Research Article
SppC Based Energy Frontier Lepton-Proton Colliders: Luminosity and Physics

Ali Can Canbay,1,2 Umit Kaya,1,2 Bora Ketenoglu,3 Bilgehan Baris Oner,1 and Saleh Sultansoy1,4

1TOBB University of Economics and Technology, Ankara, Turkey
2Department of Physics, Ankara University, Ankara, Turkey
3Department of Engineering Physics, Ankara University, Ankara, Turkey
4ANAS Institute of Physics, Baku, Azerbaijan

Correspondence should be addressed to Umit Kaya; umit.kaya@cern.ch

Received 14 April 2017; Accepted 15 June 2017; Published 1 August 2017

1. Introduction

It is known that lepton-hadron scattering had played crucial role in our understanding of deep inside of matter. For example, electron scattering on atomic nuclei reveals structure of nucleons in Hofstadter experiment [1]. Moreover, quark parton model was originated from lepton-hadron collisions at SLAC [2]. Extending the kinematic region by two orders of magnitude both in high \( Q^2 \) and small \( x \), HERA (the first and still unique lepton-hadron collider) with \( \sqrt{s} = 0.32 \) TeV has shown its superiority compared to the fixed target experiments and provided parton distribution functions (PDF) for LHC and Tevatron experiments (for review of HERA results see [3, 4]). Unfortunately, the region of sufficiently small \( x (\lesssim 10^{-5}) \) and high \( Q^2 (\gtrsim 10 \text{ GeV}^2) \) simultaneously, where saturation of parton densities should manifest itself, has not been reached yet. Hopefully, LHeC [5] with \( \sqrt{s} = 1.3 \) TeV will give opportunity to touch this region.

Construction of linear \( e^+ e^- \) colliders (or dedicated linac) and muon colliders (or dedicated muon ring) tangential to the future circular pp colliders, FCC or SppC, as shown in Figure 1, will give opportunity to use highest energy proton beams in order to obtain highest center of mass energy in lepton-hadron and photon-hadron collisions (for earlier studies on linac-ring type \( e\nu, \gamma\nu, eA, \) and \( \gamma A \) colliders, see reviews [6, 7] and papers [8–14]).

FCC is the future 100 TeV center of mass energy pp collider studied at CERN and supported by European Union within the Horizon 2020 Framework Programme for Research and Innovation [15]. SppC is the Chinese analog of the FCC. Main parameters of the SppC proton beam [16, 17] are presented in Table 1. The FCC based \( e\nu \) and \( \nu\nu \) colliders have been considered recently (see [18] and references therein).

In this paper we consider SppC based \( e\nu \) and \( \nu\nu \) colliders. In Section 2, main parameters of proposed colliders, namely, center of mass energy and luminosity, are estimated taking into account beam-beam tune shift and disruption effects. Physics search potential of the SppC based \( lp \) colliders have been evaluated in Section 3, where small Björken \( x \) region
is considered as an example of the SM physics and resonant production of color octet leptons is considered as an example of the BSM physics. Our conclusions and recommendations are presented in Section 4.

### 2. Main Parameters of the SppC Based ep and μp Colliders

General expression for luminosity of SppC based lp colliders is given by (l denotes electron or muon)

$$ L_{lp} = \frac{N_l N_p}{4 \pi \max[\sigma_{x_l} \sigma_{x_p} \sigma_{y_l} \sigma_{y_p}]} \min[f_{x_p} f_{x_l}, f_{y_p} f_{y_l}], \quad (1) $$

where $N_l$ and $N_p$ are numbers of leptons and protons per bunch, respectively; $\sigma_{x_p}$ and $\sigma_{y_p}$ are the horizontal and vertical proton beam sizes at interaction point (IP); $f_{x_p}$ and $f_{y_p}$ are LC/$\mu$C and SppC bunch frequencies. $f_c$ is expressed by $f_c = N_b f_{rep}$, where $N_b$ denotes number of bunches and $f_{rep}$ means revolution frequency for SppC/$\mu$C and pulse frequency for LC. In order to determine collision frequency of lp collider, minimum value should be chosen among lepton and hadron bunch frequencies. Some of these parameters can be rearranged in order to maximize $L_{lp}$ but one should note that there are main limitations due to beam-beam effects that should be kept in mind. While beam-beam tune shift affects proton and muon beams, disruption has influence on electron beams.

Disruption parameter for electron beam is given by

$$ D_{x_e} = \frac{2 N_r r_p \sigma_{x_p}}{\gamma_e \sigma_{x_p} (\sigma_{x_p} + \sigma_{y_p})}, \quad (2) $$

$$ D_{y_e} = \frac{2 N_r r_p \sigma_{y_p}}{\gamma_e \sigma_{y_p} (\sigma_{y_p} + \sigma_{x_p})}, \quad (3) $$

where $r_e = 2.82 \times 10^{-15}$ m is classical radius for electron, $\gamma_e$ is the Lorentz factor of electron beam, and $\sigma_{x_p}$ and $\sigma_{y_p}$ are horizontal and vertical proton beam sizes at IP, respectively. $\sigma_{x_p}$ is bunch length of proton beam. Beam-beam parameter for proton beam is given by

$$ D_{x_p} = \frac{2 N_r r_p \sigma_{x_p}}{\gamma_p \sigma_{x_p} (\sigma_{x_p} + \sigma_{y_p})}, \quad (4) $$

$$ D_{y_p} = \frac{2 N_r r_p \sigma_{y_p}}{\gamma_p \sigma_{y_p} (\sigma_{y_p} + \sigma_{x_p})}, \quad (5) $$

where $r_p$ is classical radius for proton, $r_p = 1.54 \times 10^{-18}$ m, $\beta_p^* = \beta_p \gamma_p$ is beta function of proton beam at IP, and $\gamma_p$ is the Lorentz factor of proton beam. $\sigma_{x_p}$ and $\sigma_{y_p}$ are horizontal and vertical sizes of lepton beam at IP, respectively.

Beam-beam parameter for muon beam is given by

$$ D_{x_\mu} = \frac{N_r r_\mu \sigma_{x_\mu}}{2 \gamma_\mu \sigma_{x_\mu} (\sigma_{x_\mu} + \sigma_{y_\mu})}, \quad (6) $$

$$ D_{y_\mu} = \frac{N_r r_\mu \sigma_{y_\mu}}{2 \gamma_\mu \sigma_{y_\mu} (\sigma_{y_\mu} + \sigma_{x_\mu})}, \quad (7) $$

where $r_\mu = 1.37 \times 10^{-17}$ m is classical muon radius, $\beta_\mu^* = \beta_\mu \gamma_\mu$ is beta function of muon beam at IP, and $\gamma_\mu$ is the Lorentz factor of muon beam. $\sigma_{x_\mu}$ and $\sigma_{y_\mu}$ are horizontal and vertical sizes of proton beam at IP, respectively.

#### 2.1. ep Option

Preliminary study of CepC-SppC based e-p collider with $\sqrt{s} = 4.1$ TeV and $L_{ep} = 10^{33}$ cm$^{-2}$ s$^{-1}$ has been performed in [19]. In this subsection, we consider ILC (International Linear Collider) [20] and PWFA-LC (Plasma Wake Field Accelerator-Linear Collider) [21] as a source of electron/positron beam for SppC based energy frontier ep colliders. Main parameters of ILC and PWFA-LC electron beams are given Table 2.

It is seen that bunch spacings of ILC and PWFA-LC are much greater than SppC bunch spacing. On the other hand, transverse size of proton beam is much greater than transverse sizes of electron beam. Therefore, (1) for luminosity turns into

$$ L_{ep} = \frac{N_l N_p}{4 \pi \sigma_p^2 f_c}. \quad (5) $$
Table 2: Main parameters of the ILC (second column) and PWFA-LC (third column) electron beams.

| Parameter                        | ILC    | PWFA-LC |
|----------------------------------|--------|---------|
| Beam energy (GeV)                | 500    | 500     |
| Peak luminosity (10^{34} cm^{-2} s^{-1}) | 4.90   | 6.27    |
| Particle per bunch (10^{10})     | 1.74   | 1.00    |
| Norm. horiz. emittance (nm)      | 10.0   | 10.0    |
| Norm. vert. emittance (nm)       | 30.0   | 35.0    |
| Horiz. $\beta^*$ amplitude at IP (mm) | 11.0   | 11.0    |
| Vert. $\beta^*$ amplitude at IP (mm) | 0.23   | 0.999   |
| Horiz. IP beam size (nm)         | 335    | 106     |
| Vert. IP beam size (nm)          | 2.70   | 59.8    |
| Bunches per beam                 | 2450   | 1       |
| Repetition rate (Hz)             | 4.00   | 5000    |
| Beam power at IP (MW)            | 27.2   | 40      |
| Bunch spacing (ns)               | 366    | 20 $\times$ 10^4 |
| Bunch length (mm)                | 0.225  | 0.02    |

Table 3: Main parameters of LC@SppC based $ep$ colliders.

| $E_\mu$, TeV | $E_p$, TeV | $\sqrt{s}$, TeV | $L_{\mu p}$, cm^{-2} s^{-1} | $D_\mu$ | $\xi_\mu$, 10^{-1} |
|--------------|------------|-----------------|-----------------------------|--------|-------------------|
| 0.5          | 35.6       | 8.44            | 3.35 (6.64) $\times$ 10^{30} | 0.537  | 0.5               |
| 0.5          | 68         | 11.66           | 2.69 (5.33) $\times$ 10^{31} | 0.902  | 0.7               |
| 5            | 35.6       | 26.68           | 0.98 (1.94) $\times$ 10^{30} | 0.054  | 0.3               |
| 5            | 68         | 36.88           | 0.78 (1.56) $\times$ 10^{31} | 0.090  | 0.4               |

For transversely matched electron and proton beams at IP, equations for electron beam disruption and proton beam tune shift become

$$D_\mu = \frac{N_p r_p^2 \sigma_p^2}{\gamma_p \sigma_p^2},$$
$$\xi_\mu = \frac{N_p r_p^2 \beta_p^*}{4\pi \gamma_p \sigma_p^2} = \frac{N_p r_p}{4\pi \epsilon_p},$$ (6)

where $\epsilon_p$ is normalized transverse emittance of proton beam.

Using nominal parameters of ILC, PWFA-LC, and SppC, we obtain values of $L_{\mu p}$, $D_\mu$, and $\xi_\mu$ parameters for LC@SppC based $ep$ colliders, which are given in Table 3. The values for luminosity given in parentheses represent results of beam-beam simulations by ALOHEP software [22], which is being developed for linac-ring type $ep$ colliders.

In order to increase luminosity of $ep$ collisions LHeC-like upgrade of the SppC proton beam parameters has been used. Namely, $\beta$ function of proton beam at IP is arranged to be 7.5/2.4 times lower (0.1 m instead of 0.75/0.24 m) which corresponds to LHeC [5] and THERA [23] designs. This leads to increase of luminosity and $D_\mu$ by factor 7.5 and 2.4 for SppC with 35.6 TeV and 68 TeV proton beam, respectively. Results are shown in Table 4.

In principle “dynamic focusing scheme” [24], which was proposed for THERA, could provide additional factor of 3-4. Therefore, luminosity values exceeding 10^{32} cm^{-2} s^{-1} can be achieved for all options. Concerning ILC@SppC based $ep$ colliders, a new scheme for energy recovery proposed for higher-energy LHeC (see Section 7.1.5 in [5]) may give an opportunity to increase luminosity by an additional order, resulting in $L_{\mu p}$ exceeding 10^{33} cm^{-2} s^{-1}. Unfortunately, this scheme cannot be applied at PWFA-LC@SppC.

2.2. $\mu p$ Option. Muon-proton colliders were proposed almost two decades ago: construction of additional proton ring in $\sqrt{s} = 4$ TeV muon collider tunnel was suggested in [25], construction of additional 200 GeV energy muon ring in the Tevatron tunnel was suggested in [26], and ultimate $\mu p$ collider with 50 TeV proton ring in $\sqrt{s} = 100$ TeV muon collider tunnel was suggested in [27]. Here, we consider construction of TeV energy muon colliders ($\mu C$) [28] tangential to the SppC. Parameters of $\mu C$ are given in Table 5.

Keeping in mind that both SppC and $\mu C$ have round beams, luminosity equation (1) turns to

$$L_{\mu p} = f_{\mu p} \frac{N_p^2}{4\pi \sigma_p^2},$$
$$L_{\mu p} = f_{\mu p} \frac{N_\mu^2}{4\pi \sigma_\mu^2},$$ (7)

for SppC-$pp$ and $\mu C$, respectively. Concerning muon-proton collisions one should use larger transverse beam sizes and smaller collision frequency values. Keeping in mind that $f_{\mu p}$ is smaller than $f_{\mu p}$ by more than two orders, the following correlation between $\mu p$ and $\mu C$ luminosities takes place:

$$L_{\mu p} = \left( \frac{N_p}{N_\mu} \right) \left( \frac{\sigma_\mu}{\max(\sigma_p, \sigma_\mu)} \right)^2 L_{\mu p}.$$ (8)

Using nominal parameters of $\mu C$ colliders given in Table 5, parameters of the SppC based $ep$ colliders are calculated according to (8) and presented in Table 6.
Table 6: Main parameters of SppC based $\mu p$ colliders.

| $E_\mu$, TeV | $E_p$, TeV | $\sqrt{s}$, TeV | $L_{\mu p}$, cm$^2$/s$^{-1}$ | $\xi_\mu$ | $\xi_p$ |
|-------------|-------------|-------------|-----------------|--------|--------|
| 0.75        | 35.6        | 10.33       | $5.5 \times 10^{32}$ | $8.7 \times 10^{-3}$ | $6.0 \times 10^{-2}$ |
| 0.75        | 68          | 14.28       | $12.5 \times 10^{32}$ | $8.7 \times 10^{-3}$ | $8.0 \times 10^{-2}$ |
| 1.5         | 35.6        | 14.61       | $4.9 \times 10^{32}$ | $8.7 \times 10^{-3}$ | $6.0 \times 10^{-2}$ |
| 1.5         | 68          | 20.2        | $42.8 \times 10^{32}$ | $8.7 \times 10^{-3}$ | $8.0 \times 10^{-2}$ |

Table 7: Main parameters of the ultimate SppC muon beam.

| Beam energy (TeV) | 50 |
|------------------|----|
| Circumference (km) | 100 |
| Average luminosity (10$^{34}$ cm$^{-2}$/s$^{-1}$) | 100 |
| Particle per bunch (10$^{12}$) | 0.80 |
| Norm. trans. emitt. (mm-mrad) | 8.7 |
| $\beta^*$ amplitude function at IP (mm) | 2.5 |
| IP beam size ($\mu$m) | 0.21 |
| Bunches per beam | 1 |
| Repetition rate (Hz) | 7.9 |
| Bunch spacing (μs) | 333 |
| Bunch length (mm) | 2.5 |

Table 8: Main parameters of the ultimate SppC based $\mu p$ collider.

| $E_\mu$, TeV | $E_p$, TeV | $\sqrt{s}$, TeV | $L_{\mu p}$, cm$^2$/s$^{-1}$ | $\xi_\mu$ | $\xi_p$ |
|-------------|-------------|-------------|-----------------|--------|--------|
| 50          | 68          | 116.6       | $1.2 \times 10^{34}$ | $2.6 \times 10^{-2}$ | $3.5 \times 10^{-2}$ |

Table 9: Attainable Björken $x$ values at $Q^2 = 10$ GeV$^2$.

| $E_\mu$ (TeV) | $E_p$ (TeV) | $\sqrt{s}$, TeV | $L_{\mu p}$, cm$^2$/s$^{-1}$ | $\xi_\mu$ | $\xi_p$ |
|---------------|-------------|-------------|-----------------|--------|--------|
| 0.5           | 7 x 10$^{-8}$ | 5           | $2 \times 10^{-8}$ | $7 \times 10^{-10}$ |
| 1.5           | $7 \times 10^{-9}$ | 1           | $2 \times 10^{-8}$ | $7 \times 10^{-10}$ |

3. Physics

In order to evaluate physics search potential of the SppC based $lp$ colliders we consider two phenomena; namely, small Björken $x$ region is considered as an example of the SM physics and resonant production of color octet electron and muon is considered as an example of the BSM physics.

3.1. Small Björken $x$. As mentioned above, investigation of extremely small $x$ region ($x < 10^{-5}$) at sufficiently large $Q^2 (>10$ GeV$^2$), where saturation of parton density should manifest itself, is crucial for understanding of QCD basics. Smallest achievable $x$ at $lp$ colliders is given by $Q^2/S$. For LHeC with $\sqrt{s} = 1.3$ TeV minimal achievable value is $x = 6 \times 10^{-6}$. In Table 9, we present smallest $x$ values for different SppC based lepton-proton colliders ($E_p$ is chosen as 68 TeV). It is seen that proposed machines has great potential for enlightenment of QCD basics.

3.2. Color Octet Leptons. Color octet leptons ($l_8$) are predicted in preonic models with colored preons [31]. There are various phenomenological studies on $l_8$ at TeV energy scale colliders [32–39]. Resonant production of color octet electron ($e_8$) and muon ($\mu_8$) at the FCC based $lp$ colliders (http://collider-reach.web.cern.ch/collider-reach) have been considered in [40] and [41], respectively. Performing similar analyses for SppC based $lp$ colliders we obtain mass discovery limits for $e_8$ and $\mu_8$ in $\Lambda = M_{l_8}$ case (where $\Lambda$ is compositeness scale) which are presented in Figures 2 and 3, respectively. Discovery mass limit value for LHC and SppC is obtained by rescaling ATLAS/CMS second-generation LQ results [42, 43] using the method developed by Salam and Weiler [44]. For lepton colliders, it is obvious that discovery mass limit for pair production of $l_8$ is approximately half of CM energies. It is seen that $l_8$ search potential of SppC based $lp$ colliders overwhelmingly exceeds that of LHC and lepton colliders. Moreover $lp$ colliders will give an opportunity to determine compositeness scale (for details see [40, 41]).

It should be noted that FCC/SppC based $lp$ colliders have great potential for search of a lot of BSM phenomena, such as excited leptons (see [45] for $\mu^*$), contact interactions, and R-parity violating SUSY.

4. Conclusion

It is shown that construction of linear $e^+e^-$ colliders (or dedicated linac) and muon colliders (or dedicated muon ring)
tangential to the SppC will give opportunity to handle lepton-proton collisions with multi-TeV CM energies and sufficiently high luminosities. Concerning SM physics, these machines will certainly shed light on QCD basics. BSM search potential of $pp$ colliders essentially exceeds that of corresponding lepton colliders. Also these types of colliders exceed the search potential of the SppC itself for a lot of BSM phenomena.

Acceleration of ion beams at the SppC will give opportunity to provide multi-TeV center of mass energy in $eA$ and $\mu A$ collisions. In addition, electron beam can be converted to high energy photon beam using Compton backscattering of laser photons which will give opportunity to construct LC@SppC based $pp$ and $\gamma A$ colliders. Studies on these topics are ongoing.

In conclusion, systematic study of accelerator, detector, and physics search potential issues of the SppC based $ep$, $eA$, $\gamma p$, $\gamma A$, and $\mu A$ colliders are essential to foresee the future of particle physics. Certainly, realization of these machines depends on the future results from the LHC as well as FCC and/or SppC.

**Conflicts of Interest**

The authors declare that they have no conflicts of interest.

**Acknowledgments**

This study is supported by TUBITAK under Grant no. 114F337.

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**Figure 2:** Discovery mass limits for color octet electron at different $pp, e^+e^-$, and $ep$ colliders.

**Figure 3:** Discovery mass limits for color octet muon at different $pp, \mu^+\mu^-$, and $\mu p$ colliders.
