

Muon Colliders and the Neutrino Slice

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Muon colliders provide an exciting new direction to expand the energy frontier of particle physics. We point out a new use of these facilities for neutrino and beyond the standard model physics using their main detectors. Muon decays along the accelerator rings create an intense and highly collimated neutrino beam that crosses a thin slice of the kt-scale detector. As a result, it would induce an unprecedented number of neutrino interactions, with $\mathcal{O}(10^4)$ events per second for a 10 TeV $\mu^+\mu^-$ collider. These interactions are highly energetic and possess a distinct timing signature and a large transverse displacement. We discuss promising applications of these events for instrumentation, electroweak, and beyond-the-standard model physics. For instance, a subpercent measurement of the neutrino-electron scattering rate enables new precision measurements of the Weak angle and a novel detection of the neutrino charge radius.

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The discovery of the Higgs boson by the Large Hadron Collider (LHC) in 2012 was a major triumph for the standard model (SM) of particle physics [1,2]. The new era centered around the fundamental puzzles of the SM, such as the nature of electroweak symmetry breaking, the origin of neutrino masses, and the nature of dark matter, now calls for exploration beyond TeV scales. With their compact size (10 km circumference), the high precision achievable in signal and background predictions, and the total number of Higgs bosons produced, muon colliders (MuCs) with a center-of-mass energy of $\sqrt{s} \sim (1 - 10)$ TeV are strong contenders to push this energy frontier; their inherent complexity also presents new challenges and opportunities to develop new accelerator and detector technology. A renewed interest in these facilities led to feasibility studies of $\mu^+\mu^-$ colliders by the International Muon Collider Collaboration (IMCC) [3–5] and the US muon collider community [6,7], efforts that are informed by the European Strategy for Particle Physics [8] and the P5 report in the US [9–11] as well as by past work by the Muon Accelerator Program (MAP) [12] (see also Refs. [13,14]). New ideas for μ^+ beams based on muonium cooling are also being considered at J-PARC [15,16].

Even if low-emittance muon beams are demonstrated, a MuC design still requires optimization of the detector and muon interaction region (IR) to minimize the impact of beam-induced backgrounds (BIBs) coming from $\mu^\pm \rightarrow e^\pm \nu \bar{\nu} (\gamma)$ decays and their secondaries. An accelerated bunch of N_μ muons decays at a rate of $R = (N_\mu m_\mu)/(p_\mu \tau_\mu) \sim 1.6 \times 10^5 \text{ m}^{-1} (N_\mu/10^{12}) (p_\mu/1 \text{ TeV})^{-1}$,

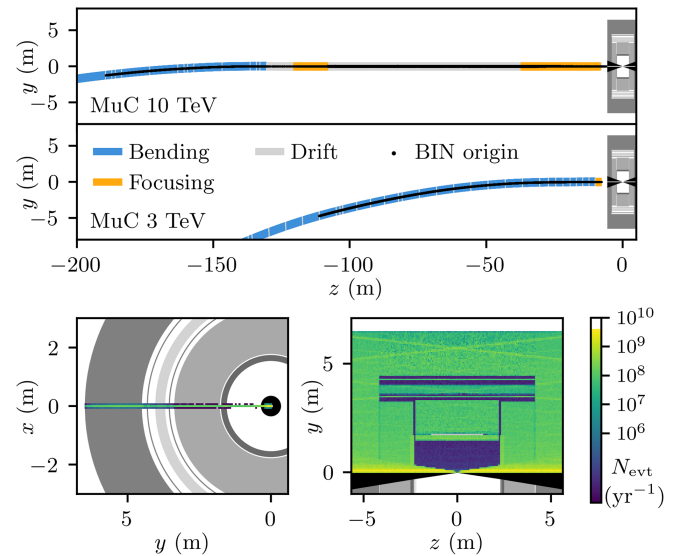


FIG. 1. Top: the positions of the muon decay (color) along the ring with a BIN crossing the main detector (gray region) for the two benchmark MuC designs, highlighting the different magnet systems. Bottom: a radial (left; the neutrino slice) and top-down (right) view of the detector barrel and the number of BIN interactions from both muon beams in a year of operation of the MuC 10 TeV design. Black regions indicate the tungsten nozzles.

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where p_μ is the momentum of the muons and $\tau_\mu = 2.2 \mu\text{s}$, m_μ the muon lifetime and mass, respectively. While the accelerator magnets deflect charged particles, neutrinos will travel tangentially to the beam and cannot be shielded against; as a result, beam-induced neutrinos (BINs) will produce highly energetic muons, electrons, and hadrons through Weak interactions with detector materials. These BIN interactions would populate the entire radius of the barrel-shaped main detector at the IR, spanning a small azimuthal slice aligned with the plane of the collider ring (hereafter referred to as the neutrino slice, see, Fig. 1). This behavior of BINs is in stark contrast with ordinary BIBs, which mostly affect the inner layers of the detector, beam pipes, and magnets in almost cylindrically symmetric ways. BINs originate from as far as $\mathcal{O}(30 - 100)$ m from the IR and can be asynchronous to the bunch crossings.

This Letter represents a first step in exploring the BIN physics program at a MuC. With current targets for muon beam power at future MuCs, BINs would provide the largest sample size of detectable neutrino-nucleus and neutrino-electron interactions and the highest-energy, most collimated, and most well-characterized neutrino beam ever produced in a laboratory. To exploit this unique neutrino beam, rejecting backgrounds from beam loss and muon-decay BIBs is crucial; this calls for future studies that leverage the distinct energy and spatiotemporal profile of BINs. Detection of the most forward part of BINs is also complementary to new ideas to tag forward-going muons to measure Higgs boson properties [17–21] and the Higgs boson width [19]. While BINs have been studied before as a radiation hazard on the surface of the Earth [22–25] and for forward detectors [26], to the best of our knowledge, this is the first study of tangential BIN interactions in a MuC detector.

Unlike a neutrino factory (a racetrack-shaped ring design to store $\mathcal{O}(10 - 20)$ GeV [27–31] or $\mathcal{O}(1 - 6)$ GeV [32] muons), a MuC would not be well suited for oscillation studies within the SM due to the higher energies involved. Instead, BINs offer the opportunity to study fundamental physics through precision measurements of the Weak force with neutrinos, overcoming flux systematics that plague conventional neutrino beams. As such, a tangential BIN physics program using the main MuC detector could complement forward physics facilities at a MuC *à la* FASER at the LHC [33–35].

Beam induced neutrinos—To evaluate the number of BIN interactions at a MuC we developed a Monte Carlo simulation of muon decays around the main collider ring. The muons are modeled according to the average behavior of the beam in the magnet lattice designs provided by the IMCC [36–38], described in more detail in the Supplemental Material [39]. The beam size and angular aperture are approximated by Gaussians with width determined by the Twiss parameters in the lattice. We assume a fixed number of muons per bunch N_μ for each collider, with

an injection rate of f_{inj} and bunch multiplicity of N_{bunch} . The number of bunch crossings per second is then approximately $f_{\text{inj}} N_{\text{bunch}} n_{\text{turns}}$, where $n_{\text{turns}} \simeq (\tau_\mu \gamma_\mu \beta_\mu c)/C$ is the typical number of turns around the ring of circumference C . The beam momentum spread is assumed to be a constant Gaussian distribution centered around $p_{\text{beam}} \simeq \sqrt{s}/2$ with $\sigma_p/p_{\text{beam}} = 0.1\%$. The spatial and angular spreads of the muons are modeled as Gaussians that follow the beam envelopes in the transverse directions [40].

We consider three benchmark designs:

(i) MuC 3 and 10 TeV: we choose the $\sqrt{s} = 3$ and 10 TeV designs defined by current muon collider benchmark studies [5,7]. More details on the IP and machine designs can be found in Refs. [4,25,38,41–43]. As we shall see, the total BIN interaction rates for these designs are 2.0×10^{10} and 1.5×10^{11} events per year, respectively.

(ii) $\mu\text{TRISTAN}$ 2 TeV: a collider inspired by the muonium cooling method for μ^+ at J-PARC [16,44]. While both $\mu^+ e^-$ or $\mu^+ \mu^+$ colliders are possible, we consider the latter where each beam has $E_\mu = 1$ TeV. Note that the bunch injection frequency and the number of bunches per cycle assumed are an order of magnitude higher than in the designs above. We also assume a polarization of $P_{\mu^+} = 0.8$ can be achieved [16]. For this design and our detector choice, we find 1.6×10^{11} BIN interactions per year.

We consider a single barrel-shaped detector design for all MuC benchmarks. It emulates the detector model for CLIC [45] with the addition of two conical tungsten nozzles to shield active detectors against BIBs [25]. The shielding was optimized for the MAP $\sqrt{s} = 1.5$ TeV collider [10], so while we expect the design to evolve on the road to a 10 TeV MuC, some of its features are general. Notably, the detector consists of thin silicon layers for the tracking system enveloped by electromagnetic and hadronic calorimeters which, in turn, are surrounded by the solenoid and muon detector layers. All materials and dimensions of individual components are detailed in the Supplemental Material. In this work, we neglect the thin tracker layers, assume a vacuum in the beam pipe, and set the density of the remaining detector regions to that of air.

Figure 1 shows the general shape of the BIN interaction region within the detector and Table I quantifies the interaction rates of our three benchmark scenarios. We characterize the kinematics and geometry of the events in greater detail in the End Matter. The BIN event rate in the entire kiloton-scale detector is of the order of $(0.005 - 0.5)$ per bunch crossing, resulting in as many as 10^{11} BIN interactions/year within the nozzles, the calorimeters, and the muon detector. This event rate corresponds to about 1×10^5 BIN interactions per Higgs boson produced at a 10 TeV MuC for an assumed luminosity of $1 \text{ ab}^{-1}/\text{year}$; for comparison, the Deep Underground Neutrino Experiment (DUNE) [45,46] expects about $10^7 - 10^8$ events per year at a 50 t near detector.

We now consider the feasibility of measuring BIN interactions in a MuC detector. A precision measurement program will rely on low background and good reconstruction levels; for the latter, there are four main event categories to consider: (i) neutral current (NC) deep inelastic scattering (DIS), (ii) ν_e charged current (CC) DIS, (iii) ν_μ CC DIS, and (iv) fully leptonic, coherent, or low-hadronic-energy events. The first three categories contain an energetic hadronic shower and are best studied in the hadronic calorimeter (HCAL) and electromagnetic calorimeter (ECAL). For (iii), the additional muon can be independently identified and its transverse momentum can be measured with the magnetic field in the detector. We note that, as per Table I, 50%–80% of BIN interactions will occur in the BIB-shielding nozzles and beam pipe and therefore cannot be precisely reconstructed; however, a large number of BINs (mainly originating from the final arcs before the IP straight section) will intersect with the HCAL, ECAL, and muon detectors, subtending an angle of $0.1^\circ - 2.5^\circ$ ($0.6^\circ - 6^\circ$) with respect to the detector axial direction at the 10 TeV (3 TeV) MuC. The reconstruction of such shallow-angle particles will greatly benefit from a longitudinally segmented detector.

The electrons and muons produced in BIN interactions in the ECAL and HCAL carry a typical transverse momentum of $\langle p_T^\ell \rangle \simeq 37$ GeV for MuC-10-TeV, 32 GeV for MuC-3-TeV, and 21 GeV for μ TRISTAN. The typical travel distance of electrons and muons in the radial direction of the ECAL and HCAL detectors is about 10 cm, 27 cm, and 27 cm, respectively. Assuming calorimeters similar to that of the HGCal at CMS [47,48], it is conceivable that these events would be reconstructed with good energy and spatiotemporal resolution. Nevertheless, we urge detector research and development studies to consider finer granularity in the radial and axial direction that subtends the neutrino slice of Fig. 1.

The BIB occupancy in the ECAL and HCAL will determine the energy resolution and threshold for BIN studies. Thanks to the tungsten nozzles around the IR, hadrons and charged particles lose most of their energy by the time they enter the active components, making BIBs with energy above 1 GeV extremely unlikely [42,49]. This is even more true in the calorimeters located much further from the IR than the tracking system. Still, within the first nanoseconds of the bunch crossing, BIB occupancy impacts energy resolution to single $\mathcal{O}(100)$ MeV energy depositions from BINs. This effect might also limit the minimum hadronic energy required to distinguish BIN interactions with and without hadronic showers.

Backgrounds—We now comment on potential sources of backgrounds to BINs, highlighting the need for future investigation by machine design studies. Products of $\mu^+\mu^-$ collisions are relatively rare and identifiable from the IP, so backgrounds to consider will arise from the beam itself. There are key distinguishing features between muon-decay

BIBs and BIN interactions. First, BIN final states carry a significant fraction of the beam energy, resulting in TeV-scale leptons and hadrons at large detector radii; this is in stark contrast with muon-decay BIB (non-BIN) particles which come in high multiplicities but are more diffuse and less energetic. Requiring a starting event (resolvable interaction vertex within the ECAL or HCAL) will be crucial to reconstructing BIN events. Second, the spatio-temporal distributions of muon-decay BIBs and BINs are very different: BIBs are distributed evenly across the detector, with an approximate ϕ symmetry (in stark contrast with the neutrino slice) and their time of detection is highly asymmetric about the bunch collision, starting about 20 ns before and lasting at least 100 ns after, sharply peaked at the bunch crossing [43]. On the other hand, the BIN time distribution is flat around the bunch crossing spanning an interval of ± 20 ns (for calorimeter events, this interval is closer to ± 14 ns). This is longer than the typical $\mathcal{O}(30\text{--}60)$ ps time span of the muon beam buckets and much shorter than the bunch revolution time of $\mathcal{O}(30)$ μ s.

Another important source of BIBs comes from beam halo losses due to large-amplitude betatron oscillations, residual gas interactions, and beam-beam effects. These halo muons escape the bucket, penetrate the shielding, and reach the neutrino slice. For earlier designs [13], a loss rate of 10^{-6} per muon-turn was targeted. Assuming uniform tangential losses along the ring, the MuC 10 TeV design would yield $\mathcal{O}(10)$ muons within detector acceptance per bunch crossing. We note, however, that loss rates remain unstudied for modern benchmarks [5,38]. These muons, though more angularly dispersed, still point toward the neutrino slice and have energies just below the beam energy. Deflection using beam extraction and scraping near the IP may reduce this [50]. Undetected muons, including those from Bethe-Heitler processes, can undergo catastrophic energy losses in calorimeters, mimicking electromagnetic final states. Mitigation may come from fiducialization and efficient vetoing using, e.g., the outer muon spectrometer end cap. While BINs, decay BIBs, and halo muons differ, addressing them requires research and development on the neutrino slice and studies of halo scraping or sweeping, detector timing, and longitudinal segmentation.

Flux uncertainty—The uncertainty in the BIN flux will be dominated by the muon beam uncertainties. It can be reduced in two main ways that are independent of the BIN measurement [51]: (i) with beam current transformers, subtracting parasitic currents, and (ii) with beam monitors that detect deflected electrons and positrons in specific momentum and spatial bites. Option (i) was studied for a low-energy neutrino factory, where it was shown that the parasitic currents are safely below the 10^{-3} level [52,53]. At the LHC, the current precision is at the 1% level [54] or better [55]. Option (ii) would also be valuable, especially at the arcs before the long straight section where most BINs

will come from. This can also allow a direct measurement of the beam polarization [56].

Considering both the high collimation and the gargantuan statistics, the uncertainty on the predicted BIN rate will likely be dominated by systematic errors on efficiencies, backgrounds, and the number density of scatterers inside the detector. Furthermore, theoretically clean BIN events like neutrino-electron elastic scattering can provide a statistical measurement of the product of BIN flux and electron density.

Neutrino cross sections—The large flux of energetic BINs at muon colliders allows a direct precision measurement of inclusive and exclusive neutrino-nucleus and neutrino-electron cross sections in the TeV range. With sufficient background control, one can achieve subpercent-level precision, an order of magnitude improvement over conventional accelerator neutrino experiments. Indeed, overcoming flux uncertainties is the hallmark of neutrino factories (and of BINs at a MuC) and would enable a rich leptonic and hadronic physics program (see, e.g., Refs. [28–31]). Neutrino-nucleus deep inelastic scattering would span a broad range of Q^2 and x values, bringing the ongoing program to extract nuclear parton-distribution functions using neutrinos at the LHC [34,57,58] to the level of subpercent precision.

Figure 2 shows the potential of a 10 TeV MuC in measuring neutrino DIS cross sections under a conservative assumption of 1.5% normalization uncertainty. We neglect nuclear effects, which can lead to a reduction of the rate shown by as much as $\mathcal{O}(10)\%$ [59]. Neutrino energy reconstruction is more challenging for NC events, so we adopt a conservative binning in E_ν (see Ref. [60] for a discussion of NC events at FASER). Other accelerator experiments are shown as gray data points, but we note that their overall normalization was often fit to global neutrino data (see Ref. [61] for a review). The latest measurements and projected sensitivity of FASER [62,63], shown as large error bars and as a gray band, respectively, are limited by hadronic uncertainties in the neutrino flux prediction. We also show how a 1.5% extraction of the charm-production cross section in both ν_μ and $\bar{\nu}_\mu$ beams compares to previous measurements [64–69]. This channel can be accessed with dimuon final states and constrains the strange content of the nucleon, the charm quark mass, and the Cabibbo-Kobayashi-Maskawa matrix element $|V_{cd}|$. Note that the total cross section is only reported by a few experiments.

Electron scattering (ES)—Neutrino scattering on electrons is sensitive to electroweak parameters like θ_w and neutrino electromagnetic properties at intermediate momentum transfers ($30 \text{ MeV} \lesssim Q \lesssim 2 \text{ GeV}$) [71–74]. The signal is a forward-going electron shower without any hadronic activity, respecting $E_e \theta_e^2 < 2m_e$, with E_e and θ_e the electron's energy and angle with respect to the incoming neutrino. Each location in the detector corresponds to a given tangential location on the ring, so θ_e can

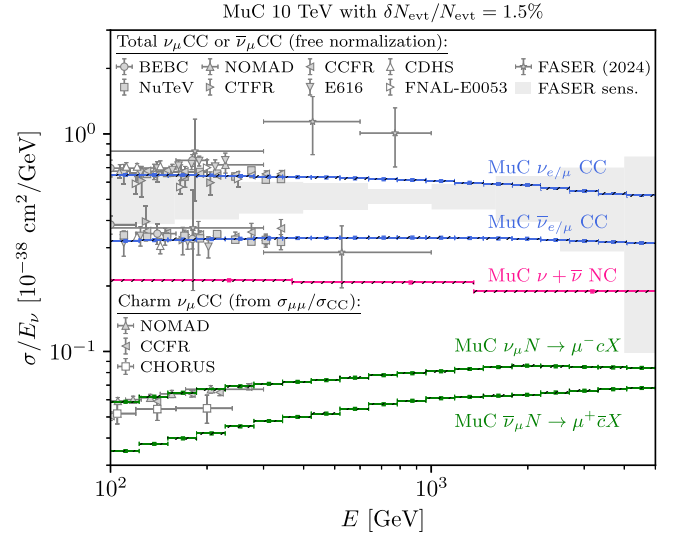


FIG. 2. The inclusive neutrino cross section as would be measured at the 10 TeV MuC as a function of energy for ν_e/μ and $\bar{\nu}_e/\mu$. Measurements of the ν_μ CC and $\bar{\nu}_\mu$ CC inclusive cross sections are shown as data points. In most cases, the measurements were normalized to global neutrino data to circumvent flux uncertainties. We also show data on charm production by normalizing the dimuon cross section $\sigma_{\mu\mu}$ by the $c \rightarrow \mu$ branching ratio reported by NOMAD [69]. In all cases, the underlying theory predictions are from Ref. [70].

be reconstructed on an event-by-event basis within a given resolution. With an unprecedented signal sample size, this measurement will be limited by systematic uncertainties, many of which can be reduced by exploiting the unique properties of BINs. To illustrate this point, let us consider a z -symmetric detector and identical μ^+ and μ^- beams. Neglecting the difference in shape of the ν_e and ν_μ fluxes, the relative difference of ES from the μ^+ and μ^- beams is

$$R_w = \frac{N_{\mu^+} - N_{\mu^-}}{N_{\mu^+} + N_{\mu^-}} = \frac{N_{\bar{\nu}_\mu} + N_{\nu_e} - N_{\nu_\mu} - N_{\bar{\nu}_e}}{N_{\bar{\nu}_\mu} + N_{\nu_e} + N_{\nu_\mu} + N_{\bar{\nu}_e}} \simeq 2s_w^2 \left(\frac{1+r}{1+4s_w^2\delta r+8s_w^4(1+2r+r^2+\delta r^2)} \right), \quad (1)$$

where $r = [m_W^2/3](\langle r_{\nu_e}^2 \rangle + \langle r_{\nu_\mu}^2 \rangle)$ and $\delta r = [m_W^2/3](\langle r_{\nu_e}^2 \rangle - \langle r_{\nu_\mu}^2 \rangle)$ parameterize the neutrino charge radius. The precision on the extraction of s_w or on the charge radius, for instance, is then dictated by the relative difference of events towards and away from the beam axis (left- and right-going electrons) in a MuC detector. The z -symmetric backgrounds and normalization systematics cancel in the ratio in an ideal geometry. Note that the four elastic scattering channels ($\bar{\nu}_\mu, \nu_e, \nu_\mu, \bar{\nu}_e$) and neutrino fluxes have different and well-known dependencies in energy. A full fit to the energy, angle, vertex location, and timing of electron events will further boost the sensitivity to physical parameters.

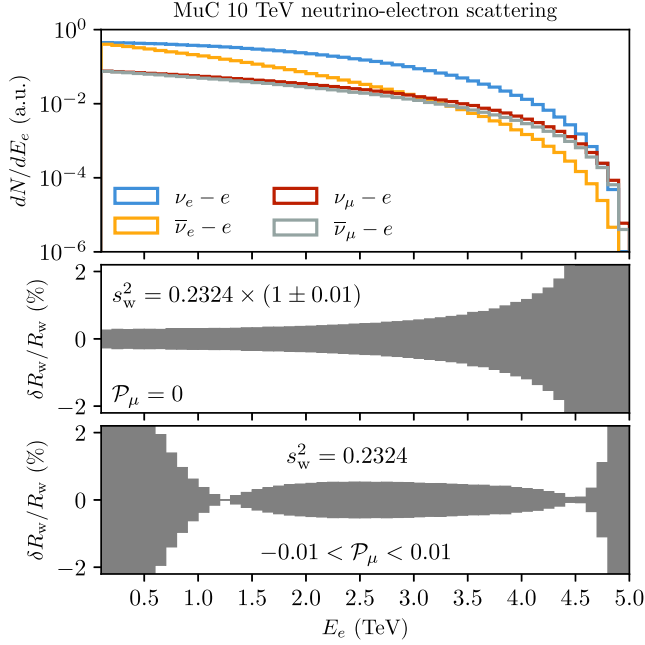


FIG. 3. Top: the central value of the electron spectrum of ES events for different neutrino flavors at the MuC 10 TeV setting $s_w^2 = 0.2324$ and $\mathcal{P}_\mu = 0$. Middle: the relative change in the ratio R_w [Eq. (1)] by varying s_w^2 by 1%. Bottom: the relative change when varying the beam polarization by 1%.

Figure 3 shows the electron recoil energy E_e dependence of R_w , accounting for the full energy dependence on neutrino fluxes. We also show the variation in R_w with s_w^2 and the muon polarization $\mathcal{P}_\mu$. A percent measurement of R_w clearly enables the 10 TeV MuC BIN events to improve on previous neutrino measurements of s_w^2 . The ES measurement at CHARM-II [75] gives $s_w^2 = 0.2324 \pm 0.0083$, which, neglecting the energy dependence, gives $R_w = (0.3244 \pm 0.0046)$ ($\delta R_w/R_w < 1.4\%$). Generally, however, atomic parity violation measurements are more sensitive probes of s_w thanks to the interference between the Z and photon diagrams. A $\delta R_w/R_w$ precision better than 0.20% and 0.06% is needed to beat the latest measurement by Qweak ($s_w^2 = 0.2383 \pm 0.0011$) [76] and future projects [77], respectively. Using such measurements as an input, one can then extract for the first time the neutrino charge radius and search for new physics. In the SM, $\langle r_{\nu_e}^2 \rangle = 4.1 \times 10^{-33} \text{ cm}^2$ and $\langle r_{\nu_\mu}^2 \rangle = 2.4 \times 10^{-33} \text{ cm}^2$ [78,79], so for the Qweak s_w value, a precision of $\delta R_w/R_w = 0.17\%$ is enough for a first detection of the ν_e and ν_μ charge radii at the 95% CL.

These are just some of the applications of a precision measurement of BINs at a MuC. In the Appendix, we present greater details of exclusive neutrino scattering channels, potential effects of muon polarization, as well as our simulation prediction for the forward neutrino fluxes. We also note that several new physics searches discussed

for the forward direction [26,80–82] and beam dumps at a MuC [83,84] could be adapted for the neutrino slice.

Summary—BIN interactions in the MuC detector are so frequent that they (i) would bring about an unavoidable physics program to MuCs and (ii) should be considered as part of ongoing machine design efforts, especially in view of its complementarity with BIB-mitigation efforts. In particular, the concentration of these events in the neutrino slice invites new detector concepts that break the ϕ symmetry of the detector, e.g., a new high-density and high-granularity slice to further enhance the neutrino program. Accelerator and detector design for future MuCs is a rapidly developing research topic. For example, alternative detector designs such as the MUSIC and MAIA concepts [38] move the solenoid inwards before the HCAL and ECAL, respectively, decreasing the BIB rate in the calorimeters and potentially enhancing the BIN reconstruction capabilities. Moving forward, a full detector simulation of BINs is in order to more accurately quantify the sensitivity of BINs as beam monitors and electroweak and new physics precision probes. With this Letter, we hope to encourage new MuC research and development to optimize the physics potential of this unique beam of neutrinos.

The code used for this research is publicly available [85].

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End Matter

Characterizing BIN events—In this appendix, we show more detailed properties of the BIN interactions. Figure 4 shows the energy spectrum of muons and electrons produced by BINs. Different flavor components are shown in different shades. The lepton energy spectra of ν_μ and ν_e events are similar, but both are lower energy than their $\bar{\nu}_\mu$ and $\bar{\nu}_e$ counterparts due to the larger inelasticity of neutrino interactions. Figure 4 also shows the opening angle between the leptons and the parent neutrino ($\theta_{\nu\ell^\pm}$) as well as the angle of the neutrino with respect to the detector axial direction (θ_ν). The structure seen in the latter is caused by the different amounts of material in the line of sight of the neutrino. While most interactions happen in the

highly forward direction, we are mostly interested in events with large θ_ν as these can be better reconstructed at large detector radii.

At these energies, BINs are emitted mainly in the forward direction given the large muon boost, $\theta_\nu \sim 1/\gamma_\mu \sim 10^{-4}$, inheriting the parent muon beam properties at the time of production. Conservation of angular momentum implies that the spectra of $\bar{\nu}_e$ in $\mu^\pm$ decays are softer than $\bar{\nu}_\mu$, resulting in a slightly higher interaction rate for the latter. Therefore, antineutrinos generally lead to harder final state leptons, albeit with a ~ 2 times smaller total cross section.

As the probability of backscatter is negligible at the TeV scale, the lepton angle is a good proxy of that of the neutrino. In 60% (90%) of ν_μ CC events at the MuC-10-TeV, the opening angle between the neutrino and the outgoing muon is smaller than 0.6° (1.7°). This correlation

becomes tighter by requiring lower hadronic energy associated with the event. The lepton charge can then be determined based on whether its momentum is tangential to the μ^+ or μ^- beam.

Beam wobbling: Neutrinos are also a radiation hazard at the locations where the beam exits the Earth's surface [22–24]. The proposed mitigation techniques, e.g., using bending magnets to induce a transverse wavelike trajectory for the muons [86–88] (see also Refs. [23,27,89]), can be accounted for and should not pose a threat to a BIN program. The proposed wobbling of the beam includes a change in the direction of the muons by no more than ± 1 mrad, with a sinusoidal longitudinal beam path and a new height that is at most 15 cm larger [88]. While a more detailed study should take this wobbling into account, we can conclude that it affects the neutrino slice only by as much as 10 cm in the most extreme cases. Note that in the forward region, this wobbling can be significant, however, as it is designed precisely to spread the exit point of neutrinos from the Earth.

Beam polarization: Muons produced from the decay in flight of pions are mildly polarized, with an average longitudinal polarization of $\mathcal{P}_\mu \sim 27\%$ [90–92]. It remains an open question whether this polarization can be enhanced or maintained throughout the acceleration and storage stages in ionization cooling. For μ TRISTAN, on the other hand, muons from muonium are polarized by as much as $\mathcal{P}_\mu = 0.9$ [16] and the proposal aims to maintain $\mathcal{P}_\mu = 0.8$ in the vicinity of the IP. Because the energy distribution of BINs varies significantly with $\mathcal{P}_\mu$, the BIN interaction rate and energy spectrum are sensitive to it and $\mathcal{P}_\mu$ can be directly measured. In the interval $0 < \mathcal{P}_\mu < 0.8$, the $\bar{\nu}_\mu(\nu_e)$ rate increases (decreases) by as much as 15% (25%); in addition, as shown in Fig. 3, the ES ratio in Eq. (1) is also sensitive to $\mathcal{P}_\mu$. This shows that a percent-level measurement of the E_e -dependent ratio in Eq. (1) can constrain the residual polarization of the muon beam at the level of 1% or better at the 10 TeV MuC.

Exclusive interaction rates—In this section, we show the makeup of the event rate in terms of exclusive scattering channels. Table I shows a list of such channels and the corresponding rate for each of our designs for a year of operation, including polarized and unpolarized versions of μ TRISTAN. The main scattering channels are deep-inelastic neutrino-nucleus CC and NC reactions. These will contain a variety of hadronic final states.

Given the high rate of neutrino interactions, it is worth asking what type of rare exclusive processes could be accessed in the MuC detector. Since the cross section for quasielastic (QE) and resonant scattering stops growing linearly with neutrino energy after about $\mathcal{O}(\text{GeV})$ energies, the relative rate of these processes is roughly suppressed by

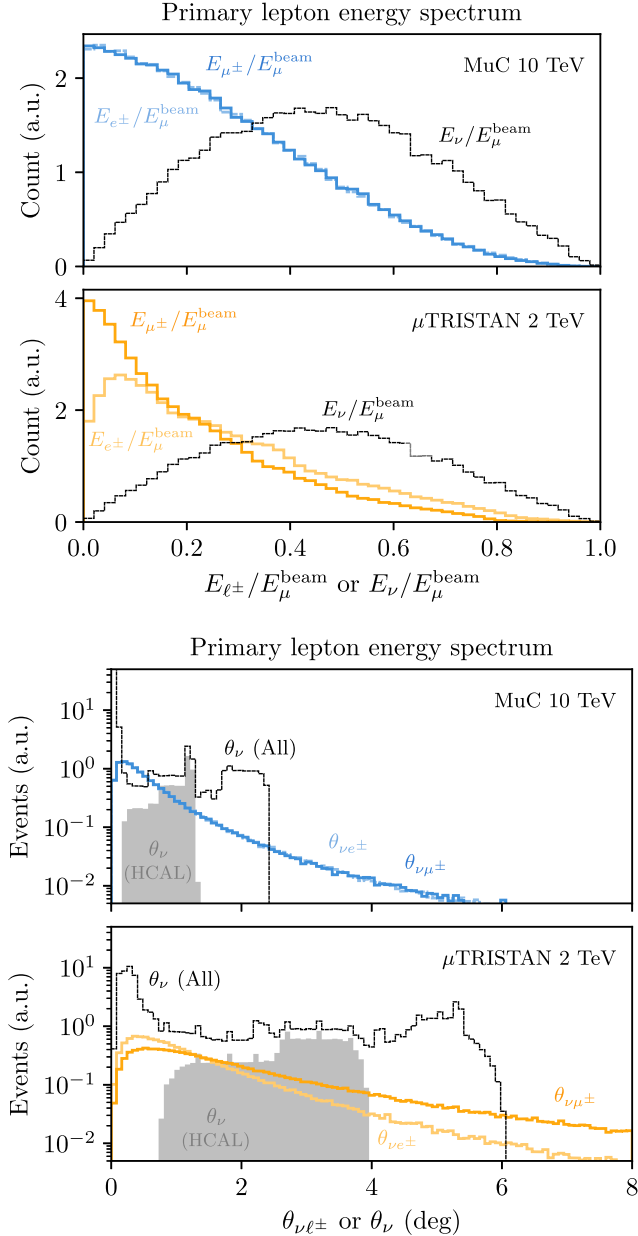


FIG. 4. Top: the energy spectrum of charged leptons produced by BINs throughout the detector barrel for MuC 10 TeV and μ TRISTAN benchmark designs. In dashed black lines, we also show the energy of the BIN (ν or $\bar{\nu}$) that initiated the process. Bottom: the opening angle between the BINs and the outgoing lepton inside the detector for the same MuC benchmarks ($\theta_{\nu\ell^\pm}$). We also show the neutrino angle with respect to the detector axial direction in dashed black lines (θ_ν), isolating the contribution of HCAL events in solid gray.

TABLE I. Total number of neutrino interactions in proposed muon collider detectors. The makeup of the event rate is shown as percentages for each detector component, excluding the magnetic solenoid. Rates for some exclusive scattering channels are also shown, including elastic scattering (ES), coherent π^0 production, resonant meson production on electrons, quasielastic (QE) neutrino scattering, inverse muon decay (IMD), inverse tau decay (ITD), and neutrino trident production on the Coulomb field of the nucleus. Channels with negligible rates due to the lack of $\bar{\nu}_e$ at μ TRISTAN or due to kinematic thresholds are indicated by N/A.

Collider	MuC 10 TeV	MuC 3 TeV	μ TRISTAN
Beams	$\mu^+\mu^-$	$\mu^+\mu^-$	$\mu^+\mu^+$
Muons/bunch	1.8×10^{12}	1.8×10^{12}	1.4×10^{10}
bunches/cycle	1	1	40
f_{inj}	5 Hz	5 Hz	50 Hz
C	8.7 km	4.3 km	4.3 km
BIN inclusive reactions			
ECal (0.15 kt)	0.9%	3.0%	3.0%
HCal (1.4 kt)	7%	15%	15%
Muon Sys (7.5 kt)	13%	33%	32%
Nozzles (0.14 kt)	79%	48%	48%
Total/bunch xs.	0.44	0.029	0.0053
Total/year	1.5×10^{11}	2.0×10^{10}	1.5×10^{11}
BIN exclusive reactions in HCal and ECal/year			
Total NC	1.5×10^9	4.6×10^8	3.4×10^9
Total ν_e CC	4.7×10^9	1.4×10^9	1.1×10^{10}
Total ν_μ CC	5.4×10^9	1.7×10^9	1.1×10^{10}
ES $\nu_e e \rightarrow \nu_e e$	2.0×10^6	6.0×10^5	7.3×10^6
ES $\nu_\mu e \rightarrow \nu_\mu e$	3.8×10^5	1.1×10^5	
ES $\bar{\nu}_e e \rightarrow \bar{\nu}_e e$	8.6×10^5	2.5×10^5	
ES $\bar{\nu}_\mu e \rightarrow \bar{\nu}_\mu e$	3.4×10^5	9.9×10^4	1.9×10^6
QE $\nu n \rightarrow \ell^- p^+$	2.6×10^6	2.5×10^6	2.8×10^7
QE $\bar{\nu} p^+ \rightarrow \ell^+ n$	2.7×10^6	2.5×10^6	3.2×10^7
Coh π^0	3.0×10^5	2.9×10^5	3.5×10^6
Res $\bar{\nu}_e e \rightarrow \rho^-$	4.2×10^5	7.7×10^5	
Res $\bar{\nu}_e e \rightarrow K^{*-}$	2.6×10^4	4.4×10^4	
IMD $\nu_\mu e \rightarrow \nu_e \mu^-$	4.2×10^6	1.2×10^6	
IMD $\bar{\nu}_e e \rightarrow \bar{\nu}_\mu \mu^-$	1.2×10^6	3.5×10^5	
ITD $\bar{\nu}_e e \rightarrow \bar{\nu}_\tau \tau^-$	9.4×10^3		
Trident $e^+ e^-$	1.2×10^6	2.9×10^5	1.7×10^6
Trident $\mu^\pm e^\mp$	2.9×10^6	6.7×10^5	5.0×10^6
Trident $\mu^+ \mu^-$	7.5×10^5	1.6×10^5	1.3×10^6
Trident $\tau^+ \tau^-$	6.1×10^4	8.7×10^3	5.0×10^4

GeV/ E_ν . Here, we quote the QE rates as these can produce electromagnetic showers with a small hadronic energy activity, providing one type of background to neutrino-electron scattering events.

At a fraction of $\mathcal{O}(m_e/m_p)$, fully leptonic reactions appear, such as elastic and inelastic neutrino-electron scattering. As discussed in the main text, these channels are calculable in the SM and provide very clean channels with which to make precision measurements of electroweak parameters, constrain new physics, or measure beam parameters. Other leptonic processes include inverse muon decay (IMD) $\nu_\mu e^- \rightarrow \mu^- \nu_e$, $\bar{\nu}_e e^- \rightarrow \bar{\nu}_\mu \mu^-$, and inverse tau decay (ITD), $\bar{\nu}_e e^- \rightarrow \bar{\nu}_\tau \tau^-$. Both are only present in μ^- beams and have thresholds of $E_\nu^{\text{IMD}} \sim 11$ GeV and $E_\nu^{\text{ITD}} \simeq 3$ TeV. In both cases, the charged lepton travels at extremely forward angles and appears without a hadronic vertex. We also show the rate of resonant production of the ρ and K^{*-} mesons, $\bar{\nu}_e e \rightarrow \rho^- \rightarrow \pi^+ \pi^0$ and $\bar{\nu}_e e \rightarrow K^{*-} \rightarrow K^- \pi^0$, characterized by peaks at $E_{\bar{\nu}_e} \sim 600$ GeV and $E_{\bar{\nu}_e} \sim 800$ GeV, respectively [93]. These are also exclusive to the μ^- beam.

Other interesting semileptonic processes include neutrino-nucleus trident scattering: the production of pairs of charged leptons in the Coulomb field of the nucleus [94–103]. At a MuC, the trident rate corresponds to a combination of $\nu_\mu + \bar{\nu}_e$ or $\bar{\nu}_\mu + \nu_e$ scattering rates. In both cases, the final rate is a combination of CC and NC scattering of neutrinos off of virtual charged leptons, representing a unique probe of flavored leptonic interactions and providing strong limits on new forces coupled to $L_\mu - L_\tau$, for instance [97]. The rates quoted in Table I are obtained using a simplified rescaling of the oxygen and hydrogen results of Ref. [100]. Nuclear effects on the incoherent scattering components can be significant, but for most channels, coherent scattering dominates and provides the more promising detection channel. With tens of millions of trident events per year at a MuC, this measurement would again be systematically limited and, with sufficient background rejection, would enable extraction of electroweak couplings and constraints on new physics coupled to the second and third lepton families. This could improve on ongoing efforts to detect the τ production channels [102,103].