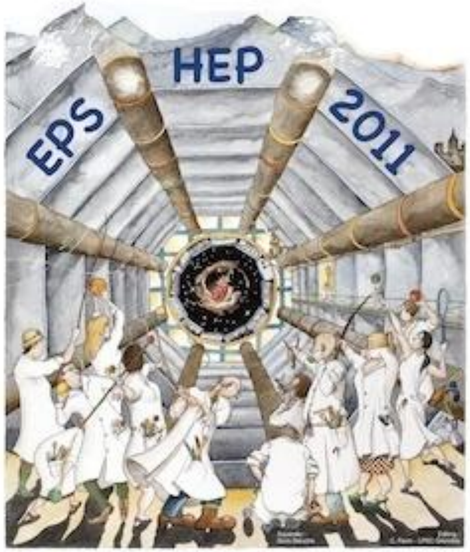
Measurement of $\bar{\nu}_e$-e^- Scattering Cross-Section and Constraints on Non-Standard Interaction of Neutrino (NSI) and Unparticle Physics (UP) at the Kuo-Sheng Nuclear Power Reactor

- Overview (Collaboration; Program; Laboratory)
- Physics Motivations & Detector Requirements
- Probing New Physics – NSI & UP with $\bar{\nu}_e - e^-$
- Analysis & Results [PRD 81, PRD 82 2010]



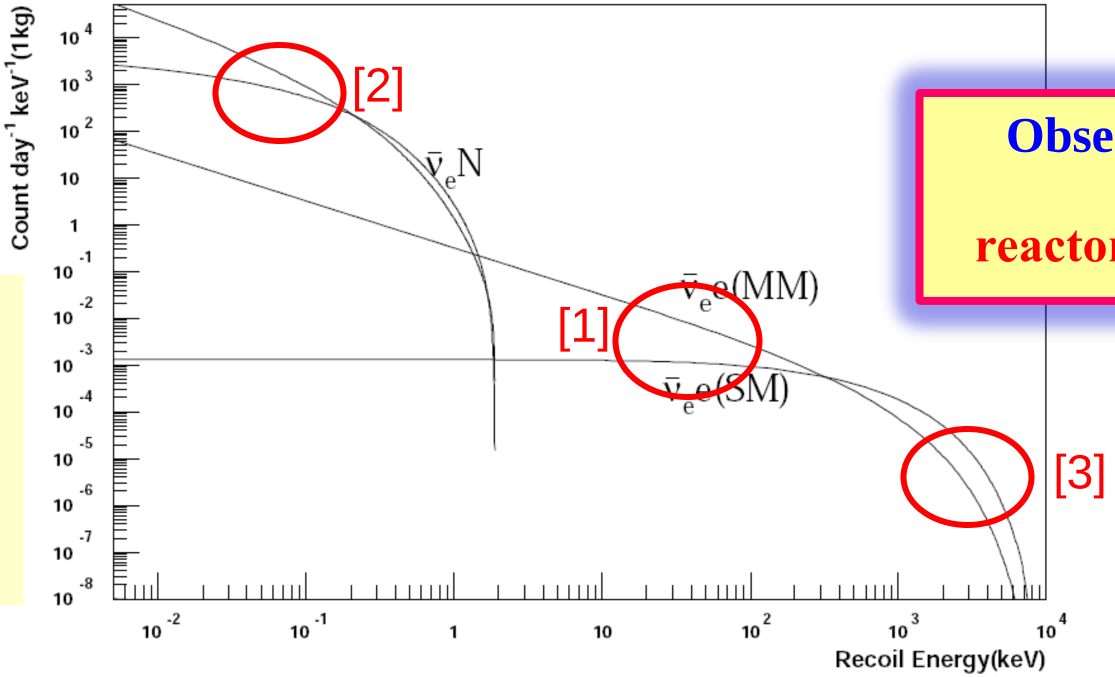
Selçuk Bilmiş

- *on behalf of TEXONO Collaboration*
- *Academia Sinica /TAIWAN*
- *METU/TURKEY*

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**



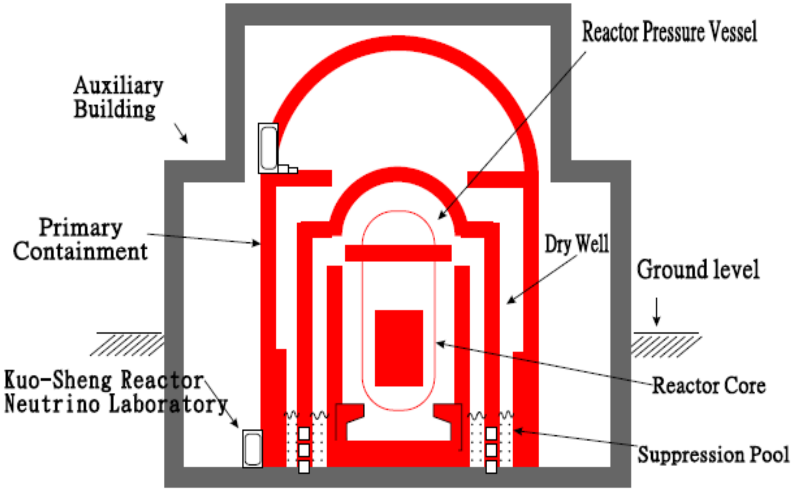
Observable Spectrum with typical reactor neutrino "beam"

T**aiwan **EX**periment **O**n **N**eutrin**O

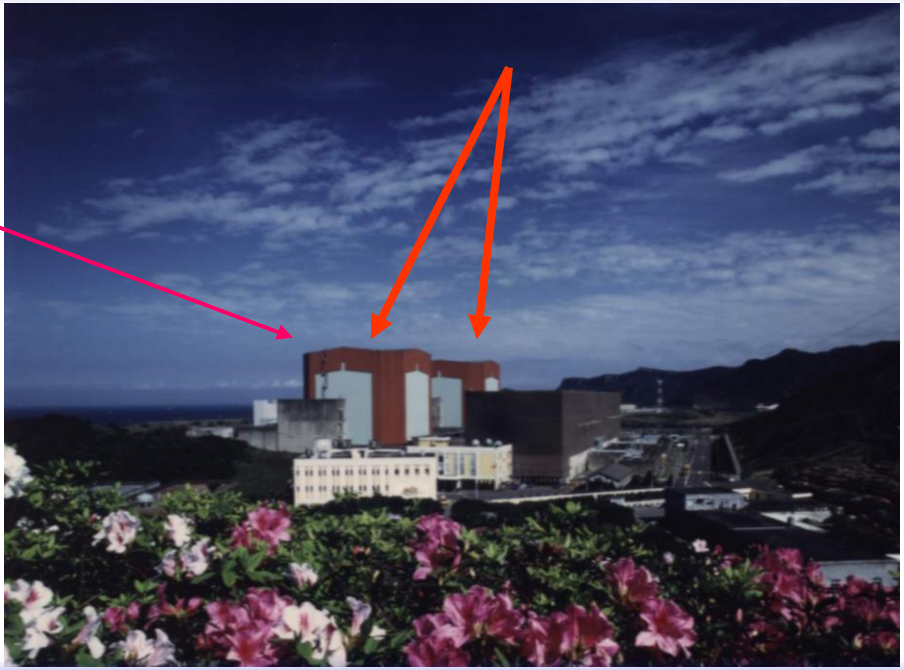
[1] **Magnetic Moment** Search at **~10 keV** → **PRL 2003, PRD 2007**
[2] **$\bar{\nu}_e$ N Coherent Scattering & WIMP** Search at **sub keV** range → **PRD-R 2009**
[3] **Cross-Section and EW Parameters** measurement at **MeV** range → **PRD 2010**
[1,2,3] **NSI & Unparticle Search** → **PRD 2010**

Kou-Sheng Reactor Power Plant

Kuo-Sheng Nuclear Power Station : Reactor Building



KS NPS -II : 2 cores × 2.9 GW



Total flux about $6.4 \times 10^{12}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

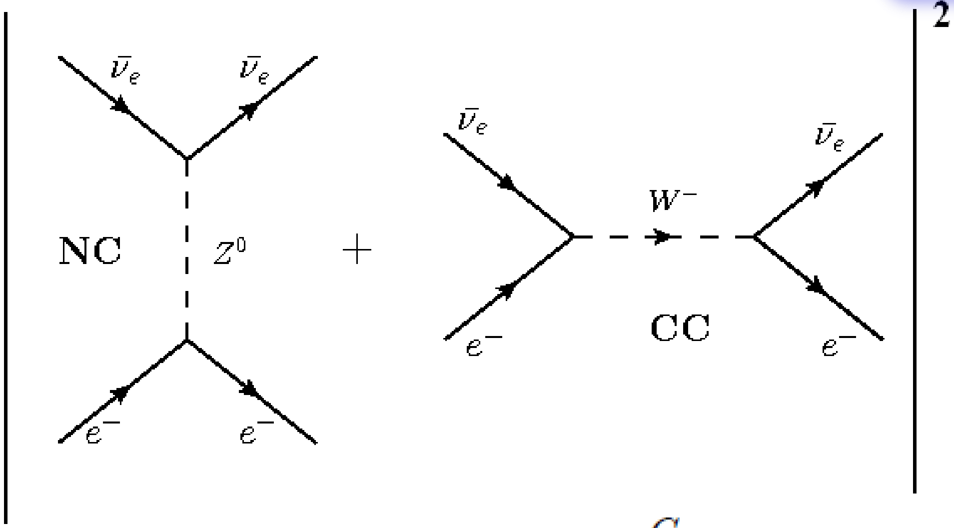
KS ν Lab: 28m from core #1

- 10 m below the surface
- Reactor Cycle : ~50 days OFF every 18 months

$\bar{\nu}_e$ - 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**



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

$$\boxed{\begin{array}{lcl} R_{SM}(\bar{\nu}_e \mathrm{e}) & \rightarrow & (0.77 : 0.92 : -0.69) \\ R_{SM}(\nu_e \mathrm{e}) & \rightarrow & (1.83 : 0.17 : -0.99) \end{array}}$$

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

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

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

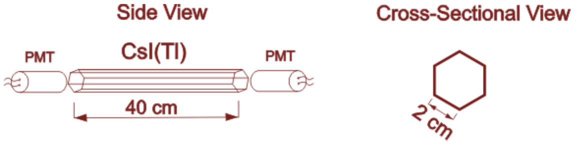
$$\pounds^{CC} = -\frac{G_F}{\sqrt{2}} \left[\bar{e} \gamma^\alpha (1 - \gamma_5) \nu_e\right] \left[\bar{\nu}_e \gamma_\alpha (1 - \gamma_5) e\right]$$

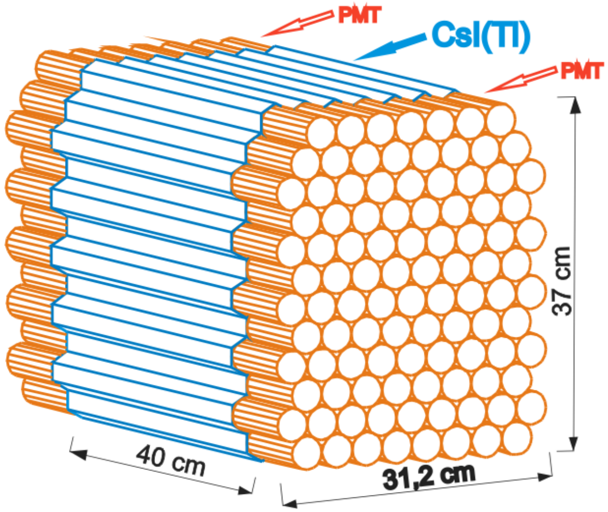
$$\frac{d\sigma_{SM}}{dT}(\bar{\nu}_e e) = \frac{G_F^2 m_e}{2\pi} \left[\begin{array}{c} (g_V - g_A)^2 + (g_V + g_A + 2)^2 \left(1 - \frac{T}{E_\nu}\right)^2 \\ - (g_V - g_A)(g_V + g_A + 2) \frac{m_e T}{E_\nu^2} \end{array} \right]$$

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

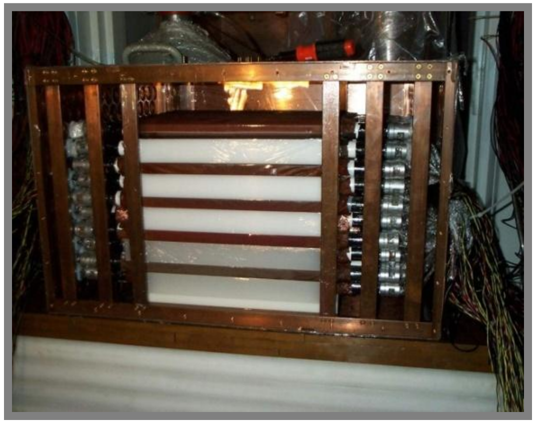
$$g_V = 2 \sin^2 \theta_W - \frac{1}{2}$$

CsI Scintillating Crystal Array

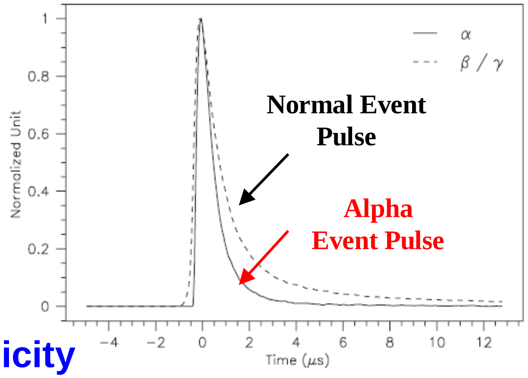




CsI(Tl) Detector
9x12 Array 200 kg



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**

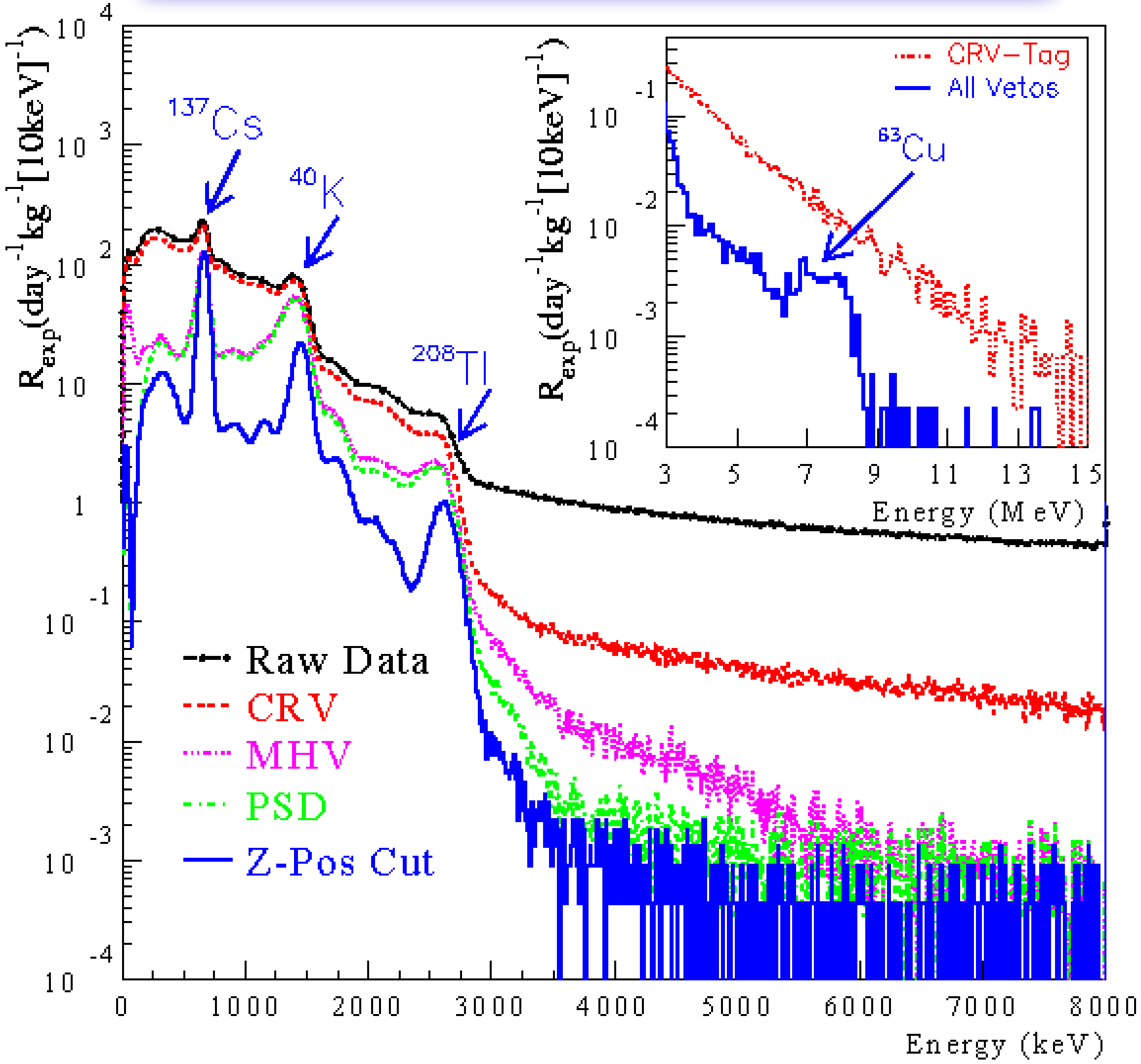
- **Energy : Total Light Collection**
  - **σ (E) ~ 6% @ E>660 keV**
- **Z-position : The variation of Ratio**
  - **σ (Z) ~ 1.3 cm @ E>660 keV**

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

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

Data Analysis: Event Selection

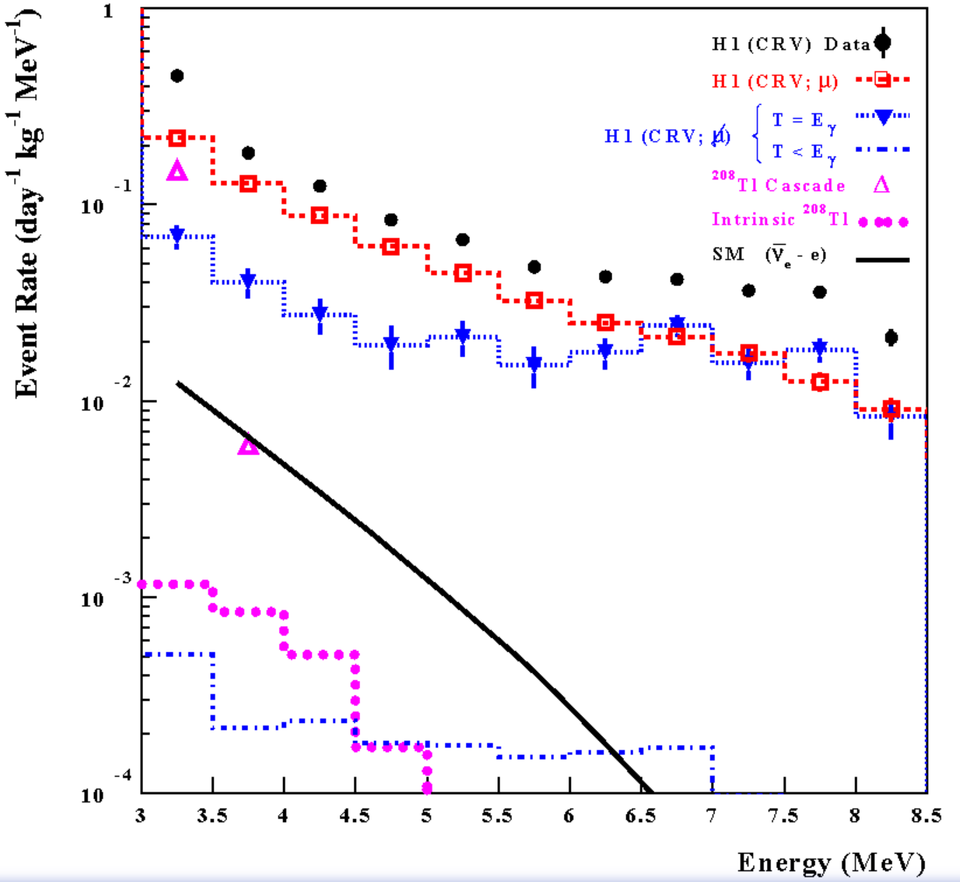
Reactor OFF



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

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

Background Understanding & Suppression



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

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

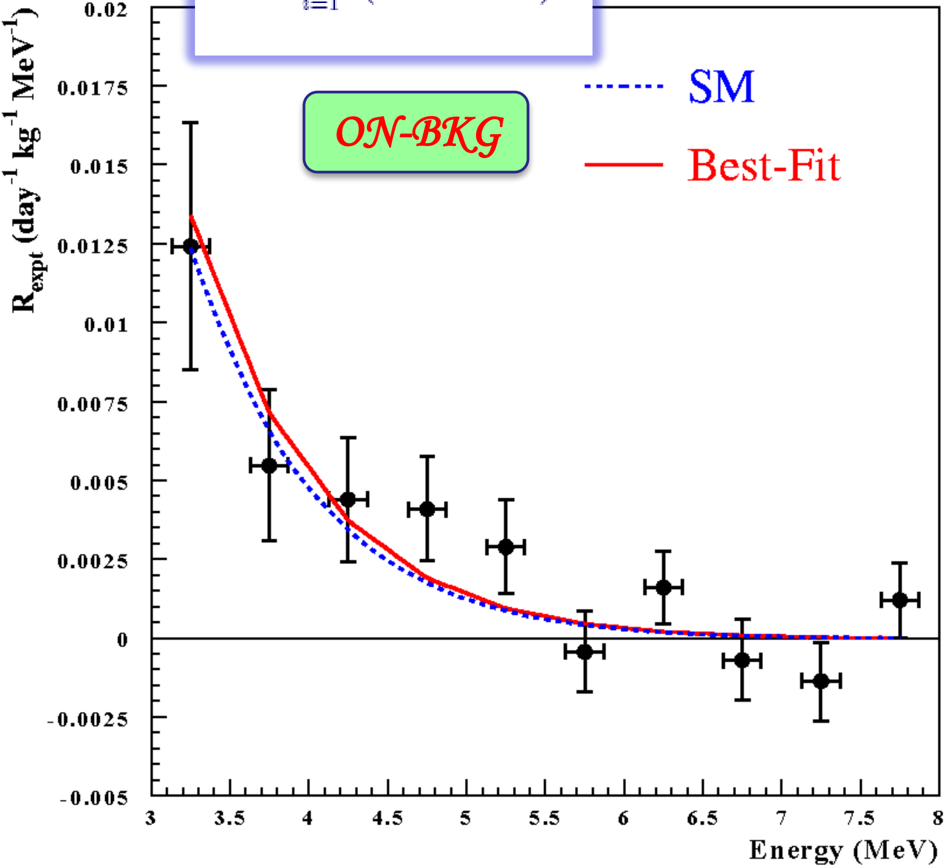
  ⊕ Predicted **BKG(SH)** from **ON(MH)**

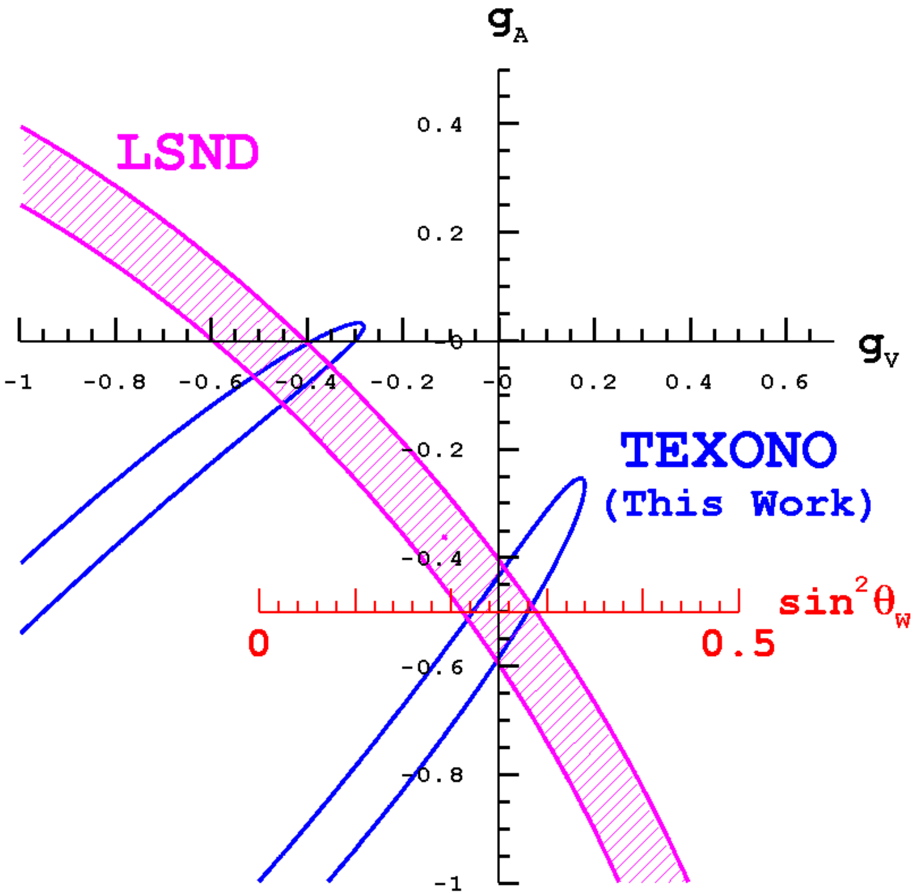
ν = ON(SH) – BKG(SH)

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 σ_{V-A} [1.70 ± 0.44] x σ_{V-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 ± 0.039

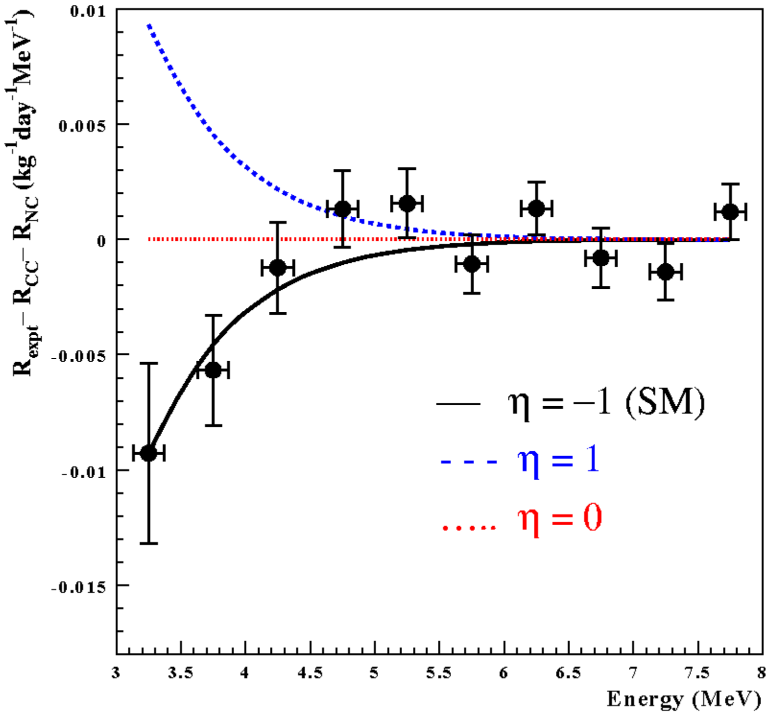
Interference, Neutrino Magnetic Moment and Charge Radius

Interference Term

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

Interference Term

$\eta = -0.92 \pm 0.30(\text{stat}) \pm 0.24(\text{sys})$



Neutrino Magnetic Moment

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

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

$$\mu_{\bar{\nu}} < 2.2\times10^{-10}\times\mu_B$$

Ge , 12keV threshold →

$$\mu_{\bar{\nu}} < 0.74\times10^{-10}\times\mu_B$$

at 90% C. L.

Neutrino Charge Radius

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

→

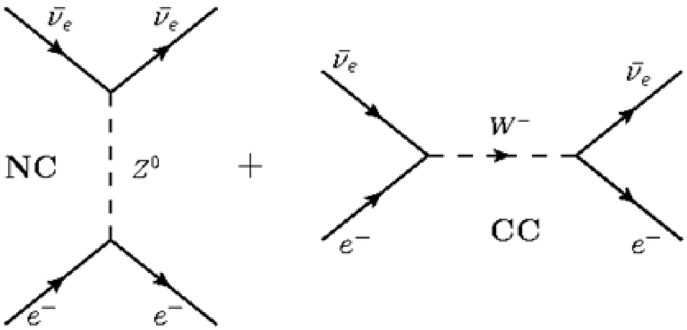
$$-2.1\times10^{-32} < \left\langle r^2_{\bar{\nu}_e}\right\rangle < 3.3\times10^{-32}\ cm^2$$

Non Standard Interactions (NSI)

Predicted by beyond the Standard model Physics, especially neutrino mass theories predict neutral current non-standard interactions:

- *From The Exchange of Heavy Gauge Boson Z` (de Gouvea & Jenkins (2006))*
- *Seesaw – type models (Schecter & Valle (1980))*
- *In SUSY Models with Broken R-parity (Hirsch & Valle (2004))*
- *In unified SUSY Models as a renormalization effect (Hall, Kostelecky & Raby (1986)*
- *In models where neutrino masses are calculable from radiative corrections due to the presence of extra Higgs boson. (Zee (1980), Babu (1988))*
- *etc…*

$\bar{\nu}_e$ - e^- Scattering in SM



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

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

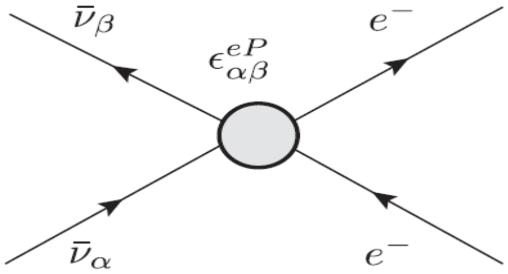
Differential cross section for the $\overline{\nu_e}\, e \rightarrow \overline{\nu_e}\, e$

$$\frac{d\sigma}{dT} = \frac{2G_F^2 M_e}{\pi}\left[g_R^2 + g_L^2\left(1 - \frac{T}{E_\nu}\right)^2 - g_L g_R \frac{m_e T}{E_\nu^2}\right]$$

$$g_L = \frac{1}{2} + \sin^2\theta_W$$

$$g_R = \sin^2\theta_W$$

$\bar{\nu}_e$ - e^- Scattering in NSI



- *Model independent way of introducing NSI is via the effective four fermion Lagrangian;*

$$\mathcal{L}^{NSI}_{eff} = -\sum_{\alpha\beta fP} \varepsilon^{fP}_{\alpha\beta} 2\sqrt{2} G_F (\bar{\nu}_\alpha \gamma_\rho L \nu_\beta)(\bar{f}\gamma^\rho P f)$$

$\alpha, \beta = e, \mu, \tau;\quad f = e;\ P = L, R;\quad L = (1-\gamma_5)/2;\quad R = (1+\gamma_5)/2$

Differential cross section for the $\overline{\nu_e}\, e \rightarrow \overline{\nu_\alpha} e$

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

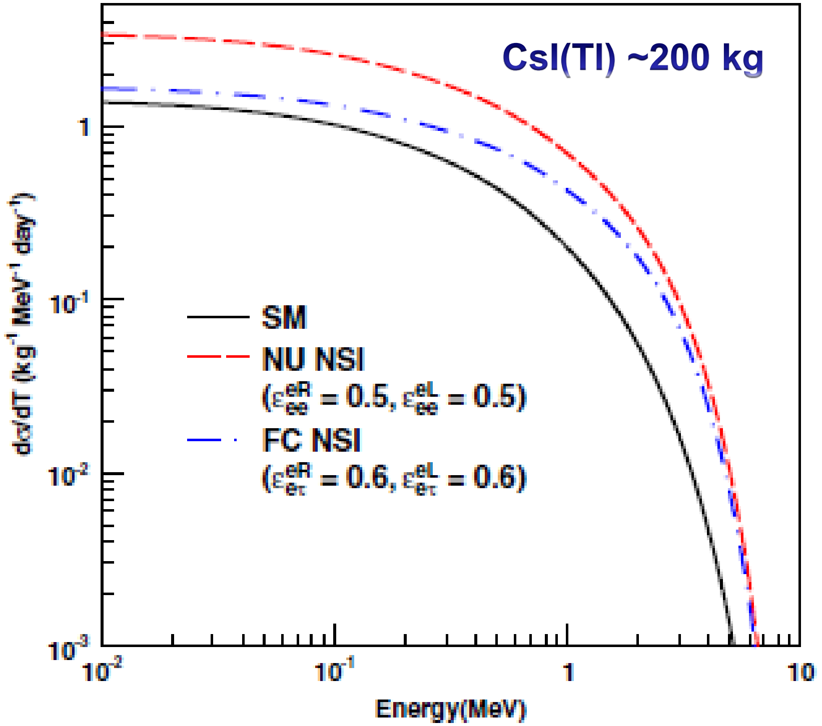
$$\tilde{g}_L = g_L + \epsilon^{eL}_{ee} \qquad \tilde{g}_R = g_R + \epsilon^{eR}_{ee}$$

(NU) NSI: ϵ^{eLR}_{ee}

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

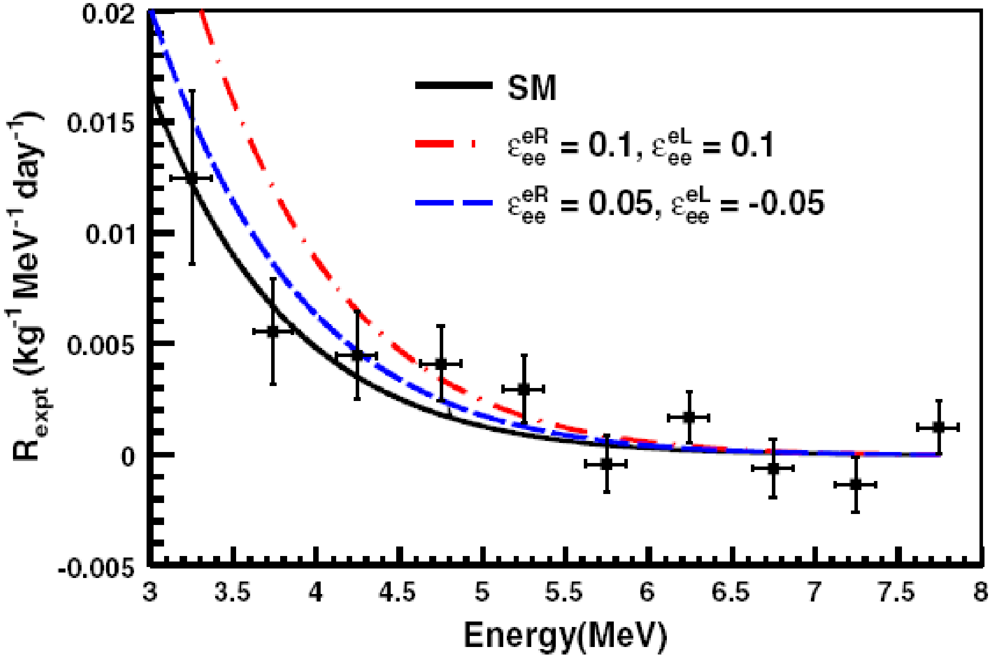
NSI of Neutrino

*The measurable recoil spectra with typical neutrino "flux" at typical values of NSI parameters for both **NU and FC NSI***



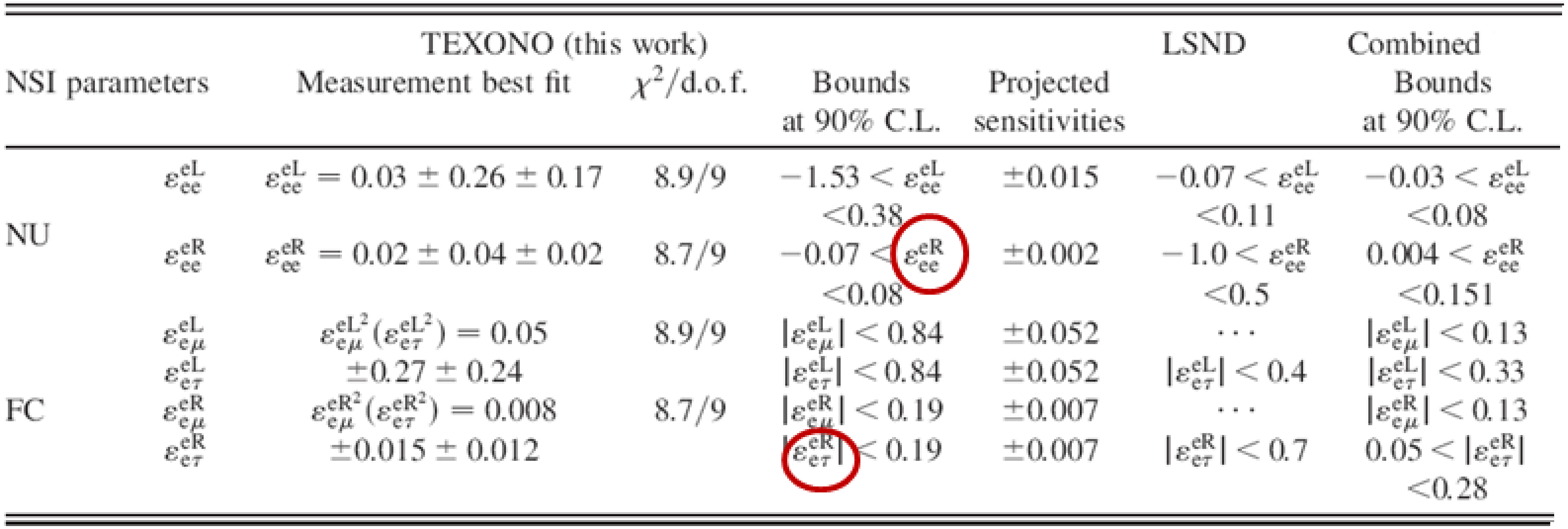
$$R_{\mathcal{NP}+\mathcal{SM}} = t\,\rho_e \int_T \int_{E_\nu} \left(\frac{d\sigma}{dT}\right)_{\mathcal{NP}+\mathcal{SM}} \frac{d\phi_{(\bar{\nu}_e)}}{dE_\nu}\, dE_\nu\, dT$$

$$\chi^2 = \sum_{i=1} \left[\frac{R_{\rm expt}(i) - [R_{\rm SM}(i) + R_X(i)]}{\Delta_{\rm stat}(i)}\right]^2,$$

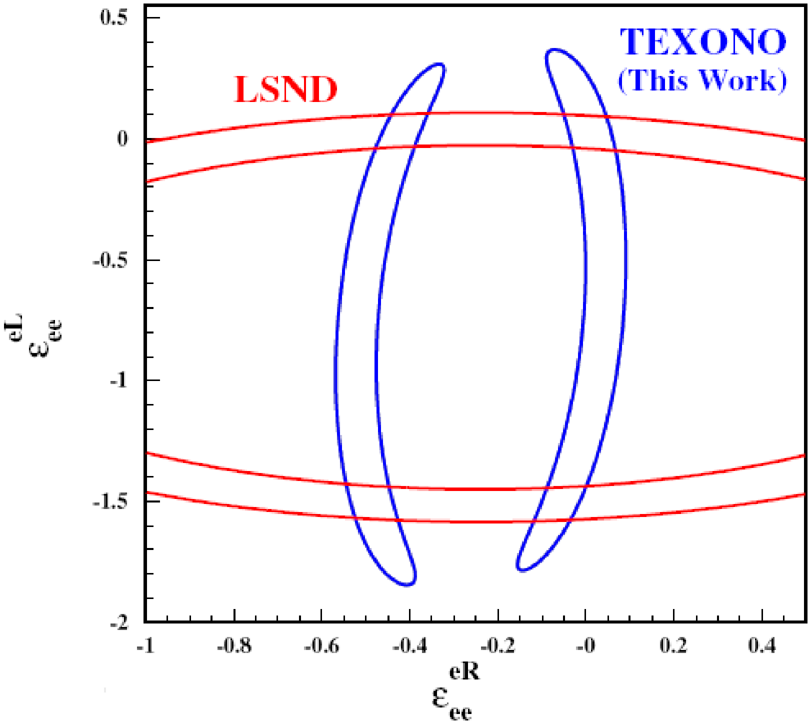


— The NSI parameters are constrained by the accuracy of the SM cross-section measurements

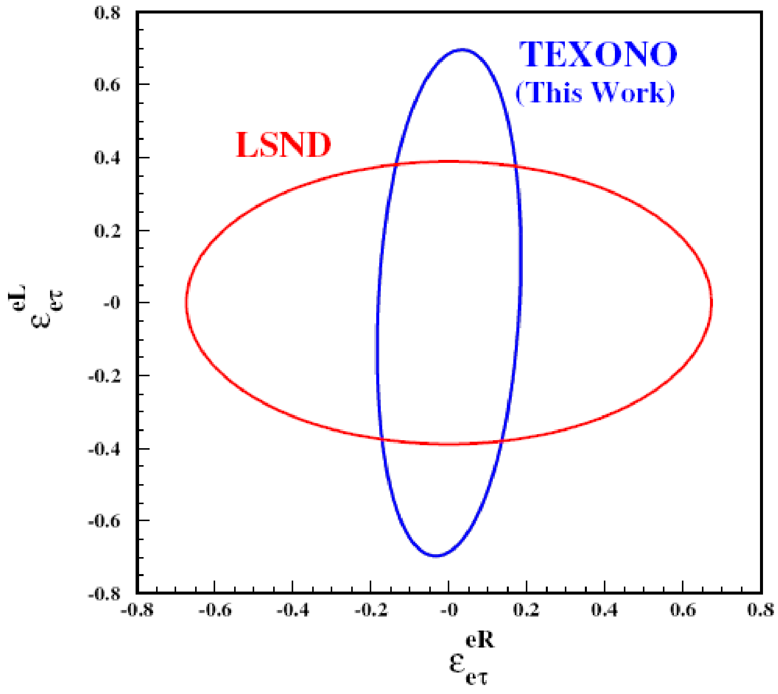
Comparison of Bounds of NSI Parameters



NSI parameters		TEXONO (this work) Measurement best fit	χ^2/d.o.f.	Bounds at 90% C.L.	Projected sensitivities	LSND	Combined Bounds at 90% C.L.
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	$-0.07 < \varepsilon_{ee}^{eL} < 0.11$	$-0.03 < \varepsilon_{ee}^{eL} < 0.08$
	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	$-1.0 < \varepsilon_{ee}^{eR} < 0.5$	$0.004 < \varepsilon_{ee}^{eR} < 0.151$
FC	$\varepsilon_{e\mu}^{eL}$	$\varepsilon_{e\mu}^{eL^2} (\varepsilon_{e\tau}^{eL^2}) = 0.05$	8.9/9	$\lvert\varepsilon_{e\mu}^{eL}\rvert < 0.84$	± 0.052	$\cdots$	$\lvert\varepsilon_{e\mu}^{eL}\rvert < 0.13$
	$\varepsilon_{e\tau}^{eL}$	$\pm 0.27 \pm 0.24$		$\lvert\varepsilon_{e\tau}^{eL}\rvert < 0.84$	± 0.052	$\lvert\varepsilon_{e\tau}^{eL}\rvert < 0.4$	$\lvert\varepsilon_{e\tau}^{eL}\rvert < 0.33$
	$\varepsilon_{e\mu}^{eR}$	$\varepsilon_{e\mu}^{eR^2} (\varepsilon_{e\tau}^{eR^2}) = 0.008$	8.7/9	$\lvert\varepsilon_{e\mu}^{eR}\rvert < 0.19$	± 0.007	$\cdots$	$\lvert\varepsilon_{e\mu}^{eR}\rvert < 0.13$
	$\varepsilon_{e\tau}^{eR}$	$\pm 0.015 \pm 0.012$		$\lvert\varepsilon_{e\tau}^{eR}\rvert < 0.19$	± 0.007	$\lvert\varepsilon_{e\tau}^{eR}\rvert < 0.7$	$0.05 < \lvert\varepsilon_{e\tau}^{eR}\rvert < 0.28$

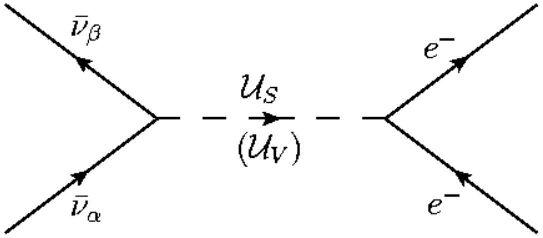


90% C. L.



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**.



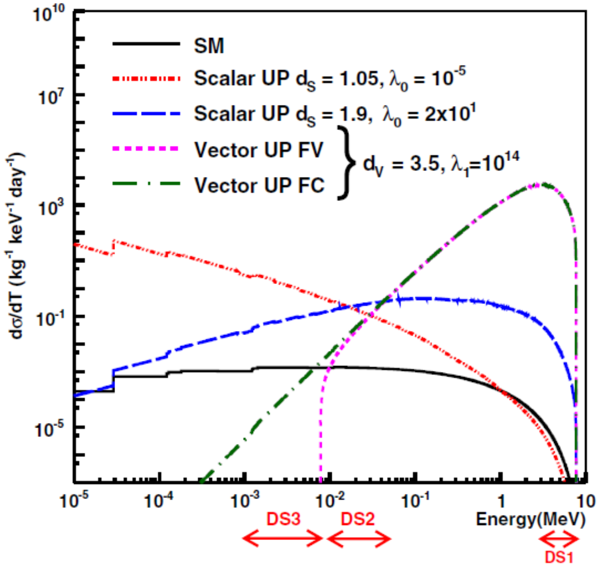
1. Exchange of Scalar Unparticles

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

2. Exchange of Vector Unparticles

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

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



i= 0(1) : Unparticle scalar/vector field

λ_0 (λ_1) : Scalar(Vector) unparticle couplings

f : e, u, d

α, β: denotes neutrino flavours

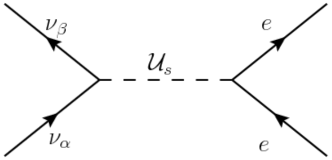
d: Unparticle mass dimension

Λ : Unparticle energy scale

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

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

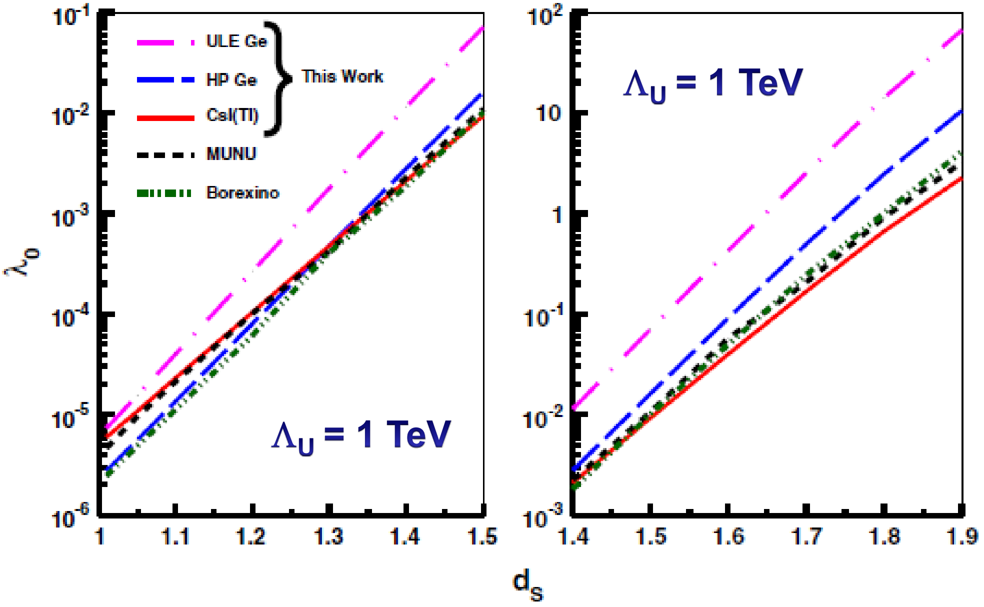
Scalar Unparticle

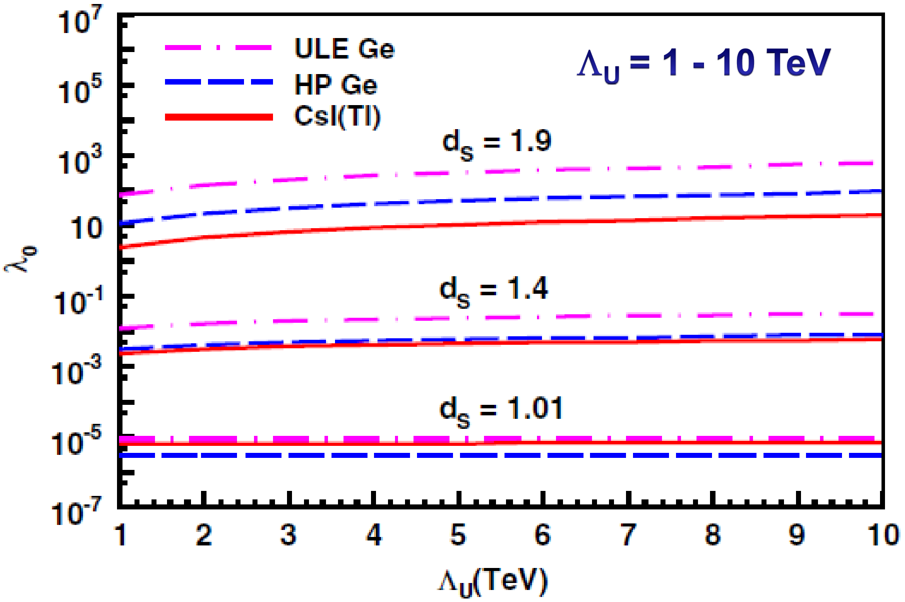


1 < d < 2

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

*For the Scalar Unparticle Case for $d < 1.3$ number of event rate increases for lower thresholds, therefore **HPGe and ULEGe** data expected to give more sensitive results. However, for $d > 1.3$ **CsI (Tl)** data is more sensitive to scalar unparticle.*





- *Since the cross sections vary as $\lambda_0{}^4$ the potential of placing more strict constants due to experimental sensitivities is only modest.*

Vector Unparticle

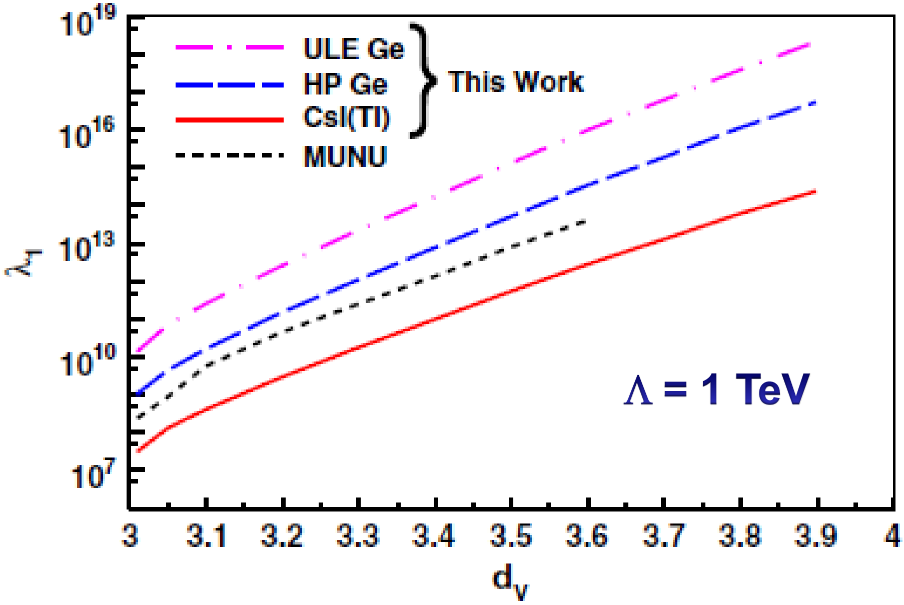
$$\frac{d\sigma_{\mathcal{U}_V}}{dT} = \frac{1}{\pi}\frac{[g_{1e}^{\alpha\beta}(d)]^2}{\Lambda^{(4d-4)}}2^{(2d-5)}(m_e)^{(2d-3)}(T)^{(2d-4)}\left[1+\left(1-\frac{T}{E_\nu}\right)^2-\frac{m_eT}{E_\nu^2}\right]$$

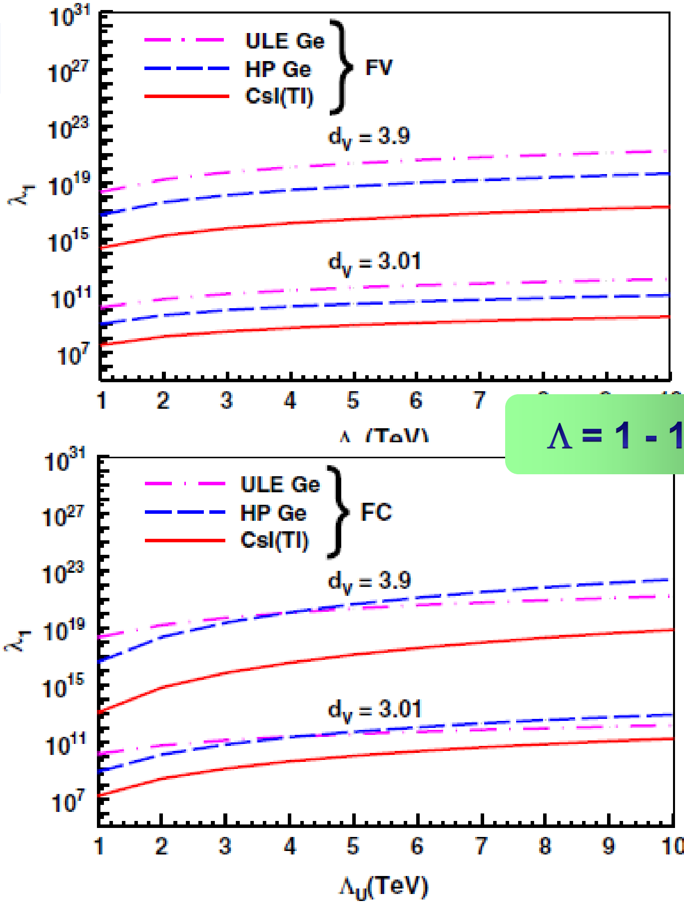
$$\frac{d\sigma_{\mathcal{U}_V-SM}}{dT} = \frac{\sqrt{2}G_F}{\pi}\frac{g_{1e}(d)}{\Lambda^{(2d-2)}}(2m_eT)^{(d-2)}m_e\left\{g_L+g_R\left(1-\frac{T}{E_\nu}\right)^2-\frac{(g_L+g_R)}{2}\frac{m_eT}{E_\nu^2}\right\}$$

d > 3

B. Grinstein, K. A. Intriligator, and I. Z. Rothstein, Phys. Lett. B 662, 367 (2008)

– *both FC and FV scenario are considered and analysed*





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

Backup Slides

Background Prediction via PAIR PRODUCTION

Residual Background Understanding & Suppression

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

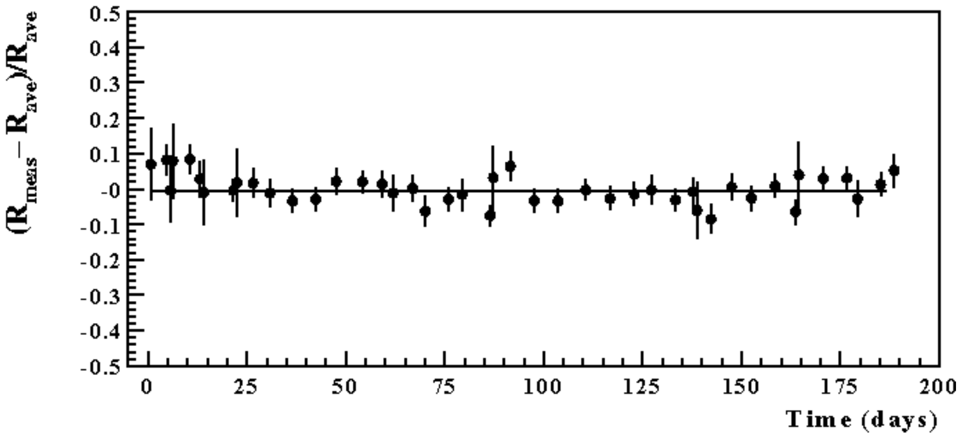
Idea -- Use Multiple Crystal Hit (**MH**) spectra to **predict** Single Crystal Hit (**SH**) Background to the neutrino events

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

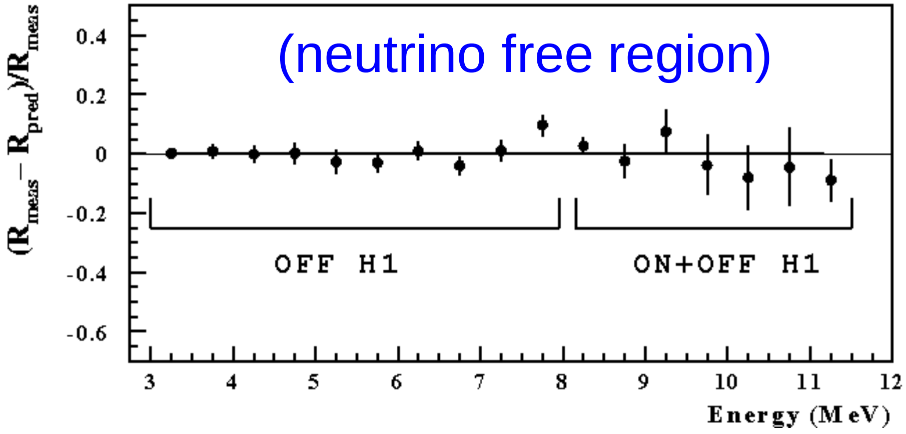
$$\frac{SH[BKG(2614+583)]}{MH[2614;583(data)]} = \frac{SH[2614+583(MC)]}{MH[2614;583(MC)]}$$

Systematic Uncertainties
Approach – Use non-ν events for demonstration

^{208}Tl Peak Events Stability



BKG – Pred.



ON-OFF Stability < ~0.5%

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

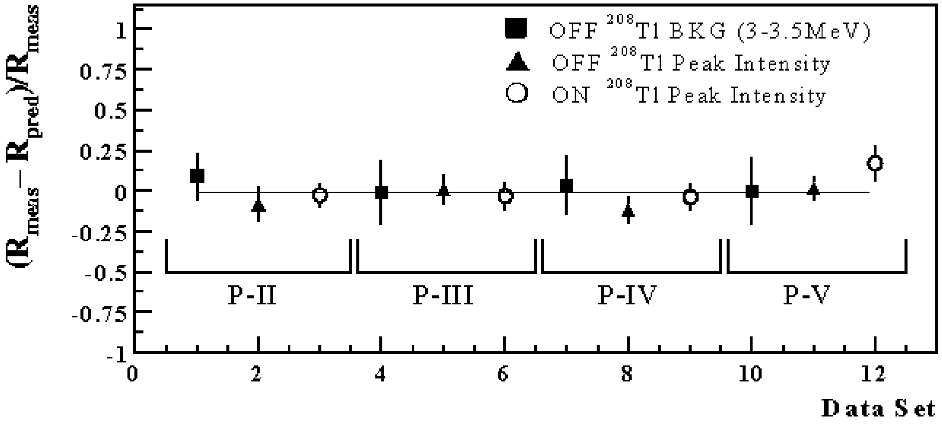
Cosmic Induced BKG(SH) Prediction < ~1 %

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

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

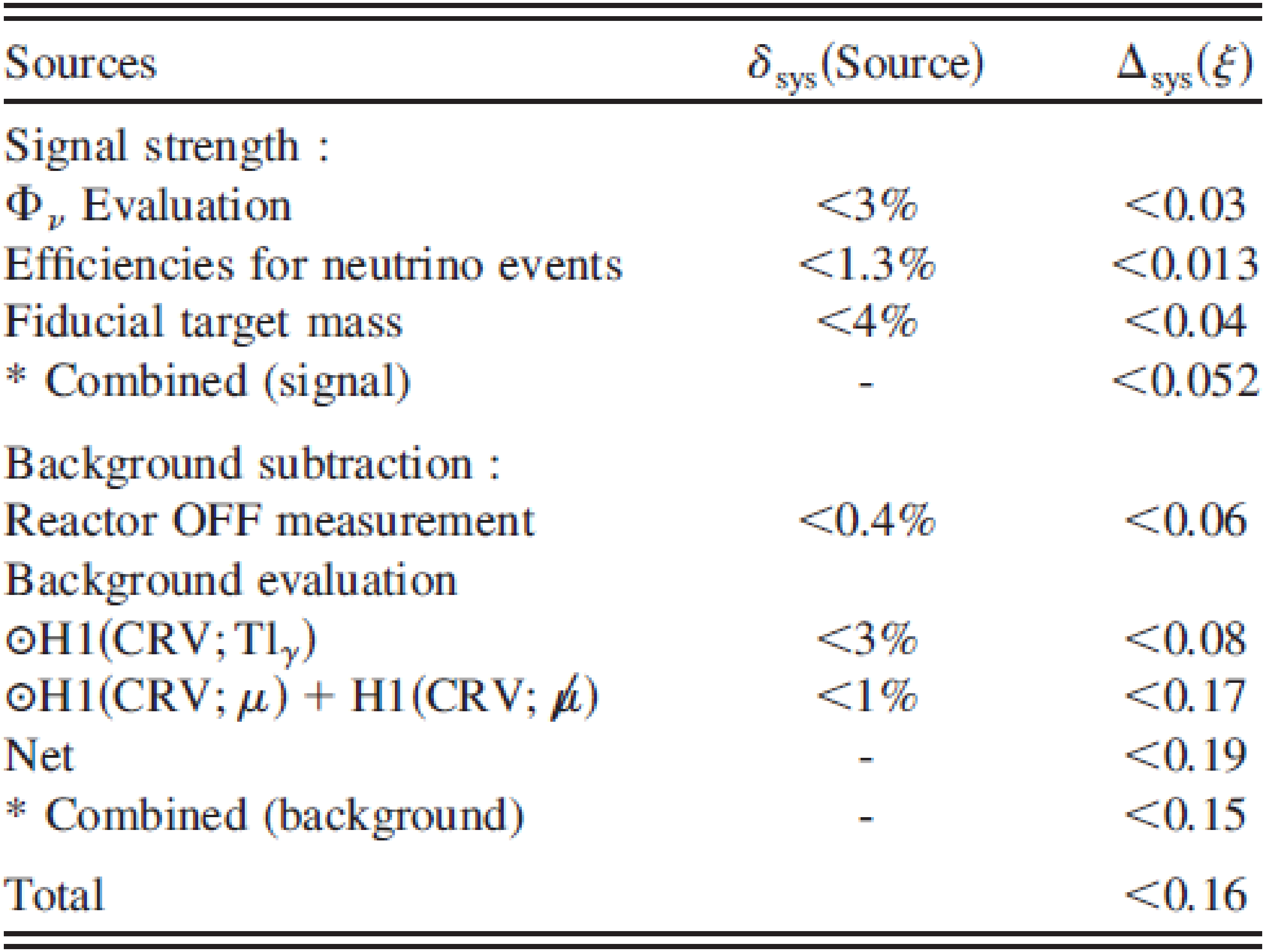
- Successfully **Predict Tl-208 Induced BKG(SH) >3MeV** at Reactor **OFF** periods
- Successfully **Predict Tl-208** peak intensity for both Reactor **ON/OFF** with the same tools **(MC)**

^{208}Tl (SH) Prediction



Systematic Uncertainties

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



Sources	$\delta_{\text{sys}}(\text{Source})$	$\Delta_{\text{sys}}(\xi)$
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