Constraints on Non-Standard Neutrino Interactions from Borexino Phase-II

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internally reviewed by Borexino collaboration

Probes of New Physics Complementary to Colliders

γ:

- CMB
- 21 cm
- Lyα
- LSS
- SNe
- Cepheids
- ...

ν:

- cosmic
- solar
- atm
- neutron star
- Supernovae
- beam
- reactor
- ...

Gravitational wave:

- primordial
- topological defects
- phase transition
- binary mergers
- ...

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- environment that is hard to achieve on Earth
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- environment that is hard to achieve on Earth
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Probes:

- Inner workings of the Sun (high- vs low-metallicity)
- bounding neutrino magnetic moment
- rejecting ν from GW150914, GW151226, GW170104 *(1706.10176)*
- Constraining new physics model independently $\leftarrow$ *this talk*

Vector Interaction in EFT – Standard Model W/ Z

$$-\mathcal{L}_{CC}^{\nu e} = \frac{G_F}{\sqrt{2}} [\bar{\nu}_e \gamma_\mu (1-\gamma_5) e] [\bar{e} \gamma^\mu (1-\gamma_5) \nu_e]$$
$$= 2\sqrt{2} G_F [\bar{\nu}_{eL} \gamma_\mu \nu_{eL}] [\bar{e}_L \gamma^\mu e_L]$$
$$-\mathcal{L}_{NC}^{\nu_\alpha e} = \frac{G_F}{\sqrt{2}} [\bar{\nu}_\alpha (1-\gamma_5) \nu_\alpha] [\bar{e} \gamma^\mu (g_V^{\nu e} - g_A^{\nu e} \gamma_5) e]$$
$$= 2\sqrt{2} G_F [\bar{\nu}_{\alpha L} \gamma_\mu \nu_{\alpha L}] [g_L^{\nu e} (\bar{e}_L \gamma^\mu e_L) + g_R^{\nu e} (\bar{e}_R \gamma^\mu e_R)]$$

combines to

$$-\mathcal{L}^{\nu_\alpha e} = 2\sqrt{2} G_F [\bar{\nu}_{\alpha L} \gamma_\mu \nu_{\alpha L}] [g_{\alpha L} (\bar{e}_L \gamma^\mu e_L) + g_{\alpha R} (\bar{e}_R \gamma^\mu e_R)]$$

with

$$g_{\alpha L} = \begin{cases} \sin^2\theta_W + \frac{1}{2} & \alpha = e \\ \sin^2\theta_W - \frac{1}{2} & \alpha = \mu, \tau \end{cases}$$
$$g_{\alpha R} = \sin^2\theta_W \qquad \alpha = e, \mu, \tau$$

$\sim$ larger coupling for ν_e, in addition to the $P_{e\to e}/P_{e\to x} > 1$
$\sim$ more events
$\sim$ better sensitivity of g_{eL} than g_{eR} than g_τ.

Vector Interaction in EFT – NSI

$$-\mathcal{L}^{\nu_\alpha e} = 2\sqrt{2}G_F\left[\bar{\nu}_{\alpha L}\gamma_\mu \nu_{\alpha L}\right]\left[g_{\alpha L}(\bar{e}_L\gamma^\mu e_L) + g_{\alpha R}(\bar{e}_R\gamma^\mu e_R)\right]$$
$$-\mathcal{L}^{\nu_\alpha e}_{NSI} = 2\sqrt{2}G_F\left[\bar{\nu}_{\alpha L}\gamma_\mu \nu_{\alpha L}\right]\left[\varepsilon_{\alpha L}(\bar{e}_L\gamma^\mu e_L) + \varepsilon_{\alpha R}(\bar{e}_R\gamma^\mu e_R)\right]$$

combines to give

$$g_{\alpha L} \to g_{\alpha L} + \varepsilon_{\alpha L},$$
$$g_{\alpha R} \to g_{\alpha R} + \varepsilon_{\alpha R}$$

NSI in Effective Operator Picture

Requirement:

- $SU(2)_W \times U(1)_Y$ invariant,
- contains $(\bar{\nu}_L \gamma_\mu \nu_L)(\bar{e}\gamma^\mu e)$

Ingredients:

$$L_\alpha = \begin{bmatrix} \nu_{\alpha L} \\ \ell^-_{\alpha L} \end{bmatrix}, H = \begin{bmatrix} \phi^+ \\ \phi_0 \end{bmatrix}, e^-_R$$

Ways of contracting $SU(2)$ indices:

$$\mathbf{1} : [\ \cdot \quad \cdot\ ] \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \cdot \\ \cdot \end{bmatrix},$$

$$\mathbf{3} : [\ \cdot \quad \cdot\ ] \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} \cdot \\ \cdot \end{bmatrix}, [\ \cdot \quad \cdot\ ] \begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix} \begin{bmatrix} \cdot \\ \cdot \end{bmatrix}, [\ \cdot \quad \cdot\ ] \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} \begin{bmatrix} \cdot \\ \cdot \end{bmatrix}$$

NSI in Effective Operator Picture – cont'd

$(\bar{\nu}_{\alpha L}\gamma_\mu \nu_{\alpha L})(\bar{e}_R \gamma^\mu e_R)$ type:

$$\frac{h^{\alpha(1)}_{0,R}}{M^2}(\bar{L}_\alpha \gamma_\mu L_\alpha)(\bar{e}_R \gamma^\mu e_R)$$

$(\bar{\nu}_{\alpha L}\gamma_\mu \nu_{\alpha L})(\bar{e}_L \gamma^\mu e_L)$ type:

$$\frac{h^{\alpha(1)}_{0,L}}{M^2}(\bar{L}_\alpha \gamma_\mu L_\alpha)(\bar{L}_e \gamma^\mu L_e) \qquad \frac{h^{\alpha(3)}_{0,L}}{M^2}(\bar{L}_\alpha \sigma^i \gamma_\mu L_\alpha)(\bar{L}_e \sigma^i \gamma^\mu L_e)$$

NSI in Effective Operator Picture – cont'd

$(\bar{\nu}_{\alpha L}\gamma_\mu \nu_{\alpha L})(\bar{e}_R \gamma^\mu e_R)$ type:

$$\frac{h_{0,R}^{\alpha(1)}}{M^2}(\bar{L}_\alpha \gamma_\mu L_\alpha)(\bar{e}_R\gamma^\mu e_R)$$

$$\frac{h_{1,R}^{\alpha(1)}}{M^2}\frac{(H^\dagger H)}{M^2}(\bar{L}_\alpha \gamma_\mu L_\alpha)(\bar{e}_R\gamma^\mu e_R)$$

$$\frac{h_{1,R}^{\alpha(2)}}{M^2}\frac{H^\dagger \sigma^i H}{M^2}(\bar{L}_\alpha \sigma^i \gamma_\mu L_\alpha)(\bar{e}_R\gamma^\mu e_R)$$

$(\bar{\nu}_{\alpha L}\gamma_\mu \nu_{\alpha L})(\bar{e}_L \gamma^\mu e_L)$ type:

$$\frac{h_{0,L}^{\alpha(1)}}{M^2}(\bar{L}_\alpha \gamma_\mu L_\alpha)(\bar{L}_e\gamma^\mu L_e)$$

$$\frac{h_{1,L}^{\alpha(1)}}{M^2}\frac{(H^\dagger H)}{M^2}(\bar{L}_\alpha \gamma_\mu L_\alpha)(\bar{L}_e\gamma^\mu L_e)$$

$$\frac{h_{1,L}^{\alpha(2)}}{M^2}\frac{H^\dagger \sigma^i H}{M^2}(\bar{L}_\alpha \sigma^i \gamma_\mu L_\alpha)(\bar{L}_e\gamma^\mu L_e)$$

$$\frac{h_{0,L}^{\alpha(3)}}{M^2}(\bar{L}_\alpha \sigma^i \gamma_\mu L_\alpha)(\bar{L}_e \sigma^i \gamma^\mu L_e)$$

$$\frac{h_{1,L}^{\alpha(3)}}{M^2}\frac{(H^\dagger H)}{M^2}(\bar{L}_\alpha \sigma^i \gamma_\mu L_\alpha)(\bar{L}_e \sigma^i \gamma^\mu L_e)$$

$$\frac{h_{1,L}^{\alpha(4)}}{M^2}\frac{(H^\dagger \sigma^i H)}{M^2}(\bar{L}_\alpha \gamma_\mu L_\alpha)(\bar{L}_e \sigma^i \gamma^\mu L_e)$$

$$\epsilon_{ijk}\frac{h_{1,L}^{\alpha(5)}}{M^2}\frac{(H^\dagger \sigma^i H)}{M^2}(\bar{L}_\alpha \sigma^j \gamma_\mu L_\alpha)(\bar{L}_e \sigma^k \gamma^\mu L_e)$$

$$-\mathcal{L}_{\rm eff}^{\nu} = 2\sqrt{2}G_F(\bar{\nu}_\alpha\gamma^\mu P_L\nu_\alpha)\left[\varepsilon_{\alpha R}(\bar{e}\gamma_\mu P_R e) + \varepsilon_{\alpha L}(\bar{e}\gamma_\mu P_L e)\right], \qquad \nu - e$$

$$-\mathcal{L}_{\rm eff}^{(1)} = 2\sqrt{2}G_F(\bar{\tau}\gamma^\mu P_L\tau)\left[\kappa_{\tau R}(\bar{e}\gamma_\mu P_R e) + \kappa_{\tau L}(\bar{e}\gamma_\mu P_L e)\right] + (\tau\to\mu) + (\tau\to e), \qquad \textit{charged lepton scattering}$$

$$-\mathcal{L}_{\rm eff}^{(2)} = 2\sqrt{2}G_F(\bar{\nu}_\tau\gamma^\mu P_L\nu_e)\left[\zeta_{\tau L}(\bar{e}\gamma_\mu P_L\tau) + h.c.\right] + (\tau\to\mu), \qquad \textit{LFV}$$

$$-\mathcal{L}_{\rm eff}^{(3)} = 2\sqrt{2}G_F(\bar{\nu}_e\gamma_\mu P_L\nu_e)\left[\xi_{\tau L}(\bar{\tau}\gamma^\mu P_L\tau) + \xi_{\nu_\tau L}(\bar{\nu}_\tau\gamma^\mu P_L\nu_\tau)\right] + (\tau\to\mu) \qquad \textit{unobservable}$$

$$+ 2\sqrt{2}G_F\xi_{\nu_e L}(\bar{\nu}_e\gamma_\mu P_L\nu_e)(\bar{\nu}_e\gamma_\mu P_L\nu_e),$$

$$-\mathcal{L}^{\nu}_{eff} = 2\sqrt{2}G_F(\bar\nu_\alpha\gamma^\mu P_L\nu_\alpha)\left[\varepsilon_{\alpha R}(\bar e\gamma_\mu P_R e) + \varepsilon_{\alpha L}(\bar e\gamma_\mu P_L e)\right], \qquad \nu - e$$

$$-\mathcal{L}^{(1)}_{eff} = 2\sqrt{2}G_F(\bar\tau\gamma^\mu P_L\tau)\left[\kappa_{\tau R}(\bar e\gamma_\mu P_R e) + \kappa_{\tau L}(\bar e\gamma_\mu P_L e)\right] + (\tau\to\mu) + (\tau\to e), \qquad \textit{charged lepton scattering}$$

$$-\mathcal{L}^{(2)}_{eff} = 2\sqrt{2}G_F(\bar\nu_\tau\gamma^\mu P_L\nu_e)\left[\zeta_{\tau L}(\bar e\gamma_\mu P_L\tau) + h.c.\right] + (\tau\to\mu), \qquad LFV$$

$$-\mathcal{L}^{(3)}_{eff} = 2\sqrt{2}G_F(\bar\nu_e\gamma_\mu P_L\nu_e)\left[\xi_{\tau L}(\bar\tau\gamma^\mu P_L\tau) + \xi_{\nu_\tau L}(\bar\nu_\tau\gamma^\mu P_L\nu_\tau)\right] + (\tau\to\mu) \qquad \textit{unobservable}$$
$$+ 2\sqrt{2}G_F\xi_{\nu_e L}(\bar\nu_e\gamma_\mu P_L\nu_e)(\bar\nu_e\gamma_\mu P_L\nu_e),$$

where the dimensionless parameters such as $\varepsilon_{\alpha R(L)}$, $\kappa_{\alpha R(L)}$ *etc. are to be identified as follows* ($\alpha = e, \mu, \tau$; $\beta = \mu, \tau$):

$$2\sqrt{2}G_F\varepsilon_{\alpha R} = \frac{1}{M^2}\left[h^{\alpha(1)}_{0,R} + Sh^{\alpha(1)}_{1,R} + Th^{\alpha(2)}_{1,R} + \cdots\right],$$

$$2\sqrt{2}G_F\kappa_{\alpha R} = \frac{1}{M^2}\left[h^{\alpha(1)}_{0,R} + Sh^{\alpha(1)}_{1,R} - Th^{\alpha(2)}_{1,R} + \cdots\right],$$

$$2\sqrt{2}G_F\varepsilon_{\beta L} = \frac{1}{M^2}\left[(h^{\beta(1)}_{0,L} - h^{\beta(2)}_{0,L}) + S(h^{\beta(1)}_{1,L} - h^{\beta(2)}_{1,L}) + T(h^{\beta(3)}_{1,L} - h^{\beta(4)}_{1,L}) + \cdots\right],$$

$$2\sqrt{2}G_F\varepsilon_{eL} = \frac{2}{M^2}\left[h^{e(1)}_{0,L} + Sh^{e(1)}_{1,L} + \cdots\right],$$

$$2\sqrt{2}G_F\kappa_{\beta L} = \frac{1}{M^2}\left[(h^{\beta(1)}_{0,L} + h^{\beta(2)}_{0,L}) + S(h^{\beta(1)}_{1,L} + h^{\beta(2)}_{1,L}) - T(h^{\beta(3)}_{1,L} + h^{\beta(4)}_{1,L}) + \cdots\right],$$

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$$2\sqrt{2}G_F\zeta_{\beta L} = \frac{2}{M^2}\left[h^{\beta(2)}_{0,L} + Sh^{\beta(2)}_{1,L} + iTh^{\beta(5)}_{1,L} + \cdots\right],$$

$$2\sqrt{2}G_F\xi_{\beta L} = \frac{1}{M^2}\left[(h^{\beta(1)}_{0,L} - h^{\beta(2)}_{0,L}) + S(h^{\beta(1)}_{1,L} - h^{\beta(2)}_{1,L}) - T(h^{\beta(3)}_{1,L} - h^{\beta(4)}_{1,L}) + \cdots\right]$$

$$2\sqrt{2}G_F\xi_{\nu_\beta L} = \frac{1}{M^2}\left[(h^{\beta(1)}_{0,L} + h^{\beta(2)}_{0,L}) + S(h^{\beta(1)}_{1,L} + h^{\beta(2)}_{1,L}) + T(h^{\beta(3)}_{1,L} + h^{\beta(4)}_{1,L}) + \cdots\right]$$

$$2\sqrt{2}G_F\xi_{\nu_e L} = \frac{1}{M^2}\left[h^{e(1)}_{0,L} + Sh^{e(1)}_{1,L} + Th^{e(2)}_{1,L} + \cdots\right]$$

c.f. hep-ph/0111137

where the dimensionless parameters such as $\varepsilon_{\alpha R(L)}$, $\kappa_{\alpha R(L)}$ etc. are to be identified as follows ($\alpha = e, \mu, \tau; \beta = \mu, \tau$):

$$
\begin{aligned}
2\sqrt{2}G_F\varepsilon_{\alpha R} &= \frac{1}{M^2}\left[h_{0,R}^{\alpha(1)} + Sh_{1,R}^{\alpha(1)} + Th_{1,R}^{\alpha(2)} + \cdots\right], \\
2\sqrt{2}G_F\kappa_{\alpha R} &= \frac{1}{M^2}\left[h_{0,R}^{\alpha(1)} + Sh_{1,R}^{\alpha(1)} - Th_{1,R}^{\alpha(2)} + \cdots\right], \\
2\sqrt{2}G_F\varepsilon_{\beta L} &= \frac{1}{M^2}\left[(h_{0,L}^{\beta(1)} - h_{0,L}^{\beta(2)}) + S(h_{1,L}^{\beta(1)} - h_{1,L}^{\beta(2)}) + T(h_{1,L}^{\beta(3)} - h_{1,L}^{\beta(4)}) + \cdots\right], \\
2\sqrt{2}G_F\varepsilon_{eL} &= \frac{2}{M^2}\left[h_{0,L}^{e(1)} + Sh_{1,L}^{e(1)} + \cdots\right], \\
2\sqrt{2}G_F\kappa_{\beta L} &= \frac{1}{M^2}\left[(h_{0,L}^{\beta(1)} + h_{0,L}^{\beta(2)}) + S(h_{1,L}^{\beta(1)} + h_{1,L}^{\beta(2)}) - T(h_{1,L}^{\beta(3)} + h_{1,L}^{\beta(4)}) + \cdots\right], \\
2\sqrt{2}G_F\kappa_{eL} &= \frac{1}{M^2}\left[h_{0,L}^{e(1)} + Sh_{1,L}^{e(1)} - Th_{1,L}^{e(2)} + \cdots\right], \\
2\sqrt{2}G_F\zeta_{\beta L} &= \frac{2}{M^2}\left[h_{0,L}^{\beta(2)} + Sh_{1,L}^{\beta(2)} + iTh_{1,L}^{\beta(5)} + \cdots\right], \\
2\sqrt{2}G_F\xi_{\beta L} &= \frac{1}{M^2}\left[(h_{0,L}^{\beta(1)} - h_{0,L}^{\beta(2)}) + S(h_{1,L}^{\beta(1)} - h_{1,L}^{\beta(2)}) - T(h_{1,L}^{\beta(3)} - h_{1,L}^{\beta(4)}) + \cdots\right] \\
2\sqrt{2}G_F\xi_{\nu_\beta L} &= \frac{1}{M^2}\left[(h_{0,L}^{\beta(1)} + h_{0,L}^{\beta(2)}) + S(h_{1,L}^{\beta(1)} + h_{1,L}^{\beta(2)}) + T(h_{1,L}^{\beta(3)} + h_{1,L}^{\beta(4)}) + \cdots\right] \\
2\sqrt{2}G_F\xi_{\nu_e L} &= \frac{1}{M^2}\left[h_{0,L}^{e(1)} + Sh_{1,L}^{e(1)} + Th_{1,L}^{e(2)} + \cdots\right]
\end{aligned}
$$

c.f. hep-ph/0111137

For other types of NSI e.g. scalar, light mediator induced, c.f. Tatsu Takeuchi's talk tomorrow
For realizing model building and light mediators, c.f. Bhaskar Dutta's talk yesterday

Constraints on ε_α

ν_μ CHARM II (strong)

ν_τ LEP

ν_e LSND

$\bar{\nu}_e$ TEXONO *c.f. Muhammed Deniz's talk*

We will focus on ε for ν_e and ν_τ.

How NSI manifests at Borexino

$$R \sim N_e \Phi_\nu \langle \sigma_\nu \rangle$$

- Detection
  $\frac{d\sigma}{dT_e}$, dominant effect
- Propagation
  $P_{ee} \sim \Phi_\nu$, small effect
- Production
  $\gamma e \to e\nu\bar{\nu}$, irrelevant $E_\nu \ll 50\ \mathrm{keV}$

How NSI manifests at Borexino – Detection

$$\frac{d\sigma_\alpha(E,T)}{dT} = \frac{2}{\pi} G_F^2 m_e \left[g_{\alpha L}^2 + g_{\alpha R}^2 \left(1 - \frac{T}{E}\right)^2 - g_{\alpha L} g_{\alpha R} \frac{m_e T}{E^2} \right] ,$$

with the recoil kinetic energy

$$0 \leq T \leq T_{\max} = \frac{E}{1 + \frac{m_e}{2E}} .$$

How NSI manifests at Borexino – Detection

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$g_{\alpha L} \to g_{\alpha L} + \varepsilon_{\alpha L}$ leads to a shift in normalization.
$g_{\alpha R} \to g_{\alpha R} + \varepsilon_{\alpha R}$ leads to a shift in T dependence, *i.e.* spectrum distortion.

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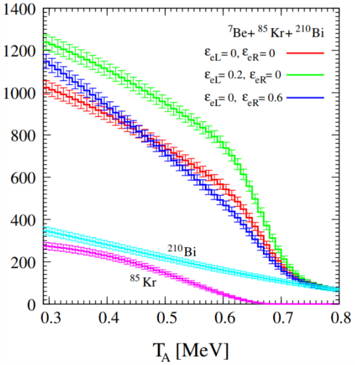

- positive correlation (partial cancellation) in ε_L and ε_R

$$\sigma \sim g_{\alpha L}^2 T_{max} - g_{\alpha R}^2 E (1 - \frac{T_{max}}{E})^3 - g_{\alpha L} g_{\alpha R} \frac{T_{max}^2}{E^2} m_e$$

- stronger correlation due to ^{85}Kr background

  ε_R change shape

  $\sim$ ^{85}Kr compensate the shape

  $\sim$ ε_L compensate the normalization

How NSI manifests at Borexino

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  $\gamma e \to e\nu\bar{\nu}$, irrelevant $E_\nu \ll 50\ \mathrm{keV}$

How NSI manifests at Borexino – Propagation

E.O.M.:

$$i\frac{d}{dx}\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{bmatrix} = \underbrace{H}\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{bmatrix}$$

H is not diagonal, b/c propagate in mass eigenstates.

$$H = \frac{1}{2E}\underbrace{U}_{\text{rot. back}}\underbrace{\begin{bmatrix}0 & & \\ & \delta m^2_{21} & \\ & & m^2_{31}\end{bmatrix}}_{\text{propagate as } e^{i\delta m^2/2E}}\underbrace{U^\dagger}_{f\to m} + \sqrt{2}G_F N_e(x)\underbrace{\begin{bmatrix}1 & & \\ & 0 & \\ & & 0\end{bmatrix}}_{\substack{\nu_e,\nu_{\mu,\tau}\text{scatter at}\\ \text{diff. rate, refraction}}}$$

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$$\varepsilon^V = \varepsilon_L + \varepsilon_R$$

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H is not diagonal, b/c propagate in mass eigenstates.

$$H = \frac{1}{2E}U\begin{bmatrix}0 & & \\ & \delta m_{21}^2 & \\ & & m_{31}^2\end{bmatrix}U^\dagger + (1 - \varepsilon_\tau^V \sin^2\theta_{23} + \varepsilon_e^V)\sqrt{2}G_F N_e(x)\begin{bmatrix}1 & & \\ & 0 & \\ & & 0\end{bmatrix}$$

$$\varepsilon^V = \varepsilon_L + \varepsilon_R$$

Note that ε shows up in propagation only on top of MSW effect.

$$H = \frac{1}{2E} U \begin{bmatrix} 0 & & \\ & \delta m_{21}^2 & \\ & & m_{31}^2 \end{bmatrix} U^\dagger + (1 - \varepsilon_\tau^V \sin^2\theta_{23} + \varepsilon_e^V)\sqrt{2} G_F N_e(x) \begin{bmatrix} 1 & & \\ & 0 & \\ & & 0 \end{bmatrix}$$

Note that ε shows up in propagation only on top of MSW effect.

Therefore, we need to look at where MSW is the strongest.

$$H = \frac{1}{2E} U \begin{bmatrix} 0 & & \\ & \delta m_{21}^2 & \\ & & m_{31}^2 \end{bmatrix} U^\dagger + (1 - \varepsilon_\tau^V \sin^2\theta_{23} + \varepsilon_e^V)\sqrt{2} G_F N_e(x) \begin{bmatrix} 1 & & \\ & 0 & \\ & & 0 \end{bmatrix}$$

Note that ε shows up in propagation only on top of MSW effect.

Therefore, we need to look at where MSW is the strongest.

$$U = \underbrace{\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix}}_{R_{23}} \underbrace{\begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix}}_{R_{13}} \underbrace{\begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}}_{R_{12}} \approx R_{23} R_{12} \, ,$$

$$H = \frac{1}{2E} U \begin{bmatrix} 0 & & \\ & \delta m_{21}^2 & \\ & & m_{31}^2 \end{bmatrix} U^\dagger + (1 - \varepsilon_\tau^V \sin^2\theta_{23} + \varepsilon_e^V)\sqrt{2} G_F N_e(x) \begin{bmatrix} 1 & & \\ & 0 & \\ & & 0 \end{bmatrix}$$

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$$U = \underbrace{\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix}}_{R_{23}} \underbrace{\begin{bmatrix} c_{13} & 0 & s_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta} & 0 & c_{13} \end{bmatrix}}_{R_{13}} \underbrace{\begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}}_{R_{12}} \approx R_{23} R_{12} \,,$$

$$\begin{aligned} R_{23}^\dagger H R_{23} &\approx \frac{1}{2E} R_{12} \begin{bmatrix} 0 & 0 & 0 \\ 0 & \delta m_{21}^2 & 0 \\ 0 & 0 & \delta m_{31}^2 \end{bmatrix} R_{12}^\dagger + \sqrt{2} G_F N_e(x)\, R_{23}^\dagger \begin{bmatrix} 1 + \varepsilon_e^V & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \varepsilon_\tau^V \end{bmatrix} R_{23} \\ &= \frac{1}{2E} \begin{bmatrix} \delta m_{21}^2 s_{12}^2 & \delta m_{21}^2 s_{12} c_{12} & 0 \\ \delta m_{21}^2 s_{12} c_{12} & \delta m_{21}^2 c_{12}^2 & 0 \\ 0 & 0 & \delta m_{31}^2 \end{bmatrix} \\ &\quad + \sqrt{2} G_F N_e(x) \begin{bmatrix} 1 + \varepsilon_e^V - \varepsilon_\tau^V s_{23}^2 & 0 & 0 \\ 0 & 0 & \mathcal{O}(\epsilon) \\ 0 & \mathcal{O}(\epsilon) & \mathcal{O}(\epsilon) \end{bmatrix} \end{aligned}$$

$$H = \frac{1}{2E} U \begin{bmatrix} 0 & & \\ & \delta m_{21}^2 & \\ & & m_{31}^2 \end{bmatrix} U^\dagger + (1 - \varepsilon_\tau^V \sin^2\theta_{23} + \varepsilon_e^V)\sqrt{2} G_F N_e(x) \begin{bmatrix} 1 & & \\ & 0 & \\ & & 0 \end{bmatrix}$$

Note that ε shows up in propagation only on top of MSW effect.

Therefore, we need to look at where MSW is the strongest.

Need a further 12 rotation $R_{12}(\phi)$ on top of the vacuum R_{12}.

Resonance conversion: $\theta_{12} + \phi = \pi/4$, (level crossing if $\theta_{12} = 0$.)

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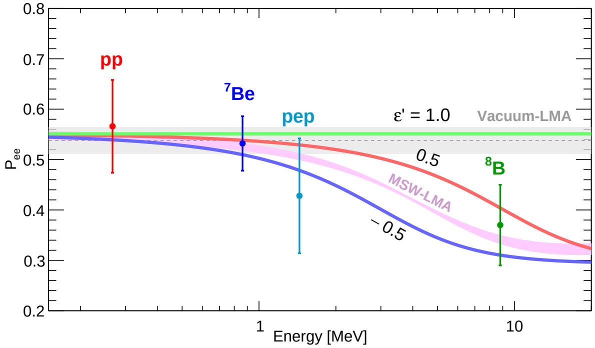
$$E_{res}(x) = \frac{\delta m_{21}^2 \cos 2\theta_{12}}{(1 - \varepsilon_\tau^V s_{23}^2 + \varepsilon_e^V) 2\sqrt{2} G_F N_e(x)}$$

$$E_{res}^{\odot}(0) \approx \frac{2\ \mathrm{MeV}}{\underbrace{(1 - \varepsilon_\tau^V s_{23}^2 + \varepsilon_e^V)}_{\substack{\text{for } E_\nu \sim \mathrm{MeV}, \\ \text{relevant if } \varepsilon \sim \mathcal{O}(1)}}} \qquad E_{res}^{\oplus}(0) \approx \frac{30\ \mathrm{MeV}}{\underbrace{(1 - \varepsilon_\tau^V s_{23}^2 + \varepsilon_e^V)}_{\text{not relevant}}}$$

How NSI manifests at Borexino – Propagation



How NSI manifests at Borexino

$$R \sim N_e \Phi_\nu \langle \sigma_\nu \rangle$$

- Detection
  $\frac{d\sigma}{dT_e}$, dominant effect
- Propagation
  $P_{ee} \sim \Phi_\nu$, small effect
- Production
  $\gamma e \to e\nu\bar{\nu}$, irrelevant $E_\nu \ll 50\ \mathrm{keV}$

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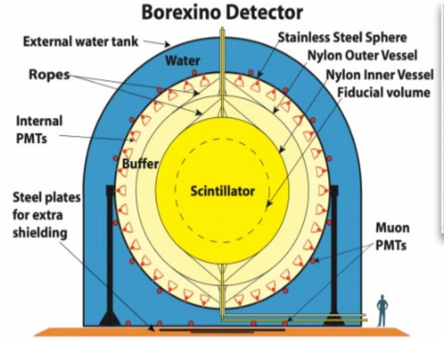
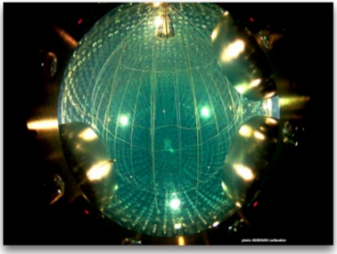
Borexino @ Laboratori Nazionali del Gran Sasso

S. Marcocci 2017



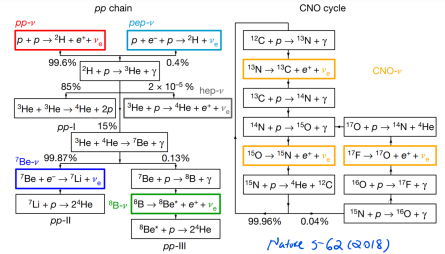
- 3800 m.w.e shielding against cosmic rays at LNGS
- active volume ~300 ton of liquid scintillator
- ~900 ton of ultra-pure buffer liquid
- 2212 PMTs detecting the scintillation light
- water Cherenkov veto equipped with 208 PMTs

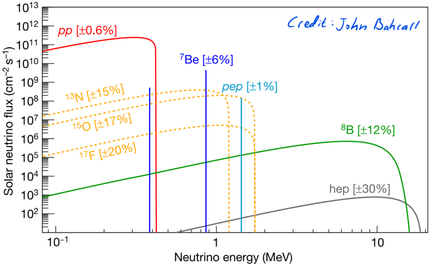


Borexino Timeline

- Phase I: 05/16/2007 - 05/08/2010, 740.7 live days, yielding 153.6 ton·year of fiducial exposure
  - Lowest energy threshold ^{8}B neutrino detection
    Phys. Rev. D82, 033006 (2010)
  - First Precision Measurement of ^{7}Be Solar Neutrino Flux
    Phys. Rev. Lett. 107, 141302 (2011)
  - First direct detection of *pep* solar neutrinos
    Phys. Rev. Lett. 108, 051302 (2012)
- Following Phase I, scintillator purification was conducted.
  - significant reduction of radioactive contaminants
  - Uranium-238 $< 9.4 \times 10^{-20}$
  - Thorium-232 $< 5.7 \times 10^{-19}$
  - ^{85}Kr reduced by ~ 4.6
  - ^{210}Bi reduced by ~ 2.3
- Phase II: 2011-, wider range energy range, $0.19\mathrm{MeV} < T < 2.93\mathrm{MeV}$
  - First realtime detection of *pp* solar neutrinos
    Nature 512, 383-386 (2014)
  - Improved measurement of ^{8}B neutrino with Phase I and Phase II data
    1709.00756
  - this analysis: 12/14/2011 – 05/21/2016, 1291.51 days × 71.3 t (252.1 ton·years) of fiducial exposure

Solar ν Source





- pp chain: pp-ν, pep-ν, ^{7}Be-ν, ^{8}B-ν
- CNO cycle: CNO-ν

- many-body decay/ fusion $\Rightarrow$ continuous spectrum: *pp*, ^{8}B, CNO
- two body process $\Rightarrow$ monochromatic spectrum: ^{7}Be, pep

c.f. Strigari's talk yesterday

Electron response to ^{7}Be ν

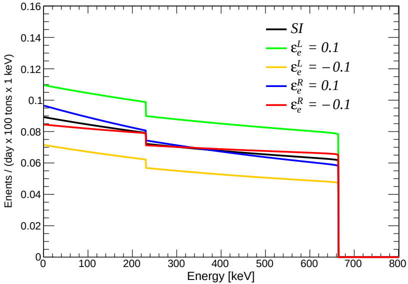
^{7}Be solar neutrinos are produced via K-shell e^- capture

$$^7\mathrm{Be} + e^- \rightarrow \begin{cases} ^7\mathrm{Li} + \nu_e & (89.6\%) \\ ^7\mathrm{Li}^*(0.48) + \nu_e & (10.4\%) \end{cases}$$

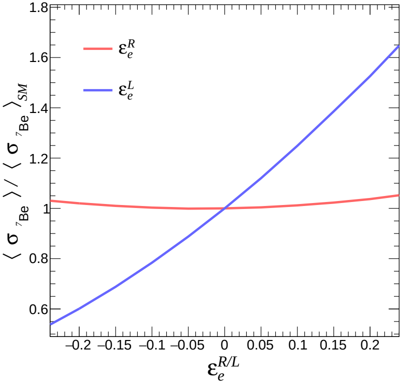
yielding mono-energetic ν of $0.862\ \mathrm{MeV}$ and $0.384\ \mathrm{MeV}$.

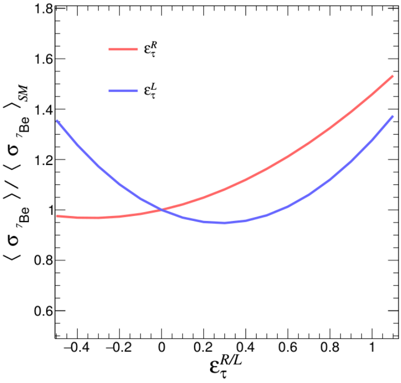
$$\frac{dR_\nu}{dT} = N_e \Phi_\nu \int dE\, \frac{d\lambda_\nu}{dE} \left[\frac{d\sigma_e}{dT} P_{ee}(E) + \left(c_{23}^2 \frac{d\sigma_\mu}{dT} + s_{23}^2 \frac{d\sigma_\tau}{dT} \right) (1 - P_{ee}(E)) \right],$$

$$T_{max} = E/(1 + m_e/2E) = 0.665\ \mathrm{MeV} \text{ and } 0.231\ \mathrm{MeV}$$

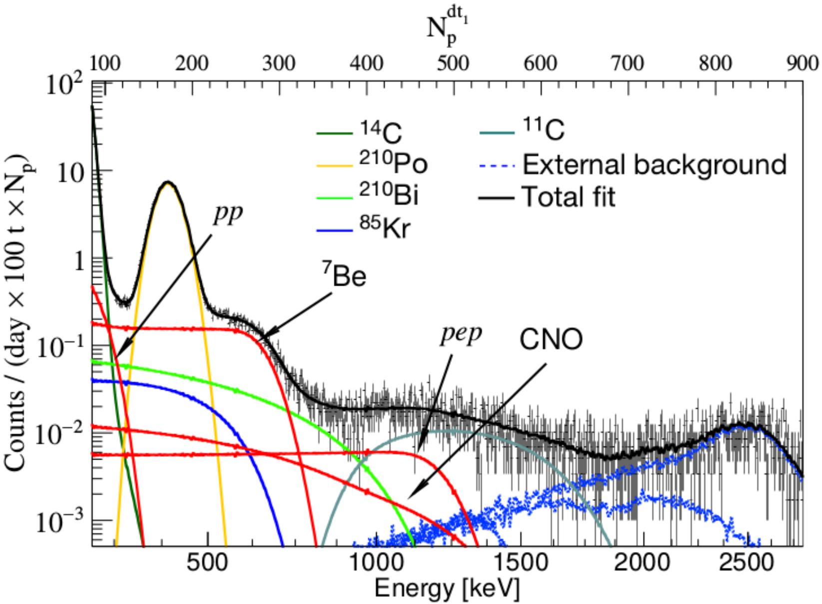


Integrated Effect of NSI

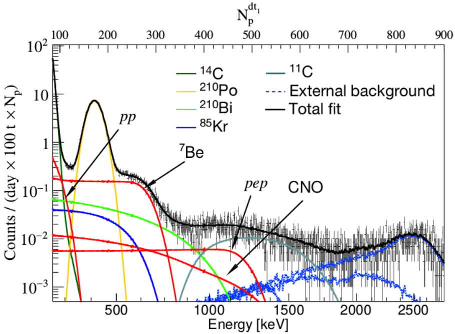




Backgrounds at Borexino



Backgrounds at Borexino



- Liquid scintillator has isotropic light emission
  - no directional information,
  - low energy sensitivity ($\sim$ 50 times larger yield than Water Cherenkov) *1308.0443*
- need to distinguish ν induced events from β or γ induced events

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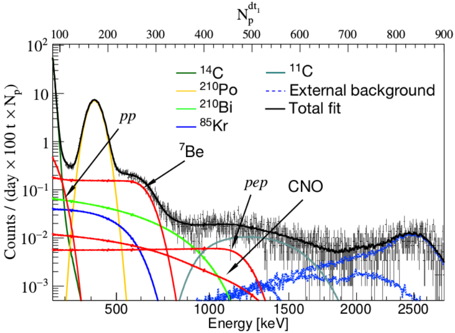


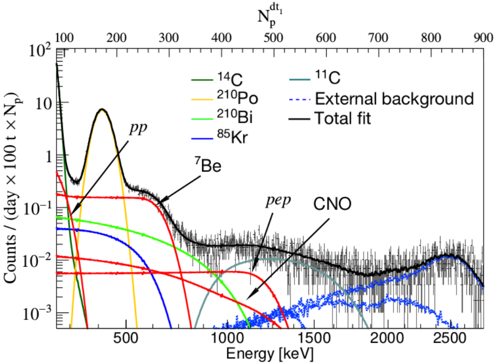
- Liquid scintillator has isotropic light emission
  - no directional information,
  - low energy sensitivity ($\sim$ 50 times larger yield than Water Cherenkov) *1308.0443*
- need to distinguish ν induced events from β or γ induced events

- Taggable BG (event-by-event cut)
  - radioactive decays from delayed coincidence,
  - muon events and those following
- cut off some exposure region (remove detector region for a time interval)
  - e.g. cosmic $\mu + {}^{12}\mathrm{C} \to \mu + {}^{11}\mathrm{C} + \mathrm{n}$ leads to ${}^{11}\mathrm{C}$, (coincidence between μ and n) ${}^{11}\mathrm{C} \to {}^{11}\mathrm{B} + \mathrm{e}^+ + \mathrm{n}$ has $\tau \sim 29.4$ min (crop out a ball of 1 m for 2 hrs)
- Majority is reconstructed through fitting
  - ${}^{85}\mathrm{Kr} \to {}^{85}\mathrm{Rb} + \mathrm{e}^- + \bar{\nu}_e$ $(Q = 0.687\ \mathrm{MeV},\ t_{1/2} \approx 10.8\ \mathrm{yrs})$
  - ${}^{210}\mathrm{Bi} \to {}^{210}\mathrm{Po} + \mathrm{e}^- + \bar{\nu}_e$ $(Q = 1.161\ \mathrm{MeV},\ t_{1/2} \approx 5\ \mathrm{d})$
  - ${}^{210}\mathrm{Po} \to {}^{205}\mathrm{Pb} + {}^{4}\mathrm{He}$ $(Q = 5.3\ \mathrm{MeV},\ t_{1/2} \approx 138\ \mathrm{d})$

Fitting w/o NSI

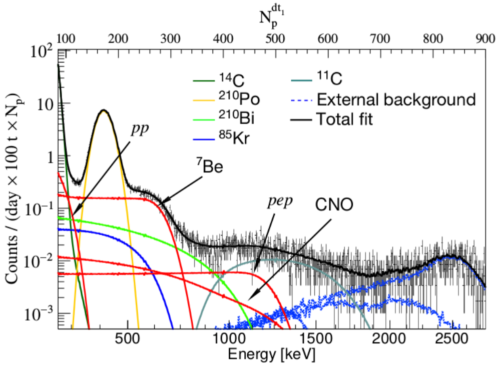
^{7}Be flux: 6% uncertainty (same for LZ and HZ, standard analysis w/o NSI leads to $\sim 2.7\%$ *1707.09279*)

Background related without NSI:



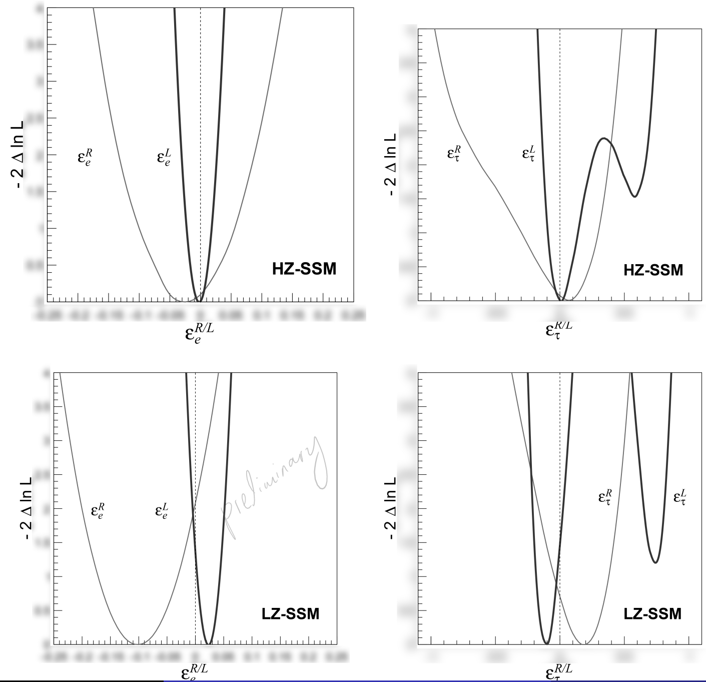
Background	Rate [cpd/100 t]
^{14}C [Bq/100 t]	40.0 ± 2.0
^{85}Kr	6.8 ± 1.8
^{210}Bi	17.5 ± 1.9
^{11}C	26.8 ± 0.2
^{210}Po	260.0 ± 3.0
Ext. ^{40}K	1.0 ± 0.6
Ext. ^{214}Bi	1.9 ± 0.3
Ext. ^{208}Tl	3.3 ± 0.1

Fitting w/ NSI



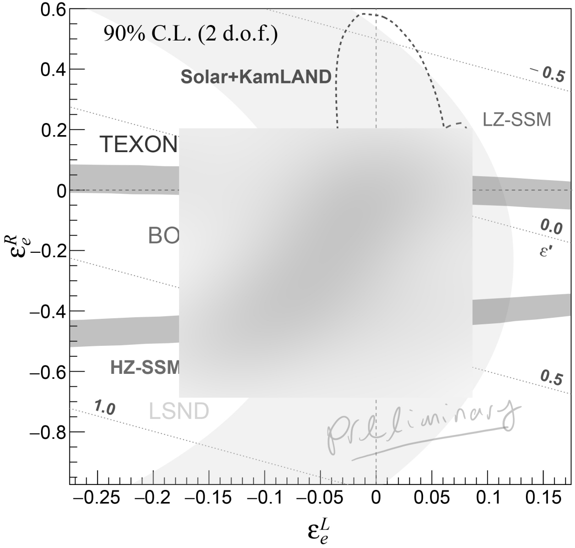
Multi-variate fitting parameters:

- light yield (energy scale)
- energy resolution
- ^{210}Po ν central and width
- ^{11}C ν starting position
- other background parameters in the detector model ($^{85}\mathrm{Kr}$, $^{210}\mathrm{Bi}$ etc.)
- $\varepsilon' s$

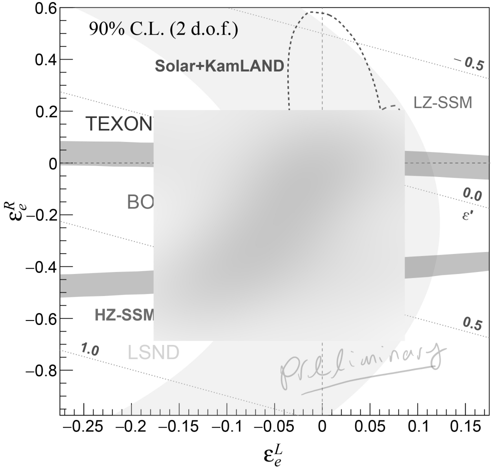

- 2 Δ ln L
ε_e^R
ε_e^L
HZ-SSM
ε_e^{R/L}
- 2 Δ ln L
ε_τ^R
ε_τ^L
HZ-SSM
ε_τ^{R/L}
- 2 Δ ln L
ε_e^R
ε_e^L
preliminary
LZ-SSM
ε_e^{R/L}
- 2 Δ ln L
ε_τ^R
ε_τ^L
LZ-SSM
ε_τ^{R/L}

	HZ-SSM	LZ-SSM	Phase I *1207.3492*	Global *0711.0698*
ε_e^R	[???, ???]	[???, ???]	[−0.21, +0.16]	[0.004, +0.151]
ε_e^L	[???, ???]	[???, ???]	[−0.046, +0.053]	[−0.03, +0.08]
ε_τ^R	[???, ???]	[???, ???]	[−0.98, +0.73]	[−0.3, +0.4]
ε_τ^L	[???, ???]	[???, ???]	[−0.23, +0.87]	[−0.5, +0.2]

Preliminary Results

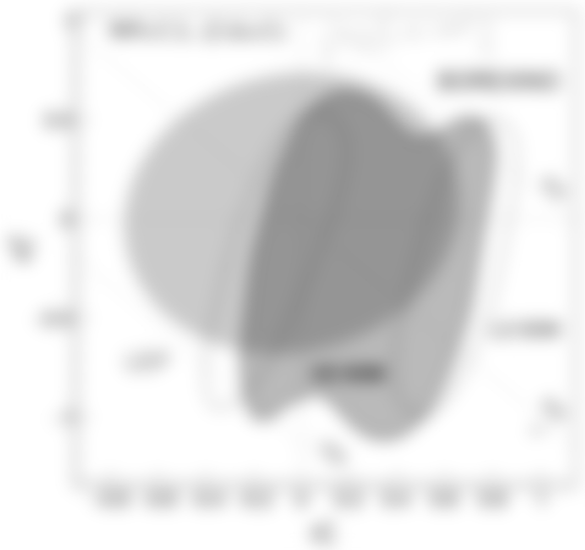


Preliminary Results

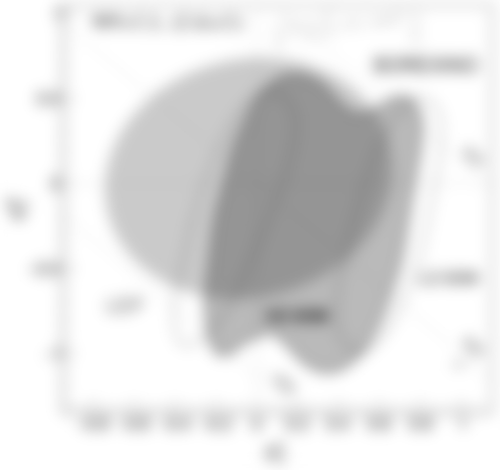


- $\varepsilon_L - {}^{85}\mathrm{Kr} - \varepsilon_R$ correlation
- orthogonal to TEXONO as ν_e v.s. $\bar{\nu}_e$
- huge improvement over LSND

Preliminary Results



Preliminary Results



- covers different region compared to LEP
- second minimum due to $g_{\tau L} \to -g_{\tau L}$ approximate symmetry, *i.e.* $\varepsilon_{\tau L} = 0$, or $-2g_{\tau L}$.

Weak mixing angle

$$g_{\alpha L} = \begin{cases} \sin^2\theta_W + \frac{1}{2} & \alpha = e \\ \sin^2\theta_W - \frac{1}{2} & \alpha = \mu, \tau \end{cases}$$

$$g_{\alpha R} = \sin^2\theta_W \qquad \alpha = e, \mu, \tau$$

- Specific direction in $\varepsilon_L - \varepsilon_R$ plane
- similar effect for both ν_e and ν_τ.

$\sin^2\theta_W$ =????±???? (stat+syst) ,	this work
$\sin^2\theta_W = 0.251 \pm 0.031\,(\text{stat}) \pm 0.024\,(\text{syst})$.	TEXONO
$\sin^2\theta_W = 0.2324 \pm 0.0058\,(\text{stat}) \pm 0.0059\,(\text{syst})$.	CHARM II

Summary

- Searching for new physics in the presence of $\nu - e$ NSI
- NSI phenomenology
  - propagation: NSI changes the ^{7}Be neutrino flux component, ν_e relative to non-$\nu_{\mu,\tau}$
  - detection: NSI changes the recoil electron spectrum
- Background
  - event-by-event cut
  - "space-time" cut
  - multi-variate fit
- Result of ε constraints, and understanding of correlations
  - ε_{eR} - $^{85}\mathrm{Kr}$
  - $\varepsilon_{eR} - \varepsilon_{eL}$
  - $\sin^2\theta_W$