Physics potential of a muon-proton collider

Kingman Cheung\textsuperscript{1, 2, \ast} and Zeren Simon Wang\textsuperscript{2, \dagger}

\textsuperscript{1}Department of Physics, Konkuk University, Seoul 05029, Republic of Korea
\textsuperscript{2}Department of Physics, National Tsing Hua University, Hsinchu 300, Taiwan

We propose a muon-proton collider with asymmetrical multi-TeV beam energies and integrated luminosities of $0.1 - 1 \text{ab}^{-1}$. With its large center-of-mass energies and yet small Standard Model background, such a machine can not only improve electroweak precision measurements but also probe new physics beyond the Standard Model to an unprecedented level. We study its potential in measuring the Higgs properties, probing the R-parity-violating Supersymmetry, and finally heavy new physics in the muon $g - 2$ anomaly. We find that for these physics cases the muon-proton collider can perform better than both the ongoing and future high-energy collider experiments.

I. INTRODUCTION

The Large Hadron Collider (LHC) in Geneva, Switzerland has culminated with the discovery of a Standard Model (SM)-like Higgs boson in 2012 \cite{1, 2}. However, the world’s largest machine has so far failed to find any new fundamental particles predicted by models beyond the Standard Model (BSM), e.g., the sleptons and squarks proposed by Supersymmetry (SUSY) models \cite{3, 4}. While the LHC program will be finished only in mid 2030’s, a wide range of next-generation colliders have been proposed and intensively discussed. For example, various $\mu\nu$ collider setups such as the LHeC \cite{5, 6}, Compact Linear Collider (CLIC) \cite{7}, the Future Circular Collider in the $ee$ mode (FCC-ee) \cite{8}, and the Circular Electron Positron Collider (CEPC) \cite{9}. Then, there are two main electron-proton collider proposals, i.e., the Large Hadron-electron Collider (LHeC) \cite{10–13} and FCC in the hadron-electron mode (FCC-he) \cite{14, 15}, to be running concurrently with and after the HL-LHC, respectively. In addition to these proposals, there are also higher-energy proton-proton colliders: High Energy LHC (HE-LHC) \cite{16–18}, FCC in the hadron-hadron mode (FCC-hh) \cite{14, 15}, and Su-Per Proton Proton Collider (SPPC) \cite{19}, as well as renewed interests in muon colliders \cite{20–32}. The experiments in these colliders would for instance excel in electroweak (EW) precision measurements, Quantum Chromodynamics (QCD) tests, or BSM physics searches.

In this work, we consider a muon-proton collider with multi-TeV beam energies. Historically this type of machine was first investigated in late 1990’s \cite{35–37}, and more recently in Refs. \cite{38, 39}, focusing either on a setup of a center-of-mass (CM) energy of several hundred GeV only or on compositeness models. Compared to the other types of colliders, a $\mu p$ collider has its unique advantages. First, while synchrotron radiation prevents a circular electron beam from obtaining high energies, this issue is much more tamed for a muon beam, allowing a $\mu p$ collider to achieve a much higher center-of-mass energy and thus much larger scattering cross sections in general than an electron-proton collider. Further, a $\mu p$ collider shares the upside of an $ep$ collider such that BSM studies on this type of machine usually suffer from smaller QCD backgrounds, than at $pp$ collisions. Moreover, with multi-TeV CM energies, a $\mu p$ collider could produce TeV-scale new particles on shell, which is, however, more difficult to achieve at, e.g., a multi-TeV muon collider.

There are admittedly downsides of a $\mu p$ collider. Notably muons are short-lived. This requires a sufficiently large acceleration for the muon beam so that the muons reach the interaction point before decaying, and a careful examination of the beam-induced background (BIB).

As Ref. \cite{33} pointed out, the BIB can be reduced by a large extent if the signal final-state particles are largely boosted towards the other beam side\textsuperscript{2}. As we will see, because of the proton parton distribution, this is indeed the case for $\mu p$ collisions even if the proton beam energy is one order of magnitude larger than the muon one.

Given the discussion of $\mu p$ collisions above, one can easily see that multi-TeV $\mu p$ colliders can probe a much higher scale in deep-inelastic scattering than other collider experiments such as the LHeC. For instance, with a CM energy of 5 TeV, the largest potential reach in momentum squared transfer, $Q^2$, can be of order $10^7$ GeV$^2$. In the present paper, however, we will focus on studying the potential of $\mu p$ colliders in probing BSM physics.

The organization of this work is as follows. In Sec. II we introduce the relevant parameters of the two tentative $\mu p$ collider setups we propose. We then study in detail in Secs. III, IV, and V, the sensitivity reach of these potential experiments in Higgs coupling measurements, R-parity-violating Supersymmetry, and finally heavy new physics (NP) in the muon $g - 2$. We summarize in Sec. V.

\textsuperscript{\ast} cheung@phys.nthu.edu.tw
\textsuperscript{\dagger} wzs@mx.nthu.edu.tw

\begin{itemize}
\item More recently electron-muon head-on collisions have also been studied for the first time in Refs. \cite{33, 34}.
\end{itemize}

\begin{itemize}
\item This strategy is, however, inapplicable for muon colliders which suffer from the BIB issue on both sides of the beams.
\end{itemize}
TABLE I. Basic parameters of the two $\mu p$ experiments considered in this work.

| Exp. | $E_p$ [TeV] | $E_{\mu^-}$ [TeV] | $\sqrt{s}$ [TeV] | $\mathcal{L}^{\text{int}}$ [ab$^{-1}$] |
|------|-------------|-------------------|-----------------|-----------------|
| $\mu p - 1$ | 7 | 1 | 5.3 | 0.1 |
| $\mu p - 2$ | 50 | 3 | 24.5 | 1 |

TABLE II. The inclusive cross sections of VBF production of the SM Higgs bosons at various experiments, in pb.

| VBF process | $\mu p - 1$ | $\mu p - 2$ | LHeC | FCC-he | LHC-14 |
|-------------|--------------|-------------|------|--------|-------|
| WW          | 0.978        | 5.103       | 0.110 [13] | 0.577 [13] | 4.233 [42] |
| ZZ          | 0.216        | 1.263       | 0.020 [13] | 0.127 [13] | |

II. COLLIDER SETUPS

In this work we focus on two possible beam combinations: (1) “$\mu p - 1$” with $E_p = 7$ TeV and $E_{\mu^-} = 1$ TeV, and (2) “$\mu p - 2$” with $E_p = 50$ TeV and $E_{\mu^-} = 3$ TeV. The proton beam energies are in agreement with the HL-LHC and FCC, while the muon energies are inspired from the current discussion on TeV-scale muon colliders.

Estimates on the instantaneous luminosity at muon-proton colliders where performed in the past [35, 40, 41]. In general, realistic estimates for the luminosity given the current technologies should be at the order of $10^{33}$ cm$^{-2}$ s$^{-1}$, which we assume for $\mu p - 1$. As for $\mu p - 2$ which is supposed to be an upgrade of $\mu p - 1$, we take a slightly optimistic value of $10^{34}$ cm$^{-2}$ s$^{-1}$. For the lifespan of these experiments, we take as a benchmark operation time $10^7$ s/year for 10 years, leading to an integrated luminosity $\mathcal{L}^{\text{int}}$ of 0.1 ab$^{-1}$ and 1 ab$^{-1}$ for $\mu p - 1$ and $\mu p - 2$, respectively. We summarize these collider parameters in Table I.

III. HIGGS PRECISION MEASUREMENTS

One of the utmost tasks in Higgs physics is the precision measurements of the Higgs boson couplings. Here we study the projected uncertainties in the measurement of the Higgs coupling to $b$-quarks at a $\mu p$ collider.

Similar to $ep$ collisions, the Higgs boson at $\mu p$ is produced mainly via the WW and ZZ vector-boson-fusion (VBF) processes. In Table II we list the inclusive production cross sections of the SM Higgs boson at $\mu p - 1$, $\mu p - 2$, LHeC, FCC-he, and the LHC with $\sqrt{s} = 14$ TeV. We find that the VBF cross sections at $\mu p - 1$ and $\mu p - 2$, obtained at leading order with MadGraph5 3.0.2 [43], can be up to about one order of magnitude larger than those at the LHeC and FCC-he, and even comparable to those at the LHC with $\sqrt{s} = 14$ TeV. Here, we choose to focus on the WW VBF process: $\mu p^- \rightarrow j\nu_j h, h \rightarrow b\bar{b}$ because of its larger rate than the ZZ process. The dominant background is the corresponding WW VBF for $Z$-boson production with $Z \rightarrow b\bar{b}$. We express the measurement uncertainty of the cross section of $\mu p^- \rightarrow j\nu_j b\bar{b}$ as $\Delta \sigma/\sigma = (N_h + N_b)/(N_h)$ including the statistical error only, where $N_{h/b}$ denotes the signal/background event numbers, and perform a cut-based analysis to estimate the sensitivity reach in $\Delta \sigma/\sigma$. We generate the parton-level events with MadGraph5, requiring $p_T^{j/b} > 5$ GeV and $|\eta^{j/b}| < 5.5$. The $p_T$ threshold avoids the collinear limit, and the $|\eta^{j/b}|$ cut corresponds to the geometry of the beam-asymmetric LHeC detector. The parton showering and hadronization for asymmetrical lepton-hadron collisions are properly treated with a patched version of Pythia 6.4.28 [44, 45]. Finally we perform jet clustering with FastJet 3.3.2 [46, 47] with the anti-$k_T$ algorithm [48], and fast detector simulation with Delphes 3.4.2 [49]. For the latter we use an LHeC-specific Delphes card which includes the beam asymmetry. For b-tagging efficiency we take 75%. The following set of cuts at the reconstructed level are imposed. We first keep only the events with exactly two $b$-jets. In Fig. 1 we show the pseudorapidity distributions of the $b$-jets. We find the produced

```
| Exp. | $m^{\text{cut}}_{h\mu}$ | $\sigma(j\nu_j b\bar{b})$ | $\epsilon_{j\nu_j}$ | $\epsilon_{h\mu}$ | $\epsilon_{\mu p}$ | $\Delta \sigma/\sigma$ | $\Delta g_{h\mu}/g_{h\mu}$ |
|------|------------------------|---------------------------|---------------------|---------------------|-----------------------|------------------------|------------------------|
| $\mu p - 1$ | 0.98 | 4.67 pb | 0.99 | 0.21 | 0.022 | 0.97% | 0.69% |
| $\mu p - 2$ | 0.91 | 25.1 pb | 0.97 | 0.17 | 0.018 | 0.15% | 0.50% |

FIG. 1. Pseudorapidity distributions of the reconstructed $b$-jets for the signal and background events at $\mu p - 1$ and $\mu p - 2$.
```
b’s are peaked at the proton beam side due to the proton radiation and expected to allow for BIB re-duction. We then select only events where the b-jet pair invariant mass, \( m_{bb} \), is close to the Higgs mass 125 GeV: \( |m_{bb} - m_h| < 25 \text{ GeV} \), intended to separate the signal and background events. After these event selections, we compute the signal and background event numbers with \( N_s = L^\text{int} \cdot \sigma(p\mu^- \to j\nu_j h) \cdot Br(h \to bb) \cdot \epsilon_{\text{pr-cut}}^{\text{sig}} \cdot \epsilon_{\text{cut}}^{\text{sig}} \) and \( N_b = L^\text{int} \cdot \sigma(p\mu^- \to j\nu_j Z) \cdot Br(Z \to bb) \cdot \epsilon_{\text{pr-cut}}^{\text{bgd}} \cdot \epsilon_{\text{cut}}^{\text{bgd}} \). The latter, in fact, offers rich phenomenology at colliders. With the broken R-parity, the superpotential of the Minimal Supersymmetric Standard Model (MSSM) is extended with:

\[
W_{\text{RPV}} = \epsilon_i L_i \cdot H_u + \frac{1}{2} \lambda_{ijk} L_i \cdot L_j E_k + \lambda'_{ijk} L_i \cdot Q_j D_k + \frac{1}{2} \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k,
\]

where the operators in the first line violate lepton numbers and those in the second line violate baryon numbers. Allowing all these terms to be non-vanishing would lead to a too fast proton decay rate unless the couplings are extremely small. For the purpose of this work, we focus on the operator \( \lambda'_{ijk} L_i \cdot Q_j D_k \) while assuming the others are vanishing.

In particular, here the RPV squark is a specific leptoquark which was used to explain a number of flavor anomalies. Ref. [37] from two decades ago performed an analytic estimate of sensitivity reach at a high-energy muon-proton collider (with \( E_{\text{cm}} = 200 \text{ GeV} \) and \( E_p = 1 \text{ TeV} \)) to the RPV couplings \( \lambda'_{ijk} \) and \( \lambda''_{ijk} \) for squark masses below 1 TeV. In this work, we focus on one Drell-Yan-like signal process as an example: \( p\mu^- \to \mu^- u \) (neutral current, or denoted as “NC”), mediated by a right-chiral down-type squark \( \bar{d}_{Rk} \) and the RPV coupling \( \lambda'_{21k} \), and perform a numerical study with Monte Carlo simulations. As in the previous section we go through the tool chain: MadGraph 5 with a RPV-MSSM UFO model file and the same parton-level cuts, Pythia 6, FastJet 3, and Delphes 3 with the LHCCard. Here we switch on only one single RPV coupling \( \lambda'_{21k} \), for which the current (36 fb\(^{-1}\)) and projected (3 ab\(^{-1}\)) LHC bounds were recast in Ref. [67] from an ATLAS mono-lepton search.

We comment that a similar improvement in measuring the other Higgs couplings such as those to the gauge bosons is also expected.

IV. R-PARITY-VIOLATING SUPERSYMMETRY

Even though no new particles have been discovered at the LHC and TeV-scale lower mass bounds on the squarks and gluinos have been established [54–58], SUSY remains one of the most motivated BSM models. In SUSY, a \( Z_2 \) parity, known as R-parity, is usually assumed, rendering the proton stable and offering the lightest supersymmetric particle as a dark matter candidate. However, it is equally legitimate to consider the R-parity-violating Supersymmetry (RPV-SUSY) scenario (see Refs. [59–61] for reviews). The latter, in fact,


\[ \Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} = 251(59) \times 10^{-11}. \]

One natural explanation could be weakly interacting NP appearing at the EW scale. However, given the nonobservation of NP at the LHC so far, two other possibilities might be more relevant: (1) light NP below the GeV scale interacting feebly with the SM, and (2) much heavier NP (above the TeV scale) strongly coupled to the SM particles. In this work, we consider the latter possibility. If the NP scale, \( \Lambda \), is much higher than the EW scale, i.e., \( \Lambda \gg 1 \) TeV, we can describe physics at energies much below \( \Lambda \) with the framework of the Standard Model Effective Field Theory (SMEFT) [74–77], of which the operators up to \( \text{dim-6} \) relevant to \( a_\mu \) are

\[
\mathcal{L} \supset \frac{C_\mu^\mu}{\Lambda^2} (\tilde{\mu}_L \sigma^{\mu\nu} \mu_R) H B_{\mu\nu} + \frac{C_\mu^W}{\Lambda^2} (\tilde{\mu}_L \sigma^{\mu\nu} \mu_R) \sigma^i H W_{\mu\nu}^i + \frac{C_\mu^T}{\Lambda^2} (\tilde{\mu}_L \sigma_{\mu\nu} \mu_R) \epsilon_{ab} (\bar{Q}_L^a \sigma^{\mu\nu} \mu_R) + h.c.
\]

The NP contributions to \( a_\mu \) stem directly from the operator \((\tilde{\mu}_L \sigma_{\mu\nu} \mu_R) H F_{\mu\nu}^a\), which may be induced by the operators in Eq. (2) at tree or one-loop level. Their corrections to \( a_\mu \) can be expressed as follows:

\[
\Delta a_\mu \approx \frac{4m_\mu v}{e^2 \Lambda^2} \left( C_\mu^\gamma - \frac{3a_\mu}{2} C_\mu^W S_W \right) \log \frac{\Lambda}{m_Z} - \sum_{q=c,t} \frac{4m_\mu m_q}{\pi^2} \frac{C_\mu^q T}{\Lambda^2} \log \frac{\Lambda}{m_q},
\]

where \( v = 246 \text{ GeV} \) is the SM Higgs vacuum expectation value, \( s_W \) and \( c_W \) are sine and cosine of the Weinberg angle, and \( C_\mu^\gamma = c_W C_{\mu B} - s_W C_{\mu W} \) and \( C_\mu^Z = -s_W C_{\mu B} - c_W C_{\mu W} \).

At a \( \mu p \) collider, only a limited set of these operators can be tested. To start with, \( C_\mu^\rho \) can be probed, either by considering the photon content inside the protons scattering an incoming muon, or by studying rare Higgs decays into a pair of muons and a photon. We find the former possibility, suppressed by the parton distribution function of the photon in the protons, is insensitive to new physics that is sufficiently small to explaining the muon \( g - 2 \) anomaly.

V. MUON \( g - 2 \) ANOMALY

One of the main drives for BSM physics has been the muon anomalous magnetic moment since about a decade ago. With the latest world consensus on the SM computation of \( a_\mu \equiv (g_\mu - 2)/2 \) [70] combined with the experimental results published by the E821 collaboration at BNL [71] and recently by the the Fermilab-based Muon g-2 experiment [72], we are now faced with a discrepancy of \( \sim 4.2 \sigma \) in \( a_\mu \); \( \Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} = 251(59) \times 10^{-11} \). One natural explanation could be weakly interacting NP appearing at the EW scale. However, given the nonobservation of NP at the LHC so far, two other possibilities might be more relevant: (1) light NP below the GeV scale interacting feebly with the SM, and (2) much heavier NP (above the TeV scale) strongly coupled to the SM particles. In this work, we consider the latter possibility. If the NP scale, \( \Lambda \), is much higher than the EW scale, i.e., \( \Lambda \gg 1 \) TeV, we can describe physics at energies much below \( \Lambda \) with the framework of the Standard Model Effective Field Theory (SMEFT) [74–77], of which the operators up to \( \text{dim-6} \) relevant to \( a_\mu \) are

\[
\mathcal{L} \supset \frac{C_\mu^\mu}{\Lambda^2} (\tilde{\mu}_L \sigma^{\mu\nu} \mu_R) H B_{\mu\nu} + \frac{C_\mu^W}{\Lambda^2} (\tilde{\mu}_L \sigma^{\mu\nu} \mu_R) \sigma^i H W_{\mu\nu}^i + \frac{C_\mu^T}{\Lambda^2} (\tilde{\mu}_L \sigma_{\mu\nu} \mu_R) \epsilon_{ab} (\bar{Q}_L^a \sigma^{\mu\nu} \mu_R) + h.c.
\]

The NP contributions to \( a_\mu \) stem directly from the operator \((\tilde{\mu}_L \sigma_{\mu\nu} \mu_R) H F_{\mu\nu}^a\), which may be induced by the operators in Eq. (2) at tree or one-loop level. Their corrections to \( a_\mu \) can be expressed as follows:

\[
\Delta a_\mu \approx \frac{4m_\mu v}{e^2 \Lambda^2} \left( C_\mu^\gamma - \frac{3a_\mu}{2} C_\mu^W S_W \right) \log \frac{\Lambda}{m_Z} - \sum_{q=c,t} \frac{4m_\mu m_q}{\pi^2} \frac{C_\mu^q T}{\Lambda^2} \log \frac{\Lambda}{m_q},
\]

where \( v = 246 \text{ GeV} \) is the SM Higgs vacuum expectation value, \( s_W \) and \( c_W \) are sine and cosine of the Weinberg angle, and \( C_\mu^\gamma = c_W C_{\mu B} - s_W C_{\mu W} \) and \( C_\mu^Z = -s_W C_{\mu B} - c_W C_{\mu W} \).

At a \( \mu p \) collider, only a limited set of these operators can be tested. To start with, \( C_\mu^\rho \) can be probed, either by considering the photon content inside the protons scattering an incoming muon, or by studying rare Higgs decays into a pair of muons and a photon. We find the former possibility, suppressed by the parton distribution function of the photon in the protons, is insensitive to new physics that is sufficiently small to explaining the muon \( g - 2 \) anomaly.

As for the rare Higgs decay, the decay branching ratio of the Higgs into \( \mu^+ \mu^- \gamma \) should be at the order of \( \sim 10^{-13} \) in order to test \( \Delta a_\mu \sim 3 \times 10^{-9} \) [24]. However, at both \( \mu p - 1 \) and \( \mu p - 2 \) the production rates of the SM Higgs bosons are estimated to be roughly \( 10^8 \) and \( 5 \times 10^6 \) (see Table II), with 0.1 ab\(^{-1}\) and 1 ab\(^{-1}\) integrated luminosities, respectively, which are far from sufficient for probing a branching ratio of \( 10^{-13} \). Consequently the only operator that could be confronted for

---

5 There is a controversy arising from a new lattice calculation [73] which shows a larger hadronic vacuum polarization contribution, such that the total SM contribution to the muon \( g - 2 \) is within \( 1 \sigma \) of the experimental value.
The expected exclusion limits of $|\Delta a_\mu|$ at $\mu p - 1$ and $\mu p - 2$.

| $\sigma^{bgd}$ [pb] | $\sigma^{sig}$ (100 TeV$^2$)$^2$ [pb] | $|\Delta a_\mu|$ |
|---------------------|-----------------------------|-----------------|
| $\mu p - 1$        | 120                         | $1.29 \times 10^{-2}$ | $1.13 \times 10^{-8}$ |
| $\mu p - 2$        | 30                          | $3.15 \times 10^{-1}$ | $9.10 \times 10^{-10}$ |

TABLE IV. Cross sections for the background ($\sigma^{bgd}$) and signal ($\sigma^{sig}$) events, as well as the integrated luminosities and the expected exclusion limits of $|\Delta a_\mu|$, at $\mu p - 1$ and $\mu p - 2$.

$\Delta a_\mu \sim 3 \times 10^{-9}$ at $\mu p - 1$ and $\mu p - 2$ is $C^{\mu c}_T$, with the parton-level process $\mu^- c \rightarrow \mu^- c$ and its $c$ counterpart. The corresponding background is $\mu^- p \rightarrow \mu^- p$. Note that the unitarity constraint requires that $\Lambda \lesssim 10$ TeV for this operator.

To explore the heavy NP in the muon $g - 2$ at $\mu p - 1$ and $\mu p - 2$, we perform truth-level Monte Carlo simulations with the event generator MadGraph5 and the model package SMEFTsim [78, 79], with the parton-level cuts $p_T^j > 5$ GeV and $|p_T^j| < 5.5$. The computed cross sections for the signal and background processes are given in Table IV, assuming the contributions arise solely from the single SMEFT operator $C^{\mu c}_T$. Therefrom we can easily obtain the signal and background event numbers, and hence the 2$\sigma$ exclusion limits on $C^{\mu c}_T/\Lambda^2$. To convert these limits into those on $|\Delta a_\mu|$, we take $\Lambda = 10$ TeV for the logarithmic function in the last term of Eq. (3), reaching $|\Delta a_\mu| = \frac{4 m_{\mu} m_{c}}{\pi^{2} x^{2}} C^{\mu c}_T Log \frac{10 TeV}{m_{c}}$. The exclusion limits on $|\Delta a_\mu|$ are given in the last column of Table IV: $1.13 \times 10^{-8}$ and $9.10 \times 10^{-10}$. We conclude that in the limit of vanishing contributions from the other operators, the low-energy effects from the high-scale NP associated with the tensor operator $C^{\mu c}_T$ that would be small enough to explain the muon $g - 2$ anomaly can be probed at $\mu p - 2$. In order to make $\mu p - 1$ sensitive enough, further improvements on e.g., luminosity and search strategies, should be implemented.

We note that since only $\Lambda \lesssim 10$ TeV is valid for the considered operator, it is necessary to check whether the typical hard-interaction CM energies for the signal are lower than 10 TeV. We find that for $\mu p - 1$, $\sim 100\%$ of the events have the invariant mass $m_{\mu c}$ of the outgoing muon and $c$ quark $m_{\mu c} < 5$ TeV, and for $\mu p - 2$ it is about $\sim 70\%$ despite the much higher CM energy.

VI. CONCLUSIONS

In this work we have proposed a muon-proton collider with two tentative configurations. We performed numerical simulations to investigate the physics potential of $\mu p - 1$ and $\mu p - 2$ in both Higgs precision measurement and search for BSM physics. Taking as benchmark physics cases the Higgs coupling to $b$-quarks, R-parity-violating MSSM, and heavy new physics in the muon $g - 2$, we conclude that a multi-TeV muon-proton collider with $0.1 - 1$ ab$^{-1}$ integrated luminosities could show better performance than both current and future collider experiments. Besides the physics scenarios studied here, we expect that this type of machine can also excel in other aspects of the SM precision measurements and BSM physics searches. We believe this work could motivate more studies of TeV-scale muon-proton colliders in the high-energy physics community.

ACKNOWLEDGMENTS

We would like to thank Florian Domingo and Jong Soo Kim for useful discussions. This work was supported by MoST with grant nos. MoST-109-2811-M-007-509 and 107-2112-M-007-029-MY3.

[1] ATLAS, G. Aad et al., Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC, Phys. Lett. B 716, 1 (2012), arXiv:1207.7214.
[2] CMS, S. Chatrchyan et al., Observation of a New Boson at a Mass of 125 GeV with the CMS Experiment at the LHC, Phys. Lett. B 716, 30 (2012), arXiv:1207.7235.
[3] R. P. Nilles, Supersymmetry, Supergravity and Particle Physics, Phys. Rept. 110, 1 (1984).
[4] S. P. Martin, A Supersymmetry primer, Adv. Ser. Direct. High Energy Phys. 21, 1 (2010), arXiv:hep-ph/9709356.
[5] ILC, G. Aarons et al., International Linear Collider Reference Design Report Volume 2: Physics at the ILC, (2007), arXiv:0709.1893.
[6] The International Linear Collider Technical Design Report - Volume 1: Executive Summary, (2013), arXiv:1306.6327.
[7] CLICdp, CLIC, T. Charles et al., The Compact Linear Collider (CLIC) - 2018 Summary Report, 2/2018 (2018), arXiv:1812.06018.
[8] FCC, A. Abada et al., FCC-ee: The Lepton Collider: Future Circular Collider Conceptual Design Report Volume 2, Eur. Phys. J. ST 228, 261 (2019).
[9] CEPC Study Group, M. Dong et al., CEPC Conceptual Design Report: Volume 2 - Physics \& Detector, (2018), arXiv:1811.10545.
[10] M. Klein, The Large Hadron Electron Collider Project, in 17th International Workshop on Deep-Inelastic Scattering and Related Subjects, p. 236, 2009, arXiv:0908.2877.
[11] ILC Study Group, J. Abelleira Fernandez et al., A Large Hadron Electron Collider at CERN: Report on the Physics and Design Concepts for Machine and Detector, J. Phys. G 39, 075001 (2012), arXiv:1206.2913.
[12] O. Bruening and M. Klein, The Large Hadron Electron Collider, Mod. Phys. Lett. A 28, 1330011 (2013), arXiv:1305.2090.
[13] LHeC, FCC-ee Study Group, P. Agostini et al., The Large Hadron-Electron Collider at the HL-LHC, (2020), arXiv:1305.2090.
[14] FCC, A. Abada et al., FCC Physics Opportunities: Future Circular Collider Conceptual Design Report Volume 1, Eur. Phys. J. C 79, 474 (2019).

[15] FCC, A. Abada et al., FCC-hh: The Hadron Collider: Future Circular Collider Conceptual Design Report Volume 3, Eur. Phys. J. ST 228, 755 (2019).

[16] X. Cid Vidal et al., Report from Working Group 3: Beyond the Standard Model physics at the HL-LHC and HE-LHC, CERN Yellow Rep. Monogr. 7, 585 (2019), arXiv:1812.07831.

[17] FCC, A. Abada et al., HE-LHC: The High-Energy Large Hadron Collider: Future Circular Collider Conceptual Design Report Volume 4, Eur. Phys. J. ST 228, 1109 (2019).

[18] P. Azzi et al., Report from Working Group 1: Standard Model Physics at the HL-LHC and HE-LHC, CERN Yellow Rep. Monogr. 7, 1 (2019), arXiv:1902.04070.

[19] J. Tang et al., Concept for a Future Super Proton-Proton Collider, (2015), arXiv:1507.03224.

[20] T. Han and Z. Liu, Potential precision of a direct measurement of the Higgs boson total width at a muon collider, Phys. Rev. D 87, 033007 (2013), arXiv:1210.7803.

[21] J. P. Delahaye et al., Muon Colliders, (2019), arXiv:1901.06150.

[22] A. Costantini et al., Vector boson fusion at multi-TeV muon colliders, JHEP 09, 080 (2020), arXiv:2005.10289.

[23] T. Han, Z. Liu, L.-T. Wang, and X. Wang, WIMPs at High Energy Muon Colliders, (2020), arXiv:2009.11287.

[24] D. Buttazzo and P. Paradisi, Probing the muon g-2 anomaly at a Muon Collider, (2020), arXiv:2012.02769.

[25] W. Yin and M. Yamaguchi, Muon g − 2 at multi-TeV muon collider, (2020), arXiv:2012.03928.

[26] R. Capdevilla, D. Curtin, Y. Kahn, and G. Krnjaic, A Guaranteed Discovery at Future Muon Colliders, (2020), arXiv:2006.16277.

[27] T. Han, D. Liu, I. Low, and X. Wang, Electroweak Couplings of the Higgs Boson at a Multi-TeV Muon Collider, (2020), arXiv:2008.12204.

[28] K. Long et al., Muon Colliders: Opening New Horizons for Particle Physics, (2020), arXiv:2007.15684.

[29] G.-y. Huang, F. S. Queiroz, and W. Rodejohann, Gauged Lµ − Lν at a muon collider, (2021), arXiv:2101.04956.

[30] R. Capdevilla, D. Curtin, Y. Kahn, and G. Krnjaic, A No-Lose Theory for Discovering the New Physics of (g − 2)µ at Muon Colliders, (2021), arXiv:2101.10334.

[31] W. Liu and K.-P. Xie, Probing electroweak phase transition with multi-TeV muon colliders and gravitational waves, (2021), arXiv:2101.10469.

[32] P. Asadi, R. Capdevilla, C. Cesaretti, and S. Homiller, Searching for Leptoquarks at Future Muon Colliders, (2021), arXiv:2104.05720.

[33] M. Lu et al., The physics case for an electron-muon collider, (2020), arXiv:2010.15144.

[34] F. Bossi and P. Ciafaloni, Lepton Flavor Violation at muon-electron colliders, JHEP 10, 033 (2020), arXiv:2003.03997.

[35] V. Shiltsev, An Asymmetric muon - proton collider: Luminosity consideration, Conf. Proc. C 970512, 420 (1997).

[36] K.-m. Cheung, Muon proton colliders: Leptoquarks, contact interactions and extra dimensions, AIP Conf. Proc. 542, 160 (2000), arXiv:hep-ph/0001275.

[37] M. Carena, D. Choudhury, C. Quigg, and S. Raychaudhuri, Study of R-parity violation at a muon proton collider, Phys. Rev. D 62, 095010 (2000), arXiv:hep-ph/0006144.

[38] A. Caliskan, S. Kara, and A. Ozansoy, Excited muon searches at the FCC based muon-hadron colliders, Adv. High Energy Phys. 2017, 1540243 (2017), arXiv:1701.03426.

[39] Y. C. Acar, U. Kaya, and B. B. ONer, Resonant production of color octet muons at Future Circular Collider-based muon-proton colliders, Chin. Phys. C 42, 083108 (2018), arXiv:1703.04030.

[40] I. Ginzburg, Physics at future e p, gamma p (linear-ring) and mu p colliders, Turk. J. Phys. 22, 607 (1998).

[41] U. Kaya, B. Ketencoglu, S. Sultansoy, and F. Zimmermann, Main parameters of HL-LHC and HE-LHC based mu-p colliders, (2019), arXiv:1905.05564.

[42] CERNYellowReportPageAt1314TeV2014, https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CERNYellowReportPageAt1314TeV2014.

[43] J. Alwall et al., The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations, JHEP 07, 079 (2014), arXiv:1405.0301.

[44] T. Sjstrand, S. Mrenna, and P. Z. Skands, PYTHIA 6.4 Physics and Manual, JHEP 05, 026 (2006), arXiv:hep-ph/0603175.

[45] Private communication with Uta Klein.

[46] M. Cacciari, G. P. Salam, and G. Soyez, FastJet User Manual, Eur. Phys. J. C 72, 1896 (2012), arXiv:1111.6097.

[47] M. Cacciari and G. P. Salam, Dispelling the myth for the k_t jet-finder, Phys. Lett. B 641, 57 (2006), arXiv:hep-ph/0512210.

[48] M. Cacciari, G. P. Salam, and G. Soyez, The anti-k_t jet clustering algorithm, JHEP 04, 063 (2008), arXiv:0802.1189.

[49] DELPHES 3. J. de Favereau et al., DELPHES 3. A modular framework for fast simulation of a generic collider experiment, JHEP 02, 057 (2014), arXiv:1307.6346.

[50] M. Ruan, Higgs Measurement at the HL-LHC and HE-LHC based mu-p colliders, Nucl. Part. Phys. Proc. 273-275, 857 (2016), arXiv:1411.5606.

[51] M. Tanaka, SM Higgs at the LHeC, https://indico.cern.ch/event/568360/contributions/2523555/attachments/1440097/2216668/mtanaka_DIS2017_SHiggs_final.pdf.

[52] CMS, Projected Performance of an Upgraded CMS Detector at the LHC and HL-LHC: Contribution to the Snowmass Process, in Community Summer Study 2013: Snowmass on the Mississippi, 2013, arXiv:1307.7135.

[53] M. Cepeda et al., Report from Working Group 2: Higgs Physics at the HL-LHC and HE-LHC, CERN Yellow Rep. Monogr. 7, 221 (2019), arXiv:1902.00134.

[54] ATLAS, M. Aaboud et al., Search for photonic signatures of gauge-mediated supersymmetry in 13 TeV pp collisions with the ATLAS detector, Phys. Rev. D 97, 092006 (2018), arXiv:1802.03158.

[55] CMS, A. M. Sirunyan et al., Search for gauge-mediated supersymmetry in events with at least one photon and missing transverse momentum in pp collisions at √s = 13 TeV, Phys. Lett. B 780, 118 (2018), arXiv:1711.08008.

[56] CMS, A. M. Sirunyan et al., Search for supersymmetry in final states with photons and missing transverse mo-
mum in proton-proton collisions at 13 TeV, JHEP 06, 143 (2019), arXiv:1903.07070.

[57] CMS, A. M. Sirunyan et al., Search for supersymmetry in proton-proton collisions at 13 TeV in final states with jets and missing transverse momentum, JHEP 10, 244 (2019), arXiv:1908.04722.

[58] ATLAS, G. Aad et al., Search for new phenomena in final states with large jet multiplicities and missing transverse momentum using $\sqrt{s} = 13$ TeV proton-proton collisions recorded by ATLAS in Run 2 of the LHC, JHEP 10, 062 (2020), arXiv:2008.06032.

[59] H. K. Dreiner, An Introduction to explicit R-parity violation, Adv. Ser. Direct. High Energy Phys. 21, 565 (2010), arXiv:hep-ph/9707435.

[60] R. Barbier et al., R-parity violating supersymmetry, Phys. Rept. 420, 1 (2005), arXiv:hep-ph/0406039.

[61] R. N. Mohapatra, Supersymmetry and R-parity: an Overview, Phys. Scripta 90, 088004 (2015), arXiv:1503.06478.

[62] L. E. Ibanez and G. G. Ross, Discrete gauge symmetries and the origin of baryon and lepton number conservation in supersymmetric versions of the standard model, Nucl. Phys. B 368, 3 (1992).

[63] H. K. Dreiner, M. Hanussek, and C. Luhn, What is the discrete gauge symmetry of the R-parity violating MSSM?, Phys. Rev. D 86, 055012 (2012), arXiv:1206.6305.

[64] E. Coluccio Leskow, G. D’Ambrosio, A. Crivellin, and D. Müller, $(g-2)_\mu$, lepton flavor violation, and $Z$ decays with leptoquarks: Correlations and future prospects, Phys. Rev. D 95, 055018 (2017), arXiv:1612.06858.

[65] A. Crivellin, C. Greub, D. Müller, and F. Saturnino, Scalar Leptoquarks in Leptonic Processes, (2020), arXiv:2010.06593.

[66] A. Crivellin, D. Mueller, and F. Saturnino, Correlating $h \rightarrow \mu^+\mu^-$ to the Anomalous Magnetic Moment of the Muon via Leptoquarks, (2020), arXiv:2008.02643.

[67] S. Bansal, A. Delgado, C. Kolda, and M. Quiros, Limits on R-parity-violating couplings from Drell-Yan processes at the LHC, Phys. Rev. D 99, 093008 (2019), arXiv:1812.04232.

[68] ATLAS, M. Aaboud et al., Search for a new heavy gauge boson resonance decaying into a lepton and missing transverse momentum in 36 fb$^{-1}$ of pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS experiment, Eur. Phys. J. C 78, 401 (2018), arXiv:1706.04786.

[69] J. I. Loukas Gouskos, Allan Sung, Top squark searches at 100 TeV, https://indico.cern.ch/event/704428/contributions/2957539/attachments/1627650/2592608/fcc-hh-susystop-20180315-1g.pdf.

[70] T. Aoyama et al., The anomalous magnetic moment of the muon in the Standard Model, Phys. Rept. 887, 1 (2020), arXiv:2006.04822.

[71] Muon g-2, G. Bennett et al., Final Report of the Muon E821 Anomalous Magnetic Moment Measurement at BNL, Phys. Rev. D 73, 072003 (2006), arXiv:hep-ex/0602035.

[72] Muon g-2, B. Abi et al., Measurement of the Positive Muon Anomalous Magnetic Moment to 0.46 ppm, Phys. Rev. Lett. 126, 141801 (2021), arXiv:2104.03281.

[73] S. Borsanyi et al., Leading hadronic contribution to the muon 2 magnetic moment from lattice QCD, (2020), arXiv:2002.12347.

[74] W. Buchmüller and D. Wyler, Effective Lagrangian Analysis of New Interactions and Flavor Conservation, Nucl. Phys. B 268, 621 (1986).

[75] B. Grzadkowski, M. Iskrzynski, M. Misiak, and J. Rosiek, Dimension-Six Terms in the Standard Model Lagrangian, JHEP 10, 085 (2010), arXiv:1008.4884.

[76] E. E. Jenkins, A. V. Manohar, and M. Trott, Renormalization Group Evolution of the Standard Model Dimension Six Operators II: Yukawa Dependence, JHEP 01, 035 (2014), arXiv:1310.4838.

[77] R. Alonso, E. E. Jenkins, A. V. Manohar, and M. Trott, Renormalization Group Evolution of the Standard Model Dimension Six Operators III: Gauge Coupling Dependence and Phenomenology, JHEP 04, 159 (2014), arXiv:1312.2014.

[78] I. Brivio, Y. Jiang, and M. Trott, The SMEFTsim package, theory and tools, JHEP 12, 070 (2017), arXiv:1709.06492.

[79] I. Brivio, SMEFTsim 3.0 – a practical guide, (2020), arXiv:2012.11343.