Sterile Neutrino Production Through a Matter Effect Enhancement at Long Baselines

Joseph Bramante

Department of Physics and Astronomy, University of Hawaii,
2505 Correa Rd., Honolulu HI, USA

(Dated: November 15, 2011)

Abstract

Motivated by the OPERA anomaly, we propose a matter effect enhancement of oscillation between muon and sterile neutrinos through a neutral $\nu_s$ coupling to fermionic matter. We demonstrate that the resulting matter effect model can evade the current MINOS bound of $P_{\nu_\mu \to \nu_s} < 0.22$ (90% CL) by participating in neutral-current interactions. We find excellent agreement between our sterile neutrino model parameters and parameters which fit LSND and MiniBooNE data. It is shown that superluminal (or "superluminal-like") sterile neutrinos are a viable candidate to explain the OPERA anomaly.

*Electronic address: bramante@hawaii.edu
A recent result from the OPERA experiment [1] measured the difference between the speed of light in vacuum and muon neutrino velocity along a 730 km baseline between the CERN CNGS beam and detection at LNGS:

\[(v_{\nu_{\mu}} - c)/c = (2.48 \pm 0.28_{\text{stat}} \pm 0.30_{\text{sys}}) \times 10^{-5} \] [OPERA]. \hspace{1cm} (1)

This has prompted proposals of new physics [2], novel applications of standard physics to explain away the observed superluminal propagation [3], and phenomenological constraints on \(\nu_{\mu}\) violation of Lorentz invariance [4, 6, 7].

A few proposals have utilized sterile neutrinos to model the OPERA anomaly. One popular mechanism involves \(\nu_s\) transport through a higher dimensional bulk [8–10], an idea first promulgated in [11, 12] wherein active neutrinos confined to a D3 brane oscillate to sterile neutrinos, whose lack of gauge charge leaves them free to travel through large extra dimensions. Despite the appeal of these propositions, a striking constraint on sterile neutrino models (and most other superluminal neutrino models being formulated) comes from measurements of neutrinos and photons arriving from SN1987a. The detection of 24 neutrino events at three sites [13] arriving \(\sim 4\) hours before SN1987a photons puts a rather stringent bound on superluminal electron neutrinos

\[(v_{\nu_{\text{e}}} - c)/c \sim 3 \times 10^{-9} \] [IMB, KII, Baksan]. \hspace{1cm} (2)

While it might be tempting to emphasize that OPERA detected muon neutrinos and SN1987a produced electron neutrino data, after additional experimental constraints on neutrino mass eigenstate velocity differences are applied [10, 14]

\[(v_{\nu_i} - v_{\nu_j})/c \lesssim 2 \times 10^{-19}, \] \hspace{1cm} (3)

active flavour-dependent velocity anomalies are ruled out (short of replacing the standard PMNS matrix with a different formalism [5]).

A distinction between [1] and [2] that does survive current bounds is the energy range of neutrinos being detected:

\[E_{\nu_{\mu}} \sim 10 - 40\, \text{GeV} \] [OPERA]
\[E_{\nu_{\text{e}}} \sim 7 - 39\, \text{MeV} \] [IMB, KII, Baksan]. \hspace{1cm} (4)

This spread in energy has motivated energy-dependent explanations of the OPERA anomaly in a number of papers, e.g., [10] constructs Lagrangians with Lorentz-violating terms coming
FIG. 1: $\nu_s$ elastic scattering through a vector singlet $B$.

from couplings to 10 GeV sterile neutrinos, and [9] suggests a PPW resonance [11] to create a $\nu_f \leftrightarrow \nu_s$ oscillation sharply peaked at OPERA energies.

However, another delineation between the SN1987a and OPERA neutrinos is that OPERA neutrinos propagated through a background of standard model fermions, while SN1987a neutrinos moved through vacuum. Motivated by these different backgrounds, in this paper we develop the phenomenology of a matter-dependent increase of sterile neutrino production through a new $\nu_s$ coupling to fermions. Thus, instead of generating sterile neutrino mixing angles at prescribed energies through a modified energy dependence in the flavour mixing Hamiltonian, we instead generate a dramatic enhancement of an otherwise small muon-sterile mixing term in matter through a sterile neutrino coupling to standard model fermions.

The contribution of the process in figure 1 to the effective potential of sterile neutrino propagation is given by

$$H_{\text{eff}}^{(B)} = -\frac{g_s g_f}{8 m_B} \bar{\nu}_s \gamma^\mu \nu_s [\bar{f}_{R,L} \gamma_\mu f_{R,L}],$$

where $f$ is a fermion abundant in matter, namely $(e^-, u, d)$, and $B$ is a neutral vector boson singlet. For the purposes of deriving a simple sterile neutrino matter effect enhancement, we employ this model throughout our discussion. Finally, we point out that $B$ couples to $(u, d)_L, (\nu_e)_L, u_R, d_R$, and $e_R$ with strength $g_f$ and couples to $\nu_s$ with strength $g_s$. The couplings to sterile neutrinos and fermions are assumed to be unequal owing to collider experiment constraints on the strength of $g_f$ (as we will see, the scale of the couplings likely exceeds that of electroweak interactions).

In principle the proposed mixing enhancement will bolster all active-sterile neutrino os-
cillations in matter, but to simplify our analysis we assume the vacuum mixing \( \nu_{e,\tau} \leftrightarrow \nu_s \) is vanishingly small even after matter effect enhancement, so that the only appreciable sterile neutrino production in matter will come from \( \nu_\mu \leftrightarrow \nu_s \). For this simple system with only \( \nu_\mu \) mixing with \( \nu_s \), the flavor evolution equation in matter is [13]

\[
\frac{d}{dt} \begin{pmatrix} A_{\nu_\mu \rightarrow \nu_\mu} \\ A_{\nu_\mu \rightarrow \nu_s} \end{pmatrix} = \begin{pmatrix} -\Delta m^2 \sin 2\theta & \frac{\Delta m^2}{4E} \sin 2\theta \\ \frac{\Delta m^2}{4E} \sin 2\theta & \frac{\Delta m^2}{4E} \cos 2\theta + \sqrt{2}NG_s \end{pmatrix} \begin{pmatrix} A_{\nu_\mu \rightarrow \nu_\mu} \\ A_{\nu_\mu \rightarrow \nu_s} \end{pmatrix}, \tag{6}
\]

where the mixing angle and squared mass difference in matter are

\[
\sin 2\theta_M = \frac{\Delta m^2_M}{\Delta m^2} \sin 2\theta \tag{8}
\]

\[
\Delta m^2_M = \Delta m^2 \sqrt{\left( \cos 2\theta - \frac{2\sqrt{2}NEG_s}{\Delta m^2} \right)^2 + \sin^2 2\theta} \tag{9}
\]

and the corresponding matter \( \nu_\mu \rightarrow \nu_s \) transition probability over a distance \( D \) is

\[
P_{\nu_\mu \rightarrow \nu_s} = \sin^2 2\theta_M \sin^2 \left( \frac{\Delta m^2_M D}{4E} \right) = \frac{\sin^2 2\theta}{\left( \cos 2\theta - \frac{2\sqrt{2}NEG_s}{\Delta m^2} \right)^2 + \sin^2 2\theta} \sin^2 \left( \frac{\Delta m^2 D}{4E} \sqrt{\left( \cos 2\theta - \frac{2\sqrt{2}NEG_s}{\Delta m^2} \right)^2 + \sin^2 2\theta} \right) \tag{10}
\]

Before we parametrize [10] to fit superluminal propagation at OPERA, we present a review of applicable constraints on superluminal sterile neutrinos. In [6] it was shown that there is a minimum fraction of neutrinos which must travel superluminally in order to reproduce the OPERA anomaly. The spectral flatness of time-binned neutrino events requires the superluminal fraction \( \chi = \Sigma U_{\nu_e \rightarrow \nu_e}^4/\Sigma |U_{\nu\mu}|^4 \) to be at least \( \sim 0.18 \) at 3\( \sigma \) and 0.28
at $2\sigma$ confidence. Furthermore, Cohen and Glashow [7] showed that superluminal active neutrinos would undergo $\nu_f \to \nu_f e^+ e^-$ Cherenkov-like radiation forcing an effective energy cutoff above $\sim 12.5$ GeV for active neutrinos travelling 730 km at 7.5 km/s faster than light. To avoid the Cohen-Glashow energy cutoff, we might decide to require that all superluminal propagation occur through sterile neutrinos (as we will see below, this may not be a sufficient condition to avoid C-G). This requirement combined with the neutrino fraction constraint demands $P_{\nu_\mu \to \nu_s} > 0.18$, though a more promising model would allow for $P_{\nu_\mu \to \nu_s} \gtrsim 0.30$.

The most stringent bound on muon neutrino oscillation to sterile neutrinos in matter comes from a MINOS measurement of neutral-current (NC) interactions of the NuMI muon neutrino beam at the end of a 730 km baseline [16]. At face value, this MINOS result of 802 NC events against an expected $754 \pm 28_{\text{stat}} \pm 37_{\text{sys}}$ event background excludes $P_{\nu_\mu \to \nu_s} > 0.22$ at 90% confidence. However, in the particular case of a sterile neutrino matter effect there is an additional contribution to NC events from the coupling of $\nu_s$ to quarks [5]. In fact, it is worth emphasizing that if $G_s \approx G_F$, sterile neutrino production could both account for muon neutrino disappearance in prior MINOS studies [17], while mimicking active neutrino neutral-current interactions. As long as the mass of the intermediary boson $B^0$ is much greater than the momentum of the sterile neutrino, the four-fermi cross-section approximation $\sigma_{NC\nu_{active}} = G_F^2 E_{\nu} N_F$ should apply to sterile neutrino NC interactions as well. Therefore to construct matter effect models that comfortably allow $P_{\nu_\mu \to \nu_s} \gtrsim 0.30$, it is sufficient to stipulate that $G_s \approx G_F$ and $m_B >> E_{\nu}$. This stipulation has important implications: although we have specified that the mixing $\nu_e \to \nu_s$ is very small, this is not well motivated, and hence $G_s \approx G_F$ reintroduces the Cohen-Glashow problem if the sterile neutrino oscillates to electron neutrinos. One possible conclusion is that sterile neutrinos are not superluminal, and some other effect accounts for the OPERA anomaly.

3+1 sterile neutrino phenomenology has undergone development for over a decade [18], spurred by a succession of $\nu$ and $\bar{\nu}$ short baseline anomalies and cosmological fits which indicate a 4th neutrino with a mass of about 0.5 eV. While this paper was in preparation, a conference proceedings was posted which used a similar $\nu_s$ matter effect to fit a 3+1 model to the LSND and MiniBooNE datasets [19]. Remarkably, the parameterization of [19] is consistent with a parameterization which allows substantial $\nu_\mu \to \nu_s$ mixing at long baseline experiments, thereby allowing superluminal sterile neutrinos at OPERA, as we will now show.
FIG. 2: We have plotted a band of black dashes which includes the region $P_{\nu_{\mu}\rightarrow \nu_s} > 0.18$ to illustrate the resonance $\Delta m^2 \sim 2E_A s$ as detailed in the text. The band centers on the maximum resonance $(0.975)\Delta m^2 = 2E_{\nu}A_s$, which is also the equation of the dashed red MINOS line (with $E_{\nu} = 3$ GeV) The dotted horizontal line indicates the smallest possible $\Delta m^2$ value which yields $P_{\nu_{\mu}\rightarrow \nu_s} \gtrsim 0.30$ at OPERA when $\sin^2 2\theta = 0.05$. The dotted vertical line marks the center value of the sterile neutrino matter potential MINOS NC mimicry condition ($G_s = G_F$). Underlaid is a scatter plot taken from [19], which fits $\Delta m^2_{41}$ and $A_s = \sqrt{2}G_sN$ to LSND and MiniBooNE neutrino oscillation data. Note that the vertical axis of these dotted and dashed lines corresponds to $\Delta m^2$ of the simplified model in this paper while the scatter plot’s vertical axis is $\Delta m^2_{41}$ for a full 3+1 model.

In summary, a matter effect superluminal sterile neutrino explanation of OPERA requires $P_{\nu_{\mu}\rightarrow \nu_s} \gtrsim 0.30$ and that the mixing angle between active and sterile neutrinos in vacuum is small. To enforce the latter requirement, we set $\sin^2 2\theta = 0.05$, which over very long distances implies a vacuum $\nu_{\mu} \rightarrow \nu_s$ transition of 0.025. Inspection of the first term in $P_{\nu_{\mu}\rightarrow \nu_s}$ (10)

$$\frac{\sin^2 2\theta}{\left(\cos 2\theta - \frac{2\sqrt{2}NEG_s}{\Delta m^2}\right)^2 + \sin^2 2\theta}$$

(11)
produces a squared-mass difference-coupling resonance condition
\[
\frac{2\sqrt{2} N E G_s}{\Delta m^2} = \frac{2E A_s}{\Delta m^2} \sim O(1); \tag{12}
\]
If \(\frac{2E A_s}{\Delta m^2} \gg 1\), \(P_{\nu_\mu \rightarrow \nu_s}\) will diminish rapidly, and if \(\frac{2E A_s}{\Delta m^2} \ll 1\), \(P_{\nu_\mu \rightarrow \nu_s}\) cannot exceed a value of 0.05. Inserting the OPERA values into the second term of \(P_{\nu_\mu \rightarrow \nu_s}\), \(D = 730\) km and \(E \sim 17\) GeV,
\[
\sin^2 \left( \frac{\Delta m^2 54 eV^{-2}}{\left( \cos 2\theta - \frac{2\sqrt{2} N E G_s}{\Delta m^2} \right)^2 + \sin^2 2\theta} \right) \tag{13}
\]
a minimum value of \(\Delta m^2\) \((0.04\) eV\(^2\)) becomes apparent. This bound follows from the maximum value of the first \(P_{\nu_\mu \rightarrow \nu_s}\) term (which is unity),
\[
\left( \cos 2\theta - \frac{2\sqrt{2} N E G_s}{\Delta m^2} \right)^2 \sim 0 \Rightarrow \frac{\sin^2 2\theta}{\cos 2\theta - \frac{2\sqrt{2} N E G_s}{\Delta m^2} + \sin^2 2\theta} \sim 1 \tag{14}
\]
\[\Rightarrow P_{\nu_\mu \rightarrow \nu_s} = (1) \sin^2 \left( (0.04\) eV\(^2\))54 eV^{-2}\sqrt{0.05} \right) \sim 0.30. \tag{15}\]

As \(\Delta m^2\) increases substantially from this value, the second term in \(P_{\nu_\mu \rightarrow \nu_s}\) will average to \(\frac{1}{2}\) and the first term will have to resonate at \(\sim \frac{3}{4}\) to produce \(P_{\nu_\mu \rightarrow \nu_s} = 0.30\).

As illustrated by the dotted horizontal line in figure (2), the MINOS neutral-current event mimicry condition \((G_F \approx G_s)\) implies a mass-squared difference of \(\Delta m^2 \sim O(10^{-1})\) eV\(^2\). While at first blush it may seem odd that \(A_s(G_F) \neq A_F(G_F) \sim 10^{-13}\) eV, the factor of \(\sim 7\) difference arises from the singlet vector coupling of \(\nu_s\) to matter which avoids the (V-A) cancellations of the MSW matter potential. It should also be noted when examining figure 2 that the choice of \(\sin^2 2\theta\) significantly impacts the location and shape of the resonance lines. Increasing the vacuum sterile mixing angle from the conservative value of \(\sin^2 2\theta = 0.05\) will both elevate and broaden the OPERA \(P_{\nu_\mu \rightarrow \nu_s} > 0.18\) inclusion band.

If we accept the hypothesis of sterile neutrinos interacting via neutral-currents with all matter fermions, in the case of a straightforward singlet vector coupling the parameter space around the upper right portion of the MINOS resonance line is ruled out. (MINOS was not bombarded with NC events in [16]). However, there are intermediate values of \(A_s\) along and beside the MINOS line, where the cross-section for sterile neutrino NC events exceeds that of active neutrinos, and sterile neutrinos are produced in significant quantities. A possible signal of this at MINOS would be an oscillation above the SM background of NC event counts with respect to energy (see figure 3).
FIG. 3: Sterile neutrino transition probability plotted against neutrino energy for the parametrization $\Delta m^2 = 0.45 \text{ eV}^2$, $A_s = 10^{-11} \text{ eV}$, $\sin^2 2\theta = 0.05$, $D = 730 \text{ km}$. If the sterile neutrinos have a neutral-current interaction cross-section $\sim 5$ larger than SM neutrinos, an oscillation around 2.5% would be observable. This particular parametrization may be ruled out by virtue of its diminution of charged-current interactions at OPERA in the 20-30 GeV range.

Before concluding, we observe that although the Winter [6] analysis, which fit the superluminal neutrino fraction $\chi = \sum U_{\mu \nu c} |U_{\mu \nu c}|^4/\sum |U_{\mu i}|^4$ to the flatness of the OPERA events and proton waveform, can be interpreted as a fraction of faster-than-light neutrinos detected by OPERA, it equally implies that if some new interaction is yielding muon-neutrino-like events and is systematically mischaracterized by $\delta t \sim 100 \text{ ns}$, such an interaction could account for the OPERA anomaly. We speculate without any immediate substantiation that owing to the fact that semi-sterile neutrino couplings have not been carefully studied, semi-sterile neutral-current interactions of sterile neutrinos could in principle mimic charged-current events.

In conclusion, we have developed a matter effect enhanced model of sterile neutrino production at long baselines. It deserves emphatic announcement that the intersection in parameter space between our squared mass-coupling resonance lines and the fit of discrepant data from LSND and MiniBooNE, posted while this paper was in preparation, was not a consequence of post-hoc fine-tuning. In fact, the intersection is necessitated both by the neutral-current MINOS mimicry condition, without which we cannot reasonably have
$P_{\nu_{\mu}\to\nu_s} > 0.30$, and moreover by the neutrino energies, baseline lengths, and assumption of relatively small vacuum $P_{\nu_{\mu}\to\nu_s}$ mixing (this last assumption actually has a surprisingly small effect in parameter space). These necessary constraints correspond to the dotted horizontal and vertical lines in figure 2. There is further work on exact fits to LBL data and a complete 3+1 model for LBL sterile neutrino matter effect enhancement that remains to be undertaken.

Acknowledgments

We wish to thank Jason Kumar along with Heinrich Pas, Danny Marfatia, John Learned, and David Yaylali for useful discussions. Special acknowledgement is owed to Sandip Pakvasa for guidance in the development of this material.

[1] T. Adam et al. [ OPERA Collaboration ], [arXiv:1109.4897 [hep-ex]].

[2] I. Y. Aref’eva, I. V. Volovich, [arXiv:1110.0456 [hep-ph]]. T. Li, D. V. Nanopoulos, [arXiv:1110.0451 [hep-ph]]. E. N. Saridakis, [arXiv:1110.0697 [gr-qc]]. T. Li, D. V. Nanopoulos, [arXiv:1110.3451 [hep-ph]]. T. R. Morris, [arXiv:1110.3266 [hep-ph]]. S. Sahu, B. Zhang, [arXiv:1110.2236 [hep-ph]]. I. Masina, F. Sannino, [arXiv:1110.1853 [hep-ph]]. S. Tanimura, [arXiv:1110.1790 [hep-ph]]. J. W. Moffat, [arXiv:1110.1330 [hep-ph]]. I. Oda and H. Taira, [arXiv:1110.0931 [hep-ph]]. J. Alexandre, J. Ellis, N. E. Mavromatos, [arXiv:1109.6296 [hep-ph]]. S. Gardner, [arXiv:1109.6520 [hep-ph]]. E. Ciuffoli, J. Evslin, J. Liu and X. Zhang, [arXiv:1109.6641 [hep-ph]]. C. Pfeifer, M. N. R. Wohlforth, [arXiv:1109.6005 [gr-qc]]. G. Dvali, A. Vikman, [arXiv:1109.5685 [hep-ph]]. M. Li, T. Wang, [arXiv:1109.5924 [hep-ph]].

[3] Broda, B. 2011, [arXiv:1110.0644 [hep-ph]]. R. Brustein, D. Semikoz, [arXiv:1110.0762 [hep-ph]]. A. Stebbins, [arXiv:1110.2170 [hep-ex]]. A. Mecozzi, M. Bellini, [arXiv:1110.1253 [hep-ph]]. S. -Y. Li, [arXiv:1110.0302 [hep-ph]].

[4] L. Maccione, S. Liberati, D. M. Mattingly, [arXiv:1110.0783 [hep-ph]]. D. Lust, M. Petropoulos, [arXiv:1110.0813 [gr-qc]]. G. Amelino-Camelia, L. Freidel, J. Kowalski-Glikman, L. Smolin, [arXiv:1110.0521 [hep-ph]]. H. Davoudiasl, T. G. Rizzo, [arXiv:1110.0821 [hep-ph]]. J. M. Carmona, J. L. Cortes, [arXiv:1110.0430 [hep-ph]]. [ ICARUS Collaboration ], [arXiv:1110.3763]
[hep-ex]]. F. Giacosa, P. K. S. Lottini, arXiv:1110.3642 [hep-ph]. S. S. Xue, arXiv:1110.1317 [hep-ph]. D. V. Ahluwalia, S. P. Horvath and D. Schritt, arXiv:1110.1162 [hep-ph]. R. Cowsik, S. Nussinov, U. Sarkar, arXiv:1110.0241 [hep-ph]. R. Ehrlich, arXiv:1110.0736 [hep-ph]. S. S. Gubser, arXiv:1109.5687 [hep-th].

[5] V. A. Kostelecky and M. Mewes, Phys. Rev. D 69, 016005 (2004) J. S. Diaz and V. A. Kostelecky, Phys. Lett. B 700, 25 (2011) arXiv:1012.5985 [hep-ph]. J. S. Diaz, arXiv:0909.5360 [hep-ph]. J. S. Diaz, arXiv:1008.0411 [hep-ph].

[6] W. Winter, arXiv:1110.0424 [hep-ph].

[7] A. G. Cohen, S. L. Glashow, arXiv:1109.6562 [hep-ph].

[8] A. Nicolaidis, arXiv:1109.6354 [hep-ph].

[9] S. Hannestad and M. S. Sloth, arXiv:1109.6282 [hep-ph].

[10] G. F. Giudice, S. Sibiryakov, A. Strumia, arXiv:1109.5682 [hep-ph].

[11] H. Pas, S. Pakvasa and T. J. Weiler, Phys. Rev. D 72, 095017 (2005) arXiv:hep-ph/0504096.

[12] J. Dent, H. Pas, S. Pakvasa and T. J. Weiler, arXiv:0710.2524 [hep-ph].

[13] R. M. Bionta et al. [IMB Collaboration], Phys. Rev. Lett. 58 (1987) 1494. E. N. Alekseev, L. N. Alekseeva, I. V. Krivosheina and V. I. Volchenko, Phys. Lett. B 205 (1988) 209.

K. Hirata et al. [KAMIOKANDE-II Collaboration], Phys. Rev. Lett. 58 (1987) 1490.

[14] J. R. Ellis, N. Harries, A. Meregaglia, A. Rubbia and A. Sakharov, Phys. Rev. D 78 (2008) 033013 [arXiv:0805.0253]. S. R. Coleman and S. L. Glashow, Phys. Rev. D 59 (1999) 116008 [arXiv:hep-ph/9812418]. A. A. Aguilar-Arevalo et al. [The MiniBooNE Collaboration], arXiv:1109.3480. A. Strumia and F. Vissani, arXiv:hep-ph/0606054.

[15] K. Nakamura et al. [ Particle Data Group Collaboration ], J. Phys. G G37, 075021 (2010). L. Wolfenstein, Phys. Rev. D17, 2369-2374 (1978). D. Dooling, C. Giunti, K. Kang, C. W. Kim, Phys. Rev. D61, 073011 (2000). hep-ph/9908513. C. Giunti and C. W. Kim (Oxford, UK: Oxford University Press) (2007).

[16] P. Adamson et al. [MINOS Collaboration], Phys. Rev. Lett. 107, 011802 (2011) arXiv:1104.3922 [hep-ex].

[17] D. G. Michael et al. [MINOS Collaboration], Phys. Rev. Lett. 97, 191801 (2006) arXiv:hep-ex/0607088. P. Adamson et al. [MINOS collaboration], Phys. Rev. Lett. 107, 021801 (2011) arXiv:1104.0344 [hep-ex].
[18] Okada N and Yasuda O 1997 *Int. J. Mod. Phys.* A**12** 3669–3694 [hep-ph/9606411] Bilenky
S M, Giunti C and Grimus W 1998 *Eur. Phys. J.* C**1** 247–253 [hep-ph/9607372] Bilenky
S M, Giunti C, Grimus W and Schwetz T 1999 *Phys. Rev.* D**60** [hep-ph/9903454] Maltoni M,
Schwetz T, Tortola M and Valle J 2004 *New J. Phys.* 6 122 [hep-ph/0405172]

[19] G. Karagiorgi, [arXiv:1110.3735 [hep-ph]].