Constraining New Physics with neutrino-electron Scattering

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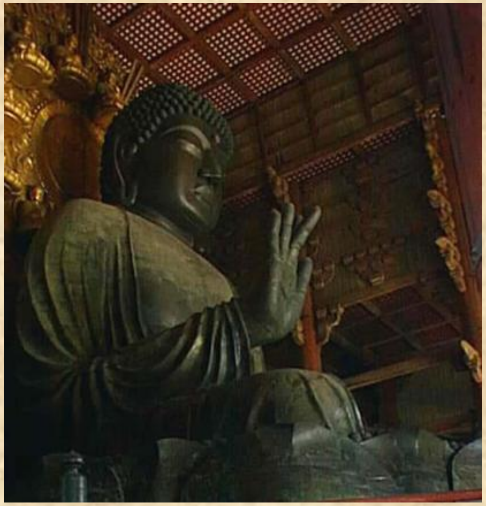
On behalf of TEXONO Collaboration



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OUTLINE

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- Theory overview $\overline{\nu_e} - e^-$ Scattering – Motivation
- TEXONO Experiment – CsI(Tl) Array and HP-Ge Detectors
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  - ✓ Summary on Data Analysis & Results & World Status
- New Physics Constraints
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  - ✓ UP Physics
  - ✓ NC Physics
- Summary

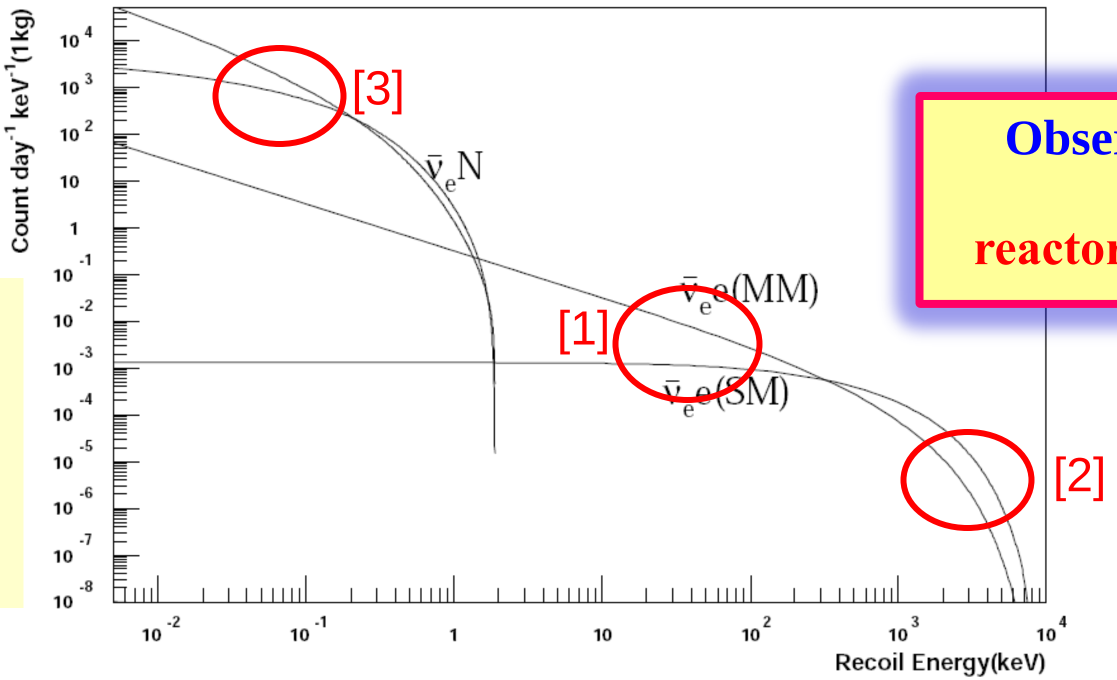
TEXONO Physics Program

TEXONO Collaboration: Taiwan (AS, INER, KSNPS, NTHU); China (IHEP, CIAE, THU, NKU, SCU); Turkey (METU, DEU); 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** with **Ge → PRL 2003, PRD 2005, PRD 2007**

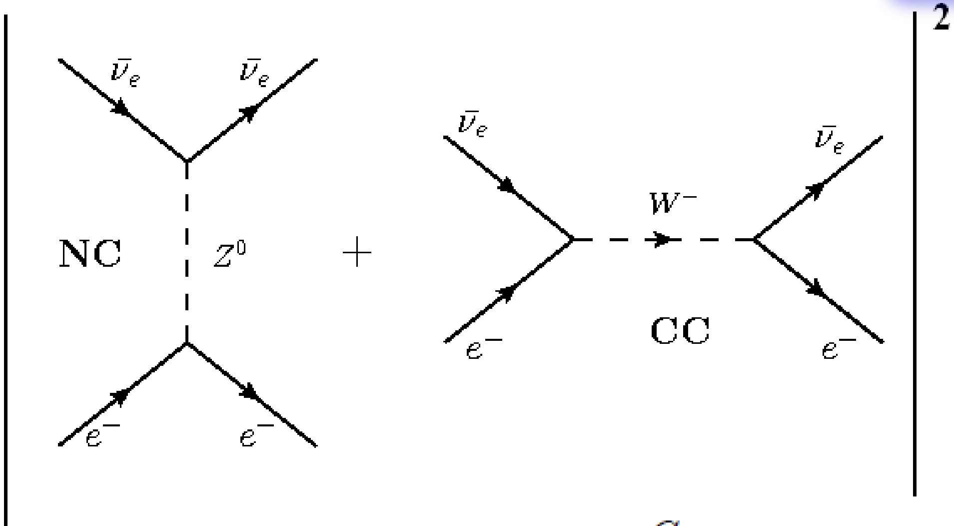
[2] **Cross-Section and EW Parameters** measurement at **MeV** with **CsI(Tl) → PRD 2010**

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

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



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

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

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

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

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

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

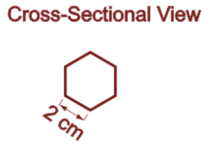
$$\frac{d\sigma_{SM}}{dT}(\bar{\nu}_e e) = \frac{G_F^2 m_e}{2\pi} \left[(g_V - g_A)^2 + (g_V + g_A + 2)^2 \left(1 - \frac{T}{E_\nu}\right)^2 - (g_V - g_A)(g_V + g_A + 2) \frac{m_e T}{E_\nu^2} \right]$$

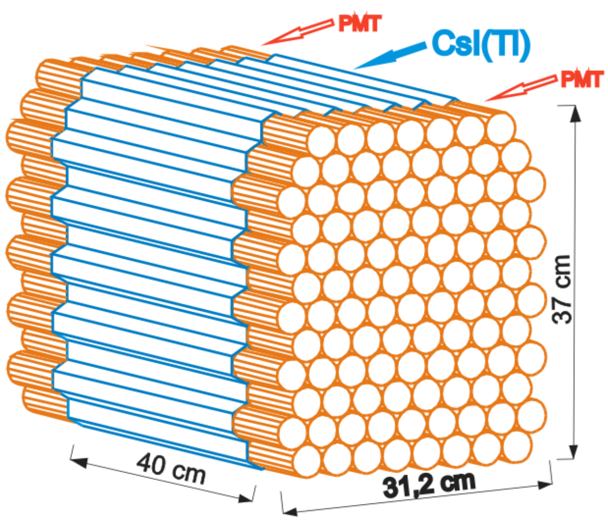
$$g_A = -\frac{1}{2}$$

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

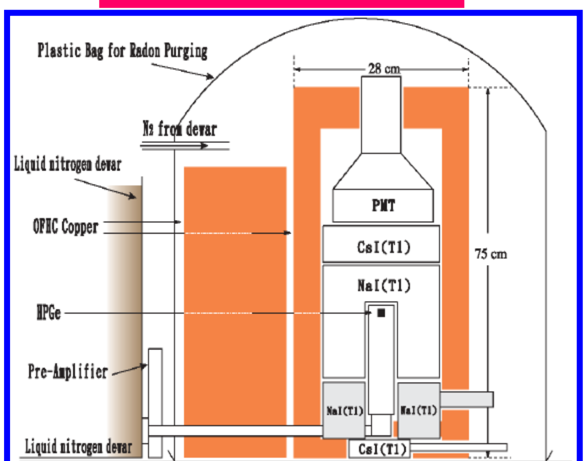
HP-Ge and CsI Scintillating Crystal Array

CsI(Tl) Detector:
9x12 Array ~ 200 kg



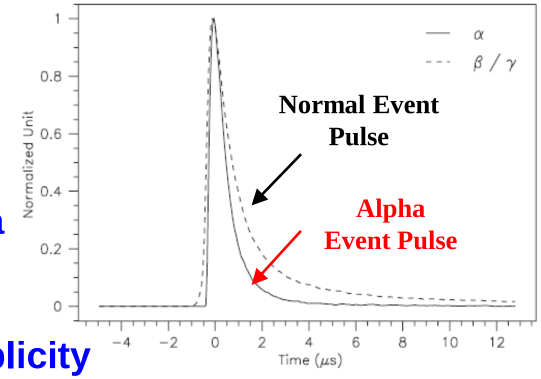


HP-Ge Detector: 1kg



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**



❑ **Analysis Threshold:**

- ➢ **HP-Ge: ~10 keV**
- ➢ **CsI(Tl) : 3 MeV** (less ambient **background** & **reactor $\bar{\nu}_e$** spectra well known)

❑ Data Volume: **HP-Ge: 571 / 128 kg-day ON/OFF**

CsI(Tl): ~ 29883 / 7369 kg-day ON/OFF

- **Energy : Total Light Collection**
  - **σ (E) ~ 10% FWHM @ E>660 keV**

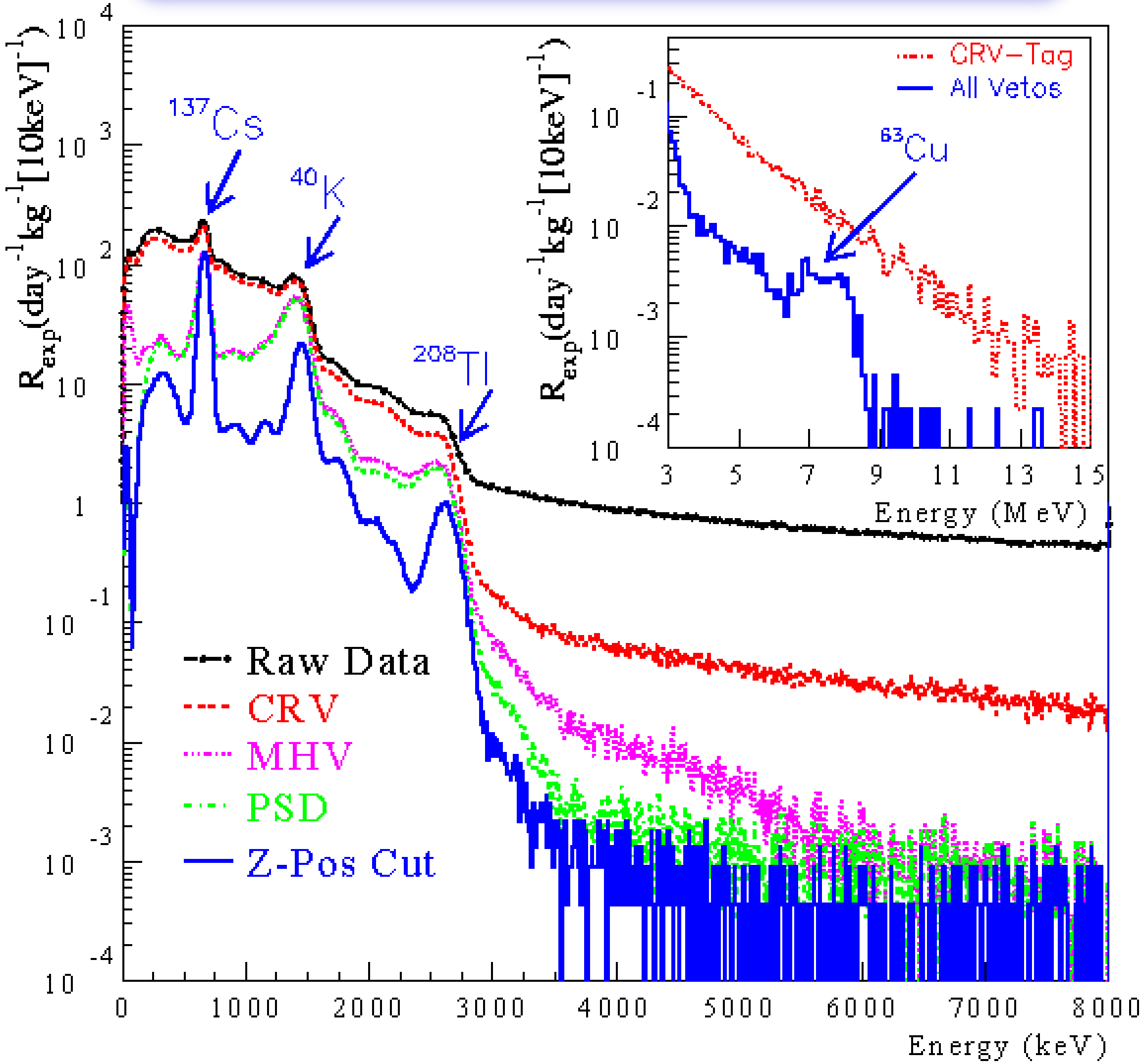
$$E \approx \sqrt{Q_L \times Q_R}$$

- **Z-position : The variation of Ratio**
  - **σ (Z) ~ 1.3 cm @ E>660 keV**

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

Data Analysis: Event Selection

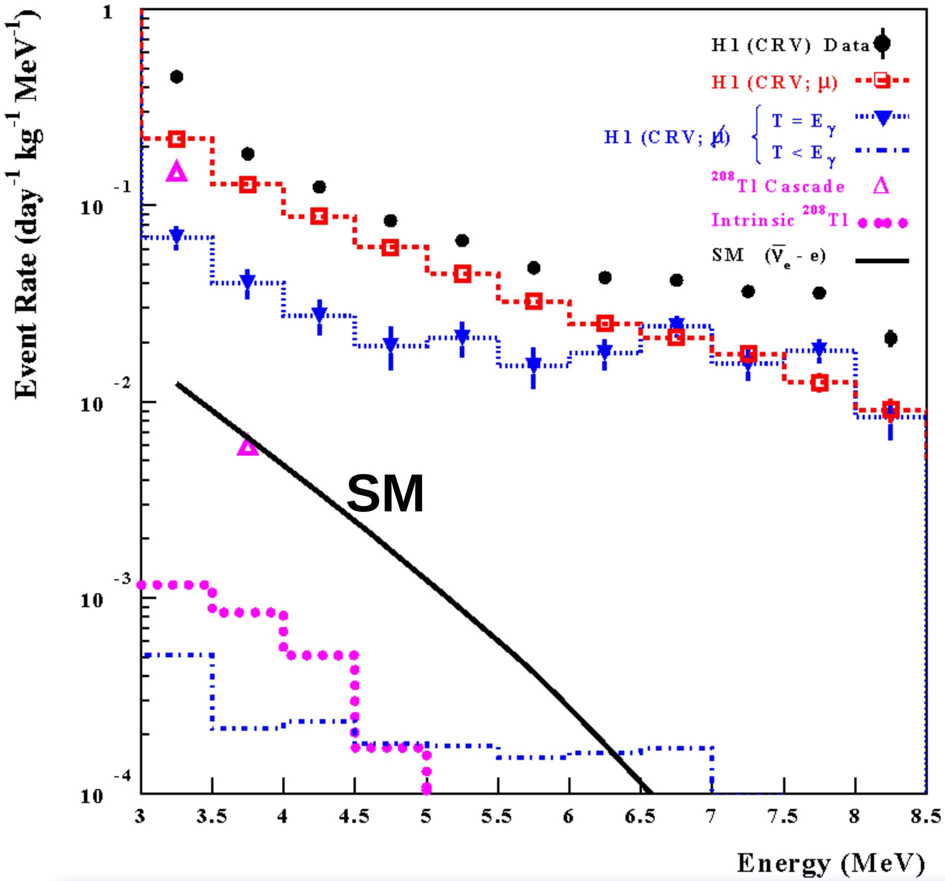
Reactor OFF



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 & Suppression



Main Background:

- ❑ **untagged cosmic-ray** ⇨ **CRV ineff.**
- ▼ **ambient γ** ⇨ **3-hit pair-production**
- ▲ **convoluted cascade ^{208}Tl** ⇨ **multi-hit**

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

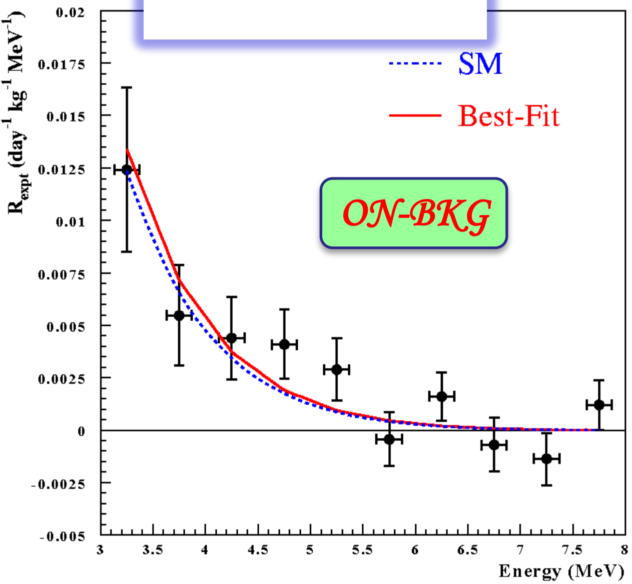
- Direct **Reactor OFF(SH)** spectra ⊕ Predicted **BKG(SH)** from **OFF(MH)**
  ⊕ Predicted **BKG(SH)** from **ON(MH)**

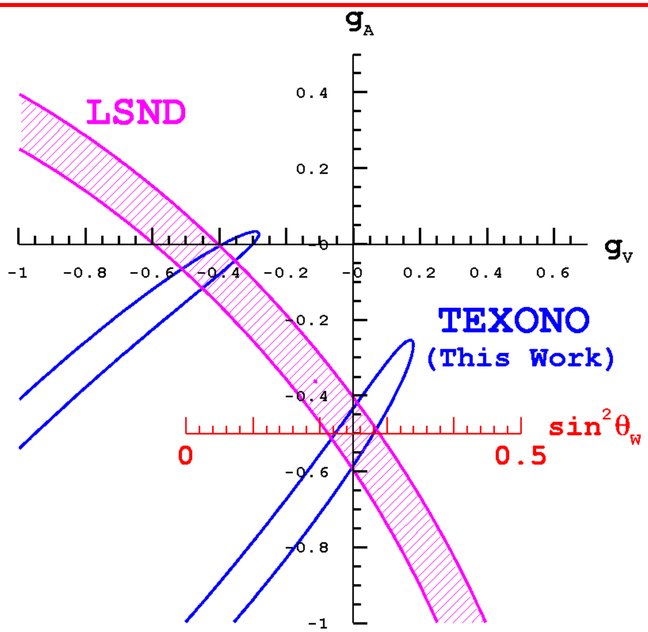
ν = ON(SH) – BKG(SH)

Cross Section & Weak Mixing Angle

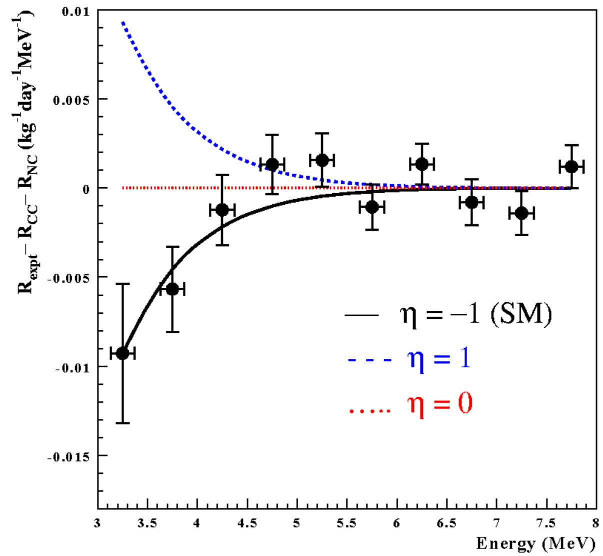
Phys. Rev. D 81, 072001 (2010)

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





Interference Term



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

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

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

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

Better sensitivity was 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
$\nu_e - e^-$	**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
$\bar{\nu}_e - e^-$	**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
$\bar{\nu}_e - e^-$	**Krasnoyarsk** (Fluorocarbon)	3.15 – 5.18	N/A	[4.5 ± 2.4] x 10^{-46} cm^2/fission	0.22 ± 0.75
$\bar{\nu}_e - e^-$	**Rovno** [Si(Li)]	0.6 – 2.0	41	[1.26 ± 0.62] x 10^{-44} cm^2/fission	N/A
$\bar{\nu}_e - e^-$	**MUNU** [CF_4(gas)]	0.7 – 2.0	68	1.07 ± 0.34 events day^{-1}	N/A
$\bar{\nu}_e - e^-$	**TEXONO** [CsI(Tl) Scin.]	3 - 8	~ 410	[1.08 ± 0.21 ± 0.16] x R_{SM}	0.251 ± 0.031(stat) ± 0.024(sys)

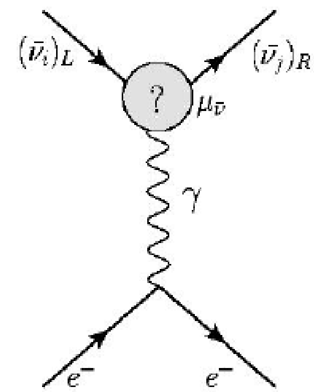
Neutrino Electromagnetic Properties: Magnetic Moment and Charge Radius

Neutrino Magnetic Moment

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

Ge Detector : 1-kg HP-Ge → $\mu_{\bar{\nu}}<7.1\times10^{-11}\times\mu_B$ **@ 90% CL**

CsI(Tl) 9x12 Array Detector : 187 kg → $\mu_{\bar{\nu}}<2.2\times10^{-10}\times\mu_B$



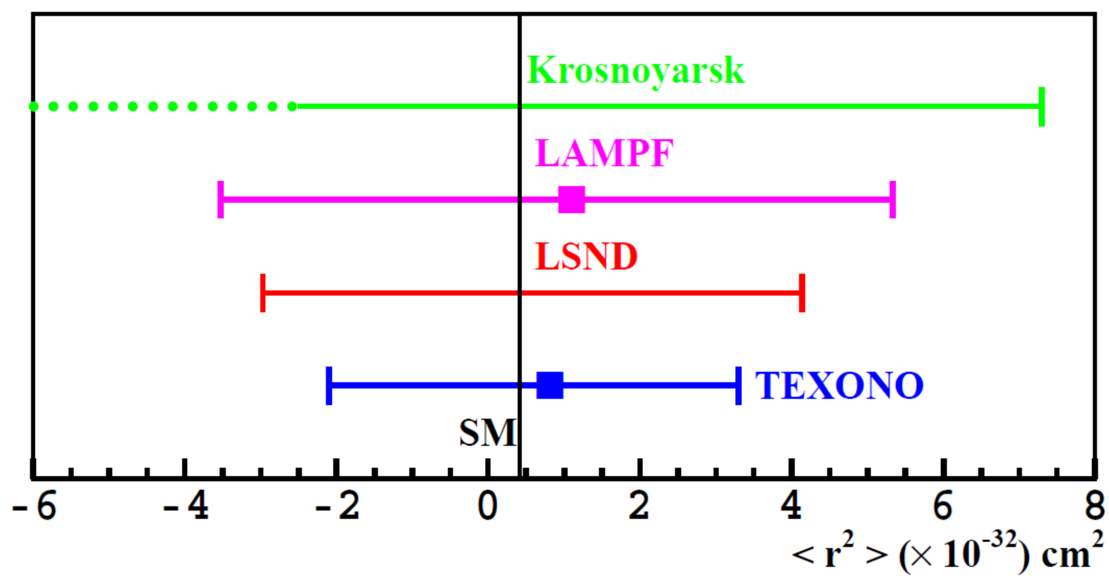
Neutrino Charge Radius

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

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

at 90% C. L.

PDG 2012 @ 90% CL



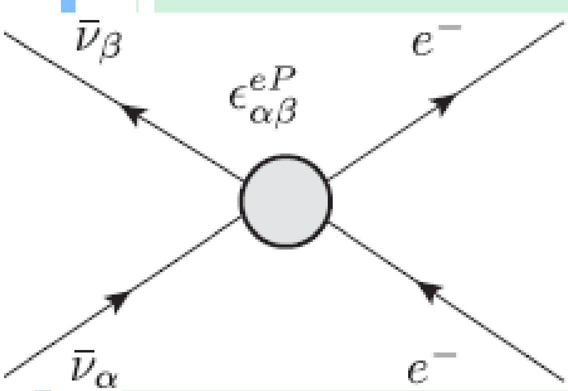
Constraining New Physics with neutrino-electron Scattering

[PRD 82, 033004 (2010)]

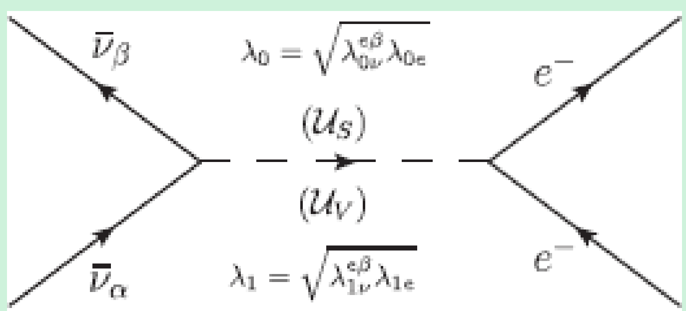
[PRD 85, 073011 (2012)]

The measurements of neutrino elastic scatterings provide a sensitive tool to probe NSI, UP as well as NC Physics since it is pure leptonic process.

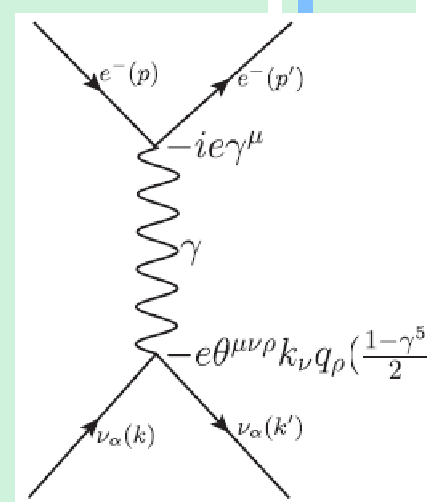
$$\left[\frac{d\sigma}{dT}\right]_{SM} + \left[\frac{d\sigma}{dT}\right]_{NP}$$



NSI

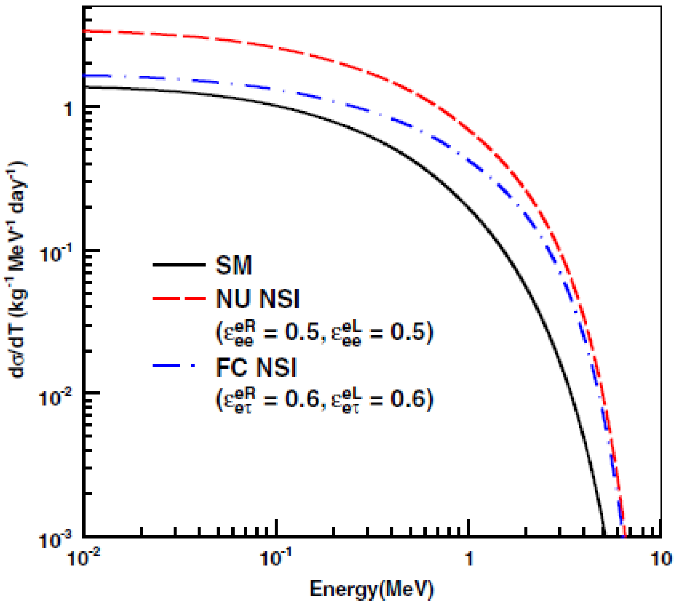


UP



NC

NSI of Neutrino



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

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

– *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_{ee}^{eLR}

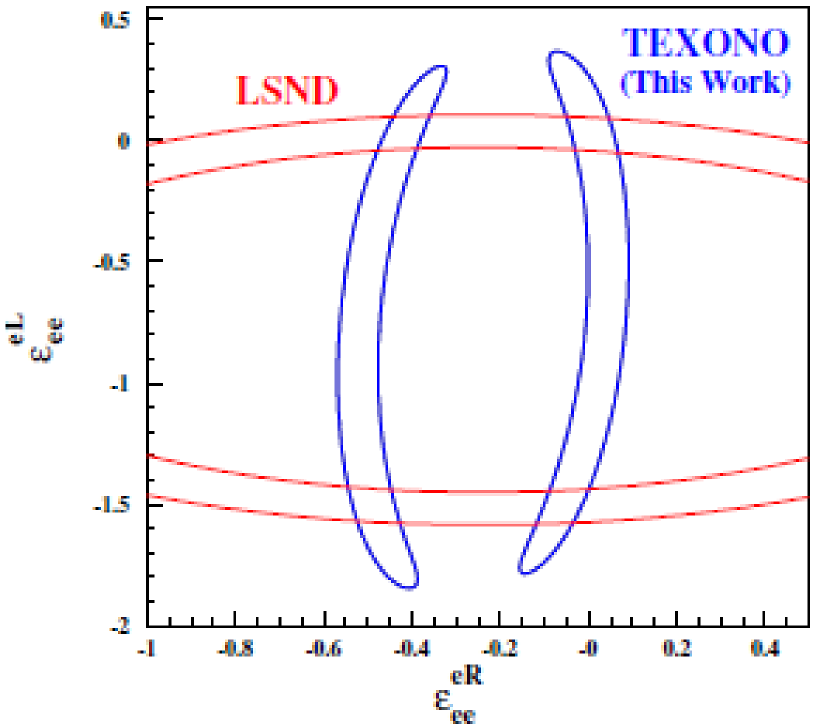
(FC) NSI: $\epsilon_{e\mu}^{eLR}$ $\epsilon_{e\tau}^{eLR}$

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

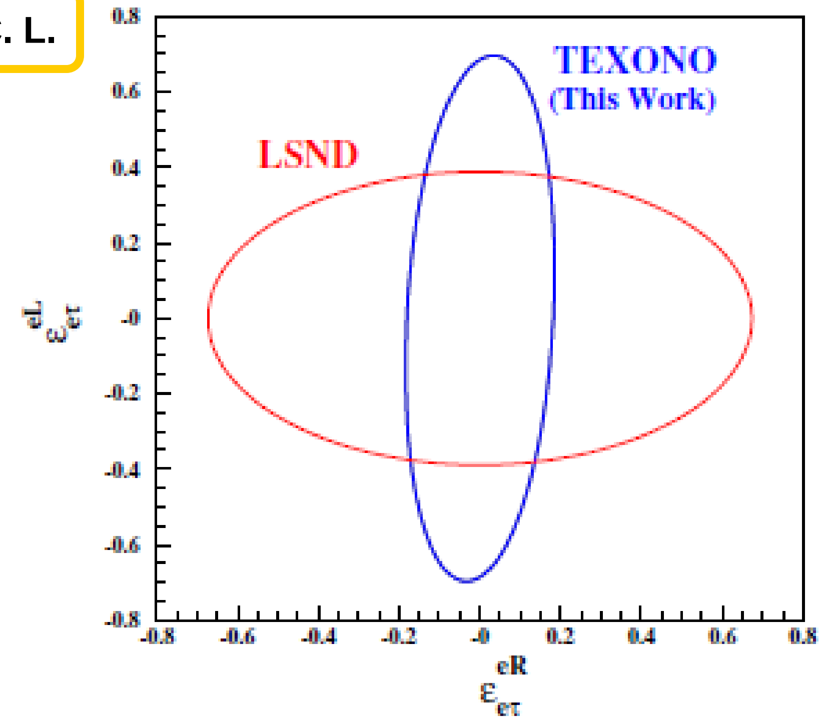
❖ There is a strict bound on $|\epsilon_{e\mu}^{eLR}| < 7.7\times10^{-4}$ derived from $\mu \rightarrow 3e$ decay

❖ The main parameters will be $\epsilon_{e\tau}^{eLR}$ for FC NSI and ϵ_{ee}^{eLR} for NU-NSI.

Comparison of Bounds of NSI Parameters



at 90% C. L.



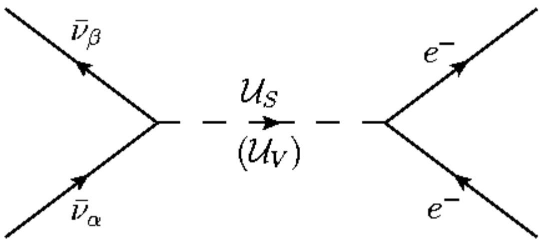
NSI parameters		TEXONO (this work) Measurement best fit	χ^2/d.o.f.	Bounds at 90% C.L.	Projected sensitivities	LSND [13]	Combined [14] Bounds at 90% C.L.	Ref. [15]
NU	ε_{ee}^{eL}	$\varepsilon_{ee}^{eL} = 0.03 \pm 0.26 \pm 0.17$	8.9/9	$-1.53 < \varepsilon_{ee}^{eL} < 0.38$	± 0.015	$-0.07 < \varepsilon_{ee}^{eL}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

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

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

2. Exchange of Vector Unparticles

For the flavour changing case:

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

For the flavour conserving case

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

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

λ_0 (λ_1) : Scalar(Vector) unparticle couplings

f : e, u, d

α, β: denotes neutrino flavours

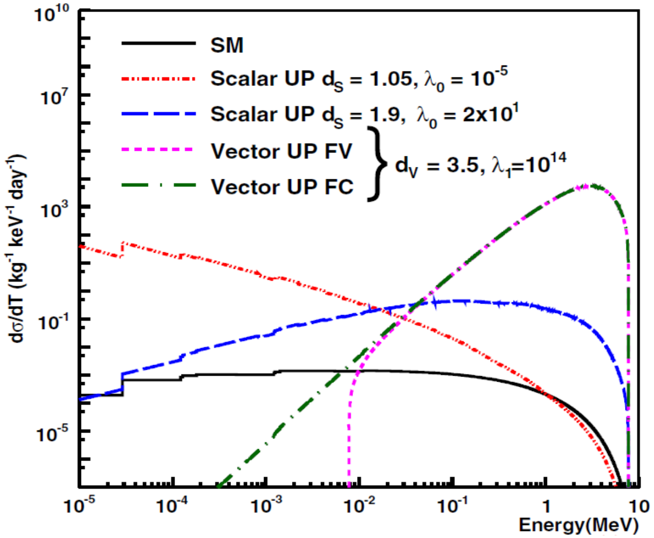
d: Unparticle mass dimension

Λ : Unparticle energy scale

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

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

Unparticle Physics



Λ_U = 1 TeV

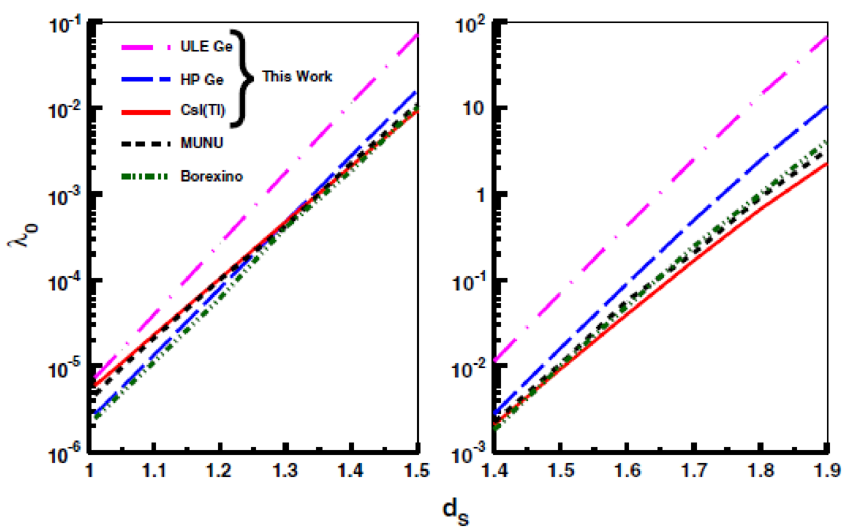
measurable recoil spectra of ν–e interaction via virtual scalar and vector unparticle exchange

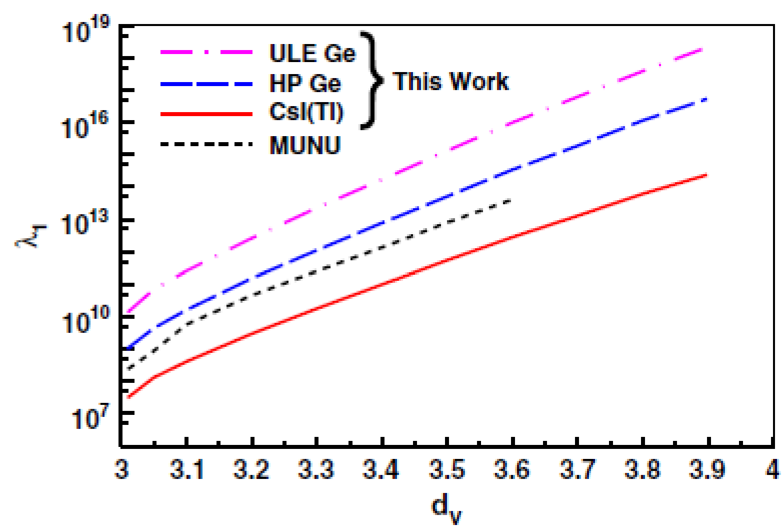
– both FC and FV scenario are considered and analyzed

***spectral shapes:** low energy threshold measurements are expected to provide better sensitivity for low values of mass dimension **d**. On the other hand, high energy experiments are preferred to probe UP due to the large values of **d**.*

*different ranges of **d** parameters give different sensitivities to the cross-section, **three data sets** are analyzed.*

Scalar UP





Vector UP

Results are improved over those from Borexino and MUNU experiments.

Noncommutative Physics

[PRD 85, 073011 (2012)]

❖ NC field theories modify the space-time commutation relation

$$[\hat{x}_\mu, \hat{x}_\nu] = i\theta_{\mu\nu} \qquad\qquad \Delta x_\mu \Delta x_\nu \geq \frac{1}{2}|\theta_{\mu\nu}|$$

$\hat{x}_\mu$ denotes NC space-time coordinates

Real, antisymmetric matrix $\theta_{\mu\nu}$ is a constant and represents the smallest observable area in (μ,ν) plane, analogous to Planck constant in space-momentum commutation relation.

❖ The idea goes back to 1940s for avoiding divergences in QFT before renormalization concept was introduced.

❖ NC physics is being interested again due to recent NC space-time studies in string theories, quantum gravity and Lorentz violation.

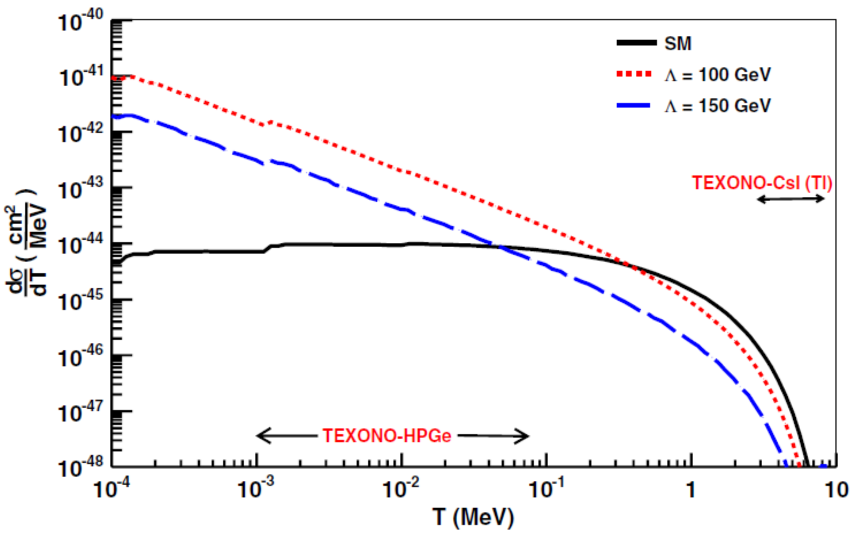
❖ NC Physics is characterized by an energy scale parameter $\Lambda_{\rm NC} = (1/\sqrt{|\theta_{\mu\nu}|})$

Noncommutative Physics

Differential cross sections averaged over the neutrino spectra as a function of recoil energy

$$\left\langle \frac{d\sigma}{dT} \right\rangle = \int \left[\frac{d\sigma}{dT}(E_\nu) \right] \phi_\nu(E_\nu) dE_\nu$$

$$\left[\frac{d\sigma(\nu e)}{dT}(E_\nu) \right]_{\rm NC} = \pi\alpha^2\Theta^2 E_\nu^2 \left[\frac{1}{T} - \frac{2}{E_\nu} + \frac{3T - 2m_e}{2E_\nu^2} - \frac{T^2 - 2m_e T}{2E_\nu^3} - \frac{m_e T^2}{4E_\nu^4}\left(1 - \frac{m_e}{T}\right) \right]$$



Experiment	ν	$<E_\nu>$	T	Measured $\sin^2\theta_W$	Best-Fit on $\Theta^2(\mathrm{MeV}^{-4})$	Λ_{NC} (95% CL)
TEXONO-HPGe	$\bar{\nu}_e$	1–2 MeV	12–60 keV	···	$(9.27 \pm 6.65) \times 10^{-22}$	>145 GeV
TEXONO-CsI(Tl)	$\bar{\nu}_e$	1–2 MeV	3–8 MeV	0.251 ± 0.039	$(0.81 \pm 5.74) \times 10^{-21}$	>95 GeV
LSND	ν_e	36 MeV	18–50 MeV	0.248 ± 0.051	$(0.38 \pm 2.06) \times 10^{-21}$	>123 GeV
CHARM-II	ν_μ	23.7 GeV	3–24 GeV	0.2324 ± 0.0083	$(0.20 \pm 1.03) \times 10^{-26}$	>2.6 TeV
	$\bar{\nu}_\mu$	19.1 GeV	3–24 GeV		$(-0.92 \pm 4.77) \times 10^{-27}$	>3.3 TeV

❖ **Best existing limit on collider experiment is from Tevatron: >1.5 TeV**

Summary

- **Detectors:** CsI(Tl) Scintillating Crystal Array (~ 200 kg) and Ge (1kg)
  - Threshold: CsI(Tl): 3 MeV and Ge: 10 keV
- **Analysis Results:**
  - $\sigma(\bar{\nu}_e - e^-)$ with ~ 25% accuracy
  - Weak Mixing Angle with ~ 15% accuracy
  - Verify SM negative interference
  - The best limit on neutrino charge radius
  - $\mu_{\bar{\nu}}$ sensitivity Ge: ~ 10^{-11} μ_B CsI(Tl): ~ 10^{-10} μ_B
- **Probing new Physics :** NSI, UP and NC Physics
  - Current bounds are improved over those from the previous experiments

Thank YOU