Weekly Journal Club for Medium Energy Physics at IPAS
2011/1/24

Studies on Neutrino-Electron Elastic Scattering in the Standard Model and Beyond

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Taipei, TAIWAN, 24 Jan 2011

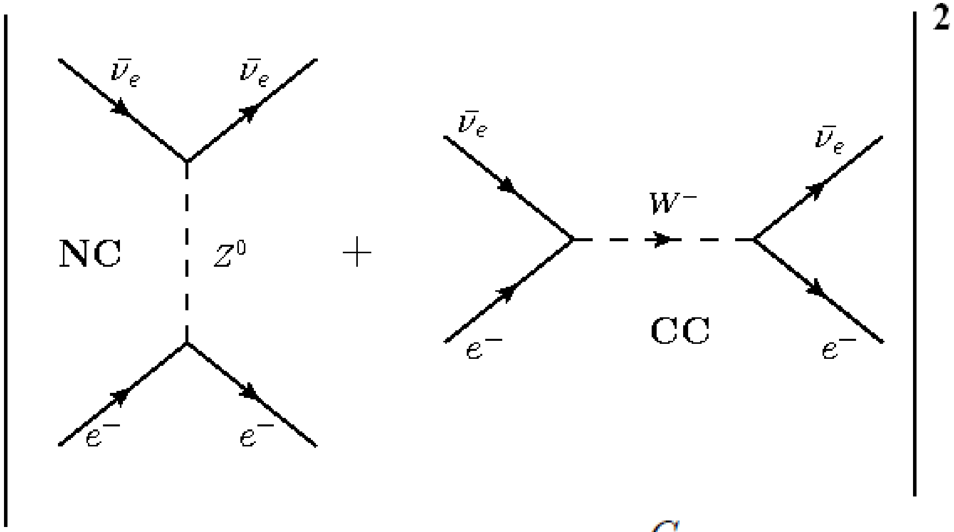
OUTLINE

- Theory overview $\bar{\nu}_e - e^-$ Scattering – Motivation
- TEXONO Physics Program
- TEXONO Experiment – CsI(Tl) Array
  - Event Selection & Data Analysis Outline
  - Background Understanding & Suppression
  - Analysis Results
- Cross Section & *EW* Parameters – World Status
- Probing New Physics – NSI & UP with $\bar{\nu}_e - e^-$
- Summary

$\bar{\nu}_e$ - e^- Scattering Formalism

$$\bar{\nu}_e + e^- \longrightarrow \bar{\nu}_e + e^-$$

- A basic SM process with **CC, NC & Interference**
- Not well-studied in reactor energy range **~ MeV**



$$(R_{CC} : R_{NC} : R_{Int})$$

$$R_{SM}(\bar{\nu}_e \mathrm{e}) \rightarrow (0.77 : 0.92 : -0.69)$$
$$R_{SM}(\nu_e \mathrm{e}) \rightarrow (1.83 : 0.17 : -0.99)$$

$$\delta[\sin^2\theta_\mathrm{W}] \sim \begin{cases} 0.14 \cdot & \delta[\xi(\bar{\nu}_e \mathrm{e})] \\ 0.32 \cdot & \delta[\xi(\nu_e \mathrm{e})] \end{cases}$$

$$\xi = \frac{R_{expt}(\nu)}{R_{\mathrm{SM}}(\nu)}$$

$$\mathcal{L}^{NC} = -\frac{G_F}{\sqrt{2}}\left[\bar{\nu}_e \gamma^\alpha (1-\gamma_5)\,\nu_e\right]\left[\bar{e}\gamma_\alpha (g_V - g_A\gamma_5)\, e\right]$$

$$\mathcal{L}^{CC} = -\frac{G_F}{\sqrt{2}}\left[\bar{e}\gamma^\alpha (1-\gamma_5)\,\nu_e\right]\left[\bar{\nu}_e \gamma_\alpha (1-\gamma_5)\, e\right]$$

$$\frac{d\sigma_{SM}}{dT}(\bar{\nu}_e e) = \frac{G_F^2 m_e}{2\pi}\left[(g_V - g_A)^2 + (g_V + g_A + 2)^2 \left(1 - \frac{T}{E_\nu}\right)^2 - (g_V - g_A)(g_V + g_A + 2)\frac{m_e T}{E_\nu^2} \right]$$

$$g_A = -\frac{1}{2}$$

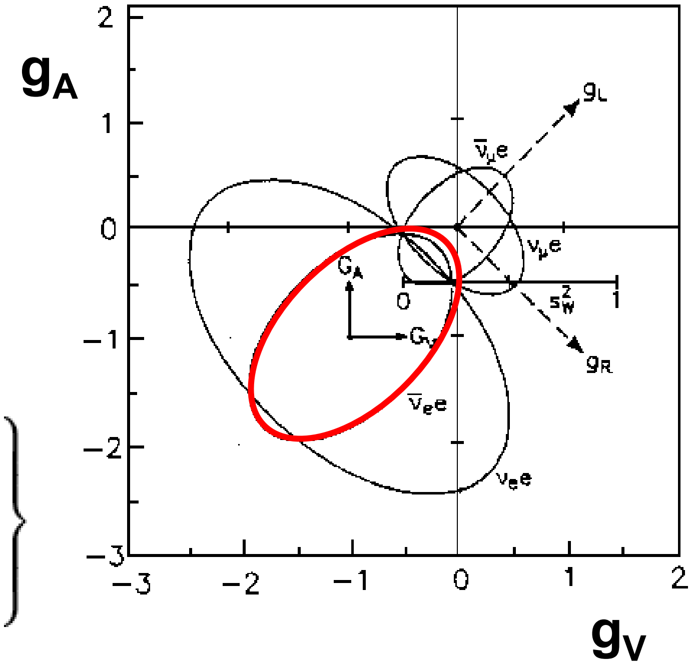
$$g_V = 2\sin^2\theta_W - \frac{1}{2}$$

Neutrino-Electron Scattering Cross-Section

$$\bar{\nu}_e + e^- \longrightarrow \bar{\nu}_e + e^-$$

$$\frac{d\sigma_{SM}}{dT}(\bar{\nu}_e e) = \frac{G_F^2 m_e}{2\pi}\left\{\begin{array}{c} (g_V+1)^2\left[1+\left(1-\frac{T}{E_\nu}\right)^2-\frac{m_e T}{E_\nu^2}\right] \\ +\ (g_A+1)^2\left[1+\left(1-\frac{T}{E_\nu}\right)^2+\frac{m_e T}{E_\nu^2}\right] \\ -\ (g_V+1)(g_A+1)\left[2-2\left(1-\frac{T}{E_\nu}\right)^2\right] \end{array}\right\}$$

$$\frac{d\sigma_{SM}}{dT}(\bar{\nu}_e e) = \frac{G_F^2 m_e}{2\pi}\left\{\begin{array}{c} 4\sin^4\theta_W\left[1+\left(1-\frac{T}{E_\nu}\right)^2-\frac{m_e T}{E_\nu^2}\right] \\ +\ 4\sin^2\theta_W\left[\left(1-\frac{T}{E_\nu}\right)^2-\frac{m_e T}{2E_\nu^2}\right]+\left(1-\frac{T}{E_\nu}\right)^2 \end{array}\right\}$$



Expected event rate for $\bar{\nu}_e e$ scattering can be written as

$$r_{SM}(T) = \int_{E_\nu} \frac{d\sigma_{SM}}{dT}\frac{d\phi}{dE_\nu}dE_\nu$$

$$R_{SM} = \rho_e \int_T r_{SM}(T)dT = \rho_e \int_T \int_{E_\nu}\left[\frac{d\sigma}{dT}\right]_{SM}\frac{d\phi}{dE_\nu}dE_\nu dT \quad = 0.0128\ day^{-1} \times kg^{-1}$$

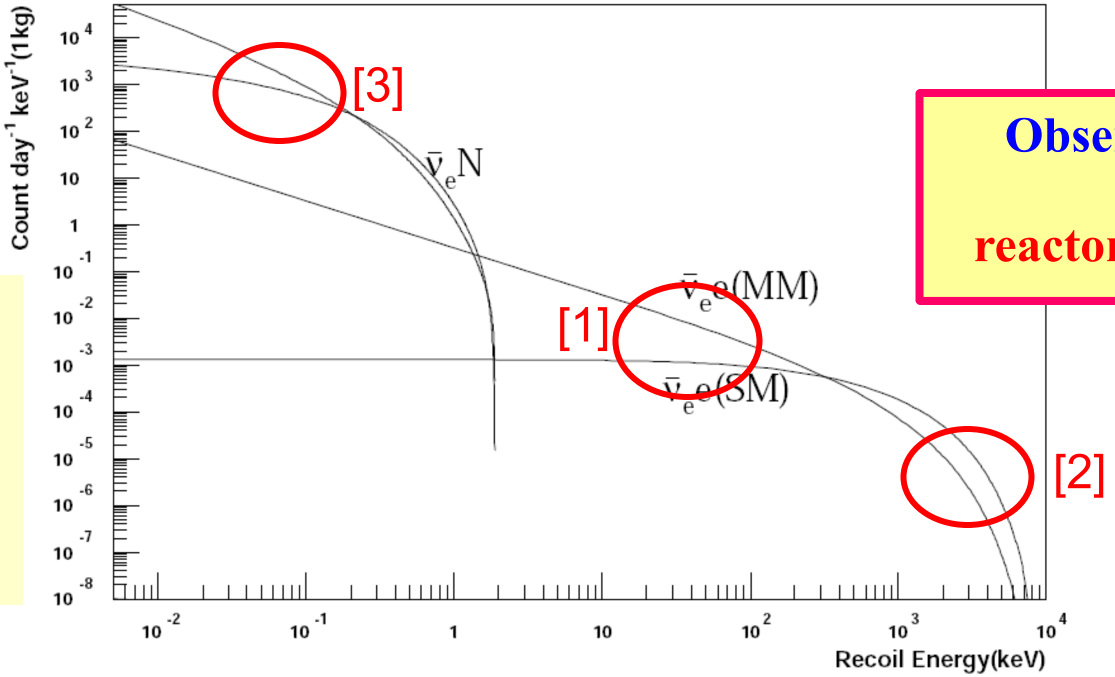
$$\text{in } 3-8\ MeV$$

TEXONO Physics Program

TEXONO Collaboration: Taiwan (AS,INER,KSNPS,NTU);
China (IHEP,CIAE,THU,NKU,SCU,LNU); Turkey (METU, KTU); India (BHU)
Program: Low Energy Neutrino & Astroparticle Physics

quality ← **Detector requirements** → **mass**

Taiwan
EXperiment
On
NeutrinO



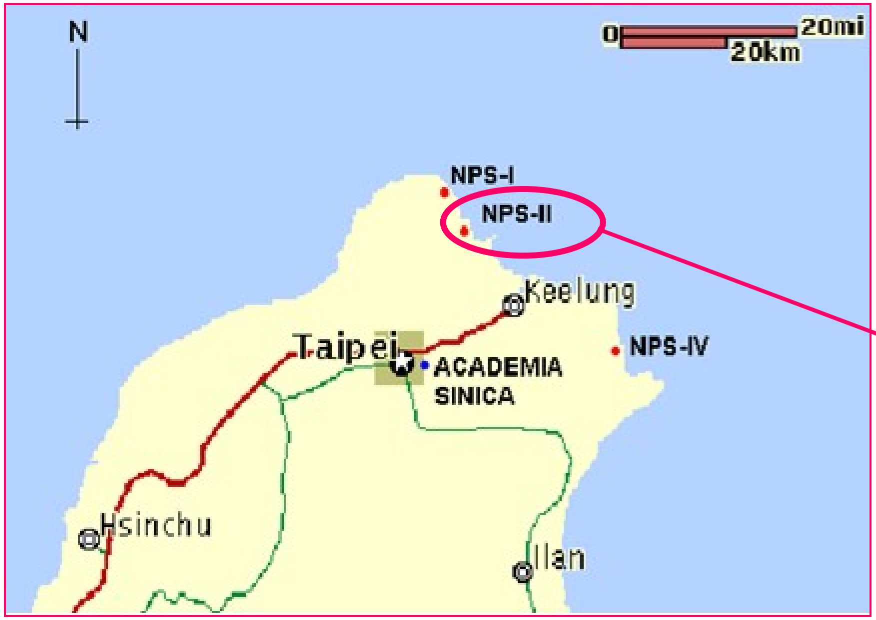
Observable Spectrum
with typical
reactor neutrino "beam"

[1] **Magnetic Moment** Search at **~10 keV → PRL 2003, PRD 2007**

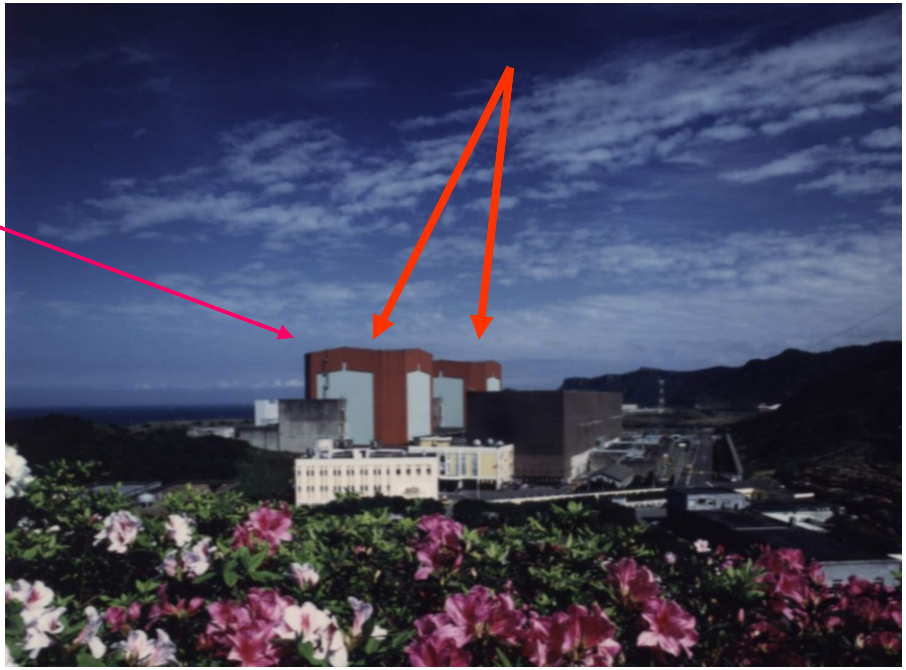
[2] **Cross-Section and EW Parameters** measurement at **MeV** range **→ PRD 2010**

[3] **$\bar{\nu}_e$ N Coherent Scattering & WIMP** Search at **sub keV** range **→ PRD-R 2009**

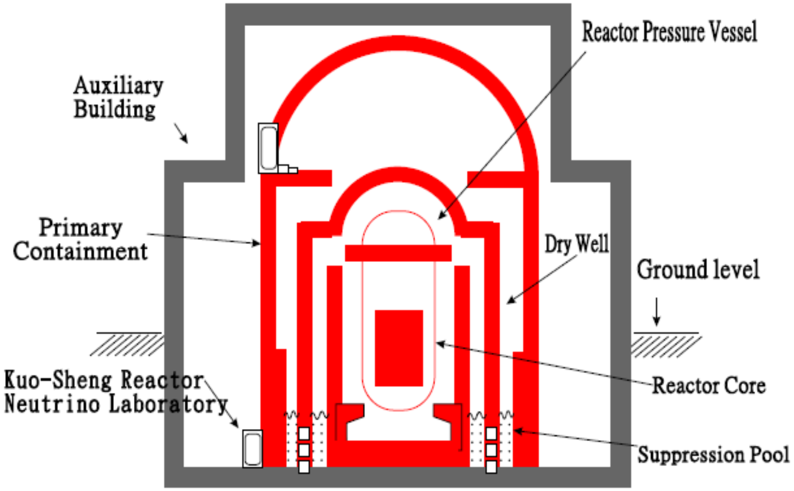
Kou-Sheng Reactor Power Plant



KS NPS -II : 2 cores × 2.9 GW



Kuo-Sheng Nuclear Power Station : Reactor Building



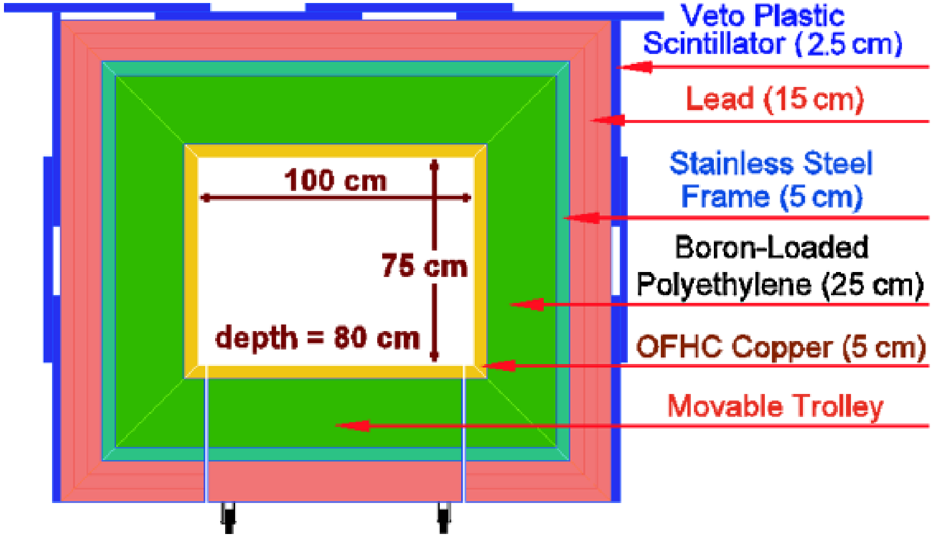
Total flux about 6.4×10^{12} cm^{-2}s^{-1}

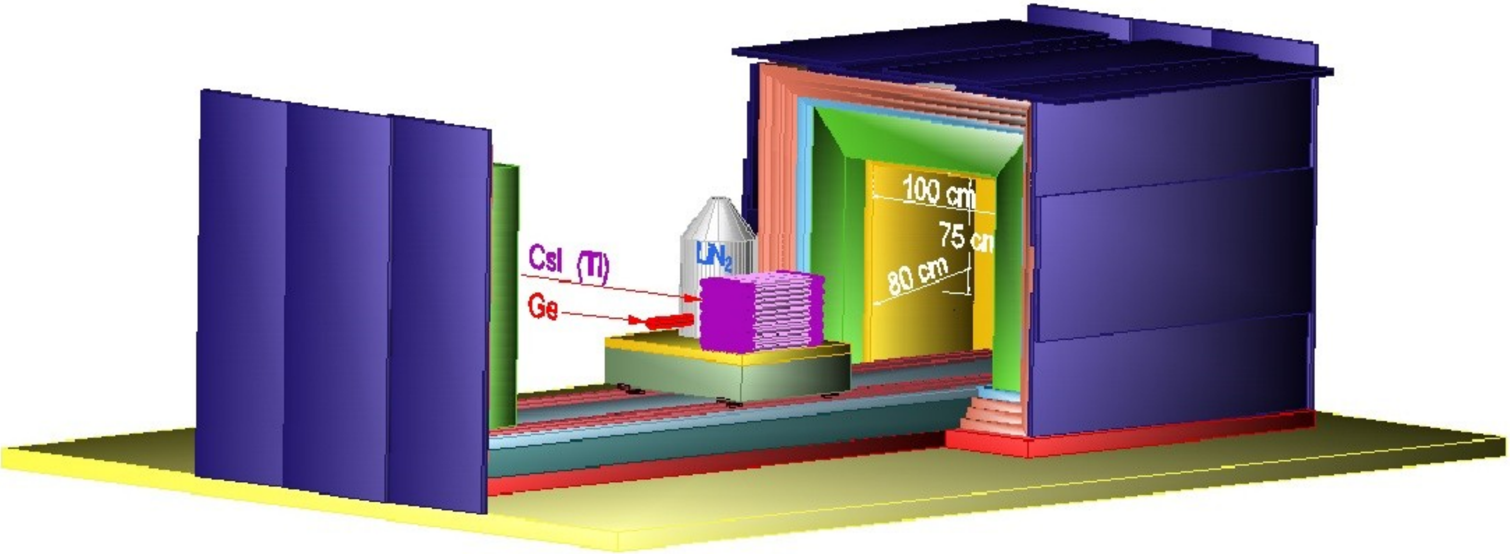
KS ν Lab: 28m from core #1

10 m below the surface
30 mwe overburden

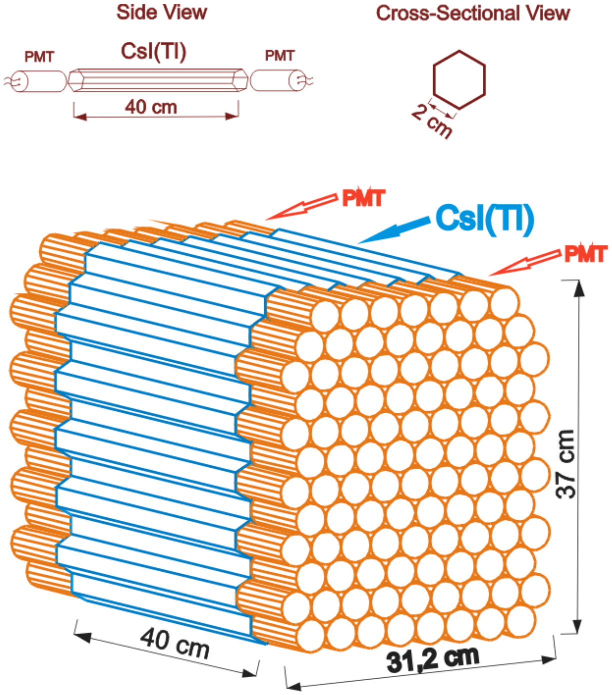
Neutrino Laboratory

Inner Target Volume & Shielding

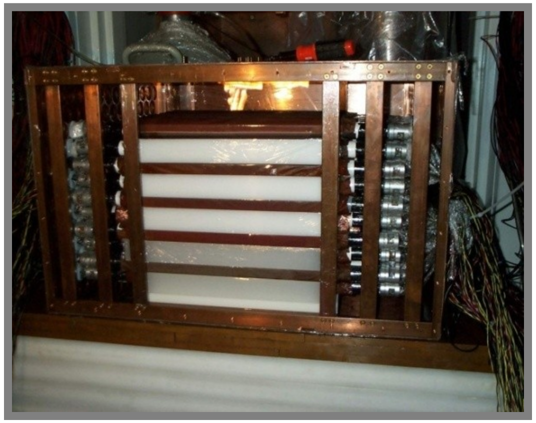




CsI Scintillating Crystal Array

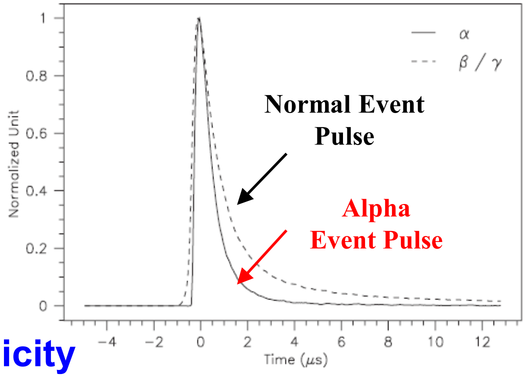


CsI(Tl) Detector
9x12 Array 200 kg



Experimental Approach; CsI(Tl) Crystal Scintillator Array:

- proton free target
(suppress $\bar{\nu}_e$-p background)
- scale to ϑ (tons) design possible
- good energy resolution, **alpha & gamma Pulse Shape Discrimination (PSD)**
- allows measure **energy, position, multiplicity**
- more information for
  - **background understanding** & **suppression**



☐ **DAQ Threshold: 500 keV**

☐ **Analysis Threshold: 3 MeV**

(less ambient **background** & **reactor** $\bar{\nu}_e$ spectra well known)

☐ Data Volume: **~ 29883 kg-day / 7369 kg-day Reactor ON/OFF**

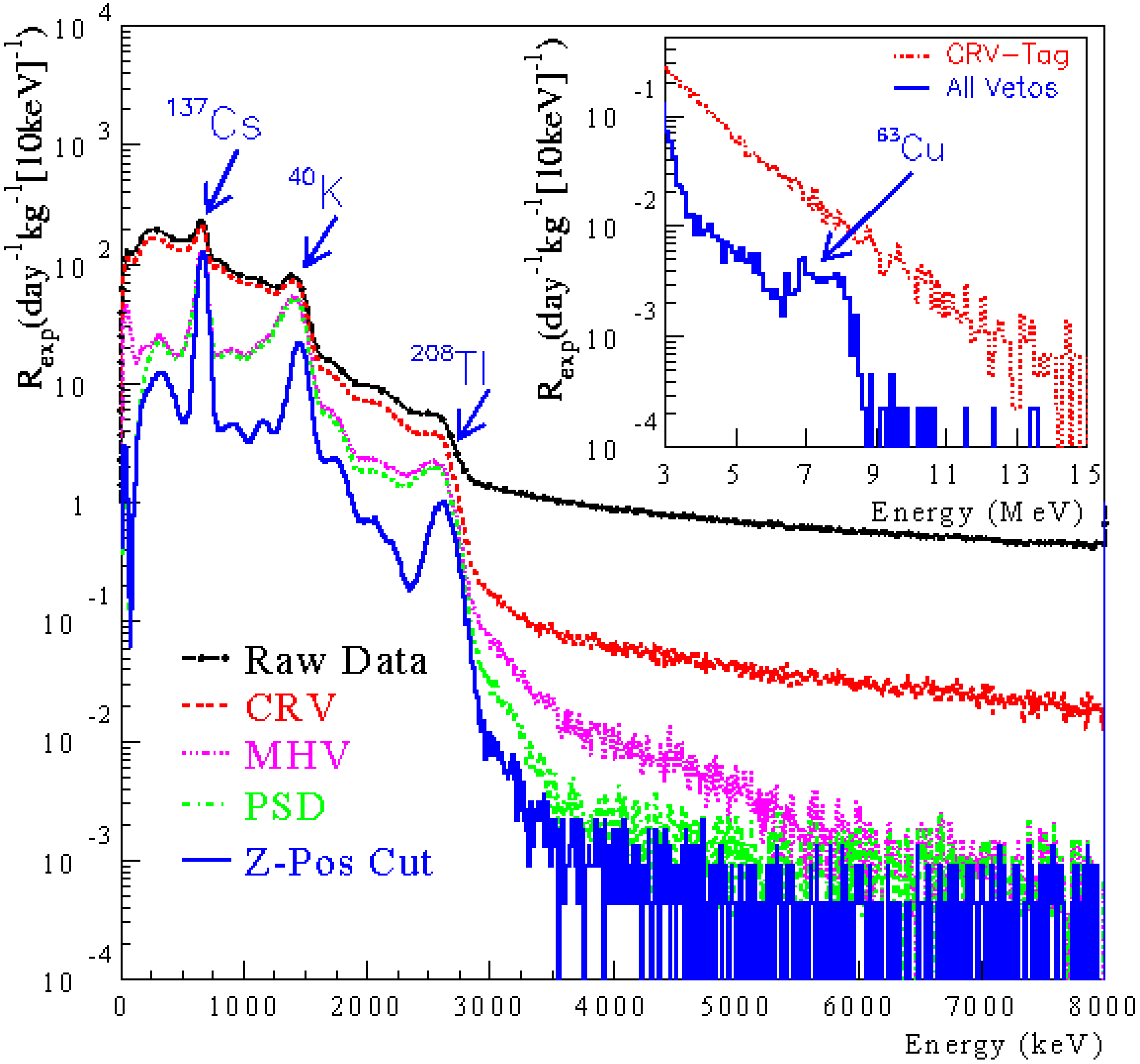
- **Energy : Total Light Collection**
  - **σ (E) ~ 6% @ E>660 keV**
- **Z-position : The variation of Ratio**
  - **σ (Z) ~ 1.3 cm @ E>660 keV**

$$E \approx \sqrt{Q_L \times Q_R}$$

$$Z \approx (Q_L - Q_R)/(Q_L + Q_R)$$

Data Analysis: Event Selection

Reactor OFF



CUTS **(3 - 8 MeV)**	**Efficiencies** DAQ Live Time Eff. **~ 90%**
CRV	**92.7 %**
MHV	**99.9 %**
PSD	**~100 %**
Z-pos	**80%**
Total	**77.1 %**

$$\frac{S}{B} \cong \frac{1}{30} \text{ at } 3 \text{ MeV}$$

Background Understanding

A. Radioactive Contaminants

- **Decays of radioactive contaminants mainly ^{232}Th and ^{238}U decay chain produce background in the region of interest. Estimate the abundance of ^{137}Cs, ^{238}U and ^{232}Th inside the detector.**

IDEA: By monitoring the **timing and position** information related β-α or α-α events can provide distinct signature to identify the decay process and the consistency of the isotopes involved.

B. Environmental Backgrounds

- **Cosmic Ray muons, Products of cosmic ray muons, Spallation neutrons and High Energy γ 's from such as ^{63}Cu, ^{208}Tl**

IDEA: **multiple-hit** analysis can give us very good understanding **^{208}Tl, High Energy γ** and **cosmic** related background in the region of interest.

- Cosmic & High Energy Gamma Ray

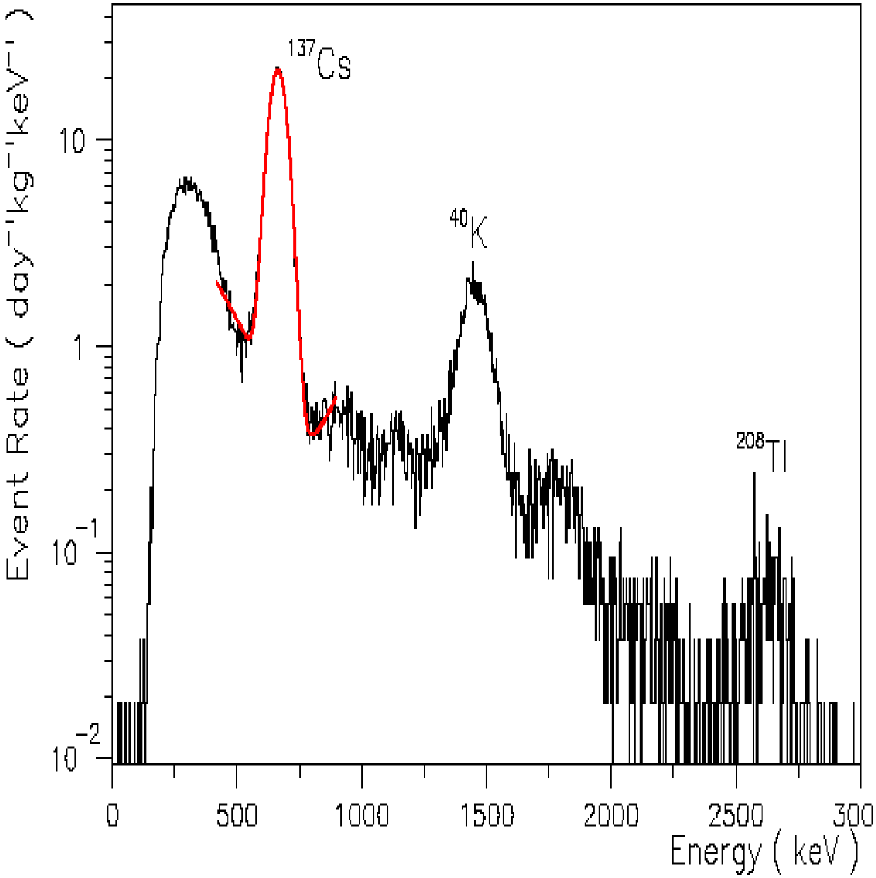
  \- By comparing **cosmic** **and** **non-cosmic** multiple-hit spectra.

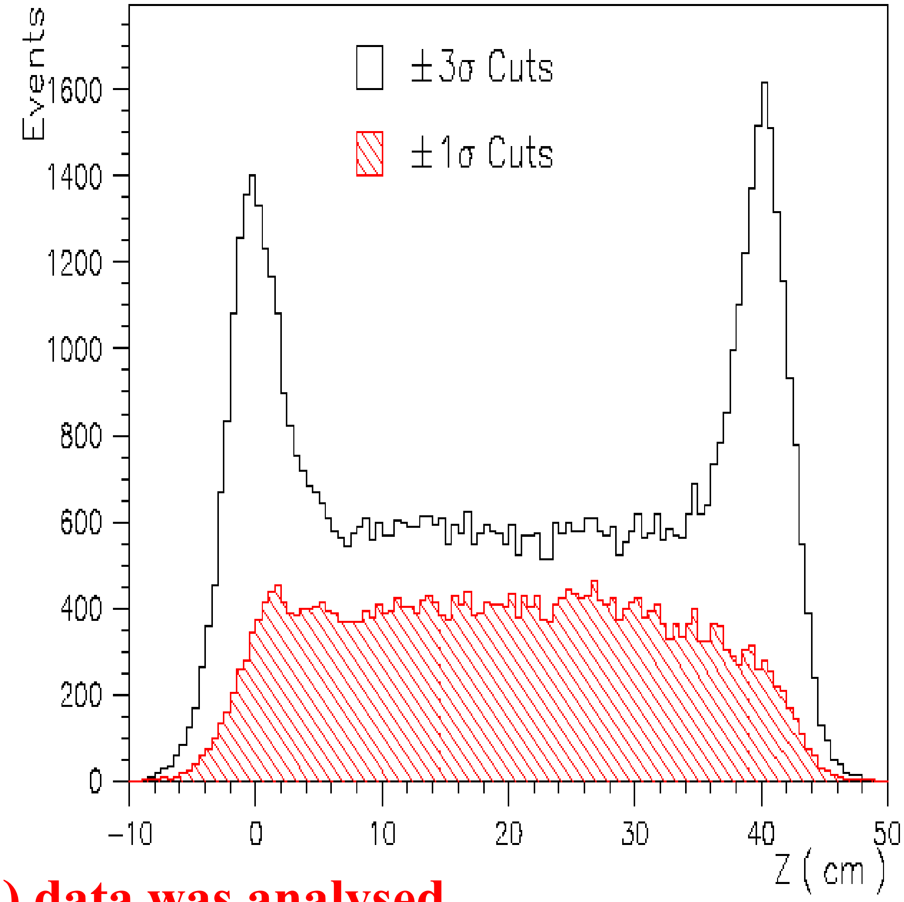
- Tl-208 Decay Cascade

  \- By examining multiple-hit spectra as well as simulation of **Tl-208** decay chain energies to **understand/suppress** background in the region of 3-4 MeV.

Intrinsic ^{137}Cs Level

Nucl. Instr. and Meth. A 557 (2006) 490-500.





31.3 kg-day of CsI(Tl) data was analysed.

^{137}Cs contamination level in CsI was derived ==>

$(1.55 \pm 0.02) \times 10^{-17}$ g/g

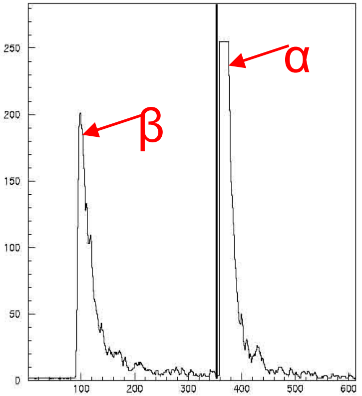
Intrinsic U and Th Contamination Level

Data: The total of 40 crystals with data size of 1725 kg·day was analyzed.

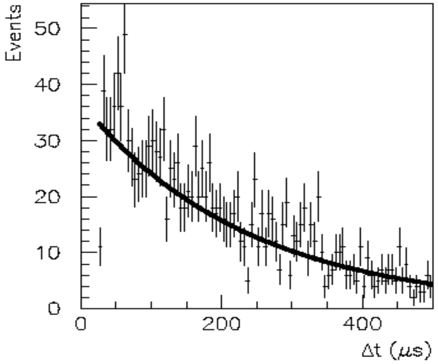
i) $^{214}\mathrm{Bi}(\beta^-) \rightarrow {}^{214}\mathrm{Po}(\alpha, 164\mu s) \rightarrow {}^{210}\mathrm{Pb}$

Selection: 1st pulse is $\gamma(\beta)$ shaped &

2nd pulse α shaped



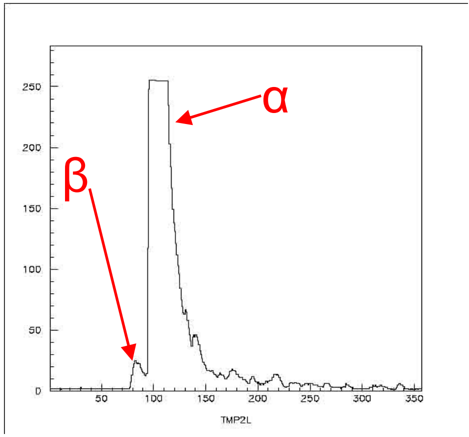
$T_{1/2} = (163 \pm 8)\ \mu s$



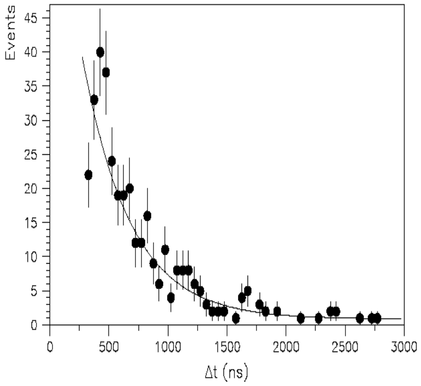
^{238}U abundance = $0.82 \pm 0.02 \times 10^{-12}$ g/g

ii) $^{212}\mathrm{Bi}(\beta^-, 64\%) \rightarrow {}^{212}\mathrm{Po}(\alpha, 299ns) \rightarrow {}^{208}\mathrm{Pb}$

Selection: β- pulse followed by a large α pulse



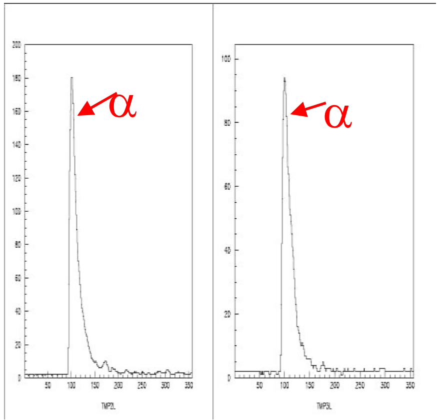
$T_{1/2} = (283 \pm 37)$ ns.



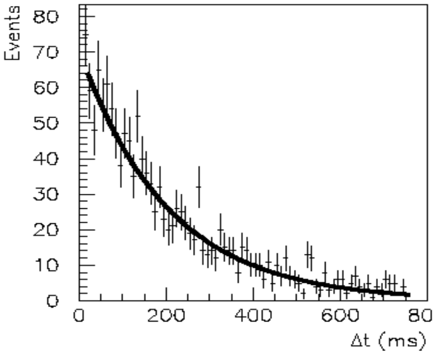
^{232}Th abundance = $2.3 \pm 0.1 \times 10^{-12}$ g/g

iii) $^{220}\mathrm{Rn}(\alpha) \rightarrow {}^{216}\mathrm{Po}(\alpha, 0.15s) \rightarrow {}^{212}\mathrm{Pb}$

Selection: two α events with time delay less than 1s

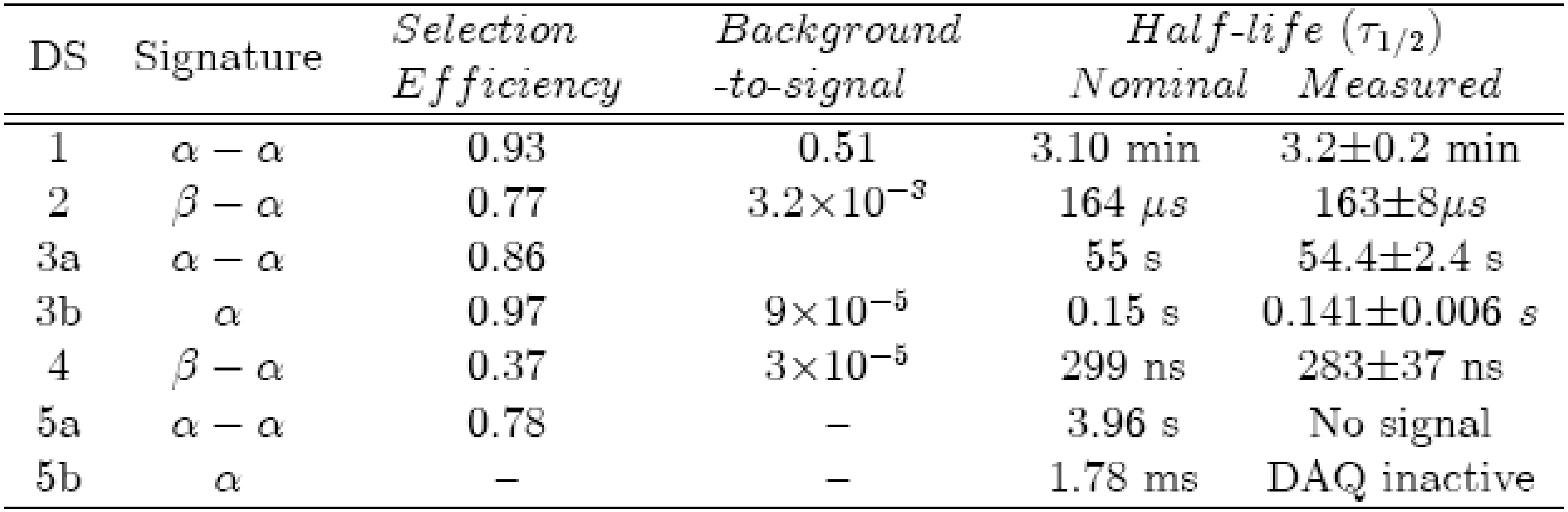


$T_{1/2} = (0.141 \pm 0.006)$ s

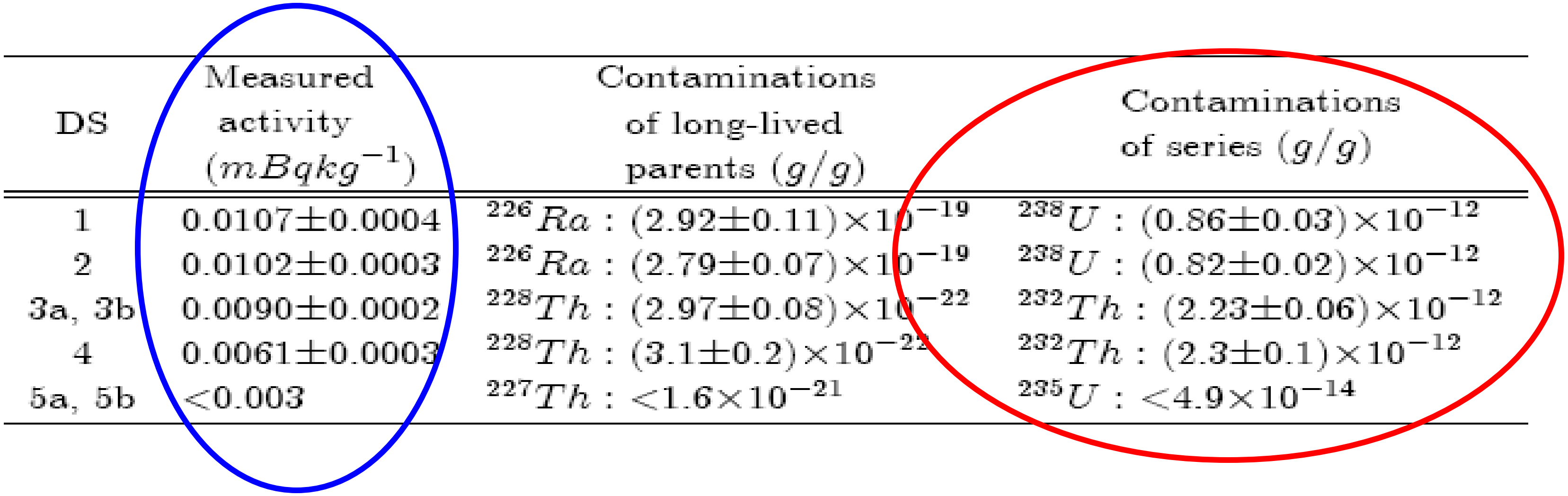


^{232}Th abundance = $2.23 \pm 0.06 \times 10^{-12}$ g/g

Intrinsic Radiopurity Measurement and Contamination Level



DS	Signature	*Selection Efficiency*	*Background -to-signal*	*Half-life* ($\tau_{1/2}$) *Nominal*	*Measured*
1	$\alpha - \alpha$	0.93	0.51	3.10 min	3.2±0.2 min
2	$\beta - \alpha$	0.77	3.2×10^{-3}	164 μs	163±8μs
3a	$\alpha - \alpha$	0.86		55 s	54.4±2.4 s
3b	α	0.97	9×10^{-5}	0.15 s	0.141±0.006 s
4	$\beta - \alpha$	0.37	3×10^{-5}	299 ns	283±37 ns
5a	$\alpha - \alpha$	0.78	–	3.96 s	No signal
5b	α	–	–	1.78 ms	DAQ inactive

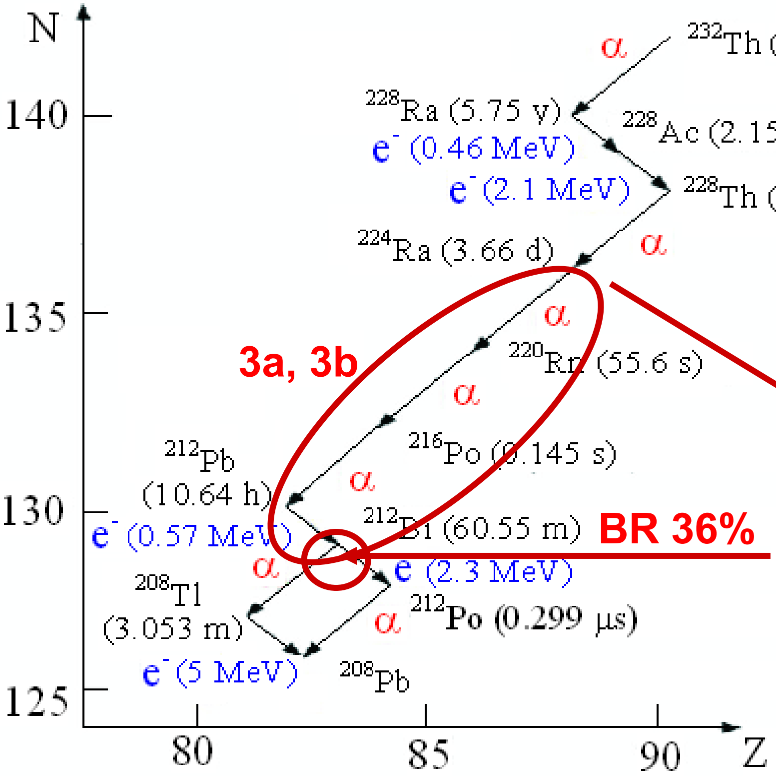


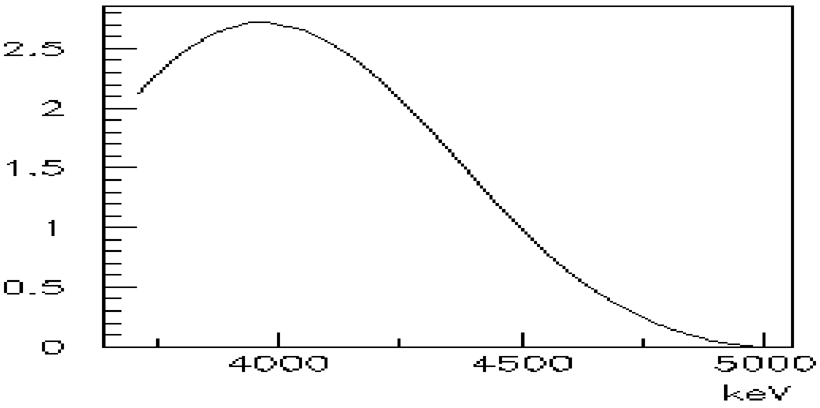
DS	Measured activity ($mBqkg^{-1}$)	Contaminations of long-lived parents (g/g)	Contaminations of series (g/g)
1	0.0107±0.0004	$^{226}Ra : (2.92\pm0.11)\times10^{-19}$	$^{238}U : (0.86\pm0.03)\times10^{-12}$
2	0.0102±0.0003	$^{226}Ra : (2.79\pm0.07)\times10^{-19}$	$^{238}U : (0.82\pm0.02)\times10^{-12}$
3a, 3b	0.0090±0.0002	$^{228}Th : (2.97\pm0.08)\times10^{-22}$	$^{232}Th : (2.23\pm0.06)\times10^{-12}$
4	0.0061±0.0003	$^{228}Th : (3.1\pm0.2)\times10^{-22}$	$^{232}Th : (2.3\pm0.1)\times10^{-12}$
5a, 5b	<0.003	$^{227}Th : <1.6\times10^{-21}$	$^{235}U : <4.9\times10^{-14}$

Estimate the background due to Intrinsic ^{208}Tl

^{232}Th (decay chain)

^{208}Tl beta with associated gammas energies deposit in one crystal.



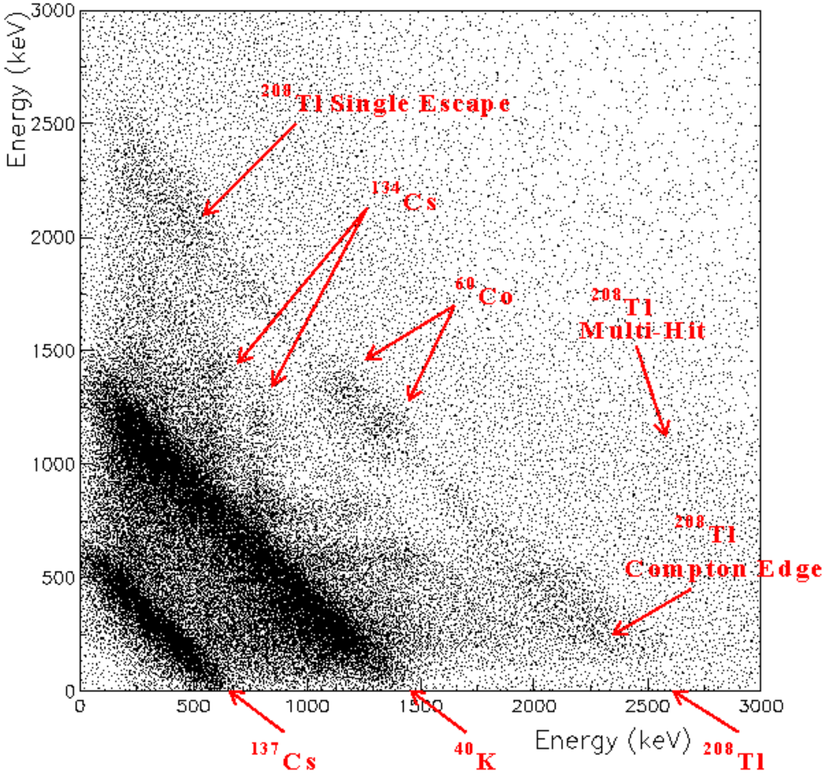


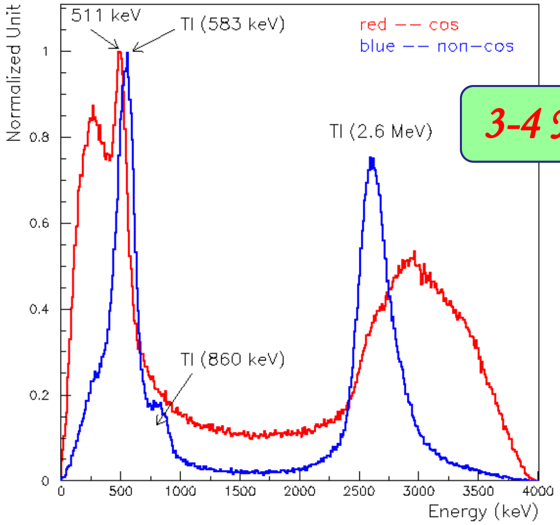
$$< 0.009\ mBq\,kg^{-1} \times 36\%\ (BR) \times 0.4\%(sim) \simeq < 0.00134\ cpd\ (kg^{-1} \times day^{-1})$$

This is 11% of signal and can be negligible in our background level of ~ 0.4 cpd in 3 - 5 MeV

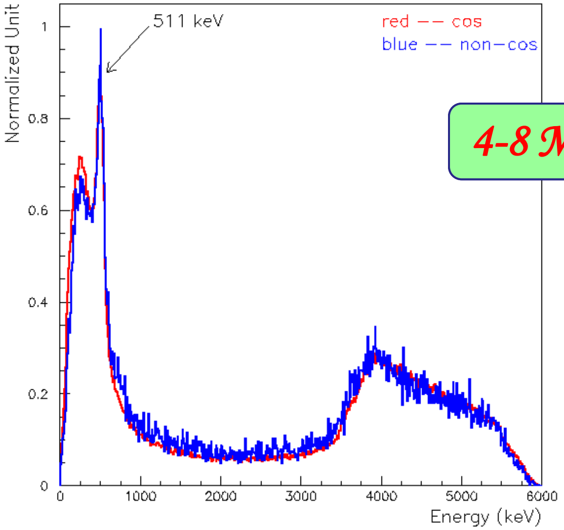
Background Understanding: via Multiple Hit Analysis

2 HIT SPECTRUM



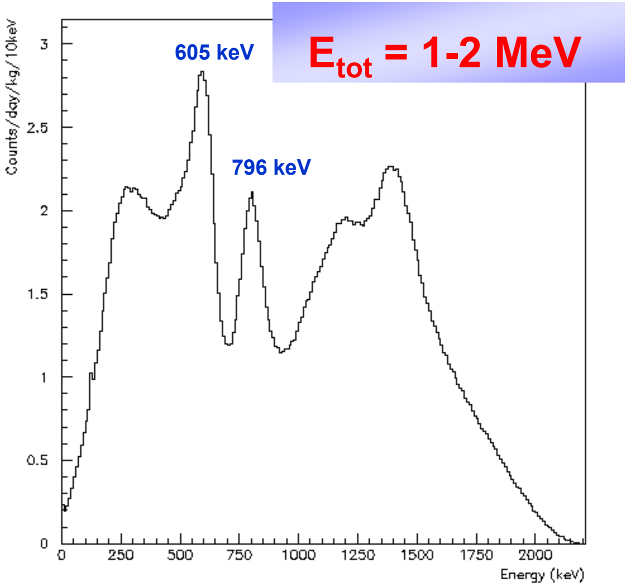


3-4 MeV



4-8 MeV

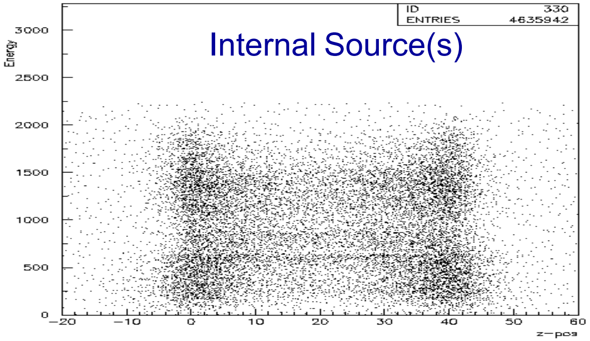
Background Understanding via Multi Hit



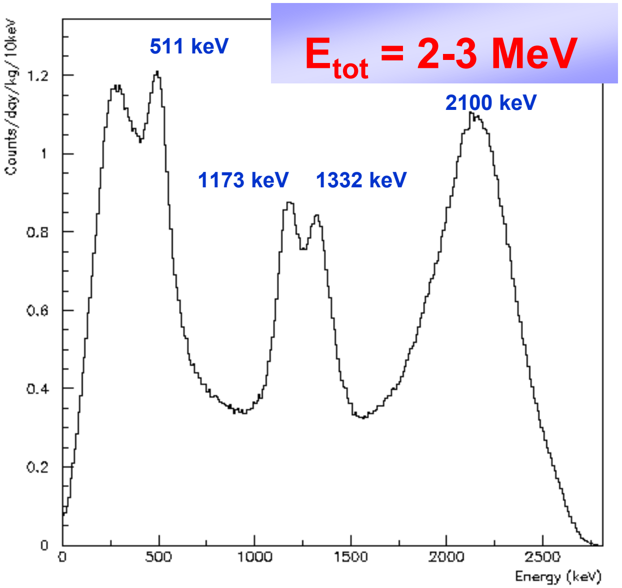
Cs-134 (n + ^{133}Cs → ^{134}Cs)

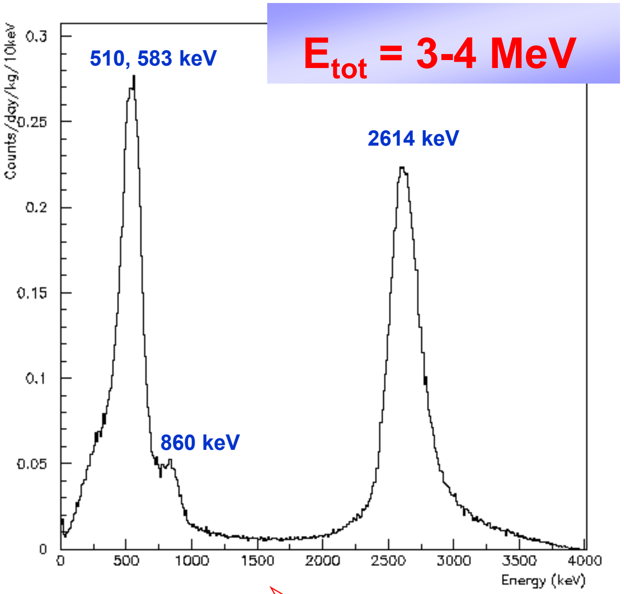
- **605** keV 97.6%;
- **796** keV 85.5%

With the Q of beta decay at 2MeV

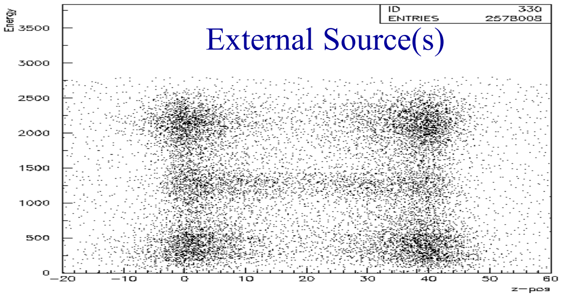


➢ **Cosmic induced neutrons can be captured by the target nuclei ^{133}Cs.**

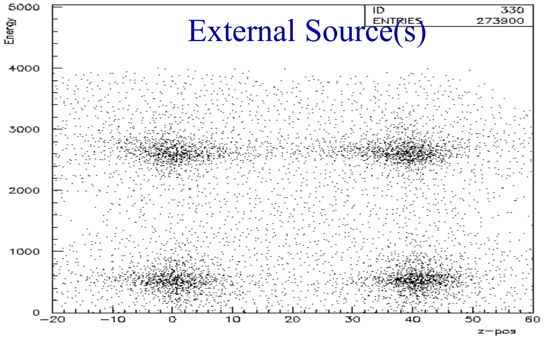




➢ **Combination of Tl gammas can affect up to around 4 MeV**



- **Co-60: 1173.2** keV 99.86% accompanied with **1332.5** keV 99.98%
  - The background related to reactor. Mostly come from the dust.
- **Tl Pair Production:** One escape peaks
  - (~ 2105 + 511 keV)



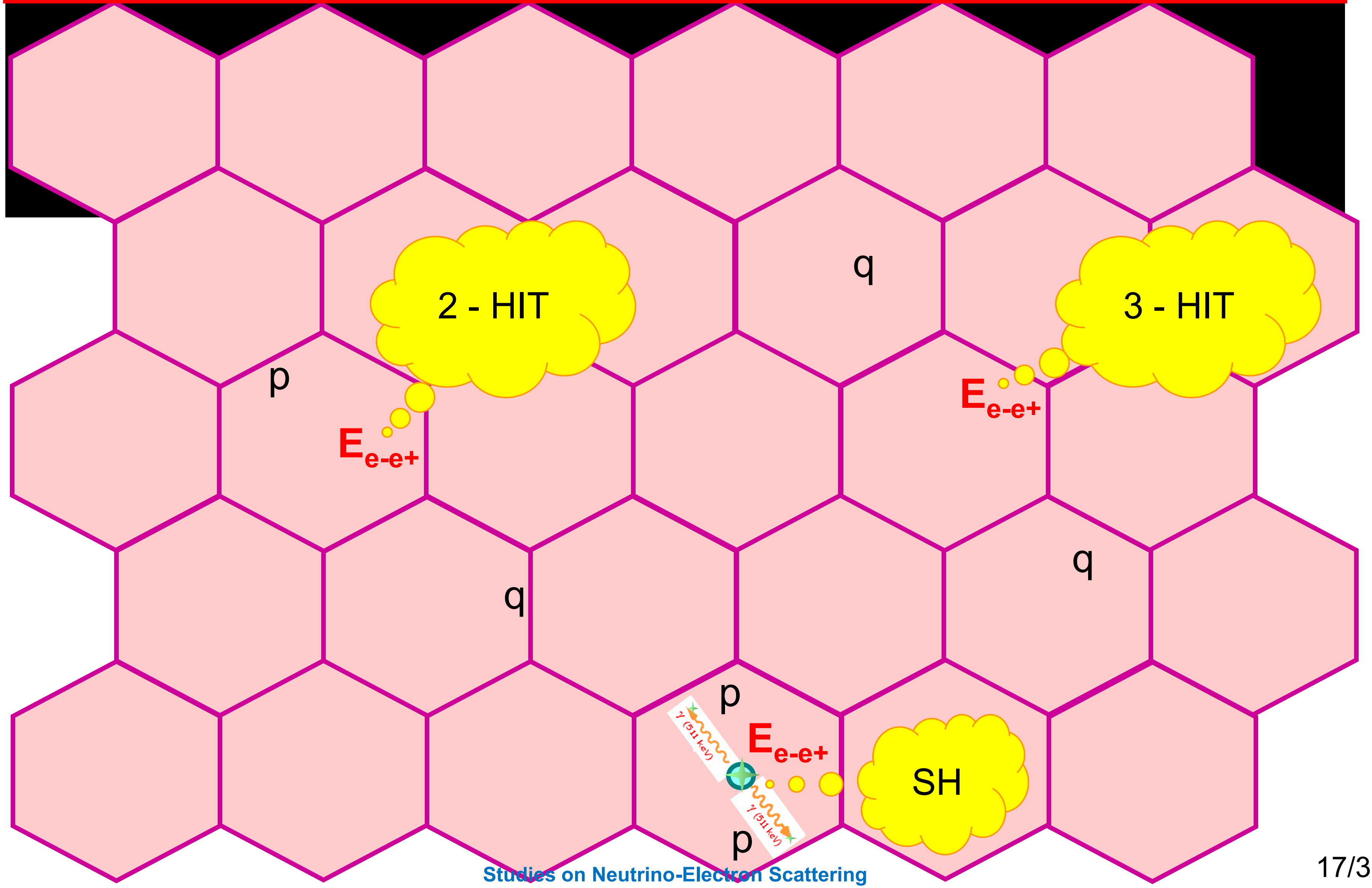
2614 keV 99 % accompanied with

583 keV 85%

510.8 keV 23%

860 keV with 13%

Background Prediction via PAIR PRODUCTION



Residual Background Understanding & Suppression

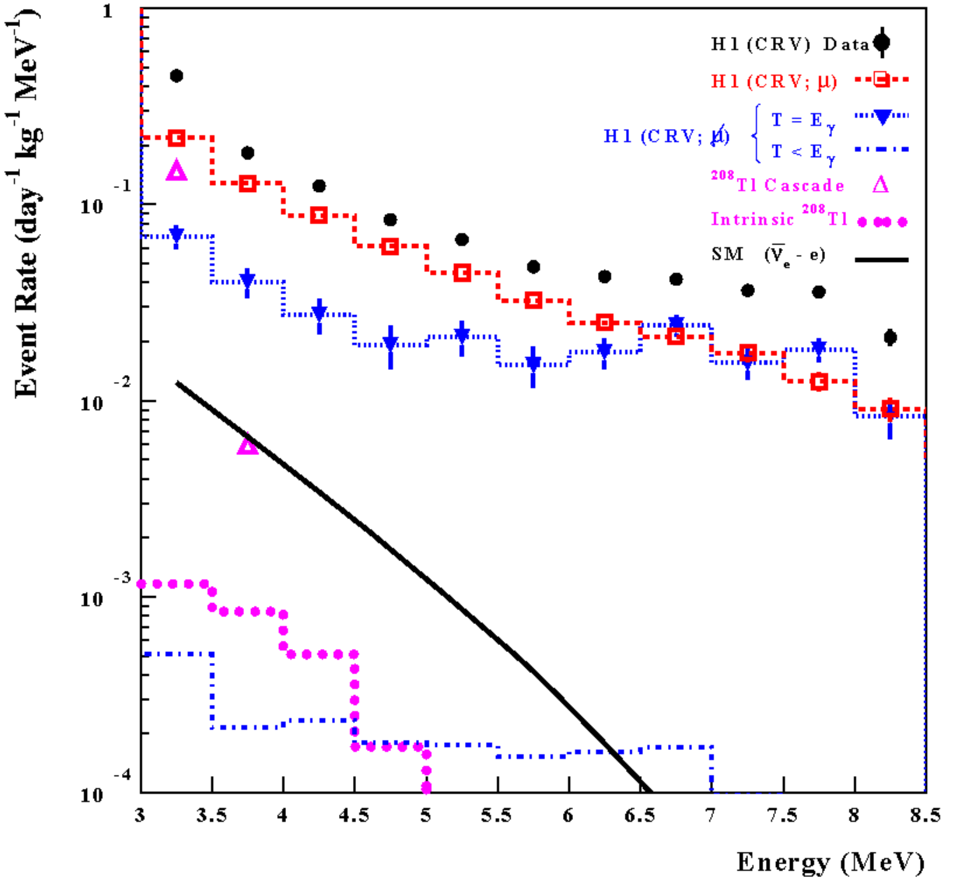
- Background Sources : **High Energy γ-rays & Cosmic Rays & ^{208}Tl**

Idea -- Use Multiple Crystal Hit (**MH**) spectra to **predict** Single Crystal Hit (**SH**) Background to the neutrino events

$$\left(\frac{MH_{non\ \cos}}{MH_{tot}}\right)_{ON,OFF} = 1 - \varepsilon = \left(\frac{SH[BKG(\cos)]}{SH_{tot}}\right)_{ON,OFF}$$

$$\frac{SH[BKG(2614+583)]}{MH[2614;583(data)]} = \frac{SH[2614+583(MC)]}{MH[2614;583(MC)]}$$

Background Understanding & Suppression



Combined *BKG(SH)* from *three measurements*:

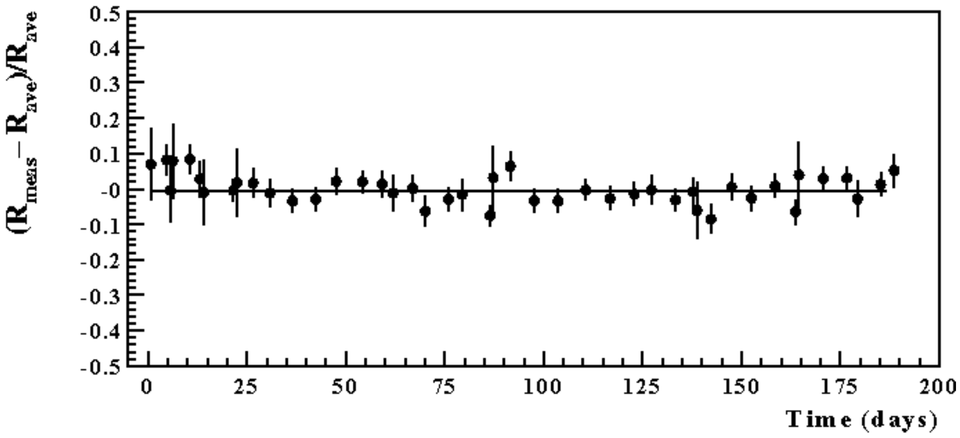
- Direct **Reactor OFF(SH)** spectra ⊕ Predicted **BKG(SH)** from **OFF(MH)**

  ⊕ Predicted **BKG(SH)** from **ON(MH)**

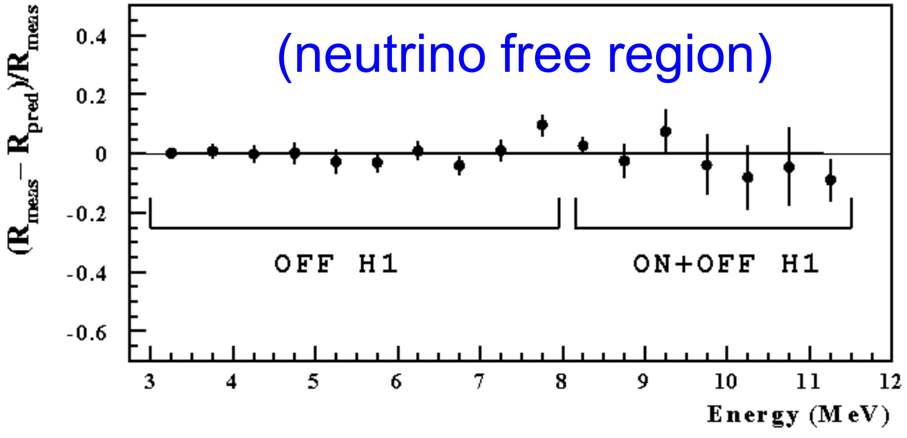
  ν = ON(SH) – BKG(SH)

Systematic Uncertainties
Approach - Use non-ν events for demonstration

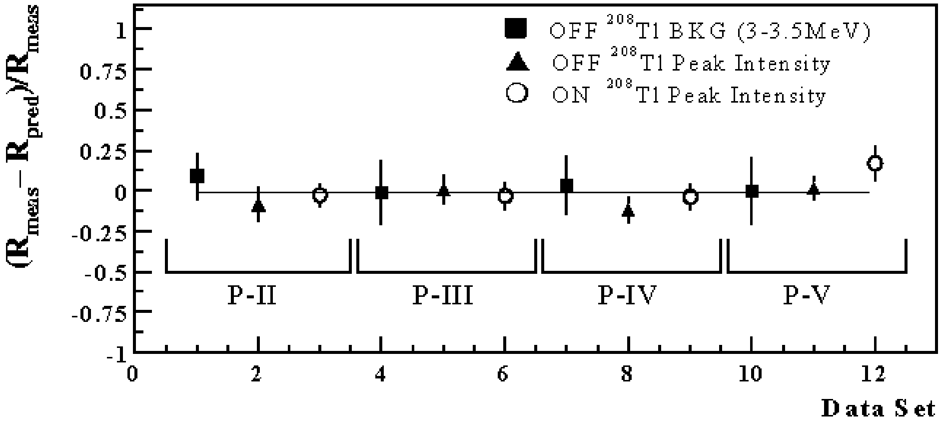
^{208}Tl Peak Events Stability



BKG – Pred.


(neutrino free region)

^{208}Tl (SH) Prediction



ON-OFF Stability < ~0.5%

- Random trigger events for **DAQ** & **Selection Cuts**
- **Stability** of **Tl-208 (2614 keV)** peak events

Cosmic Induced BKG(SH) Prediction < ~1 %

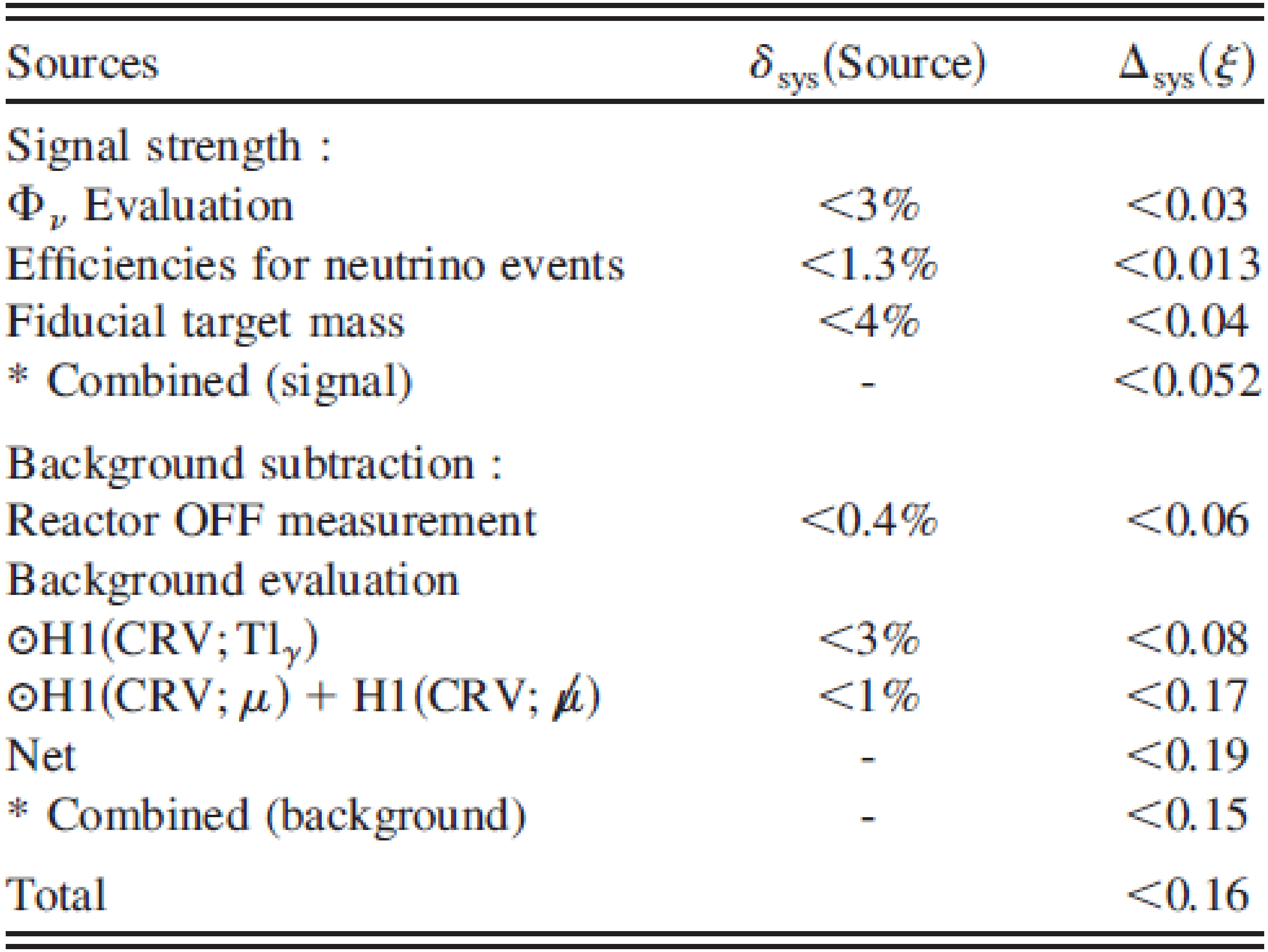
- Successfully **Predict Cosmic BKG** in **NEUTRINO FREE REGION**

Tl-208 Induced BKG(SH) Prediction <~3%

- Successfully **Predict Tl-208 Induced BKG(SH) >3MeV** at Reactor **OFF** periods
- Successfully **Predict Tl-208** peak intensity for both Reactor **ON/OFF** with the same tools **(MC)**

Systematic Uncertainties

Summary of the sources of systematic errors and their contributions to the measurement uncertainties.

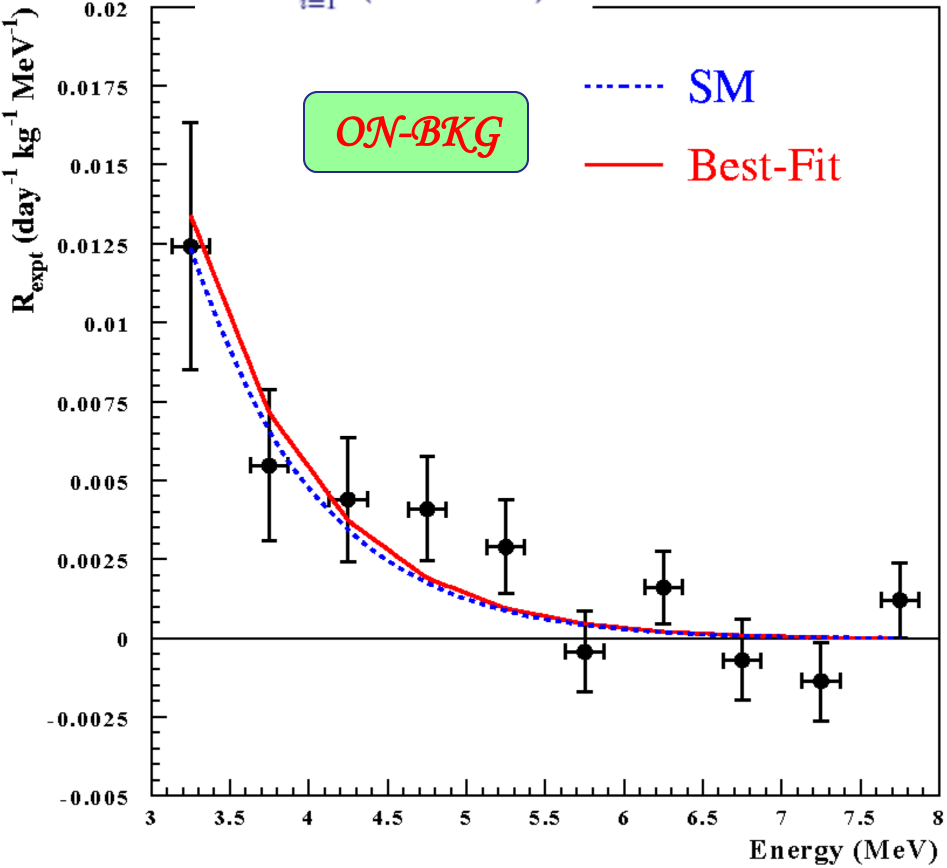


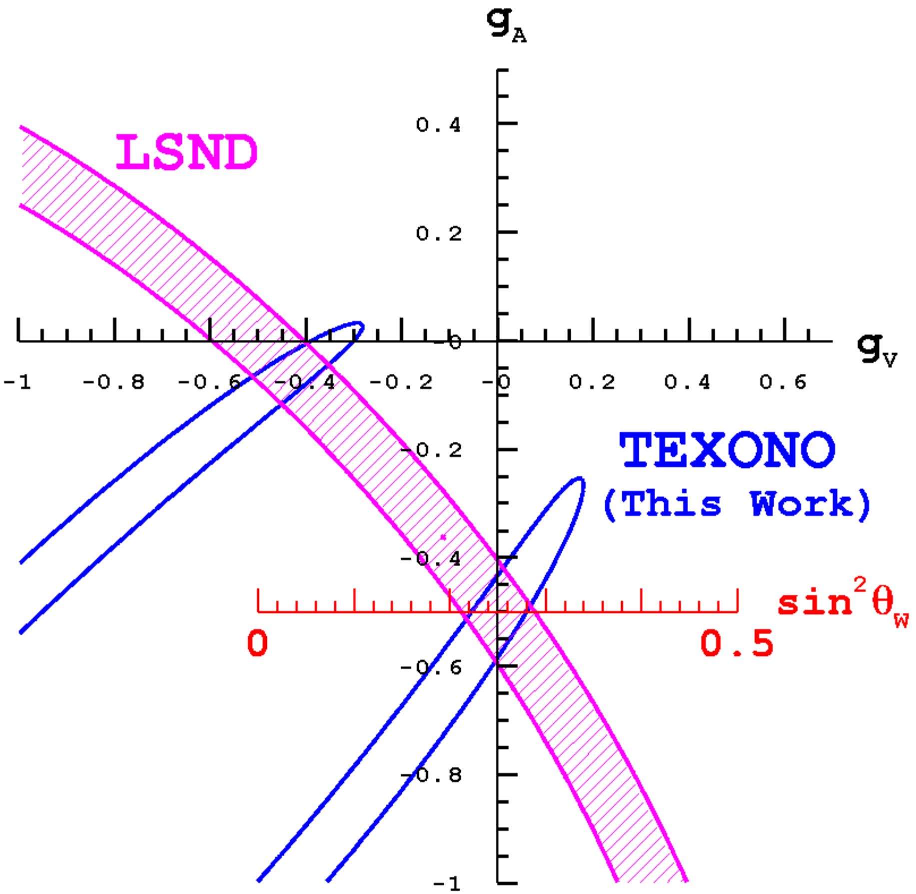
Sources	δ_{sys}(Source)	$\Delta_{sys}(\xi)$
Signal strength :		
Φ_ν Evaluation	<3%	<0.03
Efficiencies for neutrino events	<1.3%	<0.013
Fiducial target mass	<4%	<0.04
* Combined (signal)	-	<0.052
Background subtraction :		
Reactor OFF measurement	<0.4%	<0.06
Background evaluation		
$\odot$H1(CRV; Tl_γ)	<3%	<0.08
$\odot$H1(CRV; μ) + H1(CRV; $\not\mu$)	<1%	<0.17
Net	-	<0.19
* Combined (background)	-	<0.15
Total		<0.16

Cross Section & Weak Mixing Angle

Phys. Rev. D 81, 072001 (2010)

$$\chi^2 = \sum_{i=1}^{10} \left(\frac{R_i - \zeta R_i^{SM}}{\sigma_i} \right)^2$$





$$R = [1.08 \pm 0.21\,(stat) \pm 0.16(sys)] \times R_{SM}$$

$$\sin^2 \theta_W = 0.251 \pm 0.031\,(stat) \pm 0.024\,(sys)$$

Better sensitivity is achieved in the measurement of weak mixing angle

World Status: Summary Table

	Experiment	Energy (MeV)	Events	Cross-Section	$\sin^2\theta_W$
$\nu_e - e^-$	**LAMPF** [Liquid Scin.]	7 - 60	236	[10.0 ± 1.5 ± 0.9] x $E_{\nu e}10^{-45}cm^2$	0.249 ± 0.063
	LSND [Liquid Scin.]	10 - 50	191	[10.1 ± 1.1 ± 1.0] x $E_{\nu e}10^{-45}cm^2$	0.248 ± 0.051
$\bar{\nu}_e - e^-$	**Savannah-River** [Plastic Scin.]	1.5 - 3.0 3.0 – 4.5	381 71	[0.86 ± 0.25] x $\sigma_{V\text{-}A}$ [1.70 ± 0.44] x $\sigma_{V\text{-}A}$	0.29 ± 0.05
	Savannah-River **Re-analysed** (PRD1989, Engel&Vogel)	1.5 – 3.0 3.0 – 4.5	N/A	[1.35 ± 0.4] x σ_{SM} [2.0 ± 0.5] x σ_{SM}	N/A
	Krasnoyarsk (Fluorocarbon)	3.15 – 5.18	N/A	[4.5 ± 2.4] x 10^{-46} cm^2/fission	0.22 ± 0.75
	Rovno [Si(Li)]	0.6 – 2.0	41	[1.26 ± 0.62] x 10^{-44} cm^2/fission	N/A
	MUNU [CF_4(gas)]	0.7 – 2.0	68	1.07 ± 0.34 events day^{-1}	N/A
	TEXONO [CsI(Tl) Scin.]	3 - 8	~ 410	[1.08 ± 0.21 ± 0.16] x R_{SM}	0.251 ± 0.031(stat) ± 0.024(sys)

Neutrino-Electron Scattering Cross-Section

$$\bar{\nu}_e + e^- \longrightarrow \bar{\nu}_e + e^-$$

$$\sigma_{SM} = \sigma^{INT} + \sigma^{CC} + \sigma^{NC}$$

$$\sigma^{CC} = 4 \times I_2$$

$$\begin{aligned}\sigma^{NC} &= (g_V - g_A)^2 \times I_1 + (g_V + g_A)^2 \times I_2 + (g_A^2 - g_V^2)^2 \times I_3 \\ &= (4\sin^4\theta) \times I_1 + (1 - 2\sin^2\theta)^2 \times I_2 + 2\sin^2\theta(1 - 2\sin^2\theta) \times I_3\end{aligned}$$

$$\begin{aligned}\sigma^{INT} &= 4(g_V + g_A) \times I_2 + 2(g_A - g_V) \times I_3 \\ &= 4(2\sin^2\theta - 1) \times I_2 - (4\sin^2\theta) \times I_3\end{aligned}$$

$$I_1 = \frac{G_F^2 m_e}{2\pi} \rho_e \iint_{TE_\nu} \left(\frac{d\phi}{dE_\nu} \right) dE_\nu dT$$

$$I_2 = \frac{G_F^2 m_e}{2\pi} \rho_e \iint_{TE_\nu} \left(1 - \frac{T}{E_\nu} \right)^2 \left(\frac{d\phi}{dE_\nu} \right) dE_\nu dT$$

$$I_3 = \frac{G_F^2 m_e}{2\pi} \rho_e \iint_{TE_\nu} \left(\frac{m_e T}{E_\nu} \right) \left(\frac{d\phi}{dE_\nu} \right) dE_\nu dT$$

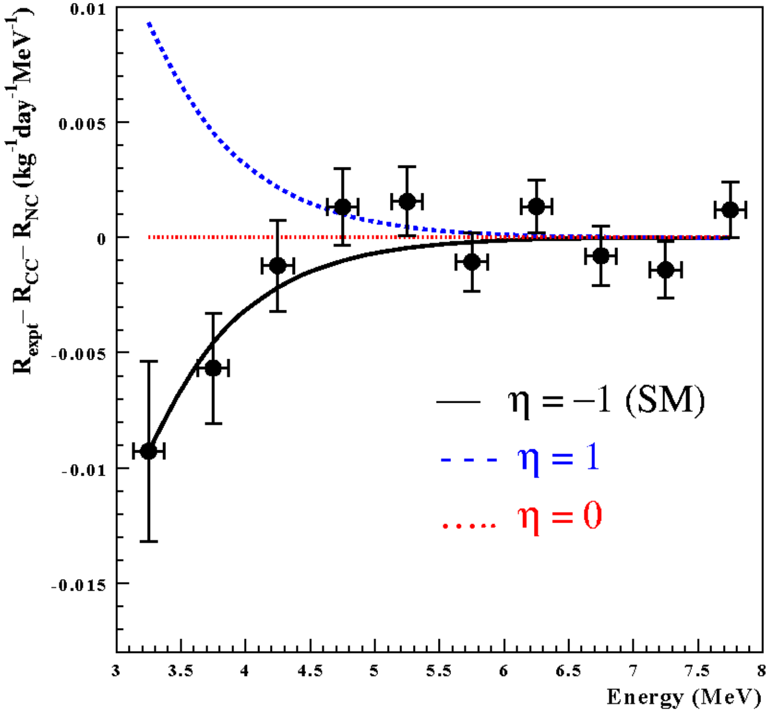
Interference, Neutrino Magnetic Moment and Charge Radius

Interference Term

$$R_{SM} = R^{CC} + R^{NC} + \eta \times R^{I}$$

Interference Term

η= -0.92 ± 0.30(stat) ± 0.24(sys)



Neutrino Magnetic Moment

$$R\,(ON - BKG) = R(SM) + \mu_\nu^2 \times R(MM)$$

$\mu_\nu^2 = [0.42 \pm 1.79(stat) \pm 1.49(sys)].\mu_B^2$

$$\mu_{\bar{\nu}} < 2.2 \times 10^{-10} \times \mu_B$$

at 90% C. L.

Neutrino Charge Radius

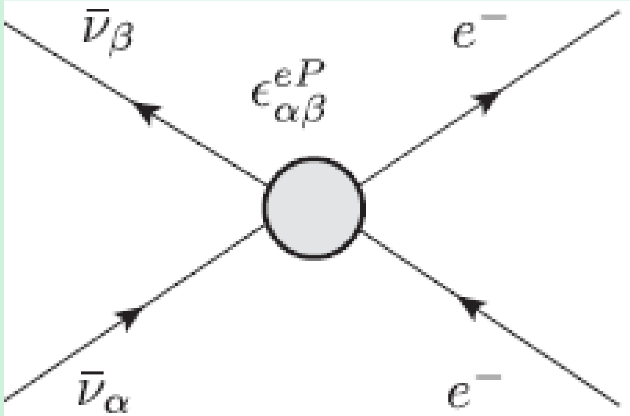
$$\sin^2\theta_W \to \sin^2\theta_W + (\sqrt{2}\pi\alpha / 3G_F)\langle r^2_{\bar{\nu}_e}\rangle$$

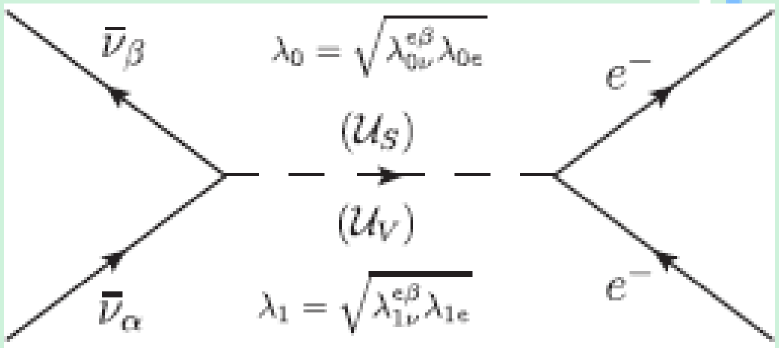
$$-2.1\times10^{-32} < \langle r^2_{\bar{\nu}_e}\rangle < 3.3\times10^{-32}\ cm^2$$

Constraints of New Physics with $\bar{\nu}_e - e^-$ Scattering

[PRD 82, 033004 (2010)]

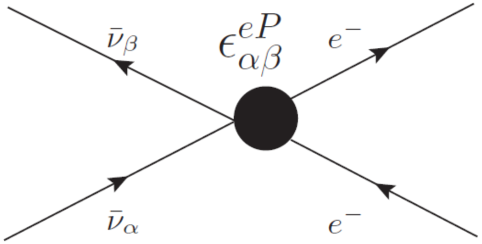
– *The measurements of neutrino scattering provide a sensitive tools to probe NSI and UP Physics*





NSI of Neutrino

$$\mathscr{L}_{\text{eff}} = -\epsilon^{eP}_{\alpha\beta} 2\sqrt{2} G_F (\bar{\nu}_\alpha \gamma_\rho L \nu_\beta)(\bar{e} \gamma^\rho P e)$$



$$\frac{d\sigma(E_\nu,T)}{dT} = \frac{2G_F^2 M_e}{\pi}[(\tilde{g}_L^2 + \sum_{\alpha\neq e}|\epsilon^{eL}_{\alpha e}|^2) + (\tilde{g}_R^2 + \sum_{\alpha\neq e}|\epsilon^{eR}_{\alpha e}|^2)\left(1-\frac{T}{E_\nu}\right)^2 - (\tilde{g}_L \tilde{g}_R + \sum_{\alpha\neq e}|\epsilon^{eL}_{\alpha e}||\epsilon^{eR}_{\alpha e}|) m_e \frac{T}{E_\nu^2}]$$

– *ν mass models all mechanisms carry some modifications to the structure of the standard EW NC & CC*

– ***V-A Form****, similar to the four Fermi*

- *exchange of Higgs*
- *Supersymmetric scalar bosons*
- *New heavy gauge boson Z'*

– *characterized by some new couplings, called NSI*

(NU) NSI: ϵ^{eLR}_{ee}

(FC) NSI: $\epsilon^{eLR}_{e\mu}$ $\epsilon^{eLR}_{e\tau}$

$$\tilde{g}_L = g_L + \epsilon^{eL}_{ee}$$
$$\tilde{g}_R = g_R + \epsilon^{eR}_{ee}$$

❖ There is a strict bound on $|\epsilon^{eLR}_{e\mu}| < 7.7 \times 10^{-4}$ derived from $\mu \rightarrow 3e$ decay

❖ The main parameters will be $\boxed{\epsilon^{eLR}_{e\tau}}$ for FC NSI and

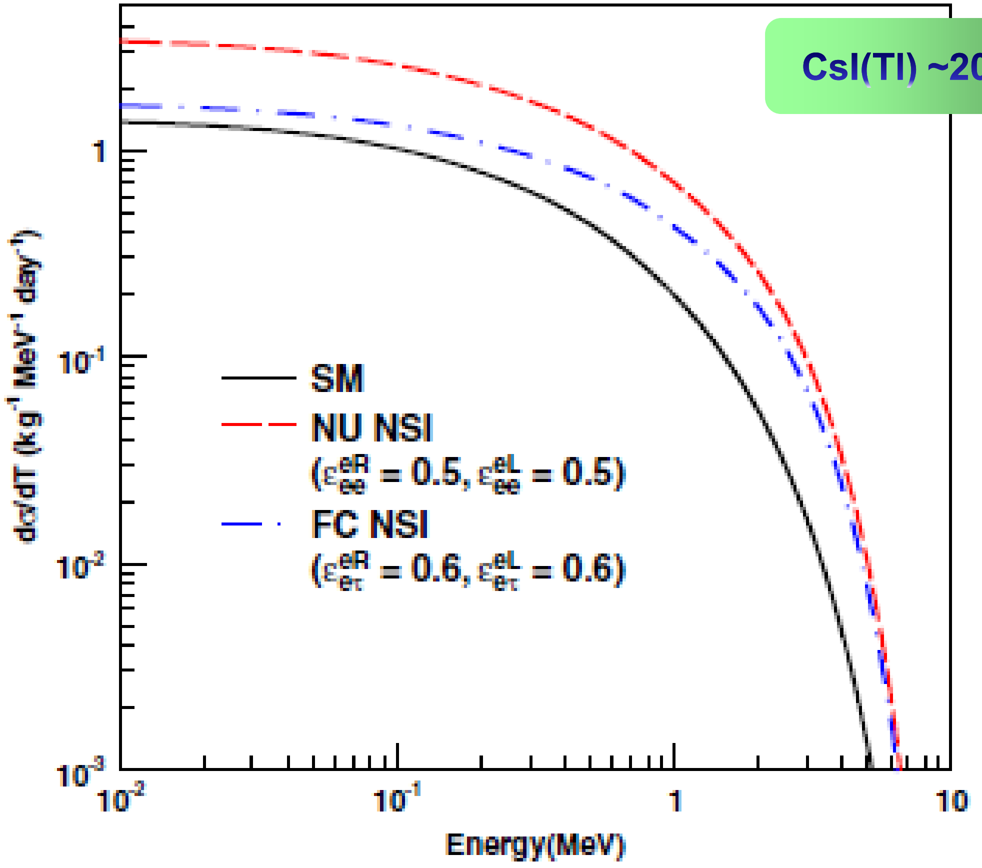
$\boxed{\epsilon^{eLR}_{ee}}$ for NU-NSI.

NSI of Neutrino

— $\bar{\nu}_e - e^-$ scattering provide a sensitive tool to probe NSI

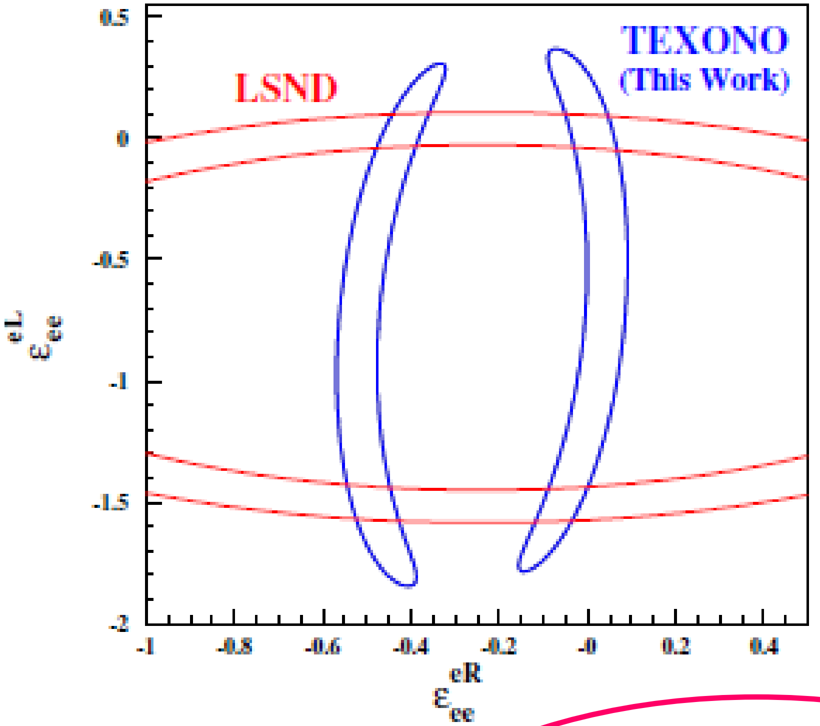
— *The NSI parameters are constrained by the accuracy of the SM cross-section measurements*

The measurable recoil spectra with typical reactor neutrino “flux” at typical values of NSI parameters for both NU and FC NSI

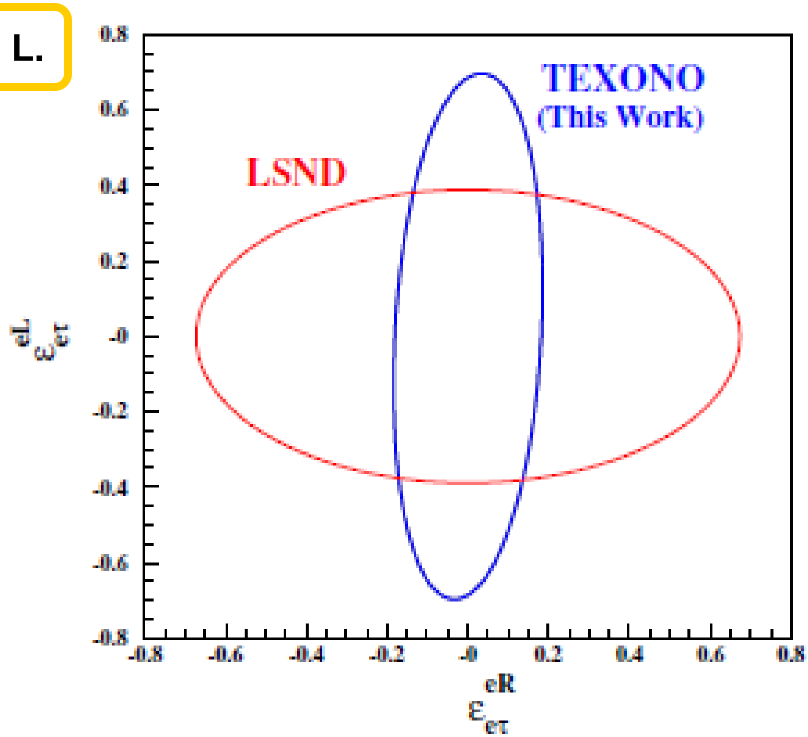


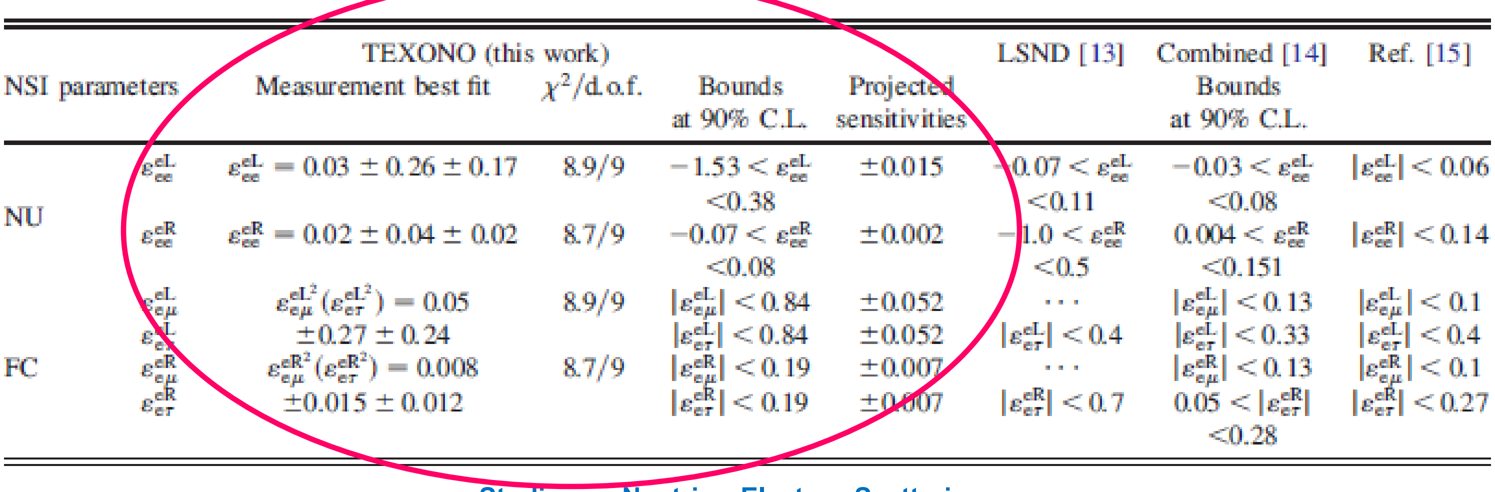
CsI(Tl) ~200 kg

Comparison of Bounds of NSI Parameters



at 90% C. L.

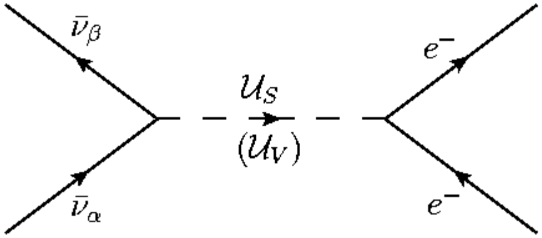




NSI parameters		TEXONO (this work) Measurement best fit	χ^2/d.o.f.	Bounds at 90% C.L.	Projected sensitivities	LSND [13]	Combined [14] Bounds at 90% C.L.	Ref. [15]
NU	ε_{ee}^{eL}	$\varepsilon_{ee}^{eL} = 0.03 \pm 0.26 \pm 0.17$	8.9/9	$-1.53 < \varepsilon_{ee}^{eL} < 0.38$	± 0.015	$-0.07 < \varepsilon_{ee}^{eL} < 0.11$	$-0.03 < \varepsilon_{ee}^{eL} < 0.08$	$\lvert\varepsilon_{ee}^{eL}\rvert < 0.06$
	ε_{ee}^{eR}	$\varepsilon_{ee}^{eR} = 0.02 \pm 0.04 \pm 0.02$	8.7/9	$-0.07 < \varepsilon_{ee}^{eR} < 0.08$	± 0.002	$-1.0 < \varepsilon_{ee}^{eR} < 0.5$	$0.004 < \varepsilon_{ee}^{eR} < 0.151$	$\lvert\varepsilon_{ee}^{eR}\rvert < 0.14$
FC	$\varepsilon_{e\mu}^{eL}$	$\varepsilon_{e\mu}^{eL^2}(\varepsilon_{e\tau}^{eL^2}) = 0.05$ $\pm 0.27 \pm 0.24$	8.9/9	$\lvert\varepsilon_{e\mu}^{eL}\rvert < 0.84$	± 0.052	···	$\lvert\varepsilon_{e\mu}^{eL}\rvert < 0.13$	$\lvert\varepsilon_{e\mu}^{eL}\rvert < 0.1$
	$\varepsilon_{e\tau}^{eL}$			$\lvert\varepsilon_{e\tau}^{eL}\rvert < 0.84$	± 0.052	$\lvert\varepsilon_{e\tau}^{eL}\rvert < 0.4$	$\lvert\varepsilon_{e\tau}^{eL}\rvert < 0.33$	$\lvert\varepsilon_{e\tau}^{eL}\rvert < 0.4$
	$\varepsilon_{e\mu}^{eR}$	$\varepsilon_{e\mu}^{eR^2}(\varepsilon_{e\tau}^{eR^2}) = 0.008$ $\pm 0.015 \pm 0.012$	8.7/9	$\lvert\varepsilon_{e\mu}^{eR}\rvert < 0.19$	± 0.007	···	$\lvert\varepsilon_{e\mu}^{eR}\rvert < 0.13$	$\lvert\varepsilon_{e\mu}^{eR}\rvert < 0.1$
	$\varepsilon_{e\tau}^{eR}$			$\lvert\varepsilon_{e\tau}^{eR}\rvert < 0.19$	± 0.007	$\lvert\varepsilon_{e\tau}^{eR}\rvert < 0.7$	$0.05 < \lvert\varepsilon_{e\tau}^{eR}\rvert < 0.28$	$\lvert\varepsilon_{e\tau}^{eR}\rvert < 0.27$

Unparticle Physics

- ❖ The notion of unparticles is introduced by Howard Georgi . A scale invariant sector which decouples at a suffciently large energy scale exists. *[Phys. Rev. Lett. 98, 221601 (2007)]*
- ❖ The signatures of Unparticles can also be observed by reactor neutrinos by searching the effects of virtual unparticle exchange between fermionic currents.
- ❖ This interaction can be either exchange of **Scalar Unparticles** or **Vector Unparticles**.



— The UP does not have any well defined invariant mass but rather has a contniuous mass spectrum

1. Exchange of Scalar Unparticles

$$\frac{d\sigma_{\mathcal{U}_S}}{dT} = \frac{[g_{0e}^{\alpha\beta}(d)]^2}{\Lambda^{(4d-4)}}\frac{2^{(2d-6)}}{\pi E_\nu^2}(m_eT)^{(2d-3)}(T+2m_e)$$

2. Exchange of Vector Unparticles

$$\frac{d\sigma_{\mathcal{U}_V}}{dT} = \frac{1}{\pi}\frac{[g_{1e}^{\alpha\beta}(d)]^2}{\Lambda^{(4d-4)}}2^{(2d-5)}(m_e)^{(2d-3)}(T)^{(2d-4)}\left[1+\left(1-\frac{T}{E_\nu}\right)^2-\frac{m_eT}{E_\nu^2}\right]$$

For the flavour changing case:

$$\frac{d\sigma_{\mathcal{U}_V-SM}}{dT} = \frac{\sqrt{2}G_F}{\pi}\frac{g_{1e}(d)}{\Lambda^{(2d-2)}}(2m_eT)^{(d-2)}m_e\left\{g_L+g_R\left(1-\frac{T}{E_\nu}\right)^2-\frac{(g_L+g_R)}{2}\frac{m_eT}{E_\nu^2}\right\}$$

For the flavour conserving case

i= 0(1) : Unparticle scalar/vector field
λ_0 (λ_1) : Scalar(Vector) unparticle couplings
f : e, u, d
α, β: denotes neutrino flavours
d: Unparticle mass dimension
Λ : Unparticle energy scale

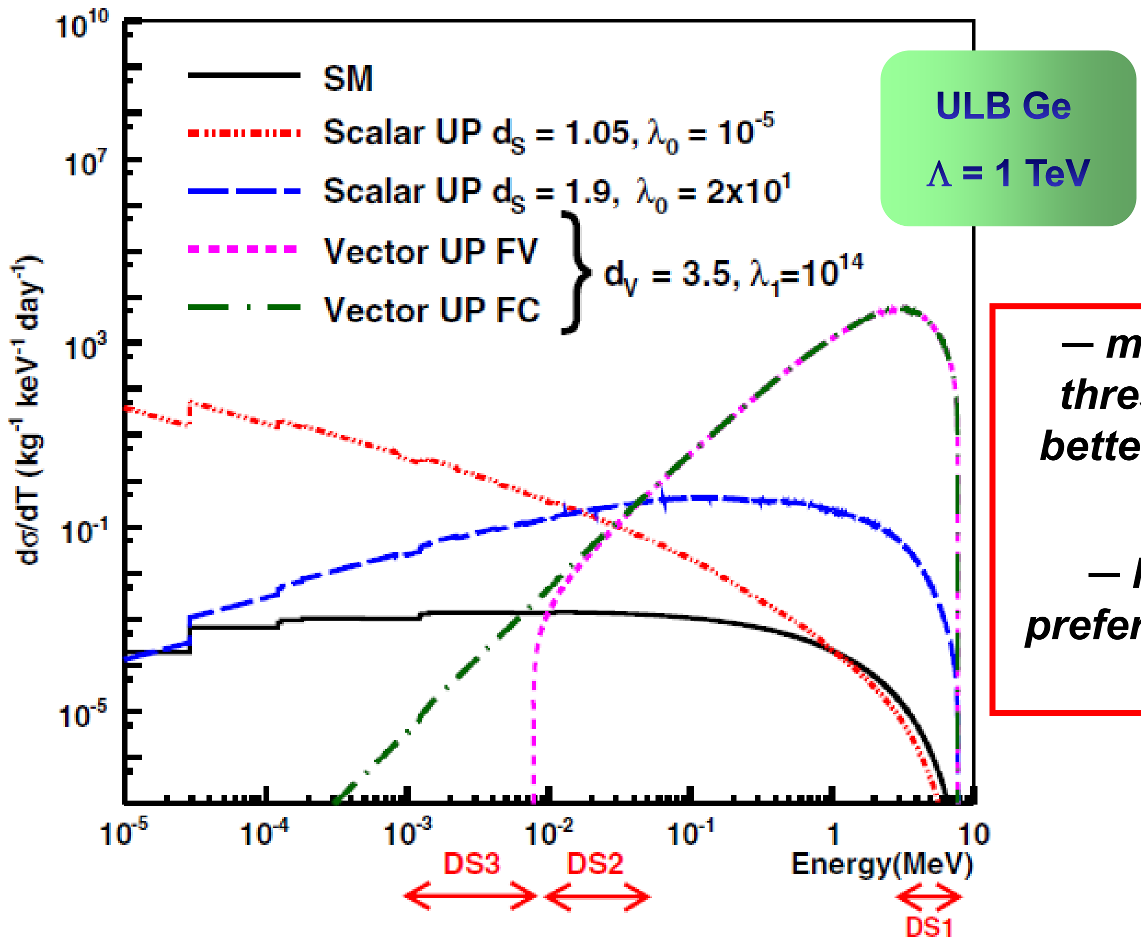
$$g_{if}^{\alpha\beta}(d) = \frac{\lambda_{i\nu}^{\alpha\beta}\lambda_{if}}{2\sin(d\pi)}A_d \qquad A_d = \frac{16\pi^{5/2}}{(2\pi)^{2d}}\frac{\Gamma(d+1/2)}{\Gamma(d-1)\Gamma(2d)}.$$

$$\lambda_0\ (\lambda_1) = \sqrt{\lambda_{0\nu}^{e\beta}\lambda_{0e}}\ \left(\sqrt{\lambda_{1\nu}^{e\beta}\lambda_{1e}}\right)$$

Unparticles

$$\bar{\nu}_\alpha + e^- \xrightarrow{UP} \bar{\nu}_\beta + e^-$$

— The differential cross-section of the interaction for $\bar{\nu}_e$-e scattering via virtual scalar and vector UP exchange

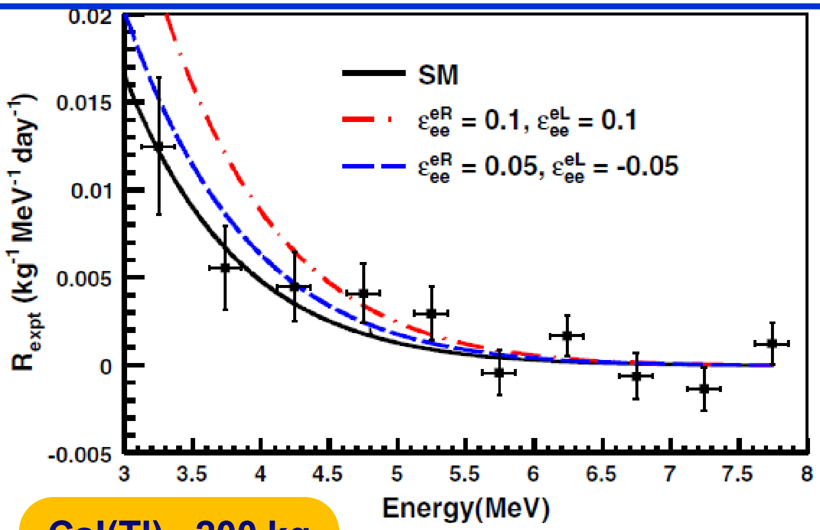


— measurements with low energy threshold are expected to provide better sensitivities for low values of mass dimension of "d"

— high energy experiments are prefered to probe UP due to the large values of "d"

Unparticle - Exclusion Plots

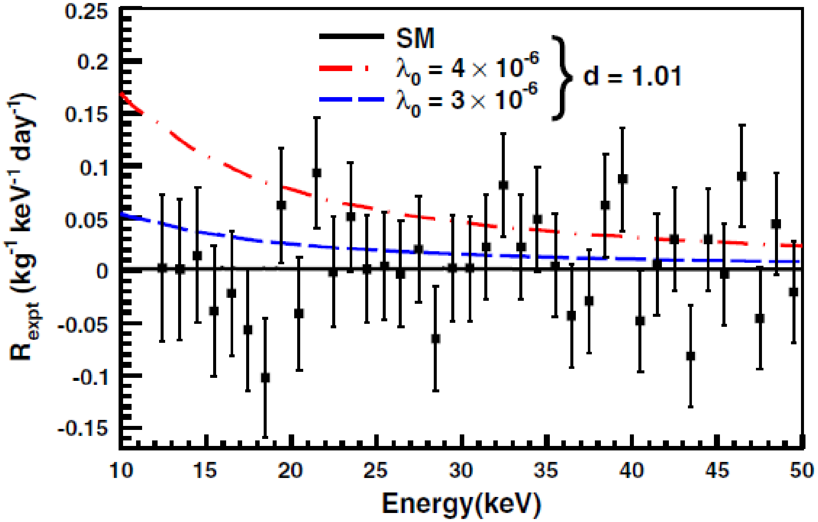
– *For the illustrations (only) the measurable spectra of an excluded and allowed parameter space where the data provides the stringent bounds for typical values of parameters*



CsI(Tl) ~200 kg

This Talk

PRD 2010



ULB Ge 1 kg

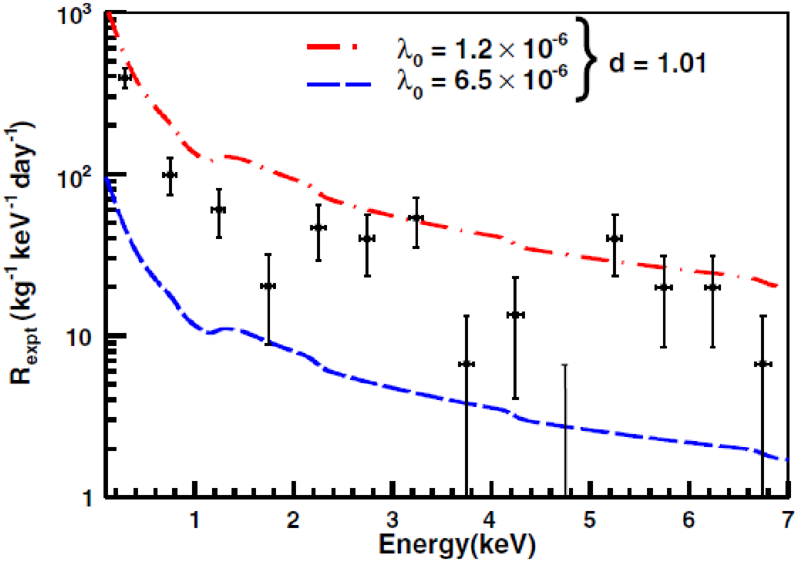
ν MM Data Set

PRD 2001, PRD 2007

ULE Ge 20 g

WIMP data set

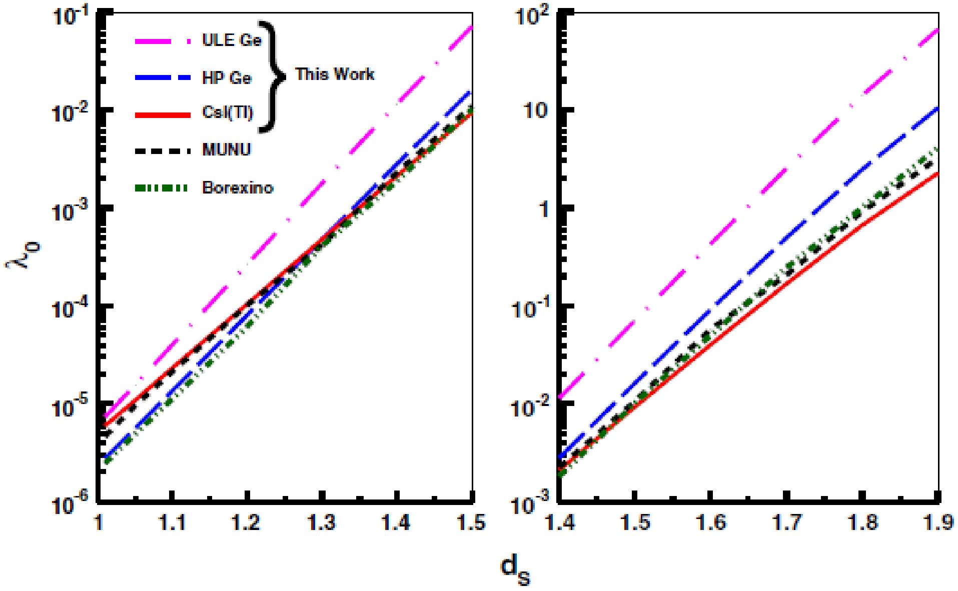
PRD 2009



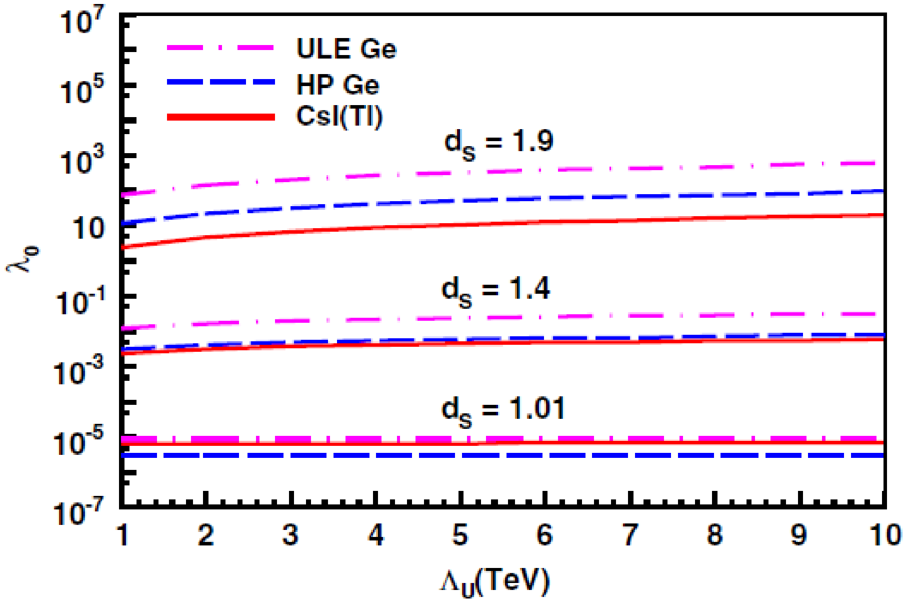
Scalar Unparticle

$$\frac{d\sigma_{\mathcal{U}_S}}{dT} = \frac{[g_{0e}^{\alpha\beta}(d)]^2}{\Lambda^{(4d-4)}}\frac{2^{(2d-6)}}{\pi E_\nu^2}(m_e T)^{(2d-3)}(T+2m_e)$$

Λ_U = 1 TeV



Λ_U = 1 - 10 TeV



Results are improved over those from Borexino and MUNU experiments

Unparticle effects decreases as Λ_U increases

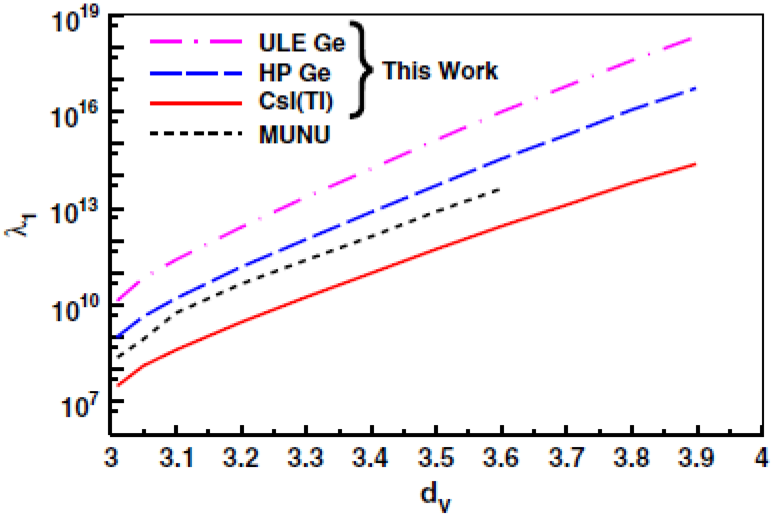
Vector Unparticle

$$\frac{d\sigma_{\mathcal{U}_V}}{dT} = \frac{1}{\pi}\frac{[g_{1e}^{\alpha\beta}(d)]^2}{\Lambda^{(4d-4)}}2^{(2d-5)}(m_e)^{(2d-3)}(T)^{(2d-4)}\left[1+\left(1-\frac{T}{E_\nu}\right)^2-\frac{m_eT}{E_\nu^2}\right]$$

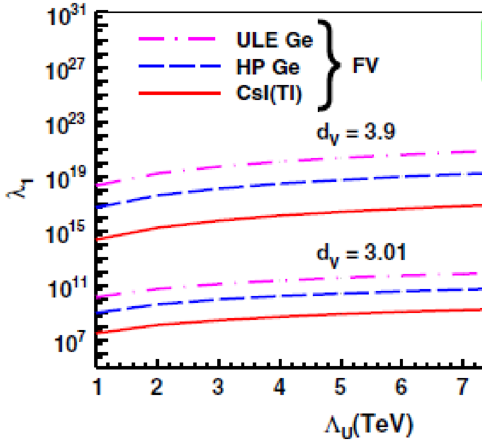
$$\frac{d\sigma_{\mathcal{U}_V-SM}}{dT} = \frac{\sqrt{2}G_F}{\pi}\frac{g_{1e}(d)}{\Lambda^{(2d-2)}}(2m_eT)^{(d-2)}m_e\left\{g_L+g_R\left(1-\frac{T}{E_\nu}\right)^2-\frac{(g_L+g_R)}{2}\frac{m_eT}{E_\nu^2}\right\}$$

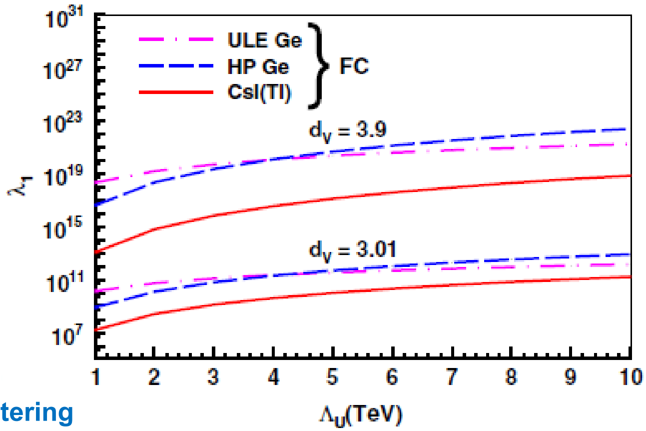
— both FC and FV scenario are considered and analysed

Λ = 1 TeV



Λ = 1 - 10 TeV





Summary

- **Detector:** CsI(Tl) Scintillating Crystal Array (~ 200 kg)
  - Threshold: 3 MeV
- **Analysis Results:**
  - $\sigma(\overline{\nu}_e - e^-)$ with ~ 25% accuracy
  - Weak Mixing Angle with ~ 15% accuracy
  - Verify SM negative interference
  - $\mu_{\bar{\nu}}$ sensitivity ~ 10^{-10} μ_B
  - neutrino charge radius sensitivity ~ 10^{-32} cm^2
- **Probing new Physics :** NSI and UP
  - Current bounds are improved over those from the previous experiments

Thank YOU