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Dark photon distortions of NOνA and T2K neutrino oscillations

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Dark photons coupling to $L_\mu - L_\tau$ lepton number difference are a highly studied light dark matter candidate, with potential to be discovered through their impact on terrestrial neutrino oscillation experiments. We re-examine this in the light of claimed tensions between the NOνA and T2K long baseline experiments, also taking into account data from the MINOS experiment. We obtain leading limits on the $L_\mu - L_\tau$ gauge coupling g' versus dark photon mass $m_{A'}$, and find no statistically significant alleviation of the tension from inclusion of the new physics effect.

1. Introduction. Dark photons are a popular light dark matter candidate, which do not suffer from the naturalness problems typical of light scalars, since the Stueckelberg mass is not radiatively corrected. If the dark photon is a gauge boson, it can couple to one of the anomaly-free currents present in the Standard Model (SM) without the need to add extra matter. Here, for concreteness, we focus on the lepton number family difference $L_\mu - L_\tau$, but very similar conclusions can be reached for $L_e - L_\mu$, $L_e - L_\tau$, and combinations of the three. For the range of gauge boson masses of interest, very small values of the gauge coupling g' can be probed through cosmology [1–9], neutron star binaries [10, 11], supernova SN1987A [12, 13], black hole superradiance [14–16], and even the LHC [17].

Moreover, the effect of such dark photons on neutrino oscillations gives the strongest limits on the gauge coupling for $m_{A'} \lesssim 10^{-11}$ eV [18–22], assuming that the polarization of $\vec{A}'$ is coherent over the neutrino baseline. This is a reasonable assumption as long as the correlation length of the field, $(m_{A'}\sigma)^{-1}$, where σ is the local dark matter velocity dispersion, is larger than the neutrino oscillation baseline. For the experiments under study here, this imposes the requirement $m_{A'} \lesssim 10^{-10}$ eV. If that is the case, the gauge interaction enters the effective neutrino Hamiltonian linearly,

$$
\begin{aligned}
H \;&= \frac{1}{2E} U \begin{bmatrix} m_1^2 & 0 & 0 \\ 0 & m_2^2 & 0 \\ 0 & 0 & m_3^2 \end{bmatrix} U^\dagger + \sqrt{2} G_F N_e \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \\
&+ g' A' \cos\phi \, \cos(m_{A'} t + \alpha) \begin{bmatrix} q_e & 0 & 0 \\ 0 & q_\mu & 0 \\ 0 & 0 & q_\tau \end{bmatrix} + \mathcal{O}(g'^2 A'^2), \quad (1)
\end{aligned}
$$

written in the ν flavor basis. Here, E is the neutrino energy, U is the PMNS matrix, N_e is the electron density in the Earth, $m_{A'}$ is the dark photon mass, α is the dark photon's phase when the neutrino is produced (which we assume to happen at $t = 0$), and ϕ is the angle between $\vec{A}'$ and the neutrino momentum $\vec{p}$. The charge assignments are restricted to satisfy $q_e + q_\mu + q_\tau = 0$, as any diagonal contribution only introduces a global phase unobservable in oscillation experiments. As mentioned above, we focus on the $L_\mu - L_\tau$ dark photon, and thus fix $q_e = 0$, $q_\mu = 1$, and $q_\tau = -1$.

In what follows, we take the dark photon background field to be at least partially polarized. Otherwise, the term linear in A' averages out and the leading order term is $\mathcal{O}(g'A')^2$, which can only affect neutrino oscillations for gauge couplings already excluded by other constraints [22].

Our study is partially motivated by a mild tension between the T2K [23] and NOνA [24, 25] long baseline experiments, present already in their first data [26]. The tension grew stronger with accumulated data, reaching a complete mismatch between NOνA and T2K allowed regions on $\sin^2\theta_{23} - \delta_{\rm CP}$ plane, which attracted attention [27–31]. Under the assumption of normal ordering of the neutrino masses, the preferred regions for the CP-violating Dirac phases are at odds between the two experiments, at the 2-σ level. The tension between NOνA and T2K persists in the new result published by NOνA collaboration after 10 years of data taking in Neutrino 2024 [32]. Recently, Ref. [22] investigated the effect of dark photons in this context, and found the tension to be alleviated by $\Delta\chi^2 = 4.8$, a 1.7σ improvement.

In this work, we re-examine the effect of $L_\mu - L_\tau$ dark photons on long baseline oscillations, incorporating as well data from the MINOS experiment [33, 34], and with attention to both possible mass orderings. We find limits on g' versus $m_{A'}$ that improve upon past analyses [18, 21], and that extend to higher $m_{A'}$ values than other studies of these datasets [22]. In agreement with previous studies, including a recent combined analysis by the NOνA

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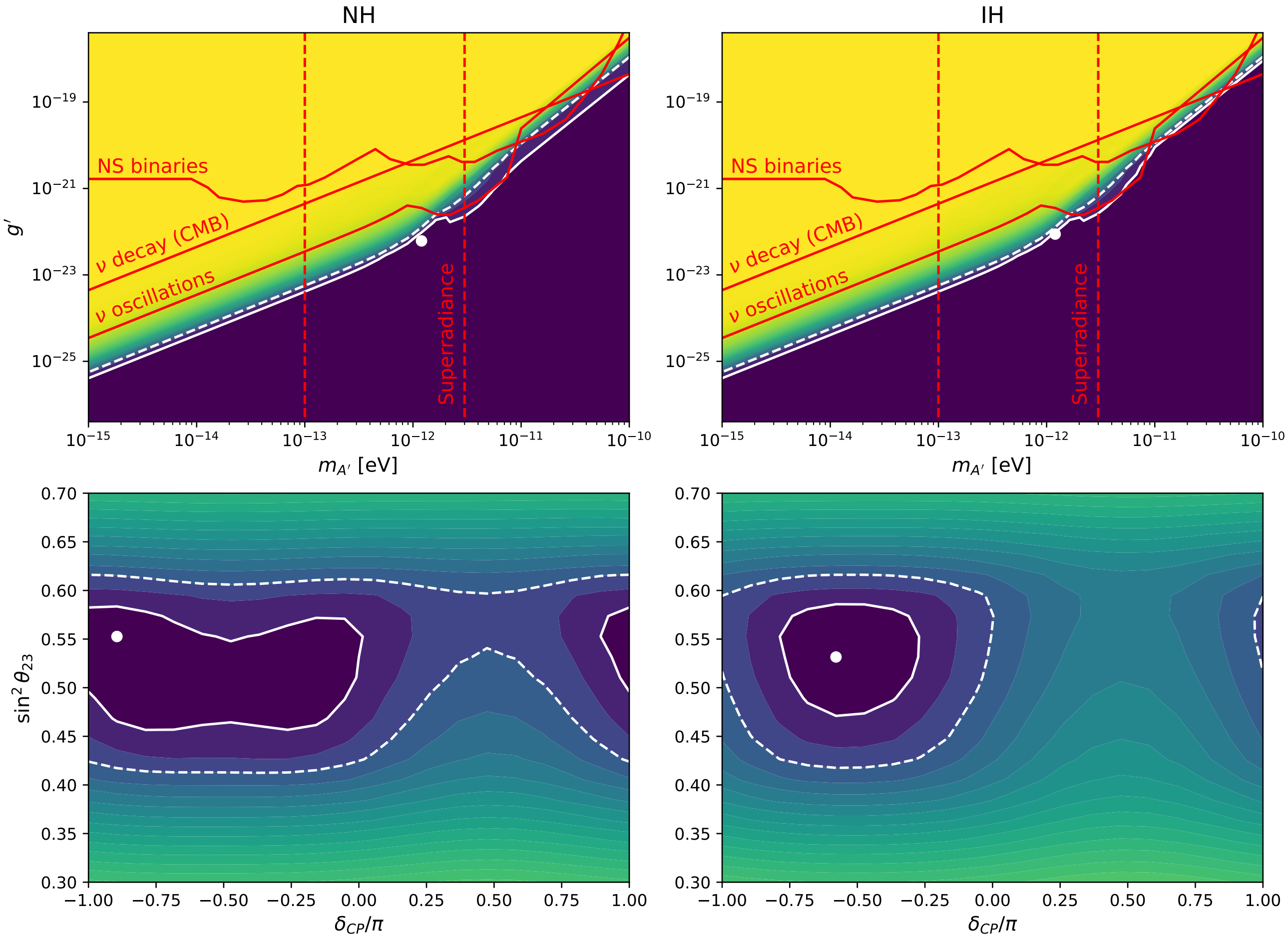

Figure 1. Top: upper bound on gauge coupling g' versus dark photon mass $m_{A'}$ assuming the normal mass hierarchy (NH, left) and inverted hierarchy (IH, right), with best fit point shown in white. Each color shade corresponds to a difference of 1-σ, and the solid and dashed white lines highlight the 1-σ and 3-σ regions, respectively. Previous limits from neutron star (NS) binaries [10, 11], cosmology [9], neutrino oscillations [21], and superradiance [16] are shown in red. Bottom: preferred regions of $\sin^2\theta_{23}$-δ_{CP} for NH (left panel) and IH (right panel) respectively. IH is preferred over NH, with a χ^2 difference of 2.01 at the respective minima.

and T2K collaborations [35], we find that the inverse mass ordering is preferred for reconciling the mild tension between the two experiments, while the new physics effects give a statistically insignificant improvement.

2. Methodology. We modify the General Long Baseline Experiment Simulator (GLoBES) [36, 37] to use the oscillation probabilities for ν_μ disappearance and ν_e appearance from beams which are initially ν_μ, coming from the Hamiltonian (1). This requires numerically solving the Schrödinger equation with initial condition $\psi_\mu = (0,1,0)^T$, in the presence of the time-varying $g'A'$ contribution; then the disappearance probability at a distance L is given by $P_d = 1 - |\langle\psi(L)|\psi_\mu\rangle|^2$, in natural units $c = 1$, while the appearance probability is $P_a = |\langle\psi(L)|\psi_e\rangle|^2$.

As the data is obtained over a time scale much larger than the dark matter oscillation frequency $1/m_{A'}$, the value of α can be assumed to be independent for each event and uniformly distributed. We therefore average the transition probabilities over α. Furthermore, the angle ϕ is also expected to vary daily due to the Earth's rotation, and one should therefore also average over it. This variation, however, is much more challenging to model as it depends on the relative orientation of the earth's rotation axis, the neutrino beam, and the dark photon's polarization, which is unknown. To simplify the analysis, we will assume $\cos\phi \sim 1$, and leave more detailed exploration of these geometrical effects to future studies. With this, there are only two new physics parameters to be considered: $g'A'$ and $m_{A'}$.

We combine the neutrino oscillation data from MINOS [33], NOνA [24, 25] and T2K [23], fixing the solar parameters at $\theta_{12} = 33.41°$ and $\Delta m^2_{21} = 7.41 \times 10^{-5}$ eV^2 [38, 39]. θ_{13} and Δm^2_{31} are varied within their 3-sigma region, which is respectively $[8.19°, 8.89°]$ and $[2.428, 2.597] \times 10^{-3}$ eV^2 for NH and $[8.23°, 8.90°]$ and

$[-2.513, -2.328] \times 10^{-3}$ eV^2 for IH. The other parameters θ_{23}, δ_{CP}, g' and $m_{A'}$ are varied over the ranges shown in Fig. 1. We assume a prior on θ_{13} with $\sin^2\theta_{13} = 0.02203 \pm 0.00057$ for NH and $\sin^2\theta_{13} = 0.02219 \pm 0.00058$ for IH.

3. Results. Since we are most interested in the case that the A' field comprises the dark matter of the Universe, we fix the value of A' to that reproducing the observed dark matter abundance. Thus, A' is determined by $m_{A'}$, since the average energy density is given by $\rho = \frac{1}{2} m_{A'}^2 A'^2$. One must distinguish between the cosmological value A'_U and the local value A', since dark matter is clustered within the galaxy and is therefore more dense on Earth than in the Universe on average. Following Ref. [21], we take $A' = 25\,\text{MeV} \times (10^{-10}\,\text{eV}/m_{A'})$. This allows to constrain the gauge coupling g' as a function of $m_{A'}$.

Our analysis finds best-fit values $g' \sim 4 \times 10^{-23}$ and $m_{A'} \sim 10^{-12}$ eV, but with only a small improvement over the SM by $\Delta\chi^2 = 1.5$ (IH) or 2 (NH), indicated on Fig. 1 (top row) by the red dots. Within the SM by itself, there is mild preference for the IH from these data, which persists within the DM models at the level of $\Delta\chi^2 \sim 2$. Since the DM model has two additional parameters, these are not statistically significant, hence we emphasize the upper limit curves for g' versus $m_{A'}$. The 3σ upper limit curve can be fit in the region shown by $y = 0.73 + 0.97\,x + 0.19\,x^2 + 0.08\,x^3$, where $y = \log_{10} g' + 24$ and $x = \log_{10} m_{A'}/\text{eV} + 13$. Outside of this region, the limit on g' can be expressed as a broken power law,

$$g' \lesssim \begin{cases} 6.3 \times 10^{-11}\,(m_{A'}/\text{eV})\,, & m_{A'} \ll 10^{-12}\,\text{eV} \\ 100\,(m_{A'}/\text{eV})^2\,, & m_{A'} \gg 10^{-12}\,\text{eV} \end{cases}\,, \quad (2)$$

whose analytic form has been explained in Refs. [20, 21]. The cross-over occurs for dark photon oscillation frequencies that are of the same order as the neutrino oscillation frequency, $m_{A'} \sim \Delta m_{23}^2/4E$. Analytic approximations can be used for large and small $m_{A'}$ to avoid having to solve the Schrödinger equation numerically in these regimes.

Comparing to previous results, we find a factor of ~ 5 stronger limit than Refs. [19, 21], which used only T2K data (taken prior to Ref. [23]). However, Ref. [22] obtains an ostensibly much stronger limit on g', by a factor of ~ 2500. Based on discussion with the authors, we believe this was due to an approximation method used by Ref. [22] to solve the Schrödinger equation, instead of solving it exactly.

The bottom row of Fig. 1 shows the confidence intervals on the $\sin^2\theta_{23}$-δ_{CP} plane in the two assumed mass hierarchies. On the NH plane, the tension between T2K and NOνA cannot be reduced by the neutrino-dark photon interaction. This can be confirmed by comparing the joint analysis to separate fits to the individual experiments. As explained in ref. [30], the tension arises from the $\nu_\mu \to \nu_e$ appearance channel. Since our neutrino-dark photon interaction model does not have similar kind of impact on the $\nu_\mu \to \nu_e$ oscillation probability, the tension at NH plane does not get reduced. The combined analysis of NOνA and T2K, along with MINOS, prefers IH over NH. For IH, the individual experiments as well as their combined data prefer $\delta_{CP} \sim -90°$. For NH, the allowed region on $\sin^2\theta_{23}$-δ_{CP} for the combined analysis is closer to the T2K allowed region, because of the larger statistics of T2K.

In Ref. [21] it was shown (in the two-flavor approximation) that for $m_{A'}$ above the critical value $m_{A'} \sim \Delta m_{23}^2/4E$ discussed above, A' oscillations can be integrated out, and their effect on the ν oscillations is described by a shift in the effective Δm_{23}^2,

$$[\Delta m_{23}^2]_{\text{eff}} = \Delta m_{23}^2 \left(1 - \left(\frac{g' A' \sin 2\theta_{23}}{2 m_{A'}}\right)^2\right). \quad (3)$$

This has the consequence that the true mass splitting Δm_{23}^2 is larger than the effective value inferred in the $L_\mu - L_\tau$ dark matter background. Eq.~(3) thus describes a degeneracy between the vacuum mixing parameters and the new physics parameters in the region $m_{A'} \gg 10^{-12}$ eV. This could lead to an interesting interplay between the mass splittings determined in local oscillation experiments and cosmological bounds on the sum of neutrino masses [40–42], which merits a separate study.

We remind the reader that A' in Eq. (3) is shorthand for the component of $\vec{A}'$ parallel to the neutrino beam. Thus A' will vary by a factor depending on the angular orientation of the baseline relative to $\vec{A}'$, which differs between various experiments, and which varies with time due to the motion of the Earth. This effect was partially considered in Ref. [19], and we hope to investigate it in greater detail in the future.

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