Neutrinos via Charm Decays in Astrophysical Sources

by

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Abstract

Acknowledgements

Abbreviations

AGN Active Galactic Nucleus

CKM Cabibbo, Kobayashi & Maskawa

EWT Electroweak Theory

GR General Relativity

GZK Greisen, Sazepin & Kusmin

PMNS Pontecorvo, Maki, Nakagawa & Sakata

QCD Quantum Chromodynamics

QED Quantum Electrodynamics

QFT Quantum Field Theory

QM Quantum Mechanics

SM Standard Model

SR Special Relativity

Contents

1. Introduction

2. Background

While traversing space, messenger particles are subjected to many different influences, both in terms of type and magnitude, before being detected at earth. Understanding this propagation requires a thorough comprehension of physical processes at all scales of application, from production in astrophysical sources, through interactions with the vast radiation and matter fields that fill the cosmos, to entering the solar system and finally the terrestial atmosphere.

The following sections provide an incomplete overview of aspects relevant to the treatment of this complex topic, as well as references for further study on the various related subjects.

2.1. Particle Physics

In the modern view, interactions and categories of elementary particles are most accurately described by a construct called the *Standard Model* (SM) of particle physics. Underlying this formalism is the mathematical framework known as *Quantum Field Theory* (QFT) that combines and generalizes properties of *Quantum Mechanics* (QM) and *Special Relativity* (SR) to produce an extremely precise description of microscopic reality.

Moreover, the SM is a gauge theory with $\mathrm{U}(1) \times \mathrm{SU}(2) \times \mathrm{SU}(3)$ as the corresponding symmetry group. Each component appearing in this direct product represents its own unitary subgroup and is associated with a different physical field. Excitations in these fields are referred to as quanta and manifest as observable particles. Similar to regular QM there exist both bosonic and fermionic fields that obey analogous commutation and anticommutation relations.

Since this work is mostly concerned with the statistical behaviour of large quantities instead of individual particle probabilistics, a more detailed explanation is omitted except for certain phenomena important to the justification of some later assumptions.

2.1.1. Fundamental Interactions

Electromagnetism is described by *Quantum Electrodynamics* (QED) and mediated by photons γ with Abelian U(1) symmetry, whereas the weak force is carried by Z and $W^{\pm}$ bosons related to the SU(2) group. In terms of *Electroweak Theory* (EWT) all these particles actually result from symmetry breaking of virtual isospin and hypercharge fields, unifying $\mathrm{U}(1) \times \mathrm{SU}(2)$ under a single coherent structure. The previously massless gauge bosons then gain their masses via the Higgs mechanism, where only the γ is excluded and remains without mass.

Notably, the weak interaction exclusively couples to left handed fermions, violating parity.

Chirality, Helicity, Decay, Mixing, Quarks, Color Charge

Carriers of the strong force are named gluons and arise from the SU(3) symmetry group.

Weak, Electromagnetic, Electroweak, Higgs

Parity Violation, Mixing

Limits, Dark Matter, Dark Energy, Neutrino Oscillation, Quantum Gravity

Vector Bosons, Scalar Boson, Boson Spins, Fermion Spins

General Relativity

Leptons

Neutrinos, Decays

Hadrons

Confinement, Asymptotic Freedom, Residual Nuclear Force, Decays

2.2. Multimessenger Astronomy

Gravitational Waves

Charged Cosmic Rays

Photons

Neutrinos

2.3. Astrophysical Sources

Magnetars

Active Galactic Nuclei

3. Methods

4. Results

5. Discussion

6. Conclusion & Outlook

Appendix

A. Reference Frames

Depending on the application, energies in particle physics are either given as viewed from a suitable rest frame or independent from the choice of coordinate system altogether. One widely adopted formulation uses the Mandelstam variables

$$s = (p_1 + p_2)^2 \qquad t = (p_1 - p_3)^2 \qquad u = (p_1 - p_4)^2$$

to assign different channels in scattering processes via the squared momentum carried by the exchanged mediating particle. Implied in this context is the Minkowski inner product, making the above quantities manifestly Lorentz invariant.

When working with parametrizations defined for use in different subdisciplines it often becomes necessary to convert from center of mass energies $\sqrt{s}$ to the energy E of a projectile in the target rest frame. With $E^2 = \boldsymbol{P}^2c^2 + M^2c^4$ as well as momenta $P = (E, \boldsymbol{P})$ and $p = (mc^2, 0)$ one finds

$$s = (P + p)^2 = (E + mc^2)^2 - \boldsymbol{P}^2 = 2Emc^2 + m^2c^4 + M^2c^4$$

for the invariant mass. This relation is typically approximated as $s = 2Emc^2$ at high energies.

B. Cross Sections

Scattering

[1]

Production

Decay

C. Spectral Distributions

D. Pulsar Spindown

E. Implementation

In order to calculate neutrino spectra from hadronic distributions, several integrals have to be computed. Discretizing this task allows the general case

$$F(x, y) = \int dz\, G(x, z)\, H(z, y)$$

to be rewritten as a Riemann sum. Assuming G and H are integrable over a given interval,

$$F_{ij} = \sum_k D_{kk}\, G_{ik}\, H_{kj}$$

converges to the exact solution for sufficiently small steps. Transforming variables

$$x \to x_i \qquad y \to y_j \qquad z \to z_k$$

and defining $D_{kk} = z_{k+1} - z_k$ leads to the above notation. It is easily shown how this expression in terms of indices translates to the product of corresponding matrices

$$\boldsymbol{F} = \boldsymbol{G}\boldsymbol{D}\boldsymbol{H}$$

as an equivalent formulation. Here the output $\boldsymbol{F} \in \mathbb{R}^{m\times n}$ is obtained from the inputs $\boldsymbol{G} \in \mathbb{R}^{m\times l}$ and $\boldsymbol{H} \in \mathbb{R}^{l\times n}$ as well as the square matrix $\boldsymbol{D} \in \mathbb{R}^{l\times l}$ that encodes all step sizes on its diagonal. These results enable quick and efficient implementation of the required calculations as program code, where array arithmetic operations can greatly increase execution speed.[1]

[1] In service of transparency and reproducability, the implementation can be viewed in this repository.

Bibliography

[1] D. Fagundes, M. Menon, *Nuclear Physics A* **880**, 1–11, ISSN: 0375-9474, DOI: 10.1016/j.nuclphysa.2012.01.017, arXiv: 1112.5115 [hep-ph] (2012).

Figures

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