

NEUTRINO FLUENCE ESTIMATES FOR FORWARD EXPERIMENTS AT A 10 TeV MUON COLLIDER

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Abstract

Intense and highly collimated neutrino beams are intrinsic by-products of muon decays in a high-energy muon collider. The large boost of the primary muons confines the emitted neutrinos within angular spreads of order of 10^{-5} rad, resulting in fluxes far exceeding those achievable in conventional neutrino facilities. Their unique properties also open opportunities for high-energy neutrino physics. In this work, the neutrino beams produced near the interaction point are characterised in terms of their spatial and energy distributions, with emphasis on their potential use for dedicated neutrino detectors. The neutrino fluence is evaluated as a function of distance from the interaction point for representative detector acceptances. At short distances, larger acceptances intercept nearly the entire neutrino core, leading to fluence saturation, while at kilometre scales the neutrino spot size becomes non negligible. These results demonstrate the strong collimation and intensity of muon-collider neutrino beams and support their potential use in high-precision, high-energy neutrino studies.

INTRODUCTION

The muon collider is a proposed next-generation particle physics facility aiming to reach centre-of-mass energies in the multi-TeV range within a compact footprint [1, 2]. By colliding muons rather than protons or electrons, it combines the high centre-of-mass energy of hadron machines with the cleaner initial state of a lepton collider. However, the short muon lifetime ($\tau_\mu \approx 2.2 \mu\text{s}$) means that a significant fraction of muons decay before reaching the interaction point (IP), making both the machine and detector design particularly challenging. In particular, the muons decay in two neutrinos and an electron/positron:

$$\begin{cases} \mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu \\ \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \end{cases}$$

Therefore, a unique feature of a muon collider is the production of intense, collimated neutrino beams. Each muon decay produces a pair of neutrinos that, in the laboratory frame at multi-TeV energies, are boosted into extremely narrow cones along the beam direction. The resulting fluxes can reach values many orders of magnitude higher than those achievable at conventional neutrino facilities, opening up possibilities for precision cross-section measurements and searches for new interactions in the neutrino sector.

Many works in the literature describe the physics potential of muon collisions [3, 4]. In addition, the exploitation of

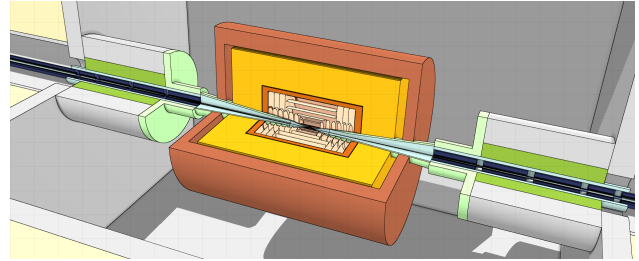


Figure 1: Machine-detector interface of a 10 TeV muon collider. In the picture, the final focus elements and the detector are shown.

neutrinos produced in muon decays is beginning to attract interest within the theory community [5]. This paper presents the neutrino fluences and spectra that could be available for a forward experiment at a 10 TeV center-of-mass energy muon collider.

The straight sections of the collider ring near the IP are particularly relevant in this context. Muon decays along these sections produce neutrinos that accumulate into intense, nearly collinear beams directed along the beam axis. These beams have two key consequences: they impose radiological constraints on the collider siting and optics design [6, 7], and they offer a remarkable opportunity for high-energy neutrino physics with a dedicated forward detector. In this paper, we focus on the latter, characterising the neutrino beams near the IP and evaluating the achievable fluence for representative detector configurations.

NEUTRINO BEAM GENERATION IN THE INTERACTION REGION

A critical aspect of the muon collider design is the Machine-Detector Interface (MDI), the region where the accelerator and detector systems must coexist. At a muon collider, the MDI faces a distinctive challenge: the decay products of the circulating muon beams (electrons and positrons) create a severe background environment for the detector [8, 9]. To suppress this background, two tungsten nozzles are placed inside the detector volume, shielding sensitive components from the secondary particles arising from muon decays [10, 11].

In Fig. 1, the main elements are shown. A large experimental cavern surrounds the detectors. The detector shown in the figure represents one of the options available in the literature [12, 13]. Immediately downstream of the detector and the nozzles, the final-focus elements are surrounded by several layers of shielding (tungsten, steel, concrete and borated polyethylene). All results presented correspond to

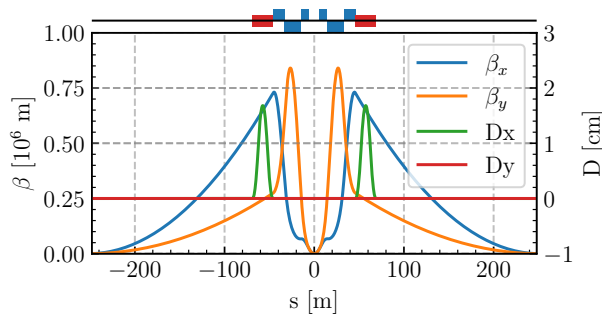


Figure 2: Optics functions and machine elements in the IR. The blue boxes represent quadrupoles (focusing when above the line), while the red ones represent dipoles. The line includes the IRs on both sides of the IP.

optics version 0.8 [14]. The Interaction Region (IR) design includes a short dipole chicane for background mitigation: it removes all secondary particles coming from the beamline.

A long straight section is required to smoothly reduce the β functions before the next sections of the collider ring. The IR elements, together with the betatron and dispersion functions, are shown in Fig. 2, which includes the total trajectory length of 497.4 m considered for the simulation. For these Twiss parameters, the angular divergence of the muon beam in the long drift region is very small, reaching values as low as ~ 0.1 mrad, as shown in Fig. 3.

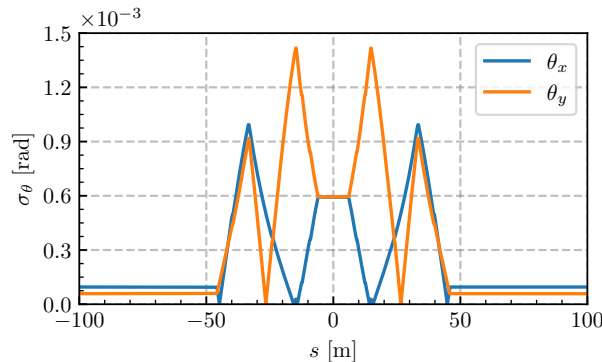


Figure 3: Angular divergence of the muon beam in the horizontal (x) and vertical (y) planes.

The primary muon particle position and direction are sampled from the matched phase space of the beam. Muon decays are then simulated using FLUKA [15, 16]. We assume unpolarized muon beams in the collider ring. Any residual polarization would need to be taken into account to accurately model the neutrino spectra.

Because of the very high energy of the primary muon beam, the decay products exhibit an extremely narrow angular distribution. As shown in Fig. 4, most neutrinos relevant for physics applications are emitted within a few 10^{-5} rad. With such small angular divergences, the beam optics become the dominant factor in determining the final direction of the emitted neutrinos. Only in the long drift does the intrinsic divergence of the neutrino emission become comparable to the beam angular spread.

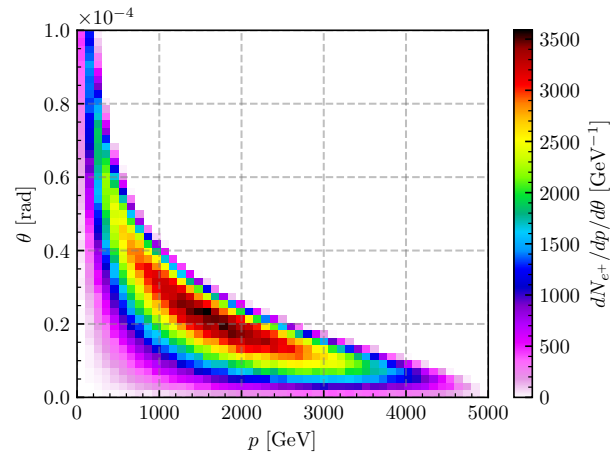


Figure 4: Angle-momentum 2D distribution of the electronic neutrino component from a 10 TeV muon decay. A very similar shape is found in the muonic neutrino component.

At present, no beam dump is assumed to be necessary for the muon beams. Therefore, it is reasonable to assume that the muons decay uniformly along the collider ring. The total intensity of the neutrino beams is then directly proportional to the injected muon beam population. The filling scheme of the muon collider assumes a single bunch containing 1.8×10^{12} muons per beam. The two counterrotating beams share the same beam pipe and they are injected at 5 Hz [2].

FLUENCE ESTIMATES

To quantify the neutrino beam intensity available to a forward physics detector, the average fluence was evaluated for two representative circular target acceptances with radii of 1 cm and 10 cm. The fluence is defined as the total number of neutrinos crossing the target divided by its area and is evaluated as a function of the distance from the IP. The target is assumed to be centred on the beam axis, with its surface perpendicular to the beam direction, and represents a purely geometrical acceptance without material effects.

The resulting distributions, shown in Fig. 5, reveal two distinct regimes. At distances below approximately 1 km, the fluence through the 10 cm target saturates: the target subtends a sufficiently large acceptance to intercept nearly the entire central core of the neutrino beam, and the fluence approaches a value determined by the total neutrino yield per muon decay. At larger distances, angular divergence causes the beam to spread transversely, and the fluences for the two target sizes converge as the beam becomes approximately uniform across each target area.

At a distance of 1 km from the IP, the neutrino beam remains extremely well collimated. Assuming a target radius of 10 cm, this corresponds to average fluences on the target of the order of $5 \times 10^{12} \text{ m}^{-2} \text{ s}^{-1}$ per neutrino flavour. Under the current machine parameters [2], the operation time per year is $1 \times 10^7 \text{ s}$. This implies that the total number of neutrinos intercepting the target per year is:

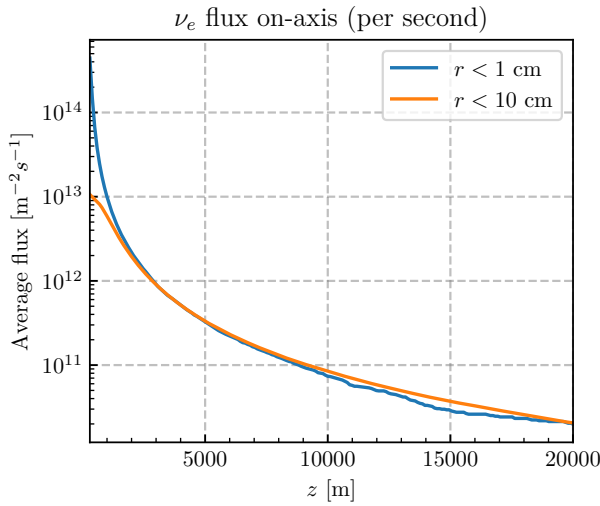


Figure 5: Average electronic neutrino flux through circular targets of radius 1 cm and 10 cm as a function of distance from the IP.

$$N = \phi A t_{\text{eff}} \approx 10^{20} \text{ y}^{-1} \quad (1)$$

where ϕ is the sum of the neutrino flavour fluences, A is the illuminated area, and t_{eff} is the fraction of time during which the beam is on per year.

The transverse profile, shown in Fig. 6, exhibits a sharp central core, with the majority of neutrinos concentrated within a narrow region around the beam axis. Tails visible in the horizontal direction arise from beam halo contributions and from decays occurring in the chicane section upstream, which introduce a slight deviation from the axial trajectory. Overall, most of the neutrino beam is contained within a few tens of centimetres in the transverse direction. Assuming different distances from the collider IP, the spot size

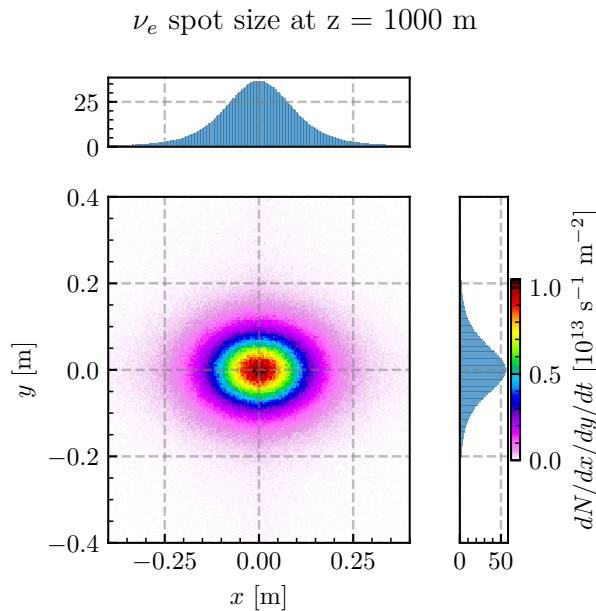


Figure 6: Transverse neutrino spot at 1 km from the IP.

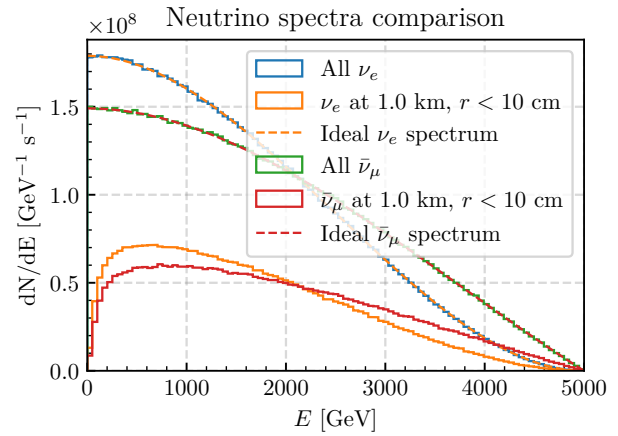


Figure 7: Energy spectrum of neutrinos intercepted by a 10 cm target at 1 km. The ideal spectrum calculated analytically, and perfectly overlaps the FLUKA simulations.

scales approximately linearly in each direction, leading to a quadratic scaling of the spot area. At very short distances, the contribution from the intrinsic muon beam spot size becomes relevant, while it is negligible beyond the first few hundred metres.

The energy spectrum of neutrinos intercepted by the 10 cm-radius target at 1 km, shown in Fig. 7, reflects the kinematics of muon decay in flight. The spectrum extends to the kinematic limit at $E_\nu \approx E_\mu$, with a strong forward boost that concentrates the yield at high energies. Since the 10 cm target fully covers the central beam core at this distance, leaving out the tails, two effects are observed in the measured spectrum. The first is a reduction in the total estimated intensity, as part of the flux is not intercepted. The second arises from the energy-angle correlation. In this case, the spectrum is distorted, as neutrinos with the largest angles tend to have lower energies.

CONCLUSION

The neutrino beams produced near the IP of a 10 TeV muon collider are characterised by exceptional collimation and intensity. The average fluence has been evaluated as a function of distance from the IP for two representative detector acceptances. A saturation regime is identified at short distances, where a 10 cm-radius target intercepts essentially the full neutrino core, while at kilometre-scale distances the fluence decreases as beam spot size becomes significant. At 1 km, the beam retains a sharp transverse core and a high-energy spectrum extending to $E_\nu \approx E_\mu$, making it a compelling source for high-precision neutrino physics.

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