Search for electron anti-neutrinos from the Sun with KamLAND detector

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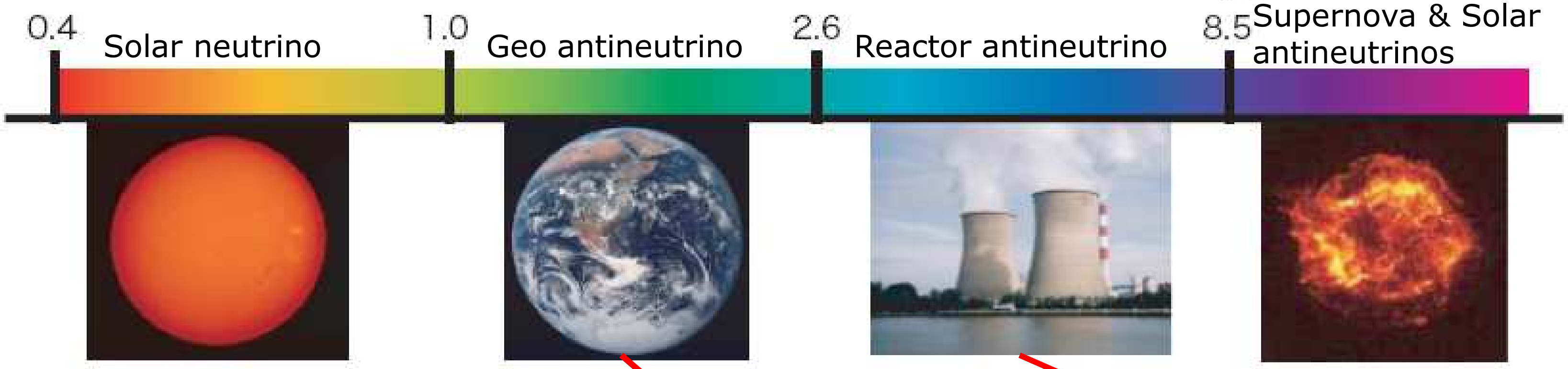
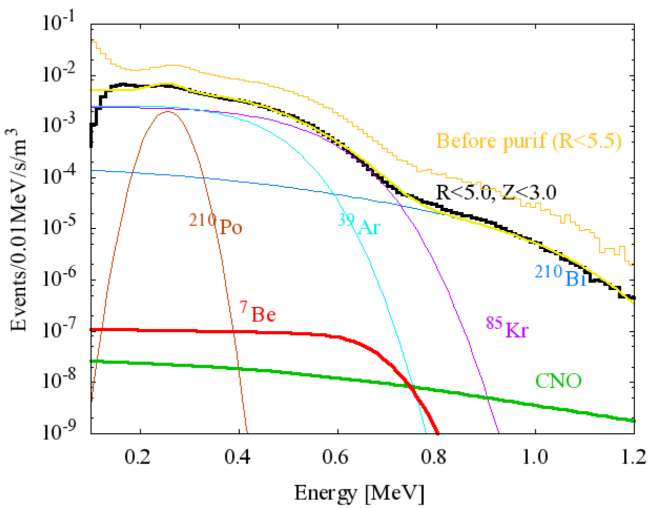
HEP Seminar at University of Virginia

October 7, 2009

Physics in KamLAND



work in progress




nature

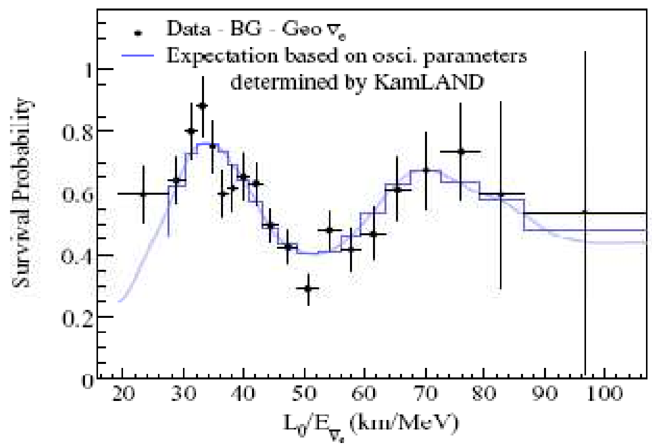
EARTHLY POWERS

Geoneutrinos reveal Earth's inner secrets

GLOBAL CLIMATE
Vital CO_2 flux from Amazon vegetation

BREAST CANCER
Gene signature for metastasis

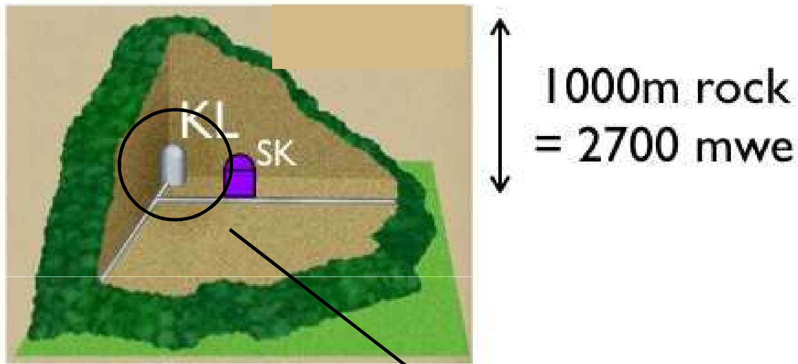
FORENSIC SCIENCE
Everything has a fingerprint



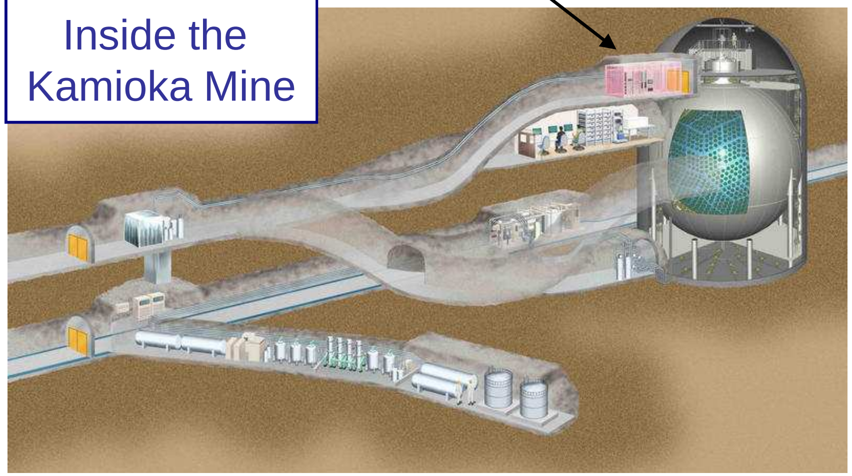
Kamioka Liquid-scintillator Anti-neutrino Detector (KamLAND)

Surrounded by 55 Japanese Reactor Units

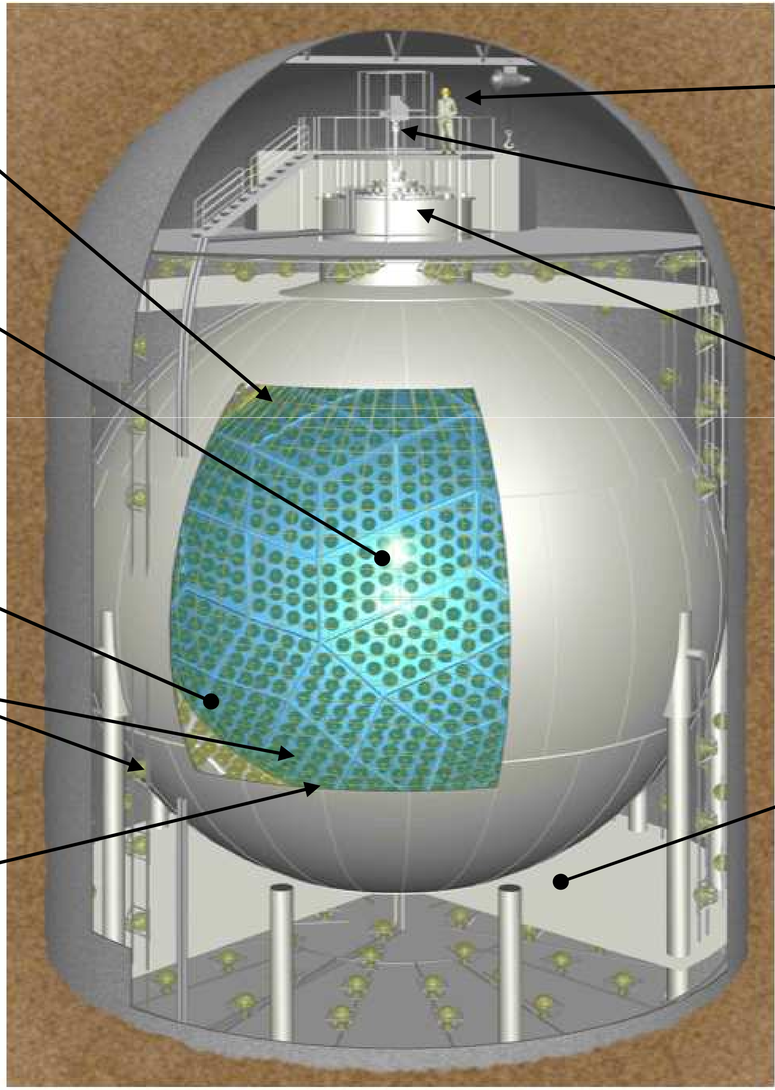
Detecting reactor $\bar{\nu}_e$ 1km beneath Mt. Ikenoyama



Inside the Kamioka Mine

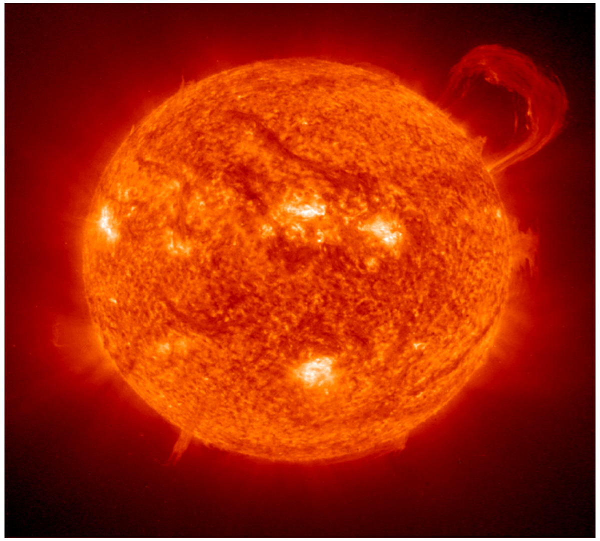


The KamLAND Detector



Solar Neutrinos Production (pp-chain)

ν_e are abundant by-products of nuclear fusion in the sun



$$p + p \rightarrow {}^2H + e^+ + \nu_e + 0.42\,MeV$$

"pp" 99.75%

$$p + e^- + p \rightarrow {}^2H + \nu_e + 1.44\,MeV$$

"pep" 0.25%

$$ {}^2H + p \rightarrow {}^3He + \gamma + 5.49\,MeV$$

86%

$$ {}^3He + {}^3He \rightarrow \alpha + 2p + 12.86\,MeV$$

14%

$$ {}^3He + \alpha \rightarrow {}^7Be + \gamma + 1.59\,MeV$$

"hep" 2.4*10^-5

$$ {}^3He + p \rightarrow \alpha + e^+ + \nu_e$$

"7Be" 99.89%

$$ {}^7Be + e^- \rightarrow {}^7Li + \gamma + \nu_e + 0.8617\,MeV$$

$$ {}^7Li + p \rightarrow \alpha + \alpha + 17.35\,MeV$$

0.11%

$$ {}^7Be + p \rightarrow {}^8B + \gamma + 0.14\,MeV$$

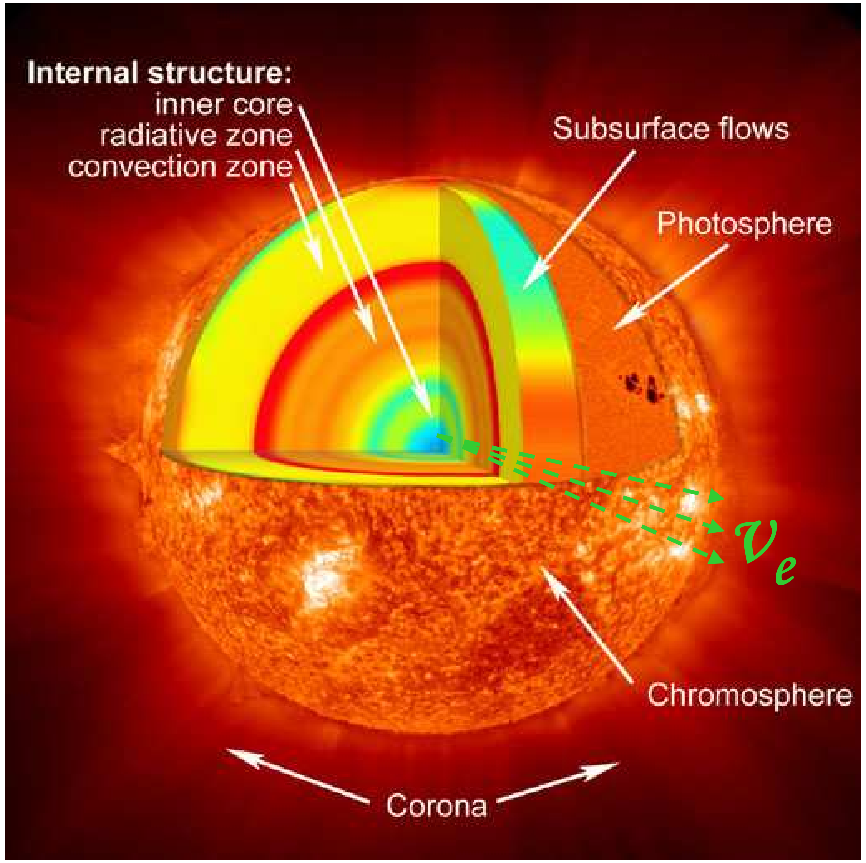
"8B" 0.11%

$$ {}^8B \rightarrow {}^8Be + e^+ + \nu_e + 14.6\,MeV$$

$$ {}^8Be \rightarrow \alpha + \alpha + 3\,MeV$$

No direct production of $\overline{\nu}_e$

Conversion Mechanism of Neutrinos

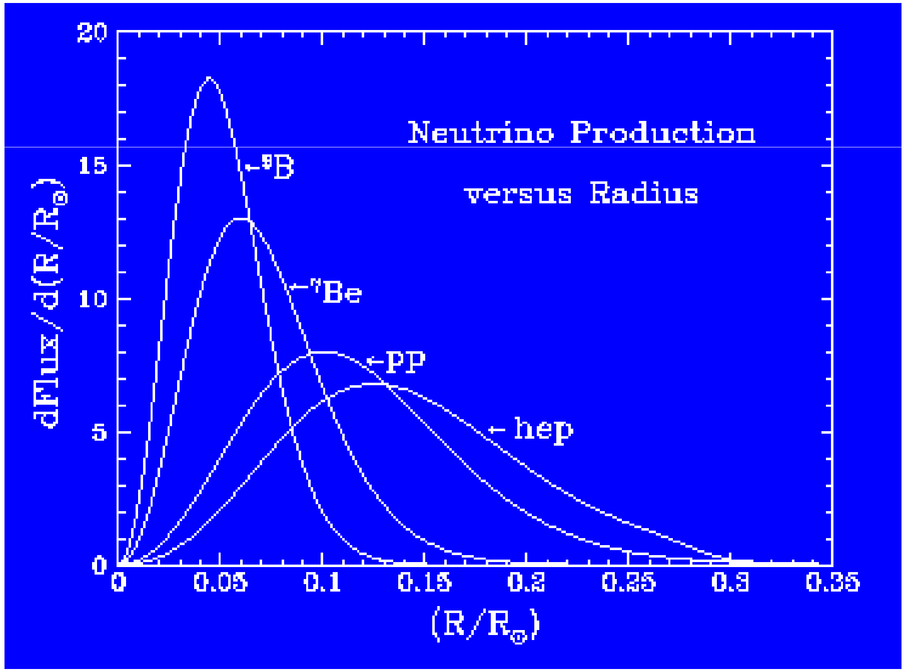


Sun Layers

E. Akhmedov and J Pulido, Phys. Lett B 553, 7 (2003)

$$\nu_{eL} \xrightarrow{\text{SFP}} \overline{\nu}_{\mu R} \xrightarrow{\text{osc.}} \overline{\nu}_{eR}$$

B_T~10^7G **Vacuum oscillations**



ν_e production as function of radius

SFP and Ocsillations

Neutrino flavor eigenstates: ν_e, ν_μ, ν_τ Neutrino mass eigenstates: ν_1, ν_2, ν_3

General form of connection between mass and flavor eigenstates

$$\left|\nu_\alpha\right\rangle = \sum_{j=1}^{3} U_{\alpha j}\left|\nu_j\right\rangle, \qquad \alpha = e, \mu, \tau$$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{23} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix},$$

$$s_{ij} = \sin\theta_{ij}, c_{ij} = \cos\theta_{ij} (i, j = 1,2,3)$$

Time evolution of the states:

$$i\frac{d}{dt}\left|\nu_j\right\rangle = E_j\left|\nu_j\right\rangle \Rightarrow \left|\nu_j(t)\right\rangle = e^{-iE_j t}\left|\nu_j(0)\right\rangle$$

$$\left|\nu_\alpha(t)\right\rangle = \sum_{j=1}^{3} U_{\alpha j} e^{-iE_j t} U^{+}_{j\alpha}\left|\nu_\alpha(0)\right\rangle$$

Oscillation probability for the simple case (only 2 flavor):

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta_\nu \sin^2\left(\frac{1.27\Delta m^2[eV^2]L[m]}{E[MeV]}\right)$$

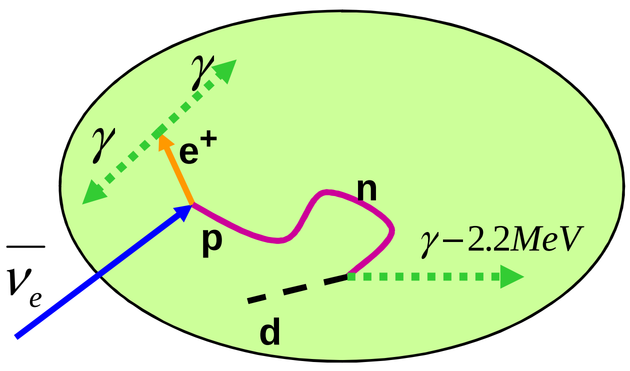
SFP at magnetic field & non zero neutrino magnetic moment

$$P(\nu_{eL} \to \bar{\nu}_{\mu R}) = 3.6\times 10^{-10}\left[\frac{\mu}{10^{-12}\mu_B}\frac{B_T(0.05R_{sun})}{10kG}\right]^2$$ (E. Akhmedov and J Pulido, Phys. Lett B 553, 7 (2003))

Final conversion probability:

$$\mathrm{P}(\nu_{eL} \to \bar{\nu}_{eR}) = 1.8\times 10^{-10}\left[\frac{\mu_\nu}{10^{-12}\mu_B}\times\frac{B_T(0.05R_s)}{10\mathrm{kG}}\right]^2 \sin^2 2\theta_{12}$$

Antineutrino detection



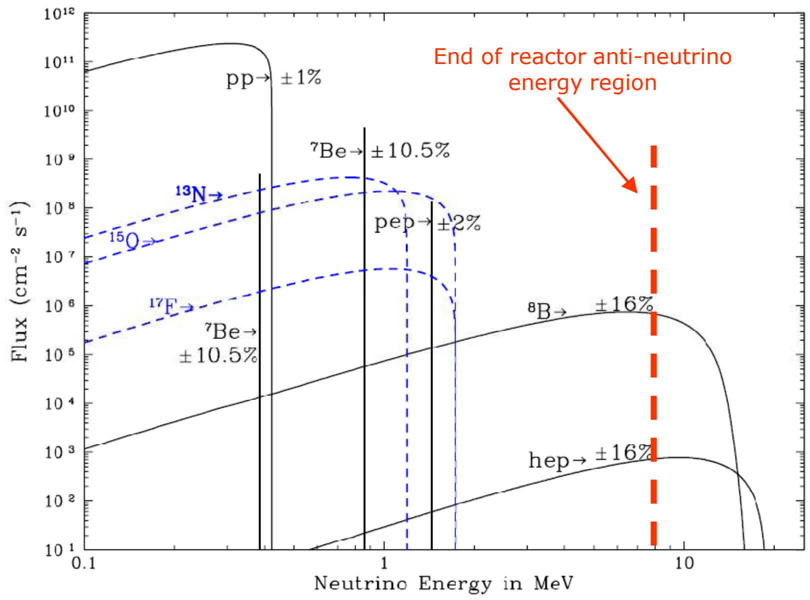
Prompt - Inverse β-decay:

$$\overline{\nu}_e + p \rightarrow e^+ + n,\ E_{threshold} = 1.8MeV$$

$$\sigma_{\bar{\nu}_e+p\rightarrow e^++n}[cm^2] = 9.3\times10^{-44}\left(\frac{E_{\bar{\nu}}}{1MeV}\right)^2\left(1-\frac{Q}{E_{\bar{\nu}}}\right)\sqrt{1-2\frac{Q}{E_{\bar{\nu}}}+\frac{Q^2-m_e^2}{E_{\bar{\nu}}^2}}\Theta(E_{\bar{\nu}})$$

$$Q = M_n - M_p,\ \Theta(E_{\bar{\nu}}) = \begin{Bmatrix} 1,\ E_{\bar{\nu}} > Q \\ 0,\ E_{\bar{\nu}} < Q \end{Bmatrix}$$

Solar neutrino spectrum



Delayed - Neutron capture (~220μsec):

$$n + p \rightarrow d + \gamma(2.22MeV)$$

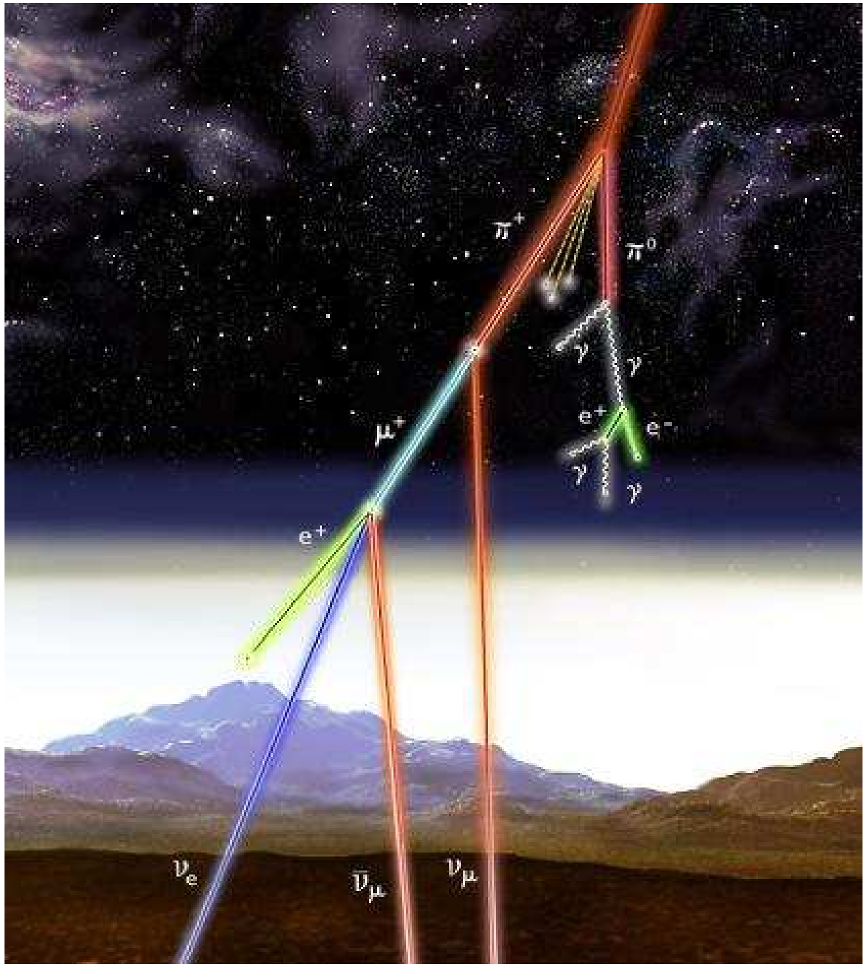
KamLAND can be sensitive only to conversion of ^{8}B neutrinos

$$^8B \rightarrow {}^8Be + e^+ + \nu_e$$

$$\Phi_{^8B} = 5.05\times10^6 cm^{-2}s^{-1}$$

$$\frac{\Phi_{Hep}}{\Phi_{^8B}} \approx 0.16\%$$

Background induced by Cosmic Rays



Muon interactions:

Eliminated by muon veto criteria during the events selection

Atmospheric neutrinos interactions:

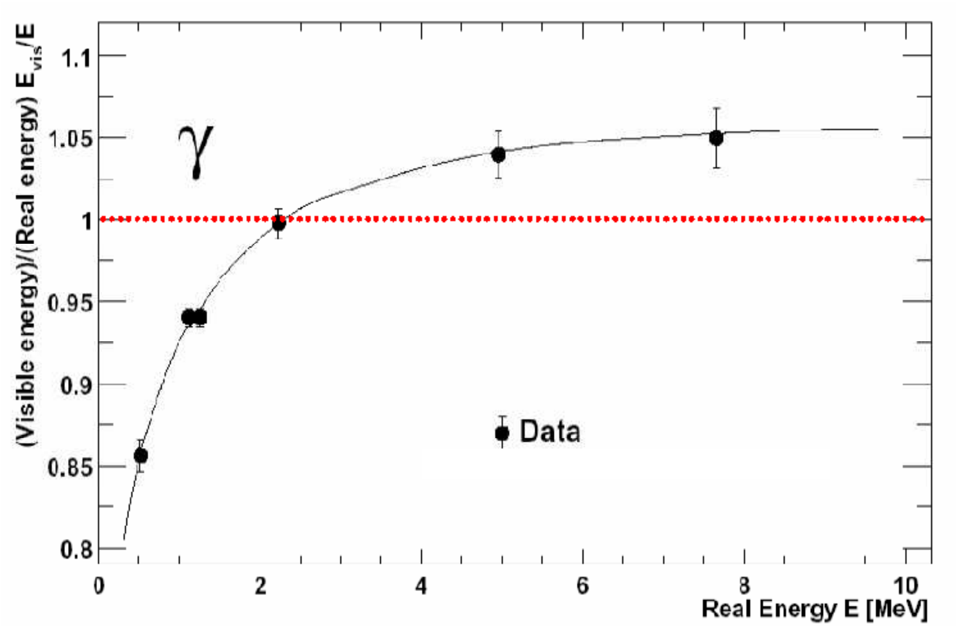
Can not be completely removed with muon veto criteria

In order to estimate this background scintillator response to all products of such interactions have to be carefully studied

Scintillator response

For correct interpretation of signals in detector it is necessary to know correspondence between light output in scintillator and deposit energy for all particles

At the early stage of experiment collaboration observed strong nonlinear behavior of scintillator (quenching) even for gammas!



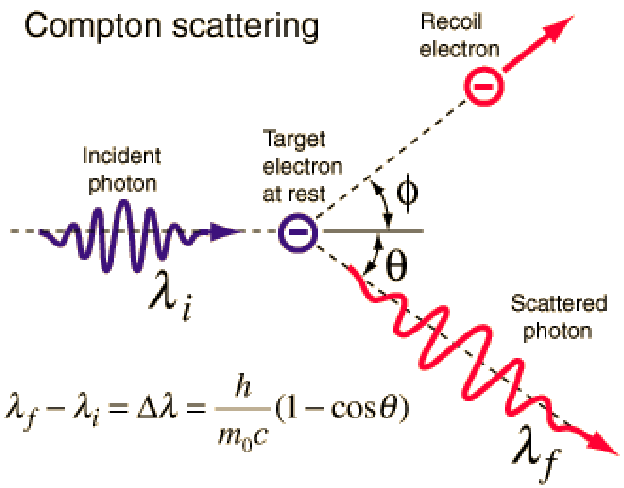
Birks' law:

$$\Delta E_{visible} = \frac{\Delta E_{expected}}{1 + k_B (dE/dx)}$$

Detailed Studies were required!!!

We started at UT comprehensive program to investigate reasons for nonlinear behavior of KamLAND scintillator

Response to electrons can be measured using Compton effect

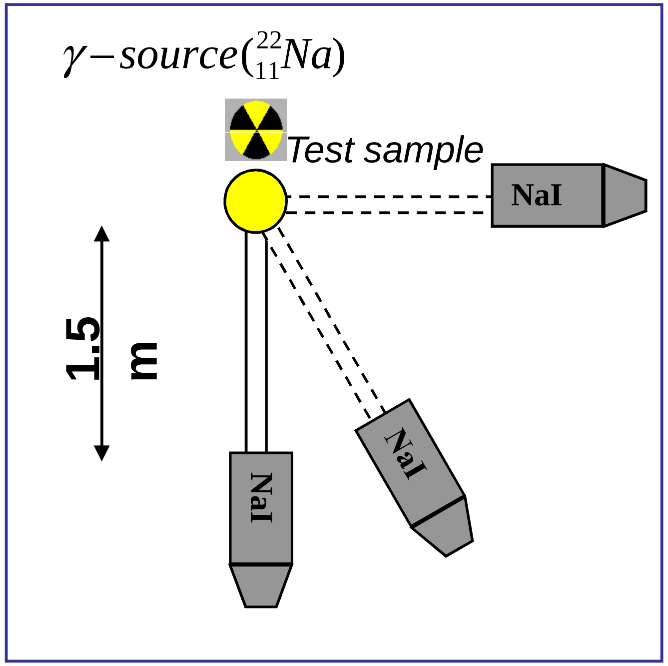


$$\lambda_f - \lambda_i = \Delta\lambda = \frac{h}{m_0 c}(1-\cos\theta)$$

Energy of recoil electron is determined by scattered photon angle and certain initial energy of the incident photon

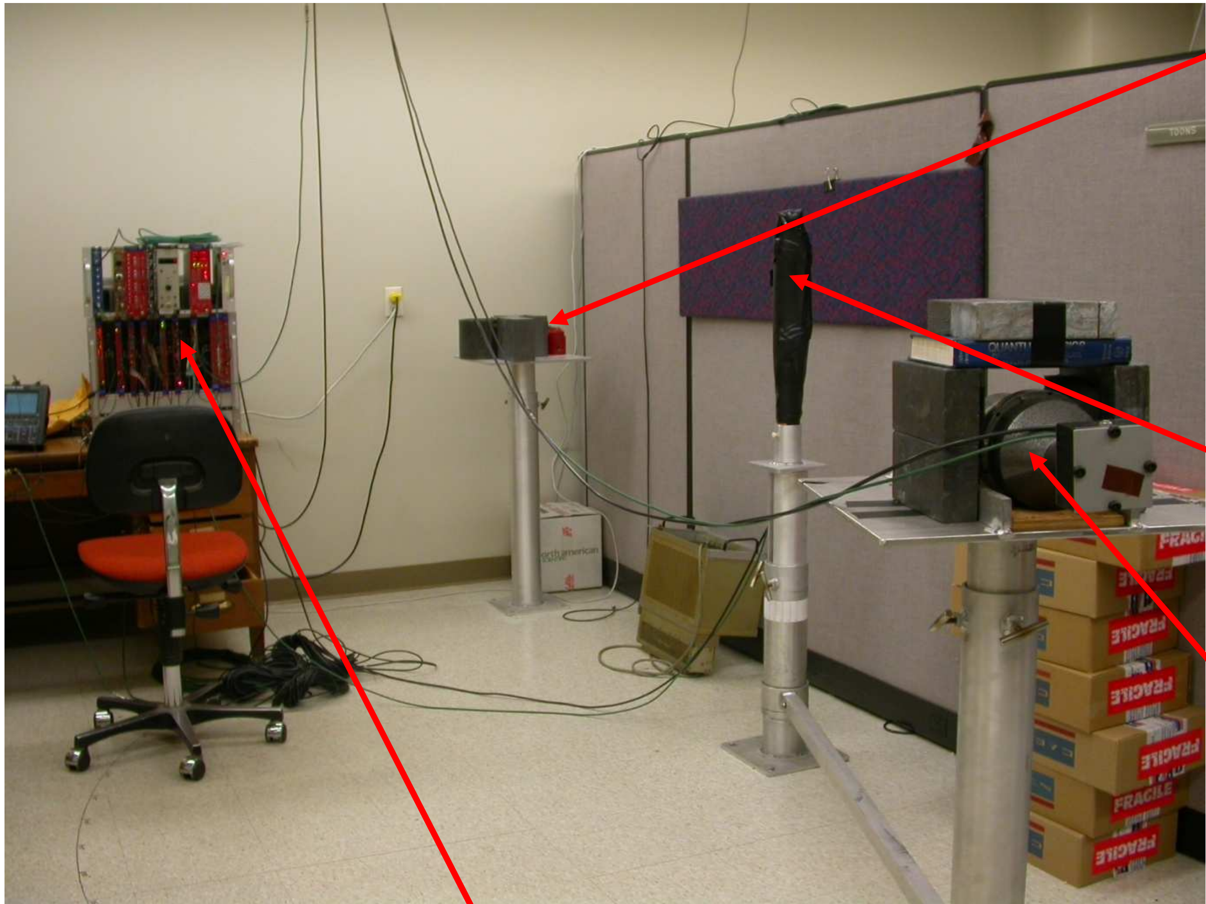
$$E_e^{kin} = E_\gamma - E_\gamma \frac{m_e}{m_e + E_\gamma(1-\cos\theta)}$$

Compton spectrometer scheme

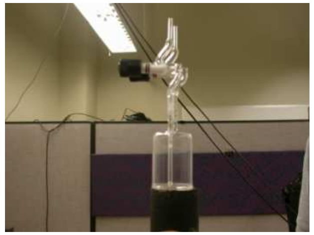


^{22}Na gamma source
0.511 MeV and 1.275 MeV

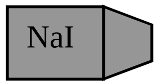
Compton Spectrometer Design



1 mCi ^{22}Na Radiation source with two gamma lines 511 and1275 keV Placed inside massive lead collimator
R_{hole}=2.5mm
L_{hole}=8.5cm



Test sample
2.5cm radius, 6.35 cm height quartz cylinder

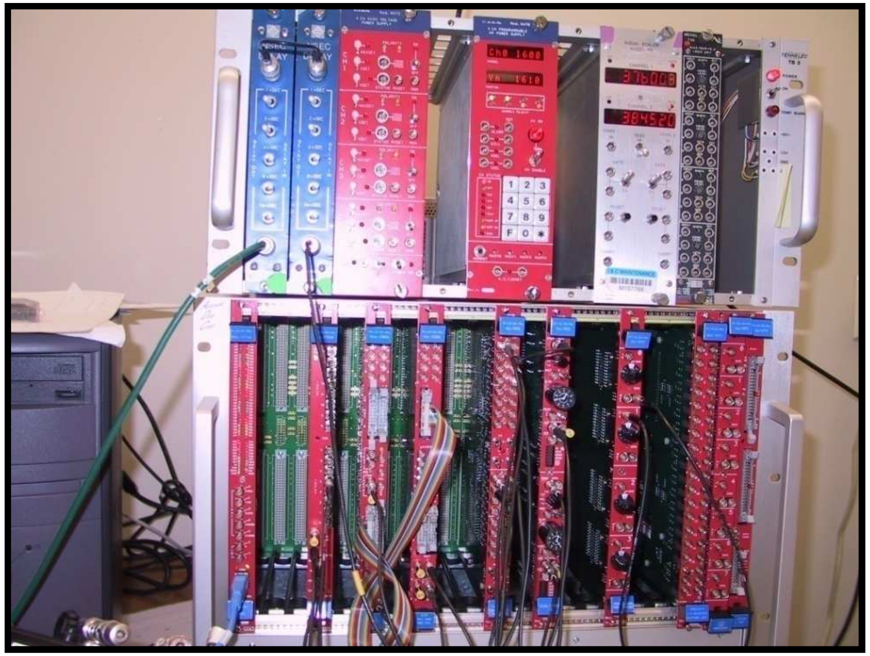


Gamma Detector ∅13 cm
With the long 1.6 m arm we have small angular dispersion

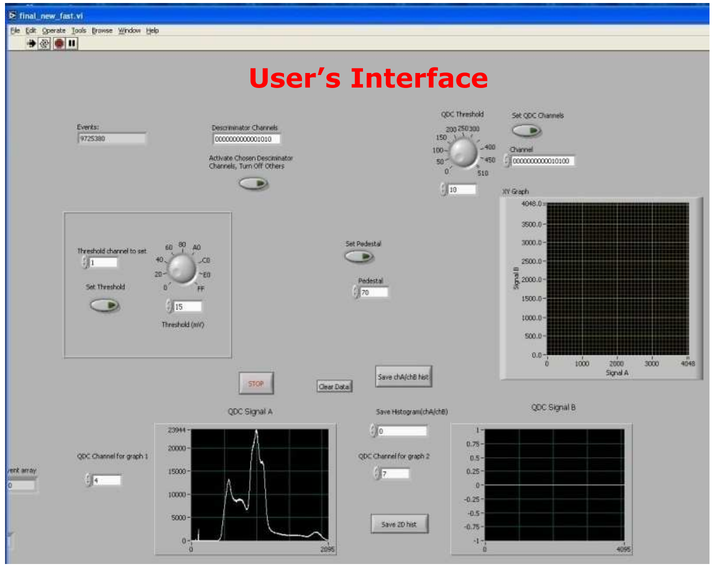
VME DAQ system

DAQ System

Crate with VME electronics

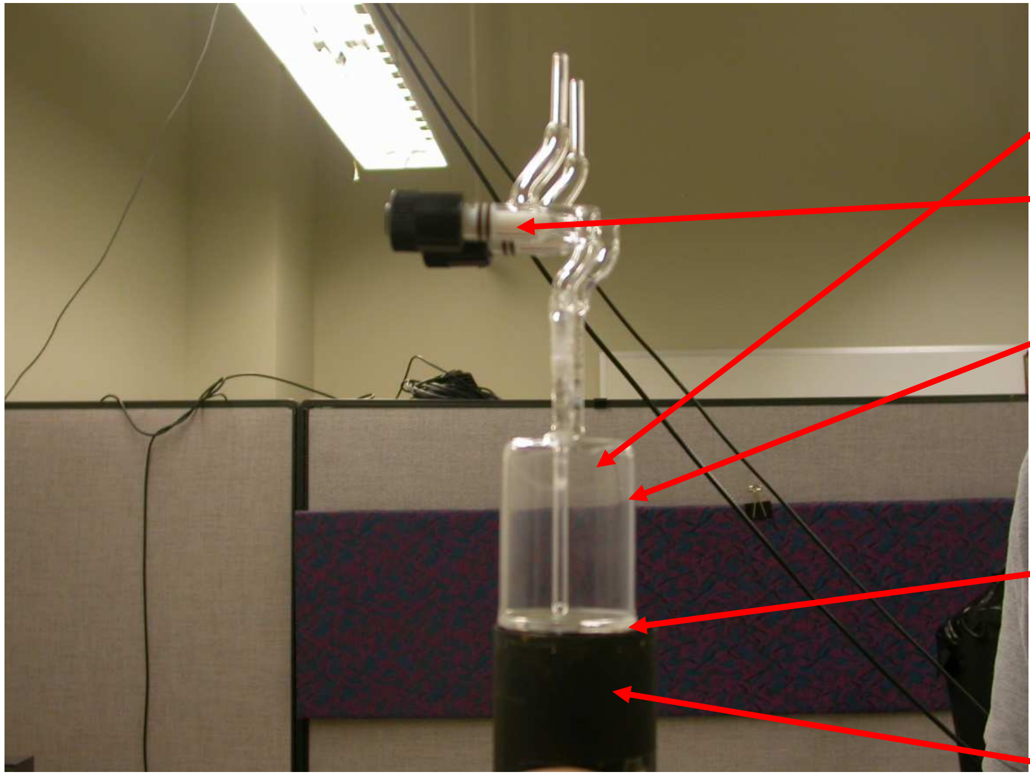


DAQ software was developed using LabView 7



Trigger rate ~30 events/min
Rate depend on angular position of NaI, angular acceptance of the spectrometer

Target Volume



KamLAND liquid Scintillator

Teflon valves

Quartz vessel
(wrapped in Tyvek)

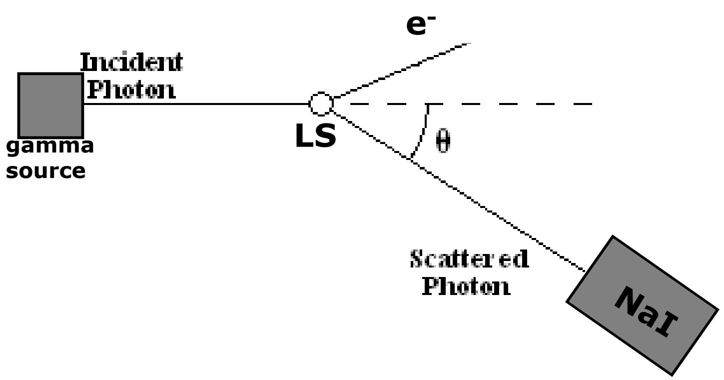
Bicron Optical Grease

Hamamatsu 1161 2” PMT
with Bialkali photocathode

Before measurements scintillator was purged with large amount of nitrogen and then vessel has been sealed with Teflon valves

Spectrometer properties

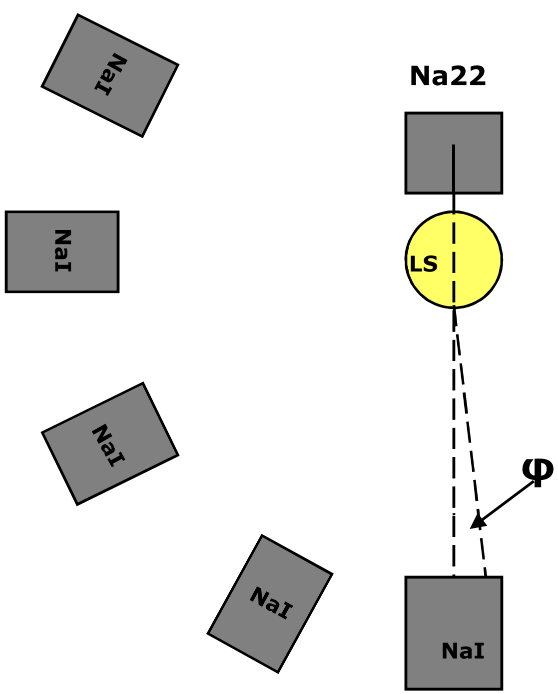
- Selection of the certain deposited energy in the scintillator by electrons is determined by the angular position of the NaI
- Measurements were done from 20 to 120 degrees of scattering angle
- Kinetic energy range for detected electrons is 29-300keV for 511keV gamma line and 166.3-1000keV for 1275keV gamma line
- Alignment of all components of the spectrometer is important part of the experiment (error in determination of the scattering angle can cause the “faked non-linearity”)

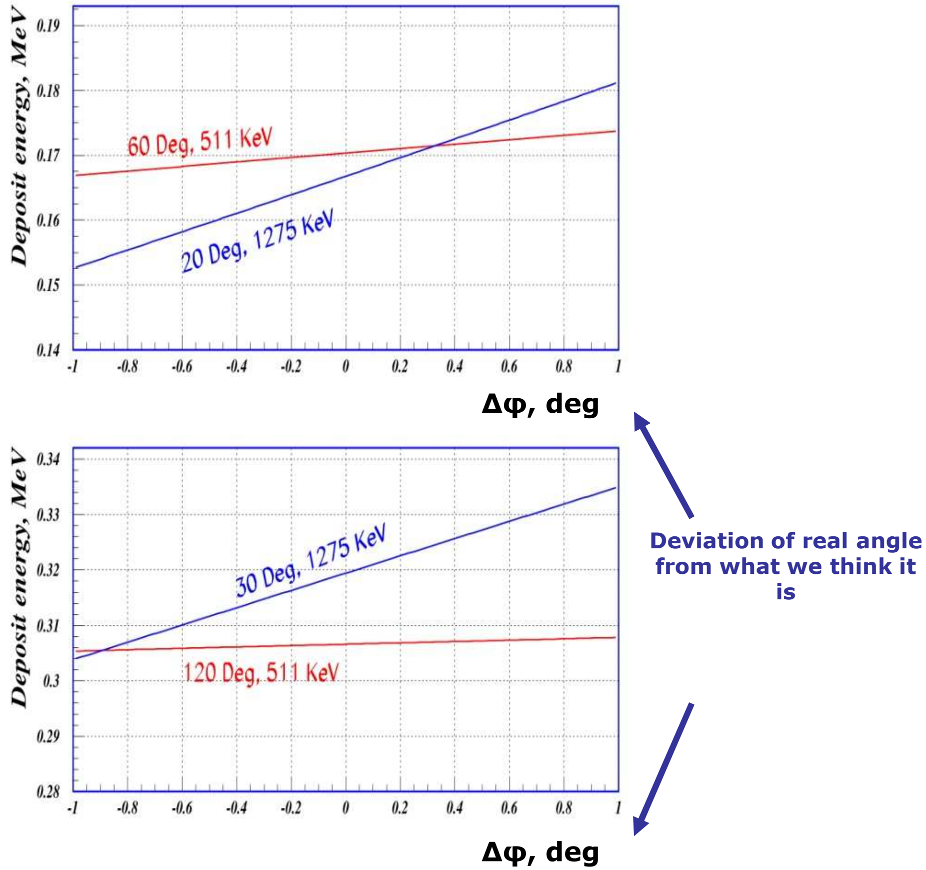


$$E_e = E_\gamma - E_\gamma \frac{m_e}{m_e + E_\gamma (1 - \cos\theta)}$$

Alignment of spectrometer

Scintillator and radiation source position along with the angular scale were aligned using theodolite (accuracy is better than 0.1 degrees)



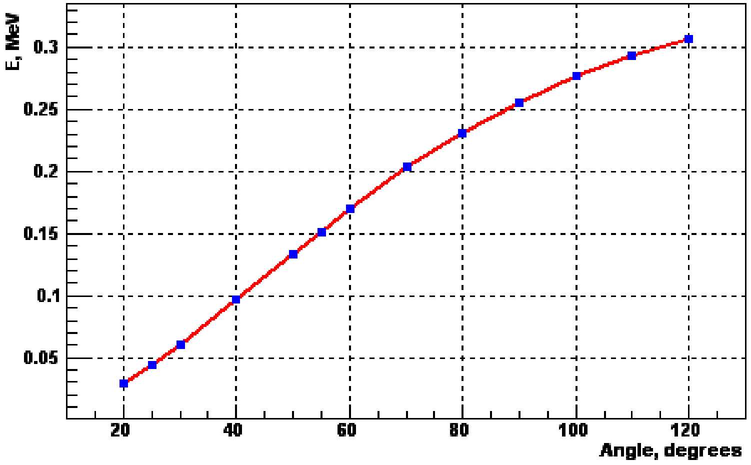


1 degree misalignment can cause up to 10% non-linearity

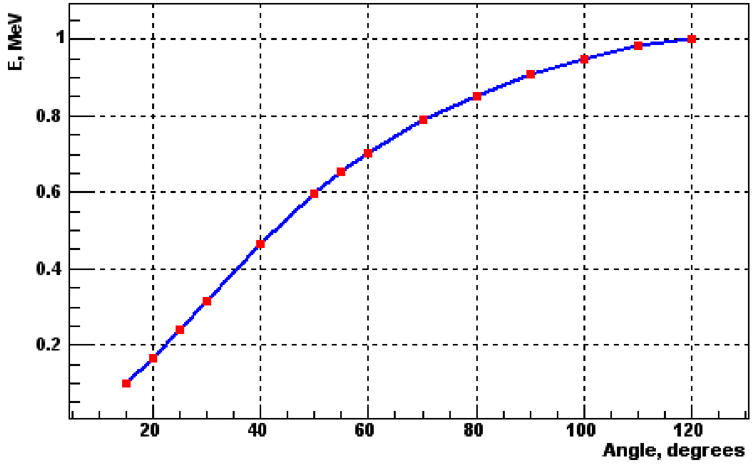
Energy deposition Monte-Carlo simulation (without quenching)

- Monte-Carlo simulation was made using GEANT
- Physical and geometrical properties of the spectrometer were described in order to define energy deposition in liquid scintillator
- Errors of energy deposition are about 0.2%
- Difference in the energy deposition in LS between MC and Compton Formula is up to 0.9%

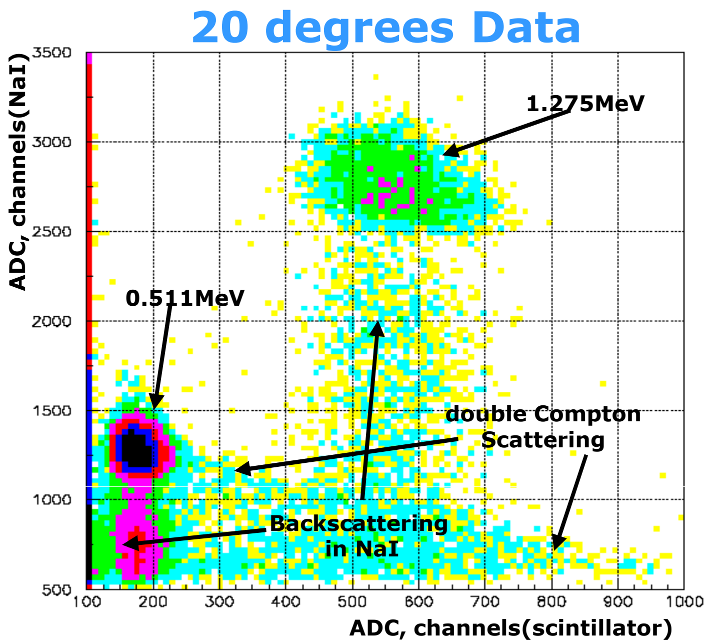
Deposited energy in LS(0.511MeV gamma line)

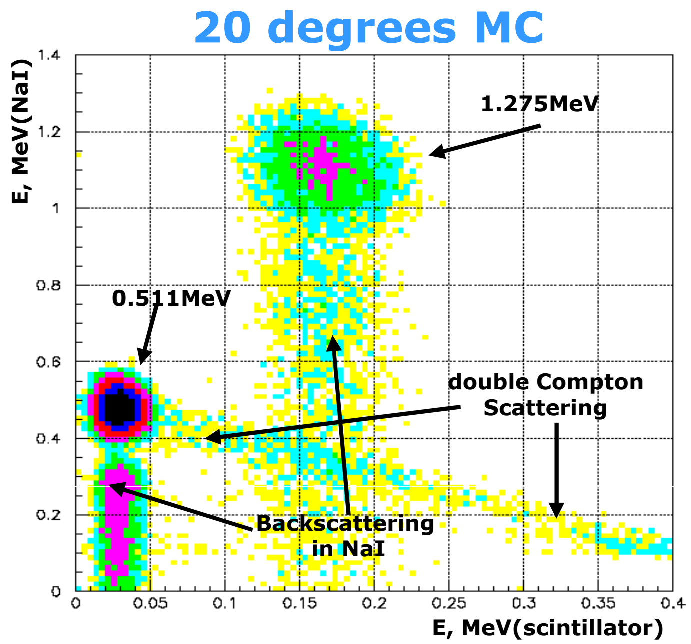


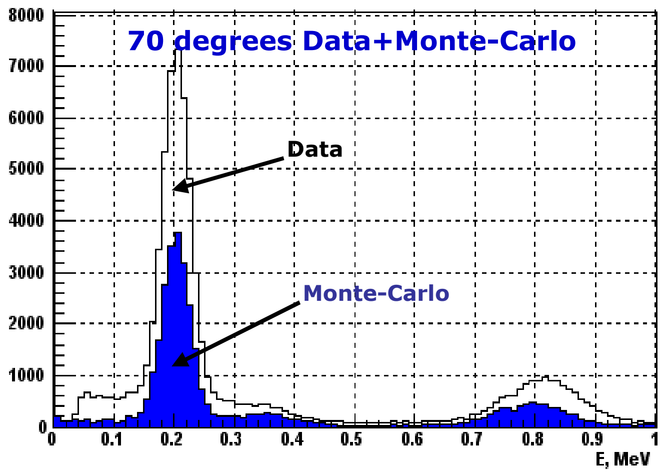
Deposited energy in LS(1.275MeV gamma line)



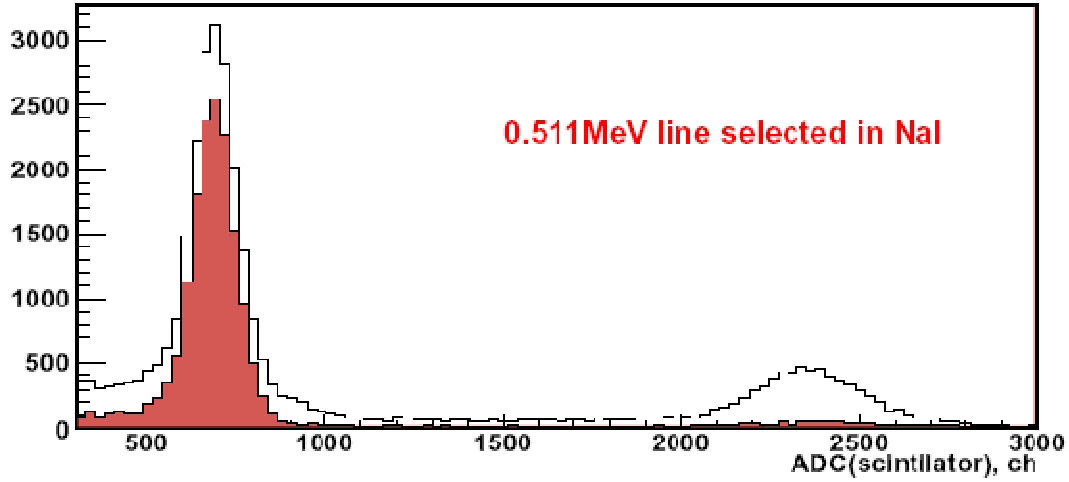
Data & Monte-Carlo

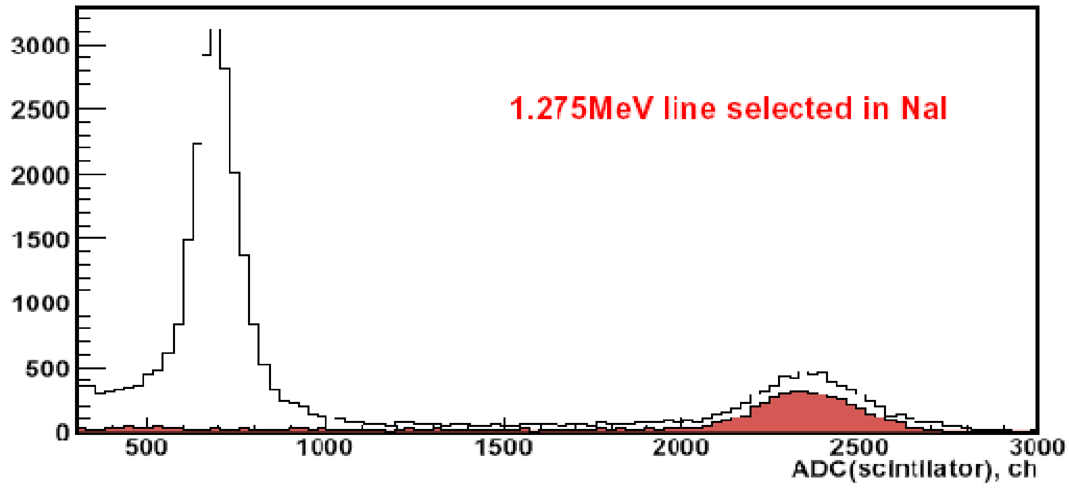






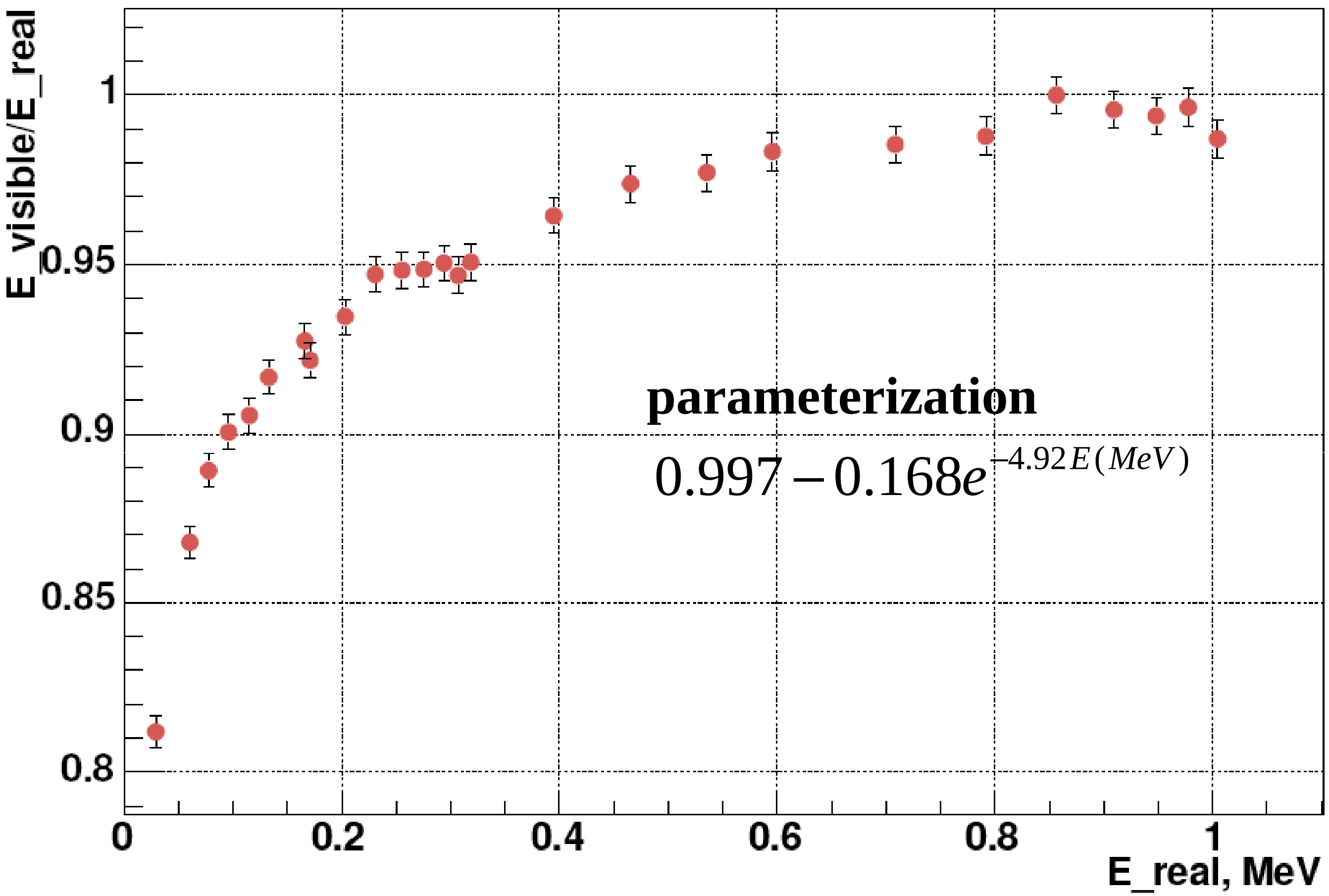
Event selection in Scintillator





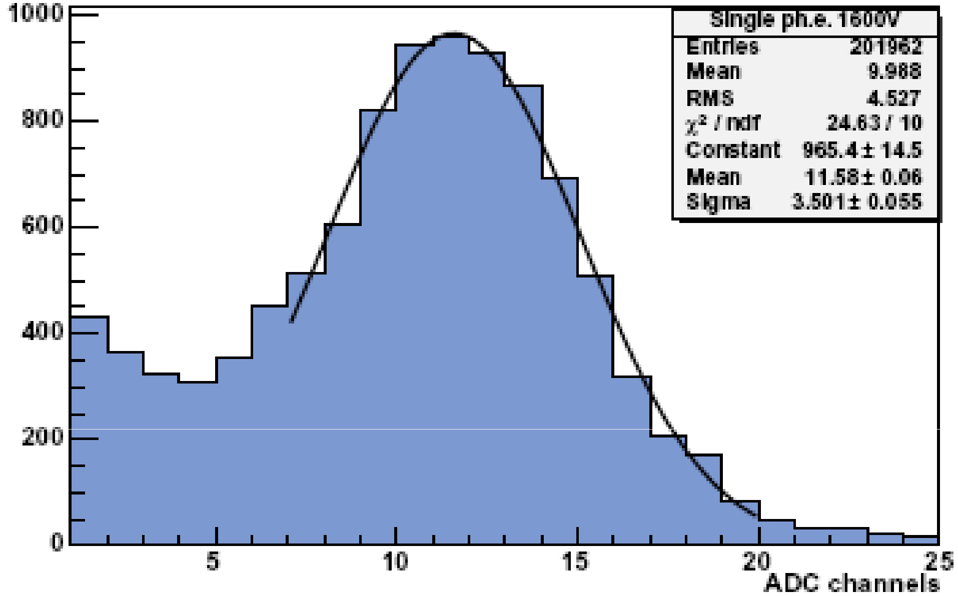
Energy cut in NaI let us clearly select Compton scattering in the test sample for both gamma lines

KamLAND LS response to electrons



Systematic errors 0.5%

Scincillator Light output calibration



1ph.e.=0.001554MeV

N=643.5+/-3.8 ph.e./MeV

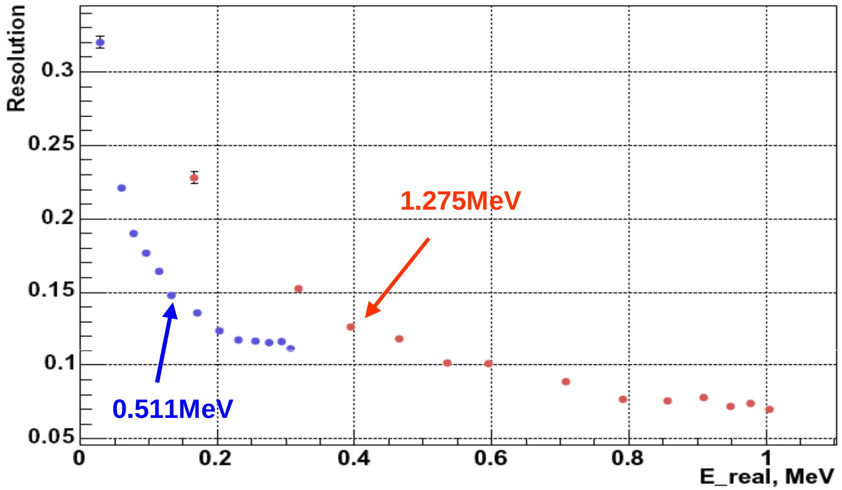
Since the single photoelectron has its own resolution it gives additional contribution to the final photo-statistic resolution

$$\frac{\delta N}{N} = \sqrt{\frac{1+\alpha^2}{N}} = \frac{1.0447}{\sqrt{N}}, \alpha = 0.3 - Single\ \ ph.e.\ resolution$$

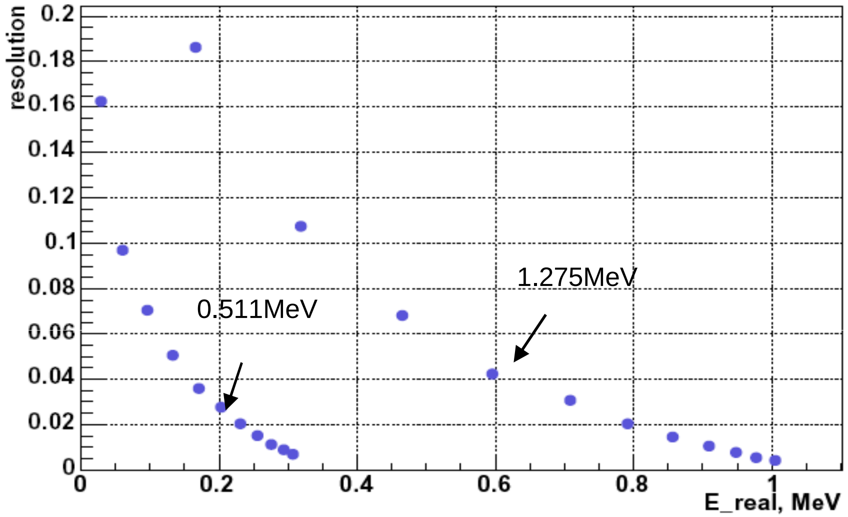
Spectrometer Resolution

Spectrometer Resolution consists of two components: pure energy resolution and energy resolution due to angular dispersion

Spectrometer Resolution (real data)



Energy resolution due to angular dispersion (Monte-Carlo)



Extracted Energy Resolution

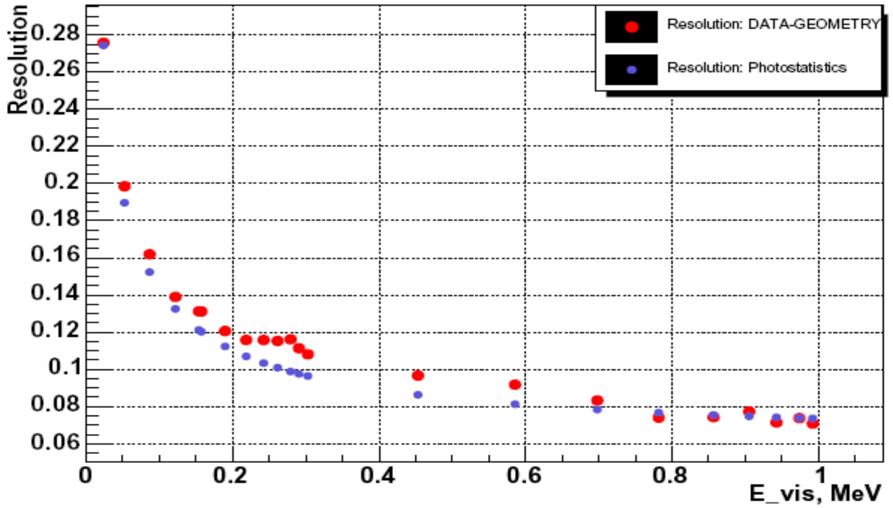


Photo-statistic resolution plus constant term (light collection uniformity)

$$\frac{\delta E}{E} = \sqrt{(0.061)^2 + \frac{(1.0447)^2}{N_{ph.e.}}}$$

Photo-statistic resolution was taken from calibration using single ph.e.

Monte-Carlo study (non-linearity)

We decided to perform M.C. study to understand which physical processes can explain this non-linearity.

- **Calculate Cherenkov contribution in photoelectrons exactly (emission, reemission, tracking, QE, etc.)**

- **Simulate energy deposition with different Birks coefficients**

- **Mix Scintillation and Cherenkov light using parameter N photoelectrons from scintillation per MeV**

Conversion Ph.e. to the Signal from PMT

Conversion deposit energy into Ph.e.

$$E_{vis} = k \cdot (E_{dep}(E) \cdot m + N_{Ch}(E))$$

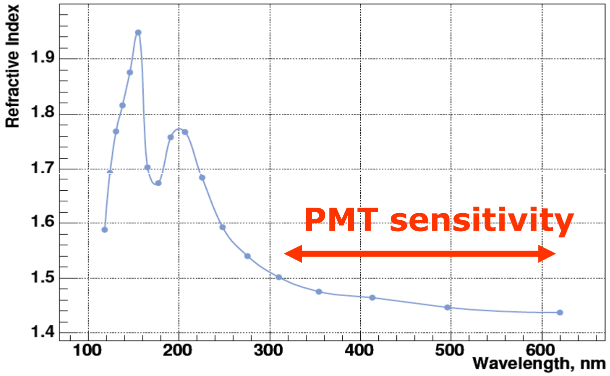
Calculated in GEANT, Birks dependent

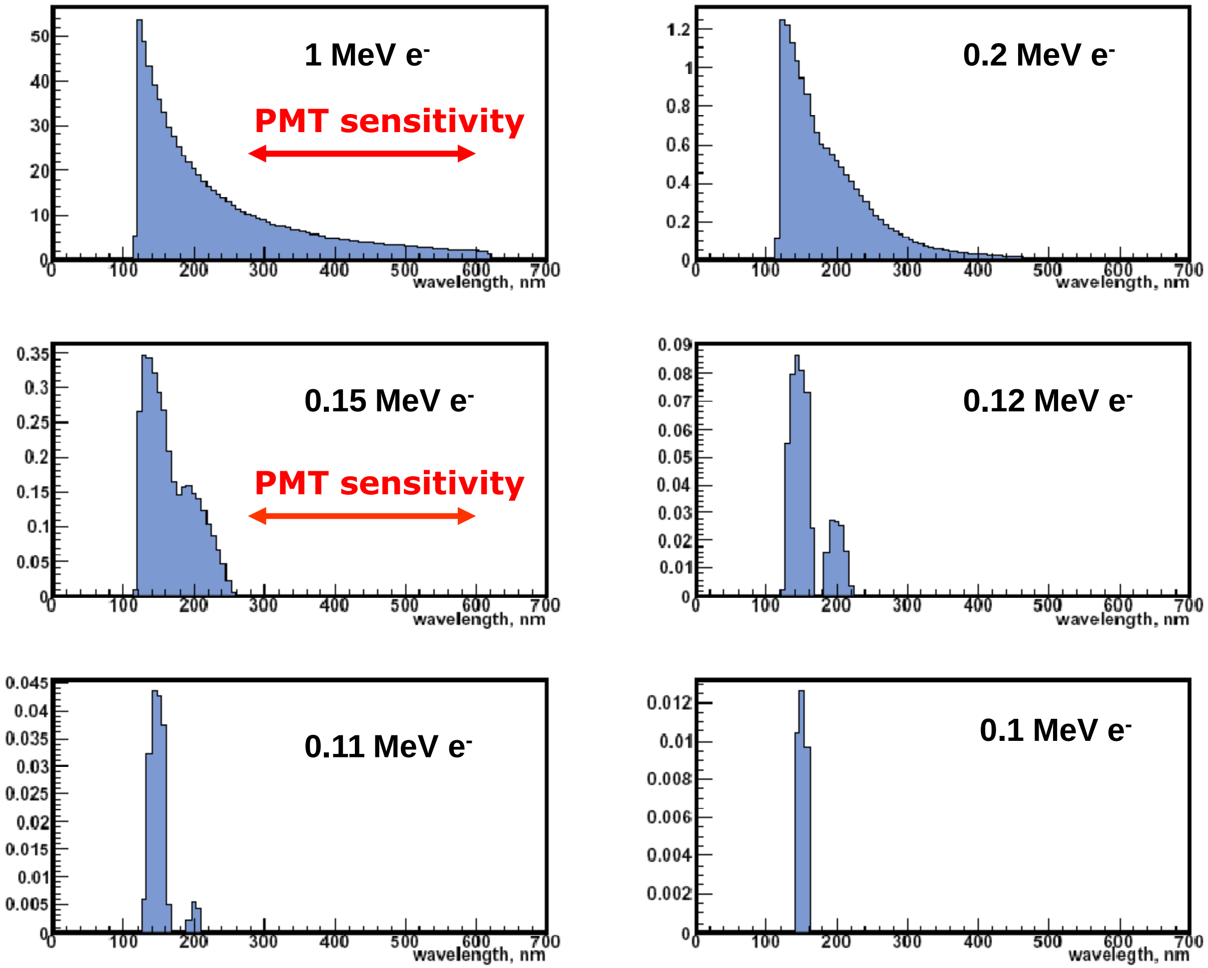
Calculated in GEANT with reemission

Cherenkov Photons Production

$$\frac{d^2N}{dx d\lambda} = \frac{2\pi\alpha z^2}{\lambda^2}\left[1 - \frac{1}{\beta^2 n^2(\lambda)}\right]$$

Reconstructed refractive index for KamLAND LS

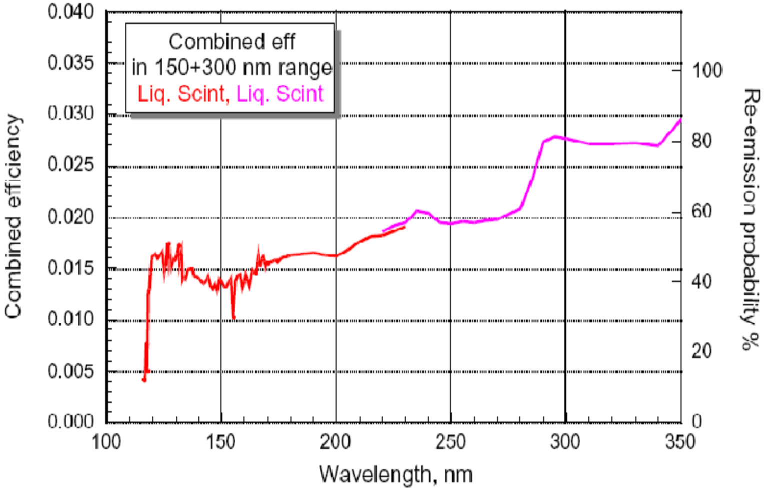




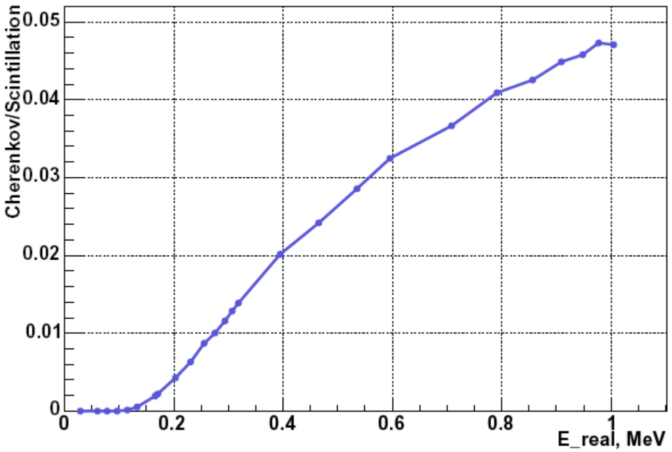
All plots normalized to one incident electron

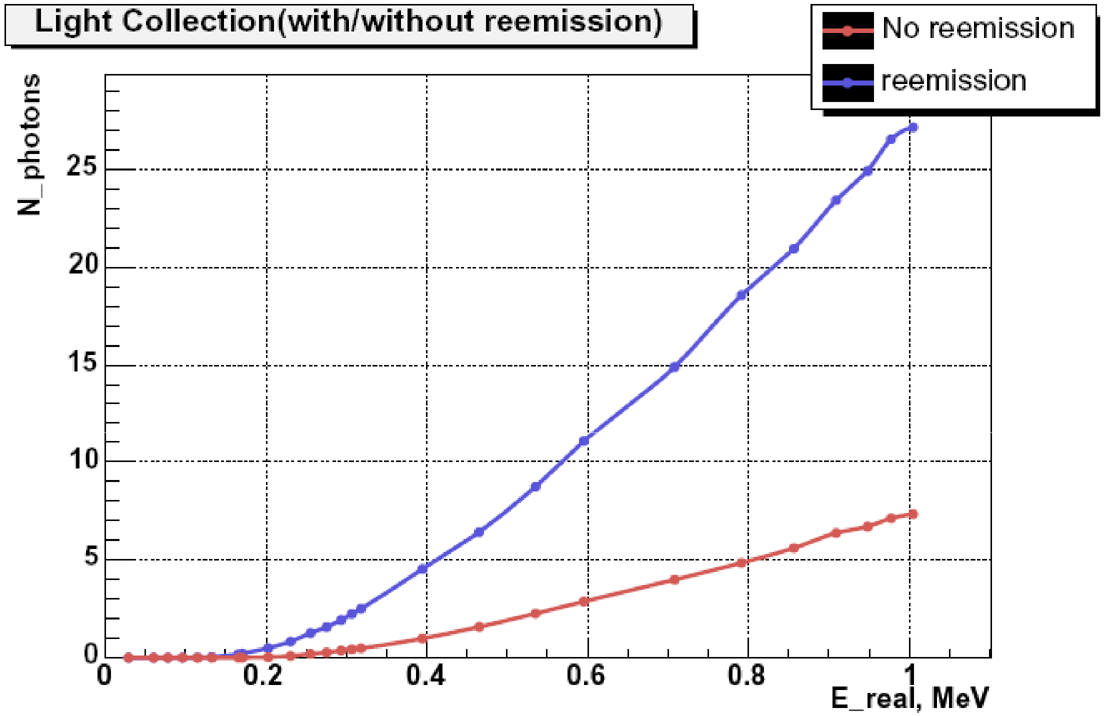
Cherenkov Light Production + Reemission (Monte-Carlo)

Reemission probability



Cherenkov light contribution





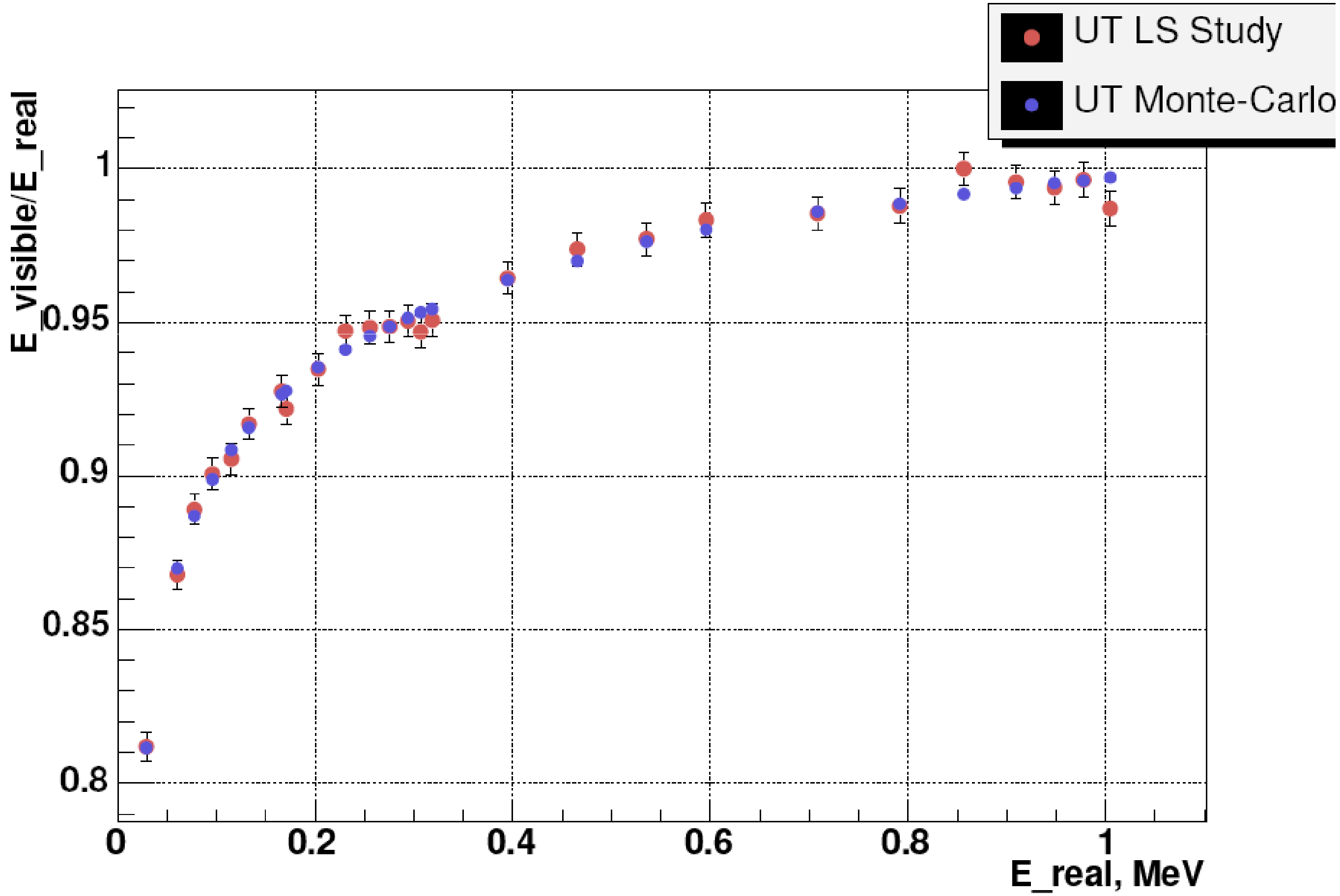
Reemission increased number of Cherenkov photons detected at 1 MeV by factor of 3.7

Cherenkov light contribution to the total light yield is 4.5% at 1MeV

Data vs. M.C.

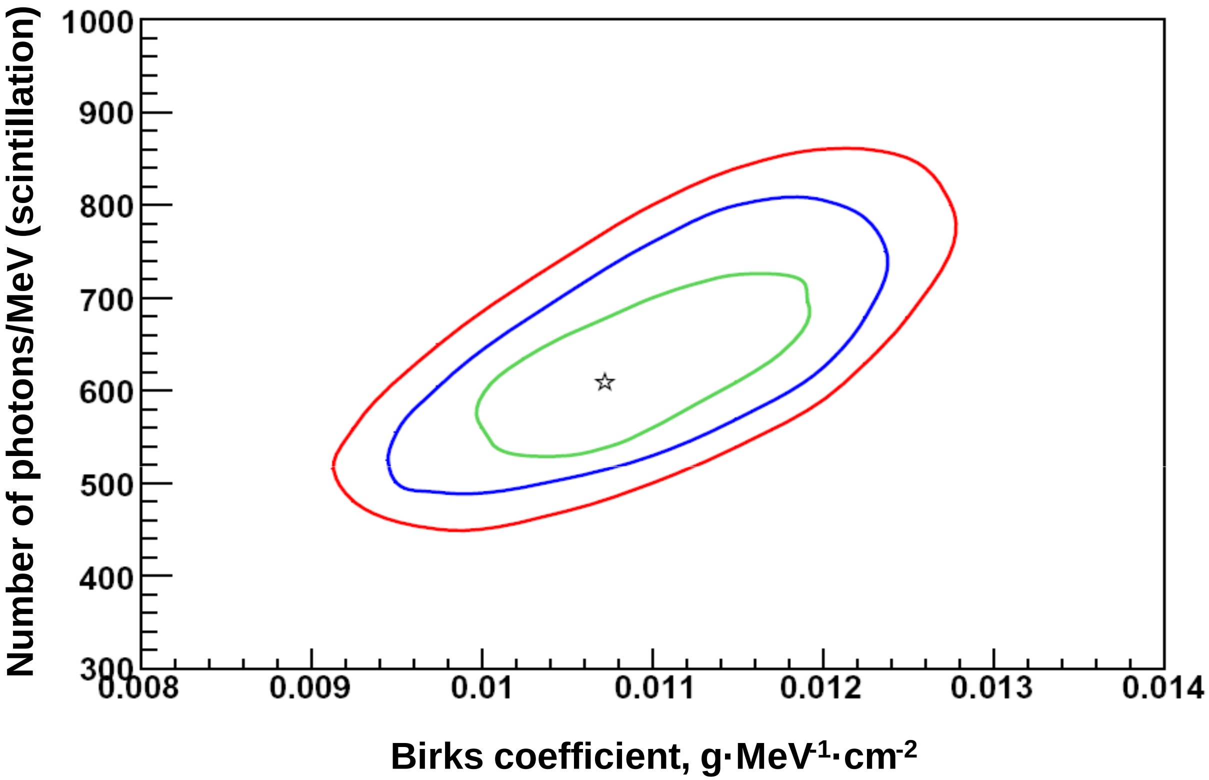
Variation of Birks coefficient and Scintillation light output was made to obtain the same shape of nonlinearity measured with Compton Spectrometer

Cherenkov light output has been calculated and fixed



Very good agreement between data and M.C.

Best fit (Monte-Carlo)



N ph.e /MeV best fit is 609 ph.e./MeV

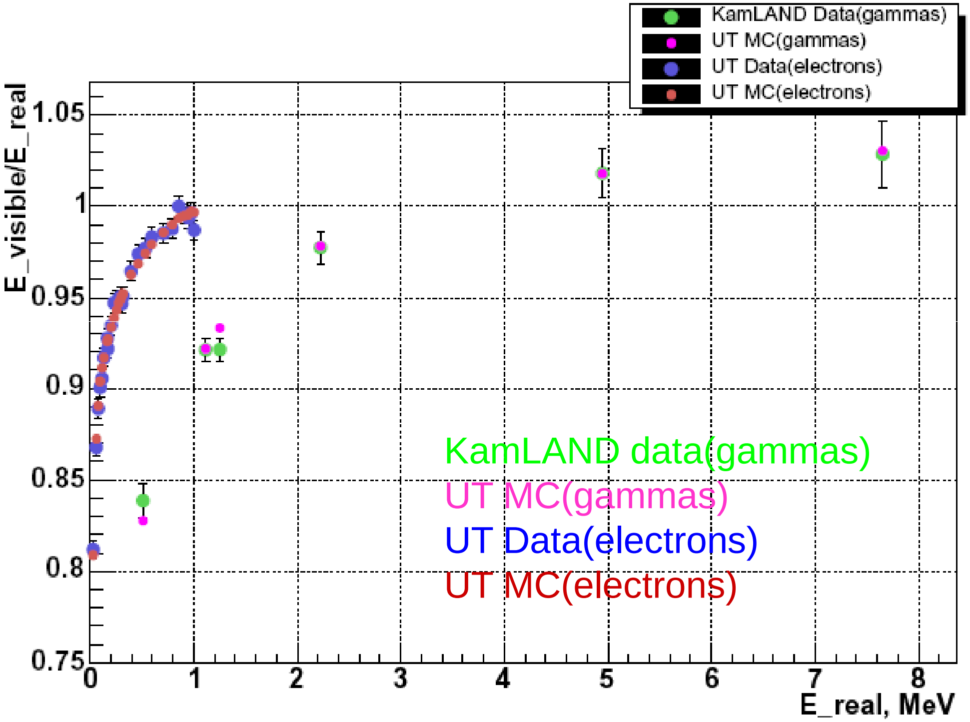
Good agreement with direct measurement (single ph.e.) N ph.e./MeV=643.5+/-3.8 ph.e.

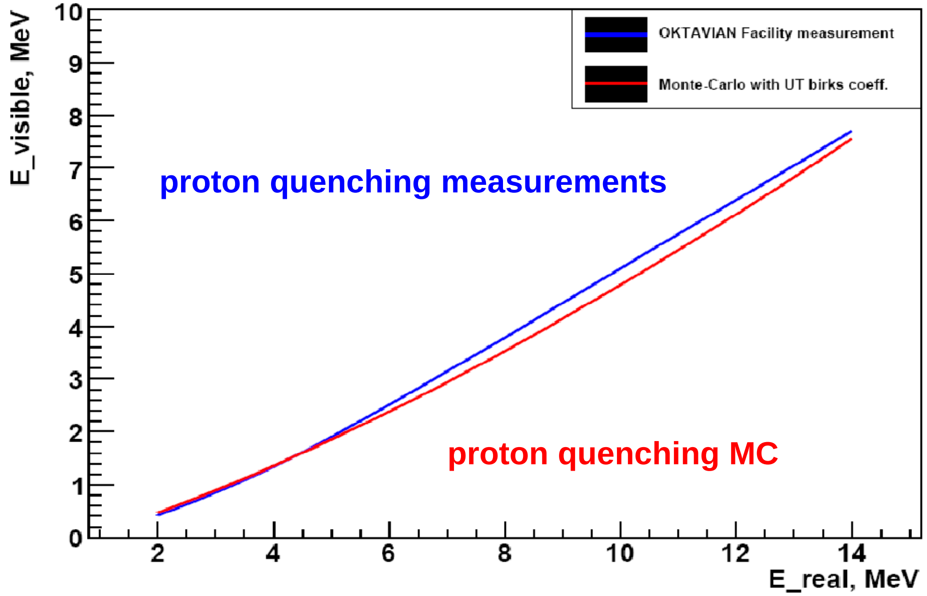
Our best Birks value is 0.01072 g/(MeV·cm^2) =0.138mm/MeV

GEANT recommended K_B =0.013g/(MeV·cm^2)

Comparison with Gammas and Protons

Current model, optimized on electrons with E<1 MeV, was applied to calculate LS response to gammas and protons

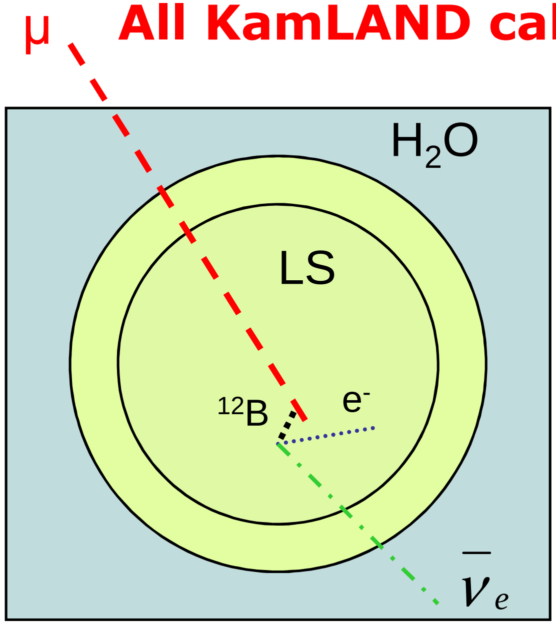




MC, developed to explain nonlinear behavior of scintillator for electrons reproduces well nonlinearity for gammas and protons!!!

Energy reconstruction (^{12}B events)

All KamLAND calibration sources have energies below 8MeV



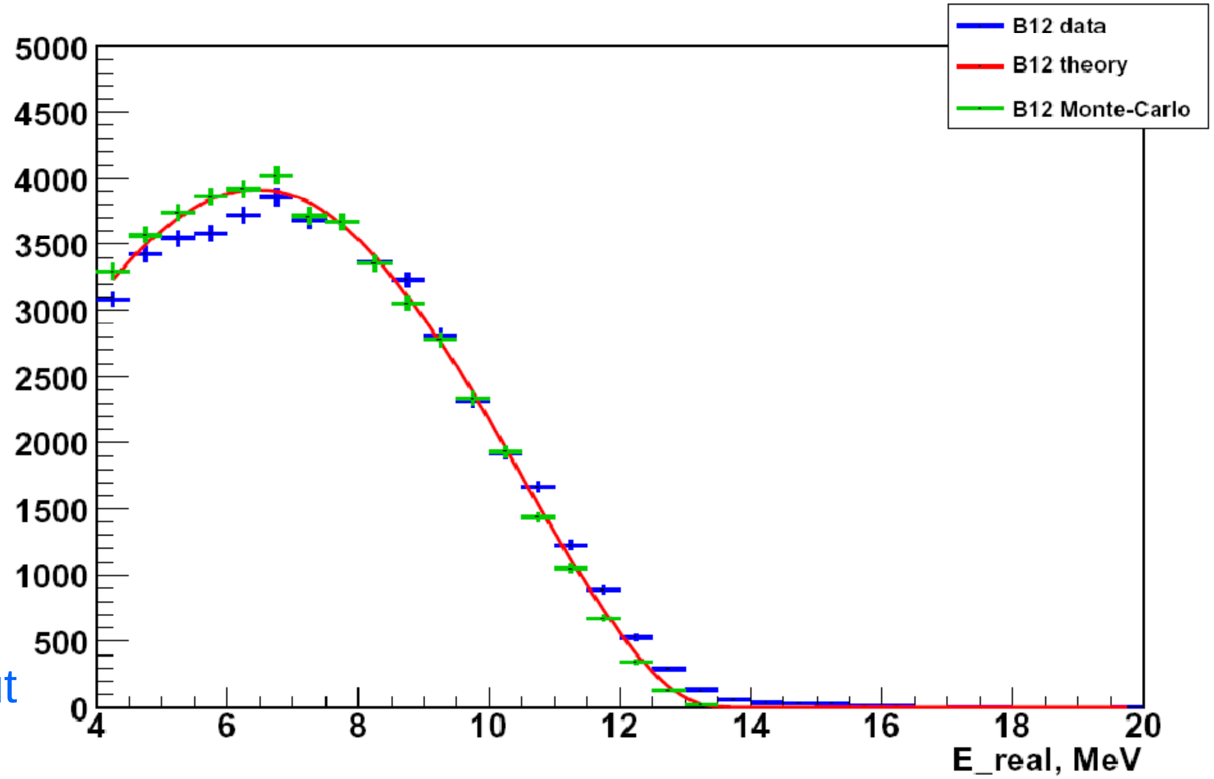
$$\mu^- + {}^{12}C \rightarrow {}^{12}B + \nu_\mu$$

~29msec

$$\rightarrow {}^{12}C + e^- + \bar{\nu}_e$$

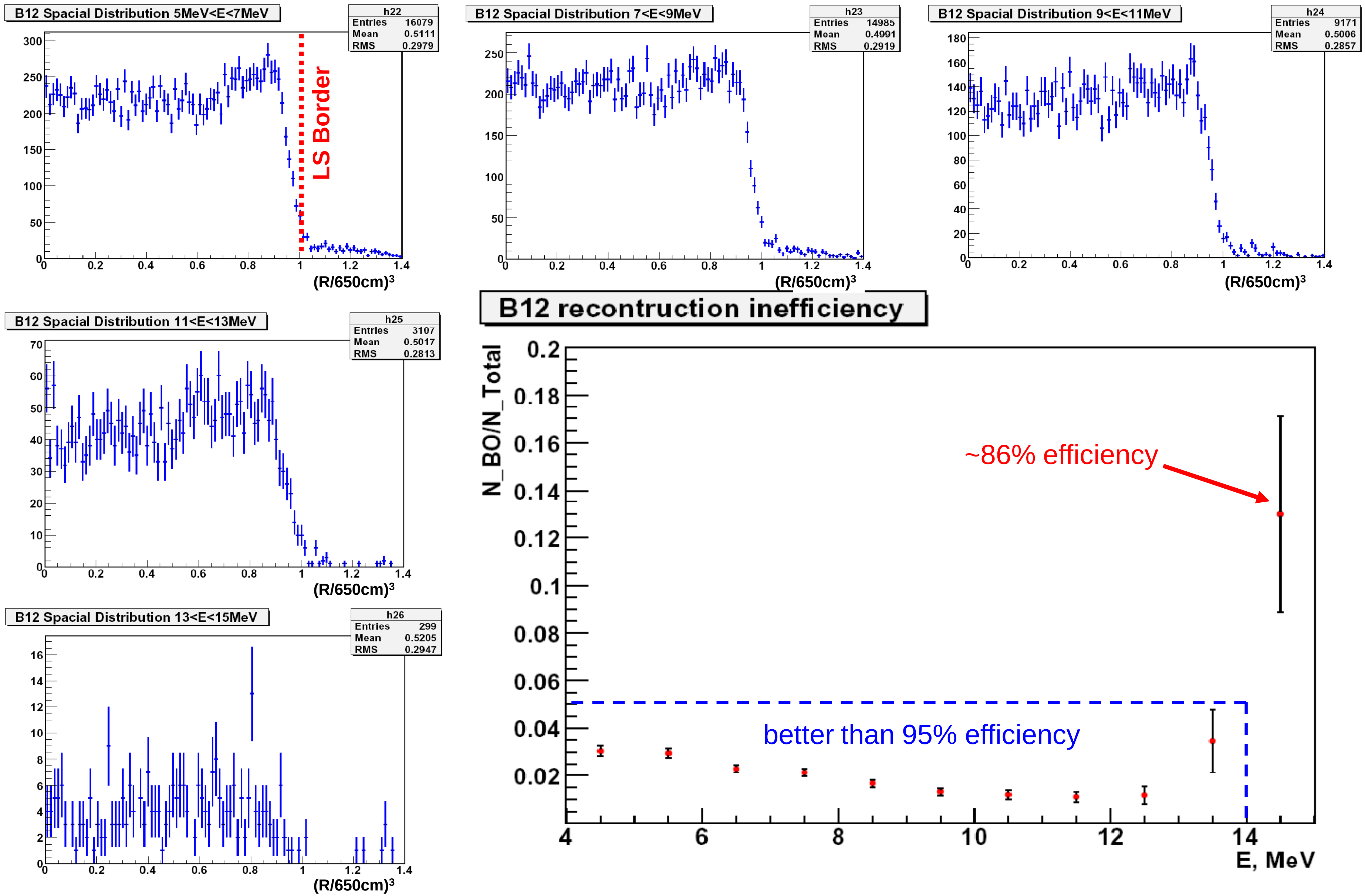
After muon signal the events have been selected during 2-60msec
Background off-timing window 502-560msec

Distance from muon track cut dL <300cm



Energy in the interval of 7.5 < MeV < 14 reconstructed reasonably well

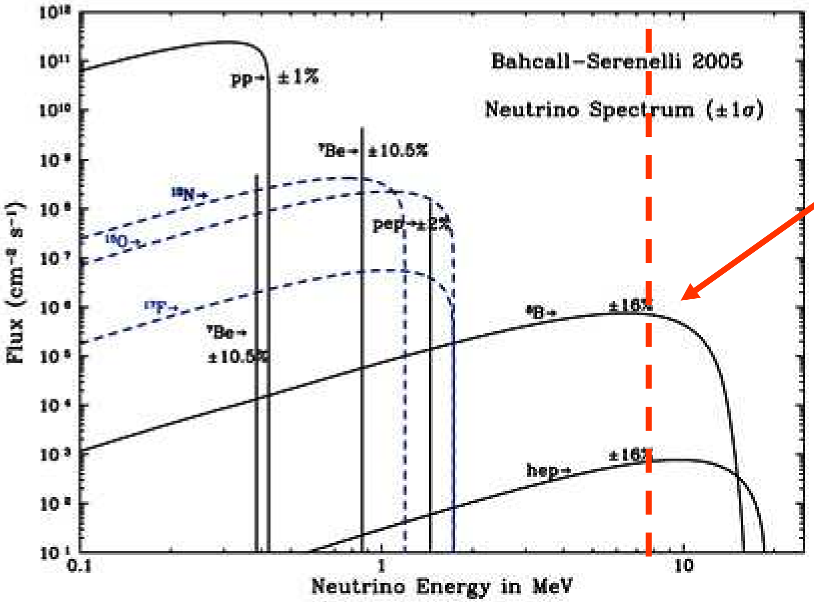
Vertex Reconstruction (^{12}B events)



Solar antineutrino analysis

- Previous result
- Electron antineutrino candidates selection
- Background calculations

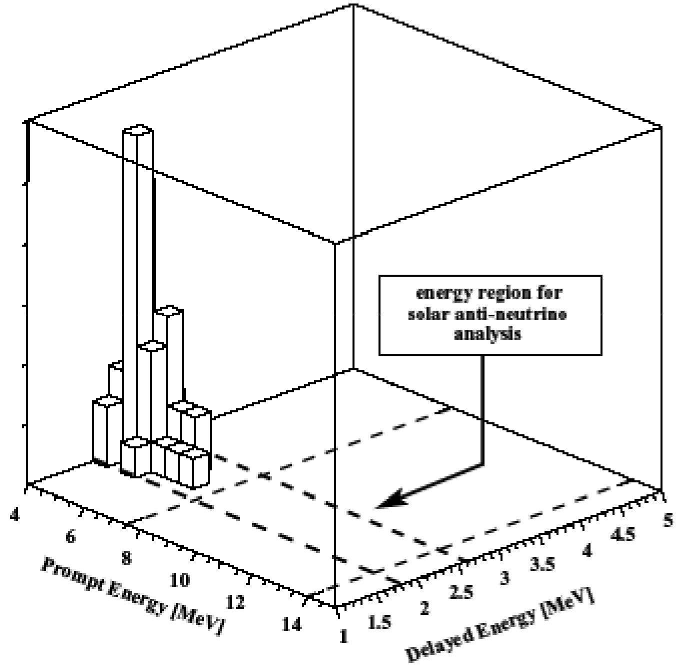
Search for Solar Antineutrinos (old KamLAND result)



^{8}B solar ν_e can transform to anti-ν_e in solar magnetic field

Phys. Rev. Lett. 92:071301, 2004

The tail from reactor antineutrinos is visible below 7.5 MeV



Current KamLAND limit on Solar electron antineutrino flux:

$\Phi<3.7\times10^{2}$ cm^{-2}s^{-1}

Or neutrino conversion probability:

$P<2.8\times10^{-4}$

Energy distribution of event candidates after 185.5 days(0.28 ton-year)

0 candidates have been found

This limit can be improved with larger in-hands statistics

High Energy Candidates Selection

Muon criteria:

TotalCharge17>10000p.e. or
(TotalCharge17>500p.e. & N200OD>5)

Veto:

Low charge muon
(TotalCharge17<40000p.e.)
2msec veto for whole volume of the detector
(TotalCharge17>13000p.e.)

Energetic muon (showering muon)
(TotalCharge17>40000p.e. & dQ>10^6p.e.)
2sec veto for whole volume of the detector

Miss reconstructed muon
(TotalCharge17>40000p.e. & badness>100)
2sec veto for whole volume of the detector

Well reconstructed non-energetic (non-showering) muon
(TotalCharge17>40000p.e. & badness<100 & dQ<10^6 p.e.)
2msec veto for whole volume of the detector
2sec veto around the muon track within 3m(delayed only)

$dQ=Q_{ID}-Q_{\mu\ track}$

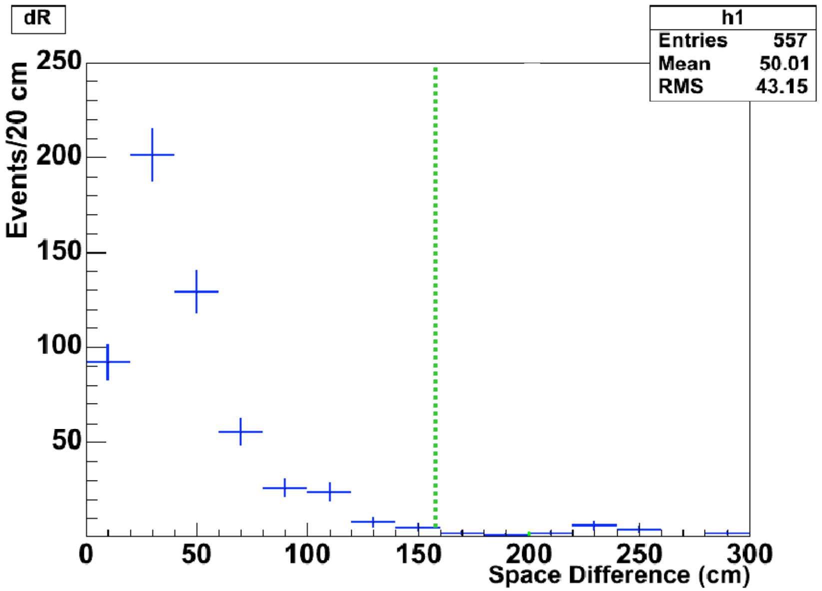
Spacial & Energy Cuts:

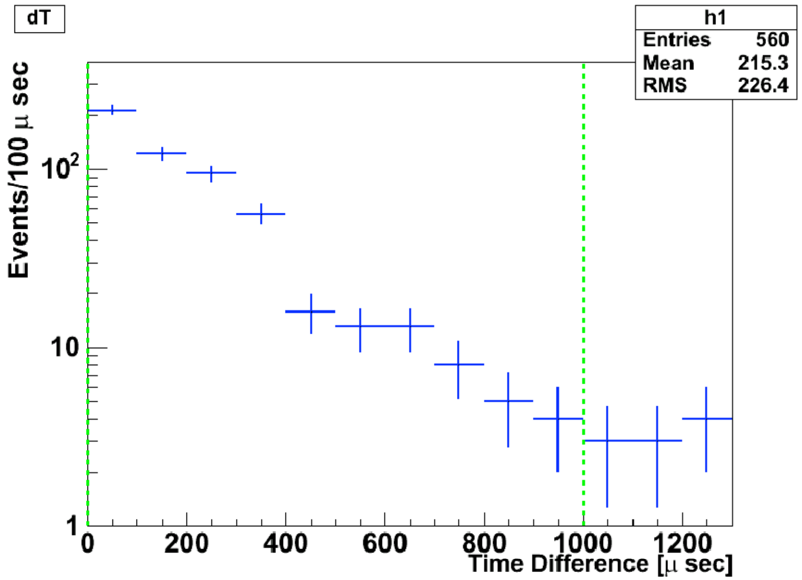
R_{prompt}, $R_{delayed}$<600cm
$|R_{prompt}-R_{delayed}|$<160cm
dT<1000μsec
7.5MeV<E_{prompt}(real)<30MeV
1.8MeV<$E_{delayed}$(visible)<2.6MeV

Improvement:
Statistics
Livetime ×7.7 statistics
185.5 days → 1425.9 days

New energy and muon fitters
New vertex reconstruction tool
New event selection criteria

Spatial & Time Correlation between prompt and delayed

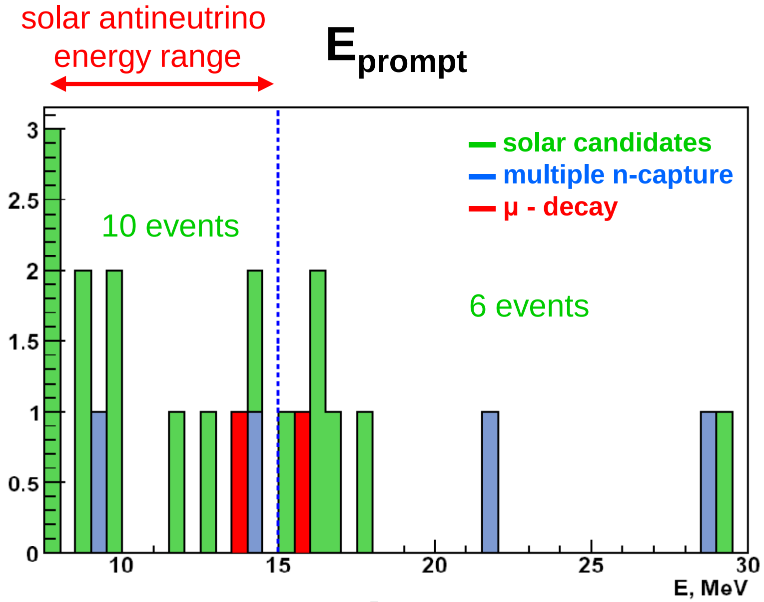




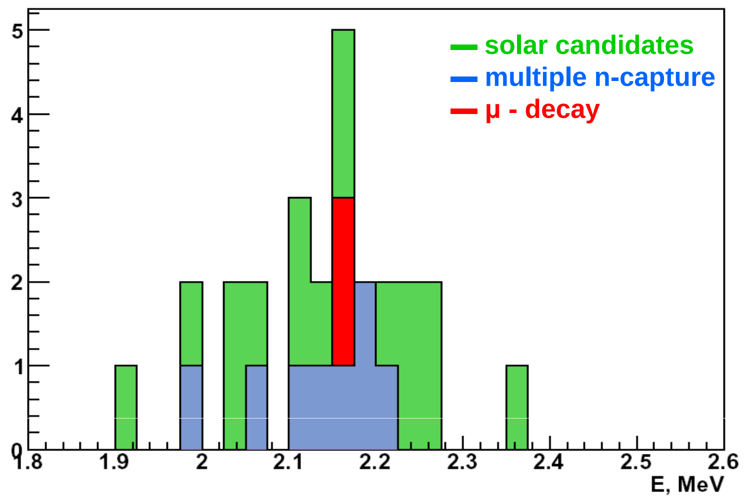
Plots were made for reactor antineutrino candidates

High Energy Candidates 6.0m fiducial volume

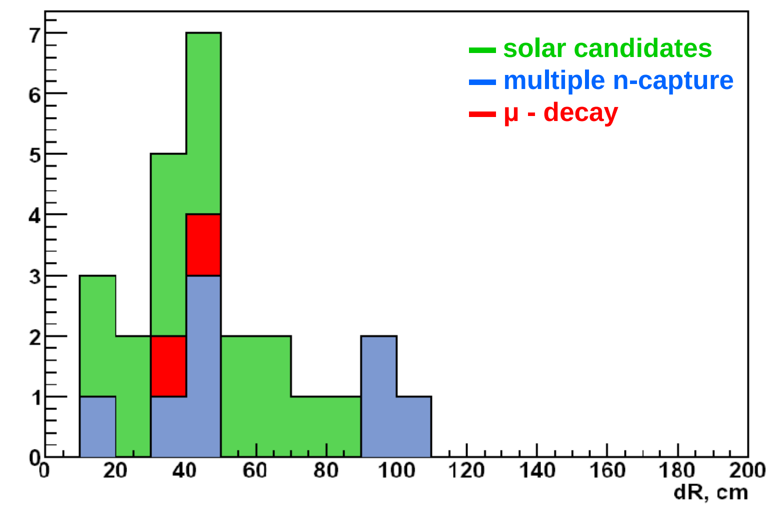
E_{prompt}



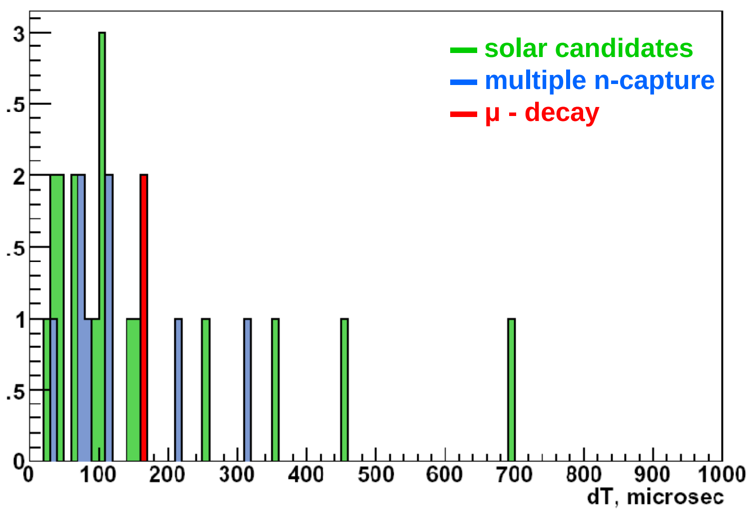
$E_{delayed}$



ΔR



ΔT



7.5->15MeV:
10 candidates has been selected

+

2 triple coincidence: multiple neutrons capture

Run# 1824, Prompt# 13658585
Delayed# 13658586, 13658587
Run# 5941, Prompt# 4644789
Delayed# 4644790, 4644791

+

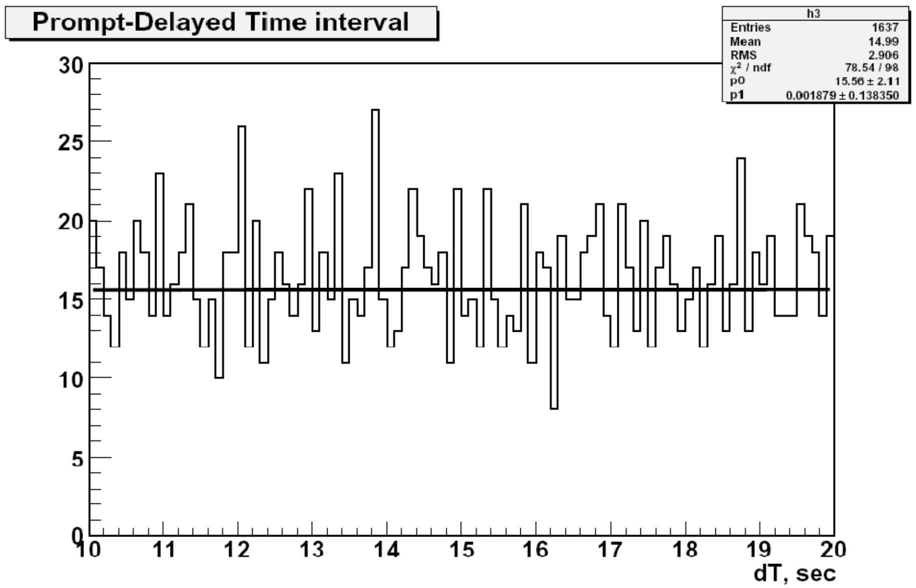
1 muon decay (triple coincidence)
Run# 5380
Prompt_1# 41470(muon, E=15.5MeV)
Prompt_2# 41471(positron, E=13.6MeV)
Delayed# 41472
dT_{1-2}=1.23μsec
dR_{1-2}=6.4 cm

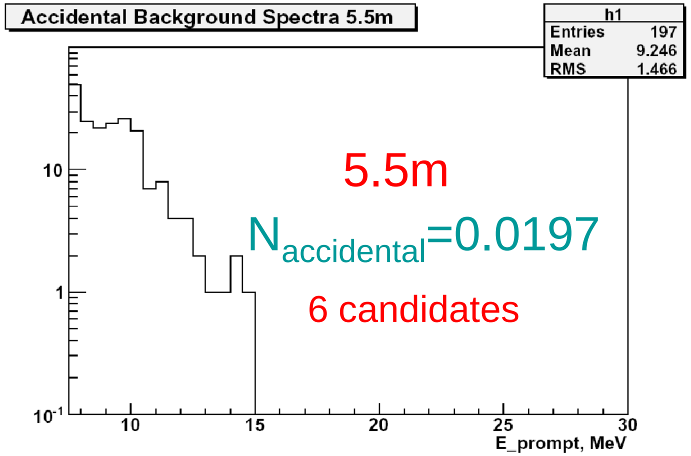
Background sources

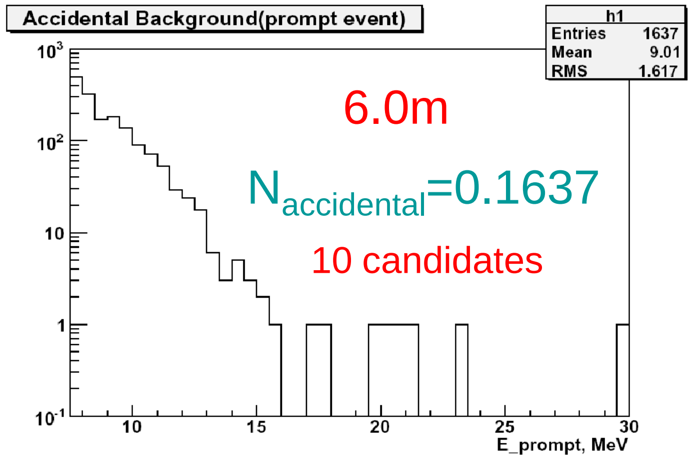
- Accidental Background
- ^{9}Li produced by cosmic muons
- Reactor antineutrinos
- Background from atmospheric neutrinos

Accidental Background

Delayed events time window:10.005sec<dT<20sec from Prompt event
10^4 scaling factor to delayed events time window in analysis

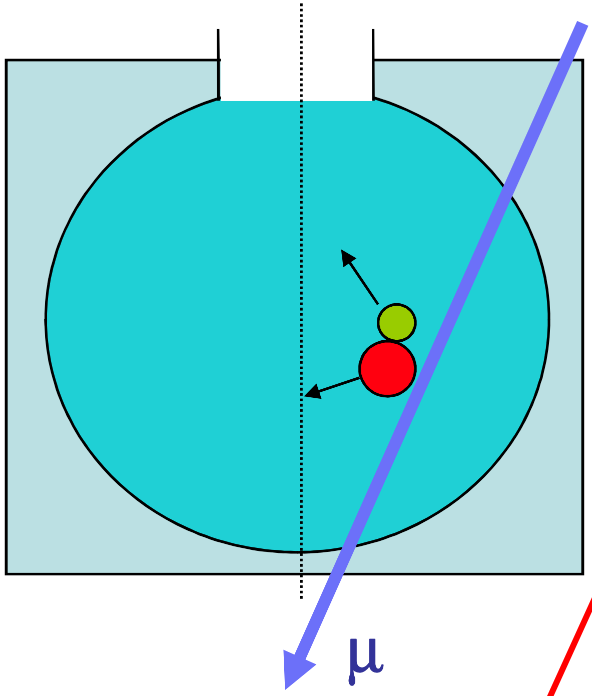






Accidental background is negligible

Spallation Products



Isotope	Half-Life	Endpoint	Decay Type
^{12}N	0.011 s	17.4 MeV	e^+
^{13}B	0.017 s	13.4 MeV	e^-
^{12}B	0.0202 s	13.4 MeV	e^-
^{11}Li	0.09 s	16.0 MeV	e^-
^{8}He	0.12 s	10.6 MeV	e^- with n
^{9}C	0.13 s	16.0 MeV	e^+ with p or α
^{9}Li	0.18 s	13.6 MeV	e^- with n
^{8}B	0.77 s	17.97 MeV	e^+ with α
^{6}He	0.81 s	3.5 MeV	e^-
^{8}Li	0.84 s	16.0 MeV	e^- with α
^{16}N	7.1 s	10.4 MeV	e^-
^{11}Be	13.8 s	11.5 MeV	e^- with α
^{10}C	19.3 s	1.9 MeV	e^+
^{14}O	71 s	5.15 MeV	e^+
^{15}O	122 s	2.76 MeV	e^+
^{11}C	20.38 min	0.96 MeV	e^+
^{13}N	9.97 min	2.22 MeV	e^+
^{7}Be	53 days	0.862 MeV	electron capture
^{10}Be	1.5×10^6 years	0.556 MeV	e^-

Dominant production: $^{12}C(\pi^-, {}^3He)$

$$^9Li \rightarrow {}^9Be + \beta^- \ (52\%)$$

$$^9Li \rightarrow {}^9Be + \beta^- + n \ (48\%)$$

^{9}Li Background

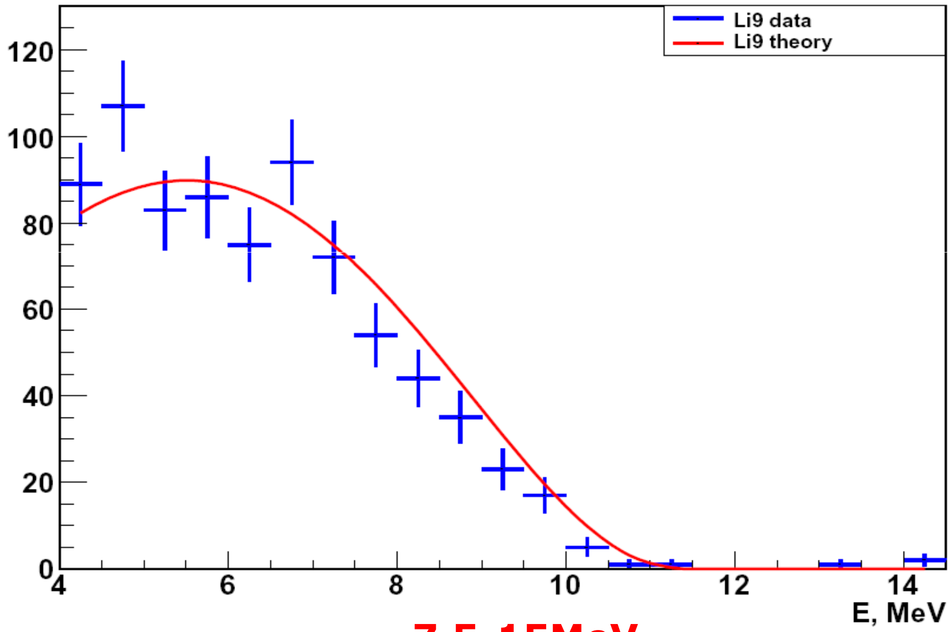
^{9}Li events time window for prompt event:
1sec after muon (^{9}Li mean lifetime 257msec)
Background time window:
5 to 6sec after muon

5.5m	4-15MeV		
	^{9}Li events	**BG**	**Li-BG**
Showering muon	790	163	627
Non-showering muon	383	38	158

6.0m	4-15MeV		
	^{9}Li events	**BG**	**Li-BG**
Showering muon	1026	216	810
Non-showering muon	498	293	205

$$\frac{N_{7.5-15\,MeV}}{N_{4-15\,MeV}} = 0.277$$

R_{prompt}, $R_{delayed}$<600cm
$|R_{prompt}-R_{delayed}|$<160cm
dT<1000μsec
E_{prompt}(real)>4MeV
1.8MeV<$E_{delayed}$(visible)<2.6MeV



7.5-15MeV

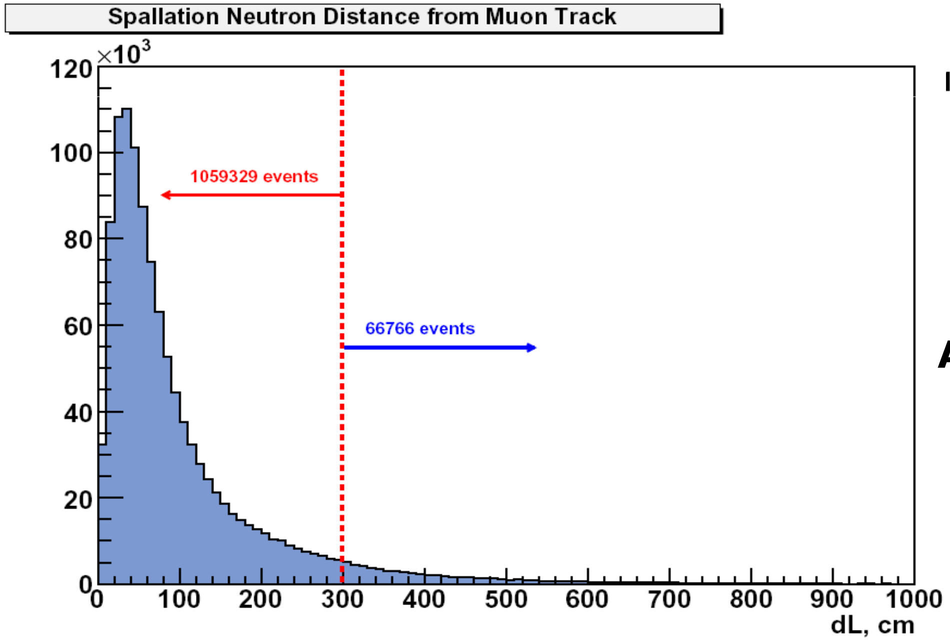
5.5m: 173.7±8.6(showering muon) & 43.7±6.6(non-showering muon)

6.0m: 224.4±9.7(showering muon) & 56.8±7.8(non-showering muon)

Showering muon veto: 2sec veto for whole volume of the detector
Non-showering muon veto: 2sec veto around the muon track within 3m(delayed only)

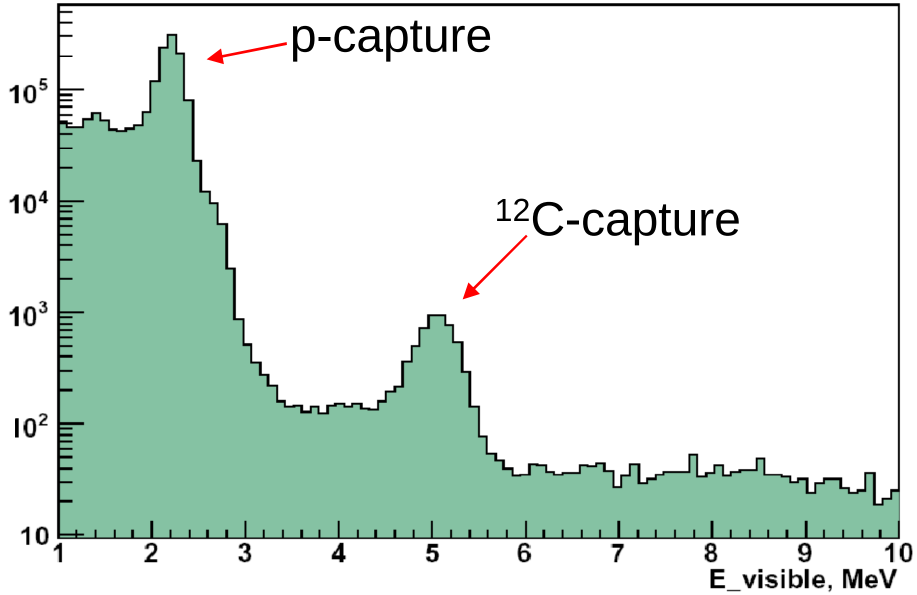
^{9}Li Background (spallation neutron)

Spallation neutron events time window:
150-1000μsec after muon
Off-timing background window:
2150-3000μsec after muon



94.1% 3m cut efficiency

Spallation neutrons spectrum

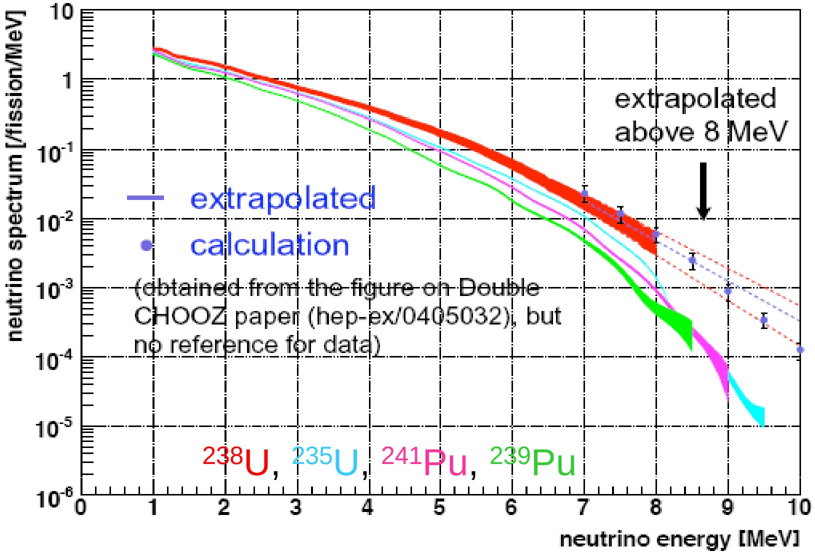


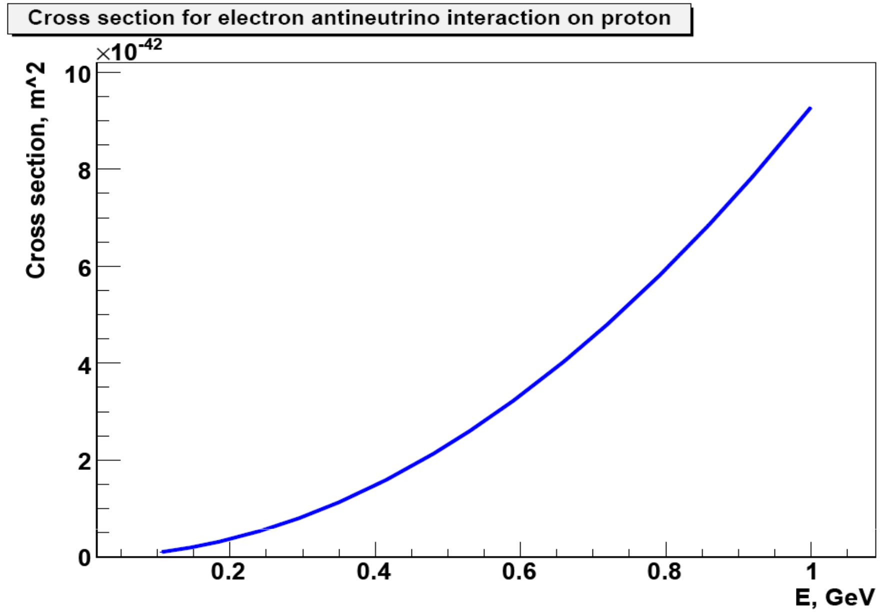
Applying 94.1% efficiency of 3m cut and 2sec cut total ^{9}Li BG within 7.5-15MeV:

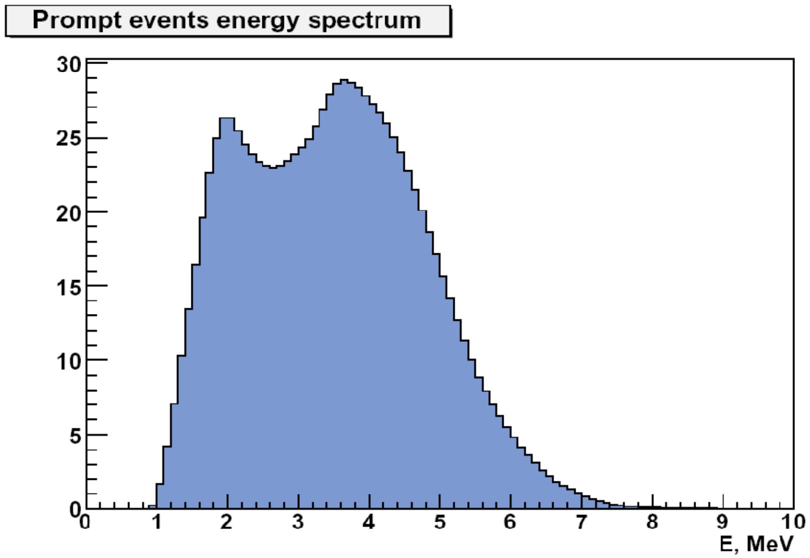
5.5m: 2.7 ± 0.4 events

6.0m: 3.5 ± 0.5 events

Reactor neutrinos background







KamLAND oscillation parameters: $\tan^2\theta_{12}=0.56$

$\Delta m^2_{21}=7.59\times10^{-5}\ \mathrm{eV}^2$

Background within 7.5-15MeV:
5.5m: 1.5 ± 0.5 events
6.0m: 1.9 ± 0.6 events

Antineutrino background from atmospheric neutrinos interactions

Neutral Current Interactions

$$\nu_{e,\mu} + {}^{12}C = n + {}^{11}C + \nu_{e,\mu}$$

$$\bar{\nu}_{e,\mu} + {}^{12}C = n + {}^{11}C + \bar{\nu}_{e,\mu}$$

Charged Current Interactions

1. $\bar{\nu}_e + p = n + e^+$
2. $\bar{\nu}_\mu + p = n + \mu^+$
3. $\nu_\mu + {}^{12}C = \mu^- + n + {}^{11}N$
4. ${}^{12}C(\bar{\nu}_\mu, \mu^+)X$

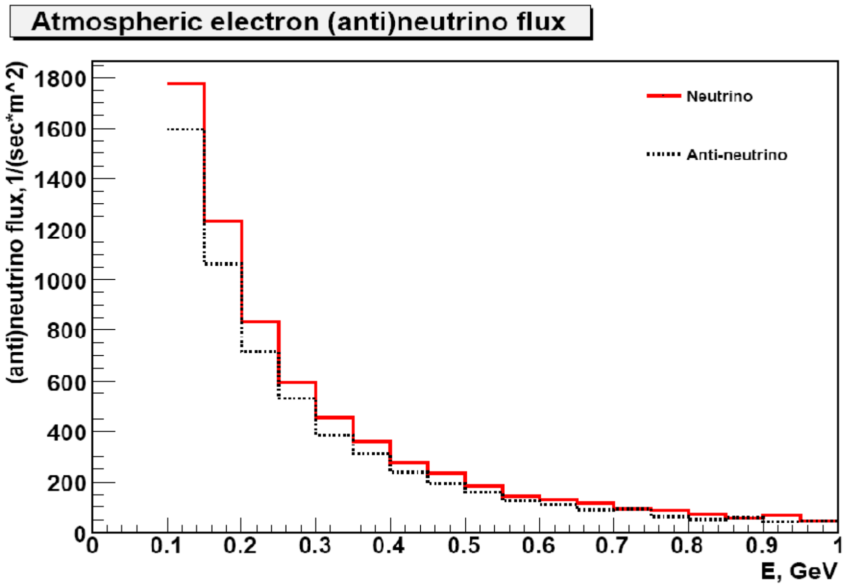
$$\Big\downarrow \text{78.8\%}$$

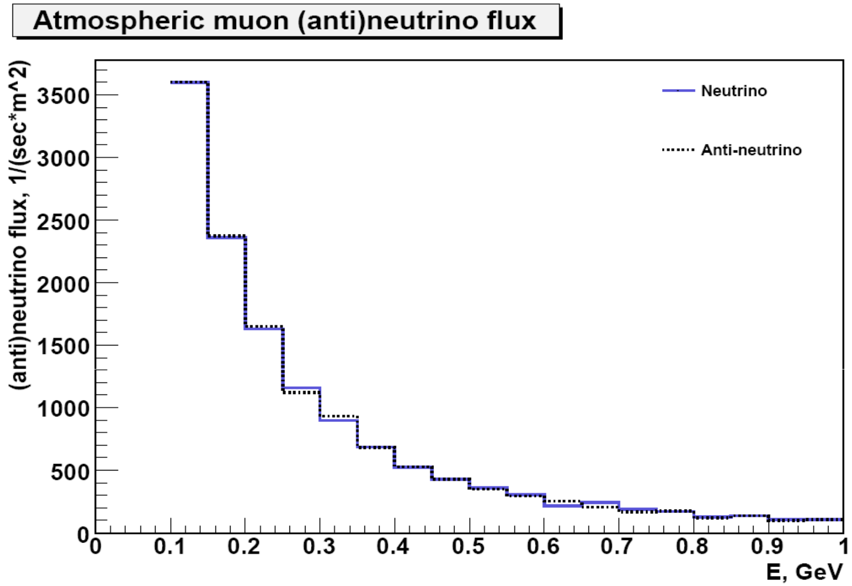
$${}^{12}C(\bar{\nu}_\mu, \mu^+ n)^{11}B^*$$

- 33.6% → ${}^{12}C(\bar{\nu}_\mu, \mu^+ n)^{11}B_{g.s.}$
- 22.0% → ${}^{12}C(\bar{\nu}_\mu, \mu^+ n\gamma)^{11}B_{g.s.}$
- 2.8% → ${}^{12}C(\bar{\nu}_\mu, \mu^+ np)^{10}C$
- 7.8% → ${}^{12}C(\bar{\nu}_\mu, \mu^+ 2n)^{10}B$
- 12.7% → ${}^{12}C(\bar{\nu}_\mu, \mu^+ n\alpha)^{7}Li$

Phys. Reviews C vol.52, number 6
E. Kolbe, K. Langanke, F.-K. Thielmann, P. Vogel

Atmospheric (anti)neutrino fluxes





Fluxes calculated by M. Honda for KamLAND detector position

MC simulation procedure for background calculation

- neutrino interactions distributed in LS+Buffer Oil

- tracking of secondary particles performed using GEANT package

- deposited energy quenched corresponding to results obtained by LS study with Compton Spectrometer at UT [K_B=0.01072 g/(MeV·cm^2)] + contribution from Cherenkov light with reemission

- following cuts were applied:

R<6.0m for prompt and delayed events

$dR_{prompt\text{-}delayed}$ <1.6m

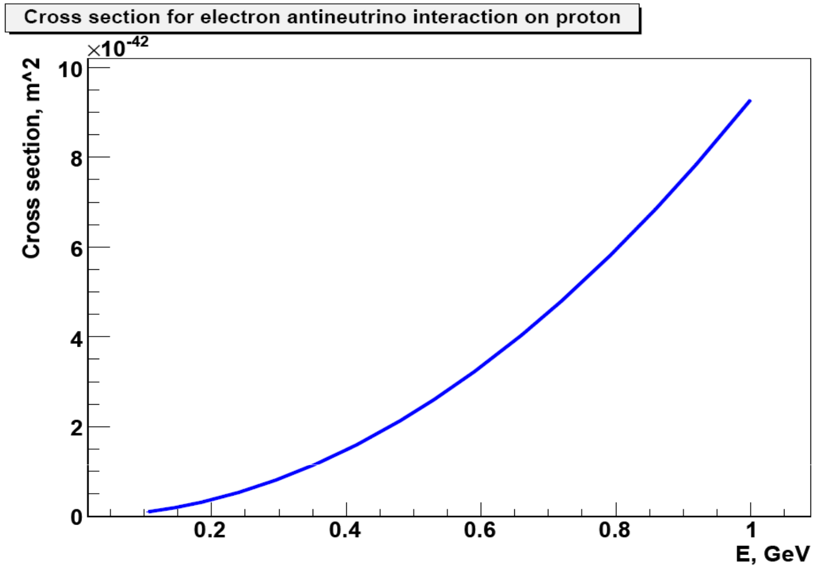
$dT_{delayed\text{-}prompt}$<1msec

1.8MeV<$E_{delayed}$<2.6MeV

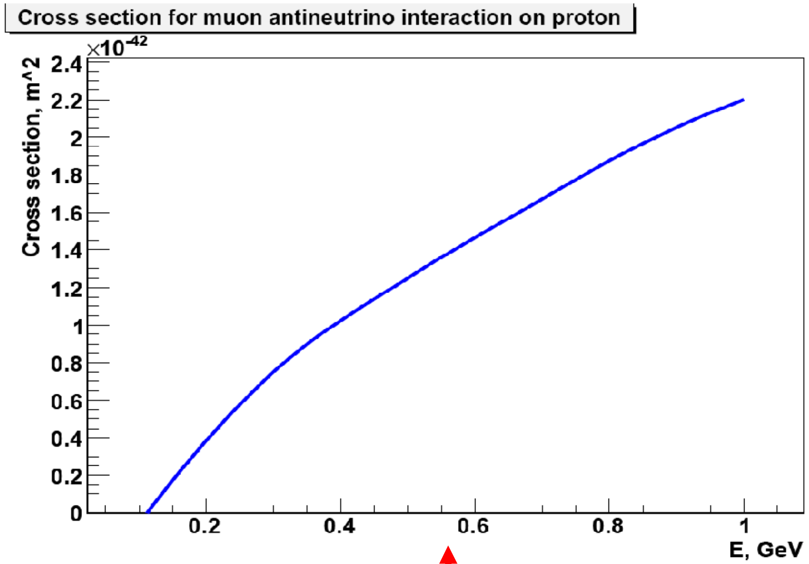
7.5MeV<E_{prompt}<15MeV

Charged current interactions

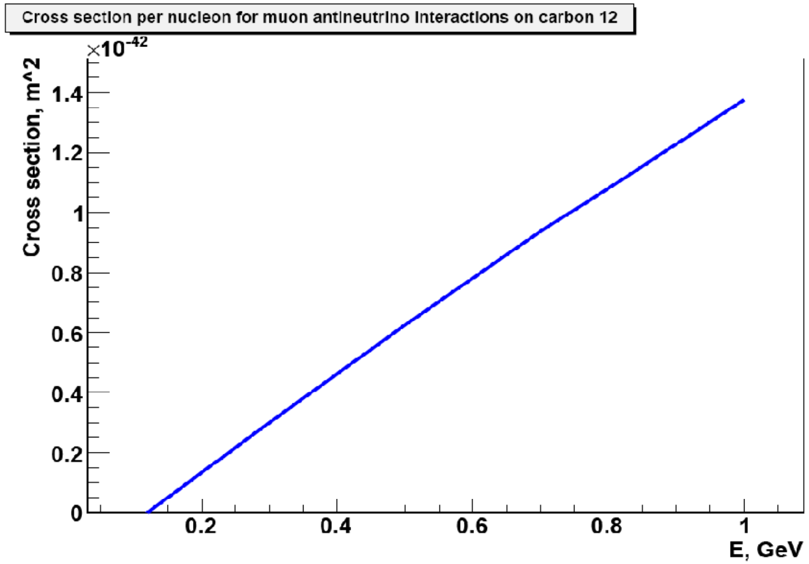
electron antineutrino interaction on proton



muon antineutrino interaction on proton



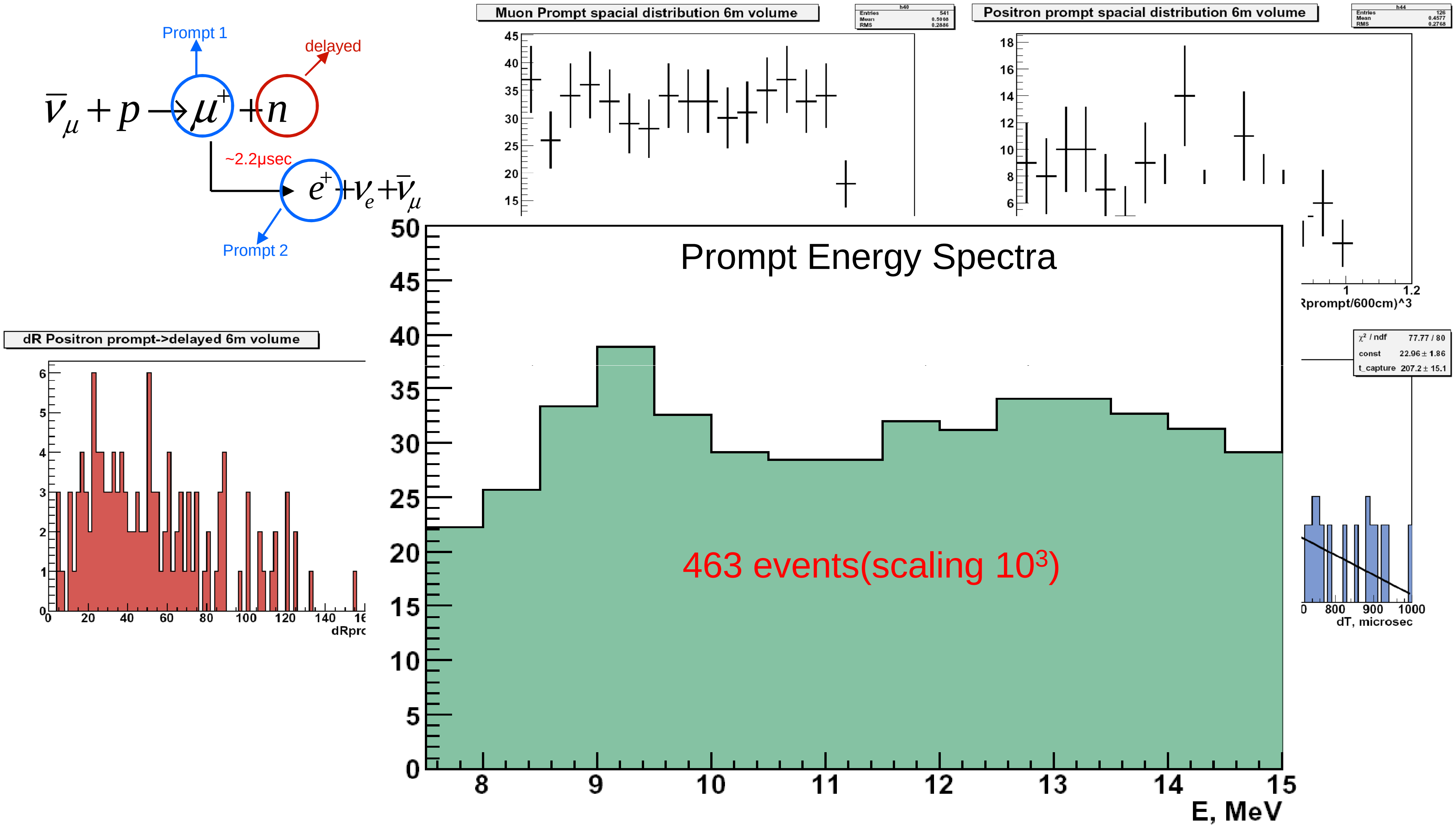
muon antineutrino interaction on carbon



MiniBooNE calculations

M. Sajjad Athar, Shakeb Ahmad, S.K. Singh, Phys. Rev. D75:093003, 2007

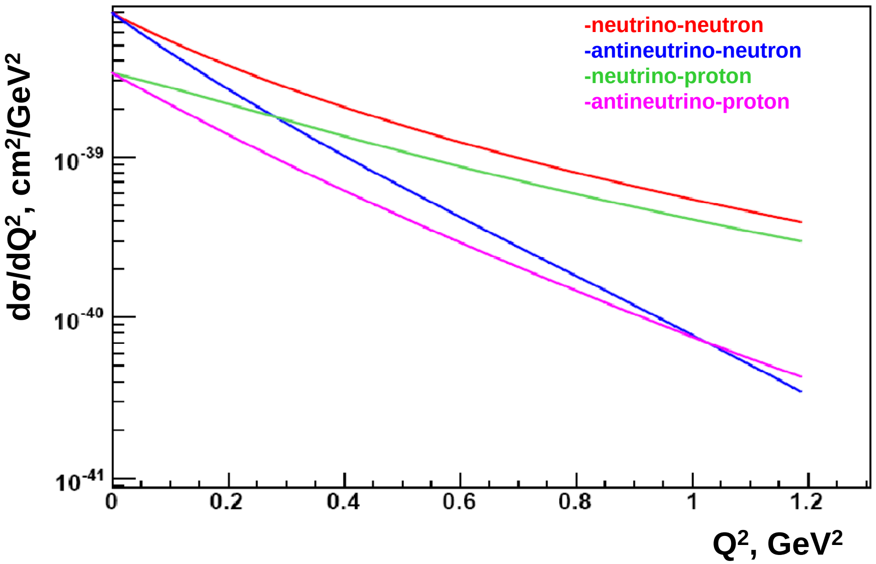
CC interactions: Muon antineutrino on proton(6.0 m analysis)



Neutral Current cross sections

$$\nu_{e,\mu} + {}^{12}C = n + {}^{11}C + \nu_{e,\mu}$$

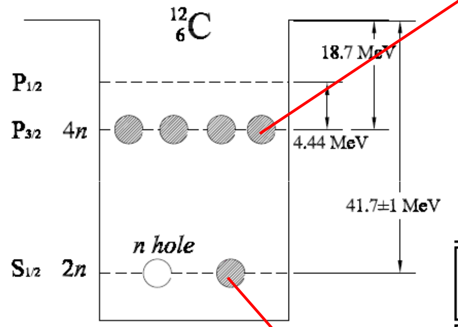
Cross section of (anti)neutrino interactions
on neutron and proton



Neutrinos energy 1.25GeV
Q^2max = 1.2GeV
(L. A. Ahrens et al., Phys. Rev. D35, 785(1987))

+Nuclear Effects.

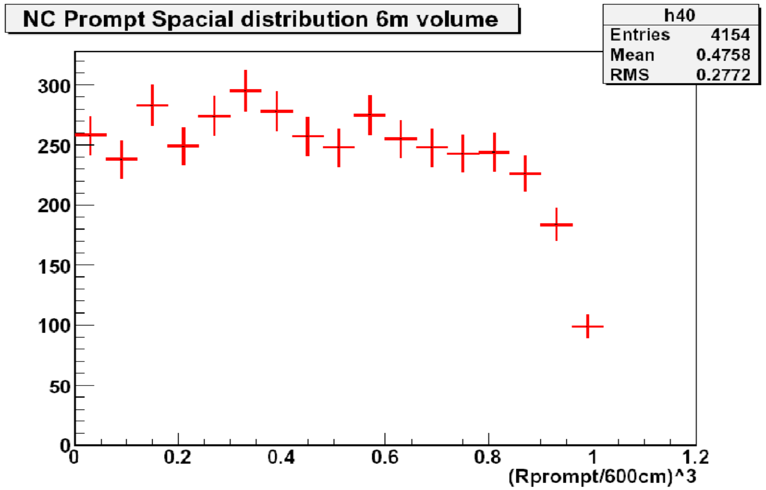
n+γ(2MeV)

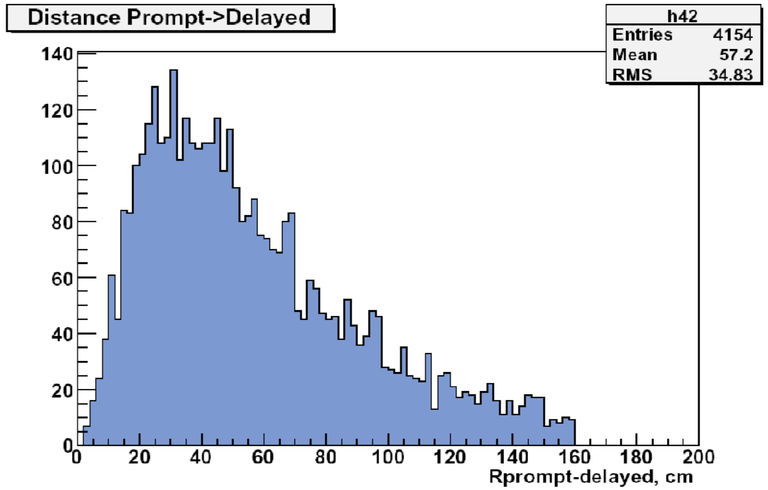


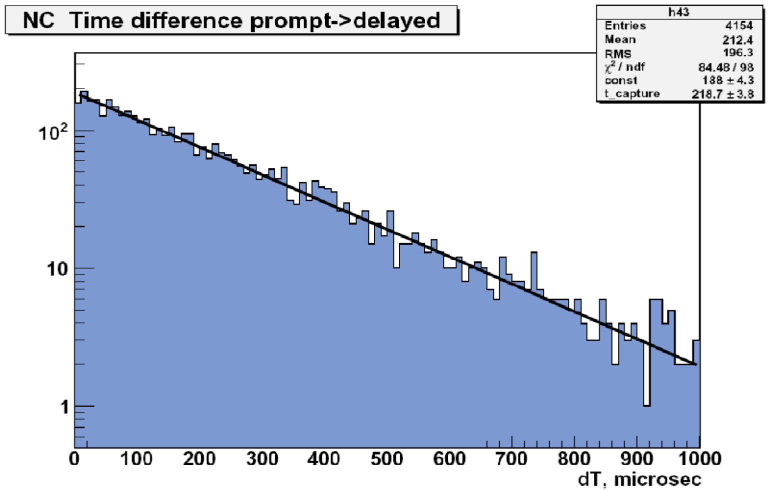
+Final States

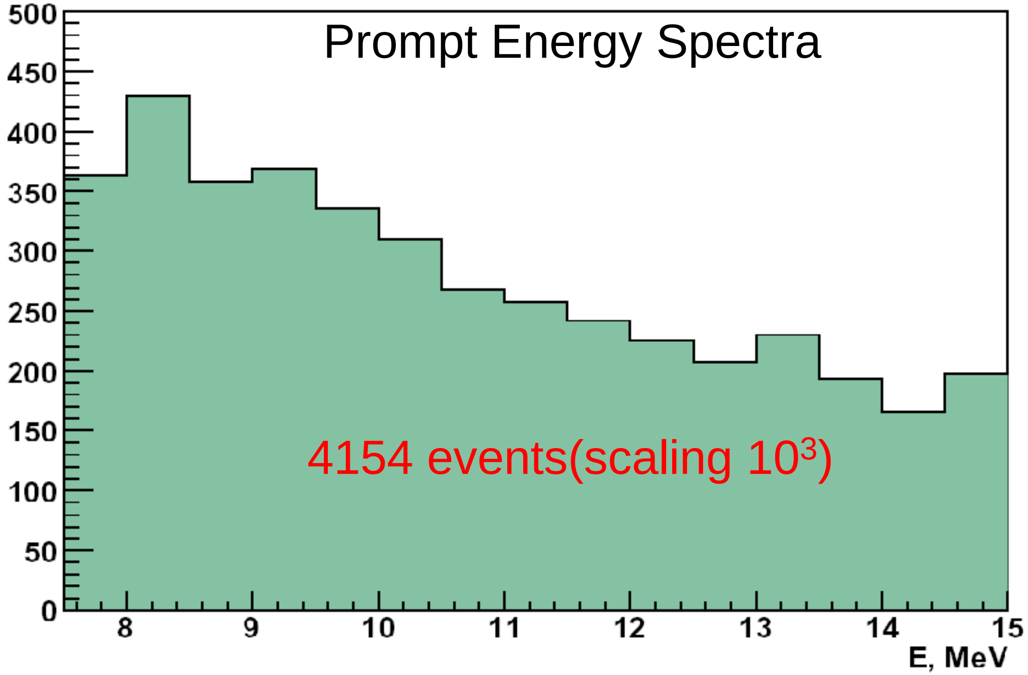
Decay mode	Daughter (decay, $T_{1/2}$ or Γ, Q_{EC} or $Q_{\beta-}$)	Mode %	Exp. sign. (hits)
$^{11}C(\gamma)$	$^{11}C_{gs}(\beta^+$; 20.4 m, 1.98 MeV)	0.7	2
$^{11}C(n\ldots)$	↓	13.8	↓
$^{11}C(p\ldots)$	↓	64.4	↓
$^{11}C(\alpha\ldots)$	↓	21.1	↓
$^{11}C(n)$	$^{10}C_{gs}(\beta^+$; 19.3 s, 3.65 MeV)	3.0	3
$^{11}C(n,\gamma)$	$^{10}C_{gs}(\beta^+$; 19.3 s, 3.65 MeV)	2.8	3
$^{11}C(n,n)$	$^{9}C(\beta^+$; 0.127 s, 16.5 MeV)	0.06	4
$^{11}C(n,p)$	$^{9}B(p+2\alpha$; 0.54 keV, 1.07 MeV)	5.7	2
$^{11}C(n,\alpha)$	$^{6}Be(2p+\alpha$; 92 keV, 4.3 MeV)	2.2	2
$^{11}C(p)$	^{10}B(stable)	2.9	1
$^{11}C(p,\gamma)$	^{10}B(stable)	19.0	1
$^{11}C(p,n)$	$^{9}B(p+2\alpha$; 0.54 keV, 1.07 MeV)	1.4	2
$^{11}C(p,p)$	^{9}Be(stable)	7.2	1
$^{11}C(p,\alpha)$	^{6}Li(stable)	33.9	1
$^{11}C(\alpha)$	$^{7}Be(\beta^+$; 53.3d, 0.86 MeV)	5.2	1*
$^{11}C(\alpha,\gamma)$	$^{7}Be(\beta^+$; 53.3d, 0.86 MeV)	4.2	1*
$^{11}C(\alpha,n)$	$^{6}Be(2p+\alpha$; 92 keV, 4.3 MeV)	0.3	2
$^{11}C(\alpha,p)$	^{6}Li(stable)	3.4	1
$^{11}C(\alpha,\alpha)$	$^{3}H(\beta^-$; 12.3y, 18.6 keV)	8.0	1*
$^{11}C\{n,p\}$	$^{9}B(p+2\alpha$; 0.54 keV, 1.07 MeV)	7.1	2
$^{11}C\{n,\alpha\}$	$^{6}Be(2p+\alpha$; 92 keV, 4.3 MeV)	2.5	2
$^{11}C\{p,\alpha\}$	^{6}Li(stable)	37.3	1

NC interactions: Outer shell (6.0 m analysys)









Background summary

5.5m analysis

	7.5-15MeV	Comments	15-30MeV	Comments
Candidates				
$\bar{\nu}_e + p \rightarrow e^+ + n$	6	1 multiple n-capture, 1 μ-decay	2	1 multiple n-capture, 1 μ-decay
Charged Current Atmospheric Neutrinos Background				
$\nu_\mu + {}^{12}C \rightarrow \mu^- + n + {}^{11}N$	0.046		0.154	
$\bar{\nu}_\mu + {}^{12}C \rightarrow \mu^+ + n + {}^{11}B + \gamma$	0.03		0.136	
$\bar{\nu}_\mu + {}^{12}C \rightarrow \mu^+ + n + {}^{7}Li + \alpha$	0.066		0.105	
$\bar{\nu}_\mu + {}^{12}C \rightarrow \mu^+ + 2n + {}^{10}B$	0.007		0.006	
$\bar{\nu}_\mu + {}^{12}C \rightarrow \mu^+ + n + {}^{11}B$	0.073		0.246	
$\bar{\nu}_\mu + p \rightarrow \mu^+ + n$	0.344		0.626	
$\bar{\nu}_e + p \rightarrow e^+ + n$	0.008		0.022	
Neutral Current Atmospheric Neutrinos Background				
$\nu + {}^{12}C \rightarrow \nu + n + {}^{11}C$	3.882		2.619	
Neutrino int. in the rock	0.1		0.05	
Others				
^{9}Li	2.7		0	
Reactor anti neutrinos	1.5		0	
Accidental background	0.02		0	
TOTAL Background				
	8.776		3.964	

6.0m analysis

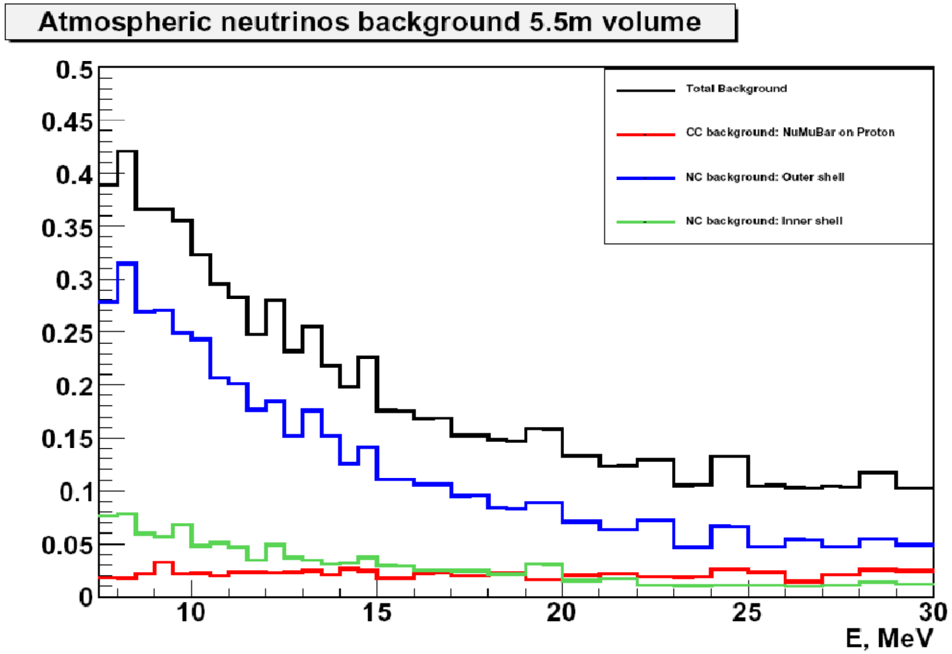
	7.5-15MeV	Comments	15-30MeV	Comments
Candidates				
$\bar{\nu}_e + p \rightarrow e^+ + n$	10	2 multiple n-capture, 1 μ-decay	6	2 multiple n-capture, 1 μ-decay
Charged Current Atmospheric Neutrinos Background				
$\nu_\mu + {}^{12}C \rightarrow \mu^- + n + {}^{11}N$	0.063		0.203	
$\bar{\nu}_\mu + {}^{12}C \rightarrow \mu^+ + n + {}^{11}B + \gamma$	0.048		0.185	
$\bar{\nu}_\mu + {}^{12}C \rightarrow \mu^+ + n + {}^{7}Li + \alpha$	0.087		0.136	
$\bar{\nu}_\mu + {}^{12}C \rightarrow \mu^+ + 2n + {}^{10}B$	0.005		0.009	
$\bar{\nu}_\mu + {}^{12}C \rightarrow \mu^+ + n + {}^{11}B$	0.1		0.324	
$\bar{\nu}_\mu + p \rightarrow \mu^+ + n$	0.463		0.837	
$\bar{\nu}_e + p \rightarrow e^+ + n$	0.011		0.028	
Neutral Current Atmospheric Neutrinos Background				
$\nu + {}^{12}C \rightarrow \nu + n + {}^{11}C$	5.144		3.449	
Neutrino int. in the rock	0.13		0.07	
Others				
^{9}Li	3.5		0	
Reactor anti neutrinos	1.9		0	
Accidental background	0.163		0.001	
TOTAL Background				
	11.614		5.242	

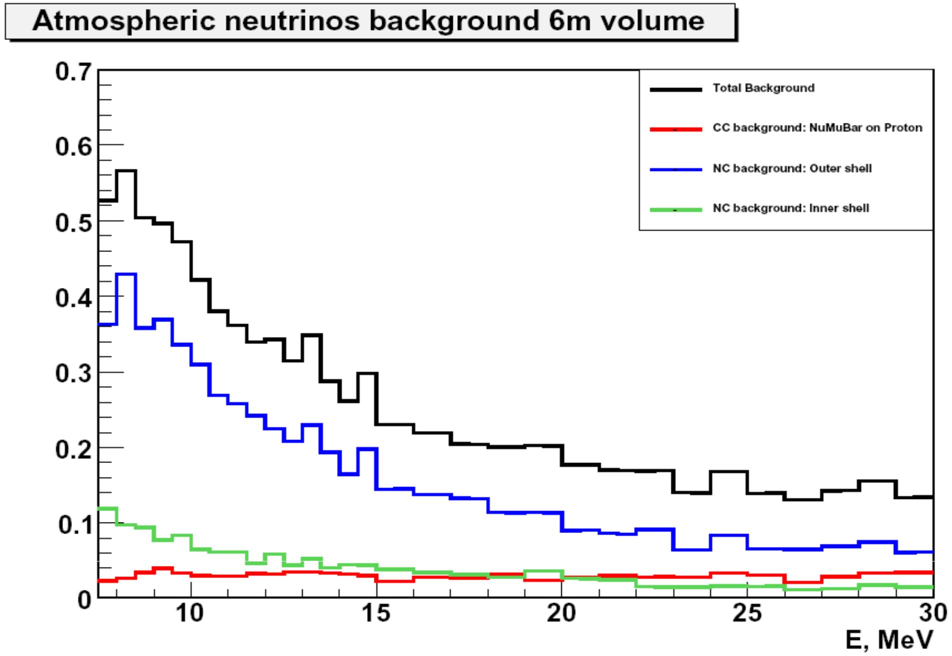
- NC cross-section uncertainty 18%
- Atmospheric neutrino flux uncertainty 22%
- Combined uncertainty 28.4%

Total BG within 7.5-15MeV:
5.5m: 8.78 ± 2.16 events
6.0m: 11.61 ± 2.78 events

Total BG within 15-30MeV:
5.5m: 3.96 ± 1.04 events
6.0m: 5.24 ± 1.38 events

Atmospheric background in 7.5-30 MeV





Triple coincidence summary

7.5-15MeV							
DATA				Background			
5.5m volume		6.0m volume		5.5m volume		6.0m volume	
multi n-capture	μ-decay	multi n-capture	μ-decay	multi n-capture	μ-decay	multi n-capture	μ-decay
1	1	2	1	0.05	0.02	0.07	0.09

New Limits on Solar Antineutrino Flux

$$\Phi_{\bar{\nu}_e} = \frac{N_{signal}}{\sigma \times \varepsilon \times T \times n_{protons}}$$

- N_{signal} – mean signal obtained with 95% C.L. for known number of the selected candidates and B.G.
- $\sigma = 6.9\times10^{-42}cm^2$ averaged cross-section
- $\varepsilon = 0.94$ detection efficiency
- $T = 1.2\times10^{8}$ sec livetime
- $n_{protons} = 4.6\times10^{31}$(5.5m) and 6.0×10^{31}(6.0m)

Upper limits on solar electron antineutrino flux for 8.8-16.3MeV:

$$\boxed{\begin{array}{l} \Phi_{\bar{\nu}_e} < 1.2\times10^{2}\ cm^{-2}s^{-1}\ for\ 5.5m \\ \Phi_{\bar{\nu}_e} < 1.3\times10^{2}\ cm^{-2}s^{-1}\ for\ 6.0m \end{array}}$$

Current best limit was <u>improved by factor of 3.6</u> normalizing to the energy range

8.8-16.3MeV energy range contains 24.05% of the total ^{8}B neutrino flux $5.05\times10^{6}cm^{-2}s^{-1}$

Neutrino conversion probability:
$P<9.8\times10^{-5}$(5.5m volume)

product of neutrino magnetic moment and magnetic field in the core of the Sun:

$$\frac{\mu}{10^{-12}\mu_B}\frac{B_T(0.05R_S)}{10kG} < 7.7\times10^{2}$$

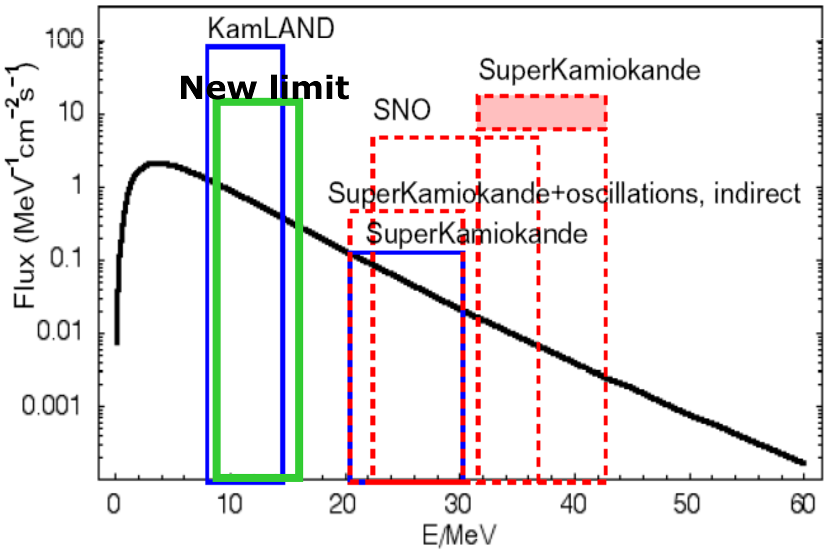
Limit on the diffuse Supenovae neutrino flux

Core-collapse Supernovae rate in the Universe is ~ 1 per second with neutrino emission rate ~10^{58} in one collapse

Current and future neutrino detectors have a possibility to detect cumulative neutrino flux from all past Core-collapse Supernovae

Current limits on DSNF

From: C.Lunardini, astro-ph/0610534

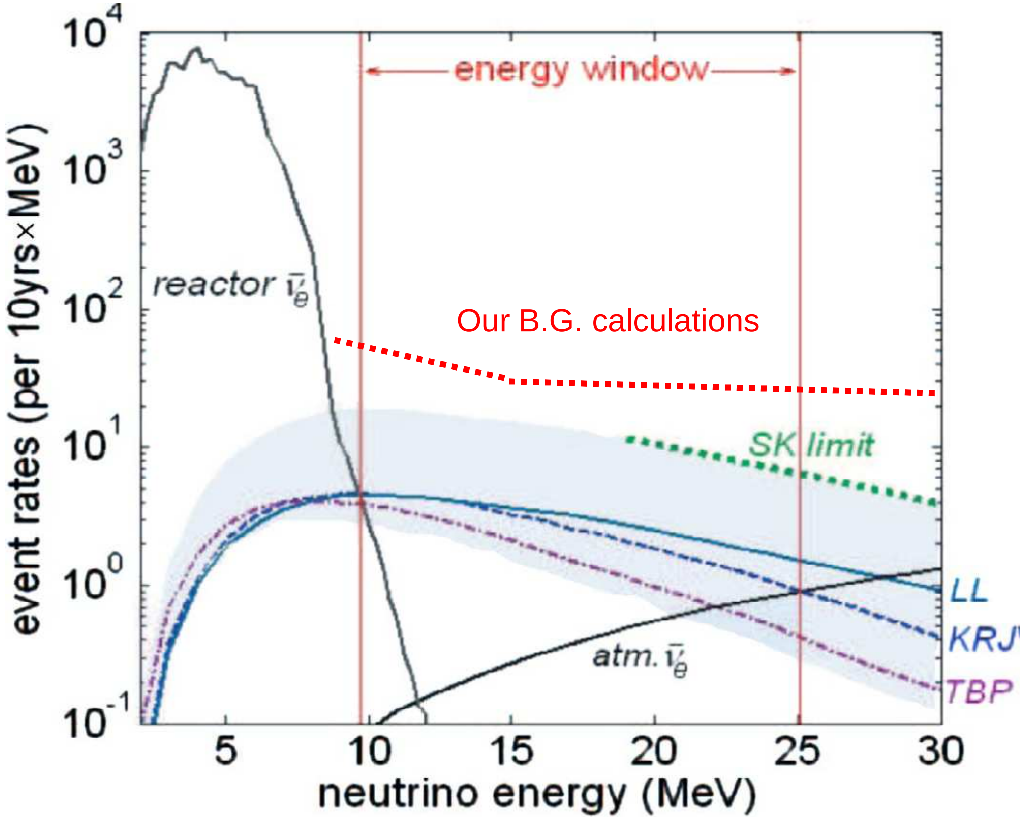


Observed limit on the electron antineutrinos from the Sun can be used for DSNF

New limit is 16cm^{-2}s^{-1}MeV^{-1}

Future neutrino detectors

Event rates in future LENA,50 kt liquid scintillator detector from the various neutrino sources (LENA proposal Phys.Rev.D75:023007)



B.G. rate from NC interactions of the atmospheric neutrinos is significantly higher than expected DSNF

Conclusion

•**Methodology:**
Based on the Compton Spectrometer measurements with KamLAND liquid scintillator we found Birks' Coefficient for electrons:

$K_B = 0.01072\ g\cdot MeV^{-1}\cdot cm^{-2}$

•**Physics:** We obtained new limit on electron antineutrino flux from the Sun within 8.8-16.3MeV neutrino energy range at 95% C.L.:

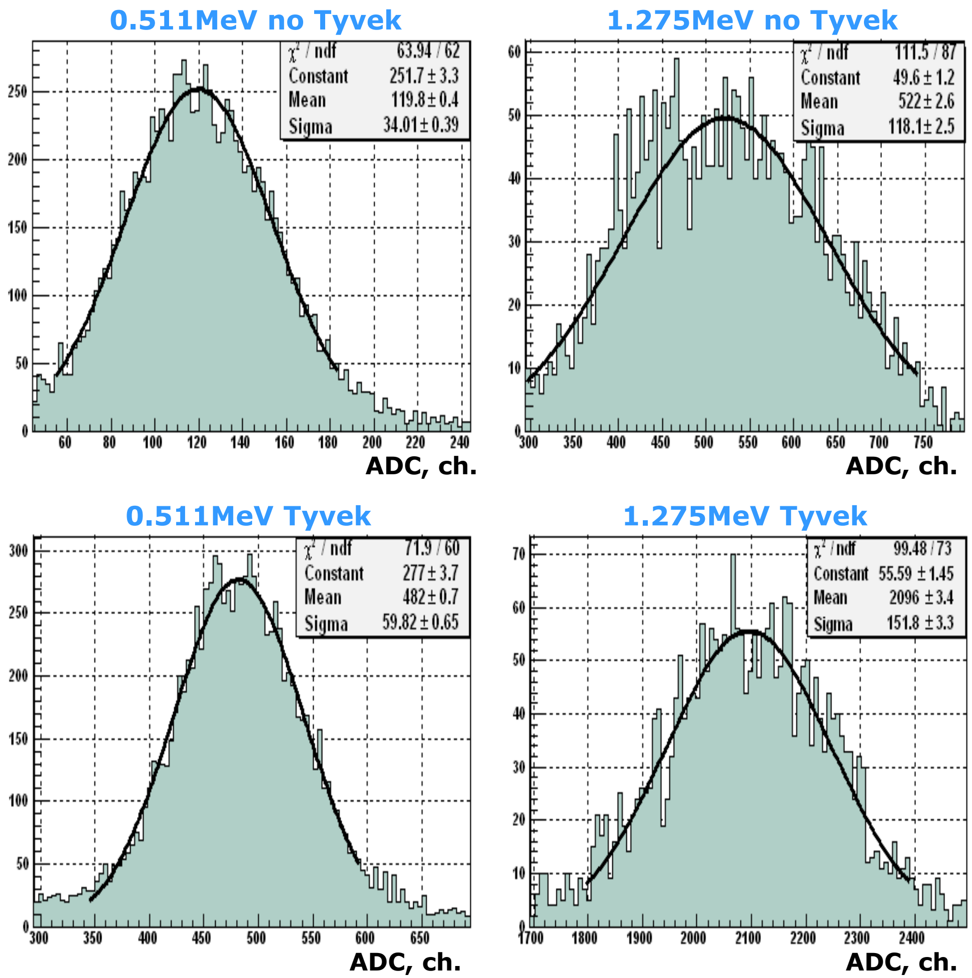
$$\Phi_{\bar{\nu}_e} < 1.2\times 10^{2}\ cm^{-2}s^{-1}$$

This limit corresponds to an upper limit on the neutrino conversion probability of 9.8×10^{-5} at 95% C.L. Observed limits improved by factor of 3.6 with respect to previous KamLAND result. More statistics will not significantly improve these limits. Same limit can be used for Diffuse Supernovae Neutrino Flux

Calculations of background induced by neutral current interactions of atmospheric neutrinos in scincillator are important for the development of future large scintillator neutrino detectors

Backup slides

Tyvek VS. no Tyvek



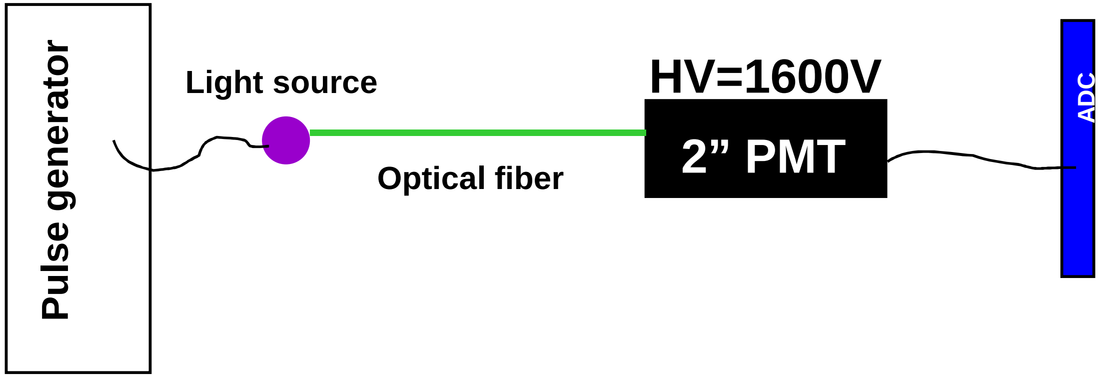
Measurements were made at 60 degrees

	No Tyvek		Tyvek	
Incident gamma E, MeV	**0.511**	**1.275**	**0.511**	**1.275**
Mean, ch.	**119.8**	**522**	**482**	**2096**
Sigma, ch.	**34.01**	**118.1**	**59.82**	**151.8**
Resolution, %	**28.4 ±0.3**	**22.6 ±0.5**	**12.4 ±0.1**	**7.2± 0.2**

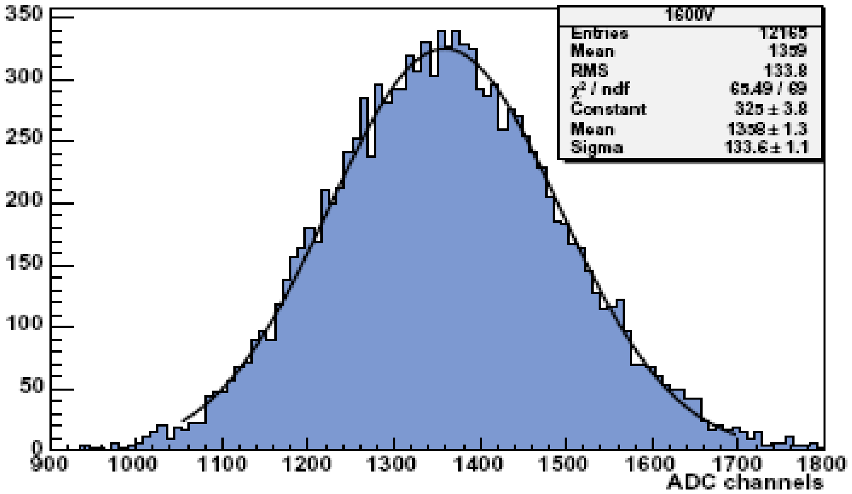
Light collection gain with Tyvek is 4.02

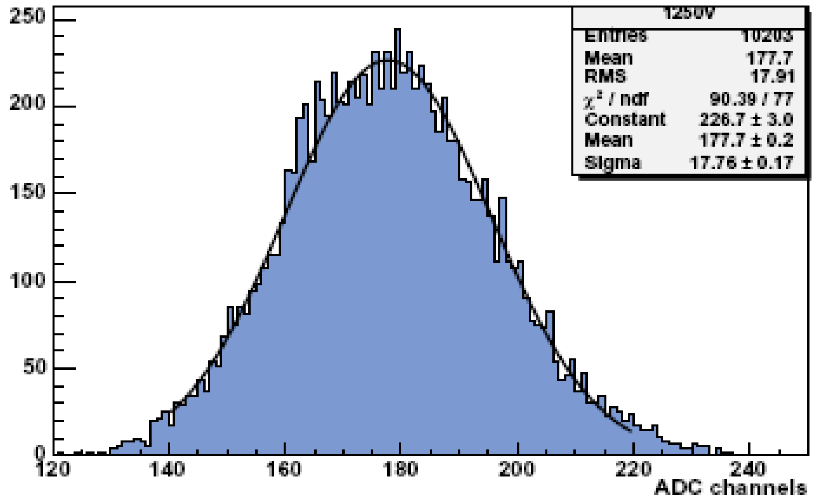
Tyvek did not change the ratio between deposited energies for both peaks $E_1/E_2=4.35$
This result shows the linearity of the PMT

Scintillator light output calibration



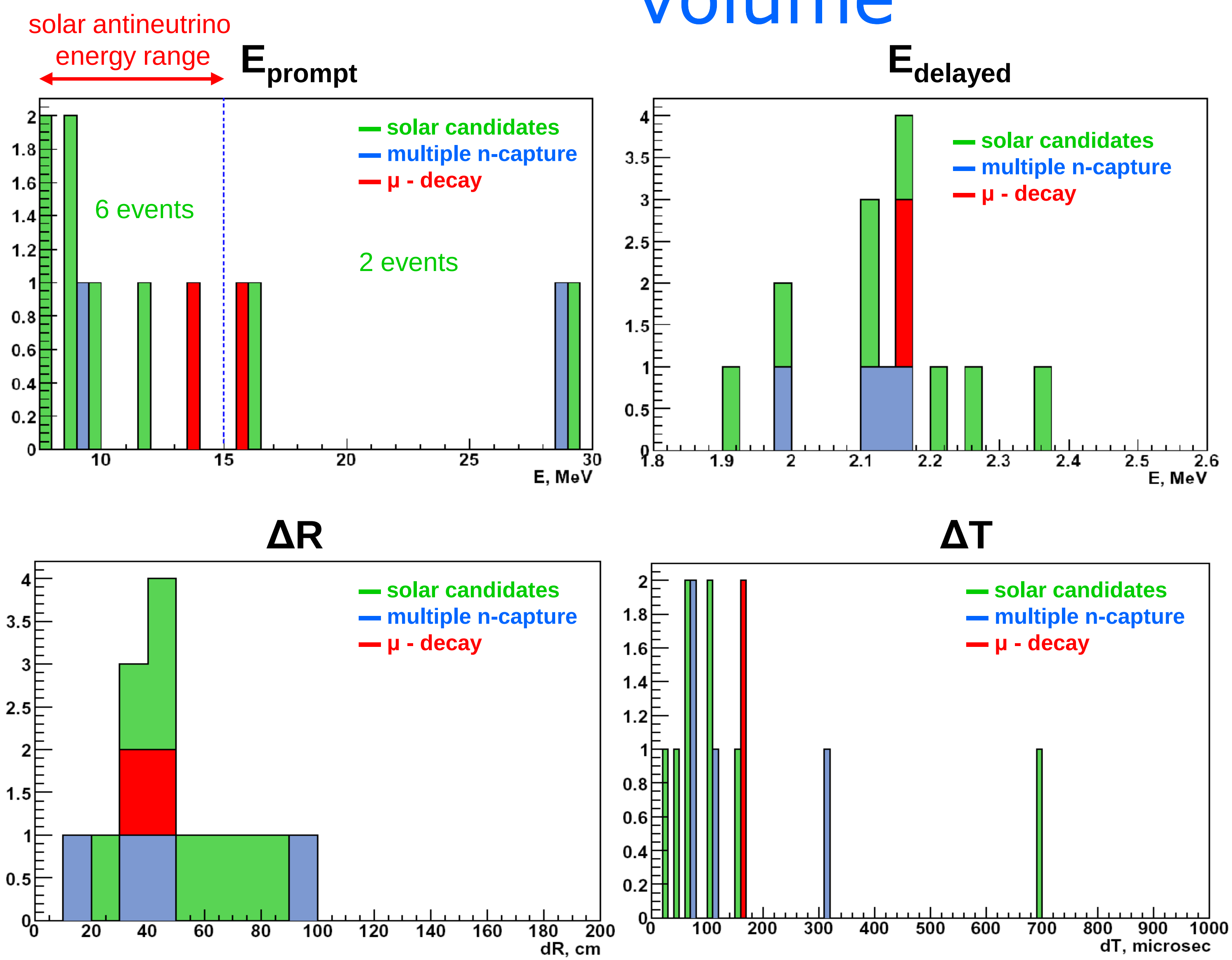
Single photoelectron have been seen with HV=1600V





PMT gain between 1250V and 1600V is 7.65

High Energy Candidates 5.5m fiducial volume



7.5->15MeV:
6 candidates has been selected
+
1 triple coincidence: multiple neutrons capture
Run# 1824, Prompt# 13658585
Delayed# 13658586, 13658587

+

1 muon decay (triple coincidence)
Run# 5380
Prompt_1# 41470(muon, E=15.5MeV)
Prompt_2# 41471(positron, E=13.6MeV)
Delayed# 41472
dT_{1-2}=1.23μsec
dR_{1-2}=6.4 cm