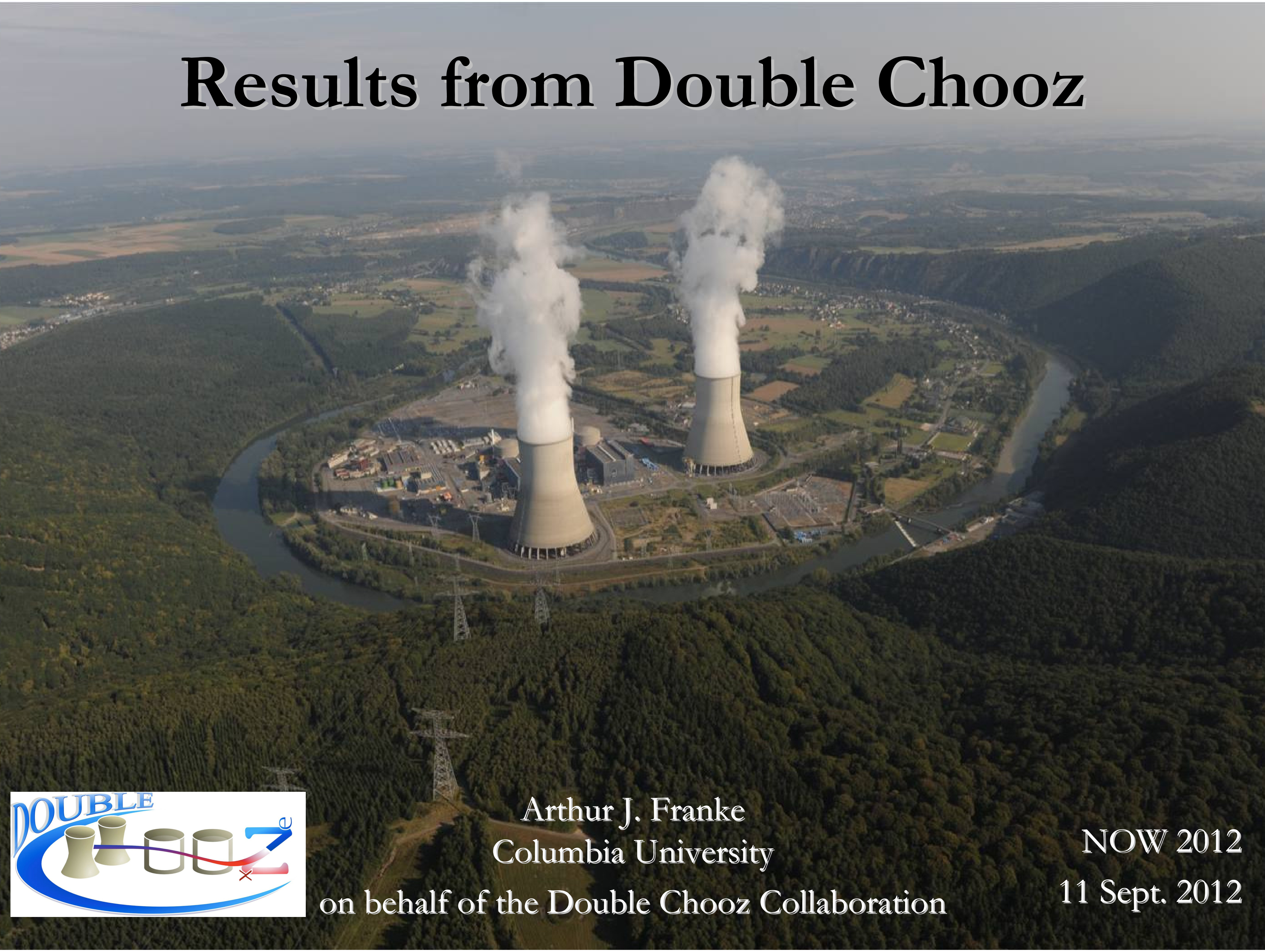
Results from Double Chooz



Arthur J. Franke
Columbia University
on behalf of the Double Chooz Collaboration

NOW 2012
11 Sept. 2012

- Neutrinos & Flavor Oscillations
  - Why is θ_{13} worth measuring?
- The Double Chooz Experiment
  - Observing neutrinos from nuclear power reactors
- Double Chooz Far Detector-Only Analysis
  - Predicted Neutrino Rate
  - Signal & Event Selection Criteria
  - Detector Systematics
  - Background Measurement & Estimation
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PMNS Matrix: What We Knew

Current Measurements: $\Delta m_{12}^2 = 8\times10^{-5}\ \text{eV}^2 \quad , \quad \Delta m_{13}^2 \approx \Delta m_{23}^2 = 2.5\times10^{-3}\ \text{eV}^2$

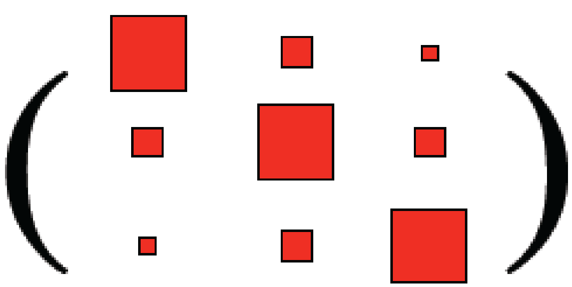
$$U = \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}$$

"Solar" $\theta_{12} \sim 33°$

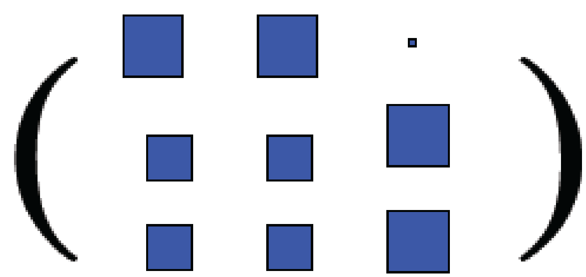
"Little mixing angle"
$\theta_{13} < 11°$ (circa 2011)

"Atmospheric" $\theta_{23} \sim 45°$

This is Quark Mixing



This is Neutrino Mixing



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The 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

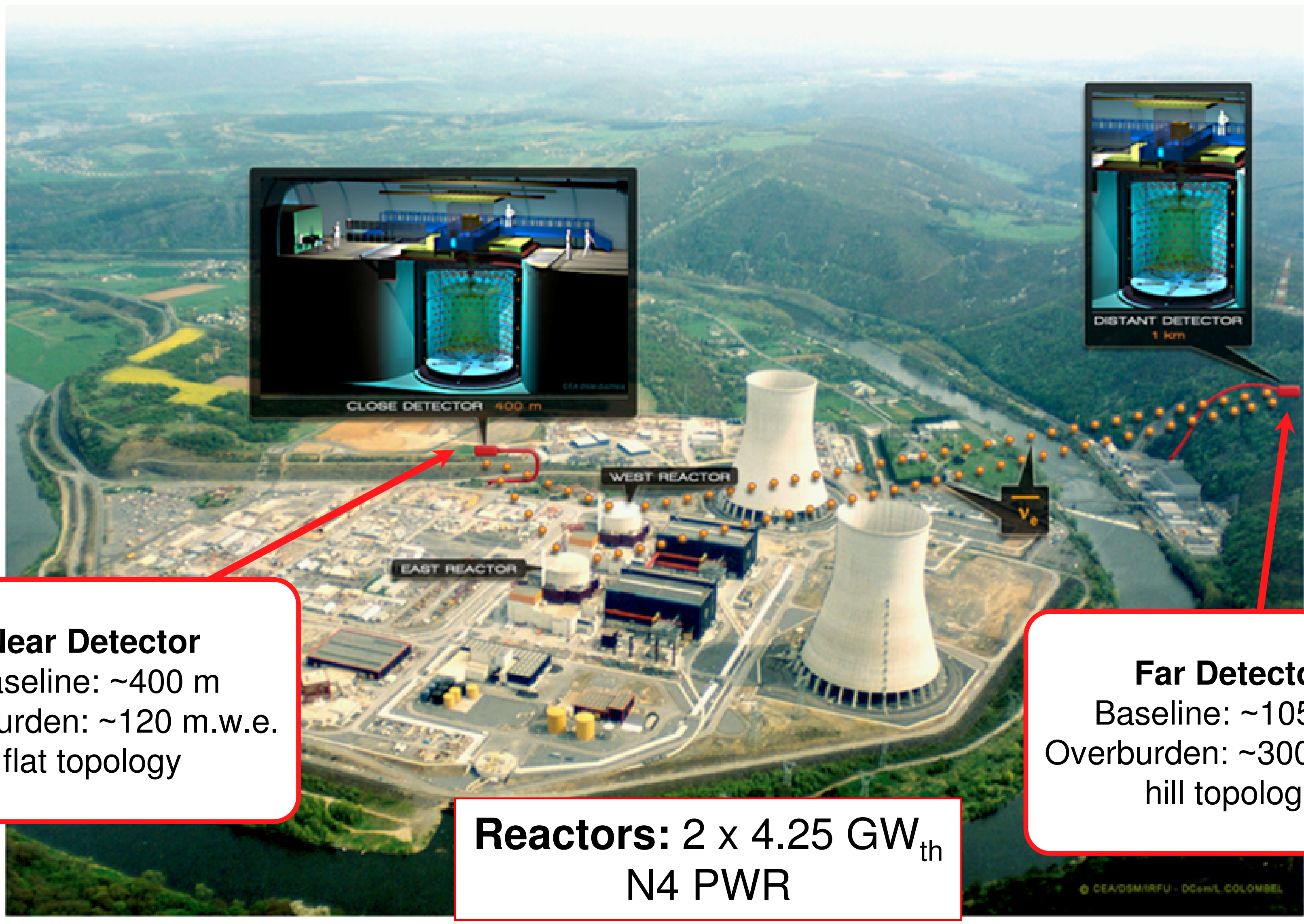
Spain
- CIEMAT-Madrid

USA
- U. Alabama
- ANL
- U. Chicago
- Columbia U.
- UCDavis
- Drexel U.
- IIT
- Kansas State
- 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/

Double Chooz Site in Ardennes, France



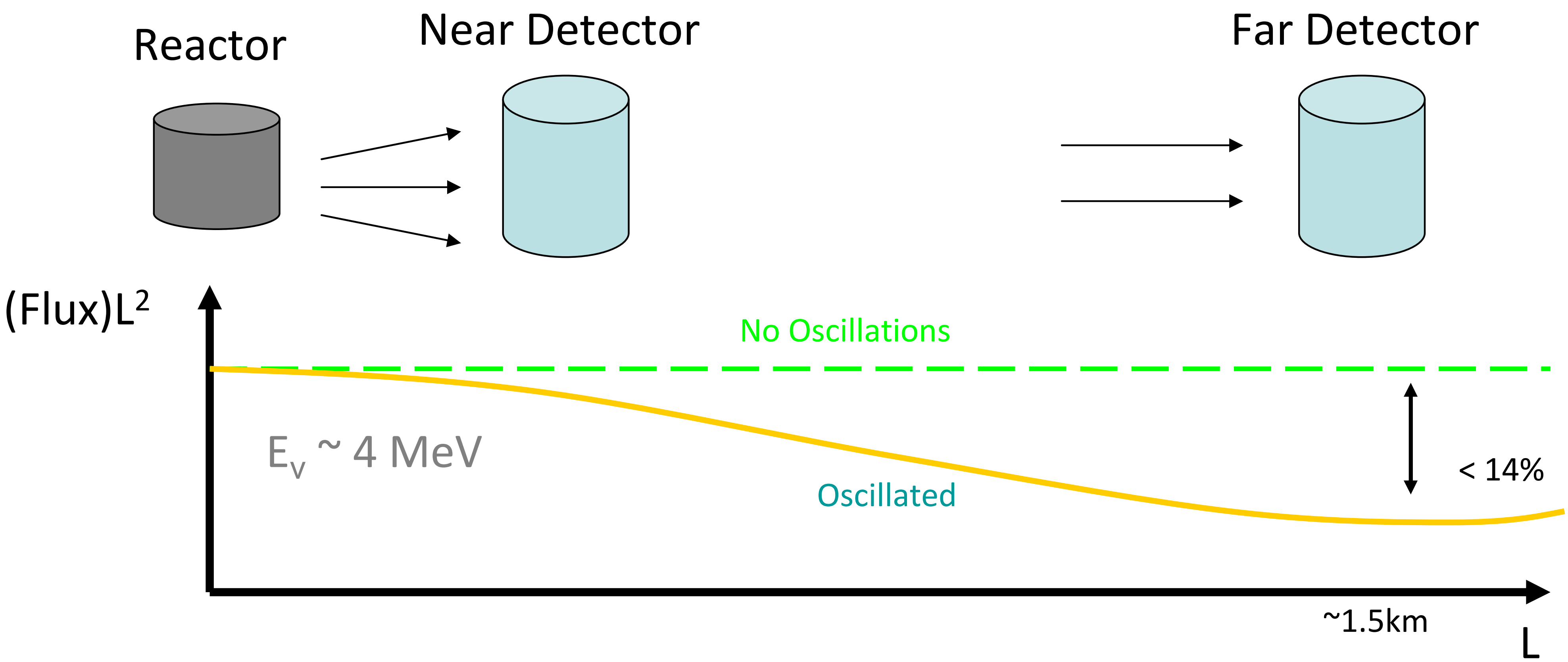
Near Detector
Baseline: ~400 m
Overburden: ~120 m.w.e.
flat topology

Far Detector
Baseline: ~1050 m
Overburden: ~300 m.w.e.
hill topology

Reactors: 2 x 4.25 GW_{th}
N4 PWR

Reactor Oscillation Experiments

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{1.27\,\Delta m^2_{31} L[\mathrm{m}]}{E_\nu[\mathrm{MeV}]}\right)$$



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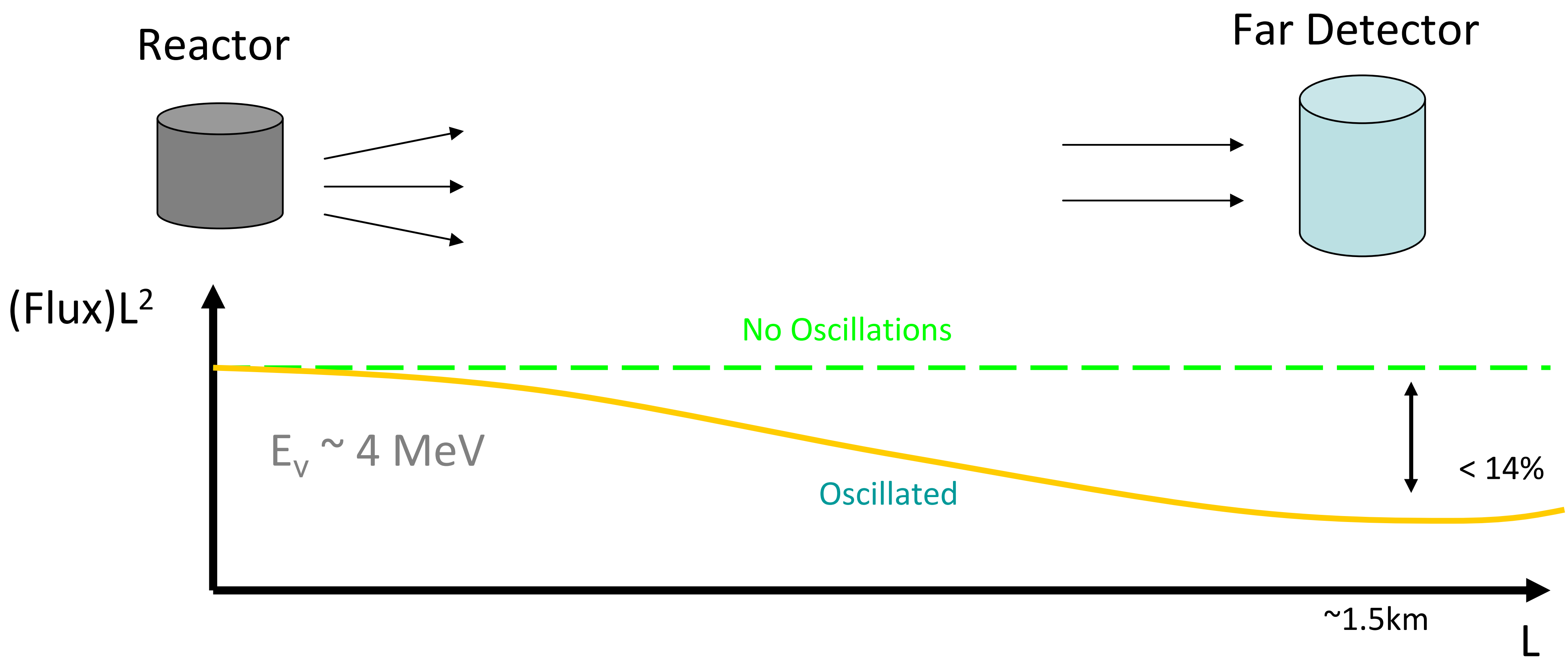
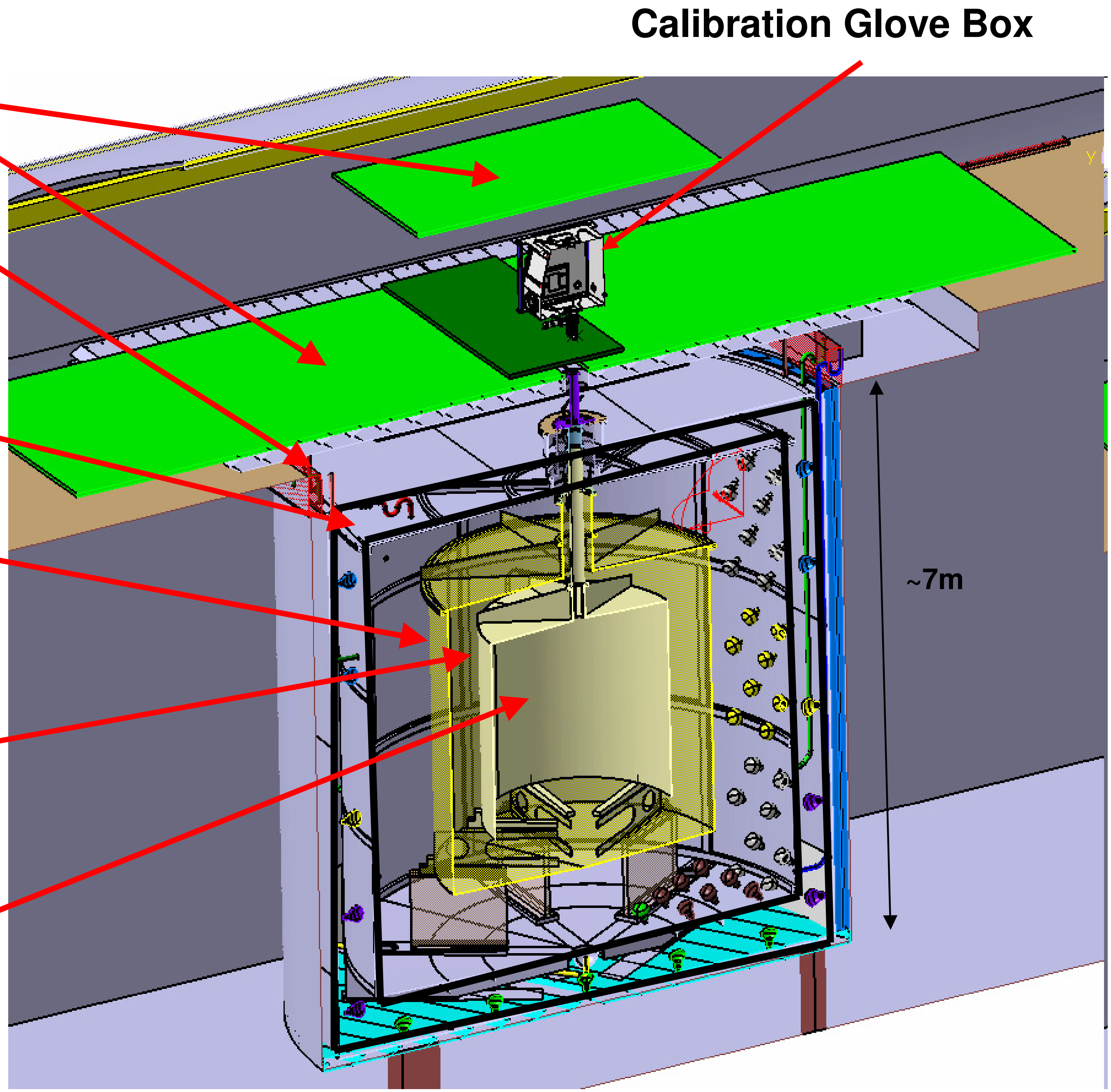


Compare measured spectrum & rate with predicted flux

(These results; near detector under construction)

The Double Chooz Far Detector



Outer Veto (OV)
plastic scintillator strips

Outer Steel Shielding
250 t steel (15 cm)

Inner Veto (IV)
90 m^3 of scintillator in a steel vessel (10 mm) equipped with 78 PMTs (8 inches)

Buffer
110 m^3 of mineral oil in a steel vessel (3 mm) equipped with 390 PMTs (10 inches)

γ-Catcher (GC)
22.3 m^3 scintillator in an acrylic vessel (12 mm)

Target
10.3 m^3 scintillator doped with 1g/l of Gd compound in an acrylic vessel (8 mm)

Experimental Signal

- <u>Inverse β-Decay (IBD), followed by neutron capture</u>
  - Two-part coincidence reduces backgrounds.

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

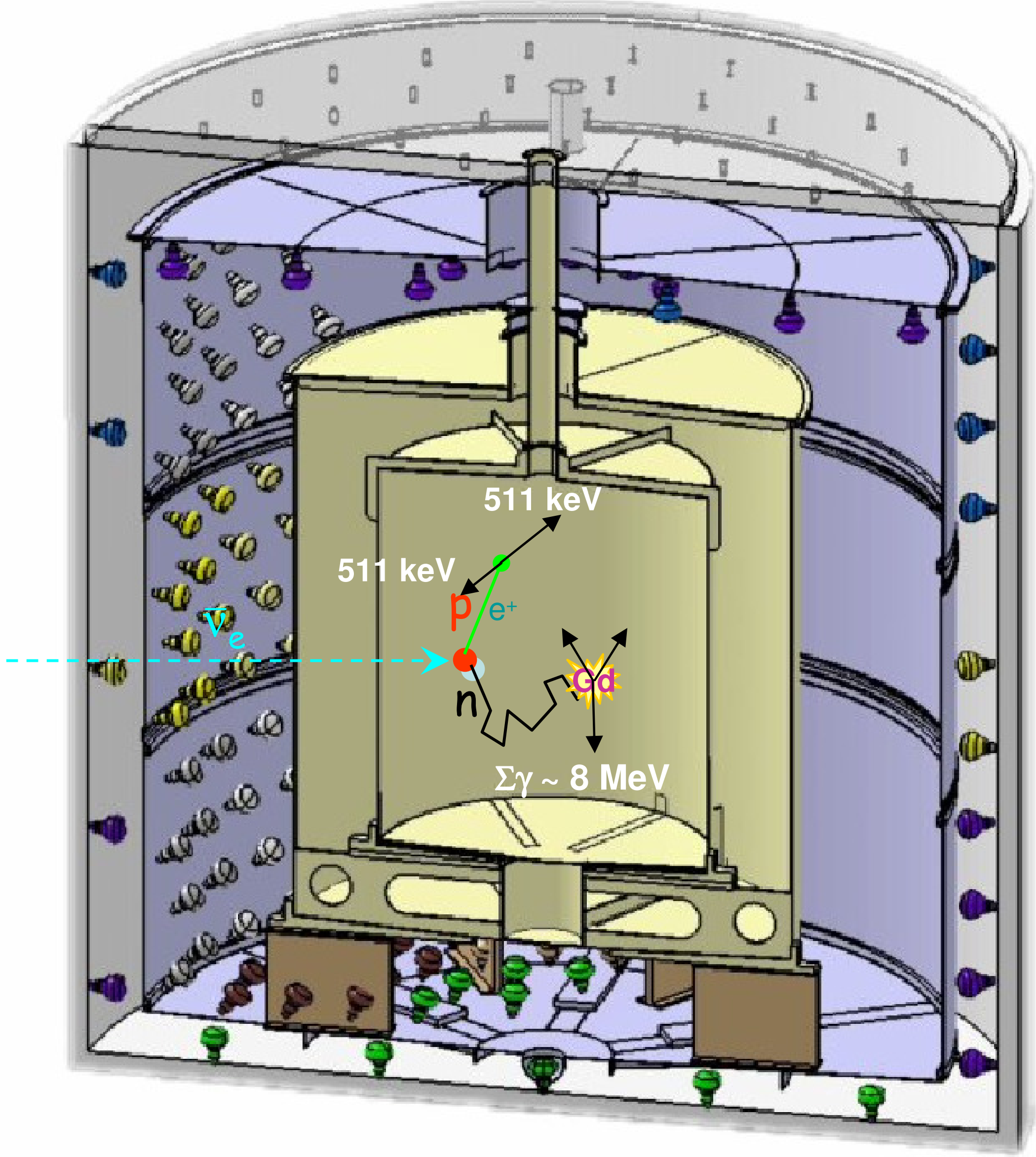
$$\hookrightarrow n\ capture$$

  - Positron energy spectrum implies the neutrino spectrum ($e^+e^- \rightarrow \gamma\gamma$)

$$E_\nu = E_{vis} + 1.8\ \text{MeV} - 2m_e$$

  - Target scintillator doped with gadolinium to enhance capture

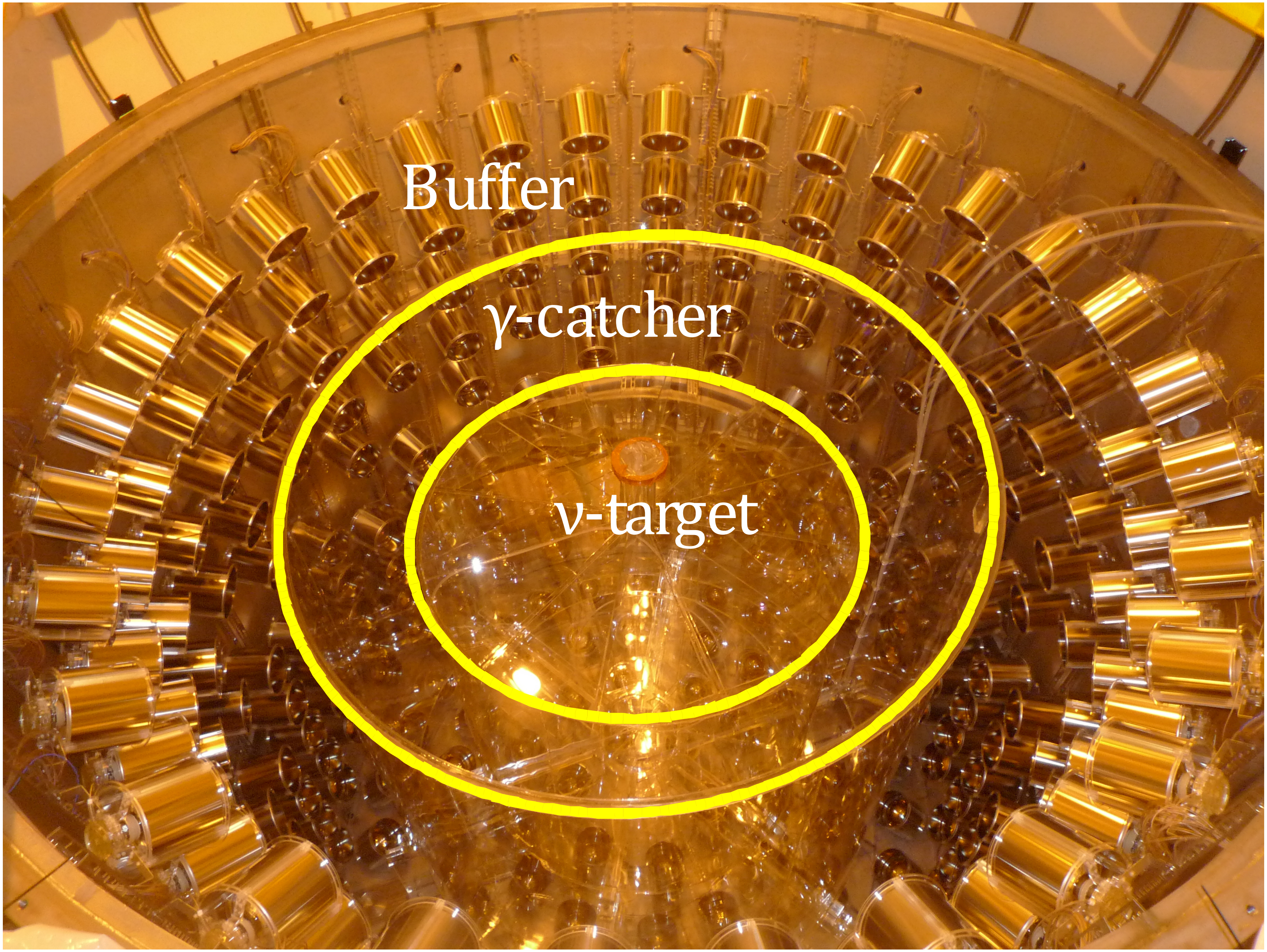
$$n\ {}^{m}\text{Gd} \rightarrow {}^{m+1}\text{Gd}\ \gamma\text{'s (8 MeV)}$$



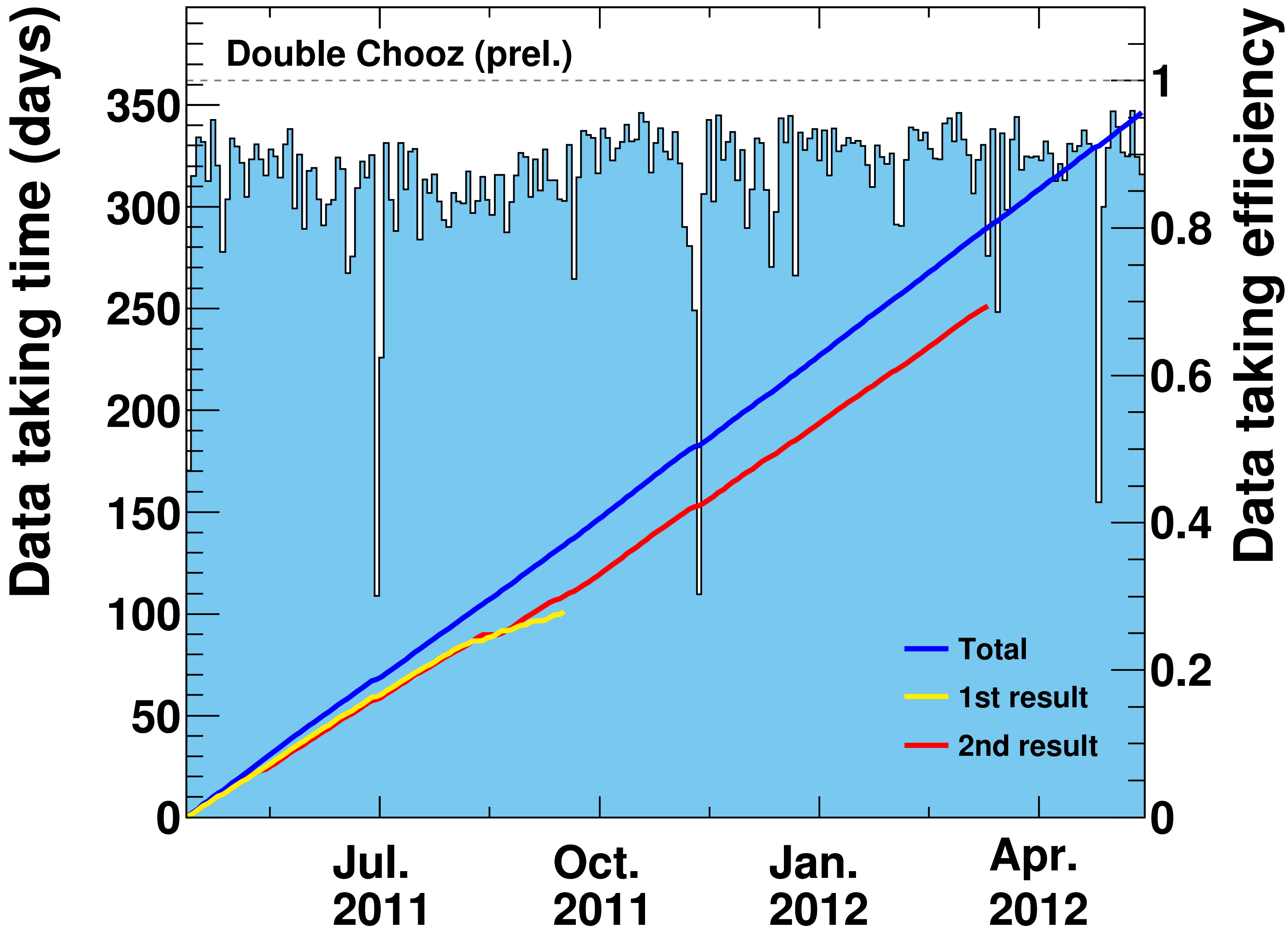
<u>Signal</u> = Positron signal + Neutron capture on Gd signal ~30 μsec after

Far Detector Construction

Three Detector Sub-Volumes



Outer Veto Installed



Run time: 251.3 days from April 2011 to March 2012

CBS Network Comedy "Big Bang Theory"

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Predicted Neutrino Rate

$$N_{\nu}^{\exp}(E,t) = \sum_{\substack{\text{Reactors} \\ R=\{1,2\}}} \frac{N_p \varepsilon}{4\pi L_R^2} \times \frac{P_{th,R}(t)}{\left\langle E_f \right\rangle_R (t)} \times \left\langle \sigma_f \right\rangle_R (E,t)$$

Predicted Neutrino Rate

Target Proton Count:

Number of protons in the Gd-doped target region of the detector. Units of [protons].

Detector Efficiency:

Fraction of the number of IBD interactions in the detector which pass selection cuts.

$$N_{\nu}^{\exp}(E,t) = \sum_{\substack{\text{Reactors} \\ R=\{1,2\}}} \frac{N_p \varepsilon}{4\pi L_R^2} \times \frac{P_{th,R}(t)}{\left\langle E_f \right\rangle_R (t)} \times \left\langle \sigma_f \right\rangle_R (E,t)$$

Baseline:

Distance-of-flight from neutrino creation in reactor to vertex of IBD interaction in detector. Units of [cm].

Predicted Neutrino Rate

Average Cross-Section Per Fission:

The probability that an average reactor fission will create a neutrino interaction with a single target proton. Units of [cm^2/(fission*proton)].

$$N_\nu^{\exp}(E,t) = \sum_{\substack{\text{Reactors} \\ R=\{1,2\}}} \frac{N_p \varepsilon}{4\pi L_R^2} \times \frac{P_{th,R}(t)}{\langle E_f \rangle_R (t)} \times \langle \sigma_f \rangle_R (E,t)$$

Average Energy Per Fission:

The average energy released by a fuel fission, based on reactor composition. Units of [MeV].

Reactor Power:

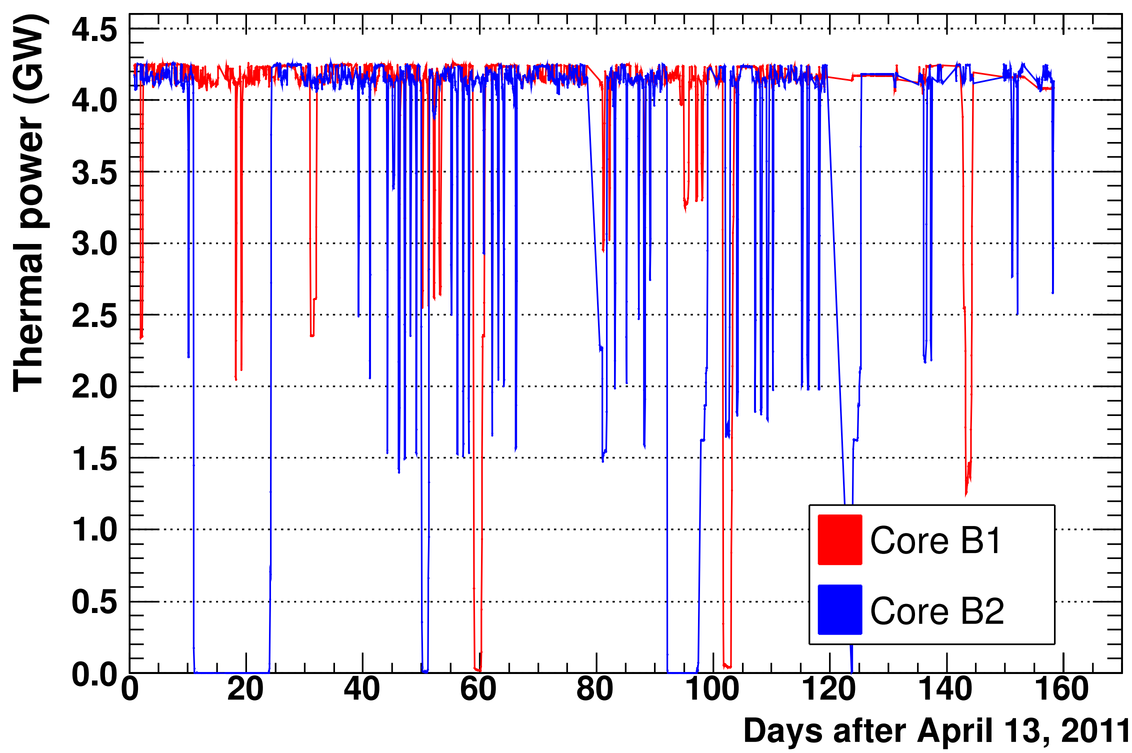
Thermal power emitted by fissioning reactor fuel. Units of [GW_{th}].

Core Thermal Power

$$N_\nu^{\exp}(E,t) = \sum_{\substack{\text{Reactors}\\ R=\{1,2\}}} \frac{N_p \varepsilon}{4\pi L_R^2} \times \frac{P_{th,R}(t)}{\langle E_f \rangle_R (t)} \times \langle \sigma_f \rangle_R (E,t)$$

- Precise weekly measurements of steam generator enthalpy balance.
- Monitoring every minute based on temperature in primary loop.
- Full error treatment by EDF

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



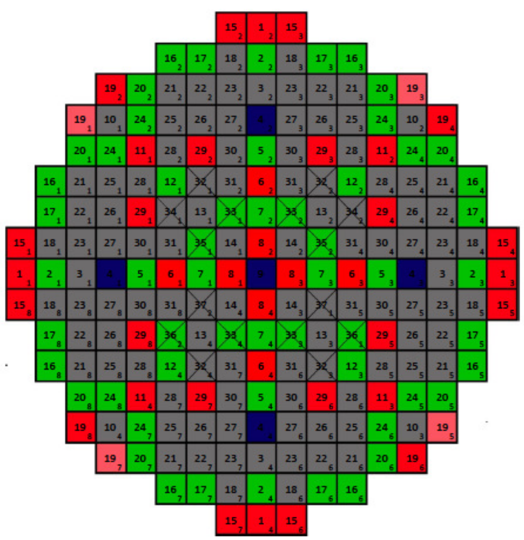
Core Fuel Composition

$$N_{\nu}^{\exp}(E,t) = \sum_{\substack{\text{Reactors} \\ R=\{1,2\}}} \frac{N_p \varepsilon}{4\pi L_R^2} \times \frac{P_{th,R}(t)}{\langle E_f \rangle_R (t)} \times \langle \sigma_f \rangle_R (E,t)$$

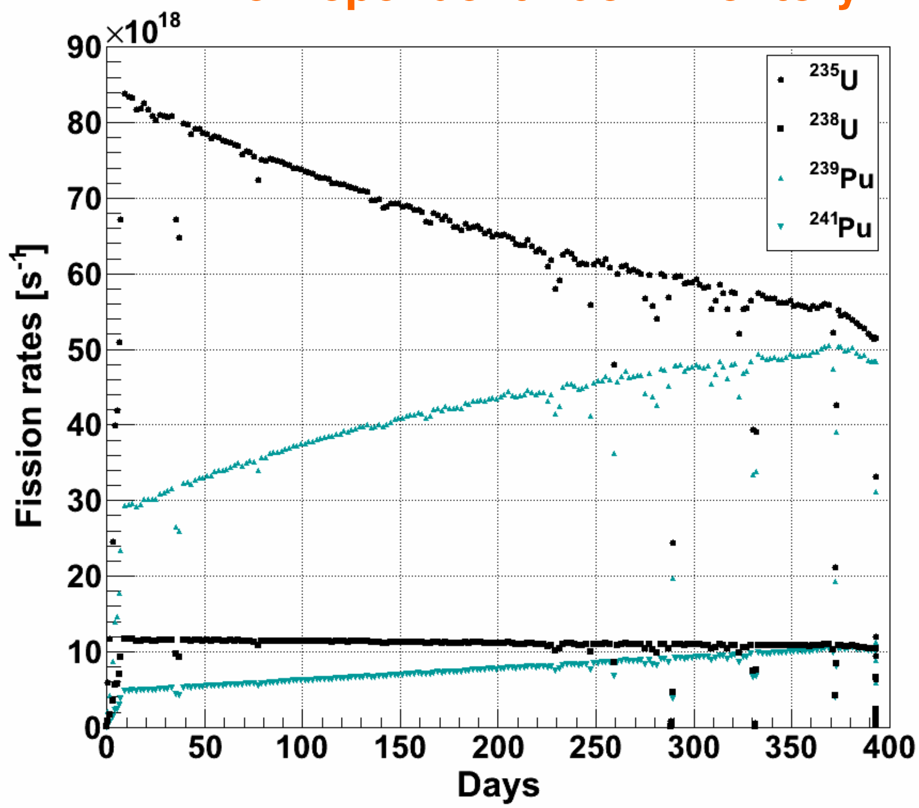
$$\langle E_f \rangle (t) = \sum_k \alpha_k(t) \langle E_k \rangle$$

Two validated reactor simulations:

- **DRAGON: deterministic**
- **MURE (MCNP Utility for Reactor Evolution): Monte-Carlo Based**
- **Benchmarked against fuel assays:**
  C. Jones et al. arxiv.org/pdf/1109.5379

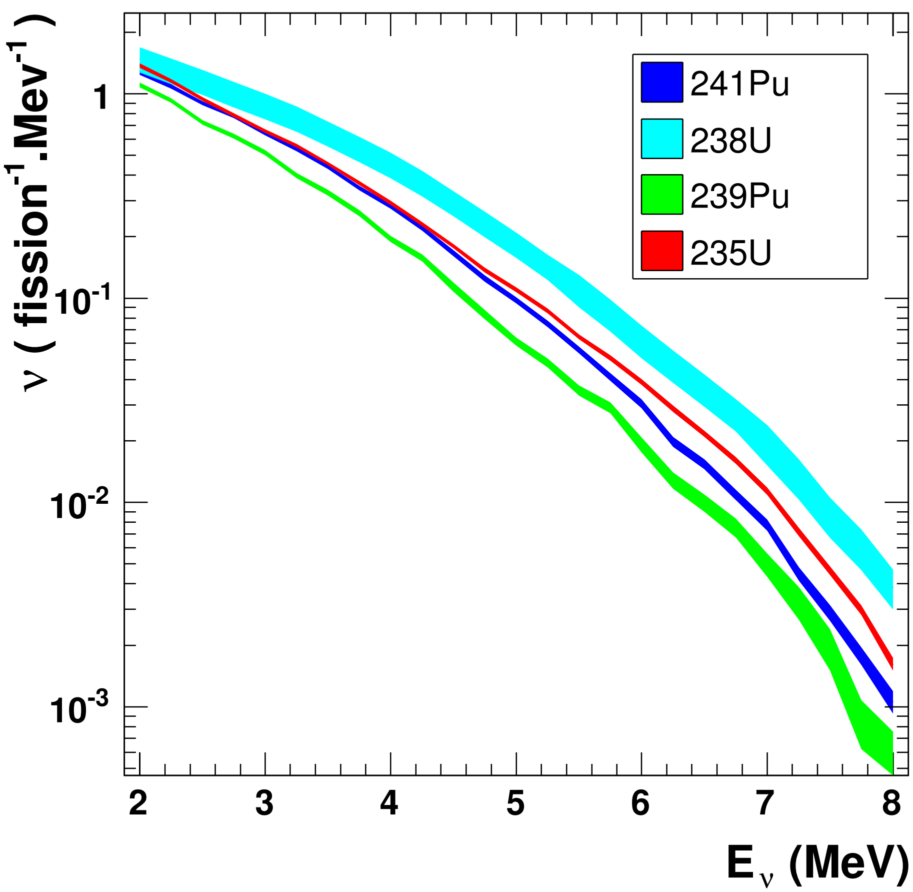


Time-Dependent Fuel Inventory



Interaction Cross-Section

$$N_\nu^{\exp}(E,t) = \sum_{\substack{\text{Reactors}\\ R=\{1,2\}}} \frac{N_p \varepsilon}{4\pi L_R^2} \times \frac{P_{th,R}(t)}{\langle E_f \rangle_R (t)} \times \langle \sigma_f \rangle_R (E,t)$$



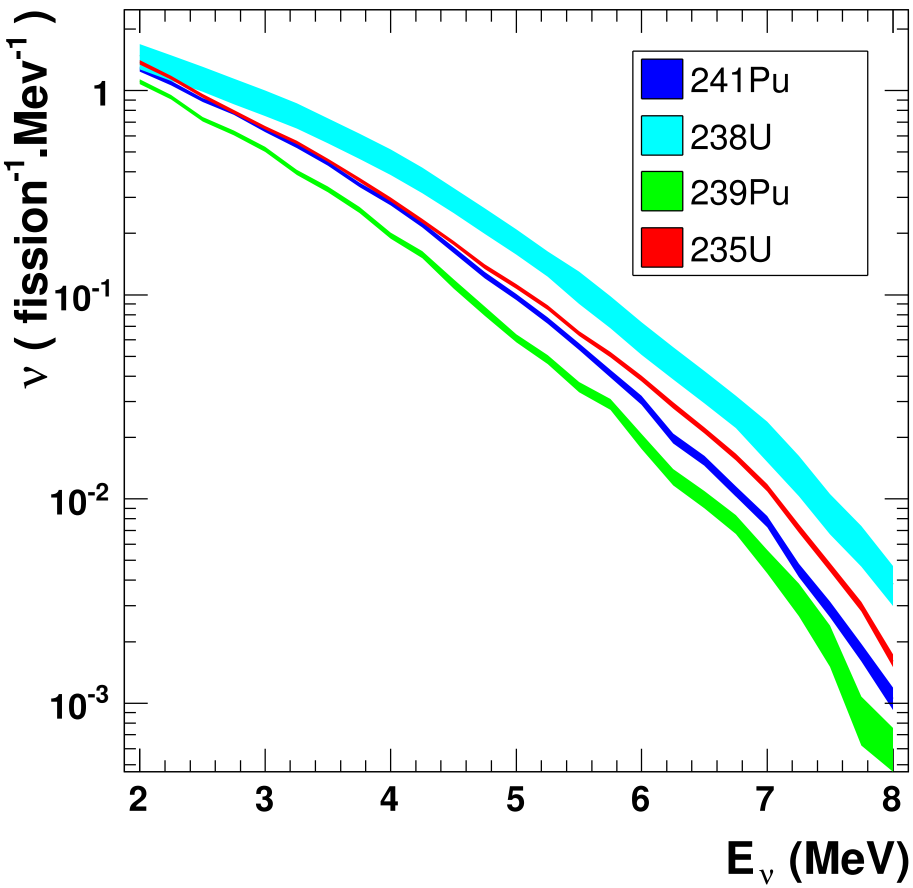
$$\langle \sigma_f \rangle_k = \int_0^\infty dE\, S_k(E)\, \sigma_{IBD}(E)$$

• Recalculations of spectra introduced normalization shift; "anomaly"?

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

Reference Spectra + Bugey4 "Anchor"

$$N_{\nu}^{\exp}(E,t) = \sum_{\substack{\text{Reactors} \\ R=\{1,2\}}} \frac{N_p \varepsilon}{4\pi L_R^2} \times \frac{P_{th,R}(t)}{\langle E_f \rangle_R (t)} \times \langle \sigma_f \rangle_R (E,t)$$



+

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

Normalize to Total Rate Measurement of Bugey4

↓

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

Reduces reactor normalization uncertainty from 2.70% to 1.76%

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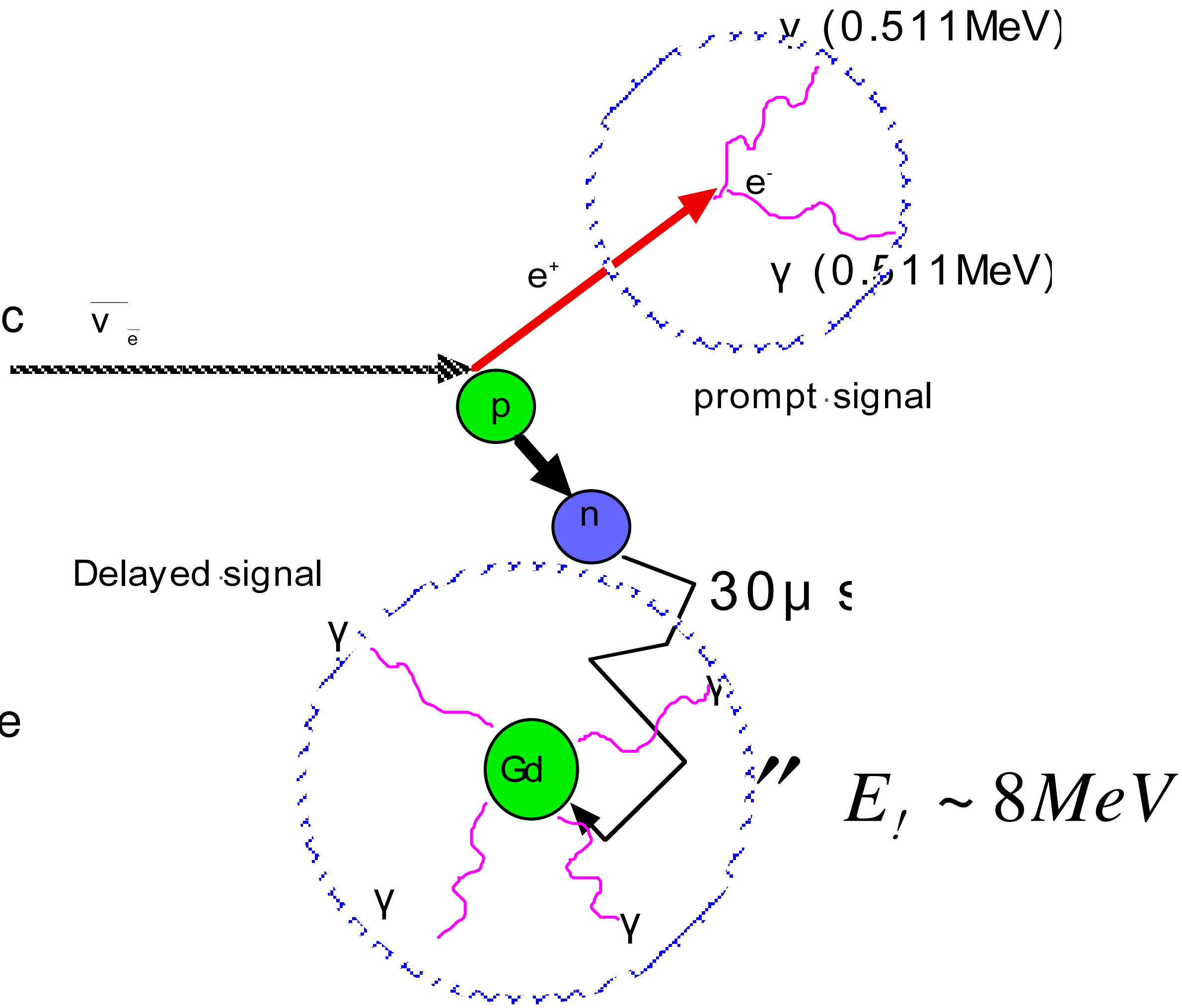
Neutrino Candidate Selection

- Prompt signal Evis = [0.7, 12.2] MeV
- Delayed signal Evis = [6.0, 12.0] MeV
- Delayed Coincidence Δt = [2, 100] μsec
- Require Δt_{μ} > 1 msec
- PMT light noise rejection cuts
  - PMT hits approx. homogeneous
  - PMT hits approx. coincident in time
- Multiplicity conditions:
  - No extra events around signal
- Background rejection:
  - No coincident signal in OV
  - Require Δt_{μ} > 500 msec if E_{μ} > 600 MeV



Plus three irreducible backgrounds:

- Accidentals
- Cosmogenic ^{9}Li
- Fast neutrons/stopping muons

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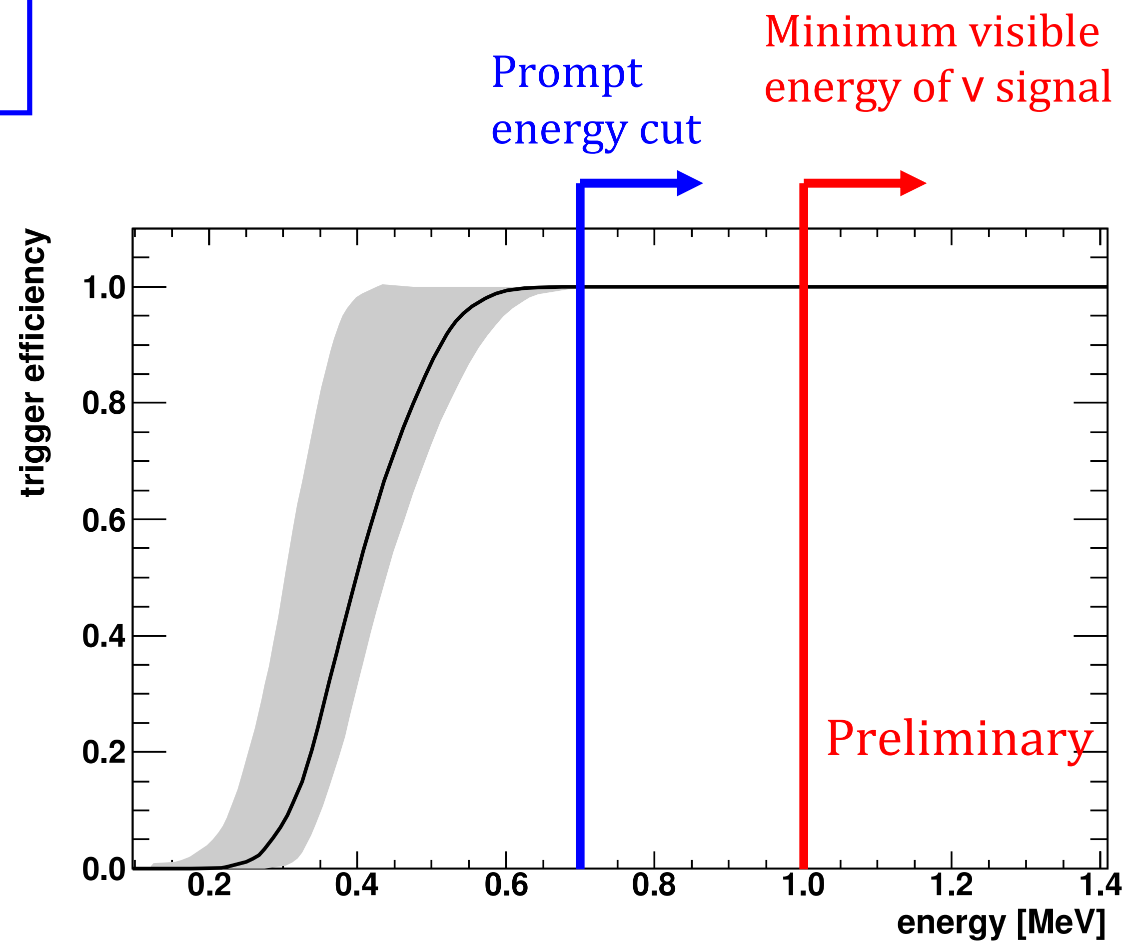

Trigger efficiency

- Threshold at 400keV (ε=50%)
- ε=100% above 700keV

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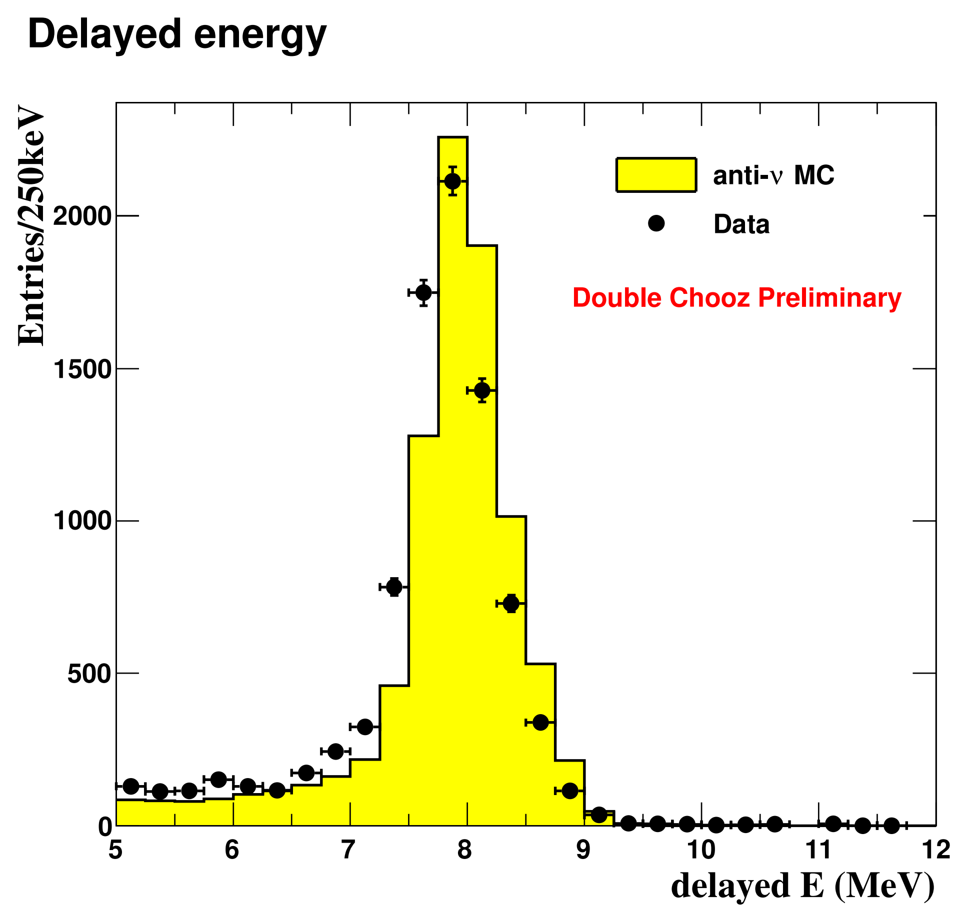

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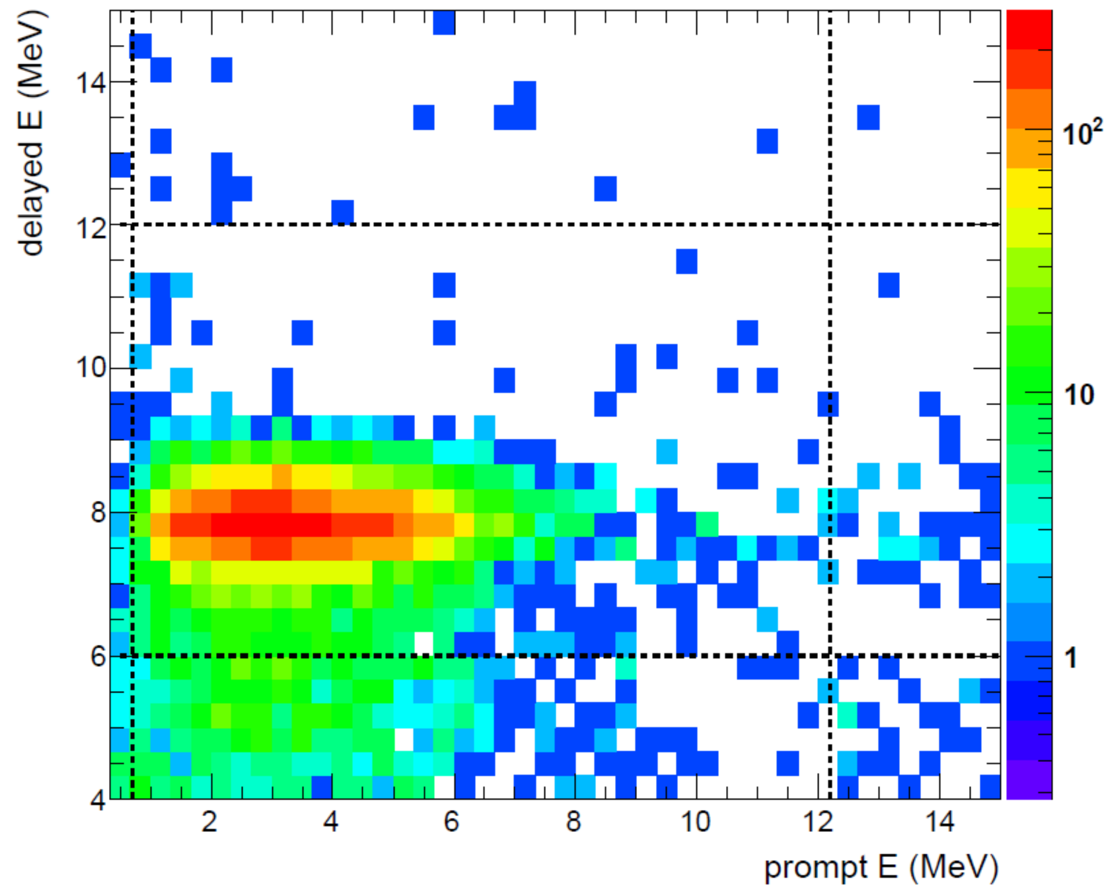

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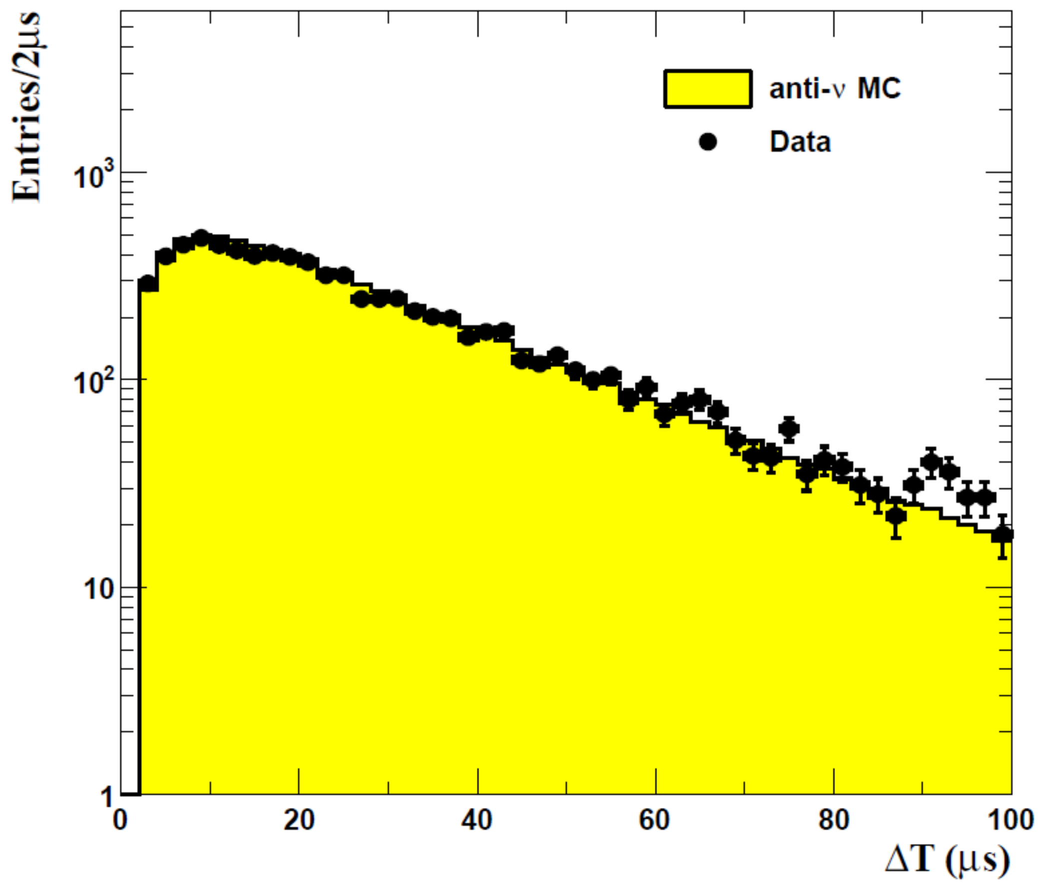

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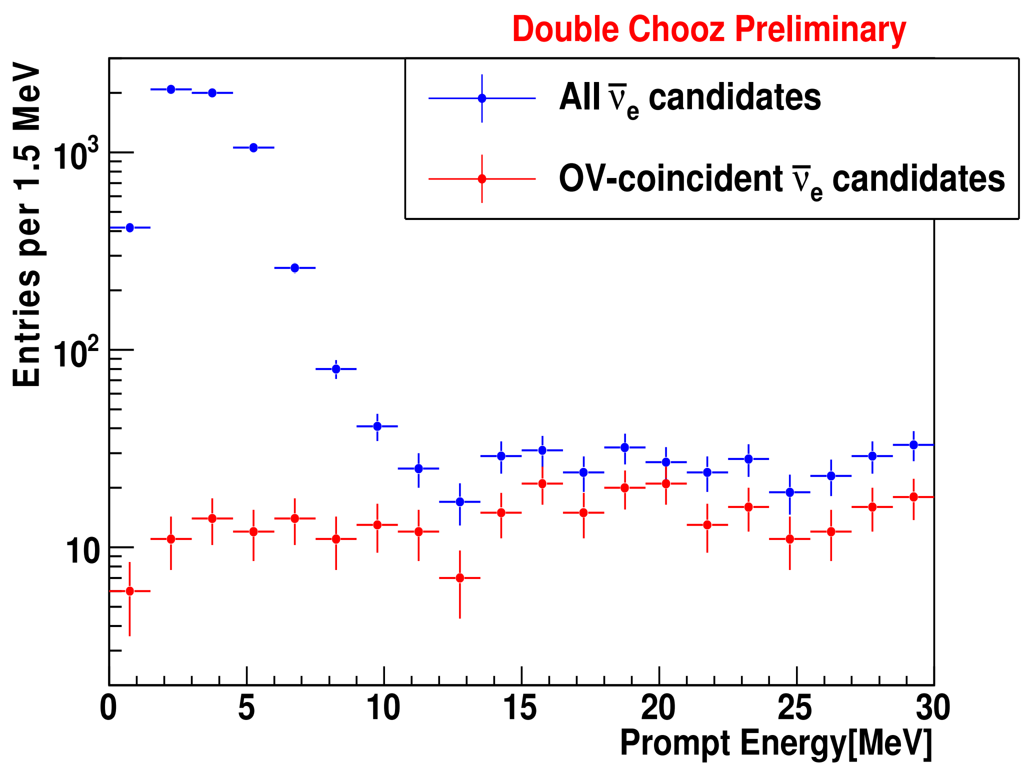
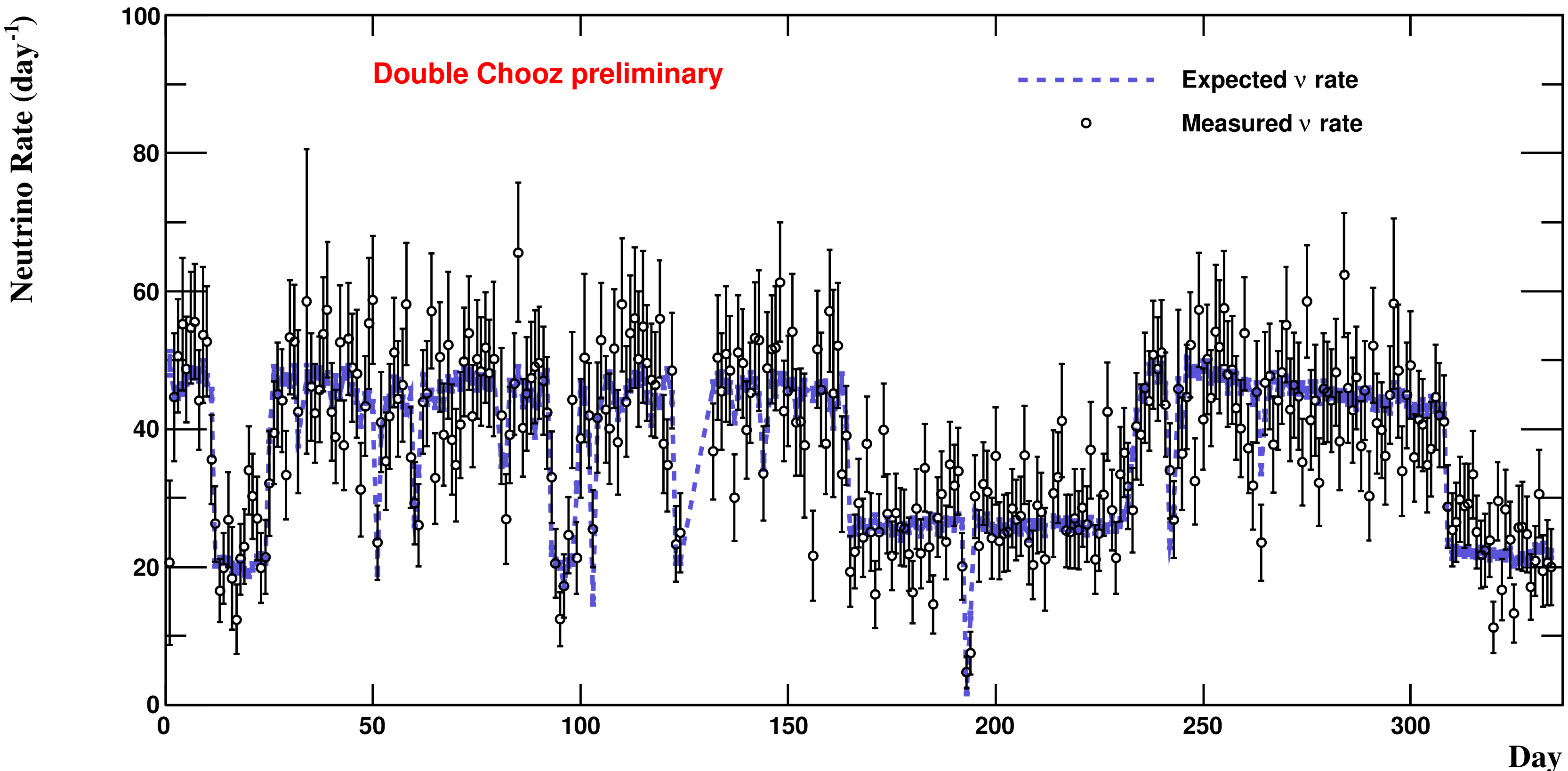


- 41% of ^{9}Li BG is rejected by additional muon veto (~5% live-time loss)
- 28% of fast neutron/stop μ BG is rejected by OV anticoincidence

Candidate Rate Variation

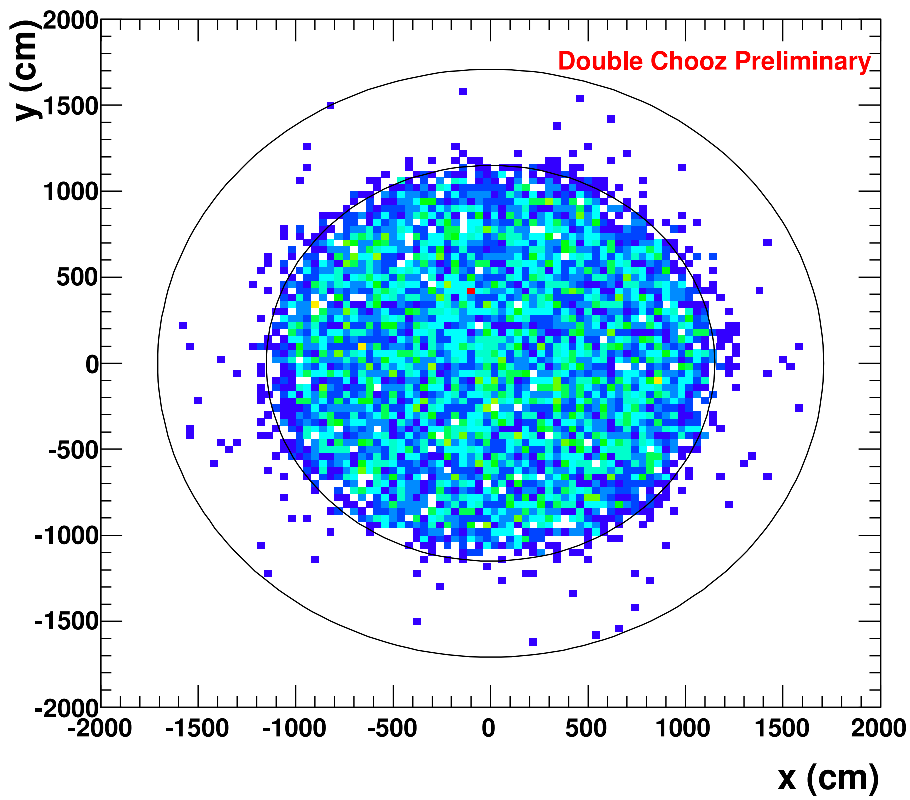
Neutrino rate



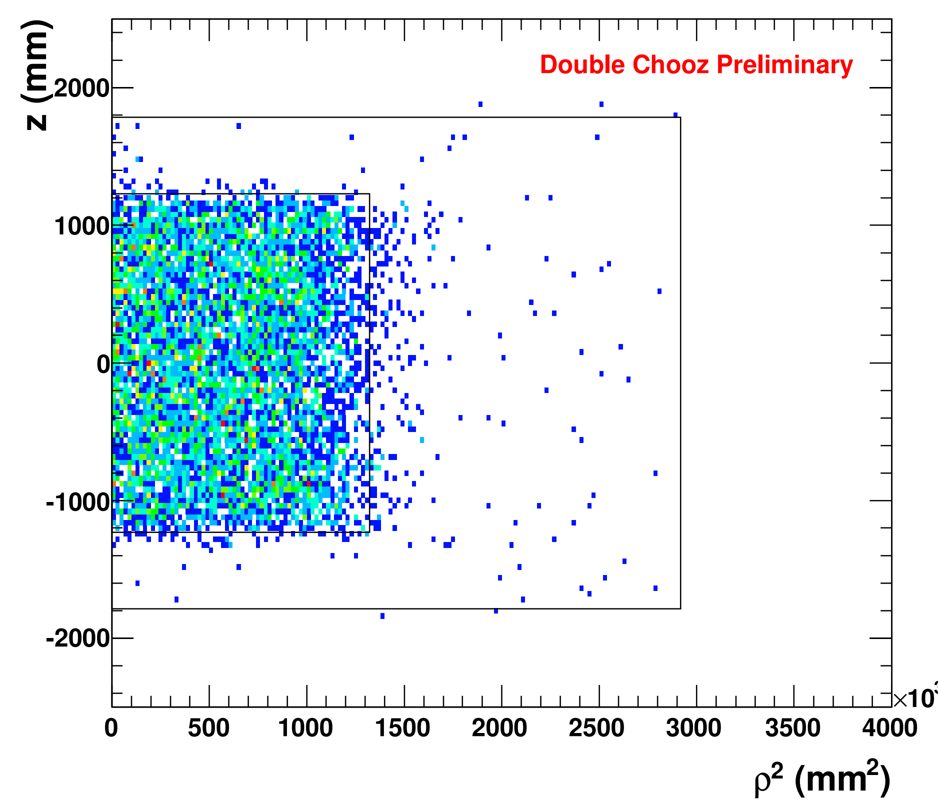
- Before 9Li reduction cut, no OV anticoincidence applied
- Not background-subtracted
- Rate consistent with expectation

Cross-check: Reconstructed Vertex Position

Prompt vertex XY position



Prompt vertex Zρ^2 position



- Events well-localized within target
- Note: no spatial cuts applied in candidate selection

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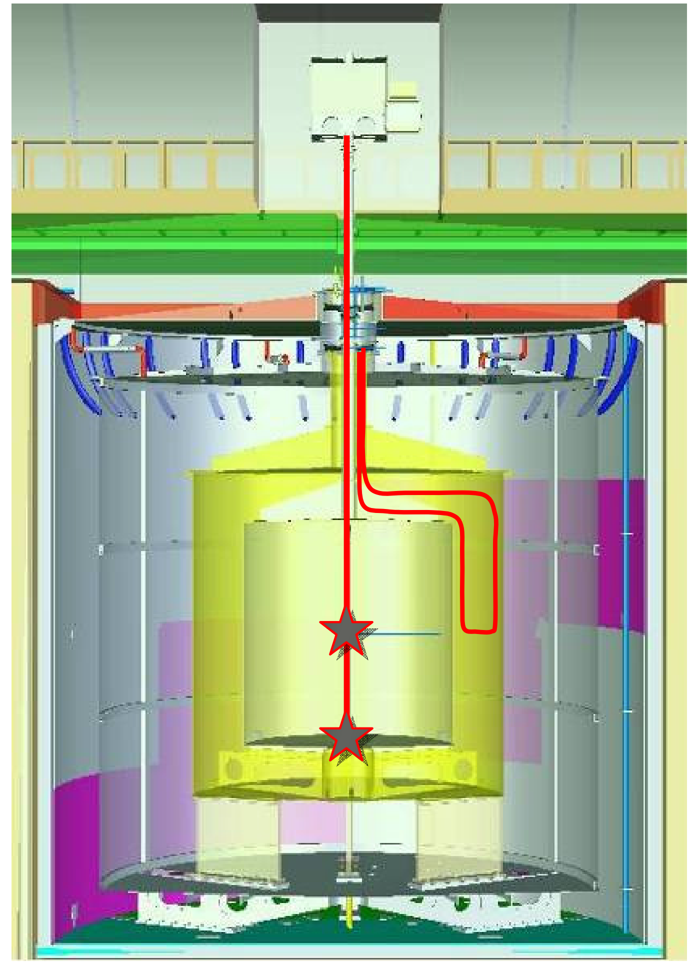
Detector Calibration

Energy Calibration

1. PMT and electronics gain non-linearity calibration
   – LED light injection system
2. Correct for position dependence
   – Spallation neutron H captures
3. Correct for time stability
   – Spallation neutron Gd captures
4. Energy scale
   – Radioactive sources deployed into ν-target and γ-catcher



Neutron Detection Efficiency

Energy & time window, Gd fraction, spill in/out effects

- ^{252}Cf source deployed into ν-target and γ-catcher

Detector Calibration

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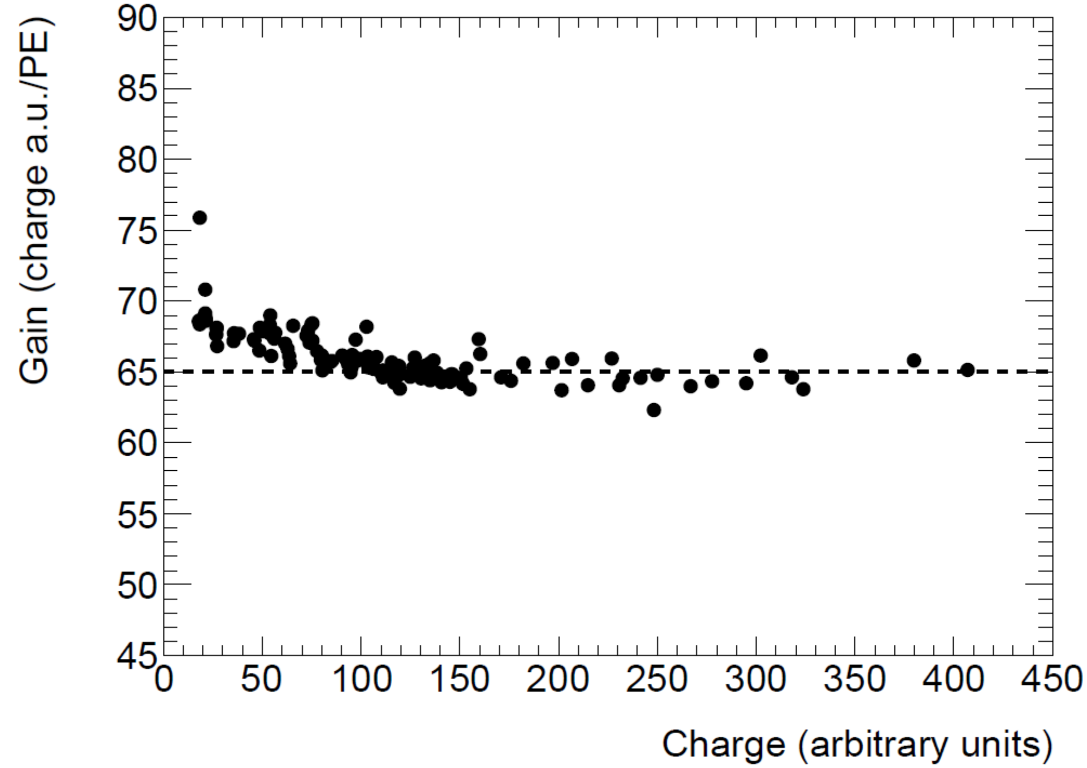

Example single-channel gain dependence

Neutron Detection Efficiency

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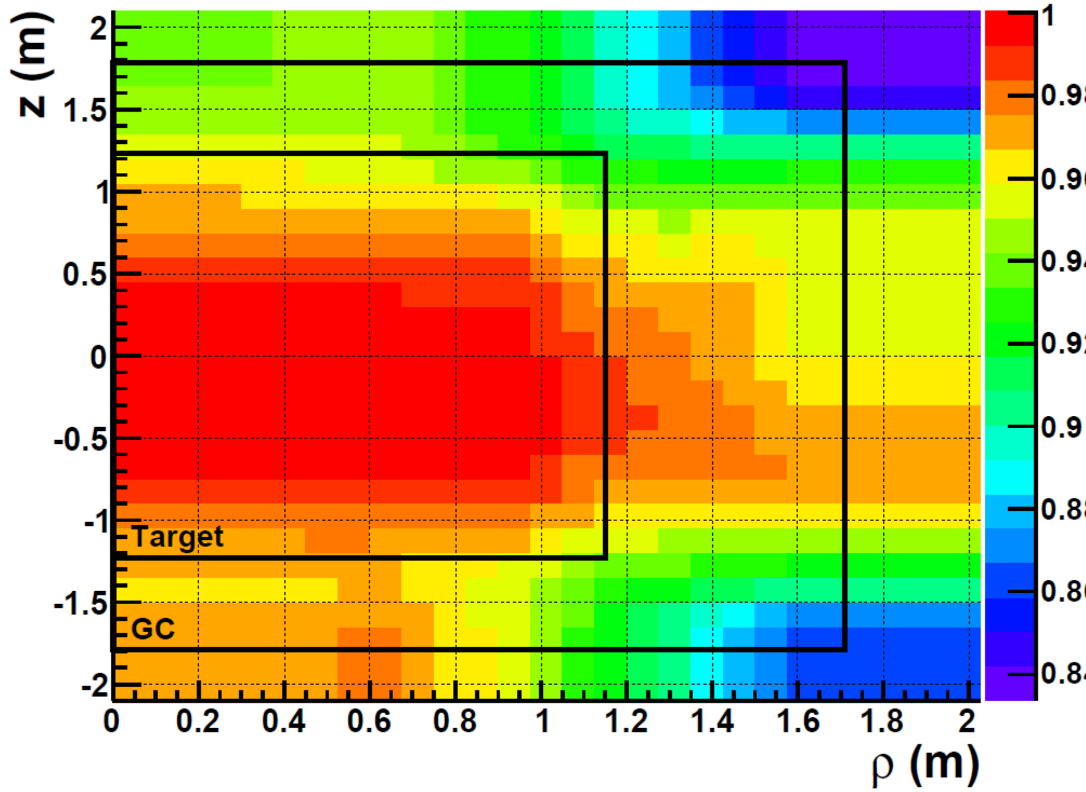

Spallation n-H Detector Response Map

Neutron Detection Efficiency

Energy & time window, Gd fraction, spill in/out effects

- ^{252}Cf source deployed into ν-target and γ-catcher

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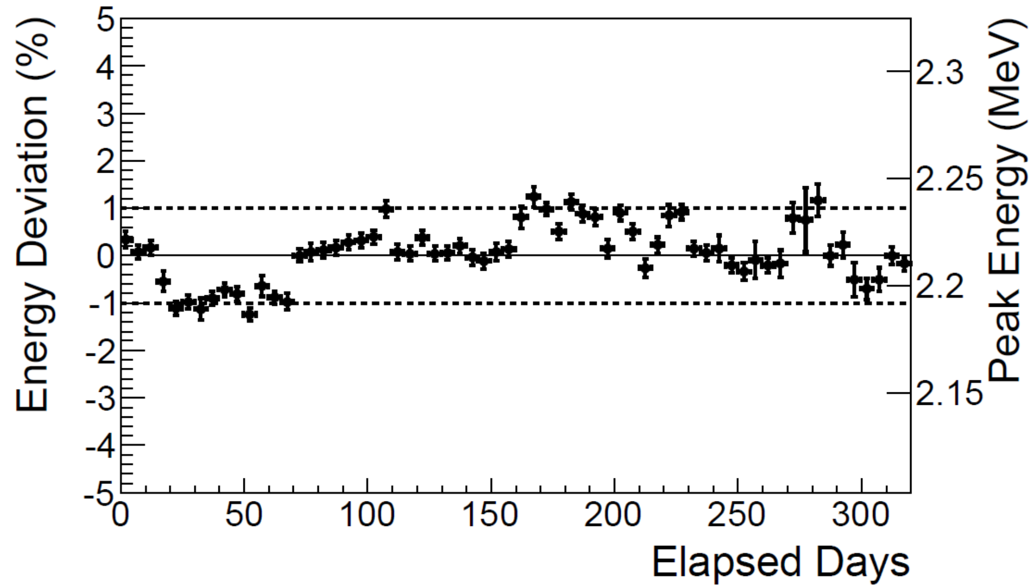

Spallation n-H capture peak position after stability correction

Neutron Detection Efficiency

Energy & time window, Gd fraction, spill in/out effects

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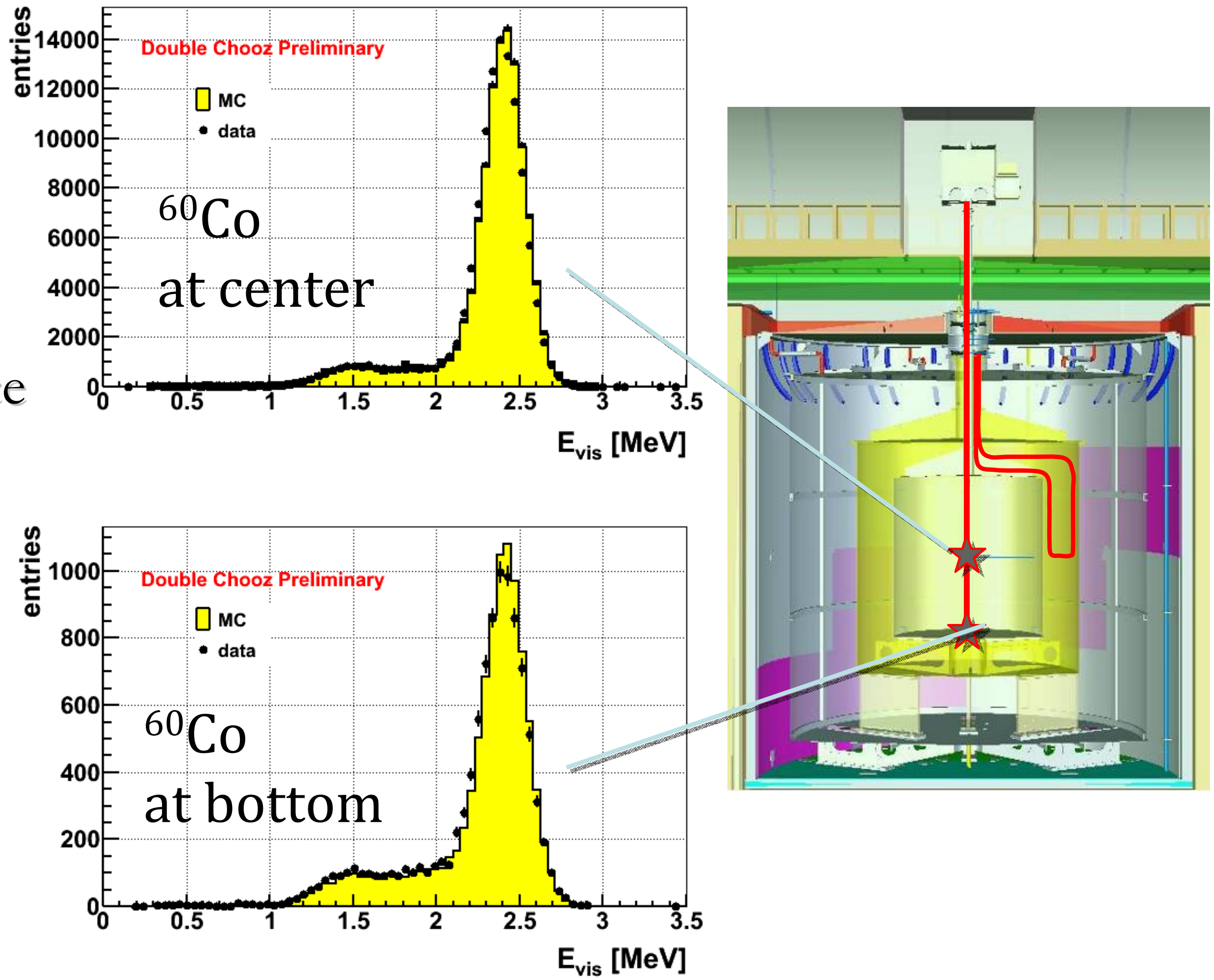


Neutron Detection Efficiency

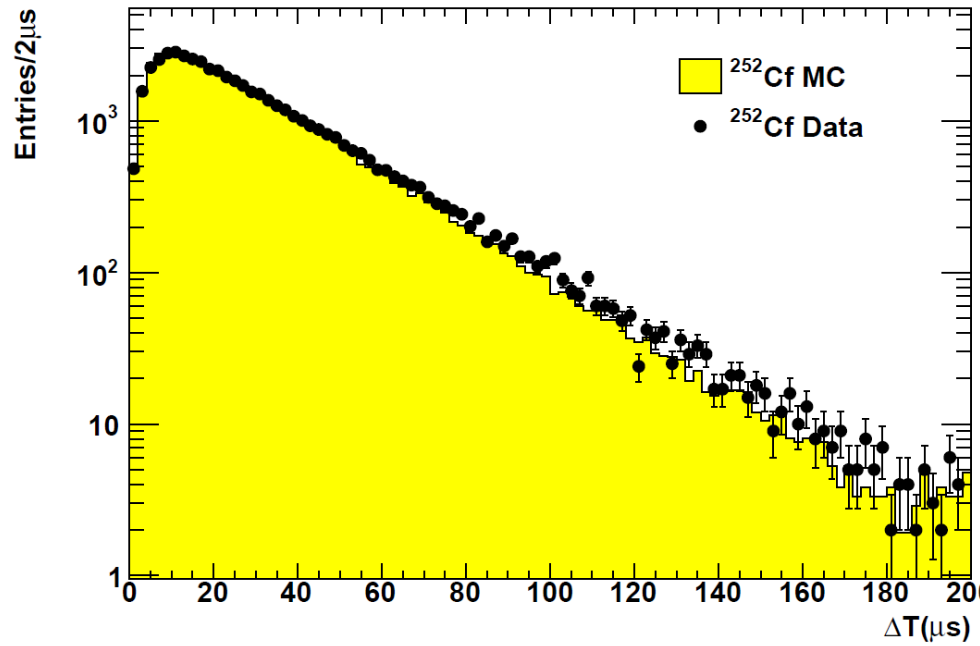
Energy & time window, Gd fraction, spill in/out effects

- ^{252}Cf source deployed into ν-target and γ-catcher

Detector Calibration

Energy Calibration

1. PMT and electronics gain non-linearity calibration
   – LED light injection system
2. Correct for position dependence
   – Spallation neutron H captures
3. Correct for time stability
   – Spallation neutron Gd captures
4. Energy scale
   – Radioactive sources deployed into ν-target and γ-catcher



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- Neutrinos & Flavor Oscillations
  - Why is θ_{13} worth measuring?
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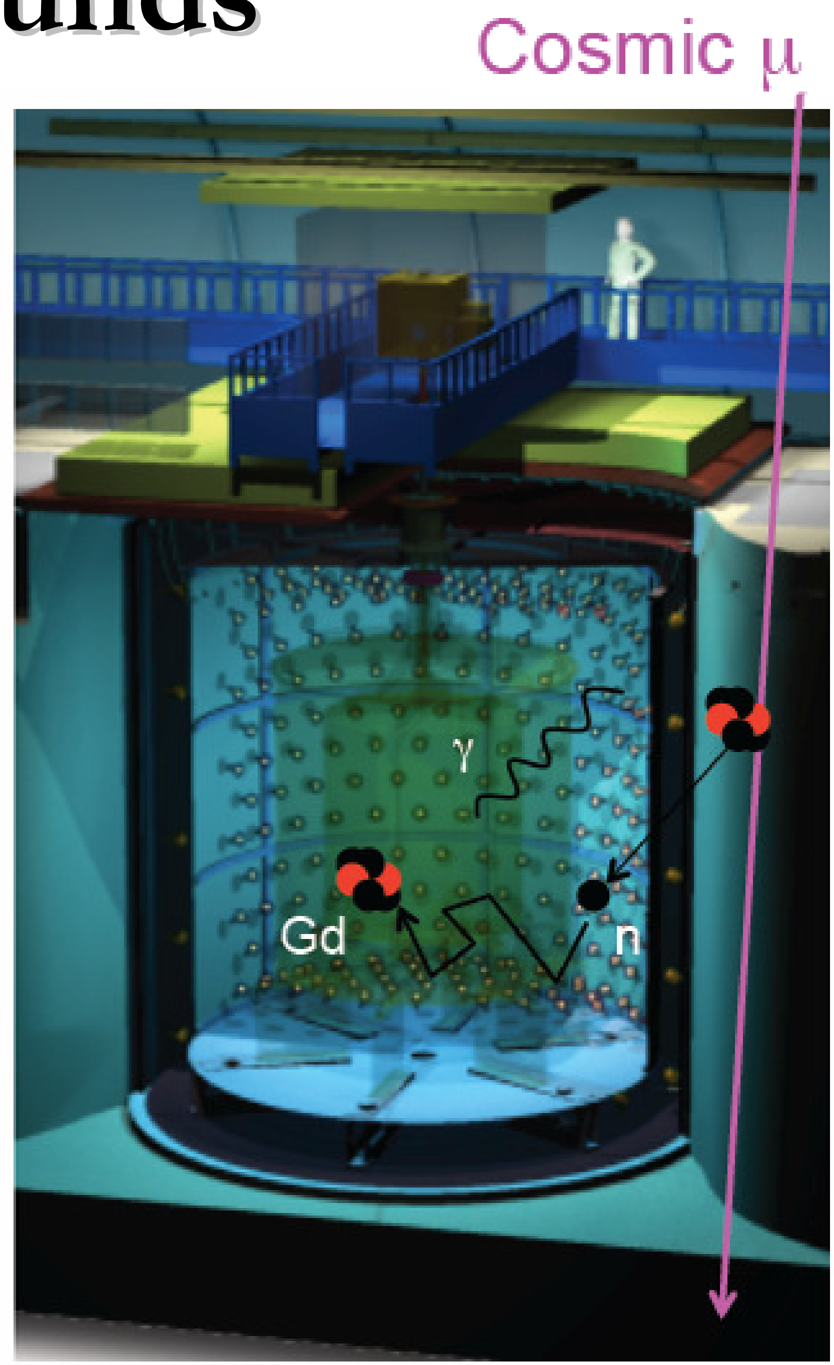
  - Observing neutrinos from nuclear power reactors
- Double Chooz Far Detector-Only Analysis
  - Predicted Neutrino Rate
  - Signal & Event Selection Criteria
  - Detector Systematics
  - Background Measurement & Estimation
- Oscillation Analysis Results & Future Prospects

Backgrounds



Accidentals

- Prompt: radiation hit on PMT
- Delayed: spallation neutron capture
- Prevented by radiopurity & shielding
- Measured from off-time windows: 0.261 +/- 0.002 day^{-1}

Cosmogenic ^{9}Li

- Prompt: beta emission
- Delayed: neutrons from long-lived decays
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Fast-n & Stopping muons

- Prompt: proton recoil or muon track
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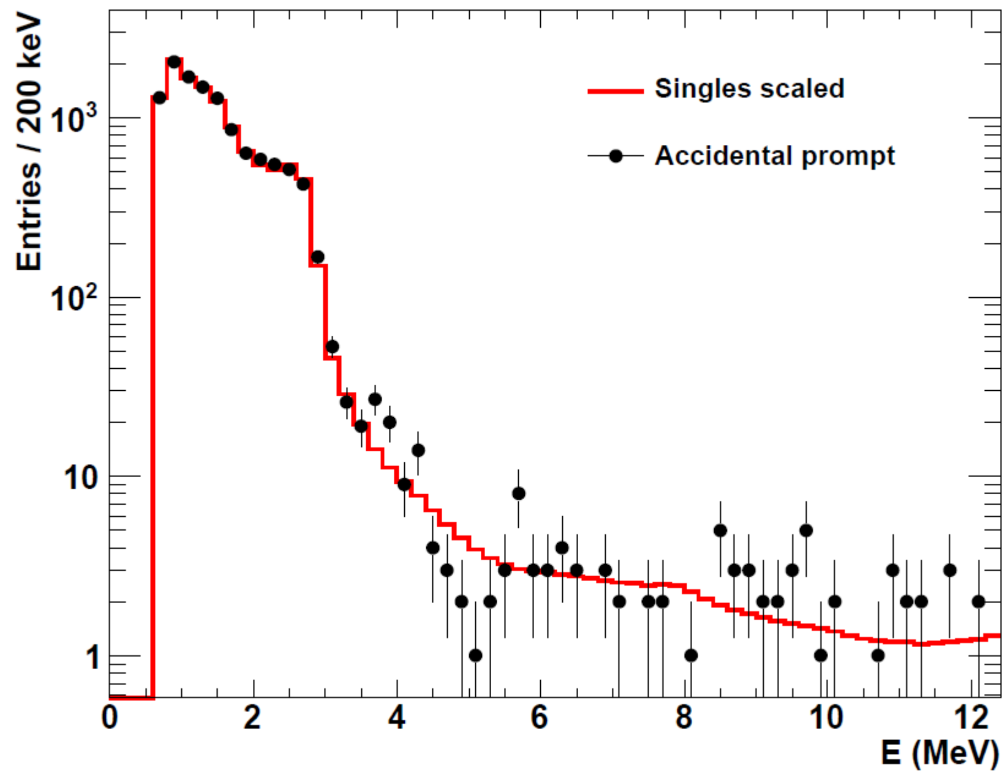

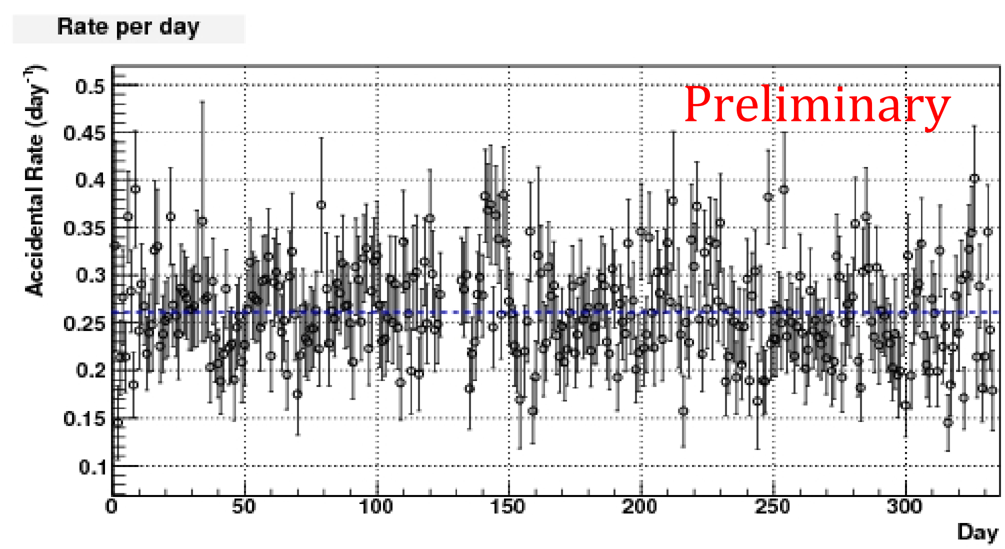

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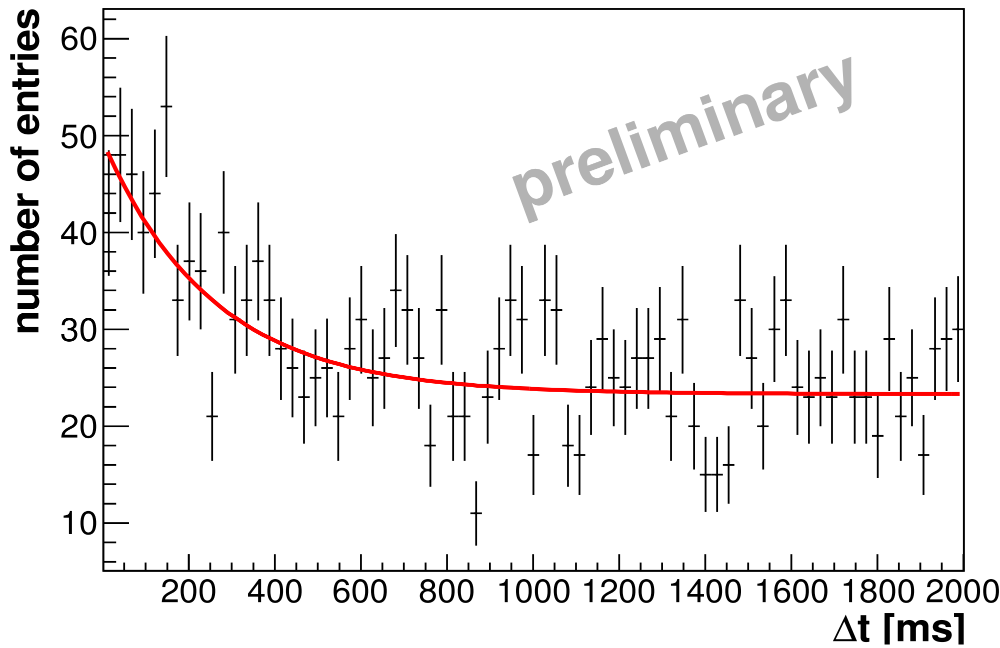

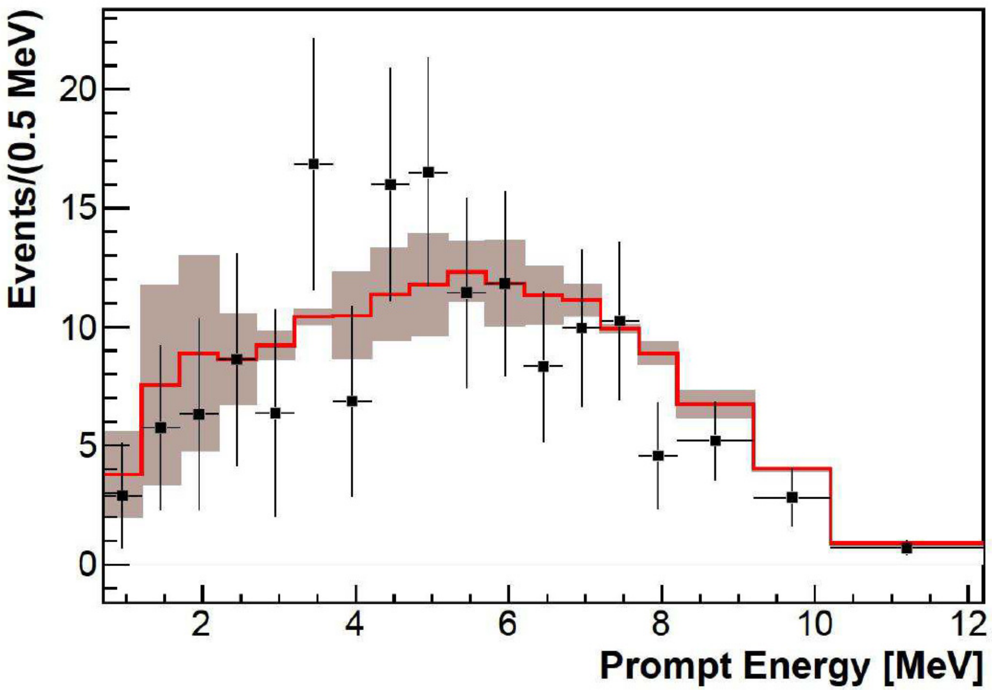

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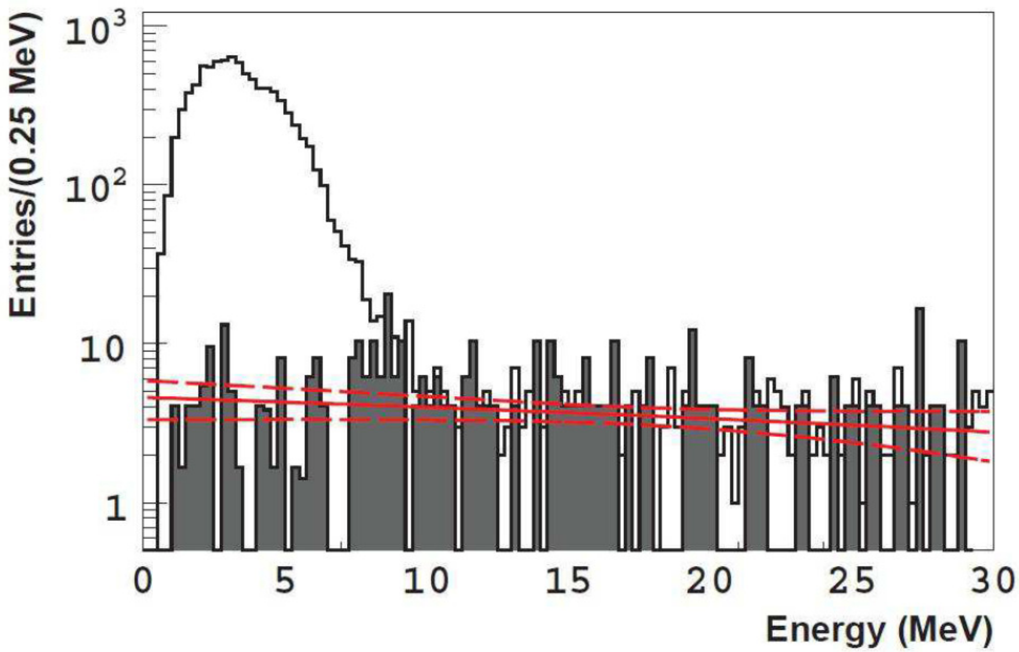

Red: Best-fit Spectrum
Grey: Tagged background events
White: IBD Signal

Summary of Rate Uncertainties

Source		Uncertainty w.r.t. signal	
Statistics		1.1%	
Flux		1.7%	
Detector	Energy response	0.3%	1.0%
	E_{delay} containment	0.7%	
	Gd fraction	0.3%	
	Δt cut	0.5%	
	Spill in/out	0.3%	
	Trigger efficiency	<0.1%	
	Target H	0.3%	
Background	Accidental	<0.1%	1.6%
	Fast-n + stop μ	0.5%	
	^{9}Li	1.4%	

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Summary of Candidates

	Both Reactors On	One Reactor $P_{th} < 20\%$	Total
Livetime [days]	139.27	88.66	227.93
IBD Candidates	6088	2161	8249
Prediction			
Reactor B1 ν	2910.9	774.6	3685.5
Reactor B2 ν	3422.4	1331.7	4754.1
^{9}Li	174.1	110.8	284.9
FN & SM	93.3	59.4	152.7
Accidentals	36.4	23.1	59.5
Total Prediction	6637.1	2299.7	8936.8

- Data divided into two integration periods based on reactor power
  - Allows use of changing signal/background ratio in fit

Oscillation Analysis Method

$$N_i^{\text{pred}} = \sum_{R=1,2}^{\text{Reactors}} N_i^{\nu,R} + \sum_{b}^{\text{Bkgnds.}} N_i^b$$

$i = \{1, \ldots, 36\}$ **Energy bins**
2 × 18 bins per integration period

$$N_i^{\nu,R} = P_(\bar{\nu}_e \rightarrow \bar{\nu}_e) N_i^{\exp,R}$$

- <u>Binned Rate + Spectral Shape Fit</u>

$$\chi^2 = \sum_{i,j}^{36} \left(N_i - N_i^{\text{pred}}\right) \times (M_{ij})^{-1} \left(N_j - N_j^{\text{pred}}\right)^{\text{T}} + \frac{\left(\epsilon_{FN/SM} - 1\right)^2}{\sigma^2_{FN/SM}} + \frac{\left(\epsilon_{^9\text{Li}} - 1\right)^2}{\sigma^2_{^9\text{Li}}} + \frac{\left(\alpha_E - 1\right)^2}{\sigma^2_{\alpha_E}} + \frac{\left(\Delta m^2_{31} - (\Delta m^2_{31})_{\text{MINOS}}\right)^2}{\sigma^2_{\text{MINOS}}}$$

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Covariance Matrix

$$M_{ij} = M_{ij}^{\text{sig.}} + M_{ij}^{\text{stat.}} + M_{ij}^{\text{eff.}} + \sum_{b}^{\text{Bkgnds.}} M_{ij}^{\text{b}}$$

Oscillation Analysis Method

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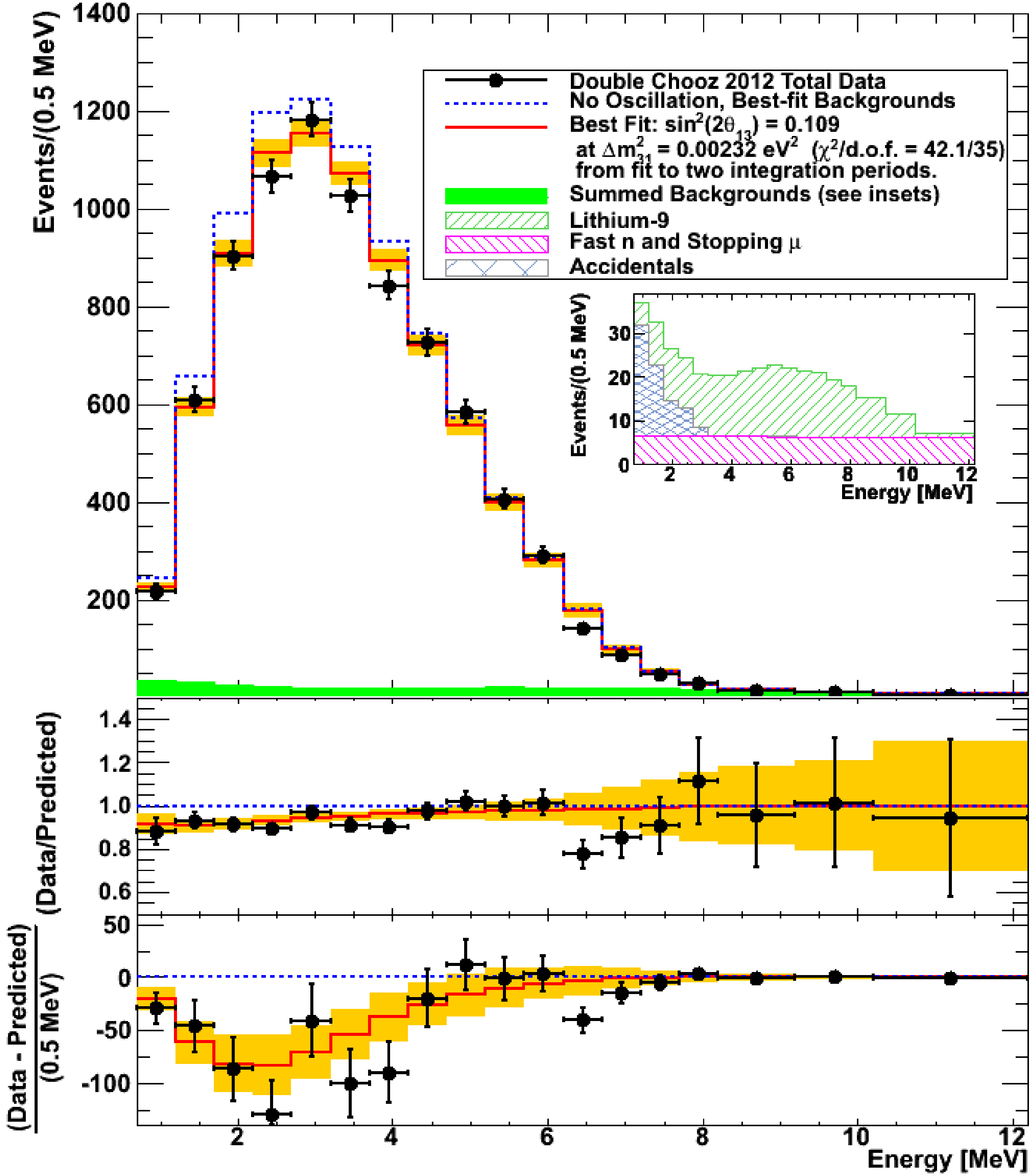
Fit Parameter "Pulled" Terms

- ^{9}Li & FN/SM Backgrounds
- Energy Scale
- Mass Splitting
- Fit outputs give diagnostics: data can constrain parameters.

Double Chooz Prompt Spectrum



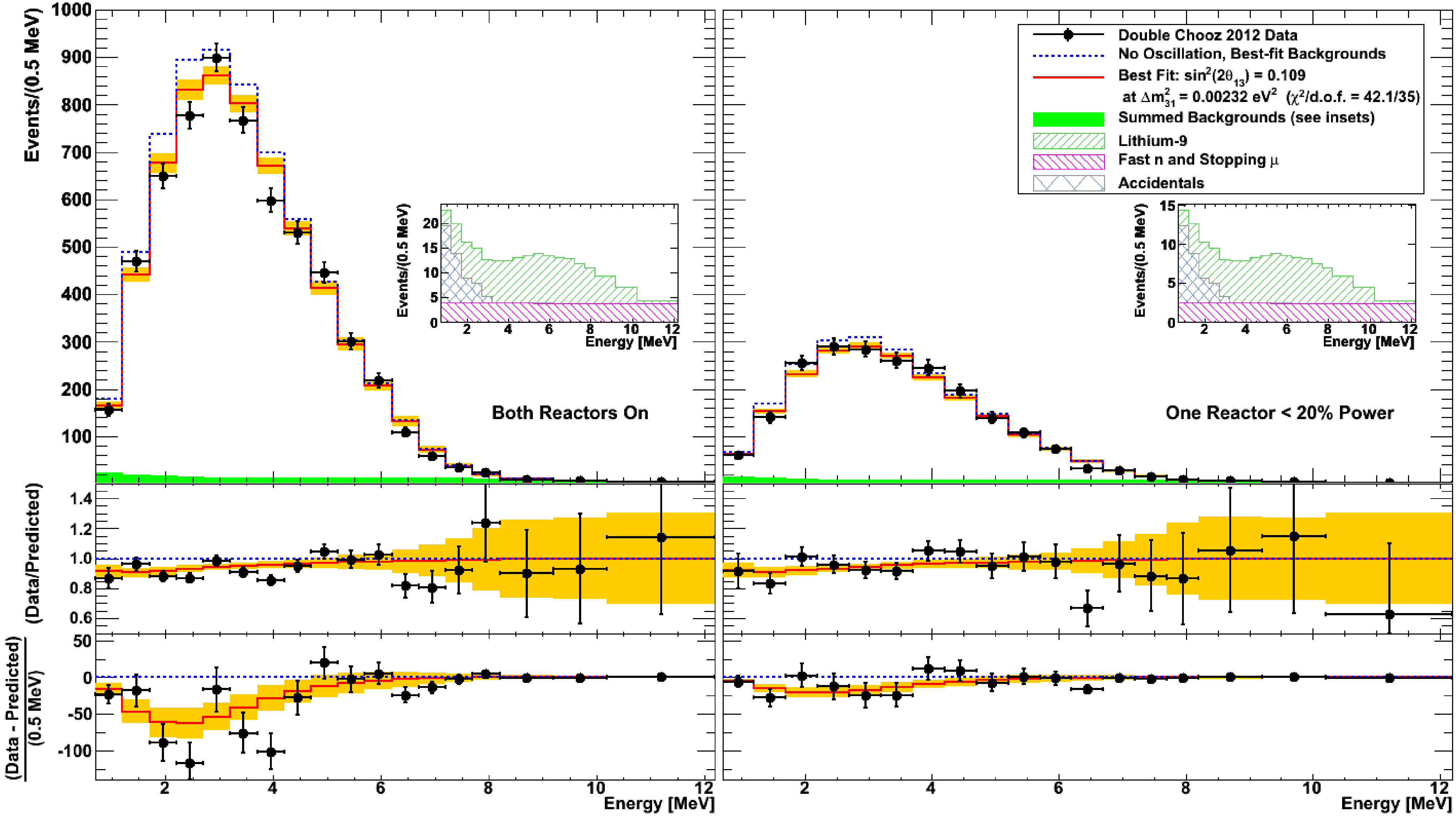
Data w/ Stat. Error Bars

Best Fit Prediction

(w/ Syst. Errors)

Null Oscillation Prediction

Backgrounds



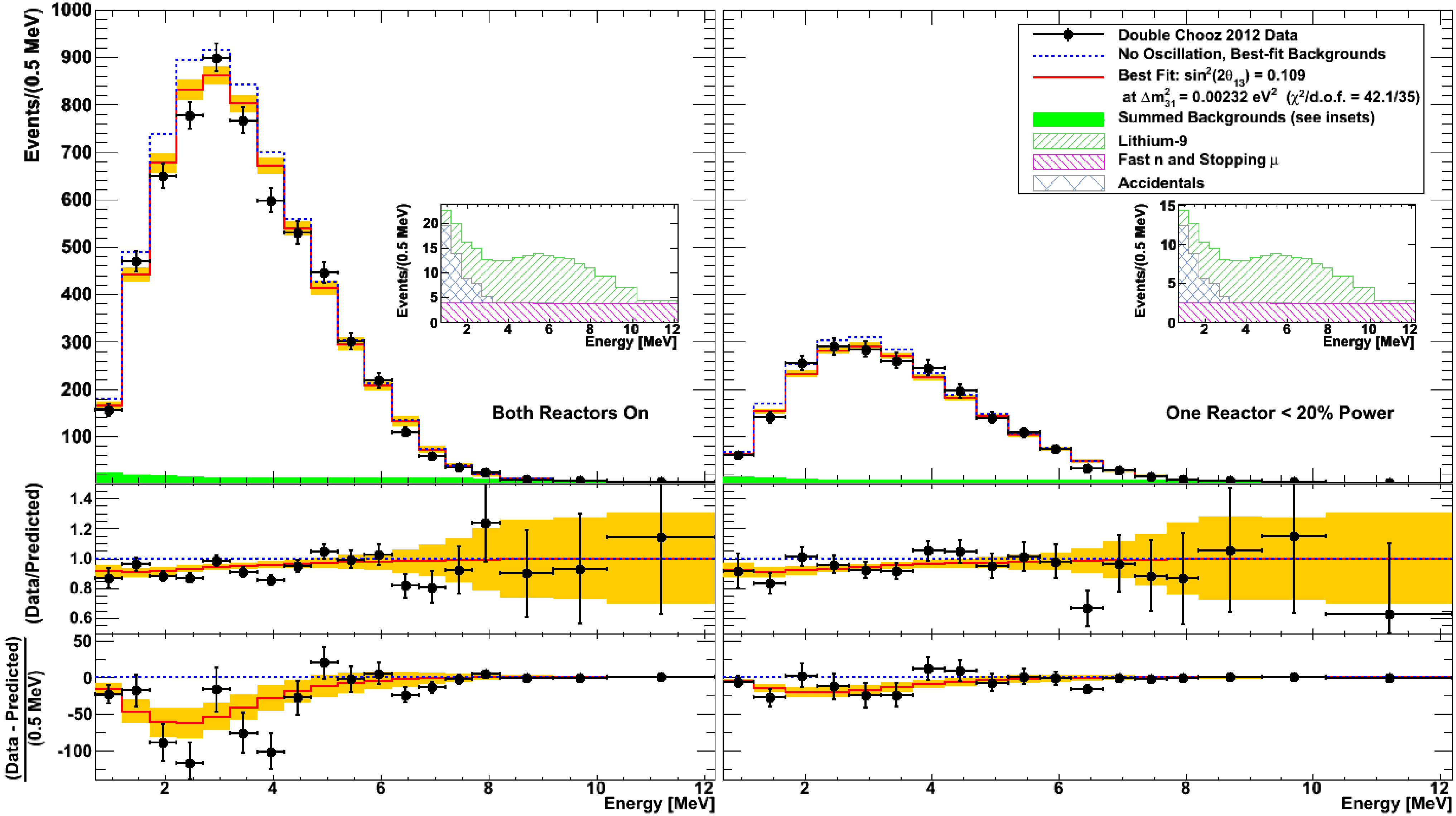
Rate+Shape: $\sin^2 2\theta_{13} = 0.109 \pm 0.030$ (stat.) ± 0.025 (syst.)

χ^2/d.o.f. = 42.1/35

Rate-only: $\sin^2 2\theta_{13} = 0.170 \pm 0.035$ (stat.) ± 0.040 (syst.)

Frequentist analysis: $\sin^2 2\theta_{13} = 0$ excluded at 99.8% (2.9σ)

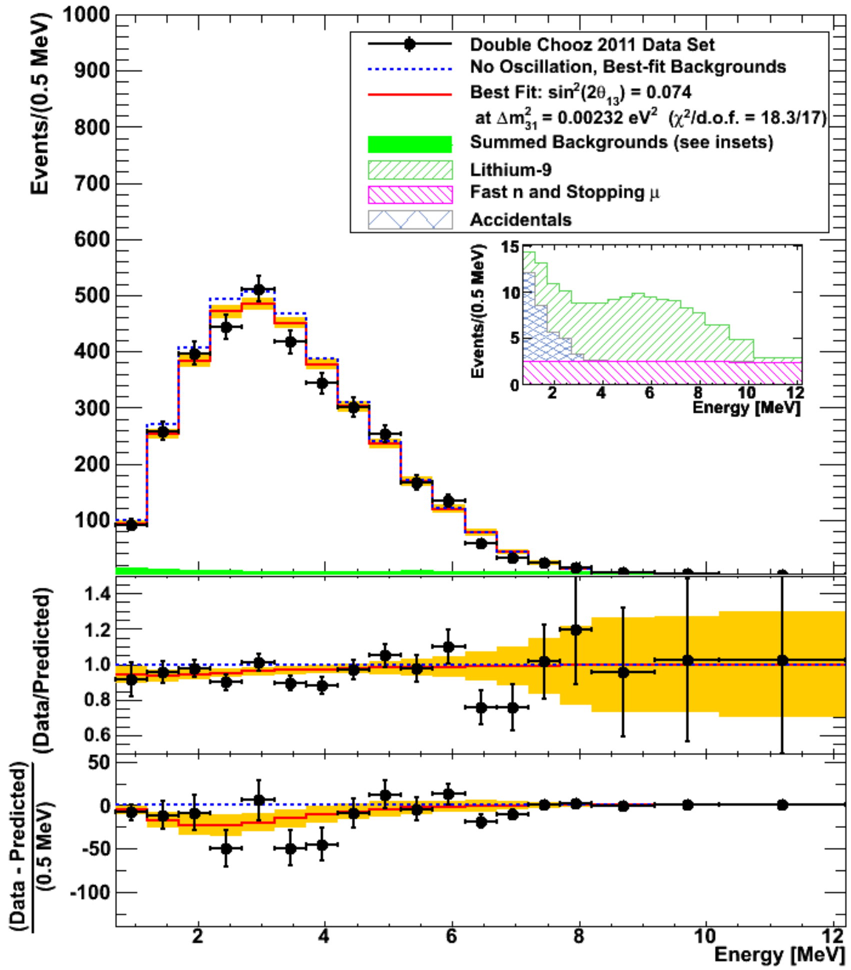
Presented in arXiv:1207.6632, accepted by PRD

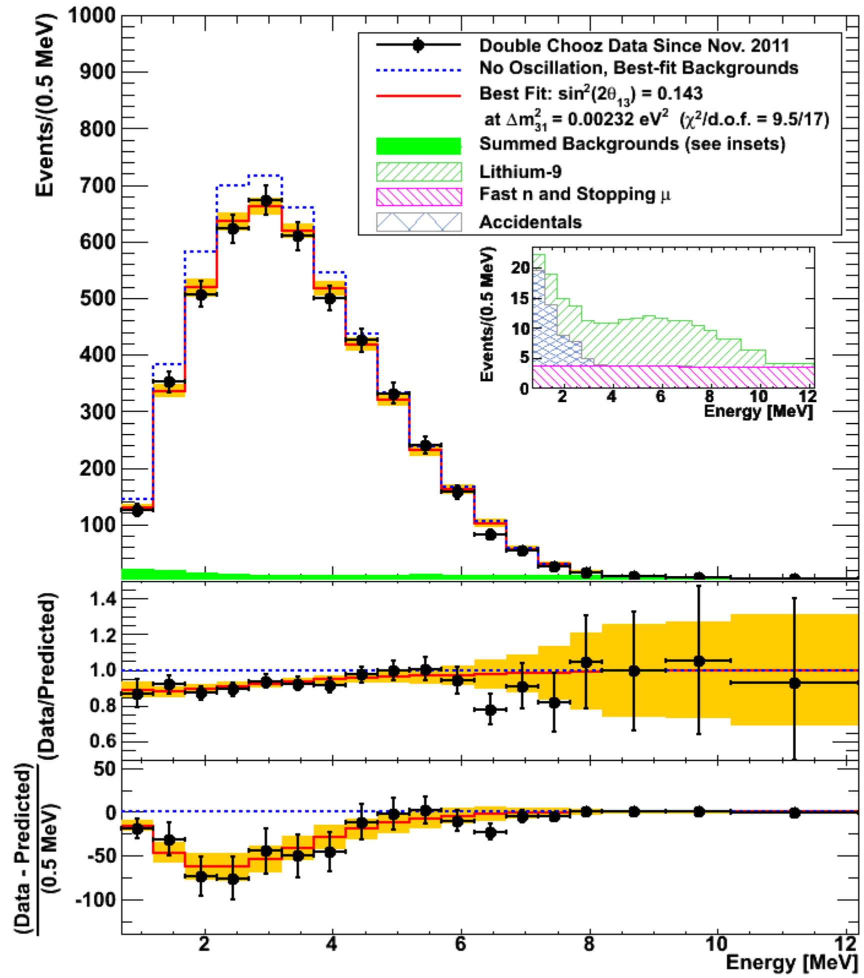


Rate+Shape: $\sin^2 2\theta_{13} = 0.109 \pm 0.030\ (\text{stat.}) \pm 0.025\ (\text{syst.})$

Fit Parameter	Initial Value	Best-Fit Value
^{9}Li Bkg. $\epsilon_{^9\mathrm{Li}}$	$(1.25 \pm 0.54)\ \mathrm{d}^{-1}$	$(1.00 \pm 0.29)\ \mathrm{d}^{-1}$
FN/SM Bkg. $\epsilon_{FN/SM}$	$(0.67 \pm 0.20)\ \mathrm{d}^{-1}$	$(0.64 \pm 0.13)\ \mathrm{d}^{-1}$
Energy Scale α_E	1.000 ± 0.011	0.986 ± 0.007
$\Delta m^2_{31}\ (10^{-3}\ \mathrm{eV}^2)$	2.32 ± 0.12	2.32 ± 0.12

Check First 85.7 days vs. Last 142.4 days





Rate+Shape

First 85.6 days: **$\sin^2 2\theta_{13}$= 0.074 ± 0.046(stat.+syst.)**

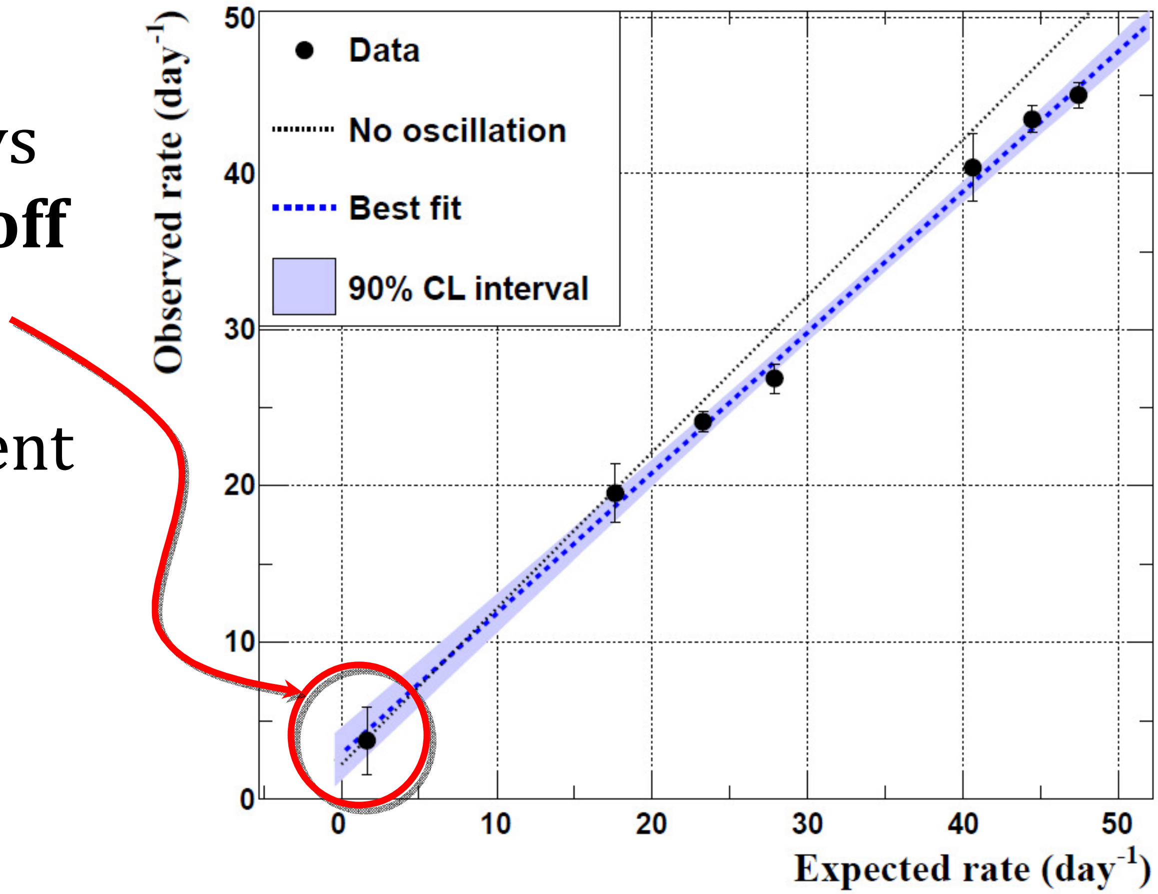
Last 142.4 days: **$\sin^2 2\theta_{13}$= 0.143 ± 0.043(stat.+syst.)**

arXiv:1207.6632

Check Rate vs. Reactor Power

2 events observed in 0.84 days livetime with **both reactors off** (= 2.2 event/day)

→ Background rate consistent with estimation (2.2 ±0.6 event/day)



Best fit to expected rate:

$\mathbf{\sin^2 2\theta_{13} = 0.19 \pm 0.06}$

BG rate = 2.9 ± 1.1 event/day

arXiv:1207.6632

Near Detector

Expected to begin taking data by end of 2013

Double Chooz On-going Projects

- Measurement of θ_{13} based on predicted reactor flux
  - Near detector to precisely measure 2-reactor flux
  - In situ background measurements with both reactors off
    - 8 days' data so far
- Other Physics Projects
  - n-H capture event analysis
  - Neutrino directionality measurements
  - Constrain $|\Delta m^2_{31}|$ with different baseline experiments
  - Lorentz violation studies

Summary

- Updated Double Chooz Oscillation Results

  arXiv:1207.6632, accepted by PRD

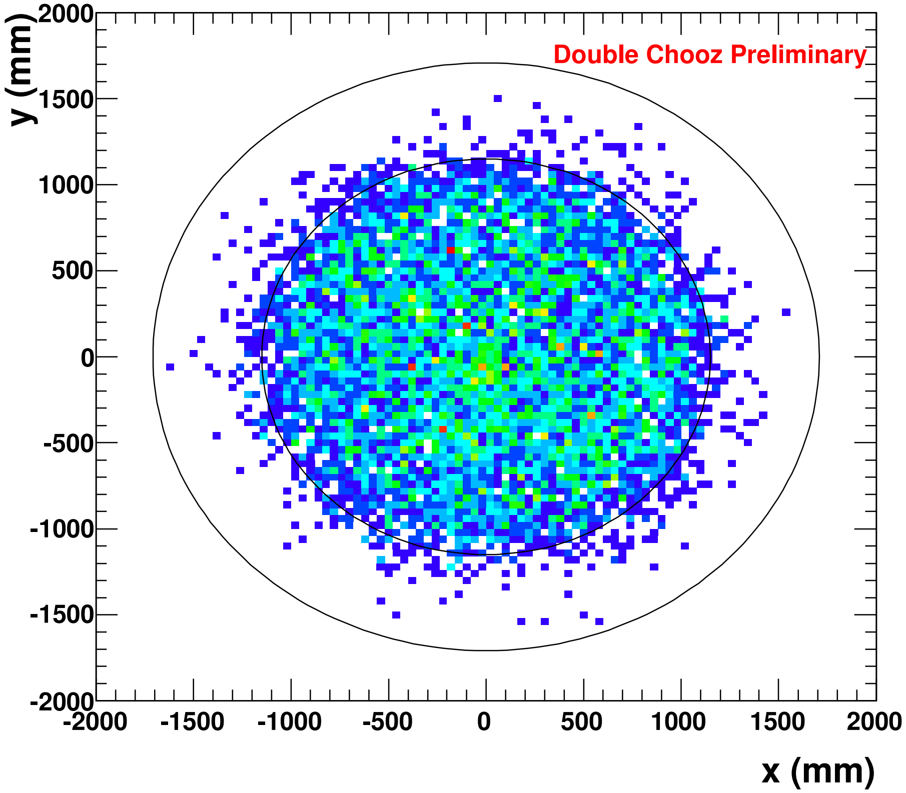
- Analysis of 8249 neutrino candidates
  - $\sin^2(2\theta_{13}) = 0.109 \pm 0.030$ (stat.) $\pm$ 0.025 (syst.)
  - $\sin^2(2\theta_{13}) = 0$ is excluded at 99.8% (2.9σ)

- One week of 2-reactors-off data taken
- Near detector operational by end of 2013
- Prospect for precise studies of θ_{13} with 2 reactors

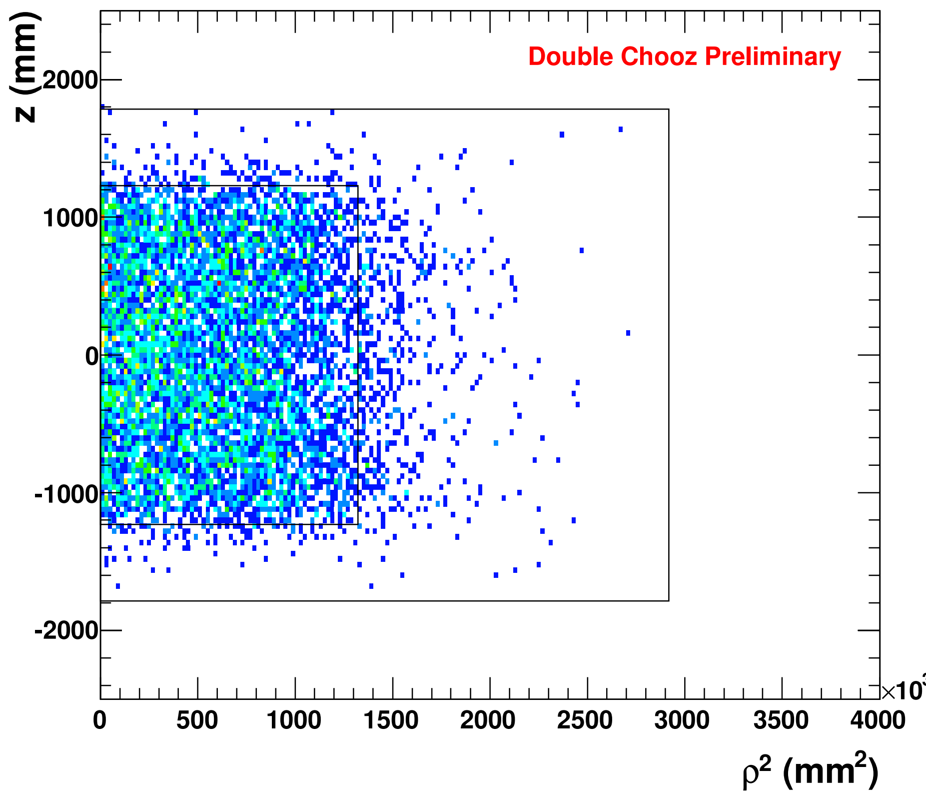
== Backup Slides ==

Delayed Vertex Position

Delayed vertex XY position

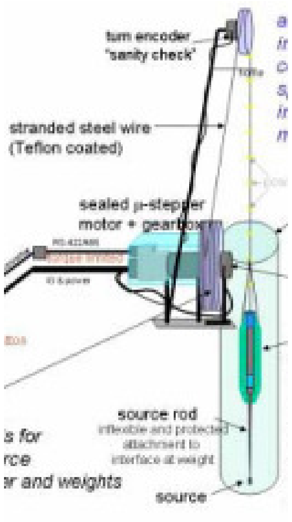


Delayed vertex Zρ^2 position



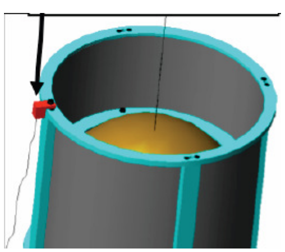
Calibration Systems

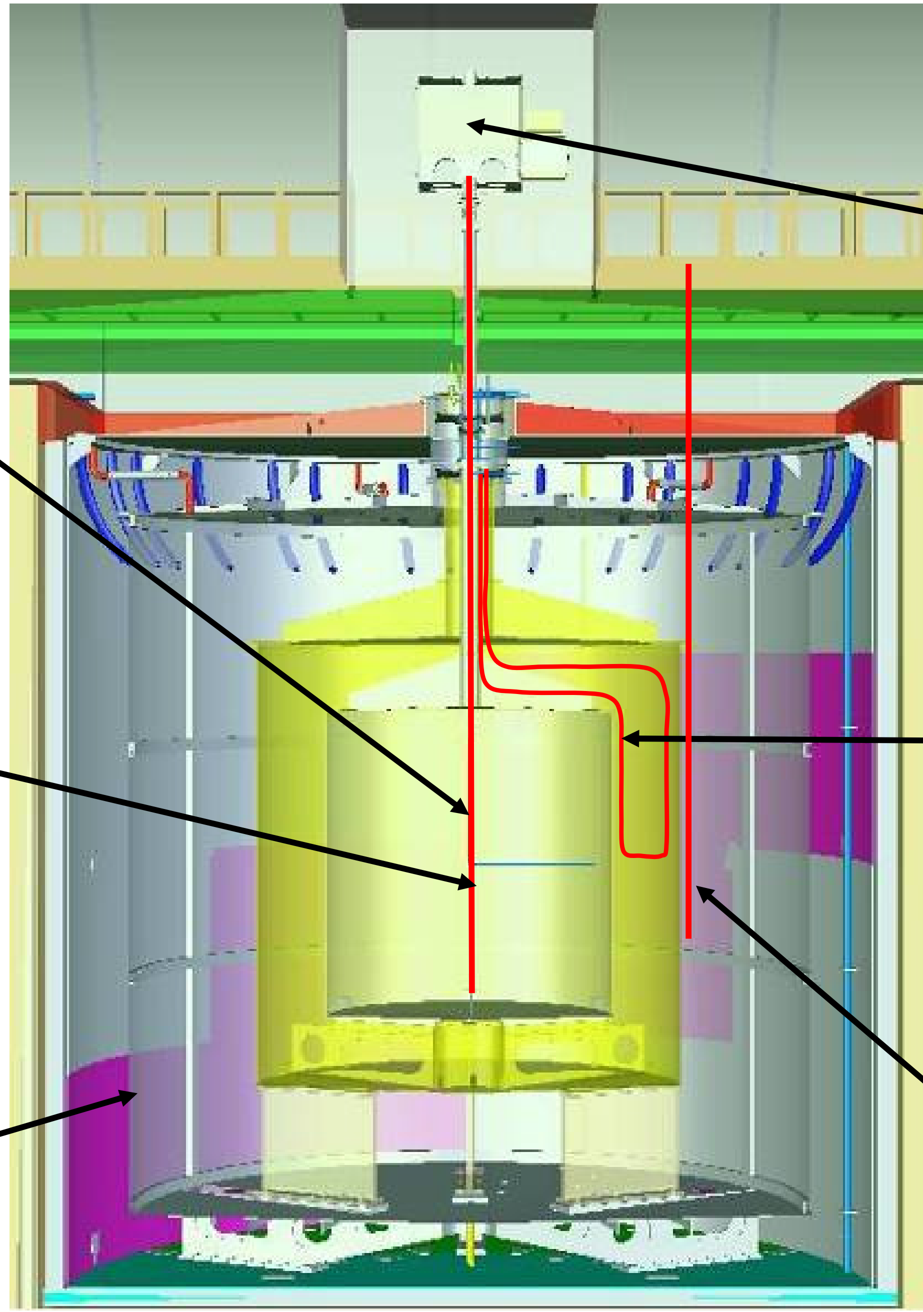
Z-Axis System



Articulated Arm

Embedded LED system 385, 420, 470 nm





Glove Box

GC Guide Tube

Buffer Guide Tube

Uncertainties in Rate+Shape Fit

- Data-Prediction in energy bins considered Gaussian-random variables:

$$N_i = \left(N_i^{\text{Data}} - \left(N_i^{\nu\,\text{Pred}} + \sum_{b=0}^{\text{Bkgnds.}} N_i^b \right) \right)$$

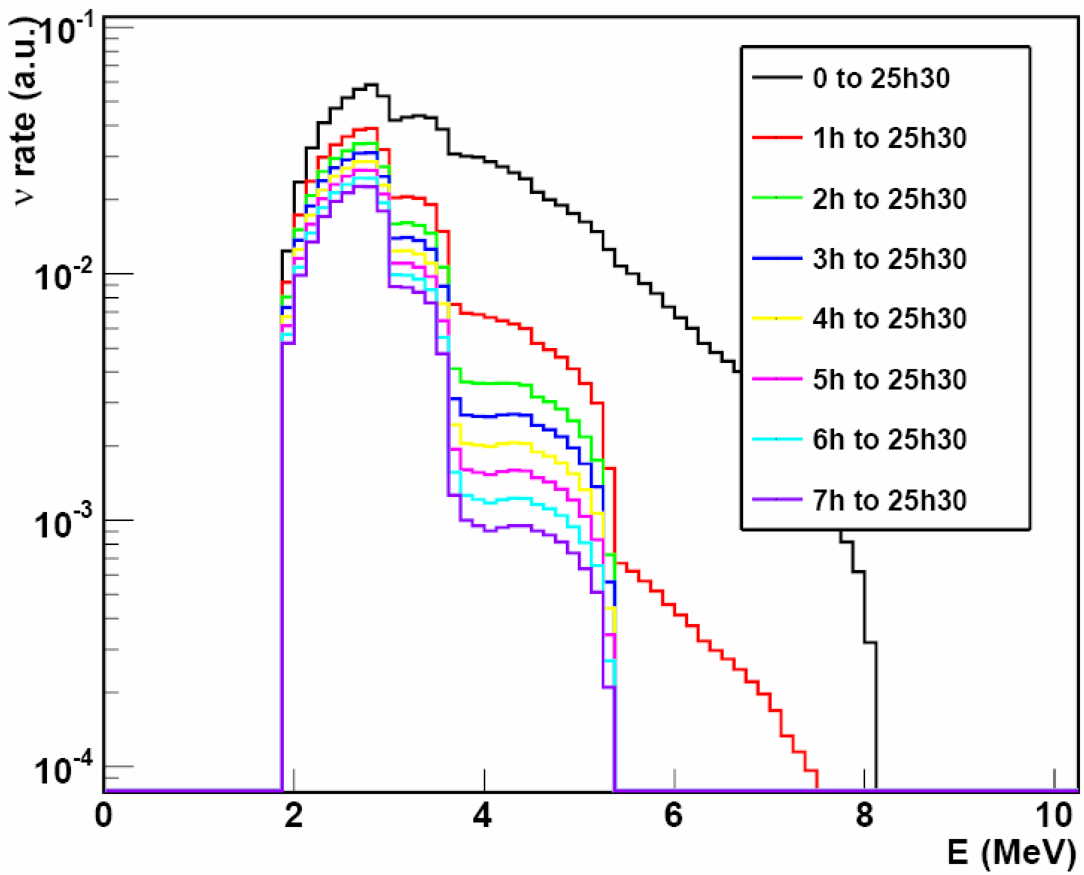
- Uncertainties propagated as contributions to covariance matrix:

$$M_{ij} = M_{ij}^{\text{Rxtr.}} + M_{ij}^{\text{Det.}} + M_{ij}^{\text{Eff.}} + M_{ij}^{\text{Stat.}} + \sum_{b=0}^{\text{Bkgnds.}} M_{ij}^{b}$$

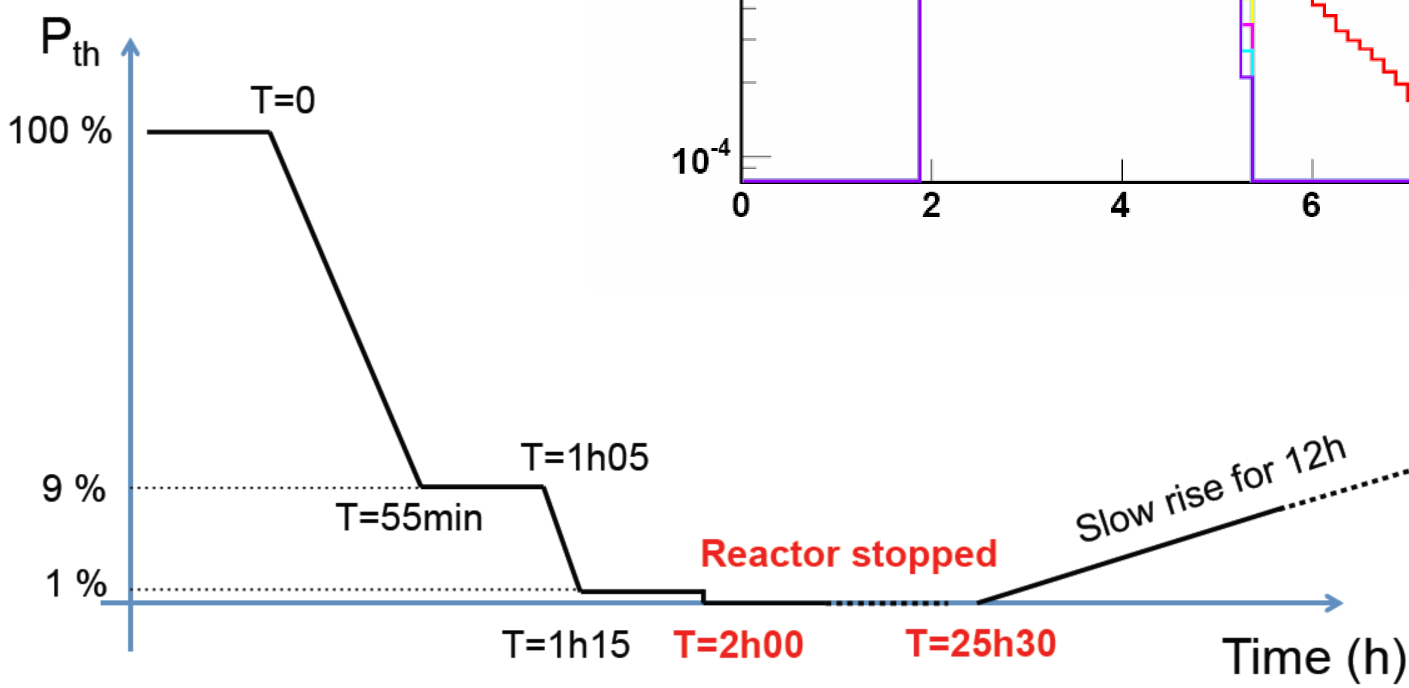
- Goodness-of-fit statistics:

$$\chi_R^2 = \left(\sum_i N_i \right)^2 \Big/ \sum_{i,j} M_{ij} \qquad \chi_{RS}^2 = \sum_{i,j} N_i M_{ij}^{-1} \left(N_j \right)^{\mathrm{T}}$$

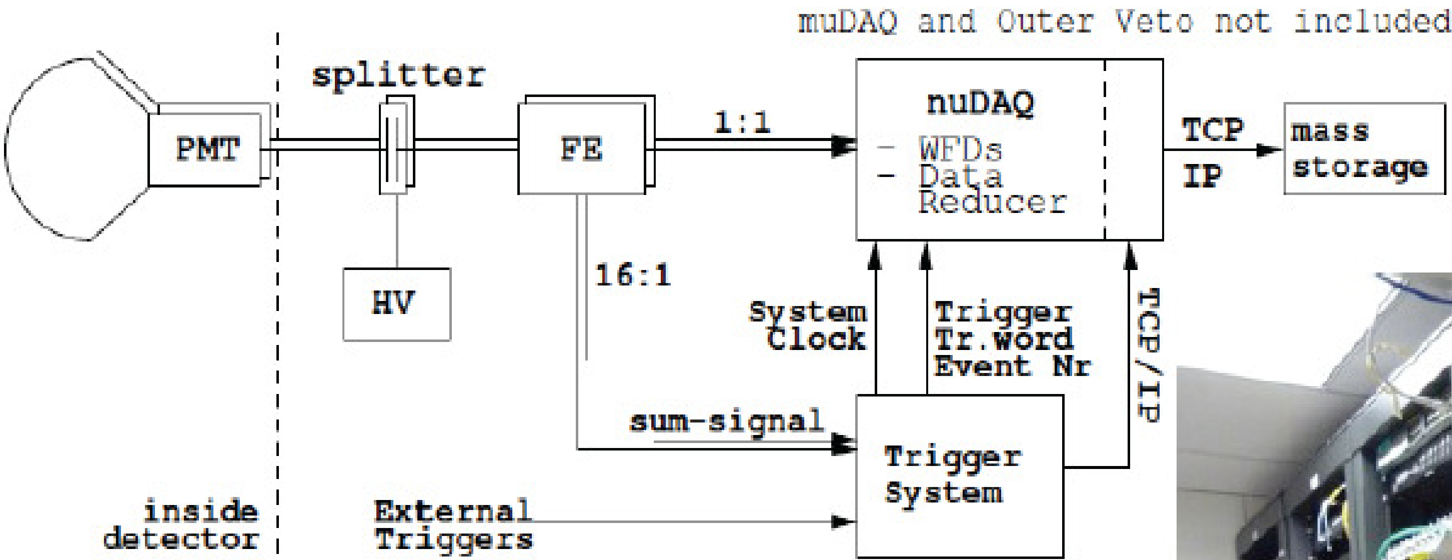
- Error bars on $\sin^2(2\theta_{13})$ determined from behavior of χ^2 vs. value at best-fit: 1σ @ $\Delta\chi^2 = 1$



ν rate (a.u.)
10^-1
10^-2
10^-3
10^-4
0
2
4
6
8
10
E (MeV)
0 to 25h30
1h to 25h30
2h to 25h30
3h to 25h30
4h to 25h30
5h to 25h30
6h to 25h30
7h to 25h30



P_th
100 %
9 %
1 %
T=0
T=55min
T=1h05
T=1h15
T=2h00
Reactor stopped
T=25h30
Slow rise for 12h
Time (h)



The Electronics:

- Signal + HV on one cable.
- Frontend cards shape pulses, corrects baseline and integrates charge.
- Analog Trigger triggers on photoelectron equivalent.
- 500MHz Caen digitizers record pulses.
- Subset of PMTs sent to second system to record muon events.