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Investigating Pseudo-Dirac Neutrino Signatures in Astrophysical IceCube Data

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Neutrino oscillations, a fundamental discovery in particle physics, suggest that neutrinos have non-zero masses. This opens the possibility of physics beyond the Standard Model, including pseudo-Dirac neutrinos, which oscillate between active and sterile states over cosmological distances. In this study, we analyze 10 years of high-energy astrophysical neutrino data from the IceCube Neutrino Observatory, focusing on prominent sources like NGC 1068, TXS 0506+056, and PKS 1424+240, to search for signatures of pseudo-Dirac neutrino oscillations. By examining event distributions, we constrain the mass-squared differences (δm^2) between active and sterile states. We find no significant deviations from the Standard Model, placing a 90% confidence level limit of $\delta m^2 < 4 \times 10^{-19}\ eV^2$ for NGC 1068. These results offer new insights into the potential existence of pseudo-Dirac neutrinos and demonstrate the unique ability of IceCube to probe neutrino physics over vast cosmic distances. Future analyses with larger datasets could improve sensitivity to even smaller δm^2 values.

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1. Introduction

The detection of high-energy neutrinos from the gamma-ray blazar TXS 0506+056 by IceCube, coincident with a flaring event, provided the first hint of an astrophysical source of high-energy neutrinos, further supported by subsequent neutrino flare observations. More recently, IceCube identified NGC 1068 as a persistent source of high-energy neutrinos [1], with time-integrated data analysis showing an excess of neutrino events, notably from NGC 1068, TXS 0506+056, and PKS 1424+240, inconsistent with a background-only hypothesis at the 3.3σ level [2].

These astrophysical neutrino sources offer a natural opportunity to explore new physics, such as the pseudo-Dirac neutrino scenario, where small mass splittings between active and sterile states may arise from tiny Majorana masses. Astrophysical neutrinos, traveling over cosmological distances, provide a unique setup to test such mass-squared differences. Current constraints come from atmospheric, solar, and supernova neutrinos, but astrophysical neutrinos, with their long propagation distances, offer enhanced sensitivity.

In this work, we analyze IceCube's public IC86 data to constrain this active-sterile mass splitting from sources NGC 1068, PKS 1424+240, and TXS 0506+056, as well as through a stacking analysis. By keeping the source flux spectral index and event counts as free parameters, we evaluate the pseudo-Dirac scenario's viability, expanding on previous studies. Results for different energy ranges are also presented.

2. Theory of Pseudo-Dirac Neutrinos

Neutrino oscillations indicate that neutrinos are not massless, sparking interest in understanding their mass generation mechanisms. One possible extension of the Standard Model (SM) introduces three additional sterile neutrinos, where at least two have nonzero Majorana masses. This results in a mass matrix involving Dirac (M_D), left-handed (M_L), and right-handed (M_R) Majorana terms. The Dirac masses come from Yukawa couplings, while Majorana masses violate lepton number conservation. In the pseudo-Dirac scenario, where the Majorana masses are small compared to the Dirac masses, the active-sterile mixing becomes significant, and the flavor states of neutrinos are superpositions of active and sterile states. The mixing matrix combines the traditional PMNS matrix and a sterile neutrino mixing matrix. This scenario leads to maximal mixing between active and sterile states, and each neutrino flavor is expressed as a combination of mass eigenstates with slightly different masses.

The survival and transition probabilities of active neutrinos over astrophysical distances in the pseudo-Dirac scenario depend on the mass-squared differences δm_i^2 between the active and sterile states as follows [3]

$$P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta)\sin^2\left(\frac{\delta m^2 L}{4E}\right).$$

The probabilities reduce to the SM case when $\delta m_i^2 = 0$. These probabilities are sensitive to the value of δm^2, and this sensitivity increases for larger distances to the neutrino source.

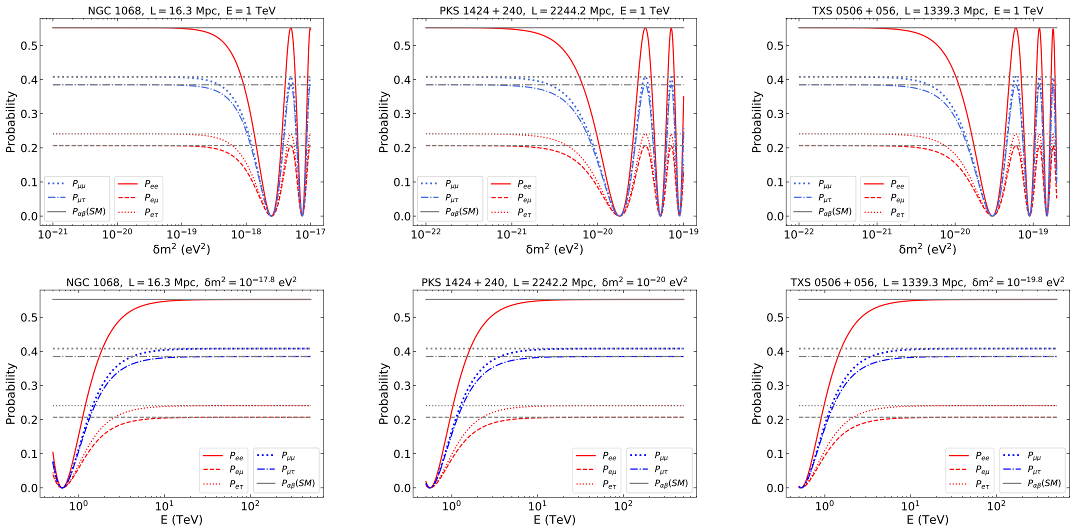

Figure 1: Upper panel: variation of oscillation probabilities for the three active neutrinos in the pseudo-Dirac scenario with respect to the δm_i^2 for $E_\nu = 1$ TeV, in the context of NGC 1068 (left), PKS 1424+240 (middle) and TXS 0506+056 (right). We considered here $\delta m_1^2 = \delta m_2^2 = \delta m_3^2 = \delta m^2$. Lower panel: Oscillation probabilities for the three active neutrinos in the pseudo-Dirac scenario with respect to the neutrino energy E_ν for different δm^2 values.

3. IceCube Data and Point Source Analysis

The IceCube Collaboration released the PSTracks v3 dataset in 2018, containing neutrino track events from both its 40-string (IC40) and full 86-string (IC86) configurations. The dataset includes one year of data for IC40, IC59, and IC79 configurations, and seven years for IC86, which features excellent angular resolution, making it ideal for correlation studies with astrophysical sources. For consistency, we use only IC86 data, focusing on the declination range $[-5°, 81°]$, where 601,163 muon neutrino or track events were recorded over seven years.

Astrophysical Sources

IceCube's analysis identified four significant point sources in the sky, associated with known astrophysical objects NGC 1068 ($z = 0.0038$), PKS 1424+240 ($z = 0.16$ & 0.604), and TXS 0506+056 ($z = 0.3365$), though there is some uncertainty regarding the redshifts of GB6 J1542+6129 [2]. We calculate comoving distances using cosmological parameters and consider only sources with confirmed redshifts. These sources emit high-energy neutrinos that are detectable by IceCube. By analyzing their neutrino fluxes, we can search for deviations from the standard flavor ratios at Earth, which would suggest the presence of pseudo-Dirac neutrinos. Fig. 1 shows that smaller δm^2 values lead to noticeable effects at lower neutrino energies, with the strongest sensitivity for the most distant sources like PKS 1424+240.

4. Statistical Analysis and Constraints on δm^2

The number of signal $\nu_\mu + \bar{\nu}_\mu$ events from an astrophysical source in an energy bin $E_k - E_{k+1}$ over a detector lifetime T is calculated using the source flux in Eqs. (1) and (2) as follows:

$$n_{s,k} = T \int d\Omega \int_{E_k}^{E_{k+1}} dE_\nu \, A_\nu^{\mathrm{eff}}(E_\nu, \Omega) \left[\phi_{\nu_\mu}^{\mathrm{src}} + \phi_{\bar{\nu}_\mu}^{\mathrm{src}}\right]$$

where A_ν^{eff} is the neutrino effective area. Background events from atmospheric and diffuse astrophysical fluxes are similarly calculated, using the Honda et al. model [4] for atmospheric neutrinos and a power-law for the diffuse astrophysical background. The diffuse background flux is modeled as

$$\phi_{\nu_\mu}^{\mathrm{ast}} = \phi_{\mathrm{ast}} \left(\frac{E_\nu}{100\ \mathrm{TeV}}\right)^{-\gamma_{\mathrm{ast}}},$$

with fixed parameters from IceCube's analysis. The analysis is performed for an energy range of 0.5 TeV to 1 PeV, with results summarized for this and other energy ranges in Table 1.

Likelihood Results

Using a likelihood method based on Braun et al. [5], we analyze the PSTracks data for point sources by calculating the probability density $P_j(E_j|\phi^{\mathrm{src}})$ for each neutrino event, incorporating the energy migration matrix $M(E_j, E_k^*)$ and expected signal events $n_{s,k}$ over energy bins. The source probability density $\mathcal{S}_j$ combines this with a Gaussian spatial profile centered on the source direction $\vec{x}_s$, accounting for the angular error σ_j. Similarly, the background probability density $\mathcal{B}_j$ is calculated assuming a uniform distribution within a solid angle $\Delta\Omega_s$, using background fluxes. We construct a likelihood function $\mathcal{L}$ over all neutrino events, incorporating both source and background contributions weighted by the number of signal events n_s, and maximize it over the parameter set $\theta = \{n_s, \gamma, \delta m^2\}$. The test statistic TS is defined based on the likelihood ratio between the null hypothesis (no signal) and the best-fit parameters, and the difference

$$\Delta\mathrm{TS} = \mathrm{TS}^{\mathrm{SM}} - \mathrm{TS}^{\mathrm{pD}}$$

is used to distinguish between the Standard Model and pseudo-Dirac scenarios, allowing us to constrain δm^2, with ΔTS expected to follow a χ^2 distribution with one degree of freedom.

5. Discussion of Results

We analyzed the impact of non-zero δm^2 in the pseudo-Dirac neutrino scenario using astrophysical neutrino data from three sources: NGC 1068, PKS 1424+240, and TXS 0506+056. By scanning the test statistic (TS) over the parameters n_s (number of signal events) and γ (spectral index), we found that non-zero δm^2 significantly affects the best-fit values of these parameters. Specifically, the pseudo-Dirac scenario leads to a decrease in n_s and a harder spectral index (lower γ) in Fig. 2, as active neutrinos convert into sterile neutrinos and fast oscillations at lower energies average out. This results in a change in the flux reaching the Earth, with a lower normalization and a harder spectrum compared to the standard case.

We obtained constraints on δm^2 from individual sources and a stacking analysis in Fig. 3, with the tightest limits provided by PKS 1424+240 due to its greater distance. The constraints are also summarized in Table 1 for energy ranges of 0.5 TeV–1 PeV and 0.1 TeV–1 PeV.

Table 1: Constraints on δm^2 at 90% confidence level and best-fit spectral index $\hat{\gamma}_{\rm SM}$ (with 1σ errors) for each source and the stacking analyses, in two energy ranges. PKS 1424+240 (I) corresponds to redshift $z = 0.604$, and PKS 1424+240 (II) corresponds to $z = 0.16$.

Energy Range	Source	Sensitivity limit δm^2 (eV^2) $\gtrsim$	Constraint δm^2 (eV^2) $\lesssim$ at 90% CL	$\hat{\gamma}_{\rm SM} \pm 1\sigma$
0.5 TeV – 1 PeV	NGC 1068	9×10^{-20}	2.2×10^{-19}	$3.1^{+0.4}_{-0.2}$
	TXS 0506+056	9×10^{-22}	1.2×10^{-20}	$2.4^{+0.2}_{-0.4}$
	PKS 1424+240 (I)	5×10^{-22}	1.5×10^{-21}	$3.7^{+1.6}_{-0.7}$
	PKS 1424+240 (II)	2×10^{-21}	6×10^{-21}	$3.7^{+1.6}_{-0.7}$
	Stacking (I)	5×10^{-22}	1.5×10^{-21}	—
	Stacking (II)	2×10^{-21}	5×10^{-21}	—
0.1 TeV – 1 PeV	NGC 1068	2×10^{-20}	1×10^{-19}	$2.9^{+0.2}_{-0.2}$
	TXS 0506+056	2×10^{-22}	1.4×10^{-20}	$2.3^{+0.2}_{-0.3}$
	PKS 1424+240 (I)	1×10^{-22}	5×10^{-22}	$3.2^{+0.6}_{-0.4}$
	PKS 1424+240 (II)	4×10^{-22}	3×10^{-21}	$3.2^{+0.6}_{-0.4}$
	Stacking (I)	1×10^{-22}	5×10^{-22}	—
	Stacking (II)	4×10^{-22}	2.5×10^{-21}	—

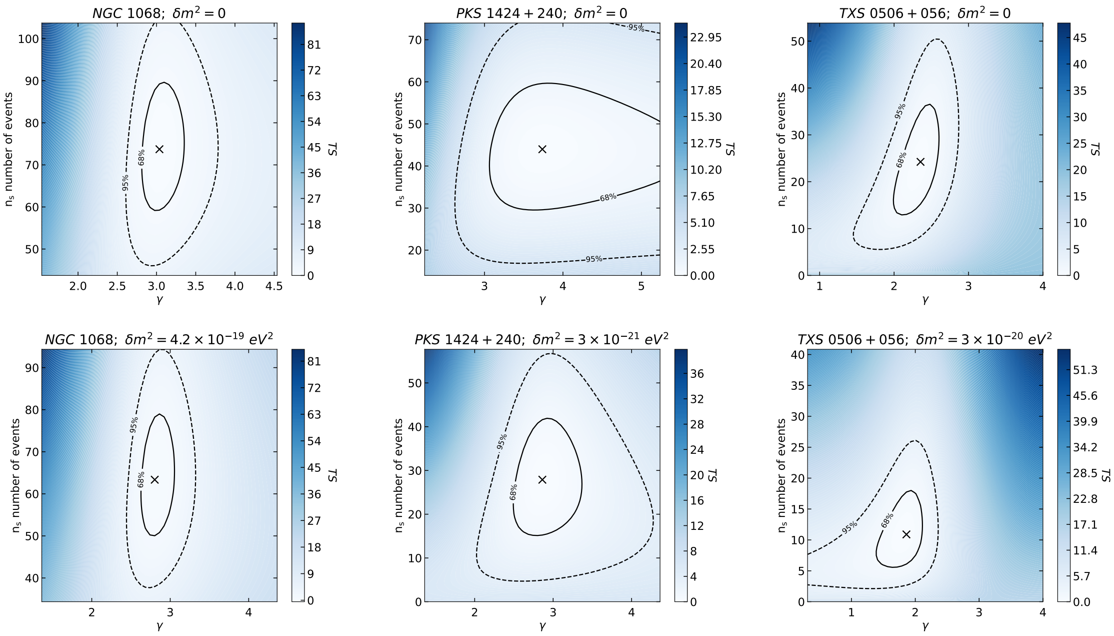

Figure 2: Contour plots of the TS scanned over the parameter n_s and γ and subtracted from the maximum TS obtained for their best-fit values $\hat{n}_s$ and $\hat{\gamma}$, have been projected in the γ-n_s plane for both $\delta m^2 = 0$ (SM) and for a nonzero δm^2 value for the first three sources in Table **??**. The best-fit point in each case is represented with 'x' and the allowed regions with 68% and 95% C.L. are shown as solid and dashed curves, respectively. The energy-range for IceCube is considered to be 0.5 TeV - 1 PeV.

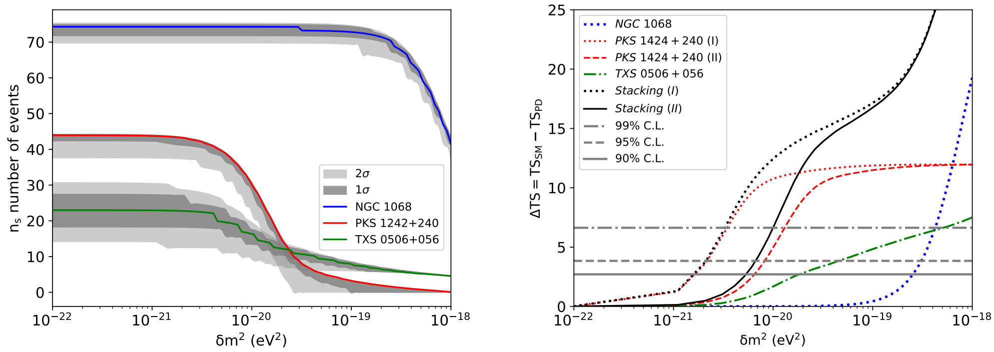

Figure 3: The statistical analysis results are presented in the figure. The left panel shows the number of events versus δm^2 for all three sources, with best-fit curves in solid blue (NGC 1068), red (PKS 1424+240), and green (TXS 0506+056), along with their 1σ and 2σ regions in dark and light gray shades. The right panel displays the ΔTS versus δm^2 curves. Constraints on the δm^2 parameter at 90%, 95%, and 99% confidence levels are provided for individual sources: blue-dotted (NGC 1068), red-dotted (PKS 1424+240 I), red-dashed (PKS 1424+240 II), and green dot-dashed (TXS 0506+056). Results from the stacking analysis are represented by black-dotted (including PKS 1424+240 I) and black-solid (including PKS 1424+240 II) curves, corresponding to the two redshift values of PKS 1424+240. The analysis considers neutrino energies in the range of 0.5 TeV to 1 PeV.

6. Conclusion and Outlook

We searched for pseudo-Dirac neutrinos using IceCube IC86 data from three astrophysical point sources—NGC 1068, PKS 1424+240, and TXS 0506+056. Our analysis in the standard three-neutrino oscillation scenario agrees with published results. In the pseudo-Dirac scenario, since the likelihood fits did not improve, we constrained the active-sterile mass splitting δm^2, assumed equal for all neutrino generations. Each source is sensitive to δm^2 above certain values, below which the scenarios are indistinguishable. Our 90% confidence level constraints are summarized in Table 1, with the most stringent limit from PKS 1424+240: $\delta m^2 \leq 1.5 \times 10^{-21}$ eV^2 for $z = 0.64$ in the 0.5 TeV–1 PeV range. We did not observe active-sterile oscillation signatures and independently constrained $\delta m^2 \leq (1.5\text{–}5.0) \times 10^{-21}$ eV^2 at 90% confidence level from a stacking analysis. Future identification of more sources may improve this bound.

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Abstract

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