Tests of Lorentz Invariance violating and other Non Standard Interaction effects with neutrino phenomenology

COST Action 18108

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Plan of the talk

- **Introduction:**

  Theoretical motivations for the study of QG and other NSI effects by means of neutrino (**υ**) physics

- **Exotic effects in υ interaction, propagation and detection:**

  Mean features in interesting cases.

- **Quantum Gravity (QG) effects and peculiarity of our model:**
  - **Geometrical and kinematic origin of Lorentz invariance violation (LIV)**
  - **Isotropy and internal symmetries preservation**
  - **Modification of the Standard Model preserving covariance**

- **Modified υ oscillation probability in presence of LIV**

- **NSI corrections:**
  - **Modification of the resonances in matter interaction (MSW effect)**
  - **Development of a tool for a full three flavor analysis**

- **Interesting phenomenological cases and possible studies**

- **Conclusions**

"Exotic" physics and neutrino phenomenology

Why to look for exotic effects?

• The Standard Model: a very successful but not a "final" theory.
(problems of neutrino mass, naturalness, dark matter, etc.)
• Apparent irreconcilability of QFT and General Relativity.
• Need to go "beyond and further", but in which direction?
(SUSY, GUT theories, dark sectors, extra dimensions, or what else?)

Need for hints by phenomenology.

• Worthwhile to look for Quantum Gravity induced effects connected with high energy structure of space-time.
Eventual small deviations from standard scenario and full restoration of Lorentz invariance at low energies.
• Multimessenger approach: look for partial anomalies in ultrahigh E cosmic rays, in γ rays and in neutrino physics.

"Exotic" physics and neutrino phenomenology

Why to look for exotic effects in neutrino physics?

Neutrino ideal candidate, because:

- It creates a link between astroparticle and elementary particles.
- Open questions (real nauture, origin and ordering of the mass and motivations for its smallness)
- Many possible natural and artificial sources (cosmic, atmospheric, solar, SN, reactor and accelerator): possibility of testing different combinations of baselines and energies.
- "Weak interaction": advantages (with respect to photons and charged cosmic ray particles) of "direct" space and time pointing to the source

Possible study of time delay effects and/or spectrum deviations.

Search for new physics as a way of improving the knowledge of "Terra cognita"

QG phenomenology in neutrino oscillations

Possible starting point: introducing kinematic modifications ⟹ **Modified Dispersion Relations**
Introduction of different MAV for every particle species (Coleman – Glashow arXiv:hep-ph/9812418)

A possible choice: our model

$$E_{(i)}^{\;2} - \left|\vec{p}_{(i)}\right|^2 \left(1 - f_{(i)}\left(p_{(i)}\right)\right) = m_{(i)}^{\;2}$$

α: perturbative coefficients

- **0-homogeneity of the perturbation function in MDR**
- **modifications depending on the particle species (i)**
- **isotropic perturbation function**

⟹

$$f_{(i)}\left(p_{(i)}\right) = \sum_{j=1}^{n} \alpha_j \frac{\left|\vec{p}_{(i)}\right|^j}{E_{(i)}^{\;j}} \approx o(1)$$

Homogeneity of the perturbation function ⟹ **Geometric origin of the MDR – Hamilton geometry of momentum space**

In the high energy limit ⟹ **different MAVs (that are species depending) introduced in the MDR**

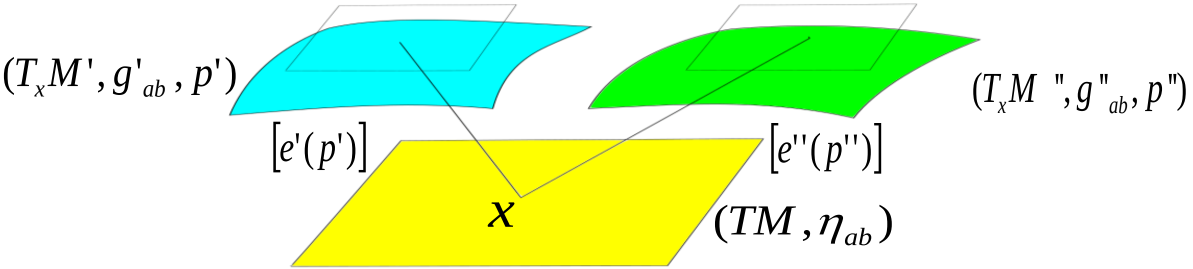
$$|\vec{v}_i| = \lim_{|\vec{p}_i|\to\infty} \sqrt{1 - f(p_i)} = 1 - \varepsilon_i$$

Induced Geometry

Momentum and coordinate space metric ⇒ $g^{\mu\nu}(p)\ or\ g_{\mu\nu}(p)=\begin{pmatrix}1 & 0\\ 0 & -(1\pm f(p))\mathrm{I}_{(3\times 3)}\end{pmatrix}$ $\quad g_{\mu\alpha}\cdot g^{\alpha\nu}=\delta_{\mu}^{\ \nu}=\mathrm{I}_{(4\times 4)}$

Vierbein used to project quantities on a common local support space (Minkowski)

$$g_{\mu\nu}(v(p))=e^{a}_{\mu}(v(p))\eta_{ab}e^{a}_{\mu}(v(p))$$



Greek indices local space

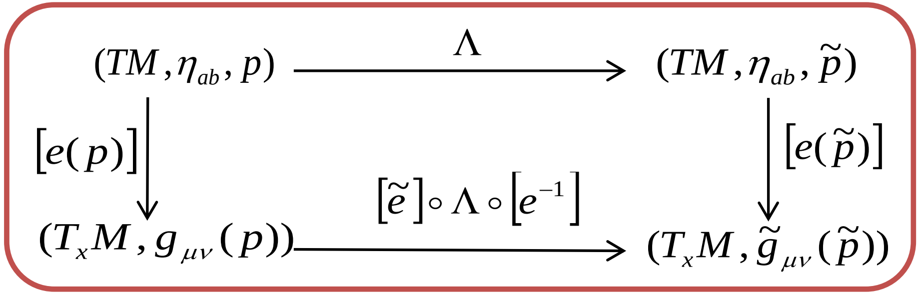
Latin indices global model

Induced momentum space diffeomorphisms connects physical quantities that live in different space-time

$$[e(\Lambda p)]^{\mu}{}_{a}\,\Lambda^{a}{}_{b}\,[e(p)]^{b}{}_{\nu}=\Lambda^{\mu}{}_{\nu}(p\rightarrow\Lambda p)$$

$$\Lambda^{\mu}{}_{\alpha}(p\rightarrow\Lambda p)g_{\mu\nu}(p)\Lambda^{\nu}{}_{\beta}(p\rightarrow\Lambda p)=g_{\alpha\beta}(\Lambda p)$$

$$MDR(\Lambda p)\Rightarrow F^{2}(\Lambda p)=F^{2}(p)\Leftarrow MDR(p)$$



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Elementary Particle Standard Model Modification

Introduction of **modified Dirac matrices (Clifford Algebra):** $\{\Gamma_\mu, \Gamma_\nu\} = 2g_{\mu\nu}(p)$

Modification of the spinors field

Modified Dirac matrices $\Gamma^0 = \gamma^0 \quad \Gamma_i = 1/\sqrt{1-f(p)} \cdot \gamma_i \quad \Gamma_5 = \frac{\varepsilon^{\mu\nu\alpha\beta}}{4!}\Gamma_\mu\Gamma_\nu\Gamma_\alpha\Gamma_\beta = \gamma_0\gamma_1\gamma_2\gamma_3 = \gamma_5$

Modified Dirac Equation $\left(i\Gamma^\mu D_\mu - m\right)\psi = 0$ **compatible with the MDR induced geometry**

Modified spinor Lagrangian $L = \sqrt{\det(g)}\;\bar{\psi}\left(i\Gamma^\mu D_\mu - m\right)\psi$

- **No "exotic" interactions (no "exotic" Feynman diagrams)**
- **No "exotic" particles**
- **Preservation of covariance even if in a modified formulation**
- **Preservation of internal** $SU(3)\times SU(2)\times U(1)$ **symmetry**

Coleman-Mandula theorem preserved (modified formulation)

LIV and neutrino oscillations

In the case of **kinematic modifications - Modified dispersion relations**:

$$E_{(i)}{}^2 - \left|\vec{p}_{(i)}\right|^2 \left(1 - \varepsilon_{(i)}\right) = m_{(i)}{}^2$$

Standard phase ruling the oscillation pattern

QG (LIV) induces modifications in the oscillation phase

$$\Delta\varphi_{ij} = -\left(\frac{m_i^2 - m_j^2}{2}\right) \times \frac{L}{E} + \frac{(\varepsilon_i - \varepsilon_j)}{2} \times \left(E \times L\right)$$

QG (LIV) perturbation

This modifications can be only perturbations (standard description works well at least in the low energy limit)

LIV correction Hamiltonian

$$\tilde{H}_{vac} = \frac{1}{2E} U \begin{pmatrix} m_1^2 & 0 & 0 \\ 0 & m_2^2 & 0 \\ 0 & 0 & m_3^2 \end{pmatrix} U^\dagger + \frac{E}{2} U \begin{pmatrix} \varepsilon_1 & 0 & 0 \\ 0 & \varepsilon_2 & 0 \\ 0 & 0 & \varepsilon_3 \end{pmatrix} U^\dagger$$

Phenomenological signals

Which QG effect can we look for?

- Main channel: time delay.
  - Quantum gravity theories (DSR, SME, ...) modifying the dispersion relations introduce possible energy dependent time delay effects in principle visible for every messenger.
  - Ideal experimental sources: high and ultra high E cosmic rays and gamma-rays, GW, cosmic neutrinos, SN neutrinos, ...
- Possible additional interferometric effects
  - In presence of quantum gravity induced LIV effects depending upon the particle species.
  - Interesting experimental cases: search for spectrum shape deformations induced by modified oscillation probabilities for:
    - high energy atmospheric neutrinos
    - solar neutrinos
    - LBL accelerator and reactor neutrinos

QG induced corrections to ν phenomenology:

- Dedicated multimessenger astronomy experiments.
  Neutrino telescopes (Ice Cube, ARCA-KM3NeT) and ultra high E cosmic ray observatories (like AugerPrime): expected observation of high energy cosmic ν with increased statistics and improved energy resolution $\rightarrow$ possible search of QG induced effects.
- Opportunities also from multipurpose experiments.
  Main goal $\neq$ (proton decay search, study of leptonic CP violation, ν mass ordering and flavor oscillation precision measurements, SN ν, dark matter searches,..), but with characteristics (statistics, E resolution, signal/noise ratio) useful for our purpose.
  - Examples connected with this presentation

• High E atmospheric ν. Improvement of LIV coefficients limits derived by SuperK. Possibility for:

- HyperKamiokande, huge Cherenkov detector: very high statistics and ν_μ-ν_e discrimination;
- JUNO, medium (53 km) baseline reactor $\bar{\nu}$ experiment: 20 kton liquid scintillator with unprecedented E resolution ($\sigma(E) = 3\%$ at 1 MeV). Flavor discrimination through events time profile.

• Solar ν: Search (at future exp., like JUNO) for spectrum deformation in the medium-high E part; discrimination from other NSI correction through D/N asymmetry and comparison with LBL reactor data

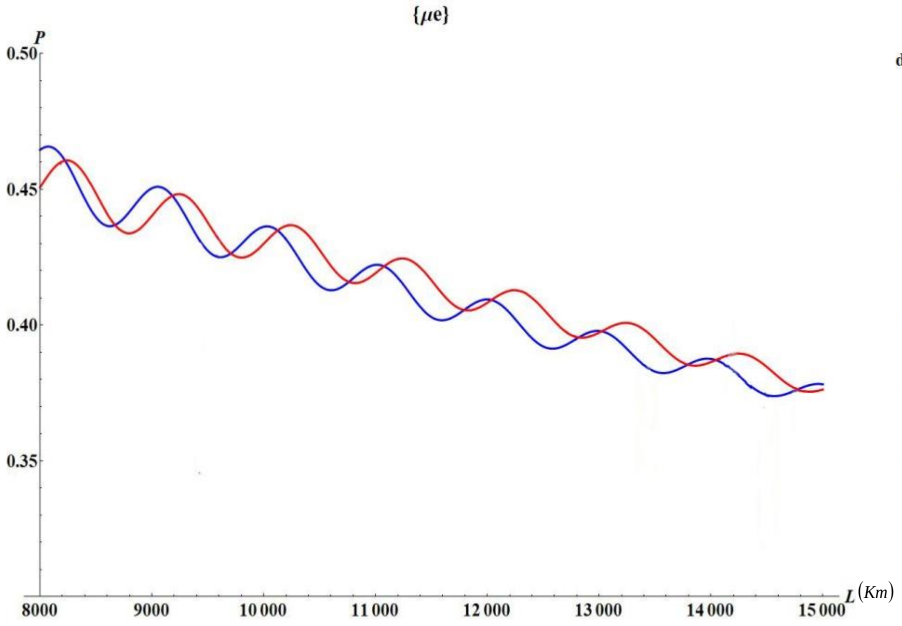
• artificial ν experiments (T2K, NOνA, DUNE)

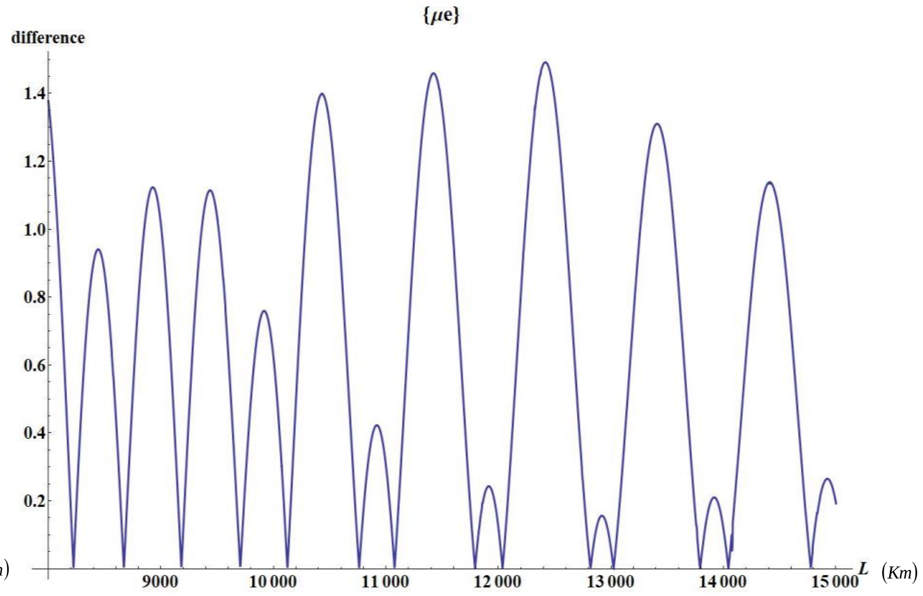
LIV and neutrino oscillations

Integrated oscillation probability convoluted with the energy beam υ flux with LIV (blue) compared to standard theory (red)

$$\frac{\int_{E\,\min}^{E\,\max} \Phi_\nu(E) P_{\nu_\mu \to \nu_e}(E)\, dE}{\int_{E\,\min}^{E\,\max} \Phi_\nu(E)\, dE}$$

$$E_{\min} = 1GeV \quad E_{\max} = 100GeV \quad \delta\varepsilon_{12} = 5\times 10^{-25} \quad \delta\varepsilon_{31} = \delta\varepsilon_{32} = 5\times 10^{-23}$$





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NSI analysis theory in solar sector

Matter effects can modify the oscillation pattern and are caused by the υ interaction with electrons.

In the standard scenario only the ν_e interaction with matter also via the charged current

Introducing NSI all neutrino flavors can interact via charged current with matter

$$L_{NSI}^{CC} = -\sum_{\alpha\beta} 2\sqrt{2} G_F \varepsilon_{\alpha\beta}^{fgX} \left(\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta\right) \left(\bar{f} \gamma_\mu P_X g\right)$$

Hamiltonian for the free propagation in flavor basis

Hamiltonian for the matter interaction via charged current in flavor basis

NSI interaction matrix

General analysis taking into account off-diagonal terms

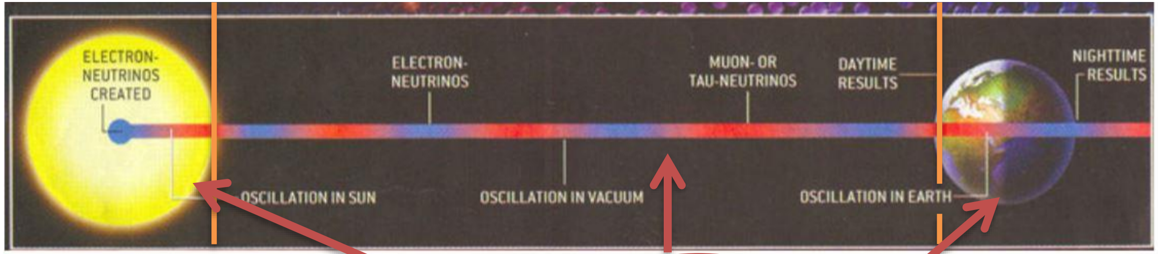
$$H_{mat}^{CC} = H_{mat}^{SM} + H_{mat}^{NSI} = \sqrt{2} G_F N_e \begin{pmatrix} 1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon_{e\tau} & \varepsilon_{\mu\tau} & \varepsilon_{\tau\tau} \end{pmatrix}$$

SME perturbation Hamiltonian (minimal SME dim=4 operators)

$$H^{SME} = \begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{12} & a_{22} & a_{23} \\ a_{13} & a_{23} & a_{33} \end{pmatrix}$$

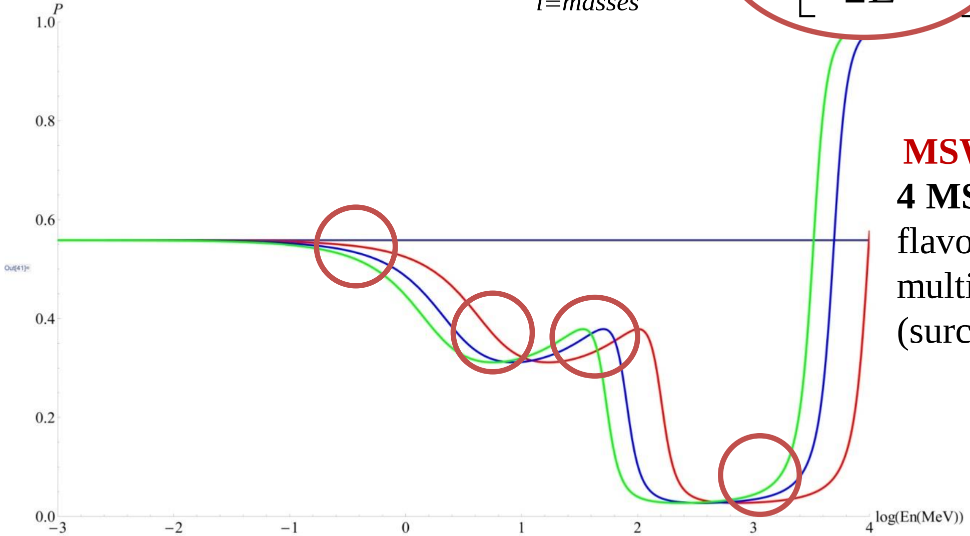
Solar Neutrinos and MSW effect

Complete description of neutrino propagation from the source to the detection



Transition probability $P_{\alpha\to\beta} = \left|A_{\alpha\to\beta}\right|^2 \Rightarrow A_{\alpha\to\beta} = \sum_{i=masses} A^S_{\alpha\to i} \cdot \exp\left[\frac{-im_i^2}{2E} L\right] \cdot A^E_{i\to\beta}$

Transition amplitude from a α flavor υ at production to a β flavor at detection



MSW survival probability of electronic ν

4 MSW resonances – 1 resonance for every flavor coupled with the other 2 flavors multiplied for 2 different matter density (surce and detection)

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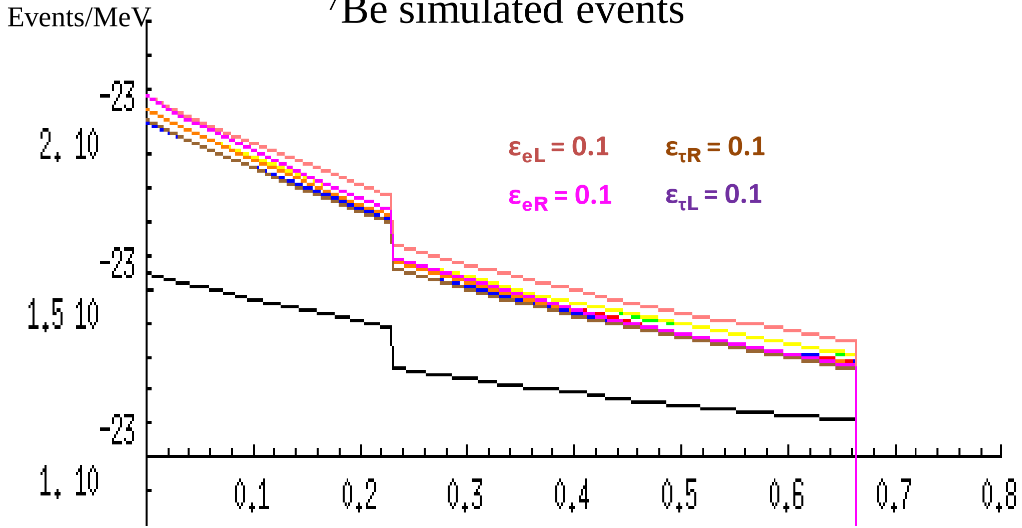
Expected ^{7}Be electron signal and comparison to the Borexino result

Expected signal from the ^{7}Be neutrinos simulated with the 3-flavors oscillation probability convoluted with the flux and the NSI elastic cross section :

$$\frac{dN(T)}{dT} = \int_{E_{min}}^{E_{max}} \sum_{\alpha=flavors} \left[\Phi_e(E_\nu) P_{e\alpha}(E_\nu) \frac{d\sigma_{e\alpha}(T)}{dT}\right] dE_\nu$$

The obtained result is compatible with the expected electron signal from the ^{7}Be neutrinos (Borexino collaboration).

^{7}Be simulated events



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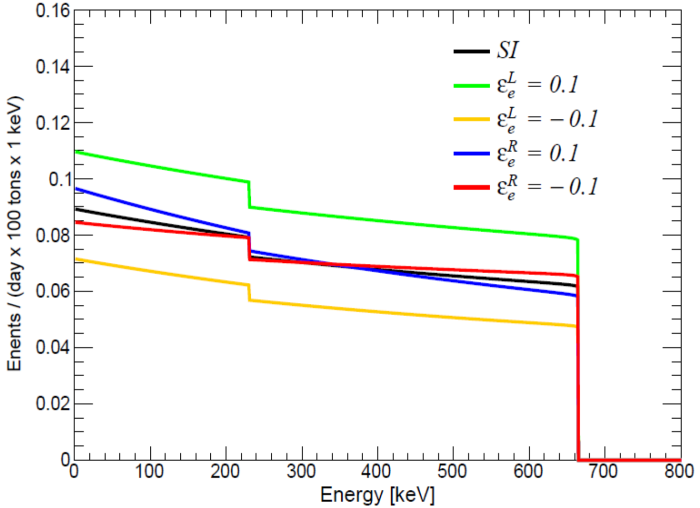

Conclusions

- Theoretical motivations and phenomenological opportunities for QG effects investigation in neutrino physics
- Theoretical set up: formulation of a geometrical inspired model predicting isotropic Lorentz invariance violation and preserving the usual Standard Model gauge symmetries
- Modified neutrino oscillation probabilty and interaction in presence of LIV
- Potential windows for QG induced experimental signals in neutrino physics
  - Time delay effects
  - Interferometric effects: corrections to the oscillation pattern
- QG induced effects and other NSI corrections.
  Analogies and discrimination strategies: development of a tool for a complete 3 flavor description of matter interactions
- Present and future phenomenological opportunities
  What shall we ask to Santa Klaus? Is SK already here?

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Thank you for your attention!!!!

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Back up slides

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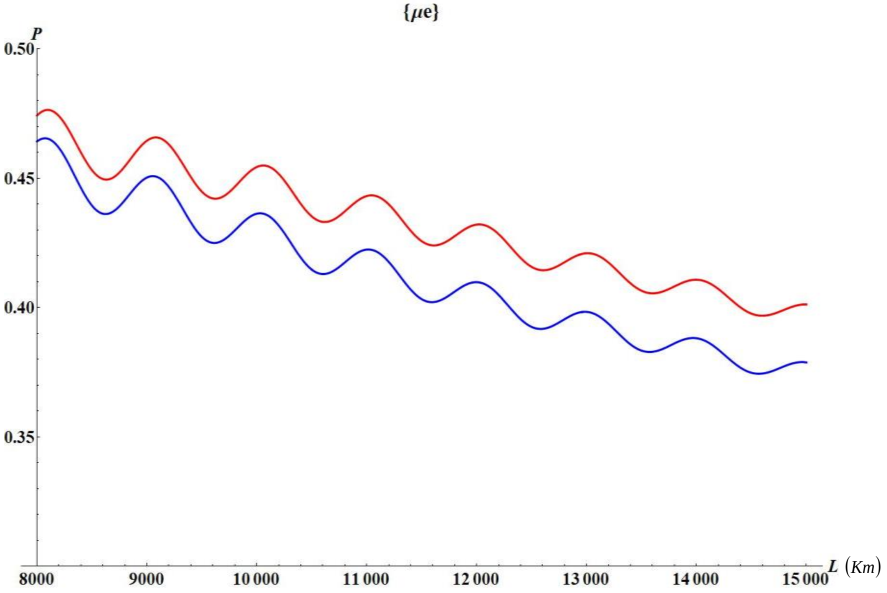
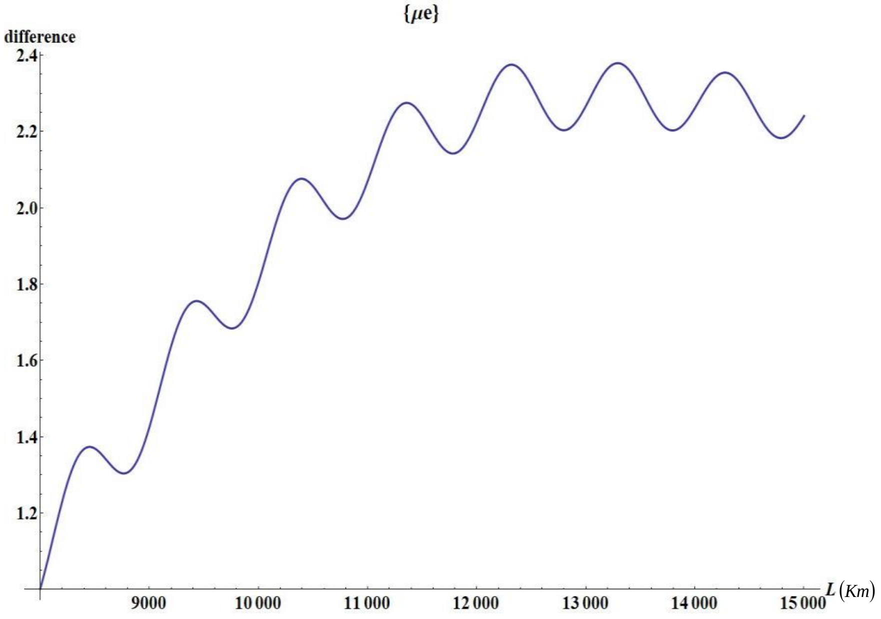
LIV and neutrino oscillations plots (1)

$$E_{\min} = 1GeV \quad E_{\max} = 10GeV \quad \delta\varepsilon_{ij} = 1\times10^{-23}$$

$$\frac{\int_{E\min}^{E\max} \Phi_{\nu}(E) P_{\nu_\mu \to \nu_e}(E) dE}{\int_{E\min}^{E\max} \Phi_{\nu}(E) dE}$$

Integrated oscillation probability with LIV (blue) compared to standard theory (red)





Comparison of two and three flavor analysis in survival probability (2)

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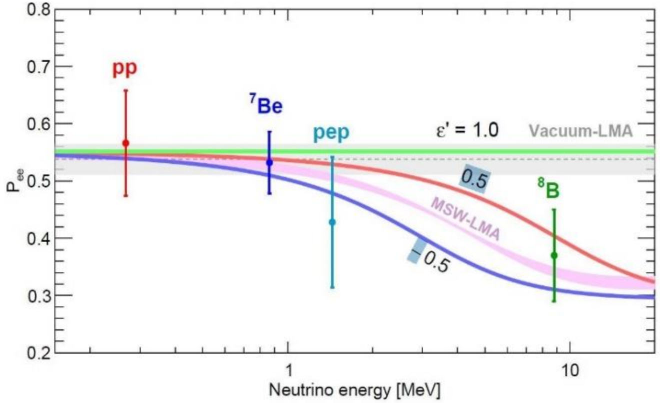
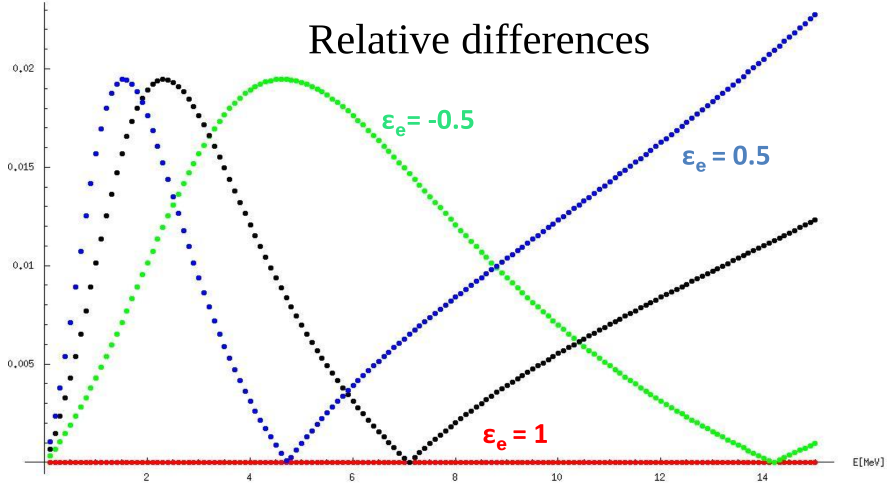
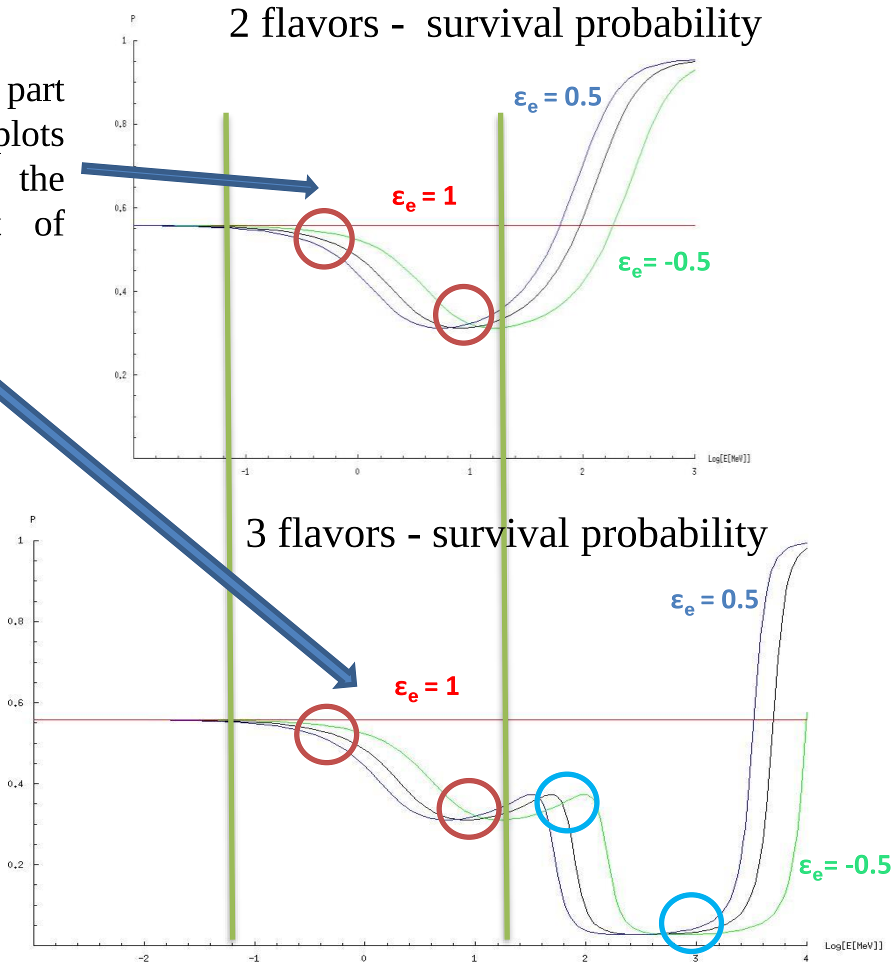


The highlighted part of the right plots corresponds to the obtained result of Borexino collaboration





Non Standard Interactions (NSI) – modified interaction cross sections

The introduction of NSI modify the **electron-matter cross section**

Example of modified cross section in the case of only diagonal NSI terms

$$\frac{d\sigma_{e\alpha}}{dT} = \frac{2}{\pi} G_F^2 \, m_e \left[\tilde{g}_{\alpha LL}^2 + \tilde{g}_{\alpha LR}^2 \left(1 - \frac{T}{E_\nu}\right)^2 - \tilde{g}_{\alpha LL} \tilde{g}_{\alpha LR} \frac{m_e T}{E_\nu^2} \right]$$

NSI modified coupling constants

$$\tilde{g}_{\alpha LL}^{\nu e} = g_{\alpha LL}^{\nu e} + \varepsilon_{\alpha L} \qquad \tilde{g}_{\alpha LR}^{\nu e} = g_{\alpha LR}^{\nu e} + \varepsilon_{\alpha R}$$

$$g_{LL}^{\nu e} = \frac{1}{2}\left(g_{LV}^{\nu e} + g_{LA}^{\nu e}\right) = -\frac{1}{2} + \sin^2\theta_W \, ,$$

$$g_{LR}^{\nu e} = \frac{1}{2}\left(g_{LV}^{\nu e} - g_{LA}^{\nu e}\right) = \sin^2\theta_W \, .$$

Modified scattered electron spectrum inside the detector

This spectrum can be computed convolving the survival probability with the incoming foreseen neutrino flux and the interaction cross section

Neutrino flux

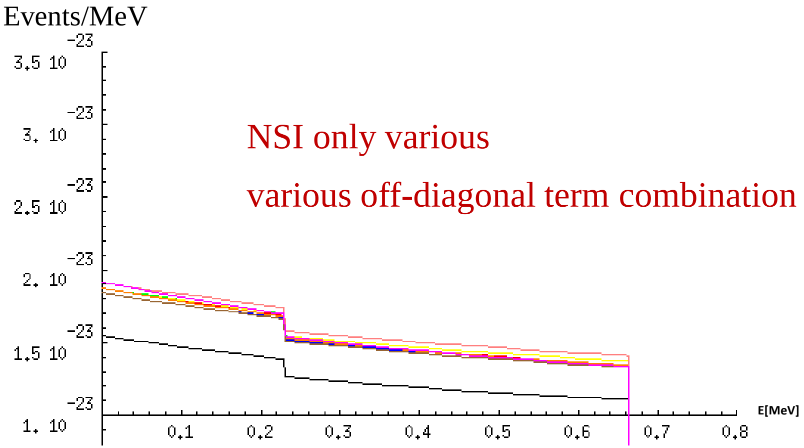
Interaction cross-section

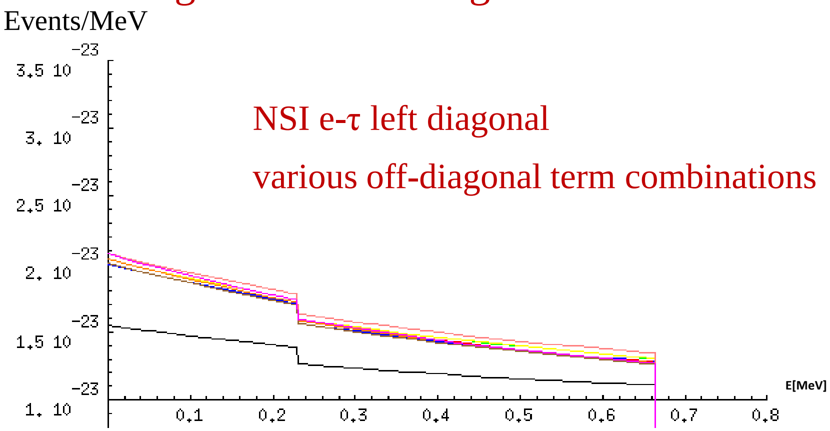
$$\frac{dN(T)}{dT} = \int_{E\,min}^{E\,max} \sum_{\alpha = flavors} \left[\Phi_e(E_\nu) P_{e\alpha}(E_\nu) \frac{d\sigma_{e\alpha}(T)}{dT} \right] dE_\nu$$

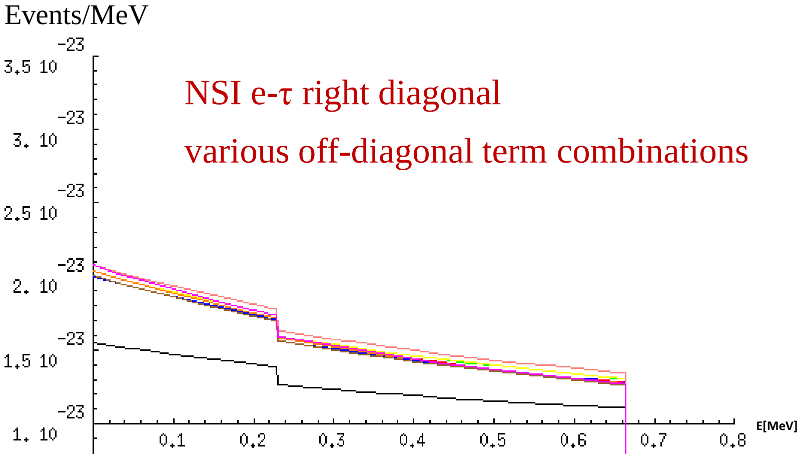
Survival probability

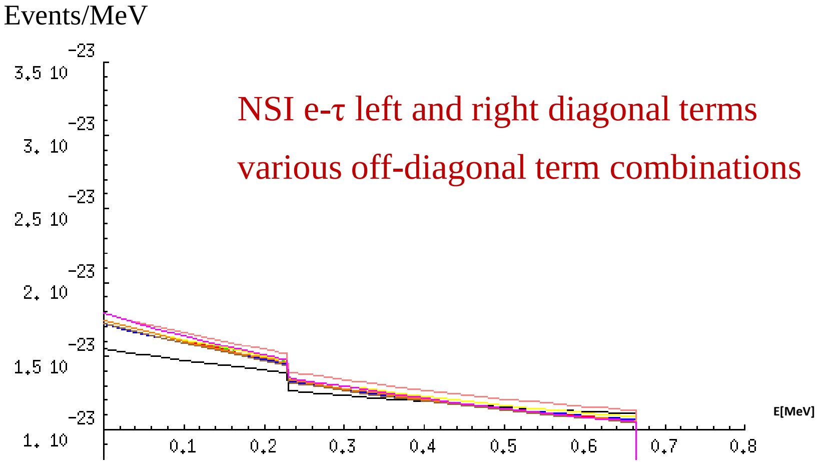
Expected ^{7}Be electron signal

^{7}Be simulated events: Various combination of NSI diagonal and off-diagonal terms







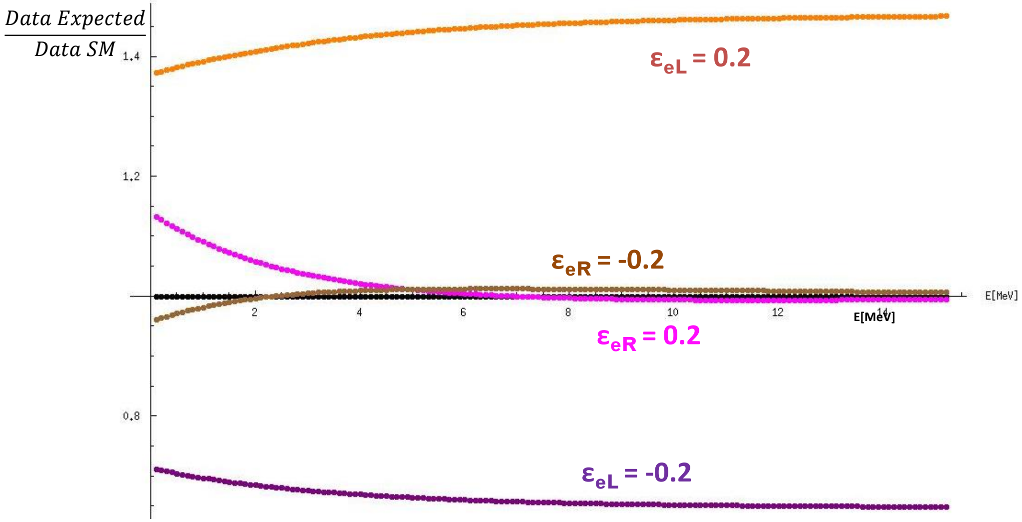


Expected ^{8}B electron signal

Expected signal from the ^{8}B neutrinos simulated with the 3-flavors probability analysis convoluted with the ^{8}B spectra and the NSI elastic cross section:

$$\frac{dN(T)}{dT} = \int_{E\min}^{E\max} \sum_{\alpha = flavors} \left[\Phi_e(E_\nu) P_{e\alpha}(E_\nu) \frac{d\sigma_{e\alpha}(T)}{dT} \right] dE_\nu$$

^{8}B simulated events



The ε_{eL} NSI coefficient changes the normalization of the signal observed and the induced variation is roughly symmetric. Instead, ε_{eR} coefficient causes expected signal shape deformation.

Result Consistent with the Borexino collaboration one.