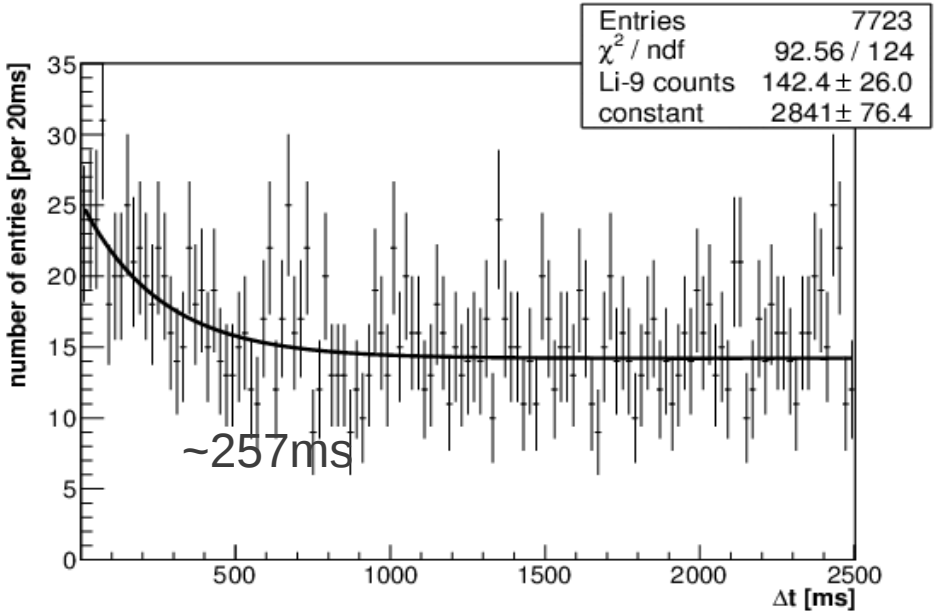
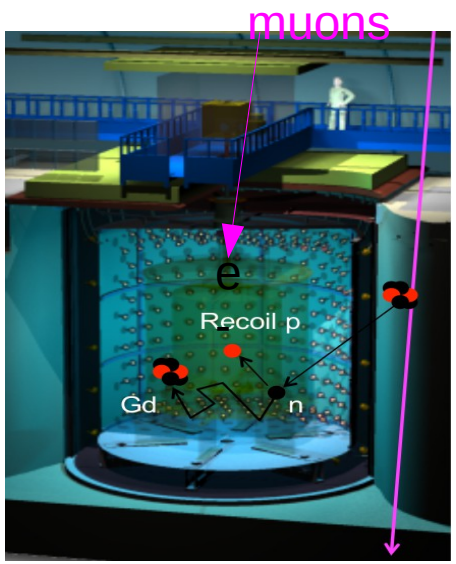




Correlated Background



Fast neutrons

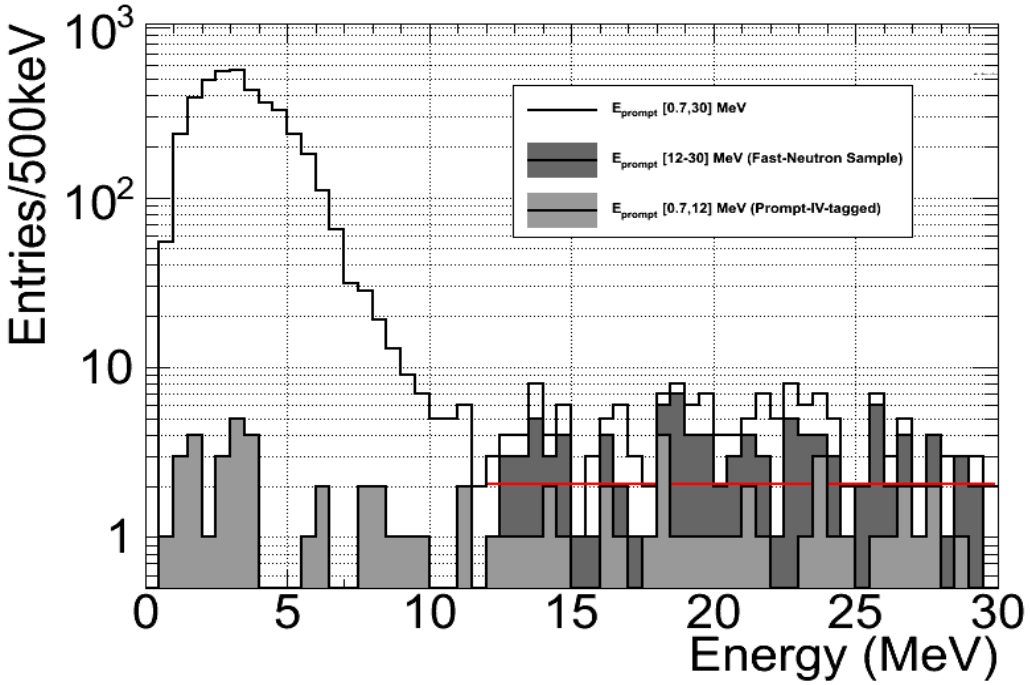
- Proton Recoil (positron-like signal) followed by neutron capture

Chimney Stopping Muons

- Muon stopping in chimney followed by Michel $e^{\pm}$

Sample events of energies > neutrinos [12,30] MeV

Tag events with Inner Veto



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^{9}Li	2.3 ± 1.2	2.8

Expected number of anti-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 target protons
ε - detector efficiency
L - distance reactor-detector

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

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

$\sigma_{IBD}(E)$ – Inverse Beta Decay cross-section
$\langle \sigma_f \rangle$ - Mean cross-section per fission

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

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

$P_{th}(t)$ - Thermal Power – monitored by EDF

Isotopic content of core:
k=^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu
α_k - fractional fission rate
Full core simulation MURE
EDF inputs: initial fuel loading, geometry etc

$S_k(E)$ – reference anti-neutrino spectra

Use Bugey-4 as reference and account for different core composition. Suppresses uncertainty on $S_k(E)$.

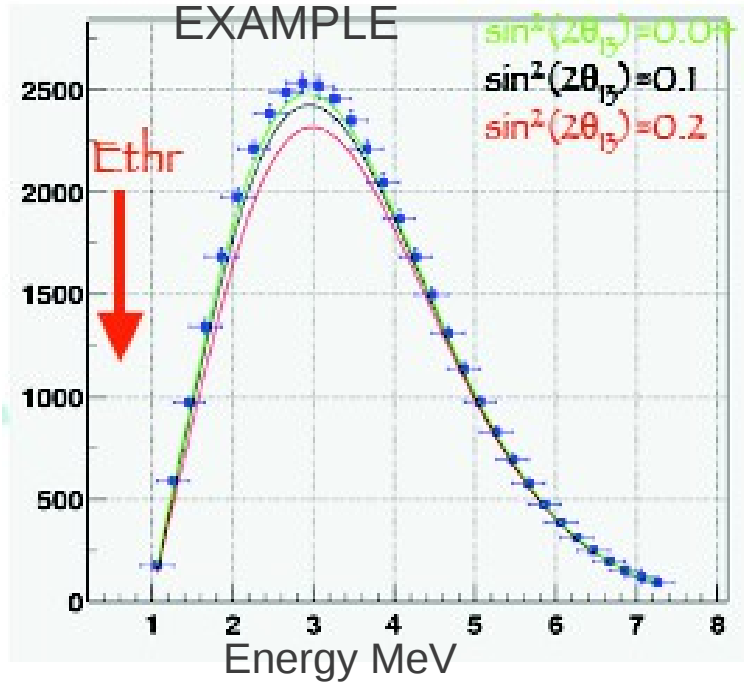
Systematics

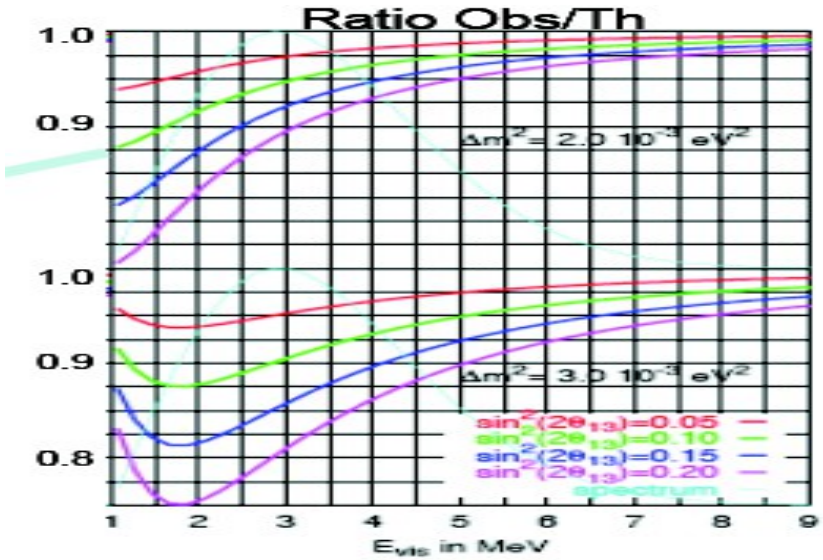
Reactor	
Bugey4 measurement	1.4%
Fuel Composition	0.9%
Thermal Power	0.5%
Reference Spectra	0.5%
Energy per Fission	0.2%
IBD Cross Section	0.2%
Baseline	0.2%
Total	1.8%

Oscillation Analysis

Two independent measures

- Normalisation (RATE)
- Spectral Distortion (SHAPE)
- Or use both





Oscillation Fitting

- Includes uncertainties in anti-neutrino signal, detector response, signal and background statistics, and background spectral shape.
- 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.

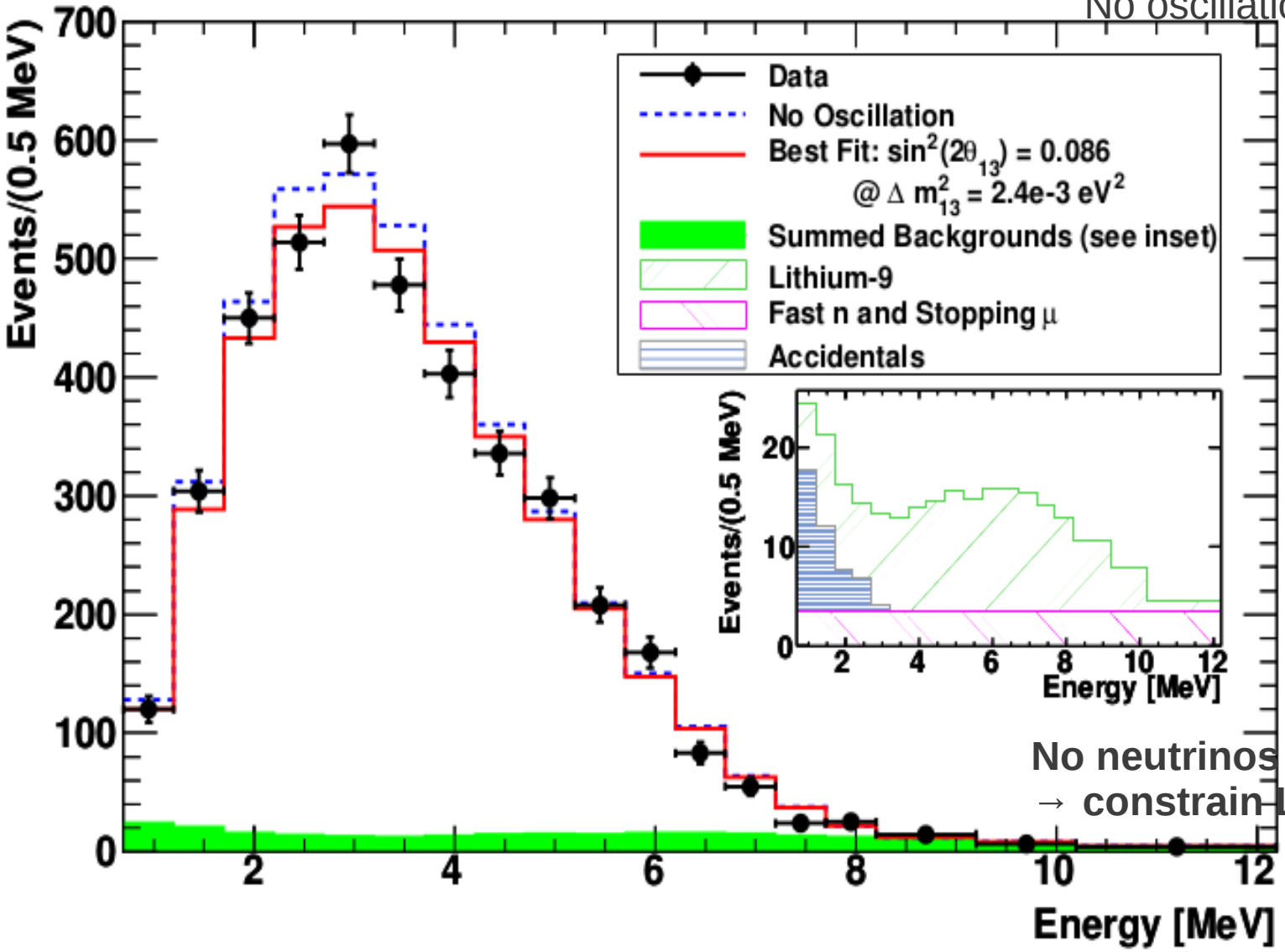
M_{ij}^{b}: Covariance matrix for background

Rate & Shape Oscillation Analysis

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

Or, $0.015 < \sin^2 2\theta_{13} < 0.16$ at 90% C.L

No oscillation excluded at 94.6%

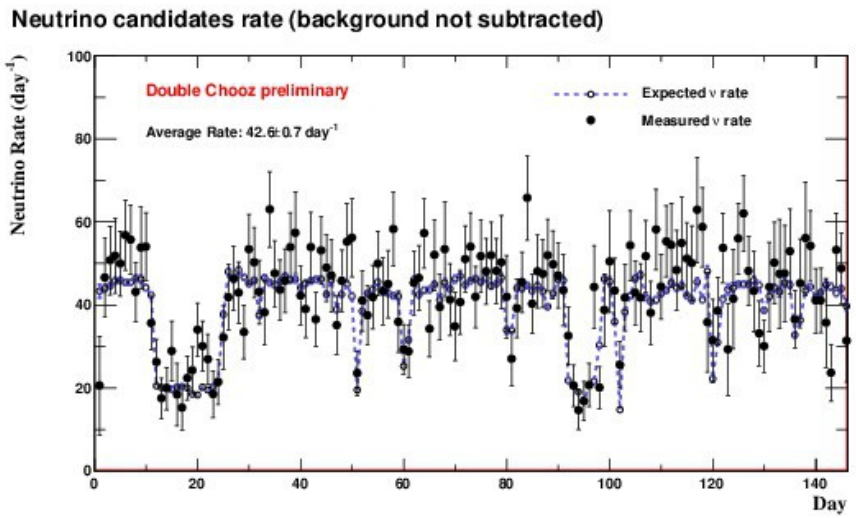


4121 neutrino candidates (inc. ~ 328 bg events)

No oscillation, expect 4344±165 events!

No neutrinos above 8 MeV → constrain Li-9 and fast neutrons

Changing Reactor Power



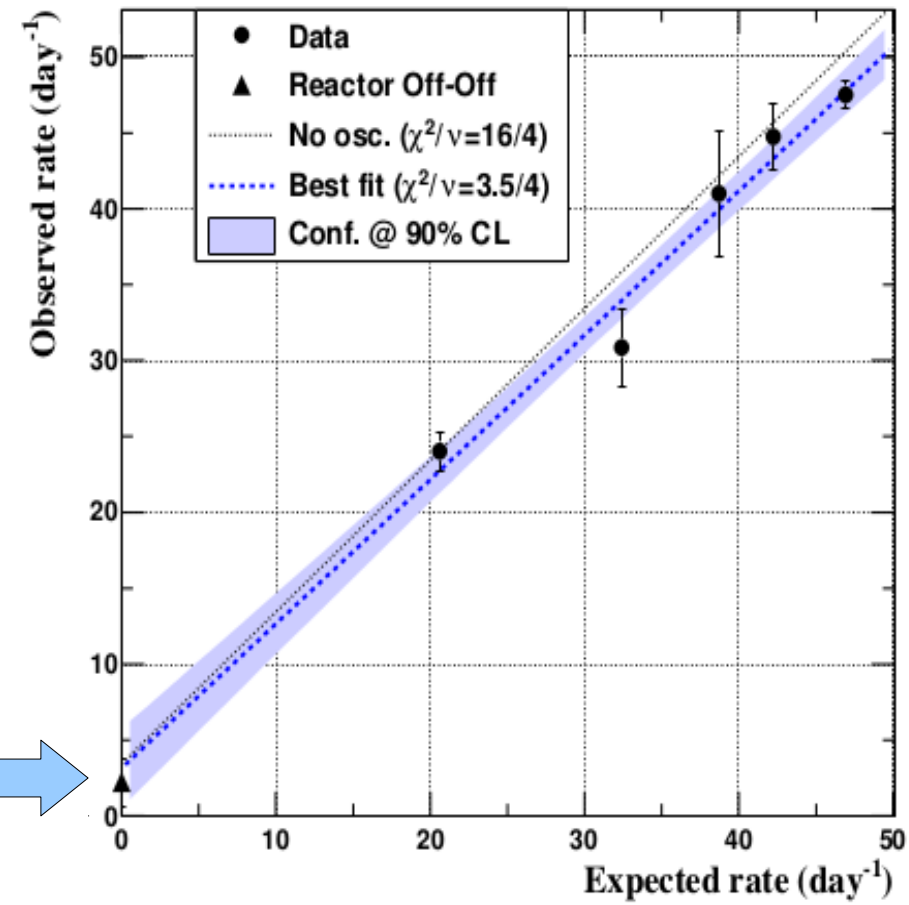
- 101 days (effective)
- 2 months with just 1 reactor
- 1 day both off

Another way of measuring θ_{13}

From slope:

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

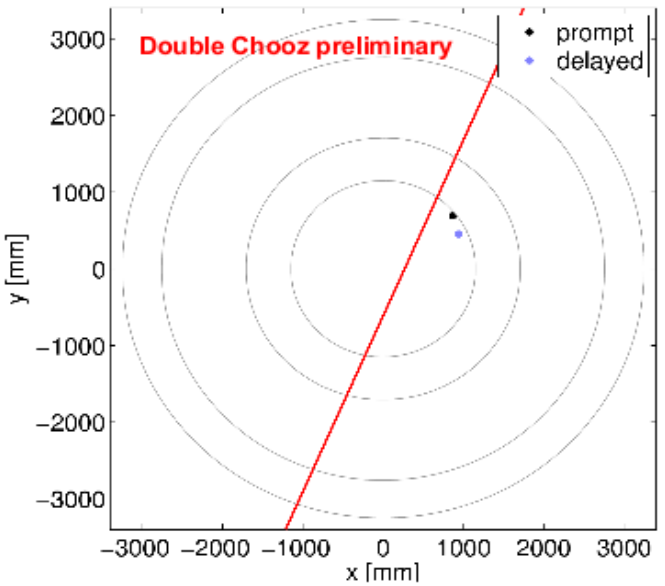
Estimate of background rate!
3.33 +/- 1.32 per day

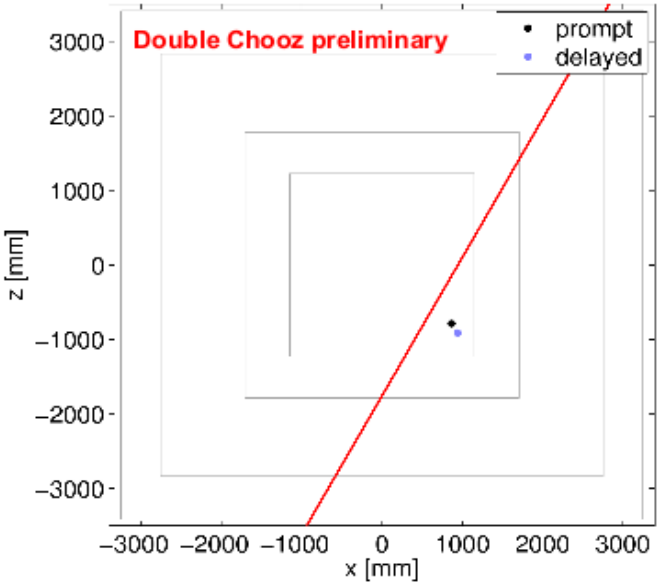


Both Reactors Off

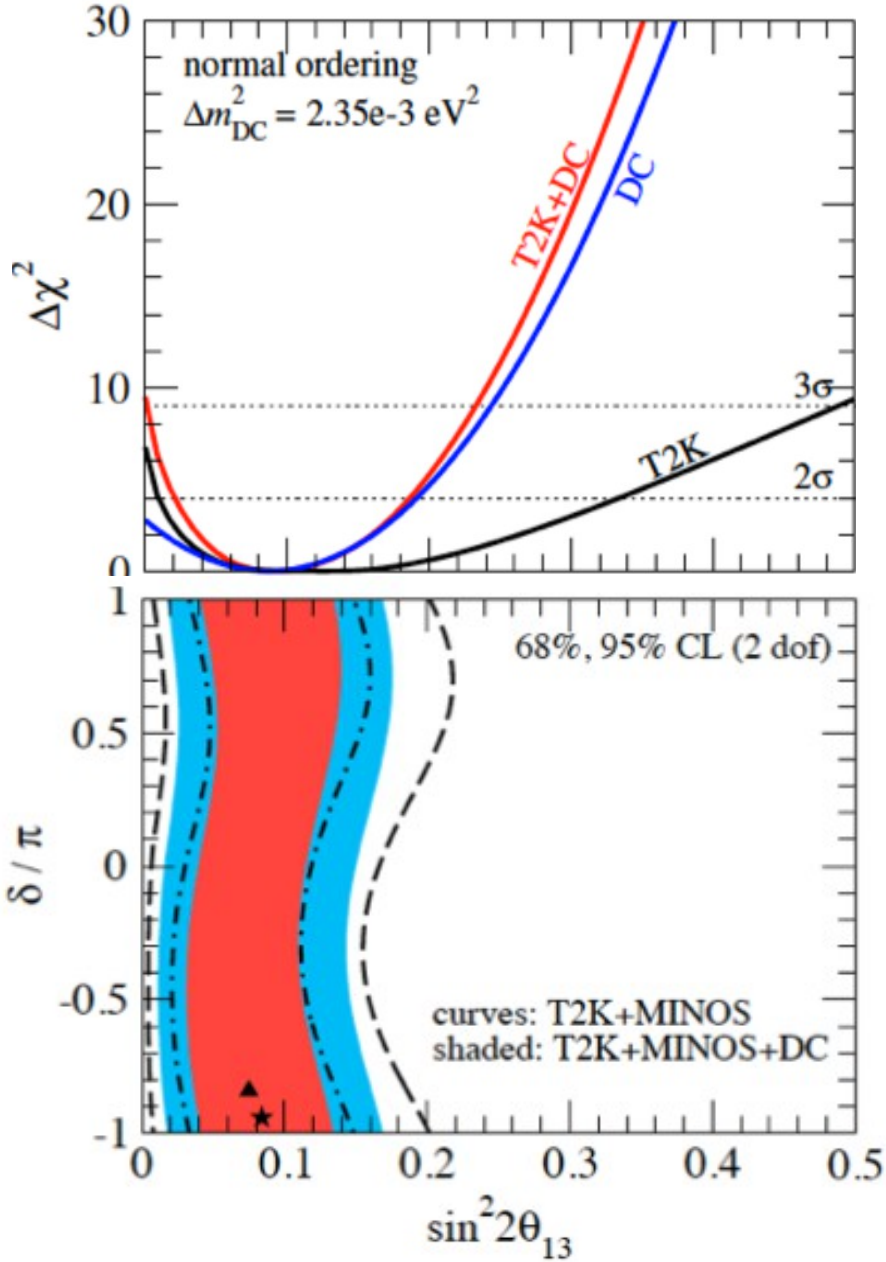
3 candidate neutrino events - 2 Li-9 candidates and 1 stopping muon in chimney

- **^{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$_{(> 600\ \mathrm{MeV})}$**
  - Inner Detector energy 627 MeV
  - Distance to prompt: 30.8 cm
  - Δt to prompt: 241 ms





Double Chooz, T2K and MINOS



$0.003 < \sin^2 2\theta_{13} < 0.219$ at 3σ

Conclusions

- First results from Double Chooz
  - 9th November 2011 LowNu11 presentation by Herve de Kerret and press release
  - 29th December 2011 publication on arXiv hep-ex:1112.6353
- Hint for a non-zero value of θ_{13}
  - $\sin^2 2\theta_{13} = 0.086 \pm 0.041\ (\text{stat}) \pm 0.030\ (\text{syst})$
  - $0.015 < \sin^2 2\theta_{13} < 0.16$ at 90% C.L.
- The near detector will be operational by early 2013
  - Aim for 1σ precision on $\sin^2 2\theta_{13} \sim 0.02$