CHANGES IN NEUTRINO OSCILLATIONS DUE TO POSSIBLE NON-STANDARD INTERACTIONS WITH MATTER

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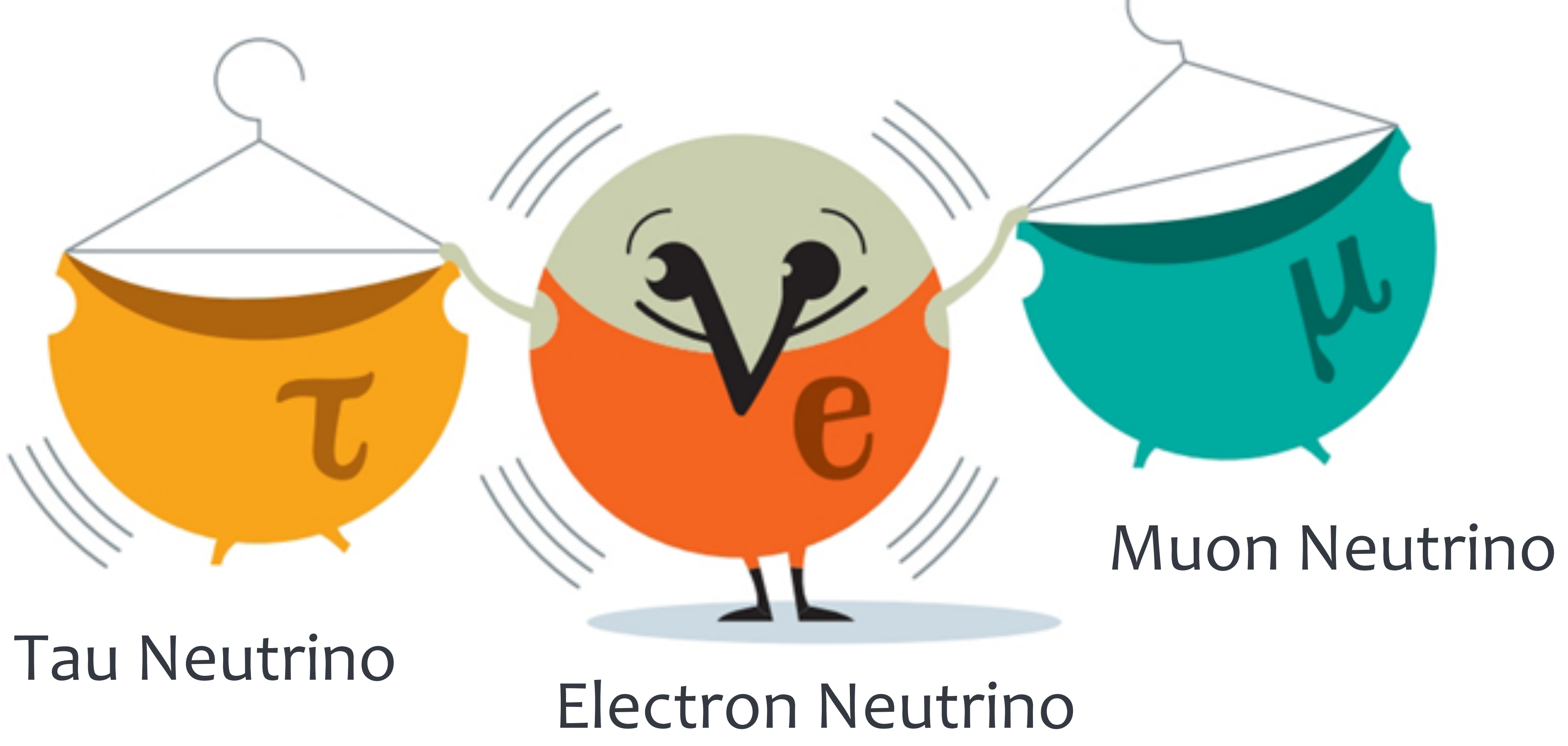
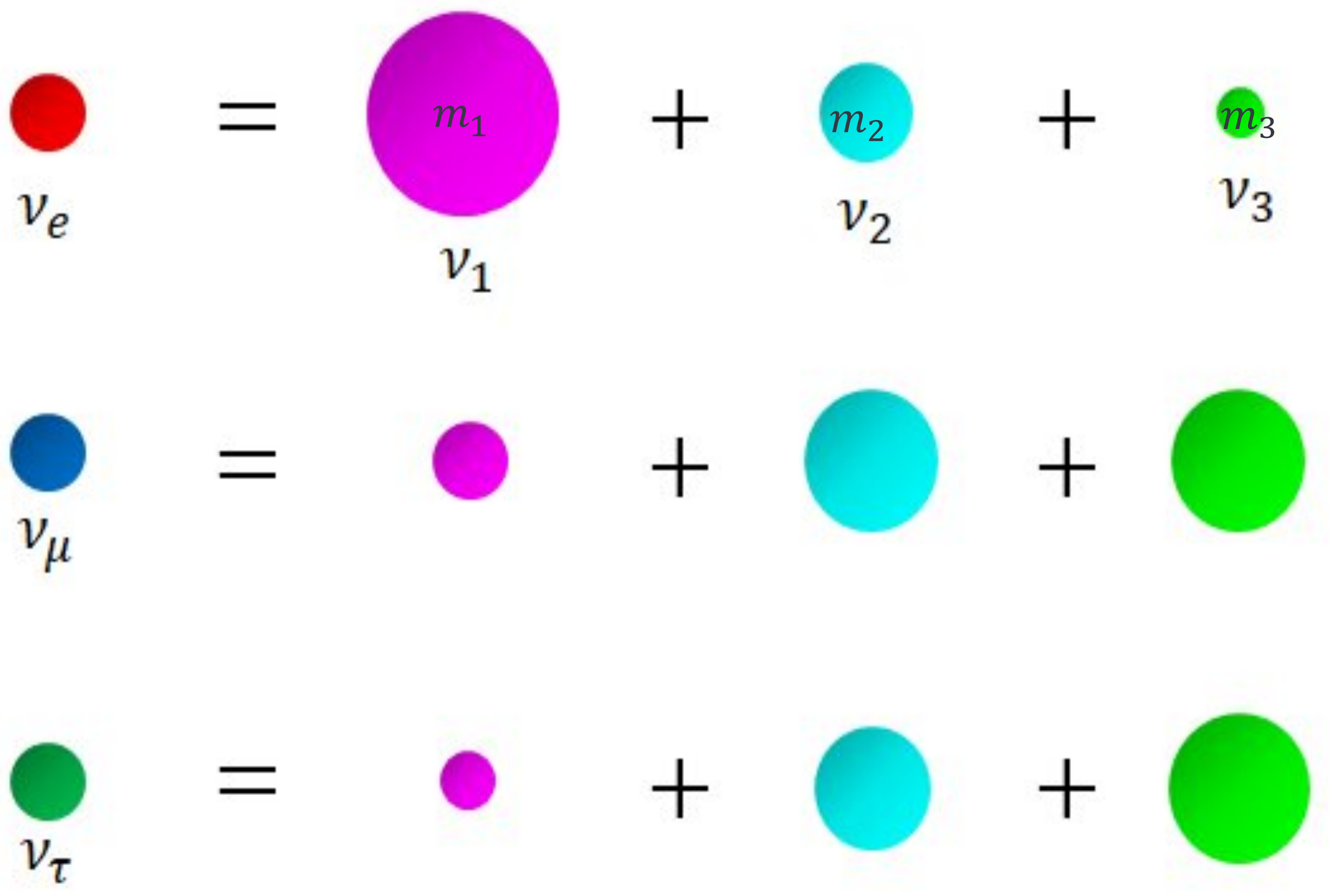
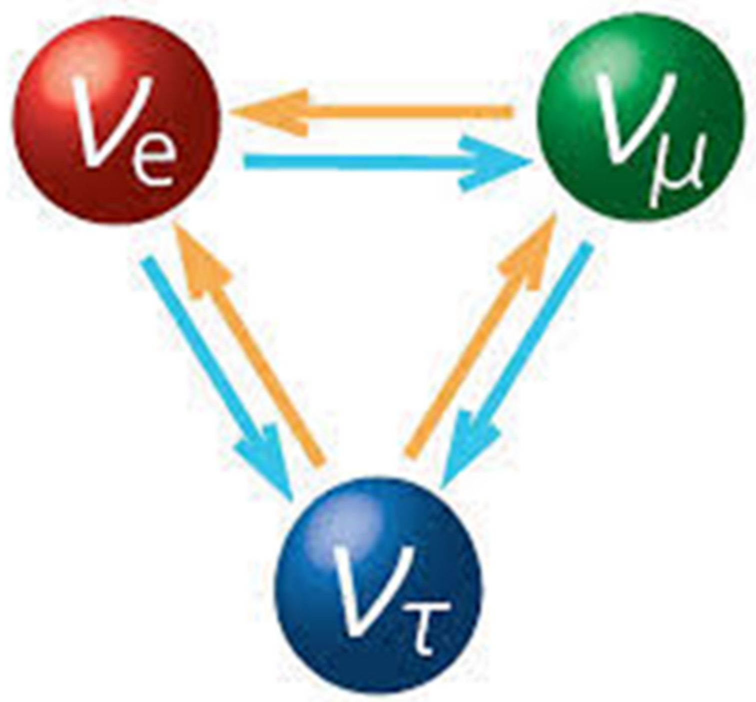


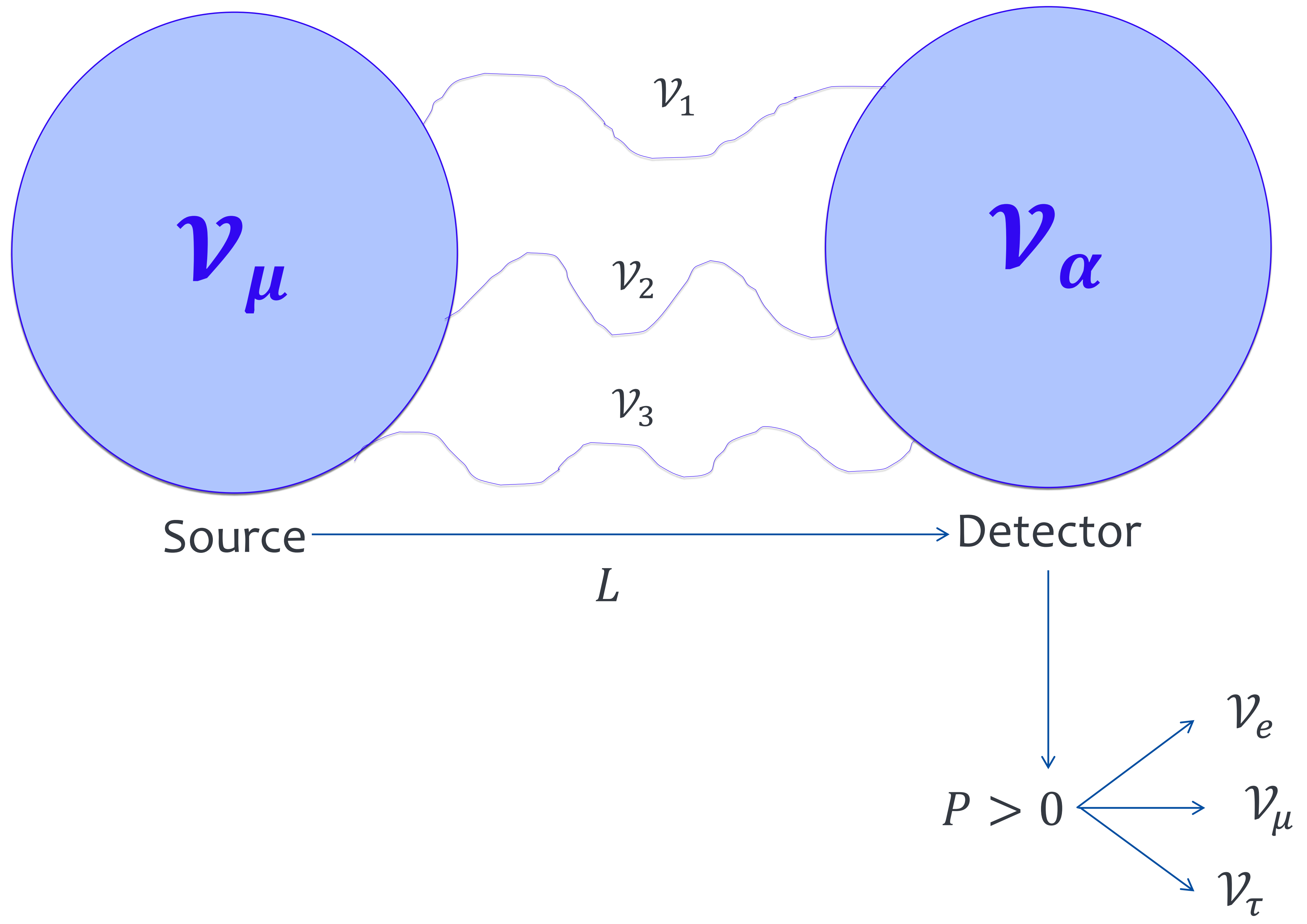




$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & C_{23} & S_{23} \\ 0 & -S_{23} & C_{23} \end{pmatrix} \begin{pmatrix} C_{13} & 0 & S_{13}e^{i\delta_{cp}} \\ 0 & 1 & 0 \\ -S_{13}e^{i\delta_{cp}} & 0 & C_{13} \end{pmatrix} \begin{pmatrix} C_{12} & S_{12} & 0 \\ -S_{13} & C_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Z. Maki, M. Nakagawa and S. Sakata, Prog. Theor. Phys. 28, 870 (1962).

Phenomenon of Oscillation



The flavor states $|\nu_\alpha\rangle$ and the mass states $|\nu_k\rangle$ are related:

$$|\nu_\alpha(t=0)\rangle = \sum_k U^*_{\alpha k}\ |\nu_k\rangle$$

- $\alpha = e, \mu, \tau$
- $k = 1,2,3$

$$|\nu_\mu\rangle = U^*_{\mu 1}|\nu_1\rangle + U^*_{\mu 2}|\nu_2\rangle + U^*_{\mu 3}|\nu_3\rangle$$

$t > 0$

$$|\nu_\mu\ (t)\rangle = U^*_{\mu 1}\ e^{-iE_1 t}|\nu_1\rangle + U^*_{\mu 2}e^{-iE_2 t}|\nu_2\rangle + U^*_{\mu 3}e^{-iE_3 t}|\nu_3\rangle$$

- $U_{\alpha k}$ represents the leptón mixing matrix

C. Giunti and C. W. Kim, "Fundamentals of Neutrino Physics and Astrophysics,"Oxford, UK: Univ. Pr. (2007) 710 p

$$P_{\nu_\alpha \to \nu_\beta}(E,L) = \sum_{kj} U^*_{\alpha k}\, U_{\alpha k} U_{\alpha k} U^*_{\beta j} e^{-i\left(\frac{\Delta m^2_{kj} L}{2E}\right)}$$

$\Delta m^2_{kj} \equiv m^2_k - m^2_j$

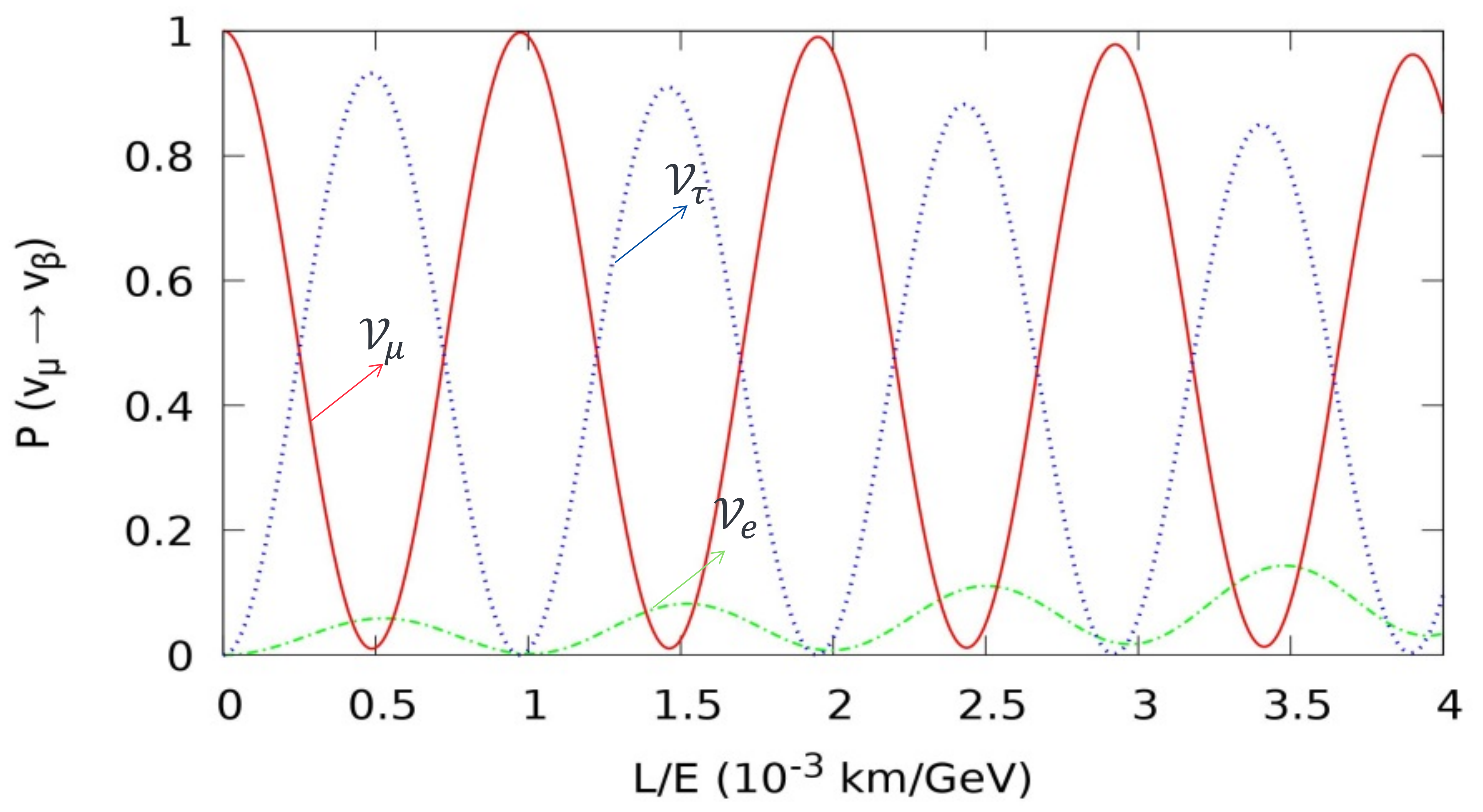
Transtition probability

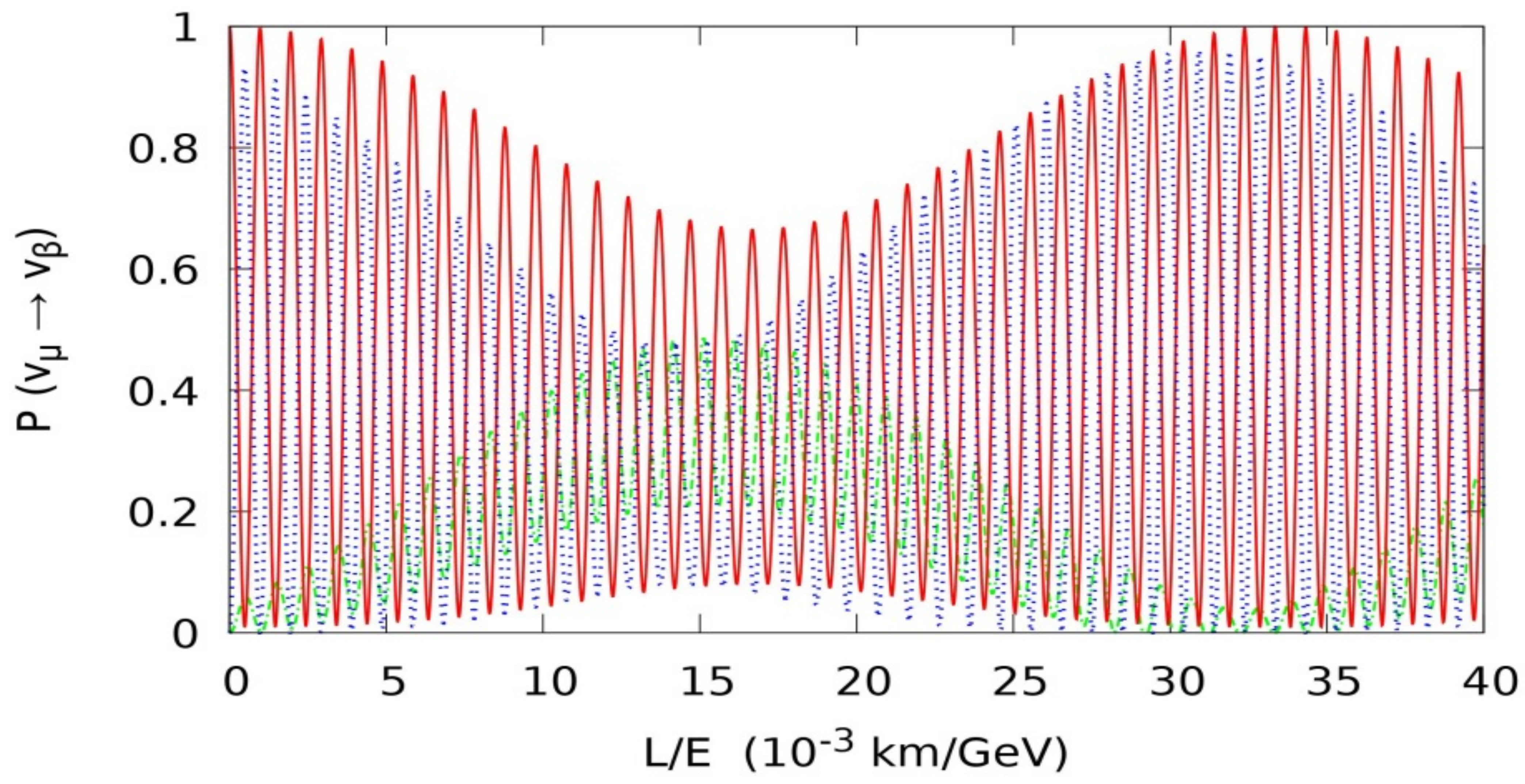
$$P_{\nu_\alpha \to \nu_\beta} = \delta_{\alpha\beta} - 4 \sum_{k>j} \Re(U^*_{\alpha k}\, U_{\alpha k} U_{\alpha k} U^*_{\beta j}) \sin\left(\frac{\Delta m^2_{kj} L}{4E}\right)^2 + 2 \sum_{k>j} \Im(U^*_{\alpha k}\, U_{\alpha k} U_{\alpha k} U^*_{\beta j}) \sin\left(\frac{\Delta m^2_{kj} L}{2E}\right)$$

Disappearance Probability

$$P_{\nu_\alpha \to \nu_\alpha} = 1 - 4 \sum_{k>j} U_{\alpha k}|^2 |U_{\alpha k}|^2 \sin\left(\frac{\Delta m^2_{kj} L}{4E}\right)^2$$

Parámetro	Valores $\pm 1\sigma$	3σ
θ_{12} (°)	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$
θ_{23} (°)	$48.6^{+1.0}_{-1.4}$	$41.1 \to 51.3$
θ_{13} (°)	$8.6^{+0.13}_{-0.13}$	$8.22 \to 8.98$
δ_{cp} (°)	221^{+39}_{-28}	$144 \to 357$
$\frac{\Delta m^2_{21}}{10^{-5} eV^2}$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$
$\frac{\Delta m^2_{31}}{10^{-3} eV^2}$	$2.528^{+0.029}_{-0.031}$	$2.436 \to 2.618$





I. Esteban, M. C. Gonzalez-Garcia, A. Hernandez-Cabezudo, M. Maltoni andT. Schwetz, JHEP1901,106 (2019) [arXiv:1811.05487 [hep-ph]]. NuFIT4.1 (2019), www.nu-fit.org.

Oscillation probability in matter

When neutrinos travel through a dense medium, they experience a forward scattering of the particles that they encounter along the way

In a material medium:

$$H = H_0 + H_1$$

$$H_1|\mathcal{V}_\alpha\rangle = V_\alpha|\mathcal{V}_\alpha\rangle$$

$$\downarrow$$

It is an effective potencial due to coherent interactions in the medium

H_E is the effective Hamiltonian in matrix form

$$H_E = \frac{1}{2E}(U\,\mathbb{M}^2\,U^\dagger + \mathbb{A})$$

$$\mathbb{M}^2 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m_{21}^2 & 0 \\ 0 & 0 & \Delta m_{31}^2 \end{pmatrix} \qquad \mathbb{A} = \begin{pmatrix} A & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$A = 2EV_{CC} = 2\sqrt{2}EG_F N_e$$

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Two – Neutrinos Mixing

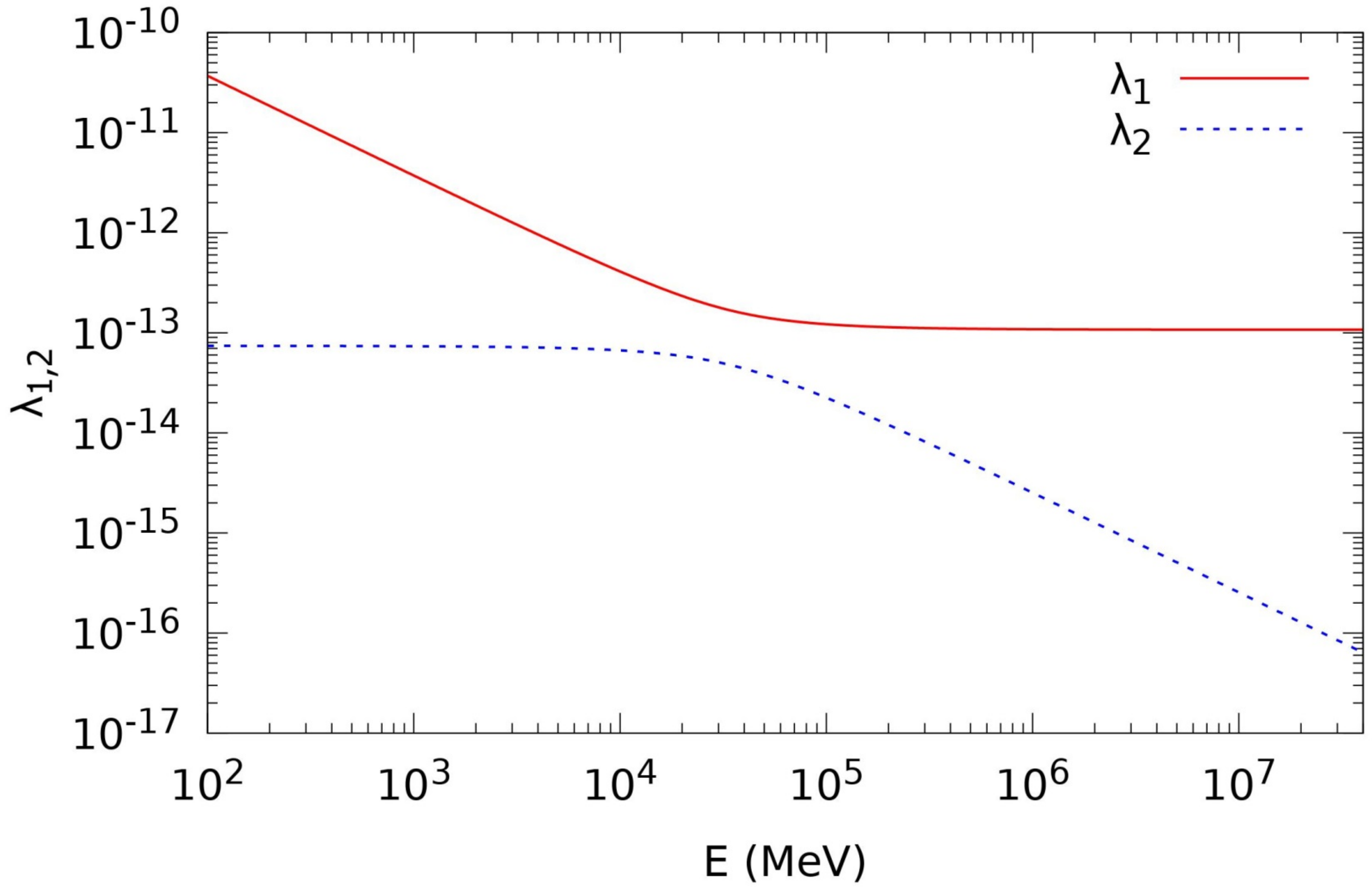
The two-neutrino effective mixing matrix

$$U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}$$

Making the matrixial producto we can get

$$H_E = \frac{1}{2E}\begin{pmatrix} A + \Delta m^2 \sin\theta^2 & \Delta m^2 \sin(2\theta) \\ \Delta m^2 \sin(2\theta) & \Delta m^2 \cos\theta^2 \end{pmatrix},$$

$$\lambda_{1,2} = \frac{\Delta m^2 + A}{4E} \pm \frac{\sqrt{(\Delta m^2 \sin 2\theta)^2 + (\Delta m^2 \cos 2\theta - A)^2}}{4E}$$



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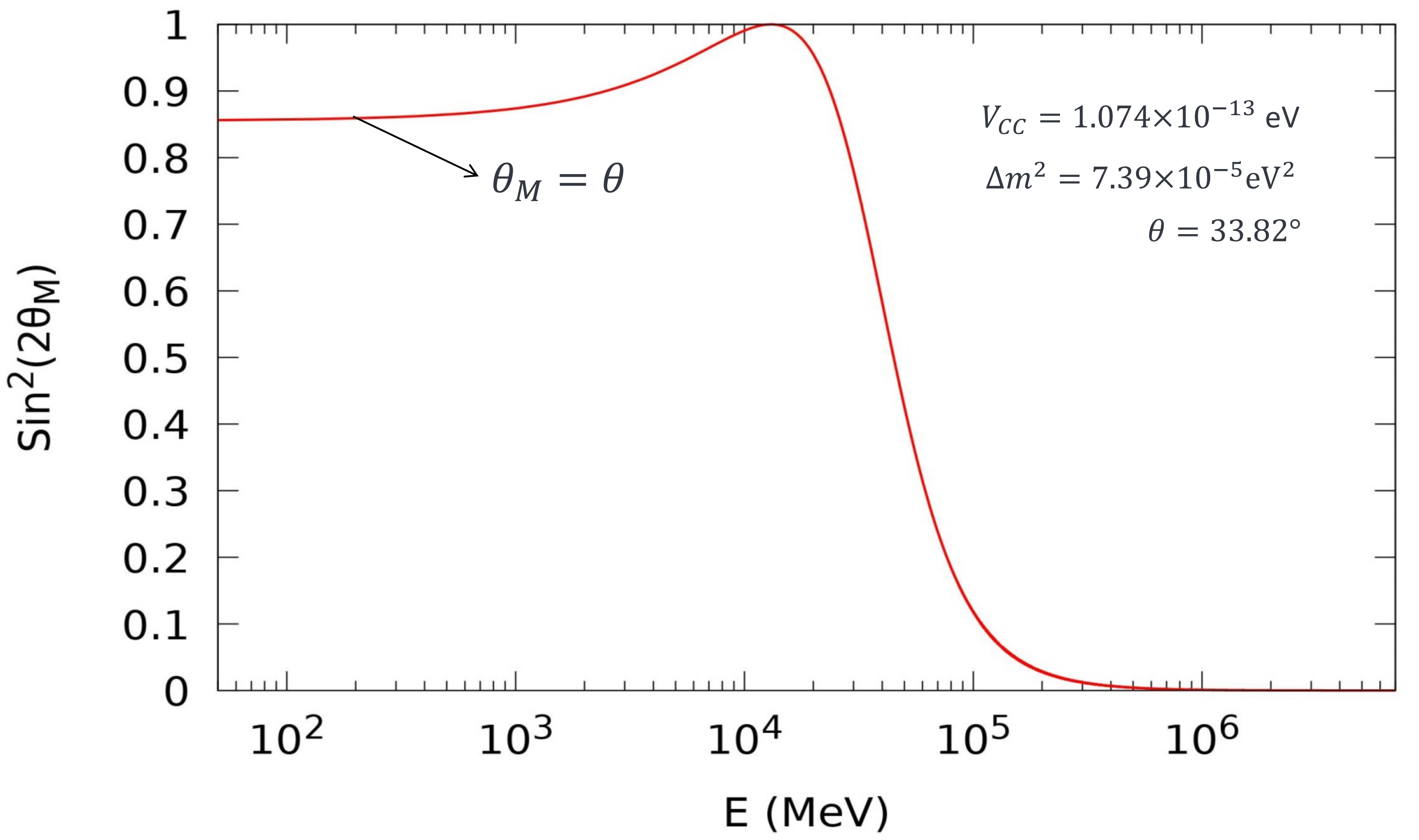

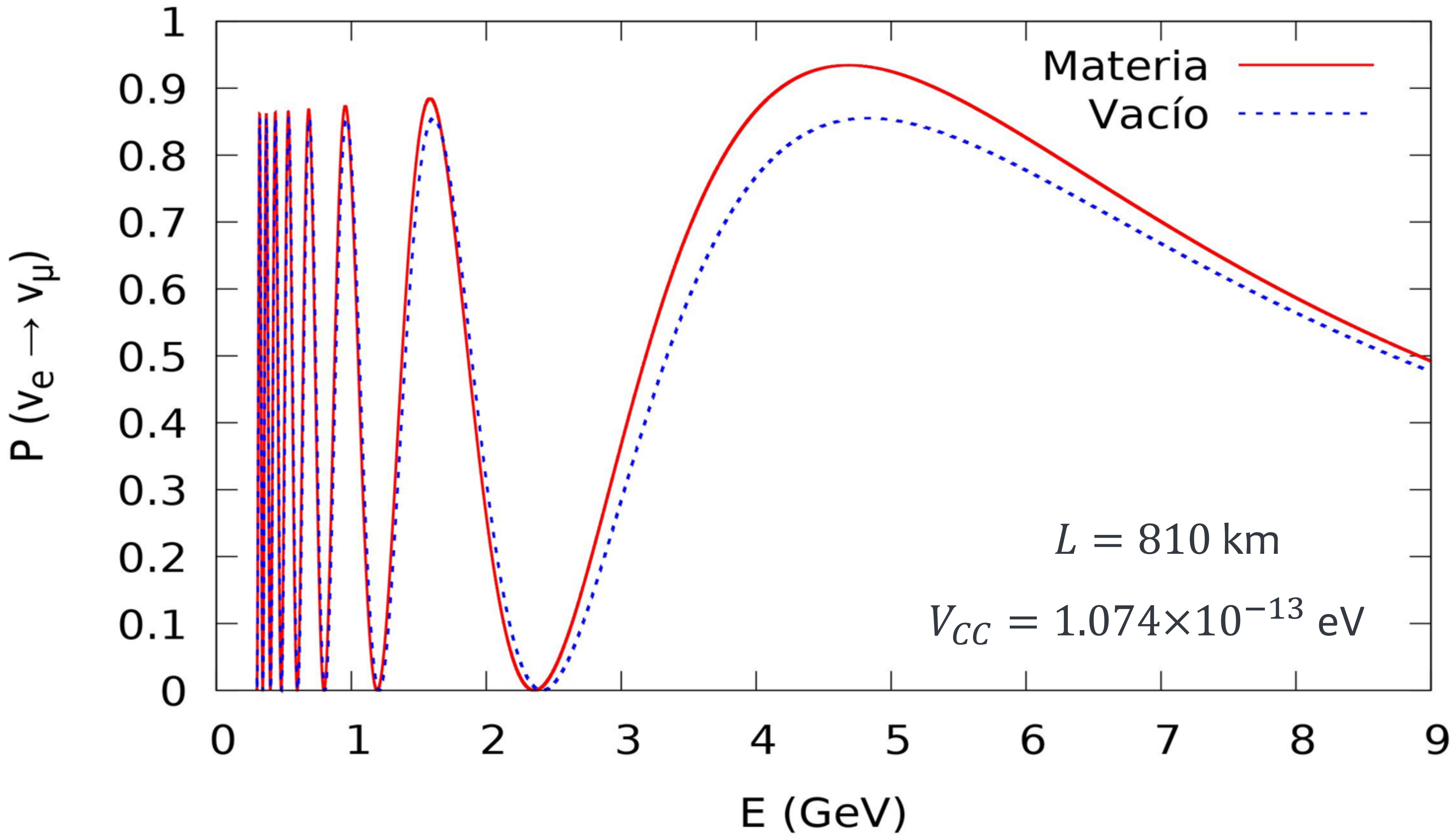

$$\sin 2\theta_M = \frac{\sin 2\theta}{\sqrt{(\sin 2\theta)^2 + \left(\cos 2\theta - \frac{A}{\Delta m^2}\right)^2}} \rightarrow \Delta m_M^2$$

$$A = 2EV_{CC} = 2\sqrt{2}EG_F N_e$$

E ≪ , $\sin^2 2\theta_M \longrightarrow \sin^2 2\theta$

E ≫ , $\sin^2 2\theta_M \longrightarrow 0$

$$P_{\nu_e \to \nu_\mu} = \sin^2 2\theta_M \sin^2\left(1.27\frac{\Delta m_M^2 L}{E}\right)$$

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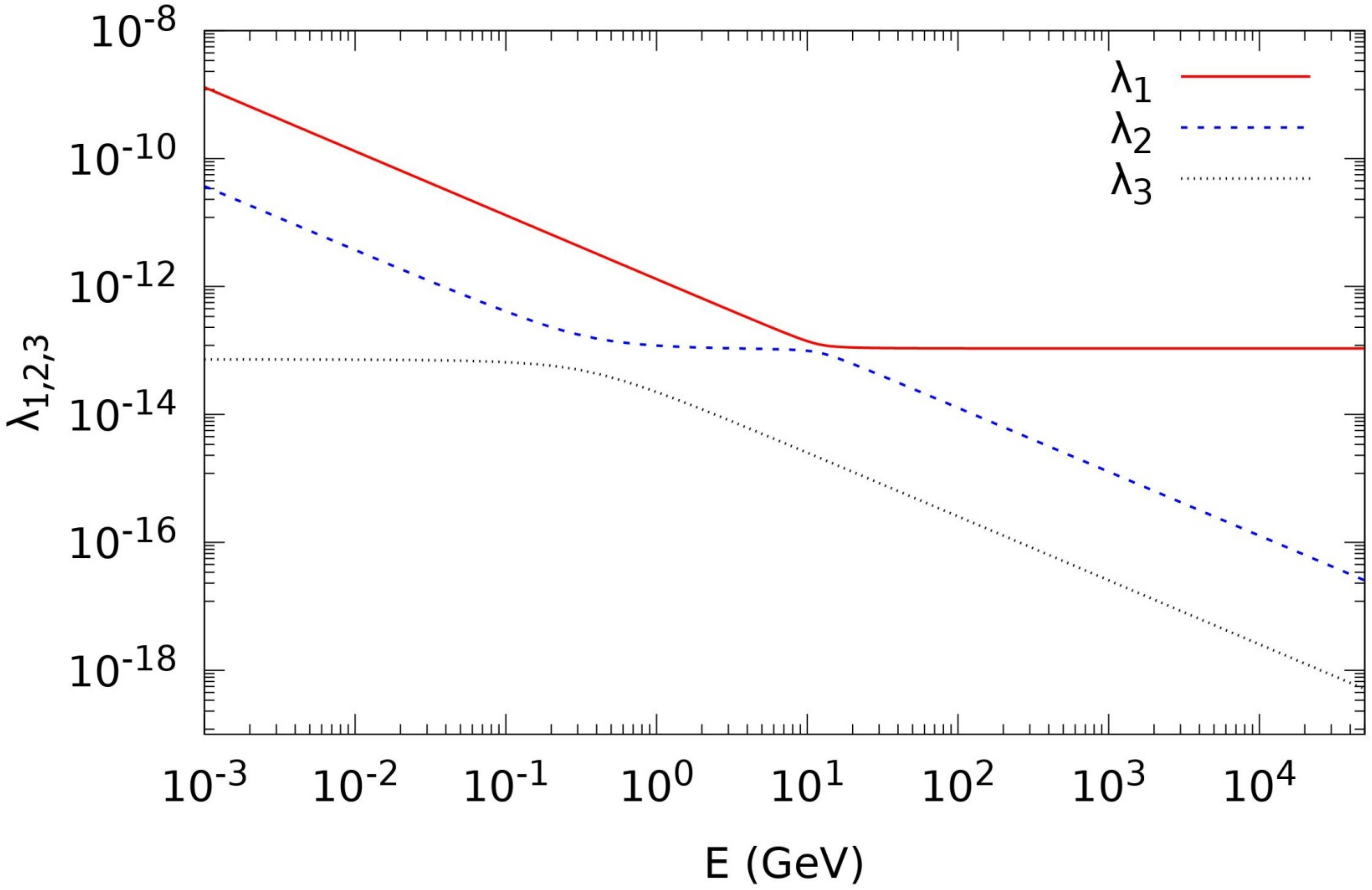
Three Neutrinos Oscillation in Matter

In this case U get the form:

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & C_{23} & S_{23} \\ 0 & -S_{23} & C_{23} \end{pmatrix} \begin{pmatrix} C_{13} & 0 & S_{13}e^{i\delta_{cp}} \\ 0 & 1 & 0 \\ -S_{13}e^{i\delta_{cp}} & 0 & C_{13} \end{pmatrix} \begin{pmatrix} C_{12} & S_{12} & 0 \\ -S_{13} & C_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

	Valores de parámetros	
Experimento	L (km)	$\rho\,(\mathrm{g\,cm^{-3}})$
DUNE	1300	2.8
NOνA	810	2.8



NOvA Collaboration, Phys. Rev. D 98, 032012 (2018) . [ar- Xiv:1806.00096 [hep-ex].

K. J. Kelly and S. J. Parke, Phys. Rev. D 98, no. 1, 015025 (2018) . [arXiv:1802.06784 [hep-ph]]

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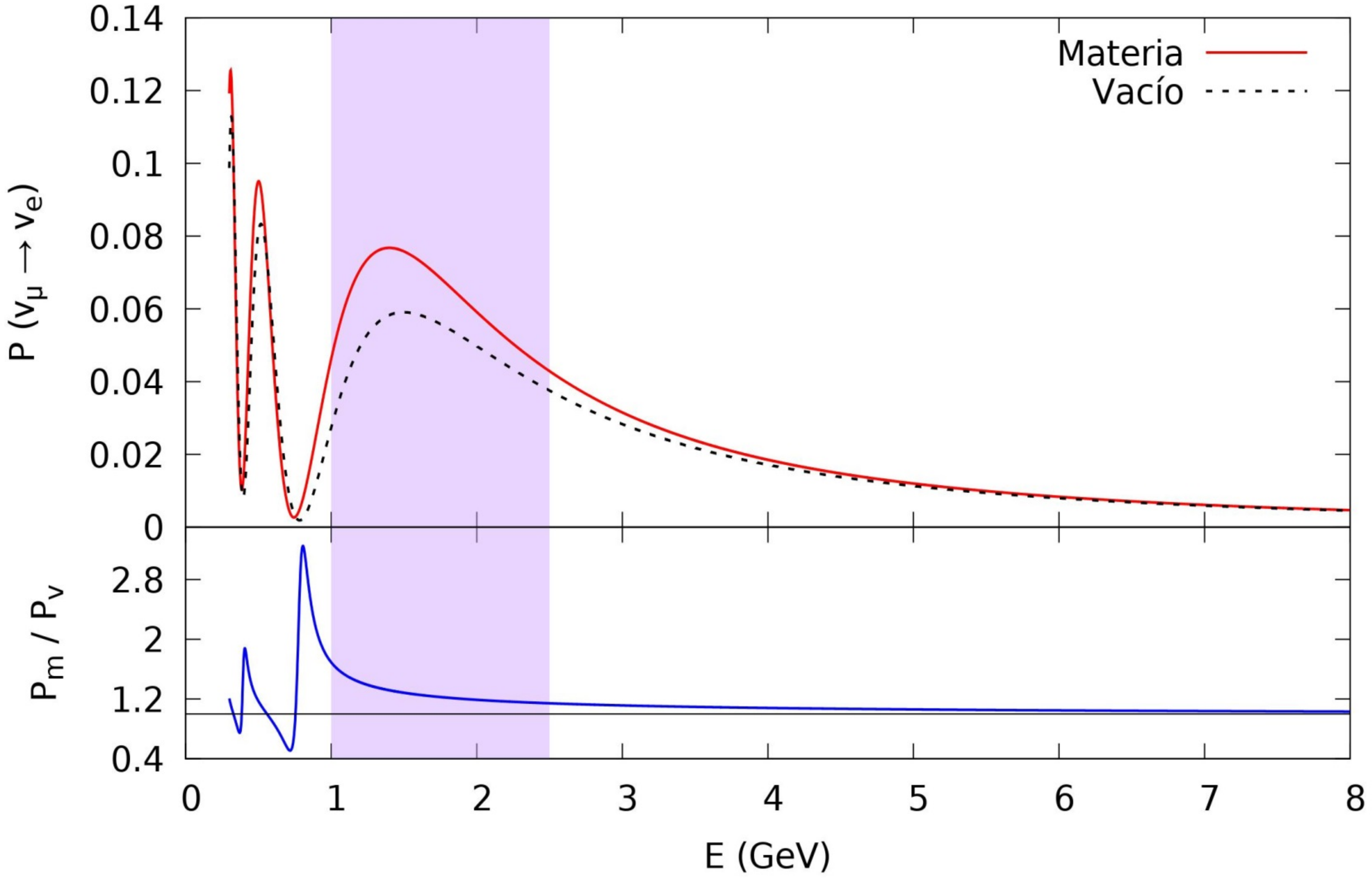
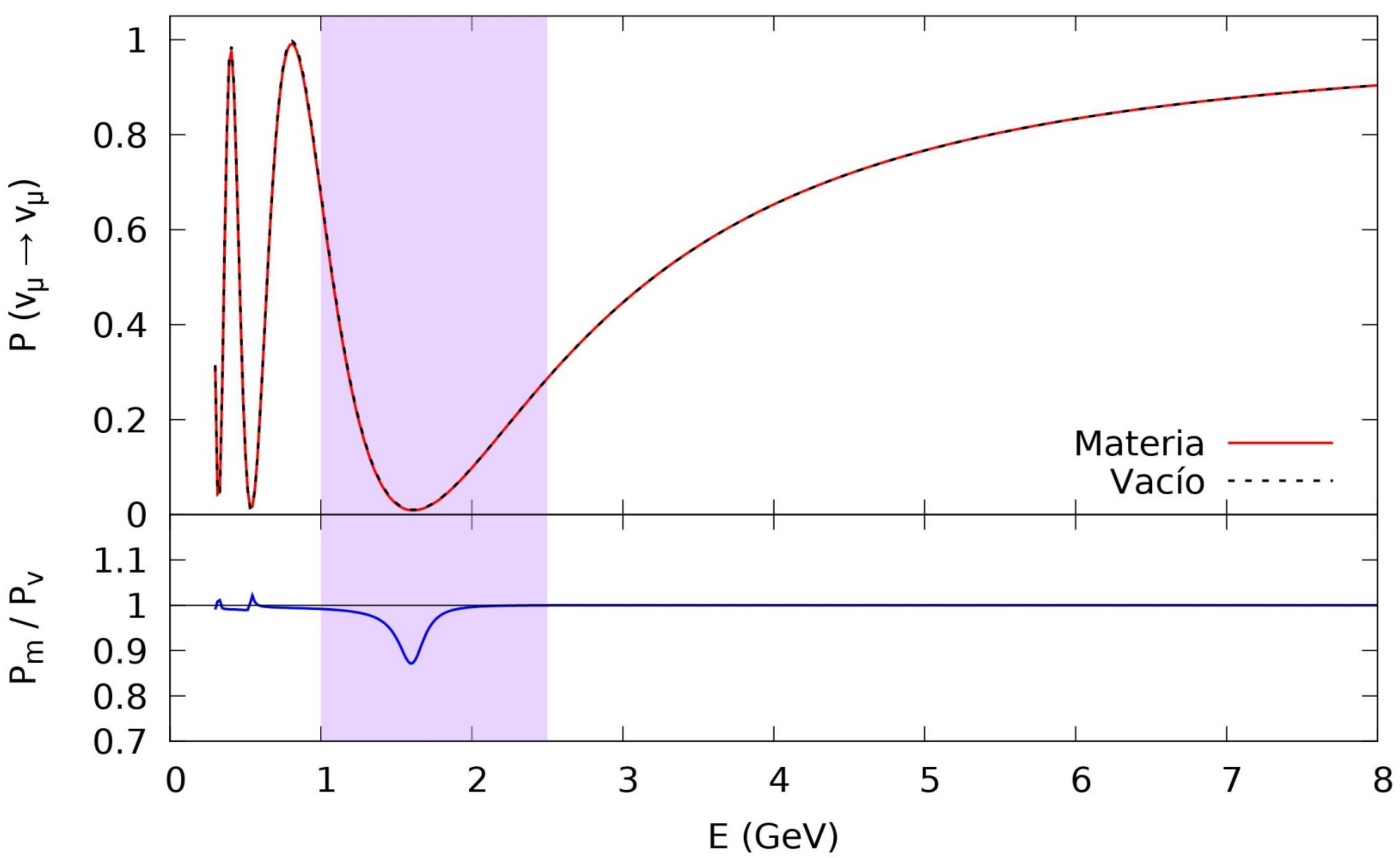
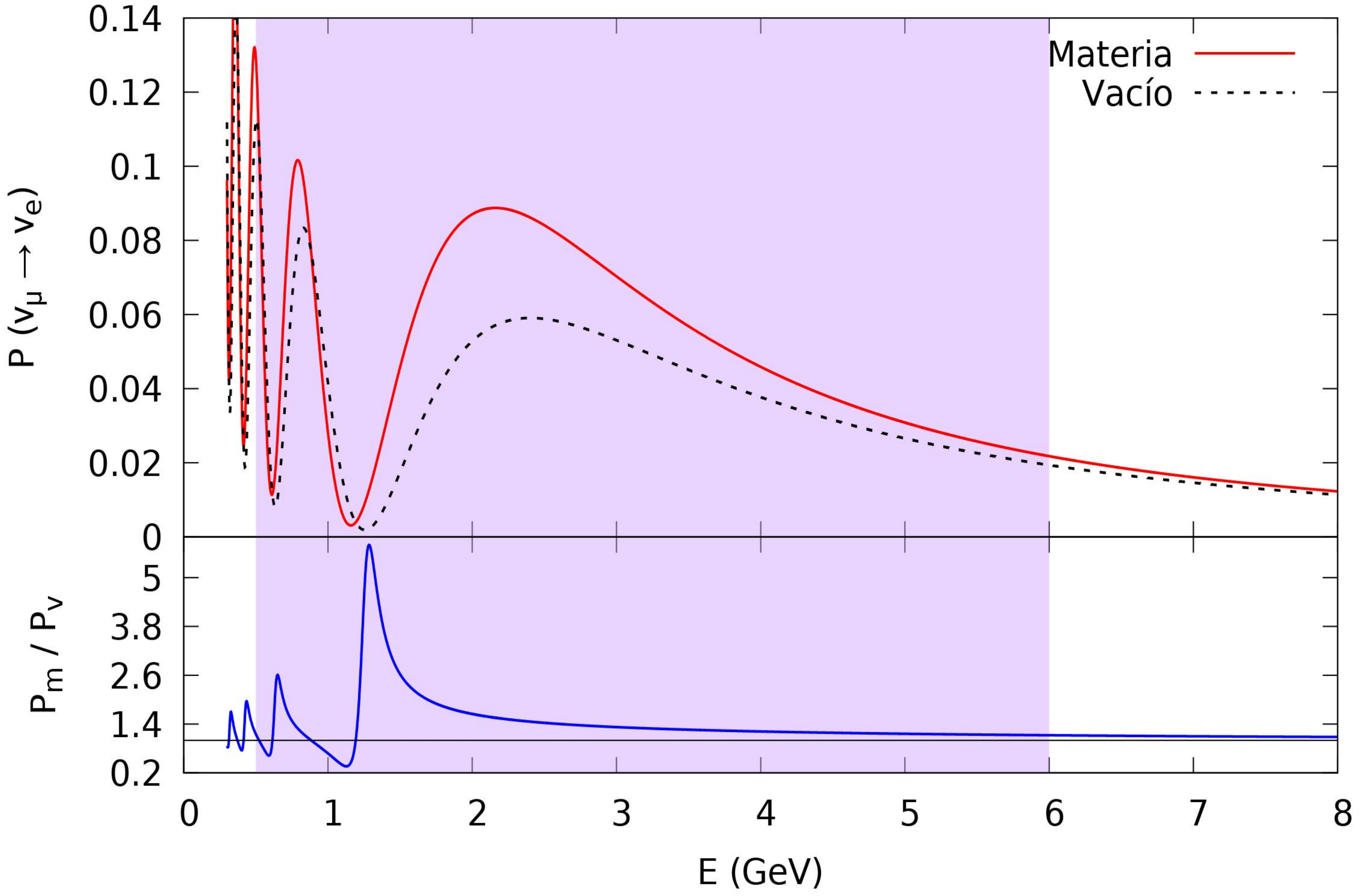
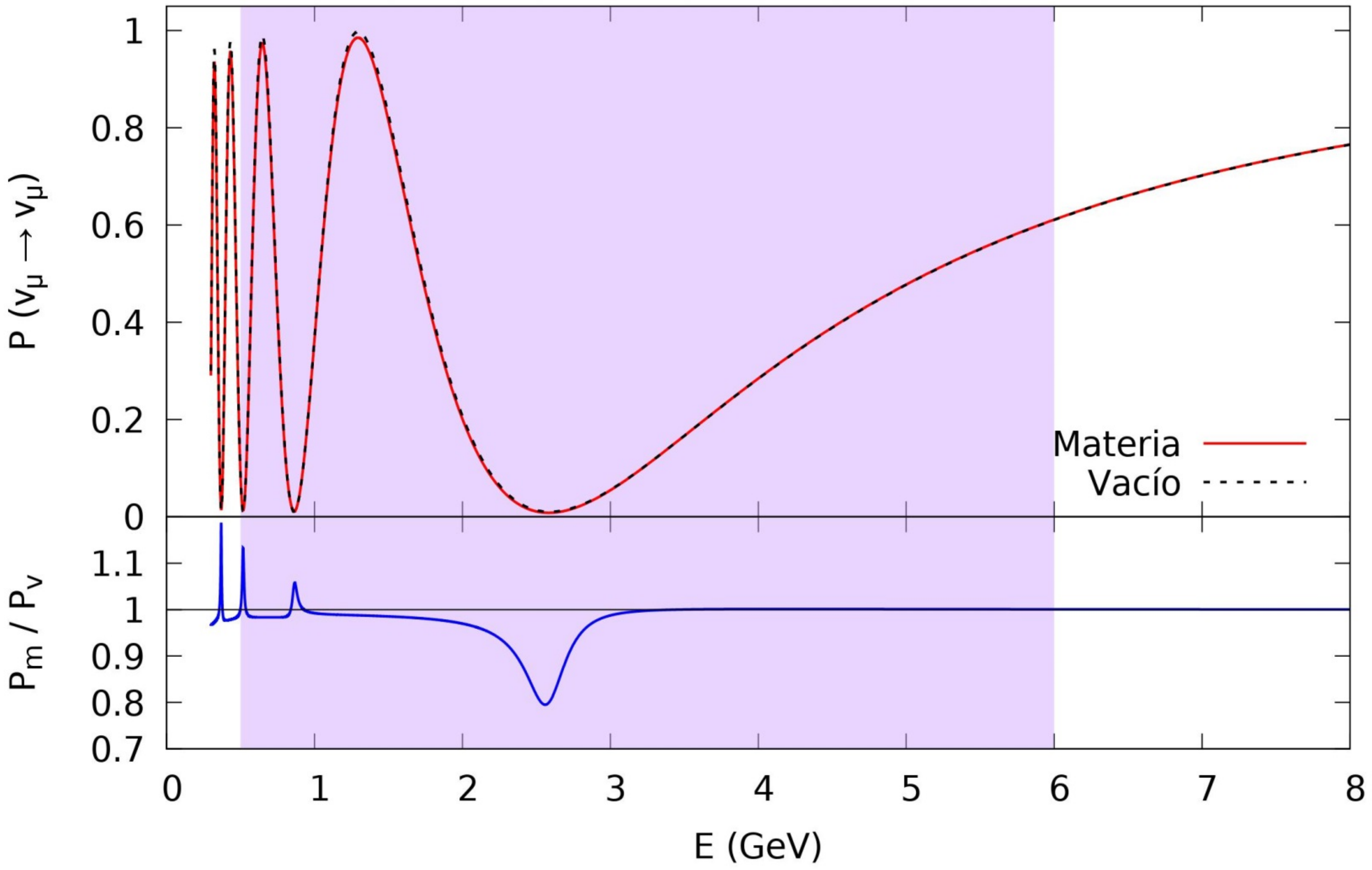

Materia
Vacío
P (νμ → νe)
Pm / Pν
E (GeV)

NOνA


Materia
Vacío
P (νμ → νμ)
Pm / Pν
E (GeV)


Materia
Vacío
P (νμ → νe)
Pm / Pν
E (GeV)

DUNE


Materia
Vacío
P (νμ → νμ)
Pm / Pν
E (GeV)

Oscillation Probability in Matter with NSI

The physics of neutrino oscillation as we have seen, has made remarkable progress as the main description of neutrino flavor transitions in recent time.

$$H_{\mathrm{NSI}} = \frac{1}{2E}\left(U\,\mathbb{M}^2\,U^{\dagger} + \mathbb{V}\epsilon^{m}\right)$$

$$\epsilon^{m} = \begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^{*}{}_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon^{*}{}_{e\tau} & \epsilon^{*}{}_{\mu\tau} & \epsilon_{\tau\tau} \end{pmatrix}$$

- $\epsilon_{\alpha\beta}$ are complex to $\alpha \neq \beta$
- $\epsilon_{\alpha\beta}$ are real to $\alpha = \beta$

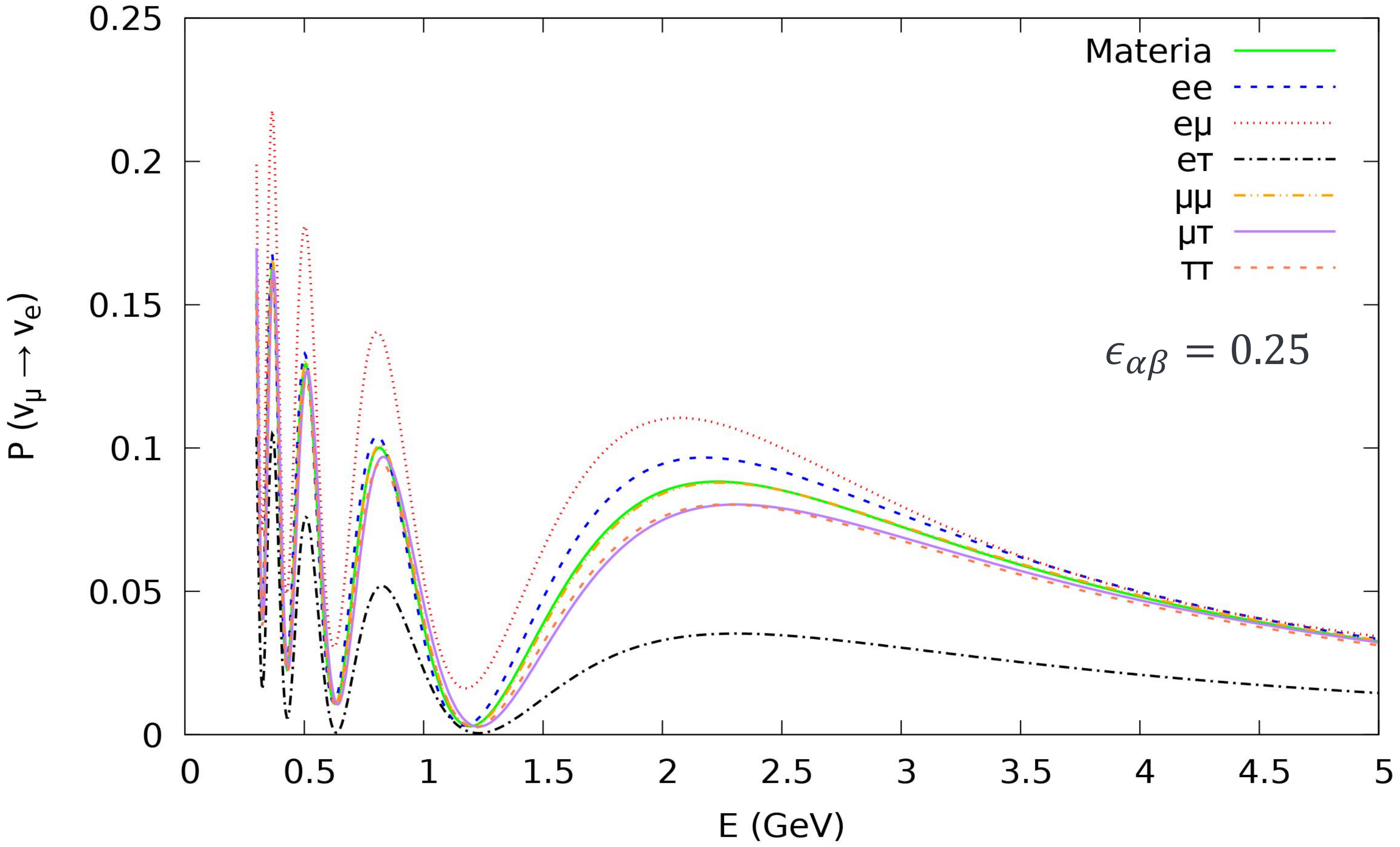
$$\epsilon_{\alpha\beta} \equiv \sum_{f=e,u,d} \epsilon^{f}_{\alpha\beta}\frac{N_f}{N_e}$$

- $\alpha, \beta = e, \mu, \tau$

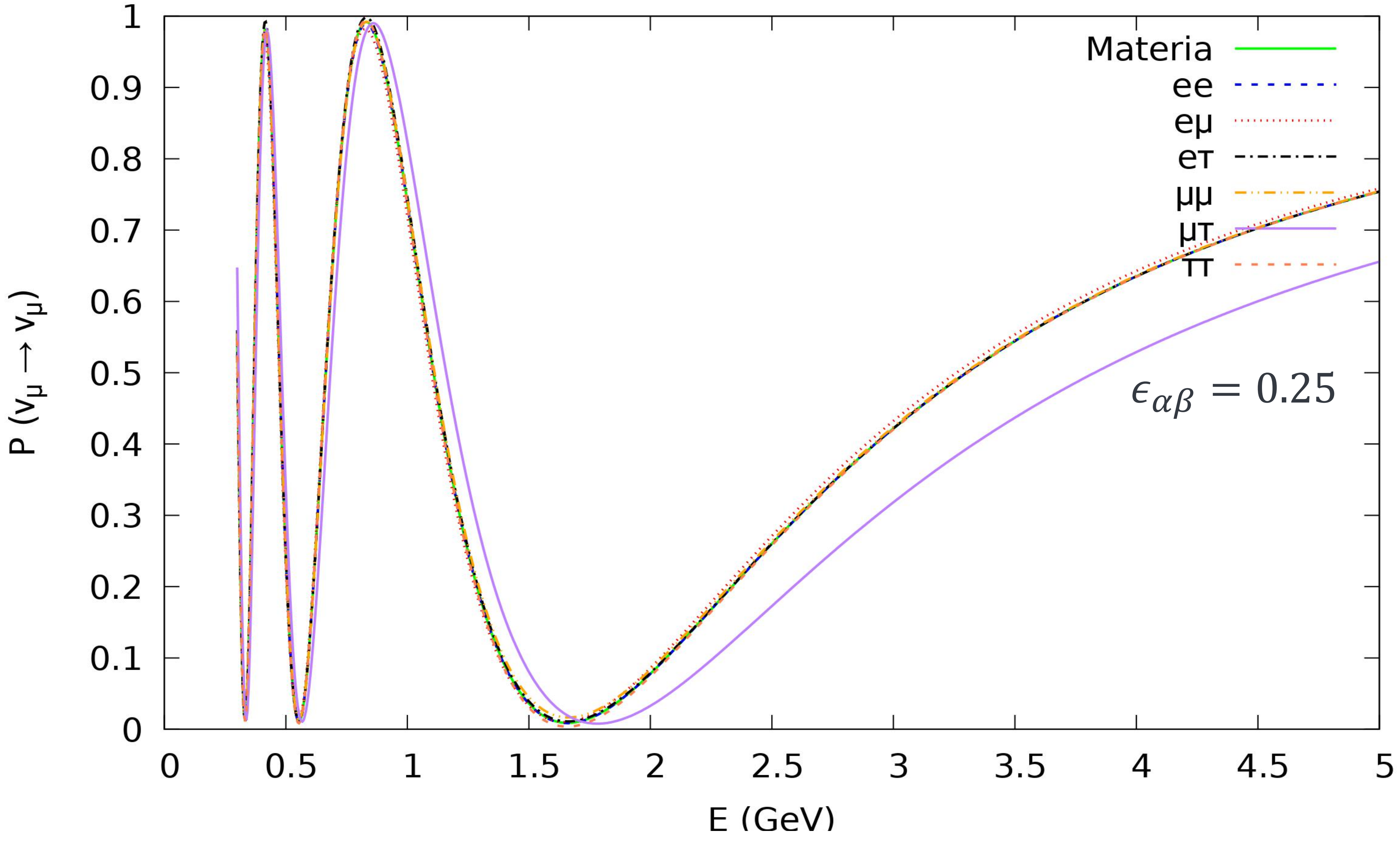
S. V. Demidov, arXiv:1912.04149 [hep-ph].

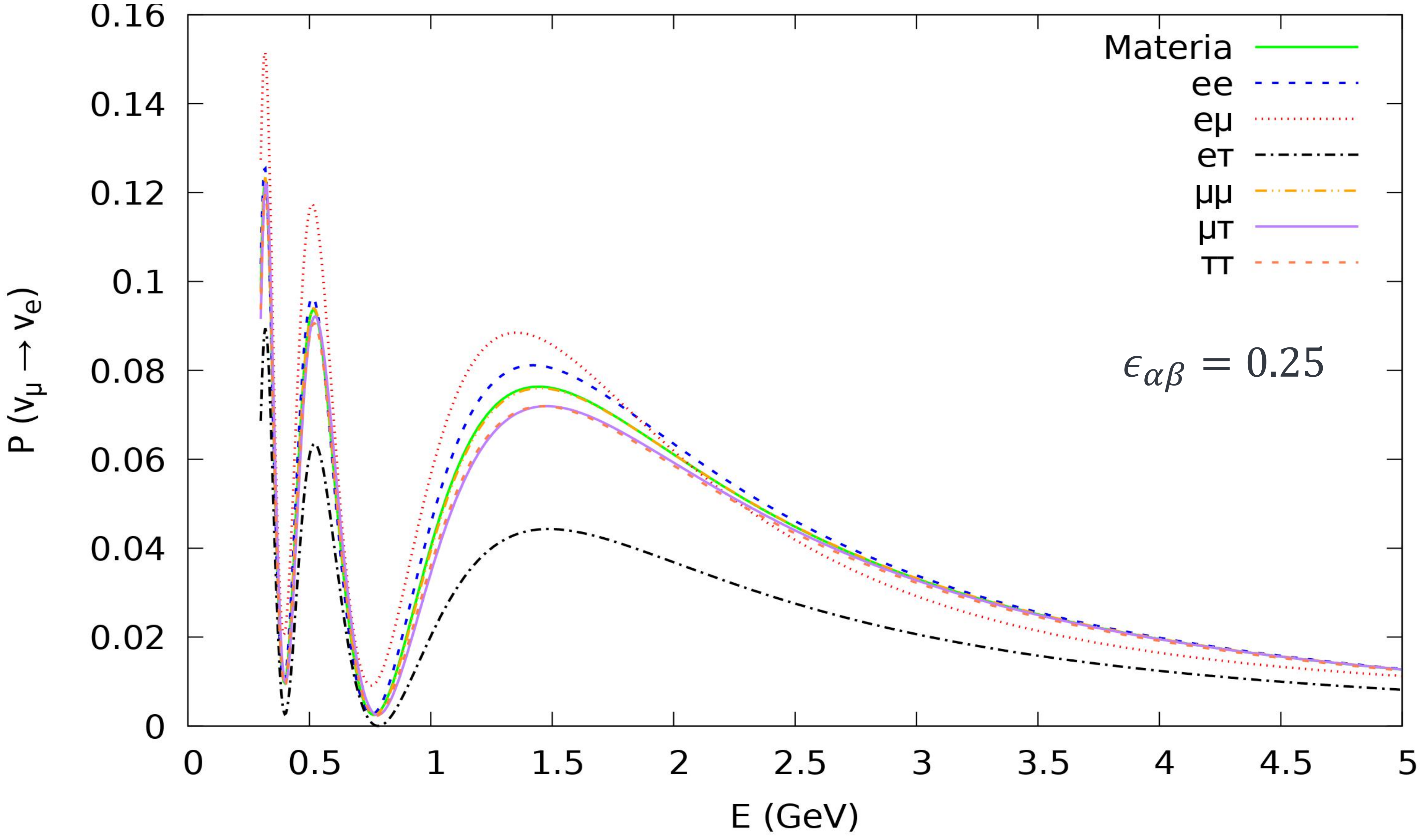
M. C. Gonzalez-Garcia, M. Maltoni and J. Salvado, [arXiv:1103.4365 [hep-ph].

F. Capozzi, S. S. Chatterjee and A. Palazzo, arXiv:1908.06992 [hep-ph].



NO$\mathcal{V}$A





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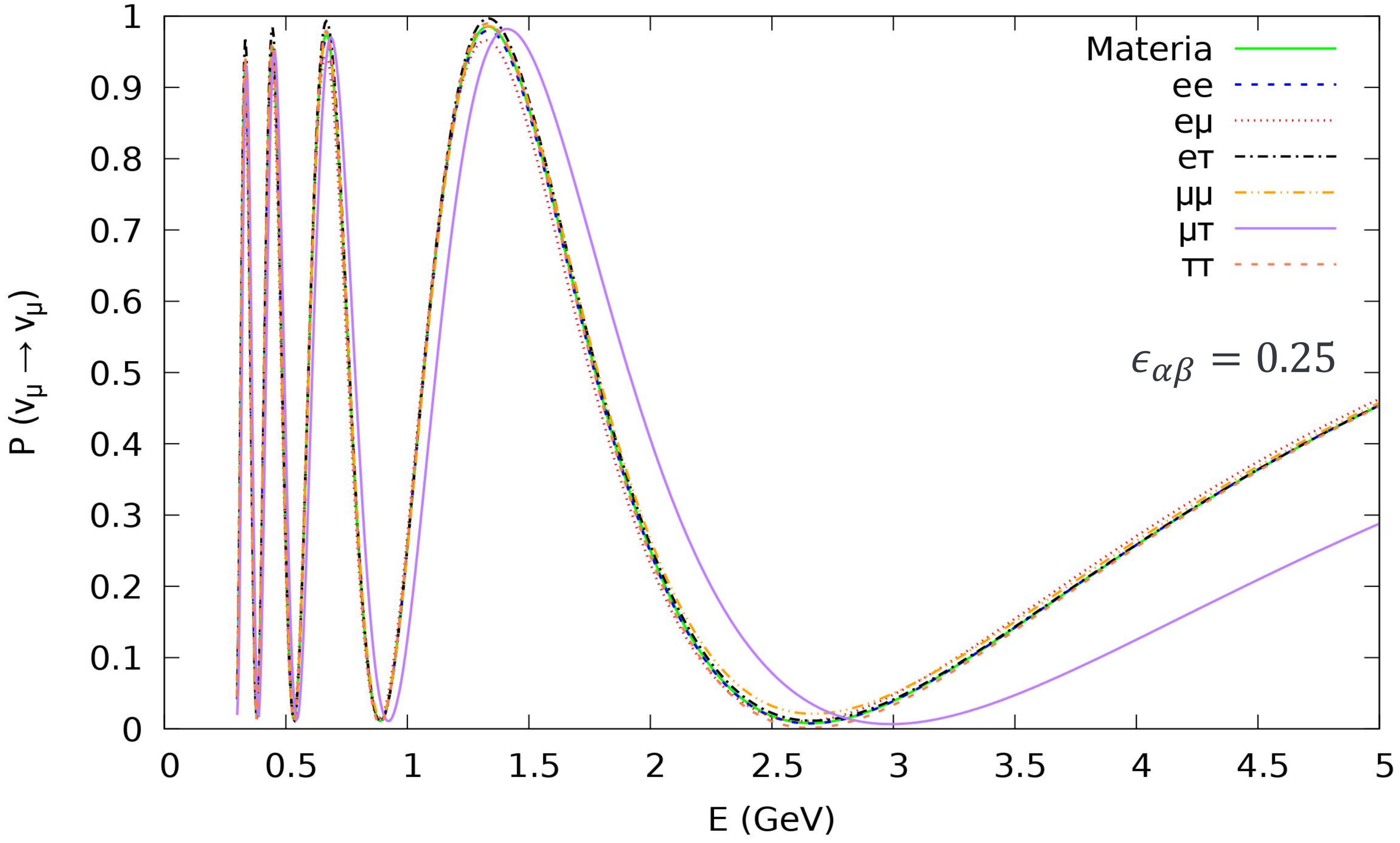

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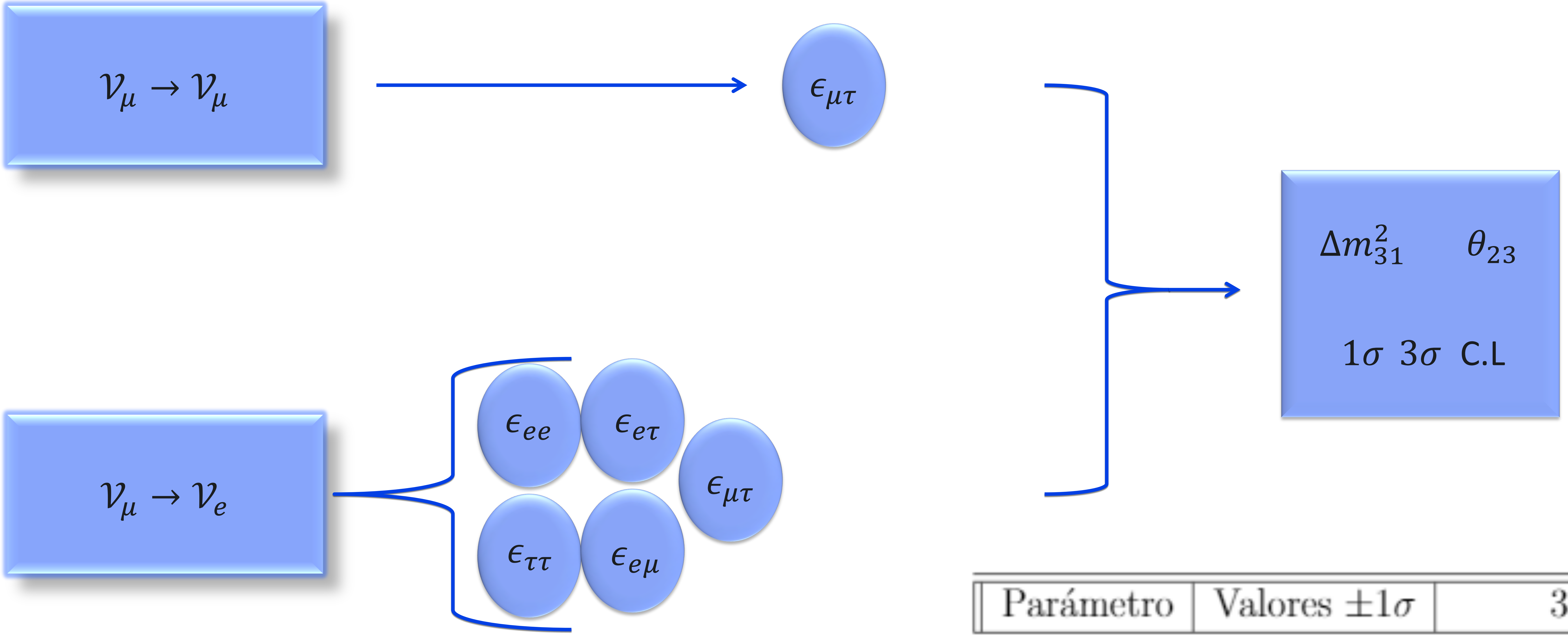

Parámetro	Valores $\pm 1\sigma$	3σ
θ_{23} (°)	$48.6^{+1.0}_{-1.4}$	$41.1 \to 51.3$
$\frac{\Delta m^2_{31}}{10^{-3}\text{eV}^2}$	$2.528^{+0.029}_{-0.031}$	$2.436 \to 2.618$

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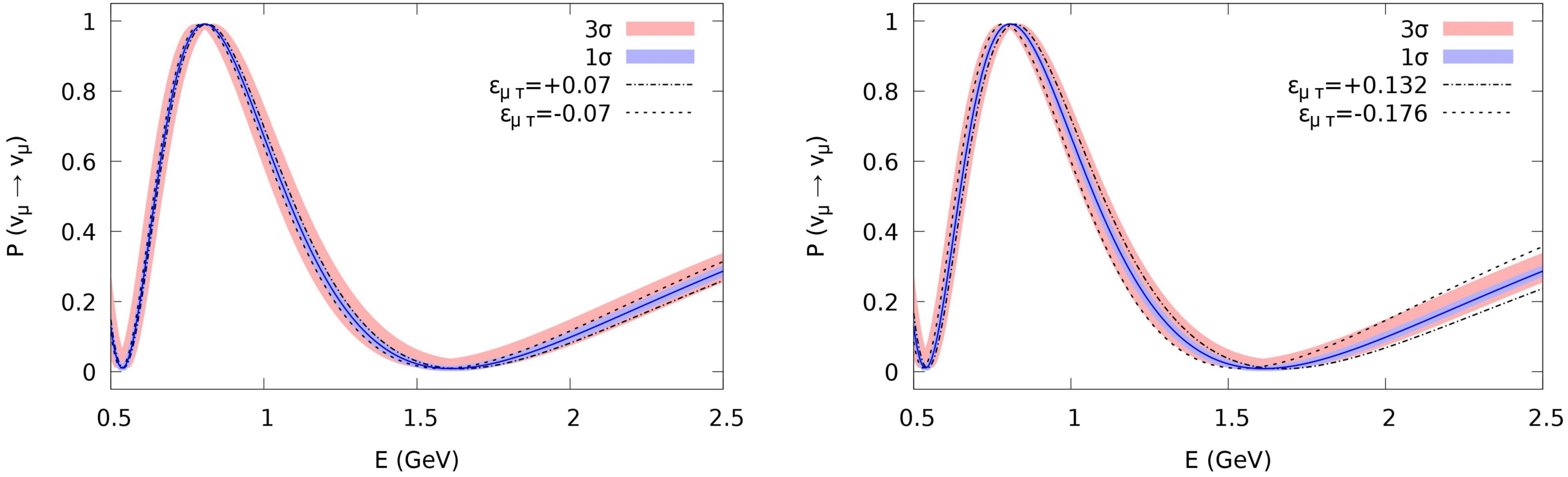
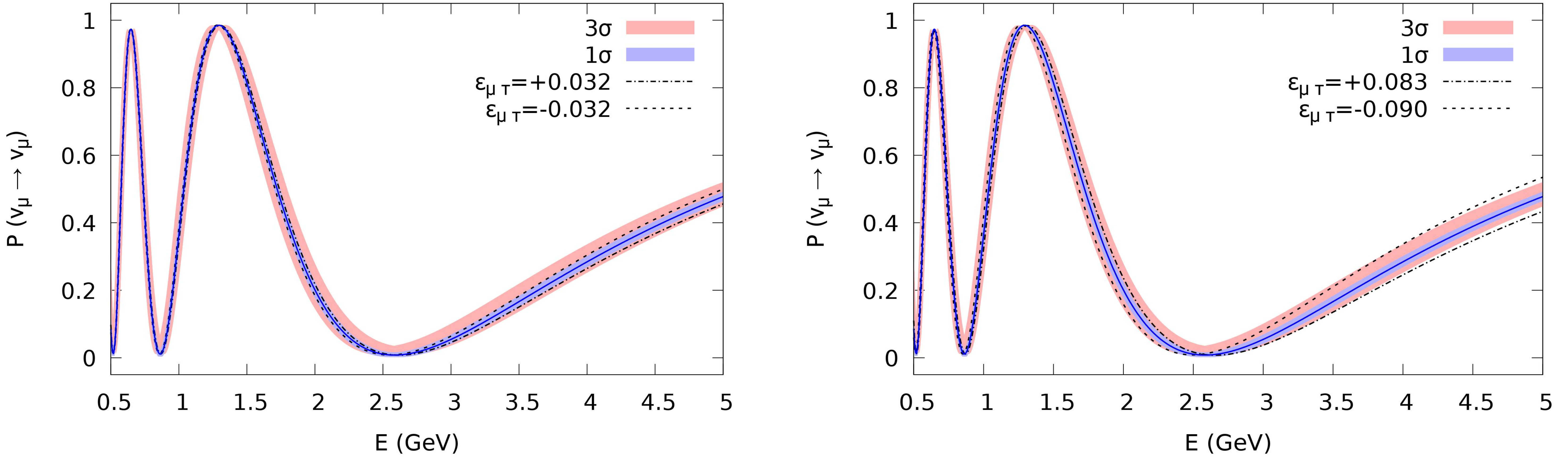
NO$\mathcal{V}$A



	1σ	3σ
NO$\mathcal{V}$A	$-0.07 \leq \epsilon_{\mu\tau} \leq 0.07$	$-0.176 \leq \epsilon_{\mu\tau} \leq 0.132$
DUNE	$-0.032 \leq \epsilon_{\mu\tau} \leq 0.032$	$-0.090 \leq \epsilon_{\mu\tau} \leq 0.083$

DUNE



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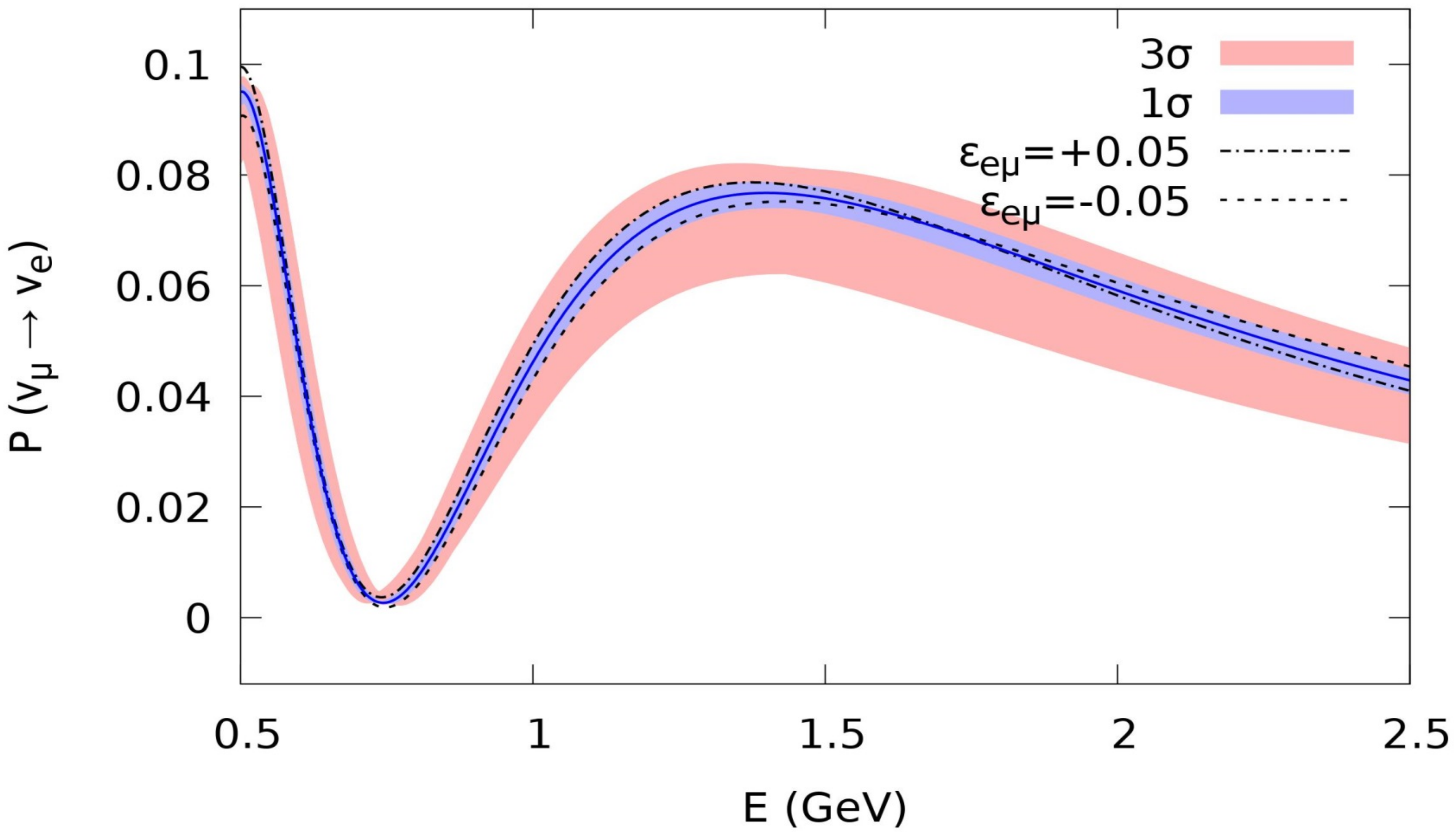
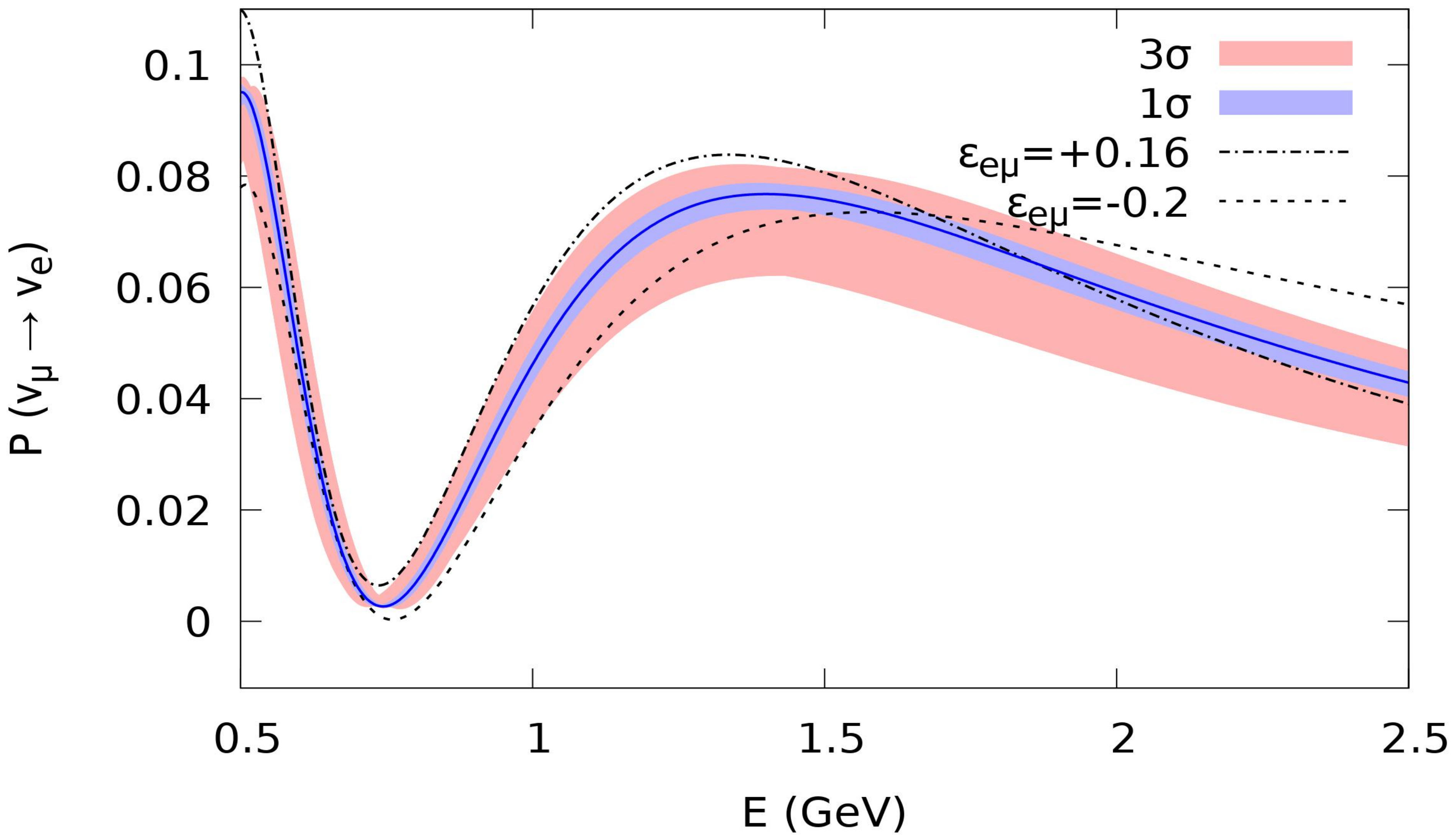
NO$\mathcal{V}$A





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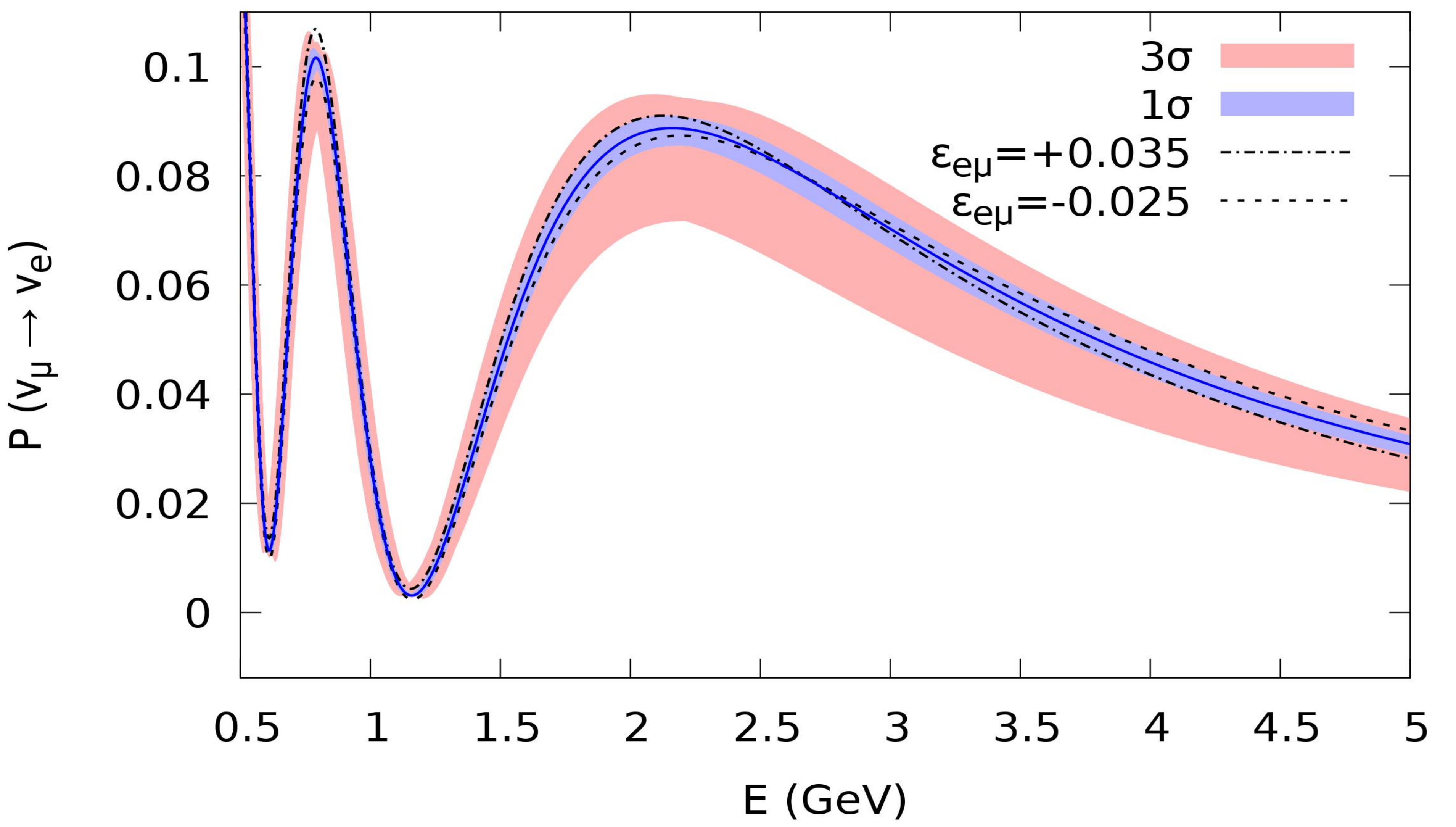

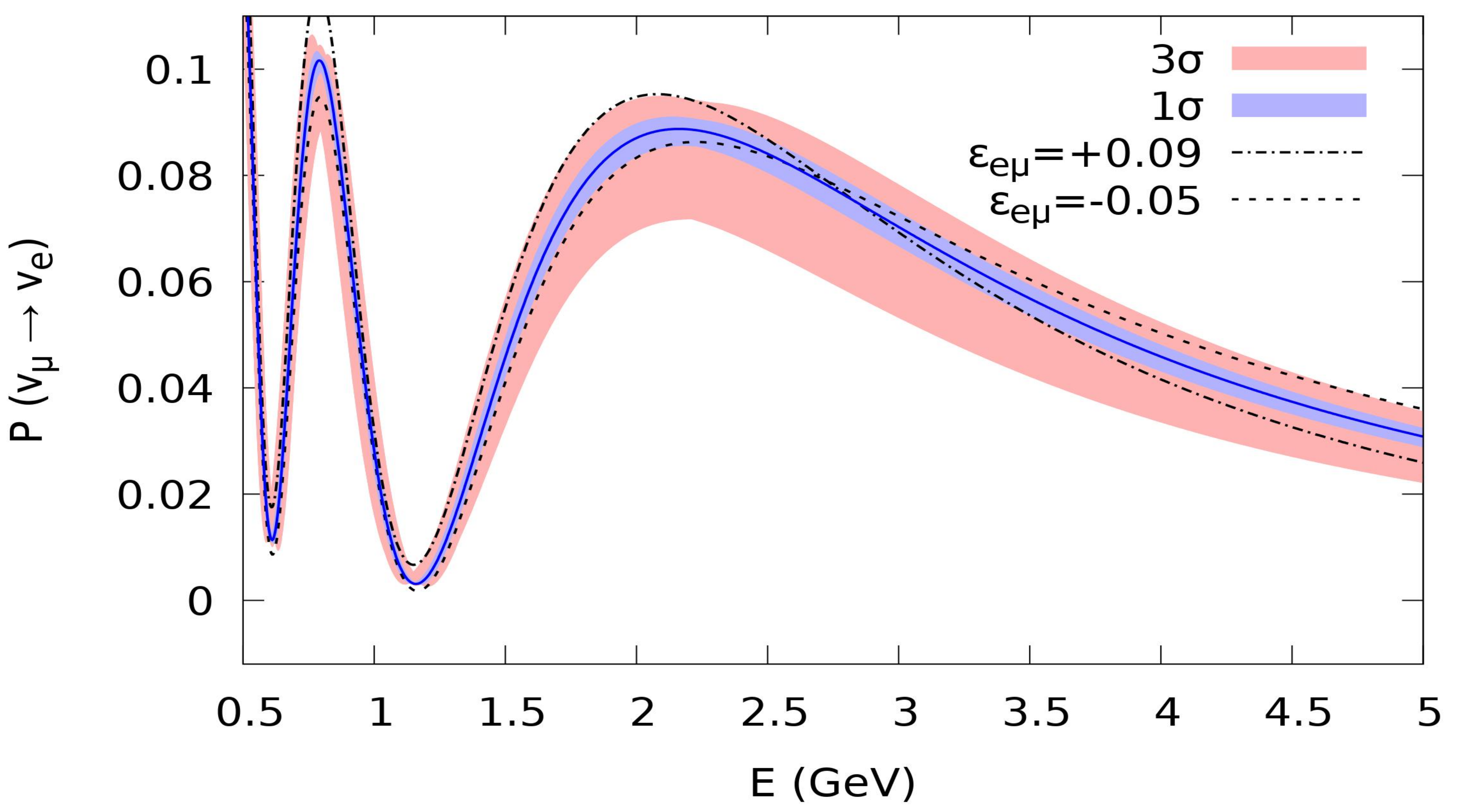

Parámetros NSI	1σ	3σ
ϵ_{ee}	$-0.23 \leq \epsilon_{ee} \leq 0.18$	$-0.6 \leq \epsilon_{ee} \leq 0.4$
$\epsilon_{e\mu}$	$-0.05 \leq \epsilon_{e\mu} \leq 0.05$	$-0.2 \leq \epsilon_{e\mu} \leq 0.16$
$\epsilon_{e\tau}$	$-0.02 \leq \epsilon_{e\tau} \leq 0.02$	$-0.07 \leq \epsilon_{e\tau} \leq 0.13$
$\epsilon_{\mu\tau}$	$-0.16 \leq \epsilon_{\mu\tau} \leq 0.18$	$-0.4 \leq \epsilon_{\mu\tau} \leq 0.5$
$\epsilon_{\tau\tau}$	$-0.28 \leq \epsilon_{\tau\tau} \leq 0.34$	$-0.4 \leq \epsilon_{\tau\tau} \leq 0.8$

NO$\mathcal{V}$A

Parámetros NSI	1σ	3σ
ϵ_{ee}	$-0.24 \leq \epsilon_{ee} \leq 0.24$	$-0.45 \leq \epsilon_{ee} \leq 0.35$
$\epsilon_{e\mu}$	$-0.025 \leq \epsilon_{e\mu} \leq 0.035$	$-0.05 \leq \epsilon_{e\mu} \leq 0.09$
$\epsilon_{e\tau}$	$-0.02 \leq \epsilon_{e\tau} \leq 0.02$	$-0.05 \leq \epsilon_{e\tau} \leq 0.1$
$\epsilon_{\mu\tau}$	$-0.1 \leq \epsilon_{\mu\tau} \leq 0.1$	$-0.35 \leq \epsilon_{\mu\tau} \leq 0.35$
$\epsilon_{\tau\tau}$	$-0.22 \leq \epsilon_{\tau\tau} \leq 0.22$	$-0.42 \leq \epsilon_{\tau\tau} \leq 0.48$

DUNE

	1σ	3σ
NO$\mathcal{V}$A	$-0.07 \leq \epsilon_{\mu\tau} \leq 0.07$	$-0.176 \leq \epsilon_{\mu\tau} \leq 0.132$
DUNE	$-0.032 \leq \epsilon_{\mu\tau} \leq 0.032$	$-0.090 \leq \epsilon_{\mu\tau} \leq 0.083$

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Conclusions and Perspectives

- The distance of source to detector of a neutrino experiment varies the probability oscillation and results in a change in the energy range.
- The interaction of charge current with electrons in the medium affects noticeably the oscillation channel $\mathcal{V}_\mu \rightarrow \mathcal{V}_e$.
- The fact that the NSI parameters have values other than zero may somehow be interfering with the measurement of the parameters that govern the neutrino oscillation.
- The NSI parameters have an effect that seems to mix both changes in amplitude and frequency.
- For future projects, it is considered that the other standard parameters will be varied in order to obtain a more precise estimate of these NSI parameters.

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