Models with isotropic Lorentz Invariance Violation and tests with Neutrinos and at JUNO

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Plan of the talk

- Introduction.
  Dispersion relations and possibility of Lorentz Invariance Violation (LIV)
- LIV in literature and peculiarity of our model
  - Geometrical and kinematic origin of LIV
  - Isotropy and internal symmetries preservation
  - **Standard Model extension with isotropic LIV**
  - **See also V. Antonelli, L. Miramonti, M.D.C. Torri, Eur.Phys.J. C78 (2018) no.8, 667 and a 2^{nd} paper that will appear soon**
- Neutrino Oscillation Probability in presence of LIV
- Basis for a phenomenological analysis: interesting cases
- LIV@JUNO?
  Connection with the study of atmospheric neutrinos

Introduction: motivations for Lorentz invariance symmetry tests

- Impossible to test space time structure up to Planck scale (looking for possible quantum gravity effects).
- Partial anomalies in ultrahigh E cosmic rays (possible GZK sphere dilatation)
- Theoretical hypothesis of Lorentz invariance as effective low E simmetry, violated at high E by quantum effects: LIV with small deviations from "standard scenario"
- LIV hypothesis in neutrino (ν) physics since '99 (Coleman-Glashow). $\rightarrow$ Possible "Exotic scenarios" (perturbation effects for ultraluminal ν, mass generation in "modified relativity framework", etc,).
- Revival of interest after recent IceCube discovery of ultra-high energy neutrino emission from blazar TXS 0506+056 .
- In our model LIV simple tiny "perturbative" corrections to the standard oscillation pattern.

Our geometrical model: from MDR to isotropic LIV

- Kinematic origin for LIV

Modified Dispersion Relations (MDR) ($\neq$ for $\neq$ particle species):

$$E_i^2 - |\overrightarrow{p}|^2(1 - f_i(p_i)) = m_i^2$$

Every lepton feels $\neq$ space-time local foliation, parametrized by its momentum (energy). Possible in (Finsler geometry).

- Choice of the model

LIV represented by homogenous functions $f\left(\frac{|\overrightarrow{p}|}{E}\right)$ and $g\left(\frac{\overrightarrow{p}}{E}\right)$

$$E^2 - \left(1 - f\left(\frac{|\overrightarrow{p}|}{E}\right) - g\left(\frac{\overrightarrow{p}}{E}\right)\right)|\overrightarrow{p}|^2 = m^2 \qquad \Rightarrow$$

a metric structure preserved: $\tilde{g}(p)^{\mu\nu} p_\mu p_\nu = m^2$

- Choice: preserve space-time isotropy: $g\left(\frac{\vec{p}}{E}\right) = 0.$

$\lim_{|\vec{p}|\to\infty} f(\frac{|\vec{p}|}{E}) = f(1+\delta) = \epsilon$ with $\delta, \epsilon << 1.$

Every massive particle i has its own max attainable velocity $\neq c$

$v_{i,\text{limit}} = \lim_{|\vec{p}|\to\infty} \sqrt{1 - f_i(p_i)} \to 1 - \frac{\epsilon}{2}$

Metric structure of the theory

Modified Dispersion Relation written as: $\tilde{g}(p)^{\mu\nu} p_\mu p_\nu = m^2$, with

$$\tilde{g}(p)^{\mu\nu} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -\left(1 - f\left(\frac{|\vec{p}|}{E}\right)\right) & 0 & 0 \\ 0 & 0 & -\left(1 - f\left(\frac{|\vec{p}|}{E}\right)\right) & 0 \\ 0 & 0 & 0 & -\left(1 - f\left(\frac{|\vec{p}|}{E}\right)\right) \end{pmatrix}$$

- Modified Lorentz transformations (isometries of MDR).
- Redefinition of "modified" Dirac γ matrices (Γ) and "modified" spinorial wave functions (ψ) in presence of our LIV corrections.

The LIV corrections to wave functions and γ matrices compensate each other.

- The gauge bosons remain Lorentz invariant.

LIV Standard Model Extension

- LIV corrections in our model modify the massive particle propagation, even ν, but the structure of currents and gauge internal symmetries ($SU(3) \times SU(2) \times U(1)$) is preserved. (Generalization of the Coleman Mandula theorem).
  e. g., the kinetic and interaction part for the leptons becomes:
  $\mathcal{L}_{lept} = \sqrt{|det[g^f])|} \left(\bar{\psi}_L^f (i\Gamma^\mu D_\mu) \psi_L^f + \bar{f}^R (i\Gamma^\mu D_\mu) f_R \right)$,
  where $f = e, \mu, \tau$; ψ_L^f is the left handed isospin doublet of the fermion fields of flavour f and
  $D_\mu = \partial_\mu - ig \frac{\tau^j}{2} W_{\mu j} - ig^{'} \frac{Y}{2} B_\mu$ is the usual $SU(2) \times U(1)$ covariant derivative.
  "Modified Minimal Extension" of Standard Model, in presence of isotropic LIV.
  (V. Antonelli, L. Miramonti, M.D.C. Torri, **EPJC 78 (2018) no.8, 667 + another paper.**)
- 2 equivalent ways to study LIV impact on ν phenomenology:
  - Hamiltionian approach (perturbation theory formalism), or
  - starting, as usual, from the oscillation probability derived by evolution operator and ν unitary mixing matrix.

Oscillation probability in presence of LIV

- In presence of MDR: $E^2 = \left(1 - f\left(\frac{|\vec{p}|}{E}\right)\right)|\vec{p}|^2 + m^2$
  using the ultrarelativistic approximation, one gets:
  $|\vec{p}| \simeq E\left(1 - \frac{1}{2} f\left(\frac{|\vec{p}|}{E}\right)\right) + \frac{m^2}{2E}$
- Given the oscillation probability (from flavor ν_α to ν_β):

$$
\begin{aligned}
P(\nu_\alpha \to \nu_\beta) =& \delta_{\alpha\beta} - 4\sum_{i>j} \mathfrak{Re}\left(U_{\alpha i}U^*_{\beta i}U^*_{\alpha j}U_{\beta j}\sin^2(\Delta\phi_{ij})\right) + \\
&+ 2\sum_{i>j} \mathfrak{Im}\left(U_{\alpha i}U^*_{\beta i}U^*_{\alpha j}U_{\beta j}\sin^2(\Delta\phi_{ij})\right)
\end{aligned}
$$

LIV corrections (CPT even) modify "phase differences":

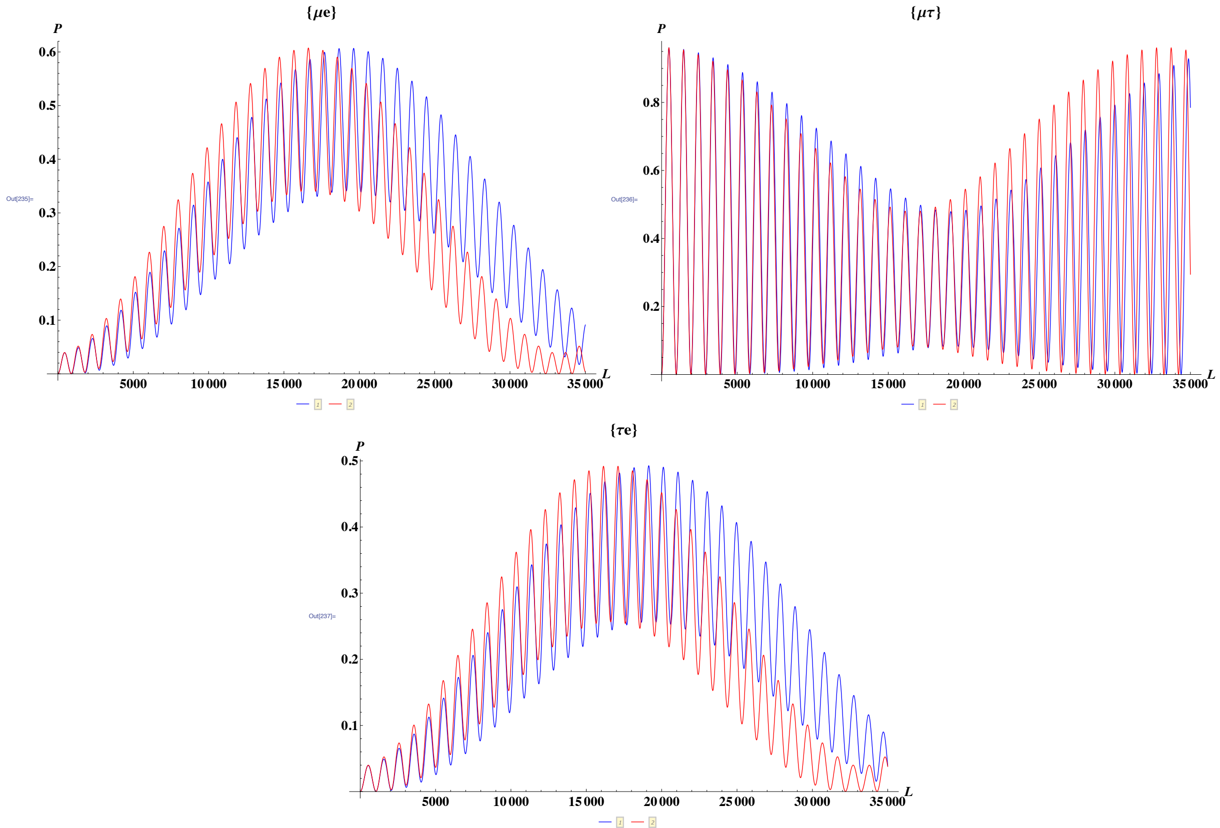
$$
\Delta\phi_{kj} = \frac{\Delta m^2_{kj} L}{2E} - \frac{f_k - f_j}{2} LE,
$$

f_i, f_k LIV coefficients for the i and k mass eigenstates of ν.

- \- $P_{\alpha,\beta}$ modified only if LIV $\neq$ for $\neq$ mass eigenstates ($\delta f_{kj} \neq 0$);
  \- LIV corrections proportional to $L\,E \to$ only tiny deviations from standard oscillation pattern

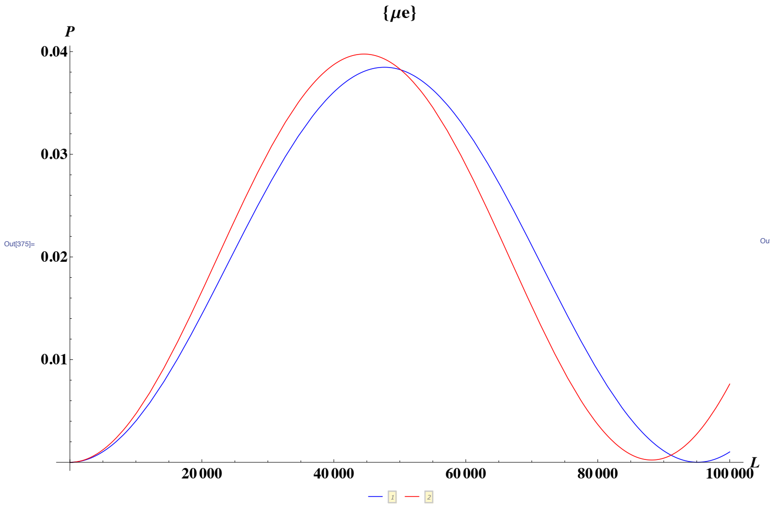
Basis for a phenomenological analysis: First examples

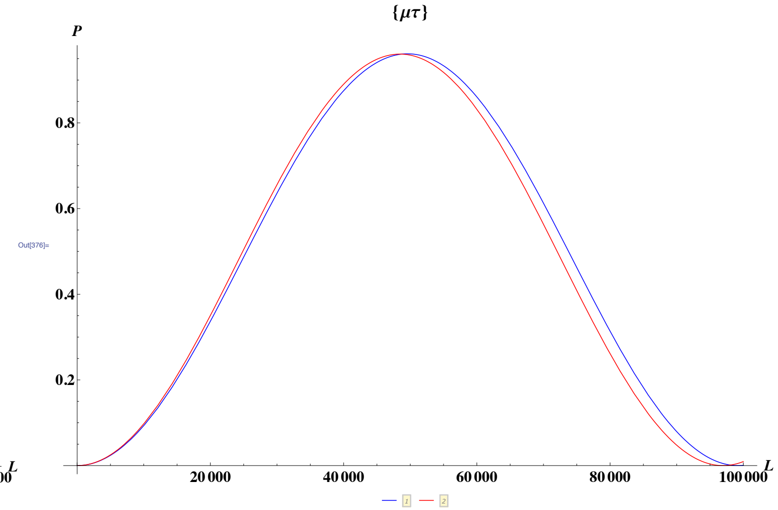
Oscillation probabilities (P_{ν_μ,ν_e}, P_{ν_μ,ν_τ} and P_{ν_τ,ν_e}) in “standard theory” (red) and with LIV (blue), for $\mathrm{E}_\nu = 1\,\mathrm{GeV}$ and $\delta f_{32} = \delta f_{21} = 1 \times 10^{-23}$.

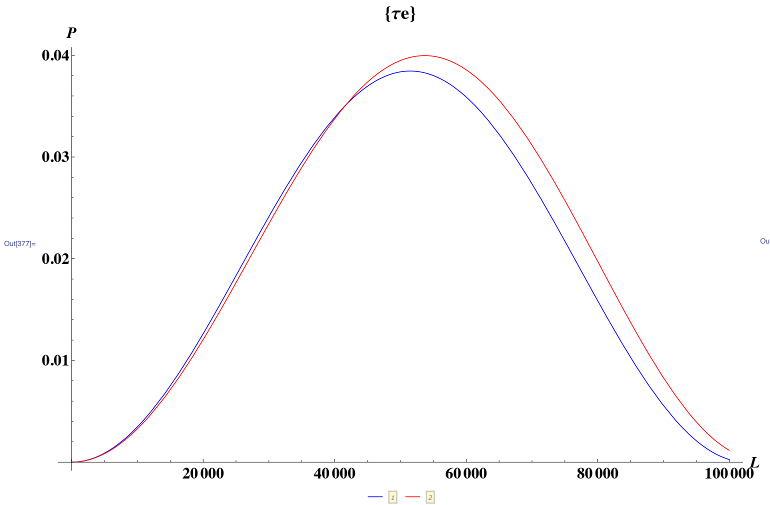


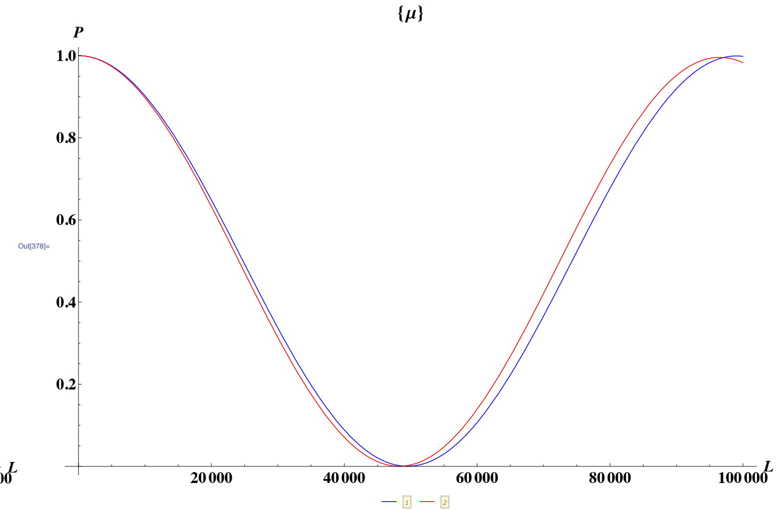
Oscillation probability analysis: comparison with SK

From SuperK analysis: δf_{kj} reduced, but still room for interesting analysis. Examples for $\delta f_{32} = \delta f_{21} = 4.5 \times 10^{-27}$ and $E_\nu = 100 GeV$.



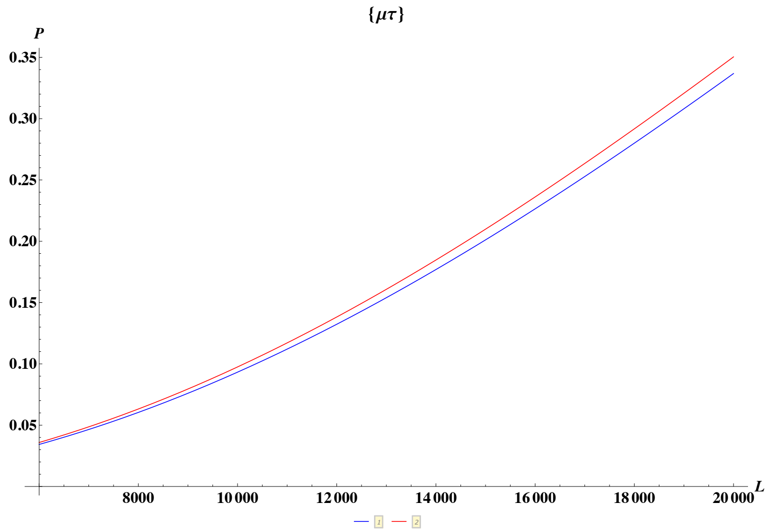


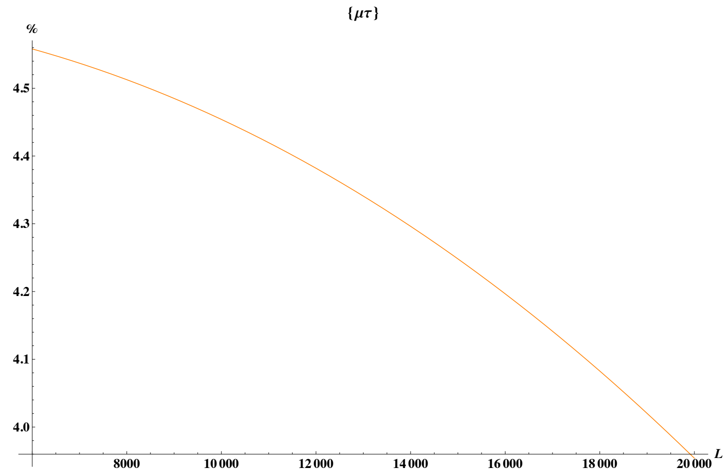


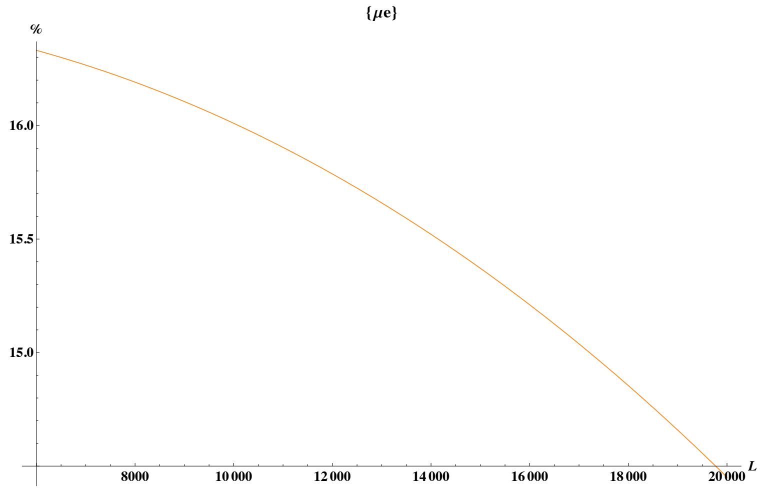


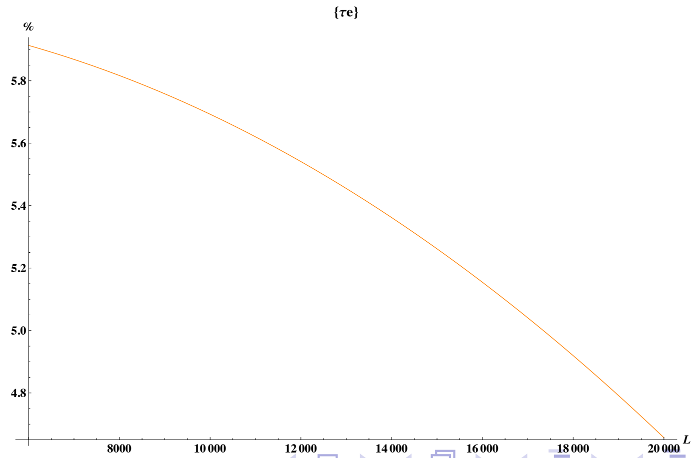
Oscillation probabilities: LIV impact on atmospheric ν

Absolute and % LIV induced variations for $E_\nu = 100\,GeV$ (for $\delta f_{kj} = 4.5 \times 10^{-27}$). P_{ν_α,ν_β} (1^{st} *plot*) and $2\frac{|P_{LIV} - P_{NO-LIV}|}{P_{LIV}+P_{NO-LIV}} \times 100$.









Phenomenological analysis

- For a complete analysis, in addition to the oscillation probability consider also neutrino flux $\Phi(L, E)$ and cross section $\sigma(E)$.
  Number of $N_{\alpha,\beta}$ of detected transition events from ν_α to ν_β:
  $N_{\alpha,\beta} \propto \Phi_\alpha(L, E)\, P_{\nu_\alpha,\nu_\beta}(L, E)\, \sigma_\beta(E)$.
  Possible integration over E (and eventually the baseline), convoluted with detector resolution and efficiency.
- Possibilities for neutrinos of high energies. Examples:
  - E from TeV to PeV @ neutrino telescopes (ANTARES, KM3NET and IceCube)
  - Ultra high E cosmic neutrinos (i.e. $E > EeV$ neutrinos investigated by Auger) ....

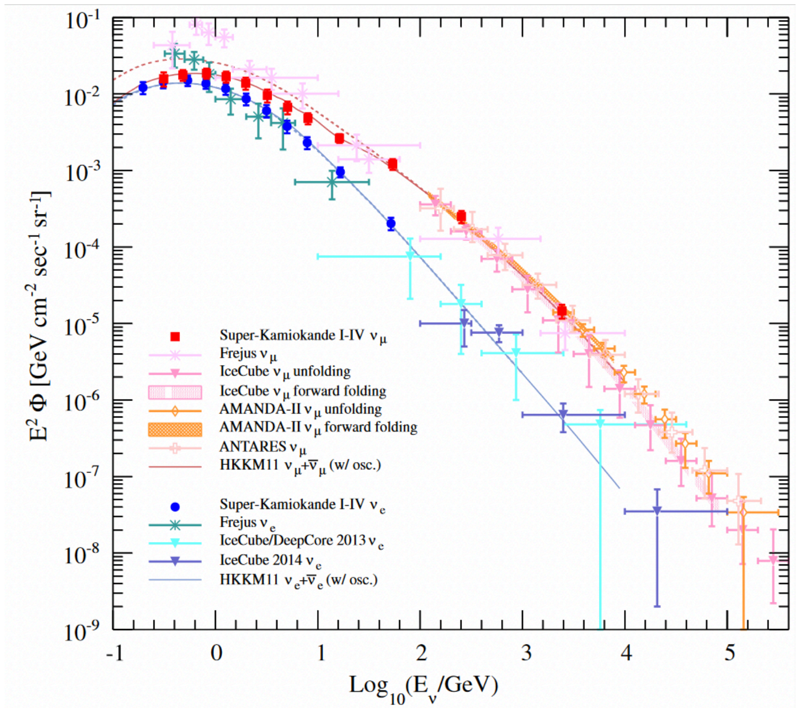
...and WHAT ABOUT JUNO ?

LIV and ν oscillations@JUNO

Challenging task but ...

What do we need?

- Observation of atmospheric ν of medium and high energies: multi-GeV region (ideally reaching $E \simeq 100 GeV$).
- Flux reduction only partially compensated by the increase of the cross section interaction.



LIV and ν oscillations@JUNO

What we would like to have?

- Flavor identification (ν_e, ν_μ and ν_τ)
- Reconstruction of the event energy.
- Good background knowledge and rejection (mainly muons simulating ν_μ induced events.)

Ideas and challenges

(see also Giulio's talk and G. Settanta, S.M. Mari, C. Martellini, P. Montini, arXiv:1901.10340)

- Scintillation light alone is not enough.
- Idea. Use:
  - 1^{st} PMT hits to reconstruct Cerenkov emission (information on lepton direction): works only partially (mainly for high energy through going events)
  - time profile of the signal for flavor identification.
  At high E, ν_μ and ν_e generated events different ranges $\rightarrow$ different light distributions. Larger time profiles expected for muons;
  - scintillation light for calorimetric information (total E of the event).

Ideas and challenges

- Energy reconstruction could be problematic for higher E events.
  - Higher E ν_μ-generated events (above $\simeq 7GeV$) will pass through the detector (needed clever E classification for up-going through passing events;)
  - For contained high E ν_e-generated events there could be problem of Large PMT saturation (presumably around 10-20 GeV).
- Idea: for higher E events possibility of using small PMT, which should not have saturation problem (even if they have a worst resolution).
- Some disadvantages, but also advantages:
  - very good E resolution;
  - good knowledge of the background.

Last developments and future perspectives

• Roma 3 group developed a first discrimination algorithm for different reaction channels to reconstruct atmospheric neutrino signal, discriminating the "flavour" of ν generating the event. Their work to extend the analysis to higher energies is going on.

• We have at disposal the full unoscillated ν flux simulation (Honda).

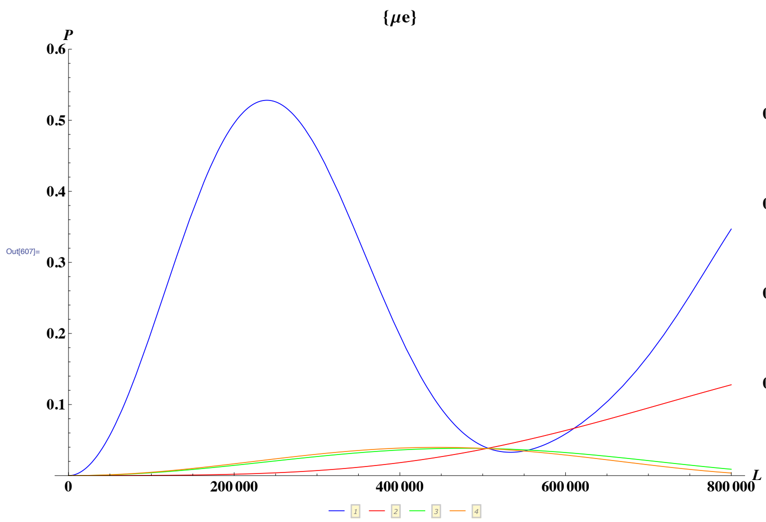
• Idea to develop: start from the flux, convoluting the different oscillation probability (and all the other factors) to make a 1^st evaluation of the statistics available in the region of interest and of the impact of LIV corrections.

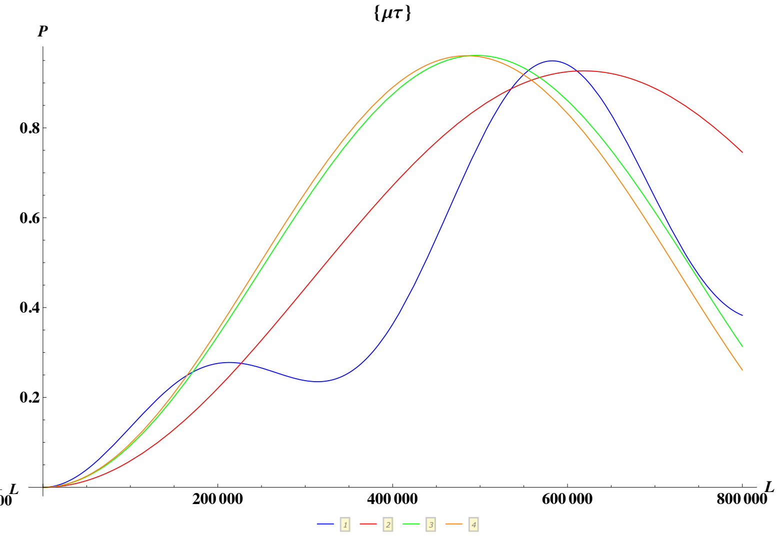
LIV and ν oscillations@JUNO

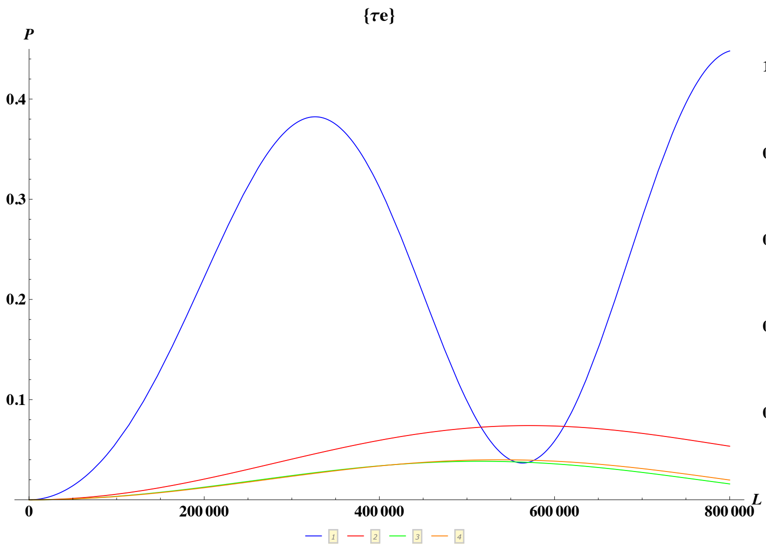
Challenging task but...

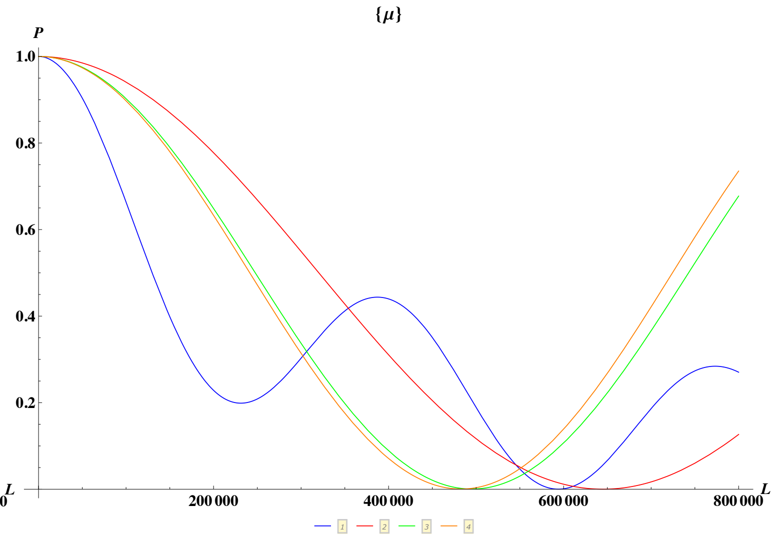
probably also interesting opportunity.

Lucidi di riserva









Oscillation probabilities: LIV impact

% variations induced by LIV. $E_\nu = 100 GeV$ and $\delta f_{32} = \delta f_{21} = 4.5 \times 10^{-27}$. Plots of $2\frac{|P_{LIV} - P_{NO-LIV}|}{P_{LIV} + P_{NO-LIV}} \times 100$. P_{ν_e,ν_μ} (blue), P_{ν_μ,ν_τ} (violet) and P_{ν_e,ν_τ} (green).

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