DOI: 10.1140/epjc/s10052-024-13323-2

Eur. Phys. J. C (2024) 84:923
https://doi.org/10.1140/epjc/s10052-024-13323-2

THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Theoretical Physics

Neutrino trident scattering at the LHC energy regime

Reinaldo Francener[1,a], **Victor P. Gonçalves**[2,3,b], **Diego R. Gratieri**[1,4,c]

[1] Instituto de Física Gleb Wataghin-UNICAMP, Campinas, SP 13083-859, Brazil
[2] Institute of Physics and Mathematics, Federal University of Pelotas, Postal Code 354, Pelotas, RS 96010-900, Brazil
[3] Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China
[4] Escola de Engenharia Industrial Metalúrgica de Volta Redonda, Universidade Federal Fluminense (UFF), Volta Redonda, RJ CEP 27255-125, Brazil

Received: 27 June 2024 / Accepted: 2 September 2024

Abstract The neutrino trident scattering process in neutrino-tungsten interactions at the LHC energy regime is investigated, and the cross-sections for different leptonic final states in coherent and incoherent interactions are estimated. Furthermore, the associated number of events at FASERν2 detector is estimated considering different predictions for the flux of incident neutrinos on the detector, based on distinct hadronic models for the particle production in pp collisions at ultra-forward rapidities. Our results indicate that the observation of the neutrino trident process is, in principle, feasible at the Forward Physics Facility.

1 Introduction

The recent detection of neutrinos by the SND@LHC [1] and FASERν [2,3] experiments has started the far-forward neutrino physics program at the Large Hadron Collider (LHC), which is expected to be boosted during the high luminosity LHC (HL-LHC) era with the experiments to be installed in the Forward Physics Facility (FPF) [4,5]. The basic idea is that a large number of neutrinos originate through the decay of hadrons produced at forward rapidities in high energy pp collisions and, consequently, LHC provides an intense and strongly collimated beam of high-energy neutrinos that can be used to study neutrino-hadron interactions in a detector centered around the beam–collision axis, as e.g. FASERν, FASERν2 and FLArE, or off axis as e.g. SND@LHC. In recent years, several studies have explored the possibility of probing Standard Model (SM) predictions, constrain the neutrino-nucleon cross-sections in an explored energy range and searching for signals of New Physics using the forthcoming results from neutrino-hadron interactions at the FPF (For a review see, e.g., Ref. [4]), strongly motivated by the huge integrated luminosity predicted for the HL-LHC run of $\mathcal{L} = 3$ ab^{-1}. Such luminosity is expected to allow us to investigate rare processes, characterized by tiny cross-sections, whose predictions have not yet tested experimentally, or that current data is still scarce.

In this paper, we will investigate the neutrino trident production, which is a weak process characterized by the production of a pair of charged leptons through the neutrino scattering in the Coulombian field of a heavy nucleus. Such process can be mediated by a $W^{\pm}$ or a Z^0 boson exchange, as represented in Fig. 1, and as the mass of these gauge boson is much larger than the relevant momentum transfer, the cross-section can be accurately estimated assuming a four lepton contact interaction. For a pair of muons in the final state, the CHARM-II [6] and CCFR [7] experiments have claimed the observation of the trident process$\nu_\mu \rightarrow \nu_\mu \mu^+ \mu^-$, with the results in agreement with the SM predictions. The NuTeV experiment [8] also searched for this process, but only was able to establish an upper limit. However, measurements for other incident neutrinos and/or final states have not yet obtained. In recent years, several theoretical studies have been carried out, showing the feasibility of observing the trident process in experiments such as DUNE [9], IceCube [10,11] and near detectors [12]. Our goal in this study is to provide, for the first time, the predictions for the trident cross-sections at the LHC energies and the event rates at the FASERν2 detector for a variety of neutrino and antineutrino-induced trident processes. As we will demonstrate below, our results indicate that a future experimental analysis of neutrino trident process at the FPF is, in principle, feasible.

[a] e-mail: reinaldofrancener@gmail.com
[b] e-mail: barros@ufpel.edu.br (corresponding author)
[c] e-mail: drgratieri@id.uff.br

2 Trident process at the LHC

In what follows, we will present our results for trident production induced by electronic and muonic (anti)neutrinos, considering the neutrino-tungsten interaction in the kinematical regime that will be covered by FASERν2 detector, which is a detector based on the emulsion technology, with a transverse size of 40 cm $\times$ 40 cm and total tungsten mass of 20 tons, centered around the beam-collision LHC axis. In our analysis, we will estimate the cross-section using the four lepton contact interaction theory, as described e.g. in Refs. [9,12], and taken into account of contribution of coherent and incoherent elastic scatterings, where the leptonic system scatters on the full nucleus or with the individual nucleons inside the nucleus, respectively. In particular, we will present separately the incoherent predictions for the interaction with a proton and with a neutron. It is important to emphasize that these two contributions are characterized by distinct final states: while in a coherent scattering the nucleus remains intact, in the incoherent one, it is expected to breakup, generating a hadronic activity in addition to the leptonic system, which is associated with the fragments of the nucleus. Such distinct topology can be used, in principle, to separate the coherent and incoherent events. As in Ref. [9], the results will be calculated considering the full $2 \to 4$ scattering process, without assume the validity of the equivalent photon approximation.

Initially, in Fig. 2, we present the cross-sections for neutrino-induced trident processes, derived using the formalism described in detail in Refs. [9,12] that was implemented in the Monte Carlo event generator proposed in Ref. [9] to estimate the trident events at DUNE. In our analysis, we have adapted this event generator for a tungsten target. In particular, the form factor used in our calculations is given by the Fourier transform of the Woods-Saxon nuclear charge distribution [13], with the parametrization provided in [14]. We will present predictions for $\sigma_{\nu_l A}$, but we also have estimated the cross-sections for an incident antineutrino and obtained similar results. The predictions in Fig. 2 are for the coherent scattering (left) and for the incoherent interaction with a proton (middle) and with a neutron (right). Black, red, and blue lines represent final states with two muons, muon plus electron, and two electrons, respectively. One has that the $\nu_\mu \to \nu_e \mu^- e^+$ process has the largest cross-section over the energy range considered. In contrast, the $\nu_e \to \nu_e \mu^+ \mu^-$ process has the smallest cross-section. It is important to emphasize that the cross-section of the $\nu_\mu \to \nu_\mu \mu^+ \mu^-$ process receives the contribution of both diagrams presented in Fig. 1, which implies a destructive interference that reduces the magnitude of the cross-section. Our results also indicate that the coherent scattering dominates, which is directly associated with the Z^2 factor present in the cross-section. Moreover, one has that the cross-section for the incoherent scattering with a proton is one order of magnitude larger than for a neutron target, which is smaller since it is electrically neutral. These conclusions are in agreement with those presented in Ref. [9] for smaller neutrino energies.

In order to quantify the contribution of coherent and incoherent scatterings for a given final state, in Fig. 3 we show the energy dependence of the ratio between these contributions to the total cross-section, which is the sum of both processes, considering $\nu_\mu\, ^{187}W$ (left) and $\nu_e\, ^{187}W$ interactions. In agreement with the results presented in Fig. 2, the coherent process dominates for all channels in the energy range considered. The incoherent contribution is more significant for the production of a pair of muons than for the production of a e^+e^- system, which is associated with the

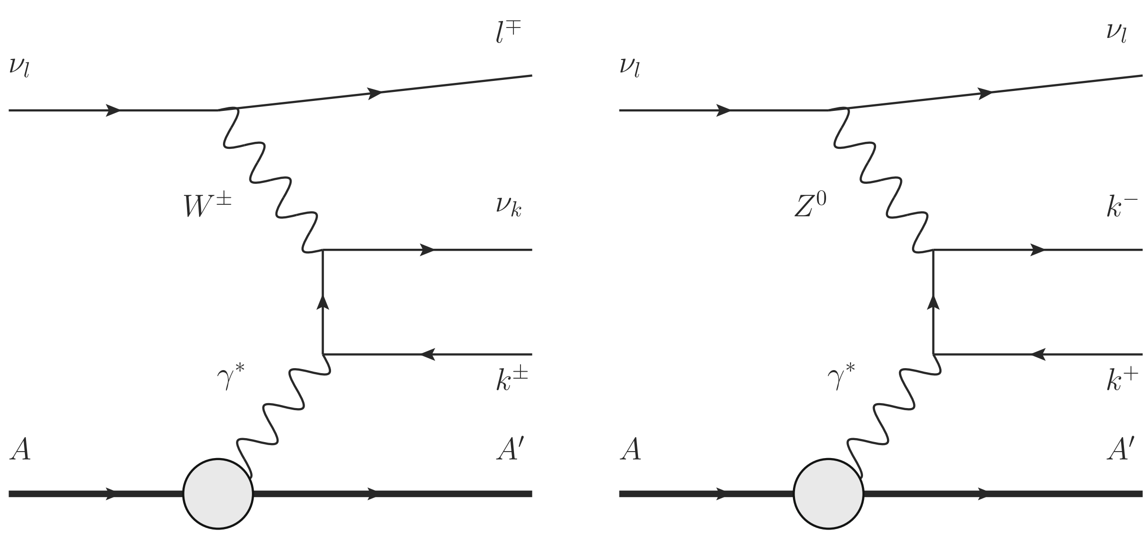

Fig. 1 Feynman diagrams for the neutrino trident scattering off a nucleus target associated with a $W^\pm$ (left) and Z^0 (right) exchange. The lepton flavors l and k can be equal or different. For a $W^\pm$ exchange, the charged lepton pair can be constituted by different flavors

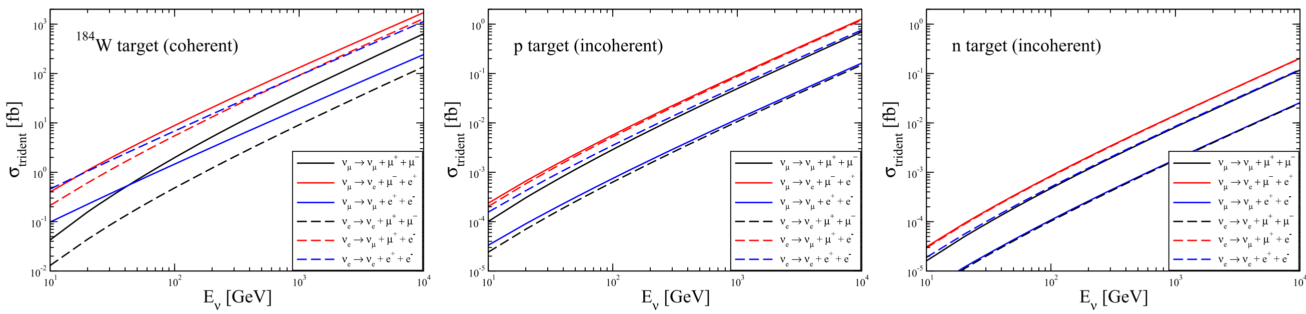

Fig. 2 Cross-sections for the trident processes as a function of the incident neutrino energy. We consider interactions of muonic (solid) and electronic (dashed) neutrinos originating muon pair (black) muon plus electron (red) and electron pair (blue). Our results are for coherent scattering with the full nucleus (left panel) and for incoherent scattering with a proton (middle panel) and a neutron (right panel) inside the nucleus

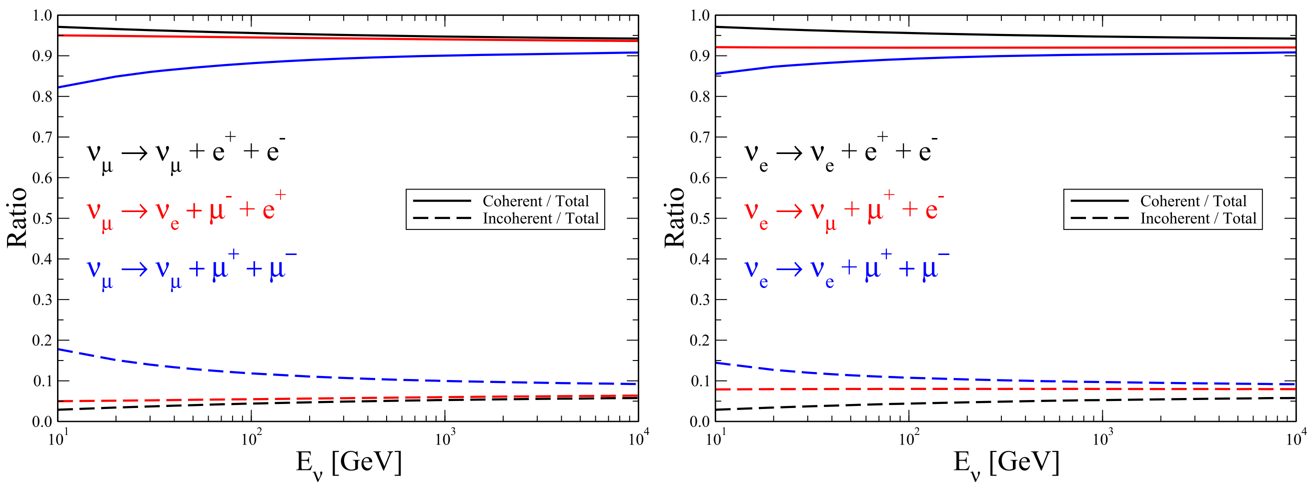

Fig. 3 Ratio between coherent (solid) and incoherent (dashed) contributions to the total cross-section for trident events induced by muonic (left) and electronic (right) neutrino, considering a tungsten target

fact that a larger value of the photon virtuality is needed in order to produce a muon pair. In this case, the probability of probing the internal structure of the nucleus is larger, which implies a larger cross-section for the incoherent interaction. It also explains why the production of muon plus electron has an intermediate contribution from the incoherent case compared to the cases mentioned before. Our results indicate that the contribution of incoherent processes is smaller than 10% in the LHC energy range.

The cross-section is one of the main ingredients for estimating the number of trident of events in a given detector. Another important ingredient is the flux of incident neutrinos. In our analysis, we will consider the neutrino flux incident on the FASERν2 estimated in Ref. [15] considering distinct modeling for the hadron production at large pseudorapidities in pp collisions at the LHC energy, implemented in different Monte Carlo generators. As demonstrated in Ref. [15], the main contributions for the neutrino fluxes comes from the decay of light mesons (pions and kaons) and from the decay of charmed hadrons. In order to quantify the uncertainty in our predictions, we will estimate the neutrino flux associated with the decay of light mesons using the following MC generators: `EPOS-LHC` [16], `DPMJET 3.2019.1` [17,18], `QGSJET II-04` [19], `SIBYLL 2.3d` [20,21] and `Pythia 8.2` [22,23]. On the other hand, the neutrino flux coming from charmed hadrons will be estimated using the results derived in Refs. [24–26] (denoted `BDGJKR`), [27] (denoted `BKRS`), [28] (denoted `BKSS` k_T), [29] (denoted `MS` k_T) and [30,31] (denoted `SIBYLL 2.3d`). In particular, we will use the same generator combinations for the total neutrino flux considered in Ref. [15].

The number of neutrino-induced events at the FASERν2 detector is given by the product of the time-integrated neutrino flux with the neutrino interaction probability, which is defined by $\sigma_{\nu A}\rho L/m_A$, where $\sigma_{\nu A}$ is the neutrino-nucleus cross-section, ρ the density of the target material (19.3 g/cm^3 for tungsten), L the length of the detector (6.6 m) and m_A the mass of the target nucleus. In Fig. 4 we present our results for

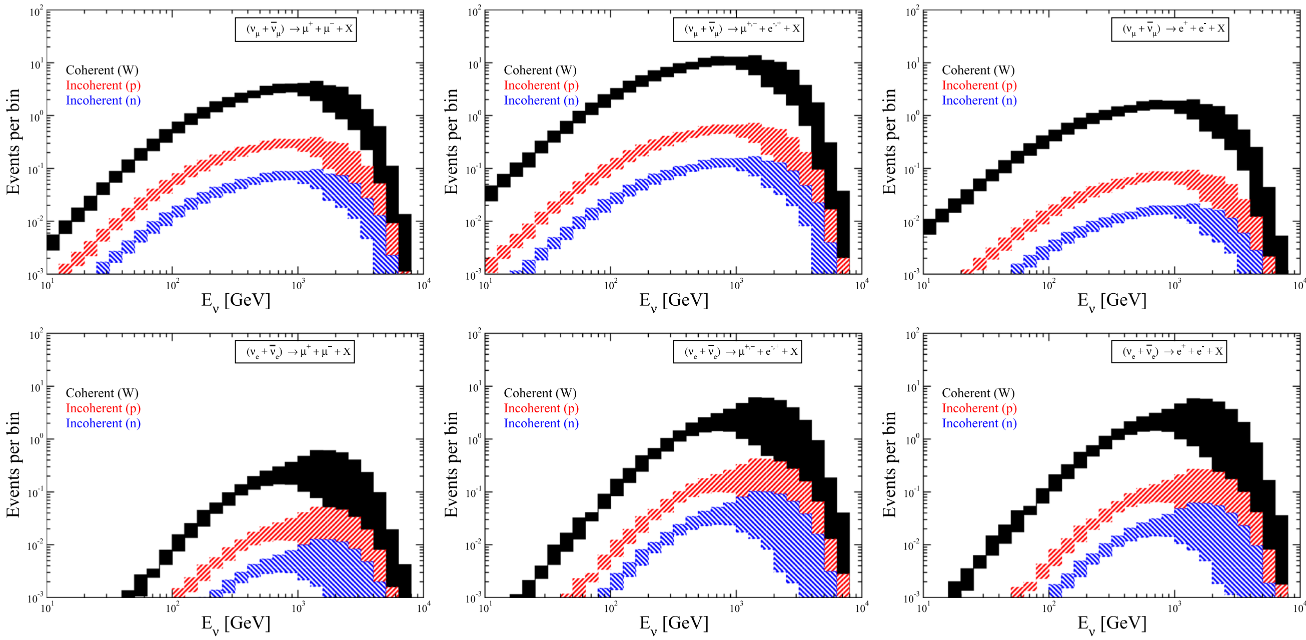

Fig. 4 Number of trident events per bin expected in the FASERν2 detector, induced by muonic (top) and electronic (bottom) neutrinos, derived assuming the expected luminosity for the HL-LHC of 3 ab^{-1}. Our results are for different leptons in the final state: muon pair (left), muon plus electron (middle) and electron pair (right). The uncertainty band was constructed considering different Monte Carlo generators for the incident neutrino flux

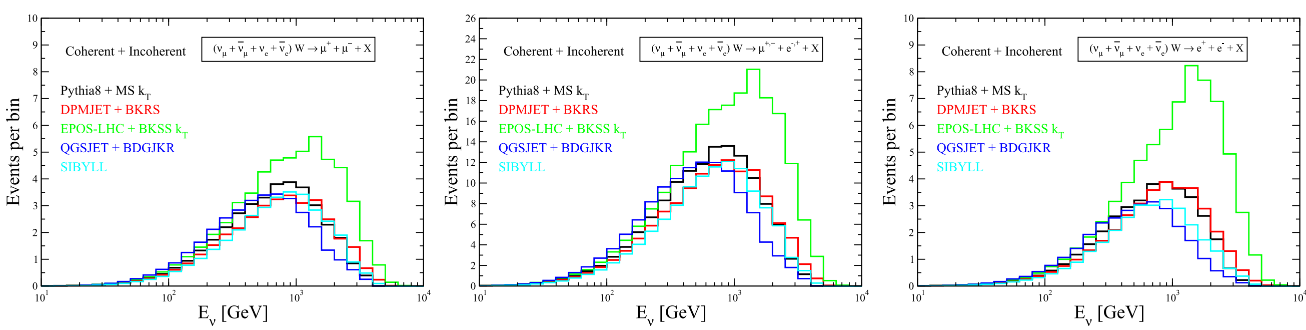

Fig. 5 Total number of trident events in the FASERν2 detector characterized by a given final state, estimated considering different MC generators for the incident neutrino flux. Results for a muon pair (left panel), a muon plus electron (middle panel) and an electron pair (right panel)

the number of trident events per bin expected in the FASERν2 detector during the high luminosity LHC regime for events induced by ν_μ (top) and ν_e (bottom). We consider three leptonic final states: muon pair (left), muon plus electron (middle), and electron pair (right). Furthermore, we present separately the coherent and incoherent scattering contributions. The uncertainty band was constructed with the different MC generators mentioned previously, limiting the maximum and minimum values with the largest and smallest predictions for the neutrino flux. We predict a larger number of trident events induced by muonic neutrinos, with the production of charged leptons of different flavors being dominant. One has that the uncertainty bands increase appreciably for events with $E_\nu \gtrsim 10^3$ GeV. Moreover, the uncertainty at high energies is larger for trident processes induced by electronic neutrinos, since it receive a greater contribution from the decay of charmed hadrons, whose predictions from the different production models still are largely distinct (See, e.g. Ref. [15]). As expected from the analysis of the cross-sections, our results also indicate that coherent interactions dominate the number of events, about an order of magnitude above the incoherent contribution.

Finally, in Fig. 5 we present our results for the expected number of trident events in the FASERν2 detector characterized by a given final state, independently of the flavor of the incident (anti)neutrino. We have summed the coherent and incoherent cross-sections, as well as the contributions associated with the neutrino and antineutrino-tungsten interac-

Table 1 Total number of trident events in the FASERν2 detector per topology during the high luminosity era of the LHC, estimated considering different MC generators for the incident neutrino flux

	$\mu^+ + \mu^-$	$\mu^\pm + e^\mp$	$e^+ + e^-$
Pythia + MS k_T	37.0	134.2	36.1
DPMJET + BKRS	34.6	126.5	36.1
EPOS-LHC + BKSS k_T	55.0	209.0	70.5
QGSJET + BDGJKR	34.4	124.0	29.6
SIBYLL	33.0	116.5	29.1

tions. Our results are presented for a muon pair (left panel), a muon plus electron (middle panel) and an electron pair (right panel) considering different MC generators for the incident (anti)neutrino flux. One has that the number of events per bin for $E_\nu \approx 10^3$ GeV is larger than 3 for a pair of leptons of the same flavor, and larger than 10 for a muon plus electron final state. In Table 1 we present the total number of events per lepton final state. Our results indicate values between 33–55, 116–209 and 29–70 for final states of muon pair, muon plus electron and electron pair, respectively. Such results indicate that the observation of the trident process is, in principle, feasible in the FASERν2 detector.

3 Summary

In this paper, we have performed an exploratory study of the trident process in LHC energy regime. We estimate the total cross-sections considering the production of different lepton final states. Moreover, we have calculated the expected number of events for the high luminosity LHC regime, using different Monte Carlo generators to estimate the incident neutrino flux. We have demonstrated that, in principle, this rare process can be observed in the FASERν2 detector, which will allow us to test the SM predictions as well as searching for the contribution of new gauge bosons predicted in some scenarios for beyond the standard model physics. The results presented here strongly motivate a more detailed analysis in terms of angular and energetic distributions of the charged leptons present in the final state, as well as the analysis of potential backgrounds. We plan to perform these studies in future publications.

Note added. After our work had been submitted to arXiv, the preprint [32] appeared, which also discusses the neutrino trident processes at the LHC. This work agrees with our predictions for the number of events at the FASERν2 detector. Moreover, the analysis of the backgrounds performed in that reference, confirms our conclusion that a future observation of the trident process is feasible, and that the FASERν2 will be able to discover this rare process.

Acknowledgements R. F. acknowledges support from the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq, Brazil), Grant No. 161770/2022-3. V.P.G. was partially supported by CNPq, FAPERGS and INCT-FNA (Process No. 464898/2014-5). D.R.G. was partially supported by CNPq and MCTI.

Data Availability Statement Data will be made available on reasonable request. [Authors' comment: The datasets generated during the current study are available from the corresponding author on reasonable request.]

Code Availability Statement This manuscript has no associated code/software. [Author's comment: Code sharing not applicable to this article as no code was generated during the current study.]

References

1. R. Albanese et al. [SND@LHC], Phys. Rev. Lett. **131**(3), 031802 (2023)
2. H. Abreu et al. [FASER], Phys. Rev. D **104**(9), L091101 (2021)
3. H. Abreu et al. [FASER], Phys. Rev. Lett. **131**(3), 3 (2023)
4. L.A. Anchordoqui, A. Ariga, T. Ariga, W. Bai, K. Balazs, B. Batell, J. Boyd, J. Bramante, M. Campanelli, A. Carmona et al., Phys. Rep. **968**, 1–50 (2022)
5. J.L. Feng, F. Kling, M.H. Reno, J. Rojo, D. Soldin, L.A. Anchordoqui, J. Boyd, A. Ismail, L. Harland-Lang, K.J. Kelly et al., J. Phys. G **50**(3), 030501 (2023)
6. D. Geiregat et al. [CHARM-II], Phys. Lett. B **245**, 271–275 (1990)
7. S.R. Mishra et al. [CCFR], Phys. Rev. Lett. **66**, 3117–3120 (1991)
8. T. Adams et al. [NuTeV], Phys. Rev. D **61**, 092001 (2000)
9. W. Altmannshofer, S. Gori, J. Martín-Albo, A. Sousa, M. Wallbank, Phys. Rev. D **100**(11), 115029 (2019)
10. Bei Zhou, John F. Beacom, Phys. Rev. D **101**, 036010 (2020)
11. S. Sarkar, *Search for TeV-Scale Neutrino Dimuon Events with 10.7 Years of IceCube Data*. PhD thesis (2023)
12. P. Ballett, M. Hostert, S. Pascoli, Y.F. Perez-Gonzalez, Z. Tabrizi, R. Zukanovich Funchal, JHEP **01**, 119 (2019)
13. R.D. Woods, D.S. Saxon, Phys. Rev. **95**, 577–578 (1954)
14. H. De Vries, C.W. De Jager, C. De Vries, Atom. Data Nucl. Data Tabl. **36**, 495–536 (1987)
15. F. Kling, T. Mäkelä, S. Trojanowski, Phys. Rev. D **108**(9), 095020 (2023)
16. T. Pierog, I. Karpenko, J.M. Katzy, E. Yatsenko, K. Werner, Phys. Rev. C **92**(3), 034906 (2015)
17. S. Roesler, R. Engel, J. Ranft, The Monte Carlo event generator DPMJET-III, in *International Conference on Advanced Monte Carlo for Radiation Physics, Particle Transport Simulation and Applications (MC 2000)*, pp. 1033–1038 (2000). arXiv:hep-ph/0012252 [hep-ph]

18. A. Fedynitch, *Cascade equations and hadronic interactions at very high energies*, PhD thesis (KIT, Karlsruhe, Dept. Phys., 11, 2015)
19. S. Ostapchenko, Phys. Rev. D **83**, 014018 (2011)
20. E.J. Ahn, R. Engel, T.K. Gaisser, P. Lipari, T. Stanev, Phys. Rev. D **80**, 094003 (2009)
21. F. Riehn, R. Engel, A. Fedynitch, T.K. Gaisser, T. Stanev, PoS **ICRC2015**, 558 (2016)
22. M. Fieg, F. Kling, H. Schulz, T. Sjöstrand, Phys. Rev. D **109**(1), 016010 (2024)
23. T. Sjöstrand, S. Ask, J.R. Christiansen, R. Corke, N. Desai, P. Ilten, S. Mrenna, S. Prestel, C.O. Rasmussen, P.Z. Skands, Comput. Phys. Commun. **191**, 159–177 (2015)
24. W. Bai, M. Diwan, M.V. Garzelli, Y.S. Jeong, M.H. Reno, JHEP **06**, 032 (2020)
25. W. Bai, M. Diwan, M.V. Garzelli, Y.S. Jeong, F.K. Kumar, M.H. Reno, JHEP **06**, 148 (2022)
26. W. Bai, M. Diwan, M.V. Garzelli, Y.S. Jeong, K. Kumar, M.H. Reno, JHEP **10**, 142 (2023)
27. L. Buonocore, F. Kling, L. Rottoli, J. Sominka, Eur. Phys. J. C **84**(4), 363 (2024)
28. A. Bhattacharya, F. Kling, I. Sarcevic, A.M. Stasto, Phys. Rev. D **109**(1), 014040 (2024)
29. R. Maciula, A. Szczurek, Phys. Rev. D **107**(3), 034002 (2023)
30. E.J. Ahn, R. Engel, T.K. Gaisser, P. Lipari, T. Stanev, arXiv:1102.5705 [astro-ph.HE]
31. A. Fedynitch, F. Riehn, R. Engel, T.K. Gaisser, T. Stanev, Phys. Rev. D **100**(10), 103018 (2019)
32. W. Altmannshofer, T. Mäkelä, S. Sarkar, S. Trojanowski, K. Xie, B. Zhou, arXiv:2406.16803 [hep-ph]