DOKUZ EYLÜL ÜNİVERSİTESİ
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The Measurements of Neutrino-Electron Scattering Cross-Section and Constrains on Non-Standard Neutrino Interactions

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On behalf of TEXONO Collaboration

AMHERST CENTER FOR FUNDAMENTAL INTERACTIONS
Physics at the interface: Energy, Intensity, and Cosmic frontiers
University of Massachusetts Amherst

INTRODUCTION

- Neutrino-electron scattering provides a convenient channel for testing the SM of electroweak theory, especially in the low energy regime since it is a pure leptonic process.
- Extra new interactions due to nonstandard properties of neutrinos often called NSIs of neutrino have not been observed experimentally yet, mainly due to poor experimental sensitivities.
- Recent and upcoming neutrino experiments will provide more precise measurements on intrinsic properties of neutrino and therefore have the potential to open a new window for the observation of NSI effect.
- Nonoscillation experiments that have measured neutrino cross section with high accuracy may provide profound information for neutrino interactions resulting in direct measurements of NSI.
- These interactions are important not only for phenomenological but also for the experimental points of view since the measurements and found evidence can suggest new physics or favor one of the existing new physics theories beyond the SM.

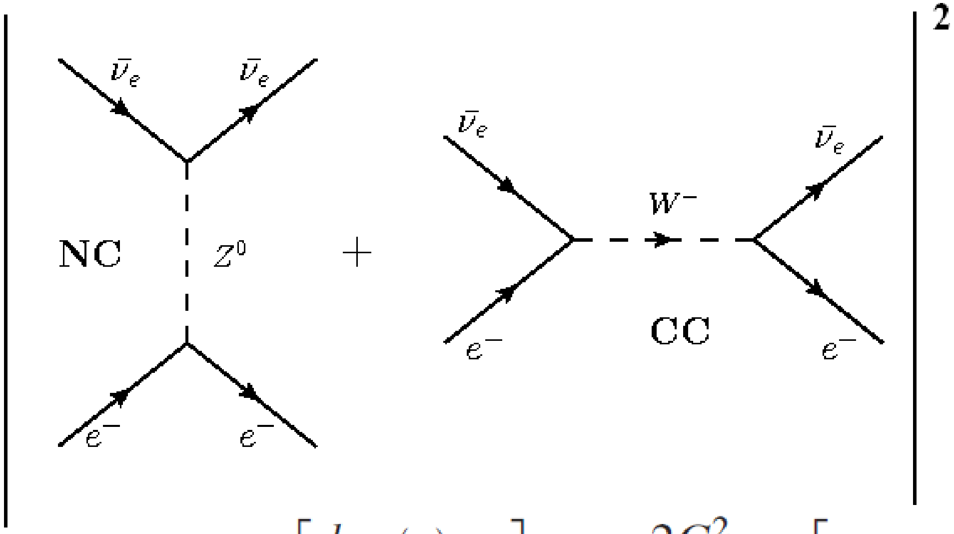
OUTLINE

- A Theory Overview $\nu_e - e^-$ 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 with $\nu_e - e^-$
- Summary

$\nu_e - e^-$ 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**



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

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

$$R_{SM}(\nu_e e) \rightarrow (1.83 : 0.17 : -0.99)$$

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

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

$$\left[\frac{d\sigma}{dT}(\overset{(-)}{\nu}_e e)\right]_{SM} = \frac{2G_F^2 m_e}{\pi}\left[a^2 + b^2\left(1-\frac{T}{E_\nu}\right)^2 - ab\frac{m_e T}{E_\nu^2}\right]$$

Coefficients	$\bar{\nu}_e - e$	$\nu_e - e$
a	$(g_V - g_A)/2$ $\sin^2\theta_W$ g_R	$(g_V + g_A + 2)/2$ $\sin^2\theta_W + 1/2$ $g_L + 1$
b	$(g_V + g_A + 2)/2$ $\sin^2\theta_W + 1/2$ $g_L + 1$	$(g_V - g_A)/2$ $\sin^2\theta_W$ g_R

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

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

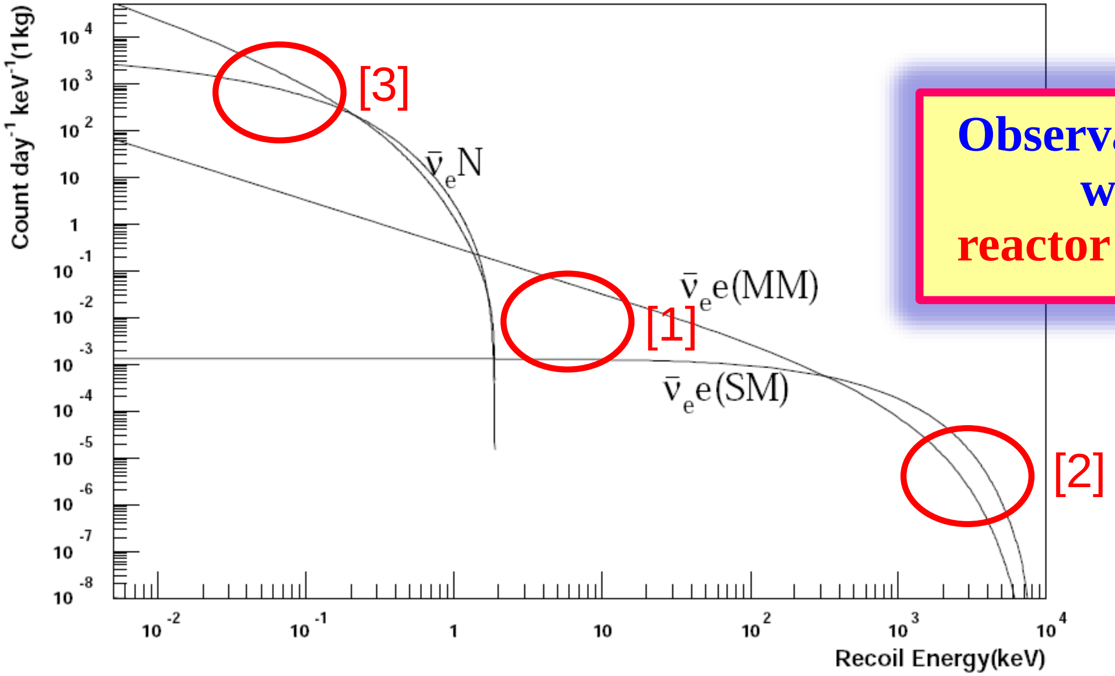
TEXONO Physics Program

TEXONO Collaboration: Taiwan (AS, INER, KSNPS, NTU, NDHU); China (IHEP, CIAE, THU, SCU); Turkey (METU, DEU); India (BHU)

Program: Low Energy Neutrino & Astroparticle Physics

Taiwan
EXperiment
On
NeutrinO

quality ← Detector requirements → mass



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 2007,2009, 2010,2013

[1] [2] [3] **New Physics Beyond the SM** → PRD 2010, 2012, 2015, 2017, 2018

TEXONO Data Sets

CsI(Tl)

- Data with 29882/7369 kg day of reactor ON/OFF
- Total mass of 187kg
- Analysis range is 3 – 8 MeV
- $\sin^2\theta_W = 0.251 \pm 0.031(\mathrm{stat}) \pm 0.024(\mathrm{sys})$

HP-Ge

- Data with 570.7/127.8 kg day of reactor ON/OFF
- Total mass is 1.06 kg
- Threshold of 10 keV is achieved.
- Analysis range is 10 – 50 keV.
- $\mu_\nu < 7.4 \times 10^{-11} \mu_B$

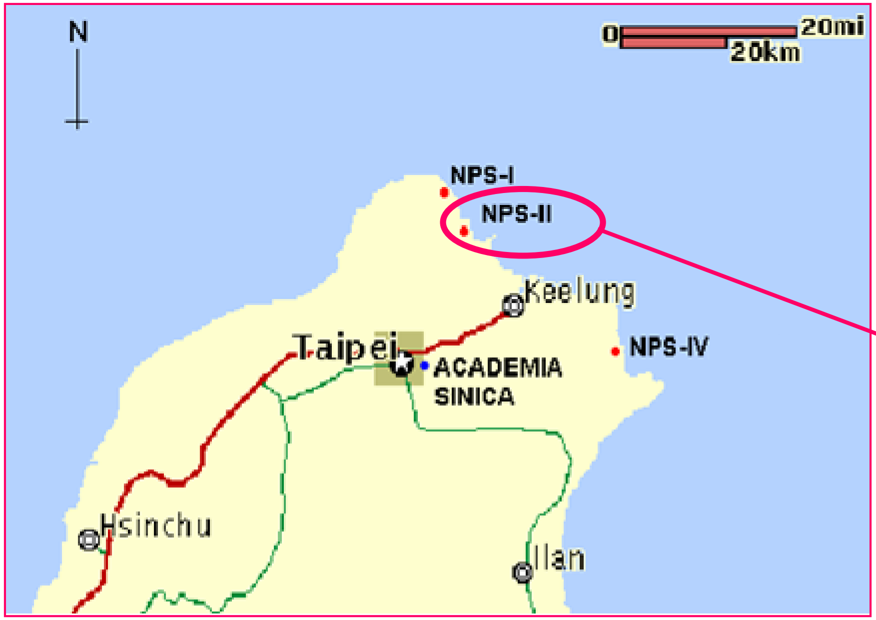
ULE-Ge

- Data with 0.338 kg days of reactor ON
- Total mass of 20 g $(4 \times 5$ g)
- Threshold of 220 ± 10 eV is achieved.
- WIMP mass $<$ 10 GeV is searched.

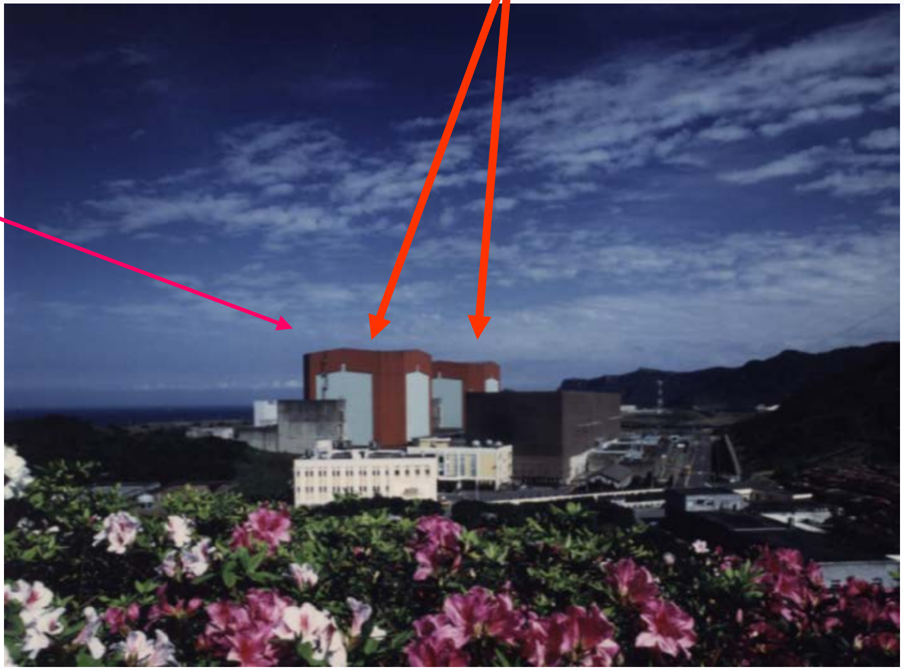
NPC-Ge

- Data with 124.2/70.3 kg day of reactor ON/OFF
- Total mass of 840 g
- Analysis range is 0.3 – 12.4 keV
- Used in search of neutrino milli-charge

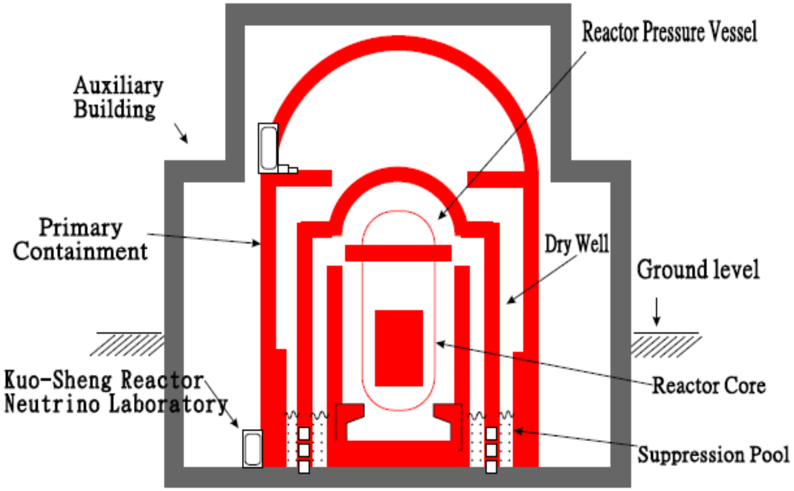
Kou-Sheng Reactor Power Plant



KS NPS -II : 2 cores × 2.9 GW



Kuo-Sheng Nuclear Power Station : Reactor Building



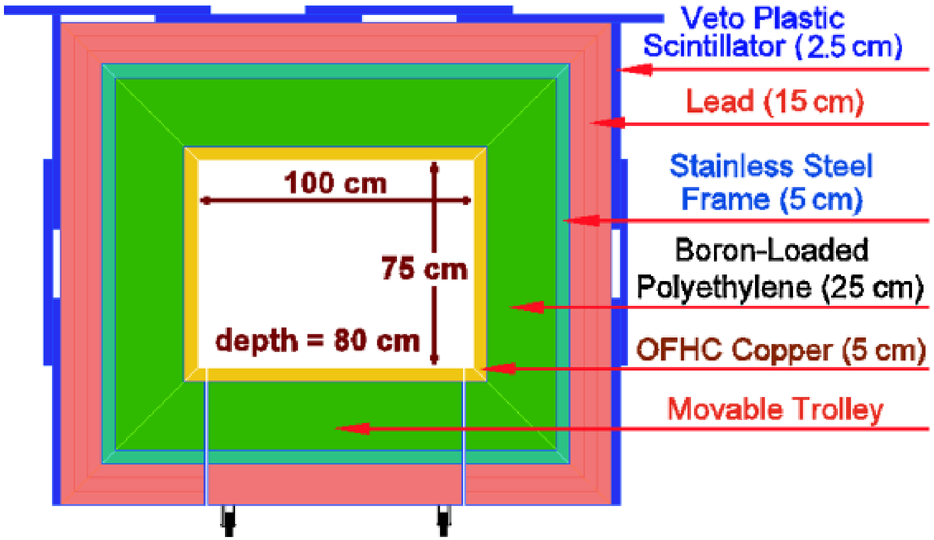
Total flux about 6.4×10^{12} $cm^{-2}s^{-1}$

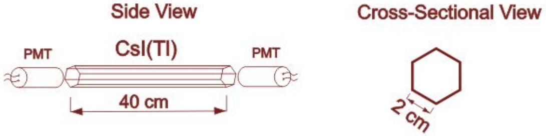
KS ν Lab: 28m from core #1

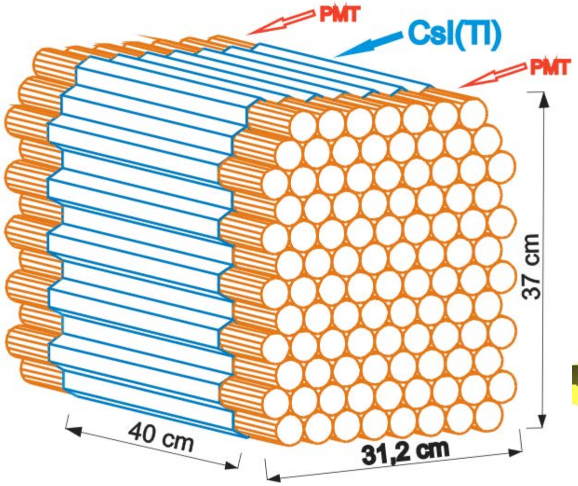
10 m below the surface
30 mwe overburden

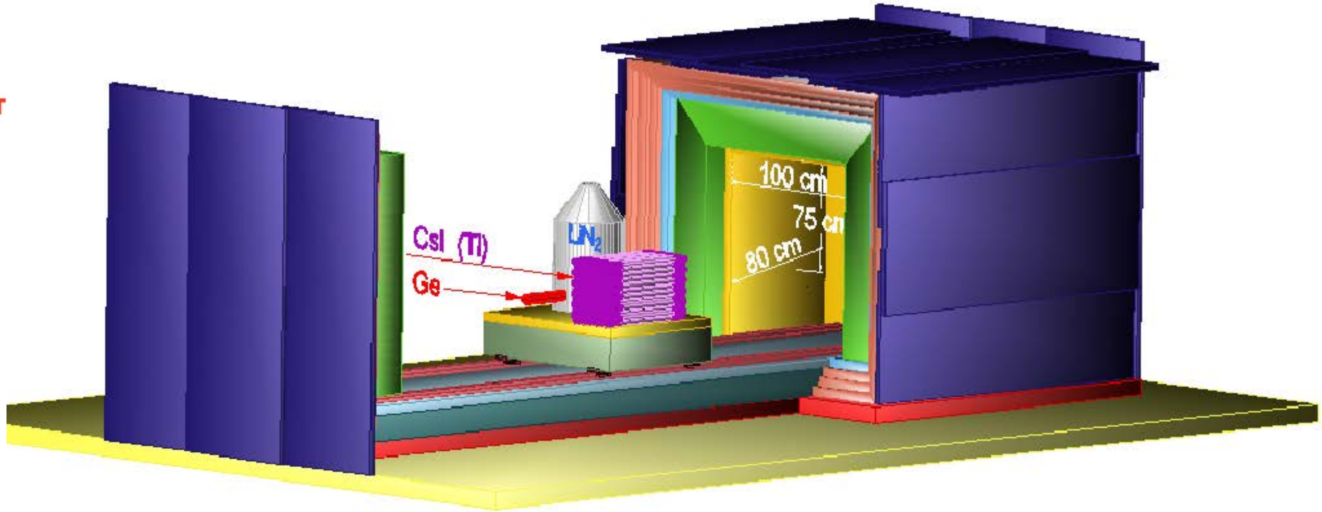
Neutrino Laboratory

Inner Target Volume & Shielding









TEXONO Physics Program on CsI(Tl) detector

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

attempt a measurement of Standard Model $\sigma(\bar{\nu}_e e^-)$

↳ $\sin^2\theta_W$ at MeV range

Measurement : Recoil Energy of e^-

- ν properties are not fully understood ⟶ intense ν-source

Reactor : high flux of low energy (MeV range) electron anti-neutrinos.

CsI(Tl) (200 kg) :

Region of Interest for $\bar{\nu}_e$ – e scattering

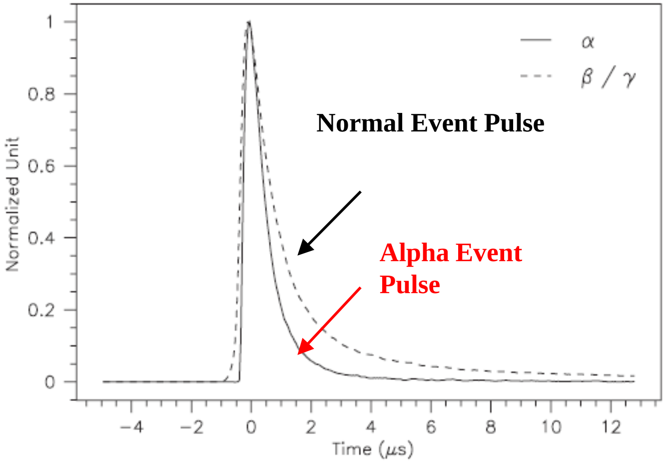
Big uncertainties of modelling in the low energy part of reactor neutrino

⟶ for SM $\sigma(\bar{\nu}_e e)$ higher energies (**T>3 MeV**)

CsI Scintillating Crystal Array

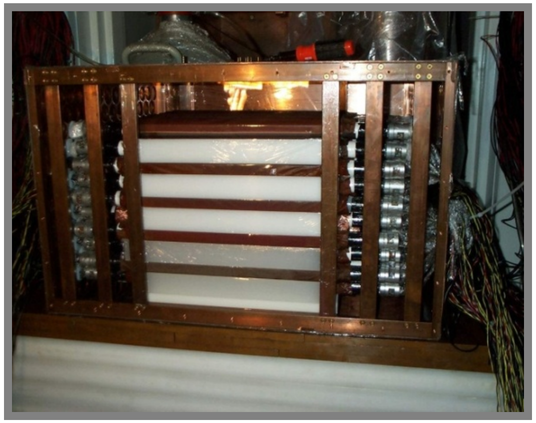
Experimental Approach; CsI(Tl) Crystal Scintillator Array:

- 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 ON/OFF (~6 years real-time data taking)**

CsI(Tl) Detector
9×12 Array ~200 kg



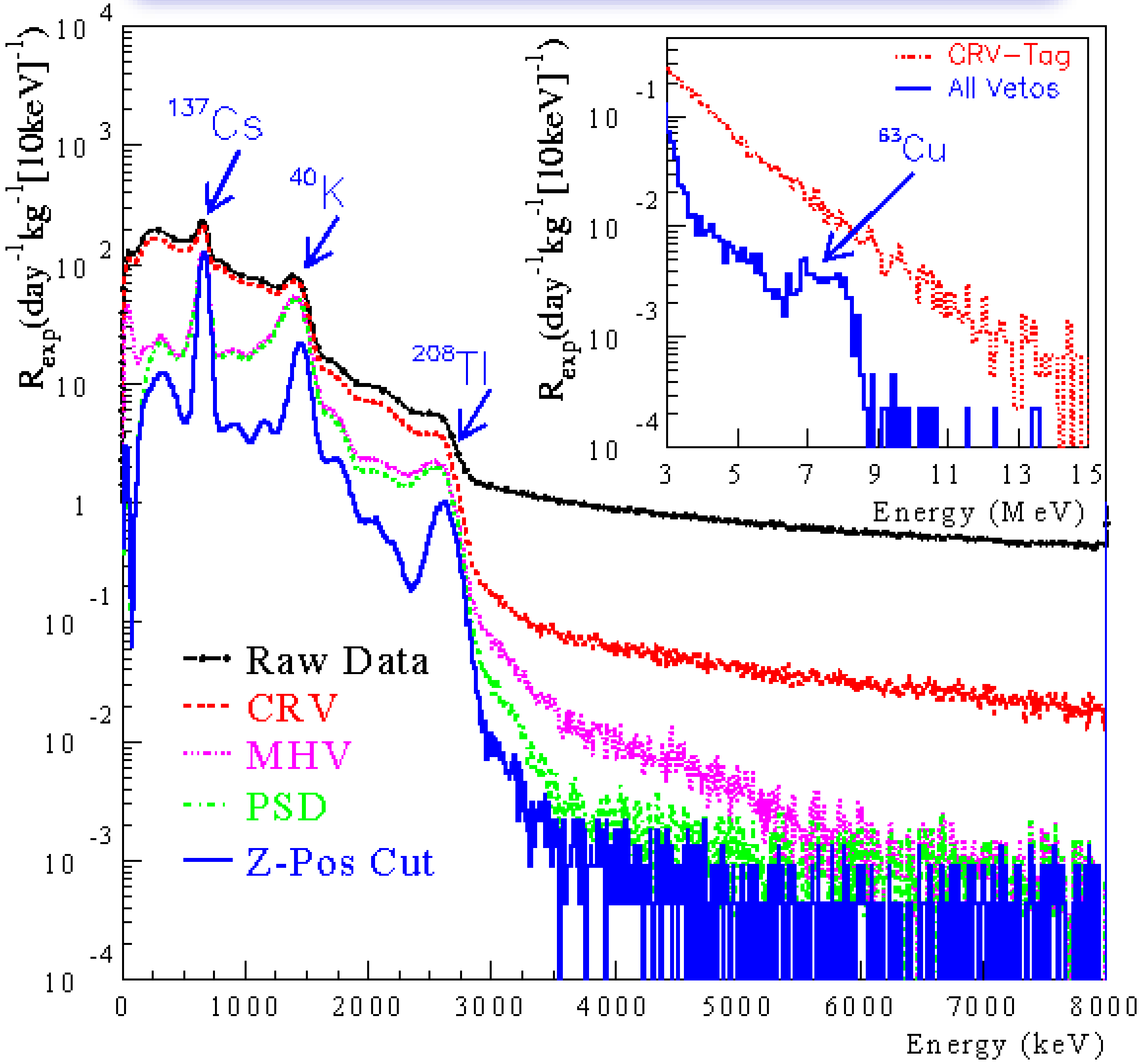
- **Energy : Total Light Collection**
  - **σ (E) ~ 10% FWHM @ E>660 keV**
- **Z-position : The variation of Ratio**
  - **σ (Z) ~ 1.3 cm @ E>660 keV**

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

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

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**

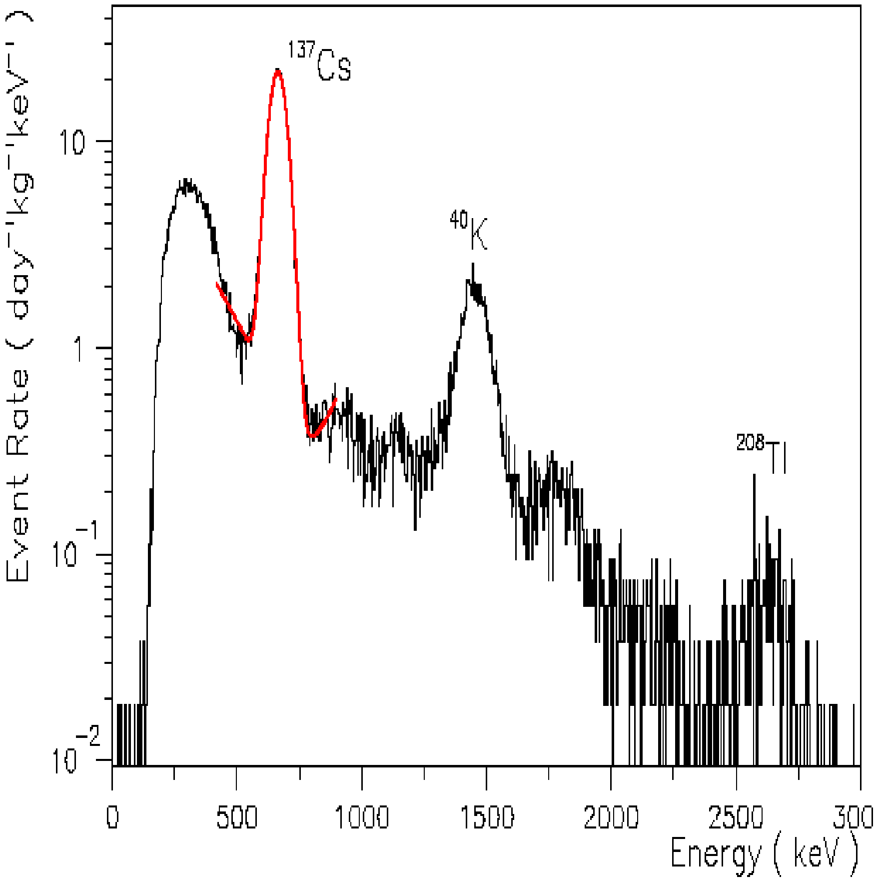
    - By comparing **cosmic and non-cosmic** multiple-hit spectra in the region of **3-8** MeV.

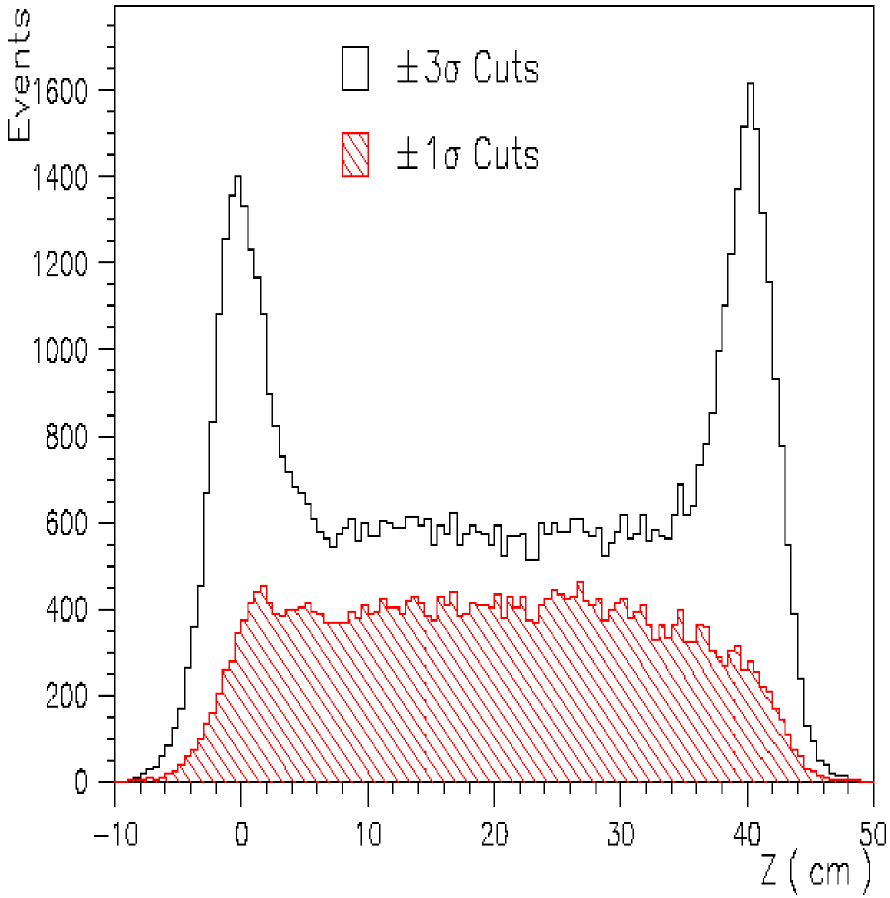
  - **Tl-208**

    - 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 drived ==>

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

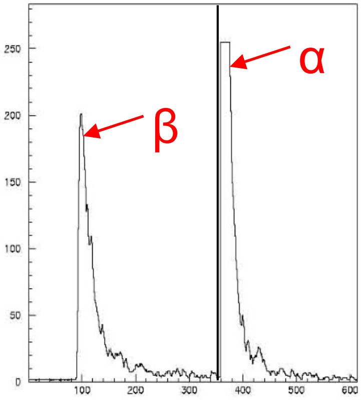
Intrinsic U and Th Contamination Level

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

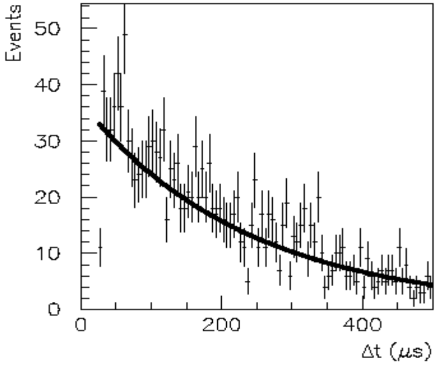
i) ^{214}Bi(β^-)→ ^{214}Po(α,164μs) → ^{210}Pb

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

2nd pulse α shaped



$T_{1/2}$ = (163 ± 8) μs

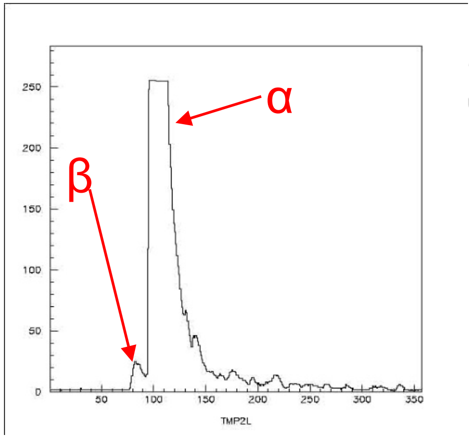


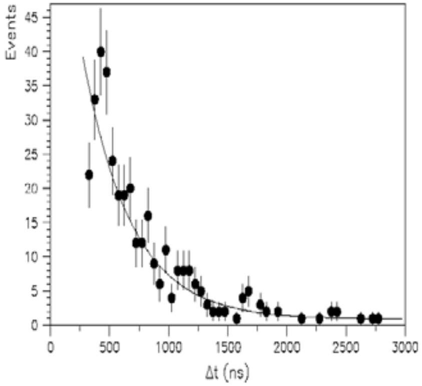
^{238}U abundance = (0.82 ± 0.02) × 10^{-12} g/g

ii) ^{212}Bi(β^-,64%) → ^{212}Po(α, 299ns) → ^{208}Pb

Selection: β pulse followed by a large α pulse

$T_{1/2}$ = (283 ± 37) ns.



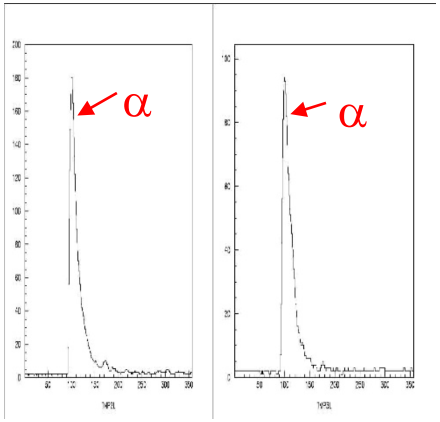


^{232}Th abundance = (2.3 ± 0.1) × 10^{-12} g/g

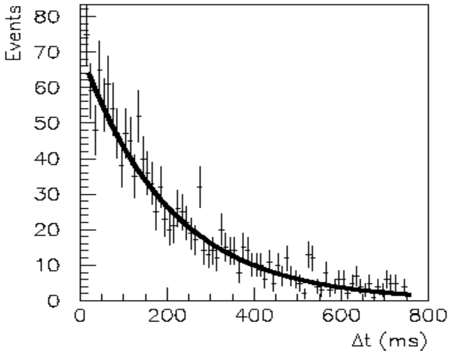
iii) ^{220}Rn(α) → ^{216}Po(α, 0.15s) → ^{212}Pb

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

^{232}Th abundance = (2.23 ± 0.06) × 10^{-12} g/g

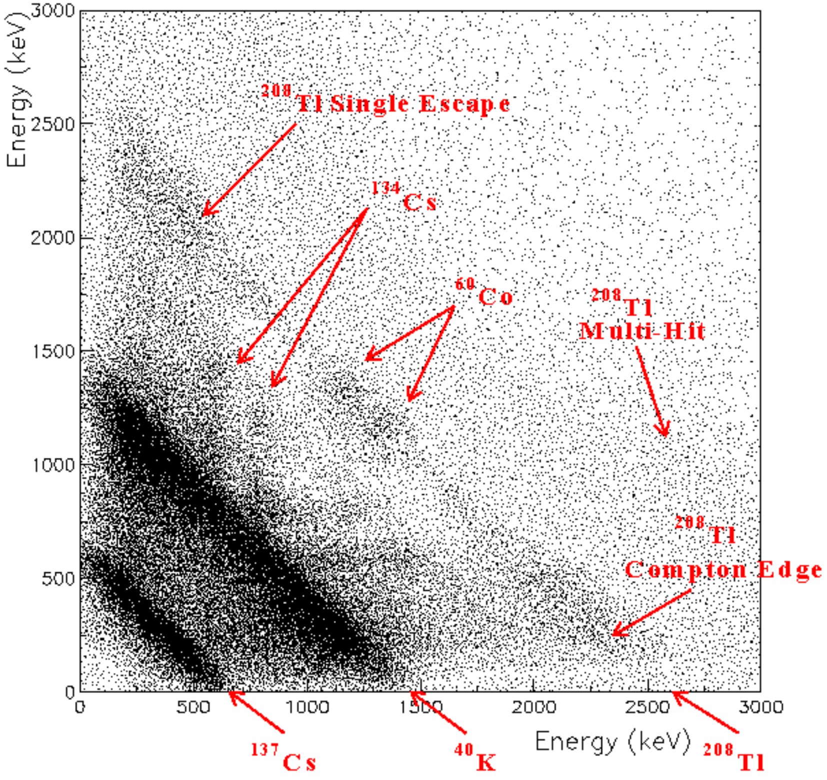


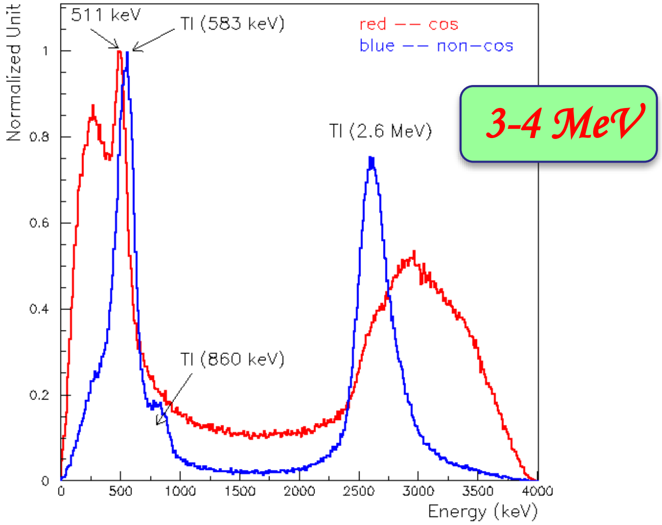
$T_{1/2}$ = (0.141 ± 0.006) s



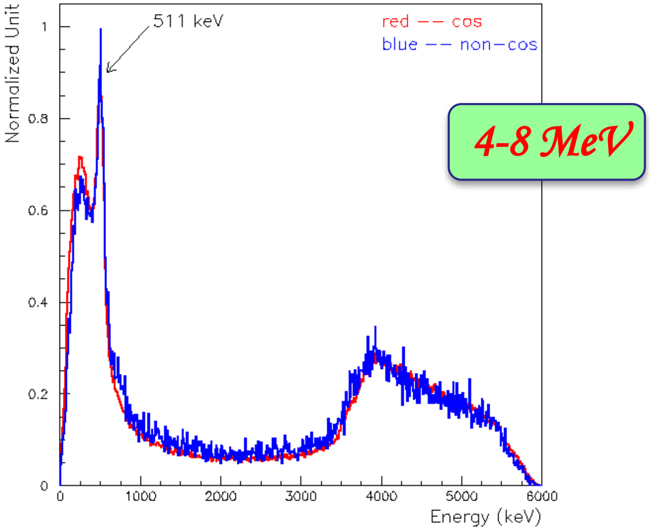
Background Understanding: via Multiple Hit Analysis

2 HIT SPECTRUM



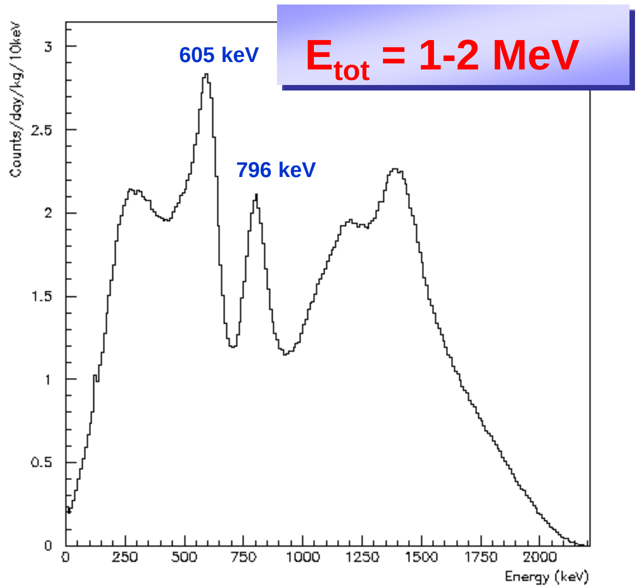


3-4 MeV



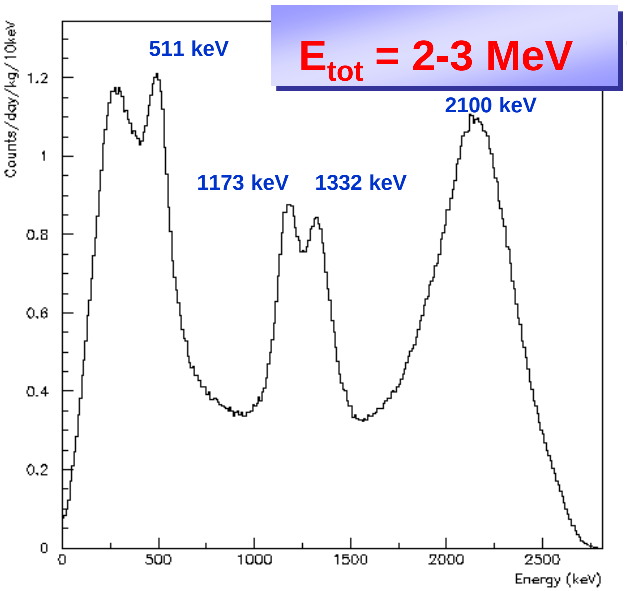
4-8 MeV

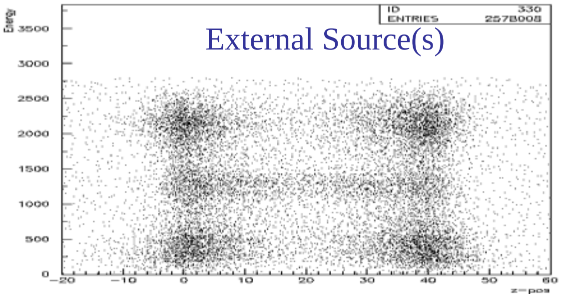
Background Understanding via Multi Hit



Cs-134 (n + ^{133}Cs → ^{134}Cs)

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

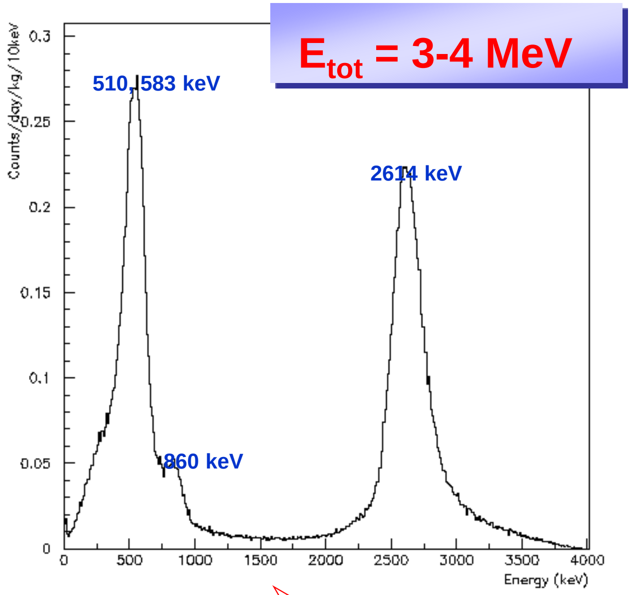


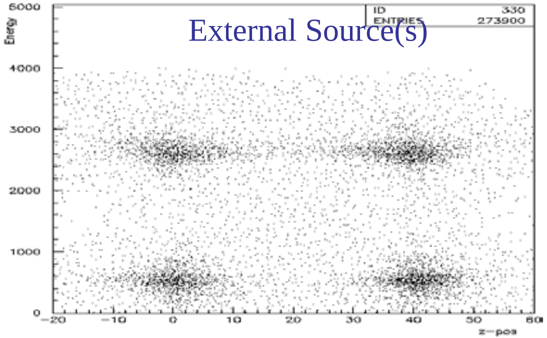


Co-60: **1173.2** keV 99.86% accompanied with **1332.5** keV 99.98%

The background related to reactor. Mostly come from the dust.

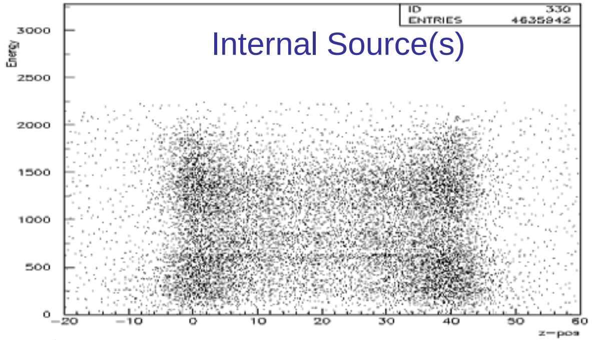
Tl Pair Production: One escape peaks (~ 2105 + 511 keV)





2614 keV 99 % accompanied with
583 keV 85%
510.8 keV 23%
860 keV with 13%

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**

Environmental Background Understanding

Cosmic Inefficiency

- cosmic/non-cosmic ratio for 3-hit pair production events

Tl-208 (3-4 MeV)

- ^{208}Tl chain 2-hit energy spectra
- Simulation with angular correlation

Residual Background Understanding & Suppression

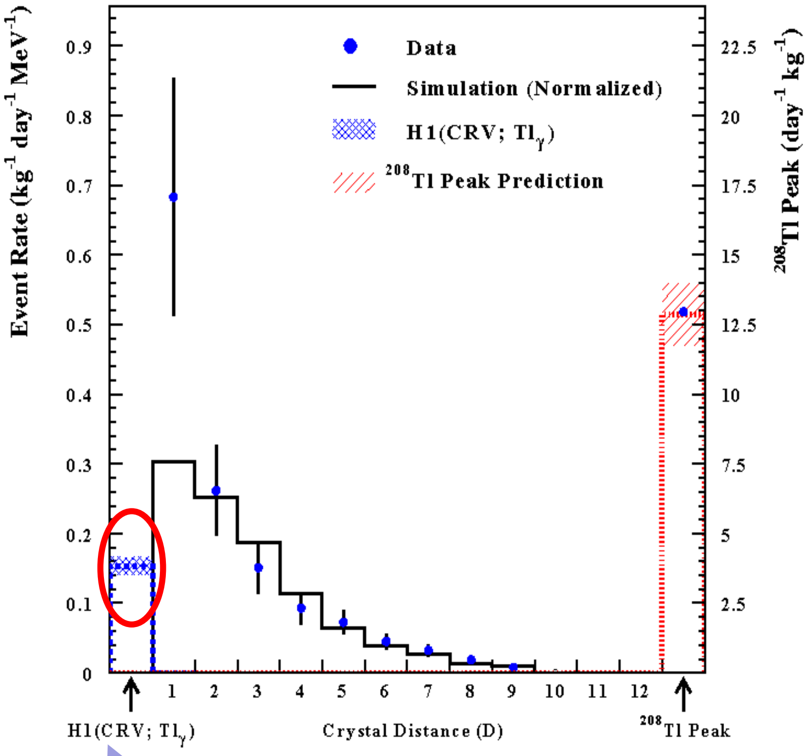
- Background Sources : **High Energy γ & Cosmic Rays & ^{208}Tl**

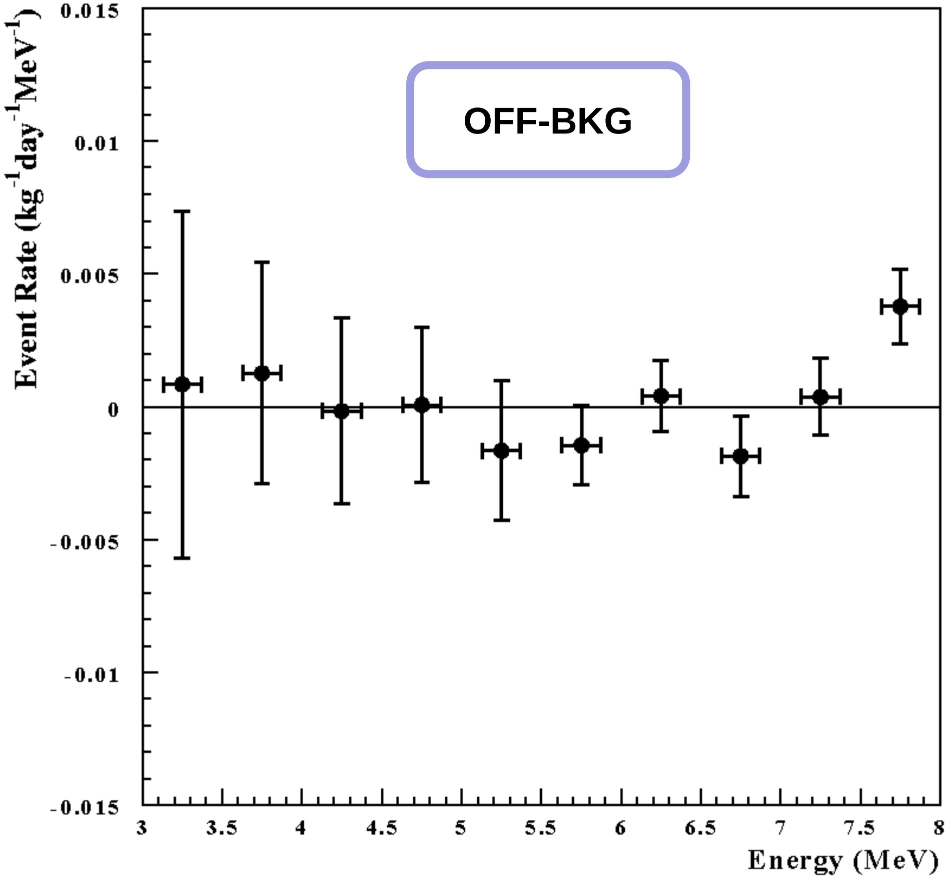
Idea -- Use Multiple Crystal Hit (**MH**) spectra to **predict** Single Crystal Hit (**SH**) background to the neutrino events

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

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

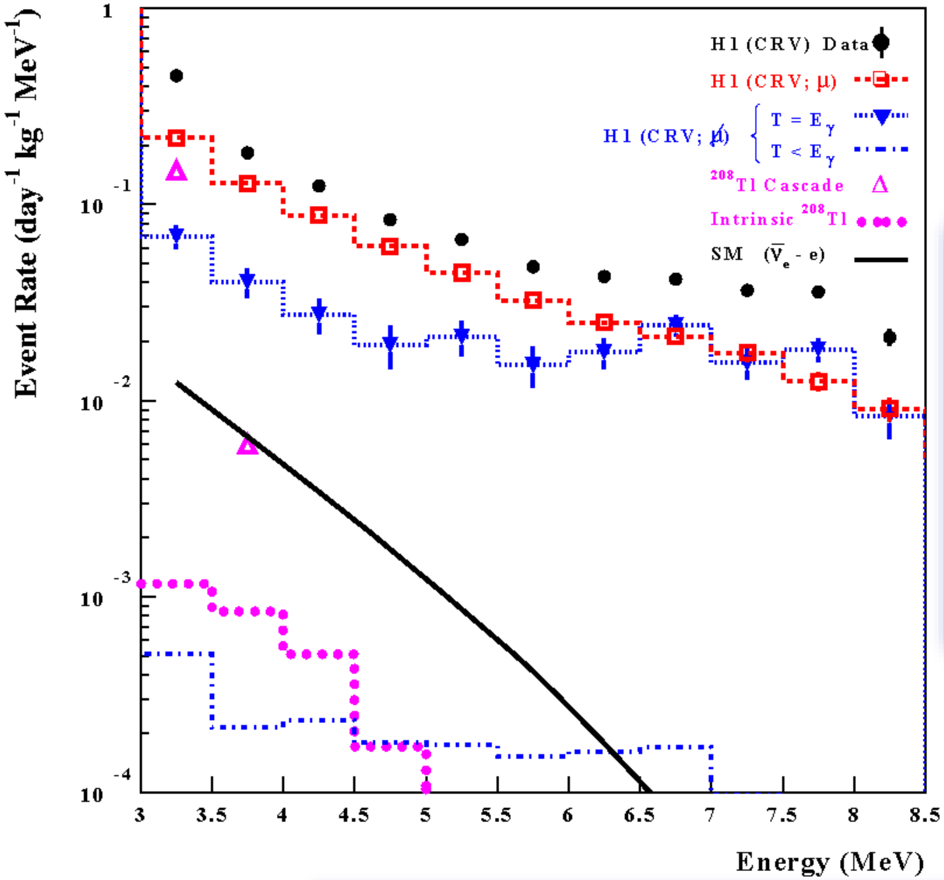
Tl-208 Induced and Cosmic SH BKG Estimation





SH → **2614** keV **γ**
⊕ **(583** keV **γ)** or
⊕ **(510** keV **γ)** or
⊕ **(860** keV **γ)**

Background Understanding & Suppression



ε_{CRV} ~ 93 %	BKG (SH) Sources		
Energy (MeV)	cosmic	HE γ	^{208}Tl
3.0 – 4.0	~ 55%	~ 20%	~ 25% (γ,γ)
4.0 – 6.5	~ 60%	~ 40%	—
6.5 – 8.0	~ 50%	~ 50%	—

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

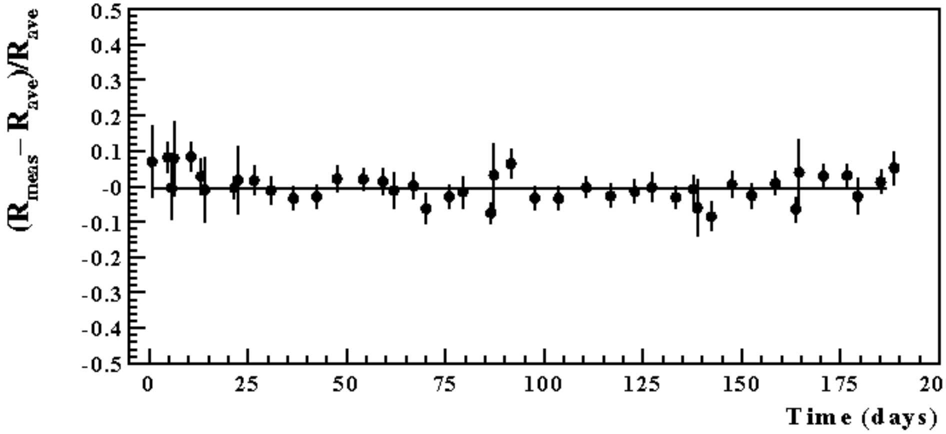
- Direct **Reactor OFF(SH)** spectra ⊕ Predicted **BKG(SH)** from **OFF(MH)** ⊕ Predicted **BKG(SH)** from **ON(MH)**

ν = ON(SH) – BKG(SH)

Systematic Uncertainties

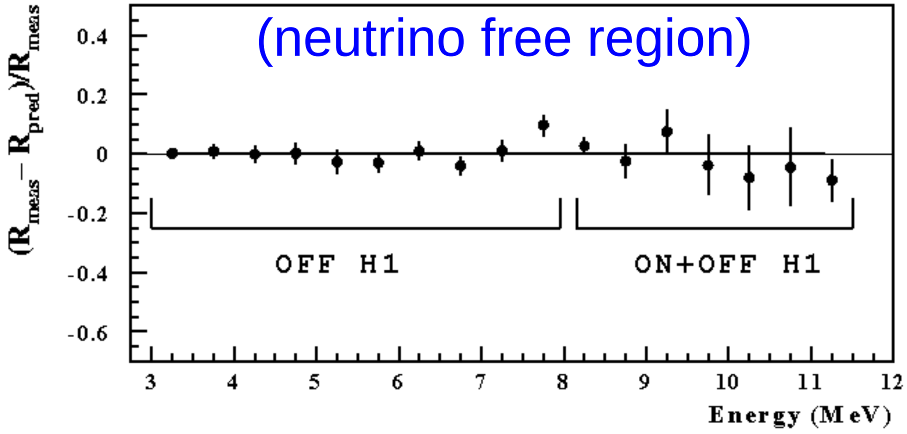
Approach – Use non-ν events for demonstration

^{208}Tl Peak Events Stability

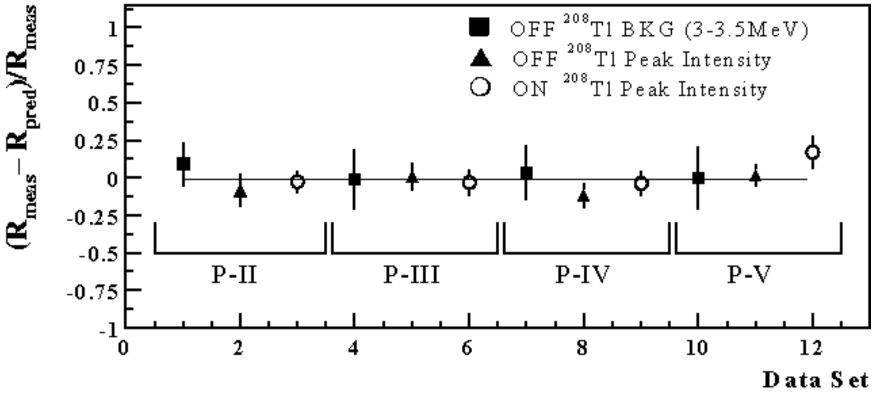


BKG – Pred.

(neutrino free region)

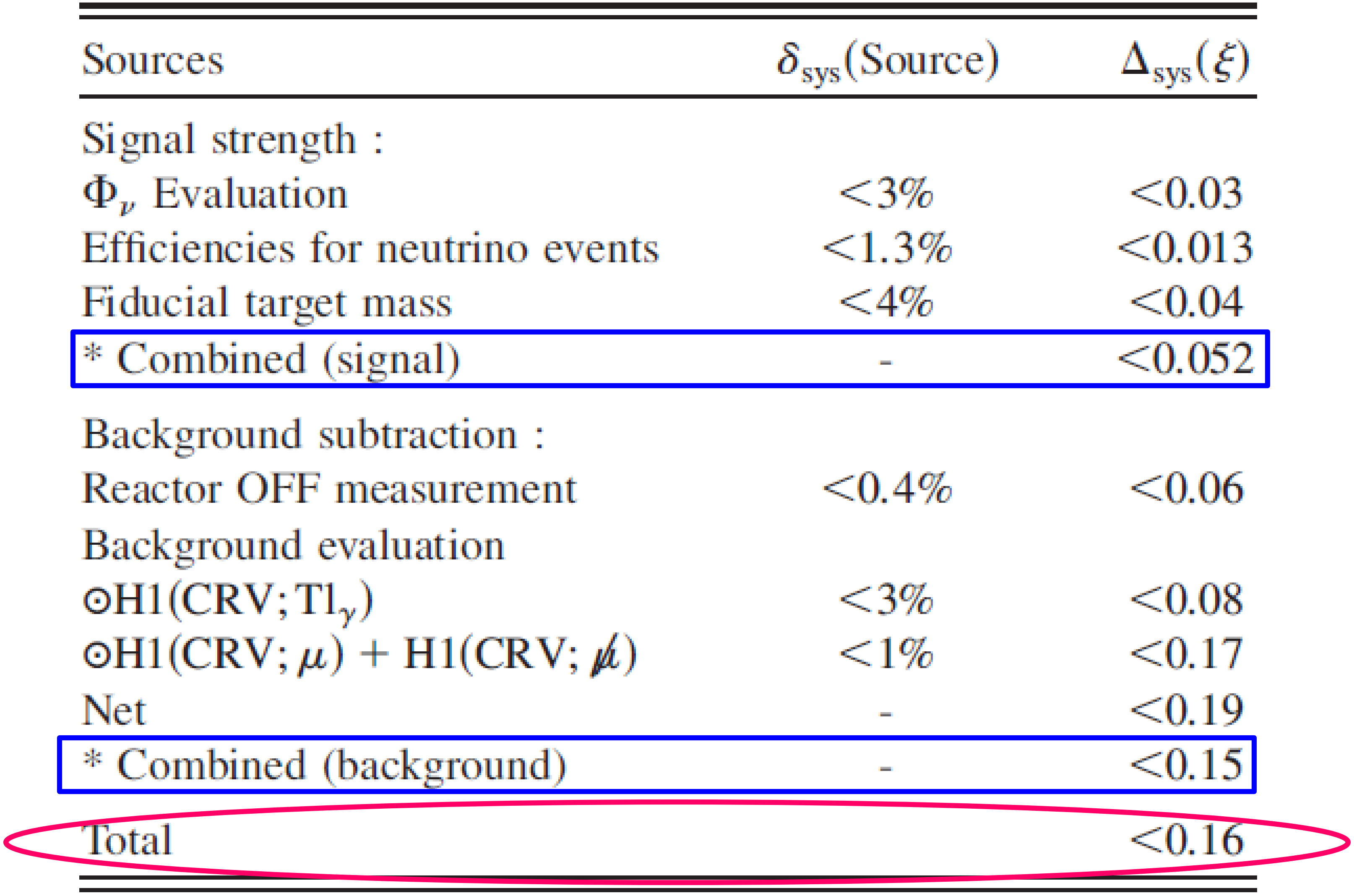


^{208}Tl (SH) Prediction



- **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)**

The Sources & Contribution of Systematic Uncertainties



Sources	$\delta_{\rm sys}$(Source)	$\Delta_{\rm sys}(\xi)$
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$_\gamma$)	$<3\%$	<0.08
$\odot$H1(CRV; μ) + H1(CRV; $\not\mu$)	$<1\%$	<0.17
Net	-	<0.19
* Combined (background)	-	<0.15
Total		<0.16

Analysis Method

Expected event rate (units of $\mathrm{kg}^{-1}\ \mathrm{day}^{-1}$)

$$R_X(\bar{\nu}_e - e) = \rho_e \int_T \int_{E_\nu} \left[\frac{d\sigma}{dT}\right]_X \frac{d\phi}{dE_\nu} dE_\nu dT \qquad ,$$

where $X\ (= SM\ and\ NSI)$, ρ_e is the electron number density per kg of target mass, and ϕ_ν denotes the neutrino flux.

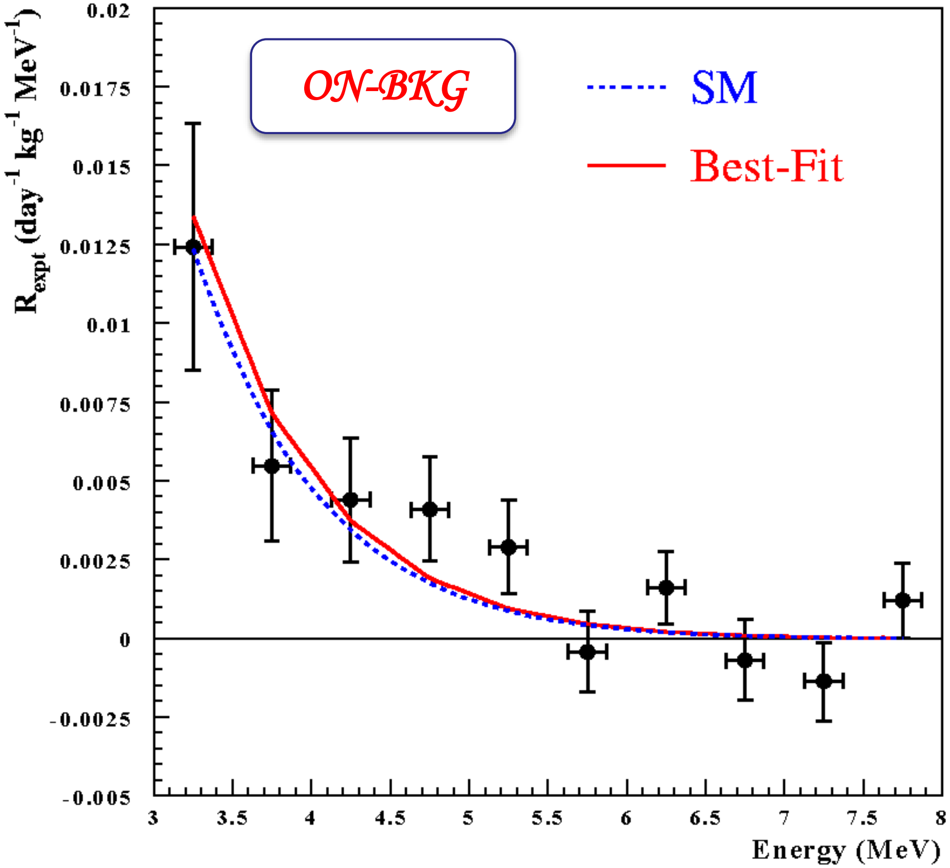
The statistical uncertainties are derived by minimum χ^2 method defined as

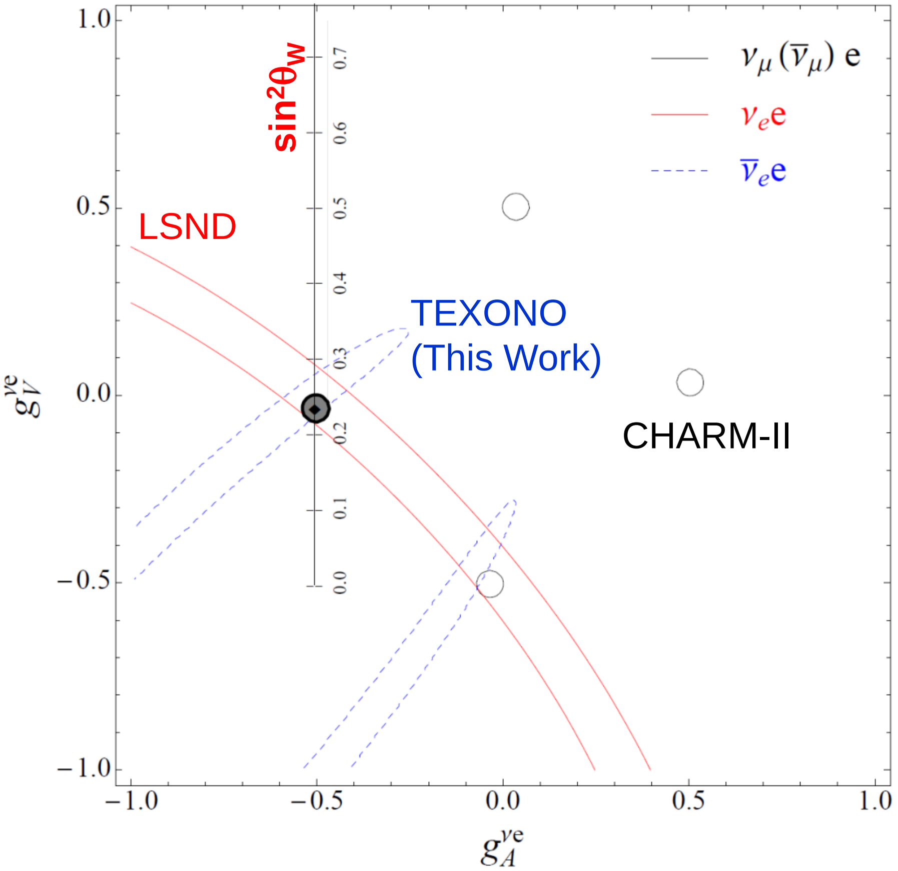
$$\chi^2 = \sum_{i=1} \left[\frac{R_{expt}(i) - R_{SM}(i) - R_{NSI}(i)}{\Delta(i)}\right]^2$$

Cross Section & Weak Mixing Angle

Phys. Rev. D 81, 072001 (2010)

PDG 2018





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

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

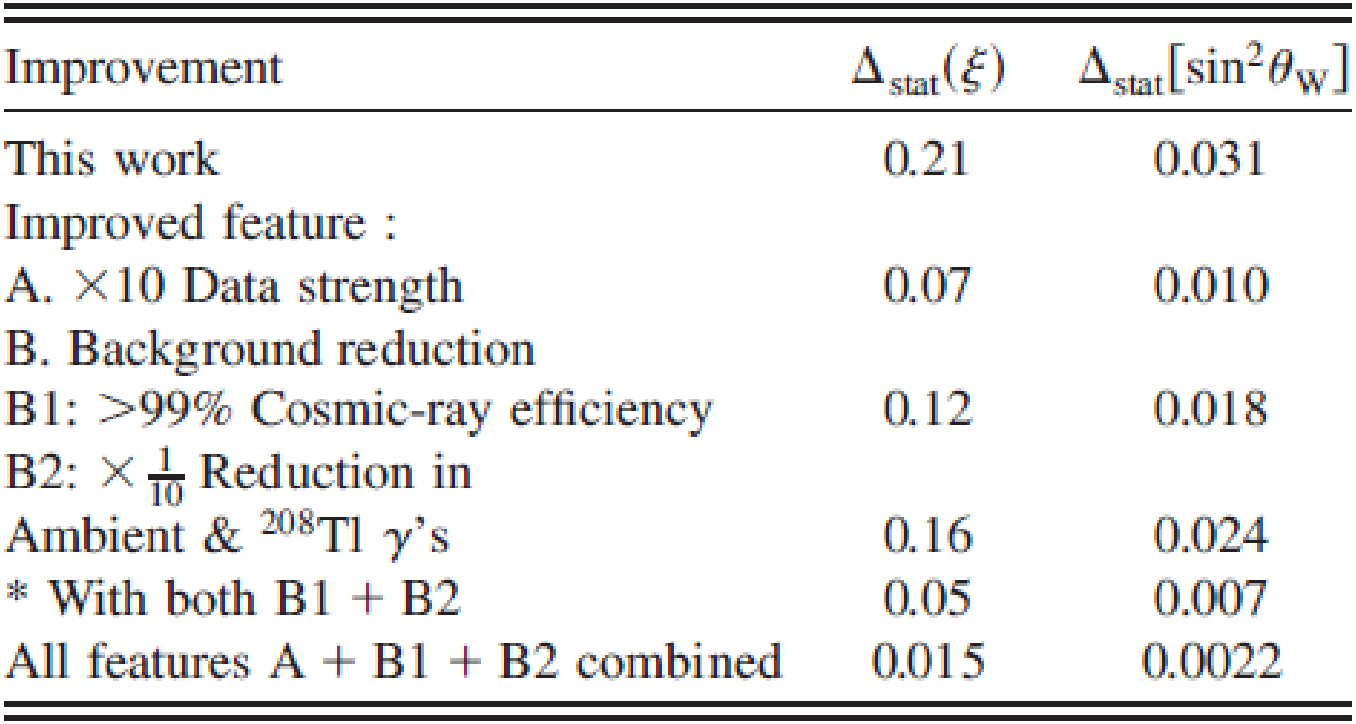
A better sensitivity is achieved in the measurement of weak mixing angle

World Status: Summary Table

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

Projected Sensitivities

Projected statistical sensitivities on the cross section ratio ξ and $\sin^2\theta_W$ under various realistically achievable improvement to the experiment.



Improvement	$\Delta_{\text{stat}}(\xi)$	$\Delta_{\text{stat}}[\sin^2\theta_W]$
This work	0.21	0.031
Improved feature :		
A. ×10 Data strength	0.07	0.010
B. Background reduction		
B1: >99% Cosmic-ray efficiency	0.12	0.018
B2: $\times\frac{1}{10}$ Reduction in Ambient & ^{208}Tl γ's	0.16	0.024
* With both B1 + B2	0.05	0.007
All features A + B1 + B2 combined	0.015	0.0022

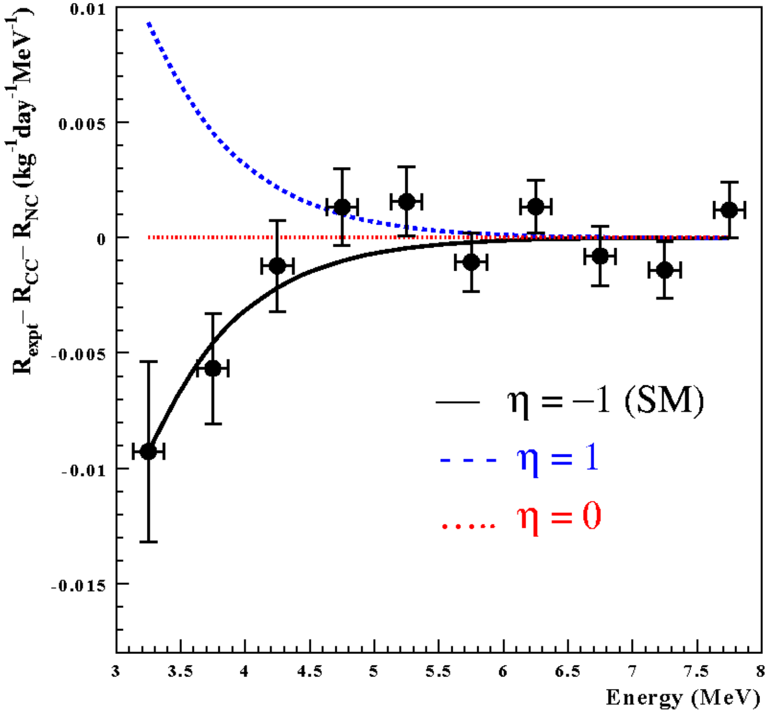
Interference, Neutrino Magnetic Moment & Charge Radius Squared

Interference Term

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

Interference Term

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



Neutrino Magnetic Moment

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

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

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

at 90 % C. L.

Neutrino Charge Radius

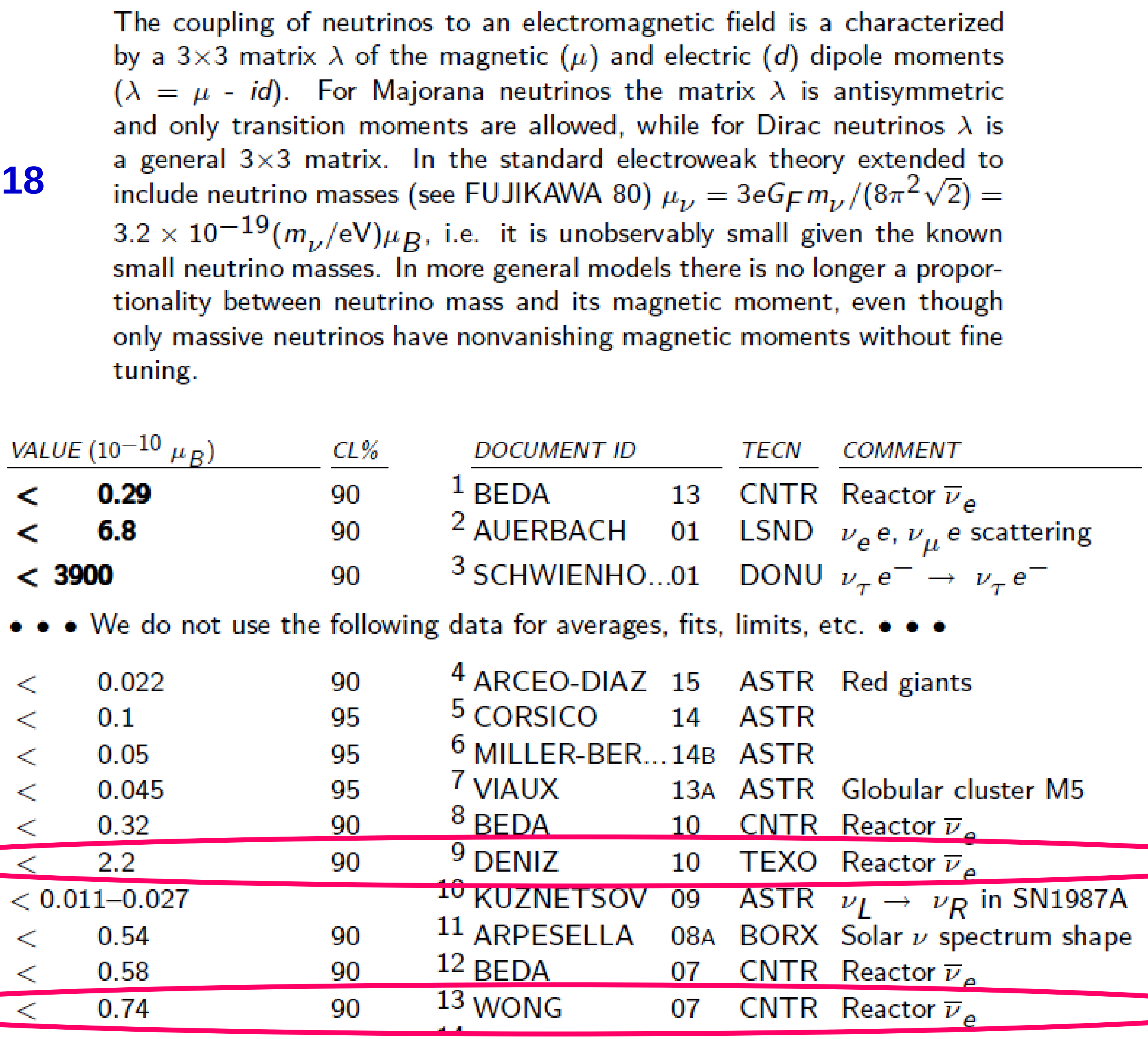
$$\sin^2\theta_W \rightarrow \sin^2\theta_W + (\sqrt{2}\pi\alpha / 3G_F)\left\langle r^2_{\bar{\nu}_e} \right\rangle$$

$$-2.1 \times 10^{-32} < \left\langle r^2_{\bar{\nu}_e} \right\rangle < 3.3 \times 10^{-32}\ cm^2$$

The Best Limit (PDG-2018)

ν MAGNETIC MOMENT

PDG 2018



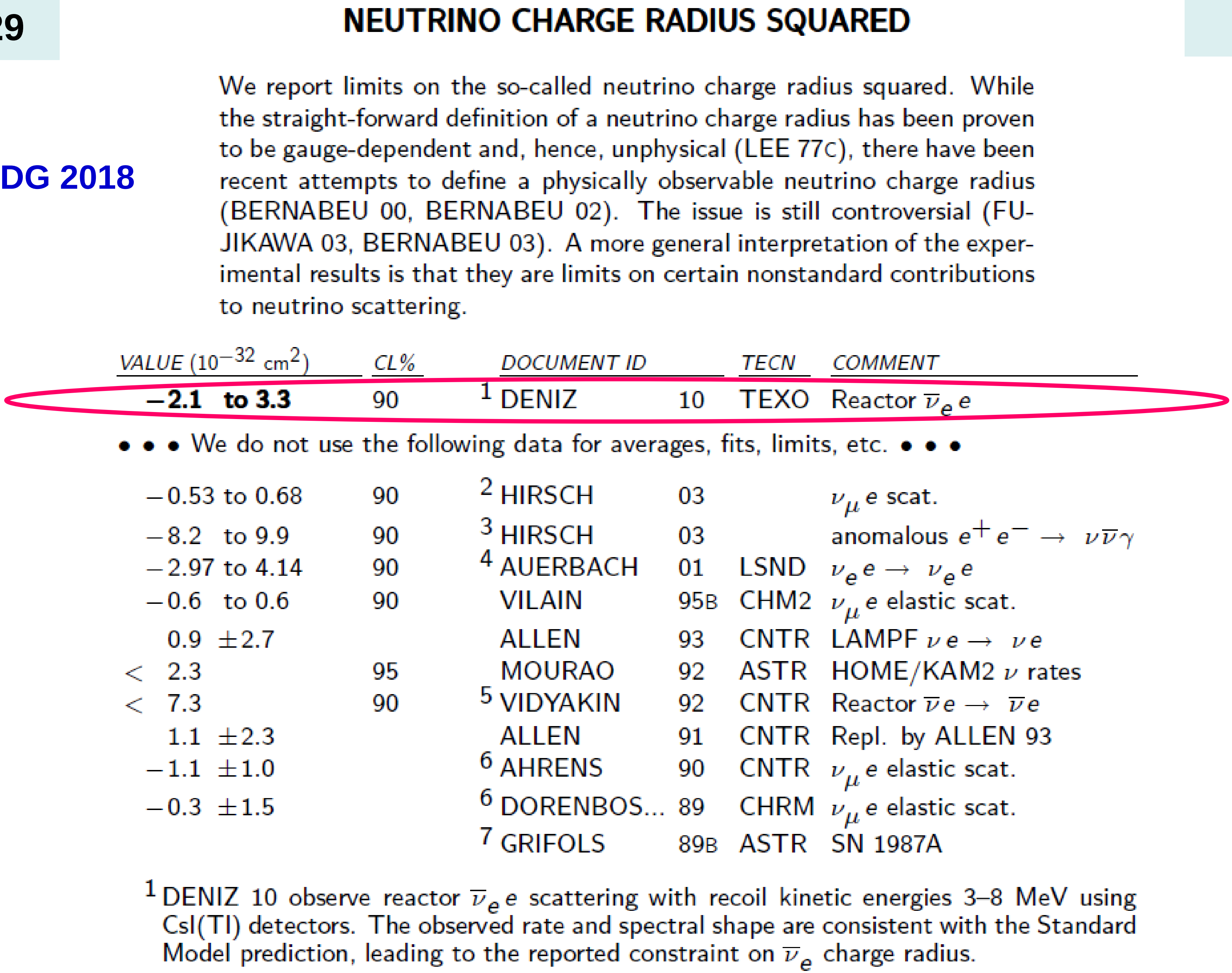
The coupling of neutrinos to an electromagnetic field is a characterized by a 3×3 matrix λ of the magnetic (μ) and electric (d) dipole moments ($\lambda = \mu$ - id). For Majorana neutrinos the matrix λ is antisymmetric and only transition moments are allowed, while for Dirac neutrinos λ is a general 3×3 matrix. In the standard electroweak theory extended to include neutrino masses (see FUJIKAWA 80) $\mu_\nu = 3eG_F m_\nu/(8\pi^2\sqrt{2}) = 3.2 \times 10^{-19}(m_\nu/\mathrm{eV})\mu_B$, i.e. it is unobservably small given the known small neutrino masses. In more general models there is no longer a proportionality between neutrino mass and its magnetic moment, even though only massive neutrinos have nonvanishing magnetic moments without fine tuning.

VALUE (10^{-10} μ_B)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
< 0.29	90	[1] BEDA	13	CNTR	Reactor $\overline{\nu}_e$
< 6.8	90	[2] AUERBACH	01	LSND	$\nu_e\,e$, $\nu_\mu\,e$ scattering
< 3900	90	[3] SCHWIENHO...	01	DONU	$\nu_\tau\,e^- \rightarrow \nu_\tau\,e^-$

• • • We do not use the following data for averages, fits, limits, etc. • • •

< 0.022	90	[4] ARCEO-DIAZ	15	ASTR	Red giants
< 0.1	95	[5] CORSICO	14	ASTR	
< 0.05	95	[6] MILLER-BER...	14B	ASTR	
< 0.045	95	[7] VIAUX	13A	ASTR	Globular cluster M5
< 0.32	90	[8] BEDA	10	CNTR	Reactor $\overline{\nu}_e$
< 2.2	90	[9] DENIZ	10	TEXO	Reactor $\overline{\nu}_e$
< 0.011–0.027		[10] KUZNETSOV	09	ASTR	$\nu_L \rightarrow \nu_R$ in SN1987A
< 0.54	90	[11] ARPESELLA	08A	BORX	Solar ν spectrum shape
< 0.58	90	[12] BEDA	07	CNTR	Reactor $\overline{\nu}_e$
< 0.74	90	[13] WONG	07	CNTR	Reactor $\overline{\nu}_e$

PDG 2018



NEUTRINO CHARGE RADIUS SQUARED

We report limits on the so-called neutrino charge radius squared. While the straight-forward definition of a neutrino charge radius has been proven to be gauge-dependent and, hence, unphysical (LEE 77C), there have been recent attempts to define a physically observable neutrino charge radius (BERNABEU 00, BERNABEU 02). The issue is still controversial (FUJIKAWA 03, BERNABEU 03). A more general interpretation of the experimental results is that they are limits on certain nonstandard contributions to neutrino scattering.

VALUE (10^{-32} cm^2)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
−2.1 to 3.3	90	[1] DENIZ	10	TEXO	Reactor $\overline{\nu}_e e$

• • • We do not use the following data for averages, fits, limits, etc. • • •

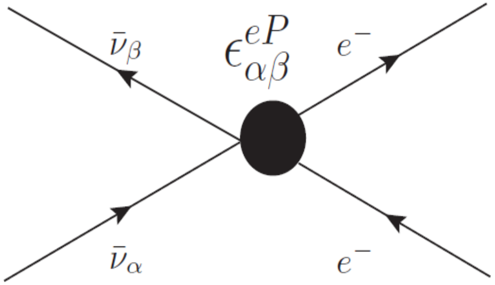
−0.53 to 0.68	90	[2] HIRSCH	03		$\nu_\mu e$ scat.
−8.2 to 9.9	90	[3] HIRSCH	03		anomalous $e^+ e^- \to \nu\overline{\nu}\gamma$
−2.97 to 4.14	90	[4] AUERBACH	01	LSND	$\nu_e e \to \nu_e e$
−0.6 to 0.6	90	VILAIN	95B	CHM2	$\nu_\mu e$ elastic scat.
0.9 ±2.7		ALLEN	93	CNTR	LAMPF $\nu e \to \nu e$
< 2.3	95	MOURAO	92	ASTR	HOME/KAM2 ν rates
< 7.3	90	[5] VIDYAKIN	92	CNTR	Reactor $\overline{\nu} e \to \overline{\nu} e$
1.1 ±2.3		ALLEN	91	CNTR	Repl. by ALLEN 93
−1.1 ±1.0		[6] AHRENS	90	CNTR	$\nu_\mu e$ elastic scat.
−0.3 ±1.5		[6] DORENBOS...	89	CHRM	$\nu_\mu e$ elastic scat.
		[7] GRIFOLS	89B	ASTR	SN 1987A

[1] DENIZ 10 observe reactor $\overline{\nu}_e e$ scattering with recoil kinetic energies 3–8 MeV using CsI(Tl) detectors. The observed rate and spectral shape are consistent with the Standard Model prediction, leading to the reported constraint on $\overline{\nu}_e$ charge radius.

NSI of Neutrino

- NSI of neutrino is first considered as an alternative mechanism for neutrino oscillation. However, NSI is now only allowed for lower pioneers effect to the neutrino oscillation and can be used to improve the sensitivities of neutrino oscillation experiments.
- Both neutrino oscillation and non-oscillation neutrino experiments are sensitive to NSI parameters and can give complementary results. Non-oscillation experiments provide direct measurement of NSI, while neutrino oscillation experiments are more sensitive to the propagation of NSI parameters due to matter effects.
- NSI can simply be considered as a modification of chiral coupling constants of $g_{L,R}$ with additional new physics parameters, in general.
- Some of the BSM model, among the few new physics scenarios, model dependent and independent NSI scenarios are chosen to investigate via neutrino-electron scattering channel.
- The model-independent NSI is considered or described as a four-Fermi point-like or so called zero-distance interaction.

Model Independent NSI of Neutrino (V-A) Form



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

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

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

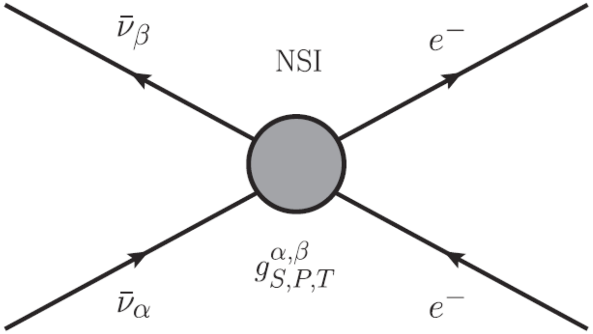
– ***V-A Form**, similar to the four Fermi*
  - *exchange of Higgs*
  - *Supersymmetric scalar bosons*
  - *New heavy gauge boson Z'*

(NU) NSI: ϵ^{eLR}_{ee}

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

- ❖ There is a strict bound on $|\epsilon^{eLR}_{e\mu}| < 7.7\times10^{-4}$ derived from $\mu \rightarrow 3e$ decay
- ❖ The main parameters will be $\epsilon^{eLR}_{e\tau}$ for FC NSI and ϵ^{eLR}_{ee} for NU-NSI.

Model Independent NSI of Neutrino (S, P, T) Form



– *Phenomenological studies of FC and FV NSIs of neutrinos have been extremely carried out with a variety of interaction channels and neutrino sources.*

– However, there are few studies that exists on scalar-, pseudoscalar-, or tensorial- type NSIs in the literature, mainly due to the motivation of ***V-A Structure*** of the SM and the assumption of their small contributions to the cross-section.

$$\left[\frac{d\sigma_{\nu_e,e}}{dT}\right]^{\mathrm{NSI}}_{\mathrm{S,P}} = \frac{2G_F^2 m_e}{\pi}\Big\{[(|g_S^{e,e}| + |g_P^{e,e}|)^2 + g_R\mathrm{Re}(g_S^{e,e} - g_P^{e,e})]\left(1 - \frac{T}{E_\nu}\right)^2 - (g_L + 1)\mathrm{Re}(g_S^{e,e} - g_P^{e,e})\frac{m_e T}{2E_\nu^2}\Big\}$$

$$\left[\frac{d\sigma_{\bar{\nu}_e,e}}{dT}\right]^{\mathrm{NSI}}_{\mathrm{S,P}} = \frac{2G_F^2 m_e}{\pi}\Big\{(|g_S^{e,e}| + |g_P^{e,e}|)^2 + g_R\mathrm{Re}(g_S^{e,e} - g_P^{e,e}) - (g_L + 1)\mathrm{Re}(g_S^{e,e} - g_P^{e,e})\frac{m_e T}{2E_\nu^2}\Big\}$$

$$\left[\frac{d\sigma}{dT}\right]^{\mathrm{NSI}}_{\mathrm{T}} = \frac{2G_F^2 m_e}{\pi}\sum_{\beta=e,\mu,\tau}(\varepsilon^{eT}_{e\beta})^2\left[2\left(1 - \frac{T}{2E_\nu}\right)^2 - \frac{m_e T}{2E_\nu^2}\right]$$

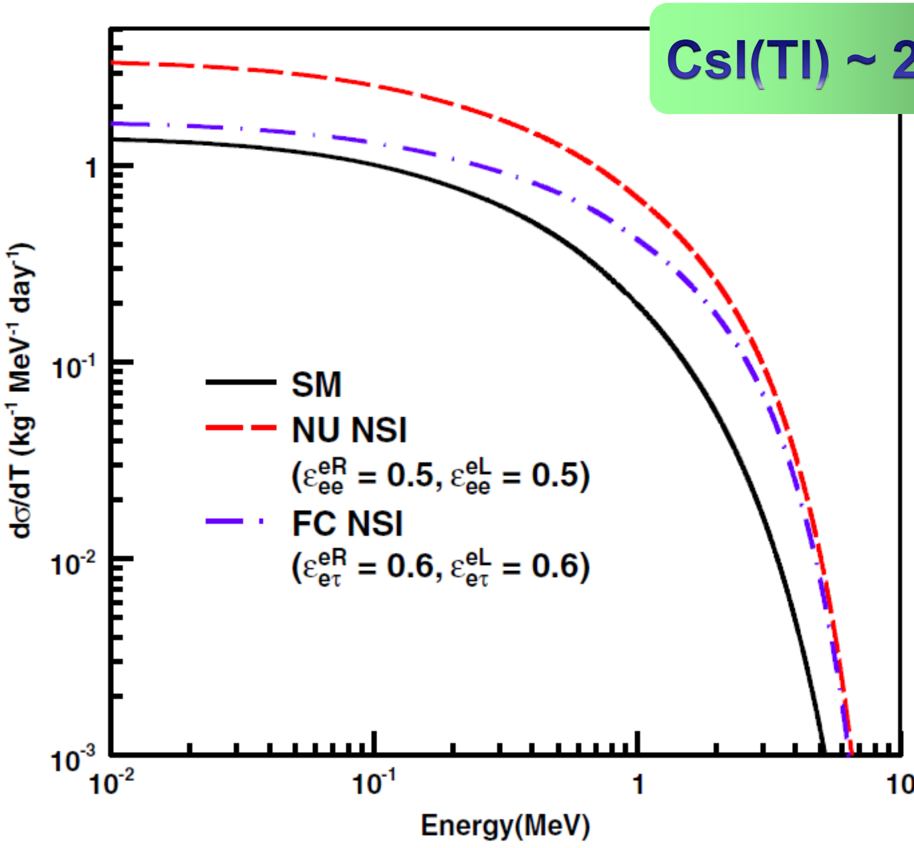
❖ The relevant fit parameters will be $\boxed{g^{e,e}_{S,P}}$ for Pseudo(scalar) NSI and $\boxed{g^{e,e}_{T}}$ for Tensorial NSI.

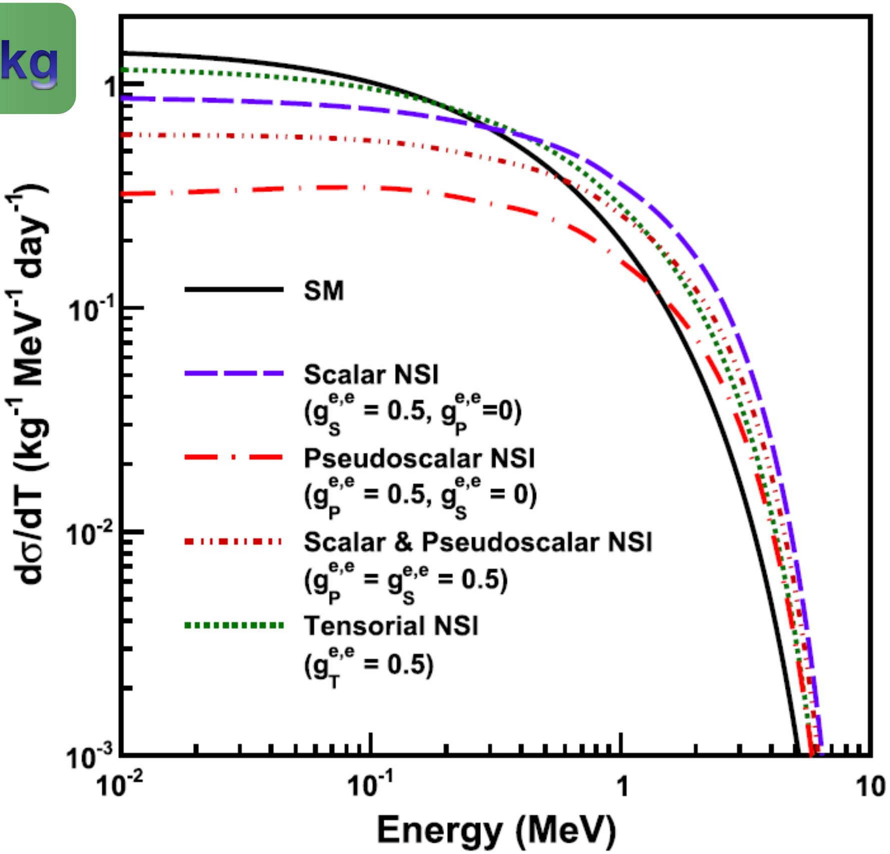
Model Independent NSI of Neutrino (V-A, S, P, T) Form

- $\nu_e - e^-$ scattering provide a sensitive tool to probe NSI

Observable spectrum with typical reactor neutrino "beam" & Typical values of NSI parameters

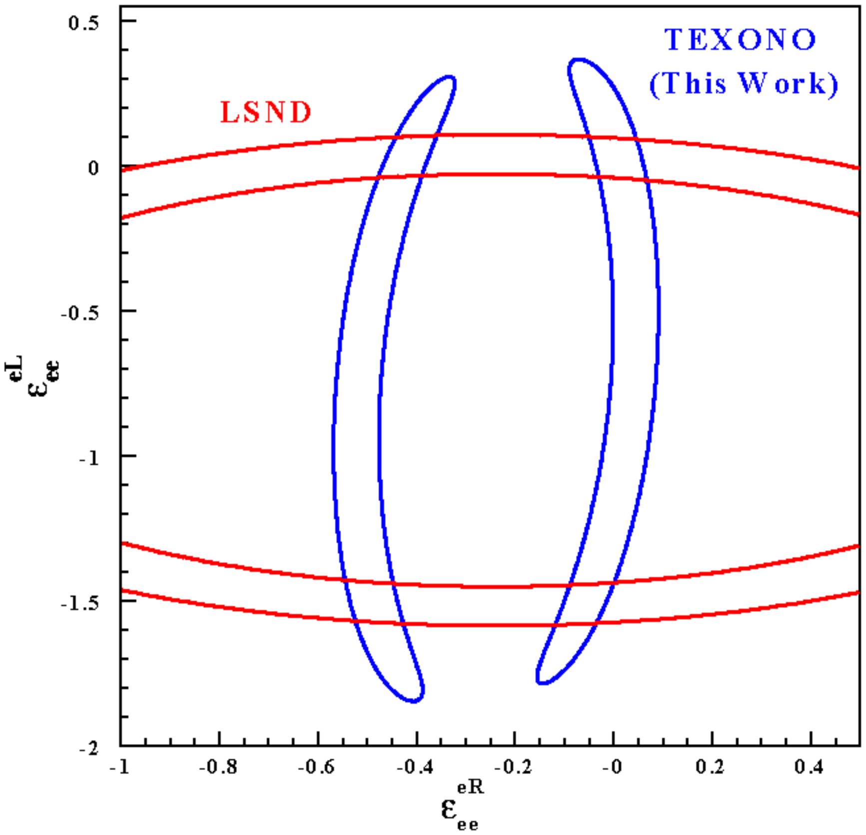
CsI(Tl) ~ 200 kg



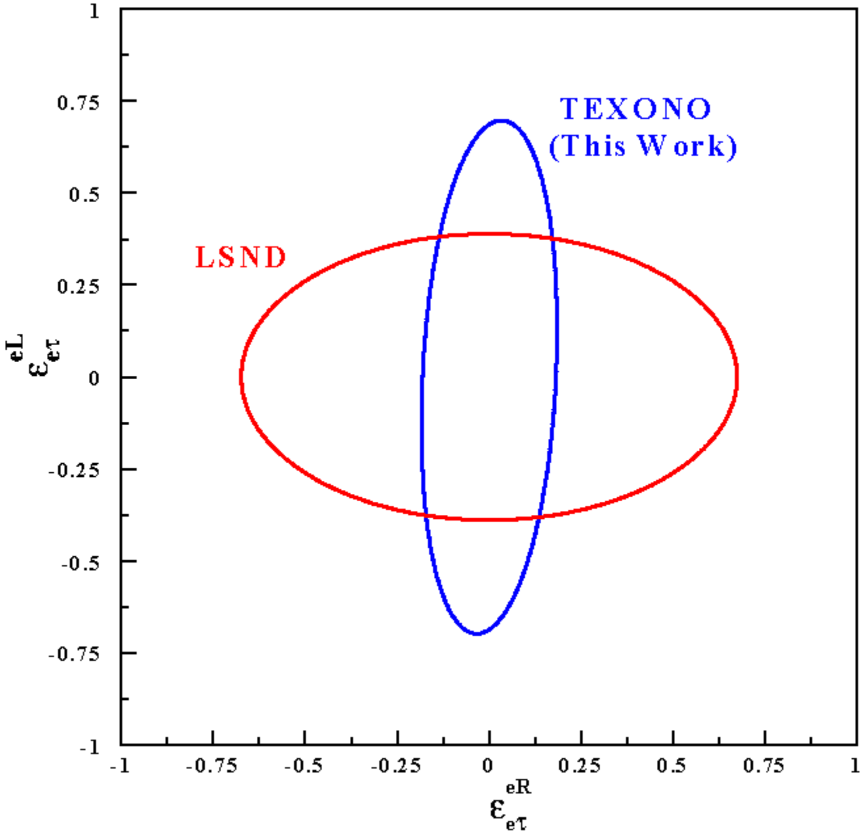


Comparison of Bounds of V-A NSI Parameters

Flavor Conserving
[Non-Universal (NU)]



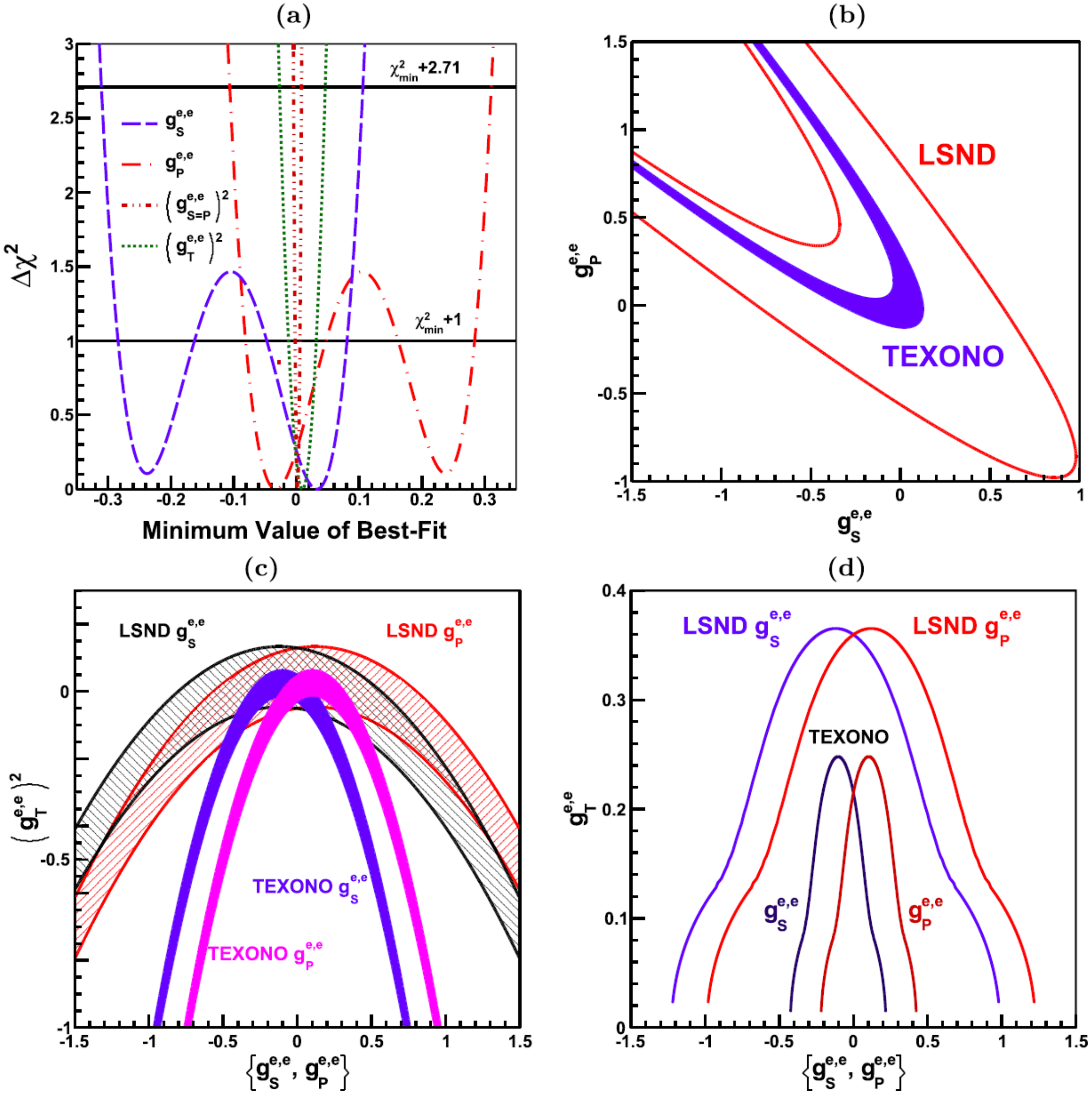
Flavor Violating
[Flavor Changing (FC)]



Phys. Rev. D 82, 033004 (2010)

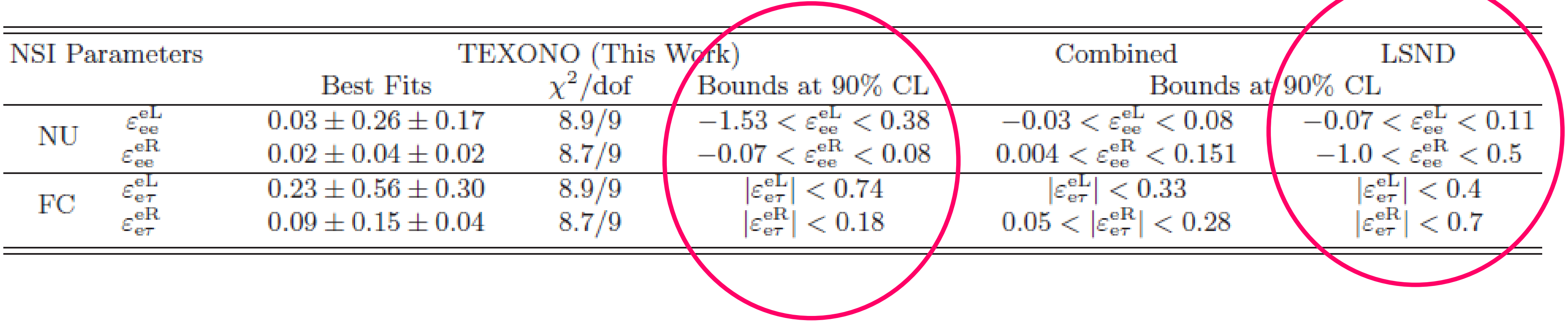
Comparison of Bounds of S-P-T NSI Parameters

Phys. Rev. D 95, 033008 (2017)

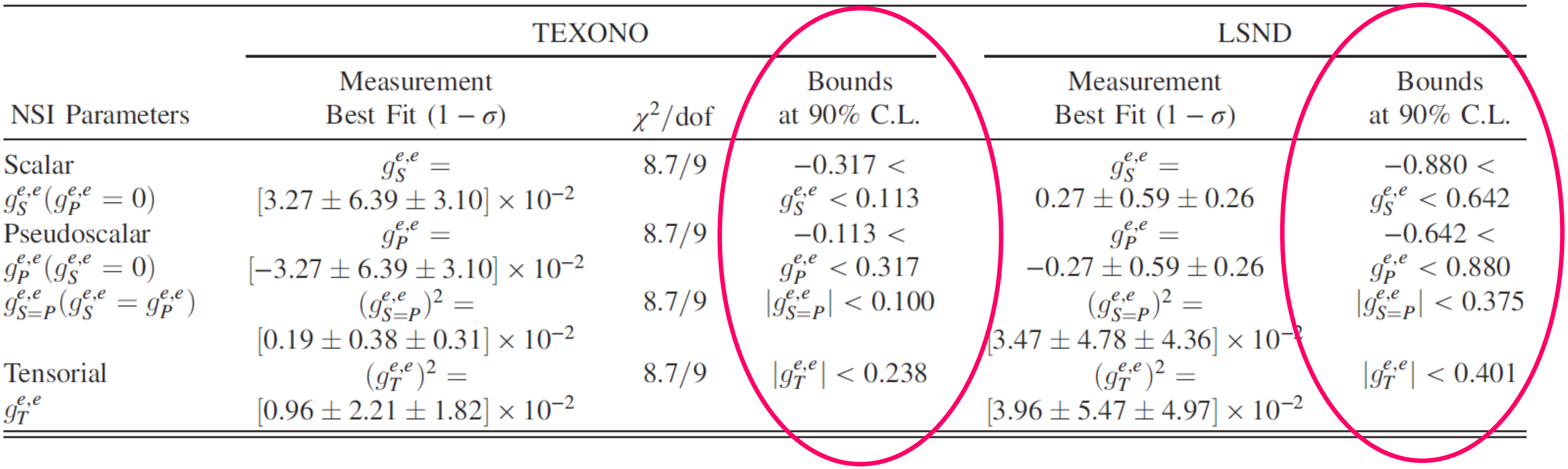


90% C.L. Bounds for one-parameter-at-a-time

Phys. Rev. D 82, 033004 (2010)
Phys. Rev. D 95, 033008 (2017)



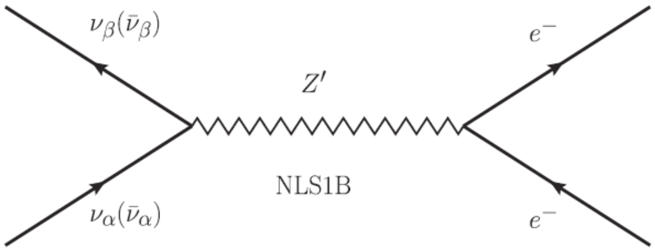
NSI Parameters		TEXONO (This Work) Best Fits	χ^2/dof	Bounds at 90% CL	Combined Bounds at 90% CL	LSND
NU	ε_{ee}^{eL}	$0.03 \pm 0.26 \pm 0.17$	8.9/9	$-1.53 < \varepsilon_{ee}^{eL} < 0.38$	$-0.03 < \varepsilon_{ee}^{eL} < 0.08$	$-0.07 < \varepsilon_{ee}^{eL} < 0.11$
	ε_{ee}^{eR}	$0.02 \pm 0.04 \pm 0.02$	8.7/9	$-0.07 < \varepsilon_{ee}^{eR} < 0.08$	$0.004 < \varepsilon_{ee}^{eR} < 0.151$	$-1.0 < \varepsilon_{ee}^{eR} < 0.5$
FC	$\varepsilon_{e\tau}^{eL}$	$0.23 \pm 0.56 \pm 0.30$	8.9/9	$\lvert\varepsilon_{e\tau}^{eL}\rvert < 0.74$	$\lvert\varepsilon_{e\tau}^{eL}\rvert < 0.33$	$\lvert\varepsilon_{e\tau}^{eL}\rvert < 0.4$
	$\varepsilon_{e\tau}^{eR}$	$0.09 \pm 0.15 \pm 0.04$	8.7/9	$\lvert\varepsilon_{e\tau}^{eR}\rvert < 0.18$	$0.05 < \lvert\varepsilon_{e\tau}^{eR}\rvert < 0.28$	$\lvert\varepsilon_{e\tau}^{eR}\rvert < 0.7$



	TEXONO			LSND	
NSI Parameters	Measurement Best Fit $(1-\sigma)$	χ^2/dof	Bounds at 90% C.L.	Measurement Best Fit $(1-\sigma)$	Bounds at 90% C.L.
Scalar $g_S^{e,e} (g_P^{e,e} = 0)$	$g_S^{e,e} = [3.27 \pm 6.39 \pm 3.10] \times 10^{-2}$	8.7/9	$-0.317 < g_S^{e,e} < 0.113$	$g_S^{e,e} = 0.27 \pm 0.59 \pm 0.26$	$-0.880 < g_S^{e,e} < 0.642$
Pseudoscalar $g_P^{e,e} (g_S^{e,e} = 0)$	$g_P^{e,e} = [-3.27 \pm 6.39 \pm 3.10] \times 10^{-2}$	8.7/9	$-0.113 < g_P^{e,e} < 0.317$	$g_P^{e,e} = -0.27 \pm 0.59 \pm 0.26$	$-0.642 < g_P^{e,e} < 0.880$
$g_{S=P}^{e,e} (g_S^{e,e} = g_P^{e,e})$	$(g_{S=P}^{e,e})^2 = [0.19 \pm 0.38 \pm 0.31] \times 10^{-2}$	8.7/9	$\lvert g_{S=P}^{e,e}\rvert < 0.100$	$(g_{S=P}^{e,e})^2 = [3.47 \pm 4.78 \pm 4.36] \times 10^{-2}$	$\lvert g_{S=P}^{e,e}\rvert < 0.375$
Tensorial $g_T^{e,e}$	$(g_T^{e,e})^2 = [0.96 \pm 2.21 \pm 1.82] \times 10^{-2}$	8.7/9	$\lvert g_T^{e,e}\rvert < 0.238$	$(g_T^{e,e})^2 = [3.96 \pm 5.47 \pm 4.97] \times 10^{-2}$	$\lvert g_T^{e,e}\rvert < 0.401$

Model Dependent NSI of Neutrino

Phys. Rev. D 96, 035017 (2017)



–*The exchange of new massive particles can be a possible origin of NSI of neutrinos, manifested as anomalies in the measurable total or differential cross sections.*

–*Constrains on couplings of several BSM physics scenarios, mediated by massive intermediate particles including extra Z', New Light Vector Boson, a charged Higgs boson, and Dark Photon are placed.*

$$\left[\frac{d\sigma}{dT}(\overset{(-)}{\nu}_e e)\right]_{\mathrm{SM}} = \frac{2G_F^2 m_e}{\pi}\left[a^2 + b^2\left(1-\frac{T}{E_\nu}\right)^2 - ab\frac{m_e T}{E_\nu^2}\right]$$

$$g_{R(L)} \to \tilde{g}_{R(L)} = g_{R(L)} + \tilde{\varepsilon}_{ee}^{R(L)}.$$

Coefficients	$\bar\nu_e - e$	$\nu_e - e$
a^2	$\tilde g_R^2 + \sum_{\ell'\neq e}\lvert\tilde\varepsilon_{e\ell'}^R\rvert^2$	$(\tilde g_L + 1)^2 + \sum_{\ell'\neq e}(\tilde\varepsilon_{e\ell'}^L)^2$
b^2	$(\tilde g_L + 1)^2 + \sum_{\ell'\neq e}\lvert\tilde\varepsilon_{e\ell'}^L\rvert^2$	$\tilde g_R^2 + \sum_{\ell'\neq e}(\tilde\varepsilon_{e\ell'}^R)^2$
ab	$\tilde g_R(\tilde g_L + 1) + \sum_{\ell'\neq e}\lvert\tilde\varepsilon_{e\ell'}^R\rvert\lvert\tilde\varepsilon_{e\ell'}^L\rvert$	

Extra Z-Prime Gauge Boson

- A possible new vector boson predicted in many extensions of the SM called the Z-prime gauge boson, which is massive, electrically neutral and color-singlet hypothetical particle of spin 1.
- *New massive U(1) gauge bosons emerge in grand unified and superstring theories such as SO(10) and* E_6 *, in theories of extra space-time dimensions of the SM gauge bosons.*
- *There are various physical models of BSM that suggests different Z' bosons. The most popular of them are the* ***E_6 String Type Model, Left-Right Symmetric Model, and the Sequential Standard Model (SSM).***

$$\boxed{E_6\ \text{String Type}}\left(Z'_\chi,\ Z'_\eta\ \text{and}\ Z'_\psi \rightarrow \cos_\beta = -1,\ 0,\ \text{and}\ \sqrt{3/8}\right)$$

$$g_{R(L)} \rightarrow \tilde{g}_{R(L)} = g_{R(L)} + \tilde{\varepsilon}_{ee}^{R(L)}$$

$$\tilde{\varepsilon}_{ee}^{R} = 2\gamma \sin^2\theta_W \rho_{\nu e}^{NC} \left(\frac{\cos_\beta}{2\sqrt{6}} - \frac{\sin_\beta}{3}\sqrt{\frac{5}{8}}\right)\left(\frac{3\cos_\beta}{2\sqrt{6}} + \frac{\sin_\beta}{3}\sqrt{\frac{5}{8}}\right)$$

$$\tilde{\varepsilon}_{ee}^{L} = 2\gamma \sin^2\theta_W \rho_{\nu e}^{NC} \left(\frac{3\cos_\beta}{2\sqrt{6}} + \frac{\sin_\beta}{3}\sqrt{\frac{5}{8}}\right)^2 \quad , \quad \gamma = \left(\frac{M_Z}{M_{Z'}}\right)^2$$

Extra Z-Prime Gauge Boson

Left-Right Model

$$g_R = A g_R + B g_L \quad , \quad g_L = A g_L + B g_R$$

$$A = 1 + \frac{\sin^4\theta_W}{1 - 2\sin^2\theta_W}\gamma \quad , \quad B = \frac{\sin^2\theta_W(1-\sin^2\theta_W)}{1-2\sin^2\theta_W}$$

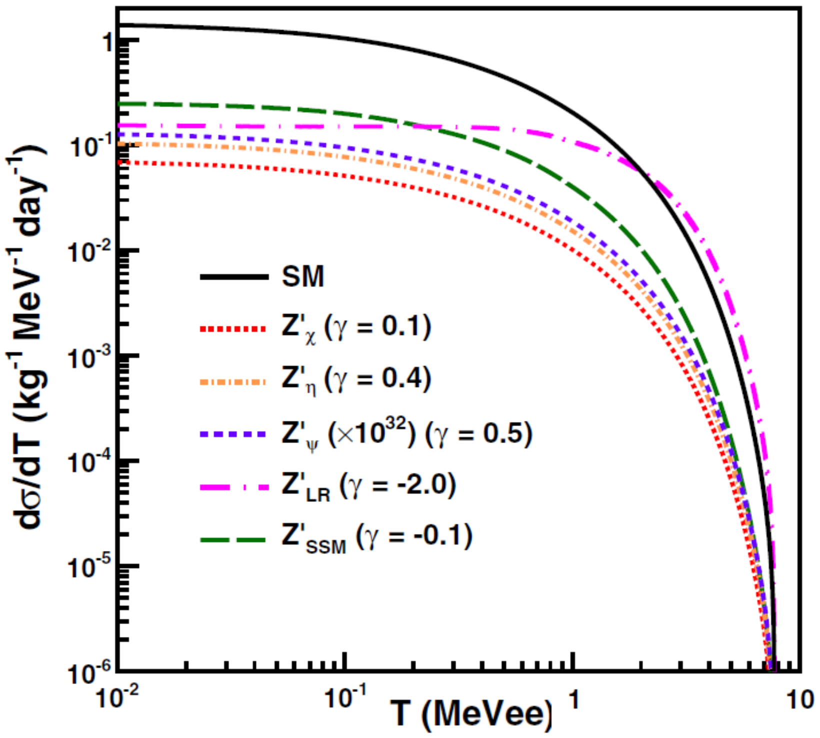
Sequential Standard Model (SSM)

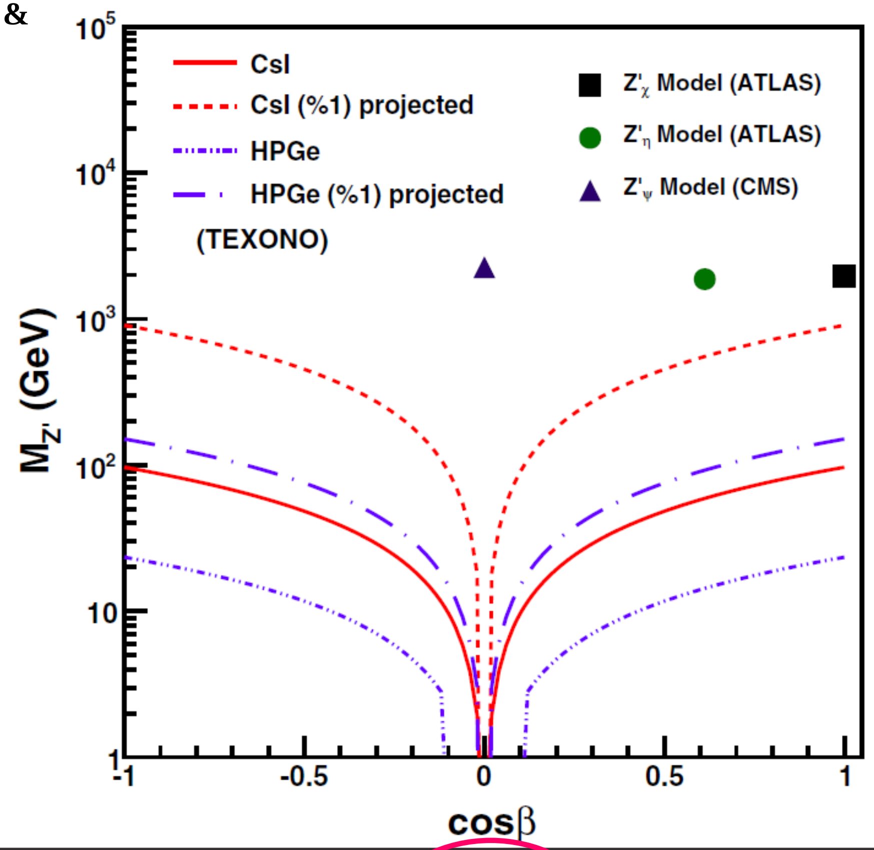
$$\left[\frac{d\sigma}{dT}(\bar{\nu}_e e)\right]_{Z'_{SSM}} = \frac{2G_F^2 m_e}{\pi}\left\{\gamma\left[4g_L\left(1-\frac{T}{E_\nu}\right)^2 - 2g_R\frac{m_e T}{E_\nu^2}\right]\right.$$

$$\left. + \gamma^2\left[g_R^2 + g_L^2\left(1-\frac{T}{E_\nu}\right)^2 - g_L g_R\frac{m_e T}{E_\nu^2}\right]\right\}$$

Extra Z-Prime Gauge Boson

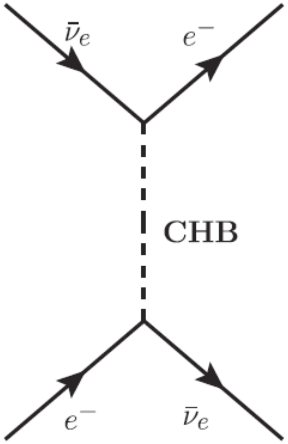
Observable spectrum with typical reactor neutrino "beam" &
Typical values of NSI parameters

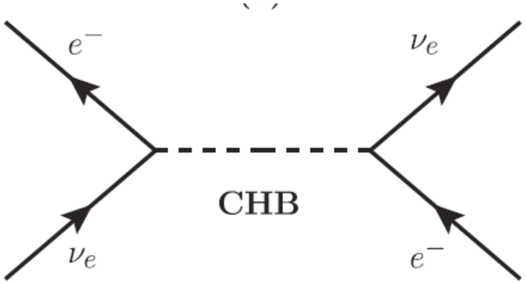




Model		Best fit for γ (1σ)	$\chi^2_{\rm min}$/dof	$M_{Z'}$ bounds at 95% C.L. (GeV)	Projected (1%) $M_{Z'}$ bounds at 95% C.L. (GeV)	Current limit [PDG 2016] at 95% C.L. (GeV)
	Z'_χ	$0.16 \pm 0.41 \pm 0.31$	8.7/9	>85	>915	>1970 (ATLAS)
E_6 string type	Z'_η	$0.43 \pm 1.01 \pm 0.83$	8.7/9	>52	>566	>1870 (ATLAS)
	Z'_ψ	$[0.44 \pm 1.13 \pm 0.95] \times 10^{-18}$	8.7/9	>0	>0	>2260 (CMS)
Z'_{LR}		$-8.02 \pm 5.28 \pm 0.61$	7.8/9	>44	>413	>1162 (RVUE)
Z'_{SSM}		$-0.04 \pm 0.14 \pm 0.06$	8.7/9	>172	>1822	>1830 (ATLAS)

Charged Higgs Boson





– Leptons, quarks and gauge Bosons acquire their mass through the Higgs Mechanism, while neutrinos still remain massless in the SM.

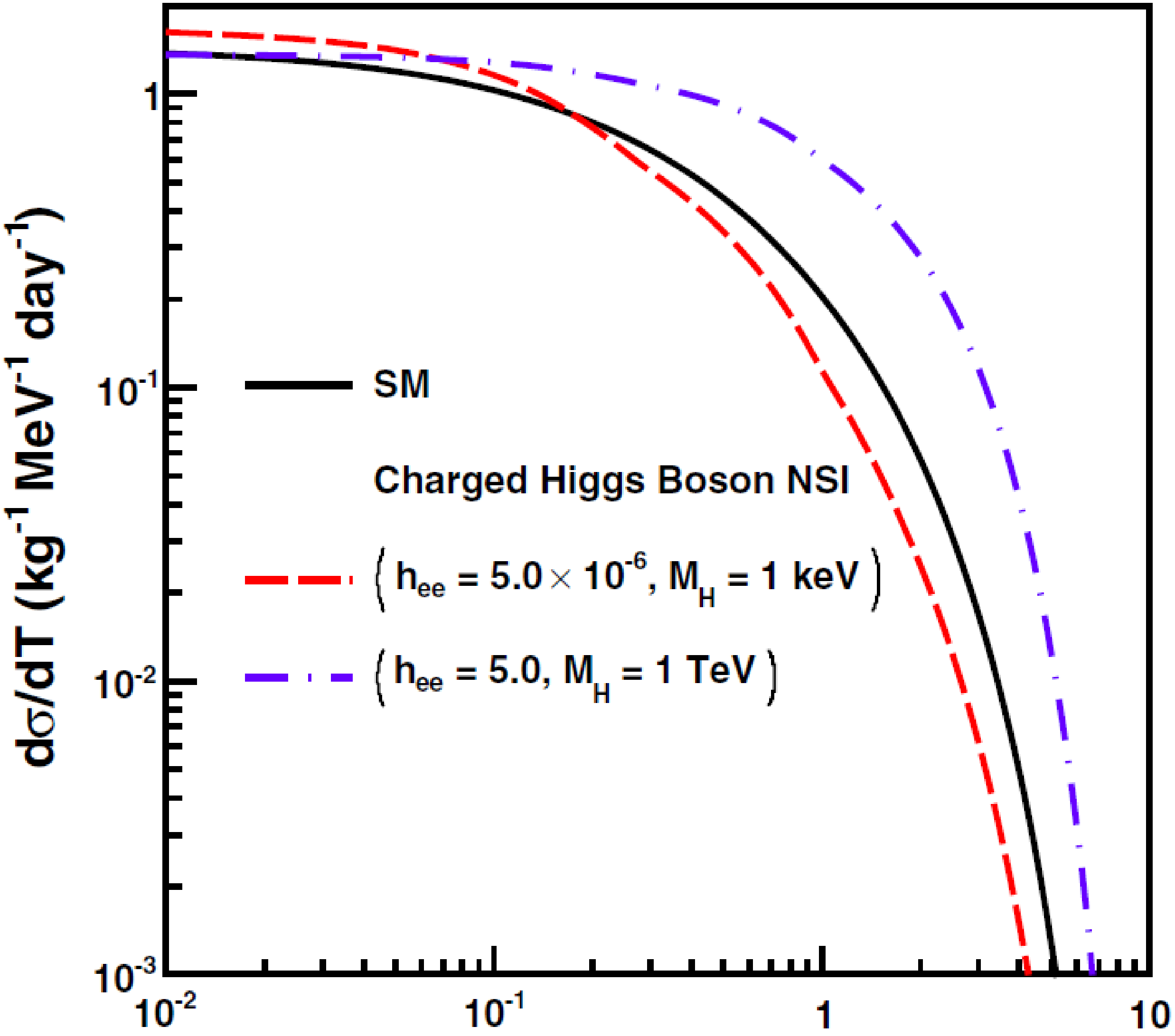
– *In order to introduce and explain the smallness of neutrino masses withouht requiring an extra right-handed neutrino, one of the simplest model is the Higgs Triplet Model (HTM).*

$$\left[\frac{d\sigma_{\bar{\nu}_e e}}{dT}\right]_{CHB} = \frac{m_e}{4\pi}\frac{[h_{ee}^2]^2}{[m_e(m_e+2E_\nu)-M_H^2]^2}$$

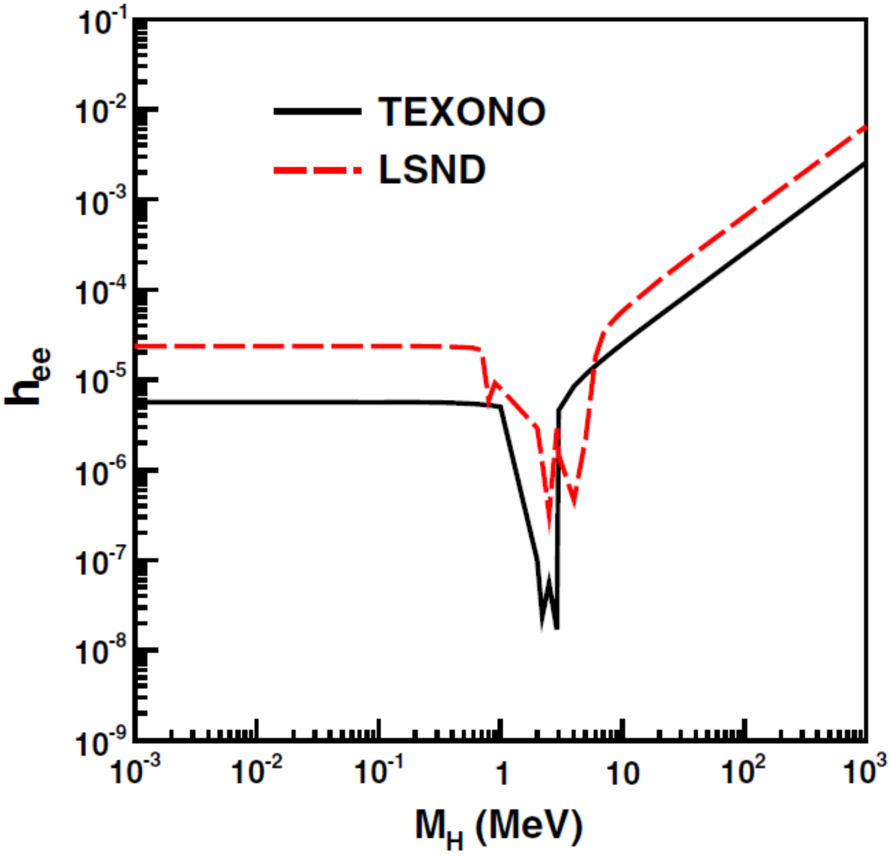
$$\left[\frac{d\sigma_{\nu_e e}}{dT}\right]_{CHB} = \frac{m_e}{4\pi}\frac{[h_{ee}^2]^2(1-T/E_\nu)^2}{[m_e^2+2m_e(E_\nu-T)-M_H^2]^2}$$

Charged Higgs Boson

Observable spectrum with typical reactor neutrino "beam" & Typical values of NSI parameters



Charged Higgs Boson



for TEXONO Experiment @ 90% C.L.

$$h_{ee} < 5.63 \times 10^{-6}$$

$$h_{ee}/M_H < 2.57 \times 10^{-3}\ \mathrm{GeV}^{-1}$$

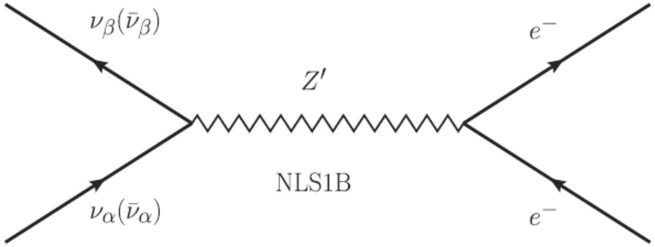
for LSND Experiment @90% C.L.

$$h_{ee} < 23.6 \times 10^{-6}$$

$$h_{ee}/M_H < 6.48 \times 10^{-3}\ \mathrm{GeV}^{-1}$$

	h_{ee} $(\times 10^{-6})$	
M_H	TEXONO	LSND
1 MeV	<4.99	<8.03
2 MeV	<0.09	<2.91
2.2 MeV	<0.02	<1.22
2.5 MeV	<0.06	<0.32
2.9 MeV	<0.02	<2.88
3 MeV	<4.58	<1.47
4 MeV	<8.45	<0.46
5 MeV	<11.46	<2.26
6 MeV	<14.27	<17.67
10 MeV	<25.02	<57.57

New Light Vector Boson



–*The mediators can be as light which is the range of low-energy experiments.*

–*A spin-1 particle could also be involved in explaining*

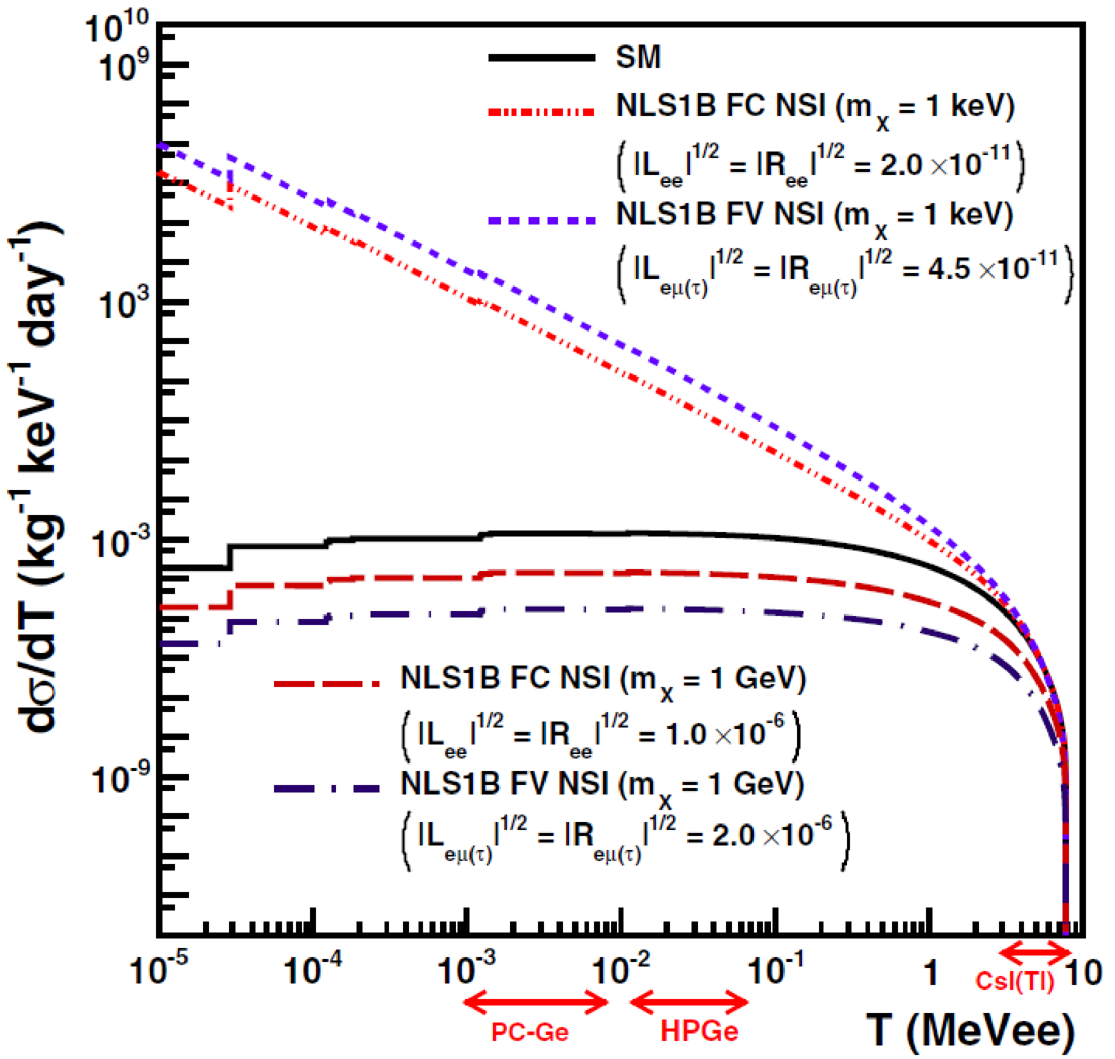
- *NuTeV anomaly*
- *muon anomalous magnetic moment value*
- *can couple to DM and non-baryonic matter in MeV scale*
- *for the annihilation that is seen as the unexplained 511 keV gamma emissions anomaly from the galactic bulge*
- *the anomalous CP-violation in the mixing of neutral B-mesons.*

$$\tilde{\varepsilon}^R_{e\ell'} = \frac{R_{e\ell'}}{2\sqrt{2}G_F(2m_eT + m_X^2)} = \frac{m_X^2}{2m_eT + m_X^2}\varepsilon^R_{e\ell'} \qquad \varepsilon^R_{e\ell'} = \frac{R_{e\ell'}}{2\sqrt{2}G_F m_X^2}$$

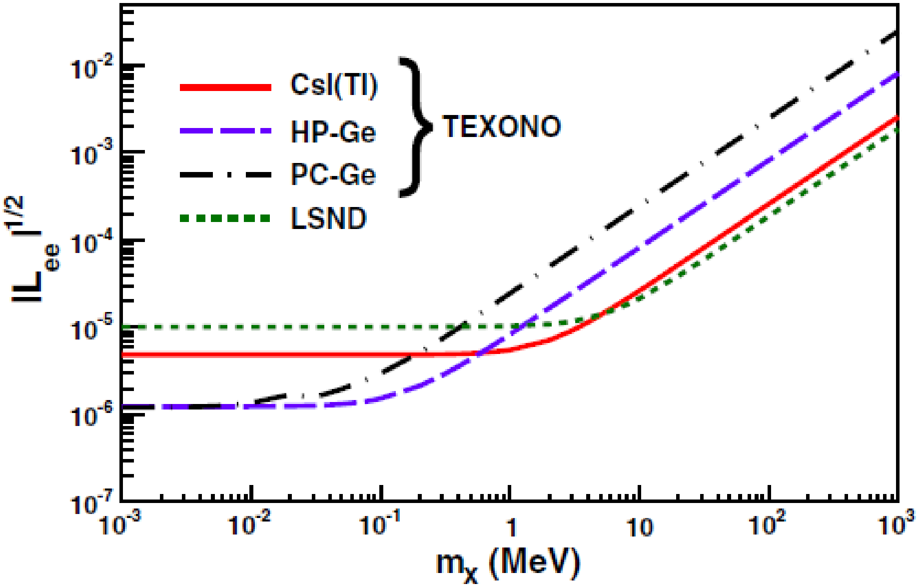
$$\tilde{\varepsilon}^L_{e\ell'} = \frac{L_{e\ell'}}{2\sqrt{2}G_F(2m_eT + m_X^2)} = \frac{m_X^2}{2m_eT + m_X^2}\varepsilon^L_{e\ell'} \qquad \varepsilon^L_{e\ell'} = \frac{L_{e\ell'}}{2\sqrt{2}G_F m_X^2}$$

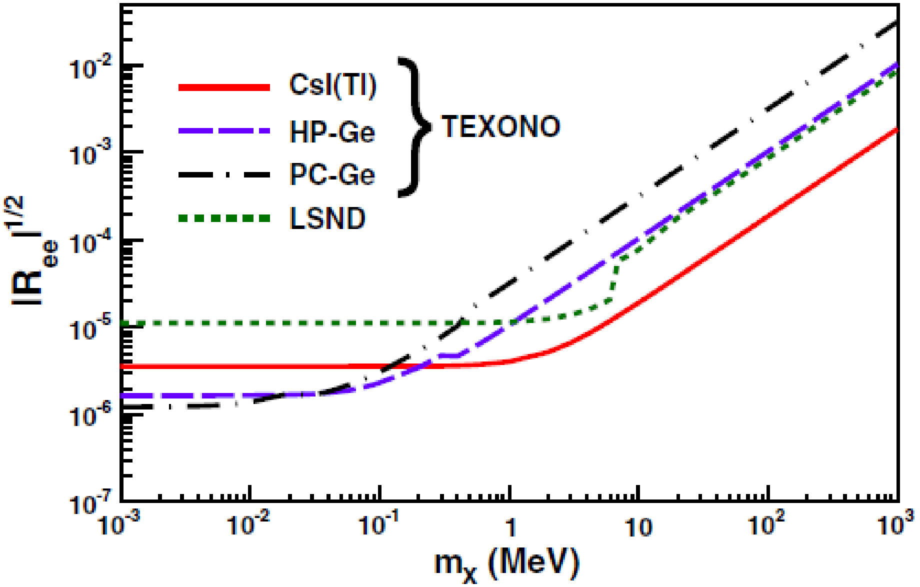
New Light Vector Boson

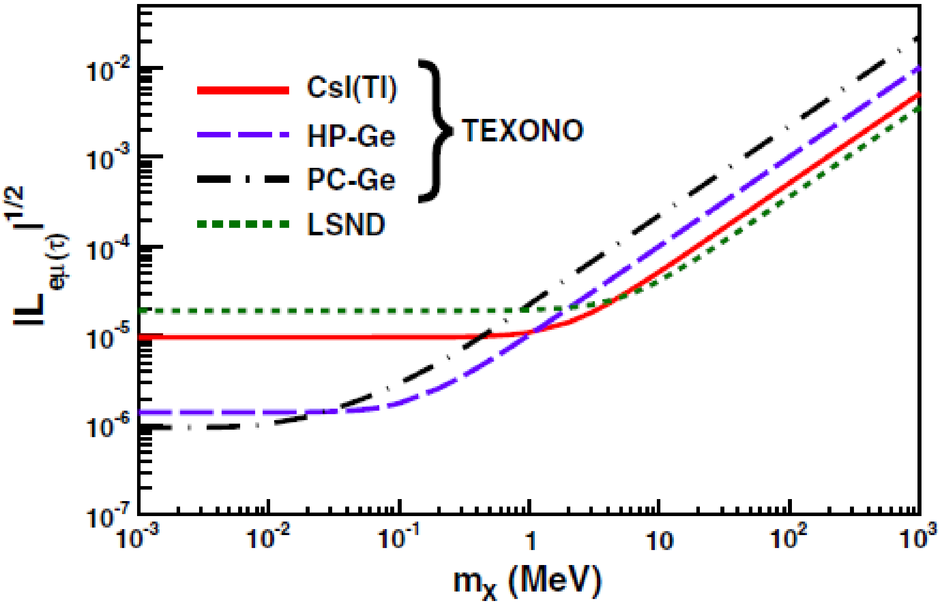
Observable spectrum with typical reactor neutrino "beam" &
Typical values of NSI parameters

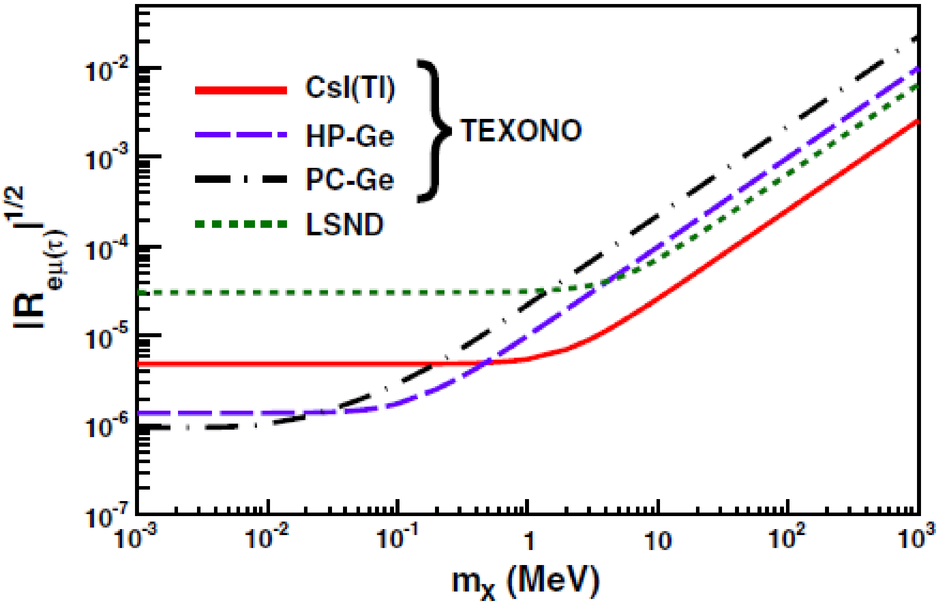


New Light Vector Boson

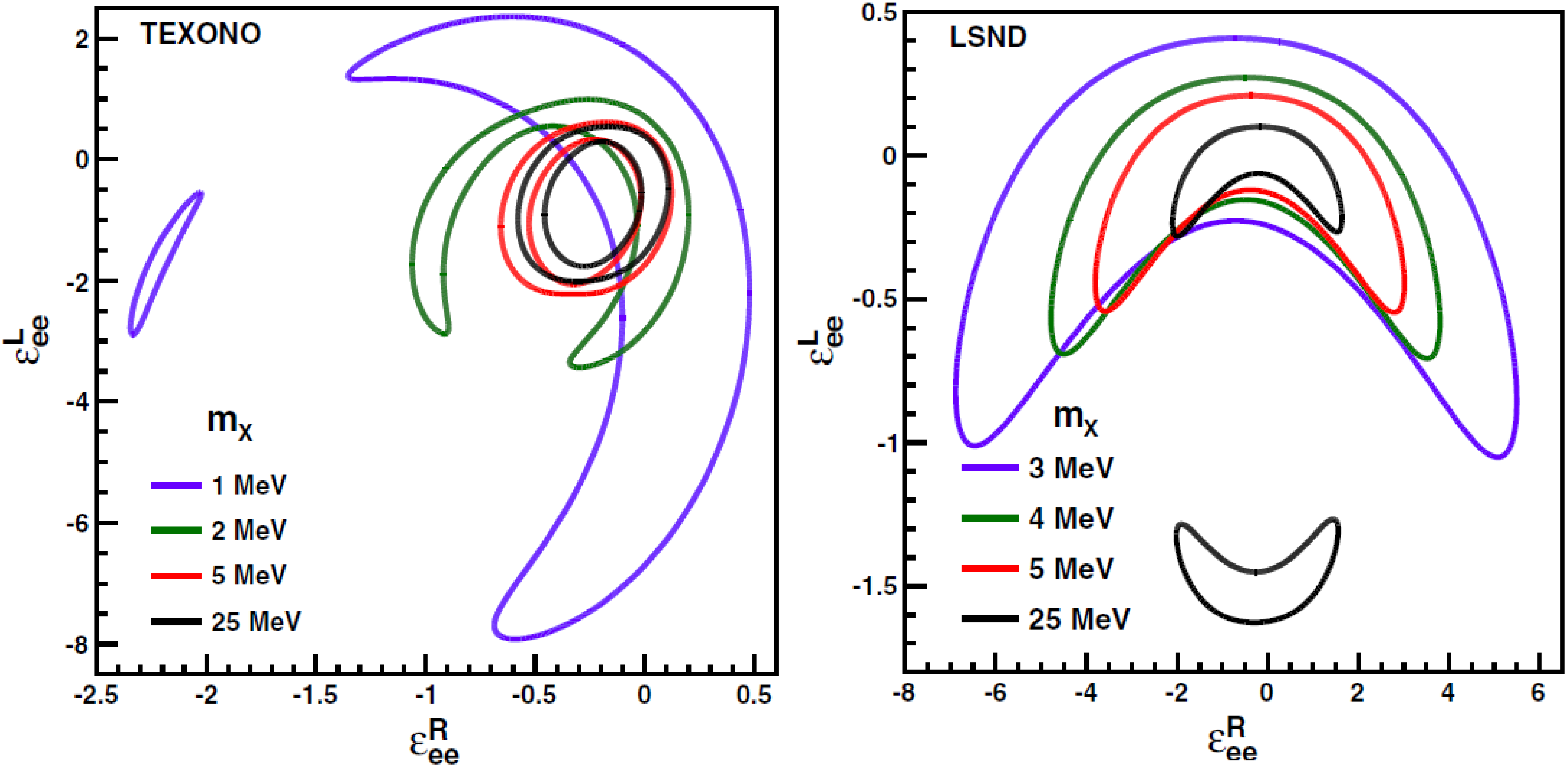




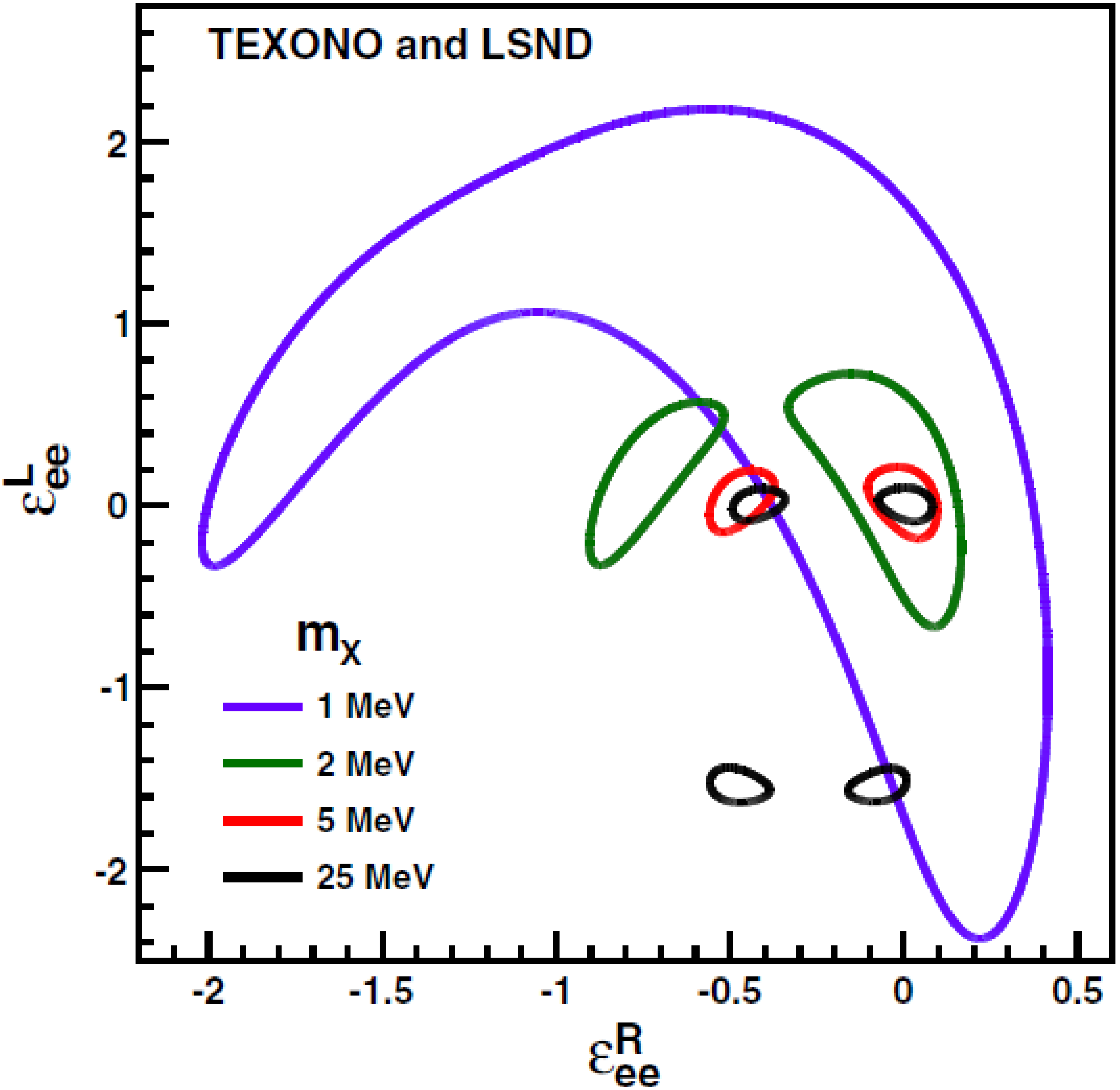




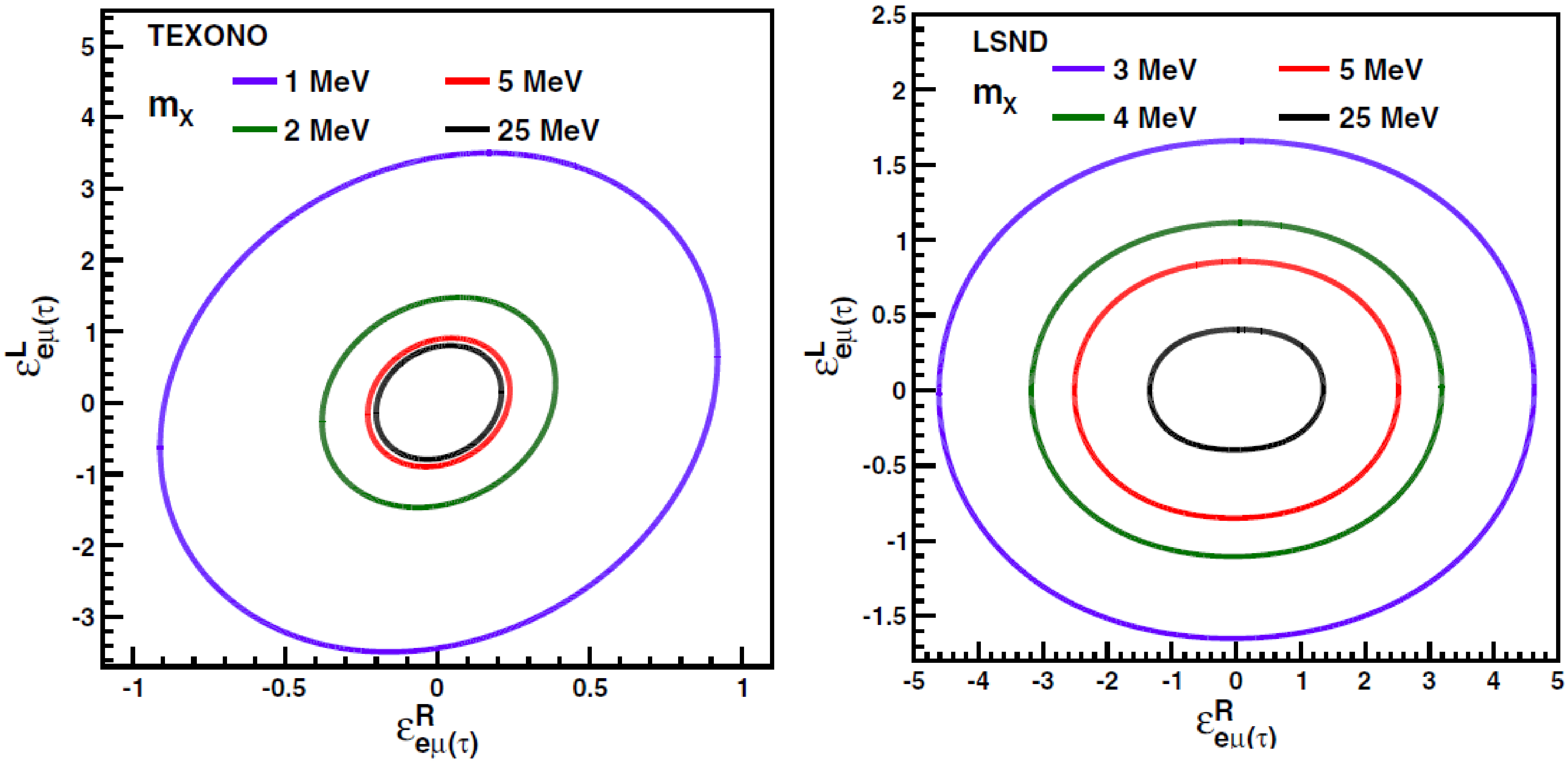
New Light Vector Boson Flavor Conserving (FC)



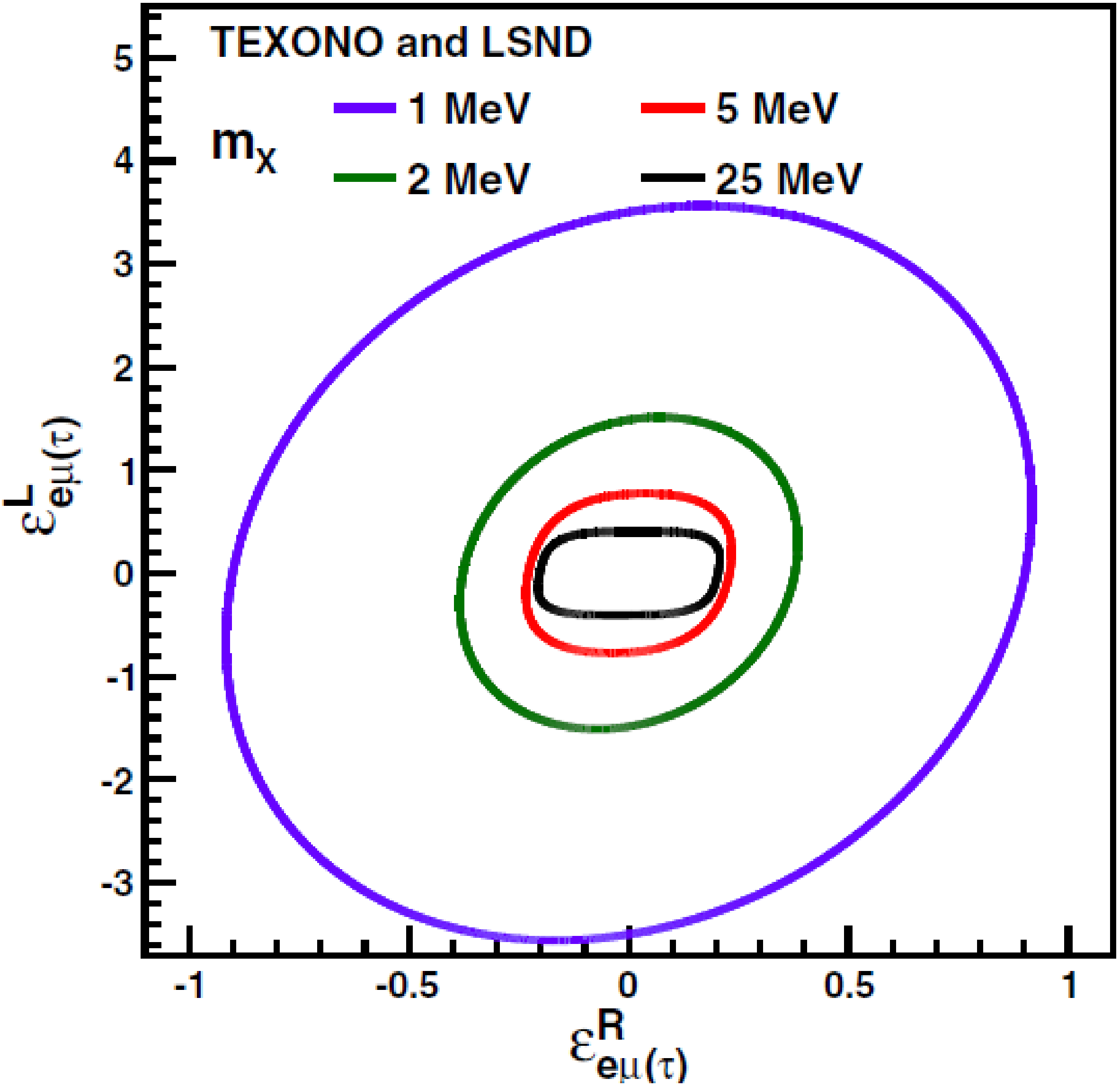
New Light Vector Boson
Flavor Conserving (FC) – Global Fitting



New Light Vector Boson Flavor Violating (FV)



New Light Vector Boson
Flavor Violating (FV) – Global Fitting



Dark Photon

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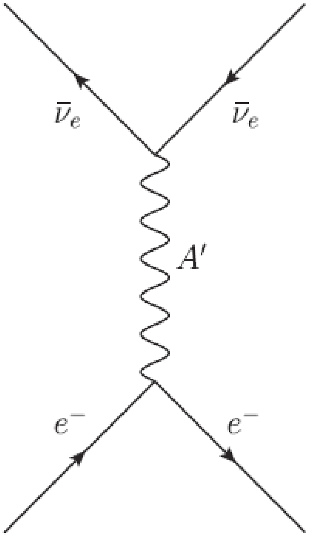
- The idea of the existence of a so-called hidden sector interacting with the SM through various portals is one such extension of the SM aiming to explain some of the issues that SM fails to explain.
- Dark Photon sector connected with SM through a U(1) gauging, like $U(1)_{B\text{-}L}$, where the DP as the gauge field of the group interacts with any SM particle with a non-zero B-L number at three level.

The interactions of neutrinos with electrons via *t*-channel dark photon A' exchange:



The kinetic mixing between DP and the SM neutral gauge bosons are ignored.

The differential cross section for neutrino-electron scattering via dark photon exchange

$$\left[\frac{d\sigma}{dT}(\nu e^- \to \nu e^-)\right]_{\rm DP} = \frac{g^4_{\rm B-L} m_e}{4\pi E_\nu^2 (M_{A'}^2 + 2m_e T)^2}(2E_\nu^2 + T^2 - 2TE_\nu - m_e T)$$

Dark Photon – Interference Term

The contribution to cross sections from the interference of this gauged B − L model with the SM cannot be neglected for most of the neutrino-electron scattering experiments.

$$\frac{d\sigma_{\mathrm{INT}}(\bar{\nu}_e e^-)}{dT} = \frac{g^2_{\mathrm{B-L}} G_F m_e}{2\sqrt{2}E_\nu^2 \pi (M^2_{A'} + 2mT)}(2E_\nu^2 + 2T^2 - T(4E_\nu + m_e) + \beta)$$

$$\frac{d\sigma_{\mathrm{INT}}(\nu_e e^-)}{dT} = \frac{g^2_{\mathrm{B-L}} G_F m_e}{2\sqrt{2}E_\nu^2 \pi (M^2_{A'} + 2mT)}(2E_\nu^2 - m_e T + \beta)$$

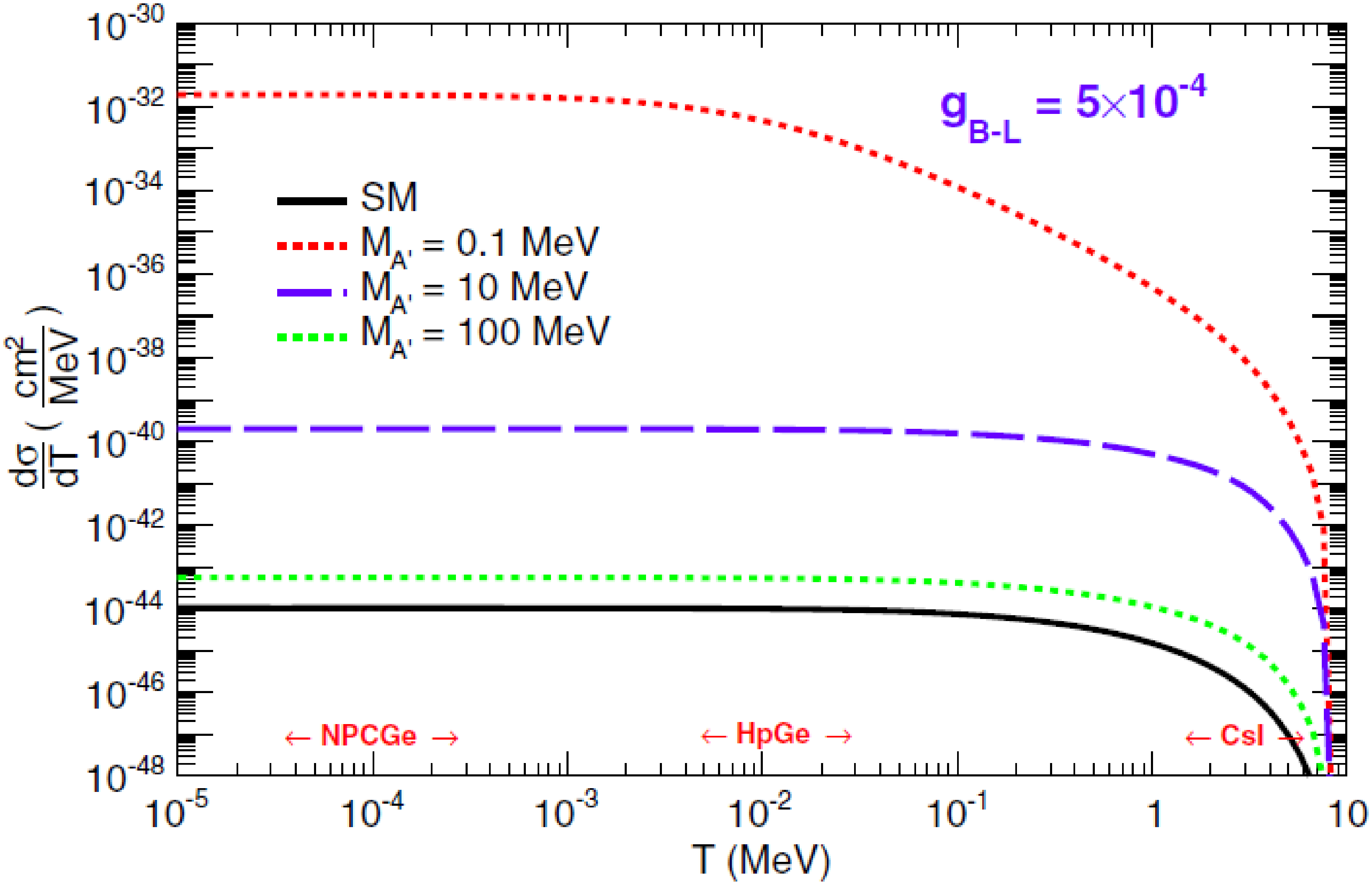
$$\frac{d\sigma_{\mathrm{INT}}(\bar{\nu}_\alpha e^-)}{dT} = \frac{g^2_{\mathrm{B-L}} G_F m_e}{2\sqrt{2}E_\nu^2 \pi (M^2_{A'} + 2mT)}(-2E_\nu^2 - 2T^2 + T(4E_\nu + m_e) + \beta)$$

$$\frac{d\sigma_{\mathrm{INT}}(\nu_\alpha e^-)}{dT} = \frac{g^2_{\mathrm{B-L}} G_F m_e}{2\sqrt{2}E_\nu^2 \pi (M^2_{A'} + 2mT)}(-2E_\nu^2 + m_e T + \beta)$$

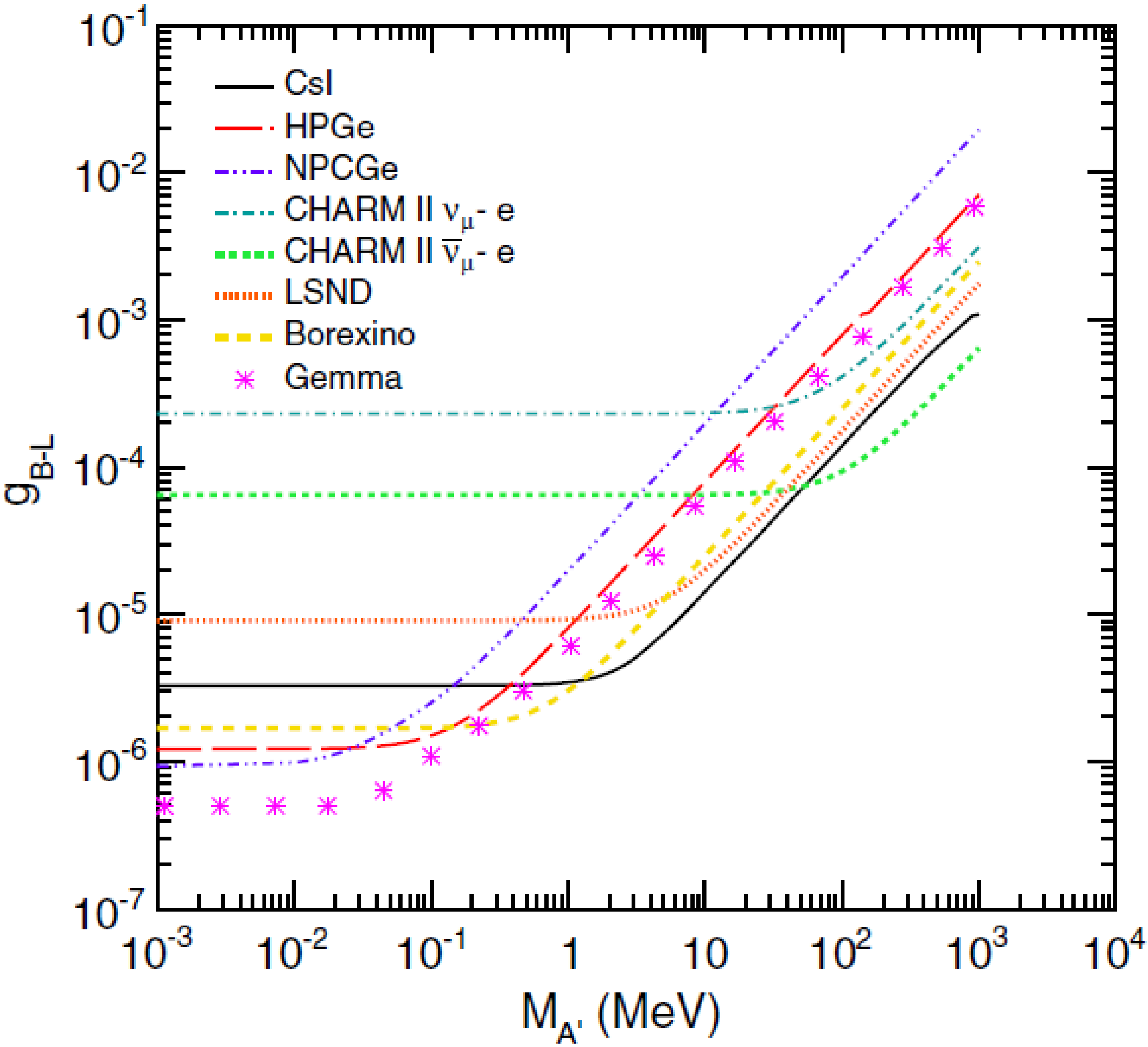
$$\boxed{\beta = \sin^2\theta_{\mathrm{W}}(8E_\nu^2 - 8E_\nu T - 4m_e T + 4T^2)}$$

Dark Photon

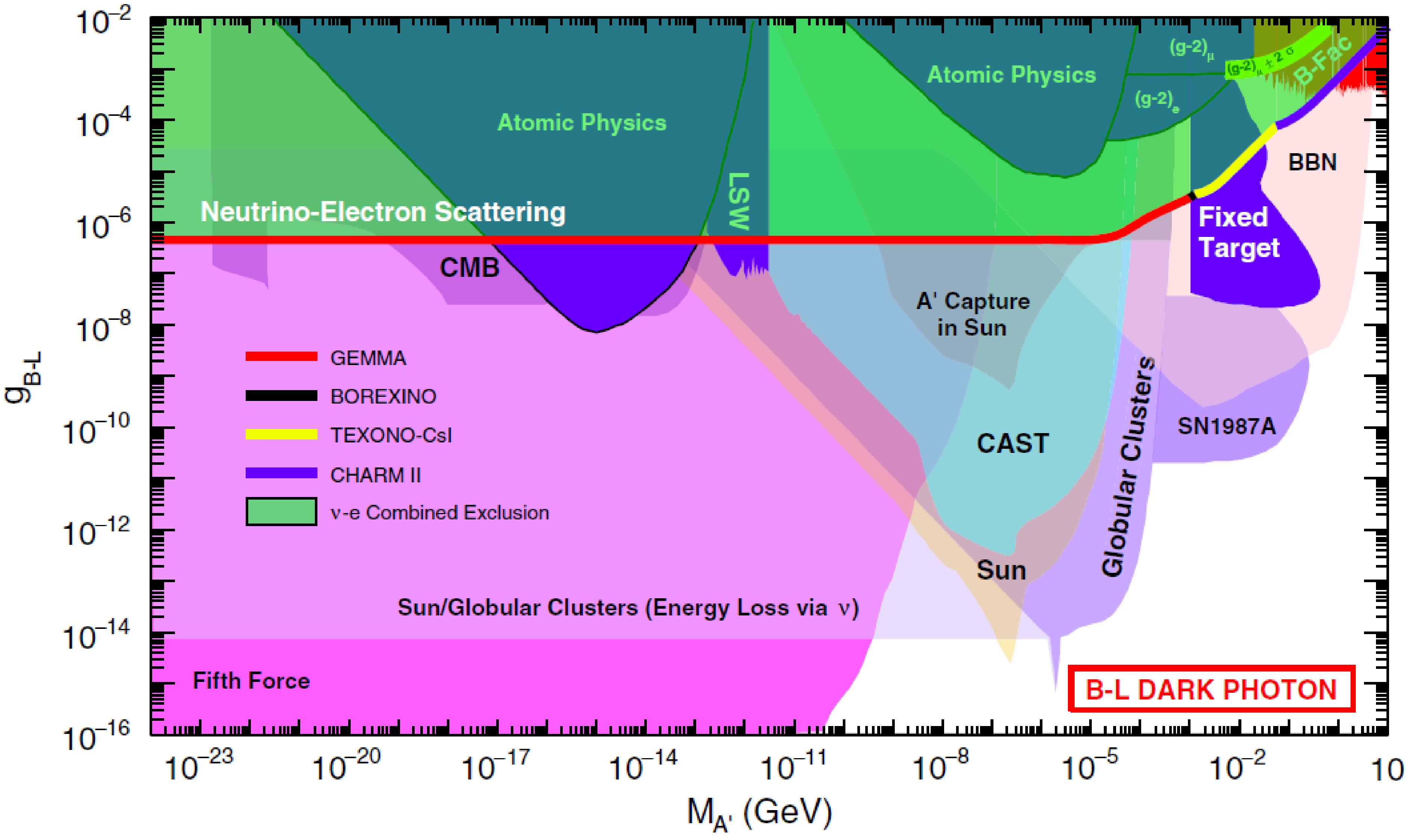
Observable spectrum with typical reactor neutrino "beam" & Typical values of NSI parameters



Dark Photon Exclusion Plot



Dark Photon – Global Exclusion Plot



Summary

- **Detector:** CsI(Tl) Scintillating Crystal Array (~ 200 kg)
  - Threshold: 3 MeV
  - $\sigma(\bar{\nu}_e - e^-)$ 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 :**

- **via Neutrino – Electron Elastic Scattering Channel:**
  - Model Dependent and Model Independent NSI have been studied.
  - Current bounds are improved over those from the previous experiments.

- **Goal: via Neutrino – Nucleus Elastic Scattering Channel:**
  - Model Dependent and Model Independent NSI analysis is on the way

  → expecting open new research windows and improve existing bounds.

Thanks!