



High-energy neutrinos flavour composition as a probe of neutrino magnetic moments

**Artem Popov,
Moscow State University**

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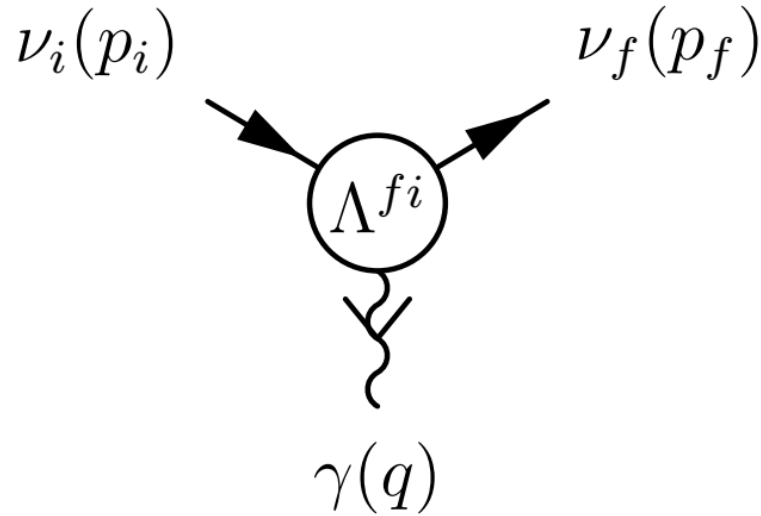


Outline of the talk

- 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**:

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

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

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**:

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

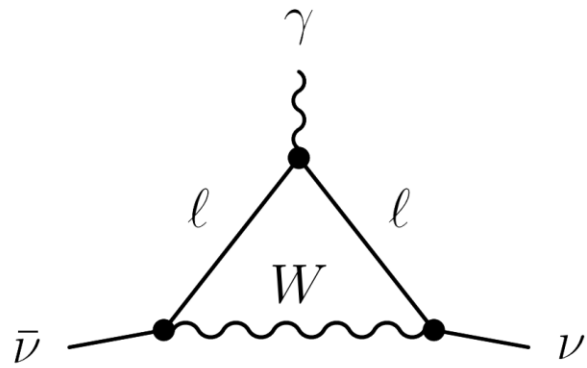
- Magnetic moments matrix for **Majorana** neutrinos is **imaginary and asymmetric**:

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

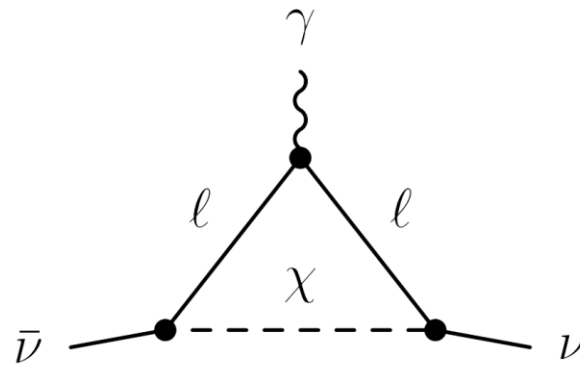
- Thus, Dirac and Majorana neutrinos can be distinguished by their **electromagnetic properties**.



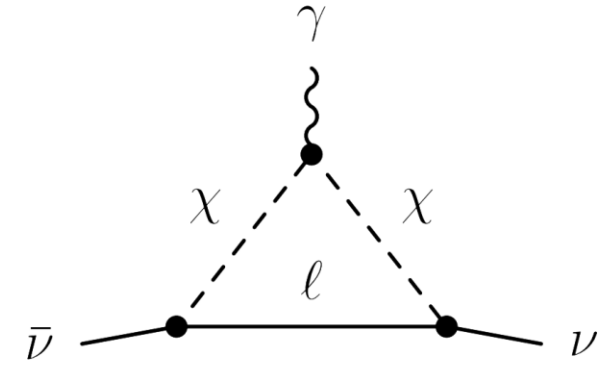
Neutrino magnetic moments



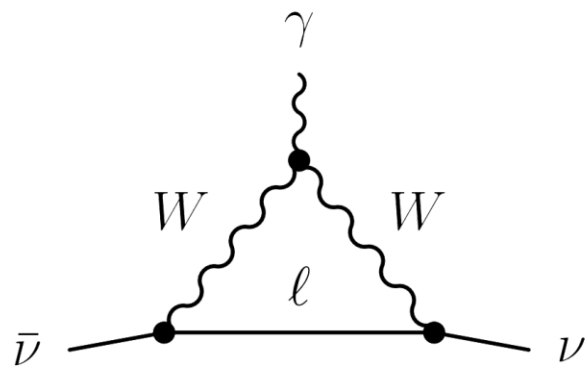
(a)



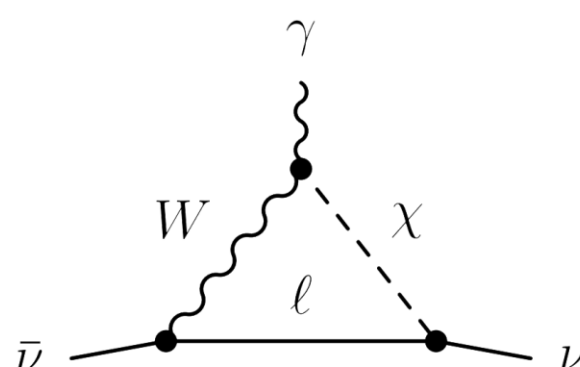
(b)



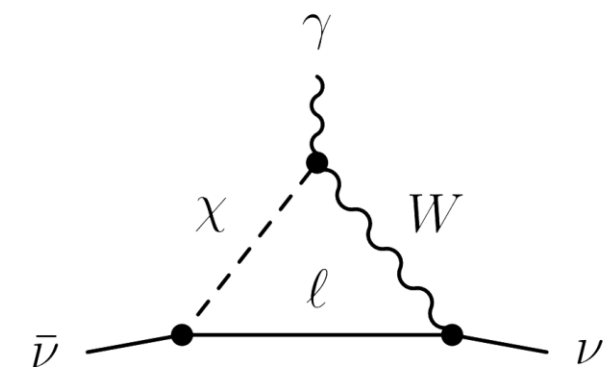
(c)



(d)



(e)



(f)

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



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)

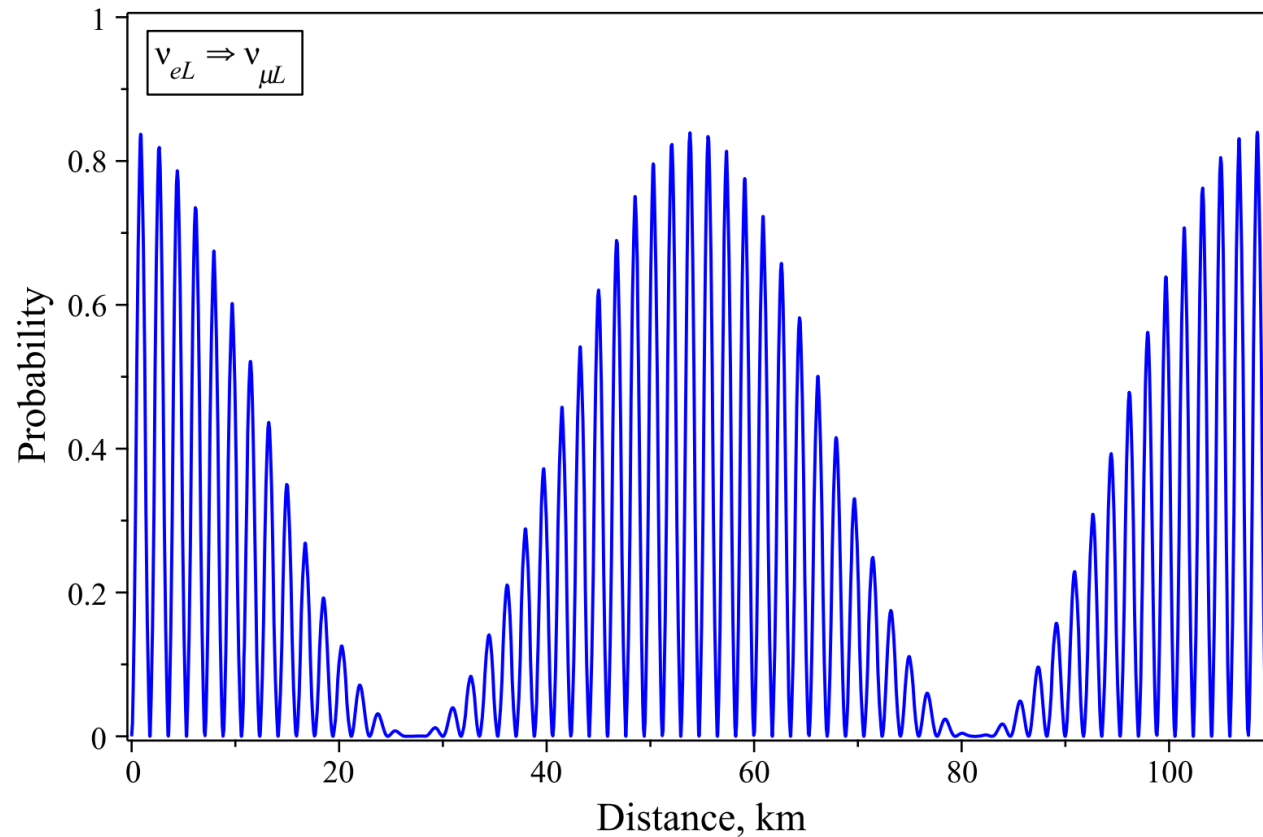
$$\mu_\nu \lesssim 10^{-12} \mu_B$$



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.



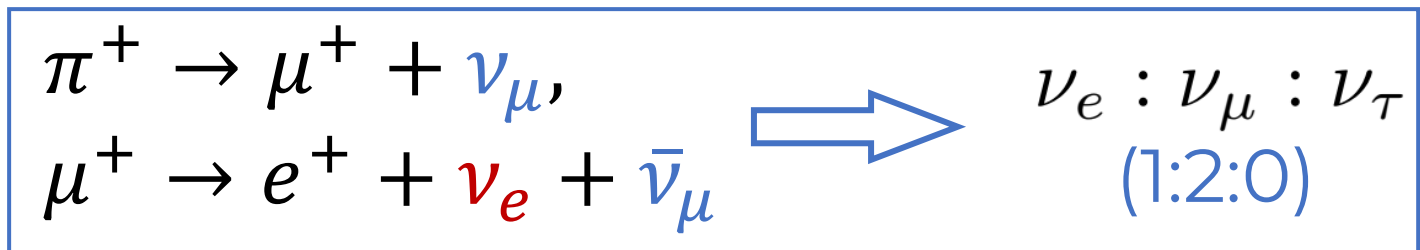
High-energy neutrinos flavour ratios

- 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**

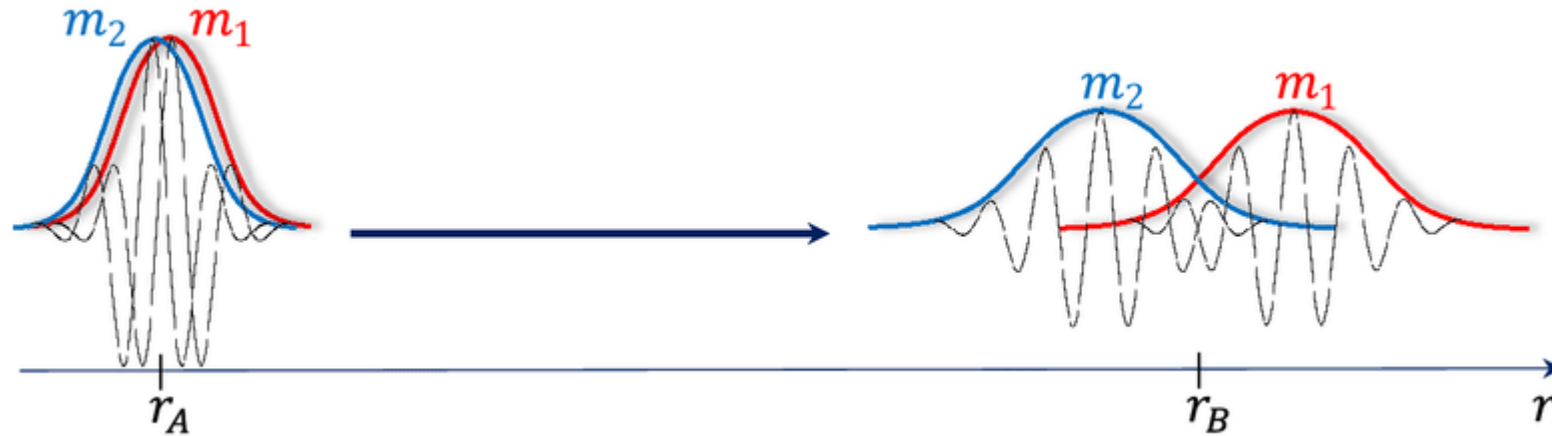
A.Esmailia , Y.Farzan, “Implications of the Pseudo-Dirac Scenario for Ultra High Energy Neutrinos from GRBs”, JCAP 12 (2012) 014

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:

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

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

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

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 $s, \sigma = \pm 1$.

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

- 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).

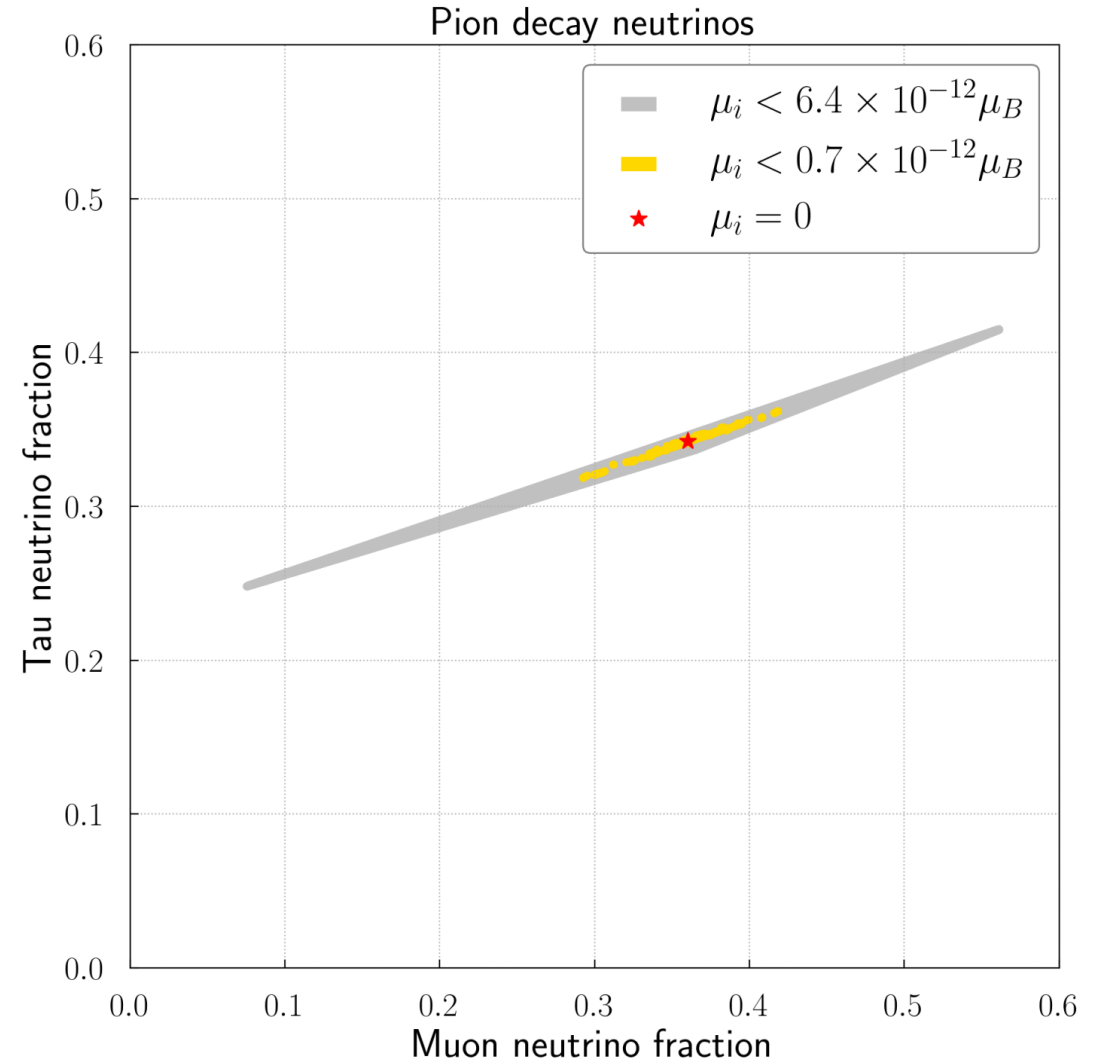
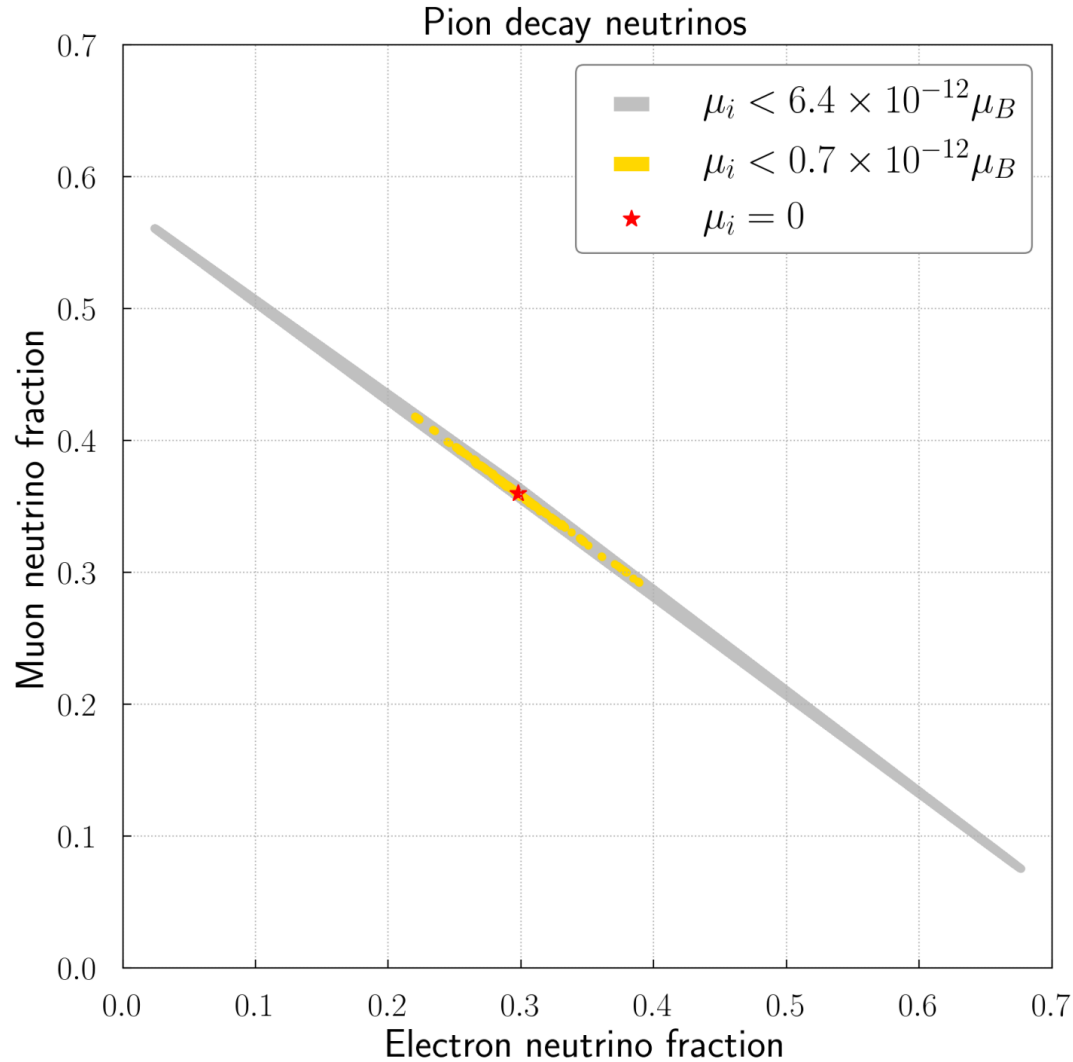


Neutrino oscillations in a Galactic magnetic field

- 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 $O(\mu G)$.
- 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.



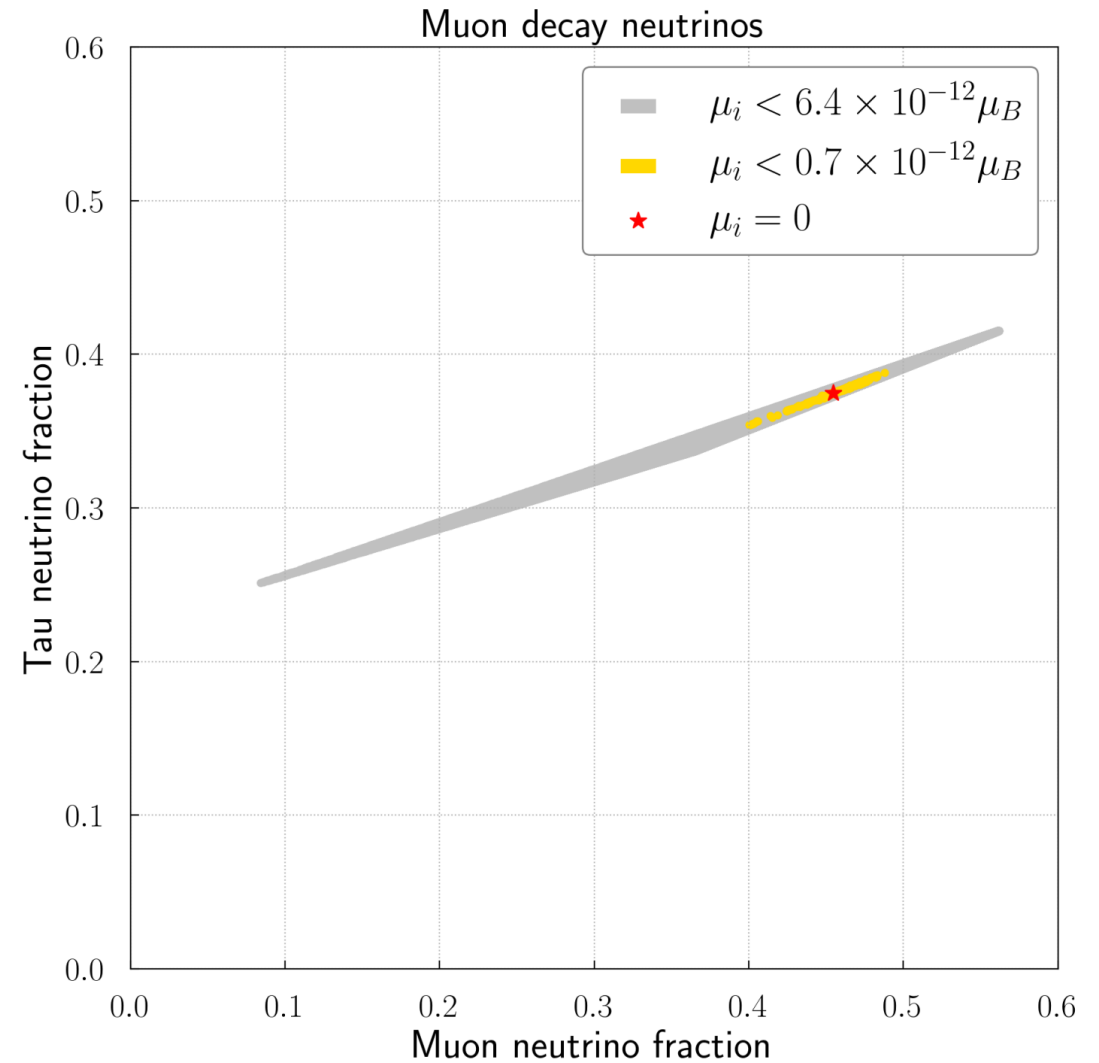
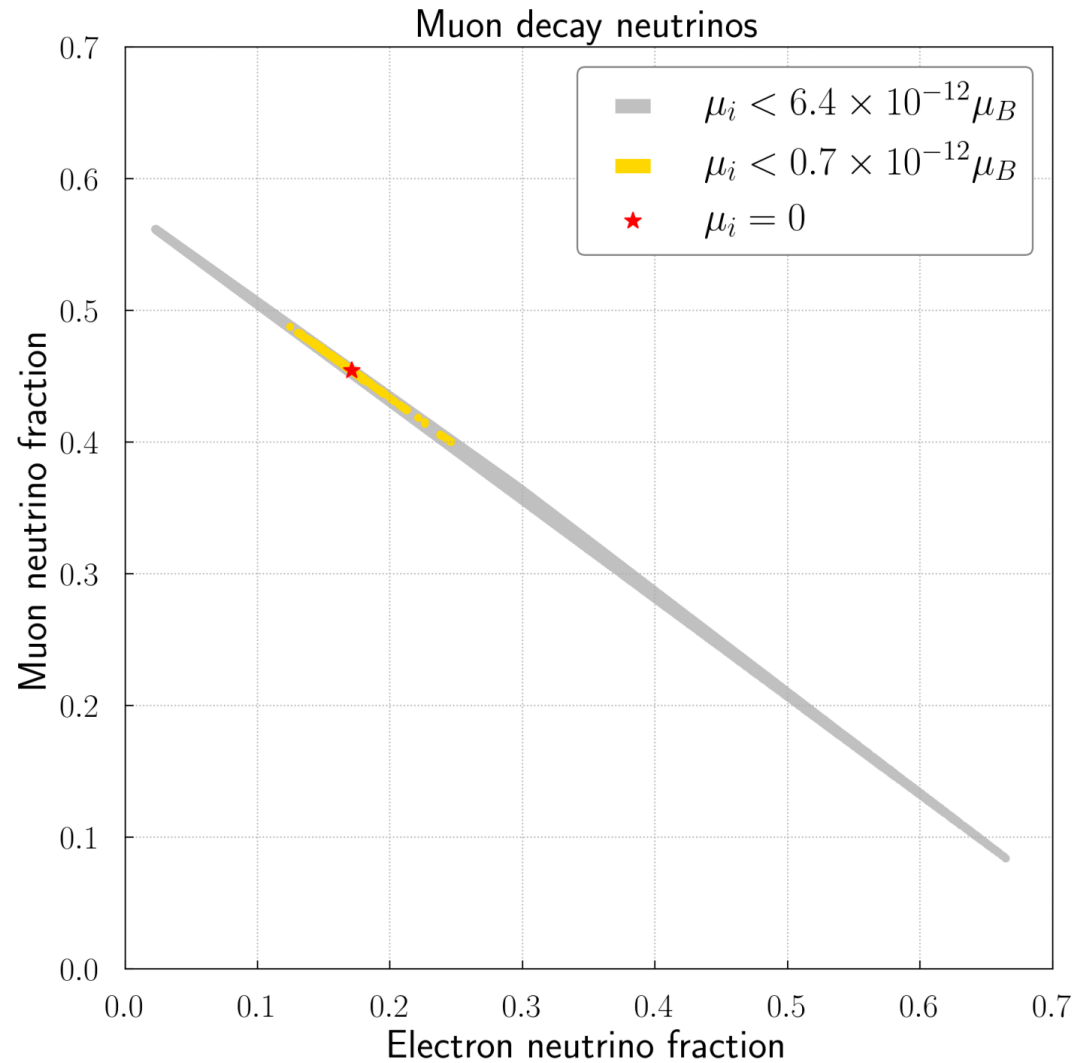
Predicted flavour ratios: π^\pm decay neutrinos



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

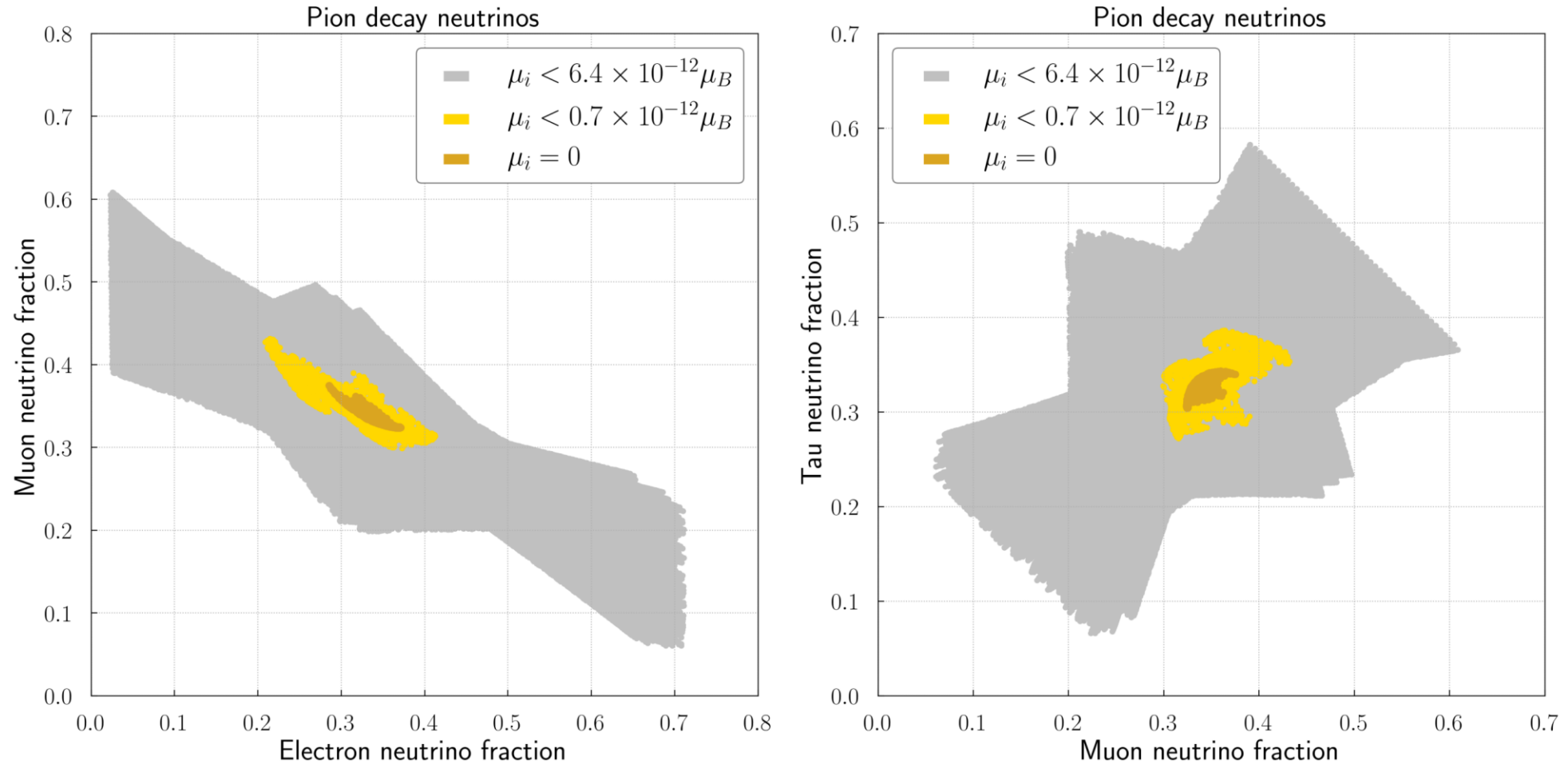


A.Popov, A.Studenikin, "High-energy neutrinos flavour composition as a probe of neutrino magnetic moments", arxiv:2404.02027



Predicted flavour ratios: π^\pm decay neutrinos

Mixing parameters uncertainties are given by NuFIT 5.3 global fit

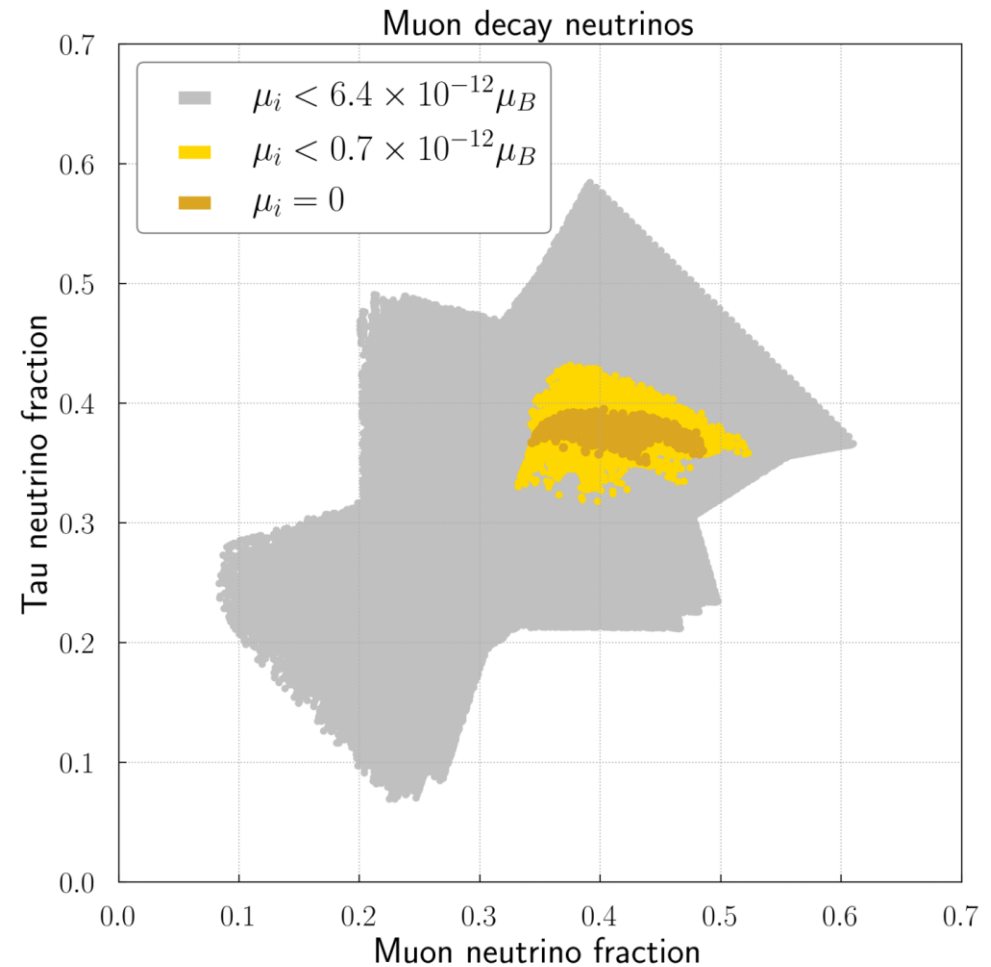
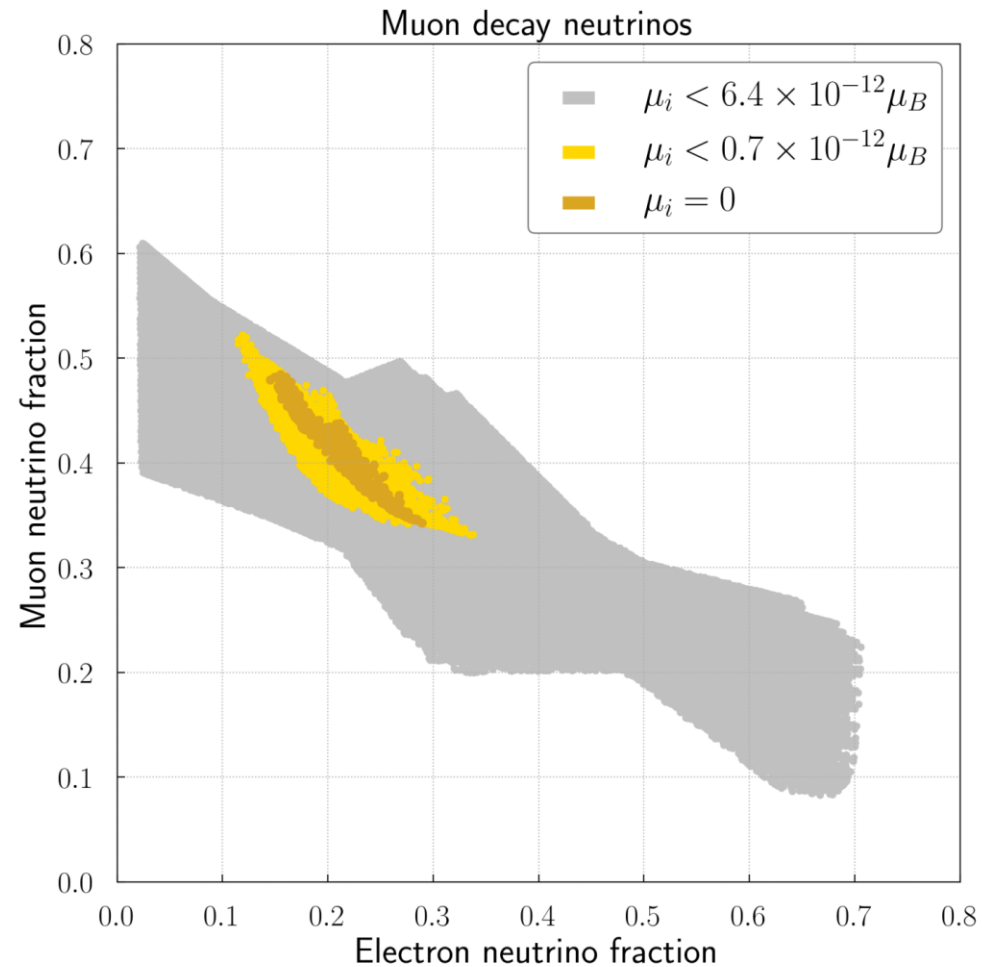


A.Popov, A.Studenikin, "High-energy neutrinos flavour composition as a probe of neutrino magnetic moments", arxiv:2404.02027



Predicted flavour ratios: μ^\pm decay neutrinos

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Conclusions

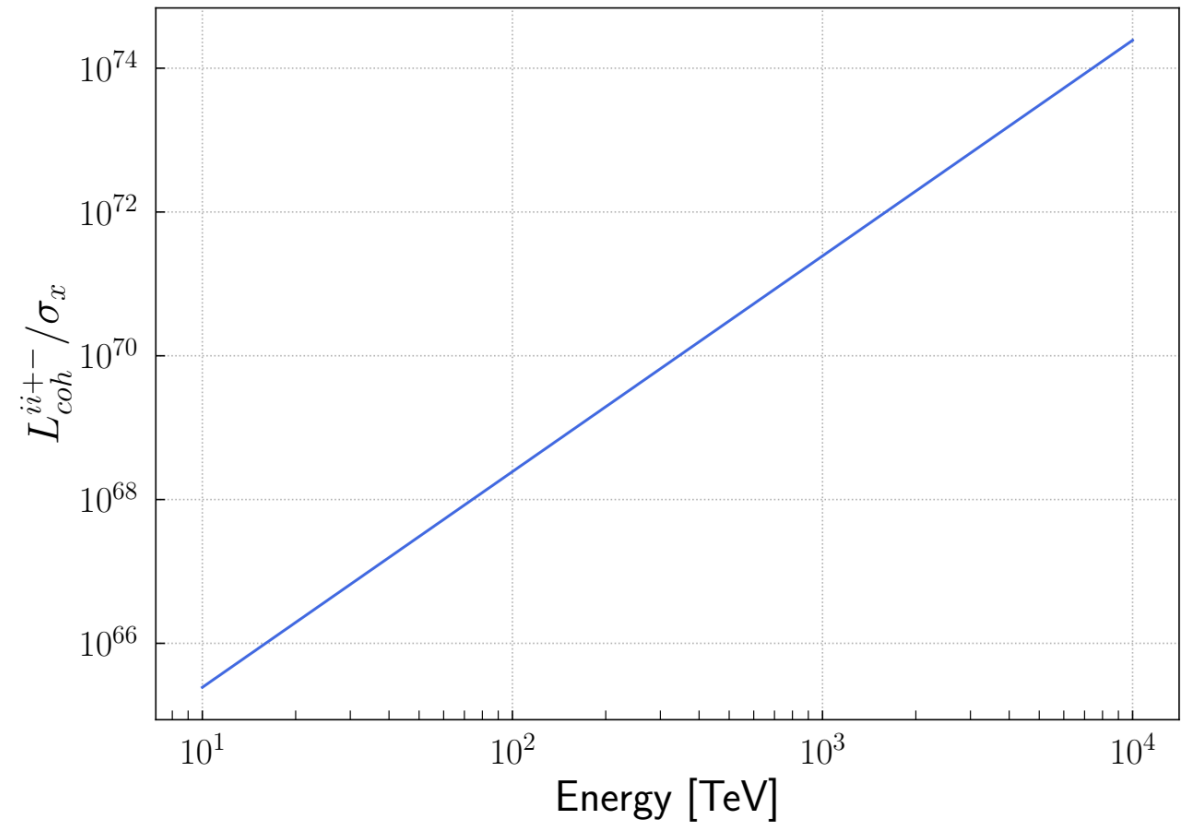
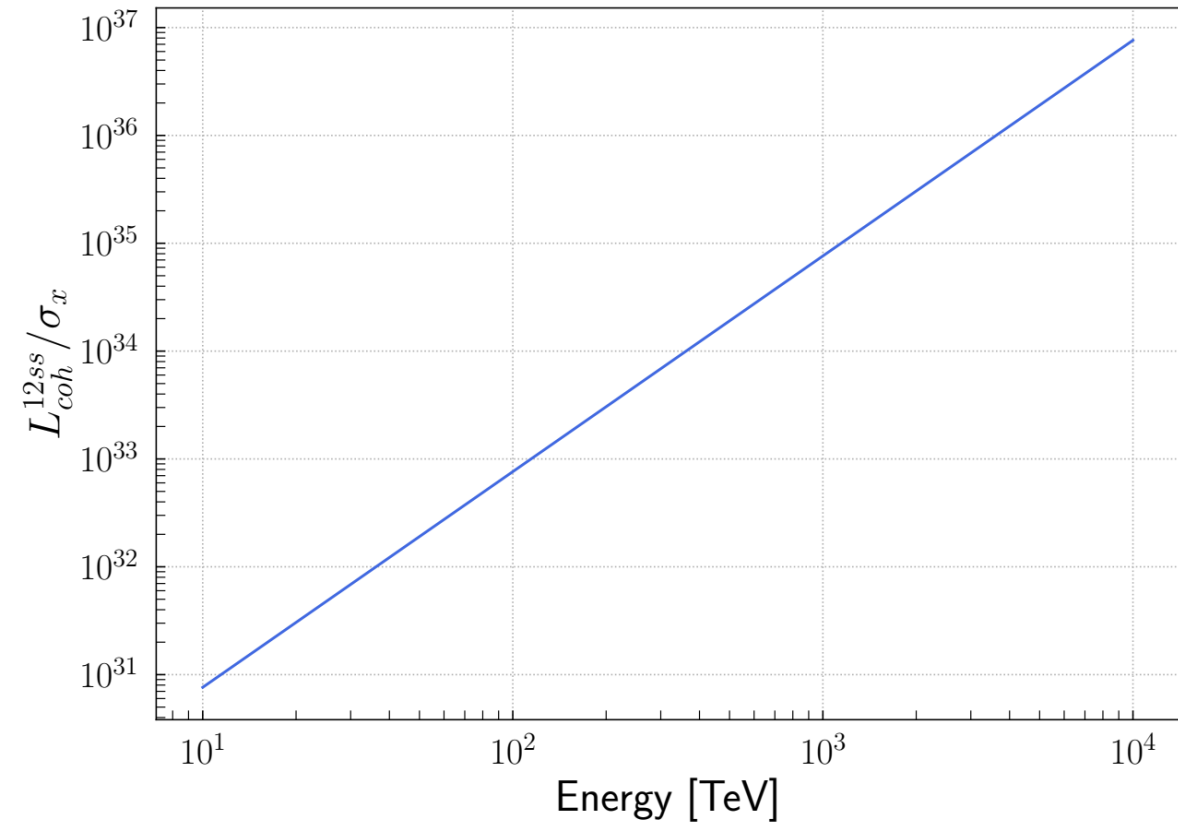
- Neutrino oscillations in a magnetic field are considered accounting for decoherence effects due to wave packets separation.
- The expressions for coherence length are obtained for oscillations on vacuum frequencies and magnetic frequencies. It is shown that the latter is proportional to E_ν^3 .
- Possible 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



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

$$\mu_1 = \mu_2/2$$

