NSI and LIV with JUNO

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JUNO-IT
Politecnico di Milano May 5-6th 2022

Istituto Nazionale di Fisica Nucleare
Sezione di Milano

Università
degli Studi
di Milano

COST Action 18108

Plan of the talk

1. **Quantum Gravity effects**

2. **Non Standard Interactions**

   - Non Standard Interaction theoretical description

   - Solar neutrino propagation and MSW effect in a complete 3 flavors scenario

   - Phenomenological applications in solar neutrinos: ^{7}Be and ^{8}B expected spectrum

3. **Potentiality of the solar neutrino studies at JUNO**

   - Spectrum studies improvements in standard and exotic (NSI) scenarios

   - Day/night asymmetry studies

4. **Conclusion**

Quantum Gravity effects in neutrino physics

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

Quantum Gravity effects can be detected with solar and atmospheric neutrinos:

- **Solar sector:** QG can modify both the survival probability and the interaction cross section
- **Atmospheric sector:** QG can modify the survival probability

Quantum Gravity analysis is analogous to the NSI analysis:

posing constraints on the magnitude of the perturbations

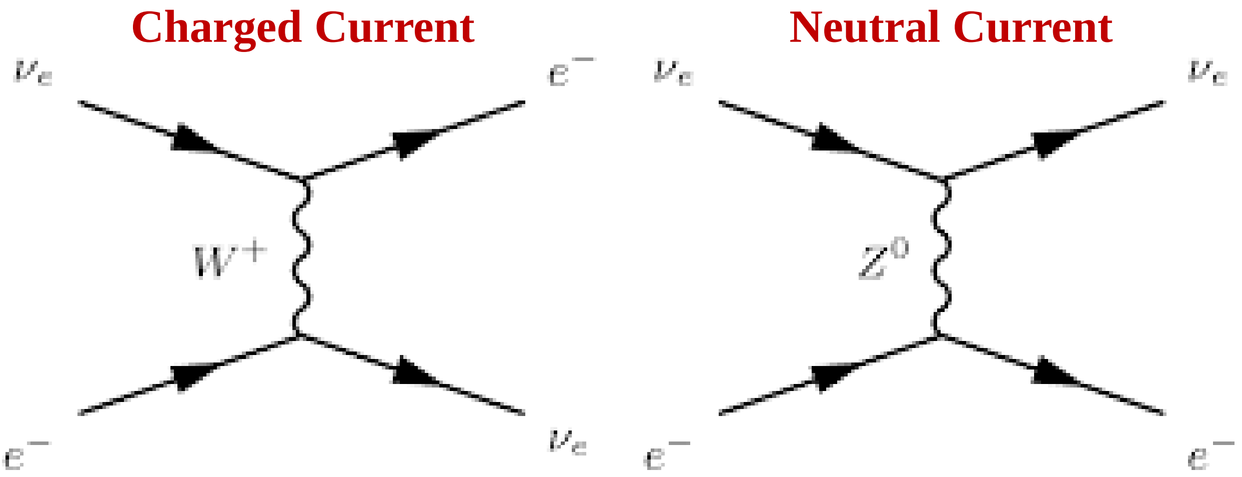
Standard Model Extension – (Kostelecky – Colladay) : spacetime isotropy violating scenario (Yellow-Book)
Alternative scenario DSR theories – Homogeneously Modified Special Relativity: preserving covariance

- **Homogeneously Modified Special Relativity (HMSR) - A new possible way to introduce an isotropic Lorentz Invariance Violation in particle Standard Model** -
  M.D.C.Torri, V.Antonelli, L.Miramonti (INFN Milan & Milan University) Jun 13, 2019. 45 pp.
  Eur.Phys.J. C79 (2019) no.9, 808 1
- **Neutrino oscillations and Lorentz Invariance Violation in a Finslerian Geometrical model -**
  V. Antonelli, L. Miramonti, M.D.C.Torri - **Eur.Phys.J. C78 (2018) n.8, 667**
- **Neutrino Oscillations and Lorentz Invariance Violation -**
  M.D.C.Torri - **Universe 2020, 6(3), 37**

Non Standard Interactions (NSI) in solar neutrino sector

Ordinary matter is made of **up/down quarks** and **electrons**:

The SM precisely calculates the interactions of neutrino with other fermions.



Charged Current

Neutral Current

Several theoretical scenarios such as:

SUSY, L-R symmetric models, dark matter, additional neutral leptons or scalar particles…

predict the possibility of: **Non Standard Interactions**

Neutrino matter interactions

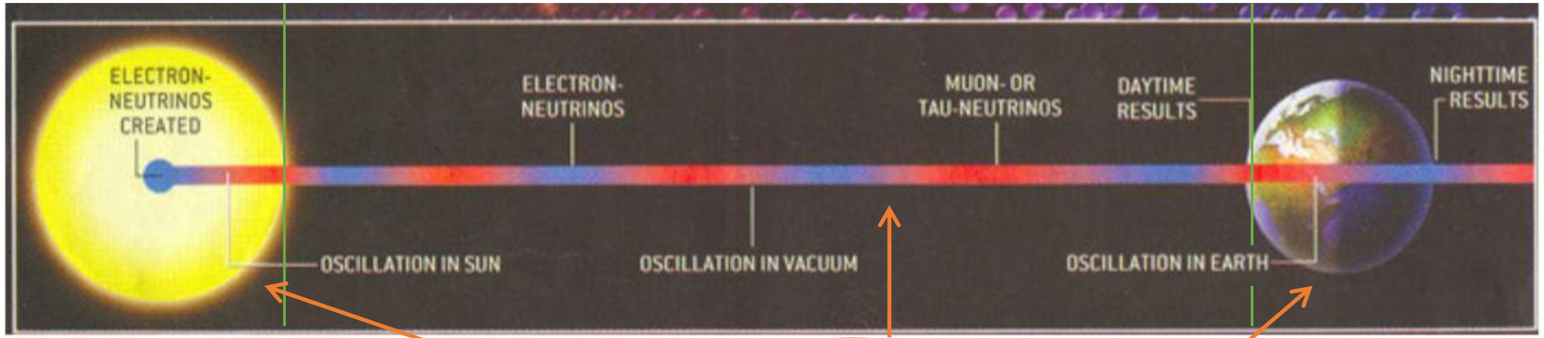
New interactions can modify neutrino-matter interactions

Solar neutrino (^{7}Be - ^{8}B and even hep) can be exploited to investigate NSI, analyzing:

- **ν production:** **NSI** modify of the interaction inside the Sun during the production – (negligible effect)
- **ν propagation:** **NSI** affect the propagation and the survival probability (the mass eigenstates are modified)
  (secondary and visible effect (more visible for **^{8}B**))
- **ν detection:** **NSI** modify the matter-neutrino cross sections inducing modifications of the electron scattered
  spectrum – (main effect)

Solar Neutrinos and MSW effect in a complete 3 flavors analysis

3 flavor analysis strategy for the MSW effect: complete description of neutrino propagation from the source to the detection



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

$$A_{\alpha\to\beta} = \sum_{i=masses} A^{S}_{\alpha\to i}\cdot\exp\left[\frac{-im_i^2}{2E}L\right]\cdot A^{E}_{i\to\beta}$$

Terms depending on the unitary matrices describing rotations of mass eigenstates (determined for matter - MSW)

Propagation inside the Sun is supposed adiabatic: solar density varies slow from the center to the surface

Oscillation probability from α to β flavor

$$P_{\alpha\to\beta} = \left|A_{\alpha\to\beta}\right|^2 = \sum_{i=masses}\left(P^{S}_{\alpha\to i}\right)\cdot\left(P^{E}_{i\to\beta}\right)\cancel{+(\ldots)\cos\left(\frac{\Delta m_{ij}^2}{2E}L+\delta_m\right)}$$

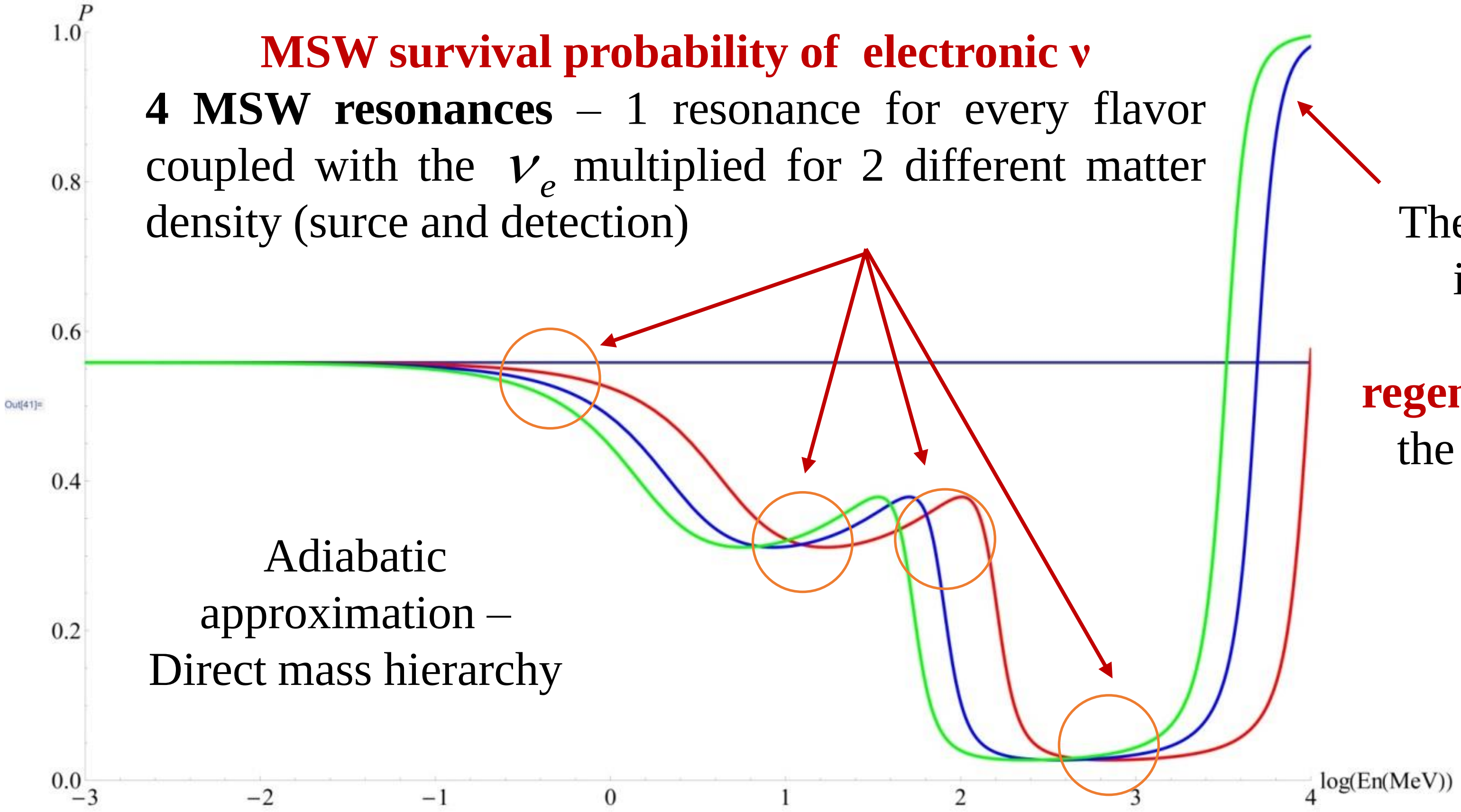
Vacuum oscillation terms can be neglected: the terms depending on the ratio L/E oscillate very fastly: their average value vanishes inside a realistic non ideal energetic bin (finite energy resolution)

Oscillation probability for MSW effect (3 flavors analysis)

The oscillation probability is obtained for **every energetic regime** in a **full 3 flavors scenario**

3 flavors analysis framework presents an improvement in precision

this feature can become relevant for present and future experiments



MSW survival probability of electronic ν

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

Adiabatic approximation – Direct mass hierarchy

The interaction with matter increases the survival probability: **regeneration effect** caused by the increasing cross section

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

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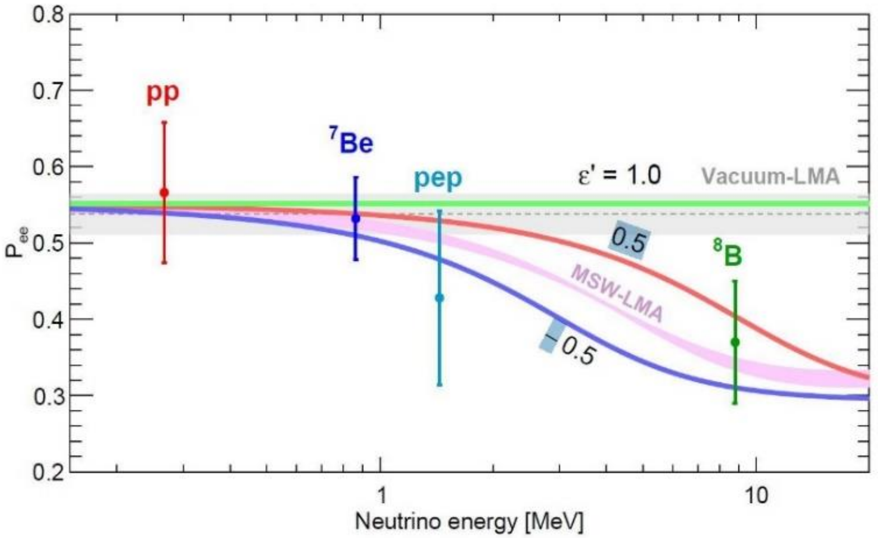
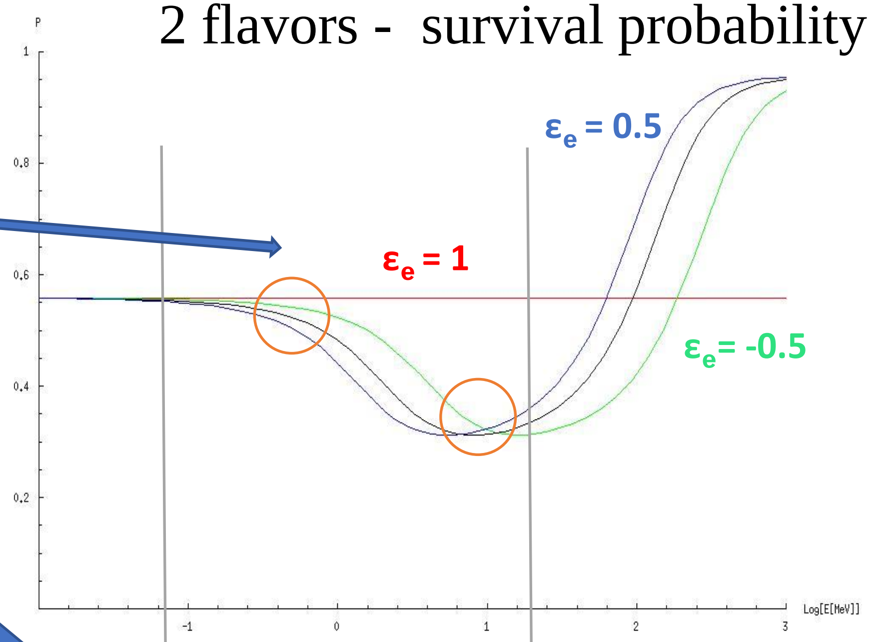
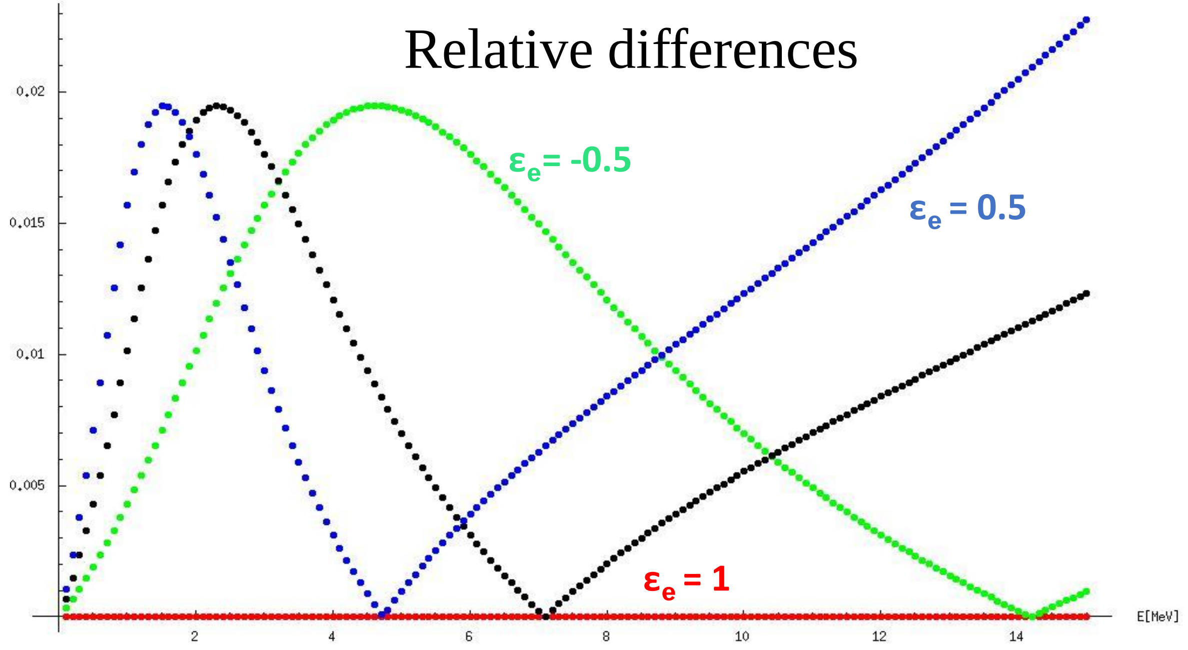


The highlighted part of the right plots corresponds to the obtained result of Borexino collaboration

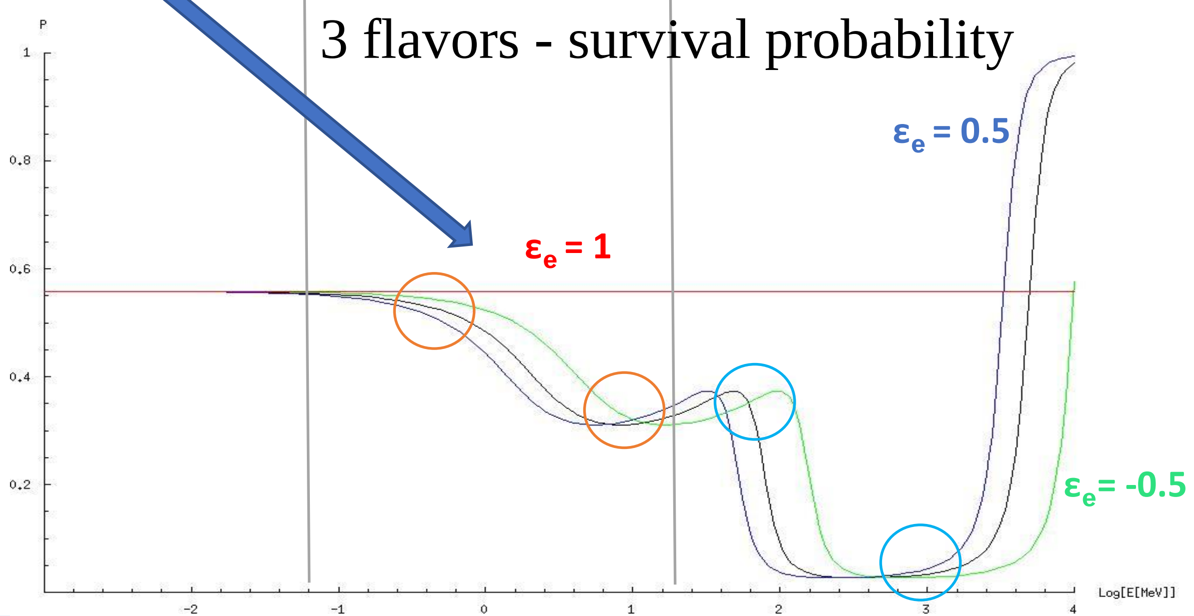
2 flavors - survival probability



Relative differences



3 flavors - survival probability



Non Standard Interactions (NSI) - theory

The introduction of NSI main effect is present in the interaction with matter: scattering inside the detector

In the standard scenario only the charged current rules the ν_e interaction with matter,
introducing NSI the matter all neutrino flavors can interact via charged non standard interactions

NSI modified matter interaction conserved current (effective Lagrangian)

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

$$X \Rightarrow Left - Right$$

NSI modified coupling constants

modified matter interaction matrix

Matter-interaction potential, it depends on the electron density in matter →

$$V(x)\begin{pmatrix} 1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon_{e\tau} & \varepsilon_{\mu\tau} & \varepsilon_{\tau\tau} \end{pmatrix}$$

$\varepsilon_{\mu\mu}$ strongly suppressed by previous experimental observations

Non Standard Interactions (NSI) – matter interaction

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

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

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

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

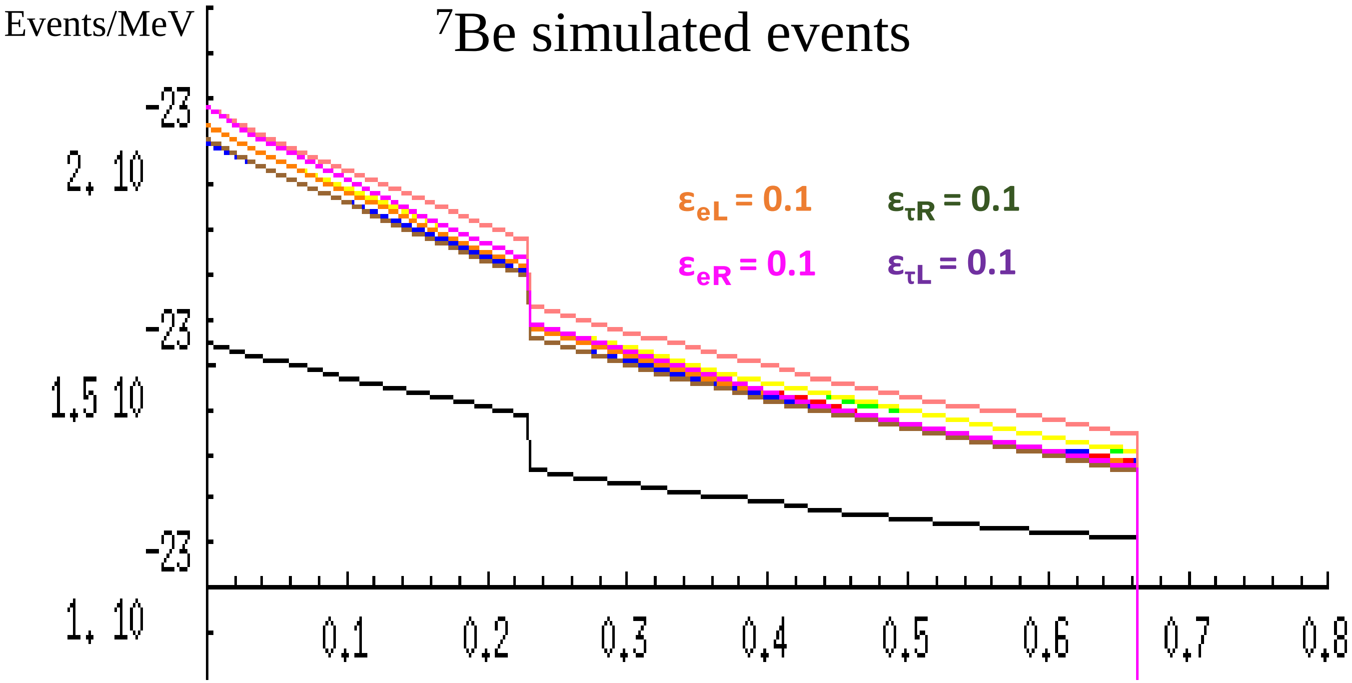
$$\frac{dN(T)}{dT} = \int_{E\,\min}^{E\,\max} \sum_{\alpha = flavors} \left[\overset{\text{Neutrino flux}}{\overset{\downarrow}{\Phi_e(E_\nu)}} \underset{\text{Survival probability}}{\underset{\uparrow}{P_{e\alpha}(E_\nu)}} \overset{\text{Interaction cross-section}}{\overset{\downarrow}{\frac{d\sigma_{e\alpha}(T)}{dT}}} \right] dE_\nu$$

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

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

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

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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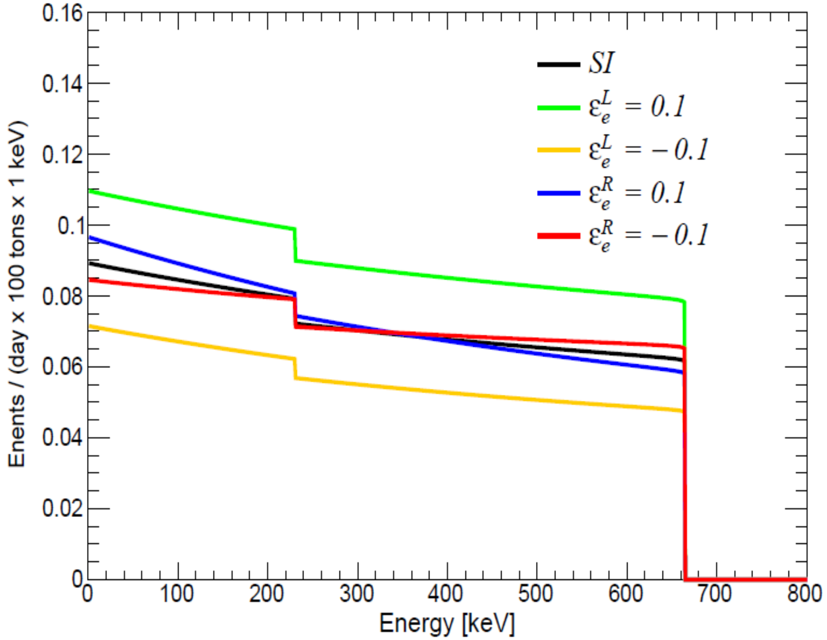
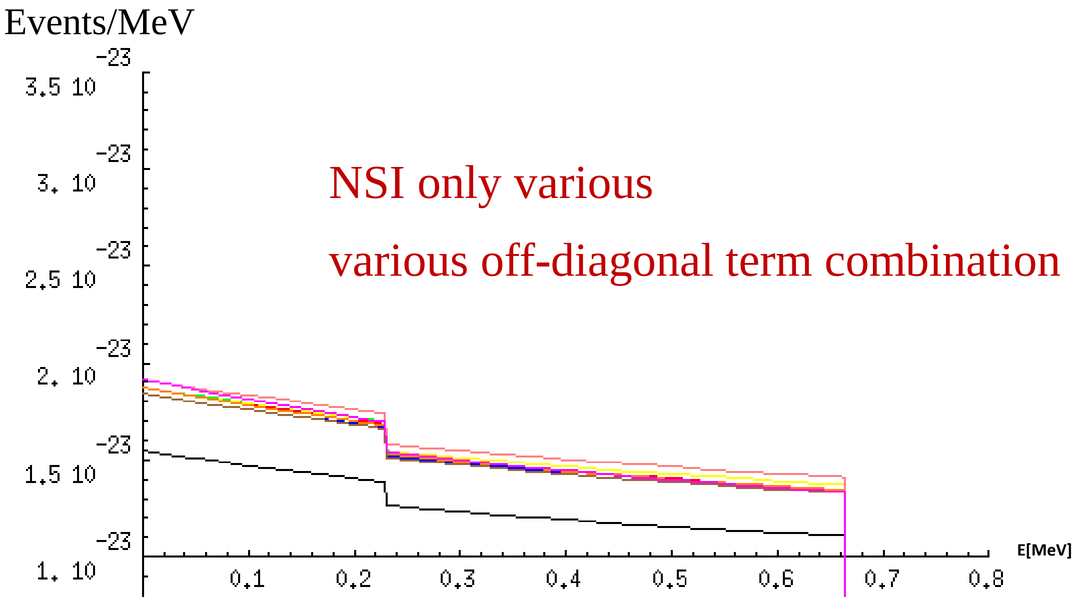


The ε_{eL} NSI coefficient changes the normalization of the signal observed and the induced variation is roughly symmetric. Instead, ε_{eR} coefficient causes expected signal shape deformation.

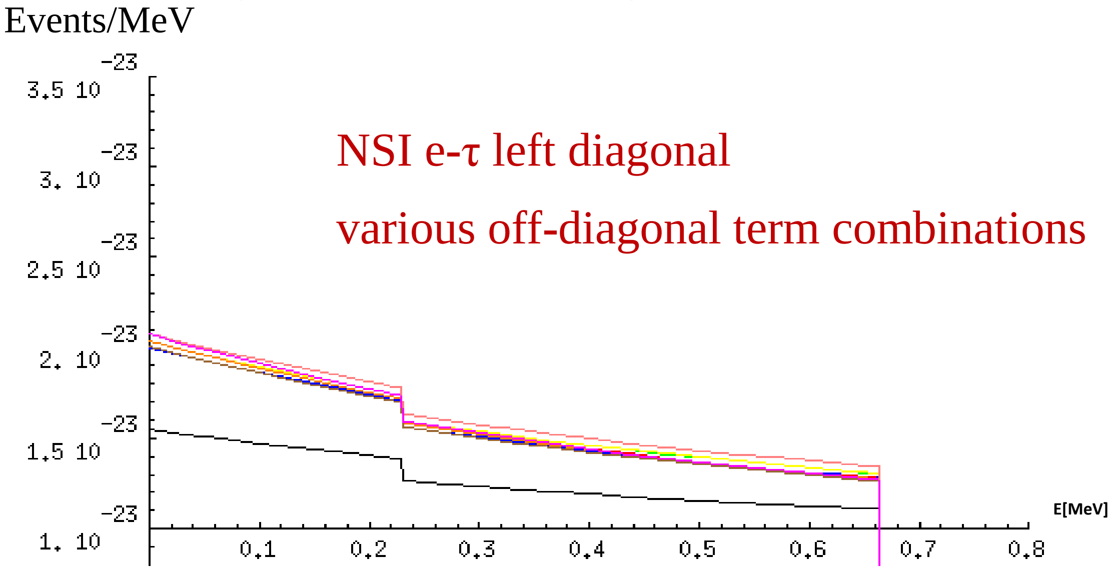
Result Consistent with the Borexino collaboration one.

Expected ^{7}Be electron signal

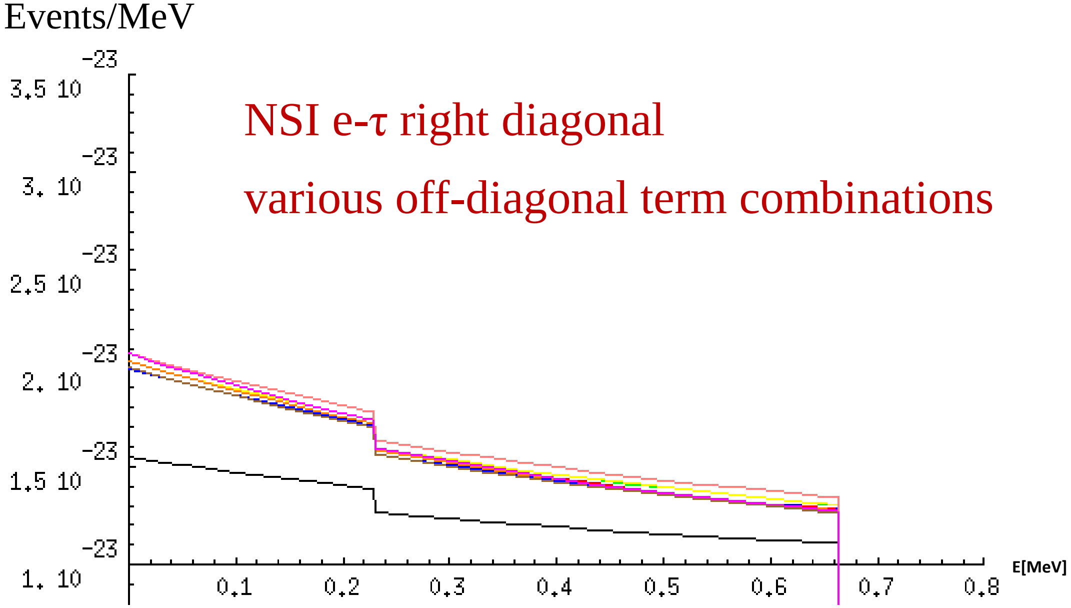
^{7}Be simulated events: Various combination of NSI diagonal and off-diagonal terms


NSI only various

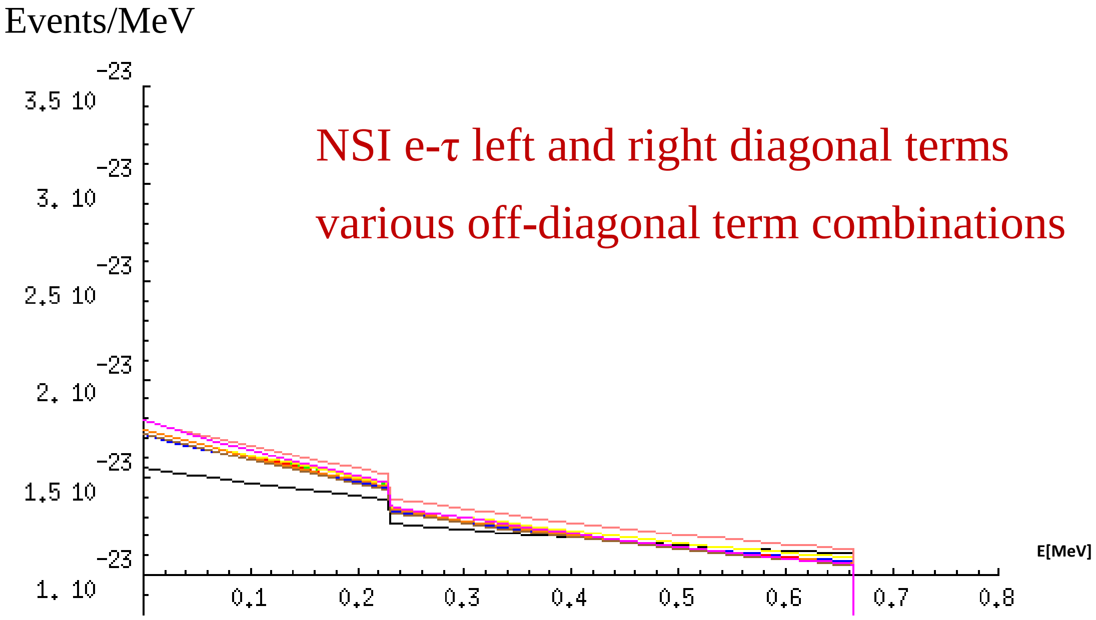
various off-diagonal term combination


NSI e-τ left diagonal

various off-diagonal term combinations


NSI e-τ right diagonal

various off-diagonal term combinations


NSI e-τ left and right diagonal terms

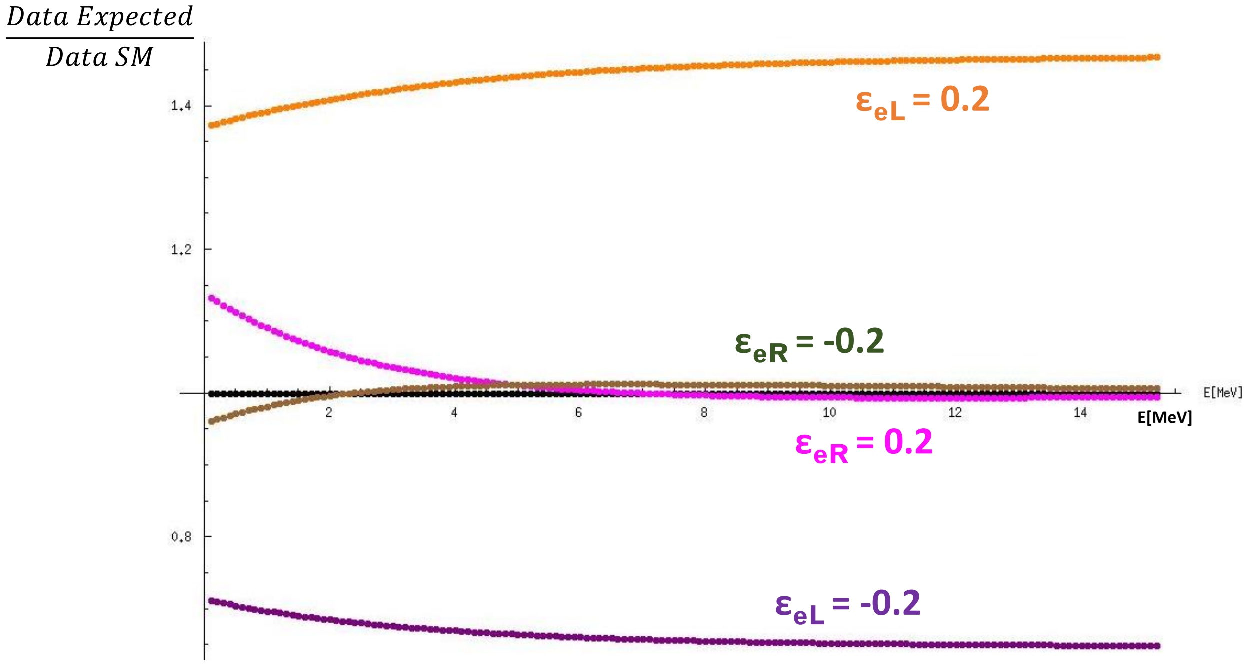
various off-diagonal term combinations

Expected ^{8}B electron signal and comparison to the Borexino result

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.

Traditional and exotic studies with solar n at JUNO
Strong points and caveat

❑ JUNO advantages

❖ **High statistics** (scintillator with m =20 kton) and **E resolution** ($\sigma(E)$ =3% at 1 MeV)

↓

Detailed **spectrum study**, including vacuum to matter transition region for ^{8}B (Additional terms in the lagrangian would modify the pattern)

Complementary study of day-night asimmetry.

❖ Cross check from solar **parameters measurement and sinergy solar ⟺ reactor**

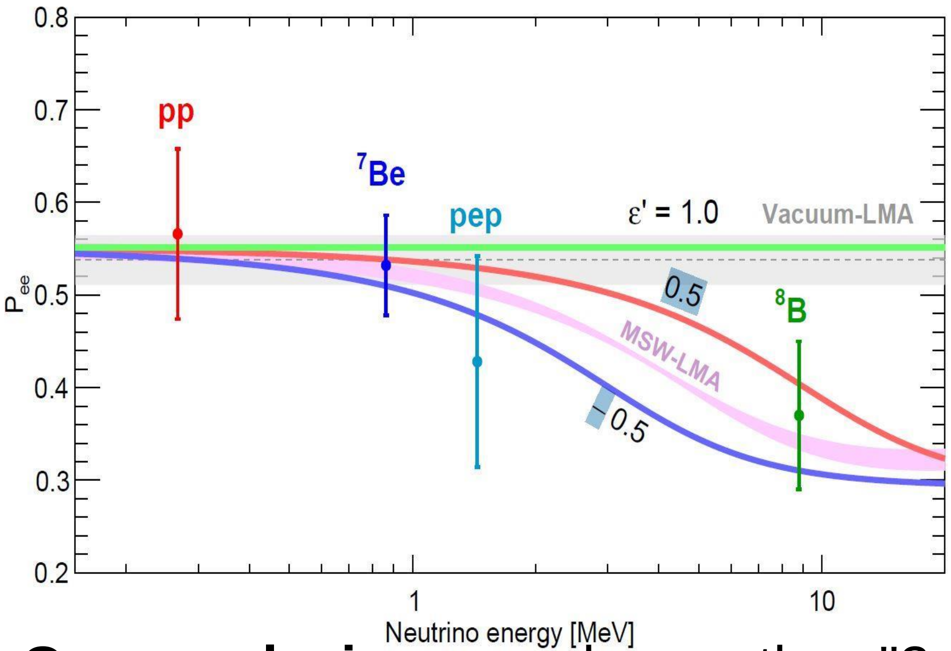
→ **Constraints on flavor diagonal NSI** and possible extension to non diagonal terms

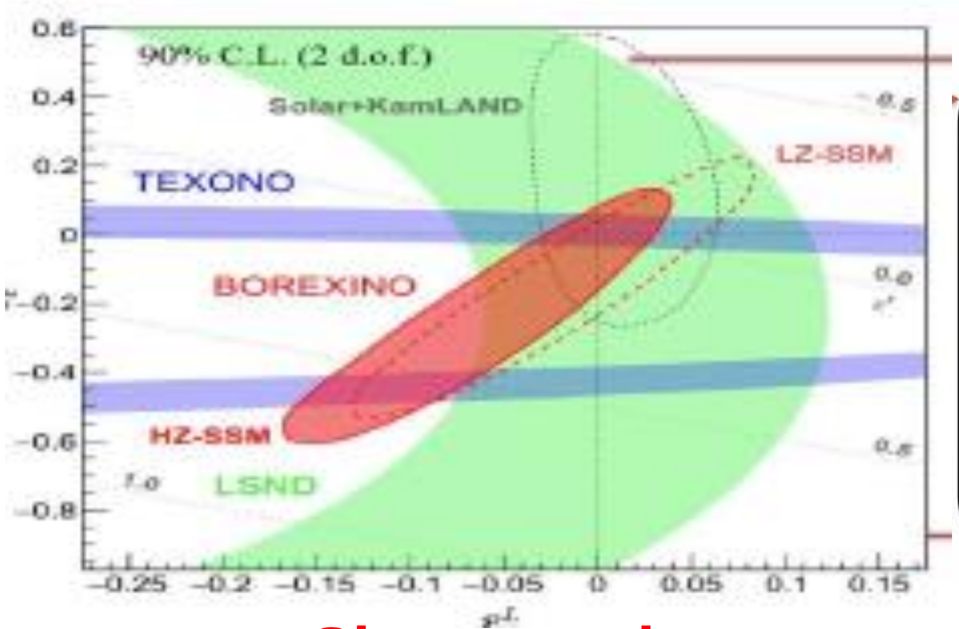
❑ Requirements

- Good **knowledge** and rejection of the **background** (external, internal and cosmogenic);
- **Radiopurity control:** to reach a **threshold** (E ≅ 2 MeV) **lower** than SNO and **SuperK**.
- Accurate **theoretical analysis, including density matter and 3 flavors effects**

Potentiality of the analysis: comparisons

Figures taken from Borexino Coll. JHEP 02 (2020) 38





Data from ^{8}B and KamLAND studies:

A. Renshaw [SuperKamiokande coll.]
Phys. Procedia 61, 345 (2015)

K. Abe [SuperKamiokande coll.]
Phys. Rev. D 94 (5): 052010, 2010

Y. Nakajima
SuperKamiokande plenary talk at Neutrino 2020

A. Gando [KamLAND coll]
Phys.Rev. D 88 (3): 033001, 2013

Our analysis reproduces the "2 flavor" results and extends them to full 3 flavor scenario, taking under control the density matter effects and paving the way for the **precision analysis of the almost the full solar ν spectrum at JUNO**

Sinergy solar-reactor

JUNO: room for improvements, by reducing the space available for NSI parameters, studying with more details the single parameters and considering new possible corrections.

Perspectives for NSI analysis with ^{8}B neutrinos at JUNO

❑Discrimination and reduction of radioactivity and main background sources

- ○ **External natural radioactivity** (^{208}Tl, n-γ reaction, …): fiducial volume reduction (R < 13 m)
- ○ **Internal radioactivity:**

  Good radiopurity level needed ($10^{-16} \div 10^{-17}$ g/g ^{238}U and ^{232}Th).

  Additional online monitoring system (Osiris) and effective background reduction methods
- ○ **Cosmogenic isotopes**

  Cosmic ray μ spallation: main problem ^{11}C (problematic for low E threshold).

  Strategy: cylindrical veto around the reconstructed μ tracks
- ○ **Reactor antineutrino background**

  2% uncertainty due to discrimination between ES of $\bar{\nu}_e - \mathrm{e}$ from ^{8}B signal

After all the cuts a 2:1 signal to background ratio is expected

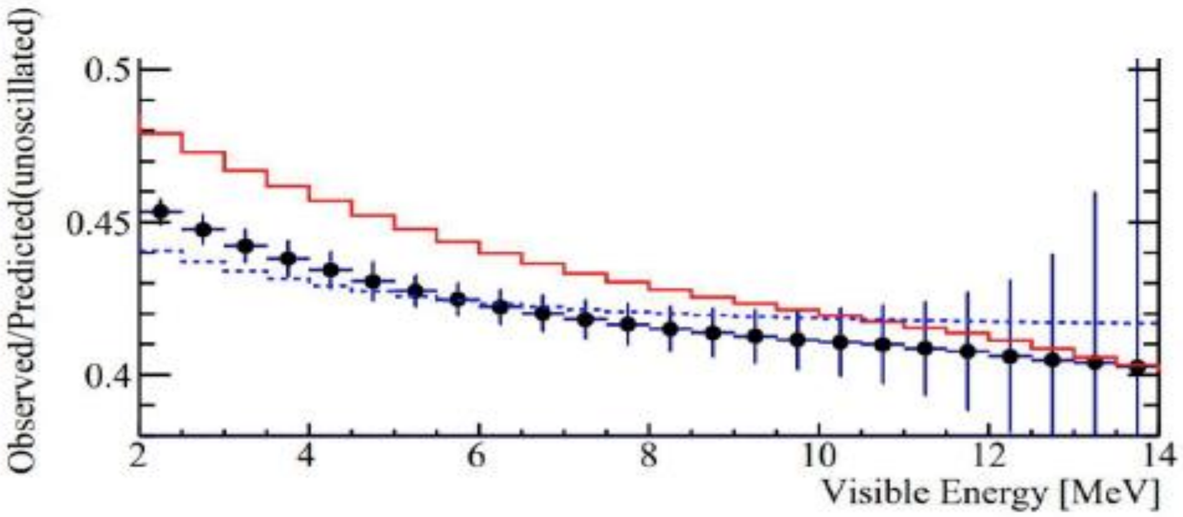
❑ANALYSIS STRATEGY:

Complementary **search for spectrum distortion and day/night asymmetry**

NSI analysis perspectives with ^{8}B solar ν at JUNO: spectrum

❑ SPECTRUM ANALYSIS

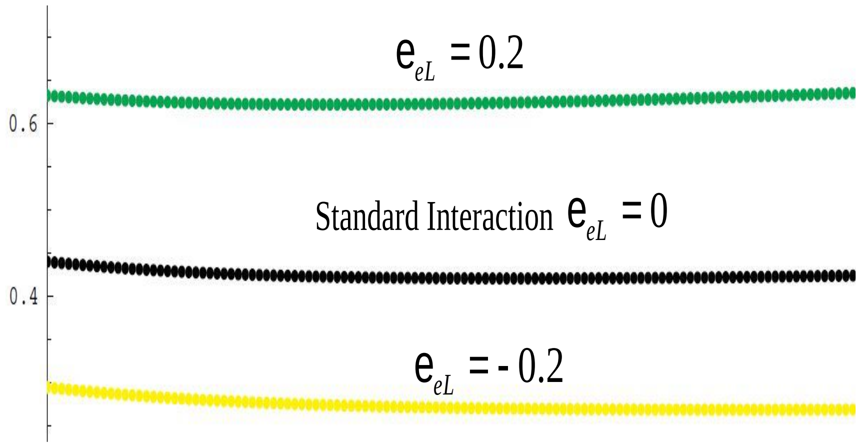
- ❑ **NSI corrections signals**: spectrum distortion (mainly in vacuum/matter transition regiona) and reduction/enhancement
- ❑ Needed detailed χ^2 analysis (**JUNO advantages**: resolution and low E threshold).
- ❑ **Expected** spectrum **in standard** oscillation **scenario**
  Reference: Abusleme et al [JUNO Coll], *Chin. Phys.C* 45 (21) 2, 023004



Black: "solar" Δm^2_{21} Red: reactor Δm^2_{21} **Blue**: constant P_{ee}=0.32

For "reactor" Δm^2_{21} larger upturn expected: higher sensitivity

- ❑ **Modified** spectrum **in presence of NSI**



Possible spectrum curves for different values of the "main" NSI parameter: **blue** curve = no NSI, green and yellow different values of NSI parameter..

Other NSI parameters can cause bigger spectrum distortion

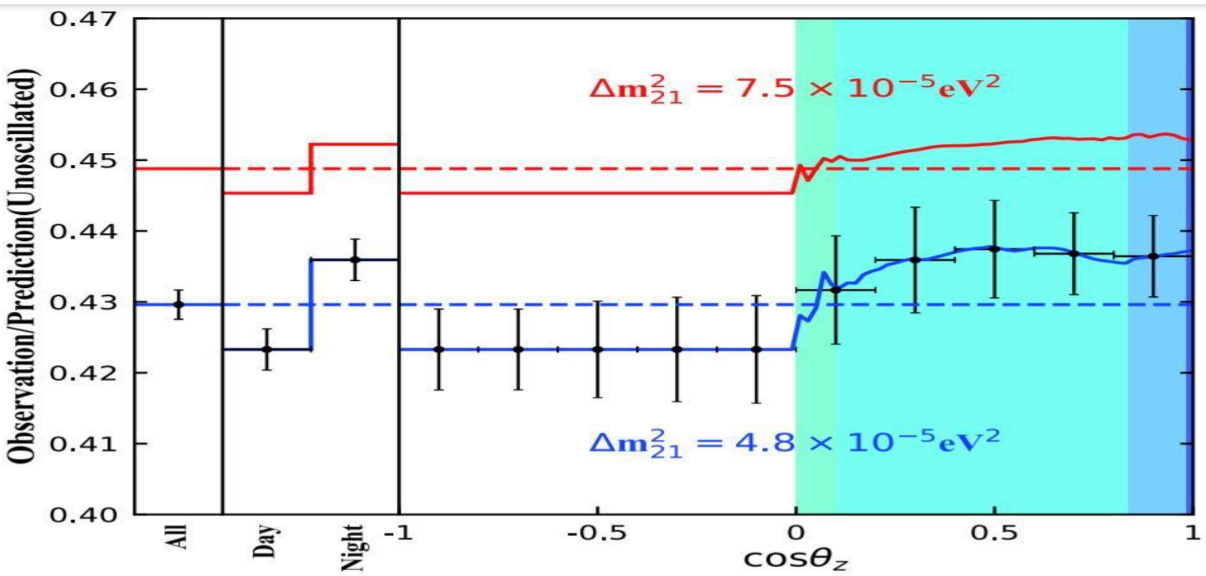
NSI analysis perspectives with solar ν at JUNO (2)

☐ DAY/NIGHT ASYMMETRY

- **Advantage**: Lower latitude with respect to SuperK
- A 3σ level D/N asymmetry is expected after 10 years of data taking for “solar” Δm^2_{21}.
- The **value** would be **modified in case of NSI** corrections

Angular dependence in standard LMA scenario

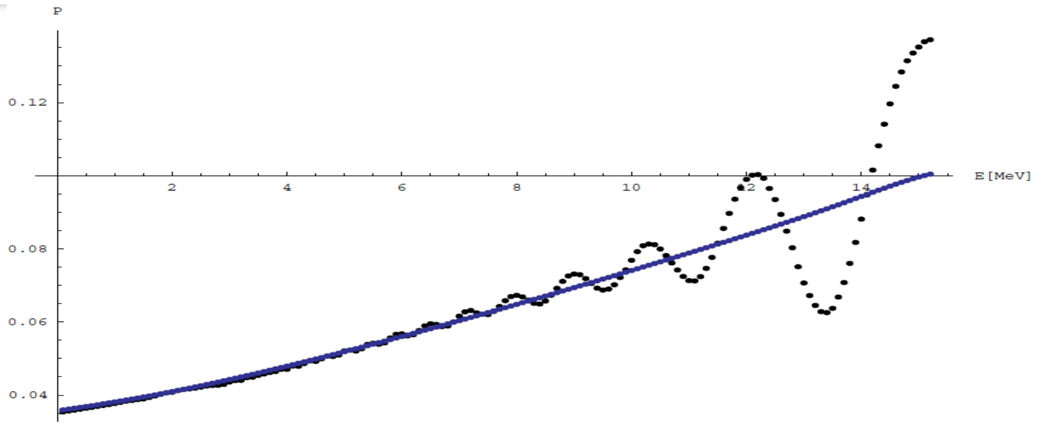
(Fig. taken from Abusleme et al [JUNO Coll])



^{8}B signal ratio: observed/unoscillated oscillation prediction for different zenith angles.

E dependence of D/N asymmetry in electron spectra

Plot of $A_{DN} = 2\,\frac{N-D}{N+D}$ obtained for constant Earth density ($\rho = 4.5\,\frac{g}{cm^3}$)



☐ The blue curve is obtained averaging of the Earth’s effect.

☐ The relative asymmetry grows linearly with the energy

☐ Matter induced oscillating effects become relevant with recoi energy above 10 MeV but the total average effect is at least o 4% of the signal.

NSI corrections can modify this values

Conclusions and importance of complementarity

❑JUNO and future experiments can still give important answers on solar ν

- Solution of the **solar metallicity problem**

(Sinergy of ^{7}Be and ^{8}B signal, **complementary** to CNO from future experiments)

- **Tests of** standard **MSW-LMA** oscillation solution **-** Window for **new physics (NSI-LIV**)

❑Complementary experimental and theoretical precision studies

Exploiting the JUNO high statistics and resolution and its (hopefully) good resolution: possible studies of the medium and high energy part of the pp chain solar ν spectrum, but essential a **complementary description of matter effects** for a detailed **study of ^{8}B spectrum and day-night asymmetries**

❑We developed a **tool of analysis for full 3 flavor** description of **matter -interaction**

- Description of matter effects in ν propagation and in the interaction with the detector
- Possible **exotic effects: Non Standard Interactions and Lorentz Invariance violating** (QG) **effects**
- **Main production of an event generator ready to be integrated with SNIPER**

Conclusions and importance of complementarity

- ❑**Complementarity** of **solar - reactor ν** measumeruments: strong point of JUNO

- ❑Possibility of **multimessenger studies** with JUNO

Connection with LIV

- ❑**Complementarity and sinergy** with other present and future experiments (LBL, neutrino telescopes, HyperKamiokande, etc.)

Possible new studies and new limits/discoveries about exotic sector of physics

Last but not least:

Usually, looking for “new worlds” helps also for a better knowledge of “terra cognita”

Thank you for your attention!

Marco Danilo Claudio Torri* –
Vito Antonelli* –
Marco Magoni –
Lino Miramonti

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Backup Slides

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NSI analysis in solar sector perspectives

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

Matter effects can modify the oscillation pattern and are caused by the charged current interaction of ν_e with electrons.

$$H_{vac} = \frac{1}{2E} U \begin{pmatrix} m_1^2 & 0 & 0 \\ 0 & m_2^2 & 0 \\ 0 & 0 & m_3^2 \end{pmatrix} U^*$$

Hamiltonian for the free propagation in flavor basis

$$H_{mat} = \sqrt{2}G_F N_e \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

Hamiltonian for the matter interaction via charged current in flavor basis

Borexino scenario

$$H_{mat}^{NSI} = \sqrt{2}G_F N_e \begin{pmatrix} 1+\varepsilon_e & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \varepsilon_\tau \end{pmatrix}$$

This analysis can be improved taking into account more sectors: more coefficients (off diagonal)

$$V(x)\begin{pmatrix} 1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon_{e\tau} & \varepsilon_{\mu\tau} & \varepsilon_{\tau\tau} \end{pmatrix}$$

LIV and neutrino oscillations

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

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

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

where: c=1

Standard phase ruling the oscillation pattern

QG (LIV) induces modifications in the phase

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

QG (LIV) perturbation

LIV correction term analogous to the NSI caused perturbation

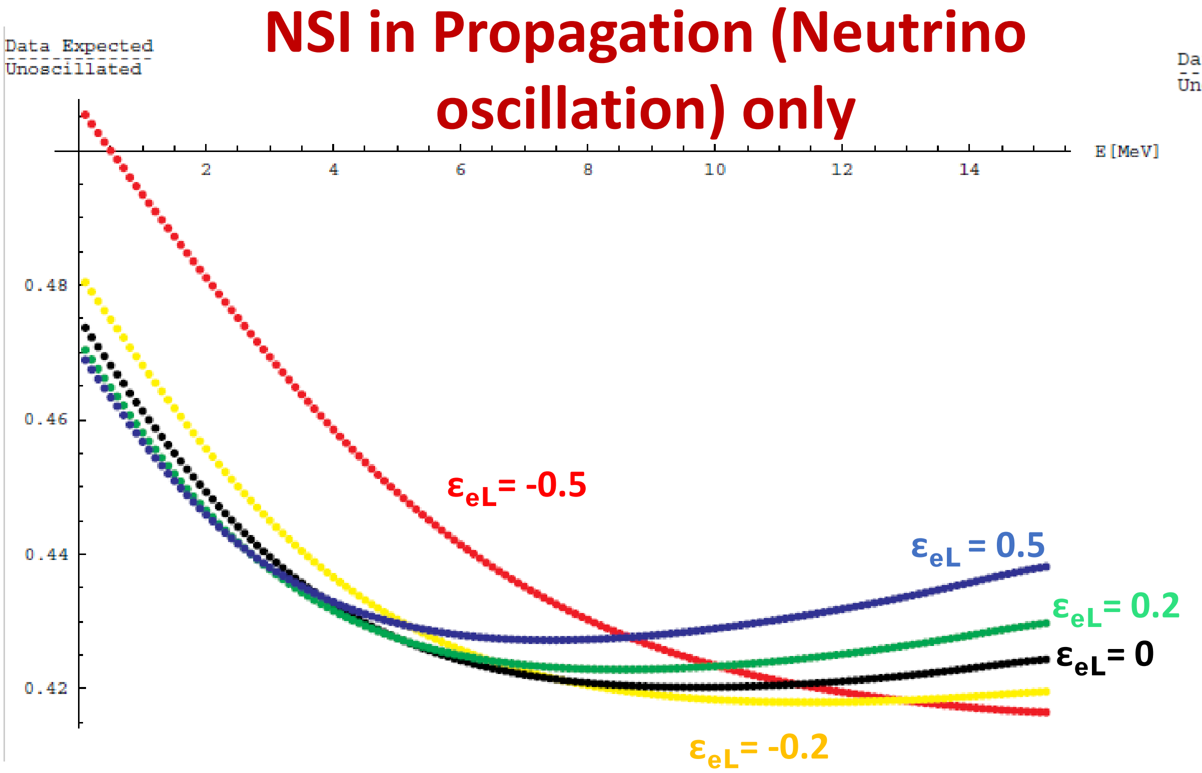
$$\tilde{H}_{vac} = \frac{1}{2E} U \begin{pmatrix} \tilde{m}_1^2 & 0 & 0 \\ 0 & \tilde{m}_2^2 & 0 \\ 0 & 0 & \tilde{m}_3^2 \end{pmatrix} U^* \approx \frac{1}{2E} U \begin{pmatrix} m_1^2 & 0 & 0 \\ 0 & m_2^2 & 0 \\ 0 & 0 & m_3^2 \end{pmatrix} U^* + \frac{E}{2} U \begin{pmatrix} \varepsilon_1 & 0 & 0 \\ 0 & \varepsilon_2 & 0 \\ 0 & 0 & \varepsilon_3 \end{pmatrix} U^*$$

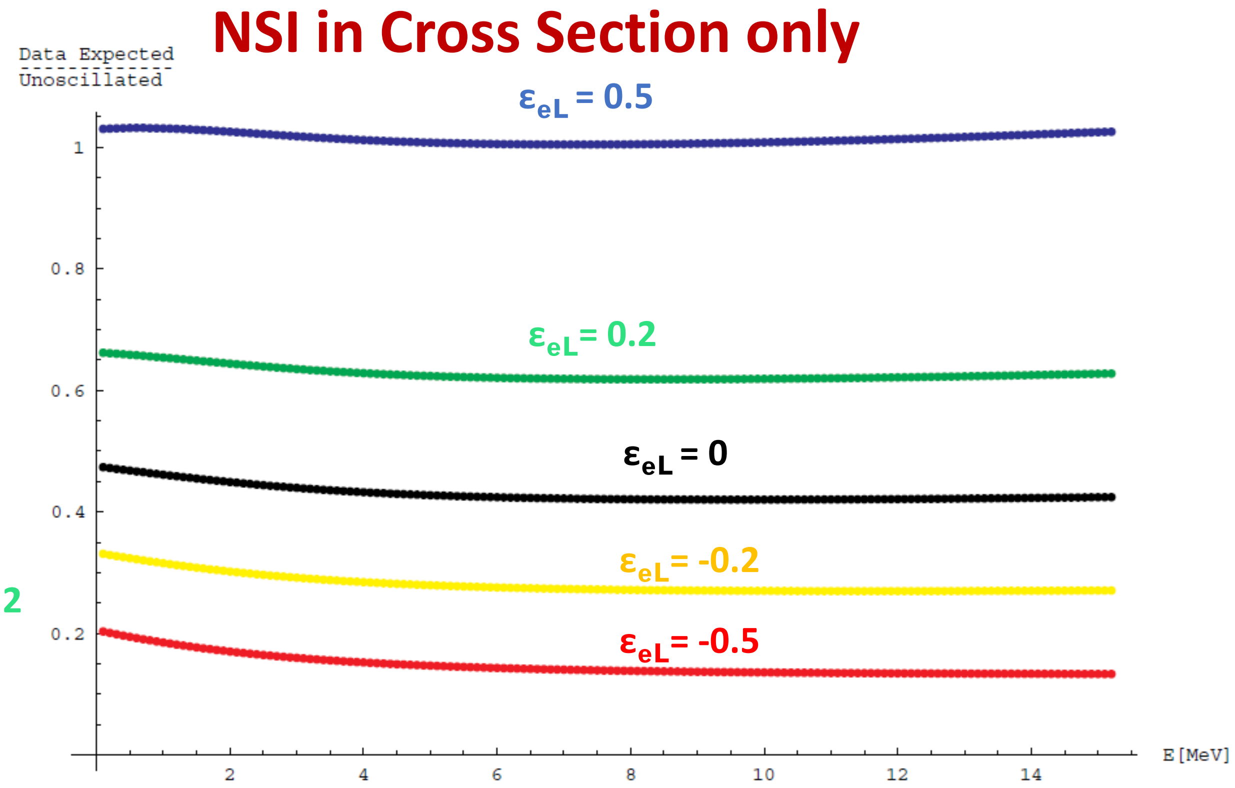
The LIV corrections are introduced for the mass eigenstates, the LIV matrix must be rotated

*** Neutrino oscillations and Lorentz Invariance Violation in a Finslerian Geometrical model -** V. Antonelli, L. Miramonti, M.D.C.Torri
Eur.Phys.J. C78 (2018) n.8, 667

*** Neutrino Oscillations and Lorentz Invariance Violation -** M.D.C.Torri
Universe 2020, 6(3), 37

Scattered ^{8}B electron signal


NSI in Propagation (Neutrino oscillation) only


NSI in Cross Section only

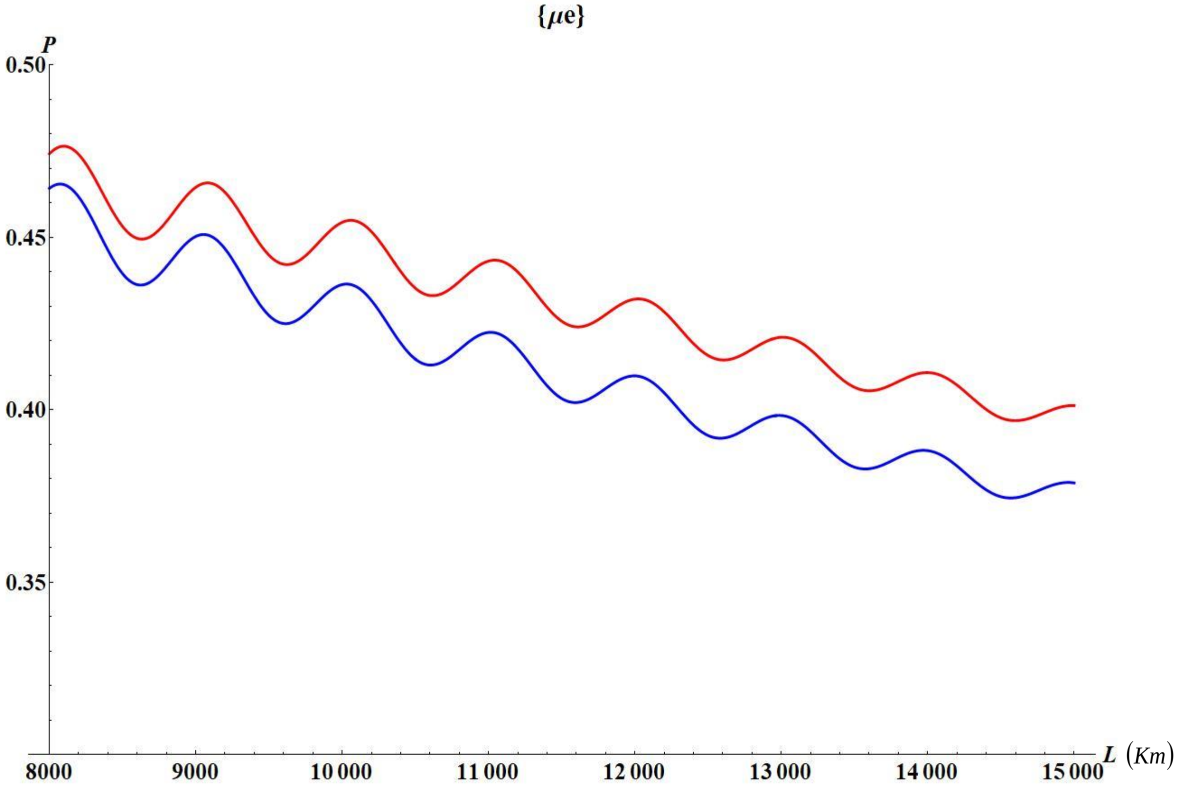
- We tested which effect is the most relevant to the electron recoil spectra when adding the NSI.
- The quantity plotted in this case is the ratio between the electron recoil spectra after oscillation and the unoscillated standard model case.
- We discovered that modifying only the propagation has a sub leading effect in comparison with the case of modification only in the cross section .

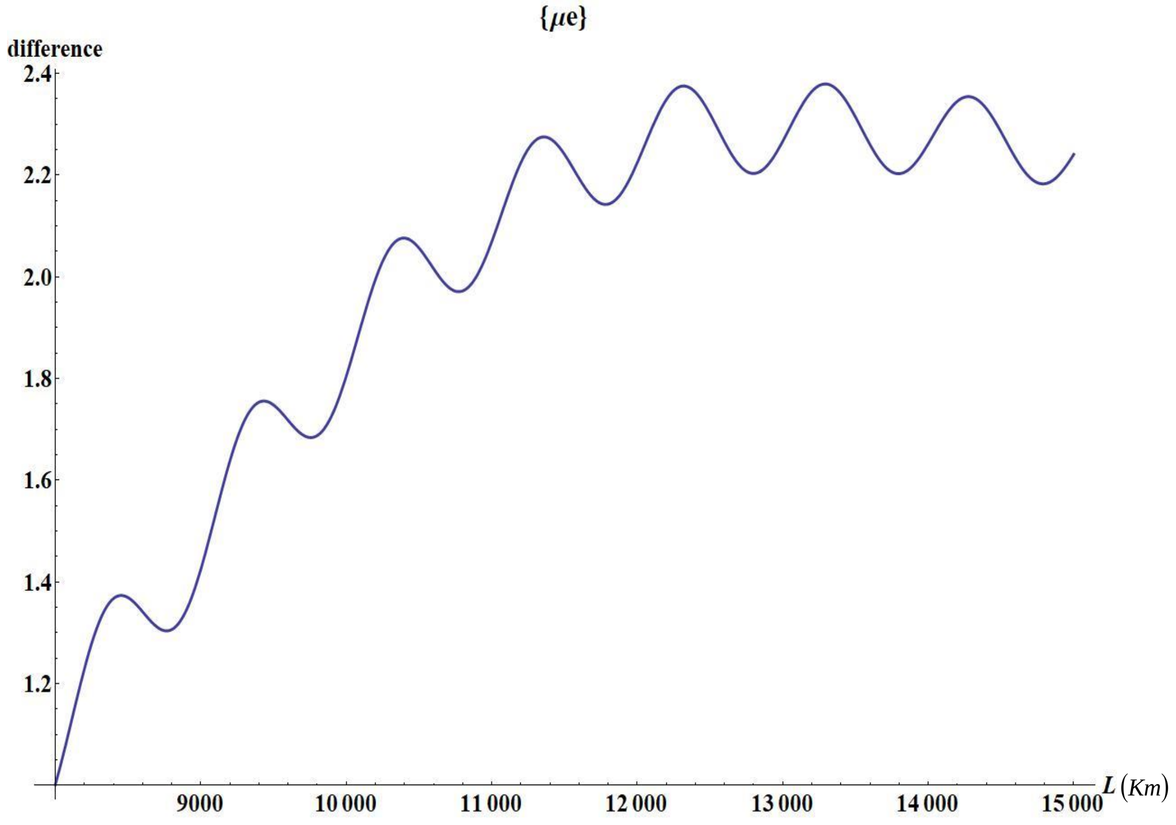
LIV and neutrino oscillations – plots (1)

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

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

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

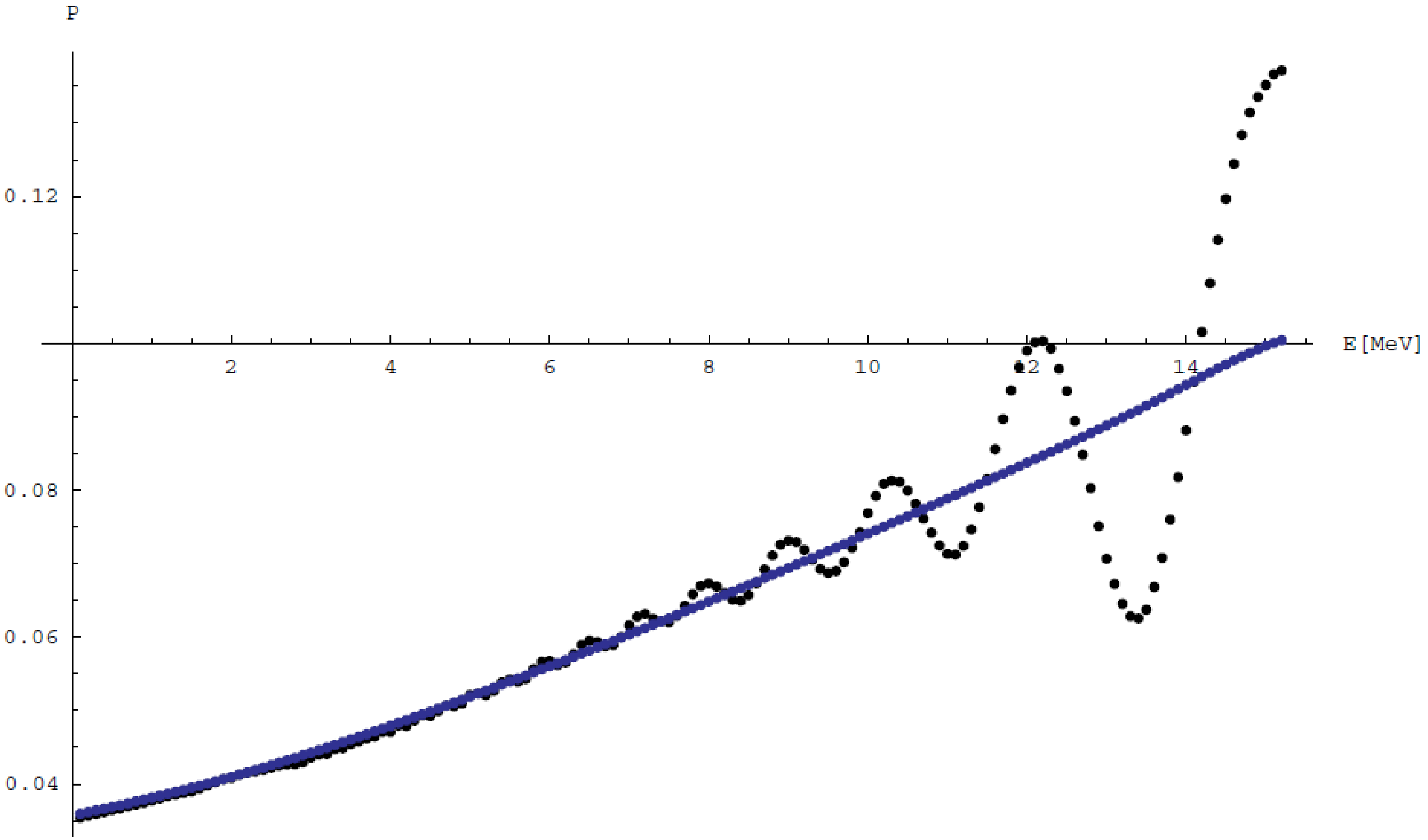




Day-Night asymmetry in electron spectra

The asymmetry plotted depends on the energy of the electron recoil signal. The two curves were obtained considering the Earth as a sphere of constant density.

(4.5 g/cm^3)



$$A_{dn} = 2\frac{N-D}{N+D}$$

- ☐ The black curve is obtained taking into account the matter gone through Earth matter. The blue curve is obtained as an average of the Earth’s effect.
- ☐ The relative asymmetry grows linearly with the energy
- ☐ The matter induced oscillating effects become relevant with recoil energy above 10 MeV but the total average effect is at least of 4% of the signal.

Event generator

- ❑ The generator output is **ready to be used as an input for SNIPER** to reproduce the Juno detector response
- ❑ The generated output can be used to study solar neutrino spectrum in a three-flavor scenario in the standard case and can include non-standard effects such as NSI and LIV.
- ❑ In the following image there is an example of the output generated by the software in the hepevt format.

```
1   3
0   14   0   0   0   0.008112317717913488   -0.009771402214811684   0
1   14   0   0   0.0001609790487839451   0.001287308800925342   -0.00002135381744982591   0
1    11   0   0   -0.0001609790487839451   0.006825008916988145   -0.009750048397361857   0.0005109989
2   3
0   12   0   0   0   0.008891854821940218   -0.0036186900703899   0
1   12   0   0   -0.00128036247937935   0.002202552470458716   -0.001516833590038065   0
1   11   0   0   0.00128036247937935   0.006689302351481501   -0.002101856480351835   0.0005109989
```