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Neutrino magnetic moments and high-energy neutrinos flavour composition

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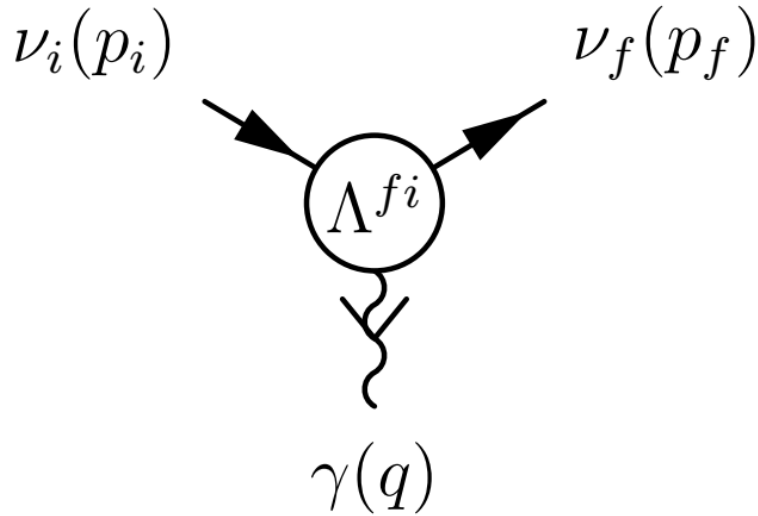


Outline of the talk

- Neutrino electromagnetic interactions.
- Neutrino oscillations in a magnetic field.
- Coherence in neutrino oscillations.
- Flavour composition of high-energy neutrinos and neutrino magnetic moments.



Neutrino electromagnetic properties



$$\mathcal{H}_{\text{em}}^{(\nu)}(x) = j_{\mu}^{(\nu)}(x) A^{\mu}(x) = \sum_{k,j=1}^N \bar{\nu}_k(x) \Lambda_{\mu}^{kj} \nu_j(x) A^{\mu}(x),$$

The vertex function is parametrized in terms of **charge, anapole, electric and magnetic form factors**:

$$\Lambda_{\mu}(q) = (\gamma_{\mu} - q_{\mu} \not{q} / q^2) [\mathbb{f}_Q(q^2) + \mathbb{f}_A(q^2) q^2 \gamma_5] - i \sigma_{\mu\nu} q^{\nu} [\mathbb{f}_M(q^2) + i \mathbb{f}_E(q^2) \gamma_5]$$

$$\mathbb{f}_M^{fi}(0) = \mu_{fi} \text{ - neutrino magnetic moments}$$

C.Giunti, A.Studenikin, "Neutrino electromagnetic interactions: A window to new physics", Rev.Mod.Phys. 87 (2015) 531



Neutrino magnetic moments matrix

CPT-invariance + hermicity:

- Magnetic moments matrix for **Dirac** neutrinos is **real and symmetric**:

$$\mu^D = \begin{pmatrix} \mu_{11} & \mu_{12} & \mu_{13} \\ \mu_{12} & \mu_{22} & \mu_{23} \\ \mu_{13} & \mu_{23} & \mu_{33} \end{pmatrix}$$

- Magnetic moments matrix for **Majorana** neutrinos is **imaginary and asymmetric**:

$$\mu^M = \begin{pmatrix} 0 & i\mu_{12} & i\mu_{13} \\ -i\mu_{12} & 0 & i\mu_{23} \\ -i\mu_{13} & -i\mu_{23} & 0 \end{pmatrix}$$

- Thus, Dirac and Majorana neutrinos can be distinguished by their **electromagnetic properties**.



Neutrino magnetic moments

Theory (Standard Model):

$$\mu_{ii}^D = \frac{3eG_F m_i}{8\sqrt{2}\pi^2} \approx 3.2 \times 10^{-19} \left(\frac{m_i}{1 \text{ eV}} \right) \mu_B$$

K.Fujikawa, R.Shrock, "*The Magnetic Moment of a Massive Neutrino and Neutrino Spin Rotation*", Phys.Rev.Lett. 45 (1980) 963

Experiment:

$$\mu_\nu < 6.4 \times 10^{-12} \mu_B$$

E.Aprile *et al.* [XENON collaboration], "*Search for New Physics in Electronic Recoil Data from XENONnT*", Phys.Rev.Lett. 129 (2022) 16, 161805

Upper bounds from astrophysical neutrinos:

R.L. Workman *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. 2022, 083C01 (2022)

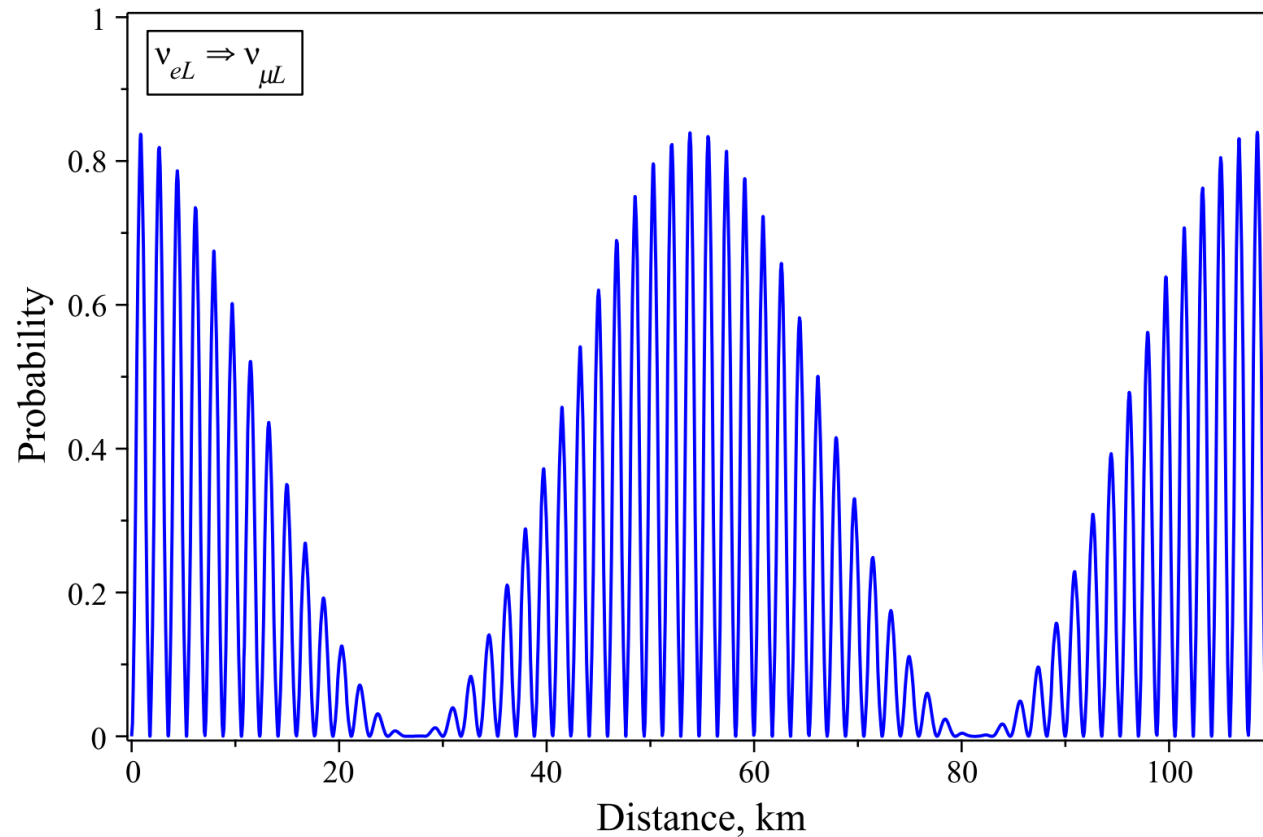
$$\mu_\nu \lesssim 10^{-12} \mu_B$$



Flavour transitions in a magnetic field

$$P_{\nu_e^L \rightarrow \nu_\mu^L} = \sin^2 2\theta \sin^2 \left(\frac{\Delta m^2}{4p} t \right) \times \left(1 - \sin^2(\mu B_\perp t) \right)$$

$$\mu_1 = \mu_2 = \mu$$



Neutrinos in astrophysics

Known types:

- Solar neutrinos
- Supernova neutrinos
- High-energy neutrinos

Hypothetical sources:

- Diffuse Supernova Neutrino Background
- Gamma-ray bursts
- Active Galactic Nuclei
- Pulsars, magnetars
- Cosmogenic neutrinos
- Relic neutrinos



High-energy neutrinos point sources

- Recent data analyses present evidence of observation of astrophysical neutrinos emanating from distant objects, such as active galactic nuclei and blazars:
 1. IceCube Collaboration, "*Evidence for neutrino emission from the nearby active galaxy NGC 1068*", *Science* 378 (2022) 6619, 538-543,
 2. IceCube Collaboration, "*TXS 0506+056 with Updated IceCube Data*", *PoS ICRC2023* (2023) 1465,
 3. Baikal-GVD Collaboration, "*Baikal-GVD Astrophysical Neutrino Candidate near the Blazar TXS~0506+056*", *PoS ICRC2023* 1457.
- Neutrinos are unique astrophysical messengers, since unlike charged particles they are not deflected by magnetic field.
However, they interact with a magnetic field via magnetic moments.



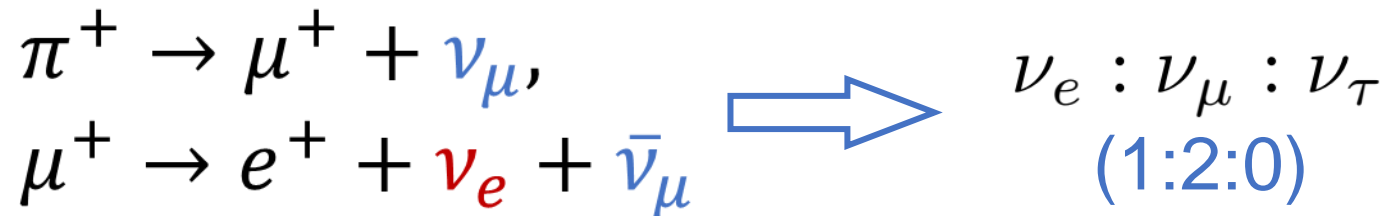
High-energy neutrinos flavour ratios

- Standard neutrino oscillations in vacuum predict the following flavour ratios at the terrestrial neutrino telescope:

$$r_{\alpha} = \sum_{\beta} r_{\beta}^0 \sum_i |U_{\alpha i}|^2 |U_{\beta i}|^2$$

where r_{β}^0 are **flavour ratios at the neutrino source** ($\alpha, \beta = e, \mu, \tau$).

- Pion decay neutrino production: $r^0 = \left(\frac{1}{2}, \frac{2}{3}, 0\right)$ and $r \approx \left(\frac{1}{3}, \frac{1}{3}, \frac{1}{3}\right)$.



M.Bustamante, J.Beacom, W.Winter, "Theoretically palatable flavor combinations of astrophysical neutrinos", Phys.Rev.Lett. 115 (2015) 16



Flavour ratios as a probe of BSM physics

- **Quantum gravity**

IceCube Collaboration, “*Searching for Decoherence from Quantum Gravity at the IceCube South Pole Neutrino Observatory*”, arXiv 2308.00105

- **Neutrino decay**

P.Baerwald, M.Bustamante, W.Winter, “*Neutrino Decays over Cosmological Distances and the Implications for Neutrino Telescopes*”, JCAP 10 (2012) 020

- **Lorentz violation**

D.Hooper, D.Morgan, E.Winstanley, “*Lorentz and CPT Invariance Violation In High-Energy Neutrinos*”, Phys.Rev.D 72 (2005) 065009

- **Sterile neutrinos**

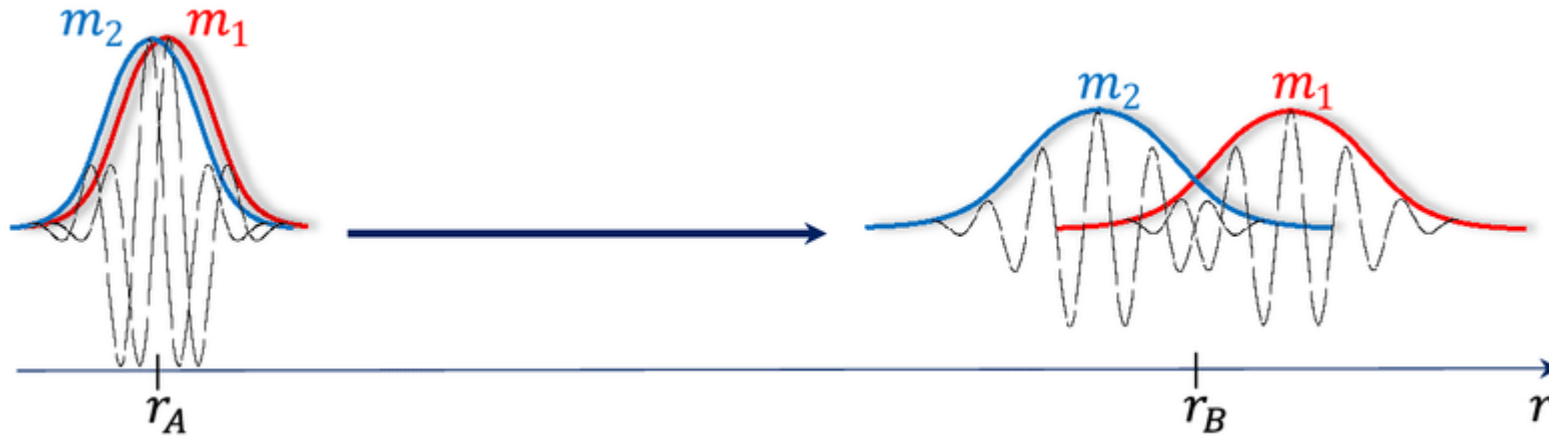
A.Esmailia , Y.Farzan, “*Implications of the Pseudo-Dirac Scenario for Ultra High Energy Neutrinos from GRBs*”, JCAP 12 (2012) 014

In this talk we report possible effects of neutrino interaction with a magnetic field on flavour ratios



Neutrino oscillations and coherence

- Plane waves description is not applicable for the case of neutrino propagation on at large distances. Instead **wave packet** description must be used.



- Massive neutrino states wave packets separation leads to the **exponential damping of neutrino flavour oscillations**.

$$P_{osc}(L) \sim \exp\left(-i2\pi\frac{L}{L_{osc}}\right) \exp\left(-\frac{L^2}{L_{coh}^2}\right)$$

[1] C. Giunti, "Coherence and wave packets in neutrino oscillations", *Found.Phys.Lett.* 17 (2004) 103-124;

[2] D.Naumov, V.Naumov, "Quantum Field Theory of Neutrino Oscillations", *Phys.Part.Nucl.* 51 (2020) 1, 1-106.

Neutrino evolution in a magnetic field

- Neutrino evolution in a magnetic field is described by the following Dirac equation:

$$(i\gamma^\mu \partial_\mu - m_i)\nu_i(x) - \sum_k \mu_{ik} \Sigma \mathbf{B} \nu_k(x) = 0, \quad (1)$$

A.Popov, A.Studenikin, "Manifestations of nonzero Majorana CP-violating phases in oscillations of supernova neutrinos", Phys.Rev.D 103 (2021) 11, 115027

- For the case of wave packet description of neutrino oscillations, and neglecting transition magnetic moments, Equation (1) can be rewritten as

$$i\gamma^0 \partial_t \nu_i(p, t) = (\gamma_3 p + m_i)\nu_i(p, t) + \mu_i \Sigma \mathbf{B}(t)\nu_i(p, t) = 0 \quad (2)$$

We solve **Equation (2)**:

1. Analytically for the case of uniform magnetic field,
2. Numerically for realistic galactic magnetic field model.



Analytical solution

- We assume that neutrino wave function is described by a Gaussian wave packet:

$$\nu_i(p, 0) \sim \exp\left(-\frac{(p - p_0)^2}{4\sigma_p^2}\right)$$

where σ_p neutrino momentum uncertainty and p_0 is average neutrino momentum.

- The probability of flavour conversion is:

$$P_{\nu_\alpha \rightarrow \nu_\beta}(L) = \frac{1}{4} \sum_{i,j} \sum_{s,\sigma} U_{\beta i}^* U_{\alpha i} U_{\beta j} U_{\alpha j}^* \exp\left(-i2\pi \frac{L}{L_{osc}^{ijs\sigma}}\right) \exp\left(-\frac{L^2}{(L_{coh}^{ijs\sigma})^2}\right),$$

where L_{osc} are oscillations lengths and L_{coh} are **coherence lengths**, $i, j = 1, 2, 3$ and $s, \sigma = \pm 1$.

$$L_{osc}^{ijs\sigma} = \frac{4\pi p}{\Delta m_{ij}^2} \quad \text{and} \quad L_{osc}^{ii-+} = \frac{\pi}{\mu_i B_\perp}$$

- Oscillations probability is a combination of oscillations on (1) vacuum frequencies

$$\omega_{ik}^{vac} = \frac{\Delta m_{ik}^2}{4p} \quad \text{and} \quad \text{(2) magnetic frequencies } \omega_i^B = \mu_i B_\perp.$$

(see A. Popov, A. Studenikin, *Neutrino eigenstates and flavour, spin and spin-flavour oscillations in a constant magnetic field*, Eur.Phys.J.C 79 (2019) 2, 144 and references therein)



Coherence lengths

For oscillations on vacuum frequencies ω_{ik}^{vac} :

$$L_{coh}^{ijss} \approx \frac{4\sqrt{2}\sigma_x p^2}{\Delta m_{ij}^2},$$

For oscillations on magnetic frequencies ω_i^B :

$$L_{coh}^{ii-+} \approx \frac{\sigma_x p^3}{\mu_i B m_i^2}.$$

where $\sigma_x = 1/2\sigma_p$ is wave packet width in the coordinate space.

A.Popov, A.Studenikin, "High-energy neutrinos flavour composition as a probe of neutrino magnetic moments", arxiv:2404.02027

$\sigma_x \sim 10^{-17} \div 10^{-9}$ km for various neutrino creation mechanisms.

- Thus, oscillations on the vacuum frequencies $\omega_{ik}^{vac} = \frac{\Delta m_{ik}^2}{4p}$ may fade away for the case of astrophysical neutrinos propagation ($L_{coh} \sim 1$ kpc).
- Oscillations on the **magnetic frequencies** $\omega_i^B = \mu_i B_{\perp}$ persist even on astrophysical scale ($L_{coh} \gg 1$ kpc).



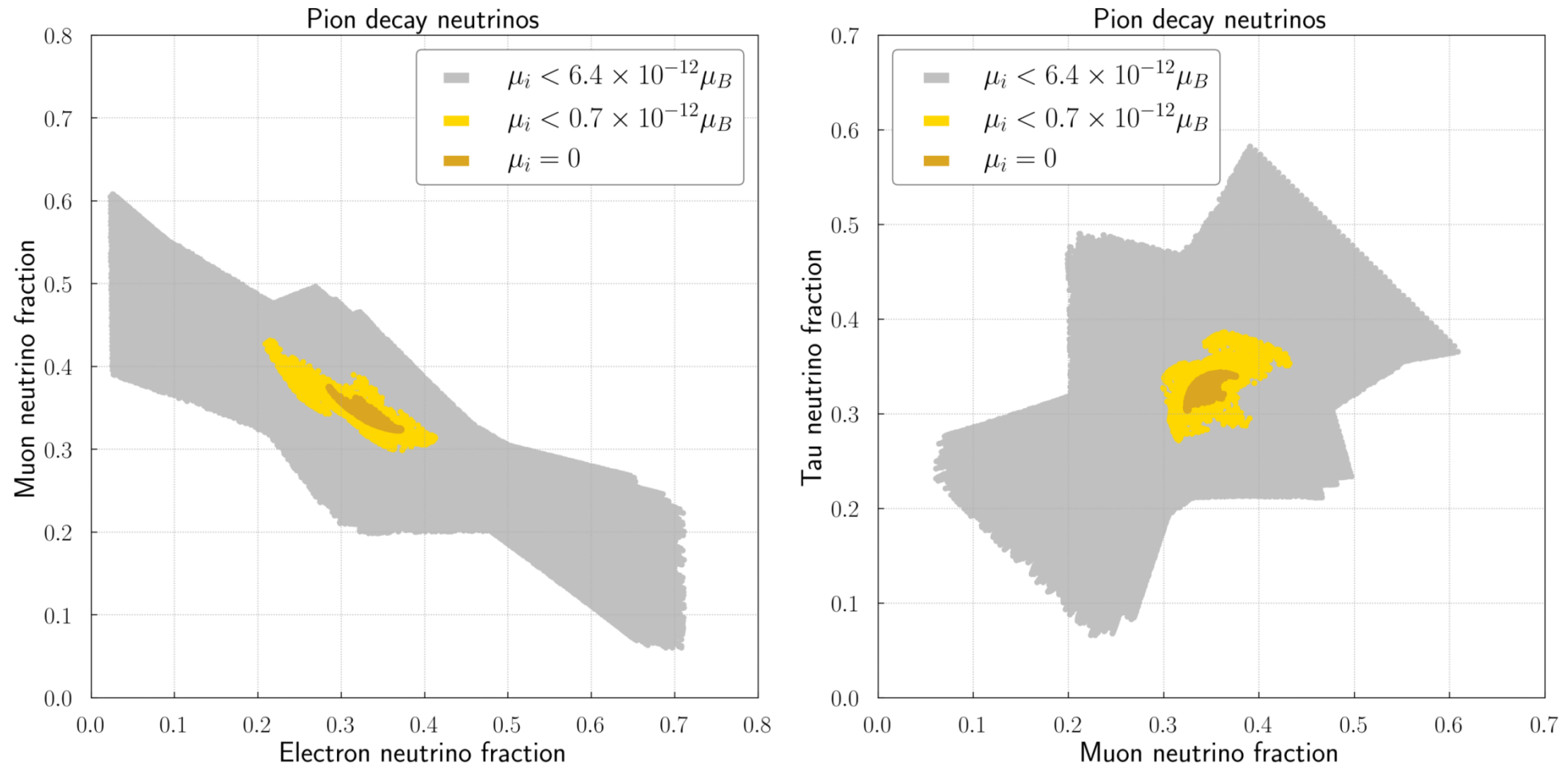
Neutrino oscillations in a Galactic magnetic field

- We use the Galactic magnetic field model provided by R.Jansson, G.Farrar, “*A New Model of the Galactic Magnetic Field*”, *Astrophys.J.* 757 (2012) 14. The field is of order of $O(\mu\text{G})$.
- We consider high-energy neutrinos originating from Galactic center (see IceCube Collaboration, “*Search for Neutrino Emission at the Galactic Center Region with IceCube*”, *PoS ICRC2023* (2023) 1051, and S.Celli, A.Palladino, F.Vissani, “*Neutrinos and γ -rays from the Galactic Center Region After H.E.S.S. Multi-TeV Measurements*”, *Eur.Phys.J.C* 77 (2017) 2, 66).
- Possible flavour ratios are calculated for different values of neutrino magnetic moments μ_1, μ_2 and μ_3 from $(10^{-13}, 6.4 \cdot 10^{-12})$ Bohr magneton range.
- The obtained flavour ratios are compared to ones predicted by standard vacuum neutrino oscillations.



Predicted flavour ratios: π^\pm decay neutrinos

Mixing parameters uncertainties are given by NuFIT 5.3 global fit

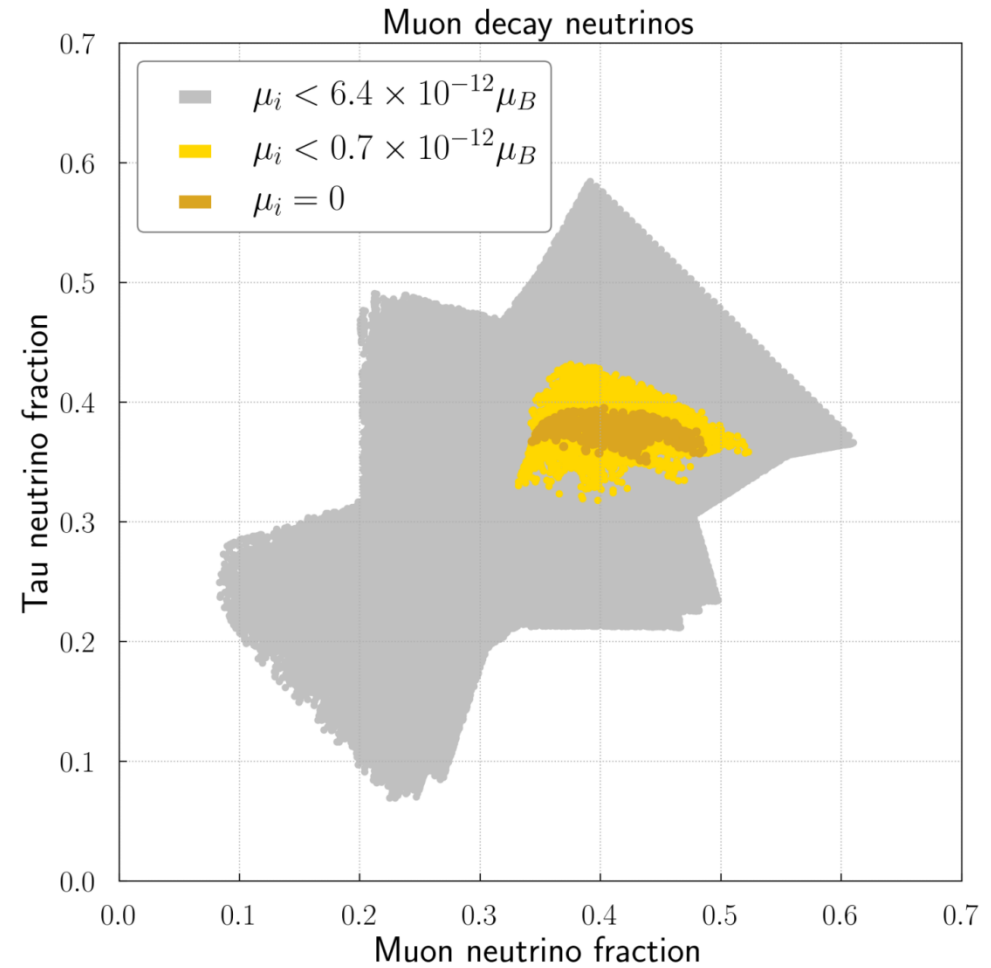
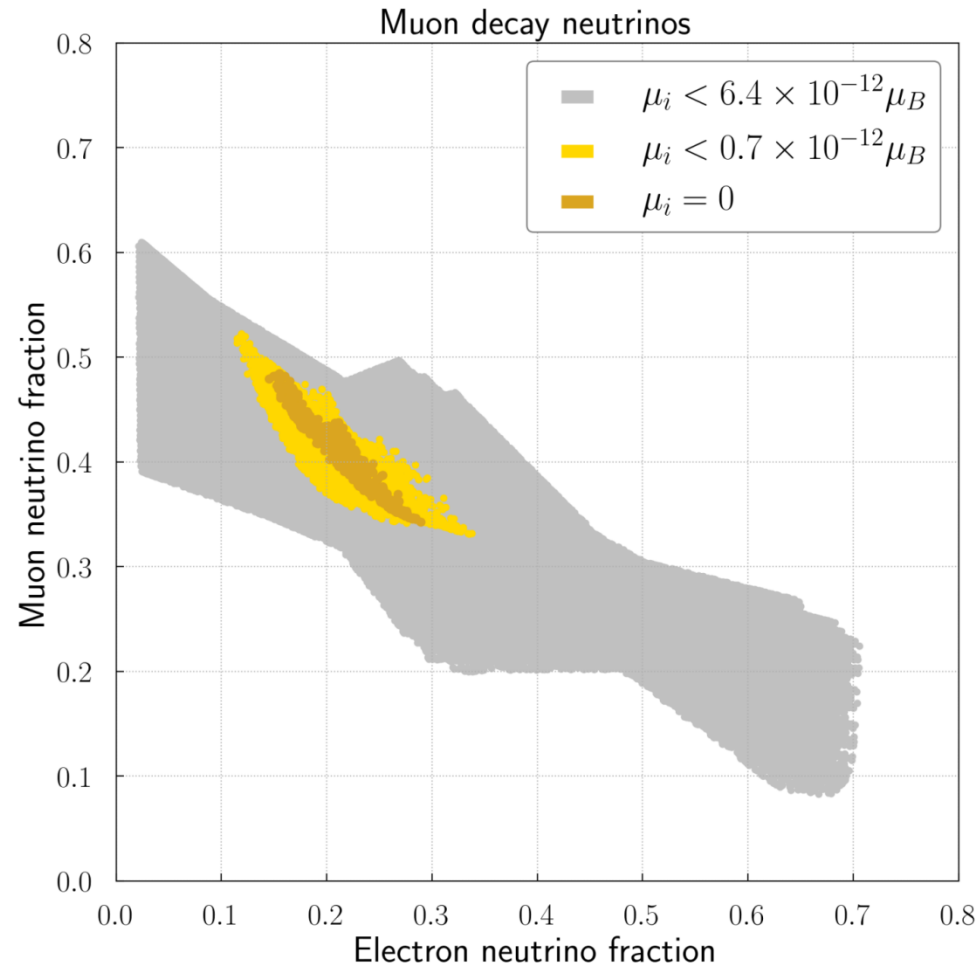


A.Popov, A.Studenikin, "High-energy neutrinos flavour composition as a probe of neutrino magnetic moments", arxiv:2404.02027



Predicted flavour ratios: μ^\pm decay neutrinos

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Conclusions

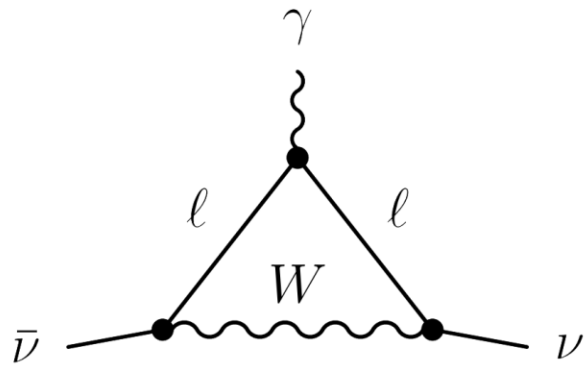
- Neutrino oscillations in a magnetic field are considered accounting for decoherence effects due to wave packets separation.
- The expressions for coherence length are obtained for oscillations on vacuum frequencies and magnetic frequencies. It is shown that the latter is proportional to E_ν^3 .
- Possible flavour ratios of neutrinos originating from the Galactic center are obtained. They significantly differ from the vacuum ones for neutrino magnetic moments $\sim 10^{-13} \mu_B$ and higher.
- For the case of Majorana neutrinos, no significant effects were found.



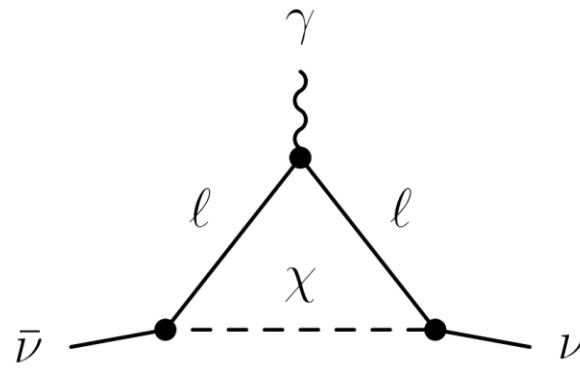
Backup



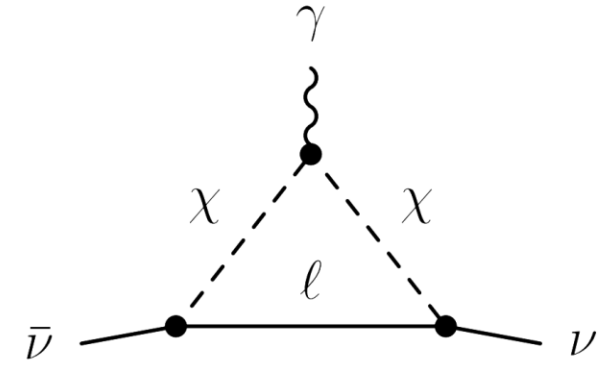
Neutrino magnetic moments



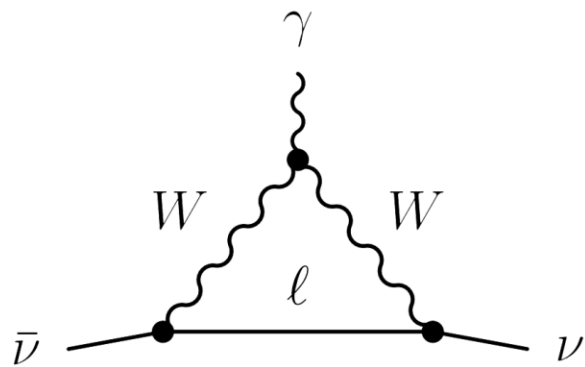
(a)



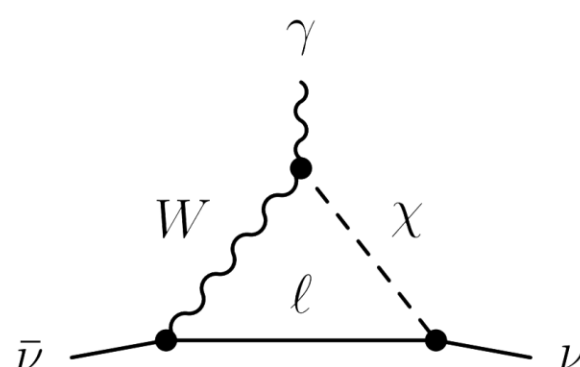
(b)



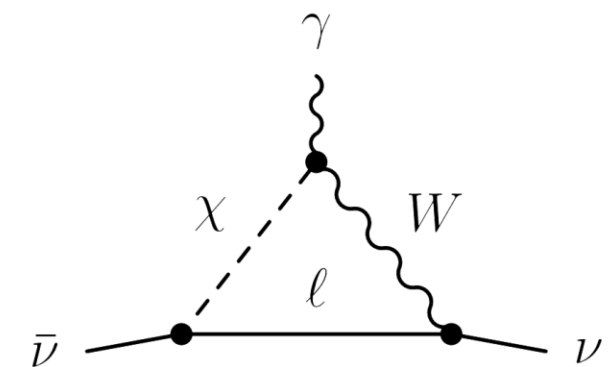
(c)



(d)



(e)

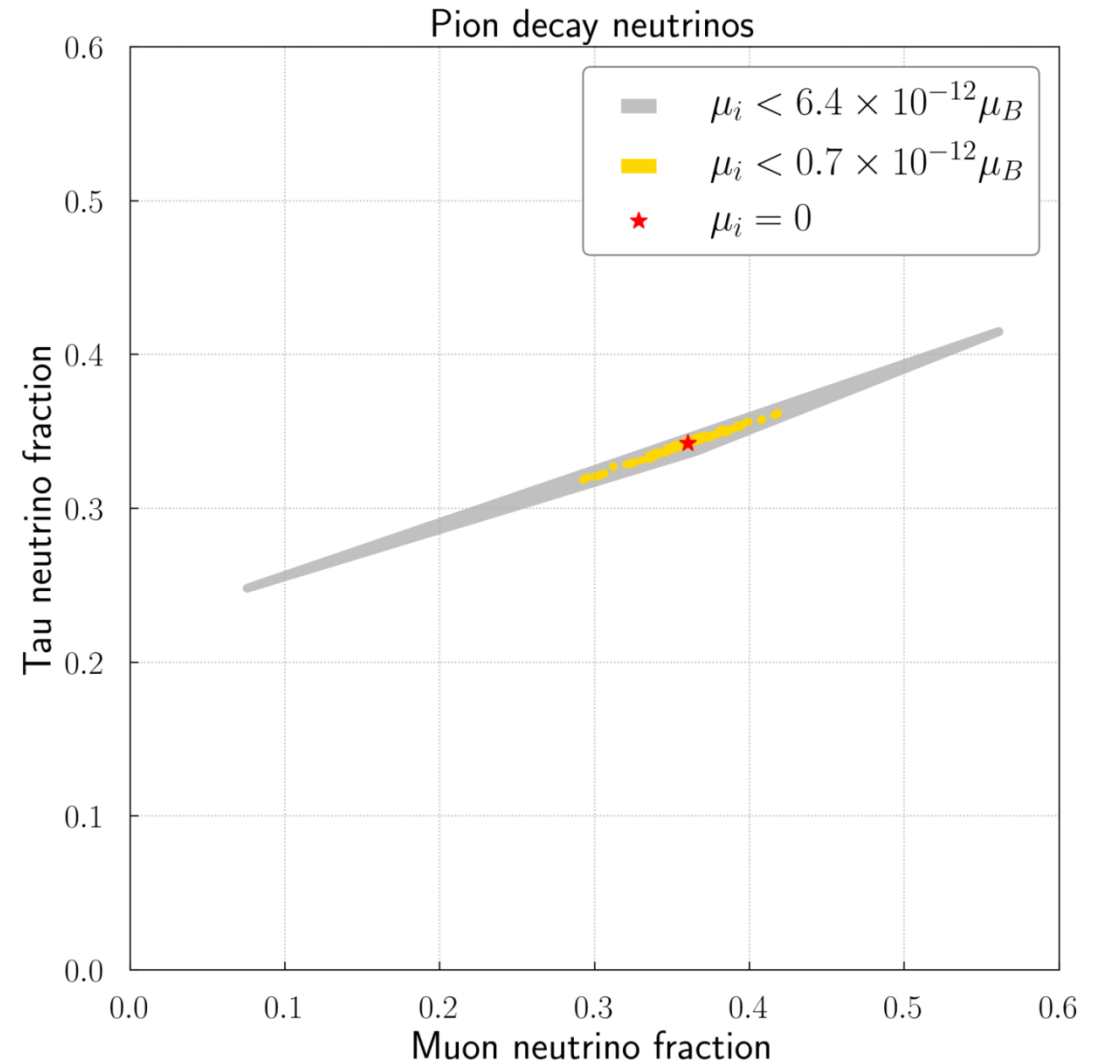
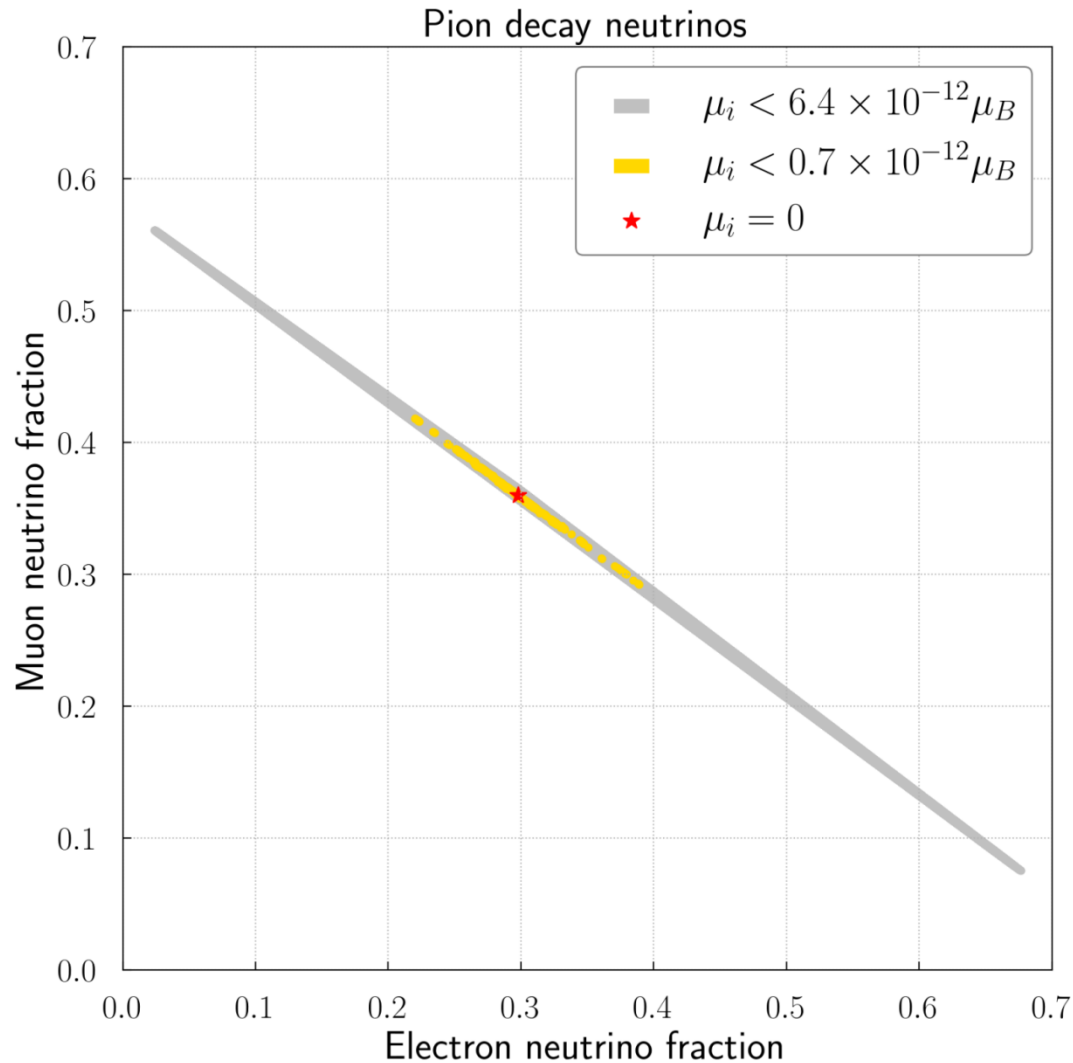


(f)

M.Dvornikov, A.Studenikin, "Electric charge and magnetic moment of massive neutrino", Phys.Rev.D. (2004)



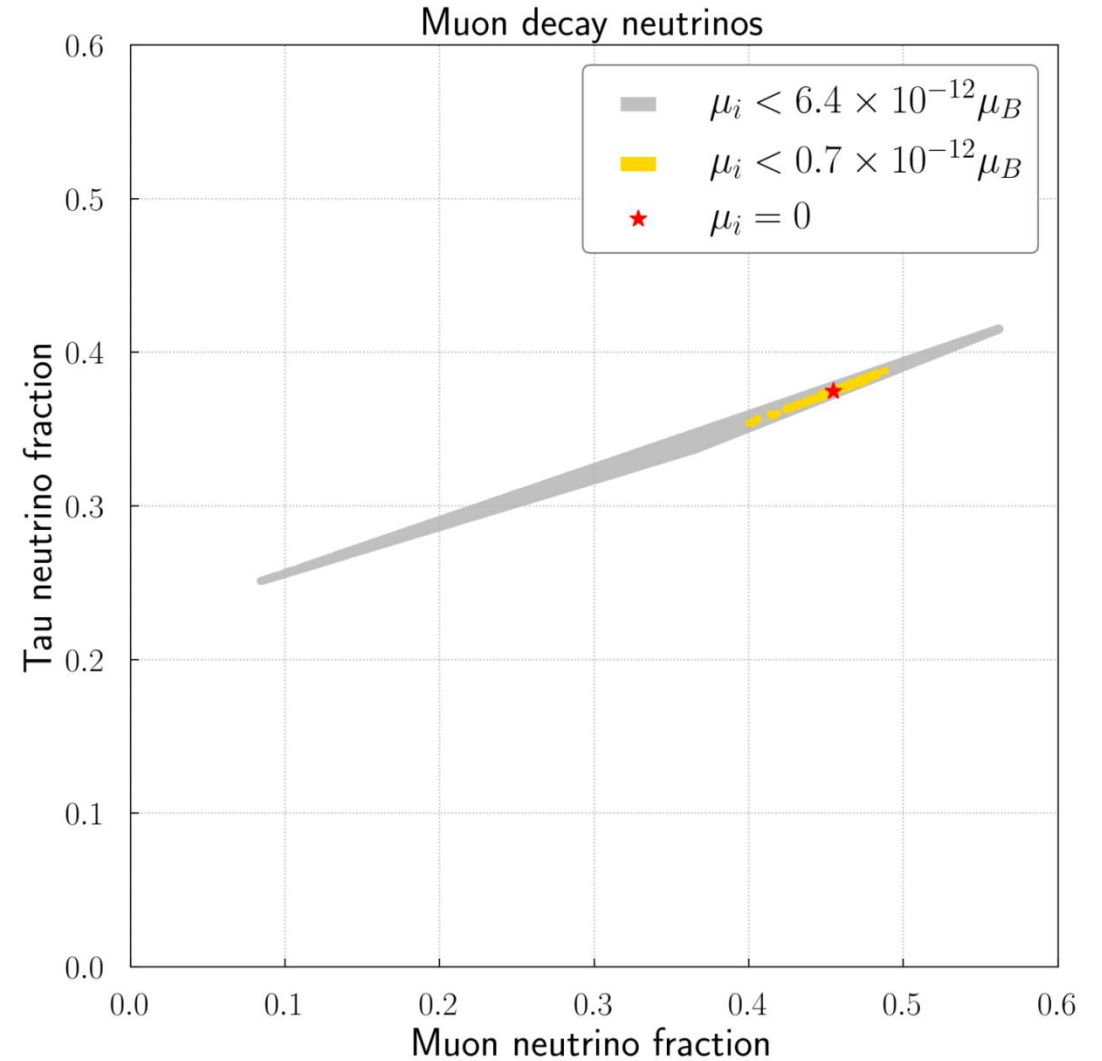
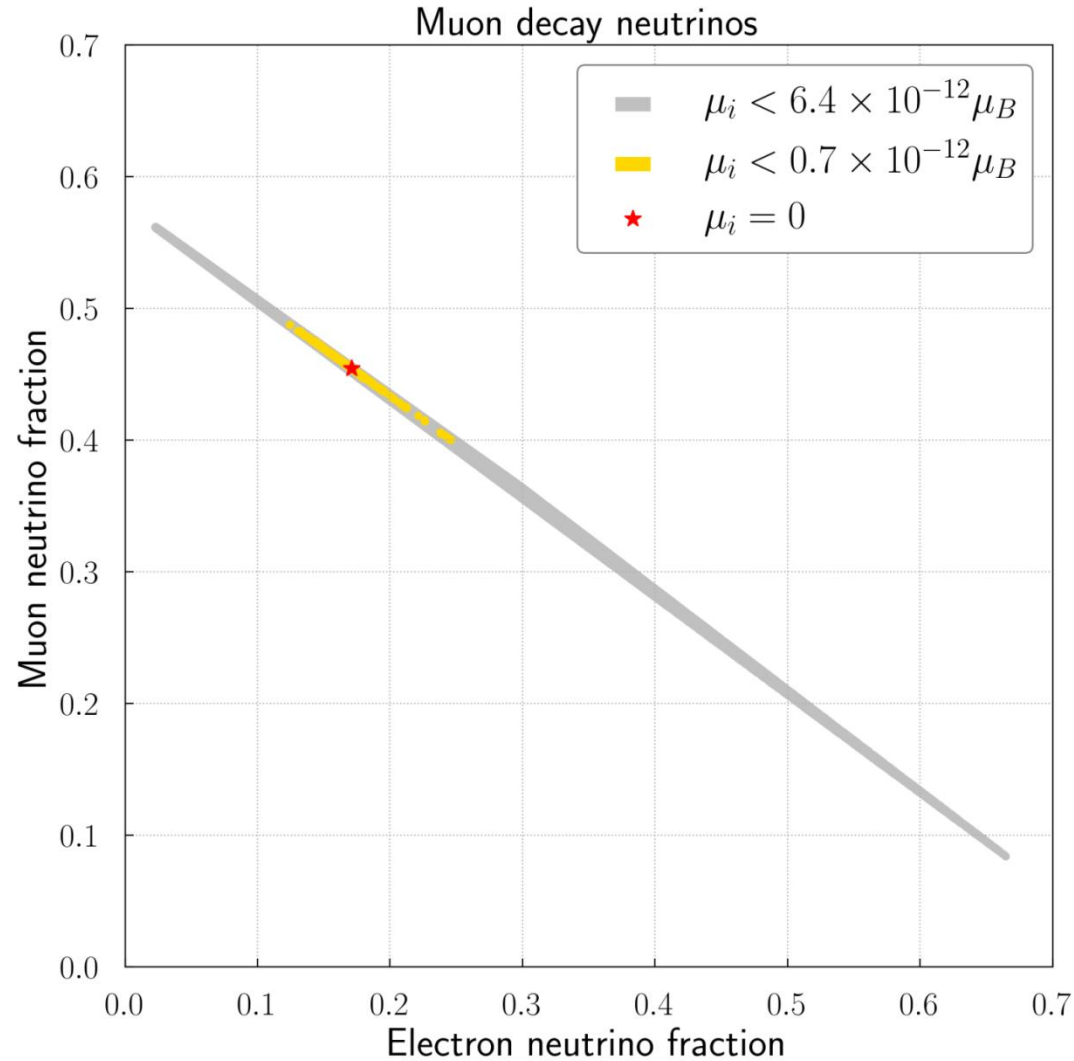
Predicted flavour ratios: π^\pm decay neutrinos



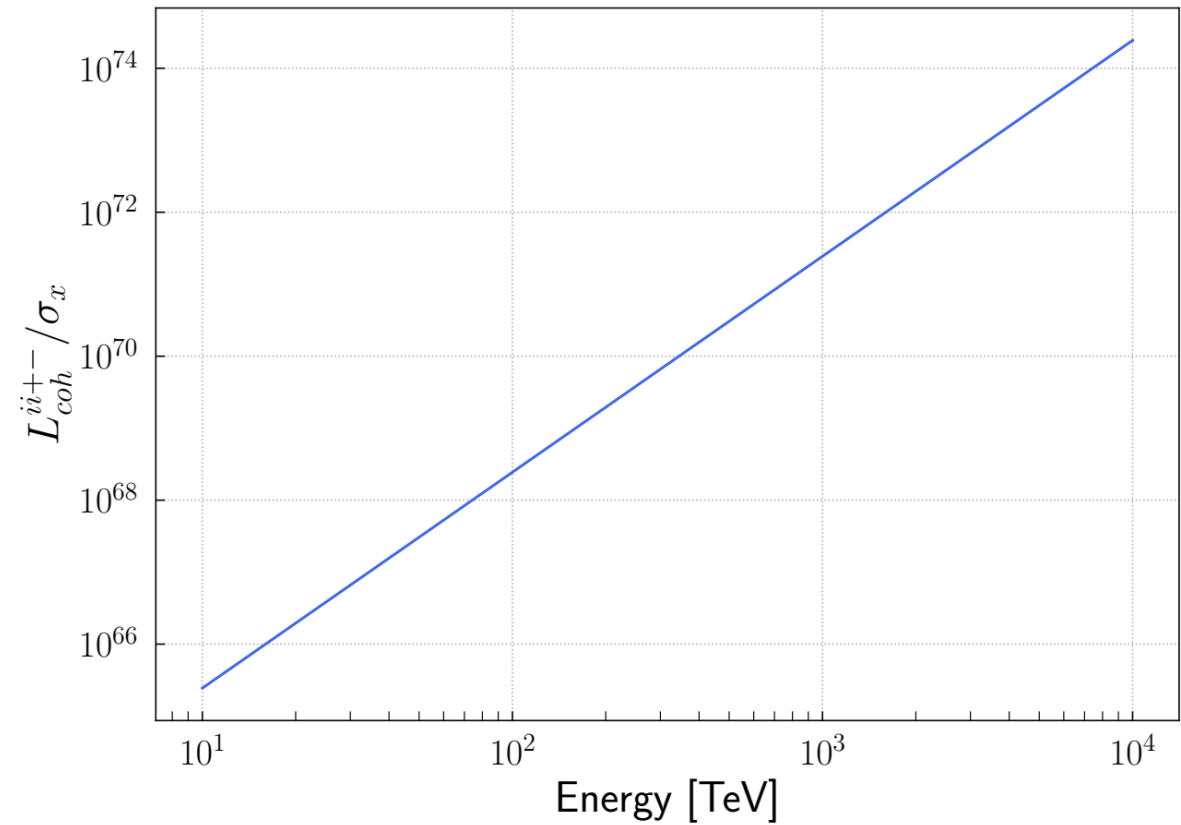
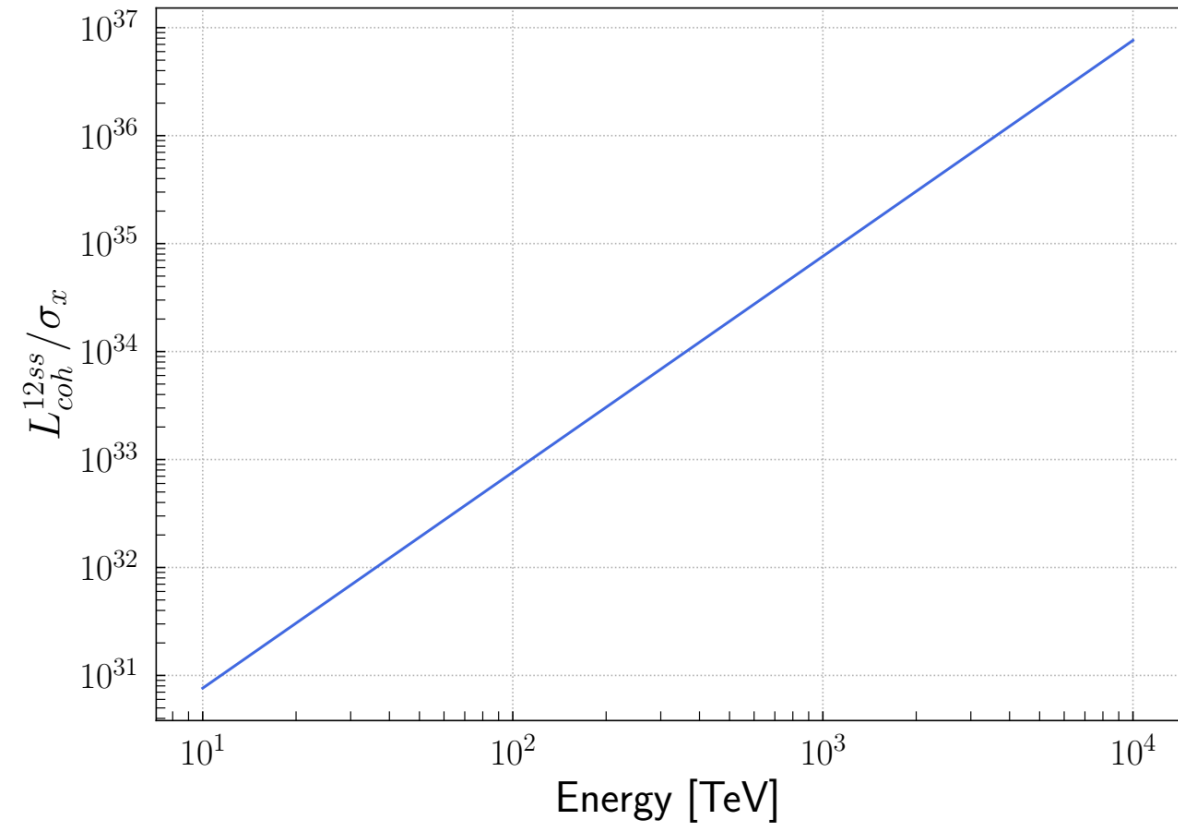
A. Popov, A. Studenikin, "High-energy neutrinos flavour composition as a probe of neutrino magnetic moments", arxiv:2404.02027



Predicted flavour ratios: μ^\pm decay neutrinos



Dimensionless coherence lengths



		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 2.3$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
without SK atmospheric data	$\sin^2 \theta_{12}$	$0.307^{+0.012}_{-0.011}$	$0.275 \rightarrow 0.344$	$0.307^{+0.012}_{-0.011}$	$0.275 \rightarrow 0.344$
	$\theta_{12}/^\circ$	$33.66^{+0.73}_{-0.70}$	$31.60 \rightarrow 35.94$	$33.67^{+0.73}_{-0.71}$	$31.61 \rightarrow 35.94$
	$\sin^2 \theta_{23}$	$0.572^{+0.018}_{-0.023}$	$0.407 \rightarrow 0.620$	$0.578^{+0.016}_{-0.021}$	$0.412 \rightarrow 0.623$
	$\theta_{23}/^\circ$	$49.1^{+1.0}_{-1.3}$	$39.6 \rightarrow 51.9$	$49.5^{+0.9}_{-1.2}$	$39.9 \rightarrow 52.1$
	$\sin^2 \theta_{13}$	$0.02203^{+0.00056}_{-0.00058}$	$0.02029 \rightarrow 0.02391$	$0.02219^{+0.00059}_{-0.00057}$	$0.02047 \rightarrow 0.02396$
	$\theta_{13}/^\circ$	$8.54^{+0.11}_{-0.11}$	$8.19 \rightarrow 8.89$	$8.57^{+0.11}_{-0.11}$	$8.23 \rightarrow 8.90$
	$\delta_{CP}/^\circ$	197^{+41}_{-25}	$108 \rightarrow 404$	286^{+27}_{-32}	$192 \rightarrow 360$
	$\frac{\Delta m_{21}^2}{10^{-5} \text{ eV}^2}$	$7.41^{+0.21}_{-0.20}$	$6.81 \rightarrow 8.03$	$7.41^{+0.21}_{-0.20}$	$6.81 \rightarrow 8.03$
	$\frac{\Delta m_{3\ell}^2}{10^{-3} \text{ eV}^2}$	$+2.511^{+0.027}_{-0.027}$	$+2.428 \rightarrow +2.597$	$-2.498^{+0.032}_{-0.024}$	$-2.581 \rightarrow -2.409$

I.Esteban, M.C.Gonzalez-Garcia, M.Maltoni, T.Schwetz, A.Zhou , "The fate of hints: updated global analysis of three-flavor neutrino oscillations", JHEP 09 (2020) 178;
 NuFIT 5.3 (2024), www.nu-fit.org



Majorana neutrinos

Dirac fermion

$$\Psi_D = \Psi_L + \Psi_R$$

Majorana fermion

$$\Psi_R = \Psi_L^c$$

A Majorana field can be written as $\Psi_M = \Psi_L + \Psi_L^c$

$\Psi_M^c = \Psi_M$ is satisfied for a Majorana field

Majorana mass term violates total lepton number by 2

$$m_i \bar{\nu}_i \nu_i = m_i \overline{(\nu_i^L)^c} \nu_i^L + m_i \overline{\nu_i^L} (\nu_i^L)^c$$



Flavour oscillations probabilities

$$\mu_1 = \mu_2/2$$

