

Weak interactions and quasi-stable particle energy loss

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Abstract. We discuss the interplay between electromagnetic energy loss and weak interactions in the context of quasistable particle propagation through materials. As specific examples, we consider staus, where weak interactions may play a role, and taus, where they don't.

1. Introduction

Large underground and under-ice neutrino telescopes detect through-going charged particles by the Cherenkov light they emit in transit. Proposals to measure tau neutrino fluxes, e.g., $\nu_\tau \rightarrow \tau$ followed by τ decay (via the double bang signal [1] or either the tau production or decay vertex) are possible in the 1-10 PeV neutrino energy range [2]. For higher energies, above about 20 PeV, taus may be considered quasi-stable particles, in that their decay lengths are larger than the size of the detector. Muons are quasi-stable particles on the scale of 1 km even for energies in the GeV range.

Recently, supersymmetry models with weak scale supersymmetry breaking [3] have led to studies of quasi-stable stau ($\tilde{\tau}$) signals in neutrino telescopes [4-7]. In these studies, pairs of staus come from the decays of supersymmetric particles produced by neutrinos interacting in the Earth. The signature would be a pair of tracks from charged particles, the staus, passing through the detector. Neutrino production of supersymmetric particles is suppressed, but the signal can be enhanced by the large effective volume of the detector, characterised by the cross sectional area of the detector multiplied by the range of the staus.

Electromagnetic energy loss is a key feature of charged particle ranges for muons, high energy taus and high energy staus. On average, the energy loss per unit distance is

$$\left\langle \frac{dE}{dX} \right\rangle = -(\alpha + \beta E) \quad (1)$$

where $\alpha \simeq 3 \times 10^{-3}$ GeV cm²/g is due to ionization energy loss, while β depends on the mass of the traveling particle with contributions from bremsstrahlung, e^+e^- pair production and photonuclear interactions. For muons, $\beta_\mu \simeq 3 \times 10^{-6}$ cm²/g, while for taus, $\beta_\tau \simeq 2 \times 10^{-7}$

cm²/g. Schematically, for staus,

$$\beta_{\tilde{\tau}} \sim \left(\frac{m_{\tau}}{m_{\tilde{\tau}}} \right) 2 \times 10^{-7} \text{ cm}^2/\text{g} . \quad (2)$$

We have evaluated the energy loss parameter β for staus more quantitatively in Ref. [7].

The parameter β can be converted to a distance scale by multiplying by a density. For the figures below, the density $\rho = 2.65 \text{ g/cm}^3$ is for standard rock. There is a weak energy dependence for the β parameters for each of the particles. For taus, $(\beta_{\tau\rho})^{-1} \simeq 10 \text{ km}$ at a PeV and decreases with energy. Muons have a characteristic distance of $(\beta_{\mu\rho})^{-1} \simeq 1 \text{ km}$. Staus, on the other hand, have $(\beta\rho)^{-1} \simeq 1000 \text{ km}$ for $E = 1 \text{ PeV}$.

Another characteristic distance relevant to muon, tau and stau propagation through ice, water or rock is the weak interaction length. For $E_{\tau} = 10^{10} \text{ GeV}$, the tau charged-current interaction length is of order 10^3 km . The muon and stau interaction lengths are of the same order of magnitude. By comparing to $(\beta\rho)^{-1}$, we see that weak interactions are potentially important for staus, but not for taus. For muons, the distance scales are even further separated, so we confine our discussion to taus and staus.

In the next section, we discuss the weak interaction contributions to stau energy loss in the Earth. We have evaluated the range of taus and staus, for specific SUSY model parameter choices, using a Monte Carlo simulation including stochastic energy loss. In the last section, we compare the stau ranges with and without including weak interactions based on the Monte Carlo simulation results.

2. Weak interactions of staus

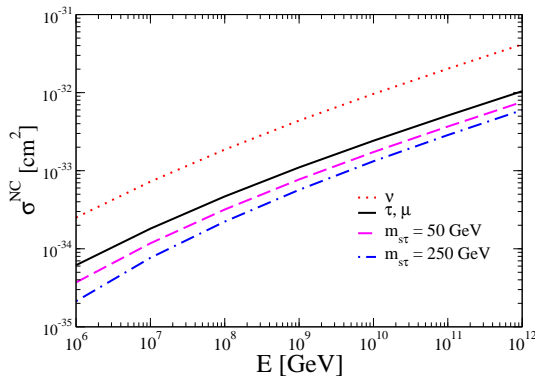


Figure 1. Neutral current cross section versus energy for neutrinos, muons, taus and staus with $m_{\tilde{\tau}} = 50, 250 \text{ GeV}$ and $\cos 2\theta_f = 1$.

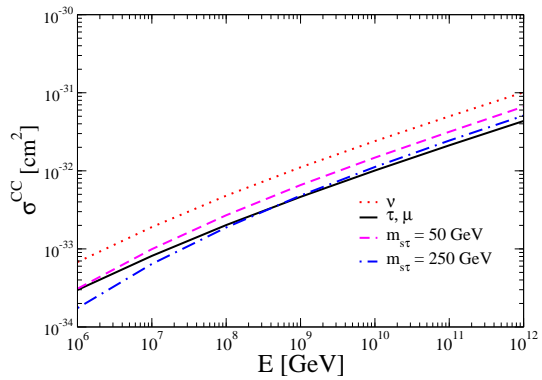


Figure 2. The charged current cross section versus energy. For staus, the curves are shown for $\sin \theta_f = 1$.

The charged current (CC) and neutral current (NC) interactions of taus are related to neutrino interactions, with the appropriate substitution of couplings and the tau spin average. Stau weak interaction cross sections depend on the stau mass, the relation between the stau mass eigenstates and the partners of the left-handed and right-handed taus and the scalar couplings with the W and Z . In these models, the next-to-lightest supersymmetric particle is the stau with

$$\tilde{\tau} = \cos \theta_f \tilde{\tau}_R + \sin \theta_f \tilde{\tau}_L .$$

We take θ_f to be a free parameter. For both NC and CC stau interactions, the couplings depend on θ_f .

In Fig. 1, we show the NC cross section for neutrinos, taus, muons and staus ($m_{\tilde{\tau}} = 50, 250$ GeV) picking $\cos 2\theta_f = 1$. We show this range of masses to give an indication of the dependence on the stau mass. LEP experiments constrain the stau mass to be larger than ~ 100 GeV [8]. Fig. 2 shows the CC cross section for the same incident particles, this time for staus with $\sin \theta_f = 1$, the maximal value. If $\tilde{\tau} = \tilde{\tau}_R$, the CC cross section for staus vanishes.

Electromagnetic and NC interactions act the same way, in that they reduce the initial energy of the incident particle to a lower energy. For taus, and even for staus, the NC energy loss is small compared to the electromagnetic energy loss. In what follows we neglect the NC interactions. The CC interaction, however, is important for staus if $\sin \theta_f = 1$. The CC interaction removes staus from the incident flux. For taus, the CC interaction is not important compared to the electromagnetic energy loss, as we show in the next section.

3. Ranges

In this section, we show results for the range for taus and staus and the effect of CC interactions [9]. For taus, one approach has been to look at the different scales: the decay length, $1/(\beta\rho)$ and the charged current interaction length L_{τ}^{CC} [10]. Here, instead, we show the results for a full stochastic treatment of tau energy loss including weak interactions [11,12]. The range for taus in rock is shown with the solid lines in Fig. 3. The dashed lines show the characteristic scales. With the exception of the decay length for low energies, none of the characteristic scales aligns with the range. For electromagnetic energy loss, this is not surprising since $1/(\beta\rho)$ is not a solution to Eq. (1). The CC interaction length is long compared to the tau range determined from electromagnetic interactions alone, so its effect is not visible on the scale of this figure.

Fig. 4 shows the characteristic scales (dashed lines) for a stau traveling through rock. The stau mass is 150 GeV and the decay parameter is $\sqrt{F} = 10^7$ GeV for this figure, where

$$c\tau = \left(\frac{\sqrt{F}}{10^7 \text{ GeV}} \right)^4 \left(\frac{100 \text{ GeV}}{m_{\tilde{\tau}}} \right)^5 10 \text{ km}. \quad (3)$$

For this choice of \sqrt{F} , ionization energy loss characterized by the distance scale E/α is relevant while $Ec\tau/m_{\tilde{\tau}}$ is not. The minimum energy of the stau for evaluating the range is $E_0 = 10^3$ GeV in Fig. 4. The upper solid line shows the range when $\sin \theta_f = 0$, namely, no CC interactions affect the range. The lower solid line shows the effect of including maximal CC interactions. Similar results are obtained for other masses [9]. We note again in Fig. 4 that the characteristic scales at high energies are only qualitative representations of the stau range.

4. Conclusions

We have shown here that the characteristic scales do not give an accurate picture of the range of staus or taus. For taus, the characteristic scale of the CC interaction length does show that the tau range is mainly unaffected by CC interactions, even at $E = 10^{12}$ GeV, as shown in Fig. 3. The stochastic treatment of the staus is essential, however, for a determination of the stau range. Because of electromagnetic energy loss, the stau range is not equal to the CC interaction length. Even when $\sin \theta_f = 1$, the range is larger than $L_{\tilde{\tau}}^{CC}$ at high energies because electromagnetic interactions degrade the stau energy, and $L_{\tilde{\tau}}^{CC}$ increases with decreasing energy.

The results of Fig. 4 show that generically for neutrino telescopes sensitive to fluxes below 10^6 GeV, maximal weak interactions of the staus will have a small numerical impact on the event rate. On the other hand, experiments sensitive to high energies like ANITA and its successors will be greatly impacted by CC interactions if $\sin \theta_f \simeq 1$ given measurable neutrino fluxes. The high energy signal of staus is currently under investigation [13].

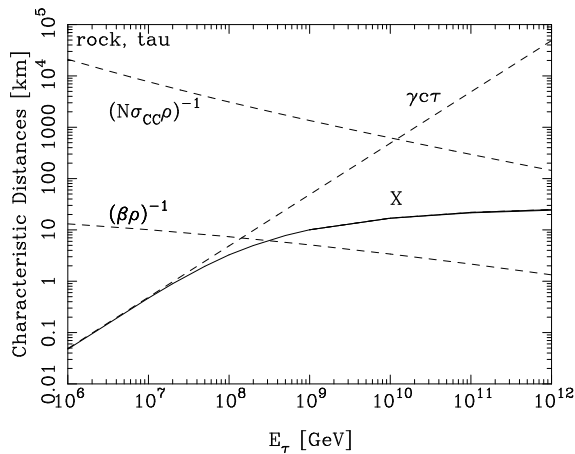


Figure 3. Characteristic distances for taus in rock: dashed lines for decay length ($\gamma c\tau$), $1/(\beta\rho)$ and $L_{\tau}^{CC} = 1/(N\sigma_{CC}\rho)$, and the solid line for the tau range. The curves with and without CC interactions are indistinguishable on the scale of this figure.

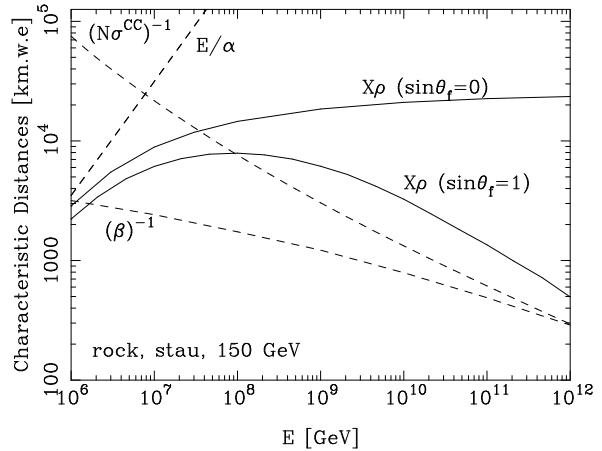


Figure 4. Characteristic distances in km.w.e. for a stau with mass of 150 GeV moving through rock. Here $\sqrt{F} = 10^7$ GeV in Eq. (3). The upper solid line is the stau range with no CC interactions ($\sin\theta_f = 0$), and the lower solid line is for maximal CC interactions.

Acknowledgments

We thank J. Beacom for bring to our attention to the similarity in distance scales for staus. We acknowledge Shufang Su's contributions to the work on electromagnetic energy loss of staus and Yiwen Huang's contribution to the work on the weak interaction cross section of staus. This work was supported in part by DOE contracts DE-FG02-91ER40664, DE-FG02-04ER41319 and DE-FG02-04ER41298 (Task C).

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