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Research Article

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

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Main parameters of Super proton-proton Collider (SppC) based lepton-proton colliders are estimated. For electron beam parameters, highest energy International Linear Collider (ILC) and Plasma Wake Field Accelerator-Linear Collider (PWFA-LC) options are taken into account. For muon beams, 1.5 TeV and 3 TeV center of mass energy muon collider parameters are used. In addition, ultimate μp collider which assumes construction of additional 50 TeV muon ring in the SppC tunnel is considered. It is shown that luminosity values exceeding 10^{32} cm^{-2} s^{-1} can be achieved with moderate upgrade of the SppC proton beam parameters. Physics search potential of proposed lepton-proton colliders is illustrated by considering small Björken x region as an example of SM physics and resonant production of color octet leptons as an example of BSM physics.

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 ($<10^{-5}$) and high Q^2 (≥ 10 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 ep, γp, eA, and γA 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 ep and μp colliders have been considered recently (see [18] and references therein).

In this paper we consider SppC based ep and μp 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

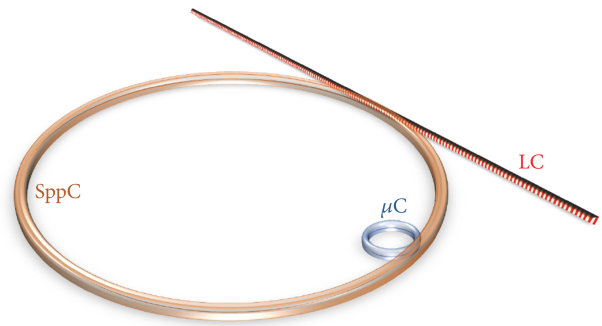

Figure 1: Possible configuration for SppC, linear collider (LC), and muon collider (μC).

Table 1: Main parameters of proton beams in SppC.

Beam energy (TeV)	35.6	68.0
Circumference (km)	54.7	100.0
Peak luminosity (10^{34} cm^{-2} s^{-1})	11	102
Particle per bunch (10^{10})	20	20
Norm. transverse emittance (μm)	4.10	3.05
β^* amplitude function at IP (m)	0.75	0.24
IP beam size (μm)	9.0	3.04
Bunches per beam	5835	10667
Bunch spacing (ns)	25	25
Bunch length (mm)	75.5	15.8
Beam-beam parameter, ξ_{pp}	0.006	0.008

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)

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

where N_l and N_p are numbers of leptons and protons per bunch, respectively; σ_{x_p} (σ_{x_l}) and σ_{y_p} (σ_{y_l}) are the horizontal and vertical proton (lepton) beam sizes at interaction point (IP); f_{c_l} and f_{c_p} are LC/μC and SppC bunch frequencies. f_c is expressed by $f_c = N_b f_{\text{rep}}$, where N_b denotes number of bunches and f_{rep} means revolution frequency for SppC/μC 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

$$D_{x_e} = \frac{2N_p r_e \sigma_{z_p}}{\gamma_e \sigma_{x_p}\left(\sigma_{x_p} + \sigma_{y_p}\right)}, \qquad D_{y_e} = \frac{2N_p r_e \sigma_{z_p}}{\gamma_e \sigma_{y_p}\left(\sigma_{y_p} + \sigma_{x_p}\right)}, \quad (2)$$

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

$$\xi_{x_p} = \frac{N_l r_p \beta_p^*}{2\pi\gamma_p \sigma_{x_l}\left(\sigma_{x_l} + \sigma_{y_l}\right)}, \qquad \xi_{y_p} = \frac{N_l r_p \beta_p^*}{2\pi\gamma_p \sigma_{y_l}\left(\sigma_{y_l} + \sigma_{x_l}\right)}, \quad (3)$$

where r_p is classical radius for proton, $r_p = 1.54 \times 10^{-18}$ m, β_p^* is beta function of proton beam at IP, and γ_p is the Lorentz factor of proton beam. σ_{x_l} and σ_{y_l} are horizontal and vertical sizes of lepton beam at IP, respectively.

Beam-beam parameter for muon beam is given by

$$\xi_{x_\mu} = \frac{N_p r_\mu \beta_\mu^*}{2\pi\gamma_\mu \sigma_{x_p}\left(\sigma_{x_p} + \sigma_{y_p}\right)}, \qquad \xi_{y_\mu} = \frac{N_p r_\mu \beta_\mu^*}{2\pi\gamma_\mu \sigma_{y_p}\left(\sigma_{y_p} + \sigma_{x_p}\right)}, \quad (4)$$

where $r_\mu = 1.37 \times 10^{-17}$ m is classical muon radius, β_μ^* is beta function of muon beam at IP, and γ_μ is the Lorentz factor of muon beam. σ_{x_p} and σ_{y_p} 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

$$L_{ep} = \frac{N_e N_p}{4\pi\sigma_p^2} f_{c_e}. \quad (5)$$

Table 2: Main parameters of the ILC (second column) and PWFA-LC (third column) electron beams.

Beam energy (GeV)	500	5000
Peak luminosity (10^{34} cm^{-2} s^{-1})	4.90	6.27
Particle per bunch (10^{10})	1.74	1.00
Norm. horiz. emittance (μm)	10.0	10.0
Norm. vert. emittance (nm)	30.0	35.0
Horiz. β^* amplitude function at IP (mm)	11.0	11.0
Vert. β^* amplitude function at IP (mm)	0.23	0.099
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	20×10^4
Bunch length (mm)	0.225	0.02

Table 3: Main parameters of LC⊗SppC based *ep* colliders.

E_e, TeV	E_p, TeV	$\sqrt{s}$, TeV	L_{ep}, cm^{-2} s^{-1}	D_e	ξ_p, 10^{-3}
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

$$D_e = \frac{N_p r_e \sigma_{z_p}}{\gamma_e \sigma_p^2}, \quad \xi_p = \frac{N_e r_p \beta_p^*}{4\pi\gamma_p \sigma_p^2} = \frac{N_e r_p}{4\pi\epsilon_{np}}, \tag{6}$$

where ϵ_{np} is normalized transverse emittance of proton beam.

Using nominal parameters of ILC, PWFA-LC, and SppC, we obtain values of L_{ep}, D_e, and ξ_p 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, β 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_e 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_{ep} exceeding 10^{33} cm^{-2} s^{-1}. Unfortunately, this scheme can not be applied at PWFA-LC⊗SppC.

Table 4: Main parameters of LC⊗SppC based *ep* colliders with upgraded β^*.

E_e, TeV	E_p, TeV	$\sqrt{s}$, TeV	L_{ep}, cm^{-2} s^{-1}	D_e	ξ_p, 10^{-3}
0.5	35.6	8.44	$2.51\ (4.41) \times 10^{31}$	4.03	0.5
0.5	68	11.66	$6.45\ (10.8) \times 10^{31}$	2.16	0.7
5	35.6	26.68	$7.37\ (13.3) \times 10^{30}$	0.403	0.3
5	68	36.88	$1.89\ (3.75) \times 10^{31}$	0.216	0.4

Table 5: Main parameters of the muon beams.

Beam energy (GeV)	750	1500
Circumference (km)	2.5	4.5
Average luminosity (10^{34} cm^{-2} s^{-1})	1.25	4.4
Particle per bunch (10^{12})	2	2
Norm. trans. emitt. (mm-rad)	0.025	0.025
β^* amplitude function at IP (cm)	1 (0.5–2)	0.5 (0.3–3)
IP beam size (μm)	6	3
Bunches per beam	1	1
Repetition rate (Hz)	15	12
Bunch spacing (ns)	8300	15000
Bunch length (cm)	1	0.5

2.2. μp 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 considered in [26], and ultimate μp 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 (μC) [28] tangential to the SppC. Parameters of μC are given in Table 5.

Keeping in mind that both SppC and μC have round beams, luminosity equation (1) turns to

$$L_{pp} = f_{pp} \frac{N_p^2}{4\pi\sigma_p^2}, \quad L_{\mu\mu} = f_{\mu\mu} \frac{N_\mu^2}{4\pi\sigma_\mu^2}, \tag{7}$$

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

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

Using nominal parameters of $\mu\mu$ colliders given in Table 5, parameters of the SppC based μp colliders are calculated according to (8) and presented in Table 6. Concerning

Table 6: Main parameters of SppC based μp colliders.

E_μ, TeV	E_p, TeV	$\sqrt{S}$, TeV	$L_{\mu p}$, cm^{-2} s^{-1}	ξ_μ	ξ_p
0.75	35.6	10.33	5.5×10^{32}	8.7×10^{-3}	6.0×10^{-2}
0.75	68	14.28	12.5×10^{32}	8.7×10^{-3}	8.0×10^{-2}
1.5	35.6	14.61	4.9×10^{32}	8.7×10^{-3}	6.0×10^{-2}
1.5	68	20.2	42.8×10^{32}	8.7×10^{-3}	8.0×10^{-2}

Table 7: Main parameters of the ultimate 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
β^* amplitude function at IP (mm)	2.5
IP beam size (μm)	0.21
Bunches per beam	1
Repetition rate (Hz)	7.9
Bunch spacing (μs)	333
Bunch length (mm)	2.5

beam tune shifts, for round and matched beams, (3) and (4) turn to

$$\xi_p = \frac{N_\mu r_p \beta_p^*}{4\pi\gamma_p\sigma_\mu^2} = \frac{N_\mu r_p}{4\pi\epsilon_{np}}, \quad (9)$$

$$\xi_\mu = \frac{N_p r_\mu \beta_\mu^*}{4\pi\gamma_\mu\sigma_p^2} = \frac{N_p r_\mu}{4\pi\epsilon_{n\mu}}, \quad (10)$$

respectively.

As one can see from Table 6, where nominal parameters of SppC proton beam are used, ξ_p is unacceptably high and should be decreased to 0.02 which seems acceptable for μp colliders [26]. According to (9), ξ_p can be decreased, for example, by decrement of N_μ which leads to corresponding reduction of luminosity (three times and four times for μp 35.6 TeV and 68 TeV, resp.). Alternatively, crab crossing [29] can be used for decreasing of ξ_p without change of the luminosity.

2.3. Ultimate μp Option. This option can be realized if an additional muon ring is constructed in the SppC tunnel. In order to estimate CM energy and luminosity of μp collisions we use muon beam parameters from [30], where 100 TeV center of mass energy muon collider with 100 km ring circumference has been proposed. These parameters are presented in Table 7.

CM energy, luminosity, and tune shifts for ultimate μp collider are given in Table 8. It is seen that the ξ_p value is approximately two times higher than the limiting value 0.02 [26]. This problem can be solved by reducing muon bunch population, which leads to decrease of luminosity by factor of 1.75. Alternatively, crab crossing can be used without change of the luminosity.

Table 8: Main parameters of the ultimate SppC based μp collider.

E_μ, TeV	E_p, TeV	$\sqrt{S}$, TeV	$L_{\mu p}$, cm^{-2} s^{-1}	ξ_μ	ξ_p
50	68	116.6	1.2×10^{33}	2.6×10^{-2}	3.5×10^{-2}

Table 9: Attainable Björken x values at $Q^2 = 10\,\text{GeV}^2$.

E_l (TeV)	0.5	5	1.5	50
x	7×10^{-8}	7×10^{-9}	2×10^{-8}	7×10^{-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 enlightening 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 (μ_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 μ_8 in $\Lambda = M_{l_8}$ case (where Λ 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 μ^*), 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)

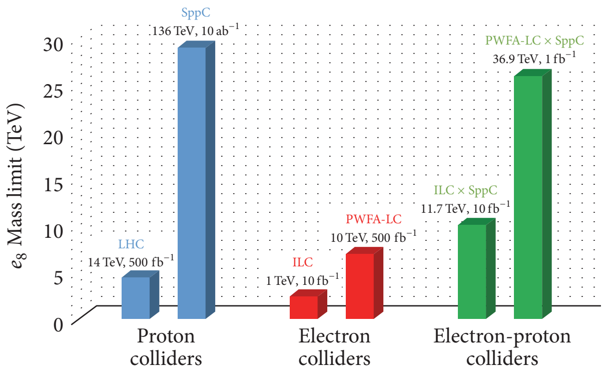

Figure 2: Discovery mass limits for color octet electron at different pp, e^+e^-, and ep colliders.

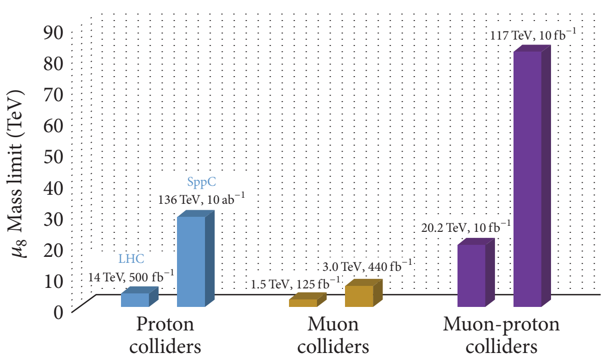

Figure 3: Discovery mass limits for color octet muon at different pp, $\mu^+\mu^-$, and μp colliders.

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 lp 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 μA 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 γp and γA 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, γp, γA, μp, and μA 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.

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