

# Low energy neutrino phenomenology

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# Outline

- 1 Low Energy Neutrino Experiments
- 2 Neutrino magnetic moment
- 3 The weak mixing angle
- 4 NSI
- 5 Conclusions

Based on B.C. Cañas, OGM, A. Parada, M. Tortola, J.W.F. Valle

PLB 753 191 (2016) and Add. PLB 757 568 (2016).

B.C. Cañas, E. A. Garces, OGM, M. Tortola, J.W.F. Valle PLB 761 450 (2016) and Add. PLB 757 568 (2016).

T.S. Kosmas, OGM, D.K. Papoulias, M. Tortola, J.W.F. Valle, PLB 750 459 (2015)

# Low Energy Neutrino Experiments

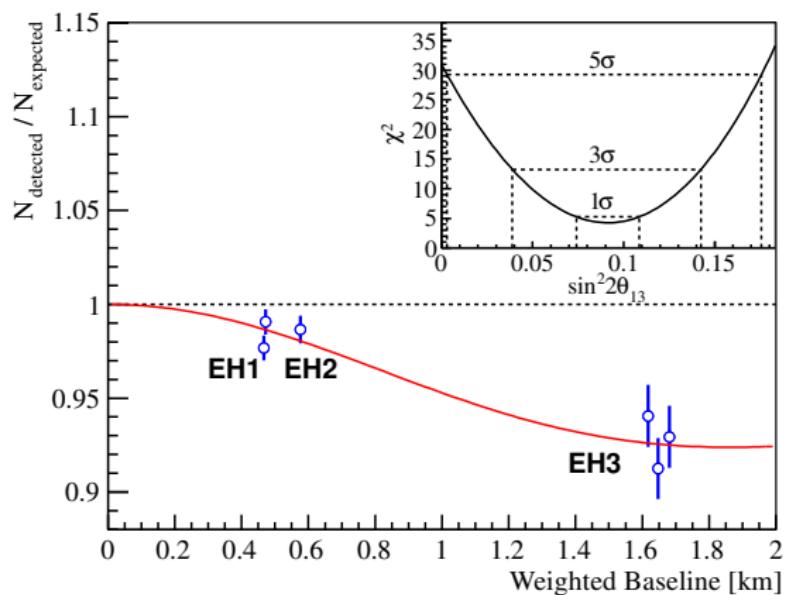
Low energy  $\nu$  experiments:

- Inverse beta decay  $\geq 2$  MeV
- neutrino scattering off electrons  $\sim 1$  MeV
- coherent elastic neutrino-nucleus scattering (CENNS) few eV up to keV

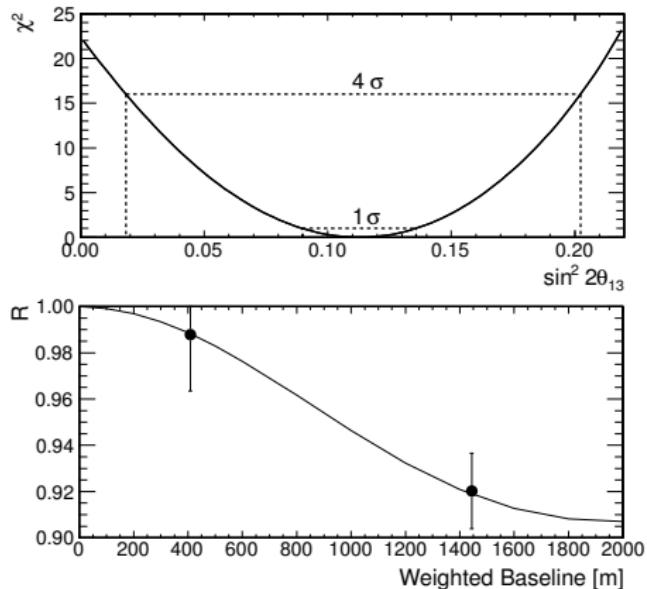
# Inverse beta decay experiments

- KamLAND experiment ( $\sin^2\theta_{12}$ )
- Daya Bay, Double Chooz, Reno ( $\sin^2\theta_{13}$ )
- ILL, Bugey, Krasnoyarsk, ROVNO, Gosgen ( $\sin^2\theta_{14}$ )

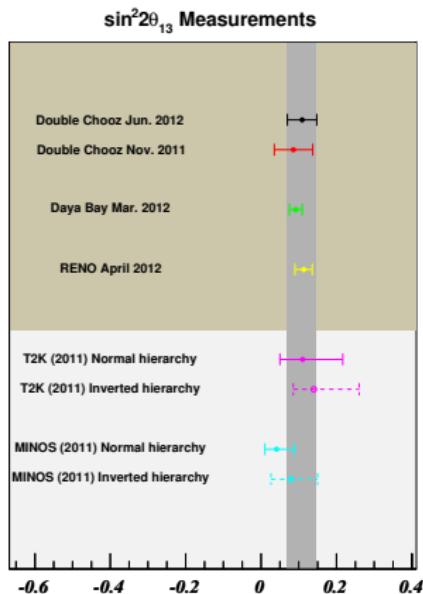
# Daya Bay



Daya Bay PRL **108** 171803 (2012)

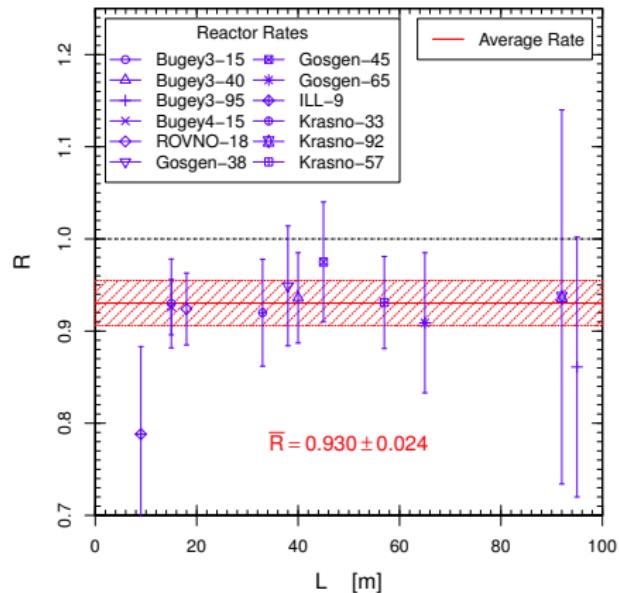
RENO PRL **108** 191802 (2012)

# Double Chooz



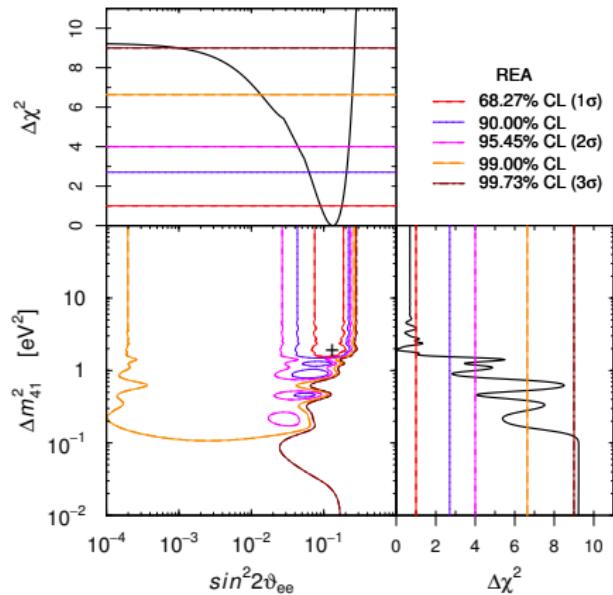
Double Chooz PRD **86** 052018 (2012)

# Very short baseline IBD experiments



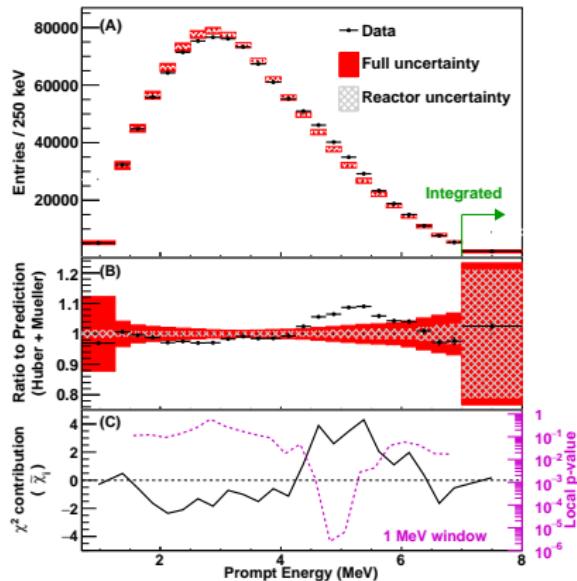
C. Giunti et al. PRD **86** 113014 (2012)

# Very short baseline IBD experiments



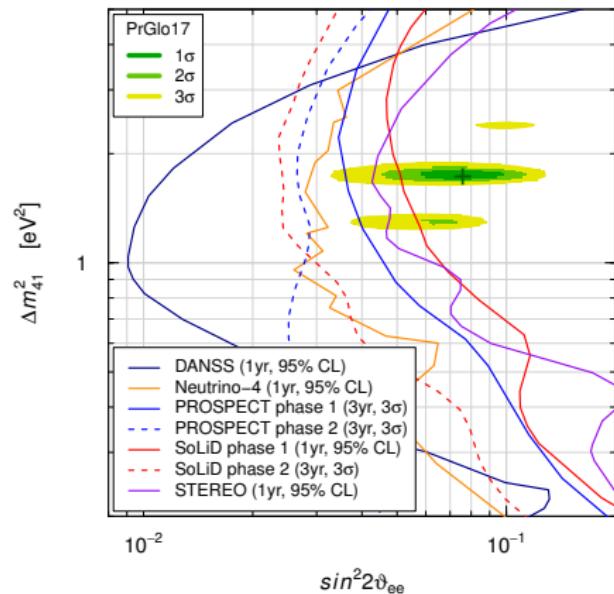
C. Giunti et al. PRD **86** 113014 (2012)

# What is the reactor spectrum?



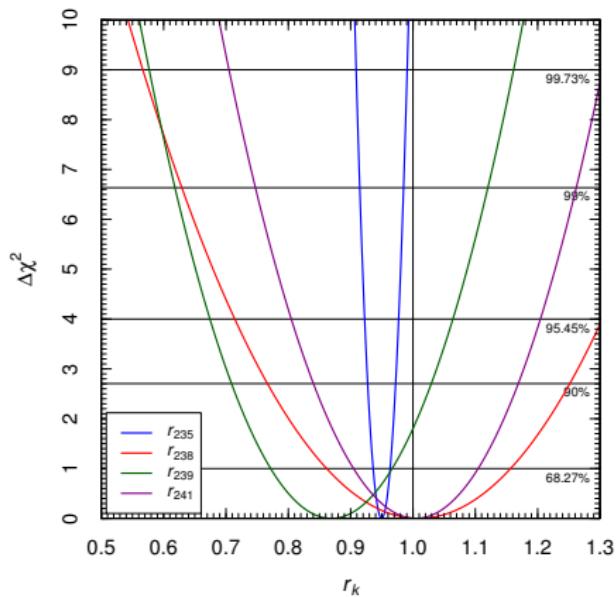
Daya Bay Chin. Phys. C41 013002 (2017)

# Very short baseline IBD experiments



S. Gariazzo, C. Giunti et al. ArXiv:1703.00860

# Very short baseline IBD experiments



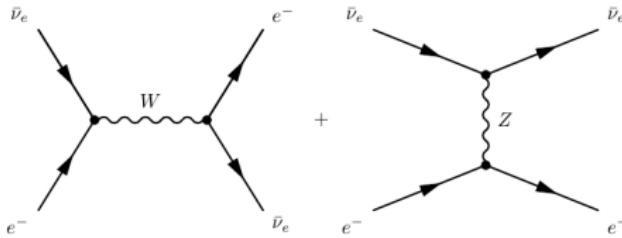
C. Giunti ArXiv:1704.05762

# Low Energy Neutrino Experiments

Low energy  $\nu$  experiments:

- Inverse beta decay  $\geq 2$  MeV
- neutrino scattering off electrons  $\sim 1$  MeV
- coherent elastic neutrino-nucleus scattering (CENNS) few eV up to keV

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



The differential weak cross section for antineutrino electron scattering, at tree level is given by

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

where

$$g_L = \frac{1}{2} + \sin^2 \theta_W; \quad g_R = \sin^2 \theta_W.$$

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

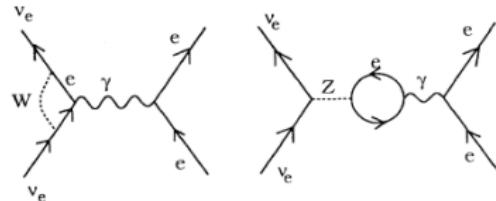


FIG. 7. Feynman diagrams for electroweak corrections to \$\nu\_e\$-e scattering.

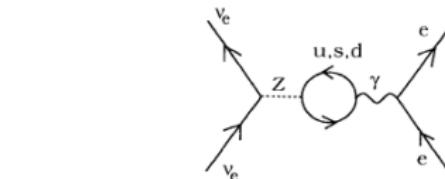


FIG. 8. Feynman diagram for QCD corrections to \$\kappa^{(\nu\_e, e)}(T)\$.

$$\begin{aligned} \frac{d\sigma}{dT} &= \frac{2G_F^2 m_e}{\pi} \left\{ g_L^2(T) \left[ 1 + \frac{\alpha}{\pi} f_-(z) \right] + g_R^2(T) (1-z)^2 \left[ 1 + \frac{\alpha}{\pi} f_+(z) \right] \right. \\ &\quad \left. - g_R(T) g_L(T) \frac{m_e}{E_\nu} z \left[ 1 + \frac{\alpha}{\pi} f_{+-}(z) \right] \right\}, \end{aligned}$$

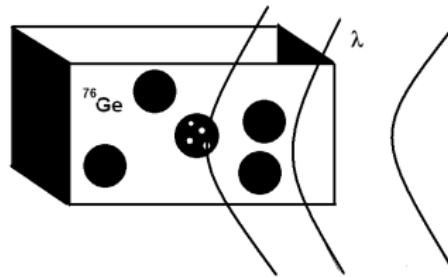
where \$z = T/E\_\nu\$, and the coupling constants are given by

$$\begin{aligned} g_L^{(\nu_e, e)}(T) &= \rho_{NC}^{(\nu, l)} \left[ \frac{1}{2} - \hat{\kappa}^{(\nu_e, e)}(T) \sin^2 \hat{\theta}_W(m_Z) \right] - 1 \\ g_R^{(\nu_e, e)}(T) &= -\rho_{NC}^{(\nu, l)} \hat{\kappa}^{(\nu_e, e)}(T) \sin^2 \hat{\theta}_W(m_Z), \end{aligned}$$

S. Sarantakos, et al., Nucl. Phys. B **217**, 84 (1983); J. N. Bahcall, et al., Phys. Rev. D **51**, 6146 (1995).

# Reactor and accelerator experiments

Experiment	$E_\nu$ (MeV)	T(MeV)	Published cross-section	$\sin^2 \theta_W$
Reactor $\bar{\nu}_e$ :				
Krasnoyarsk	3.2 – 8.0	3.3 – 5.2	$[4.5 \pm 2.4] \times 10^{-46} \text{ cm}^2/\text{fis.}$	$0.22^{+0.7}_{-0.8}$
Rovno	0.6 – 8.0	0.6 – 2.0	$[1.26 \pm 0.62] \times 10^{-44} \text{ cm}^2/\text{fis.}$	...
MUNU	0.7 – 8.0	0.7 – 2.0	$[1.07 \pm 0.34] \text{ events/day}$	...
Texono	3.0 – 8.0	3.0 – 8.0	$[1.08 \pm 0.21 \pm 0.16] \cdot \sigma_{SM}$	$0.251 \pm 0.031 \pm 0.024$
Accelerator $\nu_e$ :				
LAMPF	7 – 50	7 – 50	$[10.0 \pm 1.5 \pm 0.9] \cdot 10^{-45} \text{ cm}^2$	$0.249 \pm 0.063$
LSND	20 – 50	20 – 50	$[10.1 \pm 1.1 \pm 1.0] \cdot 10^{-45} \text{ cm}^2$	$0.248 \pm 0.051$



$$\frac{d\sigma}{dT} = \frac{G_F^2 M}{2\pi} \left\{ (G_V + G_A)^2 + (G_V - G_A)^2 \left(1 - \frac{T}{E_\nu}\right)^2 - (G_V^2 - G_A^2) \frac{MT}{E_\nu^2} \right\},$$

$M$  is the nucleus mass;

$T$  recoil nucleus energy (from 0 to  $T_{max} = 2E_\nu^2/(M + 2E_\nu)$ );

$E_\nu$  neutrino energy.

$$\begin{aligned} G_V &= [g_V^p Z + g_V^n N] F_{nucl}^V(Q^2) \\ G_A &= [g_A^p (Z_+ - Z_-) + g_A^n (N_+ - N_-)] F_{nucl}^A(Q^2) \end{aligned}$$

$$\begin{aligned} g_V^p &= \rho_{\nu N}^{\text{NC}} \left( \frac{1}{2} - 2\hat{\kappa}_{\nu N} \hat{s}_Z^2 \right) + 2\lambda^{uL} + 2\lambda^{uR} + \lambda^{dL} + \lambda^{dR} \\ g_V^n &= -\frac{1}{2} \rho_{\nu N}^{\text{NC}} + \lambda^{uL} + \lambda^{uR} + 2\lambda^{dL} + 2\lambda^{dR} \end{aligned}$$

$$\frac{d\sigma}{dT}(E_\nu, T) = \frac{G_F^2 M}{\pi} \left( 1 - \frac{MT}{2E_\nu^2} \right) \times \left\{ [Zg_V^p + Ng_V^n]^2 \right\}$$

- Axial couplings contribution is zero or can be neglected
- Coherent enhancement of cross section

# Future experiments to measure CENNS

- TEXONO: 1kg of germanium, reactor neutrinos Nucl.Instrum.Meth. A836 (2016) 67-82
- COHERENT: Spallation source with several rooms for one or even more detectors  
[arXiv:1509.08702](#), [1211.5199](#)0910.1989
- CLEAR: stopped- $\pi$   $\nu$  beam and kg-to-ton detector 0910.1989
- Connie: Reactor antineutrino experiment in Brasil JINST 11 (2016) P07024
- Kalinin: Reactor antineutrino experiment JINST 8 (2013) P10023
- MINER: Reactor antineutrino experiment Nucl.Instrum.Meth. A853 (2017) 53

# Neutrino magnetic moment

In a minimal extension of the Standard Model the neutrino magnetic moment is expected to be very small:

$$\mu_\nu = 3.2 \times 10^{-19} \left( \frac{m_\nu}{1\text{eV}} \right) \mu_B$$

B.W. Lee, R.E. Shrock, PRD **16** 1444 (1977)  
W. Marciano, A. I. Sanda PLB **67** 303 (1977)

# Electromagnetic interactions

- Charged scalar singlet

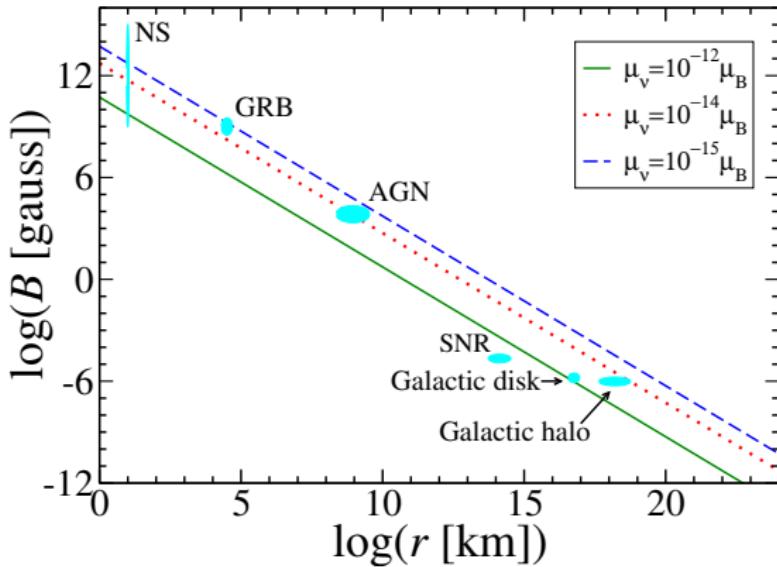
$$\mu_{ij} = e \sum_k \frac{f_{ki} g_{kj}^\dagger + g_{ik} f_{kj}^\dagger}{32\pi^2} \frac{m_{Ik}}{m_\eta^2} \left( \ln \frac{m_\eta^2}{m_{Ik}^2} - 1 \right).$$

M. Fukugita, T. Yanagida PRL **58** (1987) 1807

- Charged scalars plus additional symmetries

$$\mu_{\alpha\beta} = e \frac{ff'}{8\pi^2} \frac{m_\tau}{m_\eta^2} \ln \frac{m_\eta^2}{m_\tau^2}$$

R. Barbieri, R. N. Mohapatra PLB **218** 225 (1989) K.S. Babu, R.N. Mohapatra PRL **63** (1989) 228



J. Barranco, OGM, Moura, Parada, PLB **718** 26 (2012)

S. Hummer, M. Maltoni, W. Winter, C. Yaguna, Astropart. Phys. **34** 205 (2010)

A.M. Hillas, Ann. Rev. Astron. Astrophys. **22** 425 (1984)

# Electromagnetic interactions

- SN 1987A

$$\mu_\nu \leq 1 \times 10^{-12} \mu_B$$

R. Barbieri, R.N. Mohapatra, PRL **61** (1988) 27

A. Ayala, J.C. D'Olivo, M. Torres, PRD **59** (1999) 111901

- Red giant luminosity

$$\mu_\nu \leq 3 \times 10^{-12} \mu_B$$

G.G. Raffelt PRL **64** (1990) 2856

- Sun + SFP

$$\mu_\nu \leq \text{few} \times 10^{-12} \mu_B$$

OGM, Rashba, Rez, Valle, PRL **93** (2004) 051304

# Majorana neutrinos

$$\mathcal{H}_{em}^M = -\frac{1}{4}\nu_L^T C^{-1} (\mu - i d \gamma_5) \sigma^{\alpha\beta} \nu_L F_{\alpha\beta} = -\frac{1}{4}\nu_L^T C^{-1} \lambda \sigma^{\alpha\beta} \nu_L F_{\alpha\beta} + h.c.,$$

$$\mu^T = -\mu, \quad d^T = -d$$

J. Schechter and J. W. F. Valle, Phys. Rev. D24, 1883 (1981)

P. B. Pal and L. Wolfenstein, Phys. Rev. D25, 766 (1982)

B. Kayser, Phys. Rev. D26, 1662 (1982)

J. F. Nieves, Phys. Rev. D26, 3152 (1982)

The above discussion could be translated into a more phenomenological approach in which the NMM is described by a complex matrix  $\lambda = \mu - id$  ( $\tilde{\lambda}$ ) in the flavor (mass) basis, that for the Majorana case takes the form

$$\lambda = \begin{pmatrix} 0 & \Lambda_\tau & -\Lambda_\mu \\ -\Lambda_\tau & 0 & \Lambda_e \\ \Lambda_\mu & -\Lambda_e & 0 \end{pmatrix}, \quad \tilde{\lambda} = \begin{pmatrix} 0 & \Lambda_3 & -\Lambda_2 \\ -\Lambda_3 & 0 & \Lambda_1 \\ \Lambda_2 & -\Lambda_1 & 0 \end{pmatrix},$$

where  $\lambda_{\alpha\beta} = \epsilon_{\alpha\beta\gamma}\Lambda_\gamma$ .

The transition magnetic moments  $\Lambda_\alpha$  and  $\Lambda_i$  are complex parameters:

$$\Lambda_\alpha = |\Lambda_\alpha| e^{i\zeta_\alpha}, \quad \Lambda_i = |\Lambda_i| e^{i\zeta_i}.$$

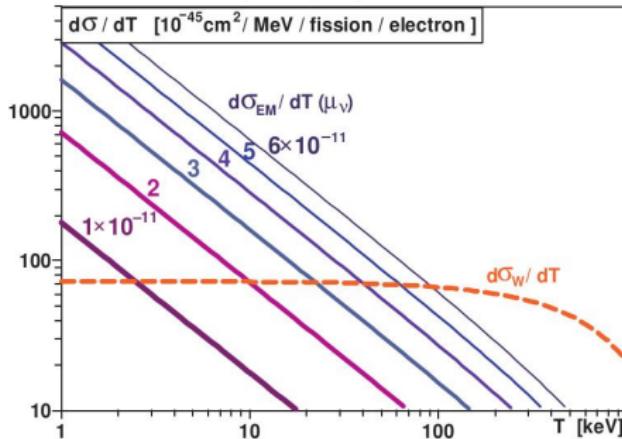
W. Grimus, T. Schwetz, NPB **587** 45 (2000)

# Neutrino-electron scattering

The electromagnetic contribution is given by

$$\left( \frac{d\sigma}{dT} \right)_{em} = \frac{\pi\alpha^2}{m_e^2\mu_B^2} \left( \frac{1}{T} - \frac{1}{E_\nu} \right) \mu_\nu^2,$$

where  $\mu_\nu$  is an effective magnetic moment.



$$\mu_{\bar{\nu}_e} \leq 7.4 \times 10^{-11} \mu_B$$

H. Wong et al. Phys Rev. D75

012001 (2007)

$$\mu_{\bar{\nu}_e} \leq 2.9 \times 10^{-11} \mu_B$$

Beda et al. Adv High Energy Phys.

2012 350150 (2012)

**Figure :** Weak and electromagnetic cross-sections calculated for several neutrino magnetic moment values.

# Effective NMM at reactor experiments.

In the flavor basis

$$(\mu_\nu^F)^2 = a_-^\dagger \lambda^\dagger \lambda a_- + a_+^\dagger \lambda \lambda^\dagger a_+.$$

In this case ( $\overline{\nu_e}$ ):  $a_+ = \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix}, \quad a_- = \begin{pmatrix} 0 \\ 0 \\ 0 \end{pmatrix}.$

$$(\mu_R^F)^2 = |\Lambda_\mu|^2 + |\Lambda_\tau|^2.$$

# Effective NMM at reactor experiments.

In the mass basis

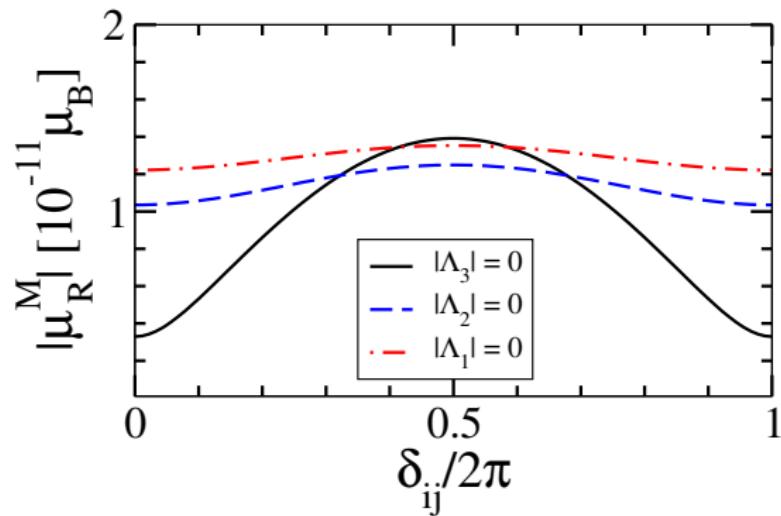
$$(\mu_\nu^M)^2 = \tilde{a}_-^\dagger \tilde{\lambda}^\dagger \tilde{\lambda} \tilde{a}_- + \tilde{a}_+^\dagger \tilde{\lambda} \tilde{\lambda}^\dagger \tilde{a}_+,$$

where  $\tilde{a}_- = U^\dagger a_- \rightarrow \tilde{a}_-^\dagger = a_-^\dagger U$ ,  $\tilde{a}_+ = U^T a_+ \rightarrow \tilde{a}_+^\dagger = a_+^\dagger U^*$ .

$$\begin{aligned} (\mu_R^M)^2 &= |\Lambda|^2 - s_{12}^2 c_{13}^2 |\Lambda_2|^2 - c_{12}^2 c_{13}^2 |\Lambda_1|^2 - s_{13}^2 |\Lambda_3|^2 \\ &- 2s_{12} c_{12} c_{13}^2 |\Lambda_1| |\Lambda_2| \cos \delta_{12} - 2c_{12} c_{13} s_{13} |\Lambda_1| |\Lambda_3| \cos \delta_{13} \\ &- 2s_{12} c_{13} s_{13} |\Lambda_2| |\Lambda_3| \cos \delta_{23}, \quad \theta_{13} \neq 0 \end{aligned}$$

$\delta_{12} = \xi_3$ ,  $\delta_{23} = \xi_2 - \delta$ , and  $\delta_{13} = \delta_{12} - \delta_{23}$ .

$$\begin{aligned}
 (\mu_R^M)^2 &= |\Lambda|^2 - s_{12}^2 c_{13}^2 |\Lambda_2|^2 - c_{12}^2 c_{13}^2 |\Lambda_1|^2 - s_{13}^2 |\Lambda_3|^2 - 2 s_{12} c_{12} c_{13}^2 |\Lambda_1| |\Lambda_2| \cos \delta_{12} \\
 &\quad - 2 c_{12} c_{13} s_{13} |\Lambda_1| |\Lambda_3| \cos \delta_{13} - 2 s_{12} c_{13} s_{13} |\Lambda_2| |\Lambda_3| \cos \delta_{23}.
 \end{aligned}$$



**Figure :** Effective Majorana TMM probed in reactor neutrino experiments, versus the relative phases  $\delta_{ij}$  for three limiting cases where one of the absolute values  $|\Lambda_k|$  vanishes.

# Effective NMM at acelerator experiments.

$$(\mu_\nu^F)^2 = a_-^\dagger \lambda^\dagger \lambda a_- + a_+^\dagger \lambda \lambda^\dagger a_+.$$

In this case  $(\overline{\nu_\mu}, \nu_e, \nu_\mu)$ :  $a_+ = \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix}$ ,  $a_- = \begin{pmatrix} 1 \\ 1 \\ 0 \end{pmatrix}$ .

$$(\mu_A^F)^2 = |\Lambda|^2 + |\Lambda_e|^2 + 2|\Lambda_\tau|^2 - 2|\Lambda_\mu||\Lambda_e| \cos \eta,$$

where  $|\Lambda|^2 = |\Lambda_e|^2 + |\Lambda_\mu|^2 + |\Lambda_\tau|^2$  and  $\eta = \zeta_e - \zeta_\mu$ .

# Effective neutrino magnetic moment in Borexino.

$$(\mu_\nu^M)^2 = \tilde{a}_-^\dagger \tilde{\lambda}^\dagger \tilde{\lambda} \tilde{a}_- + \tilde{a}_+^\dagger \tilde{\lambda} \tilde{\lambda}^\dagger \tilde{a}_+.$$

In this case

$$(\mu_{\text{sol}}^M)^2 = |\Lambda|^2 - c_{13}^2 |\Lambda_2|^2 + (c_{13}^2 - 1) |\Lambda_3|^2 + c_{13}^2 P_{e1}^{2\nu} (|\Lambda_2|^2 - |\Lambda_1|^2).$$

This expression is independent of any phase and we take into account the non-zero value of  $\theta_{13}$  for the first time in this kind of analysis.

## Borexino data.

The differential cross section is given by

$$\frac{d\sigma_\alpha}{dT_e}(E_\nu, T_e) = \bar{P}_{ee} \frac{d\sigma_e}{dT_e}(E_\nu, T_e) + (1 - \bar{P}_{ee}) \frac{d\sigma_{\mu-\tau}}{dT_e}(E_\nu, T_e),$$

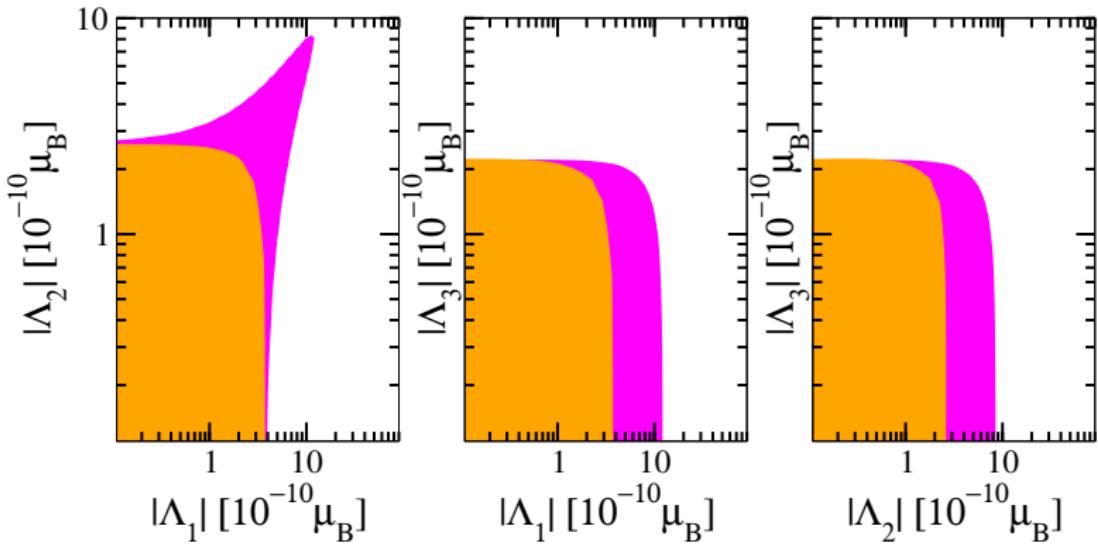
where the average survival electron-neutrino probability for the Beryllium line,  $\bar{P}_{ee}$ , determines the flavour composition of the neutrino flux detected in the experiment. According to an analysis of solar neutrino data (excluding Borexino data to avoid any correlation with the present analysis) this value is set to  $\bar{P}_{ee}^{\text{th}} = 0.54 \pm 0.03$ .

# Limits on the effective NMM from reactor and accelerator data

Experiment	Bounds
Reactors	
KRASNOYARSK	$\mu_{\bar{\nu}_e} \leq 2.7 \times 10^{-10} \mu_B$
ROVNO	$\mu_{\bar{\nu}_e} \leq 1.9 \times 10^{-10} \mu_B$
MUNU	$\mu_{\bar{\nu}_e} \leq 1.2 \times 10^{-10} \mu_B$
TEXONO	$\mu_{\bar{\nu}_e} \leq 2.0 \times 10^{-10} \mu_B$
GEMMA	$\mu_{\bar{\nu}_e} \leq 2.9 \times 10^{-11} \mu_B$
Accelerators	
LAMPF	$\mu_{\nu_e} \leq 7.3 \times 10^{-10} \mu_B$
LAMPF	$\mu_{\nu_\mu} \leq 5.1 \times 10^{-10} \mu_B$
LSND	$\mu_{\nu_e} \leq 1.0 \times 10^{-9} \mu_B$
LSND	$\mu_{\nu_\mu} \leq 6.5 \times 10^{-10} \mu_B$
Solar	
Borexino	$\mu \leq 5.1 \times 10^{-11} \mu_B$

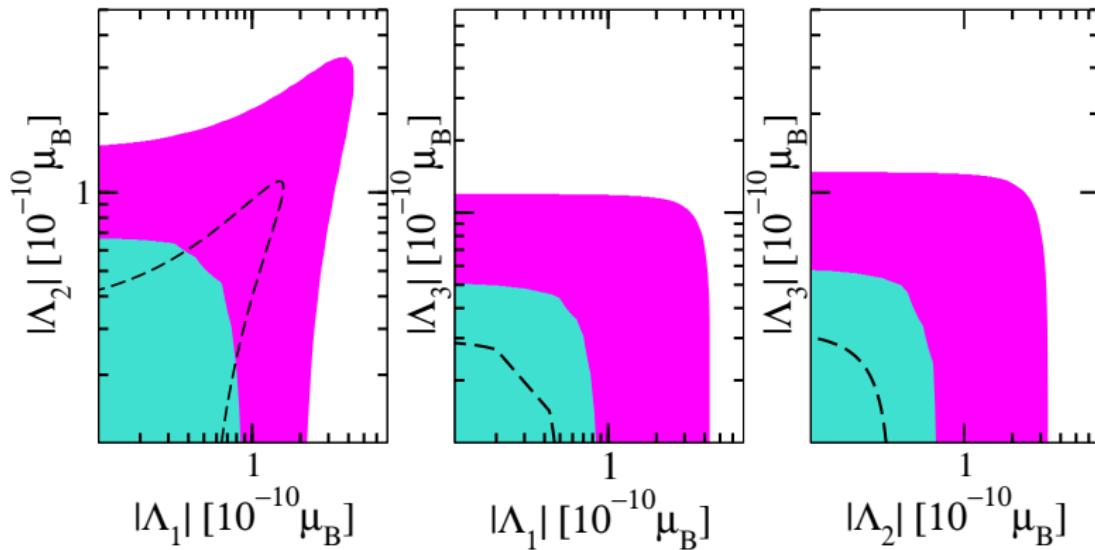
Experiment.	$ \Lambda_1 $	$ \Lambda_2 $	$ \Lambda_3 $
KRASNO	$4.7 \times 10^{-10} \mu_B$	$3.3 \times 10^{-10} \mu_B$	$2.8 \times 10^{-10} \mu_B$
ROVNO	$3.0 \times 10^{-10} \mu_B$	$2.1 \times 10^{-10} \mu_B$	$1.8 \times 10^{-10} \mu_B$
MUNU	$2.1 \times 10^{-10} \mu_B$	$1.5 \times 10^{-10} \mu_B$	$1.3 \times 10^{-10} \mu_B$
TEXONO	$3.4 \times 10^{-10} \mu_B$	$2.4 \times 10^{-10} \mu_B$	$2.0 \times 10^{-10} \mu_B$
GEMMA	$5.0 \times 10^{-11} \mu_B$	$3.5 \times 10^{-11} \mu_B$	$2.9 \times 10^{-11} \mu_B$
LSND	$6.0 \times 10^{-10} \mu_B$	$8.1 \times 10^{-10} \mu_B$	$7.0 \times 10^{-10} \mu_B$
LAMPF	$4.5 \times 10^{-10} \mu_B$	$6.2 \times 10^{-10} \mu_B$	$5.3 \times 10^{-10} \mu_B$
Borexino	$8.5 \times 10^{-11} \mu_B$	$6.7 \times 10^{-11} \mu_B$	$5.1 \times 10^{-11} \mu_B$

Table : 90% C.L. limits on the NMM components in the mass basis,  $\Lambda_i$ , from reactor, accelerator, and solar data from Borexino. In this particular analysis we constrain one parameter at a time, setting all other magnetic moment parameters and phases to zero.



**Figure :** 90% C.L. allowed regions for the TNMMs in the mass basis from the reactor experiment TEXONO. The two-dimensional projections in the plane ( $|\Lambda_i|$ ,  $|\Lambda_j|$ ) have been calculated marginalizing over the third component. The magenta (outer) region is obtained for  $\delta = 3\pi/2$  and  $\xi_2 = \xi_3 = 0$ , while the orange (inner) region appears for  $\delta = 3\pi/2$ ,  $\xi_2 = 0$  and  $\xi_3 = \pi/2$ .

# Combined analysis



**Figure :** 90% C.L. allowed regions for the TNMMs in the mass basis. The result of this plot was obtained for the two parameters  $|\Lambda_i|$  vs  $|\Lambda_j|$  marginalizing over the third component. We show the result of a combined analysis of reactor and accelerator data with all phases set to zero except for  $\delta = 3\pi/2$  (magenta region). We also show the result of the Borexino data analysis only, that is phase-independent (grey region).

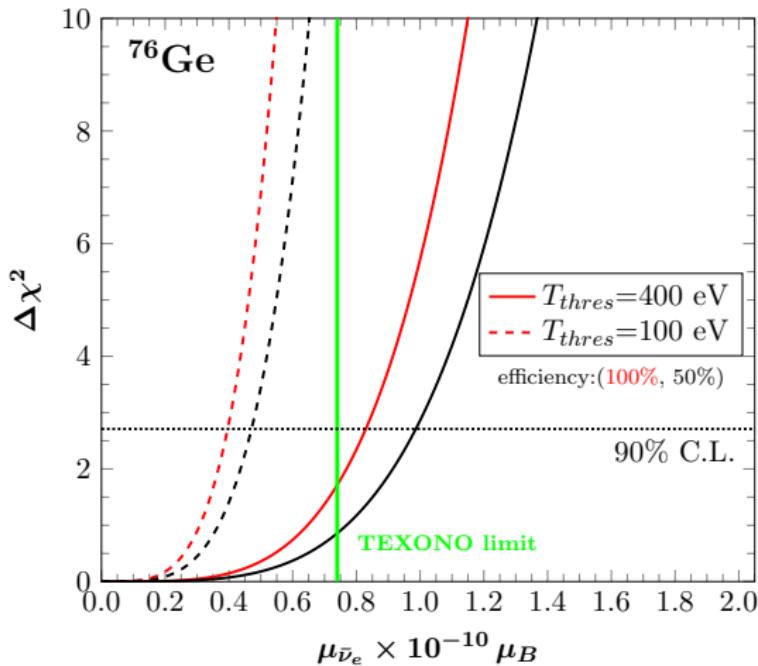
# Proposals for the future

# Texono CENNS proposal

Kuo-Sheng reactor in combination with a  $^{76}\text{Ge}$  detector

- $T_{thres} = 100 \text{ eV}$
- 1 kg detector
- $\Phi_{\nu_e} = 10^{13} \nu s^{-1} cm^{-2}$

# Texono CENNS proposal



T.S. Kosmas, OGM, D.K. Papoulias, M. Tortola, J.W.F. Valle, PLB 750 459 (2015)

# COHERENT proposal

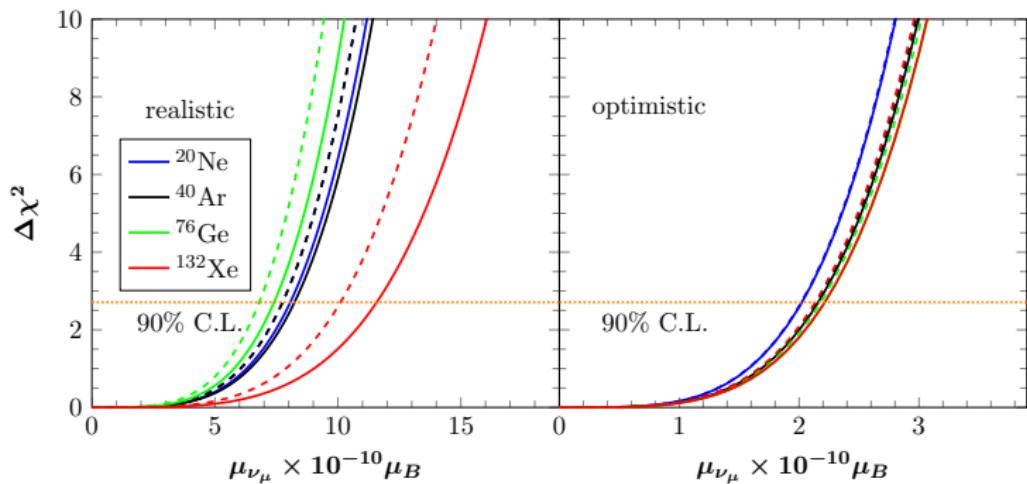
Spallation Neutron Source that produce neutrinos from muon decay at rest

- Different rooms are under consideration at different distances from the source
- Different detectors are also under consideration

# COHERENT proposal

		COHERENT experiment			
		$^{20}\text{Ne}$	$^{40}\text{Ar}$	$^{76}\text{Ge}$	$^{132}\text{Xe}$
Realistic	Mass	391 kg	456 kg	100 kg	100 kg
	Distance	46 m	46 m	20 m	40 m
	Efficiency	50%	50%	67%	50%
	Recoil window	30-160 keV	20-120 keV	10-78 keV	8-46 keV
Optimistic	mass	1 ton	1 ton	1 ton	1 ton
	Distance	20 m	20 m	20 m	20 m
	Efficiency	100%	100%	100%	100%
	Recoil window	$1\text{keV} - T_{\max}$	$1\text{keV} - T_{\max}$	$1\text{keV} - T_{\max}$	$1\text{keV} - T_{\max}$

# COHERENT CENNS



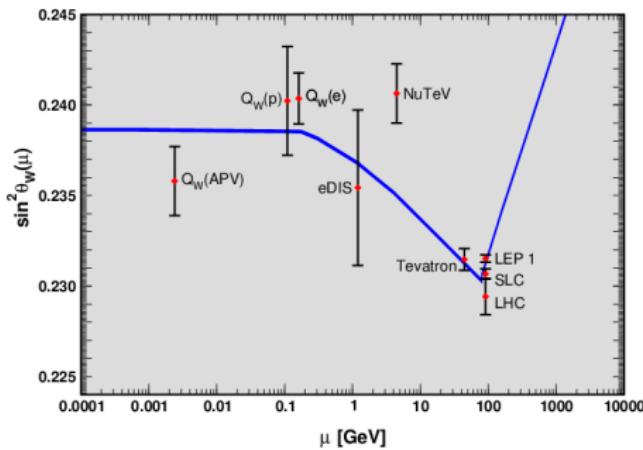
T.S. Kosmas, OGM, D.K. Papoulias, M. Tortola, J.W.F. Valle, PRD **92** 013011 (2015)

# COHERENT proposal

Nucleus	$^{20}\text{Ne}$	$^{40}\text{Ar}$	$^{76}\text{Ge}$	$^{132}\text{Xe}$
$\mu_{\nu_\mu}$	9.09 [2.31]	9.30 [2.47]	8.37 [2.54]	12.94 [2.54]
$\mu_{\bar{\nu}_\mu}$	10.28 [2.53]	10.46 [2.69]	9.39 [2.75]	14.96 [2.74]
$\mu_{\nu_e}$	10.22 [2.44]	10.55 [2.60]	9.46 [2.68]	15.20 [2.68]
$\mu_{\nu_\mu}^{\text{comb}}$	8.07 [2.02]	8.24 [2.16]	7.41 [2.22]	11.58 [2.21]

# The weak mixing angle

- The weak mixing angle is a fundamental parameter of the Standard Model and it has been measured with great precision at high energies.
- At low energies its measurement has been a difficult task, especially in the neutrino sector. On one hand, the interaction of neutrinos with quarks at low energies gave measurements that appeared to be in disagreement with the SM, although a recent evaluation of the sea quark contributions reports coincidence with the standard model (G. P. Zeller et al., Phys. Rev. Lett. 88 (2002) 091802; W. Bentz et al., Phys. Lett B 693 (2010) 462).
- Revaluation of the reactor antineutrino energy spectrum is interesting (T. Mueller, et al., Phys. Rev. C 83 (2011) 0.54615.)



K. A. Olive et al., Chin. Phys. C 38, (2014) 090001.

# Limits on the weak mixing angle

$$\chi^2(\sin^2 \hat{\theta}_W) = \sum_{ij} (N_i^{\text{theo}}(\sin^2 \hat{\theta}_W) - N_i^{\text{exp}}) \sigma_{ij}^{-2} (N_j^{\text{theo}}(\sin^2 \hat{\theta}_W) - N_j^{\text{exp}}),$$

	MS	RC	TEXONO <sup>1</sup>	MUNU <sup>2</sup>	Rovno <sup>3</sup>	Krasnoyarsk <sup>4</sup>
a)	-	-	$0.256^{+0.032}_{-0.036}$	$0.241^{+0.069}_{-0.088}$	$0.220^{+0.102}_{-0.158}$	$0.220^{+0.068}_{-0.1}$
b)	-	✓	$0.261^{+0.032}_{-0.036}$	$0.248^{+0.069}_{-0.088}$	$0.226^{+0.102}_{-0.156}$	$0.224^{+0.069}_{-0.1}$
c)	✓	-	$0.253^{+0.032}_{-0.036}$	$0.237^{+0.069}_{-0.088}$	$0.228^{+0.102}_{-0.157}$	$0.231^{+0.069}_{-0.1}$
d)	✓	✓	$0.258^{+0.032}_{-0.036}$	$0.244^{+0.068}_{-0.088}$	$0.235^{+0.102}_{-0.157}$	$0.235^{+0.069}_{-0.1}$

B. C. Cañas, et al., Phys. Lett. B **761**, 450 (2016).

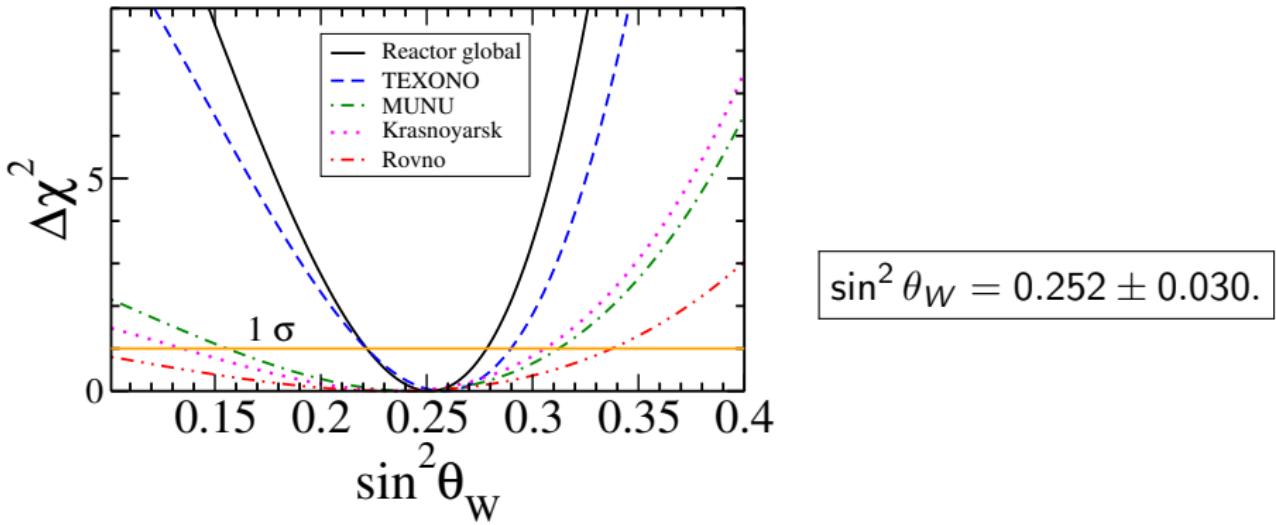
<sup>1</sup> M. Deniz, et al., Phys. Rev. D 81 (2010) 072001.

<sup>2</sup> Z. Daraktchieva, et al., Phys. Lett. B 615 (2005) 153.

<sup>3</sup> A.I. Derbin, et al., JETP Lett. 57 (1993) 768.

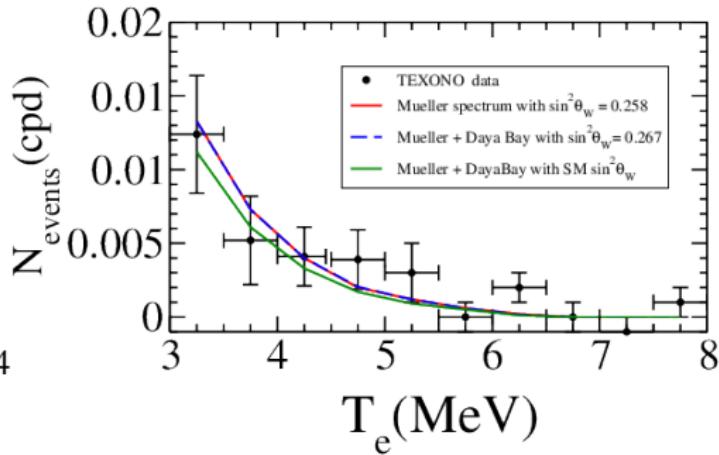
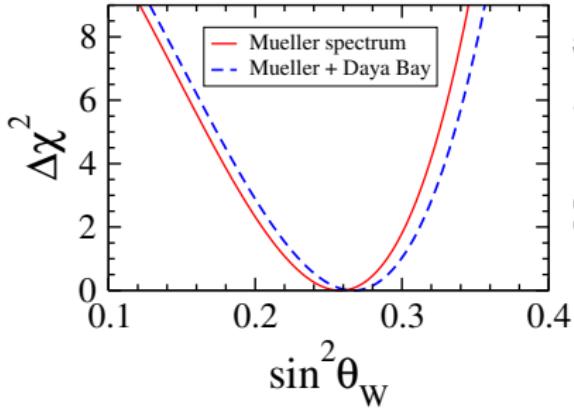
<sup>4</sup> G. Vidyakin, et al., JETP Lett. 55 (1992) 206.

# Limits on the weak mixing angle



B. C. Canas, et al., Phys. Lett. B **761**, 450 (2016).

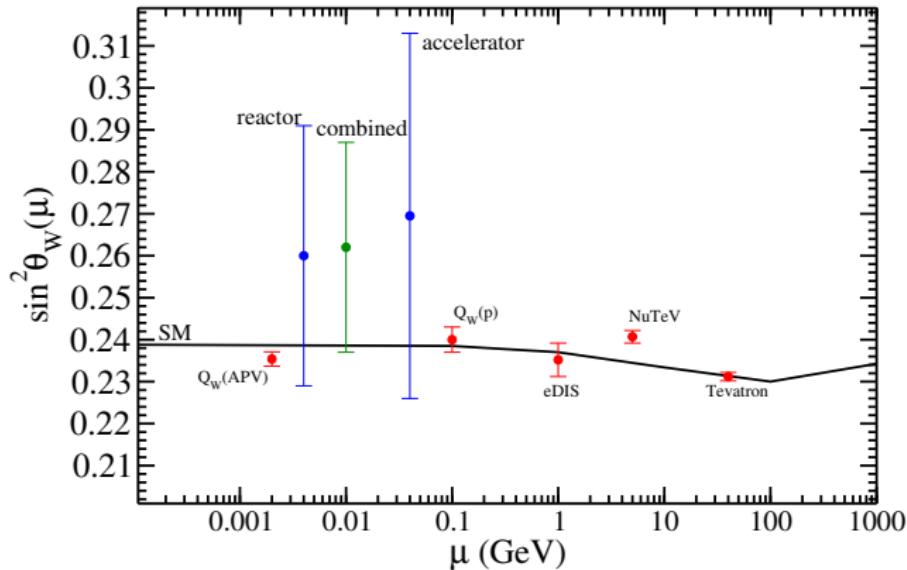
# Limits on the weak mixing angle



$$\sin^2 \theta_W = 0.267 \pm 0.033 \quad (\text{Mueller} + \text{DayaBay spectrum}).$$

B. C. Canas, et al., Phys. Lett. B **761**, 450 (2016).

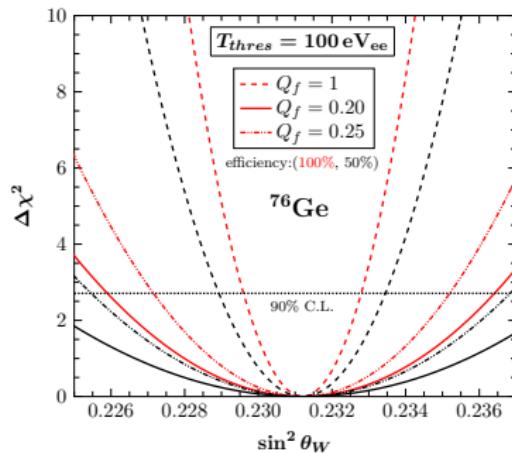
# Limits on the weak mixing angle



$$\sin^2 \theta_W = 0.254 \pm 0.024.$$

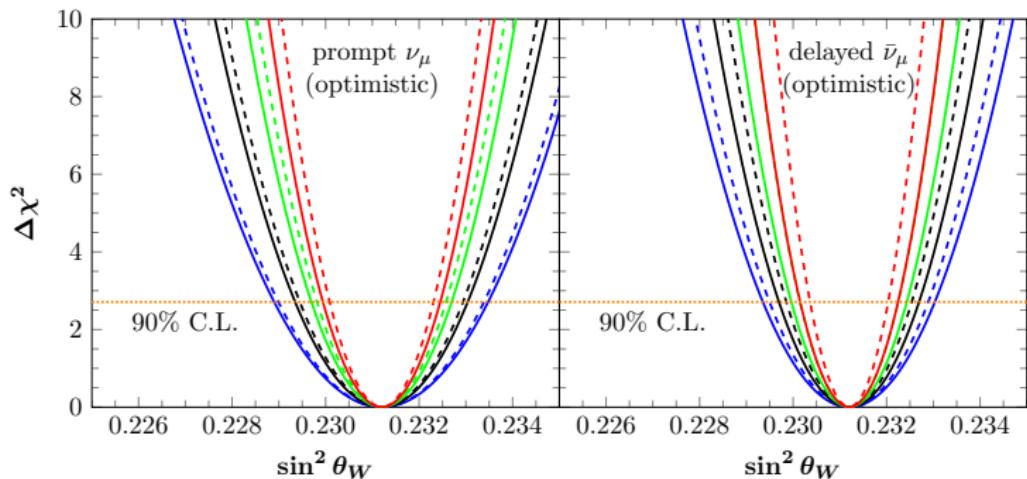
B. C. Canas, et al., Phys. Lett. B 761, 450 (2016).

# Texono CENNS proposal



T.S. Kosmas, OGM, D.K. Papoulias, M. Tortola, J.W.F. Valle, PLB 750 459 (2015)

# COHERENT CENNS



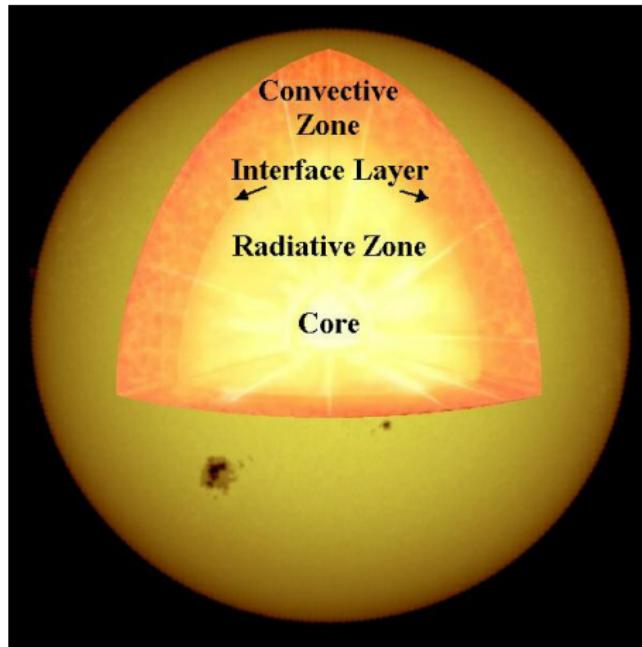
T.S. Kosmas, OGM, D.K. Papoulias, M. Tortola, J.W.F. Valle, PRD **92** 013011 (2015)

# COHERENT proposal

**Table :** Expected sensitivities to the weak mixing angle  $\sin^2 \theta_W(\nu_\mu) \equiv s_W^2(\nu_\mu)$ , through a combined analysis of the prompt and delayed beams ( $\nu_\mu + \bar{\nu}_\mu$ ).

Nucleus	$^{20}\text{Ne}$	$^{40}\text{Ar}$	$^{76}\text{Ge}$	$^{132}\text{Xe}$
$\delta s_W^2(\nu_\mu)$	0.0052 [0.0007]	0.0042 [0.0006]	0.0031 [0.0005]	0.0073 [0.0004]
Uncer. (%)	2.23 [0.30]	1.82 [0.26]	1.34 [0.22]	3.14 [0.17]

# NSI in Solar neutrino data



# Constant density case

Conversion probability  $\nu_e \leftrightarrow \nu_\mu$ :

$$P(\nu_e \rightarrow \nu_\mu; L) = \sin^2 2\theta_m \sin^2 \left( \pi \frac{L}{l_m} \right),$$

Mixing angle in matter

$$\sin^2 2\theta_m = \frac{\left( \frac{\Delta m^2}{2E} \right)^2 \sin^2 2\theta}{\left( \frac{\Delta m^2}{2E} \cos 2\theta - \sqrt{2} G_F N_e \right)^2 + \left( \frac{\Delta m^2}{2E} \right)^2 \sin^2 2\theta}$$

Resonance  $\sqrt{2} G_F N_e = \frac{\Delta m^2}{2E} \cos 2\theta$

Wolfenstein 1978, Mikheev & Smirnov 1985

# Non Standard Interactions in the Sun

$$H_{\text{NSI}} = \sqrt{2} G_F N_f \begin{pmatrix} 0 & \varepsilon \\ \varepsilon & \varepsilon' \end{pmatrix}.$$

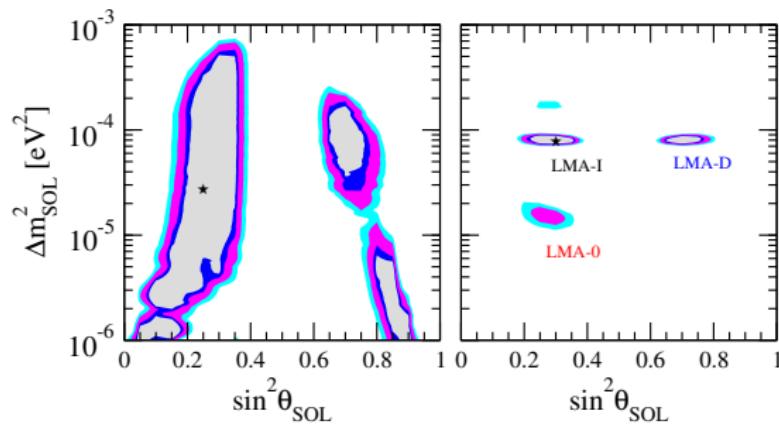
Mixing angle in matter + NSI

$$\tan 2\theta_m = \frac{\left(\frac{\Delta m^2}{2E}\right) \sin 2\theta + 2\sqrt{2} G_F \varepsilon N_d}{\frac{\Delta m^2}{2E} \cos 2\theta - \sqrt{2} G_F N_e + \sqrt{2} G_F \varepsilon' N_d}.$$

Resonance  $\frac{\Delta m^2}{2E} \cos 2\theta - \sqrt{2} G_F N_e + \sqrt{2} G_F \varepsilon' N_d = 0.$

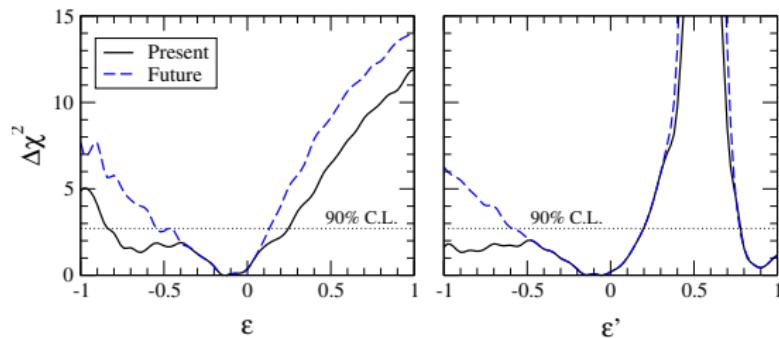
$$\varepsilon' > \frac{N_e}{N_d}$$

# Solar + KamLAND without and with NSI



Miranda, Tortola, Valle, JHEP 0610:008 (2006)

# NSI constraints from Solar + Kamland



# CENNNS + NSI

$$G_V = \left[ \left( g_V^p + 2\varepsilon_{ee}^{uV} + \varepsilon_{ee}^{dV} \right) Z + \left( g_V^n + \varepsilon_{ee}^{uV} + 2\varepsilon_{ee}^{dV} \right) N \right] F_{nucl}^V(Q^2)$$
$$G_A = \left[ \left( g_A^p + 2\varepsilon_{ee}^{uA} + \varepsilon_{ee}^{dA} \right) (Z_+ - Z_-) + \left( g_A^n + \varepsilon_{ee}^{uA} + 2\varepsilon_{ee}^{dA} \right) (N_+ - N_-) \right] F_A$$

$$\frac{d\sigma}{dT}(E_\nu, T) = \frac{G_F^2 M}{\pi} \left( 1 - \frac{MT}{2E_\nu^2} \right) \times$$
$$\times \left\{ \left[ Z(g_V^p + 2\varepsilon_{ee}^{uV} + \varepsilon_{ee}^{dV}) + N(g_V^n + \varepsilon_{ee}^{uV} + 2\varepsilon_{ee}^{dV}) \right]^2 + \right.$$
$$\left. + \sum_{\alpha=\mu,\tau} \left[ Z(2\varepsilon_{\alpha e}^{uV} + \varepsilon_{\alpha e}^{dV}) + N(\varepsilon_{\alpha e}^{uV} + 2\varepsilon_{\alpha e}^{dV}) \right]^2 \right\}$$

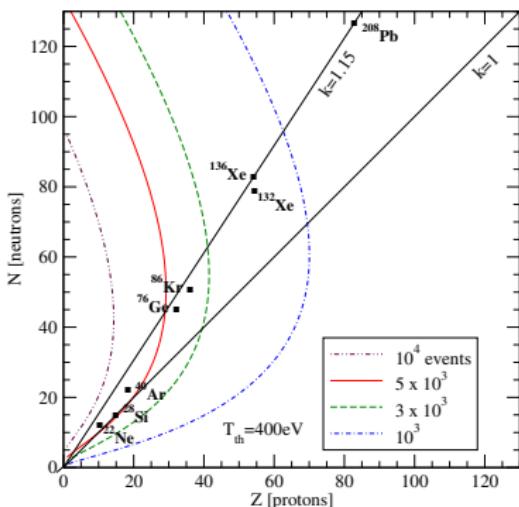
- Axial couplings contribution is zero or can be neglected
- Coherent enhancement of cross section
- Degeneracy in determination of NSI parameters

# CENNS + NSI

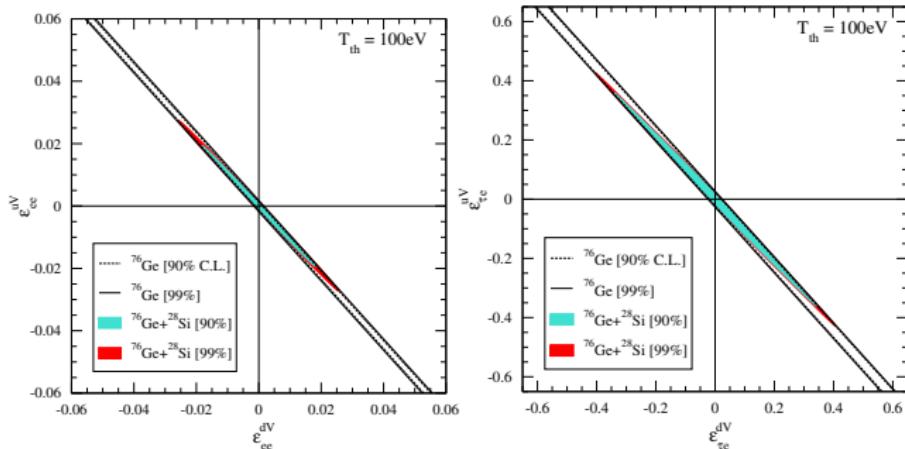
$$\left[ Z(g_V^p + 2\varepsilon_{ee}^{uV} + \varepsilon_{ee}^{dV}) + N(g_V^n + \varepsilon_{ee}^{uV} + 2\varepsilon_{ee}^{dV}) \right]^2 = \left[ Zg_V^p + Ng_V^n \right]^2$$

$$\varepsilon_{ee}^{uV}(A+Z) + \varepsilon_{ee}^{dV}(A+N) = \text{const.}$$

**Solution:** take two targets with **maximally different**  $k = (A+N)/(A+Z)$



# Estimated bounds on NSI from TEXONO (Ge+Si)



${}^{76}\text{Ge} + {}^{28}\text{Si}$ $T_{th}=100\text{eV}$
$ \epsilon_{ee}^{dV}  < 0.018$
$ \epsilon_{e\tau}^{dV}  < 0.019$
$ \epsilon_{\tau e}^{dV}  < 0.34$
$ \epsilon_{\tau e}^{uV}  < 0.37$

# Bounds on NSI from Texono

One parameter analysis to compare coherent scattering sensitivity with present bounds and  $\nu$ Factory sensitivity (taken from Davidson et al'03)

	Present Limits	$\nu$ Factory	${}^{76}\text{Ge}$ $T_{th}=400\text{eV}$ $({}^{76}\text{Ge}$ $T_{th}=100\text{eV})$	${}^{76}\text{Ge}+{}^{28}\text{Si}$ $T_{th}=400\text{eV}$ $({}^{76}\text{Ge}+{}^{28}\text{Si}$ $T_{th}=100\text{eV})$
$\epsilon_{ee}^{dV}$	$-0.5 < \epsilon_{ee}^{dV} < 1.2$	$ \epsilon_{ee}^{dV}  < 0.002$	$ \epsilon_{ee}^{dV}  < 0.003$ $( \epsilon_{ee}^{dV}  < 0.001)$	$ \epsilon_{ee}^{dV}  < 0.002$ $( \epsilon_{ee}^{dV}  < 0.001)$
$\epsilon_{\tau e}^{dV}$	$ \epsilon_{\tau e}^{dV}  < 0.78$	$ \epsilon_{\tau e}^{dV}  < 0.06$	$ \epsilon_{\tau e}^{dV}  < 0.032$ $( \epsilon_{\tau e}^{dV}  < 0.020)$	$ \epsilon_{\tau e}^{dV}  < 0.024$ $( \epsilon_{\tau e}^{dV}  < 0.017)$
$\epsilon_{ee}^{uV}$	$-1.0 < \epsilon_{ee}^{uV} < 0.61$	$ \epsilon_{ee}^{uV}  < 0.002$	$ \epsilon_{ee}^{uV}  < 0.003$ $( \epsilon_{ee}^{uV}  < 0.001)$	$ \epsilon_{ee}^{uV}  < 0.002$ $( \epsilon_{ee}^{uV}  < 0.001)$
$\epsilon_{\tau e}^{uV}$	$ \epsilon_{\tau e}^{uV}  < 0.78$	$ \epsilon_{\tau e}^{uV}  < 0.06$	$ \epsilon_{\tau e}^{uV}  < 0.036$ $( \epsilon_{\tau e}^{uV}  < 0.023)$	$ \epsilon_{\tau e}^{uV}  < 0.023$ $( \epsilon_{\tau e}^{uV}  < 0.018)$

## New references updating this subject

- M.C. Gonzalez-Garcia, Michele Maltoni JHEP 1309 (2013) 152
- P. Coloma, T. Schwetz Phys.Rev. D94 (2016) 055005
- Yasaman Farzan, Julian Heeck, Phys.Rev. D94 (2016) 053010
- Ian M. Shoemaker arXiv:1703.05774
- P. Coloma et al. JHEP 1704 (2017) 116

# Conclusions

- ✓ Low energy neutrino experiments can test different properties of Standard Model physics such as neutrino oscillation parameters or the weak mixing angle.
- ✓ Different types of physics beyond the Standard Model can also be tested through these processes.
- ✓ There are different experimental proposals that can contribute to test the observables discussed here using different reactions and different experimental set ups that can be complementary.

# Thanks