PROCEEDINGS OF SCIENCE

SHiP: a new facility with a dedicated detector for neutrino physics

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The SHiP facility recently proposed at CERN copiously produces all neutrino flavours, including tau neutrinos, the less known particle in the Standard Model. The SHiP experiment includes a neutrino detector capable of seeing all three neutrino flavours. The integrated statistics in five years run with 2×10^{20} protons on target allows to study the tau neutrino and anti-neutrino cross-sections and to provide the first direct observation of tau anti-neutrinos. Moreover, charmed hadrons are copiously produced in the high rate of neutrino interactions, thus providing good sensitivity to the strange quark distribution in the nucleon. The physics potential of the SHiP neutrino detector is outlined here including its sensitivity to dark matter searches.

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1. Introduction

The tau neutrino is the less known particle in the Standard Model. Four candidates were reported in 2001 by the DONUT experiment [1] and the observation of this particle was finally confirmed in 2008 when 9 candidates events were reported with an estimated background of 1.5 [2]. In the same paper they reported, for the first time, the tau neutrino cross-section where the constant term was measured to be $\sigma_{\nu_\tau}^{const} = (0.39 \pm 0.13 \pm 0.13) \times 10^{-38} cm^2 GeV^{-1}$. The large uncertainty is due to the poor statistical sample and to the rather scarce knowledge of the incoming flux. On top of the large uncertainty, DONUT could not separate tau neutrinos from anti-neutrinos. Moreover, the OPERA experiment [3] has detected five tau neutrinos [4, 5, 6, 7, 8], discovering the tau neutrino appearance from muon neutrino oscillations. The only leptonic decay observed by OPERA [6] shows negative charge as expected from a ν_τ interaction. Therefore, so far there is no direct evidence for tau anti-neutrinos.

A facility to search for hidden particles, i.e. particles in the GeV mass range with very small couplings to ordinary matter, has been recently proposed to operate at the SPS at CERN: the Collaboration has submitted a Technical Proposal [9] and a large group of theorists has outlined the physics case for such an experiment [10]. The facility would use 2×10^{20} 400 GeV protons, produced by the SPS accelerator complex, impinging on a 10 interaction length target made of Molybdenum and Tungsten, followed by an hadron absorber. Hidden particles in the GeV mass range would be produced mostly by the decay of charmed hadrons produced in proton interactions. D_s mesons, copiously produced among charmed hadrons, are a good source of tau neutrinos through their fully leptonic decay. Therefore, the SHiP facility is ideal also to study the physics of tau neutrinos.

The number of ν_τ and $\bar{\nu}_\tau$ emerging from the molybdenum target can be estimated as follows:

$$N_{\nu_\tau + \bar{\nu}_\tau} = 4 N_p \frac{\sigma_{c\bar{c}}}{\sigma_{pN}} f_{D_s} Br(D_s \to \tau) = 2.85 \times 10^{-5} N_p = 5.7 \times 10^{15} \tag{1.1}$$

where

- N_p is the number of interacting protons (all incoming ones);
- $\sigma_{c\bar{c}} = 18.1 \pm 1.7\ \mu$barn [11] is the associated charm production per nucleon. The corresponding cross-section per nucleus is proportional to the mass number A;
- $\sigma_{pN} = 10.7$ mbarn is the hadronic cross-section per nucleon in a Mo target. The inelastic cross-section pA shows the $A^{0.71}$ dependence [12];
- $f_{D_s} = (7.7 \pm 0.6^{+0.5}_{-0.4})\%$ [13] is the fraction of D_s mesons produced;
- $Br(D_s \to \tau) = (5.54 \pm 0.24)\%$ [14] is the D_s branching ratio into τ;
- the factor 4 accounts for the charm pair production and for the two ν_τ produced per D_s decay.

The SHiP facility is therefore a ν_τ factory, with 5.7×10^{15} tau neutrinos produced, equally divided in neutrinos and anti-neutrinos. The uncertainty on this number is about 14% but the uncertainty on the differential neutrino flux is estimated to be about 20%.

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The left plot of figure 1 shows the SHiP facility: downstream of the target, the hadron absorber filters out all hadrons, therefore only muons and neutrinos are left. An active muon shield is designed with two sections with opposite polarity to maximize the muon flux reduction: it reduces the muon flux from $\sim 5 \times 10^9$ muons/spill down to about 10^4 per spill. The tau neutrino detector is located downstream of the muon shield, followed by the decay vessel and the detector for hidden particles. The right plot of figure 1 shows a zoomed view of the tau neutrino detector. The neutrino detector is made of a magnetised target region, followed by a muon spectrometer. The neutrino target is based on the emulsion cloud chamber technology employed by the OPERA experiment [3], with a compact emulsion spectrometer, made of a sequence of very low density material and emulsion films to measure the charge and momentum of hadrons in magnetic field. Indeed, this feature would allow to discriminate between tau neutrinos and anti-neutrinos also in the hadronic decay channels of the tau lepton. The emulsion target is complemented by high resolution tracking chambers to provide the time stamp to the event and connect muon tracks from the target to the muon spectrometer.

Given the neutrino target mass of 9.6 tons, the neutrino flux, the geometrical acceptance of the detector and the standard model cross-section [15], one expects about 6700 interactions of tau neutrinos and 3400 of tau anti-neutrinos. An uncertainty smaller than 10% affects the cross-section mainly due to uncertainties on scale choices, parton distribution functions and target mass corrections [15]. Therefore the uncertainty on the expected number is dominated by the 20% error on the differential neutrino flux.

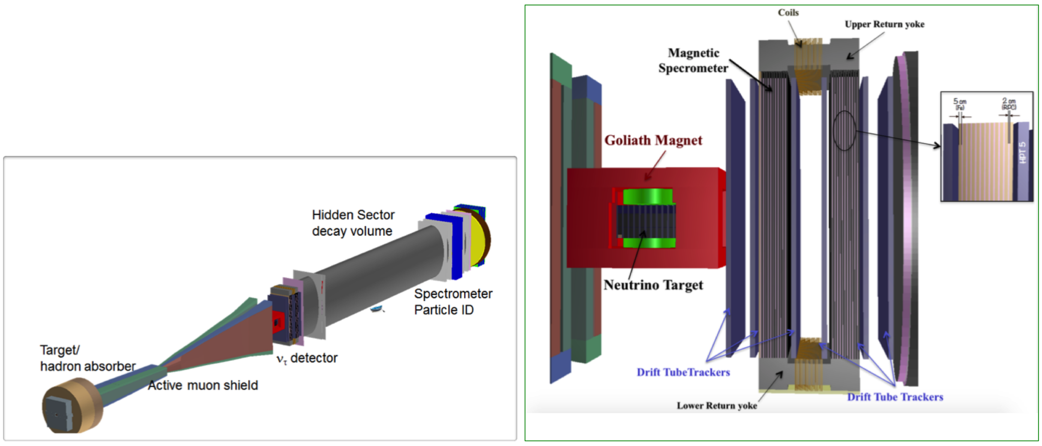

Figure 1: The SHiP detector (left). Zoom on the tau neutrino detector (right).

2. Physics performances

The charged-current ν_τ $(\overline{\nu}_\tau)$ differential cross-section is given by five structure functions:

$$\frac{d^2\sigma^{\nu(\overline{\nu})}}{dxdy} = \frac{G_F^2 M E_\nu}{\pi(1+Q^2/M_W^2)^2}\Bigg((y^2x+\frac{m_\tau^2 y}{2E_\nu M})F_1+\left[(1-\frac{m_\tau^2}{4E_\nu^2})-(1+\frac{Mx}{2E_\nu})\right]F_2$$
$$\pm\left[xy(1-\frac{y}{2})-\frac{m_\tau^2 y}{4E_\nu M}\right]F_3+\frac{m_\tau^2(m_\tau^2+Q^2)}{4E_\nu^2 M^2 x}F_4-\frac{m_\tau^2}{E_\nu M}F_5\Bigg),$$

where x, y and Q^2 are connected via the $Q^2 = 2M_N E_\nu xy$ relationship. The contribution to the cross-section of F_4 and F_5 structure functions, introduced by Albright and Jarlskog [16], is negligible in muon and electron neutrino interactions due to the charged lepton mass. On the contrary, given the non-negligible mass of the τ lepton, tau neutrino scattering is sensitive to their contribution. At the leading order, in the limit of massless quarks and target hadrons, the predicted values are $F_4 = 0$ and $2xF_5 = F_2$ [16]. Calculations at NLO show that F_4 gives a contribution to the cross-section of about 1% at the neutrino energy of 10 GeV [15].
SHiP is sensitive to F_4 and F_5. Indeed, the hypothesis of $F_4 = F_5 = 0$ would significantly increase the ν_τ and $\overline{\nu}_\tau$ charged-current deep-inelastic cross sections and the corresponding number of expected ν_τ and $\overline{\nu}_\tau$ interactions. Figure 2 shows the energy dependence of the ratio between the tau anti-neutrino cross-section when F_4 and F_5 vanish and the Standard Model prediction. The region below 40 GeV is highly sensitive to the non-zero values of these structure functions: a 3 σ excess is expected, given that the ratio exceeds 1.6 in this region.

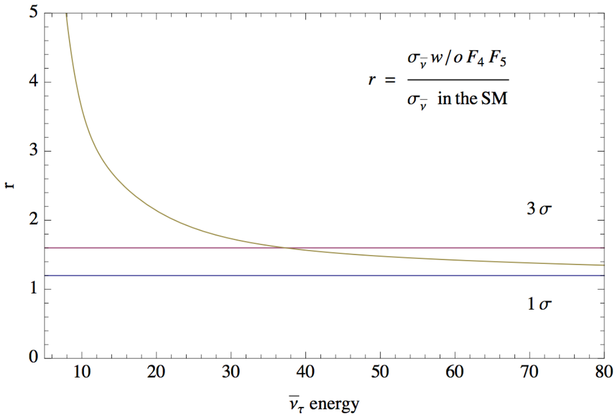

Figure 2: Energy dependence of the ratio between the DIS cross section in the $F_4 = F_5 = 0$ hypothesis and the SM prediction for $\bar{\nu}_\tau$.

2.1 Charm physics and strange parton distributions

Charmed hadrons are produced in neutrino and anti-neutrino charged-current interactions at the level of several percent. Experiments based on calorimetric technology identify charmed hadrons only in their muonic decay channel, when two opposite sign muons are produced in the final state. A cut of 5 GeV is applied to muons in order to suppress the background due to punch-through pions. The nuclear emulsion technolgy, instead, identifies topologically the charmed hadron by detecting its decay vertex. Energy cuts are therefore much looser, thus providing a better sensitivity to the charm quark mass. Moroever, a large statistical gain is provided by the use of hadronic decay modes [17]. Indeed, despite the fact that 1.280.000 ν_μ and 270.000 $\bar{\nu}_\mu$ charged-current events were collected by the NuTeV/CCFR Collaboration, only 5102 ν_μ and 1458 $\bar{\nu}_\mu$ events were identified as charm production induced by neutrino charged-current interactions. The largest number of events in an emulsion experiment was collected by CHORUS which integrated 2013 charm candidates from ν_μ and only 32 from $\bar{\nu}_\mu$ [18]. SHiP will integrate about 10^5

charm candidates, more than one order of magnitude larger than the present statistics, with a large ($\sim 30\%$) contribution from anti-neutrinos. Charm production in neutrino scattering is extremely sensitive to the strange quark content of the nucleon, especially with anti-neutrinos where the s-quark is dominant. SHiP will improve significantly the uncertainty on the strange quark distribution in the nucleon as shown in Fig. 3 in terms of $s^+ = s(x) + \bar{s}(x)$.

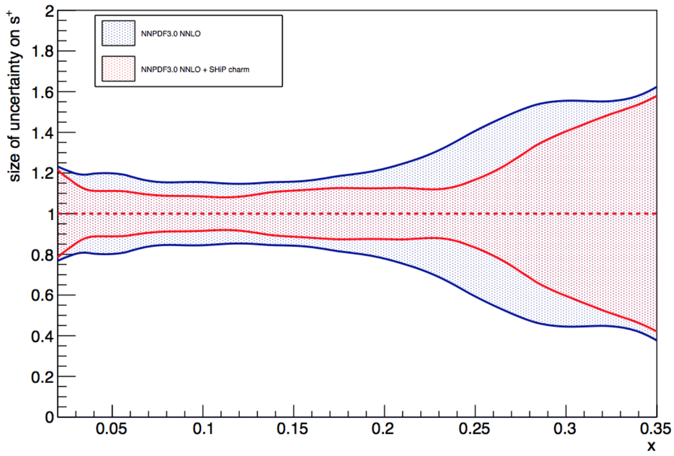

Figure 3: Improvement of the accuracy on s^+ with SHiP (red) compared to the present status (blue).

2.2 Dark matter search

The neutrino detector may also detect dark matter candidates χ produced by a dark photon decay [19] through their elastic scattering on electrons, $\chi e^- \to \chi e^-$. The signature in emulsion would be a vertex with only an electron coming out. Background processes are mostly given by charged-current quasi-elastic and resonant electron neutrino scattering off nucleons when only the electron is detected in the final state. The contribution from the elastic scattering of all neutrinos off electrons is also accounted. Cuts on the electron scattering angle, $0.01 < \vartheta < 0.02$, and on the neutrino energy, $E < 20$ GeV, reduce the background to about 284 events in five years run. Given this expected background, upper limits at 90% C.L. can be derived on the $\chi e^- \to \chi e^-$ scattering of dark matter candidates, which in turn may be translated into the dark photons parameters as shown in Fig. 4. In this plot, the excluded region by SHiP is shown together with other experiments, in the plane defined by the dark photon mass m_A and its coupling to the e.m. current ε for a choice of the dark matter mass $m_\chi = 200$ MeV and its coupling with the dark photon $\alpha' = 0.1$.

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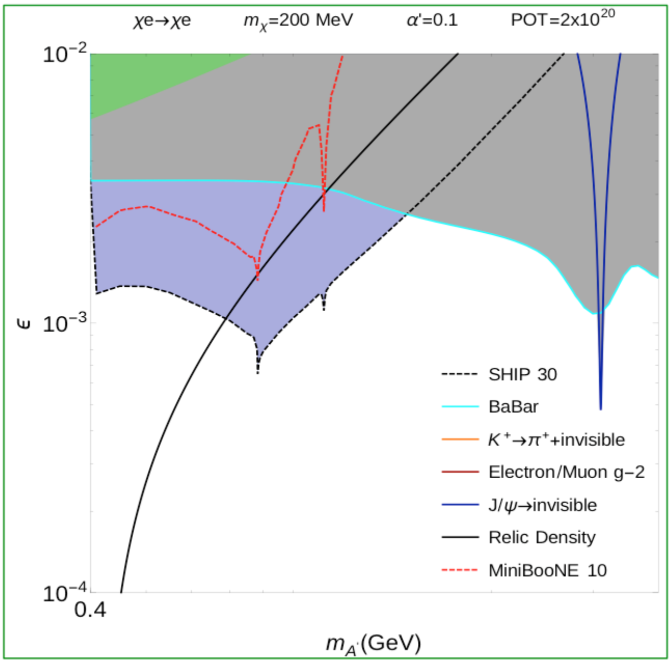

Figure 4: Excluded region on the dark photon parameters via the dark matter search.

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